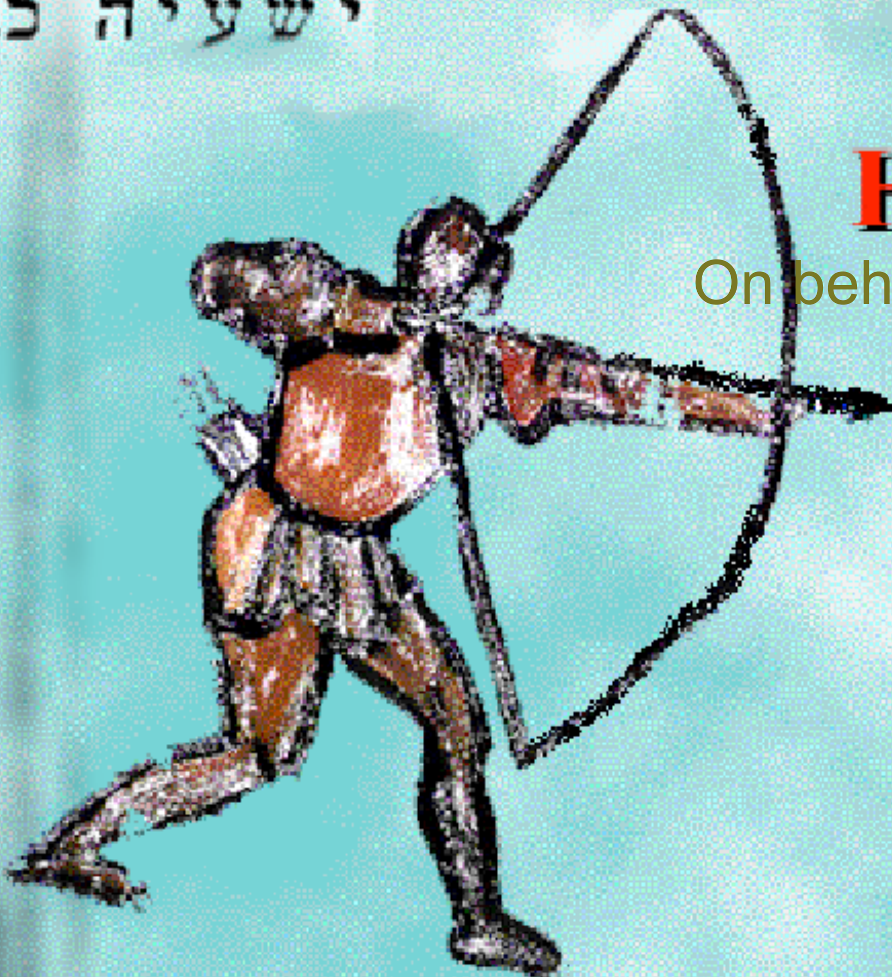
"וְעֵילָם נָשָׂא אַשְׁפָּה..."

ישעיה כב



Eilam Gross

Weizmann & CERN

Hunting the Higgs

On behalf of the LHCHCG group

Lund

Septemberh 2015

ATLAS EXPERIMENT

"And Eilam bare the quiver..."

Jesaia 22

Eilam Gross, Weizmann Institute of Science

HIGGS COUPLINGS (ATLAS+CMS)

With Marco Pieri (LHCP talk) , on behalf of LHCHCG

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

15th September 2015

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

A Phenomenological Profile of the Higgs Boson

1976

Nuclear Physics B106 (1976) 292–340

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

The situation with regard to Higgs bosons is unsatisfactory. First it should be stressed that they may well not exist. Higgs bosons are introduced to give intermediate vector bosons masses through spontaneous symmetry breaking. However, this symmetry breaking could be achieved dynamically [10] without elementary Higgs bosons. Thus the confirmation or exclusion of their existence would be an important constraint on gauge theory model building. Unfortunately, no way is known to calculate the mass of a Higgs boson, at least in the context of the popular Weinberg-Salam [11]

A Phenomenological Profile of the Higgs Boson

1976

Nuclear Physics B106 (1976) 292–340

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

A Phenomenological Profile of the Higgs Boson

Jan 2012

KCL-PH-TH/2012-04, LCTS/2012-01, CERN-PH-TH/2012-009
LBNL-, UCB-PTH-12/01
ACT-1-12, MIFPA-12-01

January 2012

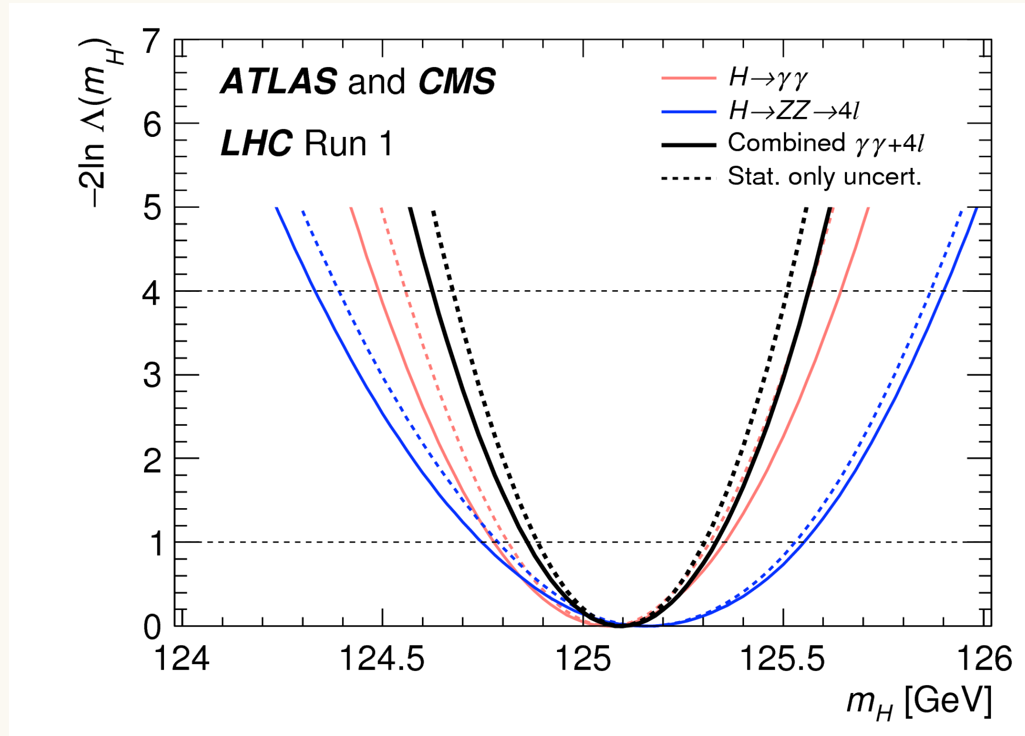
A Historical Profile of the Higgs Boson

John Ellis[a], Mary K. Gaillard[b] and Dimitri V. Nanopoulos[c]

Already in 1975, before the experimental discovery of charm was confirmed, we considered that the discovery of the Higgs boson would be the culmination of the experimental verification of the Standard Model, and we published a paper outlining its phenomenological profile [12]. At the time, the Higgs boson was not on the experimental agenda, but its star has risen over the subsequent years, first in e^+e^- collisions [13] and subsequently in $\bar{p}p$ and pp collisions [14, 15], until now it is widely (though incompletely) perceived as the primary objective of experiments at the LHC. We anticipate that the ATLAS and CMS experiments will soon deliver their verdict on the possible existence of the Higgs boson, providing closure on half a century of theoretical conjecture.

4th JULY 2012
Higgs Hunters' Independence Day

First LHC Higgs Combination Paper



$M_H = 125.09 \pm 0.24$ GeV

$= \pm 0.21$ (stat.) ± 0.11(syst.) GeV

Published May 2015

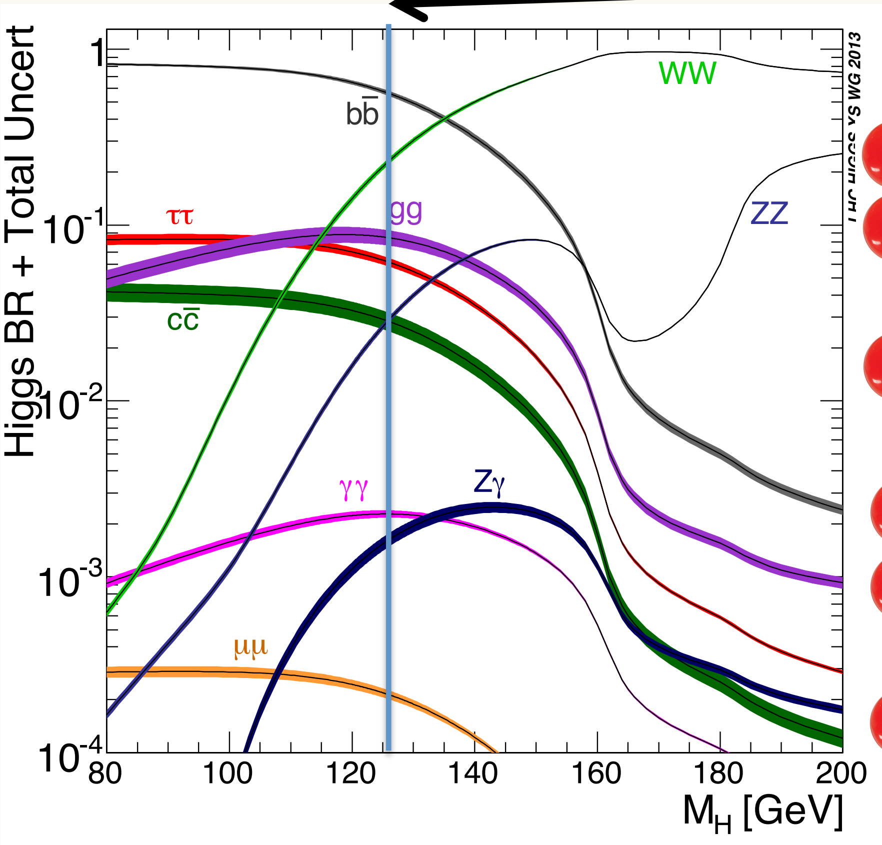
Discussions on Couplings Combination started already 10 months ago

Why did it take almost a year (and is not finished yet)?

- Combination is done within LHCHCG working group (1-2 meetings a week)
- Reports on individual channels analyses
- Report on individual channels Nuisance Parameters (NP)
- Build basic Workspaces (WS) for individual channels. WS are like special format data bases on which fits can be performed.
- Cross check WS between ATLAS and CMS (by performing basic fits to extract signal yields) and compare with publications
- Contact physicists per channel per experiment meet, discuss and give an educated recommendation on which NPs should be (if at all) correlated
- Models are discussed and agreed upon
- Combined WS for all models, are built by each experiment, then combined and crosschecked between experiments
- All models are being fit and cross checked between experiments
- A detailed support note is written with all details of the details
- A paper is being written, and turned into a note for LHCP

Theory Inputs I: Higgs Decays

m_H=125.09 GeV

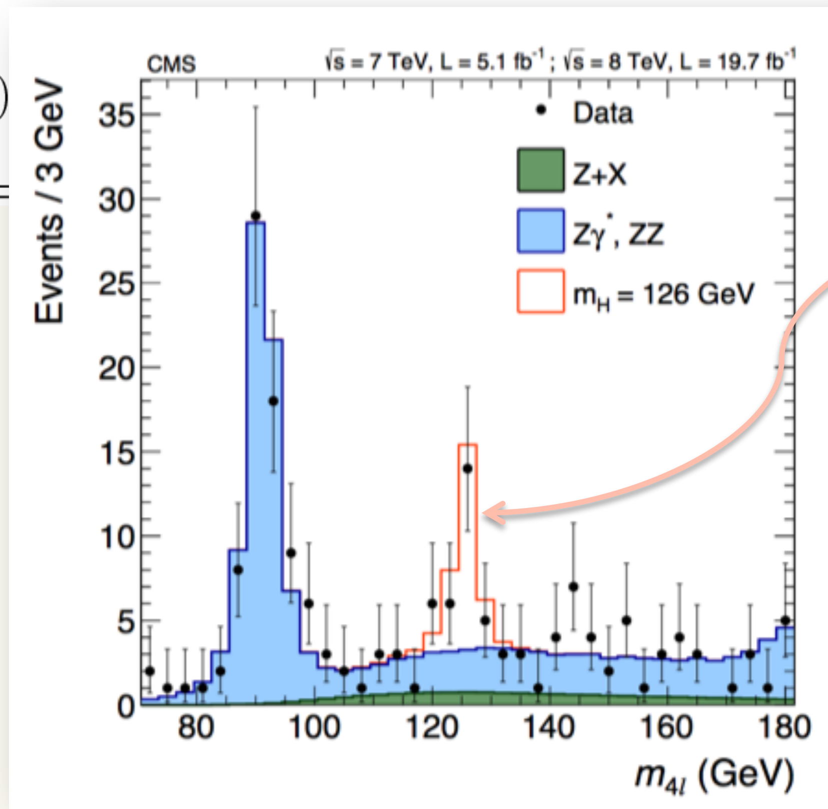


Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

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

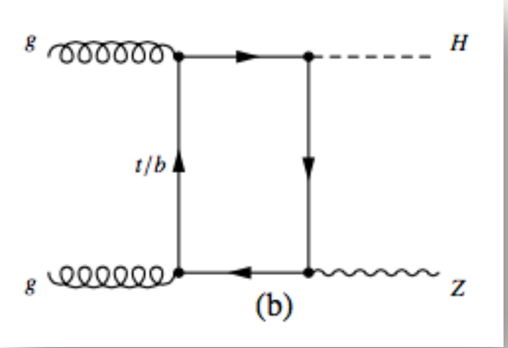
Theory Input : Event (MC) Generators

Production process	Event generator ATLAS	Event generator 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 ($qb \to tHq$)		aMC@NLO [29]
tHW ($gb \to tHW$)		aMC@NLO
bbH		PYTHIA6, aMC@NLO



Theory Input II: Event Generators

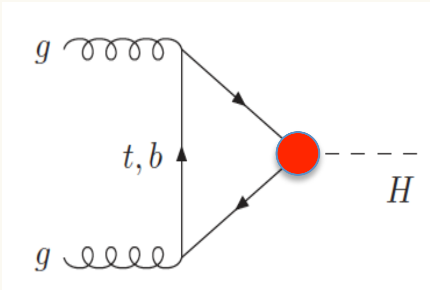
Production process	Event generator	
	ATLAS	CMS
ggF	POWHEG [30,31,32,33,34]	POWHEG
VBF	POWHEG	POWHEG
WH	PYTHIA8 [35]	PYTHIA6.4 [36]
ZH ($qq \to ZH$ or $qg \to ZH$)	PYTHIA8	PYTHIA6.4
$ggZH$ ($gg \to ZH$)	POWHEG	See text
ttH	POWHEL [44]	PYTHIA6.4
tHq ($qb \to tHq$)	MADGRAPH [46]	aMC@NLO [29]
tHW ($gb \to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



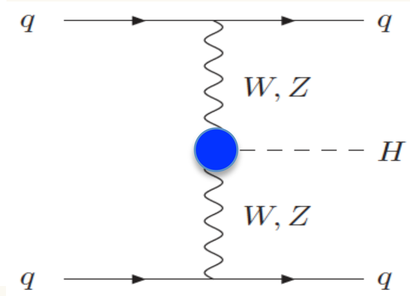
Subtlety: : the ggZH makes about 8% of the ZH cross section, yet it has harder pT spectrum and therefore contributes more to the measurement (mainly H->bb which is based on VH). CMS did not use the generator (was not in the market at the time of publication), so a pT reweighted qq->ZH spectrum sample 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

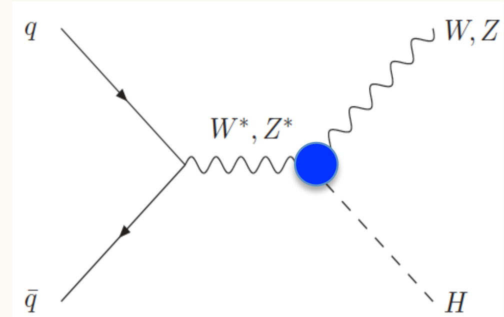
ggH



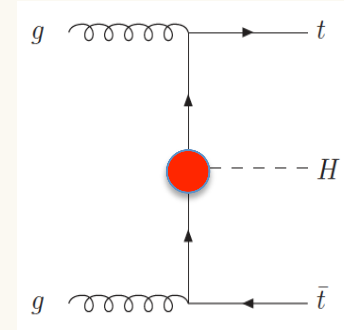
VBF

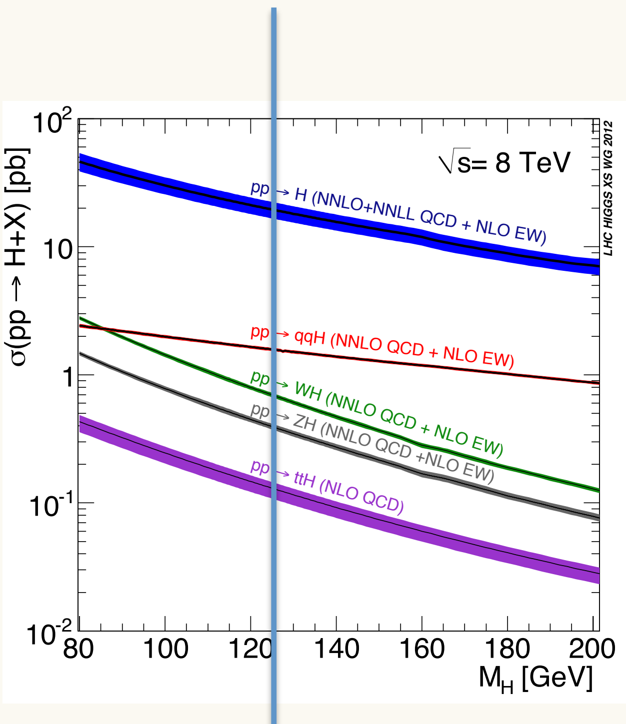


VH



ttH

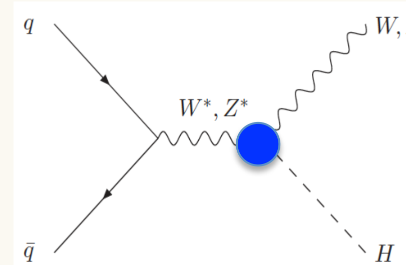




Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	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	

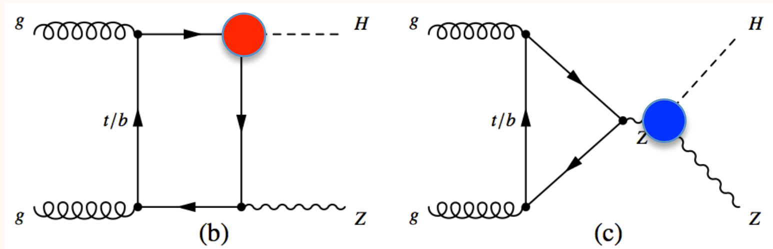
SM ggF, ttH, bbH theory uncertainty: ~10%
VBF, VH, ZH: 2-3%

Theory Inputs IV: Other Production Modes



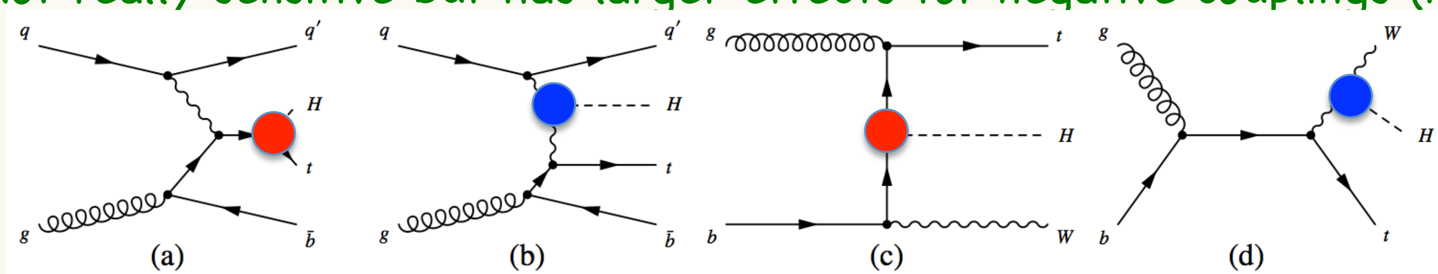
ggZH:

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



tHq + tHW

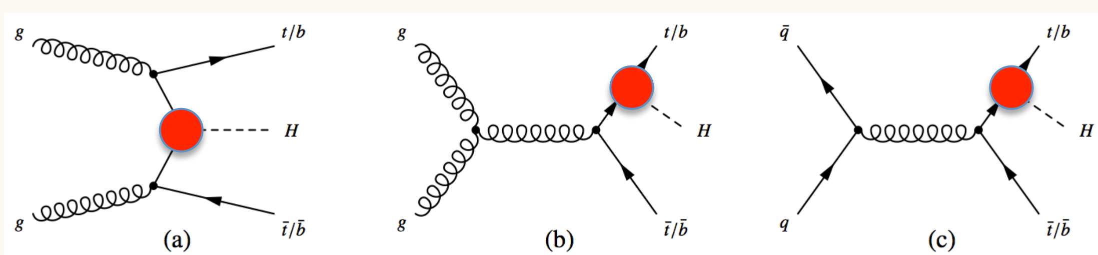
Not really sensitive but has larger effects for negative couplings (kF,kV)



bbH

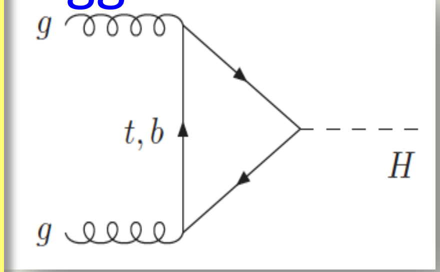
bbH is ~1% of total HXSC.

