Constraints on Higgs couplings from a combination of ATLAS and CMS measurements

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CERN LHC seminar – 21 September 2015

Outline of this presentation

① **Introduction**

② Higgs boson phenomenology & interpretation framework

③ Combination procedure & experimental inputs

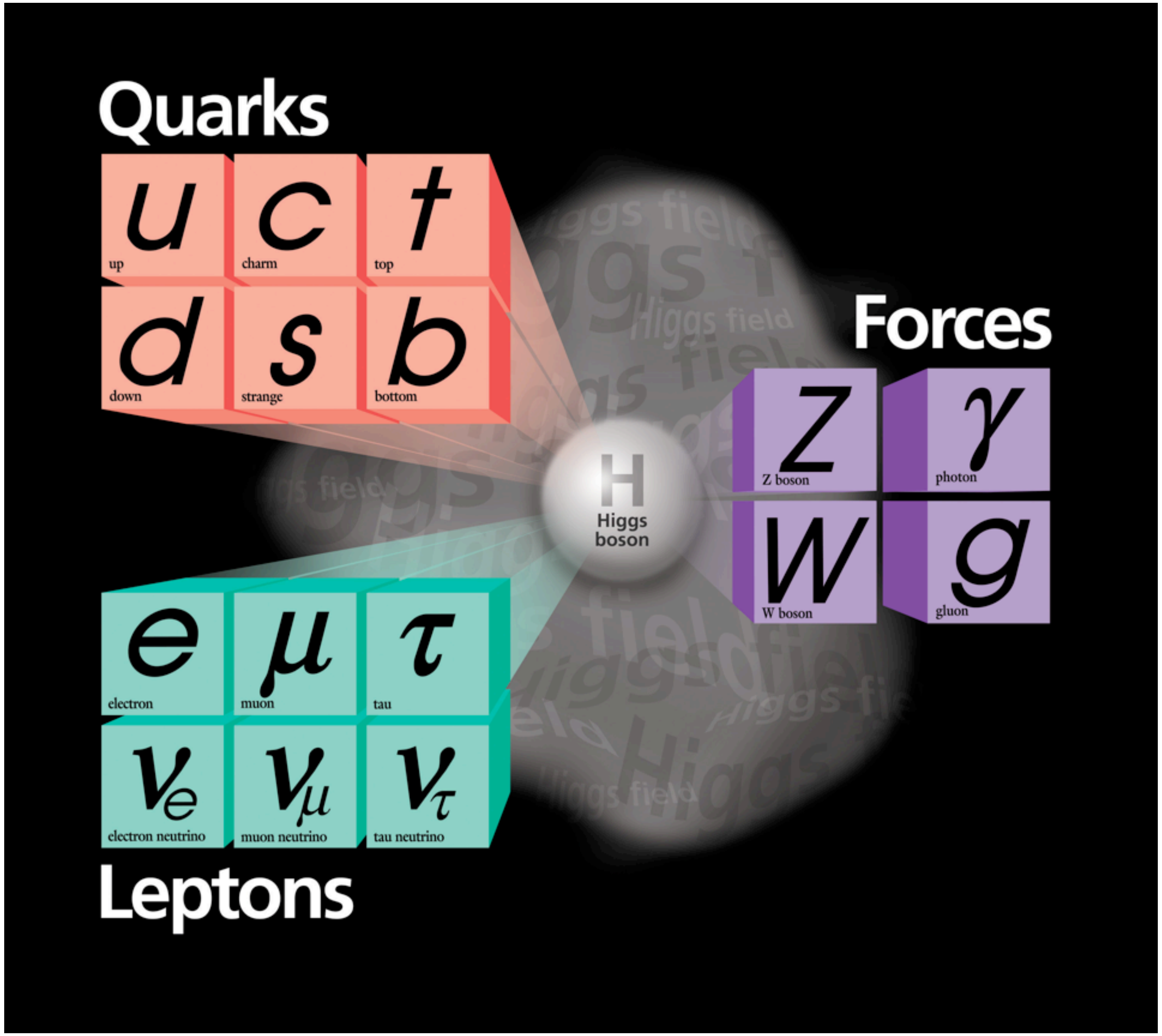
④ Signal strength measurements

⑤ Constraints on Higgs boson couplings

⑥ Most generic parametrizations

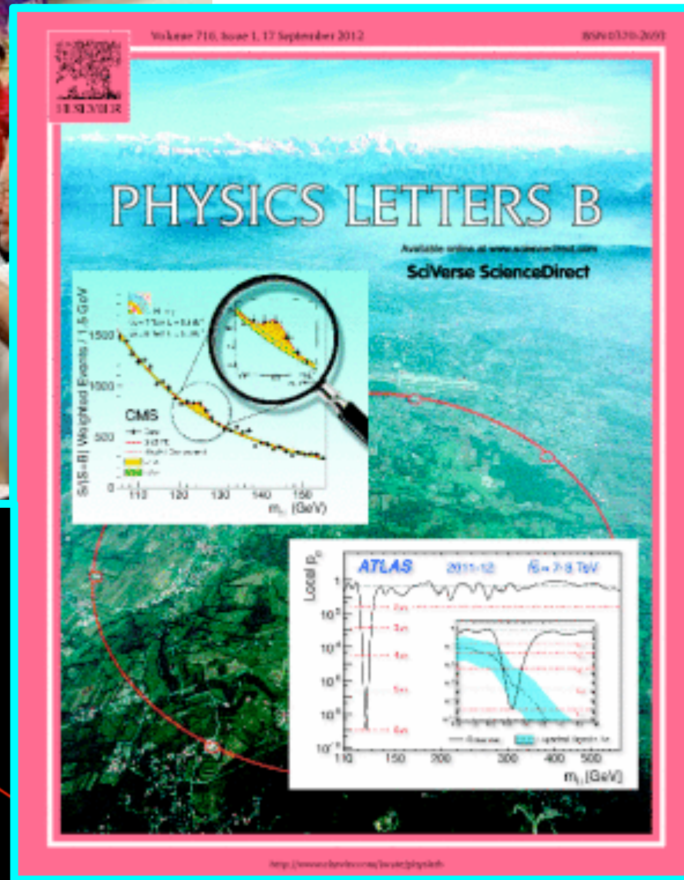
Introduction – Higgs boson in the SM

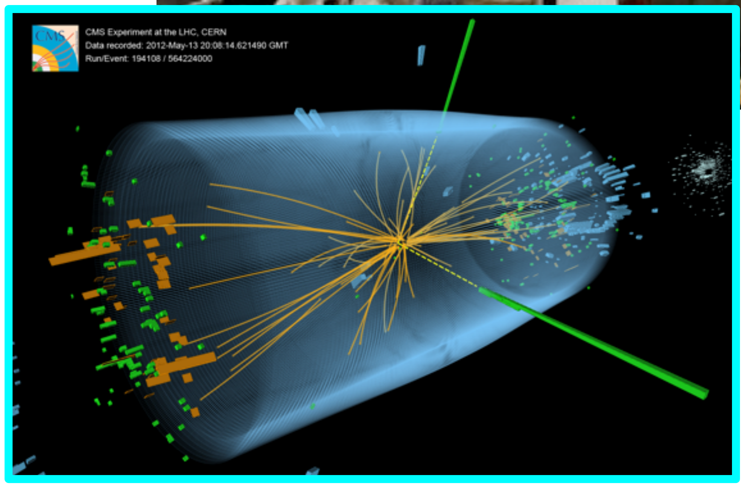
- The Higgs boson plays a pivotal role in the Standard Model

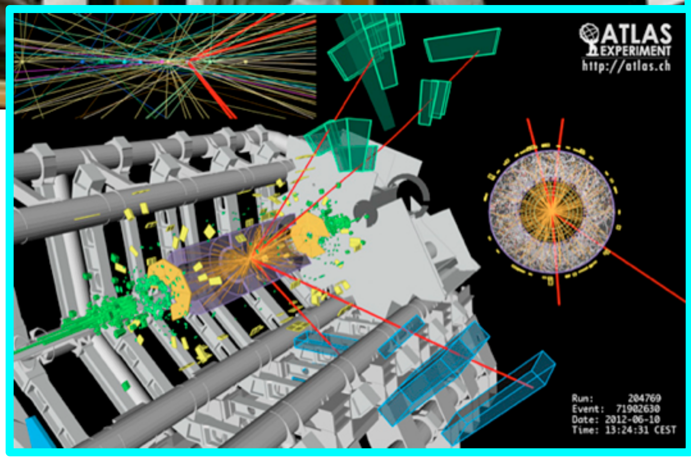


Run 1- Discovery of SM-like Higgs boson

- Discovery of Standard-Model like Higgs boson in 2012 offers opportunity to investigate Higgs sector of nature in detail



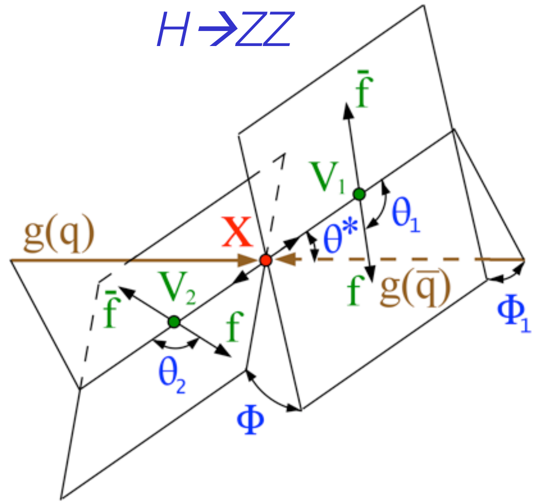




The observed Higgs boson is a spin-0 particle, compatible with CP-even

- Angular analysis of CMS and ATLAS run-1 data rules out spin-2 at >99.9% C.L.

H→ZZ



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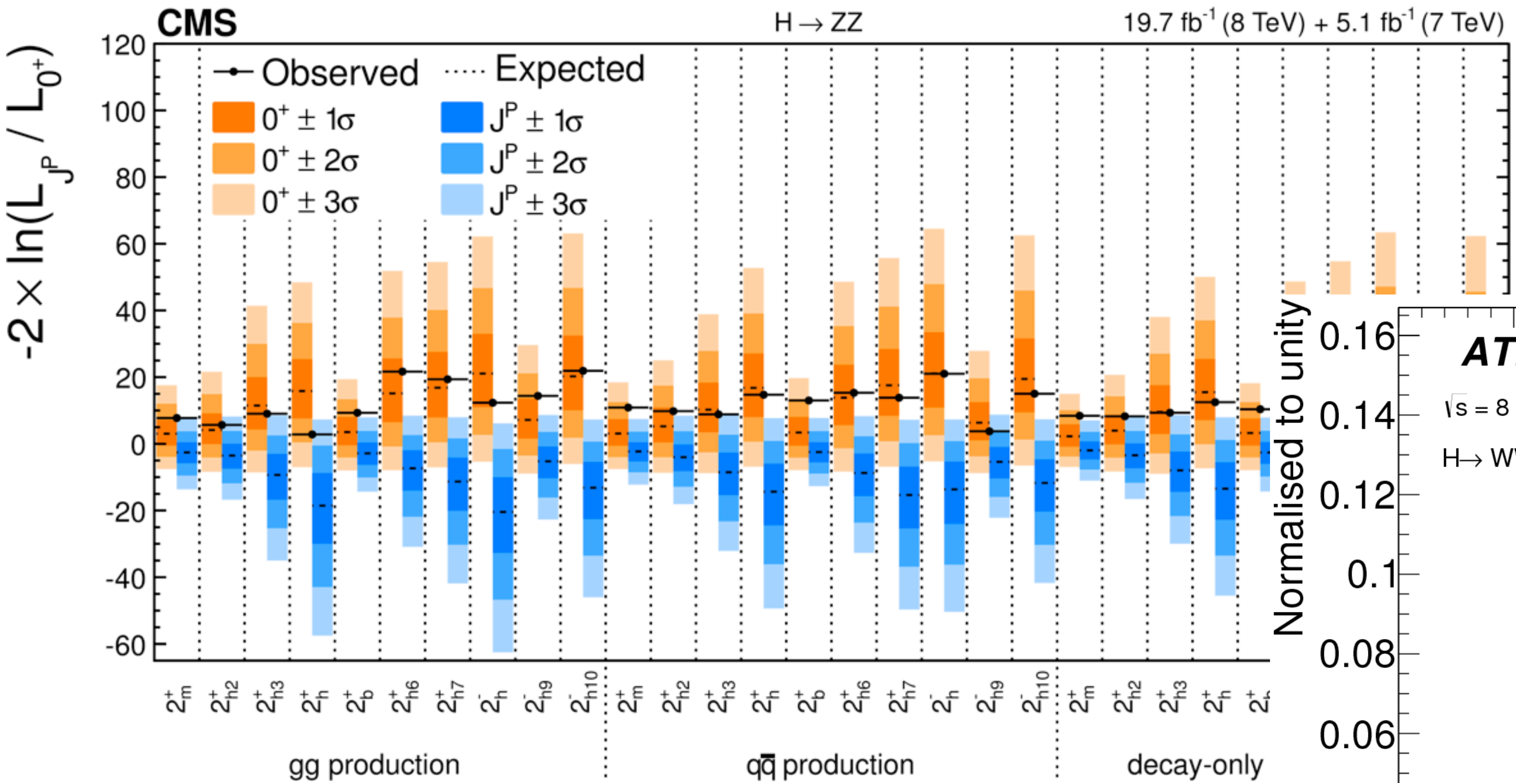

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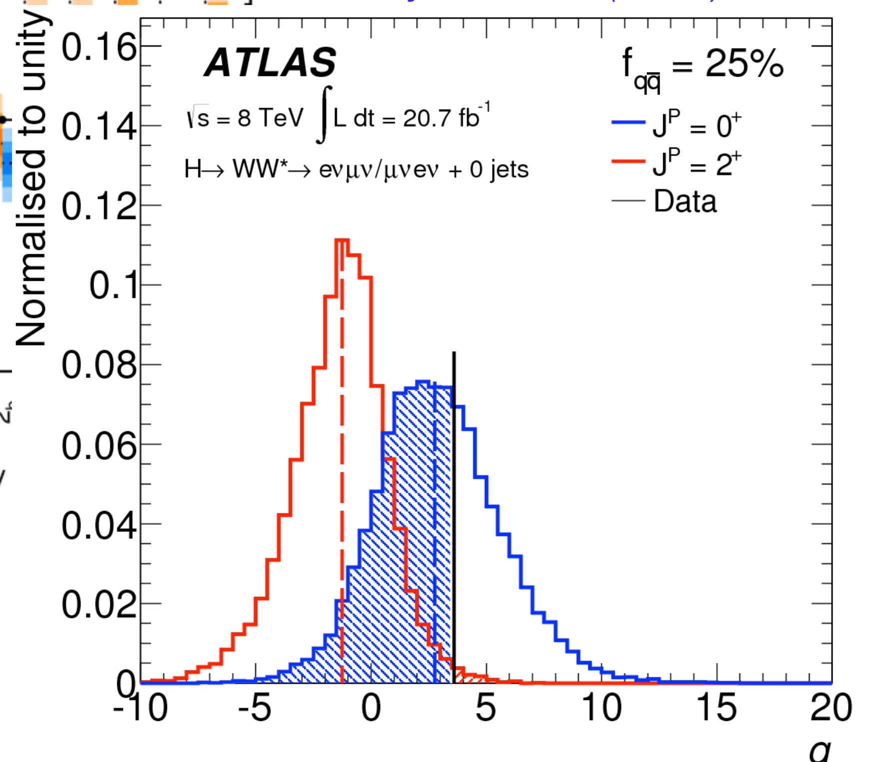
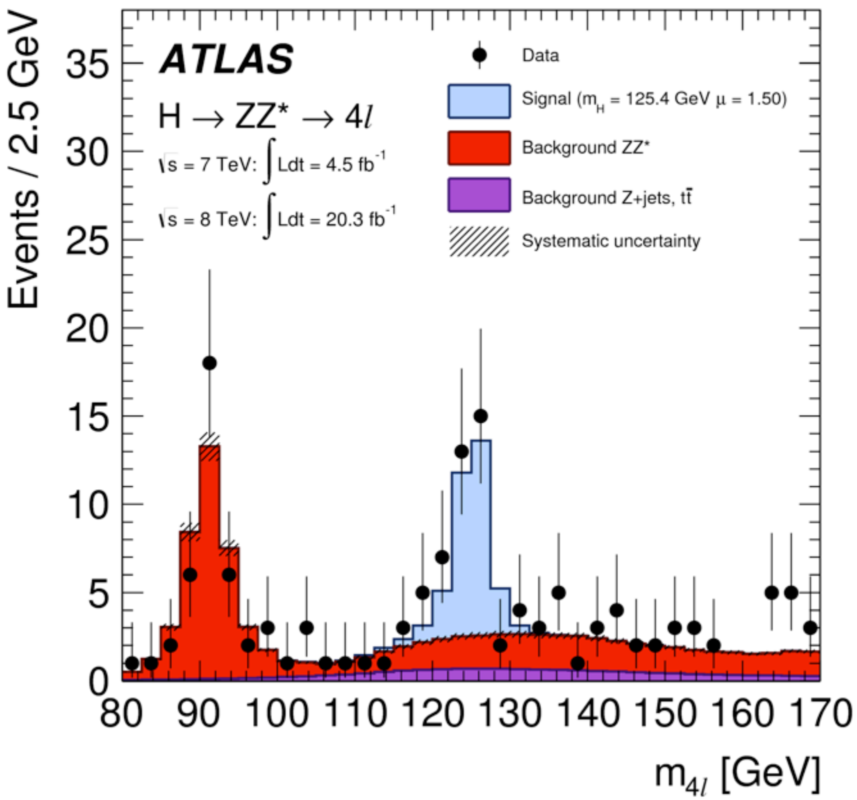
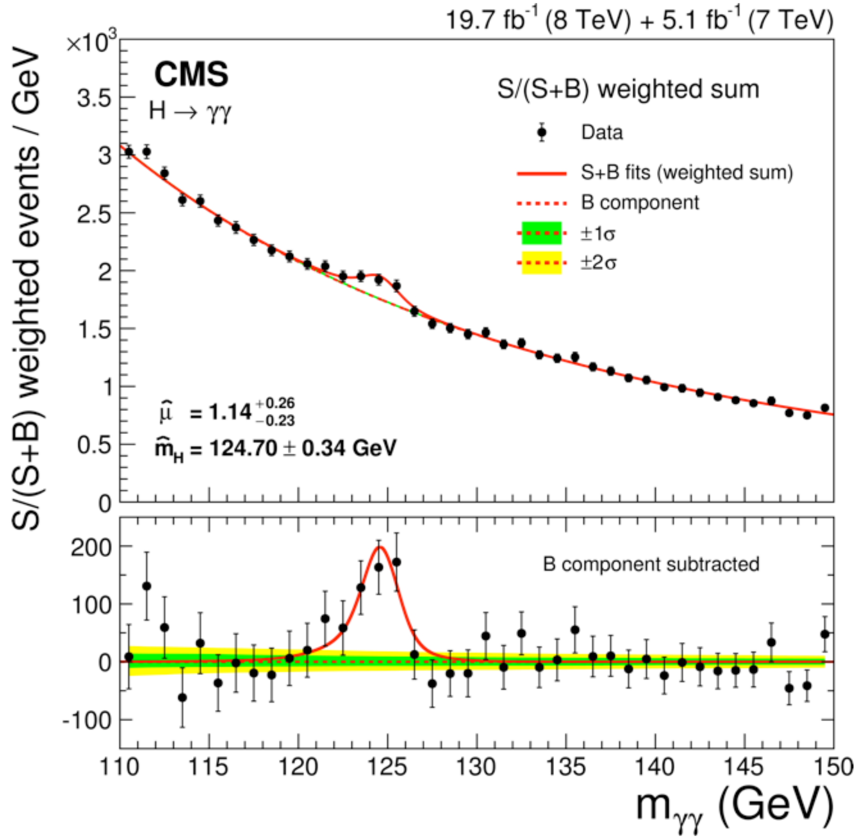


Mass of Higgs boson measured with <0.2% precision

- Higgs boson mass is only parameter unconstrained by SM
- But crucial in SM prediction of Higgs production and decay rates
- Measurement based on H→ZZ* and H→γγ final states, for which invariant mass can be reconstructed with high precision



Phys. Rev. D. 90, 052004 (2014)



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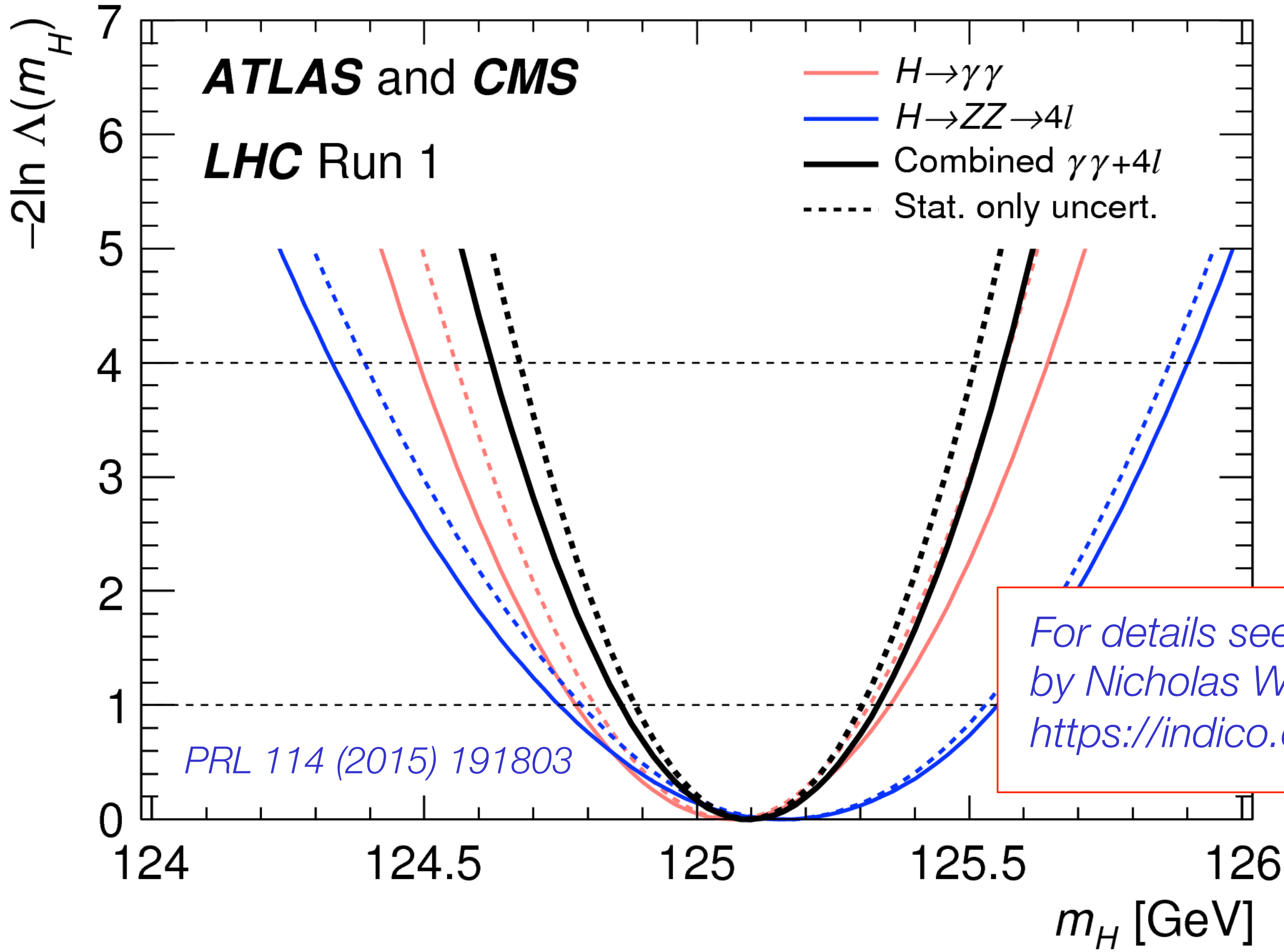
Mass of Higgs boson measured with <0.2% precision

