LHC Physics (Higgs II)

Mario Martínez

TAE, Benasque, September 2018

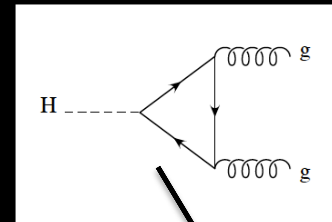
Outline for Part II

J^{PC}

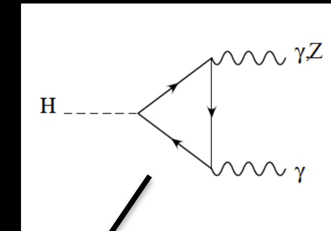
- **Other (Bronze) Channels**
- **Detailed study on Couplings**
- **Higgs width**
- **Invisibly decaying Higgs**
- **Higgs and Vacuum Stability**
- **Hierarchy Problem & SUSY**
- **Search for other Higgs (few examples)**
- **What to expect in the future ?**

Disclaimer: completely unbalanced set of results from CMS and ATLAS and no fanatic collection of latest results

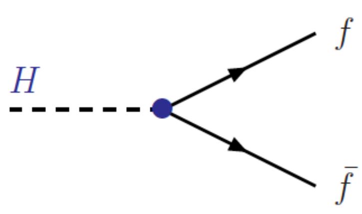
Higgs Couplings to SM



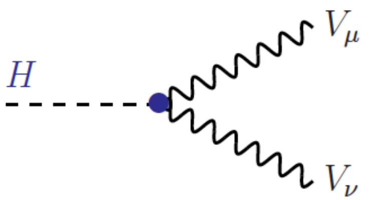
and via loops..



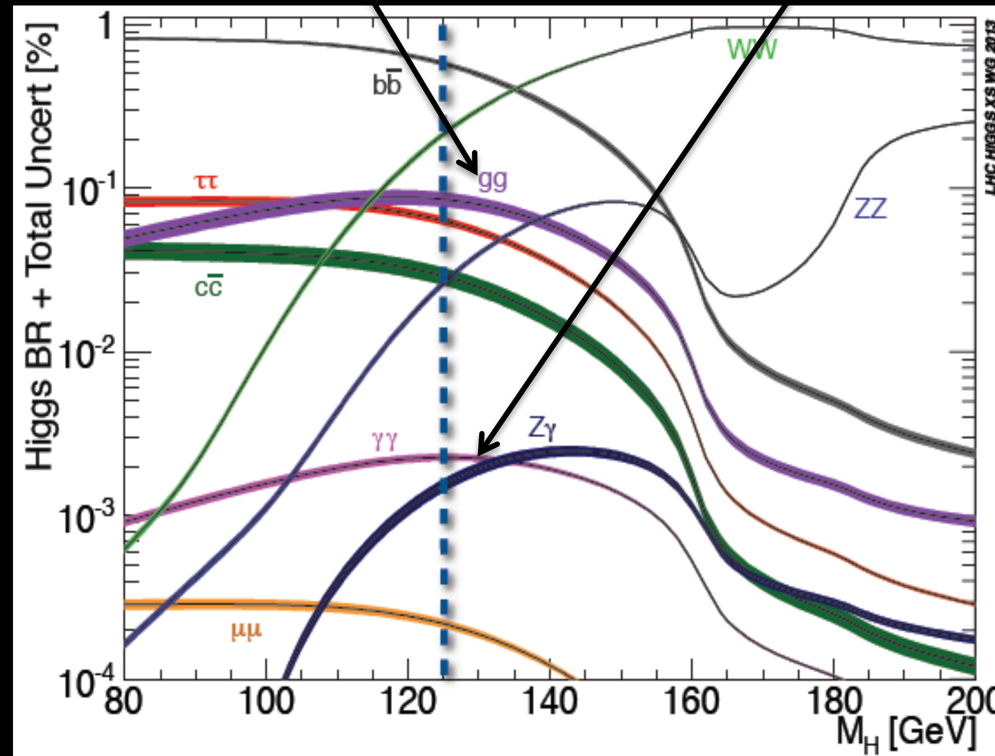
Couplings proportional to masses of particles
→ This determines the phenomenology

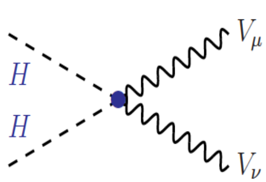


$$g_{Hff} = m_f/v$$

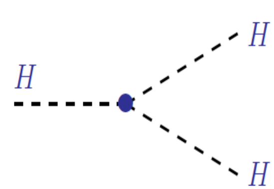


$$g_{HVV} = 2M_V^2/v$$

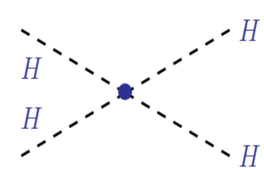




$$g_{HHVV} = 2M_V^2/v^2$$



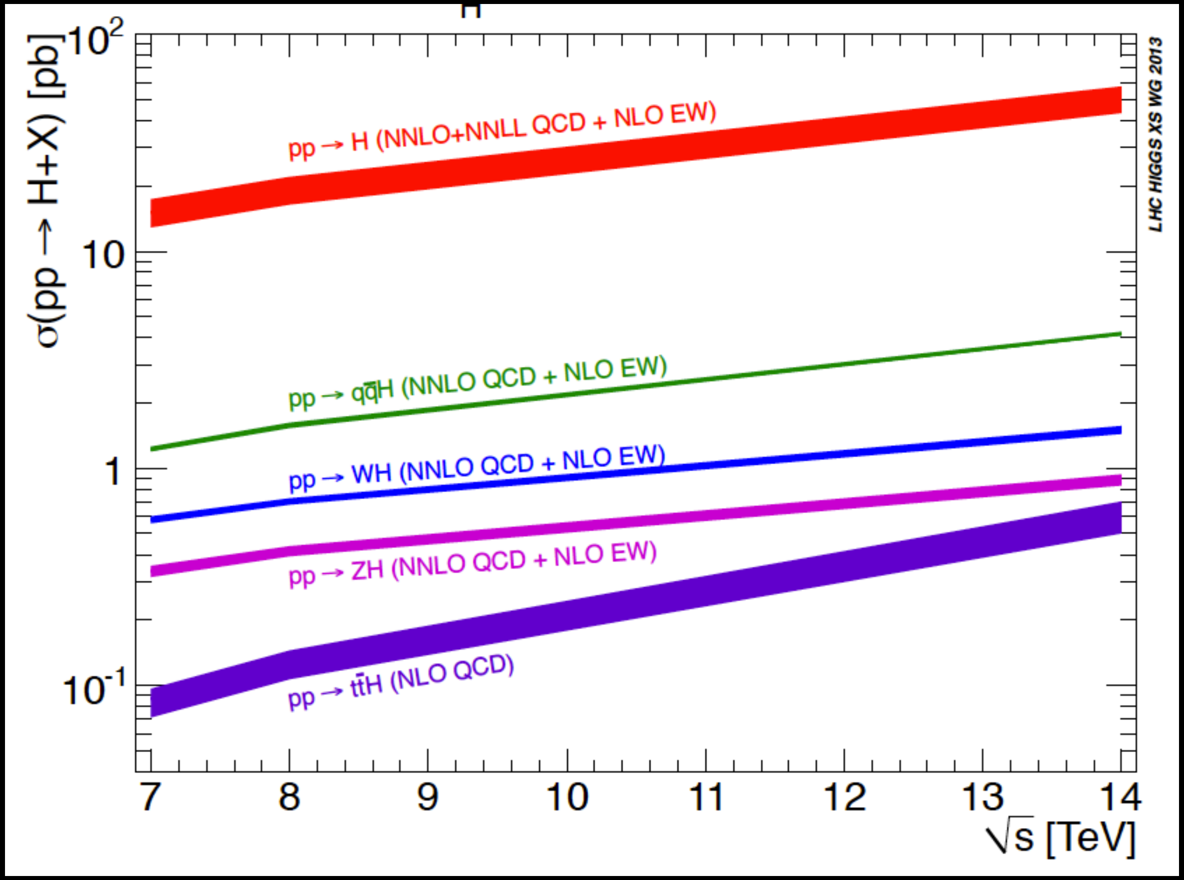
$$g_{HHH} = 3M_H^2/v$$



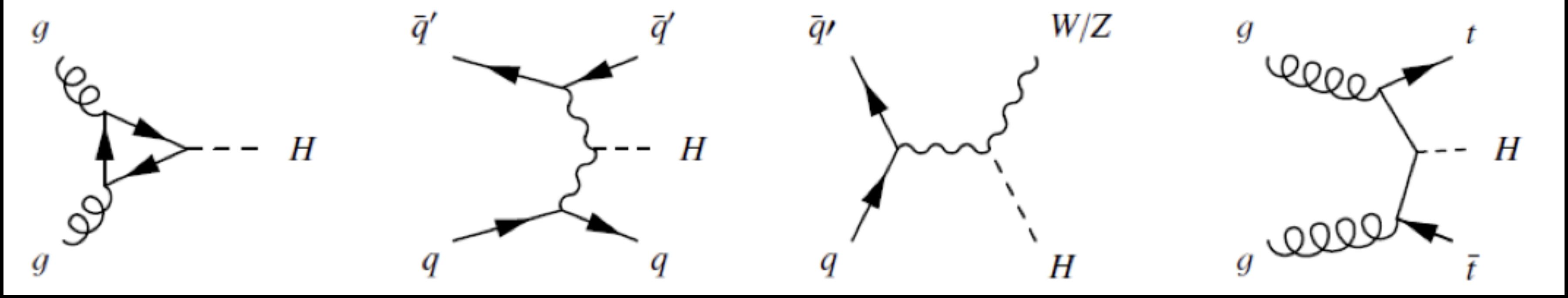
$$g_{HHHH} = 3M_H^2/v^2$$

Higgs Production (LHC)

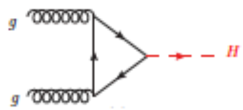
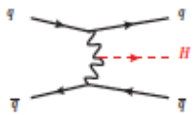
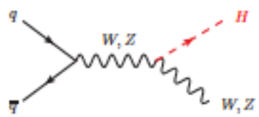
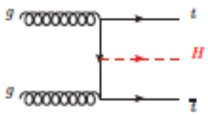
For a Higgs of 125 GeV



Decreasing cross section →

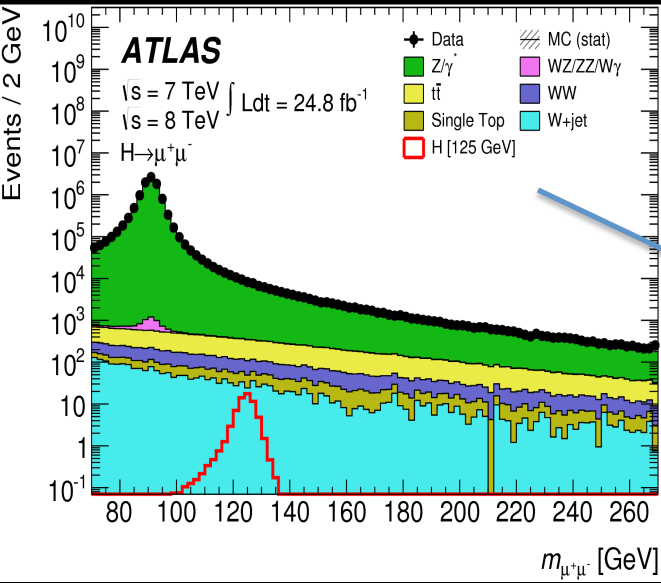


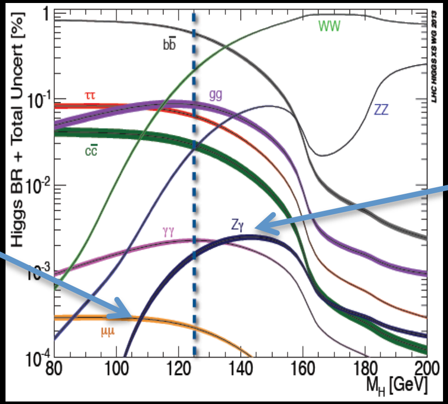
Higgs Program in a Glance

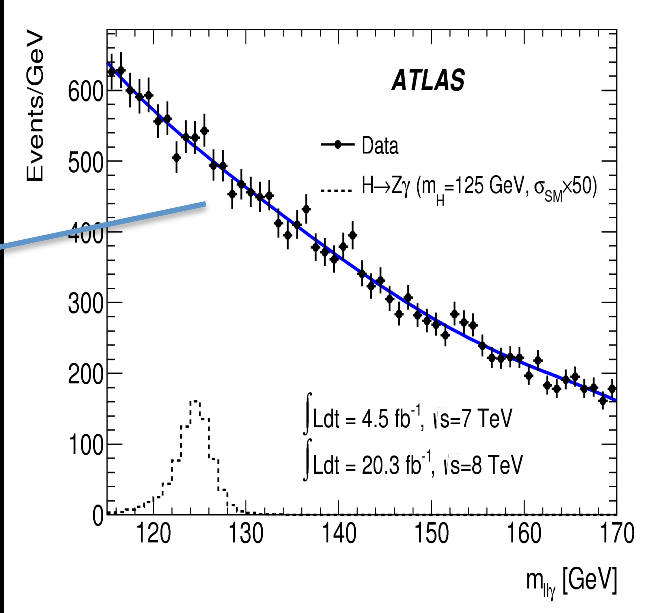
Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lnln)	✓	✓	✓	✓
ττ	X	✓	✓	✓
bb	X	✓	✓	✓
Zγ	✓	✓		
μμ	✓	✓		
Invisible	✓	✓	✓	

Rare Decays

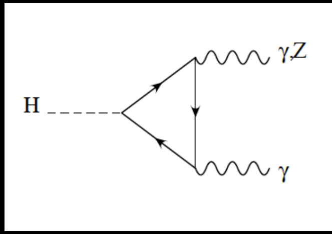
Rare Decays



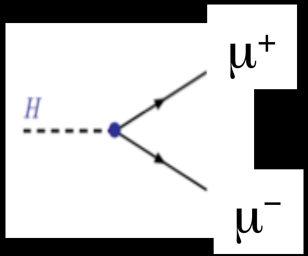


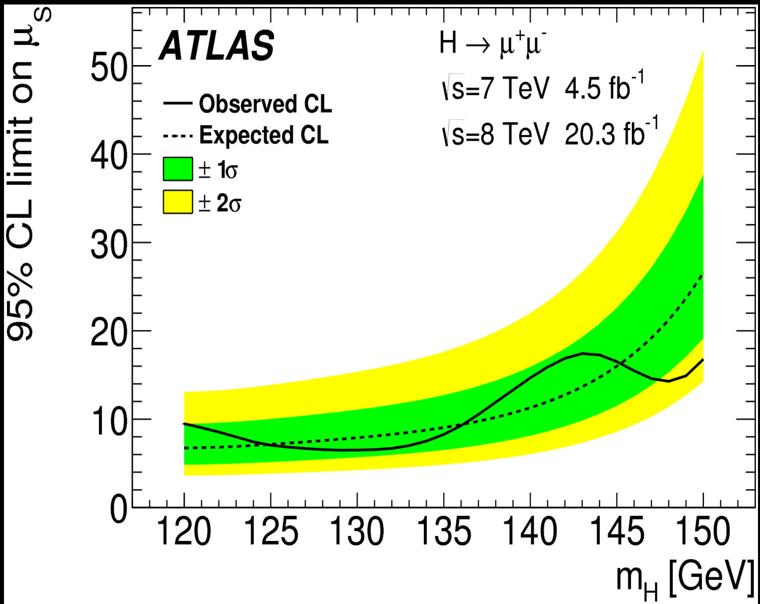


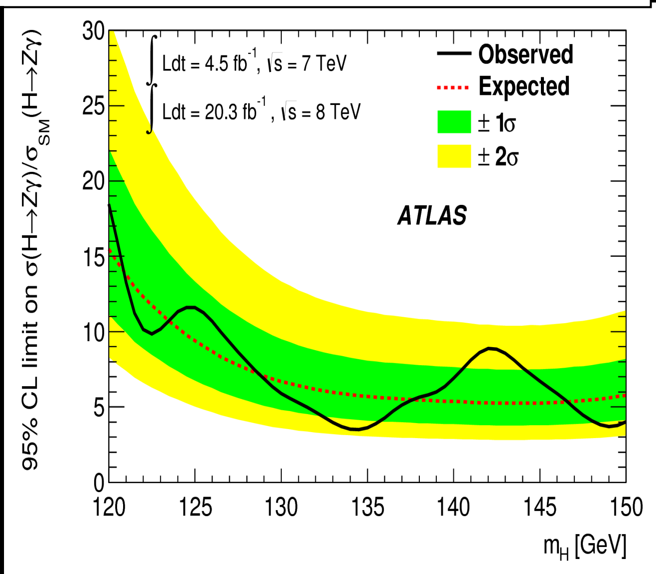
$$\sigma\,\mathrm{Br}_{\mu\mu}/\sigma^{SM} < 7 \text{ @ } 95\%\text{ CL}$$



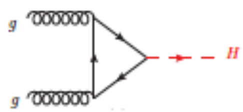
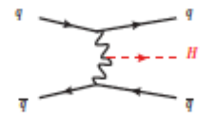
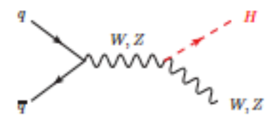
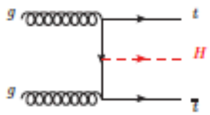
$$\sigma\,\mathrm{Br}_{Z\gamma}/\sigma^{SM} < 11 \text{ @ } 95\%\text{ CL}$$







Global Understanding

Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lnln)	✓	✓	✓	✓
ττ		✓	✓	✓
bb		✓	✓	✓
Zγ	✓	✓		
μμ	✓	✓		
Invisible	✓	✓	✓	

Detailed Study of Couplings

$$n^c_{signal} = (\sum_i \mu_i \sigma_{i,SM} \times A^c_{if} \times \varepsilon^c_{if}) \times \mu_f \times B_{f,SM} \times \mathcal{L}$$

$$i \in \{ggH, VBF, VH, ttH\}$$

$$f \in \{\gamma\gamma, WW, ZZ, bb, \tau\tau\}$$

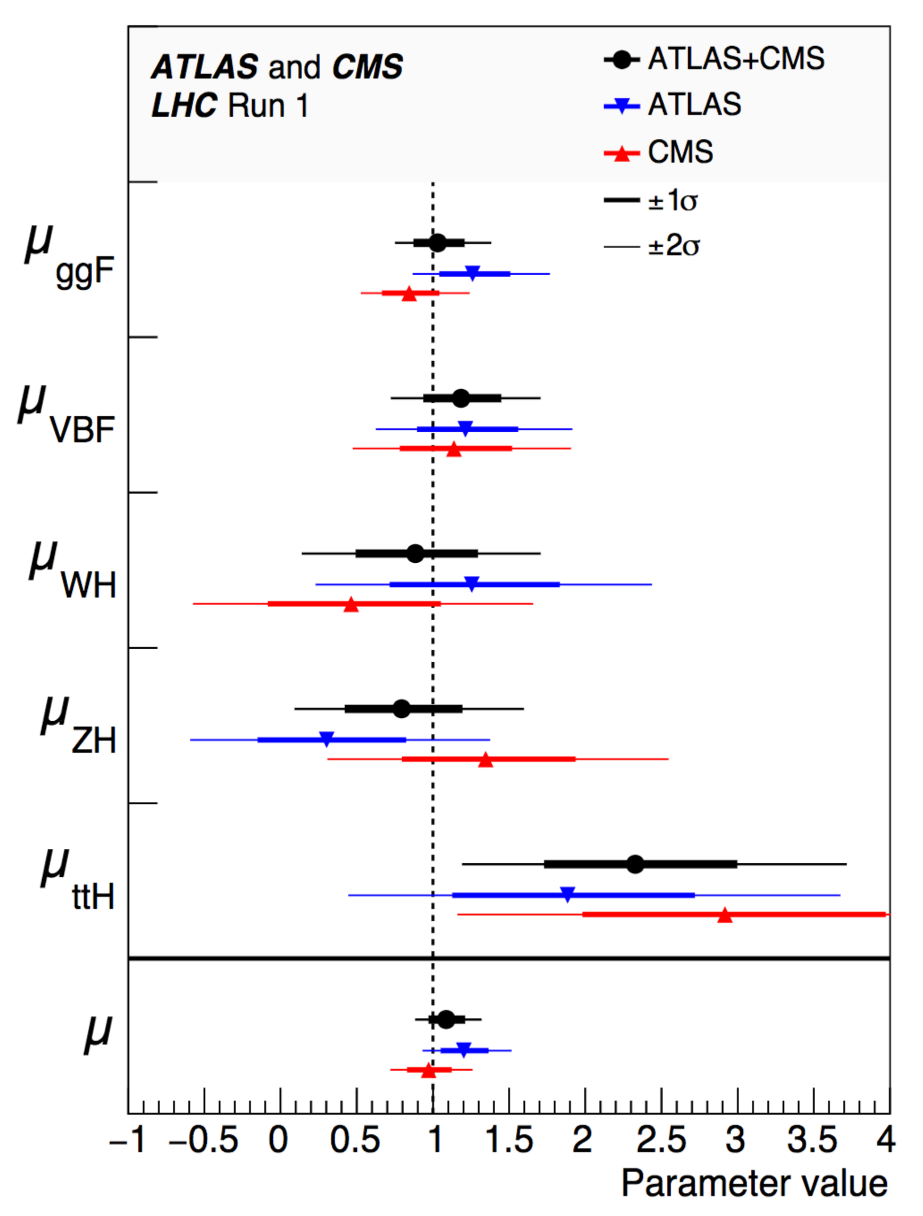
Taking some assumptions

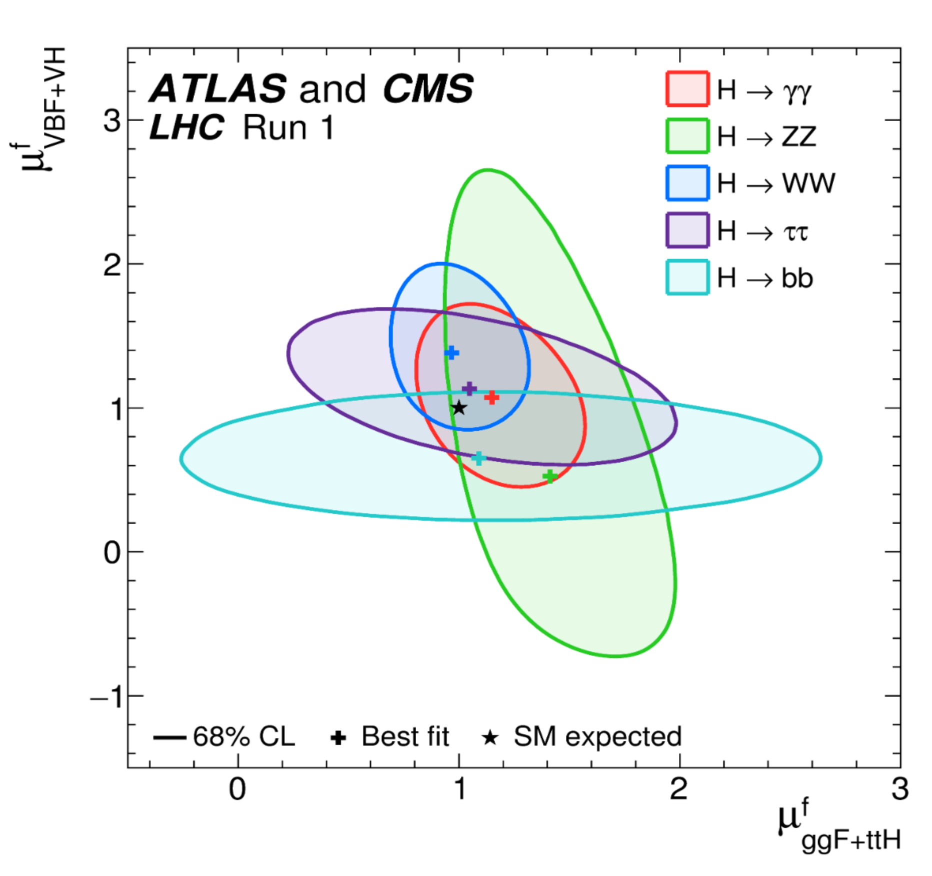
$$(\mu_{ggH+ttH} = \mu_{ggH} = \mu_{ttH}) \qquad (\mu_{VBF+VH} = \mu_{VBF} = \mu_{VH})$$

PDG 2016

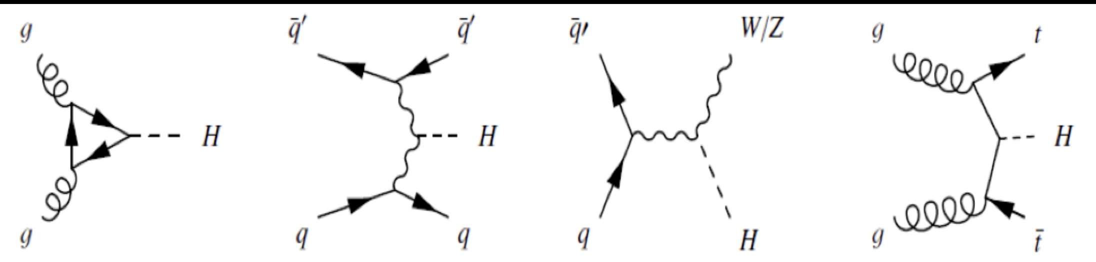
Higgs Couplings

$$\sigma^{visible} = \mu\sigma^{SM}_{HIGGS}$$





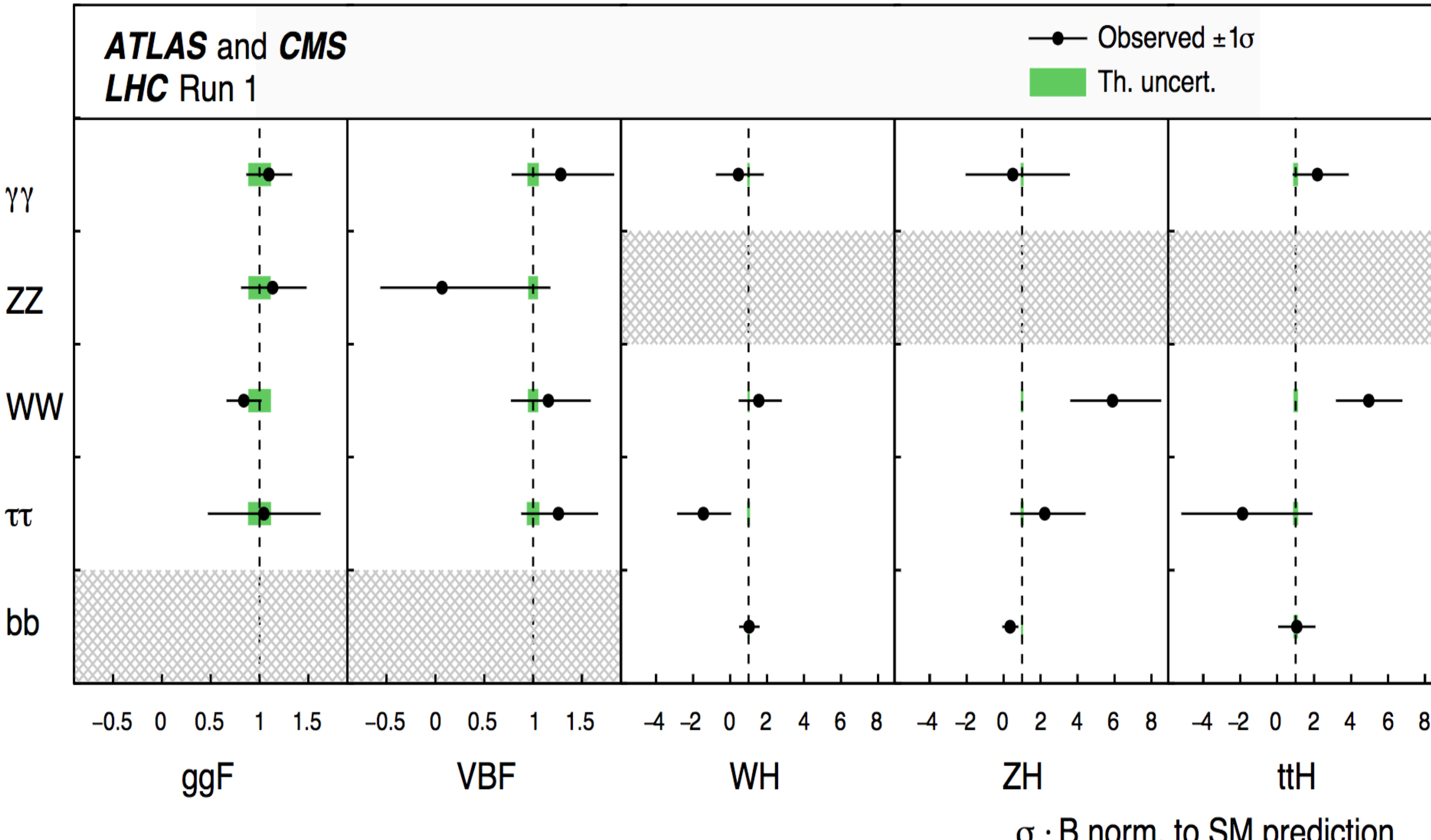
Run I:
Within the uncertainty of the data all looks consistent with a SM Higgs



ATLAS & CMS

$$\sigma^{visible} = \mu\sigma^{SM}_{HIGGS}$$

PDG 2016



Using EFT Lagrangian in Global Fit

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$+ \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu} \right) H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H$$

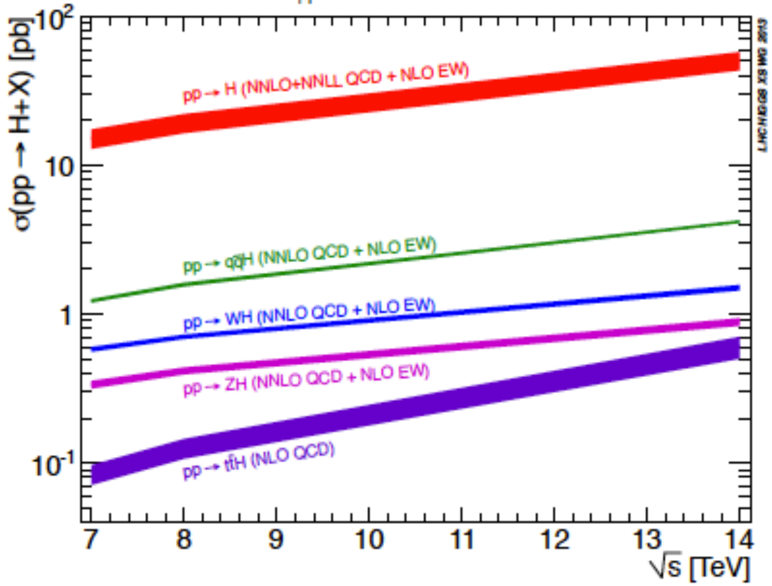
Global EFT analysis using scale factors κ_k that modify SM couplings

