# Electroweak-Scale Strong Dynamics

## Lecture #2

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Aug. 31 - Sept. 4, 2009

# Outline:

- **Lecture #1: Dynamical Electroweak Symmetry Breaking (EWSB)**

## Part 1:

-> pros and cons of the SM Higgs, why alternatives may be good
-> Dynamical EWSB (Technicolor) as an alternative,
-> E x t e n d e d Technicolor: fermion mass generation
-> problems with 'old' Technicolor

## Part 2:

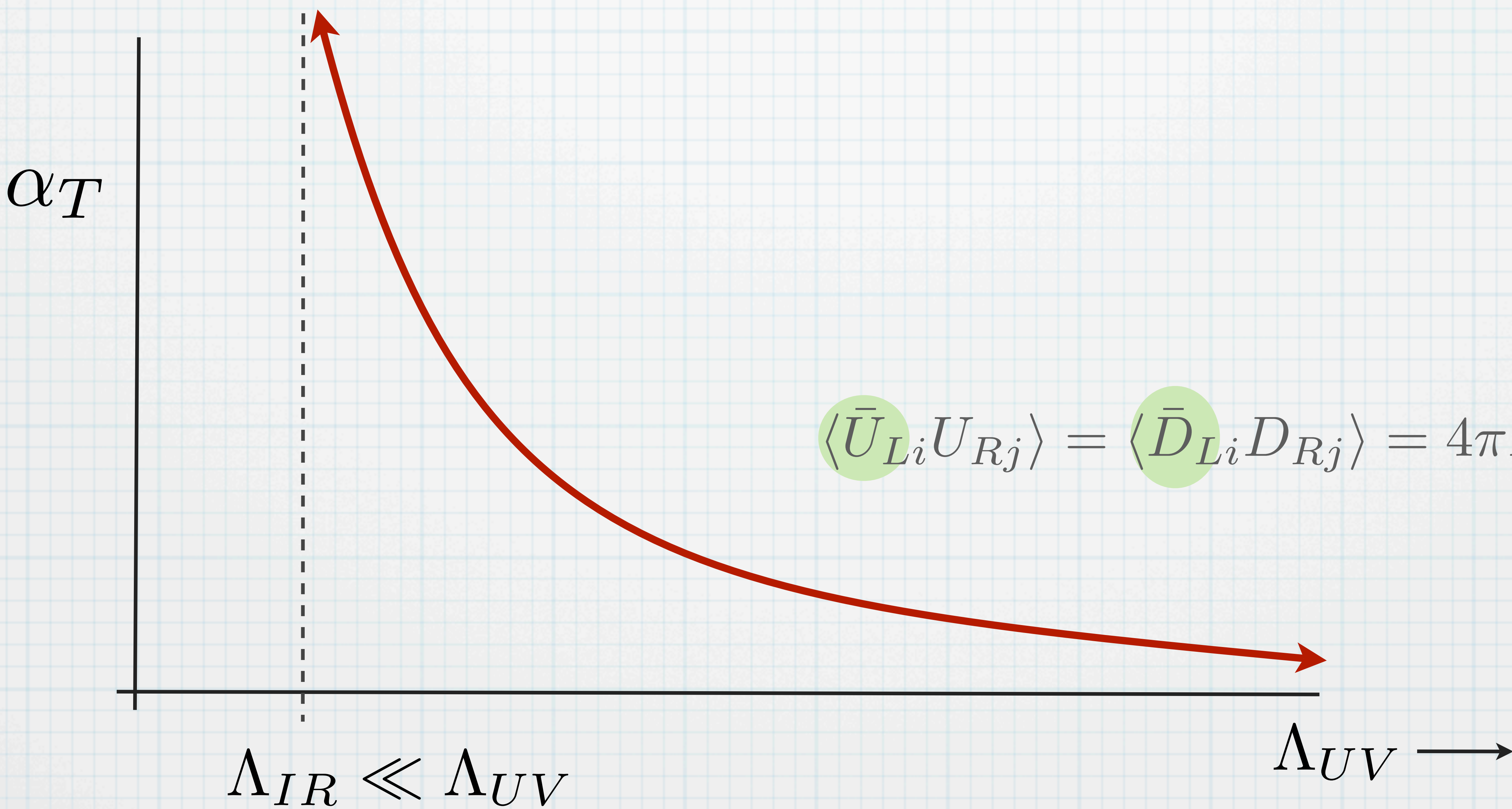
-> Peculiarities of QCD and the phases of gauge theory
-> Walking Technicolor (WTC) motivation and implementation,
-> how walking saves the day & where it fails,
-> walking studies on the lattice

- **Lecture #2: Related topics**

-> LHC phenomenology of 'modern' technicolor
-> Extra-Dimensional models of Technicolor: Higgsless models
-> Other Tev-scale strong dynamics: Composite Higgs
-> Technicolor and Dark Matter

# Dynamical EWSB Recap:

**Electroweak Symmetry breaking by new strong dynamics (Technicolor) is a compelling solution to the hierarchy problem**

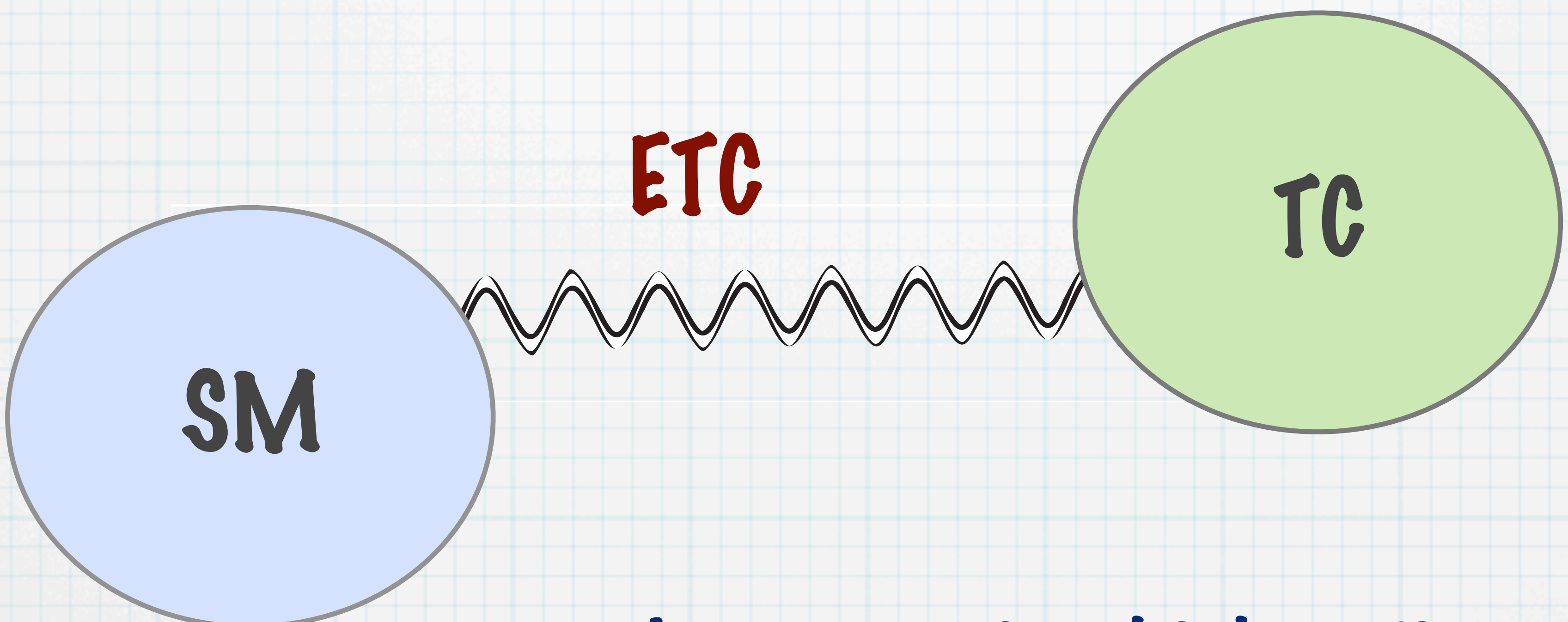



$$\langle \bar{U}_{Li} U_{Rj} \rangle = \langle \bar{D}_{Li} D_{Rj} \rangle = 4\pi F_T^3 \delta_{ij} \neq 0$$

**... but it necessarily involves strong dynamics**

# Dynamical EWSB Recap:

**Technicolor alone could not generate masses for the SM fermions. To do this we needed Extended Technicolor**




**at low energies, higher dimension operators**

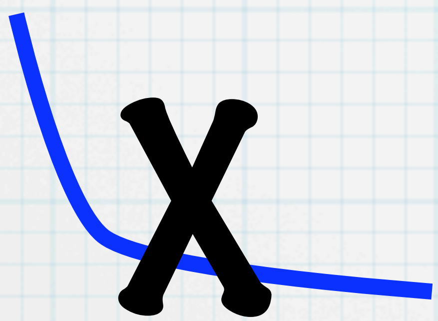
$$\alpha_{ab}\frac{g^2_{ETC}(\bar{T}\gamma_\mu t^a T)(\bar{T}\gamma^\mu t^b T)}{M^2_{ETC}} + \boxed{\beta_{ab}\frac{g^2_{ETC}(\bar{T}\gamma_\mu t^a q)(\bar{q}\gamma^\mu t^b T)}{M^2_{ETC}}} + \gamma_{ab}\frac{g^2_{ETC}(\bar{q}\gamma_\mu t^a q)(\bar{q}'\gamma^\mu t^b q')}{M^2_{ETC}}$$

$$m\,\bar{q}q$$

# Dynamical EWSB Recap:

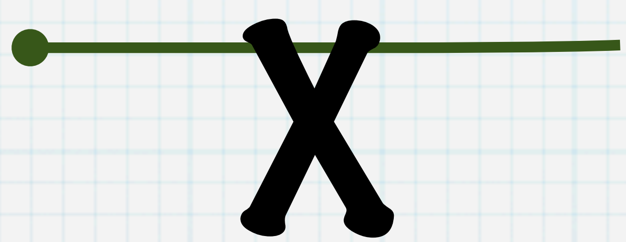
AND to avoid conflict with experiment, the new strong dynamics cannot simply be a copy of QCD. The most studied deviation from QCD-like behavior is "walking technicolor"

running coupling



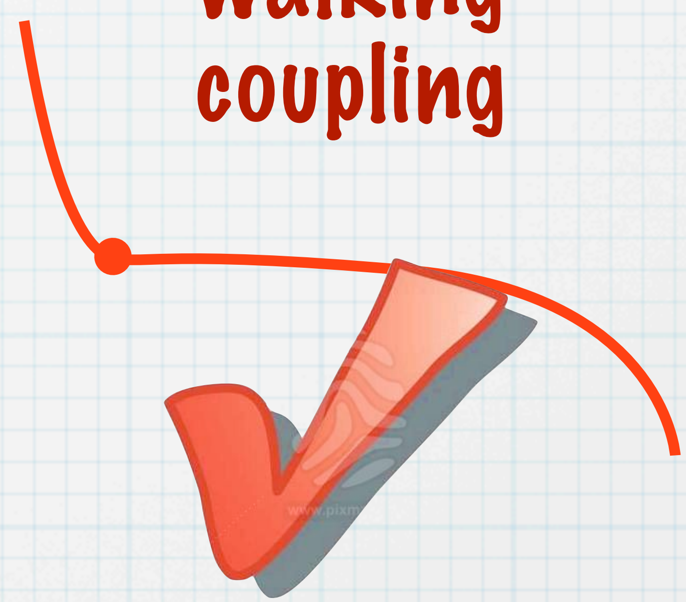
too QCD-like

conformal coupling



no confinement, $\chi SB$

walking coupling



**What will we see at the LHC if walking technicolor lurks at the EW scale?**

# Walking Technicolor Phenomenology

- walking technicolor requires a lot of techni-matter:

$$b_0 = \left(\frac{11}{3} N_C - \frac{4}{3} \sum_{F,r} C(r)\right)$$ needs to be small

- all EW-charged matter contributes to EW scale: $v^2 = \sum_i F_{Ti}^2$

$i \in \text{all } SU(2)_w$ techni-doublets

lots of matter --> generically low TC scale → techni-resonances must be light!

$N_D$ doublets: $v^2 = N_D F_T^2$

multiple reps. : $v^2 = F_{T1}^2 + F_{T2}^2 + \cdots$

new states must communicate with SM EW gauge bosons (at least), so all states have open decay channels to SM matter → no BSM missing energy!

# Walking TC: LHC implications

**a general scan over all possible resonances, their masses, their interactions would be great! but totally impractical**

... $M^{\pm}_{a_T}$ $M^{\pm}_{\rho_T}$ $g_{a_T W^+ \gamma}$ $\#\pi_T$ $g_{\rho_T W^+ W^-}$ ...

$\Gamma(a_T \to \pi_T \pi_T \pi_T)$ $M_{\pi_T}$ $g_{\pi^{\pm}_T \bar{f} f}$ $g_{\rho^{\pm}_T f f'}$ $g_{\rho_T \pi_T \pi_T}$

... $M_{\omega_T}$ $g_{\rho_T W \pi_T}$ $g_{\omega_T Z \gamma}$

$M_{\rho'_T}$ $g_{\rho_T \pi \gamma}$ $g_{\rho_T W^+ Z}$

$M_{a'_T}$ $g_{a_T W^+ Z}$ ...

$\Gamma(\rho_T \to \pi_T \pi_T)$ $g_{\omega_T f f}$ $g_{\pi_T \gamma\gamma}$ $g_{\omega_T \pi \gamma}$

techni-baryons? scalar bound states?

**WAY to many parameters, all of which have important phenomenological impact : <u>we need models</u>**

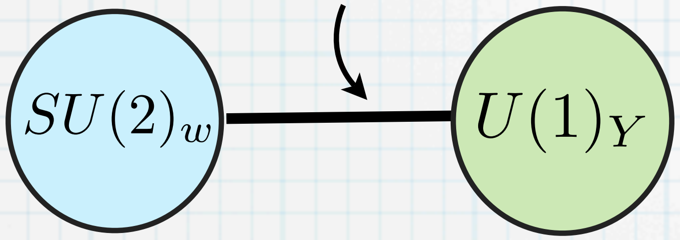
# Walking TC: LHC implications, #2

one popular tool is **Hidden Local Symmetries:**

(Kugo, Bando '80's
Callan, Coleman '70's)

start with **EW chiral lagrangian:**

$$\Sigma = e^{i\frac{\pi^a \tau_a}{v}}$$




$$\mathcal{L}_{\chi EW} = \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma^\dagger) + \cdots$$

$$D_\mu \Sigma = \partial_\mu \Sigma + ig\vec{W}_\mu \Sigma - ig'\Sigma B_\mu$$

$\pi_a$ are the eaten NGBs. Unitary gauge: $\Sigma = \mathbf{1}$

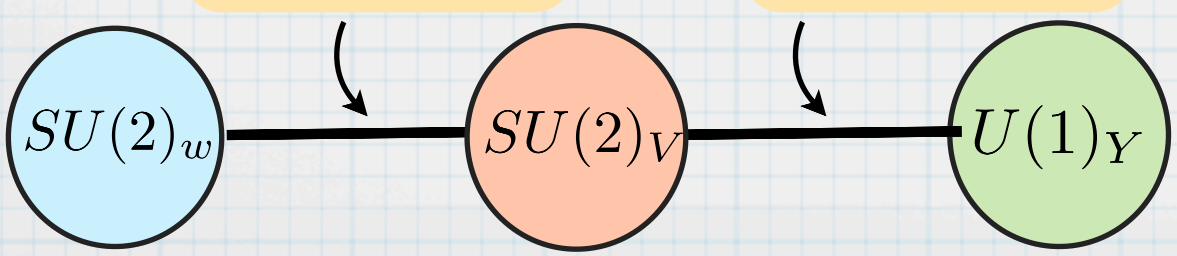
**minimal setup describes strong EWSB, but there are many more terms we can add, with unknown coefficients**

(Applequist, Bernard '79
Longhitano '79)

$$c_1\mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma^\dagger)^2 + c_2\mathrm{Tr}(D_\mu \Sigma D_\nu \Sigma^\dagger D^\mu \Sigma D^\nu \Sigma^\dagger) + c_3\mathrm{Tr}(W_{\mu\nu}\Sigma B^{\mu\nu}\Sigma^\dagger) + \cdots$$

one way to model the $c_i$ is to treat the new spin-1 resonances as new massive gauge bosons

$$\Sigma = e^{i\frac{\pi^a \tau_a}{F}} \qquad U = e^{i\frac{\eta^a \tau_a}{F}}$$




now two sets of NGB fields

three eaten by W,Z
three eaten to make massive $\rho^a_T$

# Walking TC: LHC implications, #3

$$\mathcal{L} \supset \frac{F^2}{4}\mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma^\dagger) + \frac{F^2}{4}\mathrm{Tr}(D_\mu U D^\mu U^\dagger) + a\frac{F^2}{4}\mathrm{Tr}((D_\mu \Sigma^\dagger)\Sigma(D_\mu U)U^\dagger)$$
$$+ \cdots - \frac{1}{4\tilde{g}^2}\mathrm{Tr}(V^a_\mu V^{a\mu\nu})$$

'hidden' gauge group coupling $\tilde{g} \gg g, g'$ . Kinetic term is simply added to $\mathcal{L}$, assumed to come from strong dynamics

Go to the unitary gauge: $U = \mathbf{1}, \Sigma = \mathbf{1}$

we can read off the mass matrices for the charged and neutral gauge bosons + resonances

$$M^2_\pm = \frac{\tilde{g}^2 f^2}{8}\begin{pmatrix} x^2(1+a) & -2xa \\ -2xa & 4a \end{pmatrix} \quad M^2_n = \frac{\tilde{g}^2 f^2}{8}\begin{pmatrix} x^2(1+a) & -2xa & -tx^2(1-a) \\ -2xa & 4a & -2txa \\ -tx^2(1-a) & -2txa & t^2x^2(1+a) \end{pmatrix}$$

$$M^2_W = \frac{g^2 f^2}{4} + \mathcal{O}(x^2), \; M^2_{W'} = \frac{\tilde{g}^2 f^2 a}{4} + \mathcal{O}(x^2)$$

$$x = \frac{g}{\tilde{g}}, t = \tan\theta_W$$

+ similar expressions for neutral

(see Chivukula et al, hep-ph/0607124)

# Walking TC: LHC implications, #3

$$\mathcal{L} \supset \frac{F^2}{4}\mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma^\dagger) + \frac{F^2}{4}\mathrm{Tr}(D_\mu U D^\mu U^\dagger) + a\frac{F^2}{4}\mathrm{Tr}((D_\mu \Sigma^\dagger)\Sigma(D_\mu U)U^\dagger)$$
$$+ \cdots - \frac{1}{4\tilde{g}^2}\mathrm{Tr}(V^a_\mu V^{a\mu\nu})$$

only 2 new parameters
$a, \tilde{g}$

'hidden' gauge group coupling $\tilde{g} \gg g, g'$. Kinetic term is simply added to $\mathcal{L}$, assumed to come from strong dynamics

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$$M^2_W = \frac{g^2 f^2}{4} + \mathcal{O}(x^2),\ M^2_{W'} = \frac{\tilde{g}^2 f^2 a}{4} + \mathcal{O}(x^2)$$

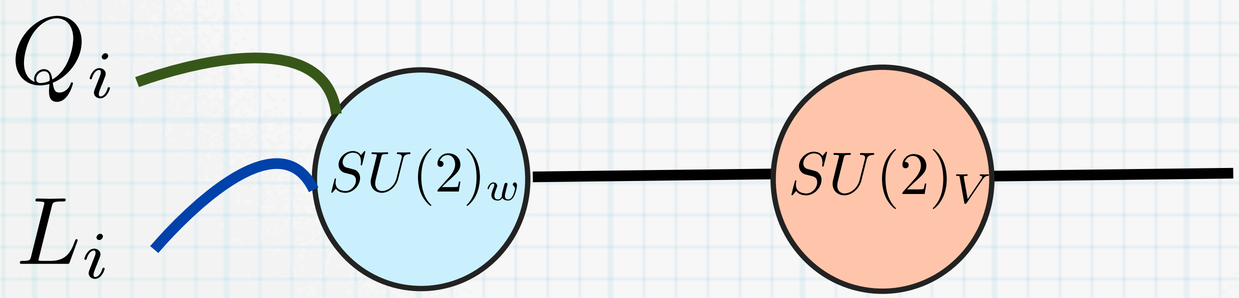
$$x = \frac{g}{\tilde{g}}, t = \tan\theta_W$$

+ similar expressions for neutral

(see Chivukula et al, hep-ph/0607124)

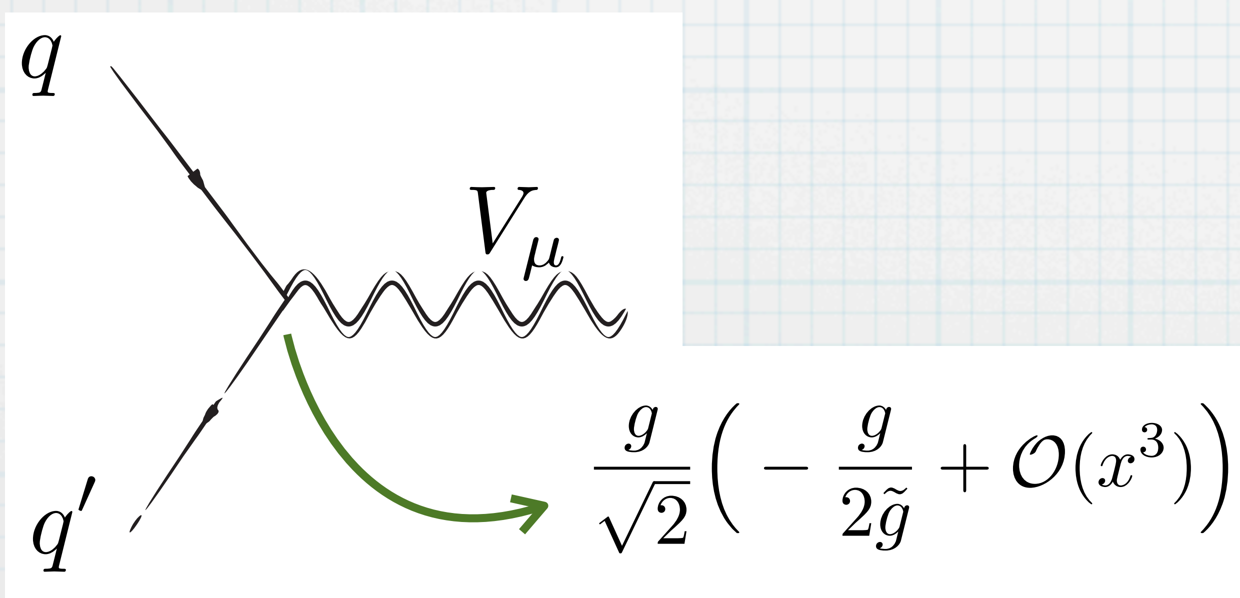
# Walking TC: LHC implications, #4

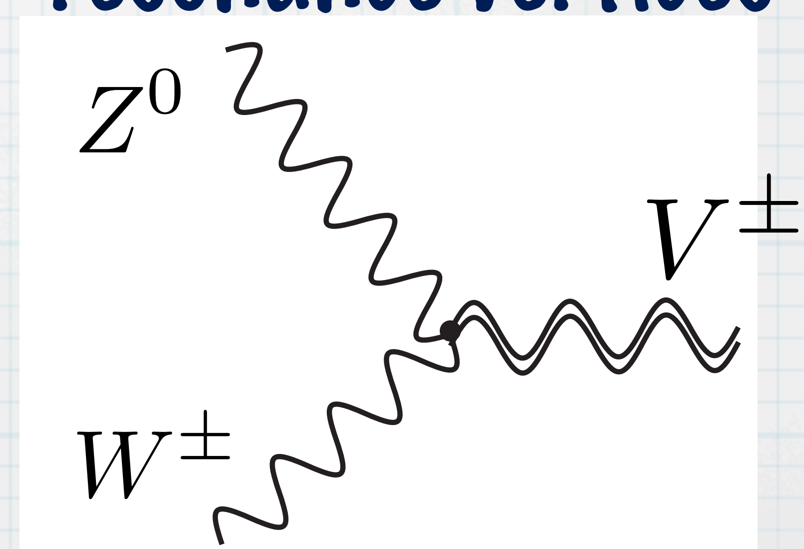
Add fermions with usual couplings only to the outer 'sites'




once the gauge boson mass matrix is diagonalized, the fermions acquire a coupling to the heavy eigenstate 'resonance'

we also get mixed gauge boson - resonance vertices




(N. Christensen)

# Walking TC: LHC implications, #5

integrating out the V, we get predictions for the $c_i$ plus we have modeled the masses and interactions of the $\rho_T^a$

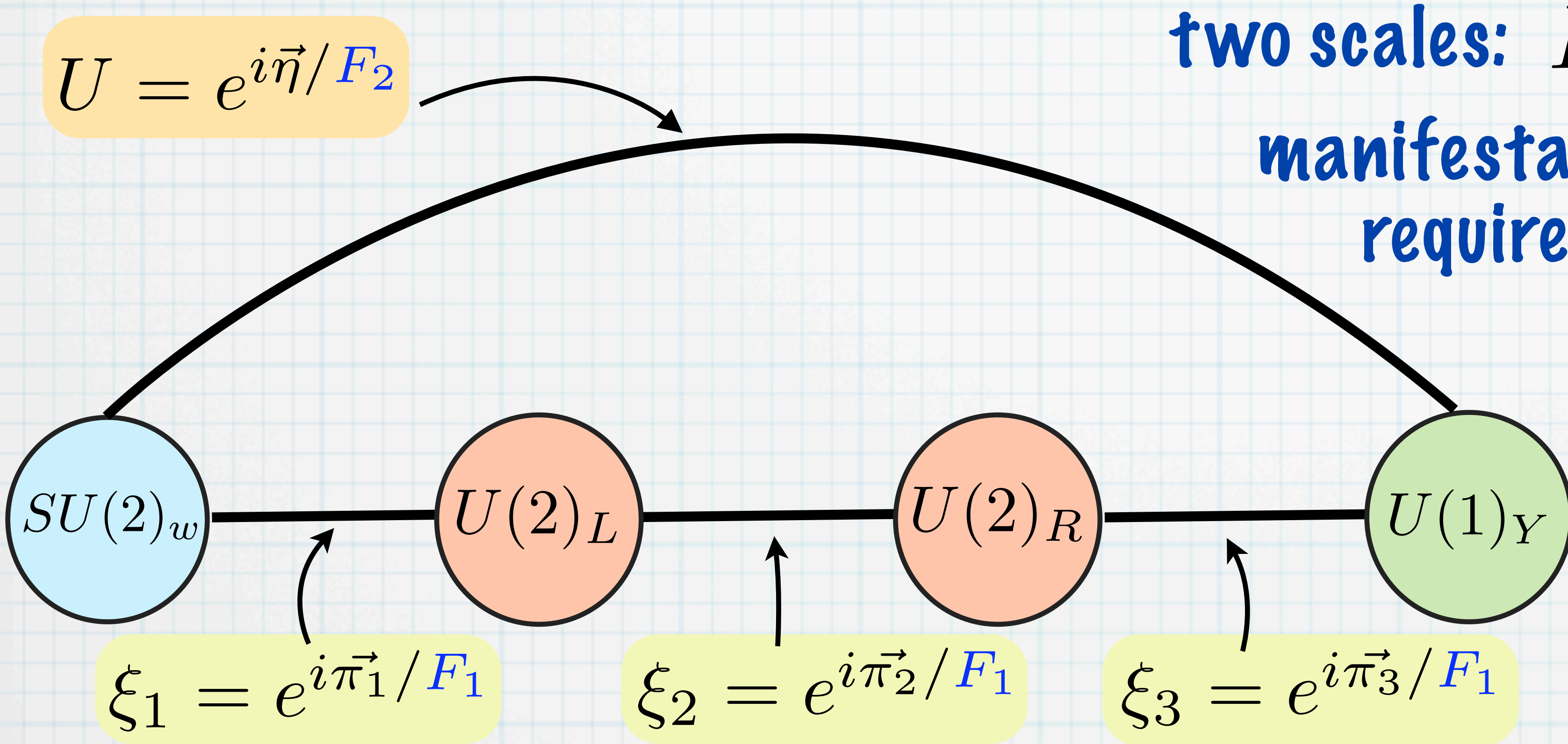
(same technique goes by many names: BESS (Casalbuoni et al), 'three-site model' (Chivukula et al))

**BUT, this setup is very restricted...**

- where has the walking entered?
- where are the technipions?
- how can we get more than one set of resonances?

# Walking TC: LHC implications, #6

more sophisticated models allow us to add more TC-features




two scales: $F_1, F_2$ as a

manifestation of the idea that walking requires multiple, different reps.

$$v^2 = F_1^2 + F_2^2$$

take $F_1 \ll F_2$

four sets of NGB fields, three are eaten by gauge interactions

- we now have a small parameter to play with: $\sin\chi = F_1/F_2$

for example: suppresses fermion-resonance couplings

$$g_{\bar{f}f\rho_T} \sim g_{EW}\left(\frac{M_W}{M_\rho}\right)\sin\chi$$

- hidden groups are $U(2)$, extra resonance is $\omega_T$
- one $\pi_T$ remains in the spectrum

(Lane, AM '09)

# Walking TC: LHC implications, #7

## HLS is still very limited:

* higher dimensional operators? can we really stop at 2-derivative, d < 4 operators in a strongly coupled theory?
* anomaly terms? global anomalies of the underlying UV theory are present in the effective theory -- WZW interactions
* spin-1 resonances only: a new strong interaction can certainly have resonances for other spins (0, 2, ..). Technibaryons should also occur, with spin depending on $N_{TC}$ and potentially having electromagnetic charge $|Q| > 1$

Model dependent, and requires introducing more unknown parameters. Very little phenomenology done for these states

# Walking TC: LHC implications, #8

HLS models should NOT be taken too seriously, but they are a useful and simple tool for making predictions. Studying the phenomenology of these models will hopefully prepare us to recognize signals of new strong dynamics should they appear at the LHC

**but we should always remember that HLS is just a model!**

# Walking TC: LHC implications, #9

**examples:** Drell-Yan production of resonances:

$$\rho_T^{\pm} \to W^{\pm} Z^0 \to \boxed{\ell^+ \ell^- \ell' \nu}$$

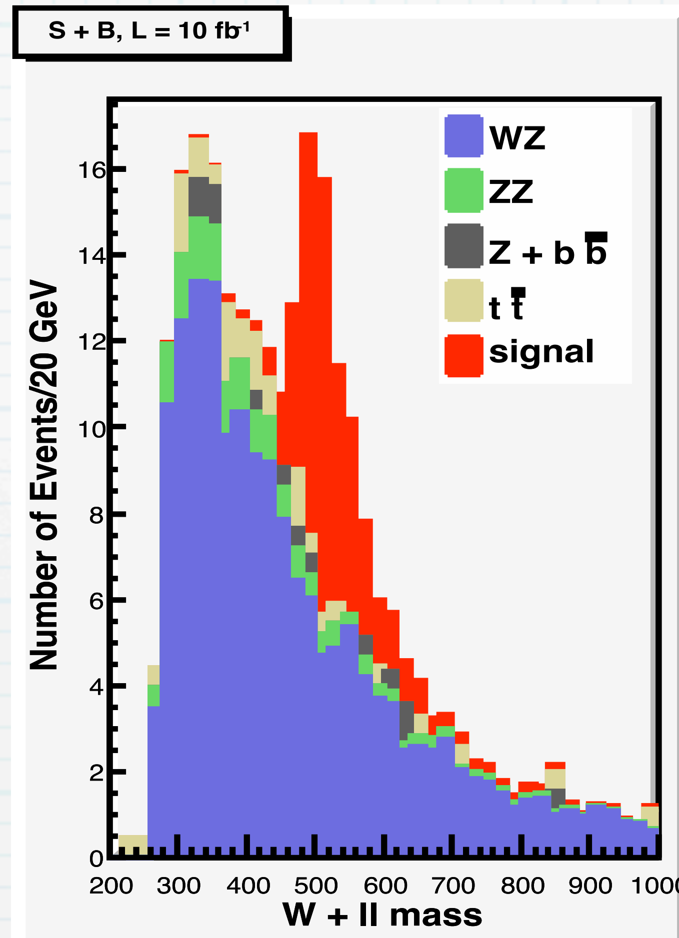
**Enhancement from decays to longitudinal polarizations**

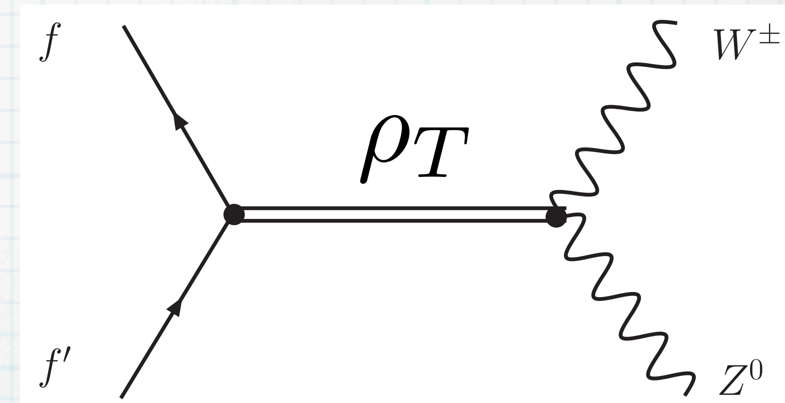
$$\sigma(pp \to \rho_T \to WZ) \propto \frac{M_{\rho_T}^4}{M_Z^2 M_W^2}$$

**Relatively Unstudied!**

past studies: $Z' \to \bar{f} f$

$W' \to \ell + \nu$




1.) $n_{lep} = 3, p_T > 10$ GeV, $|\eta| < 2.5$

$p_T > 30$ GeV for at least one

2.) $|M_{\ell^+\ell^-} - M_Z| < 3.0\Gamma_Z$

3.) $H_{T,jets} < 125$ GeV

4.) $p_{T,W},\ p_{T,Z} > 100$ GeV

**Early LHC discovery!**

- large cross section
- multi-lepton final states
- single MET source -> can reconstruct $M_{\rho_T}^2$

# Walking TC: LHC implications, # 10

**Why so narrow?** In a strongly interacting theory expect states should be broad

Unless...

1.) kinematically forbidden from decaying to most states, i.e. $\rho_T \to \pi_T \pi_T$ not allowed because $m_{\pi_T} > \frac{m_{\rho_T}}{2}$

Assuming $m_{\pi_T} > \frac{m_{\rho_T}}{2}$ is not completely ridiculous

because the $\pi_T$ mass depends on the techni-condensate and is enhanced by walking, while the $\rho_T$ mass only depends on the TC confinement scale $\Lambda_T$

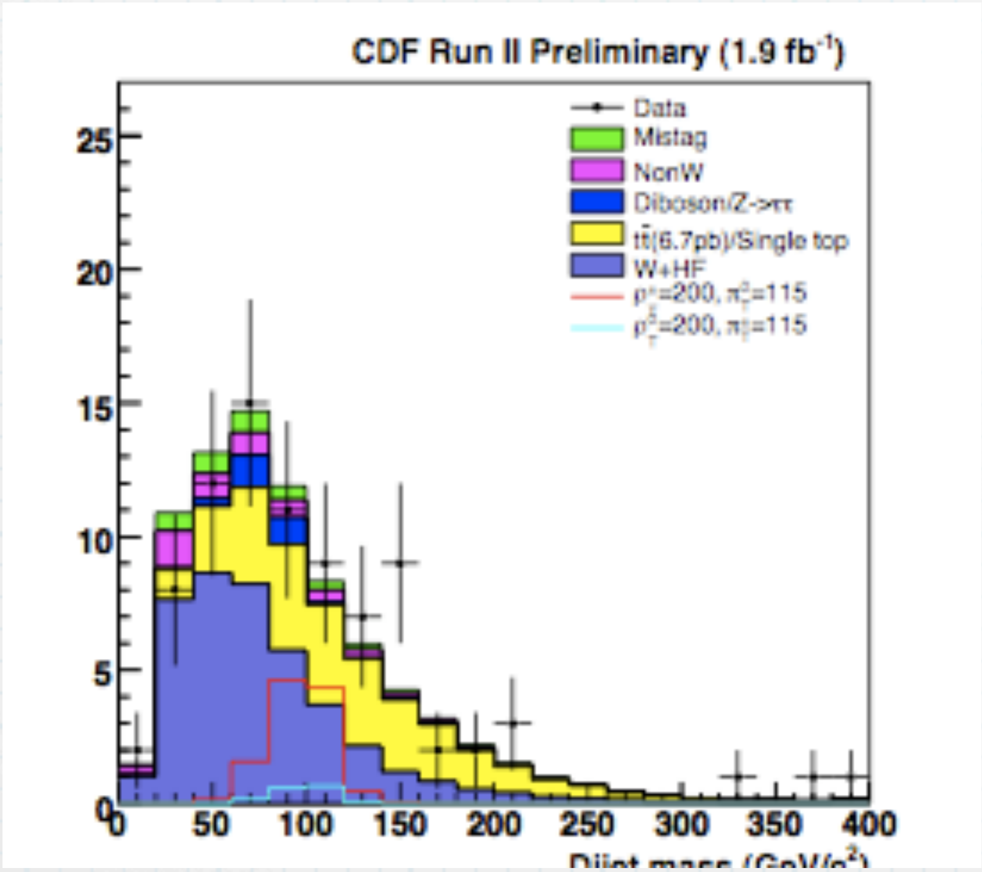
In this case, only $\rho_T \to WW, W\pi_T$ are allowed. Resonance becomes narrower, and rate of respective processes is sensitive to $m_{\rho_T} - m_{\pi_T}$

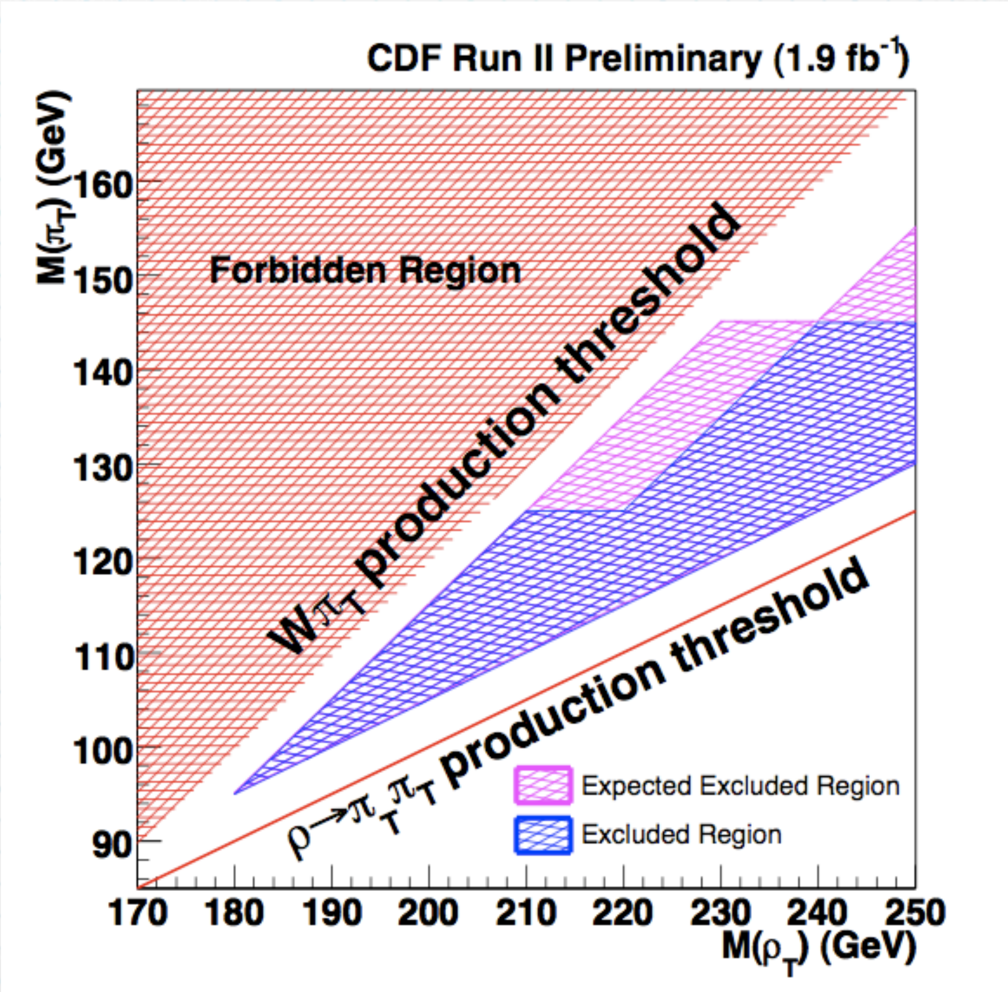
2.) Large $N_{TC}$: Result of 5D theories of strong dynmics

# Walking TC: LHC implications, # 11

I mention the narrowness of $\rho_T$ because ALL dedicated technicolor searches assume $m_{\pi_T} > \frac{m_{\rho_T}}{2}$

ex: $p\bar{p} \to \rho_T \to W\pi_T \to (\ell\nu)(bq)$ at the Tevatron



# Walking TC: LHC implications, # 11

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**WHY?**

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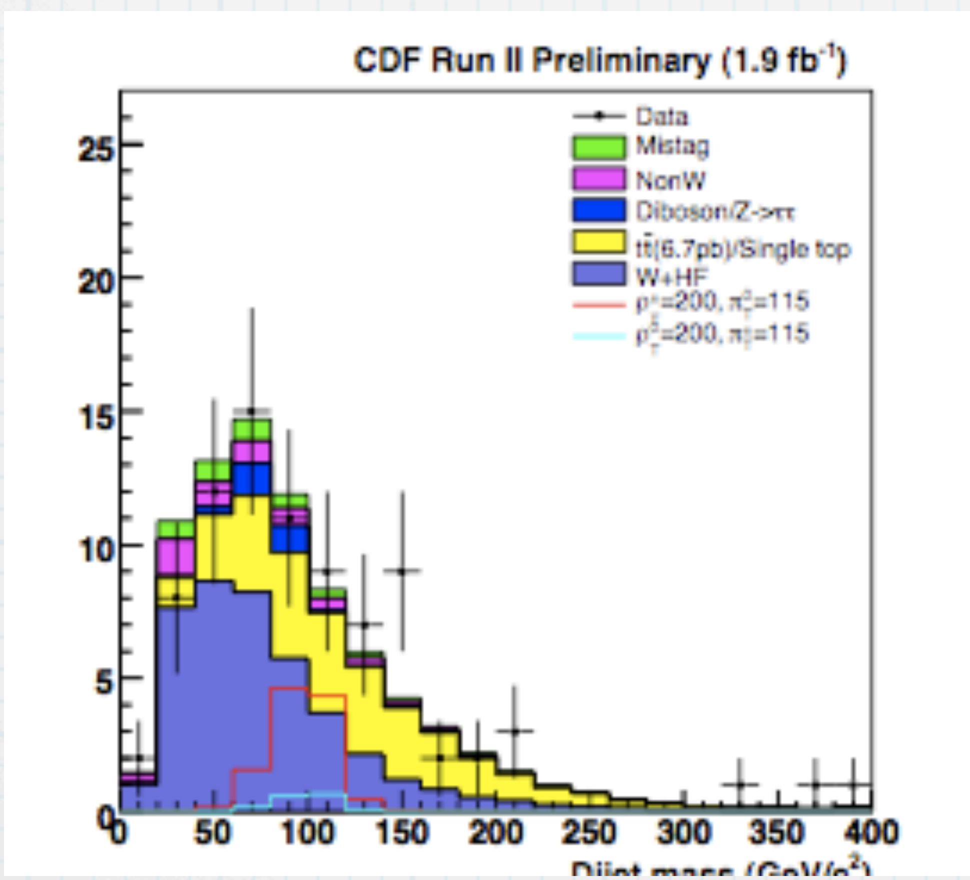


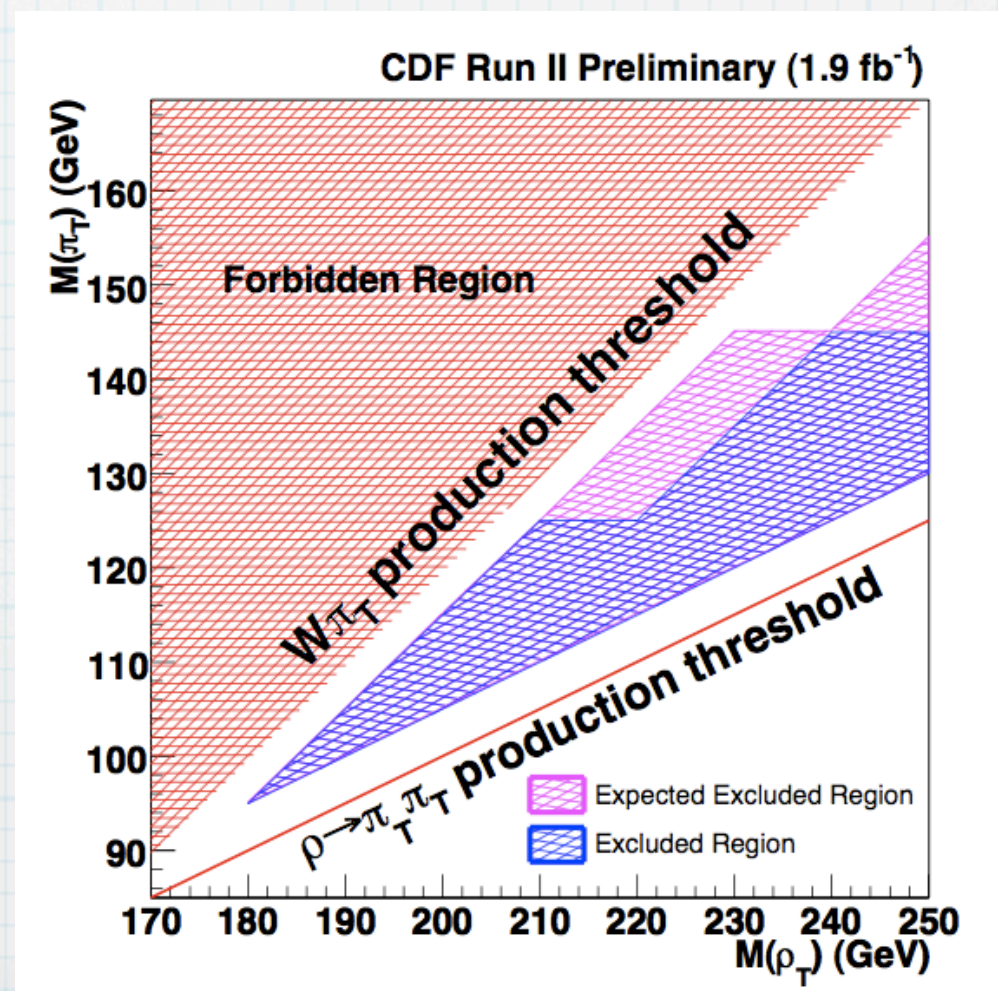

# Walking TC: LHC implications, # 11

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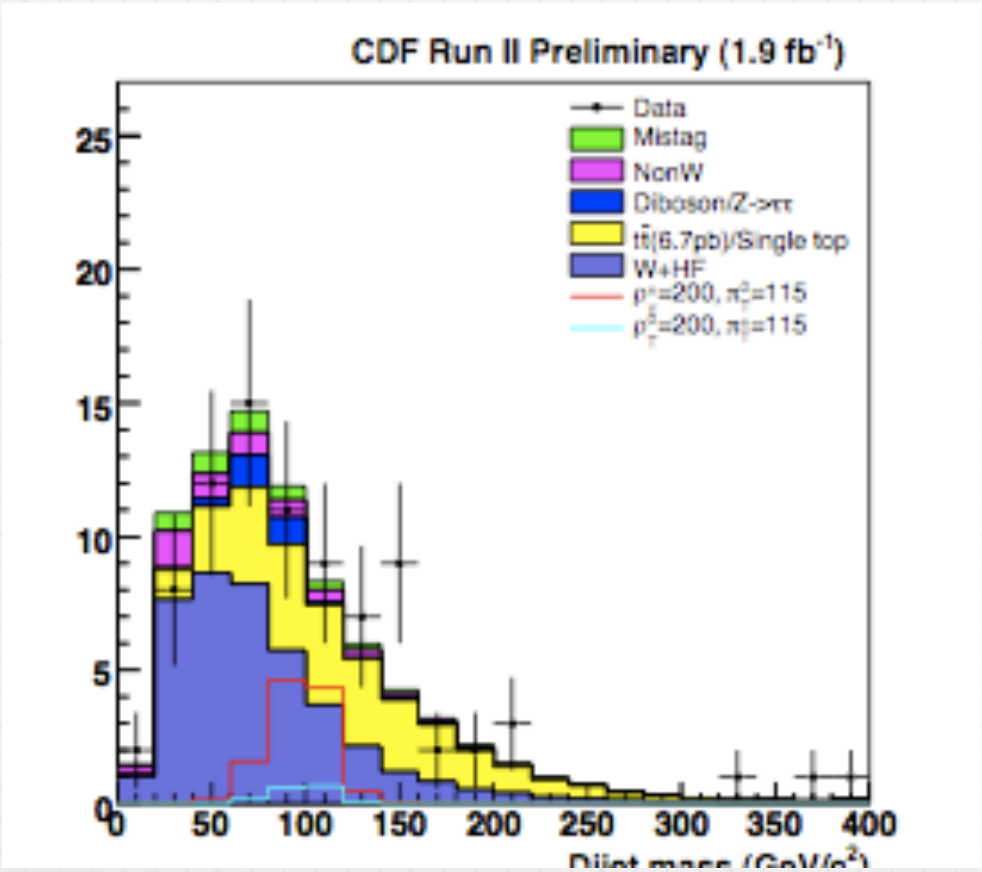
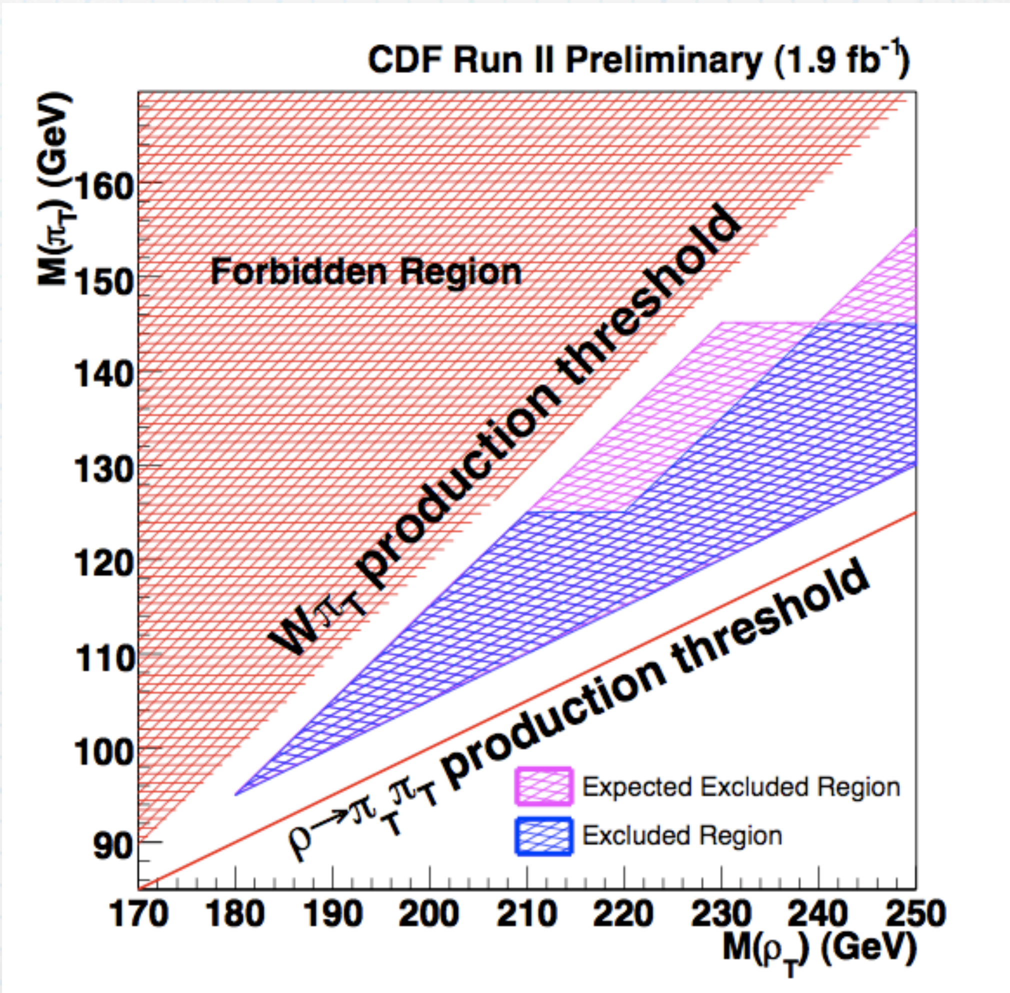
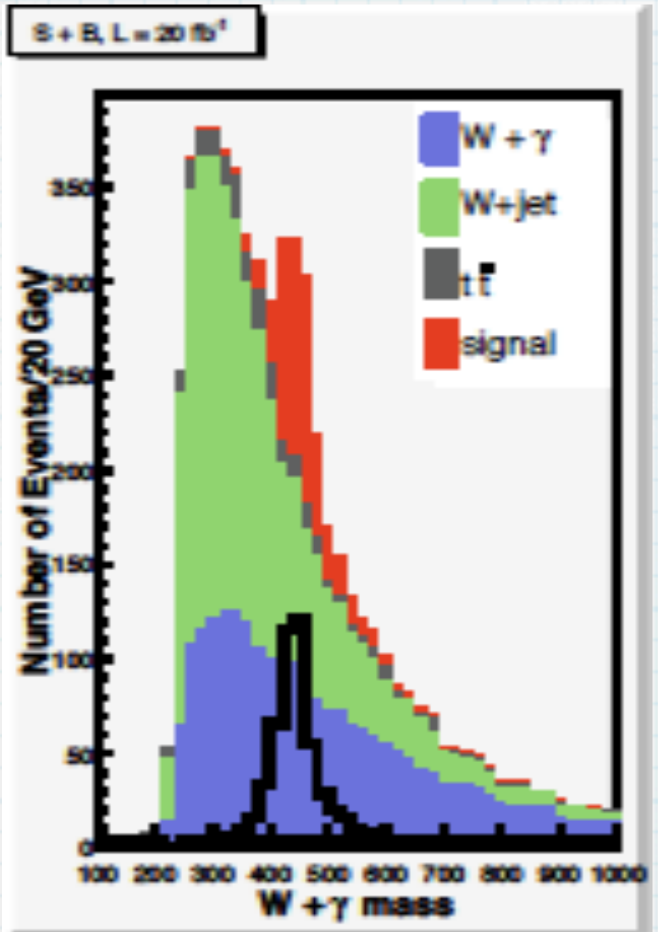
**WHY? It's in PYTHIA**

ex: $p\bar{p} \to \rho_T \to W\pi_T \to (\ell\nu)(bq)$ at the Tevatron



# Walking TC: LHC implications, #12

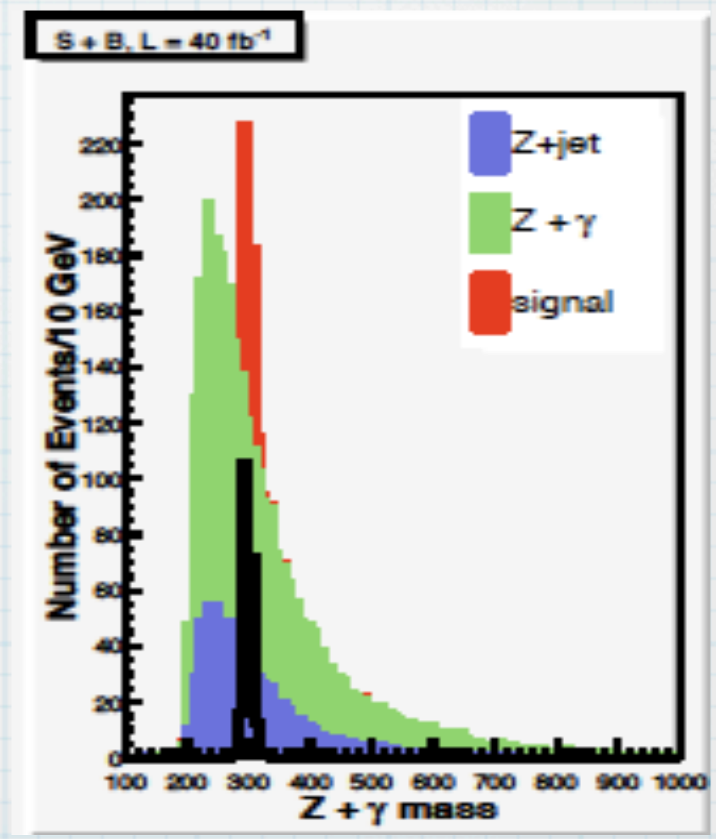



(hep-ph/0802.3714)

$$a_T^{\pm} \rightarrow \gamma W^{\pm} \rightarrow \boxed{\gamma \ell^{\pm} \nu}$$

- cannot go to $W_L^{\pm} Z_L^0$ as **technipartity** is imposed
- requires further HLS interactions! so this mode tells us something about how to best model new strong dynamics
  - very few collider studies! SUSY bias, where there are no resonance decays to $W^{\pm}Z^0, \gamma W$ at tree level

$$\omega_T \rightarrow \gamma Z^0 \rightarrow \boxed{\ell^+ \ell^- \gamma}$$




NO missing energy, only EM objects → very clean, sharp peak

- observation of $\omega_T$ tells us something about the global symmetries of TC $U(N_D)$ vs. $SU(N_D), \cdots$

