

The Standard Model of particle physics

Particle Physics

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I. Recap'

1. BEH mechanism and EWK symmetry breaking
2. Charged weak current vertex
3. Neutral weak current vertex
4. EM current vertex

II. Fermion mass term

1. Yukawa couplings (one family case)
2. The quark sector (multiple family case)

III. The CKM matrix

1. Quark rotation for EM, NC currents, kinematic term
2. Origin of the CKM matrix

IV. The SM lagrangian, putting it all together

V. Experimental test of the Higgs sector

1. Beyond LO and Higgs mass prediction
2. Higgs boson production in hadron colliders
3. Higgs boson discovery and properties
4. Higgs boson couplings

$$\mathcal{L}_{\text{BEH}} = (\mathbf{D}_\mu \phi)^\dagger (\mathbf{D}_\mu \phi) + \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$$

$$\mathcal{L}_{\text{BEH}} = \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \sqrt{\frac{\lambda}{2}} m_h h^3 - \frac{\lambda}{4} h^4$$

$$+ \left[m_W^2 W^{+\mu} W_\mu^- + \frac{m_Z^2}{2} Z^\mu Z_\mu \right] \left(1 + \frac{h}{v} \right)^2$$

$$m_h = \sqrt{2\mu^2} = \sqrt{2\lambda}v$$

$$e = g \sin \theta_w$$

$$m_Z = \frac{\sqrt{g^2 + (2g'Y_H)^2}v}{2}$$

4 parameters:

- $v, e, \sin^2\theta, m_h$
- $v, e, \sin^2\theta, \lambda$

$$m_W = \frac{gv}{2} = m_Z \cos \theta_w$$

$$\begin{pmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{pmatrix}$$

flavor

V_{CKM}

mass

$$|V_{CKM}| = \begin{pmatrix} 0.97425 & 0.2253 & 0.00413 \\ 0.225 & 0.986 & 0.0411 \\ 0.0084 & 0.04 & 0.998329 \end{pmatrix}$$

CKM quasi diagonal...

mass and flavor eigenstates similar, small mixing
 Very different from PMNS matrix (leptonic sector)

- PMNS : Ponte Corvo - Maki - Nakagawa - Sakata

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

flavor V_{PMNS} mass

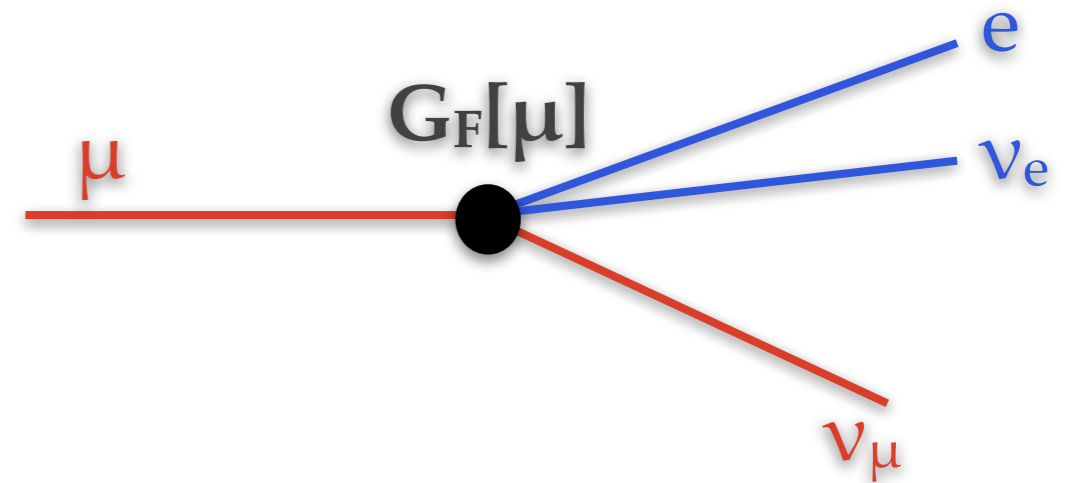
$$|V_{\text{PMNS}}| = \begin{pmatrix} 0.824398 & 0.544564 & 0.154328 \\ 0.485452 & 0.540074 & 0.6875 \\ 0.291039 & 0.641693 & 0.709596 \end{pmatrix}$$

$$\begin{aligned}
\mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
& M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w (\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)) - \\
& igs_w (\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - \\
& W_\nu^- \partial_\nu W_\mu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\
& Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
& \beta_h \left(\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\
& g\alpha_h M (H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\
& \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
& gMW_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \\
& \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
& \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
& M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + igs_w M A_\mu (W_\mu^+ \phi^- - \\
& W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
& \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)\phi^+ \phi^-) - \\
& \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
& g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_{ij}^a (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a - \bar{e}^\lambda (\gamma^\mu \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda (\gamma^\mu \partial + m_\nu^\lambda) \nu^\lambda - \bar{u}_j^\lambda (\gamma^\mu \partial + \\
& m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma^\mu \partial + m_d^\lambda) d_j^\lambda + igs_w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + \\
& \frac{ig}{4c_w} Z_\mu^0 \{ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\
& (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 + \gamma^5) u_j^\lambda) \} + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep})_{\lambda\kappa} e^\kappa) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa) + \\
& \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\kappa U^{lep\dagger})_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda) + \\
& \frac{ig}{2M\sqrt{2}} \phi^+ (-m_e^\kappa (\bar{\nu}^\lambda U^{lep})_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m_\nu^\lambda (\bar{\nu}^\lambda U^{lep})_{\lambda\kappa} (1 + \gamma^5) e^\kappa + \\
& \frac{ig}{2M\sqrt{2}} \phi^- (m_e^\lambda (\bar{e}^\lambda U^{lep\dagger})_{\lambda\kappa} (1 + \gamma^5) \nu^\kappa) - m_\nu^\kappa (\bar{e}^\lambda U^{lep\dagger})_{\lambda\kappa} (1 - \gamma^5) \nu^\kappa) - \frac{g}{2} \frac{m_\nu^\lambda}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
& \frac{g}{2} \frac{m_e^\lambda}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\nu^\lambda}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_e^\lambda}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \hat{\nu}_\kappa - \\
& \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \hat{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa}) (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa}) (1 + \gamma^5) d_j^\kappa) + \\
& \frac{ig}{2M\sqrt{2}} \phi^- (m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger) (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger) (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
& \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c + \\
& \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
& \partial_\mu \bar{X}^+ X^0) + igs_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
& \partial_\mu \bar{X}^0 X^+) + igs_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \\
& \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
& \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
& \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
& \frac{1}{2}igM (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) .
\end{aligned}$$

Beyond LO, the Fermi "constant"

- Low energy contact interaction

$$\frac{G_F^{Bare}}{\sqrt{2}} = \frac{g^2}{8m_W^2} = \frac{\pi\alpha^{Bare}}{8m_W^2(1 - m_W^2/m_Z^2)}$$



$G_F[\mu]$ measured from muon lifetime $G_F[\mu] = 1.16637(1) 10^{-5} \text{ GeV}^{-2}$

radiative corrections Δr

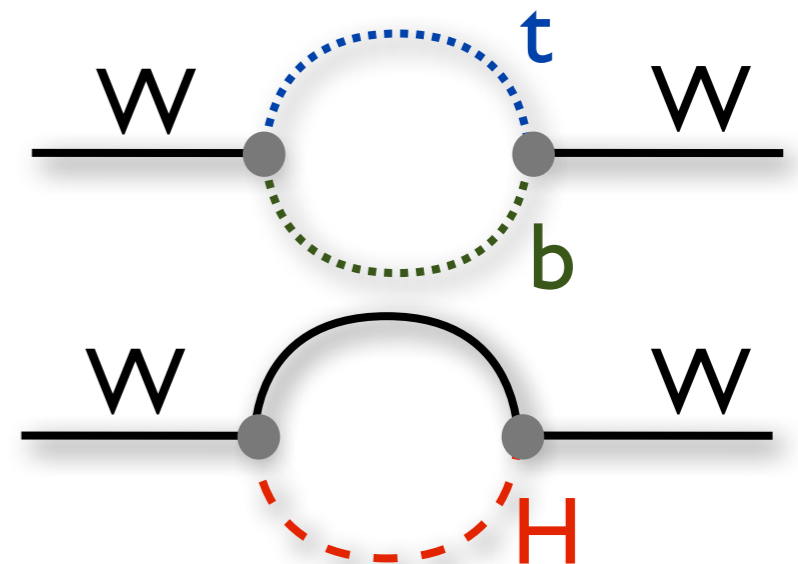
⇒ link between $m_W, m_Z, \alpha, G[\mu]$:

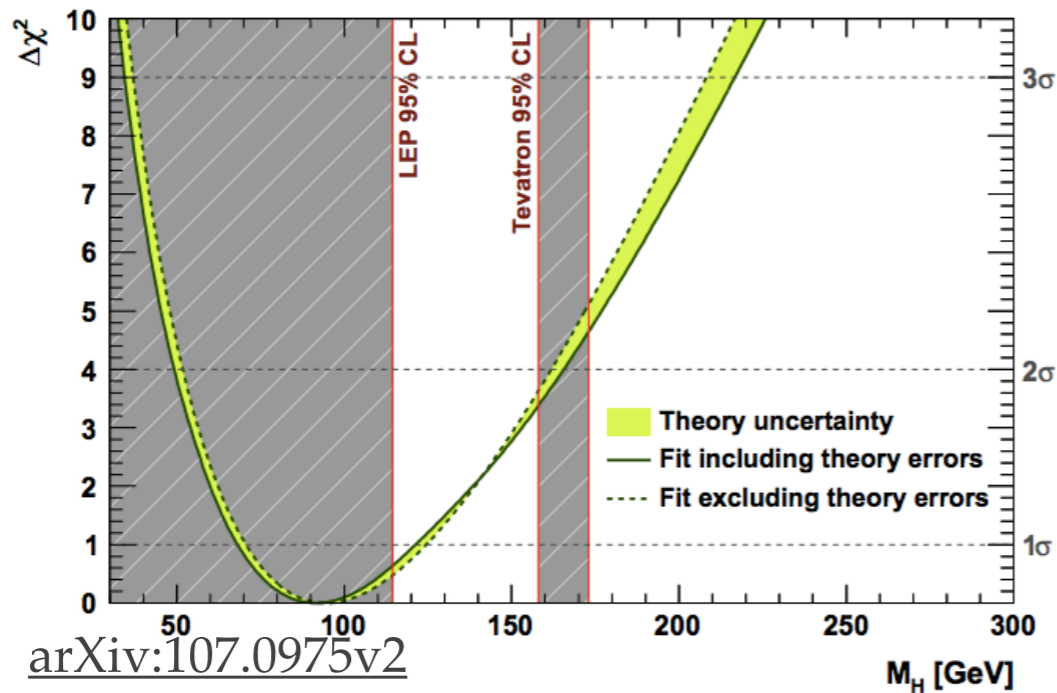
$$G_F \equiv G_F[\mu](1 - \Delta r) = \frac{\pi\alpha}{8m_W^2(1 - m_W^2/m_Z^2)}$$

$$\Delta r \simeq \frac{\alpha}{\pi s^2} \left\{ -\frac{3}{16} \frac{m_t^2}{m_W^2} \frac{c^2}{s^2} + \frac{11}{48} \ln \frac{m_H^2}{m_Z^2} \right\} + 0.070 + 2\text{loops}$$

used to predict the top mass and the Higgs mass

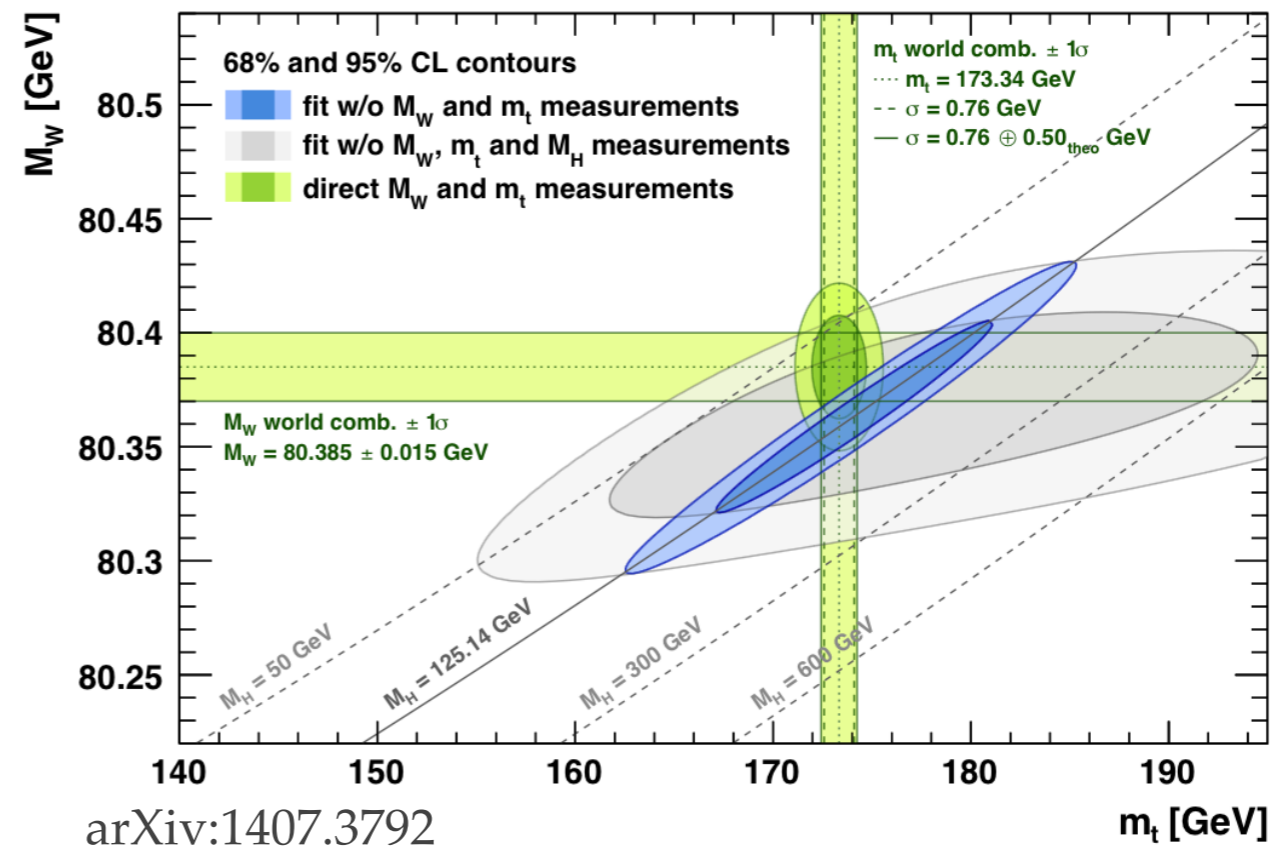
Radiative corrections to the W self-energy



