Higgs Properties at the LHC
Short and Long Term

Giovanni Petrucciani
(Univ. of California, San Diego)
CMS Collaboration

Overview

- In the context of SM Higgs boson searches,
  a new heavy boson has been observed at a mass of around 125 GeV.
- Having established that ***something*** exists there, the most natural question is now ***what*** is it:
  shift of focus from searches to measurements.
- Of course we're also still searching for

SM Higgs-centric measurements

- The H125 boson was observed relying on searches specifically tuned for the SM Higgs:
  - *Signal kinematic taken from SM Higgs prediction.*
  - *Use of specific production modes: VBF, VH, ttH*
  - *Selection of decay modes searched*
- Most measurements of properties are made by reinterpreting the results of these searches.
- Therefore, the measurements of the properties depend to some extent on SM Higgs assumptions.
- The validity of these measurements is therefore dependent on how close H125 is to

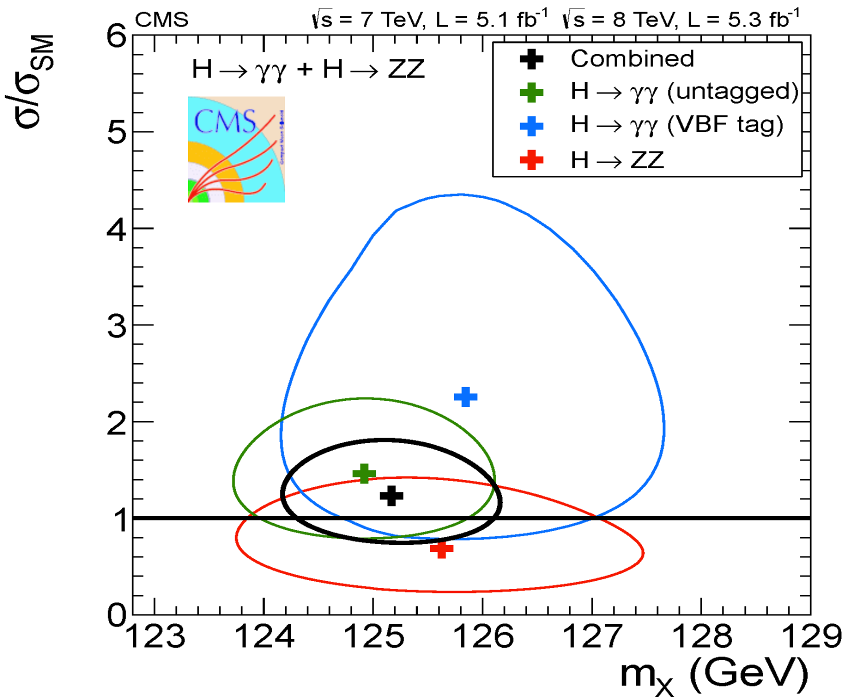
Mass measurement

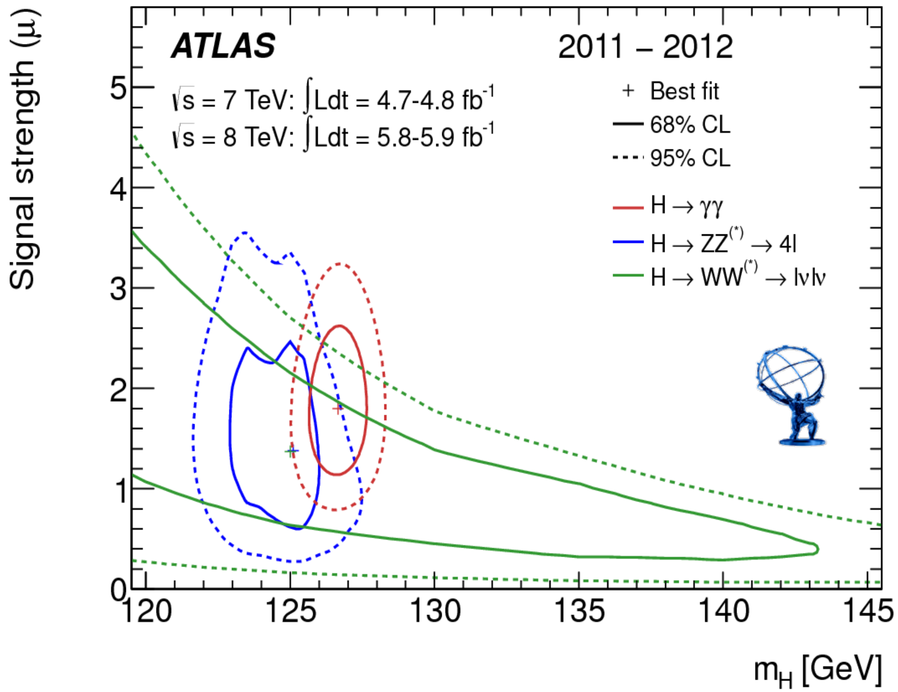
- The first and most natural thing to measure.
- Experimentally accessible in γγ, 4l decays
- Well defined theoretically, at least down to the natural width of H125 (tiny, in most models)
- If no assumption is made on the expected signal yield, the measurement is model independent, except for some effects:
  - *the modelling of the signal kinematic , which enters in the overall calibration of the mass scale from MC.*
  - *the relative weights given to the events in the measurement, which depends on the expected S/B*

Mass: experimental challenges

- The dominant systematical uncertainty on the mass measurement is from the knowledge of the energy scales for photons and leptons:
  - *Extrapolation from the standard candles (e.g. Z)*
    to the kinematic of a H125 signal (p_T, η)
  - *Extrapolation from electrons to photons.*
- The control of the energy resolution on data
  is also important

Results with Summer'12 data





$125.3 \pm 0.4^{(stat)} \pm 0.5^{(syst)}$ $126.0 \pm 0.4^{(stat)} \pm 0.4^{(syst)}$

Mass: looking in the future

- By the end of 2012 run, we expect ~ x3 data.
  - *Statistic term from about 0.4 GeV to about 0.2 GeV*
  - *Can gain also from further analysis improvements*
- The systematic can also be reduced with better calibrations, better tuning of the simulation, ...
- The ATLAS and CMS uncertainties are totally uncorrelated, also in the systematic part, so get a factor √2 from combining the two.
- Total uncertainty below 0.2 GeV by 2013?
- Unclear to me how useful it is to go beyond that

Tests of the Couplings

- For a SM Higgs, there's nothing to measure besides the mass: all the rest is well know.
  As a consequence, all production cross sections and decay rates are predicted from them.
- However, SM Higgs predictions are all that we have readily and accurately available now.
- So, rather than "measure" the couplings,

Measurement vs Test

- *Starting point:* a model, dependent on some parameters, that can be fitted to the data.
- *Measurement:* all parameter values are sensible; we search for the one best describing the data.
  e.g. measure the Z mass, combining μμ and ee.
- *Test:* only some parameter values are sensible; If the result is not compatible with those, taking into account the uncertainties, the model is rejected.
  e.g. measure the Z mass in μμ and ee as if

Tests of the couplings

1. Introduce a set of parameters {X}, intuitively related to the couplings of the Higgs
2. Compute the production cross sections in each topology and all the BRs, rescaling the SM predictions by functions of {X}

   $$\sigma(xx \to H \to yy) \sim \sigma_{xx}\, \Gamma_{yy} / \Gamma_{tot}$$

3. Fit the data and the allowed regions of {X}, or the allowed region for one X allowing all the others X's to take arbitrary values.

