STANDARD MODEL PHENOMENOLOGY

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STANDARD MODEL PHENOMENOLOGY

- Review of the SM
- SM: where are we?
- Higgs search
- Radiative corrections
- Flavoured SM
- Open problems of the SM

1. Review of the SM

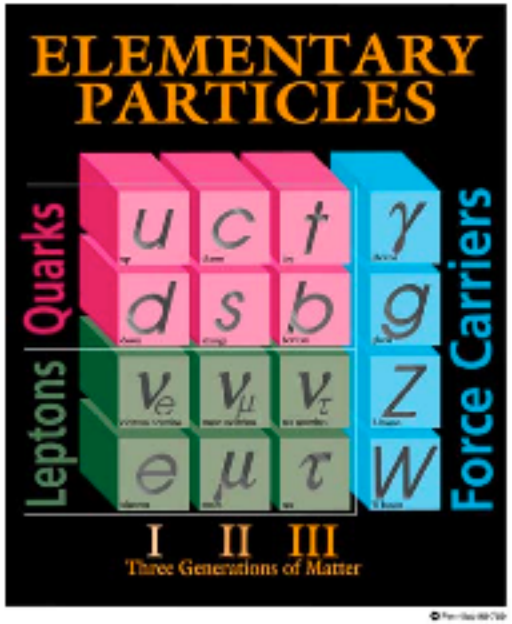
- Some good references:

- Michael Peskin, An Introduction to Quantum Field Theory

- Antonio Pich, The SM of Electroweak Interactions,
  http://arXiv.org/pdf/0705.4264

What we know:

- The photon and gluon appear to be massless
- The W and Z bosons are heavy
  - M_W = 80.404 ± 0.030 GeV
  - M_Z = 91.1875 ± 0.0021 GeV
- There are 6 quarks:
  - M_t = 172.5 ± 2.3 GeV
  - M_t >> all other fermion masses
- There are three neutrinos with tiny but non-zero masses



- The pattern of fermions appears to replicate itself 3 times. Why not more ?

Gauge invariance is guiding principle

- **SM** gauge group: $SU(3) \times SU(2)_L \times U(1)_Y \rightarrow SU(3) \times U(1)_{em}$
- Gauge bosons:
  - QCD [SU(3)]: G_μ^i, i=1,…,8
  - Electroweak:
    - $SU(2)_L$: W_μ^i, i=1,…,3
    - $U(1)_Y$: B_μ
- Gauge couplings: g_S, g, g'
- $SU(2)_L$ Higgs doublet, ϕ

Quantum electrodynamics: U(1) gauge theory

- Free Dirac fermion: $\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi$
- Phase invariance:

$$\psi \to \psi' = e^{iQ\theta}\psi \; ; \; \bar{\psi} \to \bar{\psi}' = e^{-iQ\theta}\bar{\psi}$$

- Gauge principle: phase invariance should hold locally $\theta = \theta\,(x)$
- Covariant derivative: $D_\mu \psi \equiv (\partial_\mu + ieQA_\mu)\psi$
- Spin-1 field: $A_\mu \to A_\mu - \frac{1}{e}\partial_\mu \theta$

  $\mathcal{L} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} \; , \; F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
- Mass term for A $\mathcal{L}_M = \frac{1}{2} m_\gamma^2 A_\mu A^\mu$

violates local gauge invariance ➔ massless photon

We understand why $m_\gamma = 0$

Quantum cromodynamics: SU(3)

$$\mathbf{q} \equiv \begin{pmatrix} q \\ q \\ q \end{pmatrix} \qquad \mathbf{N_c = 3}$$

Free quarks: $\mathcal{L} = \bar{q}(i\gamma^\mu \partial_\mu - m)q$

SU(3) colour symmetry: $q \to Uq \; ; \; \bar{q} \to \bar{q}U^\dagger$

$$UU^\dagger = U^\dagger U = 1 \quad , \; \det U = 1 \quad , \; U = \exp\left\{ i \frac{\lambda^a}{2} \theta_a \right\}$$

Gauge Principle: Local Symmetry $\theta_a = \theta_a(x)$

$$\mathbf{D}^\mu \mathbf{q} \equiv (\mathbf{I}_3 \, \partial^\mu + i \, g_s \, \mathbf{G}^\mu) \, \mathbf{q} \quad \to \quad \mathbf{U} \;\; \mathbf{D}^\mu \mathbf{q}$$

$$\mathbf{D}^\mu \to \mathbf{U} \; \mathbf{D}^\mu \; \mathbf{U}^\dagger \qquad ; \qquad \mathbf{G}^\mu \to \mathbf{U} \; \mathbf{G}^\mu \; \mathbf{U}^\dagger + \frac{i}{g_s} (\partial^\mu \mathbf{U}) \; \mathbf{U}^\dagger$$

$$[\mathbf{G}^\mu]_{\alpha\beta} = \frac{1}{2} (\lambda^a)_{\alpha\beta} \; G_a^\mu(x)$$

8 Gluon Fields

Non-abelian group: $\mathcal{L}_G = -\frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a$

with

$$G_a^{\mu\nu} = \partial^\mu G_a^\nu - \partial^\nu G_a^\mu - g_s f^{abc} G_b^\mu G_c^\nu$$

Mass term $\mathcal{L}_M = \frac{1}{2} m_G^2 G_a^\mu G_\mu^a$

violates local gauge invariance ➔

massless gluons, $m_G = 0$

$SU(2)_L \times U(1)_Y$ Electroweak Symmetry

Free lagrangian for massless fermions:

$$\mathcal{L}_0 = \sum_j \bar{\psi}_j \gamma^\mu \partial_\mu \psi_j$$

$SU(2)_L \times U(1)_Y$ Symmetry:

Fields	$\psi_1(x)$	$\psi_2(x)$	$\psi_3(x)$
Quarks	$\begin{pmatrix} q_u \\ q_d \end{pmatrix}_L$	$(q_u)_R$	$(q_d)_R$
Leptons	$\begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L$	$(\nu_l)_R$	$(l^-)_R$

$$\psi_1 \to e^{iy_1\beta} U_L \psi_1 \; ; \; \psi_i \to e^{iy_i\beta} \psi_i \; , \; i = 2, 3$$

$$\bar{\psi}_1 \to e^{-iy_1\beta} \bar{\psi}_1 U_L^\dagger \; ; \; \bar{\psi}_i \to e^{-iy_i\beta} \bar{\psi}_i \; , \; i = 2, 3$$

$$U_L = \exp\left\{ i \frac{\vec{\sigma}}{2} \vec{\alpha} \right\}$$

Gauge principle: $\alpha_i=\alpha_i(x)$ $\beta=\beta(x)$

$$\mathbf{D}_\mu \psi_1 \equiv \left[\partial_\mu + i\, g\, \mathbf{W}_\mu(x) + i\, g'\, y_1\, B_\mu(x)\right] \psi_1 \quad \rightarrow \quad e^{i y_1 \beta(x)}\, \mathbf{U}_L(x)\, \mathbf{D}_\mu \psi_1$$

$$\mathbf{D}_\mu \psi_k \equiv \left[\partial_\mu + i\, g'\, y_k\, B_\mu(x)\right] \psi_k \quad \rightarrow \quad e^{i y_k \beta(x)}\, \mathbf{D}_\mu \psi_k \qquad (k = 2, 3)$$

$$B_\mu(x) \quad \rightarrow \quad B_\mu(x) - \frac{1}{g'}\, \partial_\mu \beta(x)$$

$$\mathbf{W}_\mu(x) \quad \rightarrow \quad \mathbf{U}_L(x)\, \mathbf{W}_\mu(x)\, \mathbf{U}_L^\dagger(x) + \frac{i}{g}\, \partial_\mu \mathbf{U}_L(x)\, \mathbf{U}_L^\dagger(x)$$

$$U_L(x) = \exp\left\{ i \frac{\vec{\sigma}}{2} \vec{\alpha}(x) \right\} \qquad\qquad W_\mu(x) = \frac{\vec{\sigma}}{2} \vec{W}_\mu(x)$$

- 4 massless gauge bosons: $W_\mu^\pm\ ,\ W_\mu^3\ , B_\mu$
- Massless fermions: $\mathcal{L}_{m_f} = -m_f(\bar{f}_L f_R + \bar{f}_R f_L)$

➔ forbidden by gauge symmetry

Why are the W and Z masses non zero?

Spontaneous symmetry breaking **SSB** (Abelian case):

Complex scalar field with charge -e:

$$\mathcal{L}_S = (D_\mu \phi)^\dagger D^\mu \phi - V(\phi), \qquad D^\mu = \partial^\mu - ieA^\mu$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + h(\phi^\dagger \phi)^2$$

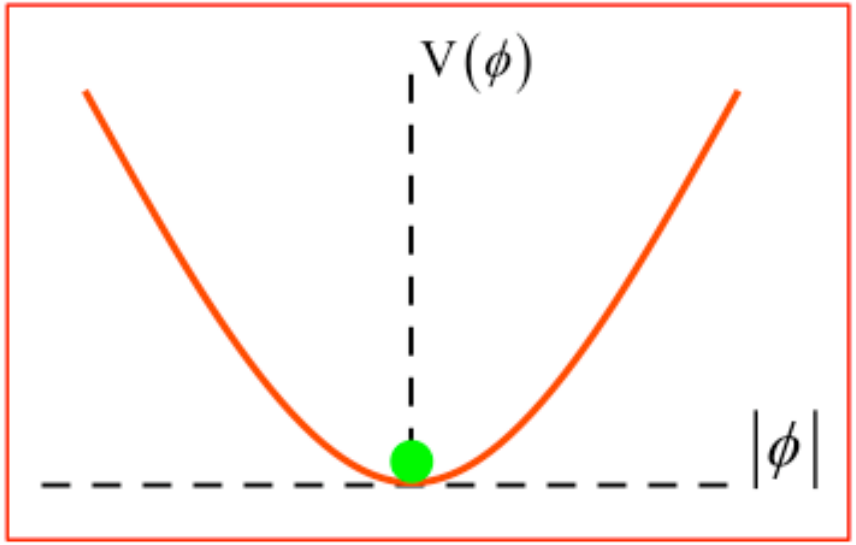
- Phase symmetry: $\phi(x) \to e^{i\theta}\phi(x)$

- Case 1: $\mu^2 > 0$

  Unique minimum at $\phi = 0$

  $M_\phi = \mu$

  Massless gauge boson

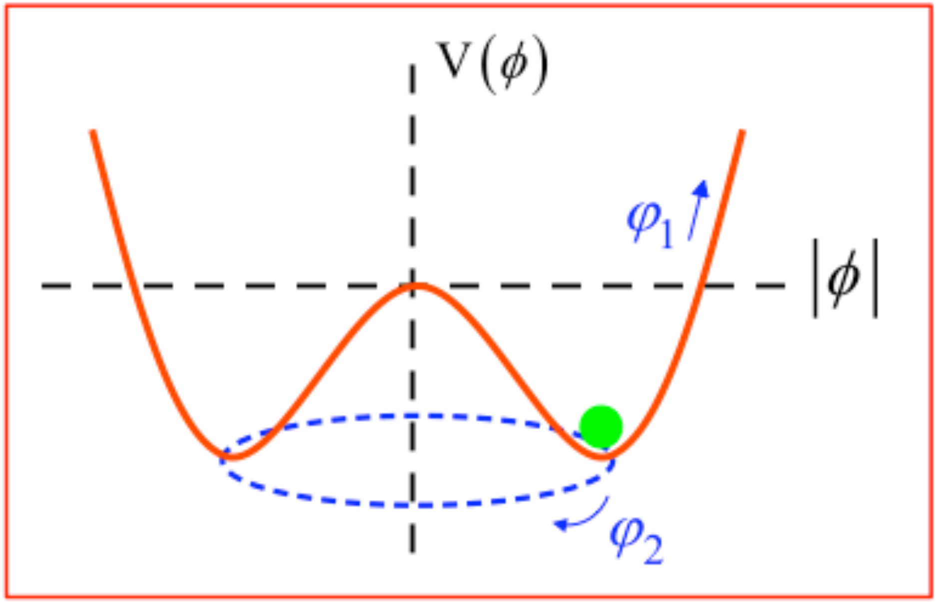


- Case 2: $\mu^2 < 0$

  Degenerate minima:

$$|\phi_0| = \sqrt{\frac{-\mu^2}{2h}} \equiv \frac{v}{\sqrt{2}}$$

$$V(\phi_0) = -\frac{1}{4} h v^4$$



Vacuum breaks U(1) symmetry

Rewrite: $$\phi = \frac{1}{\sqrt{2}}\left[v + \phi_1(x)\right] e^{i\phi_2(x)/v}$$

ϕ_1 and ϕ_2 are the 2 degrees of freedom of the complex Higgs field

$\mathcal{L}$ becomes:

$$\begin{aligned}\mathcal{L} &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{e^2v^2}{2}A^\mu A_\mu - evA_\mu\partial^\mu\phi_2 \\ &+ \frac{1}{2}(\partial_\mu\phi_1\partial^\mu\phi_1 + \partial_\mu\phi_2\partial^\mu\phi_2 + 2\mu^2\phi_1^2) \\ &+ (\phi_1, \phi_2\ interactions)\end{aligned}$$

- Theory now has:
  - Photon with mass $M_A = e\ v$
  - Scalar field ϕ_1 mass-squared $-2\mu^2 > 0$
  - Massless scalar field ϕ_2

- What about mixed ϕ_2-A propagator?
  - Remove by gauge transformation

$$A'_\mu = A_\mu - \frac{1}{ev}\partial_\mu \phi_2$$

- ϕ_2 field disappears

  - We say that it has been eaten to give the photon mass
  - ϕ_2 field called Goldstone boson
  - This is Abelian Higgs Mechanism
  - This gauge (unitary) contains only physical particles

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{e^2v^2}{2}A^\mu A_\mu + \frac{1}{2}(\partial_\mu\phi_1\partial^\mu\phi_1) - V(\phi_1)$$

Higgs mechanism summarized:

Spontaneous breaking of a gauge theory by a non-zero VEV of a scalar field results in the disappearence of a Goldstone boson and its transformation into the longitudinal component of a massive gauge boson

Goldstone boson equivalence theorem:

In the high energy limit, the amplitude for emission or absorption of a longitudinally polarized gauge boson becomes equal to the amplitude for emission or absorption of the Goldstone boson that was eaten

SM Higgs mechanism

Add a new scalar doublet: $\phi(x) \equiv \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix}$ $\quad y_\phi = 1/2$

$$\mathcal{L}_S = (D_\mu \phi)^\dagger D^\mu \phi - V(\phi), \qquad D^\mu \phi = \left[\partial^\mu + ig\frac{\vec{\sigma}}{2}\vec{W}^\mu + ig' y_\phi B^\mu\right]\phi$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + h(\phi^\dagger \phi)^2 \qquad h > 0 \qquad \mu^2 < 0$$

Why ?

