THE STANDARD MODEL HIGGS

EXAMPLE WAS LOCAL $U(1)$

STANDARD MODEL $U(1)_Y \times SU(2)_L$

→ PHYSICALLY HAVE 3 MASSIVE GAUGE BOSON

→ 3 GOLDSTONE BOSONS TO PROVIDE LONGITUDINAL DEGREES OF FREEDOM FOR W^+ W^- Z^0

→ AT LEAST ONE MASSIVE SCALAR GENERATED BY SPONTANEOUS CHOICE OF VACUUM

→ HIGGS

SIMPLEST POSSIBILITY — WHICH NATURE SEEMS TO CHOOSE.

2 COMPLEX SCALAR FIELDS

NEUTRAL GAUGE BOSON — ϕ^0

+VE GAUGE BOSON — ϕ^+

-VE GAUGE BOSON — $(\phi^+)^* = \phi^-$

WEAK ISOSPIN DOUBLETS ARE ALL THE PARTICLES SEEN BY $SU(2)_L$, PUT ϕ IN WK ISOSPIN DOUBLET

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

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi) \quad ; \quad V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

$\mu^2 < 0 \longrightarrow$ DEGENERATE MINIMA

$$\phi^\dagger\phi = \frac{1}{2}\left(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right) = \frac{v^2}{2} = -\frac{\mu^2}{2\lambda}$$

AFTER SYMMETRY BREAKING m_γ STILL 0

↳ MINIMUM OF POTENTIAL ONLY HAS VEV $\neq 0$ FOR NEUTRAL SCALAR FIELD ϕ^0

$$\langle 0|\phi|0\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$$

AGAIN EXPAND AROUND THIS MINIMUM

$$\phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1(x) + i\phi_2(x) \\ v + \eta(x) + i\phi_4(x) \end{pmatrix}$$

EXCURSION FROM MINIMUM

cf $\phi = \frac{1}{\sqrt{2}}\left(\eta + v + i\xi\right)$ IN 1-D CASE

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1(x) + i\phi_2(x) \\ v + \eta(x) + i\phi_4(x) \end{pmatrix}$$

AGAIN VACUUA ARE DEGENERATE

CAN CHOOSE WHICH TO EXPAND AROUND

CHOOSE $\phi_1 = \phi_2 = \phi_4 = 0$; $\phi_3^2 = -\frac{\mu^2}{\lambda} = v^2$

EXPAND ABOUT $\phi_0 = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

GET $\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$ ← ALREADY IN UNITARY GAUGE

IN COMPLEX SCALAR CASE

$$\phi(x) = \frac{1}{\sqrt{2}} (\eta + v + i\xi) \xrightarrow[\text{GAUGE}]{\text{UNITARY}} \phi(x) = \frac{1}{\sqrt{2}} (\eta + v)$$

↑ GOLDSTONE BOSON

PUT $\phi(x) \longrightarrow$ INTO LAGRANGIAN

IMPOSE LOCAL $SU(2)_L \times U(1)_Y$ BY

$$\partial_\mu \longrightarrow D_\mu = \partial_\mu + i g_W \bar{T} \cdot \bar{W}_\mu + i g' \frac{Y}{2} B_\mu \qquad \bar{T} = \frac{\bar{\sigma}}{2}$$

$SU(2)_L$ $\qquad$ $U(1)_Y$

REMEMBER $Y = 2(Q - I_W^{(3)})$

$$\phi(x) = \begin{pmatrix} \phi^{\pm} \\ \phi_0 \end{pmatrix} \qquad I_W^{(3)} = -\frac{1}{2} \longrightarrow Y_{TOTAL} = 1$$

SO $$D_\mu \phi = \frac{1}{2}\left[2\partial_\mu + \left(i g_W \bar{\sigma} \cdot \bar{W}_\mu + i g' B_\mu\right)\right]\phi$$

2×2

$$\partial_\mu \equiv \partial_\mu \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

GAUGE BOSON MASSES $\rightarrow (D_\mu \phi)^\dagger (D^\mu \phi)$

$$D_\mu \phi = \frac{1}{2\sqrt{2}} \begin{pmatrix} 2\partial_\mu + i g_W W_\mu^{(3)} + i g' B_\mu & i g_W \left[W_\mu^{(1)} - i W_\mu^{(2)} \right] \\ i g_W \left[W_\mu^{(1)} + i W_\mu^{(2)} \right] & 2\partial_\mu - i g_W W_\mu^{(3)} + i g' B_\mu \end{pmatrix} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$$(D_\mu \phi)^\dagger (D_\mu \phi) = \frac{1}{2} (\partial_\mu h)(\partial^\mu h)$$
$$+$$
$$\frac{1}{8} g_W^2 \left(W_\mu^{(1)} + i W_\mu^{(2)} \right)\left(W_\mu^{(1)} - i W_\mu^{(2)} \right)(v+h)^2$$
$$+$$
$$\frac{1}{8} \left(g_W W_\mu^{(3)} - g' B_\mu \right)\left(g_W W_\mu^{(3)} - g' B^\mu \right)(v+h)^2$$

TERMS QUADRATIC IN FIELDS $\rightarrow$ GAUGE BOSON MASSES

QUADRATIC TERMS ARE:

$$\frac{1}{8} v^2 g_w^2 \left(W^{(1)}_\mu W^{(1)}_\mu + W^{(2)}_\mu W^{(2)\mu} \right) \qquad W^{+-}$$

$$+$$

$$\frac{1}{8} v^2 \left(g_w W^{(3)}_\mu - g' B_\mu \right)\left(g_w W^{(3)\mu} - g' B^\mu \right) \qquad \gamma, Z^0$$

MASS TERMS FOR $W^{(1)}$ $W^{(2)}$ IN LAGRANGIAN

$$\frac{1}{2} m_w^2 W^{(1)}_\mu W^{(1)\mu} \qquad \frac{1}{2} m_w^2 W^{(2)}_\mu W^{(2)\mu}$$

$$m_w = \frac{1}{2} g_w v$$

HIGG VEV

SU(2)$_L$
COUPLING

$$\frac{1}{8} v^2 \left(g_W W^{(3)}_\mu - g' B_\mu\right)\left(g_W W^{(3)\mu} - g' B^\mu\right)$$

$$= \frac{v^2}{8} \begin{pmatrix} W^{(3)}_\mu & B_\mu \end{pmatrix} \underbrace{\begin{pmatrix} g_W^2 & -g_W g' \\ -g_W g' & g'^2 \end{pmatrix}}_{M} \begin{pmatrix} W^{(3)}_\mu \\ B^\mu \end{pmatrix}$$

$M \rightarrow$ MASS MATRIX
MIXES $W^{(3)}$ B

PHYSICAL STATES → PROPAGATE INDEPENDENTLY
→ EIGENSTATES OF HAMILTONIAN
→ BASIS STATES OF DIAGONAL MASS MATRIX

GET EIGENVALUES $\det(M - \lambda I) = 0$

$$\det(M - \lambda I) = 0$$

$$(g_W^2 - \lambda)(g'^2 - \lambda) - g_W^2 g'^2 = 0$$

SOLUTIONS $\lambda = 0$, $\lambda = g_W^2 + g'^2$

DIAGONAL BASIS $\frac{1}{8} v^2 (A_\mu, Z_\mu) \begin{pmatrix} 0 & 0 \\ 0 & g_W^2 + g'^2 \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix}$

TERM IN LAGRAGIAN $\frac{1}{2} (A_\mu, Z_\mu) \begin{pmatrix} m_A^2 & 0 \\ 0 & m_Z^2 \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix}$

$$\underset{\downarrow \, \gamma}{m_A = 0} \qquad \underbrace{m_Z = \frac{1}{2} v \sqrt{g_W^2 + g'^2}}_{\downarrow \, Z^0}$$

PHYSICAL FIELDS → NORMALIZED EIGENVECTORS

$$A_\mu = \frac{g' W_\mu^{(3)} + g_W B_\mu}{\sqrt{g_W^2 + g'^2}} \quad , \quad m_A = 0$$

$$Z_\mu = \frac{g_W W_\mu^{(3)} - g' B_\mu}{\sqrt{g_W^2 + g'^2}} \quad , \quad m_Z = \frac{1}{2} v \sqrt{g_W^2 + g'^2}$$

PHYSICAL FIELDS → MIXTURE OF MASSLESS BOSONS OF $SU(2)_L \times B_Y(1)$

$$\frac{g'}{g_W} = \tan\theta_W$$

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

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

$$\left.\begin{aligned} m_Z &= \frac{1}{2}\frac{g_W}{\cos\theta_W}\cdot v \\ m_W &= \frac{1}{2} g_W v \end{aligned}\right\} \quad \frac{m_W}{m_Z} = \cos\theta_W$$

GSW 4 PARAMETERS $\quad g_W, g', \mu, \lambda$

$v^2 = -\dfrac{\mu^2}{\lambda}$, $\quad m_H^2 = 2\lambda v \longrightarrow$ GET λ

$\hookrightarrow m_W = \frac{1}{2} g_W v \rightarrow v = 246$

KNOWN $\qquad$ KNOWN

COUPLINGS OF HIGGS TO GAUGE BOSONS

$$\left(D_\mu \phi\right)^\dagger \left(D_\mu \phi\right) = \frac{1}{2}(\partial_\mu h)(\partial^\mu h)$$

$$+$$

$$\frac{1}{8} g_W^2 \left(W_\mu^{(1)} + i W_\mu^{(2)}\right)\left(W_\mu^{(1)} - i W_\mu^{(2)}\right)(v+h)^2$$

$$+$$

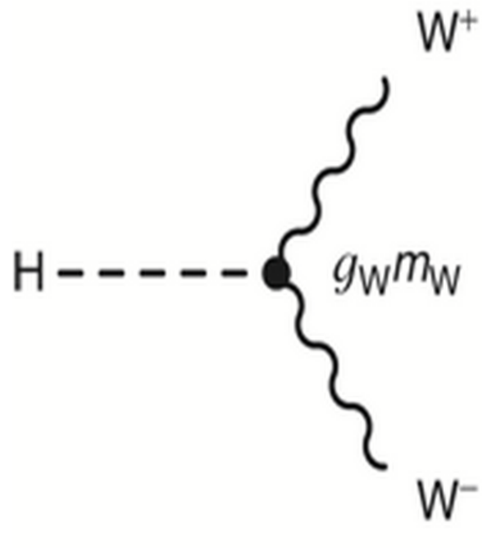
$$\frac{1}{8}\left(g_W W_\mu^{(3)} - g' B_\mu\right)\left(g_W W_\mu^{(3)} - g' B^\mu\right)(v+h)^2$$

