The Standard Model of particle physics

Particle Physics

Fabrice Couderc / Eli BenHaim

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Overview

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

BEH mechanism

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

h²

$$\mathcal{L}_{\mathrm{BEH}} = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 - \sqrt{\frac{\lambda}{2}}m_h h^3 - \frac{\lambda}{4}h^4 + \left[m_W^2 W^{+\mu}W_\mu^- + \frac{m_Z^2}{2}Z^\mu Z_\mu\right]\left(1+\frac{h}{v}\right)^2$$

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

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

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

$$e = g\sin\theta_w$$

4 parameters:

- **v, e, $\sin^2\theta$, m_h**
- **v, e, $\sin^2\theta$, λ**

CKM matrix

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

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 matrix

- PMNS : Ponte Corvo - Maki - Nakagawa - Sakata

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

flavor V_{PMNS} mass

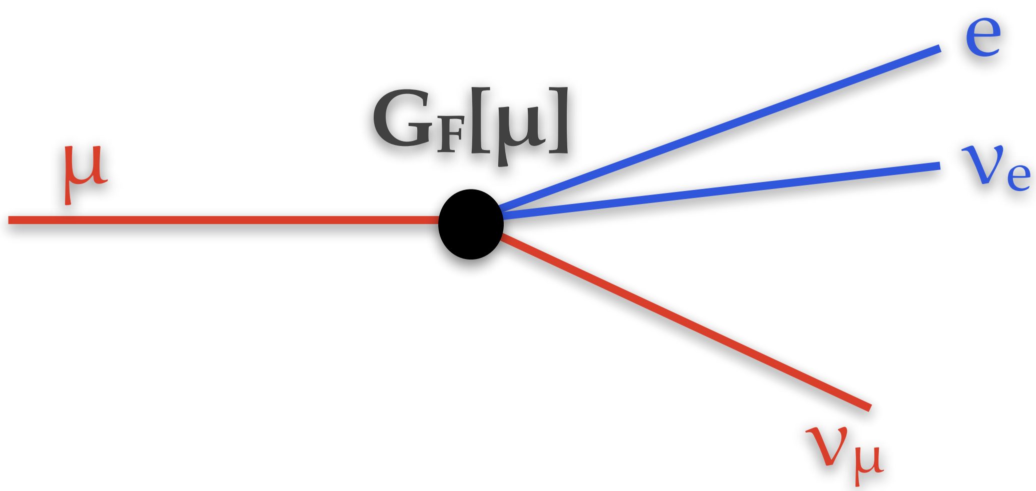
$$|V_{PMNS}| = \begin{pmatrix} 0.824398 & 0.544564 & 0.154328 \\ 0.485452 & 0.540074 & 0.6875 \\ 0.291039 & 0.641693 & 0.709596 \end{pmatrix}$$

The SM Lagrangian

$$\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) -$$
$$igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)) - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu -$$
$$Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 -$$
$$\beta_h\left(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right) + \frac{2M^4}{g^2}\alpha_h -$$
$$g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) -$$
$$\frac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w}Z^0_\mu Z^0_\mu H -$$
$$\frac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) +$$
$$\frac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) +$$
$$M\left(\frac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$
$$\frac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2+(\phi^0)^2+2\phi^+\phi^-\right) - \frac{1}{8}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu\left(H^2+(\phi^0)^2+2(2s^2_w-1)^2\phi^+\phi^-\right) -$$
$$\frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c^2_w-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^2s^2_wA_\mu A_\mu\phi^+\phi^- + \frac{1}{2}ig_s\,\lambda^a_{ij}(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar e^\lambda(\gamma\partial+m^\lambda_e)e^\lambda - \bar\nu^\lambda(\gamma\partial+m^\lambda_\nu)\nu^\lambda - \bar u^\lambda_j(\gamma\partial +$$
$$m^\lambda_u)u^\lambda_j - \bar d^\lambda_j(\gamma\partial+m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar e^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar d^\lambda_j\gamma^\mu d^\lambda_j)\right) +$$
$$\frac{ig}{4c_w}Z^0_\mu\{(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s^2_w-1-\gamma^5)e^\lambda) + (\bar d^\lambda_j\gamma^\mu(\tfrac{4}{3}s^2_w-1-\gamma^5)d^\lambda_j) +$$
$$(\bar u^\lambda_j\gamma^\mu(1-\tfrac{8}{3}s^2_w+\gamma^5)u^\lambda_j)\} + \frac{ig}{2\sqrt2}W^+_\mu\left((\bar\nu^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) +$$
$$\frac{ig}{2\sqrt2}W^-_\mu\left((\bar e^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) +$$
$$\frac{ig}{2M\sqrt2}\phi^+\left(-m^\kappa_e(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) +$$
$$\frac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_e(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \frac{g}{2}\frac{m^\lambda_\nu}{M}H(\bar\nu^\lambda\nu^\lambda) -$$
$$\frac{g}{2}\frac{m^\lambda_e}{M}H(\bar e^\lambda e^\lambda) + \frac{ig}{2}\frac{m^\lambda_\nu}{M}\phi^0(\bar\nu^\lambda\gamma^5\nu^\lambda) - \frac{ig}{2}\frac{m^\lambda_e}{M}\phi^0(\bar e^\lambda\gamma^5e^\lambda) - \frac{1}{4}\,\bar\nu_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa -$$
$$\frac{1}{4}\,\overline{\bar\nu_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa} + \frac{ig}{2M\sqrt2}\phi^+\left(-m^\kappa_d(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) +$$
$$\frac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_d(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar u^\lambda_j u^\lambda_j) -$$
$$\frac{g}{2}\frac{m^\lambda_d}{M}H(\bar d^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar u^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar G^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar G^aG^bg^c_\mu +$$
$$\bar X^+(\partial^2-M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2-\frac{M^2}{c^2_w})X^0 + \bar Y\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar X^0X^- -$$
$$\partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar YX^- - \partial_\mu\bar X^+Y) + igc_wW^-_\mu(\partial_\mu\bar X^-X^0 -$$
$$\partial_\mu\bar X^0X^+) + igs_wW^-_\mu(\partial_\mu\bar X^-Y - \partial_\mu\bar YX^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ -$$
$$\partial_\mu\bar X^-X^-) + igs_wA_\mu(\partial_\mu\bar X^+X^+ -$$
$$\partial_\mu\bar X^-X^-) - \frac{1}{2}gM\left(\bar X^+X^+H + \bar X^-X^-H + \frac{1}{c^2_w}\bar X^0X^0H\right) + \frac{1-2c^2_w}{2c_w}igM\left(\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-\right) +$$
$$\frac{1}{2c_w}igM\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + igMs_w\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) +$$
$$\frac{1}{2}igM\left(\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0\right).$$

Beyond LO, the Fermi "constant"

- Low energy contact interaction



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

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

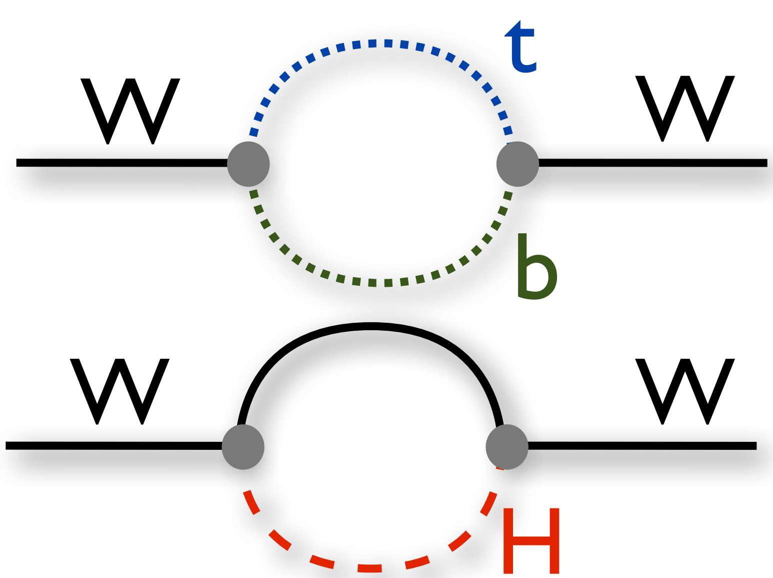
radiative corrections Δr
$\Rightarrow$ link between m_W, m_Z, α, $G[\mu]$:

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

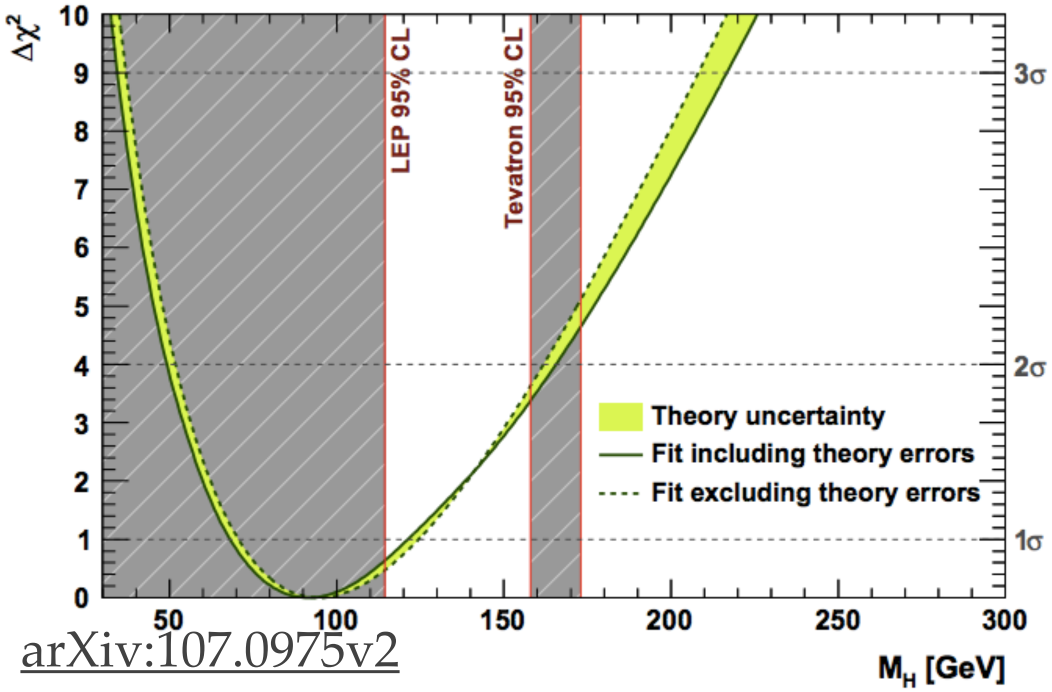
$$\Delta r \simeq \frac{\alpha}{\pi s^2}\left\{-\frac{3}{16}\frac{m_t^2}{m_W^2}\frac{c^2}{s^2} + \frac{11}{48}\ell n\frac{m_H^2}{m_Z^2}\right\} + 0.070 + 2\text{loops}$$

