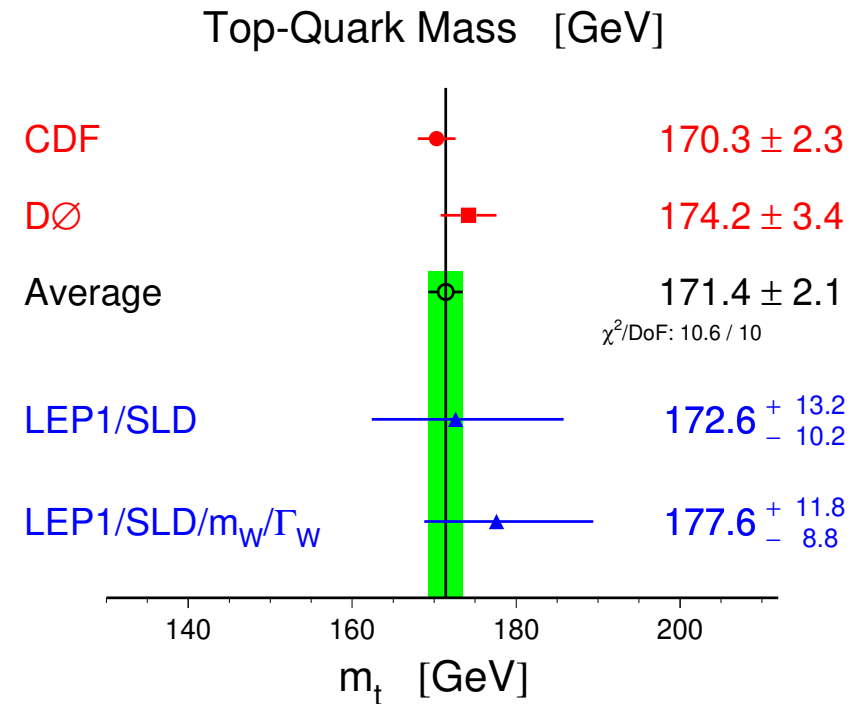
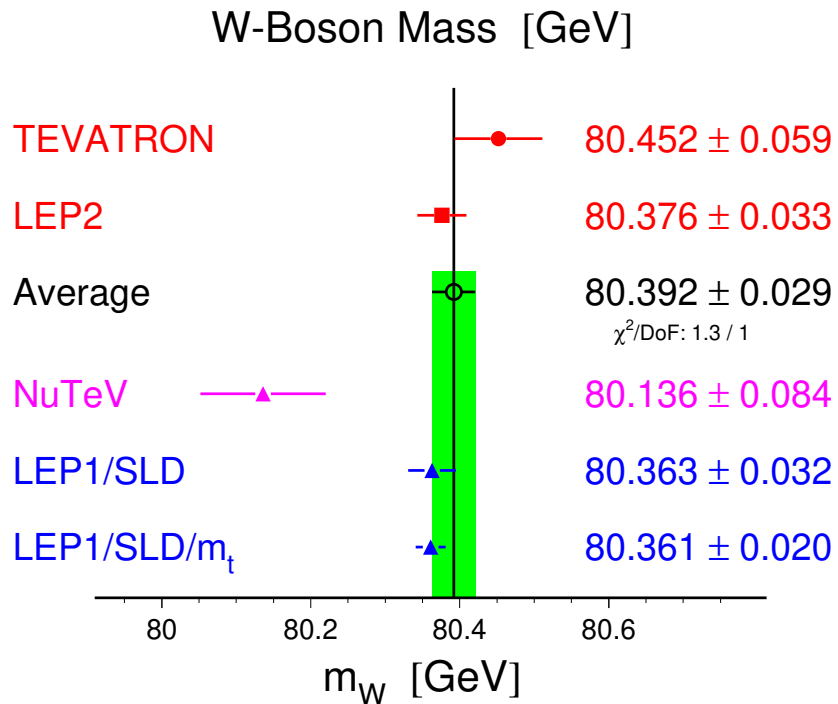


Indirect bound on m_h from M_W versus m_{top}

At one or more loop level

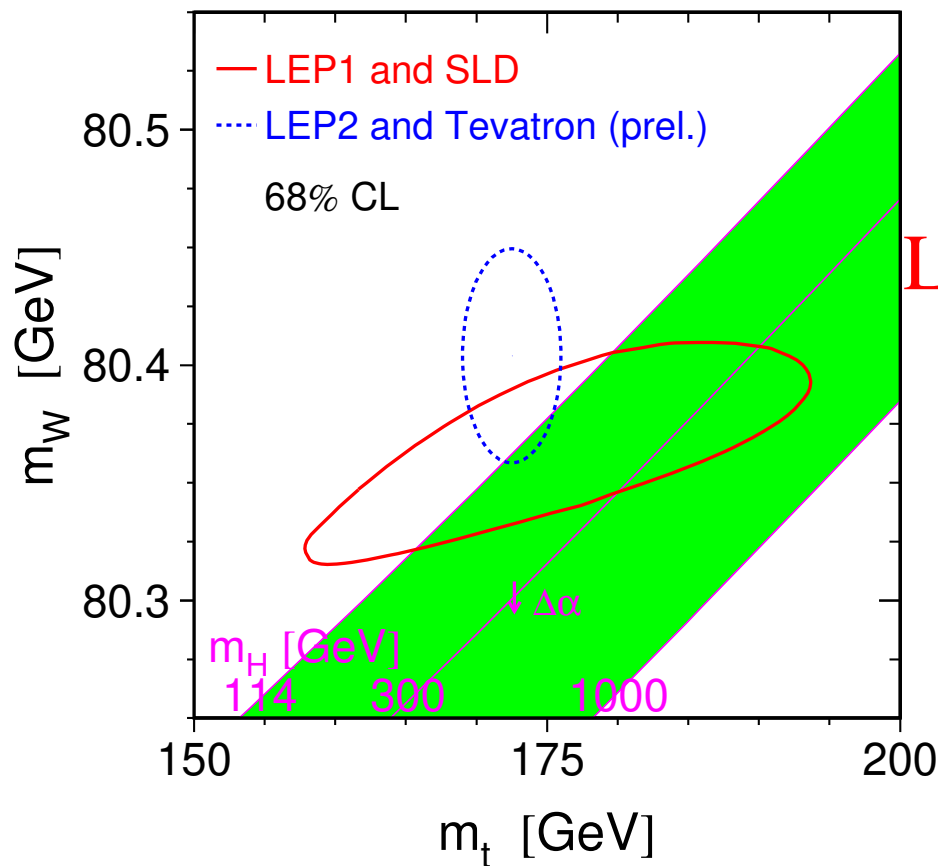
$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi\alpha}{\sqrt{2}G_F} \frac{1}{1 - \Delta r(m_{top}, m_h)}$$



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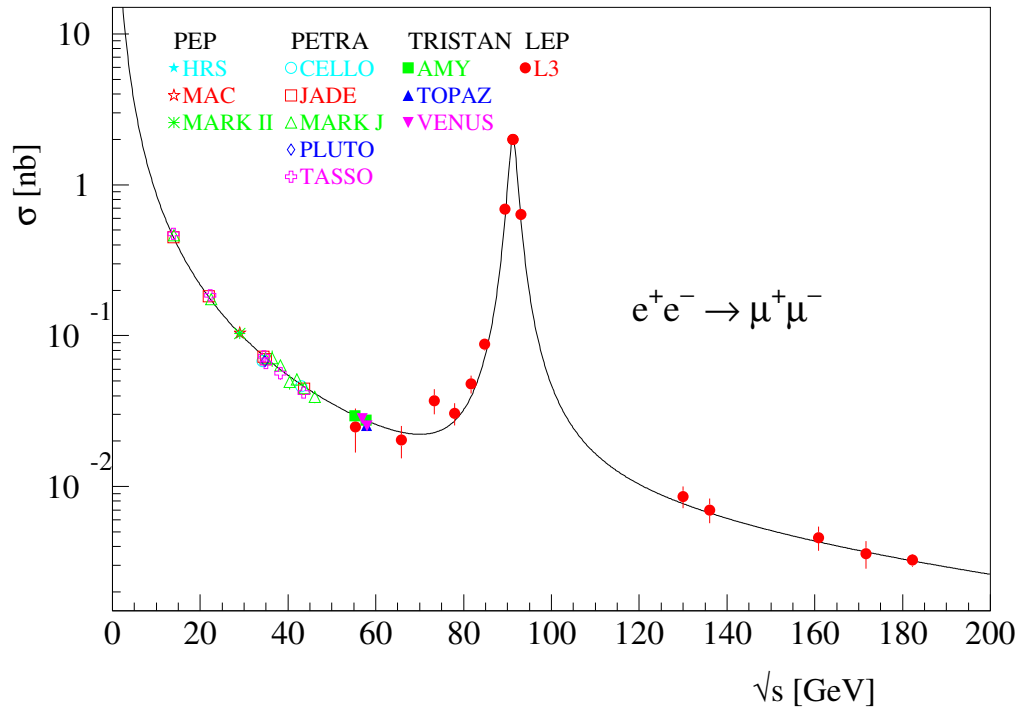