Degenerate vacuum states:

$$\phi(x) = \exp\left\{i\frac{\vec{\sigma}}{2}\vec{\theta}(x)\right\}\frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

➔ Spontaneous symmetry breaking

$$\phi(x) = \exp\left\{ i\frac{\vec{\sigma}}{2}\vec{\theta}(x) \right\} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

SU(2)$_L$ invariant ➔ $\vec{\theta}(x)$ unphysical   Unitary Gauge: $\vec{\theta}(x) = 0$

$$(D_\mu\phi)^\dagger D^\mu\phi \rightarrow \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{g^2}{4}(v+H)^2 \left\{ W_\mu^\dagger W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu \right\}$$

Massive gauge bosons:
$$\begin{cases} W_\mu^\pm = \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp i W_\mu^2\right) \\ Z_\mu = \frac{1}{\sqrt{g^2 + g'^2}}\left(g W_\mu^3 - g' B_\mu\right) \end{cases}$$

$$M_W = M_Z \cos\theta_W = \frac{1}{2} g v$$

Weak mixing angle: $\cos\theta_W = \frac{g}{\sqrt{g^2+g'^2}}$ $\sin\theta_W = \frac{g'}{\sqrt{g^2+g'^2}}$

Higgs VEV conserves electric charge

$Q = I_3 + Y$ $\qquad Y_\phi = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ $\qquad I_3 = \frac{1}{2}\sigma_3 = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \qquad Q\langle\phi\rangle = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} = 0$$

- The corresponding gauge boson (orthogonal combination to Z) is the massless photon:

$$\begin{aligned} Z_\mu &= -\sin\theta_W B_\mu + \cos\theta_W W_\mu^3 \\ A_\mu &= \cos\theta_W B_\mu + \sin\theta_W W_\mu^3 \end{aligned}$$

- A_μ has the QED interaction if: $g\sin\theta_W = g'\cos\theta_W = e$

SM boson's summary

- Generate W,Z masses using Higgs mechanism
  - Higgs VEV breaks $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$
  - One Higgs doublet is the minimal case

- Before **SSB**
  - Massless $W^{\pm}$,Z: 3x2 polarizations = 6
  - 3 Goldstone bosons: $\vec{\theta}(x)$

- After **SSB**
  - Massive $W^{\pm}$,Z: 3x3 polarizations = 9

What about fermions?

Fermi model (1932):

- Current-current interaction of 4 fermions:

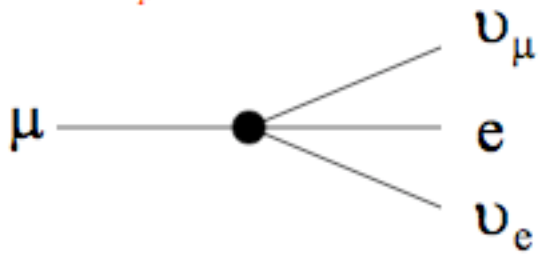
$$\mathcal{L}_F = -2\sqrt{2} G_F J_\rho^\dagger J^\rho$$

- Leptonic current:

$$J_\rho^{lept} = \bar{\nu}_e \gamma_\rho L e + \bar{\nu}_\mu \gamma_\rho L \mu + h.c. \qquad L \equiv \frac{1-\gamma_5}{2}$$

- Only left-handed fermions feel charged current weak interactions (maximal P violation) $\sigma \approx G_F^2 s$

- Induces muon decay:



This structure known since Fermi

$G_F = 1.16637 \times 10^{-5}\ \mathrm{GeV}^{-2}$

Fermion multiplet structure:

- Ψ_L couples to $W^\pm$ (Fermi theory) ➔ put in $SU(2)_L$ doublets with weak isospin $I_3=\pm 1/2$

- Ψ_R doesn't couple to $W^\pm$ ➔ put in $SU(2)_L$ singlets with weak isospin $I_3=0$

Fields	$\psi_1(x)$	$\psi_2(x)$	$\psi_3(x)$
Quarks	$\begin{pmatrix} q_u \\ q_d \end{pmatrix}_L$	$(q_u)_R$	$(q_d)_R$
Leptons	$\begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L$	$(\nu_l)_R$	$(l^-)_R$

Coupling fermions to SU(2)$_L$ x U(1)$_Y$ gauge fields

$$D_\mu = \partial_\mu + ig\frac{\vec{\sigma}}{2}\cdot\vec{W}_\mu + ig'YB_\mu \qquad \vec{\sigma}\cdot\vec{W}_\mu = \left\{ \begin{array}{cc} W^3_\mu & \sqrt{2}W^\dagger_\mu \\ \sqrt{2}W_\mu & -W^3_\mu \end{array} \right\}$$

- In terms of mass eigenstates:

$$D_\mu = \partial_\mu + i\frac{g}{2\sqrt{2}}\left(W^\dagger_\mu\sigma^+ + W_\mu\sigma^-\right) + i\frac{1}{\sqrt{g^2+g'^2}}Z_\mu\left(g^2\frac{\sigma_3}{2} - g'^2Y\right) + i\frac{gg'}{\sqrt{g^2+g'^2}}A_\mu\left(\frac{\sigma_3}{2}+Y\right)$$

- Re-arrange couplings:

$$Q = I_3 + Y \qquad e = \frac{gg'}{\sqrt{g^2+g'^2}} \qquad g = \frac{e}{\sin\theta_W} \qquad I_3 = \frac{\sigma_3}{2}$$

$$D_\mu = \partial_\mu + i\frac{g}{2\sqrt{2}}\left(W^\dagger_\mu\sigma^+ + W_\mu\sigma^-\right) + i\frac{g}{\cos\theta_W}Z_\mu(I_3 - Q\sin^2\theta_W) + ieQA_\mu$$

- Fix hypercharge to get correct coupling to photon:

$$Q = I_3 + Y$$

$$Y_{q_L} = Q_u - \frac{1}{2} = Q_d + \frac{1}{2} = \frac{1}{6}, \qquad Y_{u_R} = Q_u = \frac{2}{3}, \qquad Y_{d_R} = Q_d = -\frac{1}{3},$$
$$Y_{\ell_L} = Q_e + \frac{1}{2} = Q_\nu - \frac{1}{2} = -\frac{1}{2}, \qquad Y_{\ell_R} = Q_e = -1, \qquad Y_{\nu_R} = Q_\nu = 0.$$

- IF ν_R do exist ➔ no ν_R interactions ➔ sterile neutrino

Charged currents:

$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} W_\mu^\dagger \left[\bar{q}_u \gamma^\mu (1-\gamma_5) q_d + \bar{\nu}_\ell \gamma^\mu (1-\gamma_5) \ell \right] + h.c.$$

- Quark / lepton universality
- Left-handed interaction

Neutral currents:

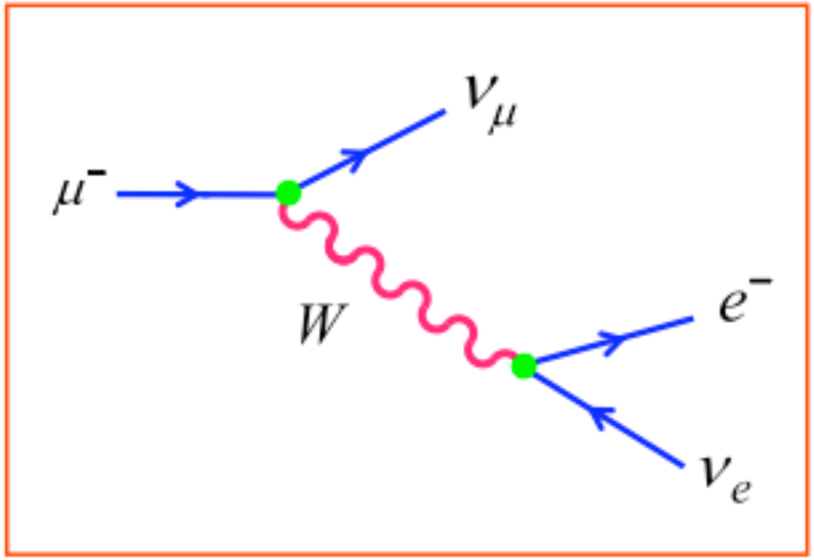
$$\mathcal{L}_{NC} = -gW_\mu^3 \bar{\psi}_1 \gamma^\mu \frac{\sigma_3}{2} \psi_1 - g' B_\mu \sum_j y_j \bar{\psi}_j \gamma^\mu \psi_j$$

$$\mathcal{L}_{NC}^Z = -\frac{g}{\cos\theta_W} Z_\mu \left\{ \bar{\psi}_1 \gamma^\mu \frac{\sigma_3}{2} \psi_1 - \sin^2\theta_W \sum_j Q_j \bar{\psi}_j \gamma^\mu \psi_j \right\}$$

$$= -\frac{g}{2\cos\theta_W} Z_\mu \sum_f \bar{f} \gamma^\mu \left[v_f - a_f \gamma_5 \right] f$$

	q_u	q_d	ν_ℓ	ℓ^-
$2v_f$	$1 - \frac{8}{3}\sin^2\theta_W$	$-1 + \frac{4}{3}\sin^2\theta_W$	1	$-1 + 4\sin^2\theta_W$
$2a_f$	1	-1	1	-1

Muon decay



$$\frac{g^2}{M_W^2 - q^2} \approx \frac{g^2}{M_W^2} = 4\sqrt{2}G_F$$

$$\frac{1}{\tau_\mu} = \Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^2}$$

- G_F measured precisely: $v = (\sqrt{2}G_F)^{-1/2} = 246\ GeV$

Fermion masses

- Fermion mass term: $\mathcal{L}_{m_f} = -m_f(\bar{f}_L f_R + \bar{f}_R f_L)$

➔ forbiden by $SU(2)_L \times U(1)_Y$ gauge symmetry

- Left handed fermions are $SU(2)_L$ doublets ➔ scalar-fermion couplings allowed by $SU(2)_L \times U(1)_Y$ gauge symmetry:

$$\mathcal{L}_Y = -Y_\ell \bar{\ell}_L \phi \, \ell_R - Y_d \bar{Q}_L \phi \, d_R - Y_u \bar{Q}_L \phi_c u_R + h.c.$$

$$\phi_c = i\sigma_2 \phi^* = \begin{pmatrix} \phi^{0*} \\ -\phi^- \end{pmatrix}$$

- After SSB: $\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right)\{m_\ell \bar{\ell}\ell + m_d \bar{q}_d q_d + m_u \bar{q}_u q_u\}$

fermion masses are new free parameters: $m_f = Y_f \frac{v}{\sqrt{2}}$

2. Standard Model: Where are we?

- Good references:

  - Antonio Pich, The SM of Electroweak Interactions, http://arXiv.org/pdf/0705.4264

  - LEP Electroweak working group home page

  - CDF and D0 home pages

- Standard Model is predictive theory
- Only missing piece is Higgs boson
- Can tests predictions experimentally

Standard Model parameters

- QCD: $\alpha_s(M_Z)$ 1
- EW gauge / scalar sector: 4

$$g,\ g',\ \mu^2,\ \lambda \qquad V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

- Trade Higgs potential free parameters, μ^2, λ, for v, M_H:

$$v^2 = -\frac{\mu^2}{2\lambda}$$
$$M_H^2 = 2\lambda v^2$$

- Large M_H → strong Higgs self-coupling
- A priori, Higgs mass can be anything

Inputs:

$$g,\ g',\ v\ , M_H \rightarrow \alpha,\ G_F,\ M_Z,\ M_H$$

- α=1/137.03599911(46) from $(g-2)_e$ and quantum Hall effect
- G_F= 1.166371(1) x 10^{-5} GeV^{-2} from muon lifetime
- M_Z = 91.1875 ± 0.0021 GeV from LEP1
- M_H ?

