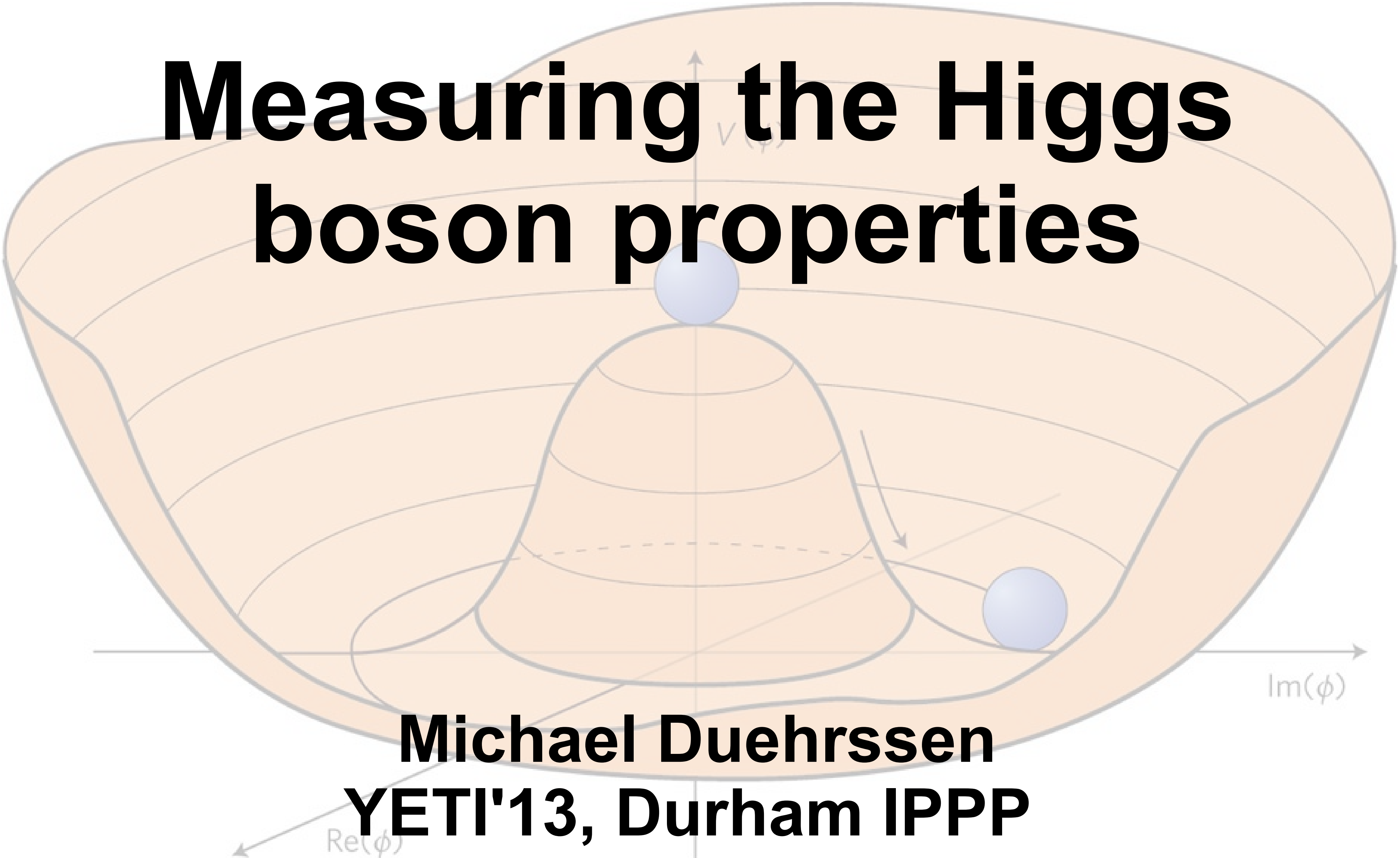
Measuring the Higgs boson properties



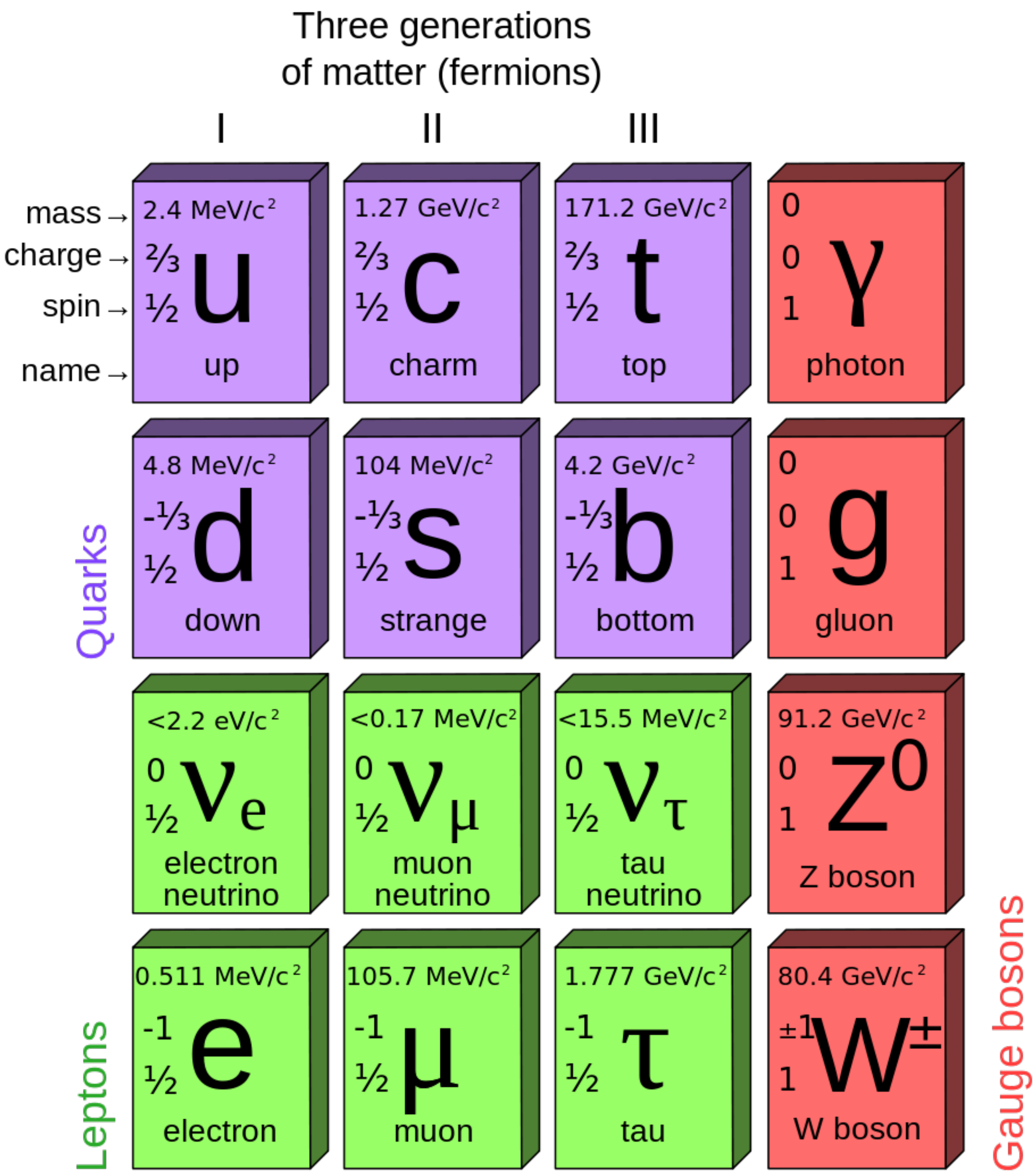
Michael Duehrssen

YETI'13, Durham IPPP

6-9 January 2013

Please interrupt whenever you have questions

The SM and the Higgs



And the odd one:

- **Higgs boson**

- **Mass ~125 GeV**
- **Charge 0, SU(2) doublet**
- **Spin 0**
- **Non-universal couplings → supposed to give mass to SM particles**
- **Has external potential!**

The SM and the Higgs

The SM Higgs boson is not just some new particle. Its a

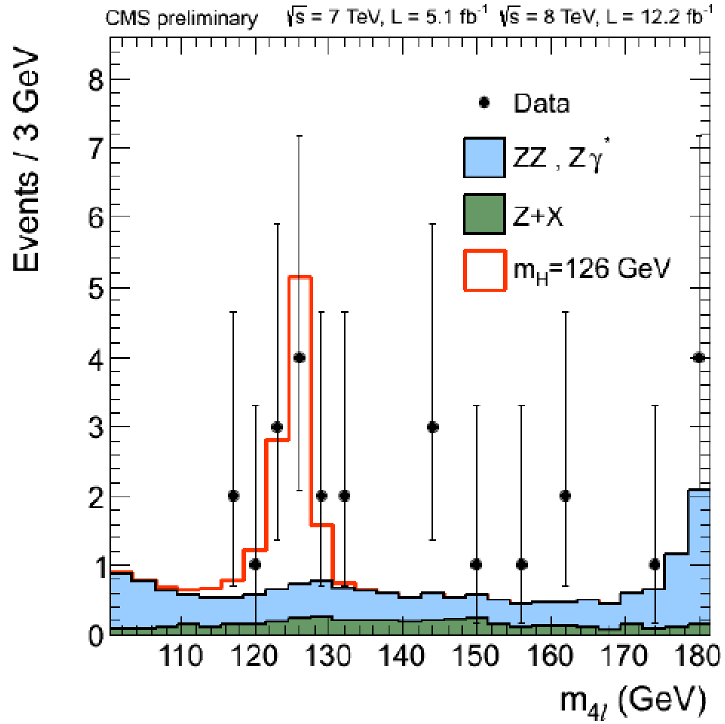
- Fundamental scalar field
- With an external potential and non-zero vev=vacuum expectation value
- SU(2) gauge interactions that generate the W and Z mass
- Yukawa interactions that generate fermion masses

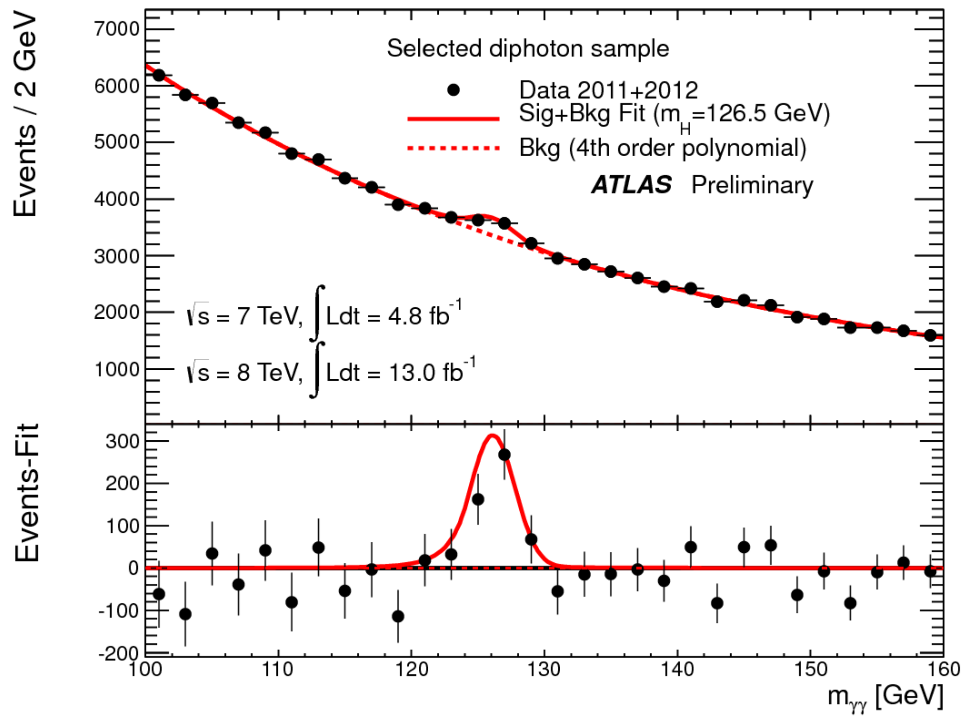
All this needs experimental tests

- How many new particles and what is there mass+width?
- Is the coupling strength compatible with the predicted SU(2) gauge and Yukawa interactions?
- Are the angular correlations of initial+final state particles compatible with a scalar particle (spin 0, CP even)?
- Is the multiple Higgs production rate compatible with the “mexican hat” external potential

Mass

- **The two sensitive channels are H→γγ and H→ZZ→4l**





- **On the theory side:**

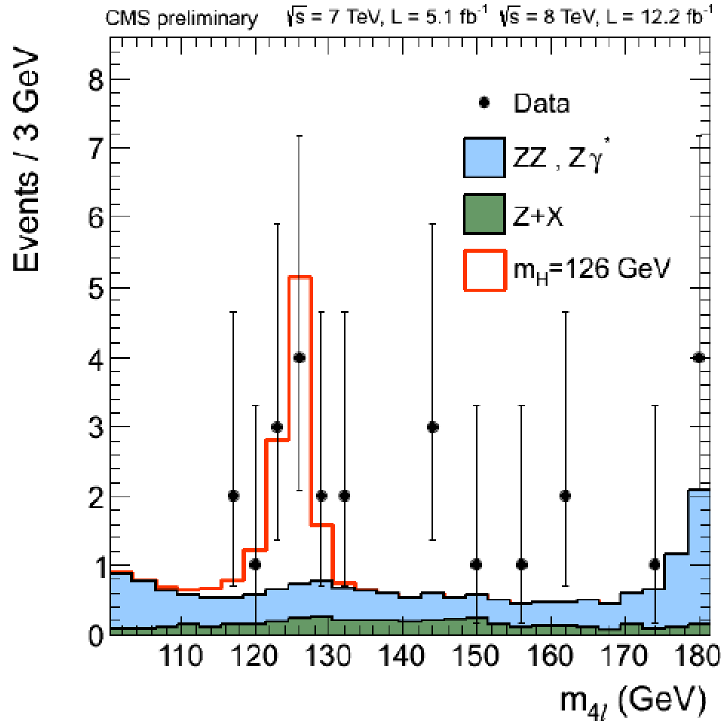
$$\mathcal{L}_H = \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - V$$
$$= \frac{1}{2}(\partial^\mu H)^2 - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

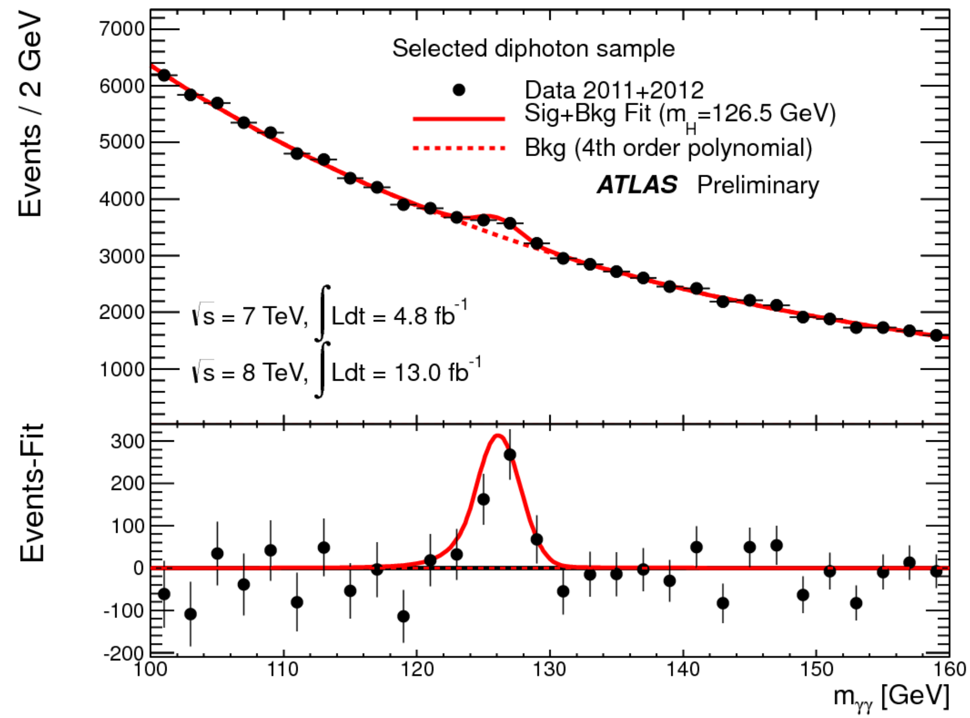
$$\longrightarrow M_H^2 = 2\lambda v^2 = -2\mu^2$$