A set of benchmark models have been defined to probe various BSM scenarios: arxiv:1209.0040

Universal vector & fermion couplings

"Rescale universally the Higgs boson couplings to fermion by $\boldsymbol{\kappa_F}$ and couplings to vector boson by $\boldsymbol{\kappa_V}$"

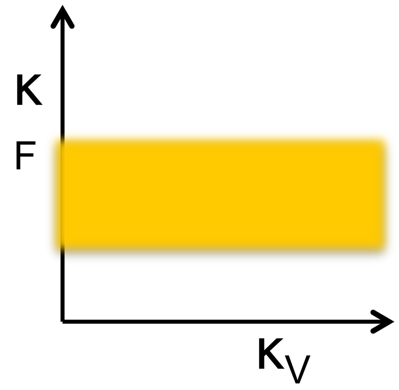
- σ_{VBF}, σ_{VH}, Γ_{WW}, Γ_{ZZ} scale as κ_V^2
- σ_{ttH}, Γ_{ff} scale as κ_F^2
- σ_{ggH}, Γ_{gg} scale as κ_F^2 *(assume they're just the SM quarks in the loop)*
- $\Gamma_{\gamma\gamma}$ scale as $|\alpha\cdot\kappa_V + \beta\cdot\kappa_F|^2$ *(assume W, t, b in the loop, as in the SM)*
- $\Gamma_{tot} = \sum \Gamma_X$ for all X decays in the SM *(assume no other BSM decay mode)*

Predictions in κ_{V}, κ_{F} model

Prod.	Decay	Signal yield scale	Approx
VH	bb	$\kappa_V^2\ \kappa_F^2\ /\ [\frac{3}{4}\ \kappa_F^2 + \frac{1}{4}\ \kappa_V^2]$	κ_V^2
ttH	bb	$\kappa_F^2\ \kappa_F^2\ /\ [\frac{3}{4}\ \kappa_F^2 + \frac{1}{4}\ \kappa_V^2]$	κ_F^2
VBF	ττ	$\kappa_V^2\ \kappa_F^2\ /\ [\frac{3}{4}\ \kappa_F^2 + \frac{1}{4}\ \kappa_V^2]$	κ_V^2
ggH	ττ	$\kappa_F^2\ \kappa_F^2\ /\ [\frac{3}{4}\ \kappa_F^2 + \frac{1}{4}\ \kappa_V^2]$	κ_F^2
ggH	WW, ZZ	$\kappa_F^2\ \kappa_V^2\ /\ [\frac{3}{4}\ \kappa_F^2 + \frac{1}{4}\ \kappa_V^2]$	κ_V^2
VBF	WW	$\kappa_V^2\ \kappa_V^2\ /\ [\frac{3}{4}\ \kappa_F^2 + \frac{1}{4}$	$\kappa_V^4\ /\ \kappa_F^2$

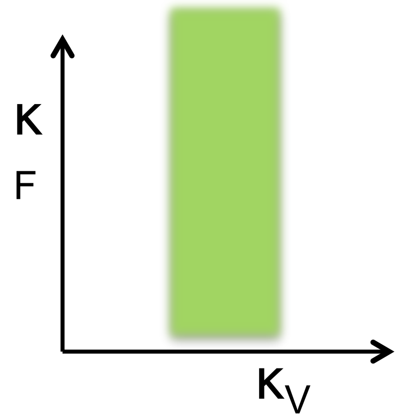
Predictions in κ_V, κ_F model

Prod.	Decay	Signal yield scale	Approx
VH	bb	$\kappa_V^2\ \kappa_F^2$ / [¾ κ_F^2 + ¼ κ_V^2]	κ_V^2
ttH	bb	$\kappa_F^2\ \kappa_F^2$ / [¾ κ_F^2 + ¼ κ_V^2]	κ_F^2
VBF	ττ	$\kappa_V^2\ \kappa_F^2$ / [¾ κ_F^2 + ¼ κ_V^2]	κ_V^2
ggH	ττ	$\kappa_F^2\ \kappa_F^2$ / [¾ κ_F^2 + ¼ κ_V^2]	κ_F^2
ggH	WW, ZZ	$\kappa_F^2\ \kappa_V^2$ / [¾ κ_F^2 + ¼ κ_V^2]	κ_V^2
VBF	WW	$\kappa_V^2\ \kappa_V^2$ / [¾ κ_F^2 + ¼	κ_V^4 / κ_F^2



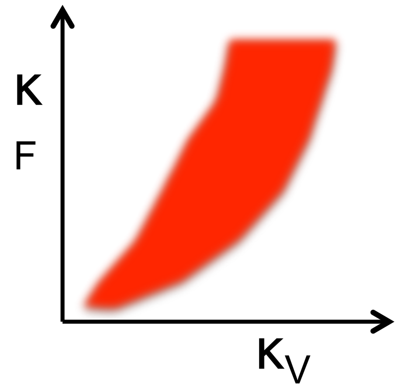
Predictions in κ_V, κ_F model

Prod.	Decay	Signal yield scale	Approx
VH	bb	$\kappa_V^2\ \kappa_F^2$ / [¾ κ_F^2 + ¼ κ_V^2]	κ_V^2
ttH	bb	$\kappa_F^2\ \kappa_F^2$ / [¾ κ_F^2 + ¼ κ_V^2]	κ_F^2
VBF	ττ	$\kappa_V^2\ \kappa_F^2$ / [¾ κ_F^2 + ¼ κ_V^2]	κ_V^2
ggH	ττ	$\kappa_F^2\ \kappa_F^2$ / [¾ κ_F^2 + ¼ κ_V^2]	κ_F^2
ggH	WW, ZZ	$\kappa_F^2\ \kappa_V^2$ / [¾ κ_F^2 + ¼ κ_V^2]	κ_V^2
VBF	WW	$\kappa_V^2\ \kappa_V^2$ / [¾ κ_F^2 + ¼	κ_V^4 / κ_F^2