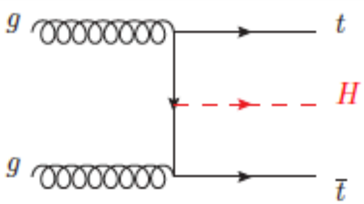
$$k \in \{Z, W, f, g, \gamma, Z\gamma\}$$

One can build the relationships between different scale factors according to the different processes…

Higgs Production Modes

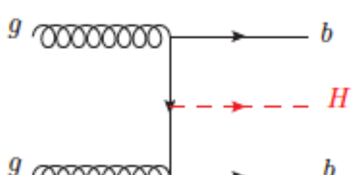
κ for m_H = 125.5 GeV





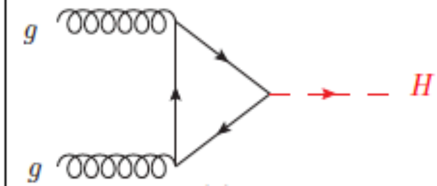
$\propto \kappa_t^2$

Top Assoc. Prod. ~3 k evts produced



$\propto \kappa_b^2$

B-quark Assoc. Prod. ~5 k evts produced

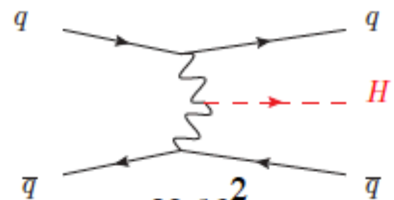


Gluon fusion process

NNnLO ~O(10%)

~0.5 M events produced

$$\kappa_g \propto 1.\times 06\kappa_t^2 - 0.07\times\kappa_t\kappa_b + 0.01\times\kappa_b^2$$



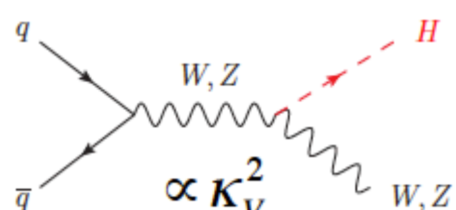
$\propto \kappa_V^2$

Vector Boson Fusion

NLO TH uncertainty ~O(5%)

Two forward jets and a large rapidity gap

~40 k events produced

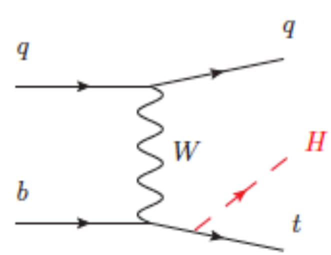


$\propto \kappa_V^2$

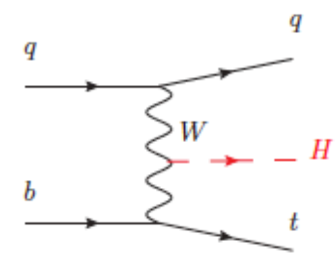
W and Z Associated Production

NNLO TH uncertainty ~O(5%)

~20 k events produced



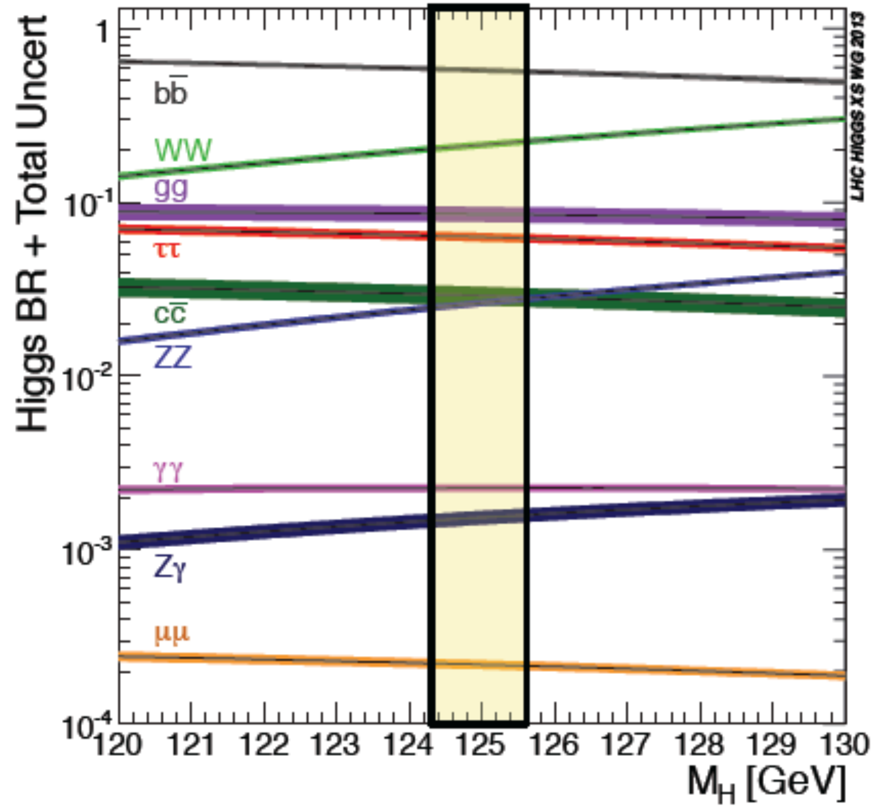
tH

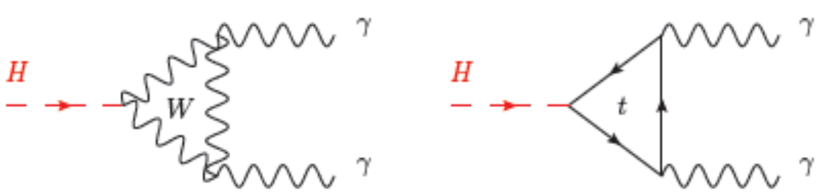


$$\propto 3.3\times\kappa_W^2 - 5.1\times\kappa_t\kappa_W + 2.8\times\kappa_t^2$$

Higgs Decay Channels

- Dominant: bb (57%) $\propto \kappa_b^2 / \kappa_H^2$
- WW channel (22%) $\propto \kappa_W^2 / \kappa_H^2$
- ττ channel (6.3%) $\propto \kappa_\tau^2 / \kappa_H^2$
- ZZ channel (3%) $\propto \kappa_Z^2 / \kappa_H^2$
- cc channel (3%) $\propto \kappa_c^2 / \kappa_H^2$
  Extremely difficult
- The γγ channel (0.2%) $\propto \kappa_\gamma^2 / \kappa_H^2$





$$\kappa_\gamma \propto 1.6 \times \kappa_W^2 - 0.7 \times \kappa_t \kappa_W + 0.1 \times \kappa_t^2$$

(when assuming no BSM charged in the loop)

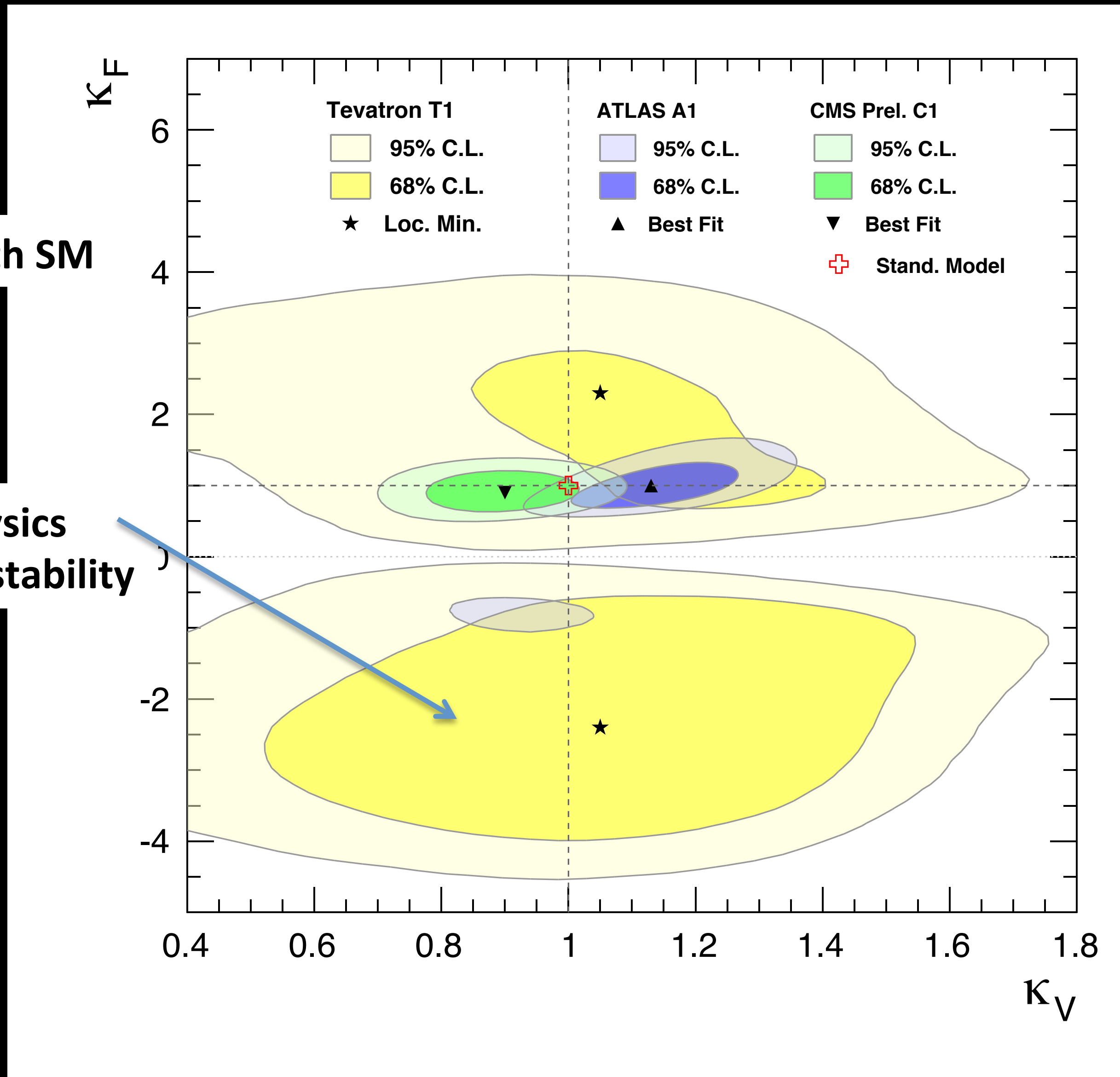
- The Zγ (0.2%) $\kappa_{Z\gamma} \propto 1.12 \times \kappa_W^2 - 0.15 \times \kappa_t \kappa_W + 0.03 \times \kappa_t^2$
- The μμ channel (0.02%) $\propto \kappa_\mu^2 / \kappa_H^2$

As in PDG (Aug 2014)

Relative Couplings to fermions/bosons

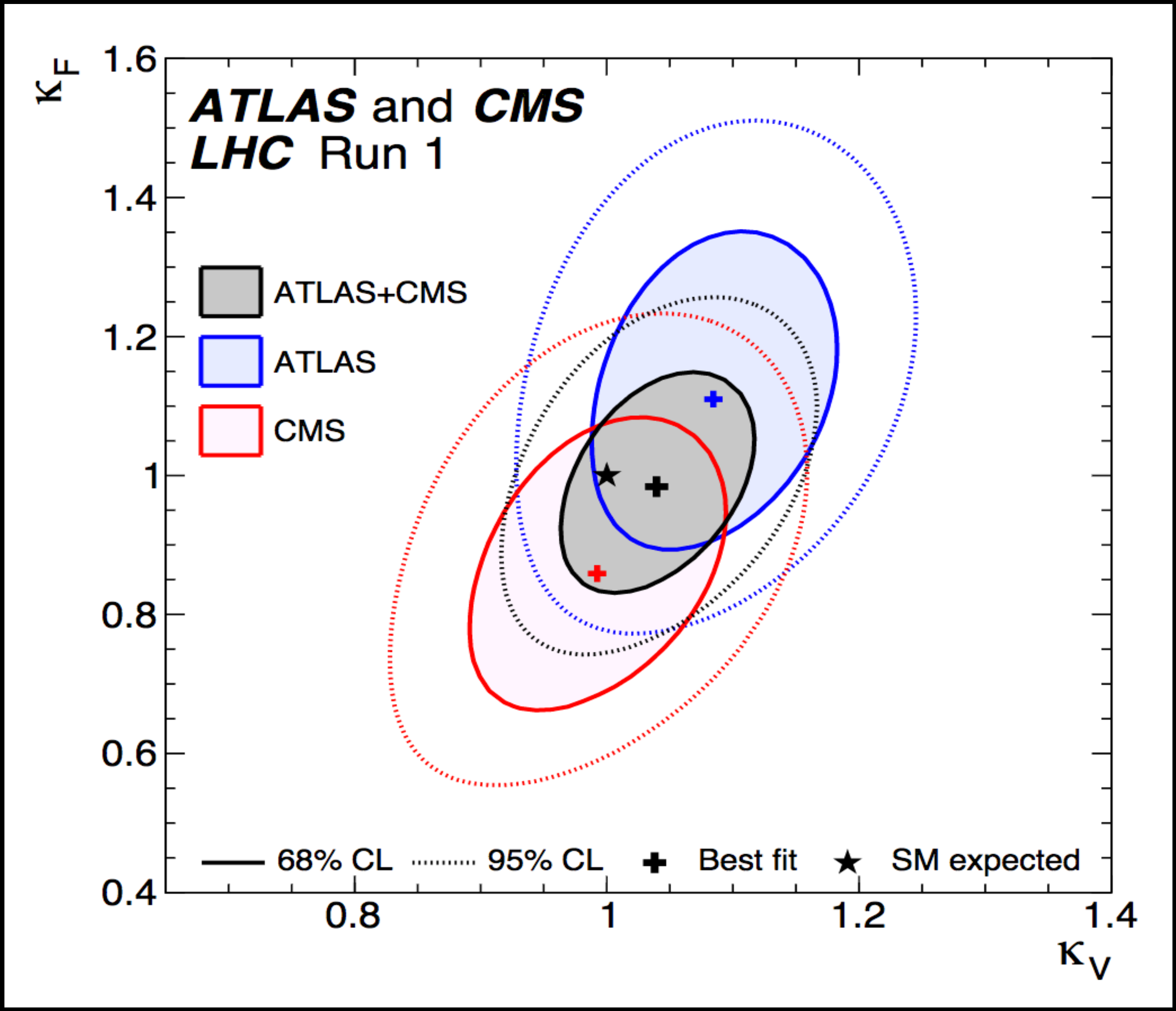
Best fit consistent with SM

That would imply new physics and compromise vacuum stability



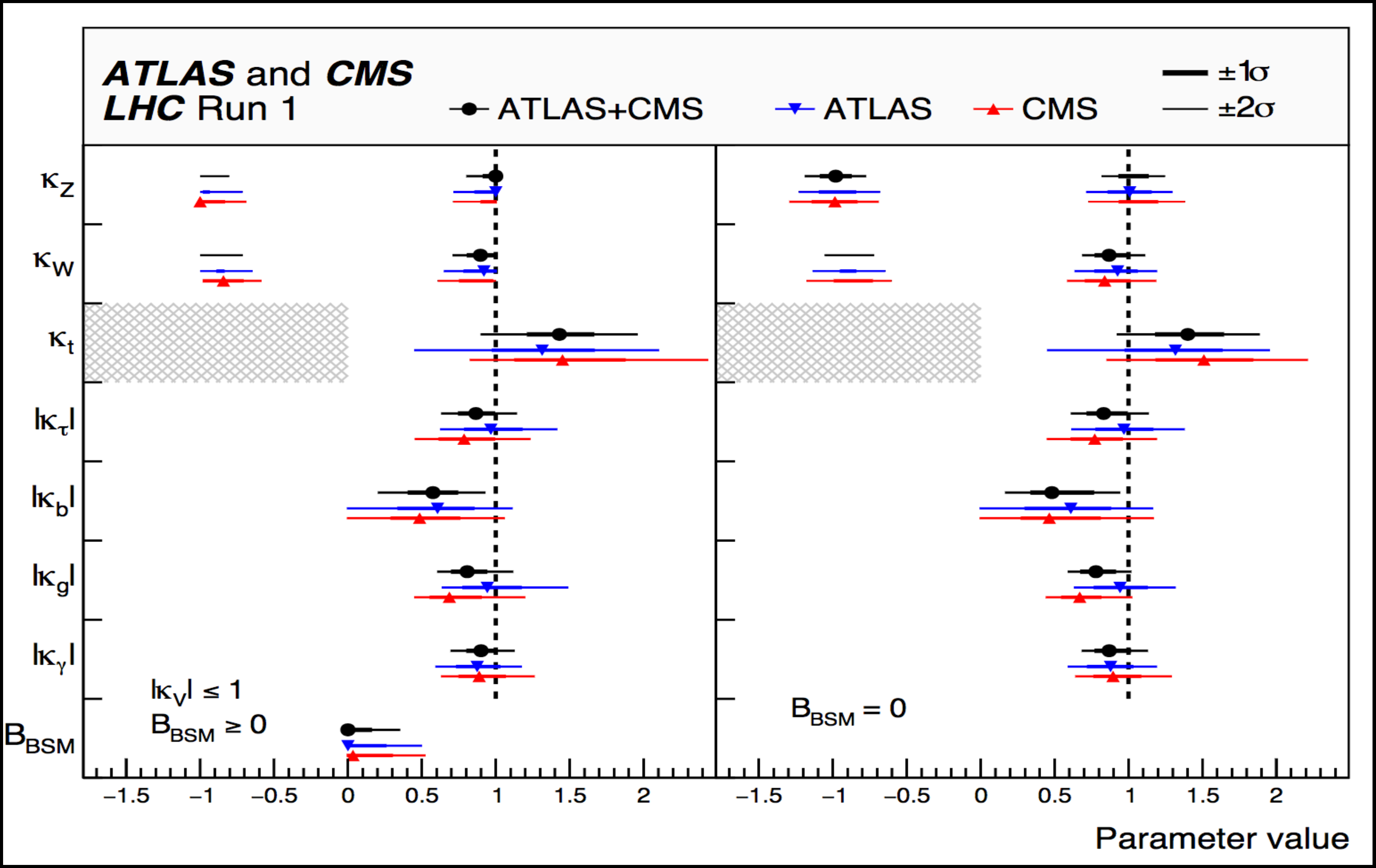
As in PDG (Aug 2016)

Relative Couplings to fermions/bosons



As in PDG (Aug 2016)

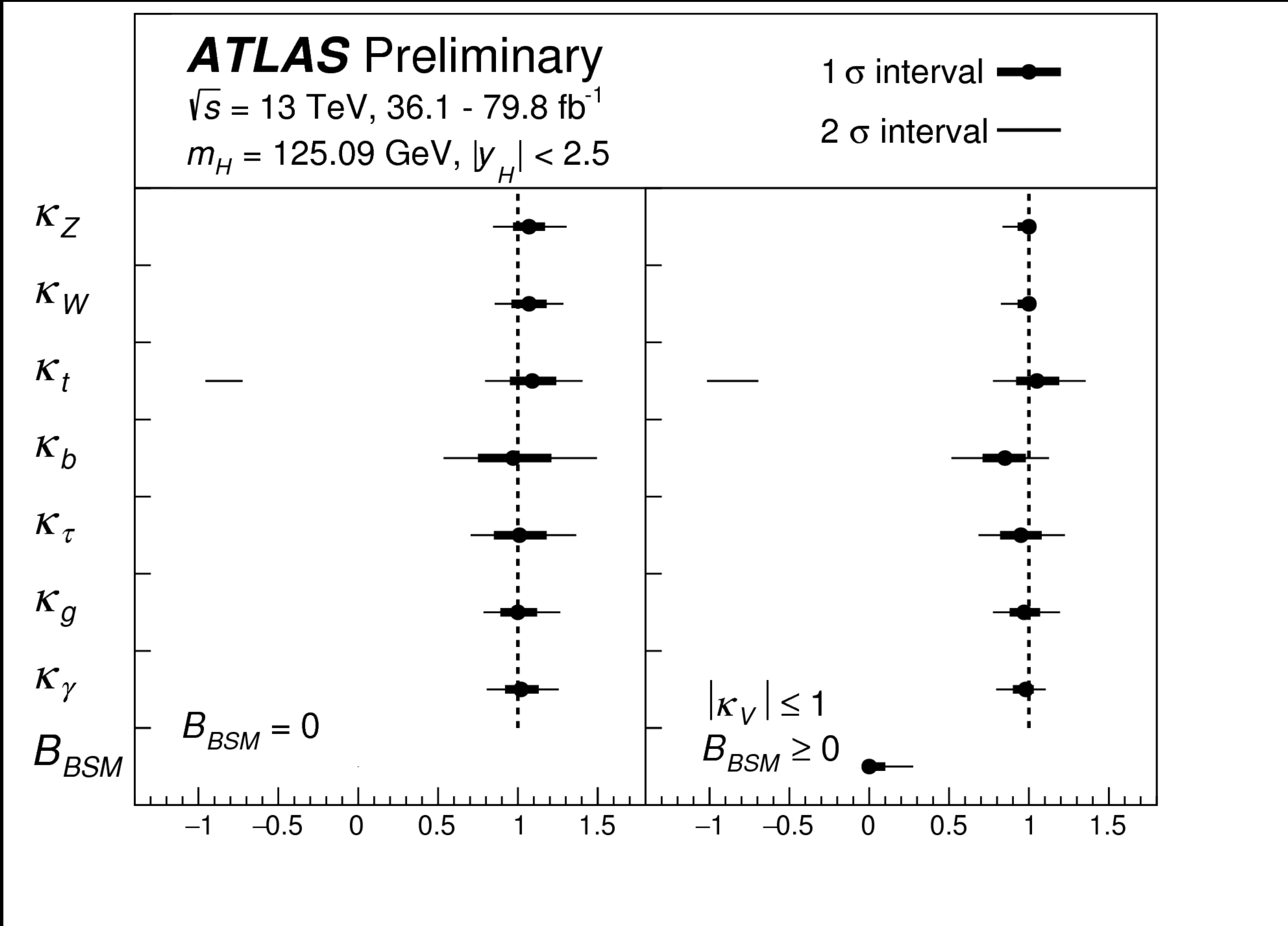
So close to 1…



Using Run II data

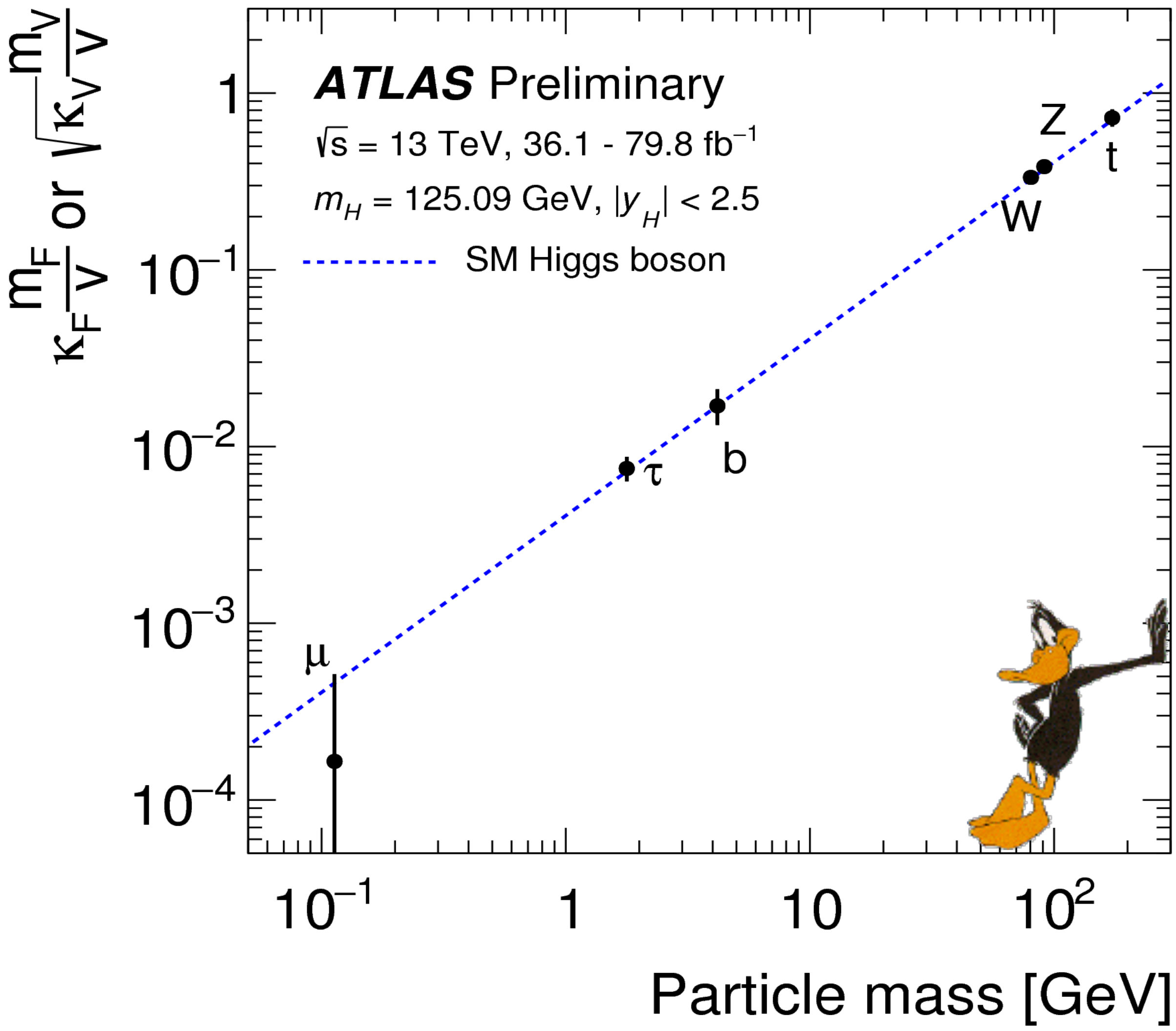
ATLAS-CONF-2018-031

So close (too close) to 1…



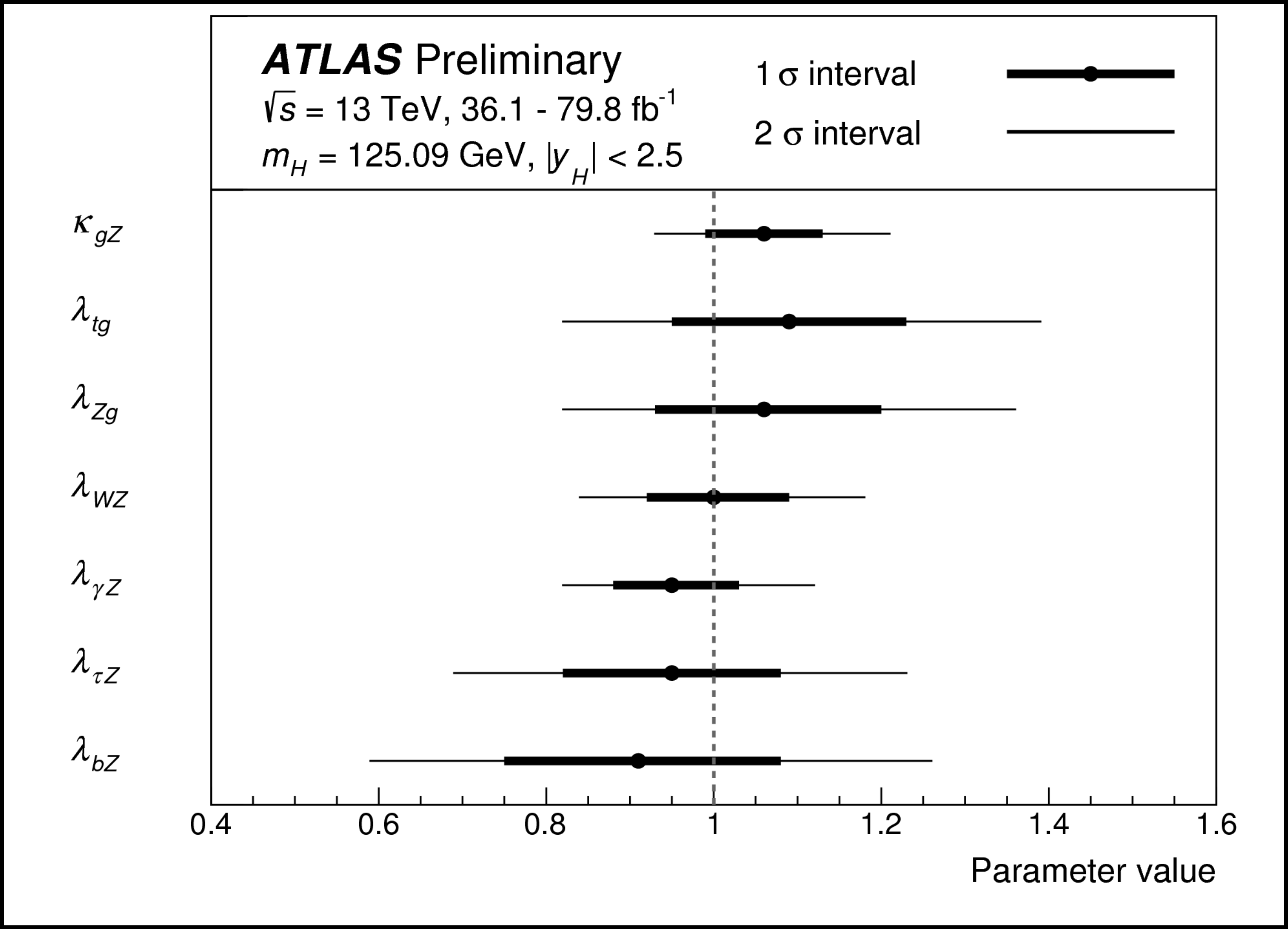
Higgs Couplings vs mass

If it looks like a duck, swims like a duck, and quacks like a duck…

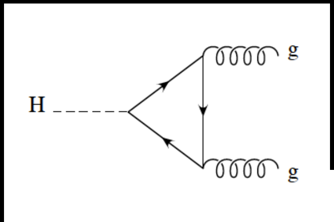


Custodial Symmetry (W/Z ratio)

