Física de Partículas

Modelo GWS

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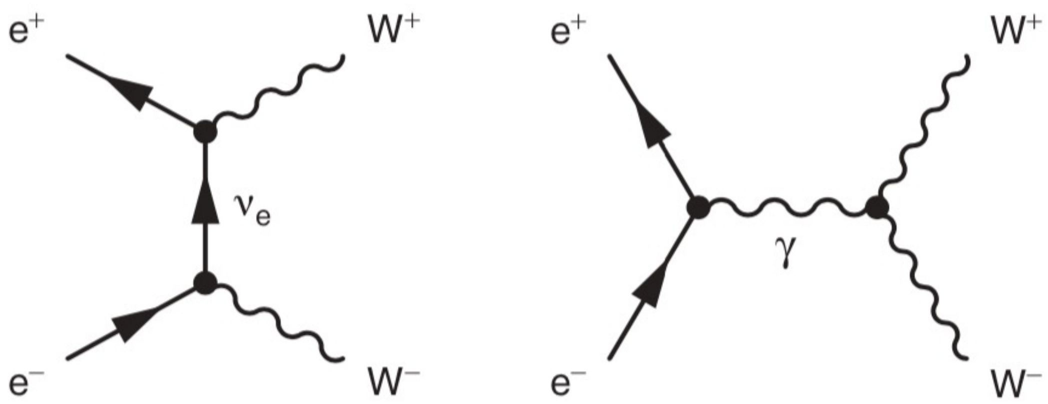
W-pair production

- Since W bosons are charged (EM charge), they couple to the photon
- W pairs can be produced in electron-positron colliders or hadron colliders



- However: the cross section diverges if only these diagrams are considered
- An additional gauge boson: the neutral Z boson

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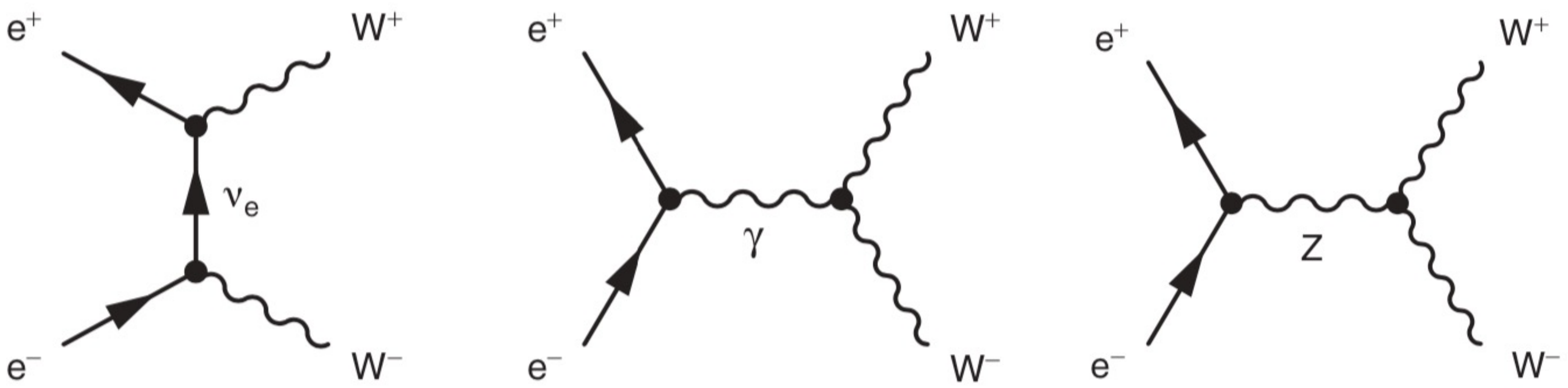


- An additional gauge boson: the neutral Z boson

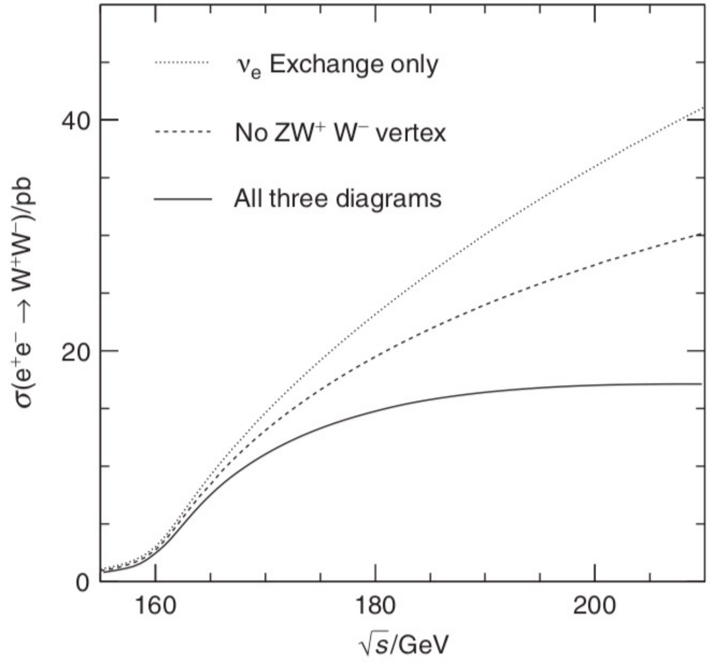
$$|\mathcal{M}_\nu + \mathcal{M}_\gamma + \mathcal{M}_Z|^2 < |\mathcal{M}_\nu + \mathcal{M}_\gamma|^2$$

W-pair production

- Since W bosons are charged (EM charge), they couple to the photon
- W pairs can be produced in electron-positron colliders or hadron colliders
- An additional gauge boson: the neutral Z boson

$$|\mathcal{M}_\nu + \mathcal{M}_\gamma + \mathcal{M}_Z|^2 < |\mathcal{M}_\nu + \mathcal{M}_\gamma|^2$$

- This only works if the couplings are all related:
  Electroweak Unification



Weak interaction gauge group

- QED and QCD are associated to U(1) and SU(3) local gauge symmetries
- The charged weak interaction can be associated with an SU(2) local gauge symmetry:

$$\varphi(x) \to \varphi'(x) = \exp\left[ig_W\,\boldsymbol{\alpha}(x)\cdot\mathbf{T}\right]\varphi(x) \qquad \mathbf{T} = \tfrac{1}{2}\boldsymbol{\sigma}$$

- 3 gauge fields: W_1, W_2, W_3
- The wave function must be a doublet: $\varphi(x) = \begin{pmatrix} \nu_e(x) \\ e^-(x) \end{pmatrix}$
- However: the weak interaction couples only to LH particles and RH anti-particles
- So RH particles and LH anti-particles are put in singlets (remain unaffected by local gauge transformation)

- QED and QCD are associated to U(1) and SU(3) local gauge symmetries
- The charged weak interaction can be associated with an $SU(2)_L$ local gauge symmetry

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, \quad \begin{pmatrix} u \\ d' \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L, \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

$$e_R^-, \quad \mu_R^-, \quad \tau_R^-, \quad u_R, \quad c_R, \quad t_R, \quad d_R, \quad s_R, \quad b_R$$

- We get an interaction term:

$$ig_W T_k \gamma^\mu W_\mu^k \varphi_L = ig_W \tfrac{1}{2}\sigma_k \gamma^\mu W_\mu^k \varphi_L \qquad \varphi_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

Weak interaction gauge group

- The weak charged current corresponding to the exchange of the physical W bosons are:

$$j_{\pm}^{\mu} = \frac{1}{\sqrt{2}}\left(j_1^{\mu} \pm i j_2^{\mu}\right) = \frac{g_W}{\sqrt{2}}\overline{\varphi}_L\gamma^{\mu}\tfrac{1}{2}(\sigma_1 \pm i\sigma_2)\varphi_L$$

$$= \frac{g_W}{\sqrt{2}}\overline{\varphi}_L\gamma^{\mu}\sigma_{\pm}\varphi_L$$

- And the W bosons are linear combinations of W_1, W_2:

$$W_{\mu}^{\pm} = \frac{1}{\sqrt{2}}\left(W_{\mu}^{(1)} \mp i W_{\mu}^{(2)}\right)$$

- Explicitly:

$$j_{+}^{\mu} = \frac{g_W}{\sqrt{2}}\overline{\varphi}_L\gamma^{\mu}\sigma_{+}\varphi_L = \frac{g_W}{\sqrt{2}}\begin{pmatrix}\overline{\nu}_L & \overline{e}_L\end{pmatrix}\gamma^{\mu}\begin{pmatrix}0 & 1\\ 0 & 0\end{pmatrix}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}$$

$$= \frac{g_W}{\sqrt{2}}\overline{\nu}_L\gamma^{\mu}e_L \equiv \frac{g_W}{\sqrt{2}}\overline{\nu}\,\gamma^{\mu}\tfrac{1}{2}(1-\gamma^5)e$$

$$j_{-}^{\mu} = \frac{g_W}{\sqrt{2}}\overline{\varphi}_L\gamma^{\mu}\sigma_{-}\varphi_L = \frac{g_W}{\sqrt{2}}\begin{pmatrix}\overline{\nu}_L & \overline{e}_L\end{pmatrix}\gamma^{\mu}\begin{pmatrix}0 & 0\\ 1 & 0\end{pmatrix}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}$$

$$= \frac{g_W}{\sqrt{2}}\overline{e}_L\gamma^{\mu}\nu_L \equiv \frac{g_W}{\sqrt{2}}\overline{e}\,\gamma^{\mu}\tfrac{1}{2}(1-\gamma^5)\nu$$

Weak interaction gauge group

- The symmetry of the weak interaction results in the charged weak currents:

$$j_{+}^{\mu} = \frac{g_{W}}{\sqrt{2}} \overline{\nu} \gamma^{\mu} \tfrac{1}{2}(1 - \gamma^{5}) e \qquad j_{-}^{\mu} = \frac{g_{W}}{\sqrt{2}} \overline{e} \gamma^{\mu} \tfrac{1}{2}(1 - \gamma^{5}) \nu$$

with the already familiar V-A structure

- The third gauge boson implies a neutral current:

$$j_{3}^{\mu} = g_{W} \overline{\varphi}_{L} \gamma^{\mu} \tfrac{1}{2} \sigma_{3} \varphi_{L}$$

$$j_{3}^{\mu} = g_{W} \tfrac{1}{2} \begin{pmatrix} \overline{\nu}_{L} & \overline{e}_{L} \end{pmatrix} \gamma^{\mu} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} \nu_{L} \\ e_{L} \end{pmatrix}$$

$$= g_{W} \tfrac{1}{2} \overline{\nu}_{L} \gamma^{\mu} \nu_{L} - g_{W} \tfrac{1}{2} \overline{e}_{L} \gamma^{\mu} e_{L}$$

$$j_{3}^{\mu} = I_{W}^{(3)} g_{W} \overline{f} \gamma^{\mu} \tfrac{1}{2}(1 - \gamma^{5}) f \qquad I_{W}^{(3)} = \pm 1/2$$

Electroweak unification

- At this point it would be natural to assume the weak neutral current W_3 corresponds to the Z boson
- However: the Z boson does couple to RH particles and LH anti-particles
- Also, W and Z bosons would have the same coupling strength – not seen experimentally
- The solution: Unify QED and the weak force – Electroweak model

Electroweak model (GWS model)

- The Glashow, Weinberg and Salam model: EM and weak interactions as different manifestations of a single unified electroweak force (Nobel Prize 1979)
- The local U(1) symmetry of QED is replaced by a local $U(1)_Y$ symmetry (weak hypercharge):

$$\psi(x) \to \psi'(x) = \hat{U}(x)\psi(x) = \exp\left[ig'\frac{Y}{2}\zeta(x)\right]\psi(x)$$

$$g'\frac{Y}{2}\gamma^\mu B_\mu \psi$$

- The photon and the Z boson can be written as combinations of the neutral gauge bosons:

$$A_\mu = +B_\mu \cos\theta_W + W_\mu^{(3)} \sin\theta_W$$

$$Z_\mu = -B_\mu \sin\theta_W + W_\mu^{(3)} \cos\theta_W$$

Electroweak model (GWS model)

- Underlying symmetry: $SU(2)_L \times U(1)_Y$
- Photon properties must be the same we found for QED – couplings are related:

$$e = g_W \sin\theta_W$$

- Z boson coupling:

$$g_Z = \frac{g_W}{\cos\theta_W} \equiv \frac{e}{\sin\theta_W \cos\theta_W}$$

- And the Z boson current:

$$j_Z^\mu = g_Z \left(c_L \bar{u}_L \gamma^\mu u_L + c_R \bar{u}_R \gamma^\mu u_R \right)$$

the Z boson couples to both LH and RH particles, but differently

Electroweak model (GWS model)

- Underlying symmetry: $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
- Analogous to the charged weak current, the Z boson current can be written as:

$$j_Z^\mu = g_Z \bar{u} \gamma^\mu \left[c_L \tfrac{1}{2}(1-\gamma^5) + c_R \tfrac{1}{2}(1+\gamma^5) \right] u$$
$$= g_Z \bar{u} \gamma^\mu \, \tfrac{1}{2} \left[(c_L + c_R) - (c_L - c_R)\gamma^5 \right] u.$$

$$j_Z^\mu = \tfrac{1}{2} g_Z \bar{u} \left(c_V \gamma^\mu - c_A \gamma^\mu \gamma^5 \right) u$$

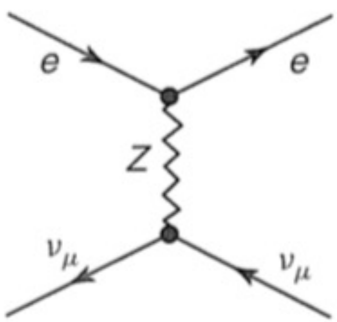
f	c_V	c_A
ν_e, ν_μ, ν_τ	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-, τ^-	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$
u, c, t	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_w$	$\frac{1}{2}$
d, s, b	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_w$	$-\frac{1}{2}$

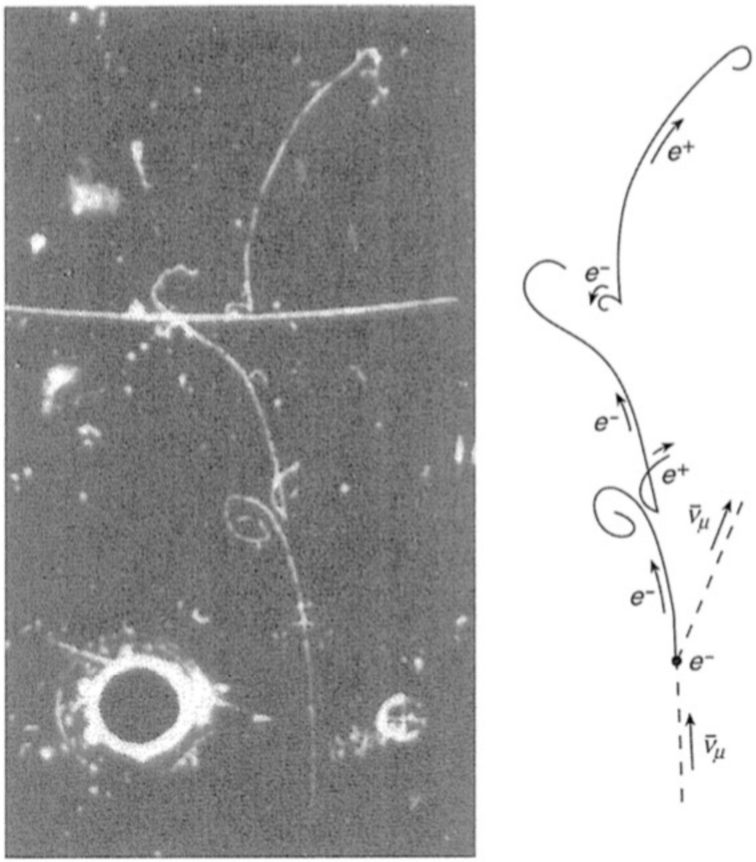
- Z boson interaction vertex:

$$-i \tfrac{1}{2} g_Z \gamma^\mu \left[c_V - c_A \gamma^5 \right]$$

Evidence for the GWS Model

- Discovery of Neutral Currents (1973): Only possible Feynman diagram (no $W^{\pm}$ diagram). Indirect evidence for Z.





