UCL

PHASM/G442 Particle Physics

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Module VIII

Standard Model, Electroweak Unification and Higgs Mechanism

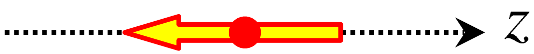
http://moodle.ucl.ac.uk/course/view.php?id=2589

Boson polarisation states

- Boson wave-function: $$\boxed{B^\mu = \varepsilon^\mu e^{-ip.x} = \varepsilon^\mu e^{i(\vec{p}.\vec{x} - Et)}}$$

- For a spin-1 boson travelling along z-axis possible polarisation 4-vectors are

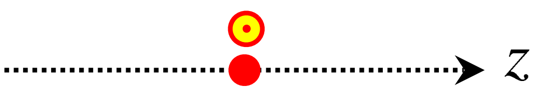
$$\varepsilon_-^\mu = \frac{1}{\sqrt{2}}(0, 1, -i, 0);$$



$$\boxed{S_z = -1}$$

transverse

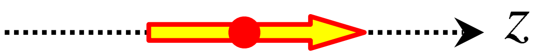
$$\varepsilon_L = \frac{1}{m}(p_z, 0, 0, E)$$



$$\boxed{S_z = 0}$$

longitudinal

$$\varepsilon_+^\mu = -\frac{1}{\sqrt{2}}(0, 1, i, 0)$$



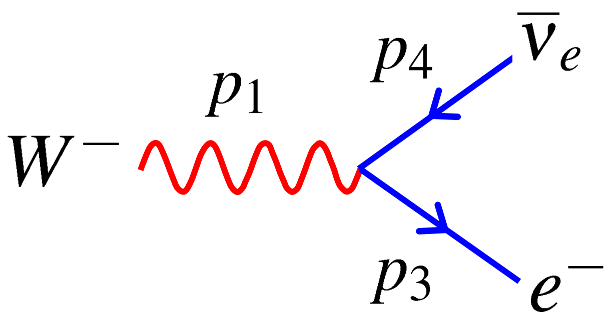
$$\boxed{S_z = +1}$$

transverse

$S_z = 0$ does not exist for on-shell massless particles

W-boson decay

- Matrix element for $W^- \rightarrow e^- \overline{\nu}_e$



Incoming W-boson : $\varepsilon_\mu(p_1)$

Out-going electron : $\overline{u}(p_3)$

Out-going $\overline{\nu}_e$ **:** $v(p_4)$

Vertex factor : $-i\frac{g_W}{\sqrt{2}}\frac{1}{2}\gamma^\mu(1-\gamma^5)$

$$-iM_{fi} = \varepsilon_\mu(p_1).\overline{u}(p_3).-i\frac{g_W}{\sqrt{2}}\gamma^\mu\tfrac{1}{2}(1-\gamma^5).v(p_4)$$

$$\Rightarrow \quad \boxed{M_{fi} = \frac{g_W}{\sqrt{2}}\varepsilon_\mu(p_1)\overline{u}(p_3)\gamma^\mu\tfrac{1}{2}(1-\gamma^5)v(p_4)}$$

- In terms of W-boson polarisation and weak charged current:

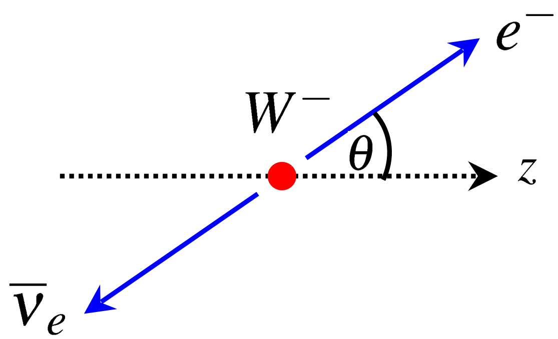
$$\boxed{M_{fi} = \frac{g_W}{\sqrt{2}}\varepsilon_\mu(p_1).j^\mu}$$

with

$$\boxed{j^\mu = \overline{u}(p_3)\gamma^\mu\tfrac{1}{2}(1-\gamma^5)v(p_4)}$$

Lepton current in W-decay

- In the CoM frame



$$p_1 = (m_W, 0, 0, 0);$$
$$p_3 = (E, E\sin\theta, 0, E\cos\theta)$$
$$p_4 = (E, -E\sin\theta, 0, -E\cos\theta)$$

with $E = \frac{m_W}{2}$

- In the ultra-relativistic limit only **LH particles** and **RH anti-particles** participate in the **weak interactions**

$$j^\mu = \overline{u}(p_3)\gamma^\mu \tfrac{1}{2}(1-\gamma^5)v(p_4) = \overline{u}_\downarrow(p_3)\gamma^\mu v_\uparrow(p_4)$$

Reminder:

$$\tfrac{1}{2}(1-\gamma^5)v(p_4) = v_\uparrow(p_4)$$

Chiral projection operator

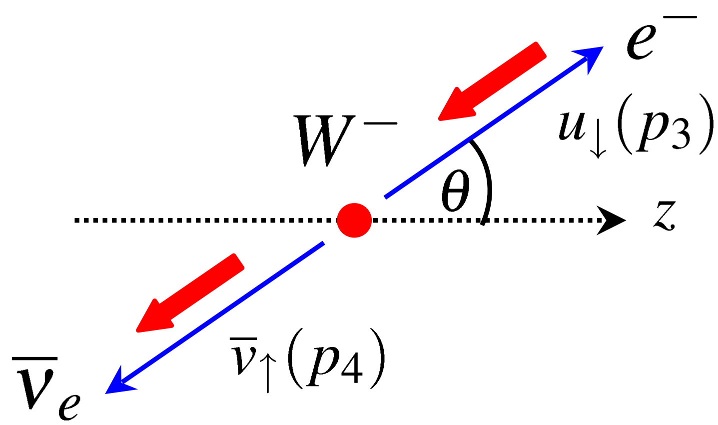
$$\overline{u}(p_3)\gamma^\mu v_\uparrow(p_4) = \overline{u}_\downarrow(p_3)\gamma^\mu v_\uparrow(p_4)$$

“Helicity conservation”

- From QED we already know $j^{\mu} = \overline{u}_{\downarrow}(p_3)\gamma^{\mu} v_{\uparrow}(p_4)$

with specific helicities $\mu_L^- \mu_R^+$ (see Module V)

$$\boxed{j^{\mu}_{\uparrow\downarrow} = 2E(0, -\cos\theta, -i, \sin\theta)}$$

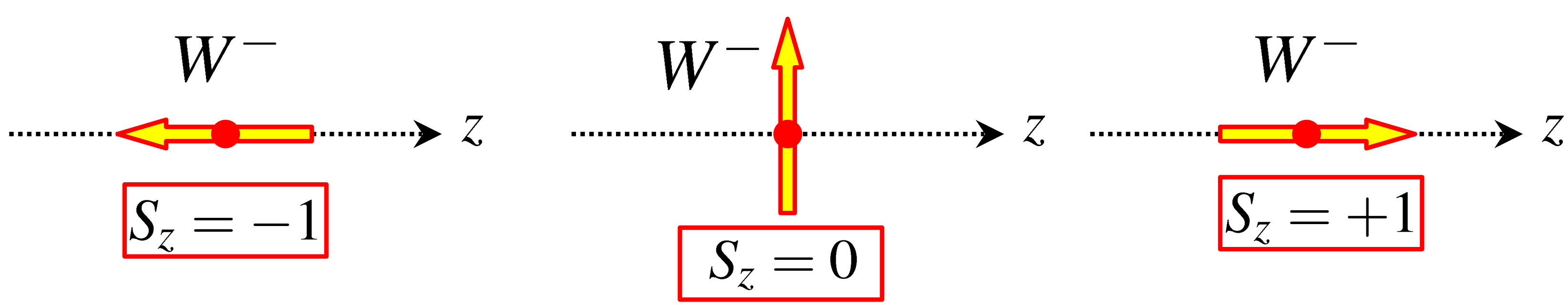


- For CC weak interaction we only have to consider this **single** combination of helicities

$$j^{\mu} = \overline{u}(p_3)\gamma^{\mu} \tfrac{1}{2}(1-\gamma^5)v(p_4) = \overline{u}_{\downarrow}(p_3)\gamma^{\mu} v_{\uparrow}(p_4) = 2E(0, -\cos\theta, -i, \sin\theta)$$

and three possible polarisation states of W-boson

$$\varepsilon^{\mu}_{-} = \frac{1}{\sqrt{2}}(0, 1, -i, 0); \quad \varepsilon_L = \frac{1}{m}(p_z, 0, 0, E) \quad \varepsilon^{\mu}_{+} = -\frac{1}{\sqrt{2}}(0, 1, i, 0)$$



- In the CoM frame:

$$\varepsilon_-^\mu = \frac{1}{\sqrt{2}}(0,1,-i,0); \quad \varepsilon_L = (0,0,0,1) \quad \varepsilon_+^\mu = -\frac{1}{\sqrt{2}}(0,1,i,0)$$

$$M_{fi} = \frac{g_W}{\sqrt{2}}\varepsilon_\mu(p_1)j^\mu \qquad j^\mu = 2\frac{m_W}{2}(0,-\cos\theta,-i,\sin\theta)$$

Decay at rest : $E_e = E_\nu = m_W/2$

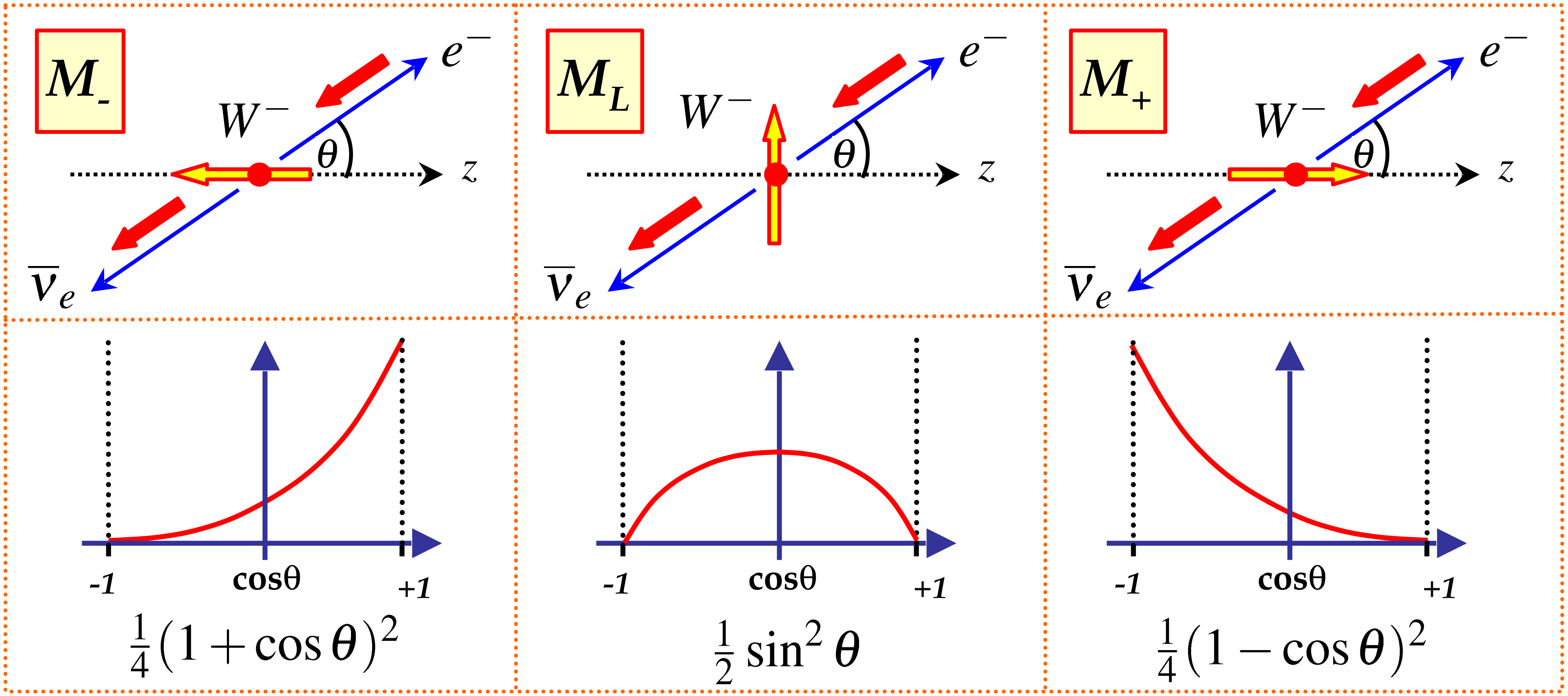
- Thus:

$$\boxed{\varepsilon_-} \quad M_- = \frac{g_W}{\sqrt{2}}\frac{1}{\sqrt{2}}(0,1,-i,0).m_W(0,-\cos\theta,-i,\sin\theta) = \frac{1}{2}g_W m_W(1+\cos\theta)$$

$$\boxed{\varepsilon_L} \quad M_L = \frac{g_W}{\sqrt{2}}(0,0,0,1).m_W(0,-\cos\theta,-i,\sin\theta) = -\frac{1}{\sqrt{2}}g_W m_W \sin\theta$$

$$\boxed{\varepsilon_+} \quad M_+ = -\frac{g_W}{\sqrt{2}}\frac{1}{\sqrt{2}}(0,1,i,0).m_W(0,-\cos\theta,-i,\sin\theta) = \frac{1}{2}g_W m_W(1-\cos\theta)$$

$$\Rightarrow \boxed{\begin{aligned} |M_-|^2 &= g_W^2 m_W^2 \tfrac{1}{4}(1+\cos\theta)^2 \\ |M_L|^2 &= g_W^2 m_W^2 \tfrac{1}{2}\sin^2\theta \\ |M_+|^2 &= g_W^2 m_W^2 \tfrac{1}{4}(1-\cos\theta)^2 \end{aligned}}$$



- Differential decay rate in the **CoM** frame

$$\frac{d\Gamma}{d\Omega} = \frac{|p^*|}{32\pi^2 m_W^2}|M|^2$$

with $p^* = \frac{m_W}{2}$

- For different W-boson polarisations

$$\frac{d\Gamma_-}{d\Omega} = \frac{g_W^2 m_w}{64\pi^2}\frac{1}{4}(1+\cos\theta)^2 \qquad \frac{d\Gamma_L}{d\Omega} = \frac{g_W^2 m_w}{64\pi^2}\frac{1}{2}\sin^2\theta \qquad \frac{d\Gamma_+}{d\Omega} = \frac{g_W^2 m_w}{64\pi^2}\frac{1}{4}(1-\cos\theta)^2$$

- Integrating over angles using $\int \frac{1}{4}(1\pm\cos\theta)^2 d\phi\, d\cos\theta = \int \frac{1}{2}\sin^2\theta\, d\phi\, d\cos\theta = \frac{4\pi}{3}$

$$\boxed{\Gamma_- = \Gamma_L = \Gamma_+ = \frac{g_W^2 m_W}{48\pi}}$$

- If we have a sample of unpolarised W-bosons each polarisation is equally likely.

$$\begin{aligned}
\langle |M_{fi}|^2 \rangle &= \tfrac{1}{3}(|M_-|^2 + |M_L|^2 + |M_+|^2) \\
&= \tfrac{1}{3} g_W^2 m_W^2 \left[\tfrac{1}{4}(1+\cos\theta)^2 + \tfrac{1}{2}\sin^2\theta + \tfrac{1}{4}(1-\cos\theta)^2\right] \\
&= \tfrac{1}{3} g_W^2 m_W^2
\end{aligned}$$

- I.e. the decay of unpolarised W-bosons is isotropic.