Light higgs favoured

$e^+e^- \rightarrow f\bar{f}$: Total cross section

$$\mathcal{L} = -eQ_f \bar{f}\gamma^\mu A_\mu f - \frac{g}{2\cos\theta_W} \bar{f}\gamma_\mu(g_V^d + g_A^f\gamma^5)f Z^\mu$$

$$\sigma = \frac{4\pi\alpha^2 N_c}{3s} Q_f^2 + \frac{N_c G_F^2 M_Z^4 s}{6\pi[(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2]} (g_V^e{}^2 + g_A^e{}^2)(g_V^f{}^2 + g_A^f{}^2) + \frac{4N_c\alpha G_F M_Z^2 (s - M_Z^2)}{3\sqrt{2}[(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2]} Q_f g_V^e g_V^f$$

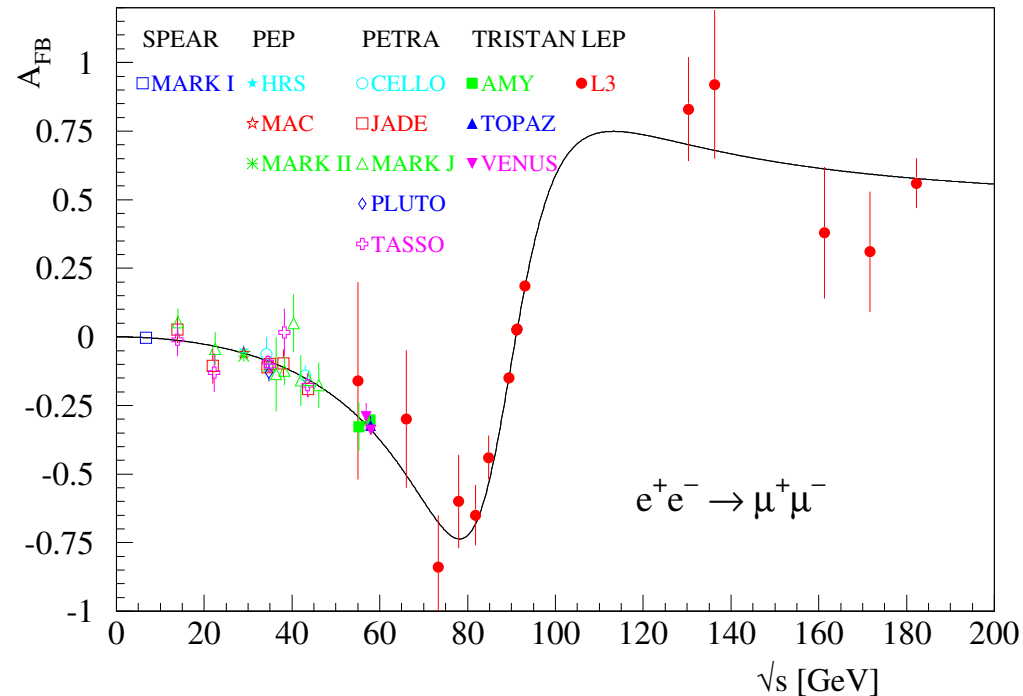


$e^+e^- \rightarrow f\bar{f}$: Forward-Backward asymmetry

$$\frac{d\sigma}{d\cos\theta} = \frac{N_c\pi\alpha^2}{2s} Q_f^2 (1 + \cos^2\theta) - \frac{N_c\alpha G_F M_Z^2 (s - M_Z^2) Q_f}{2\sqrt{2}[(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2]} \left[g_V^e g_V^f (1 + \cos^2\theta) + 2g_A^e g_A^f \cos\theta \right]$$

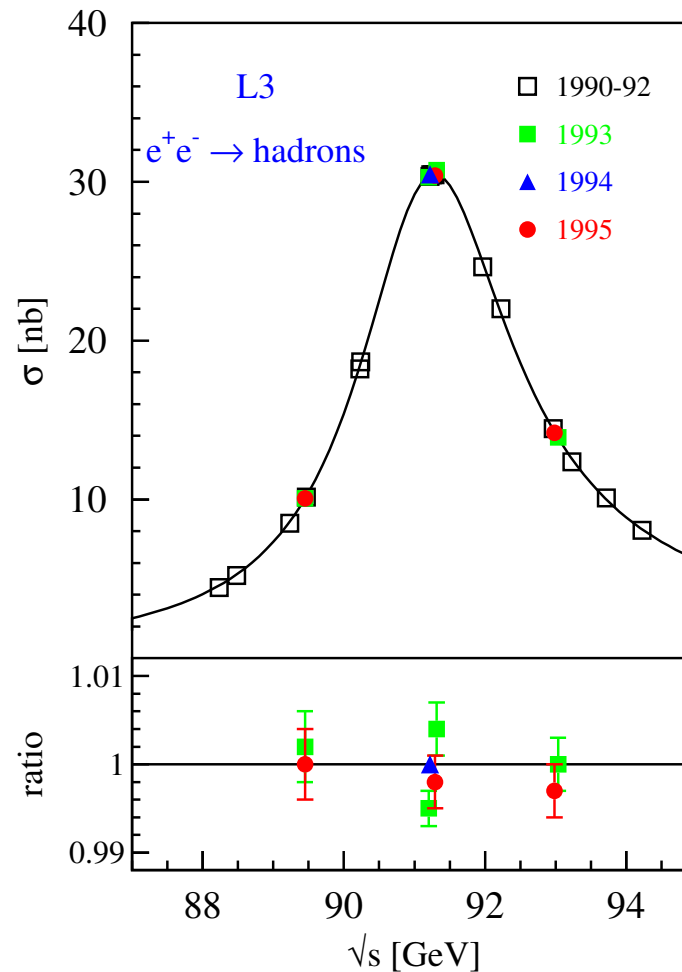
$$+ \left. \frac{G_F^2 M_Z^4 s}{16\pi[(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2]} (g_V^e{}^2 + g_A^e{}^2)(g_V^f{}^2 + g_A^f{}^2)(1 + \cos^2\theta) + 2g_V^e g_A^e g_V^f g_A^f \cos\theta \right\}$$

$$A_{FB} = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta} - \int_{-1}^0 \frac{d\sigma}{d\cos\theta}}{\int_{-1}^1 \frac{d\sigma}{d\cos\theta}}$$



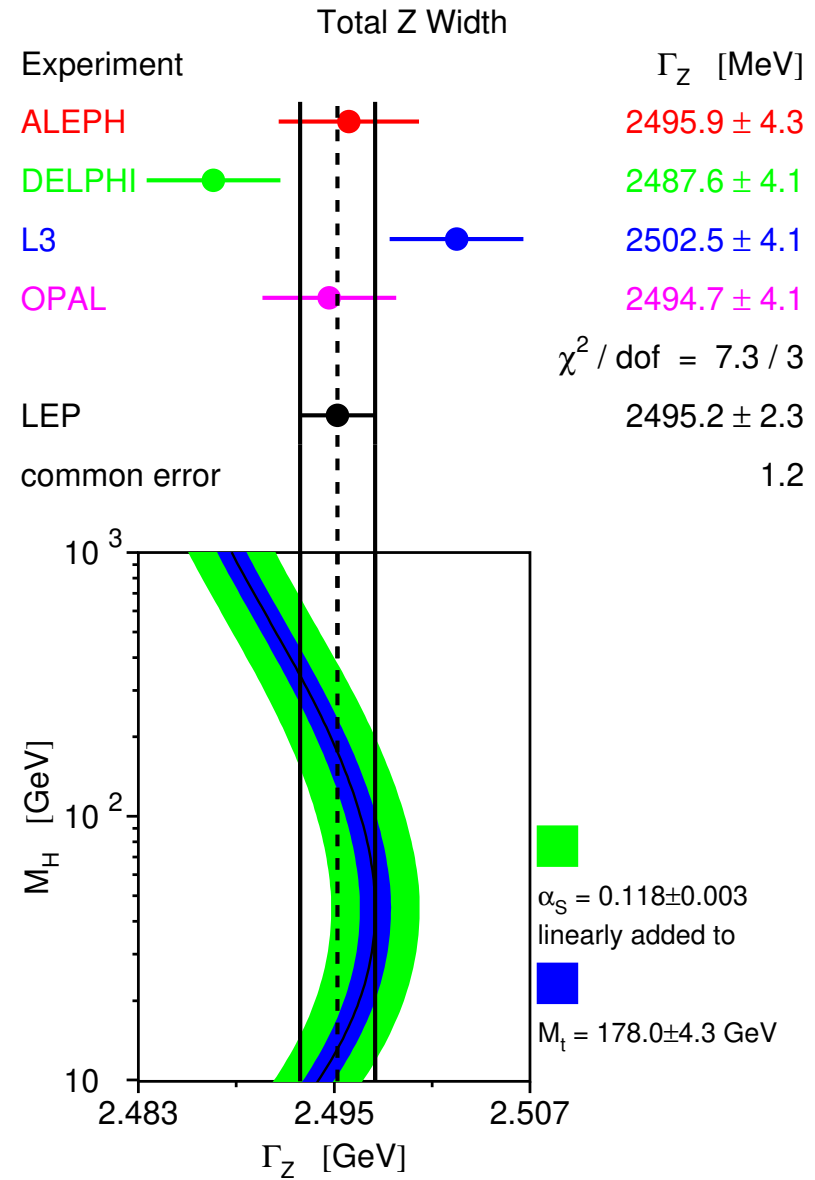
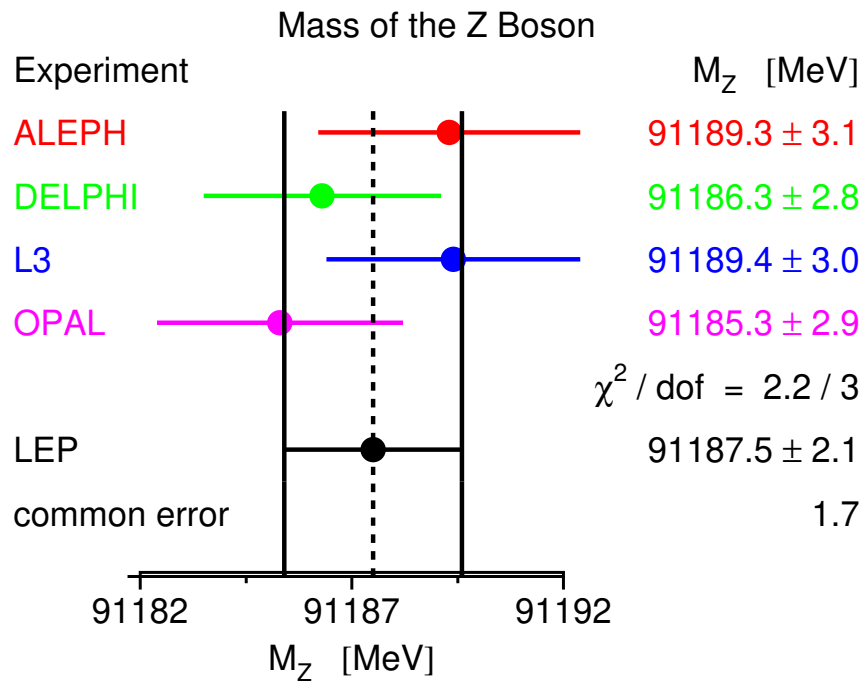
$$e^+e^- \rightarrow f\bar{f} \text{ at } \sqrt{s} \sim M_Z$$