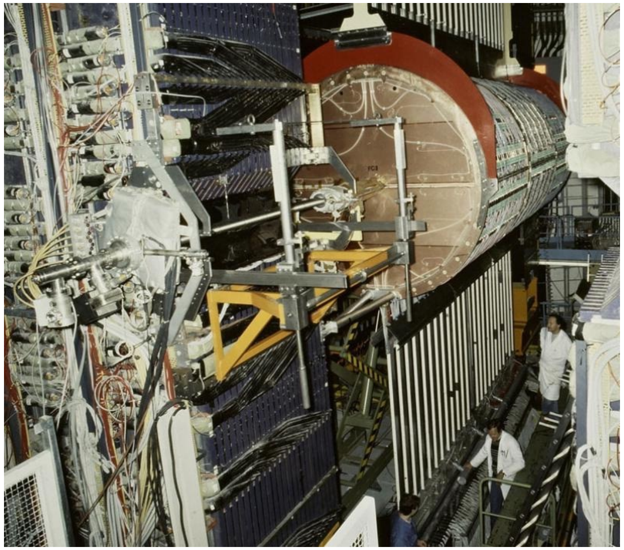
Evidence for the GWS Model

- First direct observation in $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV via decays into $p\bar{p} \rightarrow Z + X$

- Precision measurements (LEP):

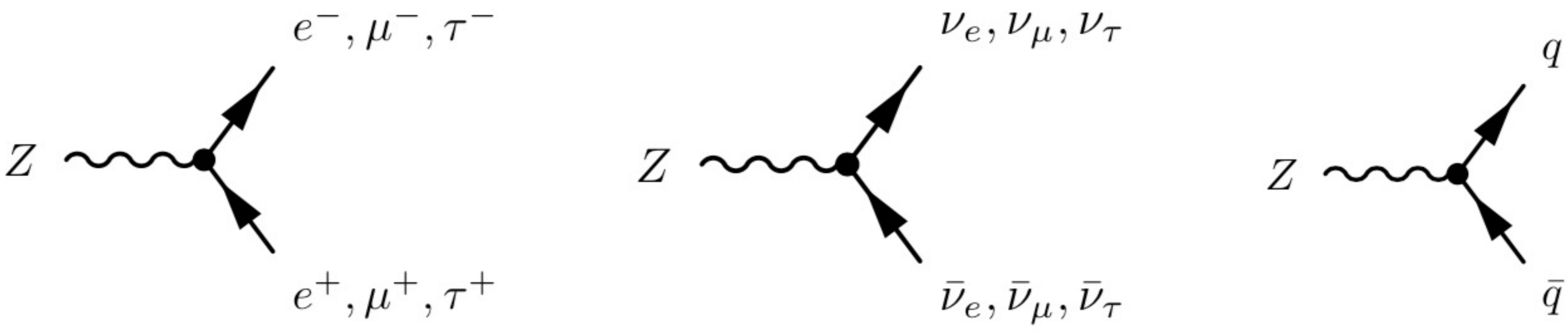
$$\sin^2\theta_W = 0.23146 \pm 0.00012$$

$$\frac{\alpha}{\alpha_W} = \frac{e^2}{g_W^2} = \sin^2\theta_W \sim 0.23$$



UA1 Experiment at CERN Used Super Proton Synchrotron (now part of LHC)

$Z \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ $\quad$ $Z \to \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau$ $\quad$ $Z \to q\bar{q}$



- The Z boson does not change flavour
- The Z coupling is a mixture of EM and weak couplings – depends on $\sin\theta_W^2$

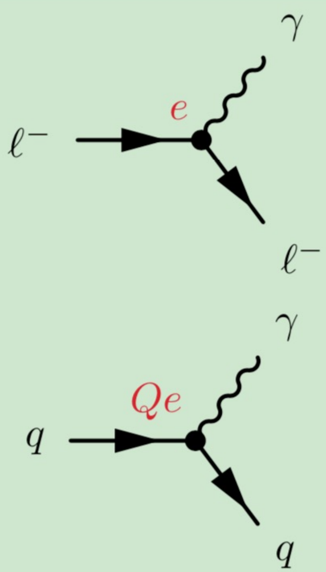
So far <u>in the model</u> the gauge bosons remain massless

Where we are so far

- The main elements of the Standard Model of particle physics have been described
- There are 12 fundamental spin-half fermions (particles and anti-particles): Dirac equation
- The interactions between particles are described by the exchange of spin-1 gauge bosons : local gauge principle
- Underlying gauge symmetry of the Standard Model is $U(1)_Y \times SU(2)_L \times SU(3)_c$: EM and weak interactions described by the unified electroweak theory
- The predictions of the Electroweak theory were confronted with precision measurements at LEP

Where we are so far

Electromagnetic (QED)

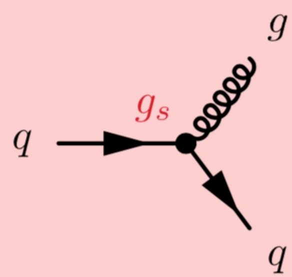


$$\alpha = \frac{e^2}{4\pi}$$

$q = u, d, s, c, b, t$

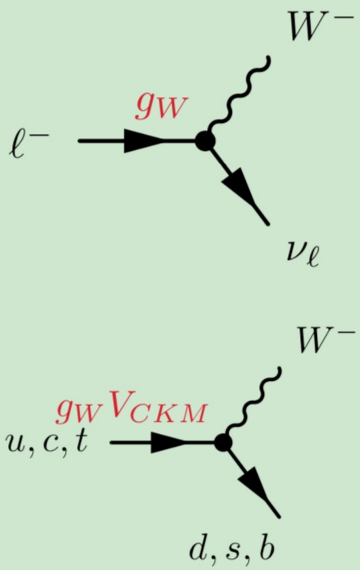
+ antiparticles

Strong (QCD)



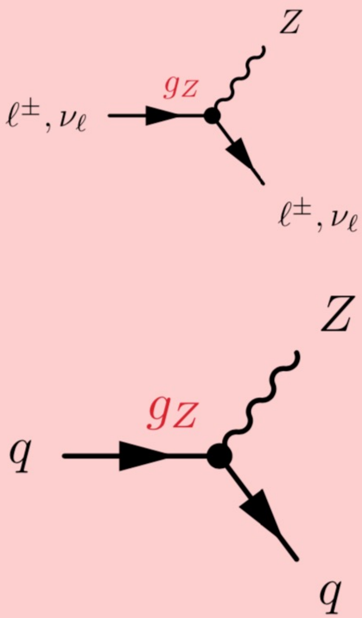
$$\alpha_s = \frac{g_s^2}{4\pi}$$

Weak CC



$$\alpha_W = \frac{g_W^2}{4\pi}$$

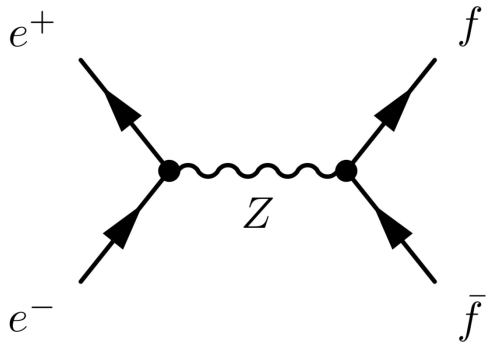
Weak NC

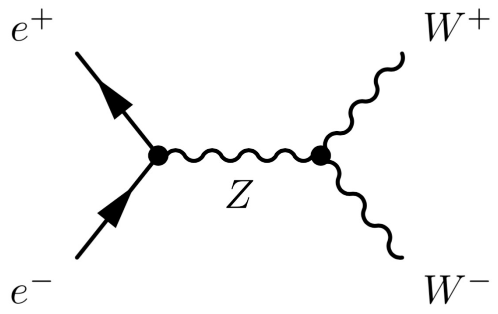


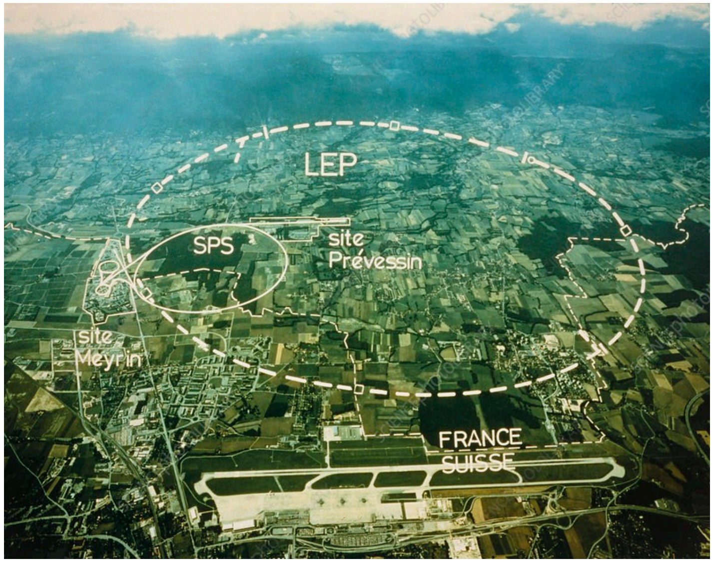
$$g_Z = \frac{g_W}{\cos\theta_W}$$

LEP

- Large Electron Positron collider at CERN (1989-2000)
- Designed as a Z and W boson factory

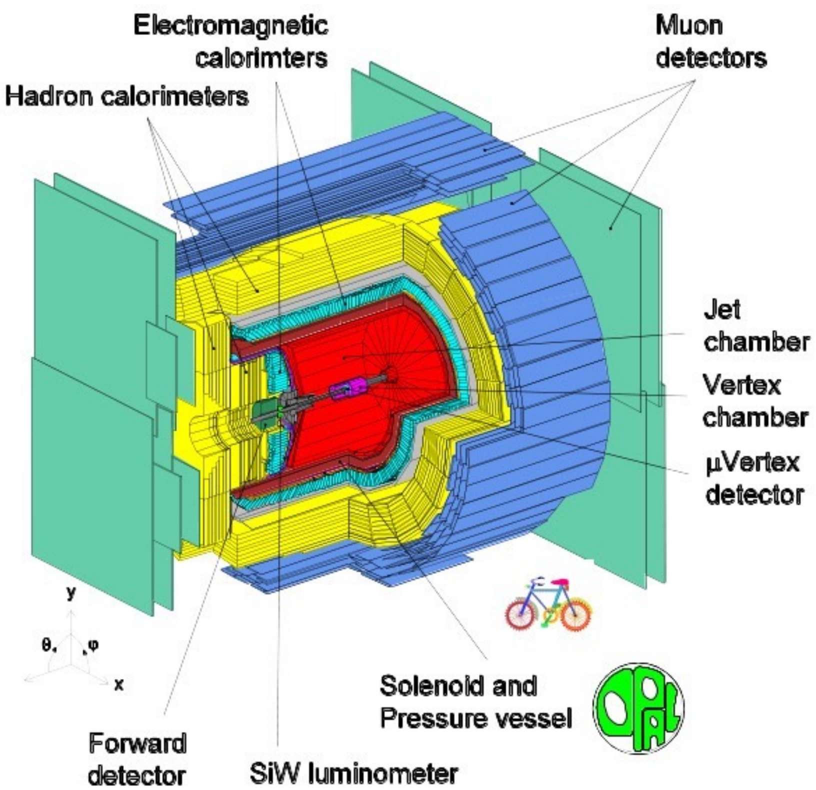


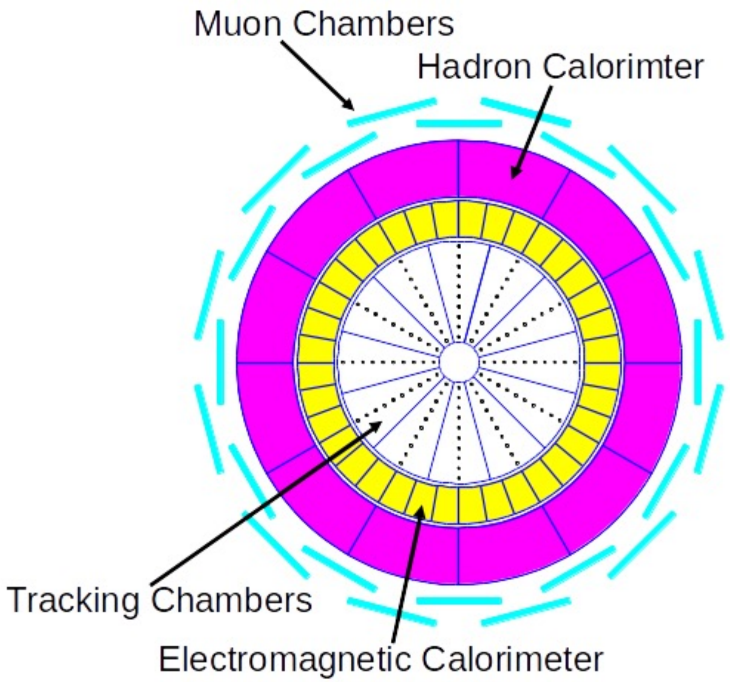




- Highest energy e^+e^- collider ever built: $\sqrt{s}$ = 90-209 GeV
- Circumference: 27 km (LEP tunnel used for the LHC)
- The 4 experiments combined: 16×10^6 Z events, 30×10^3 W events