- Therefore for **unpolarised** W-bosons

$$\boxed{\Gamma(W^- \rightarrow e^- \overline{\nu}) = \frac{g_W^2 m_W}{48\pi}}$$

- Other decay modes are calculated in a similar way (here we neglect different phase space for different final states). For quarks **colour** and **CKM** matrix must be taken into account.

$$\begin{array}{l} W^- \rightarrow e^- \overline{\nu}_e \\ W^- \rightarrow \mu^- \overline{\nu}_\mu \\ W^- \rightarrow \tau^- \overline{\nu}_\tau \end{array} \qquad \begin{array}{l} W^- \rightarrow d\overline{u} \\ W^- \rightarrow s\overline{u} \\ W^- \rightarrow b\overline{u} \end{array} \boxed{\begin{array}{l} \times 3|V_{ud}|^2 \\ \times 3|V_{us}|^2 \\ \times 3|V_{ub}|^2 \end{array}} \qquad \begin{array}{l} W^- \rightarrow d\overline{c} \\ W^- \rightarrow s\overline{c} \\ W^- \rightarrow b\overline{c} \end{array} \boxed{\begin{array}{l} \times 3|V_{cd}|^2 \\ \times 3|V_{cs}|^2 \\ \times 3|V_{cb}|^2 \end{array}}$$

no decay to top-quark

$m_t \approx 175 GeV > m_W \approx 80 GeV$

- Taking into account the **unitarity** of **CKM** (e.g. $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$)

$$BR(\mathrm{W} \rightarrow qq') = 6BR(\mathrm{W} \rightarrow \mathrm{e}\nu)$$

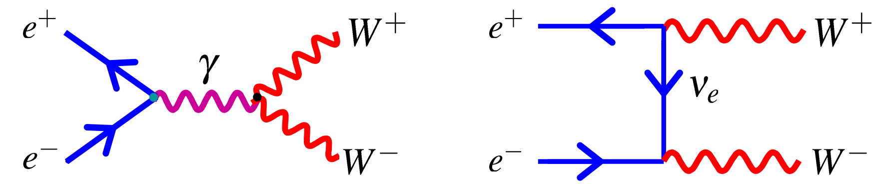
- Therefore

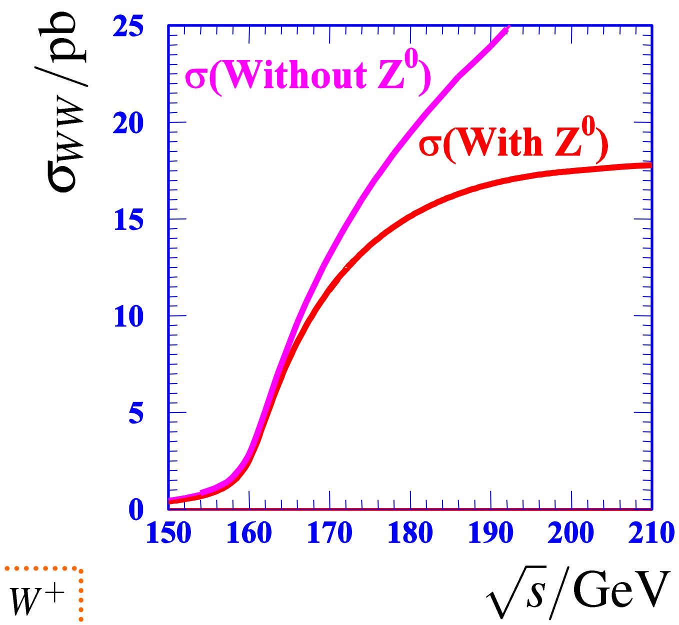
$$\boxed{\Gamma_W = 9\Gamma_{W \rightarrow e\nu} = \frac{3g_W^2 m_W}{16\pi} = 2.07\,\mathrm{GeV}}$$

Experiment: 2.14±0.04 GeV
(also neglected a 3% QCD correction to decays to quarks)

From W to Z

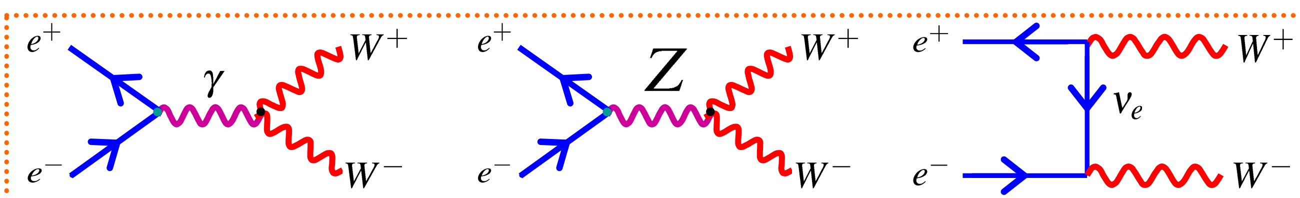
- W's can be produced in e^+e^- annihilation





- It turns out with just these two diagrams x-section increases with CoM energy **violating unitarity**

- The problem can be "fixed" by introducing a new boson (the Z)



$$|M_{\gamma WW}+M_{ZWW}+M_{\nu WW}|^2 < |M_{\gamma WW}+M_{\nu WW}|^2$$

- Only works if γ, Z, W are related $\Longrightarrow$ **Electro-Weak Unification**

SU(2)$_L$ - Weak Interaction

- Just like QED (and QCD) **Weak Interaction** arises from **gauge invariance**

$$\psi \rightarrow \psi' = \psi e^{i\vec{\alpha}(x).\frac{\vec{\sigma}}{2}}$$

$\vec{\sigma}$ are generators of SU(2) symmetry, three Pauli matrices

⇨ **3 Gauge Bosons** $\quad W_1^\mu,\ W_2^\mu,\ W_3^\mu$

- Wave-functions have two components represented by "**weak isospin**"
- **Observable** fermions are isospin **doublets** $\begin{pmatrix}\nu_e \\ e^-\end{pmatrix} \rightarrow \begin{pmatrix}\nu_e \\ e^-\end{pmatrix}' = e^{i\vec{\alpha}(x).\frac{\vec{\sigma}}{2}} \begin{pmatrix}\nu_e \\ e^-\end{pmatrix}$
- Weak Interaction couples only two **LH particles/RH anti-particles**. $\quad I_W = \frac{1}{2}$
- **RH particles/LH anti-particles** are weak isospin **singlets** $\quad I_W = 0$

Weak Isospin

$\boxed{I_W = \frac{1}{2}}$ $\quad \begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L, \begin{pmatrix}\nu_\mu \\ \mu^-\end{pmatrix}_L, \begin{pmatrix}\nu_\tau \\ \tau^-\end{pmatrix}_L, \begin{pmatrix}u \\ d'\end{pmatrix}_L, \begin{pmatrix}c \\ s'\end{pmatrix}_L, \begin{pmatrix}t \\ b'\end{pmatrix}_L$ $\quad \leftarrow \boxed{I_W^3 = +\frac{1}{2}}$ (upper), $\leftarrow \boxed{I_W^3 = -\frac{1}{2}}$ (lower)

$\boxed{I_W = 0}$ $\quad (\nu_e)_R,\ (e^-)_R, \ldots (u)_R,\ (d)_R, \ldots$

- Consider 1st generation $\chi_L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$

- Including interaction strength in currents

$$j^1_\mu = g_W \overline{\chi}_L \gamma^\mu \tfrac{1}{2}\sigma_1 \chi_L \qquad j^2_\mu = g_W \overline{\chi}_L \gamma^\mu \tfrac{1}{2}\sigma_2 \chi_L \qquad j^3_\mu = g_W \overline{\chi}_L \gamma^\mu \tfrac{1}{2}\sigma_3 \chi_L$$

- Weak Charged Currents are related to weak isospin raising and lowering operators

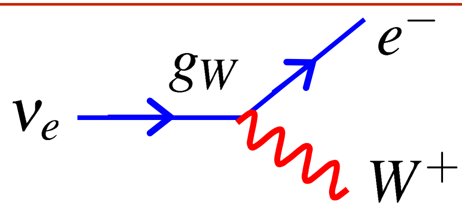
$$\sigma_\pm = \tfrac{1}{2}(\sigma_1 \pm i\sigma_2)$$

- Thus 4-vector current corresponding to the exchange of the **physical $W^\pm$** bosons:

$$j^\mu_\pm = \frac{g_W}{\sqrt{2}}(j^\mu_1 \pm i j^\mu_2) = \frac{g_W}{\sqrt{2}}\overline{\chi}_L \gamma^\mu \tfrac{1}{2}(\sigma_1 \pm i\sigma_2)\chi_L$$ with $$W^{\pm\mu} = \tfrac{1}{\sqrt{2}}(W^\mu_1 \pm W^\mu_2)$$

also written as $$j^\mu_\pm = \frac{g_W}{\sqrt{2}}\overline{\chi}_L \gamma^\mu \sigma_\pm \chi_L$$

W^+



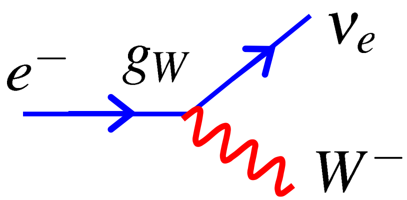
corresponds to $\boxed{j^\mu_+ = \frac{g_W}{\sqrt{2}}\overline{\chi}_L \gamma^\mu \sigma_+ \chi_L}$

writing in full:

$$j^\mu_+ = \frac{g_W}{\sqrt{2}}\overline{\chi}_L \gamma^\mu \sigma_+ \chi_L = \frac{g_W}{\sqrt{2}}(\overline{\nu}_L, \overline{e}_L)\gamma^\mu \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \nu \\ e \end{pmatrix}_L = \frac{g_W}{\sqrt{2}}\overline{\nu}_L \gamma^\mu e_L = \frac{g_W}{\sqrt{2}}\overline{\nu}\gamma^\mu \tfrac{1}{2}(1-\gamma^5)e$$

- Similarly for W^-

W⁻



corresponds to

$$\boxed{j_-^\mu = \frac{g_W}{\sqrt{2}}\overline{\chi}_L \gamma^\mu \sigma_- \chi_L}$$

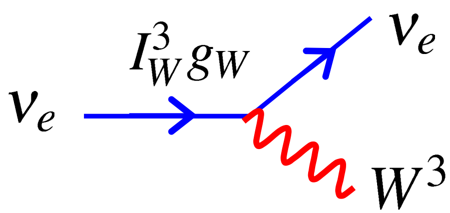
$$j_-^\mu = \frac{g_W}{\sqrt{2}}\overline{\chi}_L \gamma^\mu \sigma_- \chi_L = \frac{g_W}{\sqrt{2}}(\overline{\nu}_L, \overline{e}_L)\gamma^\mu \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \nu \\ e \end{pmatrix}_L = \frac{g_W}{\sqrt{2}}\overline{e}_L \gamma^\mu \nu_L = \frac{g_W}{\sqrt{2}}\overline{e}\gamma^\mu \tfrac{1}{2}(1-\gamma^5)\nu$$

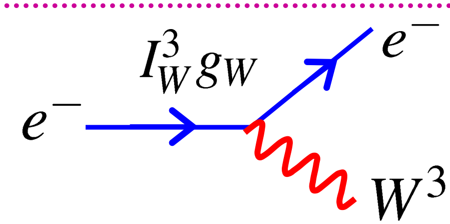
- However there is an **additional interaction** due to W^3

$$j_3^\mu = g_W \overline{\chi}_L \gamma^\mu \tfrac{1}{2}\sigma_3 \chi_L$$

$$\boxed{I_W^3 = \pm\tfrac{1}{2}}$$

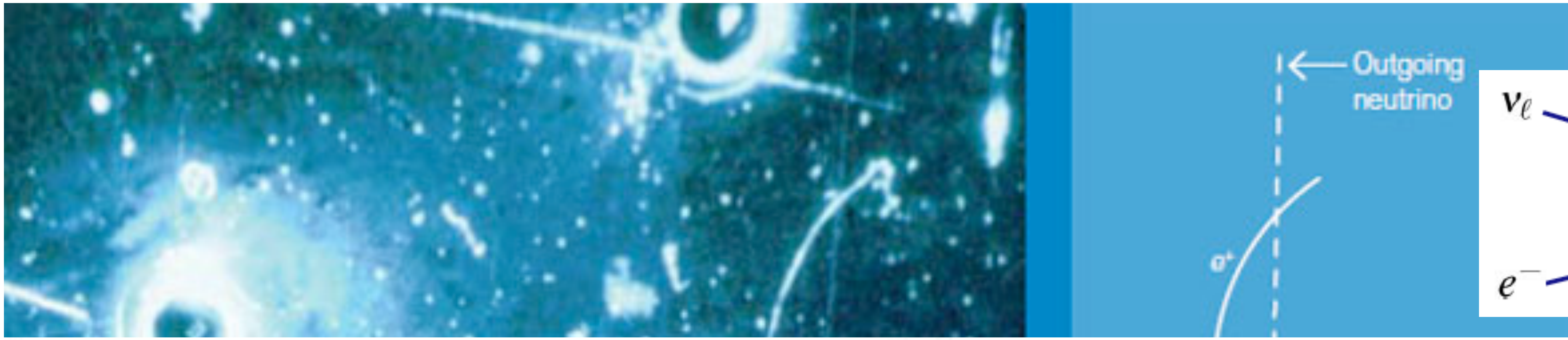
$$j_3^\mu = g_W \frac{1}{2}(\overline{\nu}_L, \overline{e}_L)\gamma^\mu \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} \nu \\ e \end{pmatrix}_L = g_W \tfrac{1}{2}\overline{\nu}_L \gamma^\mu \nu_L - g_W \tfrac{1}{2}\overline{e}_L \gamma^\mu e_L$$

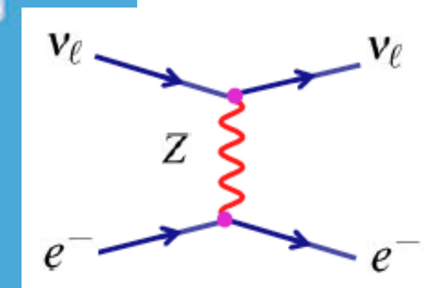




NEUTRAL CURRENT INTERACTIONS !

Neutral current discovery at CERN (1973)





Volume 46B, number 1 PHYSICS LETTERS 3 September 1973

SEARCH FOR ELASTIC MUON-NEUTRINO ELECTRON SCATTERING

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Received 2 July 1973

One possible event of the process $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$ has been observed. The various background processes are discussed and the event interpreted in terms of the Weinberg theory. The 90% confidence limits on the Weinberg parameter are $0.1 < \sin^2\theta_W < 0.6$.

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OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

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Events induced by neutral particles and producing hadrons, but no muon or electron, have been observed in the CERN neutrino experiment. These events behave as expected if they arise from neutral current induced processes. The rates relative to the corresponding charged current processes are evaluated.

UCL involvement

Electro-Weak Unification Formalism

UCL

- Glashow, Salam and Weinberg (GSW) introduced new gauge symmetry **$U(1)_Y$**

- Gauge Invariance requirement gives rise to new gauge field **B_μ** and interaction term

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

Y — **weak hyperchage**, *Qe* in $U(1)_{EM}$ replaced by $Yg'/2$

- Define **physical** bosons, the *Z* and photon field *A*

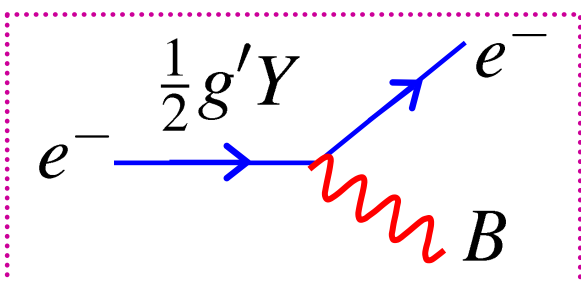
$$A_\mu = B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W$$
$$Z_\mu = -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W$$

θ_W **is the weak mixing angle**

- The charge of this symmetry is **weak hypercharge**

$$\boxed{Y = 2Q - 2I_W^3}$$

Q is the EM charge of a particle
I_W is the third comp. of weak isospin



$$e_L: \; Y = 2(-1) - 2(-\tfrac{1}{2}) = -1 \qquad \nu_L: \; Y = +1$$

$$e_R: \; Y = 2(-1) - 2(0) = -2 \qquad \nu_R: \; Y = 0$$

- Consider contributions involving neutral interactions of electrons

$\boxed{\gamma}$ $$j_\mu^{em} = e\overline{\psi}Q_e\gamma_\mu\psi = e\bar{e}_L Q_e \gamma_\mu e_L + e\bar{e}_R Q_e \gamma_\mu e_R$$

$\boxed{W^3}$ $$j_\mu^{W^3} = -\frac{g_W}{2}\bar{e}_L\gamma_\mu e_L$$

$\boxed{B}$ $$j_\mu^Y = \frac{g'}{2}\overline{\psi}Y_e\gamma_\mu\psi = \frac{g'}{2}\bar{e}_L Y_{e_L}\gamma_\mu e_L + \frac{g'}{2}\bar{e}_R Y_{e_R}\gamma_\mu e_R$$

- The relation $A_\mu = B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W$ is equivalent to

$$\boxed{j_\mu^{em} = j_\mu^Y \cos\theta_W + j_\mu^{W^3} \sin\theta_W}$$

- Writing it in full

$$e\bar{e}_L Q_e \gamma_\mu e_L + e\bar{e}_R Q_e \gamma_\mu e_R = \tfrac{1}{2}g' \cos\theta_W [\bar{e}_L Y_{e_L}\gamma_\mu e_L + \bar{e}_R Y_{e_R}\gamma_\mu e_R] - \tfrac{1}{2}g_W \sin\theta_W [\bar{e}_L\gamma_\mu e_L]$$

$$-e\bar{e}_L\gamma_\mu e_L - e\bar{e}_R\gamma_\mu e_R = \tfrac{1}{2}g' \cos\theta_W [-\bar{e}_L\gamma_\mu e_L - 2\bar{e}_R\gamma_\mu e_R] - \tfrac{1}{2}g_W \sin\theta_W [\bar{e}_L\gamma_\mu e_L]$$

which works if $\boxed{e = g_W \sin\theta_W = g' \cos\theta_W}$

- Coupling of **EM**, **weak interaction** and interaction of **U(1)$_Y$** symmetry are therefore **related**

$$\boxed{\sin^2\theta_W = 0.23146 \pm 0.00012}$$ ⇦ average of several measurements

Z-boson and its couplings

$$Z_\mu = -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W$$

for electron $I_W^3 = \frac{1}{2}$

$\boxed{I_W^3}$

$$j_\mu^Z = -\tfrac{1}{2} g' \sin\theta_W [\bar{e}_L Y_{e_L} \gamma_\mu e_L + \bar{e}_R Y_{e_R} \gamma_\mu e_R] - \tfrac{1}{2} g_W \cos\theta_W [e_L \gamma_\mu e_L]$$

$$j_\mu^Z = -\tfrac{1}{2} g' \sin\theta_W [\bar{e}_L (2Q - 2I_W^3) \gamma_\mu e_L + \bar{e}_R (2Q) \gamma_\mu e_R] + I_W^3 g_W \cos\theta_W [e_L \gamma_\mu e_L]$$

Gathering LH and RH chiral states:

$$j_\mu^Z = \left[g' I_W^3 \sin\theta_W - g' Q \sin\theta_W + g_W I_W^3 \cos\theta_W\right] \bar{e}_L \gamma_\mu e_L - \left[g' Q \sin\theta_W\right] e_R \gamma_\mu e_R$$

Using $e = g_W \sin\theta_W = g' \cos\theta_W$

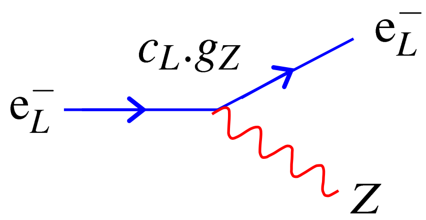
$$j_\mu^Z = \left[g' \frac{(I_W^3 - Q\sin^2\theta_W)}{\sin\theta_W}\right] \bar{e}_L \gamma_\mu e_L - \left[g' \frac{Q\sin^2\theta_W}{\sin\theta_W}\right] e_R \gamma_\mu e_R$$

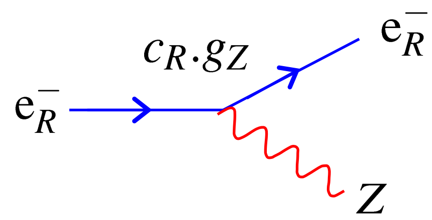
$$\boxed{j_\mu^Z = g_Z (I_W^3 - Q\sin^2\theta_W) [\bar{e}_L \gamma_\mu e_L] - g_Z Q \sin^2\theta_W [e_R \gamma_\mu e_R]}$$

with $\boxed{e = g_Z \cos\theta_W \sin\theta_W}$ **Therefore** $\boxed{g_Z = \dfrac{g_W}{\cos\theta_W}}$