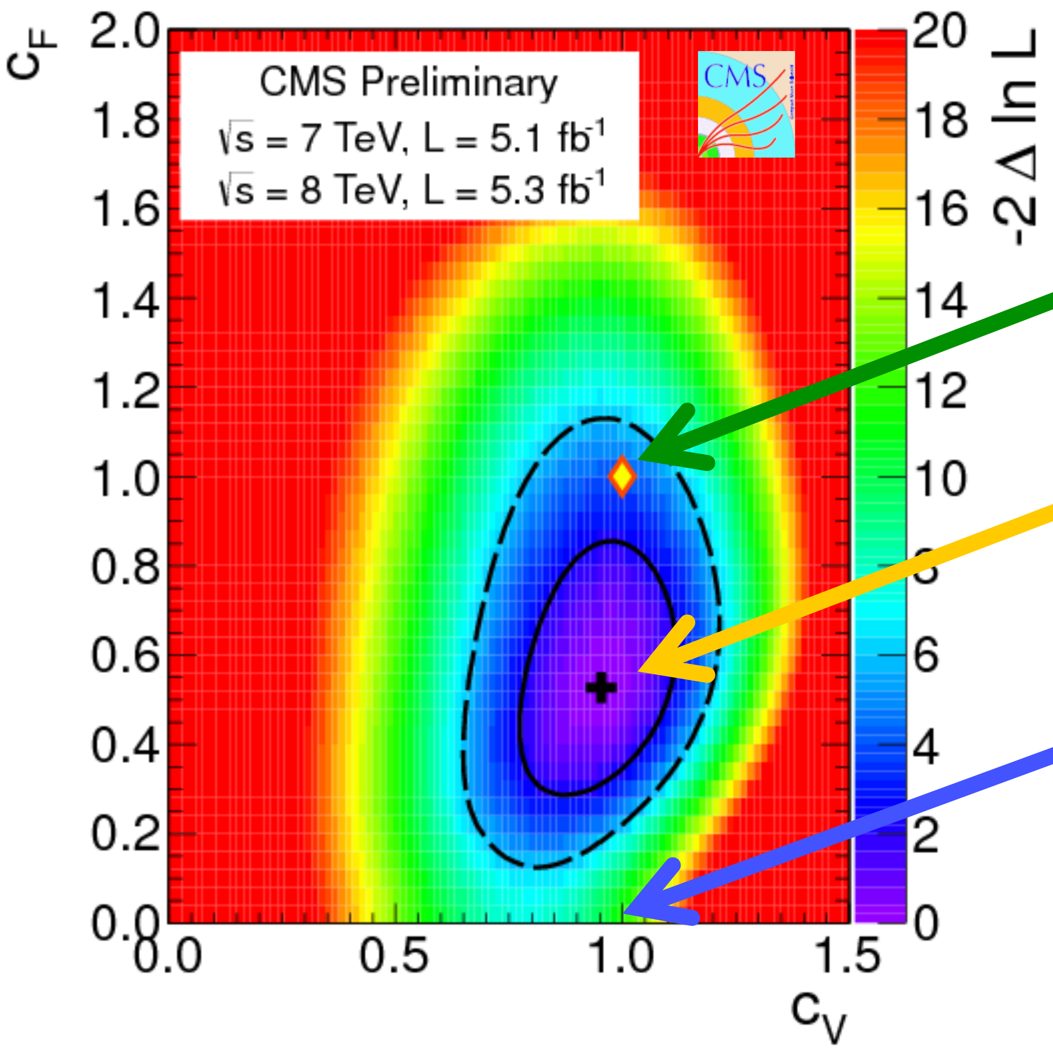


Predictions in κ_V, κ_F model

Prod.	Decay	Signal yield scale	Approx
VH	bb	$\kappa_V^2 \kappa_F^2 / [¾ \kappa_F^2 + ¼ \kappa_V^2]$	κ_V^2
ttH	bb	$\kappa_F^2 \kappa_F^2 / [¾ \kappa_F^2 + ¼ \kappa_V^2]$	κ_F^2
VBF	ττ	$\kappa_V^2 \kappa_F^2 / [¾ \kappa_F^2 + ¼ \kappa_V^2]$	κ_V^2
ggH	ττ	$\kappa_F^2 \kappa_F^2 / [¾ \kappa_F^2 + ¼ \kappa_V^2]$	κ_F^2
ggH	WW, ZZ	$\kappa_F^2 \kappa_V^2 / [¾ \kappa_F^2 + ¼ \kappa_V^2]$	κ_V^2
VBF	WW	$\kappa_V^2 \kappa_V^2 / [¾ \kappa_F^2 + ¼$	κ_V^4 / κ_F^2