- **υ is given by W mass measurements: m_H measures λ**

Mass and Width

- The two sensitive channels are H→γγ and H→ZZ→4l

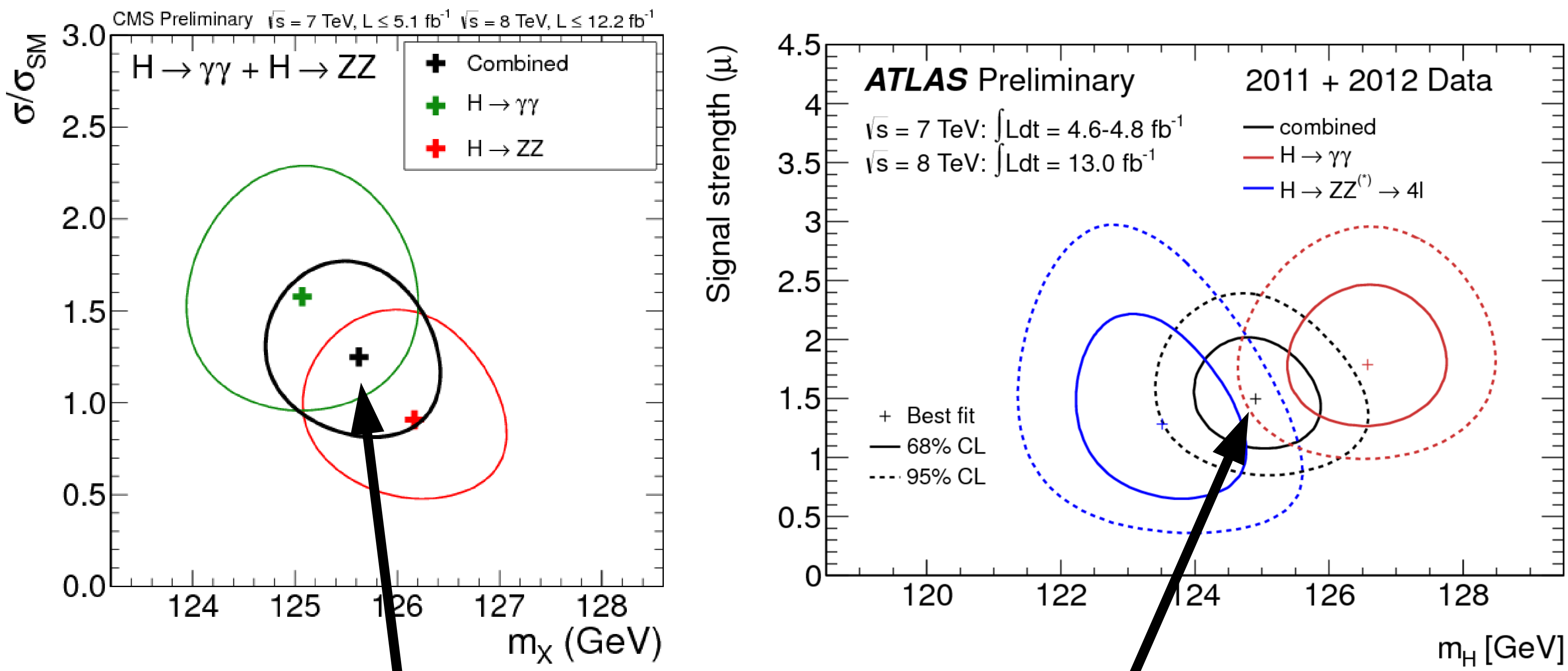




- Both channels have in principle also sensitivity to the width. However, the width of the SM Higgs is only ~ 4 MeV, while the experimental resolution is ~1 GeV!
- No public results on the width yet, but all peaks in ATLAS and CMS look "narrow". An upper limit of ~1 GeV can be expected sometime in the future

Mass measurement

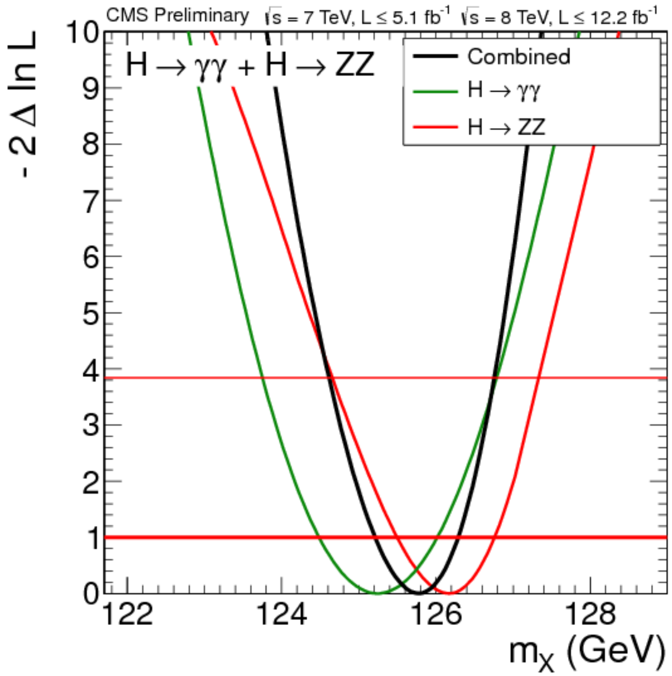
- **We want to measure the mass of the particle itself, but assuming as little as possible about other SM Higgs properties: coupling strength and structure**
  → Likelihood as function of the mass hypothesis
  → Keep the signal strength μ as a free parameter!



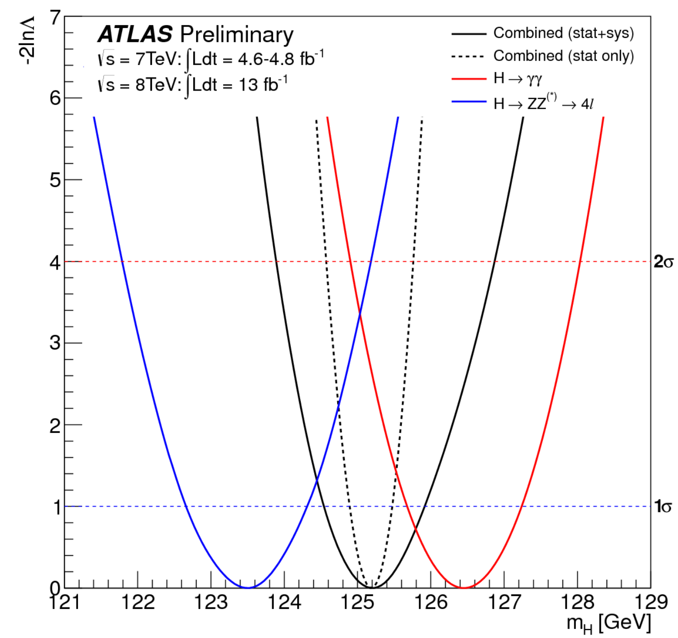
But careful: this is not the best estimate of the mass, because μ(γγ)=μ(4l)!

Mass measurement

- **We want to measure the mass of the particle itself, but assuming as little as possible about other SM Higgs properties: coupling strength and structure**
  → Keep the signal strength μ as a free parameter!



$$m_X = 125.8 \pm 0.4\ (\text{stat}) \pm 0.4\ (\text{syst})\ \text{GeV}$$



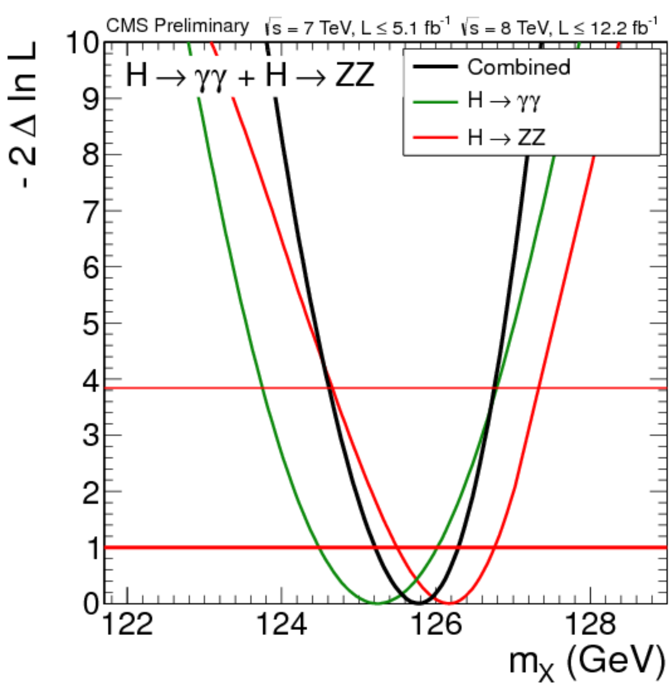
$$125.2 \pm 0.3\,(\text{stat}) \pm 0.6\,(\text{sys})\ \text{GeV}$$

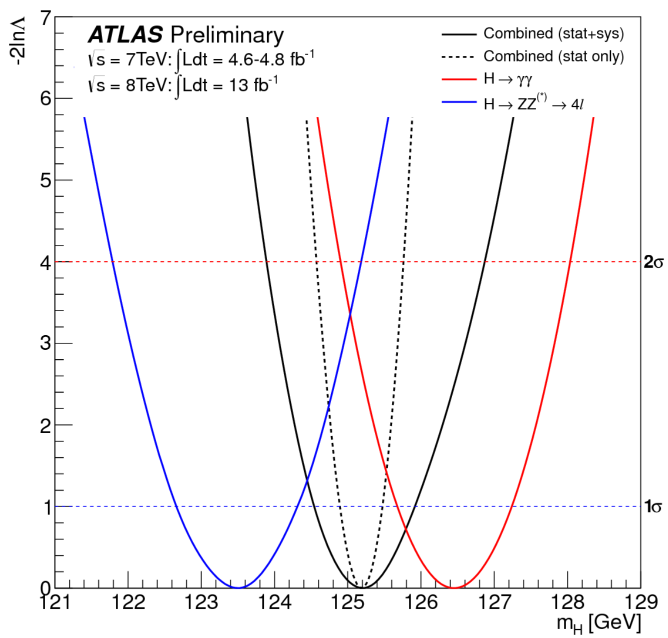
- **These plots have "hidden" dimensions, where the signal strengths μ(γγ) and μ(4l) are treated independently**
  (for CMS also μ for gg→H and VBF in H→γγ is separated)

Mass consistency

- The CMS mass measurements of H→γγ and H→ZZ are within ~1 sigma of each other. m(γγ)<m(ZZ)

- The ATLAS mass measurements of H→γγ and H→ZZ are ~3 GeV different, corresponding to ~2.7σ. m(γγ)>m(ZZ)

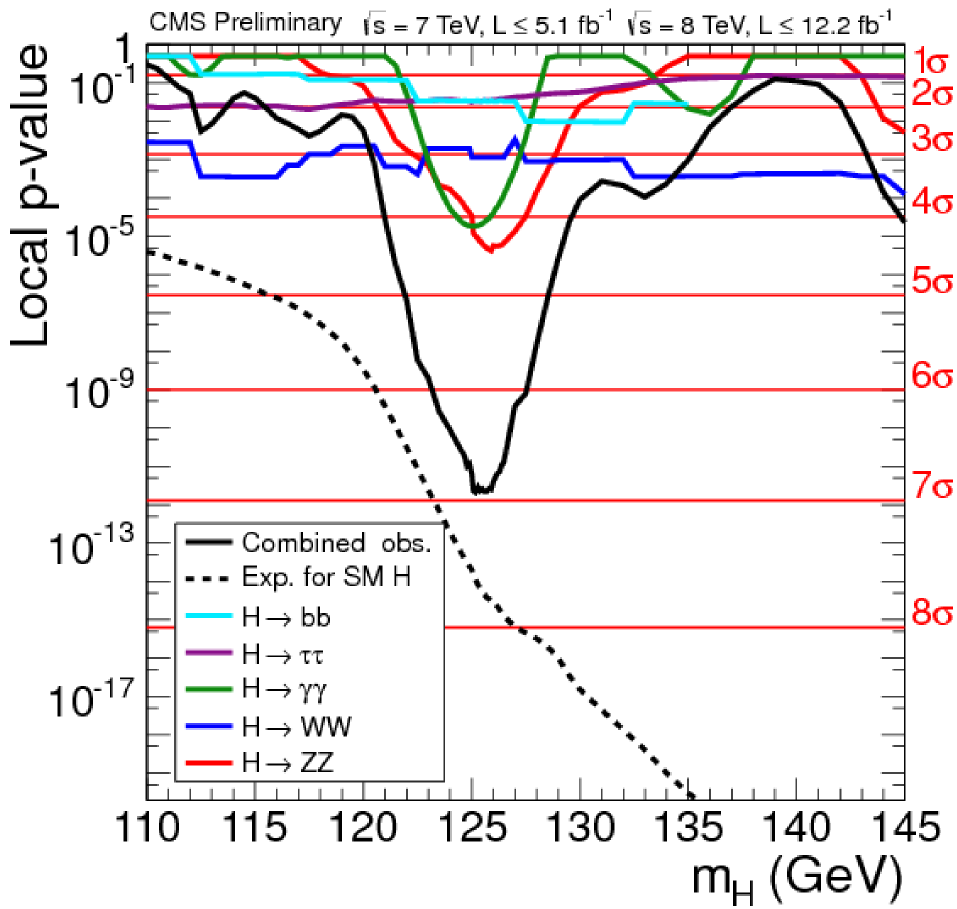




$$\Delta\hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4\ell} = 3.0 \pm 0.8\,(\text{stat})\,^{+0.7}_{-0.6}\,(\text{sys})\ \text{GeV}$$

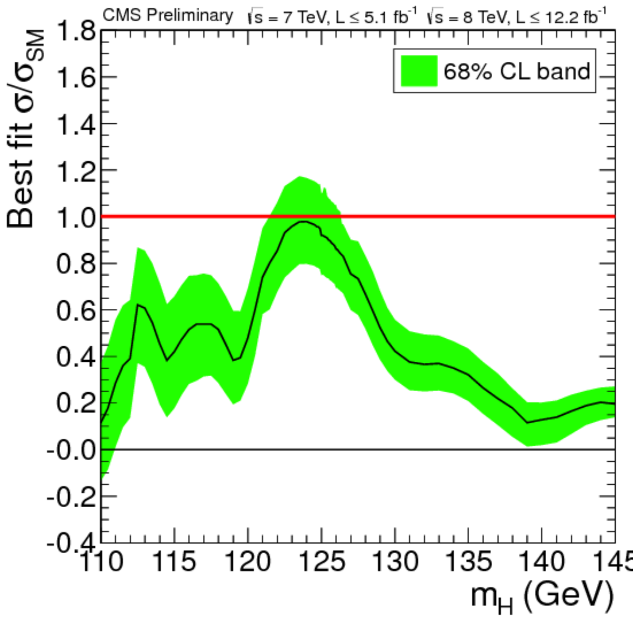
Excursion – illustration of what to ask

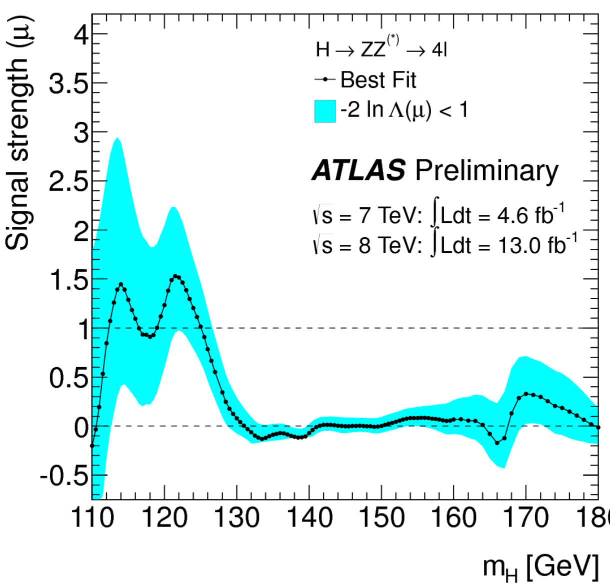
- For each property we measure we need to ask the right question to make sure that our question doesn't bias the answer we get
- Example: mass
- The p-value answers the question: how likely is it to explain the observed excess with a background fluctuation?
- This question is asked independently for different fixed mass hypothesis
- Expect to see a minimum p-value close to the mass
- BUT: background uncertainties that vary strongly as function of the mass can bias the mass point of the least likely fluctuation

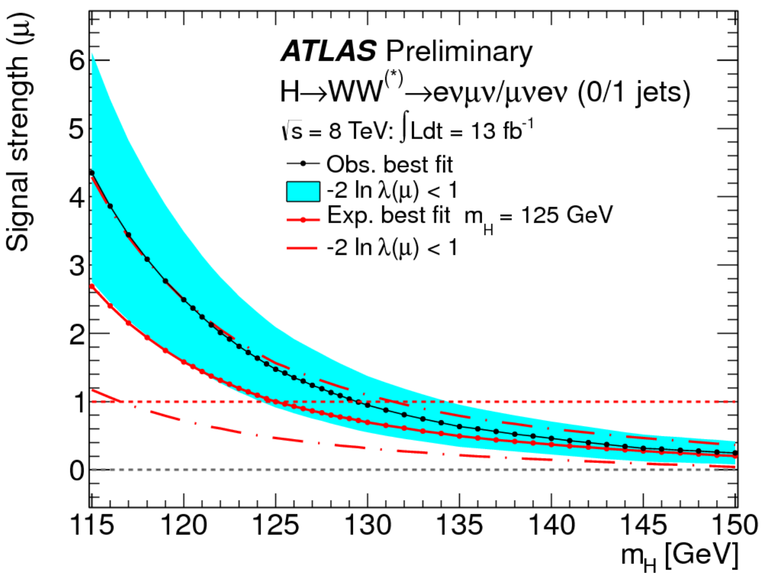


Excursion – illustration of what to ask

- For each property we measure we need to ask the right question to make sure that our question doesn't bias the answer we get
- Example: mass
- The strength μ answers the question: what is the most likely signal strength to explain the observed excess?
- This question is asked independently for different fixed mass hypothesis
- Expect to see a maximum μ close to the mass
- BUT: signal cross sections and BR that vary strongly as function of the mass can bias the mass point of the maximum μ