Similar to ttH but not really distinguishable from ggF



Theory Inputs V: Subtleties

ggH



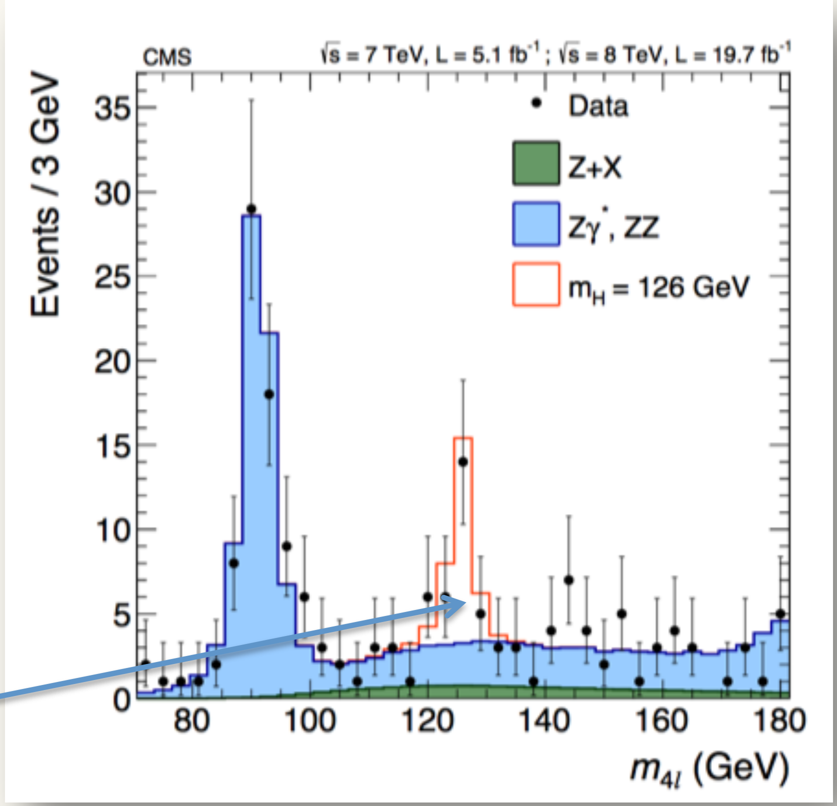
Subtleties:

- 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.

- 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

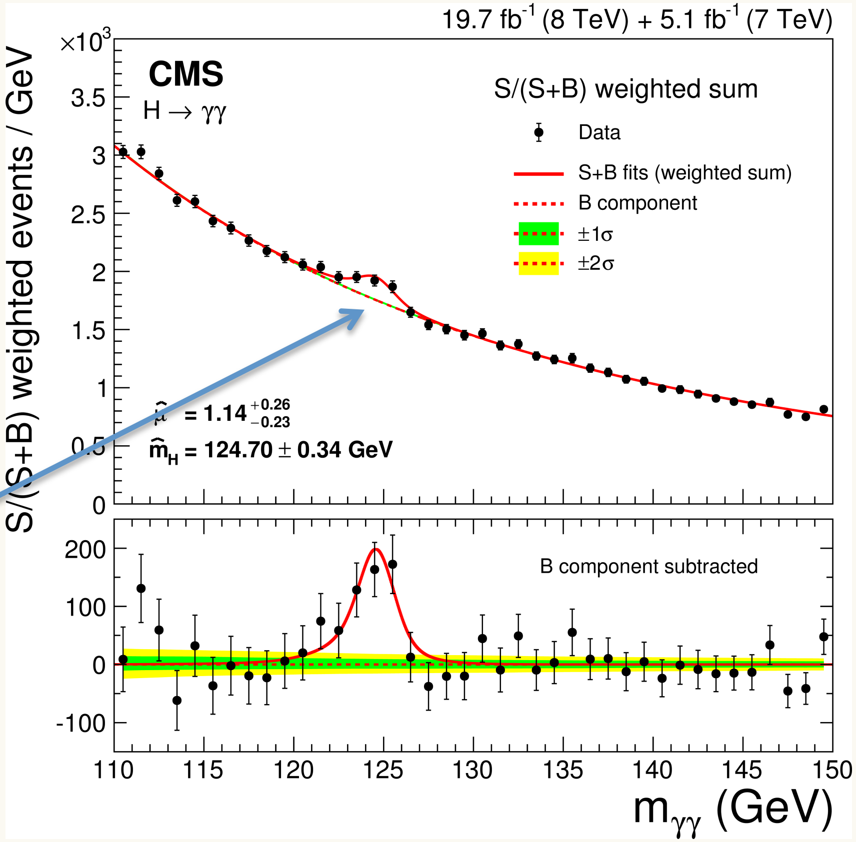
$$n_s(i \to f) = \mu^i \mu^f \times \sum_i (\sigma^i \times Br^f)_{SM} \times A^i_p \times \varepsilon^i_p \times Lumi$$

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

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

What do we measure (observables)

A simplified view:



We measure event yields

(in bins, i.e. shapes)

We want to derive couplings and signal strengths

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

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

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

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

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

Pseudo Observables

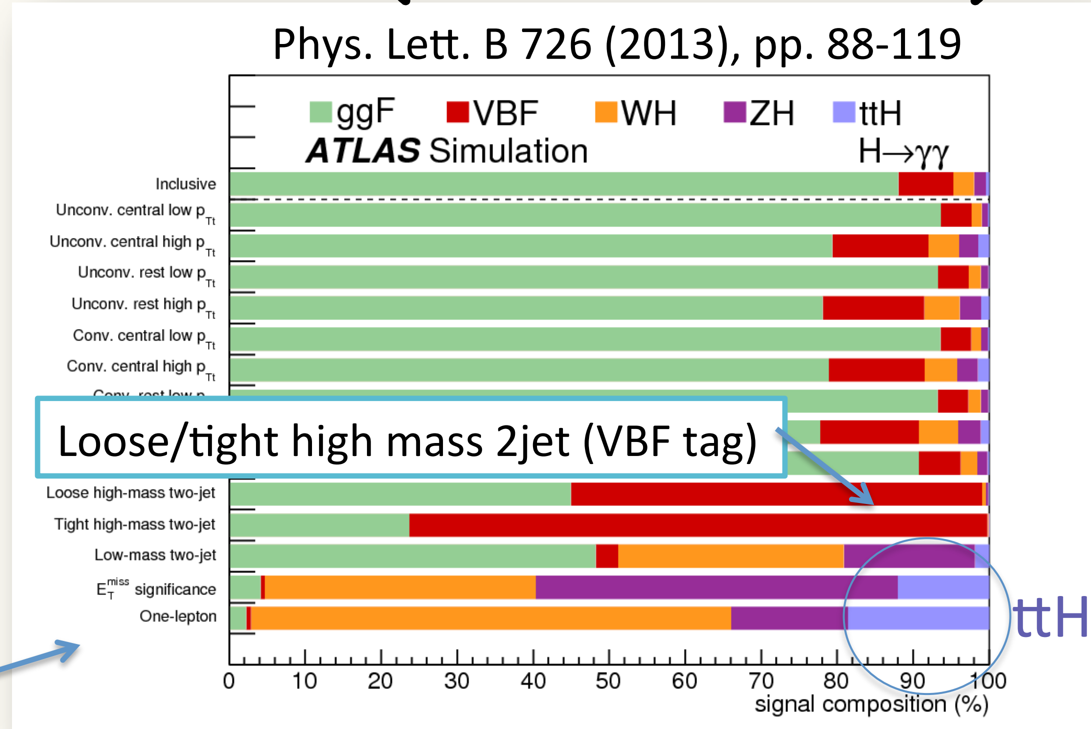
$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

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

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

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

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

PO

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

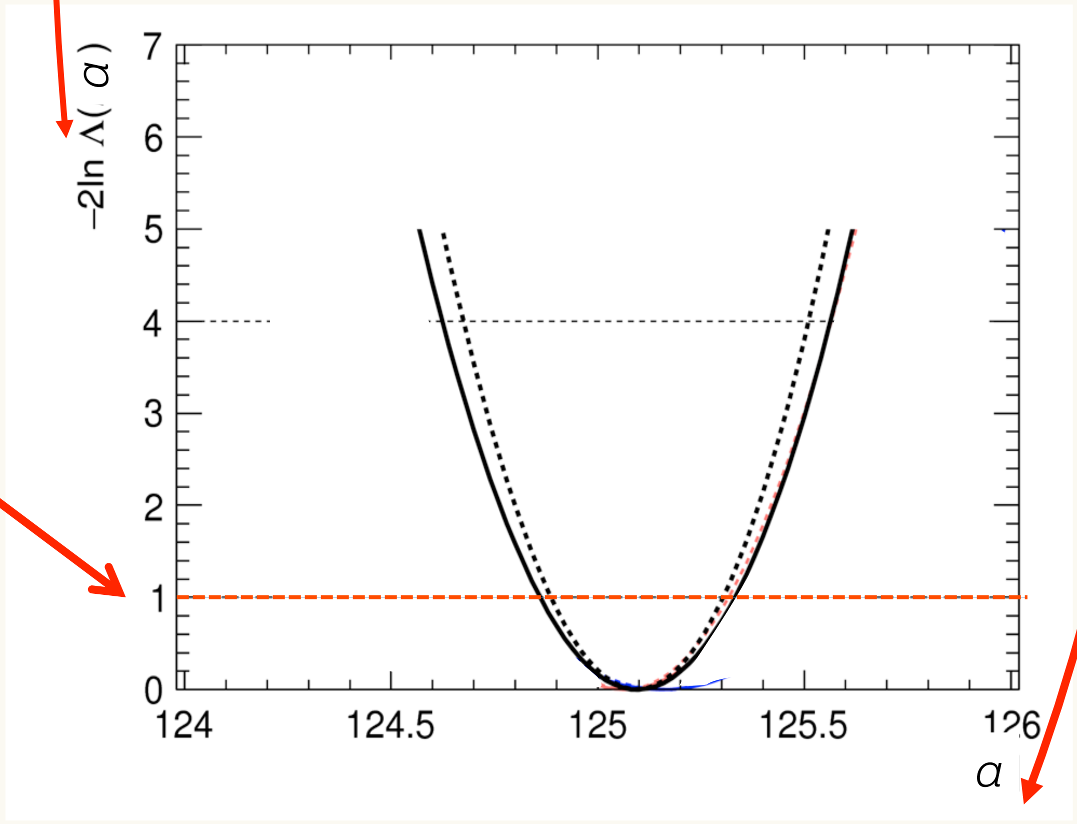
Statistical treatment – profile likelihood

From L(ATLAS+CMS) construct the **profile likelihood** for a statement on 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(α) (asymptotic limit)



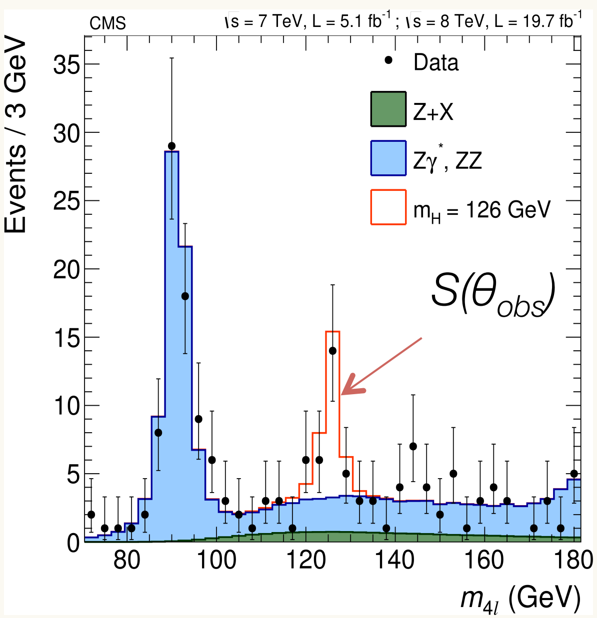
Systematics and Nuisance Parameters

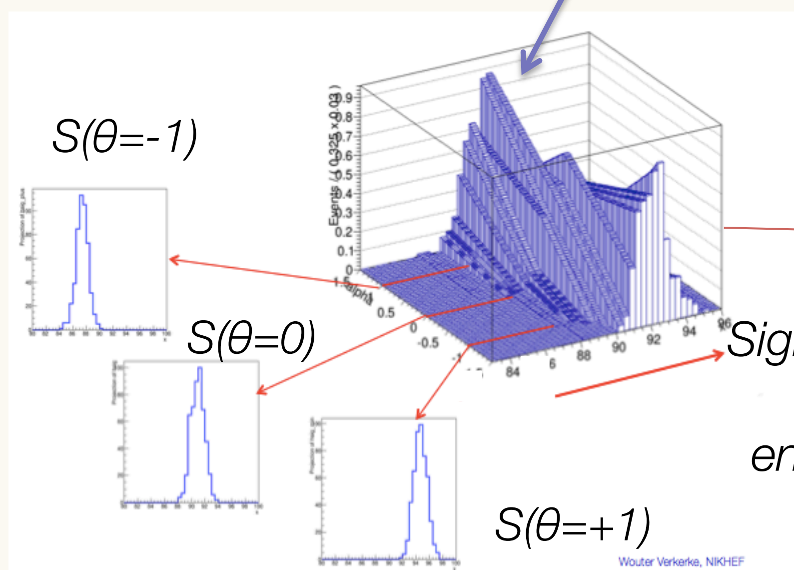
Profile likelihood ratio test statistics:

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

Illustration: modeling of energy scale uncertainty

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





S(N|θ)

Signal Probability model for any value of energy scale param θ

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 in two cases:

- the WH and ZH production processes are assumed to be fully correlated;
- the ggF and ttH production processes, which are predicted to be anti-correlated at the level of 60%, are assumed to be fully anti-correlated.

Correlating Experiments and Channels

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

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

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

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

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

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

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

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.

  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.

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.