- Unlike W-boson in CC weak interaction, **Z**-boson couples to **LH and RH** chiral components, but **not equally**

$$
\begin{aligned}
j^Z_\mu &= g_Z(I^3_W - Q\sin^2\theta_W)[\bar{\mathrm{e}}_L\gamma_\mu \mathrm{e}_L] - g_Z Q\sin^2\theta_W[\mathrm{e}_R\gamma_\mu e_R] \\
&= g_Z c_L[\bar{\mathrm{e}}_L\gamma_\mu \mathrm{e}_L] + g_Z c_R[\mathrm{e}_R\gamma_\mu e_R]
\end{aligned}
$$





$\boxed{c_L = I^3_W - Q\sin^2\theta_W}$ $\boxed{c_R = -Q\sin^2\theta_W}$

W^3 part of Z couples only to LH components (like W$^\pm$)

B$_\mu$ part of Z couples equally to LH and RH components

- Projection operators to obtain vector and axial couplings

$$
\bar{u}_L\gamma_\mu u_L = \bar{u}\gamma_\mu \tfrac{1}{2}(1-\gamma_5)u \qquad \bar{u}_R\gamma_\mu u_R = \bar{u}\gamma_\mu \tfrac{1}{2}(1+\gamma_5)u
$$

$$
j^Z_\mu = g_Z\bar{u}\gamma_\mu\left[c_L\tfrac{1}{2}(1-\gamma_5) + c_R\tfrac{1}{2}(1+\gamma_5))\right]u
$$

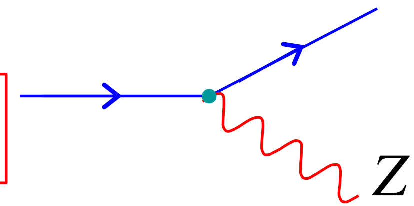
$$j^Z_\mu = \frac{g_Z}{2}\overline{u}\gamma_\mu\left[(c_L + c_R) + (c_R - c_L)\gamma_5)\right]u$$

- which in terms of **V** and **A** components gives $$j^Z_\mu = \frac{g_Z}{2}\overline{u}\gamma_\mu\left[c_V - c_A\gamma_5\right]u$$

with $\boxed{c_V = c_L + c_R = I^3_W - 2Q\sin^2\theta_W}$ $\boxed{c_A = c_L - c_R = I^3_W}$

- The vertex for Z-boson is therefore

$$\boxed{-ig_Z\tfrac{1}{2}\gamma_\mu\left[c_V - c_A\gamma_5\right]}$$



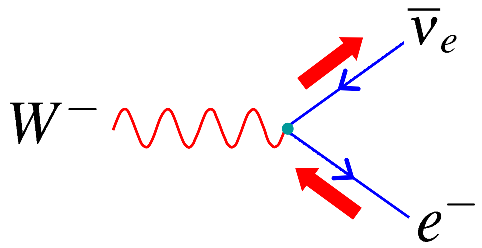
- Using experimentally determined value of weak mixing angle

$\boxed{\sin^2\theta_W \approx 0.23}$

Fermion	Q	I^3_W	c_L	c_R	c_V	c_A
ν_e, ν_μ, ν_τ	0	$+\frac{1}{2}$	$+\frac{1}{2}$	0	$+\frac{1}{2}$	$+\frac{1}{2}$
e^-, μ^-, τ^-	-1	$-\frac{1}{2}$	-0.27	0.23	-0.04	$-\frac{1}{2}$
u, c, t	$+\frac{2}{3}$	$+\frac{1}{2}$	0.35	-0.15	$+0.19$	$+\frac{1}{2}$
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	-0.42	0.08	-0.35	$-\frac{1}{2}$

Z-boson decay

- For W-boson decay we had to consider only one helicity combination

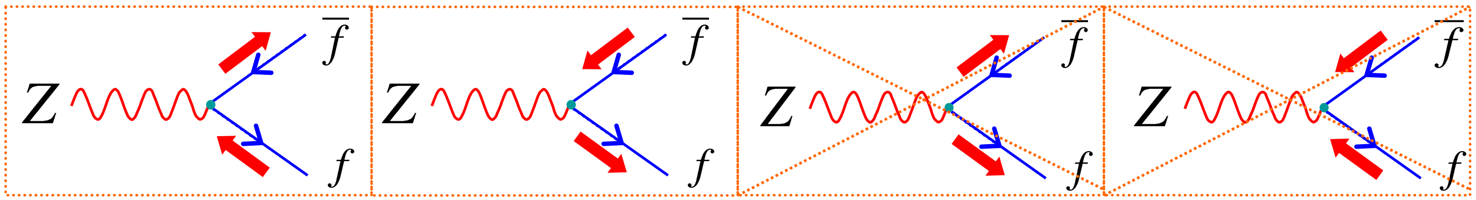


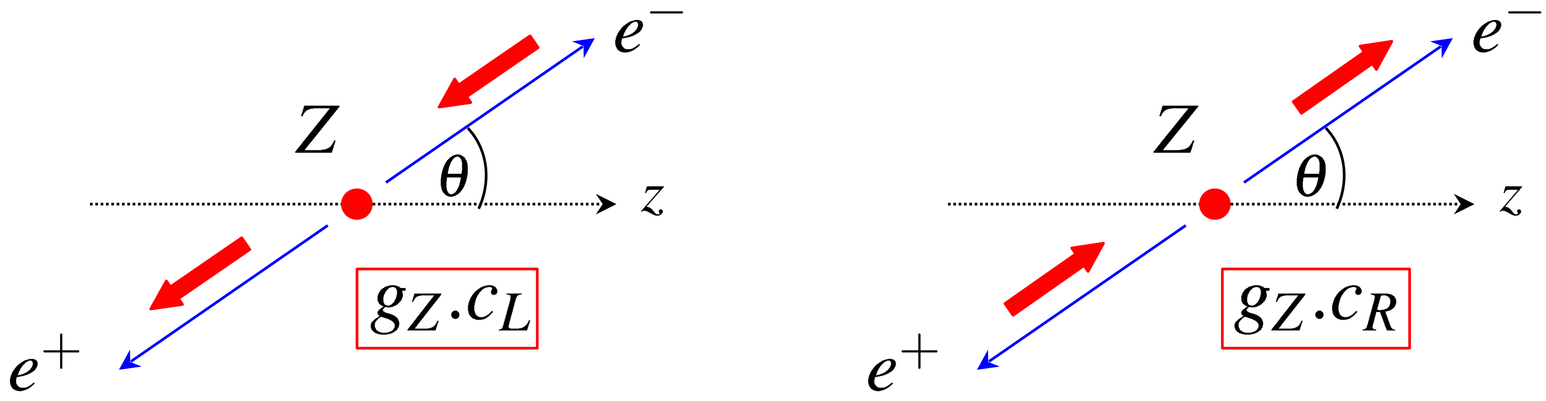
ultra-relativistic: helicity = chirality

W couples to LH particles, RH anti-particles

- But Z-boson couples to both LH and RH currents (with different strength)

- For **Z**-boson there are **two** helicity combinations





- For unpolarised Z-bosons:

$$\langle |M_{fi}|^2 \rangle = \tfrac{1}{3}[2c_L^2 g_Z^2 m_Z^2 + 2c_R^2 g_Z^2 m_Z^2] = \tfrac{2}{3} g_Z^2 m_Z^2 (c_L^2 + c_R^2)$$

Using $c_V^2 + c_A^2 = 2(c_L^2 + c_R^2)$ and $\dfrac{\mathrm{d}\Gamma}{\mathrm{d}\Omega} = \dfrac{|p^*|}{32\pi^2 m_W^2}|M|^2$

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

Z-decay Branching Ratios

- Same expression for decays to other fermions (neglecting their masses)

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

$$Br(Z \to e^+e^-) = Br(Z \to \mu^+\mu^-) = Br(Z \to \tau^+\tau^-) \boxed{\approx 3.5\%}$$

$$Br(Z \to \nu_1\overline{\nu}_1) = Br(Z \to \nu_2\overline{\nu}_2) = Br(Z \to \nu_3\overline{\nu}_3) \boxed{\approx 6.9\%}$$

$$Br(Z \to d\overline{d}) = Br(Z \to s\overline{s}) = Br(Z \to b\overline{b}) \boxed{\approx 15\%}$$

$$Br(Z \to u\overline{u}) = Br(Z \to c\overline{c}) \boxed{\approx 12\%}$$

Factor x3 due to colour

- Z decays predominantly to hadrons:

$$Br(Z \to \text{hadrons}) \approx 69\%$$

- Total decay rate

$$\Gamma_Z = \sum_i \Gamma_i = 2.5\,\text{GeV}$$

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

“Nutshell” Summary of SM and Unification

- The **Standard Model** interactions are mediated by **spin-1 gauge bosons**
- Interactions are completed specified by local phase transformation

Gauge Invariance

$U(1)_{em}$	⇨	**QED**
$SU(2)_L$	⇨	**Charged Current Weak Interaction + W^3**
$SU(3)_{col}$	⇨	**QCD**

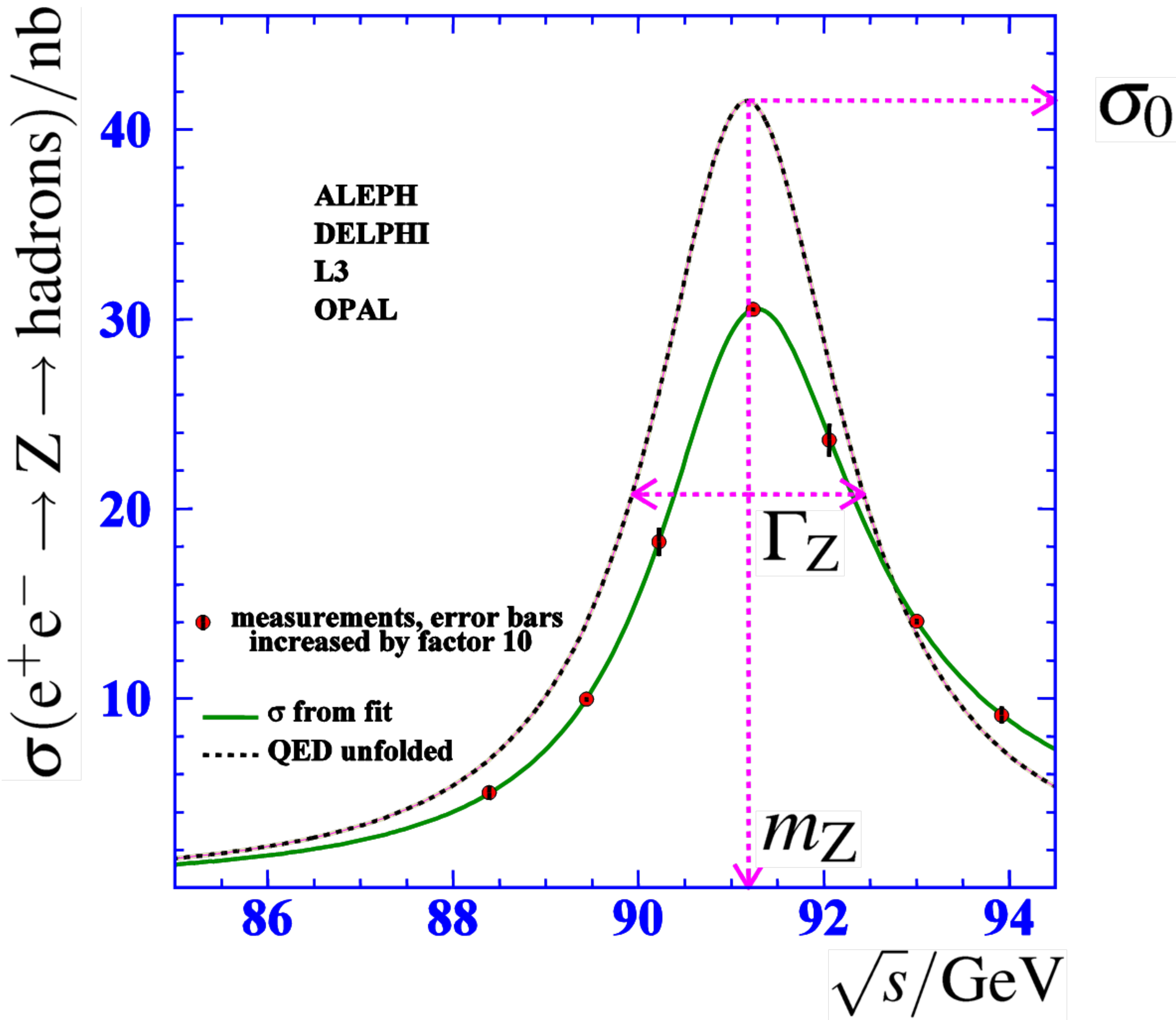
- In order to **unify EM** and **WI**, a new gauge symmetry is introduced: **$U(1)_Y$** hypercharge

$U(1)_Y$ ⇨ B_μ

- The physical **Z** boson and the photon γ are mixtures of neutral **W^3** and **B** determined by **weak mixing angle**

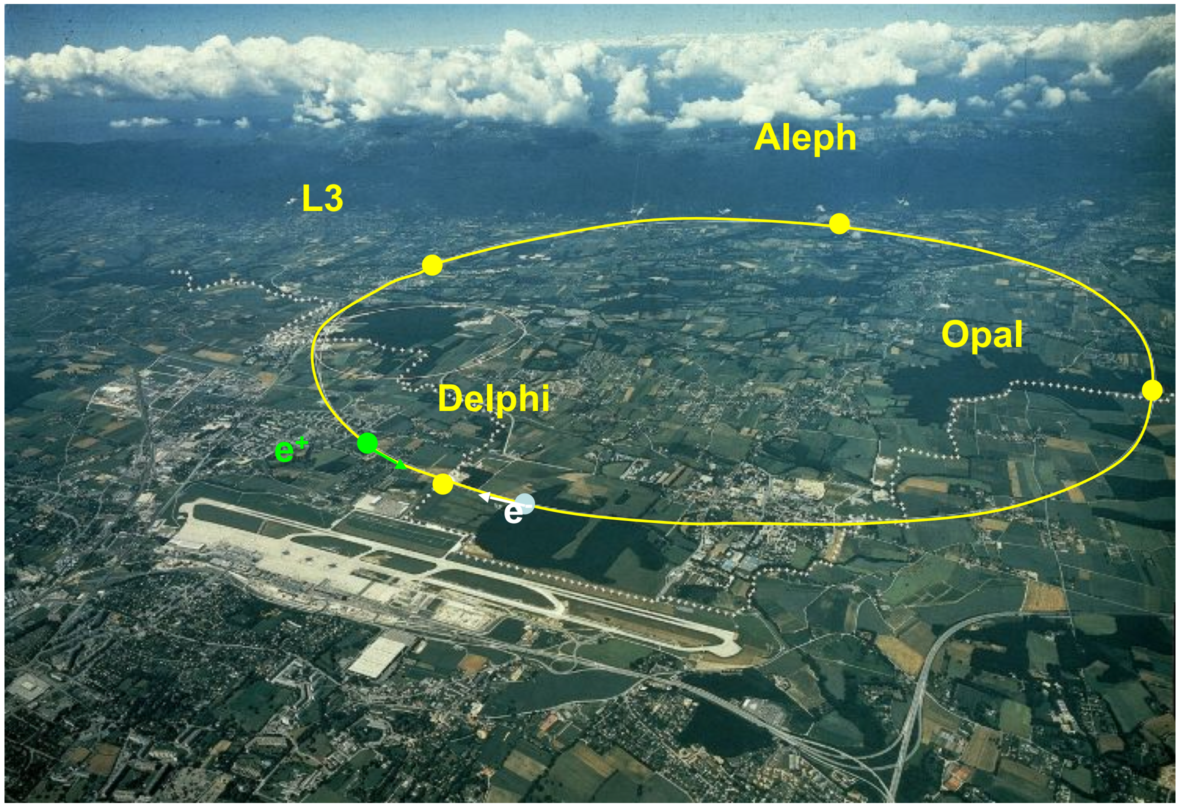
$$\boxed{\sin\theta_W \approx 0.23}$$

(Some) Precision Standard Model Tests



Electro-Weak measurements at LEP

Large Electron Positron Collider



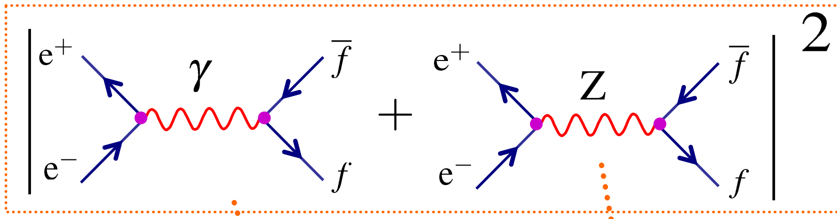
4 Large Detector Collaborations

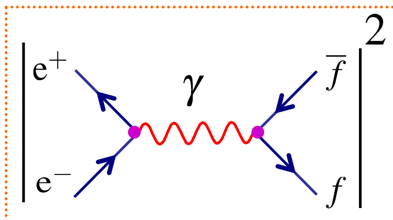
ALEPH
DELPHI
L3
OPAL (UCL involvement)

Massive Z and W factory

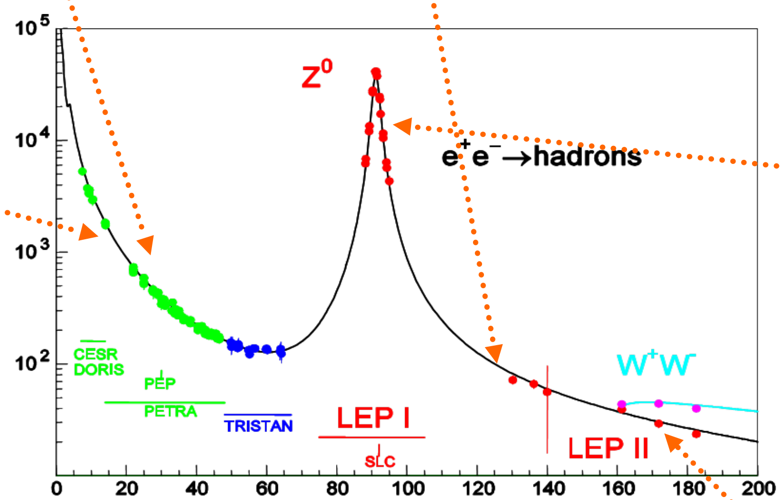
- 1989-1995 $\sqrt{s}$ = **91.2 GeV**
  17,000,000 **Z** bosons detected
- 1996-2000 $\sqrt{s}$ = **161-208 GeV**
  30,000 **$W^{\pm}$** bosons detected

