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HIGGS COUPLINGS (ATLAS+CMS)

On behalf of LHCHCG

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

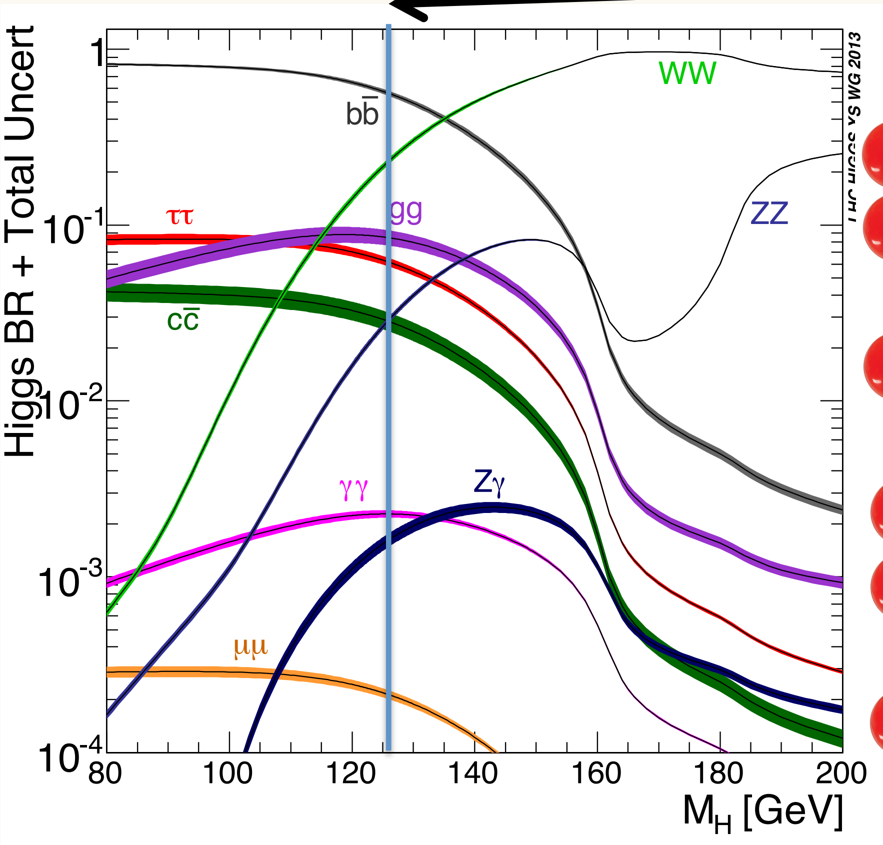
15th September 2015

A paper should come out any day
New and final measurements

Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC *pp* collision data at $\sqrt{s} = 7$ and 8 TeV

Theory Inputs I: Higgs Decays

m_H=125.09 GeV



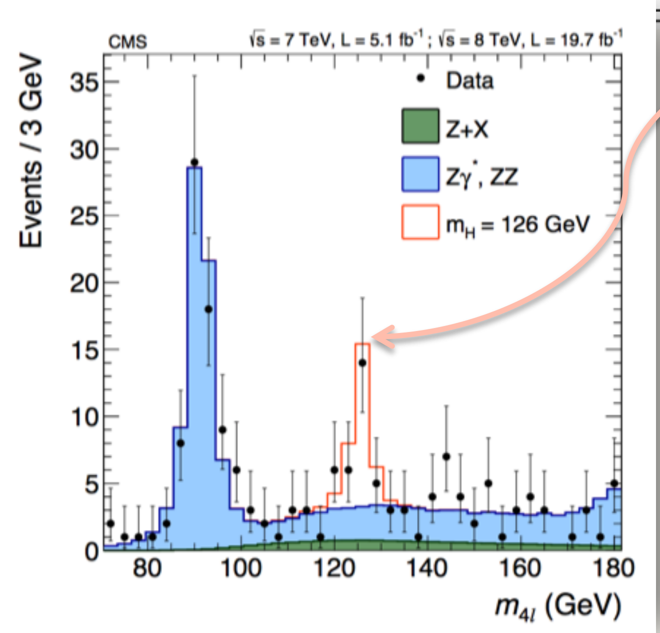
Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

(Note! No 1st or 2nd gen fermions)

The natural width of the Higgs boson is expected to be very small, 4.1 MeV (< resolution)

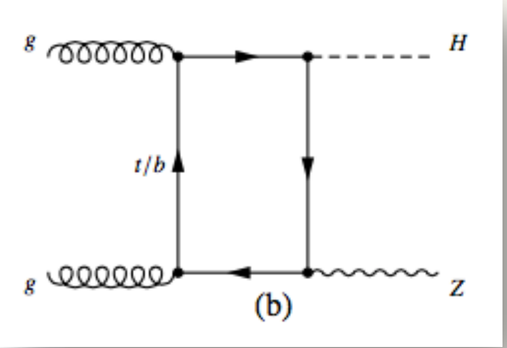
Theory Input : Event (MC) Generators

Production process	Event generator	
	ATLAS	CMS
ggF	Powheg [30,31,32,33,34]	Powheg
VBF	Powheg	Powheg
WH	Pythia8 [35]	Pythia6.4 [36]
ZH ($qq \to ZH$ or $qg \to ZH$)	Pythia8	Pythia6.4
$ggZH$ ($gg \to ZH$)	Powheg	See text
ttH	Powhel [44]	Pythia6.4
tHq ($qb \to tHq$)	MadGraph [46]	aMC@NLO [29]
tHW ($gb \to tHW$)	aMC@NLO	aMC@NLO
bbH	Pythia8	Pythia6, aMC@NLO



Theory Input II: Event Generators

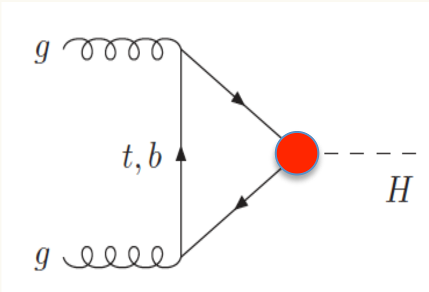
Production process	Event generator	
	ATLAS	CMS
ggF	POWHEG [30,31,32,33,34]	POWHEG
VBF	POWHEG	POWHEG
WH	PYTHIA8 [35]	PYTHIA6.4 [36]
ZH ($qq \to ZH$ or $qg \to ZH$)	PYTHIA8	PYTHIA6.4
$ggZH$ ($gg \to ZH$)	POWHEG	See text
ttH	POWHEL [44]	PYTHIA6.4
tHq ($qb \to tHq$)	MADGRAPH [46]	aMC@NLO [29]
tHW ($gb \to tHW$)	aMC@NLO	aMC@NLO
bbH	PYTHIA8	PYTHIA6, aMC@NLO



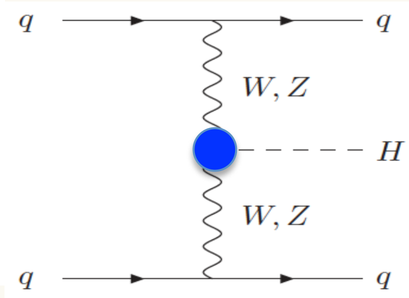
Subtlety: : the ggZH makes about 8% of the ZH cross section, yet it has harder pT spectrum and therefore contributes more to the measurement (mainly H->bb which is based on VH). CMS did not use the generator (was not in the market at the time of publication), so a pT reweighted qq->ZH spectrum sample is used (for Hbb), such that the two production processes can be considered as separate in the fit
(this is one thing that is different than the CMS publication).

Theory Inputs III: Production Modes

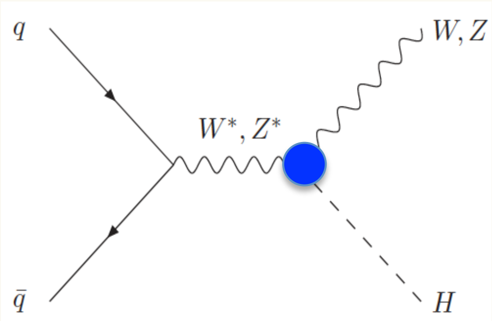
ggH



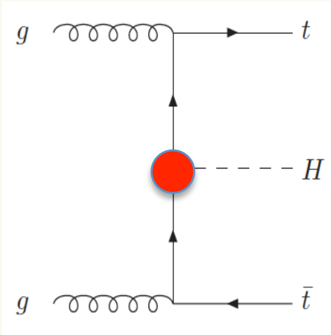
VBF

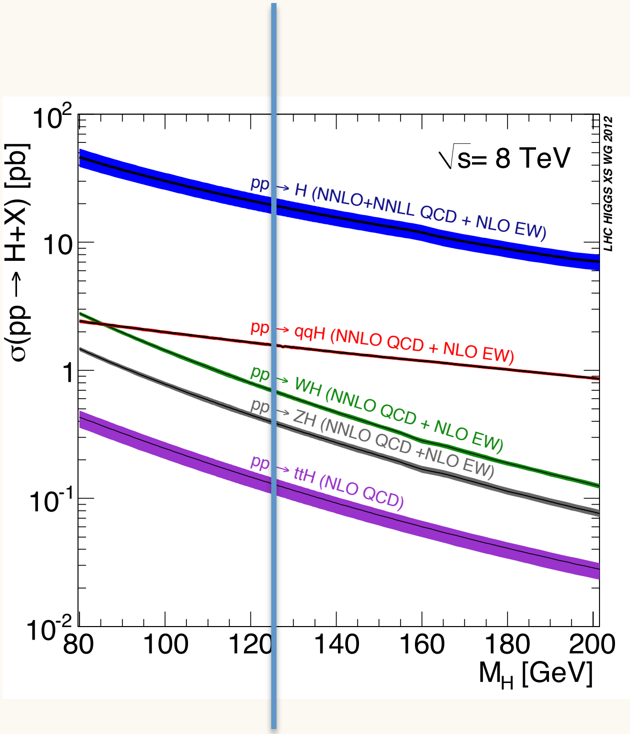


VH



ttH

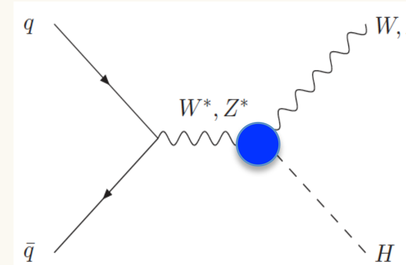




Production process	Cross section [pb] $\sqrt{s}=7$ TeV	$\sqrt{s}=8$ TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

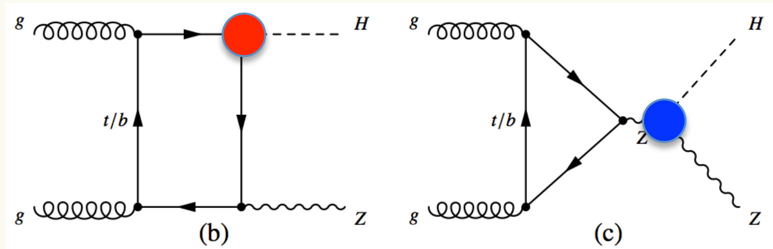
SM ggF, ttH, bbH theory uncertainty: ~10%
VBF, VH, ZH: 2-3%

Theory Inputs IV: Other Production Modes



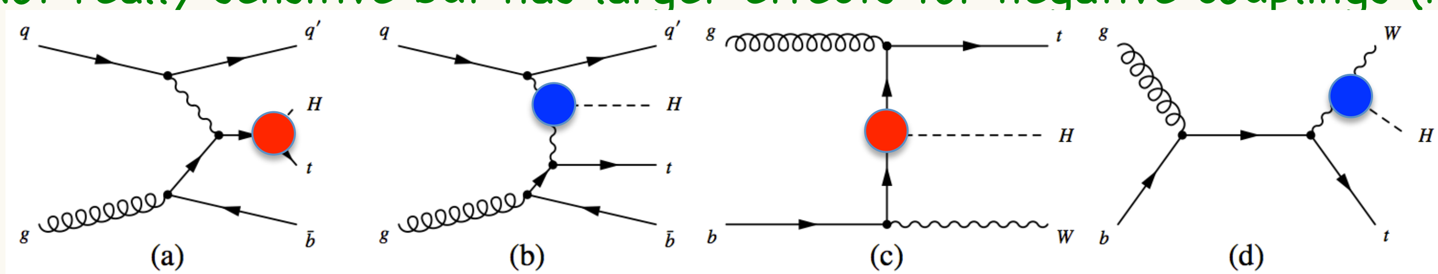
ggZH:

O(10%) effect on VHbb in SM, higher p_T than qqZH



tHq + tHW

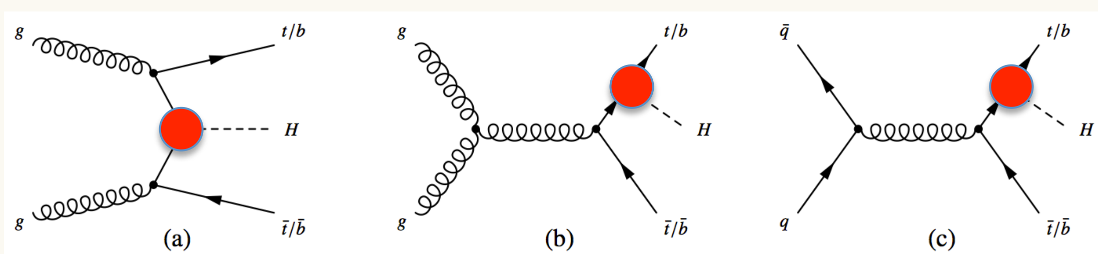
Not really sensitive but has larger effects for negative couplings (kF,kV)



bbH

bbH is ~1% of total HXSC.

Similar to ttH but not really distinguishable from ggF

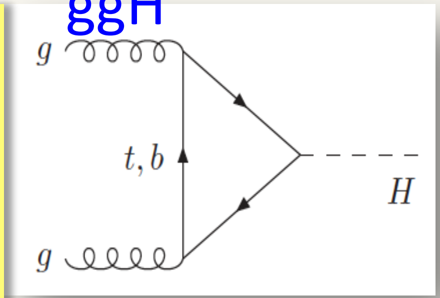


Theory Inputs V: Subtleties

Subtleties:

- pTH for ggF production is reweighted to match calculation of HRes2.1. which includes NNLO (NN Leading Order) and NNLL (NN Leading Log) corrections.
- ggH events with >=2 jets, are reweighted to match pTH from POWHEG MiNLO H+2jets predictions.

ggH



- This consistent treatment between the two experiments of the most prominent theoretical aspects of Higgs boson production and decay is quite important since all theoretical uncertainties in the various signal processes are treated as correlated for the combination.

What do we measure (observables)

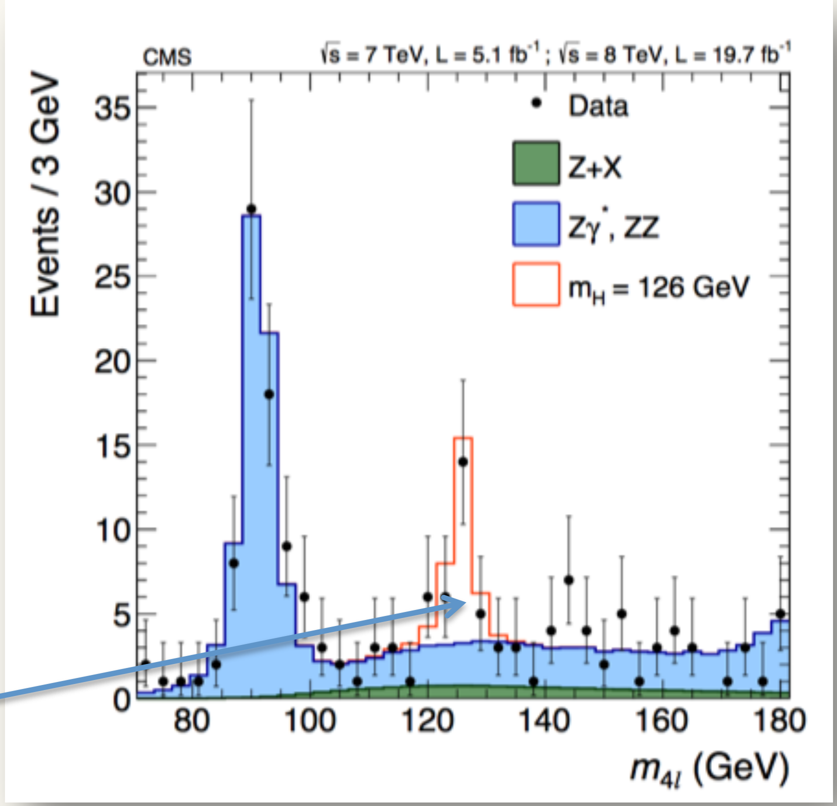
A simplified view:

We measure event yields

(in bins, i.e. shapes)

We want to derive couplings and signal strengths

The analysis is using discriminators (usually reconstructed mass related) to increase S/B



$$n_s(i \rightarrow f) = \mu^i \mu^f \times (\sigma^i \times Br^f)_{SM} \times A^i_p \times \varepsilon^i_p \times Lumi$$

$$i \in (ggF, VBF, VH, ttH) \quad f \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}} \quad \text{and} \quad \mu^f = \frac{BR^f}{(BR^f)_{SM}}$$

What do we measure (observables)

A simplified view:

We measure event yields

(in bins, i.e. shapes)

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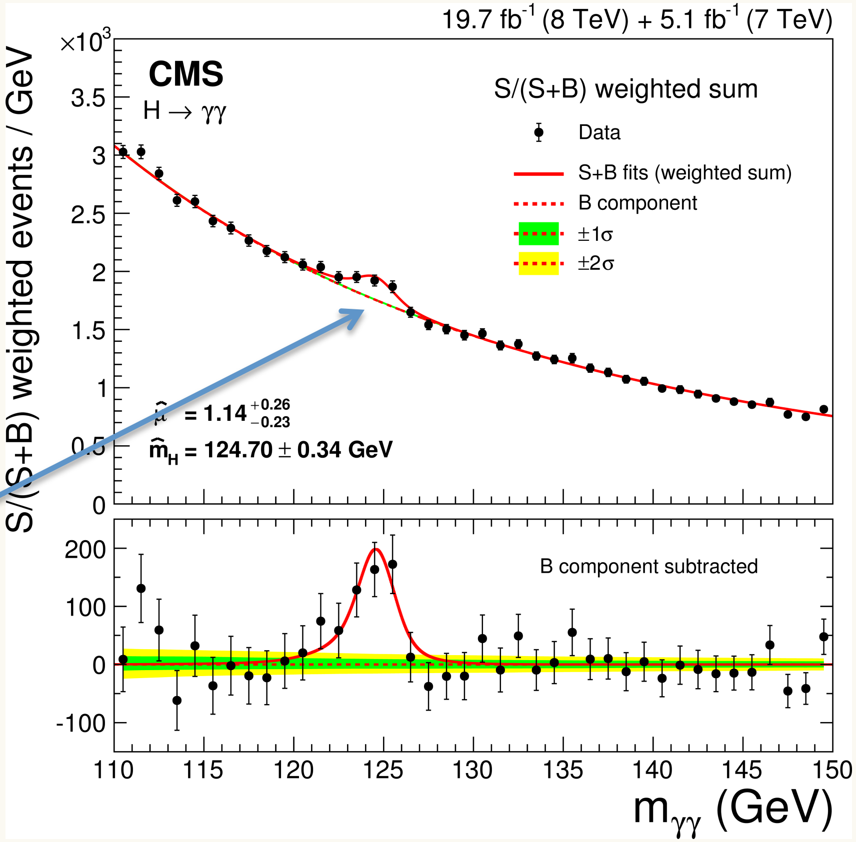


$$n_s(i \rightarrow f) = \mu^i \mu^f \times (\sigma^i \times Br^f)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

$$i \in (ggF, VBF, VH, ttH) \quad f \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

PO

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

What do we Measure?

We measure event yields

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\text{SM}}} \quad \text{and} \quad \mu^f = \frac{\text{BR}^f}{(\text{BR}^f)_{\text{SM}}}$$

Pseudo Observables

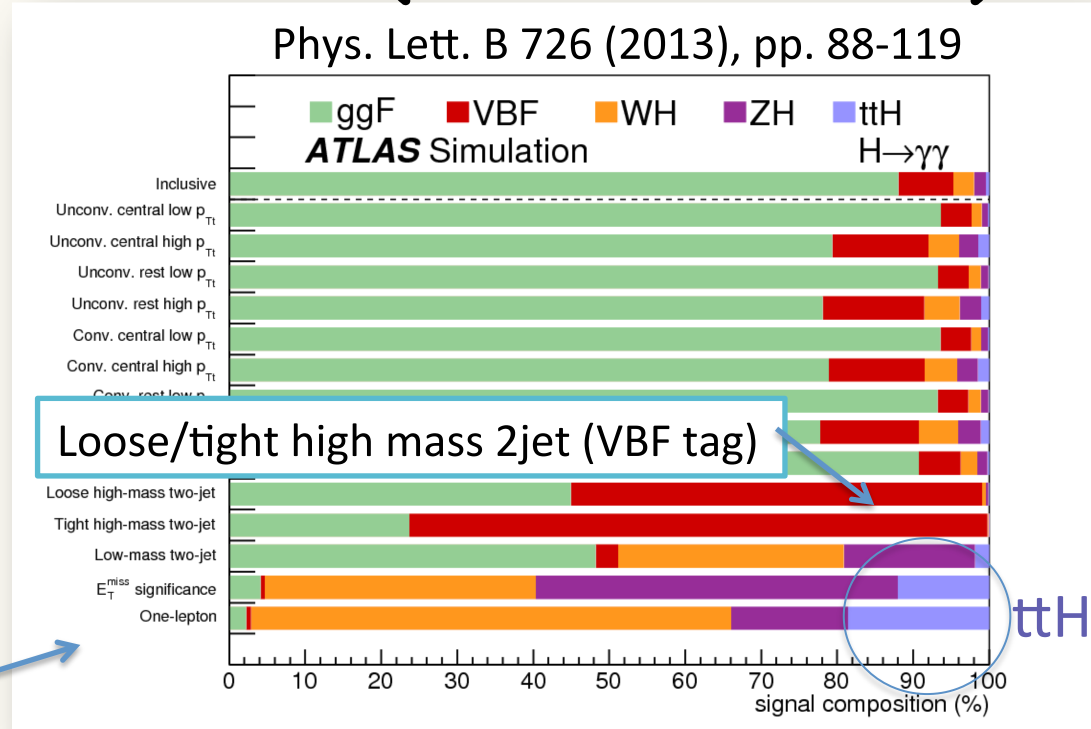
$$\mu_i^f = \frac{\sigma_i \cdot \text{BR}^f}{(\sigma_i)_{\text{SM}} \cdot (\text{BR}^f)_{\text{SM}}} = \mu_i \times \mu^f$$

$$n_s(i \to f) = \mu^i \mu^f \times (\sigma^i \times Br^f)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

Observable | PO | Theory | Theory & Experiment | Accelerator & Experiment

What do we measure (observables)

We increase sensitivity by classifying the events via categories and measure the signal strength per category and then combining them taking all the sytematic and statistical errors uncertainties into account



The categories are also sensitive to different production modes, allowing the measurement of the couplings

$$n_s^c(\gamma\gamma) = \sum_{i,c} \mu^{i,c} \times \mu^{\gamma\gamma,c} \times (\sigma^i \times Br^{\gamma\gamma})_{SM} \times A_i^{\gamma\gamma,c} \times \varepsilon_i^{\gamma\gamma,c} \times Lumi$$

$$i \in (ggF, VBF, VH, ttH)$$

PO

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

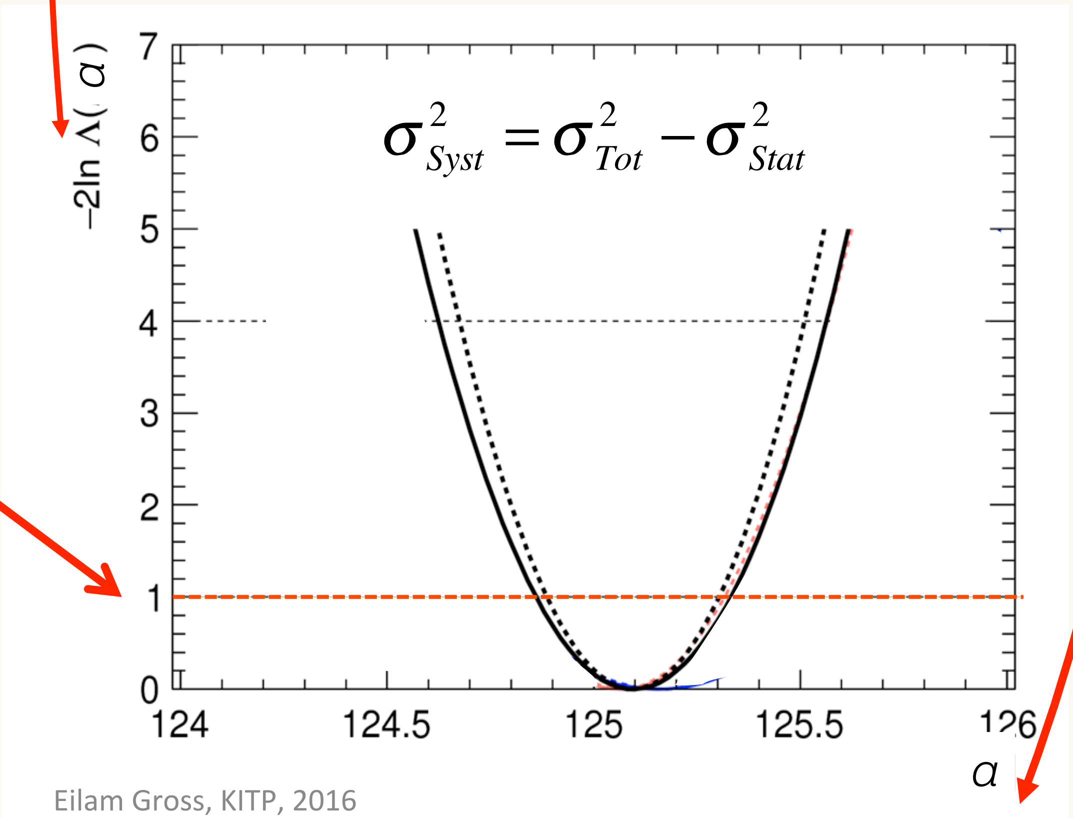
Statistical treatment – profile likelihood