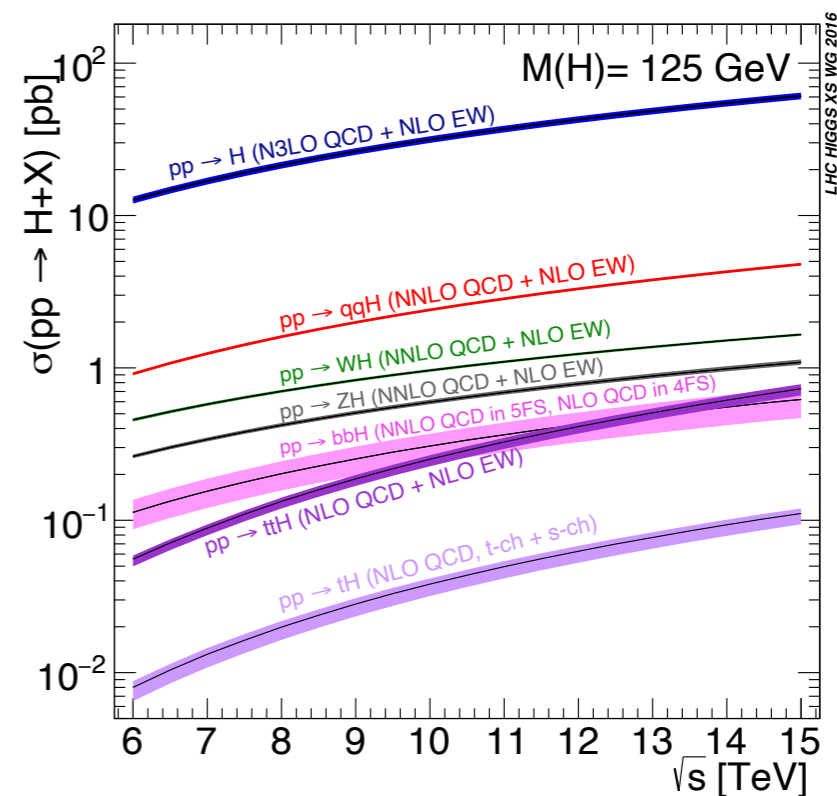
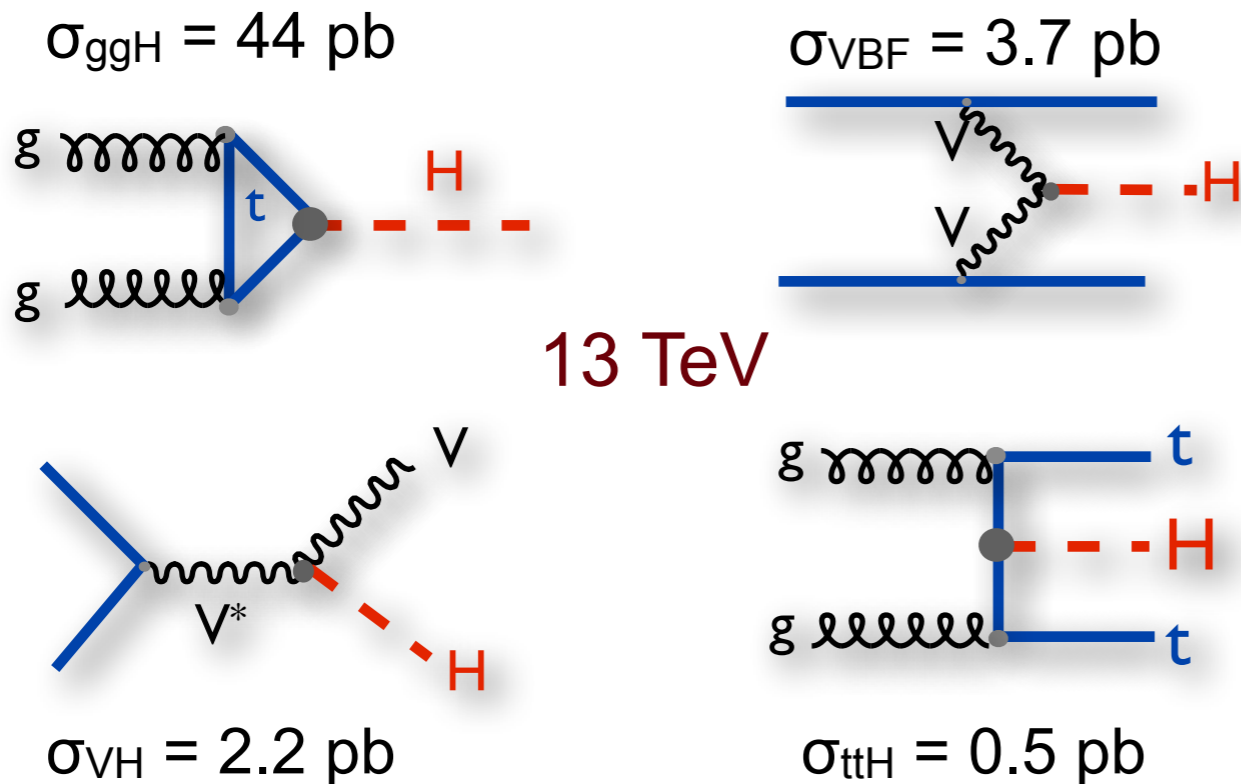


Before Higgs discovery
 $m_h(\text{indirect}) = 91^{+30}_{-23}$ GeV

After Higgs discovery
 test the consistency of
 the model



Higgs Boson production - hadron collider



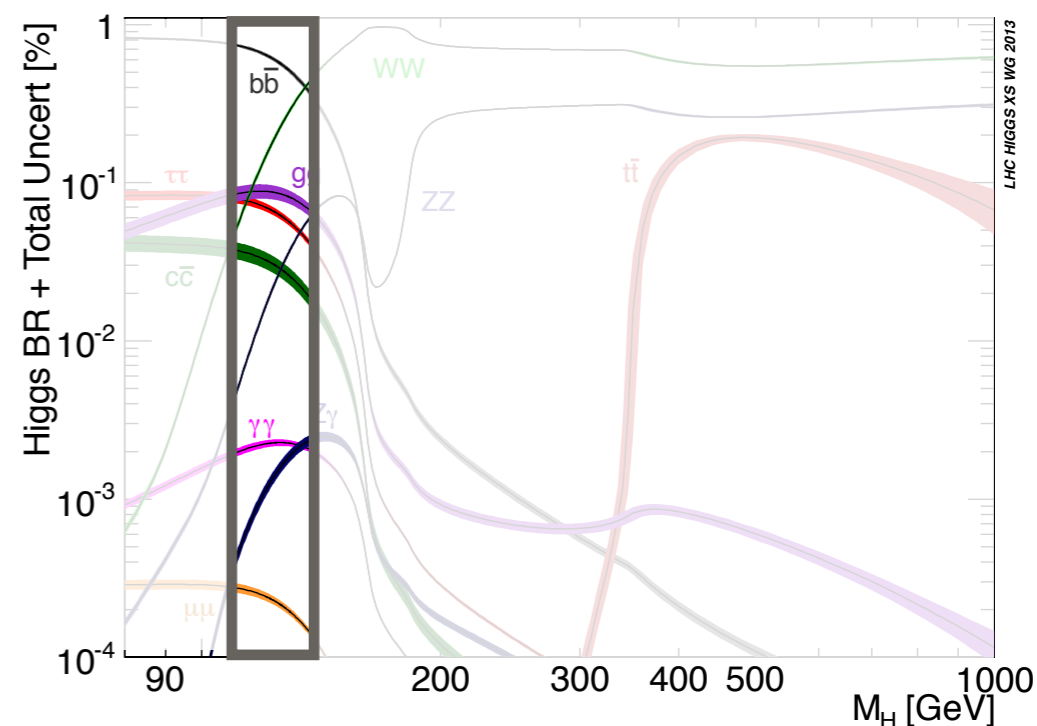
Variety of channel accessible @ $m_H = 125 \text{ GeV}$

Golden channels

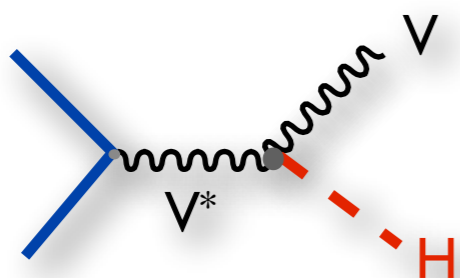
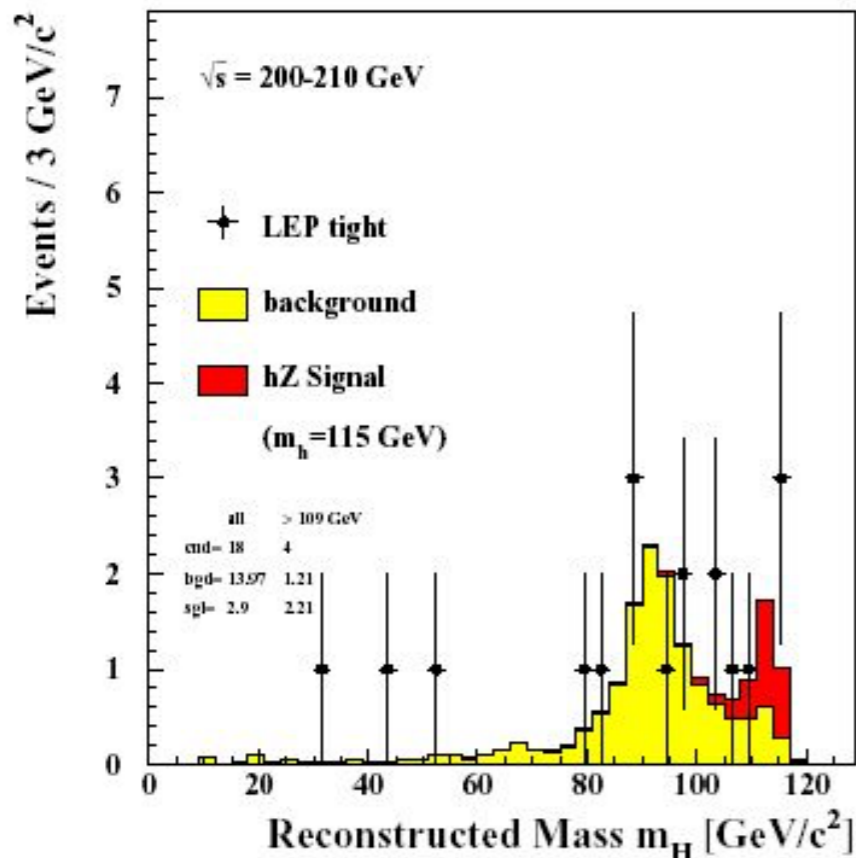
$H \rightarrow \gamma\gamma : B \approx 0.2\%$

$H \rightarrow ZZ^* \rightarrow 4l : B \approx 0.03\%$

Small branching ratios but good invariant mass resolution: probe all production modes