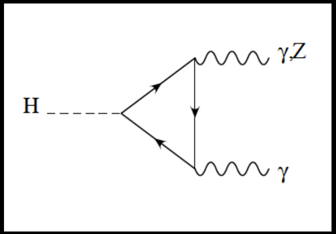
$$\lambda_{WZ} = \kappa_W / \kappa_Z$$

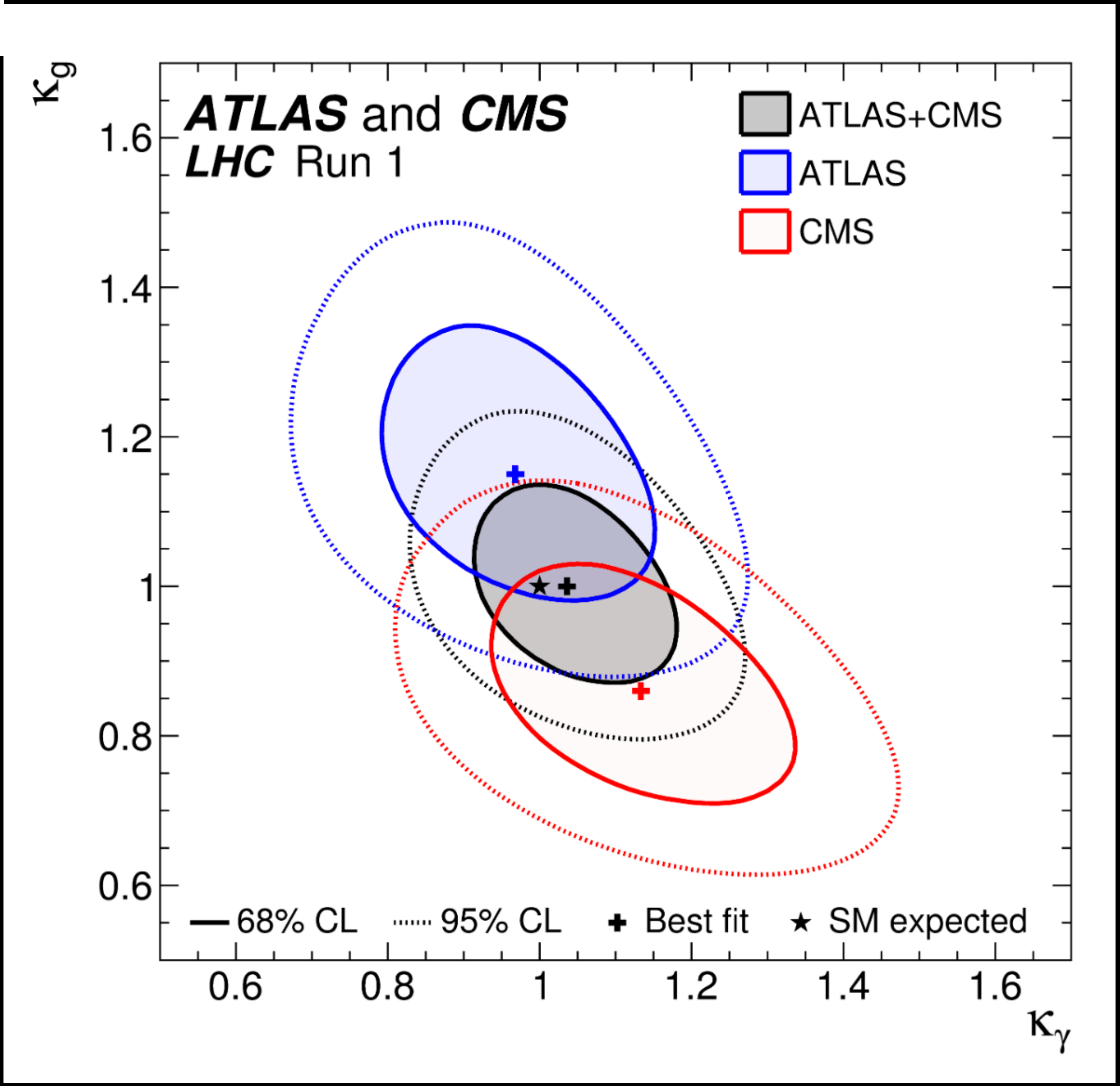


Consistent with SM $\rho = 1$



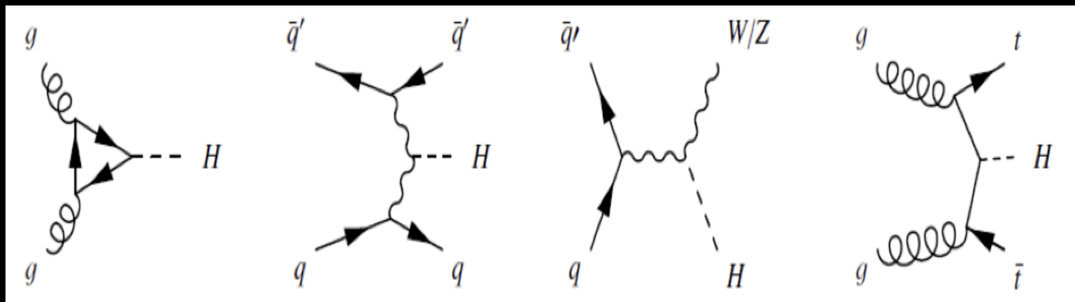
New Physics in Loops ?

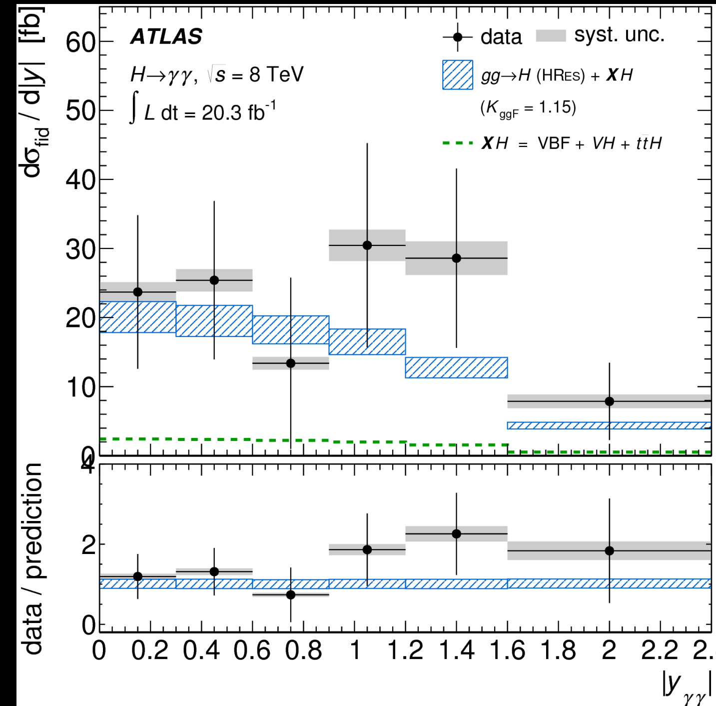




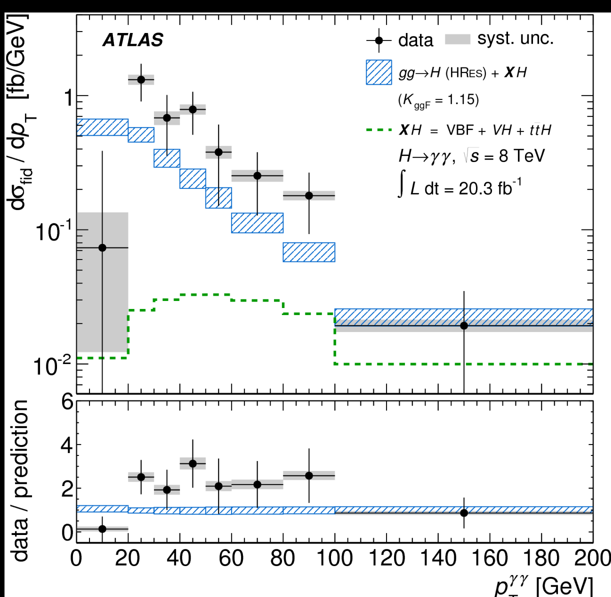
Does not look like..

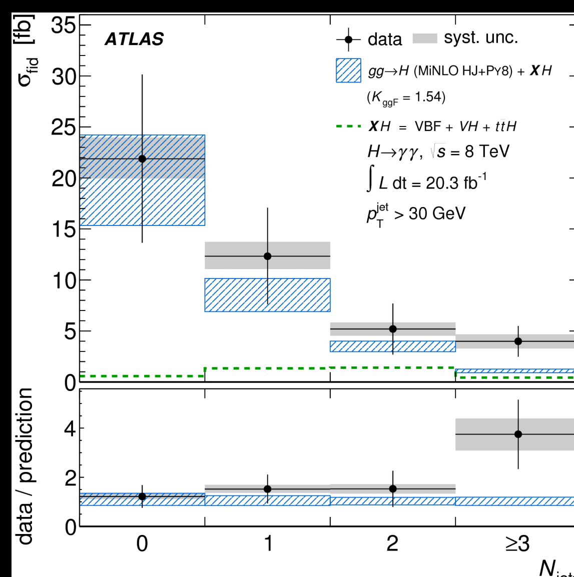
Going differential…

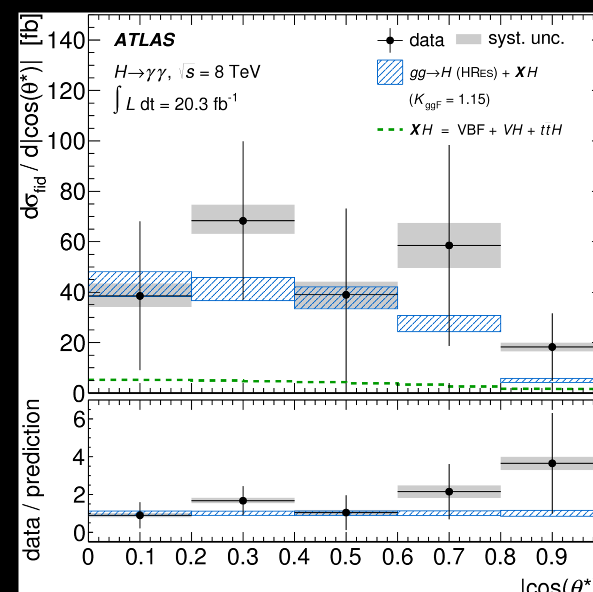




Some excess at low $p_T^{\gamma\gamma}$ and large $Y_{\gamma\gamma}$

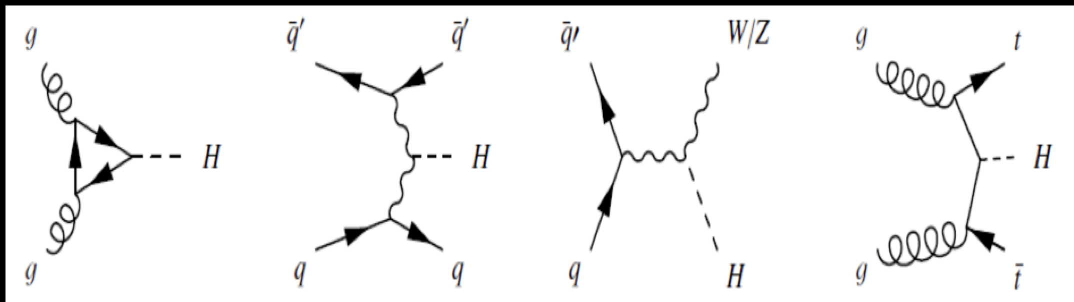




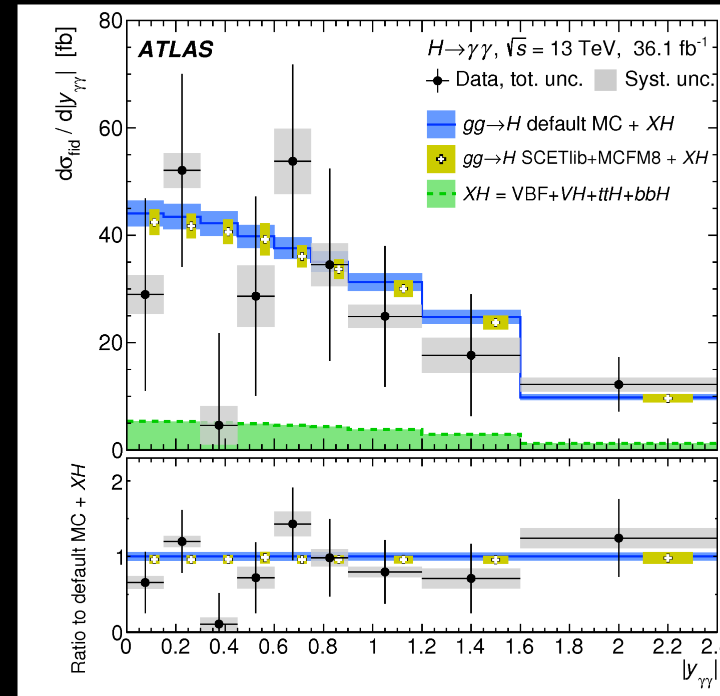


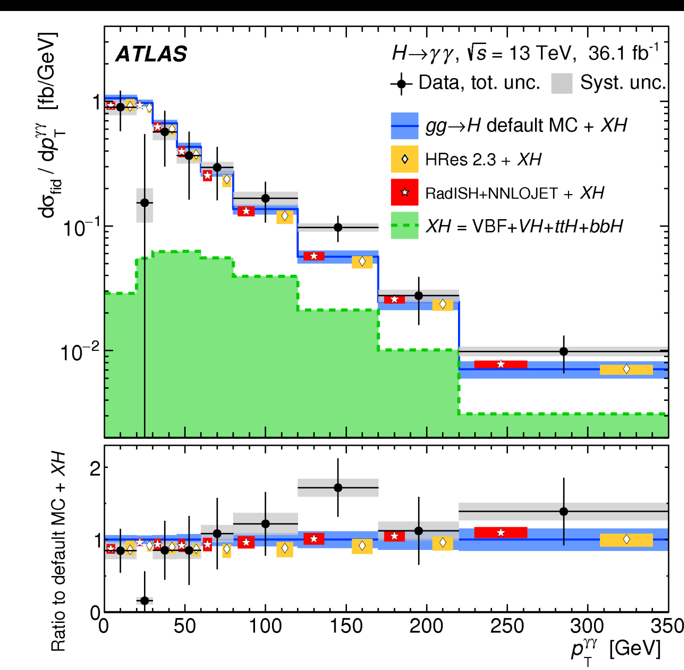
Going differential…

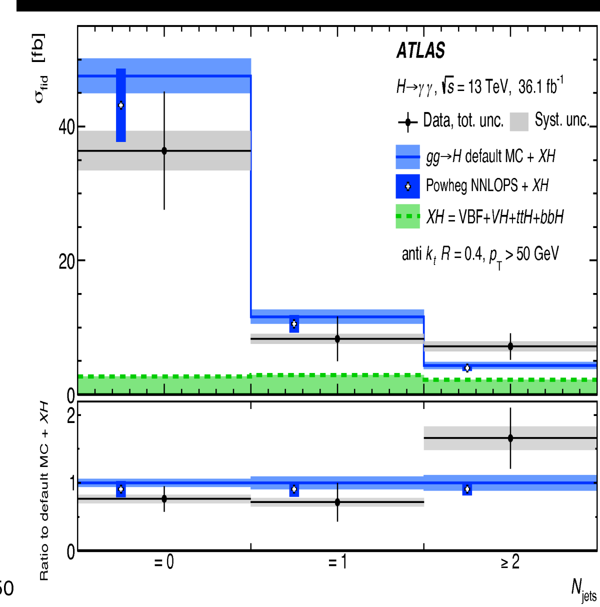
arXiv:1802.04146

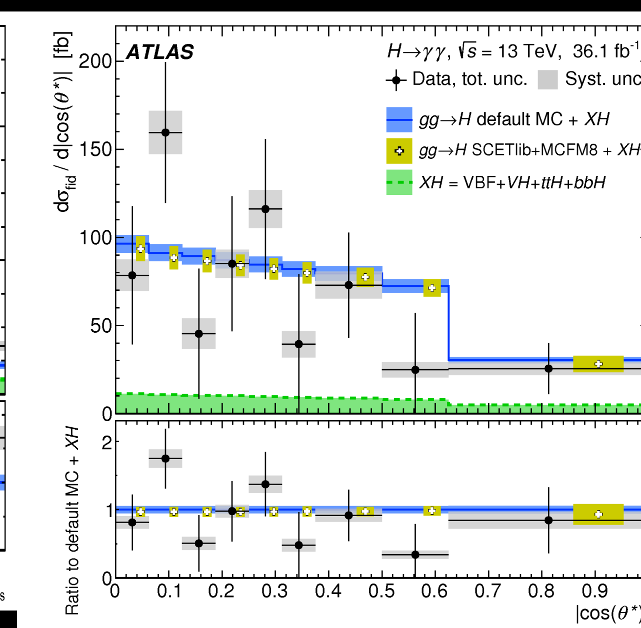


Better agreement in 13 TeV data
(much more data will be needed…..)

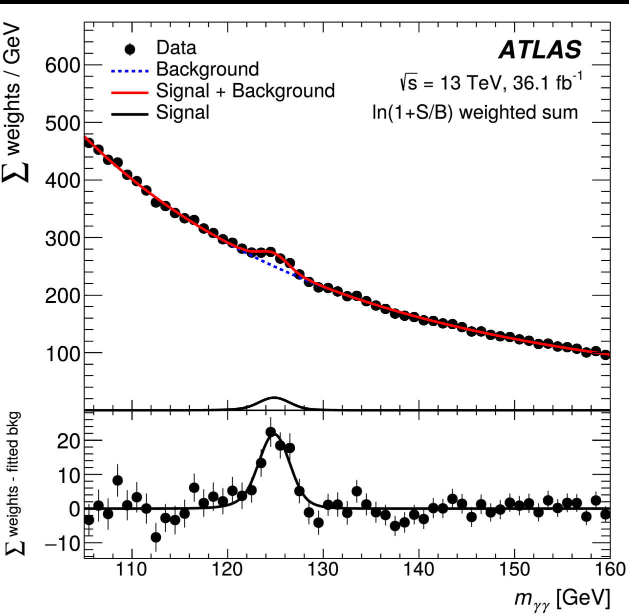


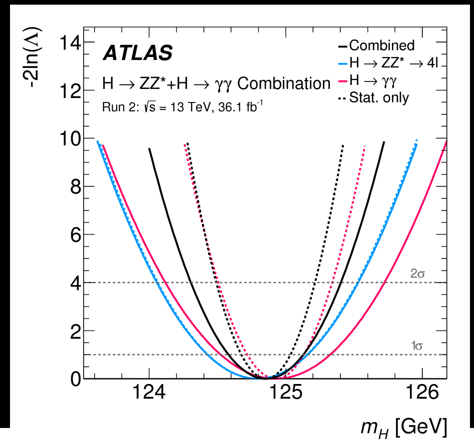


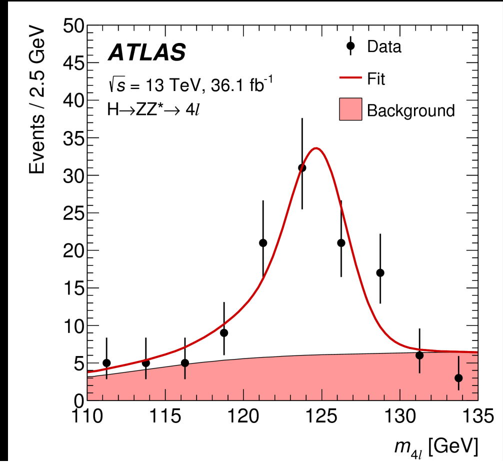


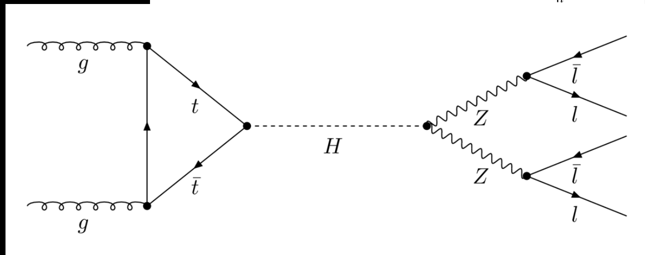


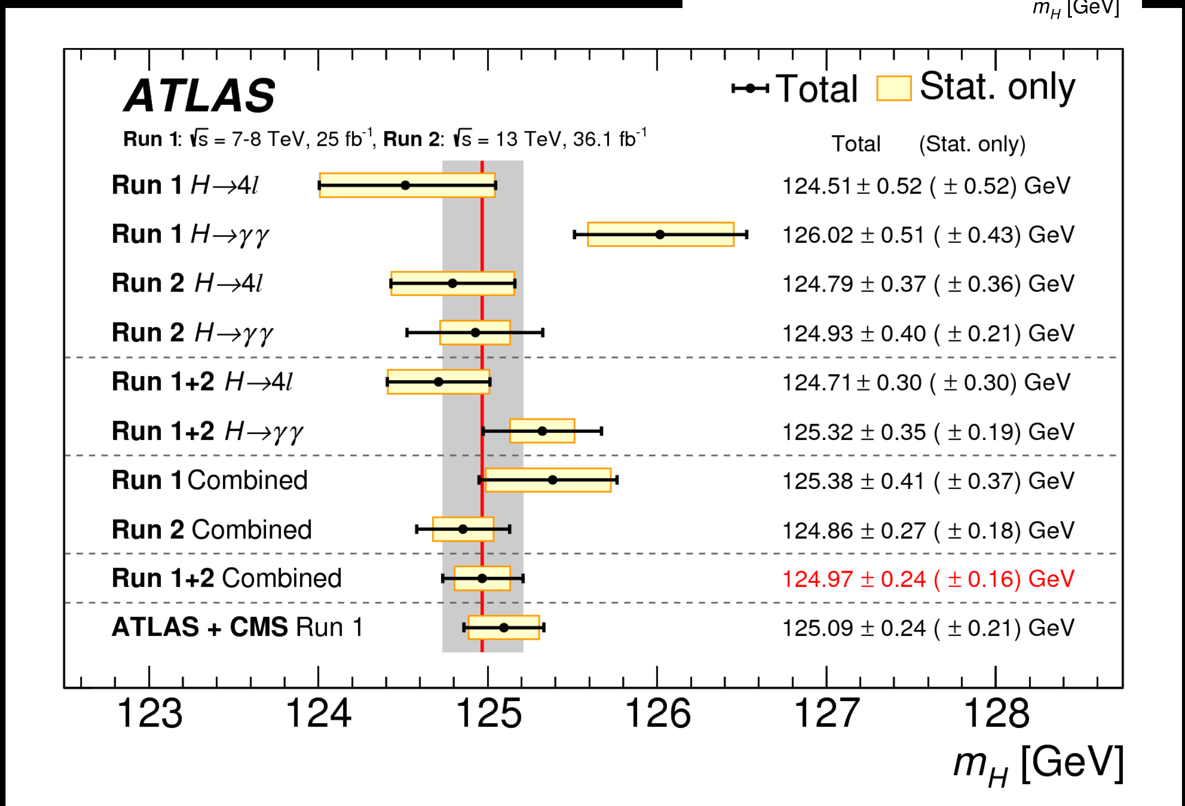
Higgs Mass





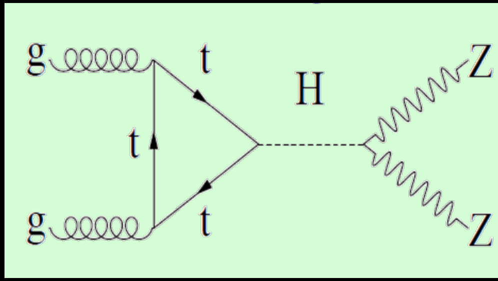






0.2% precision in mass

Higgs width



Sensitive to small contributions

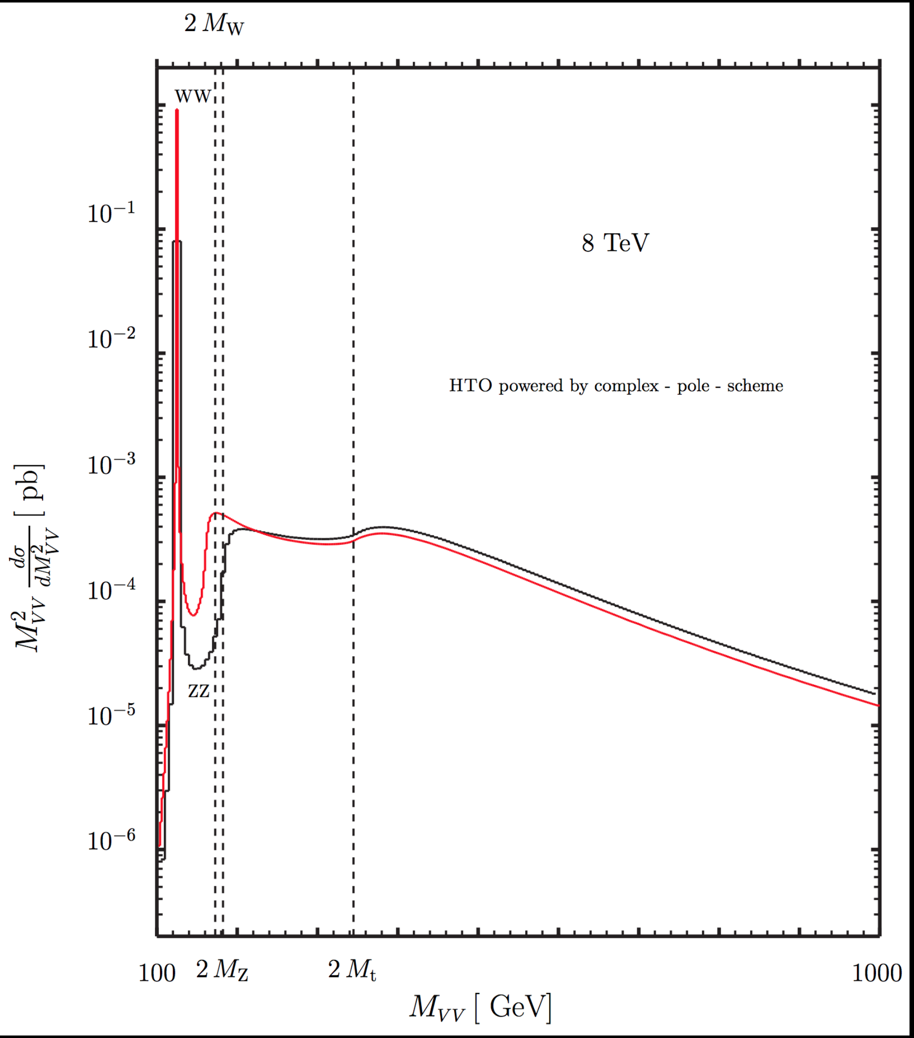
$$\Gamma_H\,(SM) = 4.2\text{ MeV}$$

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H}$$

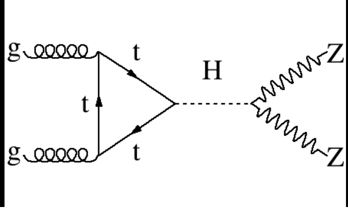
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}$$

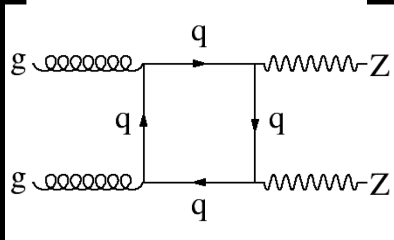
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$$

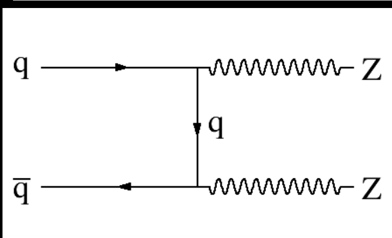
$$\frac{\sigma^{\text{off-shell}}_{gg\to H\to ZZ}}{\sigma^{\text{on-shell}}_{gg\to H\to ZZ}} \sim \Gamma_H$$

