

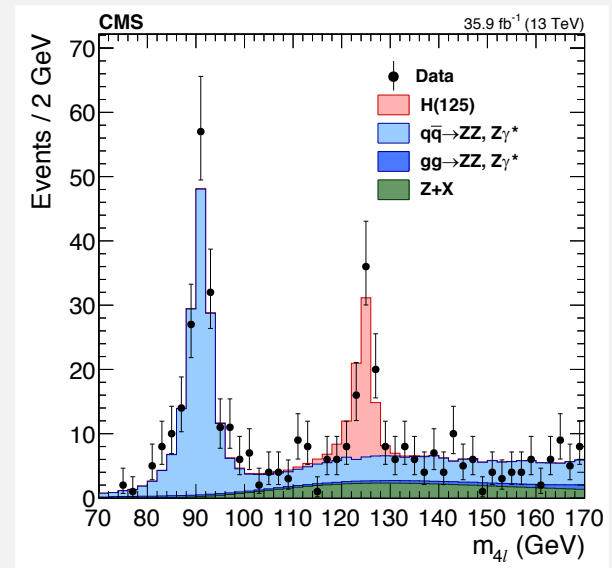
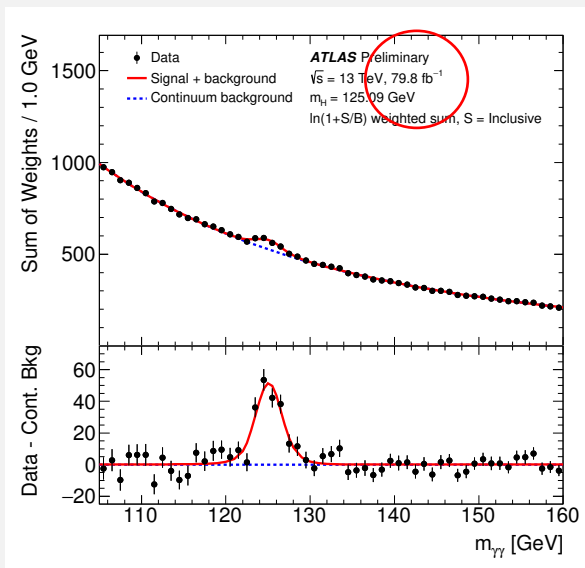
ISSUES IN HIGGS PHYSICS LECTURE I

S. Dawson, BNL

Hadron Collider Summer School, August, 2018

Please send questions or corrections to dawson@bnl.gov

WE'VE DISCOVERED A "HIGGS-LIKE" PARTICLE



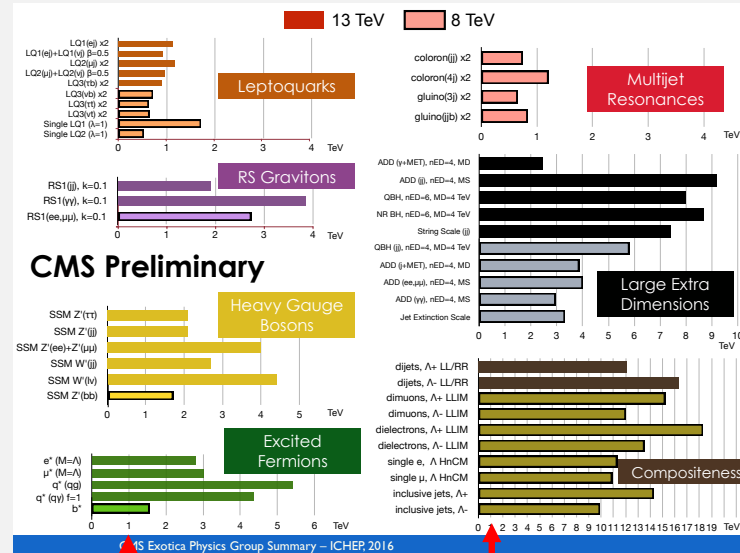
NO UNEXPECTED PARTICLES DISCOVERED

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: July 2018

ATLAS Preliminary
 $\int \mathcal{L} dt = (3.2 - 79.8) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$