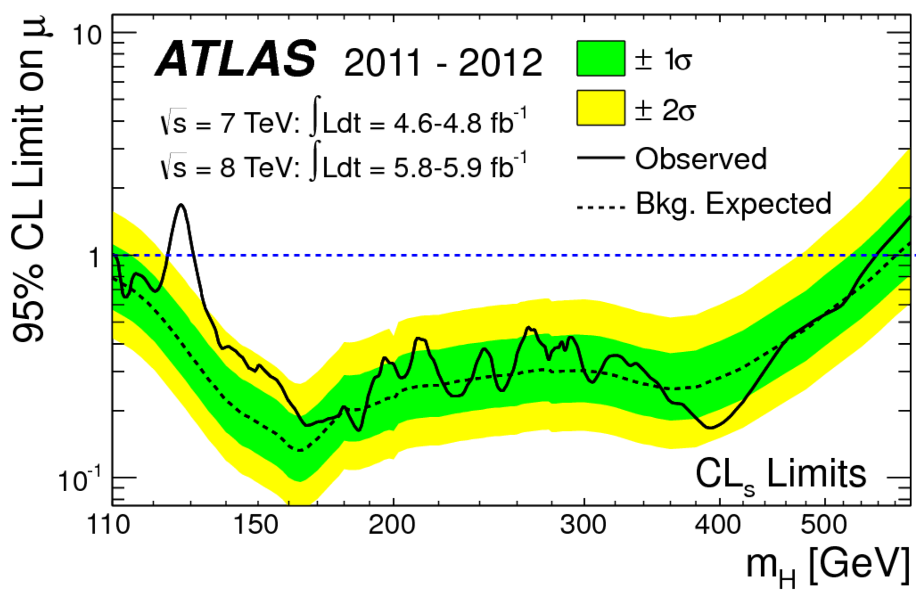


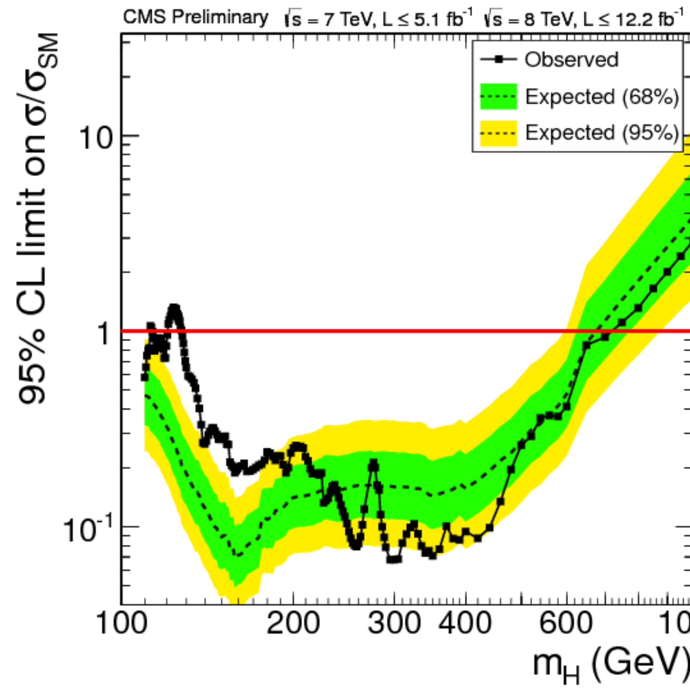
Number of Higgs bosons

- **The SM contains exactly one complex scalar doublet Φ :**

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 - i\phi_2 \\ \phi_3 - i\phi_4 \end{pmatrix} \qquad \mathcal{L}_S = (D^\mu \Phi)^\dagger (D_\mu \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

- **So far only one peak observed with m_H~125 GeV**
- **No other SM Higgs-like signal observed for any other mass**





- **However: NOT CONCLUSIVE**
  Additional Higgs bosons may not appear in the SM Higgs searches at all or might have a weaker signal

Properties of the SM Higgs boson

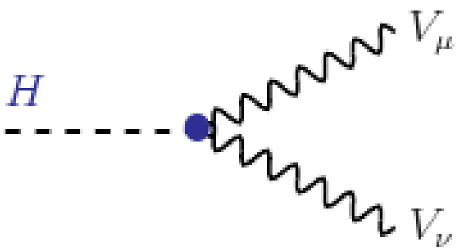
- The mass is ~125 GeV
- That's it. There is no other free parameter left in the SM !
  → see Alexander's lecture

- If the coupling strength to W and/or Z is modified:
  - W and Z mass come out wrong
  - VV→VV scattering is not unitary
  - Same argument for Higgs self-coupling
- If the coupling strength to fermions is modified:
  - All fermion masses come out wrong
  - WW→ff scattering is not unitary
- If its either spin!=0 or CP odd, for sure not the SM Higgs
- The SM is really a nice consistent model...

Measuring the Higgs properties

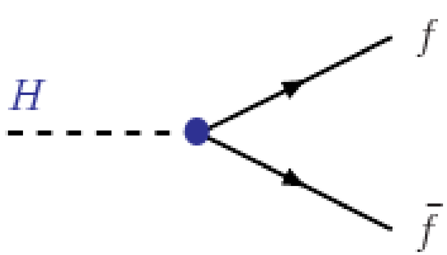
- **Of course, we also want to measure all Higgs properties**

- **Coupling strength to W and Z:**



$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2}\, M_V^2 \quad \times (-ig_{\mu\nu})$$

- **Coupling strength to fermions:**

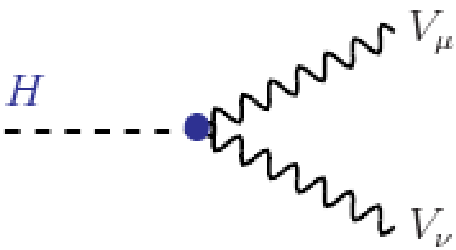


$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2}\, m_f \quad \times (i)$$

Measuring the Higgs properties

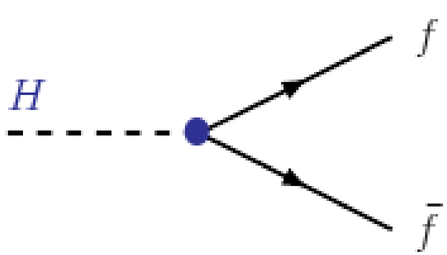
- **Of course, we also want to measure all Higgs properties**

- **Coupling structure to W and Z:**



$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2}\, M_V^2 \quad \times(-ig_{\mu\nu})$$

- **Coupling structure to fermions:**

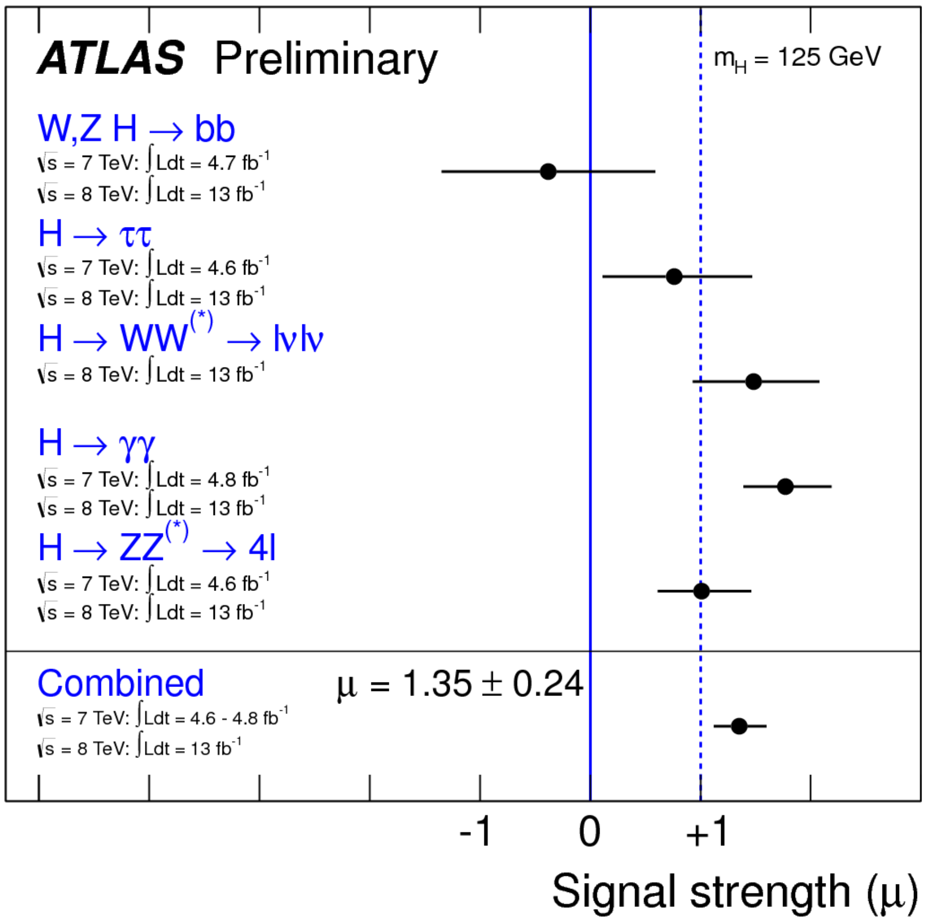


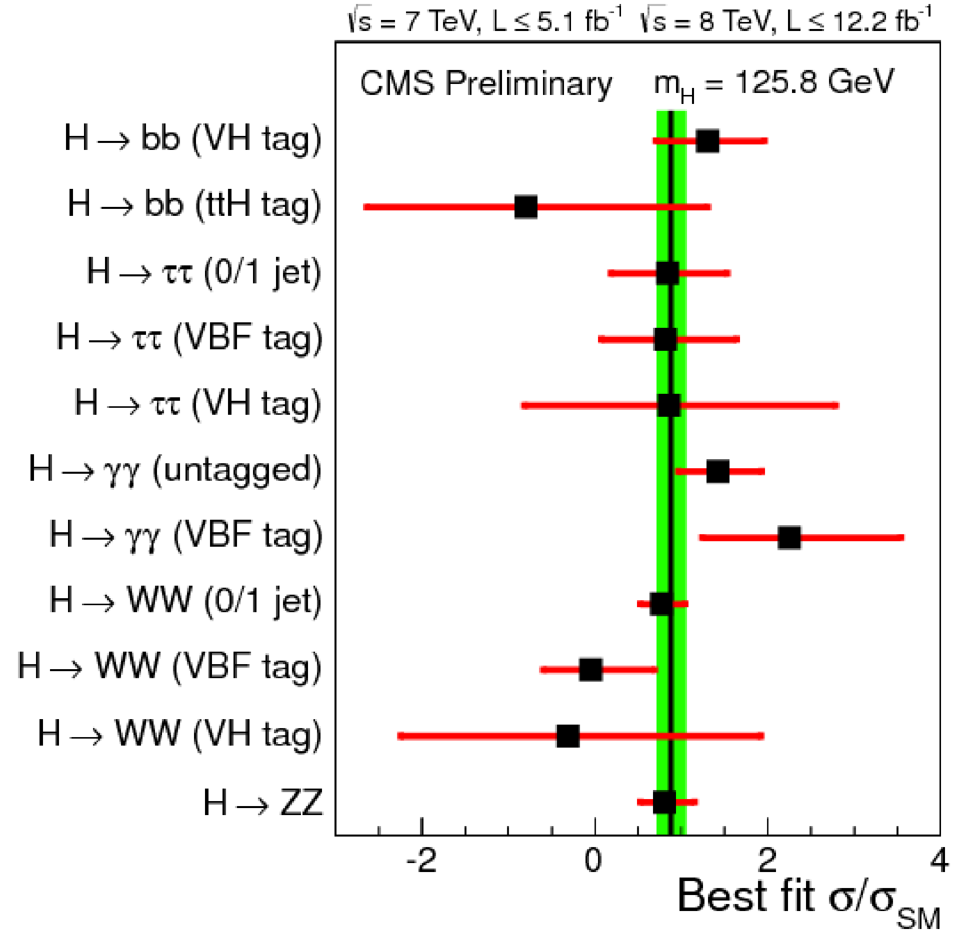
$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2}\, m_f \quad \times(i)$$

→ tomorrows lecture

Measuring the coupling strength

- **What is the input for the coupling strength measurements?**





- **Results expressed as $\mu=\sigma*BR/(\sigma*BR(SM))$**
- **But what if its not the SM Higgs?**

Measuring the coupling strength

- At first glance normalizing to the SM with
  $\mu=\sigma*BR/(\sigma*BR(SM))$
  looks just like a convenience
- However, the SM is somehow contained in all analysis at a deeper level. All acceptance estimates are done with SM Higgs MC !
  - We assume there is only one particle with a narrow resonance
    → if its not narrow, can't factorize production and decay
  - If angular correlations change, the acceptance changes
    → Spin 0, CP even is assumed in many places
  - If pT distributions change, the acceptance changes
    → this mostly assumes that inclusive production = $gg\to H$
  - Especially EW NLO calculation require the SM coupling strength. Otherwise they are just not defined
  - At LHC we almost always observe a mixture of different production modes. If their relative contribution is not SM-like, the acceptance changes
    (but this can be mostly taken into account in coupling fits)

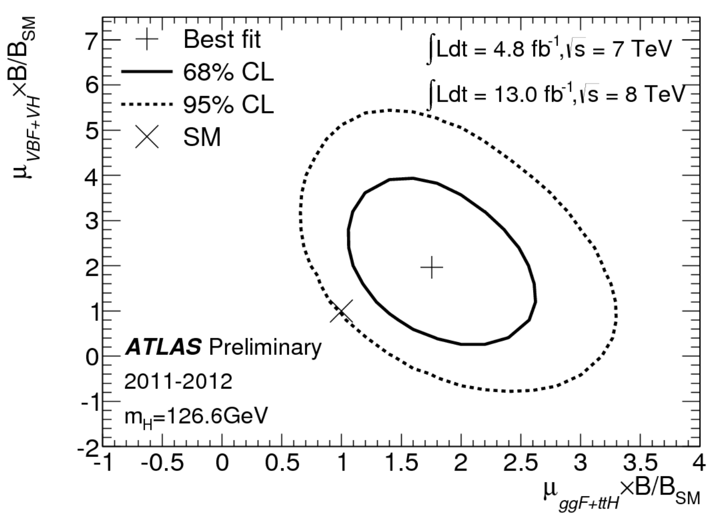
Measuring the coupling strength

- Solution: get rid of the SM predictions and base all calculations on a consistent BSM Lagrangian that allows all possible coupling modifications
- Easily said, very hard to do...
- Attempts are running. If you are interested join the LHC Higgs XS WG on the light mass Higgs (LHCHXSLM)!
- This is a project that will take several years... for both theory and experiments

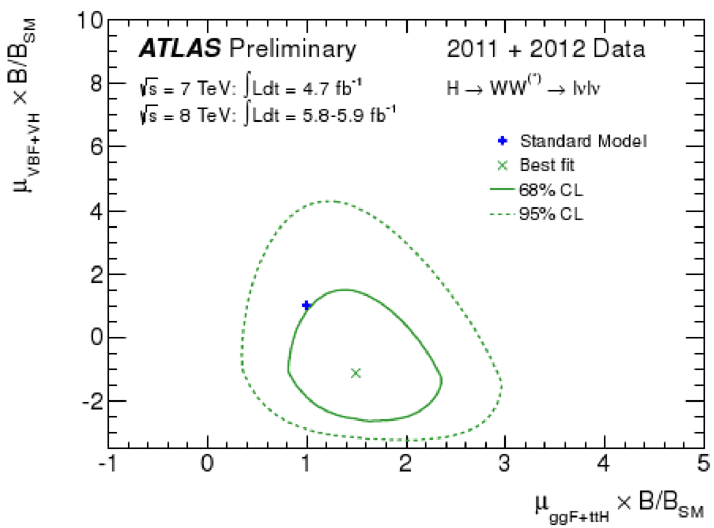
- The problem was long discussed in the LHCHXSLM group last year
- LO motivated interim recommendations proposed to get experiments going: http://arxiv.org/abs/1209.0040
- As the experimental errors are still large, this is currently not a big restrictions

Measuring the coupling strength

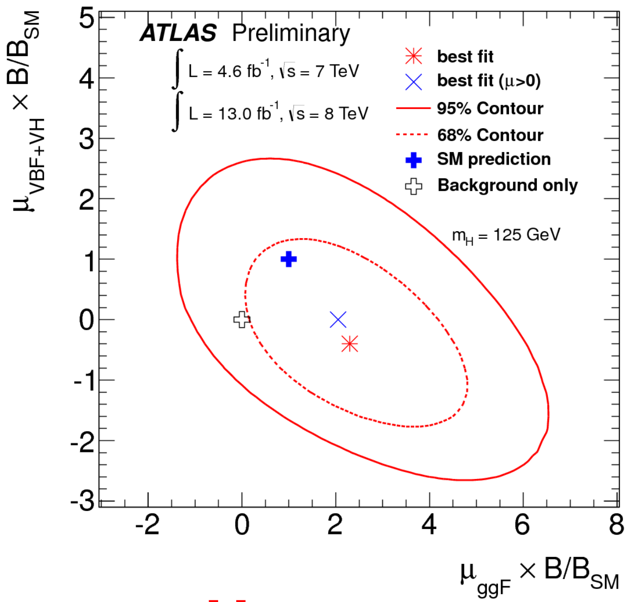
- Challenge: separating different production modes !
- Currently the main issue is to separate gg→H and VBF
  → only jets and theory predictions separate these!
  → gg→H contamination of VBF selections ~20-30% but large uncertainty of >50% on gg→H+2j
  → Alexander's talk