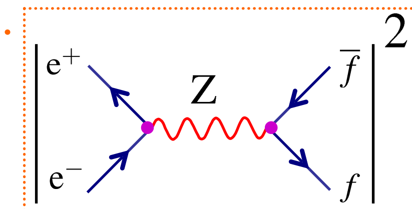
e^+e^- annihilation





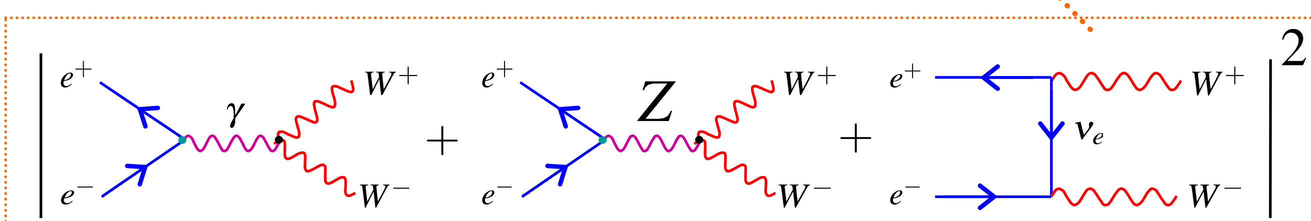
Well below Z: photon exchange dominant





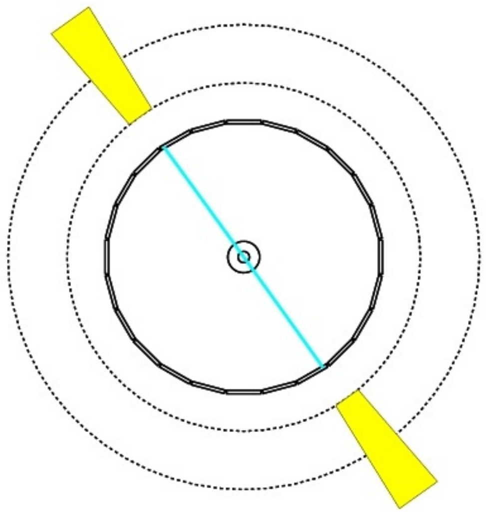
At Z resonance: Z exchange dominant

High energies: WW production

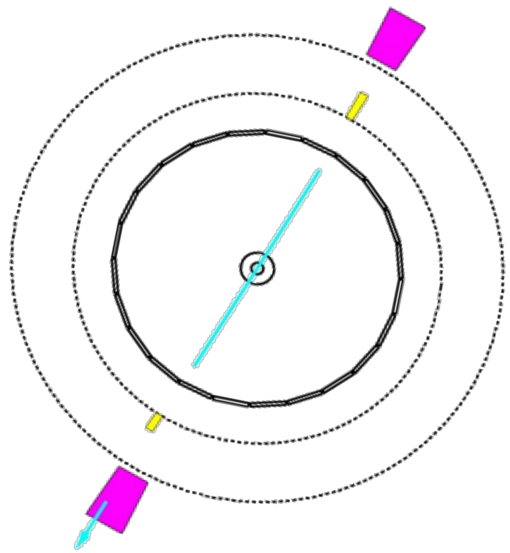


X-section measurements and Z-decay width measurements to different final states using different particle topologies in the detectors

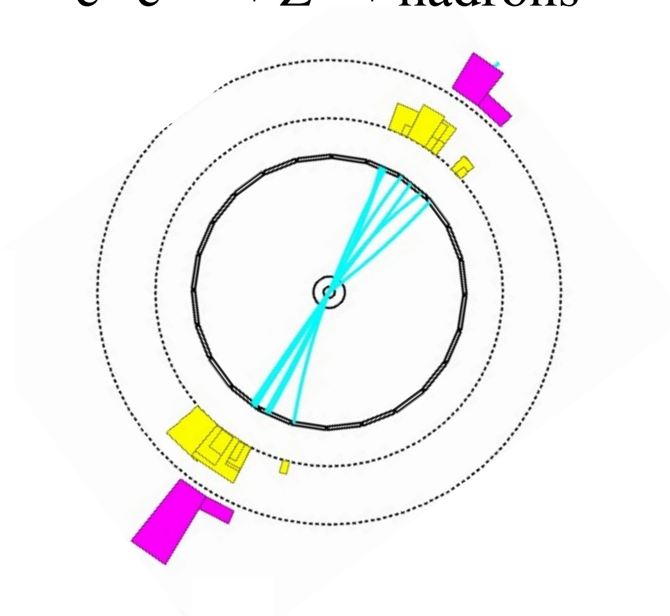
$e^+e^- \to Z \to e^+e^-$



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



$e^+e^- \to Z \to \text{hadrons}$

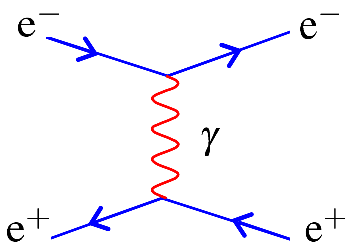


- To work out x-sections, measure N_{events} of each type
- Need to know "integrated luminosity" of colliding beams

$$N_{\text{events}} = \mathscr{L}\sigma$$

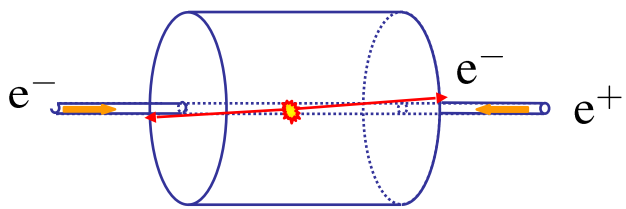
- Very difficult to know the number of e^+ and e^- and and beam profiles with < 10% accuracy

- Instead, “normalise” using another event types



- QED Bhabha scattering $\Longrightarrow$ very well understood

- Very large x-section $\Longrightarrow$ small stat. errors



$$\frac{d\sigma}{d\Omega} \propto \frac{1}{q^4} \propto \frac{1}{\sin^4 \theta/2} \Rightarrow \boxed{\frac{d\sigma}{d\theta} \propto \frac{1}{\theta^3}}$$

Photon propagator

very forward peaked

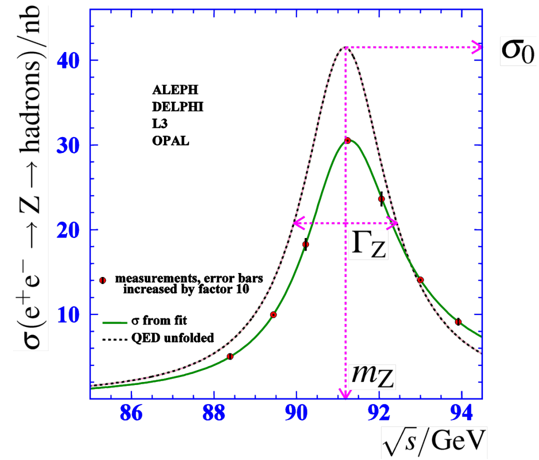
- Count events where electron is scattered in very forward direction

$$N_{\text{Bhabha}} = \mathscr{L} \sigma_{\text{Bhabha}} \Rightarrow \mathscr{L}$$

σ_{Bhabha} **known from QED calc.**

$$\boxed{\sigma_i = \frac{N_i}{N_{\text{Bhabha}}} \sigma_{\text{Bhabha}}}$$

Measurement of Z-line shape



- Measurements of the Z resonance line shape determine:
  - m_Z : peak of the resonance
  - Γ_Z : FWHM of resonance
  - Γ_f : Partial decay widths
  - N_ν : Number of light neutrino generations
- **Measure cross sections to different final states versus C.o.M. energy**

- Measure x-sections to different final states at different $\sqrt{s}$

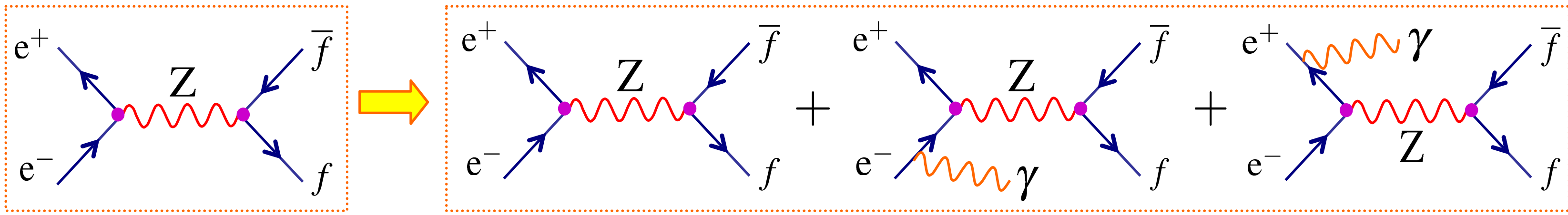
$$\sigma(e^+e^- \rightarrow Z \rightarrow f\bar{f}) = \frac{12\pi}{m_Z^2} \frac{s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2} \Gamma_{ee}\Gamma_{ff}$$

- Maximum occurs at $\sqrt{s} = m_Z$

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

$$\Gamma_Z = \frac{\hbar}{\tau_Z} = \text{FWHM of resonance}$$

- In practice, QED higher order corrections must be included, in particular **Initial State Radiation** (**ISR**)



- **ISR** reduces effective C.o.M energy

$$e^+ \xrightarrow{E} \xleftarrow{E} e^- \qquad \sqrt{s} = 2E$$

becomes

$$\xrightarrow{E} \xleftarrow{E - E_\gamma} \qquad \sqrt{s'} \approx 2E\left(1 - \frac{E_\gamma}{2E}\right)$$

- Measured x-section is

$$\sigma_{\text{meas}}(E) = \int \sigma(E') f(E', E) \mathrm{d}E'$$

Probability of e+e- colliding with C.o.M. energy E' when C.o.M energy before radiation is E

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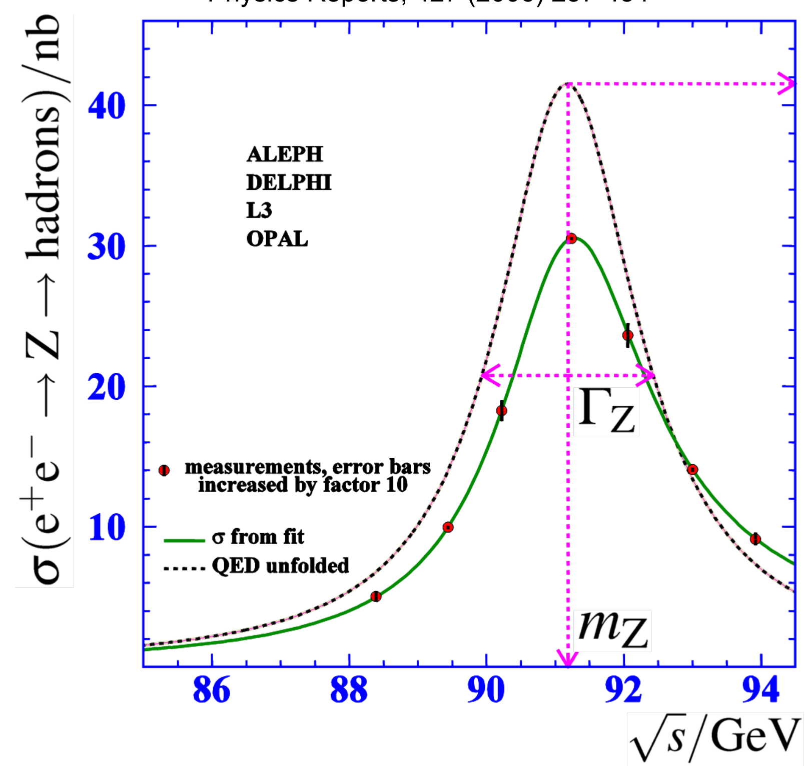


$f(E', E)$ can be precisely calculated (QED) and Z line-shape can then be "unfolded"

- To measure m_Z and Γ_Z : run accelerator at different energy, measure x-sections account for ISR, then find peak and FWHM

$$\boxed{m_Z = 91.1875 \pm 0.0021\,\mathrm{GeV}} \qquad \boxed{\Gamma_Z = 2.4952 \pm 0.0023\,\mathrm{GeV}}$$

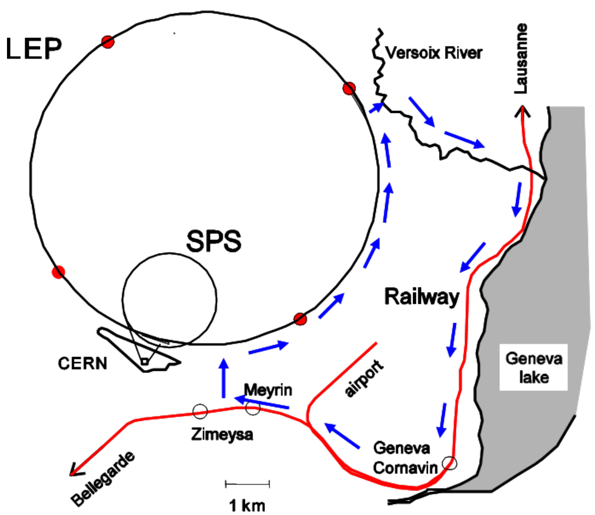
- To achieve this precision, you need to know the energy of the colliding beams to better than **0.002%**! Become sensitive to unusual systematic effects…

Moon:

- As the moon orbits the Earth it distorts the rock in the Geneva area very slightly !
- The nominal radius of the accelerator of **4.3 km** varies by **±0.15 mm**
- Changes beam energy by **~10 MeV** : need to correct for tidal effects !

Trains:

- Leakage currents from the TGV railway line return to Earth following the path of least resistance.
- Travelling via the Versoix river and using the LEP ring as a conductor.
- Each time a TGV train passed by, a small current circulated LEP slightly changing the magnetic field in the accelerator
- LEP beam energy changes by ~10 MeV



Number of neutrino generations

UCL

- Total decay width from Z line-shape $\Gamma_Z = 2.4952 \pm 0.0023\,\mathrm{GeV}$

- Can be used to determine the **number** of **neutrino** (lepton) **generations**

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\mathrm{hadrons}} + \Gamma_{\nu_1\nu_1} + \Gamma_{\nu_2\nu_2} + \Gamma_{\nu_3\nu_3} + ?$$

- Although do not observe neutrinos in the detector $Z \to \nu\bar{\nu}$ decays affect the Z resonance line shape for **all** final states

- For all other final states:

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

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

measured from Z lineshape

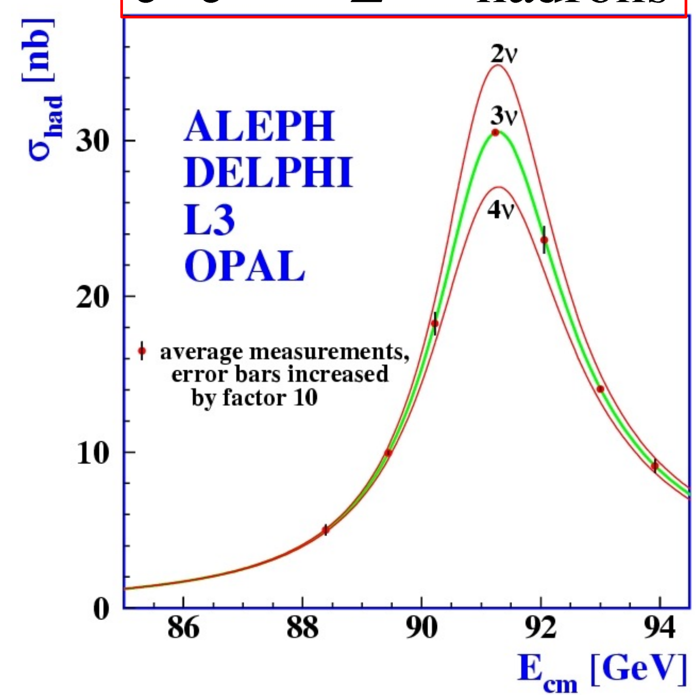
measured from peak cross sections

calculated

$$\boxed{N_\nu = 2.9840 \pm 0.0082}$$

Only 3 generations!

