Nils Ruthmann (CERN)
On Behalf of the **ATLAS** & **CMS** Collaborations

Standard Model Higgs Boson Couplings

Particles in Collisions

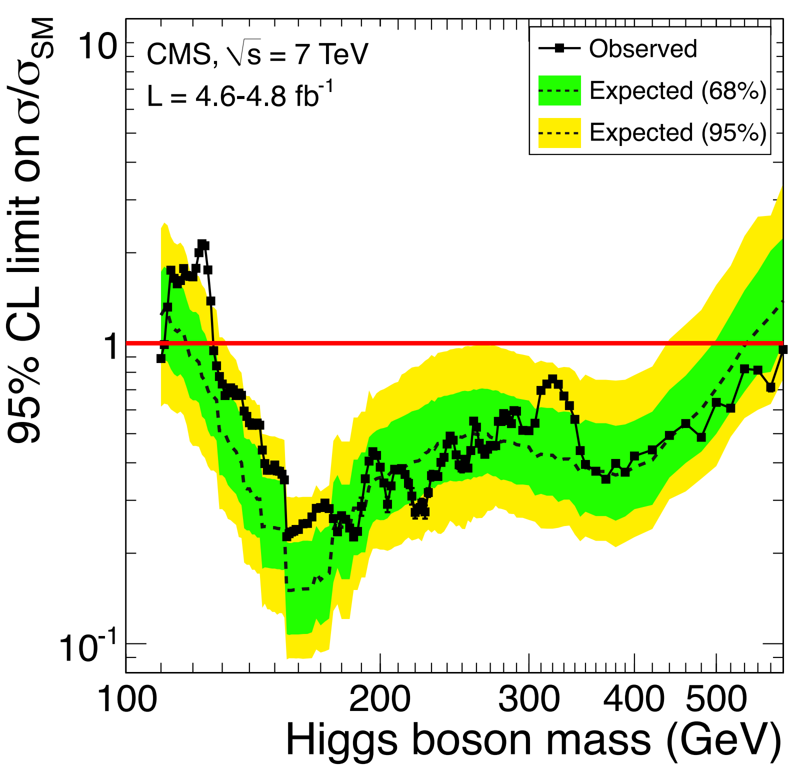
Warwick - 16.09.2015

Introduction

- LHC Run 1 was the run of the **Higgs Boson**
- Rapid transition from **searches** over **discovery** to **measurements**
- By now nearly all final Run 1 results are published

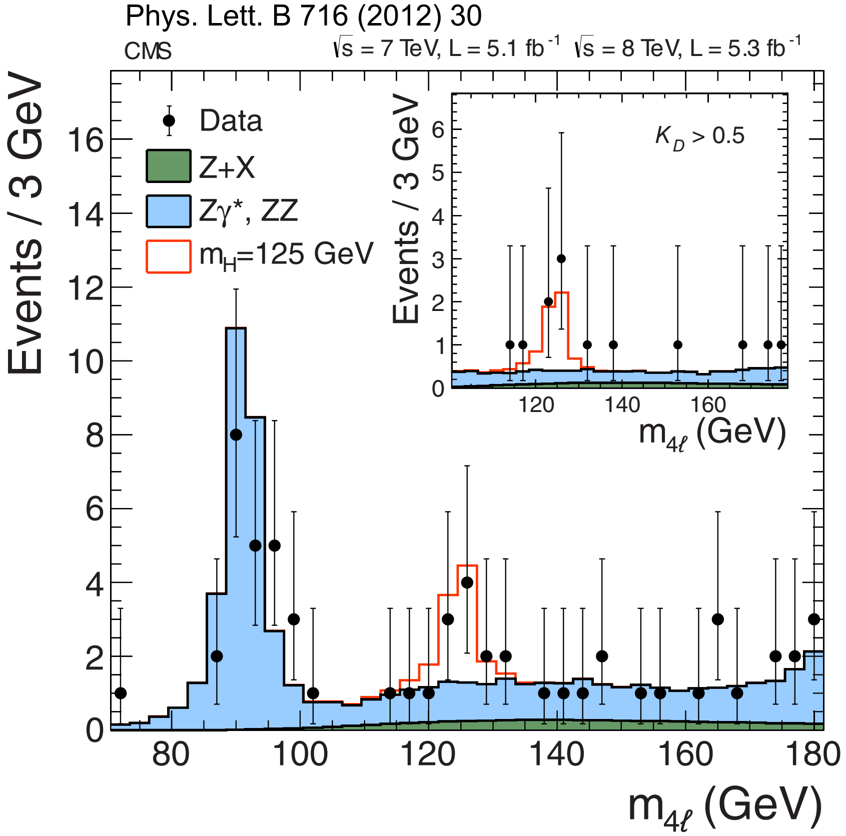
2011

Phys. Lett. B 710 (2012) 26-48



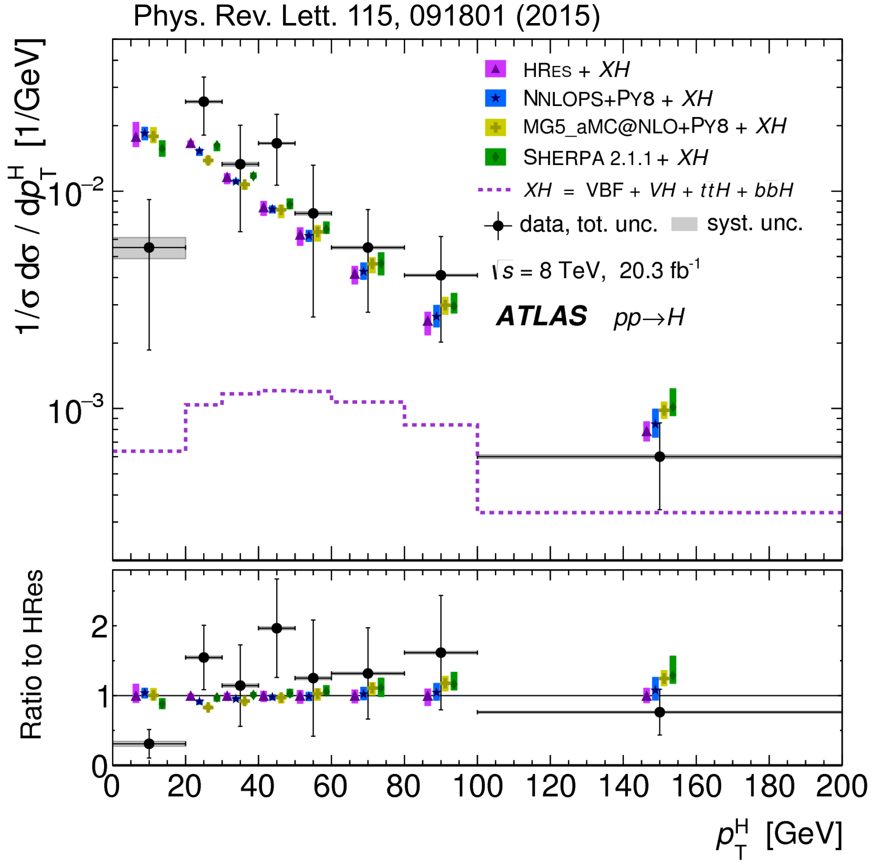
2012

Phys. Lett. B 716 (2012) 30



2015

Phys. Rev. Lett. 115, 091801 (2015)



Higgs Boson Couplings

- Higgs Boson measurements typically divided into:
  - **Coupling measurements** *(this talk)* **:**
    - Measure event counts in various phase-space regions
    - Naturally emerged from the searches
  - **Property measurements** *(next talk)* **:**
    - Measure quantum numbers and other properties using dedicated analyses
- Nomenclature slightly misleading:
  - Coupling parameters are **key properties** of the SM Higgs mechanism
  - both sectors influence each other: **m_H determines the SM expectation for couplings**

$m_W = gv/2$ $m_W/m_Z = \cos\theta_W$ m_H

$$\mathcal{L}_{EW} = \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{g^2}{4}(v+H)^2(W_\mu^+ W^{-\mu} + \frac{1}{2\cos^2\Theta_W} Z_\mu Z^\mu) + \frac{1}{2}(-2\mu^2)H^2 - \lambda v H^3 - \frac{1}{4}\lambda H^4 + \ldots$$