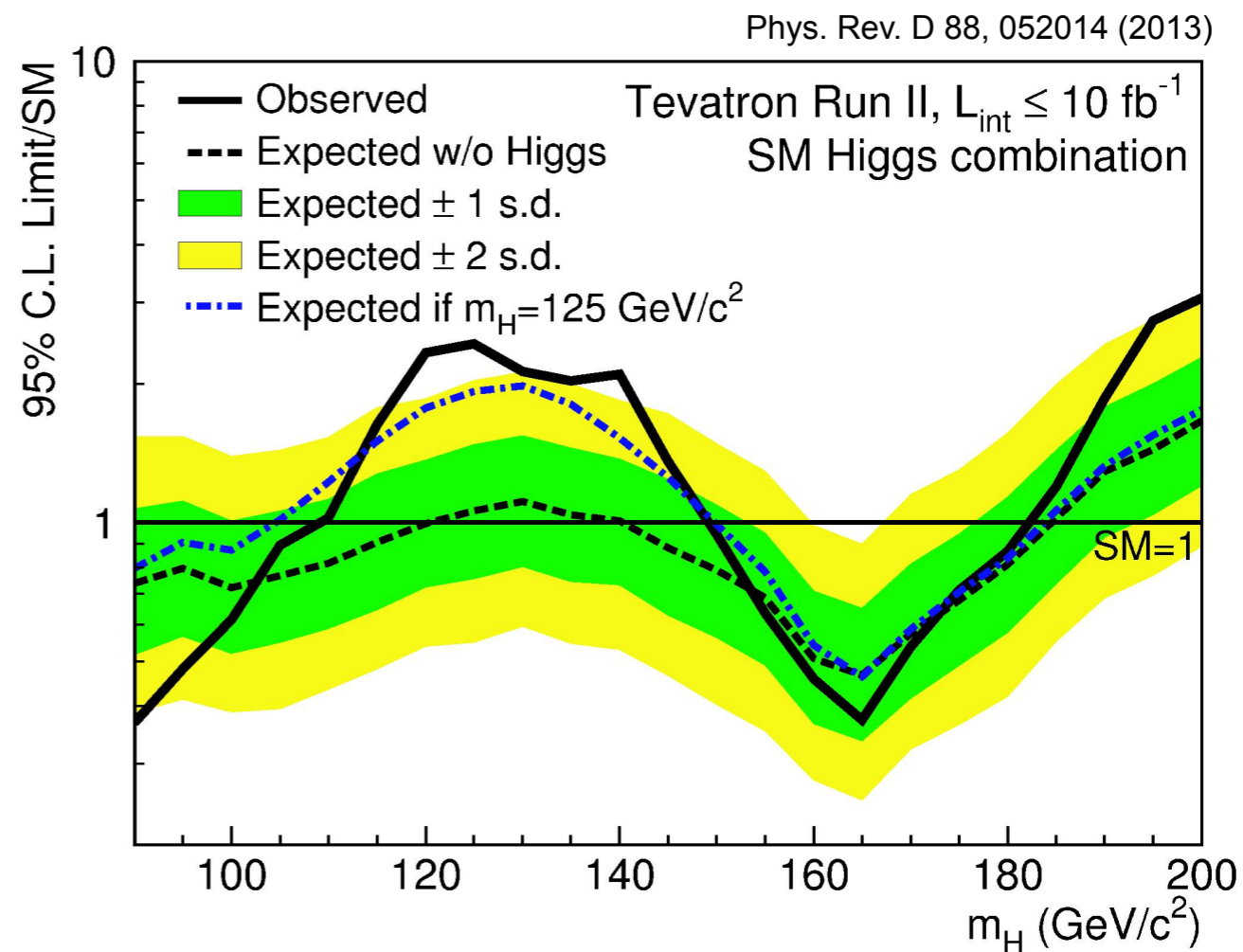


LEP



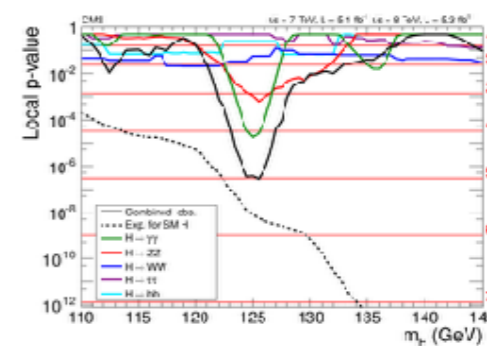
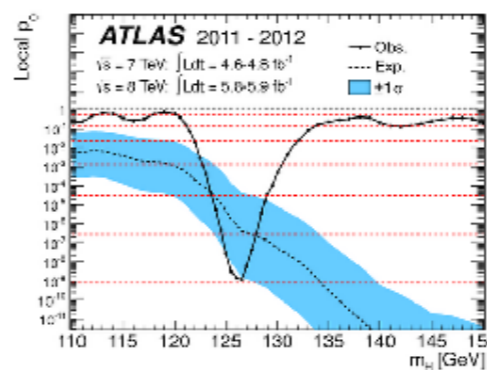
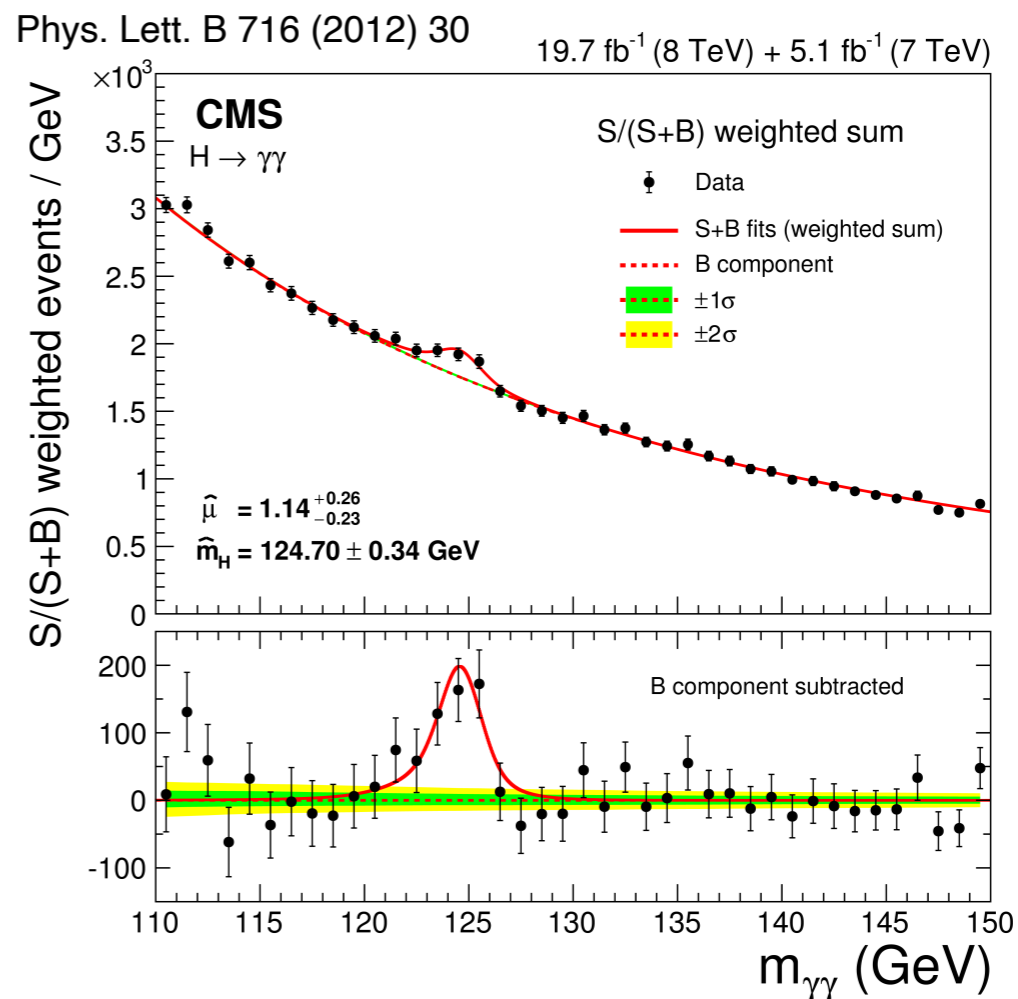
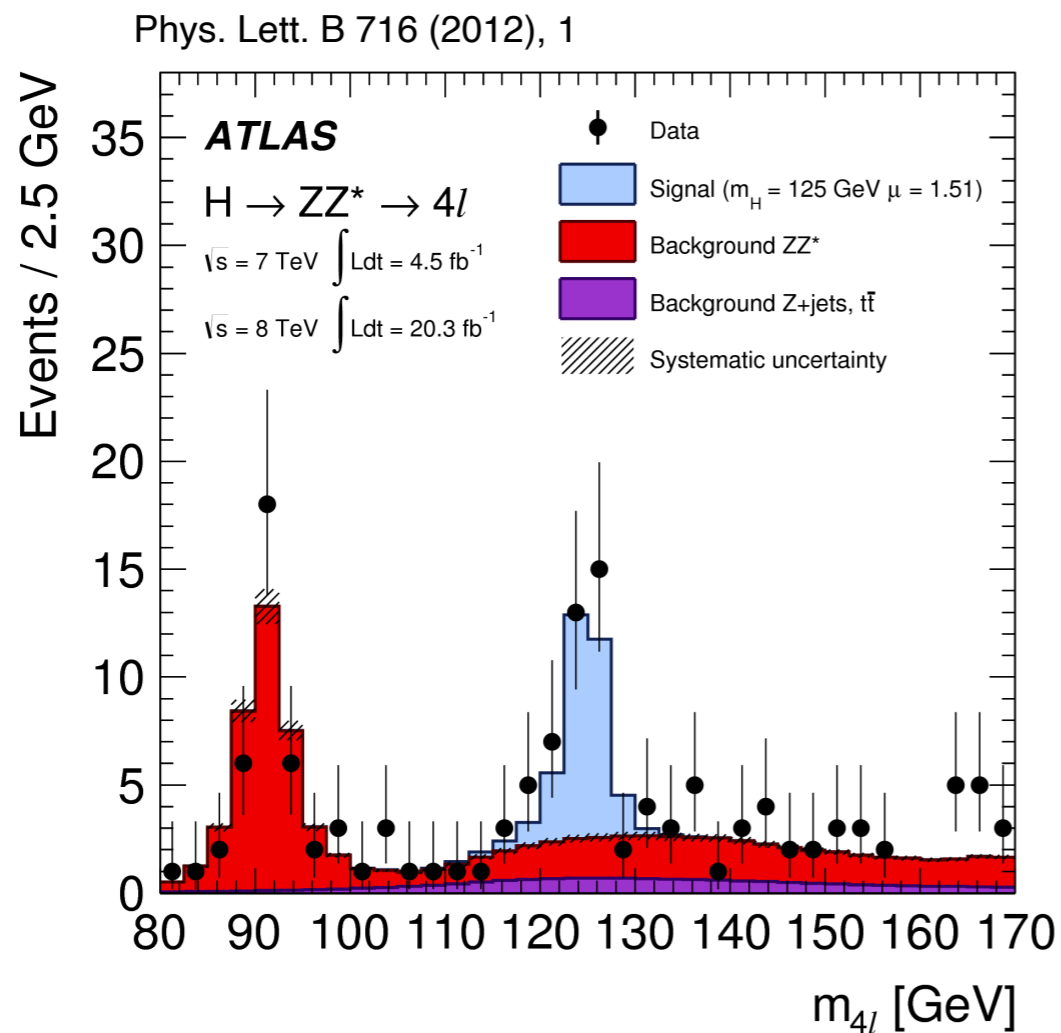
$m_H > 114 \text{ GeV}$