Model	ξ, γ	Jets [†]	$E_{\text{miss}}^{\text{min}}$	Limit	Reference
Extra dimensions					
ADD $G_{\mu} + g/4$	$0, \mu$	1-4	Yes	36.1	1711.0301
ADD non-resonant $\gamma\gamma$	2, γ	-	-	36.7	1707.26147
ADD QED	-	2	-	37.0	1707.26217
ADD BH High $\Sigma \gamma\gamma$	$\geq 1, \mu$	≥ 2	-	3.2	1606.02895
ADD BH multijet	-	≥ 3	-	3.6	1606.02918
RS1 $G_{\mu} + \gamma\gamma$	2, γ	-	-	36.7	1707.04147
Bulk RS $G_{\mu} + \gamma\gamma / ZZ$	multi-channel	-	-	36.1	CERN-EP-2018-179
Bulk RS $g_{\mu\mu} + \mu\mu$	1, μ	$\geq 1, 2, \geq 3$	Yes	36.1	1804.16823
2UD / RPP	1, μ	$\geq 2, \geq 3$	Yes	36.1	1803.09875
Charge leptoquarks					
SSM $Z' \rightarrow \ell\ell$	2, μ	-	-	36.1	1707.07424
SSM $Z' \rightarrow \tau\tau$	-	-	-	36.1	1707.07424
Lepophobic $Z' \rightarrow bb$	2, μ	-	-	36.1	1805.09299
Lepophobic $Z' \rightarrow \mu\mu$	1, μ	$\geq 1, 2, \geq 3$	Yes	36.1	1804.16823
SSM $W' \rightarrow \ell\nu$	1, μ	-	-	79.8	ATLAS-COUP-2018-017
SSM $W' \rightarrow \mu\nu$	1, μ	-	-	36.1	1801.09295
HVT $V' \rightarrow W\nu \rightarrow e\mu\mu B$	0, μ	2, γ	-	79.8	ATLAS-COUP-2018-016
HVT $V' \rightarrow W\nu / Z\nu$ model B	multi-channel	-	-	36.1	1712.26215
LRSM $W'_{\mu} \rightarrow \ell\nu$	multi-channel	-	-	36.1	CERN-EP-2018-142
CI					
CI $e\mu\mu$	-	2	-	37.0	1703.09217
CI $\tau\mu\mu$	2, μ	-	-	36.1	1707.26147
CI $\mu\mu$	$\geq 1, \mu$	$\geq 1, \geq 2$	Yes	36.1	CERN-EP-2018-174
DM					
Axial-vector mediator (Dirac DM)	0, μ	1-4	Yes	36.1	1711.0301
Coloron scalar mediator (Dirac DM)	0, μ	1-4	Yes	36.1	1711.0301
VV ₁₂ EFT (Dirac DM)	0, μ	1, 2, 3	Yes	3.2	1606.02918
LQ					
Scalar LQ 1 st gen	2, μ	≥ 2	-	3.2	1606.06335
Scalar LQ 2 nd gen	2, μ	≥ 2	-	3.2	1606.06335
Scalar LQ 3 rd gen	1, μ	$\geq 1, \geq 2$	Yes	20.3	1606.02752
Heavy bosons					
VLD $TT \rightarrow W, Z / W\gamma + X$	multi-channel	-	-	36.1	1707.07424
VLD $BB \rightarrow W, Z, \gamma + X$	multi-channel	-	-	36.1	ATLAS-COUP-2018-032
VLD $T_{\mu\nu} T_{\mu\nu} \rightarrow W + X$	$\geq 1, \mu$	$\geq 1, \geq 2, \geq 3$	Yes	3.2	CERN-EP-2018-171
VLD $Y \rightarrow W\gamma + X$	1, μ	$\geq 1, \geq 2$	Yes	3.2	ATLAS-COUP-2018-072
VLD $E \rightarrow H\gamma + X$	0, μ	$\geq 1, \geq 2, \geq 3$	Yes	79.8	ATLAS-COUP-2018-024
VLD $QQ \rightarrow W\gamma + X$	1, μ	≥ 2	Yes	20.3	1509.04281
Excited fermions					
Excited quark $q^* \rightarrow q\gamma$	-	2	-	37.0	1703.09217
Excited quark $q^* \rightarrow qg$	1, γ	1	-	36.7	1703.09450
Excited quark $q^* \rightarrow b\gamma$	2, μ	1, 2	-	36.1	1805.09299
Excited lepton ℓ^*	2, μ	-	-	36.1	1411.2921
Excited lepton ℓ^*	3, μ, τ	-	-	20.3	1411.2921
Other					
Type III Seesaw	1, μ	≥ 2	Yes	79.8	ATLAS-COUP-2018-200
LRSM Majorana	2, μ	2	-	20.3	1508.06205
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4, \mu$	μ (SB)	-	36.1	1411.2921
Higgs triplet $H^{\pm\pm} \rightarrow \ell\nu$	3, μ, τ	-	-	20.3	1411.2921
Monopole (top-req prod)	1, μ	1, 2	-	20.3	1410.04549
Multi-charged particles	-	-	-	20.3	1504.04188
Magnetic monopoles	-	-	-	7.0	1509.09039