used to predict the top mass and the Higgs mass

Radiative corrections to the W mass



W, Z, H masses



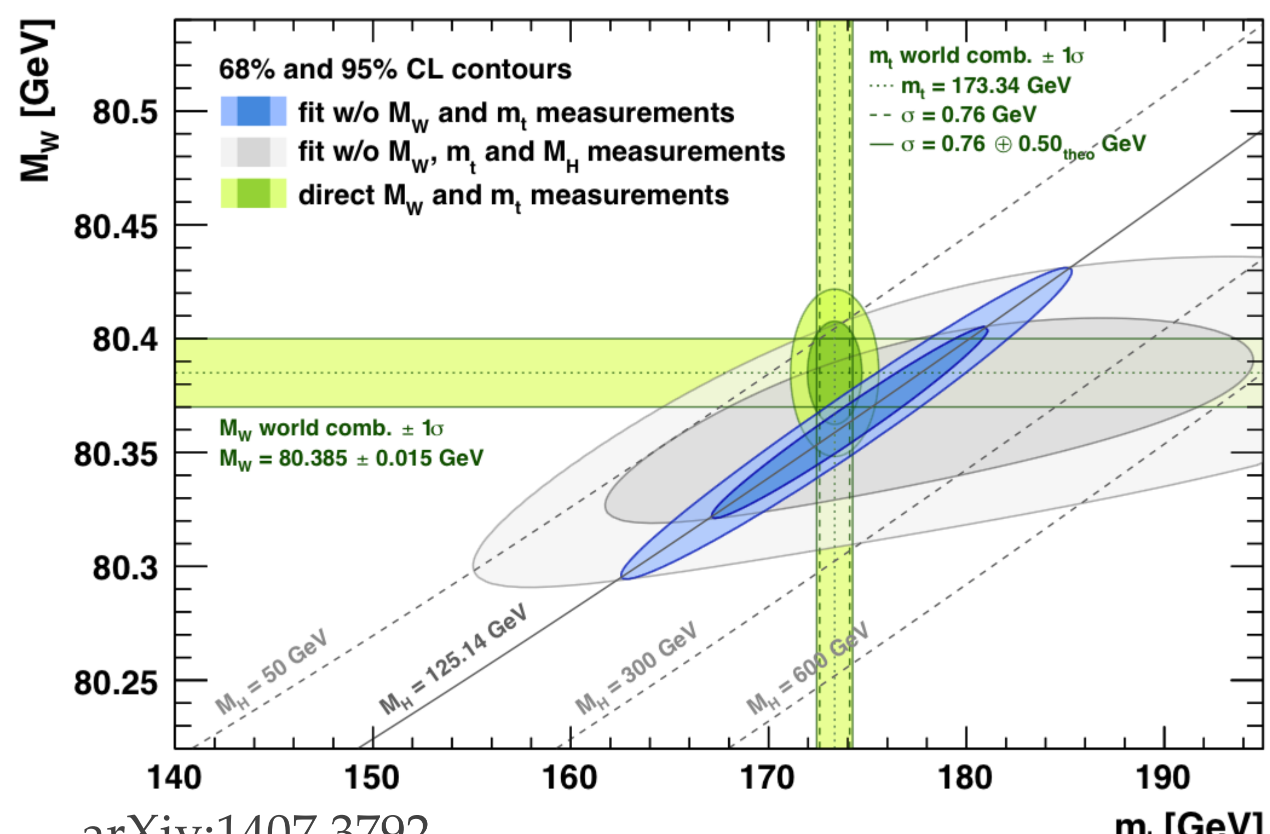
arXiv:107.0975v2

Before Higgs discovery

m_h(indirect) = 91 $^{+30}_{-23}$ GeV

After Higgs discovery

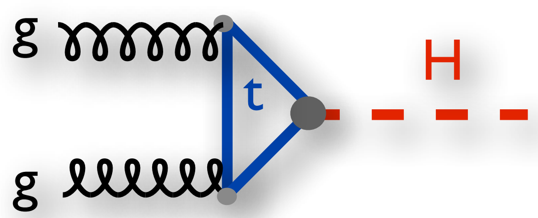
test the consistency of the model



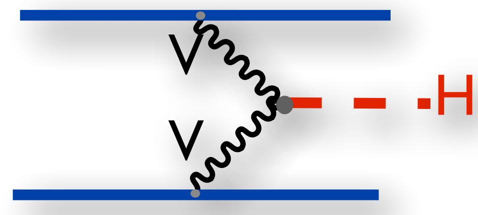
arXiv:1407.3792

Higgs Boson production - hadron collider

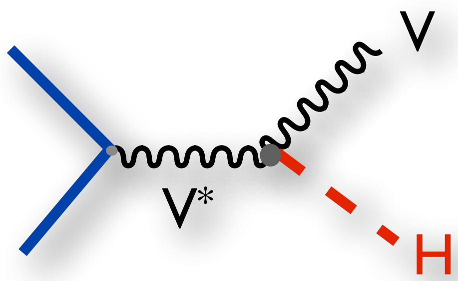
σ_{ggH} = 44 pb



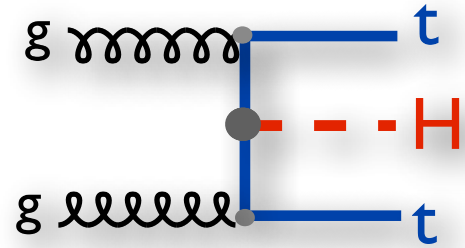
σ_{VBF} = 3.7 pb



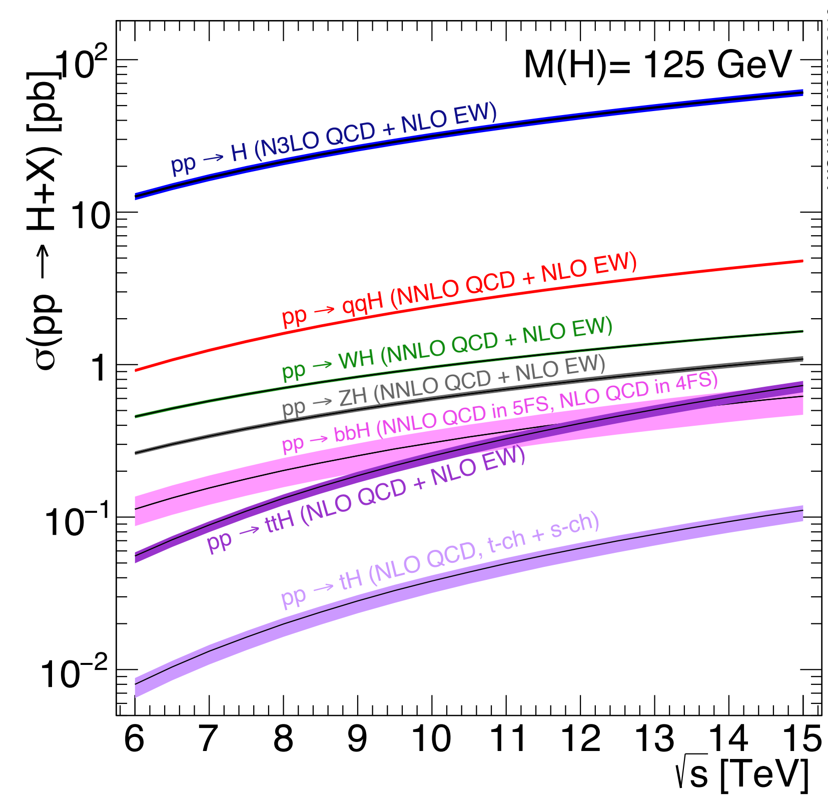
13 TeV



σ_{VH} = 2.2 pb



σ_{ttH} = 0.5 pb



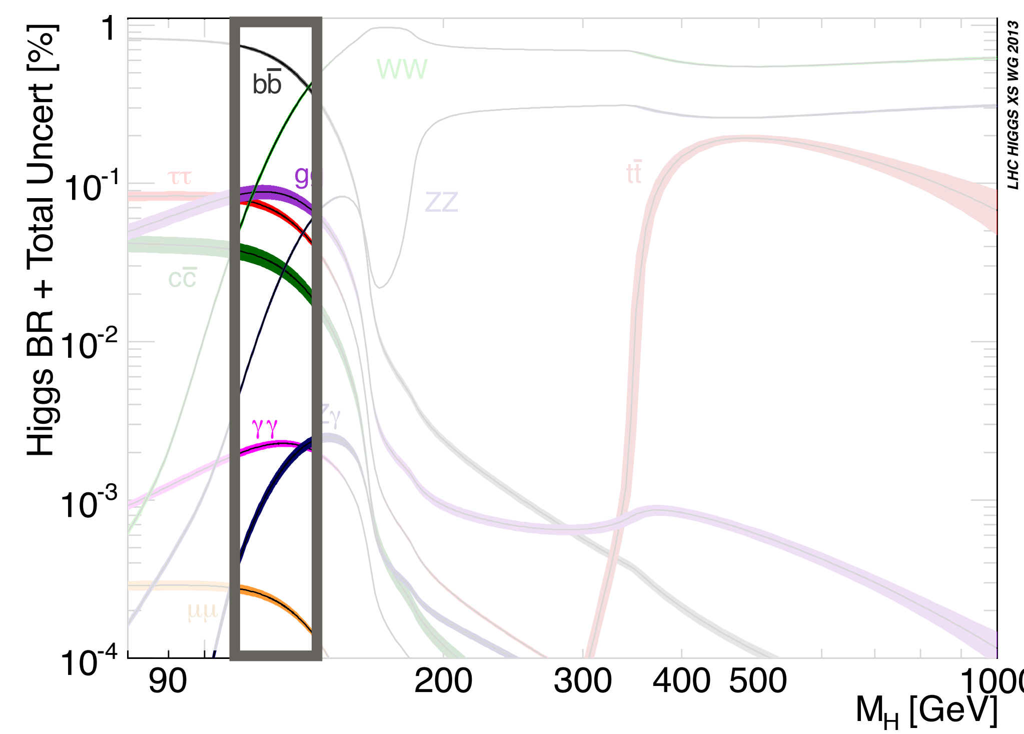
Variety of channel accessible @ m_H=125 GeV

Golden channels

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

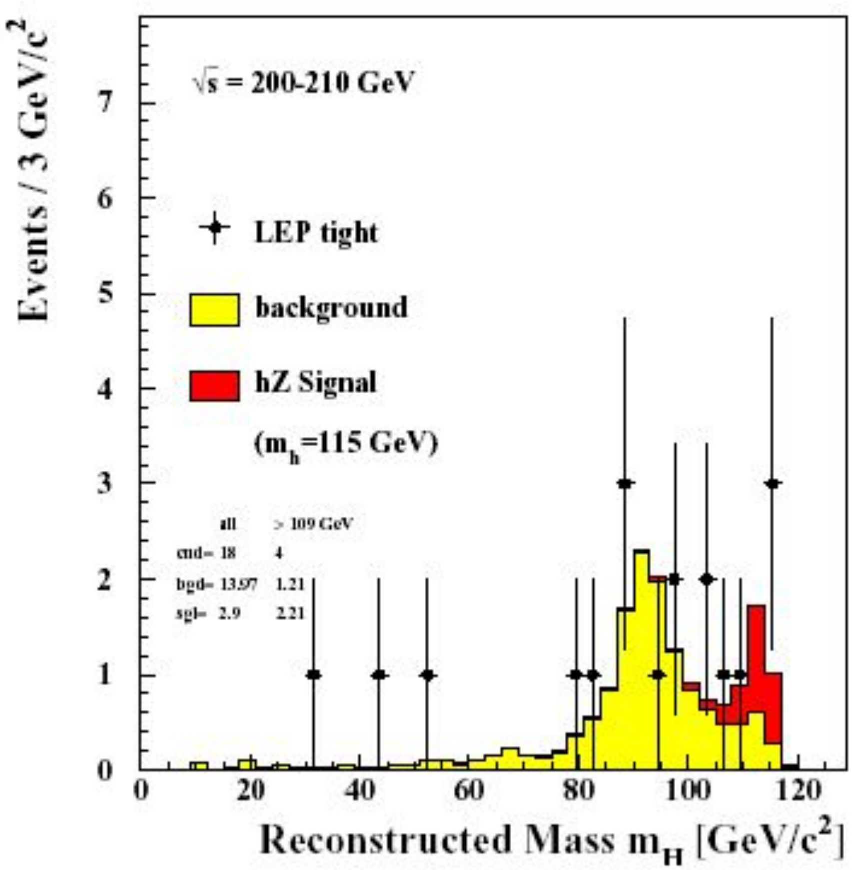
$H \rightarrow ZZ^* \rightarrow 4l$: $B \approx 0.03\%$

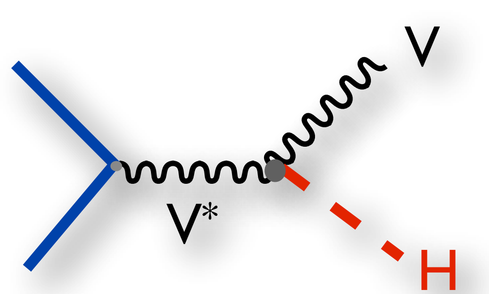
Small branching ratios but good invariant mass resolution: probe all production modes