Express everything else in terms of these parameters:

$$\left.\begin{array}{r} M_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F} \\ \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} \end{array}\right\} \Rightarrow M_W\ ,\ \sin^2\theta_W$$

Inadequacy of tree level calculations

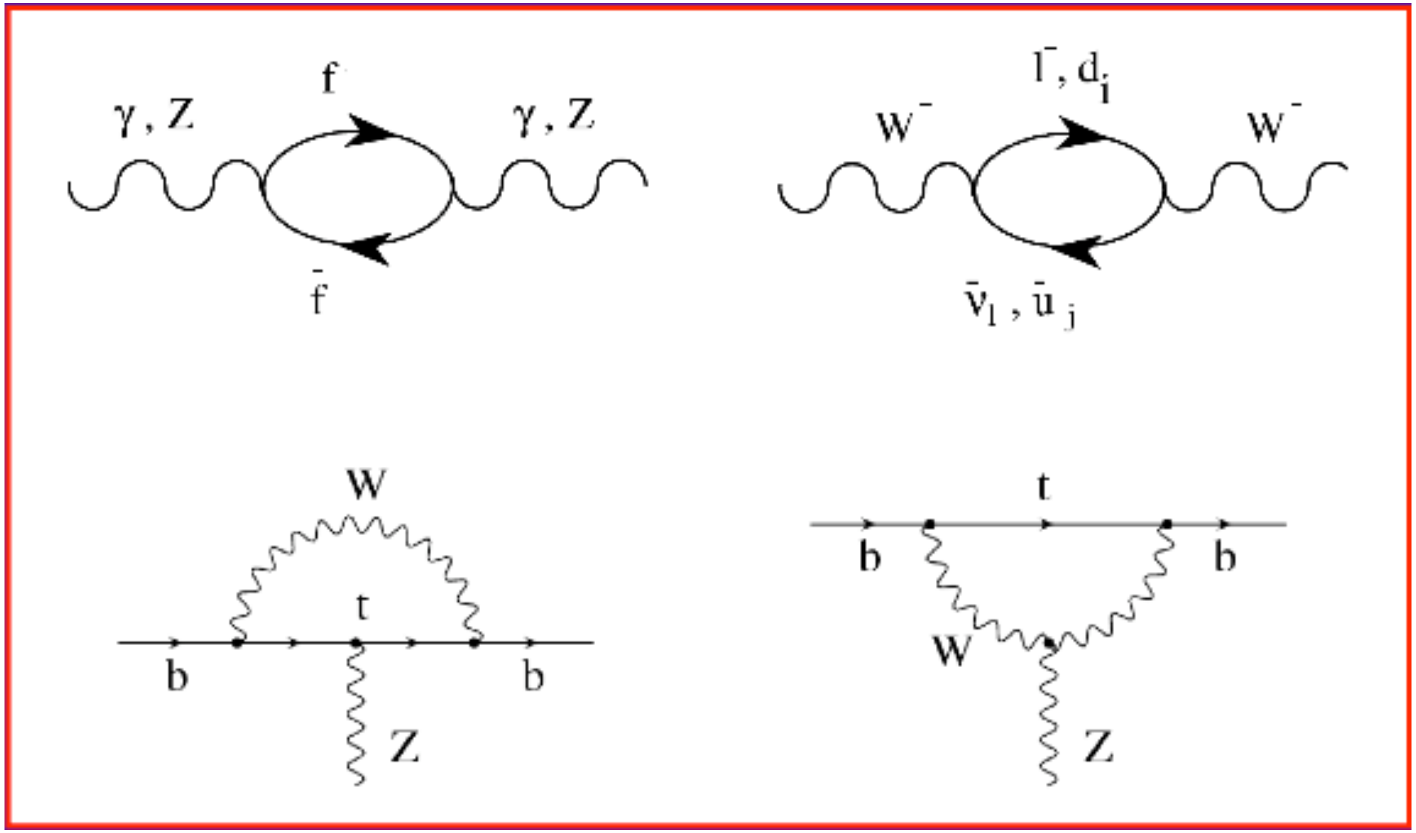
- Predicted values: $M_W = 80.938\,\mathrm{GeV}$, $\sin^2\theta_W = 0.212$
- Experiment:

$$M_W = 80.399 \pm 0.023\,\mathrm{GeV}$$
$$(\sin^2\theta_W)^{lept}_{eff} = 0.2324 \pm 0.0012$$

➔ Need to calculate beyond tree level

- Warning: definitions of $\sin^2\theta_W$ equivalent at tree level will be different at the one-loop level
  - On-shell: $\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$
  - Effective (leptons): $(\sin^2\theta_W)^{lept}_{eff} = \frac{1}{4}\left(\frac{v_\ell}{a_\ell} - 1\right)$
  - ...

Loop corrections



- $\Pi_{\gamma\gamma}$ ➔ running of α: $\alpha(M_Z^2)$ = 1/128.93 (5)
- Sensitive to heavier particles: top, Higgs, BSM

Modification of tree level relations:

$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2\theta_W} \frac{1}{1-\Delta r}$$

- Δr is a physical quantity which incorporates one-loop corrections
- Contributions to Δr from top quark and Higgs loops:

$$\Delta r^t = -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\left(\frac{\cos^2\theta_W}{\sin^2\theta_W}\right)$$

$$\Delta r^H = \frac{11 G_F M_W^2}{24\sqrt{2}\pi^2}\left(\log\frac{M_H^2}{M_W^2} - \frac{5}{6}\right)$$

➔ Extreme sensitivity of precision measurements to m_t

Z boson properties

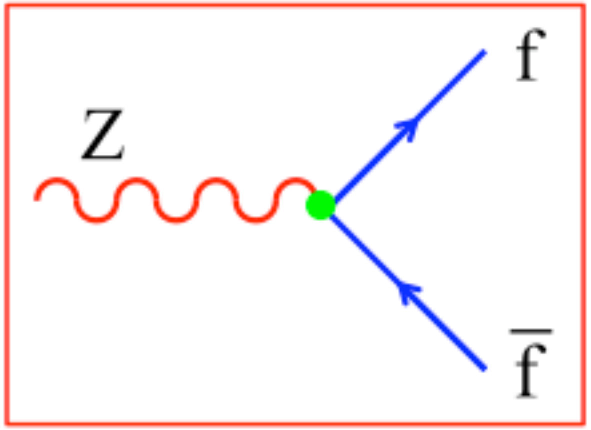
- At the Z pole:
  - 2 x 10^7 unpolarized Z's at LEP
  - 5 x 10^5 Z's at SLD with P_e 75 %
- What did we measured at the Z?
  - Z lineshape → σ, Γ_Z, M_Z
  - Z branching ratios
  - Asymmetries
- W+ W- production at 200 GeV
  - Searches for Z H

Z couplings to fermions:

- Neutral currents are flavour diagonal

- Calculate decay widths from: $\Gamma(V \to f\bar{f}) = \frac{1}{16\pi M_V}|A|^2$

$Z \to \ell^- \ell^+, \; \nu_\ell \bar{\nu}_\ell, \; q\bar{q}$ $\qquad q = u, \; d, \; s, \; c, \; b$

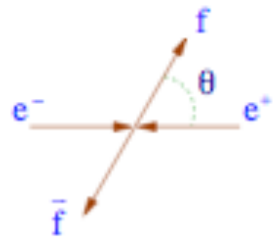


$$\Gamma(Z \to f\bar{f}) = \frac{G_F M_Z^3}{6\pi\sqrt{2}} \left(|v_f|^2 + |a_f|^2\right) N_f$$

$$N_\ell = 1 \; , \; N_q = N_C$$

- Γ_Z = 2.48 GeV
- Exp: Γ_Z = 2.4952 ± 0.0023 GeV

$$e^+e^- \to \gamma, Z \to f\bar{f}$$



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s} N_f \left\{ A(1+\cos^2\theta) + B\cos\theta - h_f \left[C(1+\cos^2\theta) + D\cos\theta \right] \right\}$$

$$N_\ell = 1 \; , \; N_q = N_C \left\{ 1 + \frac{\alpha_s(M_Z)}{\pi} + \ldots \right\}$$

$h_f = \pm 1 \Rightarrow$ helicity of fermion f

γ exchange — γ-Z interference, Changes sign at pole — Z exchange

$$A = \quad Q_f^2 \quad -2Q_f v_e v_f \mathrm{Re}(\chi) + (v_e^2 + a_e^2)(v_f^2 + a_f^2)|\chi|^2$$

$$B = \quad -4Q_f a_e a_f \mathrm{Re}(\chi) + 8 v_e a_e v_f a_f |\chi|^2$$

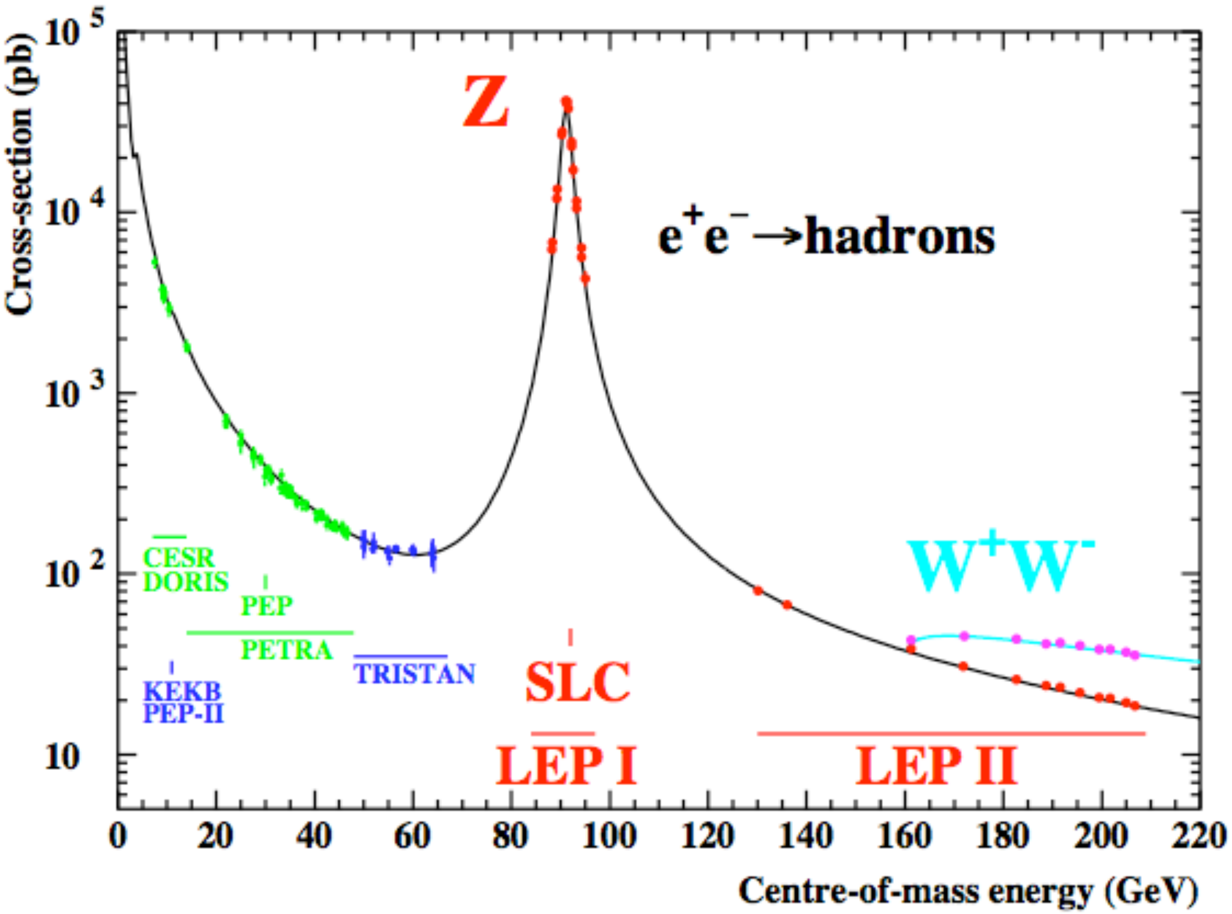
$$C = \quad -2Q_f v_e a_f \mathrm{Re}(\chi) + 2(v_e^2 + a_e^2) v_f a_f |\chi|^2$$

$$D = \quad -4Q_f a_e v_f \mathrm{Re}(\chi) + 4 v_e a_e (v_f^2 + a_f^2)|\chi|^2$$

$$\chi \equiv \frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha} \frac{s}{s - M_Z^2 + i s \Gamma_Z / M_Z}$$