From thw combined data of (ATLAS+CMS) construct the **profile likelihood** with the parameter(s) of interest α

Θ: vector of ~4200 nuisance parameters

$$t_\alpha - 2\ln\frac{L(\alpha,\hat{\hat{\theta}}_\alpha)}{L(\hat{\alpha},\hat{\theta})}$$

68% Confidence interval defined by a rise of 1 unit in $t(\alpha)$ (asymptotic limit)



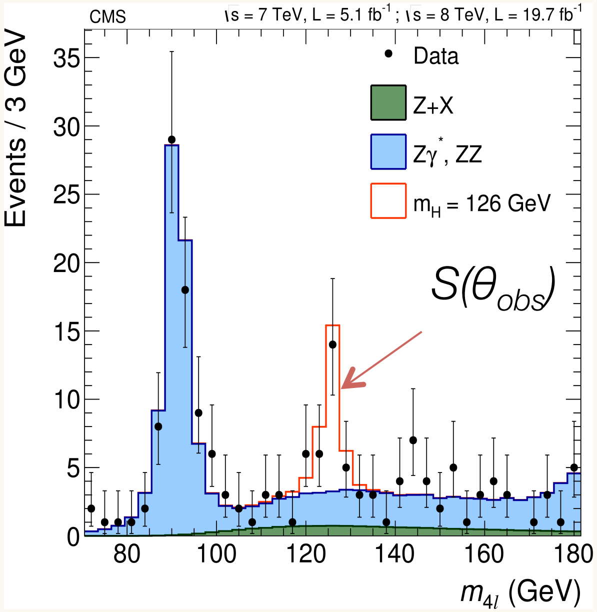
Systematics and Nuisance Parameters

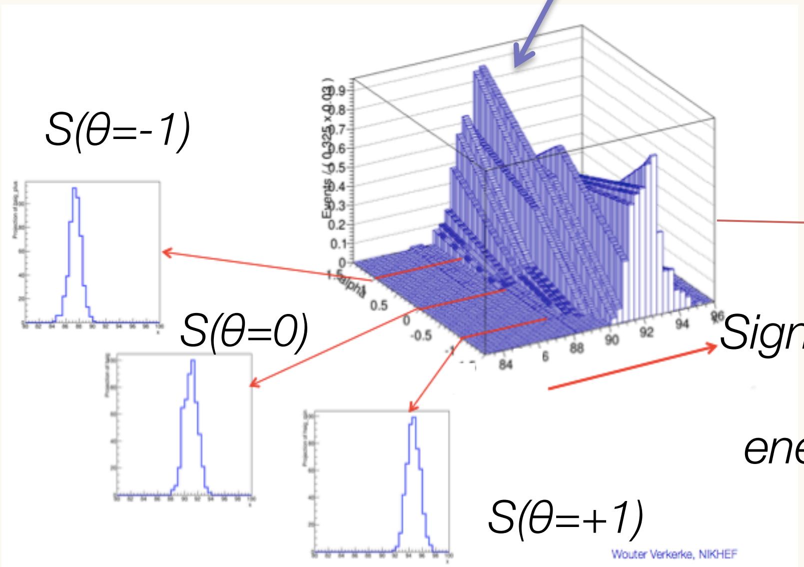
Profile likelihood ratio test statistics:

The signal/background distributions can *describe distributions under a wide range of parameters* for which the true values are unknown (energy scales, QCD scales…)

Illustration: modeling of energy scale uncertainty

$$n_{s+b}(i \to f) = \mu^i \mu^f \times s_i^f(\theta) + b$$





Systematics and Nuisance Parameters

Profile likelihood ratio test statistics:

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

for each likelihood evaluation, all systematic uncertainties (**nuisances**) are varied to maximize the profile likelihood (**profiled**)

~4200 nuisances in the combined fits

A large part related to the finite MC statistics

Signal theory normalization uncertainties

BG theory uncertainties (for BGs not using the data)

Other experimental uncertainties

Most experimental uncertainties are assumed uncorrelated between the two experiments and many tests have been carried out to check the possible impact that was found negligible

Main signal theoretical sources of uncertainties :

QCD scales,

parton distribution functions (PDF),

UEPS

Higgs boson branching ratios (BRs).

A care was taken that the state-of-the art calculations of theoretical cross sections and BR, Higgs p_T are common between the two experiments.

Sometimes this care required modifications of the analyses.

Systematics (NPs) details

The PDF uncertainties on the inclusive rates for different Higgs boson production processes are correlated between the two experiments for the same channel but are treated as uncorrelated between different channels, except one case

The WH,ZH & VBF production processes are assumed to be fully correlated

Correlating Experiments and Channels

$$L_{ATLAS,ZZ}\left(\mu.\theta_{QCDscale},\theta_{PDF},\theta_{ATLAS_{Det}},\theta,.....\right)$$

$$L_{ATLAS,\tau\tau}\left(\mu.\theta_{QCDscale},\theta_{PDF},\theta_{ATLAS_{Det}},\theta,.....\right)$$

$$L_{ATLAS,ZH}\left(\mu.\theta_{QCDscale},\theta_{PDF},\theta_{ATLAS_{Det}},\theta,.....\right)$$

$$L_{CMS,ZZ}\left(\mu.\theta_{QCDscale},\theta_{PDF},\theta_{CMS_{Det}},\theta,.....\right)$$

$$L_{CMS,ZH}\left(\mu.\theta_{QCDscale},\theta_{PDF},\theta_{CMS_{Det}},\theta,.....\right)$$

$$L_{CMS,WH}\left(\mu.\theta_{QCDscale},\theta_{PDF},\theta_{CMS_{Det}},\theta,.....\right)$$

QCD scale and UEPS uncertainties are correlated between the two experiments in the same production channels and are treated as uncorrelated between different channels.

The WH,ZH & VBF production processes are assumed to be fully correlated

Systematics (NPs) details: Background

- Background modeling Uncertainties are difficult to correlate between experiments because of different selected phase-space regions between the experiments. This is in particular true when the background is driven by data control regions.
- In cases when the BG is fully determined from MC, correlation is safe, e.g. ZZ continuum (BG to ZZ) or ttW and ttZ to ttH multi lepton. Of course in these cases one can correlate the cross section uncertainties.
- Subtlety:

  ttbb and ttb (BG to ttH,H→bb) were treated separately by CMS, while in ATLAS they were correlated (at the price of <10% systematics)

  The choice of different correlation models between the two experiments was studied and yields an impact on the signal strength measurement below 10% of the total uncertainty in this specific channel.

Systematics

In the paper the systematics will be classified to four groups and given in that way for some chosen cases:

Stat

Statistical in nature (Data control regions)

thsig

uncertanties affecting Higgs Boson signal

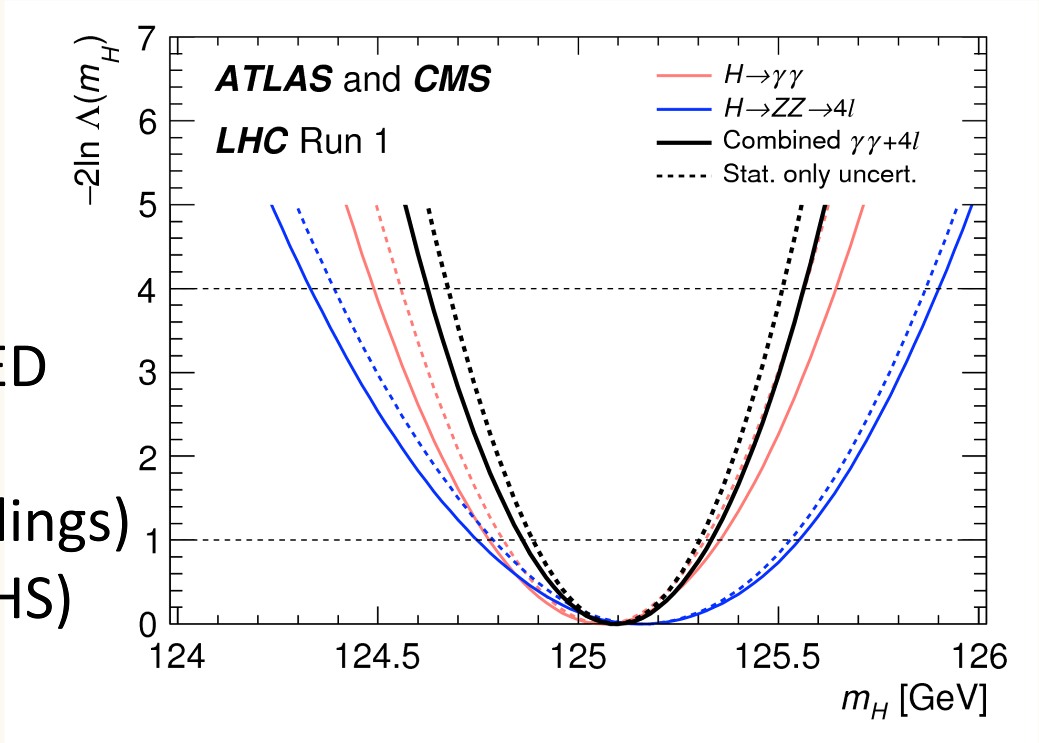
thbgd

uncertainties affecting background processes, not correlated with thsig.

expt

experimental and those related to finite size MC statistics

Effect of Higgs Mass



Effect of
Higgs mass uncertainties
MEASURED AND NEGLECTED

1. No more than2% (couplings) AND 4% (SIGNAL STRENGTHS) due to Dependence on cross section and BR

M_H = 125.09 ± 0.24 GeV
= ± 0.21 (stat.) ± 0.11(syst.) GeV

2.No more than 2% due mass dependence on resolution in the Diphoton and ZZ channels

Experimental Assumptions

- We assume a SM-like Higgs boson with $J^P=0^+$ and with a narrow width (NWA) such that production and decay are decoupled

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_\mathrm{H}}$$

- The mass of the Higgs is assumed to be

$$m_H = 125.09 \text{ GeV}$$

- We cannot separate the production from the decay @ the LHC.
  We measure event yields and deduce
  (for example)the global signal strength $\sigma_i \times BR^f$

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_\mathrm{SM} \cdot (\mathrm{BR}^f)_\mathrm{SM}} = \mu_i \times \mu^f$$

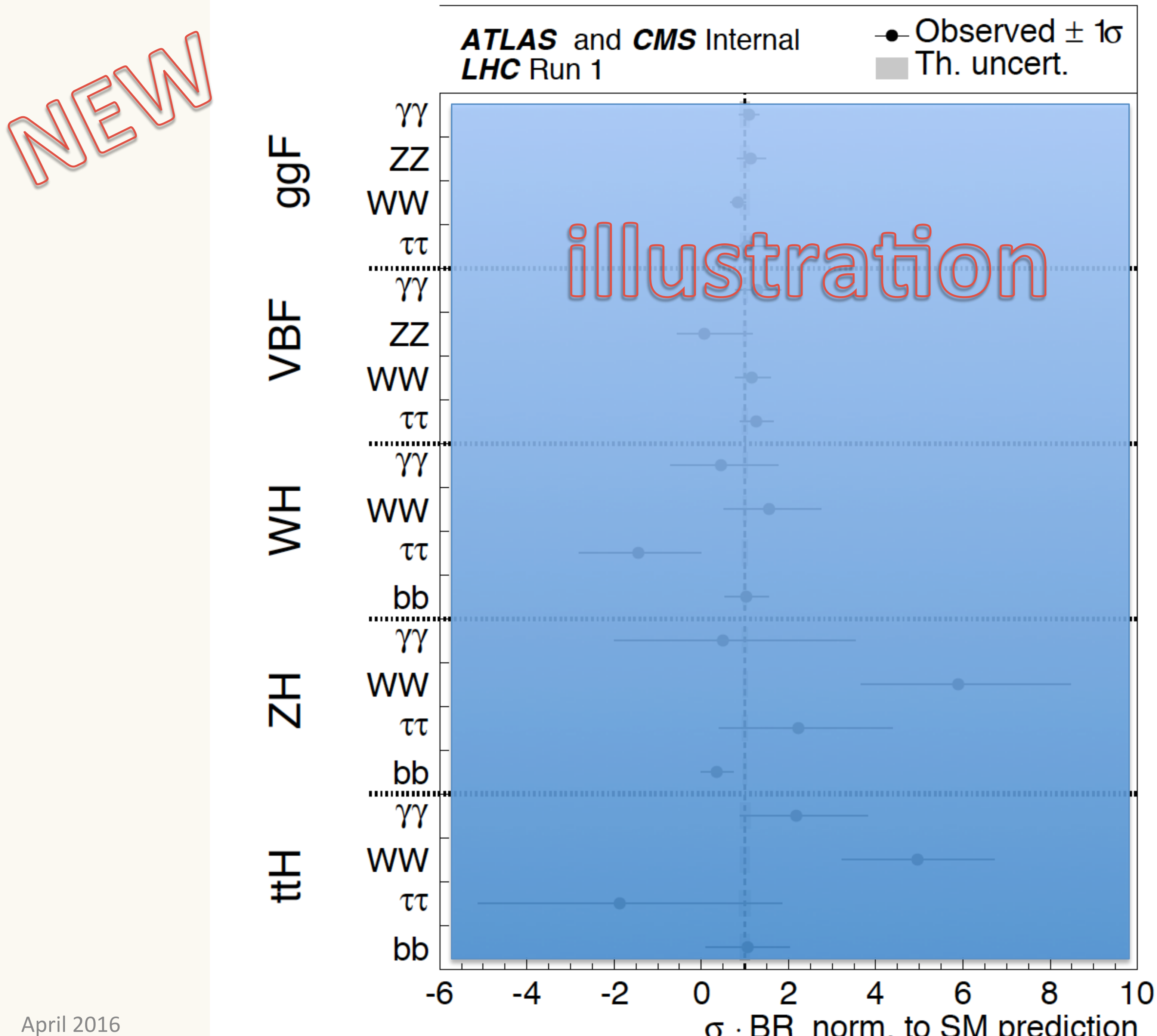
- To measure the global signal strength for a specific channel (f) we need to make assumptions, e.g. all production modes are related to each other via the SM ratios.
  Assumptions should also be made when combining 7 and 8 TeV measurements. **All these assumptions bring some model dependence**

The Mother of all Fits (5x5)

NEW

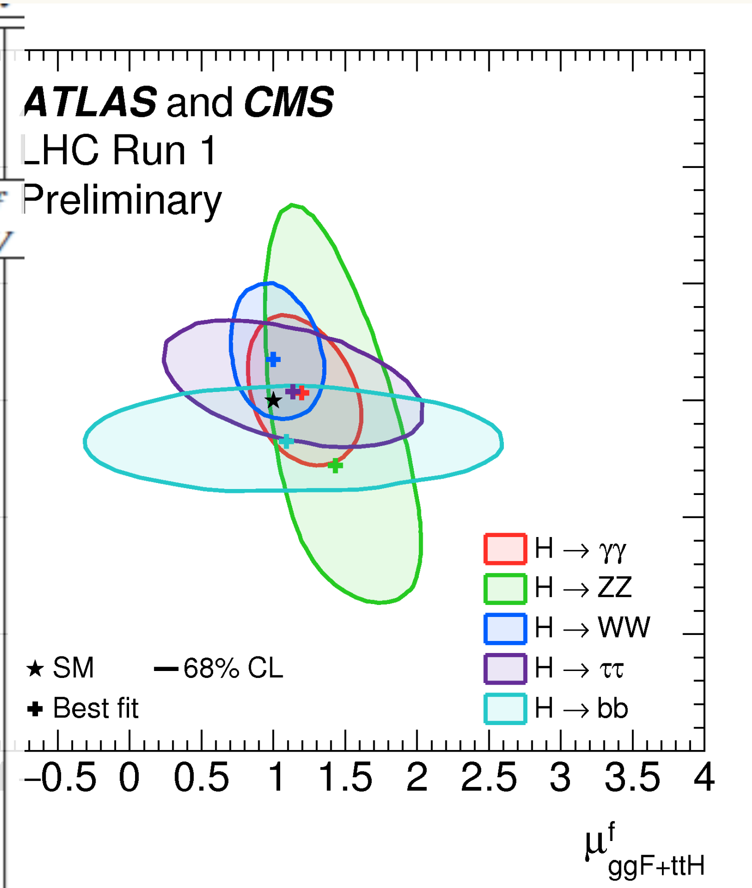
Production mode	Decay channel				
	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$
ggF	$(\sigma \cdot \mathrm{BR})^{\gamma\gamma}_{ggF}$	$(\sigma \cdot \mathrm{BR})^{ZZ}_{ggF}$	$(\sigma \cdot \mathrm{BR})^{WW}_{ggF}$	$(\sigma \cdot \mathrm{BR})^{\tau\tau}_{ggF}$	
VBF	$(\sigma \cdot \mathrm{BR})^{\gamma\gamma}_{VBF}$	$(\sigma \cdot \mathrm{BR})^{ZZ}_{VBF}$	$(\sigma \cdot \mathrm{BR})^{WW}_{VBF}$	$(\sigma \cdot \mathrm{BR})^{\tau\tau}_{VBF}$	
WH	$(\sigma \cdot \mathrm{BR})^{\gamma\gamma}_{WH}$	$(\sigma \cdot \mathrm{BR})^{ZZ}_{WH}$	$(\sigma \cdot \mathrm{BR})^{WW}_{WH}$	$(\sigma \cdot \mathrm{BR})^{\tau\tau}_{WH}$	$(\sigma \cdot \mathrm{BR})^{bb}_{WH}$
ZH	$(\sigma \cdot \mathrm{BR})^{\gamma\gamma}_{ZH}$	$(\sigma \cdot \mathrm{BR})^{ZZ}_{ZH}$	$(\sigma \cdot \mathrm{BR})^{WW}_{ZH}$	$(\sigma \cdot \mathrm{BR})^{\tau\tau}_{ZH}$	$(\sigma \cdot \mathrm{BR})^{bb}_{ZH}$
ttH	$(\sigma \cdot \mathrm{BR})^{\gamma\gamma}_{ttH}$	$(\sigma \cdot \mathrm{BR})^{ZZ}_{ttH}$	$(\sigma \cdot \mathrm{BR})^{WW}_{ttH}$	$(\sigma \cdot \mathrm{BR})^{\tau\tau}_{ttH}$	$(\sigma \cdot \mathrm{BR})^{bb}_{ttH}$

- The ggF and VBF production processes are not considered in the case of the H → bb decay channel and are assumed to have the values predicted by the SM,
- The Z H, WH, and ttH production processes cannot be measured with meaningful precision in the H → Z Z decay channel because of the low overall expected and observed yields in the current data.
- The fit results are therefore quoted only for the remaining 20 parameters.
- A CLEAR ASSUMPTION HRE IS THAT THERE IS ONLY ONE HIGGS BOSON


NEW
ATLAS and CMS Internal
LHC Run 1
Observed ± 1σ
Th. uncert.
illustration
ggF
VBF
WH
ZH
ttH
γγ
ZZ
WW
ττ
bb
-6 -4 -2 0 2 4 6 8 10
σ · BR norm. to SM prediction

Measuring Signal Strengths

Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty
10-parameter fit of μ_F^f and μ_V^f		
$\mu_V^{\gamma\gamma}$	$1.05^{+0.44}_{-0.41}$	$^{+0.42}_{-0.38}$
μ_V^{ZZ}	$0.48^{+1.37}_{-0.91}$	$^{+1.16}_{-0.84}$
μ_V^{WW}	$1.38^{+0.41}_{-0.37}$	$^{+0.38}_{-0.35}$
$\mu_V^{\tau\tau}$	$1.12^{+0.37}_{-0.35}$	$^{+0.38}_{-0.36}$
μ_V^{bb}	$0.65^{+0.30}_{-0.29}$	$^{+0.32}_{-0.30}$
$\mu_F^{\gamma\gamma}$	$1.19^{+0.28}_{-0.25}$	$^{+0.25}_{-0.23}$
μ_F^{ZZ}	$1.44^{+0.38}_{-0.34}$	$^{+0.29}_{-0.25}$
μ_F^{WW}	$1.00^{+0.23}_{-0.20}$	$^{+0.21}_{-0.19}$
$\mu_F^{\tau\tau}$	$1.10^{+0.61}_{-0.58}$	$^{+0.56}_{-0.53}$
μ_F^{bb}	$1.09^{+0.93}_{-0.89}$	$^{+0.91}_{-0.86}$



SM p-value 88% (10p)

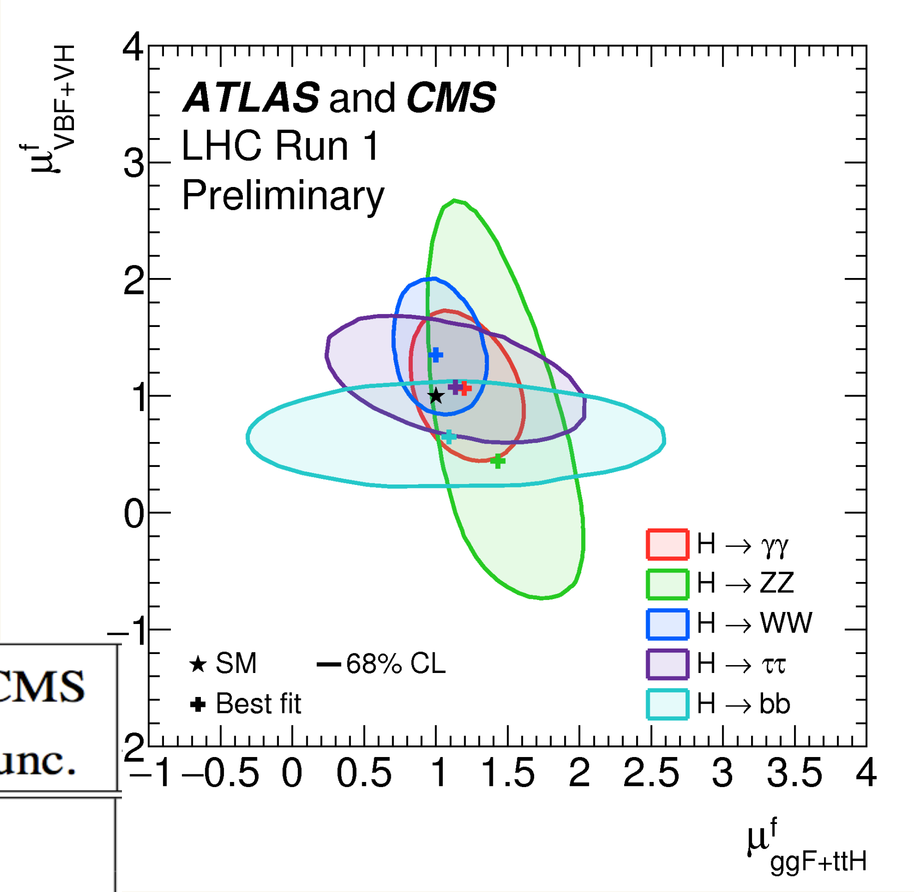
Measuring Signal Strengths

$$\frac{\mu_V^f}{\mu_F^f} = \frac{\mu_V \times BR^f}{\mu_F \times BR^f} = \frac{\mu_V}{\mu_F}$$

μ_V/μ_F can be measured in the different decay channels and combined:

$$\mu_V/\mu_F = 1.06^{+0.35}_{-0.27}$$

Parameter	ATLAS+CMS observed	ATLAS+CMS expected unc.
μ_V/μ_F	$1.06^{+0.35}_{-0.27}$	$^{+0.34}_{-0.26}$
$\mu_F^{\gamma\gamma}$	$1.13^{+0.24}_{-0.21}$	$^{+0.21}_{-0.19}$
μ_F^{ZZ}	$1.29^{+0.29}_{-0.25}$	$^{+0.24}_{-0.20}$
μ_F^{WW}	$1.08^{+0.22}_{-0.19}$	$^{+0.19}_{-0.17}$
$\mu_F^{\tau\tau}$	$1.07^{+0.35}_{-0.28}$	$^{+0.32}_{-0.27}$
$\mu_F^{b\bar{b}}$	$0.65^{+0.37}_{-0.28}$	$^{+0.45}_{-0.34}$



SM p-value 72% (6p)

Measuring Production Signal Strengths

Assuming SM BR we can measure the signal production strengths.

