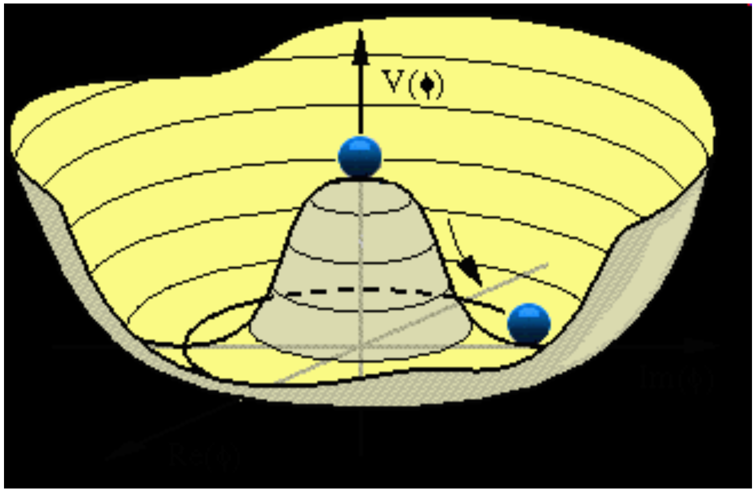
# Sally Dawson, BNL
# Introduction to Electroweak Symmetry Breaking
# Fermilab 2012

- The Higgs….
  - We found it!
  - Or did we?
  - What's next?



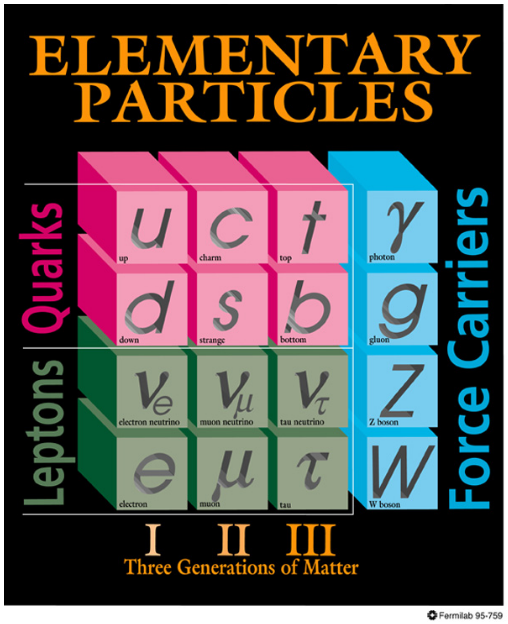

*The questions you should be asking….*

# Plan:

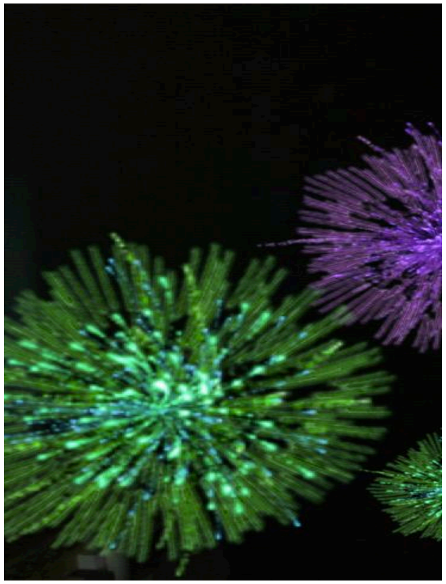
- Introduction to Electroweak Symmetry Breaking
  - Review of the SU(2) x U(1) electroweak theory
  - Constraints from precision measurements
  - How do we look for a Higgs like particle?
  - How do we know it's ***the*** Higgs?
  - What's next?
- Theoretical problems with the Standard Model
  - Why there might be more than the Standard Model

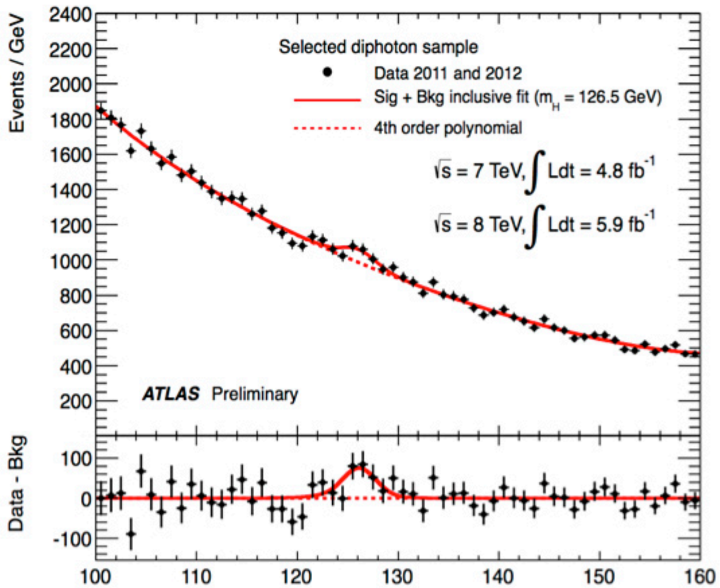
# What we know

- The photon and gluon appear to be massless
- The W and Z gauge bosons are heavy
  - $M_W$=80.385 ± 0.015 GeV
  - $M_Z$ =91.1875 ± 0.0021 GeV
- There are 6 quarks
  - $M_t$=173.2 ±0.9 GeV
  - $M_t$ >> all the other quark masses
- There appear to be 3 distinct neutrinos with small but non-zero masses
- The pattern of fermions appears to replicate itself 3 times