*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (s).



Many limits exceed 1 TeV

WHAT DO WE EXPECT TO LEARN IN THE FUTURE?

PDG, 2017

H^0

$J = 0$

Mass $m = 125.09 \pm 0.24$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States = 1.10 ± 0.11

$WW^* = 1.08^{+0.18}_{-0.16}$

$ZZ^* = 1.29^{+0.26}_{-0.23}$

$\gamma\gamma = 1.16 \pm 0.18$

$b\bar{b} = 0.82 \pm 0.30$ (S = 1.1)

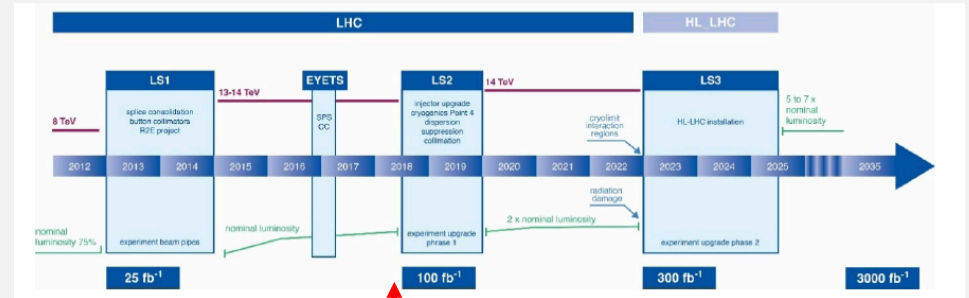
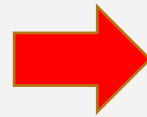
$\mu^+\mu^- = 0.1 \pm 2.5$