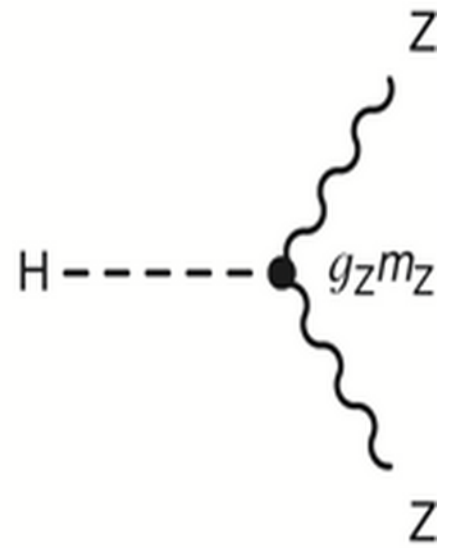
IN THIS TERM OF THE LAGRANGIAN, THE GAUGE BOSON FIELDS APPEAR AS $VV(v+h)^2$, $V = Z$ or W

THE VVh AND $VVhh$ $\rightarrow$ Higgs $\leftrightarrow$ V COUPLINGS

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

PHYSICAL FIELDS, REWRITE IN TERMS OF PHYSICAL FIELDS





$$\frac{1}{2} g_w^2 \, W^-_\mu W^{+\mu} (v+h)^2 =$$

$$\frac{1}{4} g_w^2 v^2 W^-_\mu W^{\mu +} + \overbrace{\frac{1}{2} g_w^2 v}^{g_w m_w} \, W^-_\mu W^{+\mu} h + \frac{1}{4} g_w^2 \, W^-_\mu W^{\mu +} h h$$

W MASS

TRIPLE COUPLING

QUARTIC COUPLING

$$g_{HWW} = \frac{1}{2} g_w^2 v = g_w m_w$$

$\frac{1}{4} g_w^2$

FERMION MASSES

HIGGS FOR $U(1)_Y \otimes SU(2)_L$ SPONTANEOUS SYMMETRY BREAKING GENERATES W, Z MASSES. AMAZINGLY ENOUGH IT ALSO GENERATES THE MASSES OF THE FERMIONS.

LEFT HANDED AND RIGHT HANDED CHIRAL STATES HAVE DIFFERENT TRANSFORMATIONS.

MASS TERM

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

IS NOT INVARIANT UNDER $SU(2)_L \otimes U(1)_Y$

→ SO IT CANNOT APPEAR IN A GAUGE INVARIANT LAGRANGIAN.

SO → HOW TO INCLUDE FERMION MASSES?

THEY CERTAINLY DO HAVE MASSES.

IN STANDARD MODEL

HIGGS $\phi(x) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

LH CHIRAL FERMIONS $\rightarrow \begin{pmatrix} f_u \\ f_d \end{pmatrix}_L$ DOUBLET.

RH CHIRAL FERMIONS $\rightarrow f_R$ SINGLET

INFINITESIMAL $SU(2)$

$$\left.\begin{array}{l} e^{i\bar{\varepsilon}\cdot\bar{T}} \\ \rightarrow 1 + i\bar{\varepsilon}\bar{T} \end{array}\right\} \rightarrow \quad \phi \rightarrow \phi' = \left(I + i g_w \bar{\varepsilon}(x)\cdot\bar{T}\right)\phi$$

SMALL

THIS WORKS FOR L FIELDS

FOR $\bar{L} = L^+\gamma^0$

$$\bar{L} \rightarrow \bar{L}' = \bar{L}\left(I - i g_w \bar{\varepsilon}(x)\cdot\bar{T}\right)$$

$\bar{L}\phi$ INVARIANT UNDER $SU(2)_L$

$\bar{L}\phi$ INVARIANT UNDER $SU(2)_L$

$\bar{L}\phi R \to$ INVARIANT UNDER $SU(2)_L$ AND $U(1)_Y$

$(\bar{L}\phi R)^{\dagger} = \bar{R}\phi^{\dagger} L$ ALSO INVARIANT.

SO, A TERM IN THE LAGRANGIAN LIKE

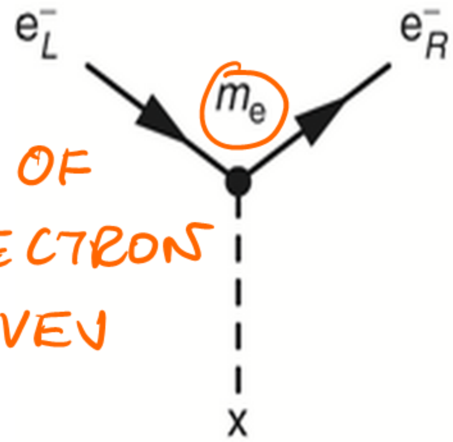
$-g_f(\bar{L}\phi R + \bar{R}\phi^{\dagger}L)$ INVARIANT UNDER $SU(2)_L \otimes U(1)_Y$

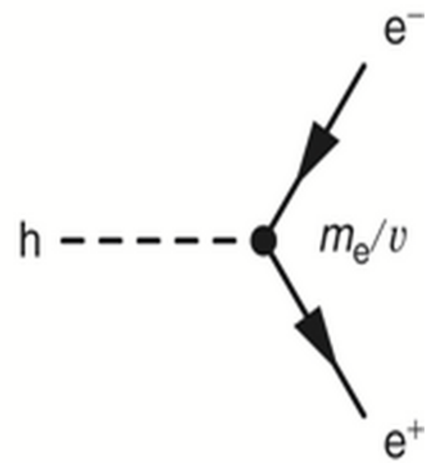
FOR THE ELECTRON DOUBLET $\begin{pmatrix}\nu_e \\ e\end{pmatrix}$

$$\mathcal{L}_e = -g_e\left[(\bar{\nu}_e\ \bar{e})_L\begin{pmatrix}\phi^{+} \\ \phi_0\end{pmatrix}e_R + \bar{e}_R(\phi^{+*}\ \phi^{0*})\begin{pmatrix}\nu_e \\ e\end{pmatrix}_L\right]$$

COUPLING OF ELECTRON FIELD TO HIGGS FIELD } YUKAWA COUPLING

INTERACTION OF MASSLESS ELECTRON WITH Higgs VEV





INTERACTION OF HIGGS BOSON WITH ELECTRON

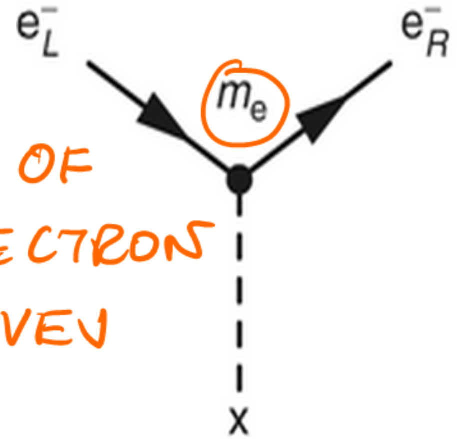
AFTER SPONTANEOUS SYMMETRY BREAKING, THE HIGGS DOUBLET IN THE UNITARY GAUGE IS:

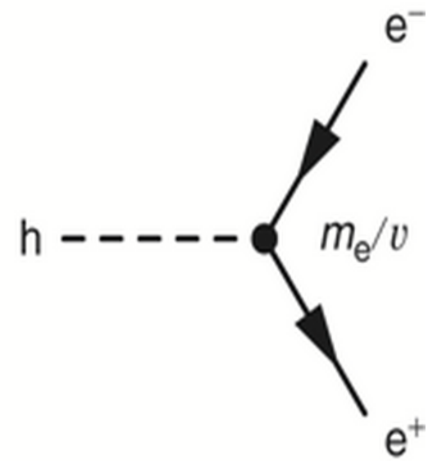
$$\phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

SO $\mathcal{L}_e$ BECOMES

$$\mathcal{L}_e = -\frac{g_e}{\sqrt{2}} v \left(\bar{e}_L e_R + e_R \bar{e}_L\right) - \frac{g_e}{\sqrt{2}} h \left(\bar{e}_L e_R + \bar{e}_R e_L\right)$$

INTERACTION OF MASSLESS ELECTRON WITH HIGGS VEV





INTERACTION OF HIGGS BOSON WITH ELECTRON

$$\mathcal{L}_e = \underbrace{-\frac{g_e}{\sqrt{2}} v\left(\bar{e}_L e_R + e_R \bar{e}_L\right)}_{\text{FERMION MASSES HIGGS VEV}} \underbrace{- \frac{g_e}{\sqrt{2}} h\left(\bar{e}_L e_R + \bar{e}_R e_L\right)}_{\text{COUPLING BETWEEN HIGGS AND ELECTRON}}$$

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

VEV IS HERE $\rightarrow$ SO $\left(\bar{L}\phi R + \bar{R}\phi^\dagger L\right)$

CAN ONLY GENERATE MASSES FOR 'DOWN' TYPE QUARKS

WHAT ABOUT "UP"-TYPE QUARKS?