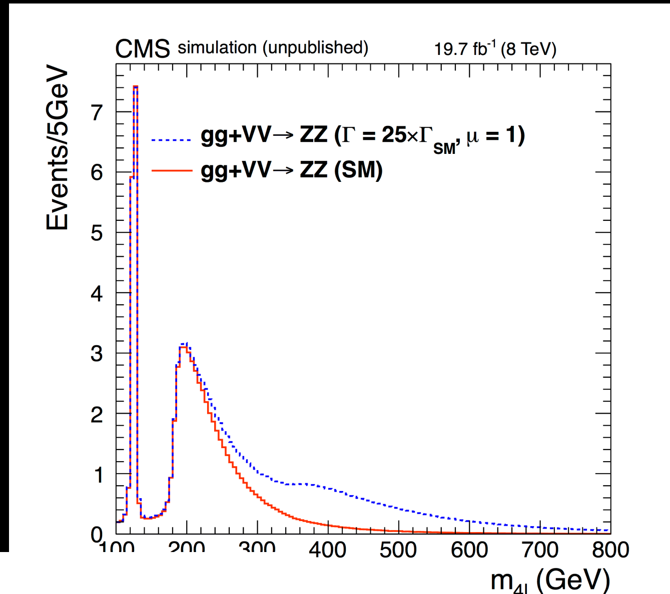


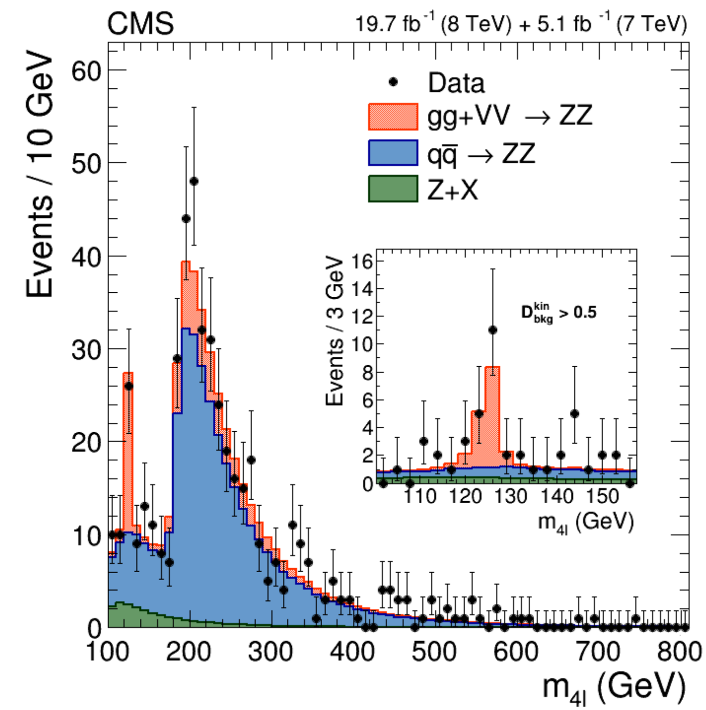
Off-Shell Higgs

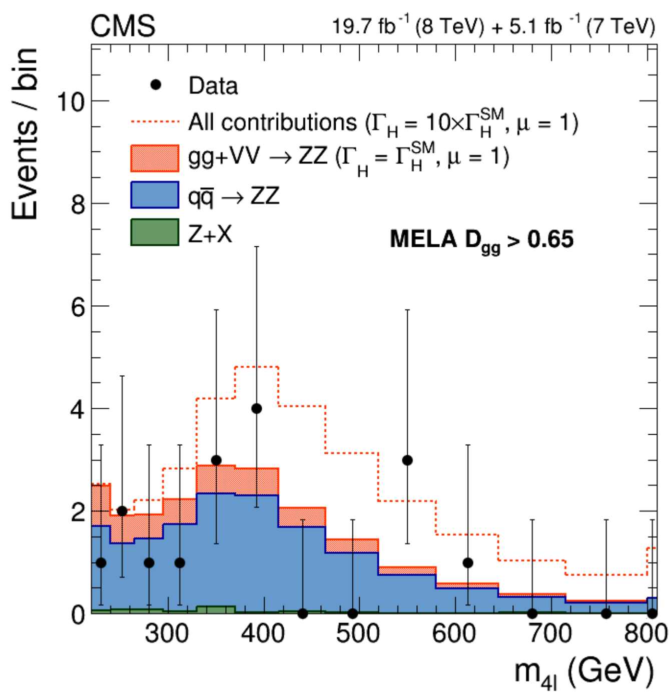




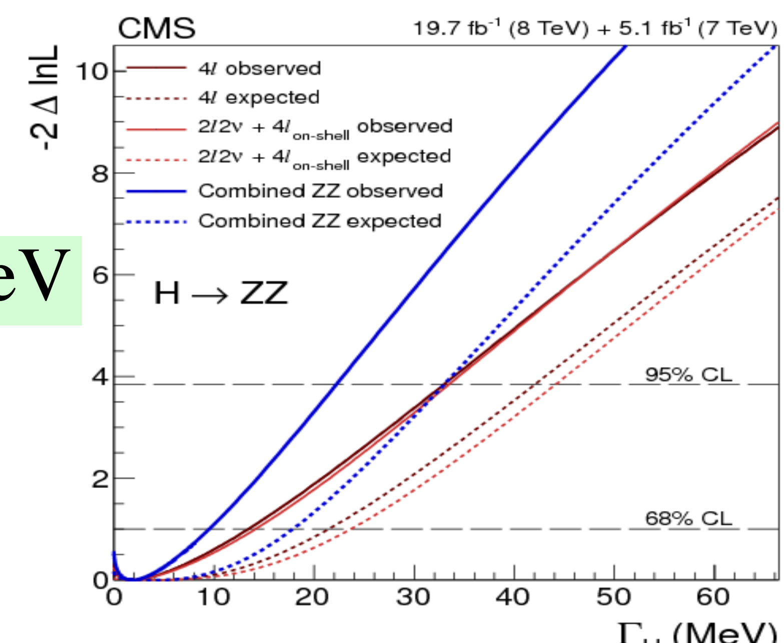






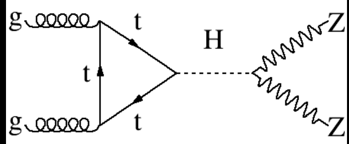


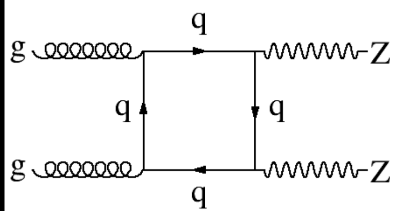
$$\Gamma_{4l} < 3\ \mathrm{GeV}$$

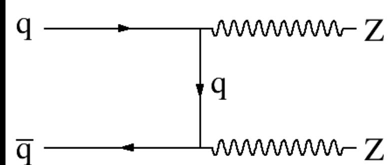


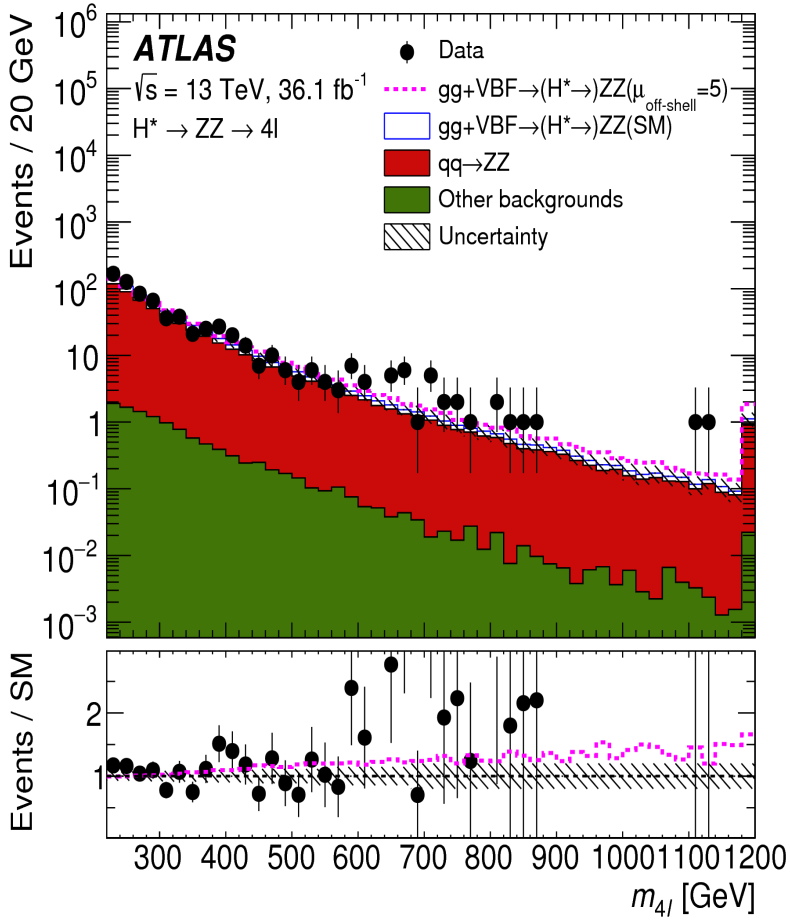
Higgs width results

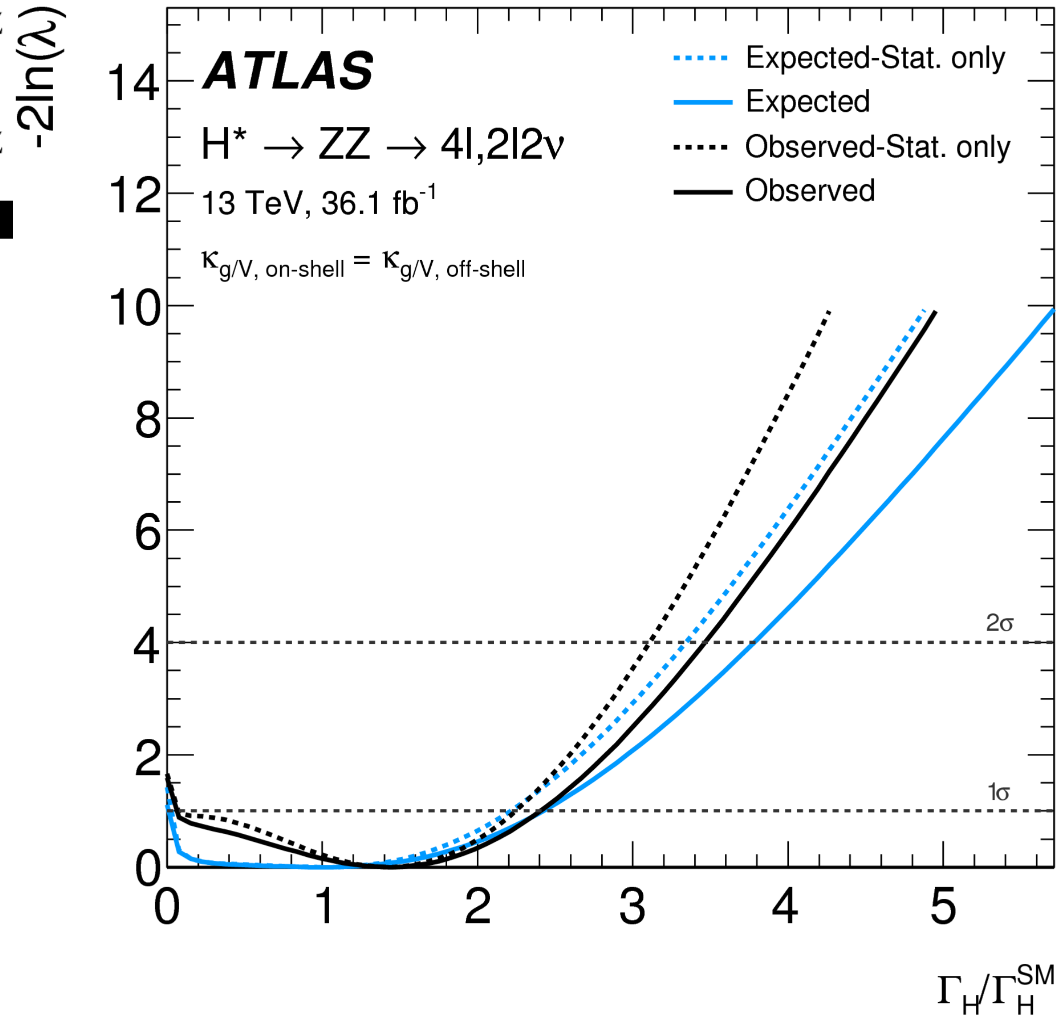
arXiv:1808.01191









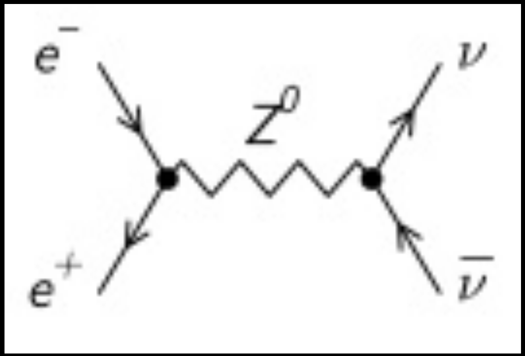


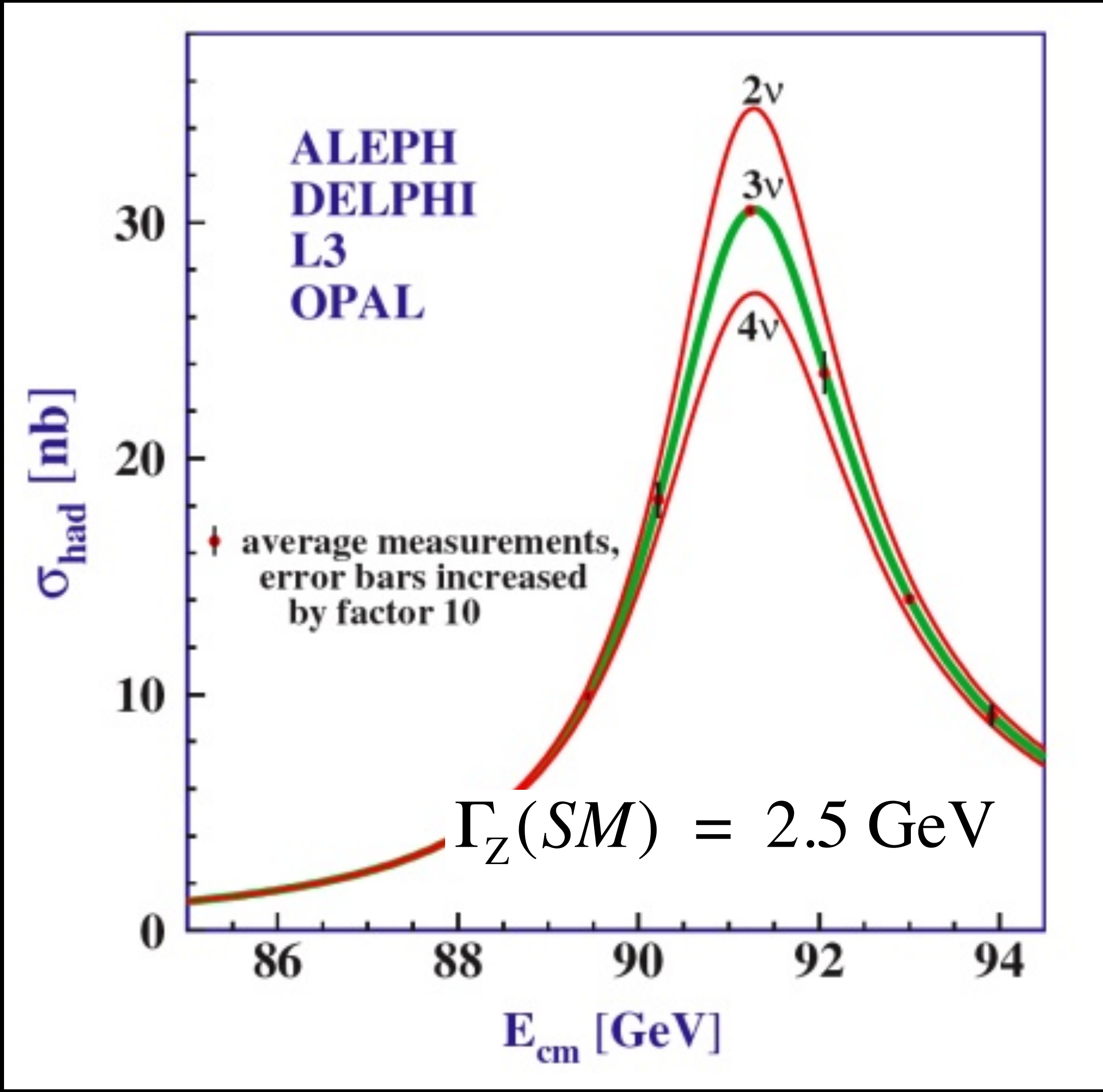
Combination of on-shell and off-shell

Γ_H < 14. 4 MeV @ 95% CL

Invisibly decaying Higgs

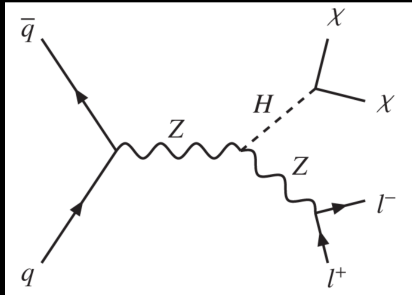
Remember Z width..

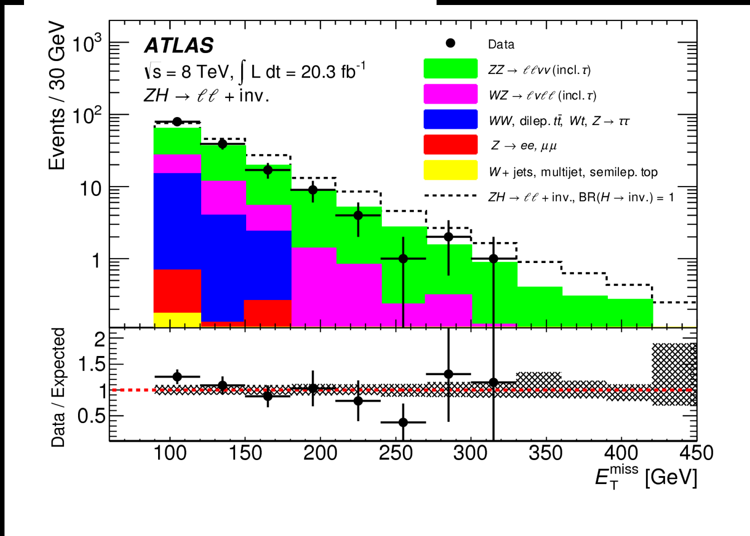


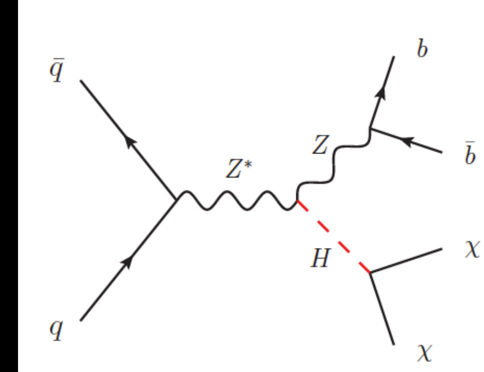


Higgs is too narrow to do this

Invisible Higgs

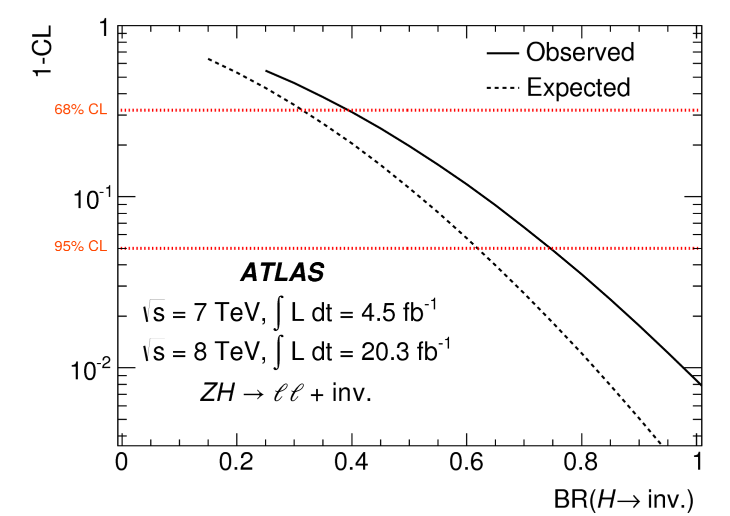


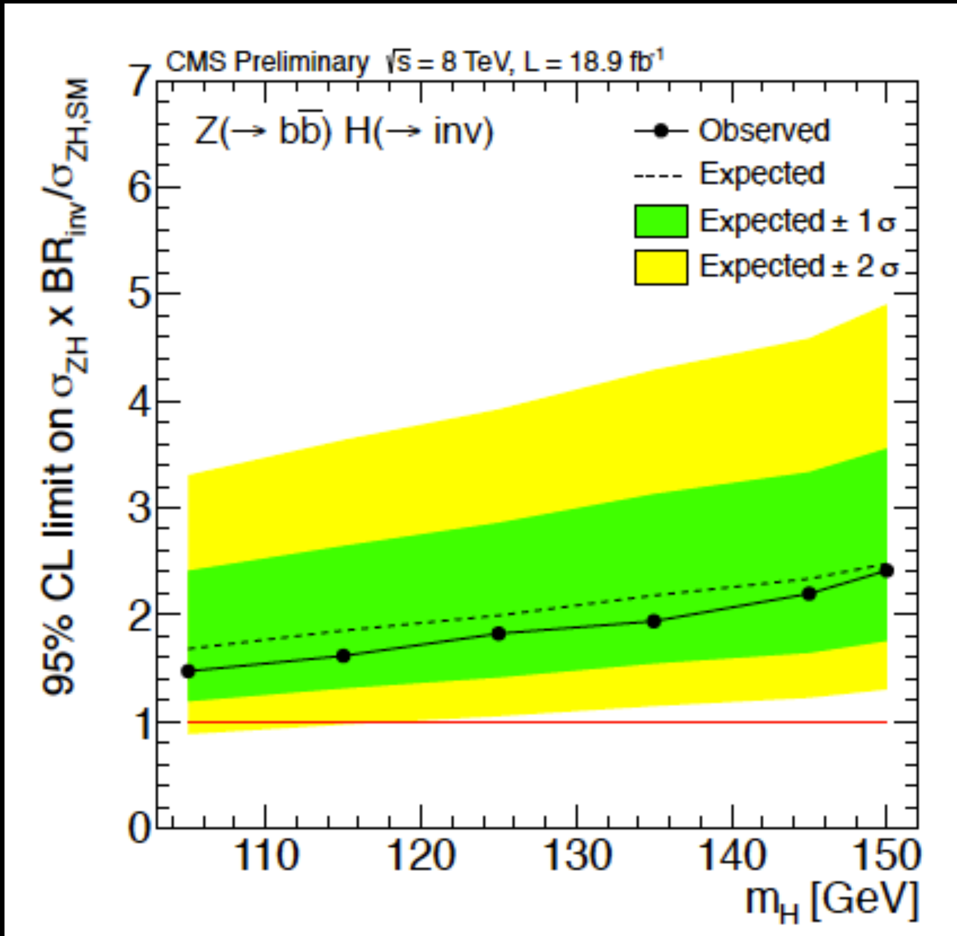




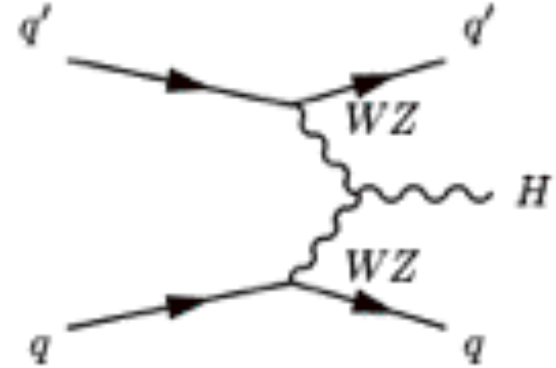
$$\sigma\,\mathrm{Br}_{inv} / \sigma^{SM} < 1.8 \text{ @ } 95\% \text{ CL}$$

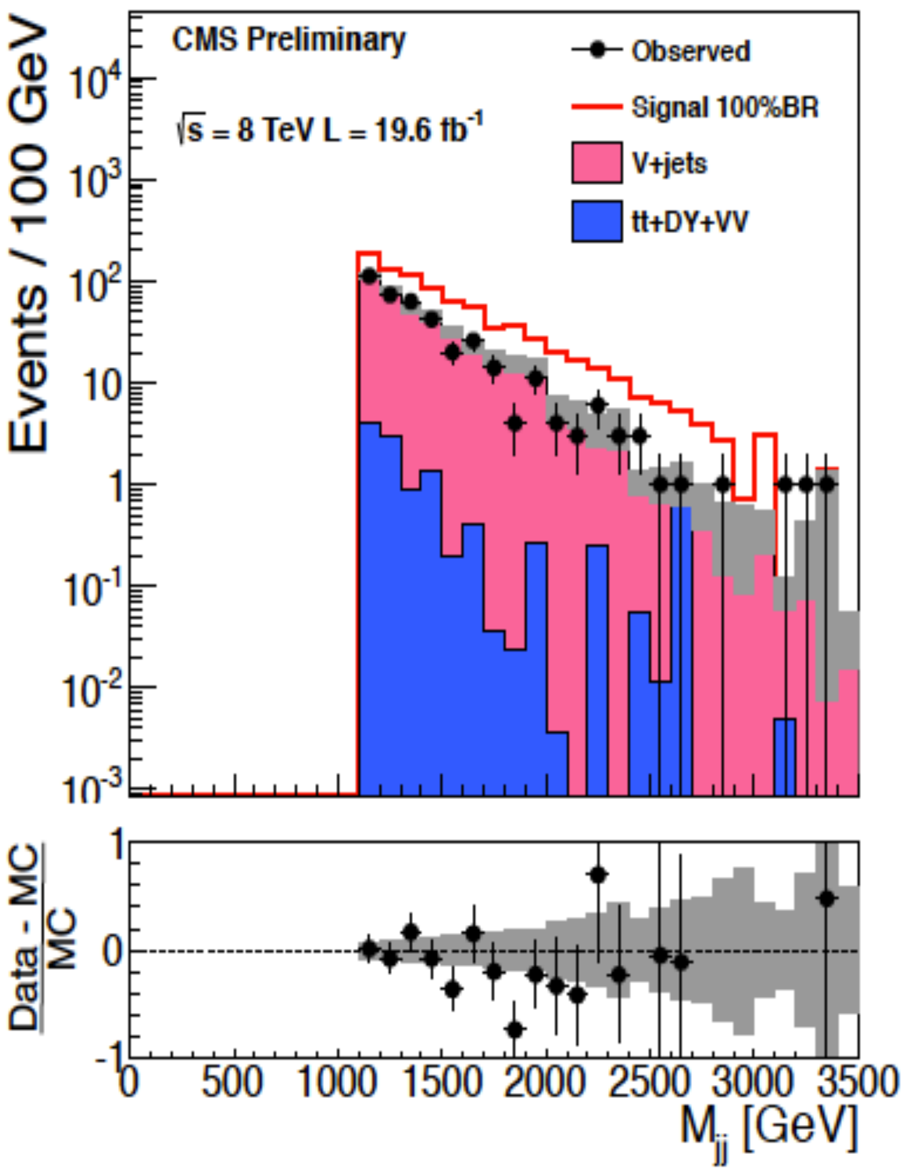
BR (invisible) < 75% @ 95% CL

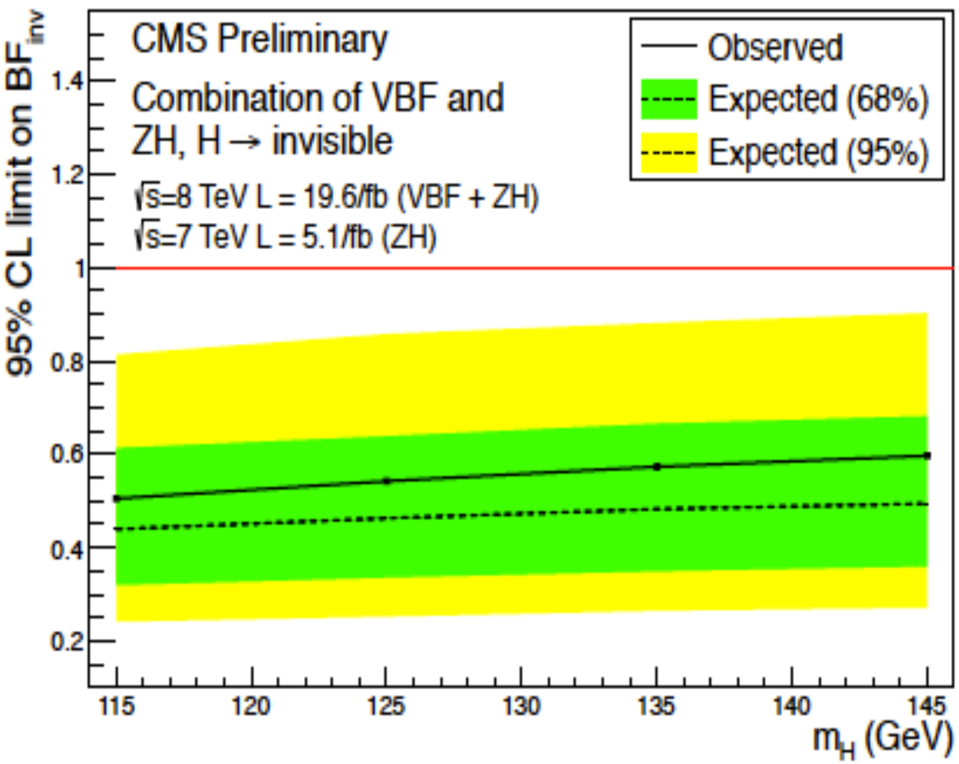




Invisible Higgs





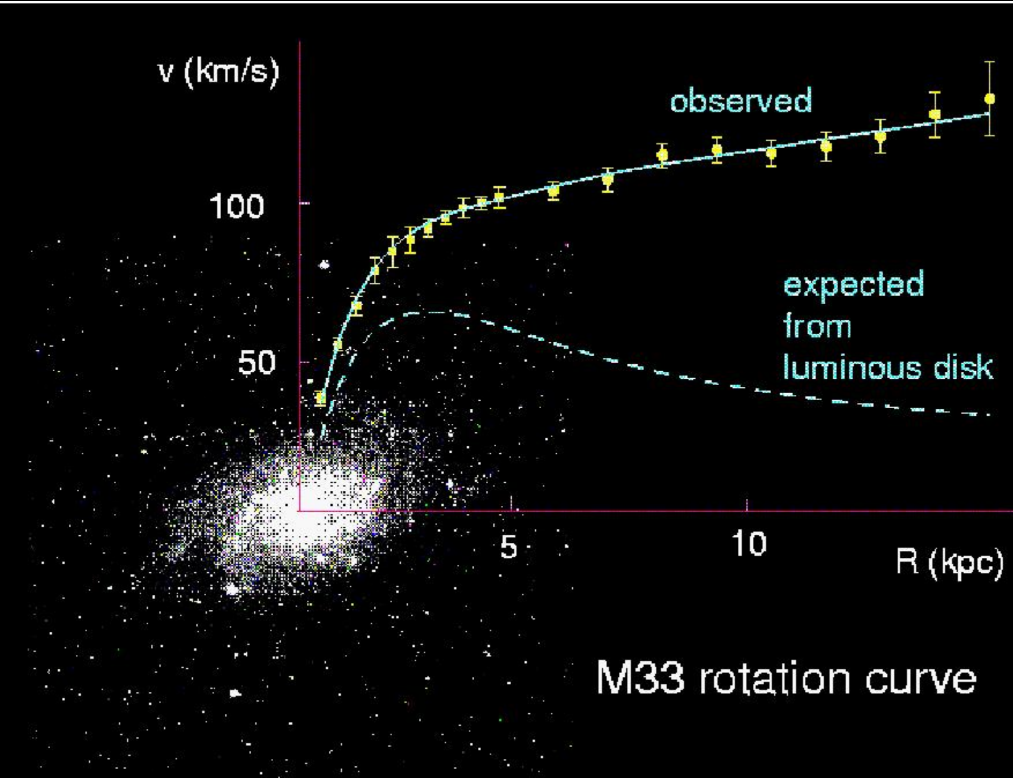


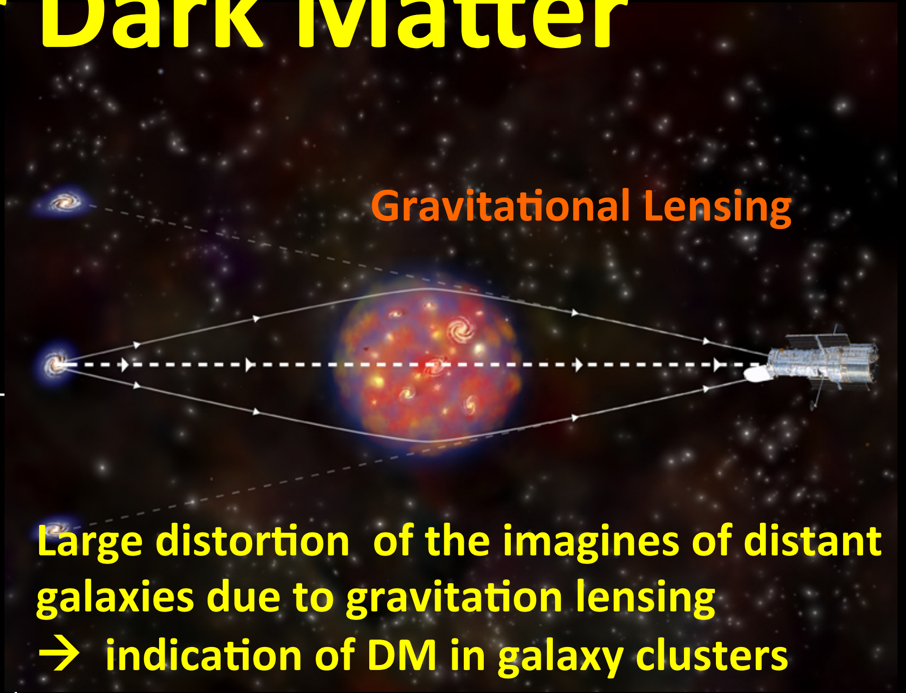
BR (invisible) < 69% @ 95% CL

Evidence for Dark Matter

The rotation of the stars around the center of the galaxies is not consistent with the amount of mass observed (L/M ratio)$_{SUN}$