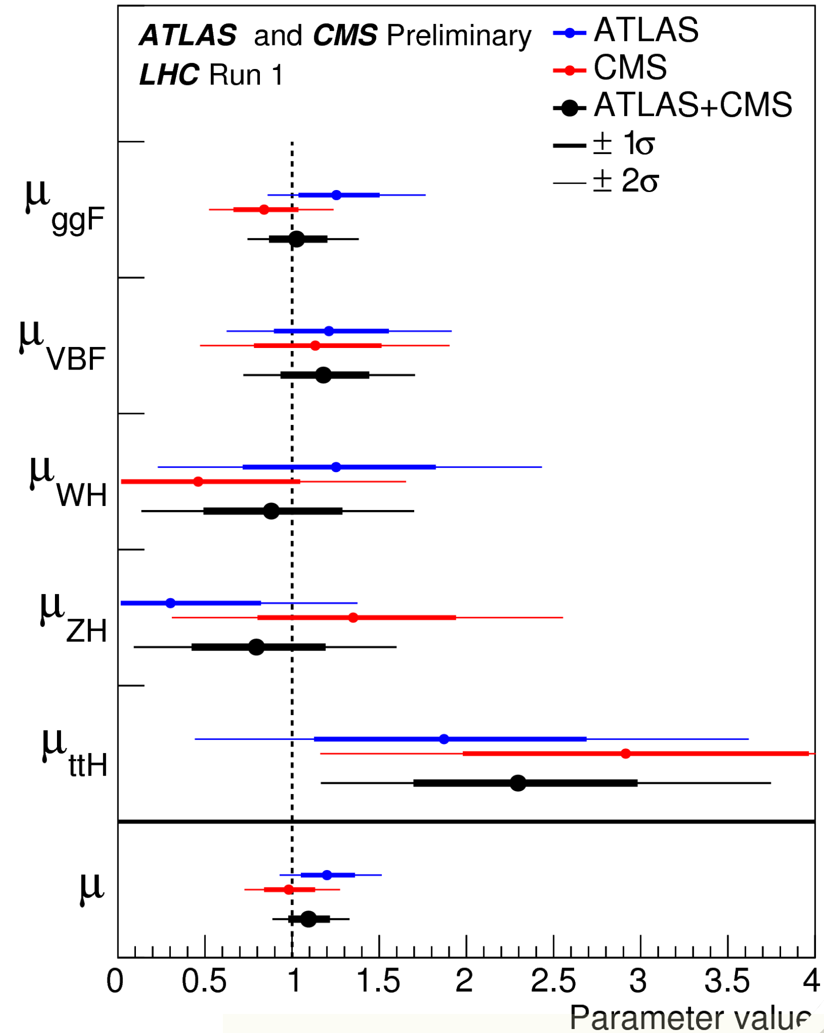
Production process	ATLAS+CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$

SM p-value 24% (5p)

A subtlety:
Assume signal strengths are equal @ 7 and 8 TeV

Largest difference in ttH: 2.3σ excess with respect to SM

Over 5 sigma in VBF



Main uncertainty from ggF xsc

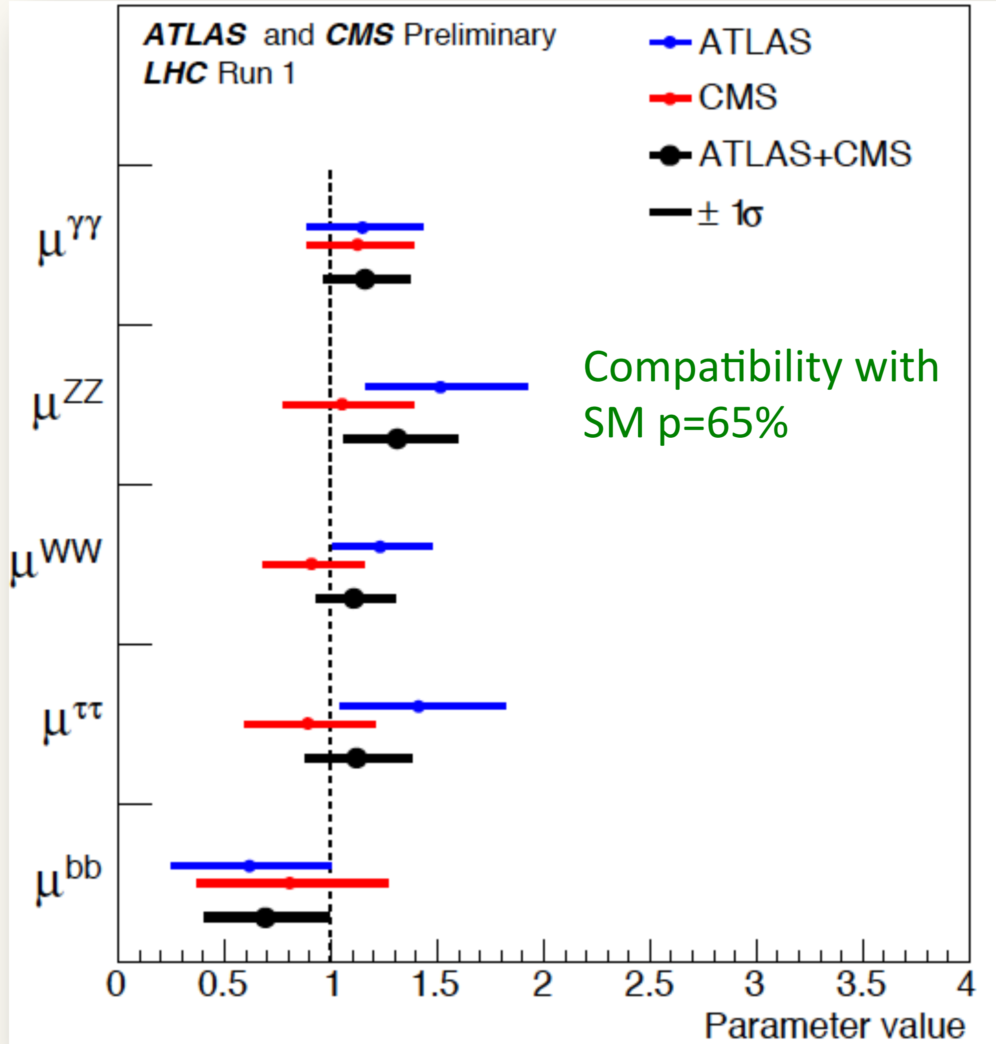
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})\,^{+0.07}_{-0.06}\,(\text{thsig})$$

Measuring the Higgs Decay Modes

Assuming SM signal production strengths, we can measure the Higgs Decay BRs

Decay channel	ATLAS+CMS
$\mu^{\gamma\gamma}$	$1.16^{+0.20}_{-0.18}$
μ^{ZZ}	$1.31^{+0.27}_{-0.24}$
μ^{WW}	$1.11^{+0.18}_{-0.17}$
$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$

Over 5 sigma in ττ



Compatibility with SM p=65%

Significance in the different channels

Comparing likelihood of the best-fit with μ_{prod}=0 and μ^{decay}=0 we obtain:

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Combination largely increases the sensitivity

VBF and H→ τ τ now established at over 5 σ.
Same as ggF and H→ZZ, γ γ, WW from single experiments

Model Independent Ratios (Generic I)

One can fit the data with ONE channel specific measurement (i→H→f) , 4 ratios of cross sections and 4 ratios of BRs

$$\sigma_x \times BR^y = \sigma(i \to H \to f)\left(\frac{\sigma_x}{\sigma_i}\right)\cdot\left(\frac{BR^y}{BR^f}\right)$$

$9\ pars$

$ref: \sigma_i \cdot BR^f,\ e.g.\ \sigma_{ggH} \cdot BR^{ZZ}$

$$\frac{\sigma_{VBF}}{\sigma_{ggH}} \quad \frac{\sigma_{WH}}{\sigma_{ggH}} \quad \frac{\sigma_{ZH}}{\sigma_{ggH}} \quad \frac{\sigma_{ttH}}{\sigma_{ggH}} \quad \frac{BR^{\gamma\gamma}}{BR^{ZZ}} \quad \frac{BR^{WW}}{BR^{ZZ}} \quad \frac{BR^{\tau\tau}}{BR^{ZZ}} \quad \frac{BR^{bb}}{BR^{ZZ}}$$

This way, we make no assumptions on the Higgs boson total width, which can freely vary, **provided the narrow width approximation is still valid.**

Furthermore, many theoretical and experimental systematic uncertainties cancel in these ratios. In particular, they are not subject to the dominant signal theoretical uncertainties on the inclusive cross sections for the various production processes.

These measurements will therefore remain valid, for example when improved theoretical calculations of Higgs boson production cross sections will become available. The remaining theoretical uncertainties are reduced to those related to the acceptances and selection efficiencies in the various categories.

This is the most generic parameterisation considered yet recast should be done with care

Model Independent Ratios (Generic I)

One can fit the data with ONE channel specific measurement (i→H→f) , 4 ratios of cross sections and 4 ratios of BRs

$9\ pars$

$ref: \sigma_i \cdot BR^f,\ e.g.\ \sigma_{ggH} \cdot BR^{ZZ}$

$\frac{\sigma_{VBF}}{\sigma_{ggH}}$

$\frac{\sigma_{WH}}{\sigma_{ggH}}$

$\frac{\sigma_{ZH}}{\sigma_{ggH}}$

$\frac{\sigma_{ttH}}{\sigma_{ggH}}$

$\frac{BR^{\gamma\gamma}}{BR^{ZZ}}$

$\frac{BR^{WW}}{BR^{ZZ}}$

$\frac{BR^{\tau\tau}}{BR^{ZZ}}$

$\frac{BR^{bb}}{BR^{ZZ}}$

reference process: $i \to f$

$$\sigma_x \cdot BR_y = \frac{\sigma_x}{\sigma_i}\frac{BR_y}{BR_f} \cdot \left(\sigma_i \cdot BR_f\right)$$

$$\mu_x^y \cdot \left(\sigma_x \cdot BR_y\right)_{SM} = \frac{\sigma_x}{\sigma_i}\frac{BR_y}{BR_f} \cdot \left(\sigma_i \cdot BR_f\right)$$

$$\mu_x^y = \frac{\mu_x}{\mu_i}\frac{\mu_y}{\mu_f} \cdot \mu_i^f$$

$e.g.$ ref=gg $\to H \to ZZ$

$$\mu_{ZH}^{bb} = \left[\frac{\mu_{ZH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right]$$

Model Independent Ratios (Generic I)

One can fit the data with ONE channel specific measurement ($i \to H \to f$), 4 ra... cross sections and 4 ratios of BRs

WHICH REF PROCESS?

9 *pars*

$ref: \sigma_i \cdot BR^f$, $e.g.\ \sigma_{ggH} \cdot BR^{ZZ}$

$\frac{\sigma_{VBF}}{\sigma_{ggH}}$

$\frac{\sigma_{WH}}{\sigma_{ggH}}$

$\frac{\sigma_{ZH}}{\sigma_{ggH}}$

$\frac{\sigma_{ttH}}{\sigma_{ggH}}$

$\frac{BR^{\gamma\gamma}}{BR^{ZZ}}$

$\frac{BR^{WW}}{BR^{ZZ}}$

$\frac{BR^{\tau\tau}}{BR^{ZZ}}$

$\frac{BR^{bb}}{BR^{ZZ}}$

...process: $i \to f$

$\sigma_x \cdot BR_y$ ... σ_i ... $BR_f)$

$\mu_x^y \cdot (\sigma_x \cdot BR_y)_{SM} = \frac{\sigma_x}{\sigma_i} \frac{\ldots}{BR_f}$ ...

$$\mu_x^y = \frac{\mu_x}{\mu_i} \frac{\mu_y}{\mu_f} \cdot \mu_i^f$$

$e.g.$ ref=$gg \to H \to ZZ$

$$\mu_{ZH}^{bb} = \left[\frac{\mu_{ZH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right]$$

WHICH REF?

Model Independent Ratios (Generic I)

One can fit the data with ONE channel specific measurement ($i \rightarrow H \rightarrow f$) , 4 ra... cross sections and 4 ratios of BRs

$9\ pars$

$ref: \sigma_i \cdot BR^f$ ... $\sigma_{ggH} \cdot BR$...

$\frac{\sigma_{VBF}}{\sigma_{ggH}}$

$\frac{\sigma_{WH}}{\sigma_{ggH}}$

$\frac{\sigma_{ZH}}{\sigma_{gg..}}$

$\frac{\sigma_{ttH}}{\sigma_{ggH}}$

$\frac{BR^{\gamma\gamma}}{BR^{ZZ}}$

$\frac{BR^{WW}}{BR^{ZZ}}$

$\frac{BR^{\tau\tau}}{BR^{ZZ}}$

$\frac{BR^{bb}}{BR^{ZZ}}$

...process: $i \rightarrow f$

$\sigma_x \cdot BR_y$ ... σ_i ... $BR_f)$

... $\frac{\sigma_x}{...}$ ... $\frac{...}{BR_f}$

$e.g.$ fo...

$\mu_{ZH}^{bb} = \left[\frac{\mu_{ZH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\frac{...}{\mu_{ZZ}} \right]$

...CH REF?

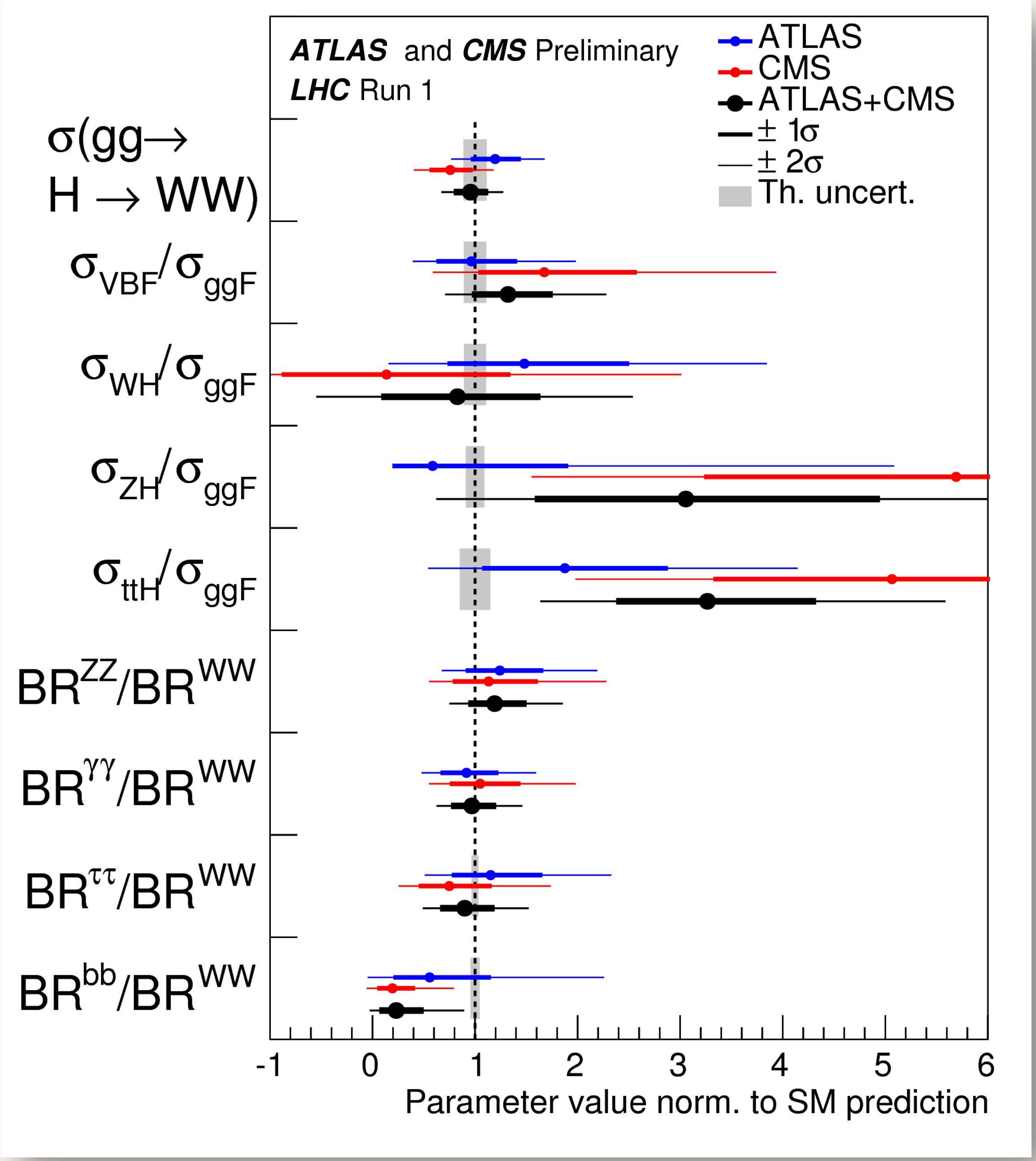
WHICH REF PROCESS?

The ggF→H→ZZ has the smallest systematics but the ggF→H→WW has a better global error

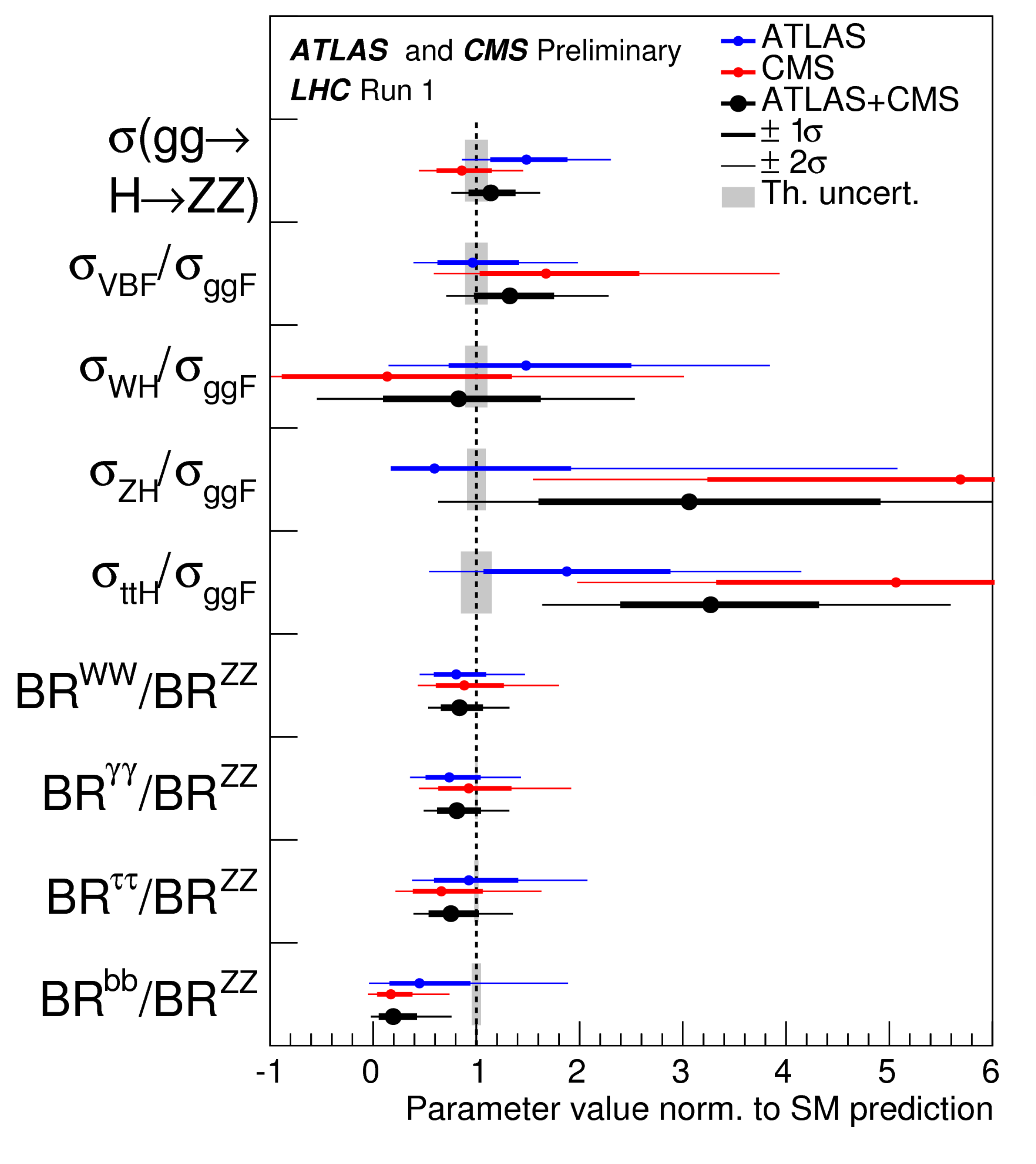
So for the sake of our children's children's children

We decided to choose……both

Model Independent Ratios (Generic I)

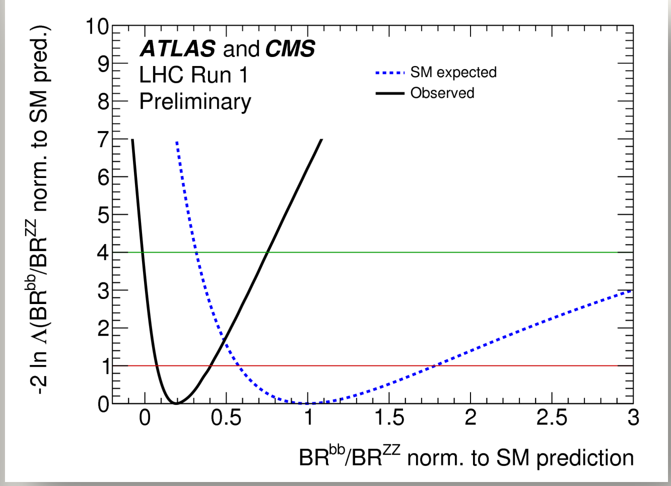


Model Independent Ratios (Generic I)



Largest deviationfrom SM is seen in BR^{bb}/BR^{ZZ}, at the level of 2.4 σ

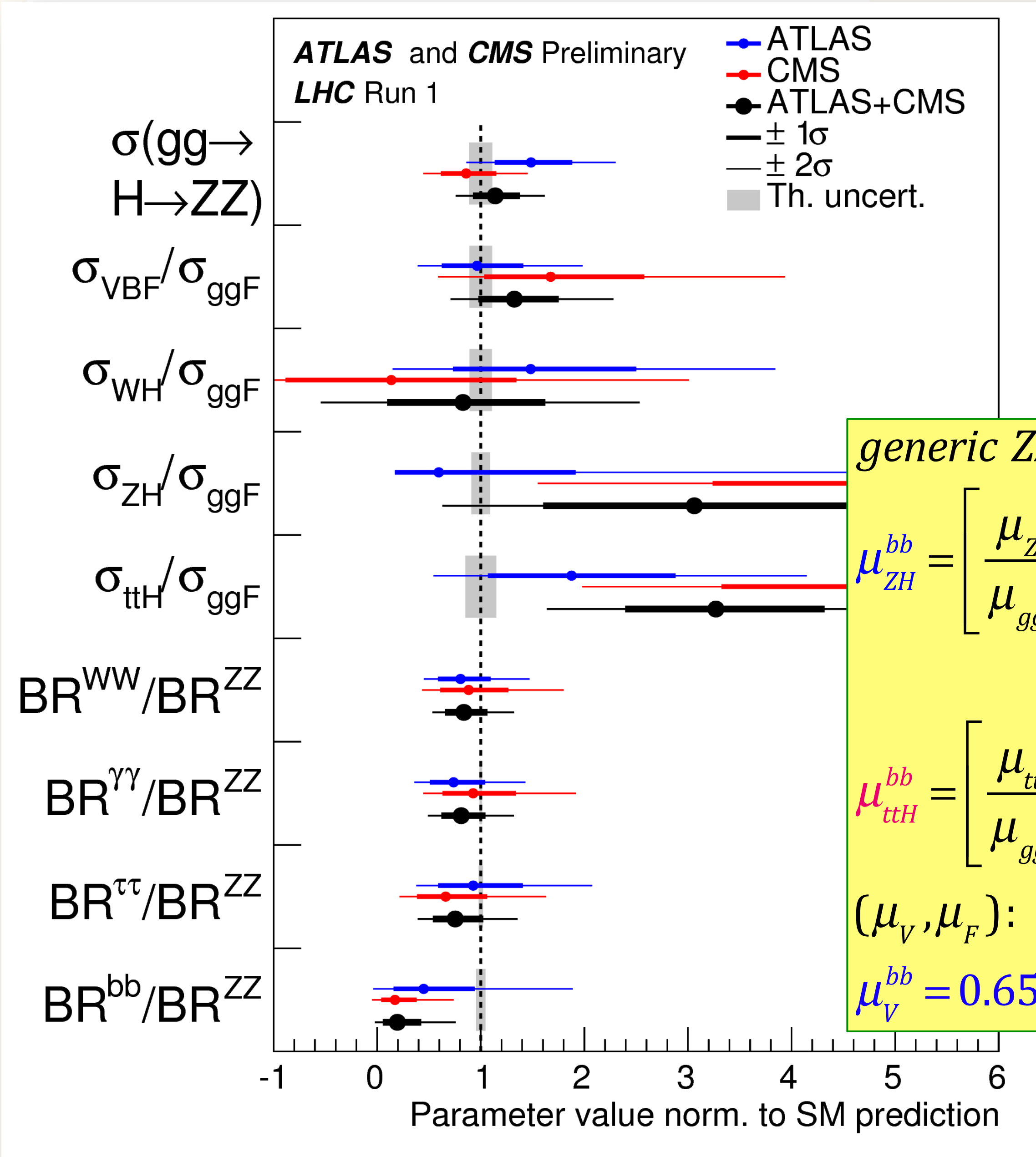
Effect mainly coming from large ZH and ttH (both ratios σ_i / σ_{ggF} ~ 3)



ttH excess due to multilepton categories

ZH excess due to CMS two-jet categories

Model Independent Ratios (Generic I)



Largest deviationfrom SM is seen in BR^{bb}/BR^{ZZ}, at the level of 2.4 σ

Effect mainly coming from large ZH and ttH (both ratios σ_i/σ_{ggF} ~ 3)

generic ZZ :

$$\mu_{ZH}^{bb} = \left[\frac{\mu_{ZH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right] \approx 3.1 \cdot 1.14 \cdot 0.2 = 0.7$$

$$\mu_{ttH}^{bb} = \left[\frac{\mu_{ttH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right] \approx 3.3 \cdot 1.14 \cdot 0.2 = 0.8$$

(μ_V, μ_F):

$$\mu_V^{bb} = 0.65, \mu_F^{bb} = 1.09$$

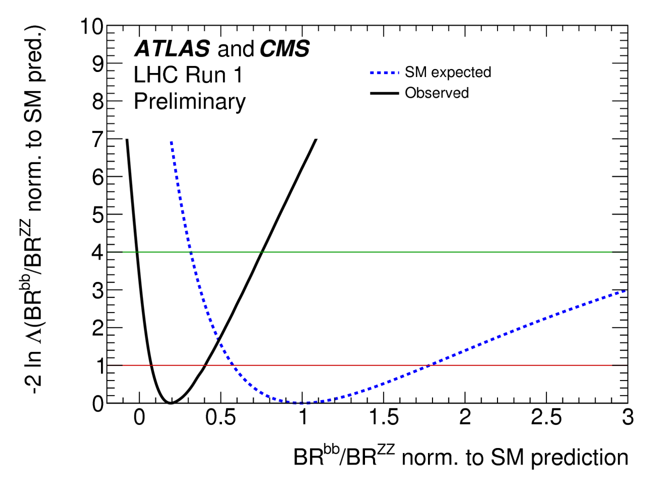
RECAST?