Tevatron ppbar collider 1.96 TeV



$O(3\sigma)$ excess @ $m_H = 125 \text{ GeV}$

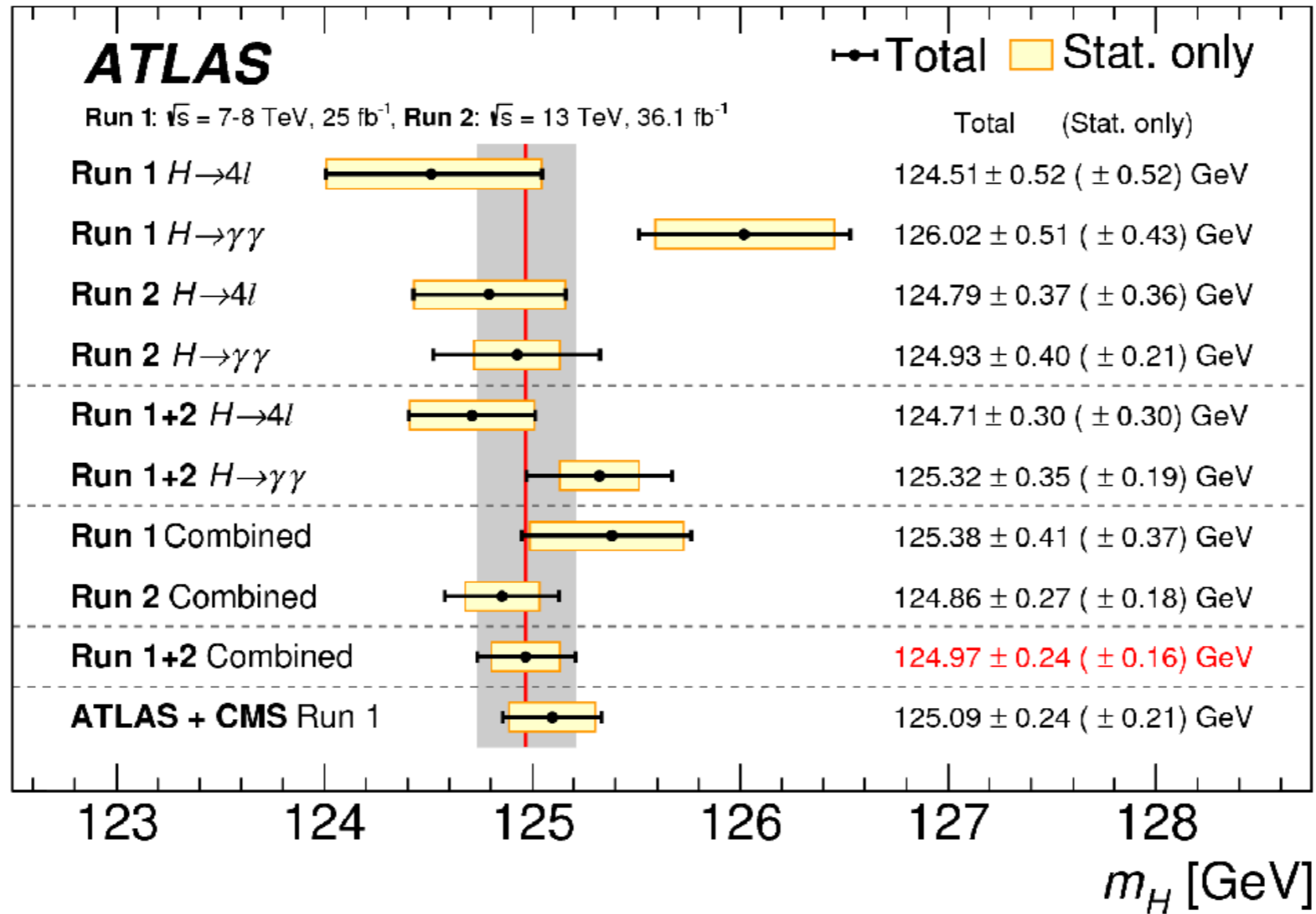
The Higgs Boson discovery, 4 July 2012



Atlas
6 σ excess
@125GeV

CMS
5 σ excess
@125GeV

Phys. Lett. B 784 (2018) 345

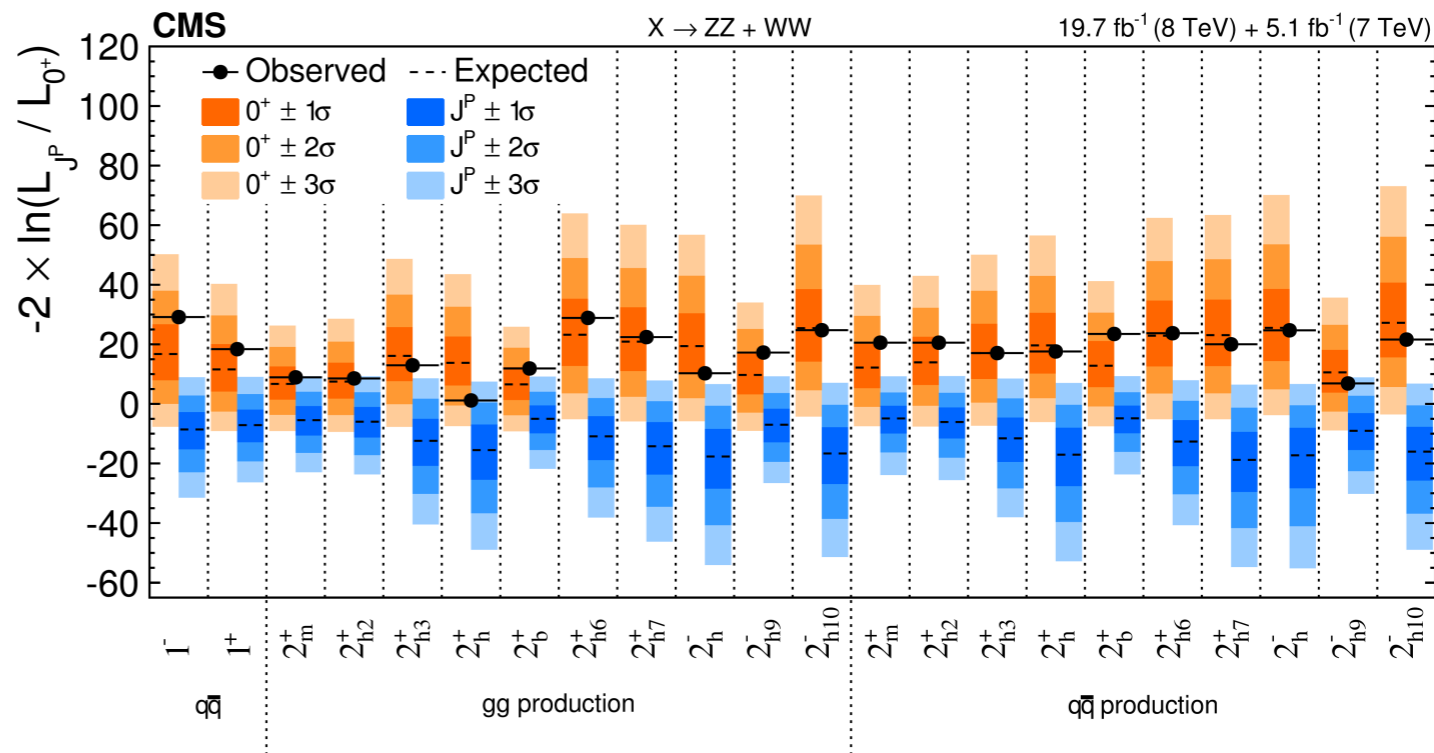


$m_H \approx 125.00 \pm 0.25$ GeV

Boson spin and CP properties

- J**: lot of spin hypothesis tested, definitely a scalar

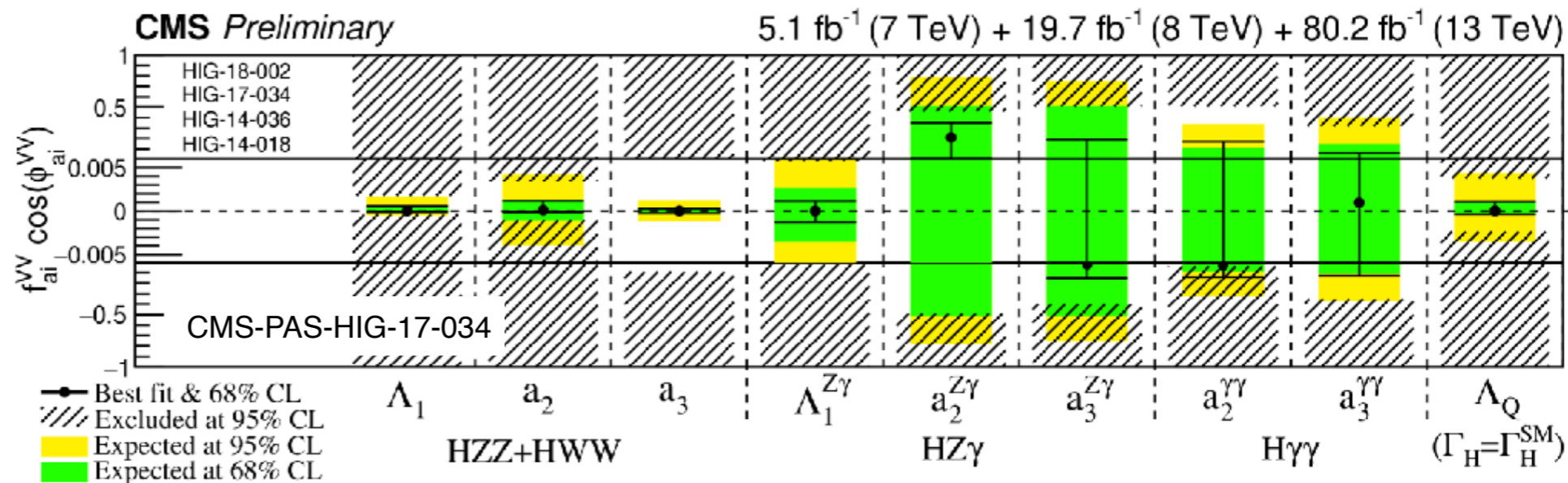
$H \rightarrow ZZ^* \rightarrow 4l$ turned out to be a very good laboratory

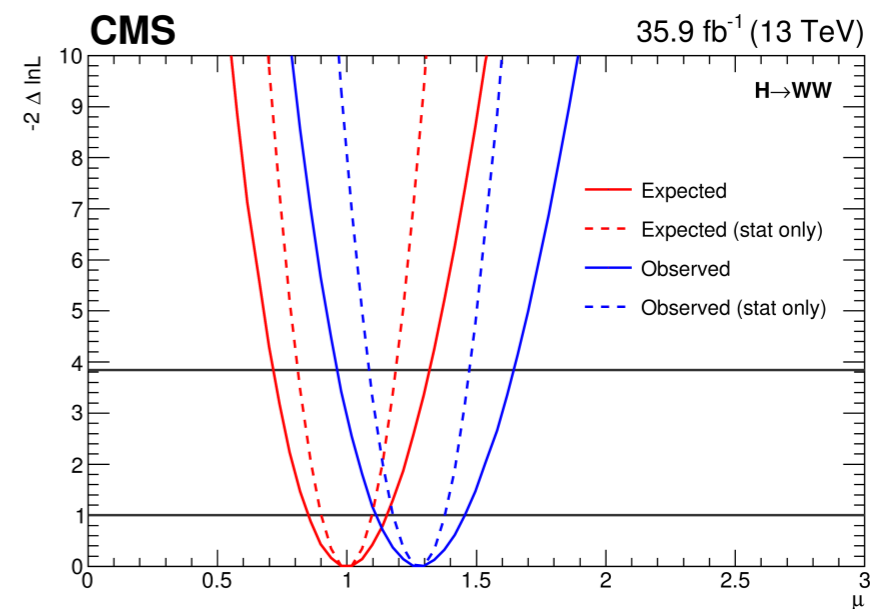
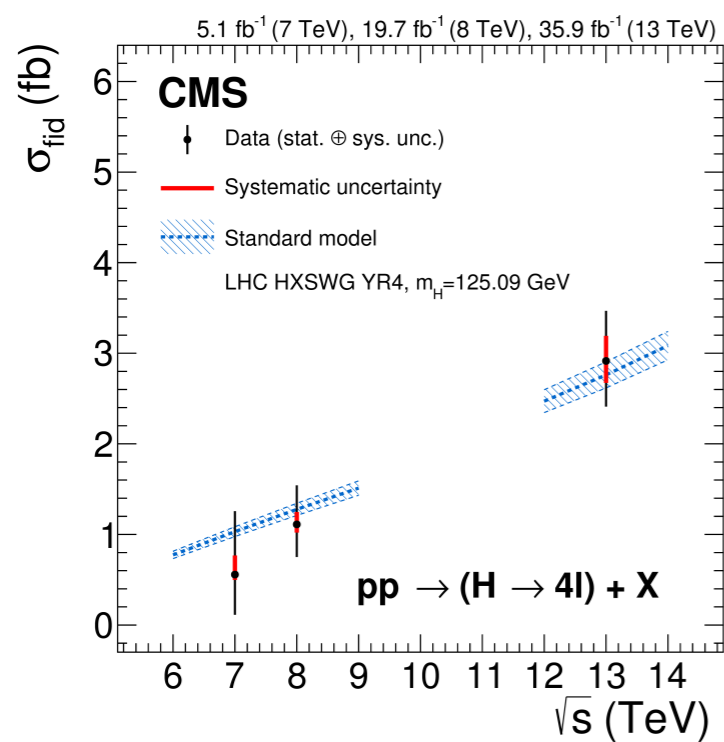
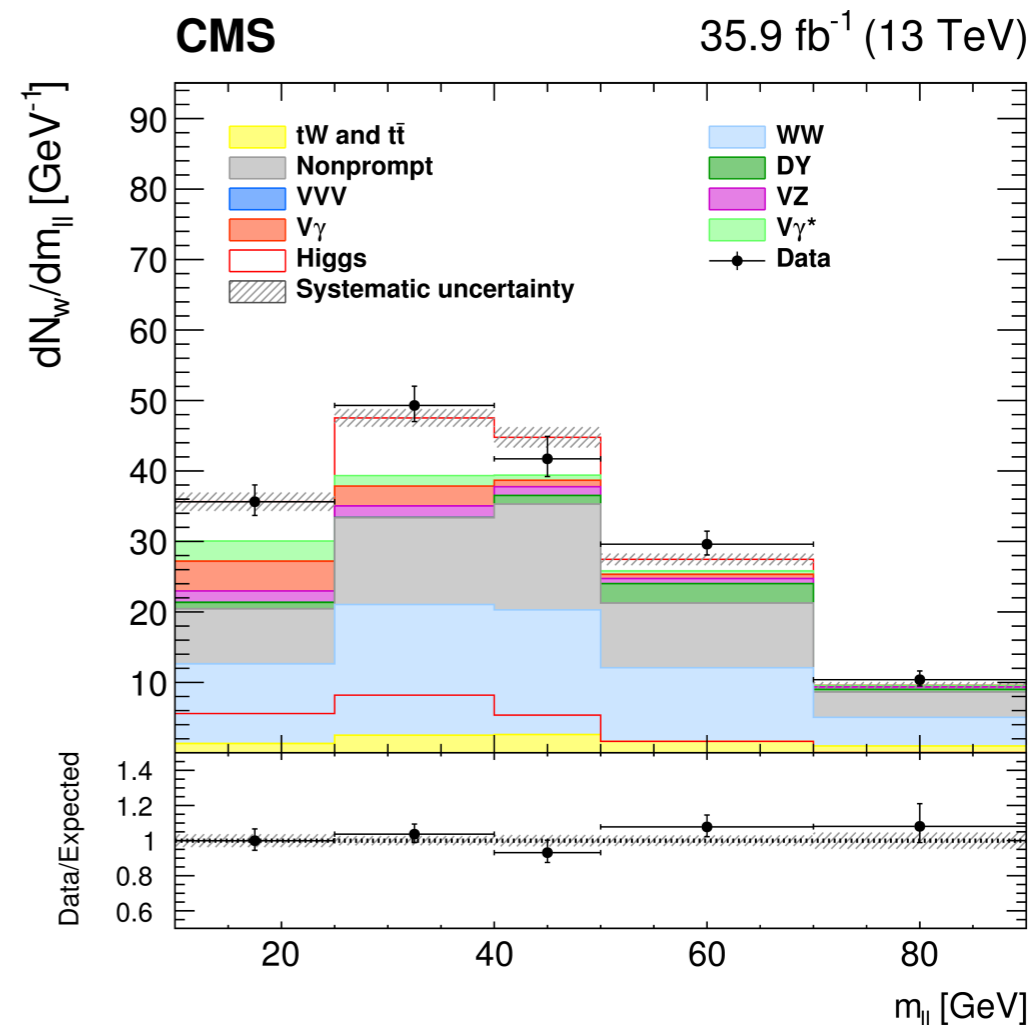
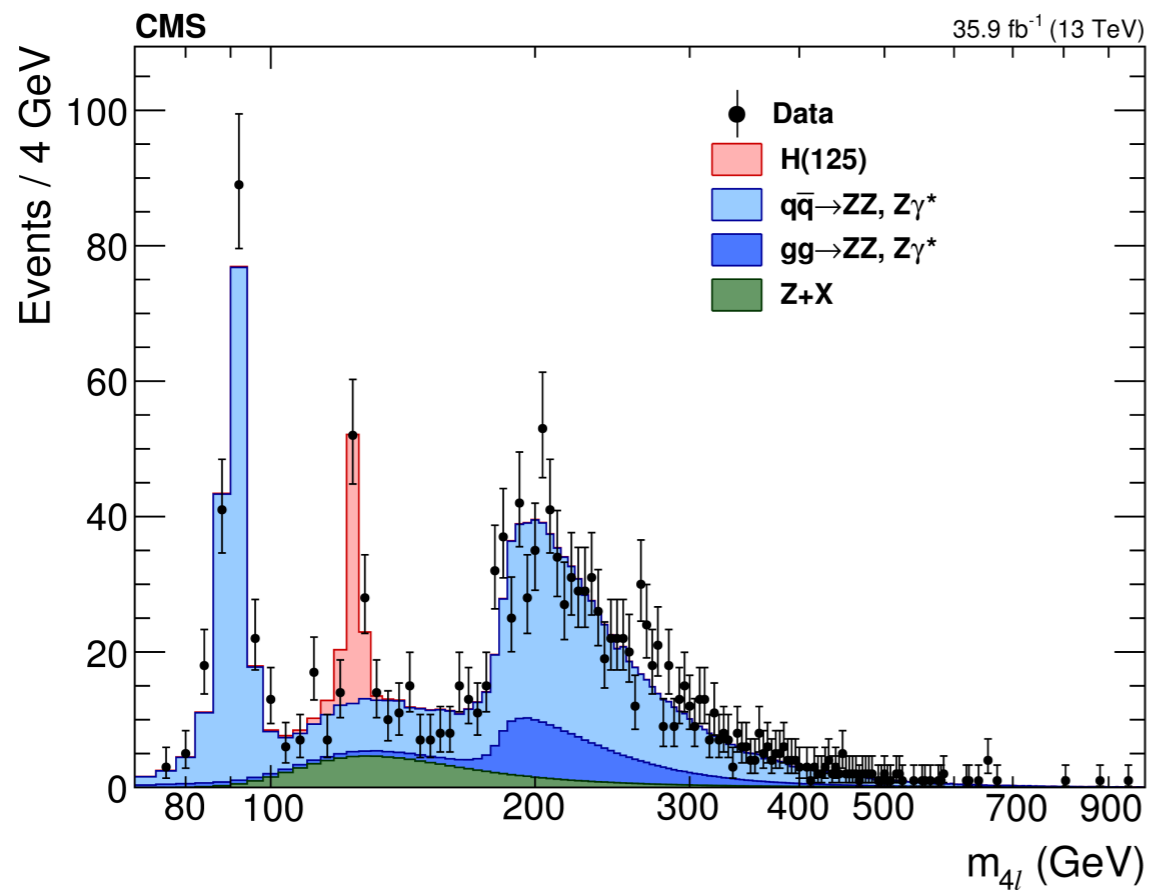