- Result from combination of ATLAS and CMS results



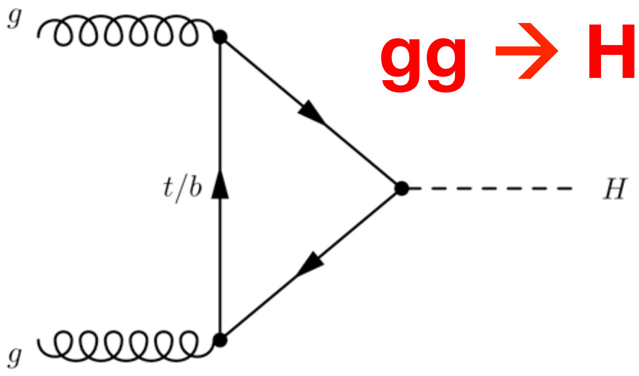
For details see CERN seminar in March by Nicholas Wardle https://indico.cern.ch/event/360243

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

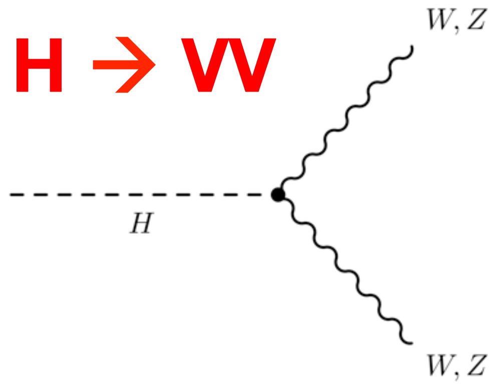
Today's focus - Higgs boson couplings

- Rich experimental area of Higgs properties:
  the Higgs coupling strength to other SM particles, e.g.

gg → H



H → VV



- All coupling strengths predicted by SM, given known Higgs boson mass
- Accessible in various combinations and admixtures.
  Large variety of ATLAS & CMS observed Higgs boson decay rates
- Powerful test of nature of Higgs boson: SM, or subtly different?

Higgs bosons – Alternatives to the SM Higgs boson

- **What else could the 125 GeV state be?**
  Many alternative theories exist, for example

- Light CP-even h(125) of a Two Higgs Doublet Model (h,H,$H^{\pm}$,A)

- Pseudo NG boson from higher energy theory (Composite Higgs)

In either case couplings of BSM h(125) candidate (slightly) different from SM Higgs boson

- Goal here is not to pick a specific model – but to develop a generic framework to quantify possible deviations in Higgs couplings from SM

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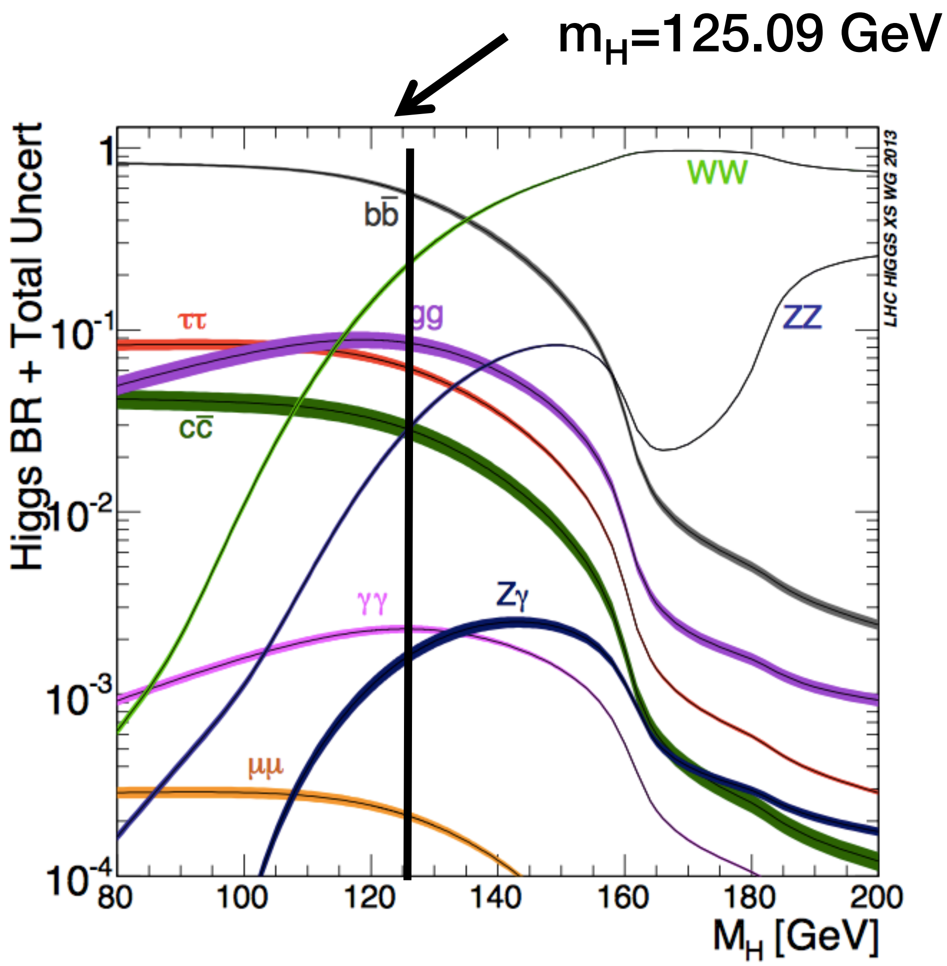
Standard Model Higgs boson decays



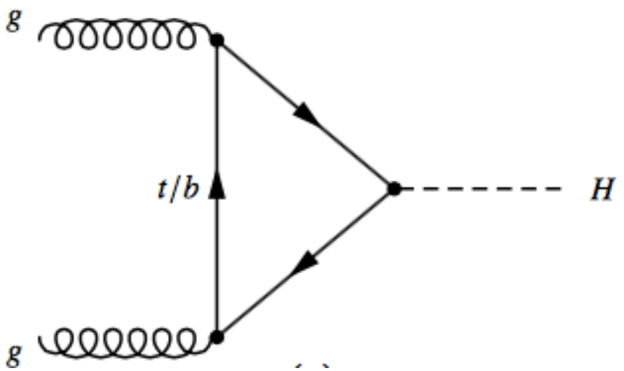
Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

SM BR theory uncertainties
2-5% for most important decays

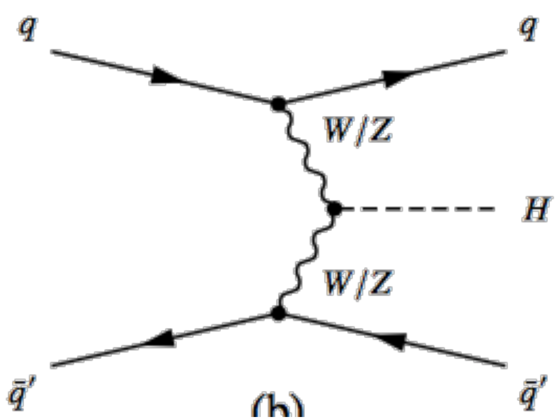
The natural width of the Higgs boson is expected to be very small (<< resolution)

See "Handbook of LHC Higgs Cross Sections: 3. Higgs Properties" (arXiv:1307.1347) for further details on Higgs phenomenology

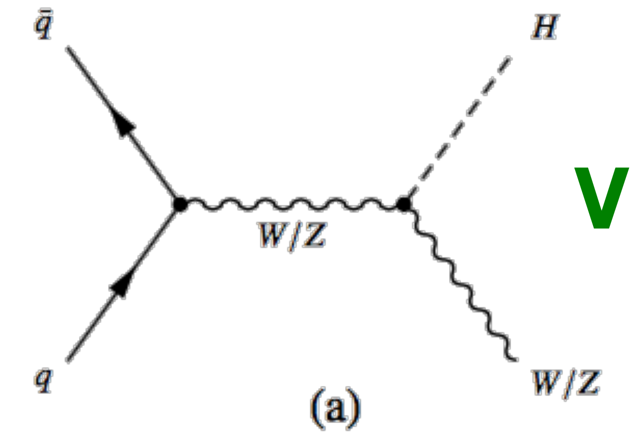
Higgs boson production in the SM



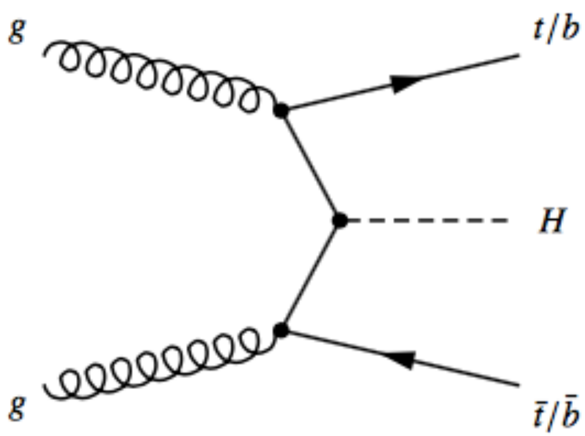
ggF



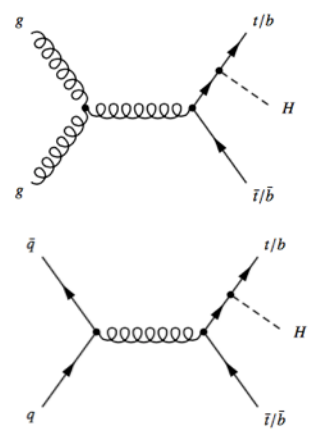
VBF

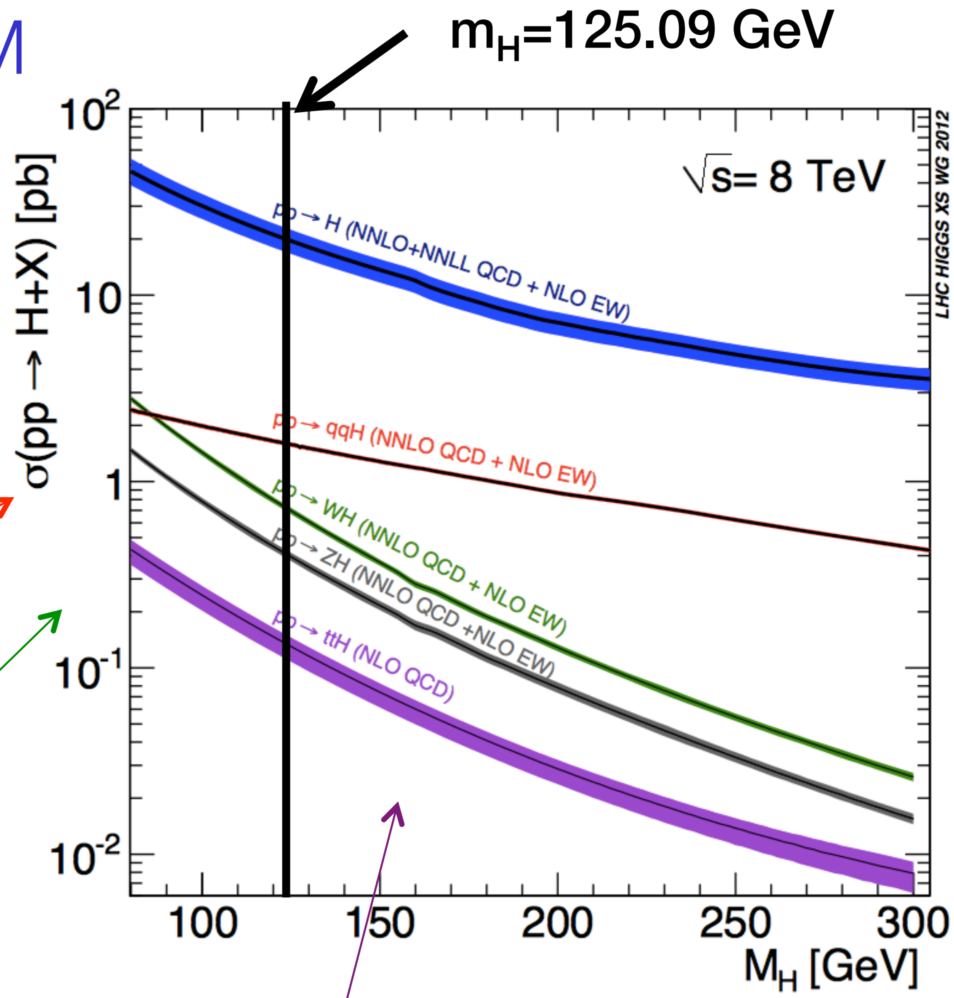


VH



ttH





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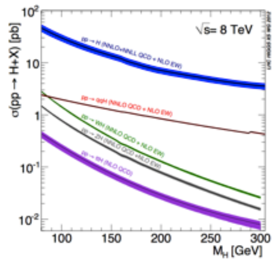
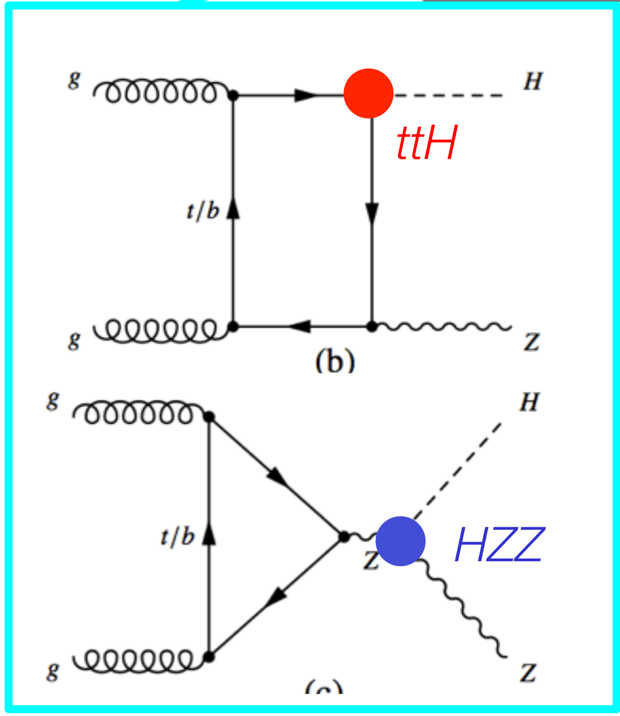


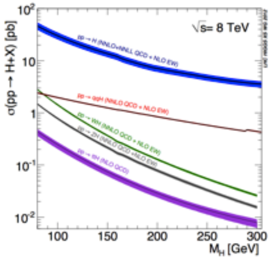
Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	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)
	17.4 ± 1.6	22.3 ± 2.0	



Gluon-initiated ZH production represents ~8% of total ZH cross-section, has harder p_T distribution

Modeled separately because Higgs coupling structure of gg→ZH is different from qq→ZH

Higgs boson production in the SM



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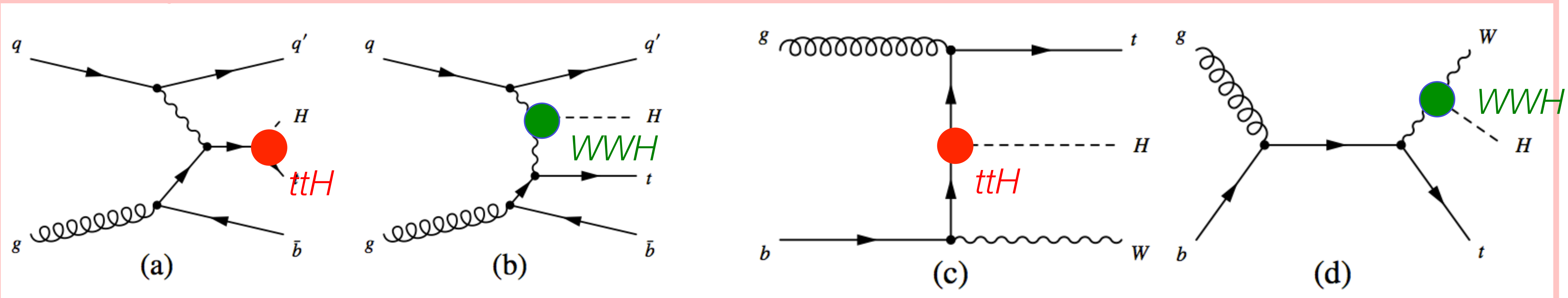
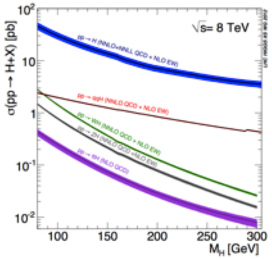


Very small SM cross-section due to almost completely destructive interference

For opposite sign W/t Higgs couplings, σ(tHqb) increases by factor 13 and σ(WtH) by factor 6

Higgs boson production in the SM



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Total	17.4 ± 1.6	22.3 ± 2.0	

Diagrams similar to ttH,
but experimentally not really distinguishable from ggF and 100x smaller in SM

Higgs production and decay – Run 1 input measurements

Channel	References for individual publications	
	ATLAS	CMS
$H \to \gamma\gamma$	[51]	[52]
$H \to ZZ \to 4\ell$	[53]	[54]
$H \to WW$	[55,56]	[57]
$H \to \tau\tau$	[58]	[59]
$H \to bb$	[38]	[39]
$H \to \mu\mu$	[60]	[61]
ttH production	[28,62,63]	[65]

ATLAS,CMS Higgs signal strength measurements, and signal searches used in this combination are documented in 17 journal publications

[28] ATLAS Collaboration, *Search for $H \to \gamma\gamma$ produced in association with top quarks and constraints on the Yukawa coupling between the top quark and the Higgs boson using data taken at 7 TeV and 8 TeV with the ATLAS detector*, Phys. Lett. **B740** (2015) 222, arXiv:1409.3122 [hep-ex].

[38] ATLAS Collaboration, *Search for the $b\bar{b}$ decay of the Standard Model Higgs boson in associated $(W/Z)H$ production with the ATLAS detector*, JHEP **1501** (2015) 069, arXiv:1409.6212 [hep-ex].

[39] CMS Collaboration, *Search for the standard model Higgs boson produced in association with a W or a Z boson and decaying to bottom quarks*, Phys. Rev. D **89** (2014) 012003, arXiv:1310.3687 [hep-ex].

[51] ATLAS Collaboration, *Measurement of Higgs boson production in the diphoton decay channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, Phys. Rev. **D90** (2014) 112015, arXiv:1408.7084 [hep-ex].

[52] CMS Collaboration, *Observation of the diphoton decay of the 125 GeV Higgs boson and measurement of its properties*, Eur. Phys. J. C **74** (2014) 3076, arXiv:1407.0558 [hep-ex].

[53] ATLAS Collaboration, *Measurements of Higgs boson production and couplings in the four-lepton channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, Phys. Rev. **D91** (2015) 012006, arXiv:1408.5191 [hep-ex].

[54] CMS Collaboration, *Measurement of the properties of a Higgs boson in the four-lepton final state*, Phys. Rev. D **89** (2014) 092007, arXiv:1312.5353 [hep-ex].

[55] ATLAS Collaboration, *Observation and measurement of Higgs boson decays to WW^* with the ATLAS detector*, Phys. Rev. **D92** (2015) 012006, arXiv:1412.2641 [hep-ex].

[56] ATLAS Collaboration, *Study of the Higgs boson decaying to WW^* produced in association with a weak boson with the ATLAS detector at the LHC*, JHEP **1508** (2015) 137, arXiv:1506.06641 [hep-ph].

[57] CMS Collaboration, *Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states*, JHEP **01** (2014) 096, arXiv:1312.1129 [hep-ex].

[58] ATLAS Collaboration, *Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector*, arXiv:1501.04943 [hep-ex].

[59] CMS Collaboration, *Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons*, JHEP **05** (2014) 104, arXiv:1401.5041 [hep-ex].

[60] ATLAS Collaboration, *Search for the Standard Model Higgs boson decay to $\mu^+\mu^-$ with the ATLAS detector*, Phys. Lett. **B738** (2014) 68, arXiv:1406.7663 [hep-ex].

[61] CMS Collaboration, *Search for a standard model-like Higgs boson in the $\mu^+\mu^-$ and e^+e^- decay channels at the LHC*, Phys. Lett. **B** (2015) , arXiv:1410.6679 [hep-ex].

[62] ATLAS Collaboration, *Search for the Standard Model Higgs boson produced in association with top quarks and decaying into $b\bar{b}$ in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, Eur. Phys. J. C **75** (2015) 349, arXiv:1503.05066 [hep-ex].

[63] ATLAS Collaboration, *Search for the associated production of the Higgs boson with a top quark pair in multi-lepton final states with the ATLAS detector*, ATLAS-CONF-2015-007 (2015).