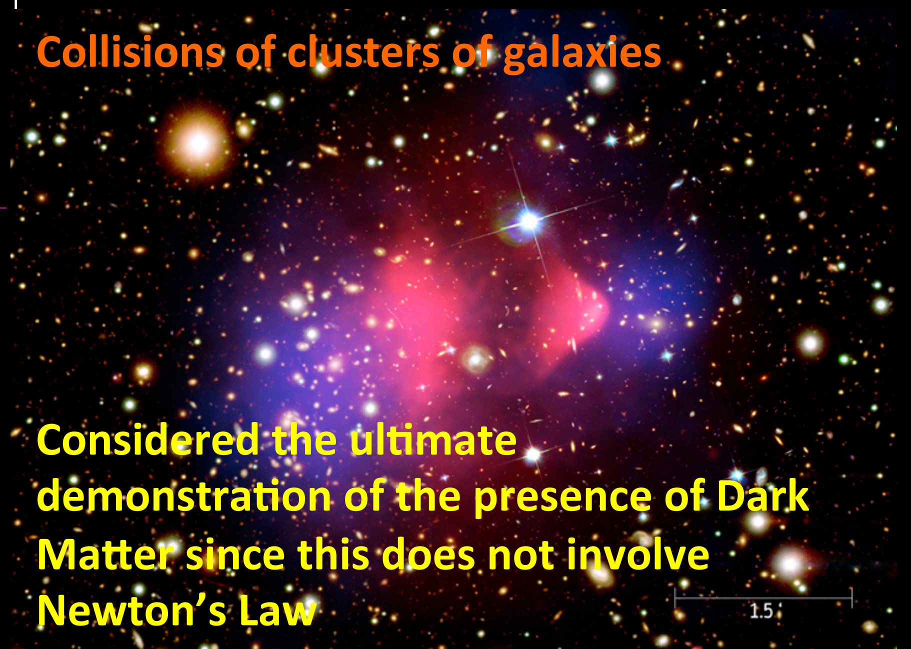
Spherical dark matter halo





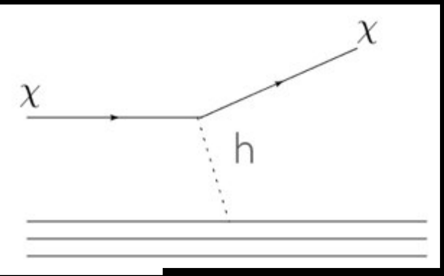
Gravitational Lensing

Large distortion of the imagines of distant galaxies due to gravitation lensing
→ indication of DM in galaxy clusters

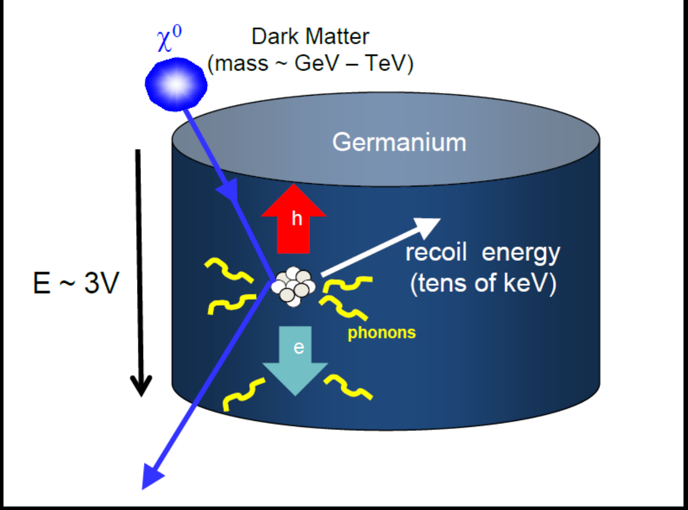


Collisions of clusters of galaxies

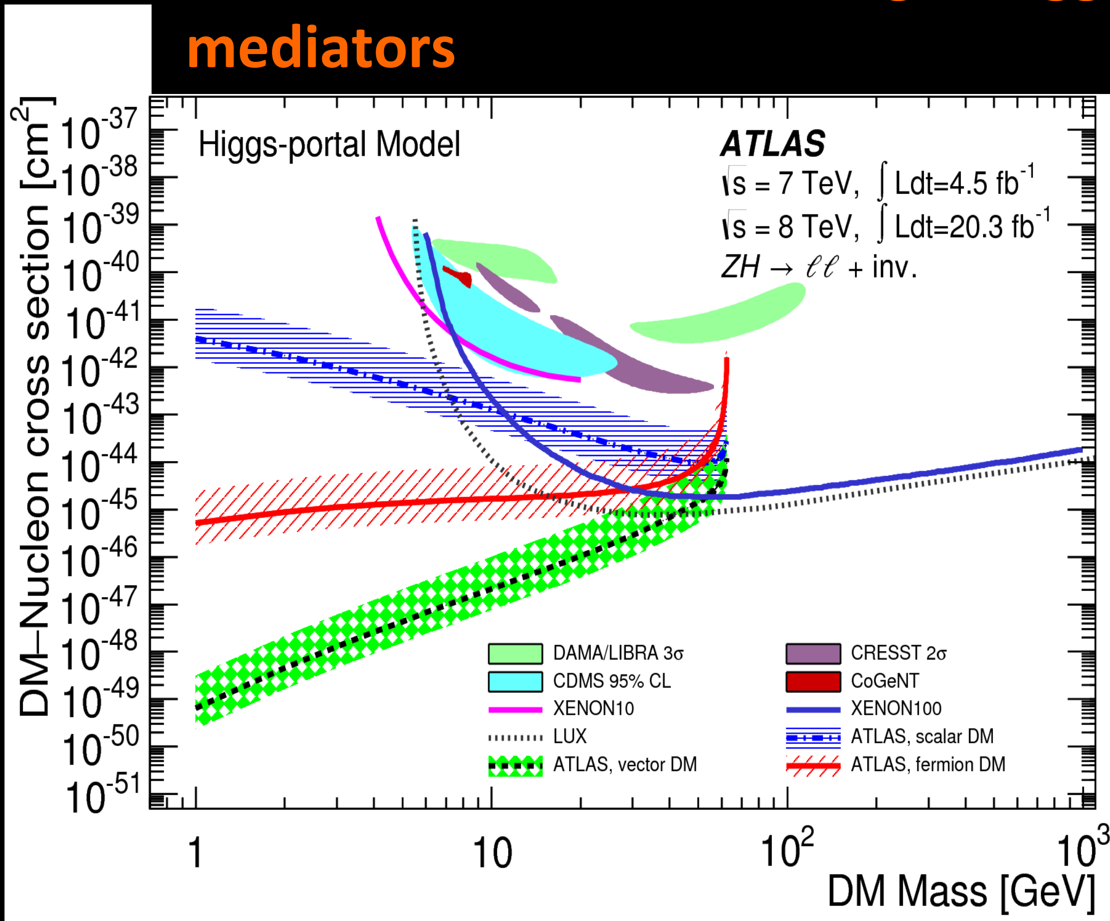
Considered the ultimate demonstration of the presence of Dark Matter since this does not involve Newton's Law

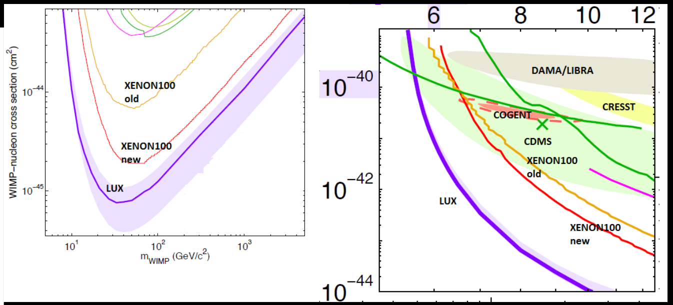


Higgs Portal



The limits on invisibly decaying Higgs can be re-interpreted in the context of SM – DM interactions via light Higgs mediators

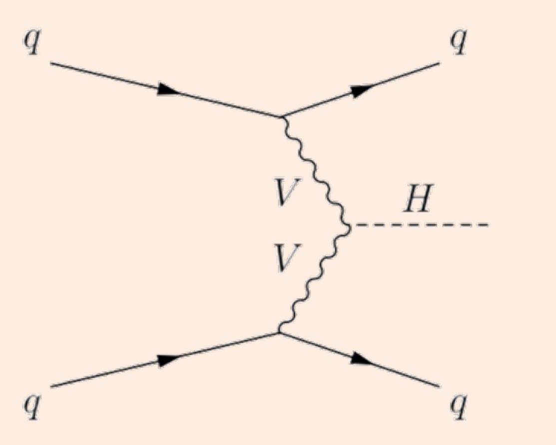


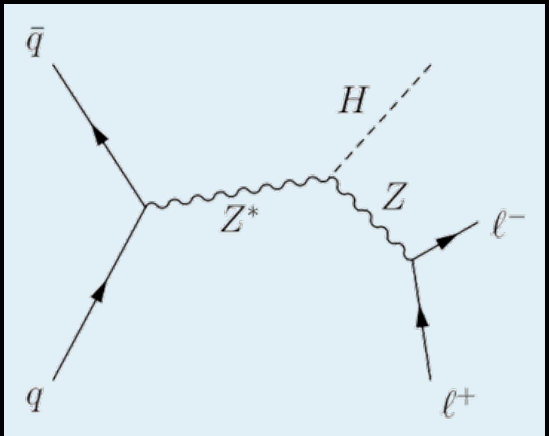


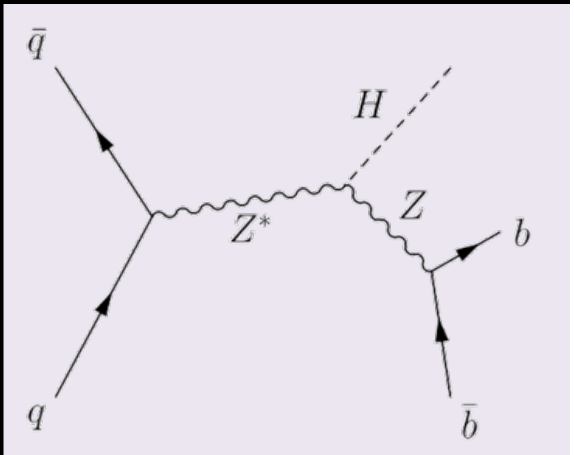
Note the LHC results provide unique access to light DM range (< 10 GeV)

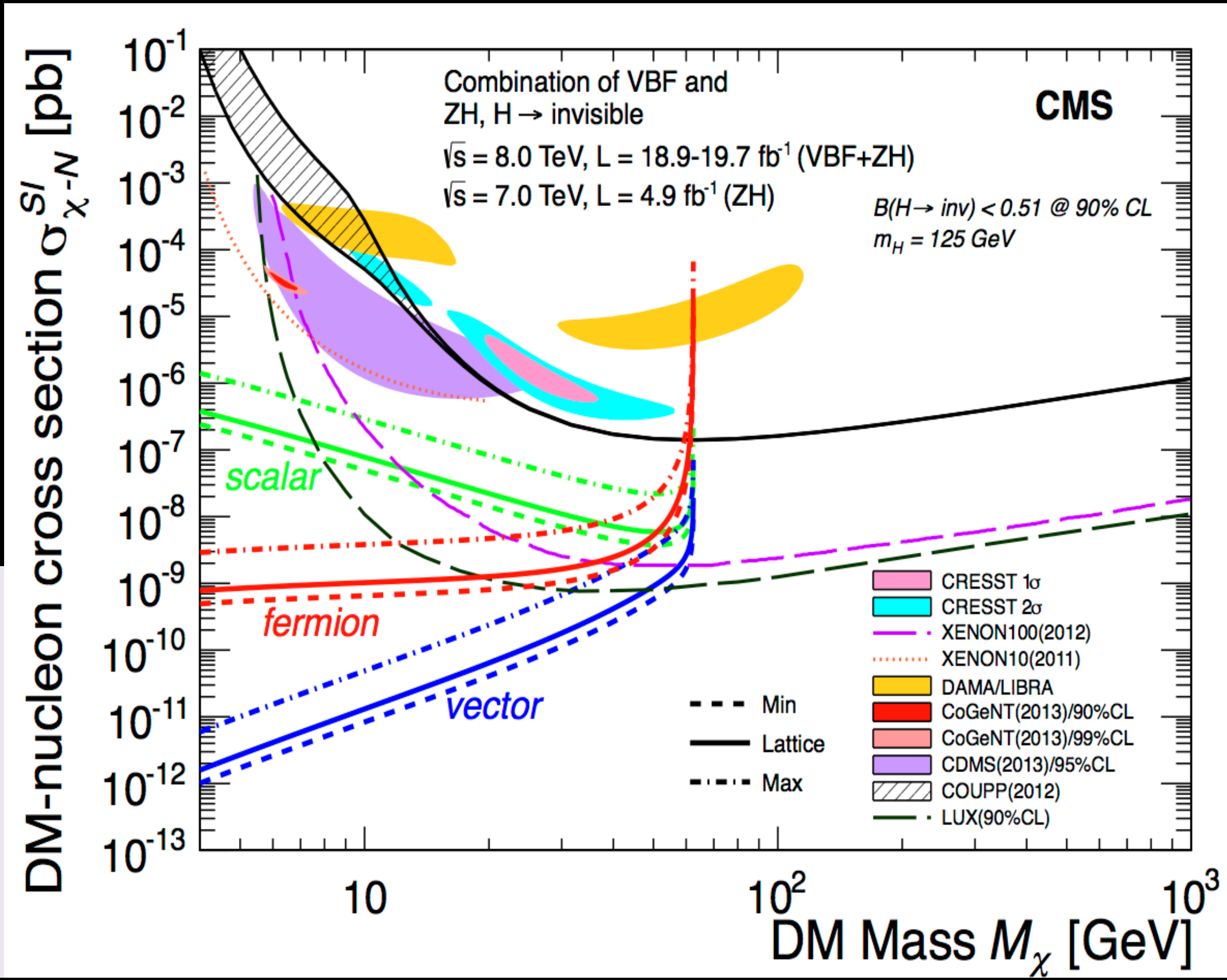
Higgs Portal

Assuming different kind of DM – Higgs Interactions

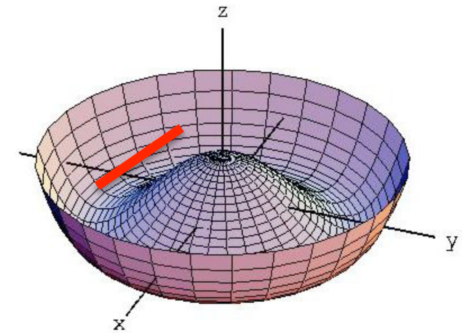








The BEH Mechanism



The scalar sector becomes more transparent in the unitary gauge:

$$\phi(x) = \frac{e^{\frac{i}{v}\vec{\chi}(x)\cdot\vec{\tau}}}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \stackrel{SU(2)}{\longrightarrow} \phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

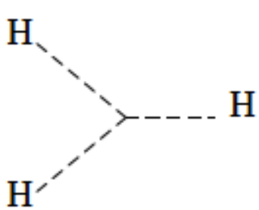
after which the Lagrangian becomes

$$\mathcal{L} = \mu^2 H^2 - \lambda v H^3 - \frac{1}{4} H^4 = -\frac{1}{2} M_H^2 H^2 - \sqrt{\frac{\lambda}{2}} M_H H^3 - \frac{1}{4} \lambda H^4$$

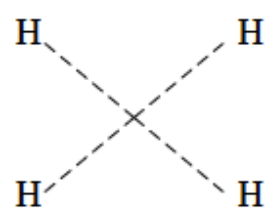
Three degrees of freedom, the $\chi^a(x)$ Goldstone bosons, have been reabsorbed into the longitudinal components of the $W_\mu^\pm$ and Z_μ^0 weak gauge bosons. One real scalar field remains:

the Higgs boson, H, with mass $\boxed{M_H^2 = -2\mu^2 = 2\lambda v^2}$

and self-couplings:

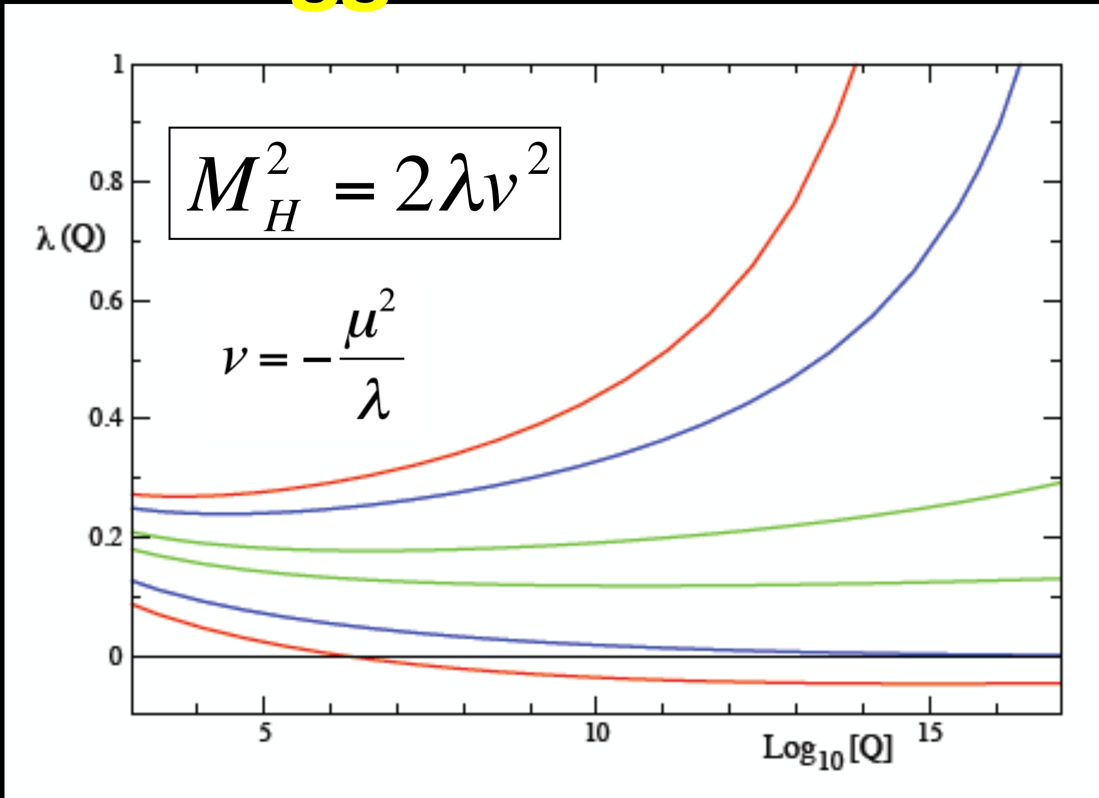


$$= -3i \frac{M_H^2}{v}$$

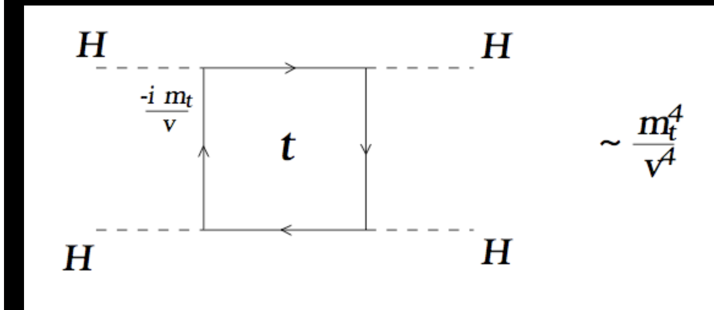


$$= -3i \frac{M_H^2}{v^2}$$

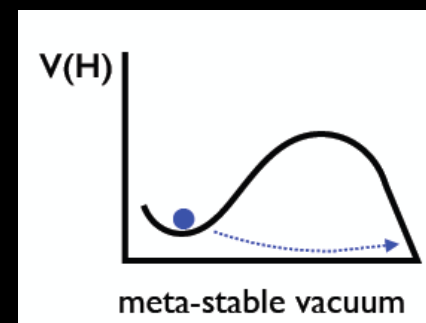
Higgs mass and Vacuum Stability



If too large it becomes non-perturbative



If too negative destabilizes the EWK vacuum

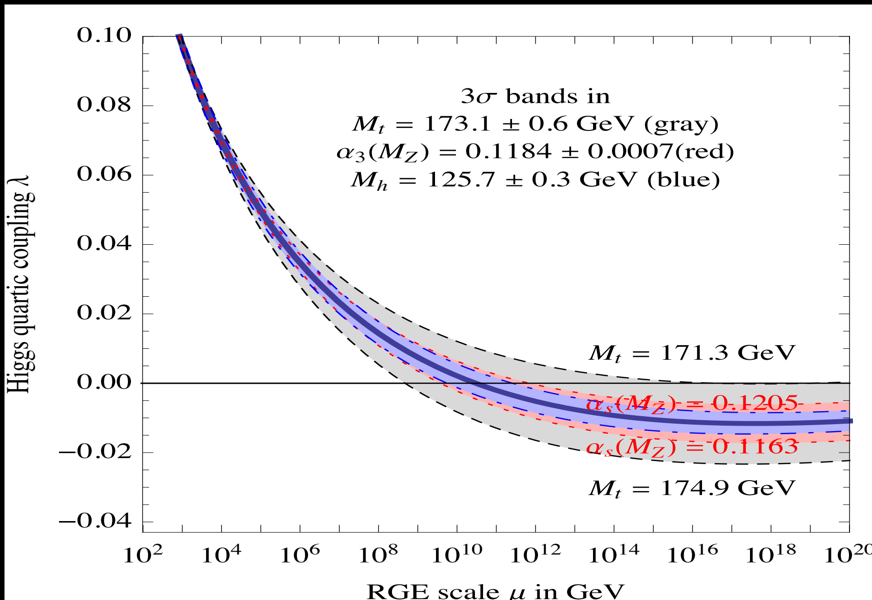


$$M_H \approx 125\ \mathrm{GeV} \;\rightarrow\; \lambda \approx 0.13$$

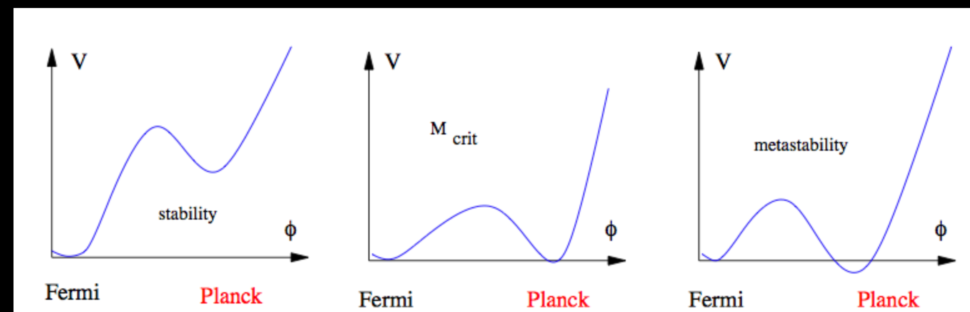
$$32\pi^2\frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2g^2 + \frac{9}{8}g^4 - 24y_t^4 + \cdots$$

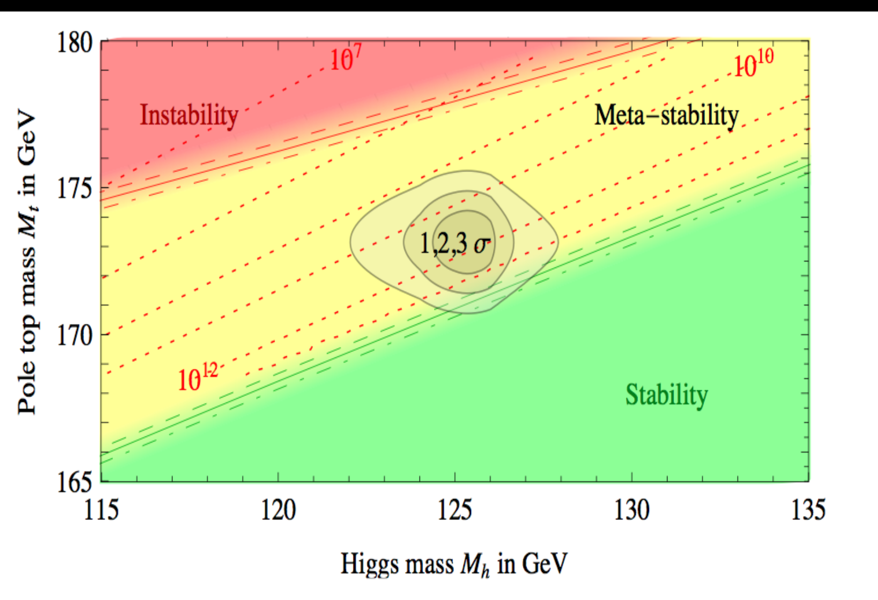
($t = \ln(Q^2/Q_0^2)$, $y_t = m_t/v \rightarrow$ top quark Yukawa coupling).

Higgs vs Vacuum Stability



$$\lambda(\Lambda) = \lambda(v) - \frac{3}{4\pi^2} y_t^2 \log\left(\frac{\Lambda^2}{v^2}\right)$$





What this really means ?

Large dependence on top and Higgs masses
Assumes no BSM physics enters in the RGE

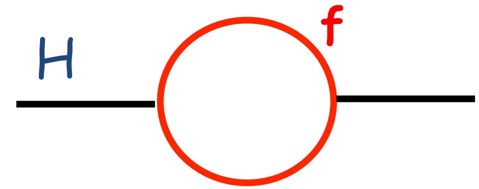
This really means that the SM is consistent all the way to the Planck scale..

Do not worry .. Lifetime probably larger than the age of the Universe.

Hierarchy Problem

From EWK to Planck scale ?

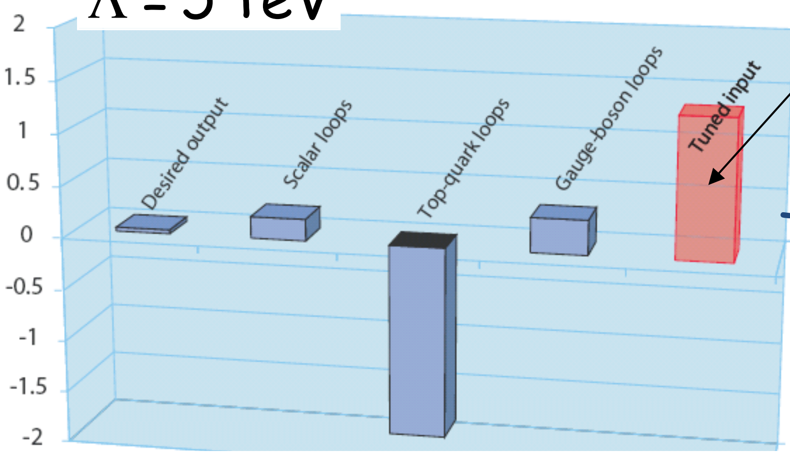
$$<H> = 174\ \text{GeV} \rightarrow m_H^2 \approx O(-100\ \text{GeV}^2)$$



$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots]$$

$$\text{if } \Lambda_{UV} \approx M_{planck} \rightarrow \text{fine tuning in } 10^{30}\ !!$$

$\Lambda = 5$ TeV



relative contributions to ΔM_H^2

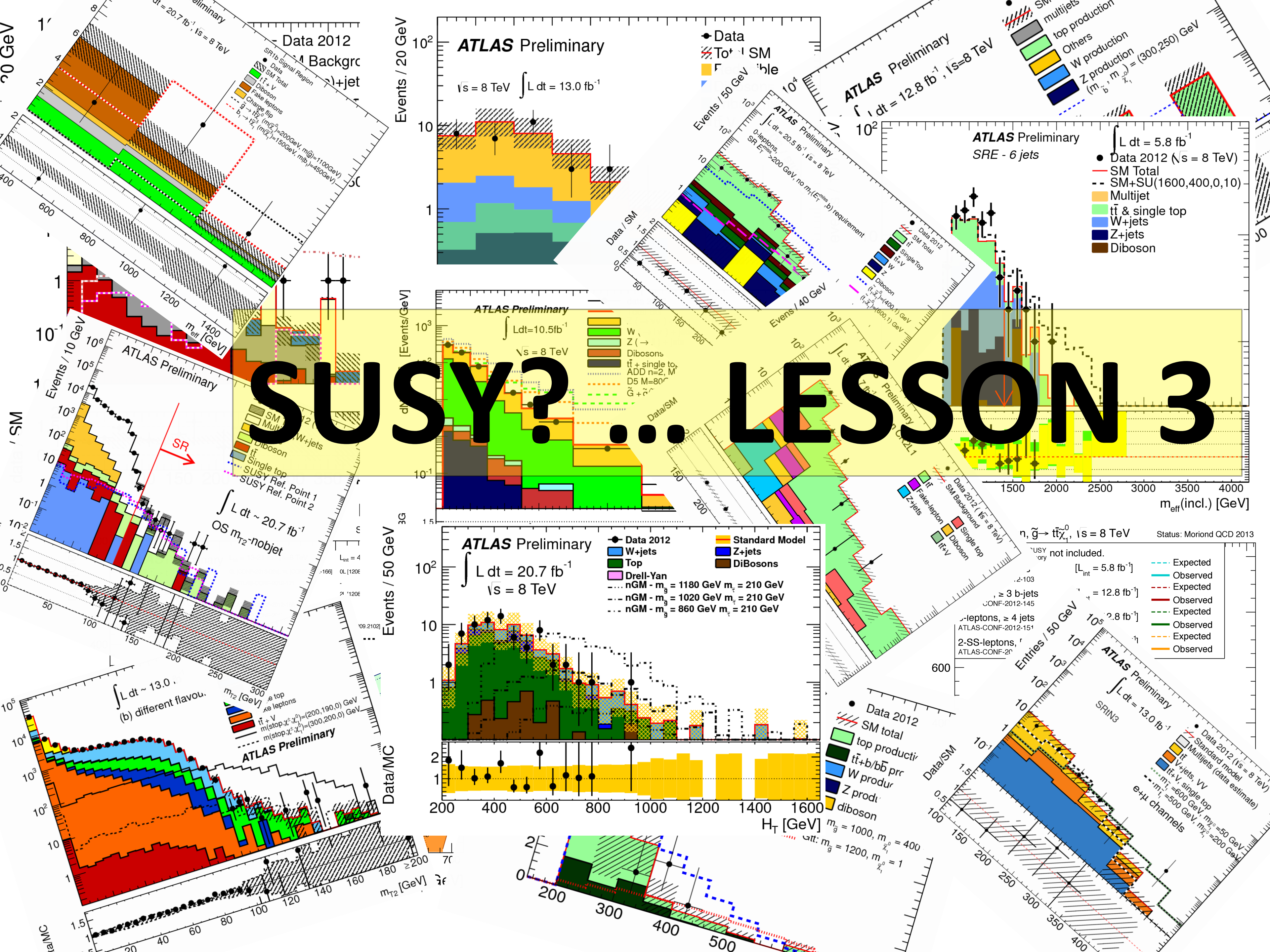
(taken from C. Quigg, hep-ph/0704.2232)

Already a serious problem at 5 TeV scale
(cancellation among top, gauge and Higgs loops)

This kind of conspiracy has name in Physics…

SuperSymmetry ?