κ_V, κ_F results: CMS

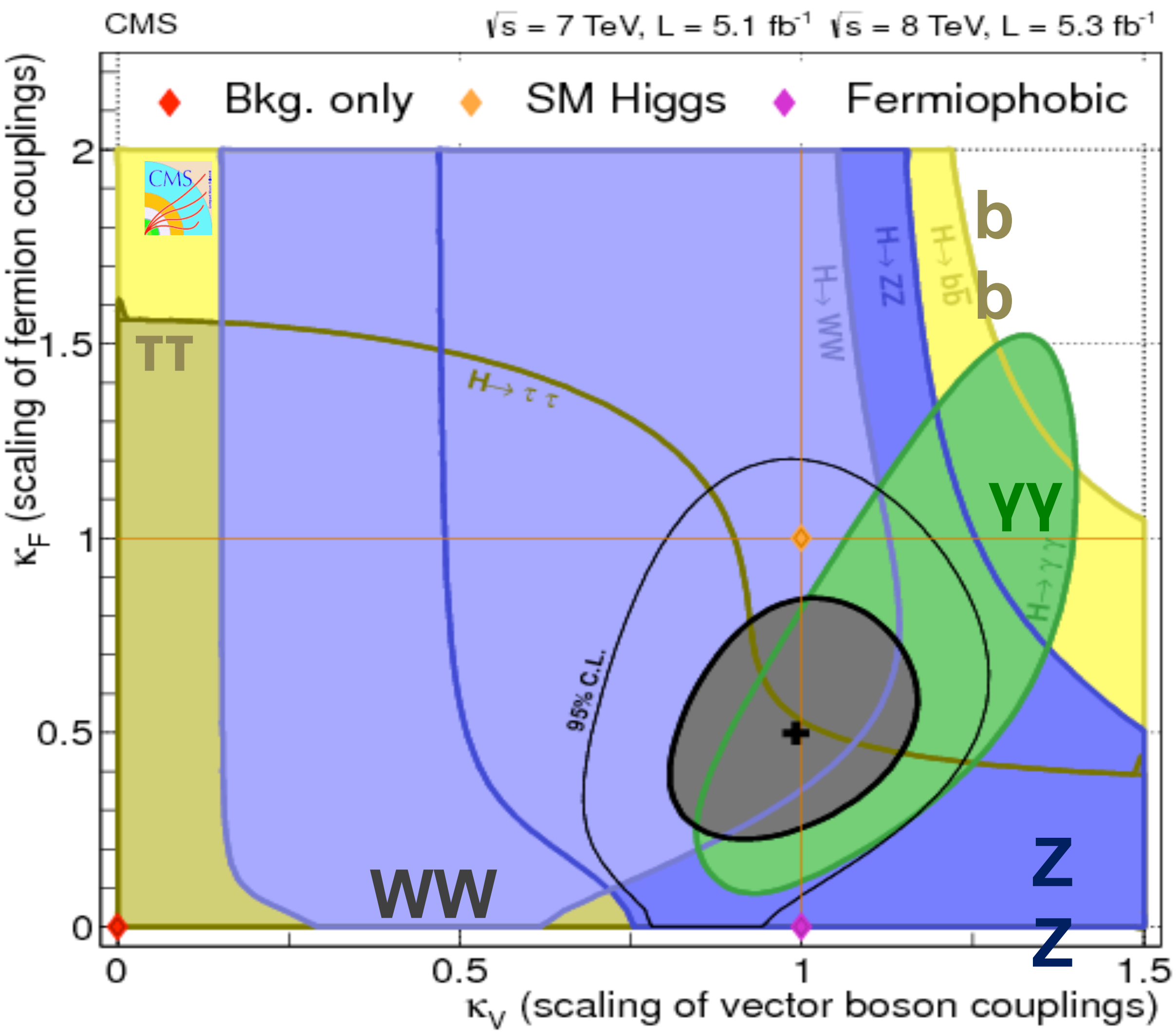


SM: $\kappa_V, \kappa_F = 1,1$

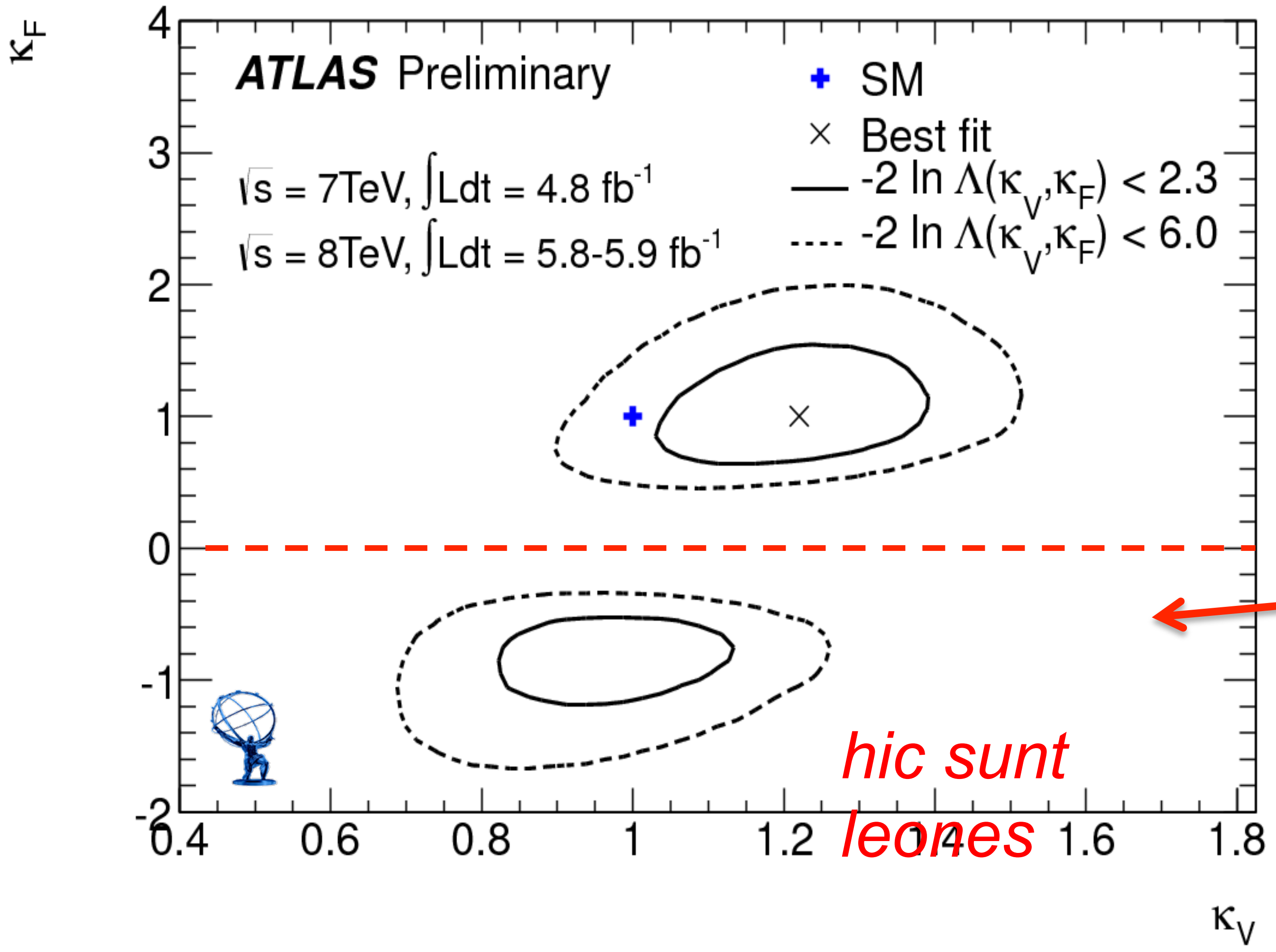
Best fit point
$\kappa_V \sim 1, \kappa_F \sim 0.5$

Fermiophobic

κ_V, κ_F results: CMS



κ_V, κ_F results: ATLAS



$\kappa_V \cdot \kappa_F < 0$: allow fermions and bosons to interfer constructively in the γγ loop.

Testing custodial symmetry

- In most alternative models to the SM, the ratio of the Higgs-like boson couplings to W and Z
  is fixed to the SM value.
- Two ways of probing it:
  - *Directly from the the measured WW, ZZ yields*
  - *From a fit to the full dataset , as in* κ_V *,* κ_F *but with independent parameters for W and Z*
- Each approach has its merits

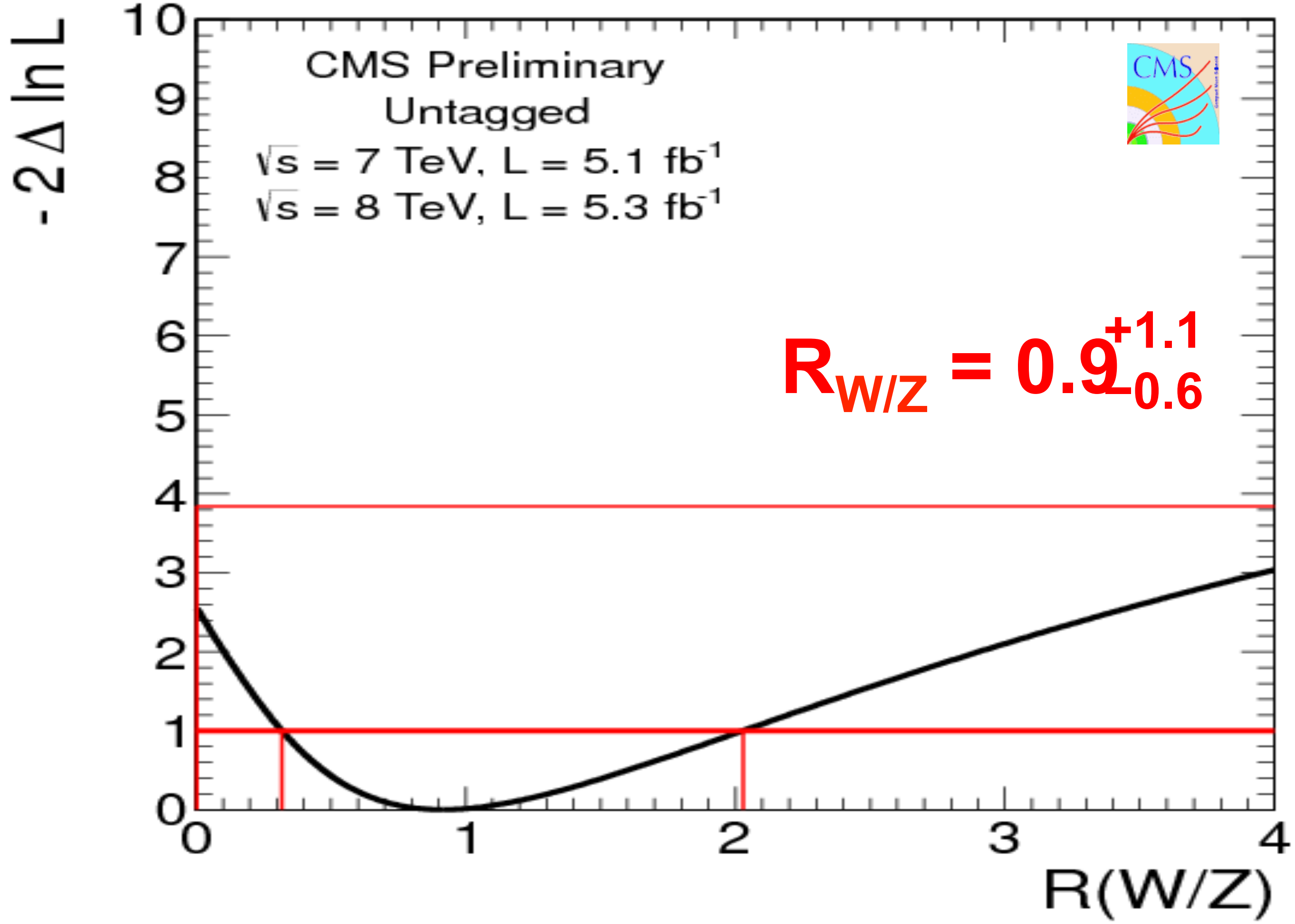
W/Z from event yields

- Ideally one would like to select WW, ZZ decays from the same ggH production mode, so that the ratio of yields depends only on the BRs.
- However, both CMS and ATLAS have an inclusive ZZ analysis, with with an O(10%) contamination from VBF and VH.