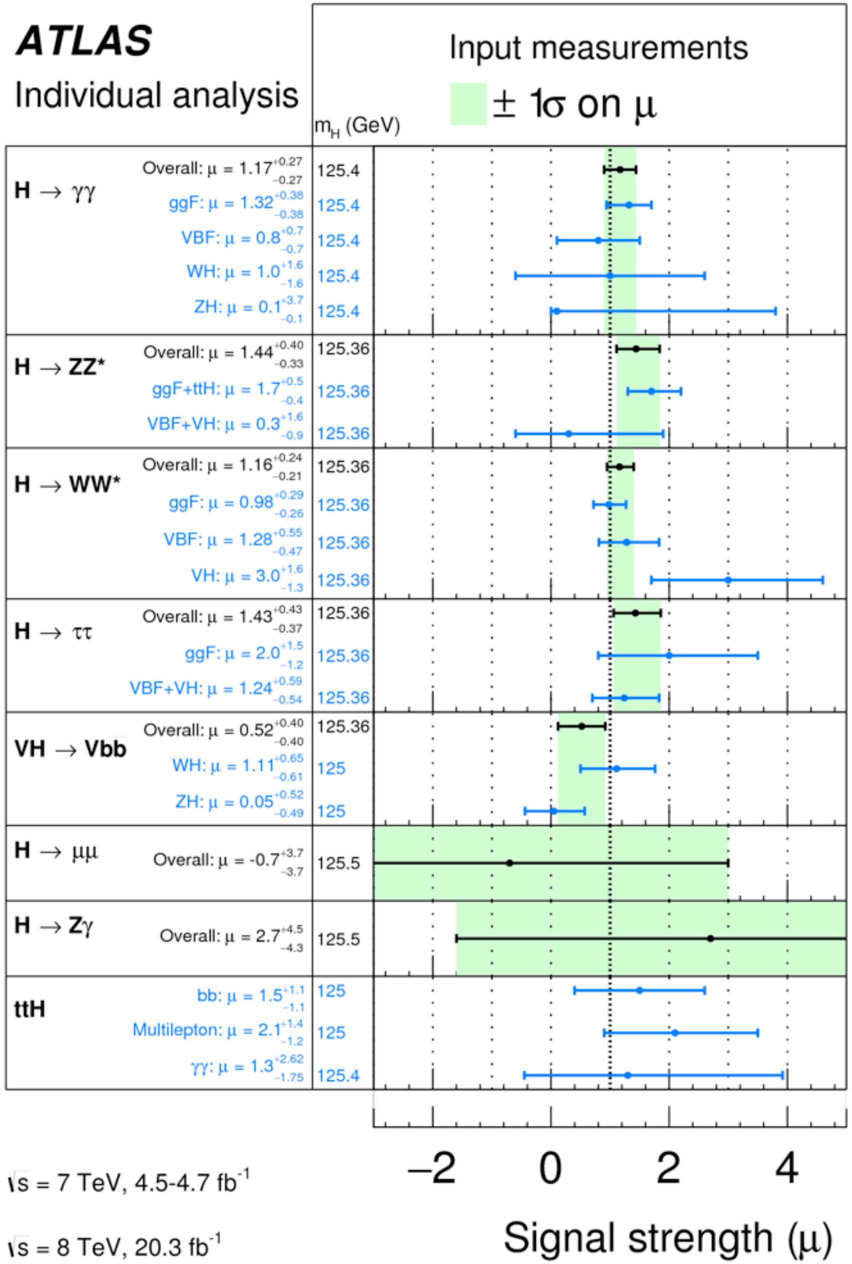
[65] CMS Collaboration, *Search for the associated production of the Higgs boson with a top-quark pair*, JHEP **09** (2014) 087, arXiv:1408.1682 [hep-ex].

Higgs production and decay – Run 1 measurements

Signal strength fits of individual experiments

arXiv:1507.04548 [hep-ex]

By fitted production mode



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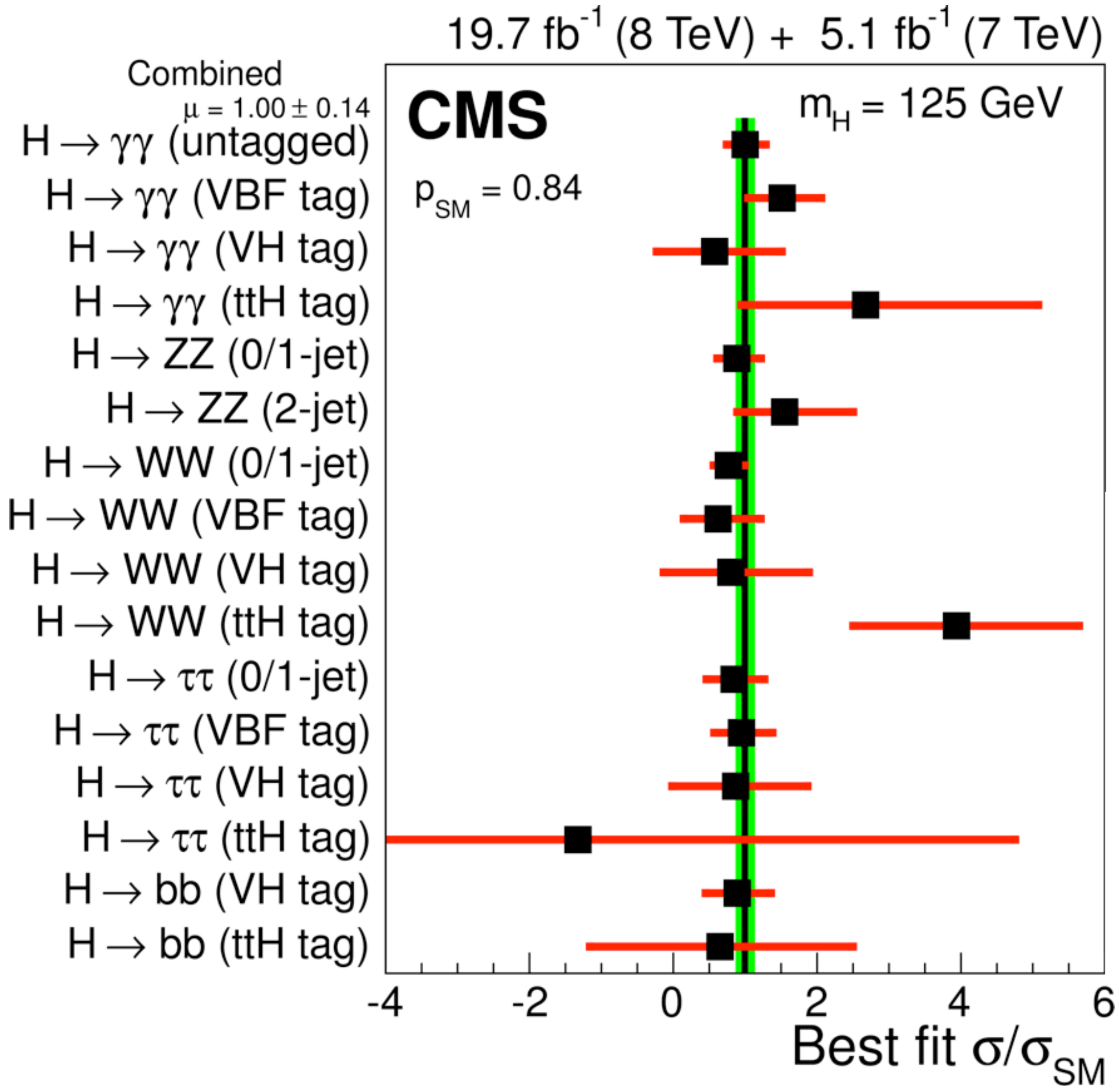
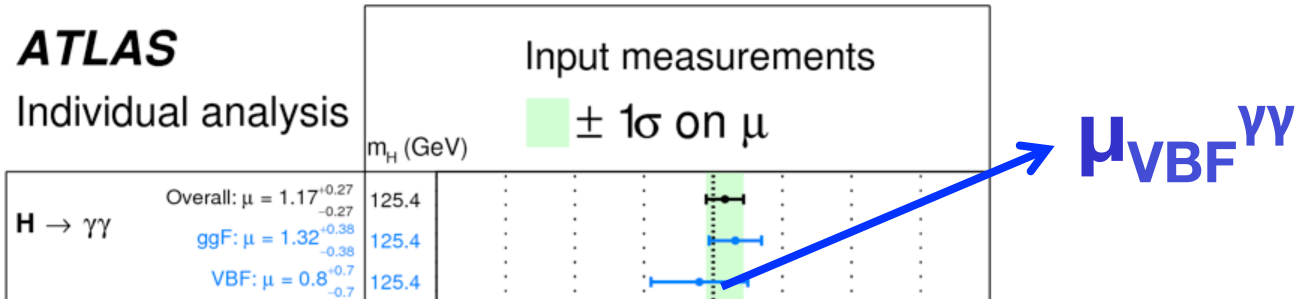


By tagged production mode

Understanding signal strengths for process i → H → f

- Signal strength μ is observed rated normalized by SM prediction

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



- Disentangling production (μ_i) & decay (μ_f) always **requires assumption of narrow Higgs width.**

- Additional assumptions required when combining measurements, e.g

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \quad \text{and} \quad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}}.$$

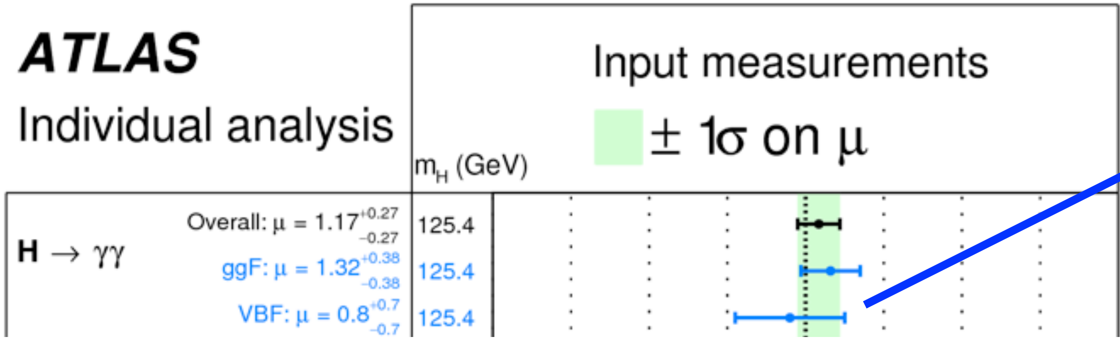
Assumes SM value of decay BRs

Assumes SM value of production σ's

Interpretation beyond signal strengths – **the κ framework**

See "Handbook of LHC Higgs Cross Sections: 3. Higgs Properties" (arXiv:1307.1347) for further details κ framework

- Alternative one can disentangle deviations in production and decay with explicit modeling of Higgs width



$\mu_{VBF}^{\gamma\gamma}$

$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

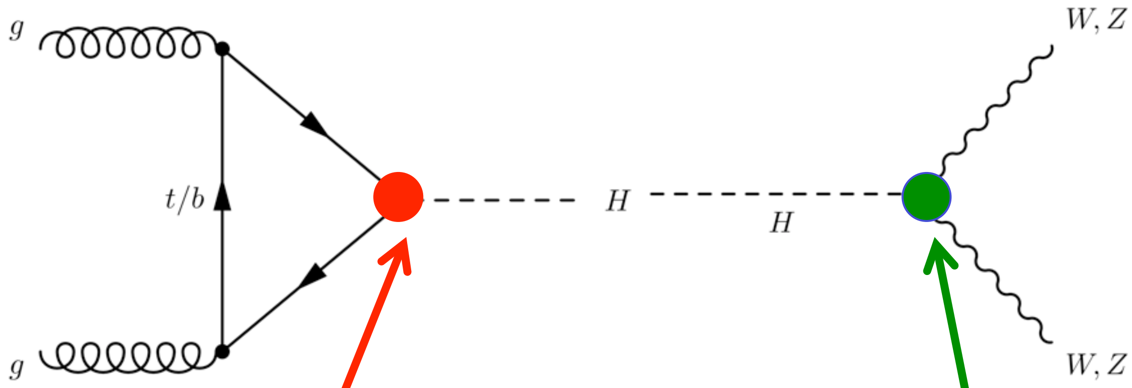
- **Introduce functions κ_j** → describe deviations from SM predictions.

$$\sigma_i = \kappa_i^2(\vec{\kappa}) \cdot \sigma_i^{SM} \qquad\qquad \Gamma^f = \kappa_f^2(\vec{\kappa}) \cdot \Gamma^{f,SM}$$

so that for κ_j=1 → σ_i, Γ_f, Γ_H give SM prediction

Interpretation beyond signal strengths – the κ framework

- Parameters κ_j correspond to LO degrees of freedom
- Example for ggF production of H→VV



$\sigma_{ggF} = (1.06\,\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_b\kappa_t)\,\sigma_{ggF}(SM)$ $\Gamma_{W,Z} = \kappa^2_{W,Z}\,\Gamma_{W,Z}(SM)$

$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

NB: σ_{ggF}(SM) from NNLO(QCD) + NLO(EW) calculation!

The κ framework – the total width

- Note that total *H* width scales all observed cross-sections

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

- Since Γ_H is not yet directly measured with a meaningful precision, must make an assumption on Γ_H to interpret cross-sections in terms of Higgs couplings.
- E.g. in absence of BSM *H* decays (invisible, undetected etc…), can assume SM width, adjusted by effect of k-rescaled couplings

$$\Gamma_H(\vec{\kappa}) = \kappa_H^2(\vec{\kappa}) \cdot \Gamma_H^{\mathrm{SM}}$$

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

The kappa framework – the dictionary

Factors depend on
- *Assumed value m_H,*
- *Calculations of σ,Γ*
- *Kinematic selections*

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	✓	–	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

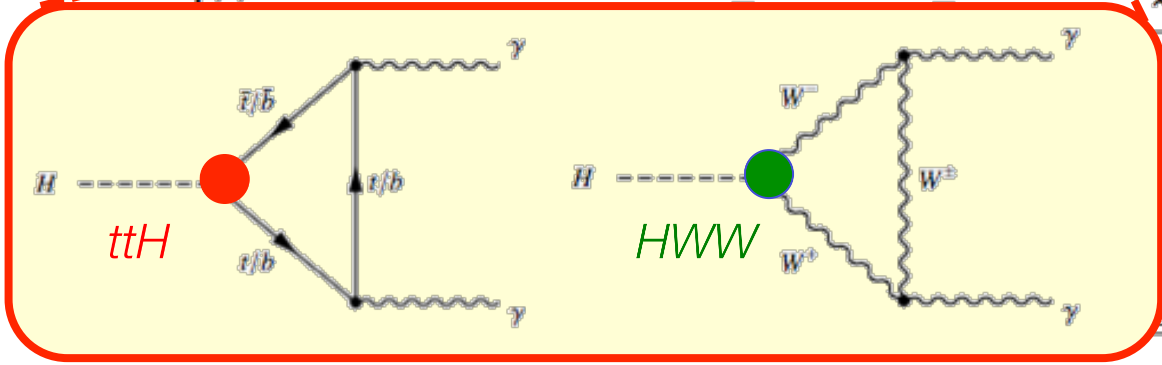
The kappa framework – the dic

Production	Loops	Interference	M		
$\sigma(ggF)$	✓	$b-t$	κ		
$\sigma(VBF)$	–	–			
$\sigma(WH)$	–	–			
$\sigma(qq/qg \to ZH)$	–	–			
$\sigma(gg \to ZH)$	✓	$Z-t$			
$\sigma(ttH)$	–	–			
$\sigma(gb \to WtH)$	–	$W-t$			
$\sigma(qb \to tHq)$	–	$W-t$			
$\sigma(bbH)$	–	–			
Partial decay width					
Γ^{ZZ}	–	–			
Γ^{WW}	–	–		$\sim$	κ_W^2
$\Gamma^{\gamma\gamma}$	✓	$W-t$	κ_γ^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
				$\sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Processes with **interference** allow (in principle) to measure the relative sign of coupling strengths

Since all interferences considered always involve the top quark, **choose sign of top coupling positive** by construction (no loss of generality)

→ can allow data to constrain sign of b,W,Z coupling w.r.t top quark coupling



Outline of this presentation

① Introduction

② Higgs boson phenomenology & interpretation framework

③ Combination procedure & experimental inputs

④ Signal strength measurements

⑤ Constraints on Higgs boson couplings

⑥ Most generic parametrizations

Signal strength measurements by ATLAS and CMS

Each experiment has O(15) signal strength measurements focusing on a wide variety of production and decay models

Measurements of μ_i^f entering combined analysis

Dominated by ggF *Includes gg→ZH* *Includes tH*

Decay / Production	Untagged	VBF	VH	ttH
H→γγ				
H→ZZ→4l				
H→WW→2l2ν				
H→ττ				
H→bb				
H→μμ				
H→invisible				

Difficult due to large backgrounds

CMS measurement exists, but not in time for combination

Extremely small cross-section

CMS and ATLAS also performed **off-shell measurements**
in WW/ZZ that allow to constrain Higgs width with assumptions

Not included in this combination
(was included in ATLAS combination)

ents by AT

ngth measure
models

CMS and ATLAS also performed searches for H→invisible
in VH, VBF production modes

Not included in this combination
(included in CMS combination,
and separate combination by ATLAS)

ninated
by ggF

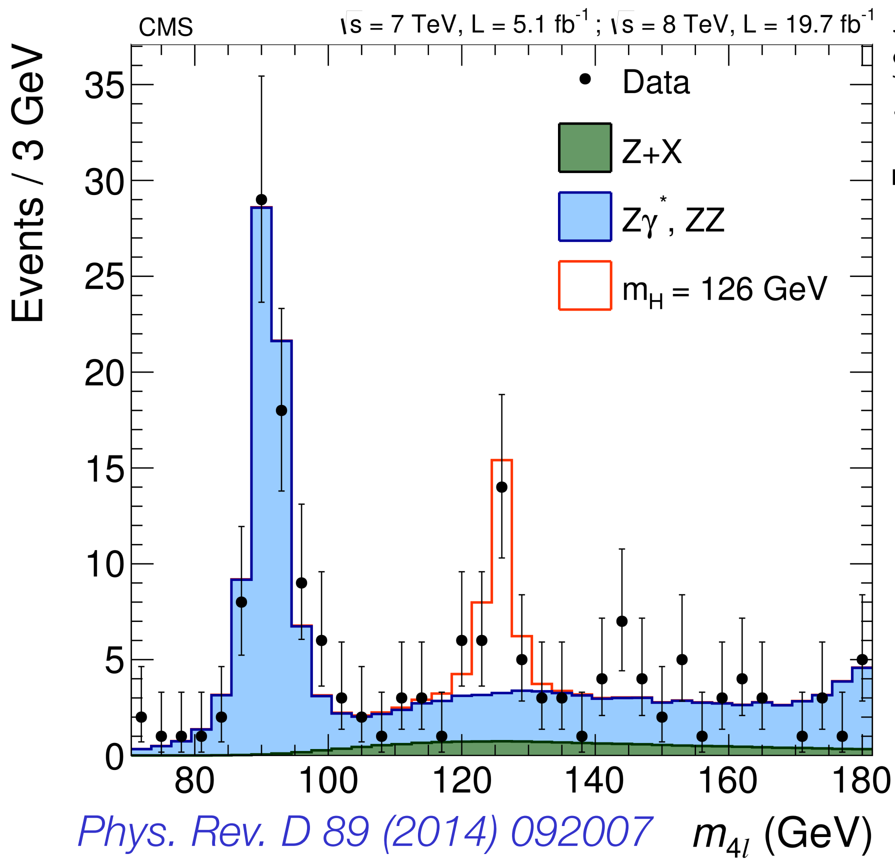
combined analysis

Decay / Production	Untagged	VBF	VH	ttH
H→γγ				
H→ZZ→4l				
H→WW→2l2ν				
H→ττ				
H→bb				
H→μμ				
H→invisible				

Anatomy of a single measurement

- Every measurement consists of one or more signal regions, designed to selected target Higgs production/decay
- Distribution of a (multivariate) discriminant is interpreted in terms of sum of signal and background contributions

"Low bkg / high mass resol." (H→ZZ*)



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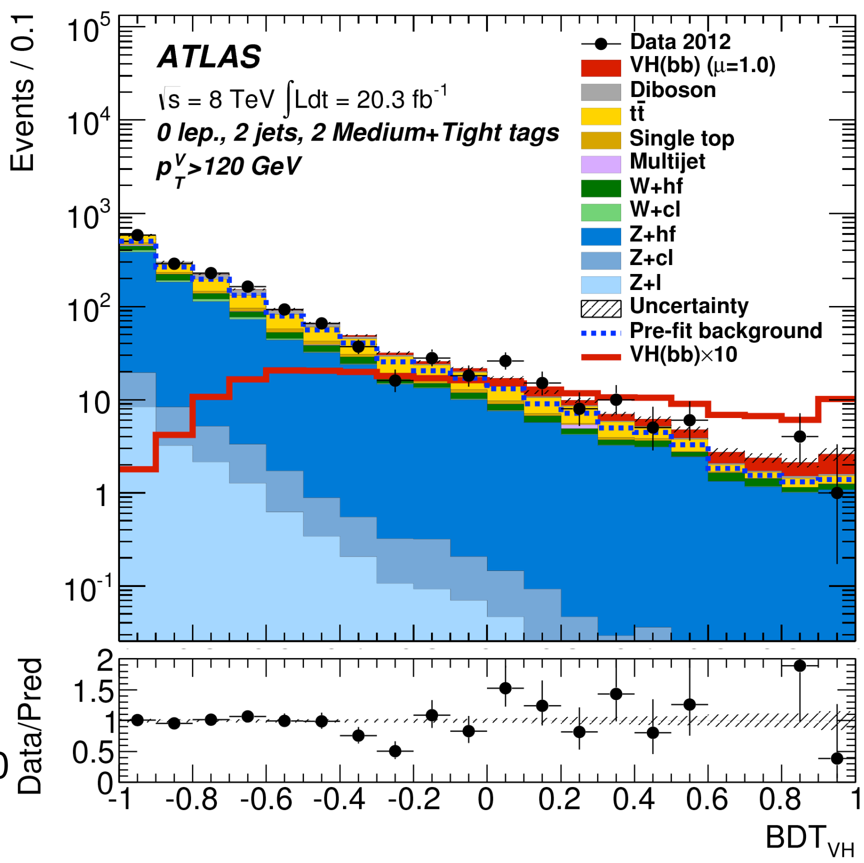
"High bkg / worse resol." (WH→bb)