Z Peak

$(s = M_Z^2)$

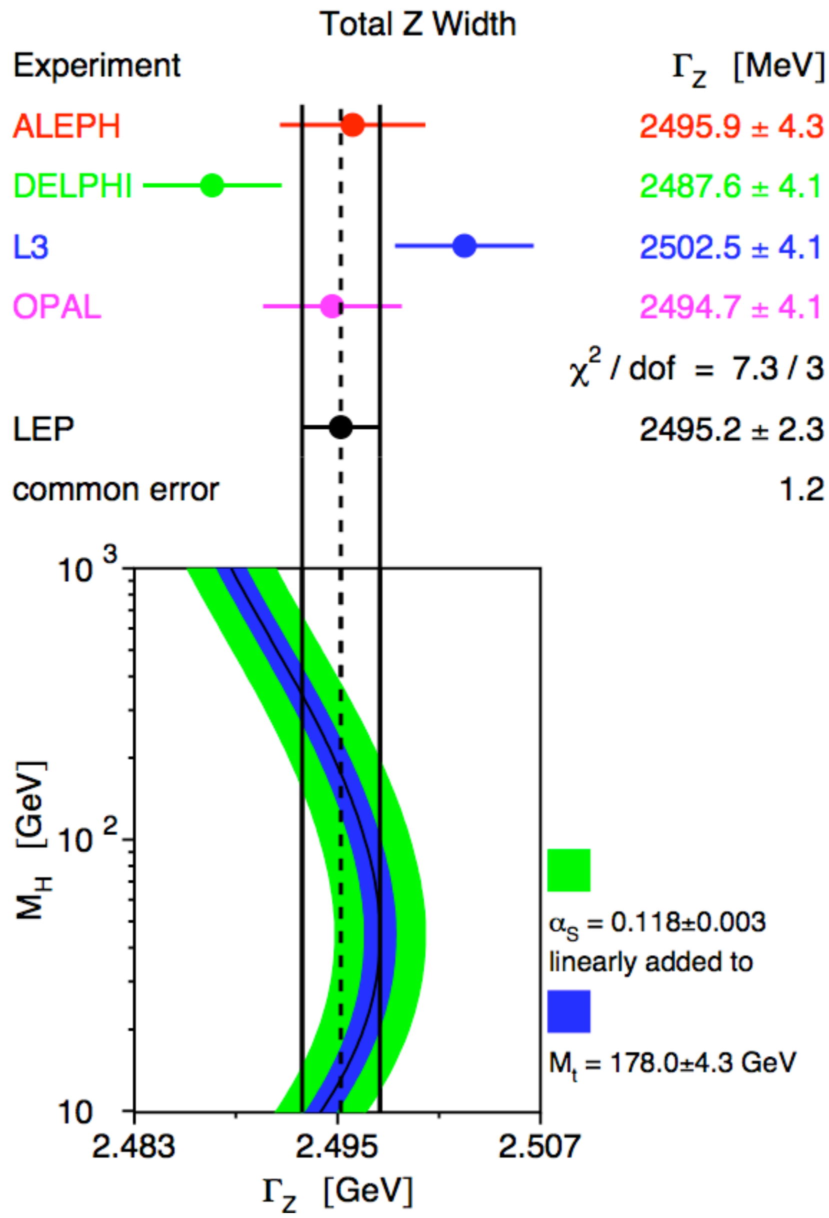


- Assume energy near Z pole, so include only Z exchange:

$$\sigma = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2} \qquad \Gamma_f \equiv \Gamma(Z \to f\bar{f})$$

Total Z width from LEP:

- Largest uncertainty is from α_s



Number of neutrino species:

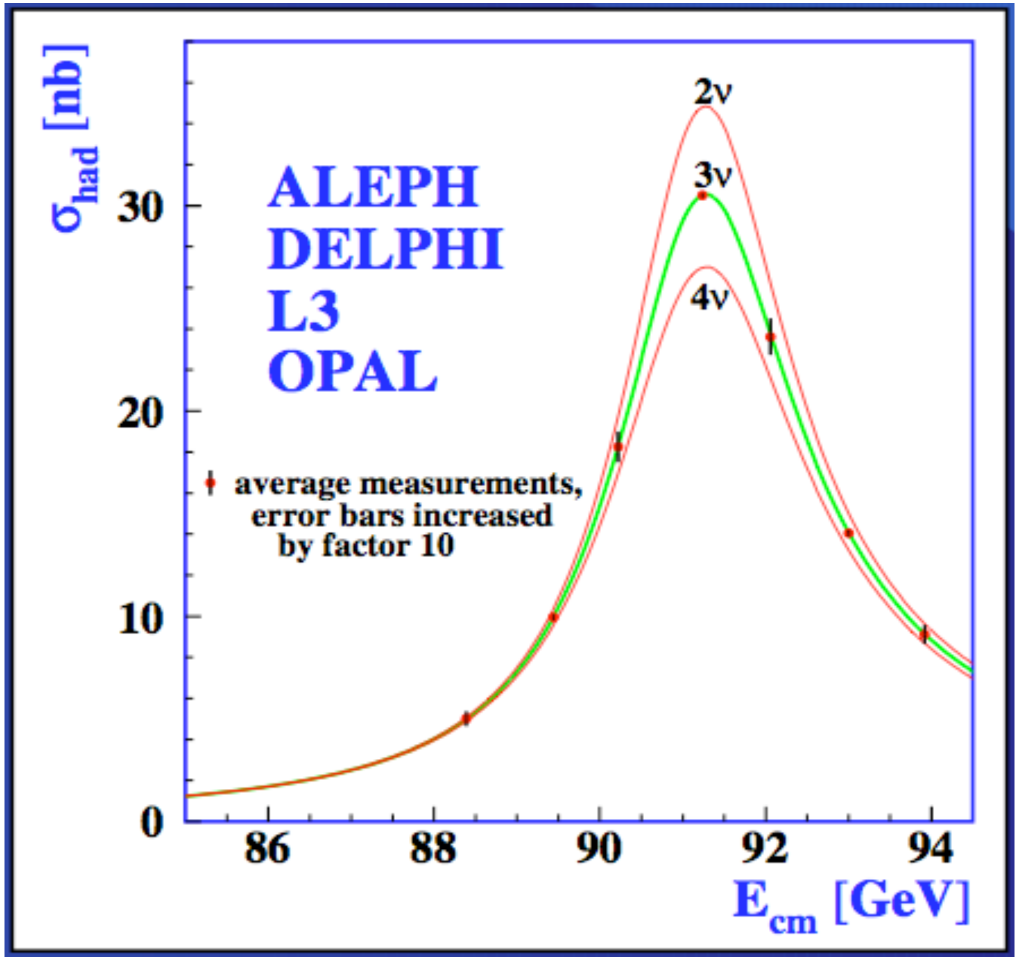
$$\frac{\Gamma_{\text{inv}}}{\Gamma_\ell} \equiv \frac{\Gamma(Z \to \text{invisible})}{\Gamma(Z \to \ell^+\ell^-)} = N_\nu \frac{\Gamma(Z \to \nu_\ell \bar{\nu}_\ell)}{\Gamma(Z \to \ell^+\ell^-)} = N_\nu \frac{2}{1 + (1 - 4\sin^2\theta_W)^2} = 1.989 N_\nu$$

- Experiment:

$$\frac{\Gamma_{\text{inv}}}{\Gamma_\ell} = 5.942 \pm 0.016$$

- Number of light neutrinos:

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



Asymmetries

- Forward-backward asymmetry:

$$\mathcal{A}_{FB} = \frac{\int_0^1 dz \frac{d\sigma}{dz} - \int_{-1}^0 dz \frac{d\sigma}{dz}}{\int_{-1}^1 dz \frac{d\sigma}{dz}} \Rightarrow \mathcal{A}_{FB,Z-peak} = \frac{3}{4}\mathcal{P}_e \mathcal{P}_f$$

$$z = \cos\theta \qquad \mathcal{P}_f = -\frac{v_f a_f}{|v_f|^2 + |a_f|^2}$$

- Final polarization (only available for f = τ):

$$\mathcal{A}_P = \frac{\sigma^{h_f=+1} - \sigma^{h_f=-1}}{\sigma^{h_f=+1} + \sigma^{h_f=-1}} \Rightarrow \mathcal{A}_{P,Z-peak} = \mathcal{P}_f$$

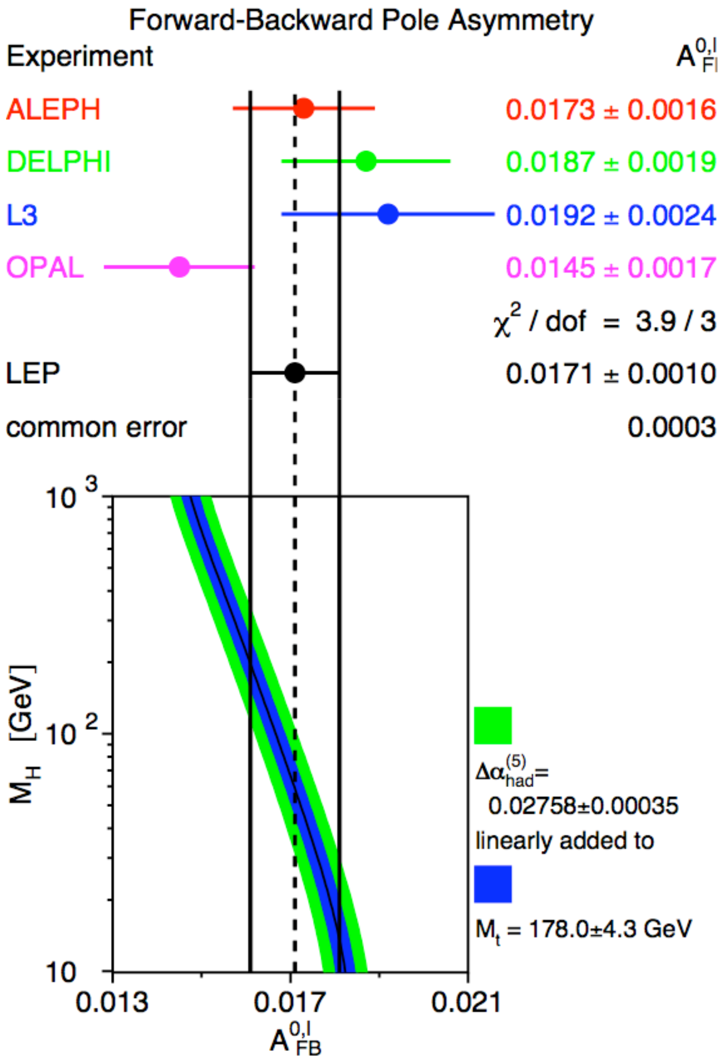
- SLD ➔ polarized beams: left-right asymmetry

$$\mathcal{A}_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \Rightarrow \mathcal{A}_{LR,Z-peak} = -\mathcal{P}_e$$

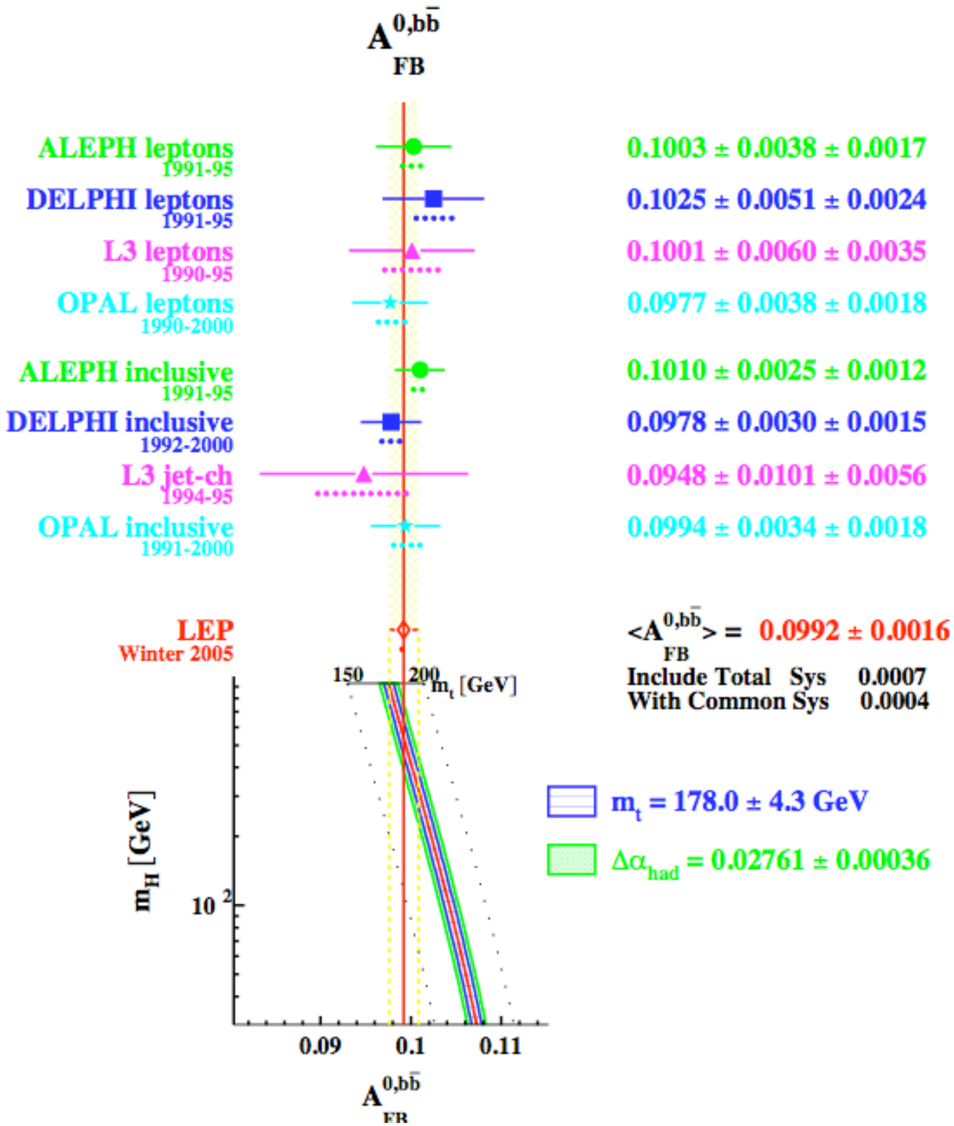
Very sensitive to lepton couplings:

$$\mathcal{P}_\ell \propto |v_\ell| = \frac{1}{2}(1 - 4\sin^2\theta_W) \ll 1$$

leptons



b quarks



Z couplings to leptons:

$$v_\ell = -\frac{1}{2} + 2\sin^2\theta_W$$
$$a_\ell = -\frac{1}{2}$$

- Radiative corrections give dependence on M_t and M_H
- Arrows point in direction of increasing M
- Low values of M_H preferred

