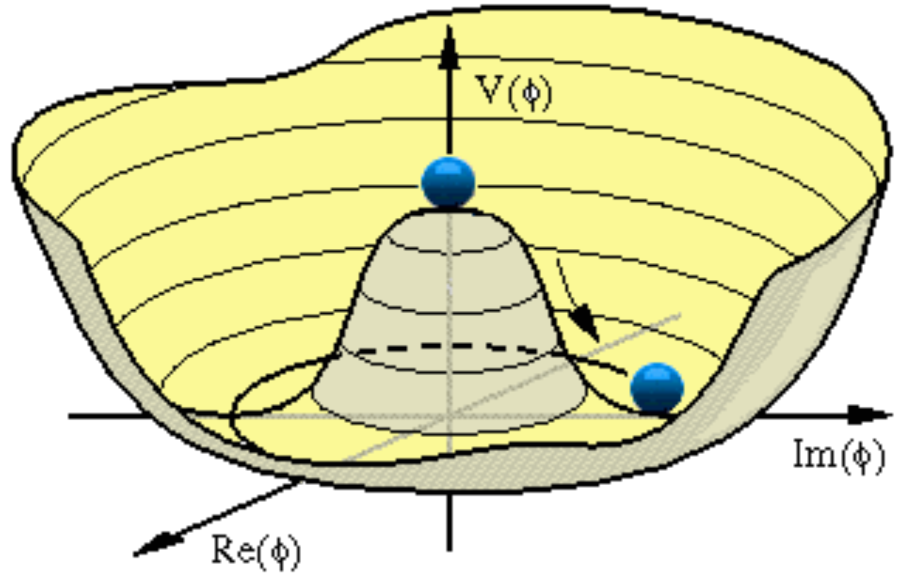


Properties of the Higgs Boson

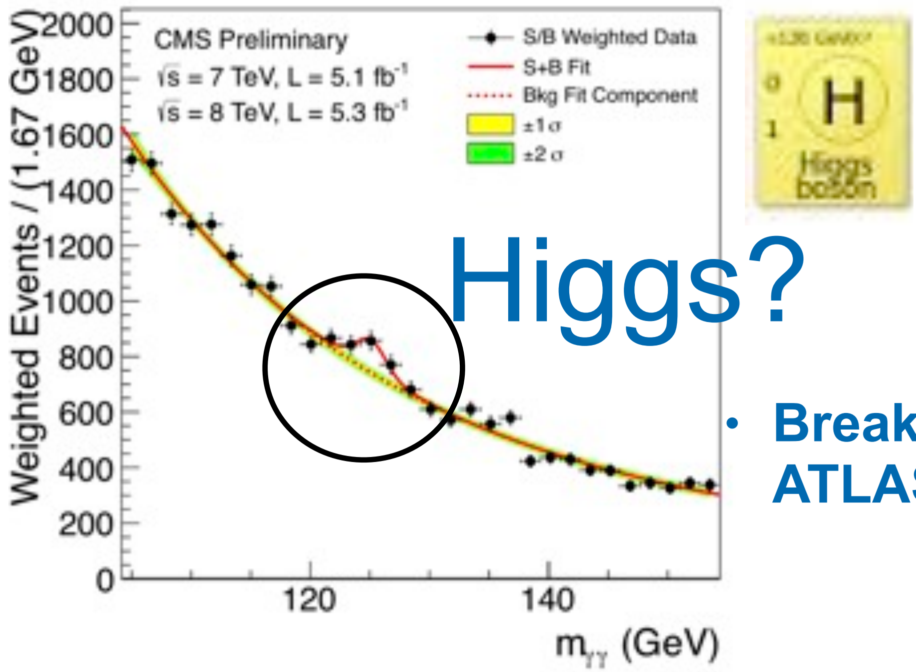
Rishi Patel

Rutgers University

On behalf of the CMS and ATLAS Collaborations

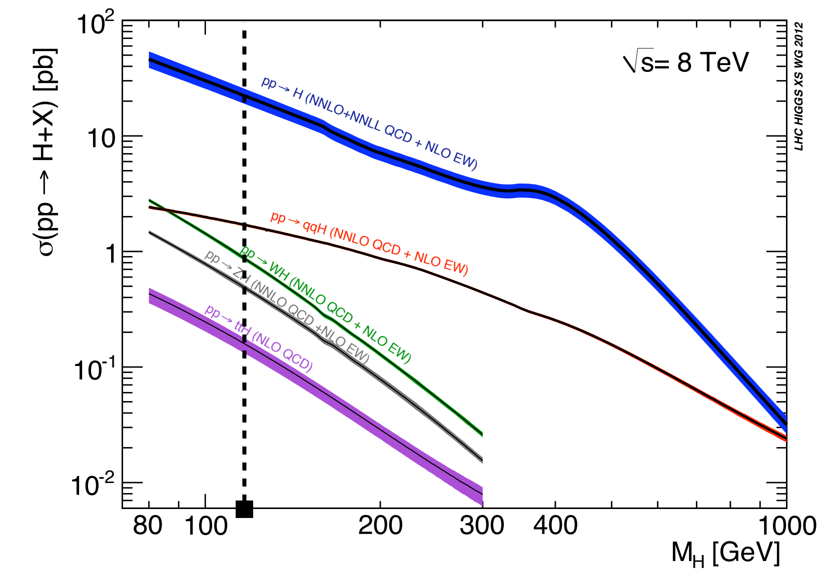
Higgs at the LHC

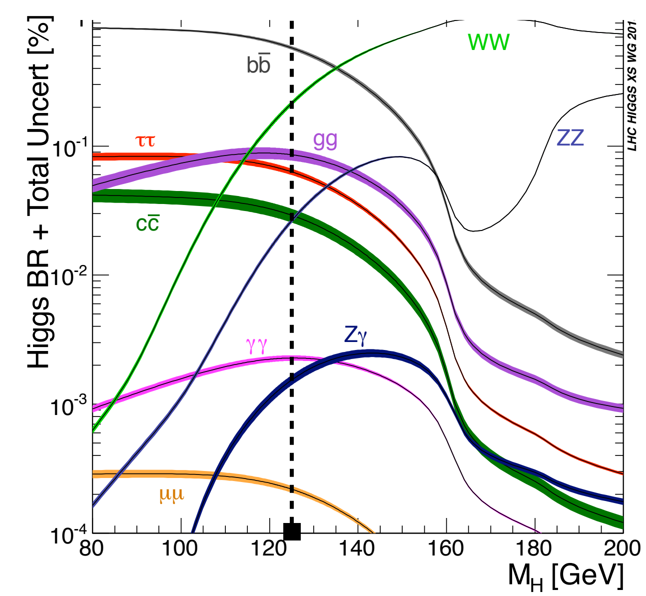
- **One of the goals of the LHC physics program is to unravel the origin of Electroweak symmetry breaking:**



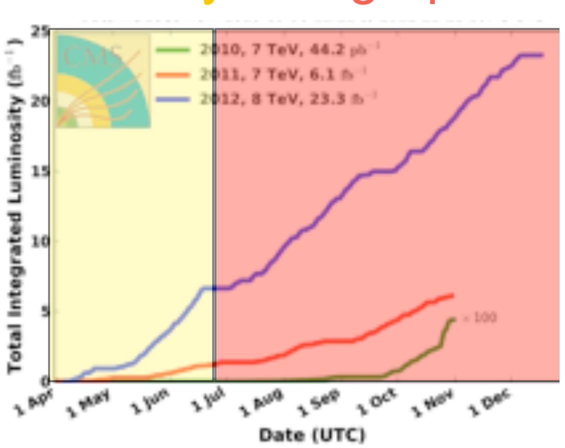
- **Breakthrough: Discovery by CMS and ATLAS of a new boson**

From LHC cross sections Group

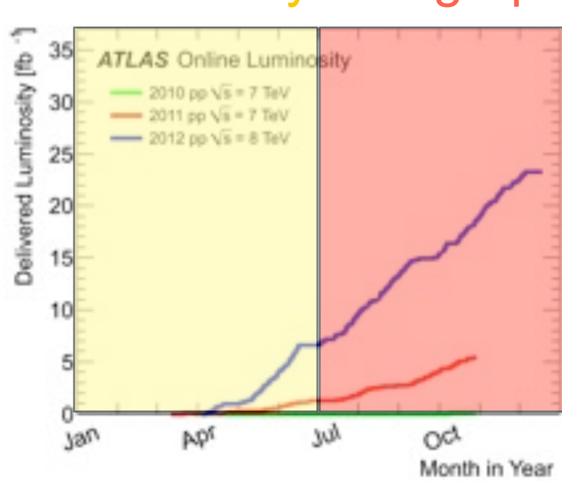




discovery fingerprint



discovery fingerprint



FUTURE:
14 TeV
SNOWMASS
Projections

- 125 GeV : Many available production modes and decay channels to test SM compatibility

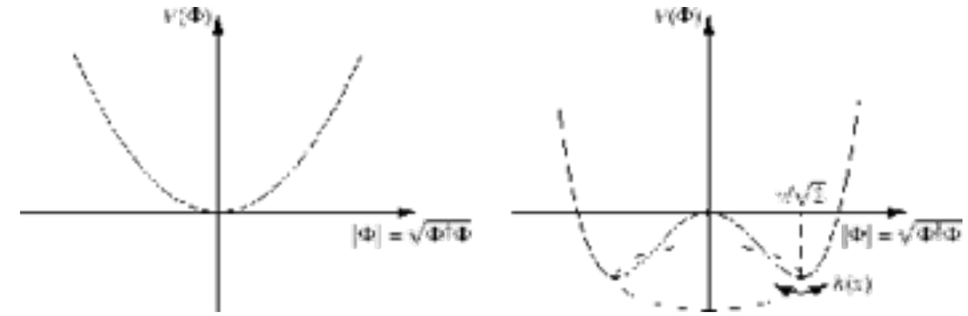
- With the full Run 1 data (~30/fb) the experiments can test the compatibility of the new boson with the prevailing theory: Standard model Higgs boson

Standard Model Higgs

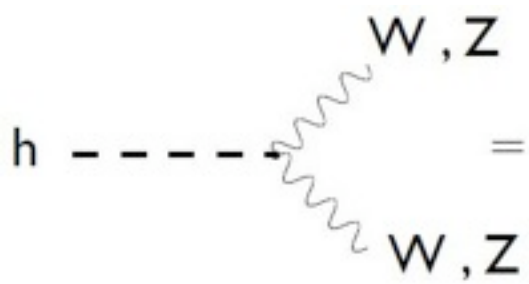
$$V(\varphi^\dagger\varphi) = \frac{1}{2}(\lambda^2|\varphi|^4 - \mu^2|\varphi|^2)$$

free parameter: $2\sqrt{\mu} = M_H$

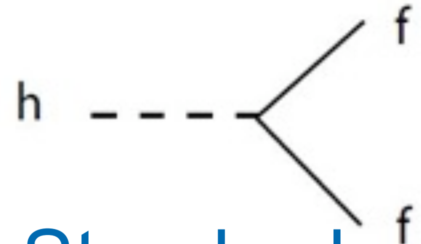
SM Higgs: $v = \mu/\sqrt{\lambda} = 2M_W/g$



Tree level



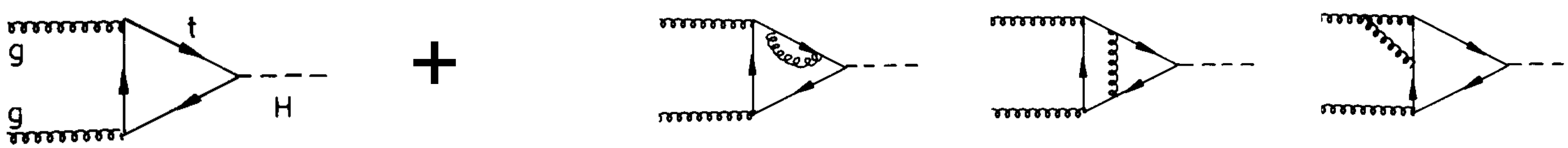
$= gM_W \ , \ \frac{gM_Z}{\cos\theta_W}$



$= \frac{gM_f}{2M_W}$

COMPATIBILITY: Compare the SM prediction to the observed for different quantities:
signal strength: $\sigma_{obs} \times BR / \sigma_{SM} \times BR_{SM}$
coupling scale: $\kappa * g_{SM} = g$

Loop level Standard



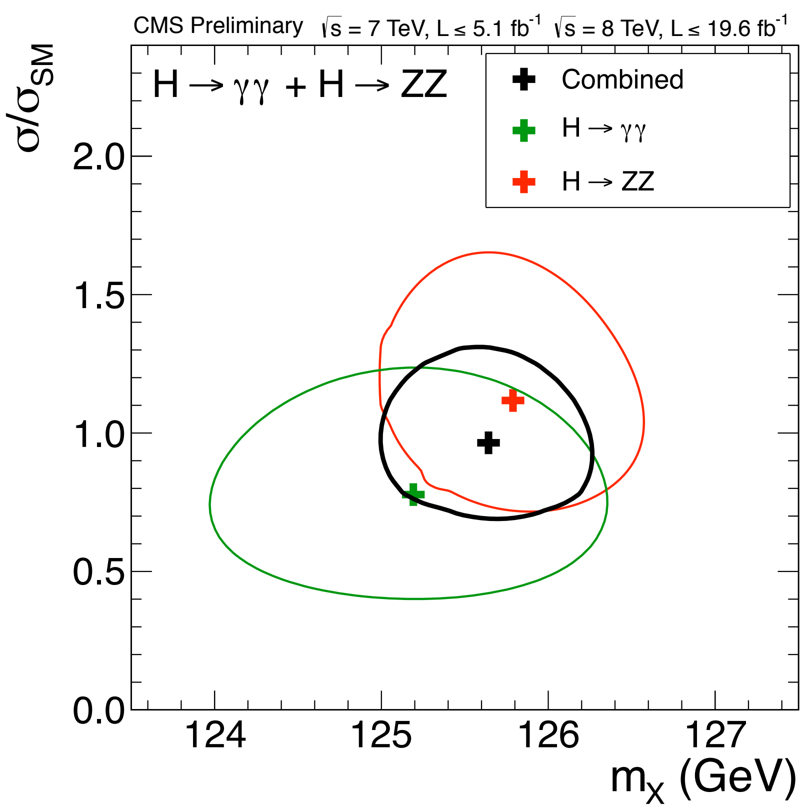
something new?