SUSY? ... LESSON 3

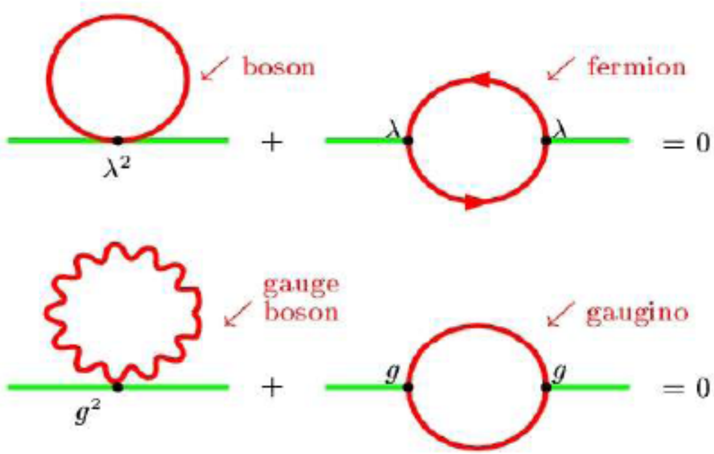


SuperSymmetry in 30"

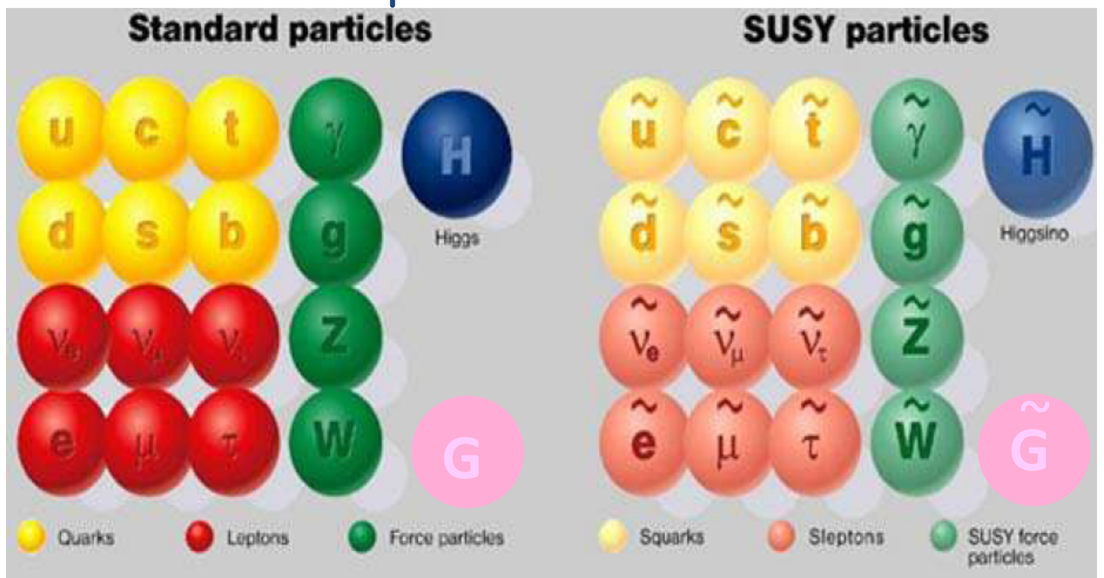
- Fermion/Boson symmetry

$$Q|\text{fermion}> = |\text{boson}>$$
$$Q|\text{boson}> = |\text{fermion}>$$

- Exact cancellation between fermion & boson loops for Higgs



Double Spectra of Particles



..will mix to form mass eigenstates..

Higgs sector with 2 doublets

$$H_U, H_D \longrightarrow h, H, A, H^{\pm}$$

..SUSY must be broken..... model-dependent phenomenology

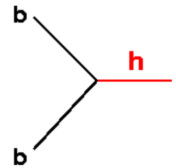
Hard to believe in SUSY if the Higgs sector stays with just h_0

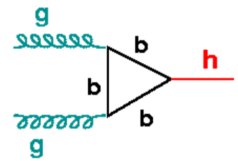
…Looking for extra Higgs particles ….

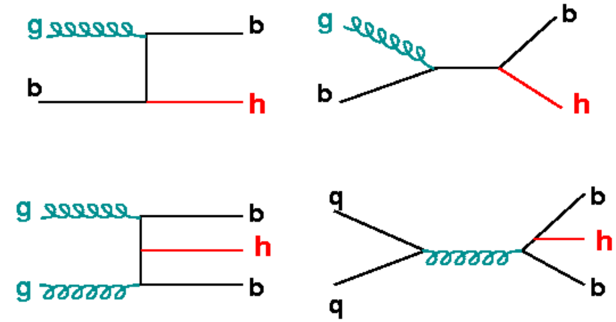
MSSM Higgs

$H_U, H_D \longrightarrow$ h,H,A and $H^{\pm}$

$\tan\beta = \langle H_U \rangle / \langle H_D \rangle$







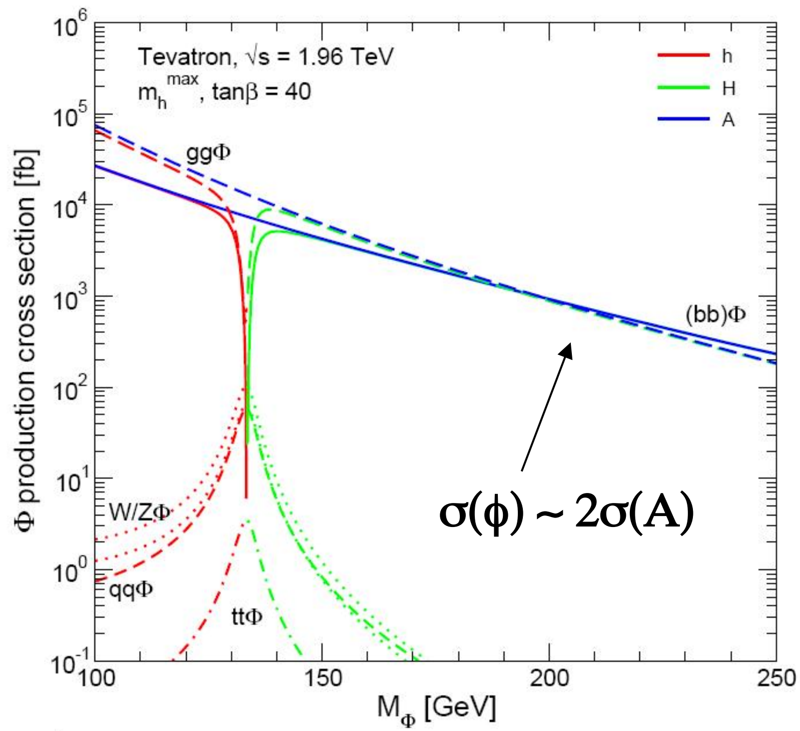
$M(h) < 135$ GeV

Tree level : M_A and $\tan\beta$ as parameters

MSSM Higgs production cross section boosted compared to SM at large tanβ

$$\sigma(b\bar{b}A) \times \mathrm{BR}(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\mathrm{SM}} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2 + 9}$$

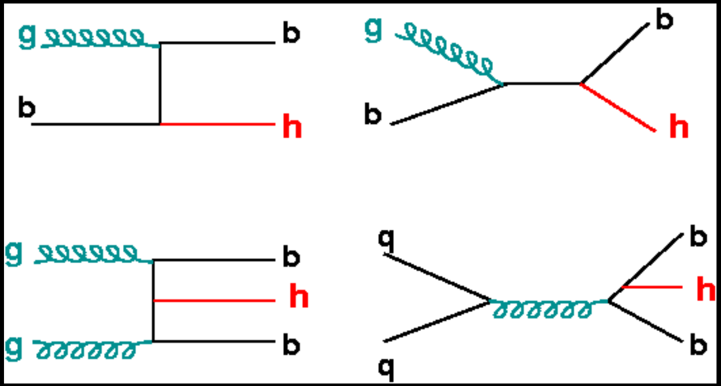
$$\sigma(gg, b\bar{b} \to A) \times \mathrm{BR}(A \to \tau^+\tau^-) \simeq \sigma(gg, b\bar{b} \to A)_{\mathrm{SM}} \frac{\tan^2\beta}{(1+\Delta_b)^2 + 9},$$

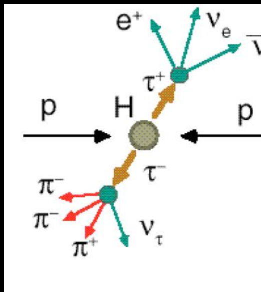


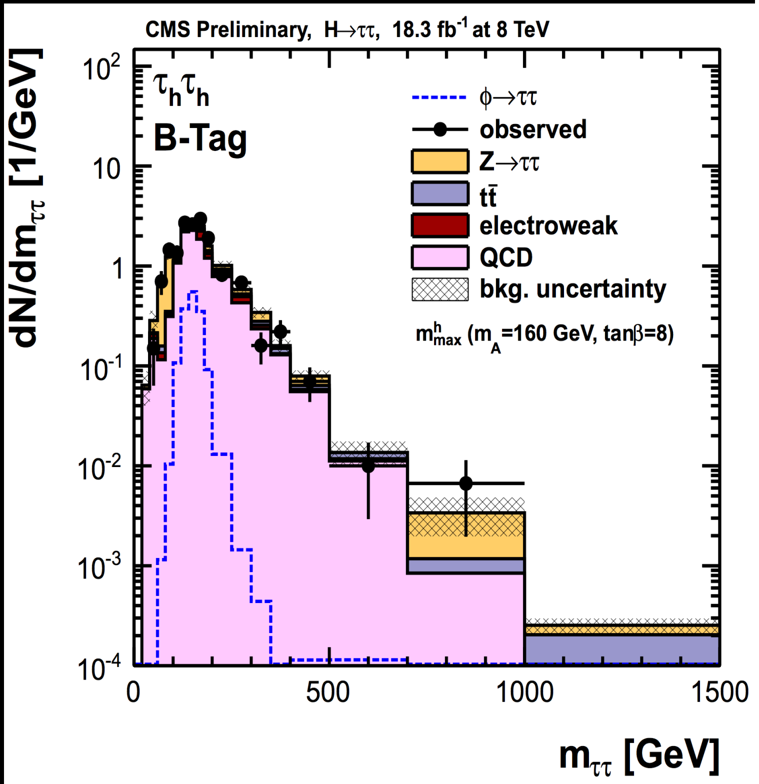
At low masses

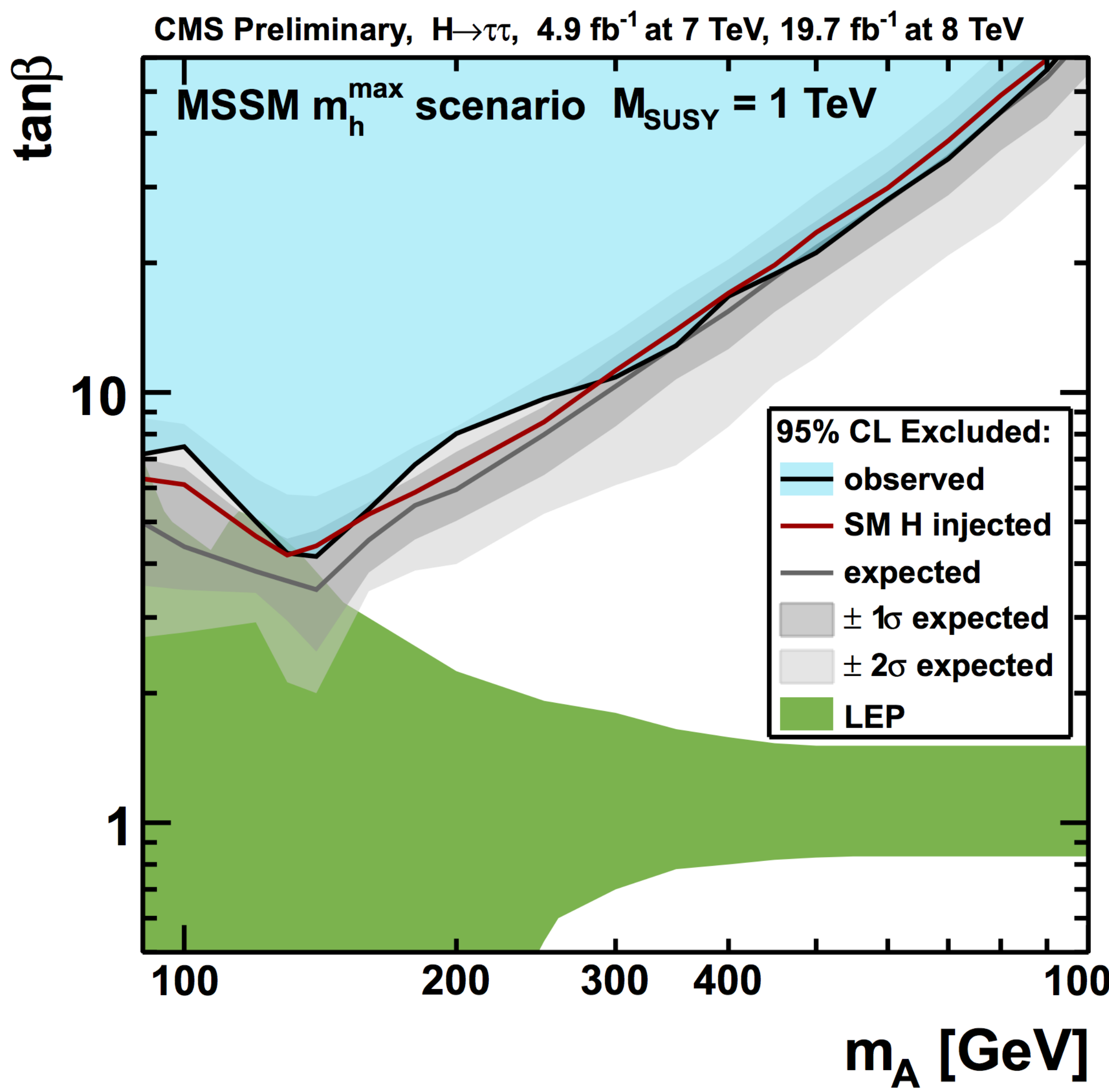
$\mathrm{Br}(h \to bb) \sim 90\%$, $\mathrm{Br}(h \to \tau\tau) \sim 10\%$