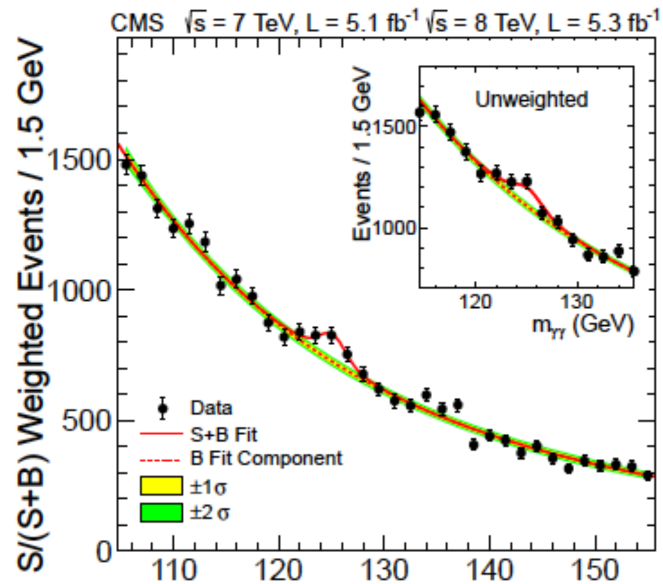


# The 4th of July!





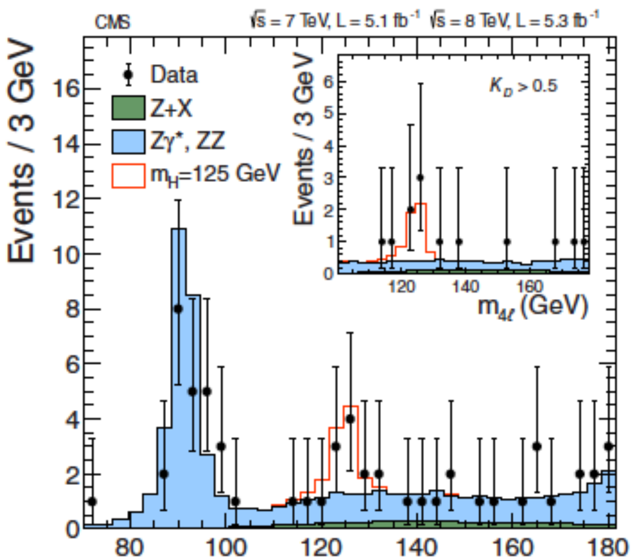

$M_{\gamma\gamma}$ (GeV)



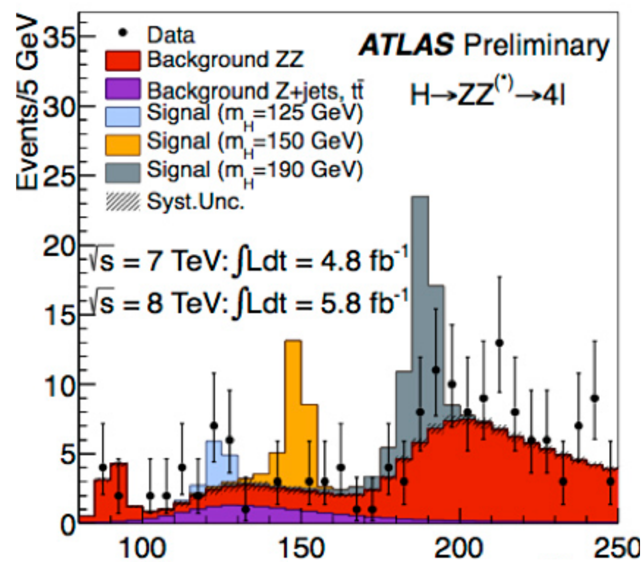

$M_{\gamma\gamma}$ (GeV)

$H \longrightarrow \gamma\gamma$

# Multiple Channels in both CMS & ATLAS



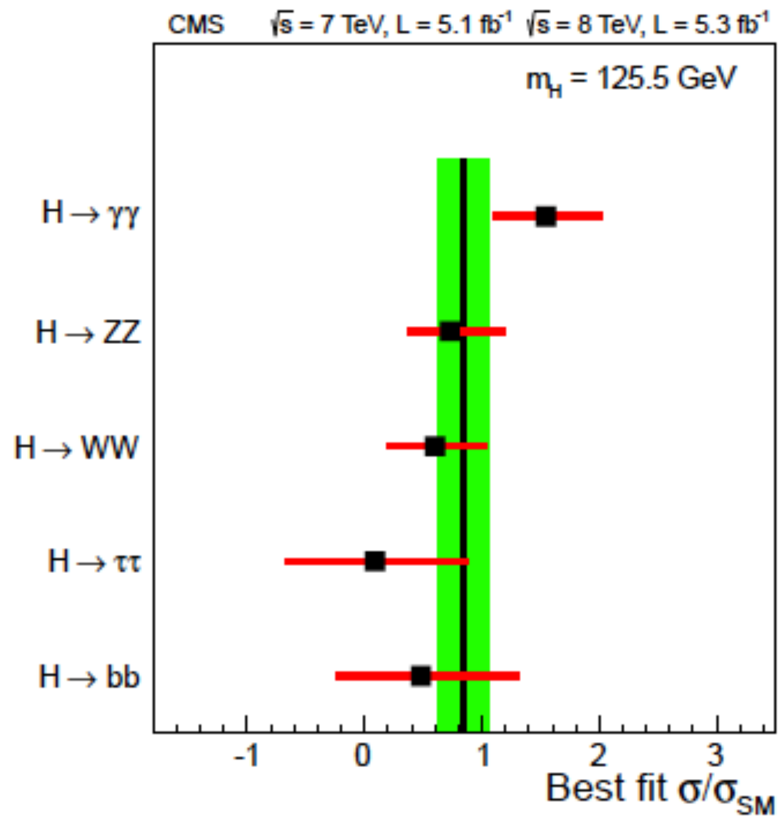

$M_{41}$ (GeV)