HVV and **HHVV** vertices **HHH** and **HHHH** self-interaction vertices

$\sim g^2 v$ ($\sim m^2/v$) **$\sim g^2$ ($\sim m^2/v^2$)**

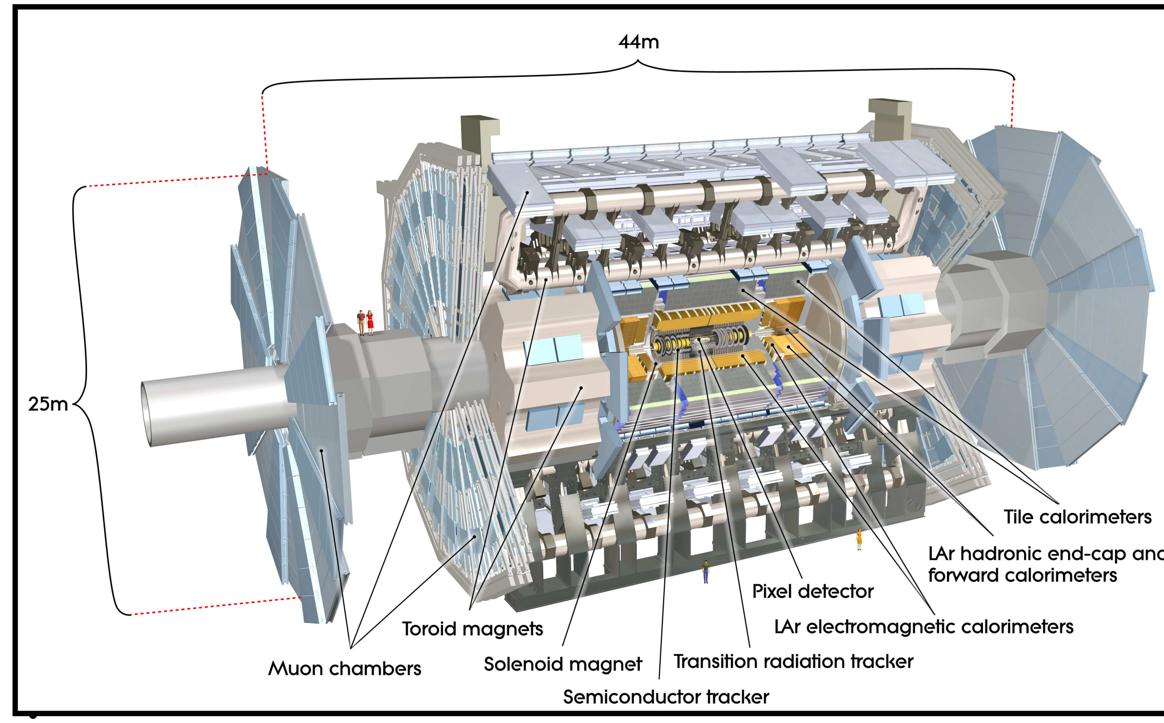
$$\mathcal{L}_{\text{Yuk,u.-gauge}} = -\frac{\lambda_f v}{\sqrt{2}}\bar{\Psi}_{f_L}\Psi_{f_R} - \frac{\lambda_f}{\sqrt{2}}\bar{\Psi}_{f_L}\Psi_{f_R}H + \ldots$$

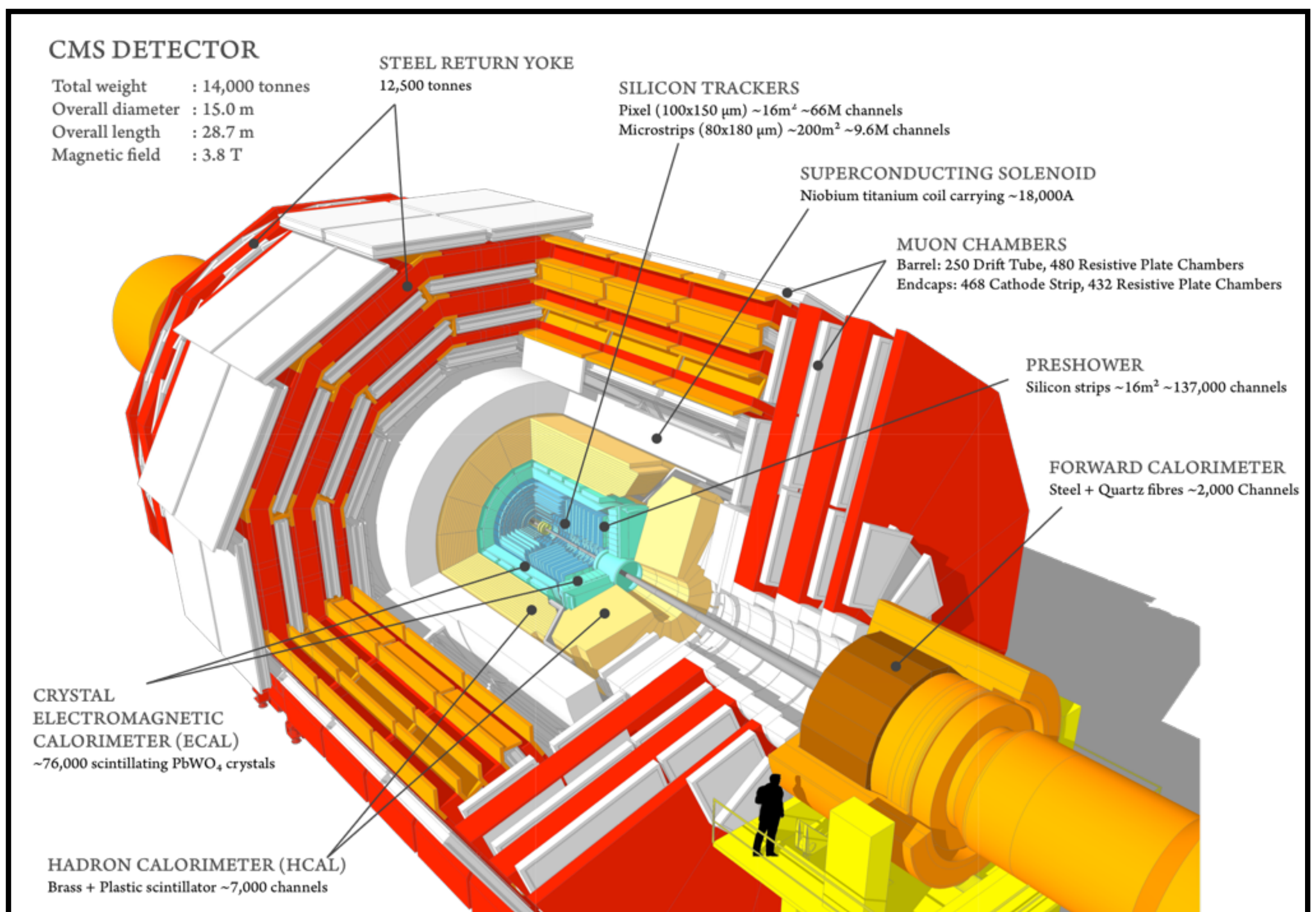
$m_f \sim \lambda_f v$ Hff vertices **$\sim m_f / v$**

