Introduction into Standard Model and Precision Physics – Lecture II –

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General overview

4 The Standard Model of electroweak interaction — flavour sector and quantization

4.1 Fermion masses and Yukawa couplings

Ordinary Dirac mass terms $m_f\overline{\psi_f}\psi_f = m_f(\overline{\psi_f^{\mathrm{L}}}\psi_f^{\mathrm{R}} + \overline{\psi_f^{\mathrm{R}}}\psi_f^{\mathrm{L}})$ not gauge invariant

$\hookrightarrow$ introduce fermion masses by (gauge-invariant) Yukawa interaction

Lagrangian for Yukawa couplings:

$$\mathcal{L}_{\mathrm{Yuk}} = -\overline{\Psi_L^{\mathrm{L}}}G_l\psi_l^{\mathrm{R}}\Phi - \overline{\Psi_Q^{\mathrm{L}}}G_u\psi_u^{\mathrm{R}}\tilde{\Phi} - \overline{\Psi_Q^{\mathrm{L}}}G_d\psi_d^{\mathrm{R}}\Phi + \text{h.c.}$$

- G_l, G_u, G_d = 3×3 matrices in 3-dim. space of generations (ν masses ignored)
- $\tilde{\Phi} = i\sigma^2\Phi^* = \begin{pmatrix} \phi^{0*} \\ -\phi^- \end{pmatrix}$ = charge conjugate Higgs doublet, $Y_{\tilde{\Phi}} = -1$

Fermion mass terms:

mass terms = bilinear terms in $\mathcal{L}_{\mathrm{Yuk}}$, obtained by setting $\Phi \to \Phi_0$:

$$\mathcal{L}_{m_f} = -\frac{v}{\sqrt{2}}\overline{\psi_l^{\mathrm{L}}}G_l\psi_l^{\mathrm{R}} - \frac{v}{\sqrt{2}}\overline{\psi_u^{\mathrm{L}}}G_u\psi_u^{\mathrm{R}} - \frac{v}{\sqrt{2}}\overline{\psi_d^{\mathrm{L}}}G_d\psi_d^{\mathrm{R}} + \text{h.c.}$$

$\hookrightarrow$ diagonalization by unitary field transformations $(f = l, u, d)$

$\hat{\psi}_f^{\mathrm{L/R}} \equiv U_f^{\mathrm{L/R}}\psi_f^{\mathrm{L/R}}$ such that $\frac{v}{\sqrt{2}}U_f^{\mathrm{L}}G_f(U_f^{\mathrm{R}})^\dagger = \mathrm{diag}(m_f)$

$\Rightarrow$ standard form: $\mathcal{L}_{m_f} = -m_f\overline{\hat{\psi}_f^{\mathrm{L}}}\hat{\psi}_f^{\mathrm{R}} + \text{h.c.} = -m_f\overline{\hat{\psi}_f}\hat{\psi}_f$

Quark mixing:

- ψ_f correspond to eigenstates of the gauge interaction
- $\hat{\psi}_f$ correspond to mass eigenstates,

  for massless neutrinos define $\hat{\psi}^{\rm L}_\nu \equiv U^{\rm L}_l \psi^{\rm L}_\nu$ $\rightarrow$ no lepton-flavour changing

Yukawa and gauge interactions in terms of mass eigenstates:

$$\begin{aligned}\mathcal{L}_{\rm Yuk} = &-\frac{\sqrt{2}m_l}{v}\left(\phi^+\overline{\hat{\psi}^{\rm L}_{\nu_l}}\hat{\psi}^{\rm R}_l + \phi^-\overline{\hat{\psi}^{\rm R}_l}\hat{\psi}^{\rm L}_{\nu_l}\right) + \frac{\sqrt{2}m_u}{v}\left(\phi^+\overline{\hat{\psi}^{\rm R}_u}V\hat{\psi}^{\rm L}_d + \phi^-\overline{\hat{\psi}^{\rm L}_d}V^\dagger\hat{\psi}^{\rm R}_u\right)\\ &-\frac{\sqrt{2}m_d}{v}\left(\phi^+\overline{\hat{\psi}^{\rm L}_u}V\hat{\psi}^{\rm R}_d + \phi^-\overline{\hat{\psi}^{\rm R}_d}V^\dagger\hat{\psi}^{\rm L}_u\right) - \frac{m_f}{v}{\rm i}\,{\rm sgn}(T^3_{{\rm I},f})\chi\,\overline{\hat{\psi}_f}\gamma_5\hat{\psi}_f\\ &-\frac{m_f}{v}(v+H)\,\overline{\hat{\psi}_f}\hat{\psi}_f,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\rm ferm,YM} = &\frac{e}{\sqrt{2}s_{\rm W}}\overline{\hat{\Psi}^{\rm L}_L}\begin{pmatrix} 0 & \not{W}^+ \\ \not{W}^- & 0\end{pmatrix}\hat{\psi}^{\rm L}_L + \frac{e}{\sqrt{2}s_{\rm W}}\overline{\hat{\Psi}^{\rm L}_Q}\begin{pmatrix} 0 & V\not{W}^+ \\ V^\dagger\not{W}^- & 0\end{pmatrix}\hat{\psi}^{\rm L}_Q\\ &+\frac{e}{2c_{\rm W}s_{\rm W}}\overline{\hat{\Psi}^{\rm L}_F}\sigma^3\not{Z}\hat{\Psi}^{\rm L}_F - e\frac{s_{\rm W}}{c_{\rm W}}Q_f\overline{\hat{\psi}_f}\not{Z}\hat{\psi}_f - eQ_f\overline{\hat{\psi}_f}\not{A}\hat{\psi}_f\end{aligned}$$

- only charged-current coupling of quarks modified by $V = U^{\rm L}_u(U^{\rm L}_d)^\dagger$ = unitary

  (Cabibbo–Kobayashi–Maskawa (CKM) matrix)

- Higgs–fermion coupling strength = $\frac{m_f}{v}$

Features of the CKM mixing:

- V = 3-dim. generalization of Cabibbo matrix U_C
- V is parametrized by 4 free parameters: 3 real angles, 1 complex phase
  $\hookrightarrow$ complex phase is the only source of CP violation in SM

  counting:

  $$\begin{pmatrix}\text{\#real d.o.f.}\\ \text{in } V\end{pmatrix} - \begin{pmatrix}\text{\#unitarity}\\ \text{relations}\end{pmatrix} - \begin{pmatrix}\text{\#phase diffs. of}\\ u\text{-type quarks}\end{pmatrix} - \begin{pmatrix}\text{\#phase diffs. of}\\ d\text{-type quarks}\end{pmatrix} - \begin{pmatrix}\text{\#phase diff. between}\\ u\text{- and } d\text{-type quarks}\end{pmatrix}$$

  $$= 18 - 9 - 2 - 2 - 1 = 4$$

- no flavour-changing neutral currents in lowest order,
  flavour-changing suppressed by factors $G_\mu(m_{q_1}^2 - m_{q_2}^2)$ in higher orders
  (“Glashow–Iliopoulos–Maiani mechanism”)

4.2 Quantization — gauge fixing and Faddeev–Popov sector

Gauge fields contain unphysical degrees of freedom that must not be quantized.

Consequences:

- gauge-boson propagators ill-defined without gauge fixing,
  e.g. for photon the (singular) operator $(g_{\mu\nu}\Box - \partial_\mu\partial_\nu)$ would have to be inverted
- in path integral $\int \mathcal{D}A_\mu^a \exp\{\mathrm{i}\int \mathrm{d}x\,\mathcal{L}\}$:
  only one representative of each gauge orbit should contribute,
  otherwise integral over gauge-equivalent fields diverges
  $\hookrightarrow$ fix gauge by δ-functions $\delta(F^a[A_\mu^a] - C^a)$ in path integral (C^a = const.)
  $\hookrightarrow$ by averaging over C^a, gauge fixing can be cast in terms of a
  gauge-fixing Lagrangian $\mathcal{L}_{\mathrm{gf}}$

Gauge-fixing Lagrangian of general R_ξ gauge:

$$\mathcal{L}_{\mathrm{gf}} = -\frac{1}{\xi_{\mathrm{W}}}F^+F^- - \frac{1}{2\xi_{\mathrm{Z}}}(F^{\mathrm{Z}})^2 - \frac{1}{2\xi_\gamma}(F^\gamma)^2$$

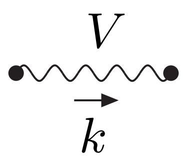
with the gauge-fixing functionals F^a: (ξ_V = arbitrary gauge-fixing parameters)

$$F^\pm = \partial W^\pm \mp \mathrm{i}\xi_{\mathrm{W}} M_{\mathrm{W}} \phi^\pm, \qquad F^{\mathrm{Z}} = \partial Z - \xi_{\mathrm{Z}} M_{\mathrm{Z}} \chi, \qquad F^\gamma = \partial A$$

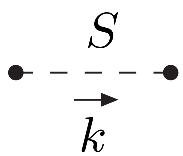
Features of the R_ξ gauge fixing:

- elimination of mixing terms $(W^\pm_\mu \partial^\mu \phi^\mp)$, $(Z_\mu \partial^\mu \chi)$ in Lagrangian
  $\hookrightarrow$ decoupling of gauge and would-be Goldstone fields (no mix propagators)

- boson propagators:



$$G^{VV}_{\mu\nu}(k) = -\mathrm{i}\left[\frac{g_{\mu\nu} - \frac{k_\mu k_\nu}{k^2}}{k^2 - M_V^2} + \frac{k_\mu k_\nu}{k^2}\frac{\xi_V}{k^2 - \xi_V M_V^2}\right], \qquad V = W, Z, \gamma$$



$$G^{SS}(k) = \frac{\mathrm{i}}{k^2 - \xi_V M_V^2}, \qquad S = \phi, \chi$$

- important special cases:
  - $\xi_V = 1$: 't Hooft–Feynman gauge
    $\hookrightarrow$ convenient gauge-boson propagators $\dfrac{-\mathrm{i}g_{\mu\nu}}{k^2 - M_V^2}$
  - $\xi_\mathrm{W}, \xi_\mathrm{Z} \to \infty$: "unitary gauge"
    $\hookrightarrow$ elimination of would-be Goldstone bosons

Faddeev–Popov ghosts

Consistent use of gauge fixing in path integral: Faddeev–Popov ansatz

$$\int \mathcal{D}A^a_\mu \; \exp\left\{\mathrm{i}\int \mathrm{d}x\,\mathcal{L}\right\}\; \delta(F^a[A^a_\mu]-C^a)\;\det\left(\frac{\delta F^a}{\delta\theta^b}\right)$$

with the gauge variation of the functionals F^a:

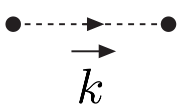
$$\left(\frac{\delta F^a(x)}{\delta\theta^b(y)}\right) = M^{ab}(x)\,\delta(x-y),$$

$$M^{VV'}(x) = \delta^{VV'}(\Box_x+\xi_V M_V^2) + \text{terms linear in vector and scalar fields}$$

Functional determinant can be written as path integral over
Grassmann-valued auxiliary fields $u^a(x), \bar{u}^a(x)$: (Faddeev–Popov ghost fields)

$$\det\left(\frac{\delta F^a}{\delta\theta^b}\right) \propto \int \mathcal{D}u^a \int \mathcal{D}\bar{u}^a\; \exp\left\{\mathrm{i}\int \mathrm{d}x\,\mathcal{L}_{\mathrm{FP}}\right\}$$

$$\mathcal{L}_{\mathrm{FP}}(x) = -\bar{u}^a(x)M^{ab}(x)u^b(x) \;=\; -\bar{u}^V(\Box+\xi_V M_V^2)u^V + \ldots$$

$\hookrightarrow$ ghost propagators: u^V  $\bar{u}^V$ $\qquad \dfrac{\mathrm{i}}{k^2-\xi_V M_V^2}$

Features of the Faddeev–Popov ghost fields:

- ghosts do not correspond to physical states
  (ghost propagators have poles at unphysical mass values $\xi_V M_V^2$)
  $\hookrightarrow$ appear only inside loops in diagrams for physical processes
- ghost fields have spin 0, but are anti-commuting
  (would violate spin-statistics theorem as physical states)
  $\hookrightarrow$ signs as for fermions in Feynman rules
- ghost fields couple to gauge and scalar fields (not to fermions):

5 Electroweak phenomenology

5.1 Brief overview

Features of the electroweak Standard Model

- Higgs boson not yet found, particle content verified otherwise
- No really significant contradictions of GSW model with experiment
- Input parameters:

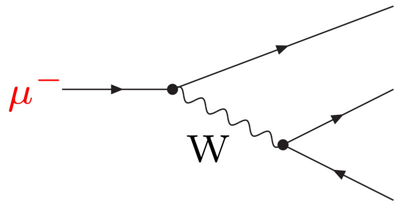
$$\alpha = \frac{e^2}{4\pi} \approx 1/137, \;\; M_\mathrm{W} \approx 80\,\mathrm{GeV}, \;\; M_\mathrm{Z} \approx 91\,\mathrm{GeV}, \;\; M_\mathrm{H} \gtrsim 100\,\mathrm{GeV}, \;\; m_f, \;\; V$$

- GSW model = consistent quantum field theory
  - ◇ matrix elements respect unitarity
  - ◇ renormalizability

$\Rightarrow$ evaluation of higher perturbative orders possible
(and phenomenologically necessary !)