H→γγ



H→WW



H→ττ

Coupling strength measurements

- Search for deviations from the SM in the Higgs coupling sector. This allows to use the best available SM calculations as reference. But not a measurement in the strict sense!
- Can also use all SM theory uncertainties! → Alexander's talk
- Assumptions:
  - Only one resonance at ~125 GeV
  - Narrow width approximation is valid:

$$\sigma \times BR(ii \rightarrow \mathrm{H} \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}} \propto \frac{\Gamma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

  - Spin 0, CP even: only the coupling strength is measured

- As long as all results are consistent with the SM, this approach is valid
- If any deviation appears, it means that the underlying reference calculation might not be valid any more
  → will need measurements based on calculations with a consistent BSM Lagrangian to make any further statements

Coupling parameter framework

- **Scale the SM production cross sections and partial decay widths with LO motivated scale factors κ_i**

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases} \quad (5)$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H) \quad (6)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2 \quad (7)$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2 \quad (8)$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2 \quad (9)$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2 \quad (10)$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2 \quad (11)$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2 \quad (12)$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2 \quad (13)$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases} \quad (14)$$

Total width

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases} \quad (21)$$

- **Example:** $(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$

Treatment of total width

- The total width is not directly observable at the LHC with an expectation of $\Gamma_H \sim 4$ MeV. Nothing indicates that the width could be >>100 times → not expected to be observable

- Imagine:

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

  - Some new physics causes all cross sections and partial decay width to take 2* the SM value
    $\sigma_{ii} \to 2^*\sigma_{ii}$; $\Gamma_{ff} \to 2^*\Gamma_{ff}$; $\Gamma_H \to 2^*\Gamma_H$
  - All observable σ*BR would go to 2* the SM value
  - But in addition the new physics is causing some unkown Higgs decay mode (e.g. to many light jets) which takes 50% of the BR. This is very likely never observable at the LHC
  - All observable σ*BR take exactly the SM value, although the theory would be extremely different
- The LHC is blind to some combination of increased coupling and new unobservable decay modes

Treatment of total width

- The total width is not directly observable at the LHC with an expectation of $\Gamma_H \sim 4$ MeV. Nothing indicates that the width could be >>100 times → not expected to be observable

- Three options (a 4th option is ignored for now):
  - No assumption: treat total width as effective parameter. However, this <u>always</u> results in one unconstrained degree of freedom at the LHC
    → absorb the ratio of two independent degrees of freedom (containing κ_H) into one effective ratio parameter

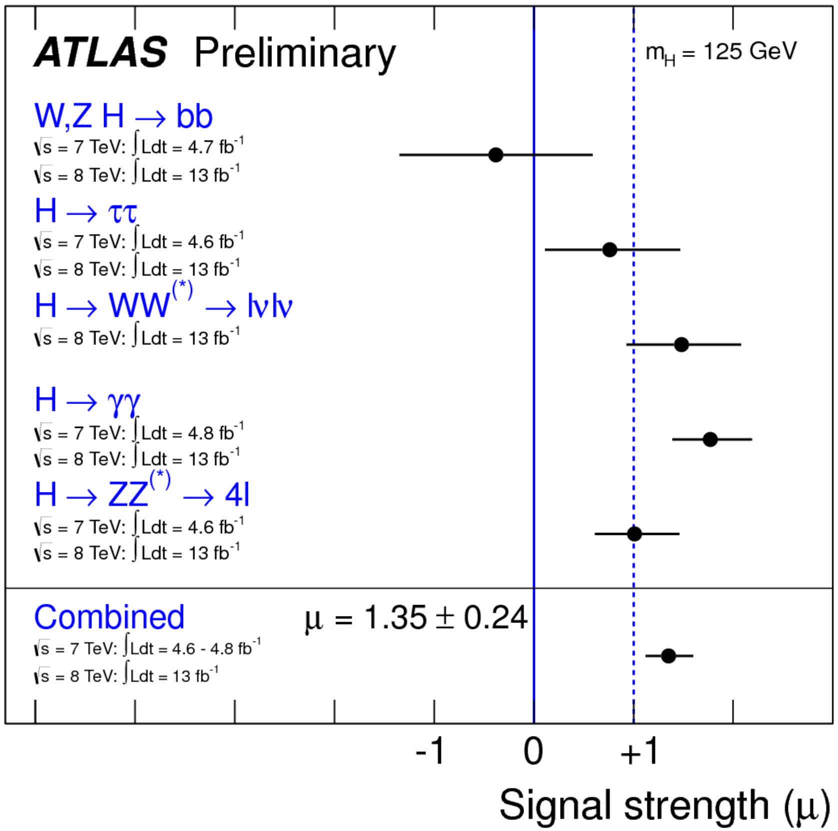
  - Assume no BSM Higgs decay modes contributing to the total width: BR(H→new,inv.,undet.)=0

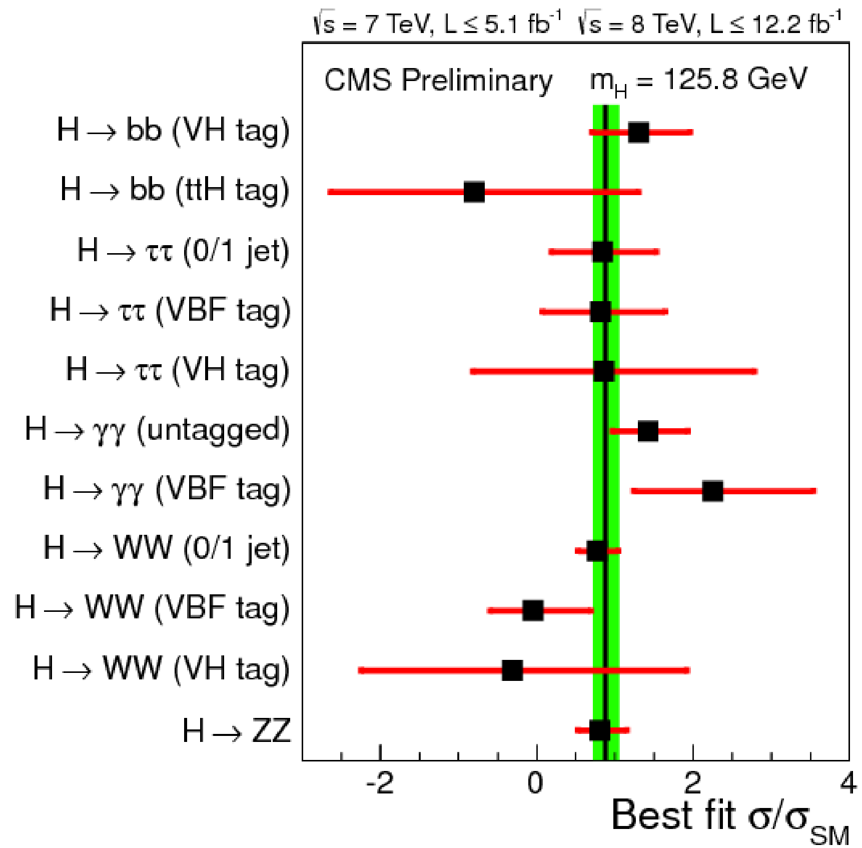
$$\kappa_H^2(\kappa_i, m_H) = \sum_{\substack{j = WW^{(*)}, ZZ^{(*)}, b\bar{b}, \tau^-\tau^+, \\ \gamma\gamma, Z\gamma, gg, t\bar{t}, c\bar{c}, s\bar{s}, \mu^-\mu^+}} \frac{\Gamma_j(\kappa_i, m_H)}{\Gamma_H^{SM}(m_H)}$$

  - Assume at least one coupling has a fixed strength κ_i=const. This has a similar impact as the no BSM decay modes assumption

Current reality

- **The statistical power of many channels is still very limited, giving statistical errors of ~100% on the rate measurements**

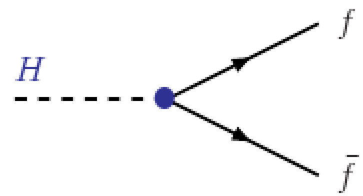




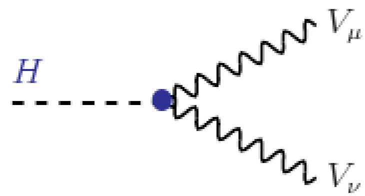
- **Can't measure many independent parameters so far**
- **Make measurements in benchmark scenarios that highlight different aspects of the SM Higgs sector properties**

Couplings to fermions and gauge bosons

- **Assume all fermion couplings scale with a common factor κ_F**
- **Assume all vector couplings scale with a common factor κ_V**

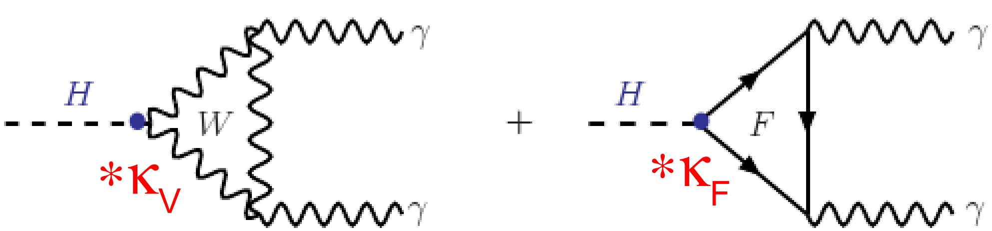


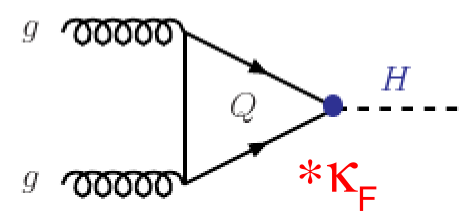
$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2}\, m_f \quad \times (i) \quad *\kappa_F$$



$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2}\, M_V^2 \quad \times (-ig_{\mu\nu}) \quad *\kappa_V$$

- **Assume no BSM particle contributions to the H→γγ and gg→H loops**

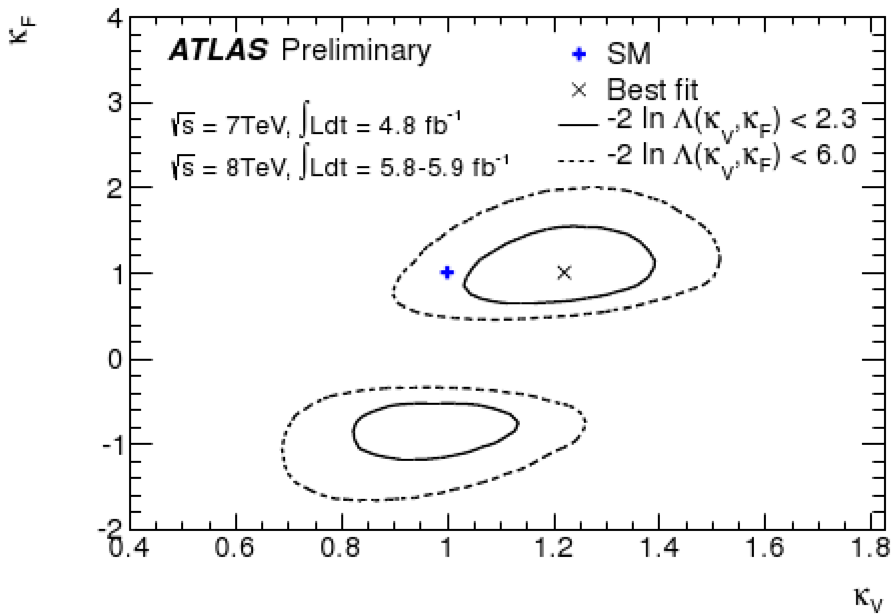


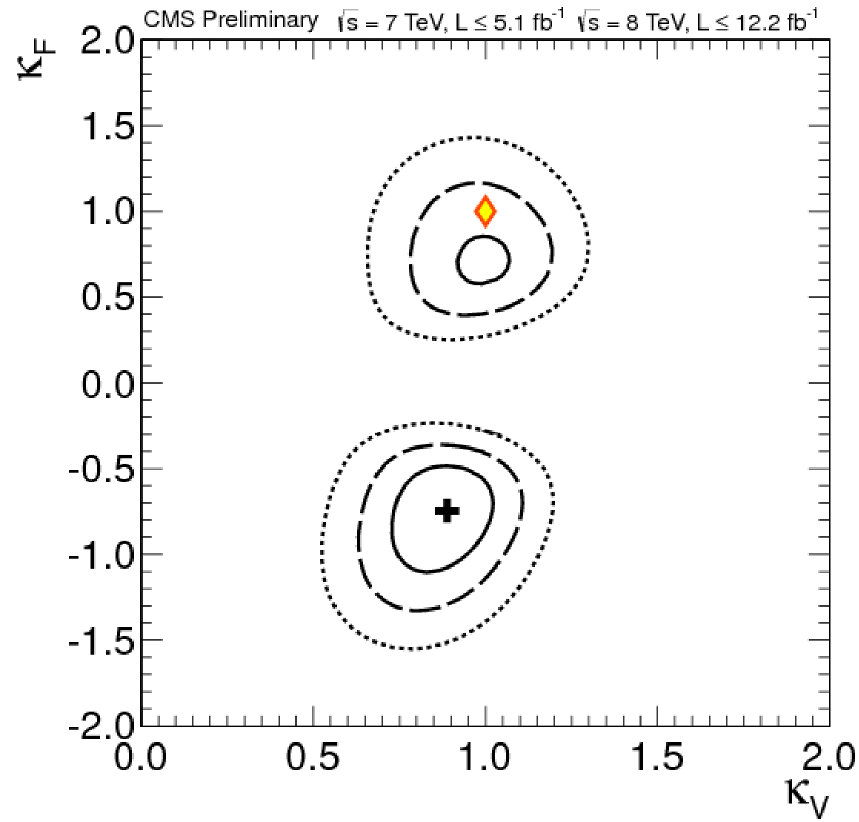


- **Assume no BSM contributions to the total width**

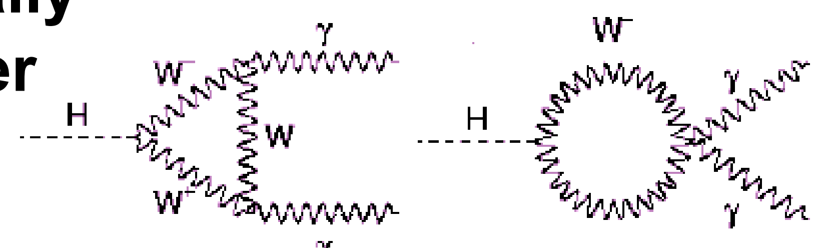
Couplings to fermions and gauge bosons

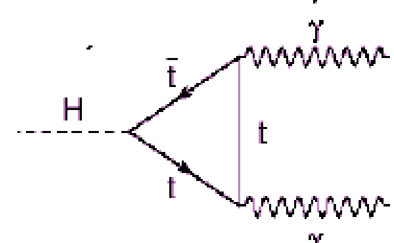
- **Correlation of κ_V and κ_F**





- **Why several minima? Should actually be 4 minima, as both κ_V and κ_F enter squared into xsec and BR**
- **However, one global sign: choose κ_V>0**
- **H→γγ decay breaks symmetry of minima**