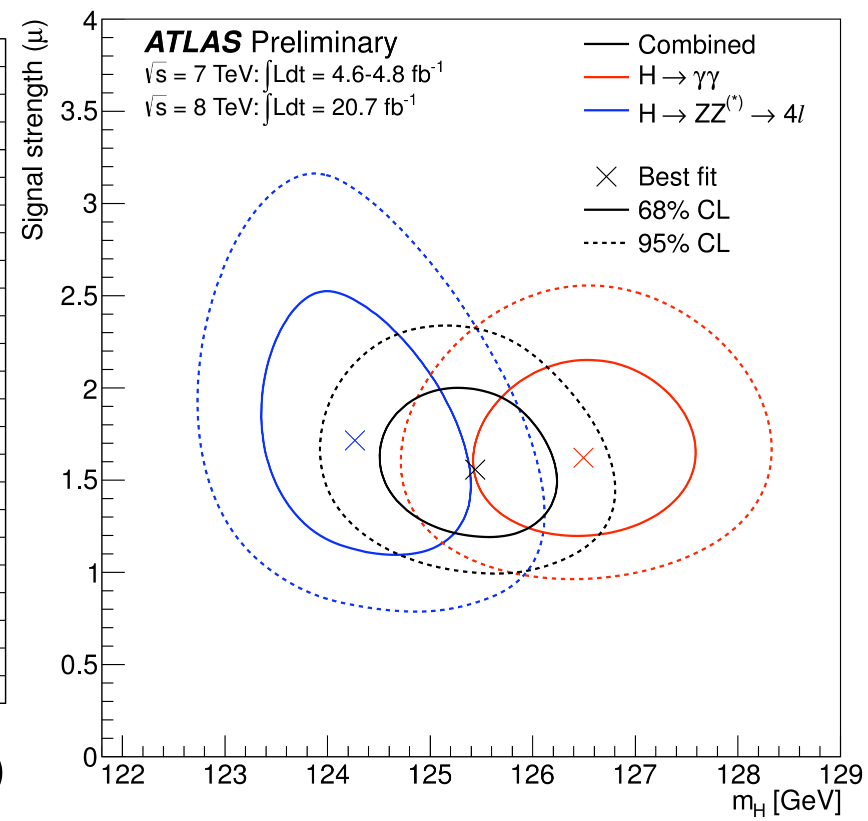
Presence of non-SM particles in the loop

Mass Measurement

Combining channels For Mass Measurement

CMS　　　　　　ATLAS



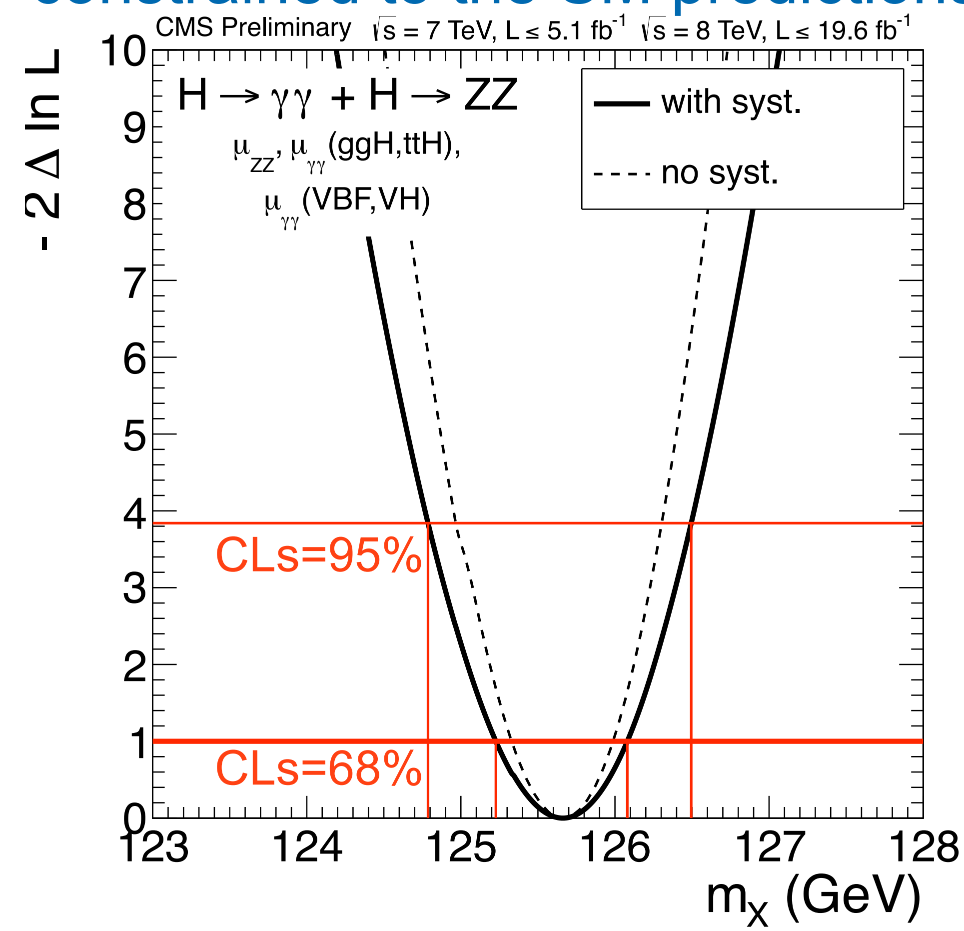


CMS: $m_H = 125.7 \pm 0.3(sys) \pm 0.3(stat)$

ATLAS: $m_H = 125.5 \pm 0.2(sys)^{+0.5}_{-0.6}(stat)$

MODEL DEPENDENT MEASUREMENT

- All productions and BR are constrained to the SM predictions.

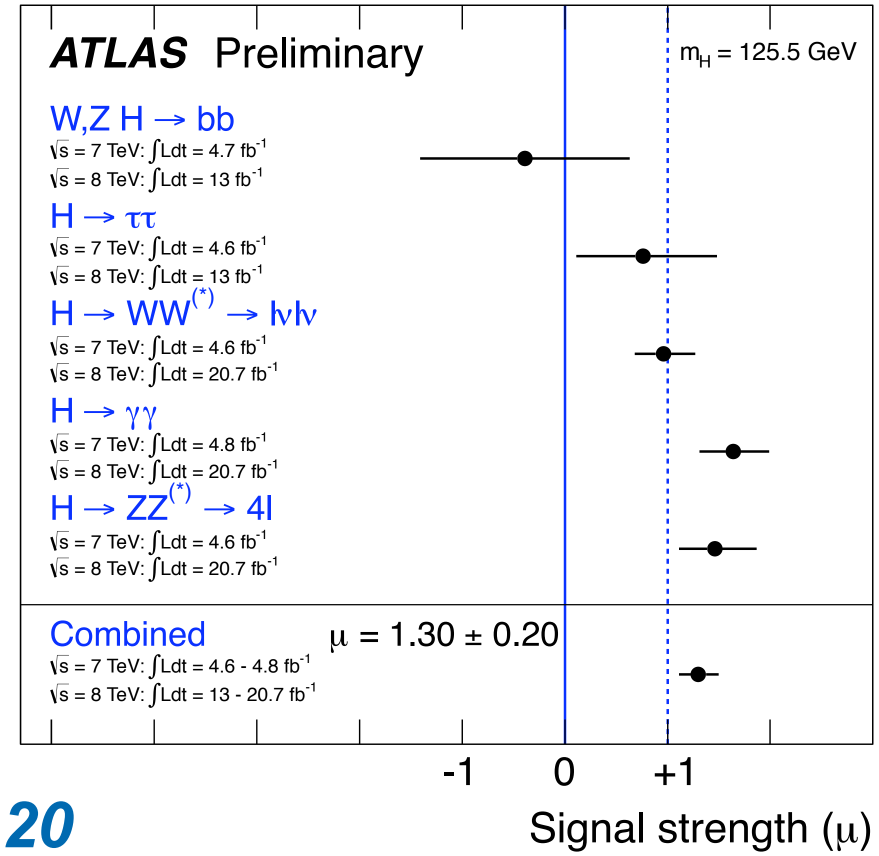


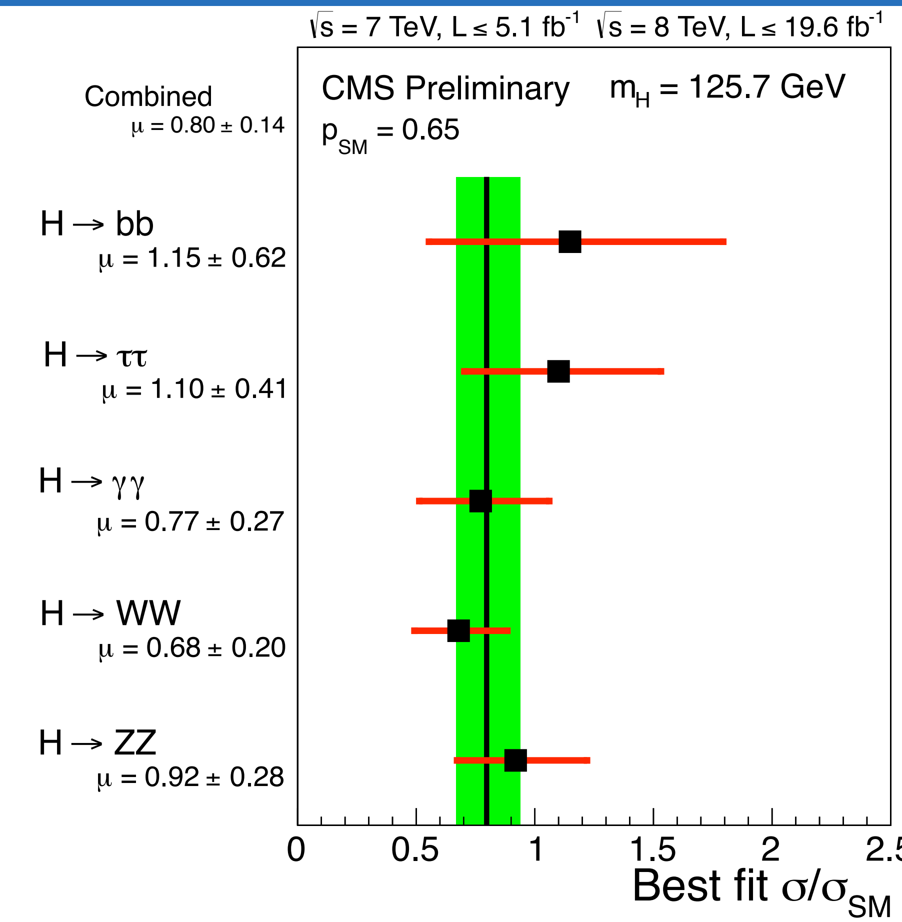
- For current data: $\Delta m \sim \pm 0.5 \mathrm{GeV}$ but projections at 300/fb (3000/fb) at 14TeV show $\Delta m \sim 100 \mathrm{MeV}$ ($50 \mathrm{MeV}$) based on Snomass projections

- Best fit mass compatible better than 0.1 GeV with the model independent

Combined Signal Strengths

- Simultaneously analyze all selected data across all decay modes and measure the overall deviation from the SM cross-section