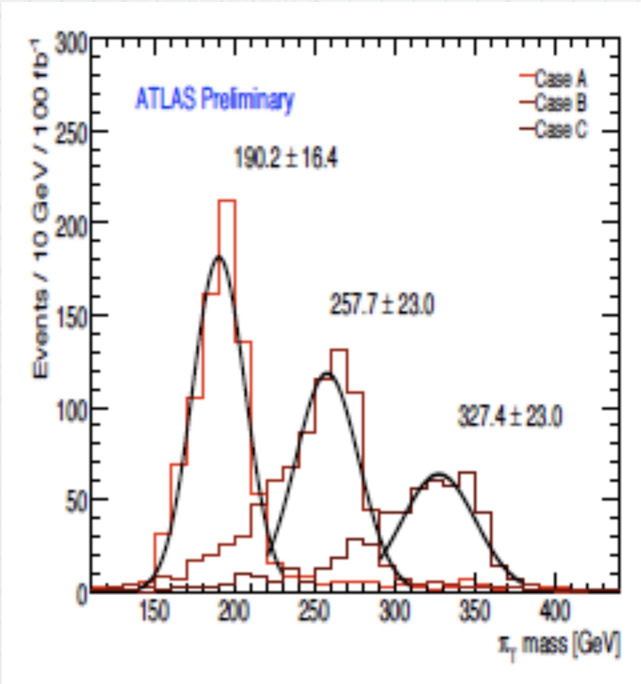
# Walking TC: LHC implications, #13

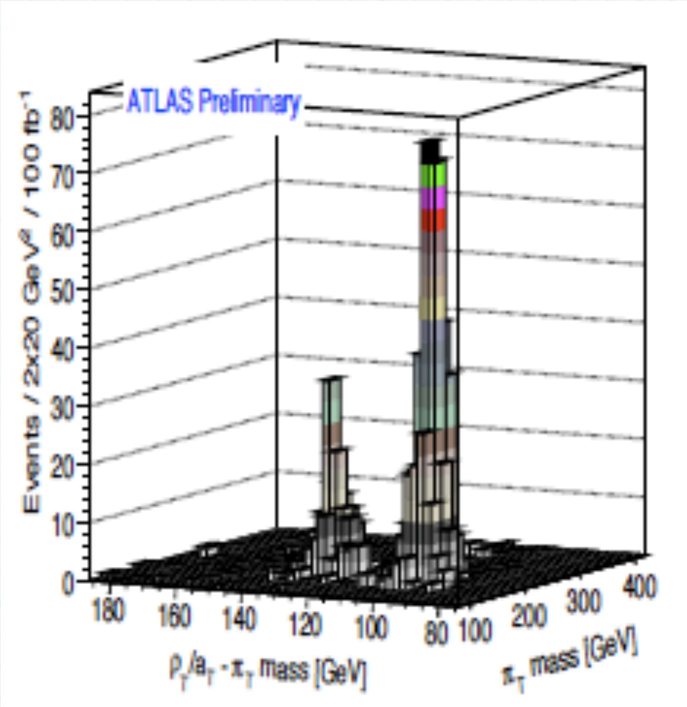
**Technipion discovery:** Important since $\pi_T$ don't exist in all models. However, few studies have been done

more model dependent, especially in the $\pi_T$ coupling to the top quark

$$pp \to \rho_T/a_T \to Z\pi_T \to \ell\ell bq$$

- with $\mathcal{L} \sim 50 \text{ fb}^{-1}$ $m_{\pi_T}, m_{\rho_T}, m_{a_T}$ all can be determined




(Azuelos et al, ATLAS-PHYS-CONF-2008-003)

## For all LSTC signals

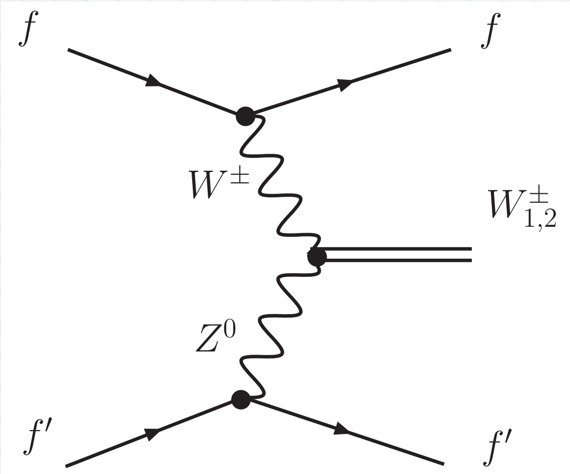
with more luminosity, detailed studies possible for

- Angular distributions: necessary to determine spin-1 (see hep-ph/0802.3714)
- Widths
- couplings

# Walking TC: LHC Implications, #14

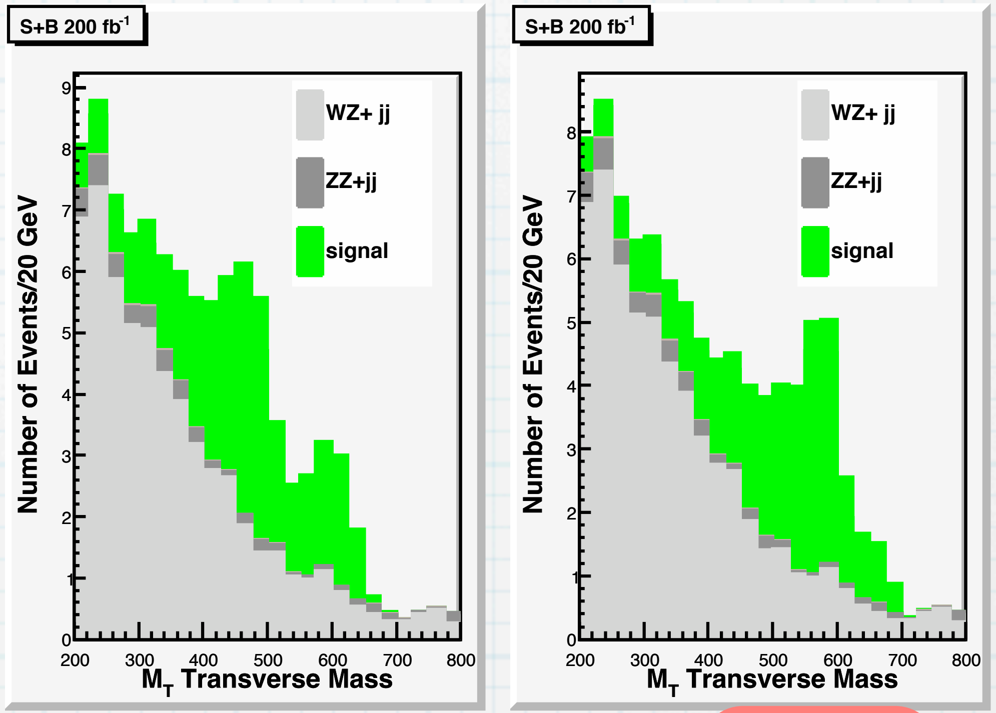
**High-luminosity signatures:** Not the `smoking gun' detection signal for TC, but important nonetheless

## Vector Boson Fusion:



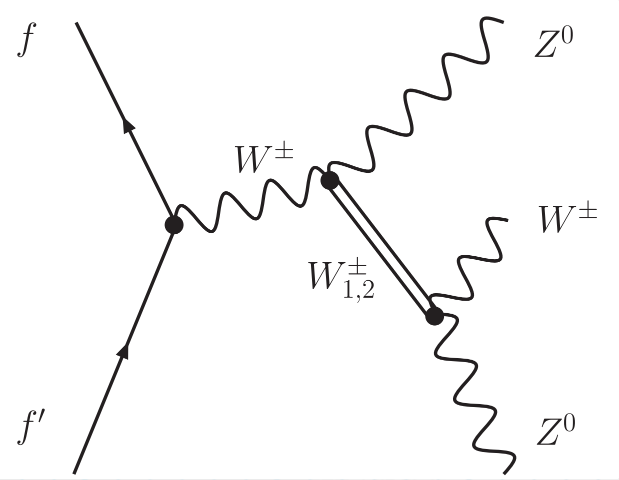

window into
$W_L W_L \to W_L W_L$
scattering

$pp \to \rho_T jj \to WZjj$

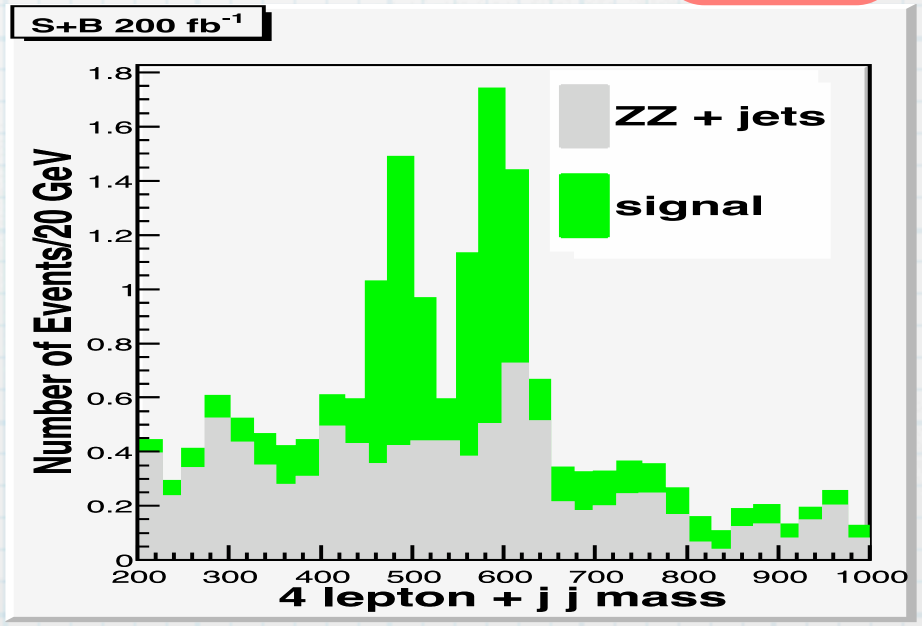



$pp \to \rho_T Z \to WZZ$

## Associated Production:




direct probe of
$g_{\rho_T WW}, g_{\rho_T WZ}$



# Summary

* **Tension** between FCNC and realistic fermion masses **can be avoided** if the technifermion bilinear has a **large (+ve) anomalous dimension**

* to have $\gamma_m \cong 1$ we expect the technicolor coupling must remain large for a wide range of energies, and is therefore nearly conformal or `walking'

* guided by the perturbative $b_0, \ b_1$, we expect walking theories will have lots of technimatter or involve large (non-fundamental) representations

# Summary so far

* Walking implies a low TC scale and therefore resonances in the 500 GeV - 1 TeV scale range

* New resonances must couple strongly to W,Z , though couplings to SM fermions are also possible. TC events will have no BSM missing energy <-> complementary to other BSM searches

* Precision Electroweak (S!!) arguments relied on technicolor being a rescaled version of QCD -- these arguments won't apply to a walking theory. There are arguments that a walking theory will have a naturally small S, but no solid evidence

# Summary so far

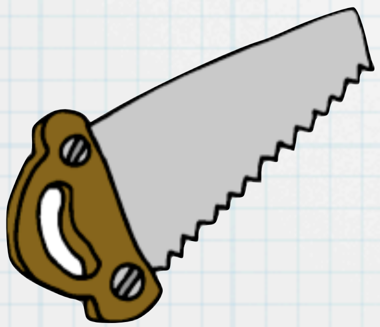
* Where does this leave us?

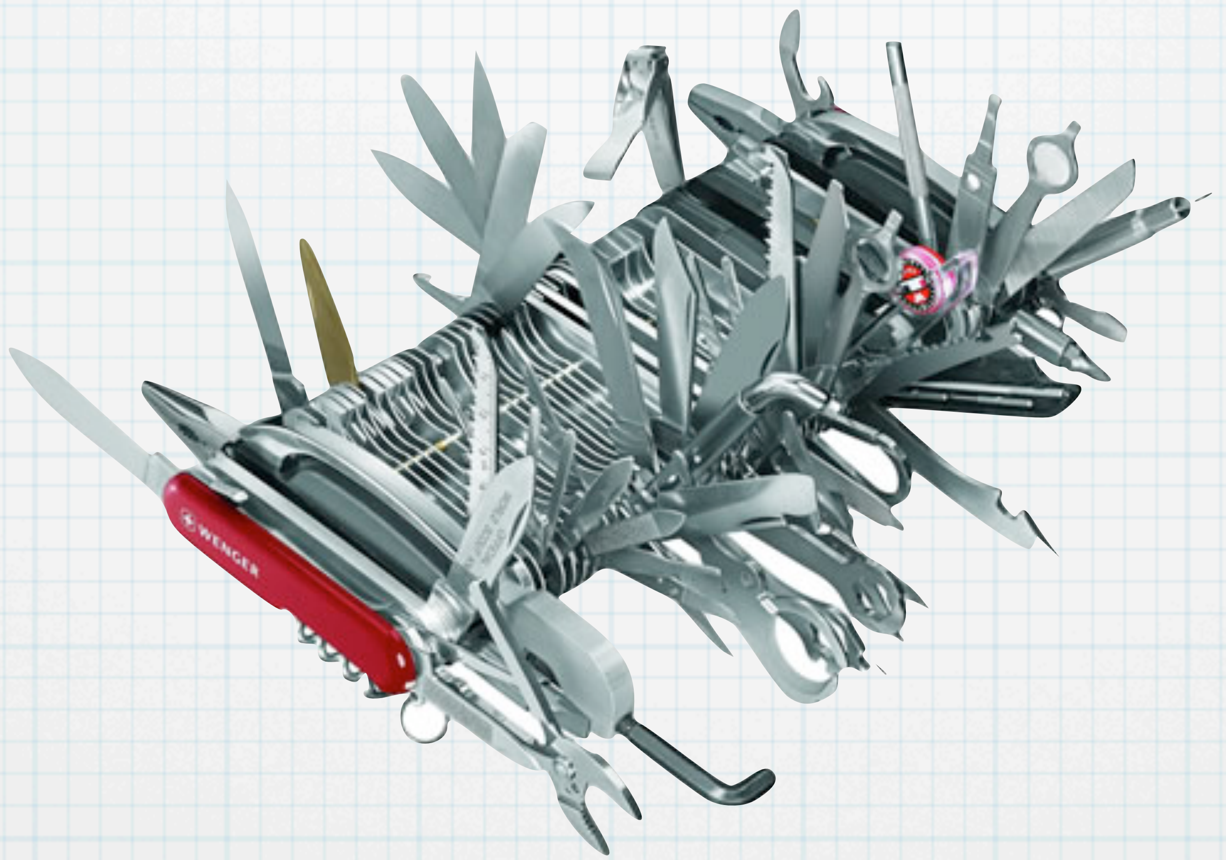
Modern Technicolor must be unlike QCD to avoid phenomenological problems -- the most investigated option is a walking technicolor theory. A walking theory CANNOT be ruled out by PEW tests, but we cannot calculate its contributions

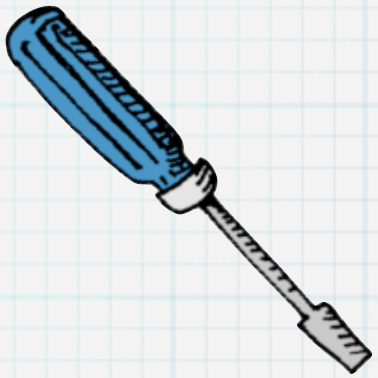
NECESSARILY will have new states at the sub-TeV level, therefore it will be found or ruled out at the LHC

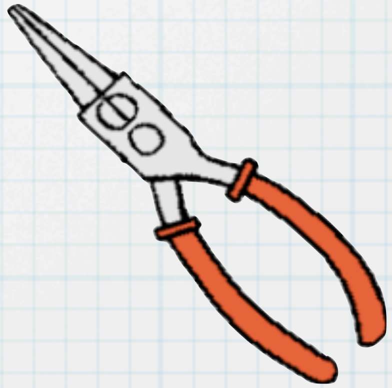
some new/better calculation tools would be great!

# A new tool for TC-Modeling:

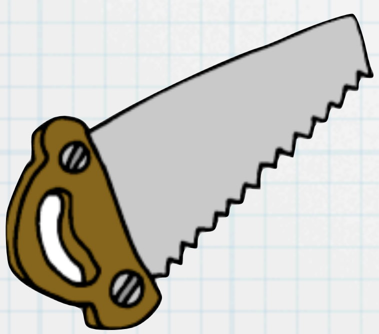


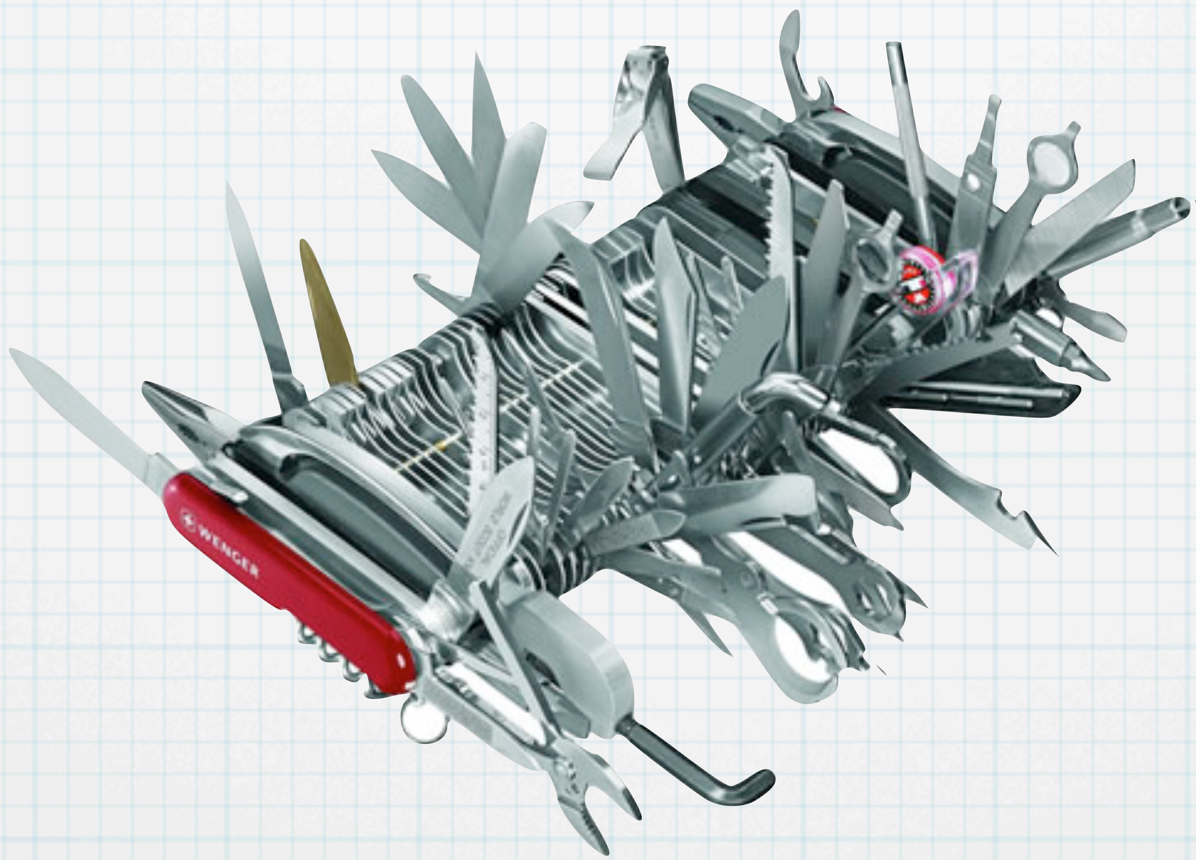


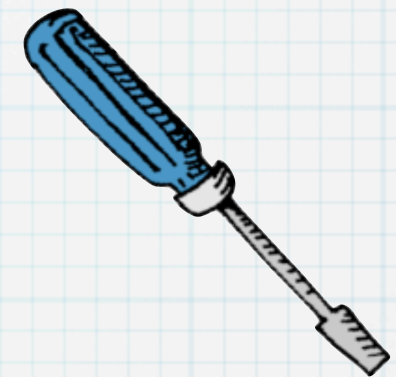



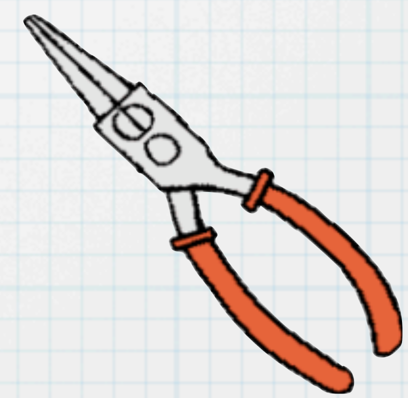


# A new tool for TC-Modeling:



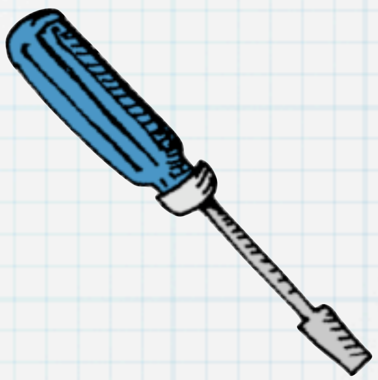




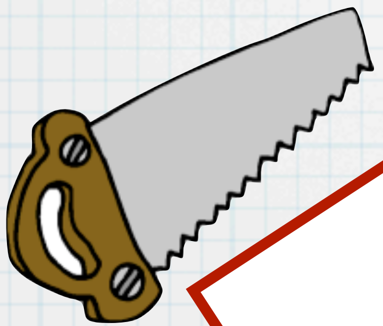


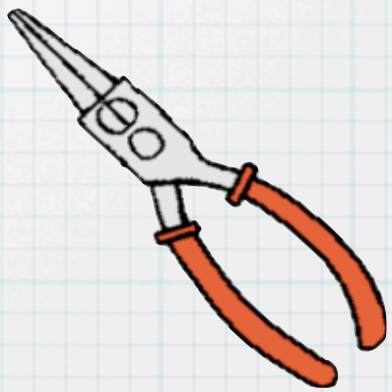
# Extra-Dimensions

# A new tool for TC-Modeling



QUICK PREVIEW





# Extra-Dimensions

# Extra-Dimensions??

- How could an extra dimension help things? we are confused enough in 4D...

- We expect a strong interaction to give us bound states whose masses form a discrete spectrum.

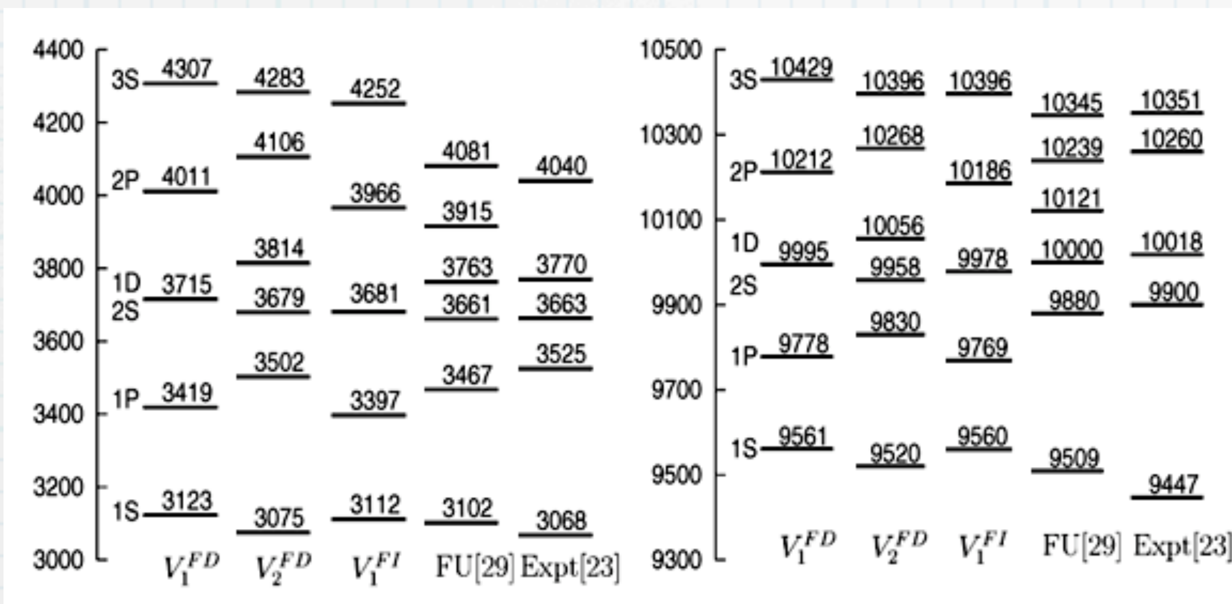
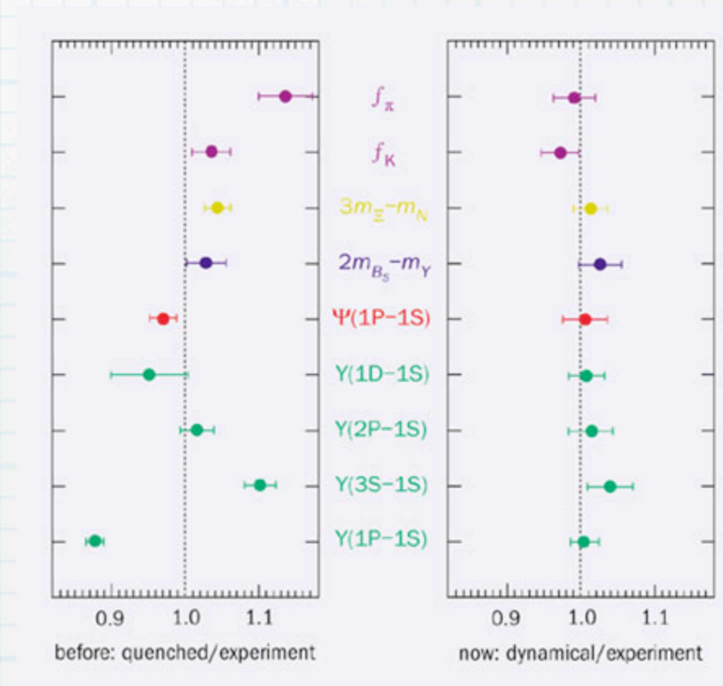



Figure 1: Charmonium (left) and Upsilom (right) energies ($MeV$) ($V_1^{FI}$ is the flavor independent potential $V_1(r)$).




- The **masses** of the new states, along with the **interactions** of the new states with the SM are EXACTLY the quantities we would like to predict, since they are what will be measured at a collider

# Extra Dimensions??

* BUT, these quantities are not computable from perturbation theory. This is a problem of any strongly coupled theory, not just technicolor

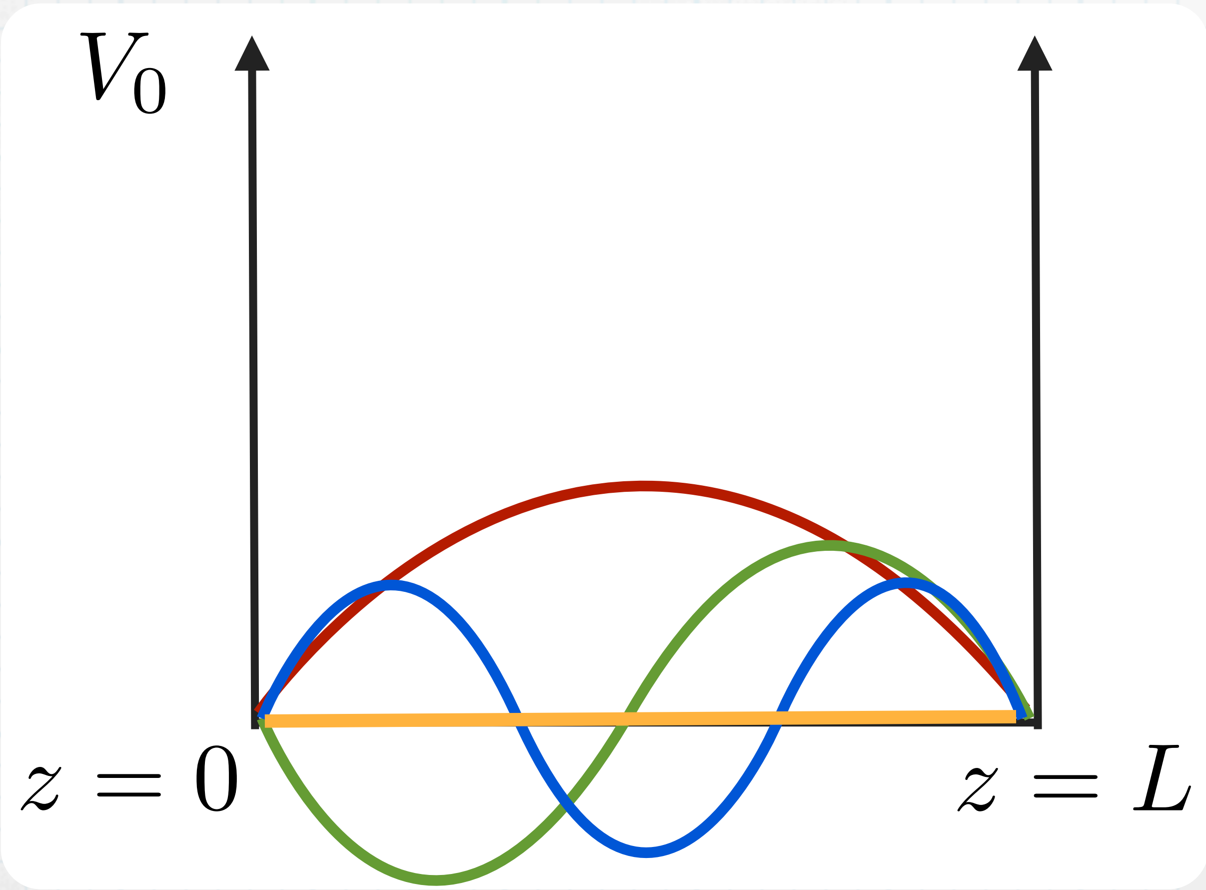
* The underlying 4D description (techifermions, technigluons, etc.) uses the wrong degrees of freedom for the EW-scale strong dynamics

  just like quarks and gluons are the wrong degrees of freedom for QCD at $1\ \mathrm{GeV}$

# Extra-Dimensions!!

* **BUT, we are ALL familiar with a setup which yields discretized energy levels**

**Quantum Mechanics: particle in a potential well**



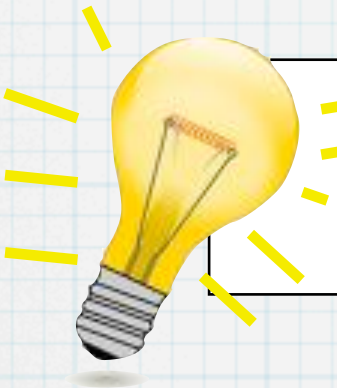

$$\psi_E(z) = \sqrt{\frac{2}{L}} \sin\left(\frac{n\pi z}{L}\right)$$

$$n = 1, 2, 3 \cdots$$

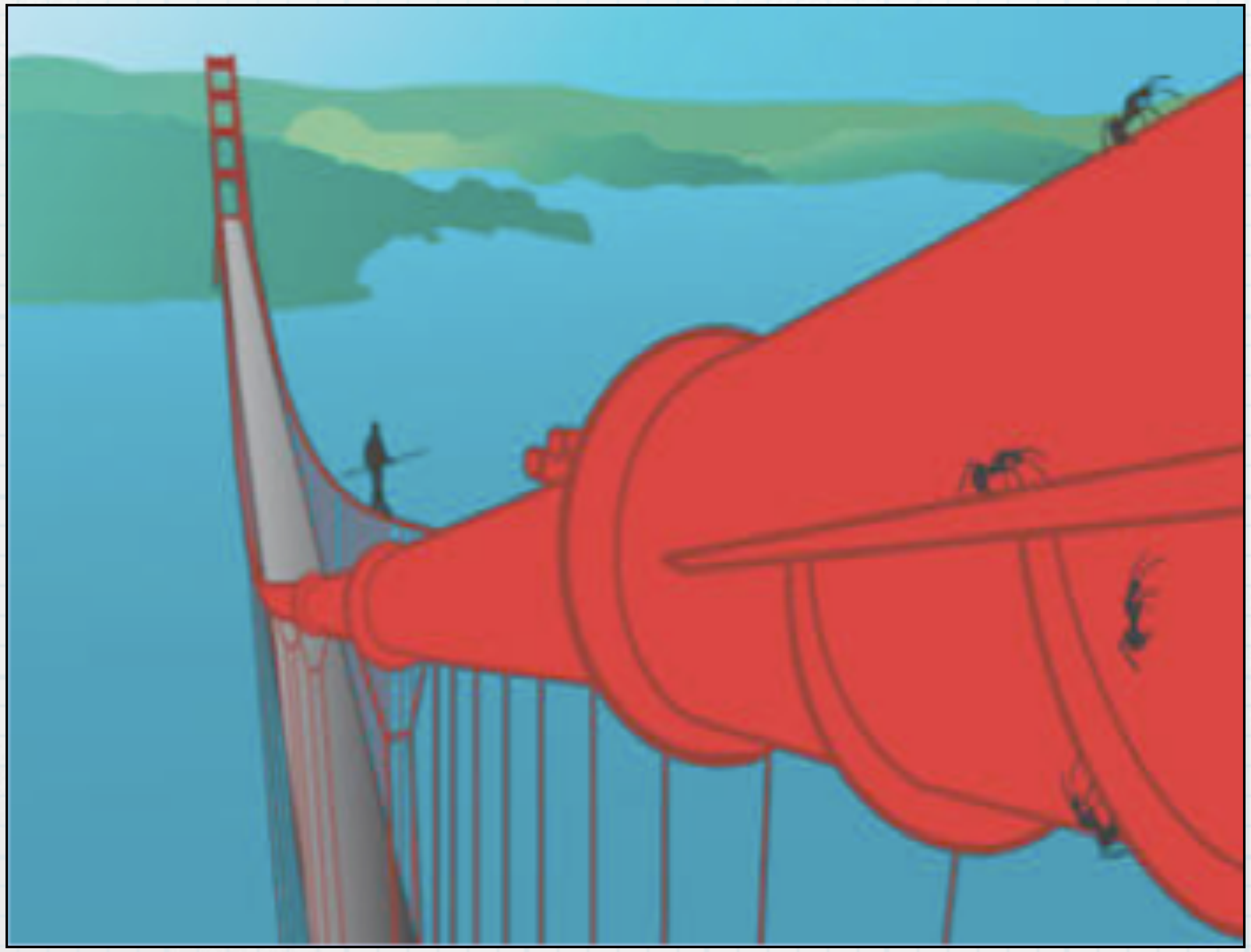
$$E = \frac{\hbar^2 n^2 \pi^2}{2mL^2}$$

# Extra Dimensions!!

* For a quantum field theory, the rules are somewhat more complicated, but the idea is the same:



**Use a compact extra-dimension to model the bound states and composites from a new strong interaction**

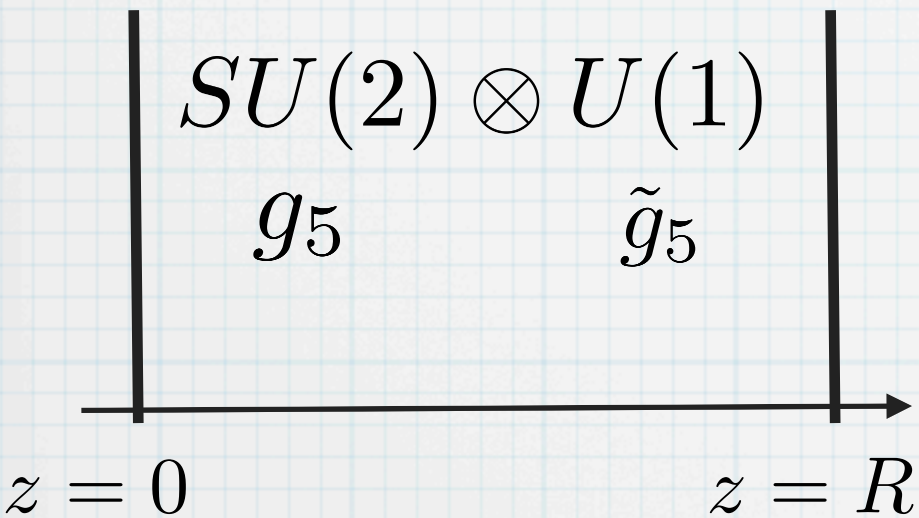


We no longer know the underlying 4D theory (the microscopic degrees of freedom), but we do model the observables which are relevant at the LHC

# A first attempt:

**Geometry** and **boundary conditions** determine the spectrum and which symmetries are broken (see lectures by C. Grojean)

For our purposes, an extra-dimensional interval is best. Let's only worry about the EW gauge fields and try a flat dimension first




**Solve classical 5D EOM by KK decomposition,**

$$\Phi(z,x) = \phi_0(x) + \sum_{n=1}^{\infty} e^{inz/R} \phi_n(x)$$

**features in extra dimensionsare masses in 4D**

$$\Box_5 \Phi \supset (\Box_4 - \partial_5^2)\phi_n = (\Box_4 + \frac{n^2}{R^2})\phi_n$$

- zero mode/first KK mode = SM gauge fields
- Higher KK modes = resonances

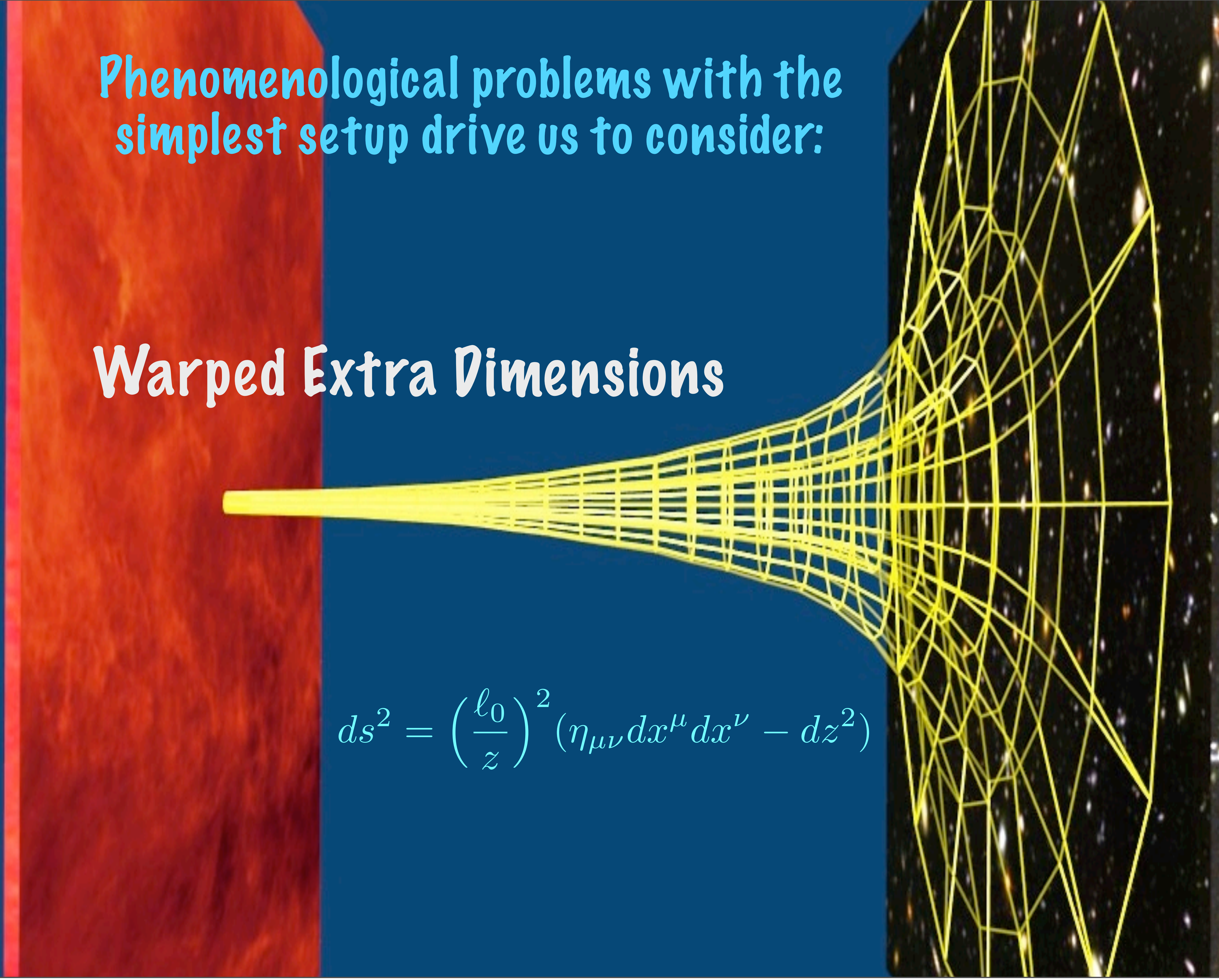
- few free parameters

Multi-resonance couplings are set by overlaps of profiles :

$$\boxed{g_{ABC} \propto \int dz \phi_A(z)\phi_B(z)\phi_C(z)}$$

## Phenomenological problems with the simplest setup drive us to consider:

# Warped Extra Dimensions



$$ds^2 = \left(\frac{\ell_0}{z}\right)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$$

# Ads/Technicolor

* **Additional motivation for AdS extra dimensions: AdS/CFT correspondence** (Maldacena '98)

type II-B string theory on $AdS_5 \otimes S_5$ ⟷ duality ⟷ large 't Hooft coupling limit of N = 4 supersymmetric Yang-Mills

## AdS/CFT Dictionary

| | | |
|---|---|---|
| Bulk of AdS | $\leftrightarrow$ | CFT |
| Coordinate ($z$) along AdS | $\leftrightarrow$ | Energy scale in CFT |
| Appearance of UV brane | $\leftrightarrow$ | CFT has a cutoff |
| Appearance of IR brane | $\leftrightarrow$ | conformal symmetry broken spontaneously by CFT |
| KK modes localized on IR brane | $\leftrightarrow$ | composites of CFT |
| Modes on the UV brane | $\leftrightarrow$ | Elementary fields coupled to CFT |
| Gauge fields in bulk | $\leftrightarrow$ | CFT has a global symmetry |
| Bulk gauge symmetry broken on UV brane | $\leftrightarrow$ | Global symmetry not gauged |
| Bulk gauge symmetry unbroken on UV brane | $\leftrightarrow$ | Global symmetry weakly gauged |
| Higgs on IR brane | $\leftrightarrow$ | CFT becoming strong produces composite Higgs |
| Bulk gauge symmetry broken on IR brane by BC's | $\leftrightarrow$ | Strong dynamics that breaks CFT also breaks gauge symmetry |

(Csaki)

# AdS/Technicolor, #2

* We don't have N=1 SUSY, not to mention N=4, so why should we care?

* To capture LHC phenomenology, we don't need an exact duality to hold. Perhaps just the essential symmetries and important operators are enough

* pure AdS (no branes) has a rescaling invariance: $z \to \lambda z, x^\mu \to \lambda x^\mu$

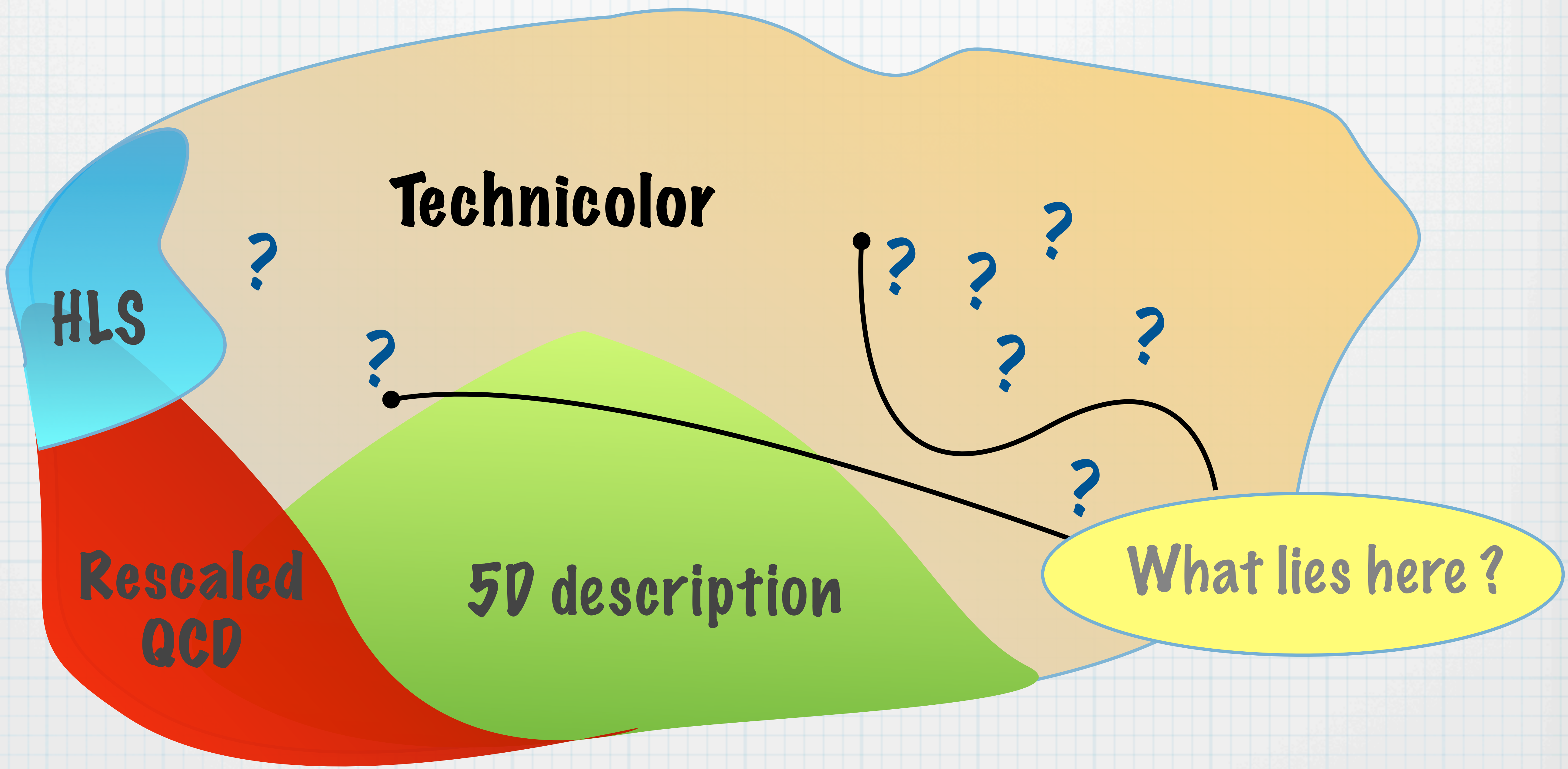
AdS dictionary: z $\longleftrightarrow$ RGE scale, therefore models 4D conformal dynamics, a perfect laboratory for modeling walking technicolor.

These AdS-based technicolor models are known as Higgsless models

see WARPED extra dimensions in lectures by C. Grojean

# Mission Accomplished?

NOPE. Extra dimensions allow us to model another subset of Technicolor theories, but there is still a lot of unknown territory out there



# Strong dynamics beyond Technicolor

# What are our options?

We need to break electroweak symmetry somehow:

* Forget strong dynamics and stick with the Standard Model or with weakly coupled UV physics (SUSY)

* Make modifications to technicolor so it is compatible with FCNC/fermion masses and precision electroweak (S,T,U): Walking TC.

* Some non-technicolor strong dynamics

# What are our options?

We need to break electroweak symmetry somehow:

* Make modifications to technicolor so it is compatible with FCNC/fermion masses and precision electroweak (S,T,U): Walking TC.
* Some non-technicolor strong dynamics

# What are our options?

We need to break electroweak symmetry somehow:

* Make modifications to tech[illegible]or so it is compatible with [illegible]asses and precision [illegible]eak (S,T,U): Walking TC.

LECTURE # 1

* Some non-technicolor strong dynamics

# Other EW-scale strong dynamics

* Are there other (non-technicolor) possibilities for strong dynamics at the EW scale? OF COURSE

Composite Higgs models/Little Higgs models

strongly coupled SM: large Yukawas
large $\lambda_H$

topcolor/top-condensation

top-seesaw

+ many variations

no time to go into detail on these, so I'll just pick one

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# Alternative Strong Dynamics, #2

* one example: Composite Higgs theories

to make the Higgs mass insensitive to high scales:

- link scalars and fermions, then chiral symmetry protects $m_h$ **(SUSY)**
- get rid of the Higgs, have strong dynamics break EWS **(TC)**
- shift symmetry: $h \to h + c$ forbids mass terms! $m^2 h^2$ NGB's have this symmetry, so lets make the Higgs a pseudo-NGB (pNGB)

this is what **composite Higgs models** try to do

(Georgi, Kaplan '84
Agashe, Contino, Nomura '04,..)

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(Georgi, Kaplan '84
Agashe, Contino, Nomura '04,..)

How do you get pNGB, naturally?? $\Rightarrow$ dynamical breaking of global symmetries

# Alternative Strong Dynamics, #3

**Composite Higgs setup:** looks similar to technicolor, but different!

start with constituent fermions, but with **non-TC charge assignments**.

$$\Psi_{CH} = \{(\chi_1, \chi_2), (\psi_1, \psi_2), \lambda\}$$

has an **SU(5)** flavor symmetry

EW doublets

these fermions have a **new strong interaction**,
which we assume causes the breaking to **SO(5) at a scale** $\Lambda_{CH}$

**chiral symmetry breaking pattern** $SU(N)/SO(N)$

**Composite Higgs: Assign underlying fermion charges/ symmetry breaking pattern such that EW symmetry unbroken by strong dynamics**

# Alternative Strong Dynamics, #4

**NOT like Technicolor, where strong dynamics breaks EWS**

## Composite Higgs

$$SU(5)/SO(5)$$

$$\Sigma = \begin{pmatrix} & & & -1 & \\ & & 1 & & \\ & 1 & & & \\ -1 & & & & \\ & & & & 1 \end{pmatrix}$$

condensate $\langle \epsilon^{ab}\chi_a\psi_b + \lambda^2 \rangle$
is an EW singlet

## Technicolor

$$SU(2N)_L \otimes SU(2N)_R / SU(2N)_V$$

$$\Sigma_{TC} = \mathbf{1}_{2N\times 2N}$$

condensate $\langle \bar{U}_L D_R \rangle$
is an EW doublet

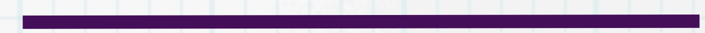
**but we do get 14 NGBs, 4 of which form a multiplet with the exact quantum numbers at the SM Higgs**

$$U = e^{i\mathbf{H}/\Lambda_{CH}}\Sigma, \quad \boldsymbol{H} = \frac{1}{\sqrt{2}}\begin{pmatrix} & & \bar{h} \\ & & h \\ \bar{h}^\dagger & h^\dagger & 0 \end{pmatrix} \in (2,2), \qquad h = \begin{pmatrix} h_1 + i\,h_2 \\ h_0 + i\,h_3 \end{pmatrix}, \; \bar{h} = i\sigma_2 h^*$$

# Alternative Strong Dynamics, #4

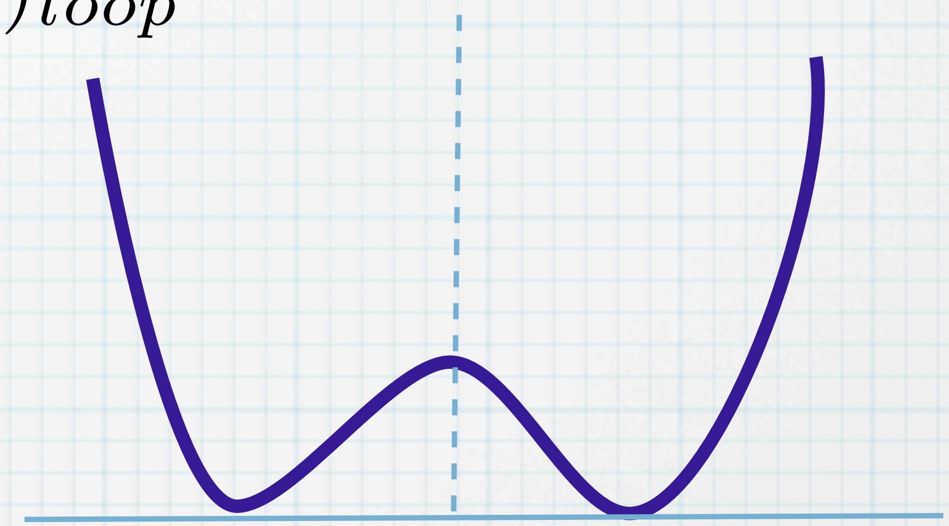
At tree level, the Higgs is an exact NGB and has no potential

$V(h)_{tree}$



BUT, the higgs develops a potential radiatively, through other interactions

$V(h)_{loop}$



SU(2) x U(1) gauge interactions, Yukawa interactions pull the Higgs potential in different directions and can result in a non-trivial minimum

Minimum at $h \neq 0$

EWSB!

# Alternative Strong Dynamics, #4

## Scales and degrees of freedom

fundamental fermions $\Psi_{CH}$ are massless
new strong interaction is asymptotically free

$f_{CH} \sim \Lambda_{CH}/(4\pi)$

new interaction confines, $\Psi_{CH}$ bound into composites

some of these composites have the same quantum numbers as the Higgs boson.

There is a physical Higgs boson in the theory. No potential at tree level, but gets a loop-level potential. If $V(H)$ minimized at $\langle H \rangle = v \neq 0$, EWSB occurs

$v = 246 \text{ GeV}$

Composite Higgs:
we can get $v \ll f_{CH}$

remember, in Technicolor
we had $v \equiv F_T$

# Alternative Strong Dynamics, #5

## strong dynamics itself does NOT break EWS

... but leads to a Higgs `pion', which ultimately gets a vev

Interesting idea, as we can have $v \ll \Lambda_{CH}$ but haunted by many familiar problems:

- calculabiliy: $m_H^2 < 0$ is vital for EWSB. Can we be sure of our potential in a strongly interacting theory? (add extra symmetry to make $V(h)$ less UV-sensitive and more predictable = Little Higgs models)

(Arkani-Hamed et al '01, '02)

- fermion masses: what generates the operators which eventually become Yukawas interactions?

- Flavor: how do we avoid FCNC from these new states

hot topic of research !

# Alternative Strong Dynamics, #5

## strong dynamics itself does NOT break EWS

...iggs 'pion', which ultimately gets a vev

Extra-dimesnional 'holographic' techniques can help here too!

..., as we can have $v \ll \Lambda_{CH}$ but haunted by many familiar problems:

- calculabiliy: $m_H^2 < 0$ is vital for EWSB. Can we be sure of our potential in a strongly interacting theory? (add extra symmetry to make $V(h)$ less UV-sensitive and more predictable = Little Higgs models)

  (Arkani-Hamed et al '01, '02)

- fermion masses: what generates the operators which eventually become Yukawas interactions?

- Flavor: how do we avoid FCNC from these new states

hot topic of research !

# Strong Dynamics is here to stay!

- still not convinced? really like SUSY?

- Supersymmetry only solves the hierarchy problem IF the superpartners are at the $\sim$ TeV scale. Though stable, you still need to naturally generate a $\text{TeV} \ll M_{pl}$ hierarchy. How?

