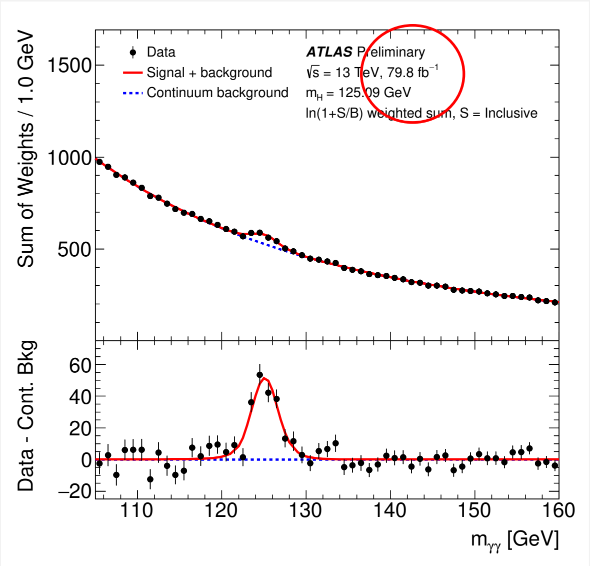
ISSUES IN HIGGS PHYSICS LECTURE 1

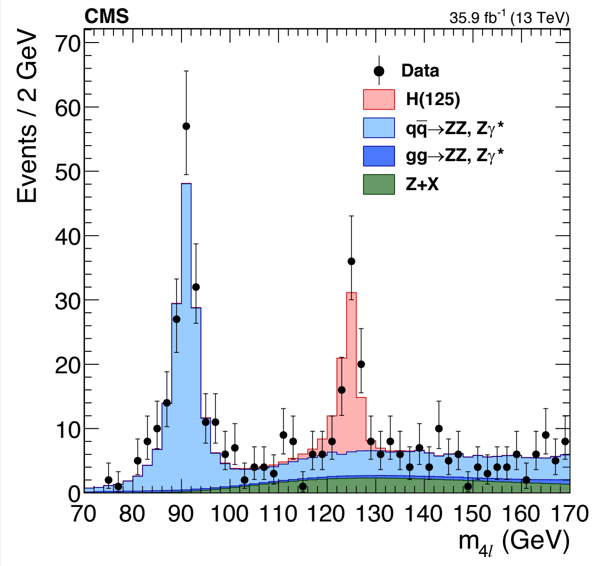
S. Dawson, BNL

Hadron Collider Summer School, August, 2018

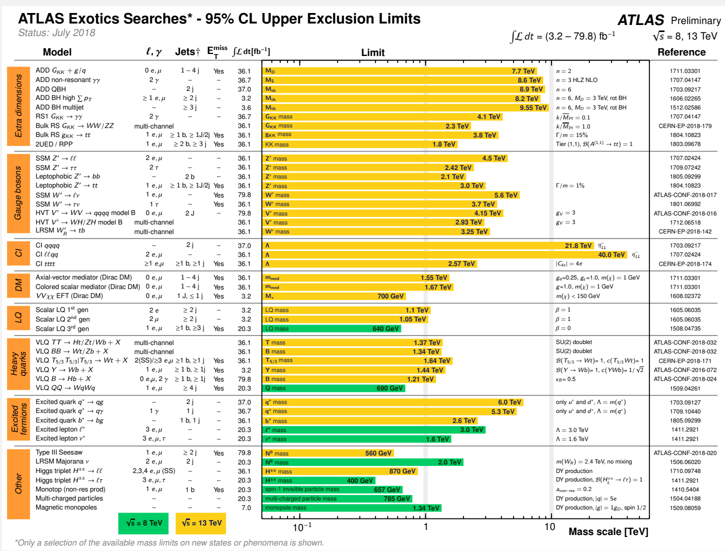
Please send questions or corrections to dawson@bnl.gov