Pre-LHC

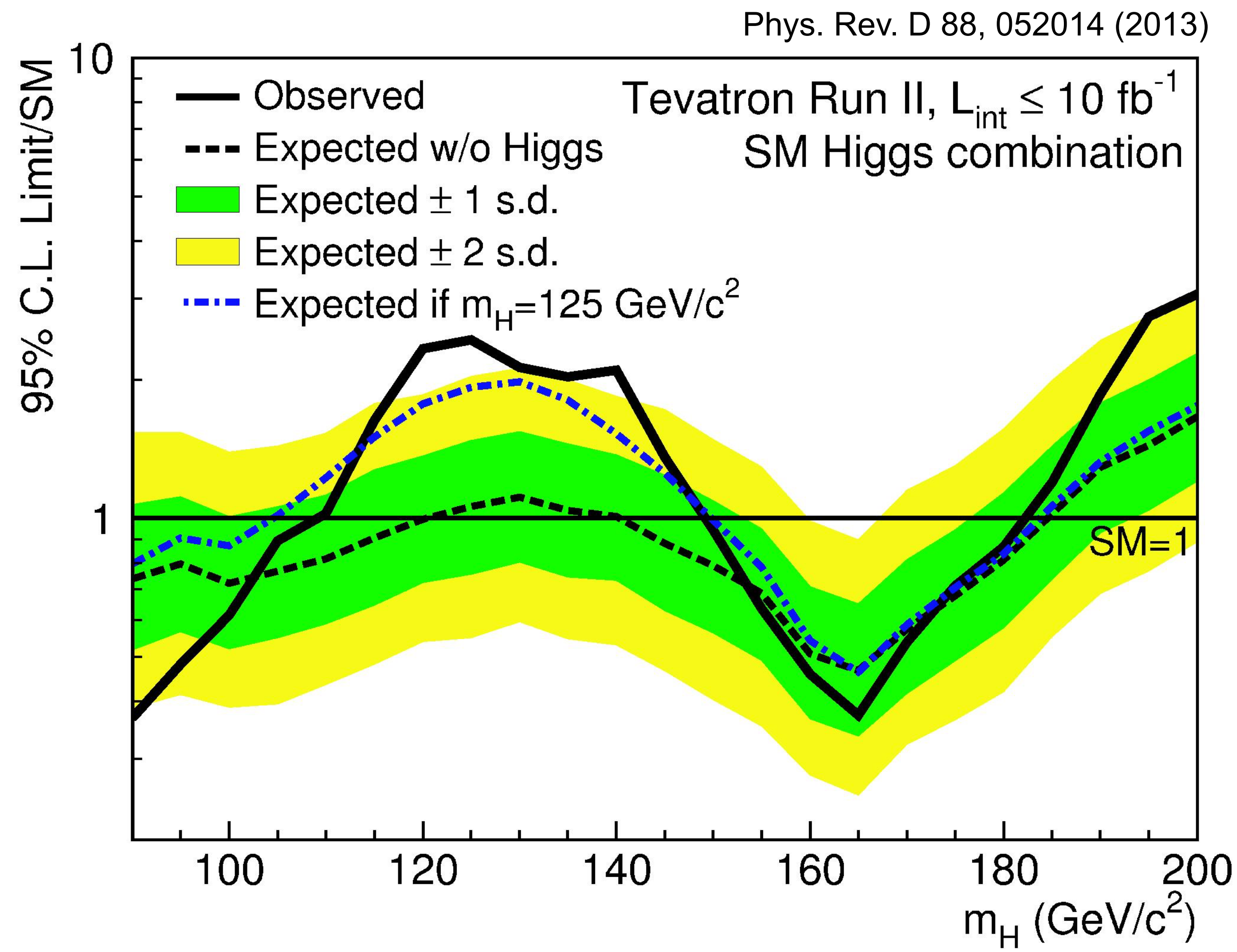
LEP





m_H > 114 GeV

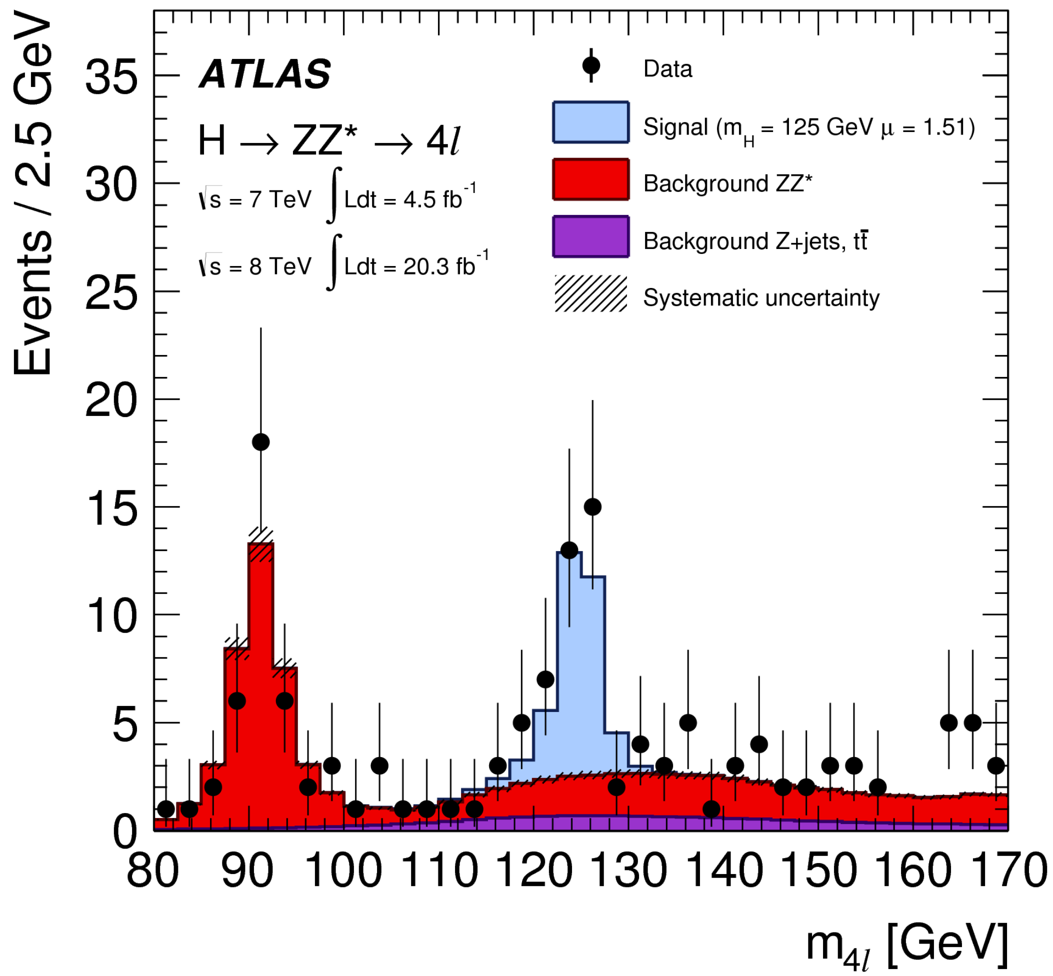
Tevatron ppbar collider 1.96 TeV



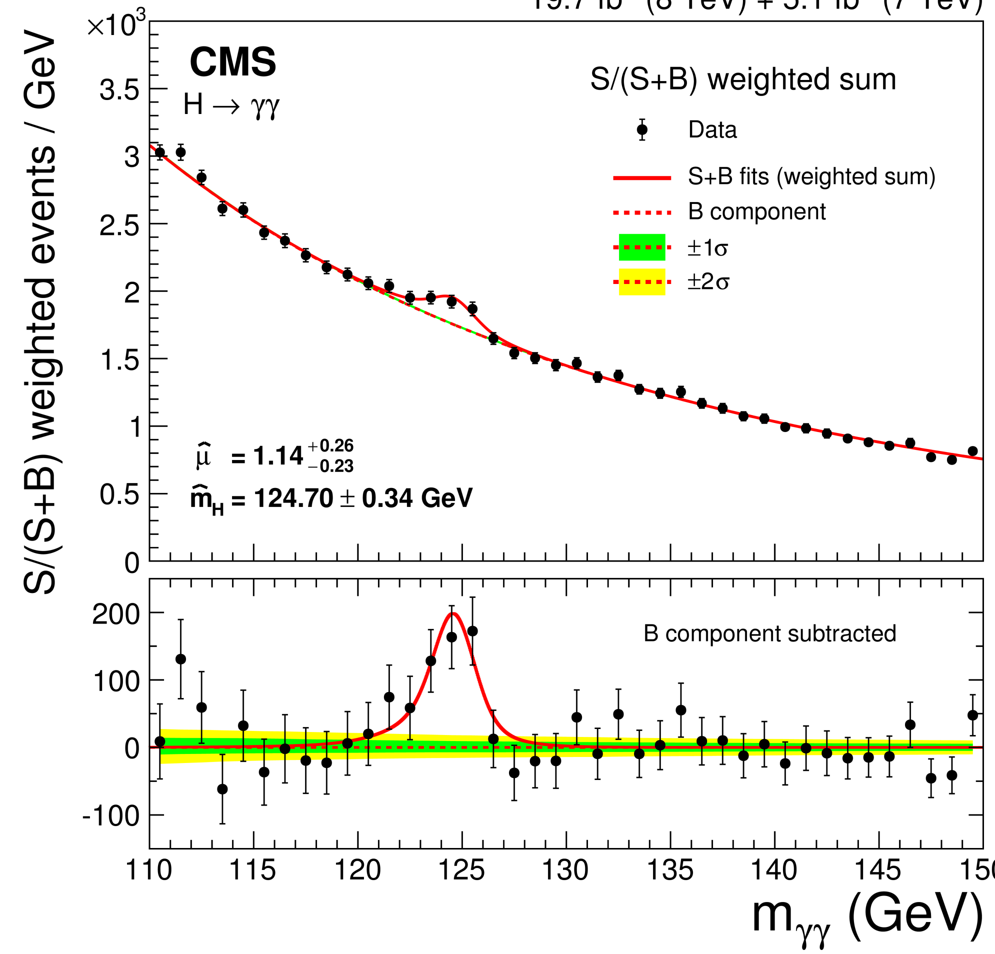
O(3σ) excess @m_H = 125 GeV

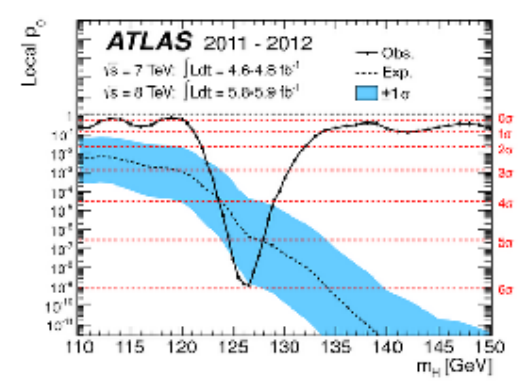
The Higgs Boson discovery, 4 July 2012

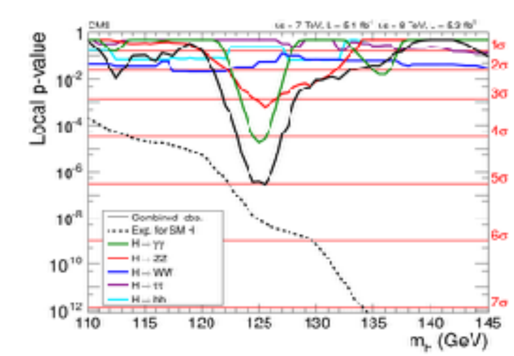
Phys. Lett. B 716 (2012), 1



Phys. Lett. B 716 (2012) 30





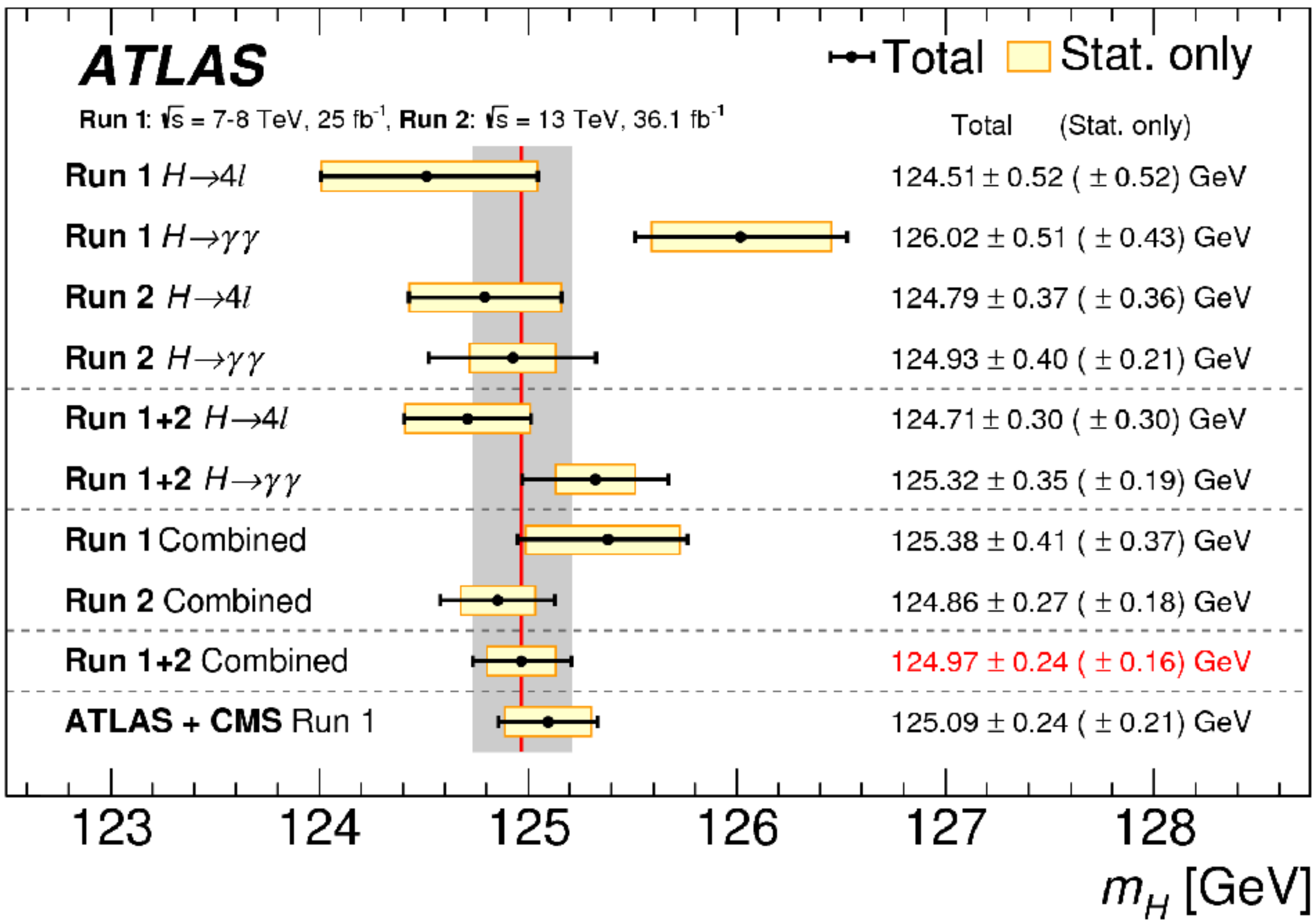


