P. Nason

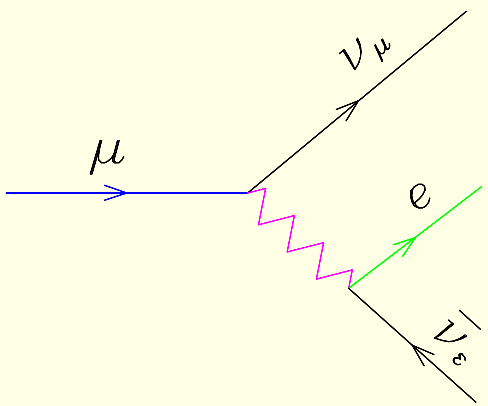
Overview of the Standard Model

- Weak Interactions
- Strong Interactions
- Where we stand now

Weak Interactions

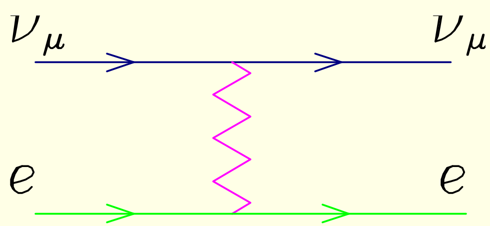
- Small scale phenomena: $G_{\mathsf{F}} \approx 1/(293\text{GeV})^2$
- low symmetry (parity violating, flavour violating)
- Rich structure and phenomenology

Charge current processes:



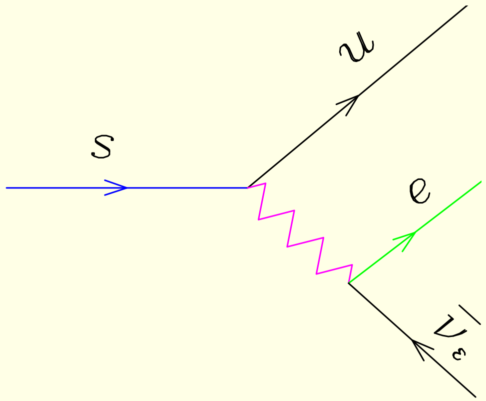
muon decay, nuclear beta decays

Neutral current processes:



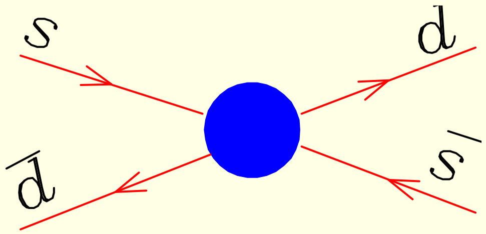
neutrino scattering off leptons and hadrons

Flavour changing charged current:



$\Lambda \rightarrow p e \bar{\nu}_e$, $K^- \rightarrow \pi^0 e \bar{\nu}_e$

Flavour changing neutral current:



K^0–$\overline{K^0}$ oscillations;

$\Delta m = 3.5 \times 10^{-6}$eV ($10^{-15}$GeV),

effective vertex: $\approx 1/(10^7\text{GeV})^2$

Other very small scale phenomena:

- CP violation in the K^0 and B^0 systems
- Neutrino oscillations

The Theory of Weak Interactions

Modern theory of weak interaction:

- Massive vector boson exchange to moderate the bad high energy properties of the 4-point Fermi interaction
- Get the vector bosons from a Yang-Mills Gauge Theory; this requirement implies unification of electromagnetic and weak forces (Schwinger (57), Glashow (58,61), Salam and Ward (64)).
- Vector boson masses from spontaneous symmetry breaking + Higgs mechanism, Weinberg (67), Salam (68)

Gauge theories were believed to be renormalizable, in analogy with QED. Renormalizability was proven by t'Hooft (71).

There are good reasons to believe that the only way to construct a weakly coupeld theory involving massive vector mesons is with spontaneous symmetry breaking via the Higgs mechanism.

Cornwall, Levin and Tiktopoulos (74) have proven that a field theorie with tree-level unitarity (the tree-level scattering amplitudes have good high energy behaviour) must have the following properties:

- must involve only fermions, scalars and vectors;
- must involve couplings with mass dimension ≥ 0 (ϕ^4, ϕ^3, ϕ^2, $\bar{\psi}\psi$, $\bar{\psi}\psi\phi$ terms in the lagrangian)
- All vectors must be associated with a gauge theory, possibly with broken symmetry, with the exception of massive vectors coupled to conserved currents.

Tree-level unitarity is believed to be implied by renormalizability

Thus, no alternatives to the introduction of fundamental scalar fields, unless one goes beyond perturbation theory (for example, with scalars that are bound states of fermions, like in composite models).

Construction of the Model

- $e_L \leftrightarrow \nu_e$, $\mu_L \leftrightarrow \nu_\mu$, $u_L \leftrightarrow d_L$, $\Longrightarrow$ $SU(2)$ gauge group;
- fermion in the same doublet have different charges; $U(1)_{\text{em}}$ cannot be an independent gauge group (must be unified);
- Add a $U(1)$ gauge field; n.c. couplings:

$$\frac{1}{2}(\bar{\nu}, e)\left\{\begin{vmatrix}1 & 0\\ 0 & -1\end{vmatrix} gW_3^\mu - \begin{vmatrix}1 & 0\\ 0 & 1\end{vmatrix} g'B^\mu\right\}\gamma_\mu \begin{pmatrix}\nu\\ e\end{pmatrix}$$

- Since ν couples to $gW_3 - g'B$, the orthogonal combination $gB + g'W_3$ must be the photon; one has

$$Z = \frac{gW_3 - g'B}{\sqrt{g^2 + g'^2}} = W_3 \cos\theta - B\sin\theta, \quad A = \frac{gB + g'W_3}{\sqrt{g^2 + g'^2}} = B\cos\theta + W_3 \sin\theta$$

- The symmetry breaking pattern is easily obtained by including a scalar ϕ with the same gauge properties as the lepton doublet; a vacuum expectation value, taken without loss of generality to be in the upper component, couples only to Z, and leaves the photon massless (gauge invariant).

- A vacuum expectation value for ϕ can easily be obtained by adding a term $(\phi^\dagger\phi - v)^2$ to the lagrangian,
- The coupling of e_L to the photon receives equal contributions from the W_3 and B term, since the two contributions cancel for the neutrino. Thus, if we want A equally coupled to e_L and e_R, e_R must couple to B with twice the charge of e.
- With the above assignement for the e_R coupling, terms of the form $\bar{L}\phi^c e_R$ are gauge invariant, and thus allowed in the lagrangian. If ϕ picks up a vacuum expectation value, they turn into mass terms for the fermions.

Several “magic” coincidences:

- The need of including a mass term for the fermions forces the photon interaction to be naturally parity conserving.
- The couplings to B (hypercharges) are such that anomalies cancels.
- The allowed Yukawa couplings can easily accommodate for Flavour Changing charged currents in the model.
- Flavour changing neutral currents are forbidden at tree level, and have further suppression at one-loop level (GIM mechanism).
- CP violating couplings can be present in the Yukawa sector, if we have at least 3 generations of quarks (and we do).
- If one accepts the existance of right-handed neutrinos, it is possible to have neutrino oscillations in the model.

Experimental tests of the model

Although the model seems quite compelling, ways out were possible;

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Neutral-current results without gauge theories

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(Received 19 June 1978)

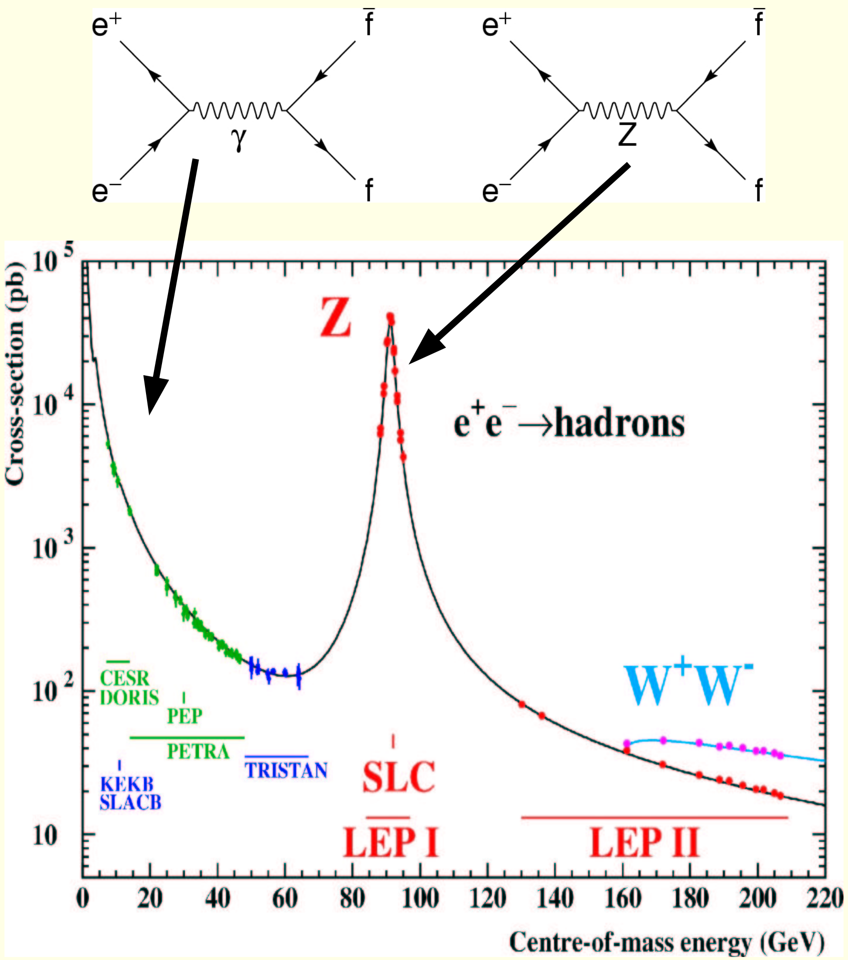
Low-energy weak interactions are phenomenologically described in terms of an intrinsic part possessing a global SU(2) symmetry plus an additional electromagnetic correction. This description reconstructs the Weinberg-Salam SU(2) ⊗ U(1) gauge-theory effective Lagrangian. Use of dispersion relations and Schwarz inequalities provides a lower bound on the range of the charged-current weak force, comparable to that obtained from gauge theories. The connection with the usual gauge-theory approach, especially the work of Georgi and Weinberg based on the group SU(2) ⊗ U(1) ⊗ *G*, is elucidated.