$\tau^+\tau^- = 1.12 \pm 0.23$

$Z\gamma < 9.5$, CL = 95%

$t\bar{t}H^0$ Production = $2.3^{+0.7}_{-0.6}$

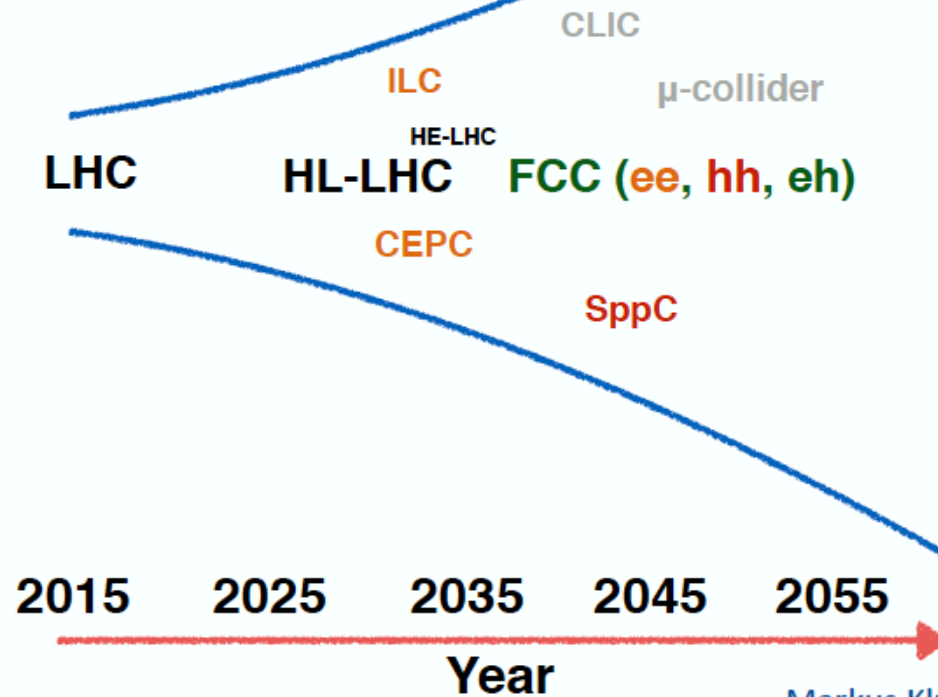
Normalized to SM



We are here

A good time to take stock of physics goals

The Road Ahead



Markus Klute, 2016

BASICS OF HIGGS PHYSICS

Lightning review

See Dawson, Englert, Plehn, 1808.01324

SIMPLE HIGGS MODEL EXAMPLE

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

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

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

- 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

HIGGS MODEL EXAMPLE, 2

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

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

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

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

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

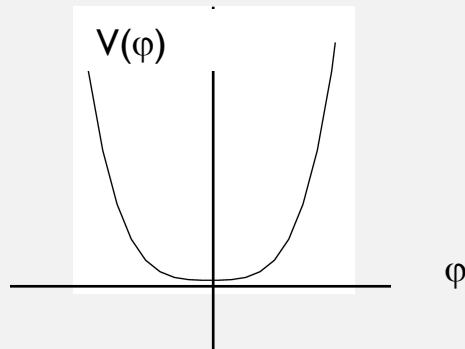
- L is invariant under local U(1) transformations:

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

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

HIGGS MODEL EXAMPLE, 3

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



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

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

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

By convention, $\lambda > 0$

HIGGS MODEL EXAMPLE, 4

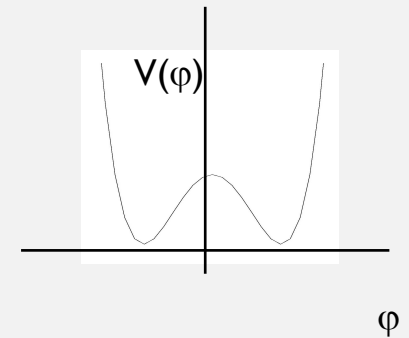
- Case 2: $\mu^2 < 0$

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

- Minimum energy state at $\langle \phi \rangle = \sqrt{-\frac{\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$
- Physical particle has minimum energy state at 0:

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

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



HIGGS MODEL EXAMPLE, 5

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

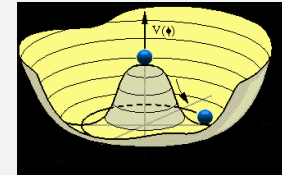
- Photon of mass $M_A = ev$
- Scalar field h with mass-squared $-2\mu^2 > 0$
- Massless scalar field χ (*Goldstone Boson*)
- χ interactions are gauge dependent

Photon got a mass without breaking the gauge symmetry

EWSB IN A NUTSHELL

- Standard Model includes complex Higgs SU(2) doublet

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$



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

$$V_{SM} = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2 \quad \text{Invariant under } \phi \rightarrow -\phi$$

- If $\mu^2 < 0$, then spontaneous symmetry breaking
- Minimum of potential at:

$$\phi = e^{\frac{\omega \cdot \sigma}{v}} \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix} \quad \langle \phi \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

ω 's correspond to longitudinal degrees of freedom— all the action is here!

- Choice of minimum breaks gauge symmetry

GAUGE SECTOR

- Couple ϕ to SU(2) x U(1) gauge bosons ($W^{\mu a}$, $a=1,2,3$; B^μ)

$$L_\phi = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi)$$

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

Couplings fixed by gauge invariance

- Gauge boson mass terms from:

$$\begin{aligned} (D_\mu \phi)^\dagger (D^\mu \phi) &\rightarrow \frac{1}{8}(0, v)(gW_\mu^a \sigma^a + g'B_\mu)(gW^{b,\mu} \sigma^b + g'B^\mu) \begin{pmatrix} 0 \\ v \end{pmatrix} + \dots \\ &\rightarrow \frac{v^2}{8} \left[g^2 (W_\mu^1)^2 + g^2 (W_\mu^2)^2 + (-gW_\mu^3 + g'B_\mu)^2 \right] + \dots \end{aligned}$$

- Free parameters in gauge sector: **g and g'**

GAUGE BOSON MASSES

$$M_W^2 = \frac{g^2 v^2}{4}, \quad M_Z^2 = (g^2 + g'^2) \frac{v^2}{4}, \quad M_\gamma = 0$$