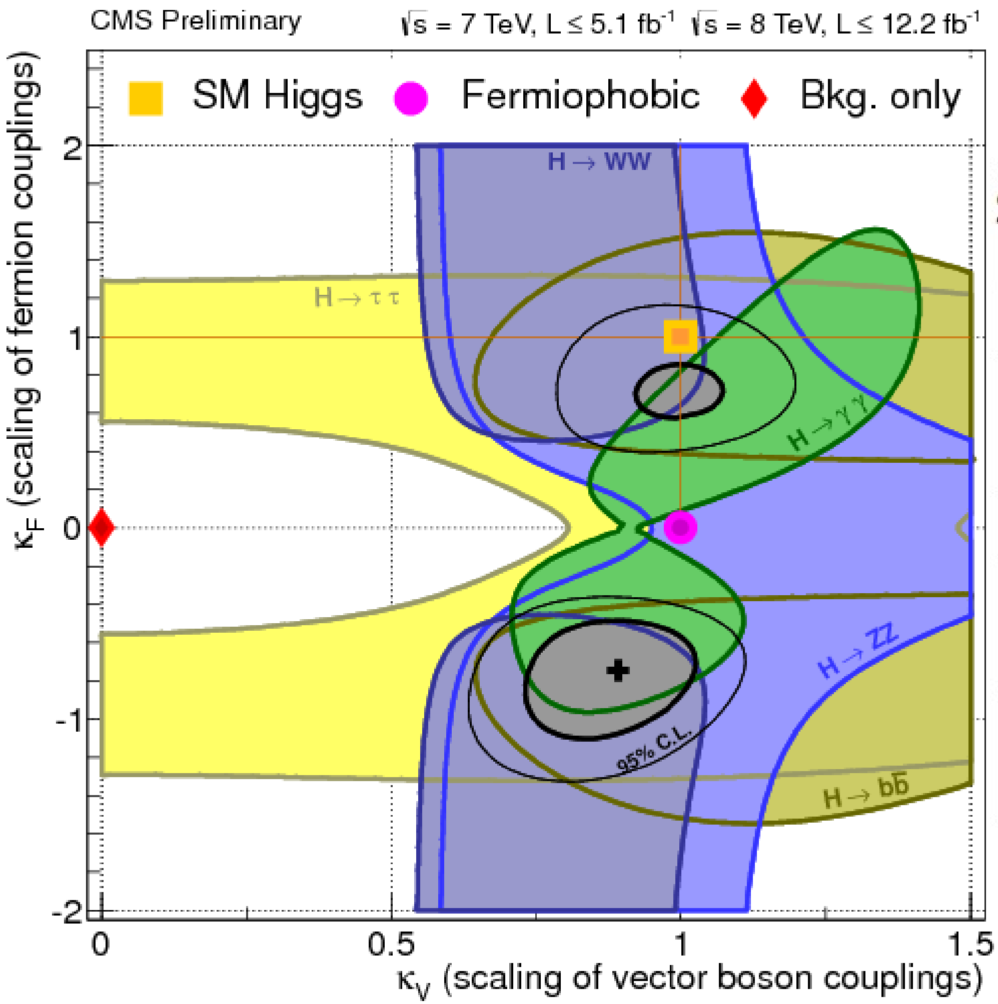




$\sim \kappa_\gamma^2 = |1.28\ \kappa_W - 0.28\ \kappa_t|^2$

Couplings to fermions and gauge bosons

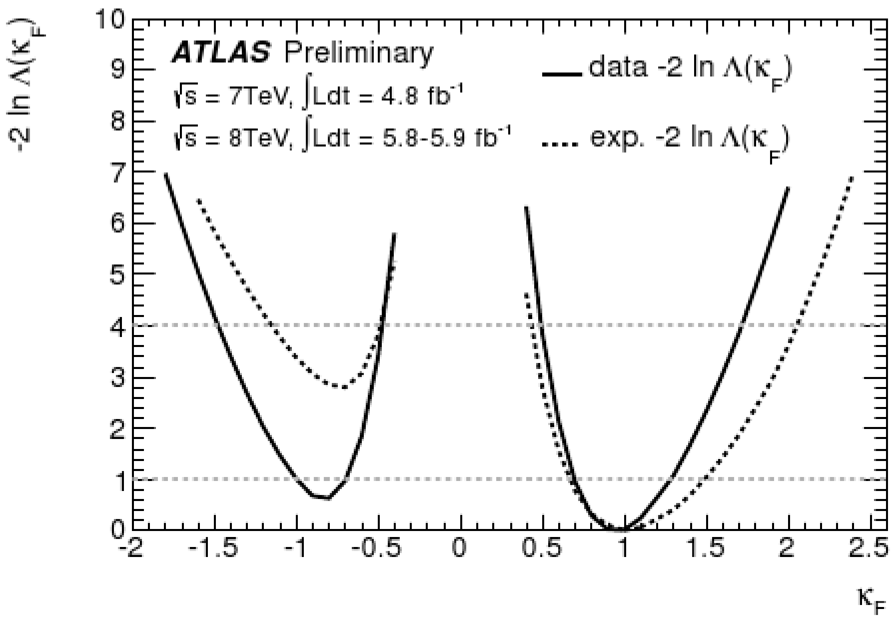
- **Which channels actually measure what?**

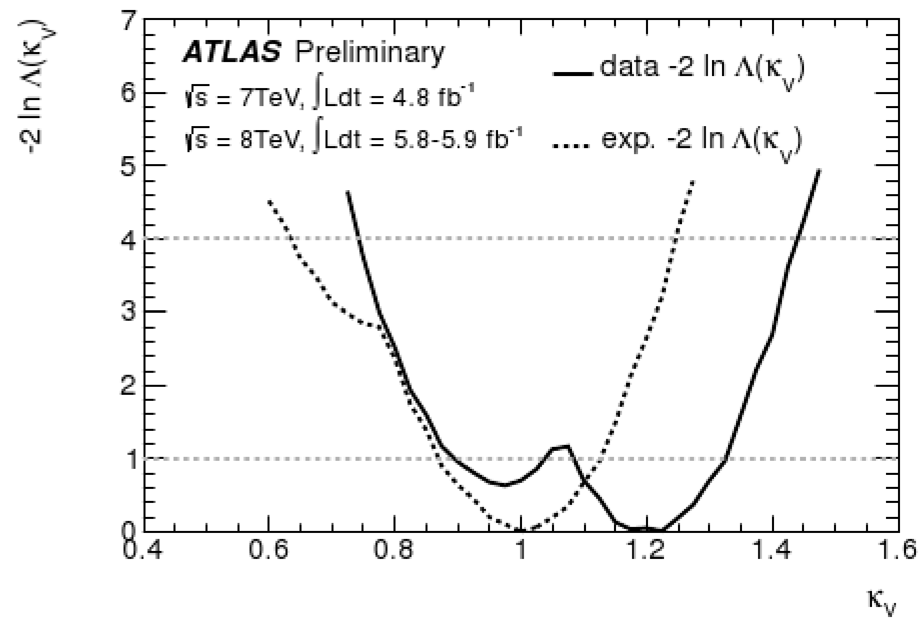


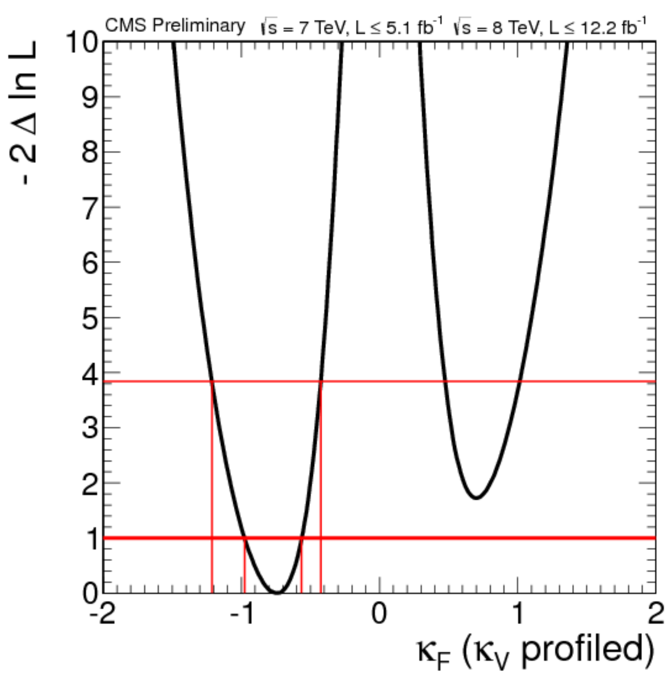
Production	Decay	LO SM	
VH	$H \to bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ttH	$H \to bb$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
VBF	$H \to \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
ggH	$H \to ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$	$\sim C_V^4/C_F^2$
ggH	$H \to \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}$	$\sim C_V^4/C_F^2$

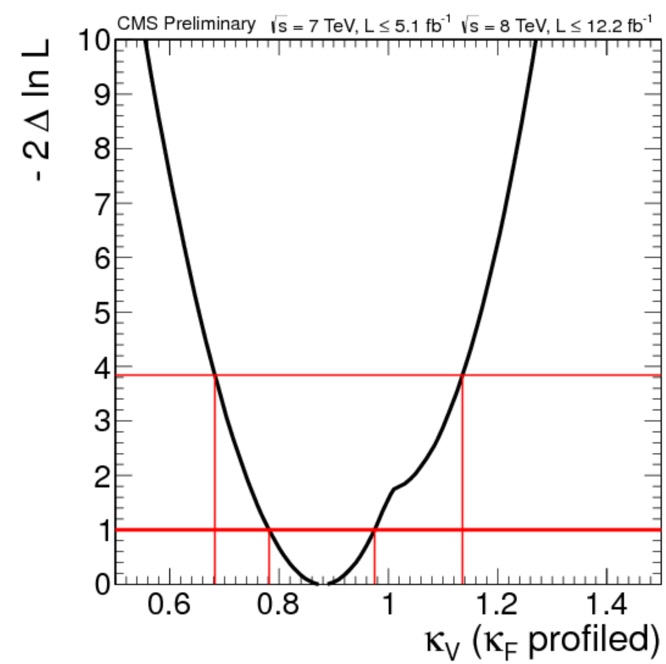
Couplings to fermions and gauge bosons

- **Measurement of κ_V and κ_F**



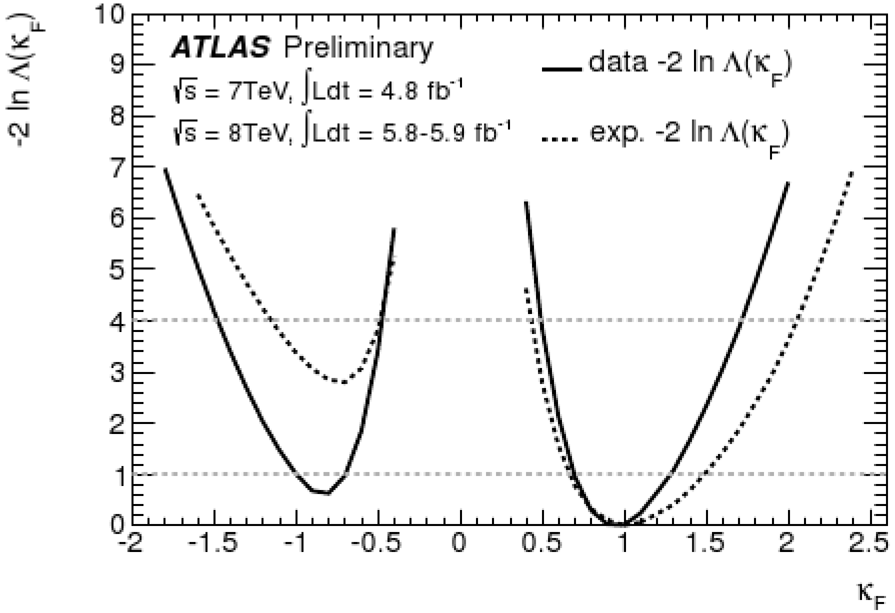


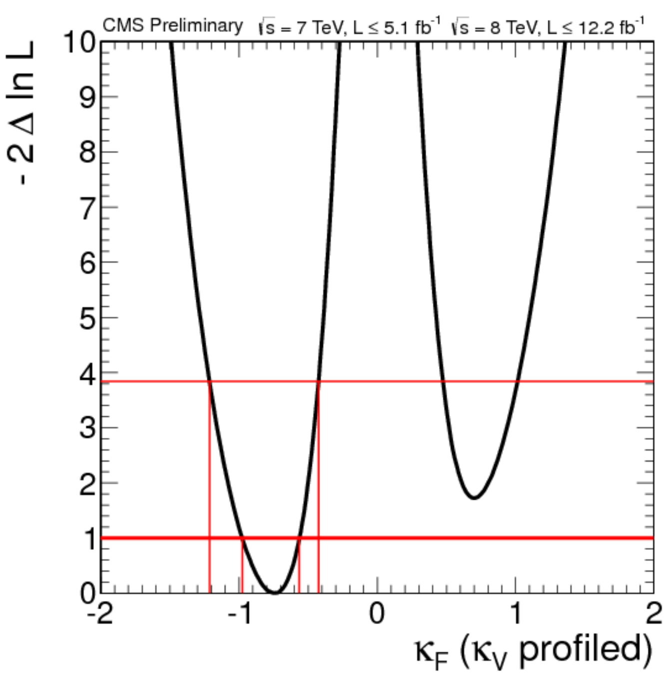




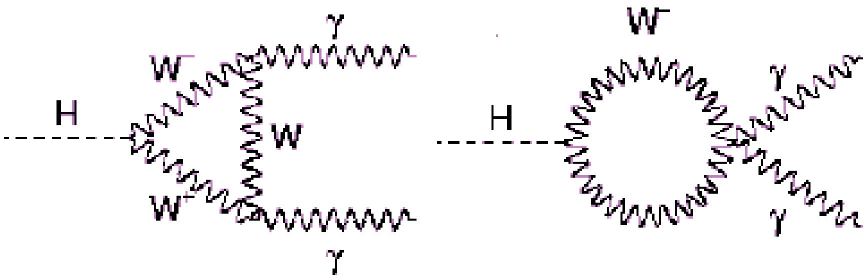
Couplings to fermions and gauge bosons

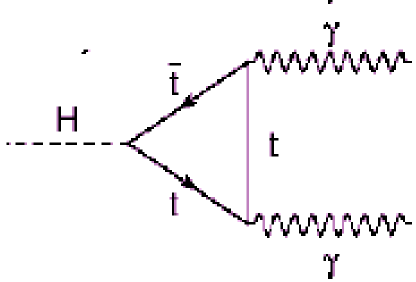
- **Measurement of κ_V and κ_F**





- **In the SM would expect a clearer minimum for κ_F>0**
- **However, H→γγ is high!**
  - **ATLAS: also WW/ZZ is high, so best fit still close to SM**
  - **CMS: best fit for flipped fermion sign, as WW/ZZ is low**

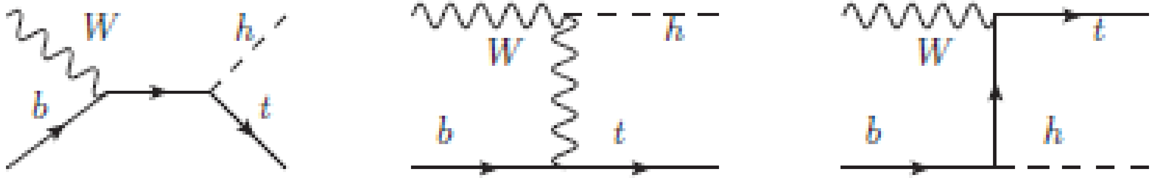




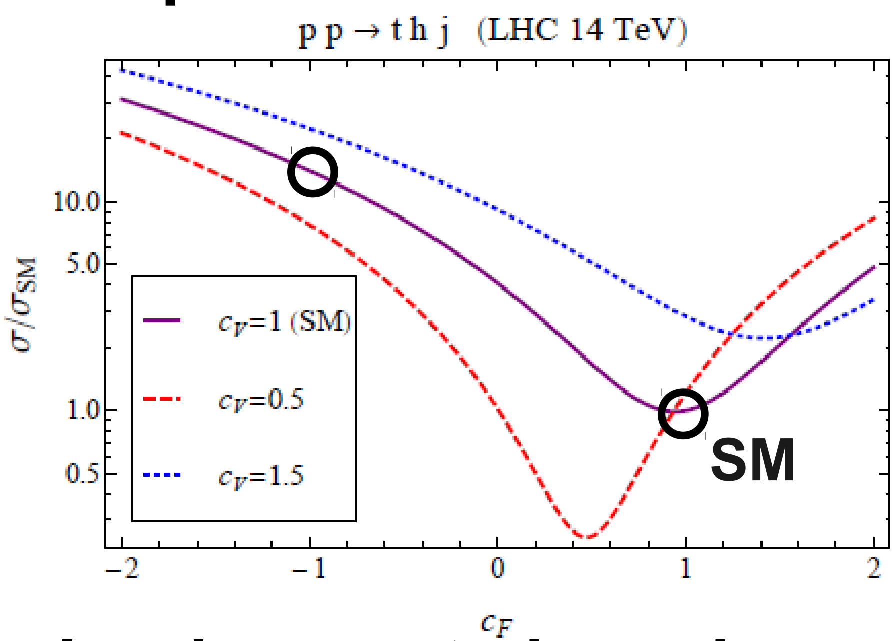
$\sim \kappa_\gamma^2 = |1.28\ \kappa_W - 0.28\ \kappa_t|^2$

Couplings to fermions and gauge bosons

- Can we solve the ambiguity of κ_V and κ_F?
- arXiv:1211.3736 : use tH production!