Important electroweak experiments

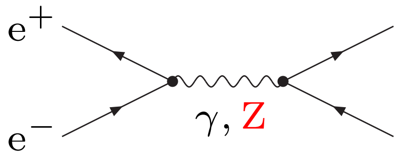
- Muon decay: $\mu^- \to \nu_\mu e^- \bar{\nu}_e$



determination of the Fermi constant

$$G_\mu = \frac{\pi \alpha M_Z^2}{\sqrt{2} M_W^2 (M_Z^2 - M_W^2)} + \ldots$$

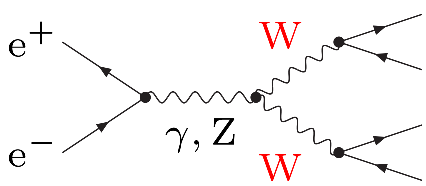
- Z production (LEP1/SLC): $e^+e^- \to Z \to f\bar{f}$

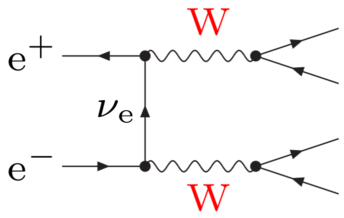


various precision measurements at the Z resonance: $M_Z, \Gamma_Z, \sigma_{had}, A_{FB}, A_{LR}$, etc.

$\Rightarrow$ good knowledge of the $Zf\bar{f}$ sector

- W-pair production (LEP2/ILC): $e^+e^- \to WW \to 4f(+\gamma)$





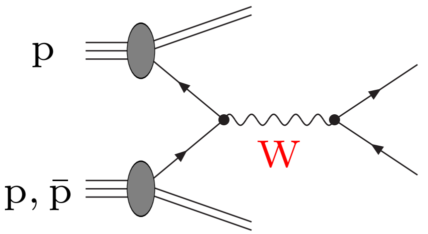
– measurement of M_W

– γWW/ZWW couplings

– quartic couplings: $\gamma\gamma WW$, γZWW

Important electroweak experiments (continued)

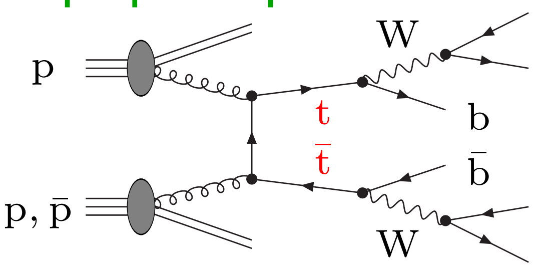
- W production (Tevatron/LHC): $\mathrm{pp}, \mathrm{p\bar{p}} \to \mathrm{W} \to l\nu_l(+\gamma)$



– measurement of M_W

– bounds on $\gamma\mathrm{WW}$ coupling

- top-quark production (Tevatron/LHC): $\mathrm{pp}, \mathrm{p\bar{p}} \to \mathrm{t\bar{t}} \to 6f$



– measurement of m_t

Theoretical predictions

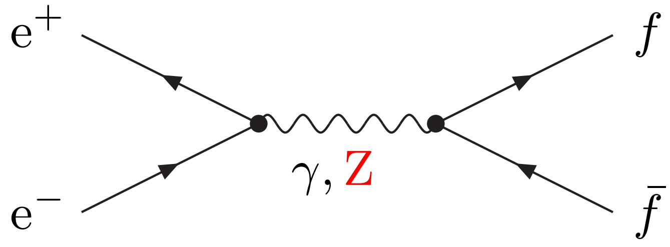
parametrized by $\alpha(M_\mathrm{Z})$, M_W, M_Z, m_t, m_f, $\alpha_\mathrm{s}(M_\mathrm{Z})$ and M_H

$\hookrightarrow$ global fit of SM to data yields bounds on M_H

But: high precision necessary,
since M_H sensitivity weak $\sim \frac{\alpha}{\pi}\log(M_\mathrm{H}/M_\mathrm{W})$

5.2 Z-boson physics at LEP1 and SLC

Precision study of the Z line shape

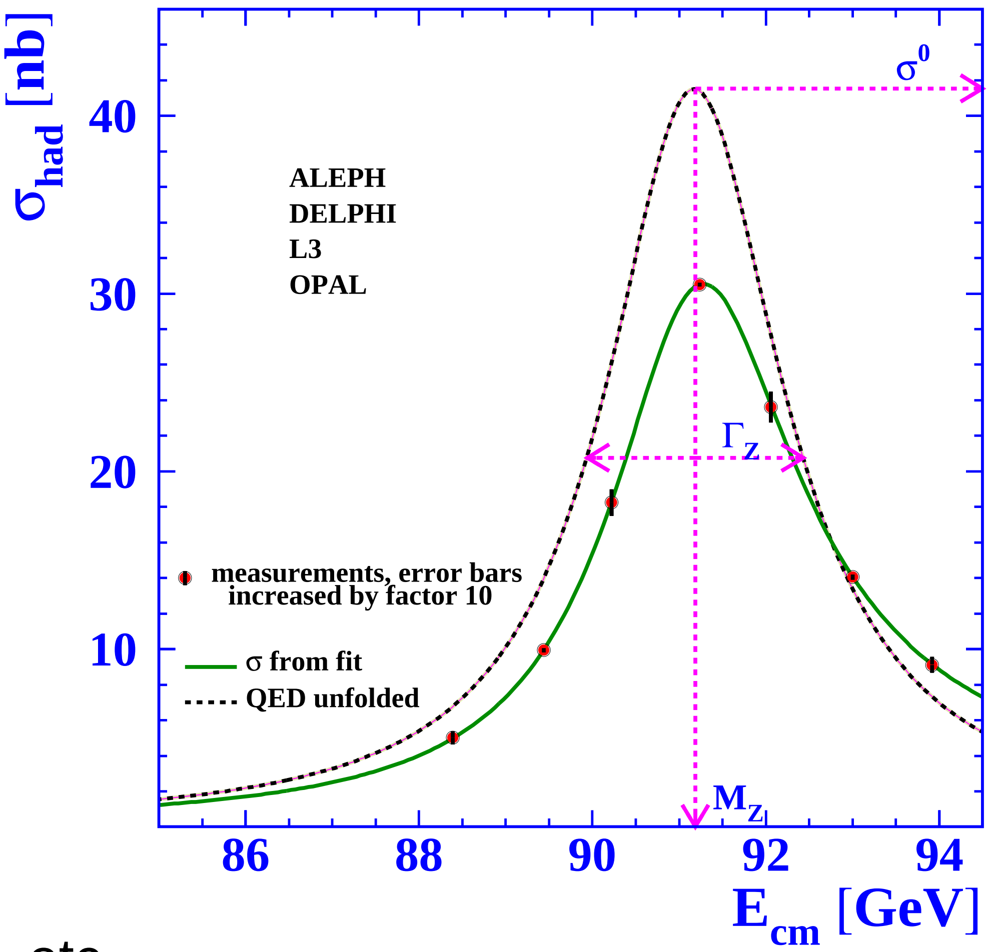


Unfolded resonance:

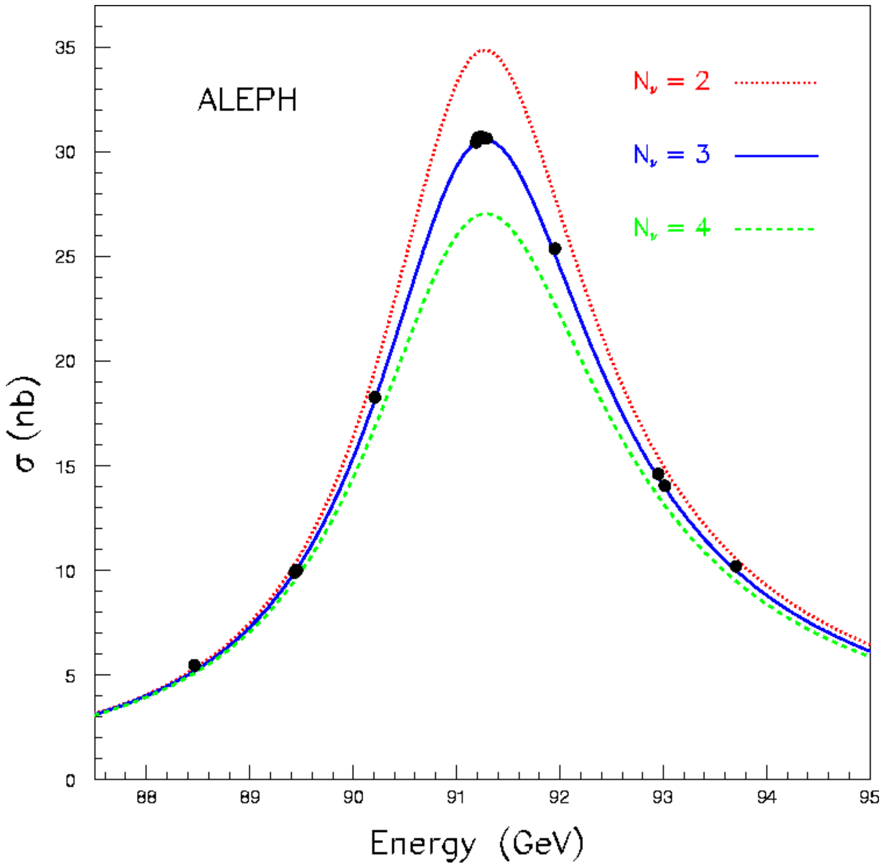
$$\sigma_{\mathrm{res}}(s) = \sigma^0 \frac{s\,\Gamma_Z^2}{\left| s - M_Z^2 + \mathrm{i} M_Z \Gamma_Z \frac{s}{M_Z^2} \right|^2}$$

Resonance observables:

- Z mass and width: M_Z, Γ_Z
- peak cross section: σ^0_{had}
- various asymmetries: $A_{\mathrm{FB}}, A_{\mathrm{LR}}$, etc.
- ratios of decay widths: $R_l = \frac{\Gamma_{\mathrm{had}}}{\Gamma_l}$, etc.