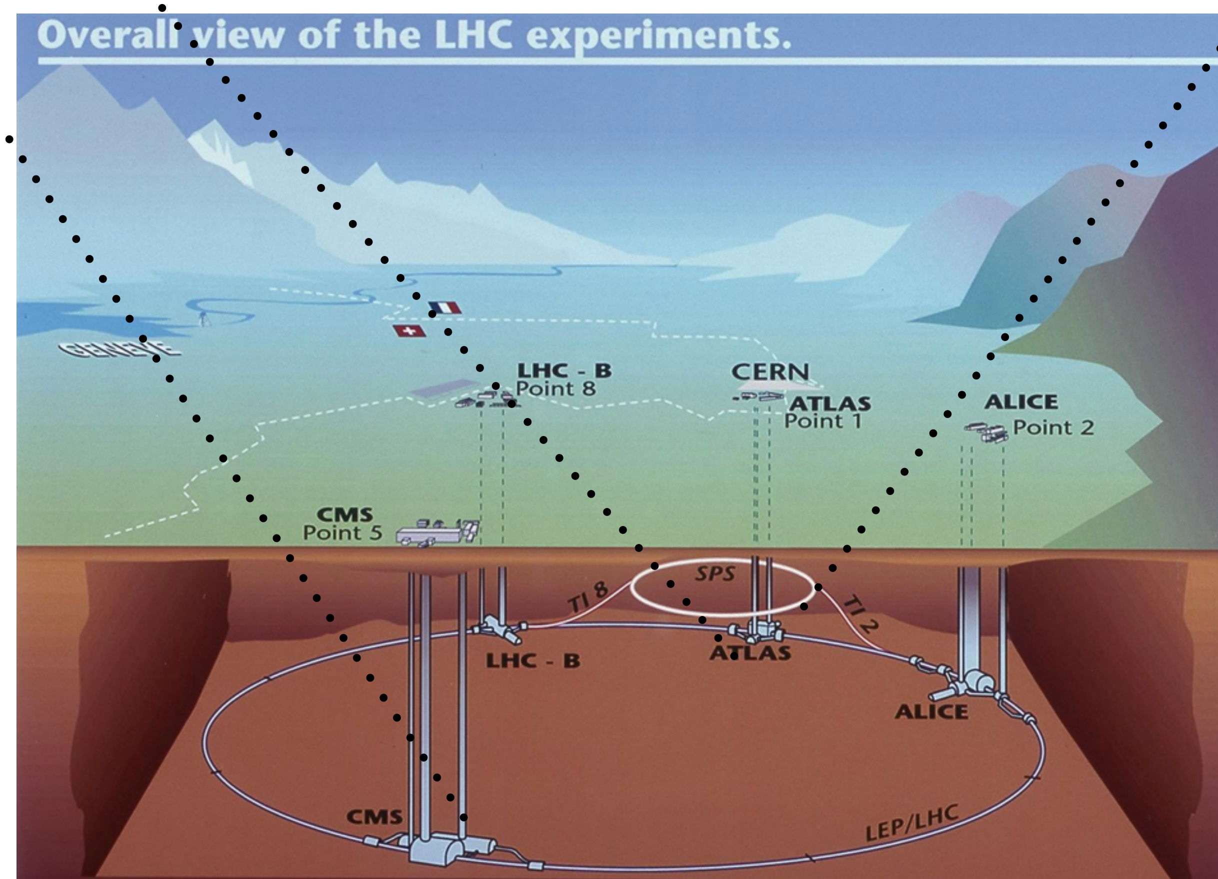
The ATLAS and CMS Experiments @ the LHC

- Two main purpose - almost - 4π detectors
- While **differing** in the **technical realization**
  - many **performance** measures are very **comparable**

- Higgs Boson analyses rely on the full detectors !
  - < 1% precision on **e/γ** energy scales
  - High **muon** efficiencies and momentum resolution
  - Hermetic coverage for excellent **MET** resolution
  - Powerful identification algorithms for **τ lepton** and **b-jet** reconstruction



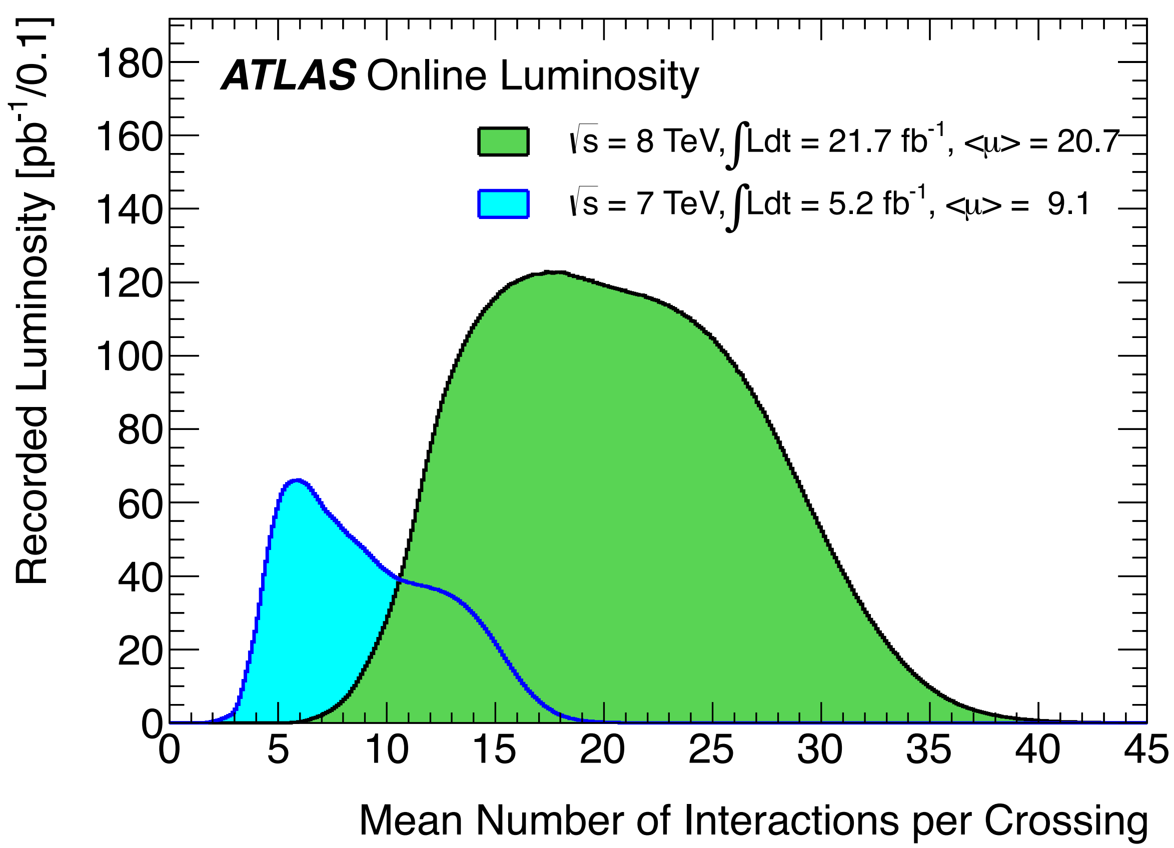


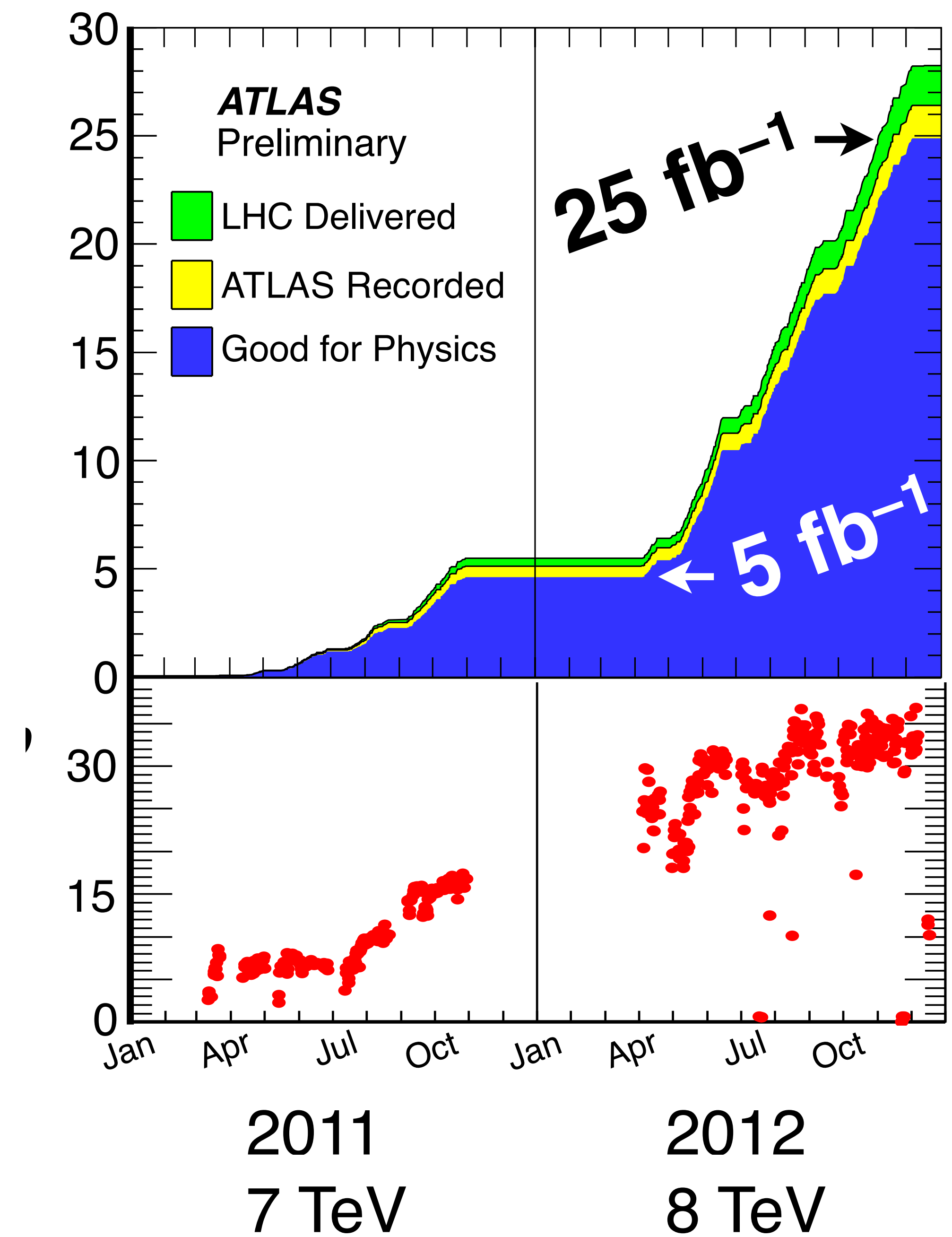


The Dataset

- LHC showed an outstanding performance in **2010-2012**
- At the end of Run 1 about **25 fb^{-1}** of p-p collision data were recorded by CMS and ATLAS
  - at centre-of-mass energies of **7** and **8 TeV**