CONSTRUCT "CONJUGATE" DOUBLET. ϕ_c

$$\phi_c = -i\sigma_2\,\phi^* = \begin{pmatrix} -\phi^{0*} \\ \phi^- \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} -\phi_3 + i\phi_4 \\ \phi_1 - i\phi_2 \end{pmatrix}$$

TRANSFORMS UNDER $SU(2)_L$ EXACTLY SAME WAY AS ϕ

GAUGE INVARIANT MASS TERM FOR "UP" TYPE QUARKS USING $\bar{L}\phi_c R + \bar{R}\phi_c^+ L$

$$\mathcal{L}_u = g_u\,(\bar{u}\ \bar{d})_L \begin{pmatrix} -\phi^{0*} \\ \phi^- \end{pmatrix} u_R \ + \ \text{HERMITIAN CONJUGATE}$$

$$\mathcal{L}_u = g_u (\bar{u}\ \bar{d})_L \begin{pmatrix} -\phi^{0*} \\ \phi^- \end{pmatrix} u_R \ + \ \text{HERMITIAN CONJUGATE}$$

AFTER SYMMETRY BREAKING THIS BECOMES:

$$\mathcal{L}_u = -\frac{g_u}{\sqrt{2}} v (\bar{u}_L u_R + \bar{u}_R u_L) - \frac{g_u}{\sqrt{2}} h (\bar{u}_L u_R + \bar{u}_R u_L)$$

YUKAWA COUPLING $\quad g_u = \dfrac{\sqrt{2}\, m_u}{v}$

$$\mathcal{L}_u = -m_u (\bar{u} u) - \frac{m_u}{v} (\bar{u} u) h$$

ALL FERMION MASS TERMS FOR EITHER

$$\mathcal{L} = -g_f \left[\bar{L} \phi R + (\bar{L} \phi R)^+ \right] \quad \text{OR} \quad \mathcal{L} = g_f \left[\bar{L} \phi_c R + (\bar{L} \phi_c R)^+ \right]$$

$$g_f = \sqrt{2}\, \frac{m_f}{v}$$

$$g_f = \sqrt{2}\,\frac{m_f}{v}$$ ← VACUUM EXPECTATION VALUE

$v = 246$ GeV

$m_t = 173.5$

$g_f = 0.997423$

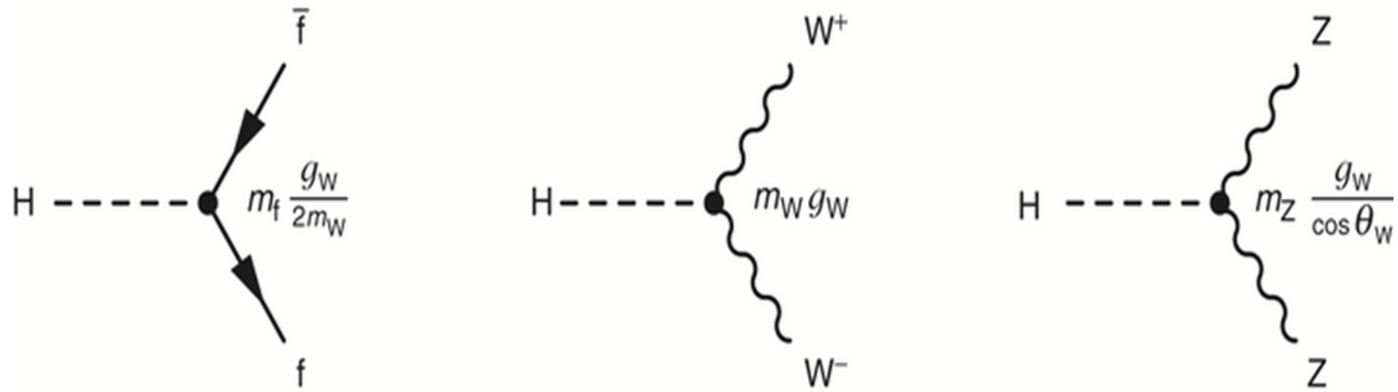
THIS LOOKS LIKE 1.0 TO ME — WHY?

IS THERE SOME OTHER CONNECTION BETWEEN THE HIGGS AND t-QUARK?

NEUTRINO MASS SO SMALL – $g_\nu \sim 10^{-12}$

→ SEESAW

HIGGS DECAY

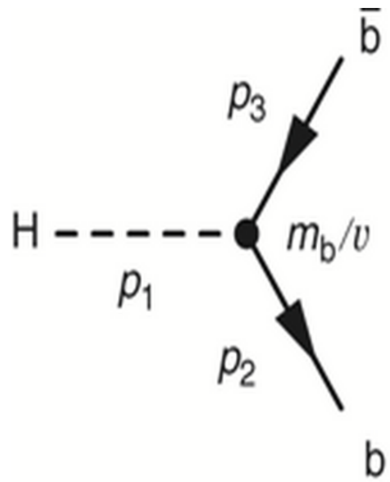


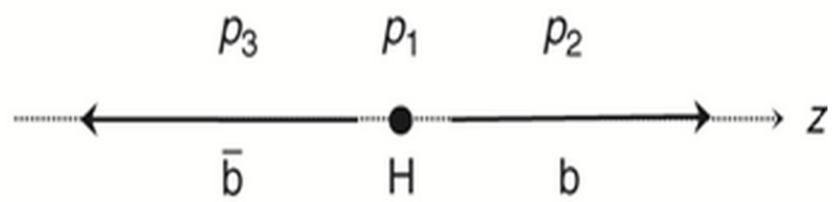
INTERACTION VERTEX $\quad -i\frac{m_f}{v} = -i\frac{m_f}{2m_W}\cdot g_W$

HIGGS CAN DECAY $\quad H \to f\bar{f}\,, \quad m_f < 2m_H$

$H \to WW, ZZ\,, \quad 2m_V < m_H$

$$H \to b\bar{b}$$





B-QUARK IS HEAVIEST QUARK HIGGS CAN DECAY TO

SPINOR

$$\mathcal{M} = \frac{m_b}{v}\,\bar{u}(p_2)\,v(p_3) = \frac{m_b}{v}\,u^{+}\gamma^{0}v$$

VEV

$$p_2 = (E, 0, 0, E) \qquad E = \frac{m_H}{2}$$

$$p_3 = (E, 0, 0, -E)$$

$$u_\uparrow(p_2) = \sqrt{E}\begin{pmatrix}1\\0\\1\\0\end{pmatrix}, \quad u_\downarrow(p_2) = \sqrt{E}\begin{pmatrix}0\\1\\0\\-1\end{pmatrix}$$

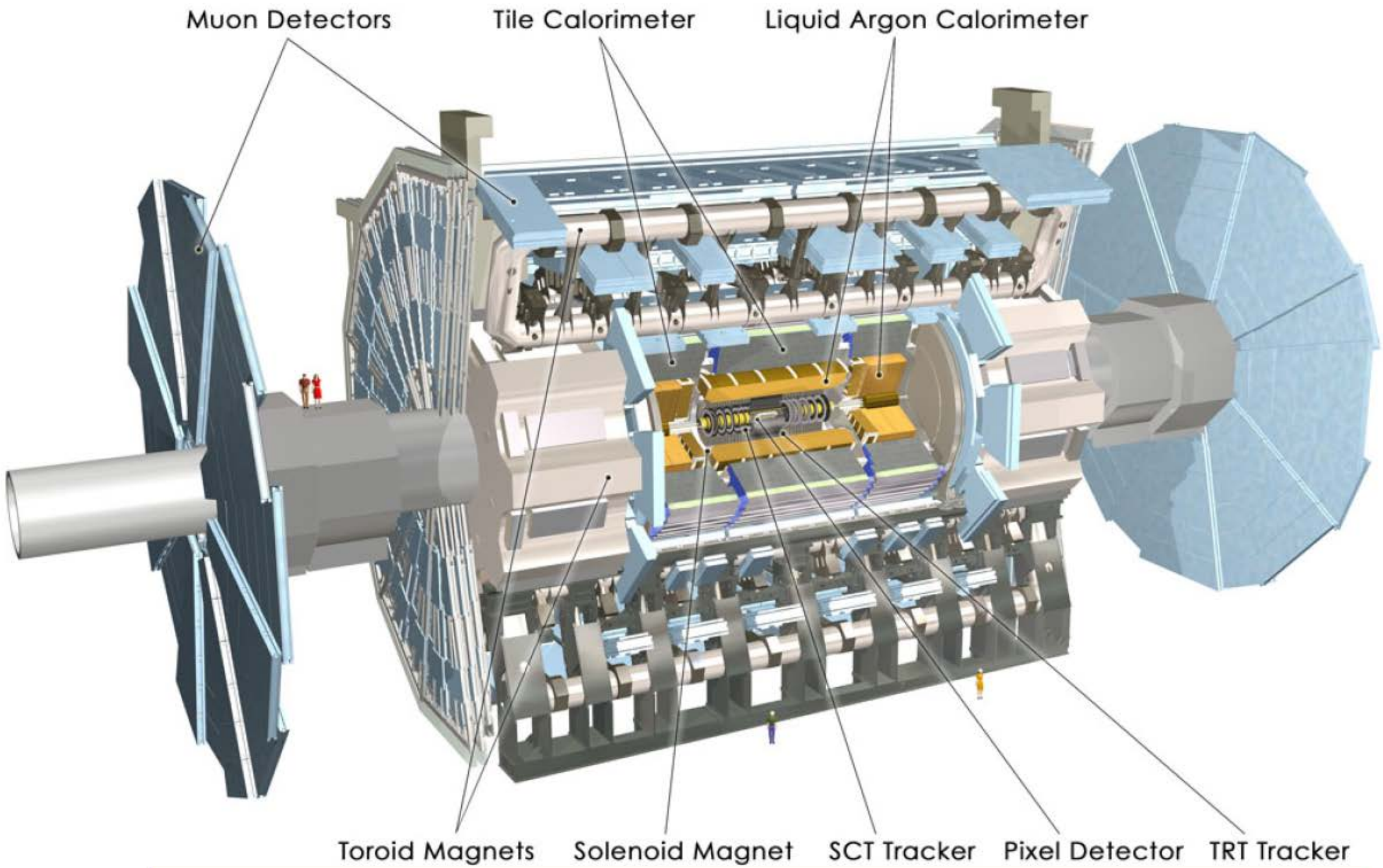
$$v_\uparrow(p_3) = \sqrt{E}\begin{pmatrix}1\\0\\-1\\0\end{pmatrix}, \quad v_\downarrow(p_4) = \begin{pmatrix}0\\-1\\0\\-1\end{pmatrix}$$