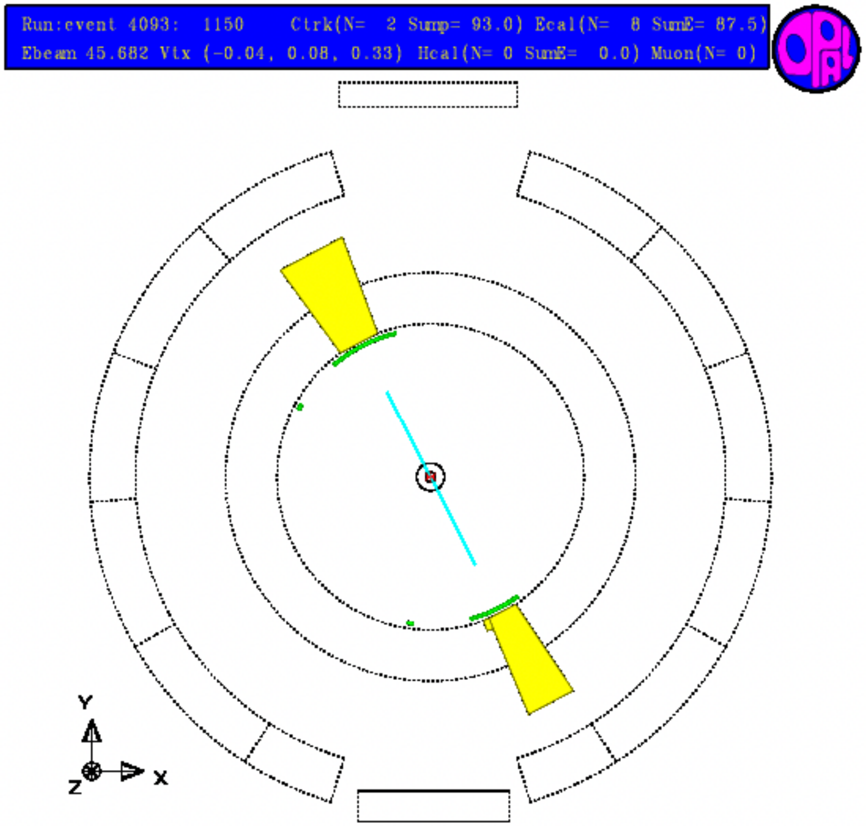
- One of the 4 experiments at LEP



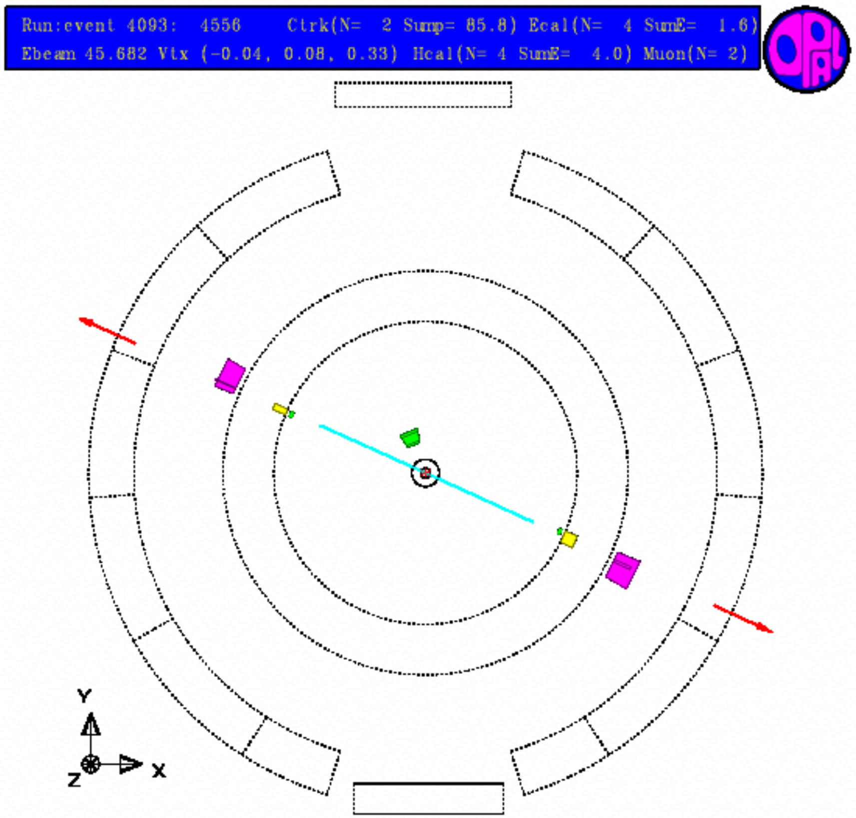


Typical Z events

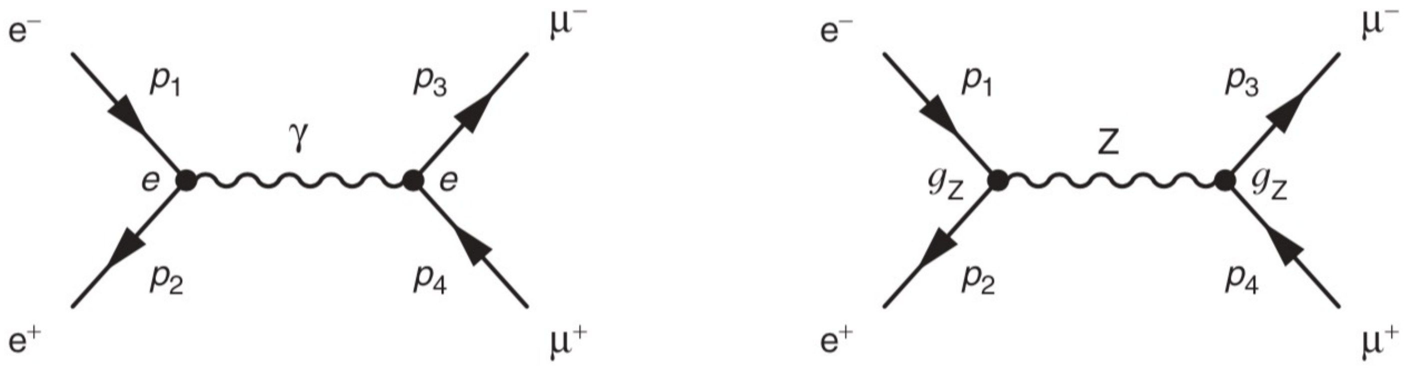
$$e^+e^- \to Z \to e^+e^-$$



$$e^+e^- \to Z \to \mu^+\mu^-$$



Z resonance

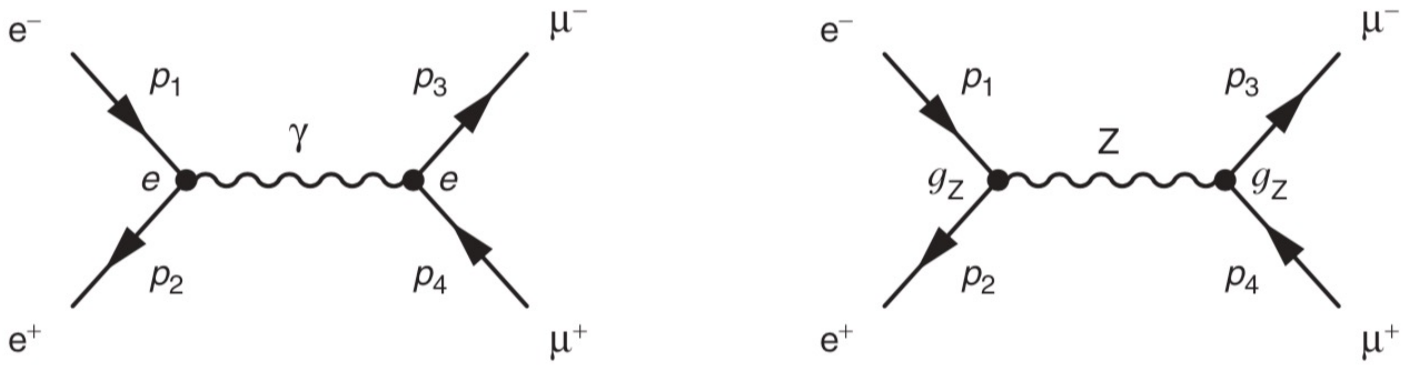


- We already calculated the QED process
- The matrix elements:

$$\mathcal{M}_\gamma \propto \frac{e^2}{q^2} \qquad \mathcal{M}_Z \propto \frac{g_Z^2}{q^2 - m_Z^2}$$

- The QED process dominates at low centre of mass energy ($q^2 = s$)
- In the region $\sqrt{s} \sim m_Z$ the Z-boson process dominates

Z resonance



- The Z boson is not a stable particle: propagator modified

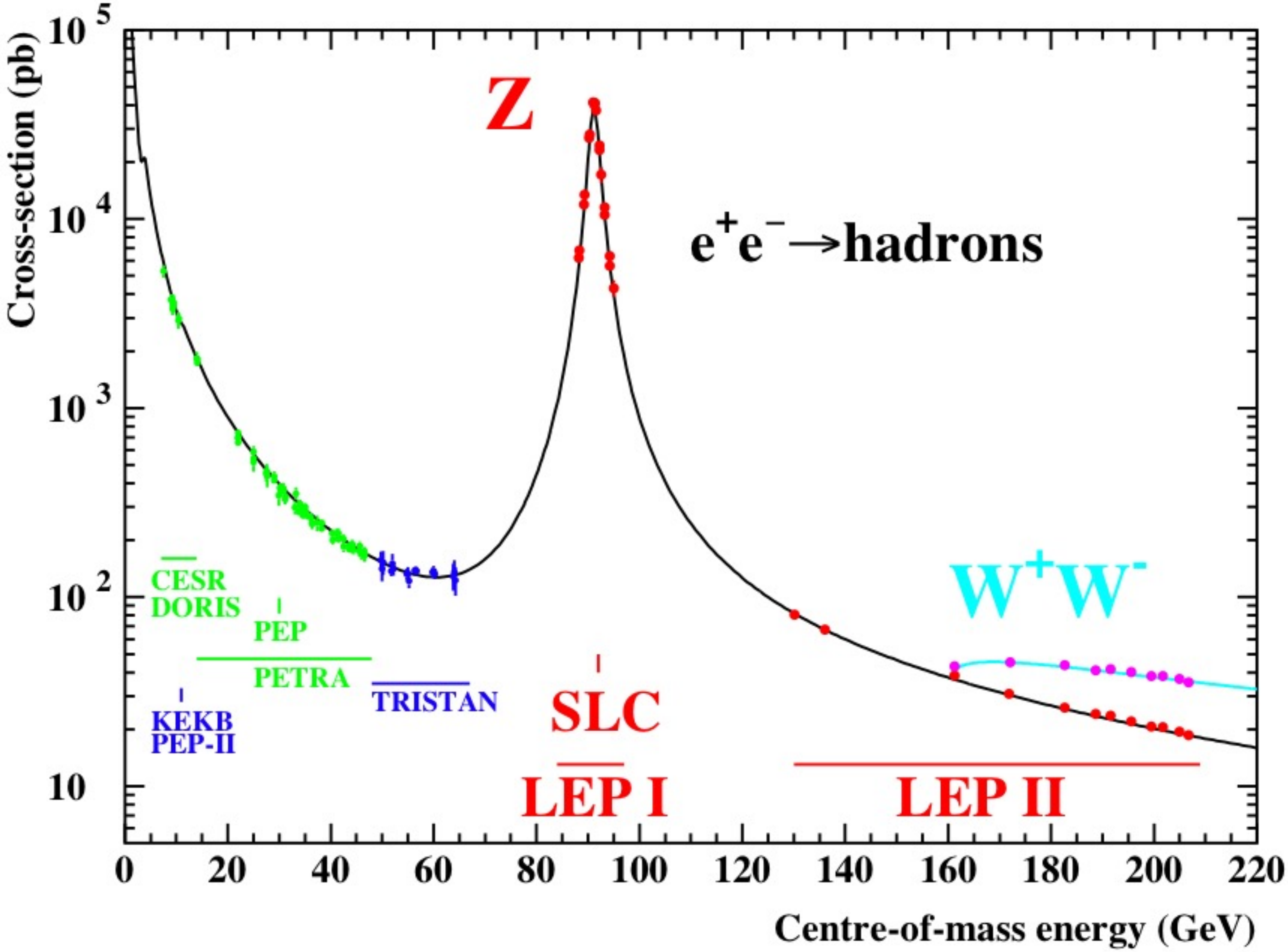
$$\frac{1}{q^2 - m_Z^2} \to \frac{1}{q^2 - m_Z^2 + i m_Z \Gamma_Z}$$

- And the cross section is proportional to:

$$\sigma \propto \frac{1}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2}$$

Breit-Wigner resonance

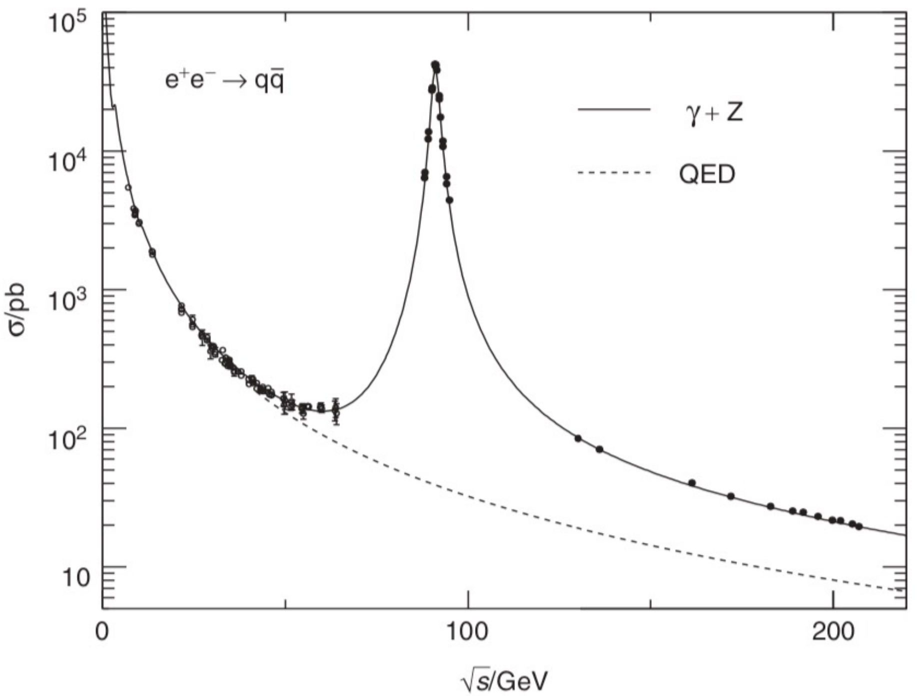
Z resonance



Cross-section (pb)
10 5
10 4
10 3
10 2
10
Z
e+e−→hadrons
CESR
DORIS
PEP
PETRA
KEKB
PEP-II
TRISTAN
SLC
LEP I
LEP II
W+W-
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)

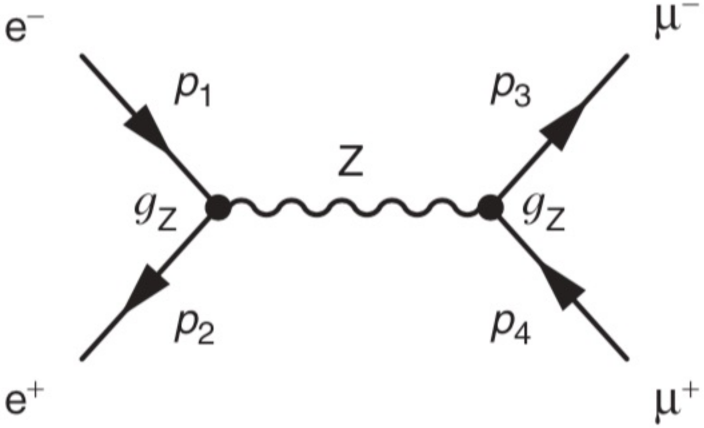
Z resonance

- Below 40 GeV: QED process dominates
- Between 50 and 80 GeV: contributions from both processes
- Around the resonance: Z boson process dominates
- Away from the resonance: both processes of the same order of magnitude (EW unification)



- The cross section calculation around the resonance would only need the Z boson contribution

$$\mathcal{M}_{fi} = -\frac{g_Z^2}{(s - m_Z^2 + i m_Z \Gamma_Z)} g_{\mu\nu} \left[\overline{v}(p_2)\gamma^{\mu}\tfrac{1}{2}\left(c_V^{e} - c_A^{e}\gamma^5\right) u(p_1)\right] \times \left[\overline{u}(p_3)\gamma^{\nu}\tfrac{1}{2}\left(c_V^{\mu} - c_A^{\mu}\gamma^5\right) v(p_4)\right],$$