JHEP01(2015)069

Profile likelihood formalism for (systematic) uncertainties

- Build likelihood function for *each* signal, control region of the data

i→H→f *Background*

$$L(\vec{N} \mid \vec{\mu}_i, \vec{\mu}_f, \vec{\theta}) = \prod_{k=0,nbins} Poisson\left(N_k \mid \sum_{i,f} \mu_i \cdot \mu^f \cdot \boxed{S^f_{i,k}(\vec{\theta})} + \boxed{\sum_m B_m(\vec{\theta})} \right)$$

Inclusive SM cross-section

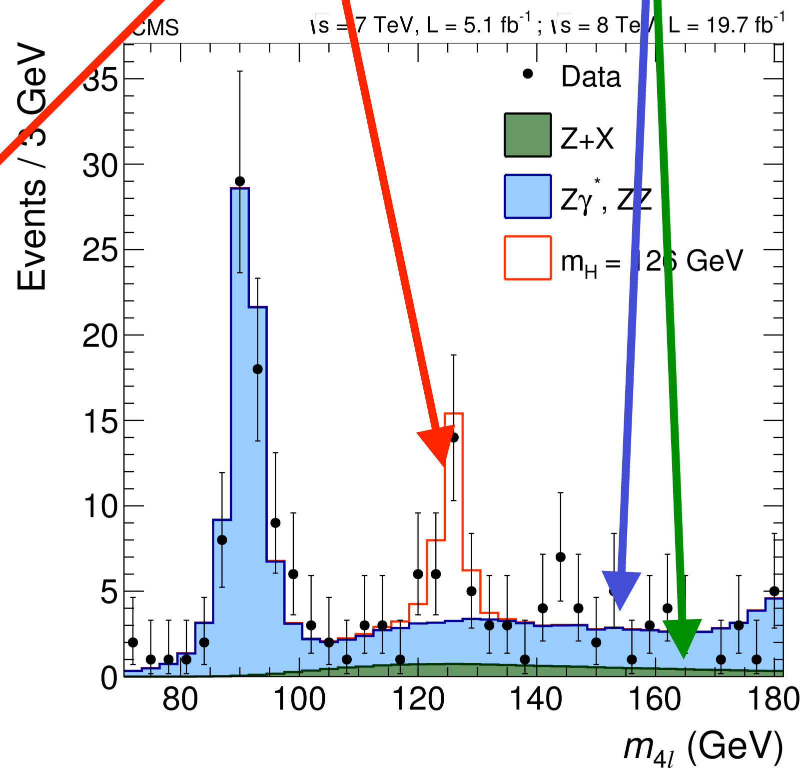
Acceptance (from MC)

Efficiency (from MC)

Higgs BR

Luminosity

$$\mathcal{L}(k) \times \left\{ \sigma_i^{\mathrm{SM}} \times A_i^f(k) \times \varepsilon_i^f(k) \times \mathrm{BR}^f_{\mathrm{SM}} \right\}$$



Profile lik

- Build lik

$L(\vec{N} \mid \vec{\mu}$

Assume SM Higgs boson for acceptance & efficiency

Production process	Event generator	
	ATLAS	CMS
ggF *	Powheg [30–34]	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

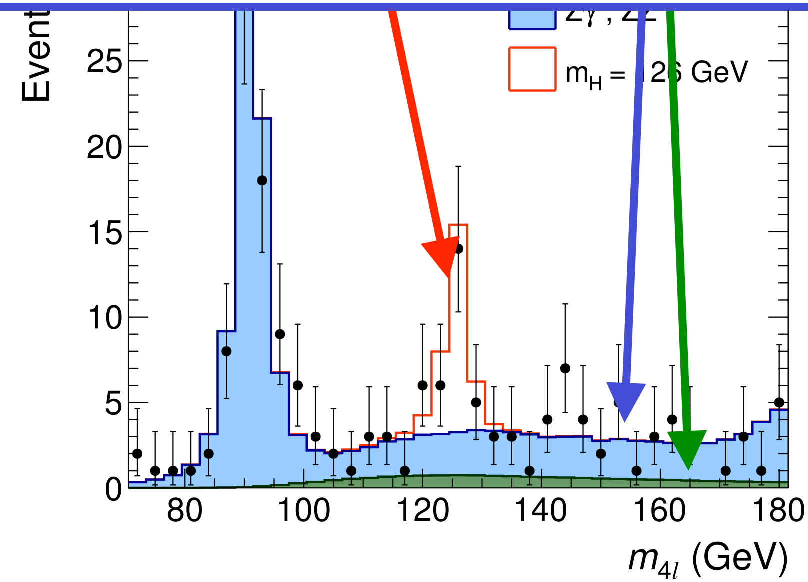
(*) Higgs p_T distribution of ggF production reweighted to match HiRes 2.1calculation (includes NNLO and NNLL QCD corrections)

Inclus

Luminosity

Higgs BR

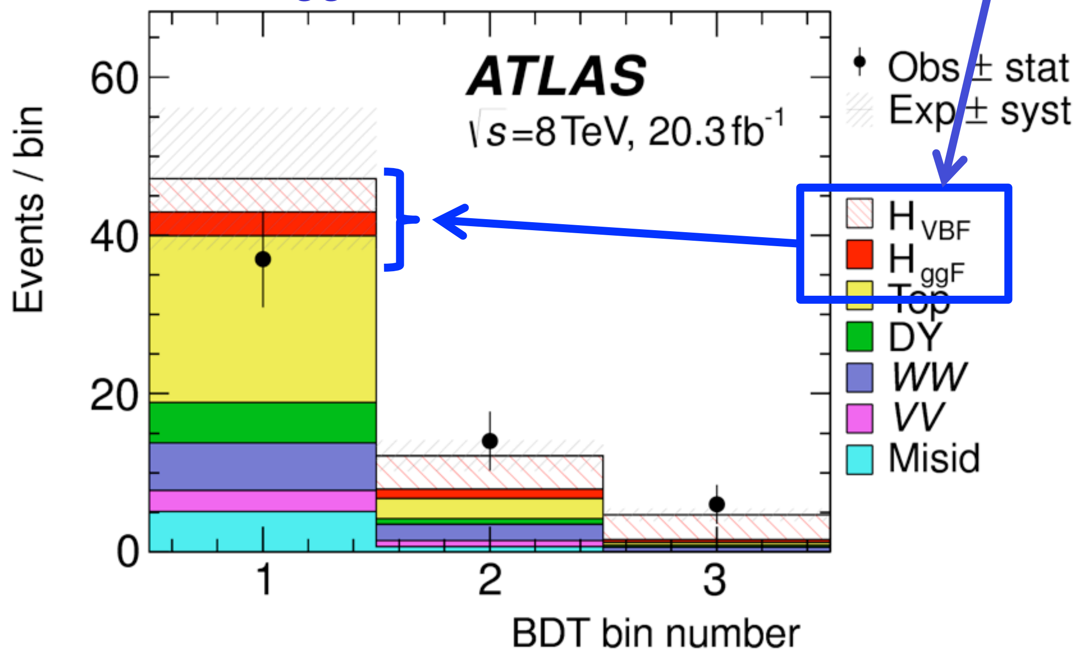
$$\mathcal{L}(k)\times\left\{\sigma_i^{\mathrm{SM}}\times\boxed{A_i^f(k)\times\varepsilon_i^f(k)}\times \mathrm{BR}_{\mathrm{SM}}^f\right\}$$



Decomposition of Higgs signal contributions in channels

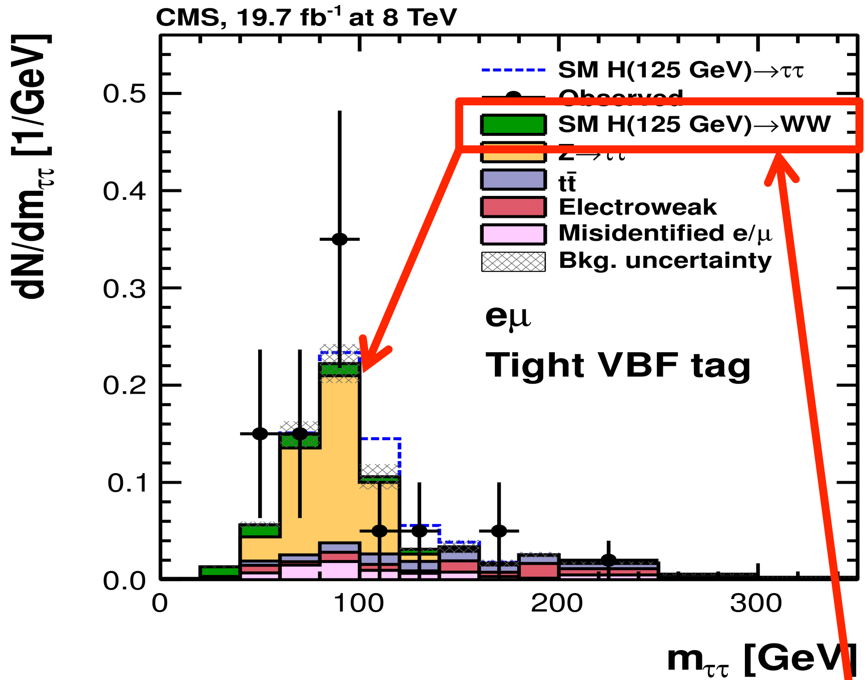
- Channels selections hardly ever 100% pure in production process (especially ‘untagged’) → separately model distributions from all contributing Higgs production processes

“Untagged” H→WW channel



Phys. Rev. D 92, 012006 (2015)

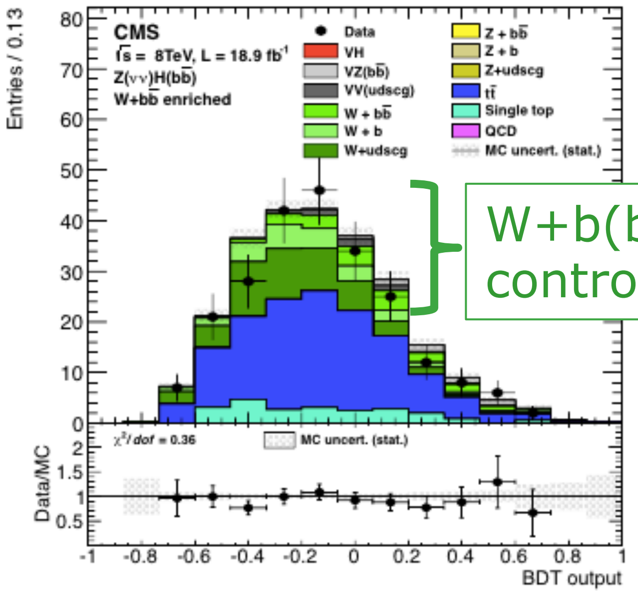
H→ττ channel



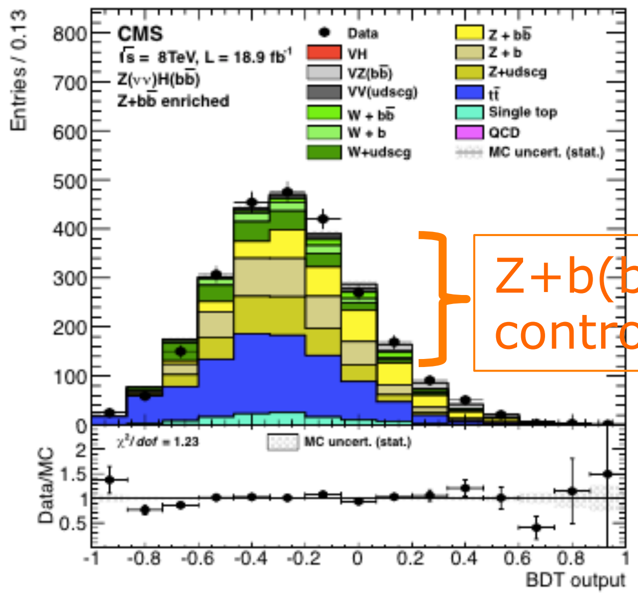
J. High Energy Phys. 05 (2014)

- Some channels also not 100% pure in decay mode (e.g. H→WW selection has contributions of H→ττ decays). Interpret such contributions as Higgs signal (of appropriate type) in coupling analysis

Measurements of backgrounds often data-driven using control regions

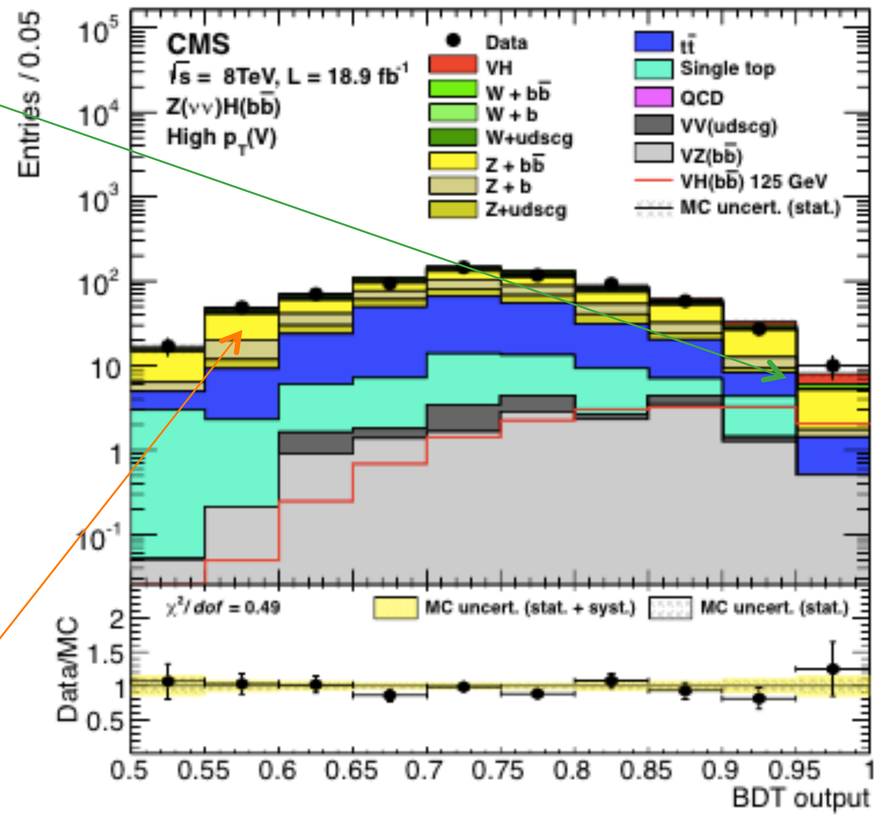


W+b(b) enriched control region



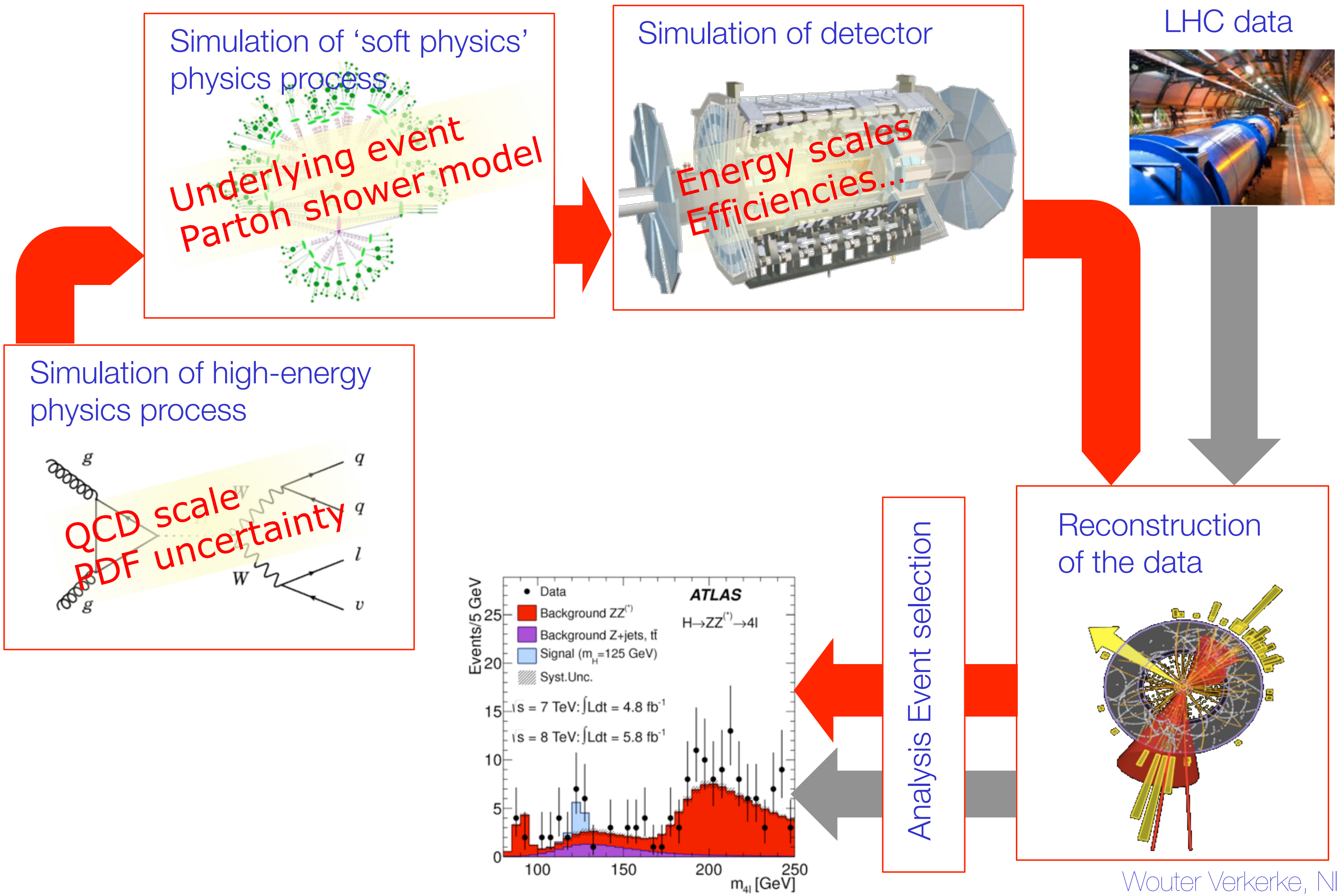
Z+b(b) enriched control region

PRD 89 (2014) 012003



Most expected distributions subject to ***systematic uncertainties***

- Expected distributions mostly derived from simulation chain



Profile likelihood formalism for (systematic) uncertainties

- **Extend description of each signal/background distribution** so that it can *describe distribution under a wide range of parameters* for which the true values are unknown (energy scales, QCD scales…)

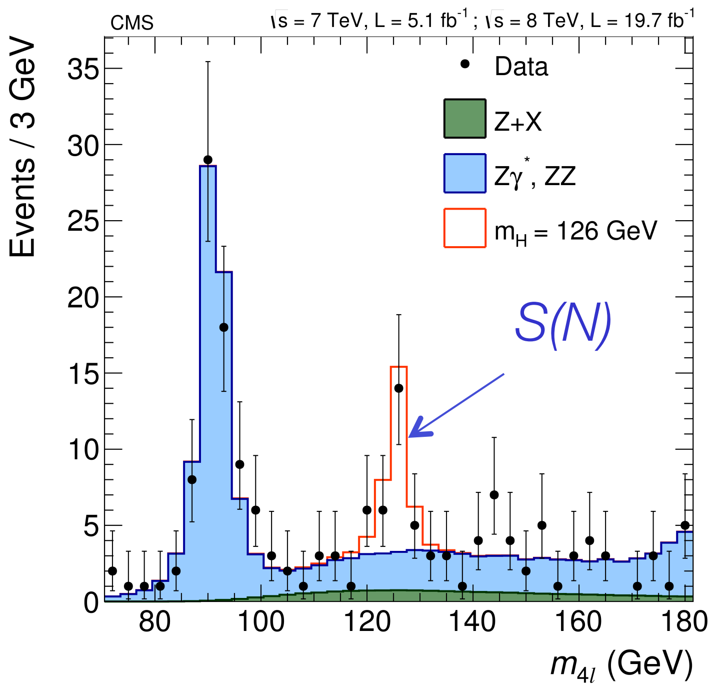
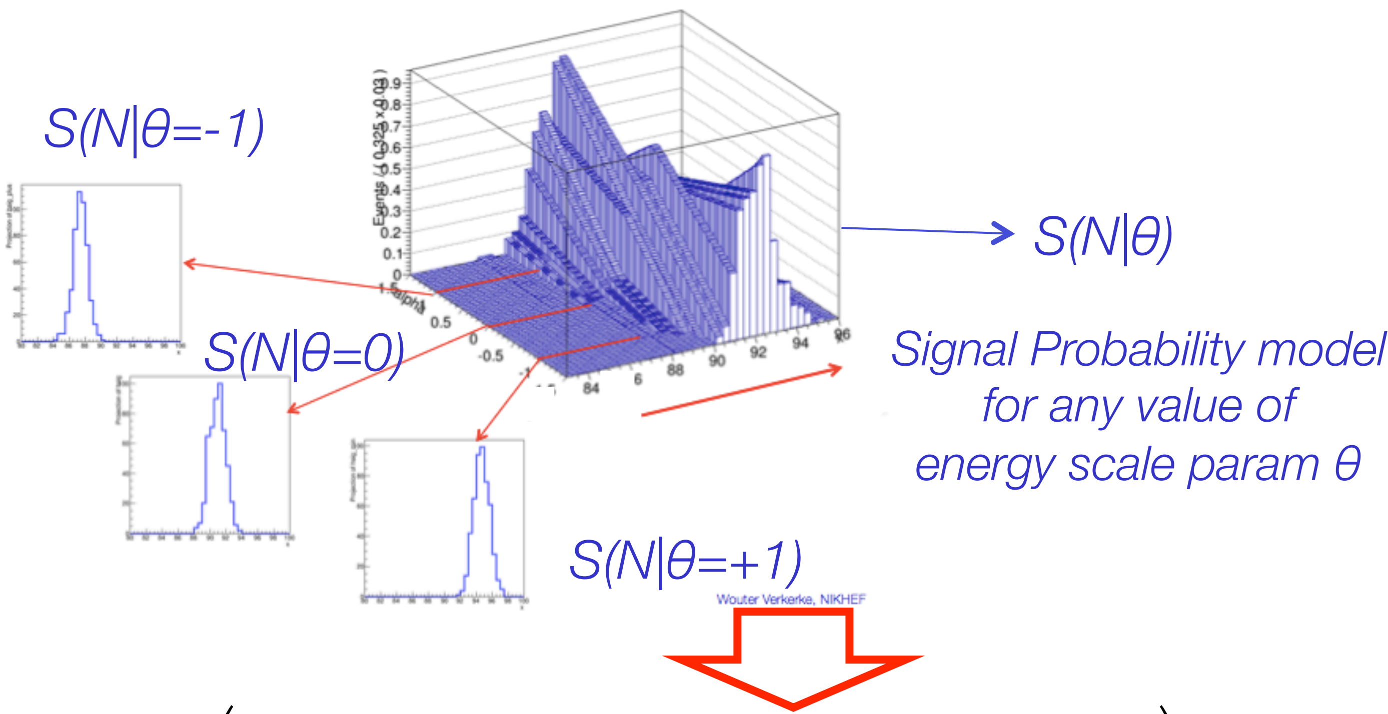