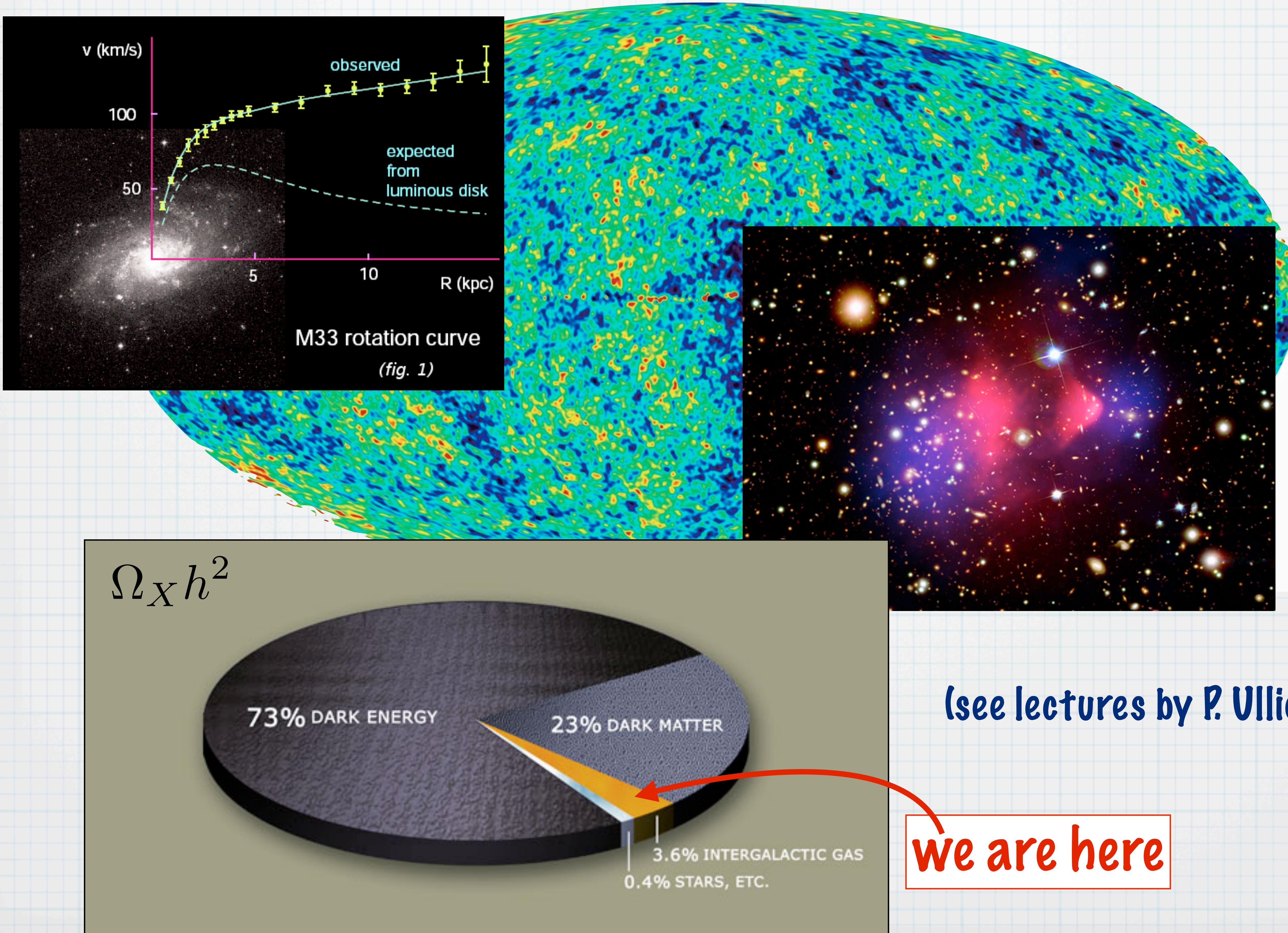
**Dynamical SUSY breaking** $M_{\cancel{SUSY}} \sim M_{pl} e^{-8\pi/g^2}$

(Witten '82, Affleck, Dine, Seiberg '80's)

strong dynamics at or above the weak scale are necessary in (almost) ANY natural BSM model, with or without SUSY

# Technicolor and Dark Matter

# Motivation for Dark Matter

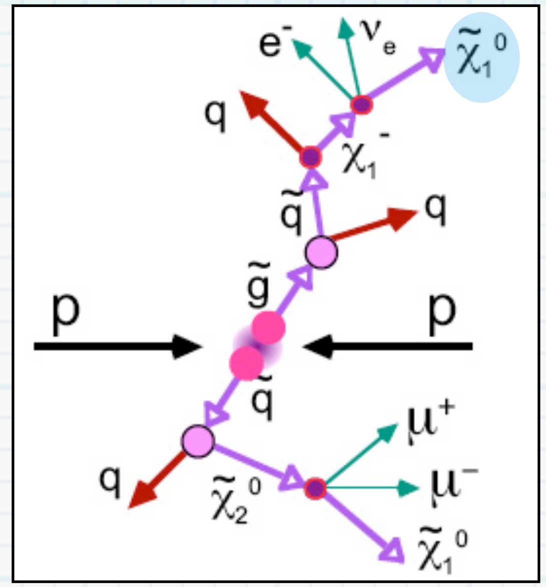


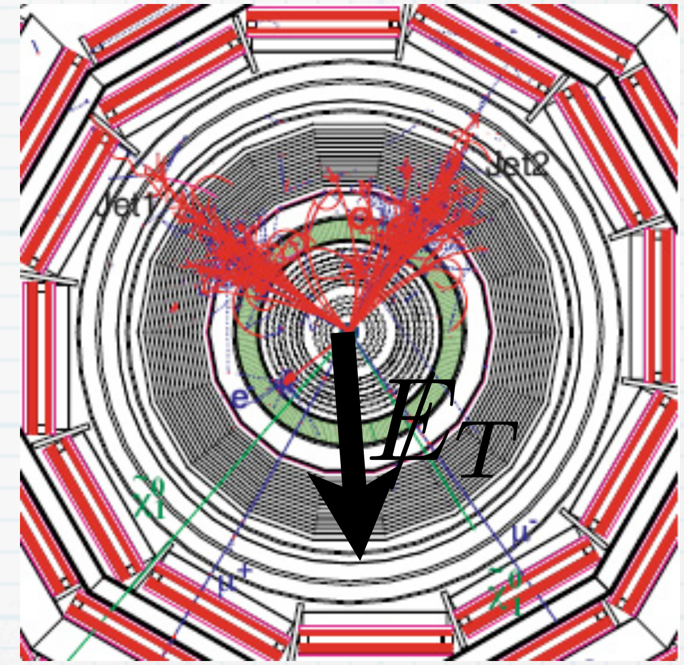

(see lectures by P. Ullio)

we are here

# Motivation for Dark Matter, #2

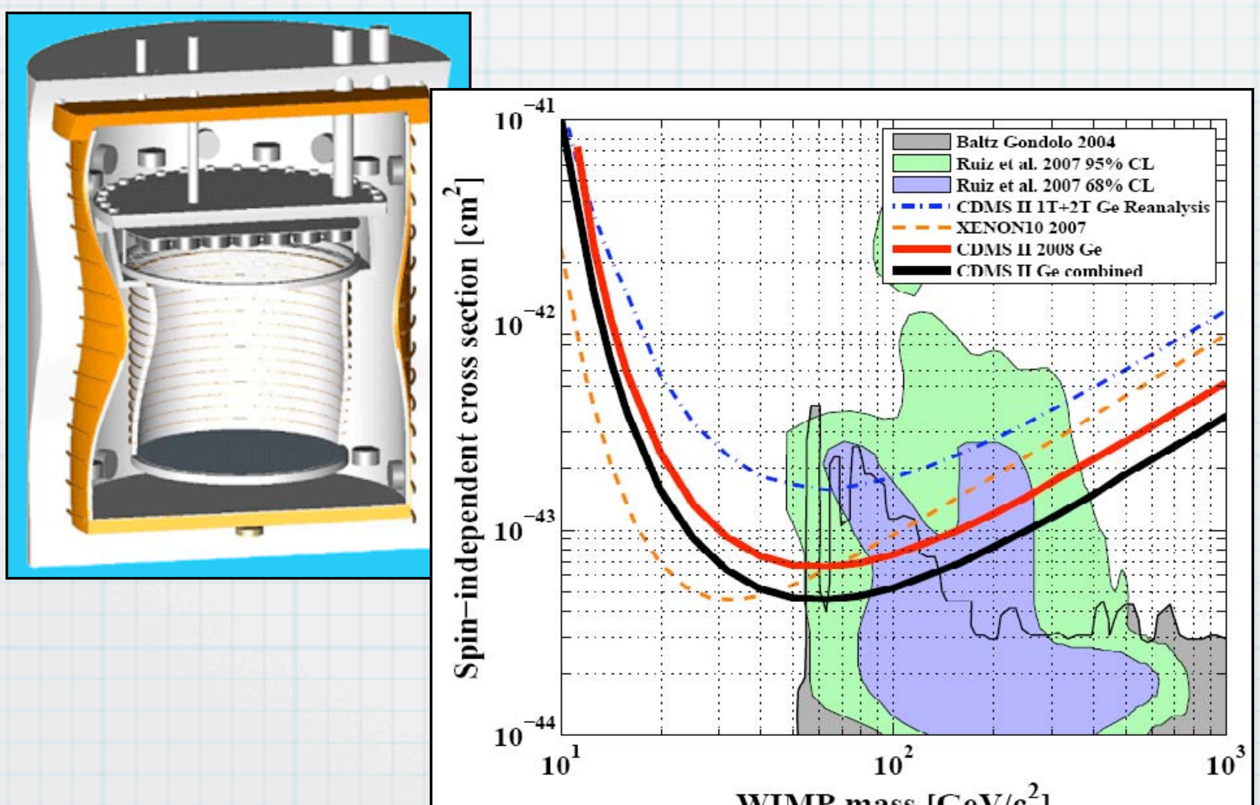
it's a 'smoking gun' signal for new physics

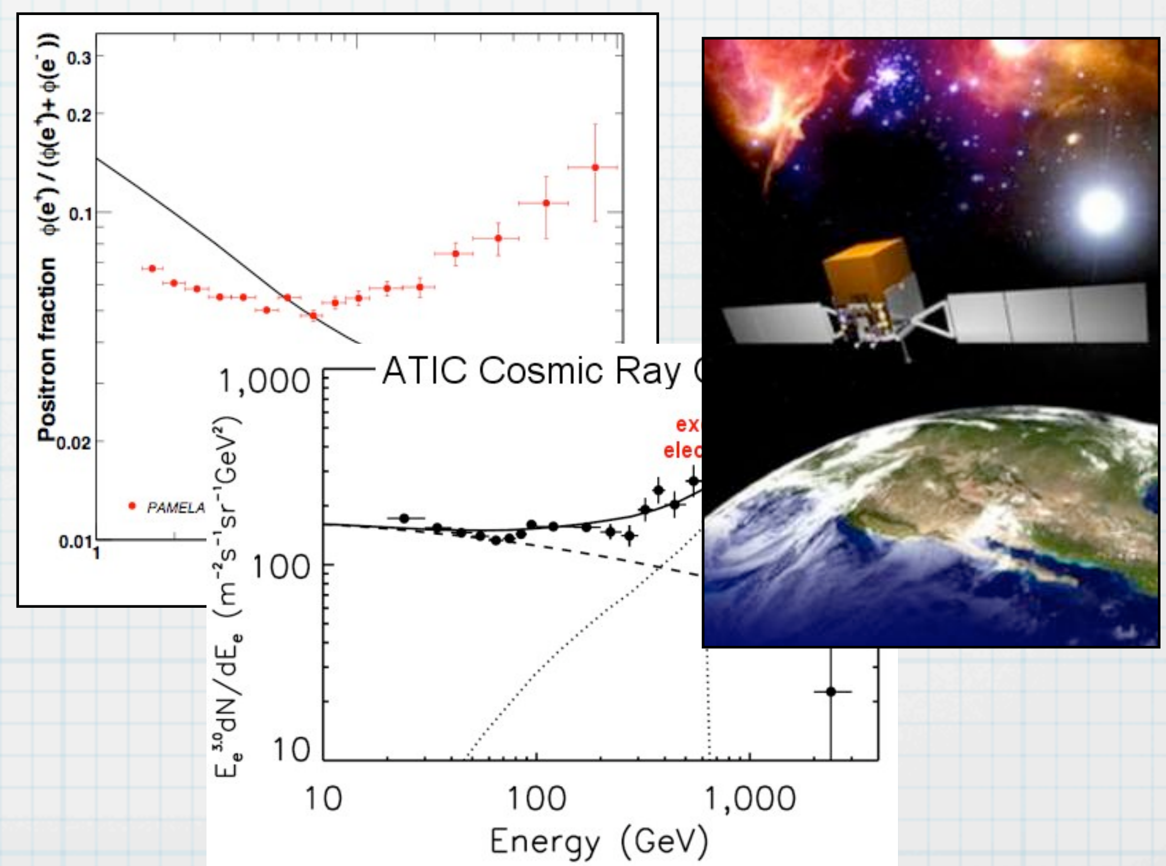



complementary experiments going on, either to detect DM directly

or indirectly..



# BSM Dark Matter, #1

* The usual story of BSM Dark Matter -- many BSM scenarios insist on a discrete symmetry under which SM particles are even, BSM particles are odd.

SM: EVEN

$$f \to f$$
$$h \to h$$
$$\ldots$$

NEW PHYICS: ODD

$$Z' \to -Z'$$
$$\tilde{f} \to -\tilde{f}$$

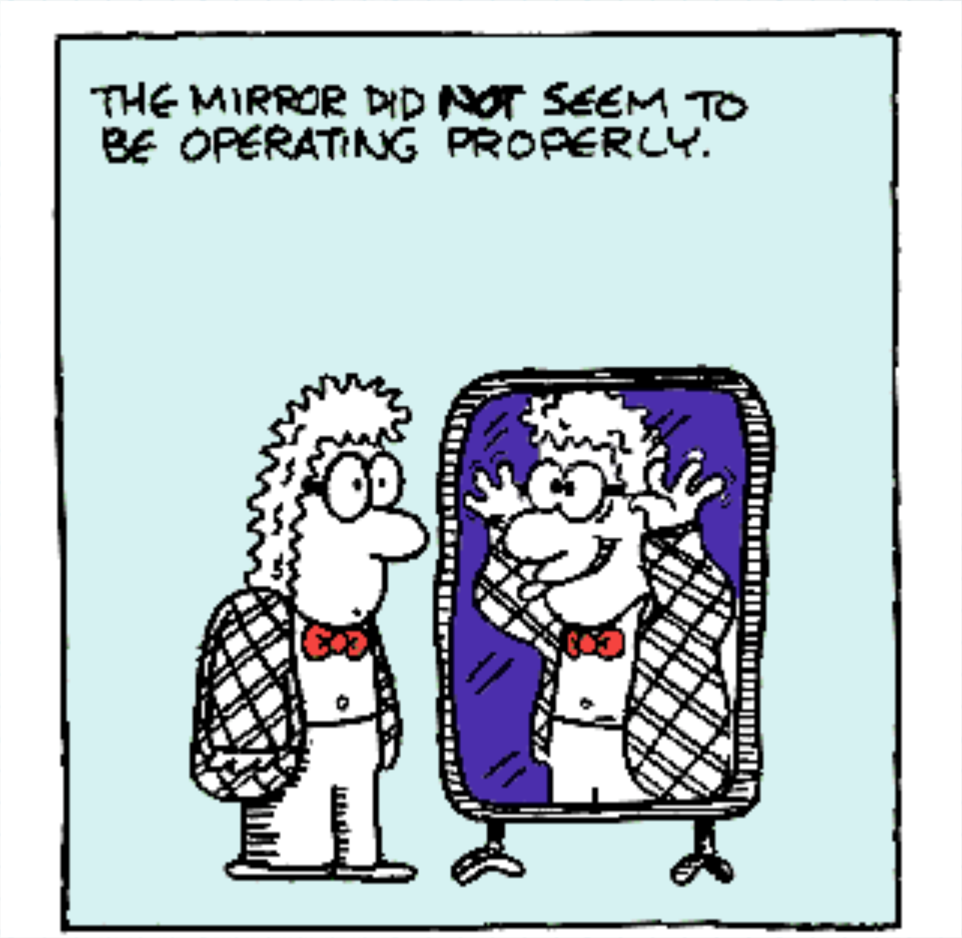
- R-parity in Supersymmetry
- KK-parity in UED models
- T-parity in Little Higgs Models
- ...

lightest odd particle is stable
DM candidate!

* this BSM-Parity is often needed for other phenomenological reasons (proton stability, FCNC, PEW)

# BSM Dark Matter, #2

* BUT **exact** discrete symmetry is a foreign concept in the Standard Model




in the SM, ALL discrete symmetries:

**C, P, CP**

are known to be violated.

In this light, imposing an exact parity on the new physics seems strange

# BSM Dark Matter, #3

- Why is the proton stable?
- No discrete symmetry protects it... Instead the low-energy SM theory has an approximate continuous symmetry, $U(1)_B$ baryon number $q_{Li} \to e^{iB/3} q_{Li}, \; q_{Ri} \to e^{iB/3} q_{Ri}$

  may be violated by higher dimensional operators, but as long as they lead to $\tau_p \gg \tau_{universe}$ , no cosmological problems
- Baryon # keeps p stable, but doesn't explain why we have more matter than anti-matter. For that we need an initial asymmetry $n_B \gg n_{\bar{B}}$ at $t = t_0$

# BSM Dark Matter, #4

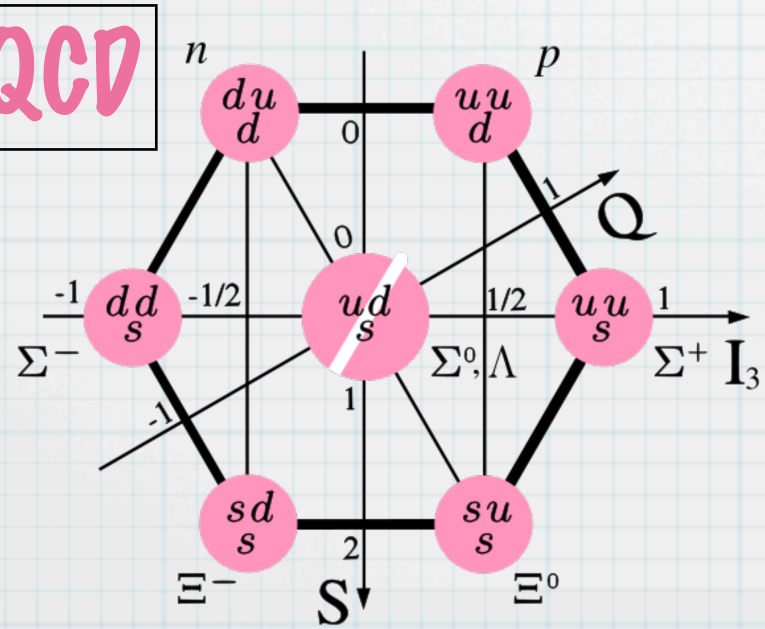
Initial $p-\bar{p}$ asymmetry + approximate $U(1)_B$ → stable proton

let's apply the same logic to BSM dark matter

**Techni-baryons are the perfect candidate**

need to make Technibaryon number an accidental symmetry of the EW-scale theory

QCD




→ TC ?

* charge, weak quantum numbers are set by Fermi statistics, $N_{TC}$, the number of technifermions and their representation

# BSM Dark Matter, #5

## Not quite that simple..

- Can't have technibaryon-number violating interactions -- constrains the ETC theory somewhat
- if the lightest technibaryon is charged -- ruled out by heavy isotope searches
- if the lightest techibaryon has EW quantum numbers -- large cross section nuclei from Z exchange, so ruled by direct DM detection experiments

## ..but still plenty of options:

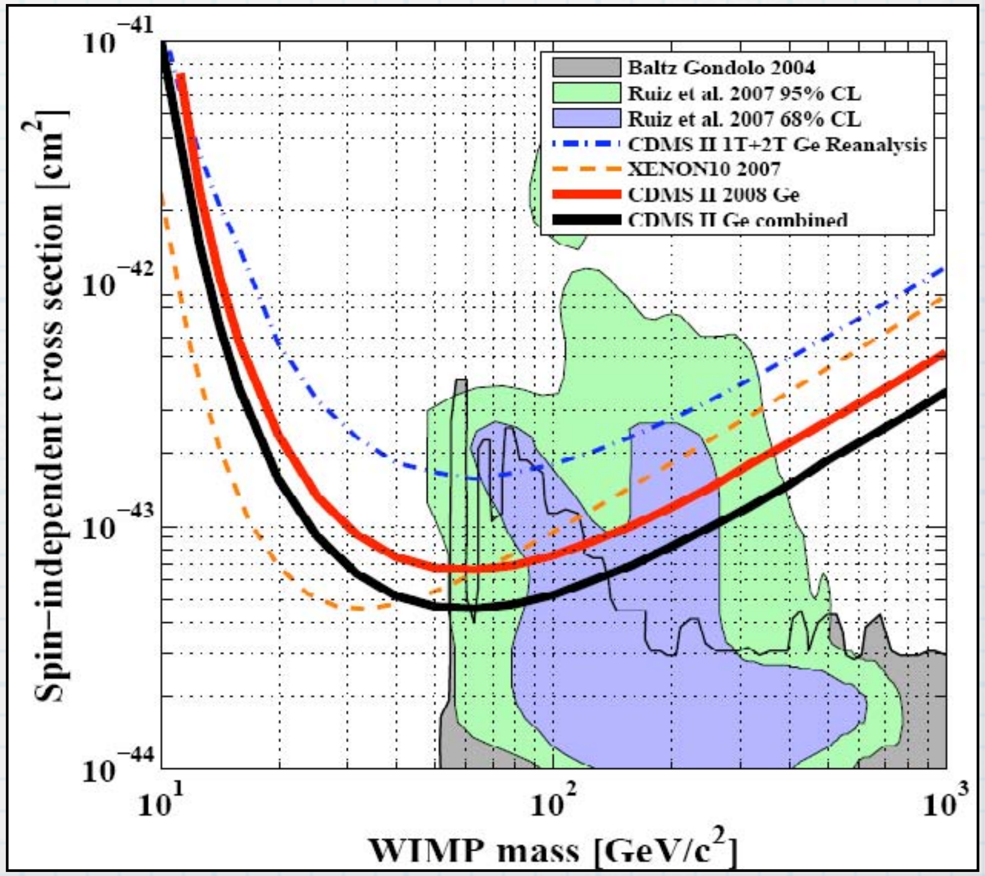
i.e.)

$N_{TC} = 4$ , one doublet: $T = \begin{pmatrix} U \\ D \end{pmatrix} \begin{matrix} Q_U = 1/2 \\ Q_D = -1/2 \end{matrix}$

lightest state: $\epsilon^{\alpha\beta\gamma\delta}(U^\alpha_\uparrow D^\beta_\downarrow U^\gamma_\uparrow D^\delta_\downarrow + \cdots)$

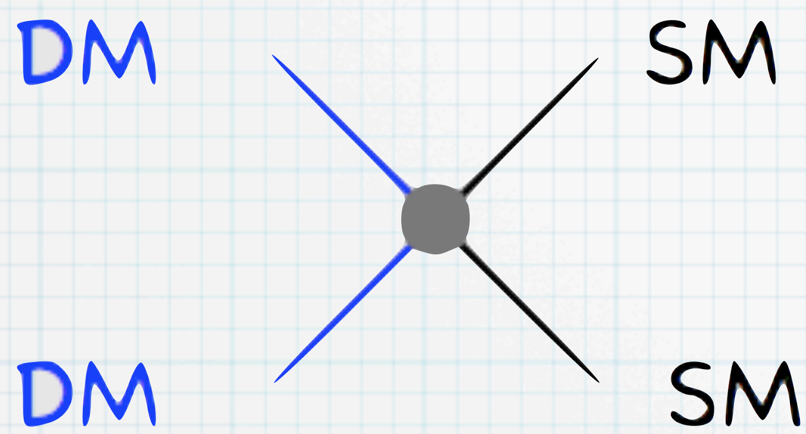
has $Q = 0, \; SU(2)_w$ singlet

(Chivukula '90)



# BSM Dark Matter, #6

* To see how viable a DM candidate is, we need its annihilation cross section:




$$\Omega_\chi h^2 \cong \frac{3 \times 10^{-27}\mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle \sigma_{ann} v \rangle}$$

BUT how do you know the annihilation cross section for a technibaryon -- a new strongly bound state?

* neat trick to get $\Omega_X h^2$ without direct calculation

(Nussinov, Barr Chivulkula Farhi, Kaplan)

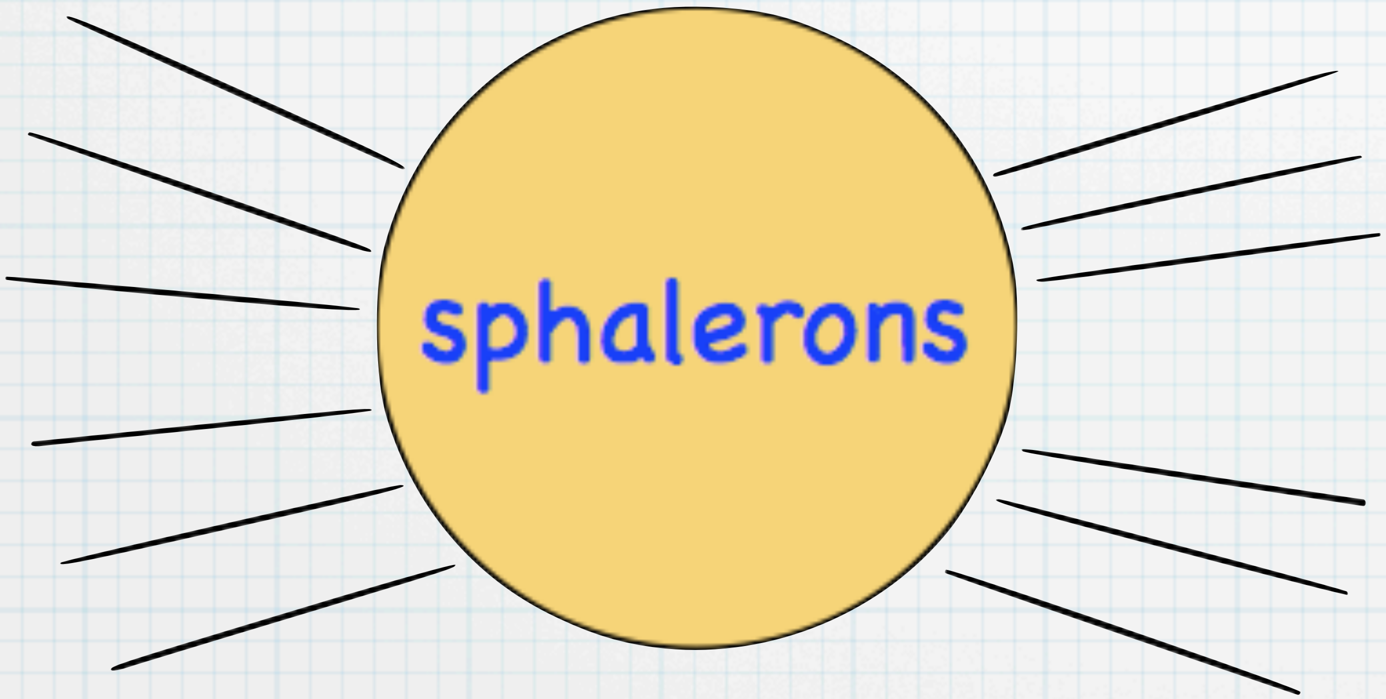
As technifermions have EW charges, technibaryon # is violated by anomalies, just like baryon # and lepton #, but the difference is not

# BSM Dark Matter, #7

* Therefore all three types of matter: quarks, leptons, technibaryons are connected by sphaleron processes

$$\partial_\mu J^\mu_{B,L,TB} \propto \frac{g^2 c_{B,L,TB}}{8\pi^2} W^a_{\mu\nu} \tilde{W}^a_{\mu\nu}$$

(Barr Chivukula Farhi '90)




When sphalerons are active

$$9\mu_q + 3\mu_\ell + N_D \mu_{TC} = 0$$

can redistribute any asymmetry between B, L, TB

# BSM Dark Matter, #8

Doesn't the fact that $\Lambda_T \gg \Lambda_{QCD}$ imply $\rho_{TC} \gg \rho_p$

not quite -- number density of heavy particles (compared to T) are **Boltzman suppressed**

$$n \sim \begin{cases} \mu_i & m \ll T \\ \mu_i e^{-m/T} & m > T \end{cases}$$

* So starting with some initial asymmetry, it gets spread in calculable ways between baryons, techibaryons, leptons

$$\rho_{TC} = \frac{6 g_{TC}}{N_{TC}} f(m^*_{TC}/T^*) \left| \frac{3}{4} + \frac{L}{3B} \right| \frac{m_{TC}}{m_p} \rho_p$$

**Accurately connects proton relic abundance to DM abundance** $\rho_{TC} \sim 5\rho_p$ **without fine tuning**

resurgent topic of research recently

# BSM Dark Matter, #9

$Q = 0, SU(2)_w$ singlet Technibaryons have very weak interactions with the SM

**no renormalizable interactions with SM**

most important terms are (for scalar technibaryon):

(in NR EFT power counting)

$$\frac{T^* T v_\mu \partial_\nu F^{\mu\nu}}{\Lambda_{TC}^2}$$ charge-radius operator

(Bagnasco, Dine, Thomas '91)

(Kribs) $$\frac{T^* T F^{\mu\nu} F_{\mu\nu}}{\Lambda_{TC}^3}$$ "polarizability" operator

(Chivukula, Cohen..)

other states with mass $\sim M_T$ possible

inelastic DM?

**LHC implications?**

# A word of caution before the fun starts

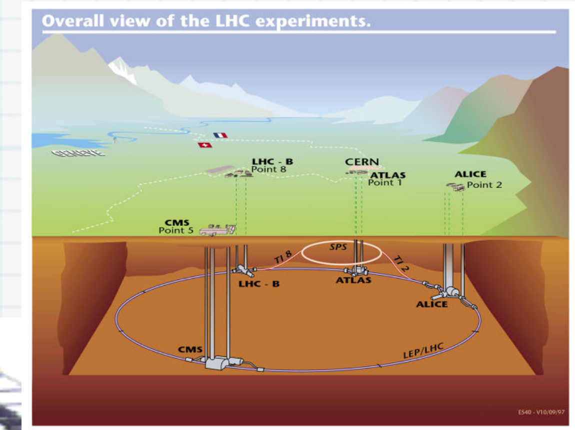
with so many ideas

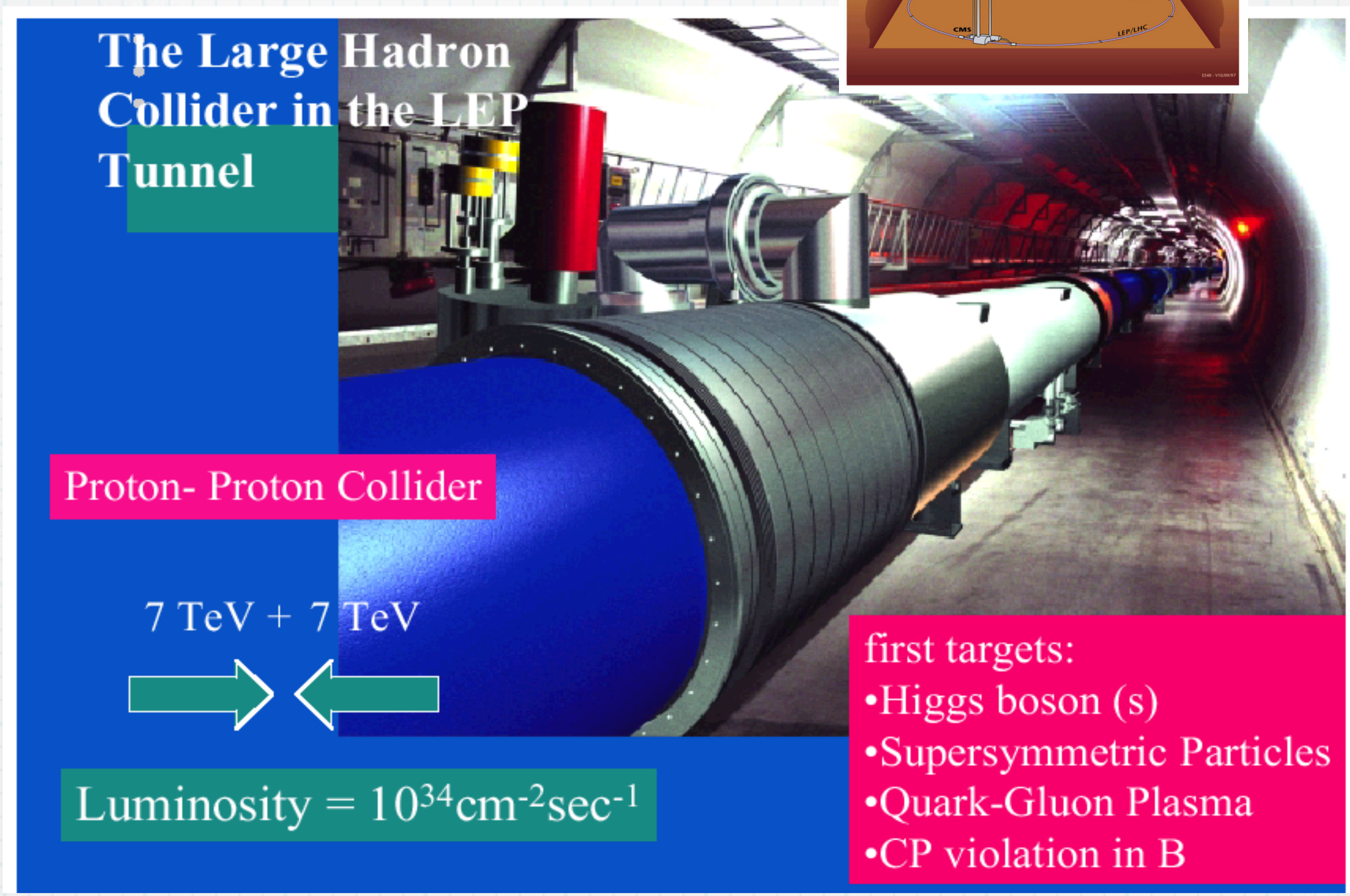

(Murayama)

you would think we would be unbiased about what we see at the LHC...

# ... but we are

LHC

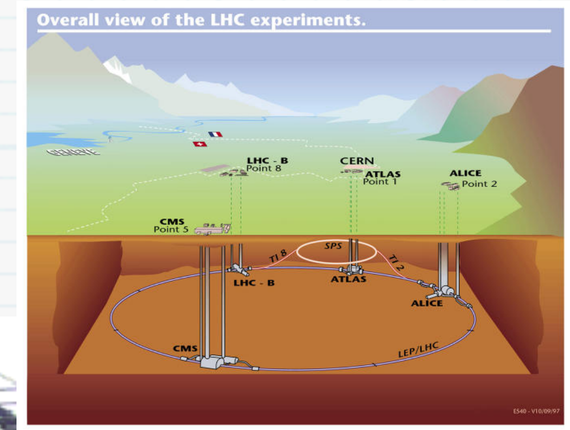


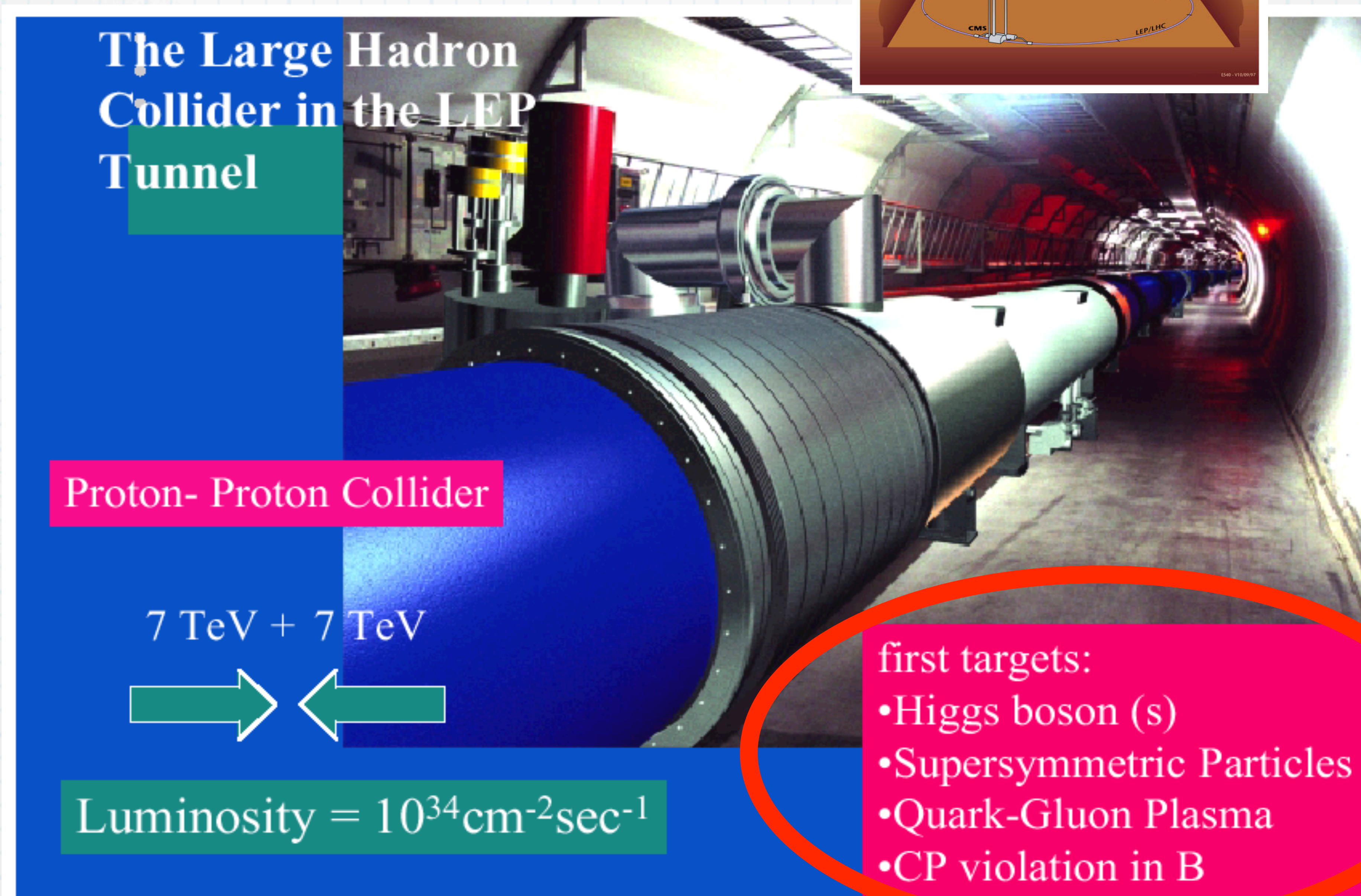




**From CERN education program webpage**

# ... but we are

# LHC




**From CERN education program webpage**

# Not convinced?

**ATLAS working groups**

## ATLAS Publications

- ATLAS Detector Paper (journal, chapt
- Expected Performance of the ATLAS

## Physics Groups

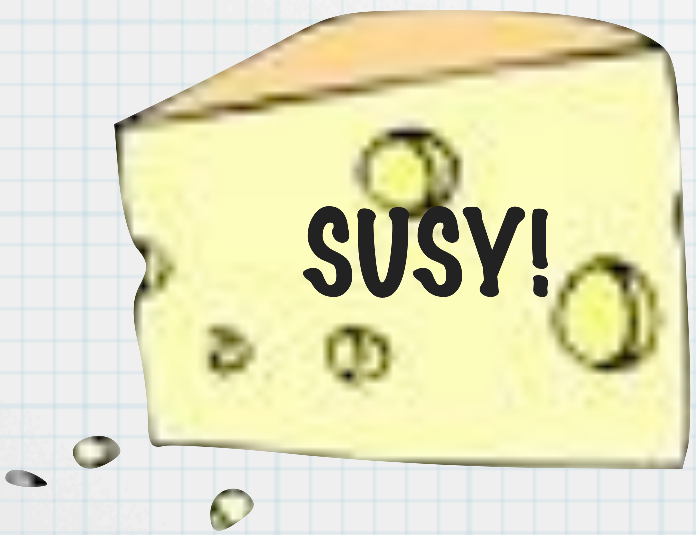
**Overall responsibility: Physics Coordinat**

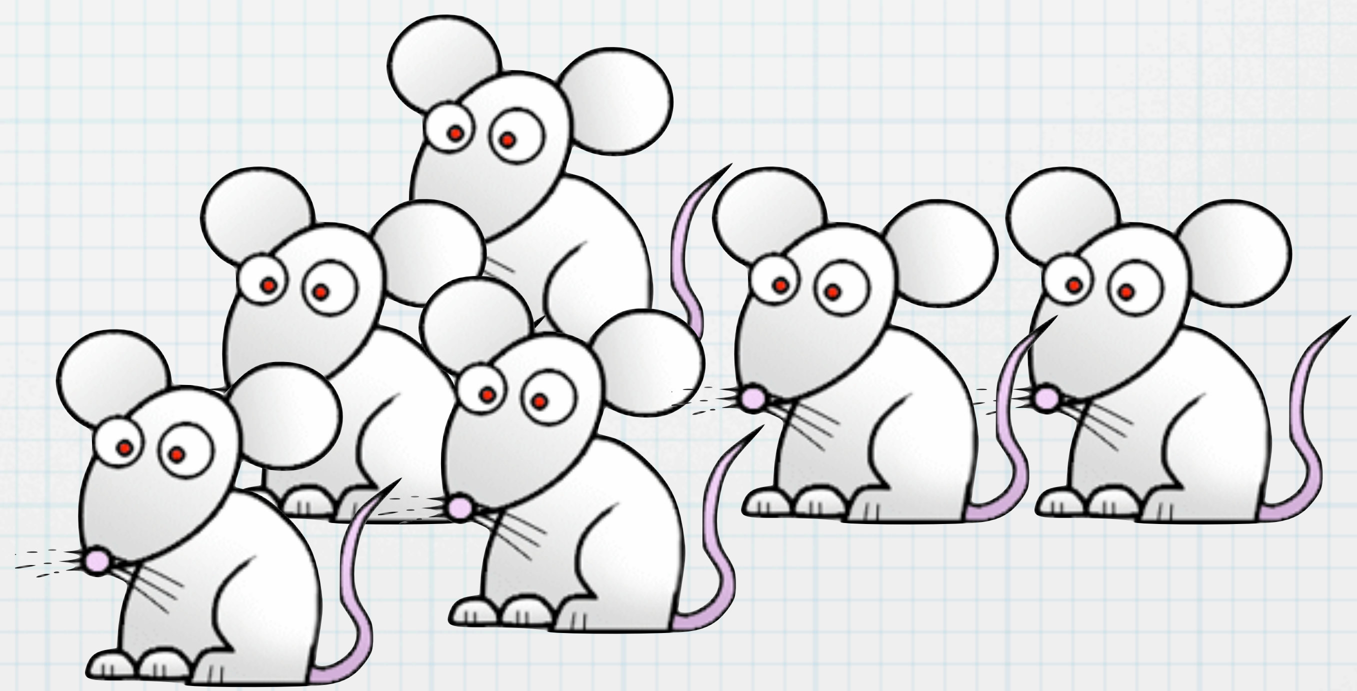
| Group | Link to public results |
|---|---|
| Standard Model | Results |
| B Physics | Results |
| Top Physics | Results |
| Higgs | Results |
| SUSY | Results |
| Exotics | Results |
| Heavy Ions | Results |
| Monte Carlo | *coming soon* |

SAME TREATMENT!?

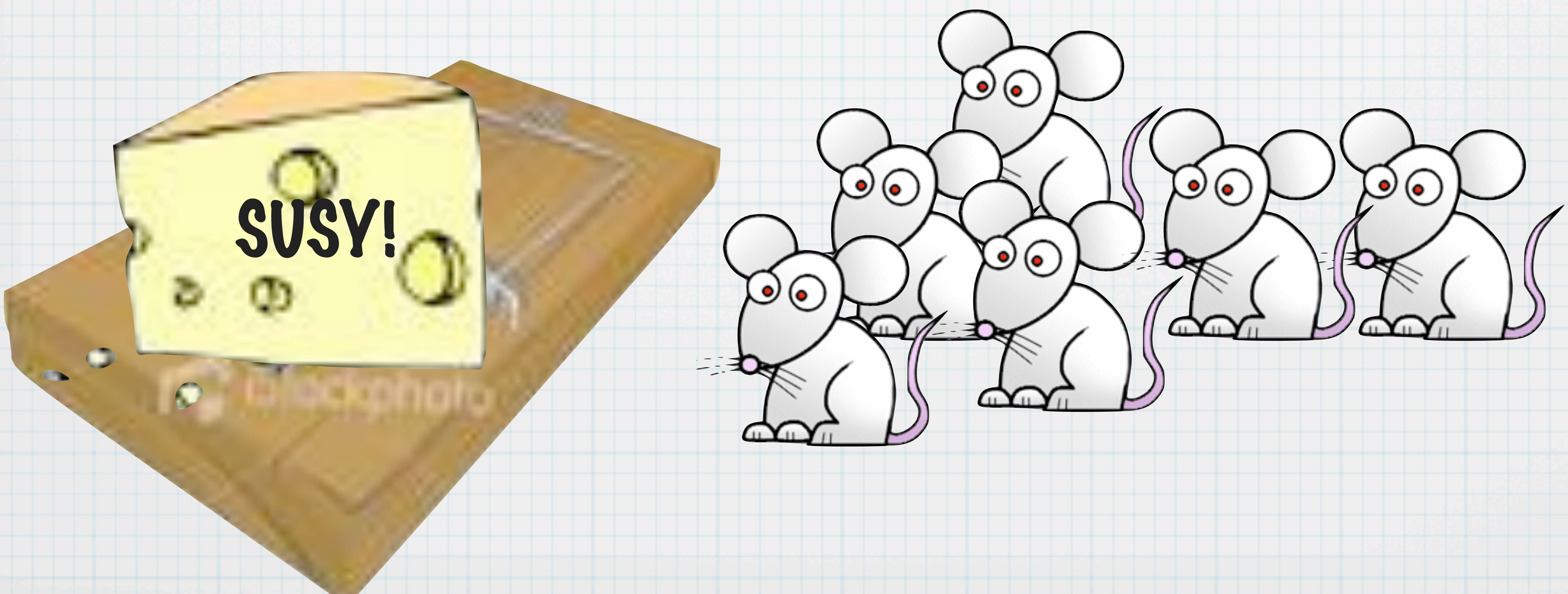
Technicolor, Little Higgs, etc.

# We should keep an open mind about what to expect at the LHC!

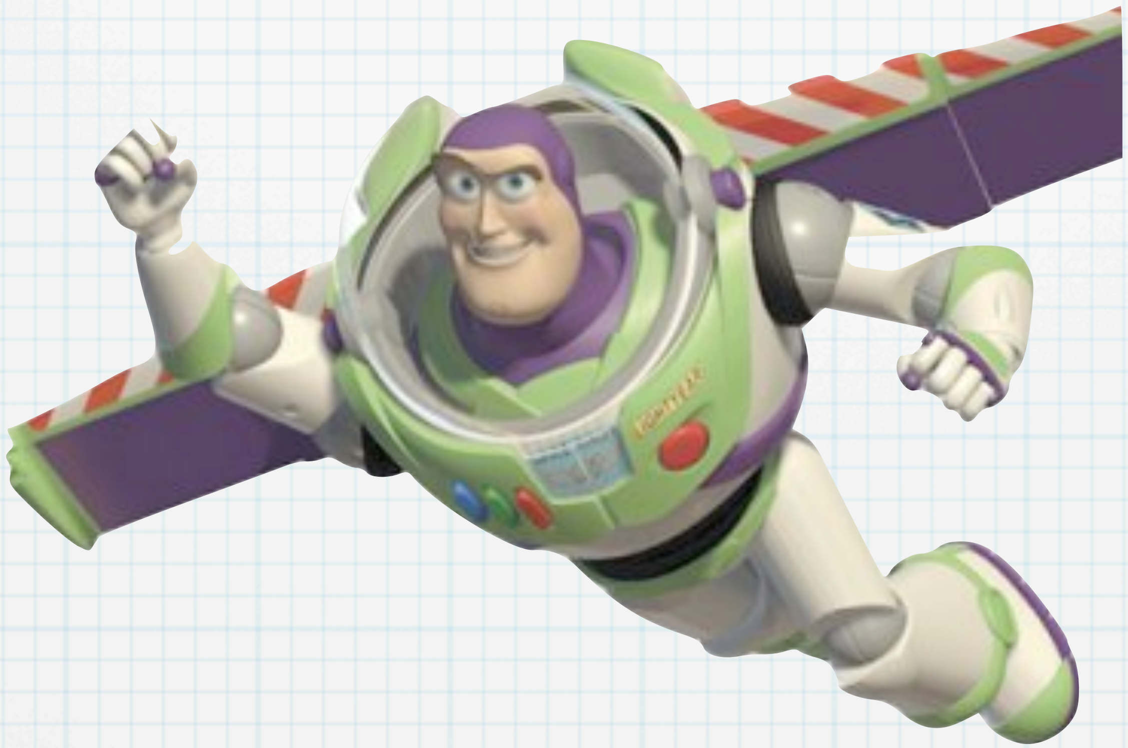


We should keep an open mind about what to expect at the LHC!



* it is an incredibly exciting time for particle physics, so we should keep an open mind and enjoy it!



# THANK YOU

# Sample References:

## On Techicolor basics:

- Hill, Simmons, hep-ph/0203079
- Chivukula, hep-ph/9803219
- Lane, hep-ph/02022025

+ references within

## On the phases of gauge theories:

- Intrilligator, Seiberg, hep-ph/9402044, 9411149
- Applequist, Sannino, hep-ph/0001043
- Appelquist et al, hep-ph/9806472

## On walking TC at the LHC:

- Eichten, Lane arXiv:0702339
- Azuelos et al, 2007 Les Houches proceedings, hep-ph/0802.3714
- Lane, Martin, arXiv:0907.3737

# Electroweak-Scale Strong Dynamics

**Lecture #1**

Adam Martin
Yale University

Parma International School of Theoretical Physics
Aug. 31 - Sept. 4, 2009

# Outline:

- **Lecture #1: Dynamical Electroweak Symmetry Breaking (DEWSB)**

Part 1:

-> pros and cons of the SM Higgs, why alternatives may be good
-> Dynamical EWSB (Technicolor) as an alternative,
-> E x t e n d e d Technicolor: fermion mass generation
-> problems with 'old' Technicolor

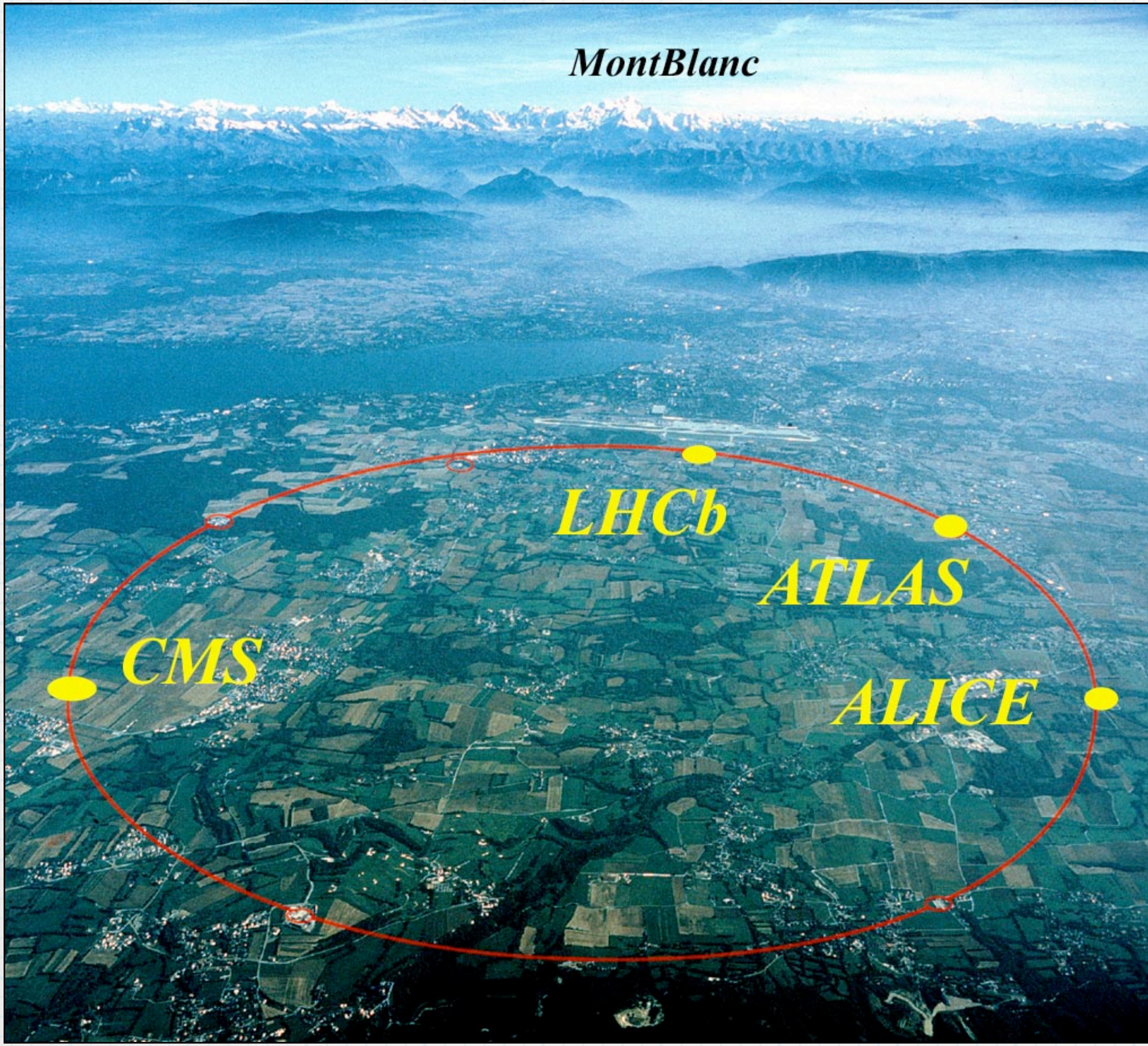
Part 2:

-> Peculiarities of QCD and the phases of gauge theory
-> Walking Technicolor (WTC) motivation and implementation,
-> how walking saves the day & where it fails,
-> walking studies on the lattice
-> LHC phenomenology of 'modern' technicolor

- **Lecture #2: Related topics**

-> Other Tev-scale strong dynamics: Composite Higgs
-> Extra-Dimensions models of Technicolor: Higgsless models
-> Technicolor and Dark Matter

# We are finally in the LHC era



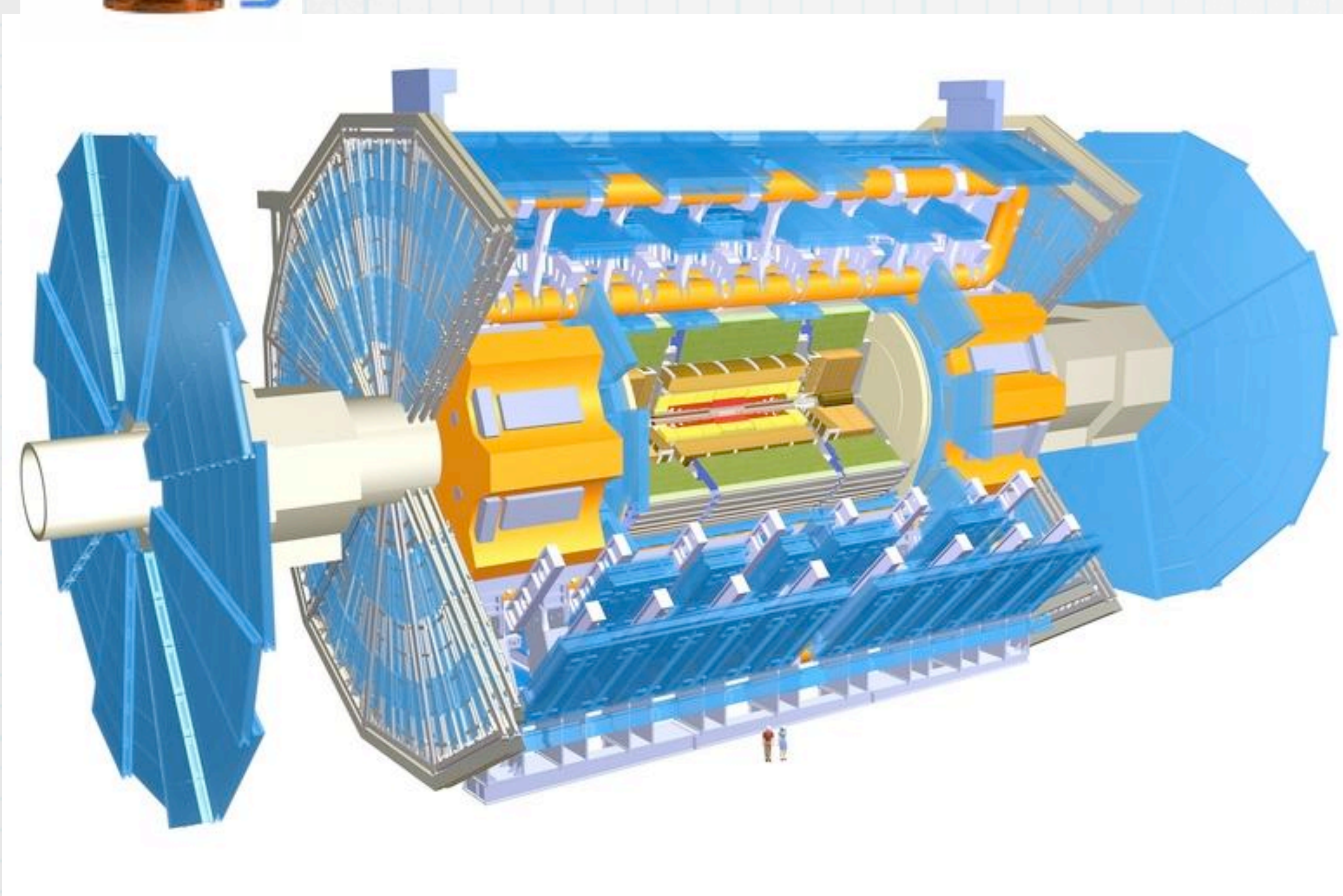

the most exciting time in particle physics in the last three decades

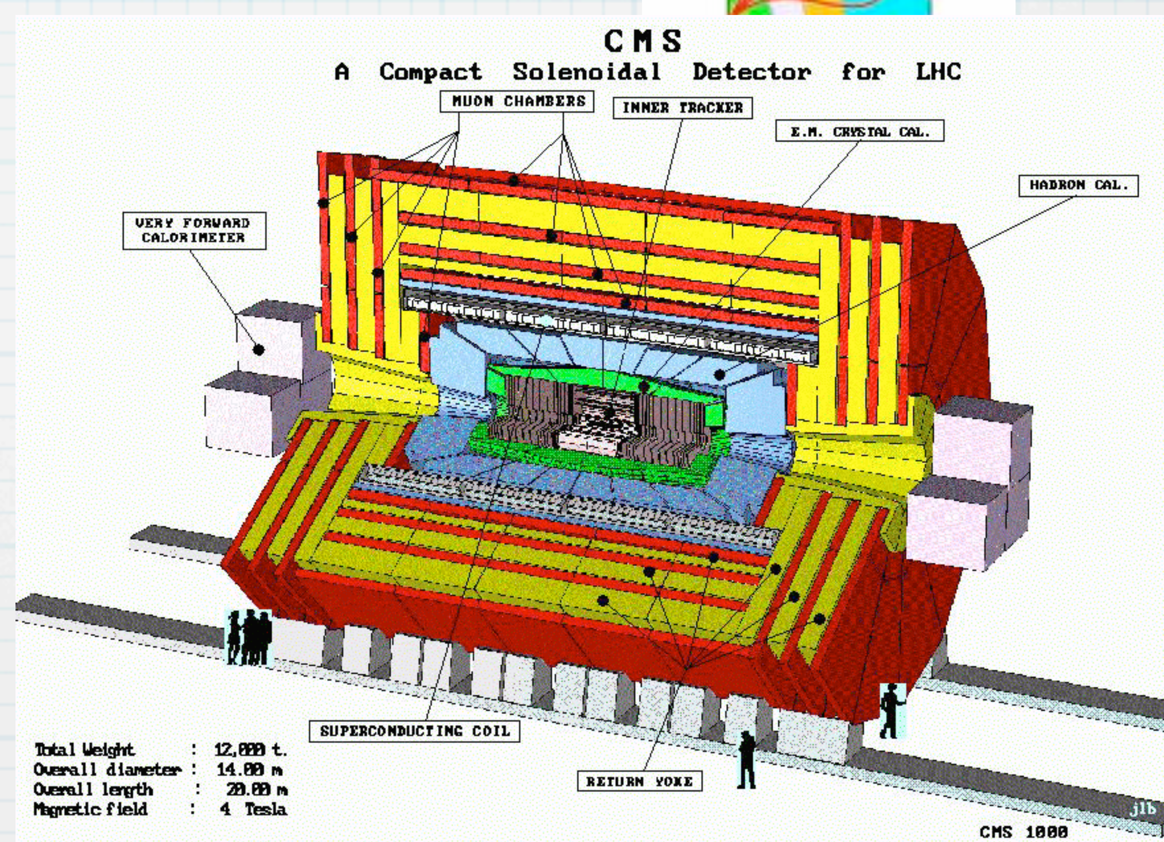
this machine is built to probe the 100 GeV - few TeV energy range

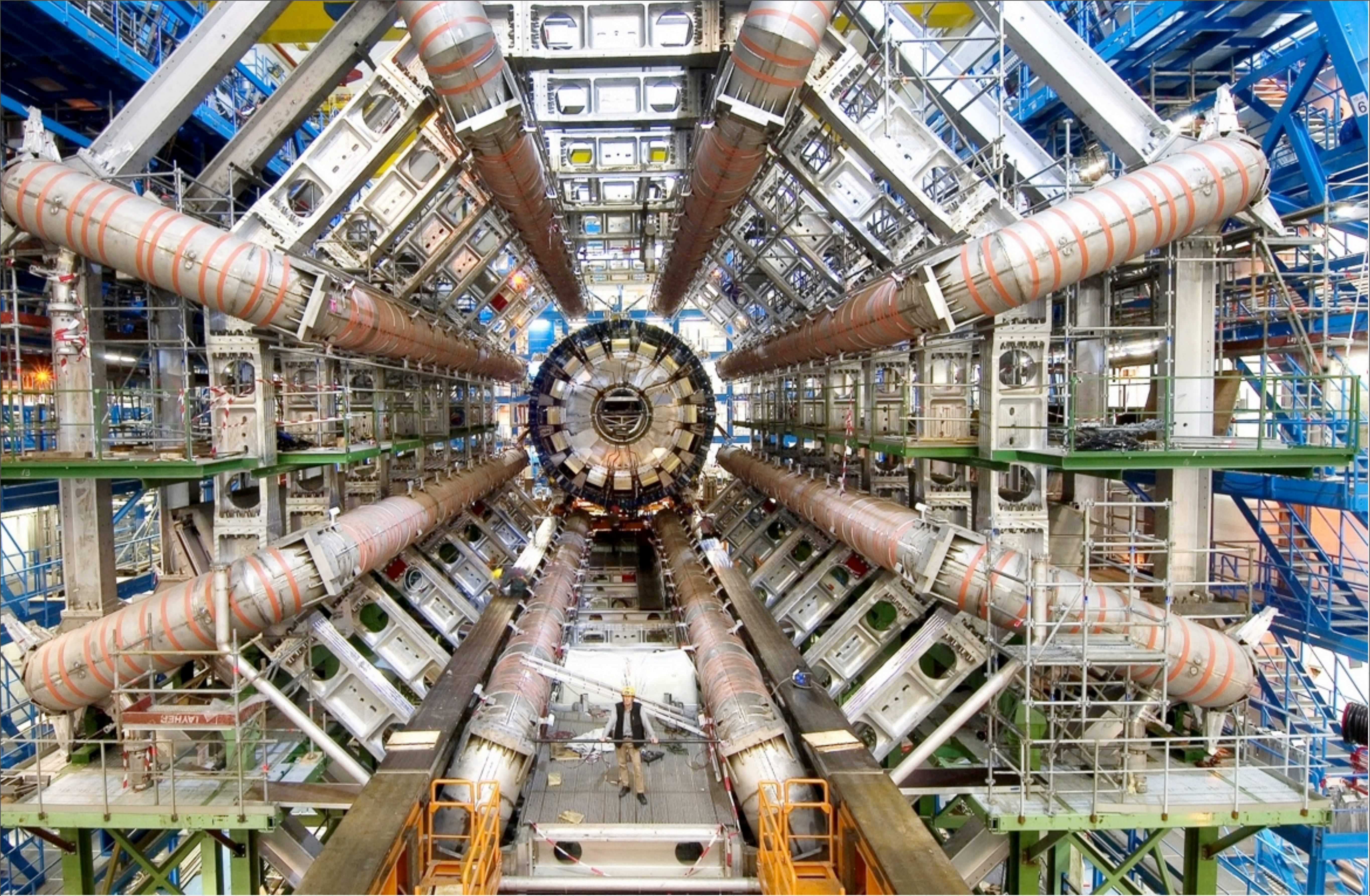
# This is an incredibly exciting time for particle physics!