CP: analyze the structure of HVV coupling

$H^* \rightarrow 4l$ good

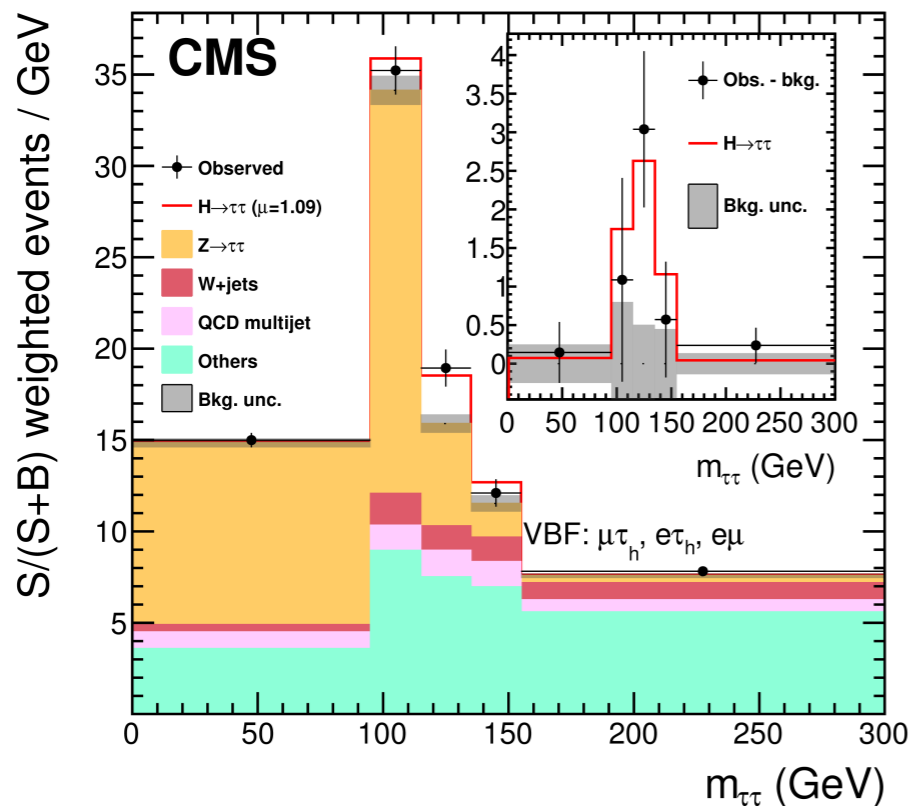
Other channels are competitive



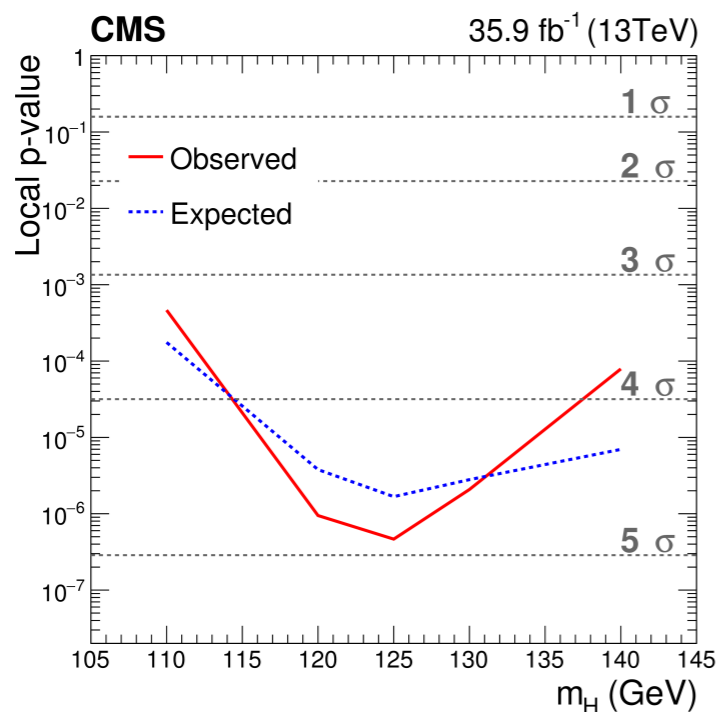


H → ττ Observation in 2017

35.9 fb⁻¹ (13 TeV)