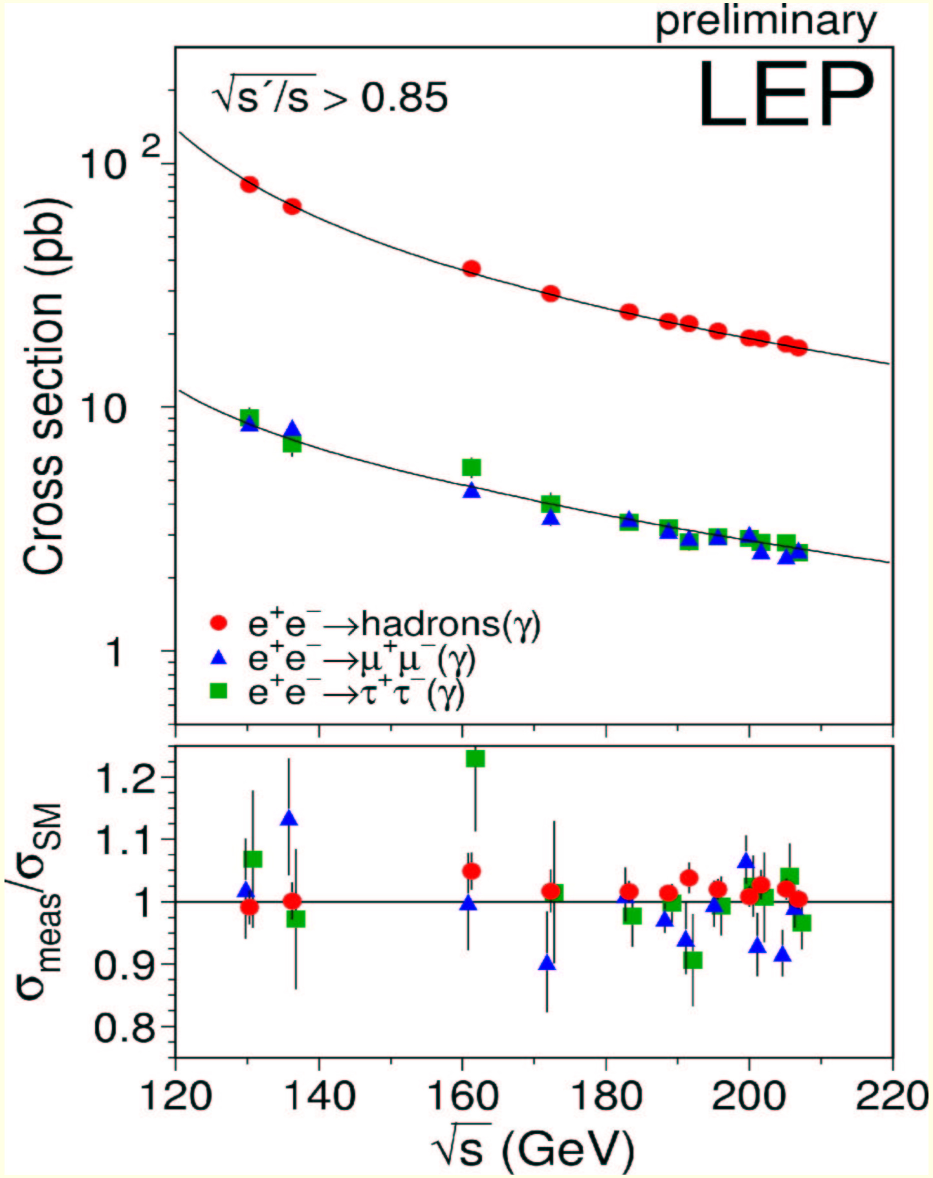
Low energy SM: $\propto\ 2J^+J^- + J^2_{\mathrm{NC}},\ J^\mu_{\mathrm{NC}} = J^\mu_3 + \sin^2\theta J^\mu_{\mathrm{em}}$ Neutral currents are detected in ν scattering; the above form can be obtained assuming an $SU(2)$ version of the Fermi current plus the assumption that the neutrino has a charge radius $\langle \nu\bar{\nu}|J^{\mathrm{em}}_\mu|0\rangle \propto \bar{\nu}\gamma_\mu\nu_\mu\, q^2$.

The only way to overcome these objections is to actually observe the heavy vector bosons (CERN, 1983-84) and study their properties. At present, plenty of evidence:

- Direct observation of W and Z, direct measurements of their couplings to leptons and quarks (hadron colliders, LEP).
- Measurements of the triple vector vertex (LEP)
- Precision tests of EW radiative corrections on the Z peak.
- Flavour Physics, Tests of CKM structure and CP violation in the K and B system

The Z Lineshape





M_Z = 91187.5 (2.1) MeV

N_ν = 2.9841 (83) [-1.9σ]

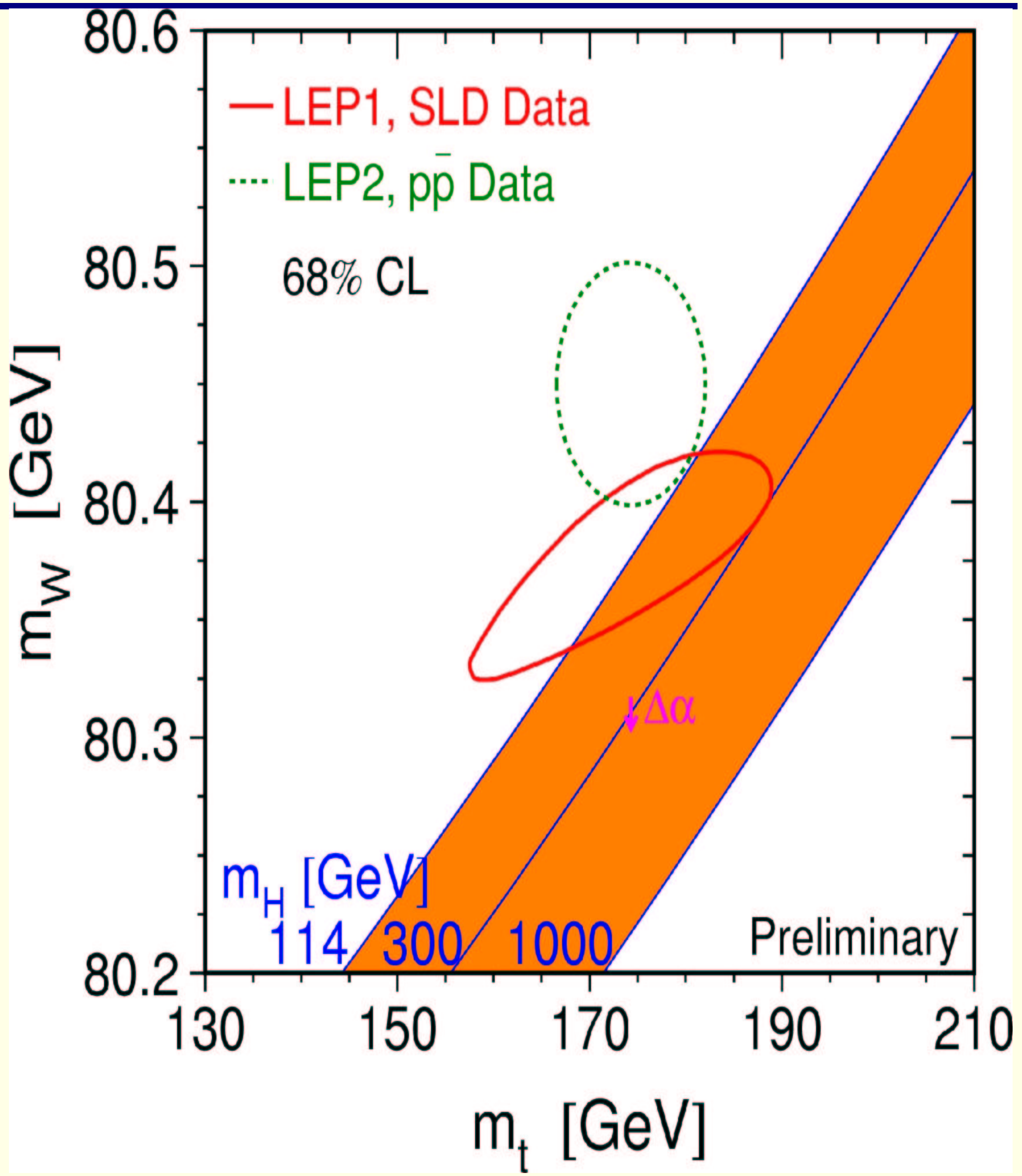
Prediction of Heavy Particle Masses W and top

Z-Pole measurements:
- Constrain electroweak radiative corrections
- Allows to predict M_W and M_{top} within SM