$\boxed{e^+e^- \to Z \to \mathrm{hadrons}}$



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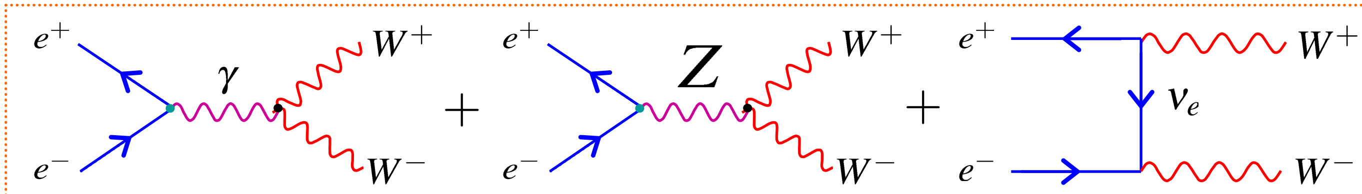
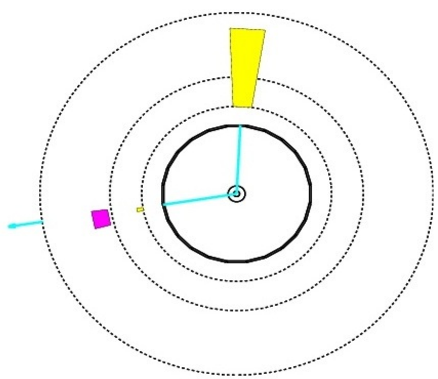
W^+W^- production

- In 1995-2000 LEP operated above the threshold for W-pair production

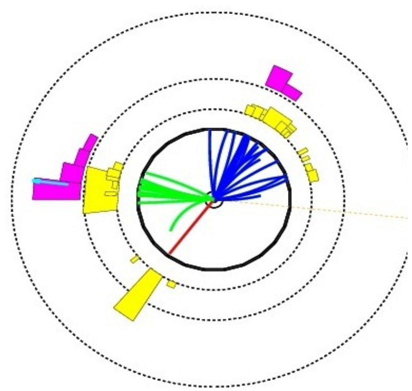


- W-bosons are then decay to hadrons and leptons

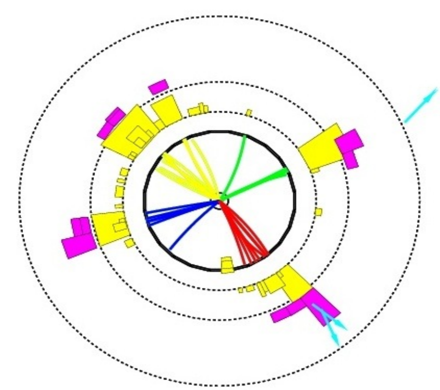
$$Br(W^- \to \text{hadrons}) \approx 0.67 \qquad Br(W^- \to e^-\overline{\nu}_e) \approx 0.11$$
$$Br(W^- \to \mu^-\overline{\nu}_\mu) \approx 0.11 \qquad Br(W^- \to \tau^-\overline{\nu}_\tau) \approx 0.11$$



$W^+W^- \to \ell^+\nu\ell^-\overline{\nu}$

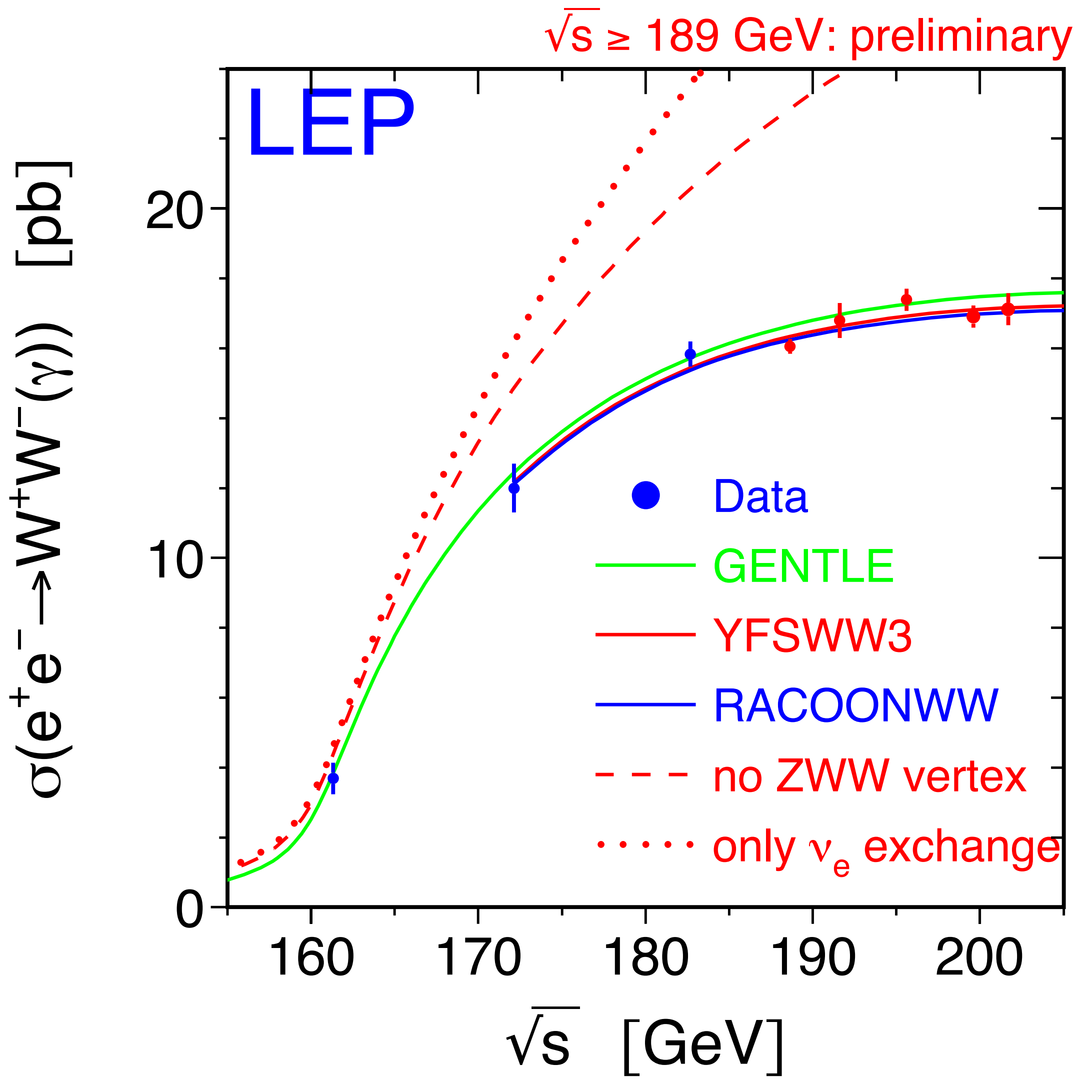


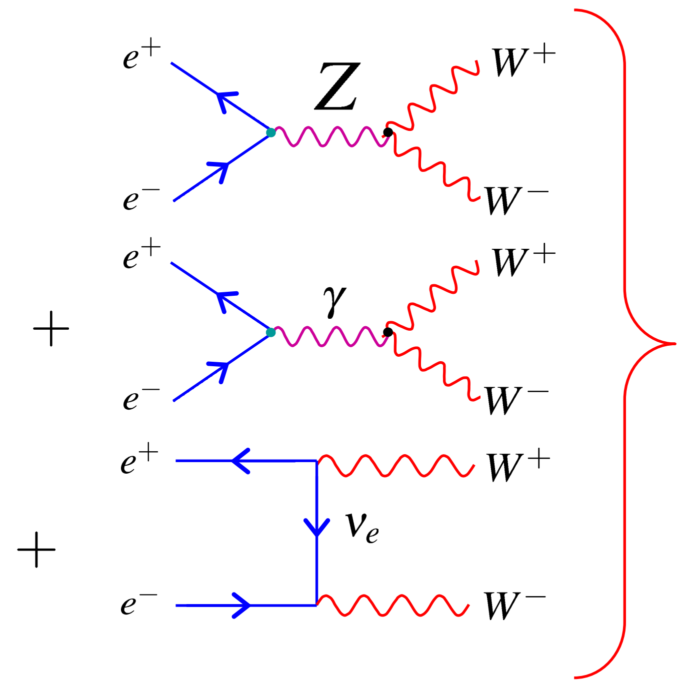
$W^+W^- \to q\bar{q}\ell\nu$



$W^+W^- \to q\bar{q}q\bar{q}$

$e^+e^- \to W^+W^-$ cross-section





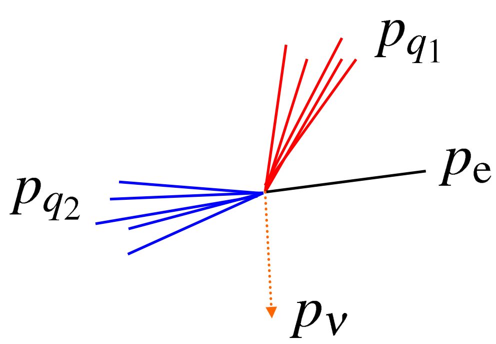
Presence of Z fixes the problem of unitarity in W^+W^- production

W-mass and W-width

$e^+e^- \to W^+W^-$ is not a resonant process $\Longrightarrow$ different method compared to Z is needed

- Measure momenta of particles produced in W-decay, e.g.

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

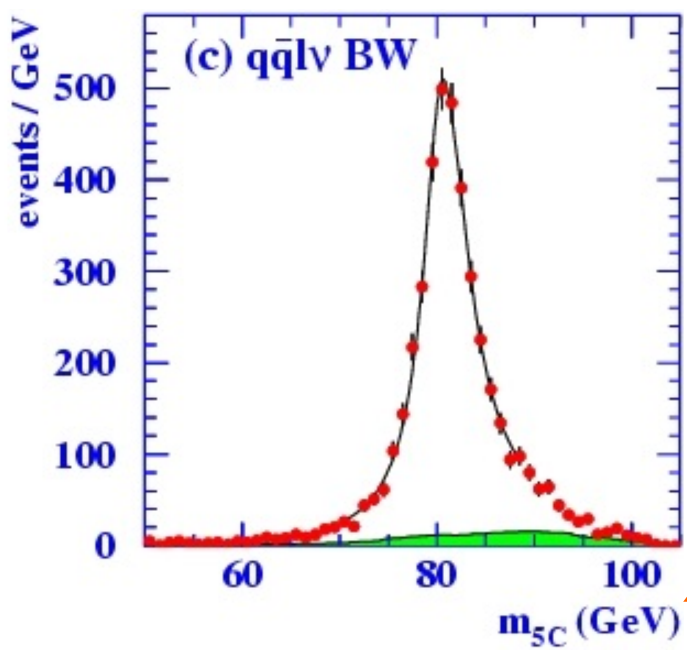


- Neutrino 4-momentum from energy-momentum conservation

$$p_{q_1} + p_{q_2} + p_e + p_\nu = (\sqrt{s}, 0)$$

- The reconstruct masses of two W's

$$M_+^2 = E^2 - \vec{p}^2 = (p_{q_1} + p_{q_2})^2$$
$$M_-^2 = E^2 - \vec{p}^2 = (p_e + p_\nu)^2$$



$\approx \frac{1}{2}(M_+ + M_-)$

- Peak of reconstructed mass distribution gives

$$\boxed{m_W = 80.376 \pm 0.033\,\mathrm{GeV}}$$

- And its width

$$\boxed{\Gamma_W = 2.196 \pm 0.083\,\mathrm{GeV}}$$

Significantly better with Tevatron data (strong UCL involvement)

The Higgs Mechanism

- **Gauge invariance** and **electroweak unification** are focal points of the **SM**

- We saw that **gauge invariance** accounts for **interactions** between particles and fields

- E.g. **QED Lagrangian**

Will use U(1) as a simpler example. (Simpler algebra)

$$L_{QED} = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m_e)\psi + e\bar{\psi}\gamma^{\mu}\psi A_{\mu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{\gamma}^2 A_{\mu}A^{\mu}$$

Dirac free particle (fermion)

Fermion-boson interaction term

Free photon field

- However only works for **massless** gauge bosons. Otherwise **gauge invariance** is lost. Ok for **QED** and **QCD**. But not for **WI**.

- The **Higgs mechanism** provides a way to give gauge bosons **mass**

Requires the concept of **Spontaneous Symmetry Breaking**.

The Higgs Mechanism

- Need to solve two problems
  - Massive gauge bosons (W,Z) break gauge invariance
  - WW scattering has probability>1 at high energies

- Higgs mechanism is the simplest (but not only) solution

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

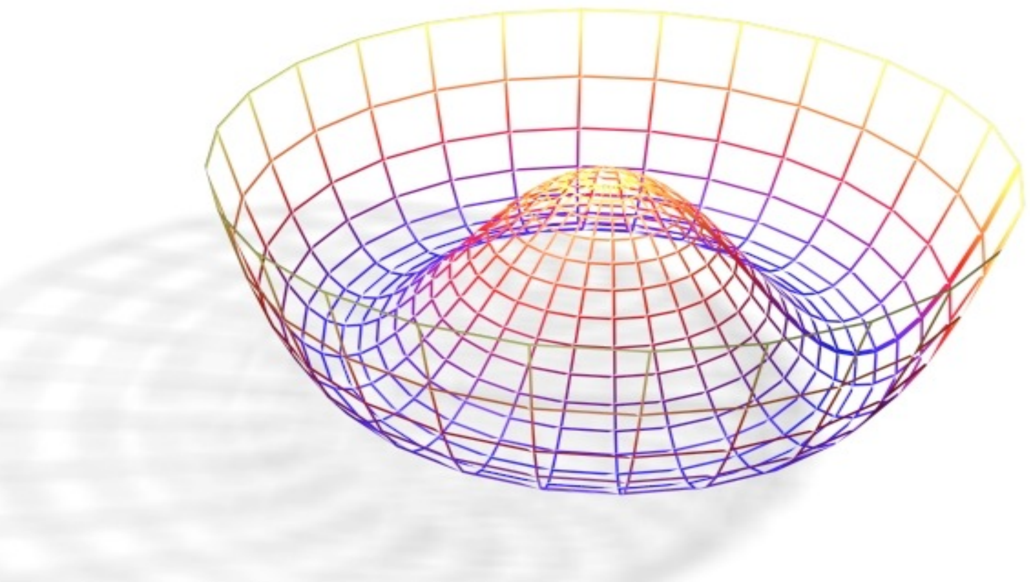
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

Spontaneous Symmetry Breaking. Analogies.

UCL



This is the shape of the Higgs potential.
Imagine putting a ball at the top (the only symmetric place to put the ball)...
It would want to roll down hill. Which way would it roll?
By picking a direction, the symmetry is broken.
This symmetry breaking is what gives mass to particles.

More Analogies

(Philip Anderson argument, 1962)

- Consider EM radiation propagating through plasma
- Plasma acts as polarisable medium $\Longrightarrow$ “dispersion relation”

$$n^2 = 1 - \frac{n_e e^2}{\varepsilon_0 m_e \omega^2} = 1 - \frac{\omega_p^2}{\omega^2}$$

n	= refractive index
ω	= angular frequency
$\omega_\mathbf{p}$	= plasma frequency

- Due to interactions with plasma wave-groups only propagate if they have minimum frequency/energy (threshold)

$$E > E_0 = \hbar\omega_p$$

- Above this energy waves propagate with group velocity $v = nc$

$$v^2 = c^2 n^2 = c^2\left(1 - \frac{\hbar^2\omega_p^2}{\hbar^2\omega^2}\right) = c^2\left(1 - \frac{E_0^2}{E^2}\right)$$

- Rearranging gives

$$\frac{E_0^2}{E^2} = 1 - \frac{v^2}{c^2} \Rightarrow \boxed{E = E_0\left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}} = \gamma m c^2}$$

with

$$m = E_0/c^2$$

Massless photons propagating through a plasma behave as massive particles propagating in a vacuum !

The Higgs Mechanism

Propose a scalar (spin 0) field with a non-zero vacuum expectation value (VEV)

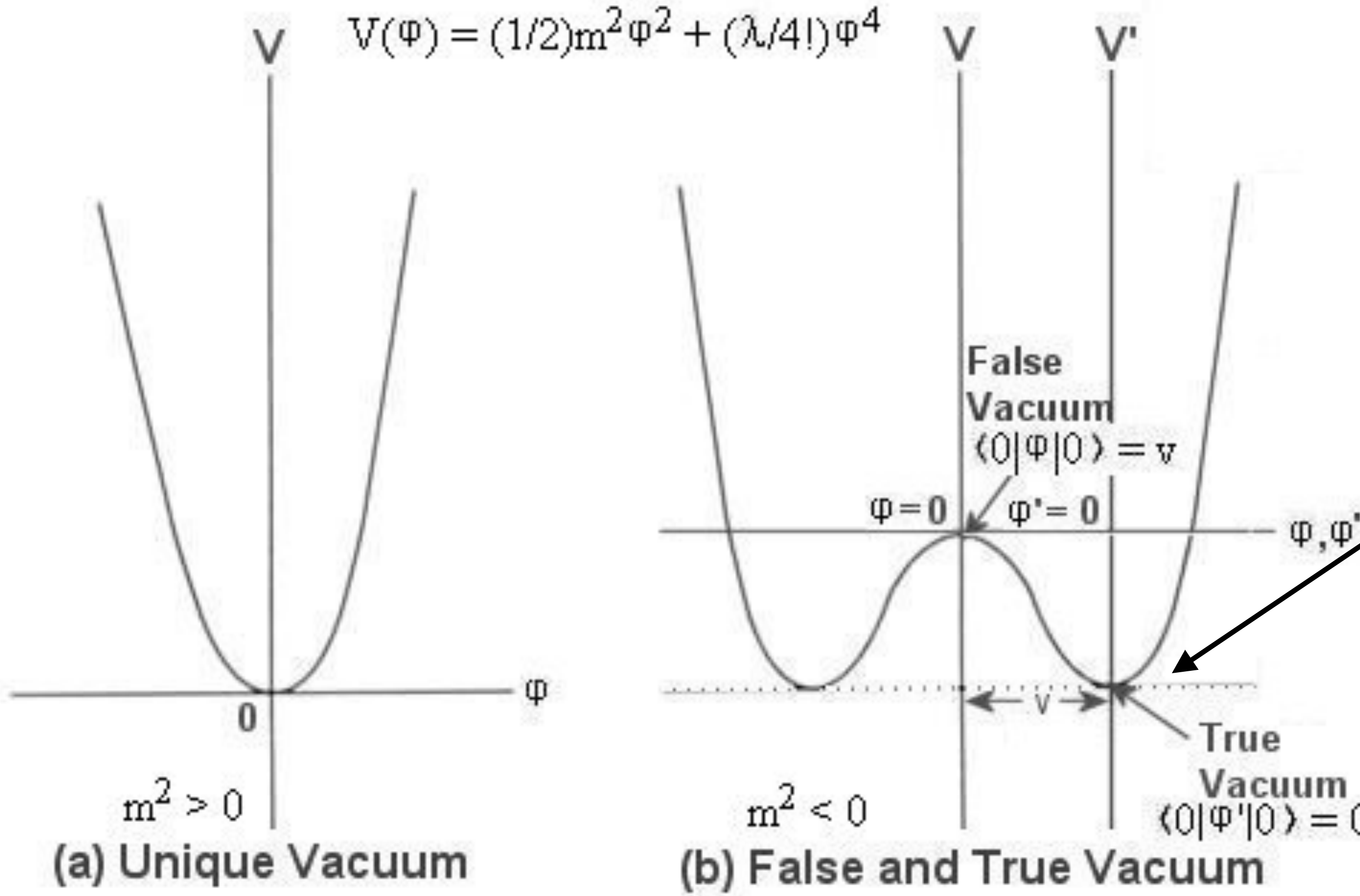
Massless Gauge Bosons propagating through the vacuum with a non-zero Higgs VEV correspond to massive particles.