LHC is a **27 km** circumference **pp collider** with center of mass energy 10-14 TeV ( 7 TeV initially)

4 main experiments, **two** dedicated to the discovery and study of new particles with mass in the **TeV range** $\mathcal{O}(100 \text{ GeV} - \text{few TeV})$



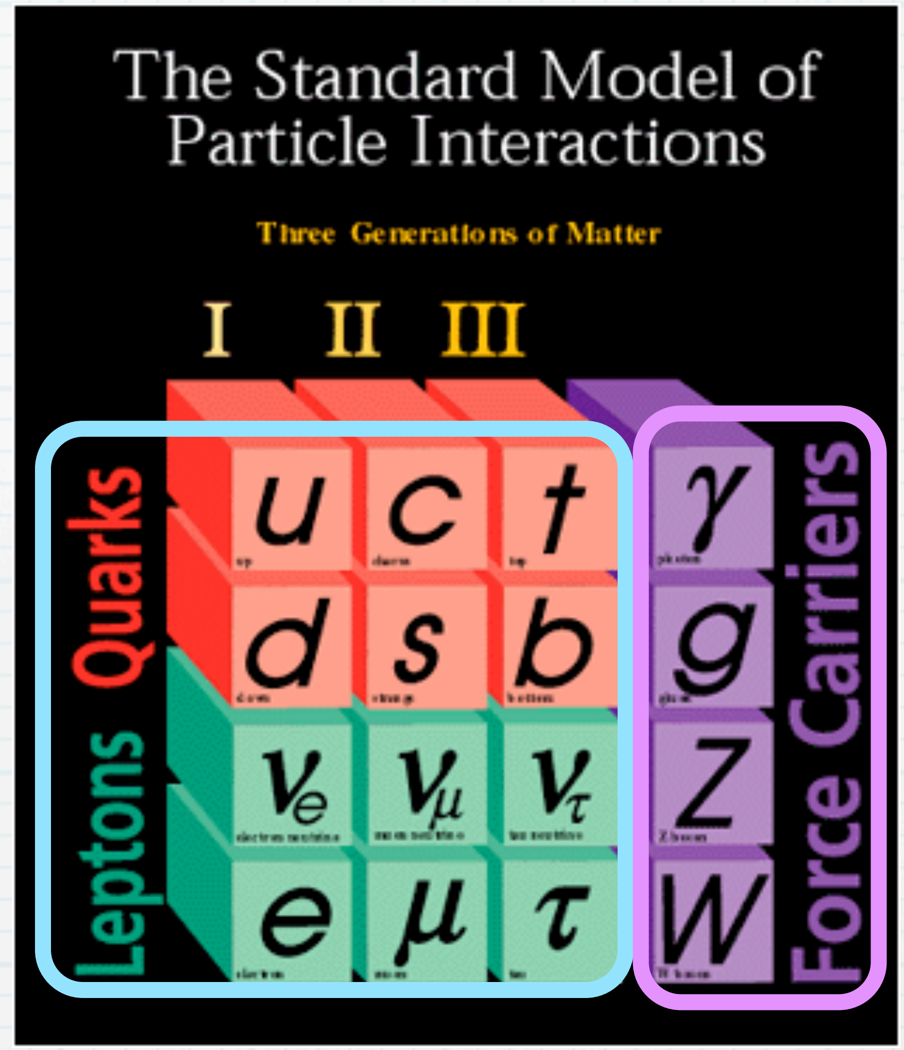




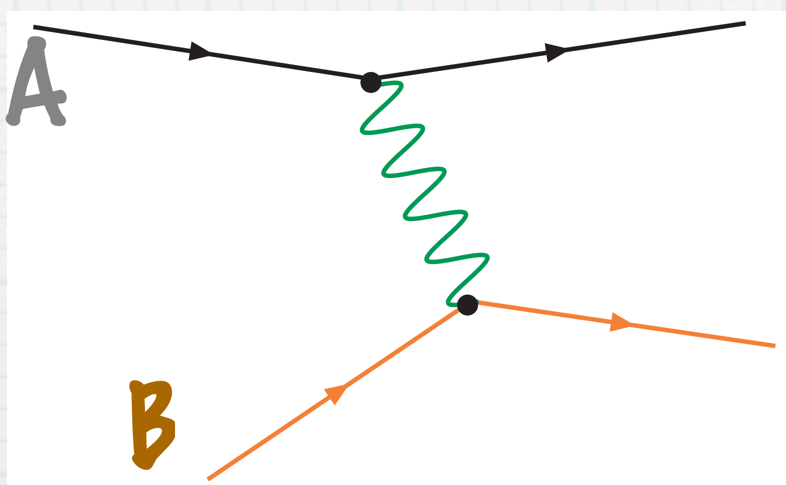
cartoons don't quite do the size of these experiments justice!

# Why did we build the LHC?

* The Standard Model is highly successful and describes all observations to date




forces between matter are described by the exchange of 'force-carrying' particles




* Guiding principles are **gauge invariance**, renormalizability
* Massless photon, gluon, while massive $W^{\pm}, Z$

# Why did we build the LHC?

* **Gauge invariance** prevents mass terms for gauge bosons or chiral fermions

under $SU(2)_W$

$$W^a_\mu \to U_L A^a_\mu U^\dagger - \frac{i}{g}(\partial_\mu U_L)U_L^\dagger$$

$$q_L \to U_L q_L, \quad q_R \to q_R$$

**forbid** $m_A^2 A^\mu A_\mu$, $m_f \bar{q}_R q_L$

* Gauge boson mass is possible only through the **HIGGS MECHANSIM**: **spontaneous breakdown** of
$$SU(2)_w \otimes U(1)_Y \to U(1)_{em}$$

* How can such a breakdown occur? Simplest idea -- use a single scalar field with a very particular potential

# Standard Model Higgs Boson

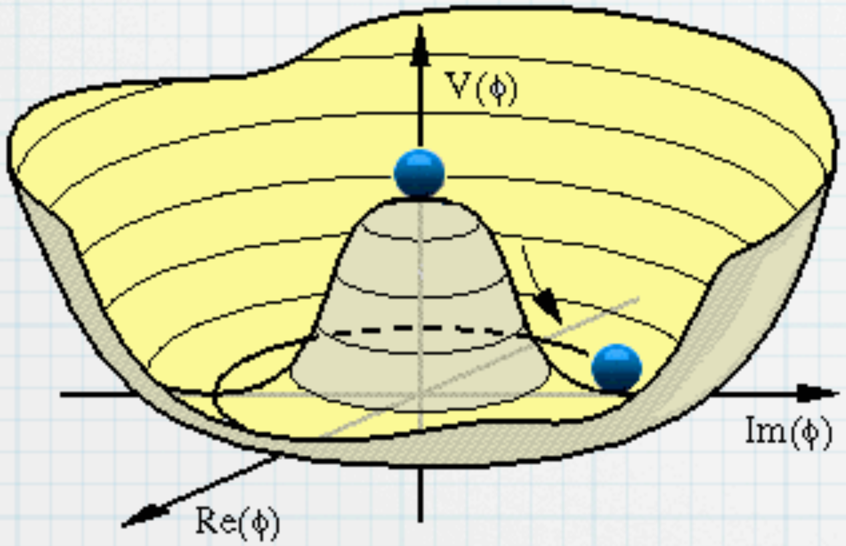
(see lectures by M. Quiros)

* Add to the Lagrangian $|D_\mu H|^2 - \lambda(H^\dagger H - \frac{v^2}{2})^2$

where $H \in (2, 1/2)$, is a complex scalar doublet (4 d.o.f)

$$D_\mu H = \partial_\mu H - igW_\mu^a \tau_a H - i\frac{g'}{2}B_\mu H$$

* The minimum of the potential is at a nonzero field value,




$$\langle H \rangle = \frac{v}{\sqrt{2}}$$

parameterize

$$H = \frac{v+h}{\sqrt{2}}U, \quad U = e^{2i\tau_a \pi^a}$$

* With this choice of potential, $W^\pm$ and one combination of $B, W_3\,(Z^0)$ become massive $M \sim gv$.

The remaining combination

$\cos(\theta_W)B + \sin(\theta_W)W_3 \equiv \gamma$ is massless

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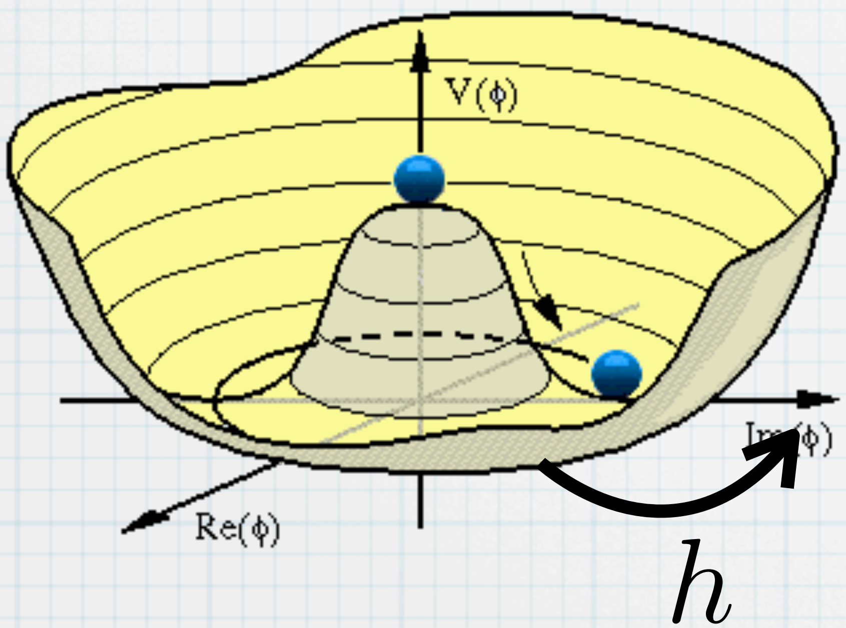


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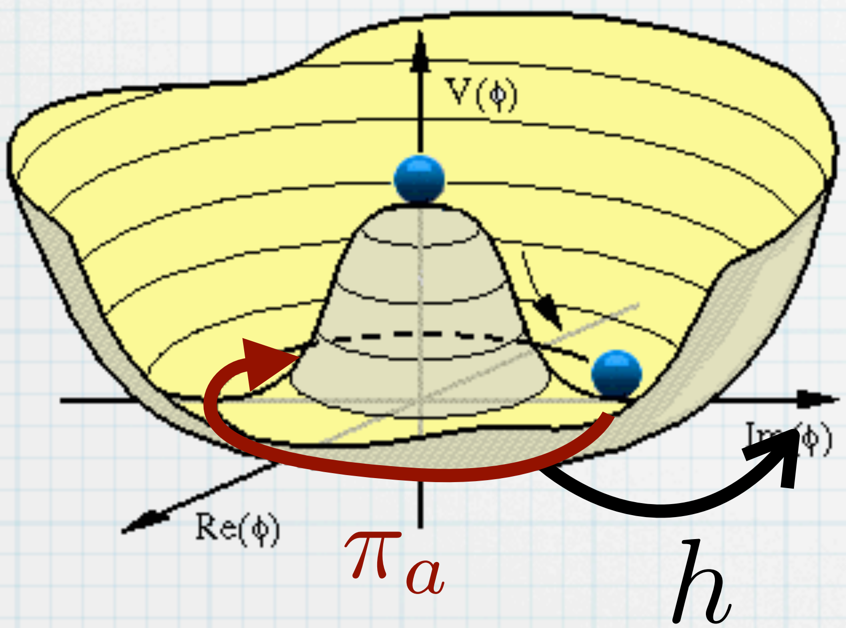


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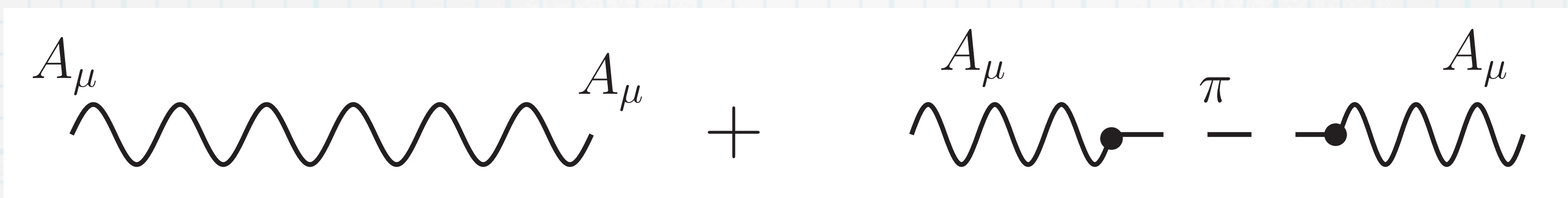
# Higgs Mechanism vs. Higgs Boson

* $\pi_a$ can be removed by an $SU(2)_W \otimes U(1)_Y$ gauge transformation --> **Unitary Gauge**

$\pi_a$ are 'eaten' by the $W^{\pm}, Z$ to become their **longitudinal degrees of freedom** **(Higgs mechanism)**



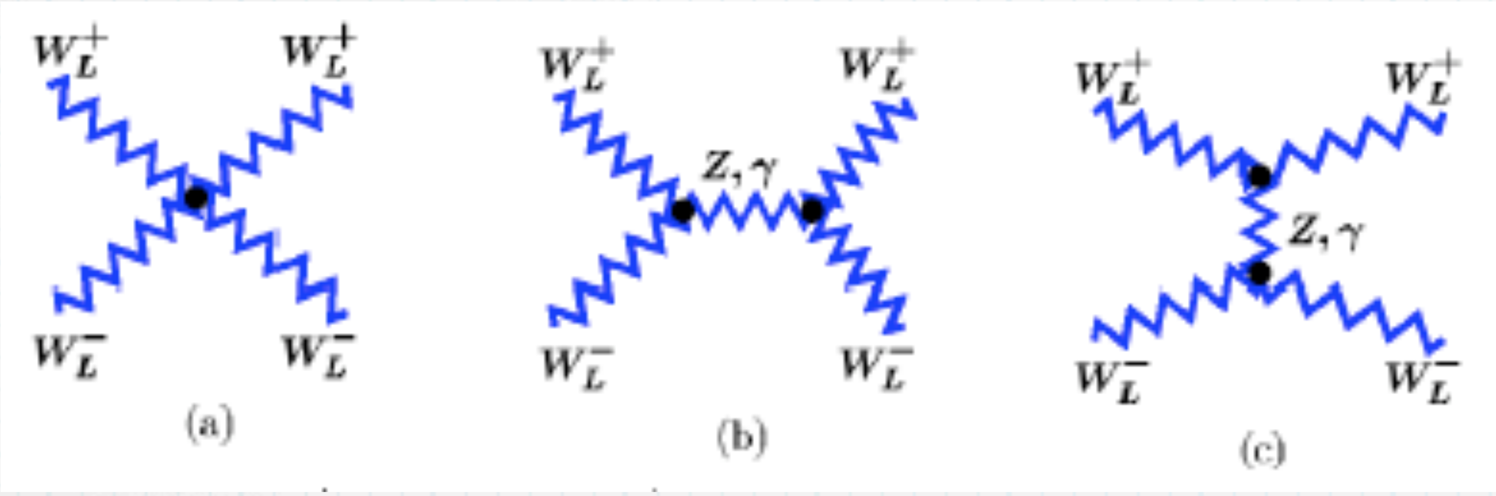

* The **Higgs mechanism** doesn't care where the three degrees of freedom come from **(independent of Higgs boson)**

**ingredients:**


**some operator, fundamental or composite, with $(2, \frac{1}{2})$ quantum numbers under $SU(2)_w \otimes U(1)_Y$**

# Why did we build the LHC?

- what's wrong with just adding mass terms for W, Z?
- Scattering amplitudes involving the longitudinal polarizations are BADLY behaved




$$\epsilon_L^\mu \sim \frac{k_\mu}{m_W}$$

so, naively

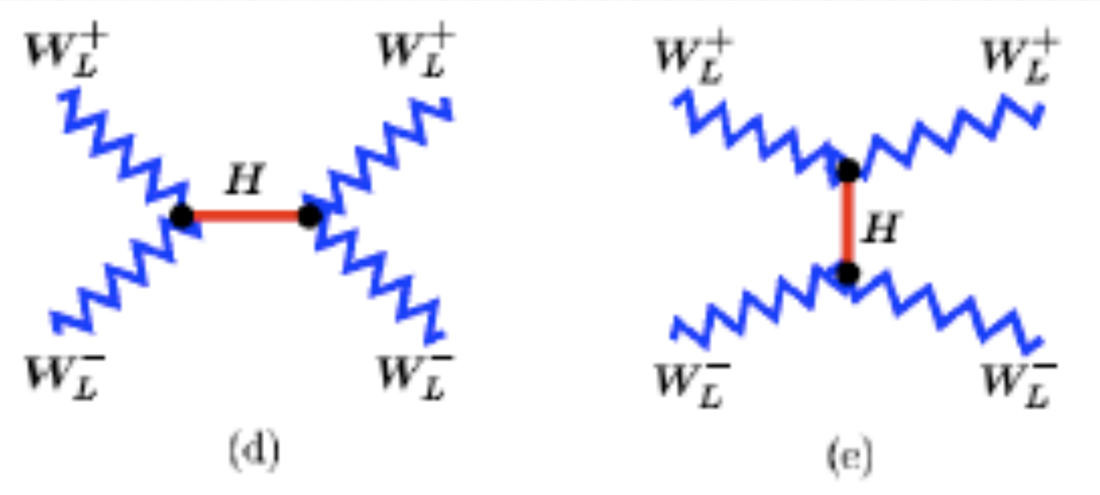
$$A \sim \frac{E^4}{m_W^4}$$

$E^4$ piece cancels between (a) - (c), but leftover $E^2$ piece

Something must cancel this growth or perturbative unitarity will be violated

$$A > 1$$

Adding the Higgs boson does this perfectly, provided it is LIGHT, $m_H \lesssim 1 \text{ TeV}$




(Dicus, Mather '73
Lee, Quigg, Thacker '77)

# Role of Custodial Symmetry

* Success of single SM Higgs tells us something deeper about whatever other mechanism for EWSB we might want to try:

* Higgs potential has a LARGER (global) symmetry:

re-express:

$$H = \begin{pmatrix} h_1 + ih_2 \\ h_0 + ih_3 \end{pmatrix}$$

then $V = \lambda(H^\dagger H - \frac{v^2}{2})^2$

depends only on $h_0^2 + h_1^2 + h_2^2 + h_3^2$

therefore is invariant under

$$SO(4) \cong SU(2) \otimes SU(2)$$

in the vacuum, $\langle h_0 \rangle = v$ breaks this down to $SO(3) \cong SU(2)$

residual $SU(2)$ is called a 'custodial symmetry'

If the rest of the Largangian were exactly $SU(2)$ invariant,

$h_1, h_2, h_3 \to W^\pm, Z^0$ would all have the same mass

# Role of Custodial Symmetry, #2

* **BUT**, SM interactions do NOT respect this symmetry, specifically hypercharge

$$|D_\mu H|^2 \supset -\frac{g}{2}(\partial_\mu \vec{h} \cdot \vec{W}^\mu) + \frac{g'}{2}(\partial_\mu h_3 B^\mu) + \cdots$$

$SU(2)$ preserving

$SU(2)$ violating

therefore

Two conditions: $\begin{cases} \text{massless photon} \\ \text{degenerate } W^\pm, Z^0 \text{ in } \lim\, g' \to 0 \end{cases}$

**completely specify the EW gauge boson mass matrix**

$$M^2 = \frac{v^2}{2}\begin{pmatrix} g^2 & & & \\ & g^2 & & \\ & & g^2 & -gg' \\ & & -gg' & g'^2 \end{pmatrix}$$

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2(\theta_W)} = 1$$

Experimentally, we measure:

$$\Delta\rho \equiv \rho - 1 < 0.4\%$$

# Role of Custodial Symmetry, #2

Yukawas also violate custodial symmetry, but they only affect gauge bosons at loop level

* **BUT**, SM interactions do NOT respect this symmetry, specifically hypercharge

$$|D_\mu H|^2 \supset -\frac{g}{2}\underbrace{(\partial_\mu \vec{h}\cdot \vec{W}^\mu)}_{SU(2)\ \text{preserving}} + \underbrace{\frac{g'}{2}(\partial_\mu h_3 B^\mu)}_{SU(2)\ \text{violating}} + \cdots$$

therefore

Two conditions: $\left\{\begin{array}{l}\text{massless photon}\\ \text{degenerate } W^\pm, Z^0 \text{ in } \lim g' \to 0\end{array}\right.$

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Experimentally, we measure:

$$\Delta\rho \equiv \rho - 1 < 0.4\%$$

# So, we've learned:

- massless photon,
- custodial symmetry when $g' \to 0$

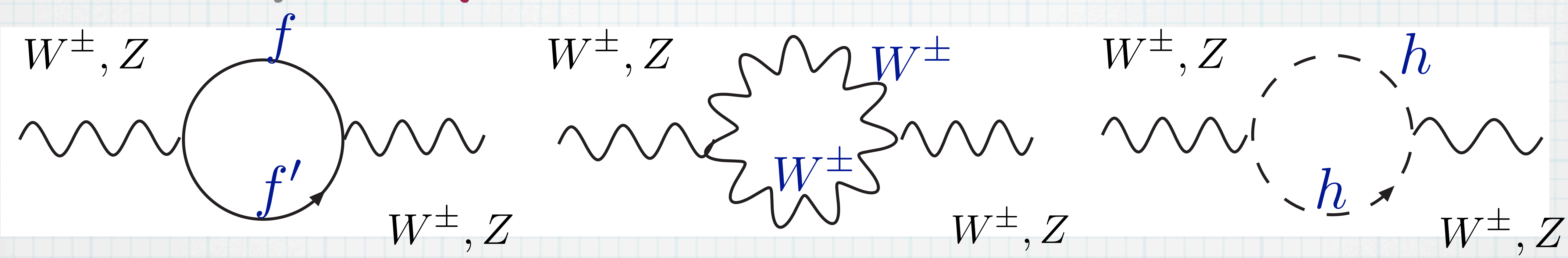
experimentally verified result $\rho \cong 1$

**Custodial Symmetry is an important part of any theory of EWSB!**

# Why theorists like a simple Higgs

* Once we consider **quantum corrections** to the tree level SM, couplings and parameters become sensitive to the Higgs properties (or other new physics)--> **indirect tests**

* Example: **oblique corrections**




$$\mathcal{L} \supset -\frac{A(q^2)}{4} F^{\mu\nu} F_{\mu\nu} - \frac{B(q^2)}{4} Z^{\mu\nu} Z_{\mu\nu} - \frac{C(q^2)}{2} W^{+,\mu\nu} W^{-}_{\mu\nu} - \frac{D(q^2)}{4} F^{\mu\nu} Z_{\mu\nu}$$
$$-\frac{M_Z^2}{2} z(q^2) Z^\mu Z_\mu - M_W^2 w(q^2) W^+_\mu W^{-\mu}$$

where $A = A(m_t, m_h, q^2 \cdots)$, etc.

depend on properties of particles in loops

now remove mixing, canonically normalize: $W^+_\mu \to \frac{W^+_\mu}{\sqrt{C(q^2)}}$, etc.

(Burgess et al '93)

# Precision Electroweak Tests

* we have **six** corrections $A, B, C, D, w, z$, but three can be absorbed into the **three** parameters which define the EW theory $g, g', v$ (more conveniently $\alpha_{em}, G_F, M_Z$ )

* The remaining three corrections parameterize new physics, and are commonly combined into the combinations **S,T,U**

* Within SM: $S(m_h, m_t, ...)$, if new physics: $S(m_h, m_t, M_X, g_X, ...)$

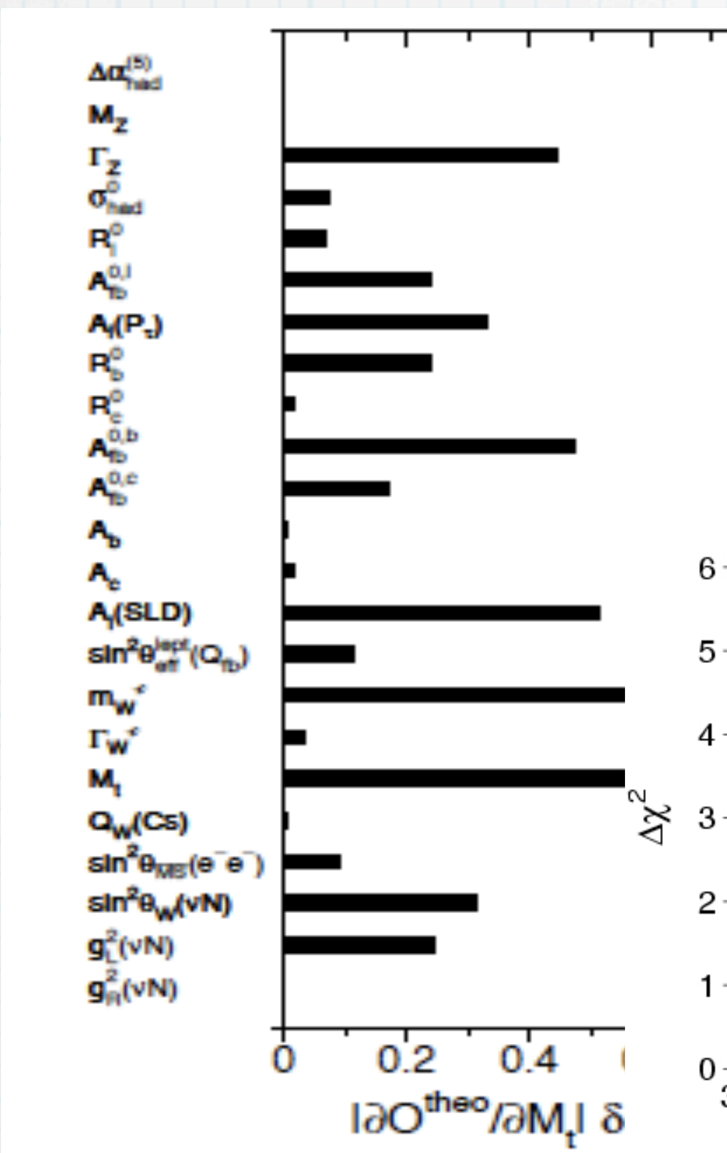
* All deviations from the tree-level SM in the EW sector can be phrased in terms of **S,T,U**

$$\delta g_{iL(R)} = \frac{\alpha T}{2} - Q_i \left( \frac{\alpha S}{4(c_w^2 - s_w^2)} - \frac{c_w^2 s_w^2 \alpha T}{c_w^2 - s_w^2} \right)$$

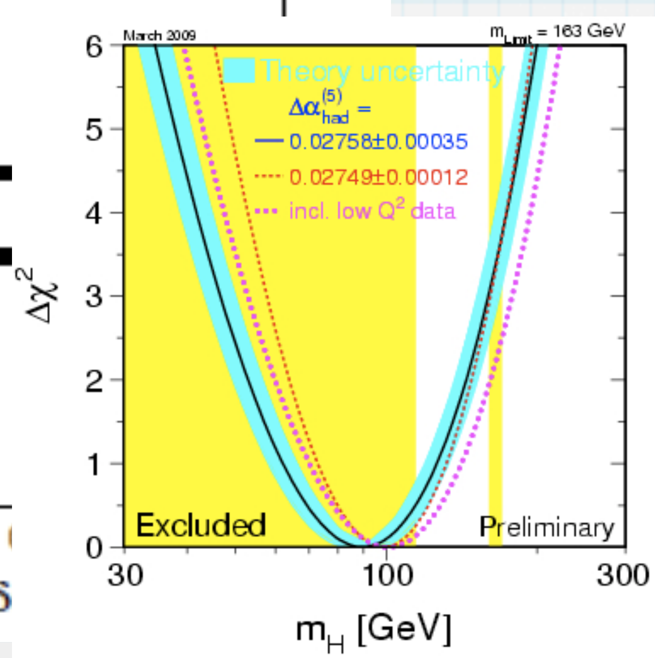
$$\frac{\delta M_W^2}{M_W^2} = -\frac{\alpha S}{2(c_w^2 - s_w^2)} + \frac{c_w^2 \alpha T}{c_w^2 - s_w^2} + \frac{\alpha U}{4 s_w^2} \quad \text{,etc}$$

# Precision Electroweak Tests

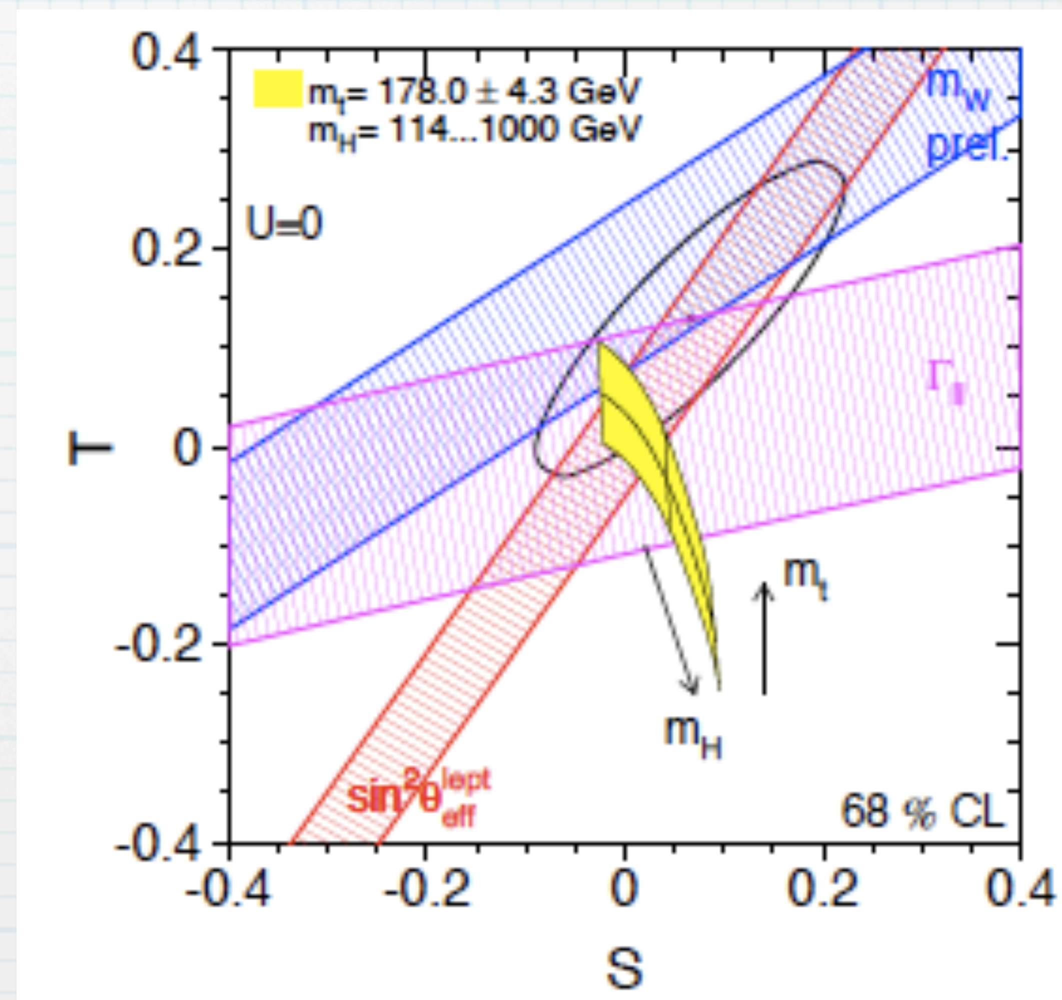
* LEP, LEP II (1989 - 2000) experiments measured $\delta g_{iL(R)}, M_W, A_{LR}$, etc. precisely. $\sqrt{s} \leq 208\ \mathrm{GeV}$




| Parameter | Average |
|---|---|
| $g_{A\nu} \equiv g_{V\nu}$ | $+0.5003 \pm 0.0012$ |
| $g_{Ae}$ | $-0.50111 \pm 0.00035$ |
| $g_{A\mu}$ | $-0.50120 \pm 0.00054$ |
| $g_{A\tau}$ | $-0.50204 \pm 0.00064$ |
| $g_{Ve}$ | $-0.03816 \pm 0.00047$ |
| $g_{V\mu}$ | $-0.0367 \pm 0.0023$ |
| $g_{V\tau}$ | $-0.0366 \pm 0.0010$ |
| Parameter | Average |




* measurements can be interpreted as limits on new physics



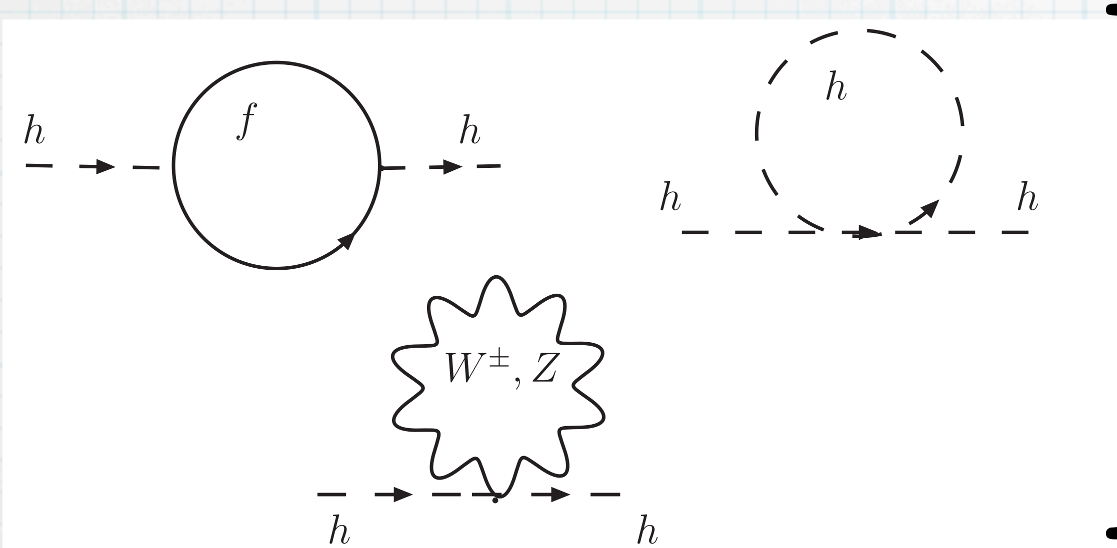

* A light, Standard Model Higgs boson is preferred by these indirect measurements

# Why theorists dislike just a SM Higgs

* **NO** fundamental scalars have been seen in nature

* Higgs potential and vev are **put in by hand:**
  chosen so that $V(0) = 0, V''(0) < 0$

* Quantum corrections in the Higgs sector are **badly divergent:**




$$\delta m_H^2 \sim \frac{\Lambda^2}{16\pi^2}$$

the Higgs mass is **quadratically sensitive** to the highest scales in the theory!

renormalization of scalar mass is additive, not multiplicitive:

no chiral symmetry!

$$m_{H,phys}^2 = m_{H,bare}^2 + \delta m_H^2$$ so we can get $m_{H,phys}^2 \ll \Lambda^2$

**ONLY** by arranging a precise cancelation, $\delta m_H^2 \cong -m_{H,bare}^2$

# Why theorists dislike just a SM Higgs, #2

**How severe a cancelation do we need?** ex.) $m^2_{H,phys} = 120 \text{ GeV}$

$$\Lambda = 10 \text{ TeV}, \; m_H^2/\Lambda^2 \cong 2\%$$

$$\Lambda = 1000 \text{ TeV}, \; m_H^2/\Lambda^2 \cong 0.01\%$$

$$\ldots$$

$$\Lambda = M_{pl} \;, \; m_H^2/\Lambda^2 \cong 10^{-32}\%$$

Are there high scales? YES

more abstractly, less in terms of diagrams:

**why is the weak scale so much less than the Planck scale?**

this question is so important it has its own name:

**THE HIERARCHY PROBLEM**

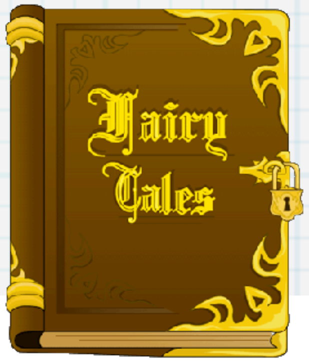
# How incredible is this?


theoretically possible, but hard to imagine within the rules we trust

either Higgs is unlike the other particles/players we know, or there is more going on

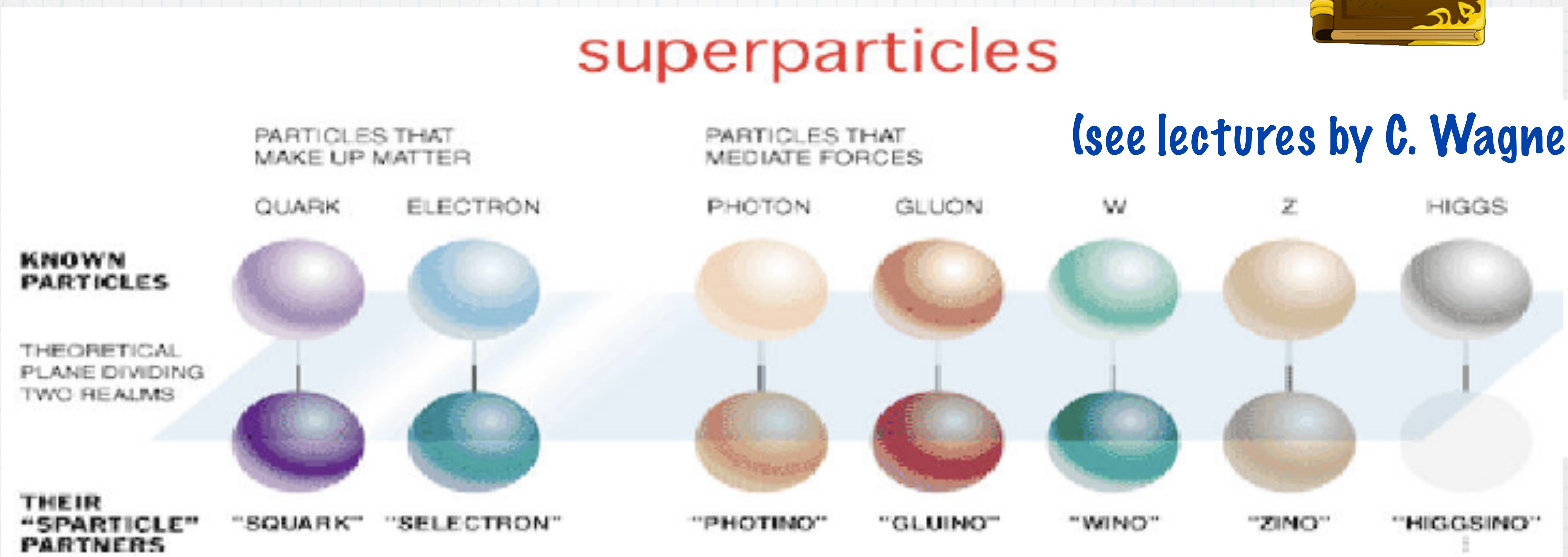
# Common Lore:

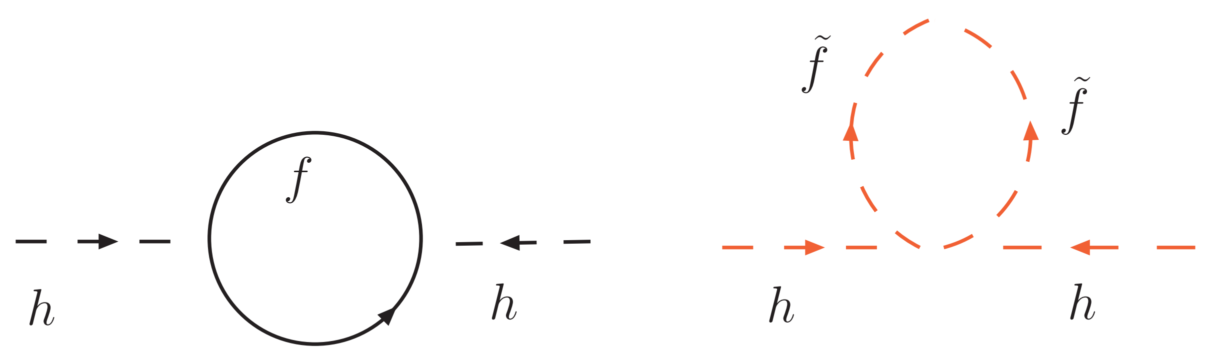
**One possible solution**: reduce the dependence on the UV by adding new particles whose effects cancel the SM effects




such as: **Supersymmetry (SUSY)**

(see lectures by C. Wagner)



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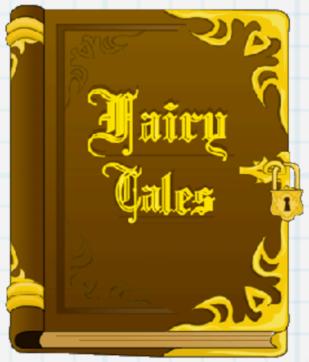


## SUSY has enticing properties

- ⋆ weakly coupled
- ⋆ DM candidate (observed)
- ⋆ Gauge coupling unification (theoretical bias)

**BUT**

- ⋆ Not necessary for EWSB
- ⋆ No SUSY particles at LEP or Tevatron
- ⋆ DM: Any model with a discrete symmetry + TeV stuff

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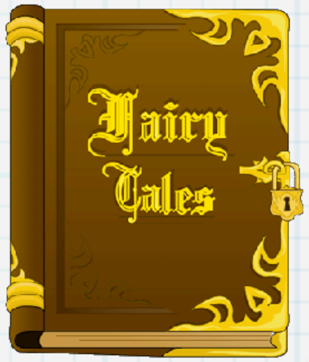


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**Instead:**

Since the Higgs boson is the source of all the theoretical issues, why don't we just get rid of it?

# Dynamical Symmetry Breaking

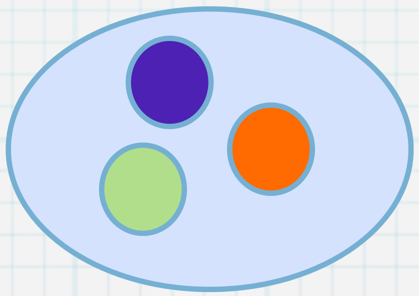
Mass generation **without** the
Higgs boson

# Why not Dynamical Symmetry Breaking?

* For mass generation **without scalars**, lets turn to **QCD** for inspiration

* No scalars, instead **strong interactions**

* **Inspired by QCD, we can imagine that the W and Z are composite objects, formed by from some new strong interaction**

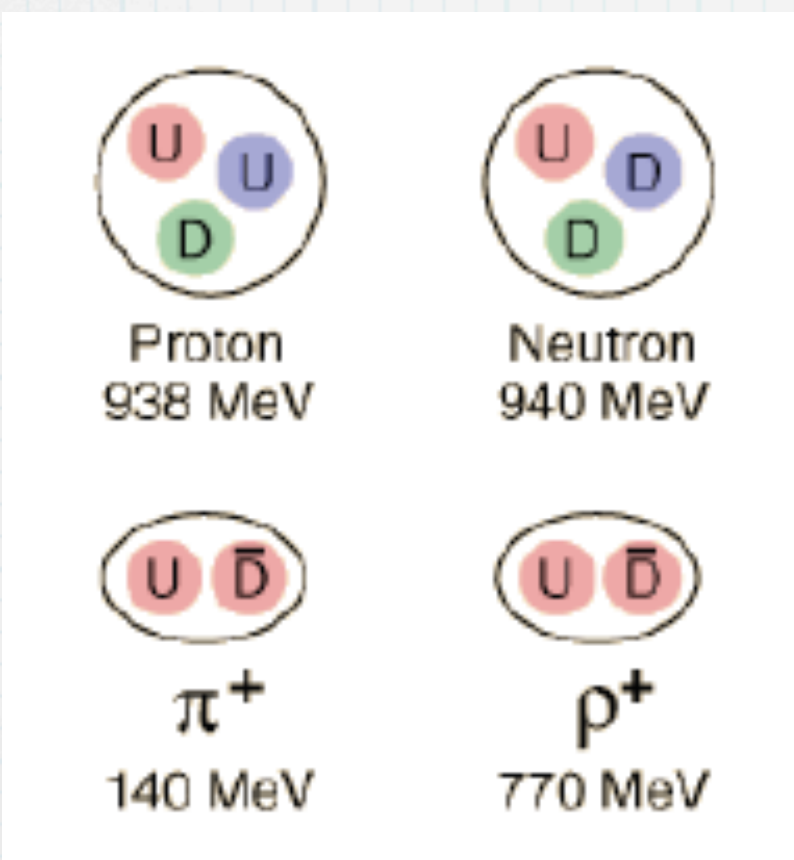
$$W^{\pm}, Z^0 \sim$$ 

**but** if there is some new strong interaction, why are the **W/Z** the only composites we see?

The other composites must be heavy .. but how can this be?

# Why not Dynamical Symmetry Breaking?

* The same question could be asked about **QCD**!
* In **QCD** we have massive hadrons composed of up and down quarks




from their constituents alone,
it is unclear why the pion is so light compared to the other (u,d) hadrons

# Dynamical Symmetry Breaking (DSB) in QCD

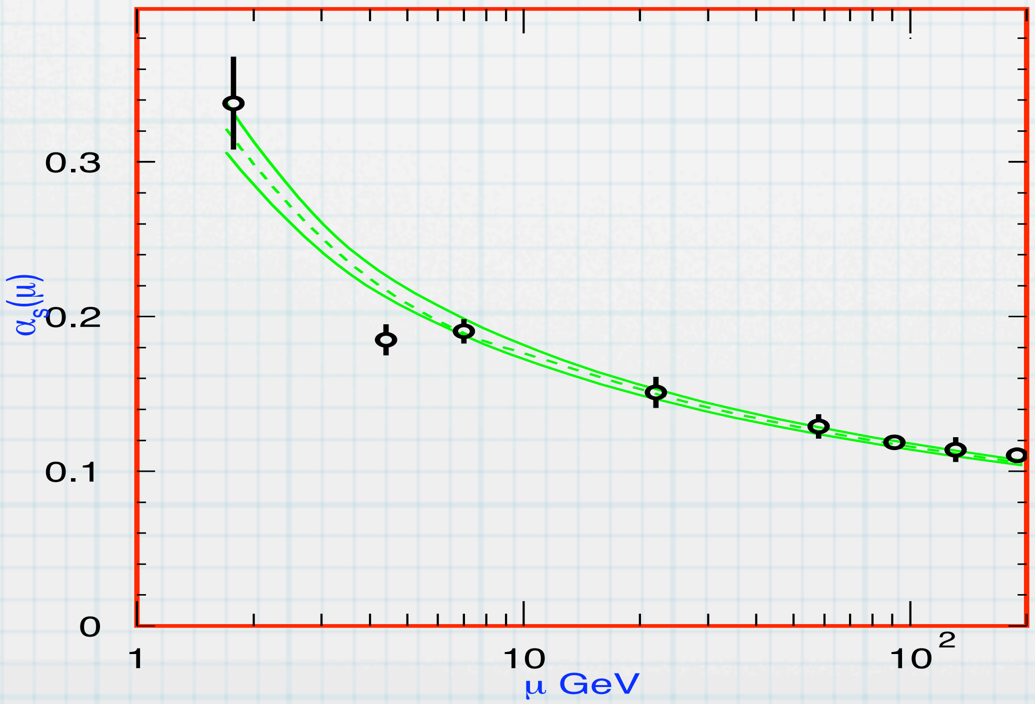
* Re-examine the Lagrangian for **QCD** (taking massless quarks)

$$\mathcal{L} = i\bar{u}_L \not{D} u_L + i\bar{d}_L \not{D} d_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R$$

displays a $SU(2)_L \otimes SU(2)_R$ global "chiral" symmetry

$$\begin{pmatrix} U'_L \\ D'_L \end{pmatrix} = V_L \begin{pmatrix} U_L \\ D_L \end{pmatrix} \quad \begin{pmatrix} U'_R \\ D'_R \end{pmatrix} = V_R \begin{pmatrix} U_R \\ D_R \end{pmatrix}$$

* The QCD coupling changes with energy,




becoming **strong** at energies $\sim 1$ GeV

# Dynamical Symmetry Breaking in QCD

- as a result of the strong QCD DYNAMICS

$$\langle \bar{q}_L q_R \rangle \neq 0 \qquad\qquad \langle \bar{q}_L q_R \rangle = 4\pi f_\pi^3$$

under a general $SU(2)_L \otimes SU(2)_R$ transformation

$$\langle \bar{q}_L q_R \rangle \to \langle \bar{q}_L U_L^\dagger U_R q_R \rangle$$

is only invariant if

$$U_L = U_R$$

the 'vectorial' subgroup

So, as a result of DYNAMICS alone

$$SU(2)_L \otimes SU(2)_R \to SU(2)_V$$

- The remaining symmetry is broken -> we get a massless Nambu-Goldstone Boson for each broken generator

- Pions $\pi = (\bar{q}_L q_R)$ are the Goldstone bosons of QCD DSB: this is how we understand the light pion

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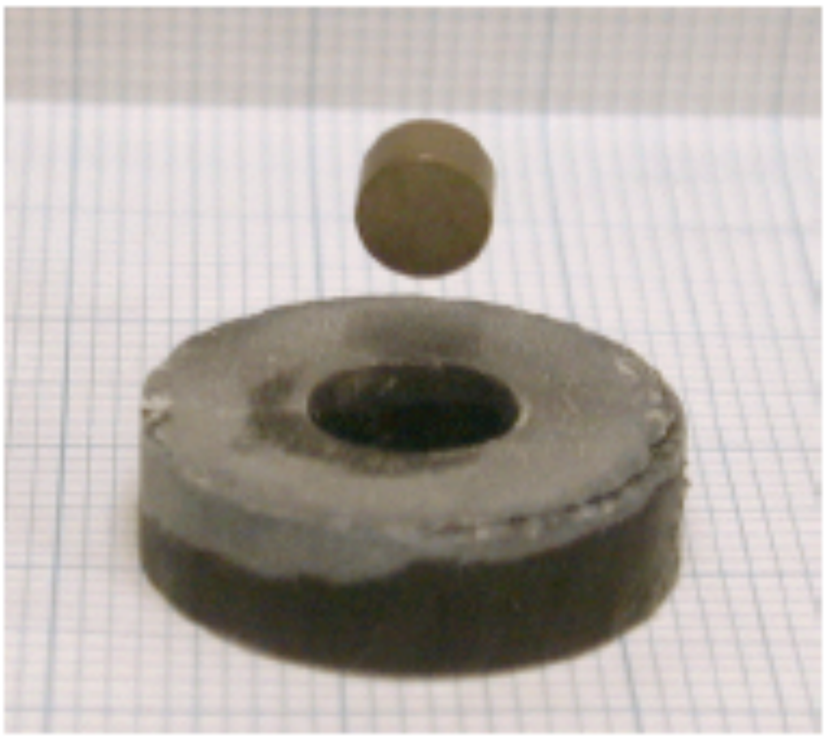
QCD DSB has a custodial symmetry !