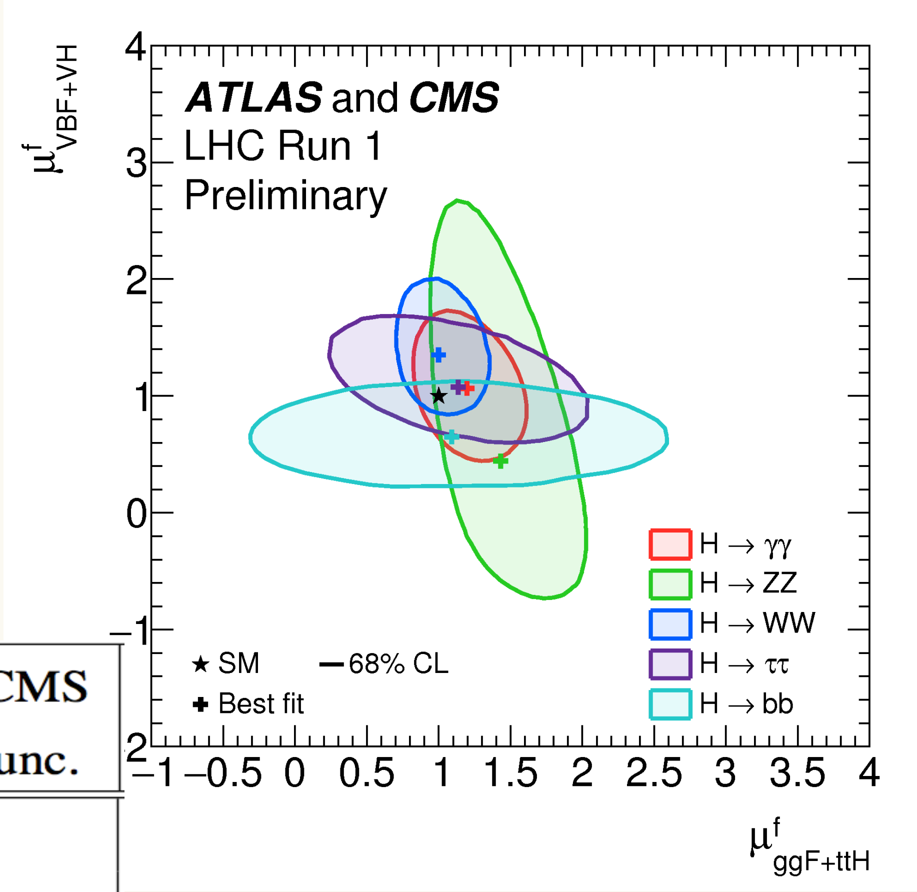
  Assumptions should also be made when combining 7 and 8 TeV measurements. **All these assumptions bring some model dependence**

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 Signal Strengths

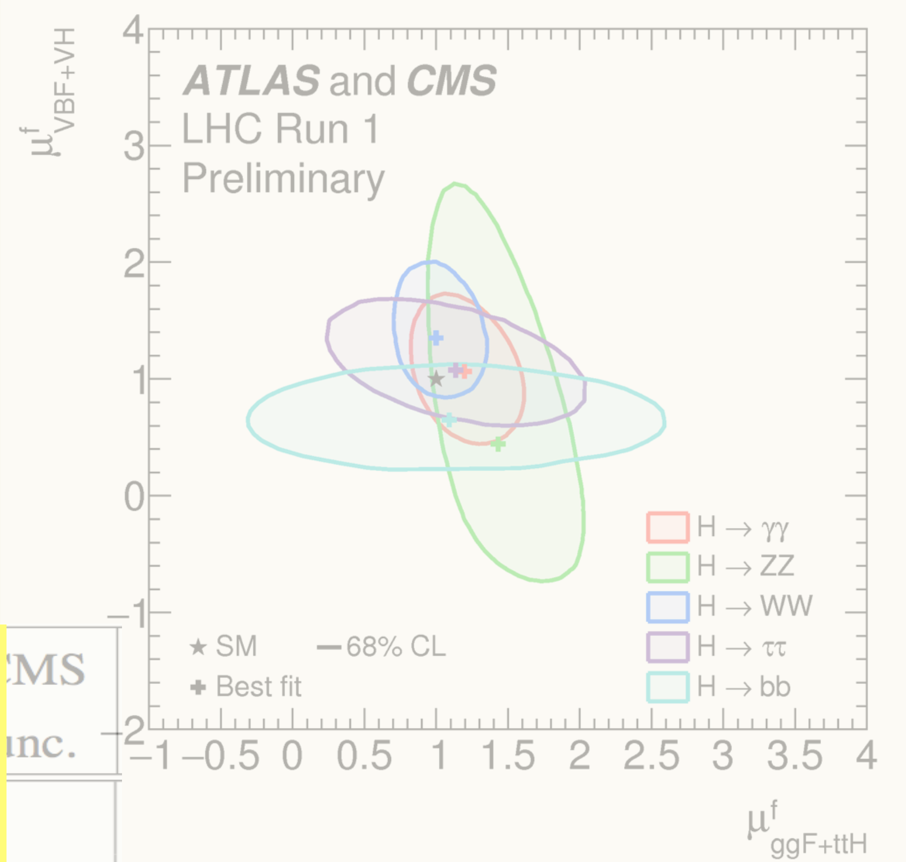
$$\frac{\mu_V^f}{\mu_F^f} = \frac{\mu_V \times BR^f}{\mu_F \times BR^f} = \frac{\mu_V}{\mu_F}$$

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

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

This made me think that μ_{VBF}/μ_{ggF} Cannot be over 5 sigma away from 0 and I lost a bet (see later)

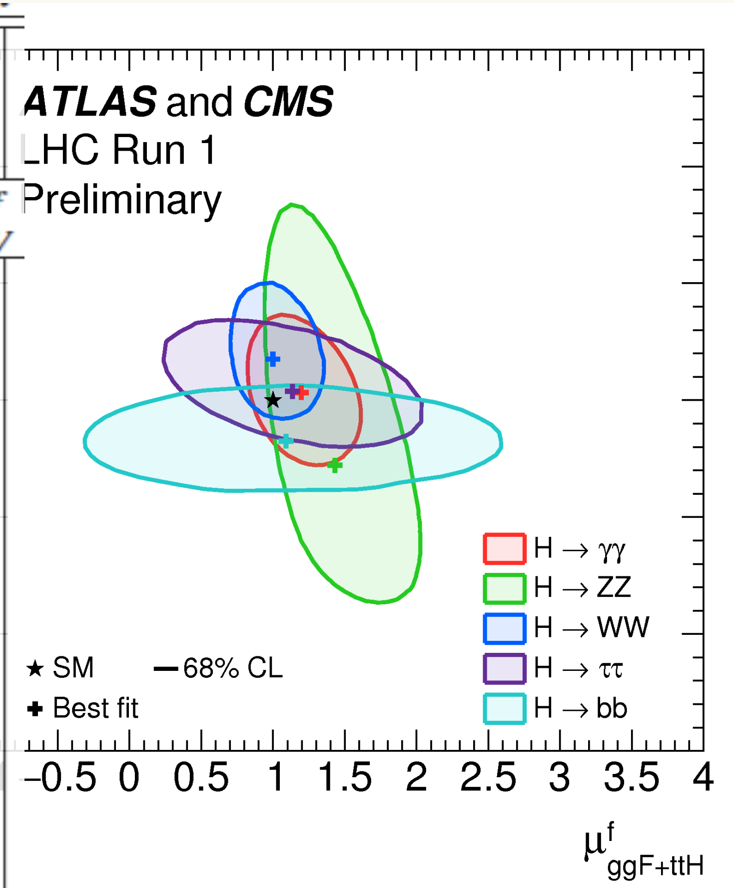
$\mu_F^{\tau\tau}$	$1.07^{+0.35}_{-0.28}$	$^{+0.32}_{-0.27}$
$\mu_F^{b\bar{b}}$	$0.65^{+0.37}_{-0.28}$	$^{+0.45}_{-0.34}$



SM p-value 62% (6p)

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 Production Signal Strengths

Assuming SM BR we can measure the signal production strengths.

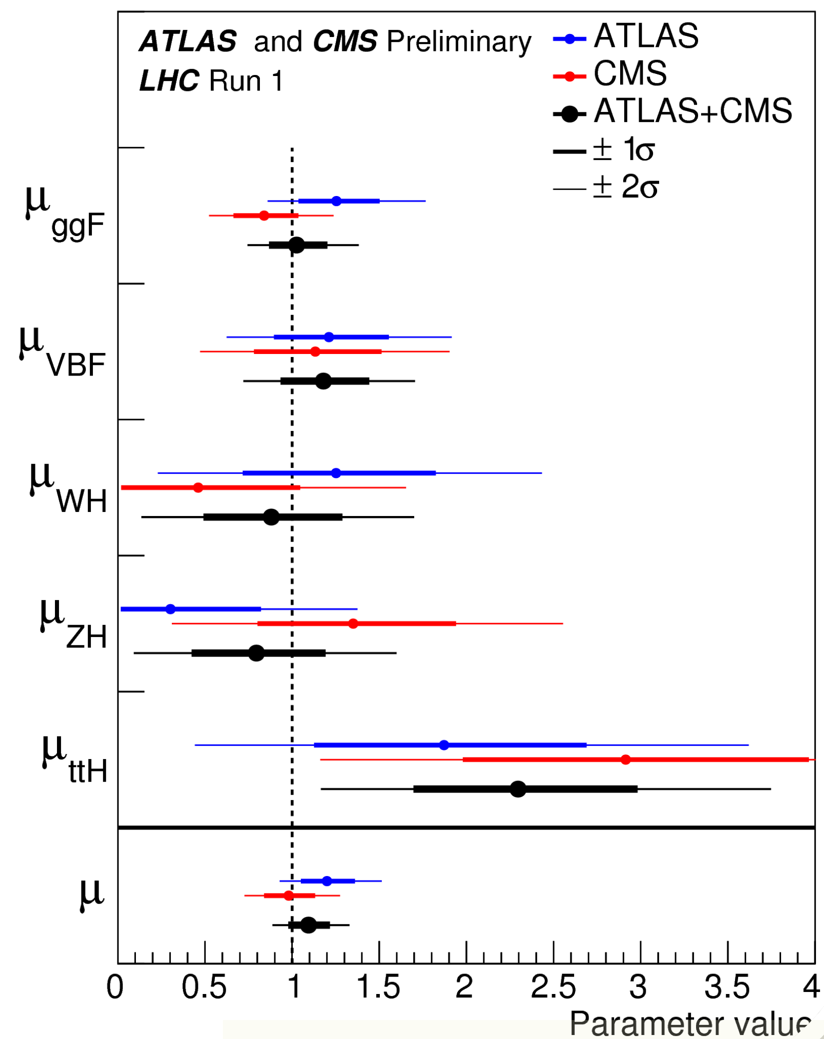
Production process	ATLAS+CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$

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



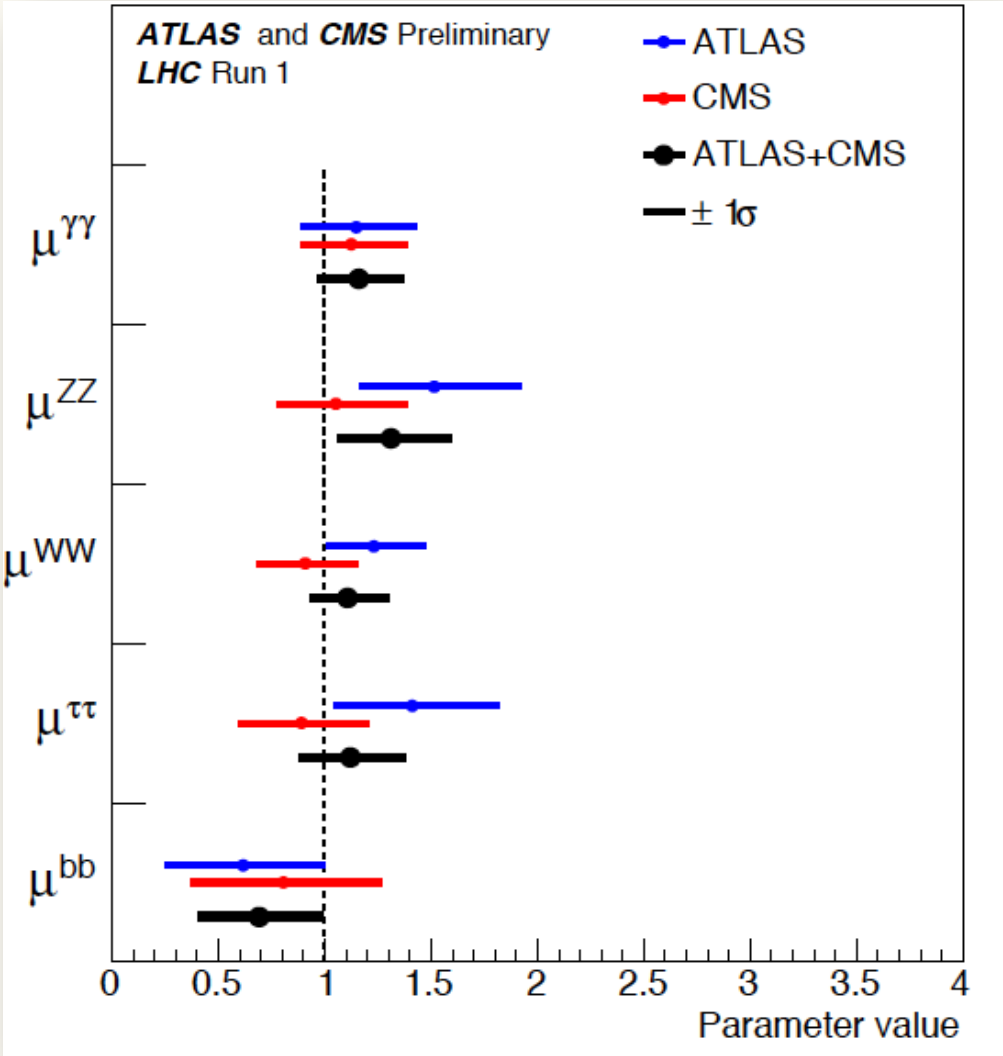
Main uncertainty from ggF xsc

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

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

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→ $\tau\ \tau$ now established at over 5 σ.
Same as ggF and H→ZZ, $\gamma\ \gamma$, 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

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

$9\ pars$

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

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

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, and from the results in terms of their central values and the full error covariance matrix, it is possible, assuming the asymptotic approximation, to derive other results of signal strength parameterisations

Model Independent Ratios (Generic I)

One can fit the data with ONE channel specific measurement ($i \rightarrow H \rightarrow f$) , 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: $i \rightarrow f$

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

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

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

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

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

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?

$9\ pars$

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

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

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

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

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

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

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

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

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

...process: $i \to f$

$$\sigma_x \cdot BR_y \ \ldots \ \sigma_i \ \ldots \ BR_f \Big)$$

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

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

$e.g.$ 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→H→f) , 4 ra… cross sections and 4 ratios of BRs

9 pars

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

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

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

$\frac{\sigma_{ZH}}{\sigma_{gg…}}$

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

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

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

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

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

…process: $i \to f$

$\sigma_x \cdot BR_y$ … σ_i … BR_f)

… σ_x … BR_f

e.g. fo…

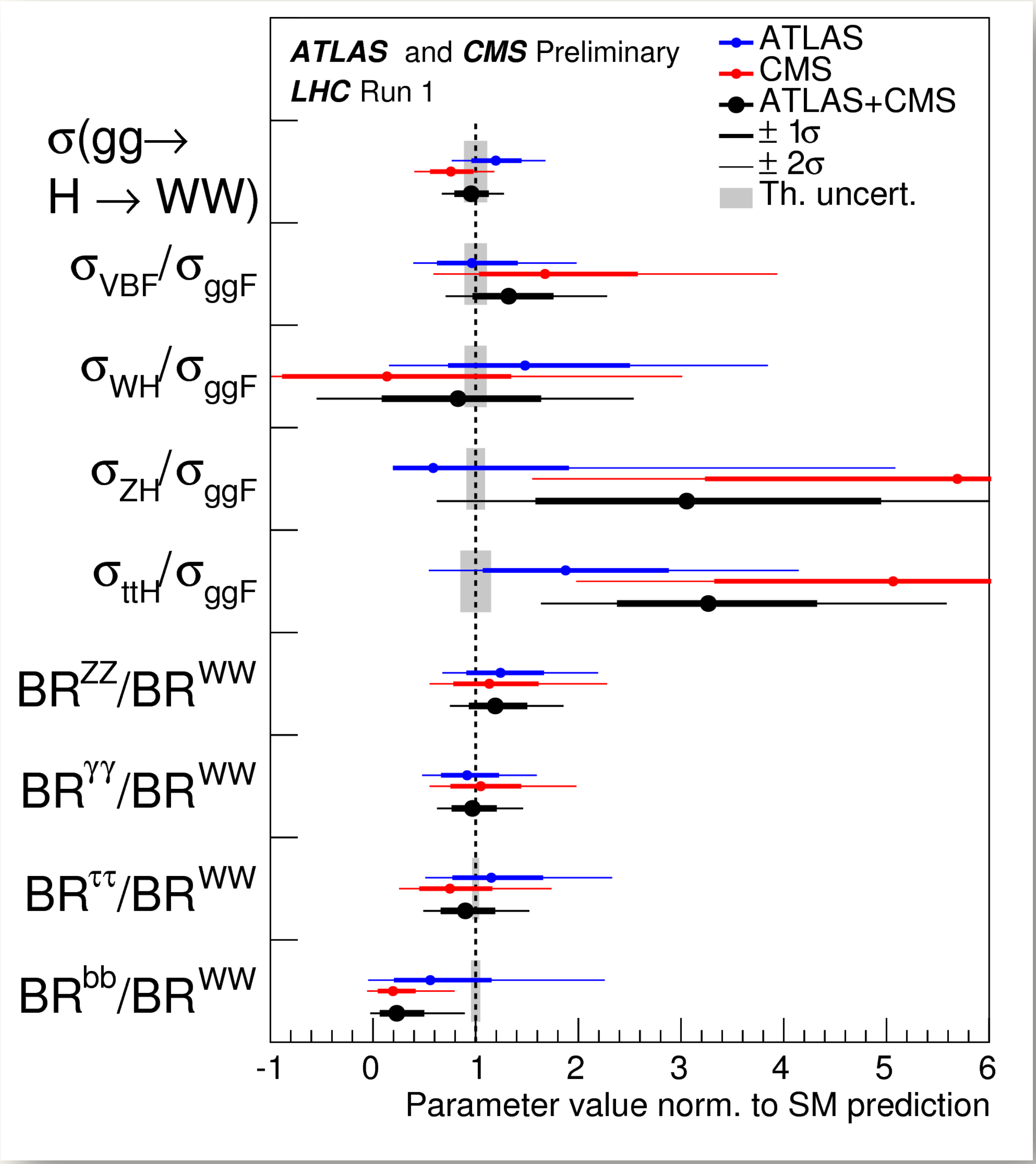
$$\mu_{ZH}^{bb} = \left[\frac{\mu_{ZH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\ \cdots\ \mu_{ZZ}\right]$$

…CH REF?

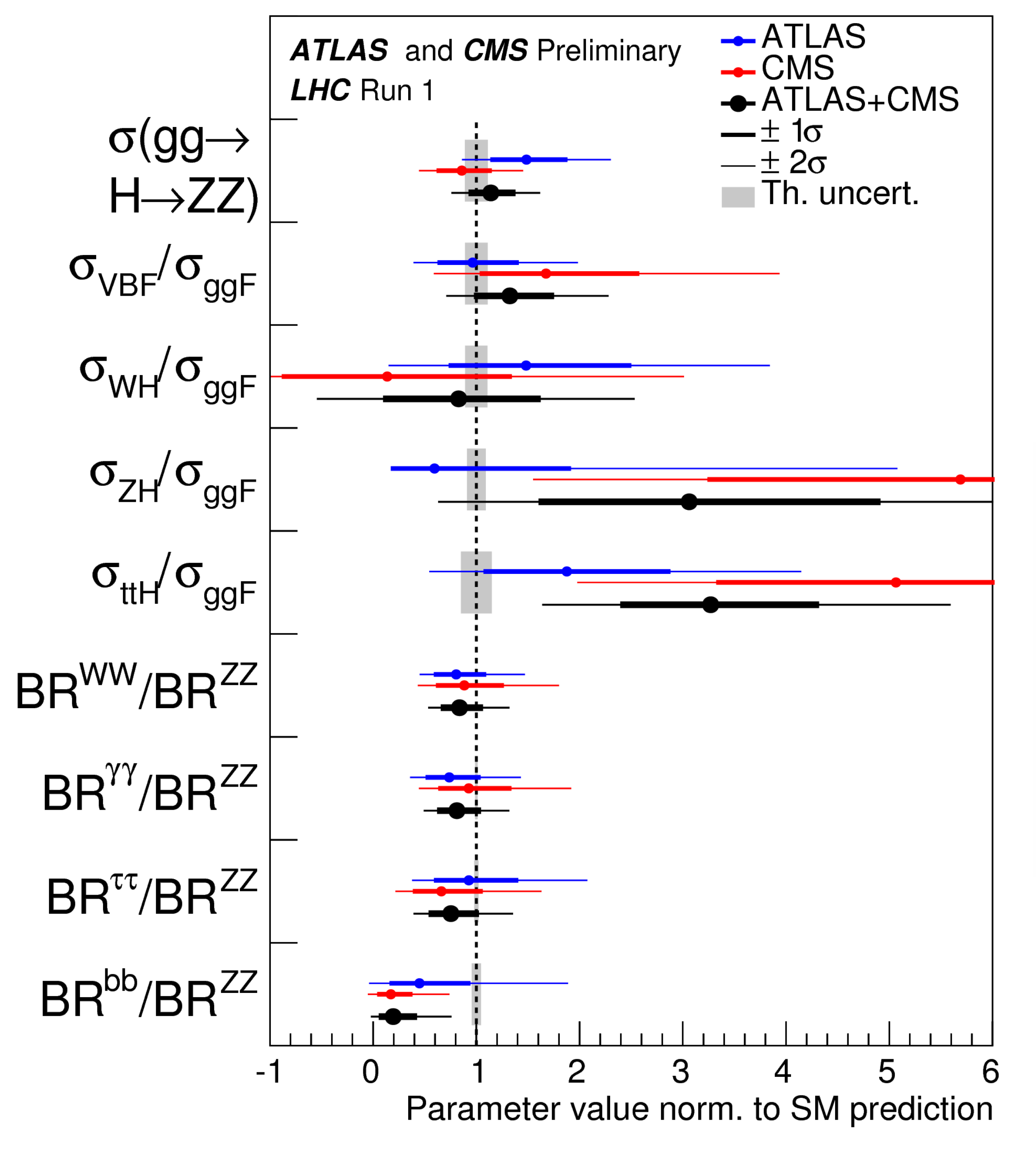
WHICH REF PROCESS?