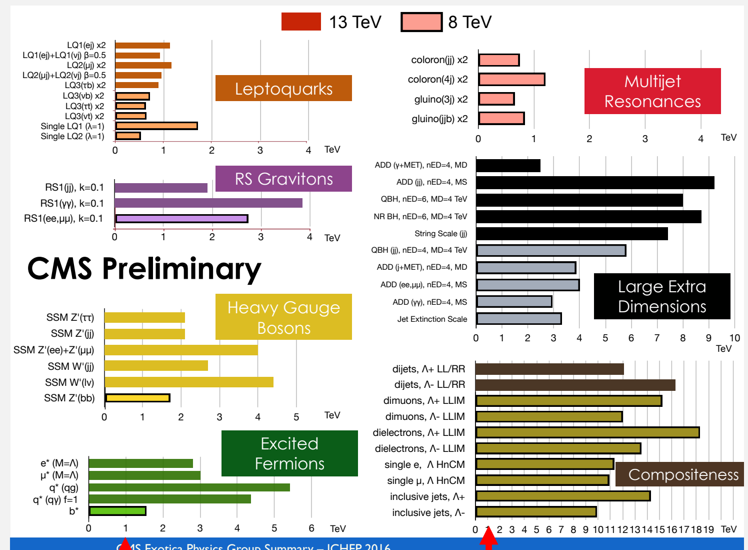
WE'VE DISCOVERED A "HIGGS-LIKE" PARTICLE





NO UNEXPECTED PARTICLES DISCOVERED





Many limits exceed 1 TeV

WHAT DO WE EXPECT TO LEARN IN THE FUTURE?

PDG, 2017

H^0 $J = 0$

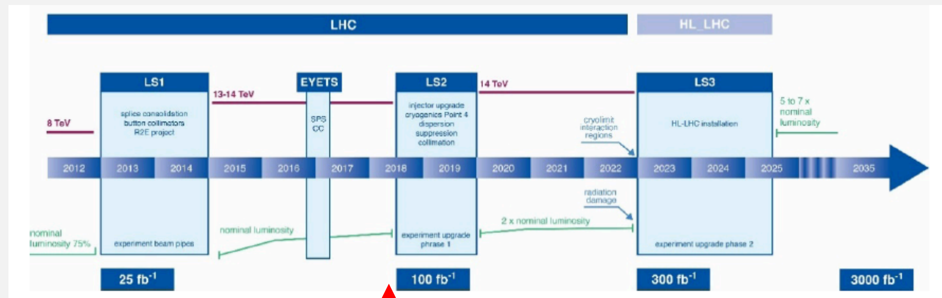
Mass $m = 125.09 \pm 0.24$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