$M_{41}$ (GeV)

H ⟶ ZZ* ⟶ 4 leptons

# Higgs Candidate looks SM-like



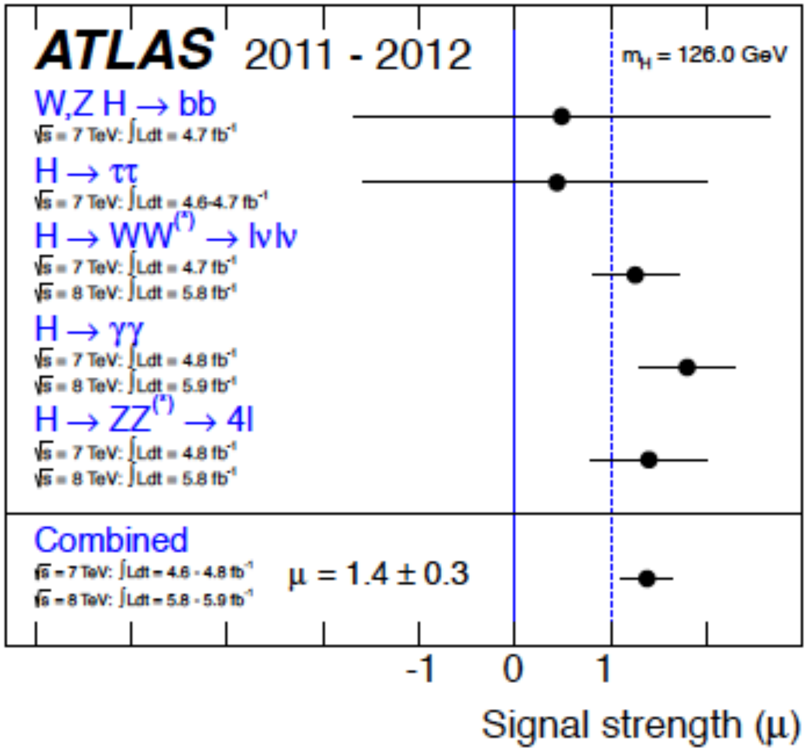

CMS

red lines are $1\sigma$ errors (systematics and statistics combined)

[CMS,arXiv:1207.7235]

# Higgs Candidate looks SM-like

- SM hypothesis $\mu$=1

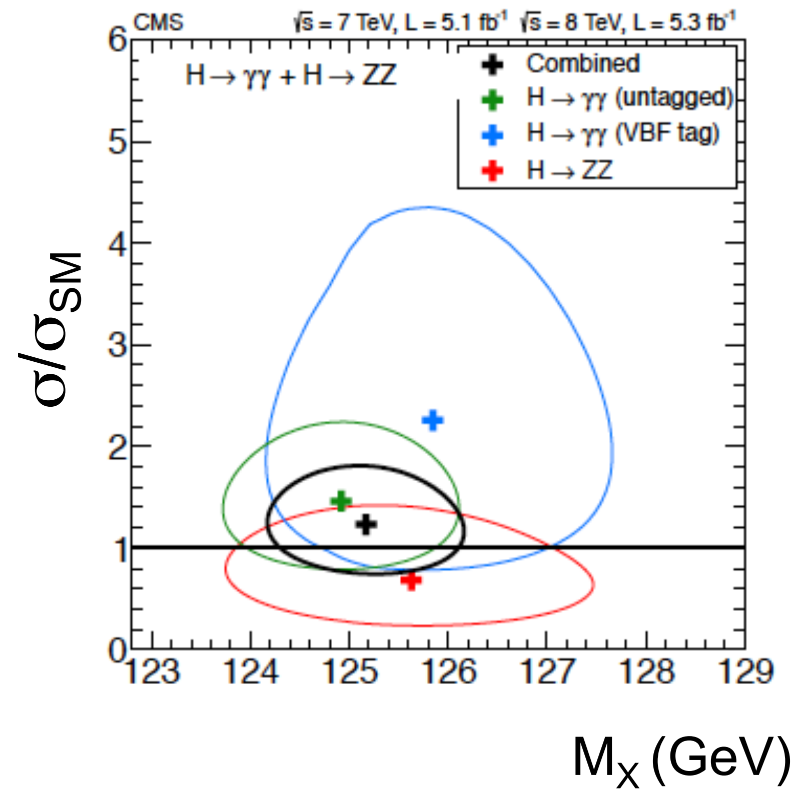



ATLAS

[ATLAS, arXiv:1207.7214]

# Higgs Candidate looks SM-Like

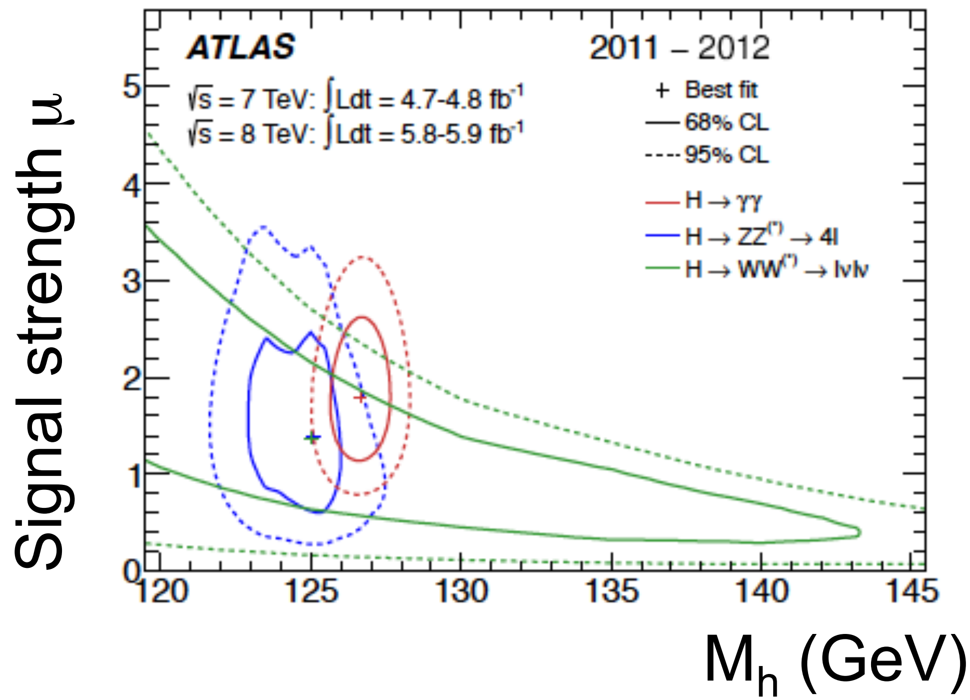
- Relative signal strengths constrained by SM expectations in this plot