The Higgs is electrically neutral but carries weak hypercharge of 1/2

The photon does not couple to the Higgs field and remains massless

The W bosons and the Z couple to weak hypercharge and become massive

Interacting Scalar Fields



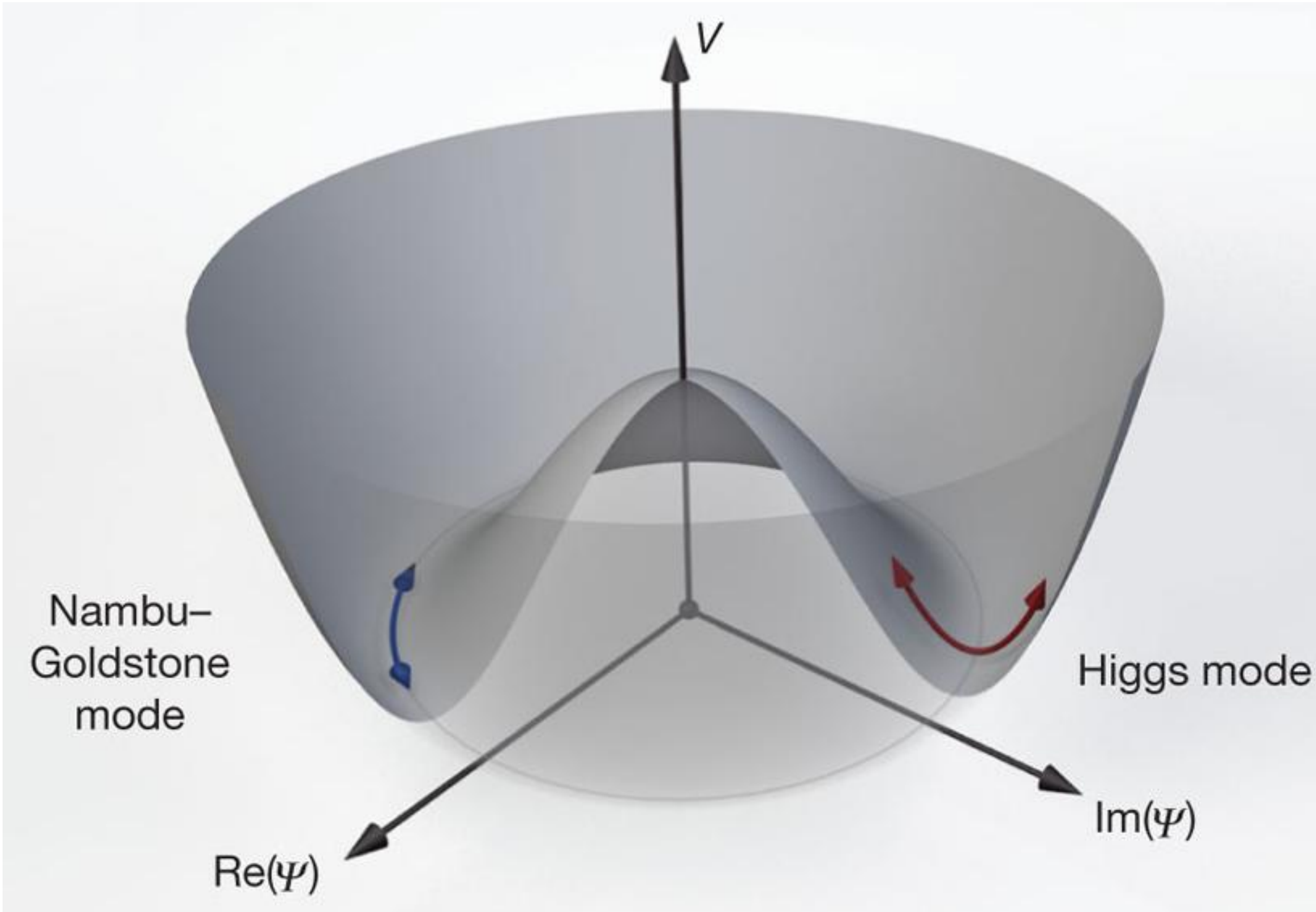
spontaneous symmetry breaking

Lagrangian: $L = \frac{1}{2}\left(\partial_\mu \phi\right)\left(\partial^\mu \phi\right) - V(\phi)$ Perturbations around vacuum state $\phi(x) = v + \eta(x)$

$$L(\eta) = \frac{1}{2}\left(\partial_\mu \eta\right)\left(\partial^\mu \eta\right) - \frac{1}{2} m_\eta^2 \eta^2 - V(\eta) \quad \text{with} \quad V(\eta) = \lambda v \eta^3 + \frac{1}{4}\lambda \eta^4$$

massive scalar field

Complex Scalar Fields



$$L(\eta)=\frac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta)-\frac{1}{2}m_\eta^2\eta^2+\frac{1}{2}(\partial_\mu\xi)(\partial^\mu\xi)-V_{\text{int}}(\eta,\xi)$$

$$V_{\text{int}}(\eta,\xi)=\lambda v\eta^3+\frac{1}{4}\lambda\eta^4+\frac{1}{4}\lambda\xi^4+\lambda v\eta\xi^2+\frac{1}{2}\lambda\eta^2\xi^2$$

The Higgs Mechanism using U(1) as example

- The Lagrangian $L = \left(\partial_\mu \phi\right)^* \left(\partial^\mu \phi\right) - V(\phi)$ is not gauge invariant under U(1) $\phi(x) \to \phi'(x) = e^{ig\chi(x)}\phi(x)$

- Usual recipe to achieve local gauge invariance $\partial_\mu \to D_\mu = \partial_\mu + igB_\mu$

$$B_\mu \to B_\mu^{'} = B_\mu - \partial_\mu \chi(x)$$

New field B_μ !

$$F^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu$$

- The new Lagrangian $L = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \left(D_\mu \phi\right)^* \left(D^\mu \phi\right) - \mu^2\phi^2 - \lambda\phi^4$

- Choosing physical vacuum state **spontaneously breaks** the Lagrangian **symmetry**

$\phi_1 + i\phi_2 = v$ $\Rightarrow$ expanding about vacuum state $\phi(x) = \frac{1}{\sqrt{2}}\left(v + \eta(x) + i\xi(x)\right)$

$$L = \underbrace{\frac{1}{2}\left(\partial_\mu \eta\right)\left(\partial^\mu \eta\right) - \lambda v^2 \eta^2}_{\text{massive } \eta} + \underbrace{\frac{1}{2}\left(\partial_\mu \xi\right)\left(\partial^\mu \xi\right)}_{\text{massless } \xi \text{ (Goldstone boson)}} \underbrace{- \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}g^2v^2B_\mu B^\mu}_{\text{massive gauge field}} - V_{\text{int}} + gvB_\mu\left(\partial_\mu \xi\right)$$

- Goldstone boson can be "absorbed" by choosing appropriate gauge transformation, i.e. choose the complex scalar field to be entirely real

$$\phi(x) = \frac{1}{\sqrt{2}}\left(v + \eta(x)\right) \equiv \frac{1}{\sqrt{2}}\left(v + h(x)\right)$$

- As a result, a Lagrangian describing a **massive Higgs scalar field h** and a *hypothetical* **massive gauge boson B** associated with U(1) local gauge symmetry:

$$\mathcal{L} = \overbrace{\tfrac{1}{2}(\partial_\mu h)(\partial^\mu h) - \lambda v^2 h^2}^{\text{massive } h \text{ scalar}} \overbrace{- \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}g^2 v^2 B_\mu B^\mu}^{\text{massive gauge boson}}$$

$$\underbrace{+ g^2 v B_\mu B^\mu h + \tfrac{1}{2}g^2 B_\mu B^\mu h^2}_{h,\ B \text{ interactions}} \underbrace{- \lambda v h^3 - \tfrac{1}{4}\lambda h^4}_{h\text{-self-interactions}}$$

$$\boxed{m_B = gv} \qquad \boxed{m_H = \sqrt{2\lambda}\, v}$$

- The **Standard Model Higgs mechanism** generates a **mass** for the **gauge boson** in essentially the same way as for the above hypothetical U(1) local gauge symmetry. However the spontaneous symmetry breaking is now embedded in **$U(1)_Y$ x $SU(2)_L$** local gauge symmetry

- The algebra however is more complex and beyond the scope of this course

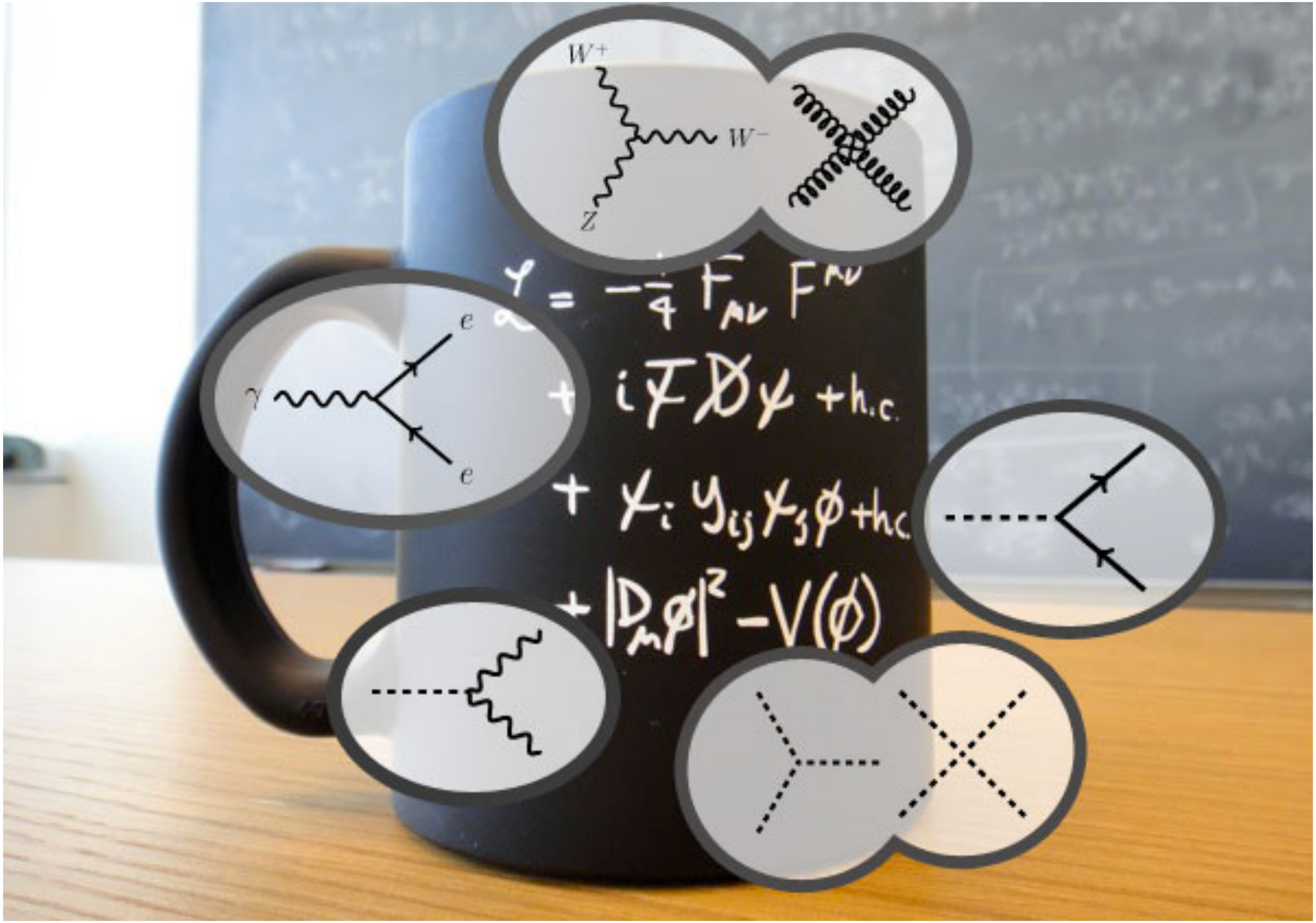
Some important relations

$$\boxed{m_W = \frac{1}{2} g_W v \quad m_Z = \frac{1}{2} \frac{g_W}{\cos\theta_W} v \quad \Rightarrow \quad \frac{m_W}{m_Z} = \cos\theta_W}$$

From data: $v = 246\ \text{GeV}$

The **Higgs mechanism** also generates the **masses** of **fermions** — **Yukawa** coupling

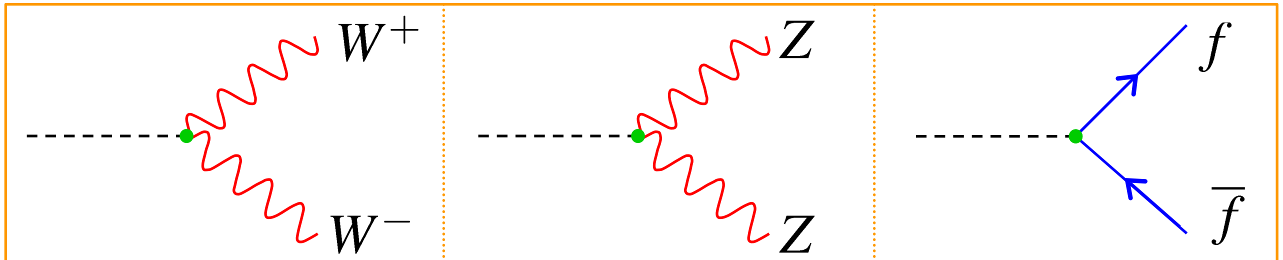
Standard Model on a mug



The Higgs mechanism is a focal point of the Standard Model. Without it the SM falls apart. It results in absolute **predictions** for **masses of gauge bosons**

In the SM, fermion masses are also ascribed to interactions with the Higgs field - however, here no prediction of the masses **– just put in by hand**

Feynman Vertex factors:



$ig_W m_W g^{\mu\nu}$	$ig_Z m_Z g^{\mu\nu}$	$-i\dfrac{g_W}{2m_W}m_f$

Higgs couples to mass!

Within the SM of Electroweak unification with the Higgs mechanism:

⇨ **Relations between standard model parameters**

$$\boxed{m_W = \left(\frac{\pi\alpha_{em}}{\sqrt{2}G_F}\right)^{\frac{1}{2}}\frac{1}{\sin\theta_W}}\qquad\qquad \boxed{m_Z = \frac{m_W}{\cos\theta_W}}$$

Hence, if you know <u>any three</u> of : $\alpha_{em}, G_F, m_W, m_Z, \sin\theta_W$ predict the other two.

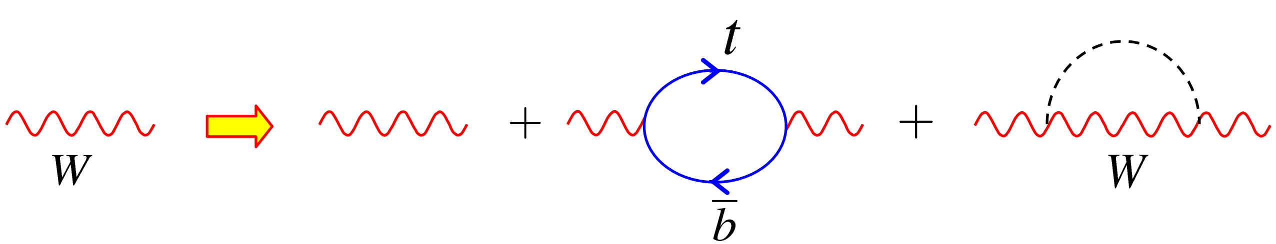
Experimentally (e.g. LEP) – can test predictions of the Standard Model !