Direct measurements:
- TEVATRON and LEP2

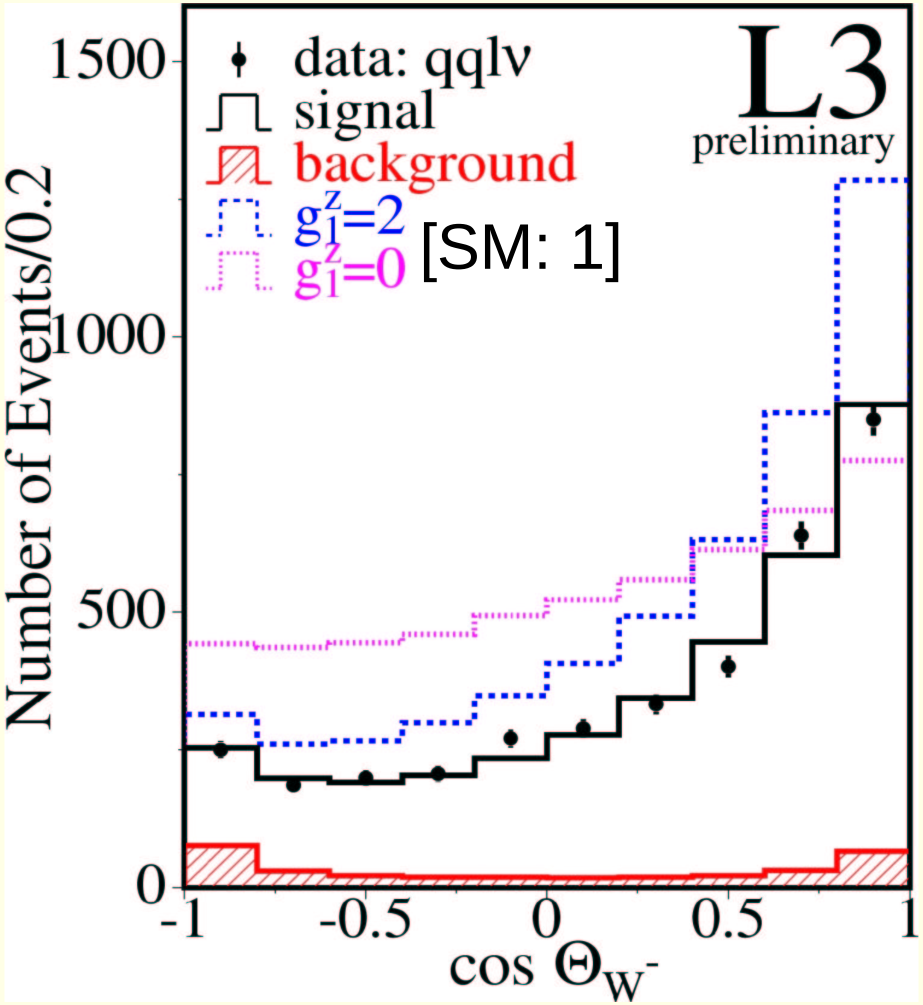
Good agreement
- Successful SM test

Both data sets prefer a
- light Higgs boson



W-Pair Production and Gauge Couplings

O(α) corrections: ~2% steeper slope



Triple gauge couplings:

g_1Z, κ_γ, λ_γ

W weak charge: g_1Z

W magnetic dipole:

$$\mu_W = \frac{e}{2M_W}\left(1+\kappa_\gamma+\lambda_\gamma\right)$$

W electric quadrupole:

$$Q_W = -\frac{e}{M_W^2}\left(\kappa_\gamma-\lambda_\gamma\right)$$

W polarisation:

Analyse decay angles

TGC analyses now based on O(α) calculations for W^+W^-

Charged Triple Gauge Couplings

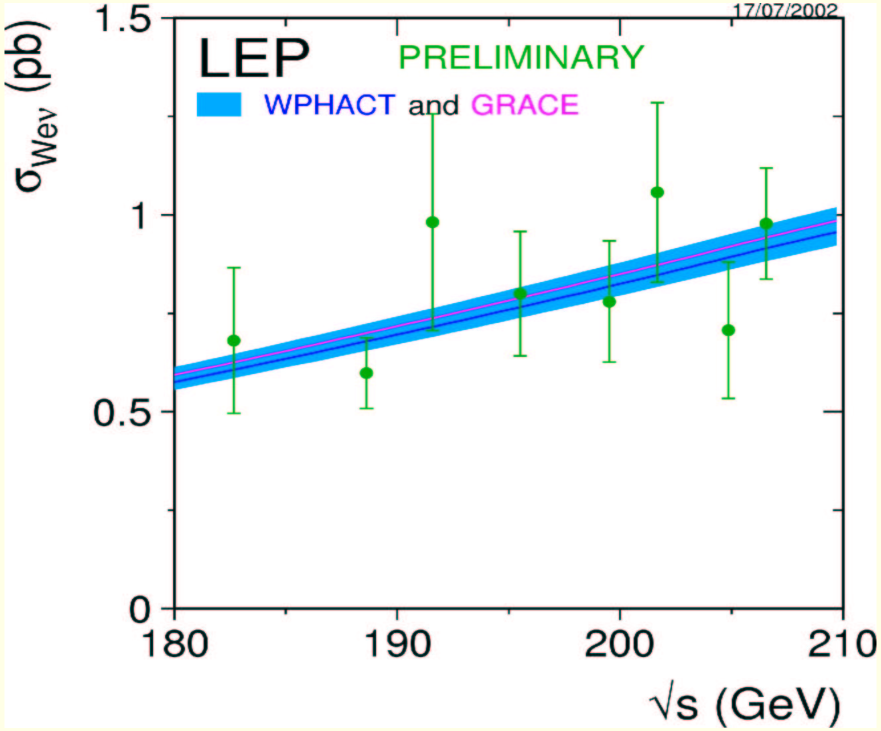
LEP single-parameter results (68%) [SM]:

g_1^Z = 0.998 (24) [1]

κ_γ = 0.943 (55) [1]

λ_γ =-0.020 (24) [0]

Also using single-W production (esp. κ_γ)



O(α) slope change currently used as theory uncertainty:

~2/3 of total error on TGCs

Ongoing studies to evaluate slope uncertainty on TGCs

Strong Interactions

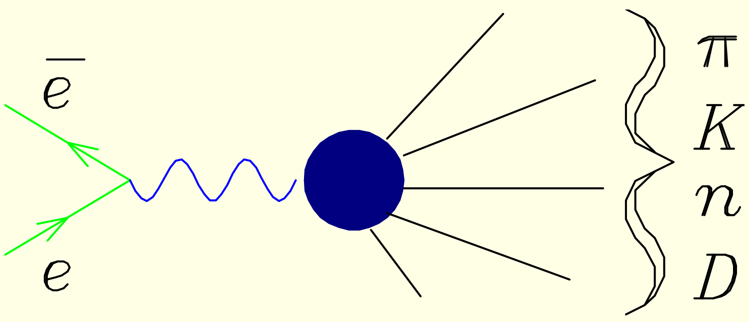
Most striking features of low energy strong interactions

- Complexity: no evidence of elementary objects and vertices
- Single characteristic scale ≈ 300 MeV. Lifetimes of strong excitations $\approx 1/300\text{MeV}^{-1}$, cross sections $\approx (1/300\text{MeV}^{-1})^2$.
- Parity conserving, isospin symmetries;

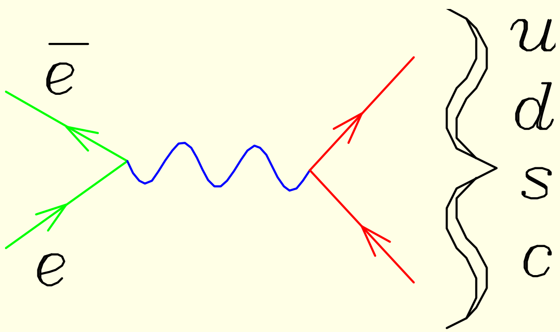
Early attempt to develop a theory of strong interactions: S matrix theories, dual models (i.e., no field theory).

Modern theory of strong interactions arises with the discovery of scaling phenomena in high energy strong interactions (SLAC, 1968).
Scaling: (certain) high energy cross section scale like $1/p^2$ when all momenta are uniformly increased.

A simple example of scaling is given by the reaction $e^+e^-\rightarrow$hadrons.
The total cross section can be computed in terms of pointlike quarks



$\approx$



- Quarks really exist!
- Strong interactions become weak at high energies (short distances)

Shortly after the SLAC discovery, it was found that the only theories that could give weak coupling at short distances are non-abelian Gauge Theories (Gross and Wilczek, Politzer, (73), t'Hooft (72)). It was soon realized that an $SU(3)$ gauge theory coupled to the colour quantum number was the only possible candidate for a theory of strong interaction.

In this case, it is difficult to maintain the interesting properties of the theory (e.g. asymptotic freedom) is one tries to give mass to the vector mesons via the higgs mechanism. It was then assumed that the growth of the coupling constant in the infrared limit could cause a confinement phenomenon, such that only color-neutral objects can form asymptotic states.

Colour (Gell-Mann (64), Zweig (64)) was introduced earlier to explain the spectrum of hadrons in the quark model.

Isospin is a very good symmetry of strong interaction.
We observe the spin 3/2 barions Δ^{++}, Δ^{+}, Δ^{0}, Δ^{-}, with nearly the same mass, that can be assigned to the same isospin miltiplet (isospin 3/2). In terms of quarks:

$$\Delta^{++} = u \uparrow u \uparrow u \uparrow, \quad \Delta^{+} = u \uparrow u \uparrow d \uparrow, \quad \Delta^{0} = u \uparrow d \uparrow d \uparrow, \quad \Delta^{-} = d \uparrow d \uparrow d \uparrow .$$

Because of the Fermi symmetry, the space wavefunction would have to be totally untisymmetric for Δ^{++} and Δ^{-}, but could have different symmetry properties for the Δ^{+} and Δ^{0}. If we admit the existance of a new quantum number (colour) with three values, the wavefunction can be antisymmetric in colour, and symmetric in space.