- The remaining symmetry is broken -> we get a massless **Nambu-Goldstone Boson for each broken generator**

- Pions $\pi = (\bar{q}_L q_R)$ are the **Goldstone bosons of QCD DSB**: this is how we understand the light pion

# ("Low-Energy" Analog)




B C S

$$\langle \phi^{++} \rangle \neq 0$$

"Abelian Higgs Model"

Weinberg: "Superconductivity for Particular Theorists"

# Naturalness

* Dynamical symmetry breaking by asymptotically free gauge interactions explains **hierarchies** between scales naturally:

asymptotic freedom

$$\mu \frac{dg}{d\mu} = -\frac{g^3}{(4\pi)^2} b_0 + \cdots$$

$$\Lambda_{QCD} \sim \Lambda_{UV} \exp\left( - \frac{8\pi^2}{g^2(\Lambda_{UV}) b_0} \right)$$

low scale automatically generated

$$\Lambda_{QCD} \ll \Lambda_{UV}$$

**In fact, it is the only explanation!**

Let's use this to solve the hierarchy problem by dynamically breaking electroweak symmetry

# What is Technicolor?

- A **new strong interaction** at the EW scale causes a **nonzero expectation value for a (techni) fermion bilinear** with $(2, \pm\frac{1}{2})$ quantum numbers $\longrightarrow$ **EWSB**

**Higgs mechanism, but no Higgs particle!**
**W/Z are the "pions" of the new strong dynamics**

- a **natural solution to hierarchy problem** , BUT we understand very little about strong interactions:

**Limited tools: QCD, lattice, and (recently) 5D theories**

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same quant. #
as higgs scalar

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# Ingredients for Technicolor #1 (Weinberg '78, Susskind '79)

$N_D$ doublets of massless (techni) fermions

$SU(N_{TC})$ strong gauge theory (technicolor)

$$\left.\begin{array}{l} T_L = (U_L, D_L) \text{ are electroweak doublets} \\ U_R, D_R \text{ are electroweak singlets} \end{array}\right\} \begin{array}{l} SU(N_{TC}) \\ \text{fundamentals} \end{array}$$

$$\mathcal{L}_{TC} = i\bar{T}_L \not{D} T_L + i\bar{U}_R \not{D} U_R + i\bar{D}_R \not{D} D_R - \frac{1}{4} G^a_{TC,\mu\nu} G^{a,\mu\nu}_{TC}$$

The global chiral symmetry is

$$SU(2N_D)_L \otimes SU(2N_D)_R \supset SU(2)_w \otimes U(1)_Y$$

Envision $SU(N)_{TC}$ is **stronger** than QCD, becoming confining at $\Lambda_{TC} \sim 1\ \mathrm{TeV}$

# Details of Technicolor #2

once TC becomes confining:

$$\langle \bar{U}_{Li} U_{Rj} \rangle = \langle \bar{D}_{Li} D_{Rj} \rangle = 4\pi F_T^3 \delta_{ij} \neq 0$$

just like in QCD, this condensate spontaneously breaks chiral symmetry

$$SU(2N_D)_L \otimes SU(2N_D)_R \rightarrow SU(2N_D)_V$$

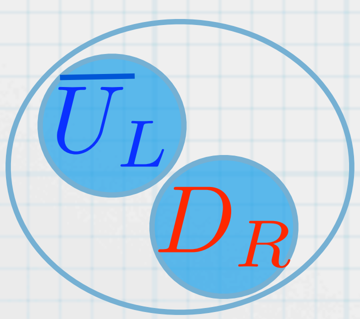
**because the TC condensate has EW quantum numbers,**

$\langle \bar{T}_L T_R \rangle \neq 0 \longleftrightarrow$ **ELECTROWEAK SYMMETRY is broken**

$$M_W^2 = \frac{g^2 N_D F_T^2}{4} = M_Z^2 \cos^2\theta_W$$

$\therefore$ **identify**

$$N_D F_T^2 = v^2$$
$$\Lambda_T \cong 4\pi F_T \sim \text{TeV}$$




$=$

| | |
|---|---|
| $(2N_D)^2 - 1$ | Nambu-Goldstone Bosons |
| $-3$ | eaten by **W/Z** |
| $(2N_D)^2 - 4$ | leftover "technipions" |

# A Technicolor Example, #1

to describe low-energy QCD, use **chiral lagrangian**

$$\mathcal{L} = i\bar{u}_L \not{D} u_L + i\bar{d}_L \not{D} d_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R$$

$$U = e^{2i\vec{\pi}/f_\pi} \quad \vec{\pi} = \pi_a \tau^a$$

$$\mathcal{L}_\chi = \frac{f_\pi^2}{4} \mathrm{tr}(\partial_\mu U \partial^\mu U^\dagger) + \cdots$$

$$U \to V_L^\dagger U V_R$$

just like $\langle \bar{q}_L q_R \rangle$

**EW chiral lagrangian:** lets take the simplest example, one technidoublet. We have to adjust for the **heavier scale**, and **new ingredient: SU(2), U(1) gauge interactions**

$$\mathcal{L}_{EW\chi} = \frac{F_T^2}{4} \mathrm{tr}(D_\mu \Sigma D^\mu \Sigma^\dagger) + \cdots \qquad \Sigma = e^{2i\vec{\pi}_T/F_T}$$

$$\vec{\pi}_T = \pi_{T,a} \tau^a$$

$$D_\mu \Sigma = \partial_\mu \Sigma - ig\vec{W}_\mu \Sigma + i\frac{g'}{2} \Sigma B_\mu$$

use gauge invariance to remove $\pi_T$ --> go to unitary gauge $\Sigma = \mathbf{1}$

$$\mathcal{L}_{EW\chi} = \frac{F_T^2}{4} g^2 W_\mu^+ W^{-\mu} + \frac{F_T^2}{8\cos^2\theta_W} Z_\mu^2 + \cdots$$

$\boxed{\text{what else?}}$

for more than two techniflavors ( $N_D > 1$ ), there will be extra $\pi_T$

# A Technicolor Example #2:

* For a more complicated examples, consider a toy model with 2 technidoublets ( $N_D = 2$ )

The chiral symmetry breaking pattern is: $SU(4)_L \otimes SU(4)_R \to SU(4)_V$

$$\Sigma = e^{2i\pi \vec{\pi}_T / F_T} \qquad \vec{\pi}_T = \pi_{T,a} X^a$$

Axial combination, $SU(4)_A$ is broken. The NGBs correspond to these broken symmetry generators: $(2N_D)^2 - 1 = 15\ \pi_T$

**decompose:**

$$X^a = \begin{pmatrix} \tau_a & 0 \\ 0 & \tau_a \end{pmatrix} \begin{pmatrix} U_{L1} \\ D_{L1} \\ U_{L2} \\ D_{L2} \end{pmatrix}$$

$$\begin{pmatrix} 0 & \tau_a \\ \tau_a & 0 \end{pmatrix}, \begin{pmatrix} 0 & -i\tau_a \\ i\tau_a & 0 \end{pmatrix}, \begin{pmatrix} \tau_a & 0 \\ 0 & -\tau_a \end{pmatrix}$$

$$\begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}, \begin{pmatrix} 0 & -iI \\ iI & 0 \end{pmatrix}, \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$$

**3 generators**

* these are the fields eaten by the W, Z

**9 generators**

* uneaten $\pi_T$ , charged under $SU(2)_W$

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**all 15 NGB accounted for**

(Hill, Simmons '03)

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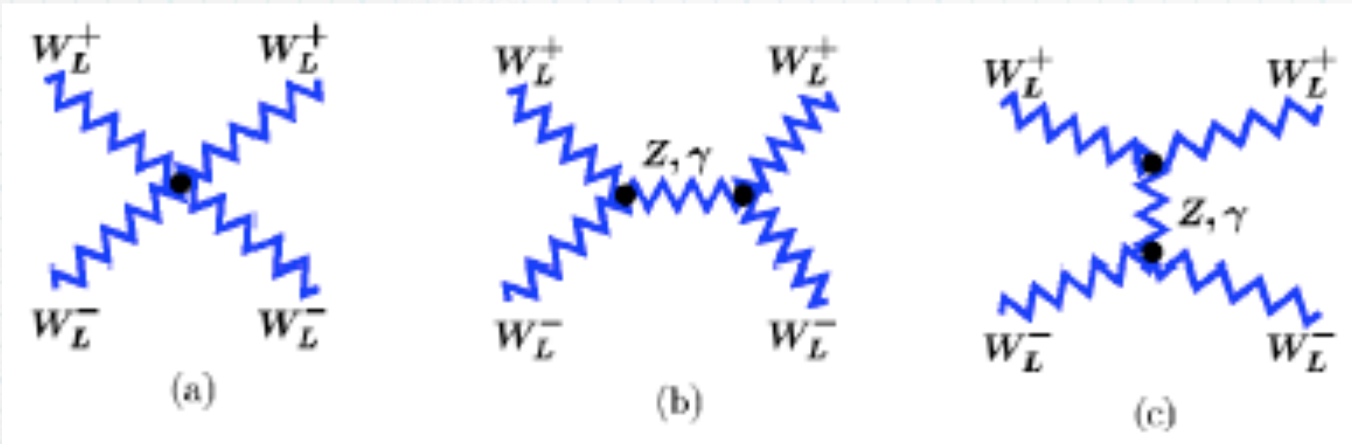
what if technifermions carried SM color?

# What about WW scattering?

how can WW scattering make sense without a Higgs?

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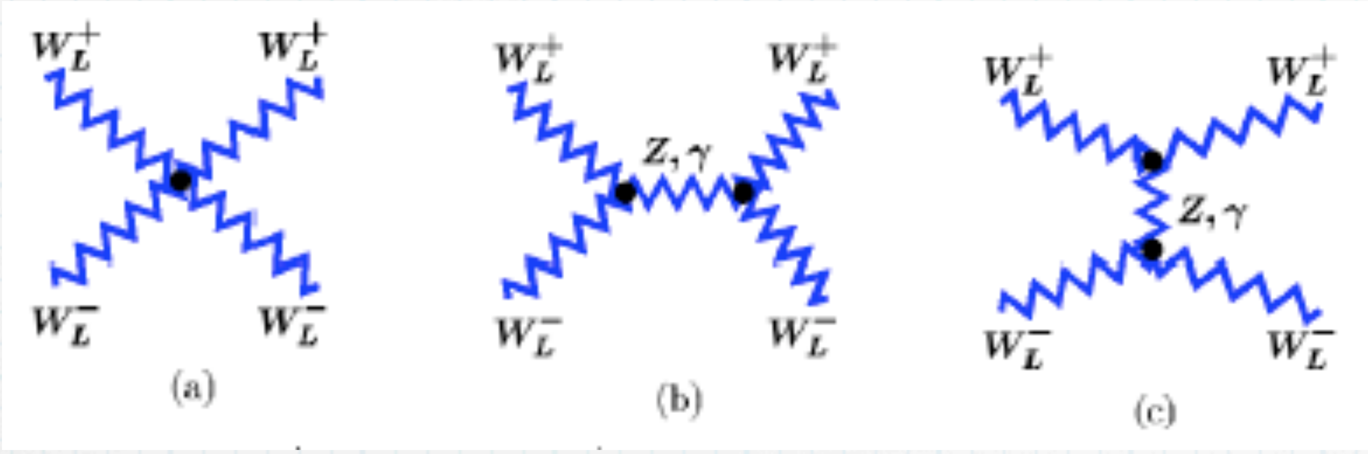


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**NOT QUITE!**

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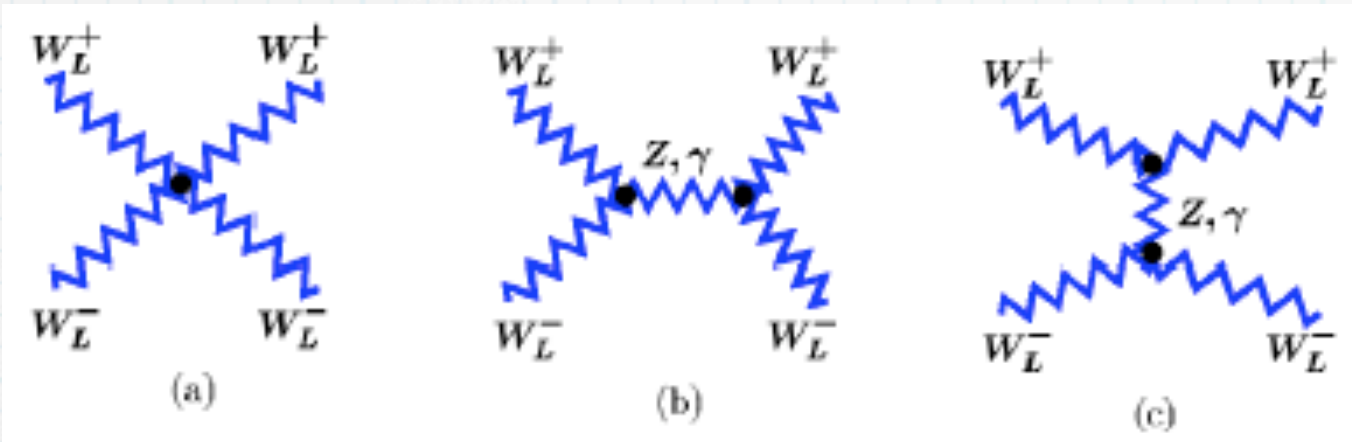


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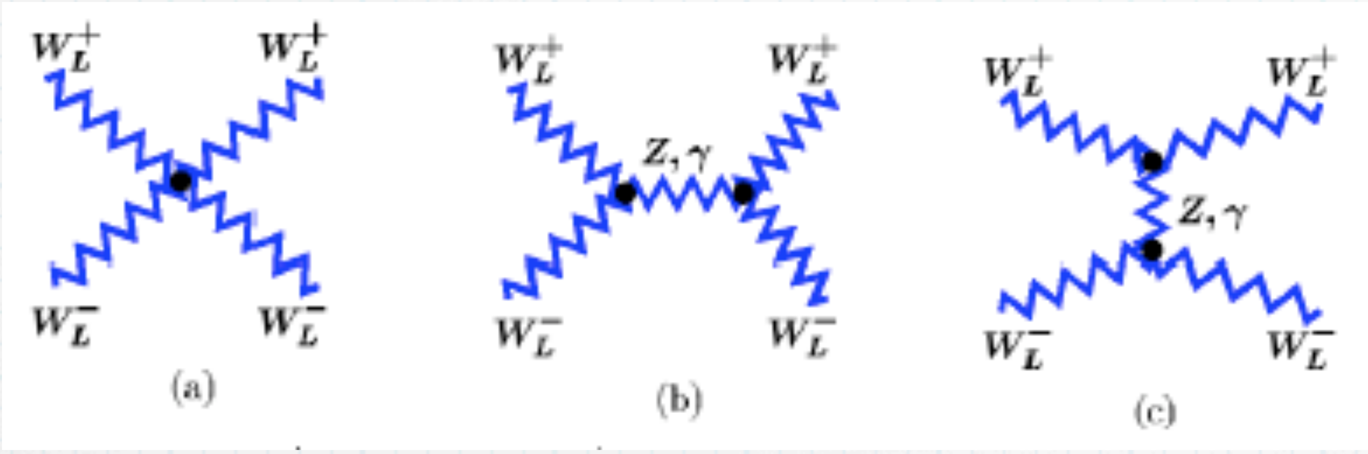


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perturbatively (or tree-level)

TRUE!

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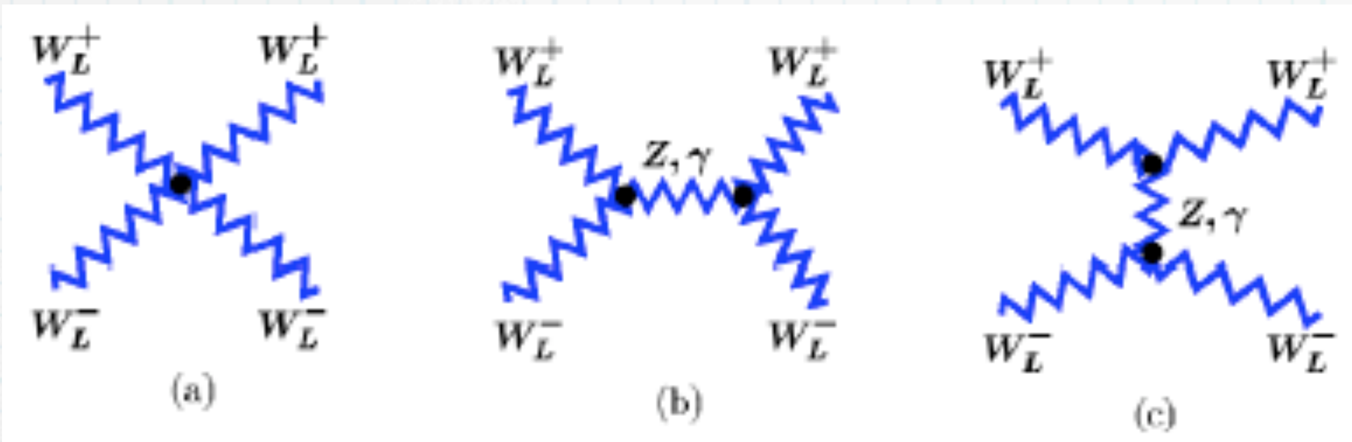


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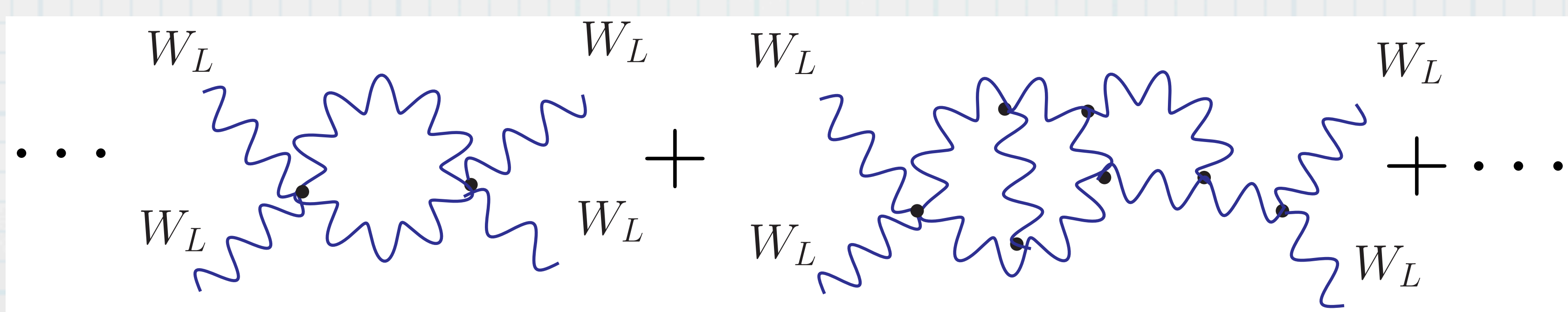
perturbatively (or tree-level)

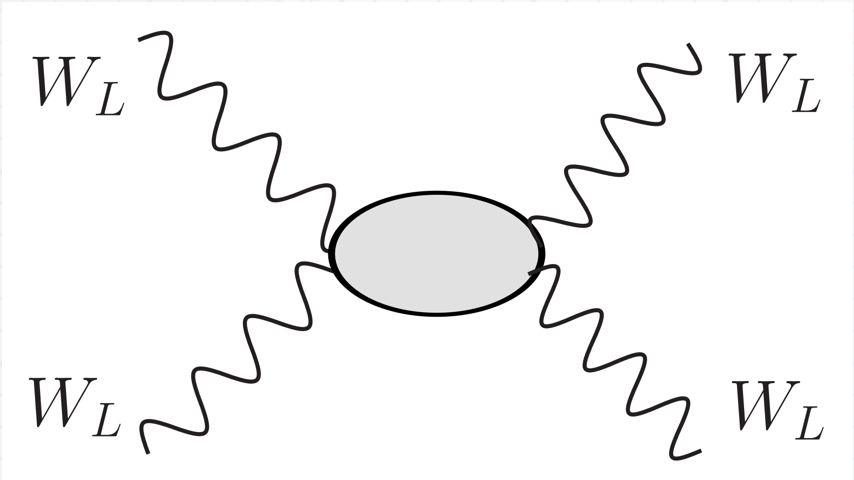
**TRUE!**

increasing **E**, higher order diagrams become important, same size as the tree-level terms.



# What about WW scattering?

... but when loop-level diagrams are as important as tree-level diagrams, we have strong coupling and cannot rely on perturbation theory

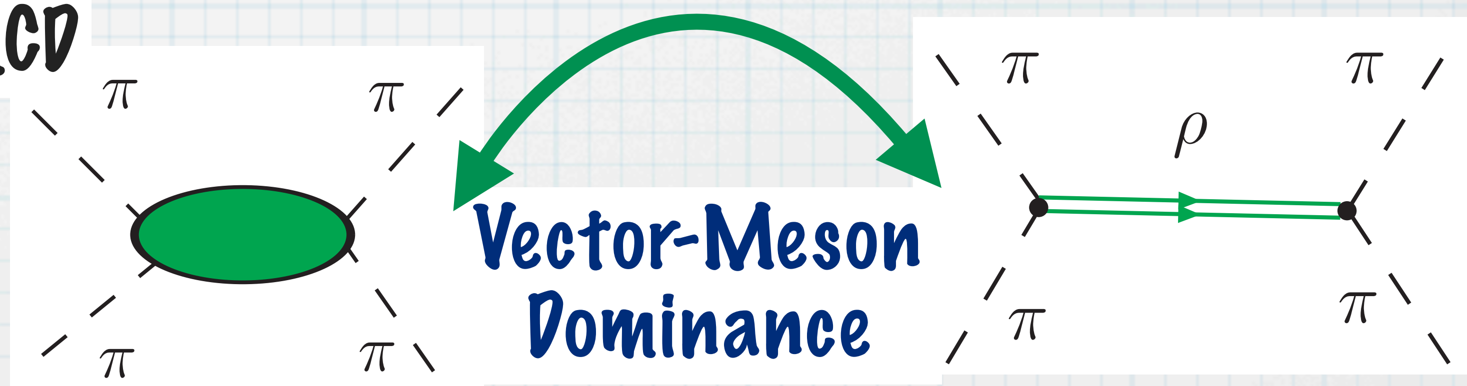



the S-matrix is perfectly unitary, we just can't calculate

in addition to the strongly-interacting W's, the strong dynamics may also lead to new resonances. The properties (mass, spin, couplings) of the new resonances depend on the details of the underlying theory and cannot be calculated from first principles.

so we must rely on phenomenological models or data

ex: QCD




WARNING: new strong interaction may not obey QCD-model rules

# Details of Technicolor #2

## What other TC bound states are there besides the $\pi_T$

* Simplest idea: **Estimate TC by rescaling QCD** + $N_C, N_D$ counting

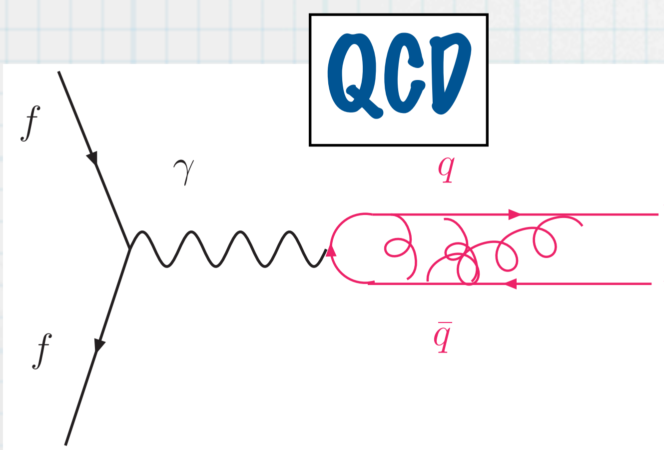
$$f_\pi \to F_T$$
$$\pi \to W^\pm, Z, \pi_T$$
$$\rho \ (\mathrm{I}=1) \ \to \rho_T^\pm, \rho_T^0$$
$$a_1 \ (\mathrm{I}=1) \ \to a_T^\pm, a_T^0$$
$$\omega \ (\mathrm{I}=0) \ \to \omega_T$$
$$\ldots$$

$$M_{\rho_T} \approx \sqrt{\frac{3}{N_{TC}}} \times 2 \text{ TeV}$$

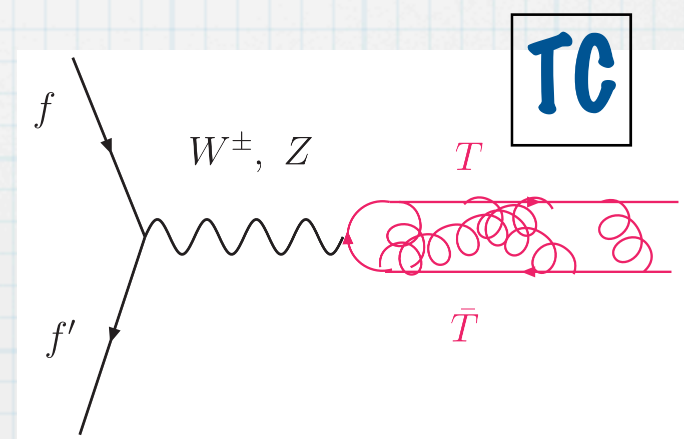
$$\Gamma(\rho_T \to W_L W_L) \approx 500 \left(\frac{3}{N_{TC}}\right)^{3/2} \text{ GeV}$$

$$\ldots$$

Vector-meson dominance

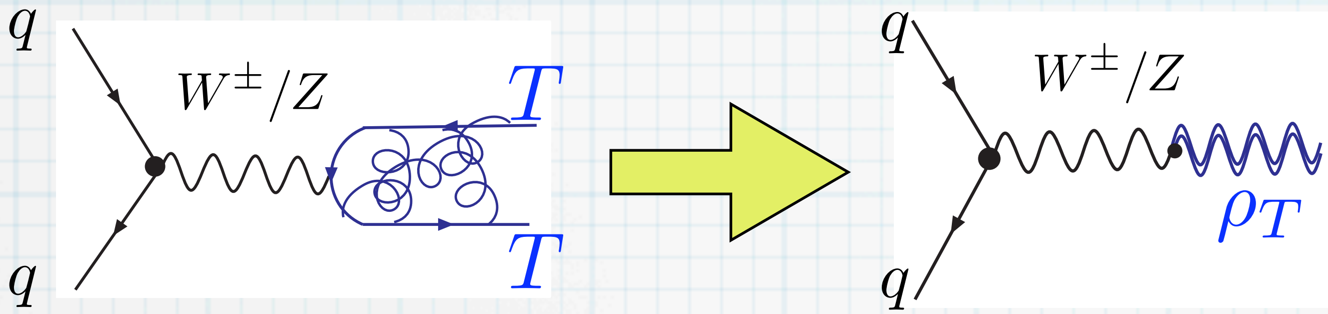



} $\rho$




} $\rho_T, a_T$

# Classic Technicolor signals at Colliders

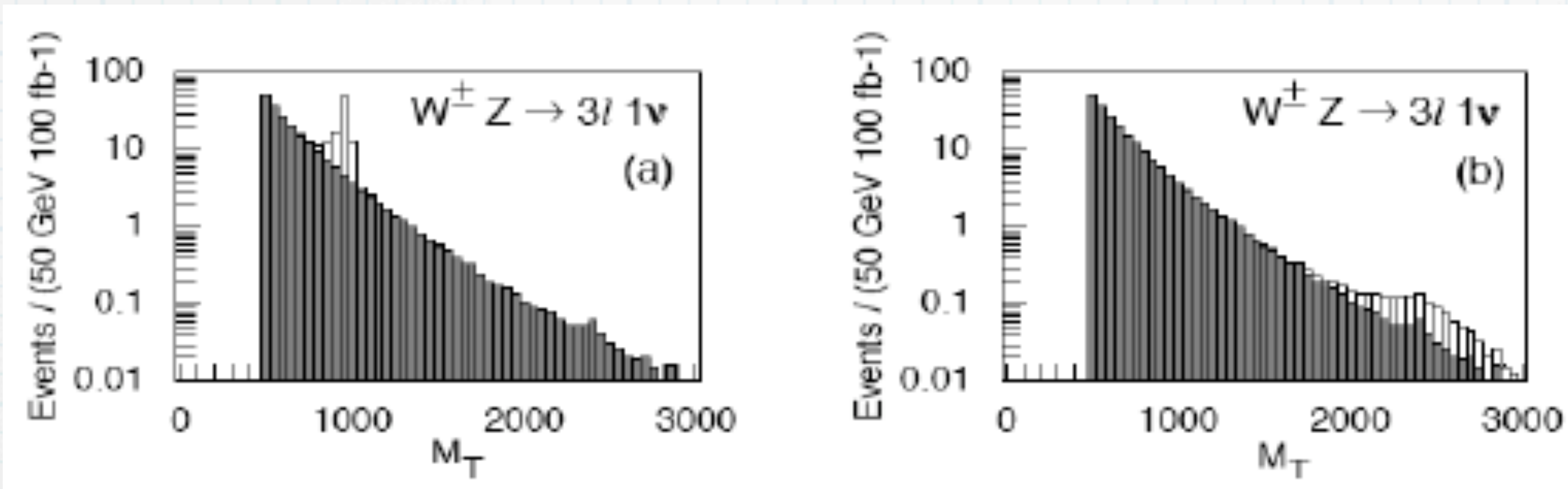



## Vector meson dominance

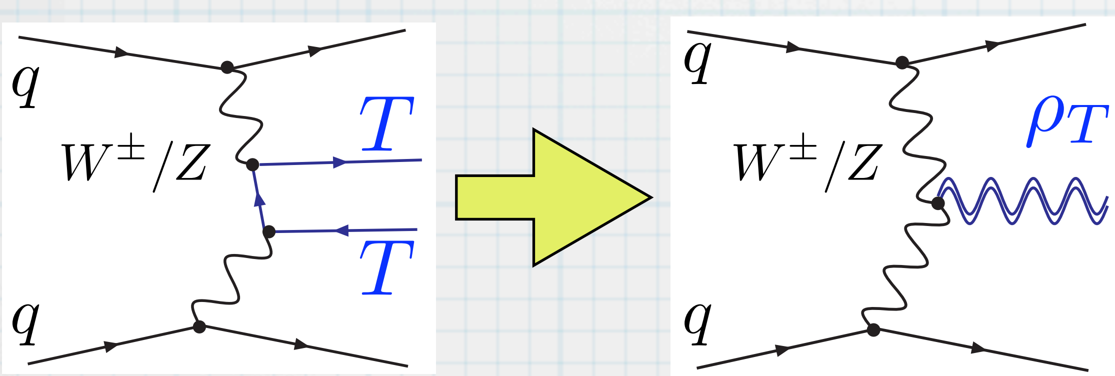
analogous to how

$e^+e^- \to \rho$

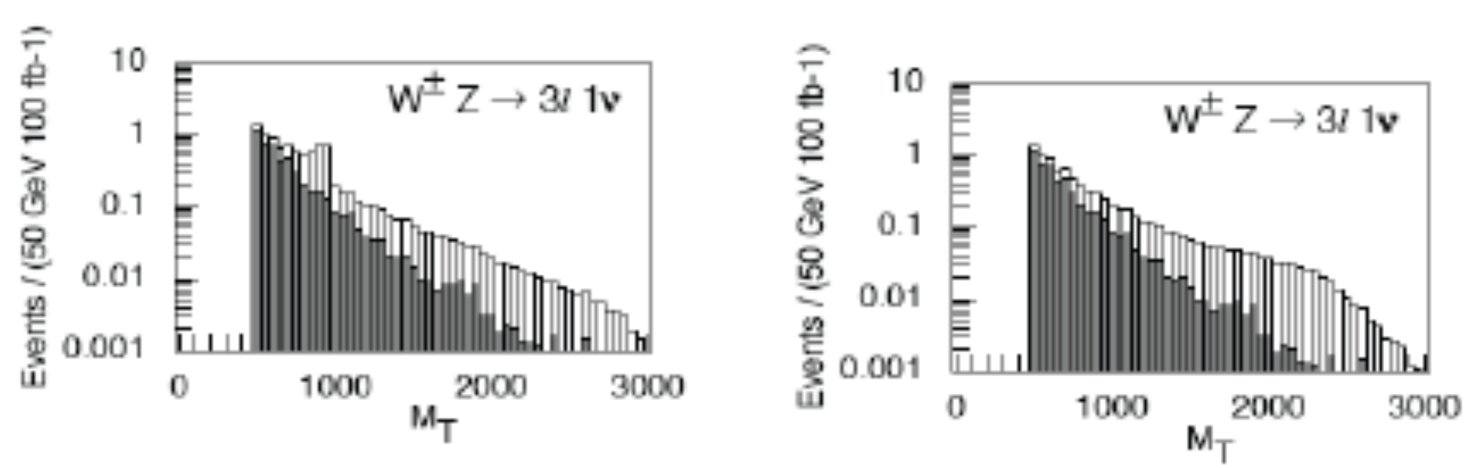
is described in QCD




## Vector Boson Fusion

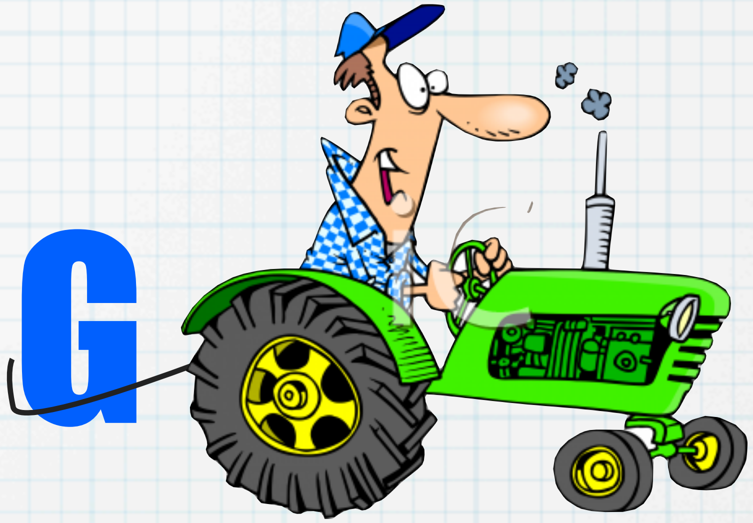



For $M_{\rho_{TC}} = 1.0$ TeV, 2.5 TeV:




for early studies, Bagger et al hep-ph/9306256, 9504426, Golden 9511206

# E X T E N D I N G



# TECHNICOLOR

# What about the fermions?

As we have seen, in Technicolor: a new strong interaction at the EW scale is responsible for breaking EW symmetry, thereby giving mass to the W,Z

But what about SM fermion masses ?

SU(2) gauge invariance prevents us from writing down explicit mass terms in $\mathcal{L}$

$$m_t(t_L^\dagger t_R + h.c.) \left\{ \begin{array}{l} t_L \text{ carries SU(2) charge} \\ t_R \text{ does NOT} \end{array} \right.$$

In the SM, Yukawa couplings between fermions and Higgs are allowed by all symmetries and become mass terms once EWSB occurs

$$y_t H Q_L^\dagger u_R \rightarrow m_t u_L^\dagger u_R$$

$$\boxed{\text{How are we going to generate a mass term with no Higgs?}}$$

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# Extending Technicolor

(Eichten & Lane '79, Dimopoulos & Susskind '79)

* SM fermions don't feel the strong TC force, but we need them to communicate somehow with the technifermions

* Simplest Idea: Create a new gauge interaction under which both SM fermions and TC fermions transform, and put them in the same representations

ex.)

$$\Psi_L = \begin{pmatrix} U_L \\ D_L \\ \cdots \\ u_L \\ d_L \end{pmatrix} \qquad \chi_{uR} = \begin{pmatrix} U_R \\ \cdots \\ u_R \end{pmatrix}, \qquad \chi_{dR} = \begin{pmatrix} D_R \\ \cdots \\ d_R \end{pmatrix}$$

* new gauge interaction , called EXTENDED TECHNICOLOR is huge. It contains all techni-flavor and SM flavor as subgroups

$$G_{ETC} \supset SU(2N_D)_L \otimes SU(2N_D)_R \otimes$$

$$SU(3)_Q \otimes SU(3)_U \otimes SU(3)_D \otimes \cdots$$

'techni-flavor'

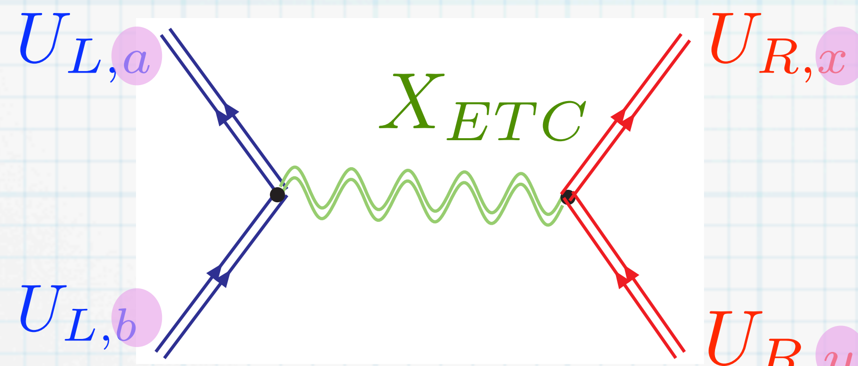
SM flavor

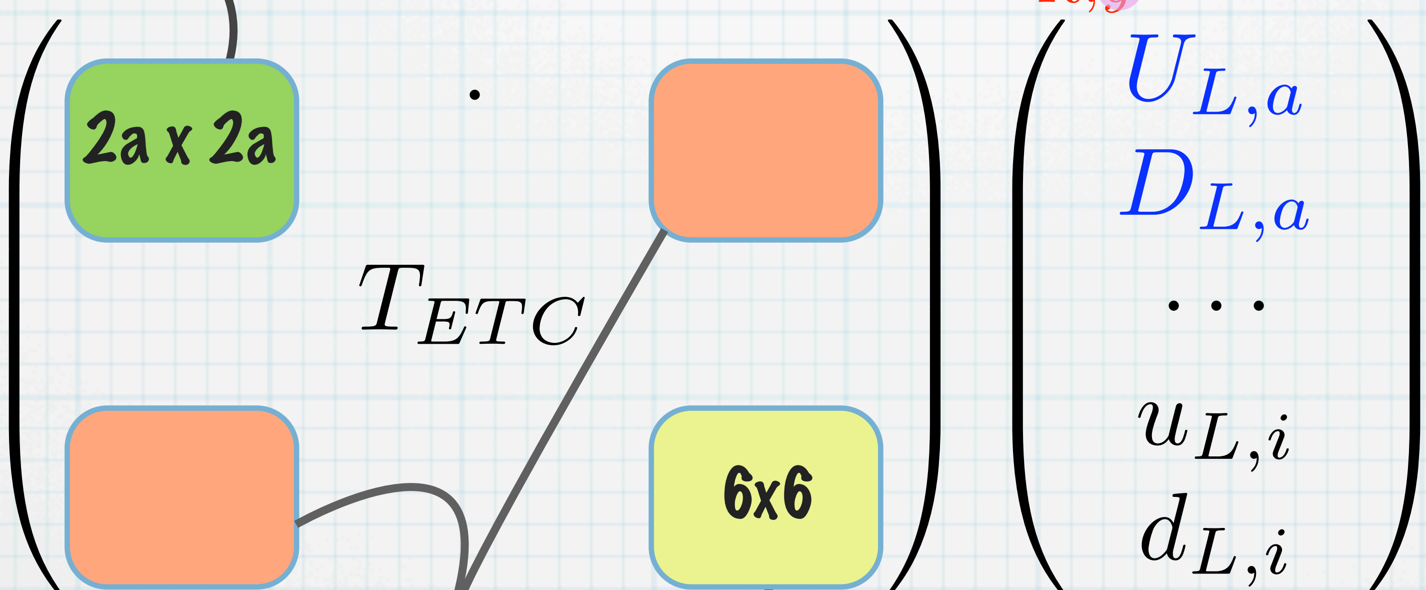
# Extended Technicolor, #2

* Acting on an ETC representation:

with flavor indices explicit

**techniflavor:**

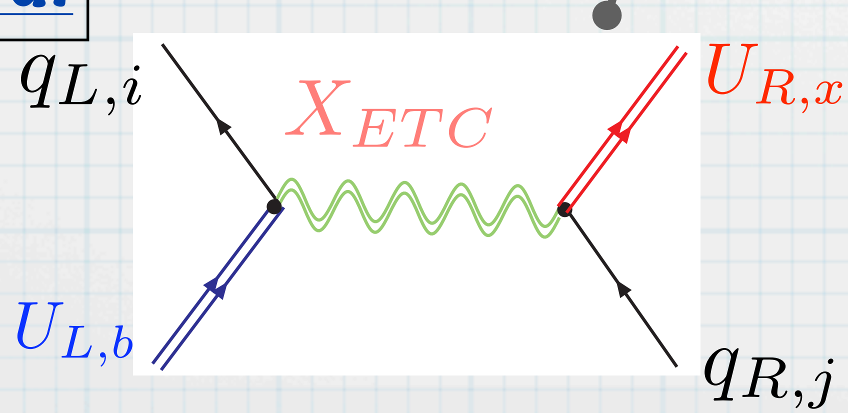


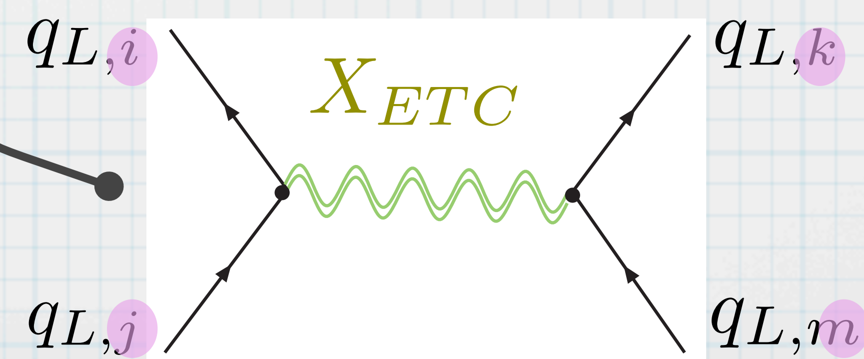

No reason for these interactions to be diagonal in the same basis as SM and TC interactions

Flavor symmetries broken by ETC

**mixed:**




**SM flavor:**



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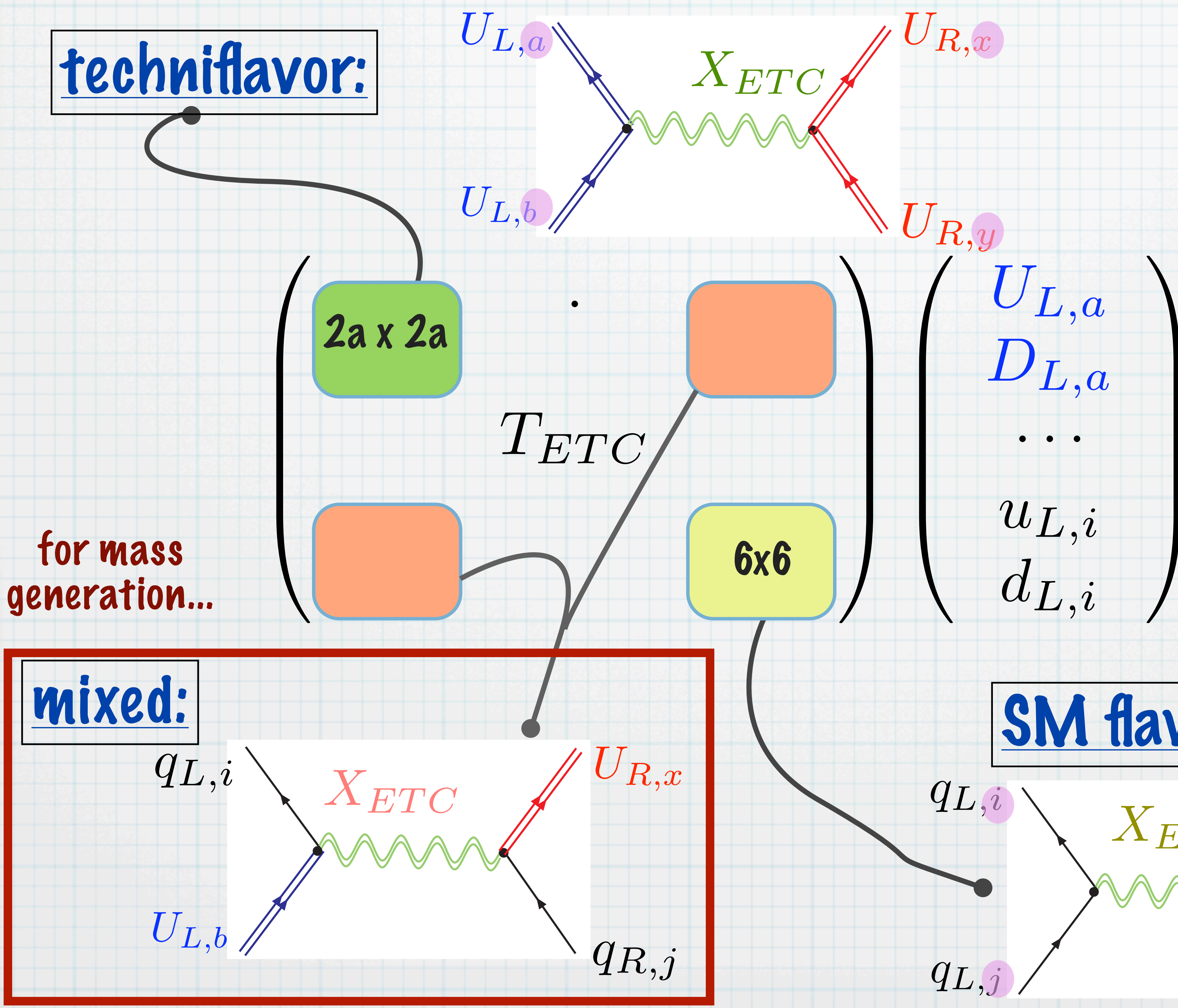



with flavor indices explicit

No reason for these interactions to be diagonal in the same basis as SM and TC interactions

Flavor symmetries broken by ETC

# Extended Technicolor, #3

- The gigantic ETC group has to be broken at some point
- **Assume** it is broken at some high scale $\Lambda_{ETC}$
- Integrating out the massive ETC gauge bosons, we are left with **higher dimension operators**...

$$\alpha_{ab}\frac{g^2_{ETC}(\bar{T}\gamma_\mu t^a T)(\bar{T}\gamma^\mu t^b T)}{M^2_{ETC}} + \beta_{ab}\frac{g^2_{ETC}(\bar{T}\gamma_\mu t^a q)(\bar{q}\gamma^\mu t^b T)}{M^2_{ETC}} + \gamma_{ab}\frac{g^2_{ETC}(\bar{q}\gamma_\mu t^a q)(\bar{q}'\gamma^\mu t^b q')}{M^2_{ETC}}$$

from 'TC flavor' terms | from 'mixed' terms | from `SM flavor' terms

Concentrating on the $\beta_{ab}$ terms and performing a Fierz rearrangement:

$$\frac{g^2_{ETC}}{M^2_{ETC}}(\bar{T}_L\gamma_\mu q_R)(\bar{q}_L\gamma^\mu T_R) \rightarrow \frac{g^2_{ETC}}{M^2_{ETC}}(\bar{T}_L T_R)(\bar{q}_L q_R)$$

this operator is generated at the scale $\Lambda_{ETC}$

# Don't get confused!!

* Technicolor and Extended Technicolor sound similar, but they have very different roles and properties

**Technicolor:** unbroken, strong gauge interaction felt only by technifermions. Causes technifermion chiral symmetry to be broken, leading to NGBs, three of which become the W/ Z longitudinal polarizations

$$\langle \bar{U}_L U_R \rangle = \langle \bar{D}_L D_R \rangle \neq 0 = \langle 4\pi F_T^3 \rangle \qquad 4\pi F_T \sim \text{TeV}$$

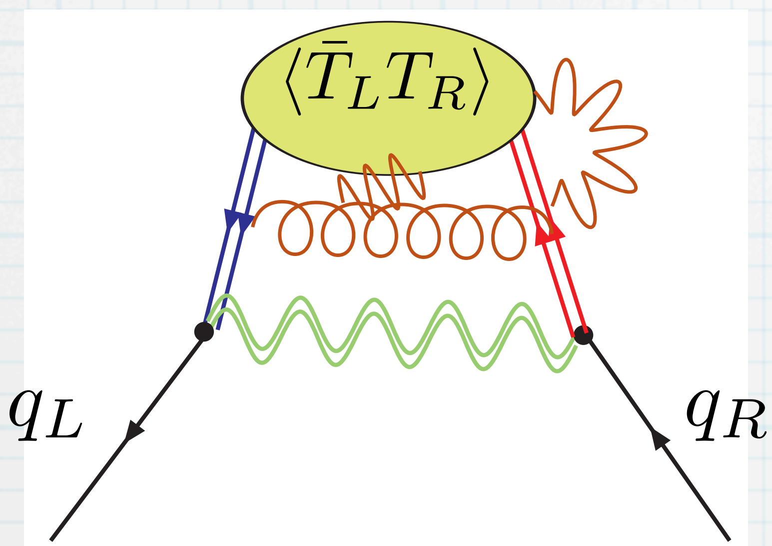
**Extended Technicolor:** broken, weak gauge interaction felt by both SM fermions and technifermions. Below the scale of ETC breaking we get higher dimension operators

$$\alpha_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a T)(\bar{T}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q)(\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \gamma_{ab} \frac{g_{ETC}^2 (\bar{q}\gamma_\mu t^a q)(\bar{q}'\gamma^\mu t^b q')}{M_{ETC}^2}$$

$$M_{ETC} \sim 10 - 1000 \text{ TeV}$$

# Extended Technicolor, #4

* When the technicolor interaction becomes strong at energies $\Lambda_{TC} \sim 1$ TeV, the **four fermion interaction becomes a mass term** for the SM fermions




$$\frac{g_{ETC}^2}{M_{ETC}^2} \langle \bar{T}_L T_R \rangle (\bar{q}_L q_R) \equiv m_q \bar{q}_L q_R$$

**Not quite so simple:**

The four fermi operator is generated at $\Lambda_{ETC}$, much higher than the scale $\sim 1$ TeV where we know the value of $\langle \bar{T}_L T_R \rangle$.

**We need a way to connect** $\langle \bar{T}_L T_R \rangle \Big|_{TC}$ **and** $\langle \bar{T}_L T_R \rangle \Big|_{ETC}$

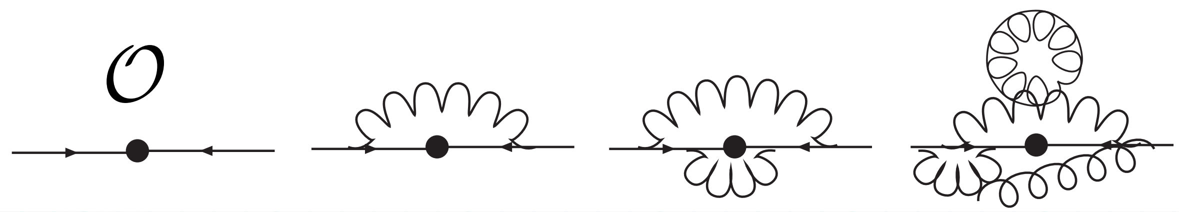
fixed by EW scale

enters SM mass formulae

Renormalization Group Equations (RGE) relates operators at differing energies

# Extended Technicolor, #5

* To connect an operator $\mathcal{O}$ at different energy scales we need to know the **anomalous dimension** ($\gamma_\mathcal{O}$) of the operator

$\gamma_\mathcal{O} =$  $+ \cdots$



* **Then: RGE is simply solved** $\mathcal{O}(\Lambda_1) = \mathcal{O}(\Lambda_0) exp\Big(\int_{\Lambda_0}^{\Lambda_1} \frac{d\mu}{\mu}\gamma_\mathcal{O}\Big)$

* For ETC-generated fermion masses

$$\langle \bar{T}_L T_R \rangle|_{ETC} = \langle \bar{T}_L T_R \rangle|_{TC} \times exp\Big(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu}\gamma_{(\bar{T}_L T_R)}(\mu)\Big)$$

* **BUT, how do we calculate the anomalous dimension of in the presence of the strong TC interaction?**

* **In QCD,** $\gamma_{(\bar{q}_L q_R)} \ll 1$ as the coupling is quickly running. **ASSUMING this is also the case for TC**, we arrive at the ETC mass formula:

$$\boxed{m_{q,\ell} \cong \frac{g_{ETC}^2}{M_{ETC}^2}(4\pi F_T^3)}$$

# Extended Technicolor, #5

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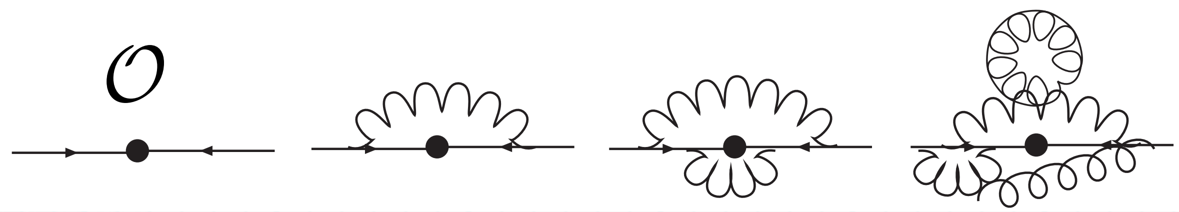
$\gamma_{\mathcal{O}} =$  $+\cdots$



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* For ETC-generated fermion masses

$$\langle \bar{T}_L T_R\rangle|_{ETC} = \boxed{\begin{aligned}\langle \bar{T}_L T_R\rangle|_{TC} \\ = 4\pi F_T^3\end{aligned}} \times exp\Big(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu}\gamma_{(\bar{T}_L T_R)}(\mu)\Big)$$

* BUT, how do we calculate the anomalous dimension of in the presence of the strong TC interaction?

* In QCD, $\gamma_{(\bar{q}_L q_R)} \ll 1$ as the coupling is quickly running. ASSUMING this is also the case for TC, we arrive at the ETC mass formula:

$$\boxed{m_{q,\ell} \cong \frac{g_{ETC}^2}{M_{ETC}^2}(4\pi F_T^3)}$$

# Extended Technicolor, #6

* ETC also plays another crucial role -- as it explicitly breaks all of the techniflavor symmetry it gives a mass to the uneaten technipions

* Without ETC , the $SU(2)_W \otimes U(1)_Y$ neutral $\pi_T$ would be massless and a phenomenological disaster

adding explicit techiflavor symmetry breaking

$$m^2_{\pi_T,ab} \sim \frac{g^2_{ETC}\Lambda^2_{TC}F^2_{TC}}{M^2_{ETC}} \mathrm{Tr}([t^a, t_{ETC}][t^b, t_{ETC}])$$

(see Georgi "Weak Interactions in Particle Physics")

* As with the SM fermion masses, the $\pi_T$ masses are generated by gauge interaction dynamics and **NOT** by fundamental scalars

# Scales and degrees of freedom:

TC: asymptotically free
ETC: unbroken
EWS: unbroken

**massless:** SM fermions, technifermions, and gauge bosons

$$\Lambda_{ETC}$$

TC: getting stronger
ETC: broken
EWS: unbroken

**massless:** SM fermions, technifermions, and SM/TC gauge bosons

**massive:** ETC gauge bosons, $M_{ETC} \sim g_{ETC}\Lambda_{ETC}$

$$M_{ETC}$$

+ dim-6 operators

$$\alpha_{ab}\frac{g_{ETC}^2(\bar{T}\gamma_\mu t^a T)(\bar{T}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab}\frac{g_{ETC}^2(\bar{T}\gamma_\mu t^a q)(\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} +$$

$$\Lambda_{TC}$$

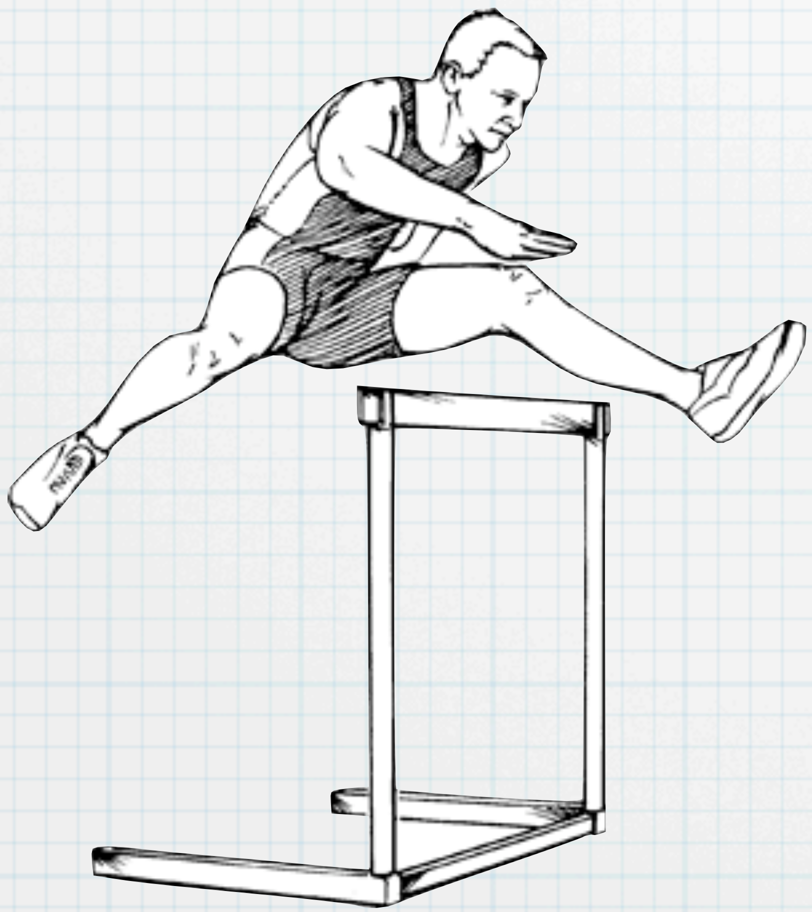
TC: confined
EWS: broken

- TC-condensate forms, causes chiral symmetry breaking/EWSB
- all technifermions confined into technihadrons
- SM fermion masses, $\pi_T$ mass

# Technicolor/Extended Technicolor Review:

* NO HIGGS: EWSB occurs as a result of spontaneous chiral symmetry breakdown in a new sector which feels a new strong interaction, technicolor
* NATURAL: $v_{EW} \ll \Lambda_{UV}$ is naturally generated
* FERMION MASSES: can't be obtained by TC dynamics alone. To keep the theme of naturalness, these masses must be generated by gauge interactions alone (no new scalars, please!). To accomplish this, we invoke EXTENDED TECHNICOLOR
* Looks good so far!

# Hurdles for Technicolor
# and Extended Technicolor

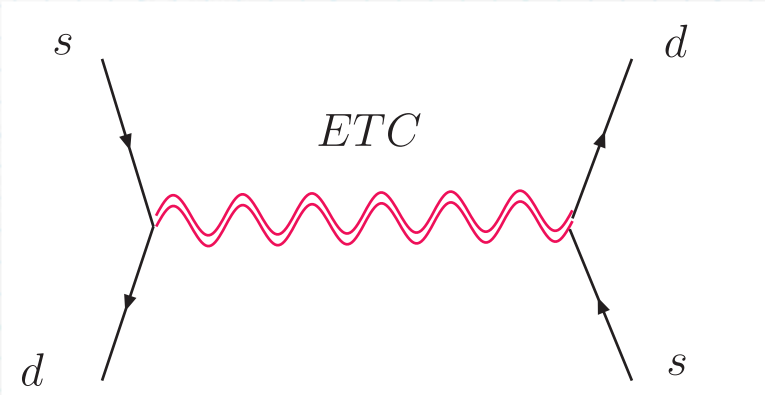


# Flavor Changing Neutral Currents (FCNC)

* Flavor is usually a problem for BSM physics, and ETC is no different

(Eichten, Lane '79)

**Generically, there is NO reason for the ETC interactions to be flavor diagonal in the quark/lepton mass basis**




ETC exchange between SM fermions ( $\gamma_{ab}$ ) terms, will lead to flavor changing interactions, both $|\Delta F| = 1$ and $|\Delta F| = 2$

**Experimentally,**

$|\Delta S| = 2$ **FCNC most stringent:**

$K^0 - \bar{K}^0$ **mixing:**

$$\Delta m_K < 3.5 \times 10^{-12} \text{ MeV}$$

**typical ETC-induced contribution:**

$$\mathcal{L}_{|\Delta S|=2} \supset \frac{g^2_{ETC}\theta^2_{ds}}{M^2_{ETC}} (\bar{s}\Gamma d)(\bar{s}\Gamma' d) + \text{h.c.}$$

# FCNC, #2

* Requiring the ETC-induced contribution to be within experimental errors, we can turn this into a constraint on one combination of ETC parameters

$$\frac{M_{ETC}}{g_{ETC}\sqrt{Re(\theta^2_{ds})}} \gtrsim 1300 \text{ TeV}, \qquad \frac{M_{ETC}}{g_{ETC}\sqrt{Im(\theta^2_{ds})}} \gtrsim 16000 \text{ TeV}$$

from $\epsilon_K$

Similar, but looser constraints from other flavor observables ( $\Delta m_{B_d}, \Delta m_{B_s} \Gamma(B \to s\gamma), \Gamma(\mu^\pm \to e^\pm\gamma), \Gamma(B \to \mu^+\mu^-)$, etc)

* Tension arises as these SAME ETC parameters enter into the quark and lepton mass formulae

satisfying FCNC conditions:

$$m_q, m_l \sim \frac{g^2_{ETC}}{M^2_{ETC}} \langle \bar{T}T \rangle_{ETC} \xrightarrow[(\gamma_m \ll 1)]{} \frac{0.5 \text{ MeV}}{N_D^{3/2} |\theta_{ds}|^2}$$

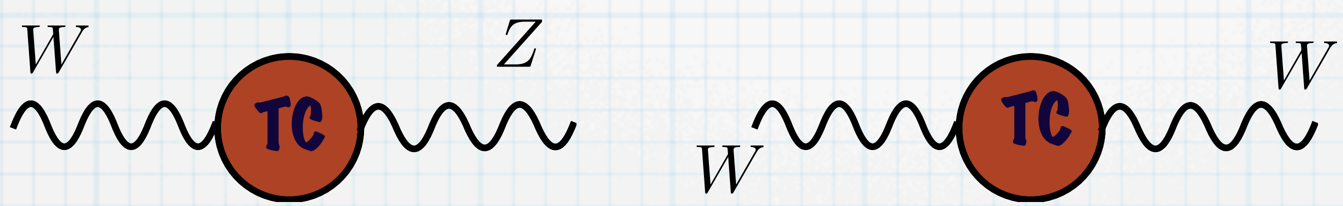
assumes QCD-like $\gamma_m$

WAY TOO SMALL!!!
even second generation (c, s) masses difficult !