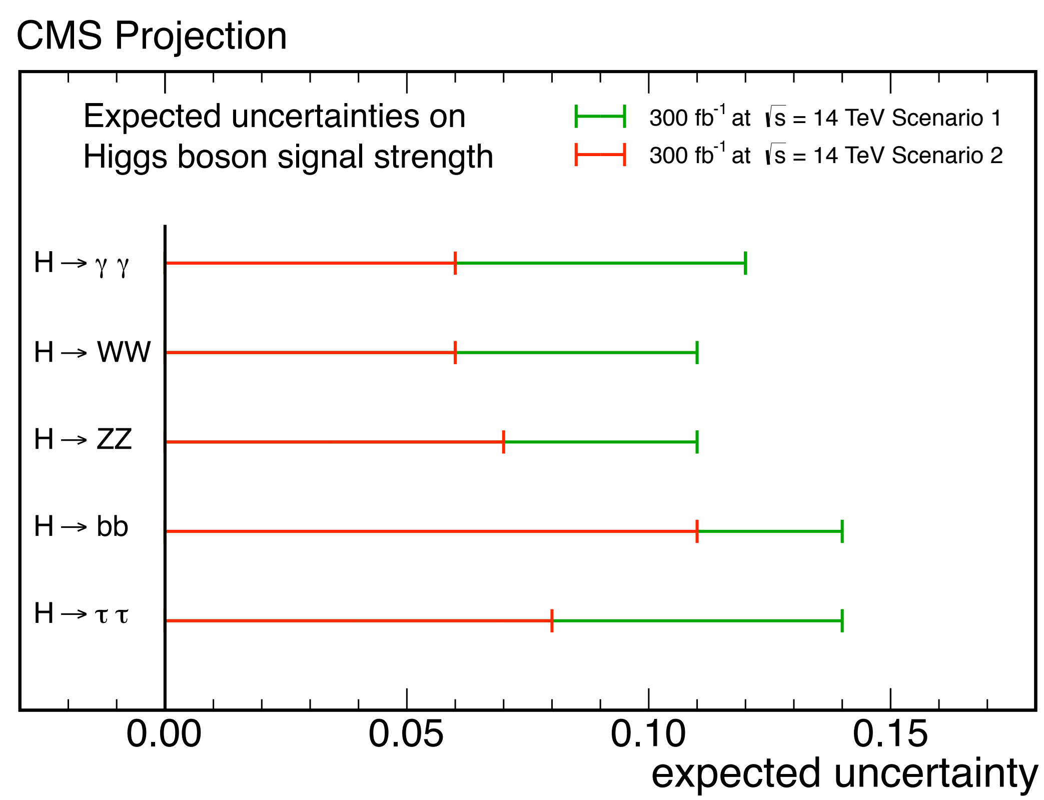




ATLAS: Combined ***μ=1.30±0.20***

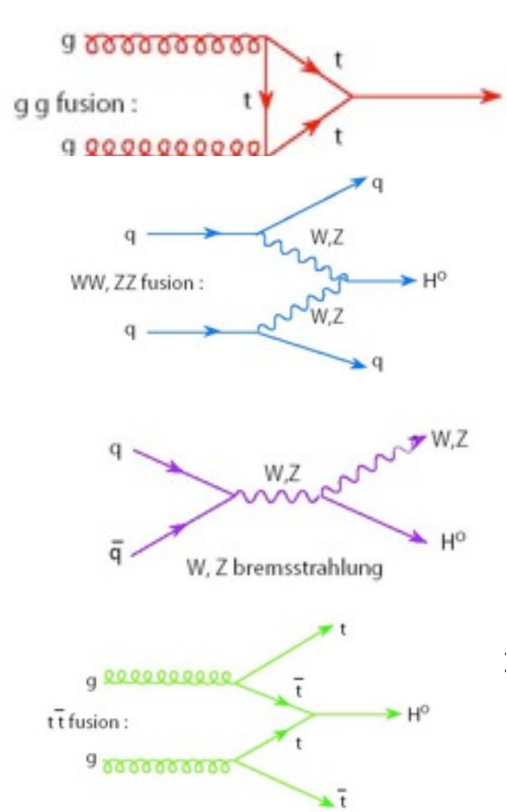
CMS: Combined ***μ=0.80±0.14***

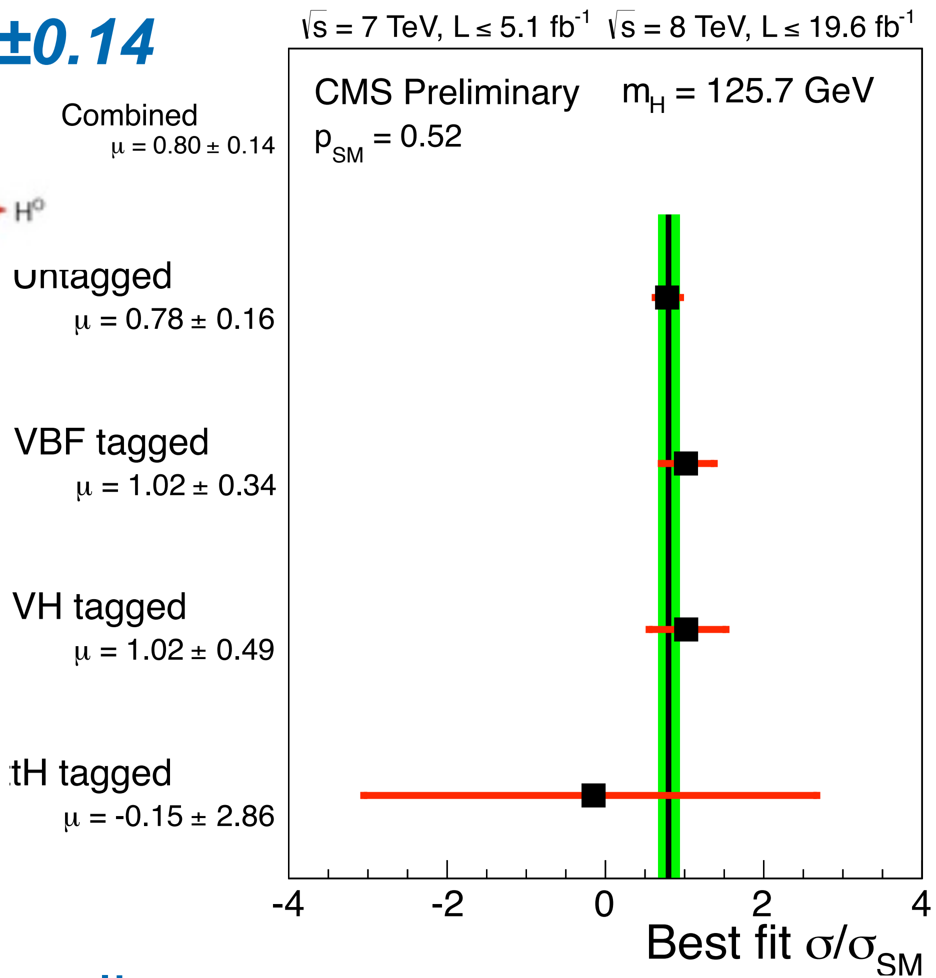
- NOW: High sensitivity decay modes basically drive the combination (~15% precision on combined signal strength)
- AT 14TeV: At high luminosity 300/fb, less sensitive decay modes have much smaller uncertainties. The combined signal strength will be even more precise

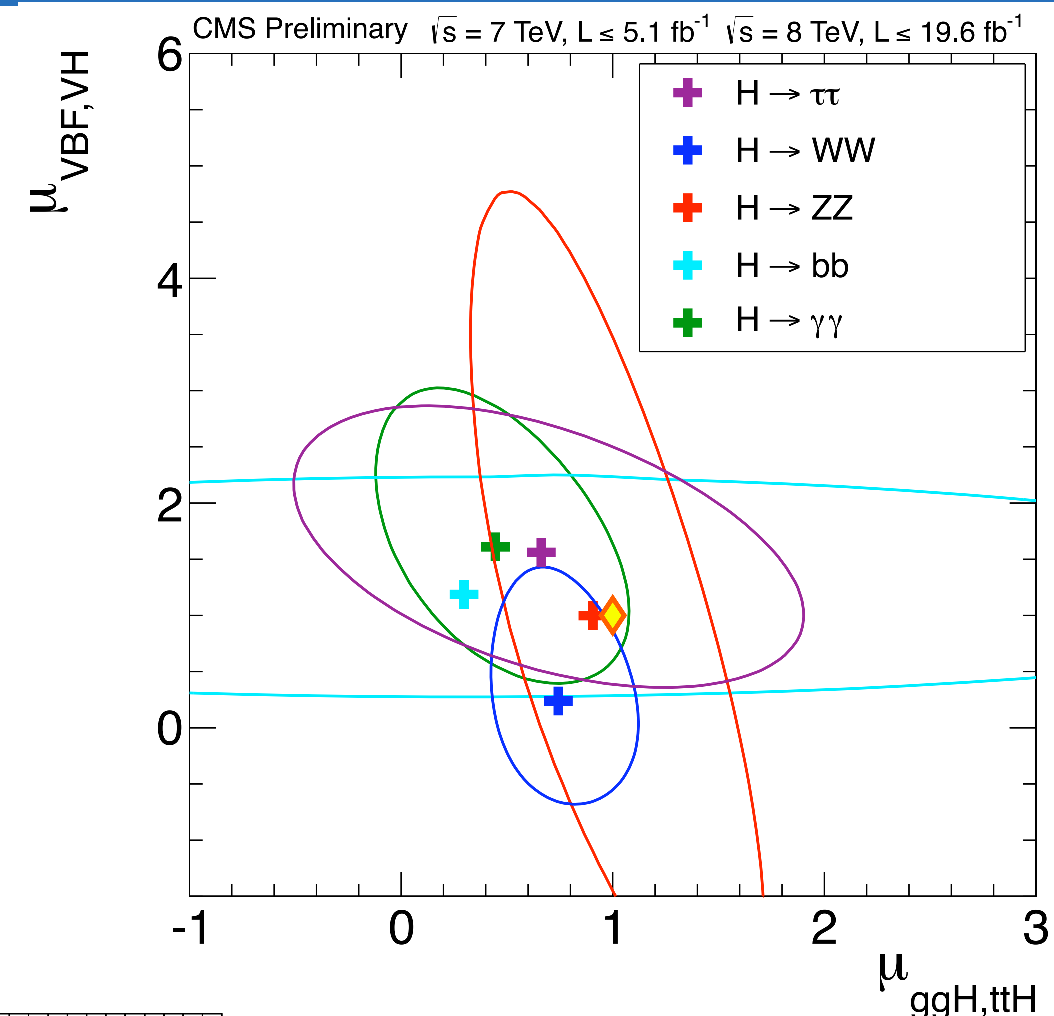


Production Modes

Combined ***μ=0.80±0.14***

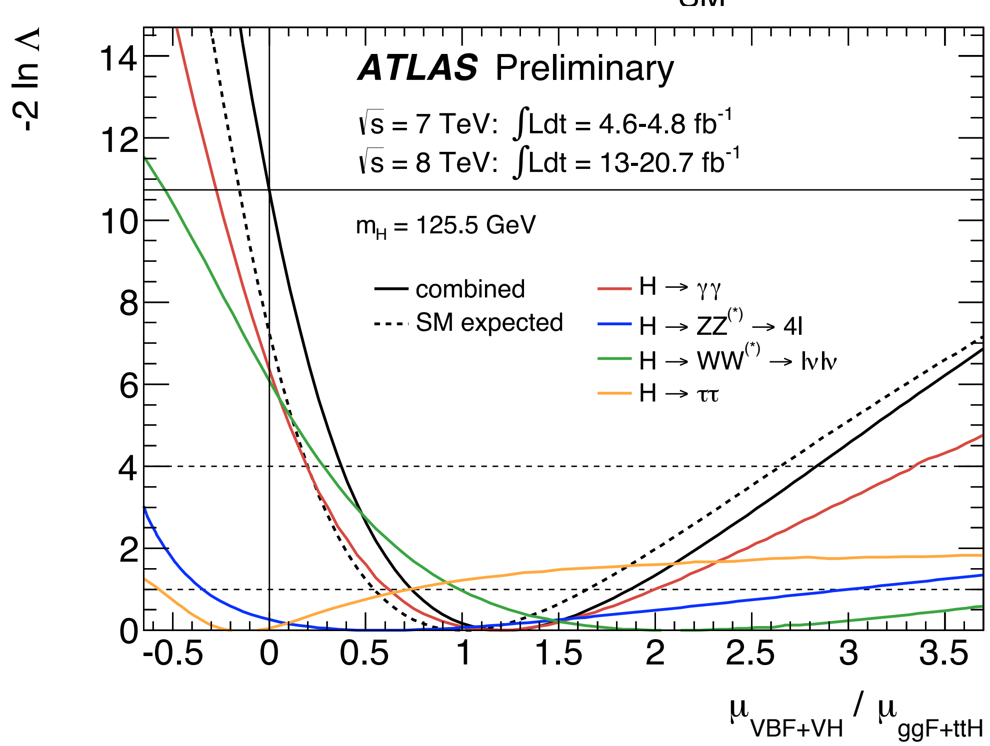




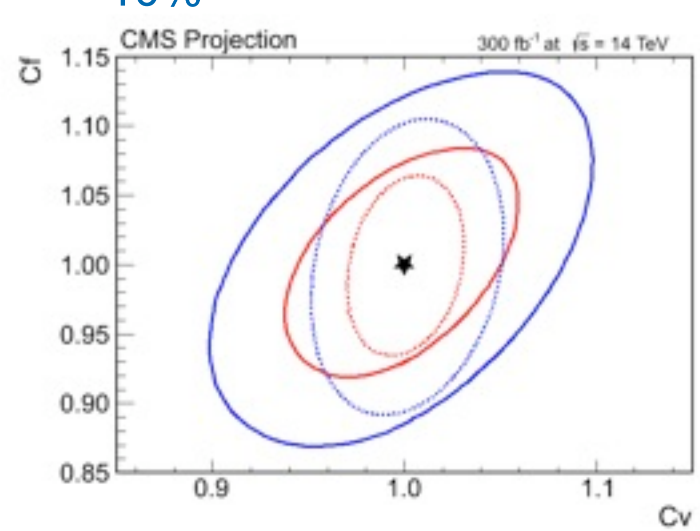


- 2D scan: Fermion coupling to Higgs vs. Vector Boson coupling: Each contour is for a different BR/BRSM so difficult to combine
- 1D Scan of ratio: Branching ratio of each decay cancels