Assuming that hadrons are made of quarks u, d, s with electric charges $2/3$, $-1/3$, $-1/3$, and each quark comes in 3 colours, and that observable states are colour neutral under the $SU(3)$ gauge group, we can accommodate all the known spectrum of hadrons.

In Summary

Assuming that the strong forces are descibed by a gauge theory coupled to colour (Quantum-Chromo-Dynamics), and assuming confinement, we

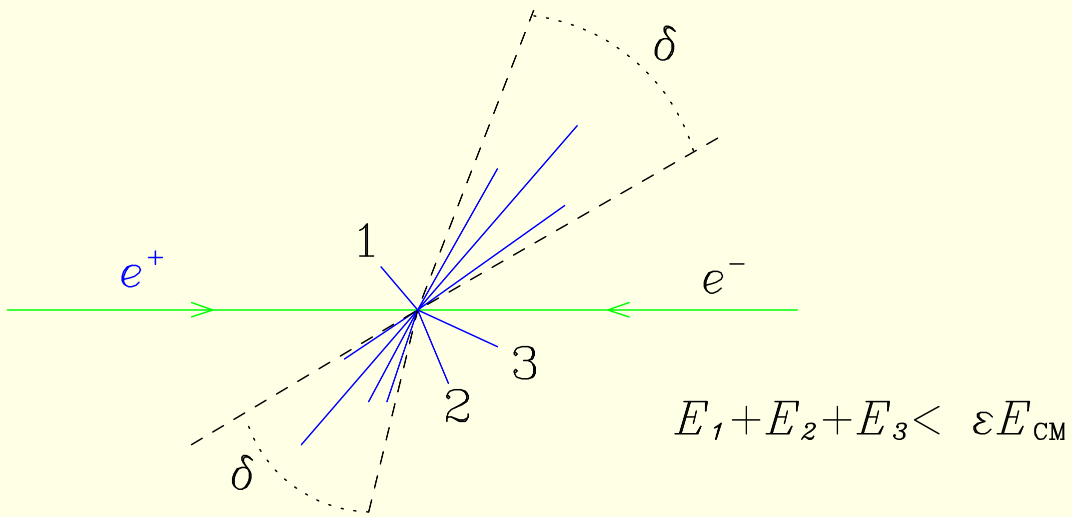
- explain the spectrum of hadrons;
- explain the independence of strong and weak interactions;
- explain scaling phenomena;
- we can compute high energy cross sections;
- open a way to unification of all forces;

Sterman and Weinberg were the first to realize that not only total cross section, but also differential distributions could be computed in QCD.

Key observation: infrared finite cross sections computed in terms of quarks and gluons should describe a corresponding physical cross section defined in terms of hadrons (quark-hadron duality).

For example: 2-Jet cross section in e^+e^- collisions (Sterman-Weinberg)
Cross section for events for which we can find two cones of aperture δ such that $E(\text{inside cone}) \geq (1-\epsilon)E_{\text{CM}}$.

It follows that in QCD at order 0 in the strong coupling constant all events are 2-jet events!



Much resistance to accept quarks, confinement, and QCD, expecially its perturbative applications.

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Heavy quarks and perturbative quantum-chromodynamic calculations

Subhash Gupta and Helen R. Quinn
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(Received 17 July 1981)

We consider a model universe in which the lightest quarks are heavy on the scale of the QCD Λ parameter (however defined). In this model universe we find that there are nonperturbative effects that are not suppressed by powers of Q^2. We discuss the implications of such effects in the real world: Residual effects at large Q^2 could cause deviations from perturbative predictions.

In the model with a heavy quark universe (Bjorken), in $e^+e^- \to q\bar{q}$ the heavy quark-antiquark cannot separate, unless a new $q\bar{q}$ pair is formed:
by tunneling (which costs a factor $\exp(-m_q/\Lambda)$)
or perturbatively (which costs a factor $\alpha_S(m_q)$).

The authors conclude that there must be $\mathcal{O}(1)$ corrections to e^+e^- jet rates in e^+e^- annihilation.

The argument is wrong by many points of view.
Interesting to see, however, that the inability to fully solve the theory has caused many interesting objections...

Another example: shortly after LEP began to run (1990), the hadronic width was found to be 2 standard deviations higher than QCD prediction ($(1+\alpha/\pi) \times$ PMV). Many speculations followed:

- QCD is wrong;
- α_S does not run;
- Pert. QCD applicable only in euclidean region;
- ...

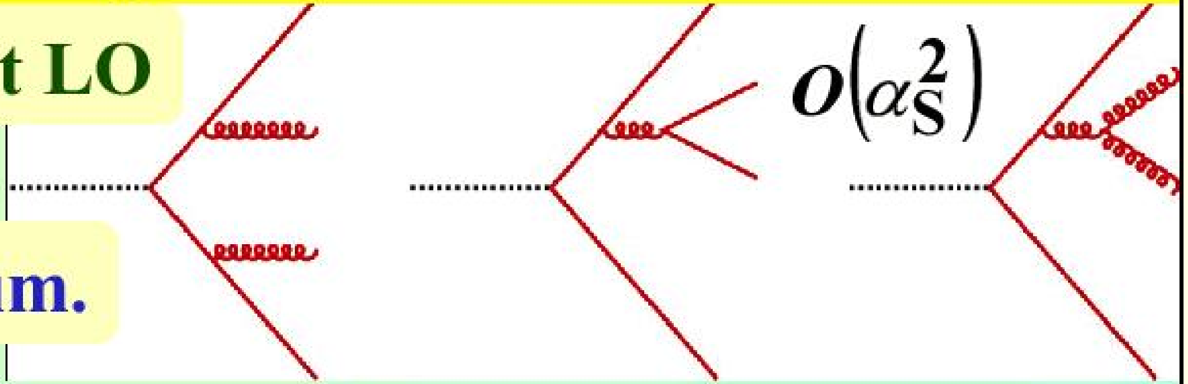
Simpler explanation: 2 standard deviations do not mean much.

Status of QCD today

- Extensive studies of 2, 3, 4 jet production at LEP confirm perturbative QCD calculations
- Several generations of ep collision experiments have confirmed the scaling violation patterns predicted by QCD
- Several production phenomena in hadron-hadron collisions have been computed, and compared successfully with experiments. In one case (top) the calculation has helped the discovery of a new particle.
- The next large effort in a discovery collider (red LHC) is based upon QCD perturbative calculation
- Well developed approach to non-perturbative QCD using computers (QCD on a space-time lattice).

α_S from 4-jet rate in e^+e^-

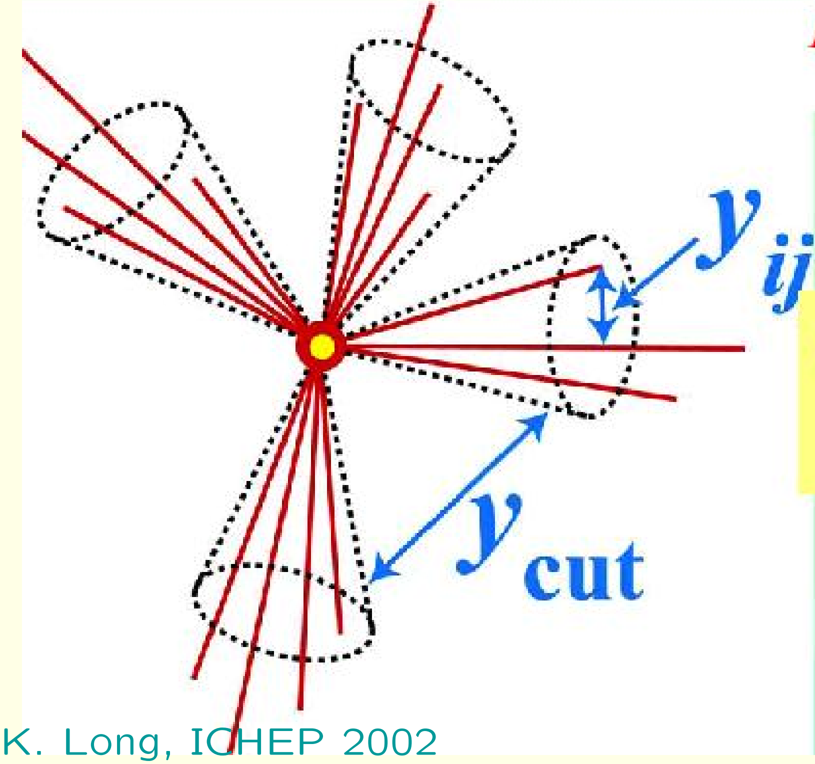
High sensitivity to α_S at LO



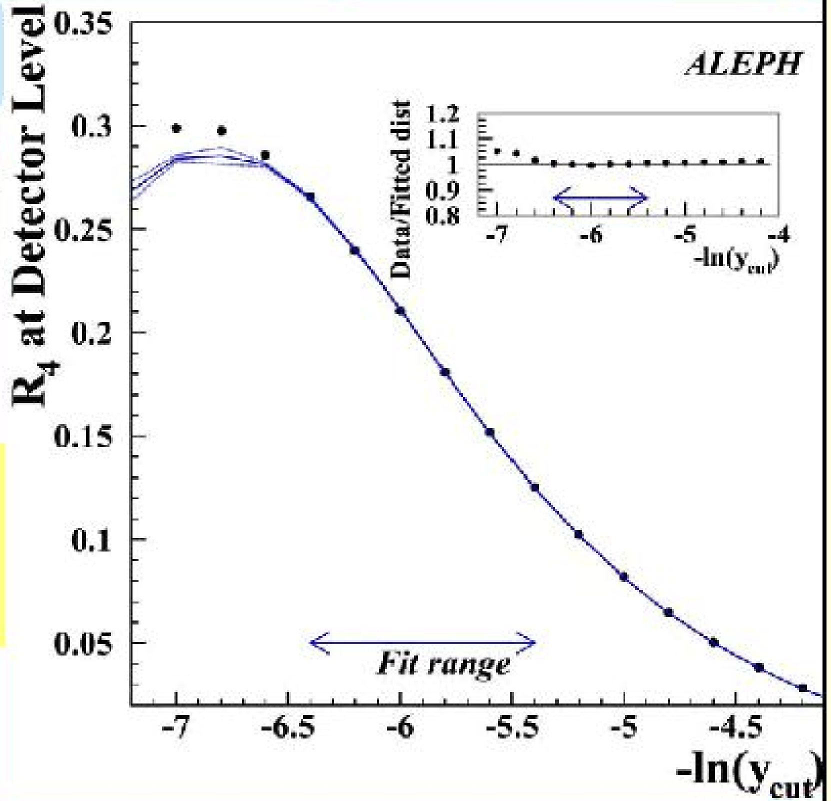
$O(\alpha_S{}^3)$ and NLL resum.