Atlas
6σ excess
@125GeV

CMS
5σ excess
@125GeV

Higgs Boson Mass

Phys. Lett. B 784 (2018) 345

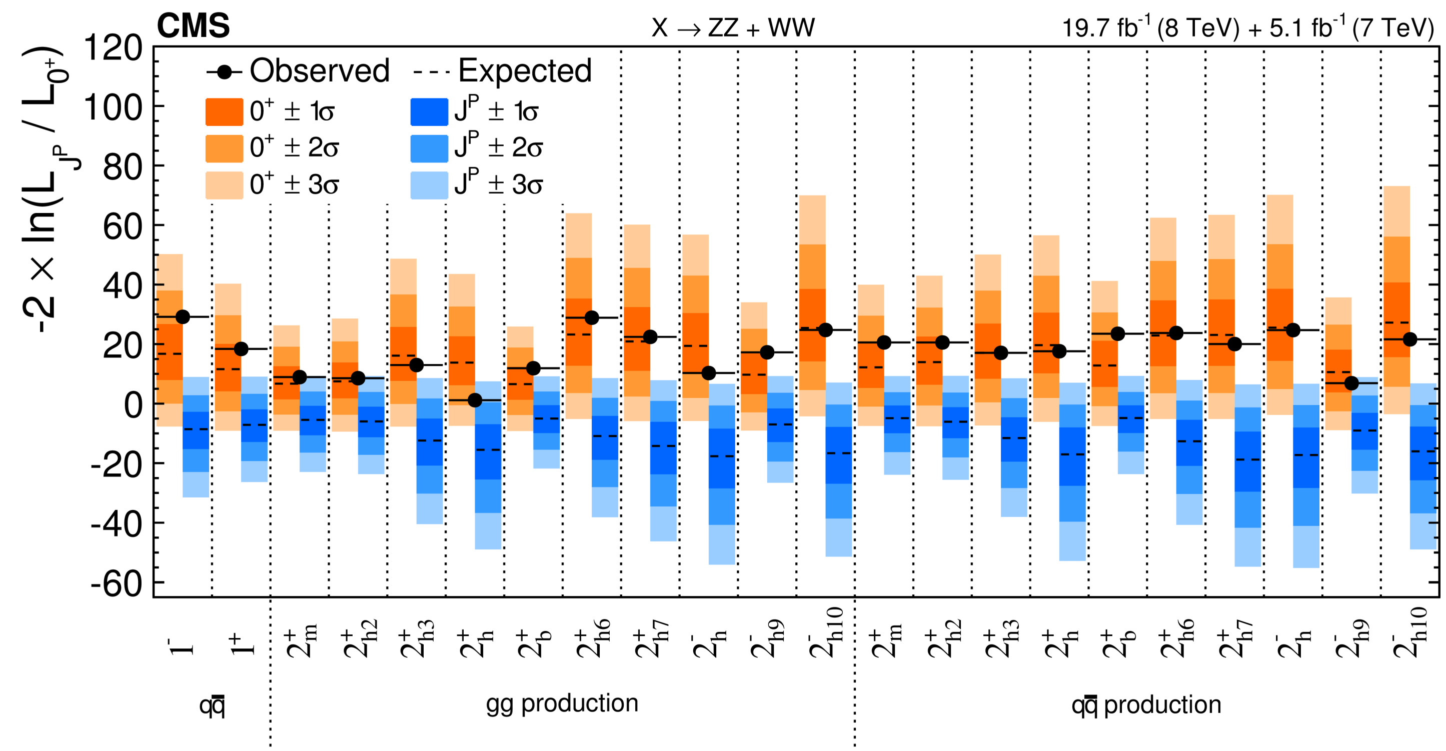


MH ≈ 125.00 ± 0.25 GeV

Boson spin and CP properties

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

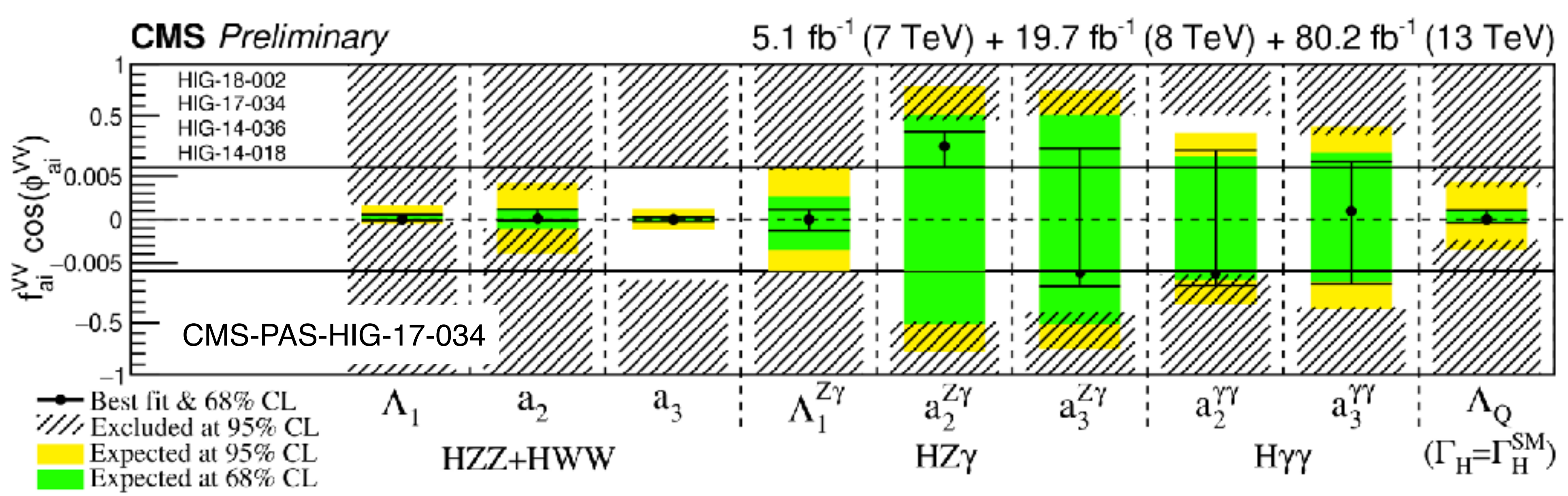
$H \rightarrow ZZ^* \rightarrow 4l$ turned out to be a very good laboratory



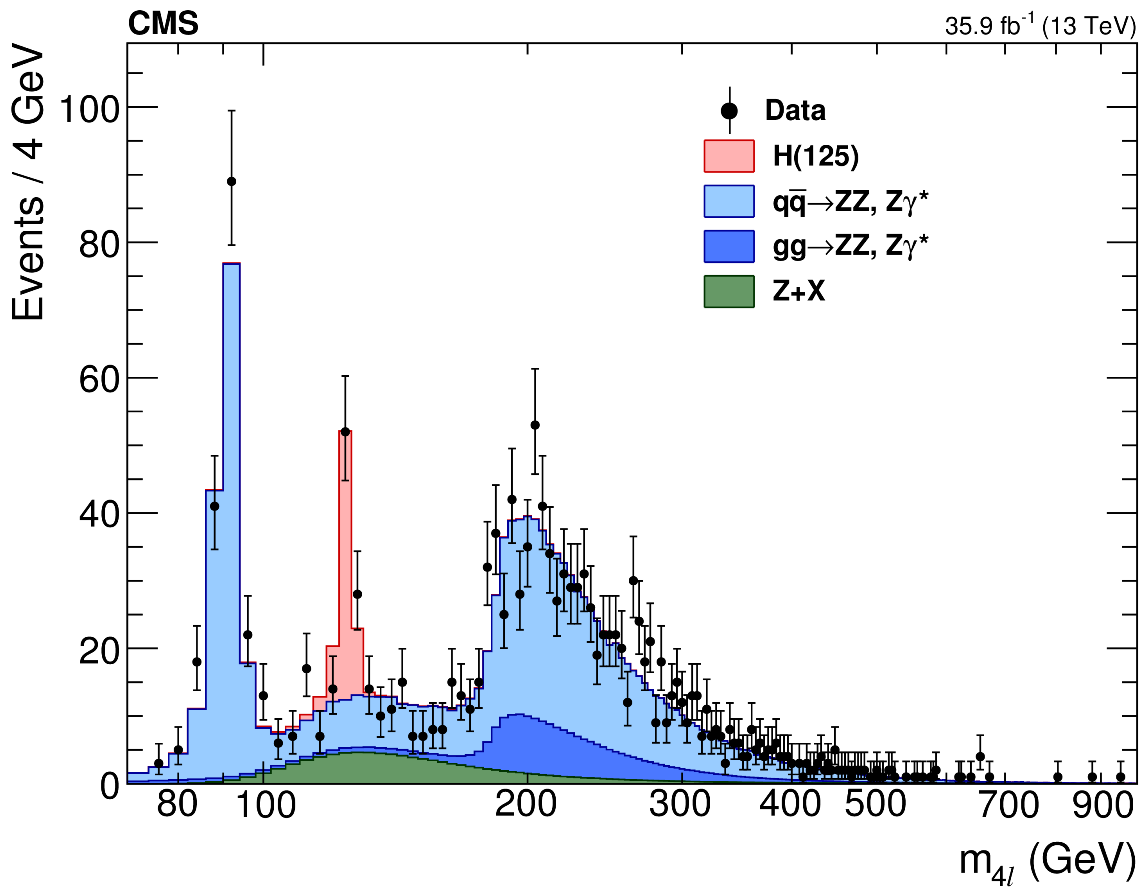
CP : analyze the structure of HVV coupling