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)

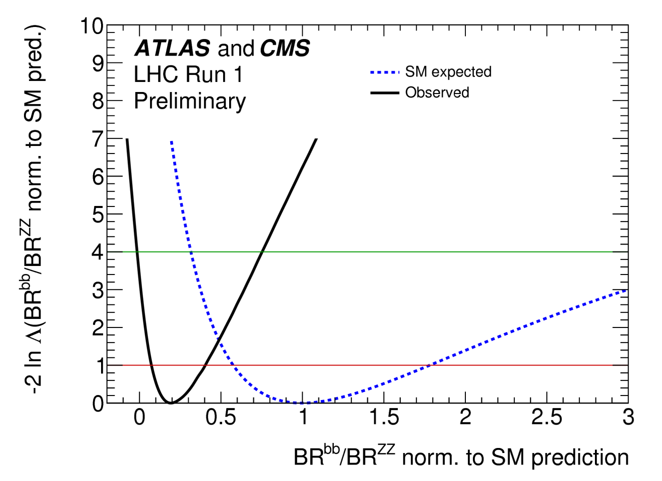


Model Independent Ratios (Generic I)

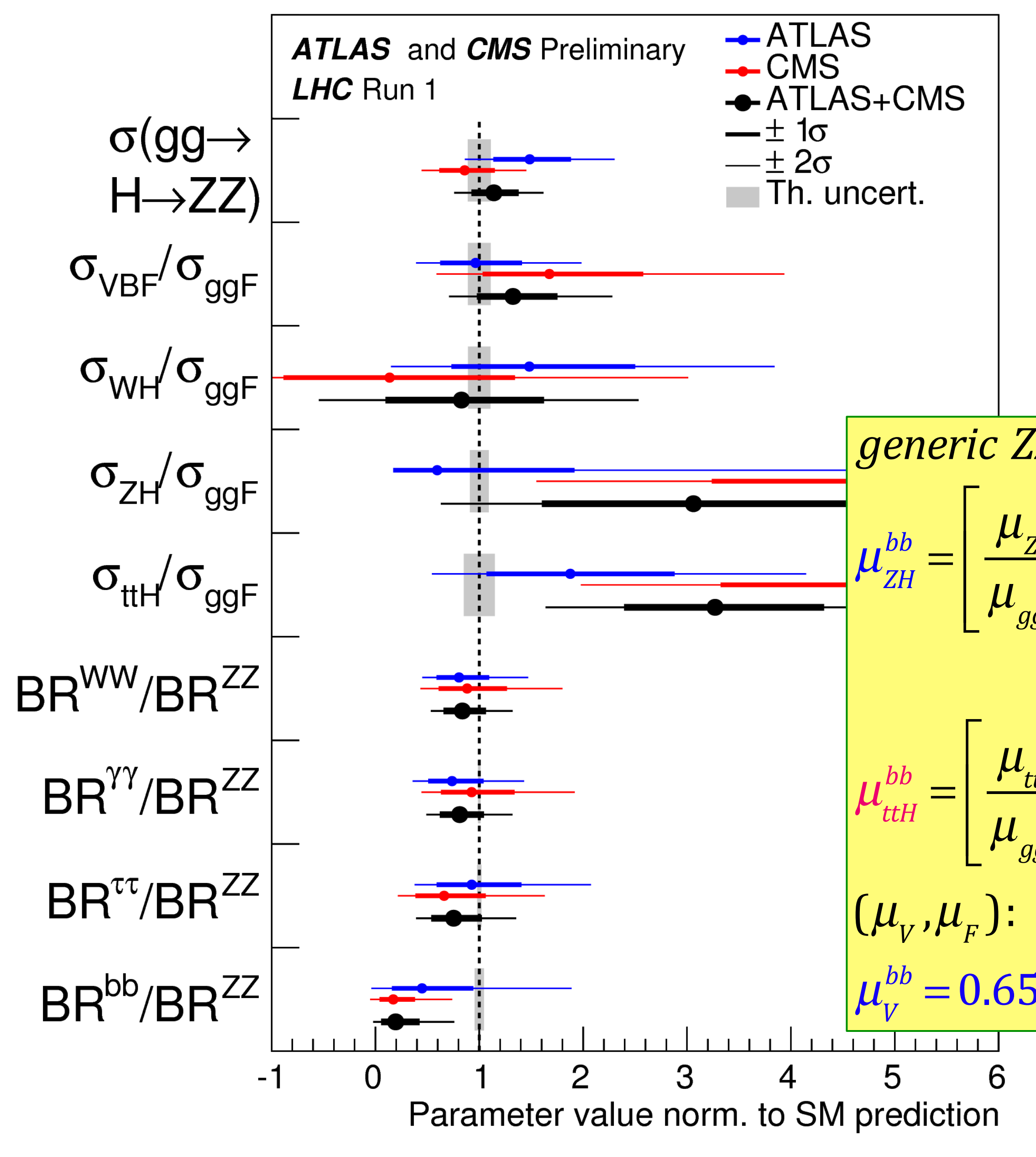


Largest deviationfrom SM is seen in BR^{bb}/BR^{ZZ}, at the level of 2.4 σ

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



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 :

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

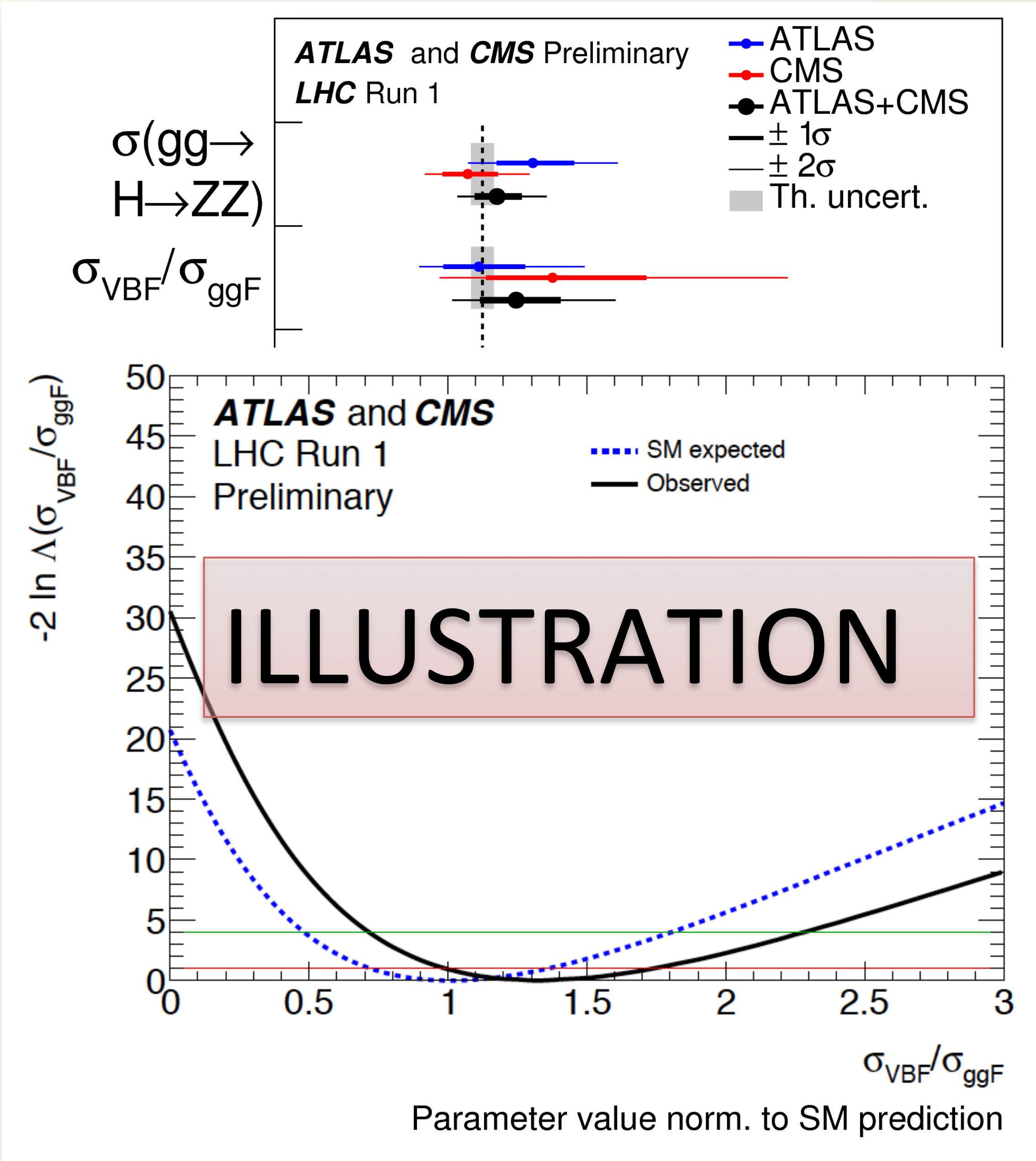
$$\mu_{ttH}^{bb} = \left[\frac{\mu_{ttH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right] \approx 3.3 \cdot 1.14 \cdot 0.2 = 0.8$$

(μ_V, μ_F):

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

Model Independent Ratios (Generic I)

Here is when I lost the bet to Guess Who



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

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

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

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

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

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

The κ –framework

Experimental Assumptions:

The current LHC data are insensitiveto 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

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

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

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

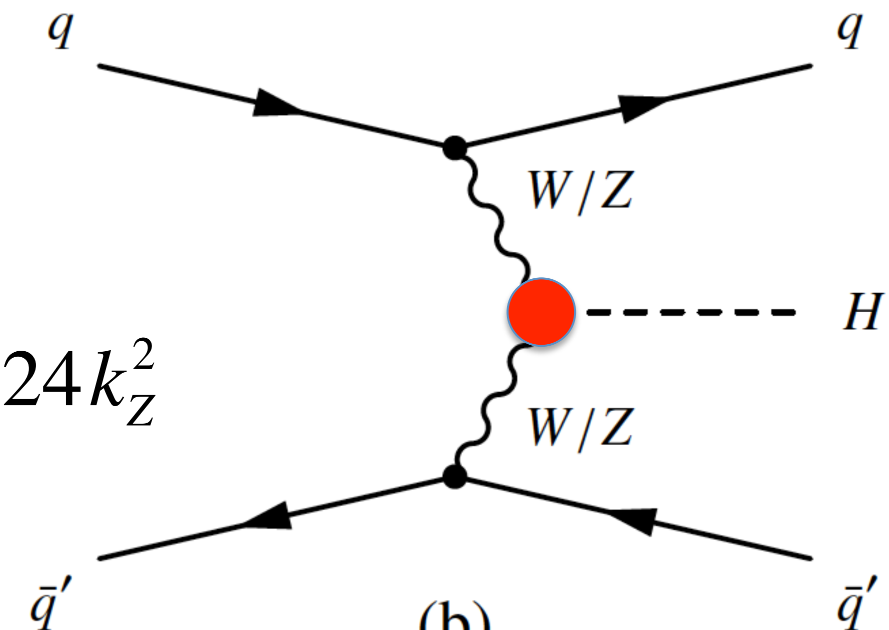
The degeneracy can be broken by parameterize the strength parameters with couplings and introduce constraints which reduce the number of p.o.i. and allow reasonable fits.

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

VBF Composition

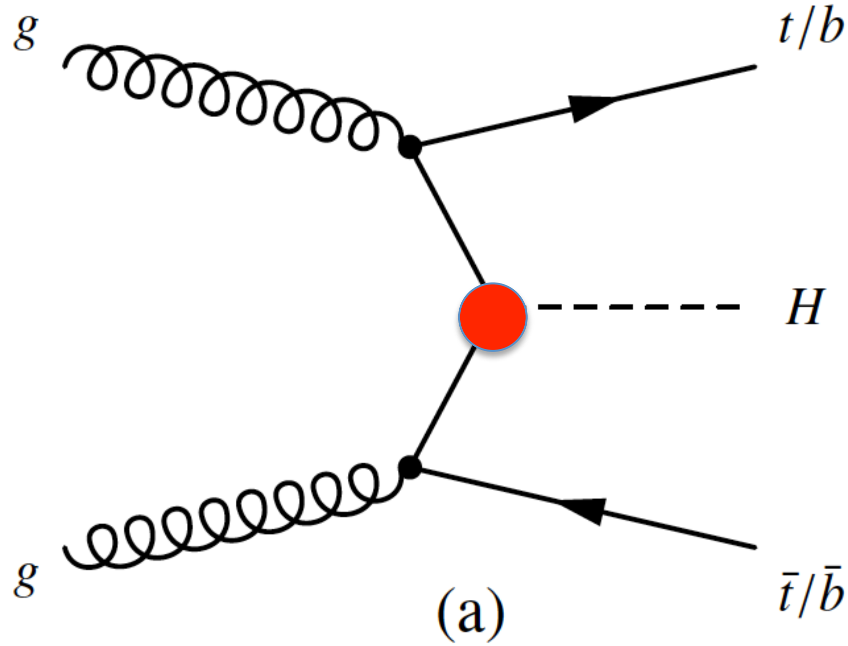
$$q\bar{q}' \to q\bar{q}'H$$

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



(b)

ttH



$$gg \rightarrow ttH, bbH$$

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

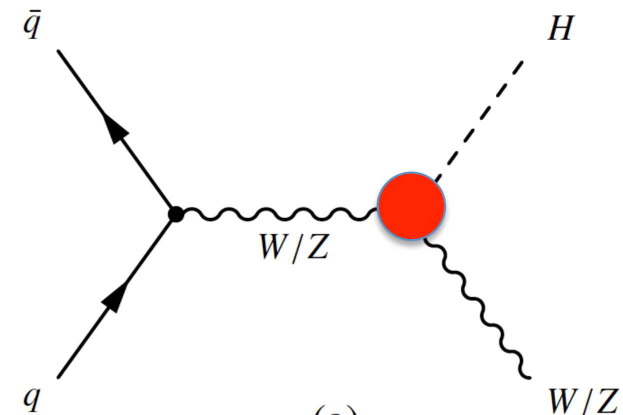
$$\mu_{bbH} = k_b^2$$

ZH Production

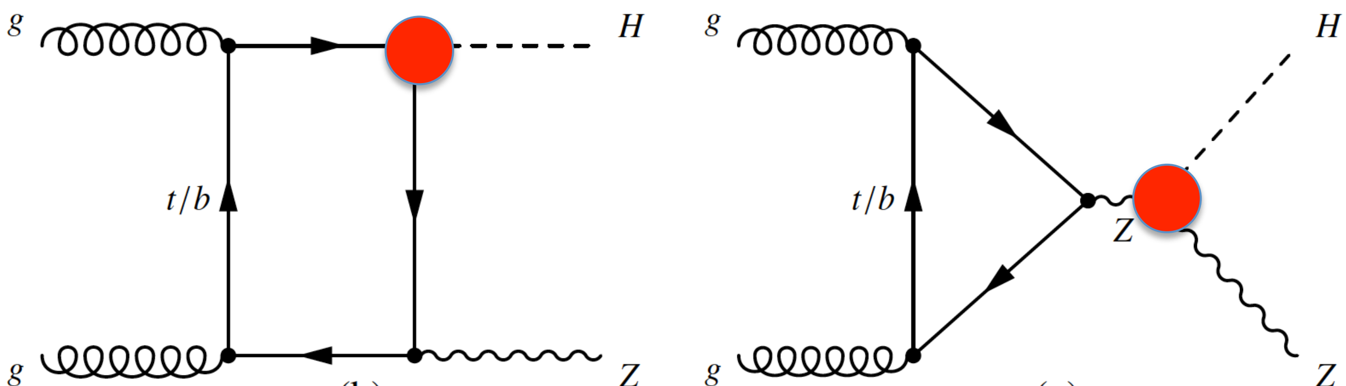
$$\sigma(q\bar{q} \to ZH) \sim k_Z^2$$

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

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



(a)

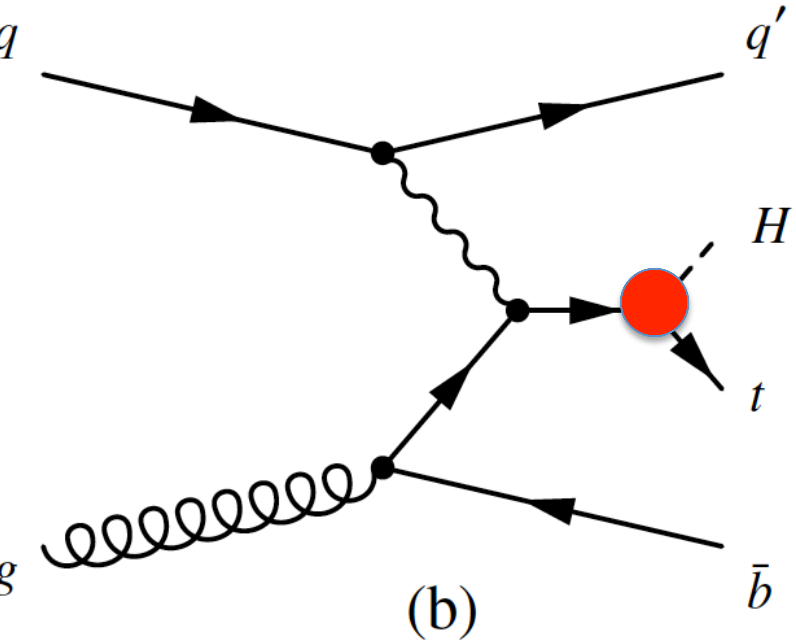


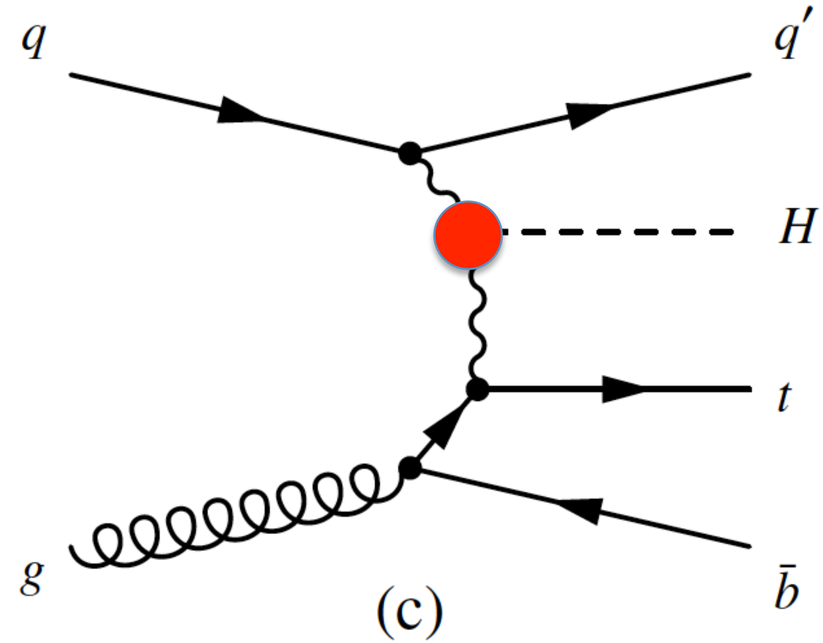
(b) (c)

(Q:Why not gWH?)