4-jet rate:

$$R_4 = \frac{\sigma_4(y_{cut})}{\sigma_{Tot}}$$

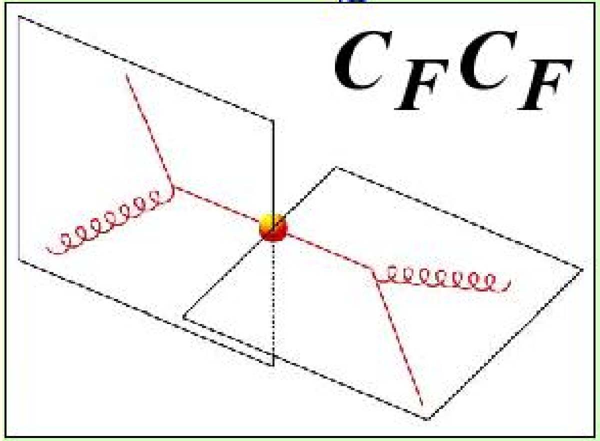


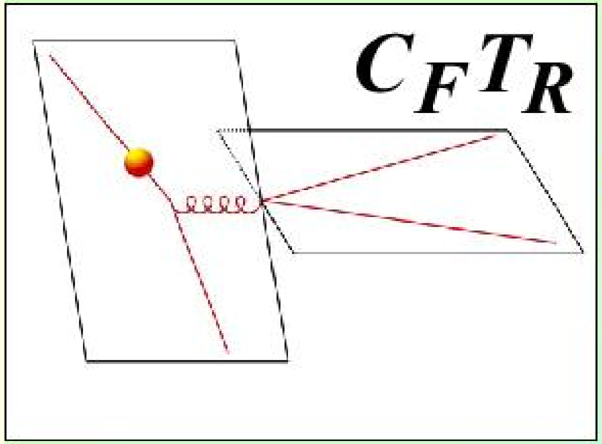
Precision!
~1%

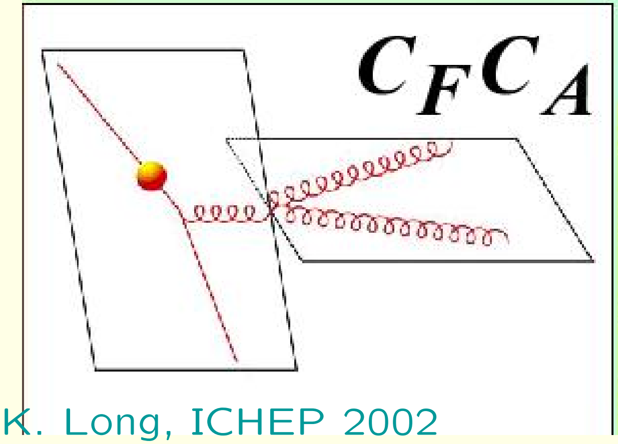


$$\alpha_S = 0.1170 \pm 0.0001 \pm 0.0013$$

α_S and colour factors from e^+e^-

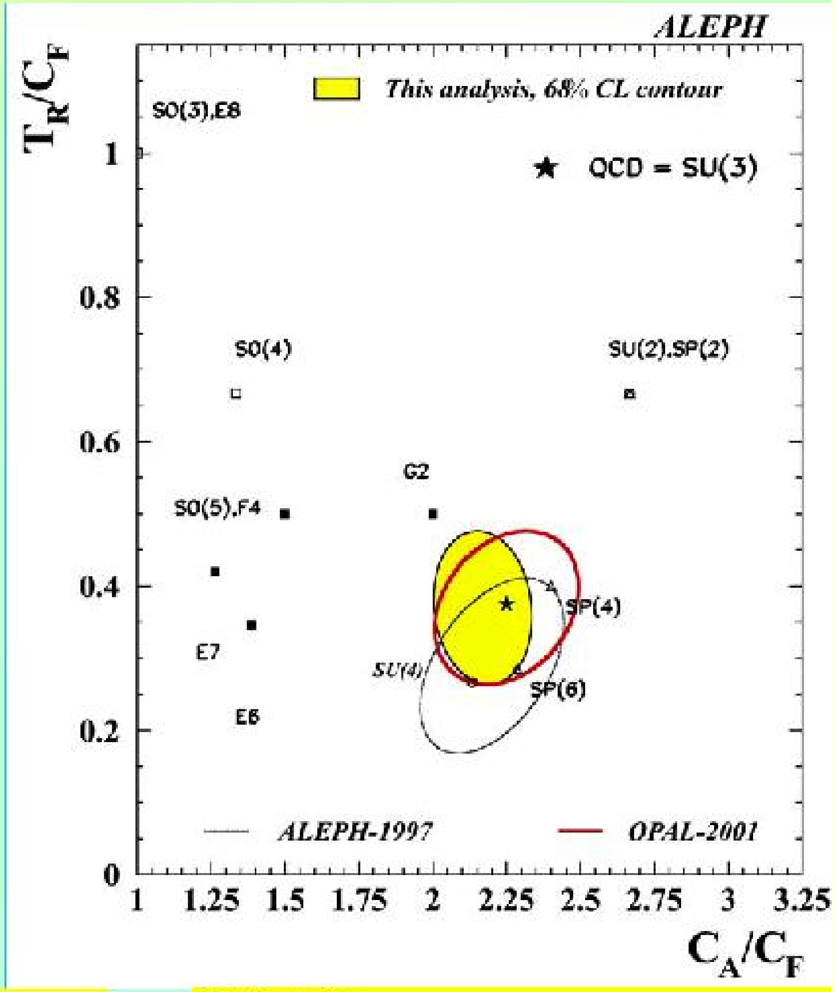






Angular correlations sensitive to colour factors

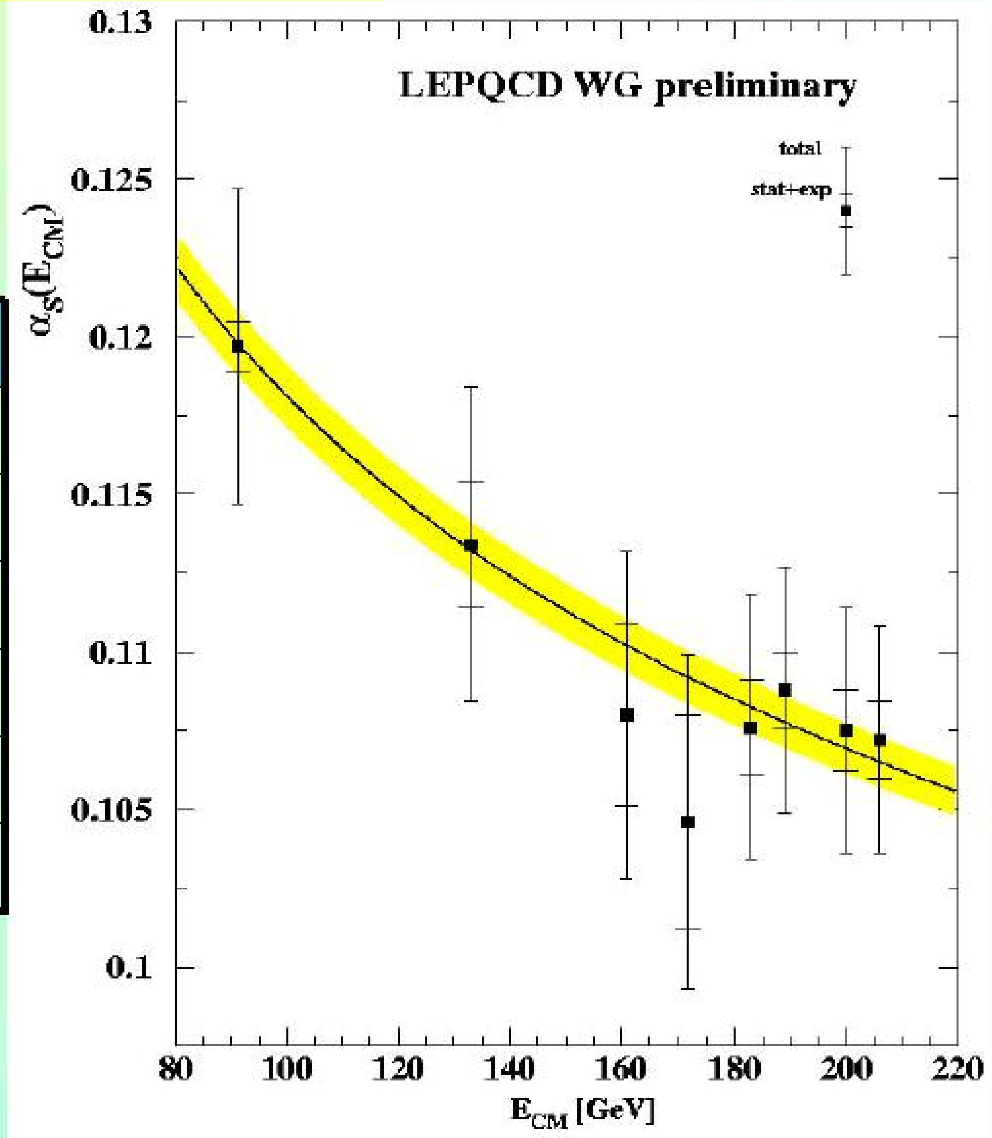
Simultaneous fit to 4 angles and R_4



ALEPH	OPAL
$\alpha_S = 0.119 \pm 0.006 \pm 0.026$	$\alpha_S = 0.120 \pm 0.011 \pm 0.020$
$C_A = 2.93 \pm 0.14 \pm 0.58$	$C_A = 3.02 \pm 0.25 \pm 0.49$
$C_F = 1.35 \pm 0.07 \pm 0.26$	$C_F = 1.35 \pm 0.13 \pm 0.22$