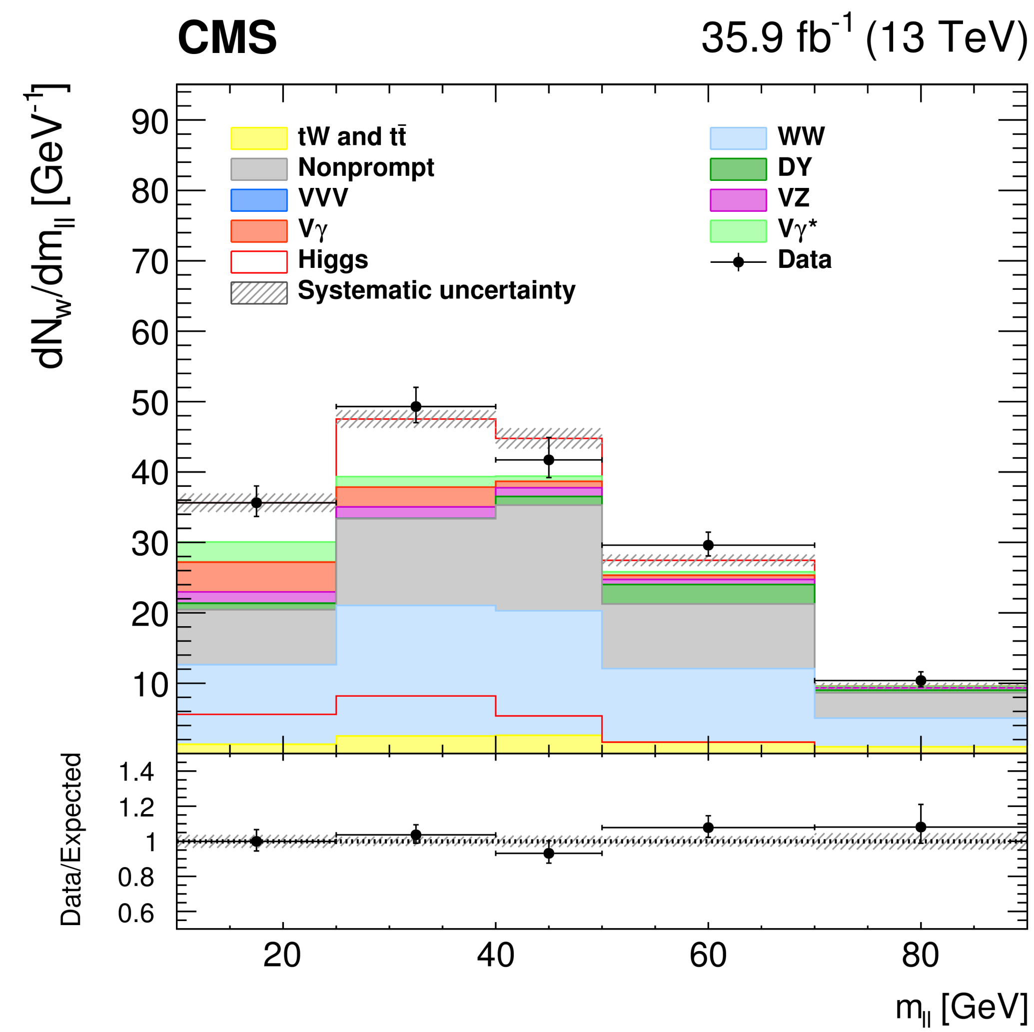
$H^* \rightarrow 4l$ good

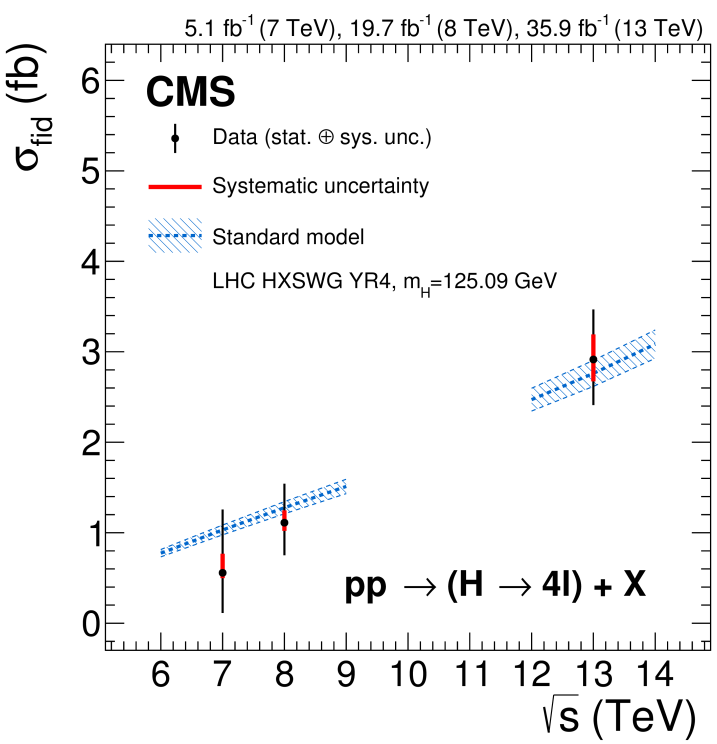
Other channels are competitive

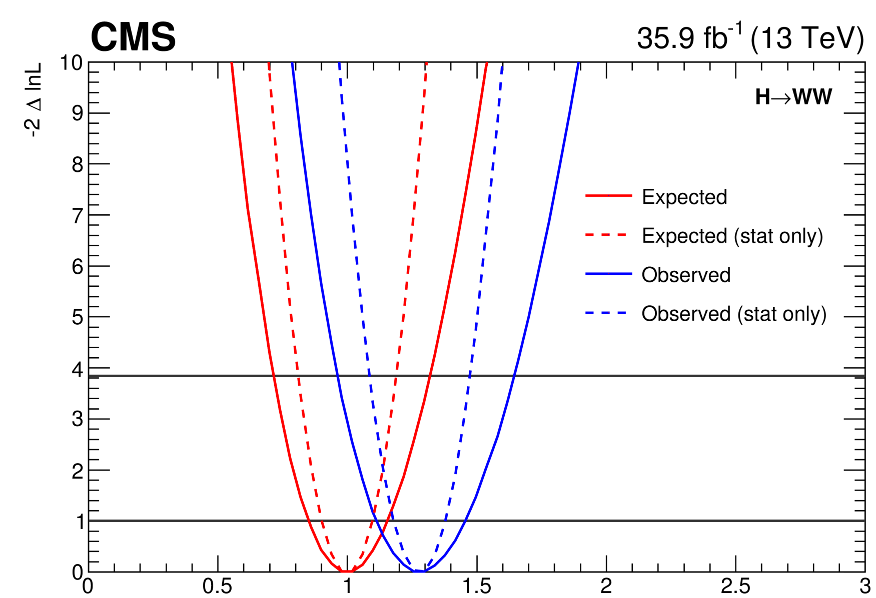


H → VV


CMS
35.9 fb-1 (13 TeV)
Events / 4 GeV
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
m4l (GeV)

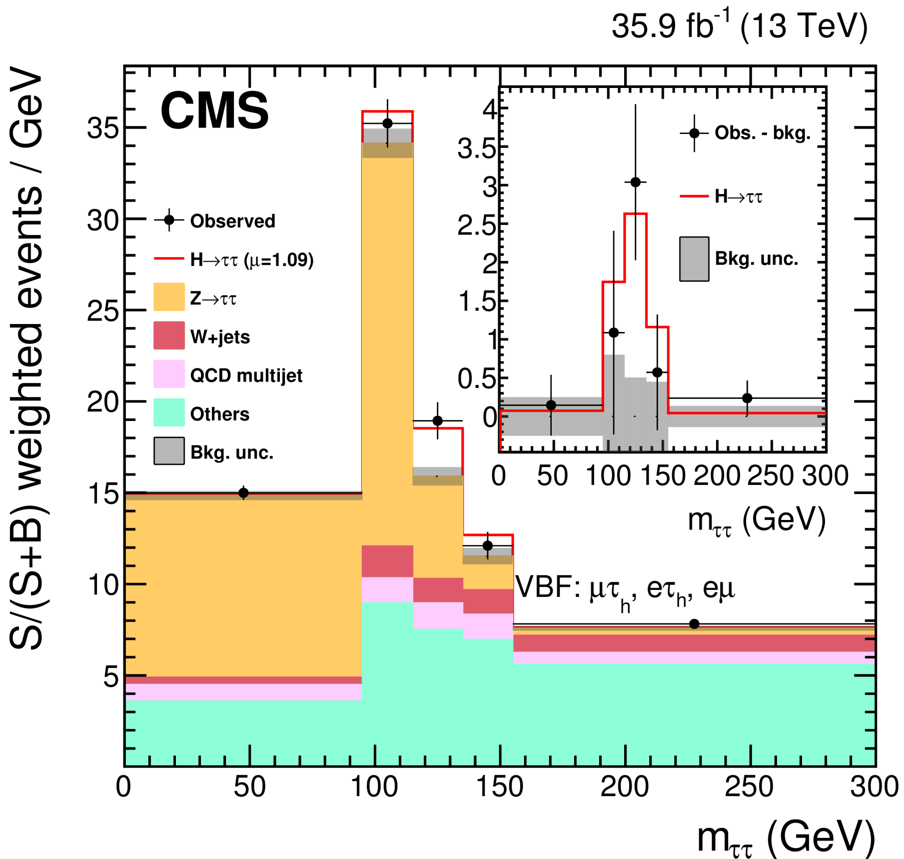

CMS
35.9 fb-1 (13 TeV)
dNw/dmll [GeV-1]
tW and tt̄
Nonprompt
VVV
Vγ
Higgs
Systematic uncertainty
WW
DY
VZ
Vγ*
Data
Data/Expected
mll [GeV]


5.1 fb-1 (7 TeV), 19.7 fb-1 (8 TeV), 35.9 fb-1 (13 TeV)
CMS
σfid (fb)
Data (stat. ⊕ sys. unc.)
Systematic uncertainty
Standard model
LHC HXSWG YR4, mH=125.09 GeV
pp → (H → 4l) + X
√s (TeV)

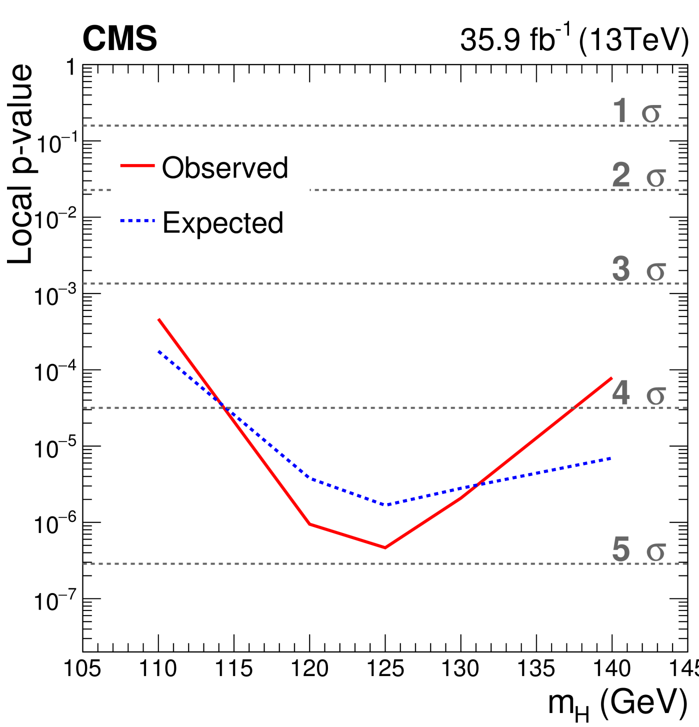

CMS
35.9 fb-1 (13 TeV)
-2 Δ lnL
H→WW
Expected
Expected (stat only)
Observed
Observed (stat only)
μ