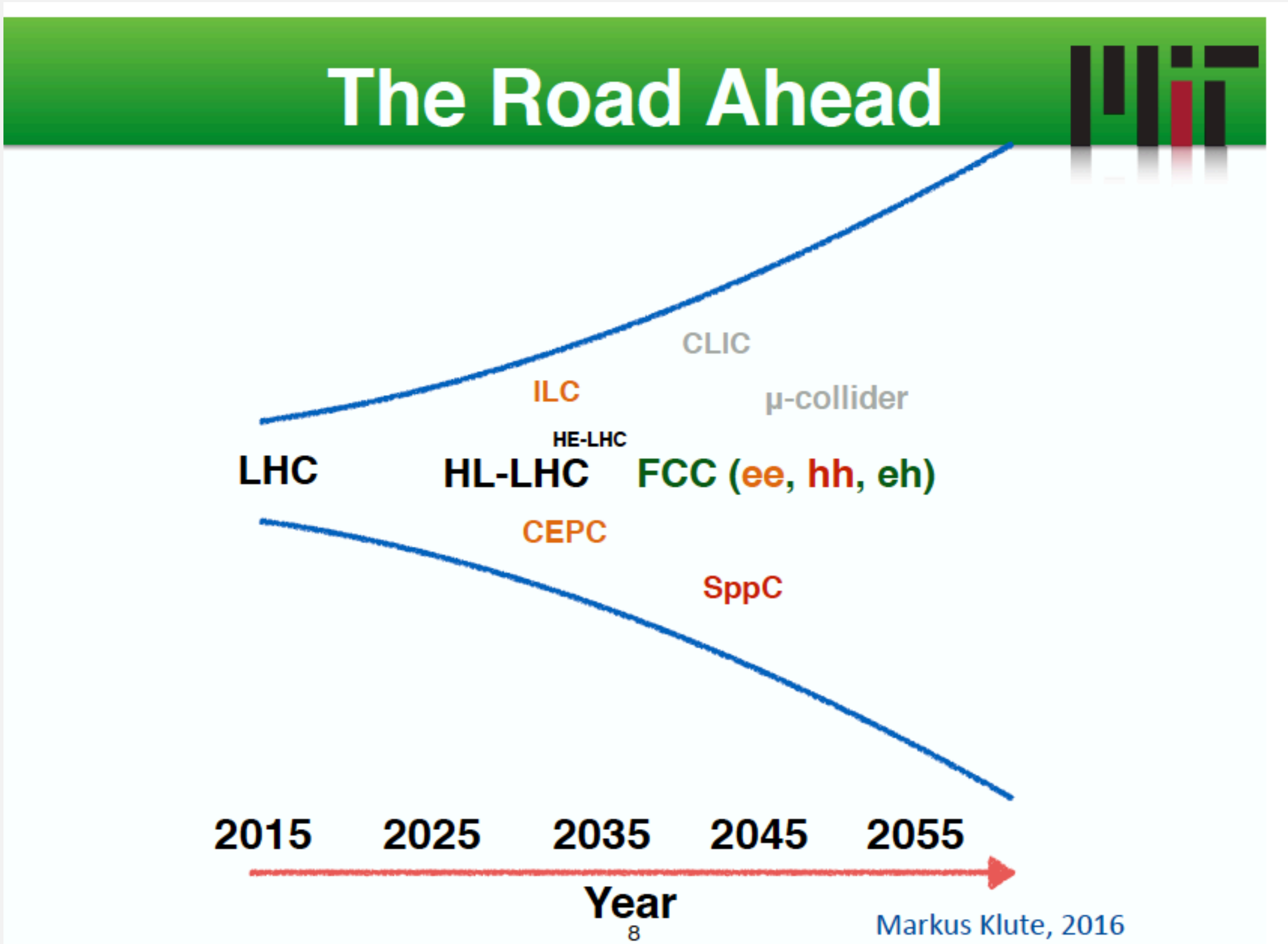
Combined Final States = 1.10 ± 0.11
$WW^* = 1.08^{+0.18}_{-0.16}$
$ZZ^* = 1.29^{+0.26}_{-0.23}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.82 \pm 0.30$ (S = 1.1)
$\mu^+\mu^- = 0.1 \pm 2.5$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma <$ 9.5, CL = 95%
$t\bar{t}H^0$ Production = $2.3^{+0.7}_{-0.6}$

Normalized to SM



We are here

A good time to take stock of physics goals


The Road Ahead
CLIC
ILC
μ-collider
HE-LHC
LHC
HL-LHC
FCC (ee, hh, eh)
CEPC
SppC
2015
2025
2035
2045
2055
Year
8
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: $A_\mu(x) \to A_\mu(x) - \partial_\mu \eta(x)$
- 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:

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

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

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

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

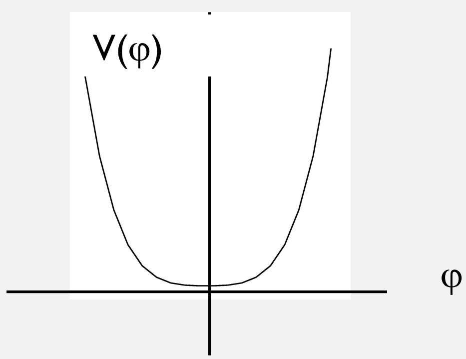
- L is invariant under local U(1) transformations:

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

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

HIGGS MODEL EXAMPLE, 3

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



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

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

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

By convention, $\lambda > 0$

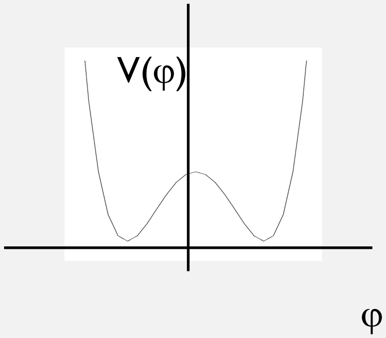
HIGGS MODEL EXAMPLE, 4

- 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:

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



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

HIGGS MODEL EXAMPLE, 5

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

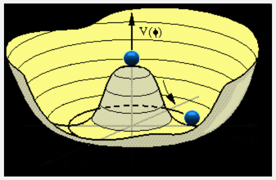
- Photon of mass M_A=ev
- Scalar field h with mass-squared –2μ^2 > 0
- Massless scalar field χ *(Goldstone Boson)*
- χ interactions are gauge dependent

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

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

Invariant under $\varphi \rightarrow -\varphi$

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

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

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:

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

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

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

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

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

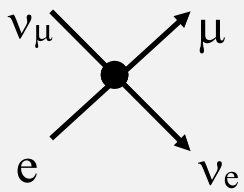
UNITARY GAUGE (NO GOLDSTONE BOSONS)

- We started with:
  - 4 massless gauge bosons, (2x4=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) x3=9 degrees of freedom
  - Massless photon (2 transverse degrees of freedom)
  - Physical scalar h of arbitrary mass
- Degrees of freedom preserved

MUON DECAY

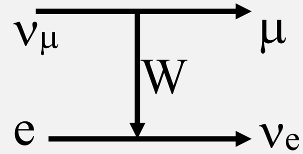
- Consider $\nu_\mu\, e \rightarrow \mu\, \nu_e$
- Fermi Theory:

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



- EW Theory:

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



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

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

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

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

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

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

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

- Trade μ^2, λ for v^2, M_h^2

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

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

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

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

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

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:

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

- Effective Higgs-fermion coupling is gauge invariant

$$L_Y = -\overline{Q}^i_L F^{ij}_u \tilde{\phi} u^j_R - \overline{Q}^i_L F^{ij}_d \phi d^j_R - \overline{l}^i_L F^{ij}_l \phi e^j_R + hc$$

i,j=1,2,3 =generation index

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

$$L \sim \overline{u}^i_L m^{ij}_u u^j_R + Y^{ij}_u \overline{u}^i_L u^j_R h + hc \qquad m^{ij}_u = \frac{v}{\sqrt{2}} F^{ij}_u \qquad Y^{ij}_u = \frac{F^{ij}_u}{\sqrt{2}}$$

Higgs has no flavor changing couplings

MASS/YUKAWA CONNECTION SPECIAL TO SM

- Higgs couples proportionally to mass

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

- Suppose there is new physics beyond the SM:

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

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

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

REVIEW OF HIGGS COUPLINGS

- Couplings to fermions proportional to mass: $\frac{m_f}{v} h \overline{f} f$
- 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:*

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

- Higgs self-couplings proportional to M_h^2:

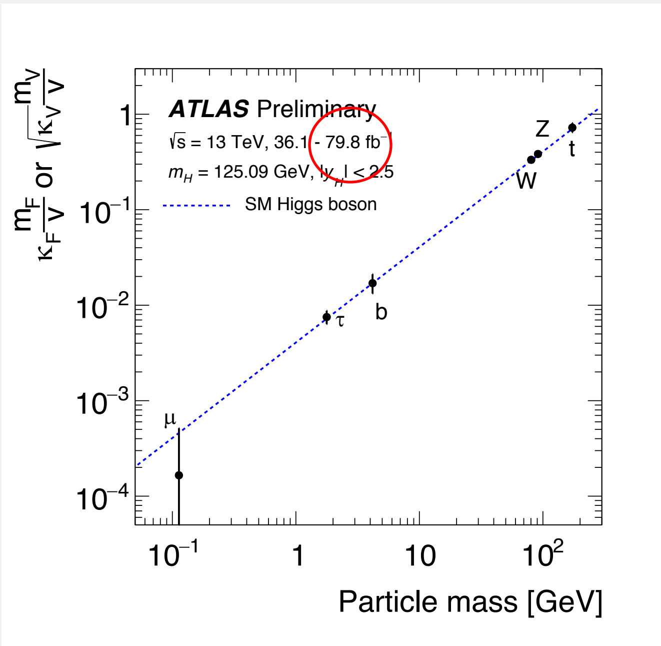
$$V = \frac{M_h^2}{2} h^2 + \frac{M_h^2}{2v} h^3 + \frac{M_h^2}{8v^2} h^4$$