Well

We were sure
But
It does not perfectly work and reproduce
Central values with correct correlations

We know you will do it

But see that we warned you



generic ZZ:

$$\mu_{ZH}^{bb} = \left[\frac{\mu_{ZH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right] \approx 3.1 \cdot 1.14 \cdot 0.2 = 0.7$$

$$\mu_{ttH}^{bb} = \left[\frac{\mu_{ttH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right] \approx 3.3 \cdot 1.14 \cdot 0.2 = 0.8$$

(μ_V, μ_F):

$\mu_V^{bb} = 0.65, \mu_F^{bb} = 1.09$

7 vs 8 TeV

In most cases we assume the ratio $\frac{\sigma(7\ TeV)}{\sigma(8\ TeV)} = \frac{\sigma(7\ TeV)_{SM}}{\sigma(8\ TeV)_{SM}}$

In the paper we will also leave this ration as a free parameter

7 TeV can only affect ggF and VBF ratios (limited statistics)

Do not expect a big difference in the results….

Couplings

The κ –framework

The k-framework has been developed within the LHC Higgs Cross Section WG

Higgs boson couplings are scaled by coupling modifiers κ

The definition is such that:

$\kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}}$ for production $\kappa_j^2 = \Gamma^j/\Gamma^j_{\mathrm{SM}}$ for decay

There are obvious drop backs to the Kappa framework
Higher order QCD and EW accuracies might not be preserved for $\kappa \neq 1$

The κ -framework

$$k_f^2 = \frac{\Gamma_f}{\Gamma_H} \qquad \Gamma_{i,u} = \Gamma_{BSM}$$

BR_{BSM} = $BR_{inv,und}$=BR invisible + undetected

$$\Gamma_H = \Sigma_f \Gamma_f + \Gamma_{i,u} \quad i = invisible, u = undetected$$

$$k_H^2 = \frac{\Gamma_H}{\Gamma_H^{SM}} = \sum_f \frac{\Gamma_f}{\Gamma_H^{SM}} + \frac{\Gamma_{i,u}}{\Gamma_H^{SM}} = \sum_f \frac{\Gamma_f}{\Gamma_f^{SM}} \frac{\Gamma_f^{SM}}{\Gamma_H^{SM}} + \frac{\Gamma_{i,u}}{\Gamma_H} \frac{\Gamma_H}{\Gamma_H^{SM}}$$

$$k_H^2 = \sum_f k_f^2 BR_f^{SM} + BR_{i,u} k_H^2$$

$$k_H^2 = \frac{\sum_f k_f^2 BR_f^{SM}}{1 - BR_{i,u}}$$

The κ –framework

Experimental Assumptions:

The current LHC data are insensitive to the coupling modifiers κ_c and κ_s, and have limited sensitivity to κ_μ.

Thus, it is assumed that κ_c varies as κ_t, κ_s as κ_b, and κ_μ as κ_τ.

Other coupling modifiers $(\kappa_u, \kappa_d$ and $\kappa_e)$ are irrelevant for the combination as long as they are order of unity.

$$BR_{BSM} = BR_{inv,und}$$

Undetected decays can be either non SM decays or come from non SM BRs of known but not measured decays such as cc, gg.

Measuring Higgs Couplings

$$n_s(i \to f) = \mu^i \mu^f \times (\sigma^i \times Br^f)_{SM} \times \mathrm{A}_p^i \times \varepsilon_p^i \times Lumi$$

$$i \in (ggF, VBF, VH, ttH) \quad f \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

Can we resolve the degeneracy, disentangle $\left[\mu^i \mu^f\right]$

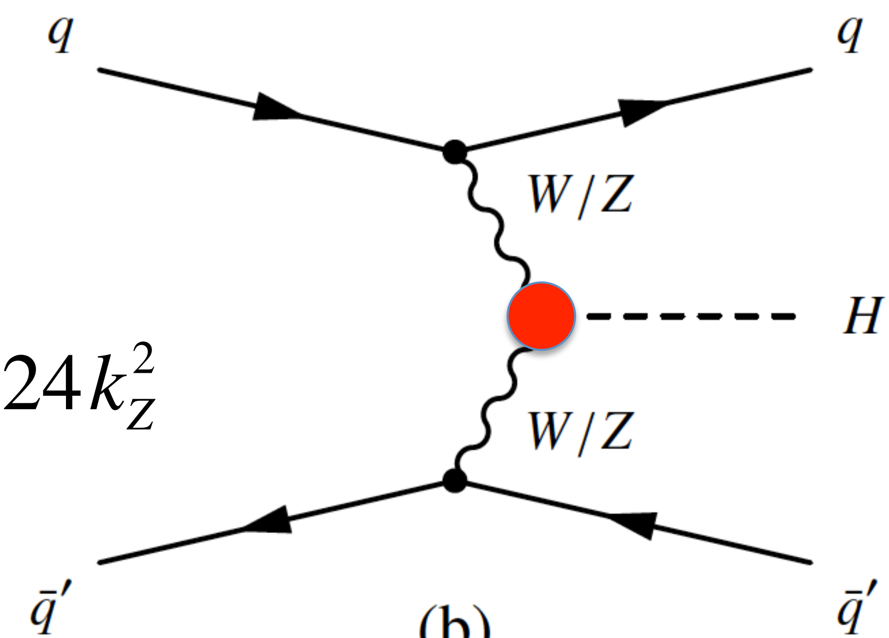
The degeneracy can be broken by parameterize the strength parameters with couplings and introduce constraints which reduce the number of p.o.i. and allow reasonable fits.

$$k_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}, \frac{\sigma_j}{\sigma_j^{SM}} \quad k_H^2 = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}} = \sum k_j^2 BR_j^{SM}$$

VBF Composition

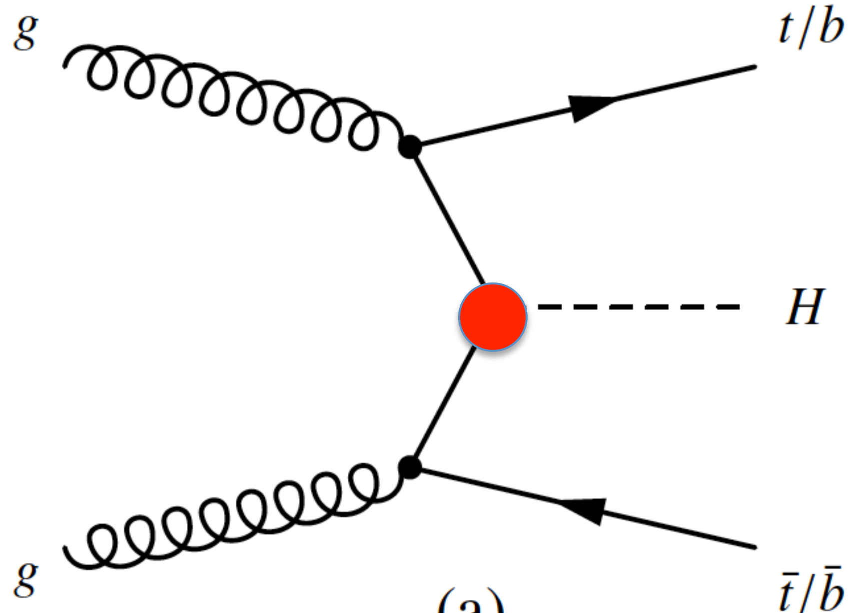
$$q\overline{q}' \to q\overline{q}'H$$

$$\mu_{VBF} = k_{VBF}^2 \approx 0.74k_W^2 + 0.24k_Z^2$$



(b)

ttH



(a)

$$gg \to ttH\,,bbH$$

$$\mu_{ttH} = k_t^2$$

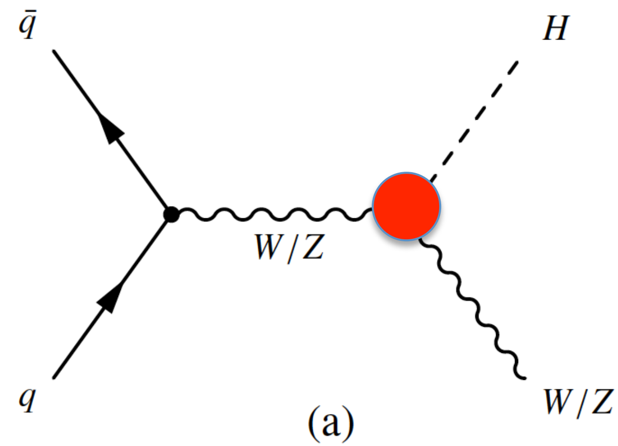
$$\mu_{bbH} = k_b^2$$

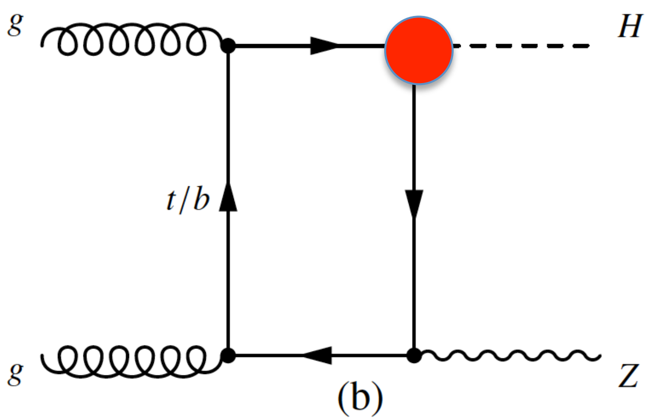
ZH Production

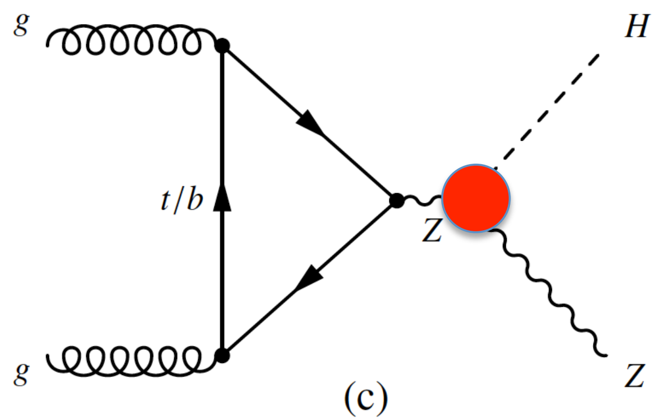
$$\sigma(q\bar{q} \rightarrow ZH) \sim k_Z^2$$

$$\sigma(q\bar{q} \rightarrow WH) \sim k_W^2$$

$$\sigma(gg \rightarrow ZH) \sim k_{ggZH}^2$$



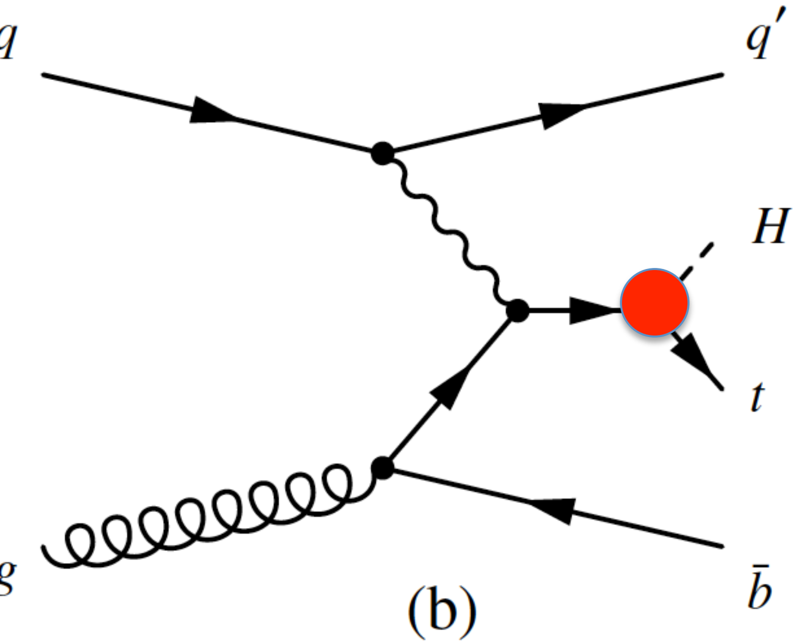


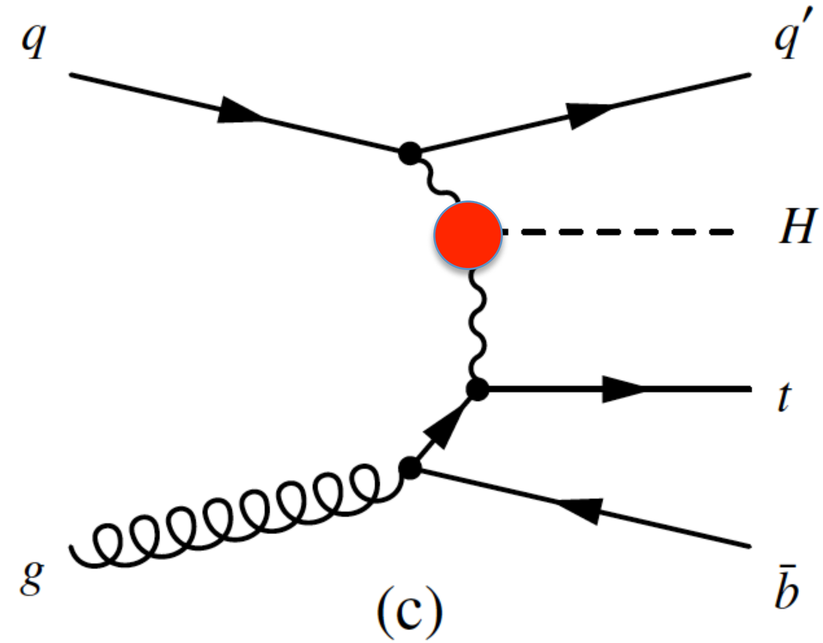


(Q:Why not gWH?)

$$\kappa_{ggZH}^2 \sim \quad 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$$

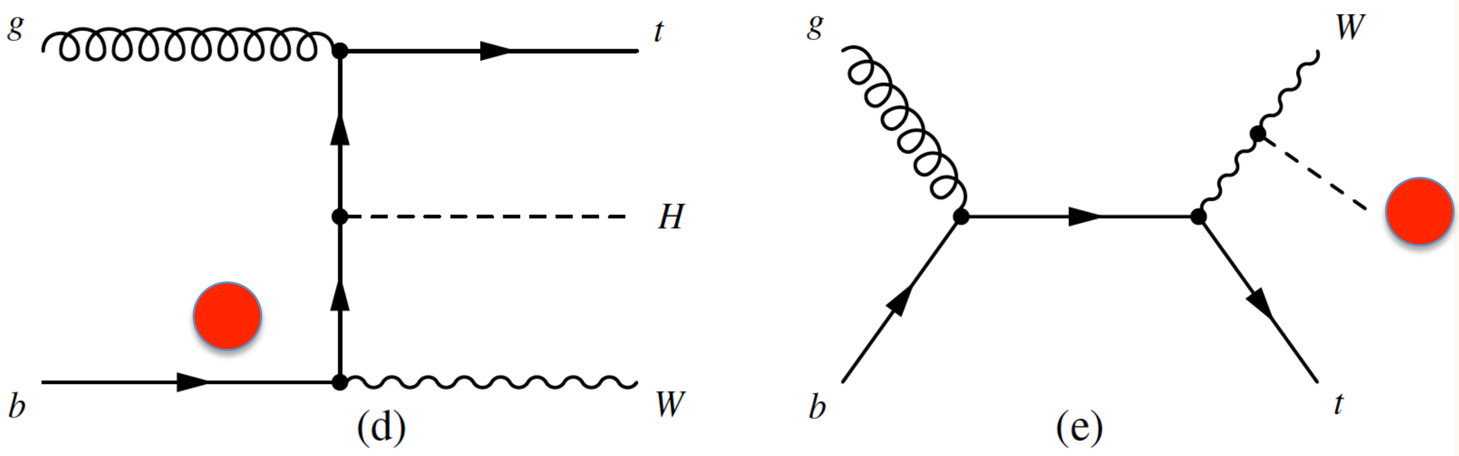
tHq composition (W,t) interference





$$\sigma\left(qg \to tHq'(b)\right) \sim \quad 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$$

WtH composition

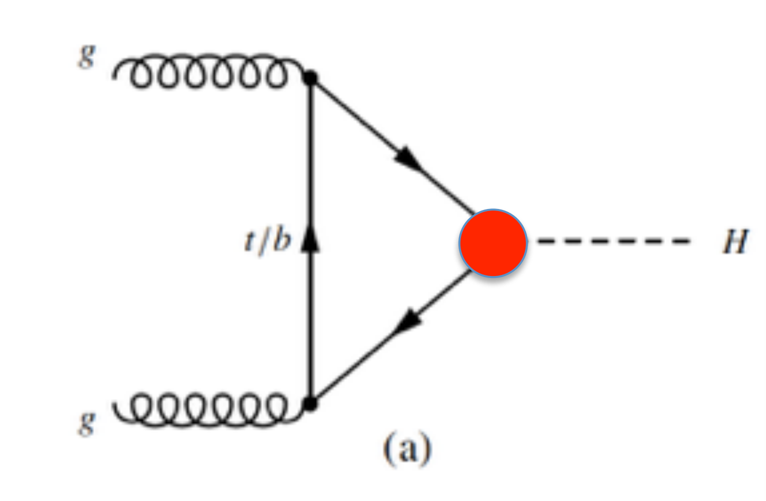


$$\sigma(gb \to tHW) \sim \quad 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$$

Note that if $K_t K_W = -1$, *tHW* increases by a factor 6,
tHq by a factor 13
tH which makes only 14% of *ttH* becomes important
We still have no sensitivity, yet
it is important to
take negative values into account

Higgs does not couple
to to Gluons and Photons
in leading order

The production of the Higgs Boson
and its discovery
are due to a pure quantum loop



$$k_g^2 \approx 1.06k_t^2 + 0.01k_b^2 - 0.07k_t k_b$$

Hgg Approximate Calculation

Why a NEGATIVE interference term?

$$\sigma_{\rm LO}(gg \to h) = \sigma_0^h m_h^2 \delta(\hat{s} - m_h^2)$$

$$\sigma_0^h = \frac{G_f \alpha_s^2}{288\sqrt{2}\pi} \left| \frac{3}{4} \sum_q A_{1/2}^H(\tau_q) \right|^2$$

$$\tau_q = 4m_q^2/m_h^2$$

$$\tau_t = 7.65 \text{ and } \tau_b = 2 \times 10^{-3} \text{ for } m_b(m_h) \approx 2.8\,\text{GeV}$$

$$A_{1/2}^H(\tau) = 2\tau \left[1 + (1-\tau) f(\tau)\right],$$

$$f(\tau) = \begin{cases} -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2 & \tau < 1 \\ \arcsin^2(1/\sqrt{\tau}) & \tau \geq 1 \end{cases}$$

$$A_{1/2}^H = \begin{cases} \tau \gg 1: & 4/3 \\ \tau \ll 1: & 2\tau\left[1 - \frac{1}{4}\left(\log\frac{\tau}{4} + i\pi\right)^2\right] \approx -\frac{\tau}{2}\left(\log\frac{\tau}{4}\right)^2 \end{cases}$$

$$\frac{\sigma_0^h}{[\sigma_0^h]_{\rm SM}} = \left| \frac{\kappa_t A_{1/2}^H(\tau_t) + \kappa_b A_{1/2}^H(\tau_b)}{A_{1/2}^H(\tau_t) + A_{1/2}^H(\tau_b)} \right|^2 = \kappa_t^2 1.09 - 0.09\kappa_b\kappa_t + 0.0021\kappa_b^2$$

The Seven Decay Modes Probes

$$\Gamma_{b\bar{b}} \sim k_b^2$$

$$\Gamma_{\tau\tau} \sim k_\tau^2$$

$$\Gamma_{WW} \sim k_W^2$$

$$\Gamma_{ZZ} \sim k_Z^2$$

$$\Gamma_{\mu\mu} \sim k_\mu^2$$

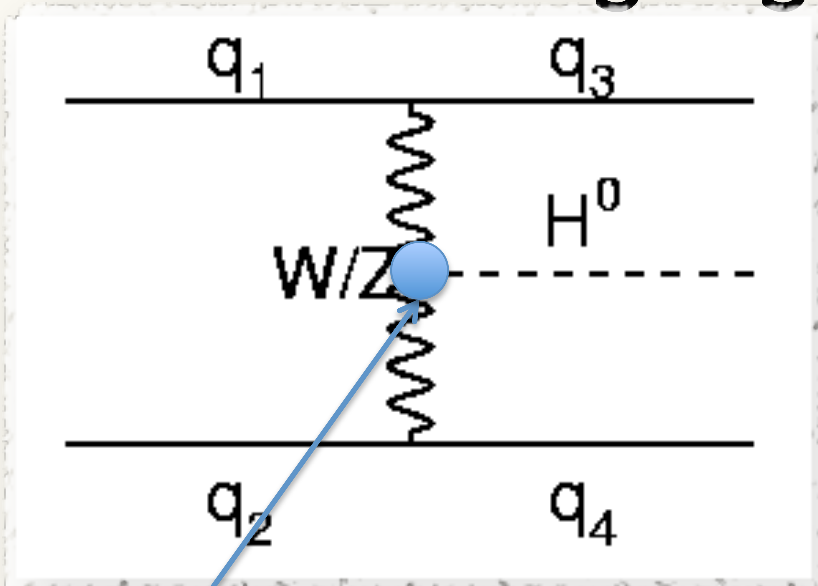
$$\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$$

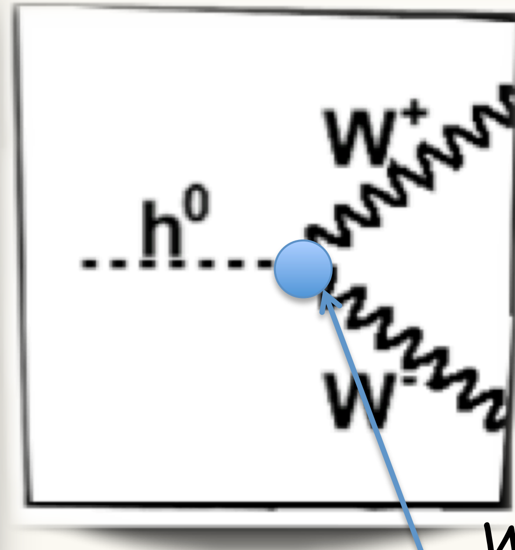
$$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$$

$$k_H^2 = \sum_f k_f^2 BR_f^{SM}$$

$$\kappa_H^2 \sim \begin{array}{l} 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + \\ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + \\ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2 \end{array}$$

Disentangling The Couplings





$$\mu^{W}_{VBF} = [\mu_{VBF}\mu^{W}]$$

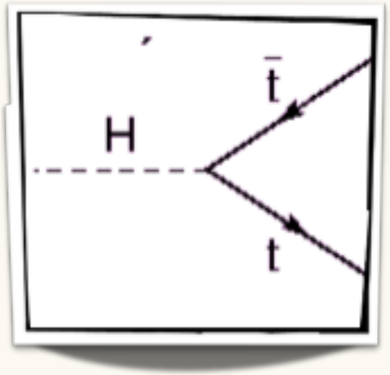
$$\mu^{W} = \frac{k^2_{W}}{k^2_{H}}$$

$$\mu_{VBF} = k^2_{VBF} = k^2_{w}BR^{WW}_{SM} + k^2_{Z}BR^{ZZ}_{SM}$$

The simplest non-trivial model is (k_F, k_V) where all Fermion couplings are set to k_F and all Boson couplings to k_V

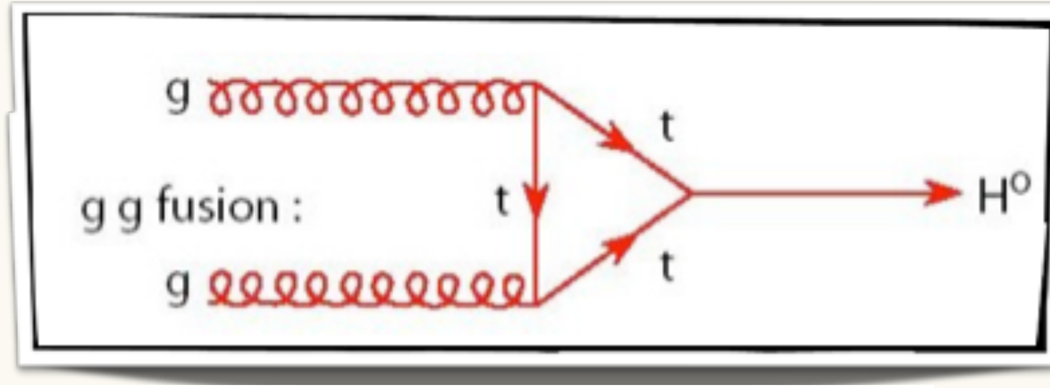
$$\frac{\sigma^{WW}_{VBF}}{\sigma^{WW}_{VBF}(SM)} = \frac{k^2_V \cdot k^2_V}{0.75k^2_F + 0.25k^2_V}$$

Indirect Sensitivity to Fermion Couplings



$$k_t^2 = \frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}}$$

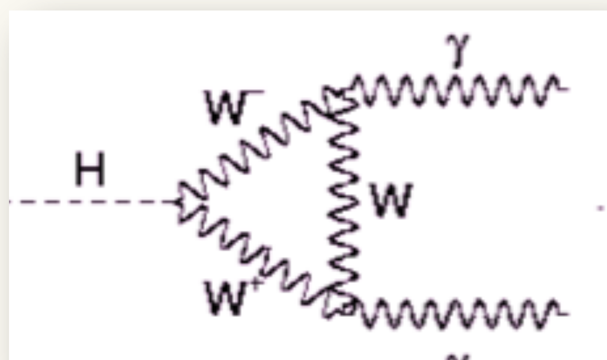
$$k_t^2 = \frac{g_t^2}{g_{t.SM}^2}$$



$$\kappa_g^2(\kappa_b, \kappa_t) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt} + \kappa_b^2 \cdot \sigma_{ggH}^{bb} + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$

Note that if all fermion couplings are set to be equal, $k_g^2 = k_F^2$

$$k_\gamma^2 = \left|1.28 k_W - 0.28 k_t\right|^2$$



The κ –framework

Production	Loops	Interference	Multiplicative factor	
$\sigma(gg\mathrm{F})$	✓	$b-t$	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(V\mathrm{BF})$	–	–	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim$	κ_W^2
$\sigma(qq/qg \to ZH)$	–	–	$\sim$	κ_Z^2
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim$	κ_t^2
$\sigma(gb \to WtH)$	–	$W-t$	$\sim$	$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim$	$3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim$	κ_b^2
Partial decay width				
Γ^{ZZ}	–	–	$\sim$	κ_Z^2
Γ^{WW}	–	–	$\sim$	κ_W^2
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim$	κ_τ^2
Γ^{bb}	–	–	$\sim$	κ_b^2
$\Gamma^{\mu\mu}$	–	–	$\sim$	κ_μ^2
Total width for $\mathrm{BR}_{\mathrm{BSM}} = 0$				
Γ_H	✓	–	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa^2 + 0.0016 \cdot \kappa_Z^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa^2$

The κ –framework

Production	Loops	Interference	Multiplicative factor	
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim$	κ_W^2
$\sigma(qq/qg \to ZH)$	–	–	$\sim$	κ_Z^2
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim$	κ_t^2
$\sigma(gb \to WtH)$	–	$W-t$	$\sim$	$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim$	$3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim$	κ_b^2
Partial decay width				
Γ^{ZZ}	–	–	$\sim$	κ_Z^2
Γ^{WW}	–	–	$\sim$	κ_W^2
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim$	κ_τ^2
Γ^{bb}	–	–	$\sim$	κ_b^2
$\Gamma^{\mu\mu}$	–	–	$\sim$	κ_μ^2
Total width for $BR_{BSM} = 0$				
Γ_H	✓	–	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Coupling Scenarios

To make reasonable fits we introduce physics motivated scenarios.