$$\mathbf{N_{WW}/N_{ZZ} = BR_{WW} / BR_{ZZ} \cdot (1 + \sigma_{VBF+VH}/\sigma_{ggH})^{-1}}$$

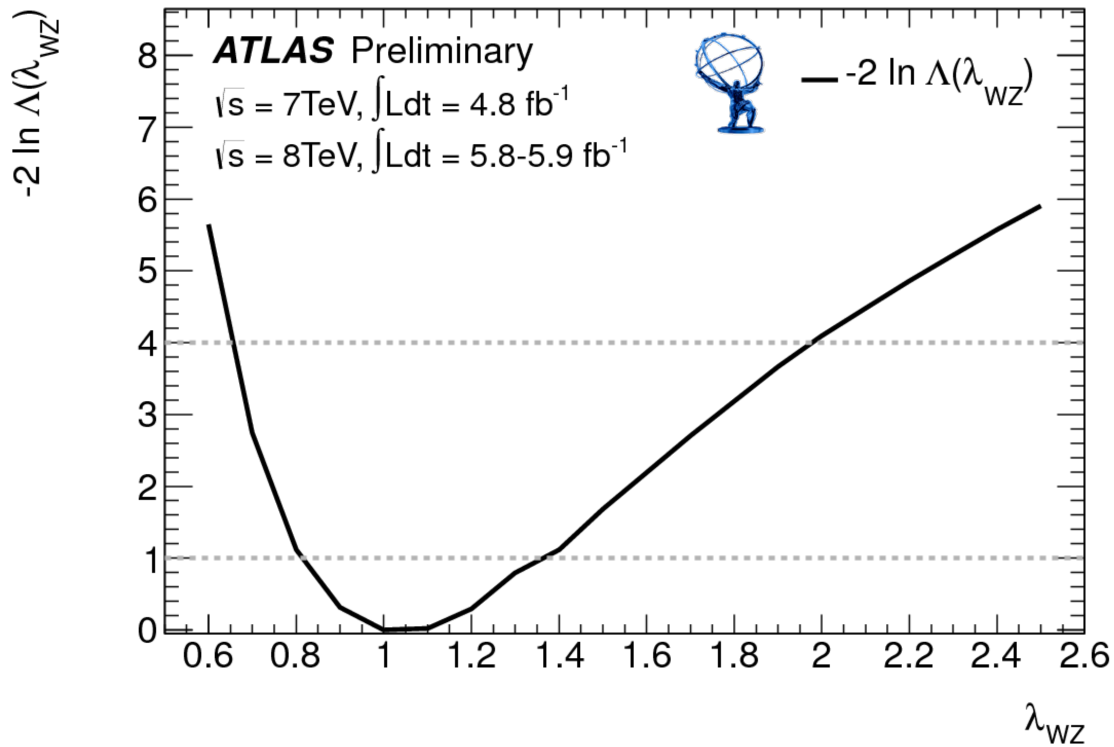
- If $\sigma_{VBF+VH}/\sigma_{ggH}$ is diffent from the SM value, the ratio of yields can depart from 1.0 even if the ratio of W and Z couplings is as in the SM.

W/Z from event yields



W/Z from couplings

- Three parameter fit: κ_F, κ_Z, $\lambda_{WZ} := \kappa_W / \kappa_Z$
- Leave κ_F, κ_Z float freely, get a constraint



$\lambda_{WZ} = 1.07^{+0.35}_{-0.27}$

Note: $R_{W/Z} \sim (\lambda_{WZ})^2$

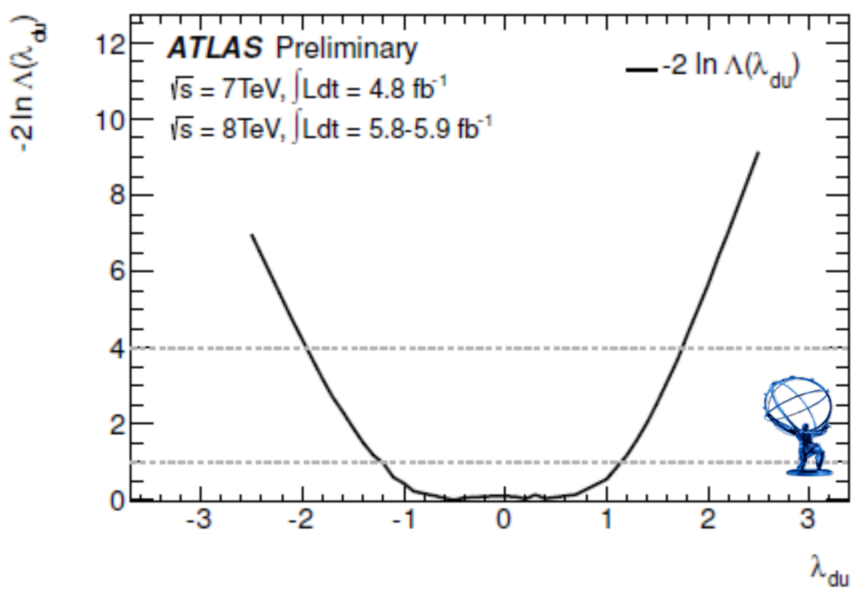
$\Delta R/R \sim 2\,\Delta\lambda/\lambda$

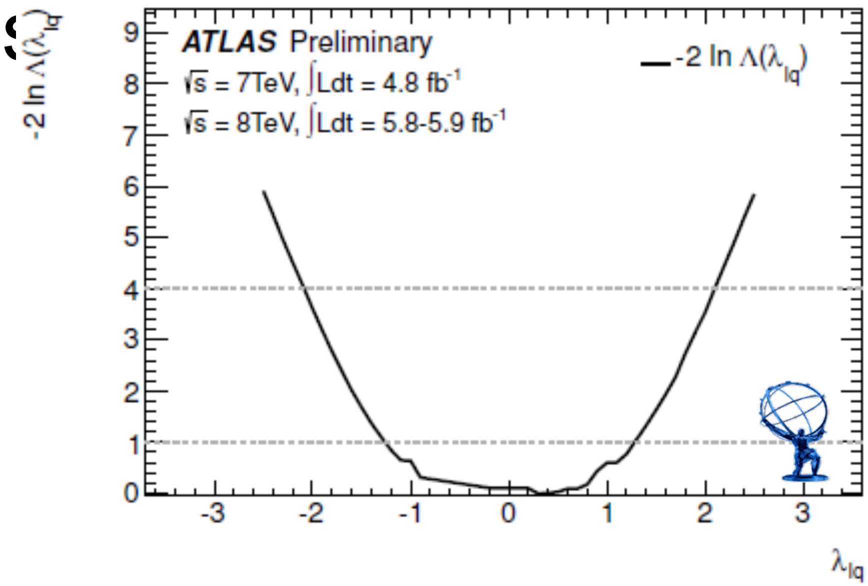
Fermion non-universality

- Several BSM models predict different couplings for the Higgs to different fermion kinds.
- Two benchmark models devised to probe this:
  - *Allow separate couplings for up-type and down-type fermions : separate **t** vs from **b, τ***
  - *Allow separate couplings to quarks and leptons*
- In both cases, the coupling to the top is measured only from the ggH production cross sectiton,

Fermion non-universality

- Due to the deficits observed bb and ττ at LHC compared with the SM Higgs predictions, the fits prefers values of $\boldsymbol{\lambda_{du}}$, $\boldsymbol{\lambda_{lq}}$ close to zero.