CMS

$M_h$=125±.4(stat)±.5(syst) GeV

# Higgs Candidate looks SM-Like

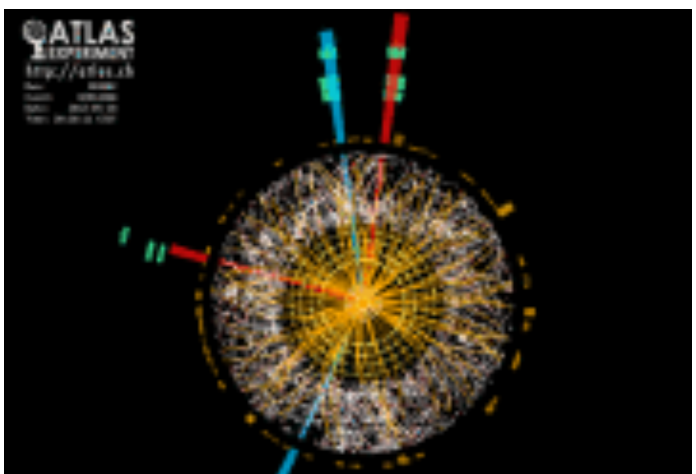



ATLAS

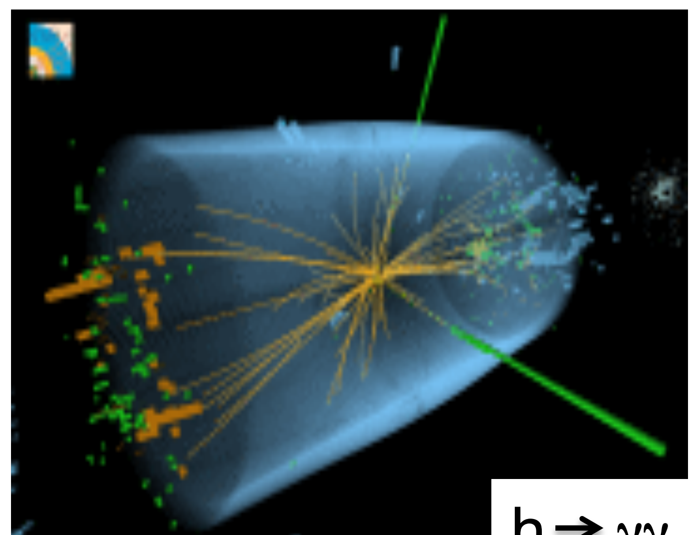
$M_h$=126 ± .4 (stat) ± .4 (syst) GeV

# What We Know

- There is something with many of the right properties to be a Higgs boson with mass ~125 GeV!
- Both CMS and ATLAS see something that quacks like a Higgs in the $\gamma\gamma$ and ZZ channels
- Combined significance roughly $5\sigma$ for each experiment




$h \to e^+e^-e^+e^-$



$h \to \gamma\gamma$

# Why Do We Need a Higgs?

- Why are the W and Z boson masses non-zero?
- U(1) gauge theory with single spin-1 gauge field, $A_\mu$

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$$

- U(1) local gauge invariance:

$$A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu \eta(x)$$

- Mass term for A would look like:

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2 A_\mu A^\mu$$

- Mass term violates local gauge invariance
- We understand why $M_A = 0$

Gauge invariance is guiding principle

# Abelian Higgs Model

- Add complex scalar field, φ, with charge –e:

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \left|D_\mu \phi\right|^2 - V(\phi)$$

- Where $D_\mu = \partial_\mu - ieA_\mu$ $\quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$$V(\phi) = \mu^2 \left|\phi\right|^2 + \lambda\left(\left|\phi\right|^2\right)^2$$

- L is invariant under local U(1) transformations:

$$A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu \eta(x)$$
$$\phi(x) \rightarrow e^{-ie\eta(x)}\phi(x)$$

Cubic term would violate this symmetry

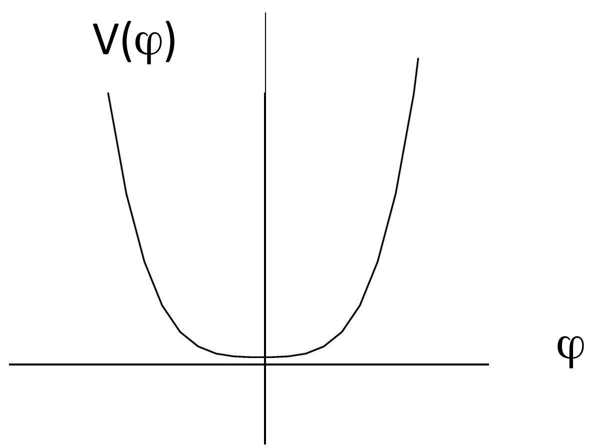
# Abelian Higgs Model

- Case 1: $\mu^2 > 0$
  - QED with $M_A$=0 and $m_\varphi=\mu$
  - Unique minimum at $\varphi$=0