- Cross section for tH production is small in the SM



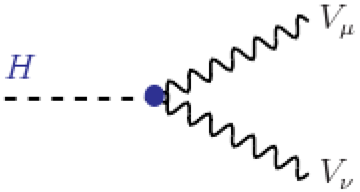
- Very good example where not observing something (SM) would be extremely valuable information

Custodial symmetry of W and Z

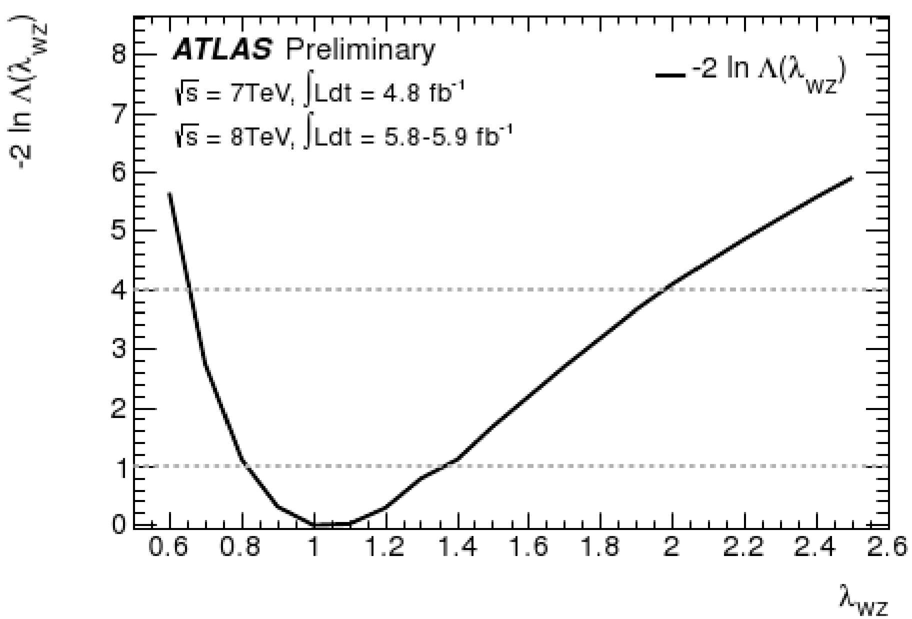
- **For the W and Z mass we get**

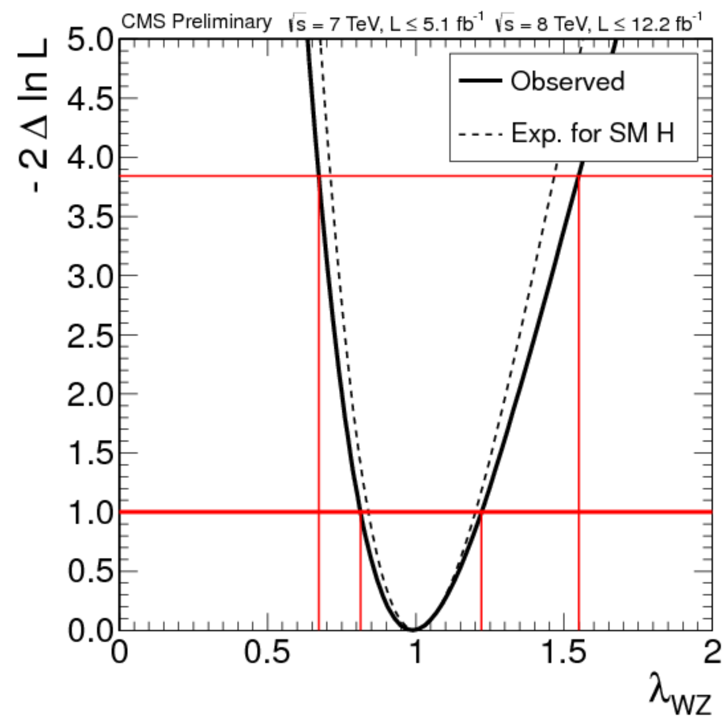
$$M_W = gv/2, \quad M_Z = \sqrt{g^2 + g'^2}\, v/2 \quad \Rightarrow \quad M_W/M_Z = \cos\Theta_W$$

- **The Higgs couplings to W and Z should mirror this ratio**
- **Essentially measure ratio of H→WW to H→ZZ**



$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2} M_V^2 \quad \times (-ig_{\mu\nu})$$

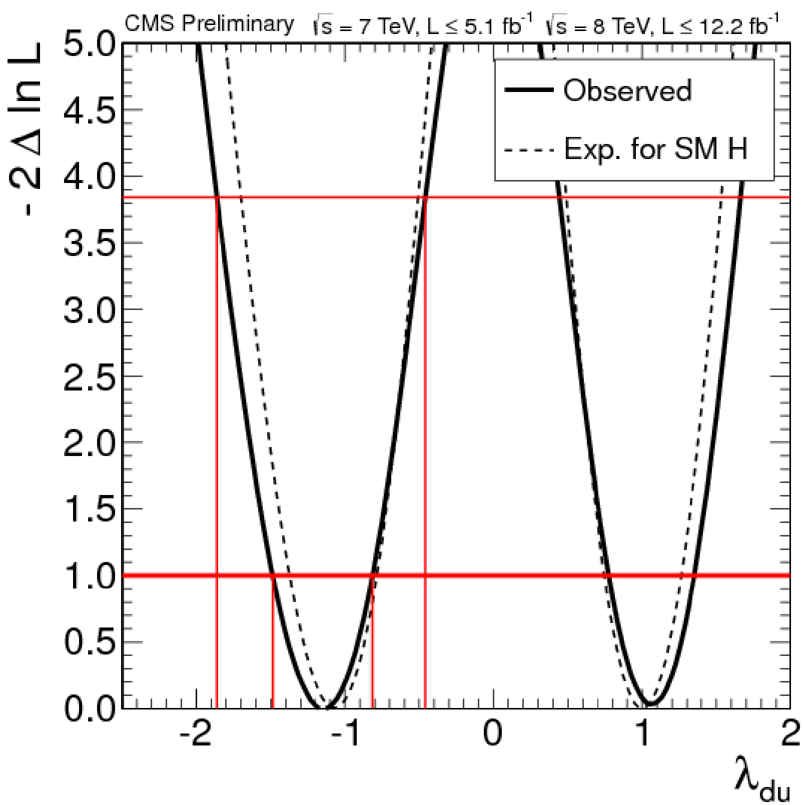


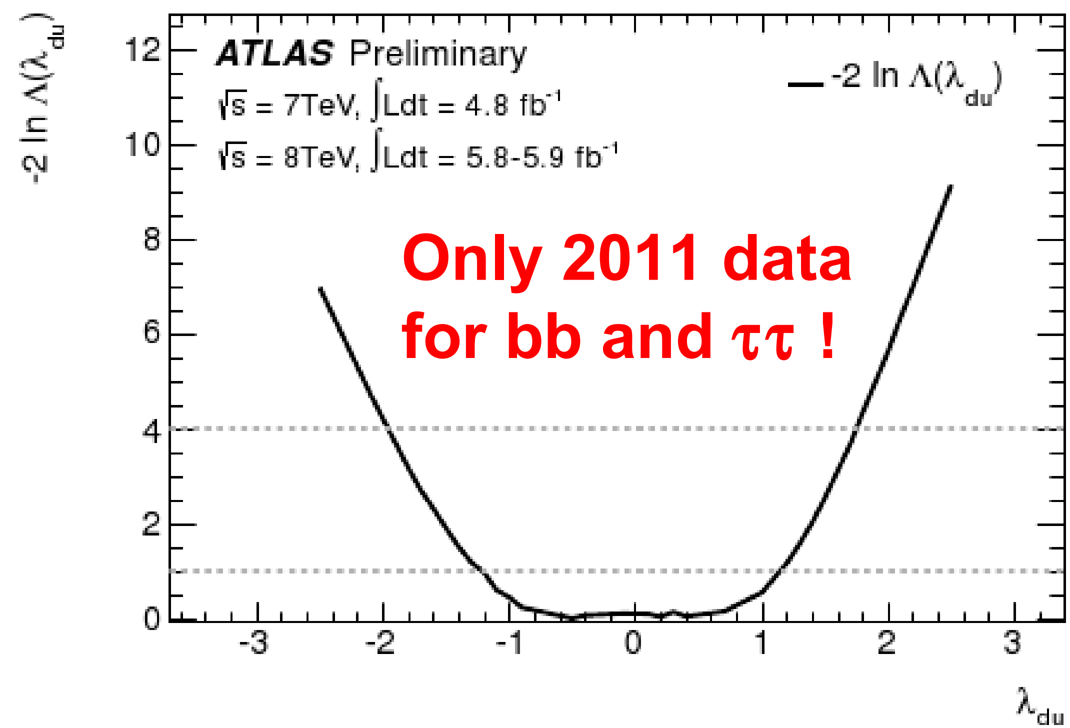


- **Small difference between ATLAS and CMS: ATLAS plot doesn't make assumption on total width, CMS has BR(H→new,inv.,undet.)=0**

Ratio of up- and down-type fermions

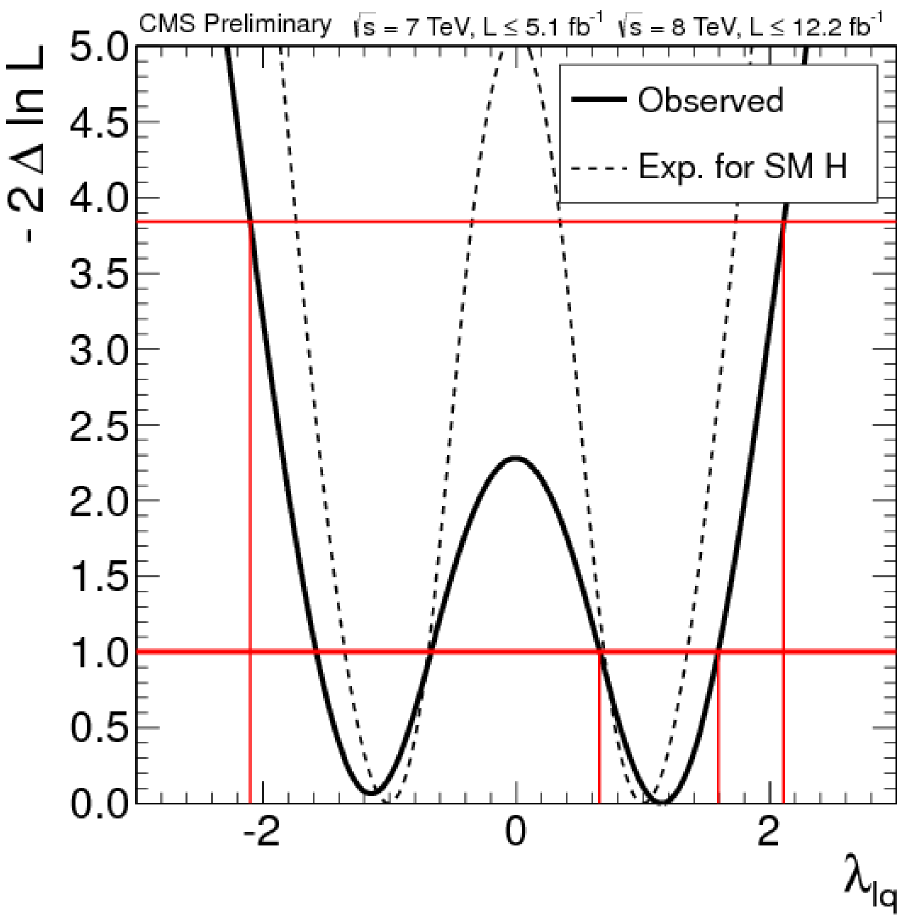
- In many BSM models (e.g. SUSY) the up- and down-type fermions couple differently
- Experimentally the up-type fermions are accessible through the gg→H production
- Experimentally the down-type fermions are accessible through the H→bb and H→ττ decay

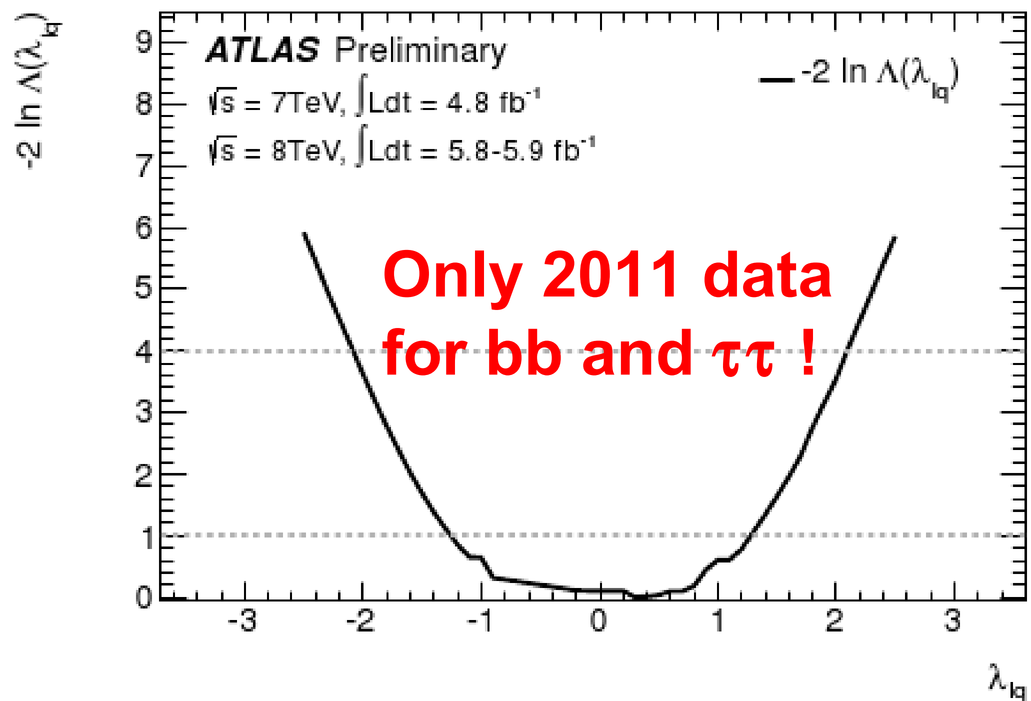




Ratio of leptons to quarks

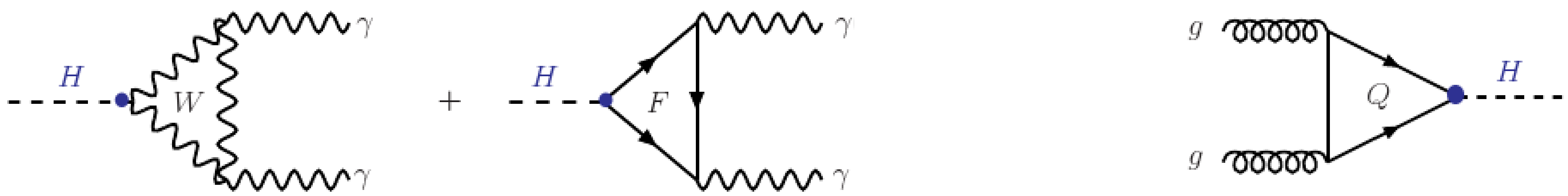
- Experimentally the lepton coupling is only accessible through the $H\rightarrow\tau\tau$ decay
- Experimentally the quark couplings are accessible through the $gg\rightarrow H$ production and the $H\rightarrow bb$ decay





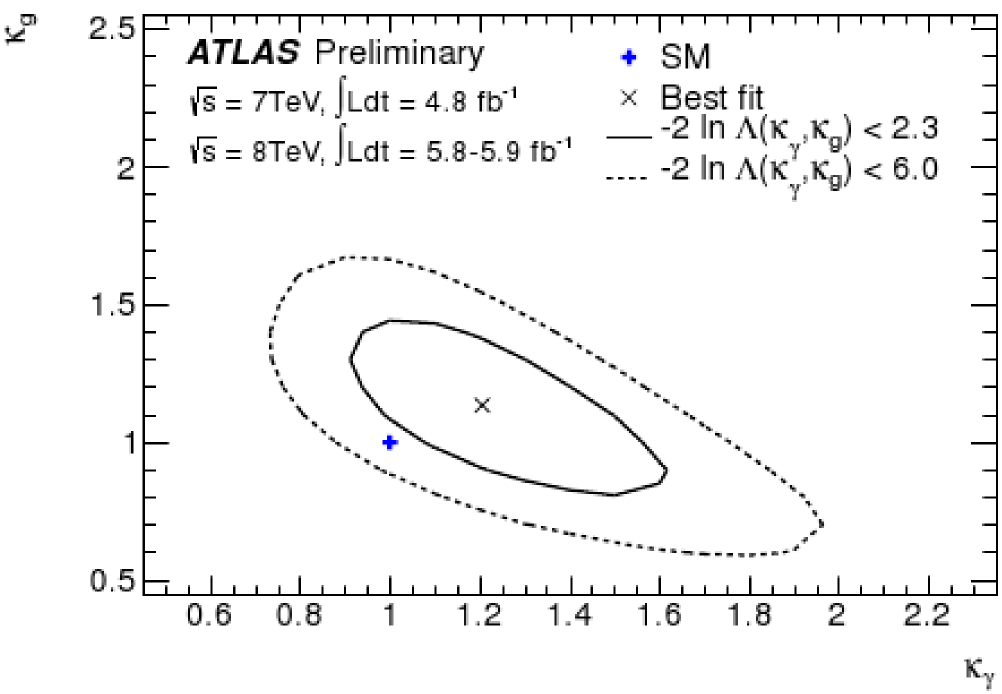
Probing possible BSM contributions

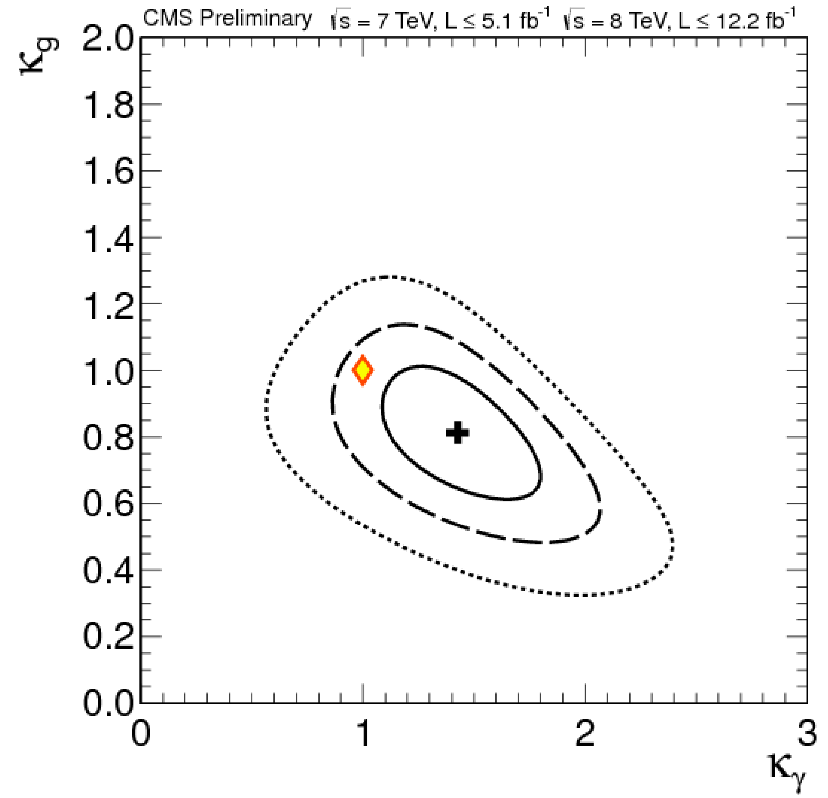
- So far all tests assumed that only the SM particles exists
- However, especially the loop processes could easily get modified by heavy new particles: W', t', ...