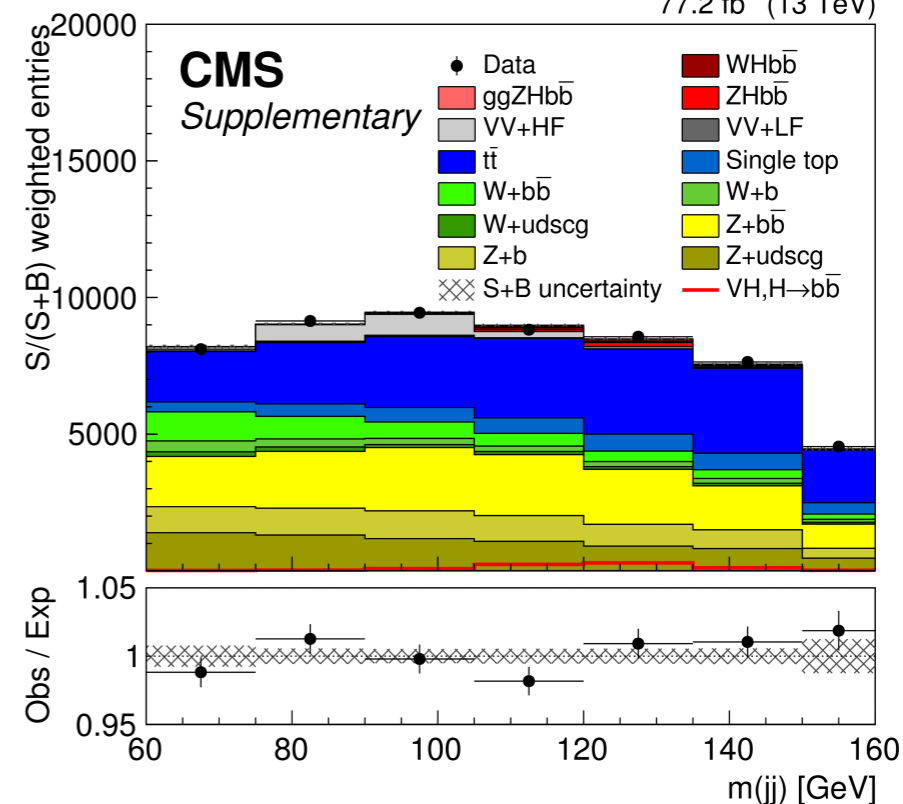


μ = 1.09 ± 0.26

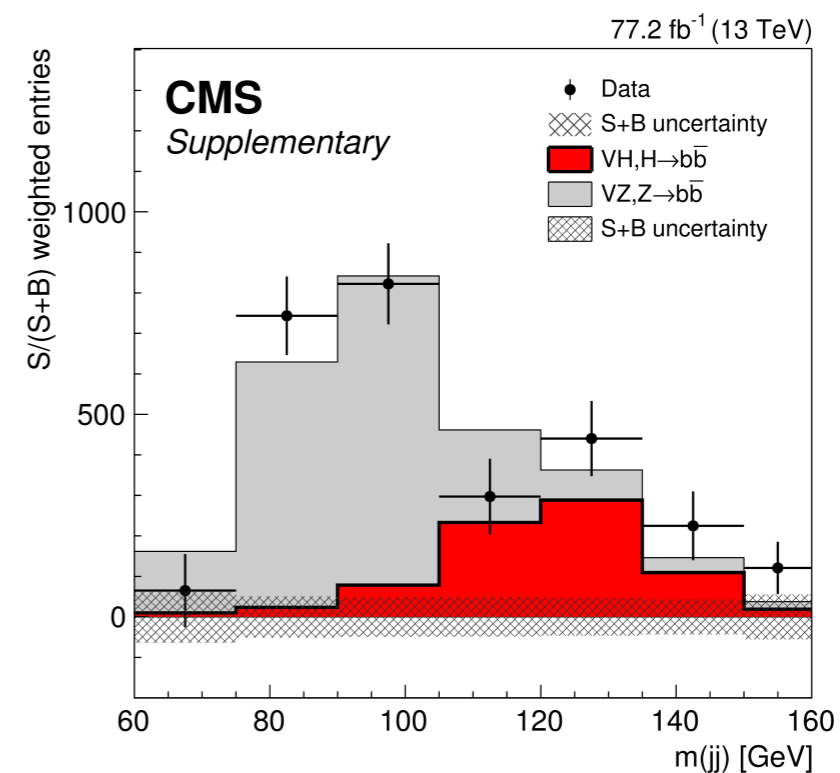


H → bb Observation in 2018

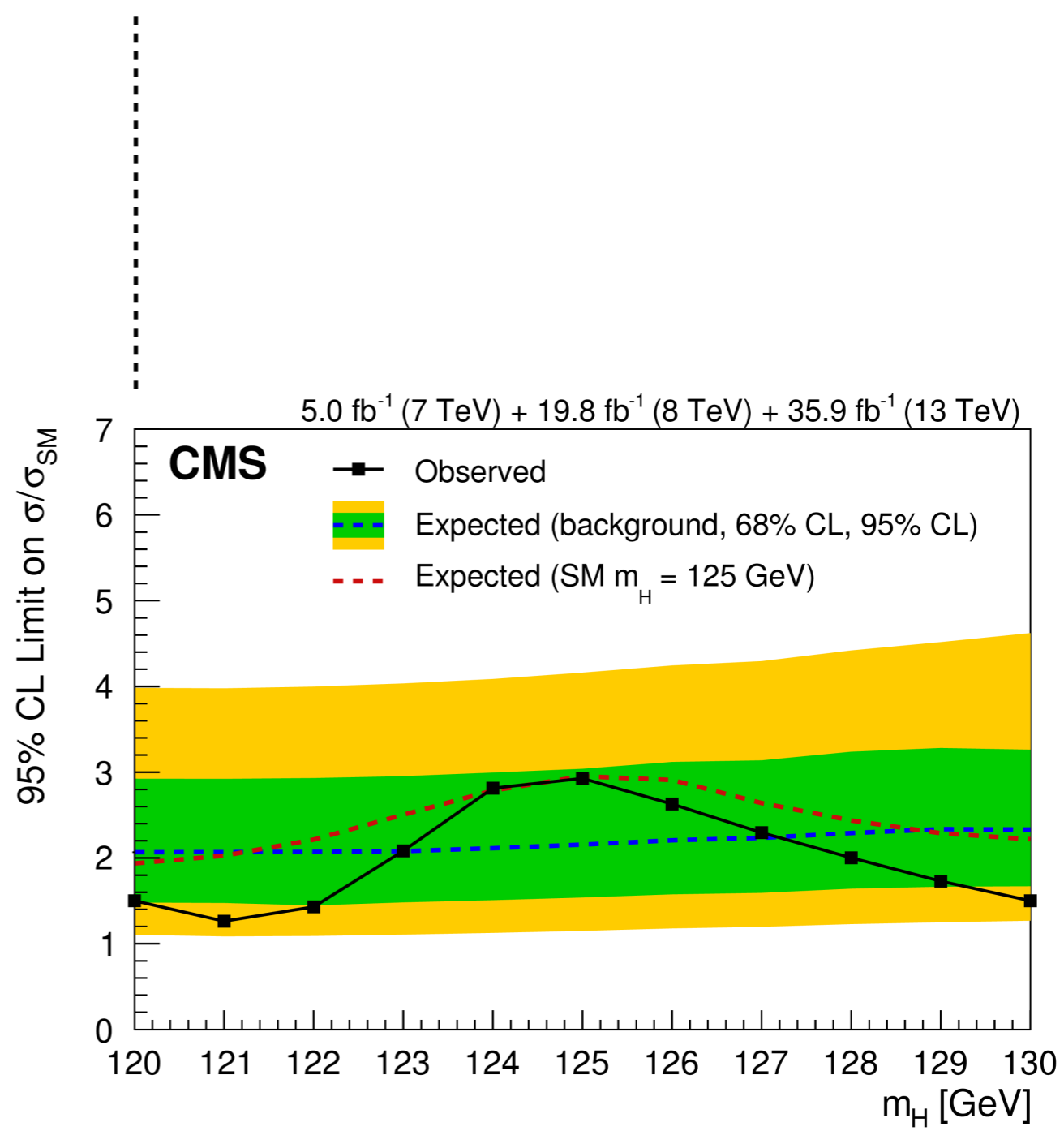
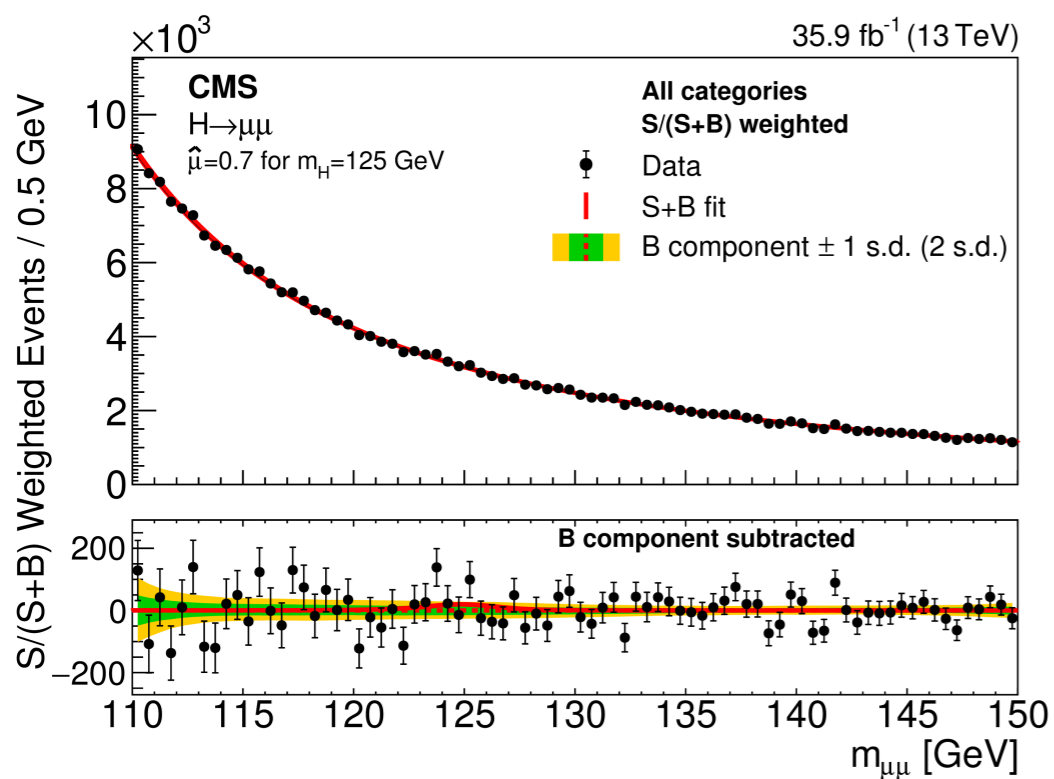
77.2 fb⁻¹ (13 TeV)

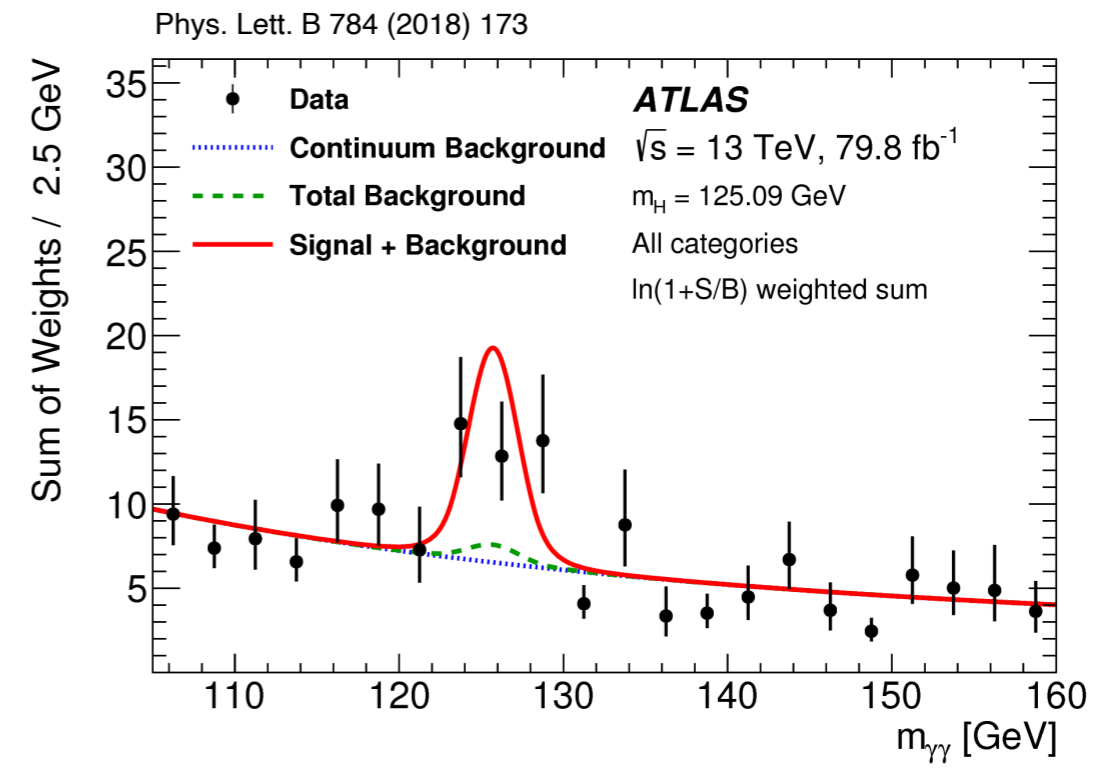
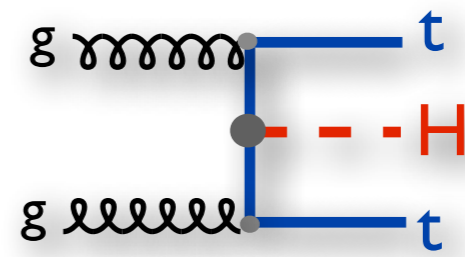
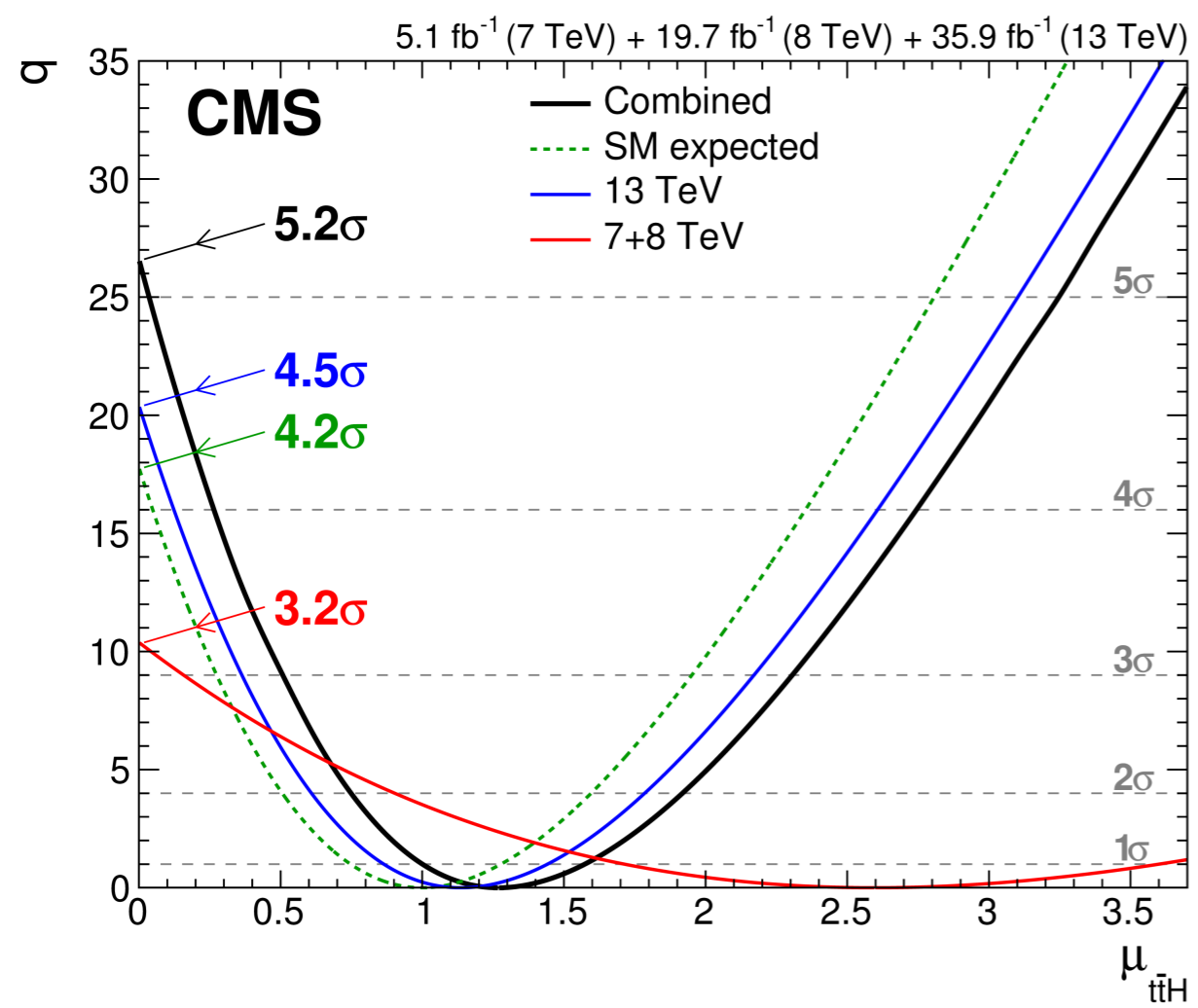