Testing the compatibility of the discovered Higgs with the SM is to test also where is it NOT compatible, spotting where NP might sneak in.

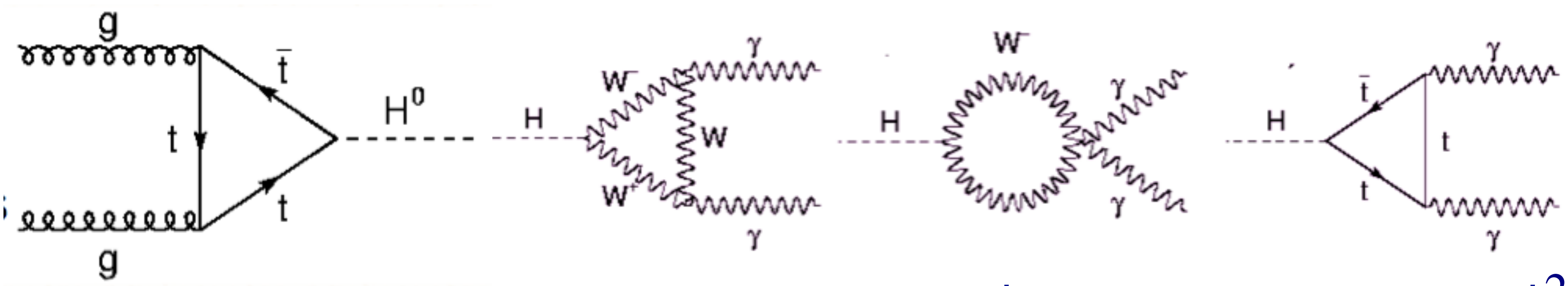
NP can appear in either the Higgs width and/or in the loops.

$$k_H^2 = \frac{\sum_{j=Z,W,t,b,\tau} k_j^2 \Gamma_j^{SM} + k_\gamma^2 \Gamma_\gamma^{SM} + k_g^2 \Gamma_g^{SM}}{\Gamma_H^{SM}} \qquad \Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$$

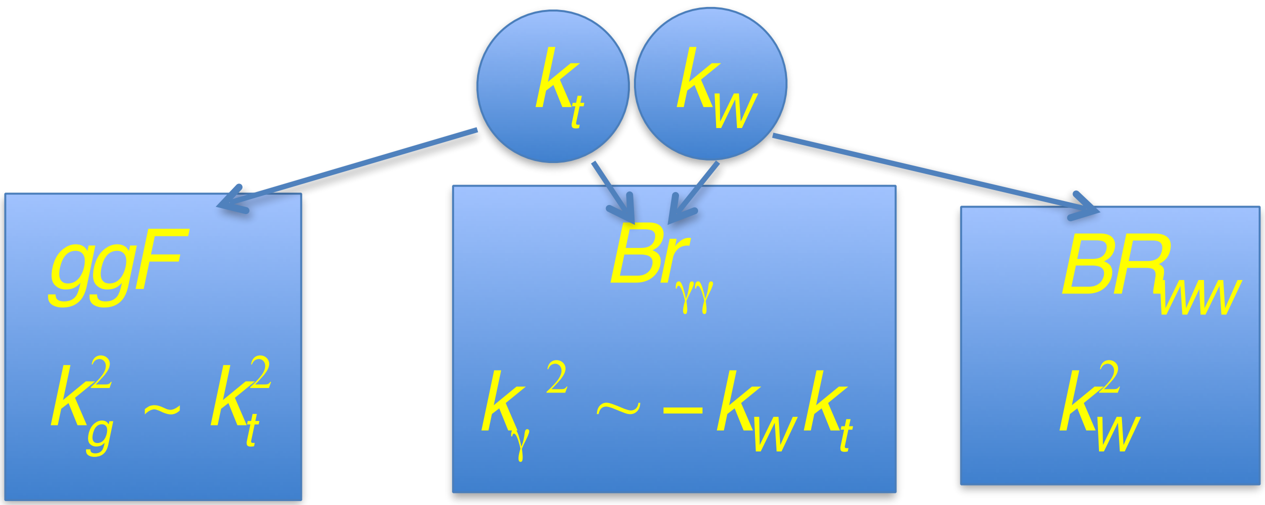
Γ_H	k_γ	k_g	Scenario
$\Gamma_H = k_H^2 \Gamma_H^{SM}$	$K_\gamma(k_t, k_W)$	$K_g(k_t, k_b)$	only SM particles in loops
$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$	k_γ	k_g	m_{NP} could be $< \frac{m_H}{2}$
$\Gamma_H = k_H^2 \Gamma_H^{SM}$	k_γ	k_g	$m_{NP} > \frac{m_H}{2}$
$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$	$K_\gamma(k_t, k_W)$	$K_g(k_t, k_b)$	NP (not in the loops)

Negative Couplings?

is



$$n_s^{\gamma\gamma} \sim k_g^2(k_t, k_b) \times k_\gamma^2(k_t, k_W) \qquad k_\gamma^2 = \left|1.28 k_W - 0.28 k_t\right|^2$$



If k_t=-1 ggF slightly affected

WW unaffected

$\gamma\gamma$ increases

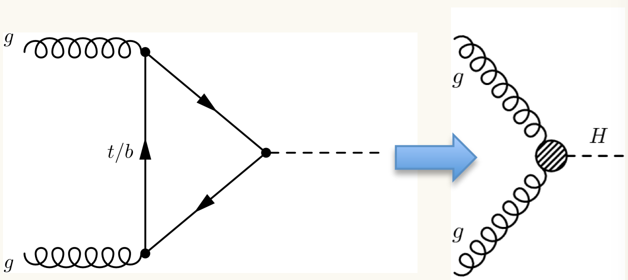
Testing negative k_t is extremely important

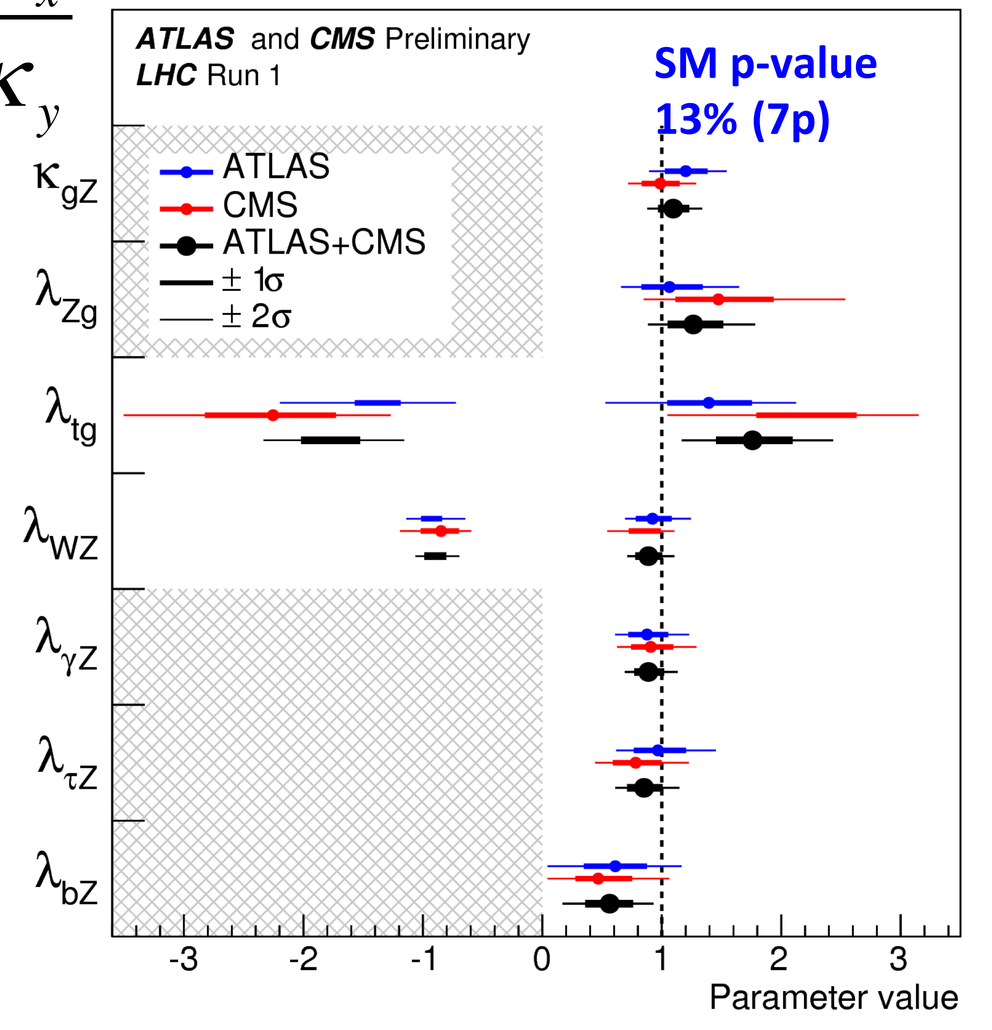
Couplings Generic Model

LHC is not able to measure the Higgs full width.

$$\lambda_{xy} = \frac{\kappa_x}{\kappa_y}$$

The only way to get minimal assumptions measurement is using ratios, and use effective couplings for Gamma and Gluon



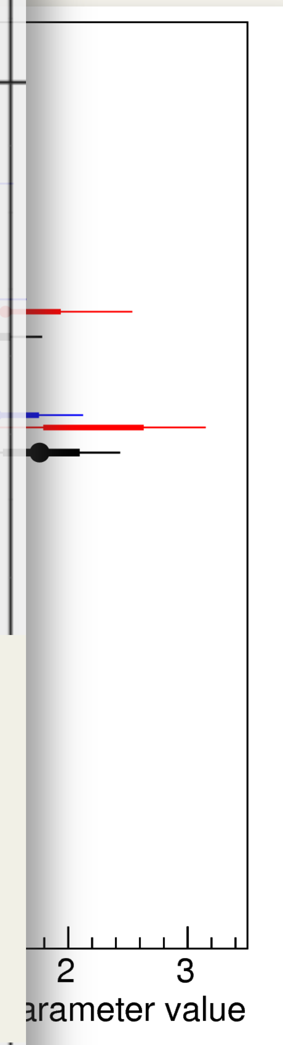


Couplings Generic Model

Parameter	Best-fit value	Stat	Expt	Thbgd	Thsig
			Uncertainty		
			ATLAS+CMS		
$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$	$1.10\ ^{+0.11}_{-0.11}$ $\left(^{+0.11}_{-0.11}\right)$	$^{+0.09}_{-0.09}$ $\left(^{+0.09}_{-0.09}\right)$	$^{+0.03}_{-0.02}$ $\left(^{+0.02}_{-0.02}\right)$	$^{+0.01}_{-0.01}$ $\left(^{+0.01}_{-0.01}\right)$	$^{+0.06}_{-0.05}$ $\left(^{+0.06}_{-0.05}\right)$
$\lambda_{Zg} = \kappa_Z / \kappa_g$	$1.26\ ^{+0.23}_{-0.19}$ $\left(^{+0.20}_{-0.17}\right)$	$^{+0.18}_{-0.16}$ $\left(^{+0.15}_{-0.14}\right)$	$^{+0.09}_{-0.07}$ $\left(^{+0.08}_{-0.06}\right)$	$^{+0.06}_{-0.05}$ $\left(^{+0.05}_{-0.04}\right)$	$^{+0.09}_{-0.08}$ $\left(^{+0.08}_{-0.07}\right)$
$\lambda_{tg} = \kappa_t / \kappa_g$	$1.76\ ^{+0.32}_{-0.29}$ $\left(^{+0.29}_{-0.39}\right)$	$^{+0.21}_{-0.20}$ $\left(^{+0.20}_{-0.21}\right)$	$^{+0.12}_{-0.11}$ $\left(^{+0.11}_{-0.12}\right)$	$^{+0.09}_{-0.09}$ $\left(^{+0.14}_{-0.19}\right)$	$^{+0.18}_{-0.13}$ $\left(^{+0.11}_{-0.08}\right)$
$\lambda_{WZ} = \kappa_W / \kappa_Z$	$0.89\ ^{+0.10}_{-0.09}$ $\left(^{+0.12}_{-0.10}\right)$	$^{+0.09}_{-0.08}$ $\left(^{+0.11}_{-0.09}\right)$	$^{+0.03}_{-0.03}$ [illegible]	$^{+0.02}_{-0.02}$ [illegible]	$^{+0.02}_{-0.01}$ [illegible]
$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$	$0.89\ ^{+0.11}_{-0.10}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.11}_{-0.09}$ $\left(^{+0.13}_{-0.11}\right)$	[illegible]	[illegible]	[illegible]
$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z$	$0.85\ ^{+0.14}_{-0.12}$ $\left(^{+0.17}_{-0.15}\right)$	$^{+0.12}_{-0.10}$ $\left(^{+0.14}_{-0.13}\right)$	[illegible]	[illegible]	[illegible]
$\lambda_{bZ} = \kappa_b / \kappa_Z$	$0.56\ ^{+0.18}_{-0.18}$ $\left(^{+0.25}_{-0.22}\right)$	$^{+0.12}_{-0.11}$ $\left(^{+0.21}_{-0.18}\right)$	-0.07 $\left(^{+0.09}_{-0.08}\right)$	-0.08 $\left(^{+0.08}_{-0.07}\right)$	-0.02 $\left(^{+0.06}_{-0.04}\right)$

NEW

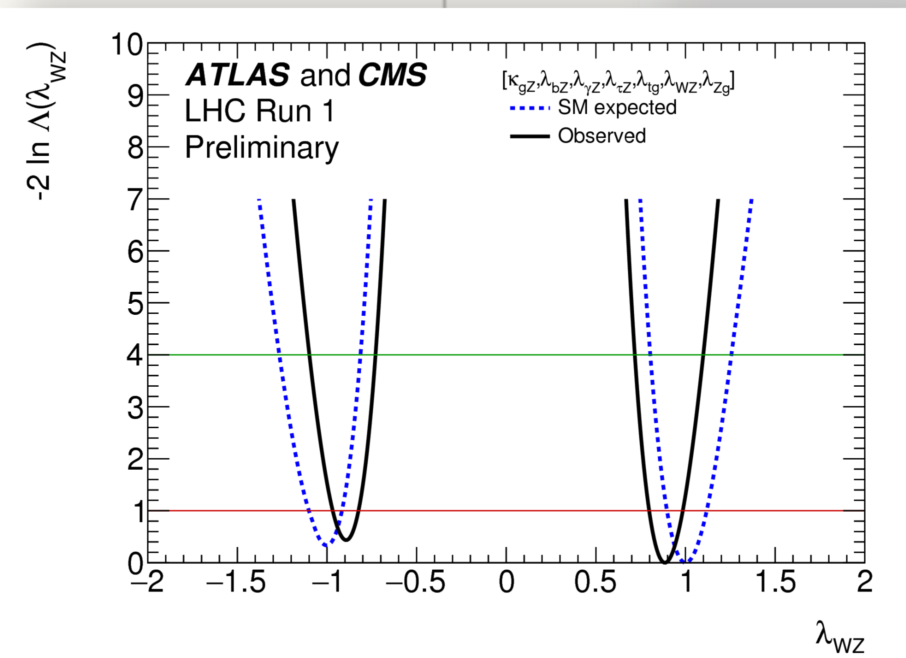
We will also give the
Complete breakdown
Of errors and the
full correlation matrix
But BEWARE OF RECAST

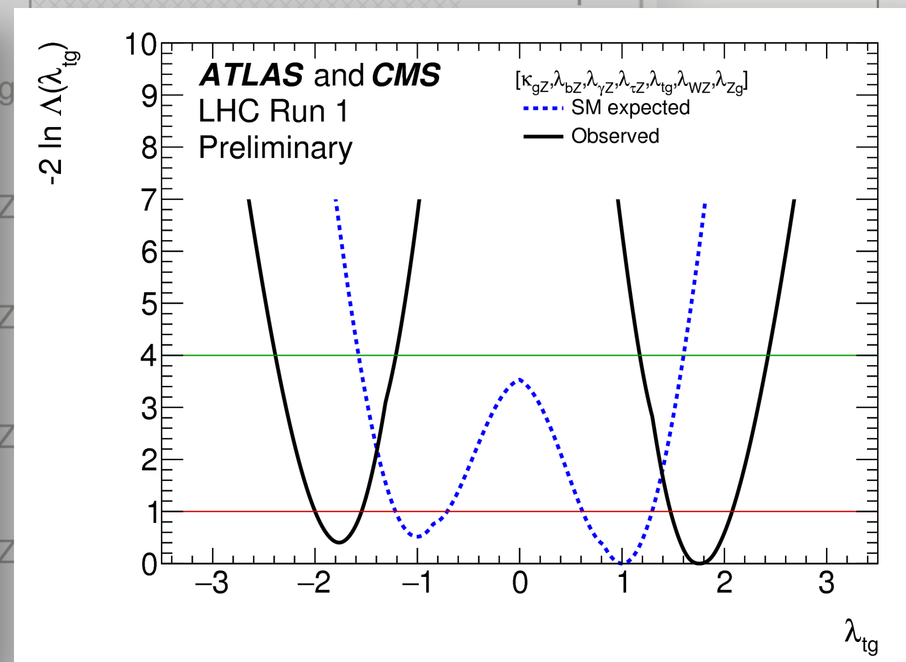


Couplings Generic Model

$ggZH$ and $tH \rightarrow$

possible solutions with negative λ_{tg} and λ_{WZ}





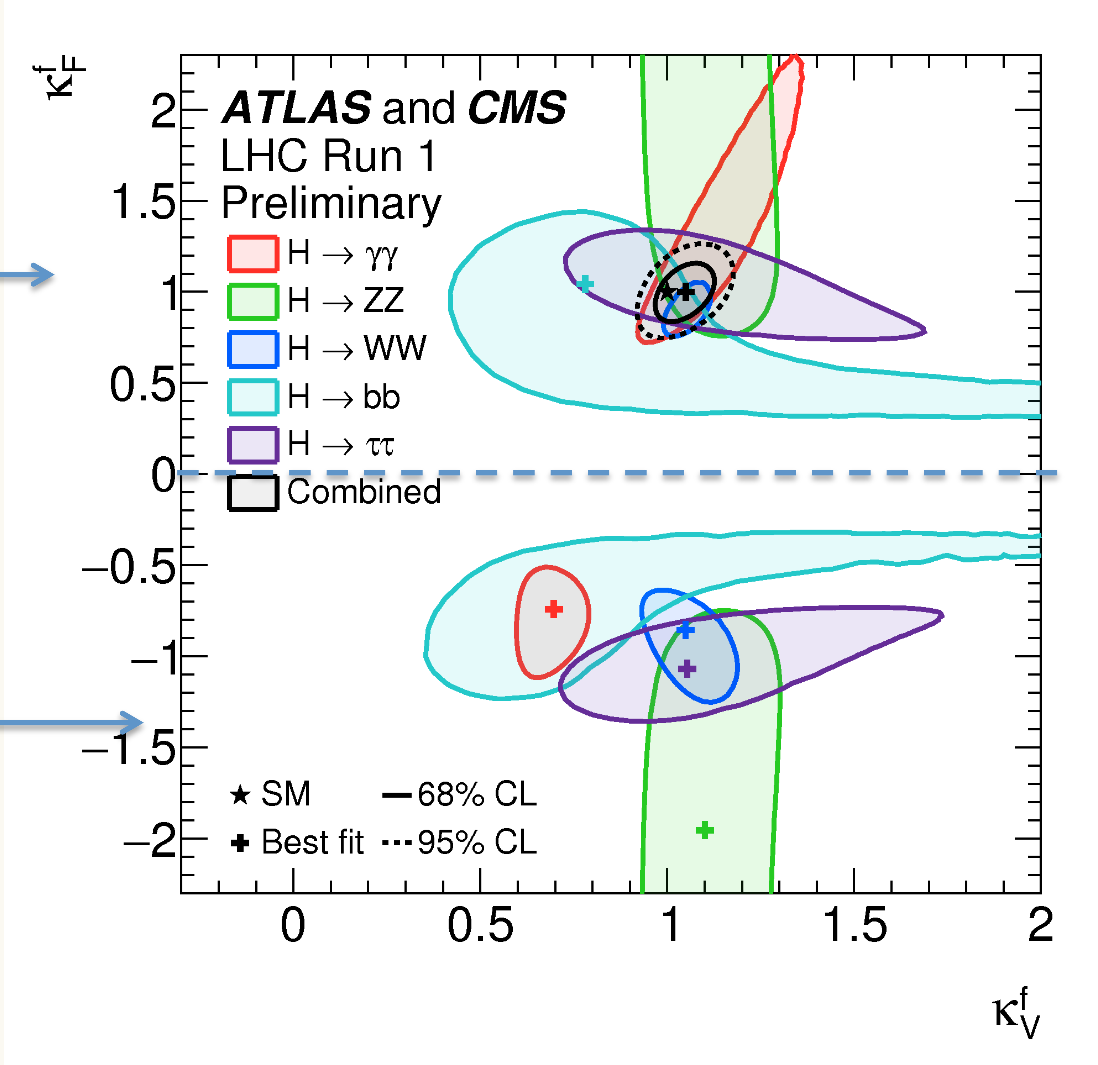
kV & kF: The pedagogic plot

HERE WE ASSUME ONLY SM PARTICLES ARE CONTRIBUTING TO THE LOOP
AND THAT ALL FERMION COUPLINGS EQUAL AND ALL VECTOR COUPLINGS EQUAL

~ 5σ exclusion of $k_F<0$

SM – No Tension

Tension Drifting apart

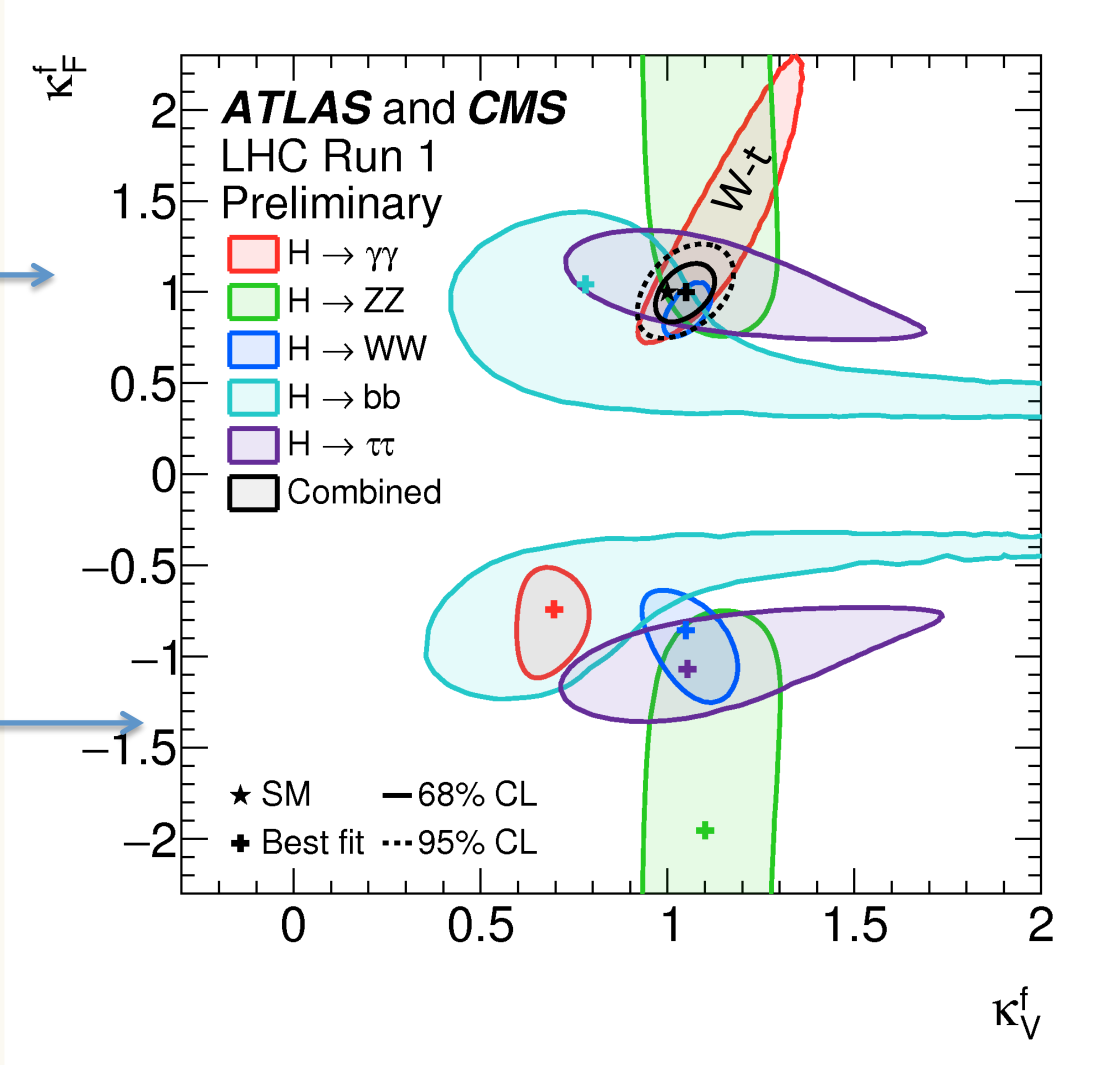


kV & kF: The pedagogic plot

HERE WE ASSUME ONLY SM PARTICLES ARE CONTRIBUTING TO THE LOOP
AND THAT ALL FERMION COUPLINGS EQUAL AND ALL VECTOR COUPLINGS EQUAL