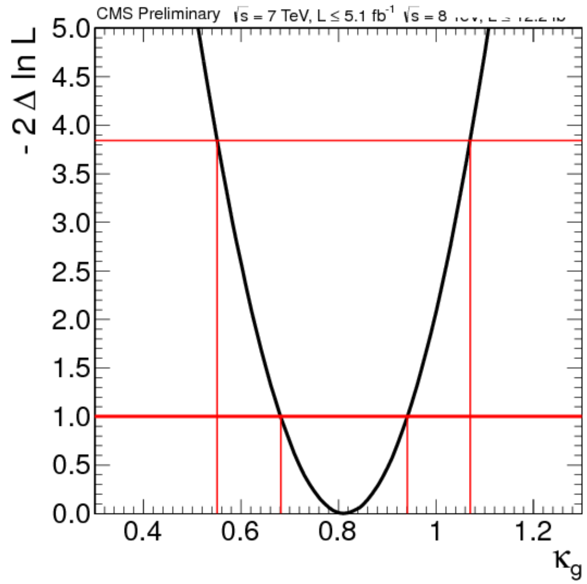
- Hence measuring the effective coupling strength κ_γ and κ_g is a very good probe for BSM physics!
- Luckily/unfortunately almost all the powerful channels have either $gg \rightarrow H$ production or the $H \rightarrow \gamma\gamma$ decay
  - Hence have to assume (for now) that all fermion and vector couplings have exactly the same strength as in the SM: κ_i=1
  - Little power so far to loosen this assumption

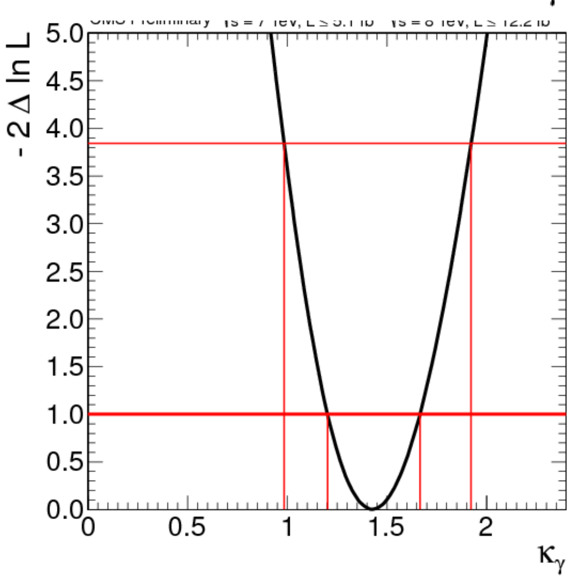
Probing possible BSM contributions





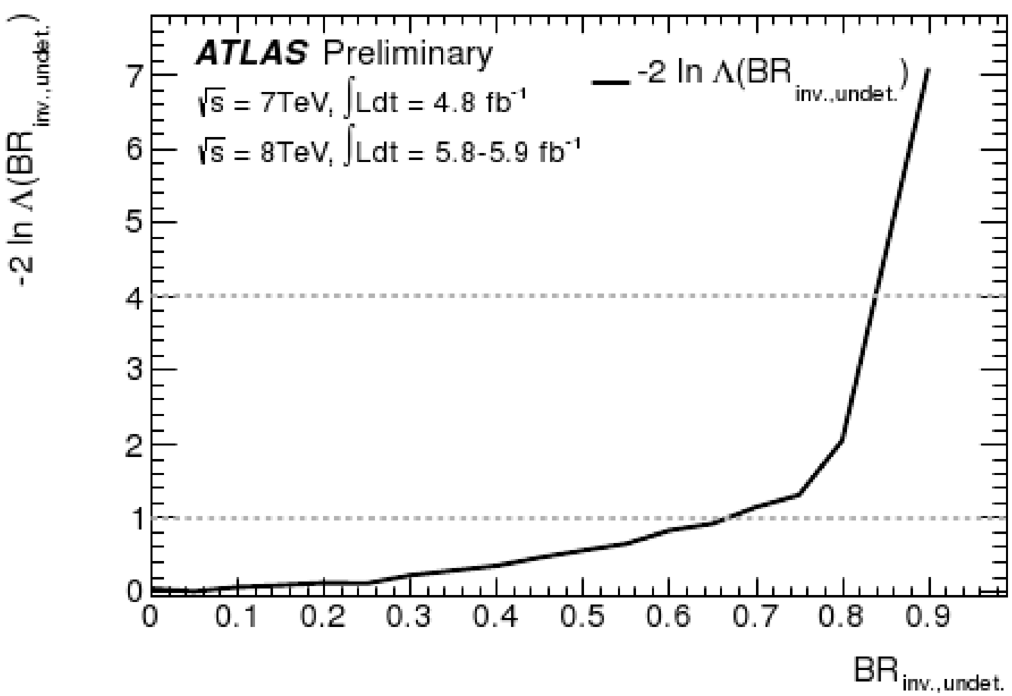
- **Essentially H→WW and H→ZZ measure κ_g**
- **H→γγ then measures κ_γ**

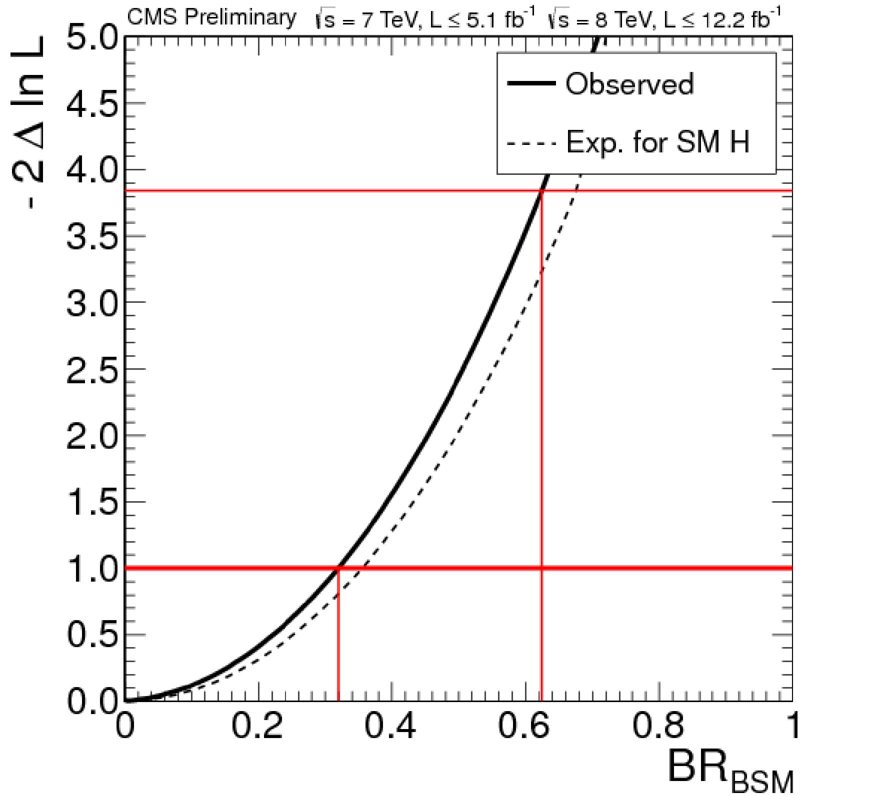




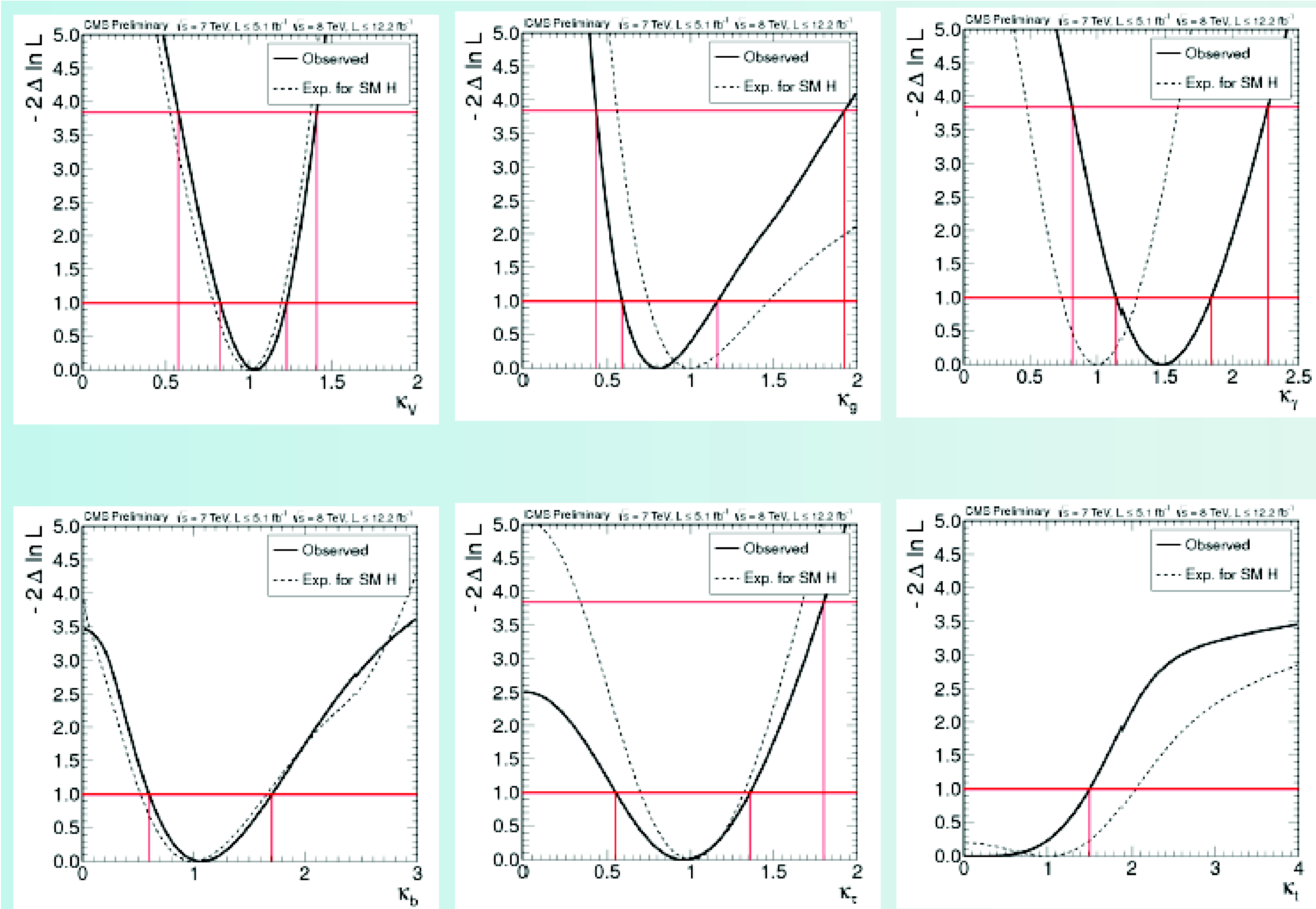
Probing possible BSM contributions

- What about possible BSM contributions to the total width?
- As discussed before, the total width can't be measured
- However, if we make assumptions, like κ_i=1 for all known SM particles, we can "measure" the effect from a BSM decay with BR(H→new,inv.,undet.)
- This would be natural in a SM extension, where the SM Higgs sector is unchanged, but heavier particles appear





Finally, all in one fit....



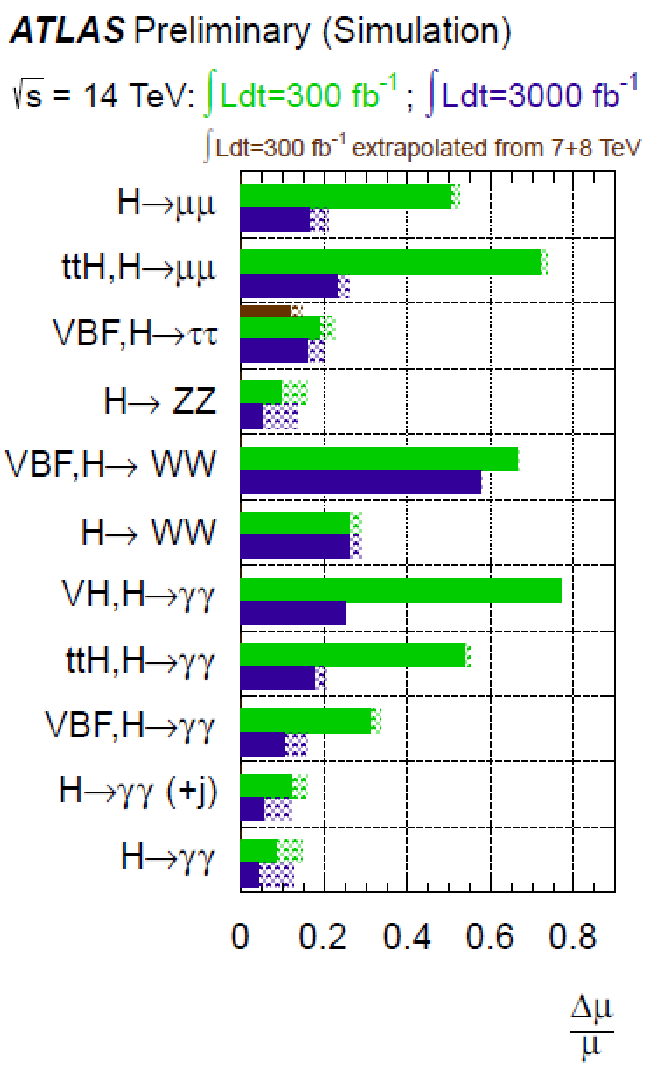
Coupling measurements : now & future

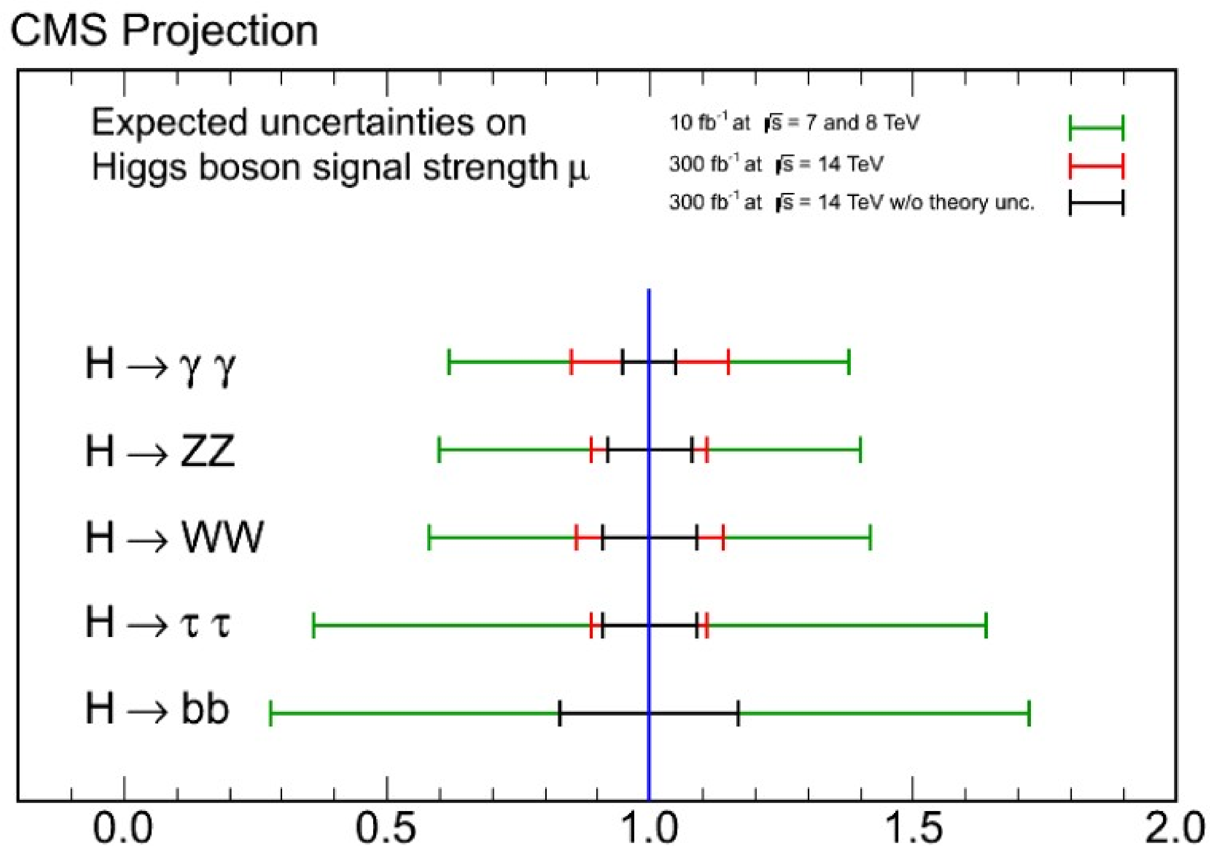
- So far no significant deviation from the SM observed in the Higgs coupling sector with the analyzed 2012 data
- The full dataset will ~ double statistics
  → don't expect huge changes
- However, more luminosity makes low rate analysis possible
  → can give crucial input to coupling measurements
  → will keep us occupied for quite some time