α_S from event shapes in e^+e^-

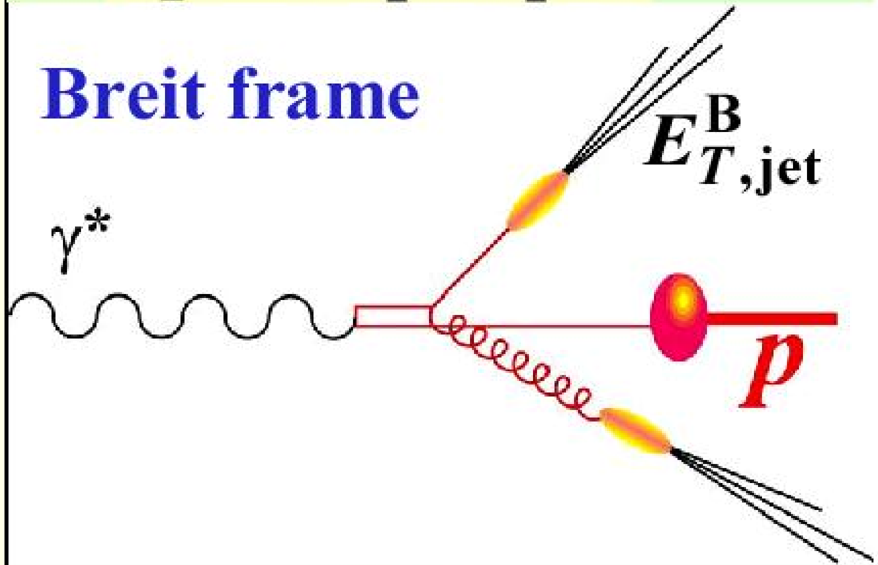
prelim	all LEP	LEP I	LEP II
$\alpha_s(M_Z)$	0.1198	0.1197	0.1197
Δ stat	0.0002	0.0002	0.0006
Δ exp	0.0009	0.0008	0.0010
Δ had	0.0008	0.0010	0.0007
Δ theo	0.0045	0.0048	0.0045
Δ tot	0.0047	0.0050	0.0047



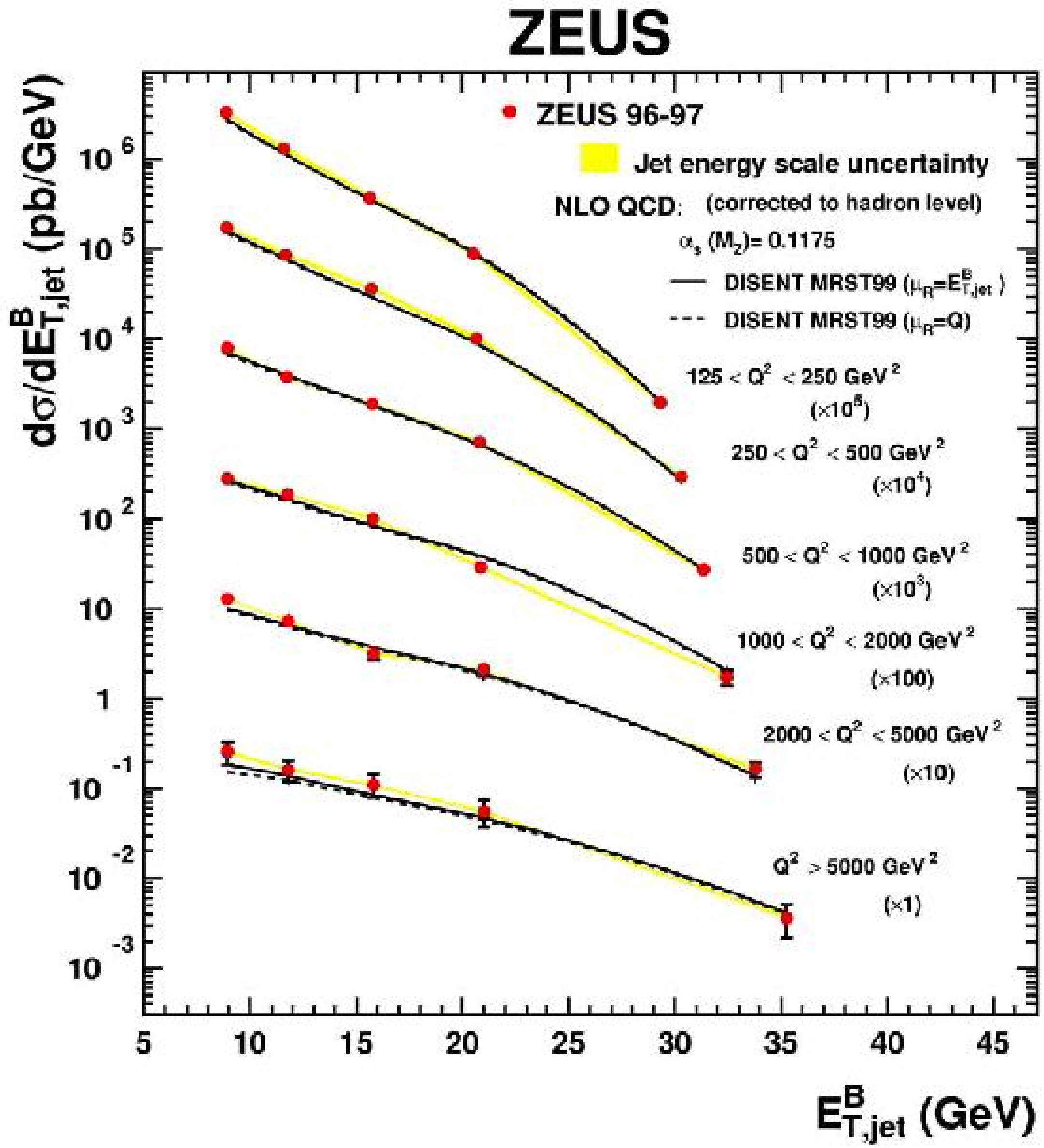
$$\alpha_S\left(M_Z\right) = 0.1198 \pm 0.0047 \text{ (LEP combined)}$$

α_S from inclusive jet production in *ep*

$ep \to e[\text{Jet}]X$

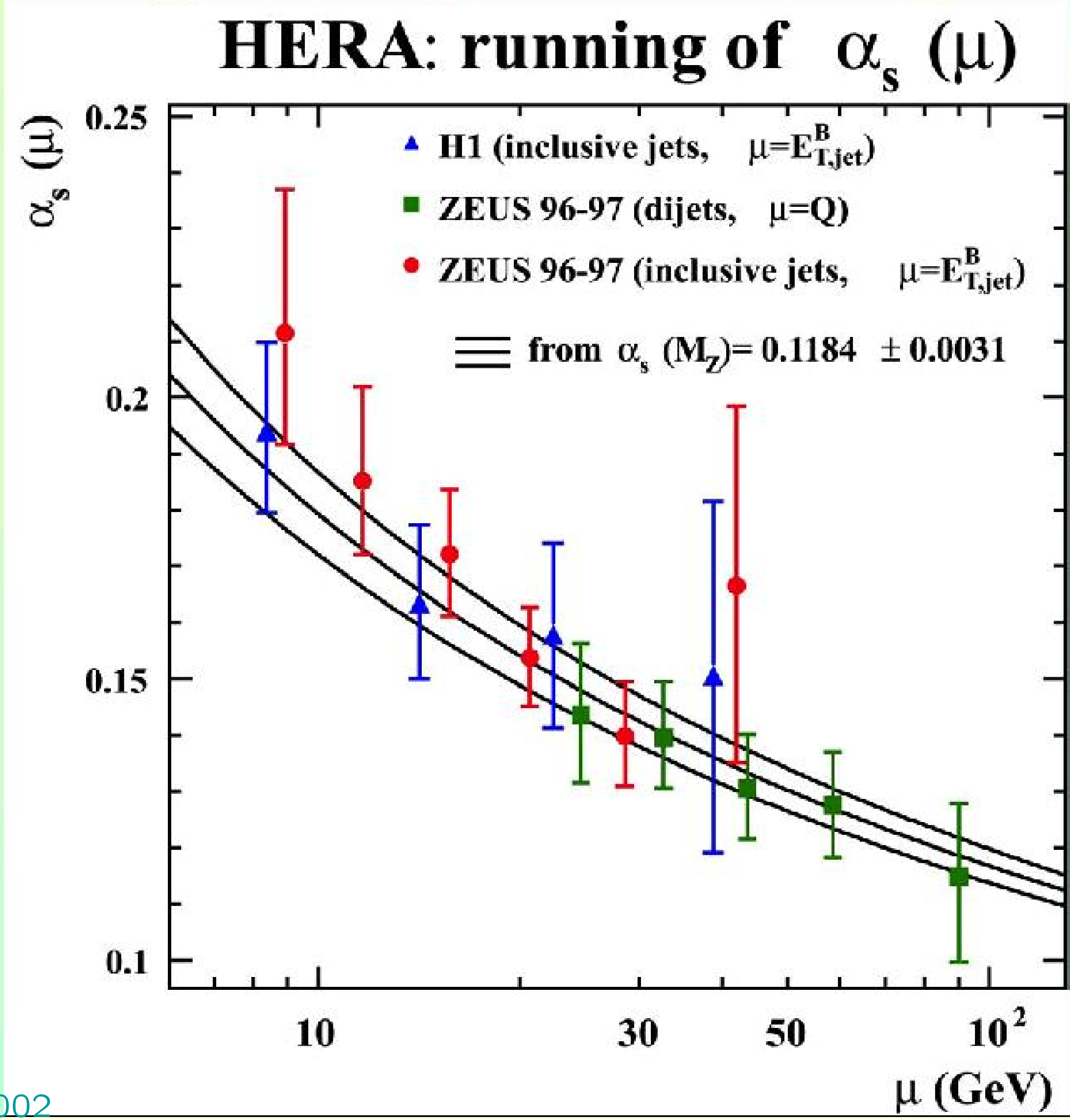


- **NLO ($O(\alpha_S{}^2)$) gives reasonable description over wide range of Q^2 and $E^B{}_{T,\text{jet}}$**
- **Fit to extract α_S**