- The amount of data came with a challenge:
  - Mean number of interactions per bunch crossing reaching 35

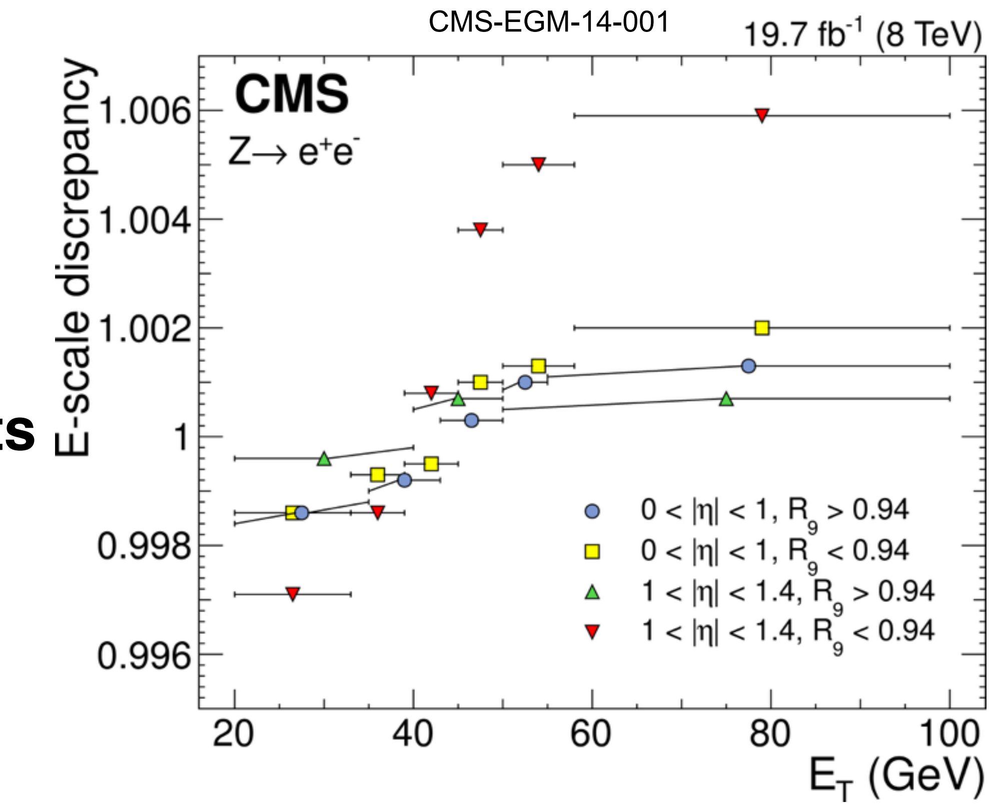




Approaching Final Run 1 results

Last two years were used to improve many aspects of the analyses:

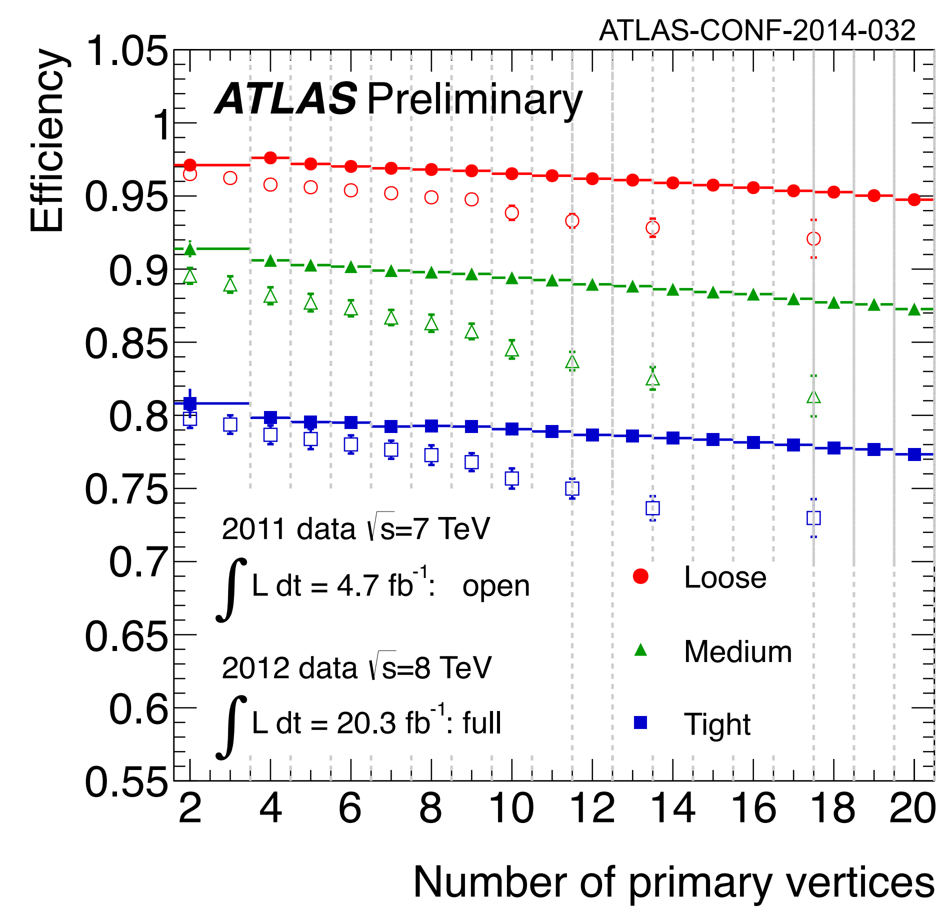
- **Refined energy calibrations** and **efficiency measurements**
- Optimized event selections and analyses techniques
- Improved theoretical predictions of signal and background processes



- ATLAS + CMS **coupling combination** released 2 week ago
- Combines measurements of the dominant production and decay modes

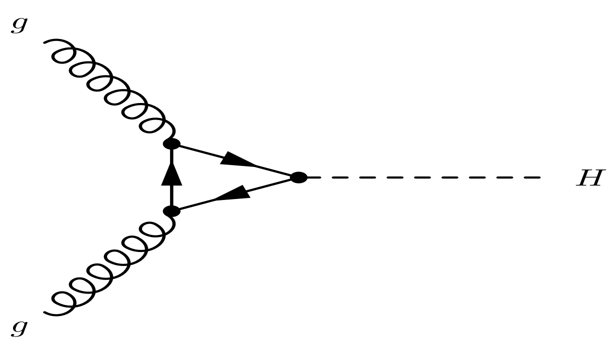
- But there are many other dedicated analyses looking for:
  - Limits on rare decays
    - μμ, Zγ, J/ψ γ
  - or rare production mechanisms:
    - HH, bbH, tH

  - Using Higgs measurements for BSM interpretations
  - Differential cross-section measurements
  - .. and many more



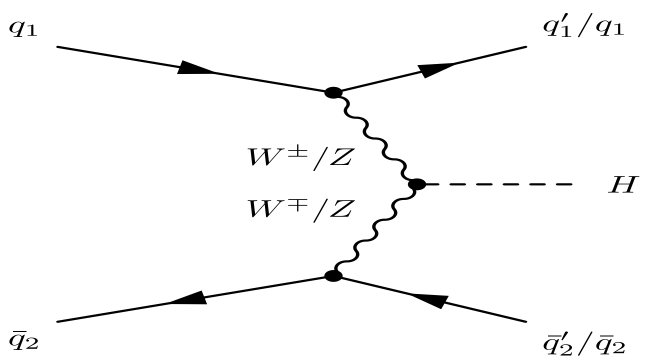
Higgs Boson Production at the LHC

σ(125 GeV) @ LHC (8 TeV)