- What can we expect from the future?
  - Assuming we get 300 fb-1 @ 14 TeV
  - Assuming we get 3000 fb-1 @ 14 TeV

Coupling measurements : σ*BR

- **ATLAS and CMS have studied the prospects for σ*BR rate measurements recently within the European Strategy process**





$\mu = \sigma * BR / \sigma * BR(SM)$

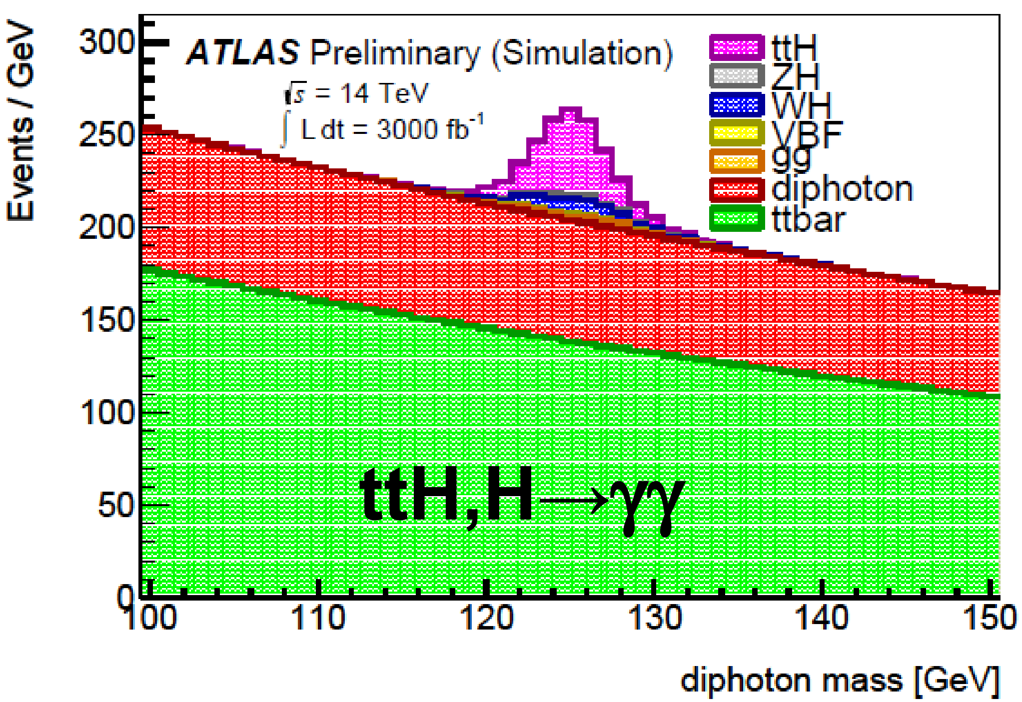
Coupling measurements : σ*BR

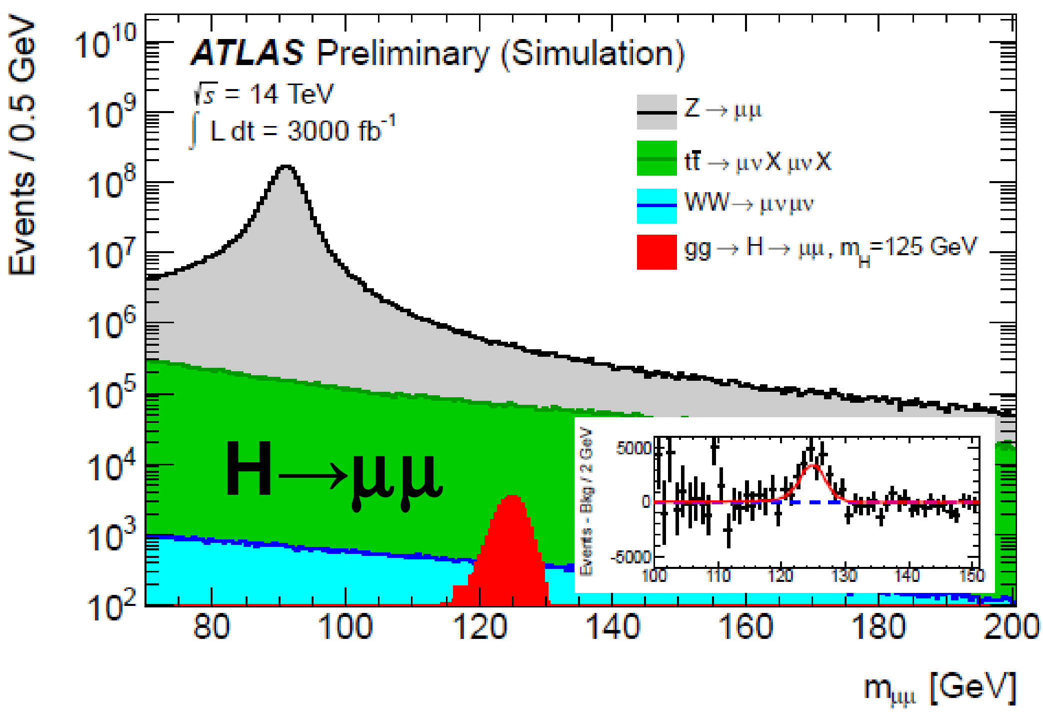
- The clean final states $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ$ are basically only statistically limited
  → final experimental uncertainties of <5% are reachable
  → current theory uncertainties are ~10%
- For other final states precisions of ~20% are reachable
- Also rare processes like $H\rightarrow\mu\mu$ or ttH are accessible and will provide direct information about the otherwise hard to access μ- or top-coupling → next slide

- Remember: these results are from selected benchmark studies for the European Strategy. In reality both experiments will optimize measurements for all combinations of initial and final states and further subdivide into categories to improve the overall sensitivity
  → this will give another substantial gain

Measuring rare processes

- With 3000fb-1 even very low rate channels can be measured at the LHC – provided the channels have a clean signature
- Examples: H→μμ; ttH,H→γγ; ttH,H→μμ; VH,H→ZZ; …
- All these measurements will help completing the Higgs picture





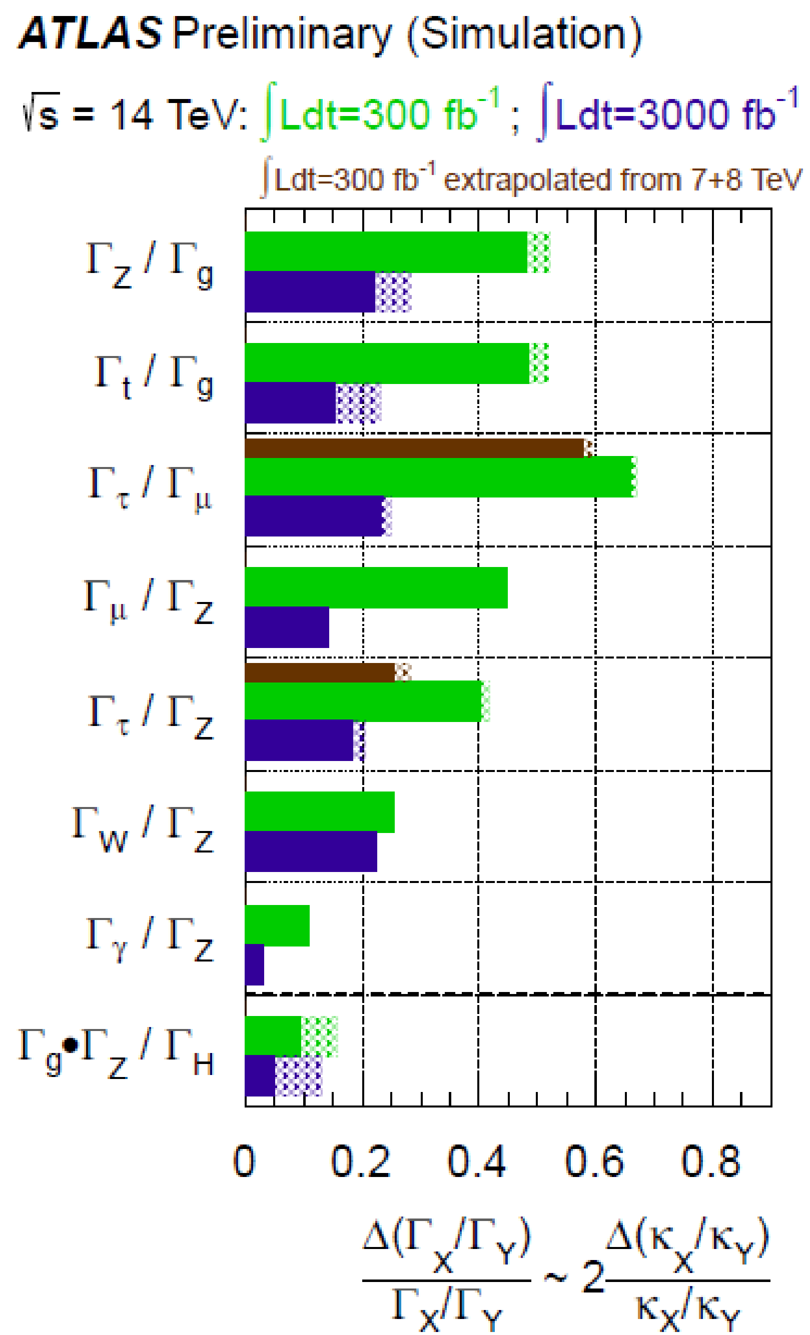
Ratios of partial width

- For a narrow Higgs the measured rates can be written as

$$\sigma(i)*BR(f)=\Gamma(i) * \Gamma(f) / \Gamma(H)$$

- Without an assumption on the total width this allows to measure only ratios of partial width Γ

- Especially interesting to test
  - $\Gamma(t) / \Gamma(g)$ ~ 20% level
  - $\Gamma(\tau) / \Gamma(\mu)$ ~ 25% level
  - $\Gamma(\gamma) / \Gamma(Z)$ < 5% level

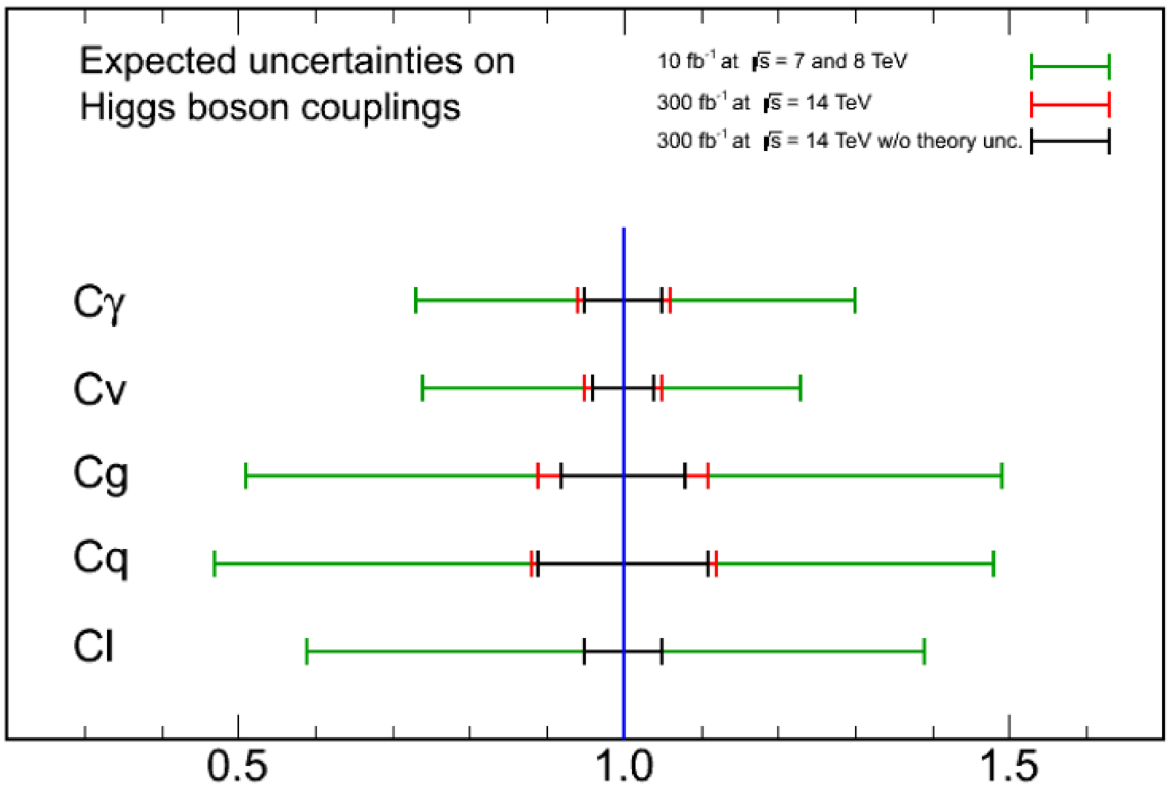


Absolute couplings

- With the assumption that no BSM Higgs decay modes have a sizeable contribution to the total width Γ(H), absolute couplings Ci can be measured.
  Notation : $\Gamma(i) \sim (Ci)^2$; $\Delta\Gamma(i)=2*\Delta Ci$

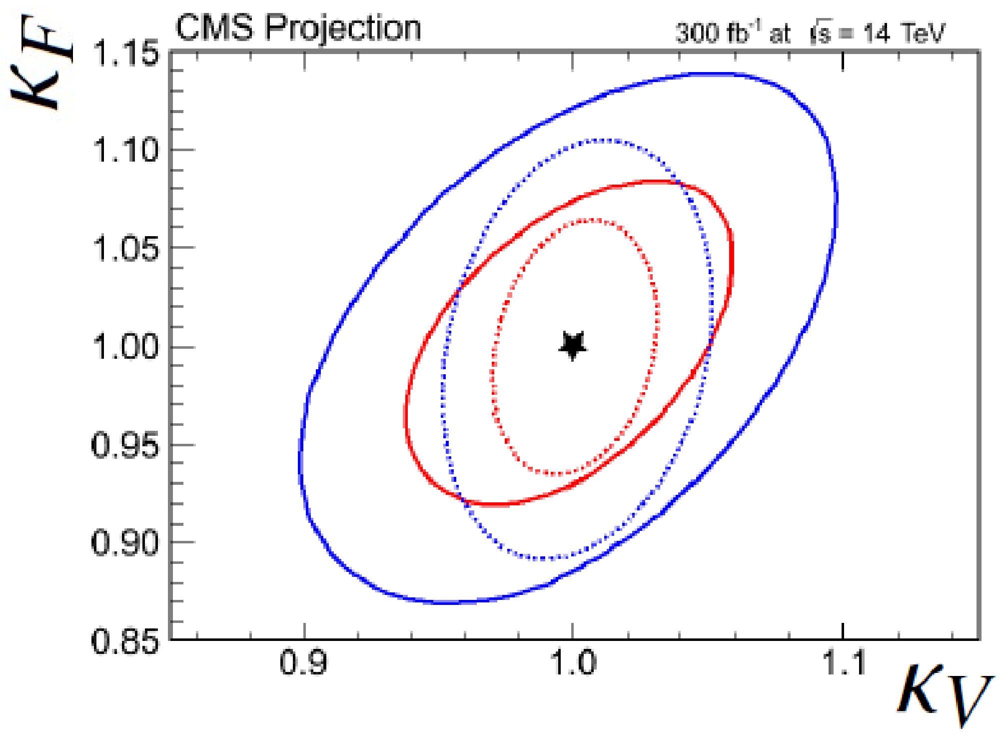
- Experimental precisions on the measurement of Ci are in the range ~5-10%
- Current theory uncertainties are sizeable, but are also expected to improve in the next years

CMS Projection



Absolute couplings

- If good agreement to the SM is seen in all general coupling fits, it is likely that coupling parameter fits of only a few parameters are made to reach the highest sensitivity for deviations from the SM Higgs sector
- An example is the model with only two coupling parameters, one describing the fermion sector (κ_F) and one describing the gauge=vector boson sector (κ_V)



ATLAS

	$300\,\mathrm{fb}^{-1}$	$3000\,\mathrm{fb}^{-1}$
κ_V	3.0% (5.6%)	1.9% (4.5%)
κ_F	8.9% (10%)	3.6% (5.9%)