Illustration: modeling of energy scale uncertainty

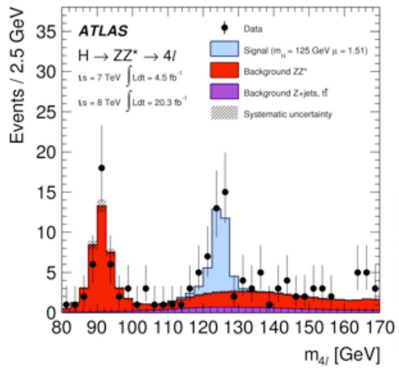


$$L(\vec{N} \mid \vec{\mu}_i, \vec{\mu}_f, \vec{\theta}) = \prod_{k=0,nbins} Poisson\left(N_k \mid \sum_{i,f} \mu_i \cdot \mu^f \cdot S^f_{i,k}(\vec{\theta}) + \sum_m B_m(\vec{\theta}) \right)$$

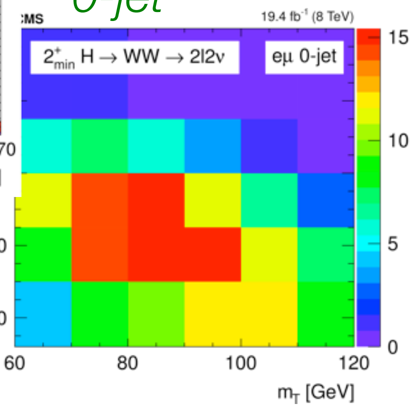
Profile likelihood formalism for (systematic) uncertainties

- Correlated parameters as needed between channels, experiments

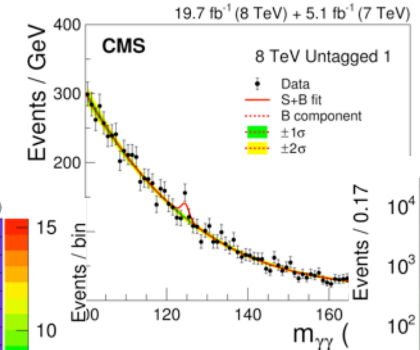
ATLAS ZZ



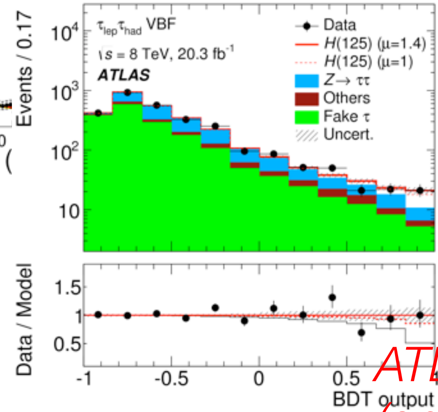
CMS WW 0-jet



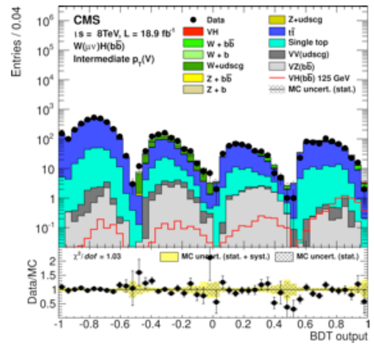
CMS γγ untagged



ATLAS ττ VBF μ-τ$_{had}$



CMS bb



ATLAS detector systematic (only correlated between ATLAS measurements)

$L_{ATLAS,ZZ}(N|\mu,\boldsymbol{\theta}_{\mathbf{QCDscale}},\boldsymbol{\theta}_{\mathbf{ATLASDet}},\theta,\theta,\theta,\ldots)$

$L_{ATLAS,\tau\tau}(N|\mu,\boldsymbol{\theta}_{\mathbf{QCDscale}},\boldsymbol{\theta}_{\mathbf{ATLASDet}},\theta,\theta,\theta,\ldots)$

Fully correlated theory uncertainty

$L_{CMS,WW}(N|\mu,\boldsymbol{\theta}_{\mathbf{QCDscale}},\boldsymbol{\theta}_{\mathbf{CMSDet}},\theta,\theta,\theta,\ldots)$

Correlated uncertainties in ATLAS/CMS combination

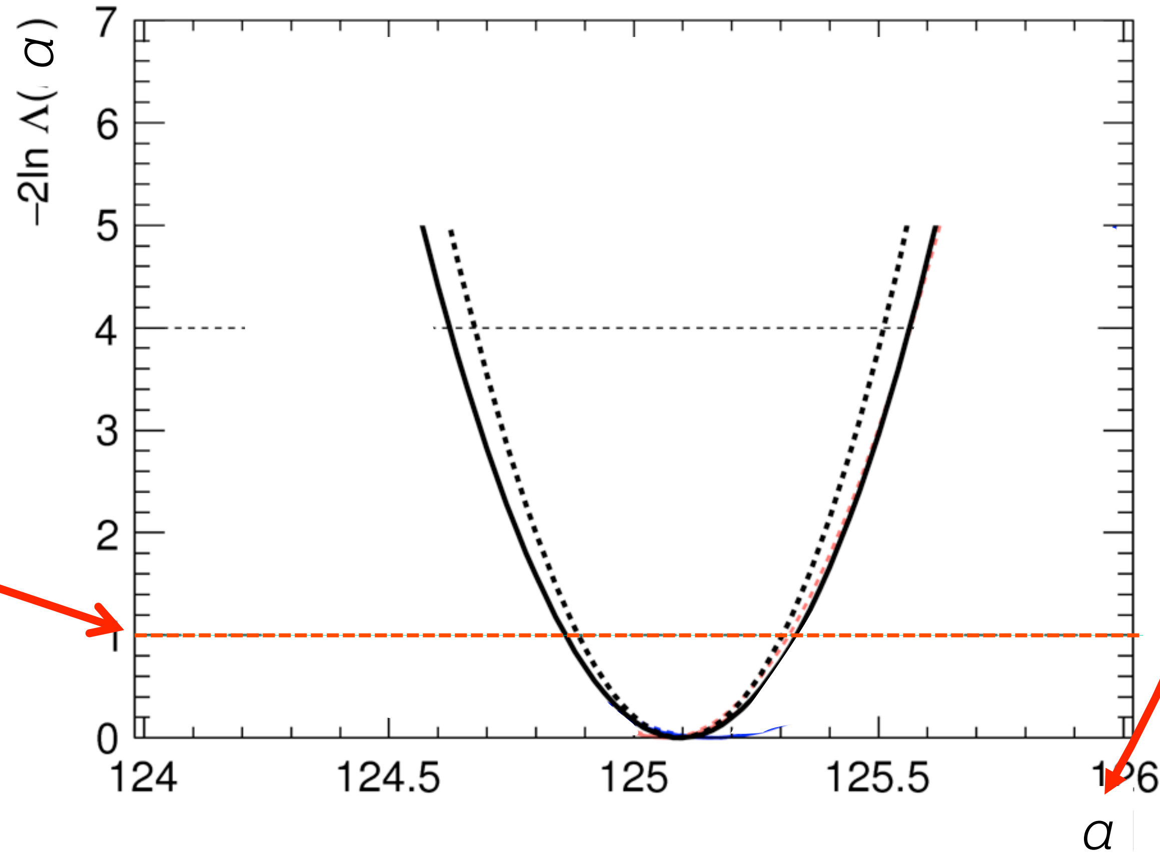
- Full combination describes ~580 signal regions & control regions from both experiments. Grand total of ~4200 nuisance parameters, related to (systematic) uncertainties
- Correlation strategy of nuisance parameters a delicate and complicated task
  - **Detector systematic uncertainties** → follow strategy of ATLAS and CMS internal combinations (**generally correlated within, not between experiments)**
  - **Signal theory uncertainties** (QCD scales, PDF, UEPS) on **inclusive cross-sections** generally **correlated between experiments.**
  - **Signal theory uncertainties on acceptance and selection efficiency** are **uncorrelated between experiments**, as these are small and estimation procedures are generally different.
  - **PDF uncertainties on signal cross-sections uncorrelated between channels**, except WH/ZH = correlated (effect of ignoring other correlations is ≤1%)
  - **No correlations assumed between Higgs BRs** (except for WW/ZZ). *Effect of ignoring correlations shown to be generally small, except for a few specific measurements, in which case full correlation structure is retained*

Statistical treatment – profile likelihood

Θ: vector of ~4200 nuisance parameters

- From L(ATLAS+CMS) construct the **profile likelihood** for a statement on the parameter(s) of interest α

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



- 68% Confidence interval defined by a rise of 1 unit in Λ(α) (asymptotic limit)

Outline of this presentation

① Introduction

② Higgs boson phenomenology & interpretation framework

③ Combination procedure & experimental inputs

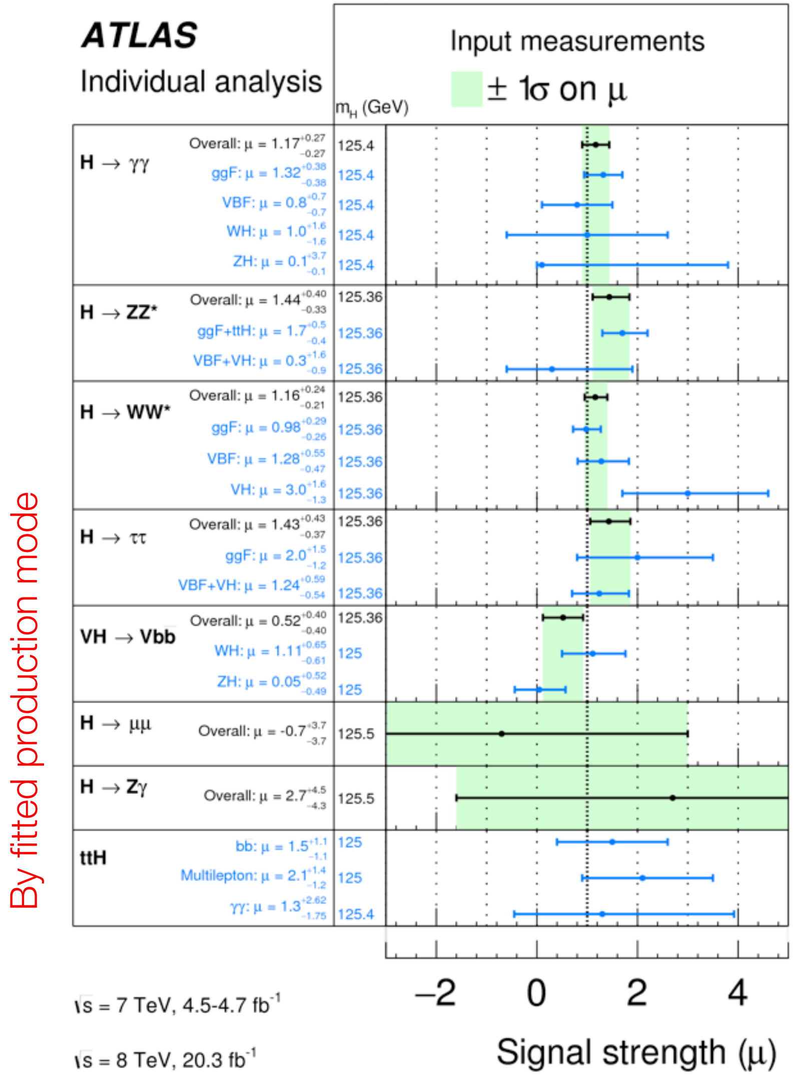
④ **Signal strength measurements**

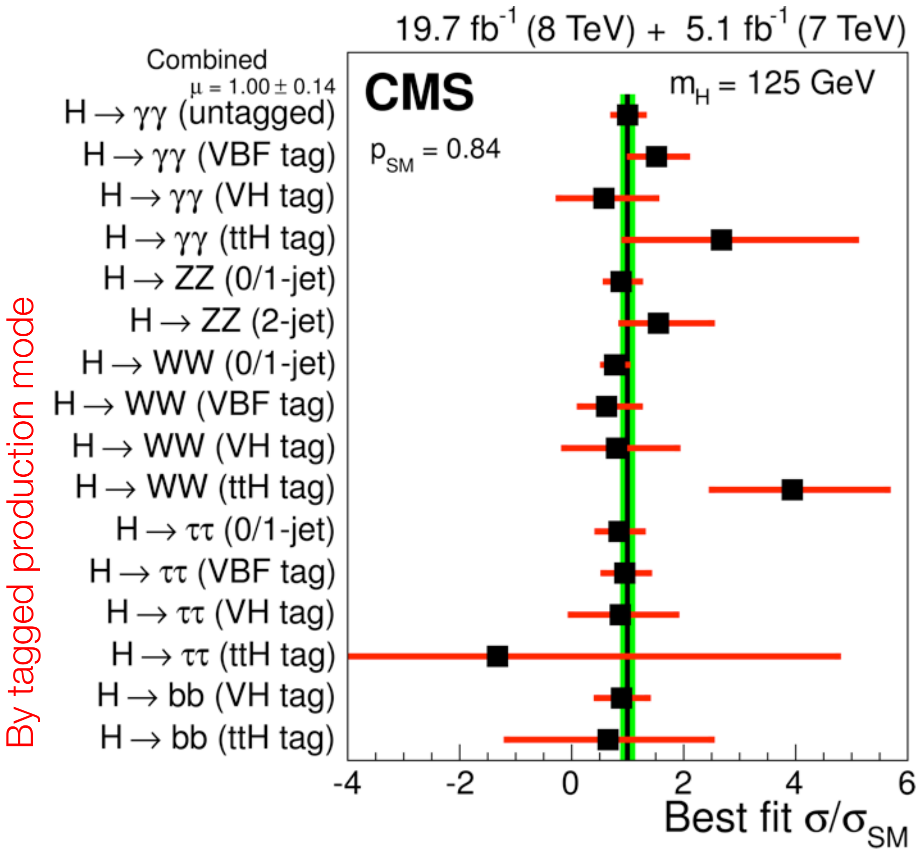
⑤ Constraints on Higgs boson couplings

⑥ Most generic parametrizations

Reminder – the signal strengths in the individual channels

Signal strength fits of individual experiments/channels





The global signal strength

- Assuming SM ratios of production cross-sections and decay rates

$$\mu = 1.09^{+0.11}_{-0.10}$$

Most precise result at the expense of the largest assumptions

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

Stat and Th.Sig of comparable size
(Th.Sig dominated by ggF cross-section uncertainty)

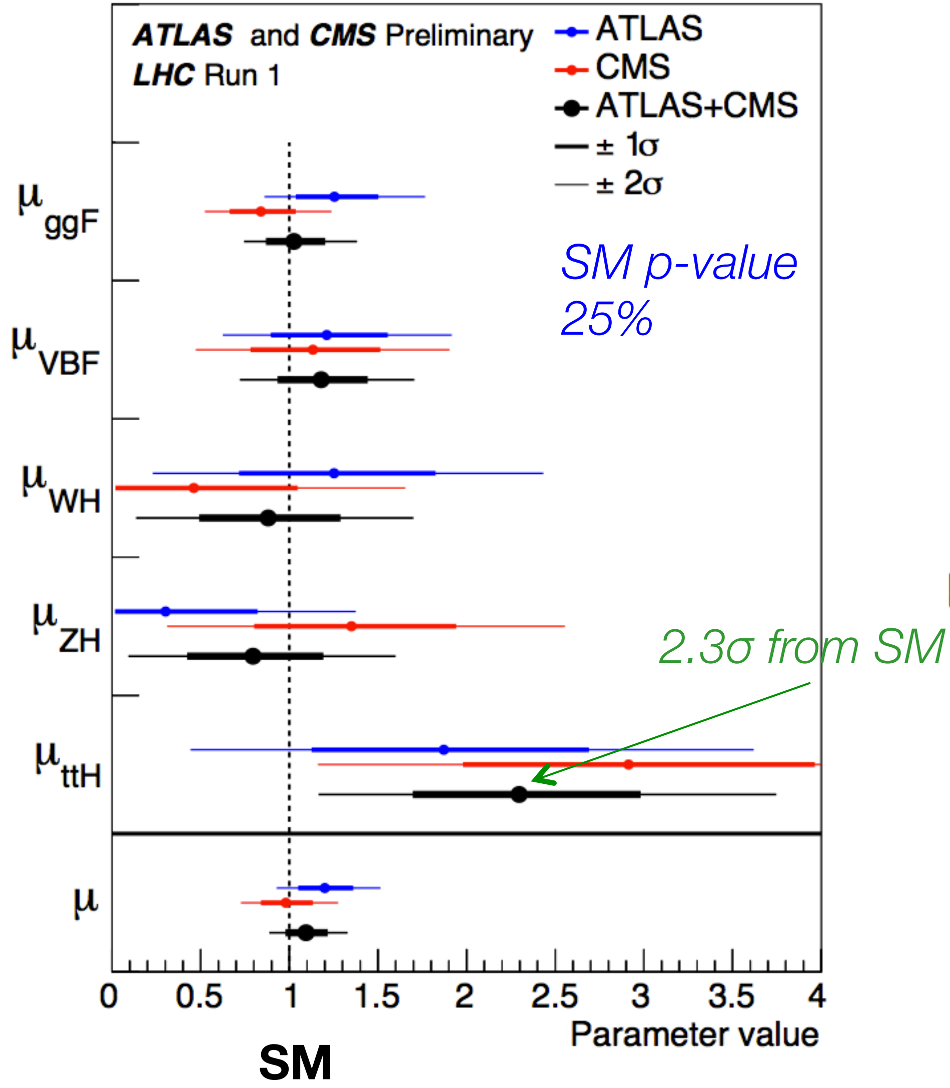
- NB: Theory uncertainties on the inclusive SM cross-section enter through denominator in Higgs signal strength

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

Higgs signal strength by production and decay mode

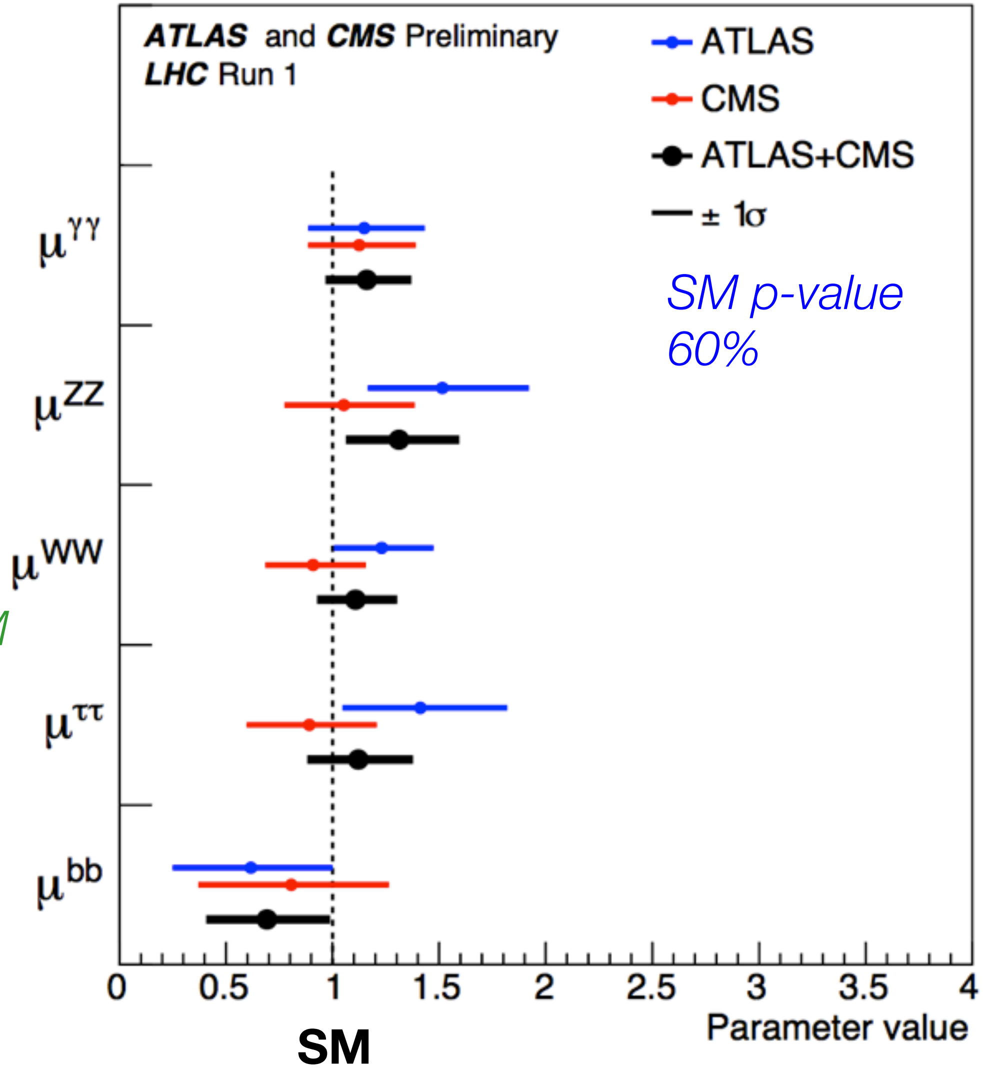
Production signal strengths

(SM values of BRs assumed)



Decay signal strengths

(SM value of production σ's assumed)



Significance of combined observations

- Comparing likelihood of the best-fit with likelihood assuming $\mu_{prod}=0$ or $\mu^{decay}=0$ we obtain:

Production process	Observed 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		
$H\rightarrow\tau\tau$	**5.5**	5.0
$H\rightarrow bb$	2.6	3.7

VBF production and H→ττ now established at over 5 σ.
ggF and H→ZZ,γγ,WW already established by each experiment