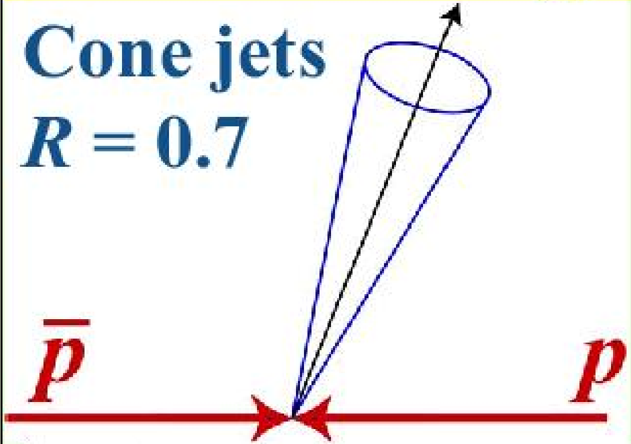


$$\alpha_S(M_Z) = 0.1212 \pm 0.0017(\text{stat.})^{+0.0023}_{-0.0031}(\text{sys.})^{+0.0028}_{-0.0027}(\text{th.})$$

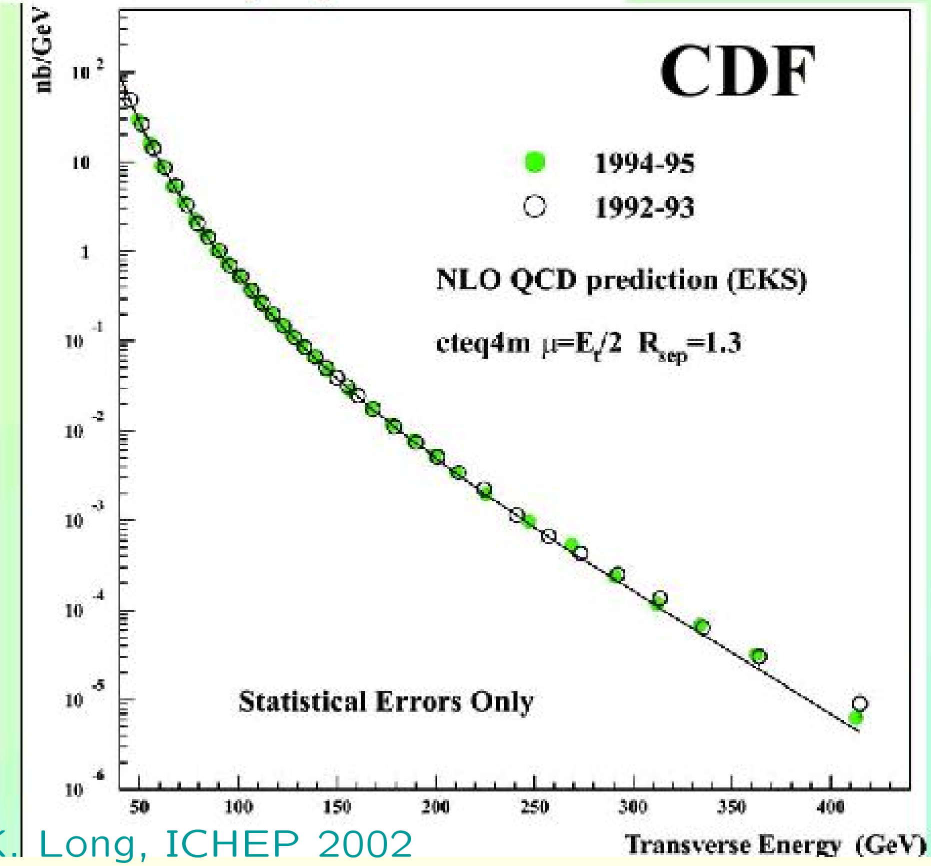
α_S from jet rates in *ep*

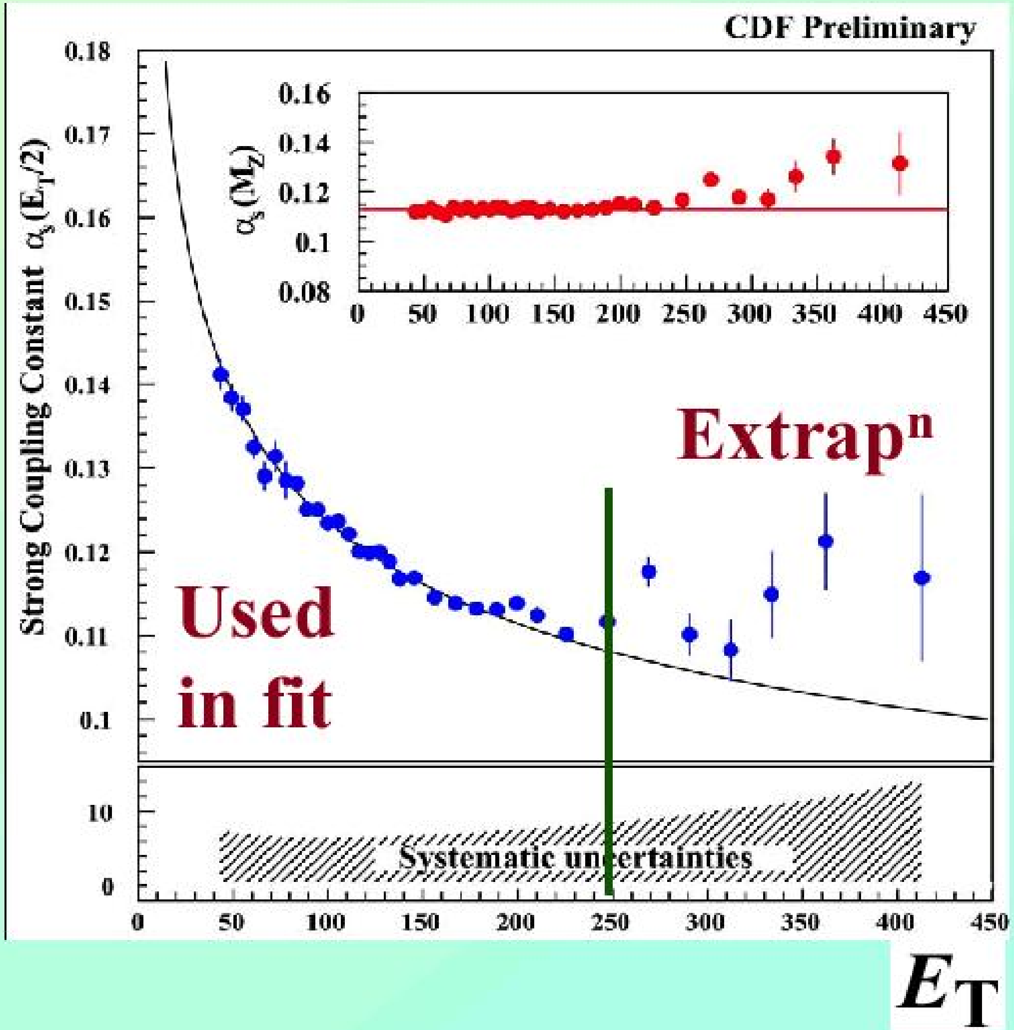


α_S from jet rates in $p\bar{p}$



$$\frac{d\sigma}{dE_T} = \alpha_S^2 \times F_{LO} + \alpha_S^3 \times F_{NLO}$$





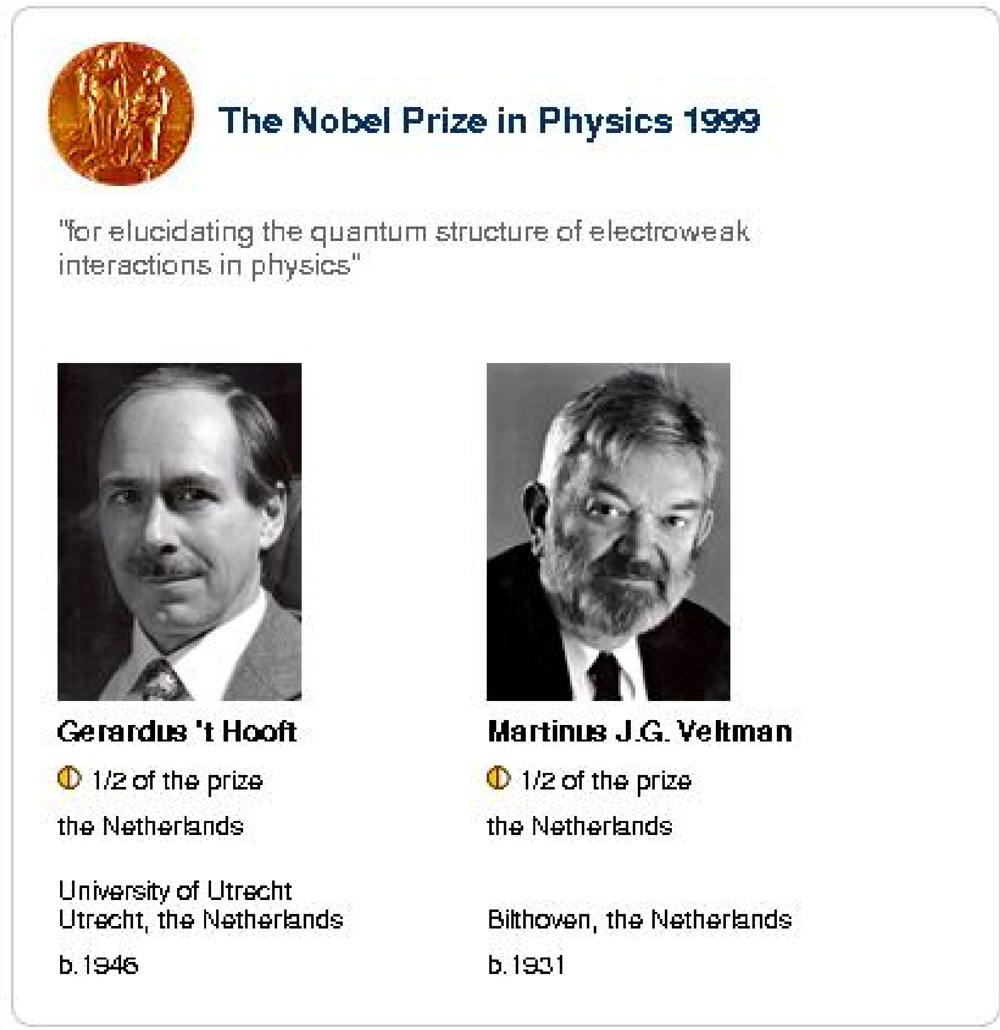
Standard Model and Computing

M. Veltman, asked why he spent so much time working on Schoonschip, answered:

Keeps me ahead of the crowd.

From his Autobiography:

… I started constructing my symbolic computer program Schoonschip. That also had its origin in the neutrino experiment: in doing the necessary algebra for vector boson production I was often exasperated by the effort that it took to get an error free result, even if the work was quite mechanical.



Both in weak and strong interaction, computer algebra has become a must.

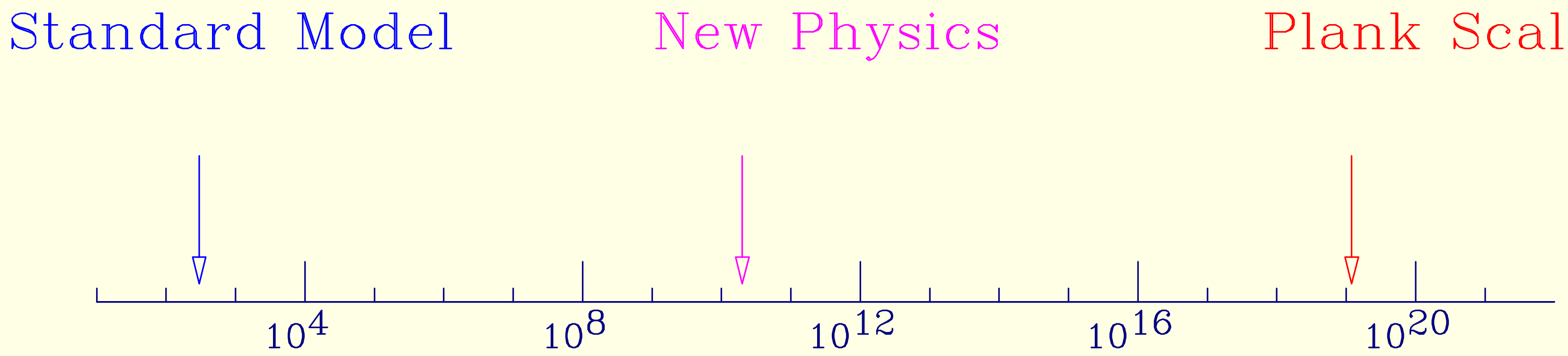
Non-Perturbative QCD has stimulated the use (and the construction!) of computers for highly intensive numerical calculations.

Undesirable features of the Standard Model

All high energy physics phenomena (except gravity) that we know can be described by the Standard Model. However, the model has many parameters, and their relative size is unexplained:

- Why is the EW scale (the scalar mass) so small? (Hierarchy problem).
- A term $\theta \tilde{F} F$ for the colour field: $\theta < 10^{-9}$ (strong CP problem).
- Wide mass range for quark masses (few MeV to hundred GeV) and lepton masses (half an MeV to 1.8 GeV).
- The Cabibbo-Kobayashi-Maskawa flavour mixing matrix is nearly diagonal.
- Neutrino masses are so small

Extensions