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \left|D_\mu \phi\right|^2 - V(\phi)$$

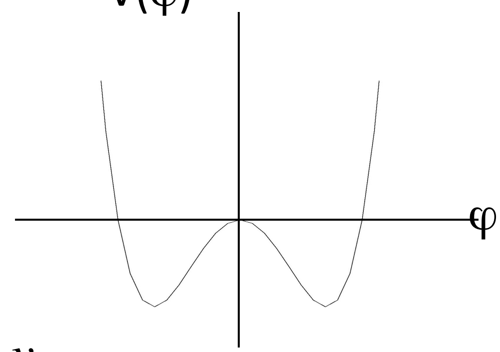
$$D_\mu = \partial_\mu - ieA_\mu$$

$$V(\phi) = \mu^2\left|\phi\right|^2 + \lambda\left(\left|\phi\right|^2\right)^2$$




By convention, $\lambda > 0$

# Abelian Higgs Model




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

$$V(\phi) = -|\mu^2||\phi|^2 + \lambda\left(|\phi|^2\right)^2$$

- Minimum energy state at $<\phi> = \sqrt{-\frac{\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$

- Physical particle has minimum energy state at 0:

$$\varphi' = \varphi - <\varphi>$$

Vacuum breaks U(1) symmetry

Aside: What fixes sign ($\mu^2$)?

v is termed vacuum expectation value (VEV)

# Abelian Higgs Model

- Rewrite $\phi \equiv \frac{1}{\sqrt{2}} e^{i\frac{\chi}{v}} (v+h)$

χ and h are the 2 degrees of freedom of the complex Higgs field

- h has minimum at 0
- L becomes:

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - evA_\mu \partial^\mu \chi + \frac{e^2v^2}{2} A^\mu A_\mu + \frac{1}{2}\left(\partial_\mu h \partial^\mu h + 2\mu^2 h^2\right)$$
$$+\frac{1}{2}\partial_\mu \chi \partial^\mu \chi + (h, \chi \text{ interactions})$$

- Theory now has:
  - Photon of mass $M_A$=ev
  - Scalar field h with mass-squared $-2\mu^2 > 0$
  - Massless scalar field χ *(Goldstone Boson)*

# Abelian Higgs Model

- What about mixed $\chi$-A propagator?
  - Remove by gauge transformation $A'_\mu \equiv A_\mu - \frac{1}{ev}\partial_\mu \chi$
  - $\chi$ field disappears
  - We say that it has been *eaten* to give the photon mass
  - $\chi$ field called Goldstone boson
  - *This is Abelian Higgs Mechanism*
  - This gauge (unitary) contains only physical particles

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{e^2v^2}{2}A'^{\mu}A'_{\mu} + \frac{1}{2}\left(\partial_\mu h \partial^\mu h\right) - V(h)$$

# Higgs Mechanism summarized

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

*Consequence: Physical Higgs particle*

Aside:
Massless $\gamma$ has 2 transverse degrees of freedom
Massive gauge boson has 2 transverse and 1 longitudinal degree of freedom

# Standard Model Synopsis

- Group: $SU(3) \times SU(2) \times U(1)$
  - QCD: $SU(3)$
  - Electroweak: $SU(2) \times U(1)$
- Gauge bosons:
  - SU(3): $G_\mu^i$, $i=1\ldots8$
  - SU(2): $W_\mu^i$, $i=1,2,3$
  - U(1): $B_\mu$
- Gauge couplings: $g_s$, $g$, $g'$
- Complex SU(2) Higgs doublet: $\Phi$

# SM Higgs Mechanism

- Standard Model includes complex Higgs SU(2) doublet

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

- With SU(2) x U(1) invariant scalar potential

$$V = \mu^2 \Phi^+ \Phi + \lambda (\Phi^+ \Phi)^2$$ Invariant under $\Phi \rightarrow -\Phi$

- If $\mu^2 < 0$, then spontaneous symmetry breaking
- Minimum of potential at: $\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$ $\quad \Phi \rightarrow e^{i\varpi^a \cdot \sigma^a / v} \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix}$
  - Choice of minimum breaks gauge symmetry

# More on SM Higgs Mechanism

- Couple Φ to SU(2) x U(1) gauge bosons ($W_i^\mu$, i=1,2,3; $B^\mu$)

$$L_S = (D_\mu \Phi)^+ (D^\mu \Phi) - V(\Phi)$$

$$D_\mu = \partial_\mu - i\frac{g}{2}\sigma^i W^i{}_\mu - i\frac{g'}{2} B_\mu$$

- Gauge boson mass terms from:

$$(D_\mu \Phi)^+ D^\mu \Phi \rightarrow \ldots + \frac{1}{8}(0, v)(gW_\mu^a \sigma^a + g' B_\mu)(gW^{b\mu}\sigma^b + g' B^\mu)\begin{pmatrix} 0 \\ v \end{pmatrix} + \ldots$$

$$\rightarrow \ldots + \frac{v^2}{8}\left(g^2 (W_\mu^1)^2 + g^2 (W_\mu^2)^2 + (-gW_\mu^3 + g' B_\mu)^2\right) + \ldots$$

Charged gauge boson masses: $g^2 (W_\mu^1)^2 + g^2 (W_\mu^2)^2$

Neutral gauge boson masses: $(-gW_\mu^3 + g' B_\mu)^2$

Masses vanish when v=0

# More on SM Higgs Mechanism

- Massive gauge bosons:

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

$$Z_\mu^0 = \left(\frac{gW_\mu^3 - g'B_\mu}{\sqrt{g^2 + g'^2}}\right)$$

$$M_W = \frac{gv}{2}$$

$$M_Z = \sqrt{g^2 + g'^2}\,\frac{v}{2}$$

- Orthogonal combination to Z is massless photon

$$A_\mu^0 = \frac{g'W_\mu^3 + gB_\mu}{\sqrt{g^2 + g'^2}}$$

# More on SM Higgs Mechanism

- Weak mixing angle defined :

$Z = -\sin\theta_W B + \cos\theta_W W^3$

$A = \cos\theta_W B + \sin\theta_W W^3$

$$\cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \qquad \sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

➡ Natural Relationship: $M_W = M_Z \cos\theta_W$

$$\rho = \frac{M_W}{M_Z \cos\theta_W} = 1$$

* Corrections from top quark/Higgs masses

# Recap of SM Higgs Mechanism

- Generate mass for W,Z using Higgs mechanism
  - Higgs VEV breaks SU(2) x U(1)
  - Single Higgs doublet is *minimal case*
- Before spontaneous symmetry breaking:
  - Massless $W_i$, B, Complex $\Phi$
- After spontaneous symmetry breaking:
  - Massive $W^{\pm}$, Z, massless $\gamma$, physical Higgs boson h

*Very economical model!*
*Easy to add more scalars, etc*

# W, Z, Higgs Couplings

- Lagrangian in terms of massive gauge bosons and Higgs boson:

$$L = gM_W W^{+\mu} W_\mu^- h + \frac{gM_Z}{\cos\theta_W} Z^\mu Z_\mu h$$

- Higgs couples to gauge boson mass
- Spontaneous symmetry breaking gives W/Z mass ⇒ longitudinal polarization

*No free parameters in couplings!*

# What about Fermions?

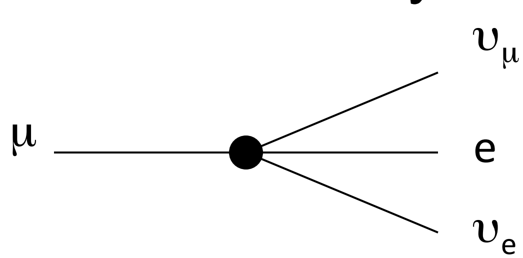
- Current-current interaction of 4 fermions

$$L_{FERMI} = -2\sqrt{2}G_F J_\rho^+ J^\rho$$

- Consider just leptonic current

$$J_\rho^{lept} = \overline{\nu}_e \gamma_\rho \left(\frac{1-\gamma_5}{2}\right) e + \overline{\nu}_\mu \gamma_\rho \left(\frac{1-\gamma_5}{2}\right) \mu + hc$$

- Only left-handed fermions feel charged current weak interactions
- This induces muon decay




This structure known since Fermi

$G_F$=1.16637 x $10^{-5}$ $GeV^{-2}$

# Fermion Multiplet Structure

- Left-handed fermions couple to $W^{\pm}$ (cf Fermi theory)
  - Put in SU(2) doublets
- Right-handed fermions don't couple to $W^{\pm}$
  - Put in SU(2) singlets
- Fix weak hypercharge to get correct couplings to photon

Put this in by hand

# Leptons

- Include an SU(2) doublet of left-handed leptons

$$\Psi_L = \begin{pmatrix} \nu_L = \frac{1}{2}(1-\gamma_5)\nu \\ e_L = \frac{1}{2}(1-\gamma_5)e \end{pmatrix}$$

$T_3 = \pm 1$

- Right-handed electron is SU(2) singlet, $e_R = (1+\gamma_5)e/2$
  - No right-handed neutrino
- Define weak hypercharge, Y, such that $Q_{em} = (T_3 + Y)/2$
  - $Y_{eL} = -1$
  - $Y_{eR} = -2$

To make charge come out right

**Standard Model has massless neutrinos—discovery of non-zero neutrino mass evidence for physics beyond the SM*

# Fermions come in generations

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad u_R, \quad d_R, \begin{pmatrix} \nu \\ e \end{pmatrix}_L, \quad e_R$$

$$\begin{pmatrix} c \\ s \end{pmatrix}_L \quad c_R, \quad s_R, \begin{pmatrix} \nu \\ \mu \end{pmatrix}_L, \quad \mu_R$$

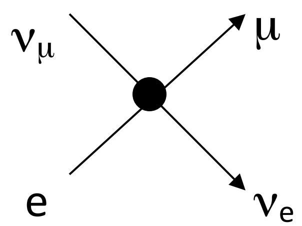
$$\begin{pmatrix} t \\ b \end{pmatrix}_L \quad t_R, \quad b_R, \begin{pmatrix} \nu \\ \tau \end{pmatrix}_L, \quad \tau_R$$

Except for masses, the generations are identical

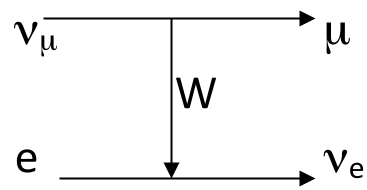
$$\psi_{L,R} = \frac{1 \mp \gamma_5}{2} \psi$$

# Muon decay

- Consider $\nu_\mu\, e \rightarrow \mu\, \nu_e$
- Fermi Theory:




- EW Theory:




$$-i2\sqrt{2}G_F g_{\mu\nu}\bar{u}_\mu\gamma^\mu\left(\frac{1-\gamma_5}{2}\right)u_{\nu_\mu}\bar{u}_{\nu_e}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)u_e$$

$$\frac{ig^2}{2}\frac{1}{k^2-M_W^2}g_{\mu\nu}\bar{u}_\mu\gamma^\mu\left(\frac{1-\gamma_5}{2}\right)u_{\nu_\mu}\bar{u}_{\nu_e}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)u_e$$