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

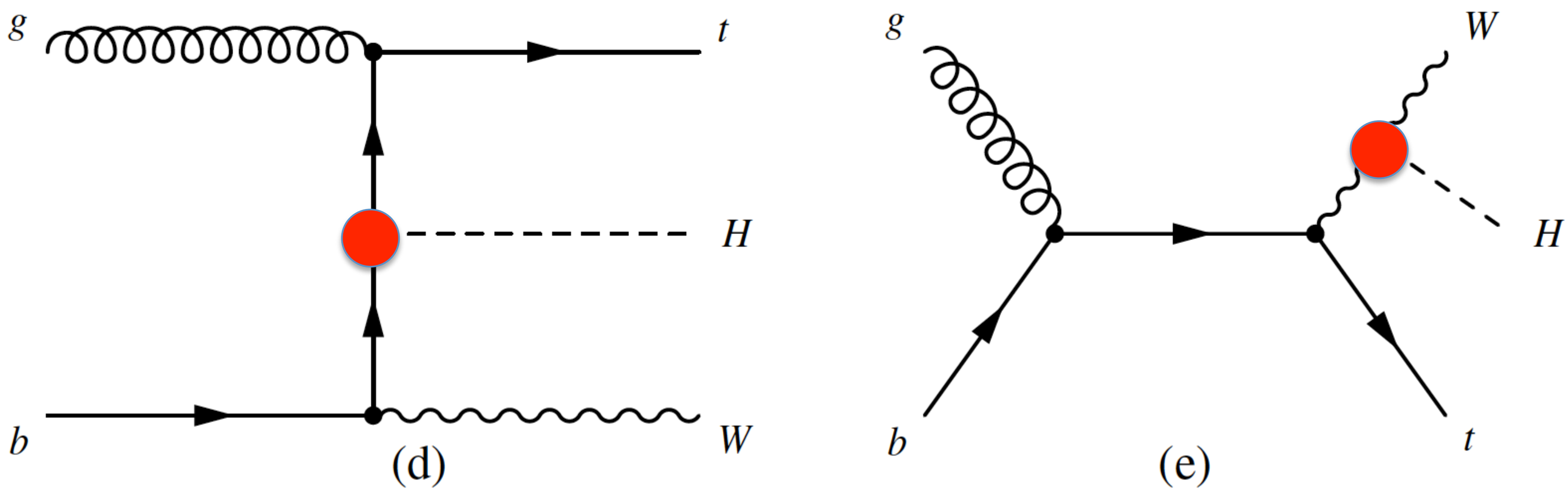
tHq composition (W,t) interference





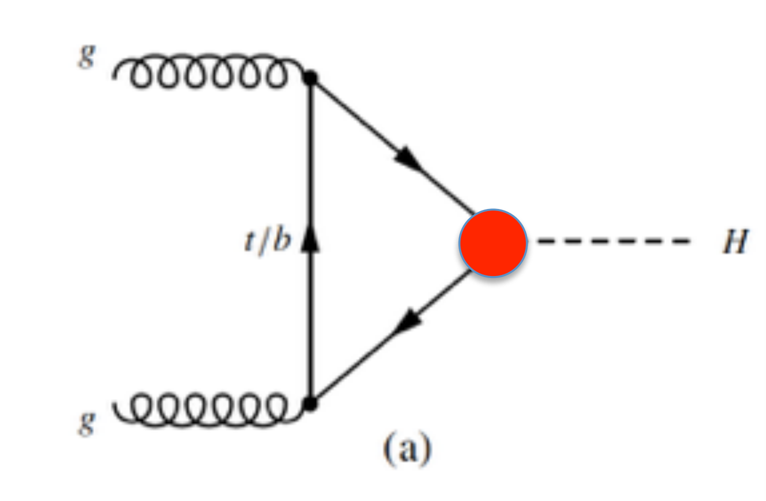
$$\sigma\left(qg \to tHq'(b)\right) \sim \quad 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$$

WtH composition



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

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

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

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

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

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

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

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

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

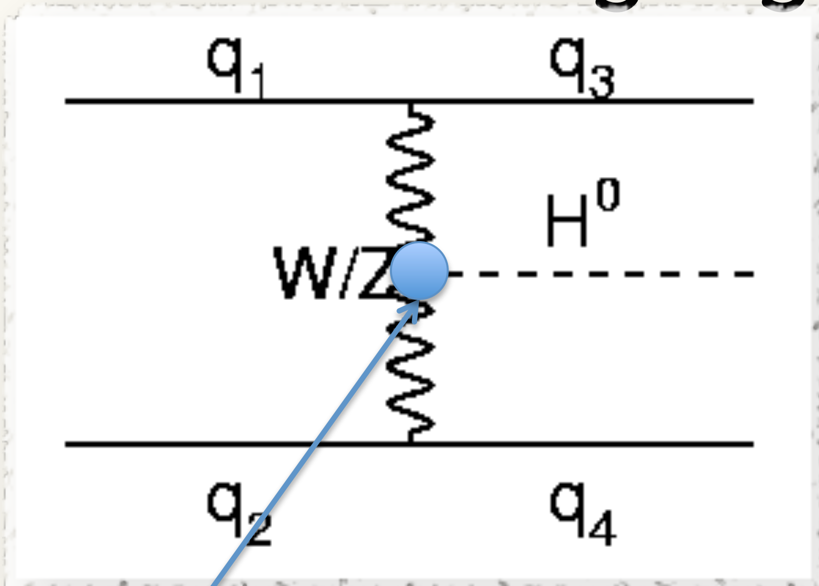
$$\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$$

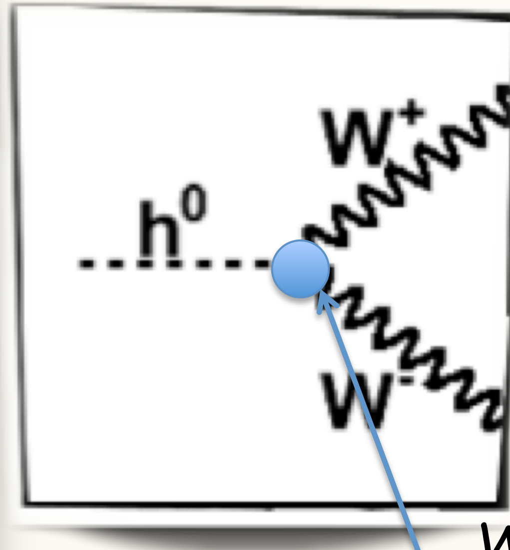
$$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$$

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

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

Disentangling The Couplings





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

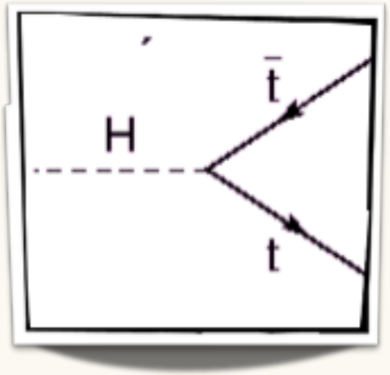
$$\mu^W = \frac{k^2_W}{k^2_H}$$

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

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

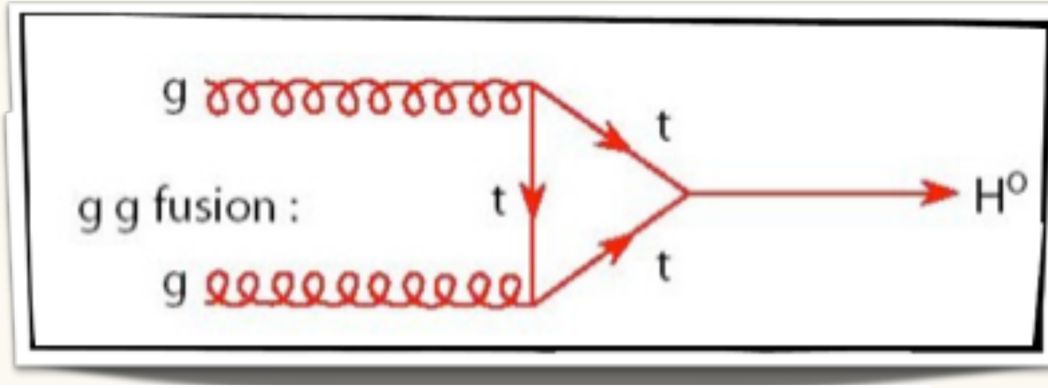
$$\frac{\sigma^{WW}_{VBF}}{\sigma^{WW}_{VBF}(SM)} = \frac{k^2_V \cdot k^2_V}{0.75k^2_F + 0.25k^2_V}$$

Indirect Sensitivity to Fermion Couplings



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

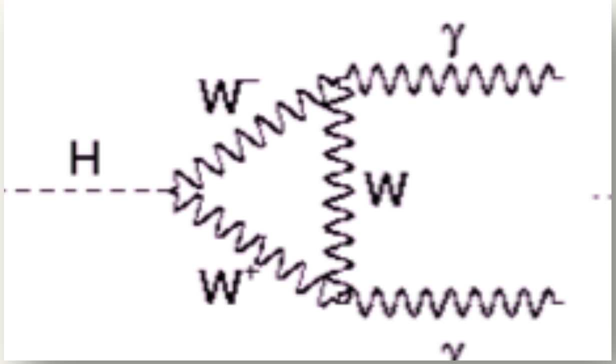
$$k_t^2 = \frac{g_t^2}{g_{t.SM}^2}$$



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

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	
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim$	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
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim$	κ_τ^2
Γ^{bb}	–	–	$\sim$	κ_b^2
$\Gamma^{\mu\mu}$	–	–	$\sim$	κ_μ^2
Total width for $BR_{BSM} = 0$				
Γ_H	✓	–	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa^2 + 0.0016 \cdot \kappa_Z^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa^2$

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
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim$	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	✓	–	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa^2 + 0.0016 \cdot \kappa_Z^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa^2$

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.

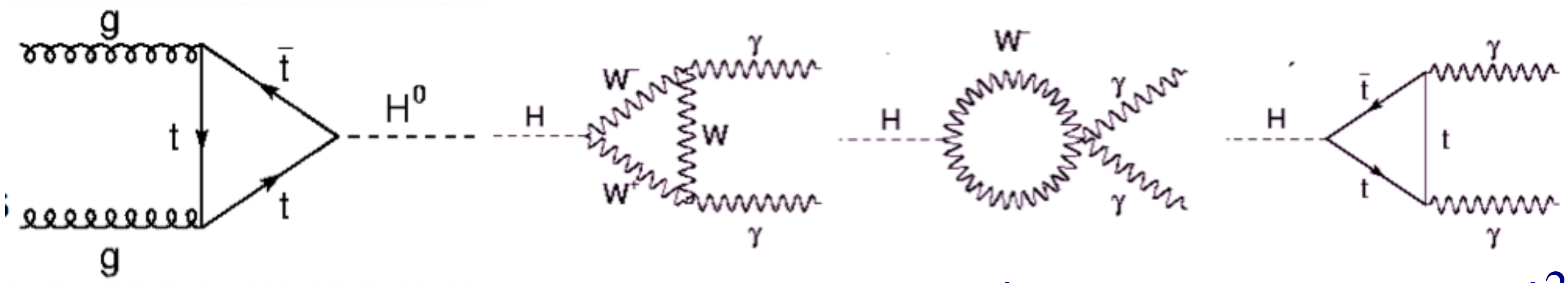
NP can appear in either the Higgs width and/or in the loops.

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

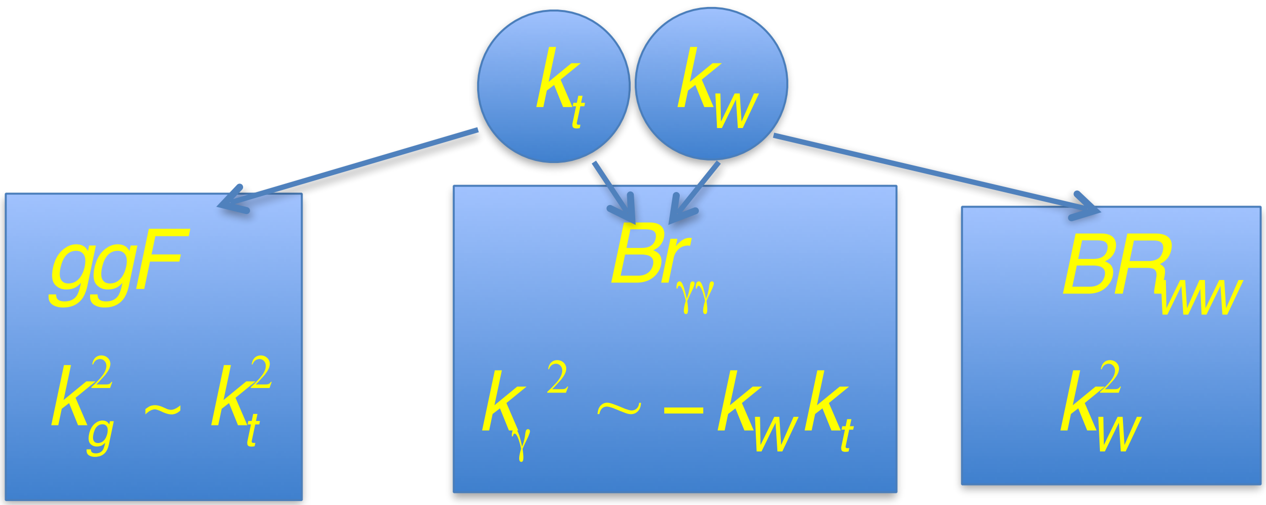
Γ_H	k_γ	k_g	Scenario
$\Gamma_H = k_H^2 \Gamma_H^{SM}$	$K_\gamma(k_t, k_W)$	$K_g(k_t, k_b)$	only SM particles in loops
$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$	k_γ	k_g	m_{NP} could be $< \frac{m_H}{2}$
$\Gamma_H = k_H^2 \Gamma_H^{SM}$	k_γ	k_g	$m_{NP} > \frac{m_H}{2}$
$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$	$K_\gamma(k_t, k_W)$	$K_g(k_t, k_b)$	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

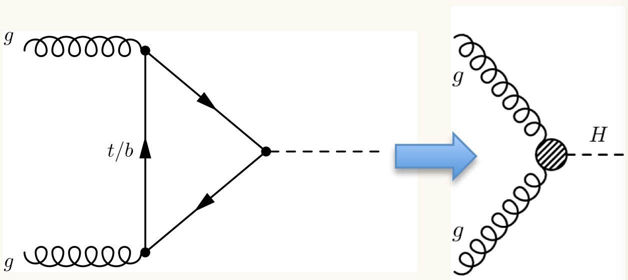
Testing negative k_t is extremely important

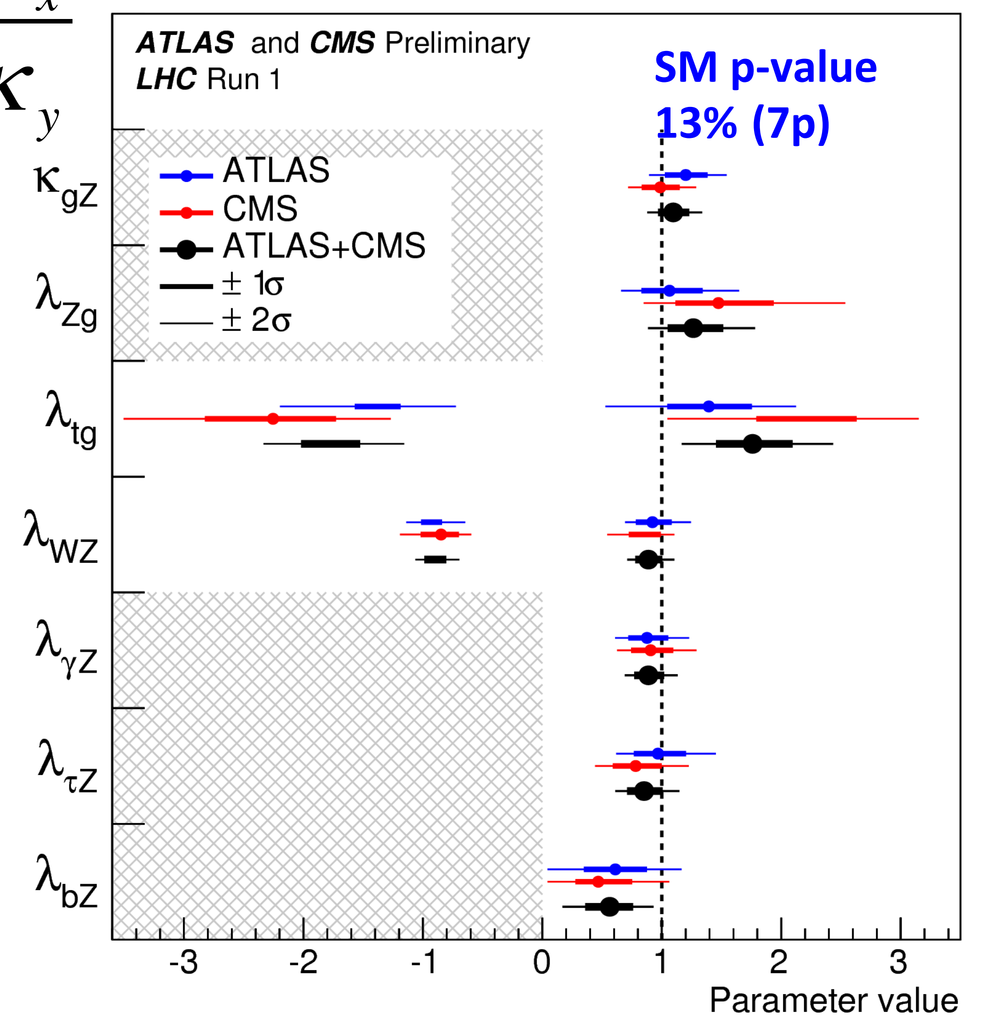
Couplings Generic Model

LHC is not able to measure the Higgs full width.