H→ff

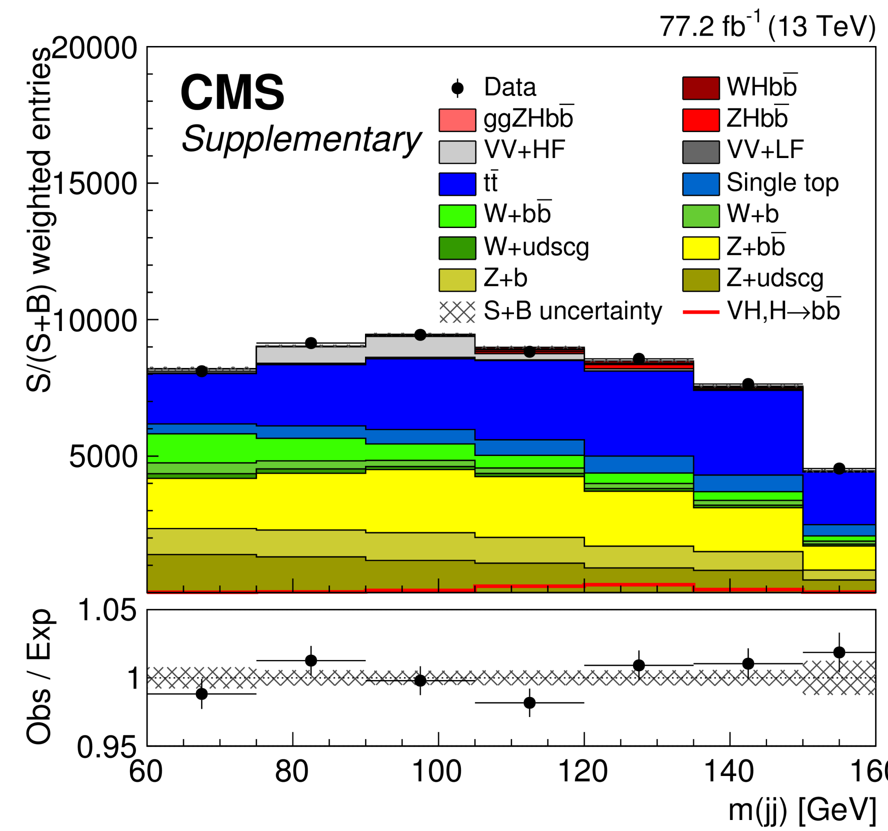
H→ ττ Observation in 2017



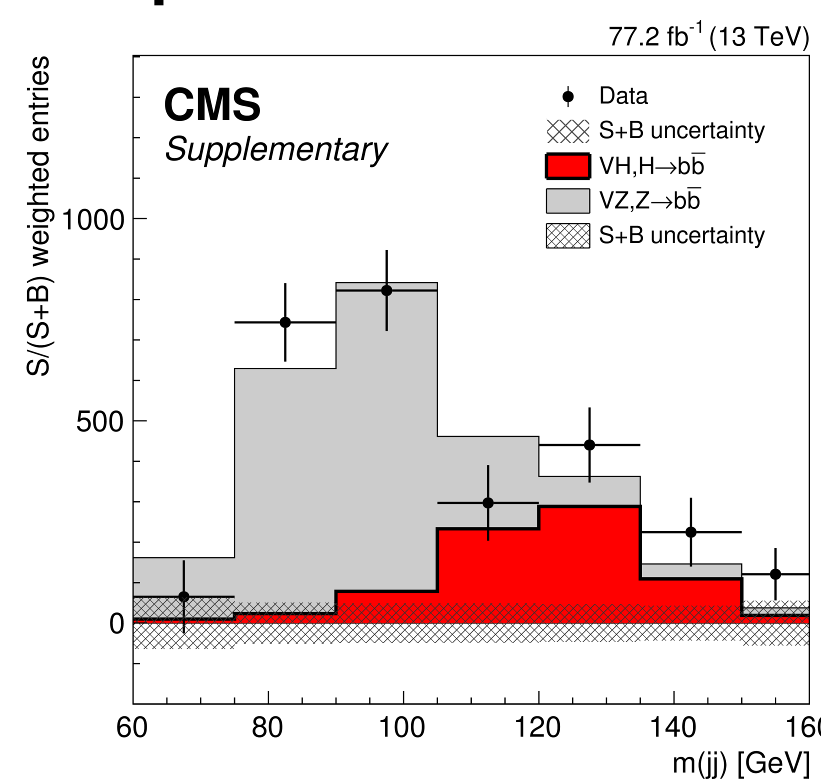
μ = 1.09 ± 0.26



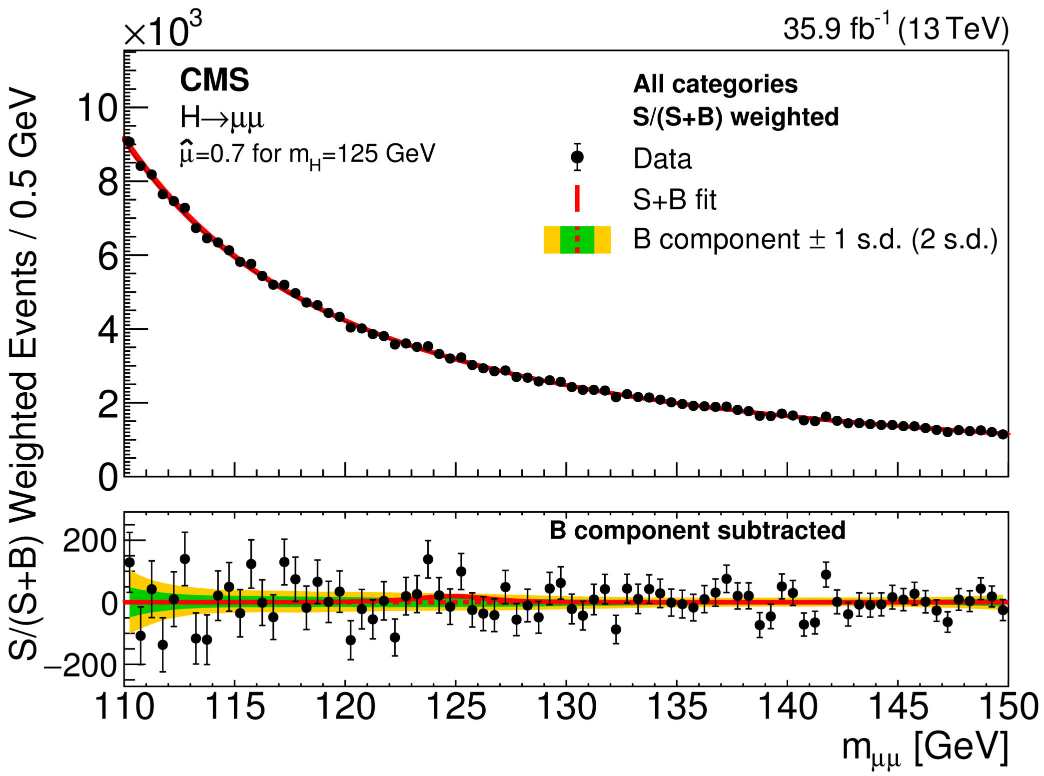
H→ bb Observation in 2018



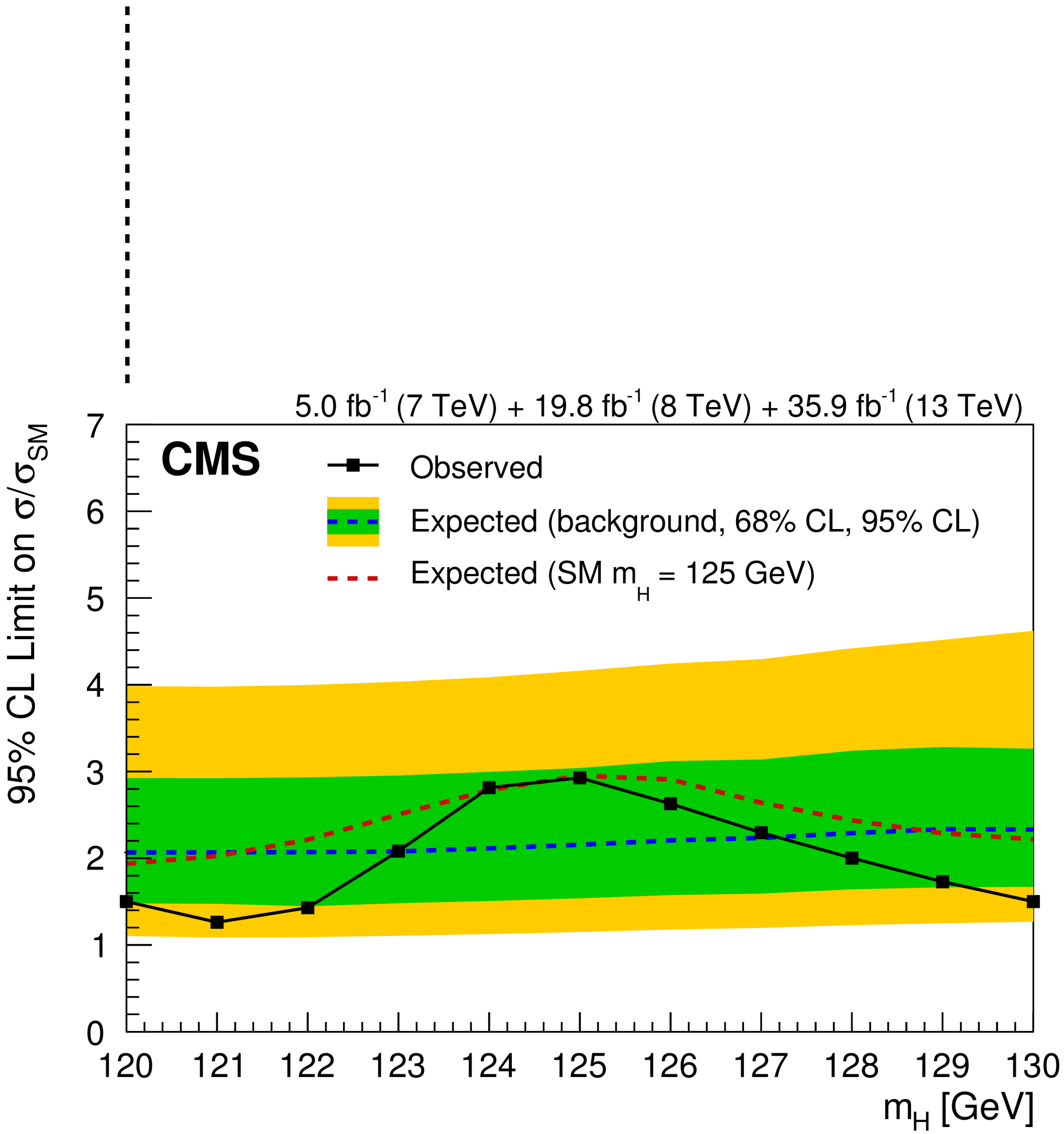
μ = 1.01 ± 0.22



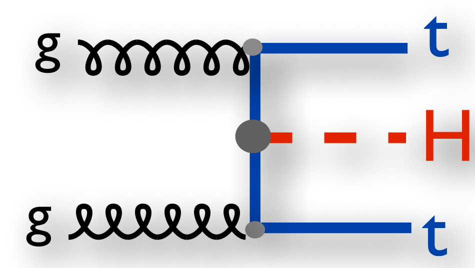
H→μμ searches

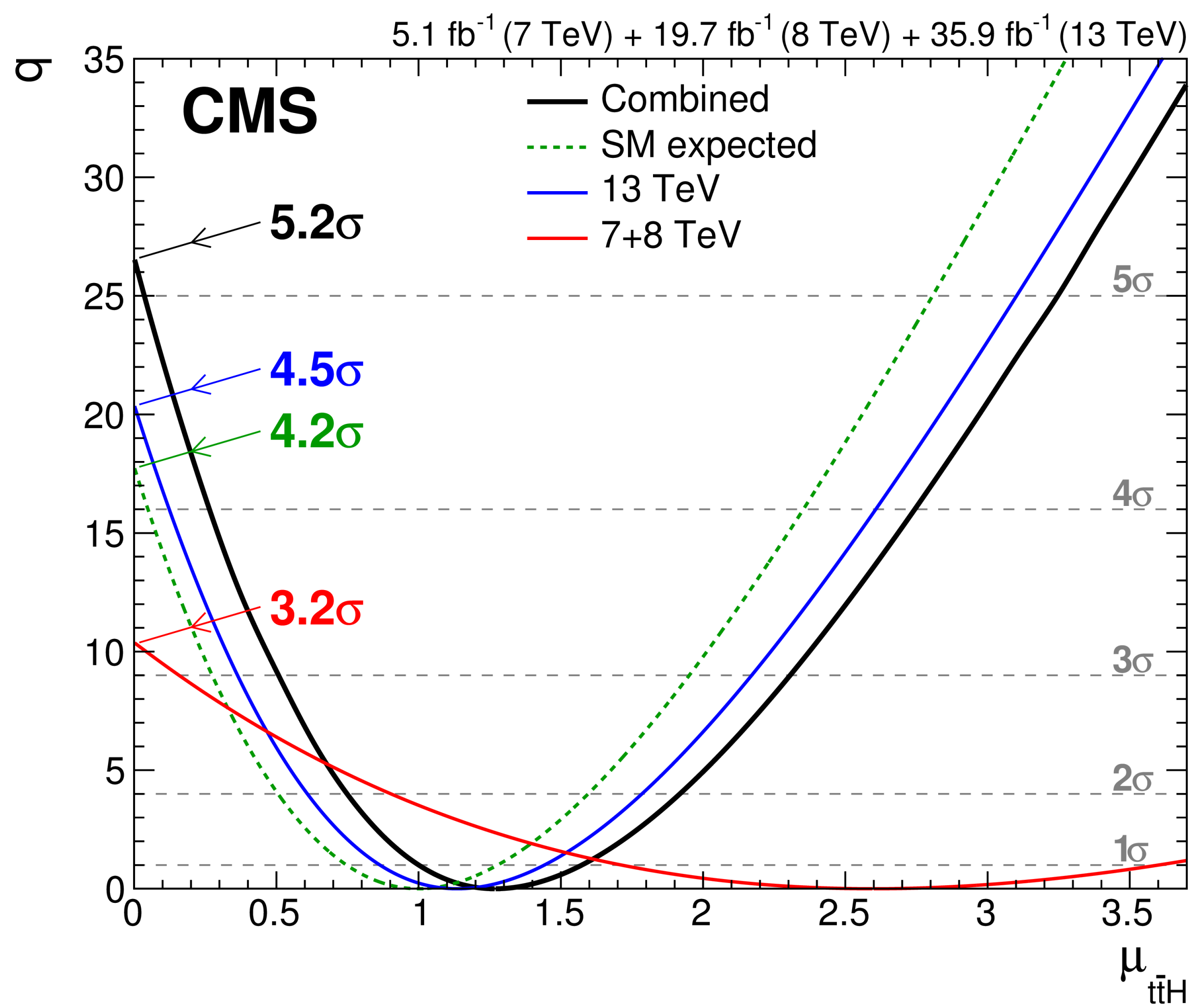


$\mu_{LFU} \approx 300$



Htt production