NONZERO $\mathcal{M}_{\uparrow\uparrow} = -\mathcal{M}_{\downarrow\downarrow} = \frac{m_b}{v}\cdot 2E$

$b\bar{b} \to$ SPIN 0

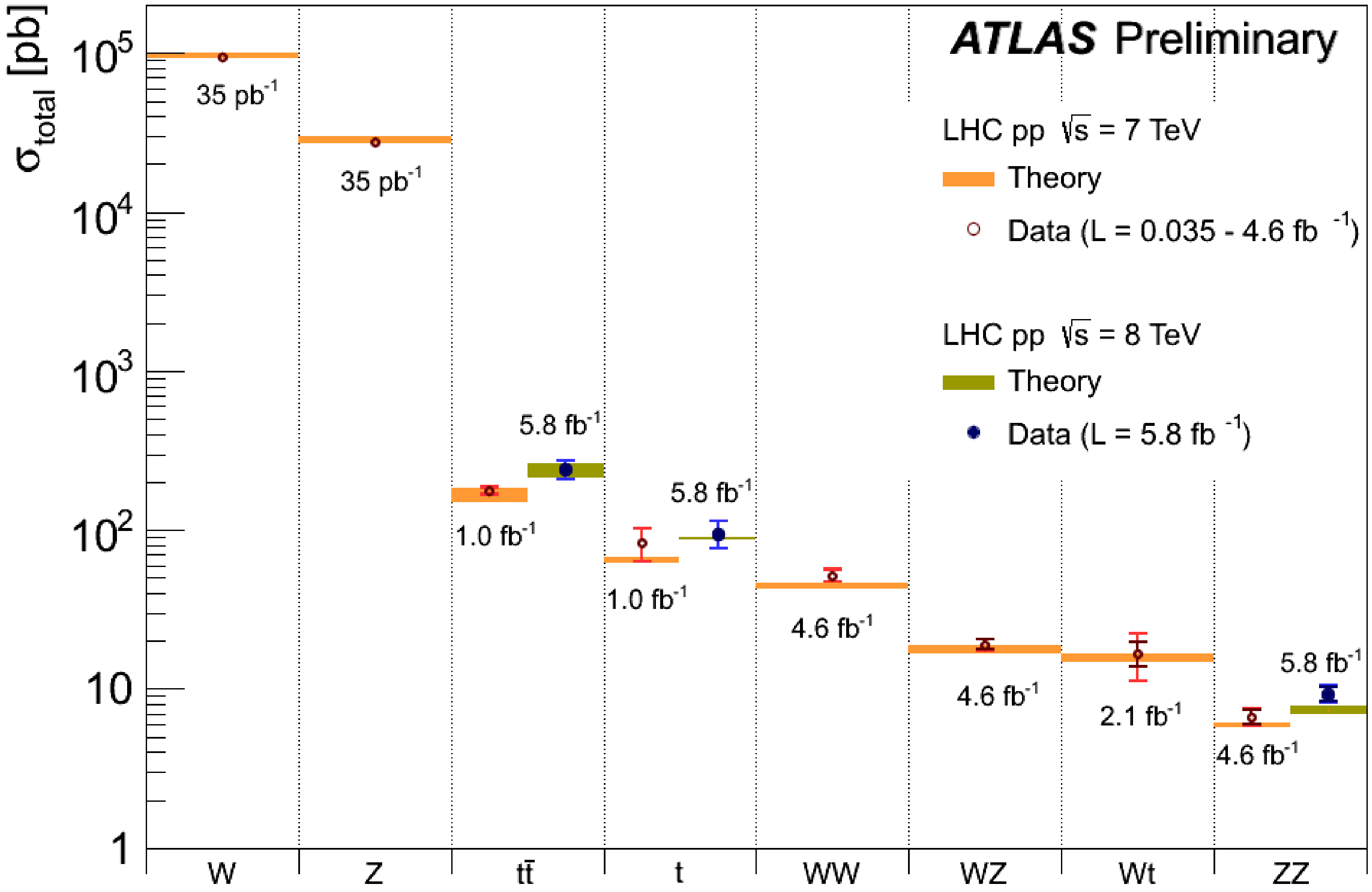
$$\langle|\mathcal{M}|^2\rangle = |\mathcal{M}_{\uparrow\uparrow}|^2 + |\mathcal{M}_{\downarrow\downarrow}|^2 = \frac{m_b^2}{v^2} 8E^2 = \frac{2m_b^2 m_H^2}{v^2}$$

$$\Gamma(H \to b\bar{b}) = 3 \times \frac{m_b^2 m_H}{8v^2}$$



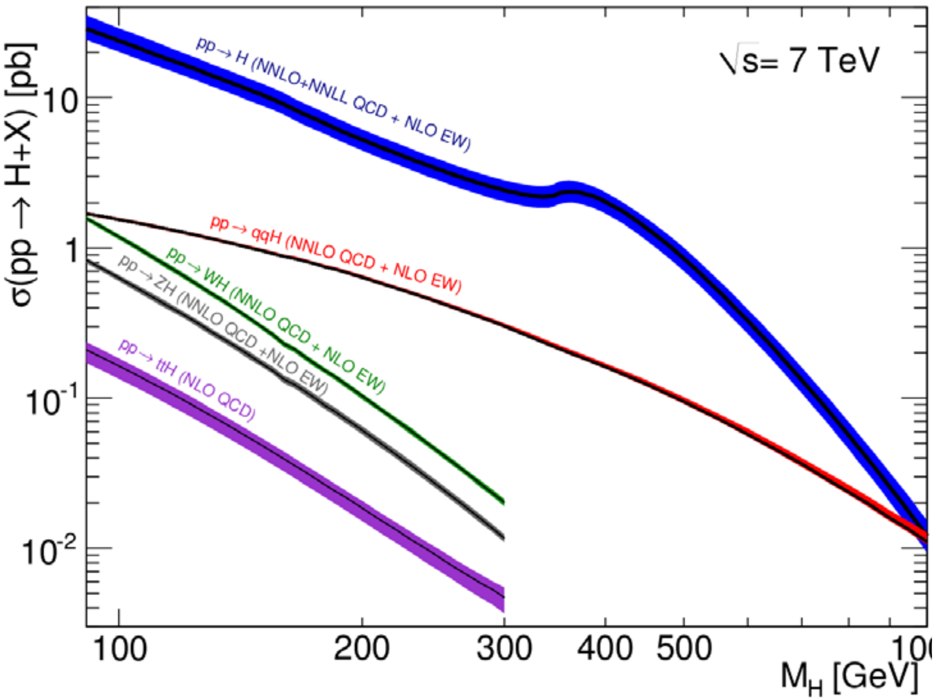
ATLAS p-p run: April-Sept. 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.3	99.5	97.0	99.6	99.9	99.8	99.9	99.9	99.7	99.2
All good for physics: 93.7%										