ATLAS: $\frac{\mu_{ggF+ttH}}{\mu_{VBF+VH}} = 1.2^{+0.7}_{-0.5}$



- Projection of 300/fb to 14TeV predicts a much tighter precision of ~10%



Coupling Scale Factors

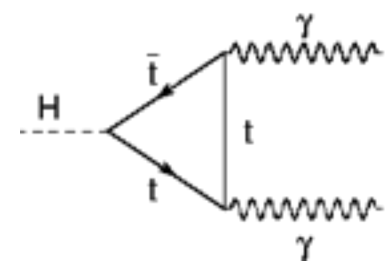
Tree level amplitudes:

$$\sigma \times BR(ii \to H \to ff) = \frac{\sigma_{ii}\Gamma_{ff}}{\Gamma_H}$$

$$\Gamma_{jj} \propto \frac{(m_{jj}\kappa_{jj})^2}{v^2} \propto \kappa_{jj}^2 \Gamma_{jj}^{SM}$$

channel can be represented as a product of coupling scale factors

Loop level for $\gamma\gamma$:



interference:

$$\Gamma_{\gamma\gamma} \propto |\alpha\kappa_W - \beta\kappa_t|^2$$

coef. fixed to SM values

Assume: SM tensor structure $J^P=0^+$ and SM BR to fermions/Vector bosons:

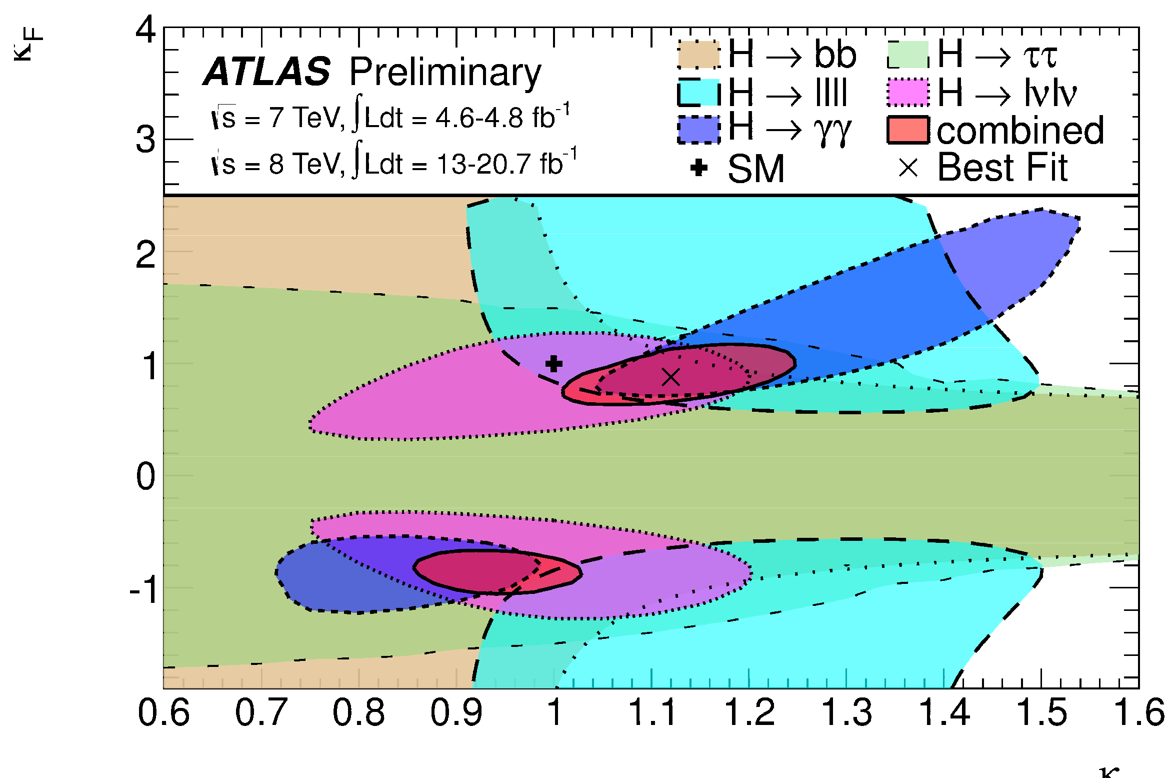
$$\Gamma_H = 0.75\kappa_f^2 + 0.25\kappa_V^2$$

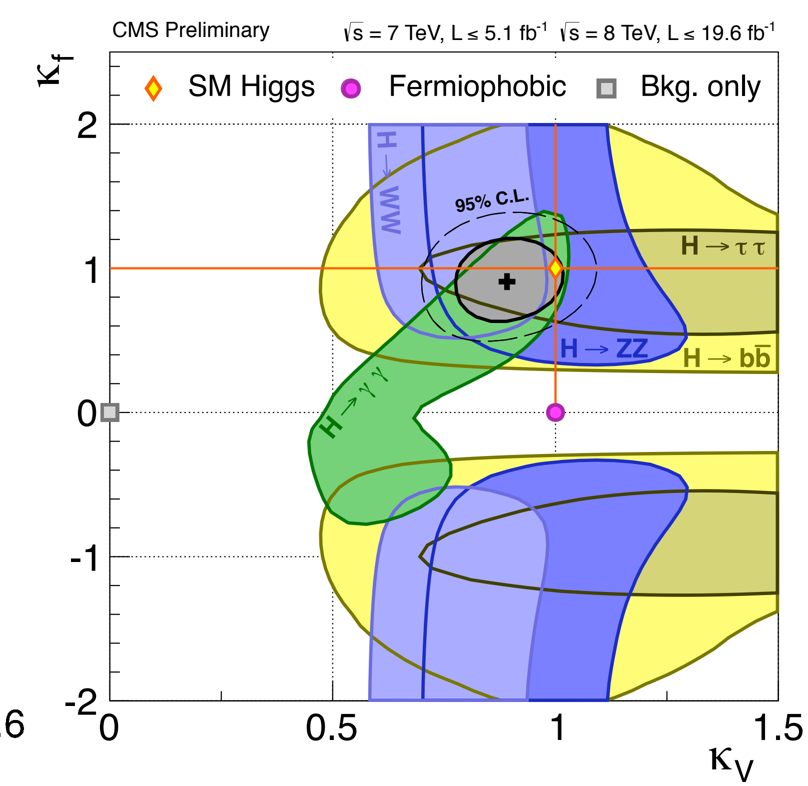
(common scale factor for all fermions)

$\kappa_F = \kappa_t = \kappa_b$ ...

(common scale factor for all vector bosons)

$\kappa_V = \kappa_W = \kappa_Z$





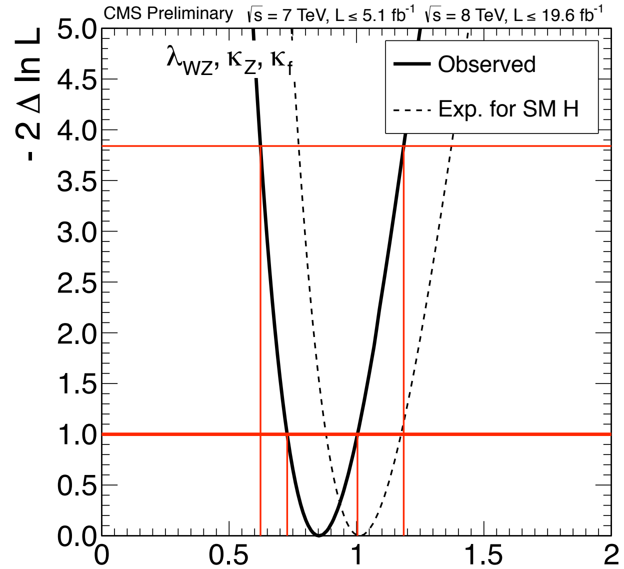
ATLAS $\kappa_F \in [0.73,1.07]$ $\kappa_V \in [1.05,1.21]$ at 68% C.L.

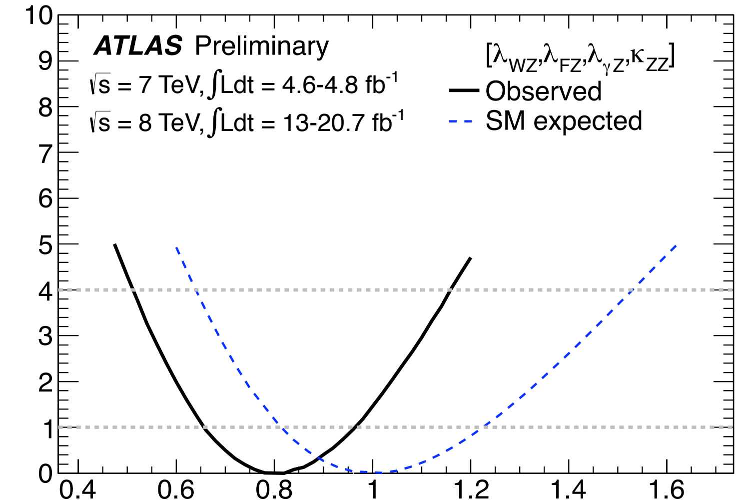
CMS $\kappa_F \in [0.61,1.33]$ $\kappa_V \in [0.74,1.06]$ at 95% C.L.

SM Compatibility Tests

Custodial symmetry: W/Z coupling to Higgs: gZ/gW ≈1

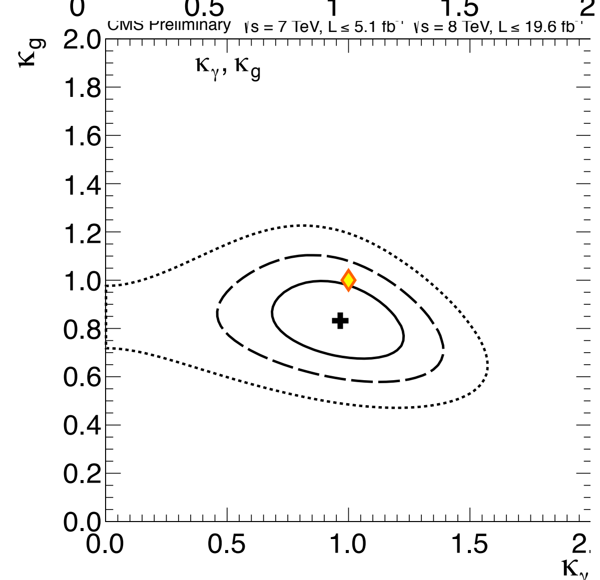
- Issue is $\Gamma_{\gamma\gamma}$ depends on κW
- CMS and ATLAS: Decouple the event rate of H→γγ from κw/κz by introducing additional free parameters in the likelihood

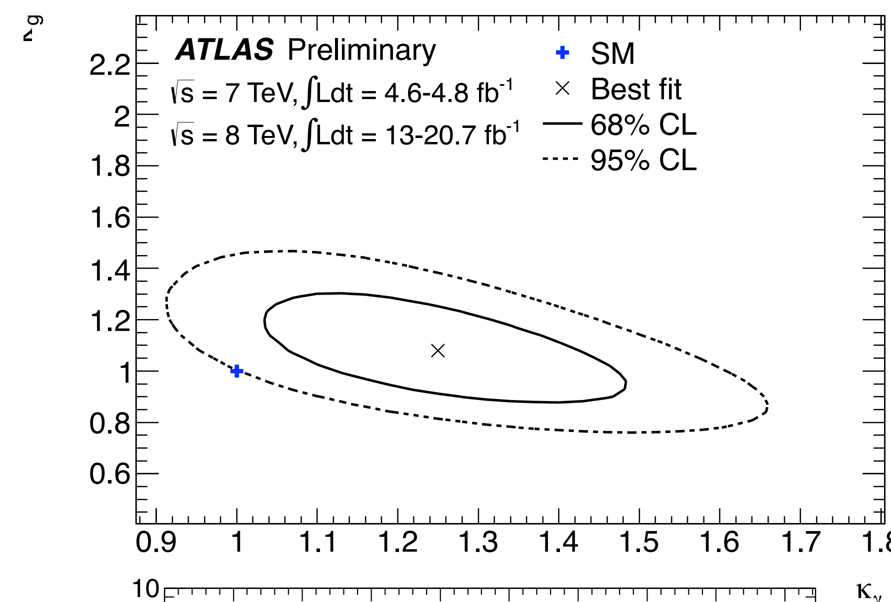




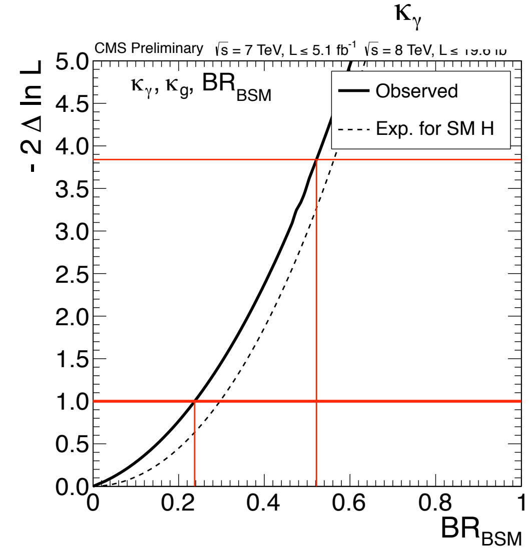
Probe Loop Corrections:

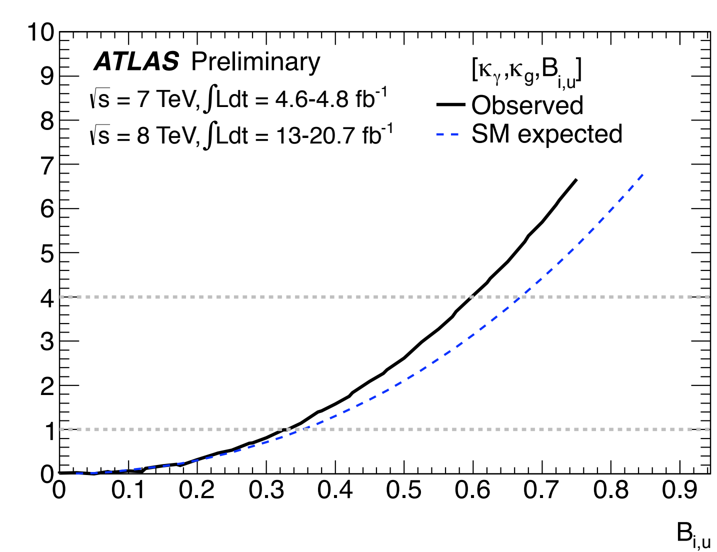
H→γγ gg→H





- Scenario 1 New particles contribute negligibly to the total width: $\Gamma_{total}=\Gamma_{SM}$
  - Fit kg kγ
- Scenario 2 Allow new particles to contribute to the total width: $\Gamma_{total}=\Gamma_{SM}+\Gamma_{BSM}$
  - Fit kg, kγ, Γ_{BSM}





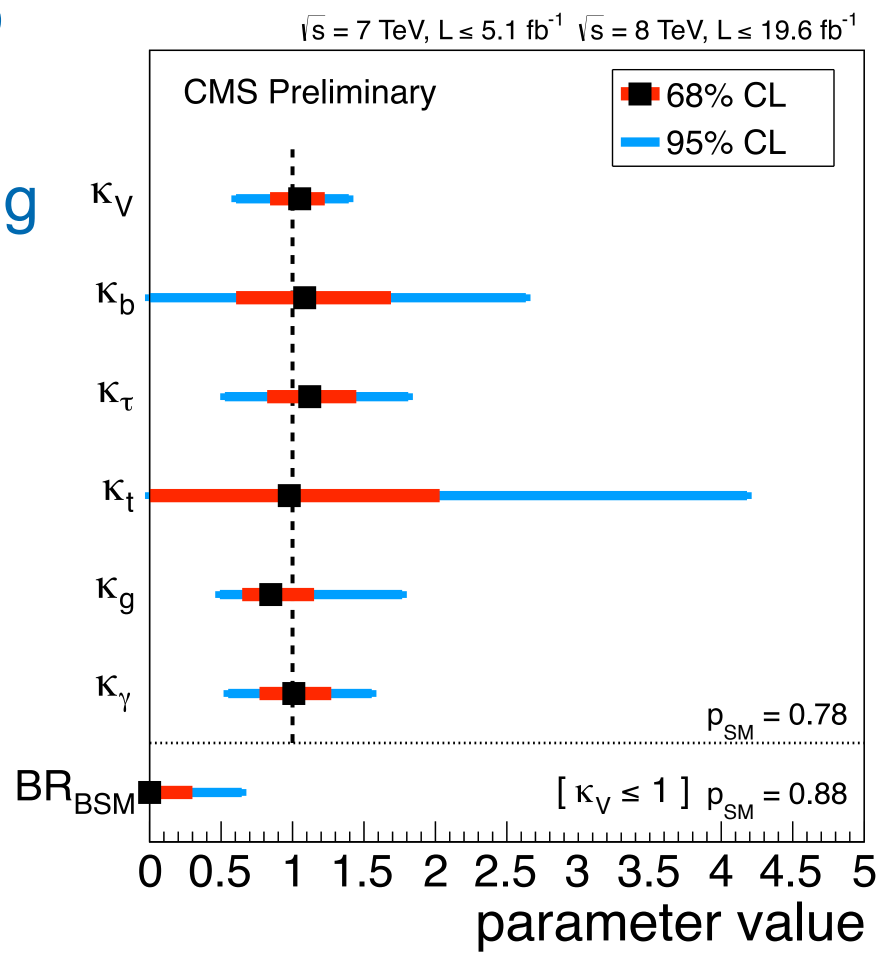
SUMMARY: Couplings and Total Width

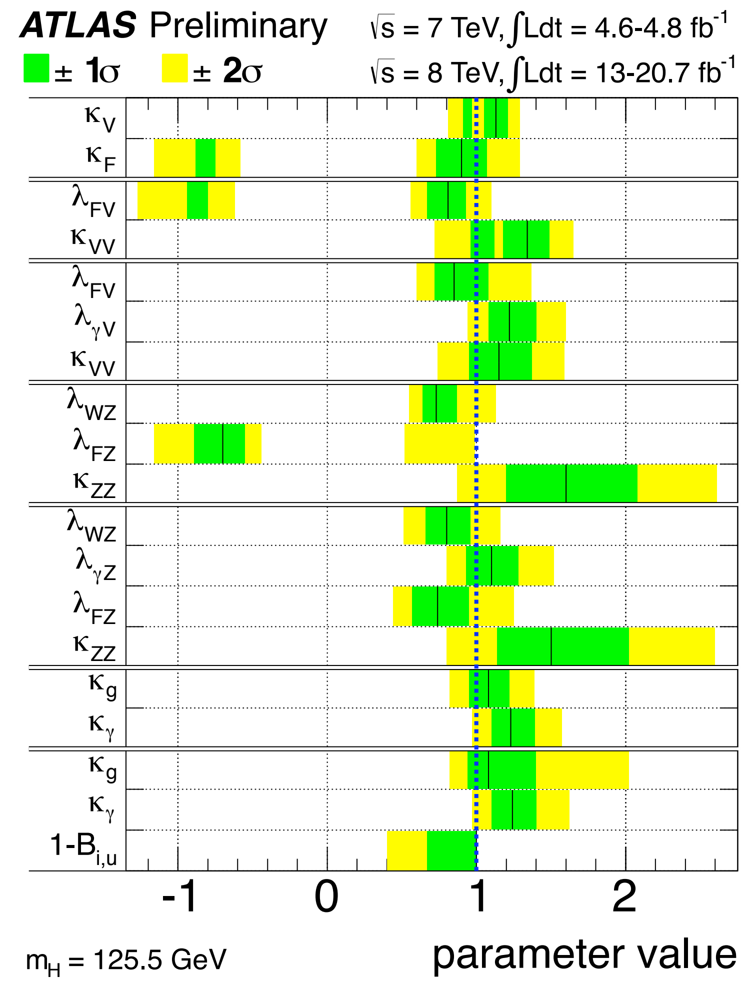
- Ratios of couplings requires no assumption on the total width
- Can include total width including extra contributions:

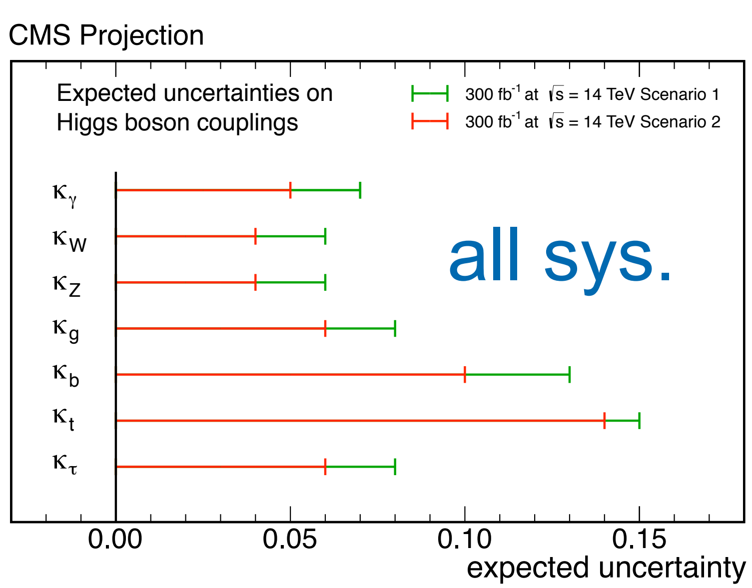
$$\Gamma_H = \Gamma_{SM} + \Gamma_{BSM}$$

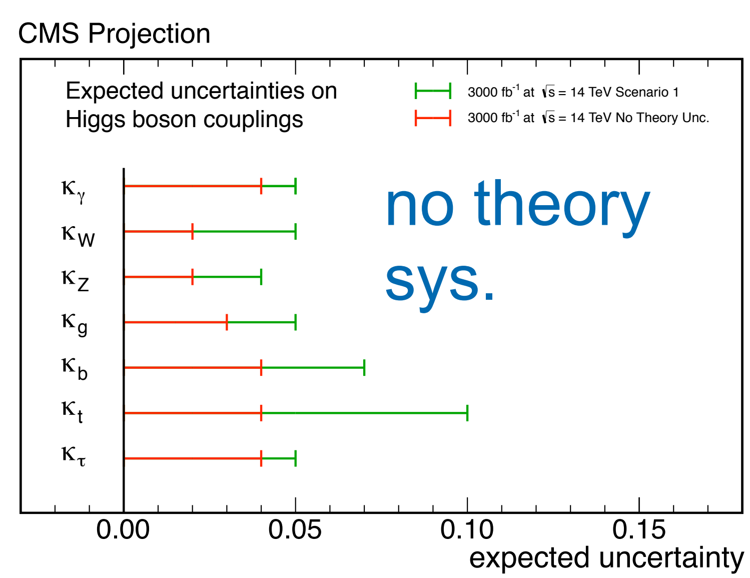
$$BR_{SM} = \frac{\Gamma_{BSM}}{\Gamma_H}$$

  - For 300/fb at 14TeV the statistical uncertainty are below 1%
  - Theory systematics most important: QCD scale, pdf uncertainties, BR uncertainties



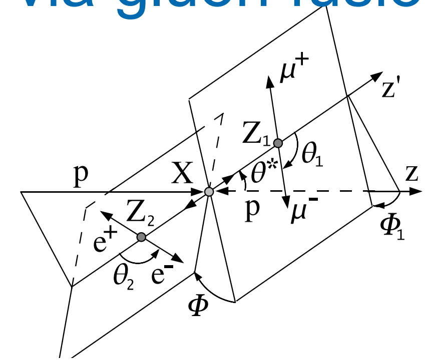






Spin Hypothesis Test

- Test Spin 0^+ SM Higgs Hypothesis vs a Spin 2^+_M hypothesis.
  - Spin 2^+_M use graviton model simulation produced via gluon fusion and quark-antiquark (giving different polarization)

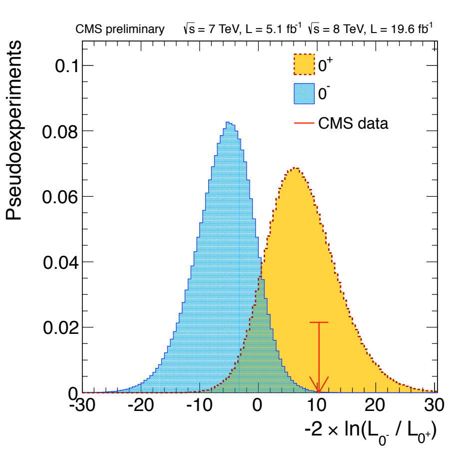


ZZ: Fully reconstructed 4-lepton final state:

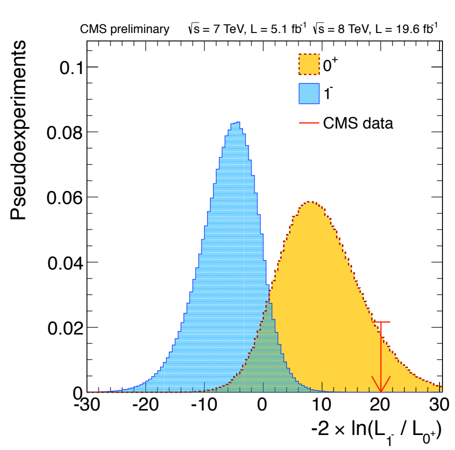
WW: Not a fully reconstructed final state but have angles computed from the 2 leptons

MVA classifier is trained with final state observables

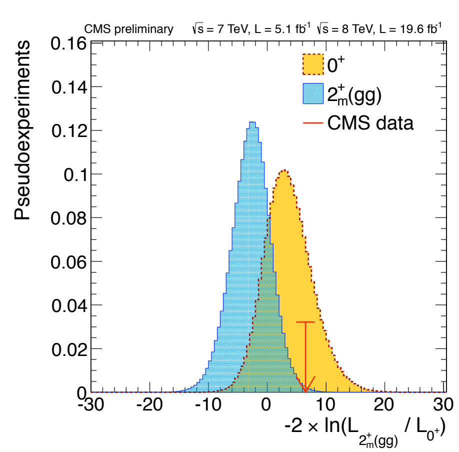
ZZ predictions:



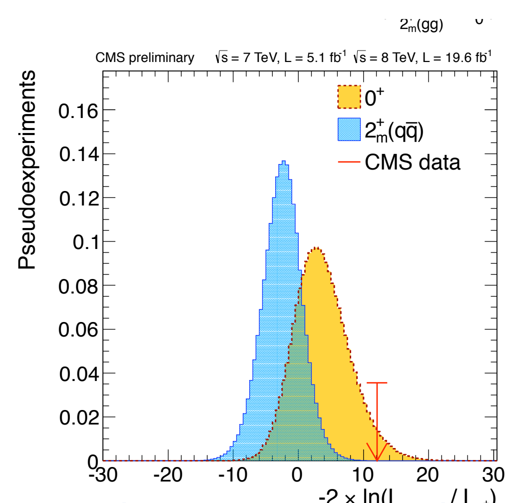
Rules out 0^-



Confirms not 1

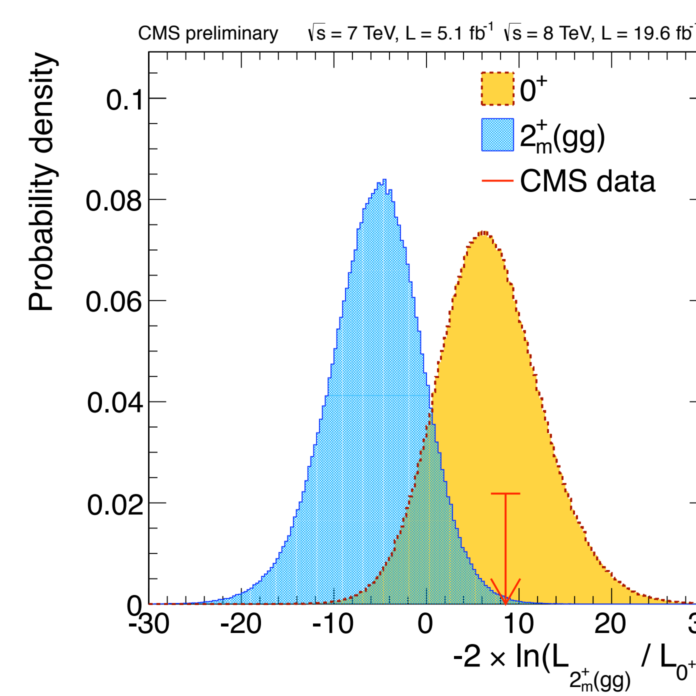


(pure gg 2m+)



(pure qq' 2m+)

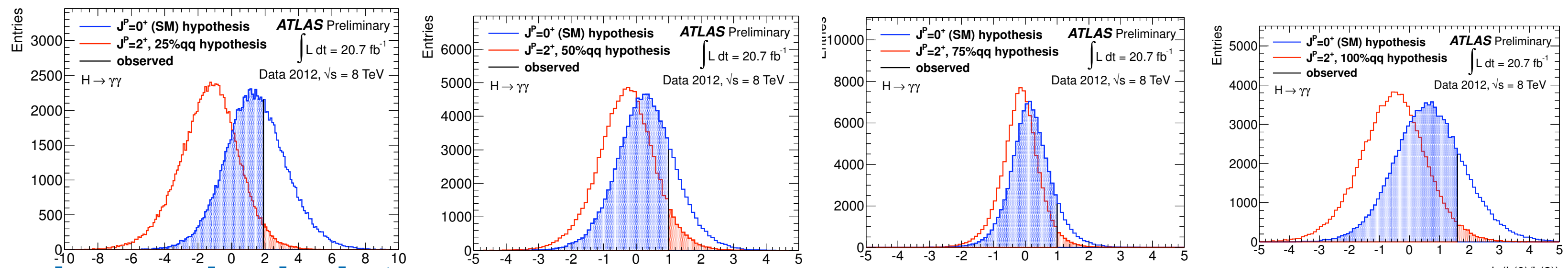
CMS WW/ZZ Combination: Exclude 2^+_m for pure ggH model at 2.84σ



Combined Spin Tests

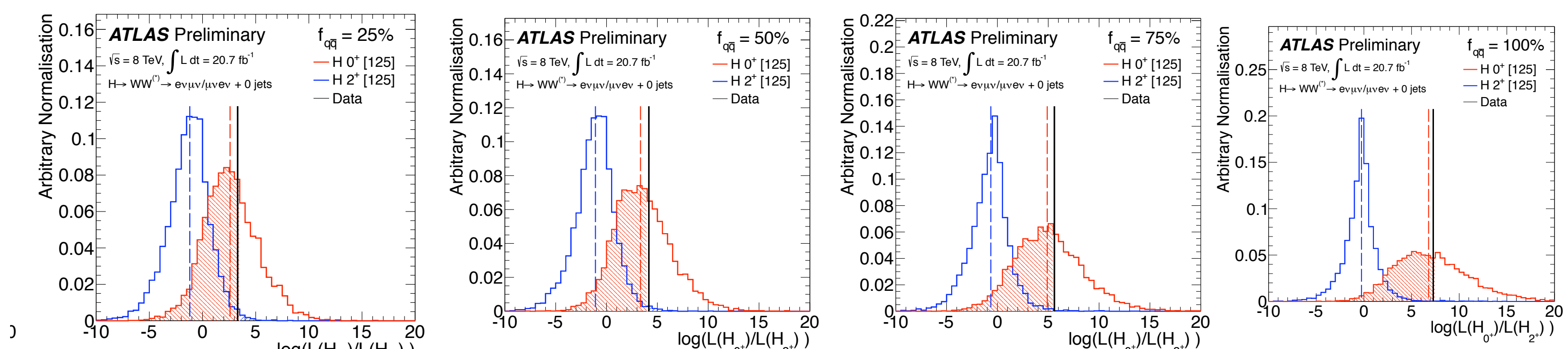
γγ CS frame: use angle between the photons in the collins-soper frame: Spin 0^+ the angular distribution is isotropic as opposed to spin 2

γγ sensitive at low qq'admixture



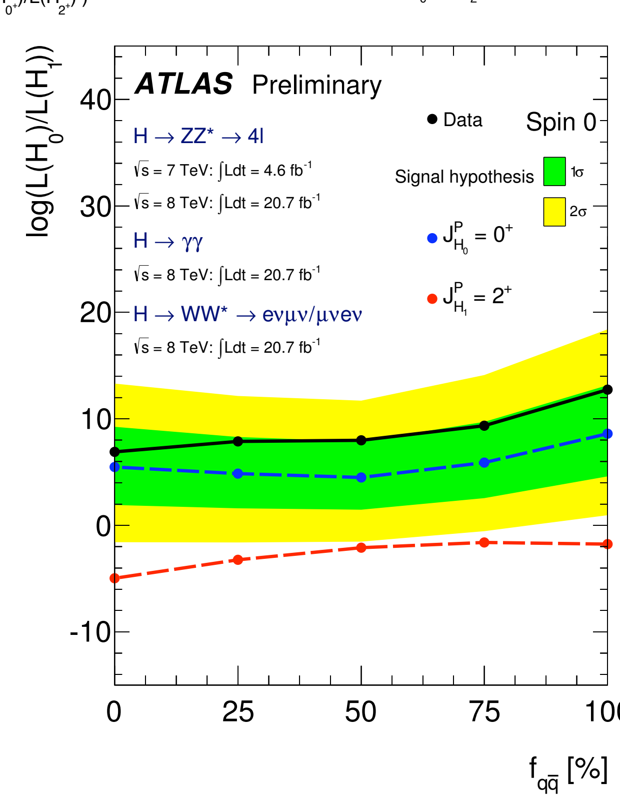
Increasing qq' admixture

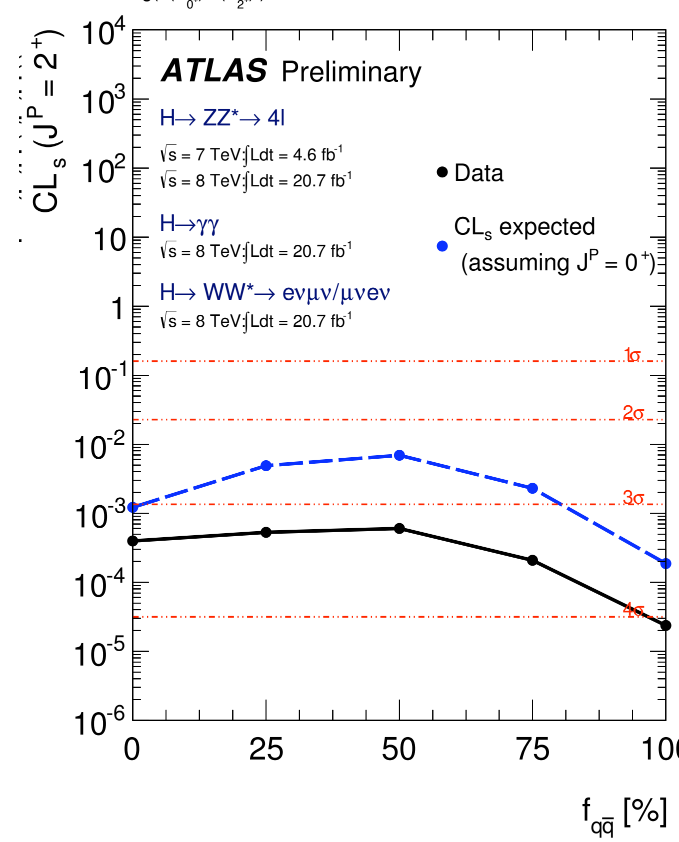
WW sensitive at high qq'admixture



ATLAS: WW, ZZ, γγ

- Expected exclusion of spin 2^+_m depends on fqq' very weakly
- Data is consistent with 0^+ and 2^+_m is excluded at 99.9 % confidence level

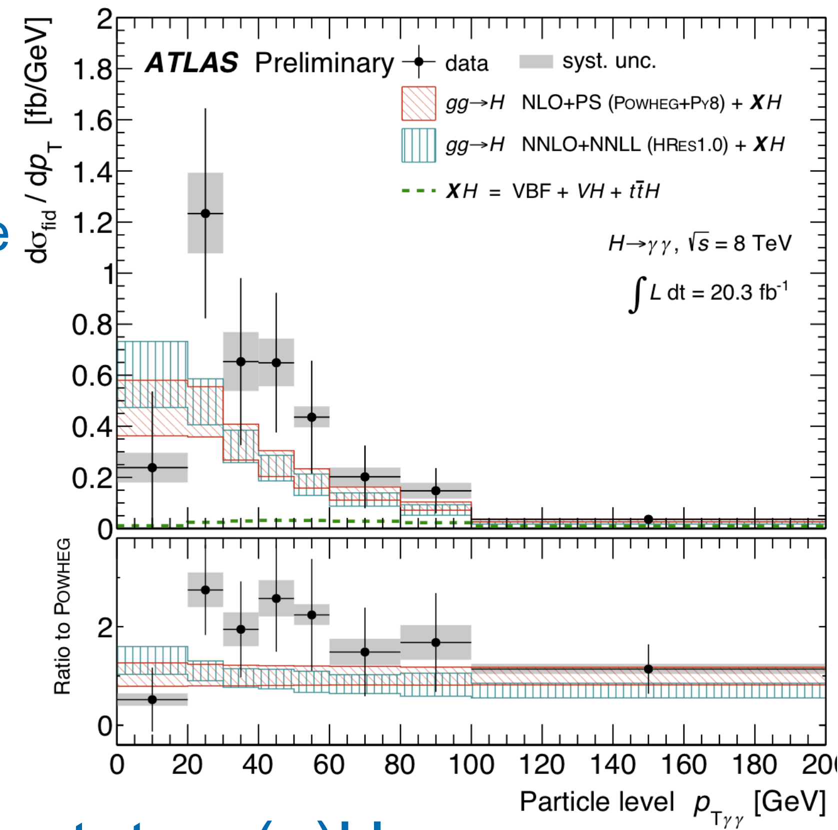


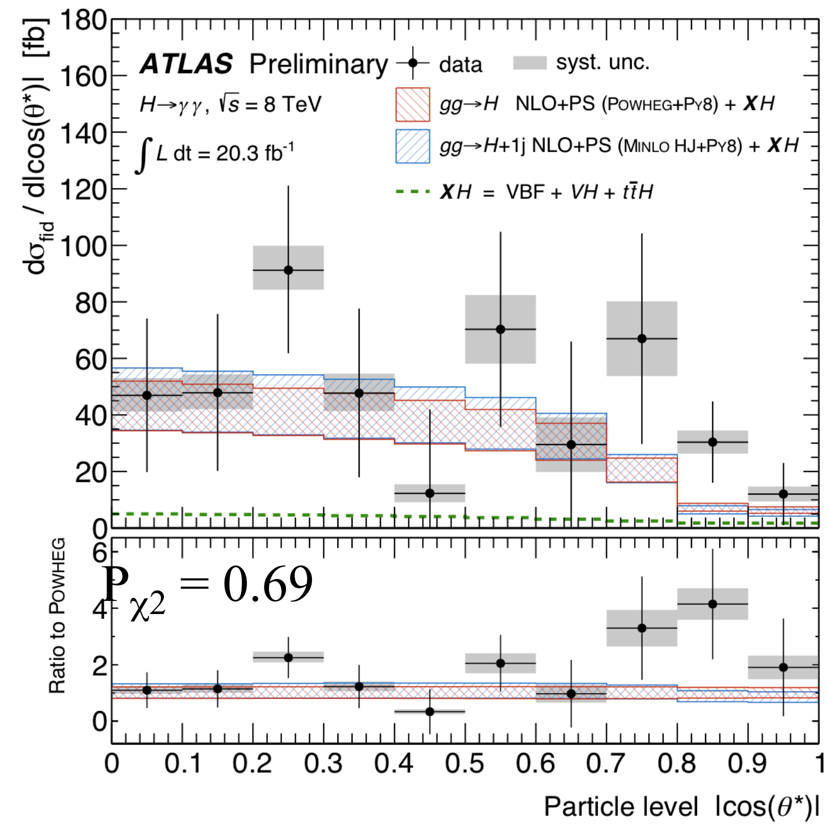


New Studies

Use high signal yield mode: H→γγ to probe kinematic properties of production/decay:

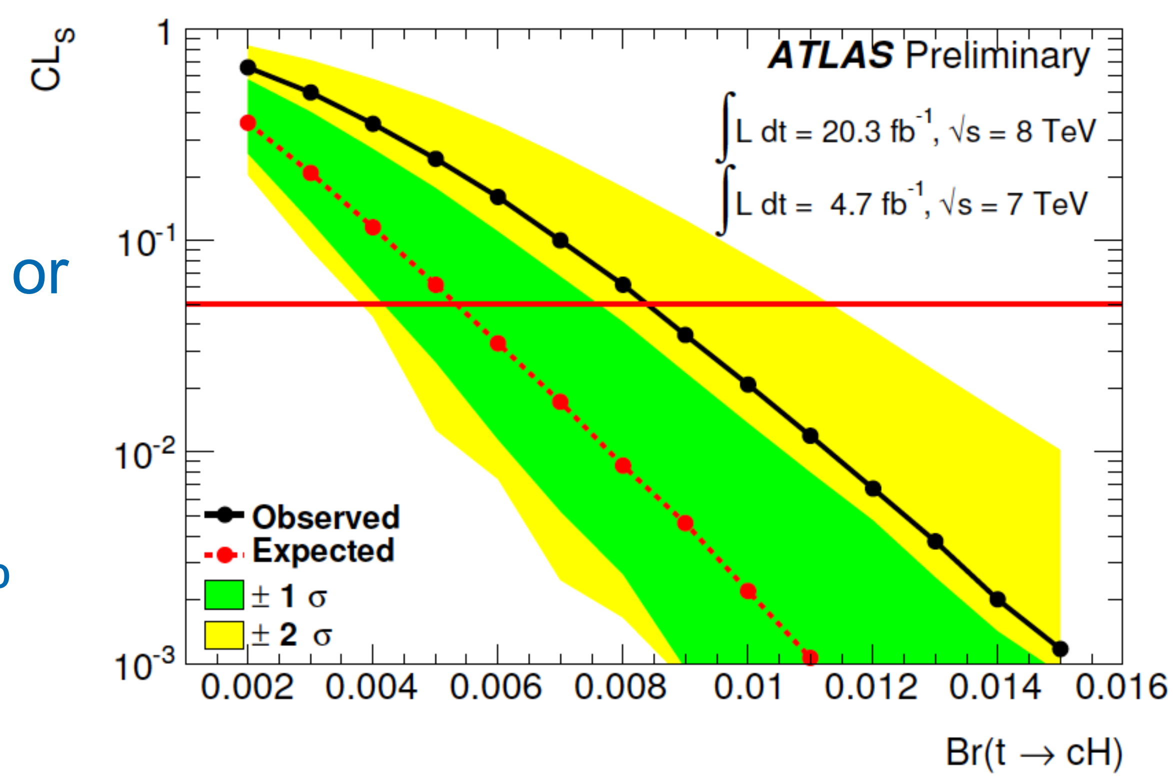
- Extract a signal yield for bins of a kinematic variable
  - correct yield for acceptance x efficiency, resolution etc. to compare to theory predictions
  - (Left) Compare data to simulation (NLO and NNLO for ggH) Chi2: NLO=0.55 and NNLO=0.39.
  - (Right) signal strength in bins of CS angle offers a potentially model independent spin measurement





Flavor changing neutral current: t→c(u)H

- Very good indicator of new physics
- Select tt events with one top in fully hadronic or 1lepton channel
- Use H→γγ search selection
- Br(t→c(u)H)<0.83% (0.53% expected) at 95% confidence



Conclusion

- How compatible is the new boson with the Standard Model?
- Measured properties all compatible with the SM Higgs:
  - Combined signal strengths across all decay modes and also for the different production modes are compatible with SM production
  - Couplings do not deviate from the SM predictions. Custodial symmetry is preserved
  - Data is consistent with 0^+ spin hypothesis
  - No strong sign of Γ_{BSM}
- Starting to probe differential signal strengths and directly search for new physics (Flavor Changing Neutral Current)
- All of the above measurements will be much more precise at 14TeV with more data and also smaller theoretical uncertainties
- REFERENCE: HIG-13-005, ATLAS-CONF-034,CMS Public Note 2013/002, ATLAS-2013-072, ATLAS-2013-081
- PUBLIC TWIKI: CMS https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

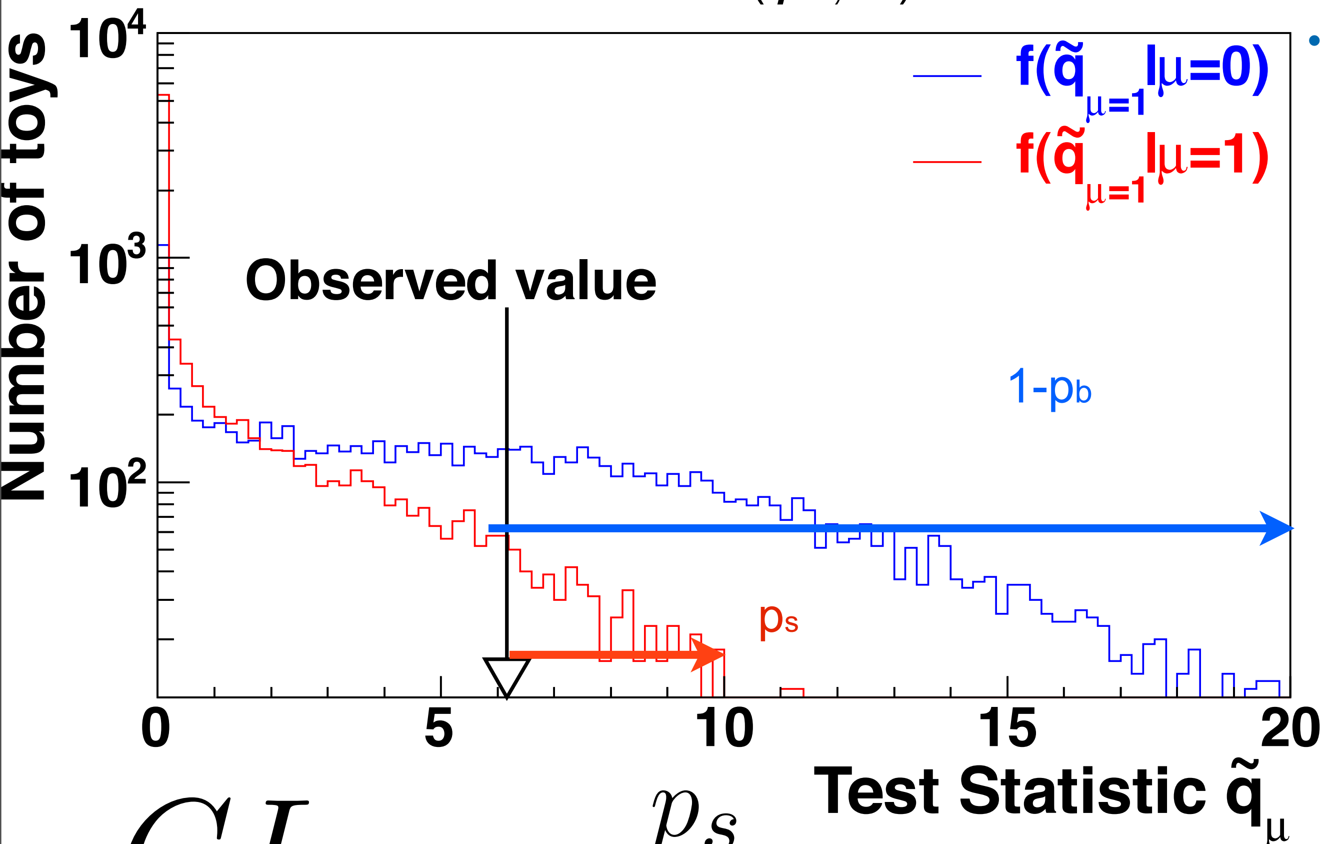
  ATLAS https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

Additional Material

Test Statistic

$$q_\mu = -2\log\frac{L(\mu,\theta_\mu)}{L(\hat{\mu},\hat{\theta})}$$

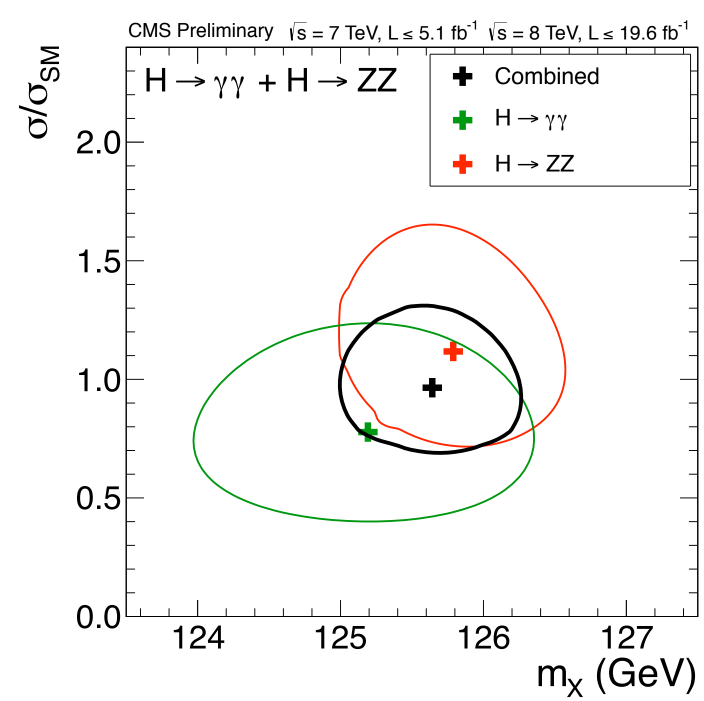
- hypothesis μ, θ_μ model of uncertainty
- Denominator maximized Likelihood



- Example of Signal + Background hypothesis testing:
  - Red psuedo-data (statistical toys) of signal +background (expected signal predicted by SM cross-section)
  - Blue psuedo-data (statistical toys) background only
  - Observed value is the value that minimizes the the above ratio in data (value of μ,θ most compatible with the data known as the best fit values)
  - Distribution of test statistics follows a χ^2 distribution: p-value obtained by integrating from the obs value to inf. Used to compute the confidence interval

$$CL_s = \frac{p_s}{1-p_b}$$

- CLs quantifies the significance of the observed value (consistent with a fluctuating background? Or an excess consistent with signal hypothesis
- Can include more than one hypothesis value (increase ndof in the chi2). Here there are two hypotheses variables included in the likelihood: mass, σ_{obs}/σ_{SM} (signal strength based on SM cross-section)
- CLs corresponding to 68% is the contour around the best fit values (cross)