# Precision Electroweak Observables

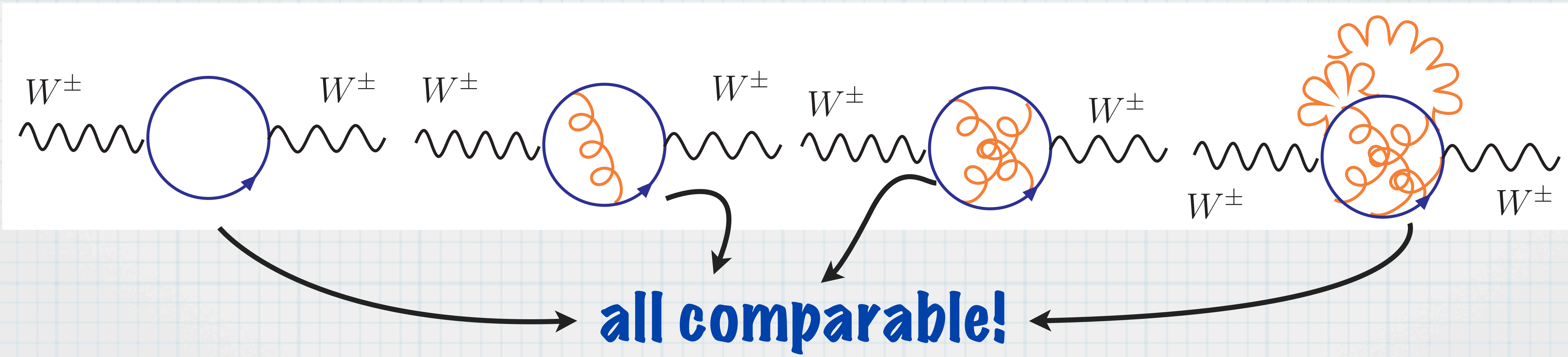
* As we've seen, we can indirectly probe new physics by making precise measurements at lower energies

* To test Technicolor with this approach we must compute the TC effects in the EW gauge boson sector




, etc.

**Unfortunately, in generic strongly interacting theories we have NO idea how to calculate these effects**



# Precision Electroweak, #2

custodial symmetry protects T,U

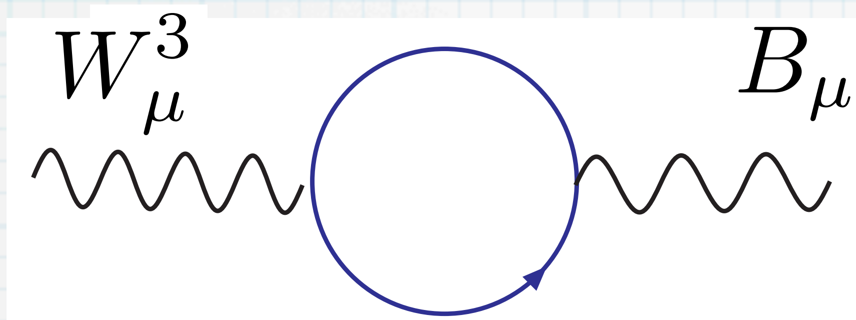
**S parameter** is the most important/unknown:

$$S = 4\pi \frac{d}{dq^2}\left(\Pi_{VV}(q^2) - \Pi_{AA}(q^2)\right)\Big|_{q^2=0}$$

## Some ideas in how to calculate S in a TC theory

i.) stick with lowest order perturbation theory

$S \propto$




simple result:

$$S_{pert} = \frac{N_T N_D}{6\pi}$$

but NO reason why lowest order perturbation theory should be adequate/accurate (the theory confines, makes bound states, etc. none of which can be captured in pert. theory)

ii.) Take QCD result from data ( $\pi\pi$ scattering), then rescale from QCD scale to TC scale

(Golden, Randall '91
Peskin, Takeuchi '91)

in this approach it is more convenient to rewrite S as a 'dispersion integral' over the spectrum

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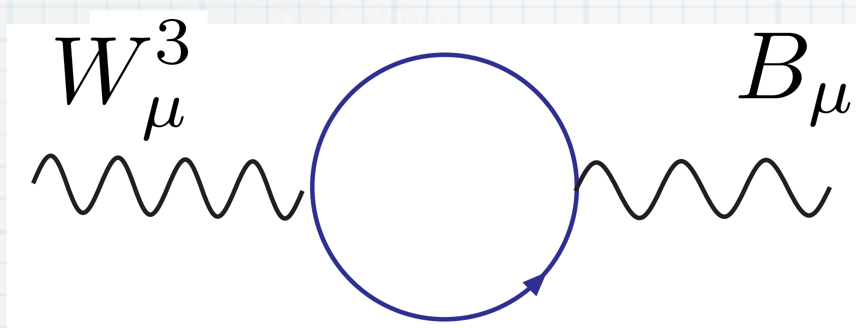


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# Precision Electroweak, #3

* Dispersion techniques: $$S = 4\pi \frac{d}{dq^2}\left(\Pi_{VV}(q^2) - \Pi_{AA}(q^2)\right)\Big|_{q^2=0}$$

what we really want to compute is a current-current correlator

$$J^3_\mu = \frac{1}{2}(J_{V,\mu} - J_{A,\mu}), \quad J^Q_\mu = J_{V\mu} + \frac{1}{2}J^Y_\mu$$

$$S \propto i\int d^4x e^{iq\cdot x}\langle T\{J_{3\mu}(x)J^\mu_Q(0)\}\rangle \equiv -\frac{i}{4}\int d^4x e^{iq\cdot x}\left(\langle T\{J_{V\mu}(x)J^\mu_V\}\rangle - \langle T\{J_{A\mu}(x)J^\mu_A\}\rangle\right.$$

but each of these can be rewritten as a integral in the complex momentum plane

$$\int d^4x e^{ip\cdot x}\langle T\{J_{V,\mu}(x)J_{V,\nu}(0)\}\rangle \equiv \eta_{\mu\nu}\Pi_{VV}(p^2) + (p^\mu p^\nu \ \text{pieces})$$

$$\Pi_{VV}(t) = \frac{1}{\pi}\int ds \frac{\mathrm{Im}(\Pi_{VV}(s))}{t - s + i\epsilon}$$ , + similar for axial part

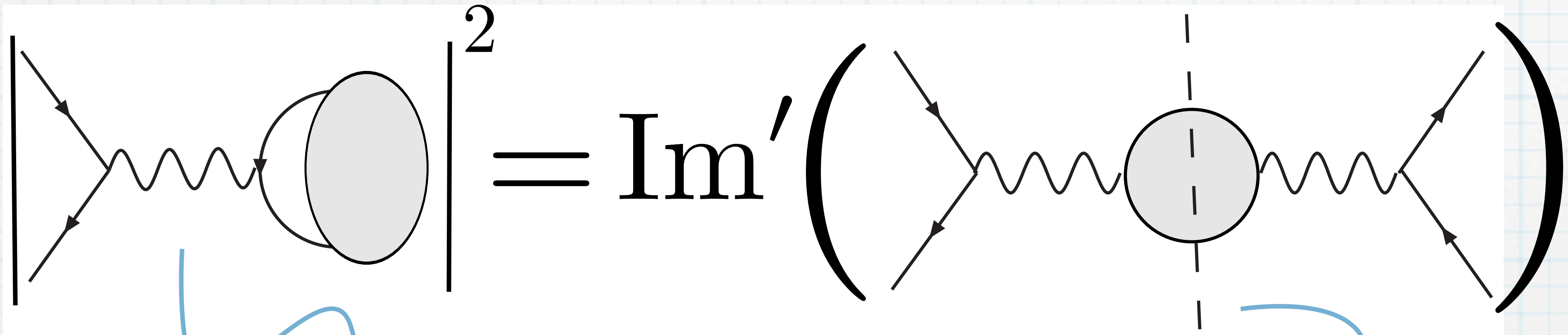
current conservation tells us:
$$\begin{aligned}\Pi_{VV}(q^2) &= q^2\Pi'_{VV}(q^2) + \cdots \\ \Pi_{AA}(q^2) &= \Pi_{AA}(0) + q^2\Pi'_{AA}(q^2) + \cdots\end{aligned}$$

In this language: $$\mathbf{S} \equiv 4\pi\int_0^\infty \frac{ds}{\pi}\frac{\left(\mathrm{Im}(\Pi'_{VV}(s)) - \mathrm{Im}(\Pi'_{AA}(s))\right)}{s}$$

# Precision Electroweak, #4

* Why does this help?

UNITARITY (Optical Theorem) tells us that there is a relation




goes beyond perturbation theory!

physical, measurable cross section
$\sigma(e^+e^- \to \text{technihadrons})$

$\mathrm{Im}'(\Pi)$, exactly what we need for S calculation

of course, we don't have $\sigma(e^+e^- \to \text{technihadrons})$ but we can:

MODEL it without relying on lowest order perturbation theory.

Or we can try to make an educated guess by using something we have measured, $\sigma(e^+e^- \to \text{QCD hadrons})$

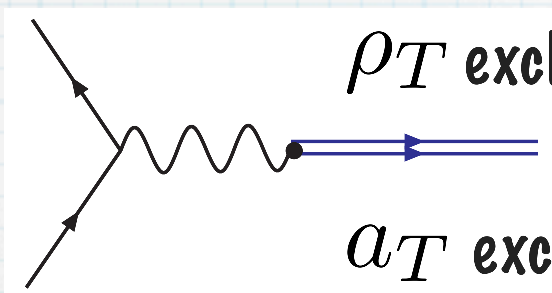
(Peskin, Takeuchi '91)

# Precision Electroweak, #5

Simple model: saturate the vector and axial spectral functions with **single (narrow) resonances**

$$\mathrm{Im}(\Pi'_{VV}(s)) = F^2_{\rho_T}\delta(s - m^2_{\rho_T}), \quad \mathrm{Im}(\Pi'_{AA}(s)) = F^2_{a_T}\delta(s - m^2_{a_T})$$

we approximate TC blob with



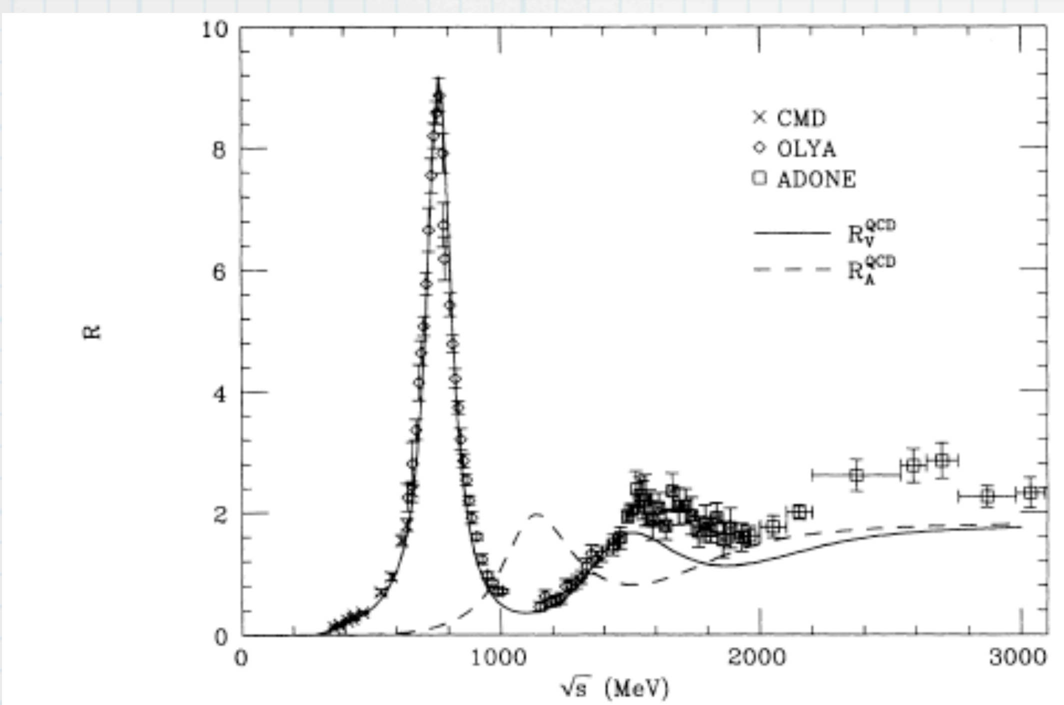
$\rho_T$ exchange $\Pi_{VV}$

$a_T$ exchange $\Pi_{AA}$

$$S = 4\pi \frac{F_T^2}{m^2_{\rho_T}}\left[1 + \frac{m^2_{\rho_T}}{m^2_{a_T}}\right]$$

$$\boxed{S \cong 0.25 N_D \frac{N_{TC}}{3}}$$

or, from data :




Obtain $\Pi_{VV}, \Pi_{AA}$ from QCD $e^+e^- \to \text{hadrons}$ data,

then rescale by: $\frac{F_T}{f_\pi}, N_C, N_D$

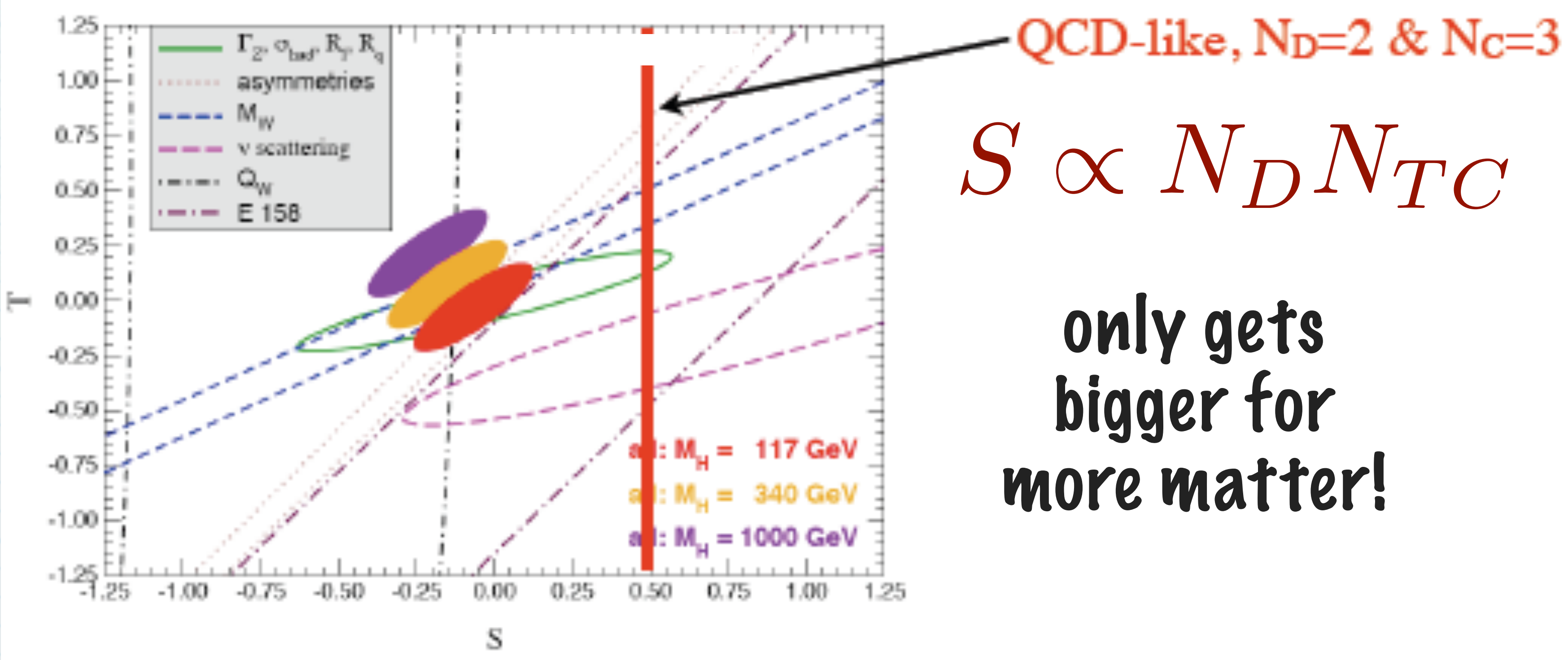
incorporates resonance widths

$$\boxed{S \cong 0.30 N_D \frac{N_{TC}}{3}}$$

(for more details, see Peskin, Takeuchi '91)

# Precision Electroweak

## Either way, results are STRONGLY disfavored by current bounds on S



PDG2006: Erler and Langacker

$$S \propto N_D N_{TC}$$

only gets bigger for more matter!

# TECHNICOLOR

# Precision Electroweak

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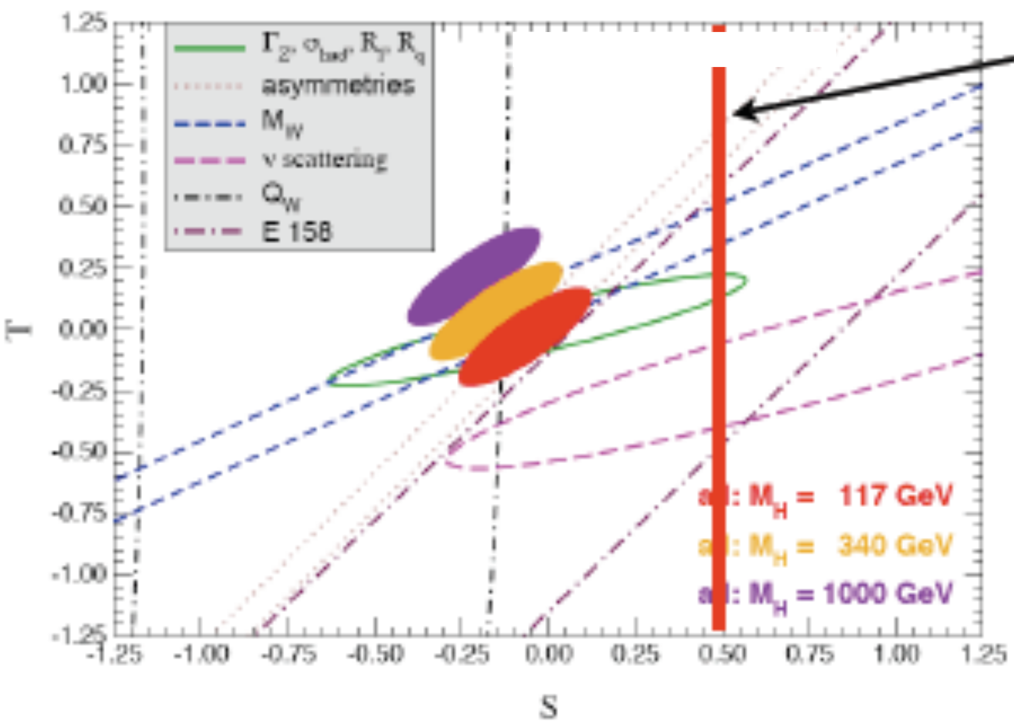



QCD-like, $N_D$=2 & $N_C$=3

$$S \propto N_D N_{TC}$$

only gets bigger for more matter!

PDG2006: Erler and Langacker

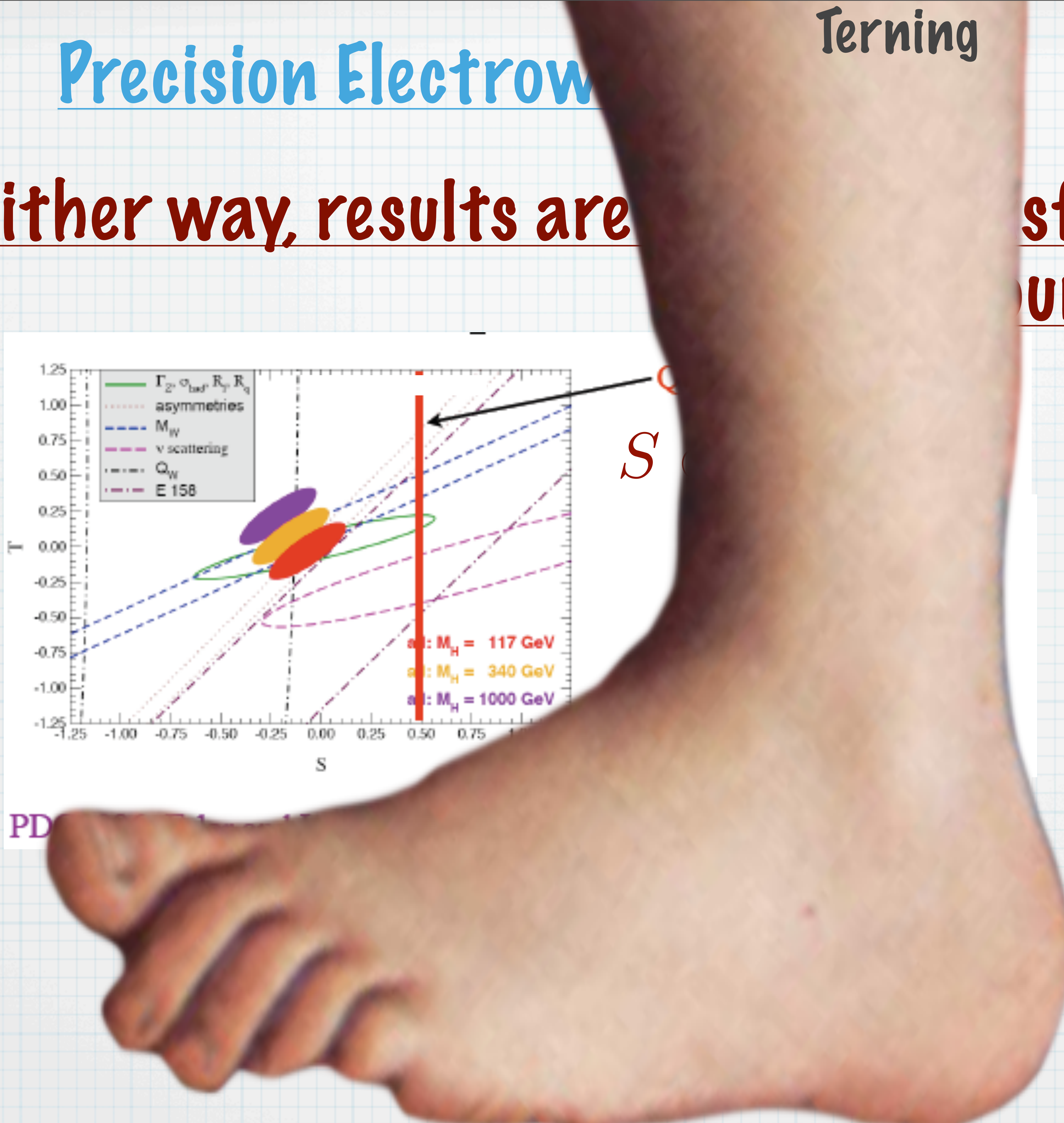
(QCD-like)

^TECHNICOLOR

Terning

# Precision Electrow

## Either way, results are sfavored by
## unds on S



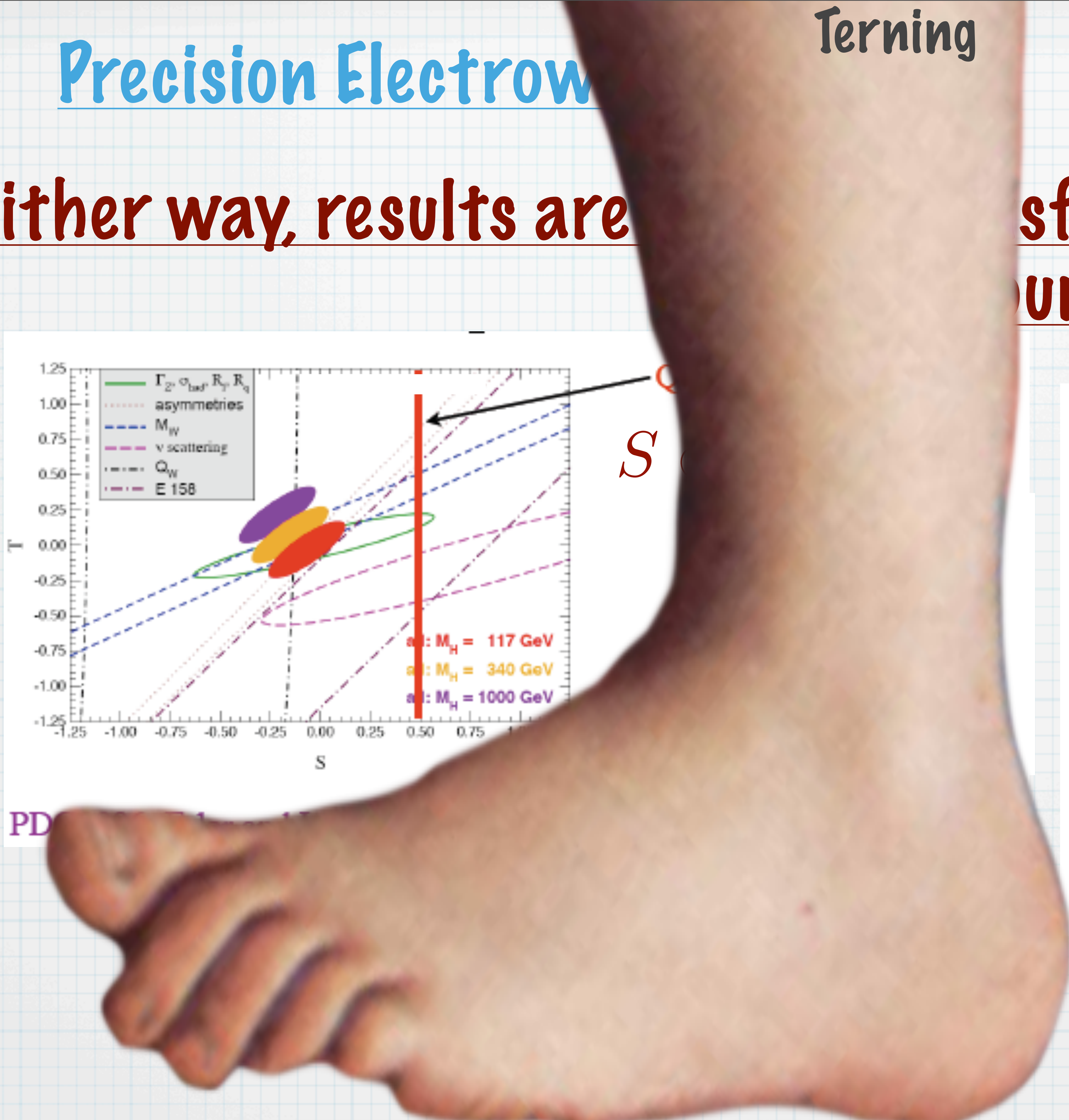

$S$

PD

Terning

# Precision Electrow

## Either way, results are sfavored by
## unds on S




PD

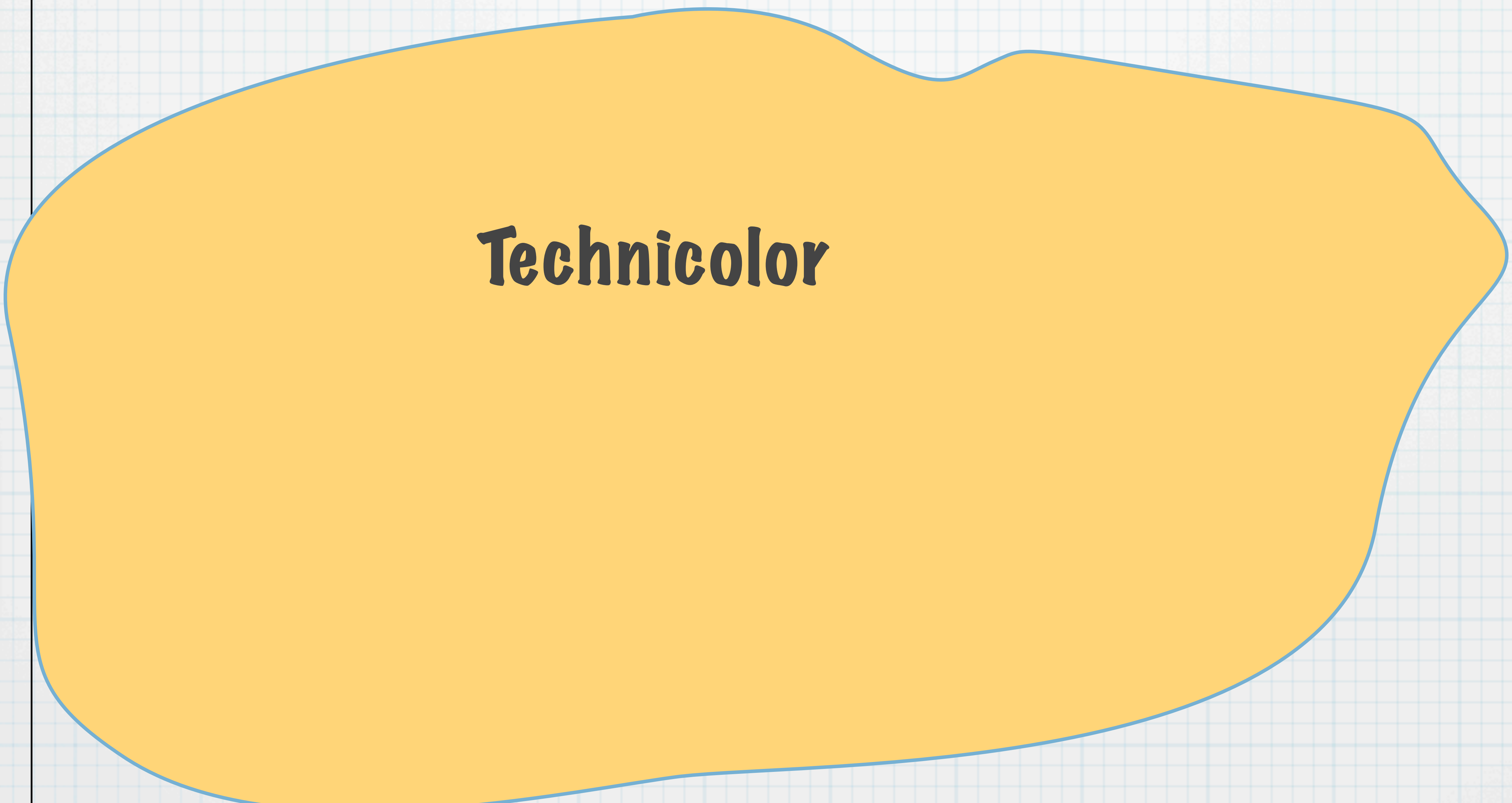
$S$

**SQUASHED by LEP (1989-2000)**

...but is that the end of the story?

# NO!

Technicolor (strong EW-scale dynamics) is a huge class of theories



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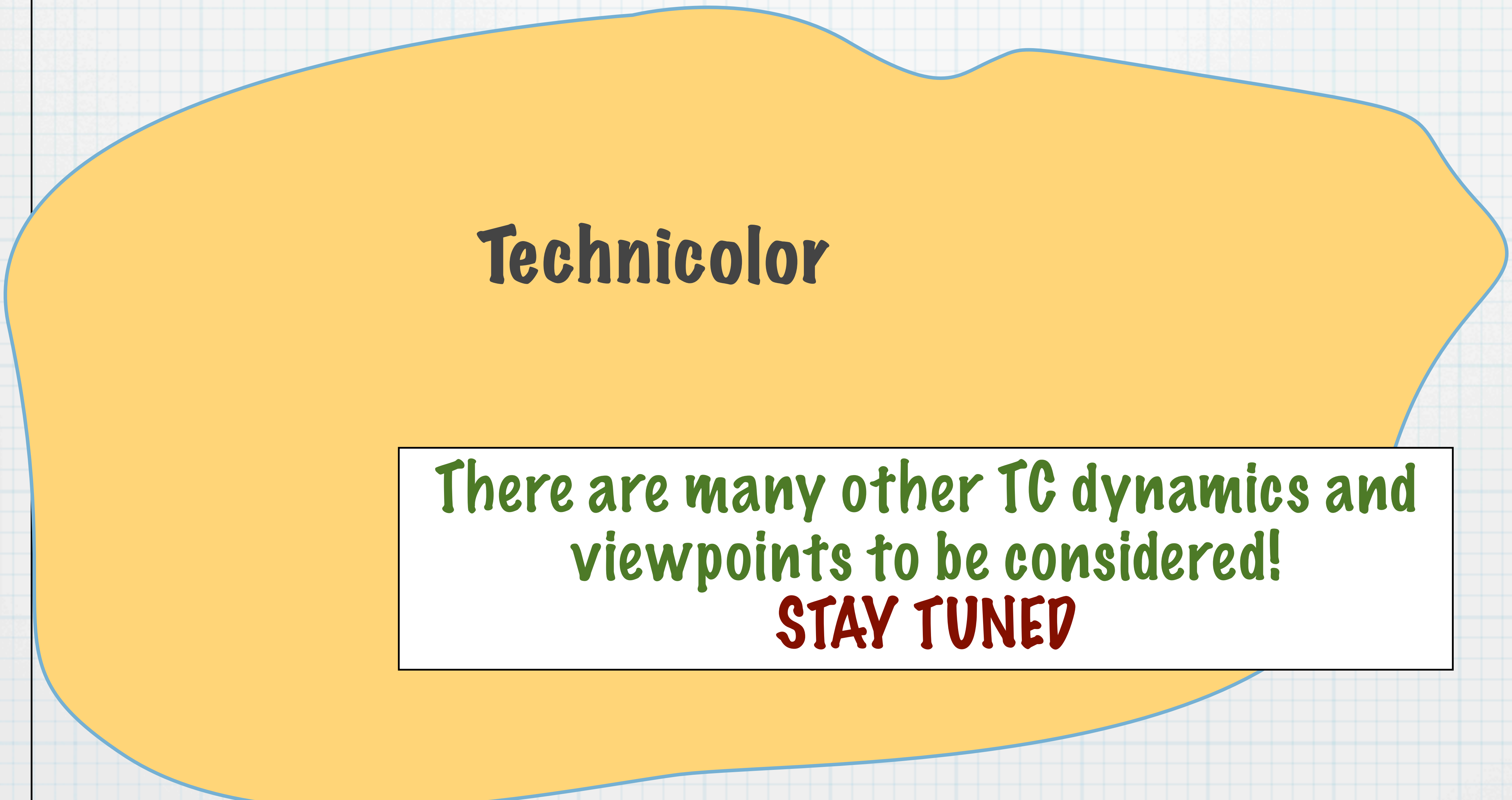


There are many other TC dynamics and viewpoints to be considered!
STAY TUNED

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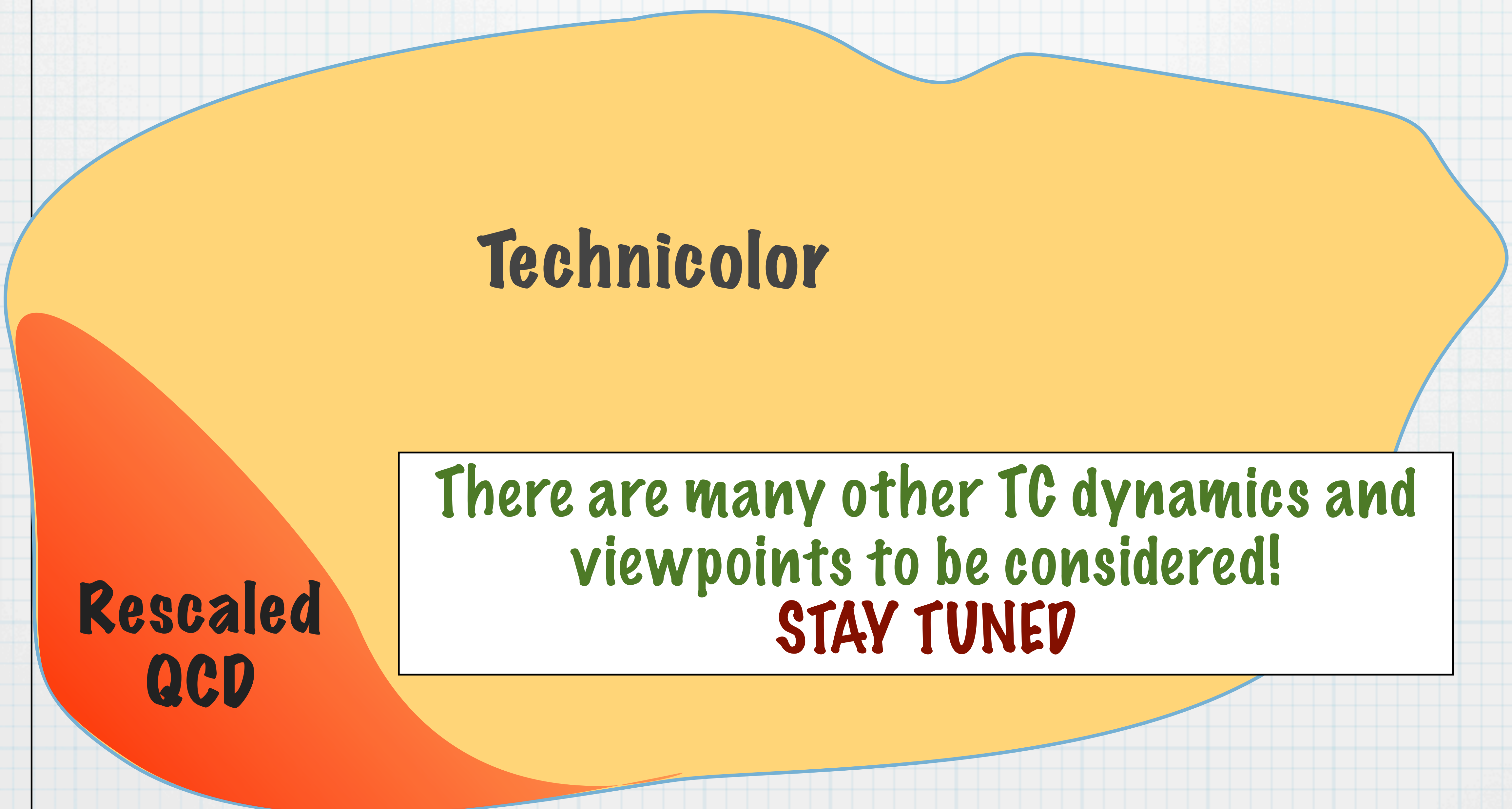
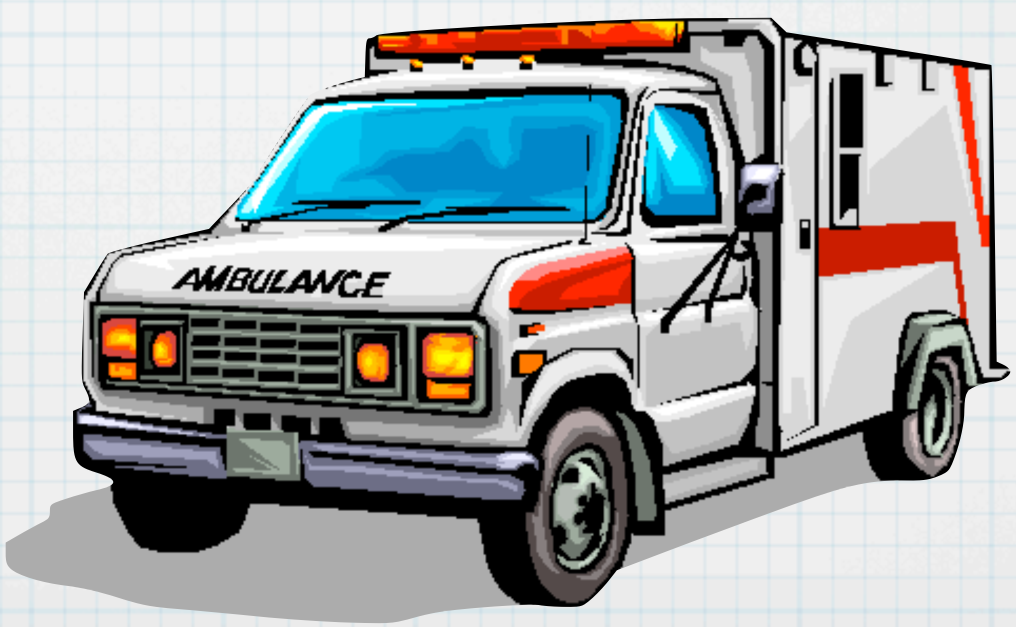



There are many other TC dynamics and viewpoints to be considered!
STAY TUNED

# Part 2:

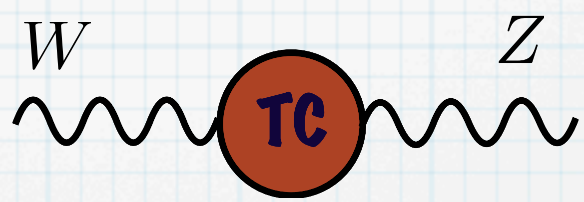

# RESCUING TECHNICOLOR

# Peculiarities of QCD

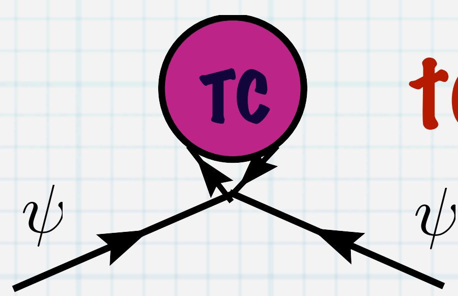
* All of our troubles in Technicolor came from **assuming that QCD-like dynamics at the EW scale was a good model for Technicolor**

* Precision Electroweak:




too BIG!

* Quark masses:



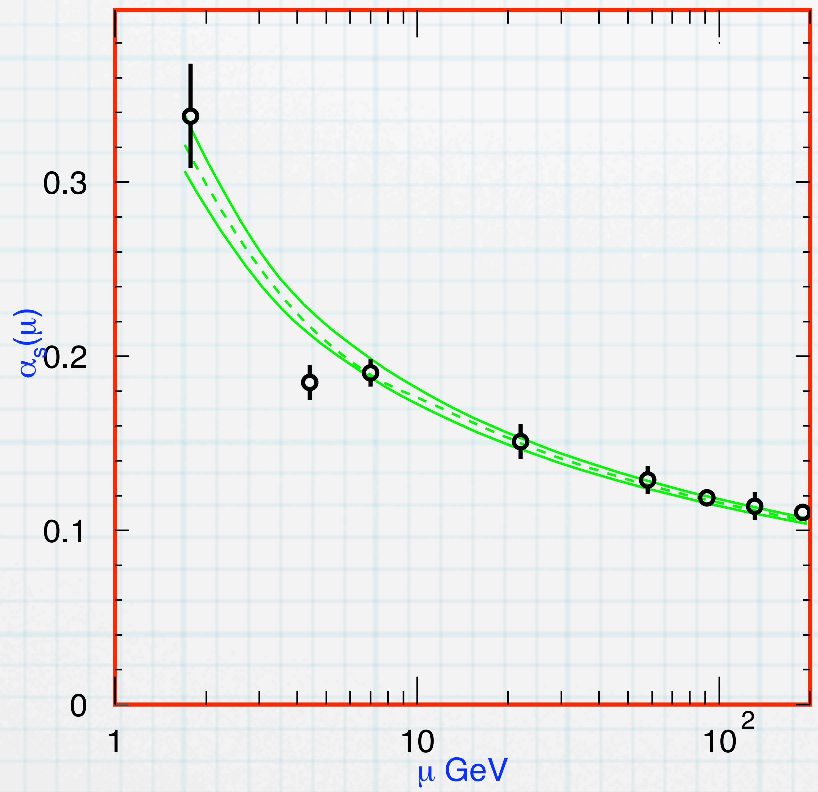

too SMALL!

**but why should a generic strong interaction be just like QCD?**

# "Peculiarities" of QCD

QCD is the only strong interaction we know, BUT

- only **one** complex representation: fundamental
- **all** colored fermions carry SU(2) X U(1) charge
- quickly running coupling:




$$\alpha(\mu) \sim \frac{2\pi}{\beta_0 \log \Lambda/\mu}$$

- $m_\rho < m_\sigma$
- leptons are required to cancel gauge anomalies

what happens if we relax some of these?

# Different phases of gauge theories

Lets think about the running behavior of QCD and how we might change it

**the running of the gauge coupling is described by the beta function $\beta(\alpha)$**

$$\beta(\alpha) = \frac{-2b_0}{4\pi}\alpha^2 - \frac{2b_1}{(4\pi)^2}\alpha^3 + \cdots$$

gauge group:
SU(N), SO(N), Sp(N), etc

matter representations:
fundamental, Adj,
(anti)-symmetric, etc.

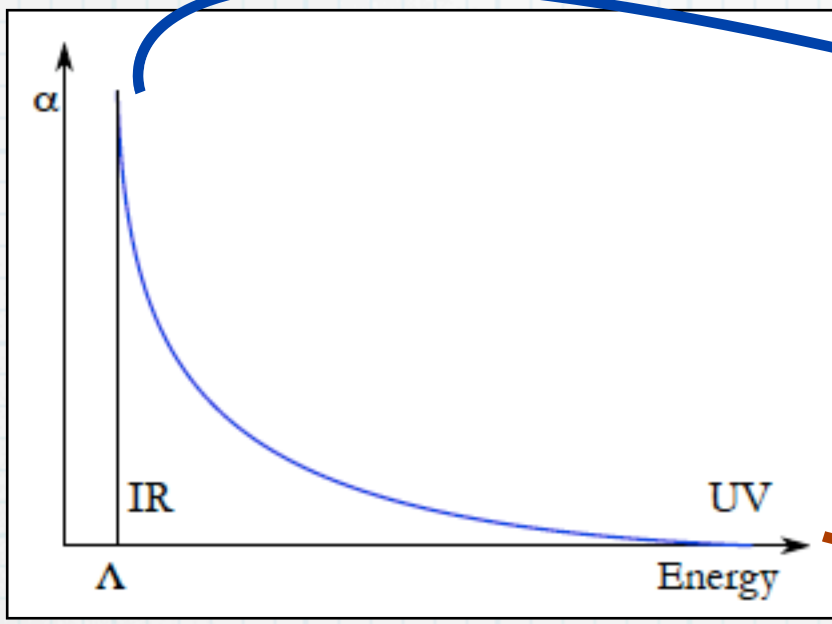

amount of matter:
$N_{F,r}$

confinement scale
$\Lambda$

$$b_0 = \left(\frac{11}{3}N_C - \frac{4}{3}\sum_{F,r} C(r)\right) \qquad b_1 = \frac{34}{2}N_C^2 - \frac{20}{3}\sum_{F,r} C(r) N_F N_C - 2\sum_{F,r} C_2(r) N_F$$

# Phases of gauge theories

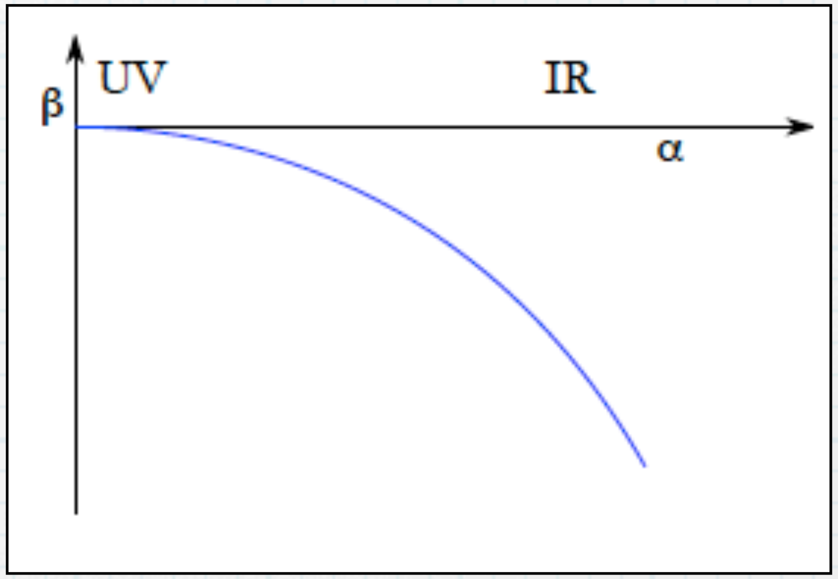
* We are used to seeing the QCD coupling pictured as




confinement/IR slavery

asymptotic freedom

but an alternative picture is $\beta(\alpha)$ as a function of $\alpha$




...this picture is helpful when we consider possibilities other than QCD-like behavior

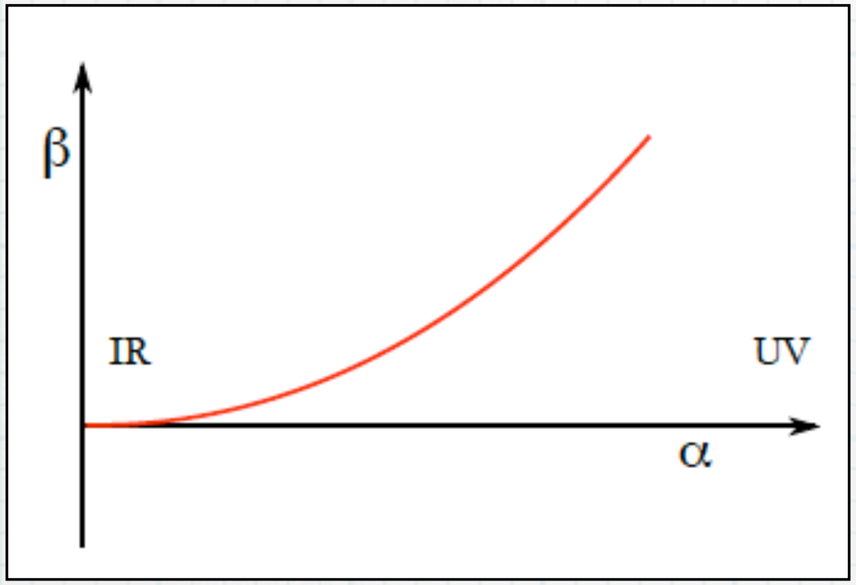
asymptotic freedom appears as $\alpha \to 0$ in the UV

# Phases of gauge theories, #2

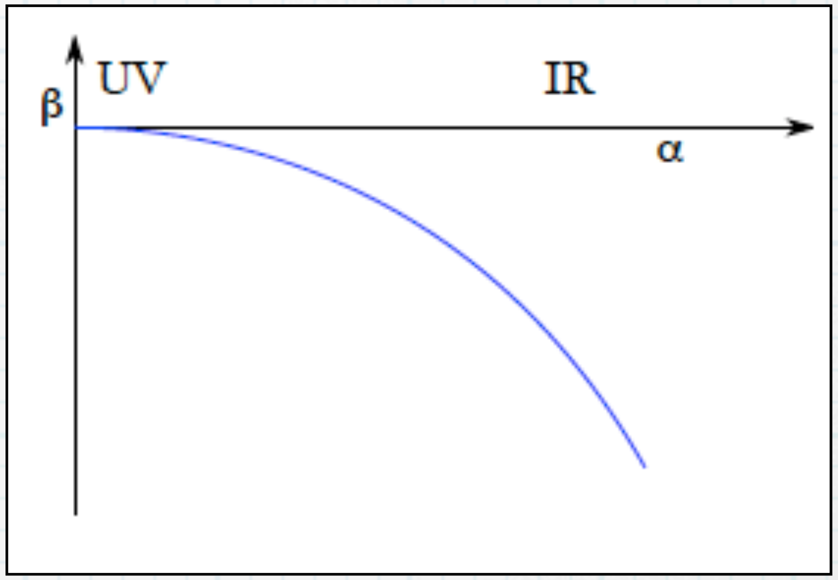
* How could we change things? Well, if we add enough matter, eventually we lose asymptotic freedom

non-aymptotically free

for example, QED!




QCD-like




Notice the different locations of the UV and IR scales!!