For $|k| \ll M_W$, $2\sqrt{2}G_F = g^2/2M_W^2$

# Higgs Parameters

- $G_F$ measured precisely

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^{\ 2}} = \frac{1}{2v^2}$$

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

- Higgs potential has 2 free parameters, $\mu^2$, $\lambda$

$$V = \mu^2\Phi^+\Phi + \lambda(\Phi^+\Phi)^2$$

- Trade $\mu^2$, $\lambda$ for $v^2$, $M_h^2$

$$V = \frac{M_h^{\ 2}}{2}h^2 + \frac{M_h^{\ 2}}{2v}h^3 + \frac{M_h^{\ 2}}{8v^2}h^4$$

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

$$M_h^{\ 2} = 2v^2\lambda$$

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

# What about fermion masses?

- Fermion mass term:

$$L = -m\bar{\Psi}\Psi = -m\left(\bar{\Psi}_L\Psi_R + \bar{\Psi}_R\Psi_L\right)$$

← Forbidden by SU(2)xU(1) gauge invariance

- Left-handed fermions are SU(2) doublets

- Scalar couplings to fermions:

$$L_d = -\lambda_d \bar{Q}_L \Phi d_R + h.c. \qquad Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

- Effective Higgs-fermion coupling

$$L_d = -\lambda_d \frac{1}{\sqrt{2}} (\bar{u}_L, \bar{d}_L) \begin{pmatrix} 0 \\ v + h \end{pmatrix} d_R + h.c.$$

- Mass term for down quark:

$$\boxed{\lambda_d = \frac{M_d\sqrt{2}}{v}}$$

# Fermion Masses

- $M_u$ from $\Phi_c = i\sigma_2\Phi^*$ (not allowed in SUSY)

$$\Phi_c = \begin{pmatrix} \bar{\phi}^0 \\ -\phi^- \end{pmatrix}$$

$$\lambda_u = \frac{M_u\sqrt{2}}{v}$$

$$L = -\lambda_u \overline{Q}_L \Phi_c u_R + hc$$

- For 3 generations, $\alpha$, $\beta$=1,2,3 (flavor indices)

$$L_Y = -\frac{(v+h)}{\sqrt{2}} \sum_{\alpha,\beta} \left( \lambda_u^{\alpha\beta} \overline{u}_L^{\alpha} u_R^{\beta} + \lambda_d^{\alpha\beta} \overline{d}_L^{\alpha} d_R^{\beta} \right) + h.c.$$

# Fermion masses

- Unitary matrices diagonalize mass matrices

$$u_L^\alpha = U_u^{\alpha\beta} u_L^{m\beta} \qquad d_L^\alpha = U_d^{\alpha\beta} d_L^{m\beta}$$
$$u_R^\alpha = V_u^{\alpha\beta} u_R^{m\beta} \qquad d_R^\alpha = V_d^{\alpha\beta} d_R^{m\beta}$$

  - Yukawa couplings are ***diagonal*** in mass basis
  - *No flavor changing effects in Higgs sector*
  - Not necessarily true in models with extended Higgs sectors

Fermion masses NOT a prediction of SM

UV*=CKM matrix

# Review of Higgs Couplings

- Higgs couples to fermion mass
  - Largest coupling is to heaviest fermion

$$L = -\frac{m_f}{v}\bar{f}fh = -\frac{m_f}{v}\left(\bar{f}_L f_R + \bar{f}_R f_L\right)h$$

  - Top-Higgs coupling plays special role?
  - No Higgs coupling to neutrinos
- Higgs couples to gauge boson masses

$$L = gM_W W^{+\mu} W_\mu^- h + \frac{gM_Z}{\cos\theta_W} Z^\mu Z_\mu h + \ldots.$$

- *Only free parameter is Higgs mass!*

# Model Makes Predictions!

- Four free parameters in gauge-Higgs sector (g, g', $\mu$, $\lambda$)
  - Conventionally chosen to be
    - $\alpha$=1/137.0359895(61)
    - $G_F$ =1.16637(1) x $10^{-5}$ GeV $^{-2}$
    - $M_Z$=91.1875 ± 0.0021 GeV
    - $M_h$
  - Express everything else in terms of these parameters

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{\pi\alpha}{2\left(1-\frac{M_W^2}{M_Z^2}\right)M_W^2}$$

$\Rightarrow$ Predicts $M_W$

# Inadequacy of Tree Level Calculations

– Predict $M_W$

$$M_W^2 = \pi\sqrt{2}\,\frac{\alpha}{G_F}\left(1-\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F M_Z^2}}\right)^{-1}$$

– Plug in numbers:

- $M_W$ predicted =80.939 GeV
- $M_W$ experimental =80.385 ± 0.015 GeV

– Need to calculate beyond tree level

# Modification of tree level relations

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

- $\Delta$r is a physical quantity which incorporates 1-loop corrections

- Contributions to $\Delta$r from top quark and Higgs loops

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

Extreme sensitivity of precision measurements to $m_t$

$$\Delta r^h = \frac{11 G_F M_W^2}{24\sqrt{2}\pi^2}\left(\ln\frac{M_h^2}{M_W^2}\right)$$