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

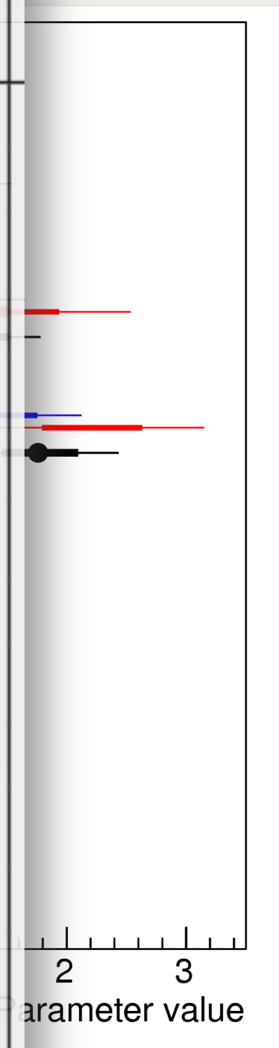
$$\lambda_{xy} = \frac{\kappa_x}{\kappa_y}$$





Couplings Generic Model

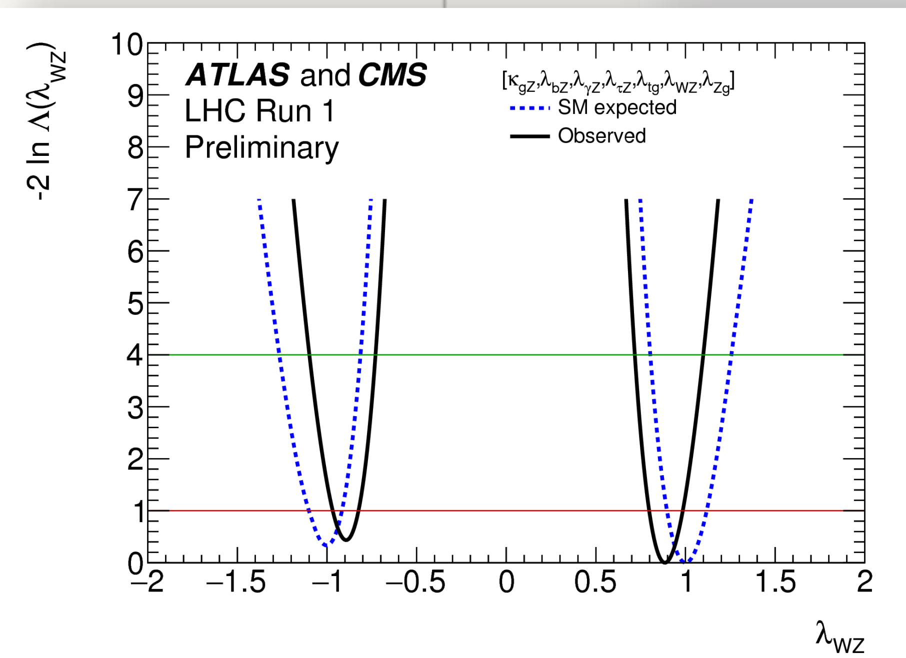
Parameter	Best-fit value	Stat	Expt	Thbgd	Thsig
		ATLAS+CMS			
$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$	$1.10^{+0.11}_{-0.11}$ $\left(^{+0.11}_{-0.11}\right)$	$^{+0.09}_{-0.09}$ $\left(^{+0.09}_{-0.09}\right)$	$^{+0.03}_{-0.02}$ $\left(^{+0.02}_{-0.02}\right)$	$^{+0.01}_{-0.01}$ $\left(^{+0.01}_{-0.01}\right)$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