- Masses satisfy: $\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1$ $e = g \sin \theta_W = g' \cos \theta_W$
- Can add as many scalar singlets and doublets as you like

$$\rho = \frac{\sum_i \left[T_i(T_i + 1) - \frac{Y_i^2}{4} \right] v_i^2}{\frac{1}{2} \sum_i Y_i^2 v_i^2} \quad Q = T_3 + \frac{Y}{2}$$

- $T_i = 1/2$ for a doublet and 0 for a singlet
- Triplet scalars ($T_3 = 1$) would have $\rho \neq 1$ Experimentally, $\rho \sim 1$

UNITARY GAUGE (NO GOLDSTONE BOSONS)

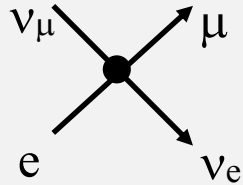
- We started with:
 - 4 massless gauge bosons, ($2 \times 4 = 8$ transverse polarizations)
 - Complex scalar doublet (4 degrees of freedom)
- After redefining scalar so it has minimum energy state at 0, we have:
 - 3 massive gauge bosons (2 transverse, 1 longitudinal polarization) $\times 3 = 9$ degrees of freedom
 - Massless photon (2 transverse degrees of freedom)
 - Physical scalar h of arbitrary mass
- Degrees of freedom preserved

MUON DECAY

- Consider $\nu_\mu e \rightarrow \mu \nu_e$

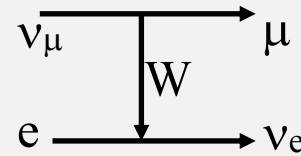
- Fermi Theory:

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



- EW Theory:

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



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

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

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

HIGGS PARAMETERS

- G_F measured precisely

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

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

- Higgs potential has 2 free parameters, μ^2, λ

$$V_{SM} = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$

- Trade μ^2, λ for v^2, M_h^2

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

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

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

Why is $\mu^2 < 0$?

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

STANDARD MODEL IS VERY ECONOMICAL

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

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

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

Except for masses, the generations are identical

5 multiplets with 3 generations each: $U(5)^3$ flavor symmetry (broken explicitly by Yukawas)

Reasons for flavor symmetry not understood

WHAT ABOUT FERMION MASSES?

- Left-handed fermions $SU(2)_L$ doublets, right-handed fermions $SU(2)_L$ singlets
- Dirac mass term **forbidden** by $SU(2)_L$ gauge invariance:

$$L = -m\bar{\psi}\psi = -m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

- Effective Higgs-fermion coupling is gauge invariant

$$L_Y = -\bar{Q}_L^i F_u^{ij} \tilde{\phi} u_R^j - \bar{Q}_L^i F_d^{ij} \phi d_R^j - \bar{l}_L^i F_l^{ij} \phi e_R^j + hc \quad i,j=1,2,3 = \text{generation index}$$

- Mass terms generated with $\phi^0 = (h+v)/\sqrt{2}$
- **Diagonalizing mass matrix diagonalizes Higgs Yukawa couplings**

$$L \sim \bar{u}_L^i m_u^{ij} u_R^j + Y_u^{ij} \bar{u}_L^i u_R^j h + hc \quad m_u^{ij} = \frac{v}{\sqrt{2}} F_u^{ij} \quad Y_u^{ij} = \frac{F_u^{ij}}{\sqrt{2}}$$

Higgs has no flavor changing couplings

MASS/YUKAWA CONNECTION SPECIAL TO SM

- Higgs couples proportionally to mass

$$\frac{BR(h \rightarrow b\bar{b})}{BR(h \rightarrow \tau^+\tau^-)} \sim N_c \left(\frac{m_b^2}{m_\tau^2} \right)$$

- Suppose there is new physics beyond the SM:

$$\delta L = -\frac{c_{ij}}{\Lambda^2} \bar{Q}_L^i \phi f_R^j (\phi^\dagger \phi) + hc$$

$$Y_{ij} = \frac{m_i}{v} \delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2} c_{ij}(\dots)$$

- Mass and Yukawas no longer proportional
- Can have FC Higgs decays!
 - eg: $h \rightarrow \mu\tau$