MSSM Neutral Higgs

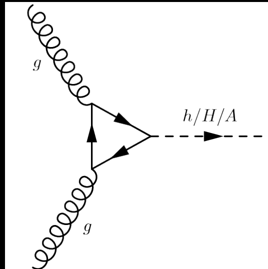


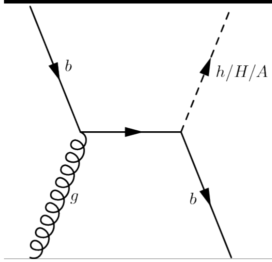


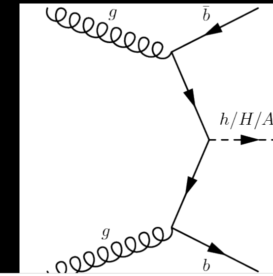


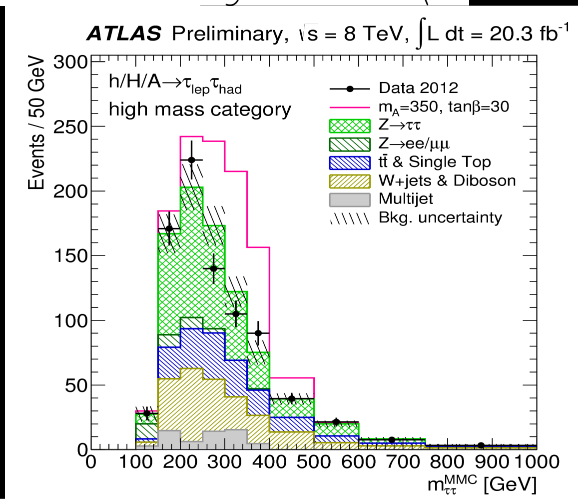


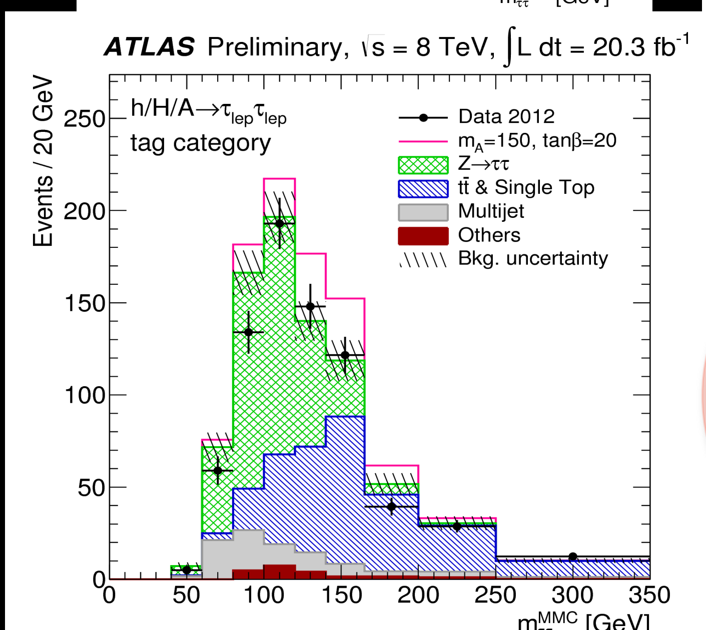
MSSM Neutral Higgs

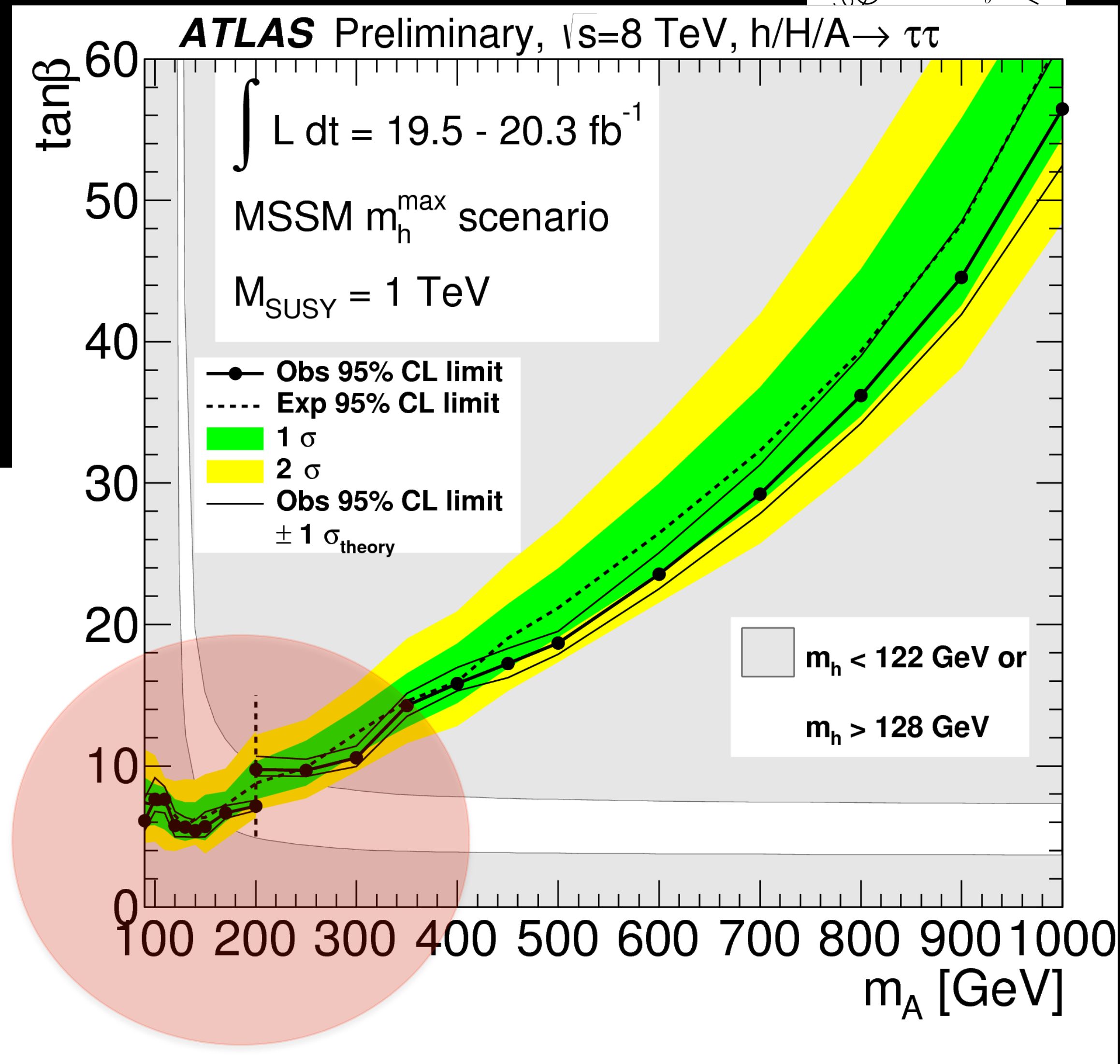




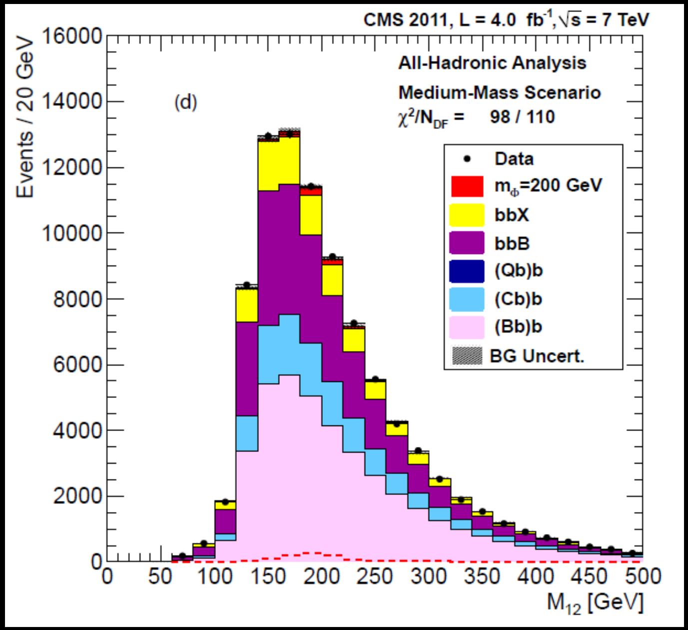




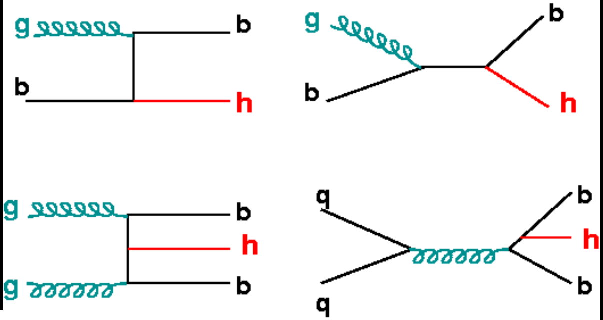


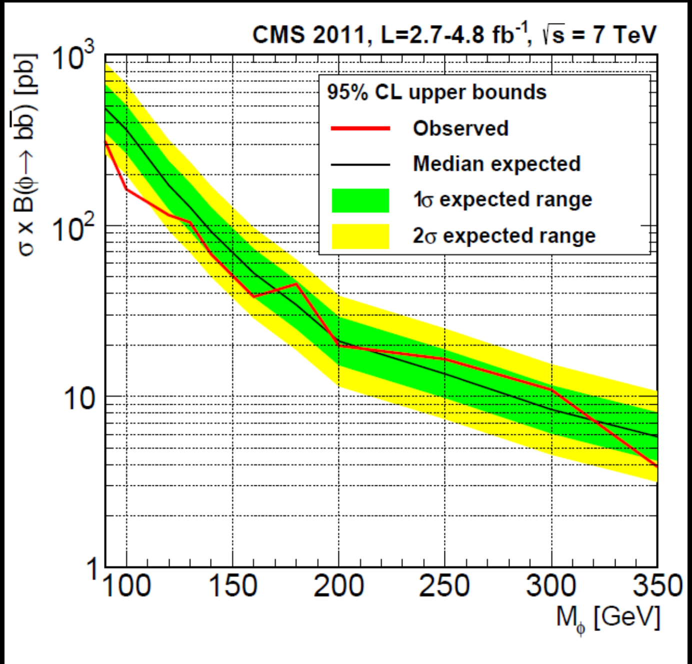


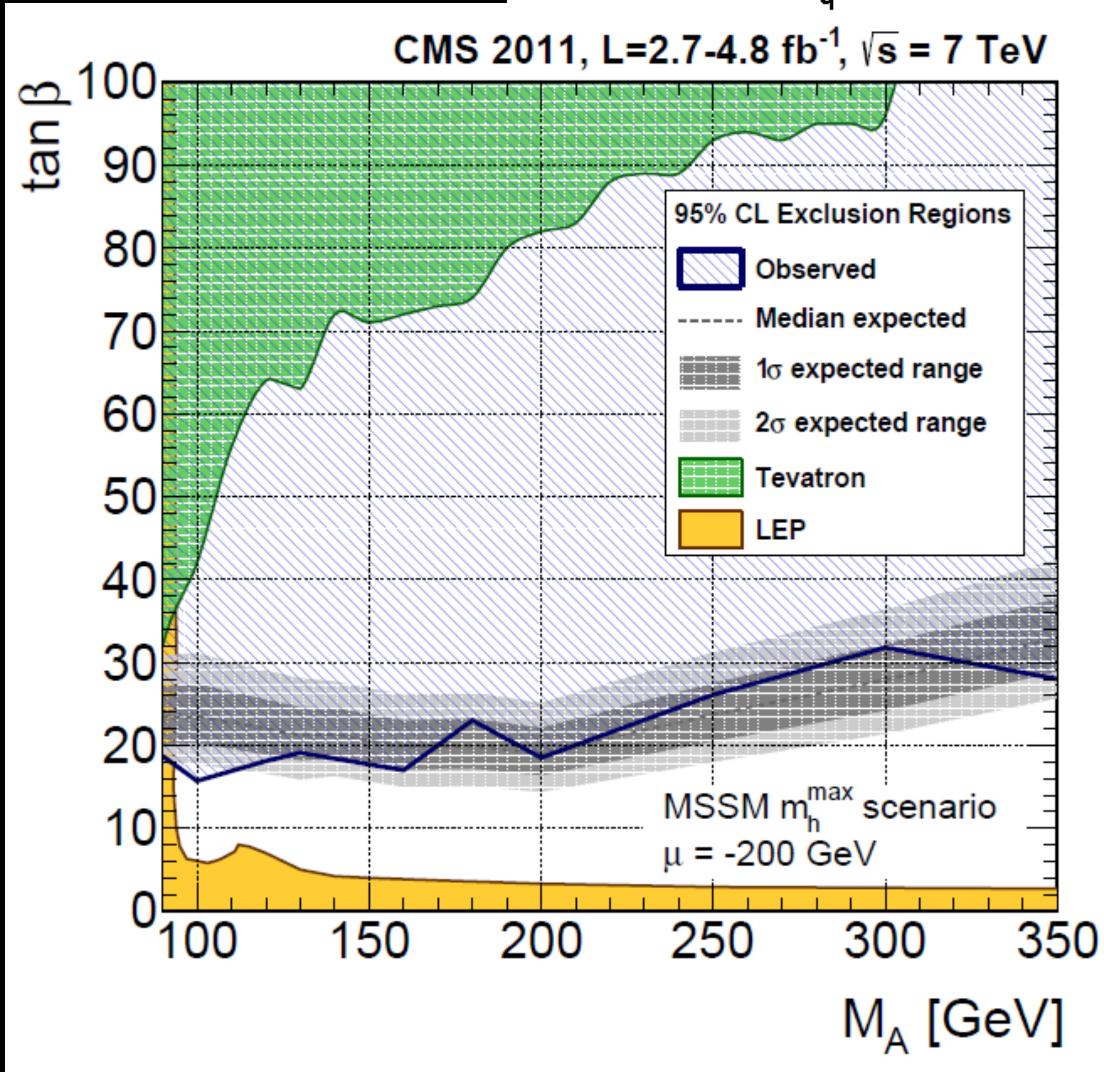
MSSM Higgs



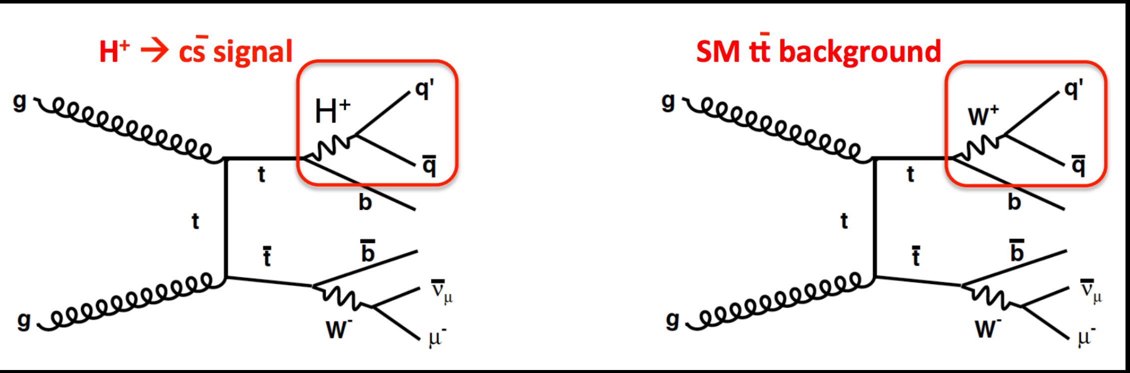
h → bb



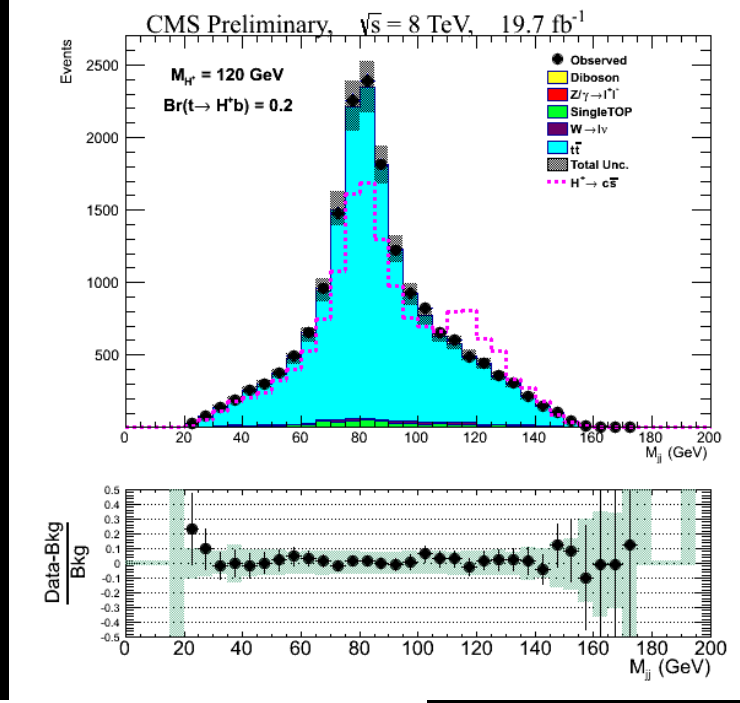


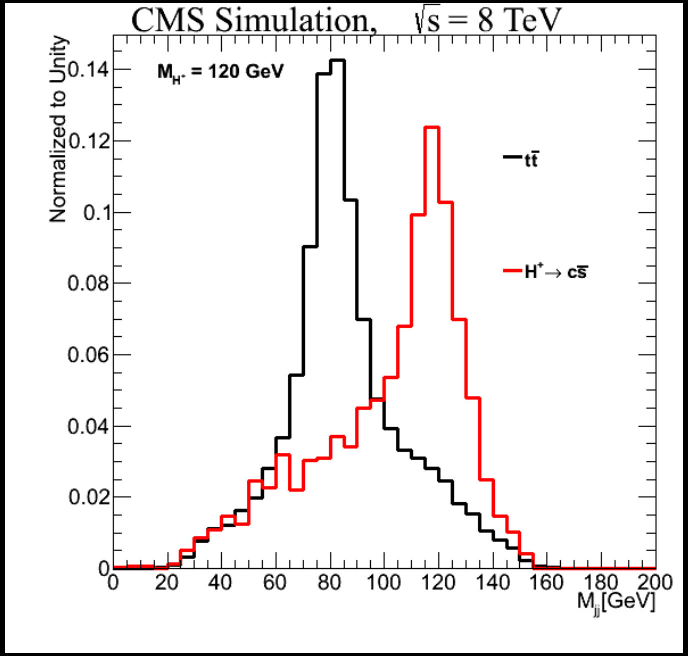


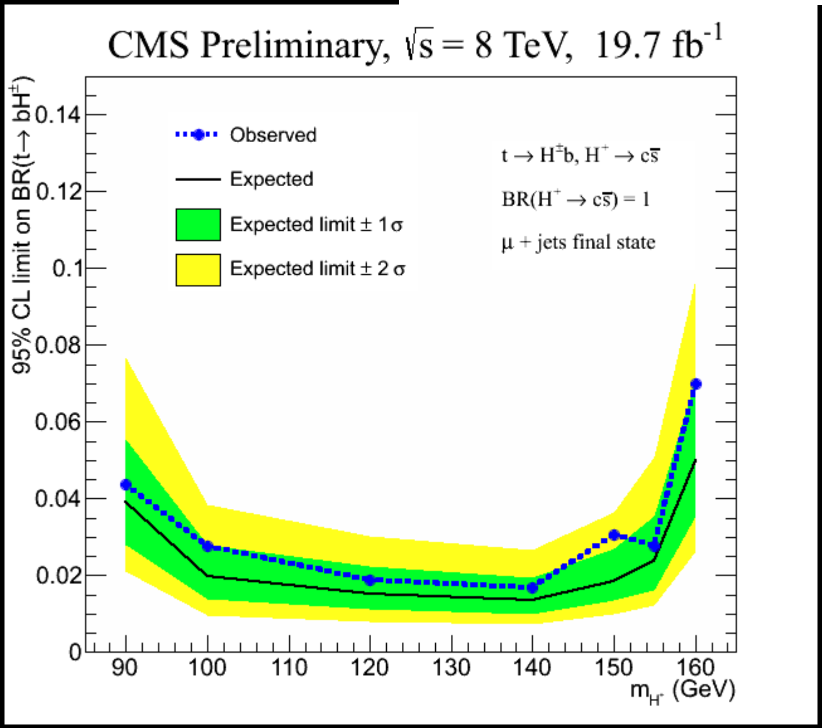
$H^+ \rightarrow c\bar{s}$

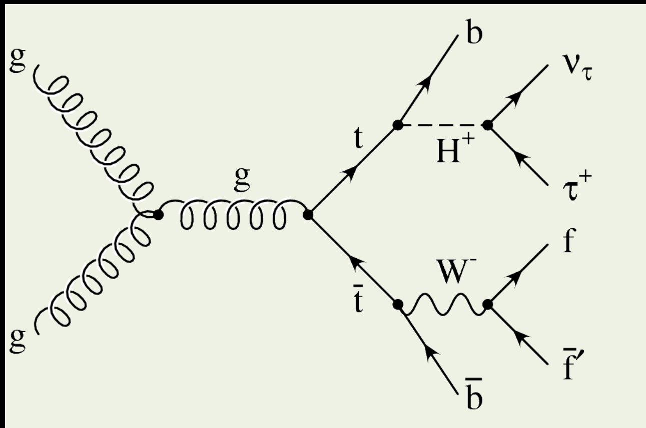


Expressed in terms of limits on BR in top decays

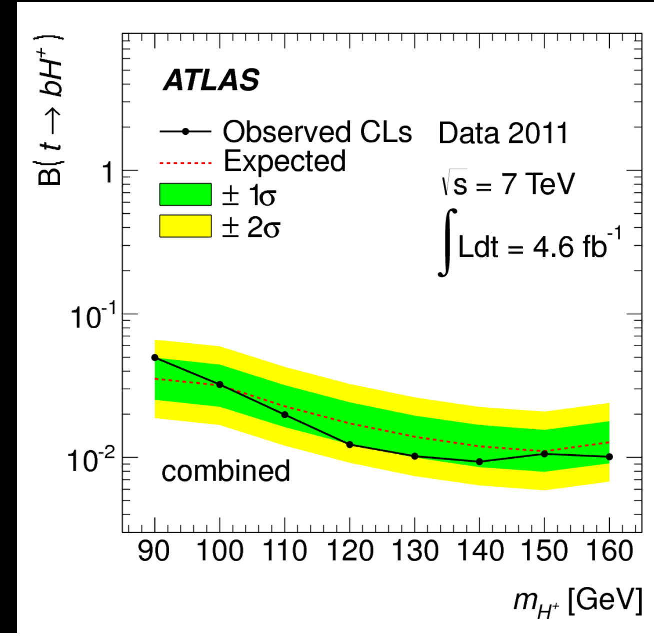






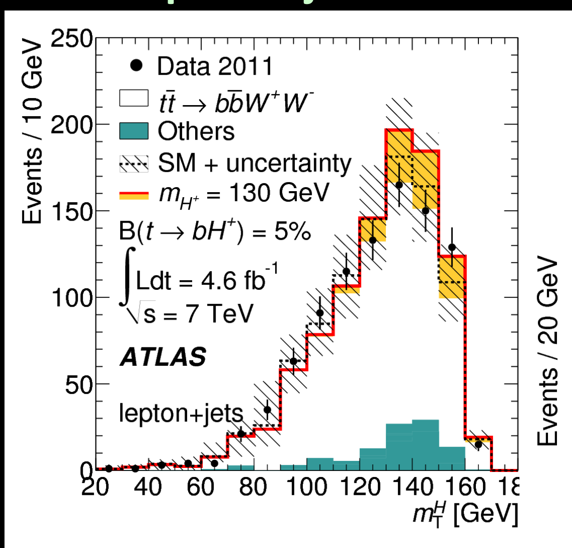


$H^+ \rightarrow \tau\,\nu$

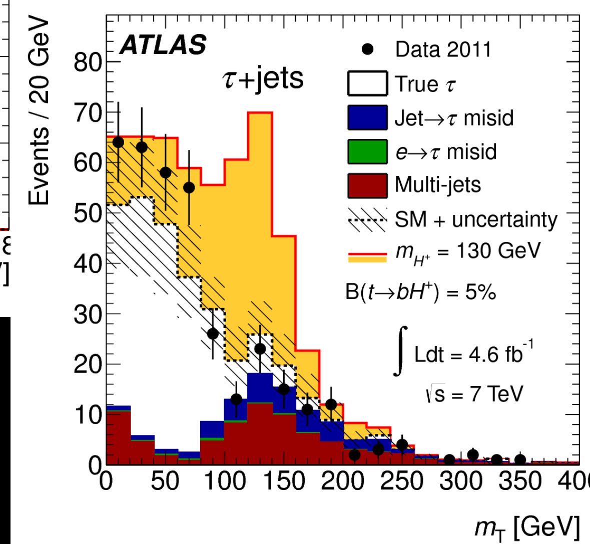


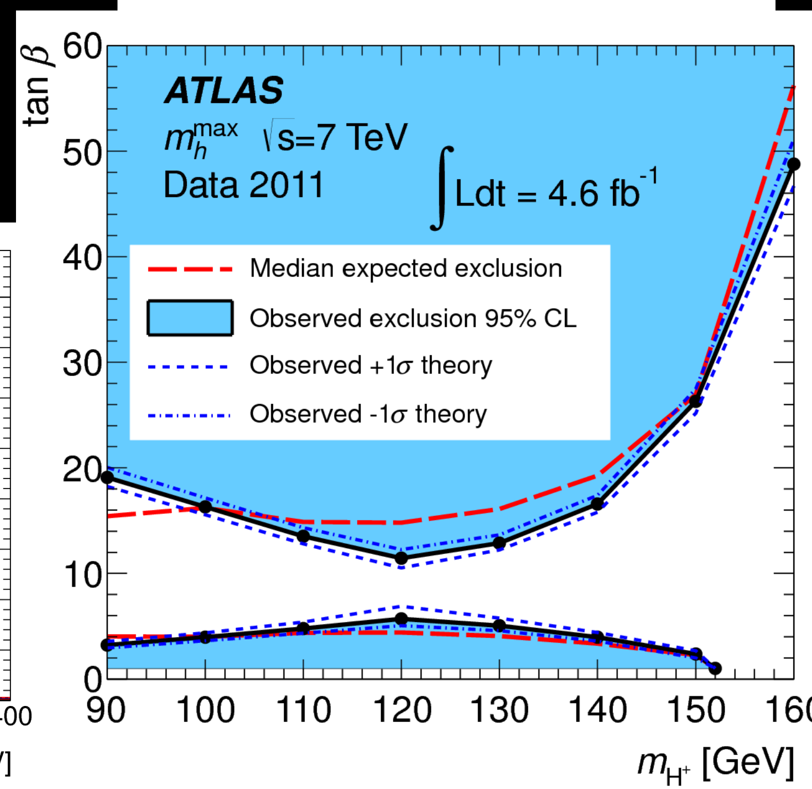
Limits on top BR and SUSY MSSM parameters

lepton + jets



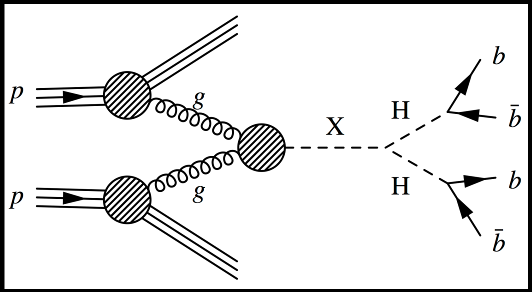
Tau-ID + jets

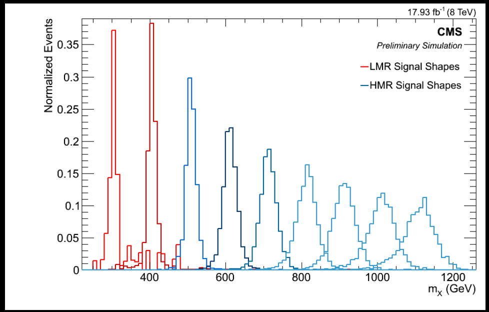


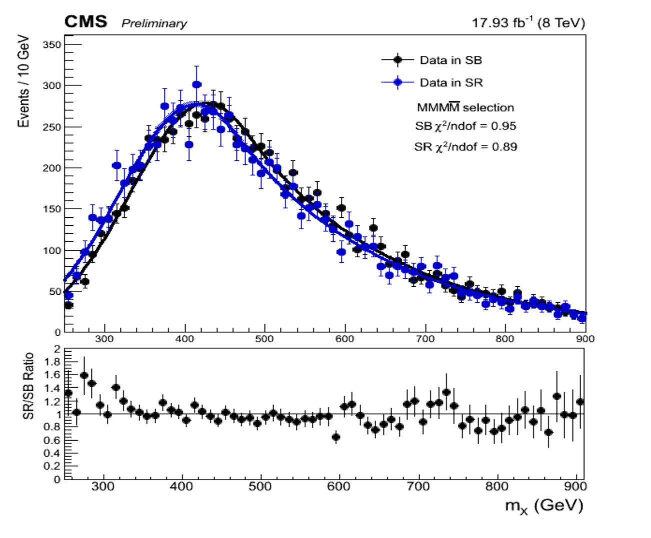


X → HH (→ bbbb)

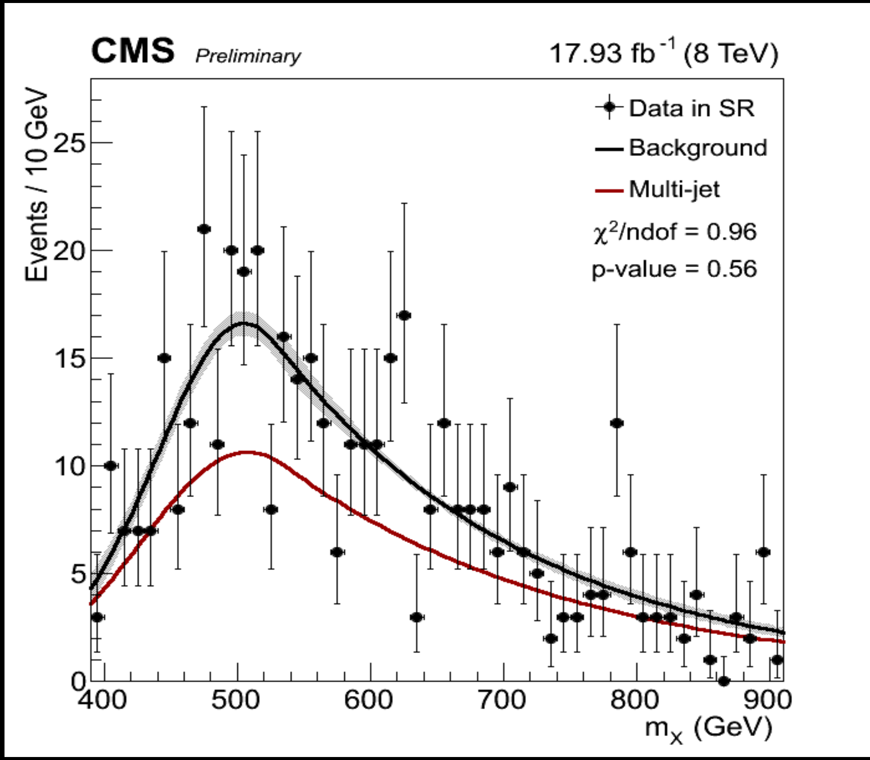
3-b control region

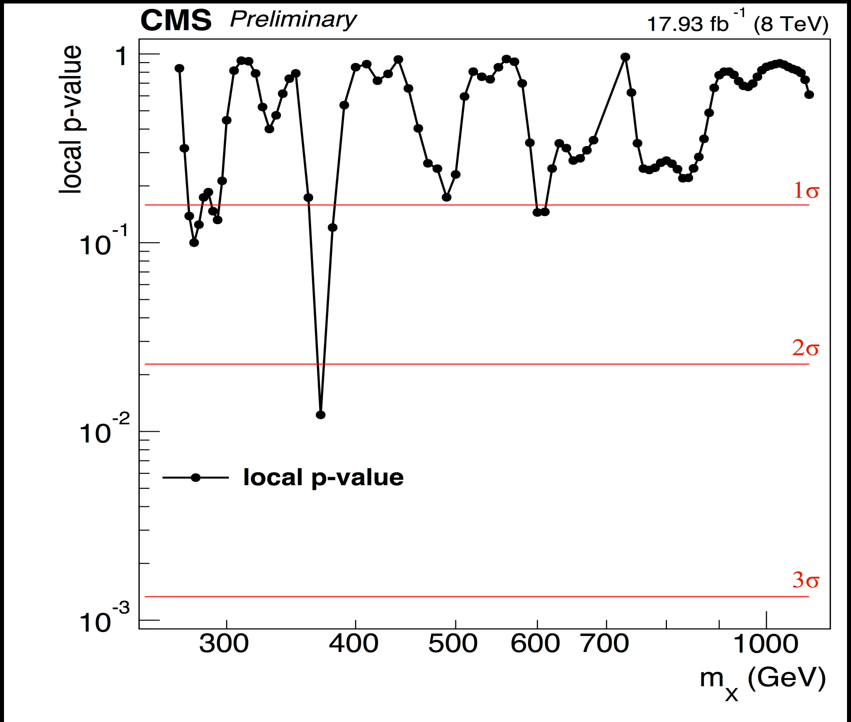






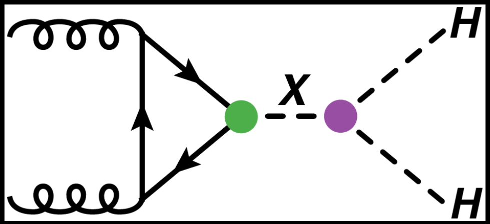
Very difficult analysis (huge QCD and ttbar)

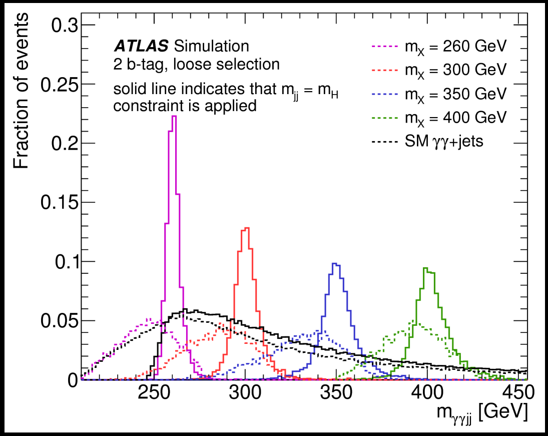


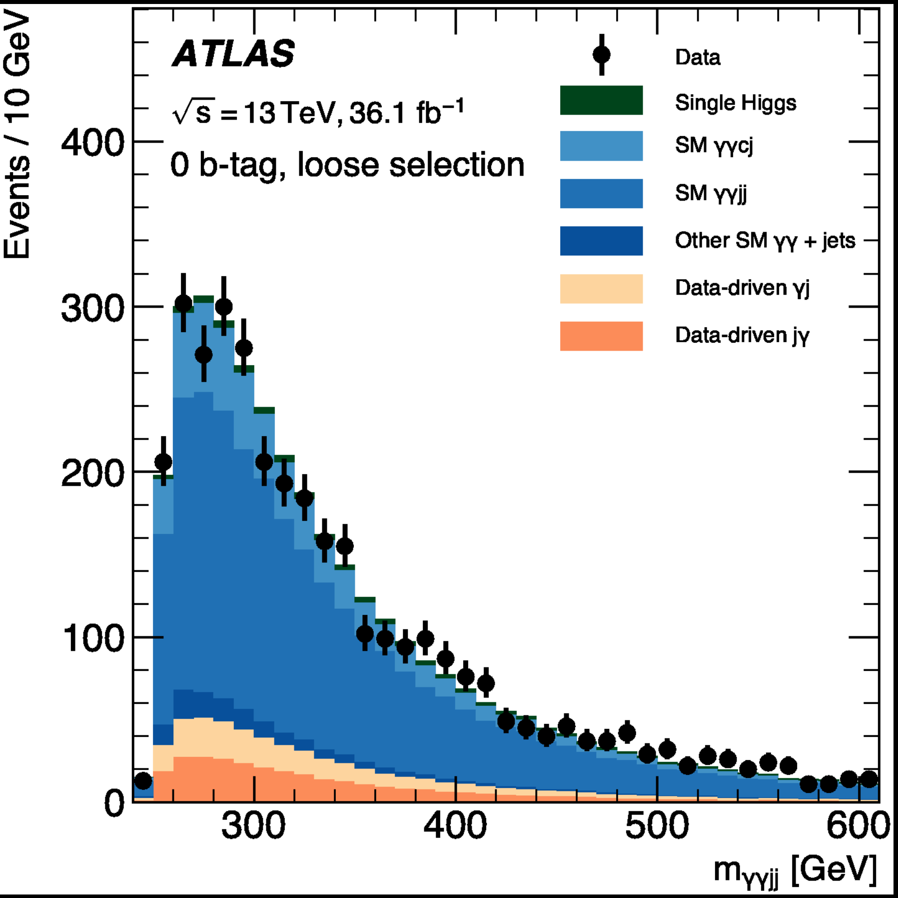


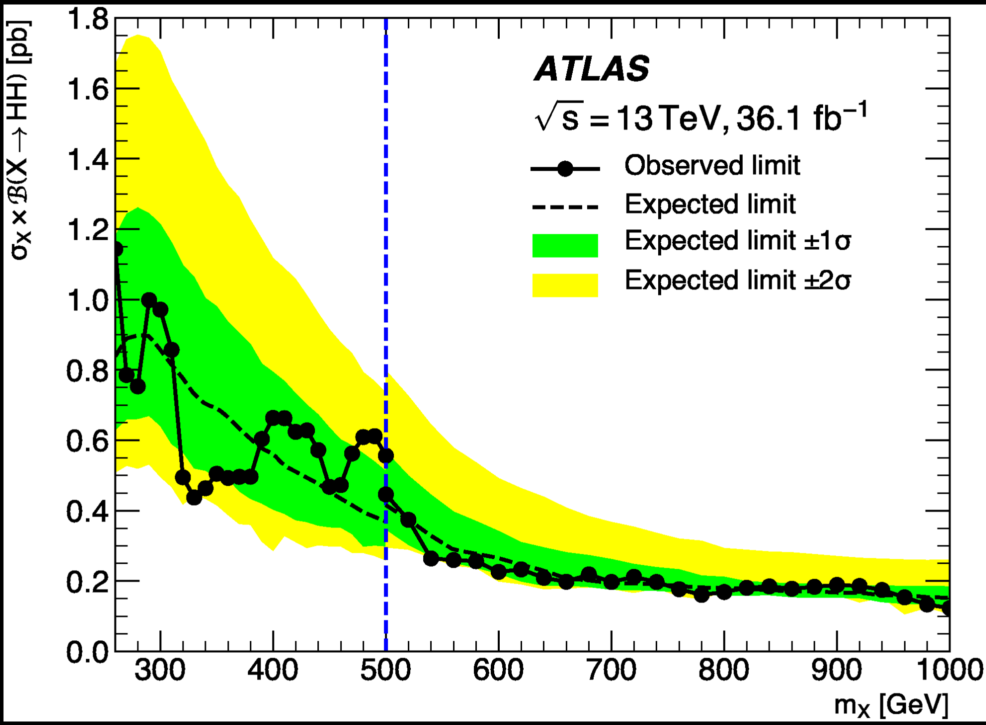
arXiv:1807.04873

X → HH (γγ bb)