Number of light neutrinos



$$\Gamma_{\mathrm{Z}} = \Gamma_{\mathrm{had}} + \Gamma_{\mathrm{e}} + \Gamma_{\mu} + \Gamma_{\tau} + \Gamma_{\mathrm{inv}}$$

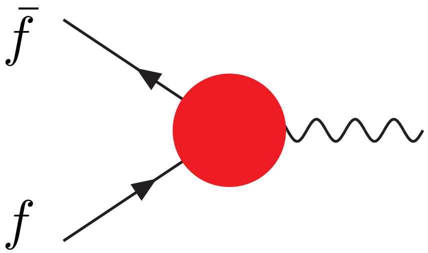
- Γ_{Z} measured from Z line shape
- Γ_{had} and $\Gamma_{l=\mathrm{e},\mu,\tau}$ from

$$R_l = \frac{\Gamma_{\mathrm{had}}}{\Gamma_l} \quad \text{and} \quad \sigma^0_{\mathrm{had}} = \frac{12\pi}{M_{\mathrm{Z}}^2} \frac{\Gamma_{\mathrm{e}}\Gamma_{\mathrm{had}}}{\Gamma_{\mathrm{Z}}^2}$$

Fit of Γ_{Z}, R_l, and σ^0_{had} yields invisible Z-decay width: $\Gamma_{\mathrm{inv}} = N_\nu \, \Gamma^{\mathrm{theory}}_{\mathrm{Z}\to\nu\bar{\nu}}$

$\hookrightarrow \quad N_\nu = 2.9840 \pm 0.0082$

Effective Z-boson–fermion couplings



$$Z_\mu \quad = \quad \mathrm{i}e\gamma_\mu(g_{Vf} - g_{Af}\gamma_5)$$

Leptonic couplings from LEP1 asymmetry measurements, e.g.:

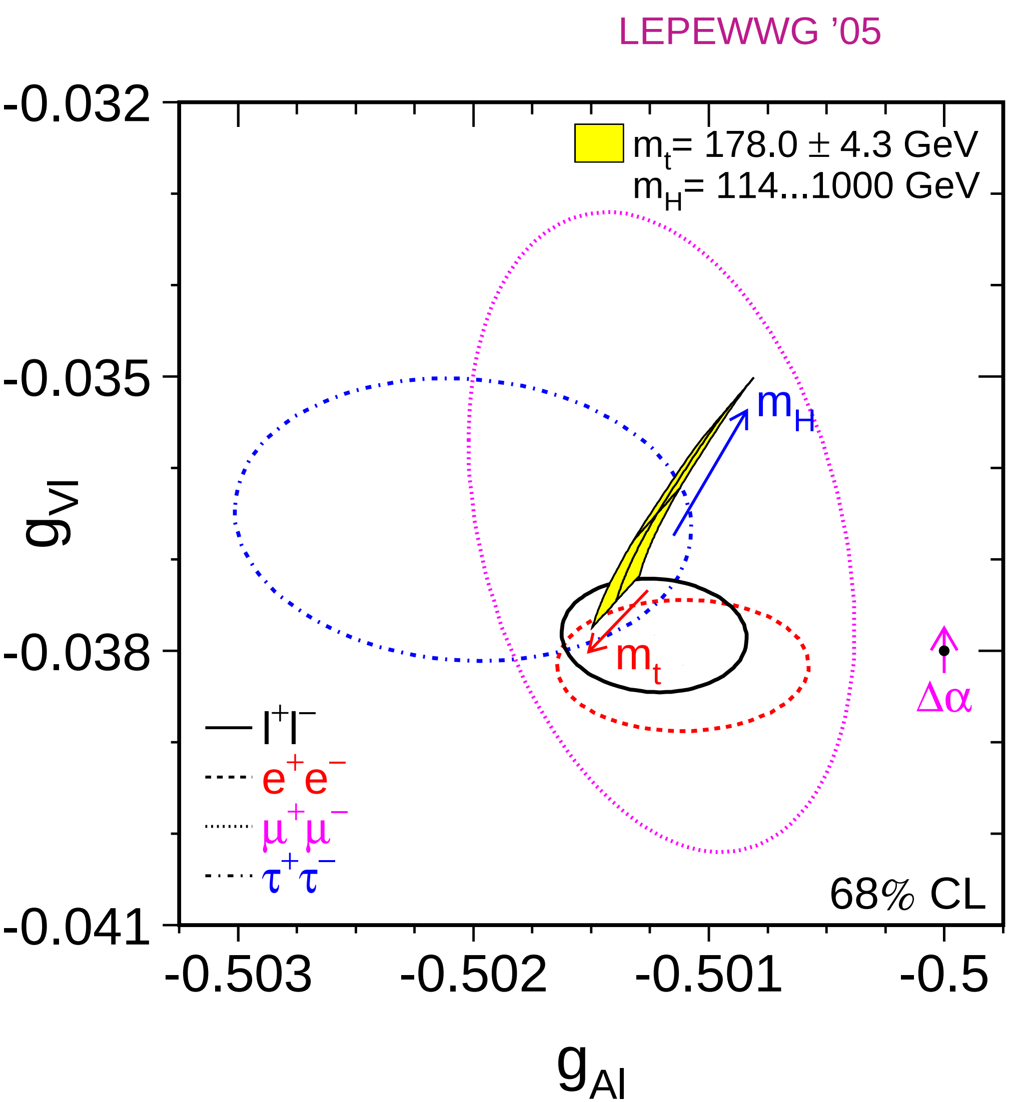
$$A_{\mathrm{FB}}^{0,f} = \frac{\sigma^0_{f,\mathrm{F}} - \sigma^0_{f,\mathrm{B}}}{\sigma^0_{f,\mathrm{F}} + \sigma^0_{f,\mathrm{B}}} = \frac{3}{4}\mathcal{A}_\mathrm{e}\mathcal{A}_f$$

$(\mathrm{F/B} =$ For/Backward hemisphere)

with $\mathcal{A}_f = \dfrac{2g_{Vf}g_{Af}}{g_{Vf}^2 + g_{Af}^2}$

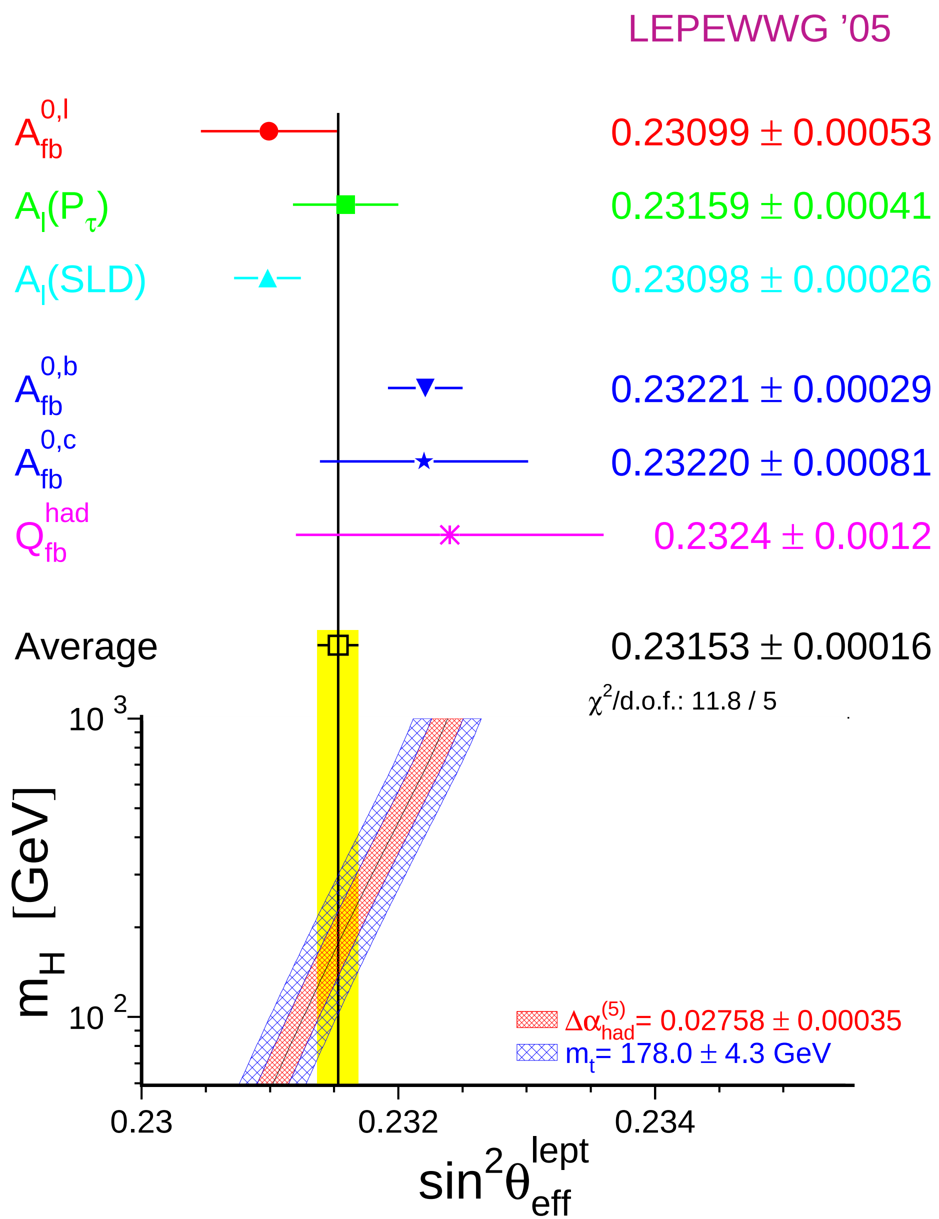
Good agreement with SM

- lepton universality confirmed
- constraints on m_t and M_H



Translation of effective couplings into effective weak mixing angle

$$\sin^2\theta_{\rm eff}^{\rm lept} = \frac{1}{4}\left(1 - \frac{{\rm Re}\{g_{Vl}\}}{{\rm Re}\{g_{Al}\}}\right)$$



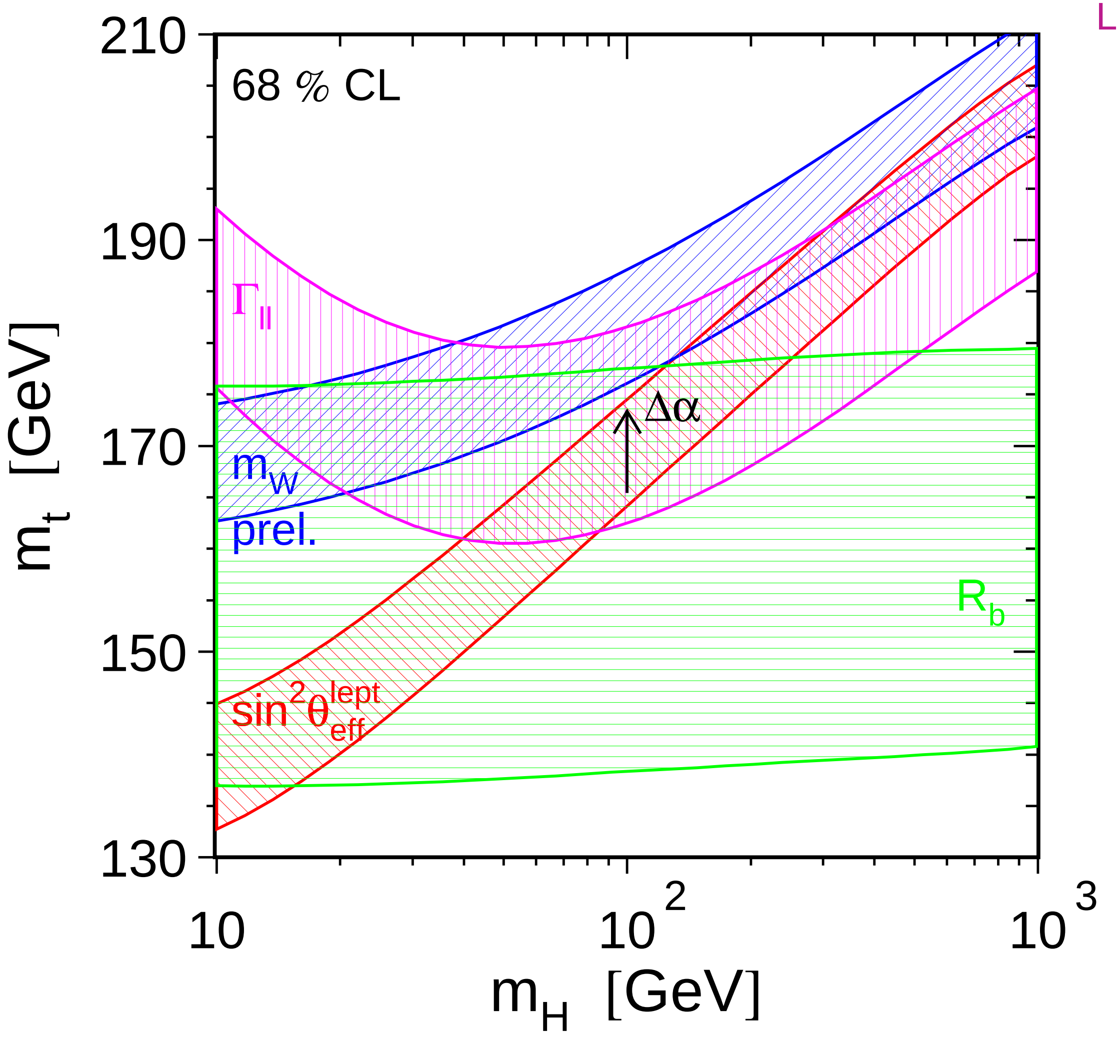
Important features:

- high sensitivity to $M_{\rm H}$
- combination of very different observables
- $\sim 3\sigma$ difference between $A_{\rm FB}^{0,b}$(LEP) and $A_{\rm LR}^{0,l}$(SLD)

  with the initial-state pol. asymmetry

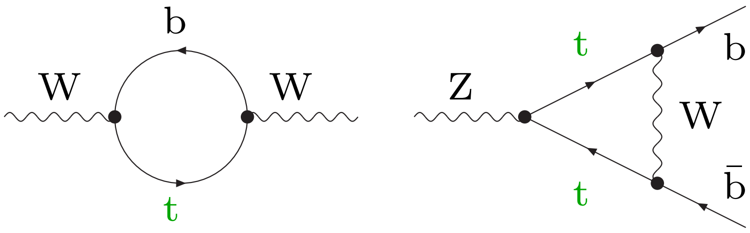
$$A_{\rm LR}^{0,l} = \frac{\sigma_{\rm L}^0 - \sigma_{\rm R}^0}{\sigma_{\rm L}^0 + \sigma_{\rm R}^0}\,\frac{1}{\langle|\mathcal{P}_{\rm e}|\rangle}$$

Observables most sensitive to m_t and M_H

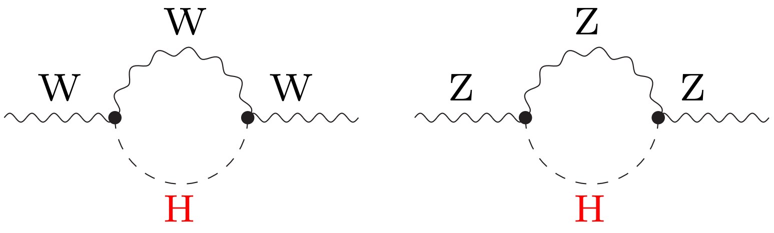


LEPEWWG '05

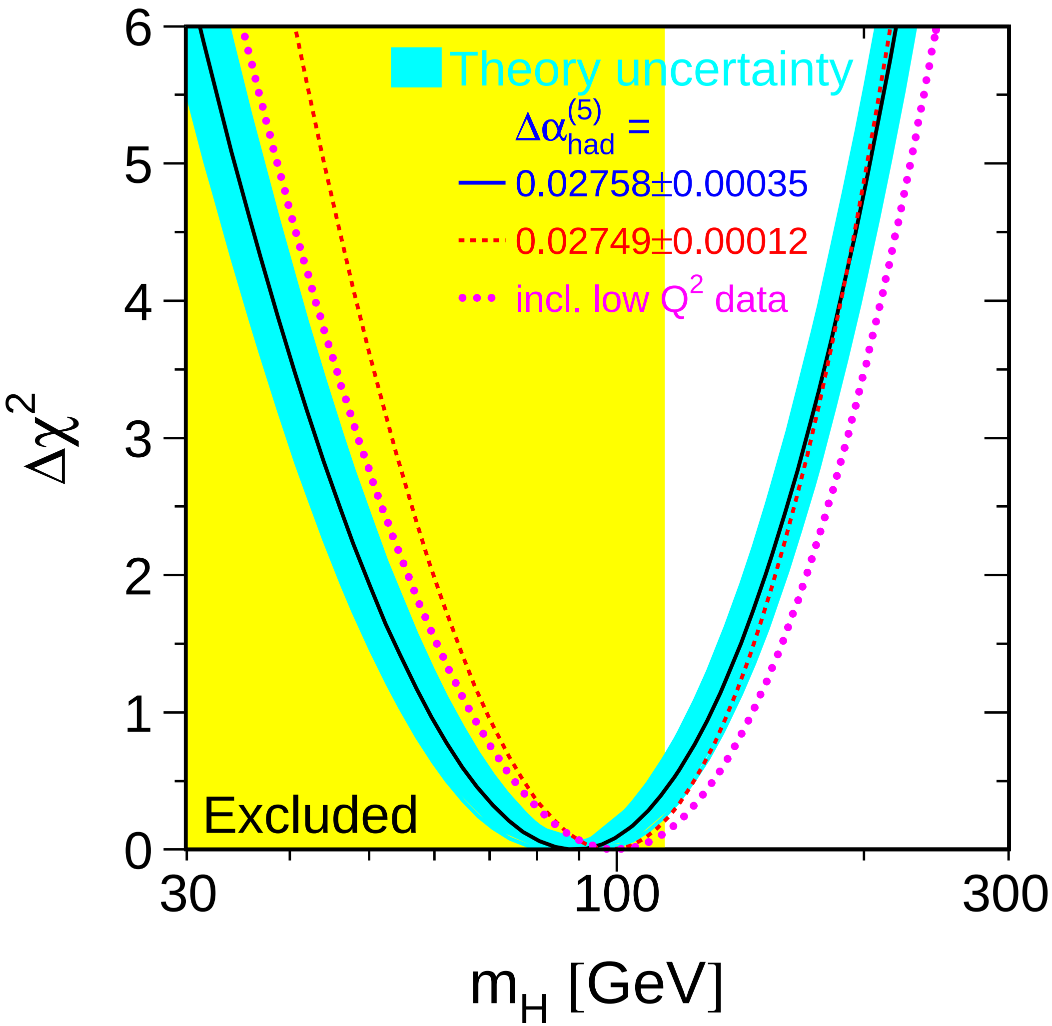
main sensitivity to m_t via



main sensitivity to M_H via



Bounds on M_{H} (95% C.L.)

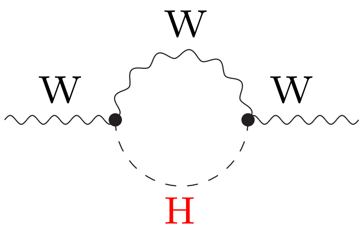


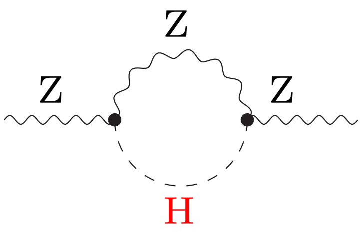
– $M_{\mathrm{H}} > 114.4\,\mathrm{GeV}$ (LEPHIGGS '02)

$\mathrm{e}^+\mathrm{e}^- \not\to \mathrm{ZH}$ at LEP2

– $M_{\mathrm{H}} < 175\,\mathrm{GeV}$ (LEPEWWG '06)

fit to precision data,
i.e. via quantum corrections





Sensitivity via "high-precision observables": m_{t}, M_{W}, $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$, etc.

$\hookrightarrow$ precise measurement is possible at future ILC !

$\Rightarrow$ stronger bounds on M_{H}

5.3 W-boson physics at LEP2

W-pair production $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f(+\gamma)$

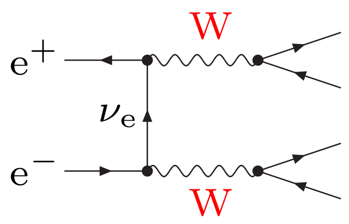


diagram dominates near W-pair threshold

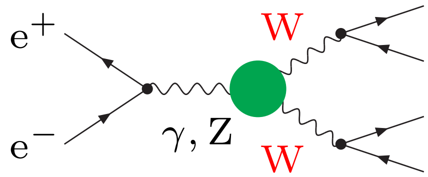


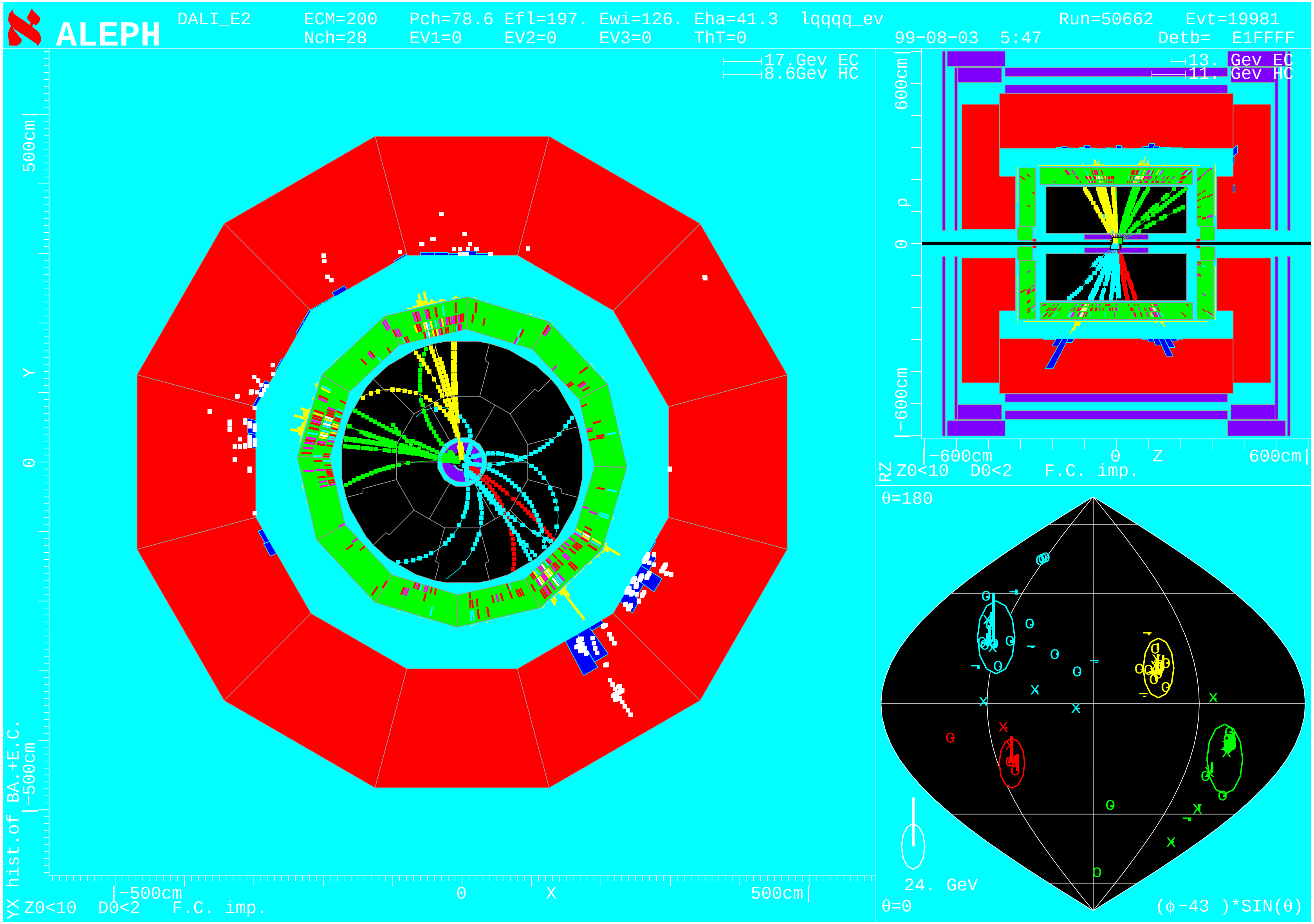
diagram contains $\gamma\mathrm{WW}$/ZWW couplings