Signal strength in V,F-mediated production by decay

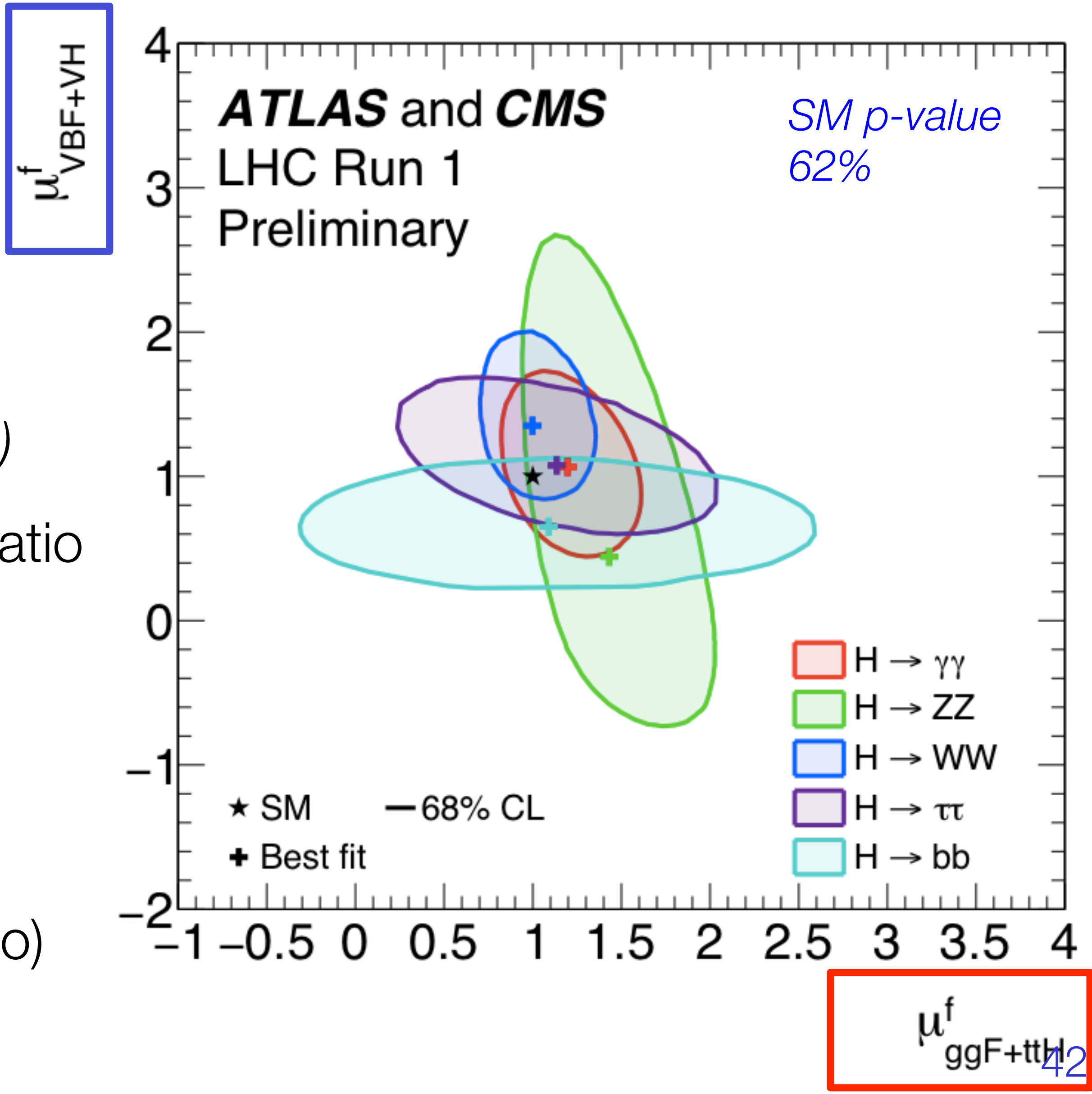
- Measure ggF+ttH production "fermion-mediated" and VBF+VH production "boson-mediated" for each decay mode

  (No assumption on SM production or decay rates needed for individual channels)

- Can also measure combined ratio

  $$\underline{\mu_{VBF+VH}}/\underline{\mu_{ggF+ttH}} = 1.06^{+0.35}_{-0.27}$$

  over all decay modes **without** assumptions on SM decay rates (BRs cancel in ratio)



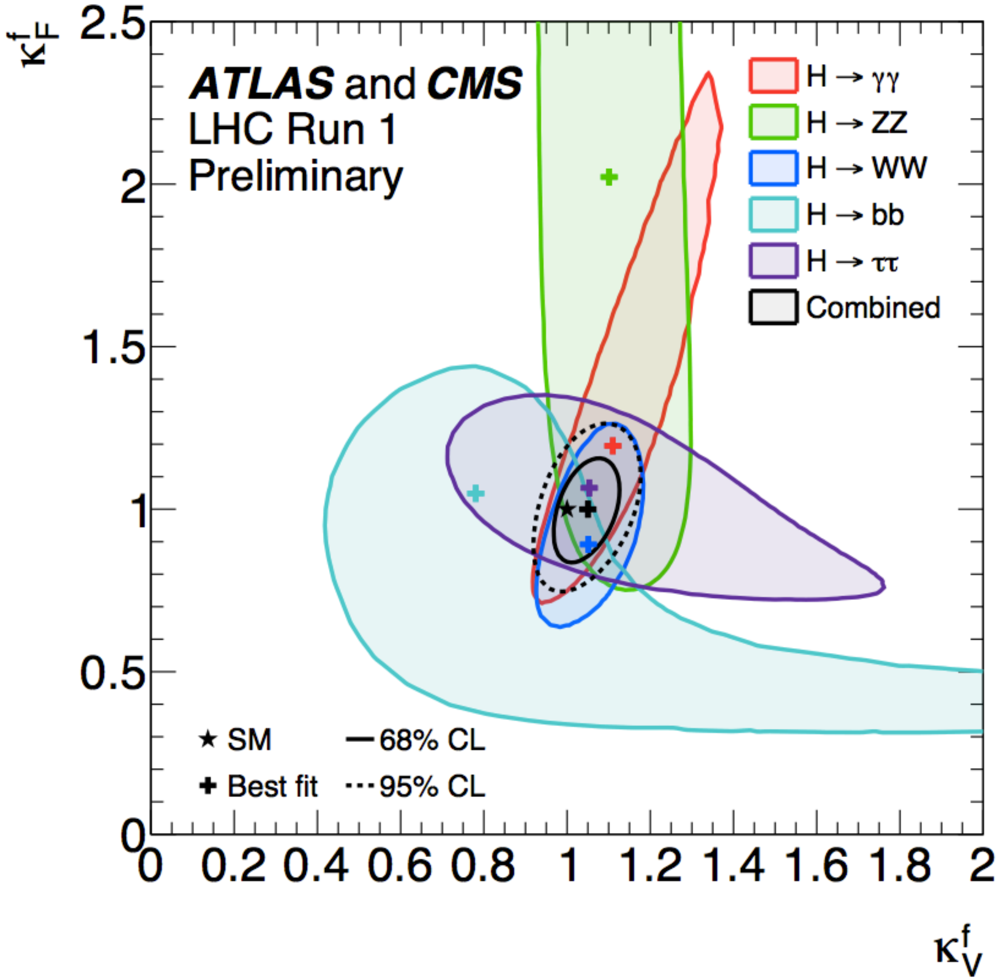
Outline of this presentation

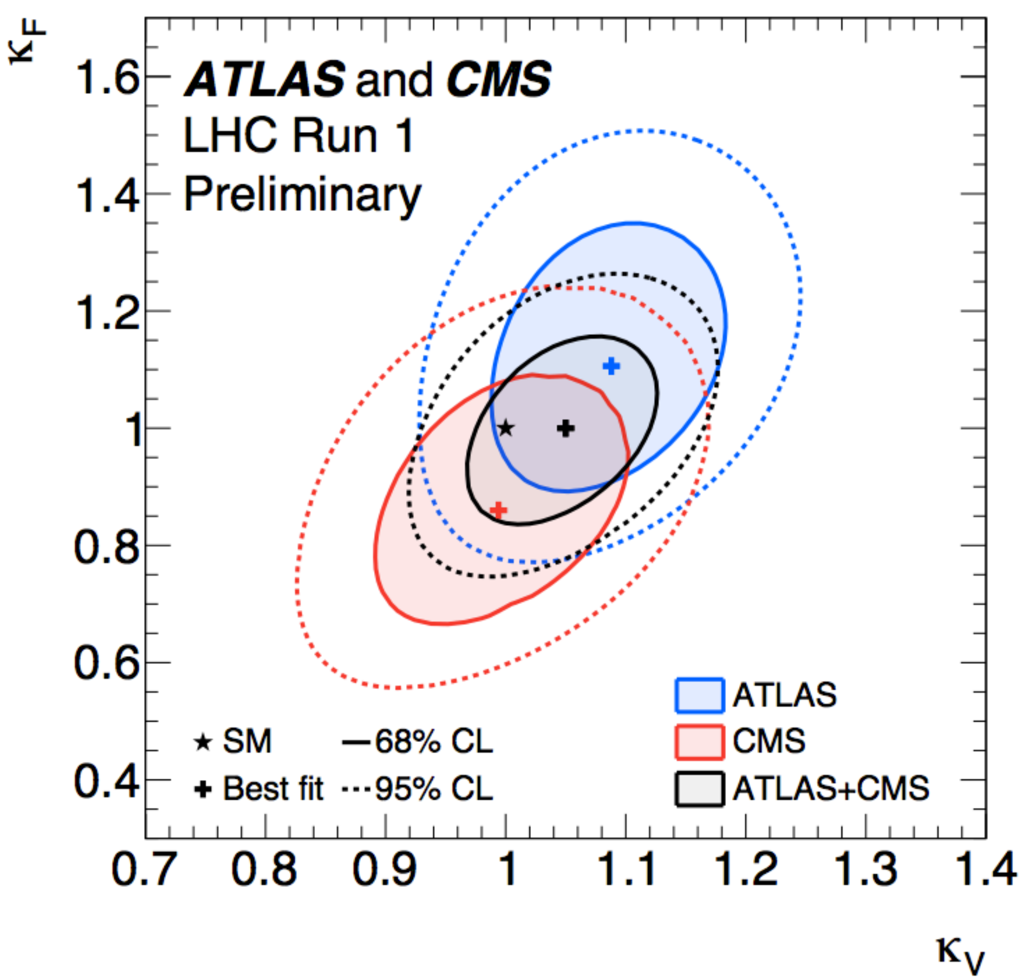
Constraints for Higgs couplings to fermions, bosons

- Assume universal scaling parameters for Higgs couplings to fermions (κ_F), bosons (κ_V)

$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

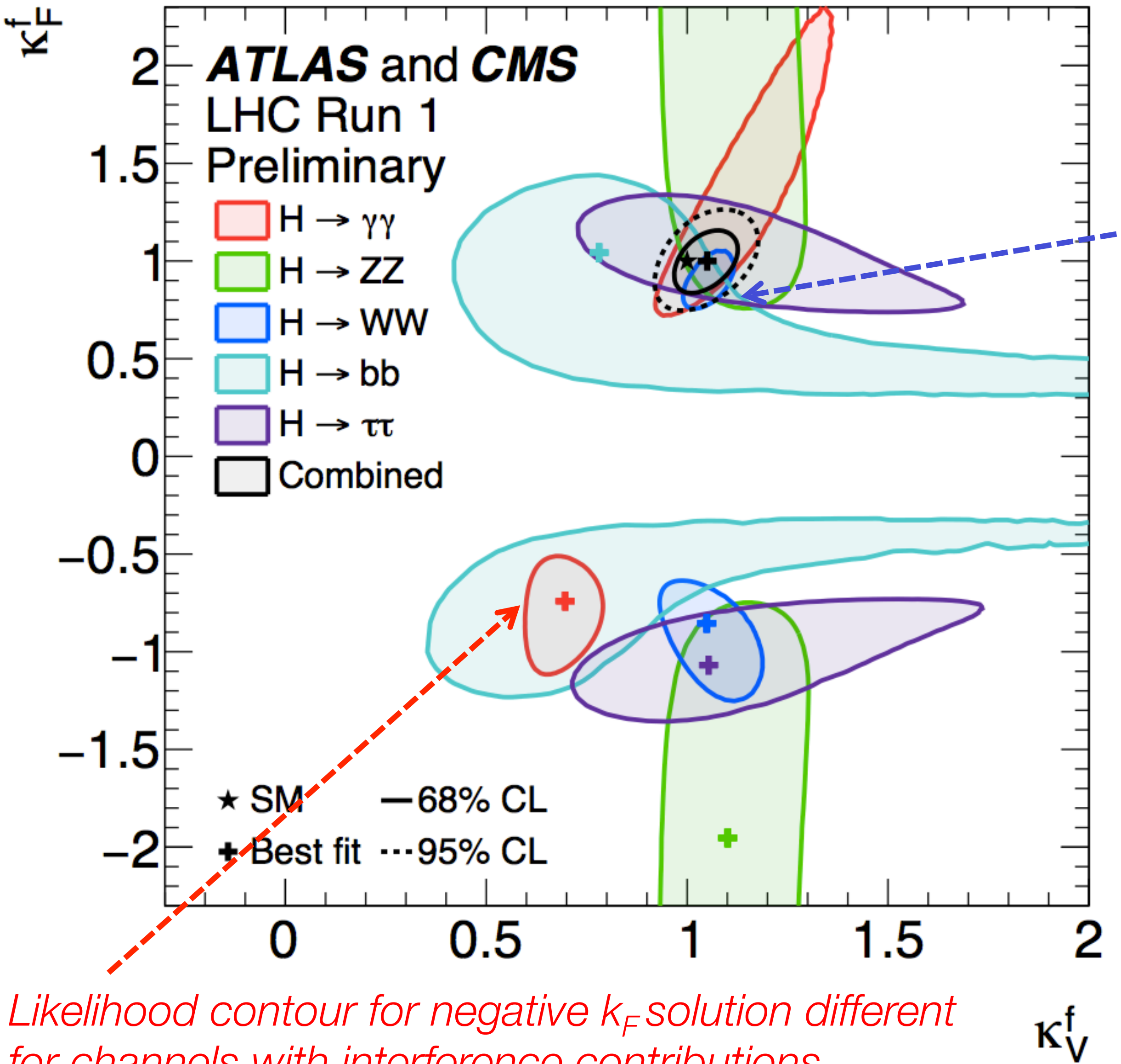
- Assume only SM physics in loops, no invisible Higgs decays, $\kappa_{F,V} \geq 0$



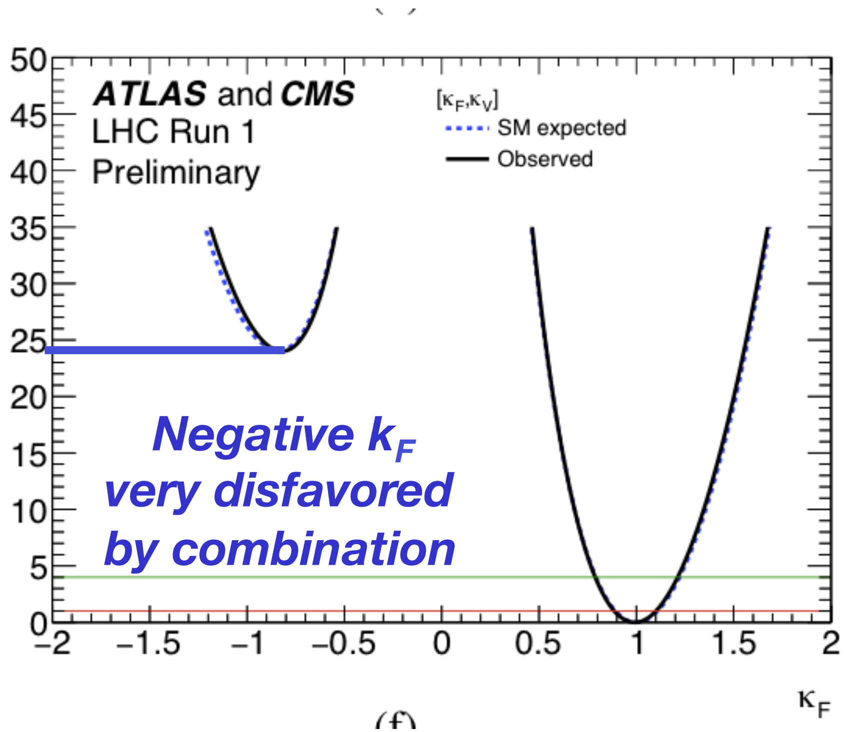


Constraints for Higgs couplings to fermions, bosons

- Expanding parameter ranges to include negative couplings



Positive WW contour reduced due to preferred negative solution



Negative k_F very disfavored by combination

Likelihood contour for negative k_F solution different for channels with interference contributions

Constraints on tree-level Higgs couplings

- Assume only SM physics in loops, no invisible Higgs decays
- Fit for scaling parameters for Higgs couplings to

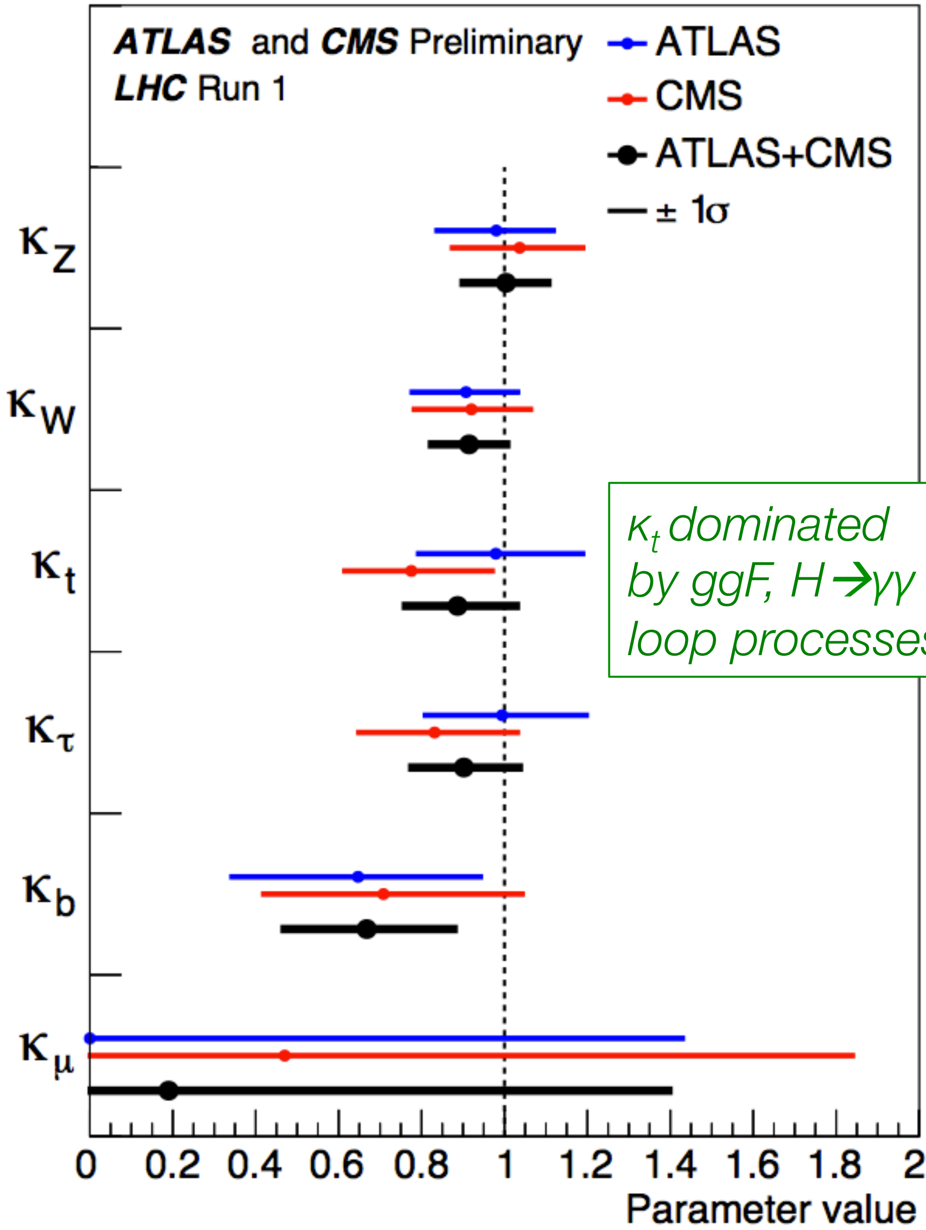
  W, Z, b, t, τ, μ

- *NB: low measured value of κ_b reduces total width Γ_H*

  → all κ_i measured low [w.r.t μ=1.09]

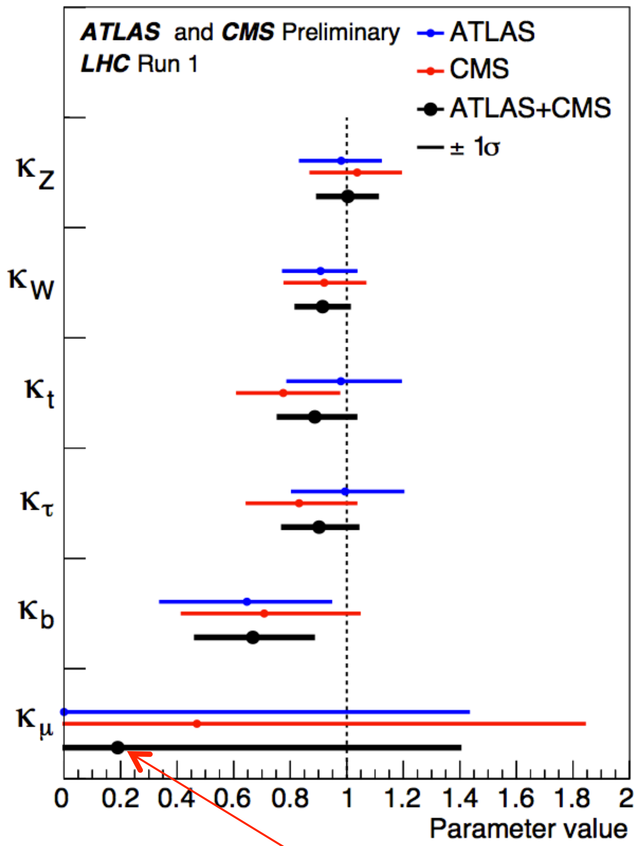
$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