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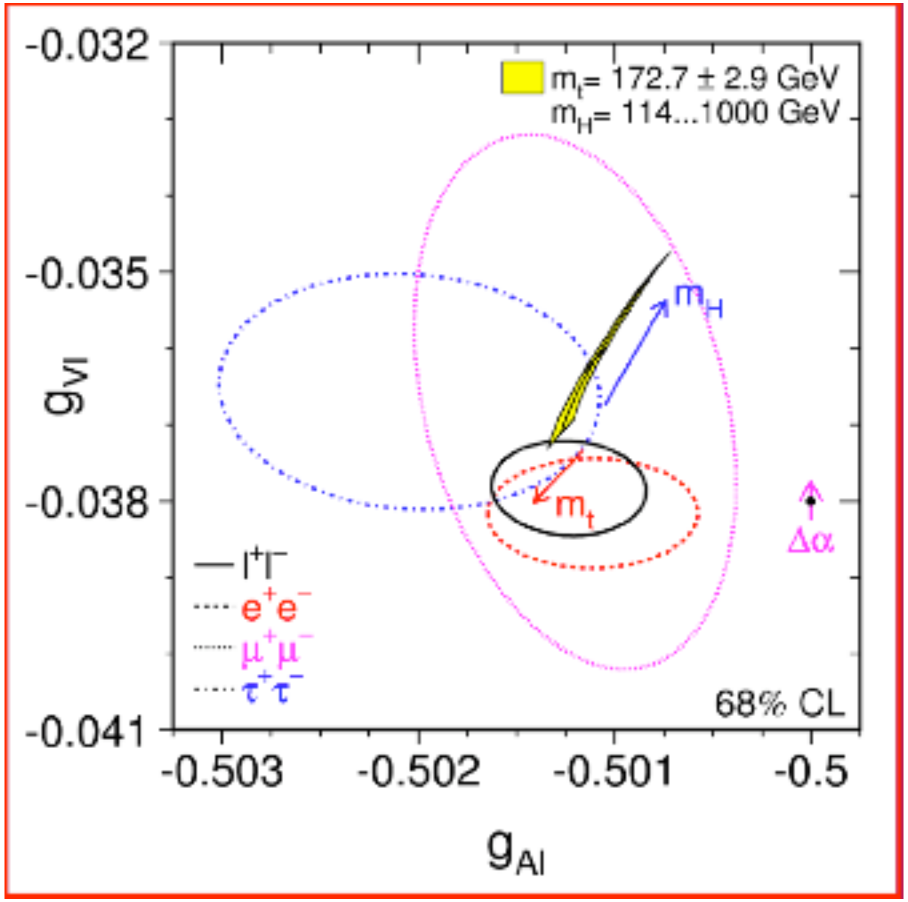

Z couplings to fermions:

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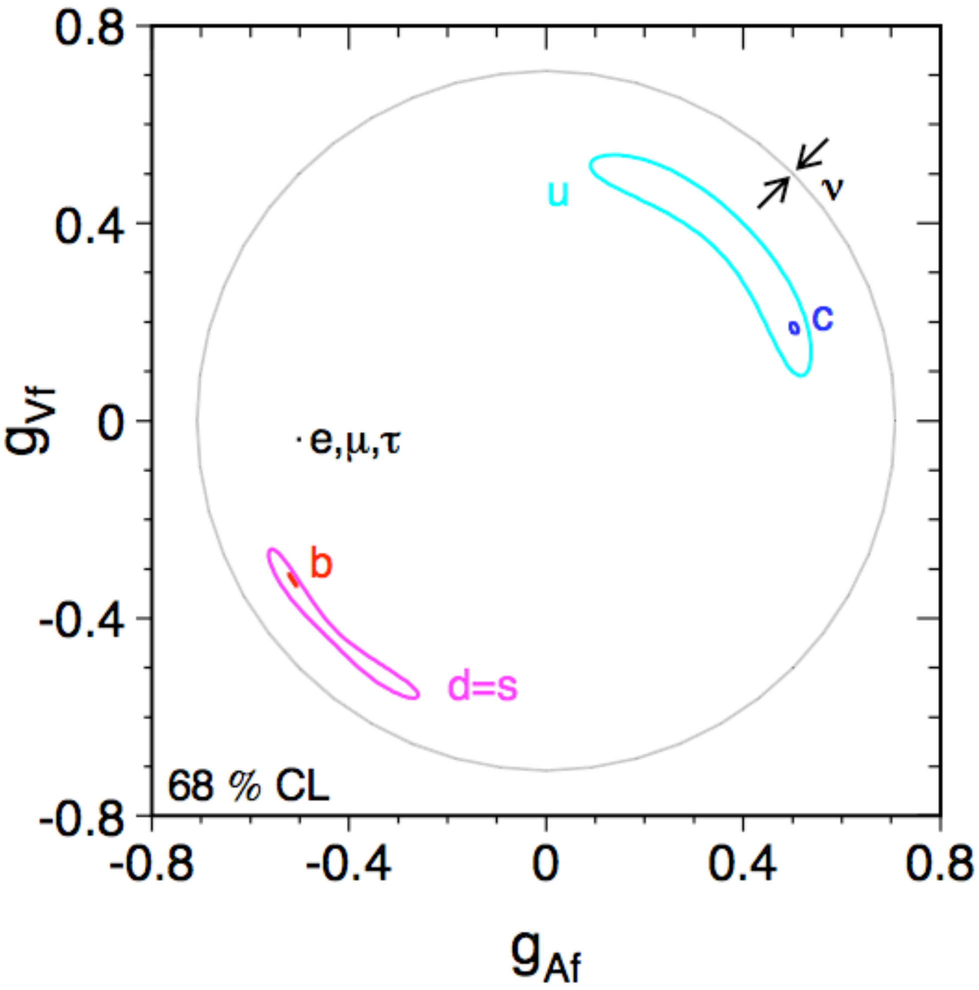
$$g_V^u = \frac{1}{2} - \frac{4}{3}\sin^2\theta_W$$
$$g_A^u = \frac{1}{2}$$
$$g_V^d = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$$
$$g_A^d = -\frac{1}{2}$$



The global fit

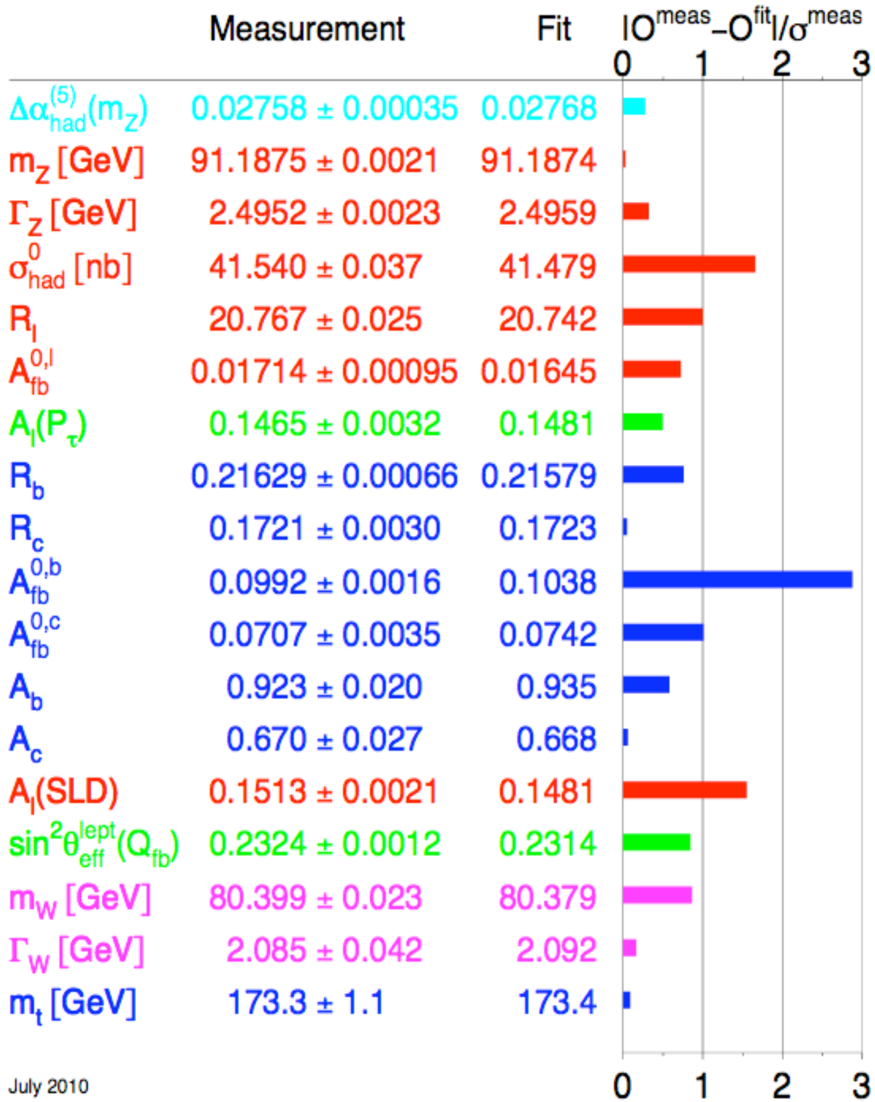
- Observables are expressed in terms of the input parameters: G_F, $\alpha(M_Z)$, M_Z, M_t, M_H, $\alpha_S(M_Z)$

$$\chi^2(\text{parameters}) = \sum_i \left(\frac{O^i_{\text{th}}(\text{parameters}) - O^i_{\text{exp}}}{\Delta O^i} \right)^2$$

- By minimizing χ^2, one determines the parameters and gives predictions for the rest of observables, which can be compared back with the measured values:

$$\text{Pull}_\text{i} = \frac{O^i_{\text{th}}(\text{fitted} - \text{parameters}) - O^i_{\text{exp}}}{\Delta O^i}$$

Electroweak Theory is precision theory



	Z-pole fit
M_Z	91.1874 ± 0.0021 GeV
M_H	$111 \pm^{190}_{60}$ GeV
m_t	$173 \pm^{13}_{10}$ GeV
$\alpha_S(M_Z)$	0.1190 ± 0.0028
$1/\alpha(M_Z)$	127.918 ± 0.018

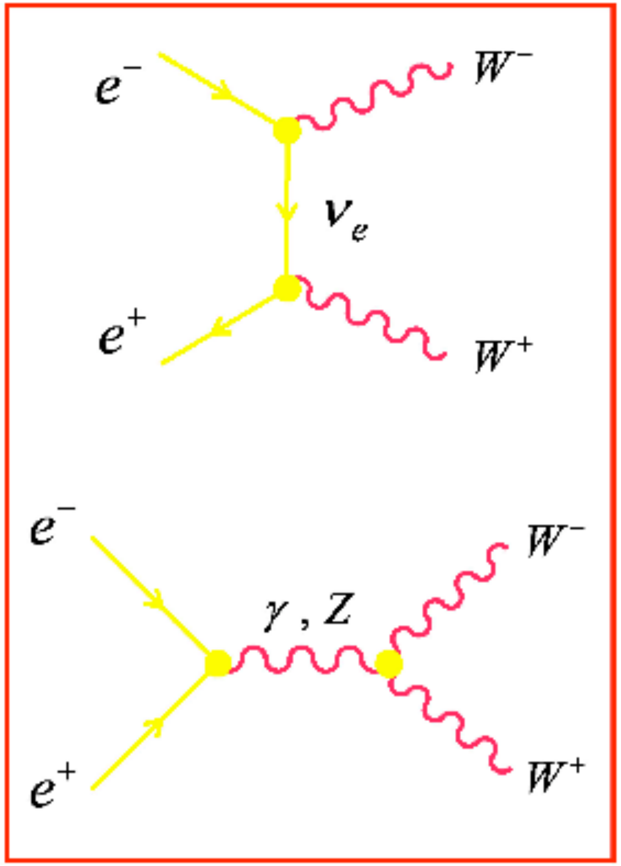
To be compared with the direct measurement of m_t at the Tevatron:

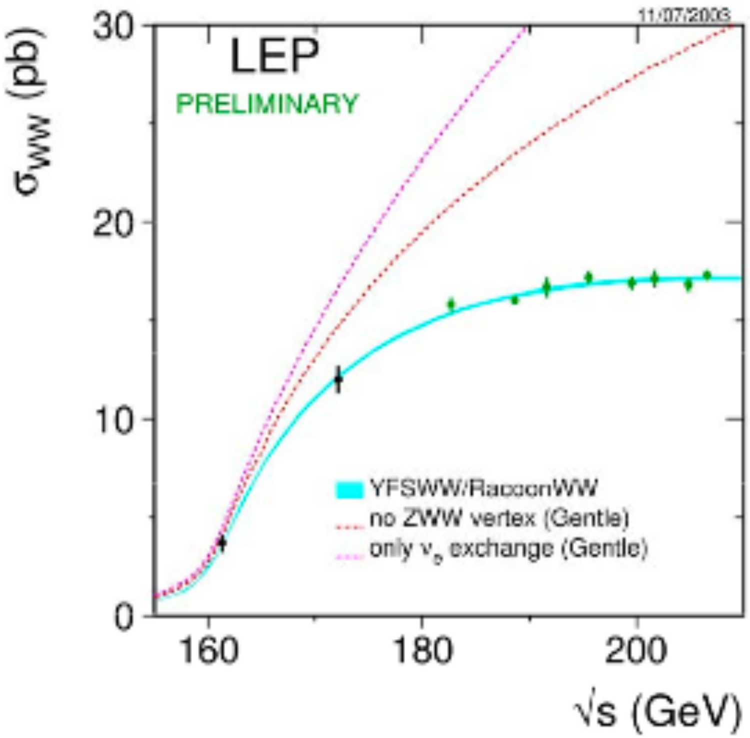
172.5 ± 2.3 GeV

Evidence of gauge self-interactions

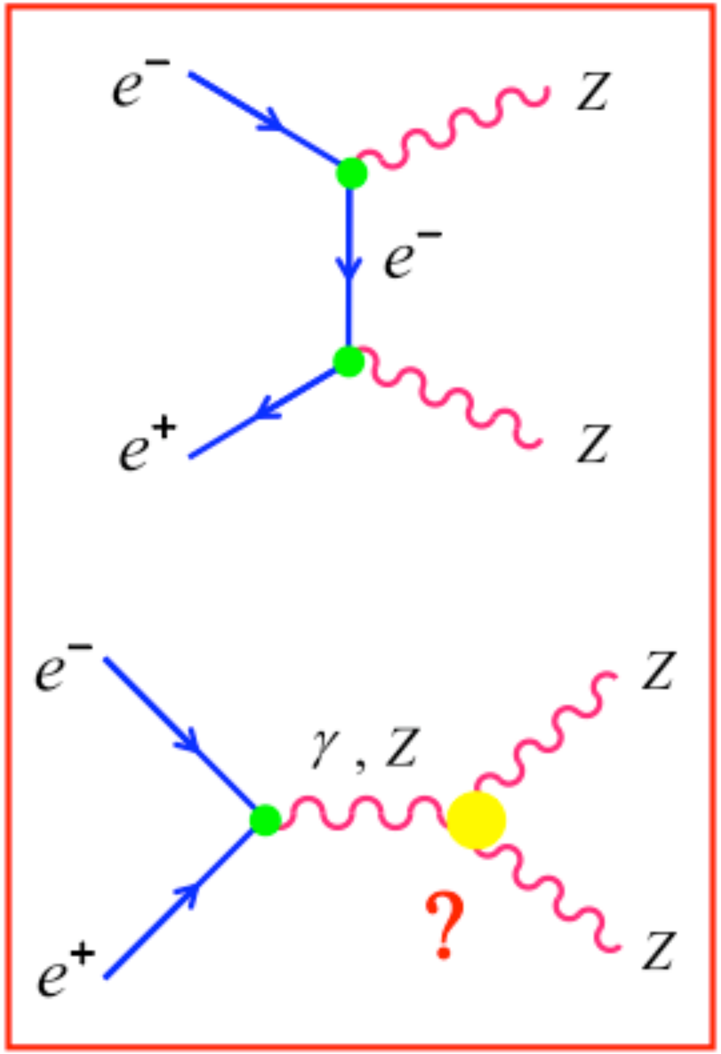
- Contributions which grow with energy cancel between t- and s- channel (Z exchange) diagrams
- Depends on special form of 3-gauge boson couplings

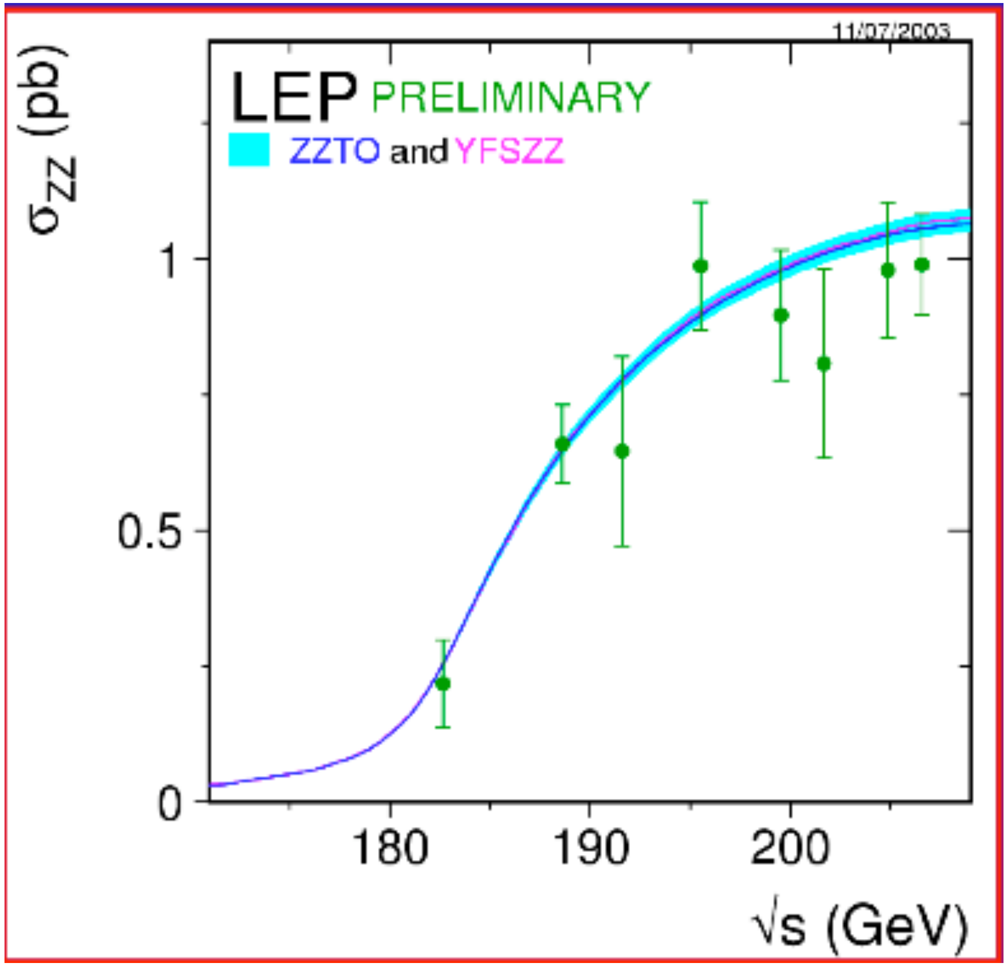
➔ No deviations from SM at LEP2





No evidence of γZZ or ZZZ couplings:





Hadron colliders

Tevatron: $p\bar{p}$ @ 2 TeV

LHC: pp @ 7 TeV

- Partons have a range of energy
- Can reach higher energies than e^+e^- colliders
- Can get very large statistics in single W production, gauge boson pair production, top quark pair production

Z's at the Tevatron

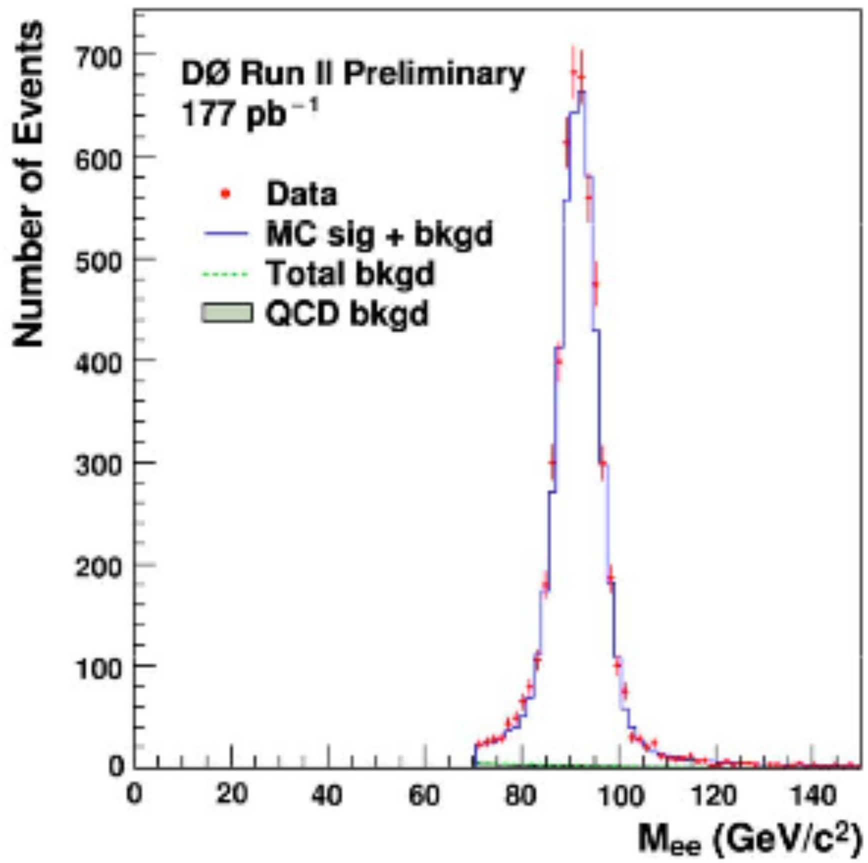
- Z production: $q\bar{q} \to Z \to e^+e^-$

- Amplitude has pole at M_Z

$$\frac{1}{(p_e + p_{\bar{e}})^2}$$

- Invariant mass distribution of $e^+ e^-$:

$$m_{ee}^2 = (p_e + p_{\bar{e}})^2 \approx M_Z^2$$



W's at the Tevatron

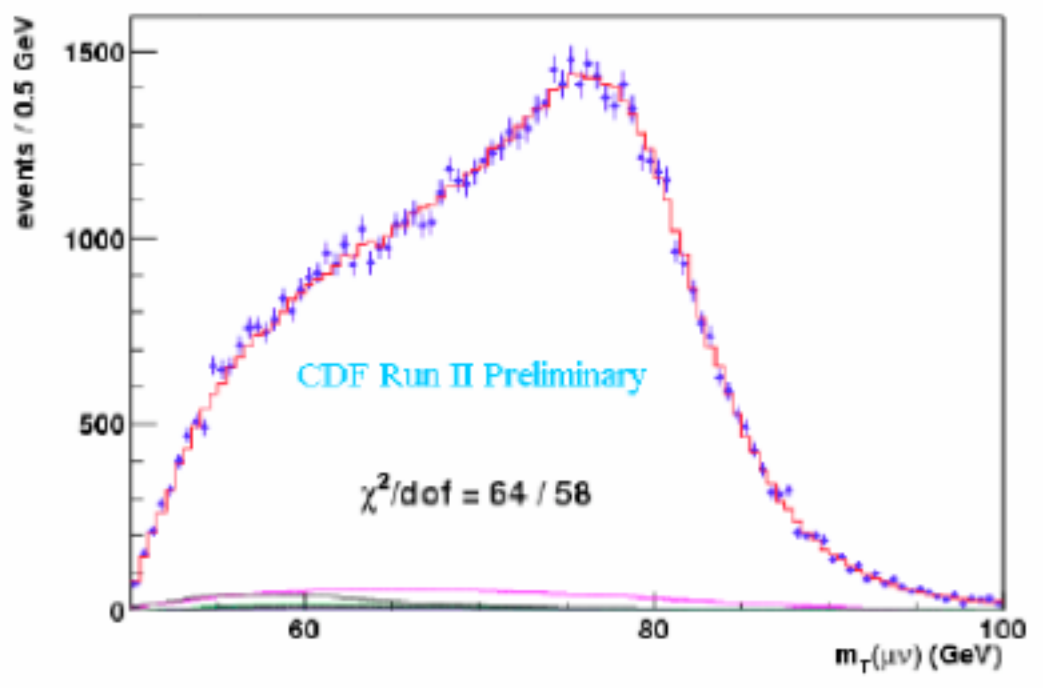
- Consider W → e ν
- Invariant mass of the leptonic system:

$$m_{e\nu}^2 = (E_e + E_\nu)^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2 - (p_{ez} + p_{\nu z})^2$$

- Missing transverse energy of neutrino inferred from observed momenta
- Can't reconstruct invariant mass
- Define transverse mass observable:

$$m_T^2 = (E_{eT} + E_{\nu T})^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2 = 2E_{eT}E_{\nu T}(1 - \cos\phi)$$

W mass measurement

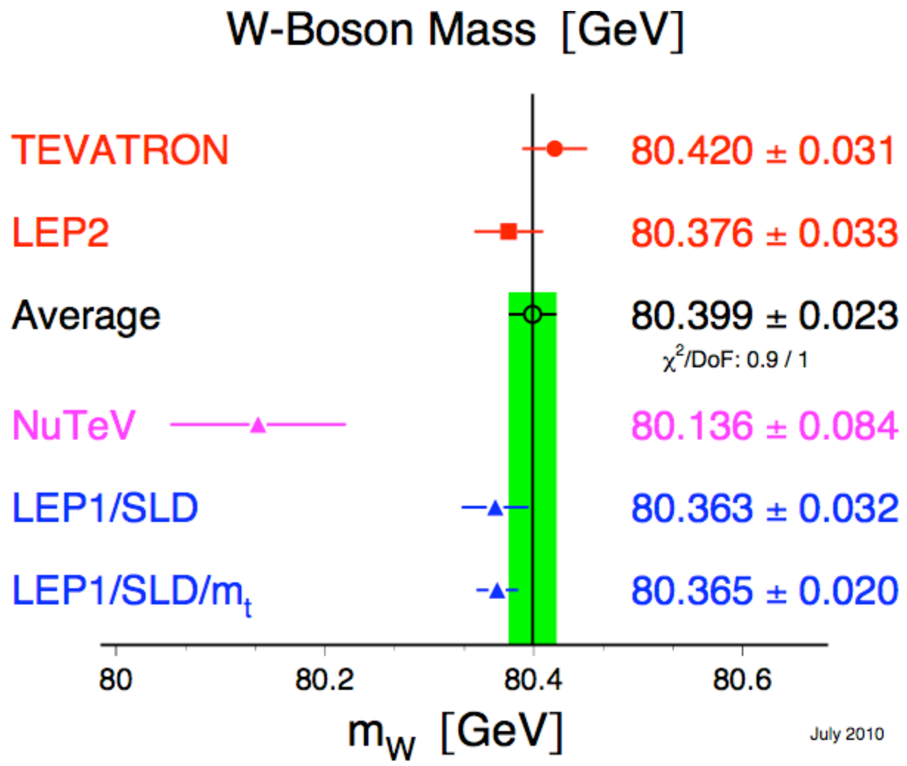


- Location of peak gives M_W
- Shape of distribution sensitive to Γ_W

World average for W mass

- Direct measurements (LEP2/Tevatron) and indirect measurements (LEP1/SLD) in excellent agreement.