Physics issues:

- test of non-abelian structure of triple gauge-boson couplings (TGCs)
  $\hookrightarrow$ constraint on non-standard $\gamma\mathrm{WW}/\mathrm{ZWW}$ couplings
- precision measurement of W-pair cross section
- precision measurement of W mass M_{W}
- first bounds on non-standard quartic gauge-boson couplings (QGCs)

$\Rightarrow$ Theoretical requirement:
precise understanding of $2 \to 4$ process (0.5% level for cross section)

A typical 4-jet event observed at ALEPH



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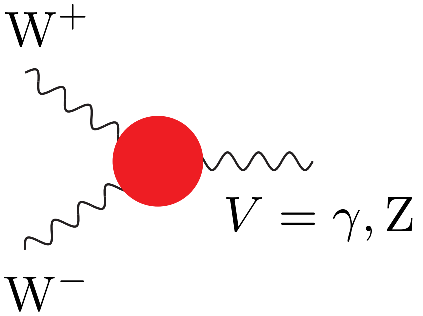
(Non-)standard TGCs

Gaemers, Gounaris '79; Hagiwara, Hikasa, Peccei, Zeppenfeld '87; Bilenky, Kneur, Renard, Schildknecht '93; etc.

General parametrization (C- and P-conserving):



$$\mathcal{L}_{VWW} = -\mathrm{i}eg_{VWW}\Big\{ g_1^{\mathrm{V}}\left(W^+_{\mu\nu}W^{-,\mu}V^\nu - W^{-,\mu\nu}W^+_\mu V_\nu\right) + \kappa_{\mathrm{V}} W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_{\mathrm{V}}}{M_{\mathrm{W}}^2} W^+_{\rho\mu} W^{-,\mu}_{\nu} V^{\nu\rho} \Big\}$$

Meaning for static W^+ bosons:

$$Q_{\mathrm{W}} = eg_1^\gamma = \text{electric charge } (= e \text{ by charge conservation})$$

$$\mu_{\mathrm{W}} = \frac{e}{2M_{\mathrm{W}}}\left(g_1^\gamma + \kappa_\gamma + \lambda_\gamma\right) = \text{magnetic dipole moment}$$

$$q_{\mathrm{W}} = -\frac{e}{M_{\mathrm{W}}^2}\left(\kappa_\gamma - \lambda_\gamma\right) = \text{electric quadrupole moment}$$

Standard Model values:

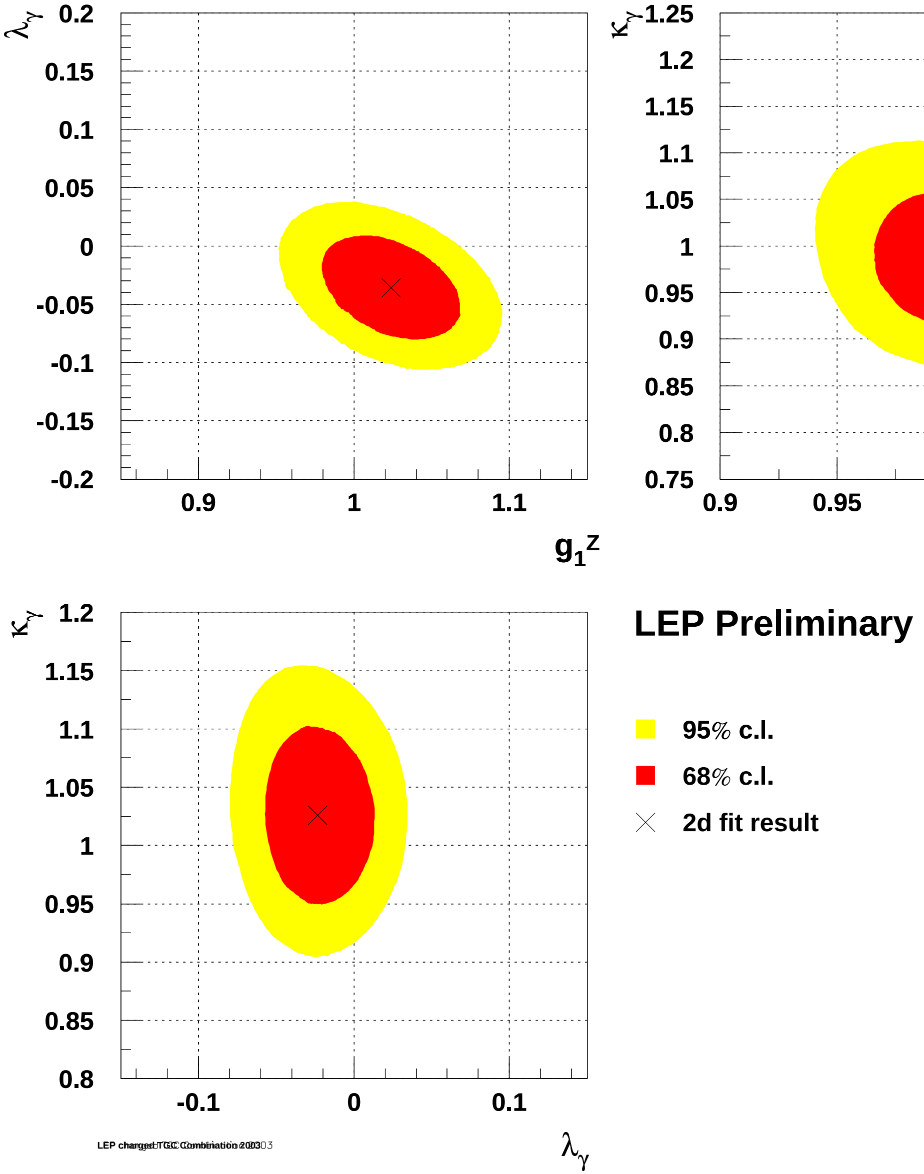
$$g_1^{\mathrm{V}} = \kappa_{\mathrm{V}} = 1, \qquad \lambda_{\mathrm{V}} = 0$$

Restriction to SU(2)×U(1)-symmetric dim-6 operators:

$$\kappa_{\mathrm{Z}} = g_1^{\mathrm{Z}} - (\kappa_\gamma - 1)\tan^2\theta_{\mathrm{W}}, \qquad \lambda_{\mathrm{Z}} = \lambda_\gamma$$

LEP2 constraints on charged TGCs

LEPEWWG '04



$$\Delta g_1^Z = -0.009^{+0.022}_{-0.021}$$

$$\Delta\kappa_\gamma = -0.016^{+0.042}_{-0.047}$$

$$\lambda_\gamma = -0.016^{+0.021}_{-0.023}$$

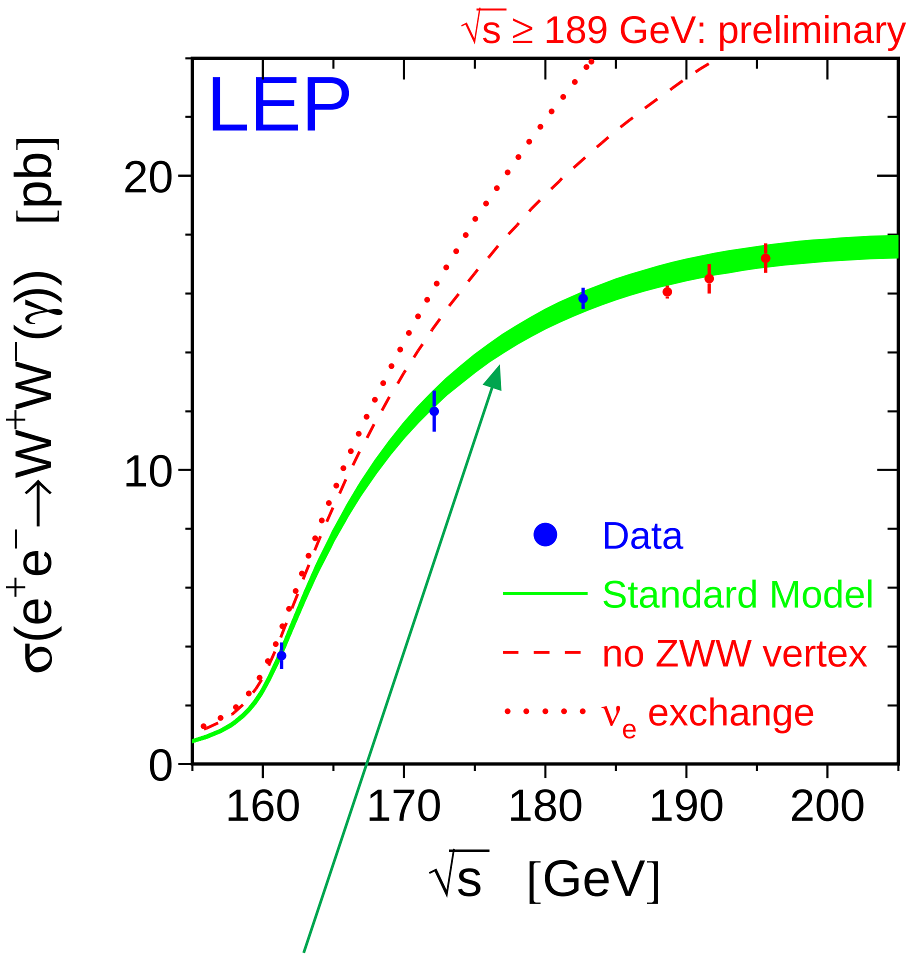
Standard Model values verified at the level of 2–4%