- LEP (CERN) produced 2×10^7 unpolarized Z's
- SLD (SLAC) produced 2×10^5 Z's with $P_e \sim 75\%$



$\Rightarrow M_Z$ and Γ_Z

$$e^+e^- \rightarrow f\bar{f} \text{ at } \sqrt{s} \sim M_Z$$



$$e^+e^- \rightarrow f\bar{f} \text{ at } \sqrt{s} \sim M_Z$$

- The decay width into the different fermions:

$$\Gamma(Z \rightarrow \bar{f}f) = \frac{G_F M_Z^3}{6\sqrt{2}\pi} N_C^f (g_V^{f^2} + g_A^{f^2})$$

- The forward-backward asymmetry

$$A_{FB}(M_Z) = 3 \frac{g_V^f g_A^f}{(g_V^{f^2} + g_A^{f^2})} \frac{g_V^e g_A^e}{(g_V^{e^2} + g_A^{e^2})}$$

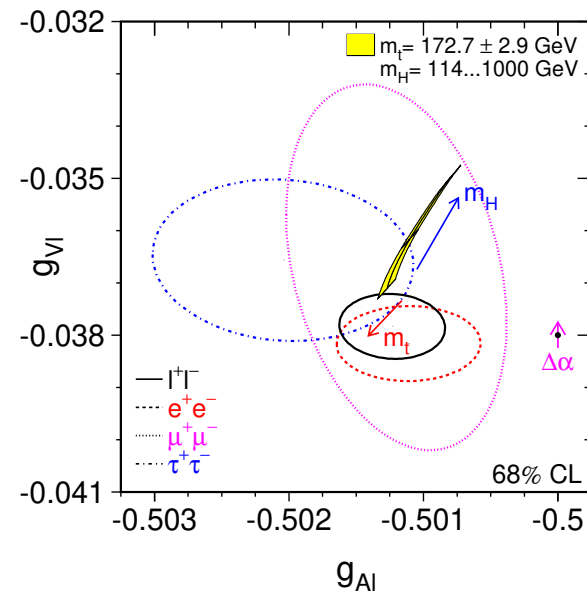
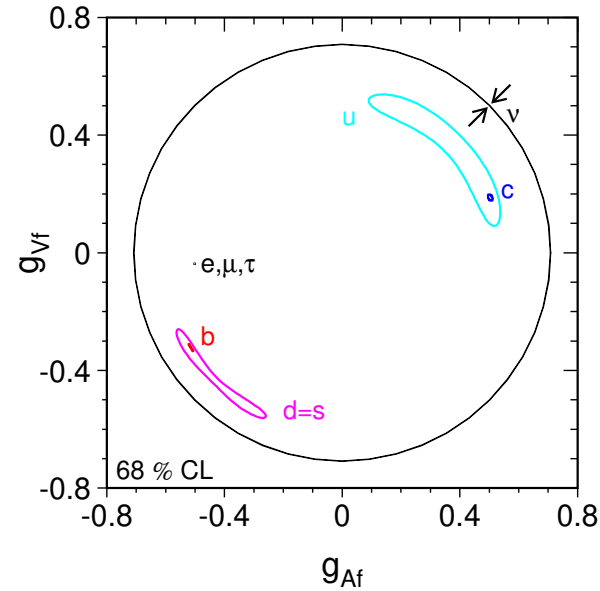
⇒ Good determination of couplings

$$g_V^f = T_3^f - 2Q_f \sin^2 \theta_W$$

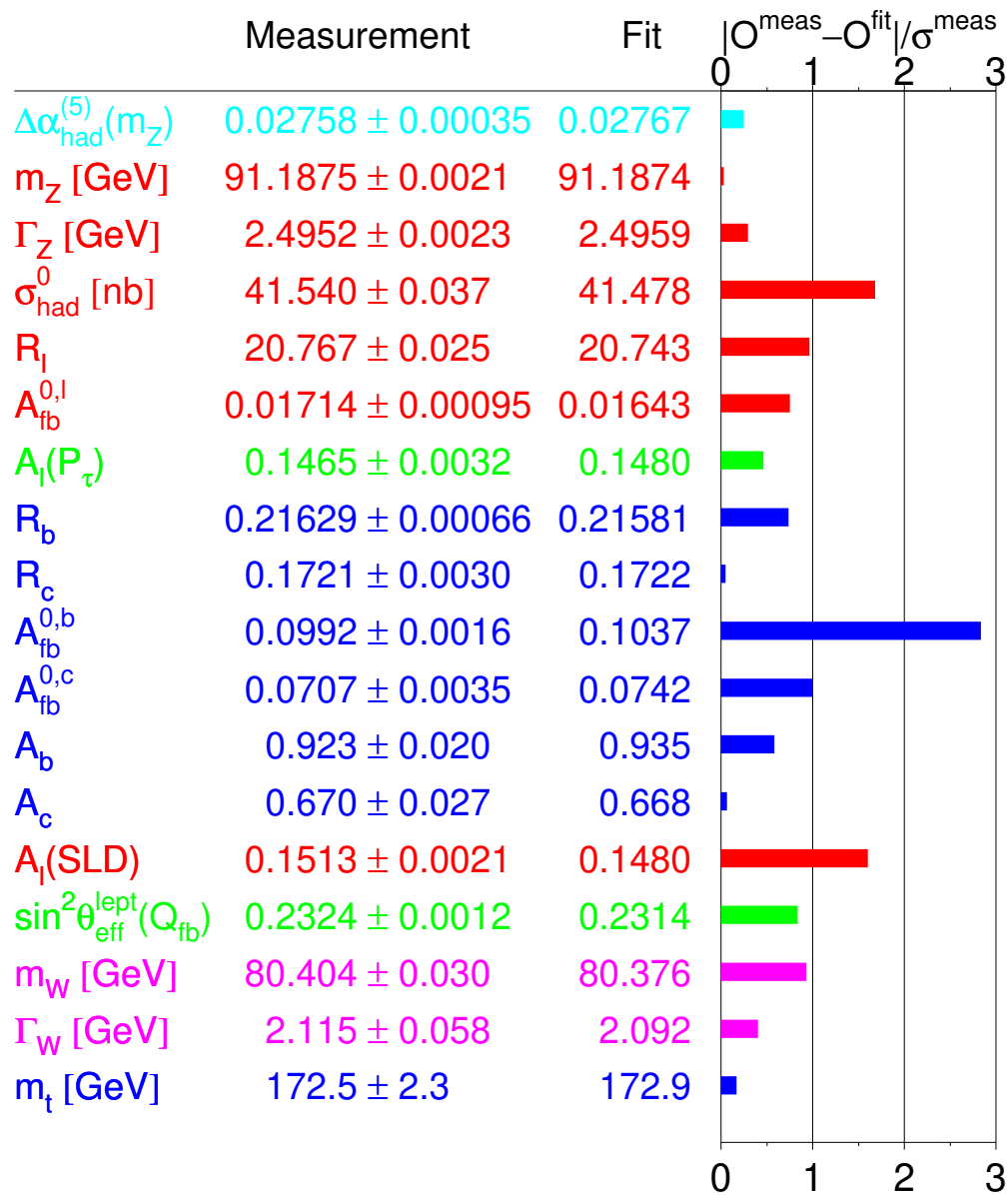
$$g_A^f = T_3^f$$

Where including loop corrections

$$\overline{\sin^2 \theta_W} = \left(1 - \frac{M_W^2}{M_Z^2} \right) \Delta(m_{\text{top}}, M_H)$$