μ = 1.01 ± 0.22

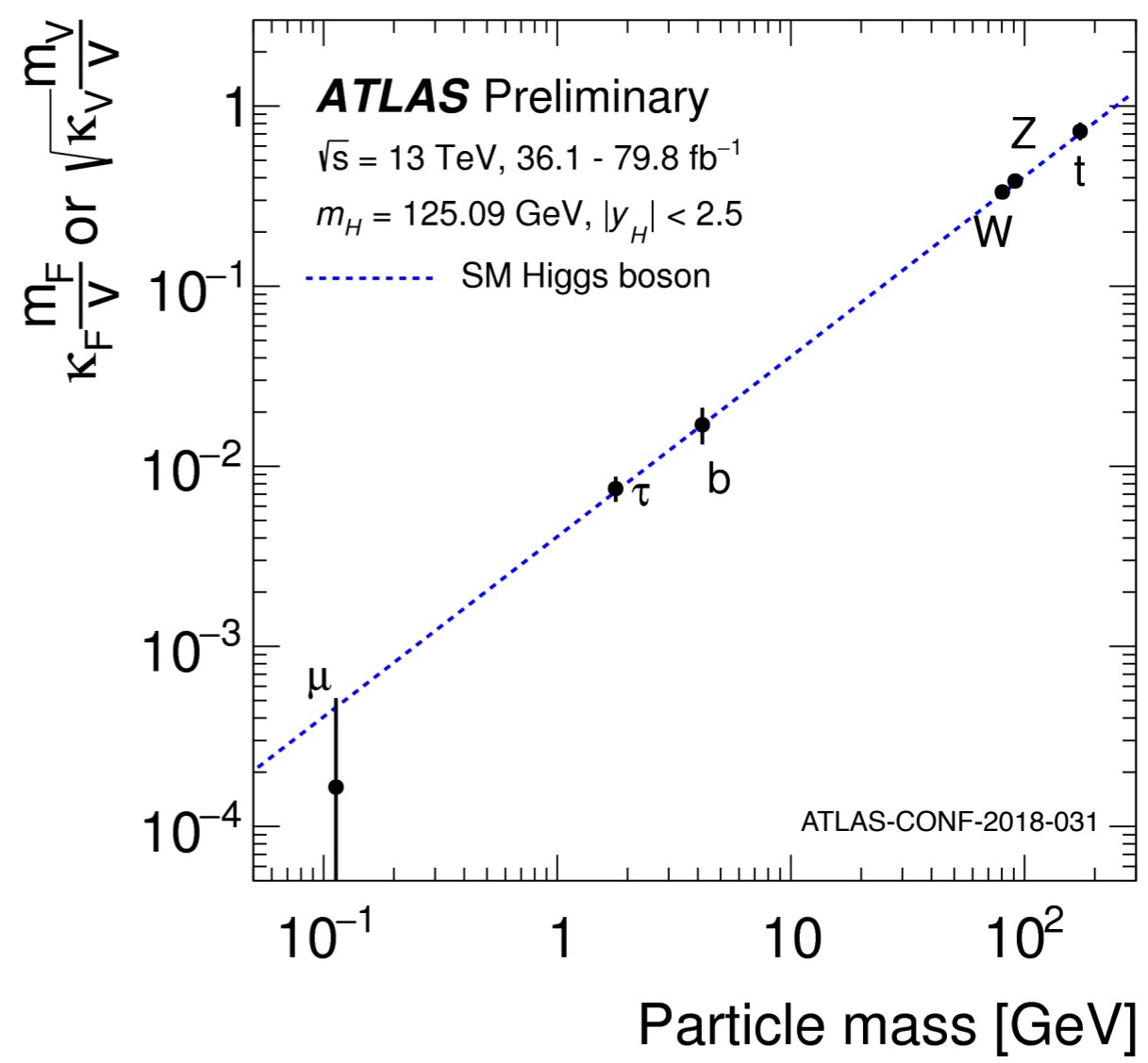
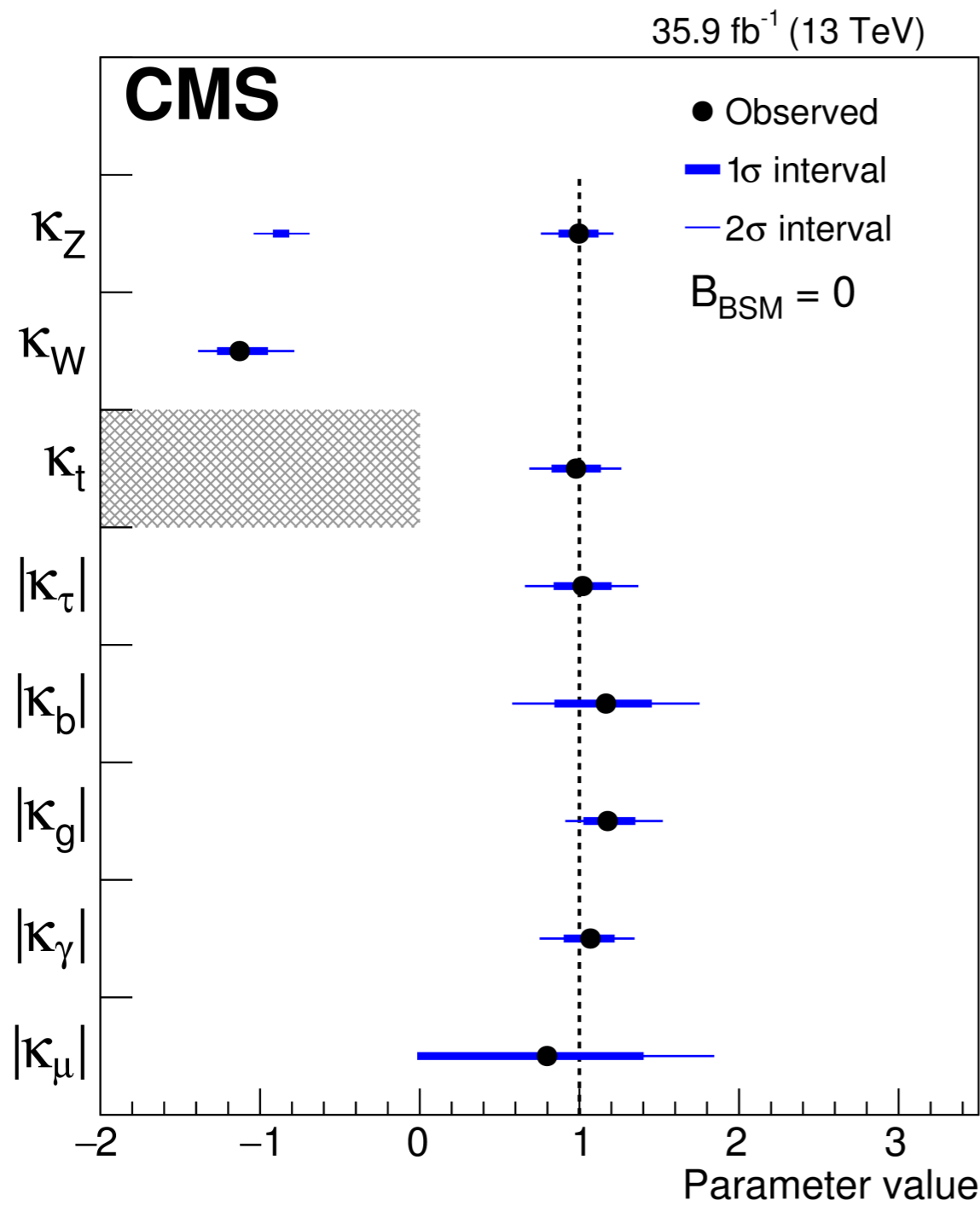