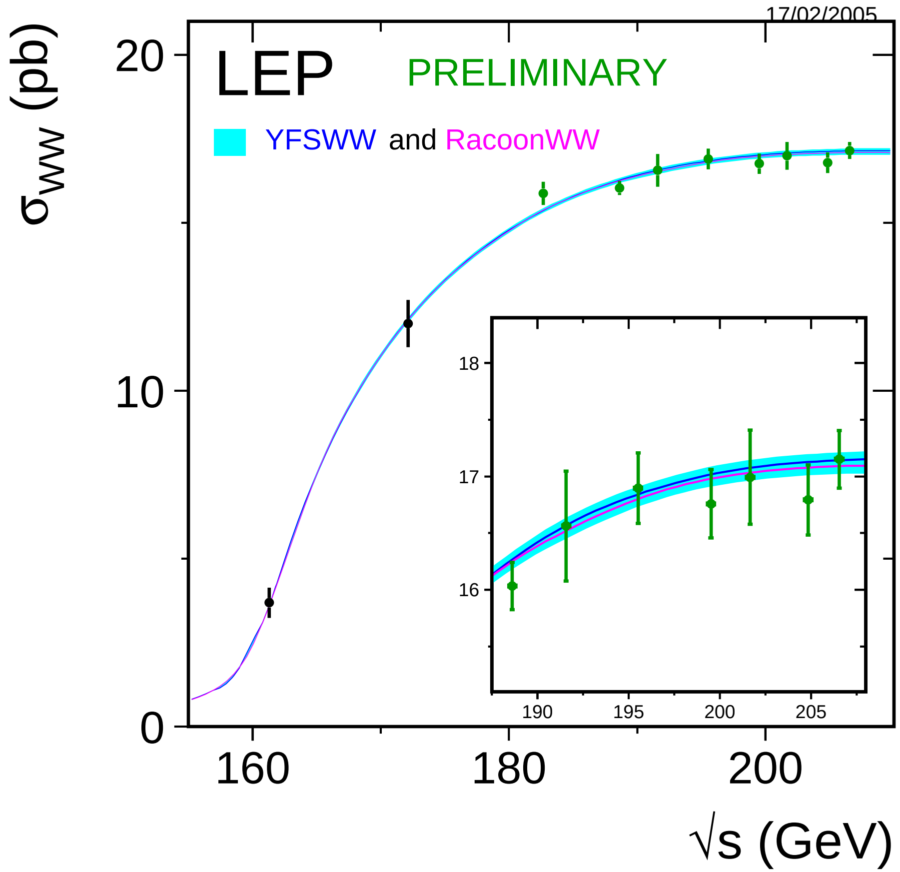
Note: TGC bounds $\sim \mathcal{O}$(EW corrections)

Total WW cross section at LEP2

Status of 1999: (LEPEWWG '99)

Final (?) result: (LEPEWWG '05)





GENTLE (Bardin et al.)

only universal EW corrections

$\hookrightarrow$ theoretical uncertainty $\sim \pm 2\%$

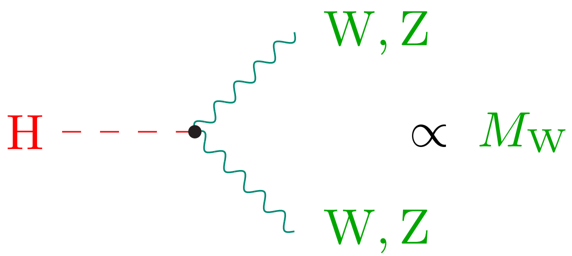
YFSWW (Jadach et al.) / RacoonWW (Denner et al.)

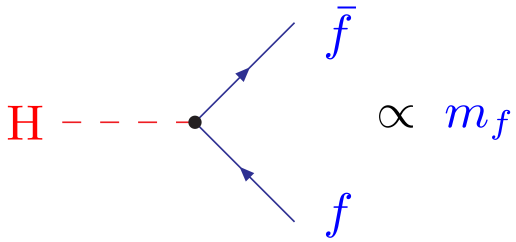
non-universal corrections included

$\hookrightarrow$ th. uncertainty $\sim \pm 0.5\%$ for $\sqrt{s} > 170\,\mathrm{GeV}$

5.4 Higgs search at present and future colliders

Higgs bosons couple proportional to particle masses:

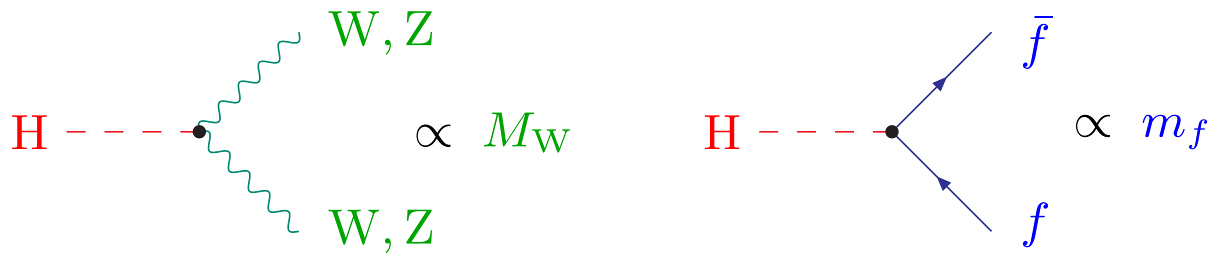




⇒ Higgs production mainly via coupling to W/Z bosons or top quarks

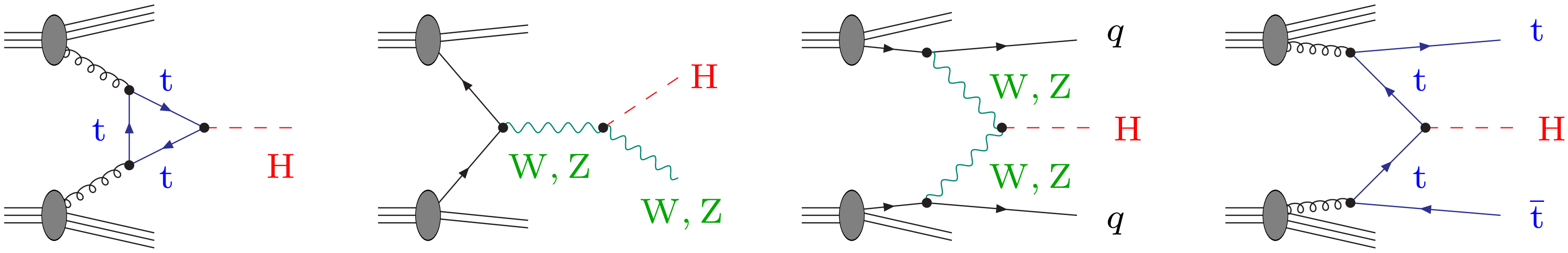
5.4 Higgs search at present and future colliders

Higgs bosons couple proportional to particle masses:



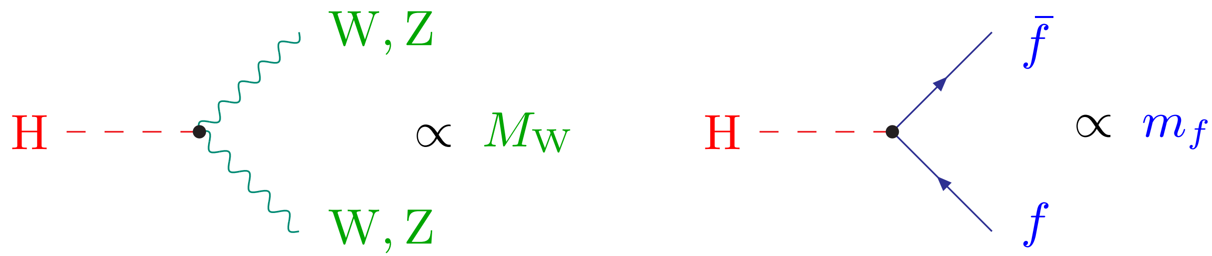
⇒ Higgs production mainly via coupling to W/Z bosons or top quarks

Processes at hadron colliders ($p\bar{p}/pp$):



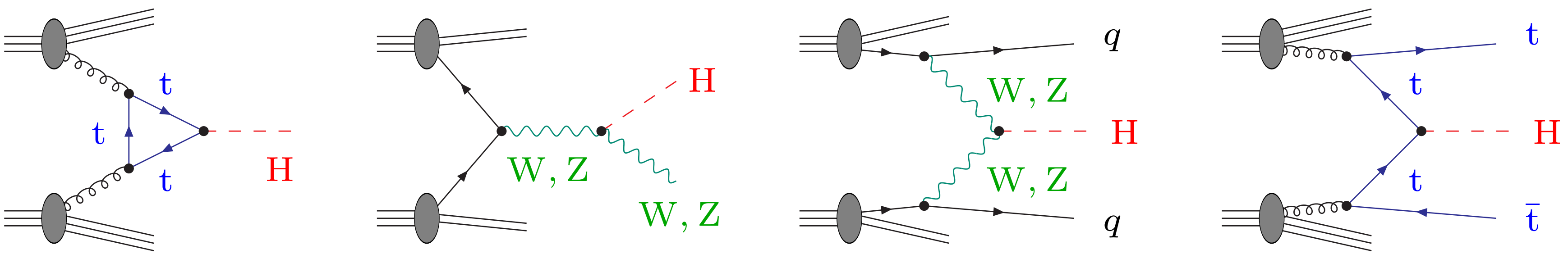
5.4 Higgs search at present and future colliders

Higgs bosons couple proportional to particle masses:

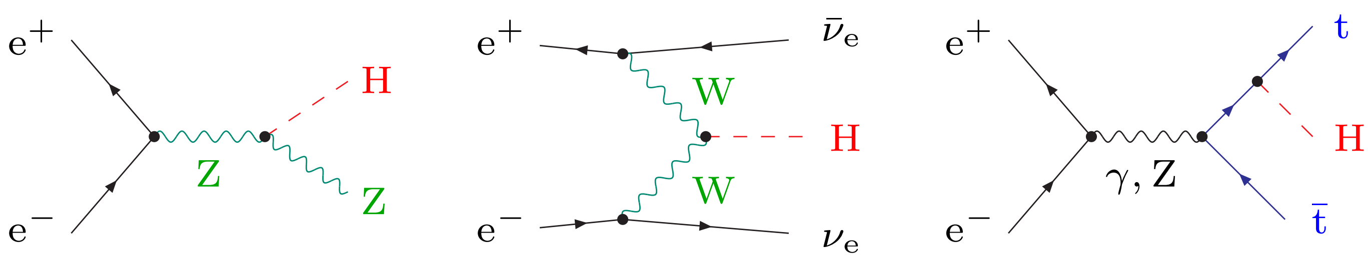


$\Rightarrow$ Higgs production mainly via coupling to W/Z bosons or top quarks

Processes at hadron colliders ($\mathrm{p\bar{p}/pp}$):

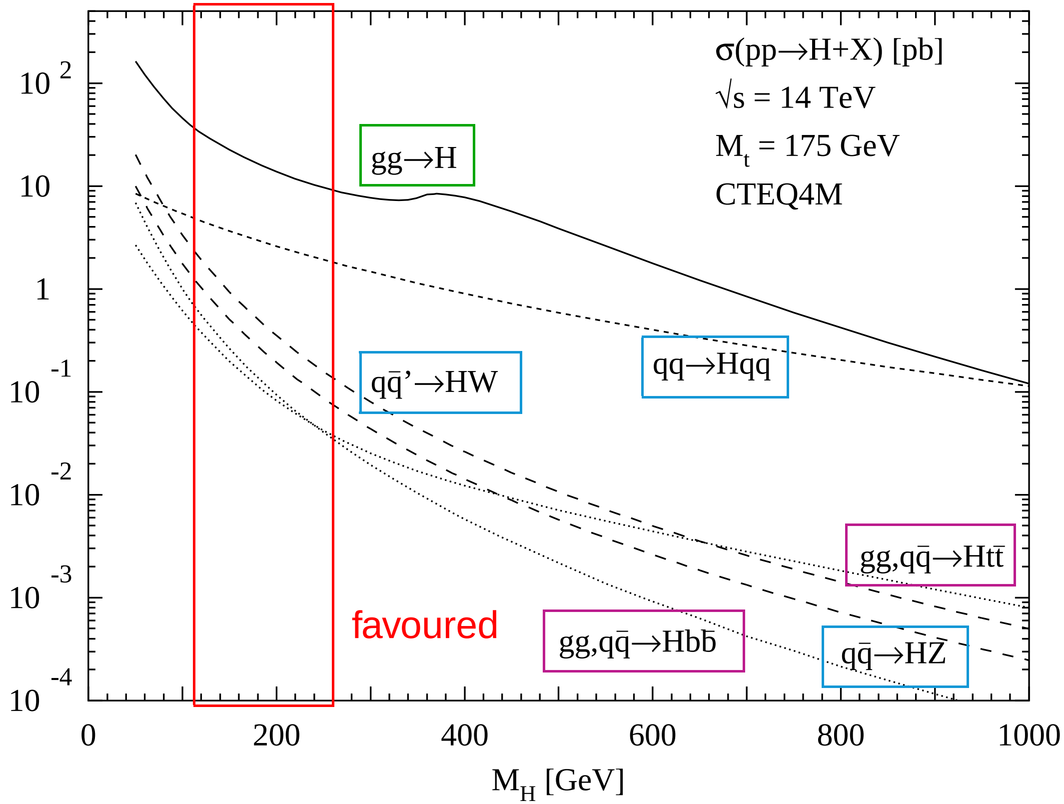


Processes at $\mathrm{e^+e^-}$ colliders:

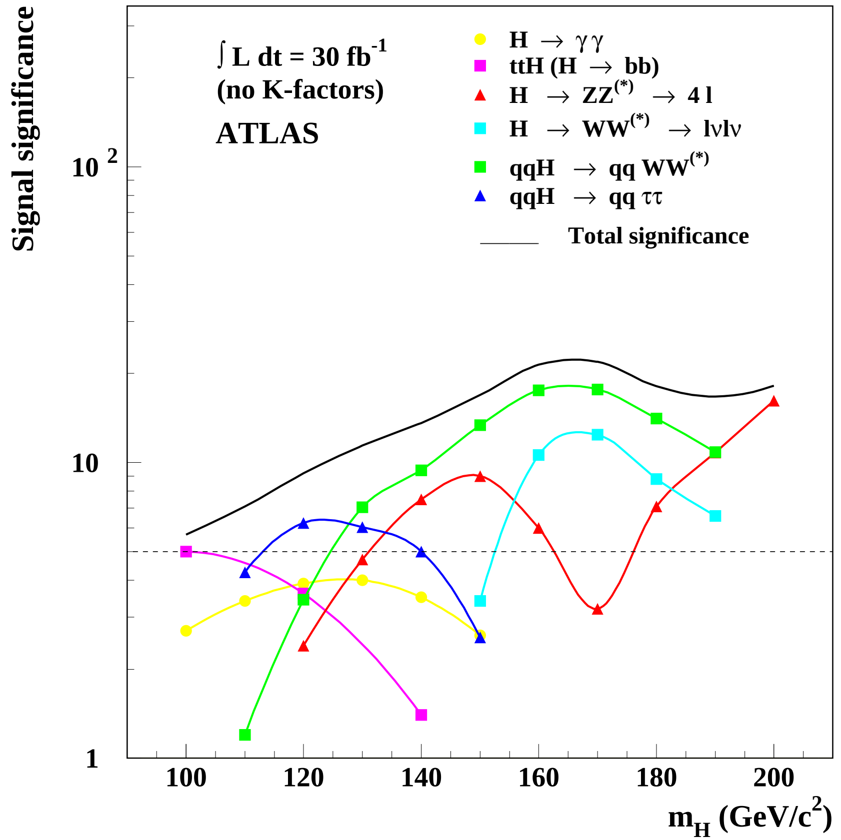


Cross sections and significance of the Higgs signal at the LHC

Spira et al. '98



ATLAS '03



Physics goals:

– Higgs discovery, M_{H} measurement, decay analyses

– ratios of couplings to W/Z bosons and quarks

– extended Higgs sectors (MSSM: $\mathrm{h}, \mathrm{H}, \mathrm{A}, \mathrm{H}^{\pm}$)

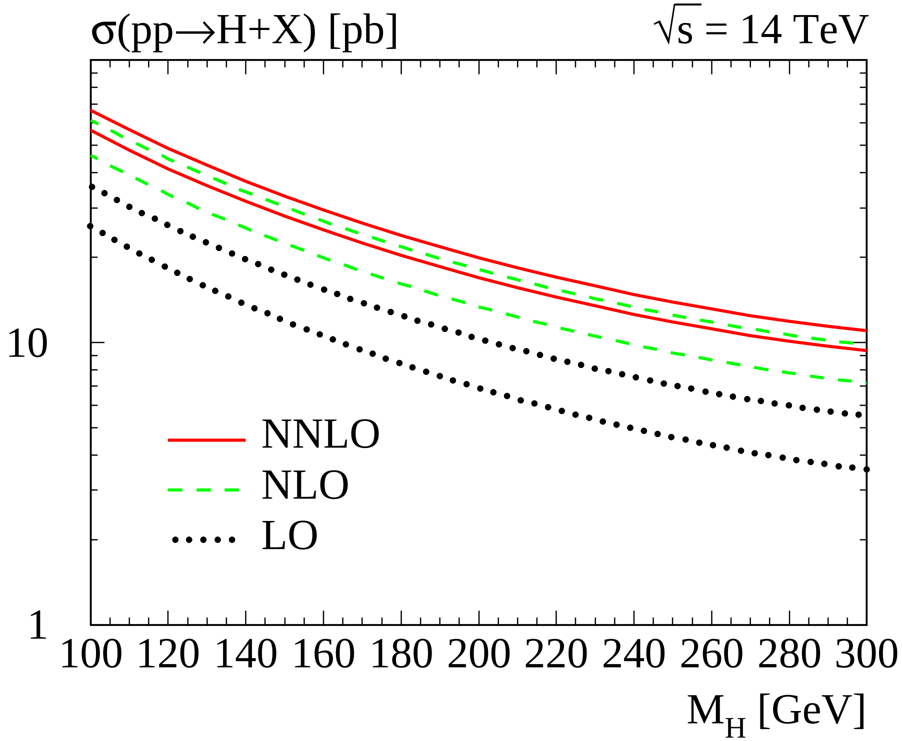
The issue of QCD radiative corrections — reduction of scale uncertainties

Two examples:

$\mathrm{pp} \to \mathrm{H} + X$ in NNLO:

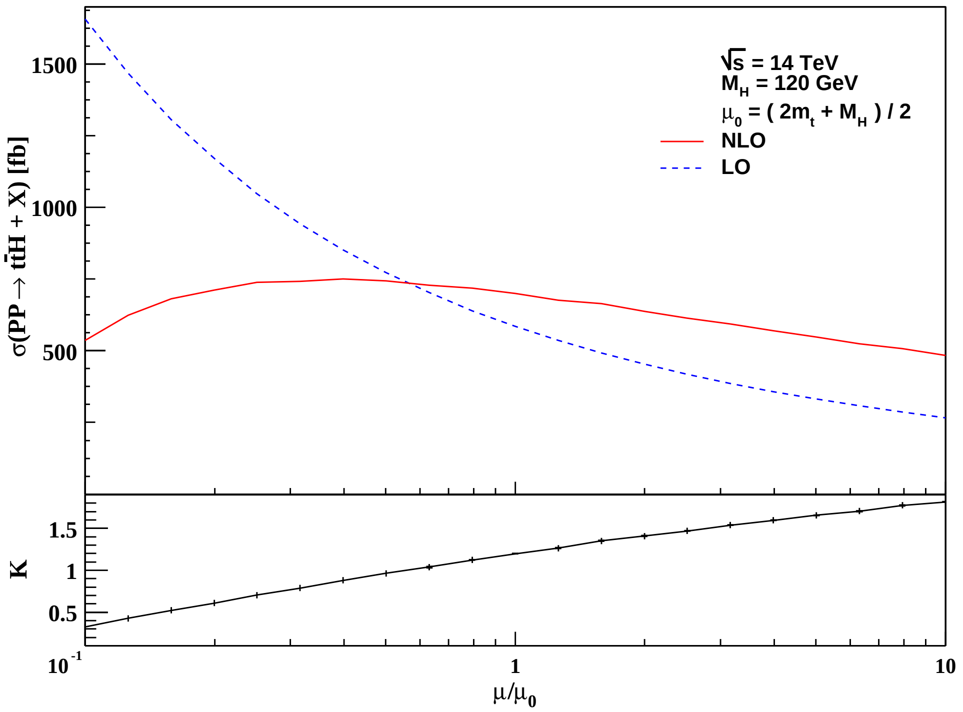
$(M_\mathrm{H}/2 < \mu_\mathrm{ren} = \mu_\mathrm{fact} < 2M_\mathrm{H})$

Harlander, Kilgore '02



$\mathrm{pp} \to \mathrm{t\bar{t}H} + X$ in NLO:

Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '01



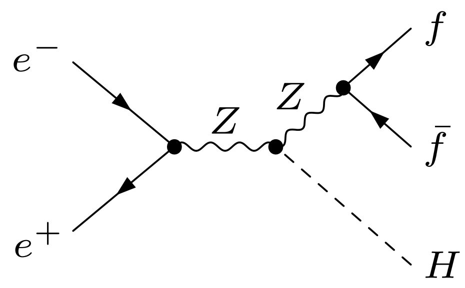
$\Rightarrow$ Reduction of scale uncertainties in LO $\to$ NLO $\to$ NNLO

$$\frac{\Delta\sigma_\mathrm{NNLO}}{\sigma_\mathrm{NNLO}} \sim 15\%$$

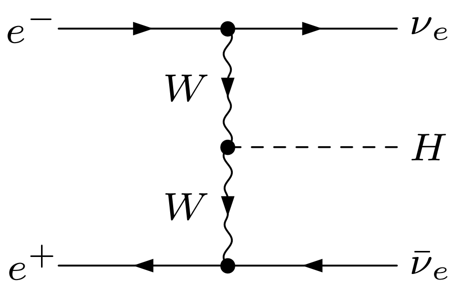
$$\frac{\Delta\sigma_\mathrm{NLO}}{\sigma_\mathrm{NLO}} \sim 20\%$$

Higgs-boson production in e^+e^- annihilation

ZH production ("‘Higgs-strahlung"’)



WW fusion

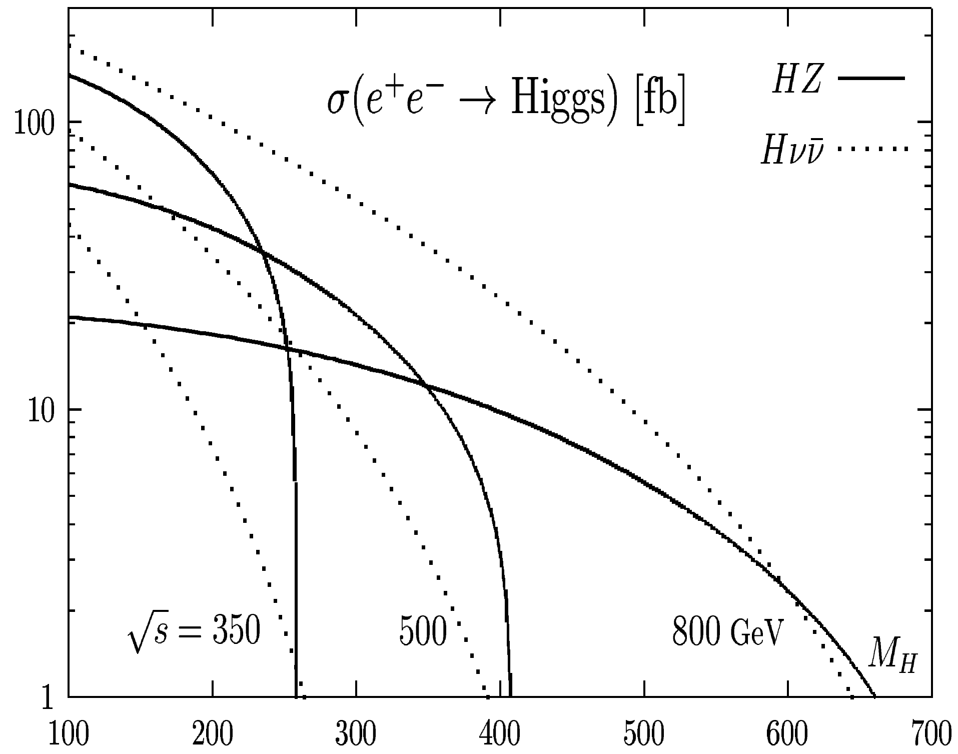


WW fusion dominates at high energies ($\sqrt{s} \gg M_{\rm H}$):