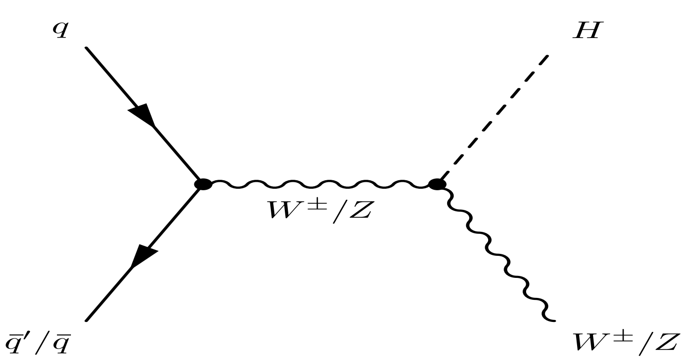
- **Gluon-Fusion:**
  - proceeding via a (mostly top) loop
  - Dominant contribution @ LHC

19.27 pb



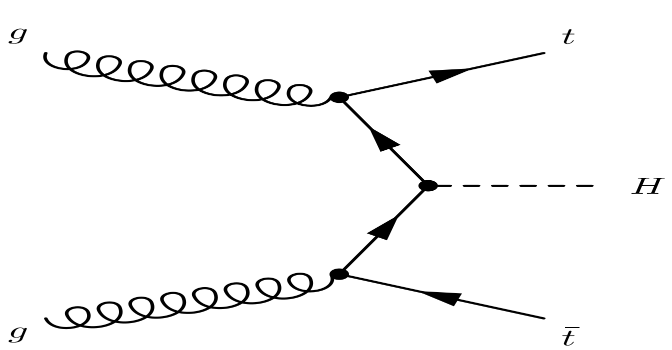
- **Vector-Boson-Fusion:**
  - 2 Jets at tree level

1.58 pb



- **Higgs-Strahlung:**
  - Vector boson decay offers objects to trigger on
  - Interesting for fully hadronic Higgs boson decays

1.1 pb

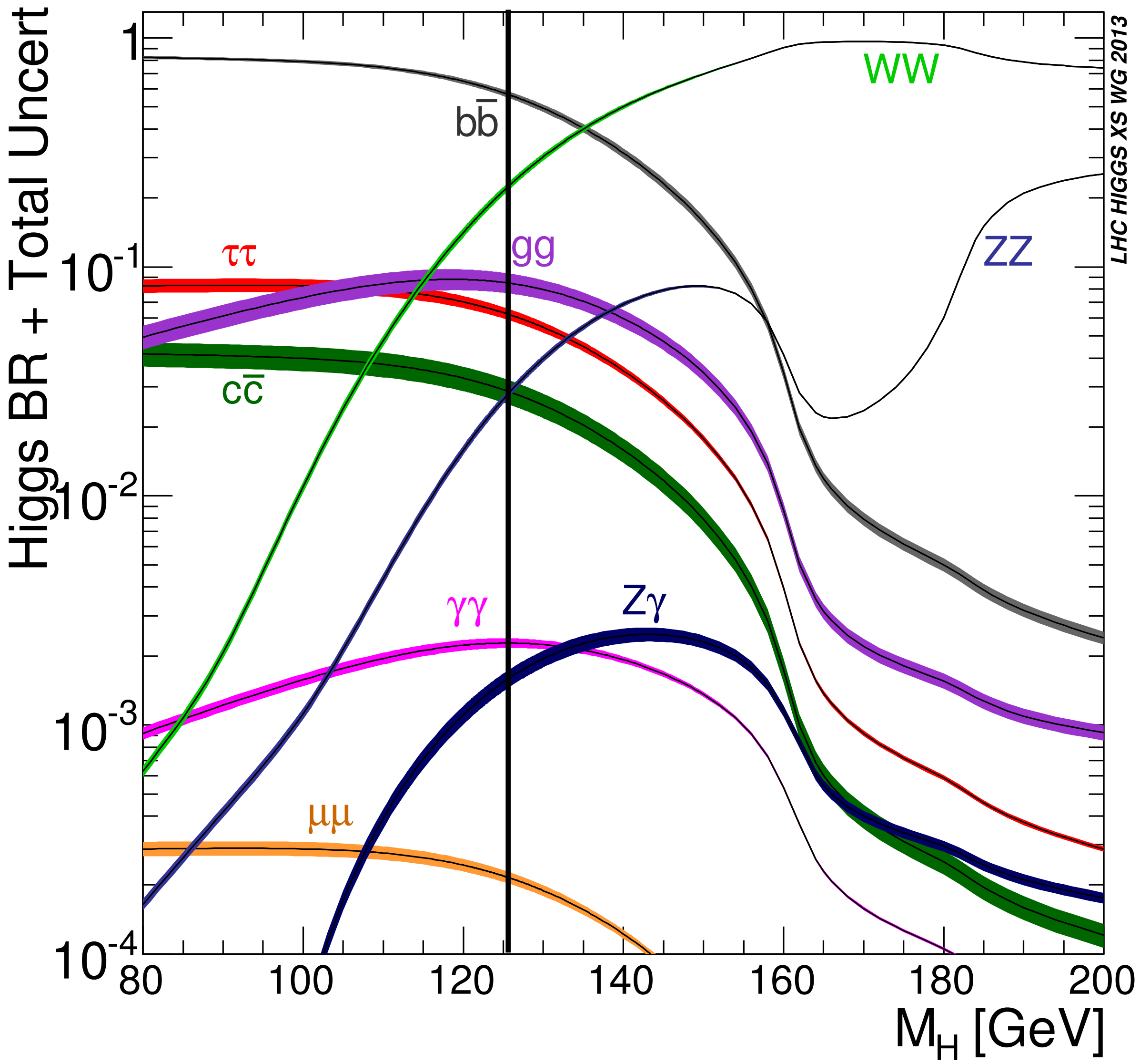


- **Associated production with tt :**
  - Direct access to top Yukawa coupling

0.13 pb

SM Higgs Boson Decays

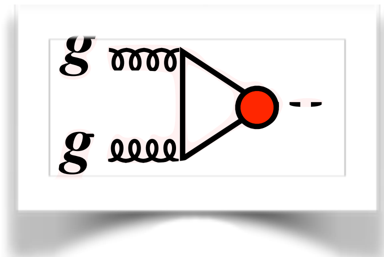
H →	BR
bb	0.58
WW	0.22
ττ	0.06
ZZ	0.027
γγ	0.0023
Zγ	0.0016
μμ	0.0002

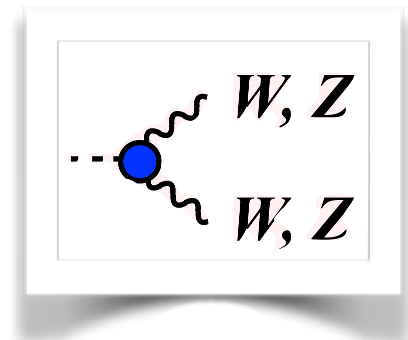


- m_H = 125 GeV is a sweet spot for a diverse Higgs Boson physics program
  - **γγ**: Clean signature and good mass resolution
  - **ZZ**: Low background and good mass resolution
  - **WW**: Large BR but complex background mixture
  - **bb**: Overwhelming hadronic background - Analysis targets it via VH
  - **ττ**: Large background but direct access to a fermionic Yukawa coupling

Signal strength parameter

- Can attempt to isolate different production and decay modes
  - Measure **event yields** in various phase-space regions **enriched in different production/decay modes**





- Primary observable: Number of events per bin
  ➡ after accounting for background:
  The **signal strength:**

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

Combination of production and decay targeted by at least one ATLAS or CMS analysis:
(and included in the combination)

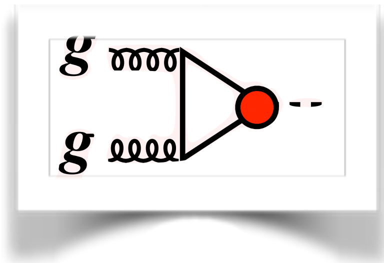
	WW	ZZ	γγ	bb	ττ	μμ
ggH	✓	✓	✓		✓	✓**
VBF	✓	✓	✓	✓*	✓	✓**
WH	✓	✓	✓	✓	✓	
ZH	✓	✓	✓	✓	✓	
ttH	✓		✓	✓	✓	

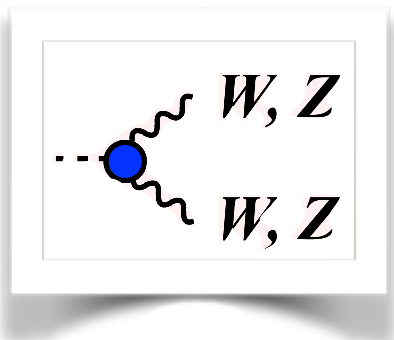
* not in the combination

** only used for mass-scaling test

Signal strength parameter

- Can attempt to isolate different production and decay modes
  - Measure **event yields** in various phase-space regions **enriched in different production/decay modes**





- Primary observable: Number of events per bin

➡ after ***accounting**** for background:

The signal strength:

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

*) The main backgrounds are mostly fitted simultaneously with the signal strength parameter.