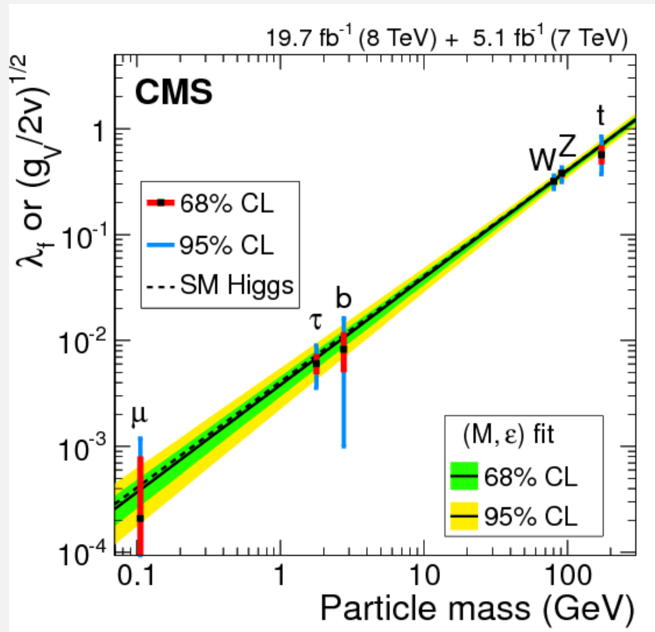
Only unpredicted parameter is M_h

* Normalization is such that F→1 for m_t, M_W→ ∞

png

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

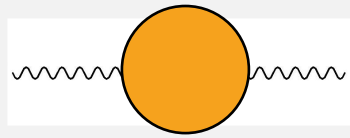
M_W predicted =80.935 GeV

M_W experimental =80.379 $\pm$ 0.012 GeV

QUANTUM CORRECTIONS

- Relate tree level to one-loop corrected masses

$$-i\Pi_{XY}^{\mu\nu} =$$



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

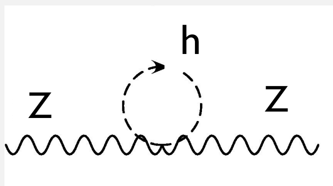
$$M_{V0}^2 = M_V^2 + \Pi_{VV}(M_V^2)$$

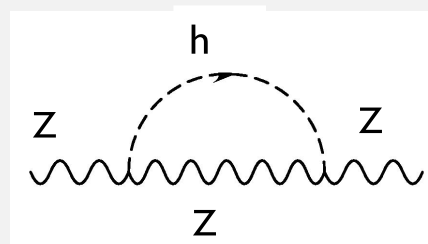
- Majority of corrections at one-loop are from 2-point functions

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

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

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

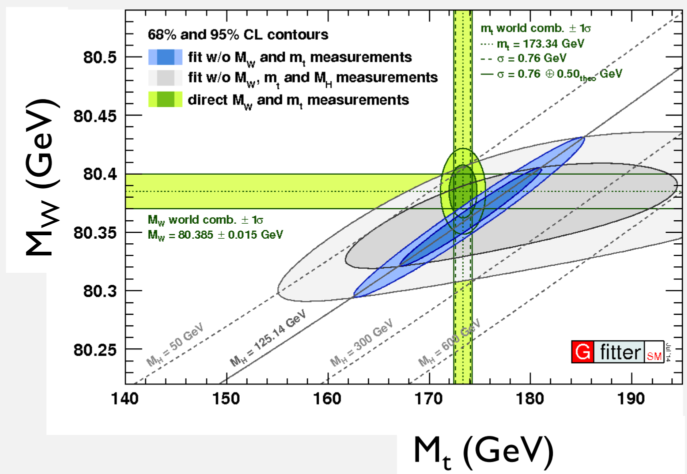
- Need to calculate beyond tree level

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

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

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

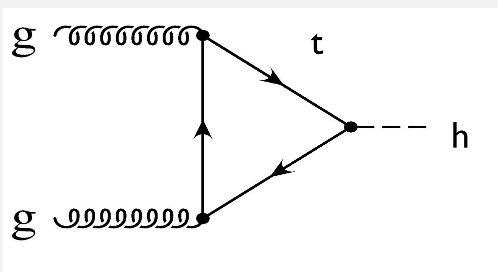
Corollary: New Physics highly restricted by data