SM –
No Tension

Tension
Drifting
apart

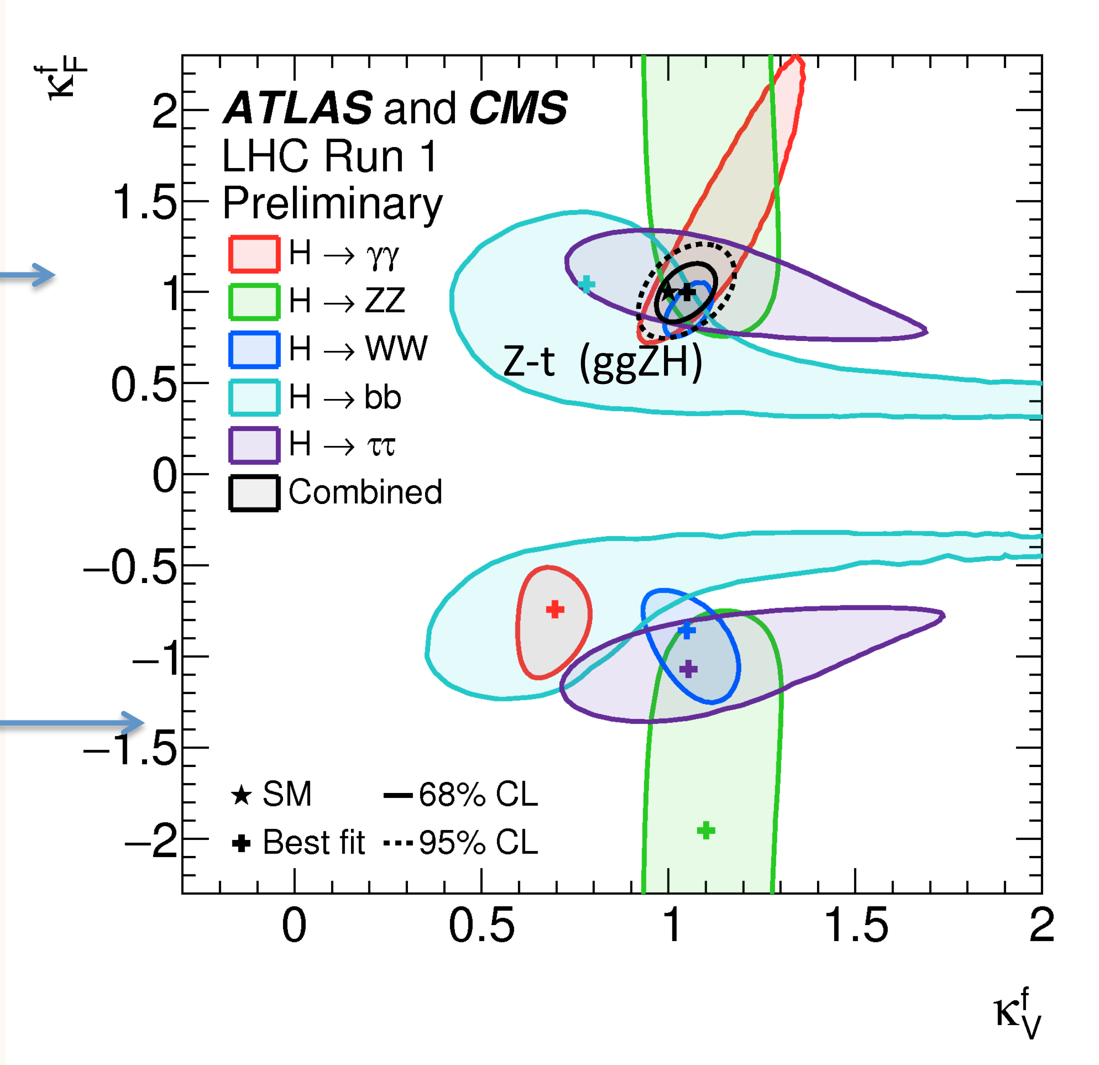


kV & kF: The pedagogic plot

HERE WE ASSUME ONLY SM PARTICLES ARE CONTRIBUTING TO THE LOOP
AND THAT ALL FERMION COUPLINGS EQUAL AND ALL VECTOR COUPLINGS EQUAL

SM –
No Tension

Tension
Drifting
apart



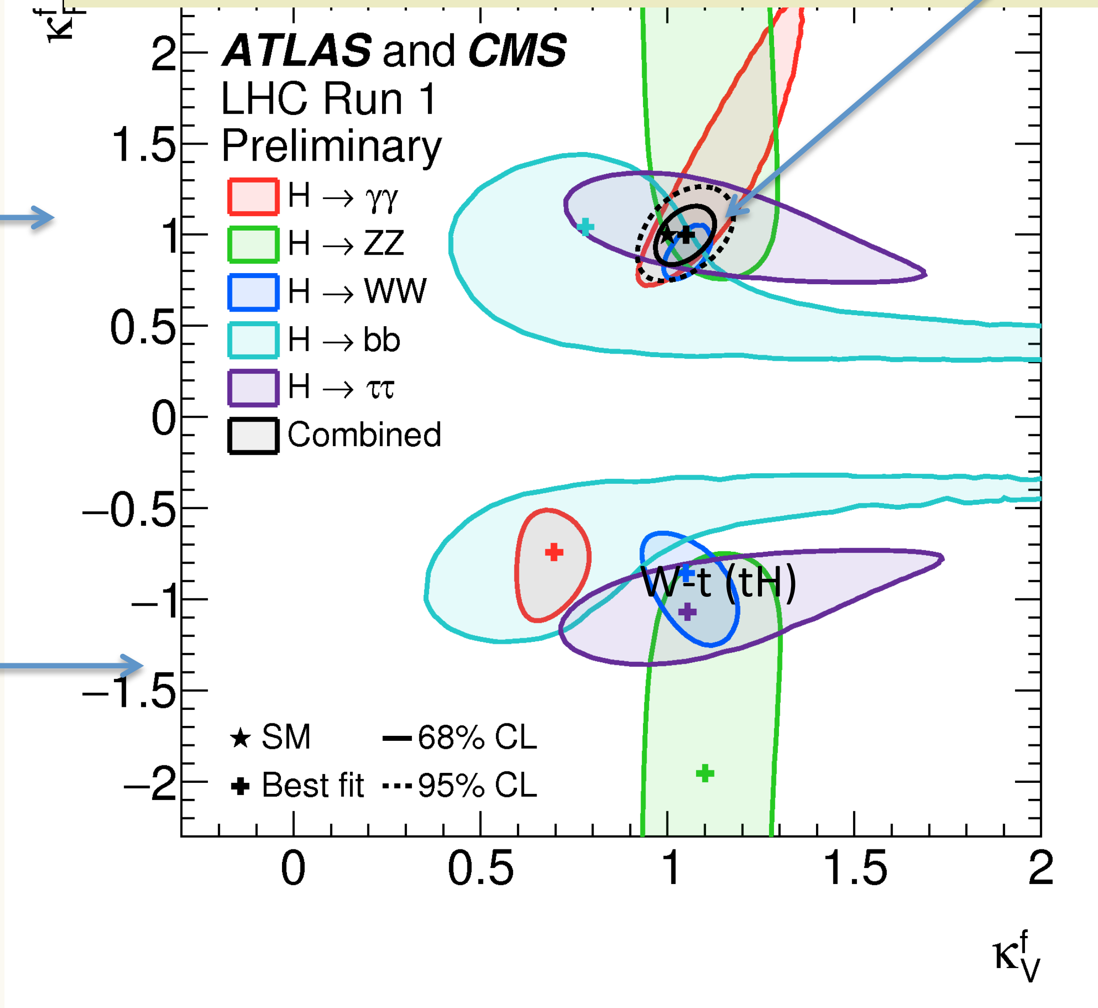
kV & kF: The pedagogic plot

HERE WE ASSUME ONLY SM PARTICLES ARE CONTRIBUTING TO THE LOOP
AND THAT ALL FERMION COUPLINGS EQUAL AND ALL VECTOR COUPLINGS EQUAL

Looks like we get better resolution with WW alone

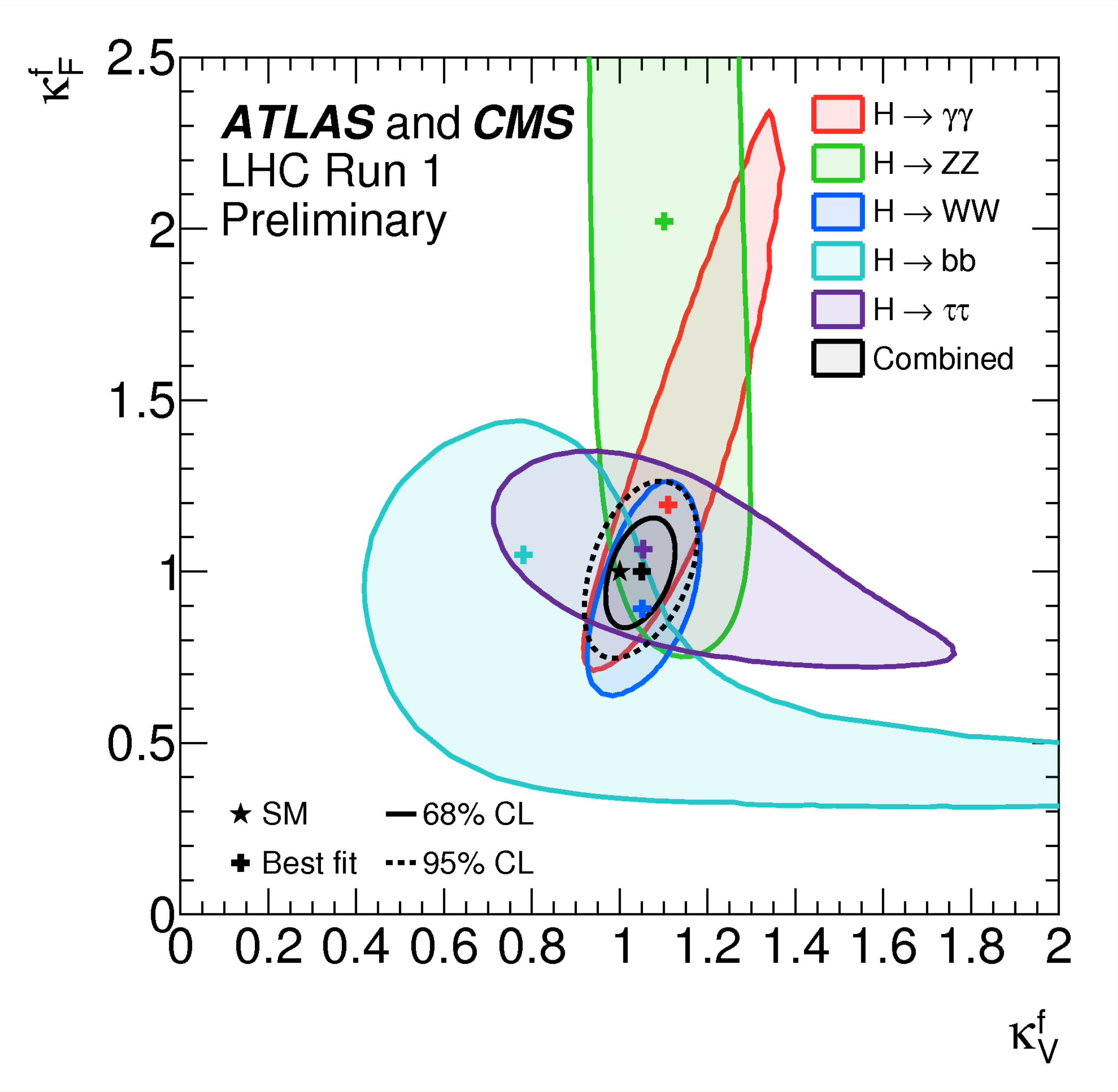
SM – No Tension

Tension Drifting apart



kV & kF: The pedagogic plot

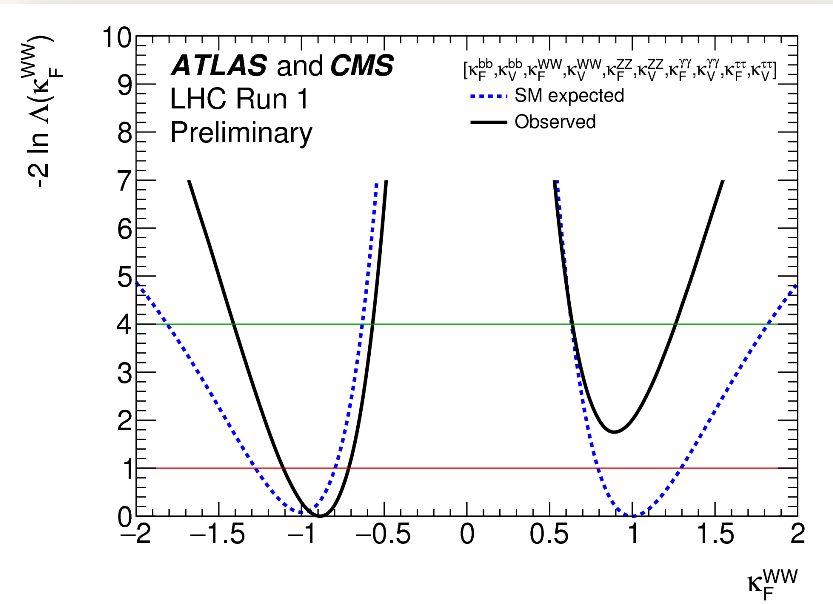
Fitting only positive Kappas, tautology resolved

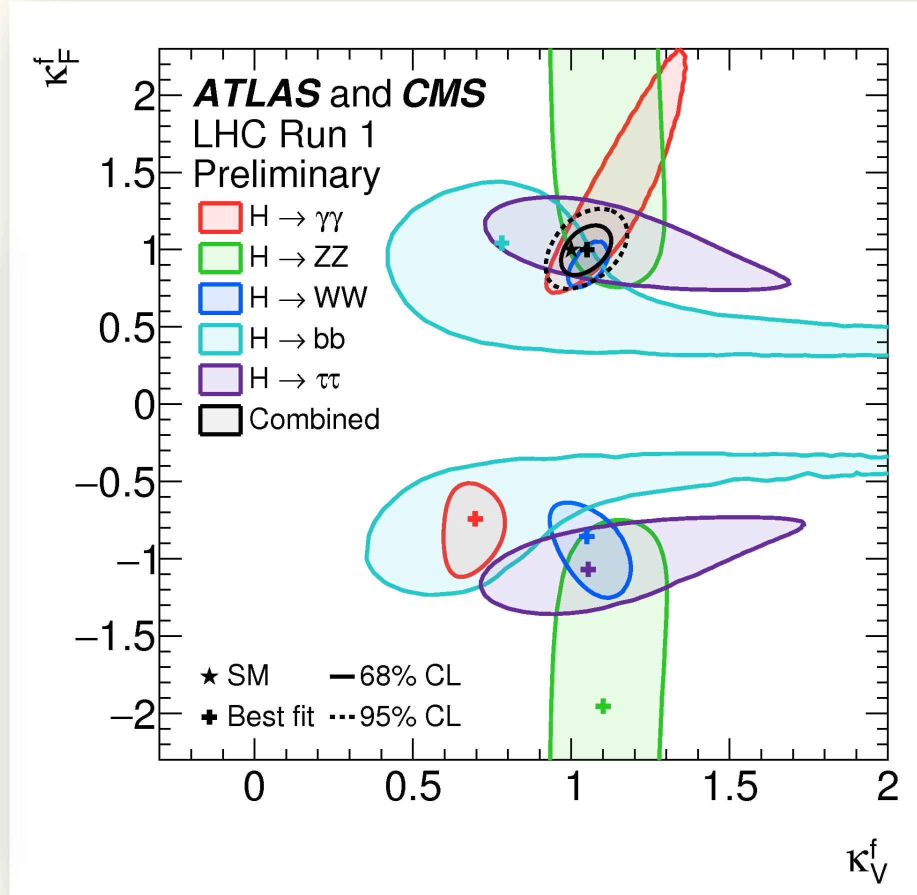


kV & kF: The pedagogic plot

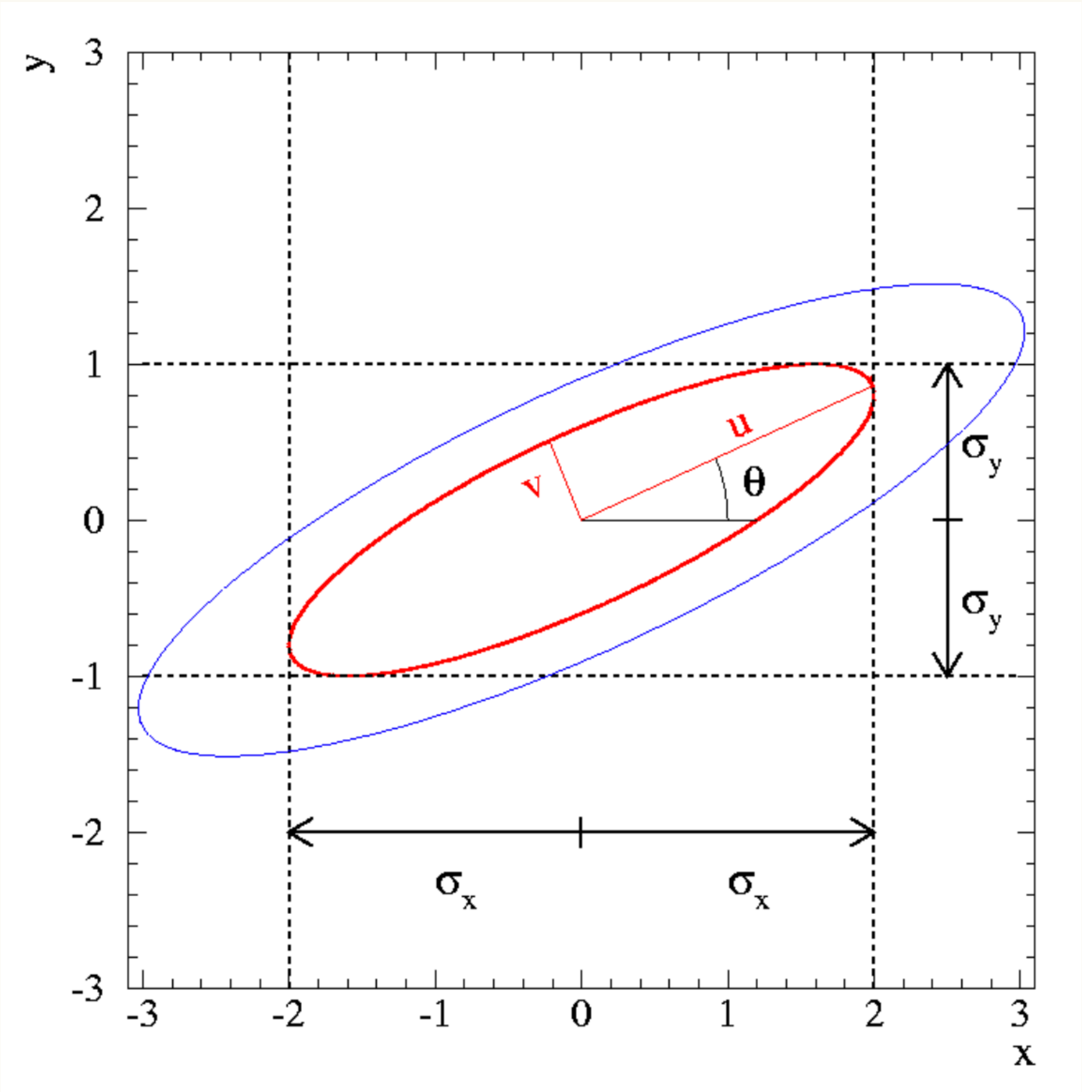
Another interesting point

Why in 1D we do not see a positive Confidence Interval for WW





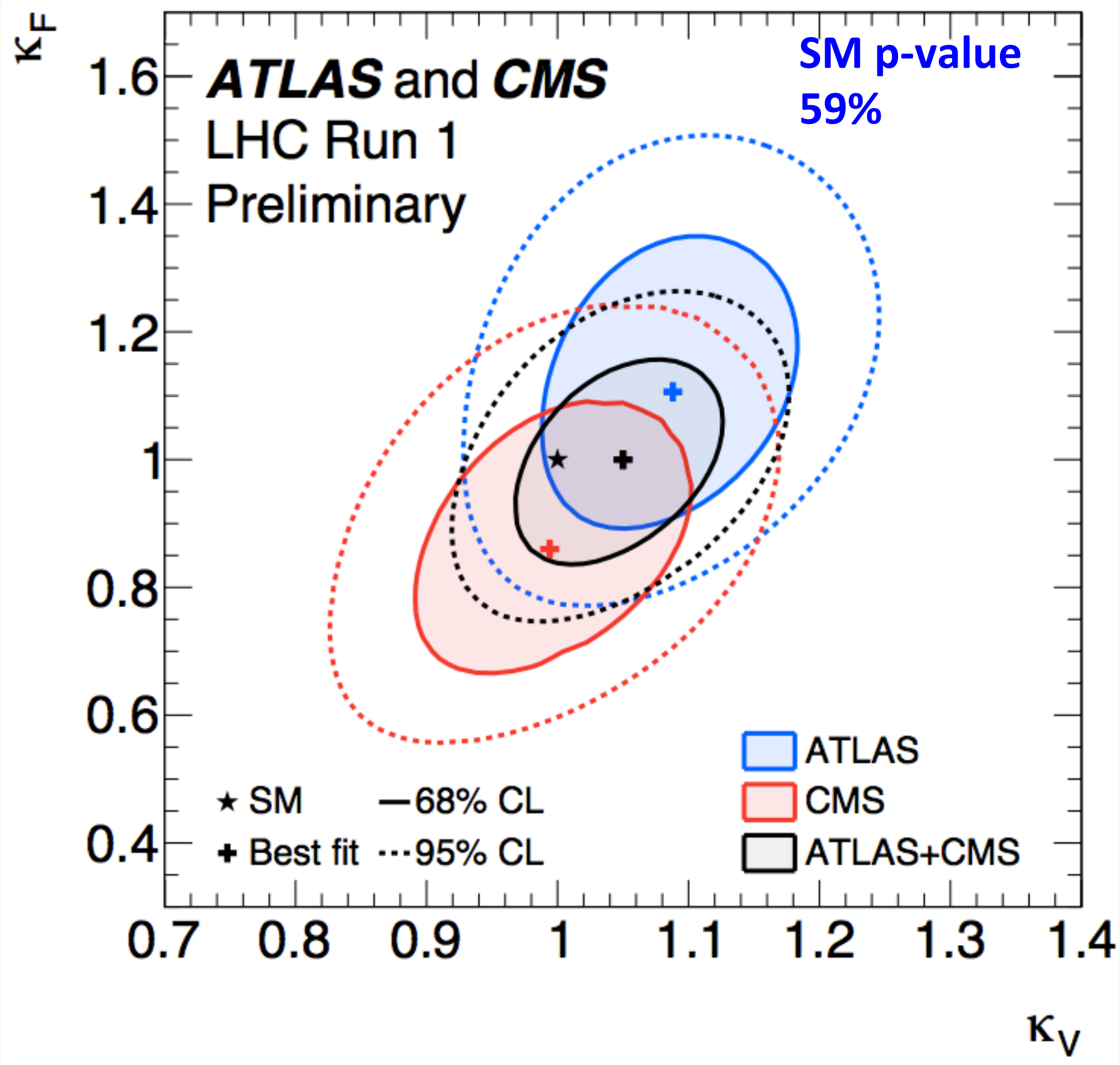
1D vs 2D Confidence Interval



$\Delta\chi^2 = 1$

$\Delta\chi^2 = 2.3 \;\; (68\%\ CL)$

The CERN Courier PR plot



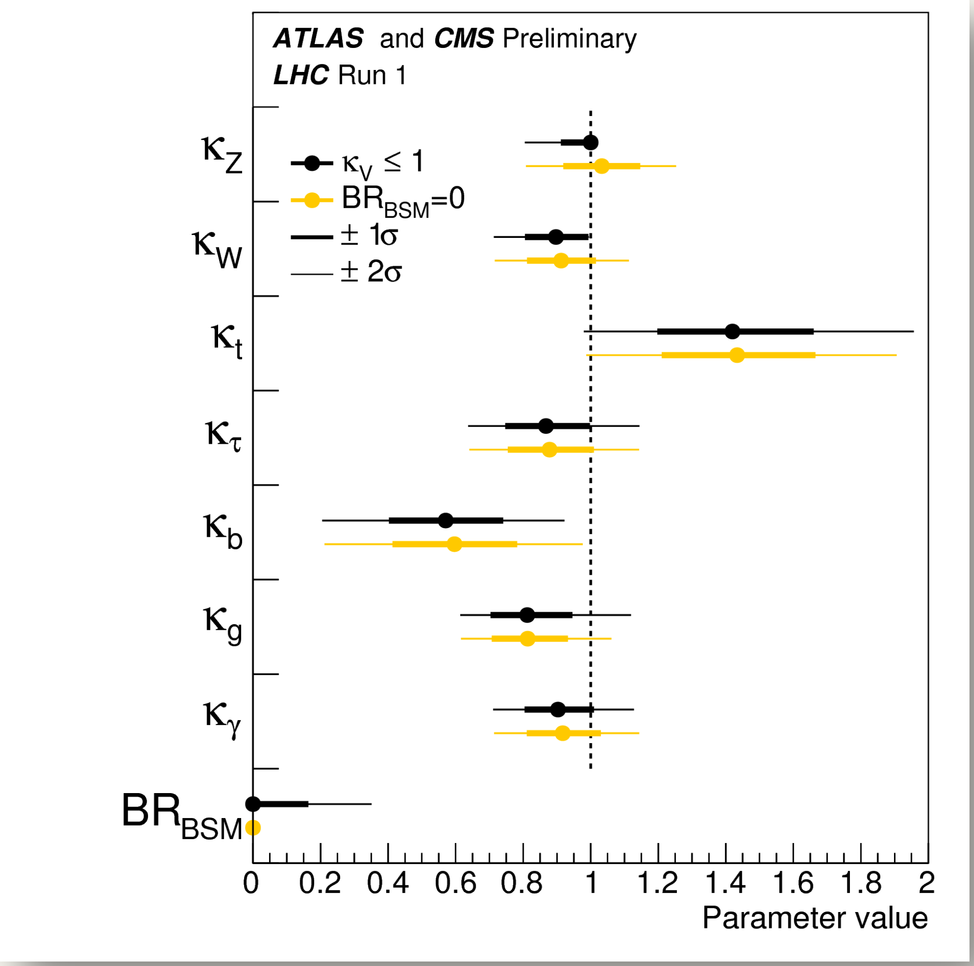
In the presence of NewPhysics

Here NP will enter in the loop and might contribute to BR_{BSM}

We introduce effective couplings k_γ, k_g

To be able to fit we need to constrain the width by either assume $BR_{BSM}=0$ (NP>mH/2)

or $k_V \leq 1$ and $BR_{BSM}>0$ (like in many BSM physics such as MSSM)