- Multiple signal and control regions are included in such fits.

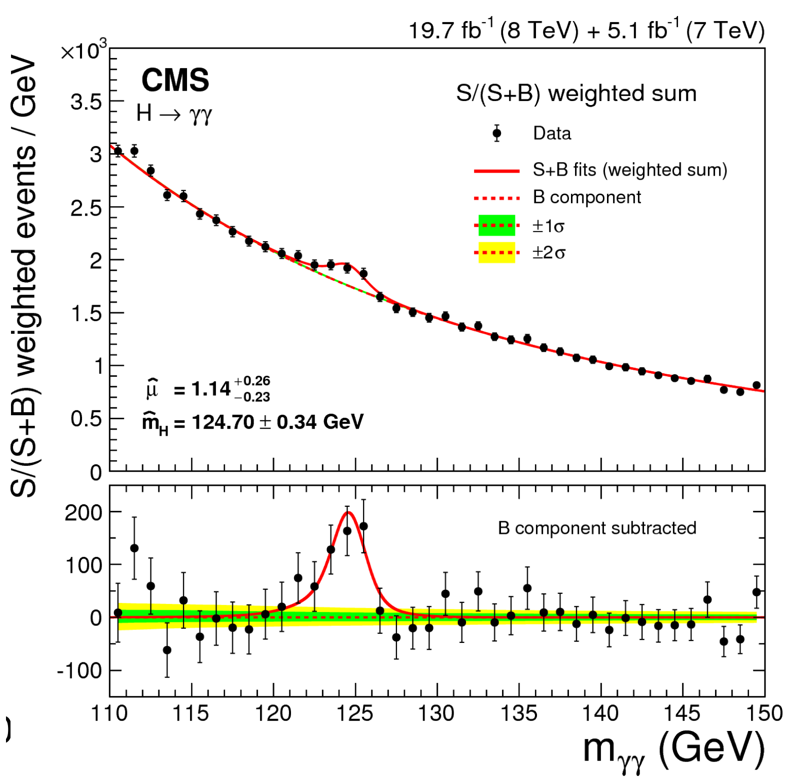
- These fits are the heart of the analyses
- offering enough material for dedicated talks.. Not possible to explain them here in detail

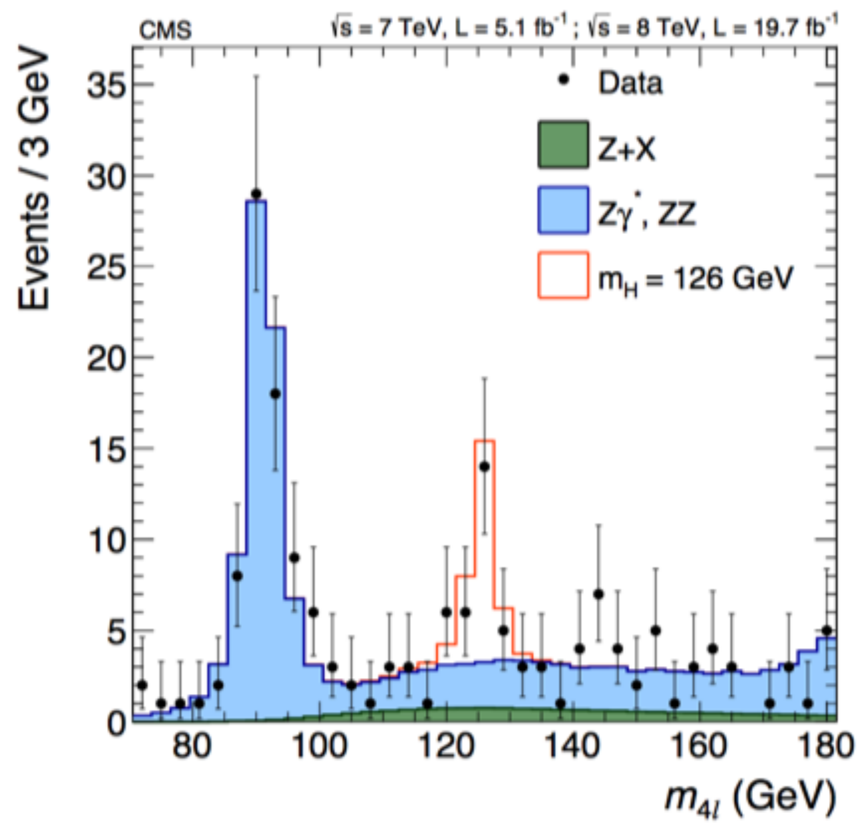
H → γγ/ WW/ ZZ

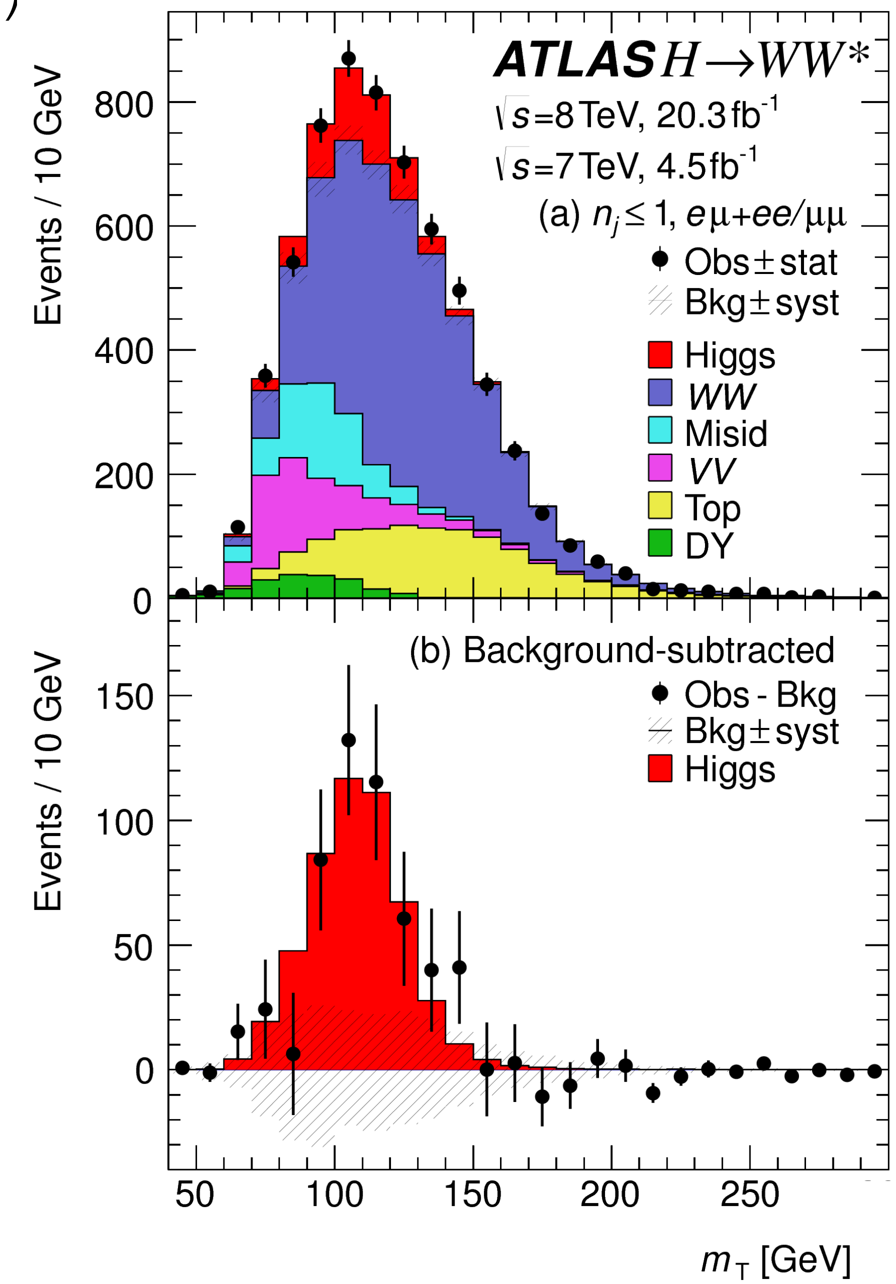
ATLAS γγ Phys. Rev. **D90** (2014) 112015
ZZ Phys. Rev. **D91** (2015) 012006
ww Phys.Rev. D92 (2015) 1, 012006