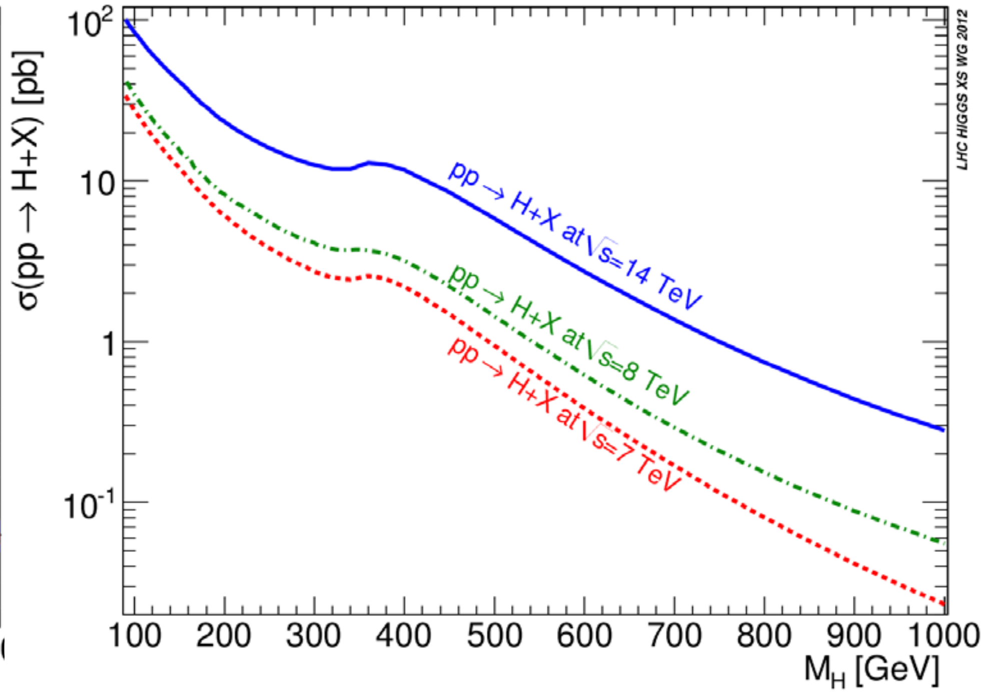
Standard Model Cross Sections

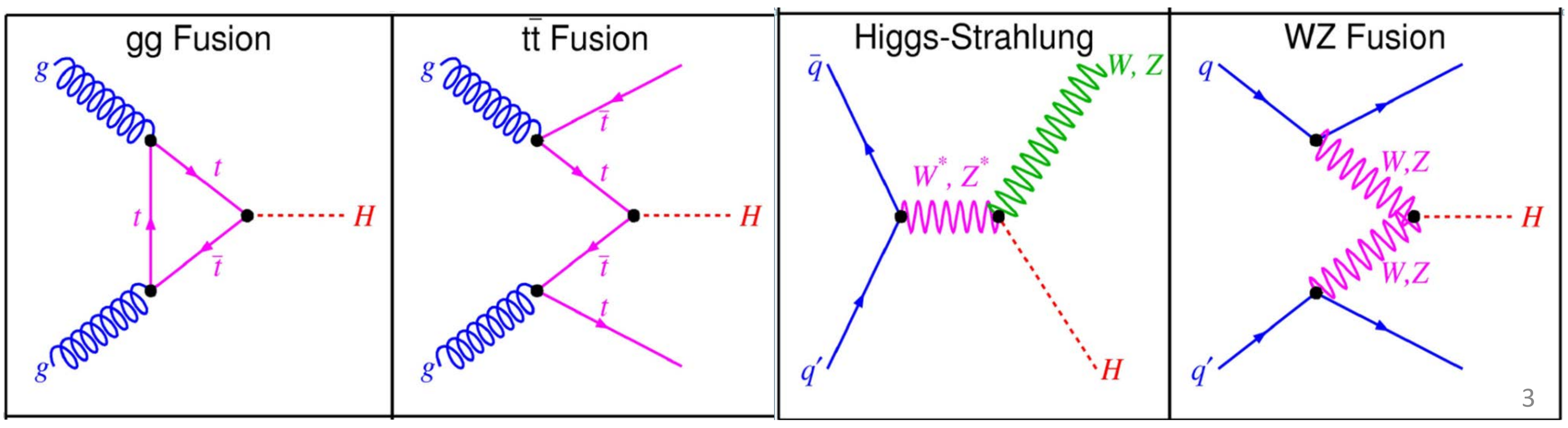


- Higgs cross section in observable modes

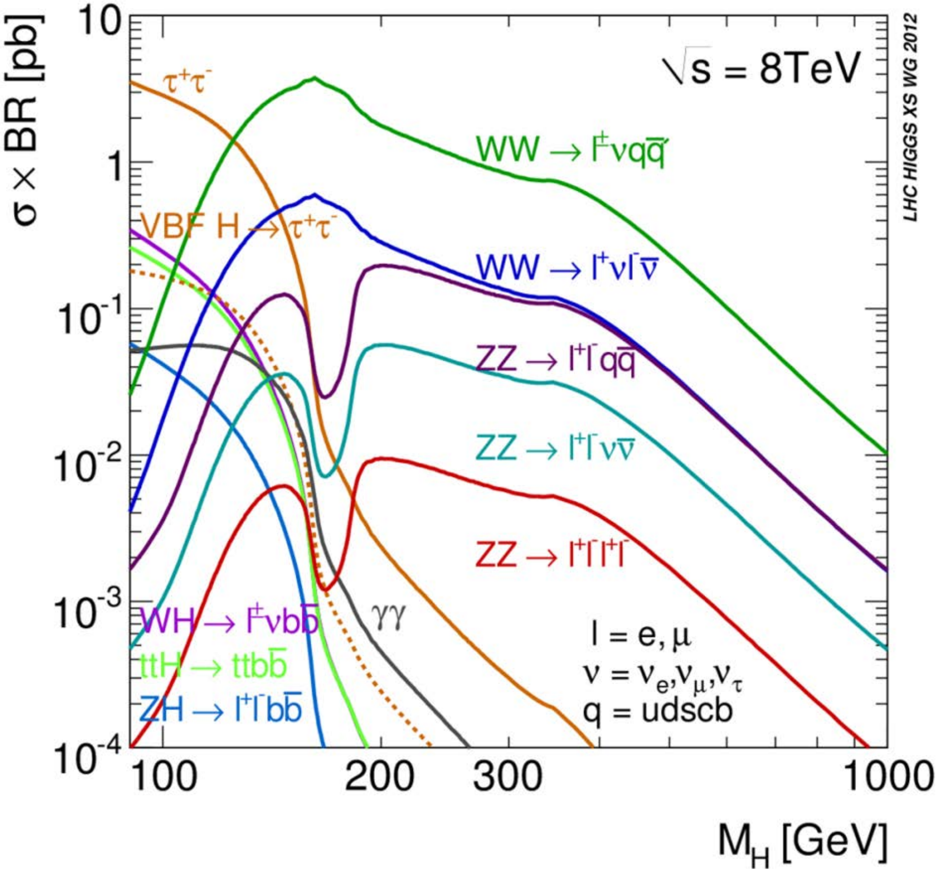
Production Mechanisms

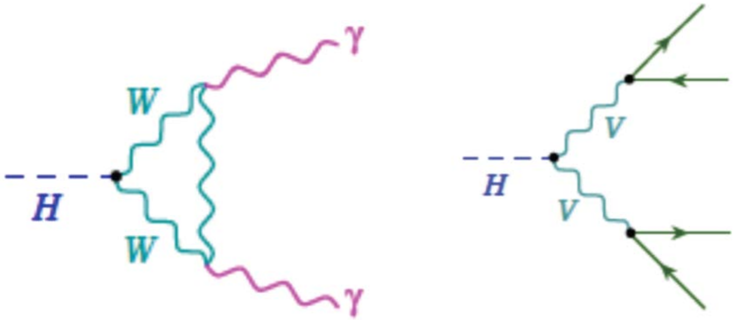


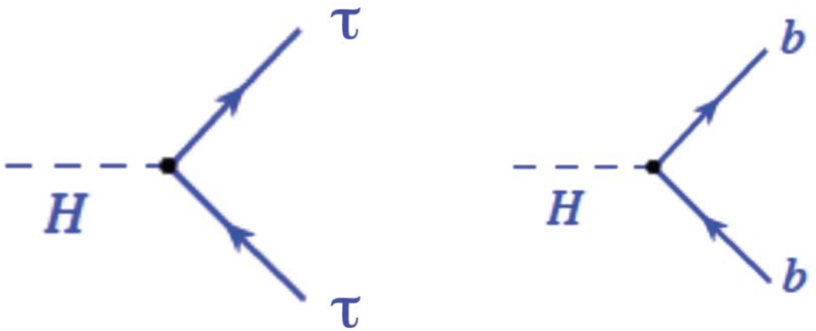




Decay Mechanisms



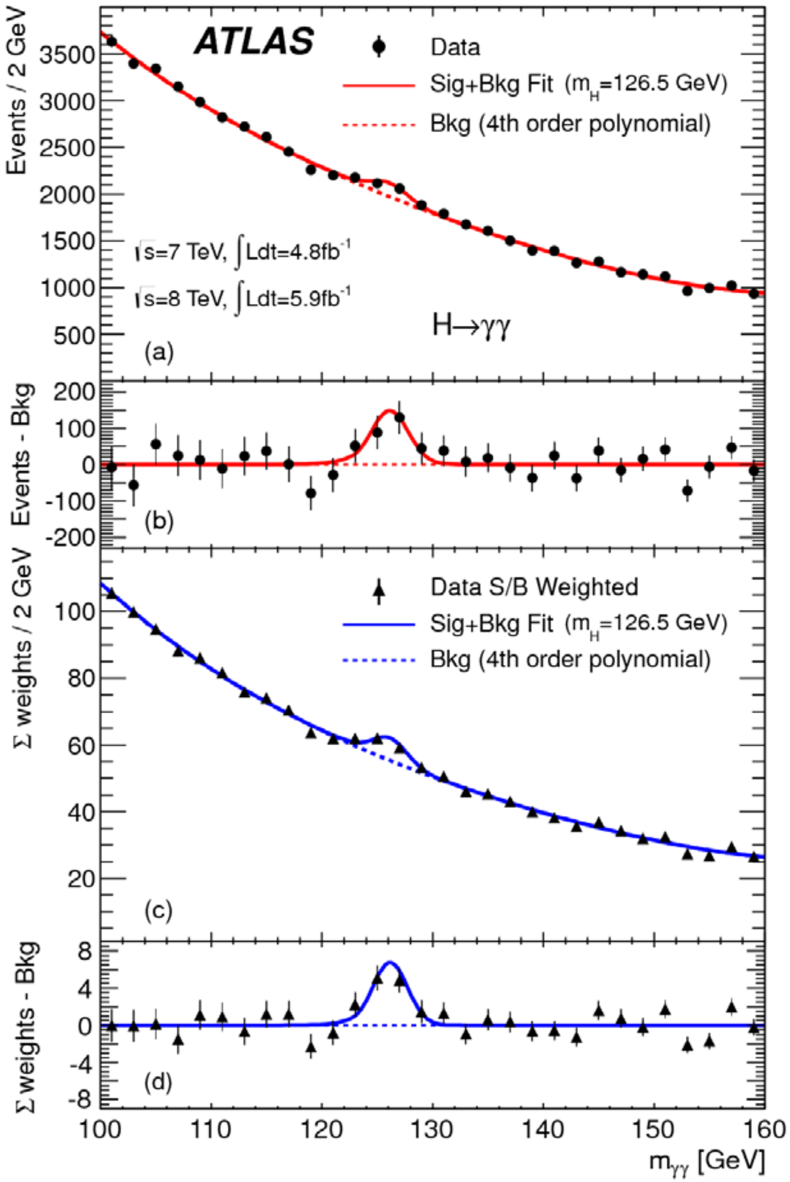