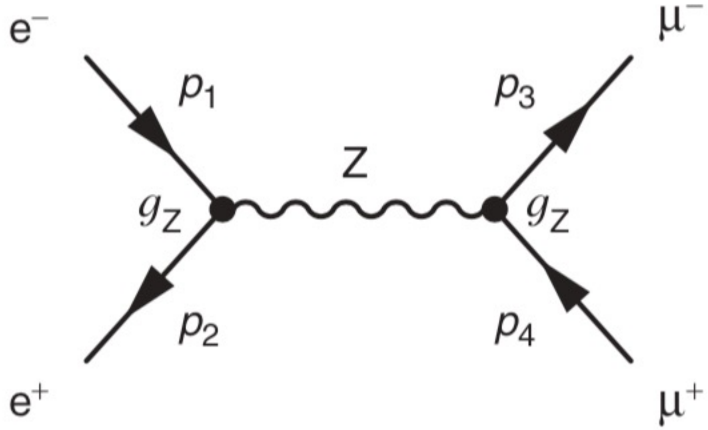


  with the corresponding vector and axial couplings to the Z boson
- The rest of the procedure is similar to the QED calculation
- Around the resonance, the masses of the leptons can be ignored
- In this scenario, the helicity and chiral states are the same

Z production cross section

- The cross section calculation around the resonance would only need the Z boson contribution

$$\mathcal{M}_{fi} = -\frac{g_Z^2}{(s - m_Z^2 + i m_Z \Gamma_Z)} g_{\mu\nu} \left[\bar{v}(p_2)\gamma^\mu \tfrac{1}{2}\left(c_V^e - c_A^e \gamma^5\right) u(p_1)\right] \times \left[\bar{u}(p_3)\gamma^\nu \tfrac{1}{2}\left(c_V^\mu - c_A^\mu \gamma^5\right) v(p_4)\right],$$



with

$$c_V = (c_L + c_R)$$
$$c_A = (c_L - c_R)$$

$$\mathcal{M}_{fi} = -\frac{g_Z^2}{(s - m_Z^2 + i m_Z \Gamma_Z)} g_{\mu\nu} \left[c_L^e \bar{v}(p_2)\gamma^\mu P_L u(p_1) + c_R^e \bar{v}(p_2)\gamma^\mu P_R u(p_1)\right] \times \left[c_L^\mu \bar{u}(p_3)\gamma^\nu P_L v(p_4) + c_R^\mu \bar{u}(p_3)\gamma^\nu P_R v(p_4)\right]$$

Z production cross section

- The cross section calculation around the resonance would only need the Z boson contribution

$$\mathcal{M}_{fi} = -\frac{g_Z^2}{(s - m_Z^2 + i m_Z \Gamma_Z)} g_{\mu\nu} \left[c_L^{e} \overline{v}(p_2)\gamma^{\mu} P_L u(p_1) + c_R^{e} \overline{v}(p_2)\gamma^{\mu} P_R u(p_1) \right] \times \left[c_L^{\mu} \overline{u}(p_3)\gamma^{\nu} P_L v(p_4) + c_R^{\mu} \overline{u}(p_3)\gamma^{\nu} P_R v(p_4) \right]$$

here $m_Z \gg m_\mu$, so:

$$P_L u = u_\downarrow \quad P_R u = u_\uparrow \quad P_L v = v_\uparrow \quad P_R v = v_\downarrow$$

and only 4 contributions to the matrix element are non zero:

$$\mathcal{M}_{RR} = -P_Z(s)\, g_Z^2\, c_R^{e} c_R^{\mu}\, g_{\mu\nu} \left[\overline{v}_\downarrow(p_2)\gamma^{\mu} u_\uparrow(p_1)\right] \left[\overline{u}_\uparrow(p_3)\gamma^{\nu} v_\downarrow(p_4)\right]$$

$$\mathcal{M}_{RL} = -P_Z(s)\, g_Z^2\, c_R^{e} c_L^{\mu}\, g_{\mu\nu} \left[\overline{v}_\downarrow(p_2)\gamma^{\mu} u_\uparrow(p_1)\right] \left[\overline{u}_\downarrow(p_3)\gamma^{\nu} v_\uparrow(p_4)\right]$$

$$\mathcal{M}_{LR} = -P_Z(s)\, g_Z^2\, c_L^{e} c_R^{\mu}\, g_{\mu\nu} \left[\overline{v}_\uparrow(p_2)\gamma^{\mu} u_\downarrow(p_1)\right] \left[\overline{u}_\uparrow(p_3)\gamma^{\nu} v_\downarrow(p_4)\right]$$

$$\mathcal{M}_{LL} = -P_Z(s)\, g_Z^2\, c_L^{e} c_L^{\mu}\, g_{\mu\nu} \left[\overline{v}_\uparrow(p_2)\gamma^{\mu} u_\downarrow(p_1)\right] \left[\overline{u}_\downarrow(p_3)\gamma^{\nu} v_\uparrow(p_4)\right]$$

Z production cross section

- The cross section calculation around the resonance would only need the Z boson contribution

$$\mathcal{M}_{RR} = -P_Z(s)\, g_Z^2\, c_R^e c_R^\mu\, g_{\mu\nu}\, [\overline{v}_\downarrow(p_2)\gamma^\mu u_\uparrow(p_1)]\, [\overline{u}_\uparrow(p_3)\gamma^\nu v_\downarrow(p_4)]$$
$$\mathcal{M}_{RL} = -P_Z(s)\, g_Z^2\, c_R^e c_L^\mu\, g_{\mu\nu}\, [\overline{v}_\downarrow(p_2)\gamma^\mu u_\uparrow(p_1)]\, [\overline{u}_\downarrow(p_3)\gamma^\nu v_\uparrow(p_4)]$$
$$\mathcal{M}_{LR} = -P_Z(s)\, g_Z^2\, c_L^e c_R^\mu\, g_{\mu\nu}\, [\overline{v}_\uparrow(p_2)\gamma^\mu u_\downarrow(p_1)]\, [\overline{u}_\uparrow(p_3)\gamma^\nu v_\downarrow(p_4)]$$
$$\mathcal{M}_{LL} = -P_Z(s)\, g_Z^2\, c_L^e c_L^\mu\, g_{\mu\nu}\, [\overline{v}_\uparrow(p_2)\gamma^\mu u_\downarrow(p_1)]\, [\overline{u}_\downarrow(p_3)\gamma^\nu v_\uparrow(p_4)]$$

with $P_Z(s) = 1/(s - m_Z^2 + i m_Z \Gamma_Z)$

- The combinations are identical to the ones derived for QED:

$$|\mathcal{M}_{RR}|^2 = |P_Z(s)|^2\, g_Z^4 s^2 (c_R^e)^2 (c_R^\mu)^2 (1 + \cos\theta)^2$$
$$|\mathcal{M}_{RL}|^2 = |P_Z(s)|^2\, g_Z^4 s^2 (c_R^e)^2 (c_L^\mu)^2 (1 - \cos\theta)^2$$
$$|\mathcal{M}_{LR}|^2 = |P_Z(s)|^2\, g_Z^4 s^2 (c_L^e)^2 (c_R^\mu)^2 (1 - \cos\theta)^2$$
$$|\mathcal{M}_{LL}|^2 = |P_Z(s)|^2\, g_Z^4 s^2 (c_L^e)^2 (c_L^\mu)^2 (1 + \cos\theta)^2$$

Z production cross section

- Analogous to the QED calculation, averaging over the initial state spin configurations:

$$\langle|\mathcal{M}|^2\rangle = \frac{1}{4}\left(|\mathcal{M}_{RR}|^2 + |\mathcal{M}_{LL}|^2 + |\mathcal{M}_{LR}|^2 + |\mathcal{M}_{RL}|^2\right)$$

$$\langle|\mathcal{M}|^2\rangle = \frac{1}{4}\frac{g_Z^4 s^2}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2} \times \left\{\left[(c_R^e)^2(c_R^\mu)^2 + (c_L^e)^2(c_L^\mu)^2\right](1+\cos\theta)^2 + \left[(c_R^e)^2(c_L^\mu)^2 + (c_L^e)^2(c_R^\mu)^2\right](1-\cos\theta)^2\right\}$$

- Going back to the vector and axial couplings, the differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{1}{256\pi^2 s}\cdot\frac{g_Z^4 s^2}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2} \times \left\{\frac{1}{4}\left[(c_V^e)^2 + (c_A^e)^2\right]\left[(c_V^\mu)^2 + (c_A^\mu)^2\right]\left(1+\cos^2\theta\right) + 2c_V^e c_A^e c_V^\mu c_A^\mu \cos\theta\right\}$$

Z production cross section

- And the total cross section:

$$\sigma(\mathrm{e^+e^-} \to \mathrm{Z} \to \mu^+\mu^-) = \frac{1}{192\pi}\frac{g_Z^4 s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}\left[(c_V^e)^2 + (c_A^e)^2\right]\left[(c_V^\mu)^2 + (c_A^\mu)^2\right]$$

- This can be expressed in terms of the partial decay rates of the Z boson:

$$\Gamma_{ee} = \frac{g_Z^2 m_Z}{48\pi}\left[(c_V^e)^2 + (c_A^e)^2\right] \quad \Gamma_{\mu\mu} = \frac{g_Z^2 m_Z}{48\pi}\left[(c_V^\mu)^2 + (c_A^\mu)^2\right]$$

$$\sigma(\mathrm{e^+e^-} \to \mathrm{Z} \to \mu^+\mu^-) = \frac{12\pi s}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{\mu\mu}}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}$$

Z production cross section

- The cross section calculation around the resonance would only need the Z boson contribution

$$\sigma(e^+e^- \to Z \to \mu^+\mu^-) = \frac{12\pi s}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{\mu\mu}}{(s - m_Z^2)^2 + m_Z^2\Gamma_Z^2}$$

- The cross section for other final state fermions can be obtained replacing the partial decay rates into muons with the corresponding partial decay rates: Γ_{ff}

- The maximum value for the cross section:

$$\sigma_{ff}^0 = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2}$$

Z production cross section

- The cross section calculation around the resonance would only need the Z boson contribution

$$\sigma(e^+e^- \to Z \to \mu^+\mu^-) = \frac{12\pi s}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{\mu\mu}}{(s - m_Z^2)^2 + m_Z^2\Gamma_Z^2}$$

- The maximum value for the cross section:

$$\sigma^0_{ff} = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2}$$

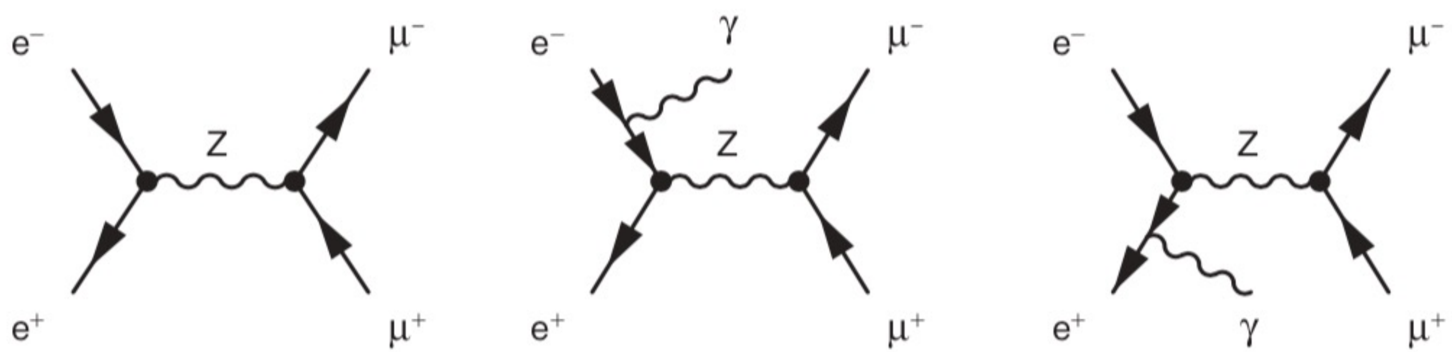
- The cross section falls to half the maximum value at:

$$\sqrt{s} = m_Z \pm \Gamma_Z/2$$

- So the total decay rate is the width of the cross-section distribution

Z mass measurement

- In practice, initial state radiation diagrams should be included
- This reduces the centre of mass energy of the collision and smears out the resonance



- At LEP, the mass of the Z boson and its decay width were measured by measuring the cross section for $e^+e^- \rightarrow Z \rightarrow q\bar{q}$ at different centre-of-mass energies

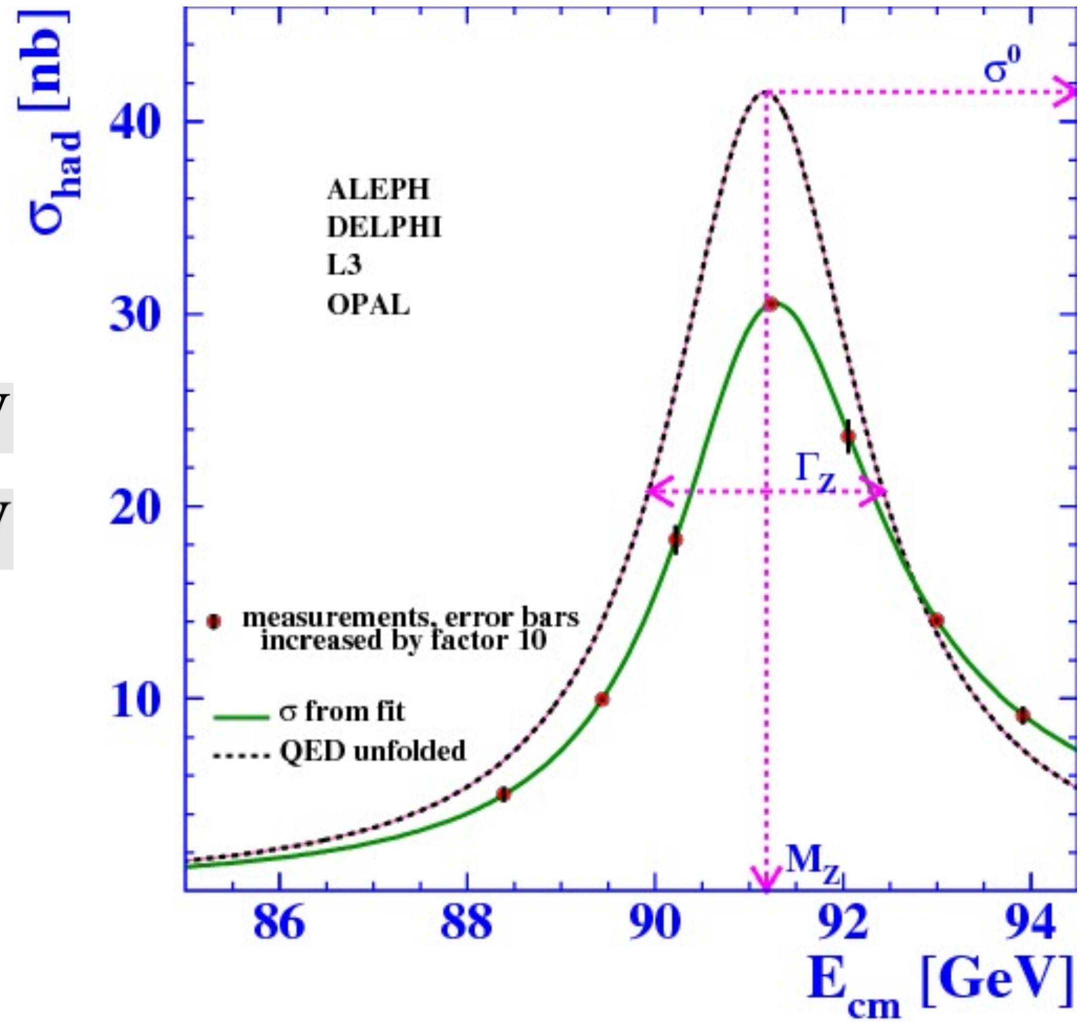
Z mass measurement

- Mass of the Z boson
- Total decay width
- Peak cross-section

$$m_Z = 91.1875 \pm 0.0021\,\text{GeV}$$

$$\Gamma_Z = 2.4952 \pm 0.0023\,\text{GeV}$$

- Measured with high level precision



Number of generations

- The Z boson couples to all fermions
- The total decay width has contributions from all fermions