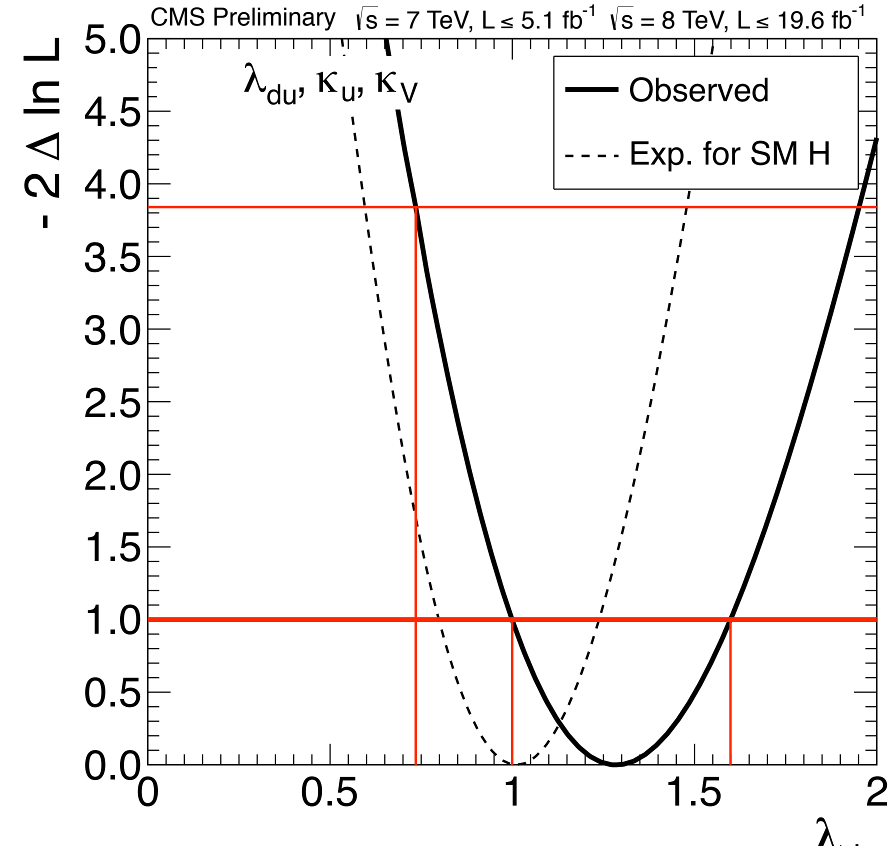


14TEV PROJECTIONS

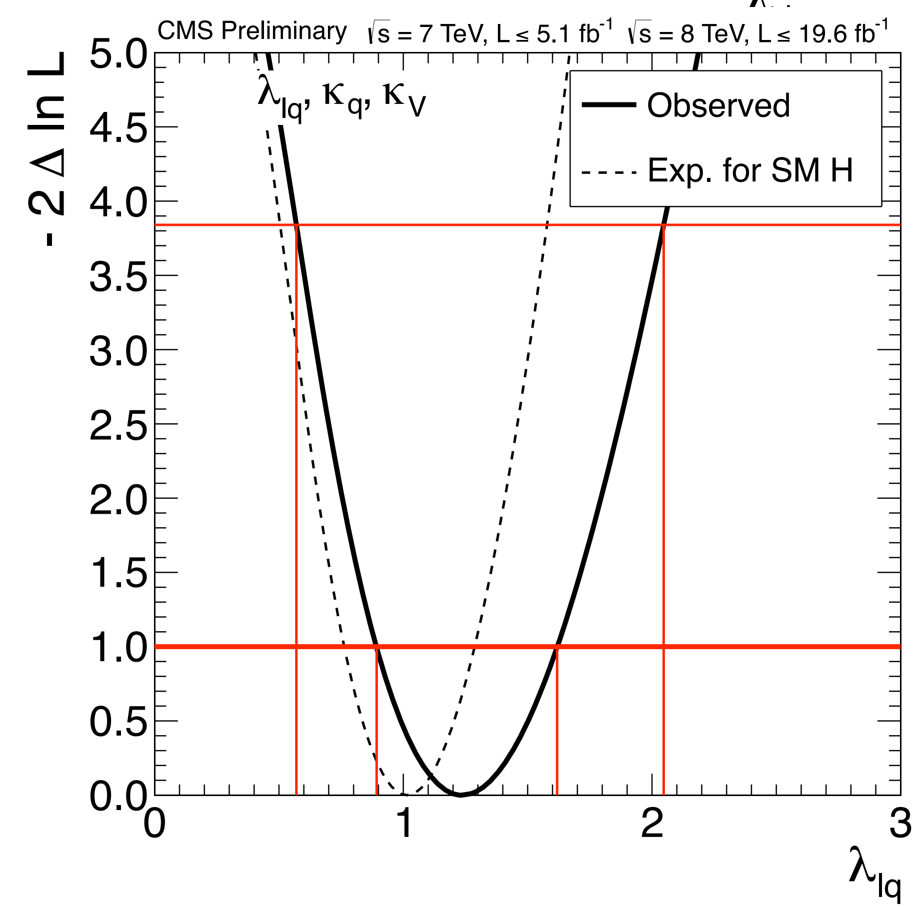
- Based on SNOWMASS studies:
  - Extrapolate from current dataset to 300/fb (3000/fb) at 14TeV with the present level of detector performance
  - 2 Scenarios for projected uncertainties:
    - SCENARIO 1: all systematic uncertainties are left unchanged
    - SCENARIO 2: Theoretical uncertainties scale by 1/2 and other systematic uncertainties scale by 1/sqrt(Luminosity) (more optimistic scenario)

Higgs Doublets

- In two Higgs Doublet models the yukawa couplings of fermions to neutral Higgs can be substantially modified
  - MSSM check u,d coupling ratio

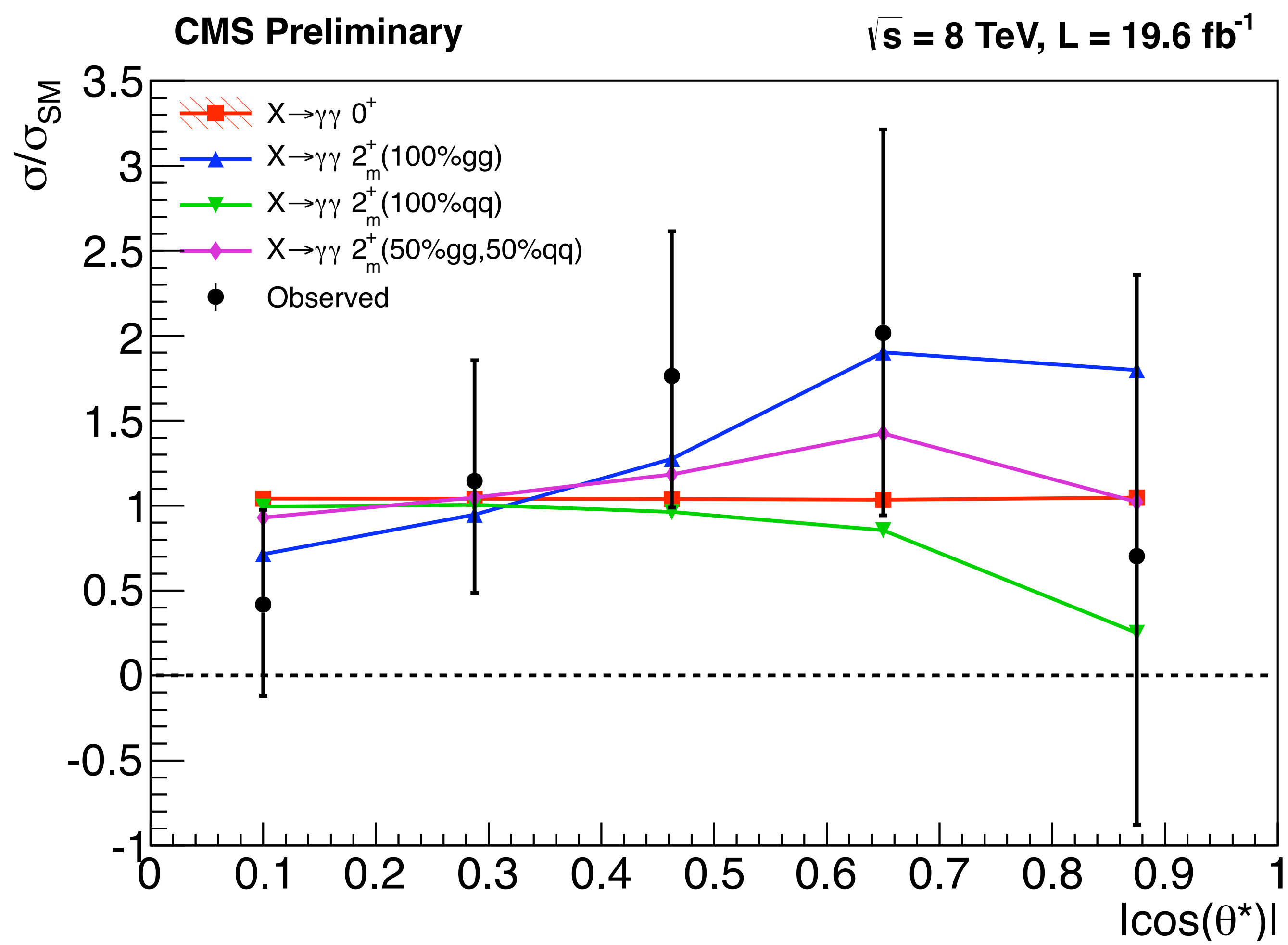


- Also in more general scenarios leptons can virtually decouple from the Higgs so test lepton/quark coupling ratio



- one is within the 68% CL for both

SPIN in CS Frame



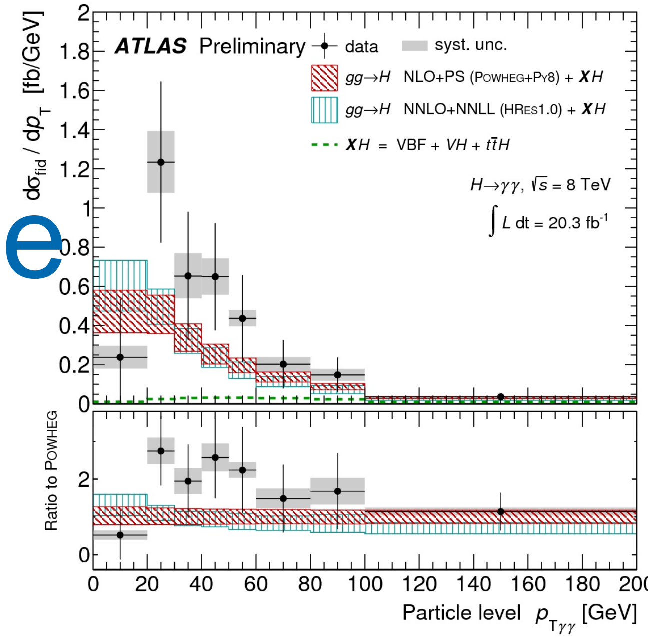
Differential Mu

Agreement at low statistics is fair:

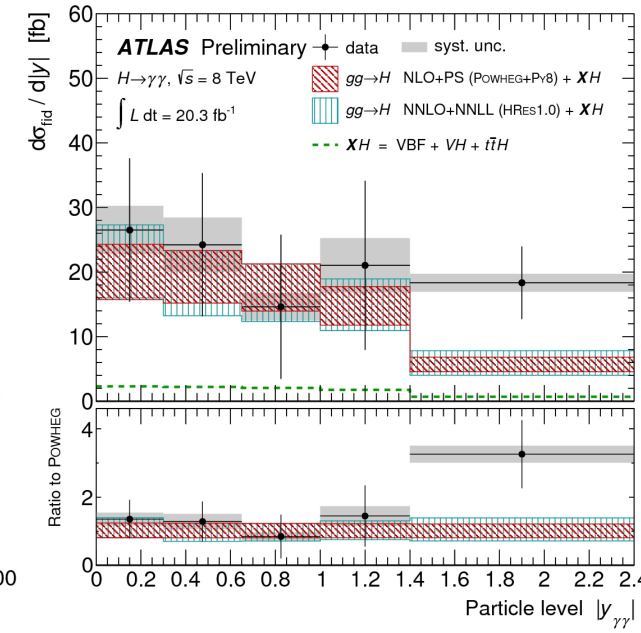
χ^2/ndof	p-value
6.9/8	0.55
5.3/5	0.38
7.9/10	0.64

χ^2/ndof	p-value
4.6/4	0.33
4.6/4	0.33

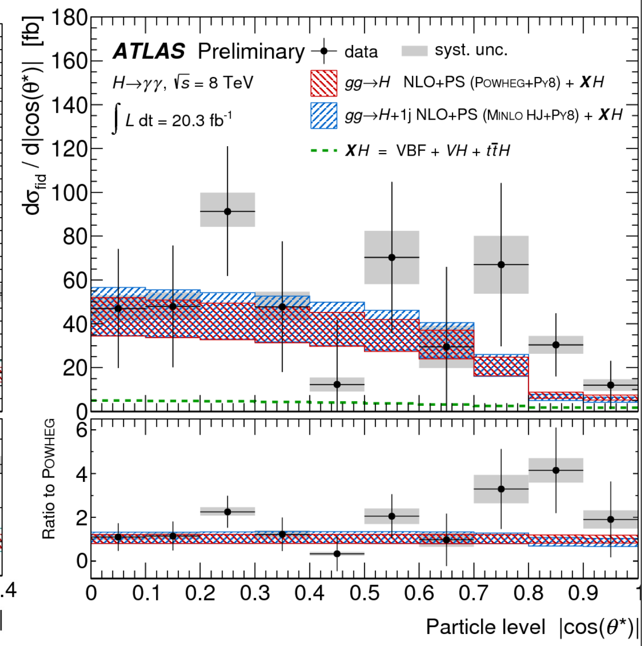
$P_{T\gamma\gamma}$



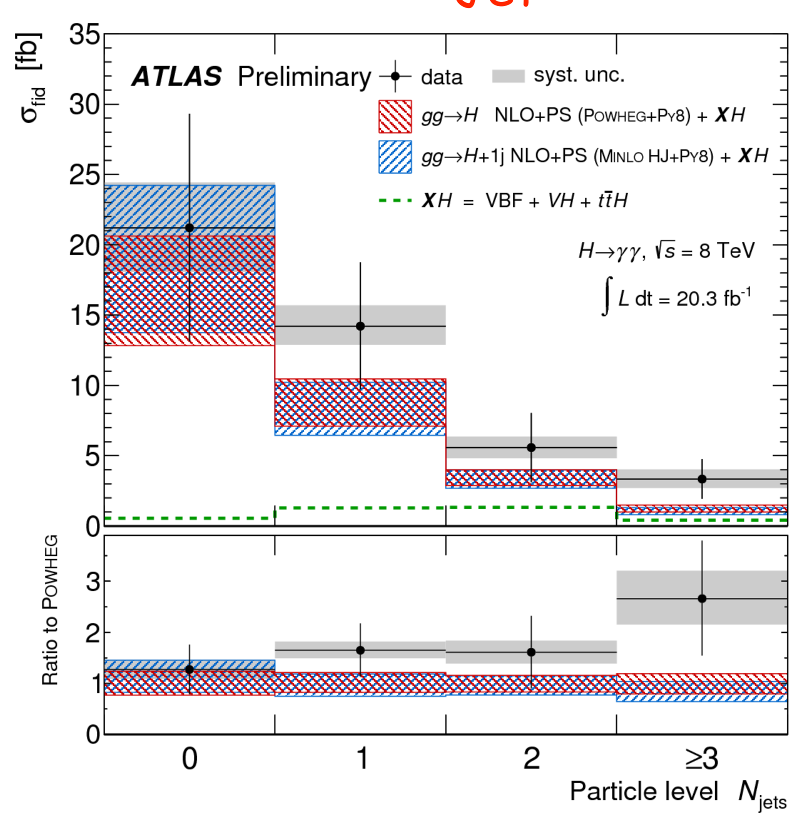
$\eta_{\gamma\gamma}$



cos θ*



N_{Jet}



$\Delta\phi_{JJ}$