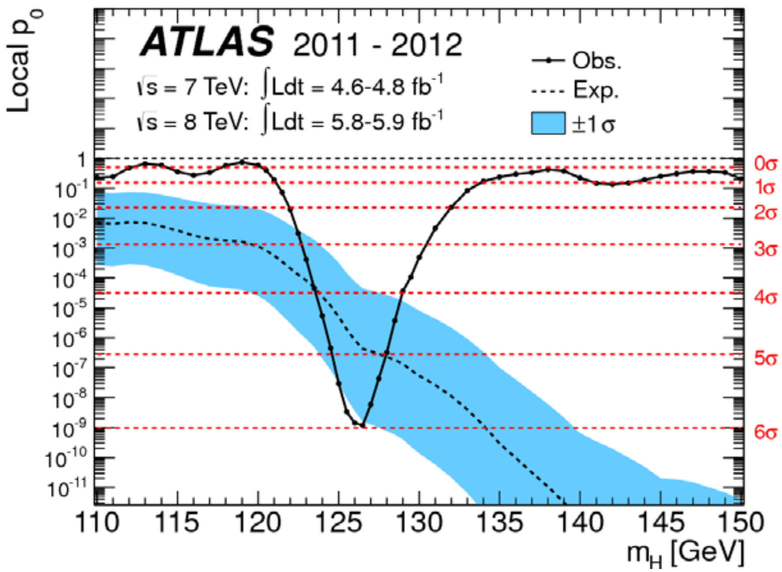


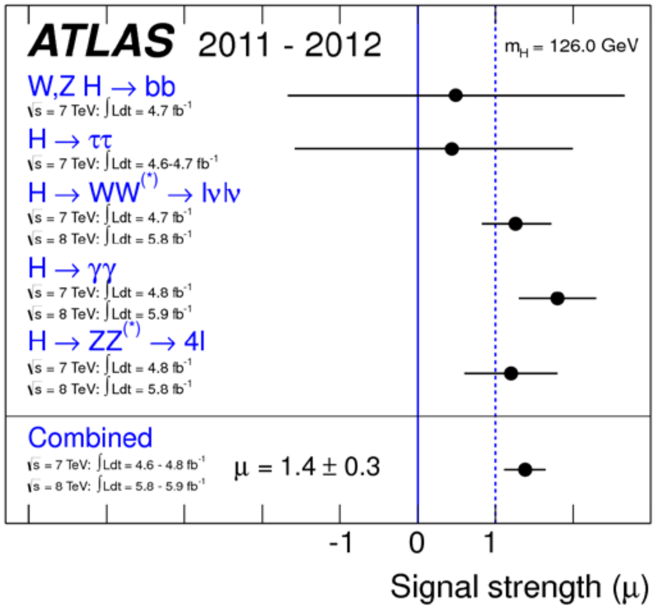
- Bosons
- Fermions

Memoire on Discovery

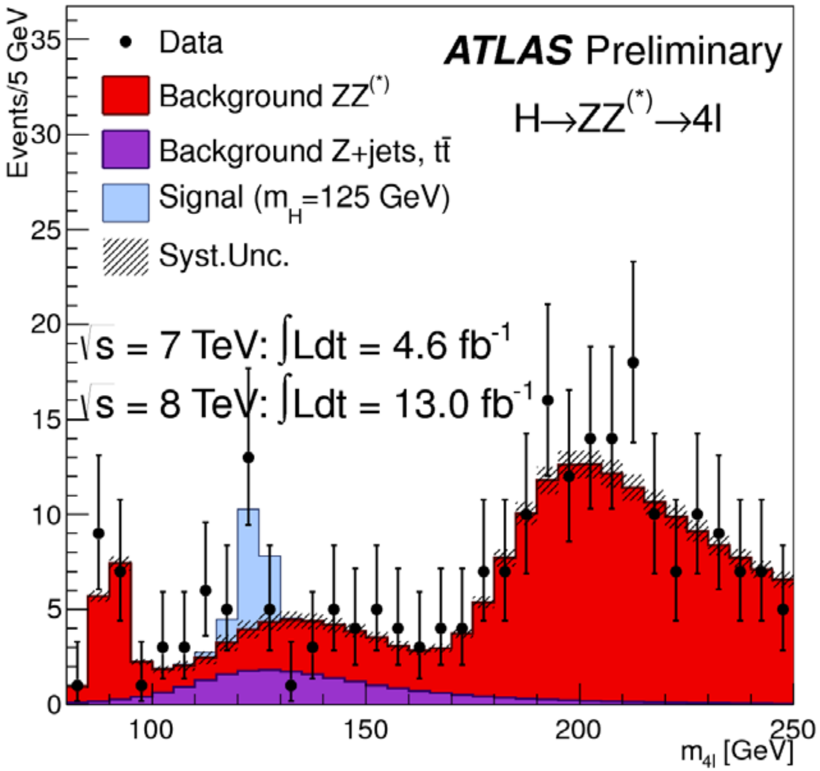
Phys. Lett. B (2012) 1-29. July 2012

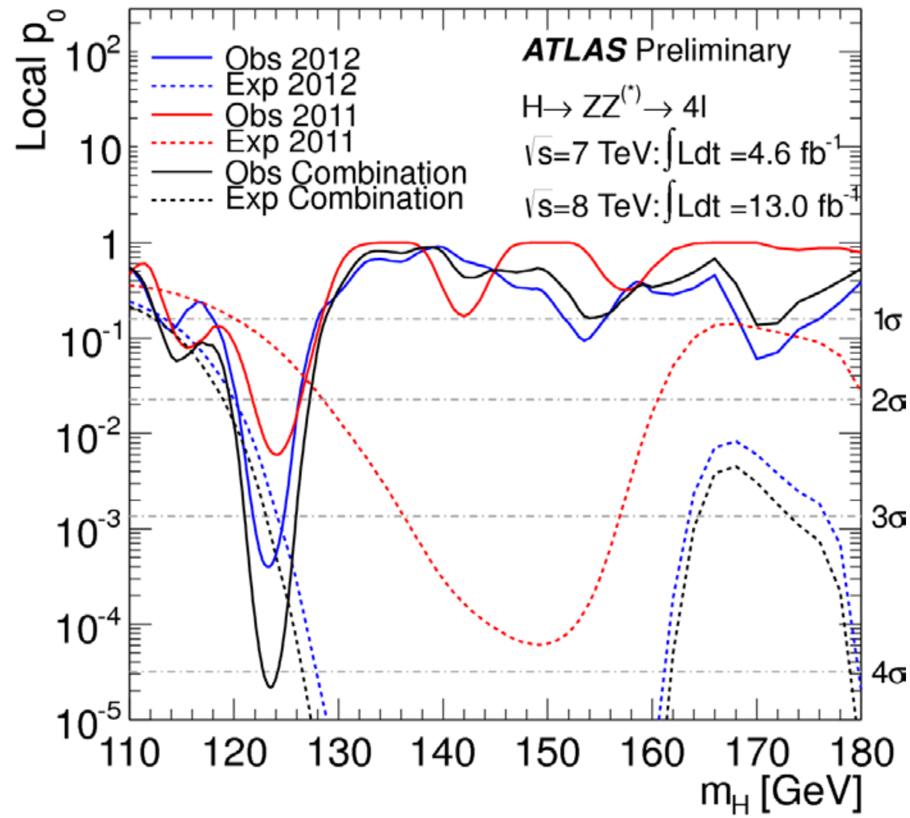






$H \to ZZ^{(*)} \to 4l$

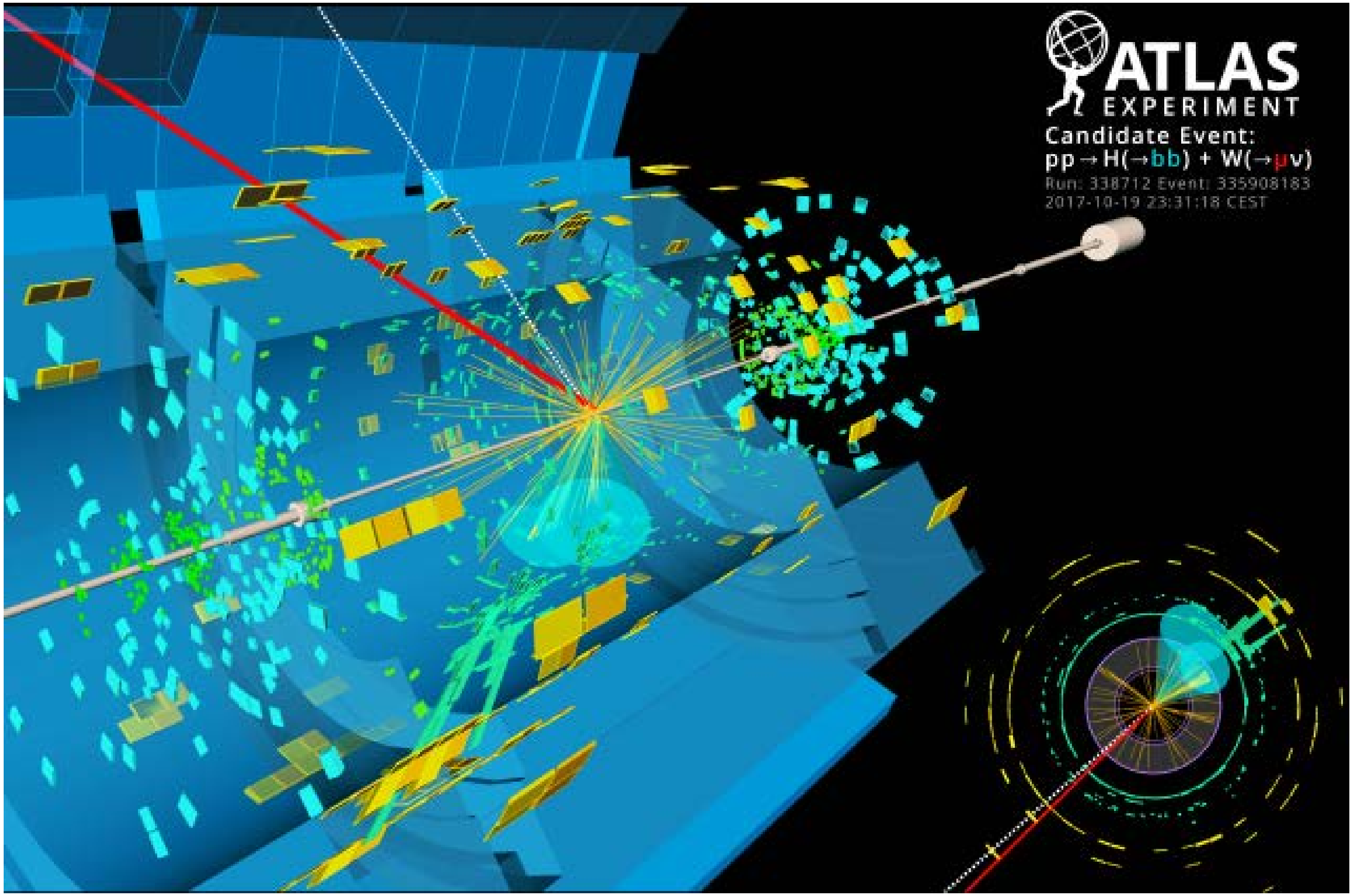




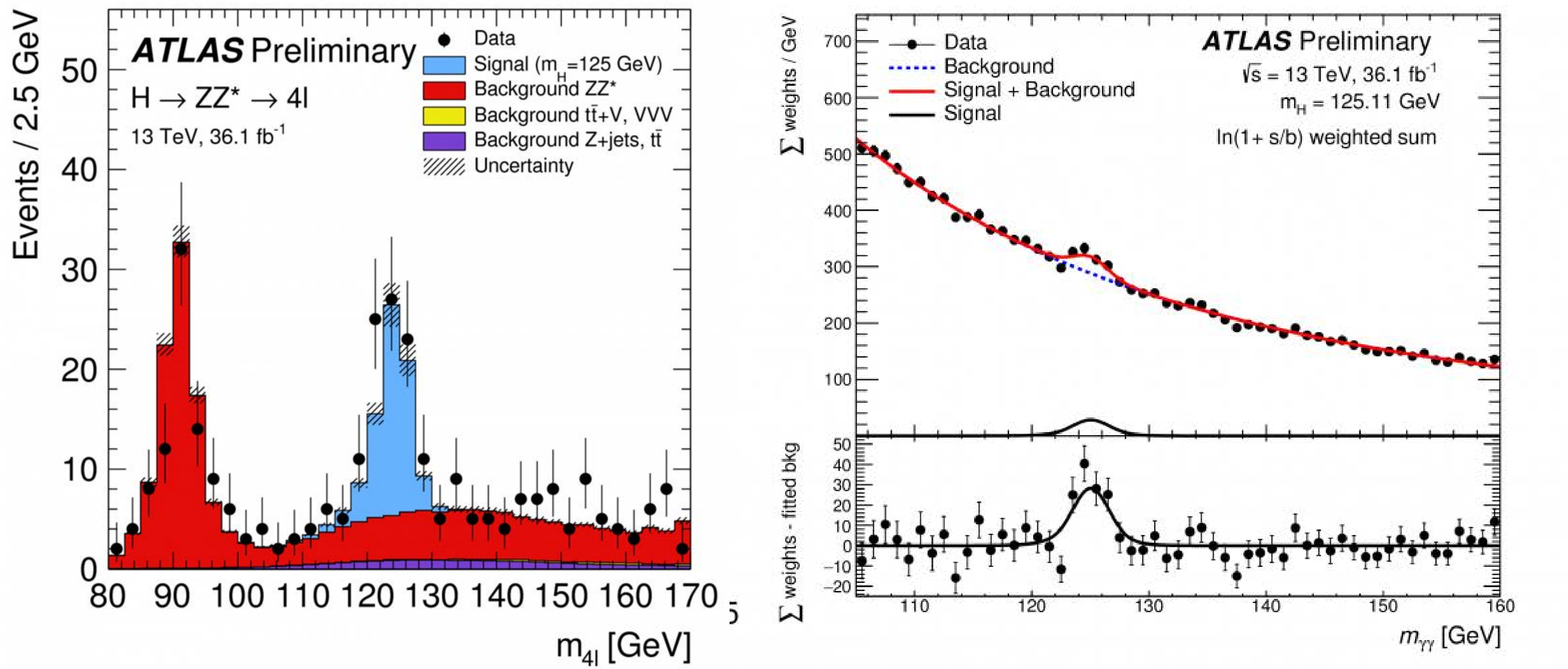
- Events in signal region 125 ± 5 GeV