REVIEW OF HIGGS COUPLINGS

- Couplings to fermions proportional to mass: $\frac{m_f}{v} h \bar{f} f$
- Couplings to massive gauge bosons proportional to (mass)²:

$$2M_W^2 \frac{h}{v} W_\mu^+ W^{-\mu} + M_Z^2 \frac{h}{v} Z_\mu Z^\mu$$

- Couplings to gauge bosons at 1-loop:*

$$F(m_f) \frac{\alpha_s}{12\pi} \frac{h}{v} G_{\mu\nu}^A G^{A,\mu\nu} + F(m_f, M_W) \frac{\alpha}{8\pi} \frac{h}{v} F_{\mu\nu} F^{\mu\nu} + F(m_f, M_W) \frac{\alpha}{8\pi s_W} \frac{h}{v} F_{\mu\nu} Z^{\mu\nu}$$

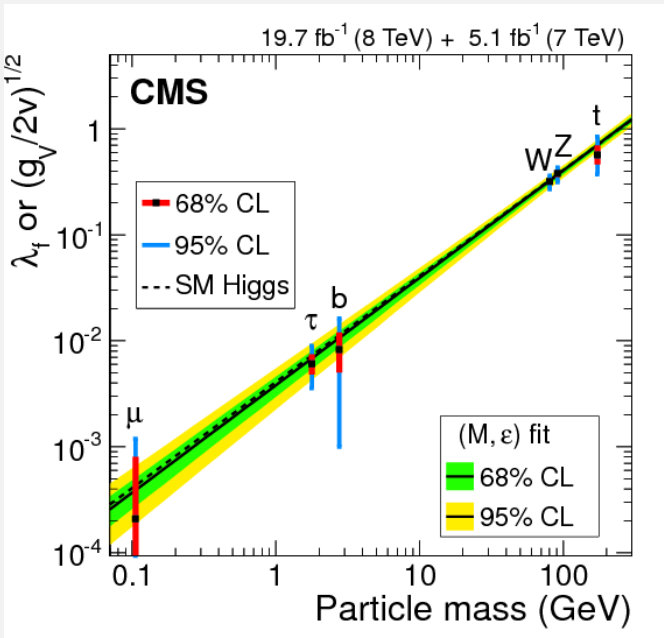
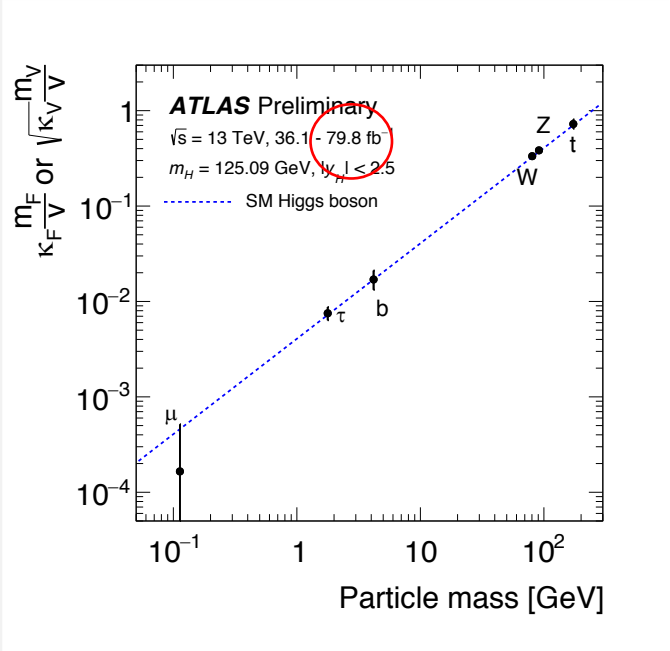
- Higgs self-couplings proportional to M_h^2 :

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

Only unpredicted parameter is M_h

* Normalization is such that $F \rightarrow 1$ for $m_f \rightarrow 0$, $M_W \rightarrow \infty$

GENERICALLY, IT LOOKS LIKE SM COUPLINGS!