- **e.g. predict:** $\boxed{m_W = m_Z \cos\theta_W}$ **measure** $\boxed{m_Z = 91.1875 \pm 0.0021\,\mathrm{GeV}}$ $\boxed{\sin^2\theta_W = 0.23154 \pm 0.00016}$

- **Therefore expect:**

$\boxed{m_W = 79.946 \pm 0.008\,\mathrm{GeV}}$ **but measure** $\boxed{m_W = 80.376 \pm 0.033\,\mathrm{GeV}}$

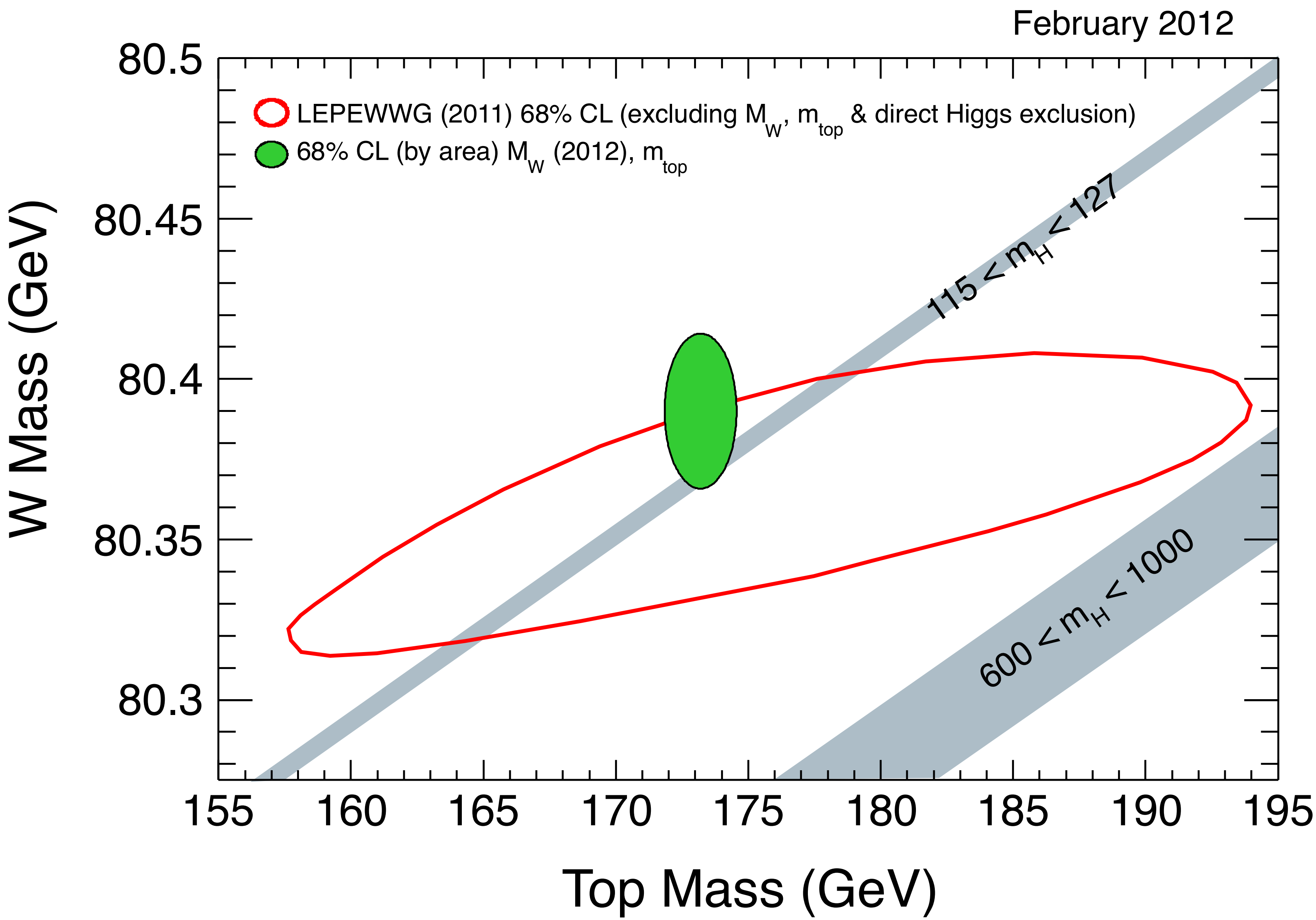
Close, but not quite right – but have only considered lowest order diagrams



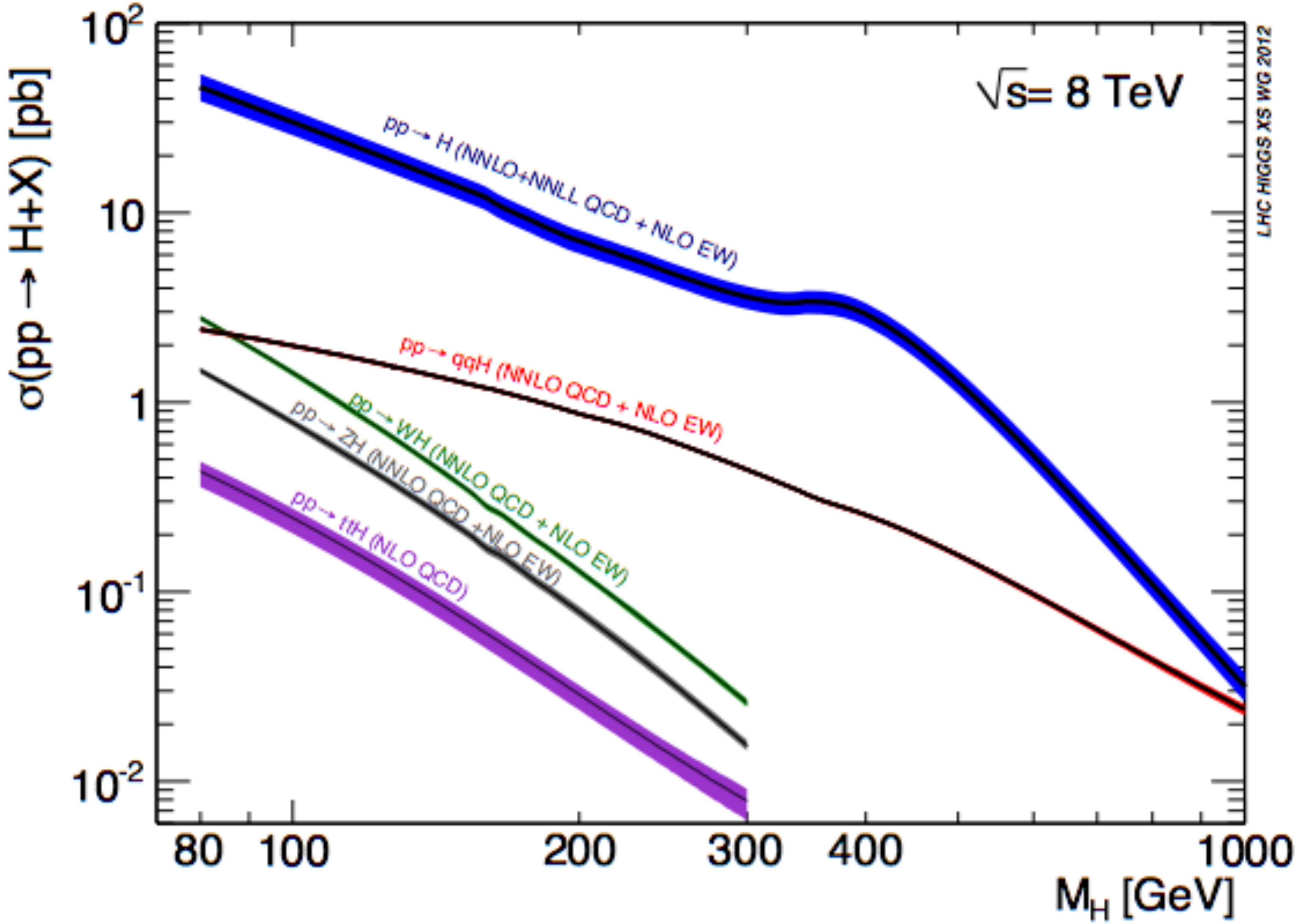
$$\boxed{m_W = m_W^0 + a m_t^2 + b \ln\left(\frac{m_H}{m_W}\right)}$$

Above "discrepancy" due to these virtual loops, i.e. by making very high precision measurements become sensitive to the masses of particles inside the virtual loops !