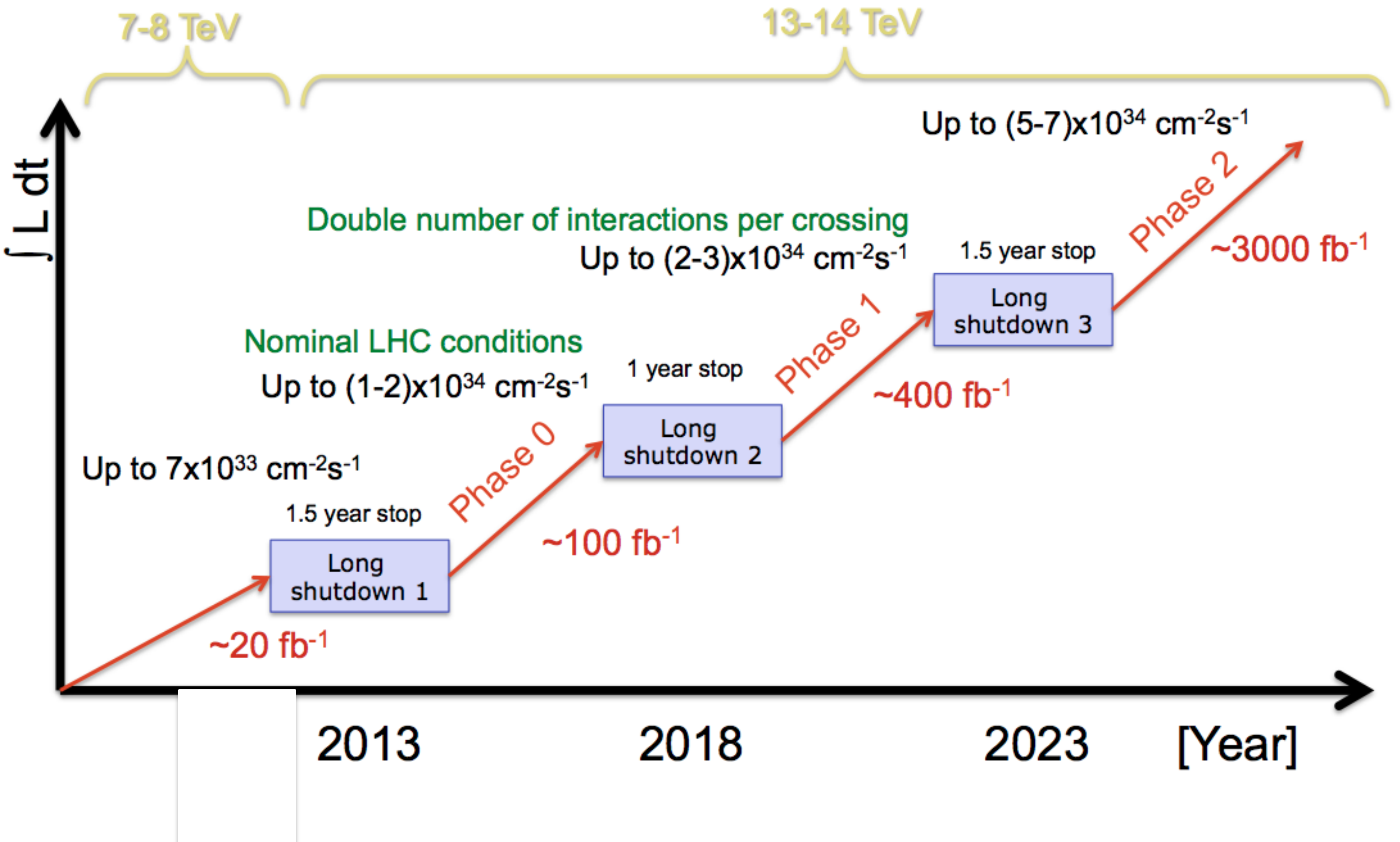


LHC BEYOND RUN I+II

HL-LHC

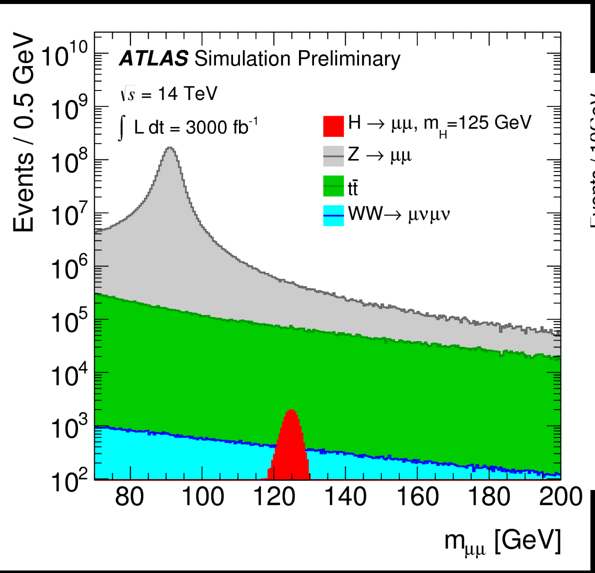
LHC Plan

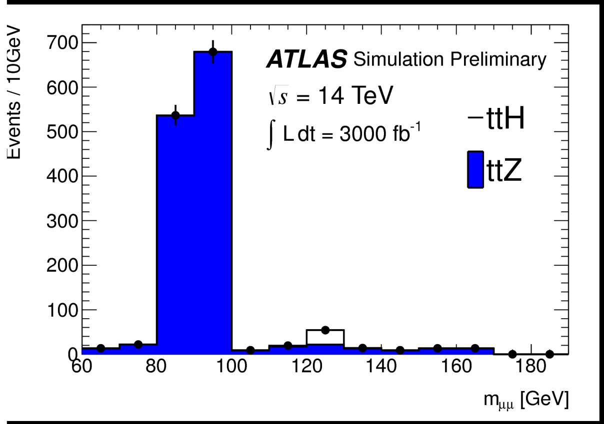
Producción
174M Higgs

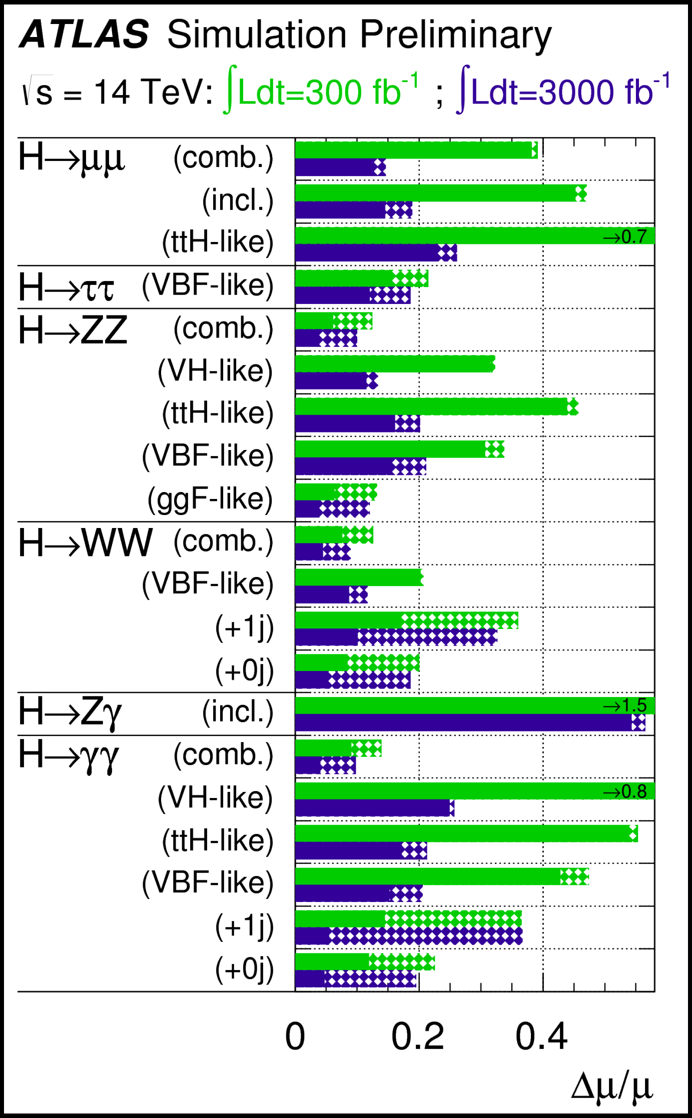


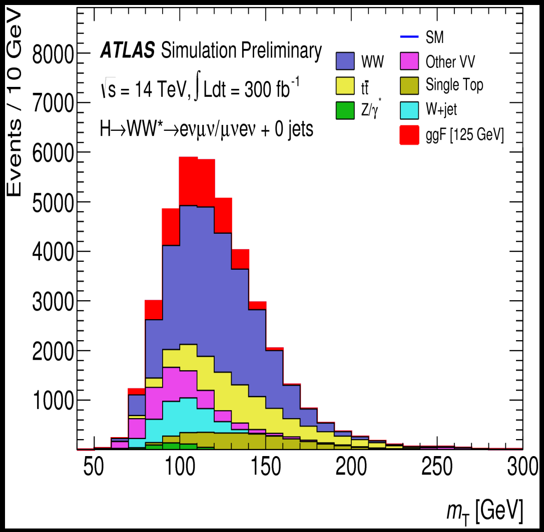
Higgs signal strength

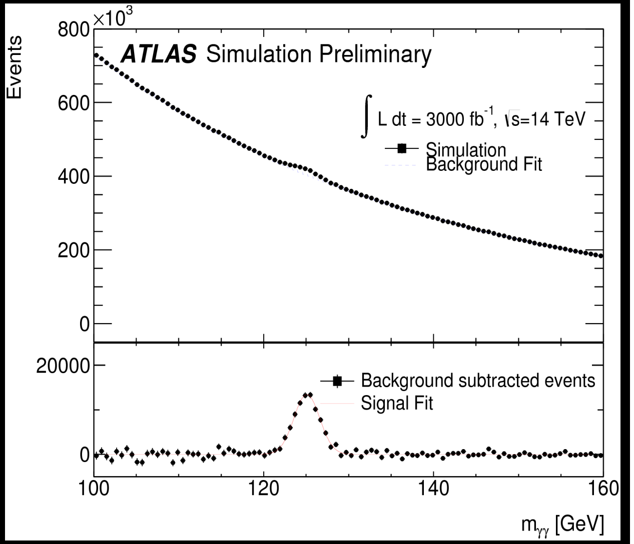
10 – 20 % accuracy after long time





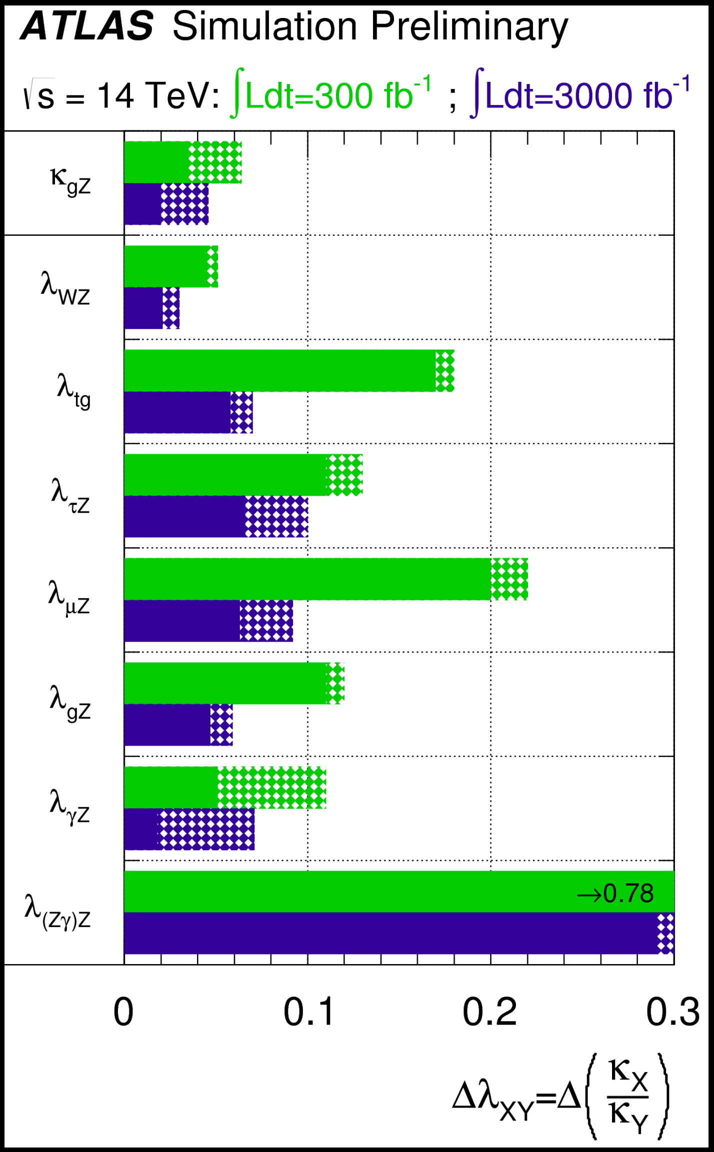


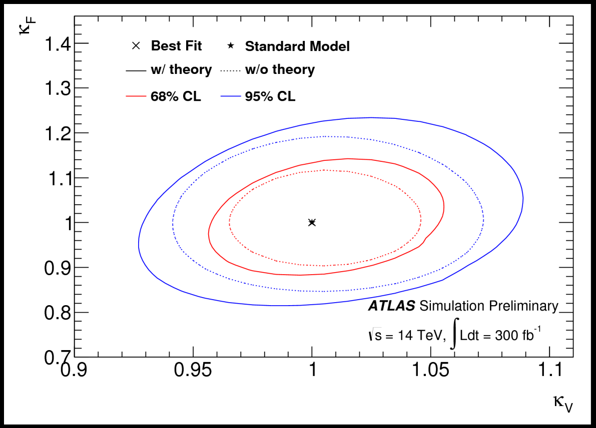


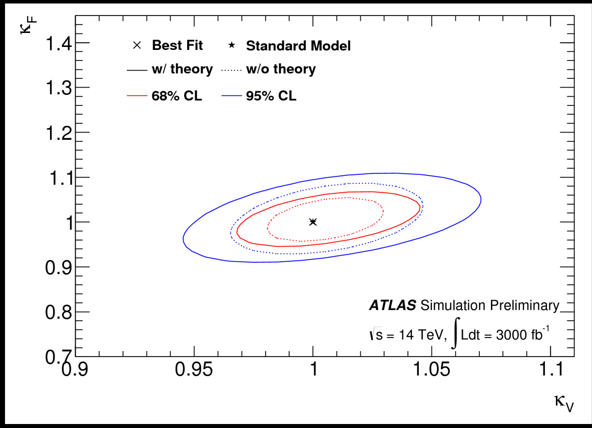


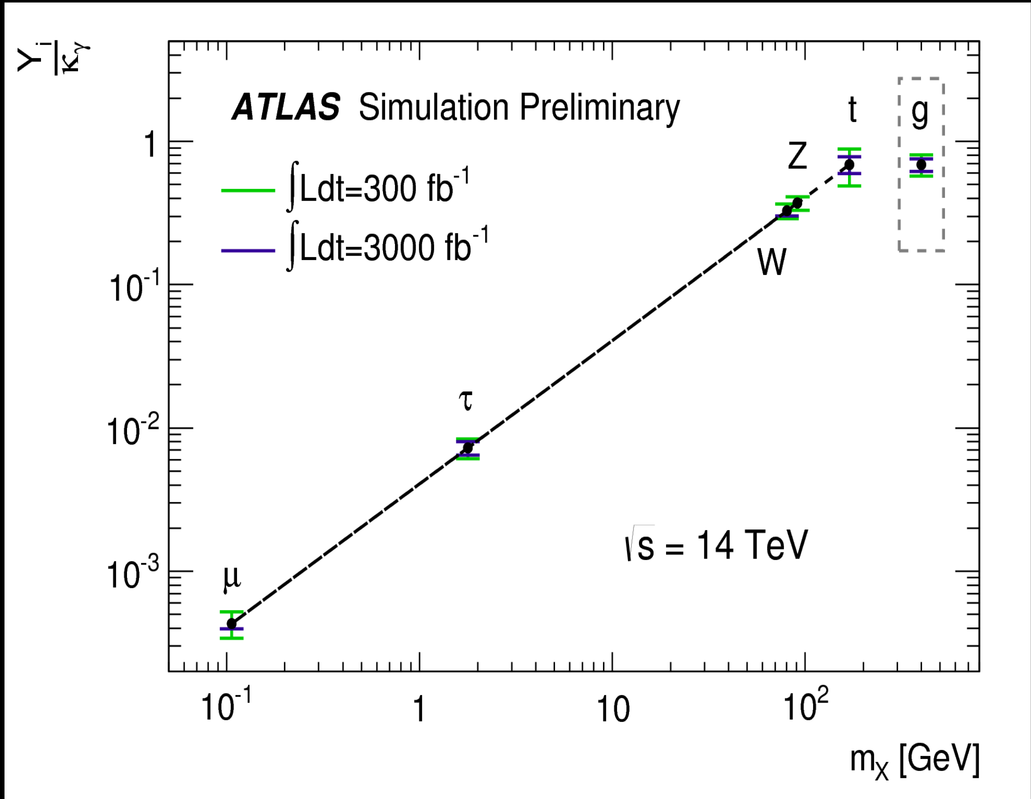
Higgs Couplings

5-10% accuracy on couplings



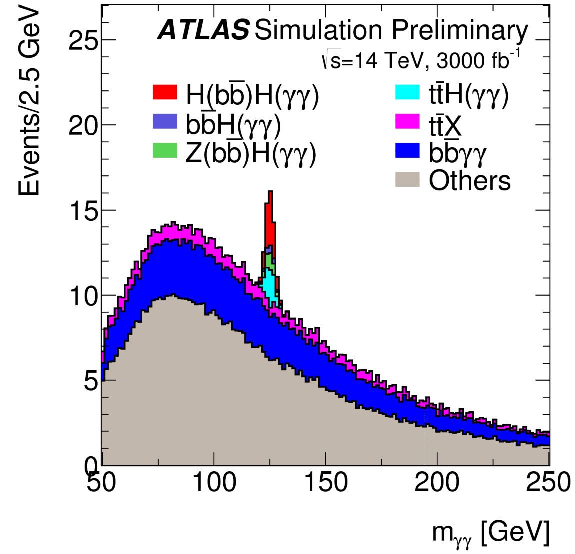






ATL-PHYS-PUB-2014-019
ATL-PHYS-PUB-2014-016

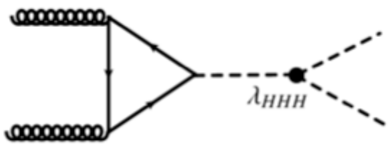
LHC-HL prospects

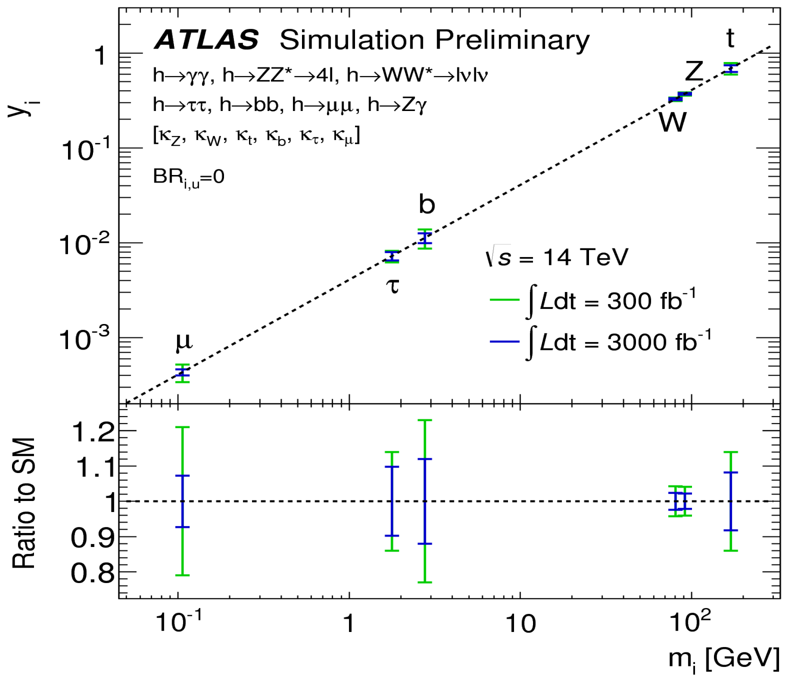


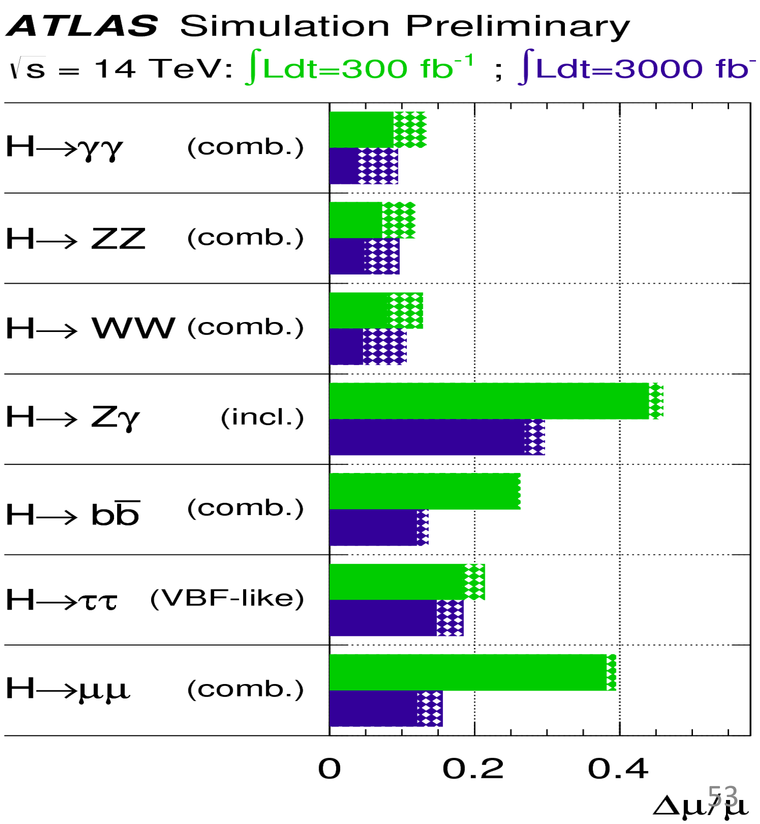
Higgs couplings (assuming SM Γ_H)

- **2-5% in most cases**
- **10% for rare processes ($H \rightarrow \mu\mu$, $ttH \rightarrow tt\gamma\gamma$)**

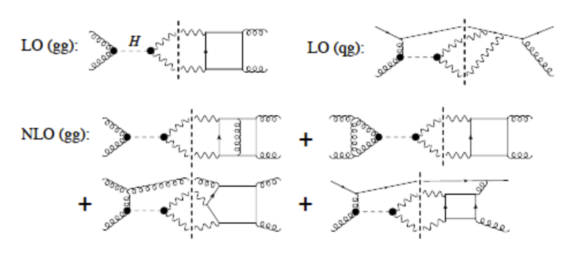
- **may measure Higgs self couplings to 30% ?**







Higgs width

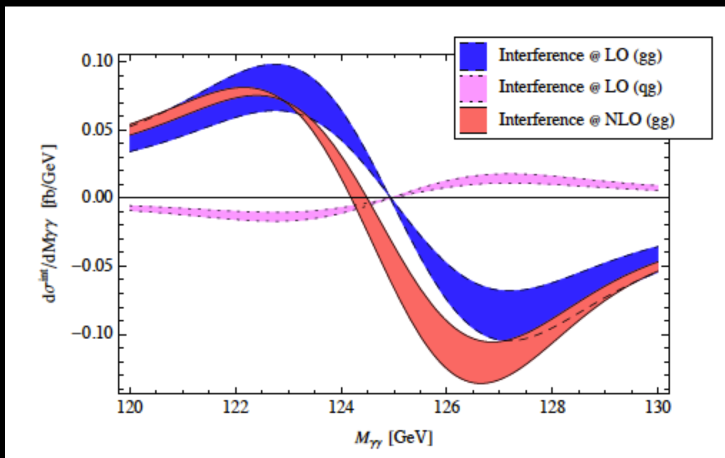


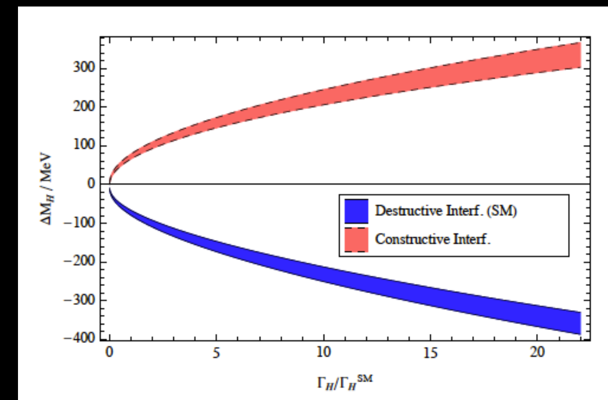
Lance J. Dixon[1] and Ye Li[1]

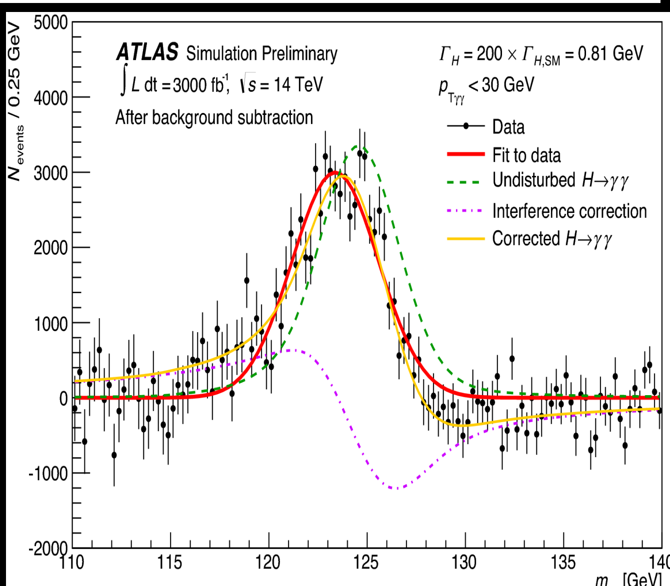
Bounding the Higgs Boson Width Through Interferometry

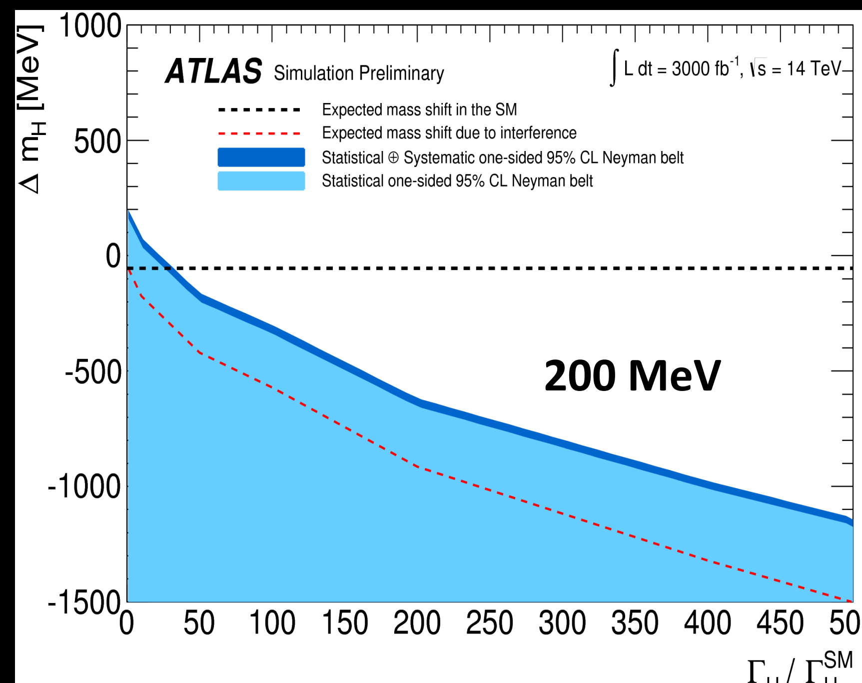
$$\frac{d\sigma^{\rm sig}}{dM_{\gamma\gamma}} = \frac{S}{(M_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}\,,$$

$$\frac{d\sigma^{\rm int}}{dM_{\gamma\gamma}} = \frac{(M_{\gamma\gamma}^2 - m_H^2)R + m_H\Gamma_H I}{(M_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}\,.$$

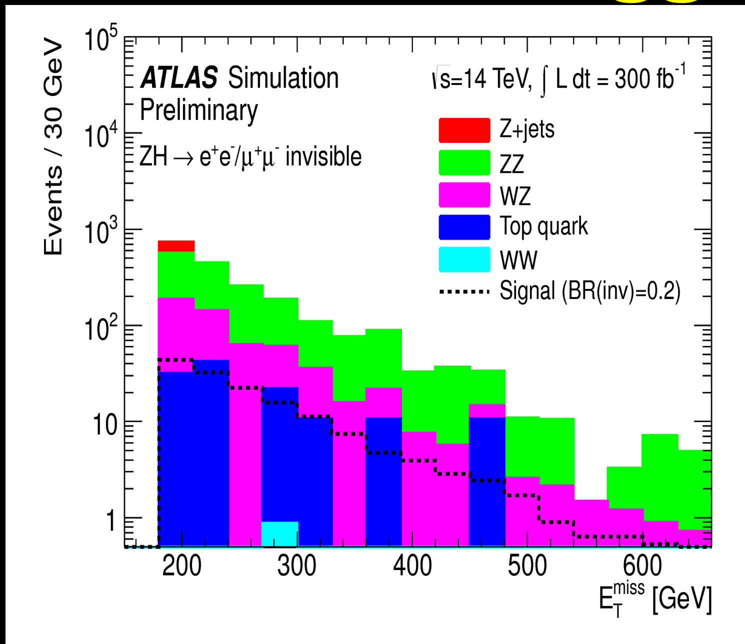


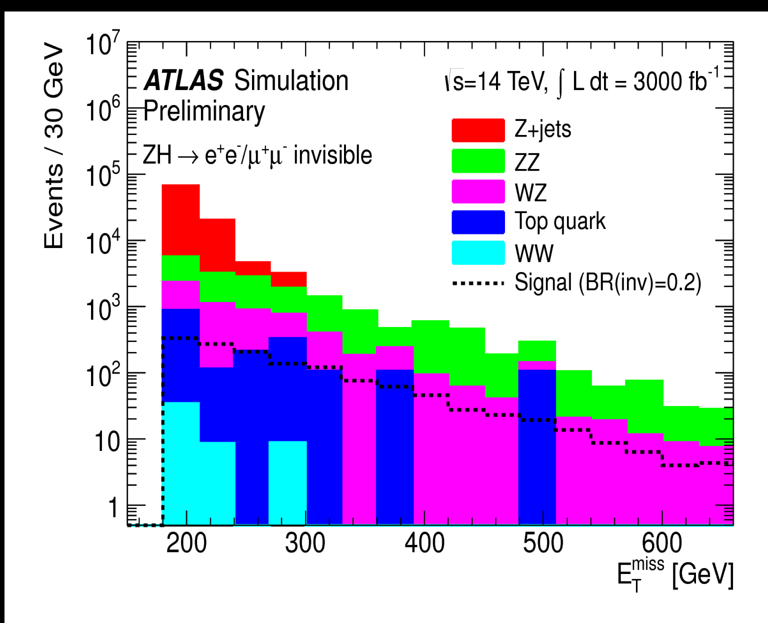


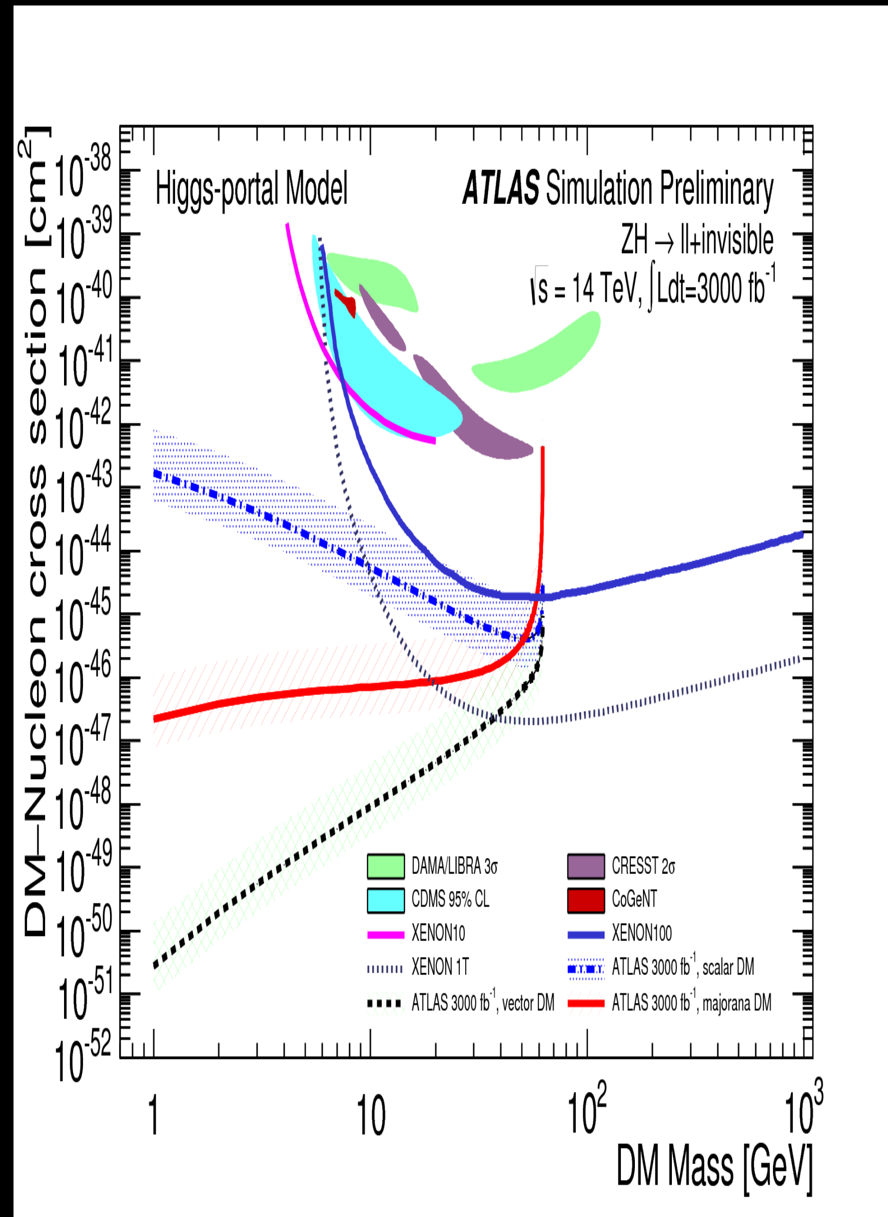




Higgs Portal to DM







End Part II