**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 ~ M_f/v)
- Not a direct measurement of tth coupling since there could be new particles in loop

Contribution of b quark ~ -4%



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

HIGGS COUPLINGS TO PHOTONS

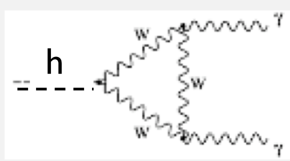
- Dominant contribution is W loops
- Contribution from top is small

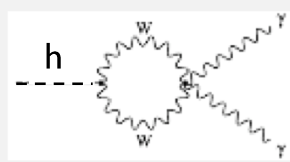
Note opposite signs of t/W loops: Sensitive to sign of top Yukawa

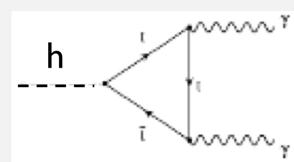
$$\Gamma(H \to \gamma\gamma) \sim \frac{\alpha^3}{256\pi^2 s_W^2} \frac{M_H^3}{M_W^2} \mid 7 - \frac{16}{9} + \ldots \mid^2$$

*limits are small M_h limit

W top



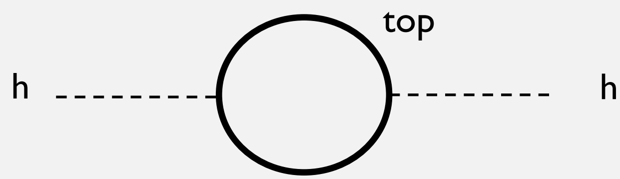




Loops imply sensitivity to new physics

WHY DO WE EXPECT SOMETHING NEW IN THE HIGGS SECTOR?

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



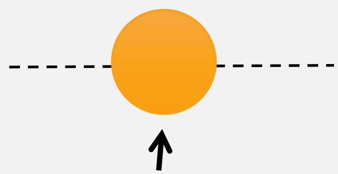
$$\delta M_h^2 = -\frac{3M_t^2}{8\pi^2 v^2}\Lambda^2$$

- Λ is the largest mass scale in the theory, maybe $M_{planck} = 10^{18}$ 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?

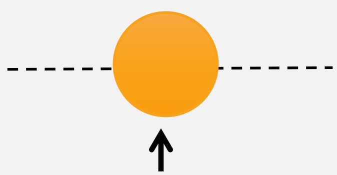
- Generically, solutions to ***naturalness*** involve new particles



SM particles

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

Λ is scale of new physics



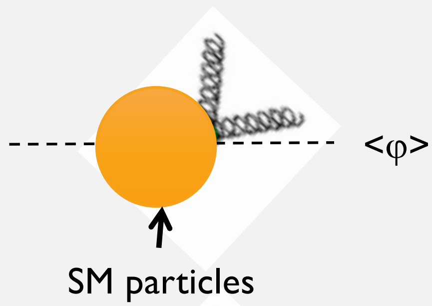
New stuff

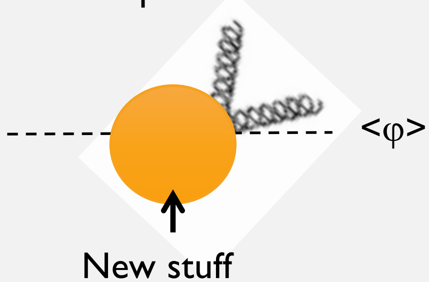
$$\delta M_h^2 \sim +(125\ GeV)^2 \left(\frac{\Lambda}{M_{new}}\right)^2$$

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 $h \to gg$, $h \to \gamma\gamma$