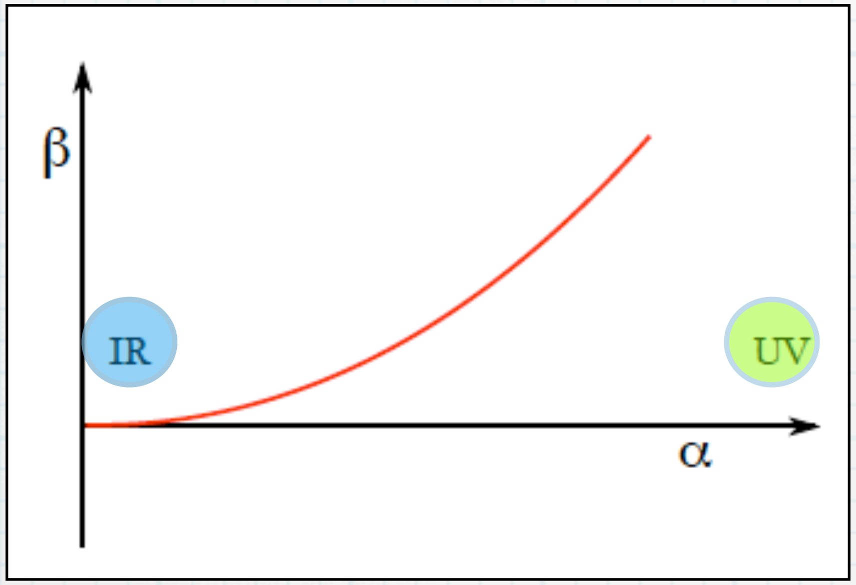
* interesting, but a non-asymptotically free theory gets **weaker in the IR** so it won't spontaneously break EWSB

# Phases of gauge theories, #2

* How could we change things? Well, if we add enough matter, eventually we lose asymptotic freedom

for example, **QED!**

non-aymptotically free

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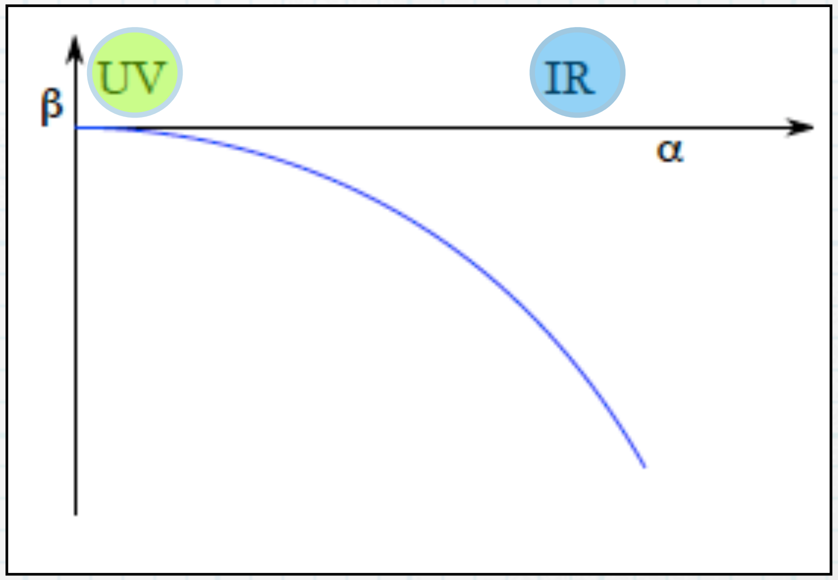
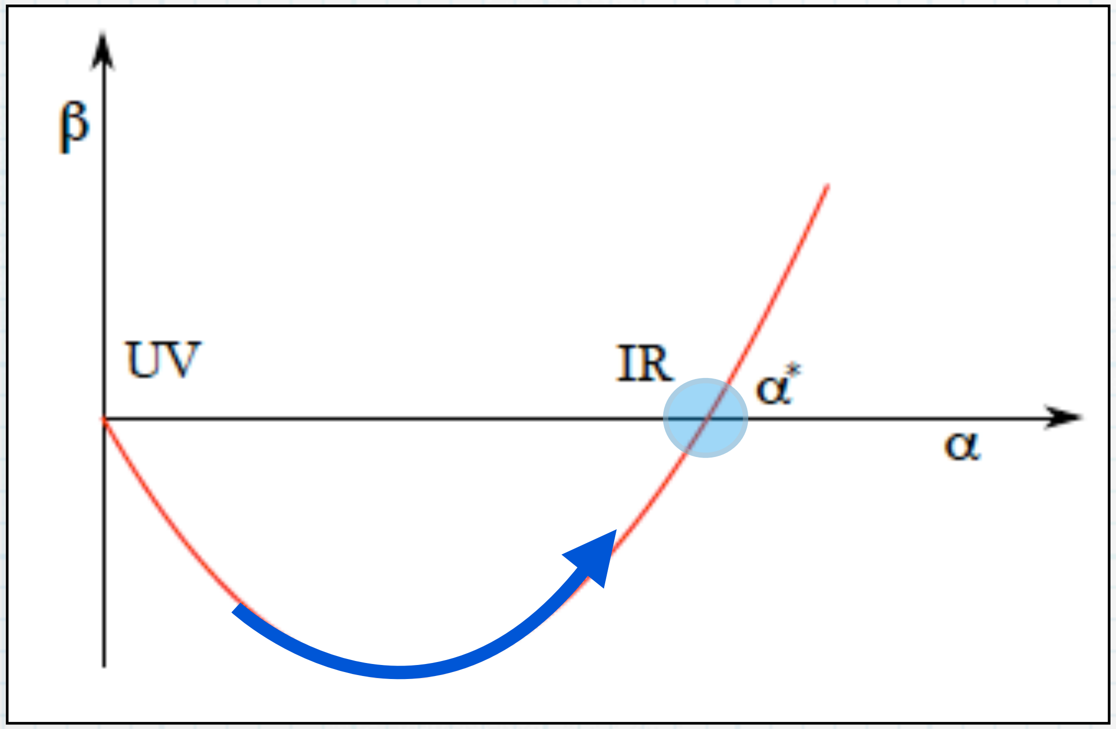



**Notice the different locations of the UV and IR scales!!**

* interesting, but a non-asymptotically free theory gets **weaker in the IR** so it won't spontaneously break EWSB

# Phases of gauge theories, #3

* What about a theory which has $\beta(\alpha^*) = 0$ at some nonzero value of $\alpha^* \neq 0$




as we go from the UV to the IR the coupling flows towards $\alpha^*$

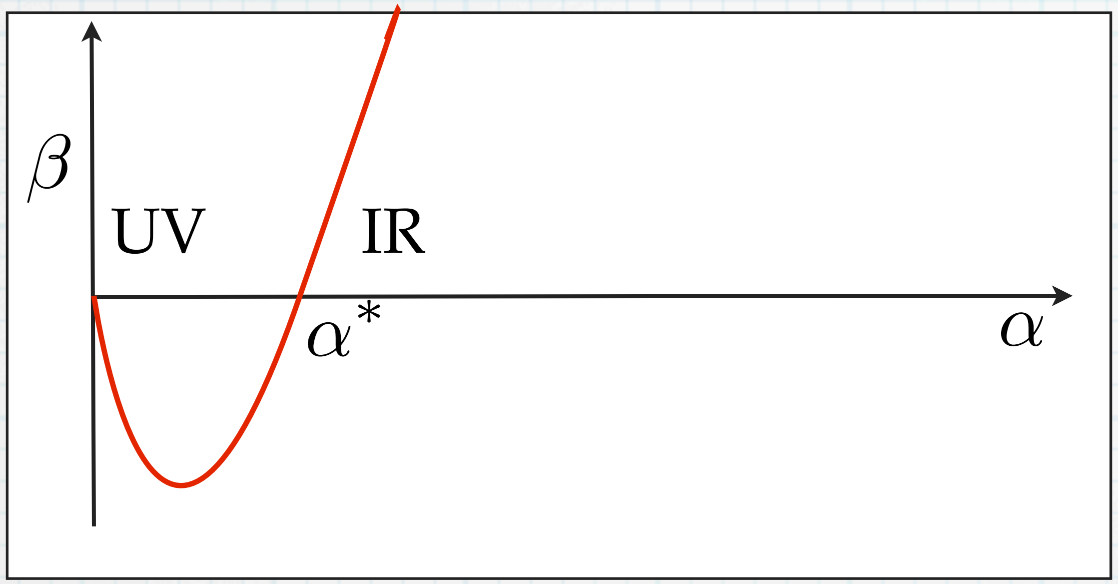
once $\alpha \to \alpha^*$ , $\beta = 0$ :
the coupling STOPS RUNNING-> it remains fixed for all lower energies

$\alpha^*$ is known as a fixed point, where the theory becomes conformal

to say more, we need to know how strong the fixed point coupling is

# Phases of gauge theories, #4

weakly coupled fixed point $\alpha^* \ll 1$

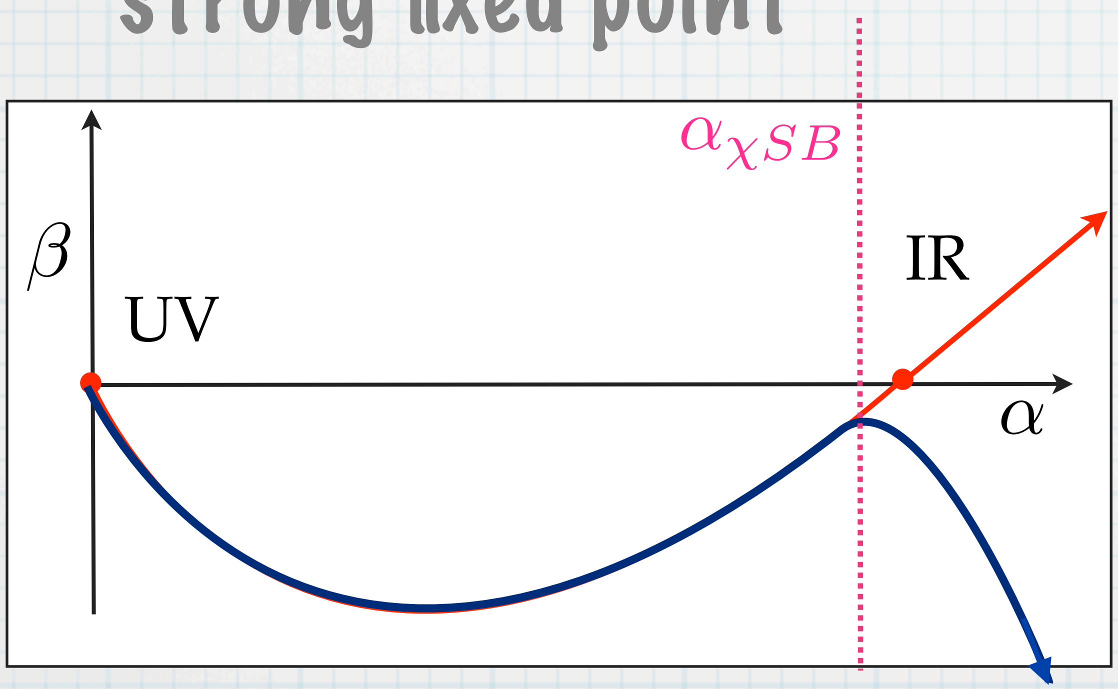



* weak fixed point: no symmetry breaking or confinement occurs.. the theory consists of **weakly interacting matter and gluons**

* increasing $\alpha^*$ eventually we pass another important value, the value where the coupling is strong enough for **chiral symmetry breaking** to happen,

$$\alpha^* > \alpha_{\chi SB}$$

strong fixed point

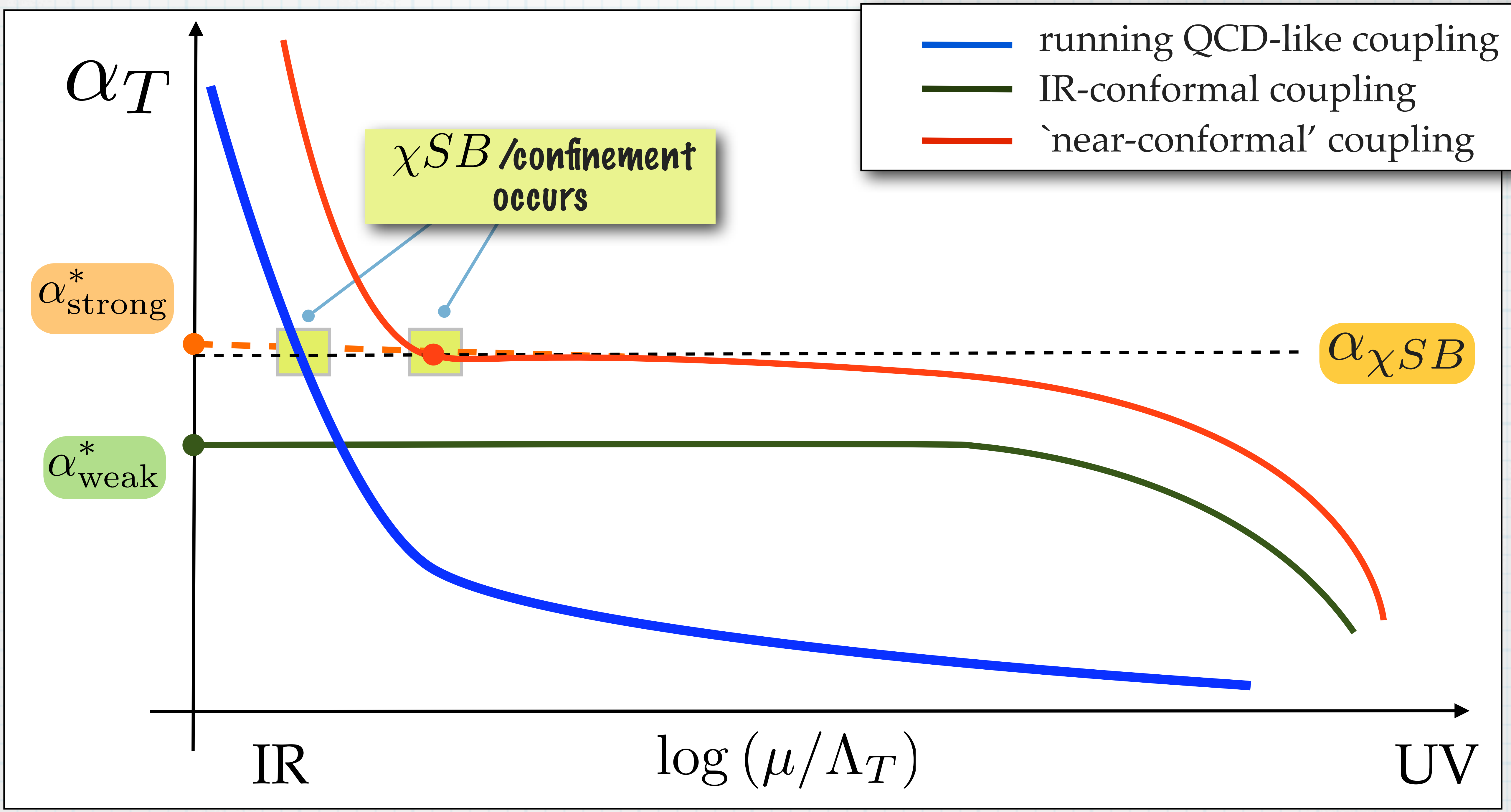



once confining, **states become massive (dynamically) and decouple, changing the beta function**

**in this scenario we never actually hit the fixed point**

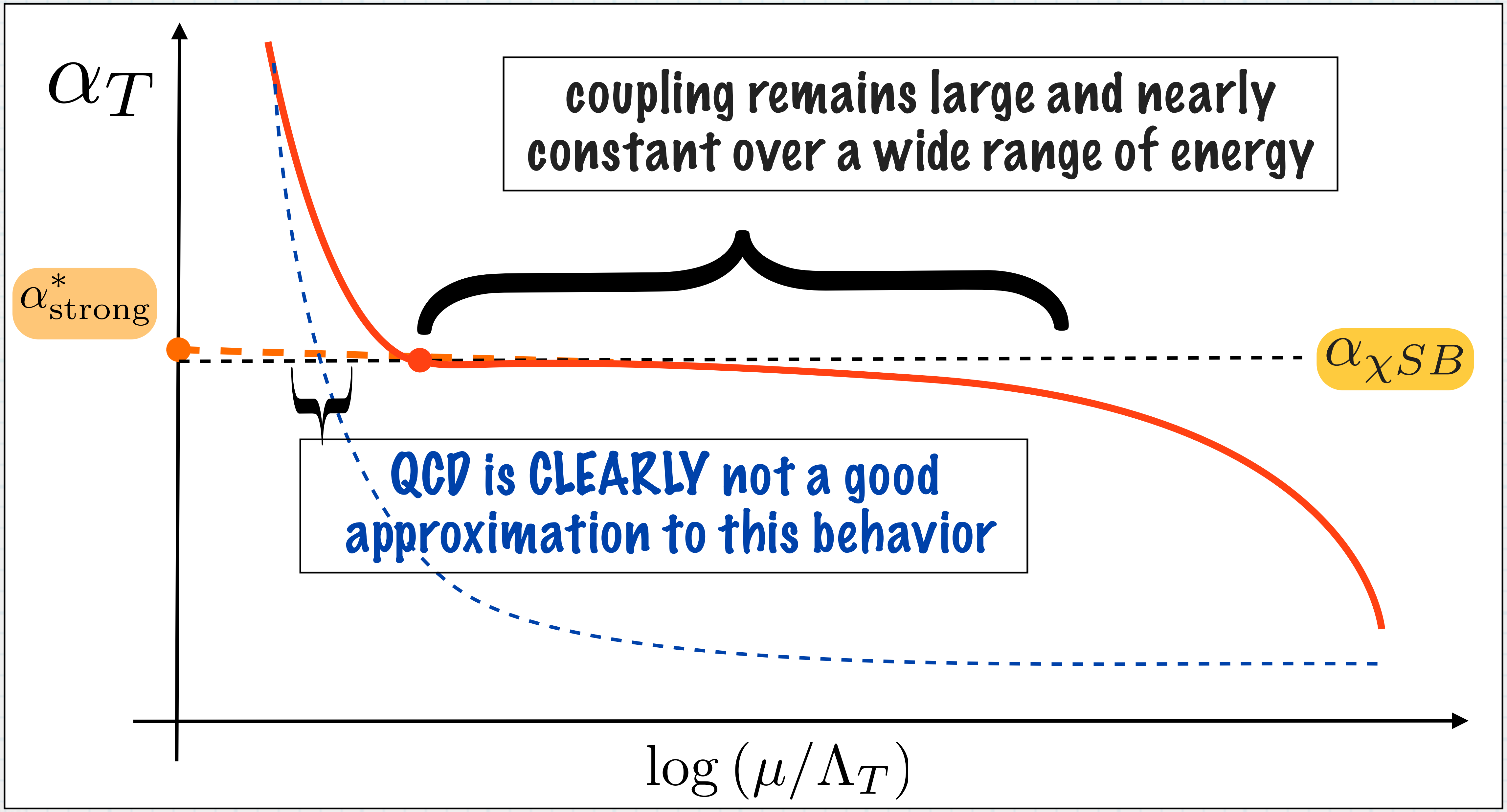
# Phases of gauge theories, #5

* What does this "near conformal" theory look like?



# Phases of gauge theories, #6

Near conformal theories are also called **"Walking" theories**
the coupling changes with energy, but very slowly

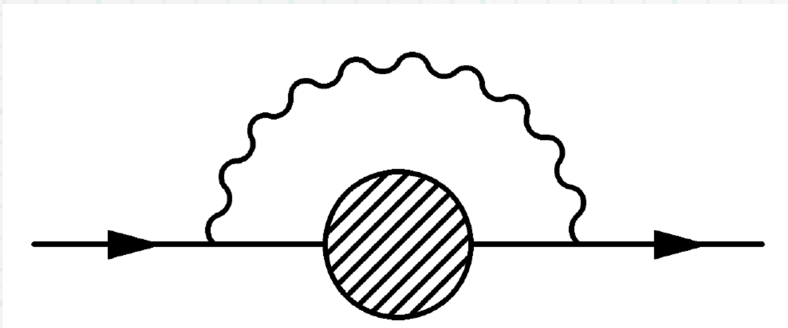



BUT where does a walking theory differ from a running theory, quantitatively?

# Schwinger-Dyson (SD) approach

(Kugo, Fukuda '70's)

* To demonstrate **how walking effects physical quantities**, compute the technifermion propagator at 1-loop



$$iS^{-1}(p) = Z(p)\left(\not p - \Sigma(p)\right)$$

working in Landau gauge: $Z(p) = 1$

$$\Sigma(p^2) = \frac{3C_2(r)}{(2\pi)^4}\int d^4k \frac{g_T^2\cancel{((k-p)^2)}}{(k-p)^2}\frac{\Sigma(k^2)}{k^2 - \cancel{\Sigma^2(p^2)}}$$

approximate the coupling as constant, linearize, and perform the angular integral using $(k-p)^2 = (k^2 + p^2 - 2pk\cos\psi)$

$$\Sigma(p^2) = \frac{3C_2(r)g_T^2}{(2\pi)^4}\left(\int_0^{p^2} d(k^2)\frac{\Sigma(k^2)}{p^2} + \int_{p^2}^{\Lambda^2} d(k^2)\frac{\Sigma(k^2)}{k^2}\right)$$

# Schwinger-Dyson approach, #2

* Derivatives $\frac{d}{dp^2}$ convert this integral equation into a differential one

$$\frac{d}{dp^2}\left(p^4 \frac{d\Sigma(p^2)}{dp^2}\right) = \frac{3C_2(r)g_T^2}{4\pi}\Sigma(p^2)$$

Solving: $\Sigma(p^2) \sim const.\left(\frac{\mu}{p}\right)^{1\pm\sqrt{1-4r}}, \quad r = \frac{3C_2(r)g_T^2}{4\pi}$

$m_F\langle\bar\psi\psi\rangle$ is independent of $\mu$ so we can convert the $\mu$ dependence of $\Sigma(p^2)$ into the anomalous dimension of $\langle\bar\psi\psi\rangle$

$$\gamma_{(\bar\psi\psi)} = 1 - \sqrt{1 - \frac{\alpha_T}{\alpha_c}} \quad \text{where} \quad \alpha_c = \frac{\pi}{3C_2(r)}$$

this reproduces the perturbative result for $\gamma_m$ when $\alpha_T \ll \alpha_c$
but, for large coupling $\alpha_T \sim \alpha_c$ we find large anomalous dimension:

$$\boxed{\text{Walking theory (in SD analysis) has } \gamma_m \sim 1}$$

# Schwinger-Dyson approach, #3

* Large anomalous dimension is a nice, intuitive result of walking, BUT we had to make many approximations (some severe!) in order to use the SD method

    - constant coupling
    - linearized fermion propagator
    - gauge specific
    - tree-level technigluon propagator
    - ONE LOOP RESULT

* Also, some subtleties in interpreting the solution we have:

    - two solutions
    - what happens when $\alpha_T > \alpha_c$ ?

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(Appelquist et al '88
Cohen, Georgi '89
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**chiral symmetry breaking happens when $\alpha_T \geq \alpha_c$**

# Take-home message:

**A near-conformal/walking coupling leads to large anomalous dimensions**

Calculating the anomalous dimension in a strongly interacting theory is no easy task...

## Schwinger-Dyson approach:

The method has many shortcomings, so it is difficult to judge the exact numerics, but the conclusion that $\gamma_m \sim 1$ appears robust

**Further Evidence:** SUSY conformal field theories

O(1) anomalous dimensions for $(\bar{Q}Q)$ in certain SQCD theories (Seiberg hep-ph/9411149, 9402044)

# Why do we want a walking coupling?

* An extremely important place where the anomalous coupling played a role is in calculating the SM fermion mass $m_f \propto \langle \bar{T}_L T_R \rangle|_{ETC}$

* The anomalous dimension of the techicondensate $\langle \bar{T}_L T_R \rangle$ appears when we connect the ETC and TC scales

$$\langle \bar{T}_L T_R \rangle|_{ETC} = \langle T_L T_R \rangle|_{TC} \times exp\Big( \int_{\Lambda_{TC}}^{\Lambda_{ETC}} \frac{d\mu}{\mu} \gamma_{\bar{T}_L T_R}(\mu) \Big)$$

for QCD-like, we assumed $\gamma_{(\bar{T}_L T_R)} \ll 1$

* What do we get for a WALKING technicolor theory?

then: $\gamma_{(\bar{T}_L T_R)} \approx 1$ is big

$$\langle \bar{T}_L T_R \rangle|_{ETC} \sim \langle T_L T_R \rangle|_{TC} \times exp\Big( \int_{\Lambda_{TC}}^{\Lambda_{ETC}} \frac{d\mu}{\mu} \Big)$$

$$\cong \langle T_L T_R \rangle|_{TC} \times \Big( \frac{\Lambda_{ETC}}{\Lambda_{TC}} \Big)$$

condensate ENHANCED by large ratio of scales

# Benefits of a walking coupling, #2

plugging in to get the fermion masses

$$m_q, m_l \sim \frac{g_{ETC}^2}{M_{ETC}^2}\langle \bar{T}T\rangle_{ETC} \quad \sim \frac{g_{ETC}^2}{M_{ETC}^2}(4\pi F_T^3)\left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)$$

for ETC scales compatible with FCNC we get

$$m_{q,\ell} \cong \frac{50 - 500 \text{ MeV}}{N_D^{3/2}|\theta_{ds}|^2}$$

femion masses $\lesssim m_b$ are now possible

**consistent with FCNC and without fine tuning!!**

Similar enhancement for the technipion masses

for simplicity: $m_\pi^2 \sim \frac{g_{ETC}^2}{M_{ETC}^2 F_T^2}\langle \bar{T}T\bar{T}T\rangle_{ETC} \sim \frac{g_{ETC}^2}{M_{ETC}^2 F_T^2}\langle \bar{T}T\rangle_{ETC}^2$

plug in $\gamma_m \sim 1$

$$m_{\pi_T}^2 \sim \frac{g_{ETC}^2\Lambda_{TC}^2 F_{TC}^2}{M_{ETC}^2}\left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^2 \gtrsim \mathcal{O}(100 \text{ GeV})$$

# Where are the walking theories?

* OK, walking techicolor sounds helpful, but how do we get it?
* Perturbative analysis suggests that there is a regime before asymptotic freedom is lost where the theories become conformal in the infrared: a "conformal window"

$$\beta(g) \equiv \mu \frac{dg}{d\mu} = -\frac{b_0 \; g^3}{(4\pi)^2} - \frac{b_1 \; g^5}{(4\pi)^4} + \cdots$$

$$b_0 = \left(\frac{11}{3} N_C - \frac{4}{3} \sum_{F,r} C(r)\right) \qquad b_1 = \frac{34}{2} N_C^2 - \frac{20}{3} \sum_{F,r} C(r) N_F N_C - 2 \sum_{F,r} C_2(r) N_F$$

$\boxed{\text{increasing the matter content, } b_0 \text{ decreases}}$

at least within 2-loop perturbation theory, there is a range where $b_0$ is small enough that the $b_1$ term, despite being , $\mathcal{O}(g^5)$ can compensate and cause $\beta(g) = 0$ at some nonzero value, $g^*$

# Where are the walking theories?, #2

* Exactly where this regime is depends on $N_C$ and the matter content of the theory (number of fermions, their representations)

* Further evidence for conformal windows comes from supersymmetry:

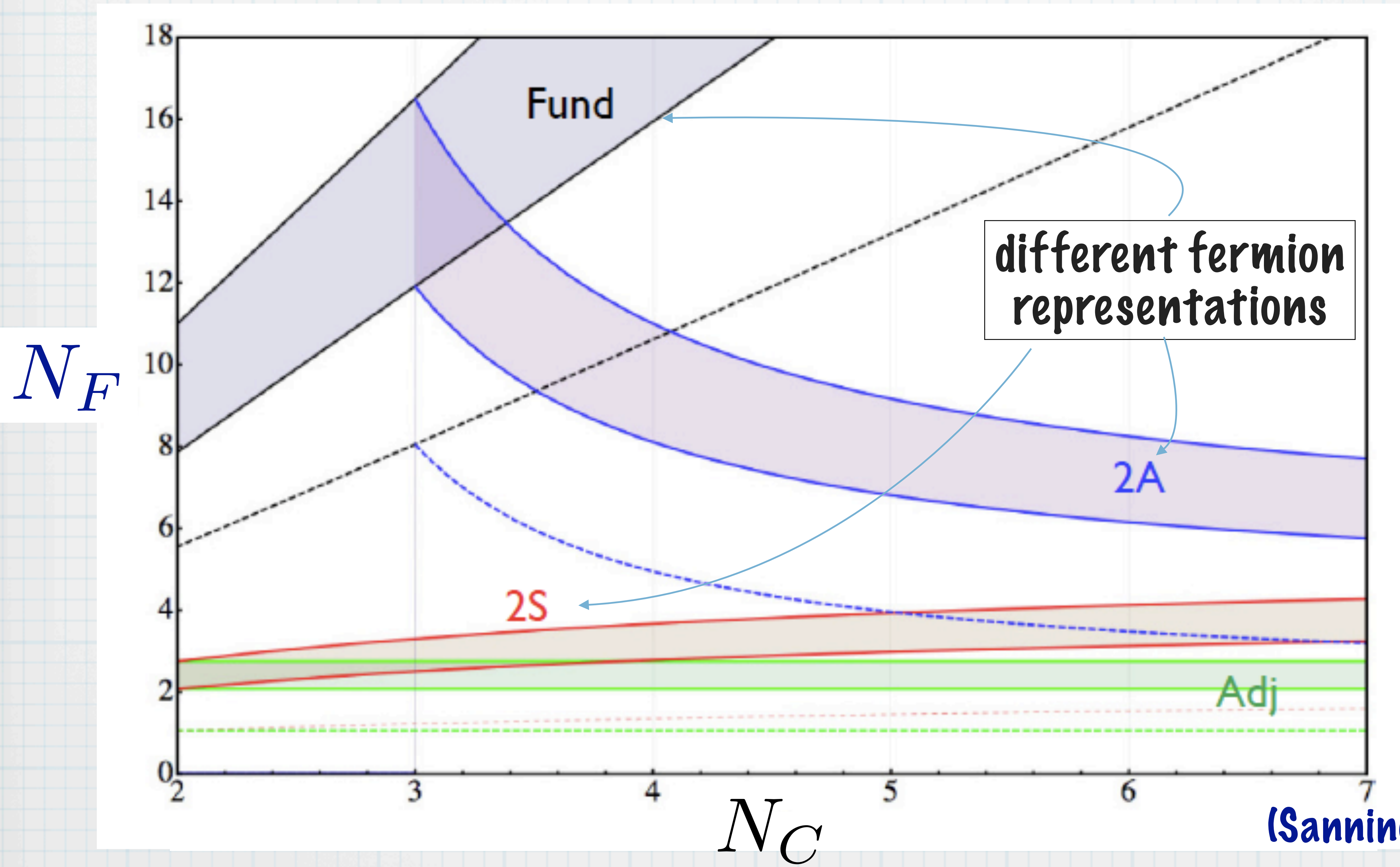
specifically for Super Yang Mills + fundamental matter (SQCD), Seiberg et al mapped out this window

SU(N) SQCD conformal window: $\frac{3}{2}N_C < N_F < 3N_C$

but conformal SUSY has a lot of powerful tools: holomorphy, non-renormalization, R-symmetry, etc.

# Where are the walking theories? #3

* Similar attempts have been made in non-SUSY gauge theories, though the tools available are less powerful




shaded regions are estimates of conformal window

(Sannino)

# Where are the walking theories? #4

* What is going on in this plot?

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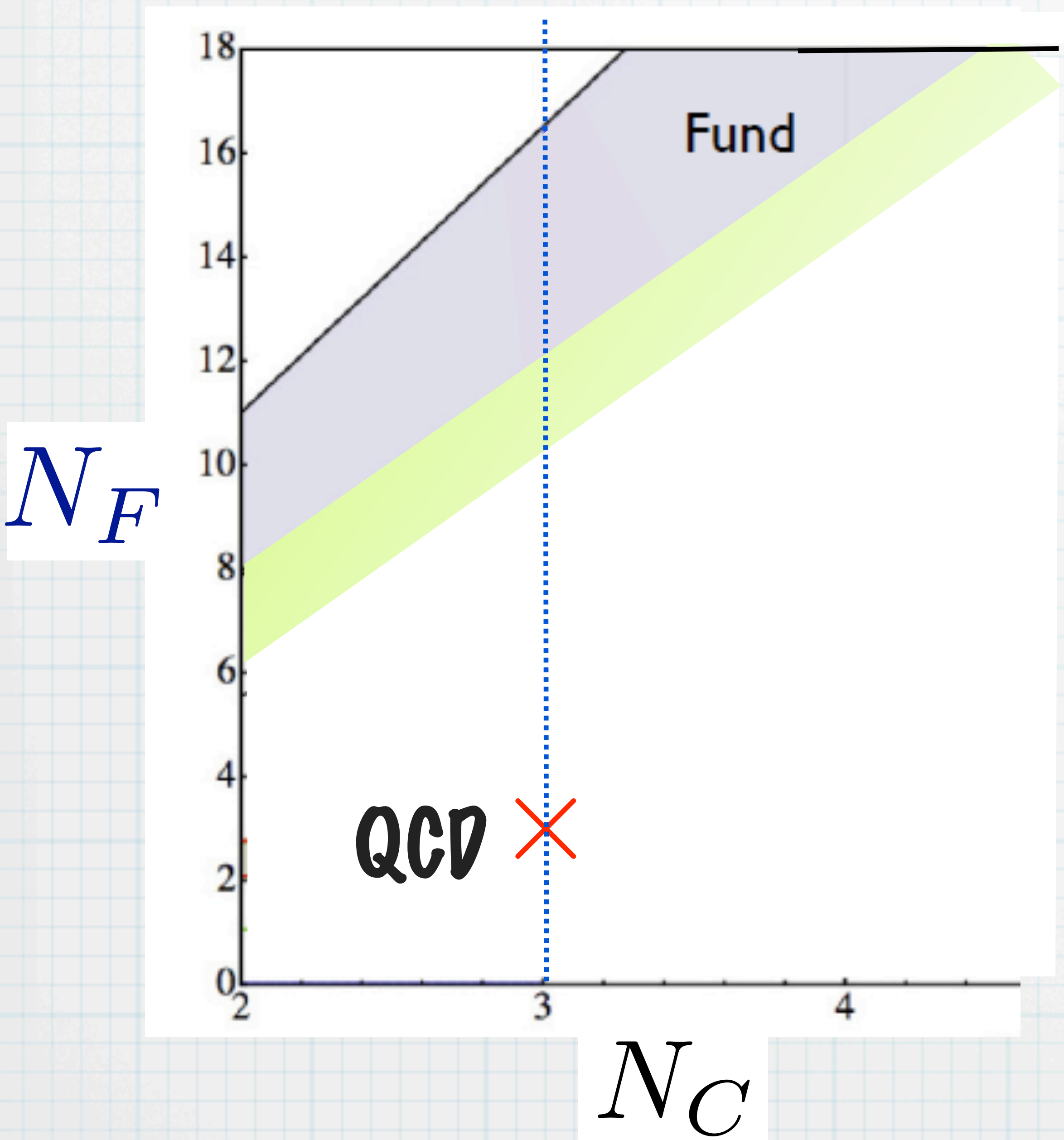

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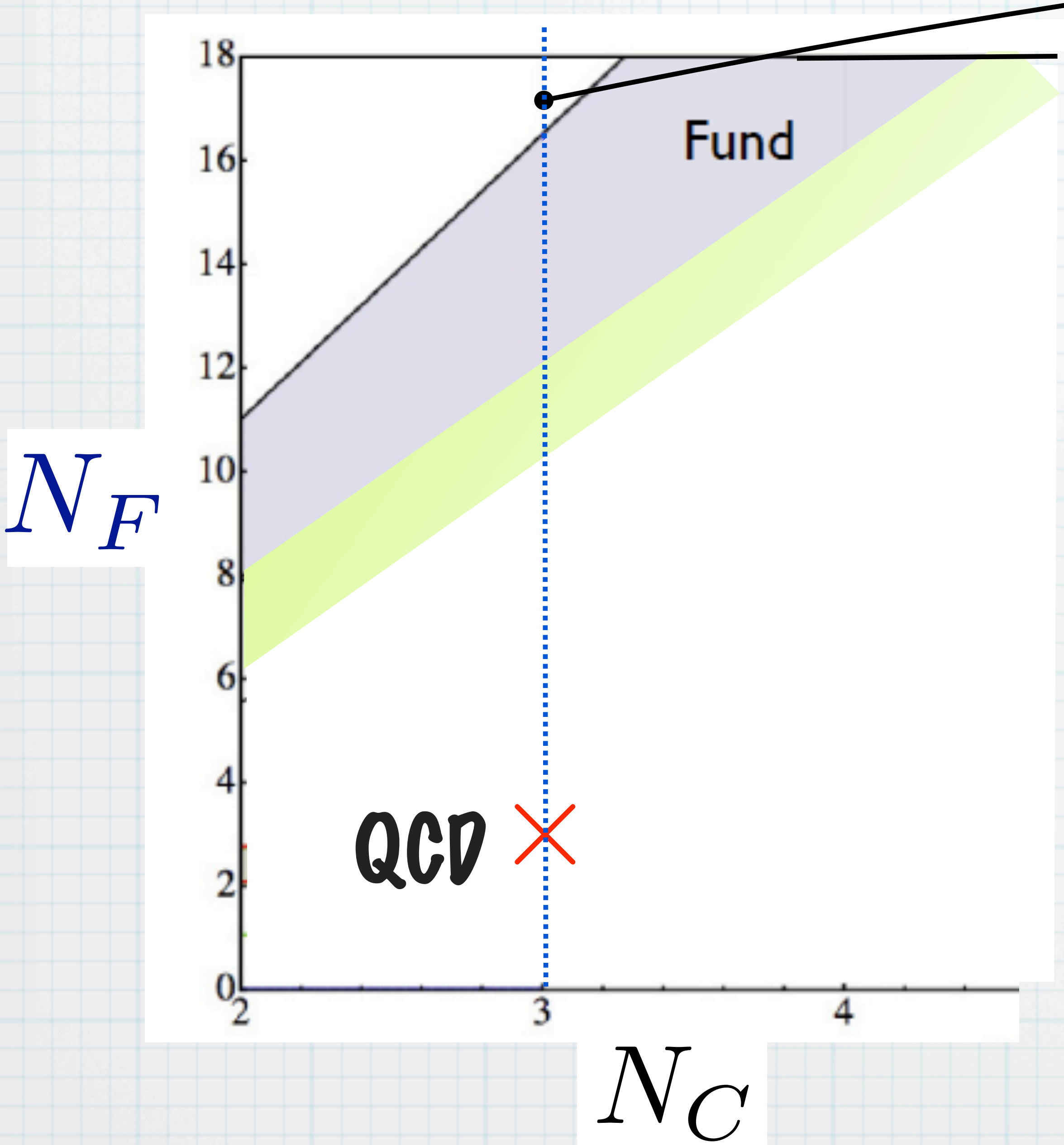


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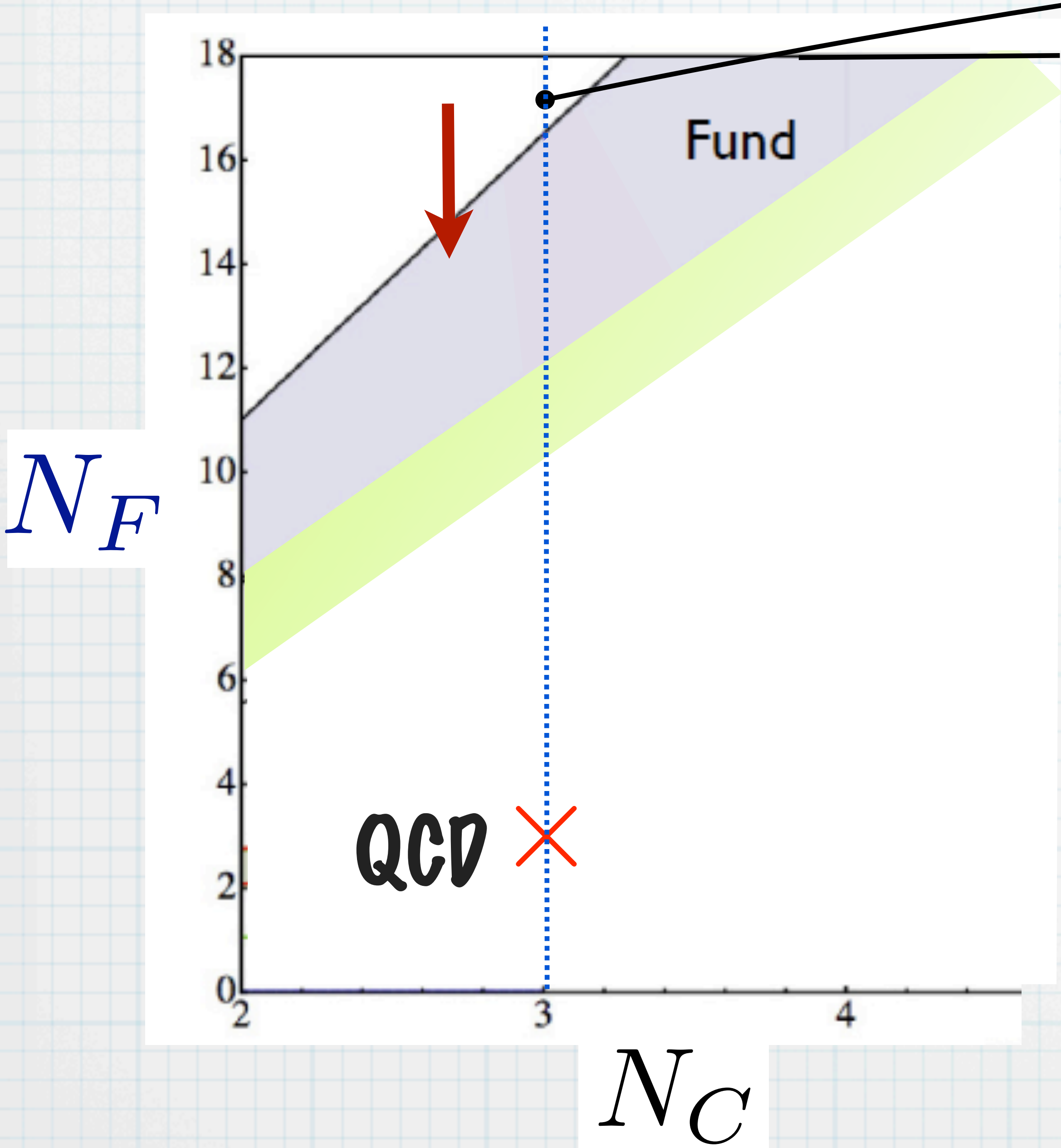


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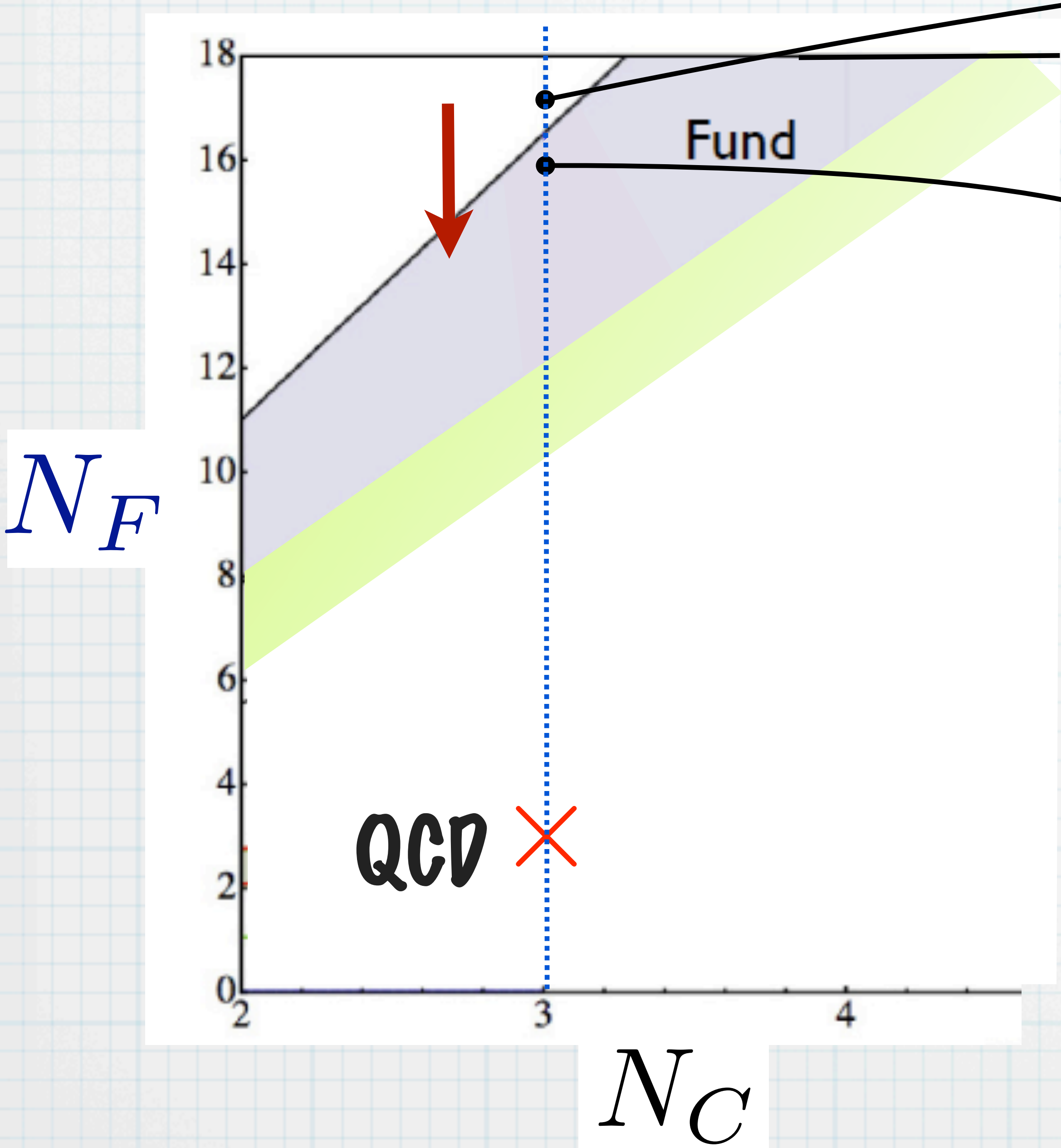


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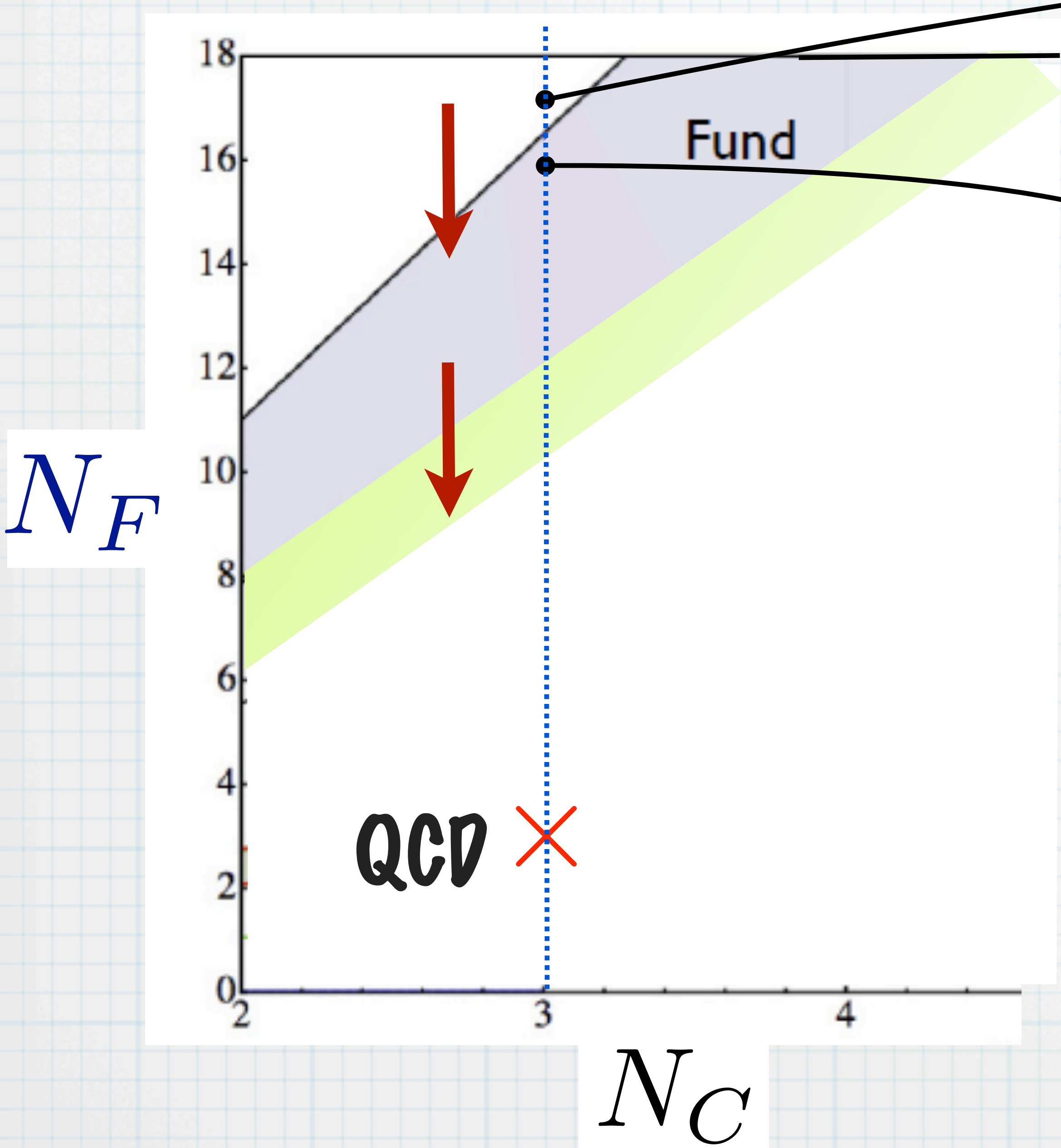


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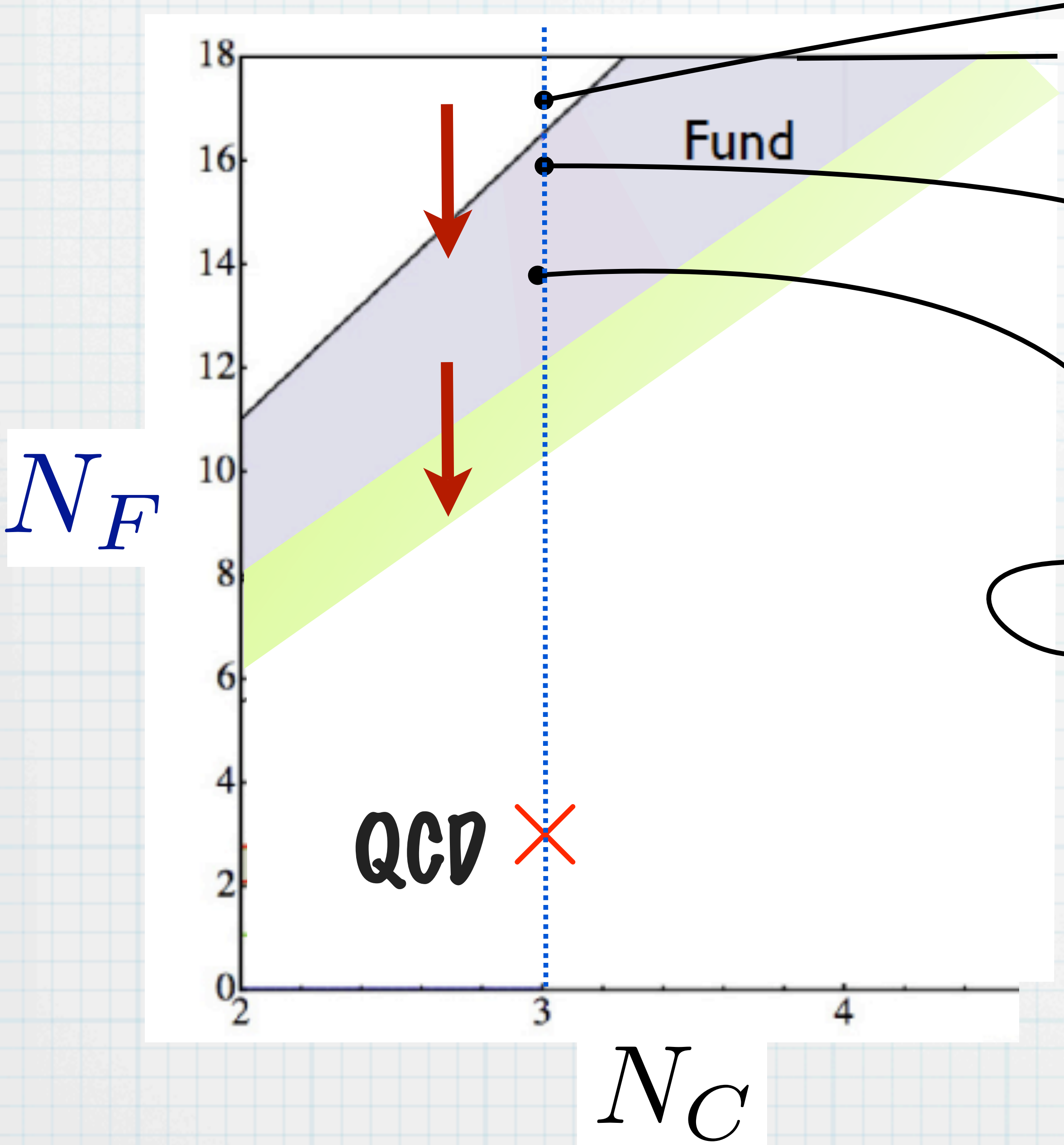


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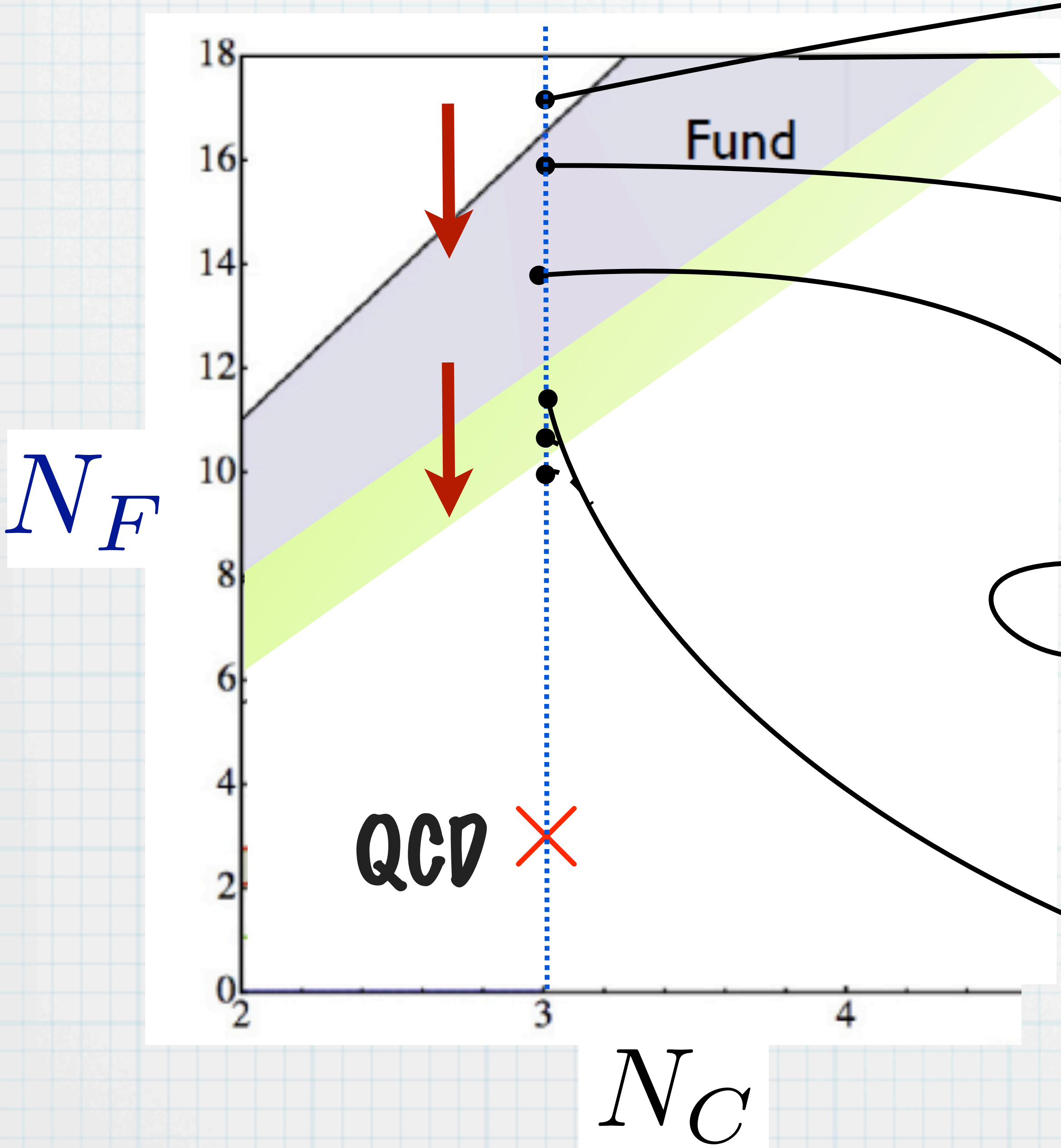


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walking theories are right on the border of conformal and confining behavior. Exact $N_C$, $N_F$ range unknown

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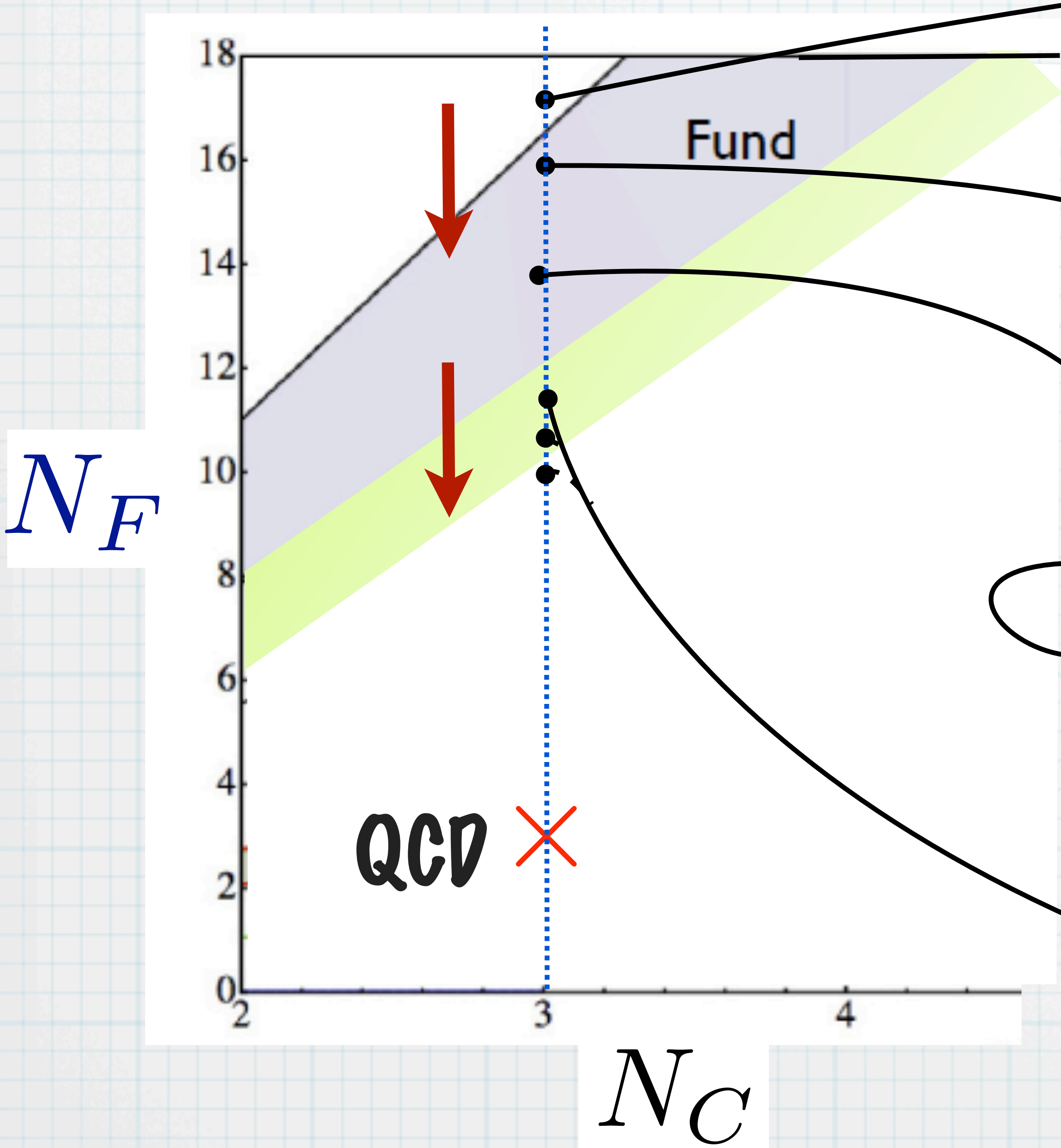


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for strong enough coupling, confinement occurs

we want to be just outside of the "conformal window"

walking theories are right on the border of conformal and confining behavior. Exact $N_C$, $N_F$ range unknown

# Can we actually get a walking theory?

* Inspiration for walking comes from looking at beta functions in perturbation theory

$$b_0 = \left(\frac{11}{3}N_C - \frac{4}{3}\sum_{F,r} C(r)\right) \qquad b_1 = \frac{34}{2}N_C^2 - \frac{20}{3}\sum_{F,r} C(r)N_F N_C - 2\sum_{F,r} C_2(r)N_F$$

* We would like some proof that conformal/walking behavior can exist which doesn't rely on perturbation theory

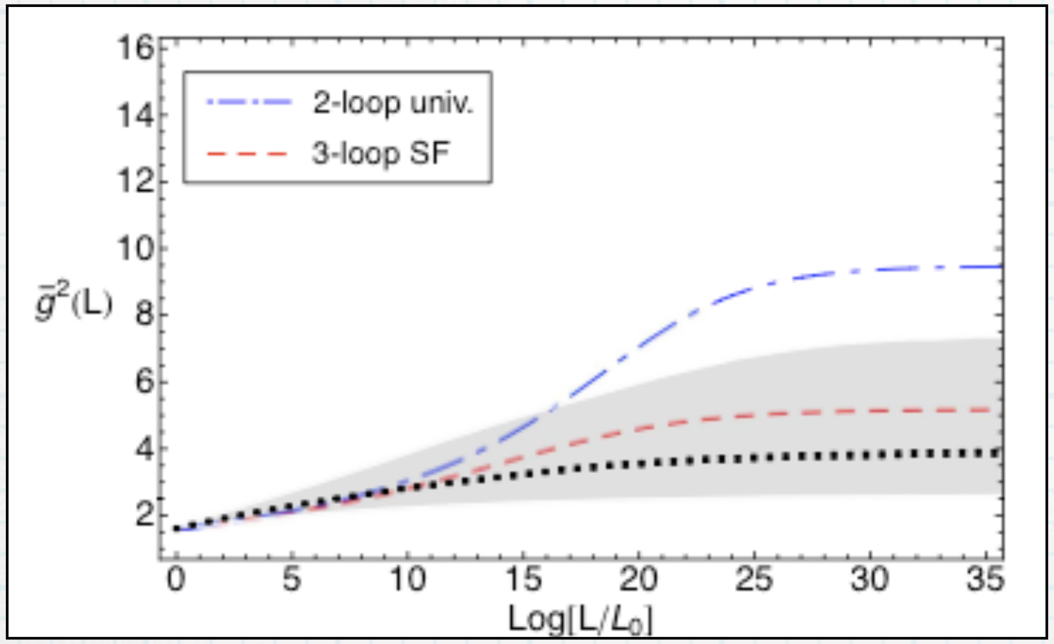
## Lattice is the perfect place for this!