Several extension possible; common problems:

- Scalar mass quadratically divergent in P.T.; thus $m_\phi \approx \Lambda_{\mathrm{EW}} \approx \Lambda_{\mathrm{NP}}$ is natural (hierarchy problem).
- Effective interactions with couplings $1/\Lambda_{\mathrm{NP}}^m$ can arise; this could spoil precision physics at LEP, generate new 4-fermion interactions (dimension 6) (proton decay, lepton flavour violation, flavour changing neutral currents).

Few examples:

- Grand unified theories: the 3 coupling constants of the standard model become almost the same at $\Lambda_{NP} \approx 10^{15}$ GeV. No explanation of the smallness of the scalar mass. Small effective couplings (only sensitive to proton decay limits).

- Models with a composite scalar; to avoid large scalar mass Λ_{NP} near Λ_{EW}; problems with LEP precision data and with FCNC.

- Supersymmetry; $\Lambda_{NP} \approx \Lambda_{EW}$; scalar masses naturally small; better unification of couplings and larger proton lifetime; problems with FCNC; NOT SEEN AT LEP.

- Extra-dimensions at EW scale; $\Lambda_{NP} \approx \Lambda_{EW}$; problems with non-renormalizable effective interactions.

At present: hints for unification and supersymmetry, but no consistent explanation of present phenomenology:

NEED NEW EXPERIMENTAL INPUT!

To make progress, we must explore the higgs sector.

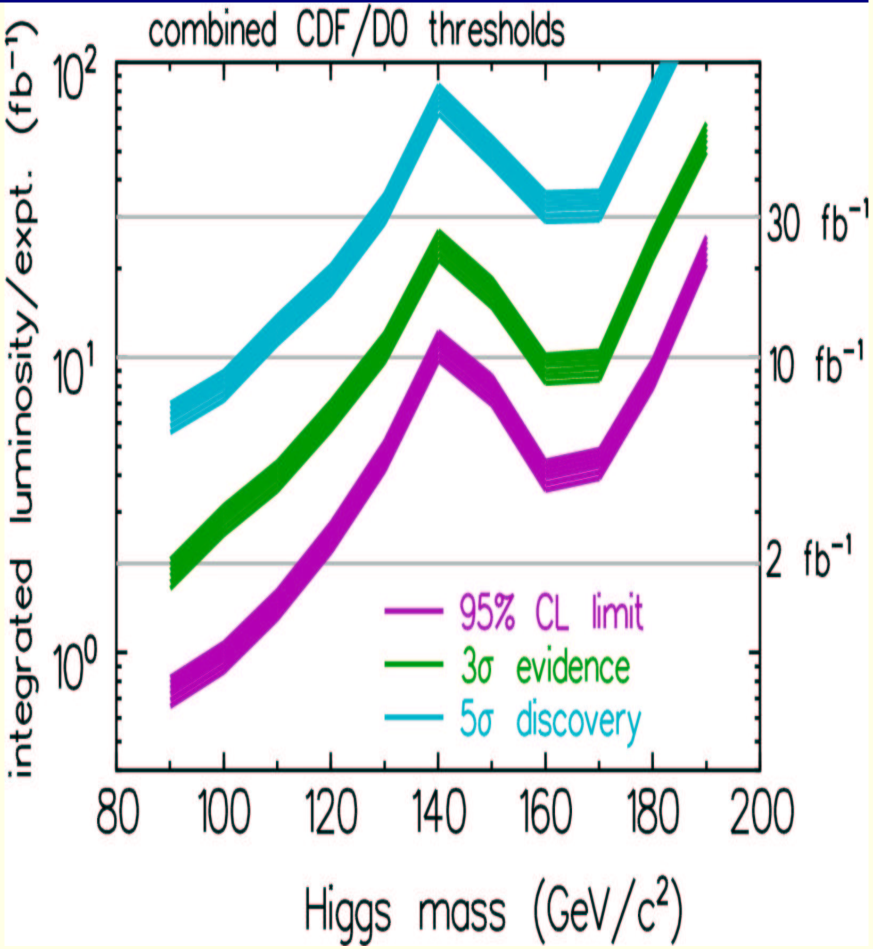
Future Higgs Search

TEVATRON:
Search in the most probable mass range

Run-2a with $2fb^{-1}$:
95% C.L. exclusion limit up to 115 GeV

Run-2b with $15fb^{-1}$:
3σ evidence up to 135 GeV

LHC (ATLAS, CMS):
Search in the full mass range



M.W. Grünewald, ICHEP 2002

LHC is needed to fully explore the nature of EW symmetry breaking, and perhaps to give some hint on the solution of the hierarchy problem.