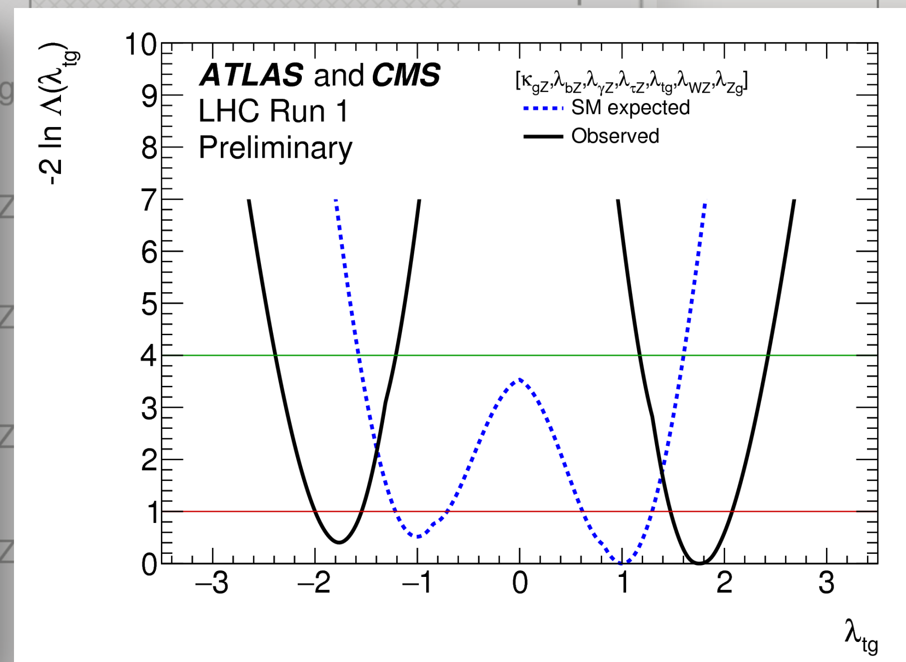


Couplings Generic Model

$ggZH$ and $tH \rightarrow$

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





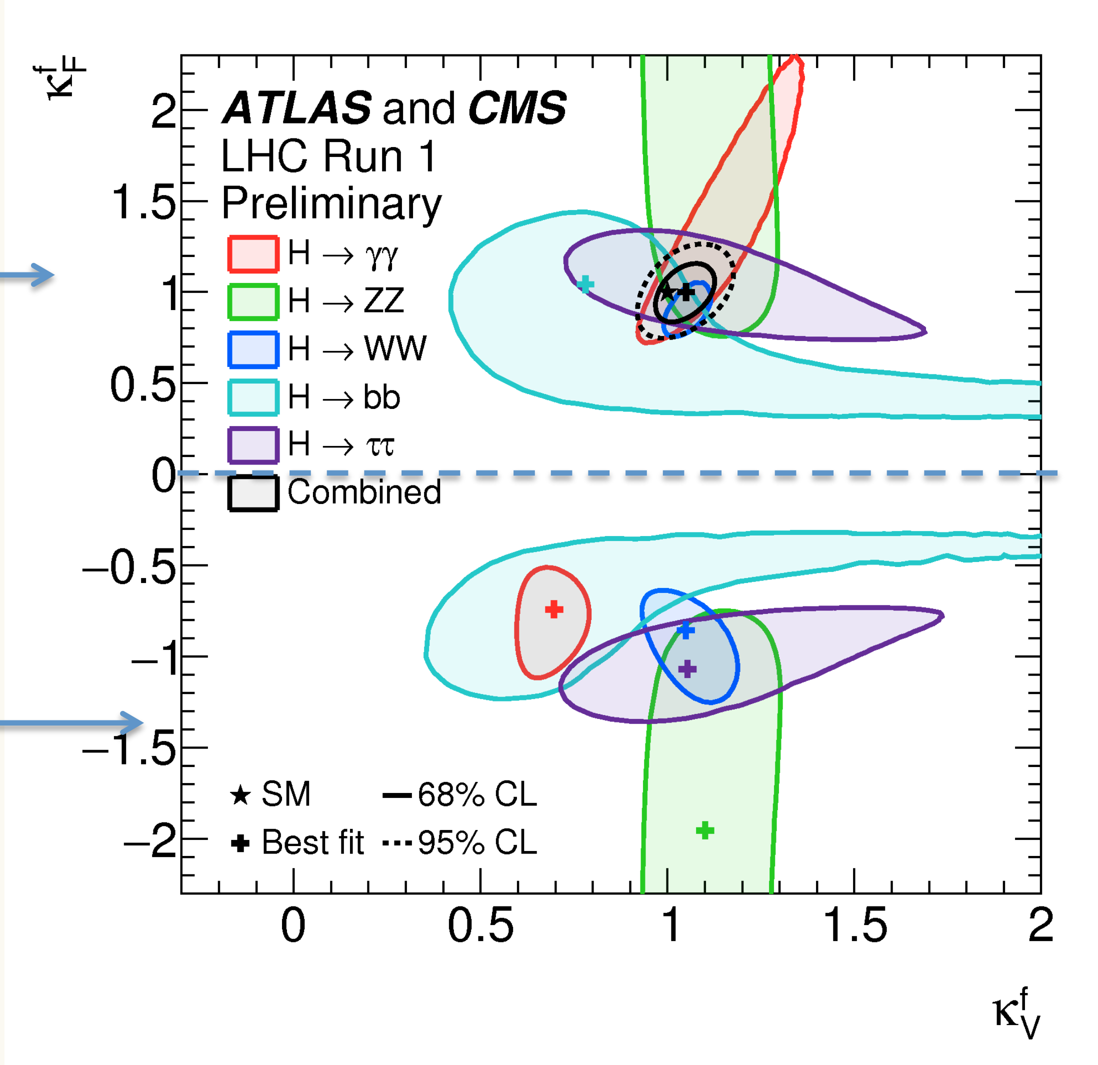
kV & kF: The pedagogic plot

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

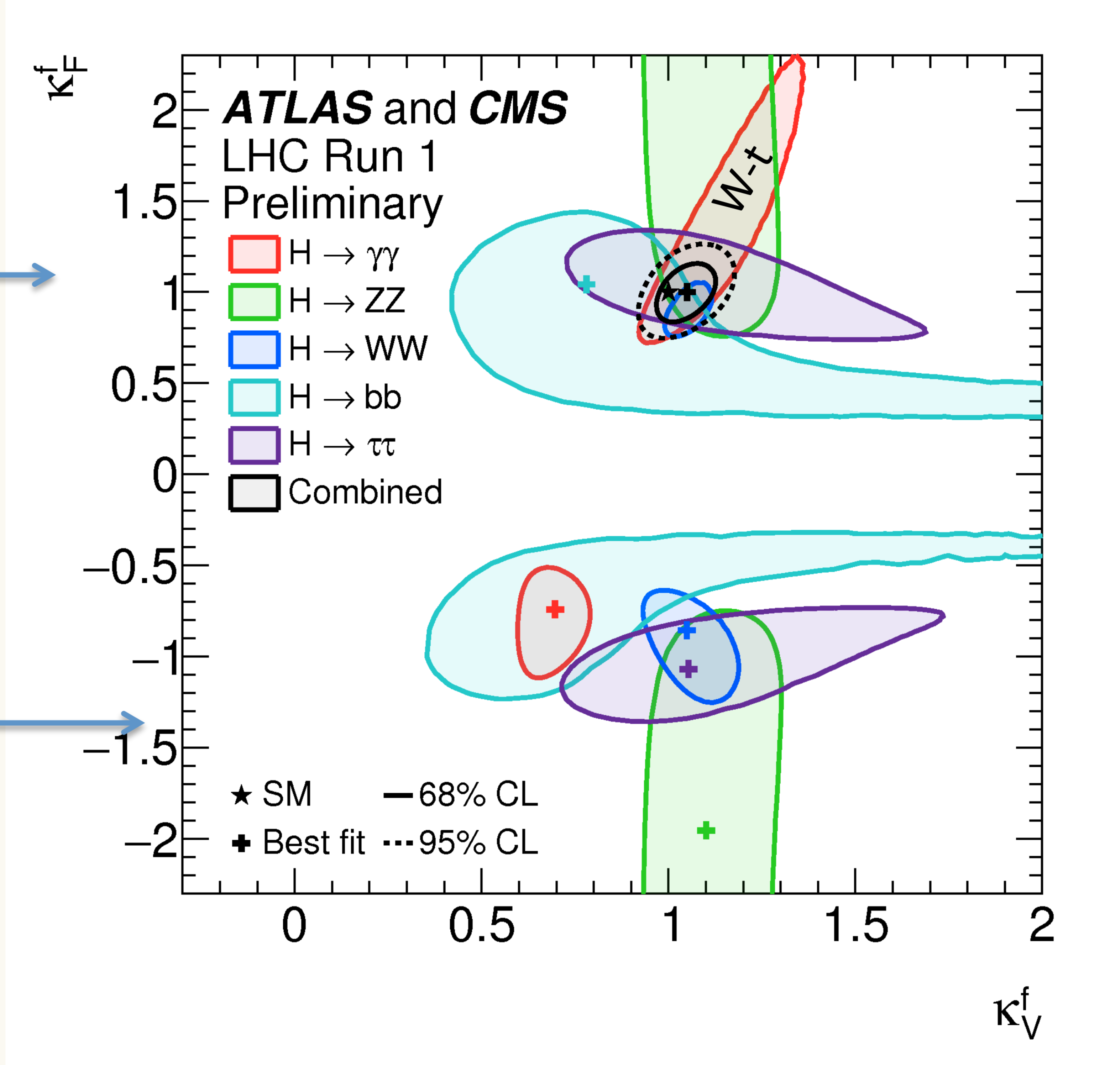


kV & kF: The pedagogic plot

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

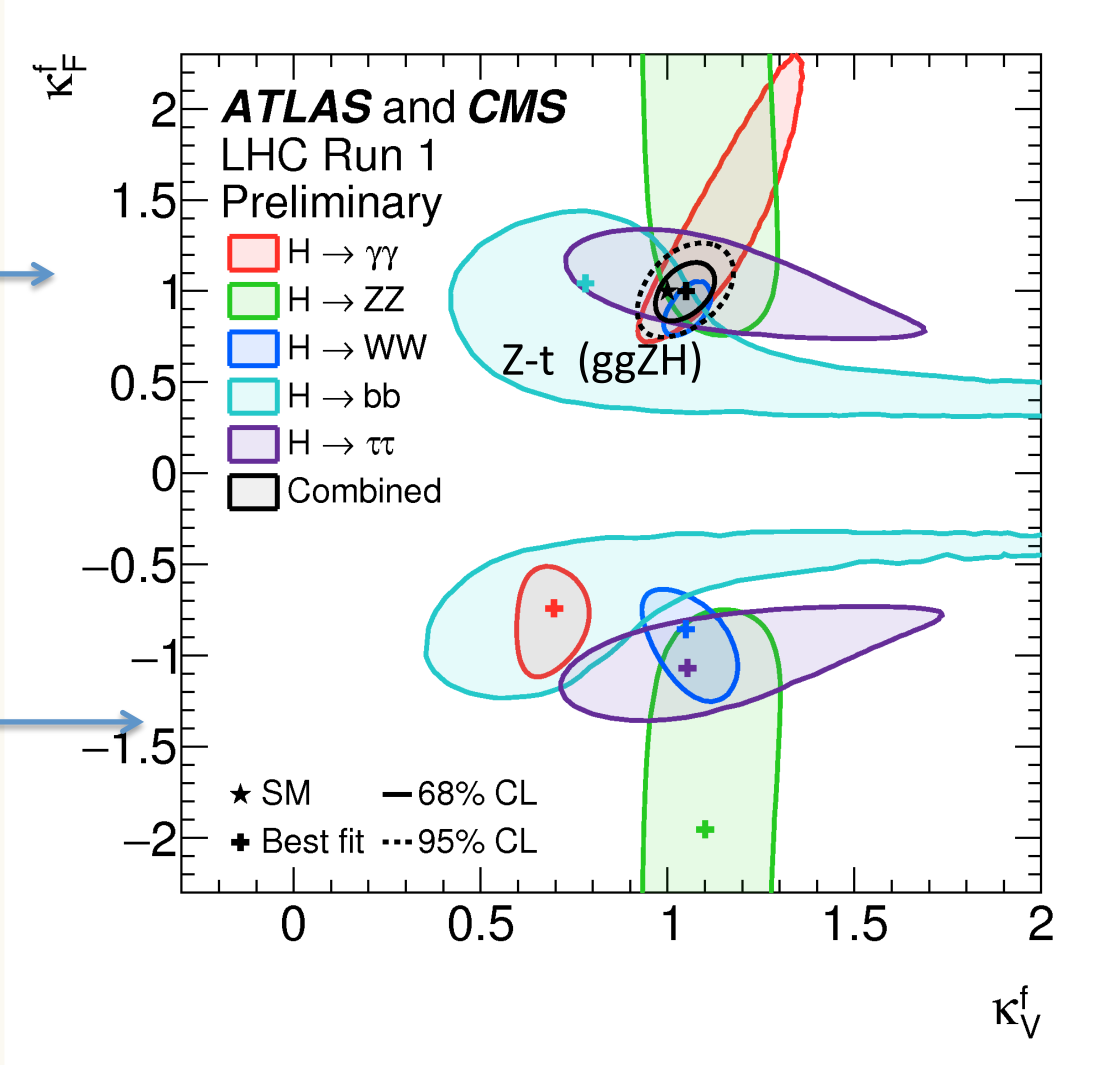


kV & kF: The pedagogic plot

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



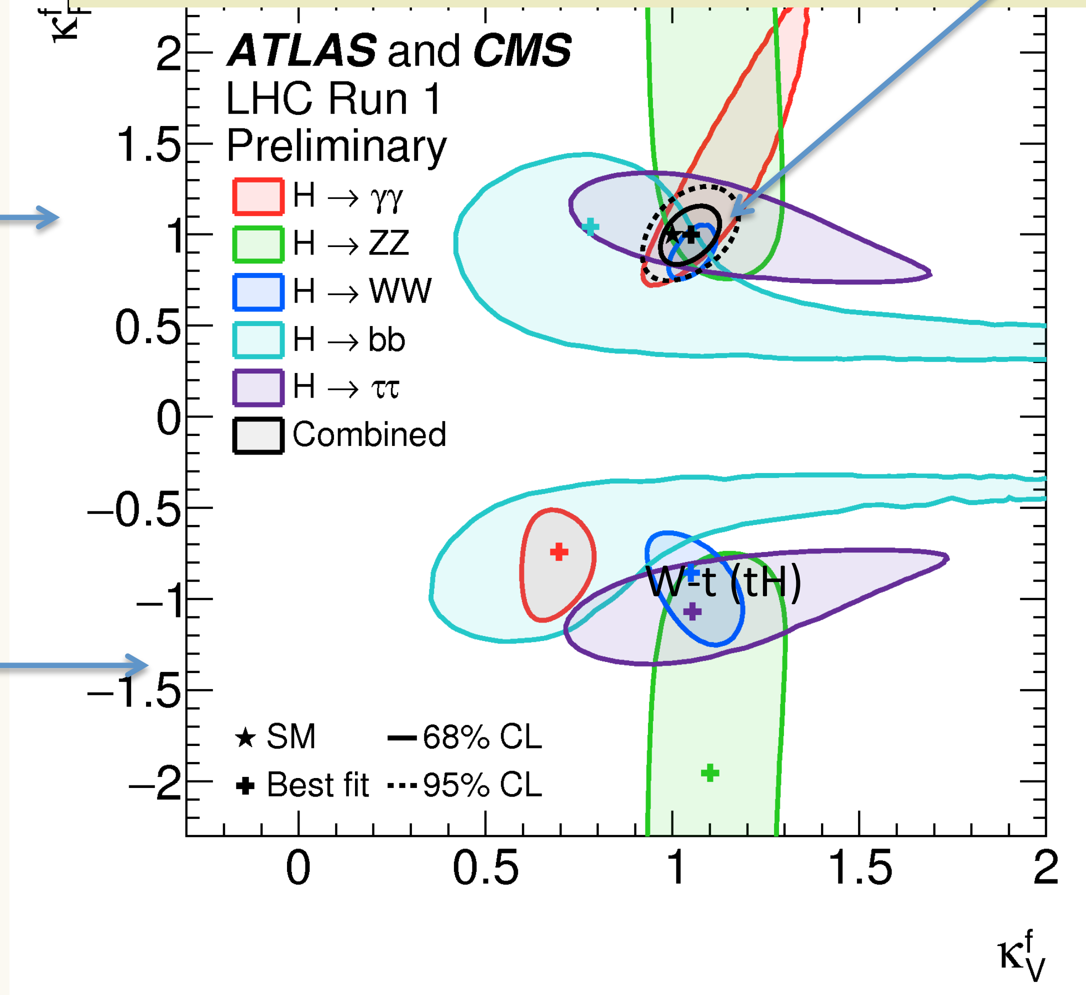
kV & kF: The pedagogic plot

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

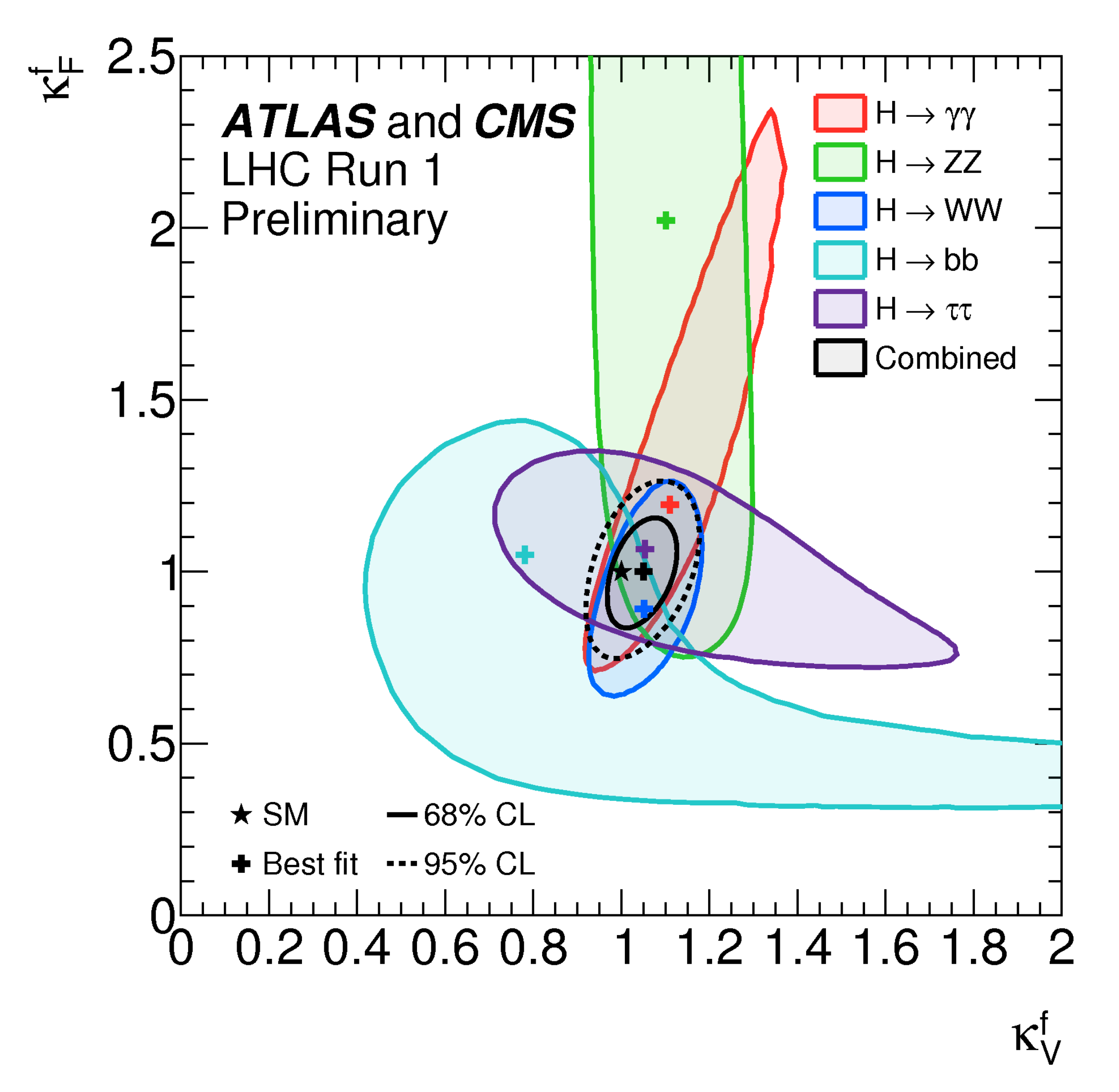
SM –
No Tension

Tension
Drifting
apart



kV & kF: The pedagogic plot

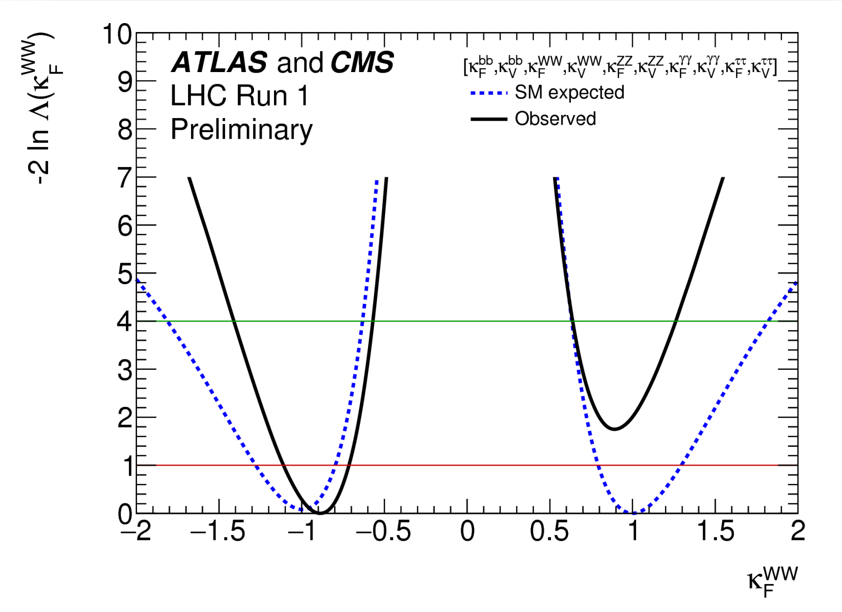
Fitting only positive Kappas, tautology resolved

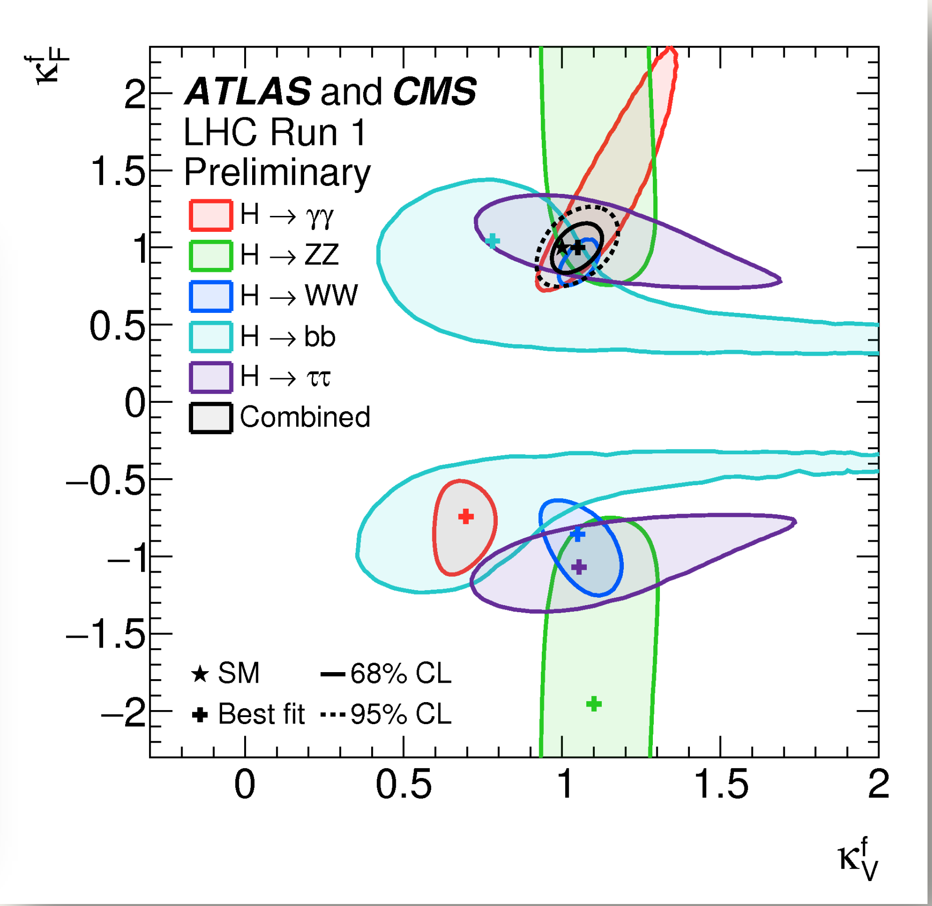


kV & kF: The pedagogic plot

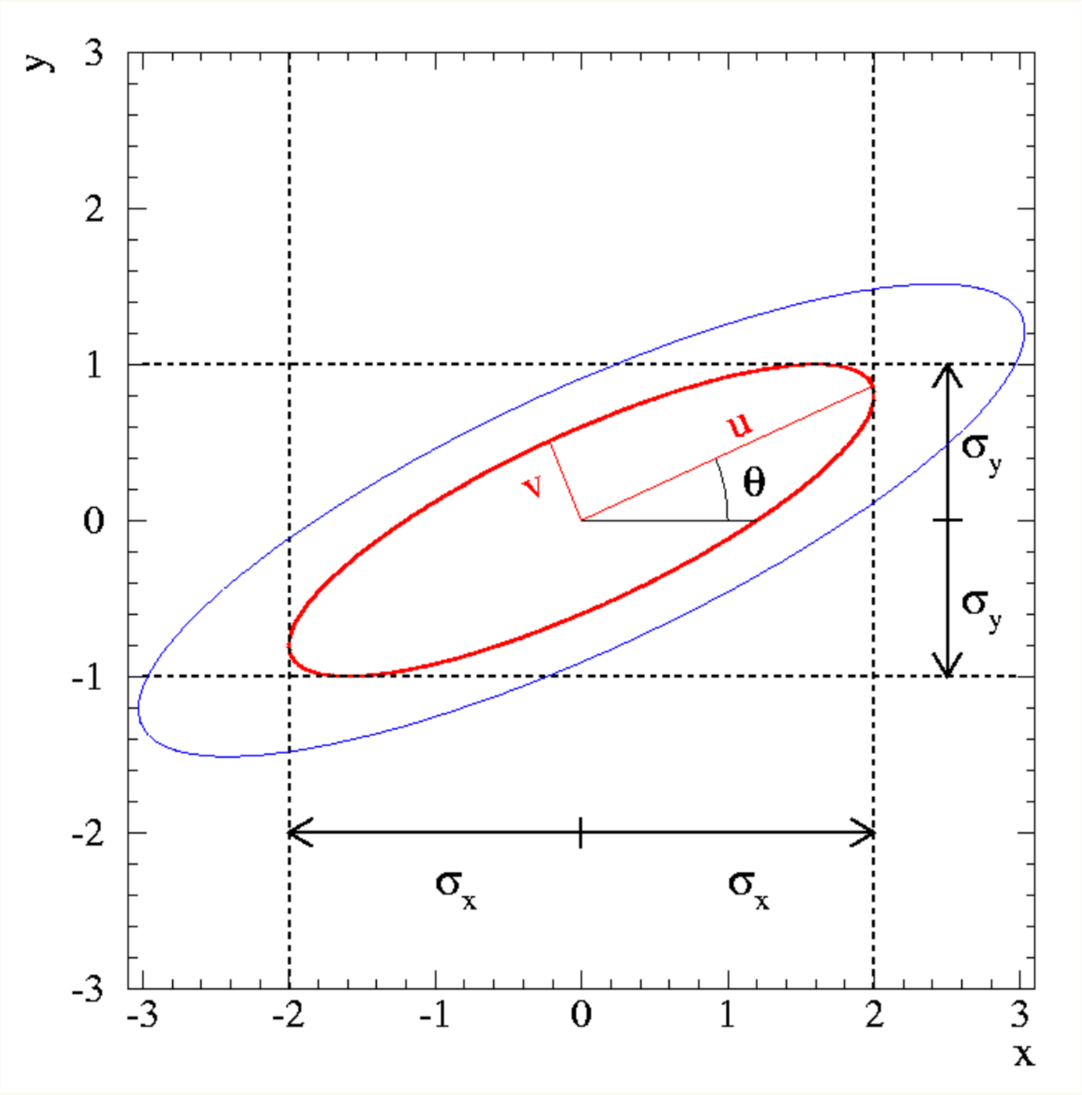
Another interesting point

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





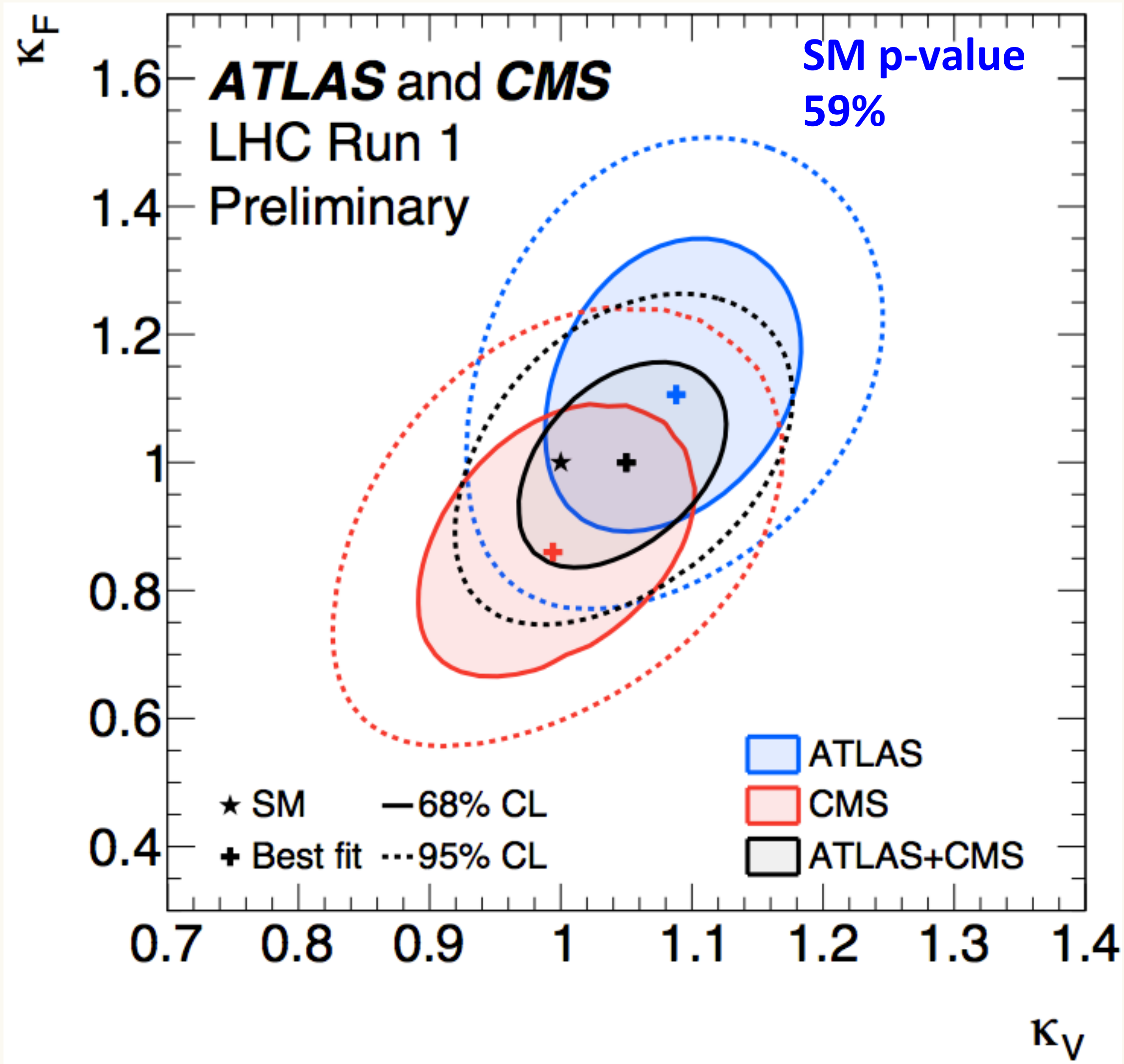
1D vs 2D Confidence Interval



$$\Delta\chi^2 = 1$$

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

The CERN Courier PR plot



In the presence of NP

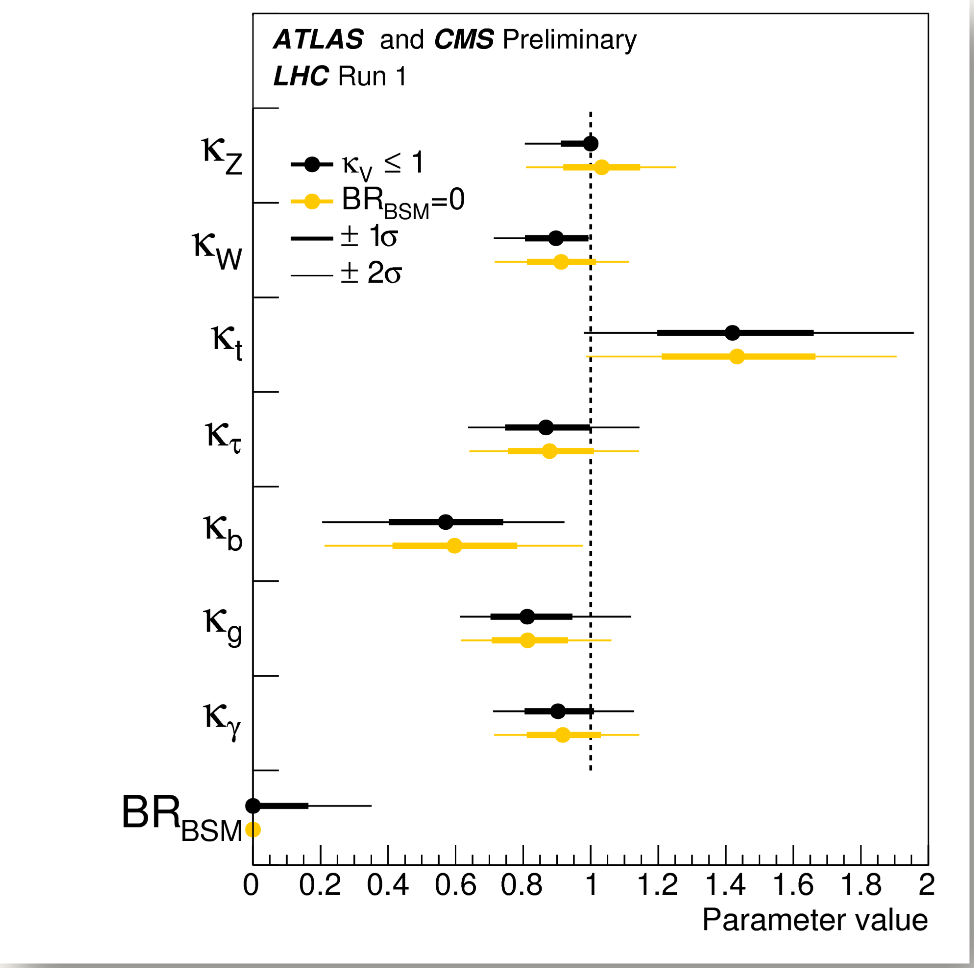
Here NP will enter in the loop and might contribute to BR_{BSM}