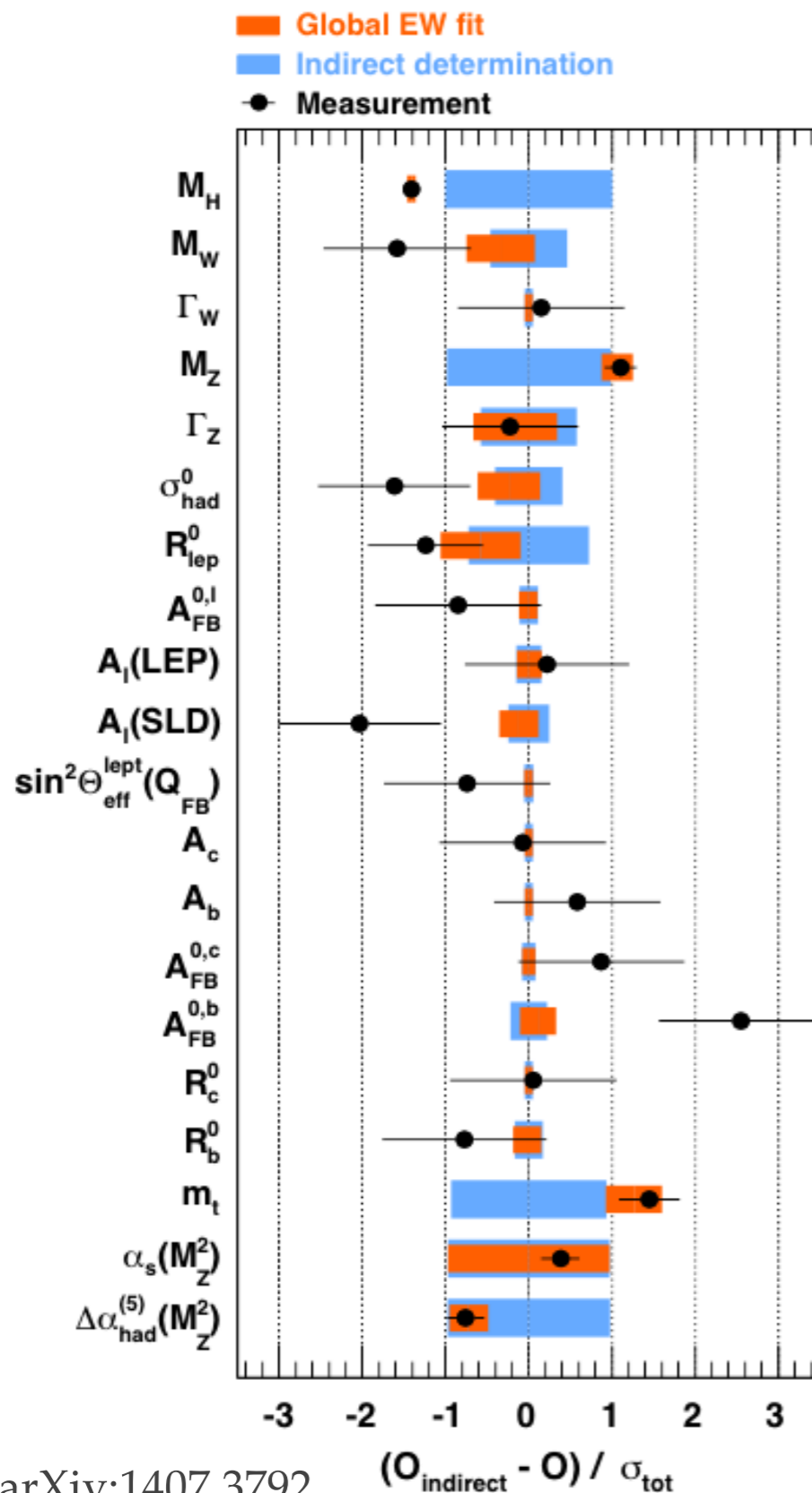
$\mu_{LFU} \approx 300$





Higgs production summary





Indirect determination:
EW fit without the measurement

Global EW fit:
EW fit including the measurement

Measurement: Measurement

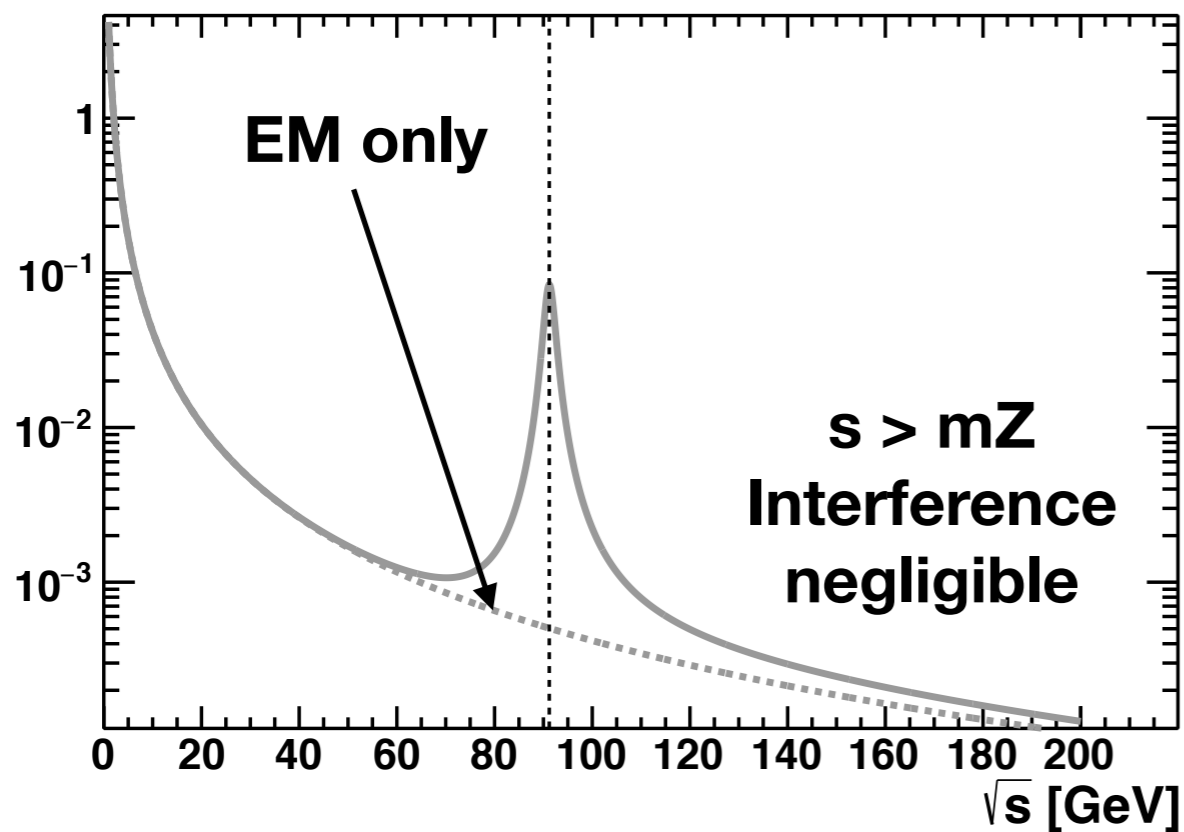
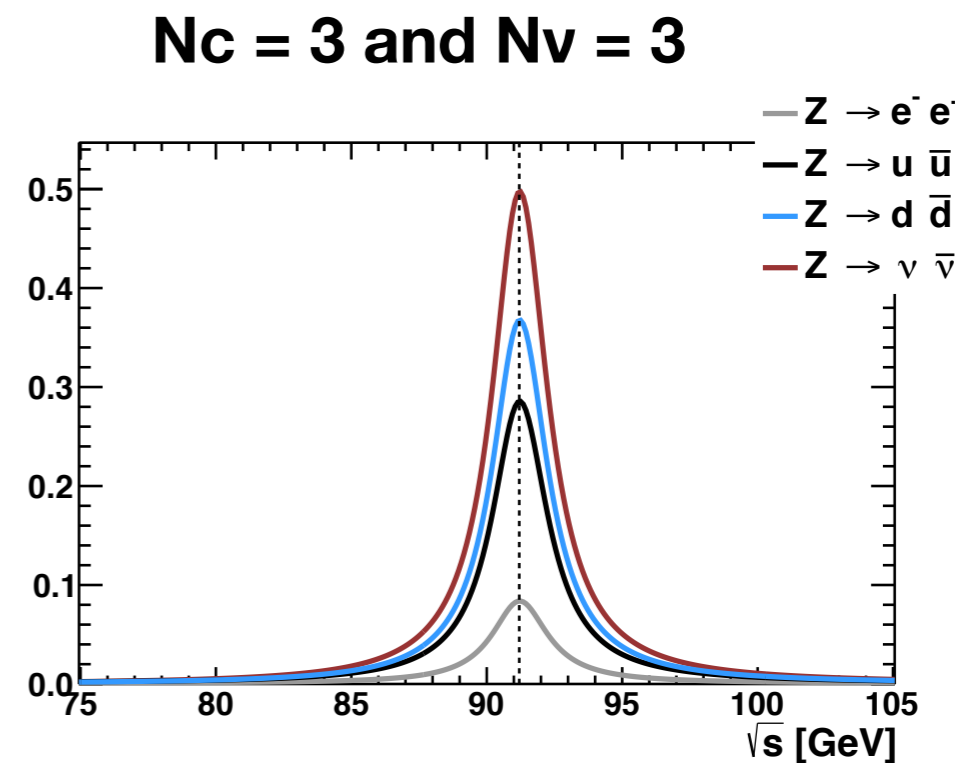
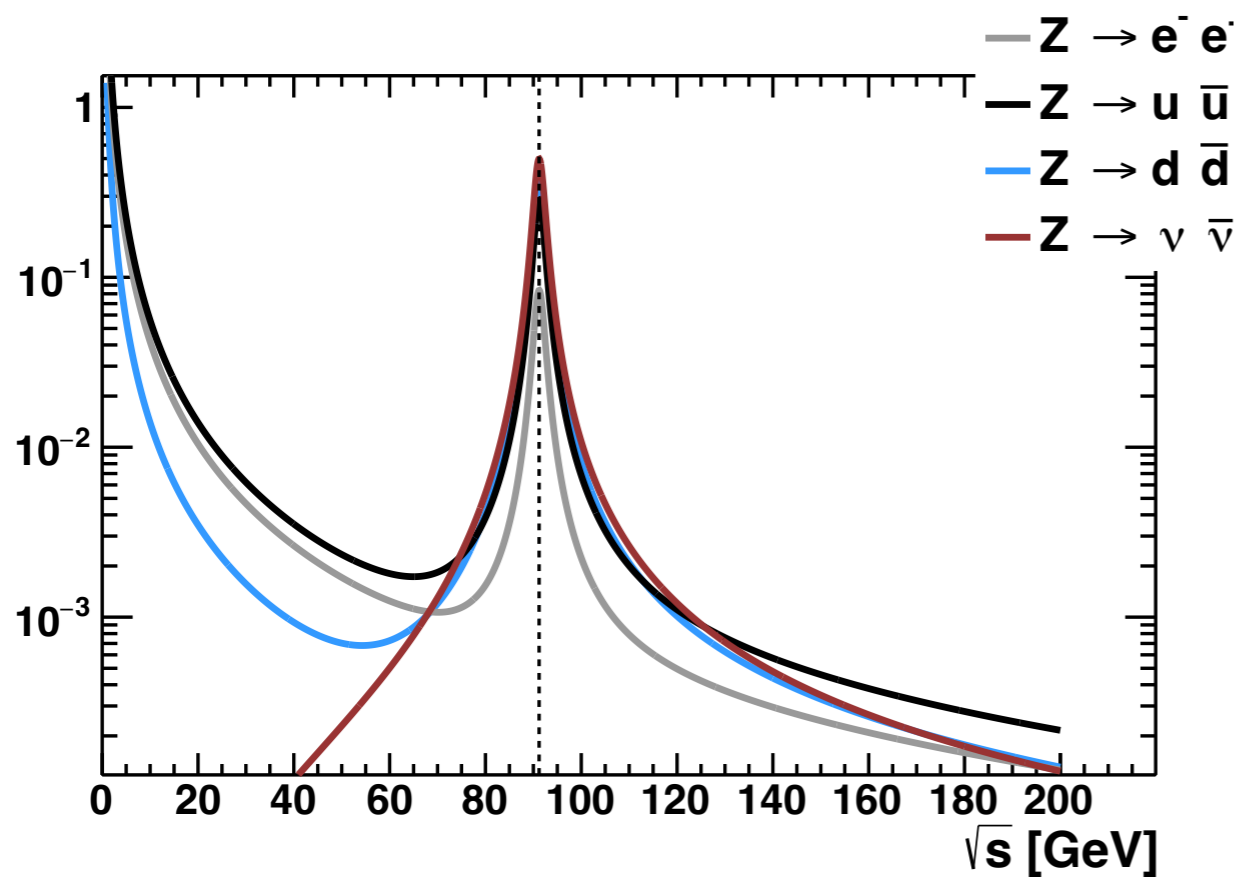
Predictions @ NLO

W mass includes 4 loops $O(\alpha_s^3 \alpha_t)$

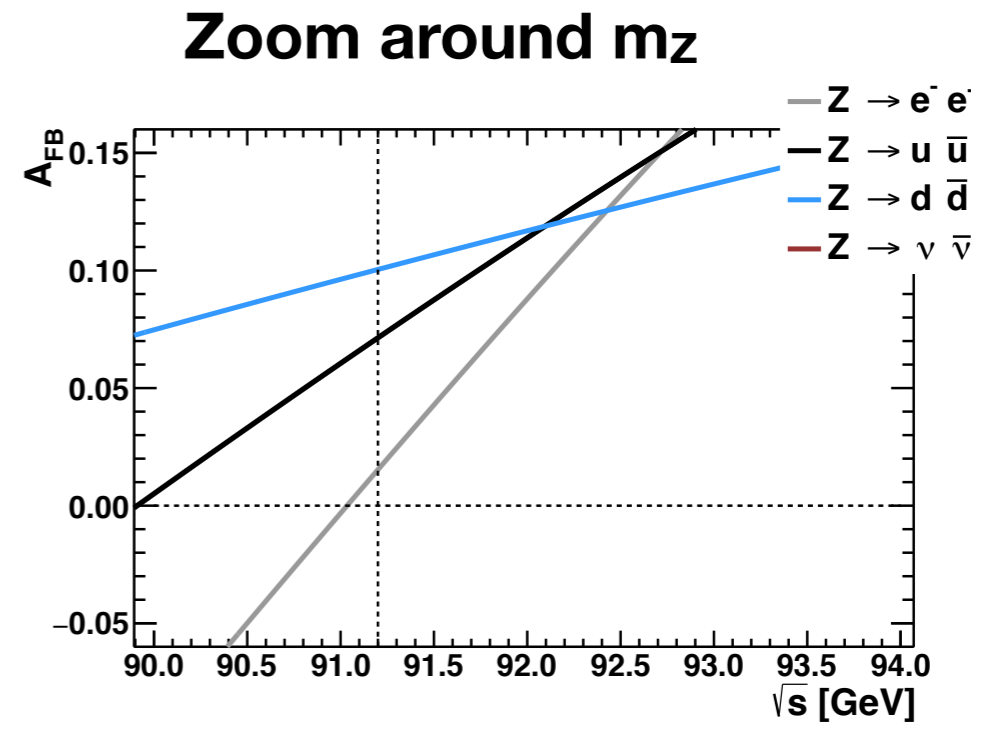
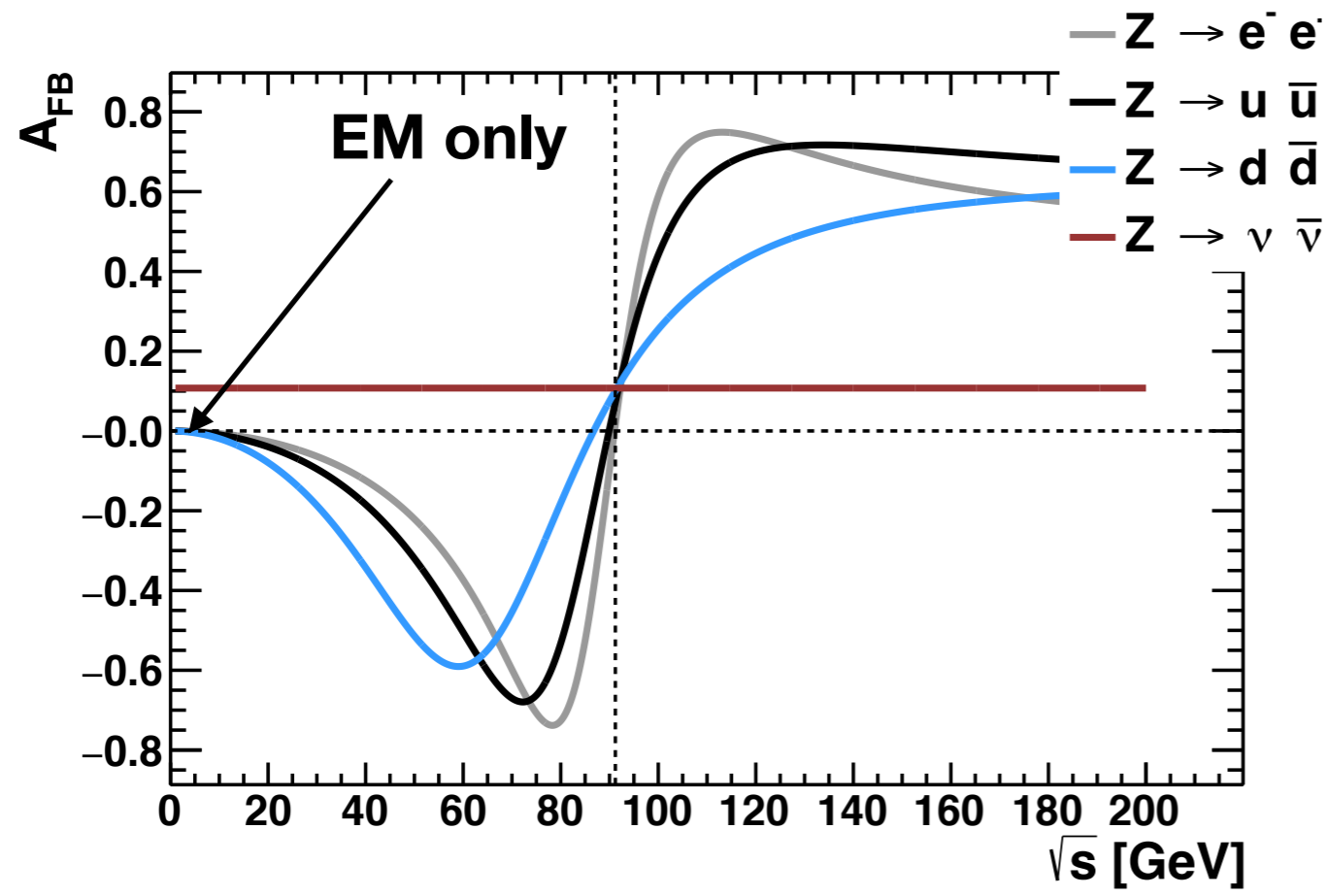
Γ_Z 2 loops

Following...
Exercise sheet 8
some plots

ES5: $Z - \gamma^*$ interference



ES5: Z - γ^* interference - A_{FB}



Neutrinos: not measurable but show the Z only asymmetry

\Rightarrow interference Z- γ^* dominant contribution to A_{FB}
(expect at the Z pole where it is zero)