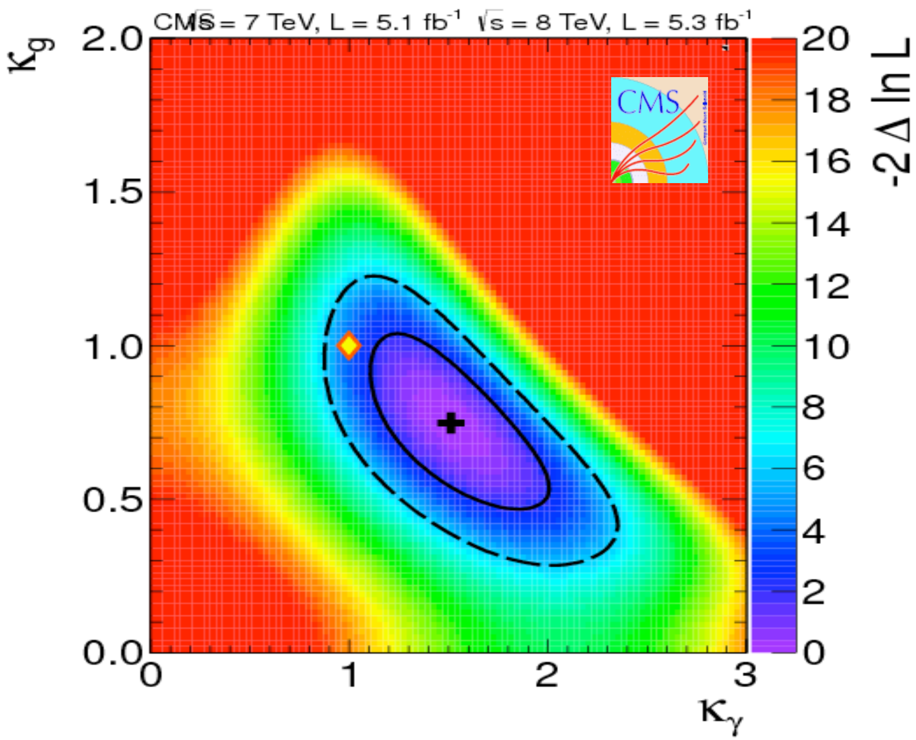
Search for BSM physics in loops

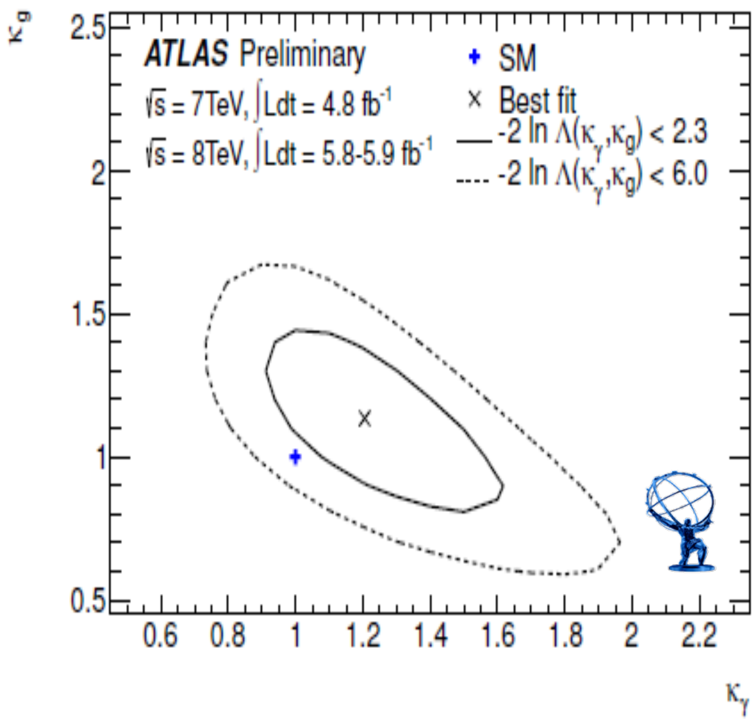
Alternative benchmark model:

- Assume the tree-level couplings between Higgs and the other particles are as in the SM
- However, allow extra contributions to the loops that give the effective gluon and γ couplings:
  treat κ_g, κ_γ as free parameters and scale

$$\sigma_{ggH} \sim \kappa_g^2 \quad \Gamma_{gg} \sim \kappa_g^2 \quad \Gamma_{\gamma\gamma} \sim \kappa_\gamma^2$$

Search for BSM physics in loops





Note anti-correlation from $\sigma \cdot BR(gg \to H \to \gamma\gamma) = \kappa_g^2\,\kappa_\gamma^2$

Search for BSM physics in decays

- As the previous model, but allow also for BSM decays of the Higgs boson in modes not searched for.
- Constrain BSM decays through the total width

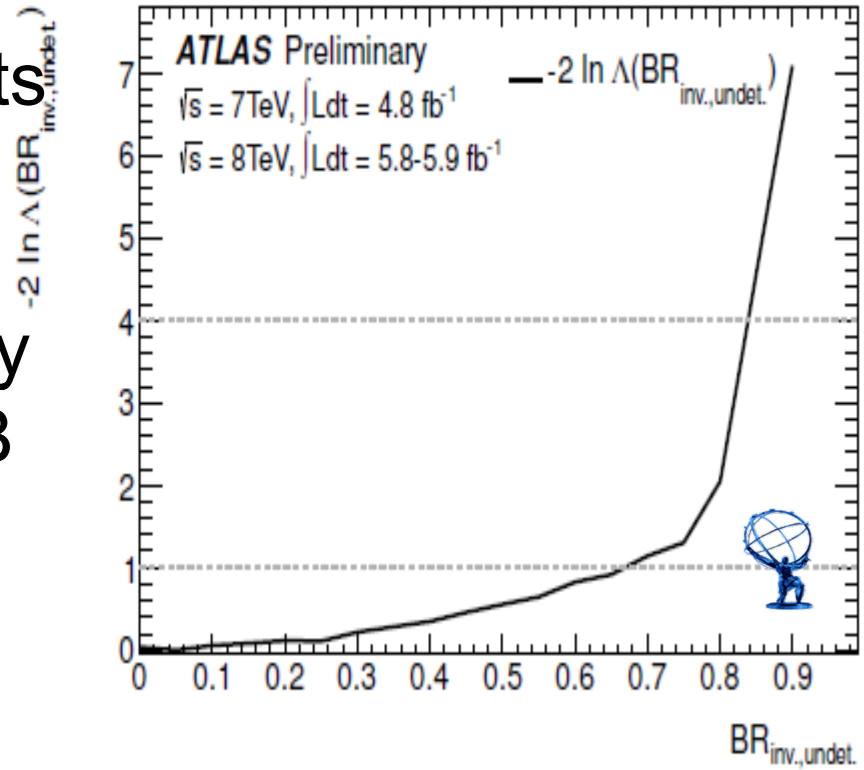
$$\Gamma_{tot} = \Gamma_{SM} + (\kappa_g^2 - 1) \cdot \Gamma_{gg} + \Gamma_{BSM}$$

- Hard to do for unconstrained κ_g, κ_γ values, as most of the really sensitive modes rely on ggH production or on γγ decay.