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)

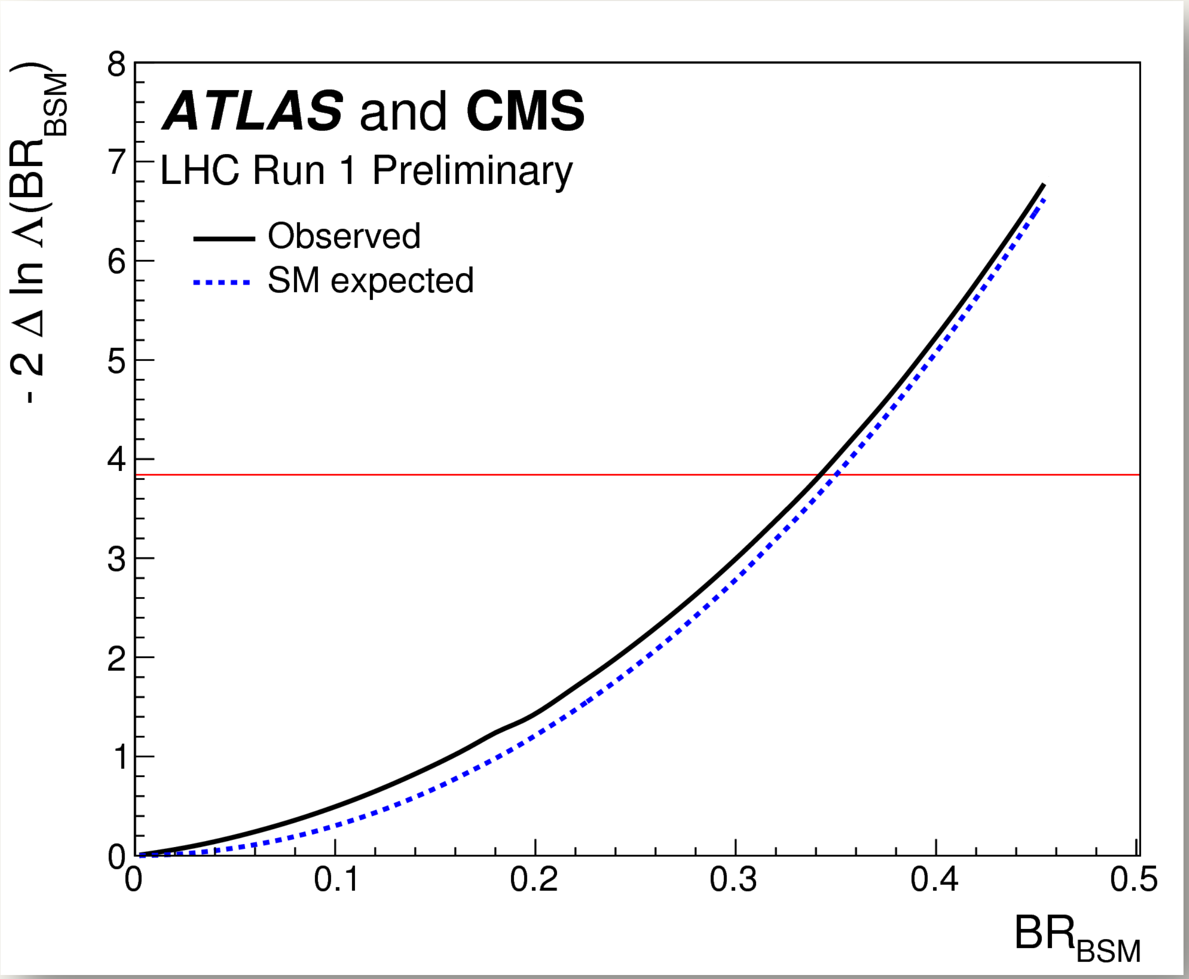


Bounds on BR_{BSM}

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

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

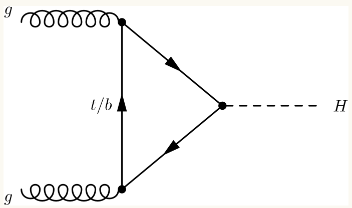
Which does not Allow negative BRs, leading to Possible Overcoverage (conservative)



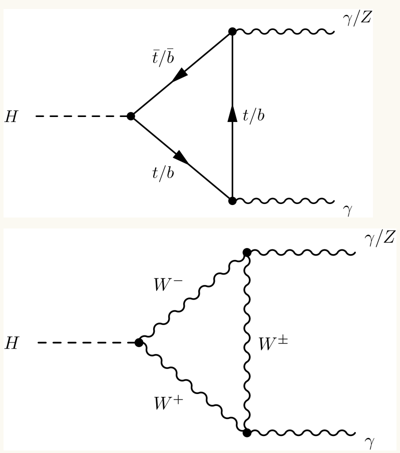
κ_g and κ_γ

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

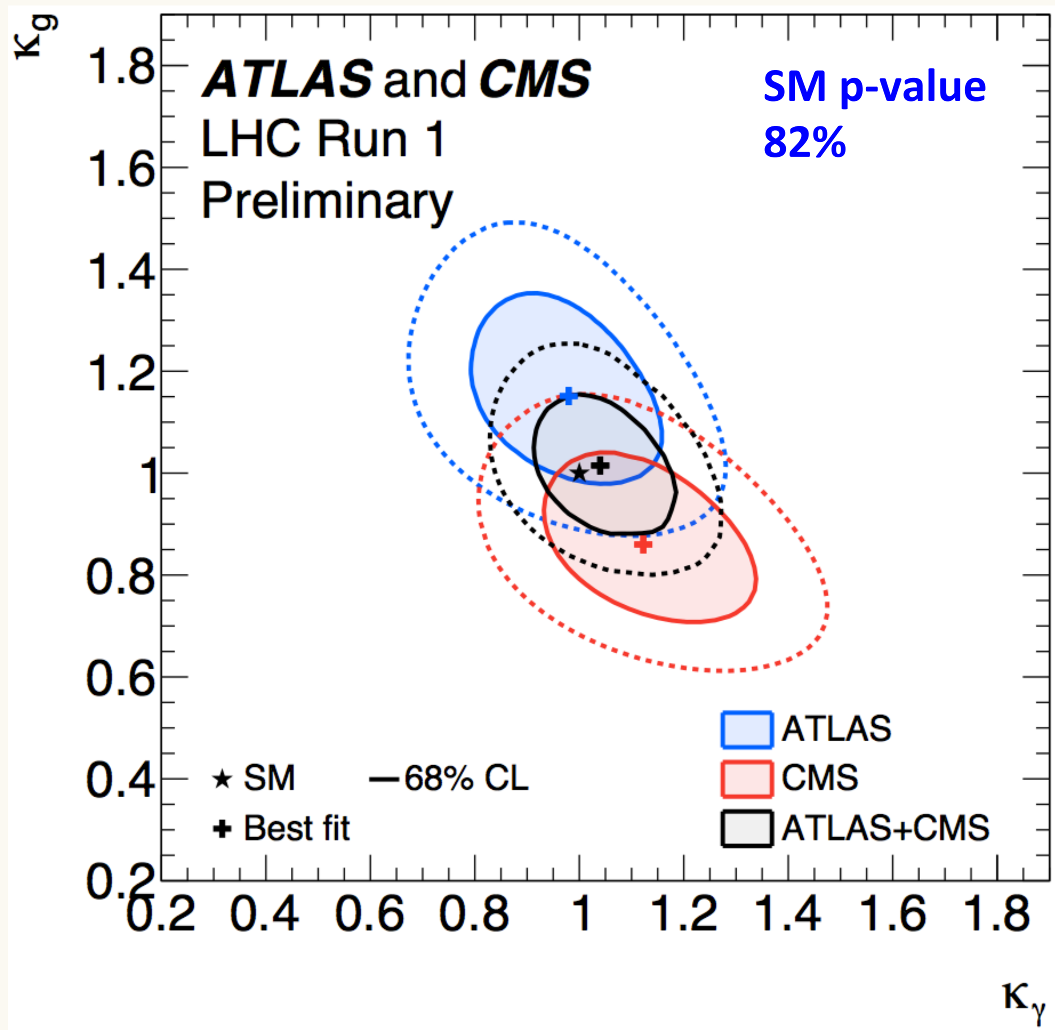
ggF loop



H→γγ loop



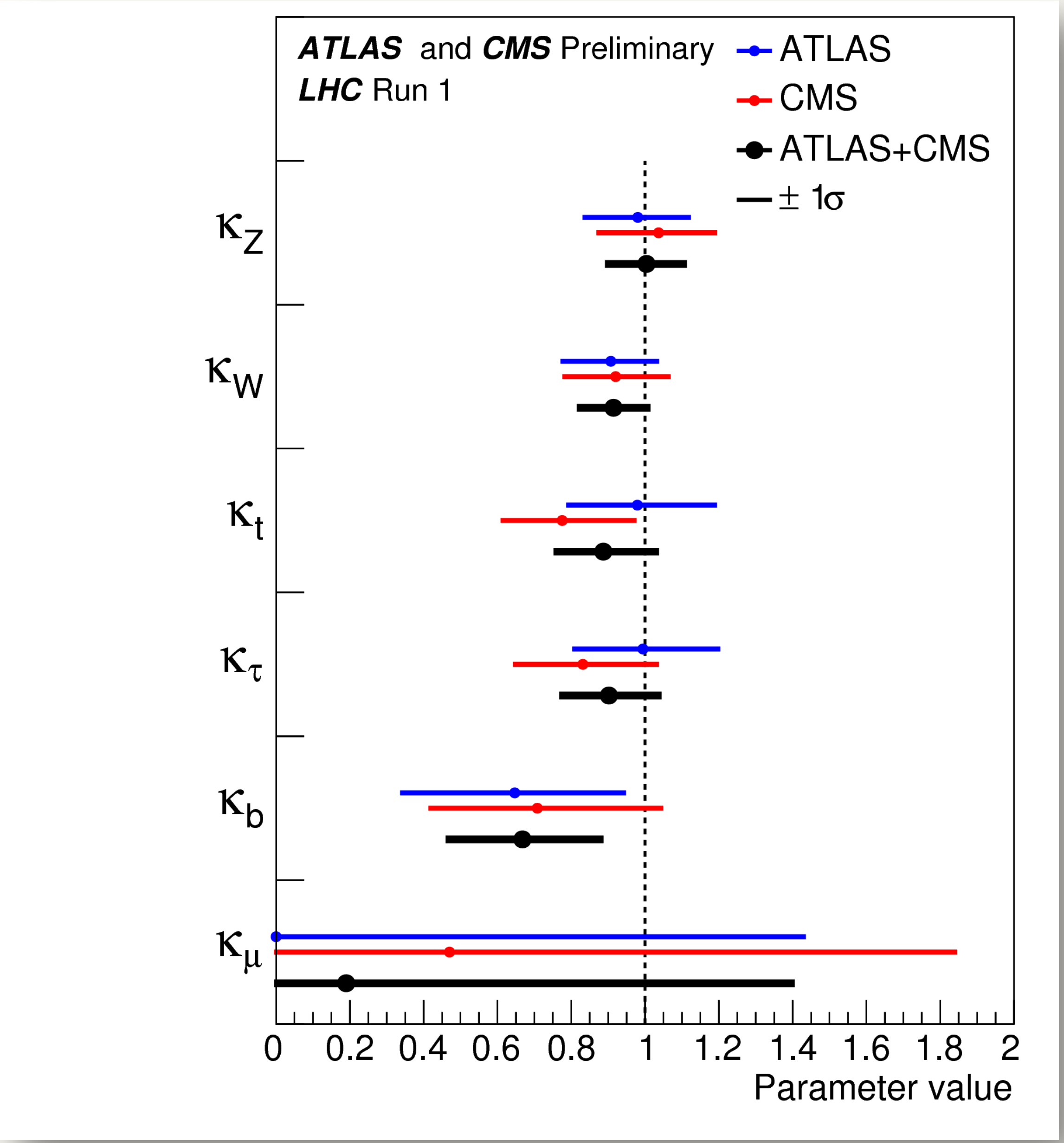
Additional heavy fermions or charged Higgs boson would modify the effective couplings



“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.

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

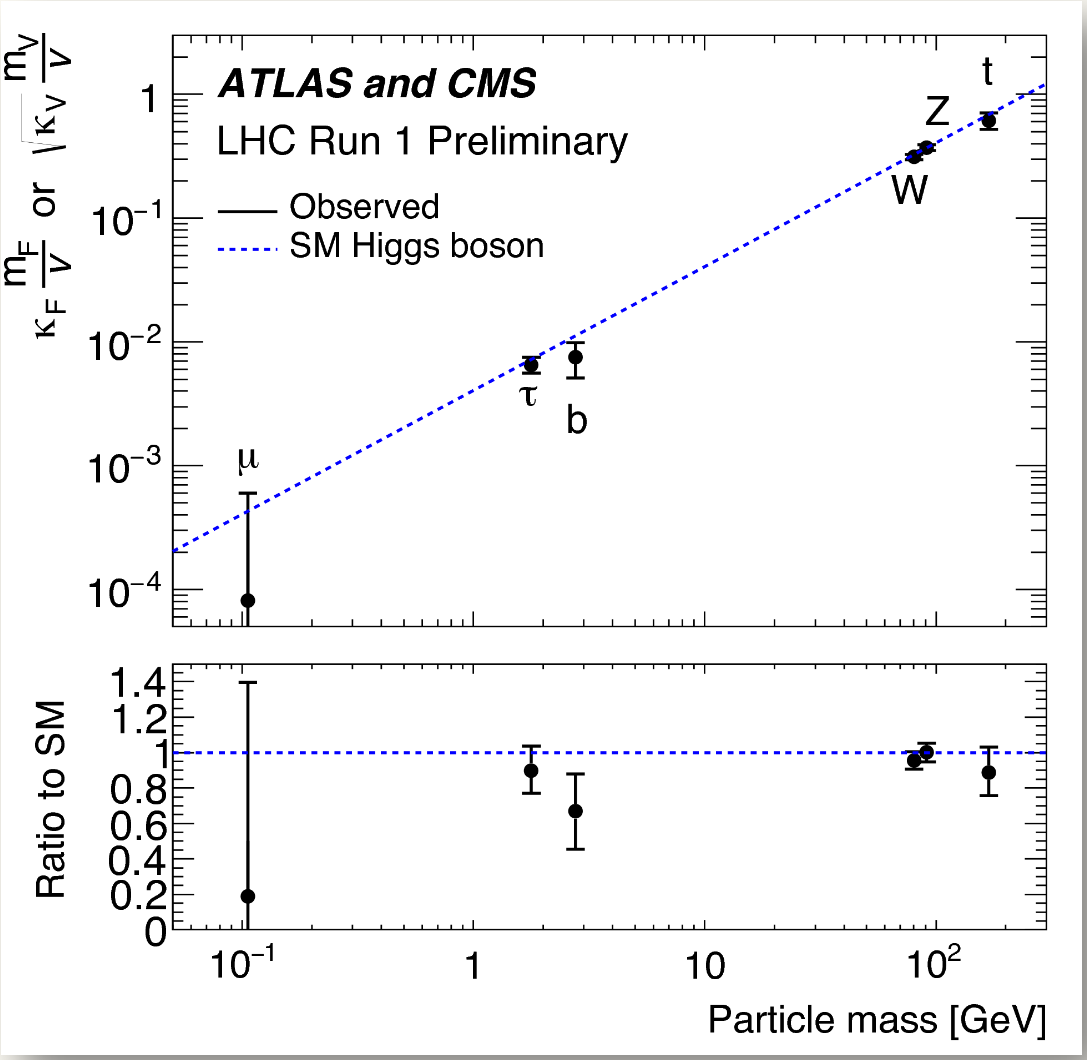


The PR Plot (an alternative version)

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

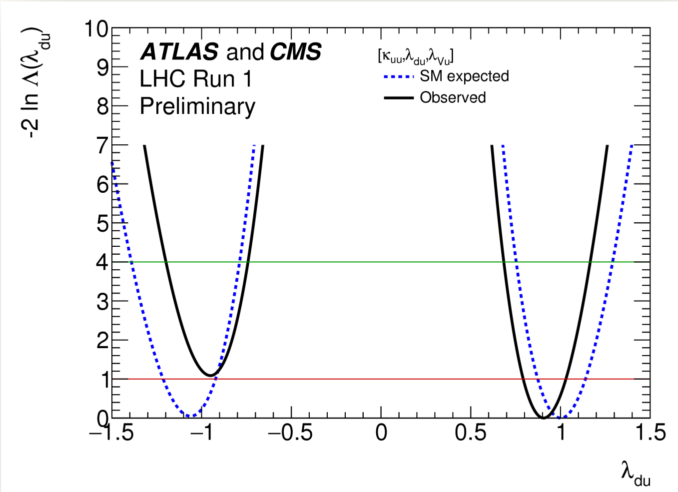
$$g_{HVV} = \frac{g_{HVV}}{g_{HVV}^{SM}} g_{HVV}^{SM} = \kappa_V g_{HVV}^{SM} \sim \kappa_V m_V^2$$

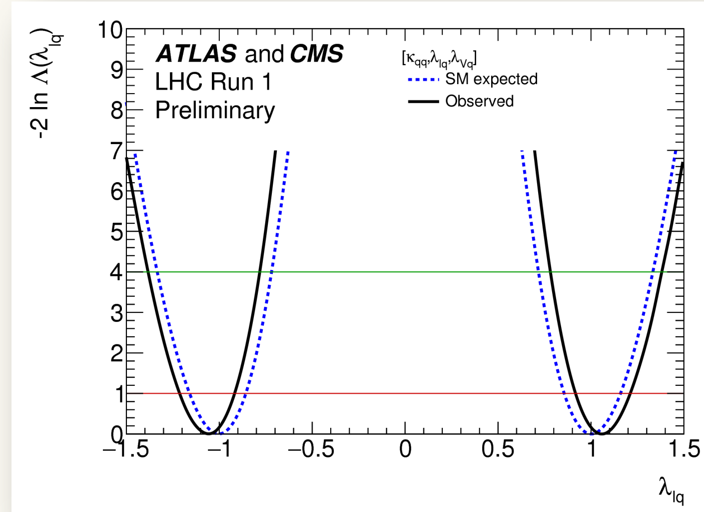
reduced coupling $\sqrt{g_{HVV}} \sim \sqrt{\kappa_V} m_V$



k_F 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	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%

Conclusions

Concluded?

Not Yet

We will conclude when the paper is out.

What would be the life time of this Legacy result?

Hopefully as short as possible…

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.