SM PREDICTS M_W

- Inputs: $g, g', v, M_h \rightarrow M_Z, G_F, \alpha, M_h$
- Predict M_W

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

- Need to calculate beyond tree level

M_W predicted = 80.935 GeV

M_W experimental = 80.379 ± 0.012 GeV

QUANTUM CORRECTIONS

- Relate tree level to one-loop corrected masses

$$-i\Pi_{XY}^{\mu\nu} = \text{wavy line} \text{---} \text{orange circle} \text{---} \text{wavy line}$$

$$\Pi_{XY}^{\mu\nu}(k^2) = g^{\mu\nu} \Pi_{XY}(k^2) + k^\mu k^\nu B_{XY}(k^2)$$

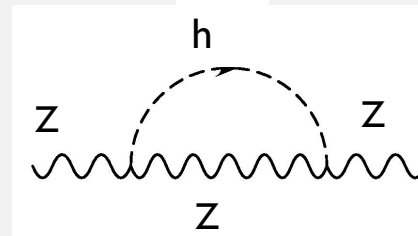
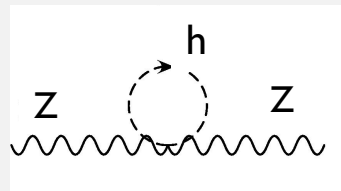
$$M_{V0}^2 = M_V^2 + \Pi_{VV}(M_V^2)$$

- Majority of corrections at one-loop are from 2-point functions

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta} = 1 + \delta\rho$$

$$\delta\rho = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

HIGGS CONTRIBUTION TO $\delta\rho$



- Higgs contributions have divergences which are cancelled by contributions of gauge boson loops
- Higgs contributions alone aren't gauge invariant
- Keep only terms which depend on M_h

$$\delta\rho = \frac{-3\alpha}{16\pi c_W^2} \log\left(\frac{M_h^2}{M_W^2}\right)$$

Logarithmic dependence
on Higgs mass

M_W AT 1-LOOP

- Predict M_W

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

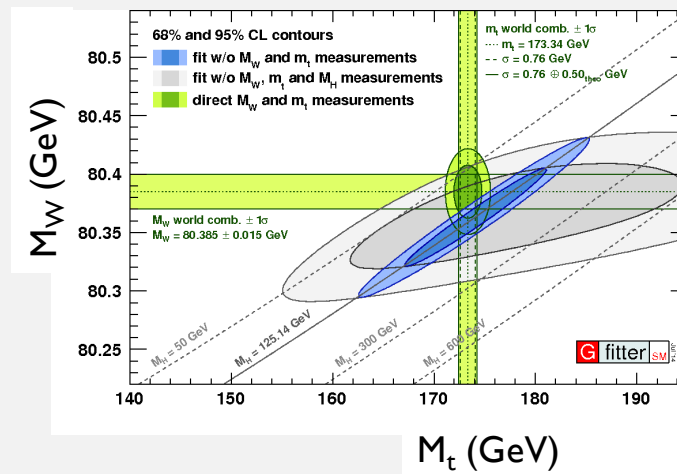
Δr contains all the radiative corrections

- Need to calculate beyond tree level

$$\Delta r^t = -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2} \left(\frac{\cos^2 \theta_W}{\sin^2 \theta_W} \right) \quad \Delta r^h = \frac{11G_F M_W^2}{24\sqrt{2}\pi^2} \left(\ln \frac{M_h^2}{M_W^2} \right)$$

In general: quadratic dependence on top mass,
logarithmic dependence on Higgs mass

THE SM WORKS! (GLOBAL FIT)



Measurements
sensitive to
 $\ln(M_h)$ terms

Heavy Higgs excluded by
precision measurements
even without observation

Corollary: New Physics highly restricted by data

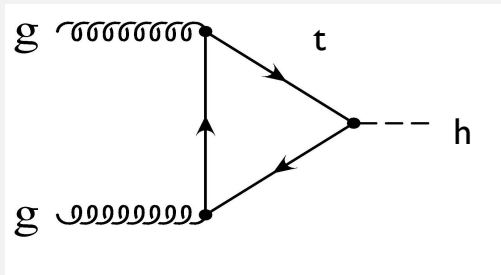
**So why are we still talking about BSM physics in the Higgs sector?*

HIGGS COUPLINGS TO GLUONS

- Largest contribution in SM is from top quarks
- (hff coupling $\sim M_f/v$)
- Not a direct measurement of tth coupling since there could be new particles in loop