Search for BSM physics in decays

For now can only constrain BR_{BSM} to be below ~90%

Expect larger improvements when non-ggH modes become more sensitive: currently they're statistically limited, but have better S/B

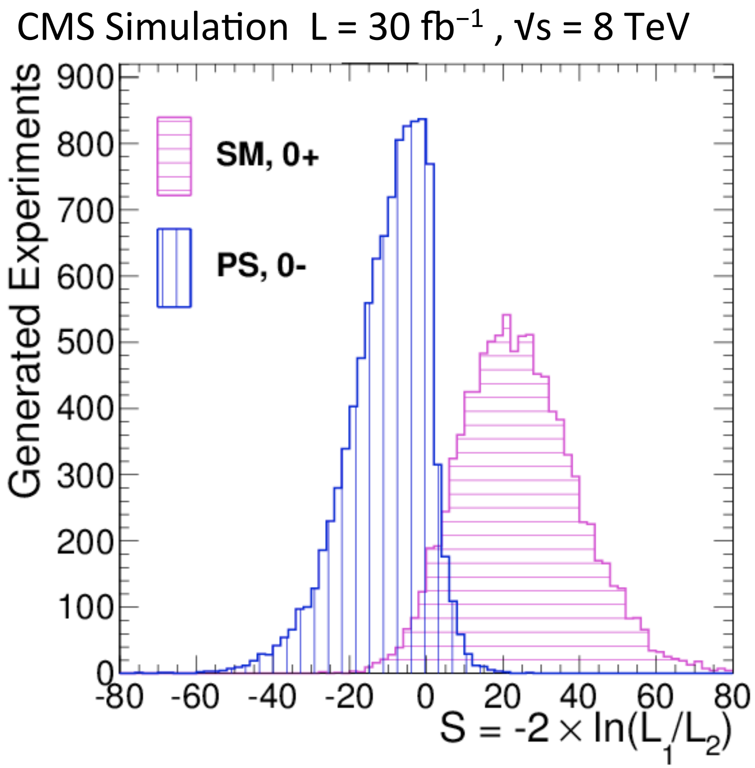


Spin and parity

- Previous coupling tests all assumed $\mathbf{J^{CP} = 0^+}$
- The picture becomes increasingly more complex if this requirement is dropped. Especially true for J=2, where there are potentially many tensor couplings to consider.
- So far, studies done only trying to separate between SM H and another fixed alternative hypothesis (e.g. minimal $\mathbf{0^-}$). However, we might be dealing with a mixed parity state, or with non-minimally coupled particle.

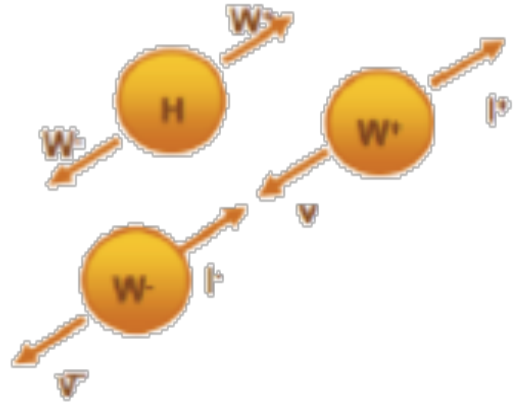
Spin and parity: ZZ

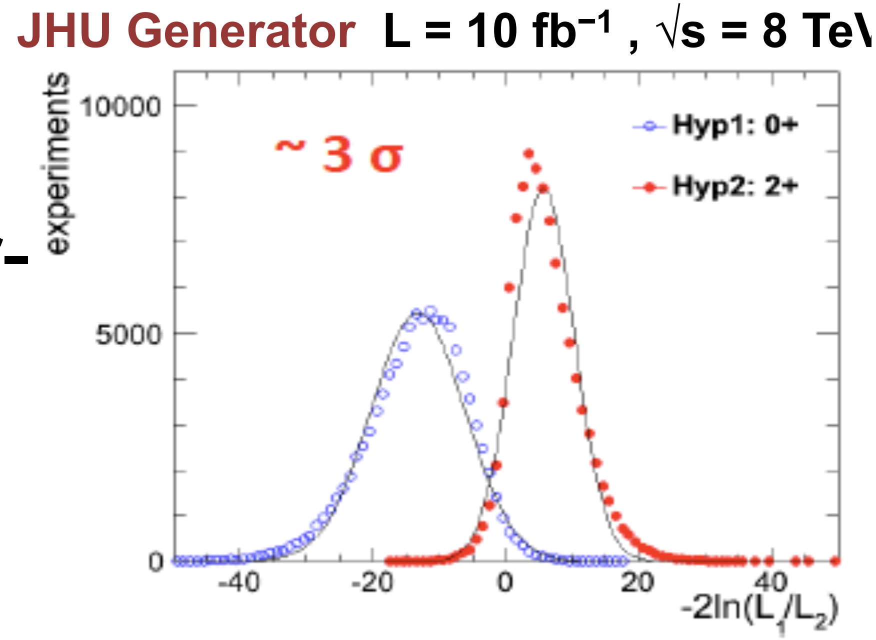
- From angular distribution of ZZ decay products: full analysis done at CMS, expect 2-3σ separation between SM Higgs and a minimal pseudo-scalar Higgs model.
- Spin 2 case more complex.
  For a graviton-like H, expect little or no separation with this year data.



Spin and parity: WW

- Spin alignment is already used in the WW search:
  the fact we see a signal supports J=0 vs J=2.
- No full analysis done yet, but from generator-level studies one expects 2-3σ separation of J=0 vs J=2 with this year data.





Spin parity: γγ and VH modes

- Other ways of testing the spin and parity have been proposed:
  - *from angular distribution in γγ, inclusive and VBF*
  - *from transverse mass distribution of V+H system*
- However, it will likely take a while before results from this approach will be ready. Maybe first results for Moriond?

Beyond this LHC run

- Some first projections have been done to estimate the sensitivity of the LHC with higher integrated luminosity and beam energy.
- Improvement expected in two directions:
  - *The sensitivity in the currently explored decay modes will be increase: larger event yields in signal region, larger control and calibration samples, ...*
  - *New modes with low yield but good S/B will start to be accessible.*