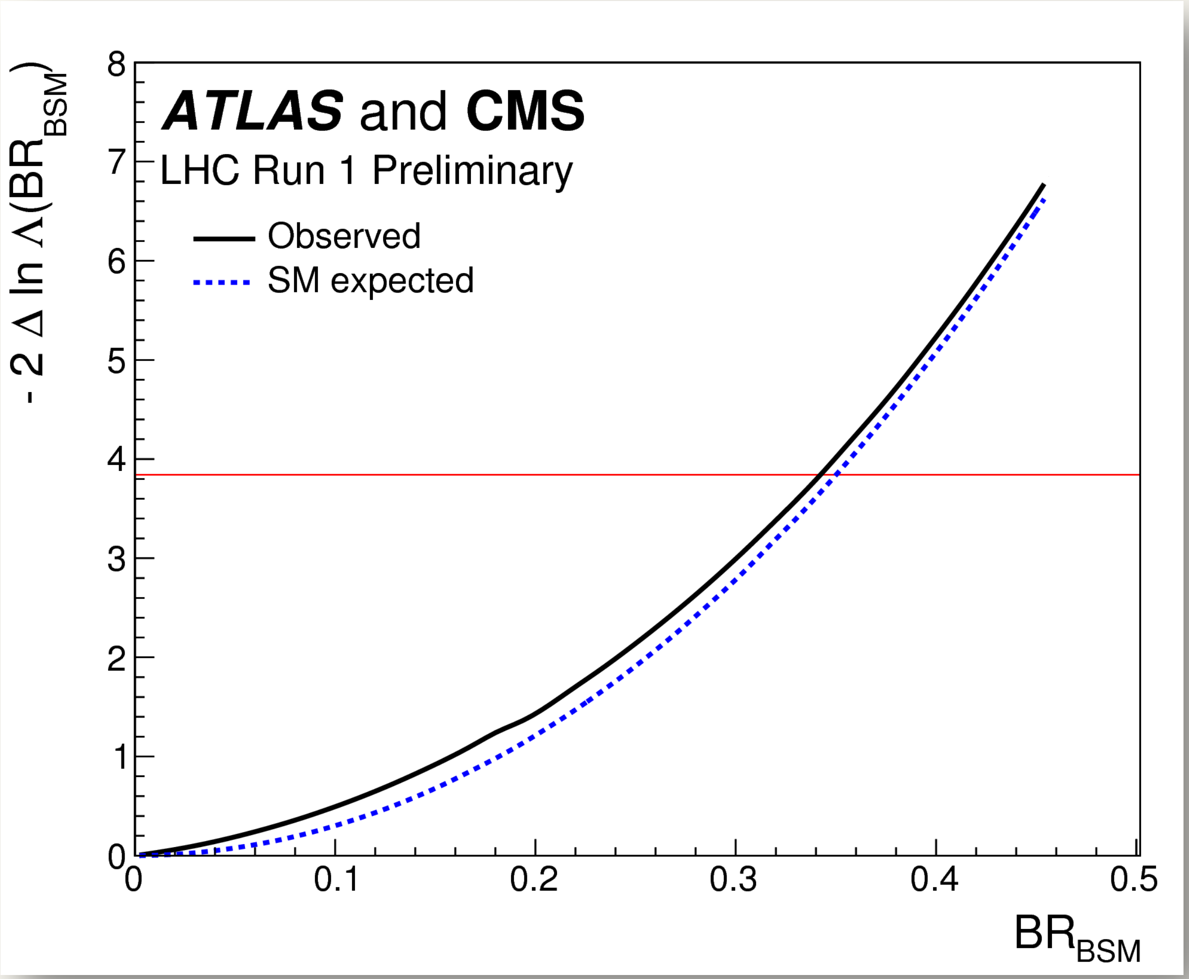


Bounds on BR_{BSM}

$BR_{BSM} < 0.34$ @ 95% CL

This is using a $\tilde{t}_{BR}$ (BR>0; FC) test statistics

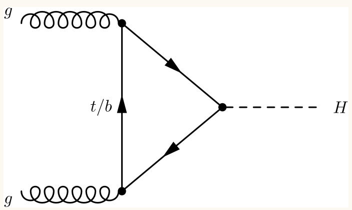
Which does not Allow negative BRs, leading to Possible Overcoverage (conservative)



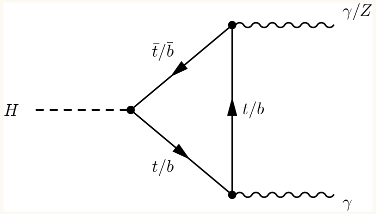
κ_g and κ_γ

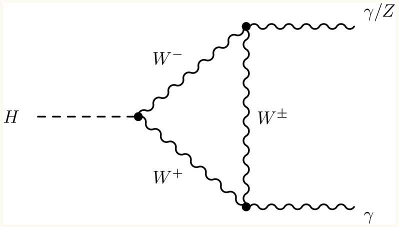
Assuming tree level couplings as in the SM and only modifications to the two main loops of ggF and H→ $\gamma\gamma$

ggF loop

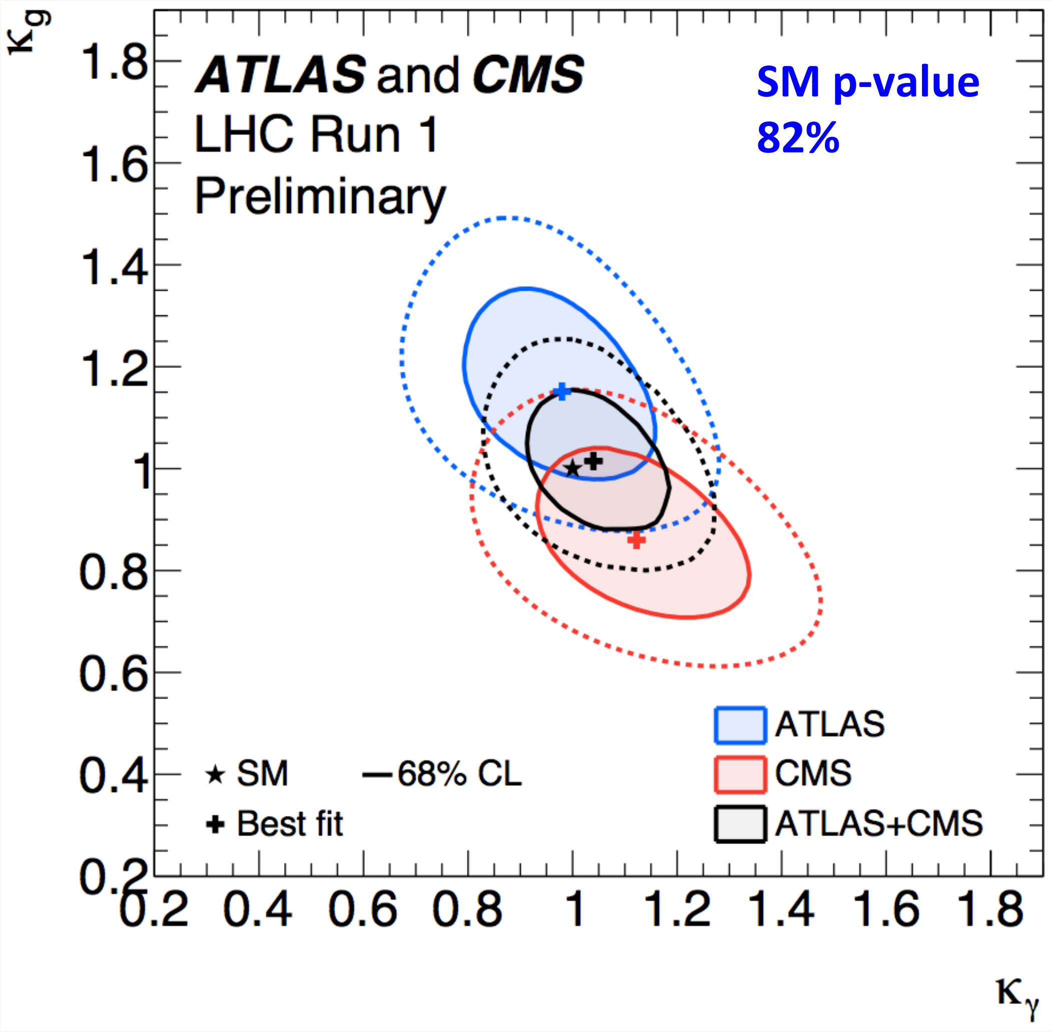


H→γγ loop





Additional heavy fermions or charged Higgs boson would modify the effective couplings



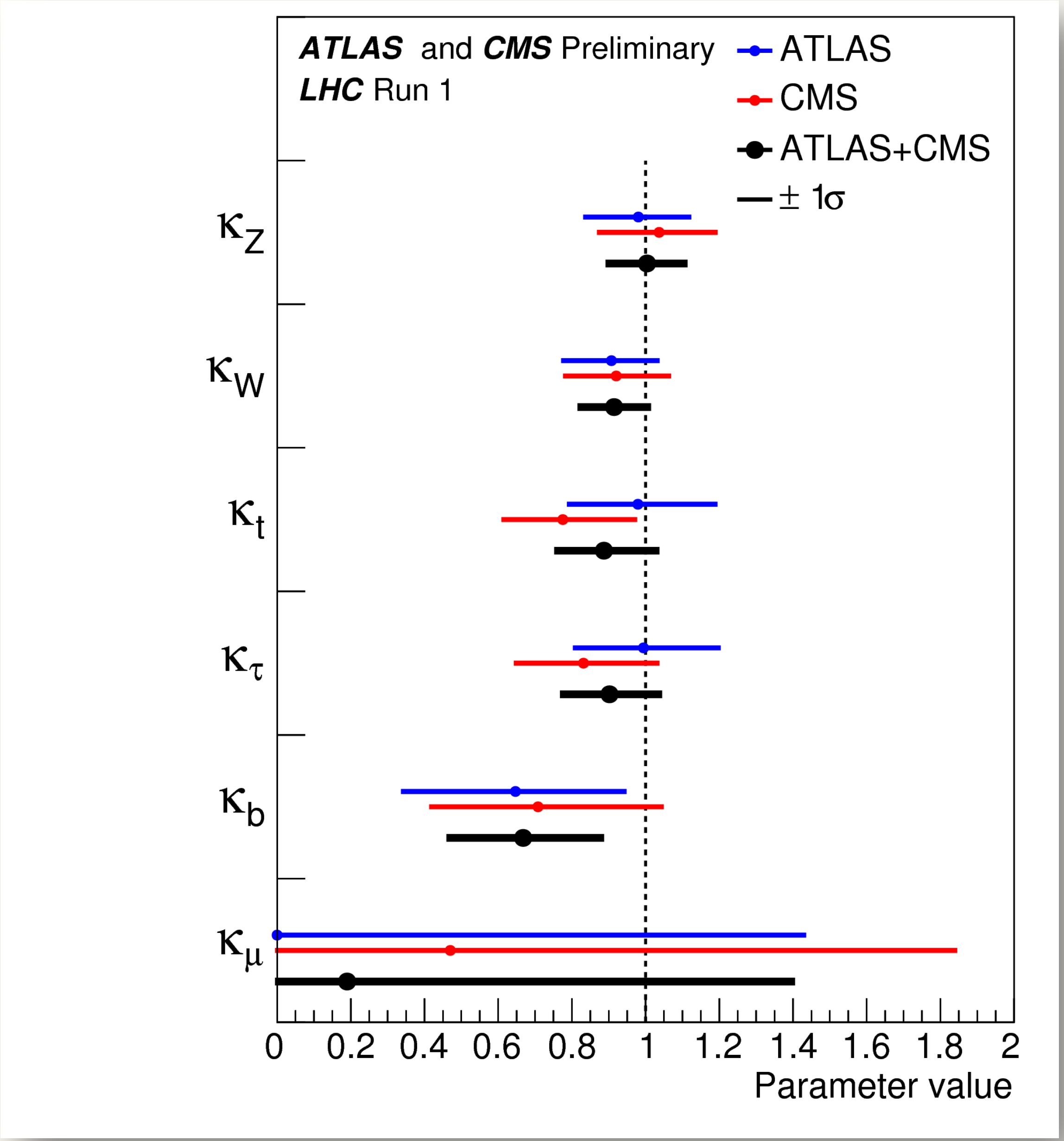
“SM” fit

This is the olny fit where the MuMu coupling was included in the 6p fit. Loops content was assumed (all loops resolved) and BR_{BSM}=0 was assumed.

Why all values<1?

Kb is low and it dominates the width (makes it small, reducung all Kappas)

This is actually a SM fit which leads to the “Money Plot”



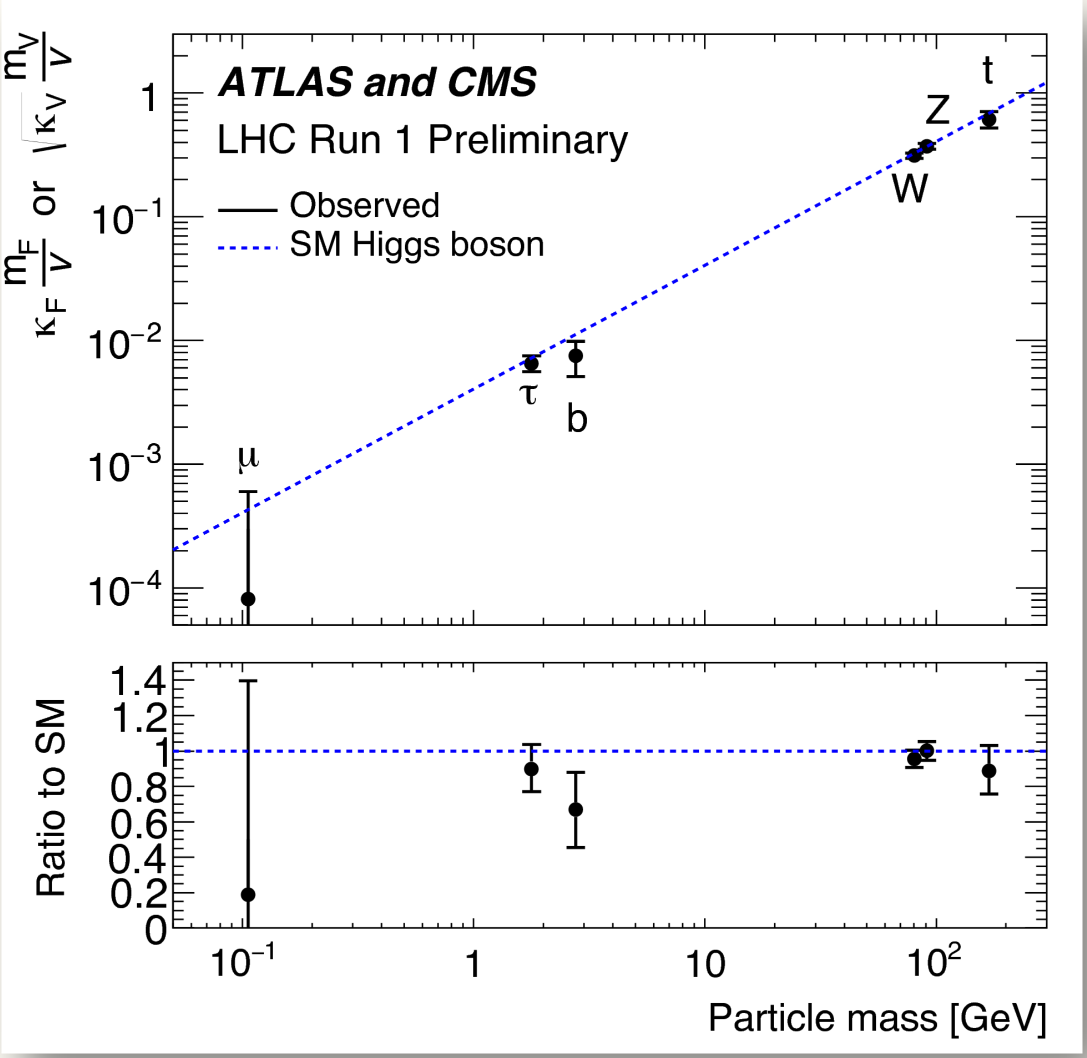
The PR Plot (an alternative version)

$$g_{Hff} = \frac{g_{Hff}}{g_{Hff}^{SM}} g_{Hff}^{SM} = \kappa_f g_{Hff}^{SM} \sim \kappa_f m_f$$

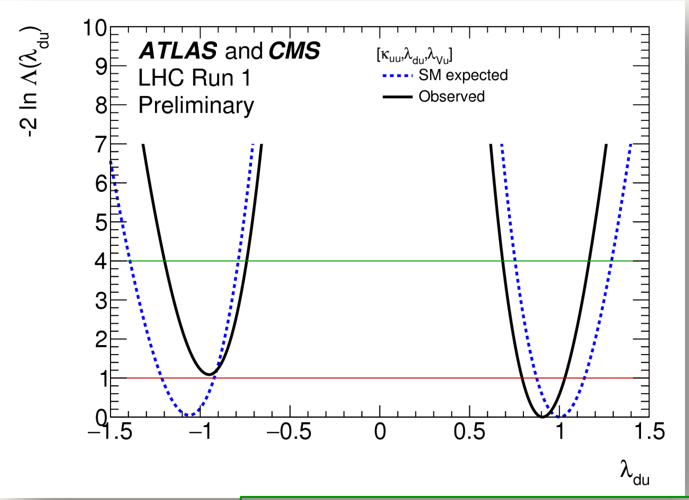
$$g_{HVV} = \frac{g_{HVV}}{g_{HVV}^{SM}} g_{HVV}^{SM} = \kappa_V g_{HVV}^{SM} \sim \kappa_V m_V^2$$

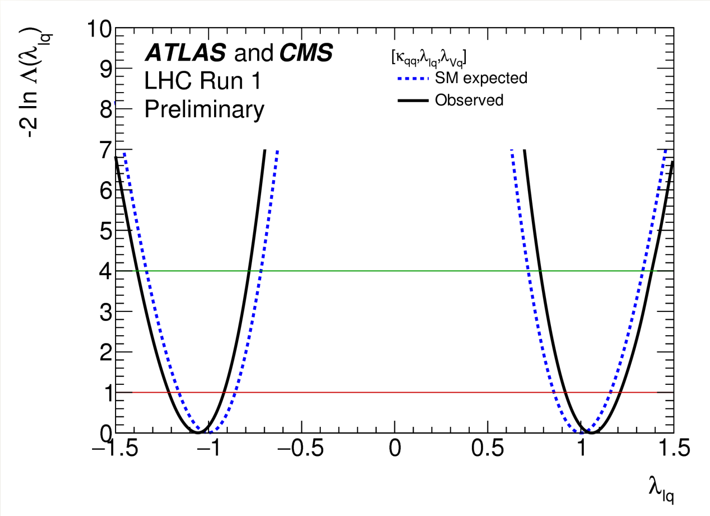
reduced coupling $\sqrt{g_{HVV}} \sim \sqrt{\kappa_V}\, m_V$

$$k_F \text{ or } \sqrt{k_V}$$



lq and du





$$\lambda_{du} = \frac{\kappa_d}{\kappa_u} \qquad \lambda_{lq} = \frac{\kappa_l}{\kappa_q}$$

Parameter	ATLAS+CMS observed	ATLAS+CMS expected unc.
λ_{du}	$0.91^{+0.12}_{-0.11}$	$[-1.21, -0.92] \cup [0.87, 1.14]$
λ_{Vu}	$0.99^{+0.13}_{-0.12}$	$^{+0.20}_{-0.12}$
κ_{uu}	$1.09^{+0.22}_{-0.19}$	$^{+0.20}_{-0.27}$
λ_{lq}	$[-1.21, -0.92] \cup [0.92, 1.21]$	$[-1.16, -0.86] \cup [0.86, 1.16]$
λ_{Vq}	$1.09^{+0.14}_{-0.13}$	$^{+0.13}_{-0.11}$
κ_{qq}	$0.94^{+0.17}_{-0.15}$	$^{+0.18}_{-0.16}$

SM p-value 67%

SM p-value 78%

Is it a SINGLE particle?

NEW

Rank 5 analysis:

25 free parameters

5 production modes X 5 decay modes

General matrix parameterisation: rank($\mathcal{M}$) = 5

Signal model	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$
ggF	$\mu_{ggF}^{\gamma\gamma}$	μ_{ggF}^{ZZ}	μ_{ggF}^{WW}	$\mu_{ggF}^{\tau\tau}$	μ_{ggF}^{bb}
VBF	$\lambda_{VBF}^{\gamma\gamma}\ \mu_{ggF}^{\gamma\gamma}$	$\lambda_{VBF}^{ZZ}\ \mu_{ggF}^{ZZ}$	$\lambda_{VBF}^{WW}\ \mu_{ggF}^{WW}$	$\lambda_{VBF}^{\tau\tau}\ \mu_{ggF}^{\tau\tau}$	$\lambda_{VBF}^{bb}\ \mu_{ggF}^{bb}$
WH	$\lambda_{WH}^{\gamma\gamma}\ \mu_{ggF}^{\gamma\gamma}$	$\lambda_{WH}^{ZZ}\ \mu_{ggF}^{ZZ}$	$\lambda_{WH}^{WW}\ \mu_{ggF}^{WW}$	$\lambda_{WH}^{\tau\tau}\ \mu_{ggF}^{\tau\tau}$	$\lambda_{WH}^{bb}\ \mu_{ggF}^{bb}$
ZH	$\lambda_{ZH}^{\gamma\gamma}\ \mu_{ggF}^{\gamma\gamma}$	$\lambda_{ZH}^{ZZ}\ \mu_{ggF}^{ZZ}$	$\lambda_{ZH}^{WW}\ \mu_{ggF}^{WW}$	$\lambda_{ZH}^{\tau\tau}\ \mu_{ggF}^{\tau\tau}$	$\lambda_{ZH}^{bb}\ \mu_{ggF}^{bb}$
ttH	$\lambda_{ttH}^{\gamma\gamma}\ \mu_{ggF}^{\gamma\gamma}$	$\lambda_{ttH}^{ZZ}\ \mu_{ggF}^{ZZ}$	$\lambda_{ttH}^{WW}\ \mu_{ggF}^{WW}$	$\lambda_{ttH}^{\tau\tau}\ \mu_{ggF}^{\tau\tau}$	$\lambda_{ttH}^{bb}\ \mu_{ggF}^{bb}$

Is it a SINGLE particle?