  - observed 18
  - expected background 8.3 ± 0.3
  - expected signal 9.9 ± 1.3

- Observed local sig: 4.1σ
- Expected local sig: 3.1σ

Higgs Event in ATLAS



Higgs at ATLAS/LHC



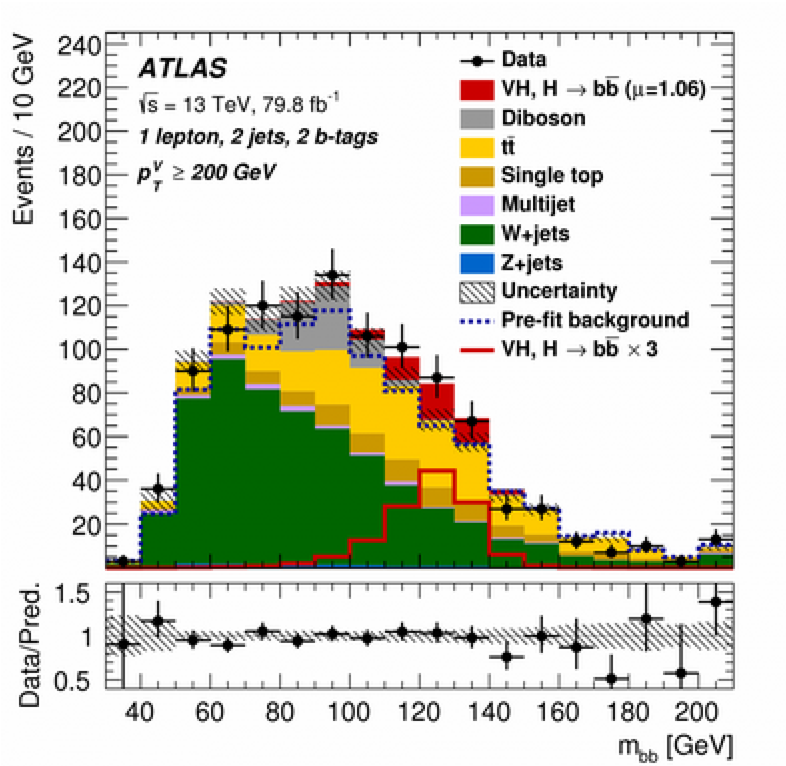


Figure 1: Distribution of mbb in the (W→ℓν)(H→bb) search channel. The signal is shown in

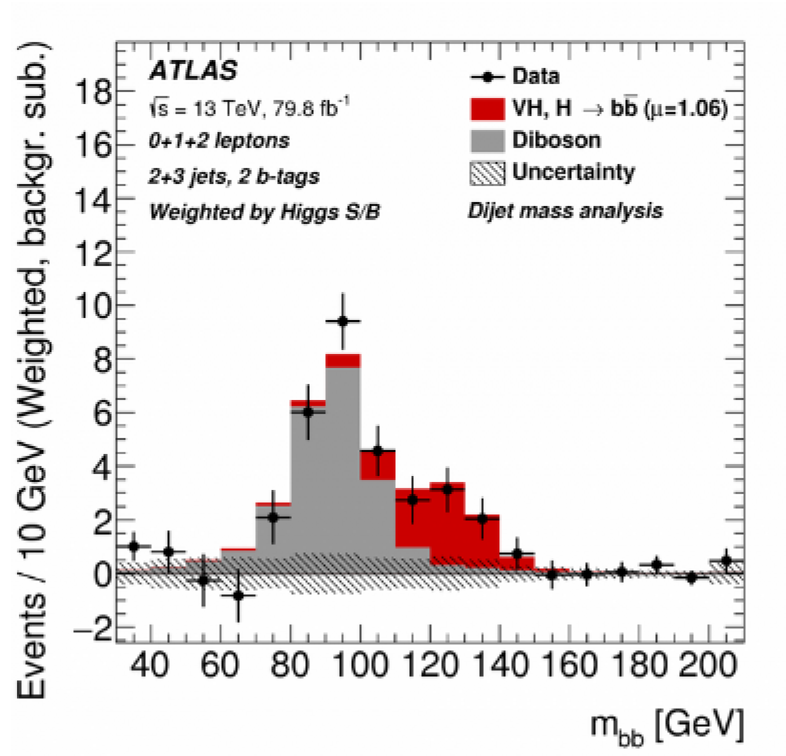
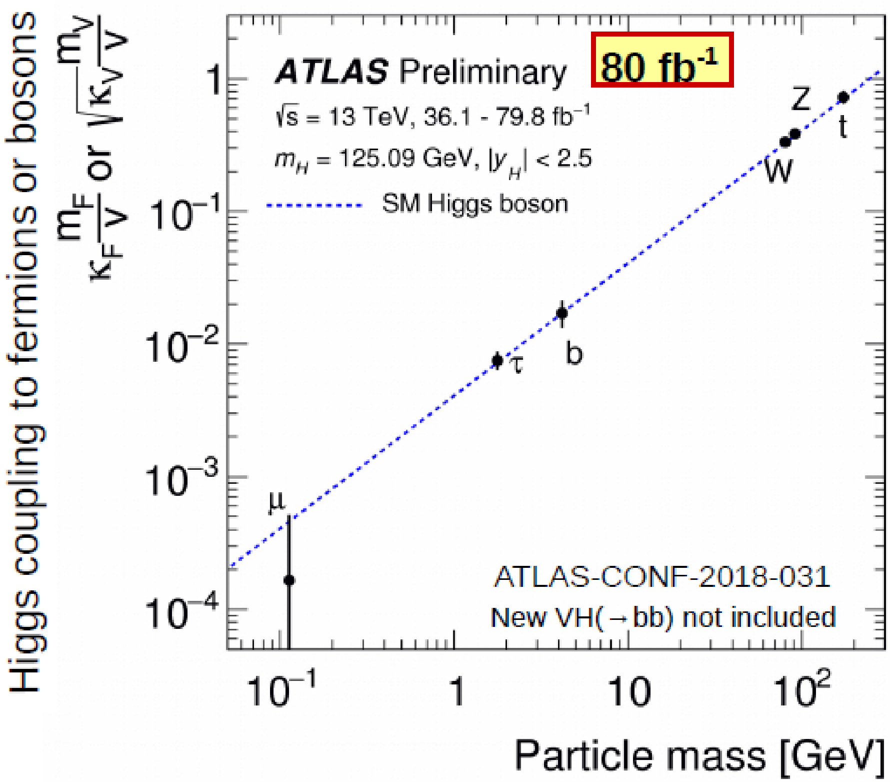