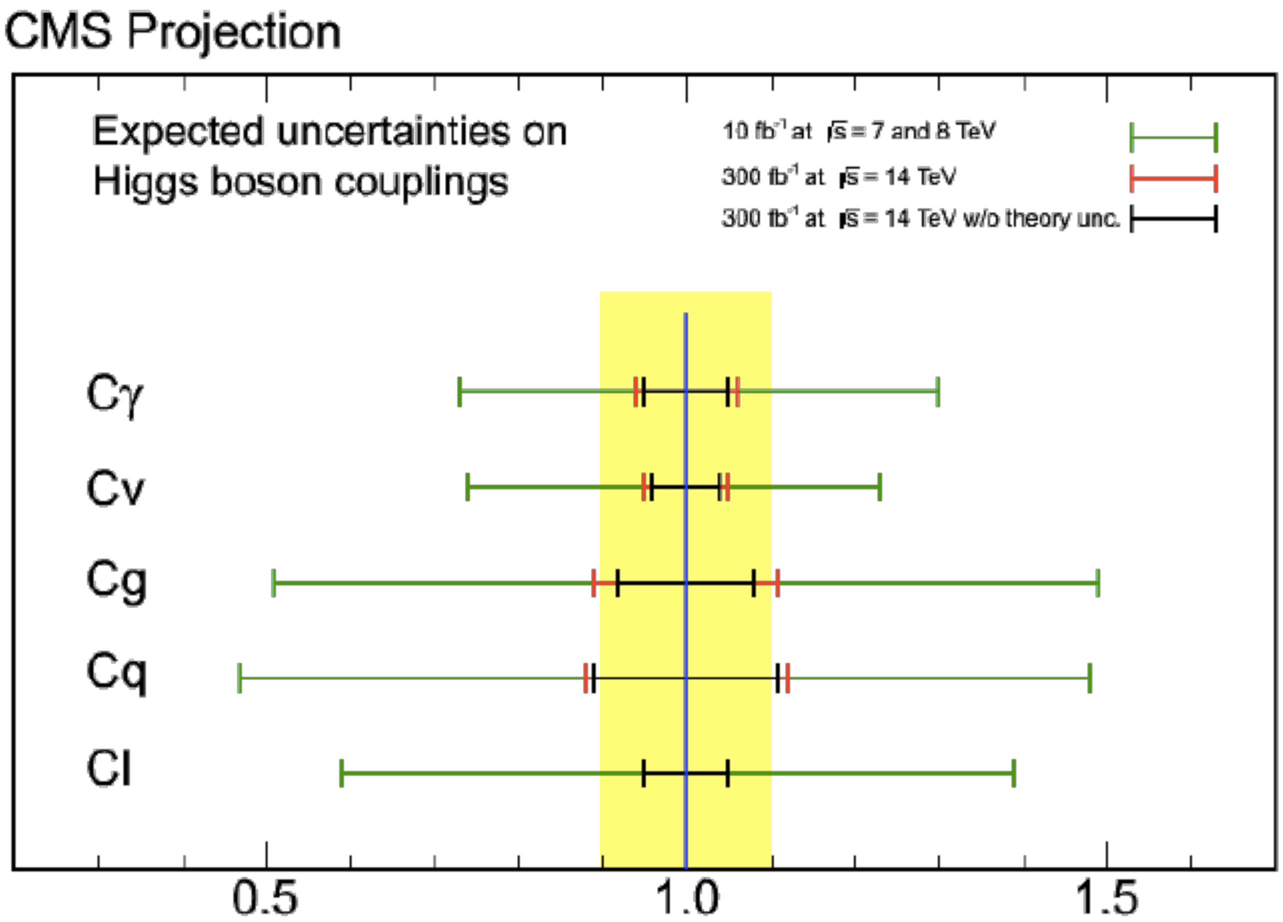
More precision

Naïve rescaling of uncertainties on σ×BR with √(σ×L),

NOT AN OFFICIAL CMS PROJECTION

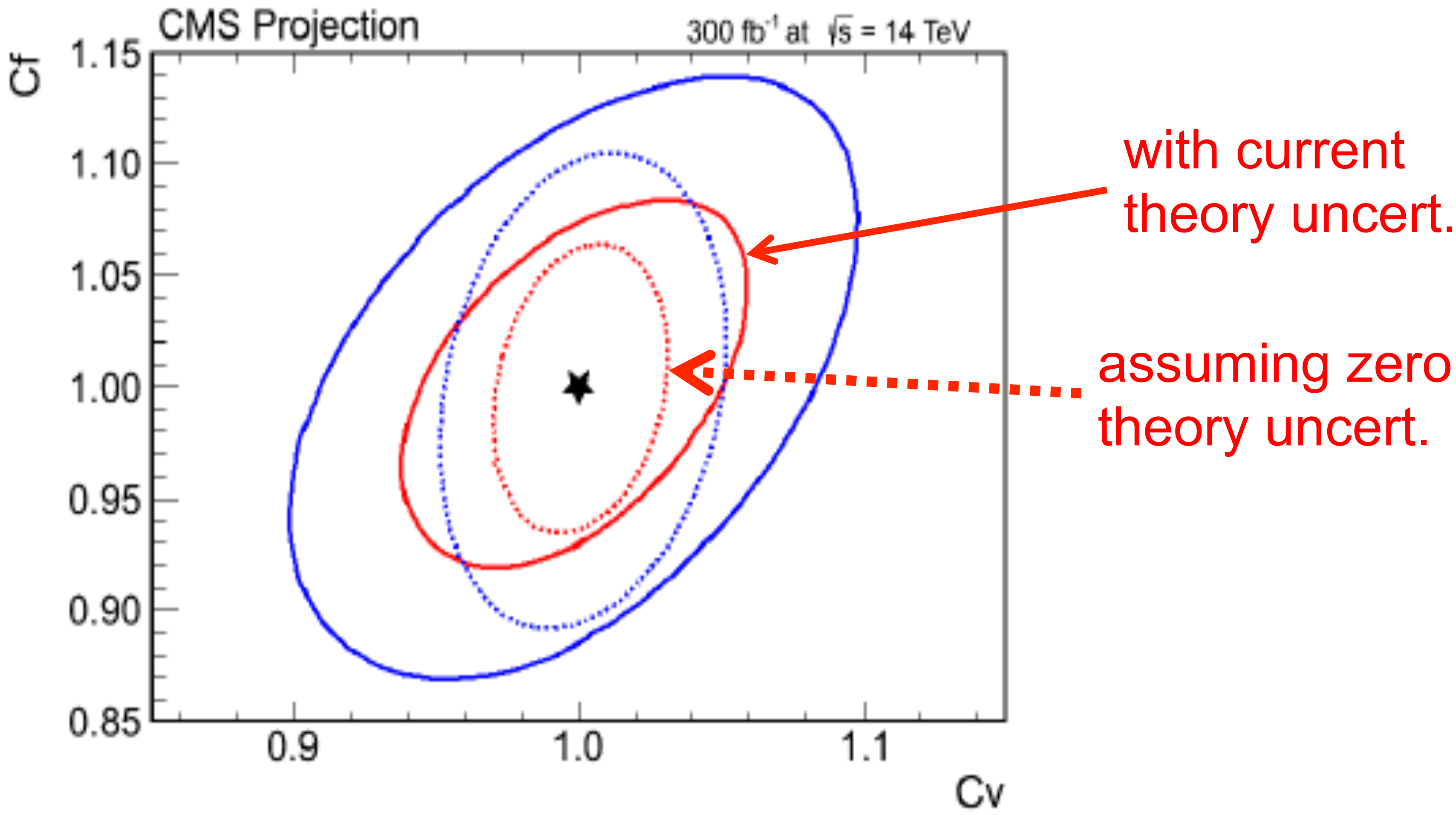
Decay	Prod.	30+30 fb^{-1} @ 8 TeV	300fb^{-1} @ 14 TeV
$H \to bb$	VH	30%	10%
$H \to bb$	ttH	60%	10%
$H \to \tau\tau$	ggH	40%	10%
$H \to \tau\tau$	qqH	40%	10%
$H \to \gamma\gamma$	ggH	20%	6%
$H \to \gamma\gamma$	qqH	40%	10%
$H \to WW$	ggH	16%	5%
$H \to WW$	qqH	60%	16%
$H \to ZZ$	ggH	16%	5%

Measure couplings at 10%



http://indico.cern.ch/contributionDisplay.py?contribId=144&confId=175067

Theory uncertainties become important



More modes

- ttH, H→bb: expect to reach $\Delta\sigma/\sigma$ ~ 100% with this year data, and σ grows fast with energy. Important to probe top coupling at tree level.
- VBF, VH to ZZ: expect just ~1 event with 30 fb^{-1}
- H → Zγ: another constraint to BSM H→ γγ
- H → μμ: 3σ evidence in reach with ~3000 fb^{-1} ?
- H+H → bb+γγ: ??? Still to be studied.
- Note: some of these measurements are not trivial to do at a low-luminosity linear e^+e^- collider

Conclusions

- After the observation of H125, now we are focusing on measuring its properties.
- Mass already measured to better than 0.5%
- Started to probe the couplings: currently with O(50%) uncertainties, but could gain a factor 2 this year, and reach ~10% with $300 fb^{-1}$ @14TeV
- Effort also ongoing for J^{CP} measurements. Some results expected on this year data.