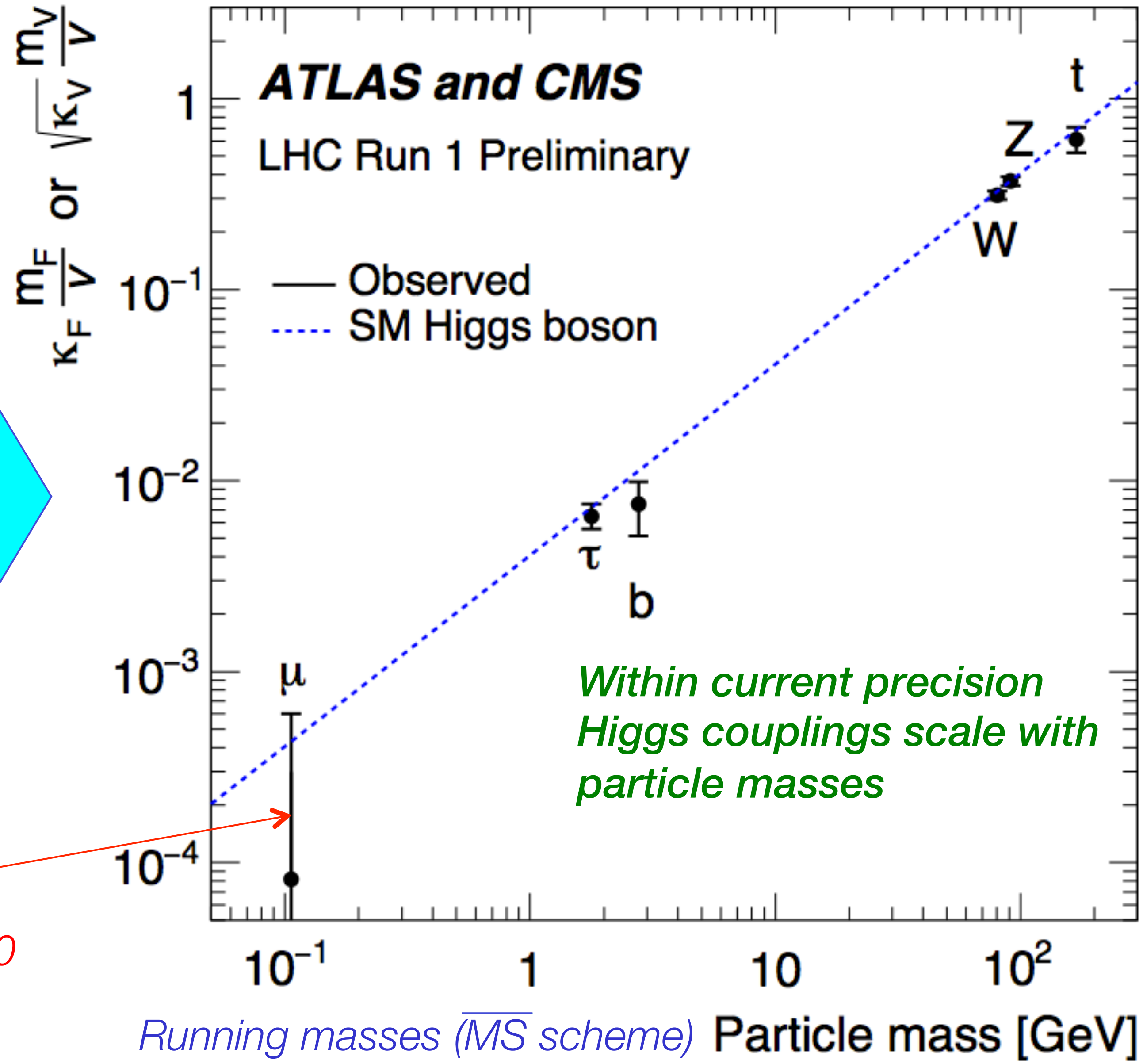
$$\kappa_H^2 \sim \begin{array}{l} \boxed{0.57 \cdot \kappa_b^2} + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + \\ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + \\ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2 \end{array}$$



κ_t *dominated by ggF, H→γγ loop processes*

Constraints on tree-level Higgs couplings





Within current precision Higgs couplings scale with particle masses

Observed κ_μ compatible with 0

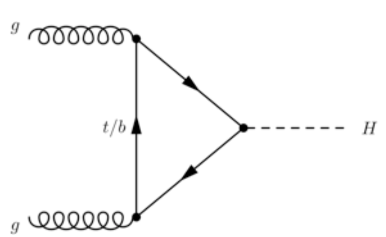
Running masses ($\overline{MS}$ scheme)

Allowing for BSM contributions in Higgs coupling interpretations

- Results shown so far assumed no invisible (BSM) Higgs decays nor BSM contributions to loops. Now drop these assumptions.

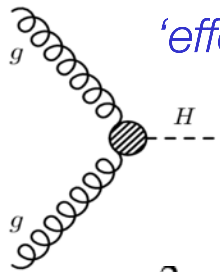
1. Represent loop processes (ggF, H→Z/γγ) with effective params (κ_g,κ_γ), rather than assuming SM content

'SM resolved'



$$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$$

'effective coupling'



$$\kappa_g^2$$

Measurement of κ_t dominated by ttH

2. Allowing BSM Higgs decays (invisible, undetected etc…) to increase the total width

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$$

If BR_{BSM} >0 then all observed cross-sections lowered by common factor

$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

Limit on invisible Higgs decays from Higgs couplings

- Concept: set limit on BR to (invisible, undetected) Higgs decays

$$\Gamma_{\mathrm{H}} = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

- When κ_H is modeled by 6+2 κ_i's it has no strong upper bound
  → $\mathrm{BR}_{\mathrm{BSM}}$ not bounded (Γ_H due to large κ_H or to large BR_{BSM}?)
  → Must introduce some assumptions to bound κ_H
- Scenario 1 – Assume 6 tree-level couplings at SM ($k=1$),
  but leaving 2 effective couplings for loops floating
- Scenario 2 – Keep all 6+2 coupling parameters floating,
  but bound vector boson couplings $\kappa_W,\kappa_Z \leq 1$

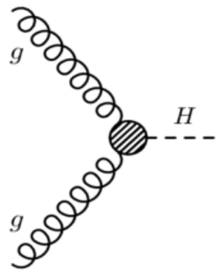
(Bound $k_V \leq 1$ occurs naturally in many BSM physics models, e.g. Electroweak Singlet, 2HDM, MCHM…)

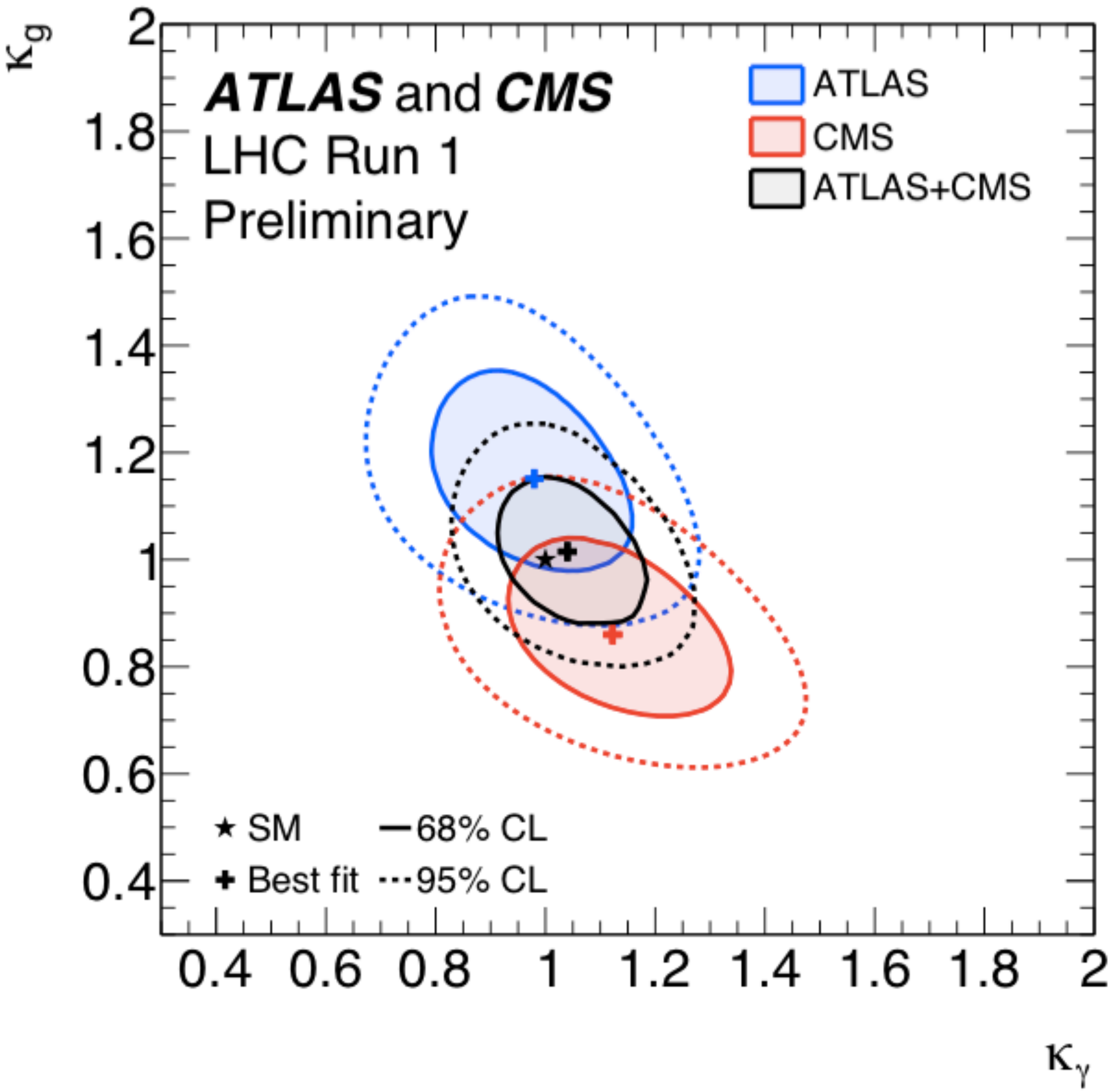
(alternatively, use off-shell coupling strength measurements to constrain Γ_H, albeit with additional assumptions)

Focus on effective couplings for loop processes

'Scenario 1'

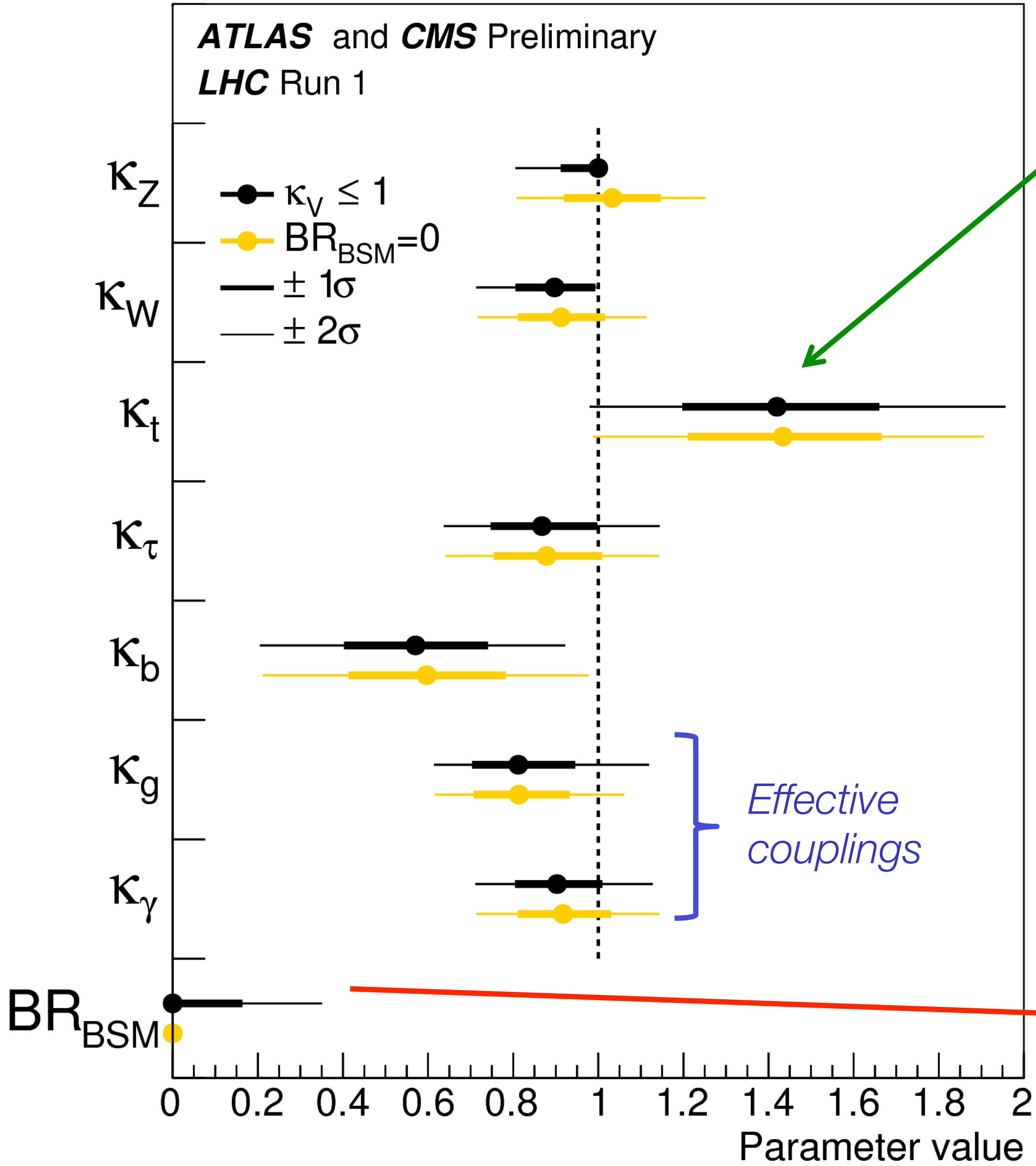
- Fix all tree-level Higgs couplings to SM ($\kappa_W, \kappa_Z, \kappa_b, \kappa_t, \kappa_\mu, \kappa_\tau = 1$) and $BR_{inv} = 0$





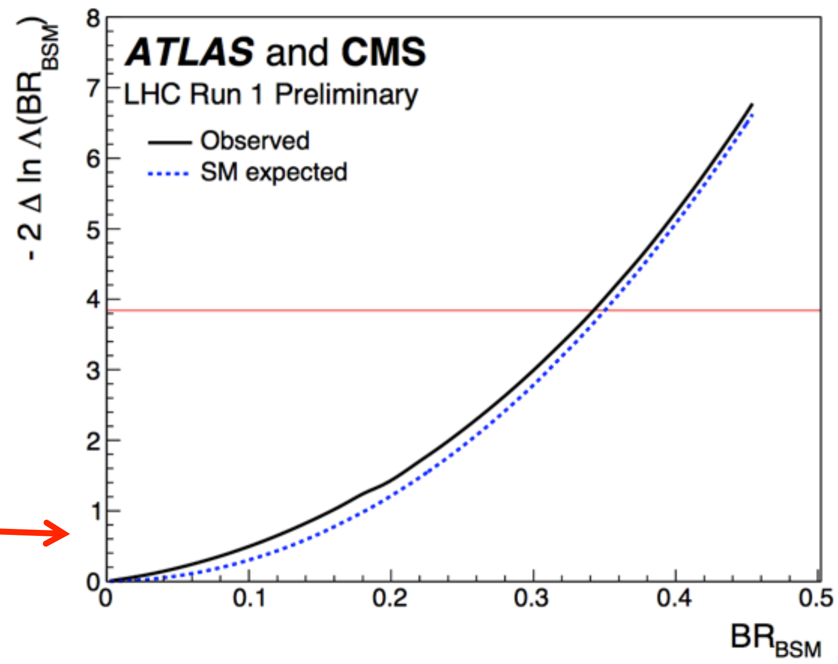
Constraints on Higgs couplings allowing BSM physics in loops & decays

'Scenario 2'



κ_t dominated by ttH process (ggF,Hγγ loops no longer contribute)

BR_{BSM} < 0.34 at 95% C.L. (assuming $\kappa_V \leq 1$)



Focus on up/down-type fermion and lepton/quark asymmetries

- Several BSM physics models (notably 2HDM), predict asymmetries in couplings between up-type and down-type fermion couplings, and between lepton and quark couplings
- Since goal is to measure asymmetry, directly parameterize model in terms of ratios of coupling strength modifiers

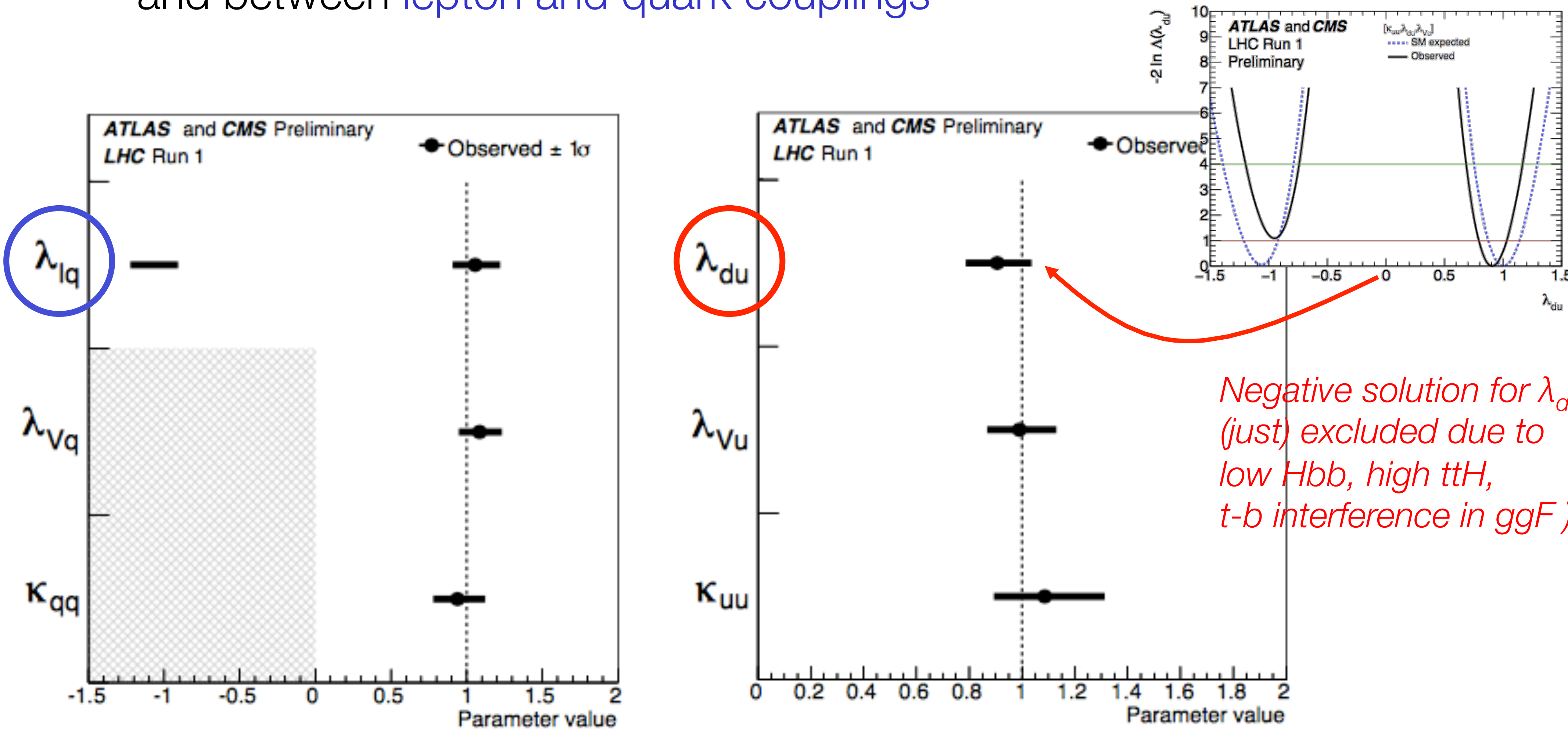
$$\boxed{\lambda_{du} = \kappa_d/\kappa_u}$$
$$\lambda_{Vu} = \kappa_V/\kappa_u$$
$$\kappa_{uu} = \kappa_u \cdot \kappa_u/\kappa_H.$$

$$\boxed{\lambda_{\ell q} = \kappa_\ell/\kappa_q}$$
$$\lambda_{Vq} = \kappa_V/\kappa_q$$
$$\kappa_{qq} = \kappa_q \cdot \kappa_q/\kappa_H.$$

- Assume no BSM physics in loop processes.
  No assumption on invisible decays needed, since no assumption on Γ_H needed (total width cancels in ratio of couplings)

Focus on up/down-type fermion and lepton/quark asymmetries

- Several BSM physics models (notably 2HDM), predict asymmetries in couplings between up-type and down-type fermion couplings, and between lepton and quark couplings



Negative solution for λ_{du} (just) excluded due to low Hbb, high ttH, t-b interference in ggF)