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{hadrons} + \Gamma_{\nu_e\nu_e} + \Gamma_{\nu_\mu\nu_\mu} + \Gamma_{\nu_\tau\nu_\tau}$$

- If there were more generations, the decay width of the Z boson would be affected by it

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- If there were more generations, the decay width of the Z boson would be affected by it

$$\Gamma_Z = 3\Gamma_{\ell\ell} + \Gamma_{\text{hadrons}} + N_\nu \Gamma_{\nu\nu}$$

$$N_\nu = \frac{(\Gamma_Z - 3\Gamma_{\ell\ell} - \Gamma_{\text{hadrons}})}{\Gamma_{\nu\nu}^{\text{SM}}}$$

Number of generations

- The Z boson couples to all fermions
- The total decay width has contributions from all fermions

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\text{hadrons}} + \Gamma_{\nu_e\nu_e} + \Gamma_{\nu_\mu\nu_\mu} + \Gamma_{\nu_\tau\nu_\tau}$$

- If there were more generations, the decay width of the Z boson would be affected by it
- The decay width to fermions can be calculated using the vertex coupling:

$$\Gamma(Z \to f\bar{f}) = \frac{g_Z^2 m_Z}{48\pi}(c_V^2 + c_A^2)$$

- In particular for neutrinos:

$$\Gamma(Z \to \nu_e\bar{\nu}_e) = \frac{g_Z^2 m_Z}{48\pi}\left(\frac{1}{4} + \frac{1}{4}\right)$$

Number of generations

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measured calculated

Number of generations

- The Z boson couples to all fermions
- The total decay width has contributions from all fermions

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{hadrons} + \Gamma_{\nu_e\nu_e} + \Gamma_{\nu_\mu\nu_\mu} + \Gamma_{\nu_\tau\nu_\tau}$$

- If there were more generations, the decay width of the Z boson would be affected by it

$$\Gamma_Z = 3\Gamma_{\ell\ell} + \Gamma_{hadrons} + N_\nu \Gamma_{\nu\nu}$$

$$N_\nu = \frac{(\Gamma_Z - 3\Gamma_{\ell\ell} - \Gamma_{hadrons})}{\Gamma_{\nu\nu}^{SM}}$$

- And from the cross section peak of the Z resonance:

$$\sigma^0(e^+e^- \to Z \to f\bar{f}) = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2}$$

Number of generations

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Number of generations

- The Z boson couples to all fermions
- The total decay width has contributions from all fermions

$$N_\nu = \frac{(\Gamma_Z - 3\Gamma_{\ell\ell} - \Gamma_{\text{hadrons}})}{\Gamma_{\nu\nu}^{\text{SM}}}$$

$$\Gamma(Z \to \nu_e \bar{\nu}_e) = \frac{g_Z^2 m_Z}{48\pi}\left(\frac{1}{4} + \frac{1}{4}\right) = 167\,\text{MeV}$$

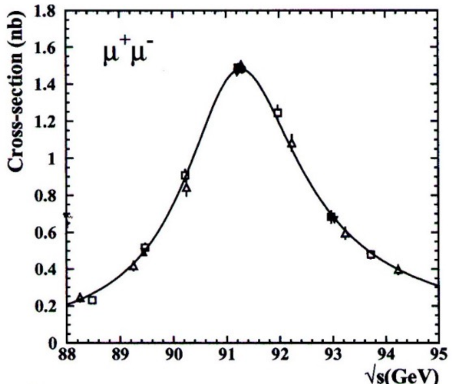
$$N_\nu = 2.9840 \pm 0.0082$$

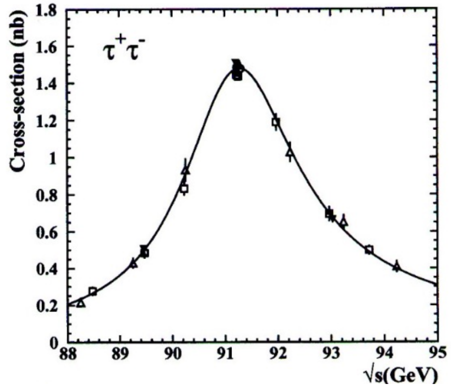
Γ_Z	**2495.2 ± 2.3 MeV**
Γ_{ee}	83.91 ± 0.12 MeV
$\Gamma_{\mu\mu}$	83.99 ± 0.18 MeV
$\Gamma_{\tau\tau}$	84.08 ± 0.22 MeV
Γ_{qq}	1744.4 ± 2.0 MeV
$N_\nu \Gamma_{\nu\nu}$	499.0 ± 1.5 MeV

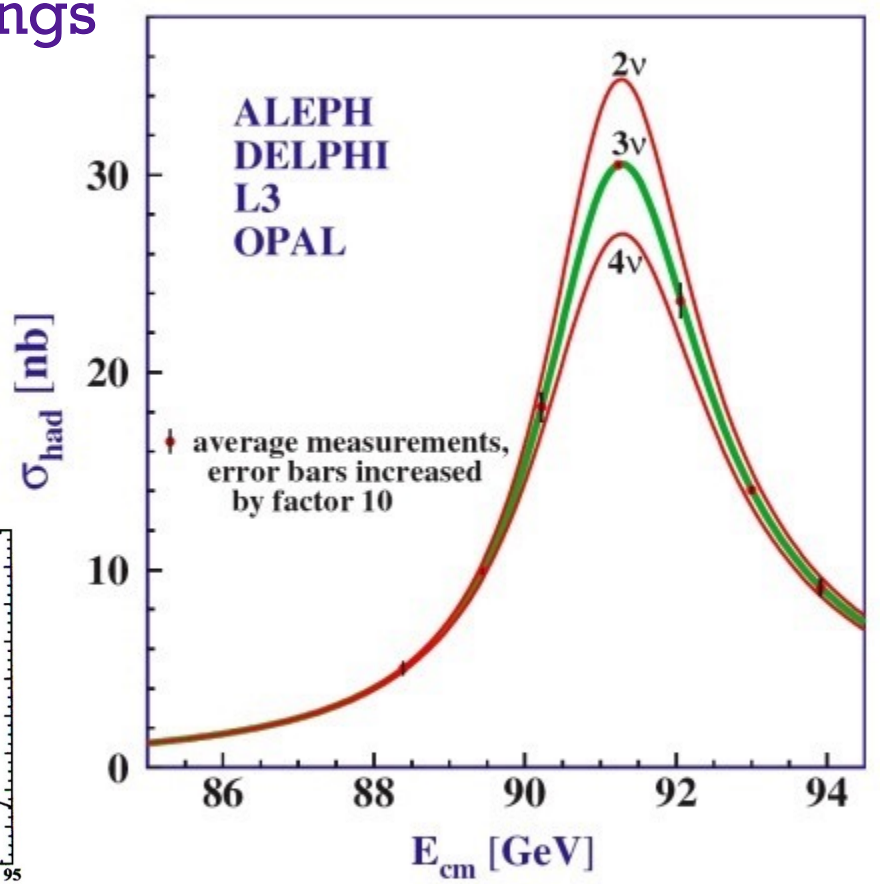
Number of generations

- Most likely, only 3 generations of fermions
- Universality of lepton couplings
- Calculated cross section assumes 3 colours

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







Weak mixing angle

- The weak mixing angle relates all couplings in the EW model and is therefore a fundamental parameter
- It can be measured through the ratio between vector and axial couplings:

$$\frac{c_V}{c_A} = 1 - \frac{2Q\sin^2\theta_{\rm W}}{I_{\rm W}^{(3)}}$$

For charged leptons:

$$\frac{c_V^\ell}{c_A^\ell} = 1 - 4\sin^2\theta_{\rm W}$$

- At LEP this could be measured by measuring the forward-backward asymmetry of leptons produced

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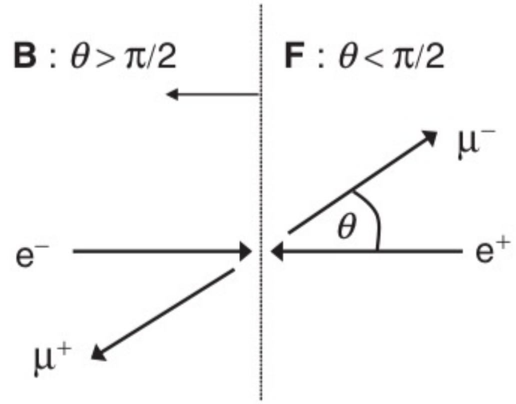

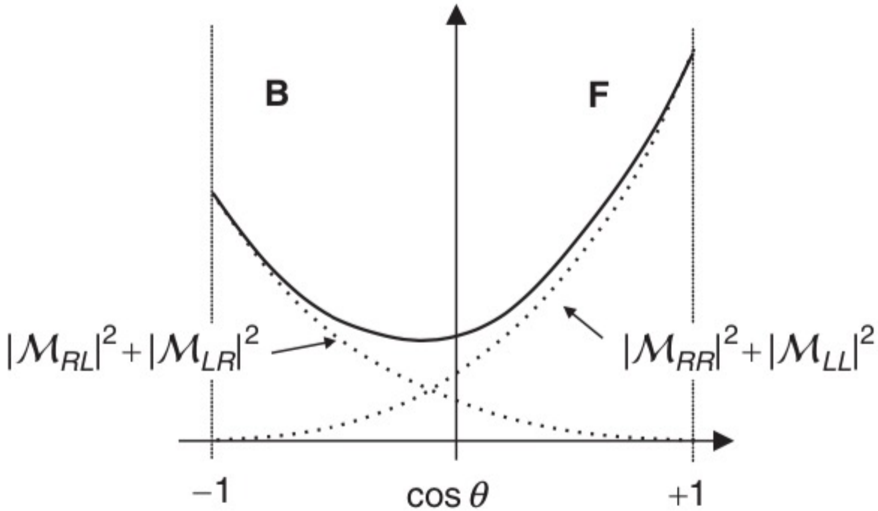

- The cross section has the form:

$$\frac{d\sigma}{d\Omega} \propto a(1+\cos^2\theta) + 2b\cos\theta$$

if the couplings were the same, b would be zero and the angular distribution would have the same form as in QED

Weak mixing angle

- At LEP this could be measured by measuring the forward-backward asymmetry of leptons produced

$$A^{\ell}_{\rm FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

where the forward and backward cross sections can be obtained integrating in different hemispheres:

$$\sigma_F \equiv 2\pi \int_0^1 \frac{d\sigma}{d\Omega} d(\cos\theta) \qquad \sigma_B \equiv 2\pi \int_{-1}^0 \frac{d\sigma}{d\Omega} d(\cos\theta)$$

$$\sigma_F \propto \int_0^1 \left[a(1+\cos^2\theta) + 2b\cos\theta\right] d(\cos\theta) = \int_0^1 \left[a(1+x^2) + 2bx\right] dx = \left(\tfrac{4}{3}a + b\right)$$

$$\sigma_B \propto \int_{-1}^0 \left[a(1+\cos^2\theta) + 2b\cos\theta\right] d(\cos\theta) = \int_{-1}^0 \left[a(1+x^2) + 2bx\right] dx = \left(\tfrac{4}{3}a - b\right)$$

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$$A^{\ell}_{\mathrm{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

where the forward and backward cross sections can be obtained integrating in different hemispheres:

$$A_{\mathrm{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3b}{4a}$$

$$a = \left[(c_L^{\mathrm{e}})^2 + (c_R^{\mathrm{e}})^2\right]\left[(c_L^{\mu})^2 + (c_R^{\mu})^2\right] \qquad b = \left[(c_L^{\mathrm{e}})^2 - (c_R^{\mathrm{e}})^2\right]\left[(c_L^{\mu})^2 - (c_R^{\mu})^2\right]$$

$$A_{\mathrm{FB}} = \frac{3}{4}\left[\frac{(c_L^{\mathrm{e}})^2 - (c_R^{\mathrm{e}})^2}{(c_L^{\mathrm{e}})^2 + (c_R^{\mathrm{e}})^2}\right] \cdot \left[\frac{(c_L^{\mu})^2 - (c_R^{\mu})^2}{(c_L^{\mu})^2 + (c_R^{\mu})^2}\right]$$

Weak mixing angle

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$$A^{\ell}_{\mathrm{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

where the forward and backward cross sections can be obtained integrating in different hemispheres:

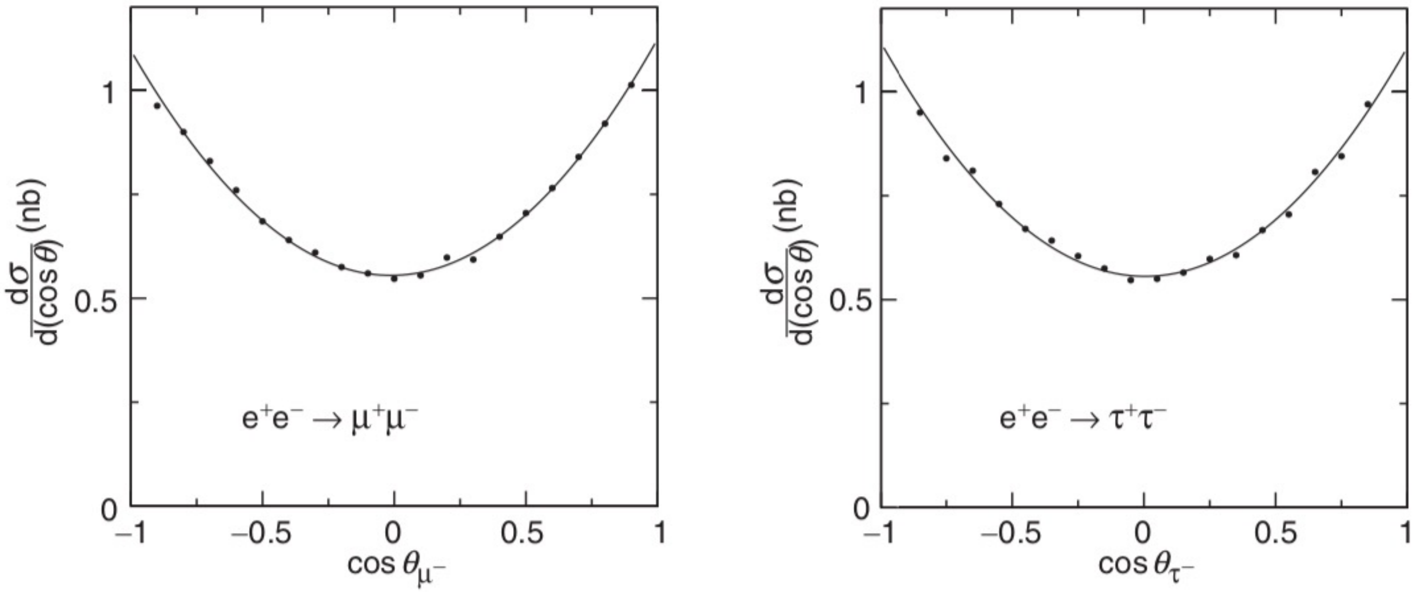
$$A_{\mathrm{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3b}{4a}$$