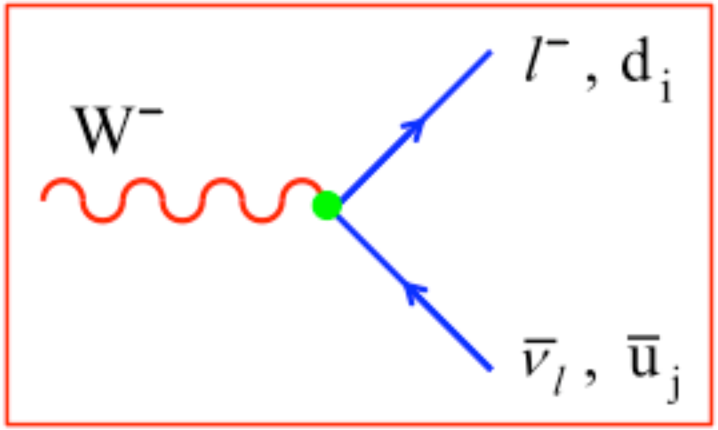
- Indirect measuremets assume a Higgs mass



LEP EWWG home page

W boson properties

- W decays: $W^- \to e^- \bar{\nu}_e,\ \mu^- \bar{\nu}_\mu,\ \tau^- \bar{\nu}_\tau,\ d\bar{u},\ s\bar{c}$
  - Constrain V_{ud}, V_{cs}
  - Test lepton universality



$$\Gamma(W^- \to \ell^- \bar{\nu}_\ell) = \frac{G_F M_W^3}{6\pi\sqrt{2}}$$

$$\Gamma(W^- \to d_i \bar{u}_j) = \frac{G_F M_W^3}{6\pi\sqrt{2}} |V_{ij}|^2 N_C$$

$$BR(W^- \to \ell^- \bar{\nu}_\ell) \equiv \frac{\Gamma(W^- \to \ell^- \bar{\nu}_\ell)}{\Gamma(W^- \to \mathrm{all})} = \frac{1}{3 + 2N_C} = 11.1\%$$

- **QCD:** $N_C \left\{ 1 + \frac{\alpha_s(M_Z)}{\pi} \right\} \approx 3.115 \Longrightarrow BR(W^- \to \ell^- \bar{\nu}_\ell) \approx 10.8\%$

Experiment:

$$BR(W^- \to e^- \bar{\nu}_e) = (10.65 \pm 0.17)\%$$
$$BR(W^- \to \mu^- \bar{\nu}_\mu) = (10.59 \pm 0.15)\%$$
$$BR(W^- \to \tau^- \bar{\nu}_\tau) = (11.44 \pm 0.22)\%$$

- Hadron colliders measure:

$$\frac{\sigma(p\bar{p} \to W \to \ell\nu)}{\sigma(p\bar{p} \to Z \to \ell\bar{\ell})} = \frac{\sigma(p\bar{p} \to W)}{\sigma(p\bar{p} \to Z)} \frac{1}{BR(Z \to \ell\bar{\ell})} \frac{\Gamma(W \to \ell\nu)}{\Gamma_W}$$

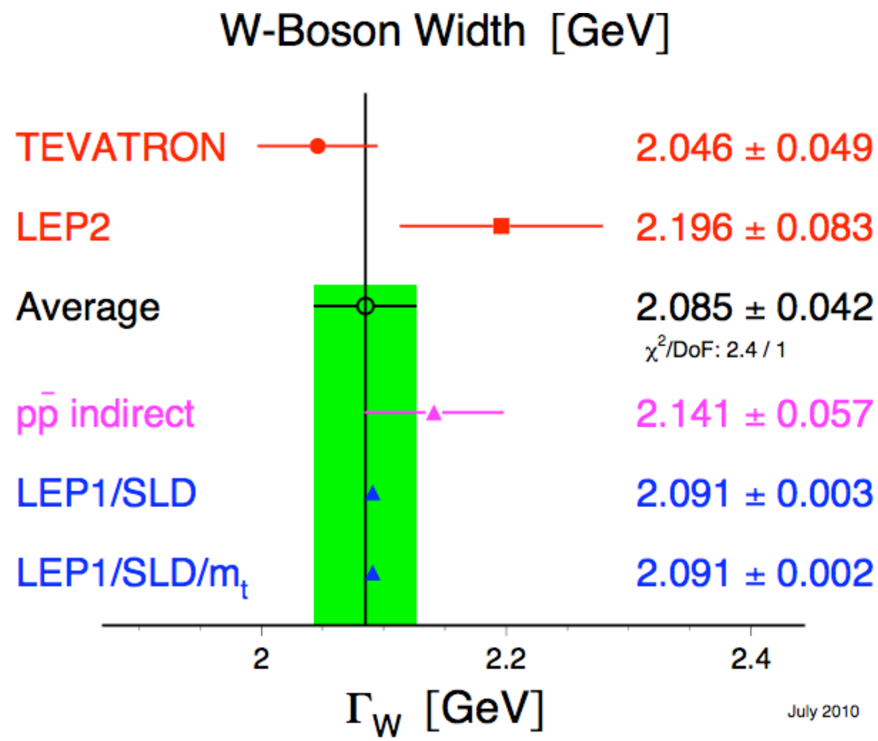
- Calculated at NNLO → $\sigma(p\bar{p} \to W)/\sigma(p\bar{p} \to Z)$

LEP → $BR(Z \to \ell\bar{\ell})$

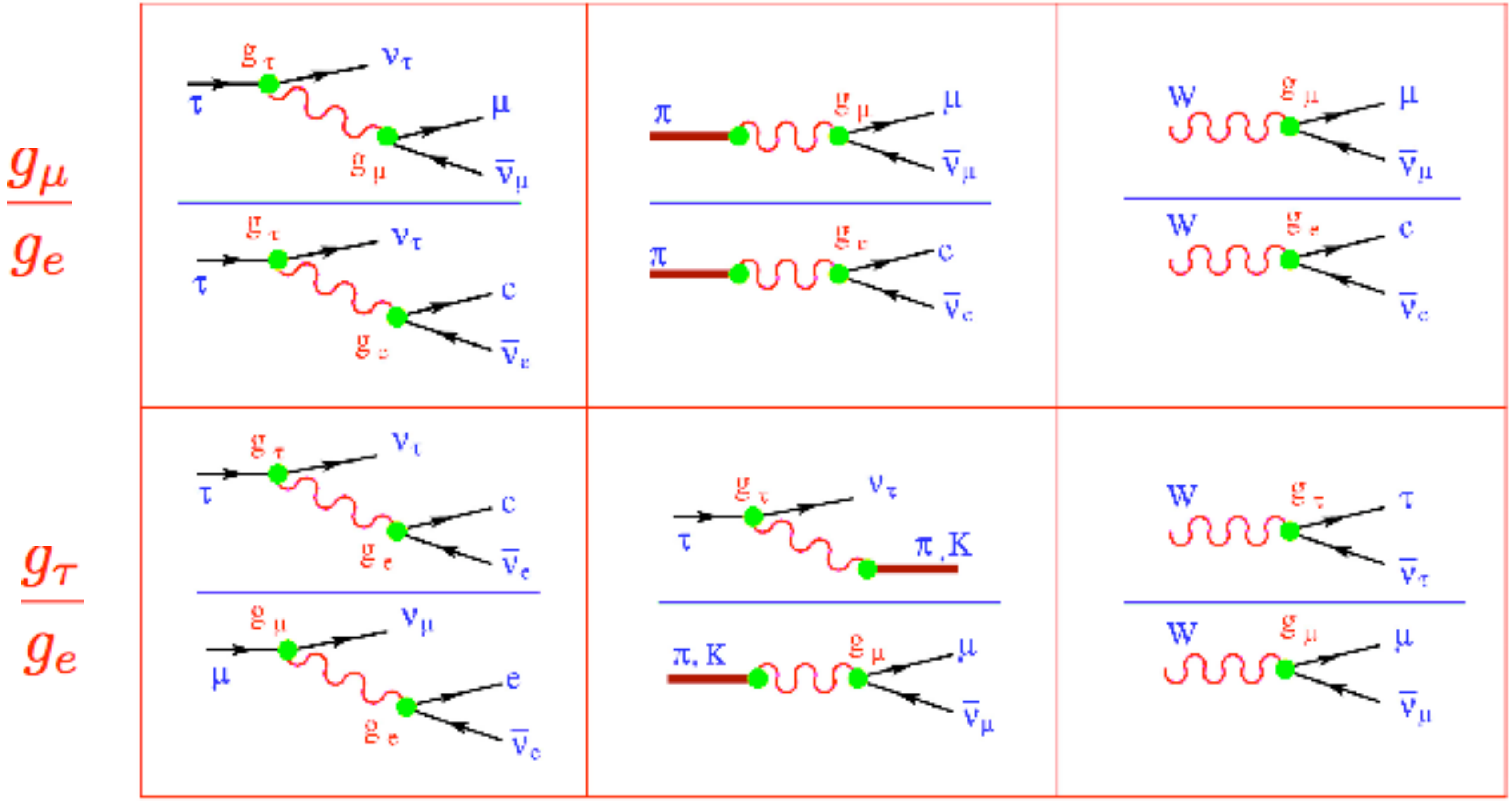
- Luminosities and some uncertainties cancel in the ratio

W decay width:

$\Gamma_W = 2.09$ GeV   Exp: 2.098 ± 0.048 GeV



Universal $W\ell\nu_\ell$ couplings



Charged current universality

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0018 ± 0.0015
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0021 ± 0.0016
$B_{K\to\mu}/B_{K\to e}$	1.004 ± 0.007
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.002 ± 0.002
$B_{W\to\mu}/B_{W\to e}$	0.997 ± 0.010