Outline of this presentation

① Introduction

② Higgs boson phenomenology & interpretation framework

③ Combination procedure & experimental inputs

④ Signal strength measurements

⑤ Constraints on Higgs boson couplings

⑥ Most generic parameterizations

Generic parameterizations

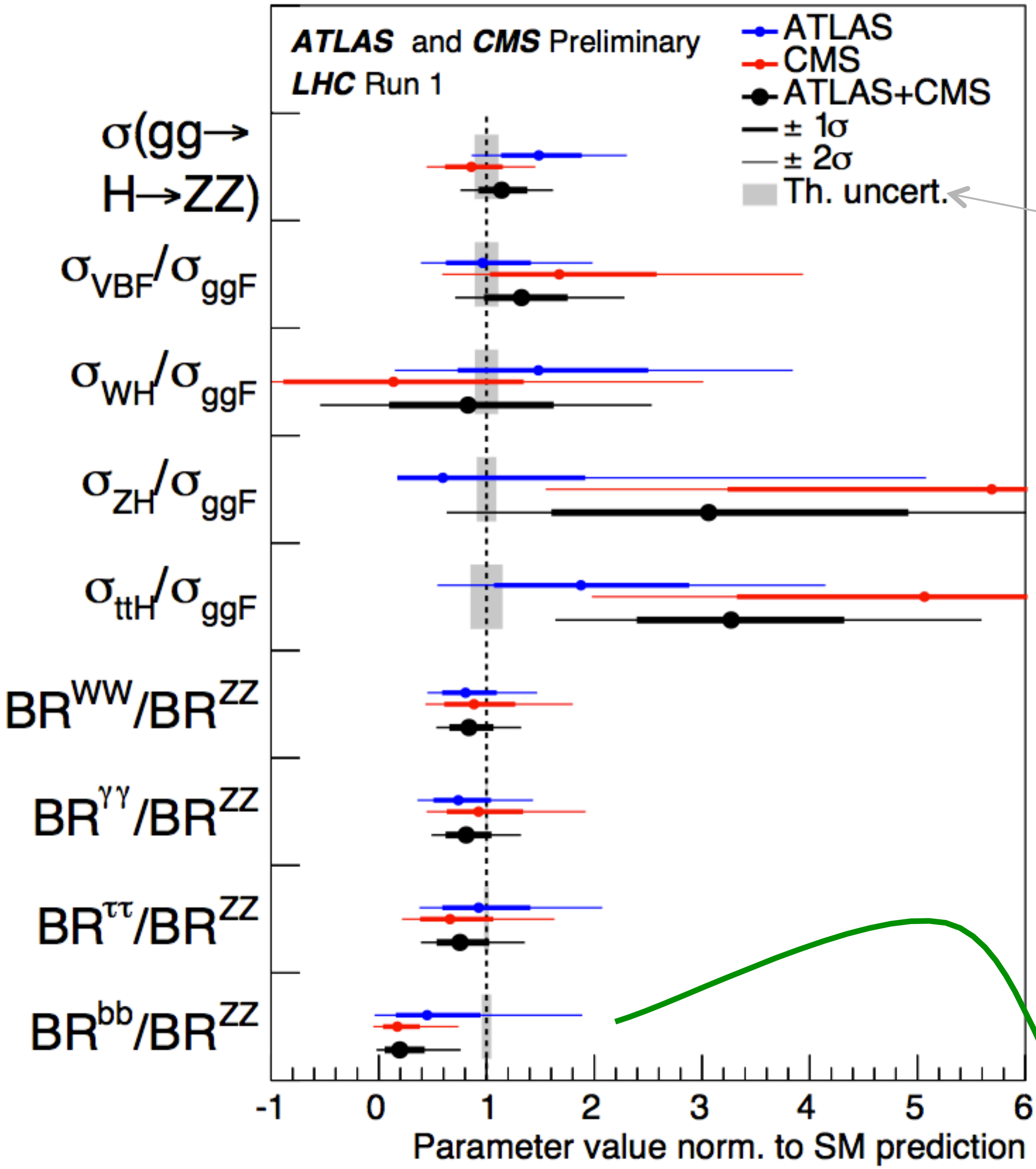
- Goal of (most) generic parameterizations is to provide summary of Higgs coupling constraints while make minimal number of assumptions and with minimal exposure to theory uncertainties
  - **All results shown today can be derived from these generic parametrizations** once correlation matrix is provided
  - Will allow legacy Run-1 Higgs coupling results to be re-evaluated in future, e.g. when new theory calculations are available with reduced uncertainties

- Most generic model is signal strength model with ratios

$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right),$$

  - Choose ggF H→ZZ as reference channel since it is the cleanest channel and has the smallest systematic uncertainty
  - Ratios of cross-sections and BRs reduce exposure to dominant theoretical uncertainties on inclusive cross-sections

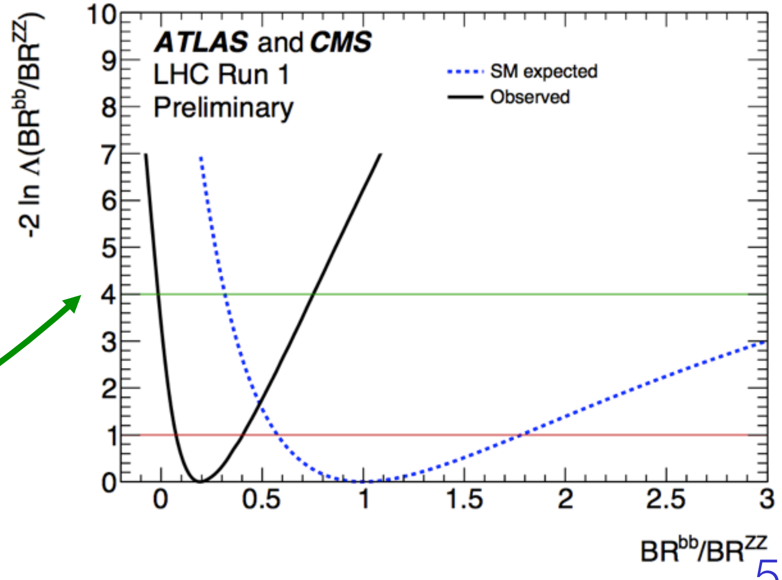
Signal strength models with ratios



Inclusive theory uncertainties shown on SM prediction

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

Driven by combination of high ttH→leptons, ZH→ZZ, low VH→bb (while ttH→bb is not high)



NB: Correlation matrix will be provided for final paper version

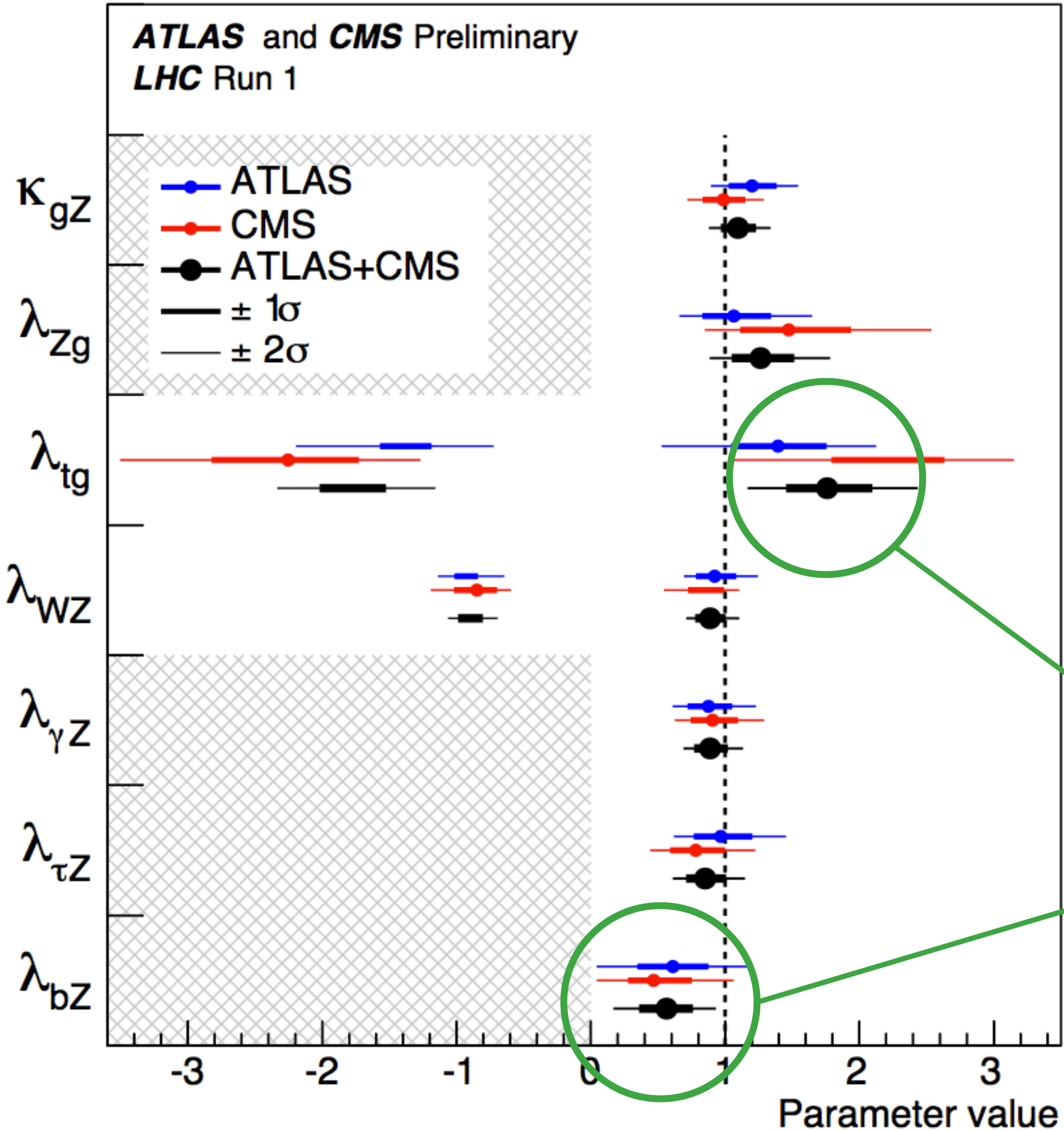
Alternatively, measure **ratio of coupling strengths**

- No assumption on Higgs total width needed, as Γ_H cancels in all expressions

σ and BR ratio model	Coupling-strength ratio model
$\sigma(gg \to H \to ZZ)$	$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$
$\sigma_{VBF}/\sigma_{ggF}$	
σ_{WH}/σ_{ggF}	
σ_{ZH}/σ_{ggF}	$\lambda_{Zg} = \kappa_Z / \kappa_g$
$\sigma_{ttH}/\sigma_{ggF}$	$\lambda_{tg} = \kappa_t / \kappa_g$
$\mathrm{BR}^{WW}/\mathrm{BR}^{ZZ}$	$\lambda_{WZ} = \kappa_W / \kappa_Z$
$\mathrm{BR}^{\gamma\gamma}/\mathrm{BR}^{ZZ}$	$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$
$\mathrm{BR}^{\tau\tau}/\mathrm{BR}^{ZZ}$	$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z$
$\mathrm{BR}^{bb}/\mathrm{BR}^{ZZ}$	$\lambda_{bZ} = \kappa_b / \kappa_Z$

(these can be fully expressed in terms of λ_{WZ} and λ_{Zg})

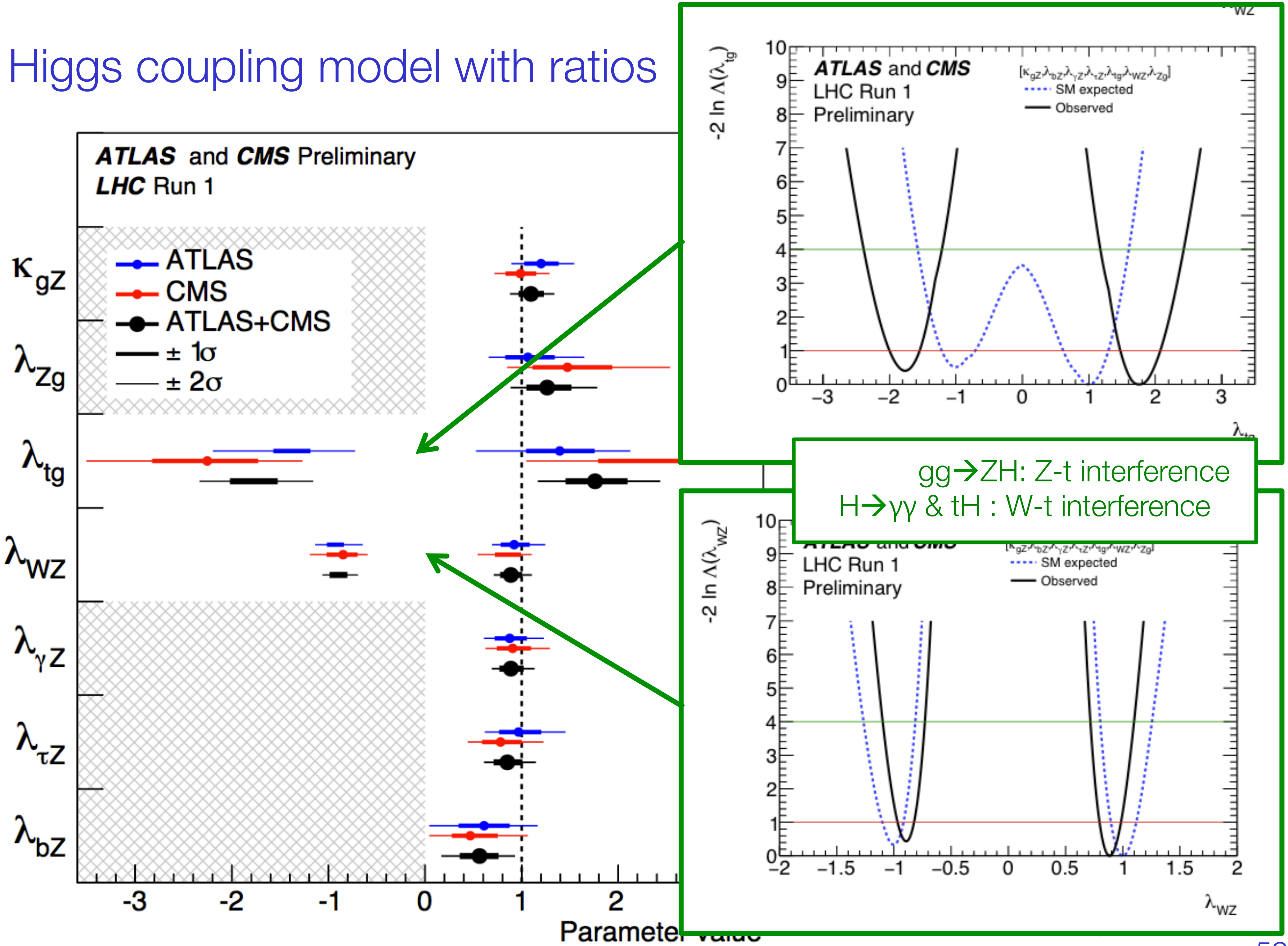
Higgs coupling model with ratios



Same qualitative features as generic signal strength ratio model

NB: Correlation matrix will be provided for final paper version

Higgs coupling model with ratios



NB: Correlation matrix will be provided for final paper version

Summary & outlook

- ATLAS and CMS Higgs boson coupling results have been combined, sensitivity on signal strength improved by almost √2
  - Higgs to ττ and VBF production established at more than 5σ level
  - The most precise results on Higgs production and decay and constraints on its couplings have been obtained at O(10%) precision
  - Different parameterizations have been studied:
    all results all consistent with the SM predictions within uncertainties:
    SM p-value of all combined fits in range 10%-88%

- LHC Run-2 at 13 TeV, precision will be improved during the coming years thanks to higher energy, larger integrated luminosity, progress in the theory predictions, and ability to integrate more measurements (differential σ) when moving beyond κ-framework.

ATLAS+CMS run-1	*stat.unc*	*syst.unc*
$\lambda_{WZ} = \kappa_W/\kappa_Z$	$^{+0.09}_{-0.08}$	$^{+0.04}_{-0.04}$
$\lambda_{tg} = \kappa_t/\kappa_g$	$^{+0.21}_{-0.20}$	$^{+0.23}_{-0.20}$

√s=8 → 13 TeV
σ(ggF) x 2.3
σ(VBF) x 2.4
σ(ttH) x 3.9

(Backup slides)

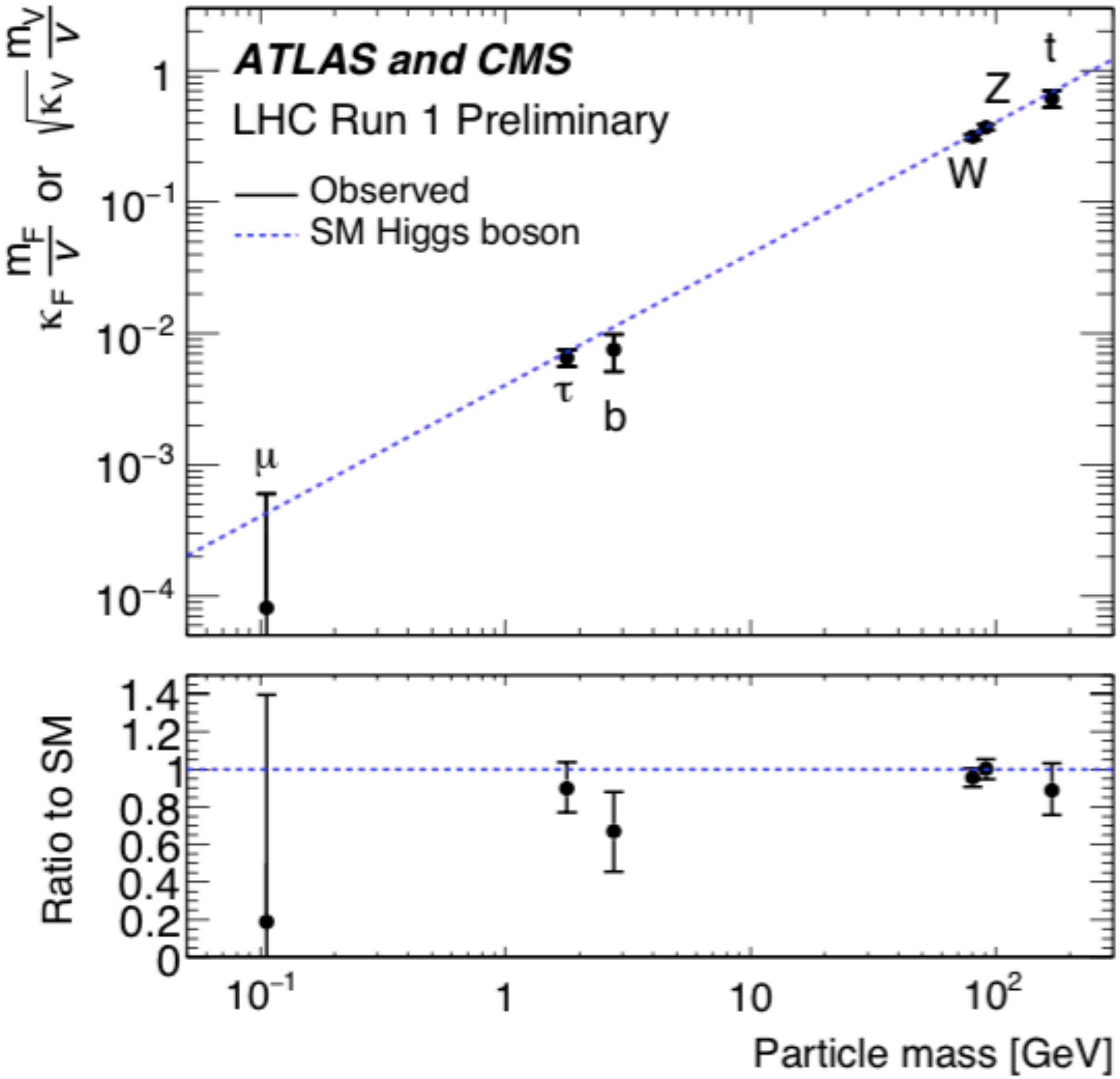
P-values w.r.t Standard Model for all models

Model	p-value	DoF	Parameters
Global signal strength	34%	1	μ
Production processes	24%	5	$\mu_{\text{ggF}}, \mu_{\text{VBF}}, \mu_{WH}, \mu_{ZH}, \mu_{ttH}$
Decay modes	60%	5	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{b\bar{b}}$
μ_V and μ_F per decay	88%	10	$\mu_V^{\gamma\gamma}, \mu_V^{ZZ}, \mu_V^{WW}, \mu_V^{\tau\tau}, \mu_V^{b\bar{b}}, \mu_F^{\gamma\gamma}, \mu_F^{ZZ}, \mu_F^{WW}, \mu_F^{\tau\tau}, \mu_F^{b\bar{b}}$
μ_V/μ_F ratio	72%	6	$\mu_V/\mu_F, \mu_F^{\gamma\gamma}, \mu_F^{ZZ}, \mu_F^{WW}, \mu_F^{\tau\tau}, \mu_F^{b\bar{b}}$
Ratios of σ and BR relative to $\sigma(gg \to H \to ZZ)$	16%	9	$\sigma(gg \to H \to ZZ)$, $\sigma_{\text{VBF}}/\sigma_{\text{ggF}}$, $\sigma_{WH}/\sigma_{\text{ggF}}$, $\sigma_{ZH}/\sigma_{\text{ggF}}$, $\sigma_{ttH}/\sigma_{\text{ggF}}$, $\text{BR}^{WW}/\text{BR}^{ZZ}$, $\text{BR}^{\gamma\gamma}/\text{BR}^{ZZ}$, $\text{BR}^{\tau\tau}/\text{BR}^{ZZ}$, $\text{BR}^{b\bar{b}}/\text{BR}^{ZZ}$
Ratios of σ and BR relative to $\sigma(gg \to H \to WW)$	16%	9	$\sigma(gg \to H \to WW)$, $\sigma_{\text{VBF}}/\sigma_{\text{ggF}}$, $\sigma_{WH}/\sigma_{\text{ggF}}$, $\sigma_{ZH}/\sigma_{\text{ggF}}$, $\sigma_{ttH}/\sigma_{\text{ggF}}$, $\text{BR}^{ZZ}/\text{BR}^{WW}$, $\text{BR}^{\gamma\gamma}/\text{BR}^{WW}$, $\text{BR}^{\tau\tau}/\text{BR}^{WW}$, $\text{BR}^{b\bar{b}}/\text{BR}^{WW}$
Coupling ratios	13%	7	$\kappa_{gZ}, \lambda_{Zg}, \lambda_{tg}, \lambda_{WZ}, \lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{bZ}$
Couplings, SM loops	65%	6	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\mu$
Couplings, BSM loops	11%	7	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_g, \kappa_\gamma$
BSM loops only	82%	2	κ_g, κ_γ
Up vs down couplings	67%	3	$\lambda_{du}, \lambda_{Vu}, \kappa_{uu}$
Lepton vs quark couplings	78%	3	$\lambda_{lq}, \lambda_{Vq}, \kappa_{qq}$
Fermion and vector couplings	59%	2	κ_V, κ_F

Adjustments made to the input measurements

- Apart from correlations, some other adjustments were made to individual ATLAS and CMS measurements to achieve consistency
- All ATLAS and CMS channels modified to assume a Higgs boson mass of 125.09 GeV (value of combined mass measurement)
- CMS includes bbH, tH, ggZH production processes where relevant
- ATLAS now uses Stewart-Tackman prescription of jet-bin uncertainties for the H→WW channel (so uncertainties have understandable correlation with CMS H→WW measurement)
- CMS adopts signal cross-section calculations from YR3 for all channels
- CMS adopts unified prescription of treatment of Higgs boson p_T
- Cross section values for dominant backgrounds estimated from simulation have been harmonized between ATLAS & CMS
- Both experiments have adopted the same correlation scheme for the signal theory uncertainties

Couplings vs mass



Couplings k_V vs k_F – likelihood scans by channel