- In terms of the coupling constants: $A_{\mathrm{FB}} = \frac{3}{4}\mathcal{A}_{\mathrm{f}}\mathcal{A}_{\mathrm{f}'}$

$$\mathcal{A}_{\mathrm{f}} = \frac{2c^{\mathrm{f}}_V c^{\mathrm{f}}_A}{(c^{\mathrm{f}}_V)^2 + (c^{\mathrm{f}}_A)^2}$$

Weak mixing angle

- At LEP the cleanest way of measuring A_{FB} is in lepton final states



$$A^{e}_{FB} = 0.0145 \pm 0.0025 \qquad A^{\mu}_{FB} = 0.0169 \pm 0.0013 \qquad A^{\tau}_{FB} = 0.0188 \pm 0.0017$$

$$A^{e}_{FB} = \frac{3}{4}\mathcal{A}_{e}^{2} \qquad A^{\mu}_{FB} = \frac{3}{4}\mathcal{A}_{e}\mathcal{A}_{\mu} \qquad A^{\tau}_{FB} = \frac{3}{4}\mathcal{A}_{e}\mathcal{A}_{\tau}$$

Weak mixing angle

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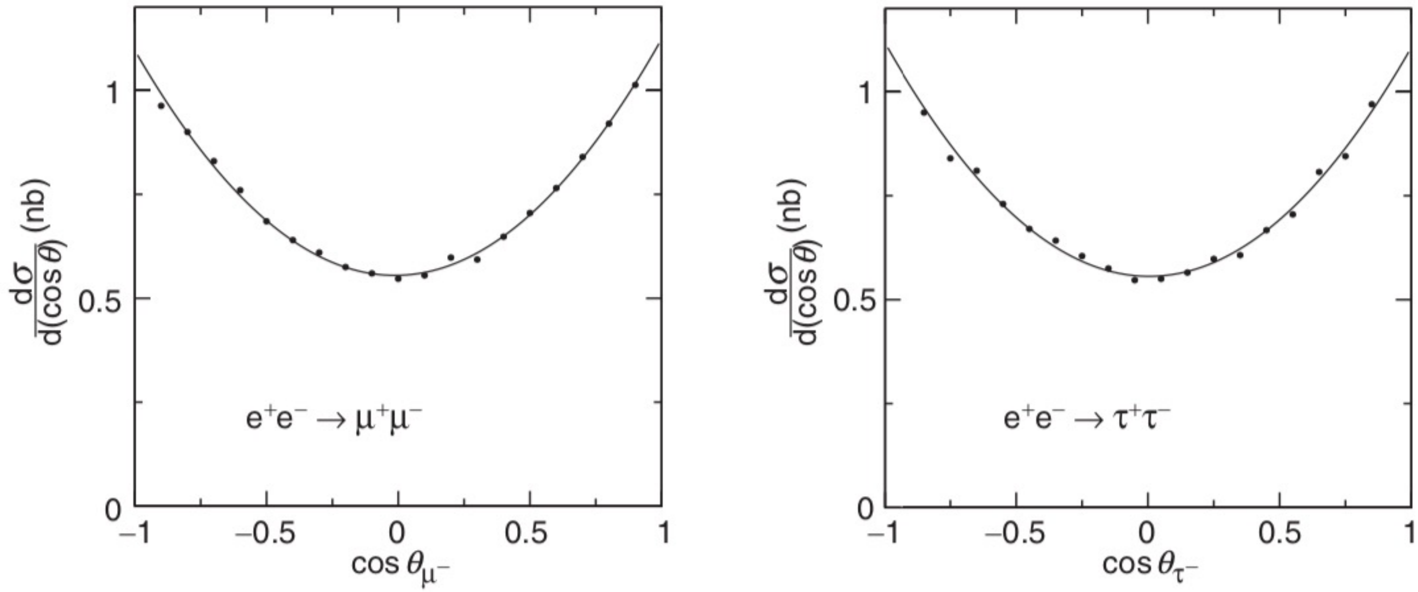

$A^e_{FB} = 0.0145 \pm 0.0025$ $\quad A^\mu_{FB} = 0.0169 \pm 0.0013$ $\quad A^\tau_{FB} = 0.0188 \pm 0.0017$

$\mathcal{A}_e = 0.1514 \pm 0.0019$ $\quad \mathcal{A}_\mu = 0.1456 \pm 0.0091$ $\quad \mathcal{A}_\tau = 0.1449 \pm 0.0040$

Weak mixing angle

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$A^{e}_{FB} = 0.0145 \pm 0.0025$ $\quad A^{\mu}_{FB} = 0.0169 \pm 0.0013$ $\quad A^{\tau}_{FB} = 0.0188 \pm 0.0017$

$\mathcal{A}_{e} = 0.1514 \pm 0.0019$ $\quad \mathcal{A}_{\mu} = 0.1456 \pm 0.0091$ $\quad \mathcal{A}_{\tau} = 0.1449 \pm 0.0040$

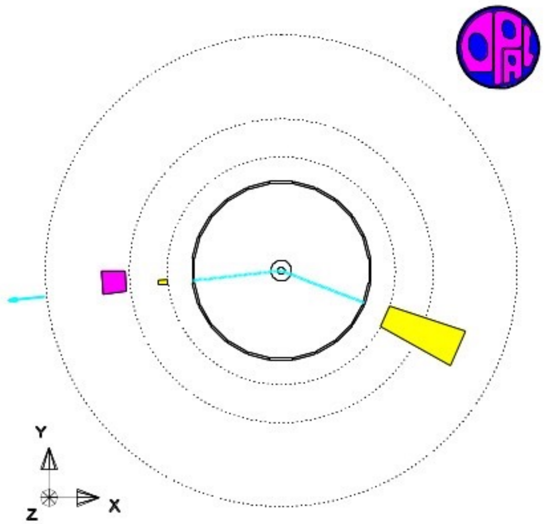
$$\mathcal{A} = \frac{2c_V/c_A}{1 + (c_V/c_A)^2}$$

$$\frac{c_V}{c_A} = 1 - 4\sin^2\theta_{\mathrm{W}}$$

- Combining all measurements:

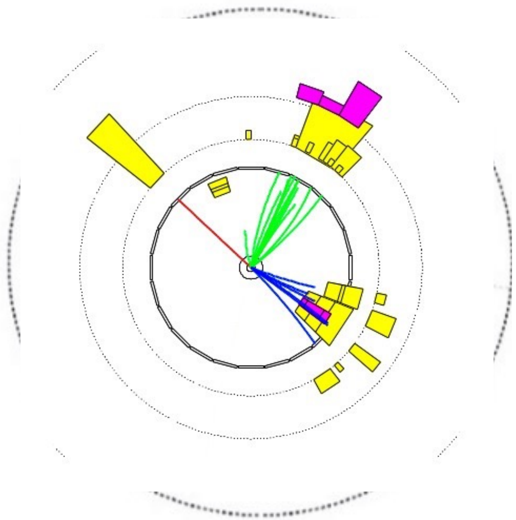
$$\sin^2\theta_{\mathrm{W}} = 0.23146 \pm 0.00012$$

- W bosons were produced in pairs at LEP



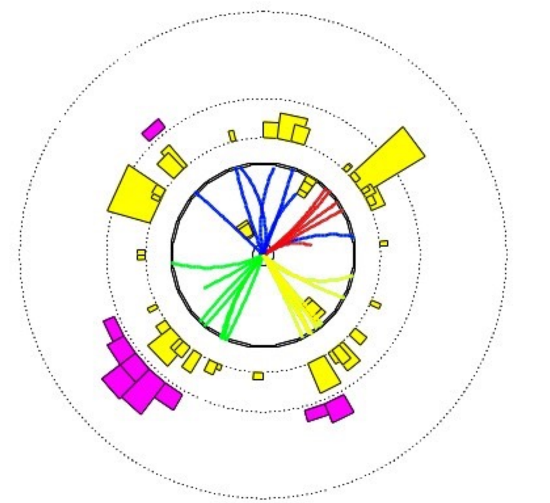
$W^+W^- \to e^-\bar{\nu}_e\mu^+\nu_\mu$

leptonic



$W^+W^- \to e^-\bar{\nu}_e q_1\bar{q}_2$

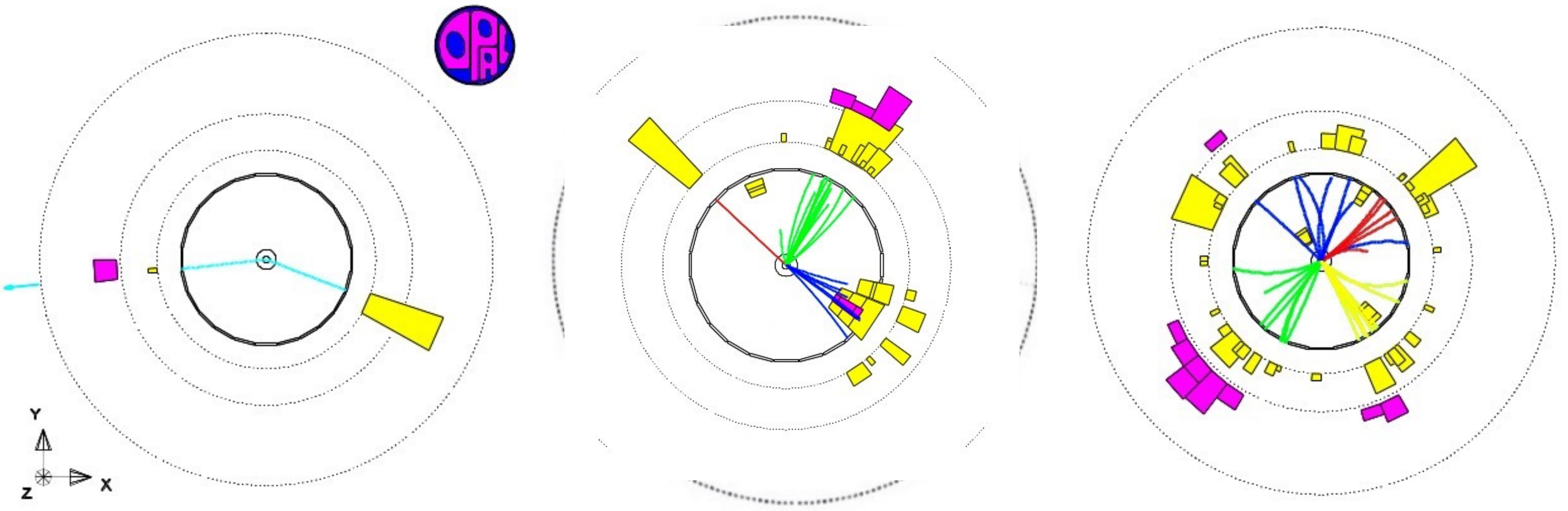
semi-leptonic



$W^+W^- \to q_1\bar{q}_2 q_3\bar{q}_4$

hadronic

- W bosons were produced in pairs at LEP



$W^+W^- \to e^-\bar{\nu}_e\mu^+\nu_\mu$ $W^+W^- \to e^-\bar{\nu}_e q_1\bar{q}_2$ $W^+W^- \to q_1\bar{q}_2 q_3\bar{q}_4$

leptonic semi-leptonic hadronic

- We know the cross section is proportional to the decay rates, so we can measure the branching fractions

W bosons at LEP

- We know the cross section is proportional to the decay rates, so we can measure the branching fractions

$$N_{\mathrm{qqqq}} \propto \left[BR(\mathrm{W} \to \mathrm{q\bar{q}'})\right]^2 \qquad N_{\ell\nu\ell\nu} \propto \left[1 - BR(\mathrm{W} \to \mathrm{q\bar{q}'})\right]^2$$

$$BR(\mathrm{W} \to \mathrm{q\bar{q}'}) = 67.41 \pm 0.27\%$$

W bosons at LEP

- We know the cross section is proportional to the decay rates, so we can measure the branching fractions

$$N_{qqqq} \propto \left[BR(W \to q\bar{q}')\right]^2 \qquad N_{\ell\nu\ell\nu} \propto \left[1 - BR(W \to q\bar{q}')\right]^2$$

$$BR(W \to q\bar{q}') = 67.41 \pm 0.27\%$$

- From the EW Model:

$$\Gamma(W^- \to e^-\bar{\nu}_e) = \frac{g_W^2 m_W}{48\pi}$$

$$\Gamma(W^- \to e^-\bar{\nu}_e) = \Gamma(W^- \to \mu^-\bar{\nu}_\mu) = \Gamma(W^- \to \tau^-\bar{\nu}_\tau)$$

$$\Gamma(W^- \to d\bar{u}) = 3|V_{ud}|^2\,\Gamma_{e\nu} \qquad \Gamma(W^- \to d\bar{c}) = 3|V_{cd}|^2\,\Gamma_{e\nu}$$

$$\Gamma(W^- \to s\bar{u}) = 3|V_{us}|^2\,\Gamma_{e\nu} \qquad \Gamma(W^- \to s\bar{c}) = 3|V_{cs}|^2\,\Gamma_{e\nu}$$

$$\Gamma(W^- \to b\bar{u}) = 3|V_{ub}|^2\,\Gamma_{e\nu} \qquad \Gamma(W^- \to b\bar{c}) = 3|V_{cb}|^2\,\Gamma_{e\nu}$$

W bosons at LEP

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$$BR(\mathrm{W} \to \mathrm{q\bar{q}'}) = 67.41 \pm 0.27\%$$

- From the EW Model:

$$\Gamma(\mathrm{W}^- \to \mathrm{q\bar{q}'}) = 6\,\Gamma(\mathrm{W}^- \to \mathrm{e}^-\bar{\nu}_\mathrm{e})$$

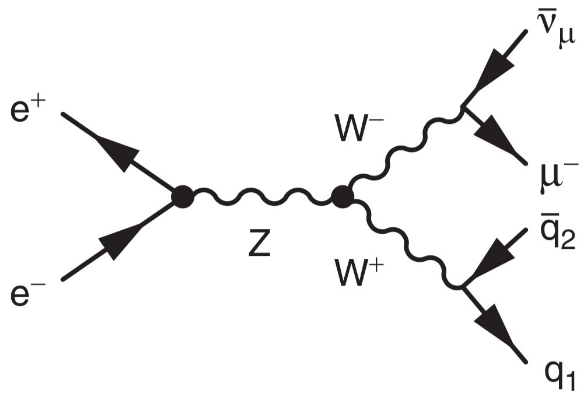
$$\kappa_{QCD} = \left[1 + \frac{\alpha_S(m_\mathrm{W})}{\pi}\right] \approx 1.038$$

$$\Gamma_\mathrm{W} = (3 + 6\,\kappa_{QCD})\,\Gamma(\mathrm{W}^- \to \mathrm{e}^-\bar{\nu}_\mathrm{e}) \approx 9.2 \times \frac{g_\mathrm{W}^2 m_\mathrm{W}}{48\pi} = 2.1\,\mathrm{GeV}$$

$$BR(\mathrm{W} \to \mathrm{q\bar{q}'}) = \frac{6\,\kappa_{QCD}}{3 + 6\,\kappa_{QCD}} = 67.5\%$$