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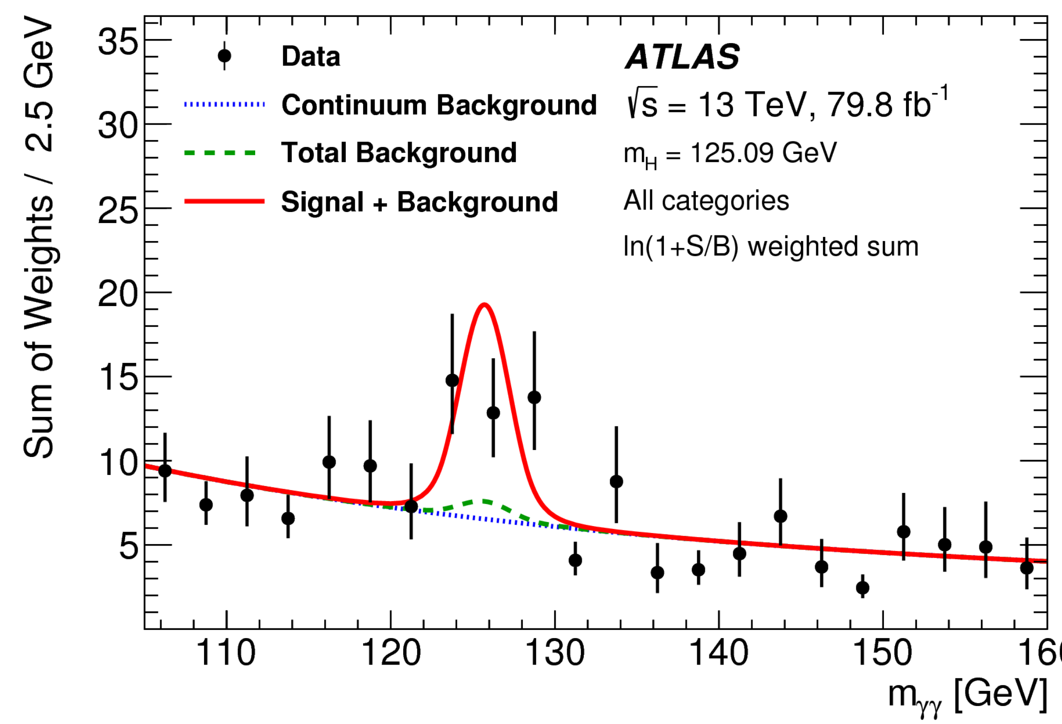
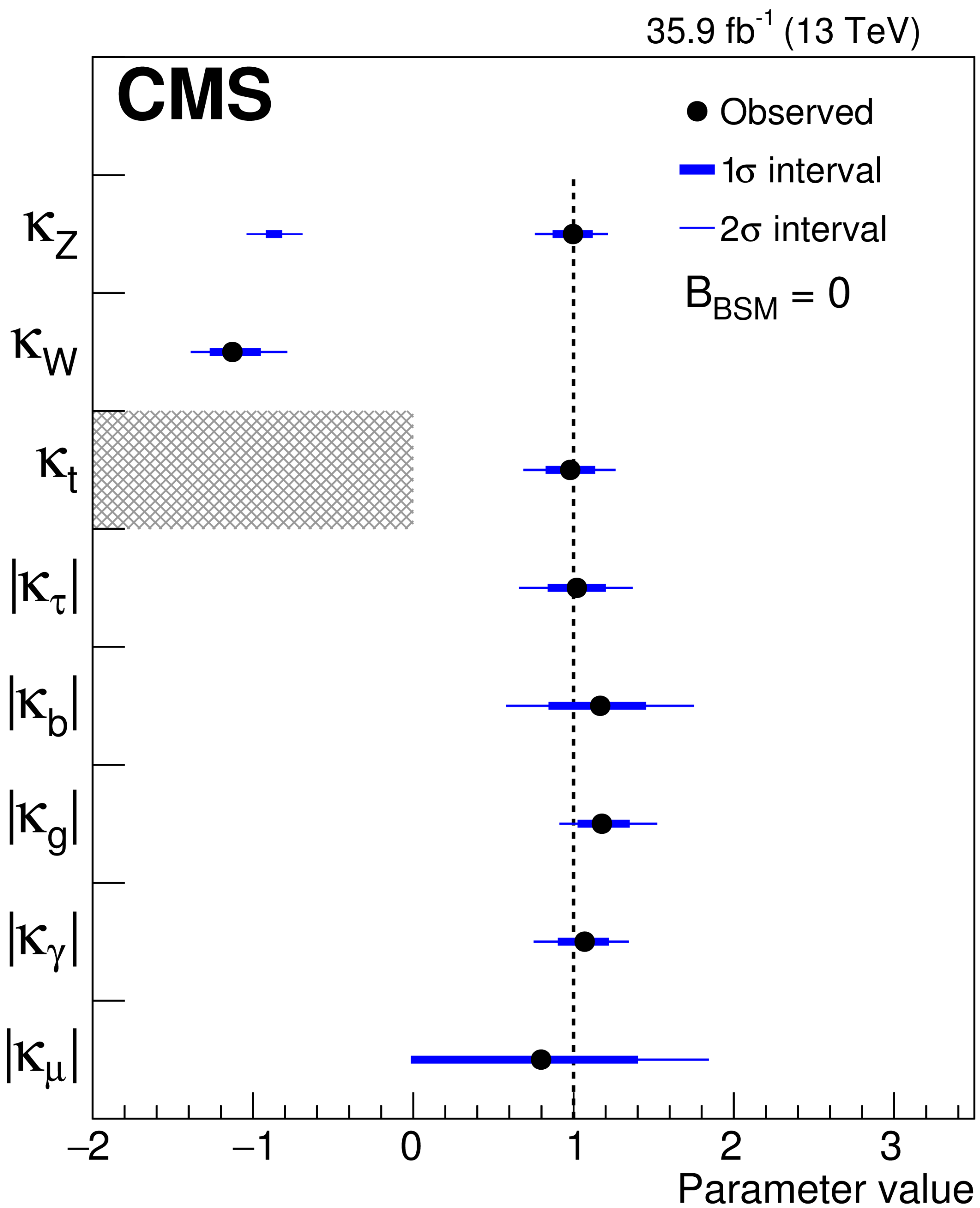
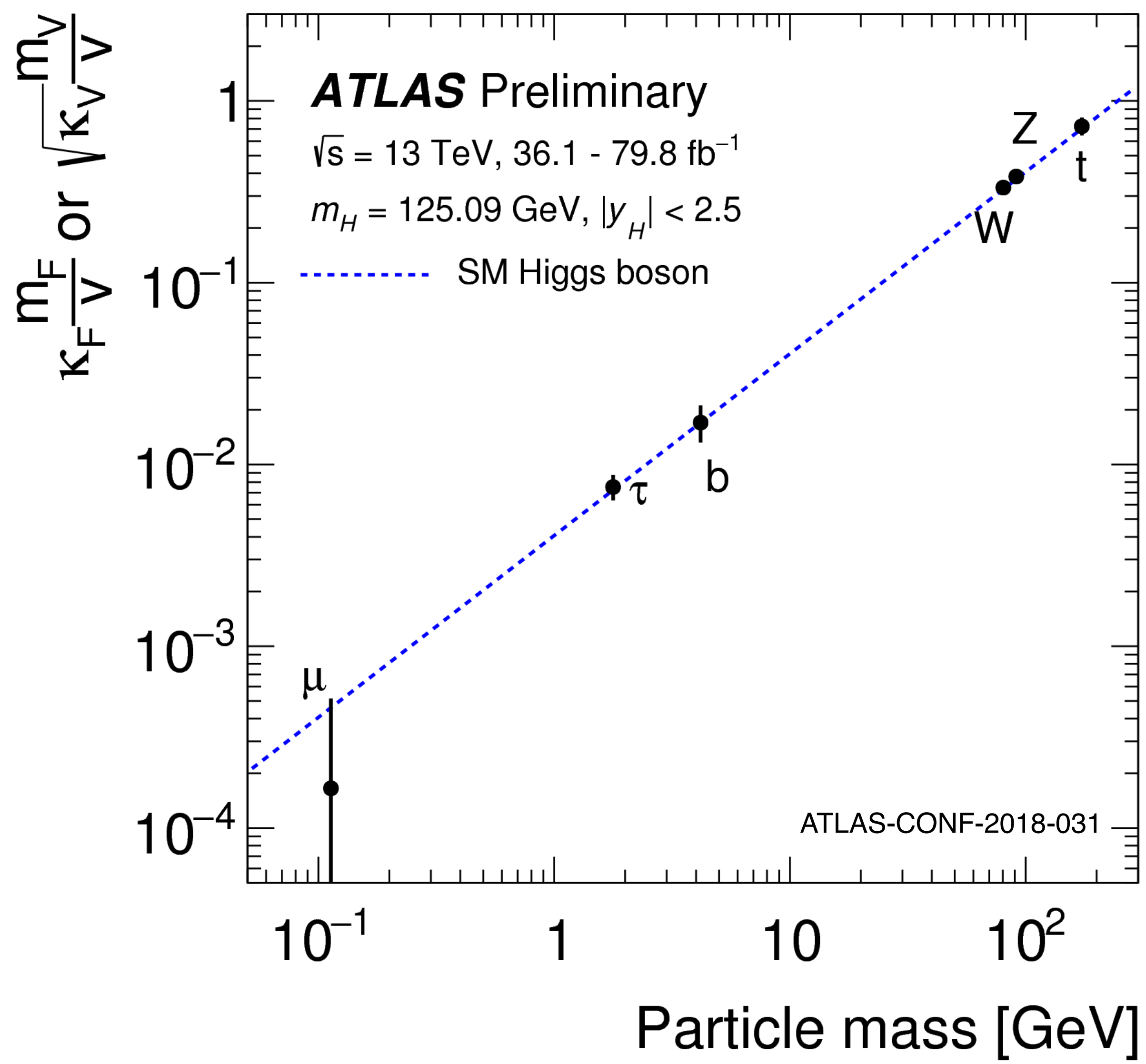


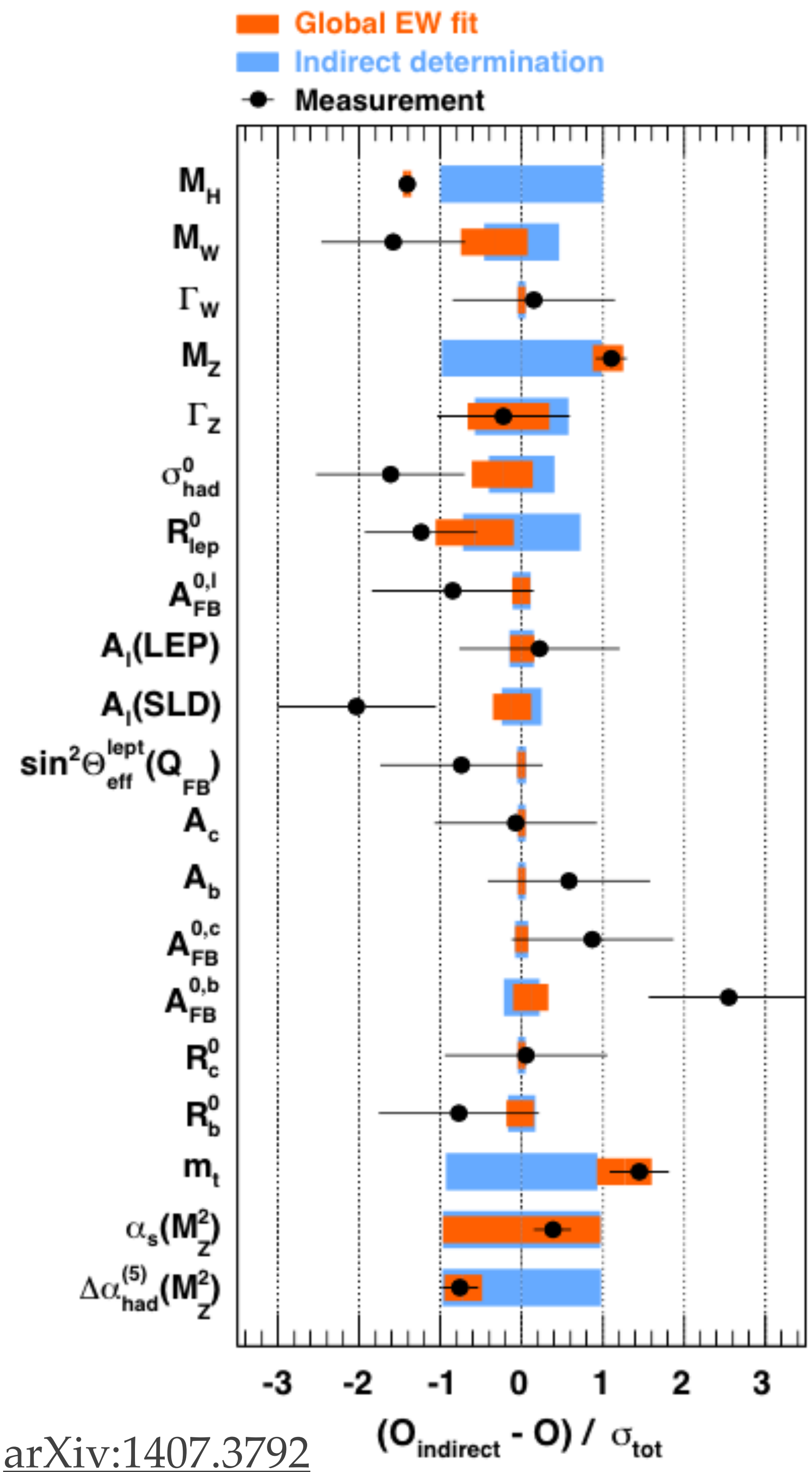
Higgs production summary





Following...
Exercise sheet 5
some plots

SM glory



arXiv:1407.3792

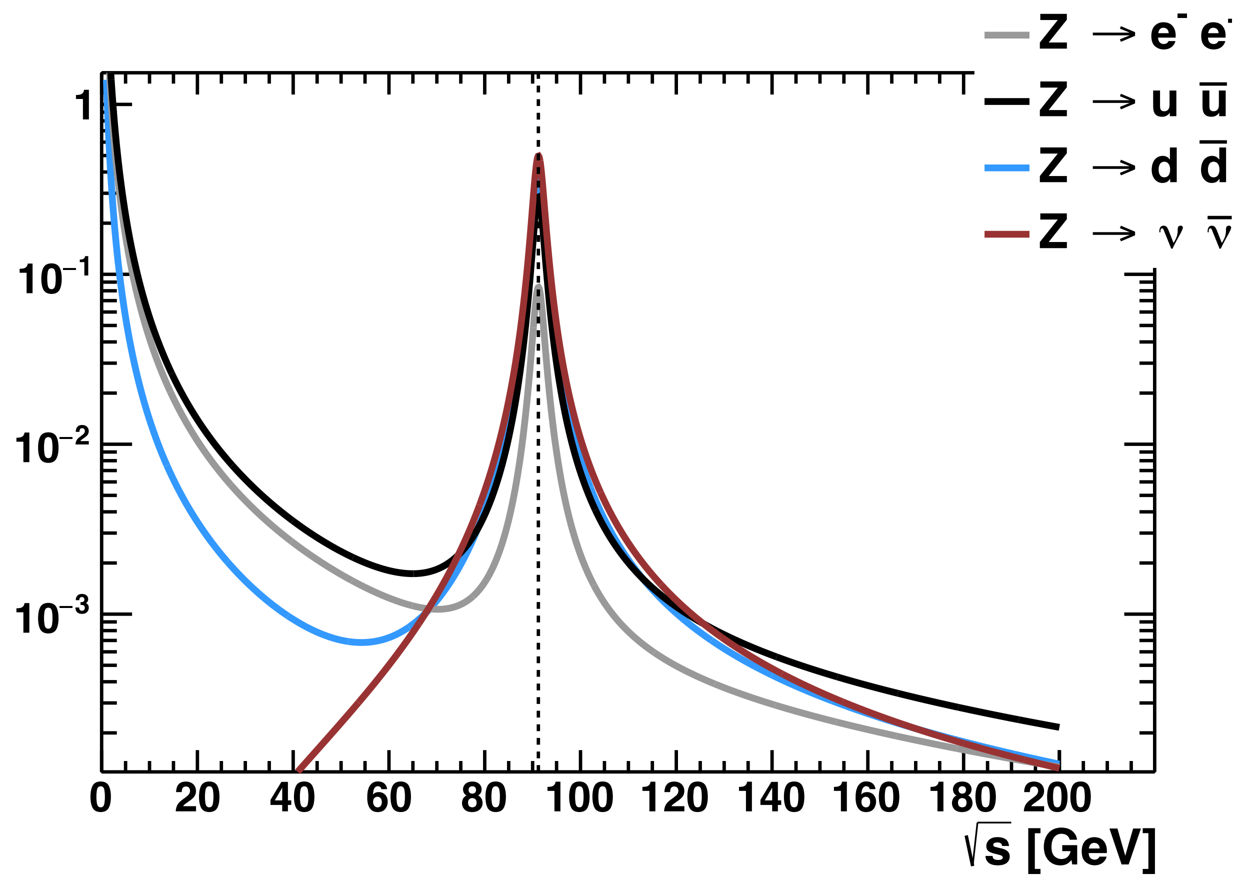
Indirect determination:
EW fit without the measurement