NEW

Rank 1 analysis:

9 free parameters

5 COMMON production modes with

5 COMMON decay modes

Single-state matrix parameterisation: $\text{rank}(\mathcal{M}) = 1$

Signal model	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$
ggF	$\mu^{\gamma\gamma}_{ggF}$	μ^{ZZ}_{ggF}	μ^{WW}_{ggF}	$\mu^{\tau\tau}_{ggF}$	μ^{bb}_{ggF}
VBF	$\lambda_{VBF}\, \mu^{\gamma\gamma}_{ggF}$	$\lambda_{VBF}\, \mu^{ZZ}_{ggF}$	$\lambda_{VBF}\, \mu^{WW}_{ggF}$	$\lambda_{VBF}\, \mu^{\tau\tau}_{ggF}$	$\lambda_{VBF}\, \mu^{bb}_{ggF}$
WH	$\lambda_{WH}\, \mu^{\gamma\gamma}_{ggF}$	$\lambda_{WH}\, \mu^{ZZ}_{ggF}$	$\lambda_{WH}\, \mu^{WW}_{ggF}$	$\lambda_{WH}\, \mu^{\tau\tau}_{ggF}$	$\lambda_{WH}\, \mu^{bb}_{ggF}$
ZH	$\lambda_{ZH}\, \mu^{\gamma\gamma}_{ggF}$	$\lambda_{ZH}\, \mu^{ZZ}_{ggF}$	$\lambda_{ZH}\, \mu^{WW}_{ggF}$	$\lambda_{ZH}\, \mu^{\tau\tau}_{ggF}$	$\lambda_{ZH}\, \mu^{bb}_{ggF}$
ttH	$\lambda_{ttH}\, \mu^{\gamma\gamma}_{ggF}$	$\lambda_{ttH}\, \mu^{ZZ}_{ggF}$	$\lambda_{ttH}\, \mu^{WW}_{ggF}$	$\lambda_{ttH}\, \mu^{\tau\tau}_{ggF}$	$\lambda_{ttH}\, \mu^{bb}_{ggF}$

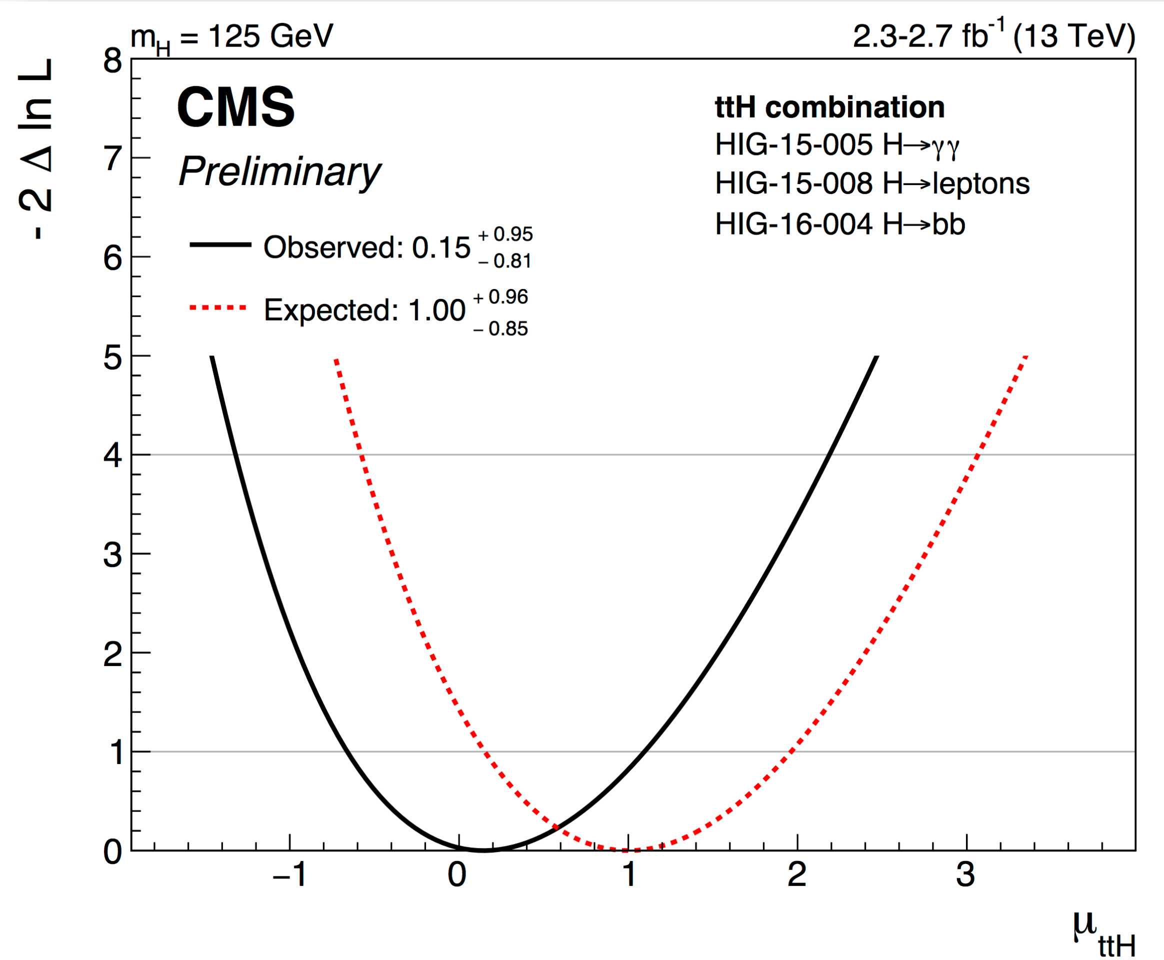
Is it a SINGLE particle?

The TEST of the compatibility between the single state to the Multiple state

We will test if the compatibility of the data with the single state is plausible (i.e. not 2%.....)

$$q_\lambda = -2\ln \frac{\mathcal{L}(\text{data}|\lambda_i^j = \hat{\lambda}_i, \hat{\mu}^j_{ggF})}{\mathcal{L}(\text{data}|\hat{\lambda}_i^j, \hat{\mu}'^j_{ggF})}$$

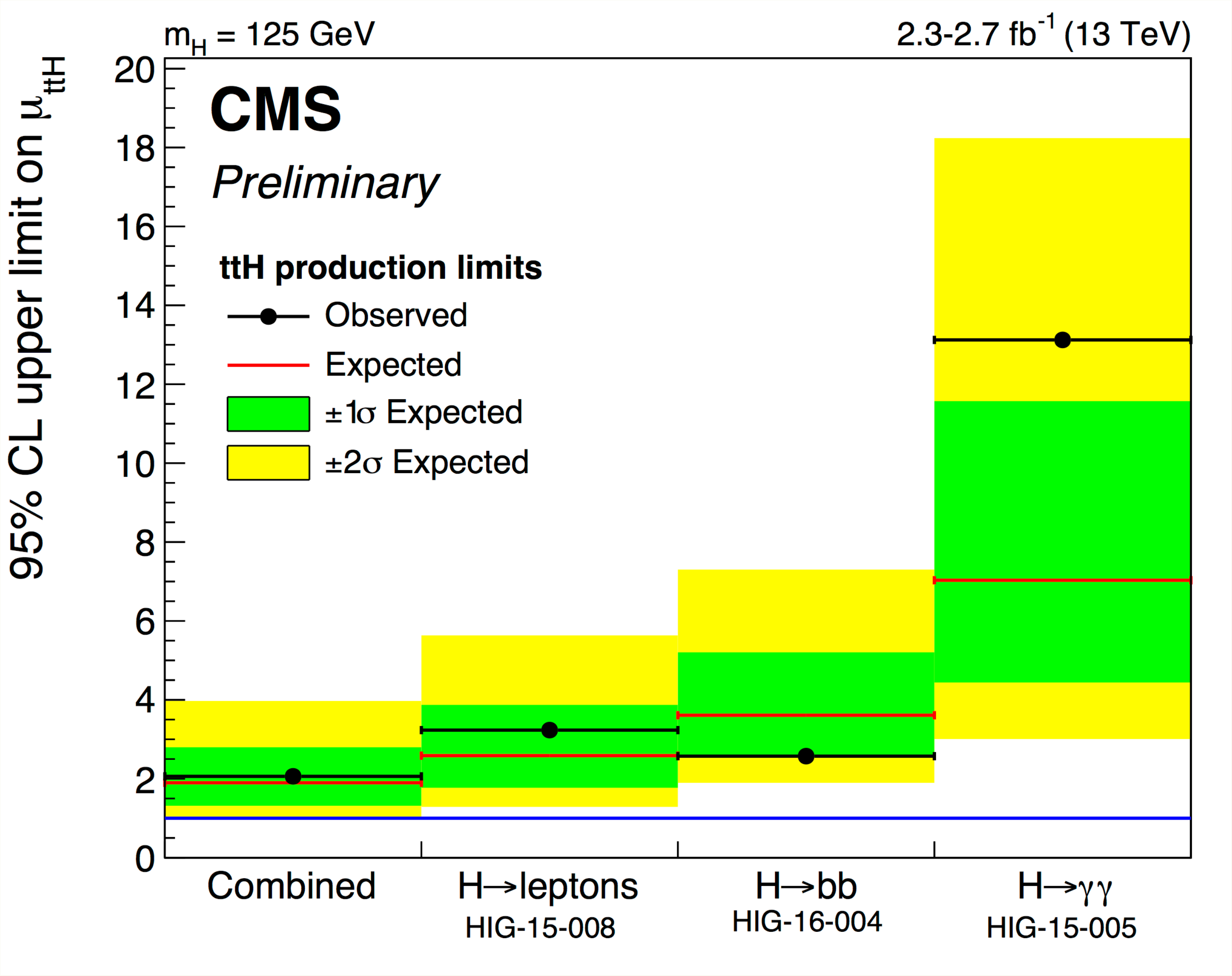
13 TeV: ttH CMS PAS HIG 16-04



$$\mu_{ttH} = 0.15^{+0.95}_{-0.85}$$

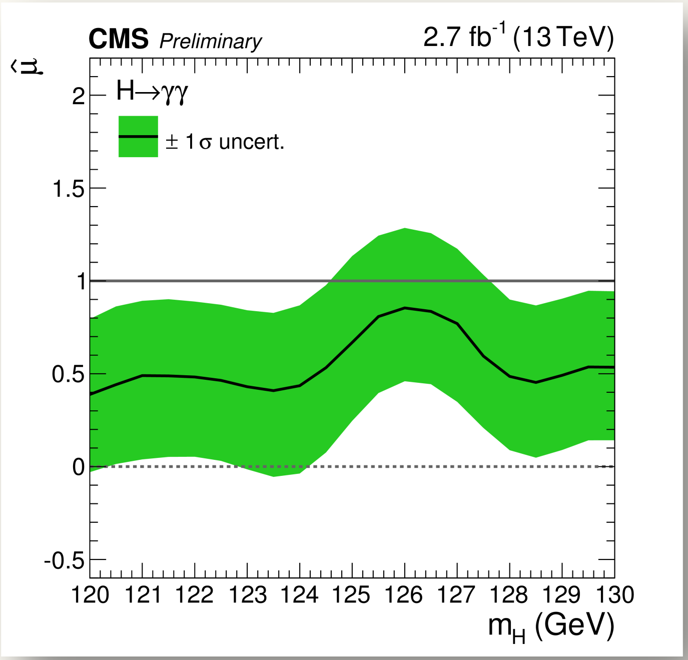
$$\mu^{SM}_{ttH} = 1.00^{+0.96}_{-0.85}$$

13 TeV: ttH CMS PAS HIG 16-04



13 TeV: $H \to \gamma\gamma$

CMS PAS HIG 15-05



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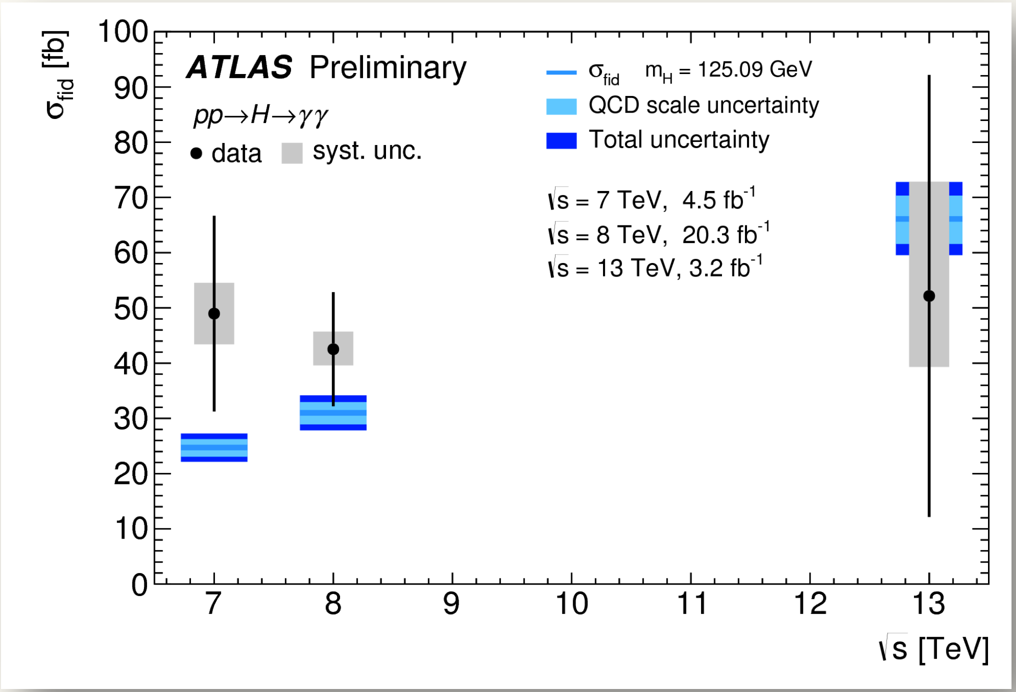


$$H \to \gamma\gamma$$

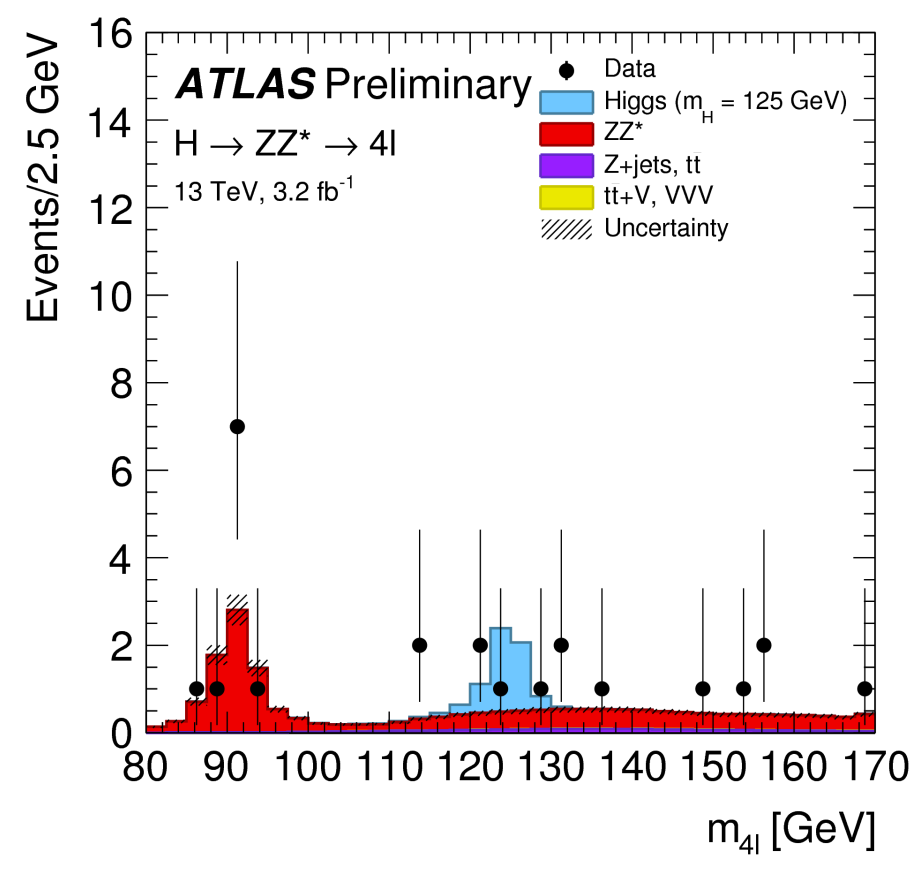
$$1.7\sigma (2.5\sigma \ exp)$$

$$H \to \gamma\gamma$$

$$\sigma < 106\, pb (112\, pb \ exp)$$

13 TeV: $H \to 4\ell$

Data set [TeV]	N_s	$\sigma^{fid}_{4\ell}$ [fb]	σ^{fid}_{theory} [fb]	σ^{tot} [pb]	σ^{tot}_{theory} [pb]
7	$4.5\,^{+2.8}_{-2.2}$	$1.9\,^{+1.2}_{-0.9}$	1.03 ± 0.11	$33\,^{+21}_{-16}$	17.5 ± 1.6
8	$24.0\,^{+6.0}_{-5.3}$	2.1 ± 0.5	1.29 ± 0.13	$37\,^{+9}_{-8}$	22.3 ± 2.0
13	$1.0\,^{+2.3}_{-1.5}$	$0.6\,^{+1.3}_{-0.9}$	2.74 ± 0.28	$12\,^{+25}_{-16}$	$50.9\,^{+4.5}_{-4.4}$



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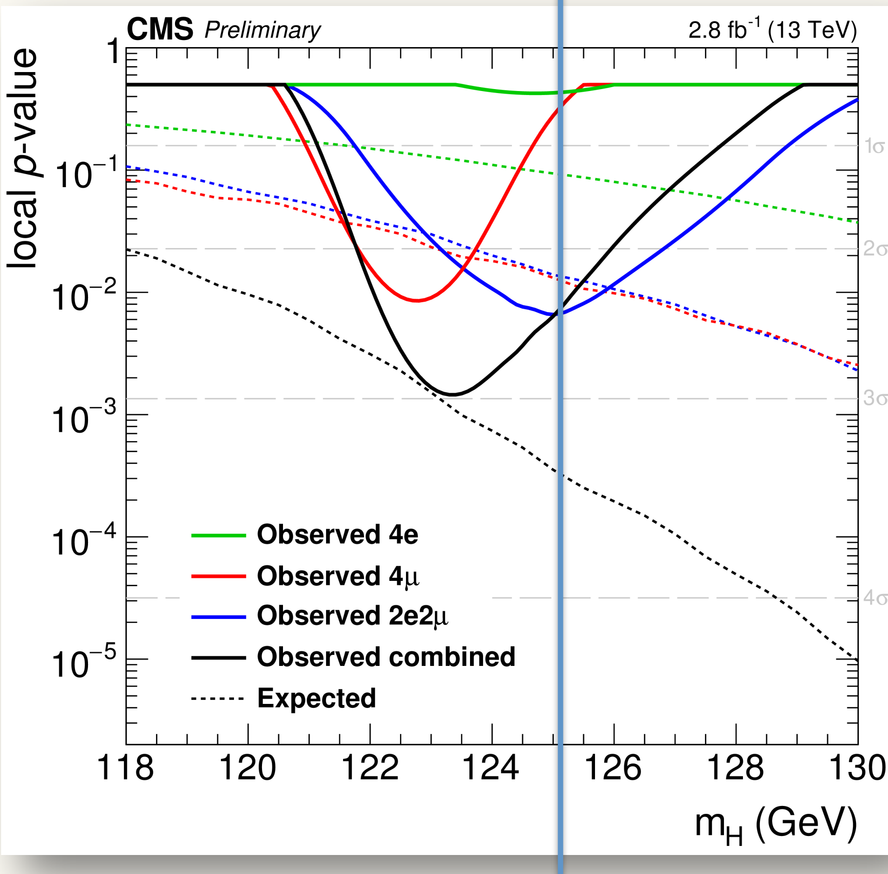
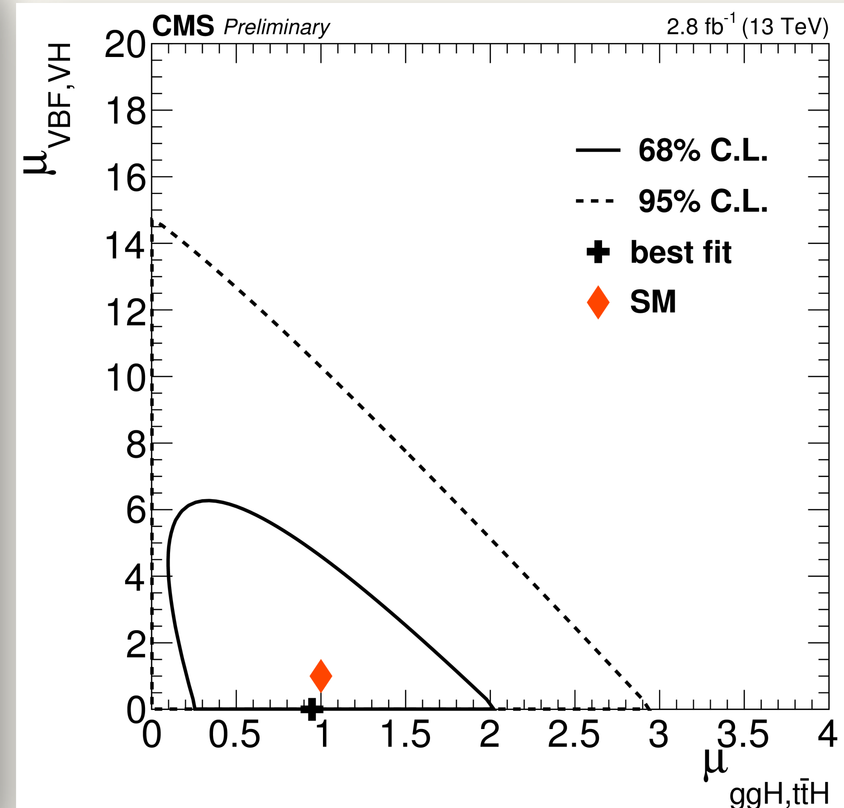
CMS PAS HIG-15-004

13 TeV: $H \rightarrow 4\ell$





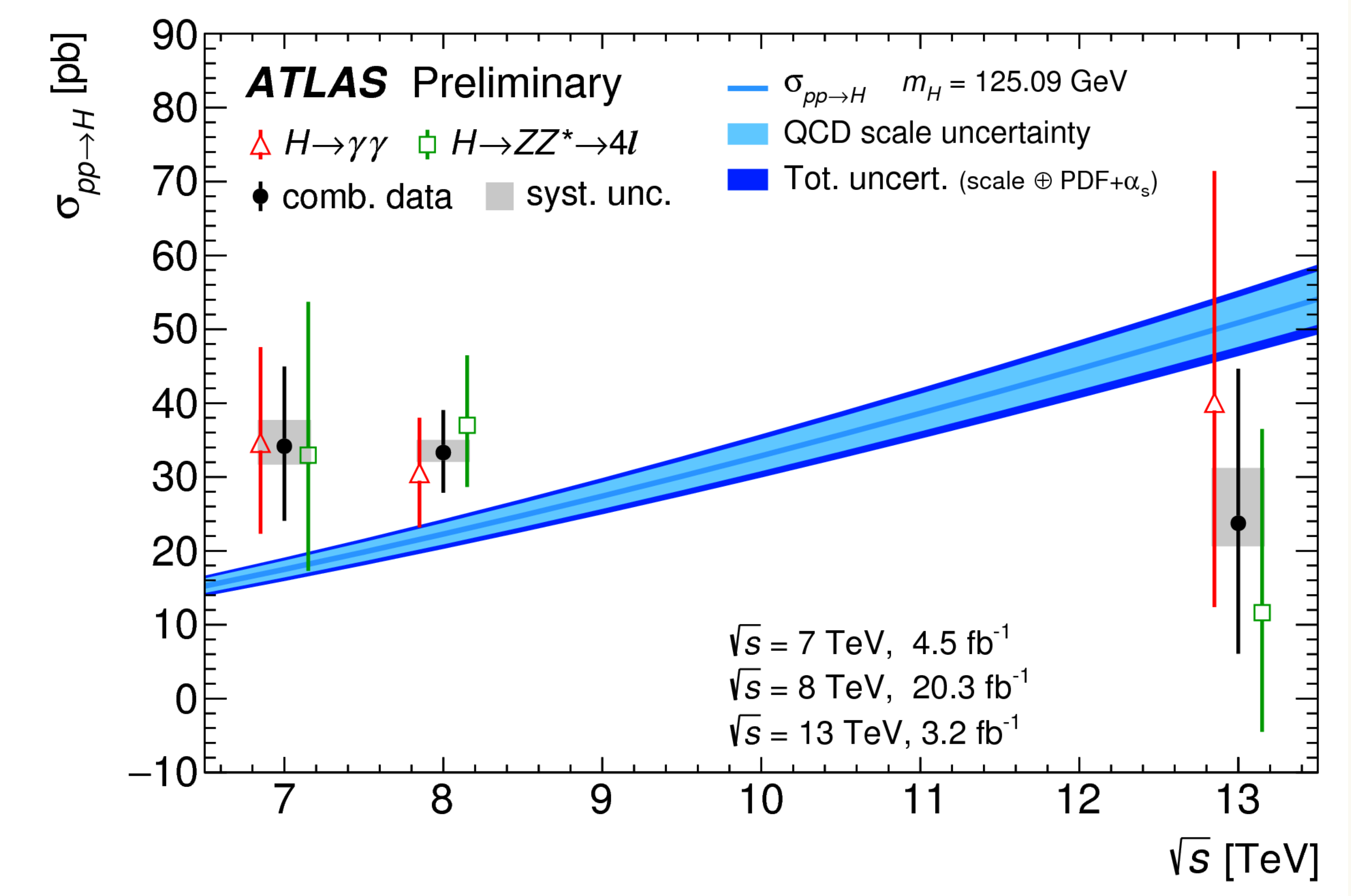
$H \rightarrow 4\ell$

$$\mu_{VBF} = 0.0^{+2.5} \qquad \mu_{ggF} = 0.95^{+0.64}_{-0.49}$$

$H \rightarrow 4\ell$

$$2.5\sigma (3.4\sigma \; exp)$$

13 TeV: pp->H ATLAS-CONF-2015-069



Conclusions

Concluded?

Not Yet

We will conclude when the paper is out.

13 TeV is coming

But also a 750 GeV which steals the attention from everything else…

BACKUP

Signal Theory Uncertaintoes

- Signal Theory Uncertainties
  - PDF
    - PDF uncertainties on the inclusive rates for different Higgs production processes, are correlated between the experiments for the same production mode classes (called for historical reasons gg,qq and qg see below), but uncorrelated between themselves.
    - The so called gg class include (for signal): ggH,bbH and (anticorrelated with) ttH
      the so called qq class include qqH,WH,ZH and (antocorrleated with) ggZH
      the gq class is gq->tH production
    - No correlations between signal and background.
    - 100% anti-correlation between ggF and ttH (both gg generated)
    - tH (WtH and tHbj) are correlated between ttH, H->γγ, H→multileptons and H→bb
    - VBF, WH and qqZH are correlated between themselves and anti-correlated with gg initiated ggZH

Signal Theory Uncertaintoes

- Signal Theory Uncertainties
  - UEPS

    PDF and UEPS could be correlated between signal and BG, but since lots of BG is data driven its too complicated and assumed to be uncorrelated (between signal and BG)

    - UEPS are correlated between experiments for the same production mode
      The qq and gg generated UEPS (for inclusive 0+1 jet) are split within the VBF tag and VH tag ckasses (for 2 jets)
    - QCD Scale

    Similarly, QCD Scale is correlated between experiments **in the same production channel**, but assumed to be uncorrelated between different production channels
  - For BR the full corrleation matrix is implemented for L1 which is the most sensitivie model.
  - Other th uncertainties on signal acceptance and efficiency (which are small) are taken uncorrelated because they are treated differently by the experiments and it is impossible to asses the correlation.