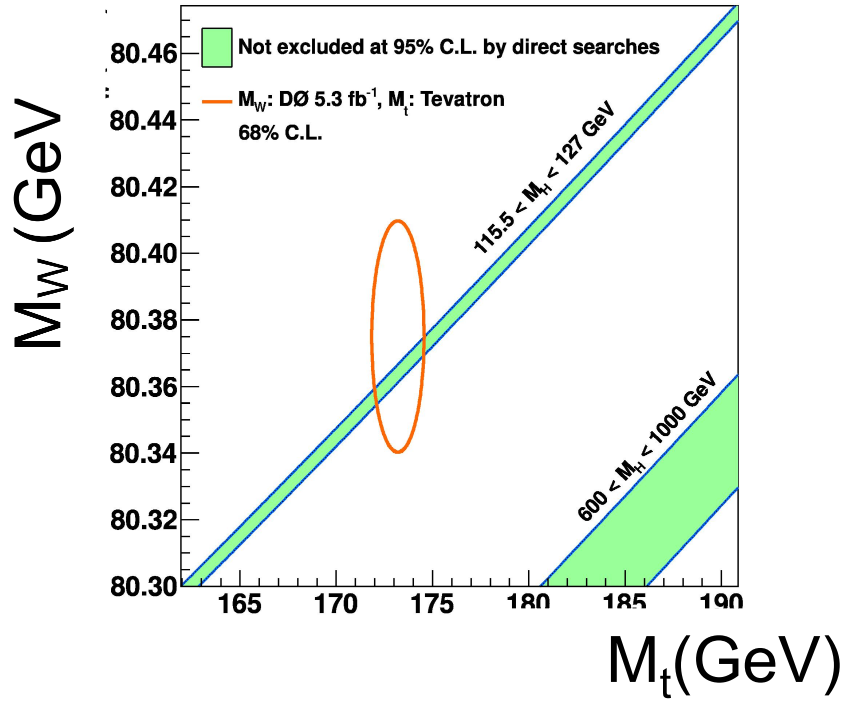
If we removed the Higgs, these formulas would be infinite

# $M_W$ vs $m_t$

- Logarithmic dependence on $M_h$

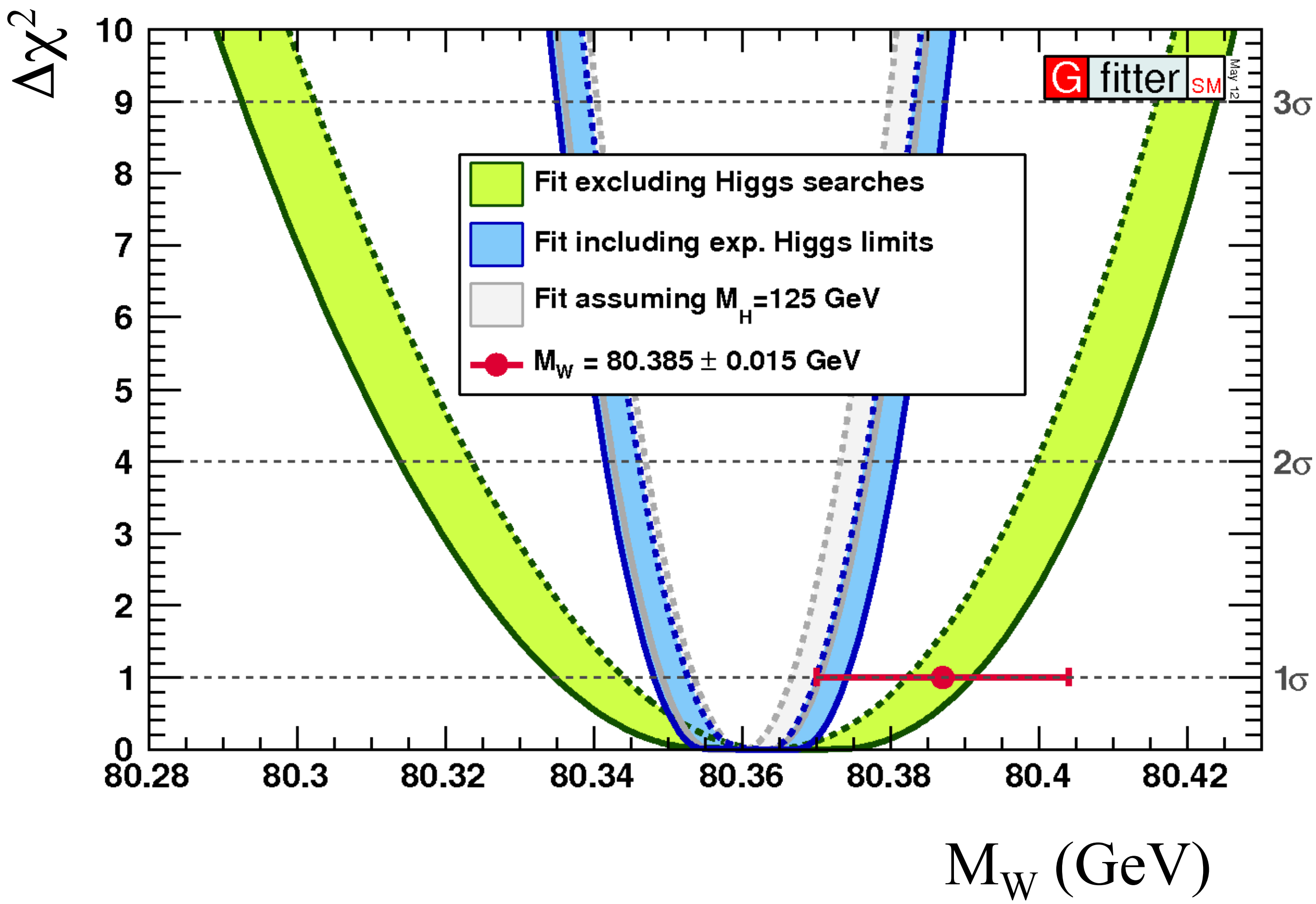
Direct measurement of W and top masses

Masses inferred from precision measurements




Higgs boson wants to be light

# Global Fit



$\Delta\chi^2$
10
9
8
7
6
5
4
3
2
1
0
80.28
80.3
80.32
80.34
80.36
80.38
80.4
80.42
$M_W$ (GeV)
3σ
2σ
1σ
G fitter SM
May 12
Fit excluding Higgs searches
Fit including exp. Higgs limits
Fit assuming $M_H$=125 GeV
$M_W$ = 80.385 ± 0.015 GeV