* Lots of lattice effort underway:

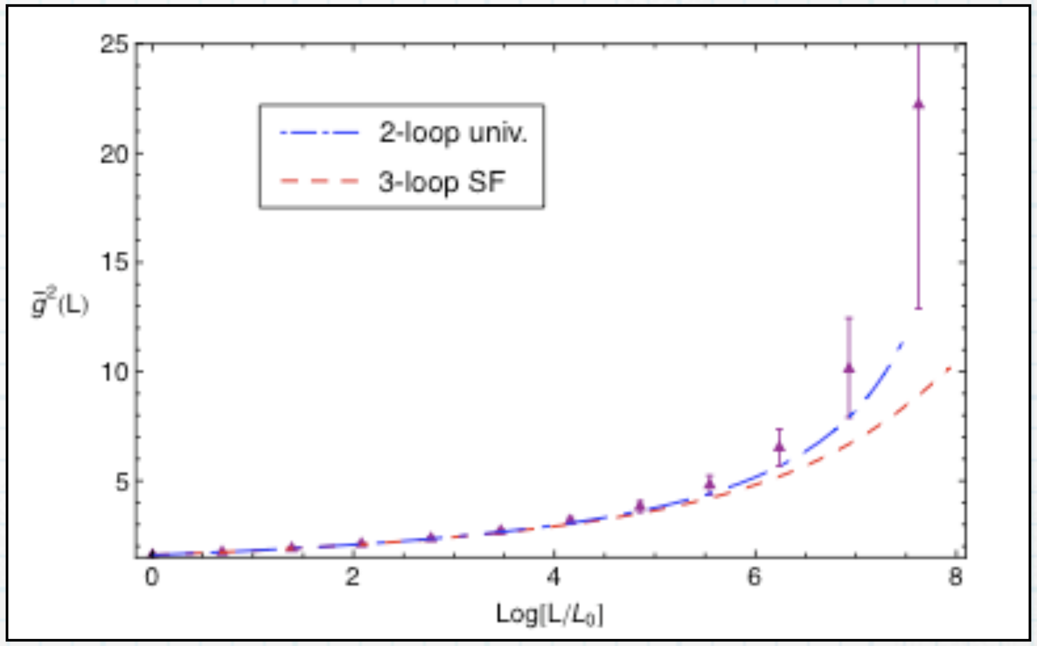
- Appelquist, Fleming, et al
- DeGrand, Shamir, Svetivsky
- Catterall, Sannino
- Fodor, Holland, Kuti, et al
- Deuzeman, Lombardo, Pallante
- Bilgici et al
- Hietanen, Rummukainen, Tuominen
- ...

# Summary of Lattice results

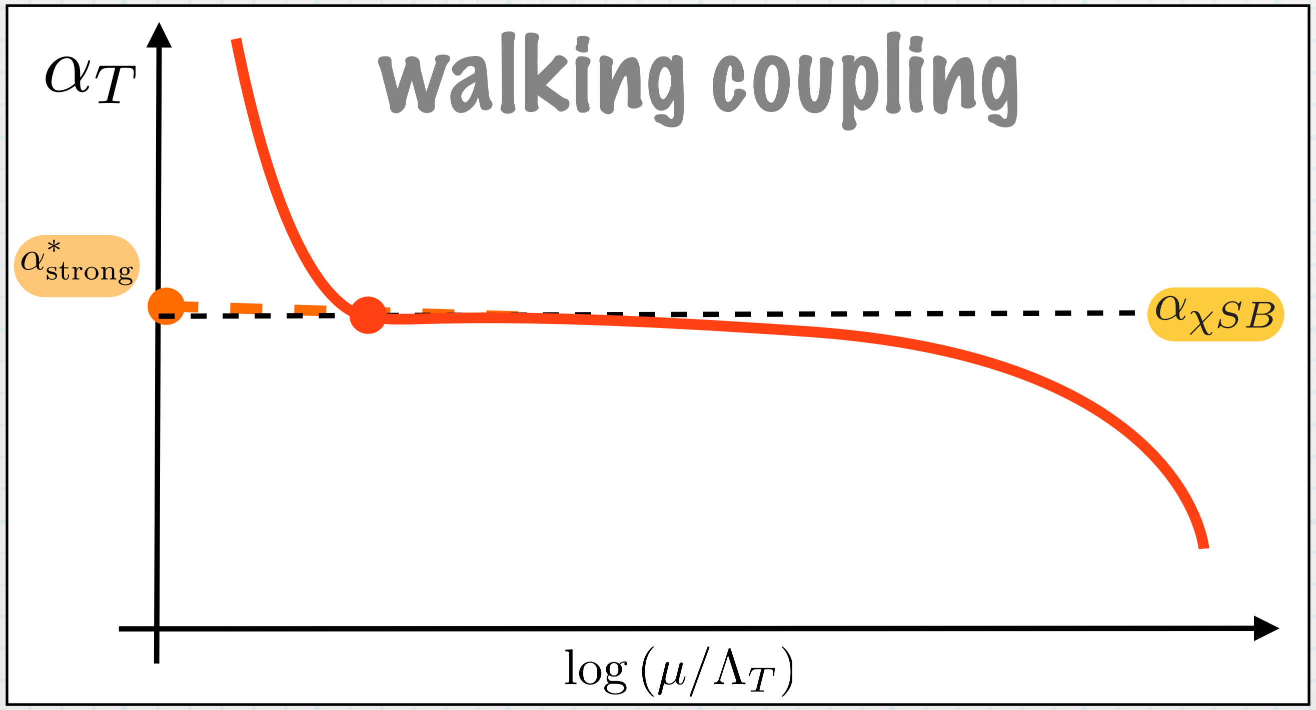
## Appelquist, Fleming, Neil (arXiv:0712.0609, 0901.3766)




$N_C = 3, N_F = 12$




$N_C = 3, N_F = 8$




confining behavior seen at $N_F$ = 8, while $N_F$ = 12 theory appears to be conformal

neither one is walking, but shape of $\beta(\alpha)$ doesn't look so crazy anymore

looking into $N_F = 10$ now!

# Summary of Lattice results

being checked by other methods/groups now!

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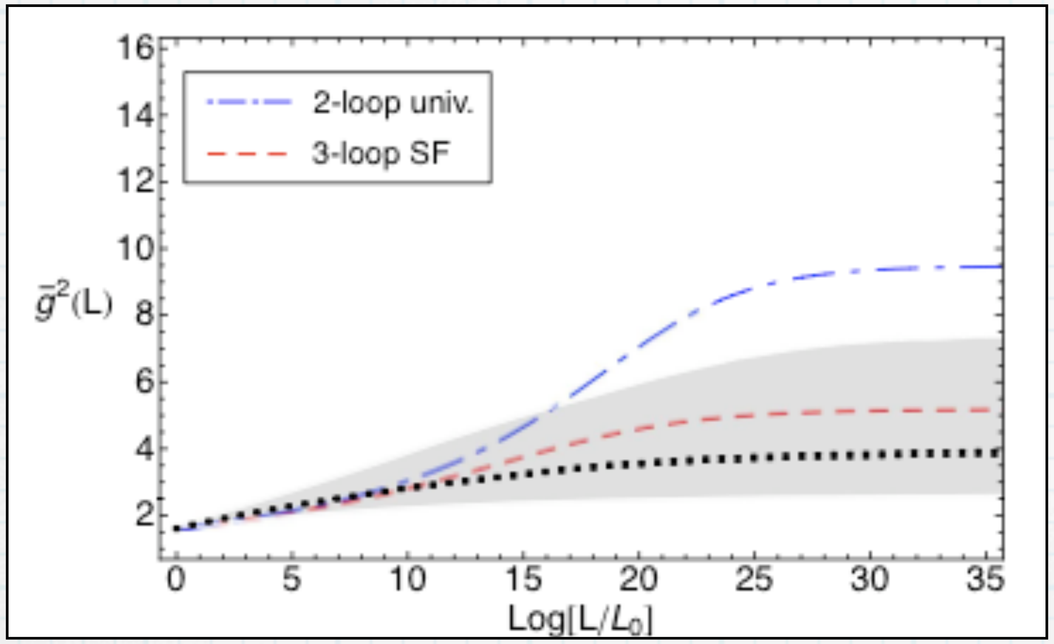


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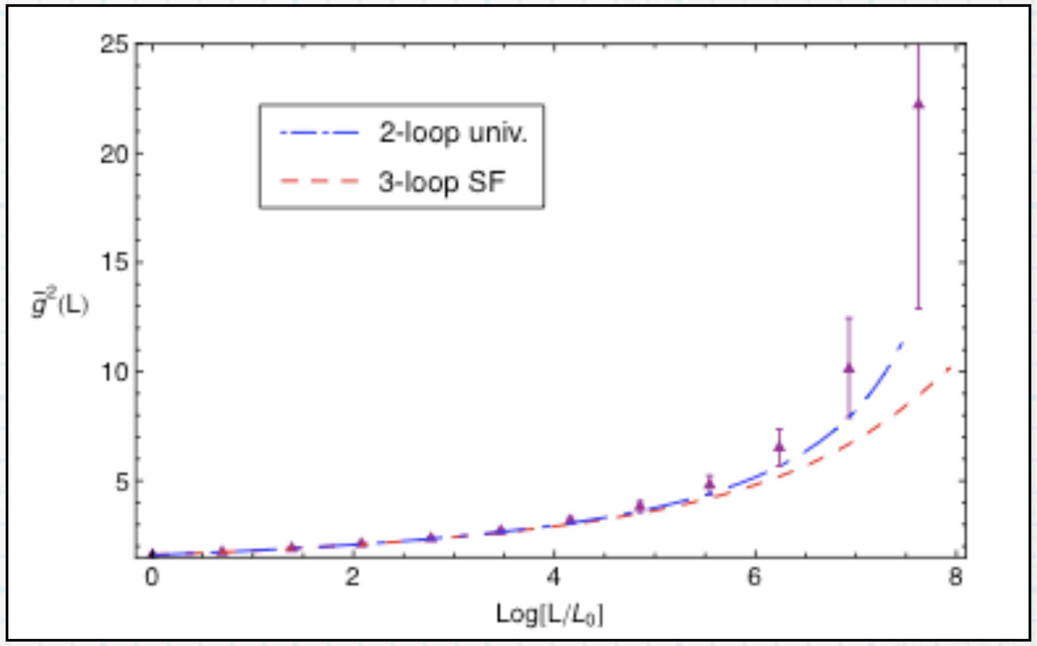


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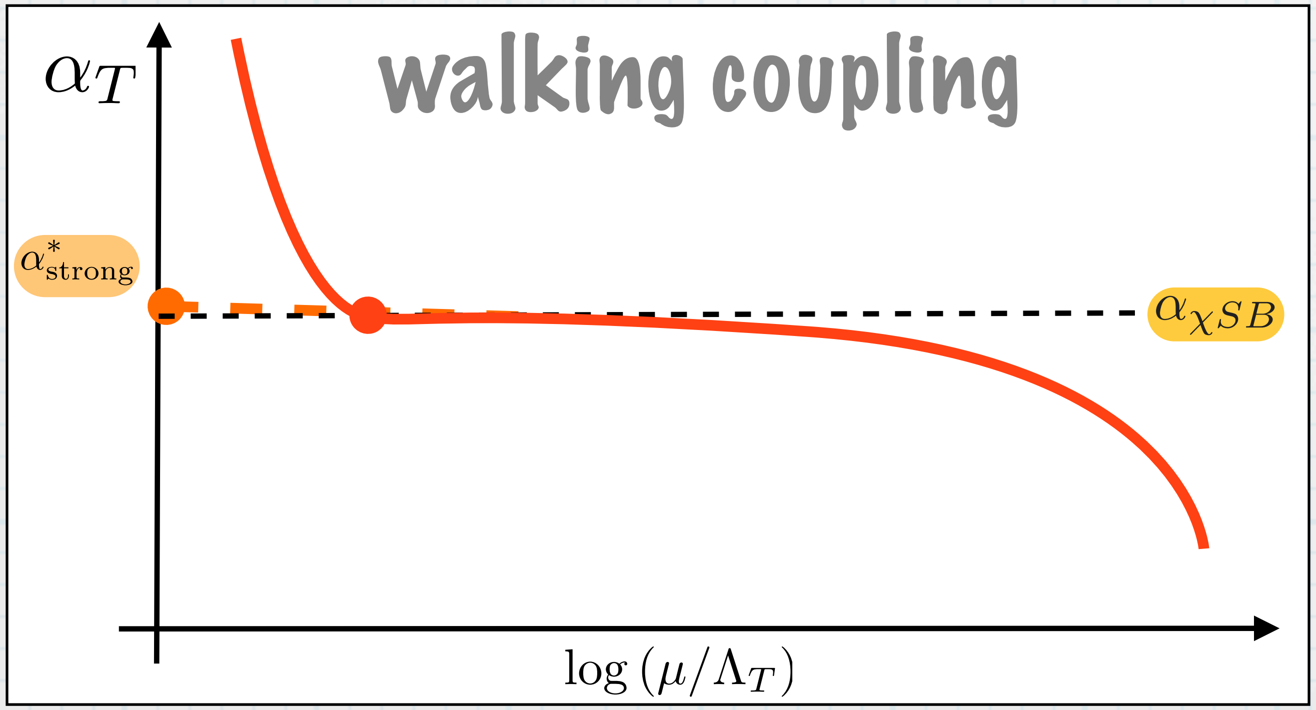


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looking into $N_F = 10$ now!

# Summary of Lattice results, #2

Appelquist et al result is the running coupling, but the beta function is a **scheme-dependent** quantity beyond two loops

$$\beta(\alpha) = -\frac{b_0}{2\pi}\alpha^2 - \frac{2b_1}{(4\pi)^2}\alpha^3 - \frac{b_2}{(4\pi)^3}\alpha^4 + \cdots$$

coefficients of these terms are universal

coefficient of this and higher terms depend on what observable is used, how subtraction is done

in a strongly-coupled theory, $\alpha \gg 1$ so we may worry scheme dependence is interfering with how we interpret our results

**Can we see evidence of conformality (or walking) a in scheme-independent way?**

- scaling dimension of operators
- free energy

...

lots of active research on this tricky problem!

# Walking and Precision Electroweak

* Assuming we have a walking theory, the tension between quark masses and FCNC can be relieved... but FCNC weren't technicolor's only problem

$$S \sim 4\pi \frac{N_D F_T^3}{M_{\rho_T}^2}\left(1 + \frac{M_{a_T}^2}{M_{\rho_T}^2}\right) \sim 0.25 N_D \frac{N_{TC}}{3}$$

(Peskin, Takeuchi '91)

* However this result came from assuming the techni-meson spectrum is analogous to QCD, and saturating dispersive form of S

$$S = 4\pi \int \frac{dm^2}{m^4}\left(\rho_V^3(m^2) - \rho_A^3(m^2)\right)$$ with single resonances

$1 \ \rho_T, a_T$

**Not a valid assumption in a walking theory!**
**CANNOT use the QCD-based argument**

# Walking and Precision Electroweak, #2

* lots of speculation that S should be smaller in a walking theory:
  - large coupling implies spectral integrals converge more slowly, manifest in whole tower of spin-1 vector and axial resonances (Lane '94)
  - near conformal behavior leads to a parity-doubled spectrum, and therefore: (Appelquist '97 Shrock, Kurachi '06)

    $$M_{\rho_T} \sim M_{a_T}, g_{\rho_T} \sim g_{a_T}$$

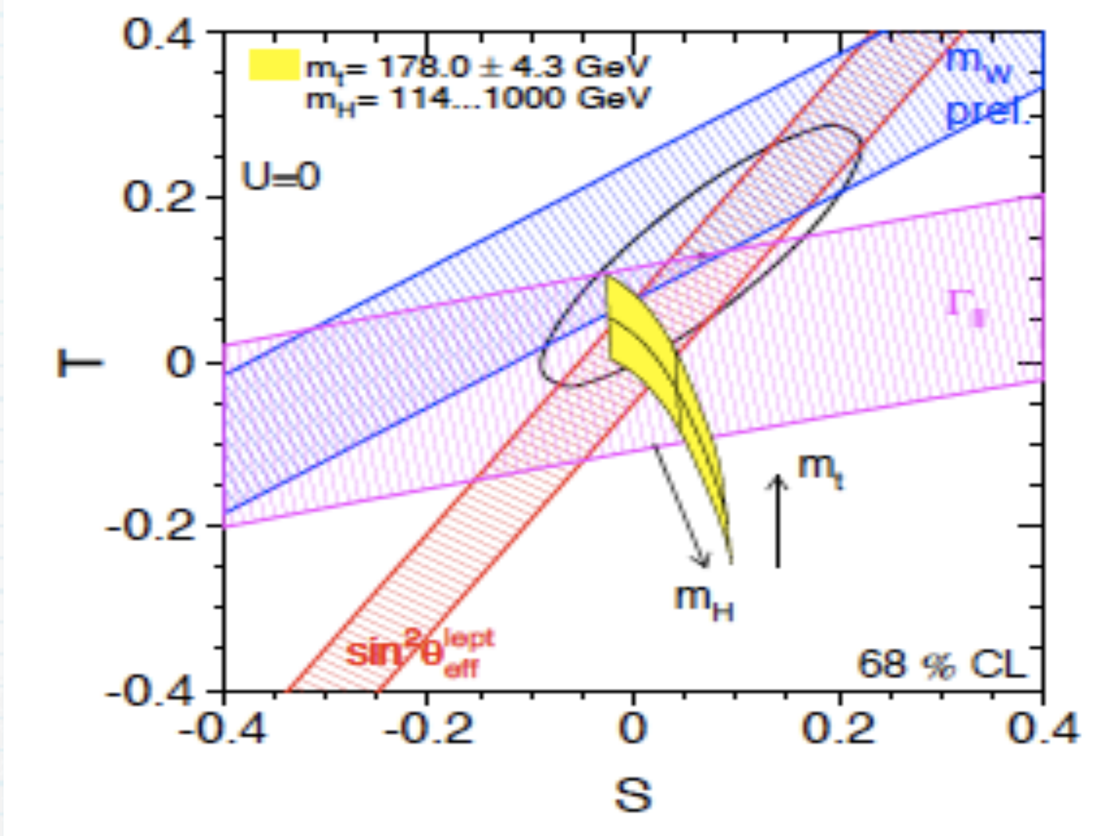
    which leads to a reduced (or even negative) S parameter
  - OPE analysis suggests large $\langle\bar{\psi}\psi\rangle$ anomalous dimension leads to smaller S (Sundrum, Hsu '90)
* but NO systematic complete derivation of S in non-QCD theory

# Walking and Precision Electroweak, #3

* Is speculation the best we can do?

* Additional positive corrections to **T** are rather easy to generate, and help the overall fit.

$$\Delta T = \frac{M_D^2 + M_U^2}{16\pi M_W^2 \sin^2\theta_W}$$




* Extra multiplets, with appropriate mass ratios and charges can generate negative contributions to S

$$S_{Dirac} = \frac{1}{6\pi}\left(1 - 2Y \log\left(\frac{M_U^2}{M_D^2}\right)\right)$$

$$S_{Maj} = \frac{1}{6\pi}\left(c_\theta^2 \log\left(\frac{M_1^2}{M_E^2}\right) + s_\theta^2 \log\left(\frac{M_2^2}{M_E^2}\right) + \frac{3}{2} - s_\theta^2 c_\theta^2\left(\frac{8}{3} + f_1(M_1, M_2) - f_2(M_1, M_2)\log\left(\frac{M_1^2}{M_2^2}\right)\right)\right)$$

* Loops of technipions could have a big effect too, depending on their mass and number -- difficult to estimate

* No clear path to take which resolves all problems

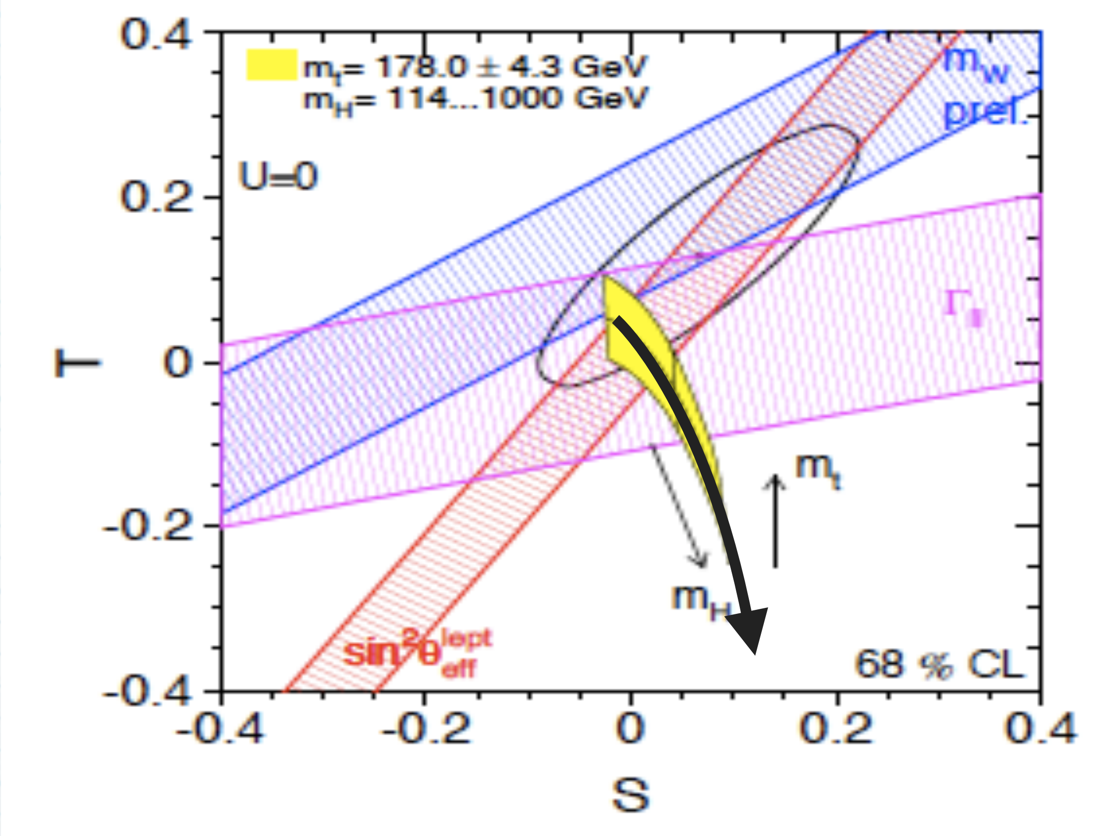
Lattice efforts underway! (JLQCD, LSD)

# Walking and Precision Electroweak, #3

- **Is speculation the best we can do?**

- Additional positive corrections to **T** are rather easy to generate, and help the overall fit.

$$\Delta T = \frac{M_D^2 + M_U^2}{16\pi M_W^2 \sin^2\theta_W}$$

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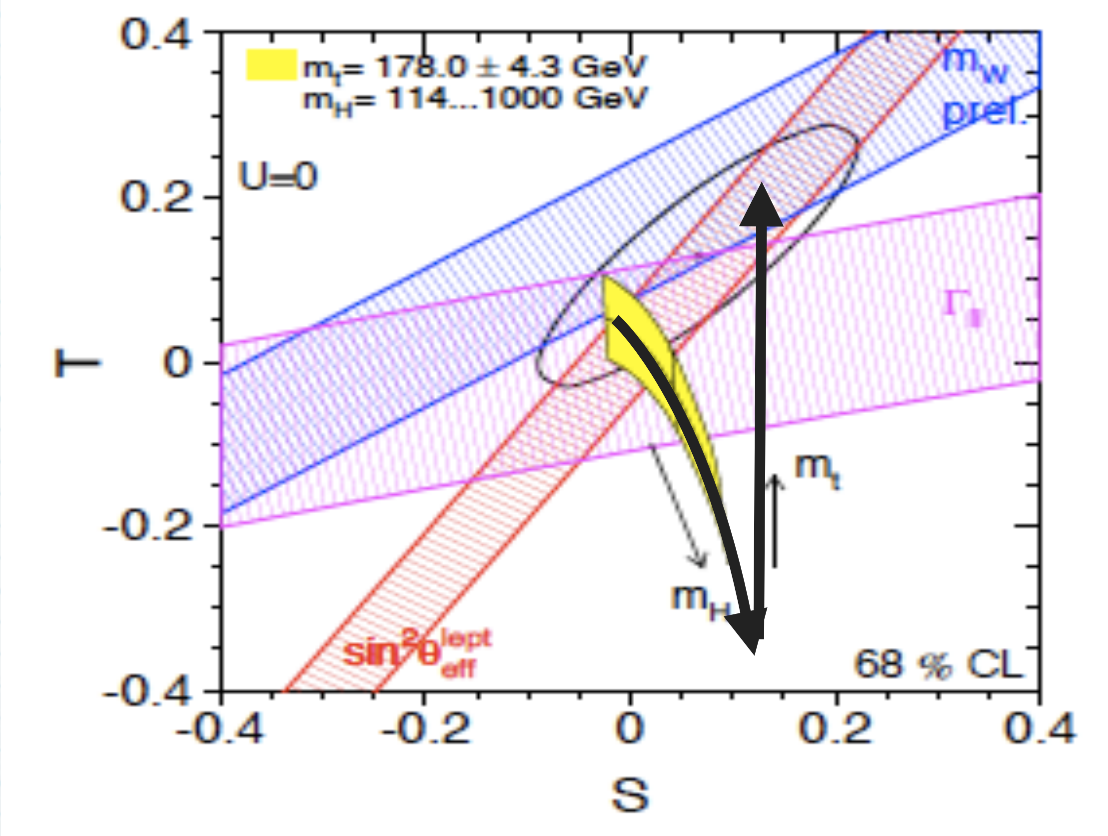


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# Walking and the third generation

- Even with $\gamma_m \cong 1$, large $m_t$ is still a problem

Several `solutions':

i.) Several ETC scales, dynamical 'tumbling'

$$
\begin{array}{ccc}
 & SU(N_{TC}+3) & \\
\Lambda_1 & \downarrow & m_1 \approx \frac{4\pi F^3}{\Lambda_1^2} \\
 & SU(N_{TC}+2) & \\
\Lambda_2 & \downarrow & m_2 \approx \frac{4\pi F^3}{\Lambda_2^2} \\
 & SU(N_{TC}+1) & \\
\Lambda_3 & \downarrow & m_3 \approx \frac{4\pi F^3}{\Lambda_3^2} \\
 & SU(N_{TC}) &
\end{array}
$$

(Baluni '79, Dimopoulos & Susskind '80
Appelquist + Shrock '04)

ii.) Special 3rd generation dynamics

$$SU(3)_1 \otimes SU(3)_2 \to SU(3)_c$$
$$U(1)_1 \otimes U(1)_2 \to U(1)_Y$$

Topcolor-Assisted Technicolor (Hill '94)

iii.) More exotic UV behavior, $\gamma_m > 1$

Conformal Technicolor (Luty '04)

...none are completely satisfactory

# Walking TC summary

**There is good evidence, from perturbation theory and the lattice that walking 4D gauge theories do exist**

- expect large anomalous dimensions, especially for $\langle\bar{\psi}\psi\rangle$ from SDE-analysis and similar SUSY calculations
- large anomalous dimension eases tension between FCNC and realistic quark masses
- $\gamma_m \sim 1$ also opens the possibility of consistent PEW and top quark mass, though the exact mechanism is less clear

**All of this is completely irrelevant if we don't know what to expect at the LHC!**

# Walking Technicolor Phenomenology

**What will we see at the LHC if walking technicolor lurks at the EW scale?**

walking technicolor requires lots of matter. all EW-charged matter contributes to EW scale:

lots of matter -- >
generically low TC scale

techni-resonances must be light!

$$v^2 = \sum_i F_{Ti}^2$$

$i \in$ all $SU(2)_w$ techni-doublets

$N_D$ doublets: $v^2 = N_D F_T^2$

multiple reps. : $v^2 = F_{T1}^2 + F_{T2}^2 + \cdots$

new states must communicate with SM EW gauge bosons (at least), so all states have open decay channels to SM matter

no BSM missing energy!

# Walking TC: LHC implications

a general scan over all possible resonances, their masses, their interactions would be great! but totally impractical

... $M^{\pm}_{a_T}$ $M^{\pm}_{\rho_T}$ $g_{a_T W^+ \gamma}$ $\#\pi_T$ $g_{\rho_T W^+ W^-}$ ...

$\Gamma(a_T \to \pi_T \pi_T \pi_T)$ $M_{\pi_T}$ $g_{\pi^{\pm}_T \bar{f} f}$ $g_{\rho^{\pm}_T f f'}$ $g_{\rho_T \pi_T \pi_T}$

... $M_{\omega_T}$ $g_{\rho_T W \pi_T}$ $g_{\omega_T Z \gamma}$

$M_{\rho'_T}$ $g_{\rho_T \pi \gamma}$ $g_{\rho_T W^+ Z}$

$M_{a'_T}$ $g_{a_T W^+ Z}$ ...

$\Gamma(\rho_T \to \pi_T \pi_T)$ $g_{\omega_T f f}$ $g_{\pi_T \gamma\gamma}$ $g_{\omega_T \pi \gamma}$

techni-baryons? scalar bound states?

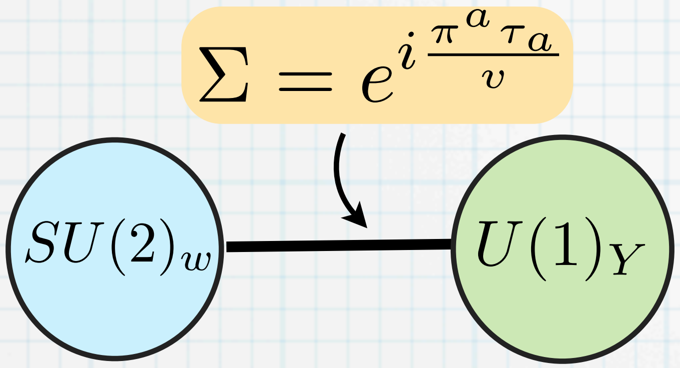
WAY to many parameters, all of which have important phenomenological impact : **we need models**

# Walking TC: LHC implications, #2

one popular tool is **Hidden Local Symmetries:**

(Kugo, Bando '80's
Callan, Coleman '70's)

start with **EW chiral lagrangian:**




$$\mathcal{L}_{\chi EW} = \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma^\dagger) + \cdots$$

$$D_\mu \Sigma = \partial_\mu \Sigma + ig\vec{W}_\mu \Sigma - ig'\Sigma B_\mu$$

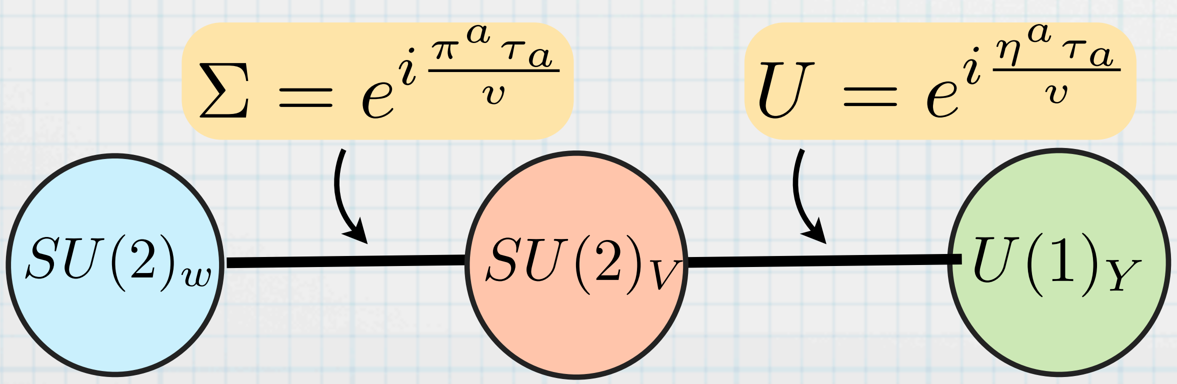
$\pi_a$ are the eaten NGBs. Unitary gauge: $\Sigma = \mathbf{1}$

minimal setup describes strong EWSB, but there are many more terms we can add, with unknown coefficients

(Applequist, Bernard '79
Longhitano '79)

$$c_1 \mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma^\dagger)^2 + c_2 \mathrm{Tr}(D_\mu \Sigma D_\nu \Sigma^\dagger D^\mu \Sigma D^\nu \Sigma^\dagger) + c_3 \mathrm{Tr}(W_{\mu\nu}\Sigma B^{\mu\nu}\Sigma^\dagger) + \cdots$$

one way to model the $c_i$ is to treat the new resonances as **new massive gauge bosons**




**now two sets of NGB fields**

three eaten by W,Z
three eaten to make massive $\rho_T^a$

# Walking TC: LHC implications, #3

$$\mathcal{L} \supset \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma D^\mu \Sigma^\dagger) + \frac{v^2}{4}\mathrm{Tr}(D_\mu U D^\mu U^\dagger) + a\frac{v^2}{4}\mathrm{Tr}((D_\mu \Sigma^\dagger)\Sigma(D_\mu U)U^\dagger) + \cdots - \frac{1}{4g_T^2}\mathrm{Tr}(V^a_{\mu\nu}V^{a\mu\nu})$$

'hidden' gauge group coupling $g_T \gg g, g'$ . Kinetic term is simply added to $\mathcal{L}$, assumed to come from strong dynamics

integrating out the V, we get predictions for the $c_i$ plus we have modeled the masses and interactions of the $\rho_T^a$

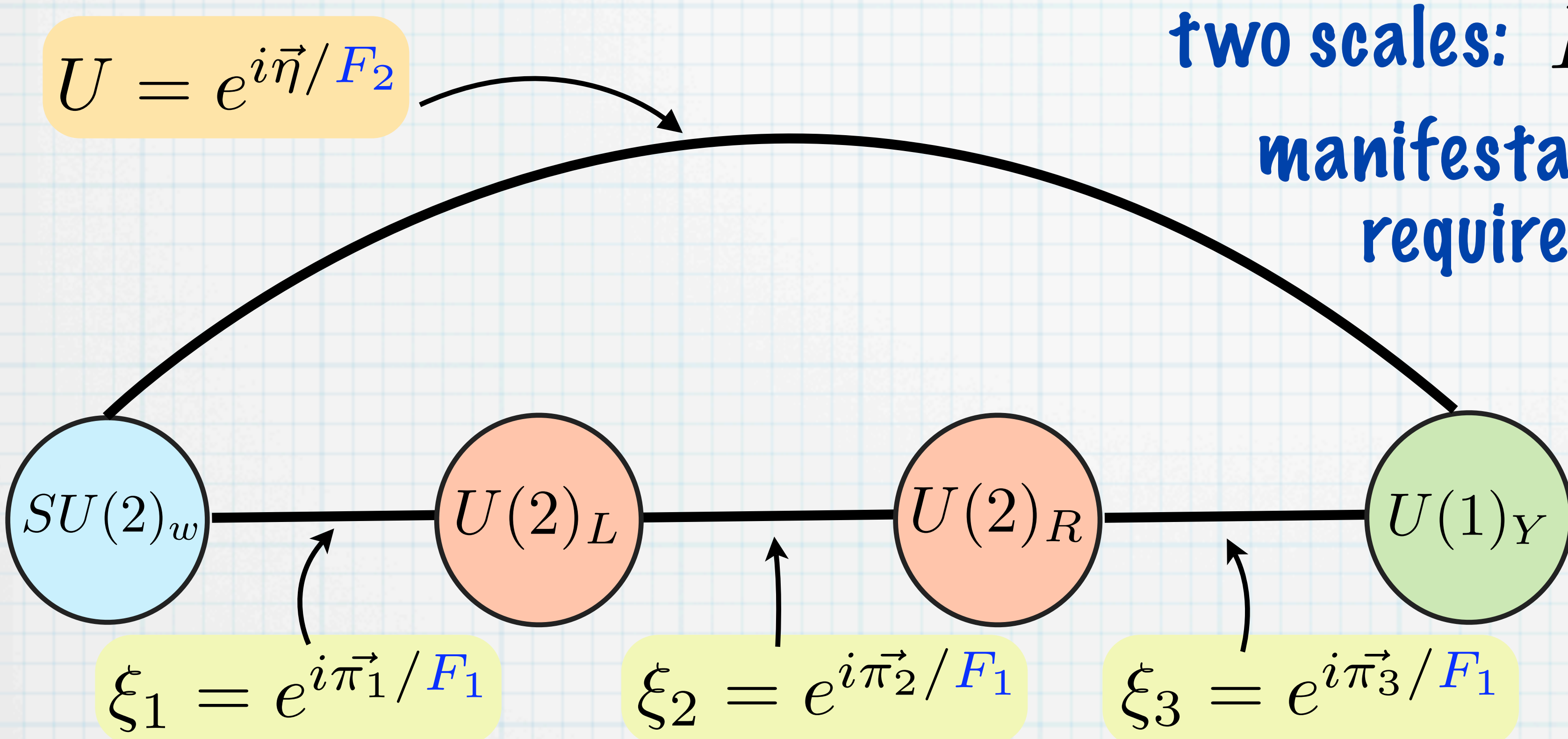
(same technique goes by many names: BESS (Casalbuoni et al), three-site model (Chivukula et al))

**BUT, this setup is very restricted...**

- where has the walking entered?
- where are the technipions?
- how do the fermions enter?
- how can we get more than one set of resonances?

# Walking TC: LHC implications, #4

more sophisticated models allow us to add more TC-features




two scales: $F_1, F_2$ as a manifestation of the idea that walking requires multiple, different reps.

$$v^2 = F_1^2 + F_2^2$$

take $F_1 \ll F_2$

four sets of NGB fields, three are eaten by gauge interactions

- we now have a small parameter to play with: $\sin\chi = F_1/F_2$

  for example: suppresses fermion-resonance couplings $\quad g_{\bar{f}f\rho_T} \sim g_{EW}\left(\frac{M_W}{M_\rho}\right)\sin\chi$

- hidden groups are $U(2)$, extra resonance is $\omega_T$
- one $\pi_T$ remains in the spectrum

(Lane, AM '09)

# Walking TC: LHC implications, #5

## HLS is still very limited:

* higher dimensional operators? can we really stop at 2-derivative, d < 4 operators in a strongly coupled theory?
* anomaly terms? global anomalies of the underlying UV theory are present in the effective theory -- WZW interactions

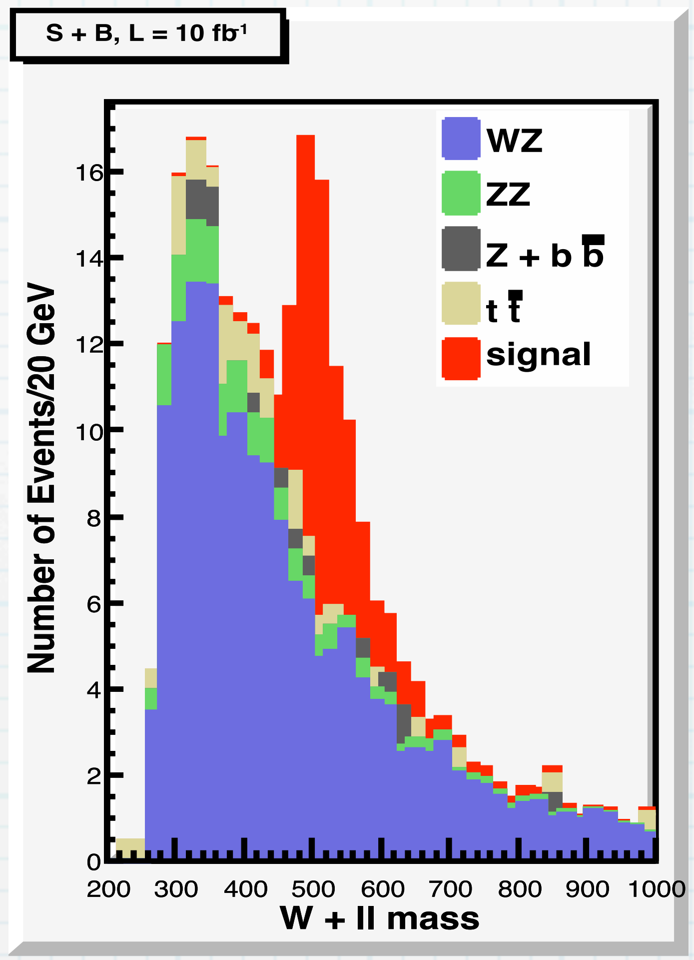
...

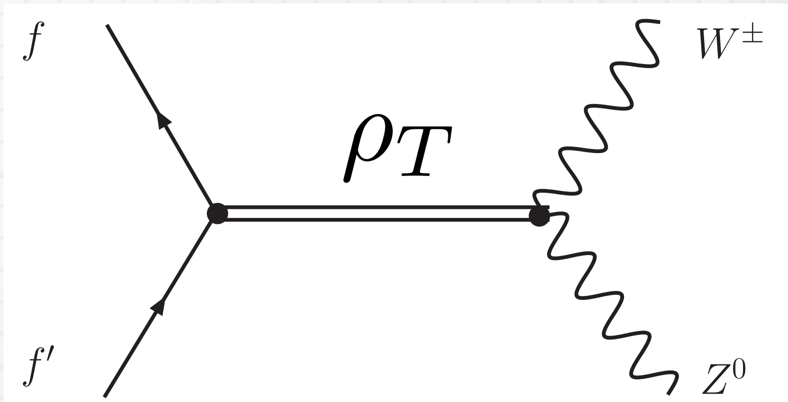
HLS models should NOT be taken too seriously, but they are a useful and simple tool for making predictions. Studying the phenomenology of these models will hopefully prepare us to recognize signals of new strong dynamics should they appear at the LHC

# Walking TC: LHC implications, #6

**examples:** Drell-Yan production of resonances:

$$\rho_T^{\pm} \to W^{\pm} Z^0 \to \boxed{\ell^+ \ell^- \ell' \nu}$$




Enhancement from decays to longitudinal polarizations

$$\sigma(pp \to \rho_T \to WZ) \propto \frac{M_{\rho_T}^4}{M_Z^2 M_W^2}$$

1.) $n_{lep} = 3, p_T > 10$ GeV, $|\eta| < 2.5$
$p_T > 30$ GeV for at least one

2.) $|M_{\ell^+\ell^-} - M_Z| < 3.0\Gamma_Z$

3.) $H_{T,jets} < 125$ GeV

4.) $p_{T,W},\ p_{T,Z} > 100$ GeV

**Relatively Unstudied!**

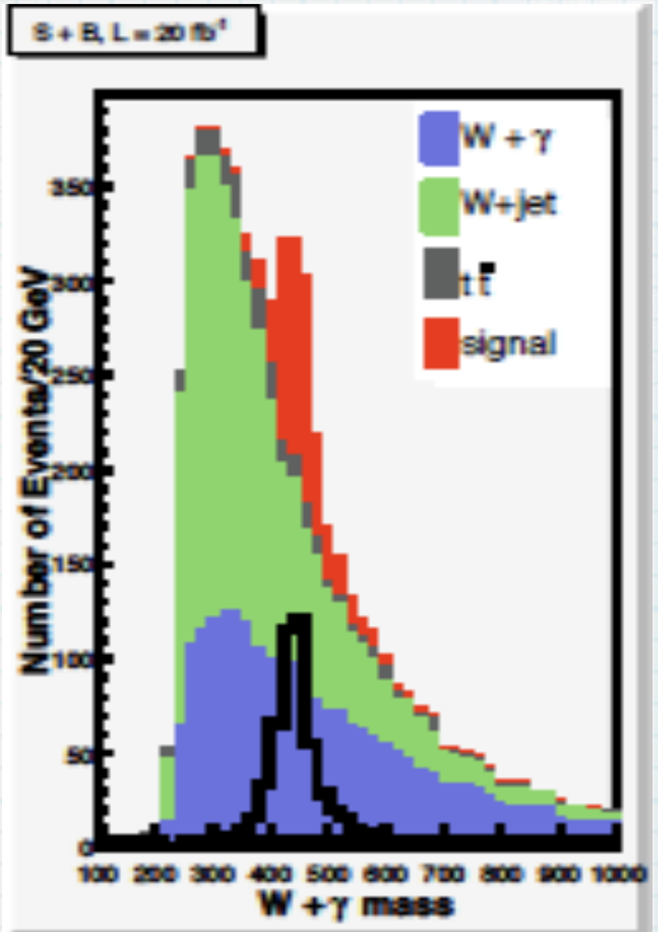
past studies: $Z' \to \bar{f} f$

$W' \to \ell + \nu$

**Early LHC discovery!**

- large cross section
- multi-lepton final states
- single MET source -> can reconstruct $M_{\rho_T}^2$

# Walking TC: LHC implications, #7



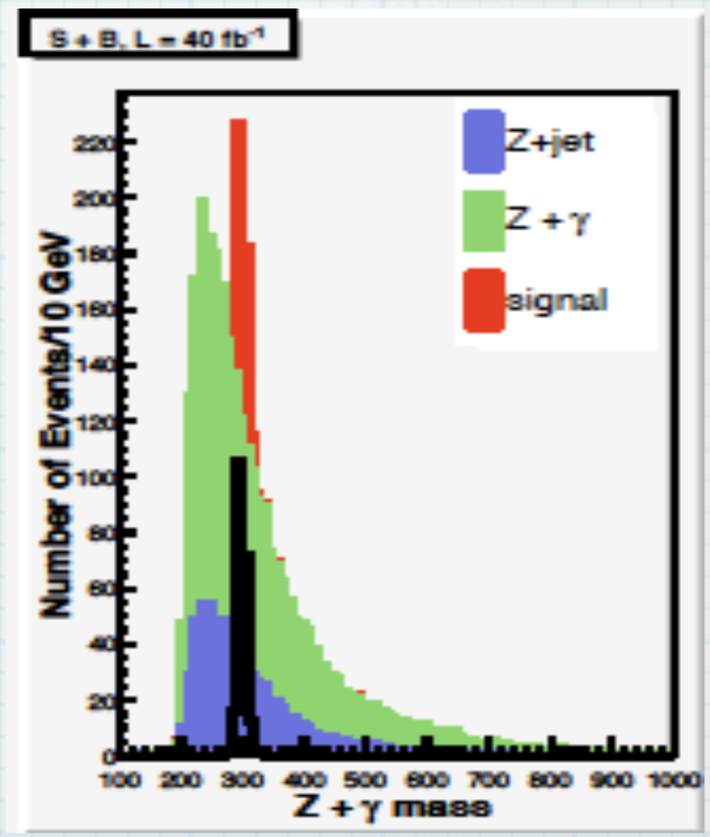

(hep-ph/0802.3714)

$$a_T^{\pm} \to \gamma W^{\pm} \to \boxed{\gamma \ell^{\pm} \nu}$$

- cannot go to $W_L^{\pm} Z_L^0$ as **techniparity** is imposed
- requires further HLS interactions! so this mode tells us something about how to best model new strong dynamics
  - very few collider studies! SUSY bias, where there are no resonance decays to $W^{\pm}Z^0, \gamma W$ at tree level

$$\omega_T \to \gamma Z^0 \to \boxed{\ell^+ \ell^- \gamma}$$

NO missing energy, only EM objects → very clean, sharp peak




- observation of $\omega_T$ tells us something about the global symmetries of TC $U(N_D)$ vs. $SU(N_D), \cdots$

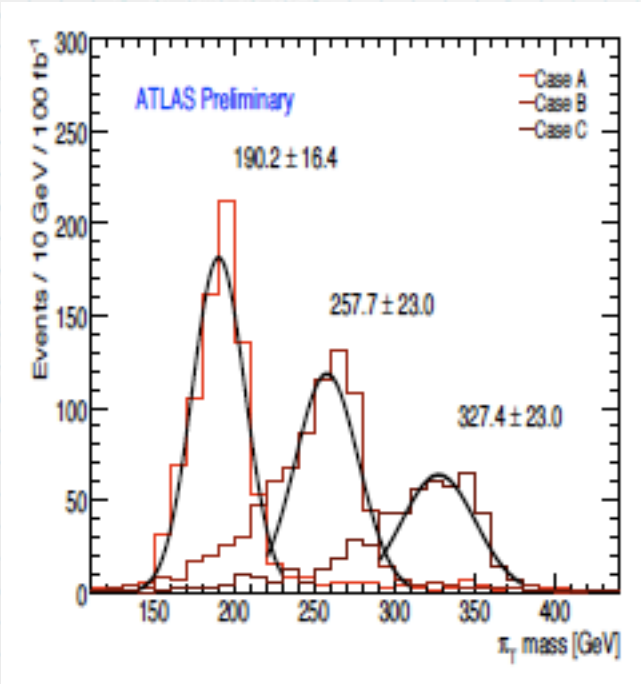
# Walking TC: LHC implications, #8

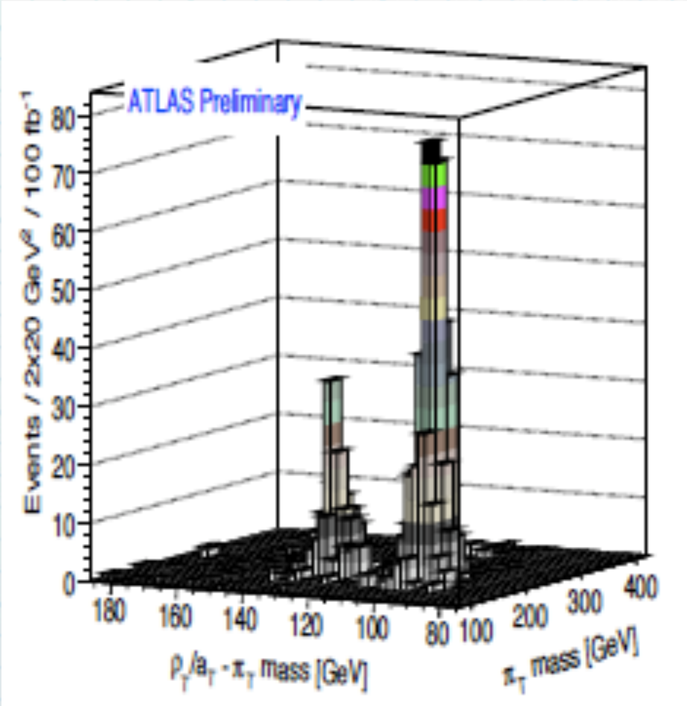
**Technipion discovery:** Important since $\pi_T$ don't exist in all models. However, few studies have been done

more model dependent, especially in the $\pi_T$ coupling to the top quark

$$pp \to \rho_T/a_T \to Z\pi_T \to \ell\ell bq$$

- with $\mathcal{L} \sim 50\ \text{fb}^{-1}$ $m_{\pi_T}, m_{\rho_T}, m_{a_T}$ all can be determined




(Azuelos et al, ATLAS-PHYS-CONF-2008-003)

## For all LSTC signals

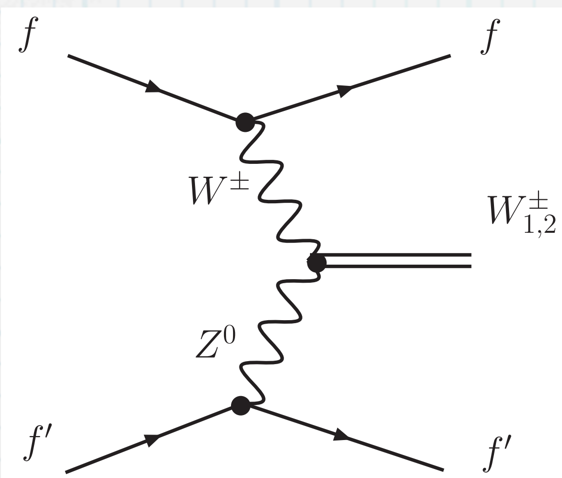
with more luminosity, detailed studies possible for

- Angular distributions: necessary to determine spin-1 (see hep-ph/0802.3714)
- Widths
- couplings

# Walking TC: LHC Implications, #9

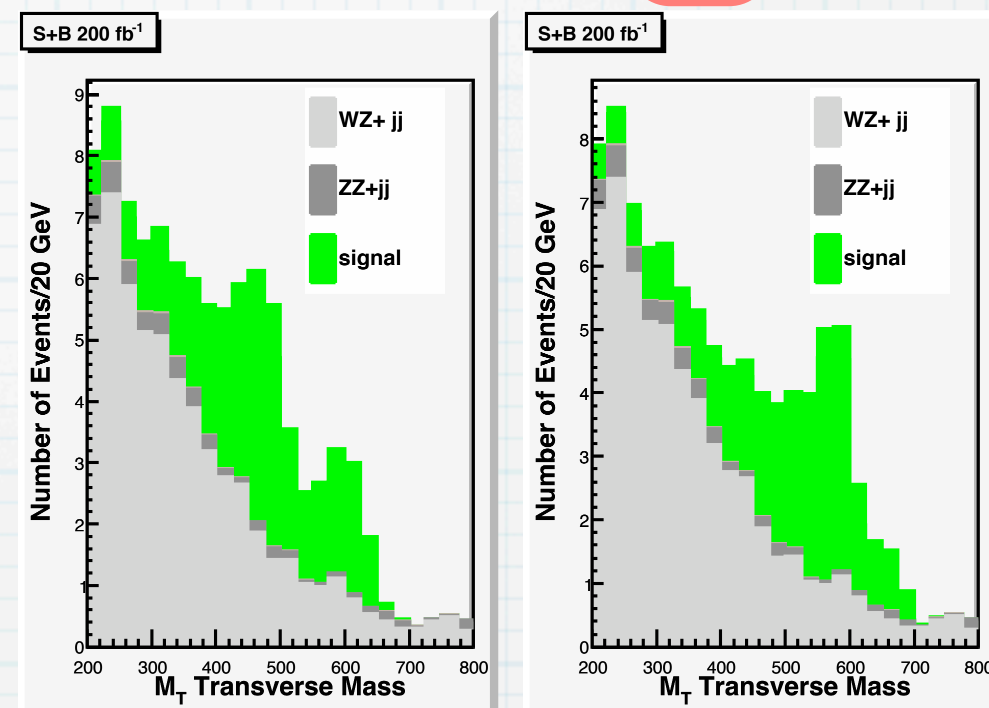
**High-luminosity signatures:** Not the `smoking gun' detection signal for TC, but important nonetheless

## Vector Boson Fusion:

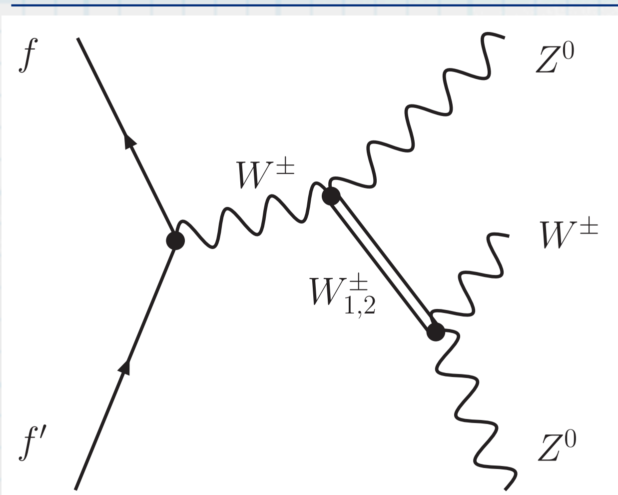



window into
$W_L W_L \to W_L W_L$
scattering

$$pp \to \rho_T jj \to \boxed{WZ} jj$$

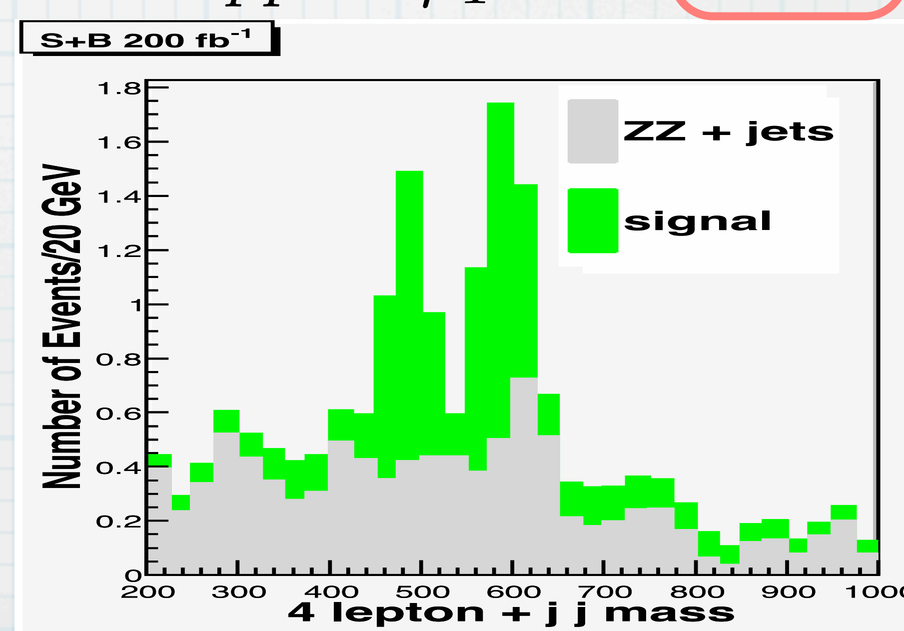



## Associated Production:




direct probe of
$g_{\rho_T WW}$, $g_{\rho_T WZ}$

$$pp \to \rho_T Z \to \boxed{WZZ}$$



# Summary so far

* **Tension** between FCNC and realistic fermion masses **can be avoided** if the technifermion bilinear has a **large (+ve) anomalous dimension**

* to have $\gamma_m \cong 1$ we expect the technicolor coupling must remain large for a wide range of energies, and is therefore nearly conformal or `walking'

* guided by the perturbative $b_0, \; b_1$, we expect walking theories will have lots of technimatter or involve large (non-fundamental) representations

# Summary so far

* Walking implies a low TC scale and therefore resonances in the 500 GeV - 1 TeV scale range
* New resonances must couple strongly to W,Z , though couplings to SM fermions are also possible. TC events will have no BSM missing energy <-> complementary to other BSM searches
* Precision Electroweak (S!!) arguments relied on technicolor being a rescaled version of QCD -- these arguments won't apply to a walking theory. There are arguments that a walking theory will have a naturally small S, but no solid evidence

# Summary so far

* Where does this leave us?

Modern Technicolor must be unlike QCD to avoid phenomenological problems -- the most investigated option is a walking technicolor theory. A walking theory CANNOT be ruled out by PEW tests, but we cannot calculate its contributions

NECESSARILY will have new states at the sub-TeV level, therefore it will be found or ruled out at the LHC

some new/better calculation tools would be great!

# Sample References:

## On Techicolor basics:

- Hill, Simmons, hep-ph/0203079
- Chivukula,  hep-ph/9803219
- Lane, hep-ph/02022025

+ references within

## On the phases of gauge theories:

- Intrilligator, Seiberg, hep-ph/9402044, 9411149
- Applequist, Sannino, hep-ph/0001043
- Appelquist et al, hep-ph/9806472

## On walking TC at the LHC:

- Eichten, Lane arXiv:0702339
- Azuelos et al, 2007 Les Houches proceedings, hep-ph/0802.3714
- Lane, Martin, arXiv:0907.3737