Contribution of b quark $\sim -4\%$

No direct ggh , $\gamma\gamma h$ couplings since Higgs couples to mass



HIGGS COUPLINGS TO PHOTONS

- Dominant contribution is W loops
- Contribution from top is small

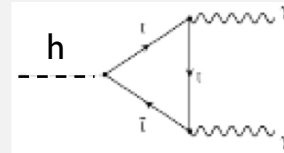
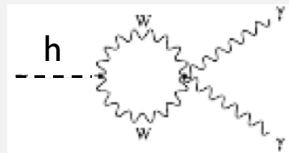
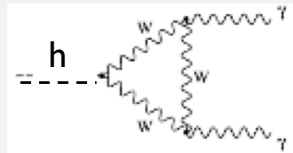
Note opposite signs of t/W loops: Sensitive to sign of top Yukawa

$$\Gamma(H \rightarrow \gamma\gamma) \sim \frac{\alpha^3}{256\pi^2 s_W^2} \frac{M_H^3}{M_W^2} \left| 7 - \frac{16}{9} + \dots \right|^2$$

W

top

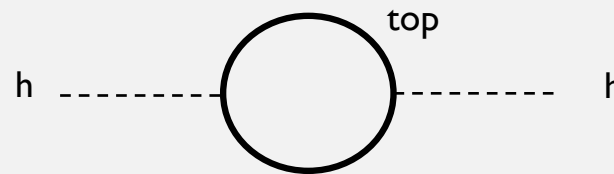
*limits are small M_h limit



Loops imply sensitivity to new physics

WHY DO WE EXPECT SOMETHING NEW IN THE HIGGS SECTOR?

- The Higgs mass has quantum corrections that we can calculate:



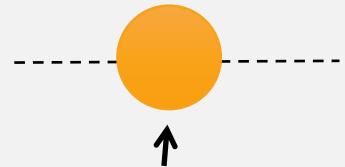
$$\delta M_h^2 = -\frac{3M_t^2}{8\pi^2 v^2} \Lambda^2$$

- Λ is the largest mass scale in the theory, maybe $M_{\text{planck}} = 10^{18}$ GeV?
- Need to arrange for these large contributions to be cancelled since $M_h = 125$ GeV
- Term this the **naturalness** problem

* Can cancel this with counterterm in QFT

WHY DO WE EXPECT NEW PHYSICS IN LOOPS?

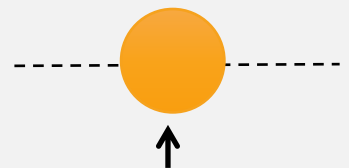
- Generically, solutions to *naturalness* involve new particles



A diagram showing a loop of Standard Model (SM) particles. It consists of a dashed horizontal line with an orange circle in the middle. An upward-pointing arrow is below the circle, and the text "SM particles" is below the arrow.

$$\delta M_h^2 \sim -(125 \text{ GeV})^2 \left(\frac{\Lambda}{600 \text{ GeV}} \right)^2$$

Λ is scale of new physics



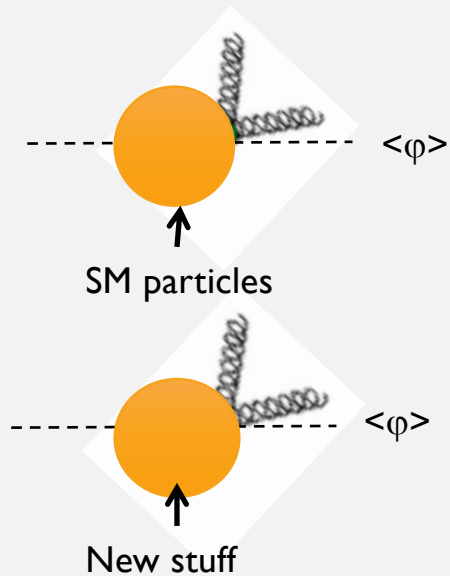
A diagram showing a loop of new physics particles. It consists of a dashed horizontal line with an orange circle in the middle. An upward-pointing arrow is below the circle, and the text "New stuff" is below the arrow.

$$\delta M_h^2 \sim +(125 \text{ GeV})^2 \left(\frac{\Lambda}{M_{new}} \right)^2$$

For this cancellation to work, new stuff can't be too much above TeV scale

New stuff invented just for this cancellation with + sign

WHY DO WE EXPECT NEW PHYSICS IN LOOPS?



- New physics will show up in $h \rightarrow gg$, $h \rightarrow \gamma\gamma$