Figure 2: Distribution of mbb from all search channels combined after subtraction of all

Higgs coupling measurements

Key feature:
Higgs coupling depends on the particle mass



All couplings to high mass particles measured.
Next challenge: muon, charm-quark...

\+ detailed cross-section measurements !

Interaction with gauge bosons:

$H \to ZZ^*$ ATLAS-CONF-2018-018
Well established in run-1

$H \to WW^*$ ATLAS-CONF-2018-004
6.3 (5.2) σ obs (exp) (run-2 only)

Yukawa coupling to fermions:

Top-quark: ttH — 80 fb^{-1}
6.3σ (5.1σ) obs (exp) — arXiv:1806.00425

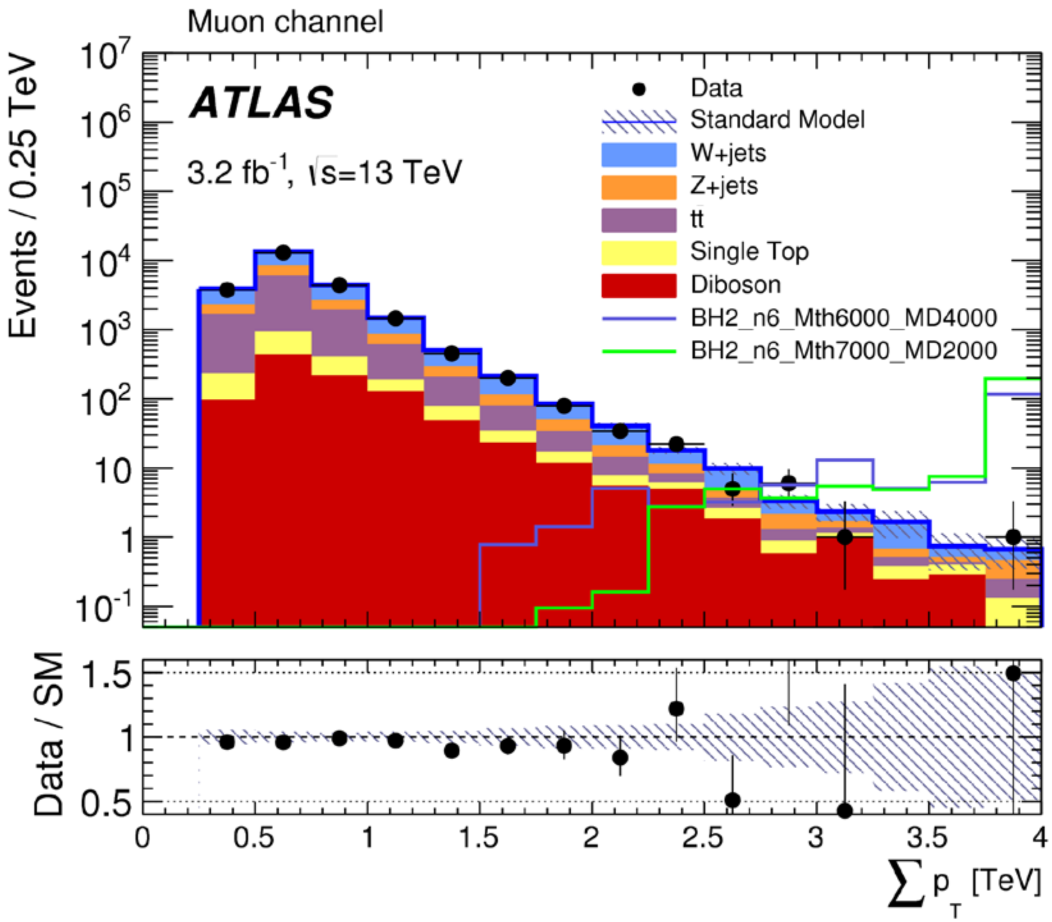
Beauty-quark $H \to bb$: 80 fb^{-1} — New
5.4σ (5.5σ) obs (exp) — ATLAS-CONF-2018-036

Tau-lepton: $H \to \tau\tau$
6.4σ (5.4σ) obs (exp) — ATLAS-CONF-2018-021

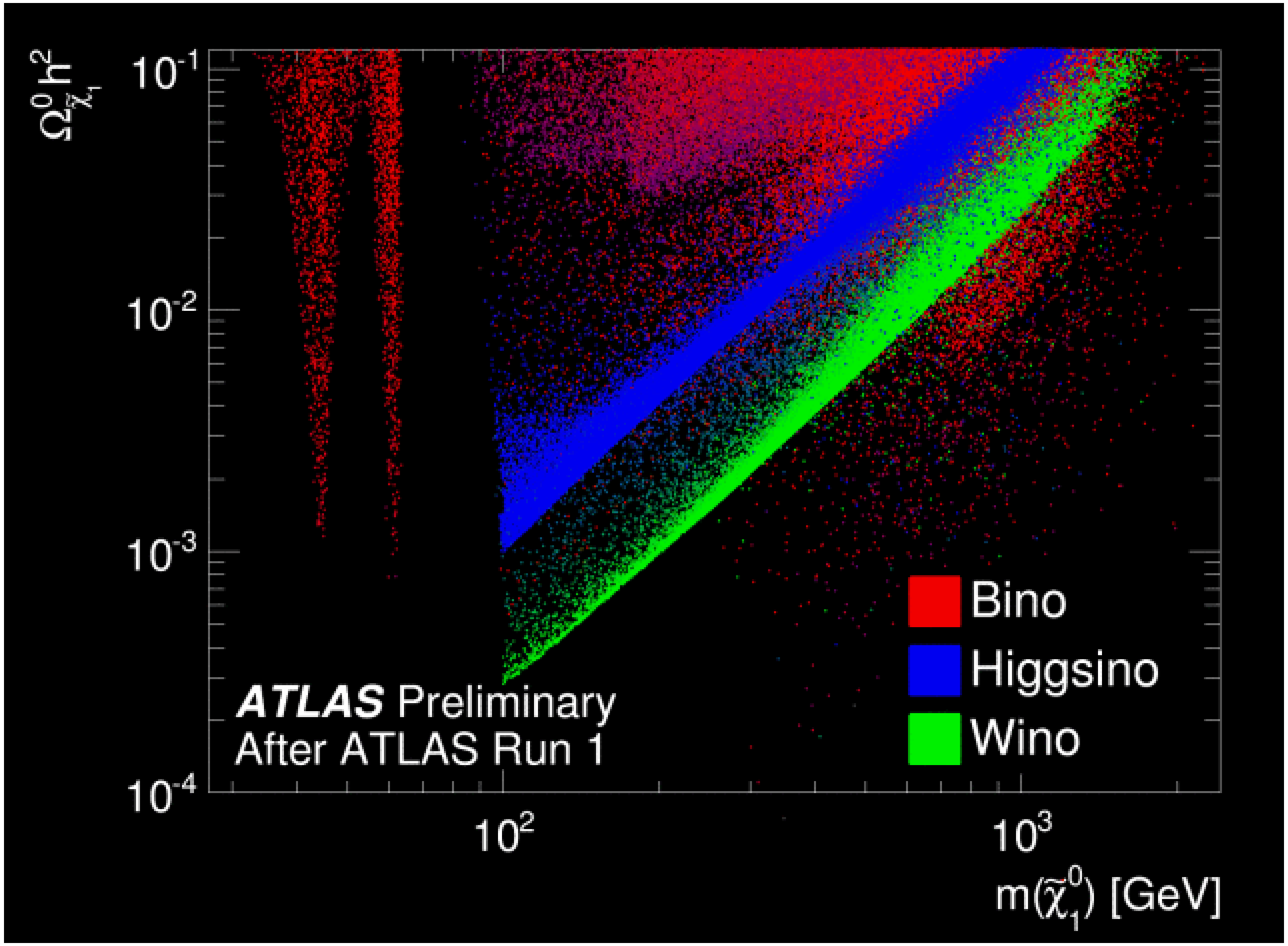
Muon $H \to \mu\mu$: 80 fb^{-1} — New
$\sigma_{limit}/\sigma_{SM}$<2.1 (obs) — ATLAS-CONF-2018-026

Charm-quark: $H \to cc$:
$\sigma_{limit}/\sigma_{SM}$<104 (obs) — PRL 120 (2018) 211802

Search for Extra Dimensions



Search for Dark Matter



Search for SuperSymmetric Particles