$$\left|\frac{g_\mu}{g_e}\right|$$

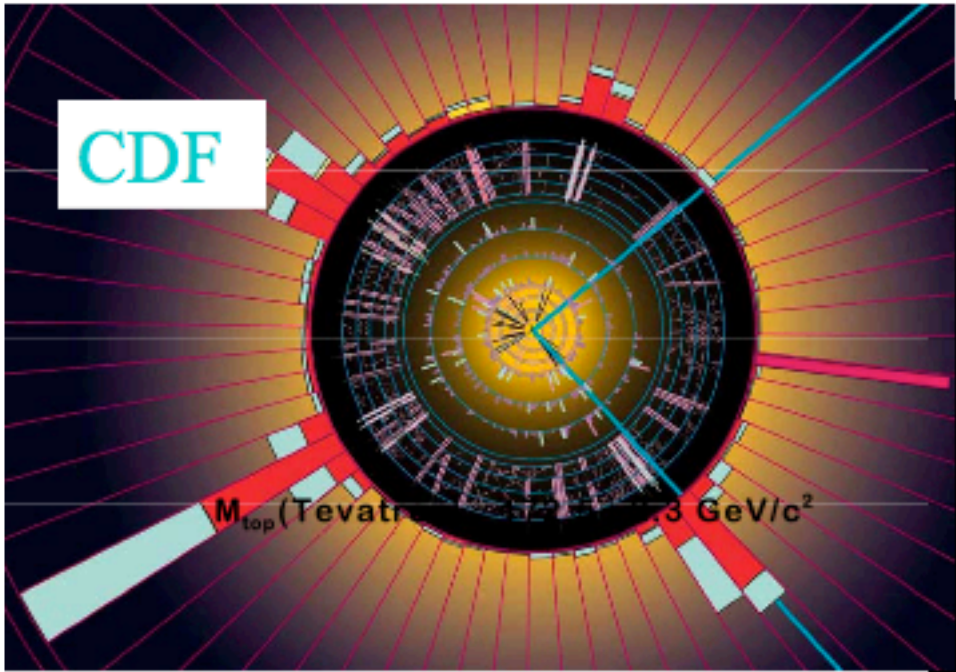
$$\left|\frac{g_\tau}{g_\mu}\right|$$

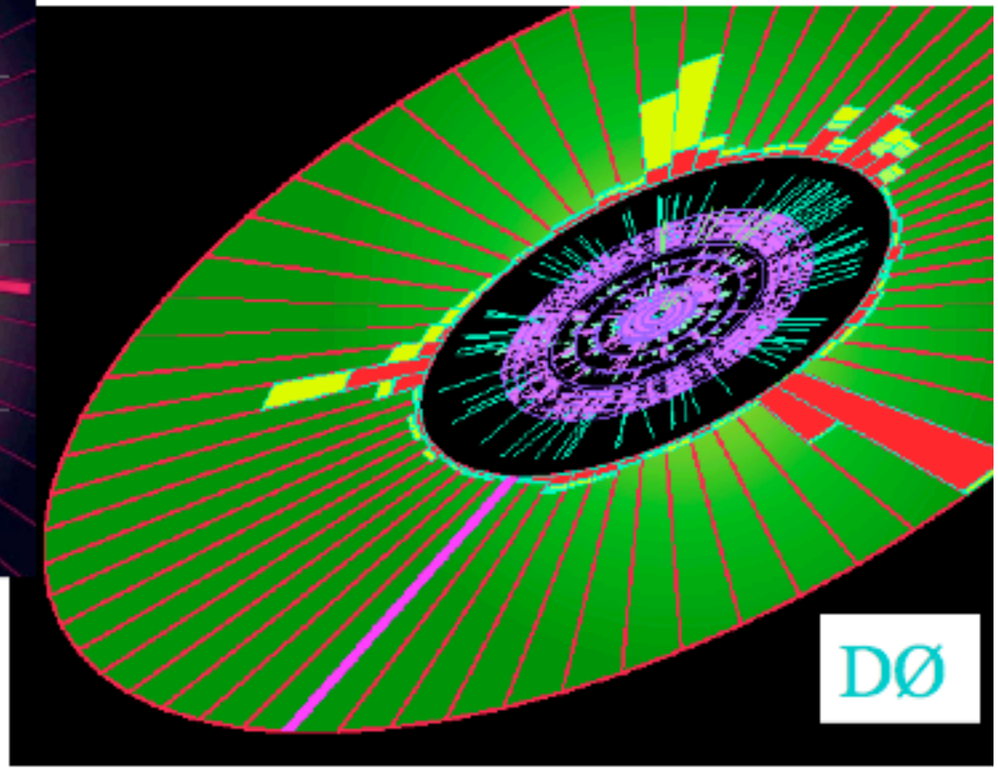
$B_{\tau\to e}\tau_\mu/\tau_\tau$	1.0006 ± 0.0022
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.996 ± 0.005
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.979 ± 0.017
$B_{W\to\tau}/B_{W\to\mu}$	1.039 ± 0.013

$B_{\tau\to\mu}\tau_\mu/\tau_\tau$	1.0005 ± 0.0023
$B_{W\to\tau}/B_{W\to e}$	1.036 ± 0.014

$$\left|\frac{g_\tau}{g_e}\right|$$

Top quark discovered at Fermilab



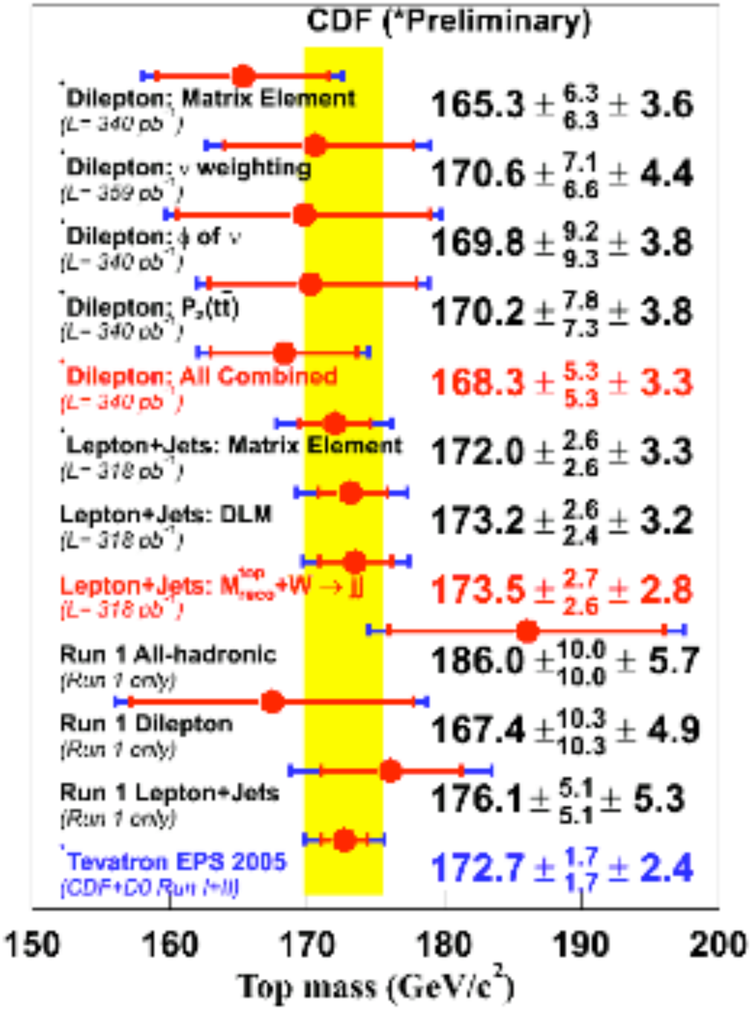


Why is it so heavy?

M_{top}(Tevatron) = 172.5 ± 2.3 GeV

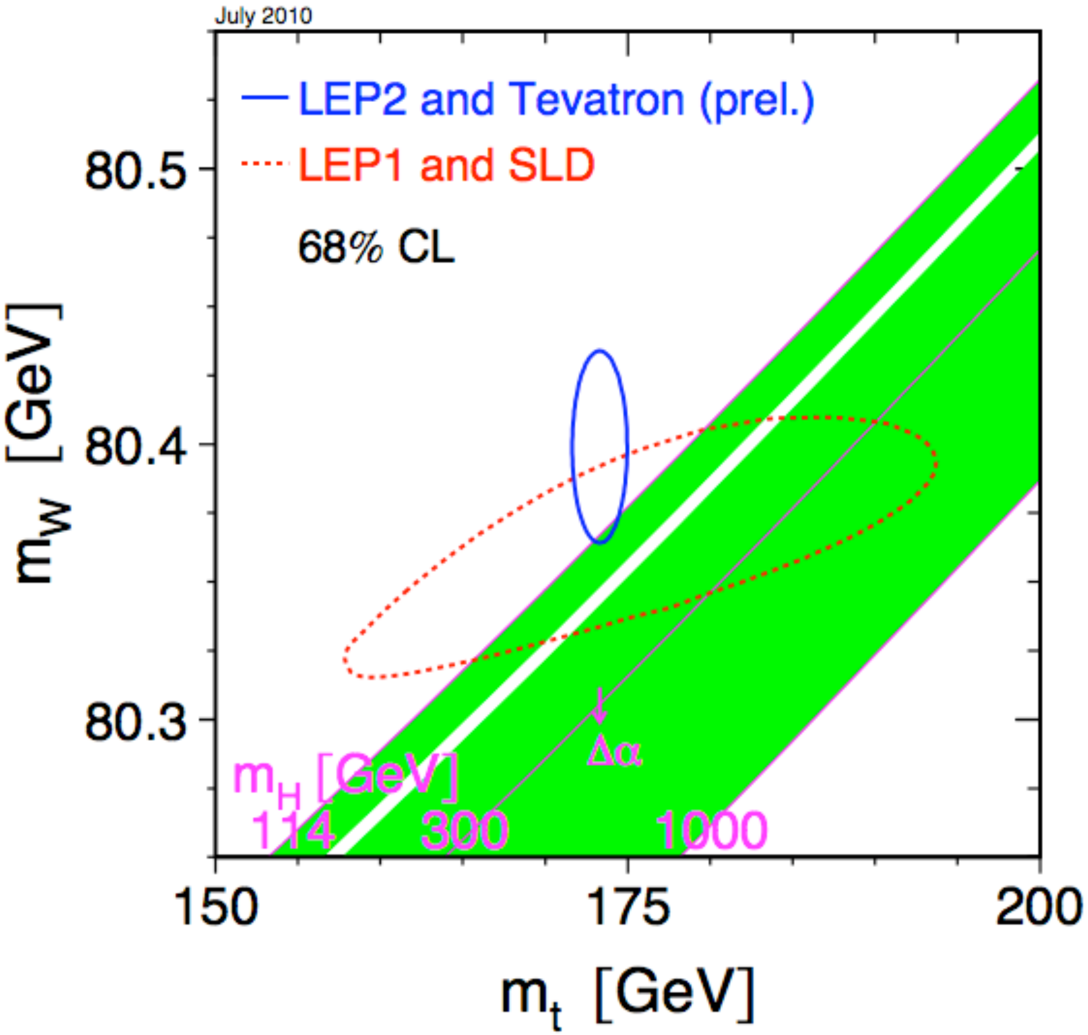
$\Gamma_{top} > \Lambda_{QCD}$ ➔ decays before hadronizing

Top quark mass measured in many channels:



Top quark mass pins down Higgs mass

- Data prefer a light Higgs



Top forward-backward asymmetry at the Tevatron

- Top is the only known fermion with mass of order of the electroweak symmetry breaking (EWSB) scale → special role in many beyond SM theories of EWSB

- Top quark pair production may be sensitive to unknown heavy particles: axigluons, Z′, Kaluza-Klein excitations of SM gauge bosons, …

- Different vector and axial couplings of new resonances to top and anti-top → charge asymmetric effects

- Example: top forward-backward asymmetry at the Tevatron

- A_{FB} in the $t\bar{t}$ CM frame is the top quark forward-backward asymmetry in the angle θ (between the top quark momentum and the initial proton direction)

$$\mathcal{A}_{FB} = \frac{N_t(\cos\theta > 0) - N_t(\cos\theta < 0)}{N_t(\cos\theta > 0) + N_t(\cos\theta < 0)}$$

- Since in the CM frame $N_t(\cos\theta < 0) = N_{\bar{t}}(\cos\bar{\theta} > 0)$, it can be written as:

$$\mathcal{A}_{FB} = \frac{N_t(\cos\theta > 0) - N_{\bar{t}}(\cos\bar{\theta} > 0)}{N_t(\cos\theta > 0) + N_{\bar{t}}(\cos\bar{\theta} > 0)}$$

That is, a charge asymmetry

- **QCD** at tree level FB symmetric [V coupling; compare with A_{FB} at LEP] ➔ A_{FB} is generated at NLO in QCD, electroweak corrections also known: $\mathcal{A}_{FB}^{SM} = 0.088 \pm 0.013$

$$\mathcal{A}_{FB}^{SM} = 0.088 \pm 0.013$$

- A_{FB} measured at the tevatron by CDF and D0:

$$\mathcal{A}_{FB}^{\exp} = 0.158 \pm 0.074 \qquad \mathcal{A}_{FB}^{\exp}(m_{t\bar{t}} > 450\,\mathrm{GeV}) = 0.475 \pm 0.114$$

- Total cross-section in agreement with SM:

$$\sigma_t^{SM} = 7.46^{+0.66}_{-0.80}\,\mathrm{pb} \qquad \sigma_t^{\exp} = 7.50 \pm 0.48\,\mathrm{pb}$$

$$\sigma_t = \sigma^F + \sigma^B = \sigma_t^{SM}$$

$$\sigma^{F,B} = \sigma_{SM}^{F,B} + \sigma_{int}^{F,B} + \sigma_{new}^{F,B}$$

$$\mathcal{A}_{FB} = \frac{\sigma^F - \sigma^B}{\sigma^F + \sigma^B} \neq \mathcal{A}_{FB}^{SM}$$

- Axial coupling: $\sigma_{int}^F + \sigma_{int}^B = 0$

- Large new interactions: $\sigma_{int}^F + \sigma_{int}^B = -(\sigma_{new}^F + \sigma_{new}^B)$

Top charge asymmetry at the LHC

- LHC is a pp collider, harder to define "forward" and "backward" (it can be done event by event)

- t more "forward" than $\bar{t}$ at the parton level (initial q larger momentum fraction than $\bar{q}$) ➔ tops larger (pseudo)rapidities in the LAB frame

$$\eta \equiv -\log \tan(\theta/2) \approx y = \frac{1}{2} \log \left(\frac{E + p_L}{E - p_L} \right)$$

- Charge asymmetries:

$$\mathcal{A}_C = \frac{N(\Delta > 0) - N(\Delta < 0)}{N(\Delta > 0) + N(\Delta < 0)} \qquad \Delta = |\eta_t| - |\eta_{\bar{t}}|$$

- In the SM top pair events produced by gluon-gluon fusion ➔ A_C tiny $\mathcal{A}_C^{SM} = 0.0130(11)$

- CMS: $\mathcal{A}_C^{\text{exp}} = 0.060 \pm 0.134(\text{stat.}) \pm 0.026(\text{stat.})$