Global EW fit:
EW fit including the measurement

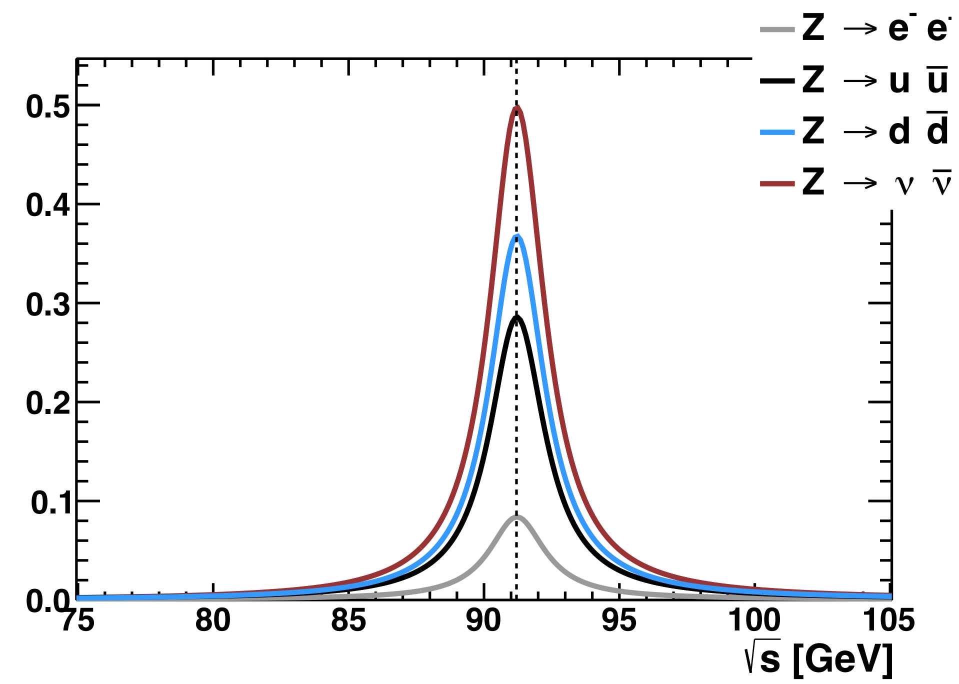
Measurement: Measurement

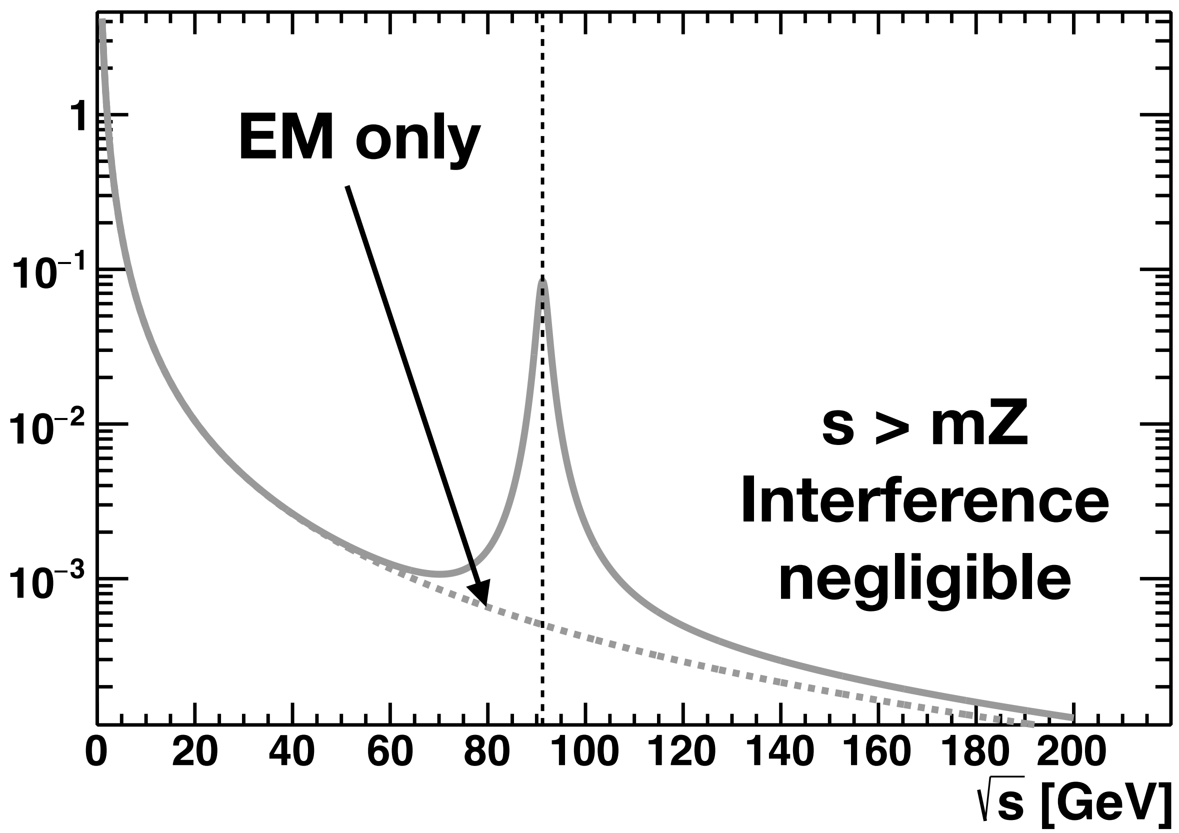
Predictions @ NLO
W mass includes 4 loops $O(\alpha_s^3\alpha_t)$
Γ_Z 2 loops

ES5: Z -γ* interference

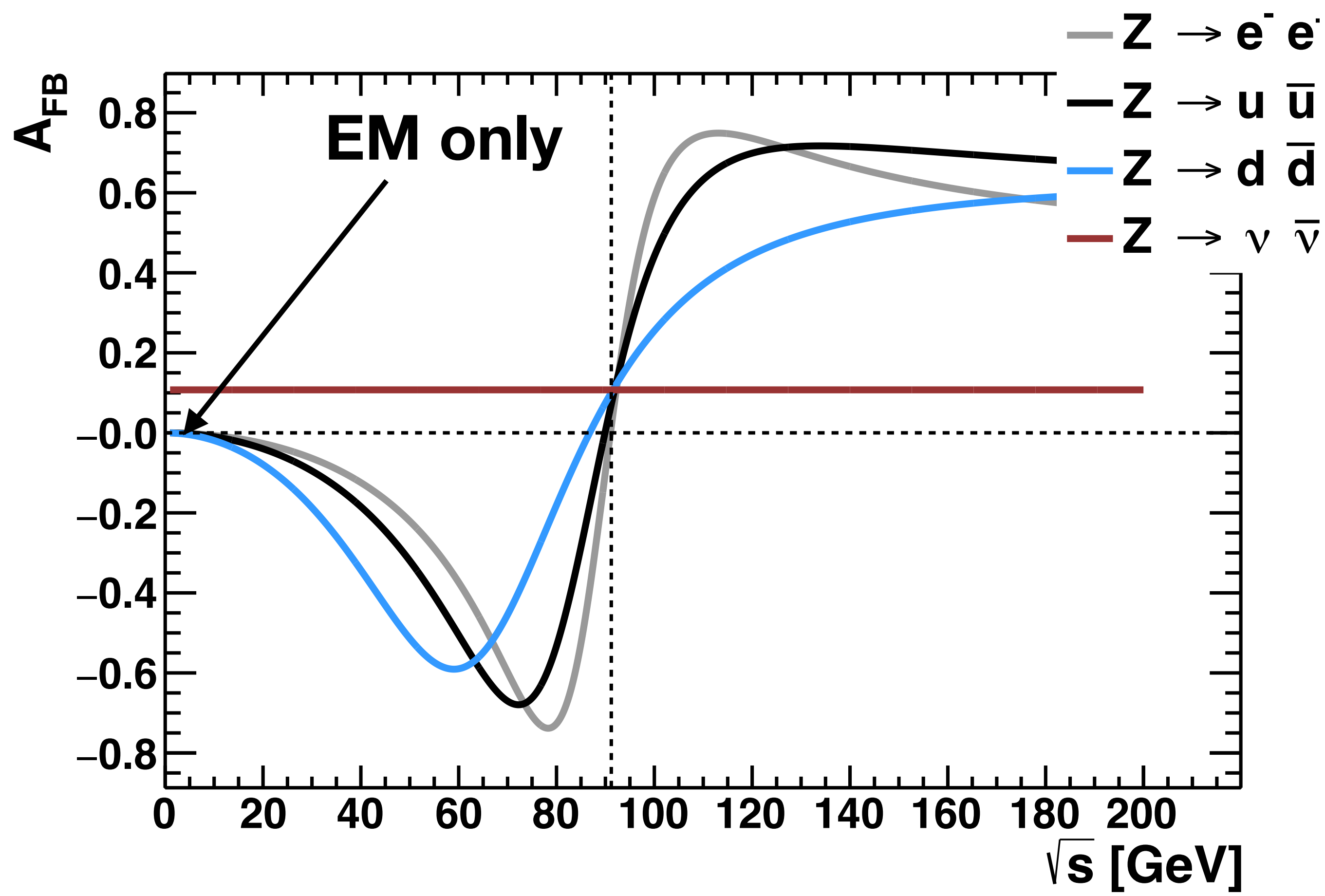


Nc = 3 and Nν = 3

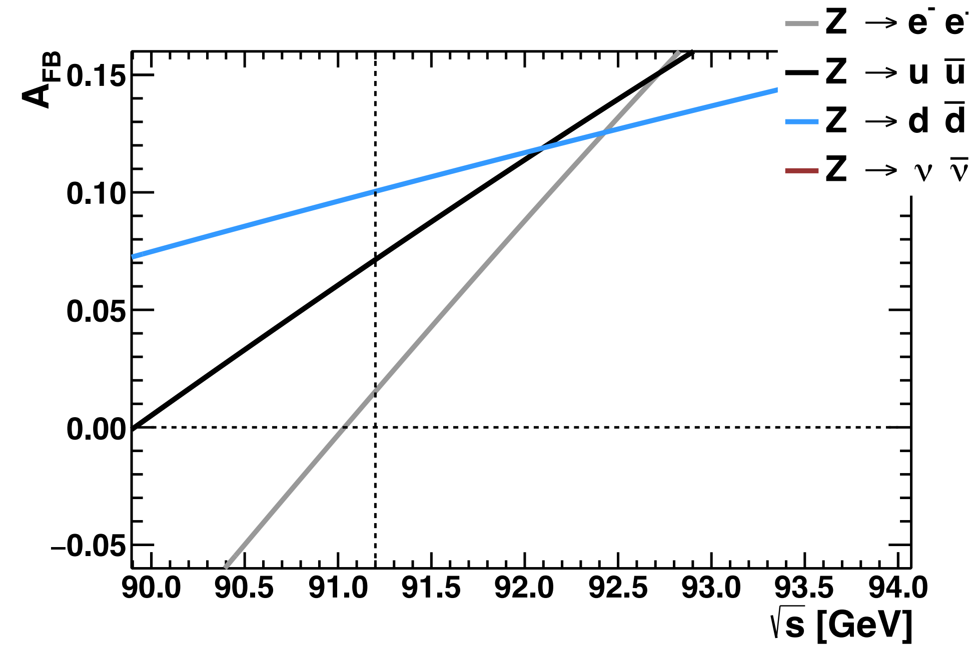




ES5: Z -γ* interference - A_{FB}



Zoom around m_Z



Neutrinos: not measurable but show the Z only asymmetry

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

Digression hypothesis test

- We observe *x*, realization of a random variable *X*
- Different models have different X distribution
  - ✓ model 1: H_1 *e.g.* signal + background H_{s+b}
  - ✓ model 2: H_2 *e.g.* background only H_b
- Likelihood: $L(H, x) = P(X{=}x \mid H)$, known a priori for the 2 models
- Evidence that data x supports H_1 over H_2 if $L(H_1, x) > L(H_2, x)$
- Define likelihood ratio test λ

$$\lambda = L(H_1, x)/L(H_2, x)$$

- ✓ $\lambda > 1$ data supports H_1 over H_2
- ✓ $\lambda < 1$ data supports H_2 over H_1