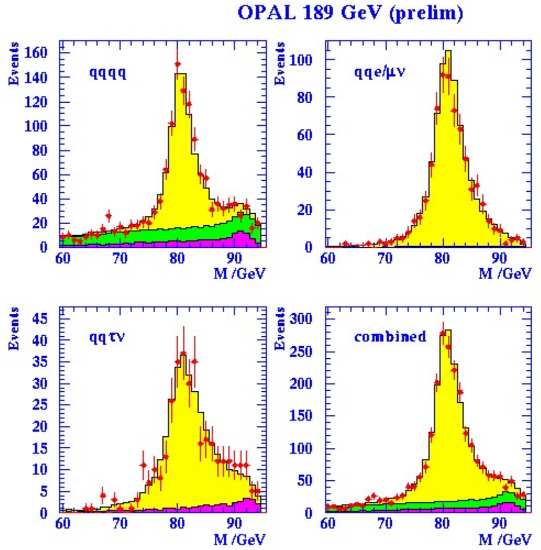
W boson mass and width

- The W-pair production at LEP is not a resonant process, like the Z boson production
- The mass and width can be obtained through direct reconstruction of the invariant masses of the W decays



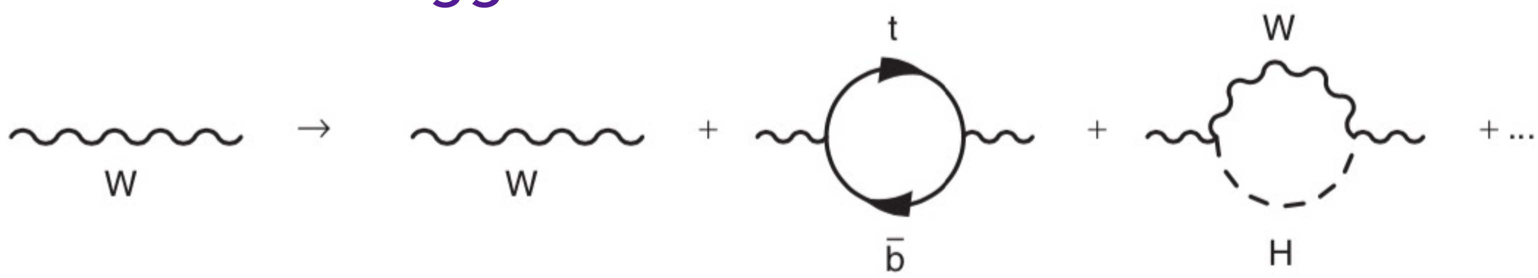
$$m_W = 80.376 \pm 0.033\,\text{GeV}$$

$$\Gamma_W = 2.195 \pm 0.083\,\text{GeV}$$



W mass loop corrections

- When comparing to the precise measurements from LEP, higher order corrections must be taken into account
- For example, the W mass has corrections related to the top quark and the Higgs boson



$$m_W = m_W^0 + a\, m_t^2 + b \ln\left(\frac{m_H}{m_W}\right) + \cdots$$

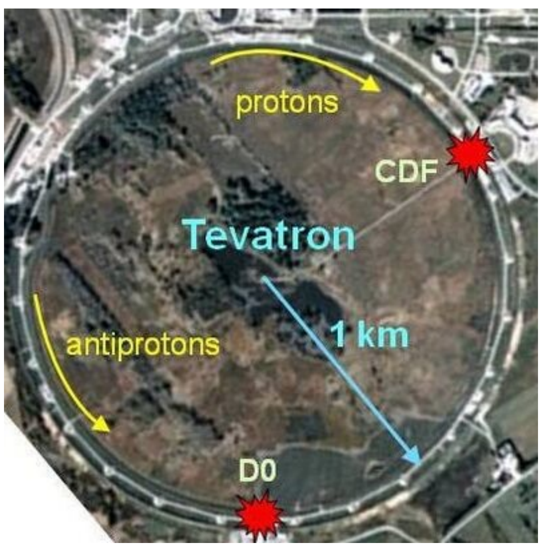
- The measurements from LEP for the EW parameters, together with the quantum loop effects, predict a top quark mass of 175 ± 11 GeV…

The Top quark

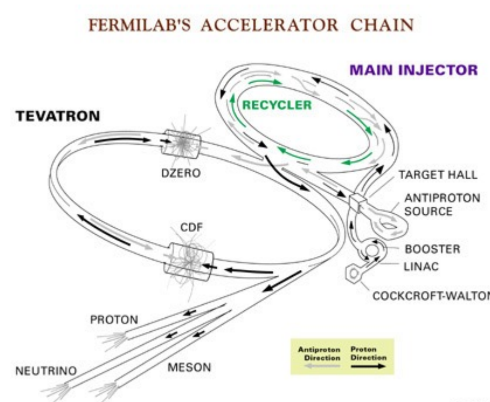
- The top quark is the “heaviest” fundamental particle we know
- It could not be observed at LEP, it was discovered at the Tevatron in 1994

- It is possible to achieve higher centre of mass energies with hadron colliders than with e^+e^- colliders
- They are central in the production of new heavy particles
- Underlying process: parton-parton scattering

TeVatron (1987-2010)



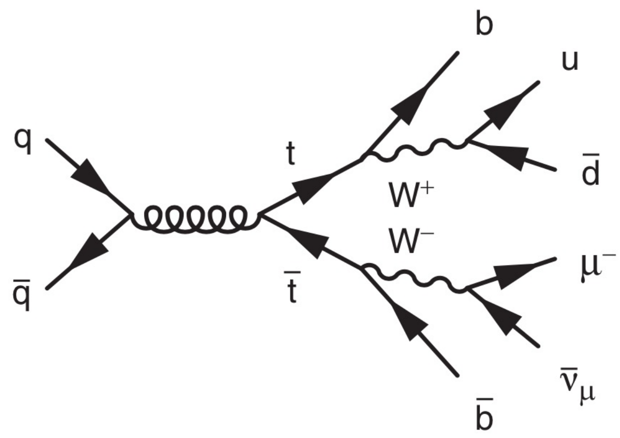
- Located at Fermilab, Chicago, USA
- $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV
- Two main experiments: CDF and D0



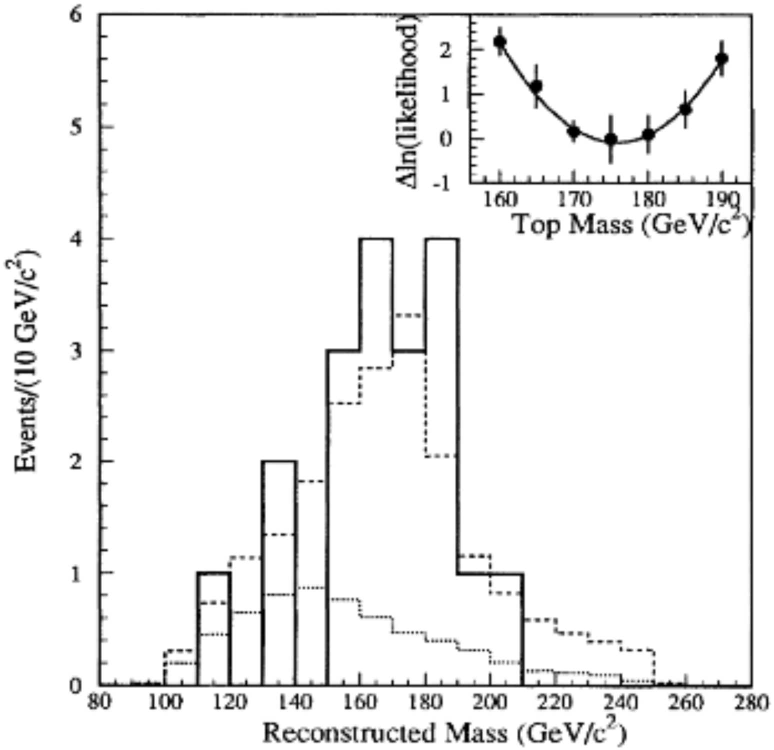
The Top quark

- The top quark is the "heaviest" fundamental particle we know
- It could not be observed at LEP, it was discovered at the Tevatron in 1994
- It has a short lifetime and decays before hadronisation
- It decays almost exclusively into a W boson and a *b* quark
- At hadron colliders it is easier to look for the semi-leptonic channel:

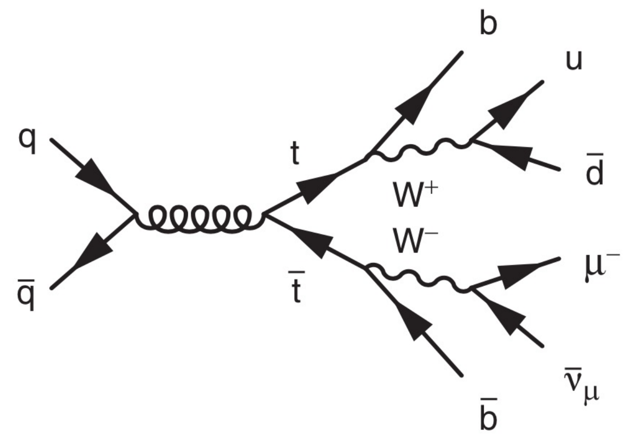
$$q\bar{q} \rightarrow t\bar{t} \rightarrow bW^{+}\,\bar{b}W^{-}$$



- At hadron colliders it is easier to look for the semi-leptonic channel
- First observation of top quark (CDF)

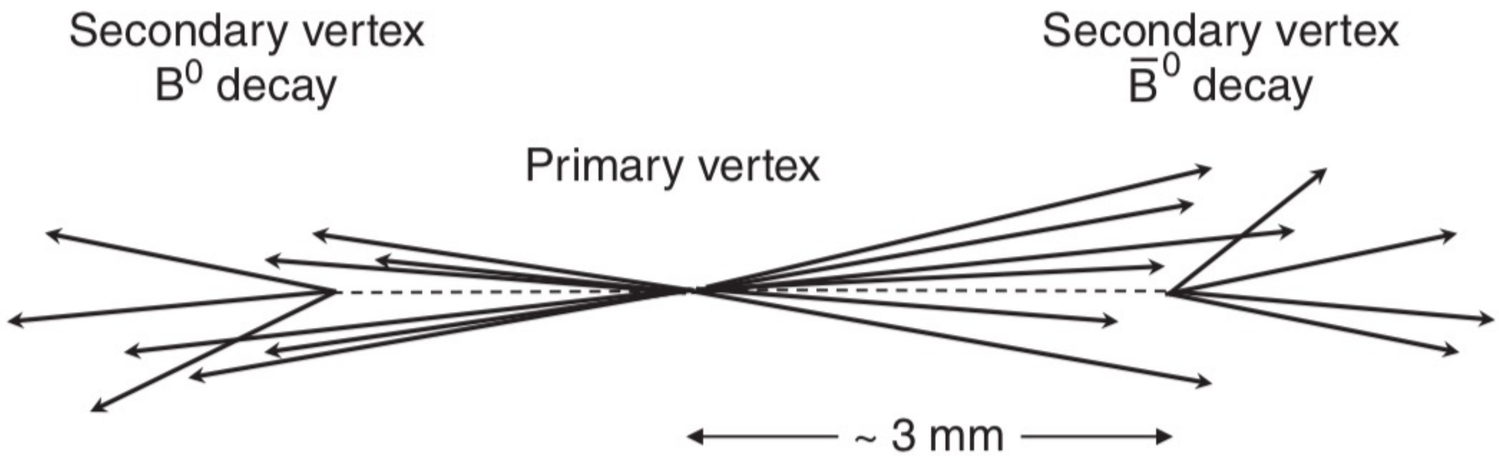


$$q\bar{q} \rightarrow t\bar{t} \rightarrow bW^{+}\,\bar{b}W^{-}$$



The Top quark

- To measure the top quark mass we reconstruct the invariant mass of its decay products (as with the W)
- Need to identify the b-jet: b-tagging
- b quarks have a longer lifetime than the other quarks
- The b quark travels some distance from the interaction point before decaying: secondary vertex



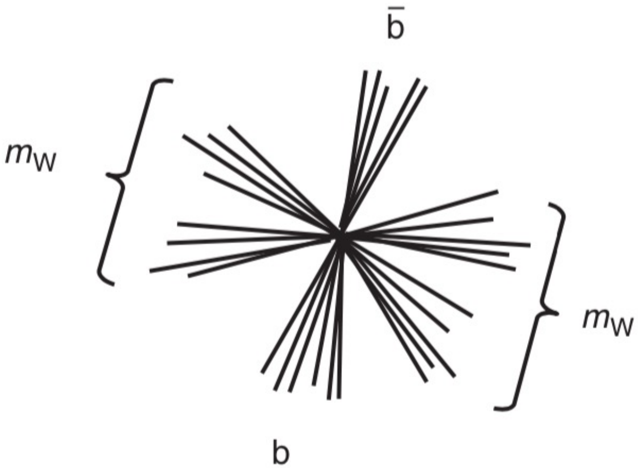
The Top quark

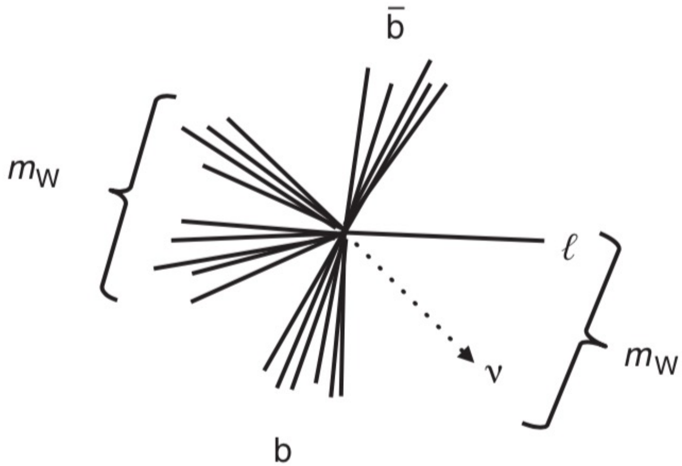
- To measure the top quark mass we reconstruct the invariant mass of its decay products (as with the W)

$$t\bar{t} \to (bW^+)(\bar{b}W^-) \to (b\,q_1\bar{q}_2)\,(\bar{b}\,q_3\bar{q}_4) \to 6 \text{ jets},$$

$$t\bar{t} \to (bW^+)(\bar{b}W^-) \to (b\,q_1\bar{q}_2)\,(\bar{b}\,\ell^-\bar{\nu}_\ell) \to 4 \text{ jets} + 1, \text{ charged lepton} + 1\nu$$

$$t\bar{t} \to (bW^+)(\bar{b}W^-) \to (b\,\ell^+\nu_\ell)\,(\bar{b}\,\ell'^-\bar{\nu}_{\ell'}) \to 2 \text{ jets} + 2 \text{ charged leptons} + 2\nu\text{s}$$





Tevatron average result: $m_t = 173.5 \pm 1.0\,\text{GeV}$

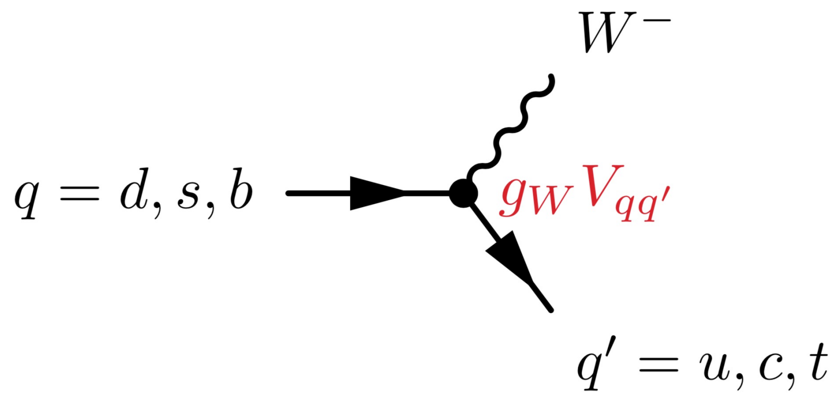
Summary

- The weak current has a V-A structure
- W boson coupling to leptons constant (lepton universality)

$$\frac{-ig_W}{\sqrt{2}}\frac{1}{2}\gamma^\mu(1-\gamma^5)$$

$$\alpha_W = \frac{g_W^2}{4\pi} = \frac{8m_W^2 G_F}{4\sqrt{2}\pi} \approx \frac{1}{30}$$

$$G_F = 1.166\,38 \times 10^{-5}\,\text{GeV}^{-2}$$



- W boson coupling to quarks depends on CKM matrix
- The W boson always changes quark flavour
- Mixing between different families can occur but less likely
- Parity and Charge conjugation is violated by the charged weak current: only couples to LH particles (RH anti-particles)