$$\sigma_{\rm ZH} \sim \text{const} / s$$

$$\sigma_{\rm WW} \sim \text{const} \times \ln(s/M_{\rm W}^2)$$

TESLA-TDR ’01



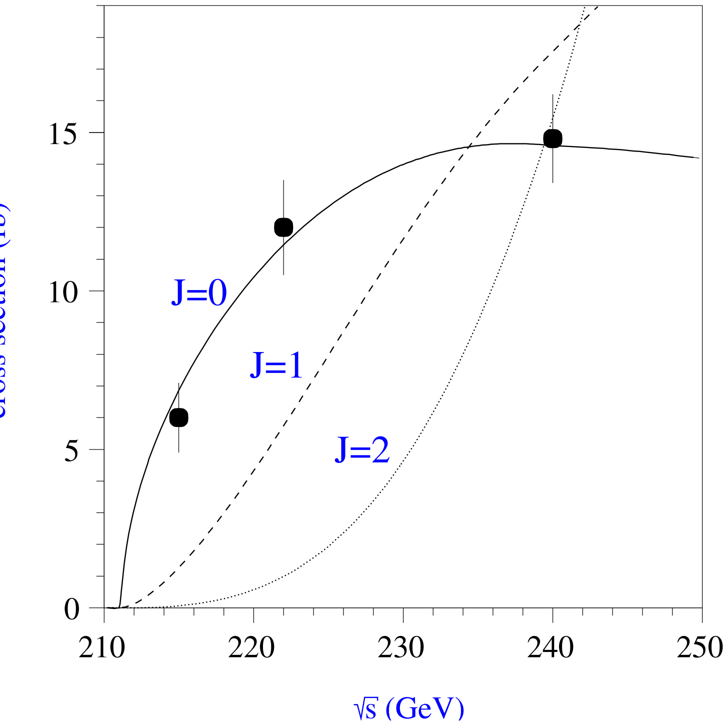
Physics issues:

- Higgs decay width
- quantum numbers (spin, P, CP)
- measurement of couplings
- extended Higgs sectors ?

Examples for Higgs studies at the ILC:

A qualitative study – spin:

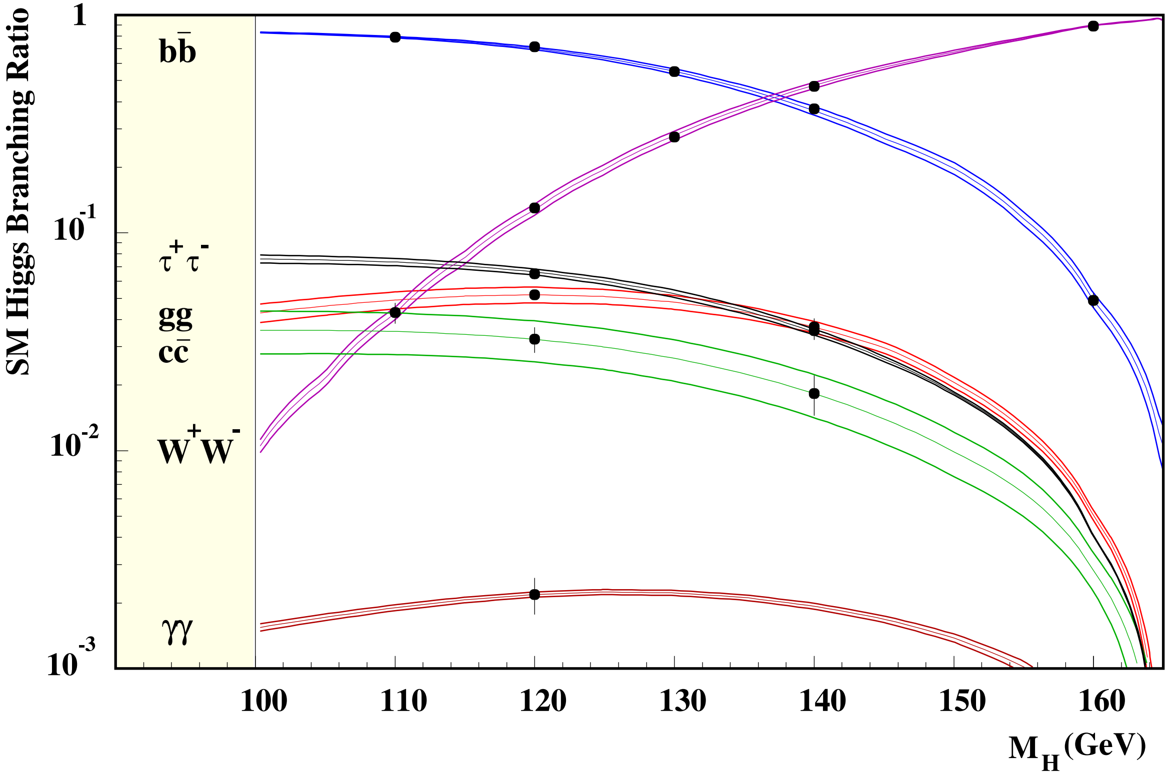
Miller et al. ’01; TESLA-TDR ’01



$\hookrightarrow$ spin J from rise of cross section

Precision BR measurements:

Battaglia ’00; TESLA-TDR ’01

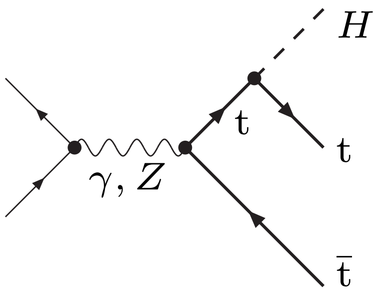


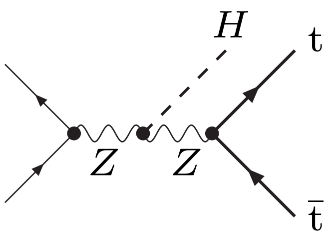
(assumed data versus theory error bands)

$\hookrightarrow$ precision test of Higgs mechanism, demarcation of SUSY Higgs bosons

Channel for analyzing the top-Yukawa coupling:

Associated Higgs production: $e^+e^- \to t\bar{t}H$



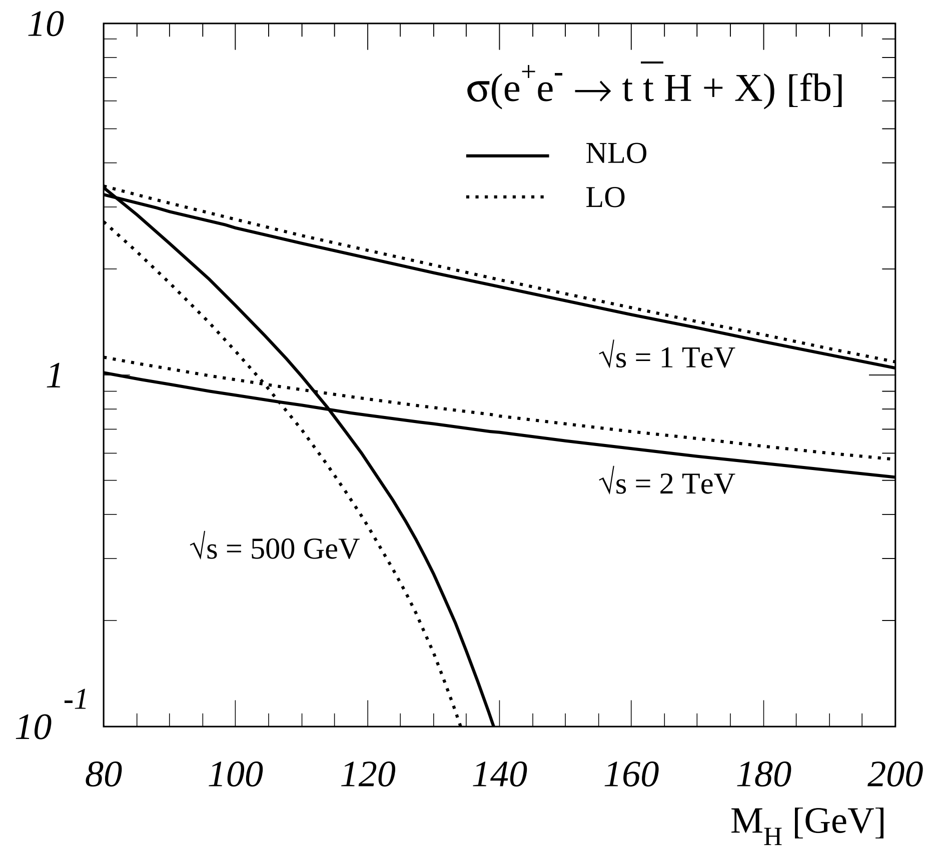


expected accuracy:

$\Delta g_{\mathrm{ttH}}/g_{\mathrm{ttH}} \sim 5\%$

QCD-corrected cross section:

Dittmaier, Krämer, Liao, Spira, Zerwas '98



5.4 The role of precision at LHC and ILC

LHC: the discovery machine (Higgs & EWSB, SUSY, etc.?)

- QCD corrections (at least NLO) are substantial parts of predictions

  typical LO uncertainties $\sim$ several $10\%-100\%$

  corrections needed for signals and many background processes

- EW corrections also important for many observables

  (precision physics, searches at high scales, particle reconstruction, etc.)

ILC: the high-precision machine (precision $\to$ window to higher energy)

- old and new physics with high accuracy (typically $\delta\sigma/\sigma \lesssim 1\%$)

  $\hookrightarrow$ QCD and EW corrections required

- the ultimate precision at GigaZ/MegaW:

  precision increases by factor ~ 10 w.r.t. LEP/SLC

  EXP: $\Delta \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} \sim 0.00001, \qquad \Delta M_{\mathrm{W}} \sim 7\,\mathrm{MeV}$

  TH: go from a few 10^2 to a few 10^4 (more complicated) diagrams

$\Rightarrow$ Precision calculations mandatory for LHC and ILC !

Literature

- Textbooks:
  - Böhm/Denner/Joos: "Gauge Theories of the Strong and Electroweak Interaction"
  - Cheng/Li: "Gauge Theory of Elementary Particle Physics"
  - Ellis/Stirling/Webber: "QCD and Collider Physics"
  - Peskin/Schroeder: "An Introduction to Quantum Field Theory"
  - Weinberg: "The Quantum Theory of Fields, Vol. 2: Modern Applications"
- Some reviews on dedicated topics:
  - Z-boson production at LEP1/SLC:
    "Z Physics at LEP1", eds. G. Altarelli, R. Kleiss and C. Verzegnassi (CERN 89-08), Vol. 1;
    "Reports of the Working Group on Precision Calculations for the Z Resonance", eds. D. Bardin, W. Hollik and G. Passarino (CERN 95-03);
    D.Y. Bardin, M. Grünewald and G. Passarino, hep-ph/9902452.
  - W-pair production at LEP2:
    W. Beenakker *et al.*, in "Physics at LEP2", eds. G. Altarelli, T. Sjöstrand and F. Zwirner (CERN 96-01, Geneva, 1996), Vol. 1, p. 79 [hep-ph/9602351];
    M. W. Grünewald *et al.*, in "Reports of the Working Groups on Precision Calculations for LEP2 Physics", eds. S. Jadach, G. Passarino and R. Pittau (CERN 2000-009), p. 1 [hep-ph/0005309].
  - SM Higgs physics:
    A. Djouadi, hep-ph/0503172 and references therein
- Experimental results widely taken from:
  - LEPEWWG: http://lepewwg.web.cern.ch/LEPEWWG/
  - LEPHiggs: http://lephiggs.web.cern.ch/LEPHIGGS/www/Welcome.html