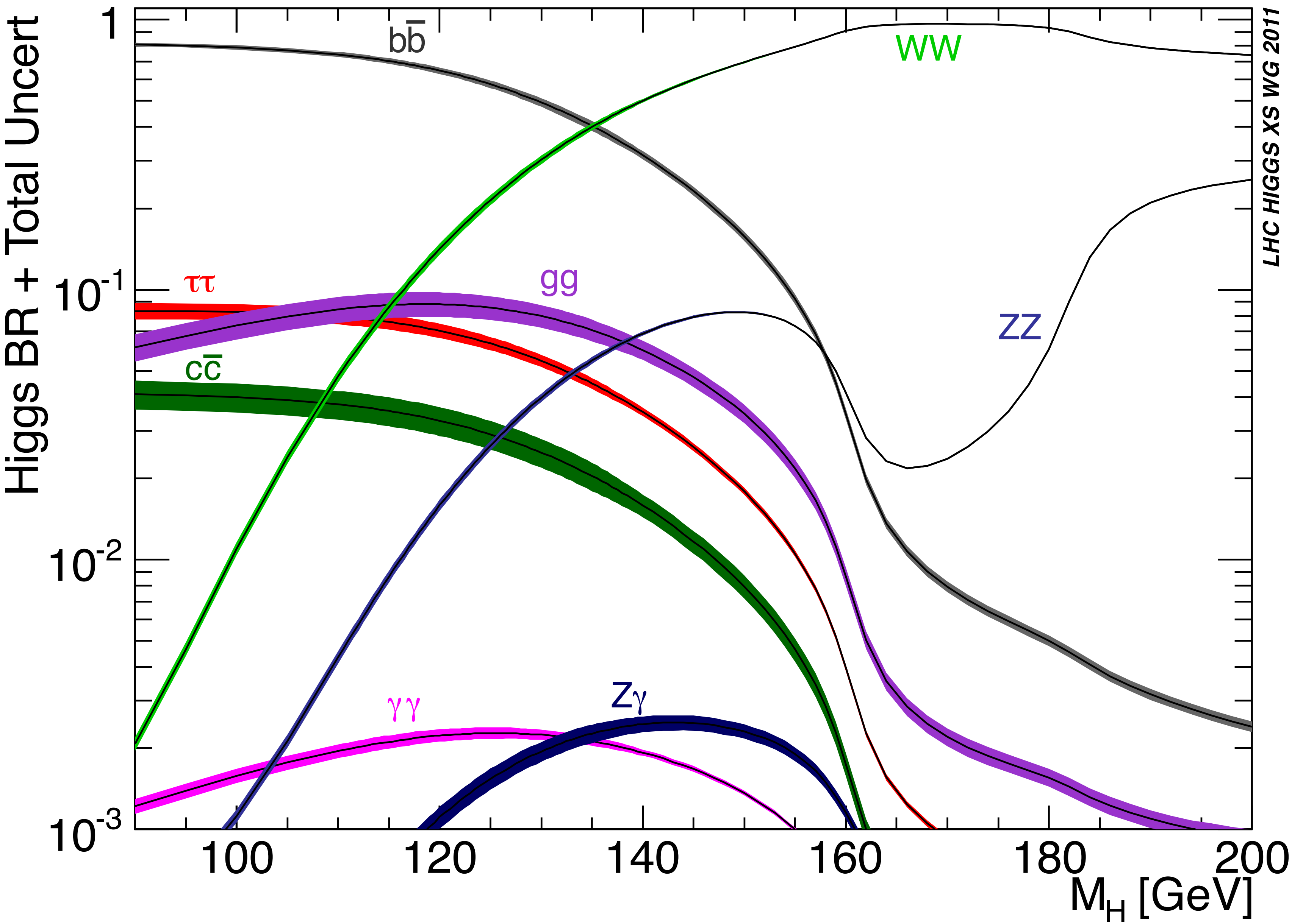
Electroweak tests



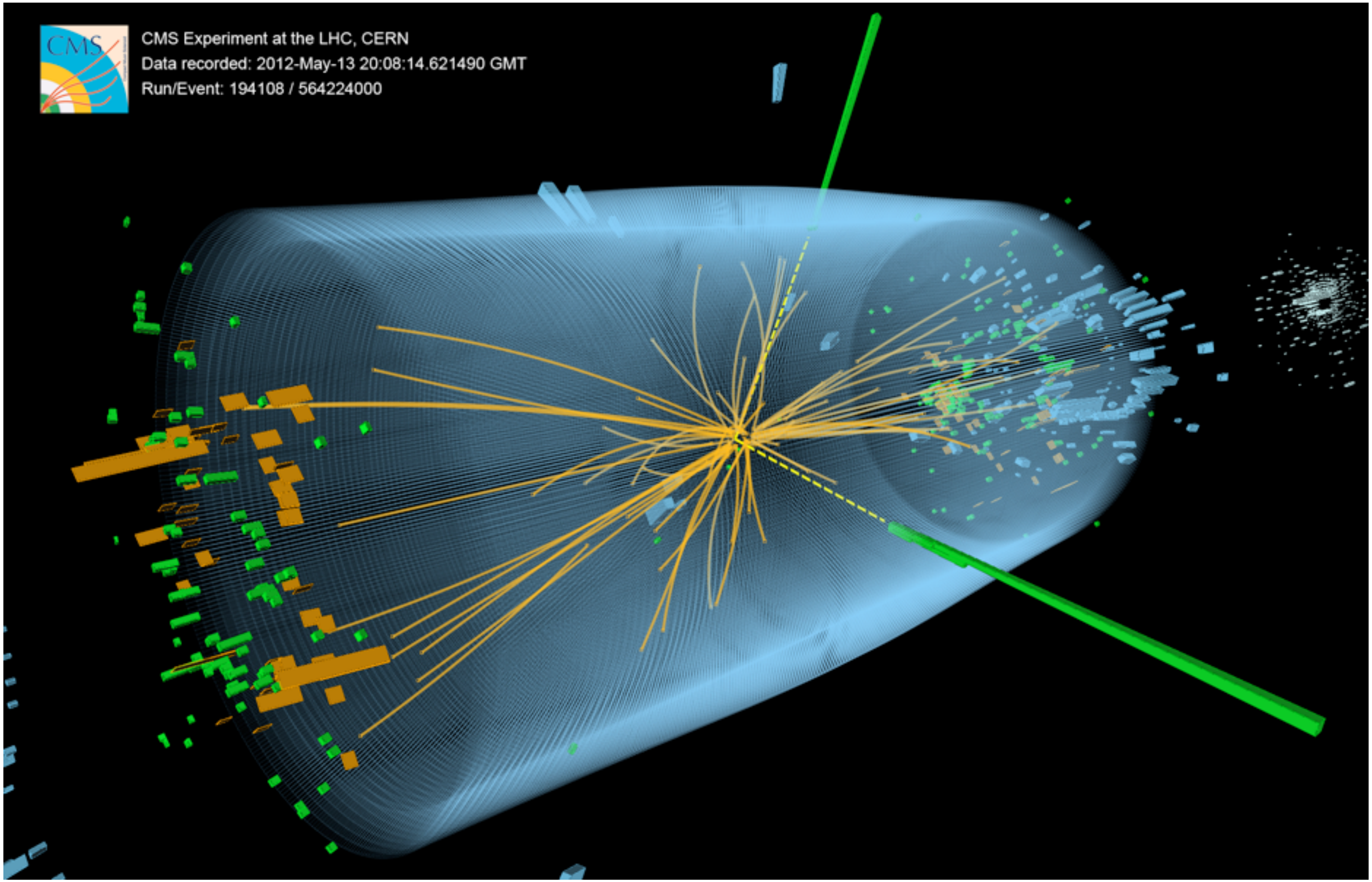
Making a Higgs Boson at LHC



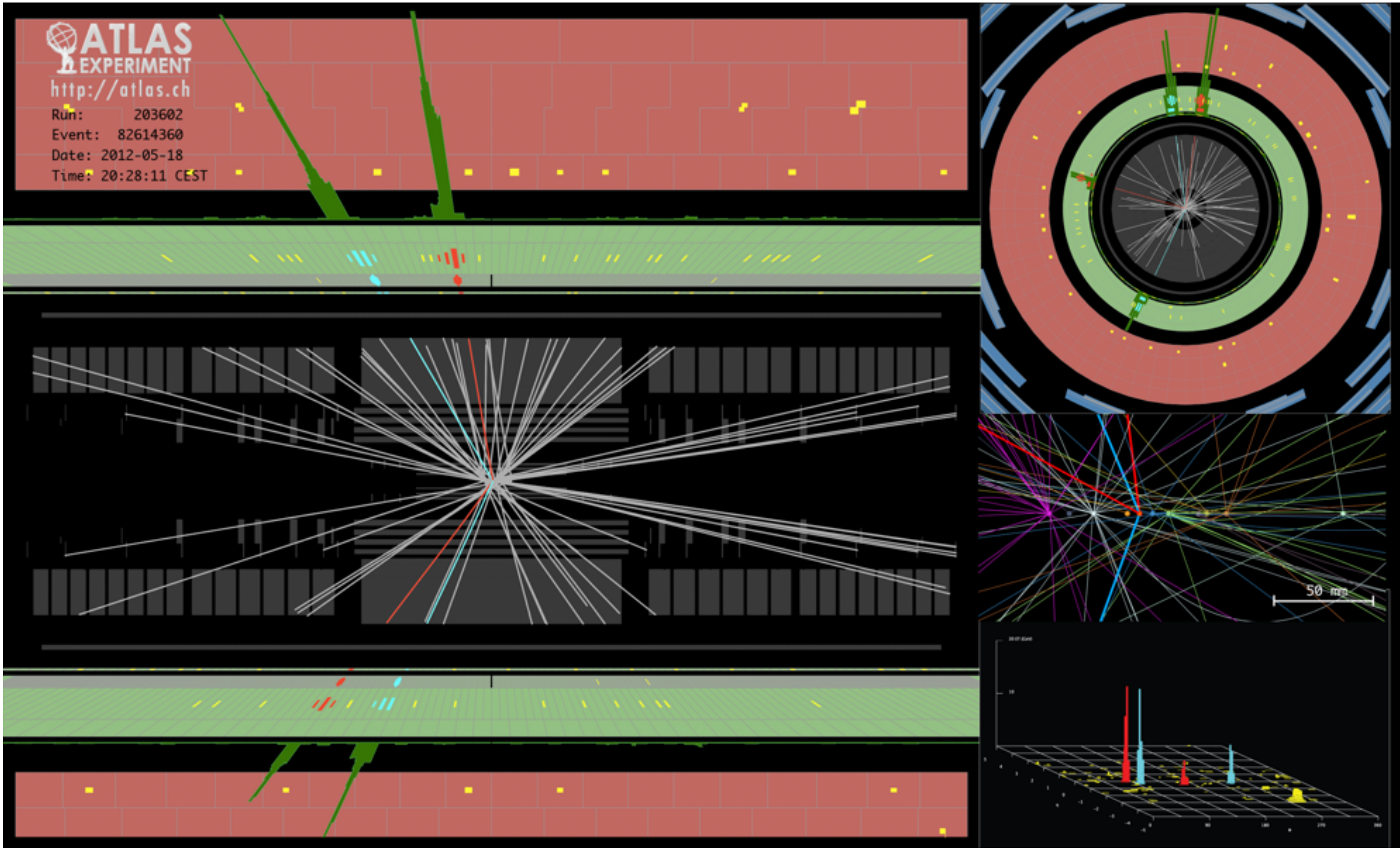
Detecting Higgs Boson at LHC



Higgs to gamma-gamma candidate



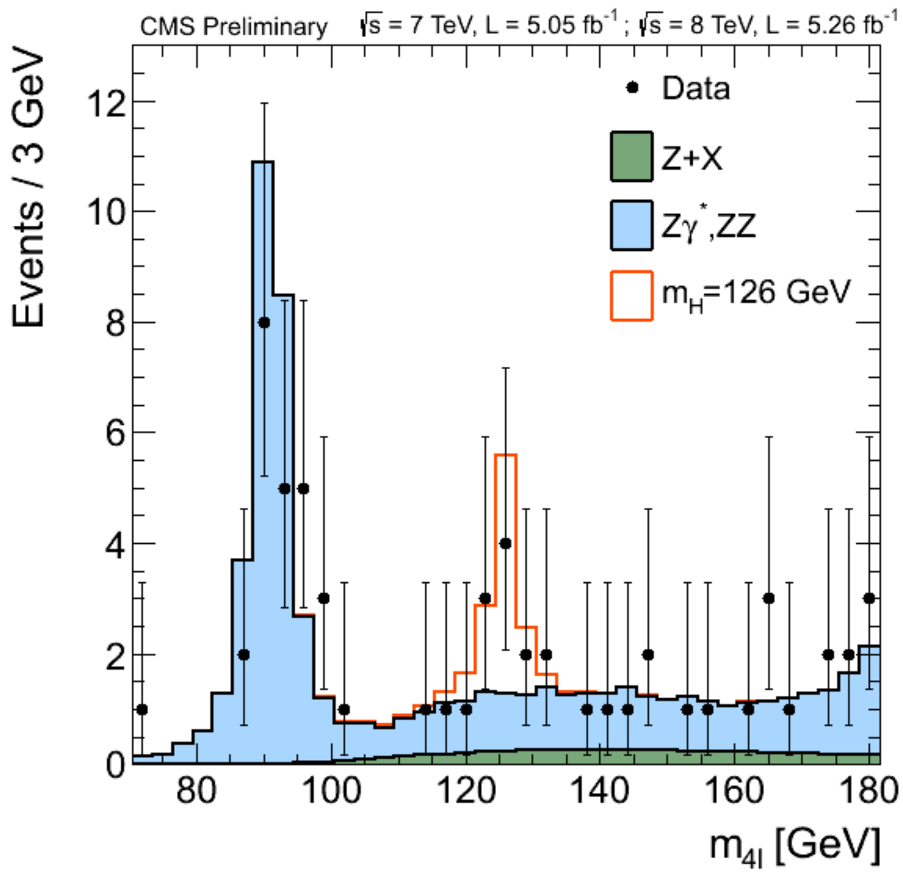
Higgs ==> ZZ ==> 4e

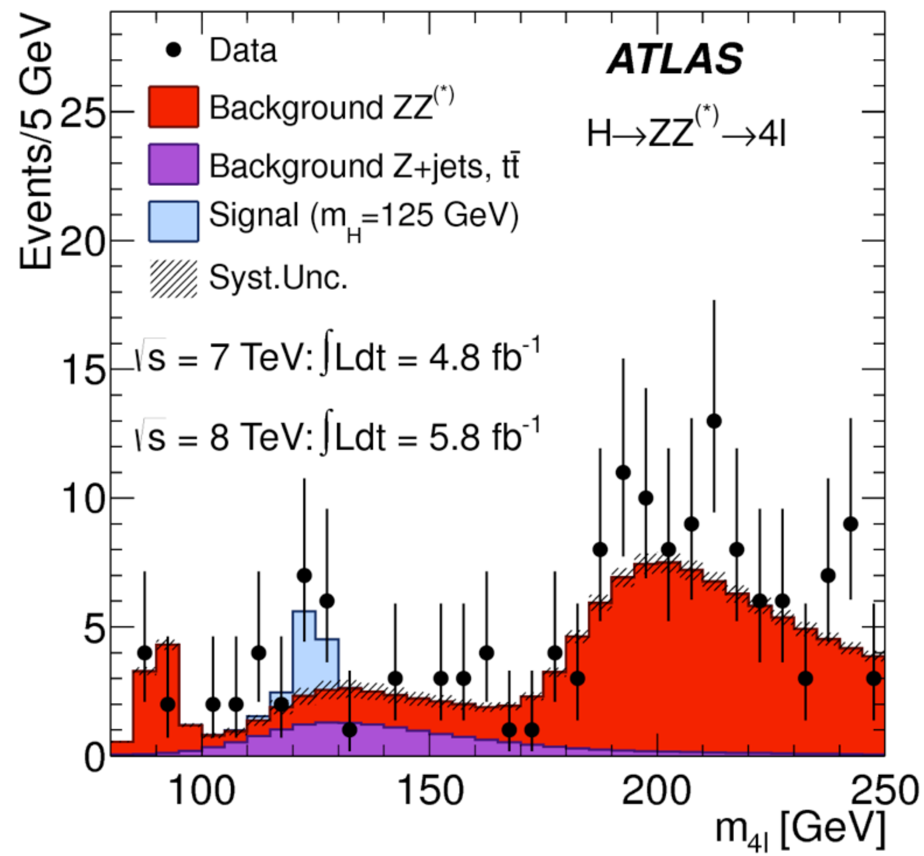


ATLAS
EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST
50 mm

Higgs Results 2012

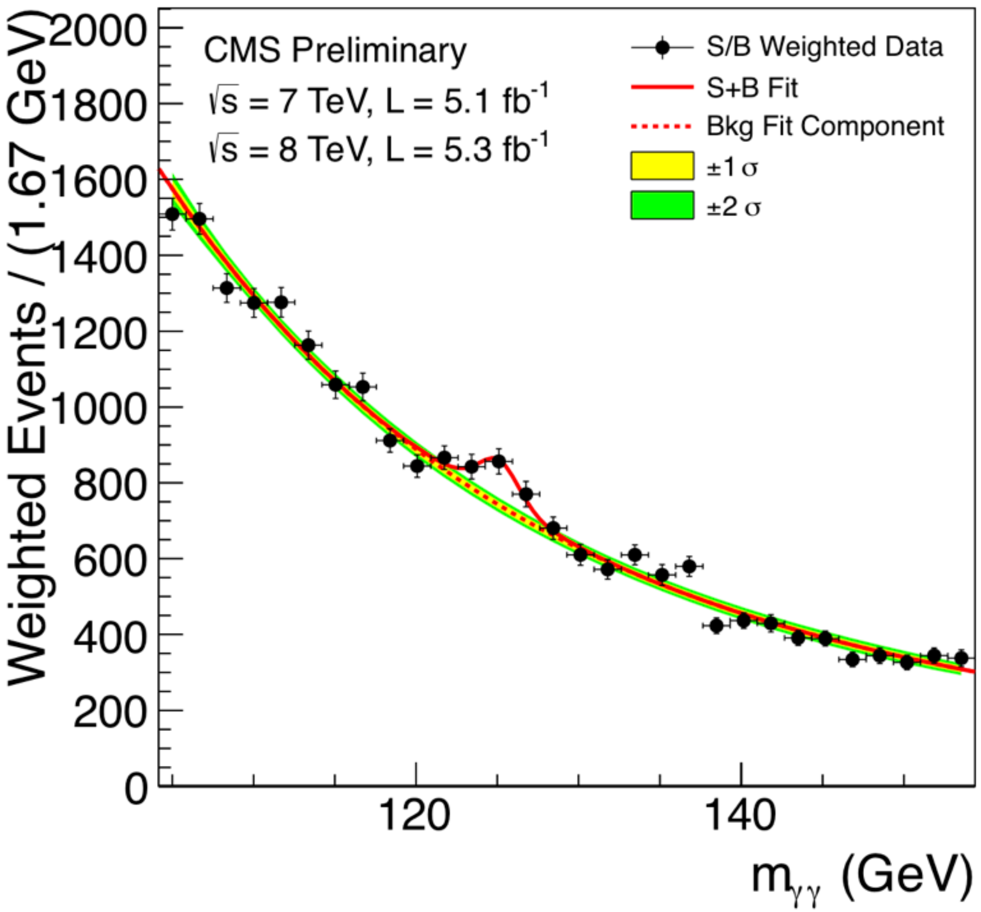
H —> ZZ —> 4l

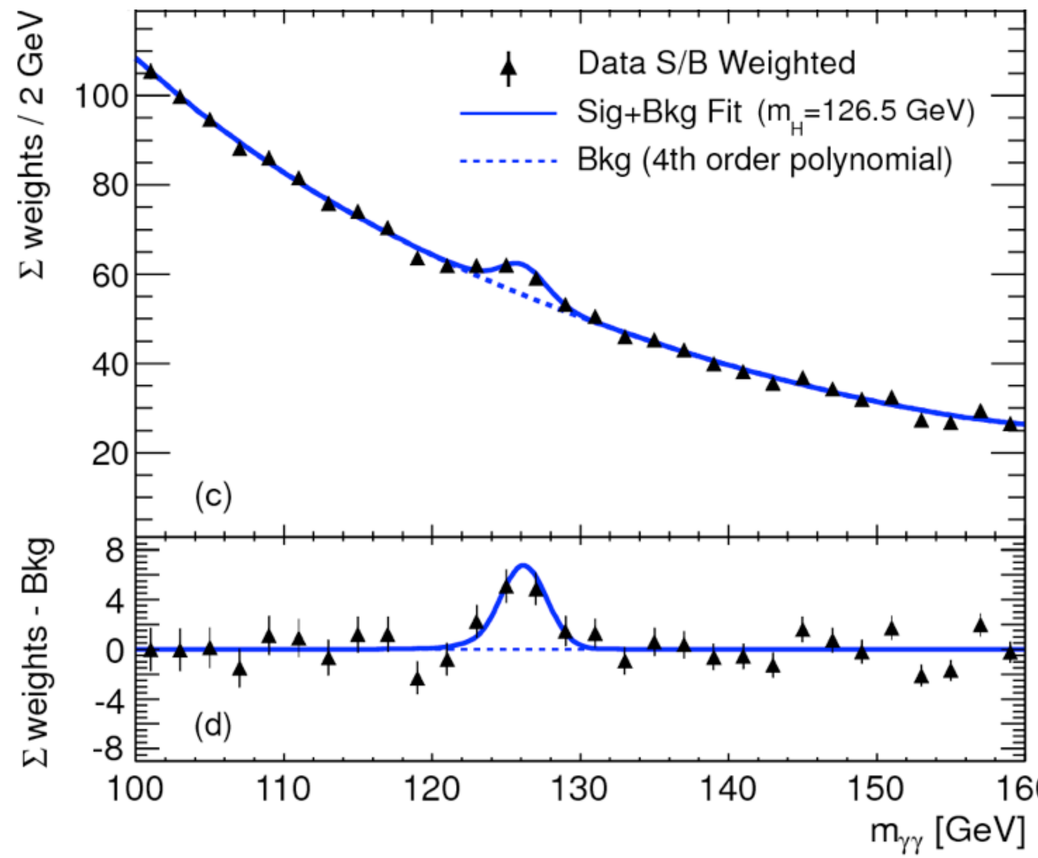




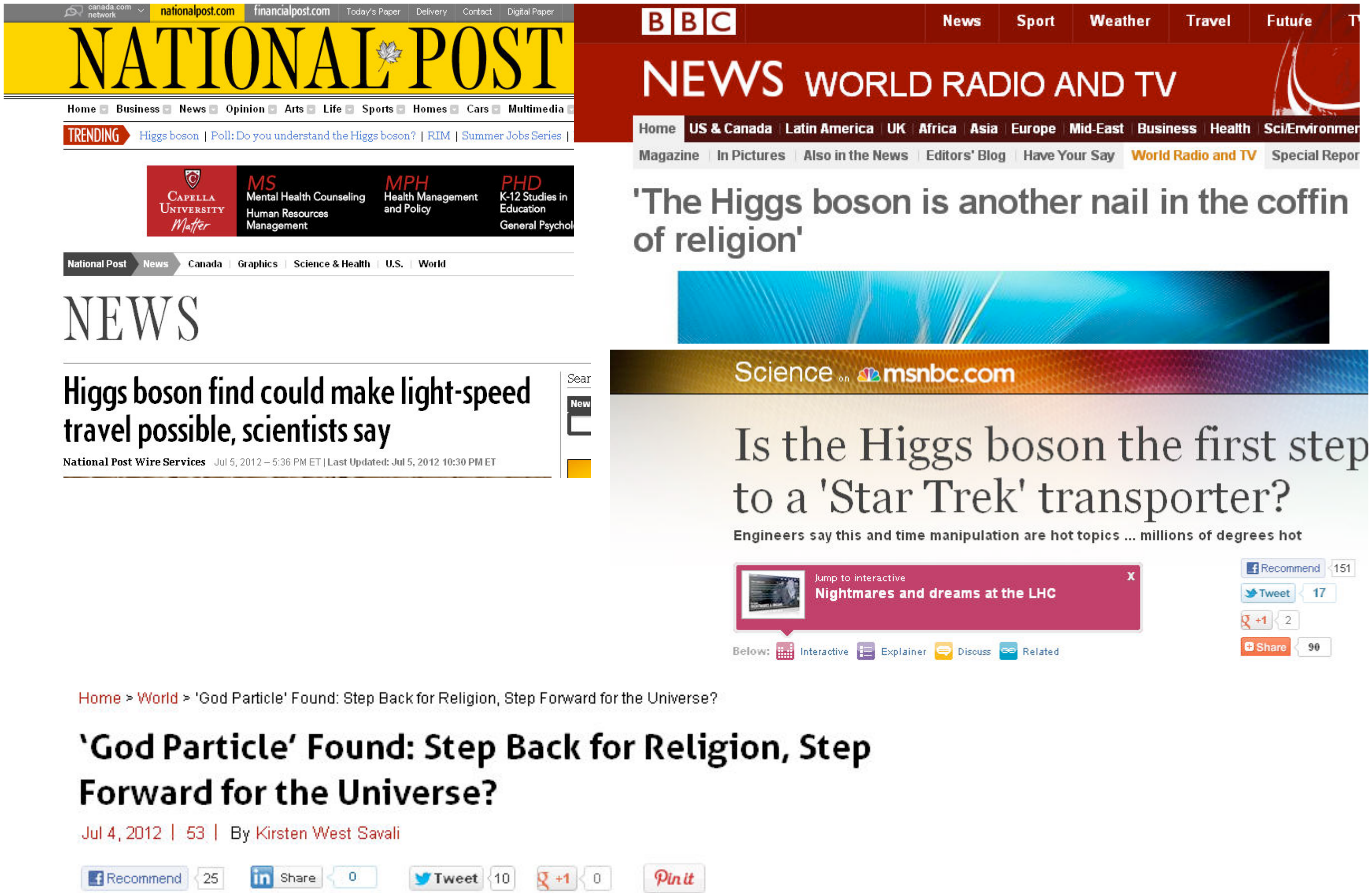
Higgs Results 2012

$H \to \gamma\gamma$





Higgs in the news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National Post Wire Services Jul 5, 2012 – 5:36 PM ET | Last Updated: Jul 5, 2012 10:30 PM ET

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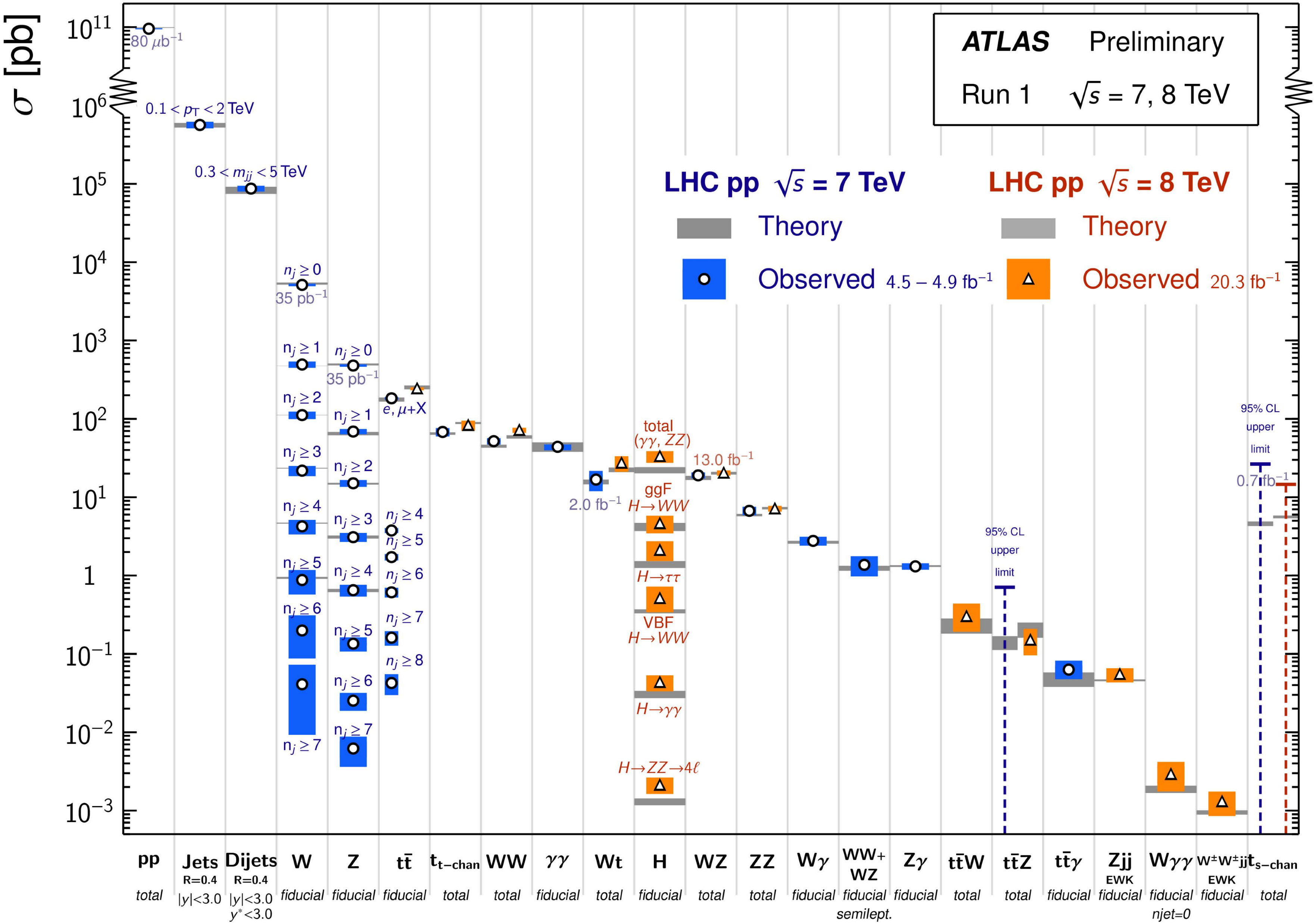
'God Particle' Found: Step Back for Religion, Step Forward for the Universe?

Jul 4, 2012 | 53 | By Kirsten West Savali

And Nobel prize 2013 to Higgs and Englert

Standard Model Production Cross Section Measurements



Excellent performance of Standard Model so far.

But we know it's far from a full story (Module 9)