Summary

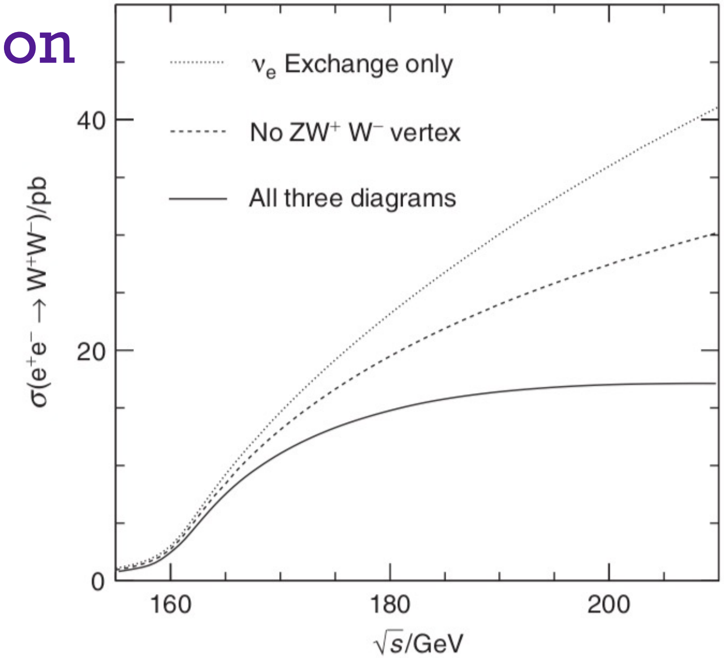
- The charged weak interaction alone does not fully explain W-pair production (cross section diverges)
- Neutral gauge boson needed: Z boson
- Unified $SU(2)_L \times U(1)_Y$ gauge theory
- One new parameter relates all couplings:

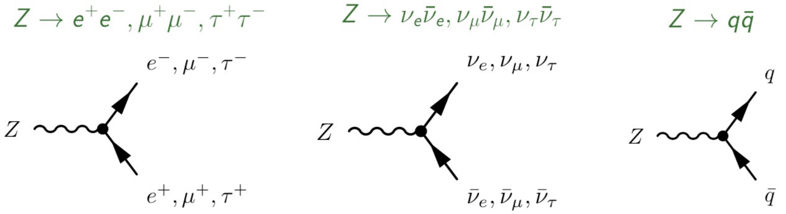
$$\sin^2\theta_W = 0.23146 \pm 0.00012$$

$$\frac{\alpha}{\alpha_W} = \frac{e^2}{g_W^2} = \sin^2\theta_W \sim 0.23$$

$$g_Z = \frac{g_W}{\cos\theta_W} \equiv \frac{e}{\sin\theta_W \cos\theta_W}$$

$$-i\frac{1}{2}g_Z\gamma^\mu\left[c_V - c_A\gamma^5\right]$$





Summary

- LEP made some impressive precise tests of the EW Model:

$$m_Z = 91.1875 \pm 0.0021\,\mathrm{GeV}$$

$$m_W = 80.385 \pm 0.015\,\mathrm{GeV}$$

$$\alpha(m_Z^2) = \frac{1}{128.91 \pm 0.02}$$

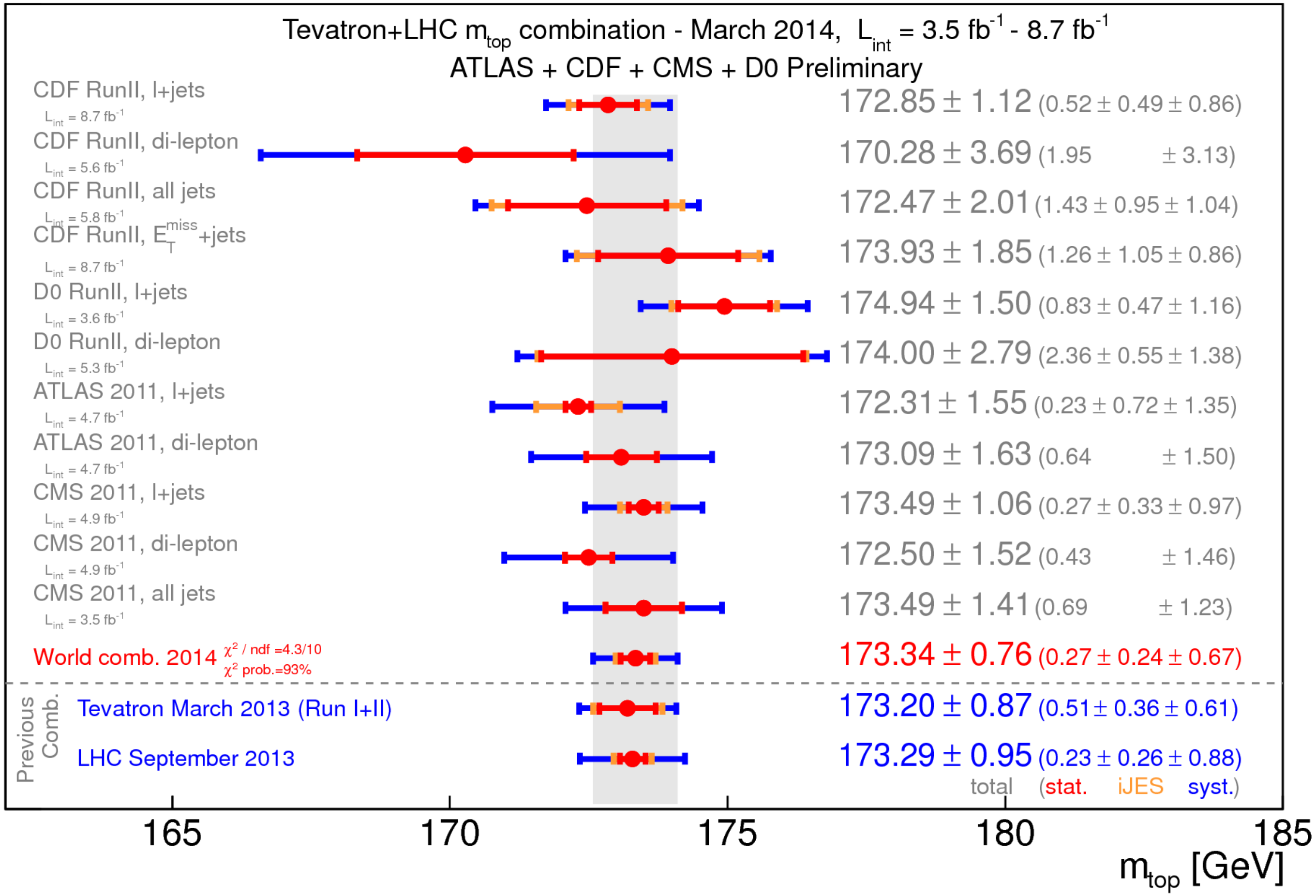
$$G_F = 1.166\,378\,7(6) \times 10^{-5}\,\mathrm{GeV}^{-2}$$

$$\sin^2\theta_W = 0.23146 \pm 0.00012$$

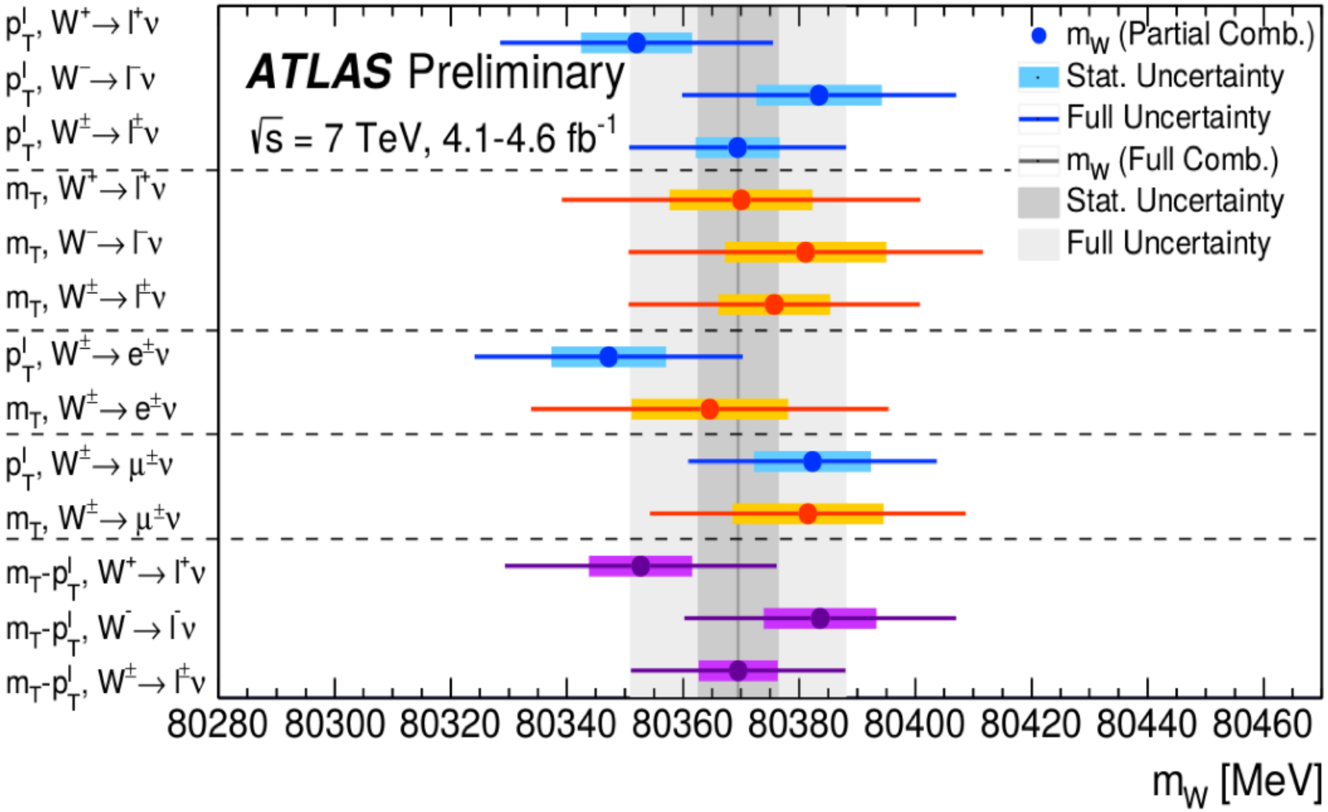
$$N_\nu = 2.9840 \pm 0.0082$$

- These measurements are consistent with the relations between constants established in the EW model
- The model works! (we are missing a way of giving mass to the W and Z)
- The top quark discovered at the Tevatron completes the spectrum of quarks: $m_t = 173.5 \pm 1.0\,\mathrm{GeV}$
- This value is as predicted by the quantum loop corrections of the EW model – impressive!

- Top mass world combination

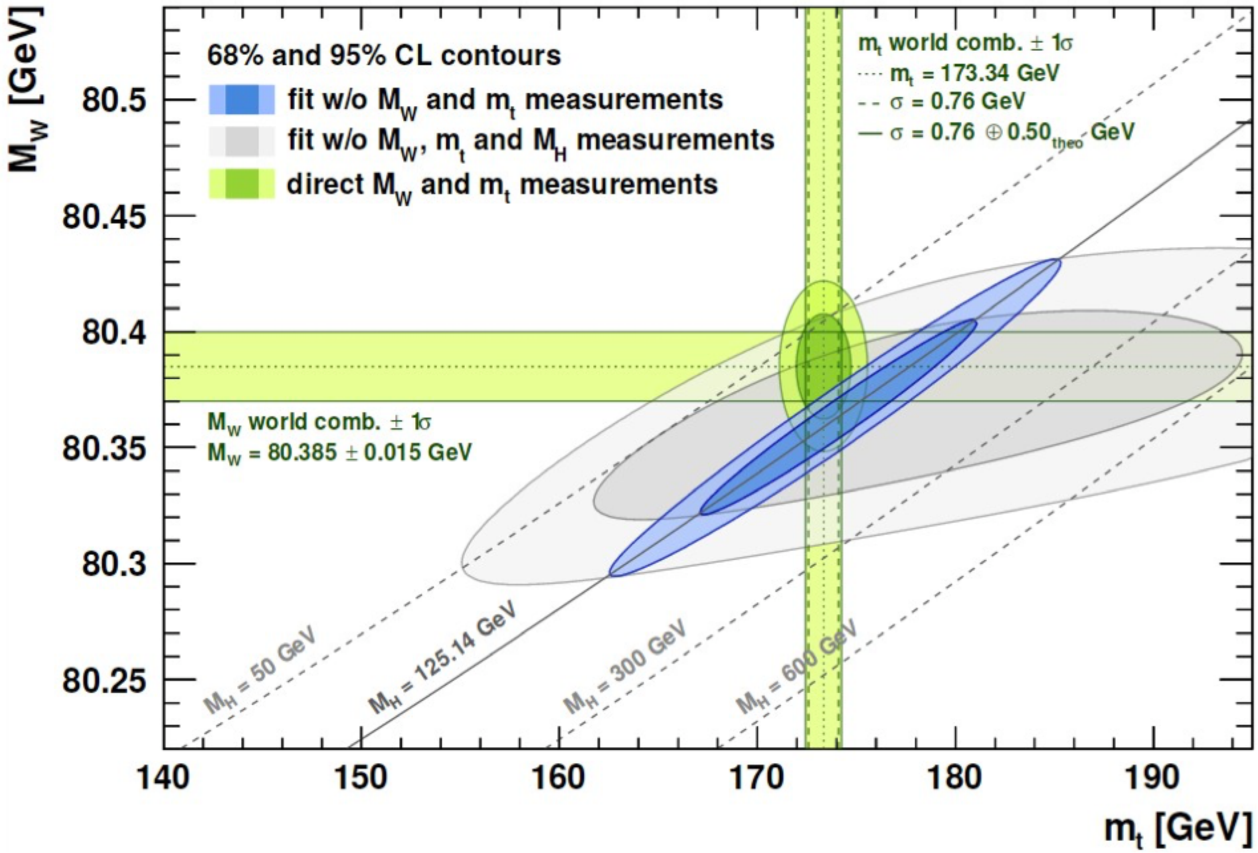


- W boson mass


ATLAS Preliminary
√s = 7 TeV, 4.1-4.6 fb-1
mW (Partial Comb.)
Stat. Uncertainty
Full Uncertainty
mW (Full Comb.)
Stat. Uncertainty
Full Uncertainty
80280 80300 80320 80340 80360 80380 80400 80420 80440 80460
mW [MeV]

Summary

- Top mass vs. W boson mass



* arXiv:1407.3792