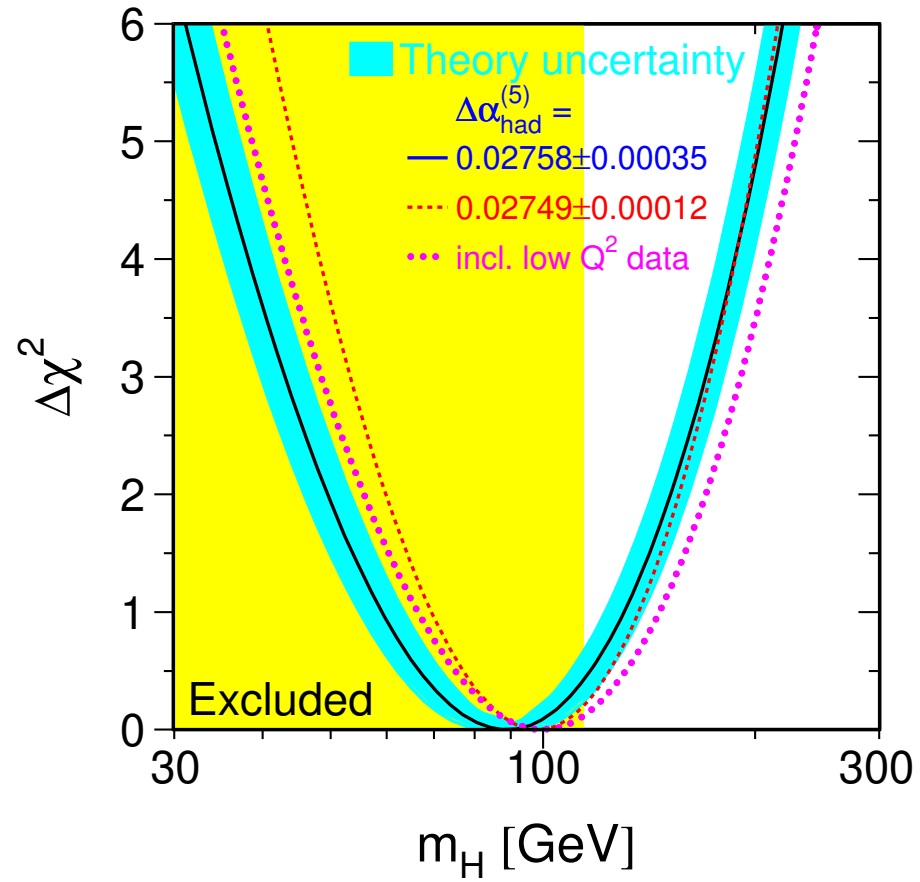


Precision Electroweak Observations



Tested with 1% precision, but...

Light Higgs Required !!!



The Higgs Decay Modes

$$\Gamma(h \rightarrow f\bar{f}) = \frac{G_F m_f^2 (N_c)}{4\sqrt{2}\pi} M_h (1 - r_f)^{\frac{3}{2}} \quad r_i \equiv \frac{4M_i^2}{M_h^2}$$

$$\Gamma(h \rightarrow W^+W^-) = \frac{G_F M_h^3}{8\pi\sqrt{2}} \sqrt{1 - r_W} (1 - r_W + \frac{3}{4}r_W^2)$$

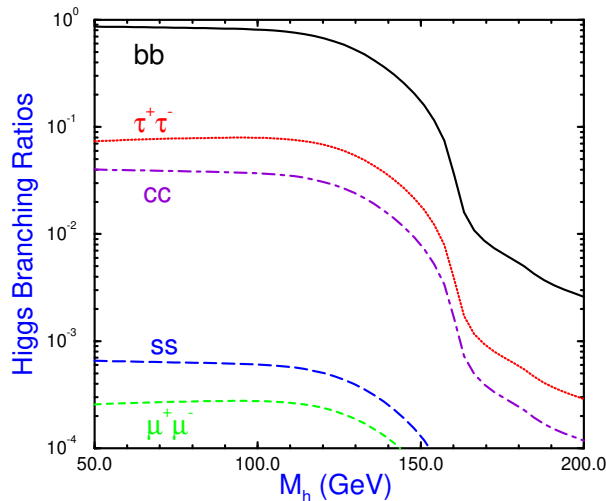
$$\Gamma(h \rightarrow ZZ) = \frac{G_F M_h^3}{8\pi\sqrt{2}} \sqrt{1 - r_Z} (1 - r_Z + \frac{3}{4}r_Z^2)$$

$$\Gamma_0(h \rightarrow gg) = \frac{G_F \alpha_s^2 M_h^3}{64\sqrt{2}\pi^3} \left| \sum_q F_{1/2}(r_q) \right|^2 \quad \Gamma(h \rightarrow \gamma\gamma) = \frac{\alpha^2 G_F}{128\sqrt{2}\pi^3} g_V M_h^3 \left| \sum_{q,W} N_{ci} Q_i^2 F_i(r_i) \right|^2$$

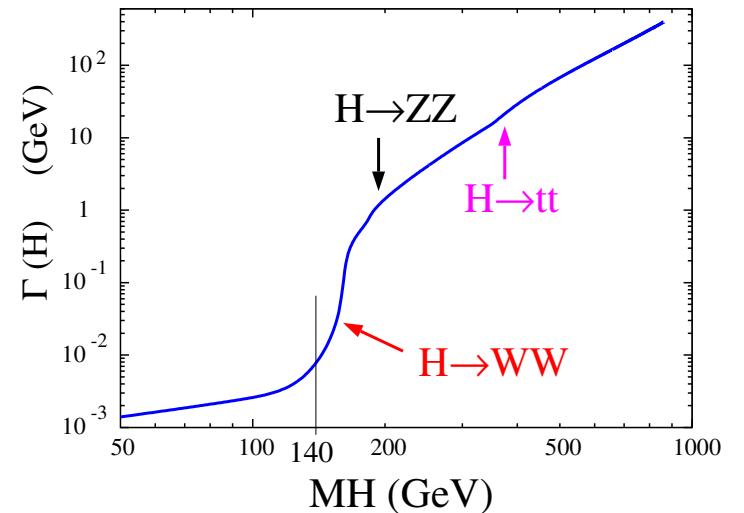
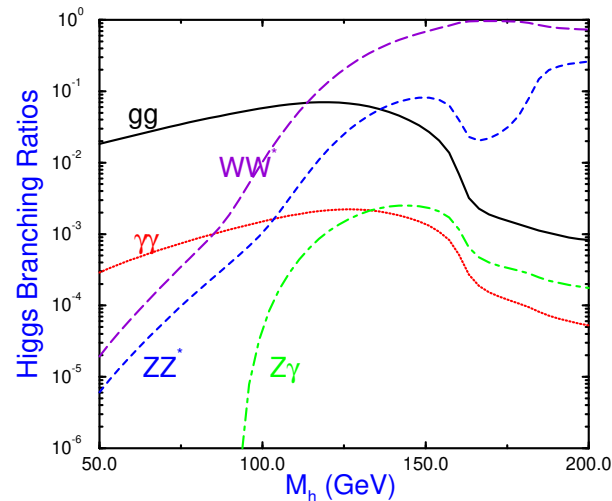
$$F_{1/2}(r_q) \equiv -2r_q [1 + (1 - r_q)f(r_q)] \quad F_W(r_W) = 2 + 3r_W [1 + (2 - r_W)f(r_W)]$$

$$f(x) = \begin{cases} \sin^{-2}(\sqrt{1/x}), & \text{if } x \geq 1 \\ -\frac{1}{4} \left[\log \left(\frac{1 + \sqrt{1-x}}{1 - \sqrt{1-x}} \right) - i\pi \right]^2, & \text{if } x < 1, \end{cases}$$

Higgs Branching Ratios to Fermion Pairs



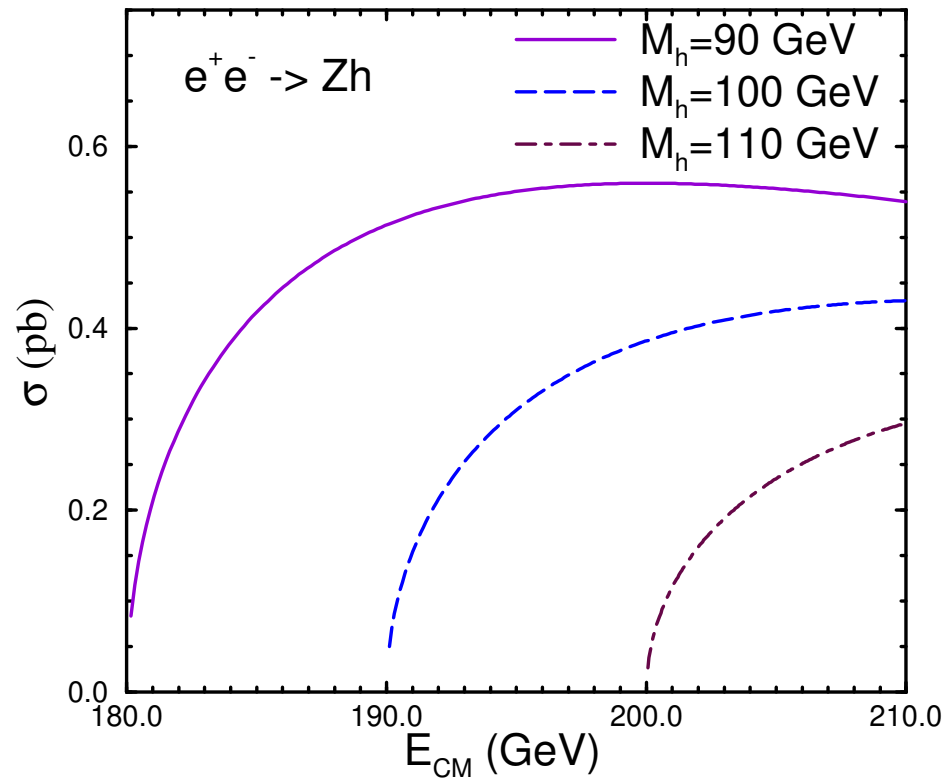
Higgs Branching Ratios to Gauge Boson Pairs



Higgs Production at e^+e^-

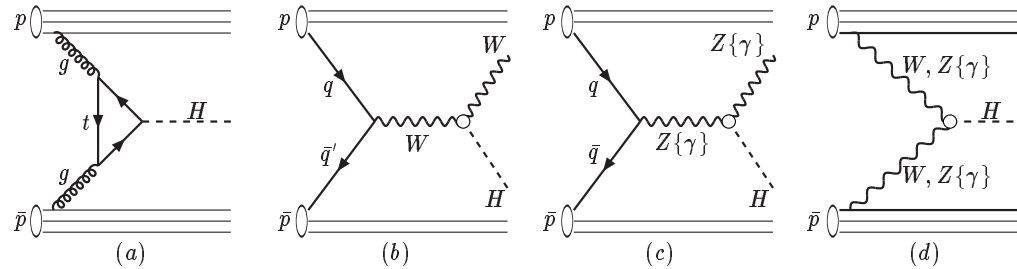
$$\sigma(e^+e^- \rightarrow Zh) = \frac{\pi\alpha^2 \lambda_{Zh}^{1/2} [\lambda_{Zh} + 12 \frac{M_Z^2}{s}] [1 + (1 - 4 \sin^2 \theta_W)^2]}{192s \sin^4 \theta_W \cos^4 \theta_W (1 - M_Z^2/s)^2}$$

$$\lambda_{Zh} \equiv \left(1 - \frac{M_h^2 + M_Z^2}{s}\right)^2 - \frac{4M_h^2 M_Z^2}{s^2} \quad s = (p_{e^+} + p_{e^-})^2$$

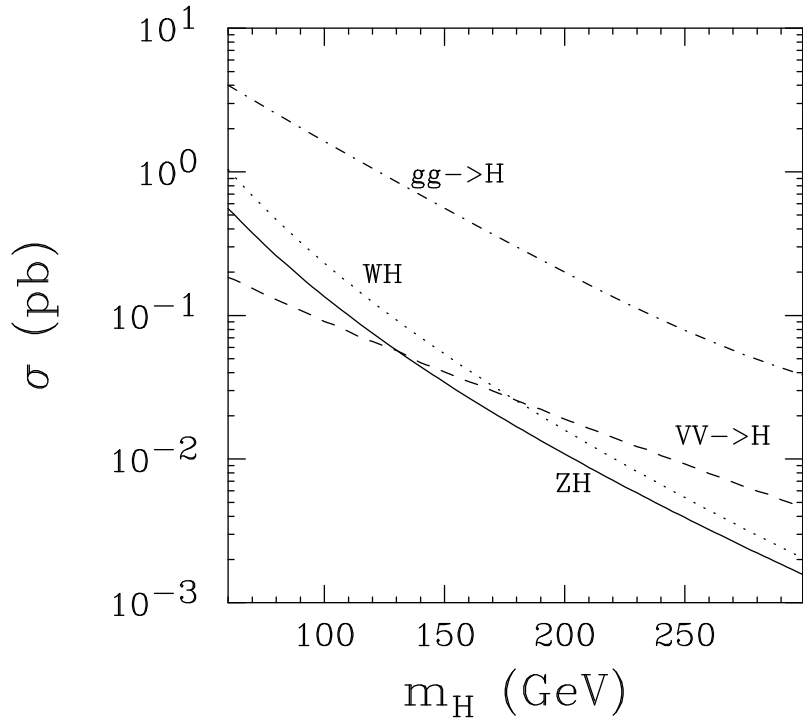


Searches at LEP (e^+e^- $\sqrt{s} = 90 - 210$ GeV) $\Rightarrow M_H \geq 114.4$ GeV

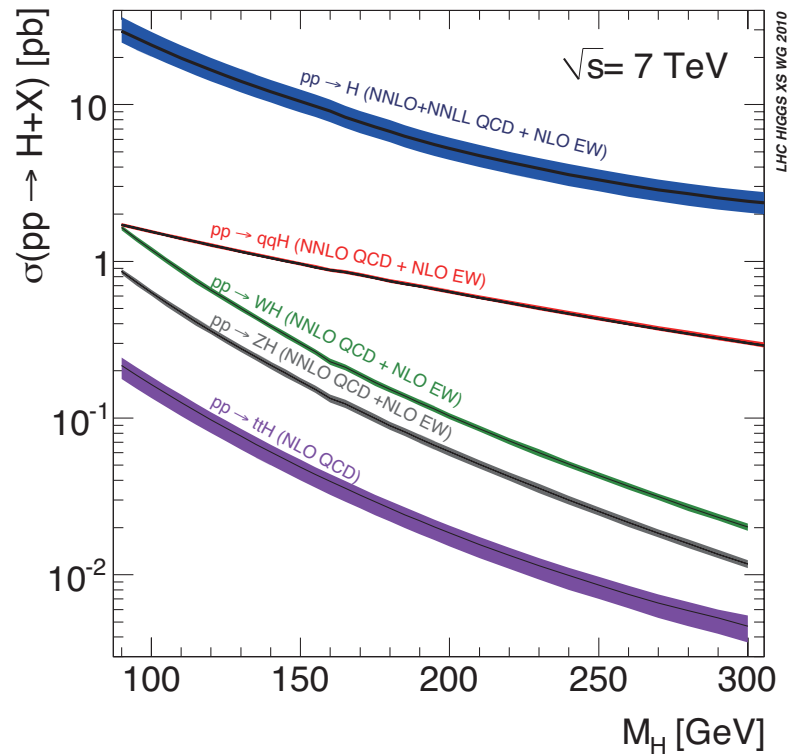
Higgs Production at Hadron Colliders



Tevatron ($p\bar{p}$ $\sqrt{s} = 2$ TeV)



LHC (pp $\sqrt{s} = 7-14$ TeV)



Higgs Production at LHC 7-8 TeV

SM main discovery modes for $\simeq 125$ GeV:

$pp \rightarrow \gamma\gamma$

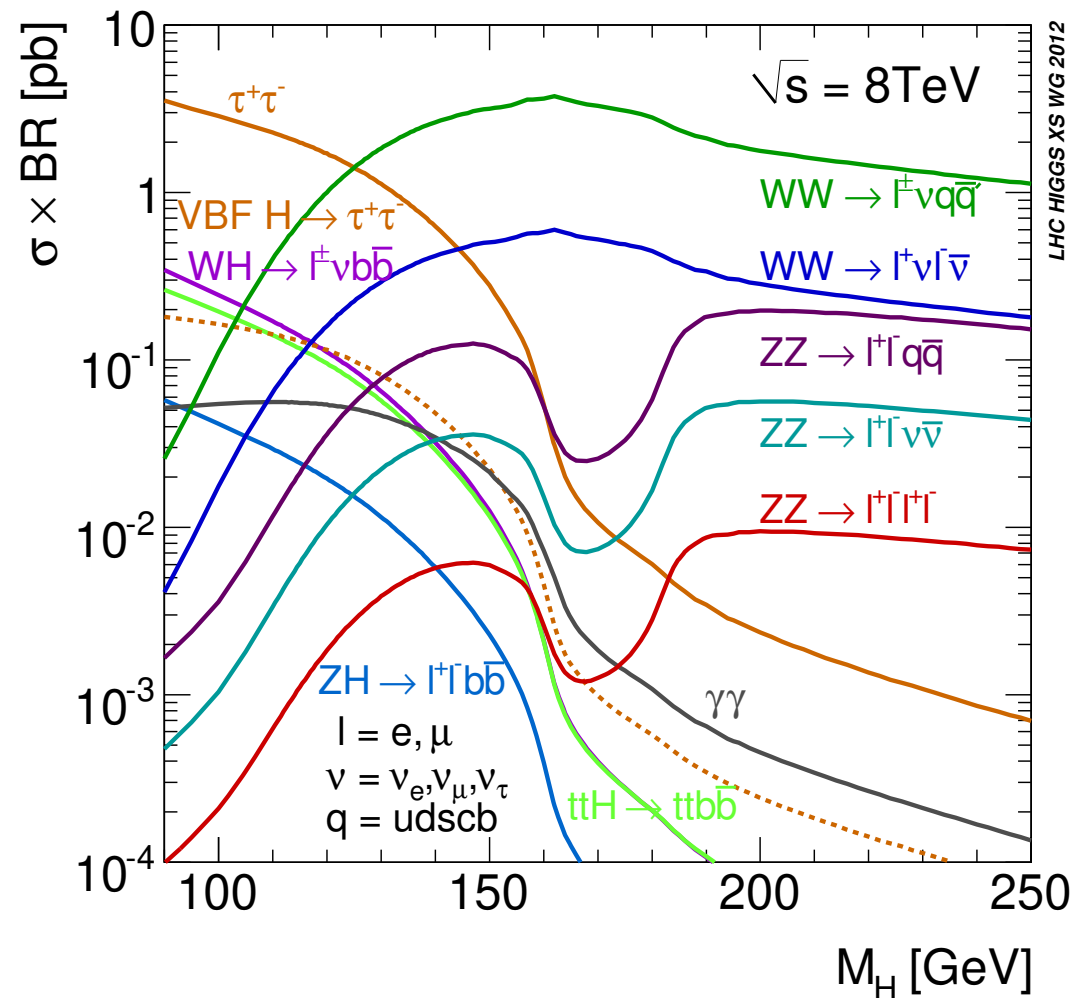
$pp \rightarrow ZZ \rightarrow llll$

$pp \rightarrow WW \rightarrow l\nu l\nu$

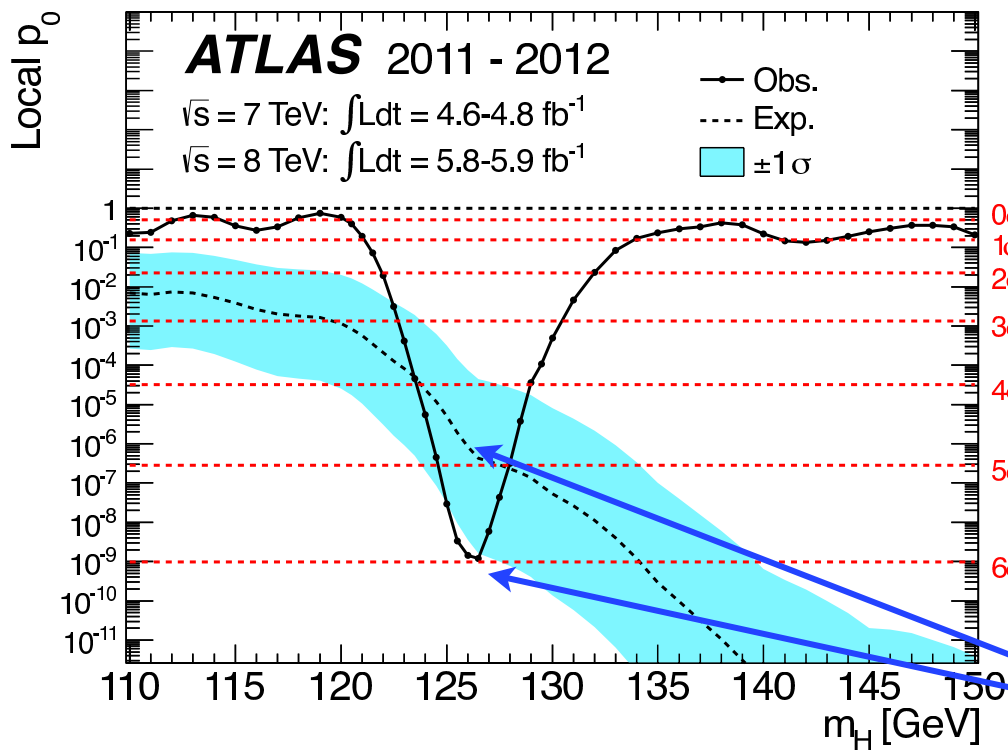
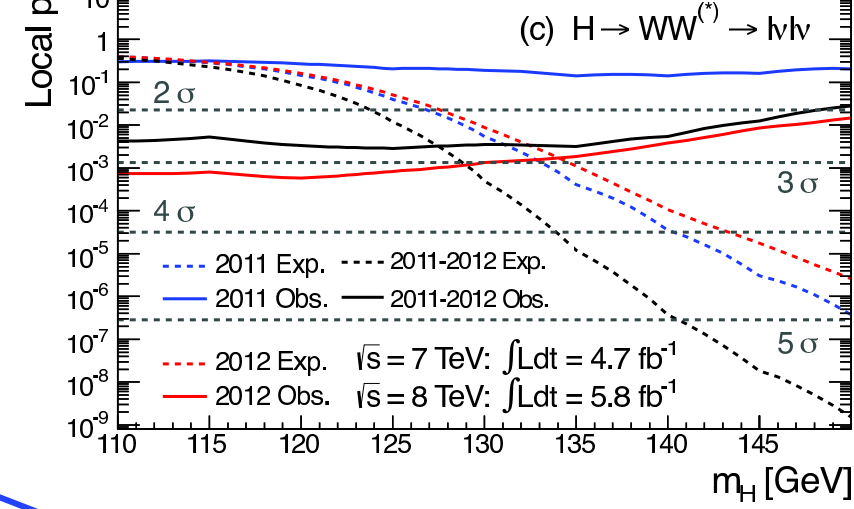
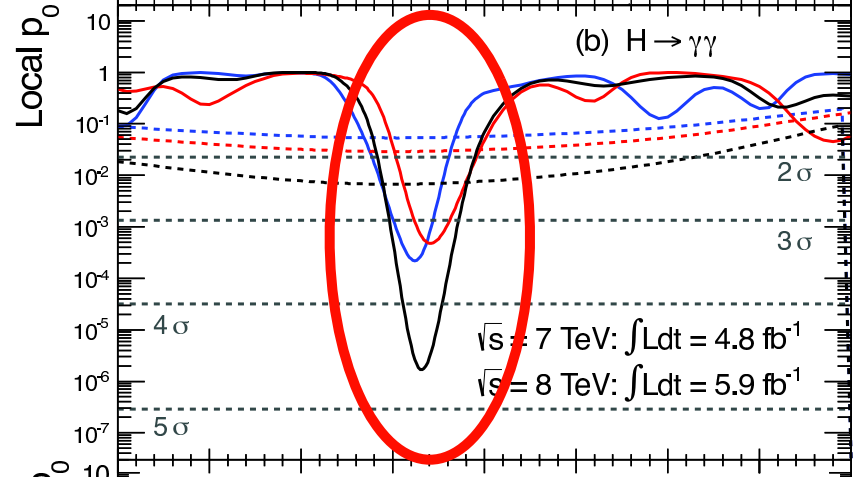
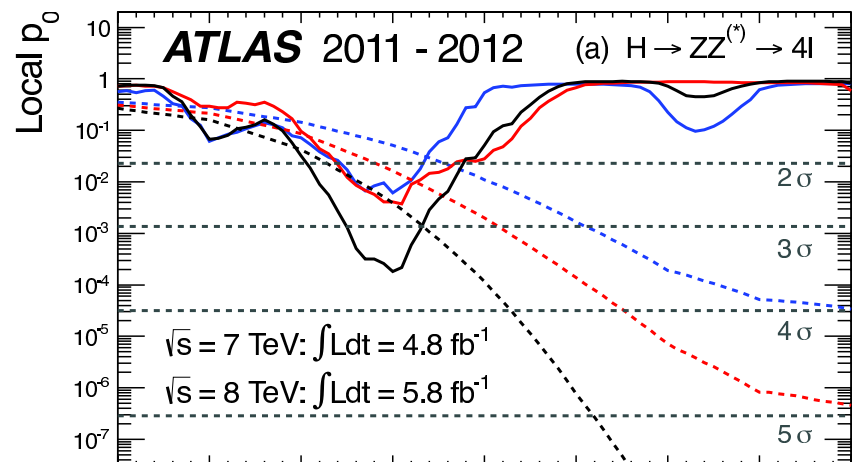
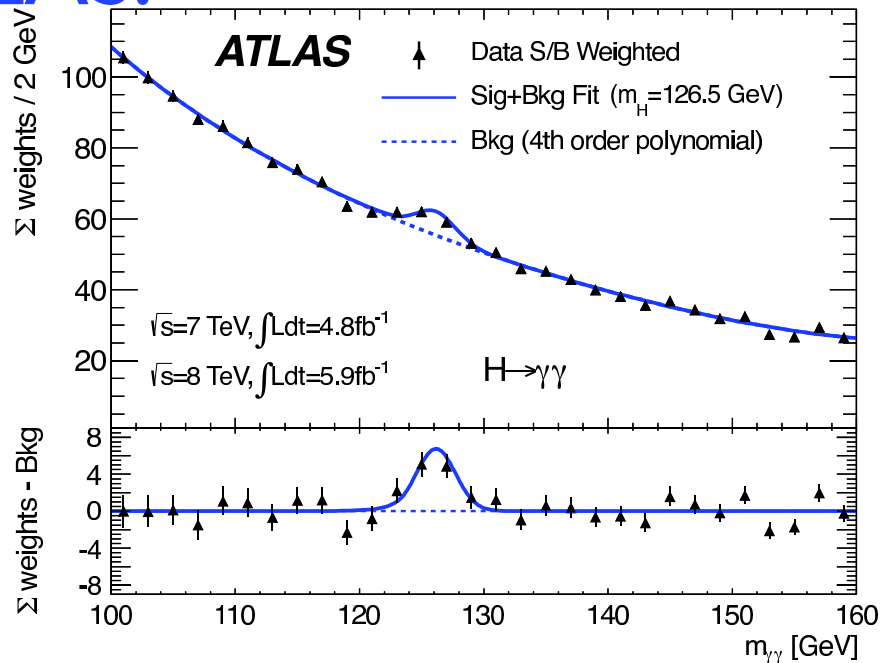
Also may be possible in:

$pp \rightarrow b\bar{b}$ (only VH)

$pp \rightarrow \tau\bar{\tau}$



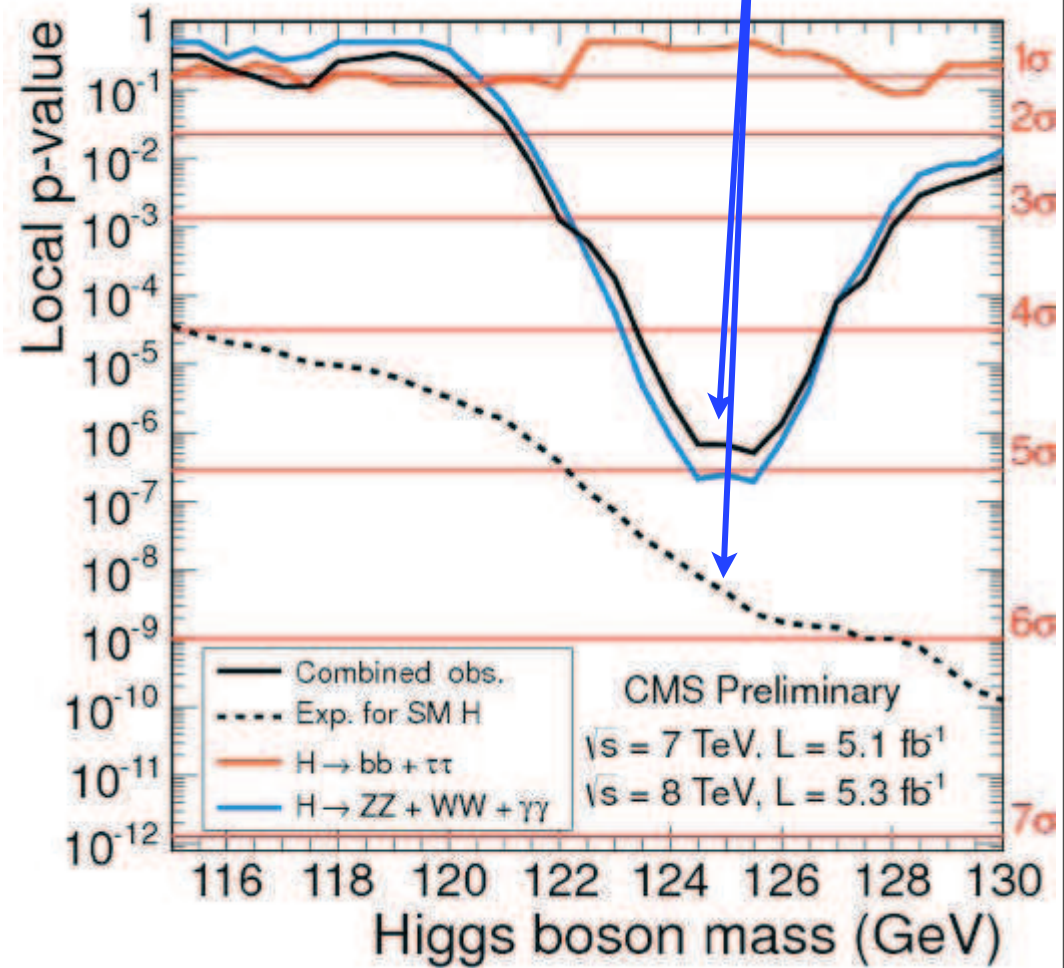
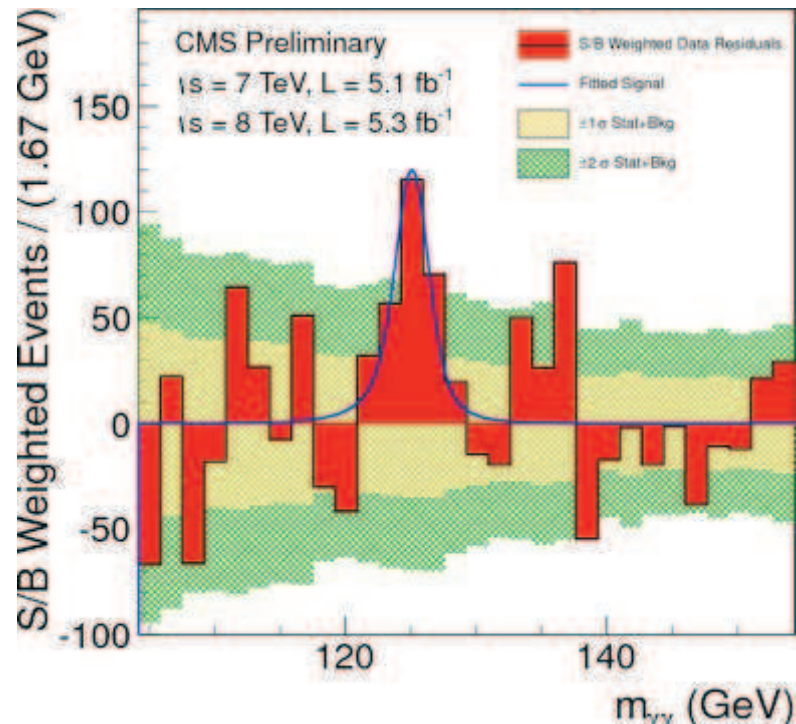
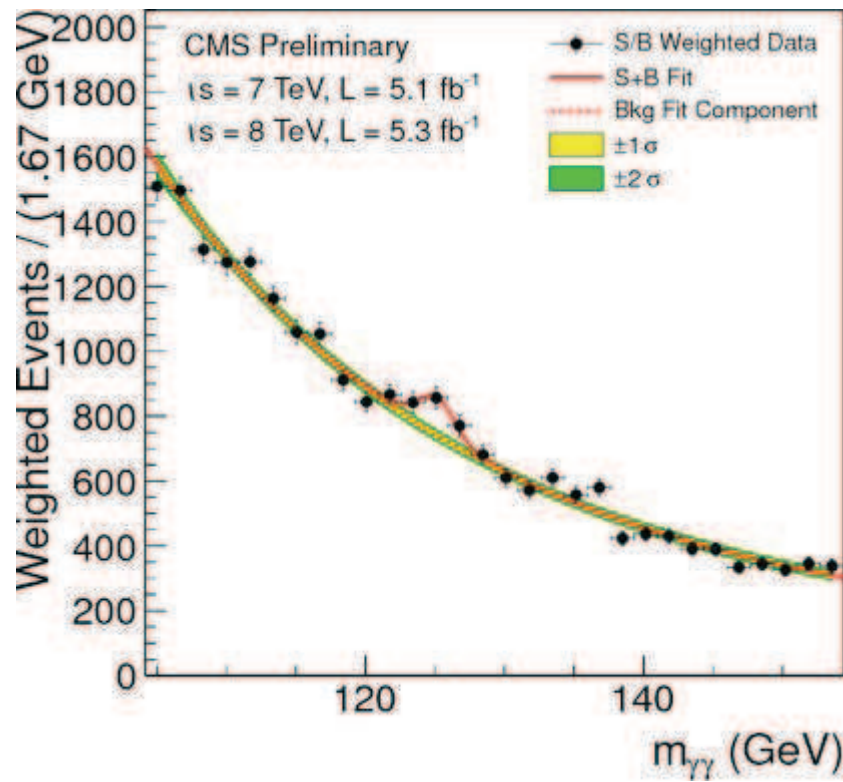
ATLAS:



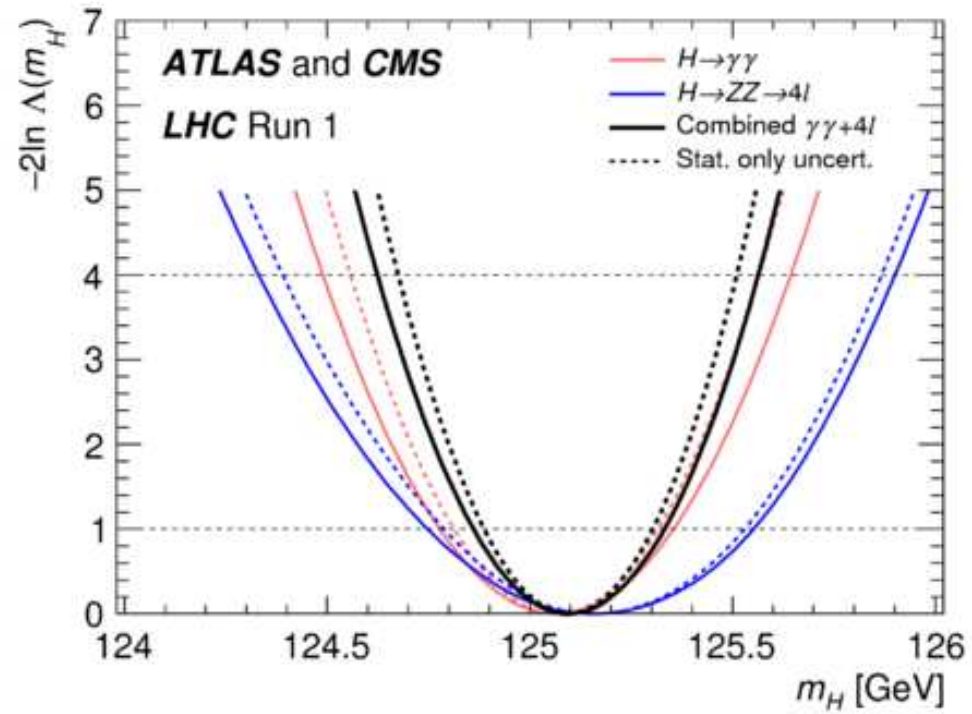
better than expected

CMS:

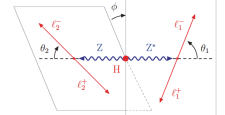
less than expected



Measured Higgs Mass

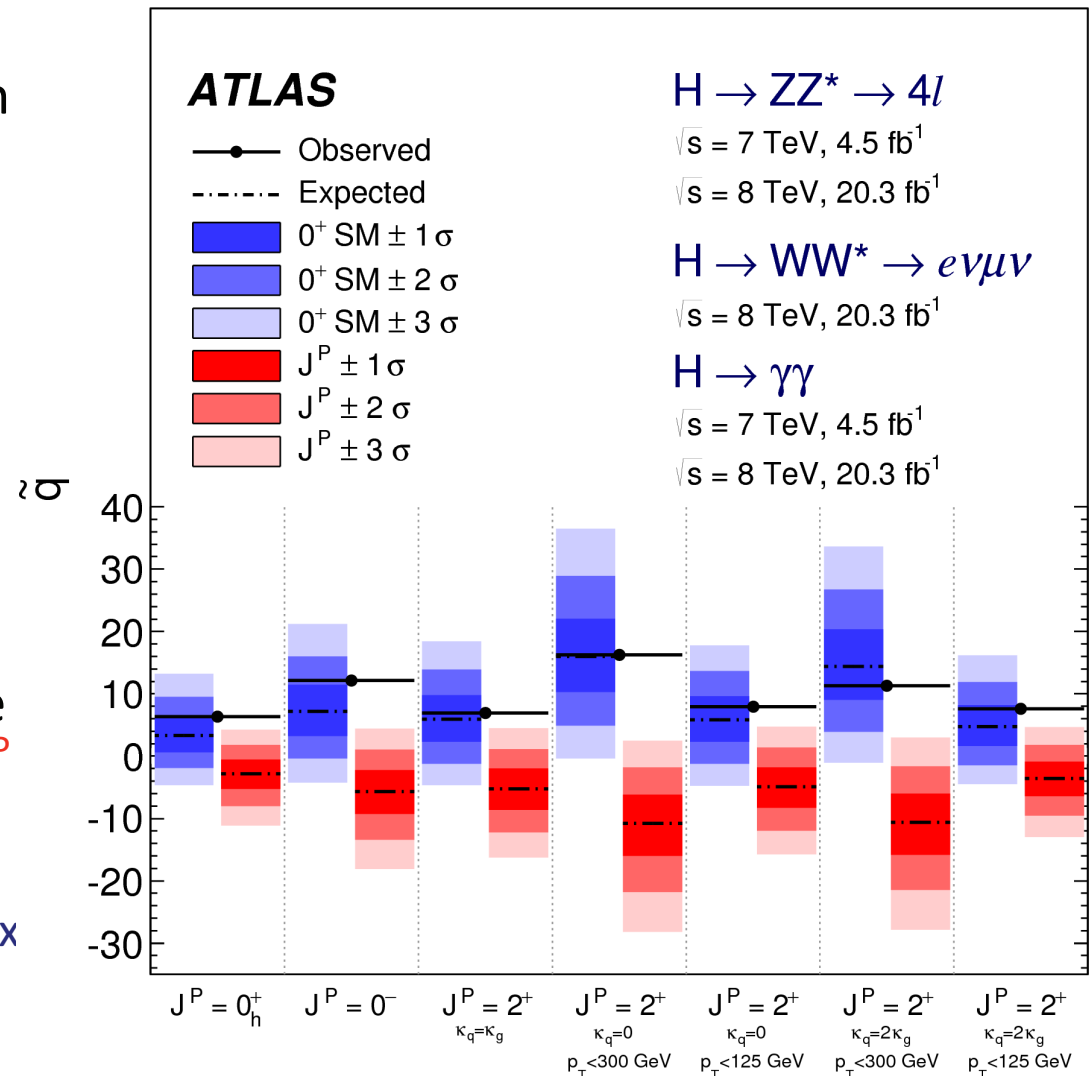


Spin-Parity Determination



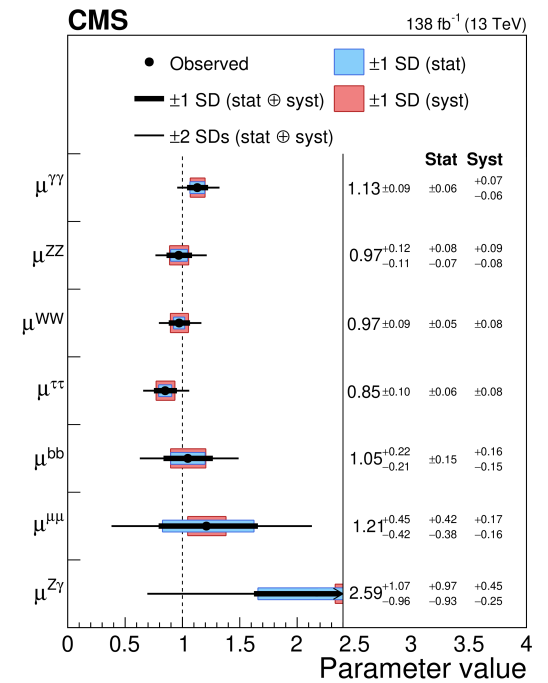
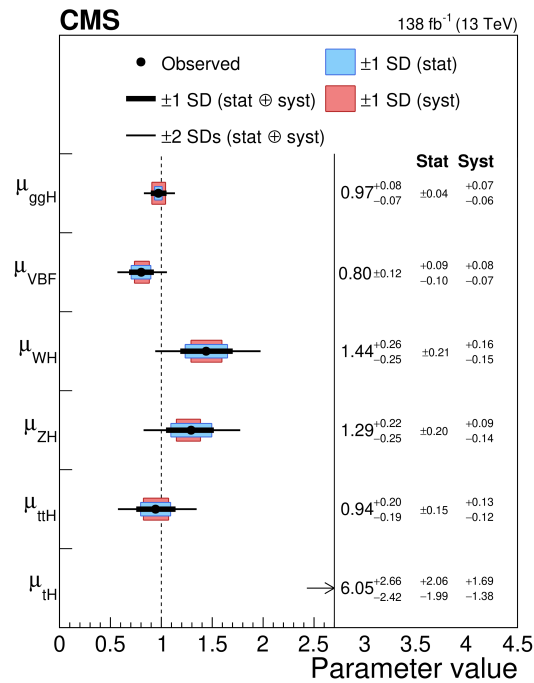
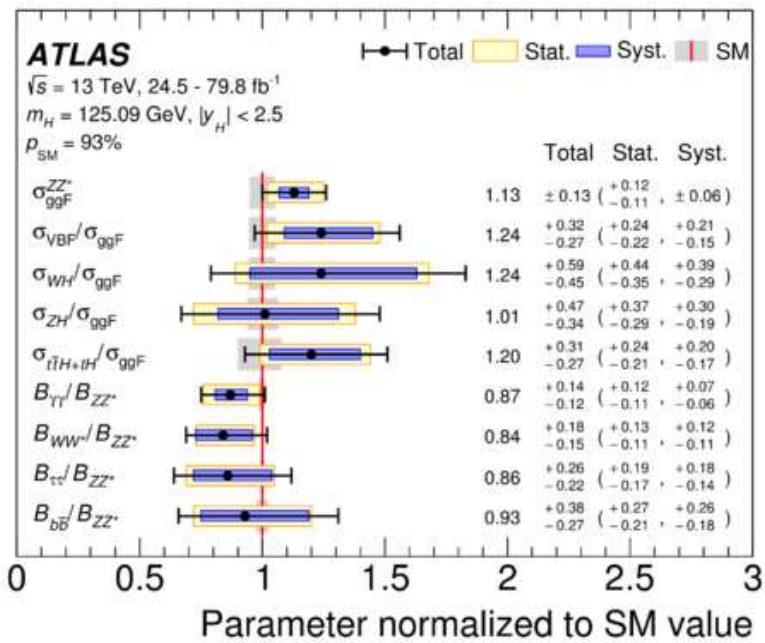
Analyzed channels:

- $H \rightarrow \gamma\gamma$ decay angle $\cos(\theta^*)$ in Collins-Sopper frame sensitive to J
- $H \rightarrow WW^* \rightarrow e\nu e\nu$ Several variables sensitive to J^P
 - $\Delta\phi_{ee}, M_{ee}, \dots$
 - Combined with Boosted-Decision-Tree (BDT)
- $H \rightarrow ZZ^* \rightarrow 4\ell$: Full final state reconstruction sensitive to J^P
 - 2 masses (M_{Z1}, M_{Z2}) and 5 angles
 - Combined with BDT or Matrix Element-based discriminant D_{JP}



Observed Production+Decay Channels in Brief

$$\mu = \frac{(\sigma)_{obs}}{(\sigma)_{SM}} \times \frac{(BR)_{obs}}{(BR)_{SM}}$$



Higgs Couplings to SM Particles