CMS γγ Eur. Phys. J. C **74** (2014) 3076
ZZ Phys. Rev. D **89** (2014) 092007,
WW JHEP **01** (2014) 096

- Three decay channels with the largest overall sensitivity (> 5σ)
- Exclusive categories targeting all main production modes
- Especially the ZZ and γγ final state furthermore provide the most stringent mass measurements







- Individual signal strengths:

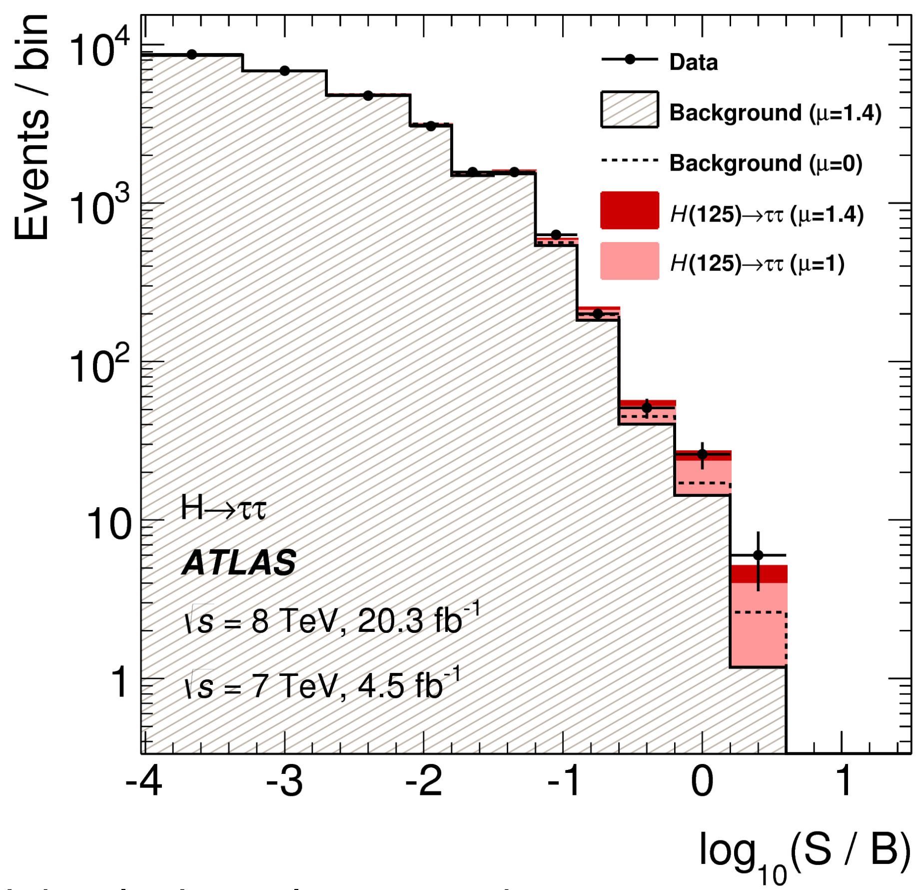
	γγ	ZZ	WW
ATLAS	1.15 ± 0.27	1.52 ± 0.38	1.23 ± 0.22
CMS	1.12 ± 0.24	1.05 ± 0.30	0.91 ± 0.23

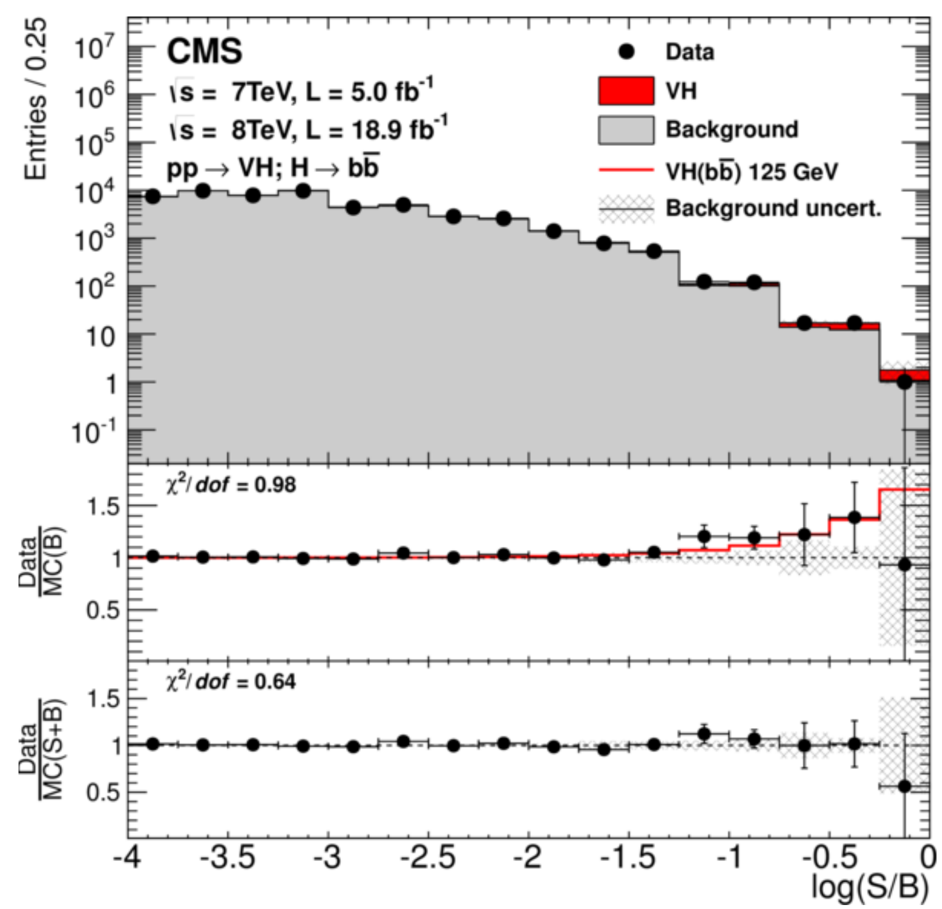
H → bb / ττ

ATLAS ττ: JHEP 1504 (2015) 117
bb: JHEP 1501 (2015) 069

CMS ττ:JHEP **05** (2014) 104
bb: Phys. Rev. D **89** (2014) 012003
Combination: Nature Phys. 10 (2014) 557-560

- Direct evidence for Higgs boson decays to fermions since last year
  - ττ : 4.5 (3.4) / 3.3 (3.7) σ *ATLAS/CMS observed (expected)*
  - VH -> V (bb) : 1.4 (2.6) / 2.1 (2.1) σ
- Interesting as these channels offer a **direct handle on Yukawa couplings**
- Complex final states with very large backgrounds
- Analyses often make use of **multivariate techniques** to maximize discriminating power





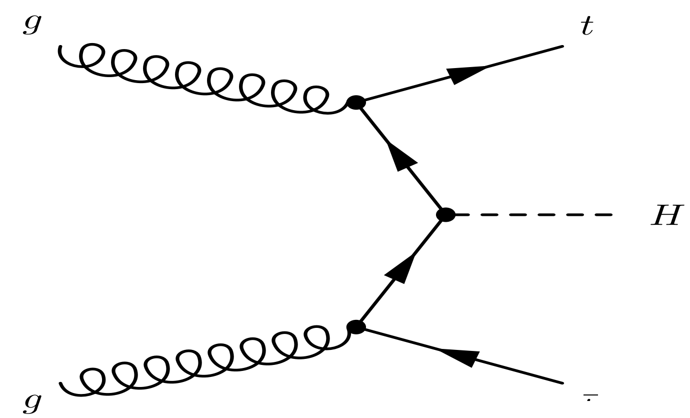
- Individual signal strengths:

	ττ	bb
ATLAS	1.41 ± 0.38	0.62 ± 0.37
CMS	0.89 ± 0.30	0.81 ± 0.44

ttH production

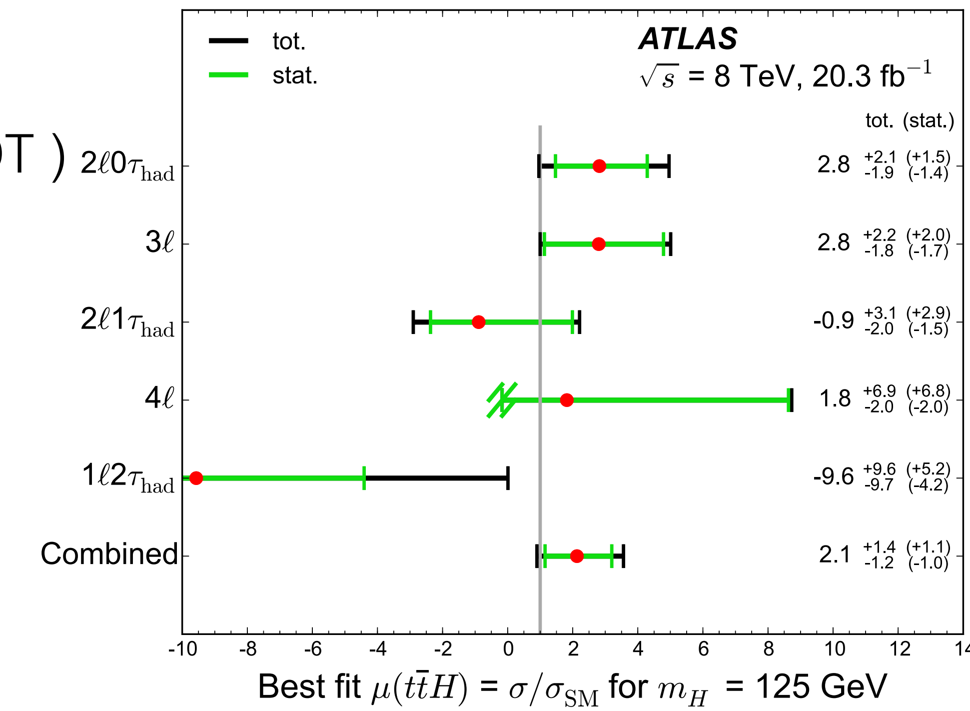
ATLAS
Eur.Phys.J. C75 (2015) 7, 349
Phys. Lett. **B740** (2015) 222

CMS
JHEP **09** (2014) 087



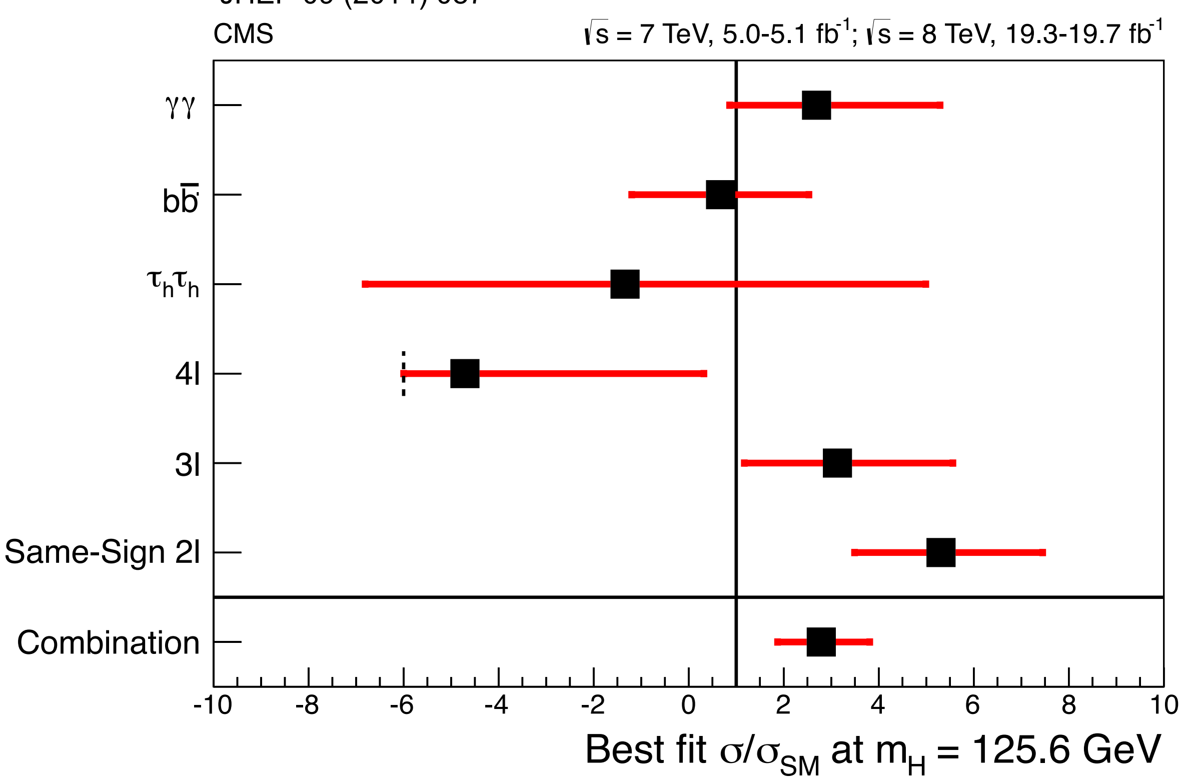
- Very interesting production mechanism
  - gives access to the **top-quark Yukawa coupling**
    - why is it as only Yukawa coupling of order 1 ?
- All major Higgs decay modes considered in analyses !
- Complex backgrounds and analyses techniques (MEM, BDT)
- Will benefit majorly from additional data in **Run 2**

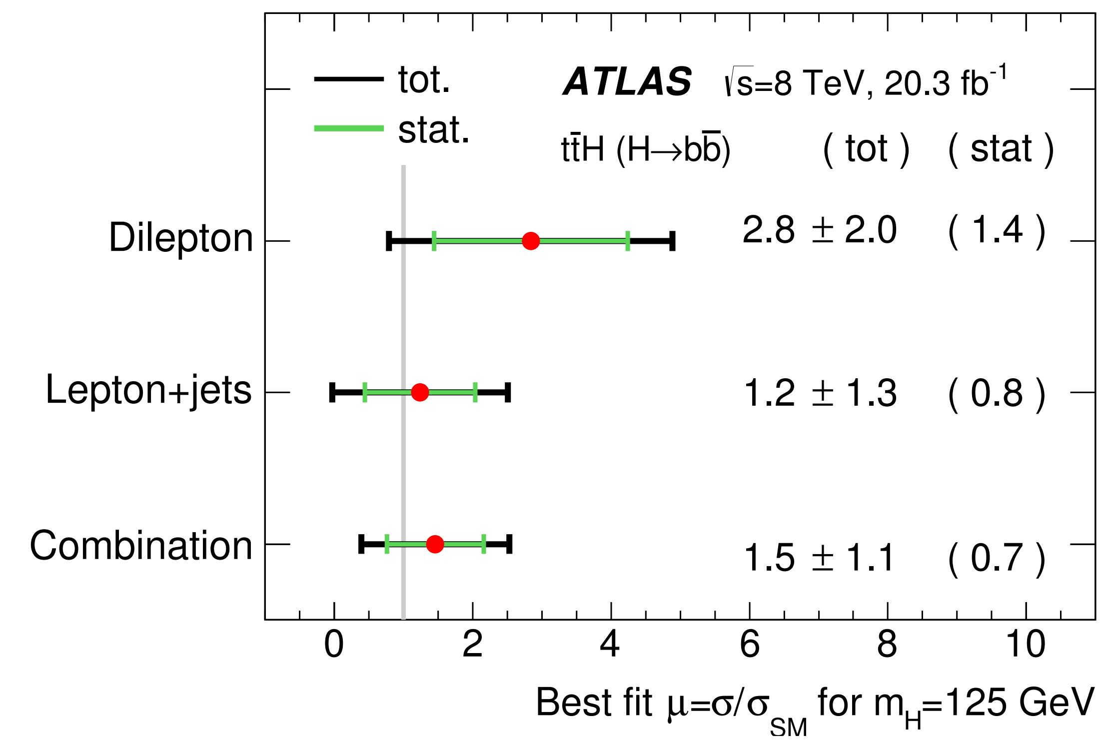
arxiv:1506.05988v1



arxiv:1503.05066v3

JHEP 09 (2014) 087





- Individual signal strengths:

ATLAS	1.87 ± 0.76
CMS	2.90 ± 0.80

ATLAS + CMS Combination

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

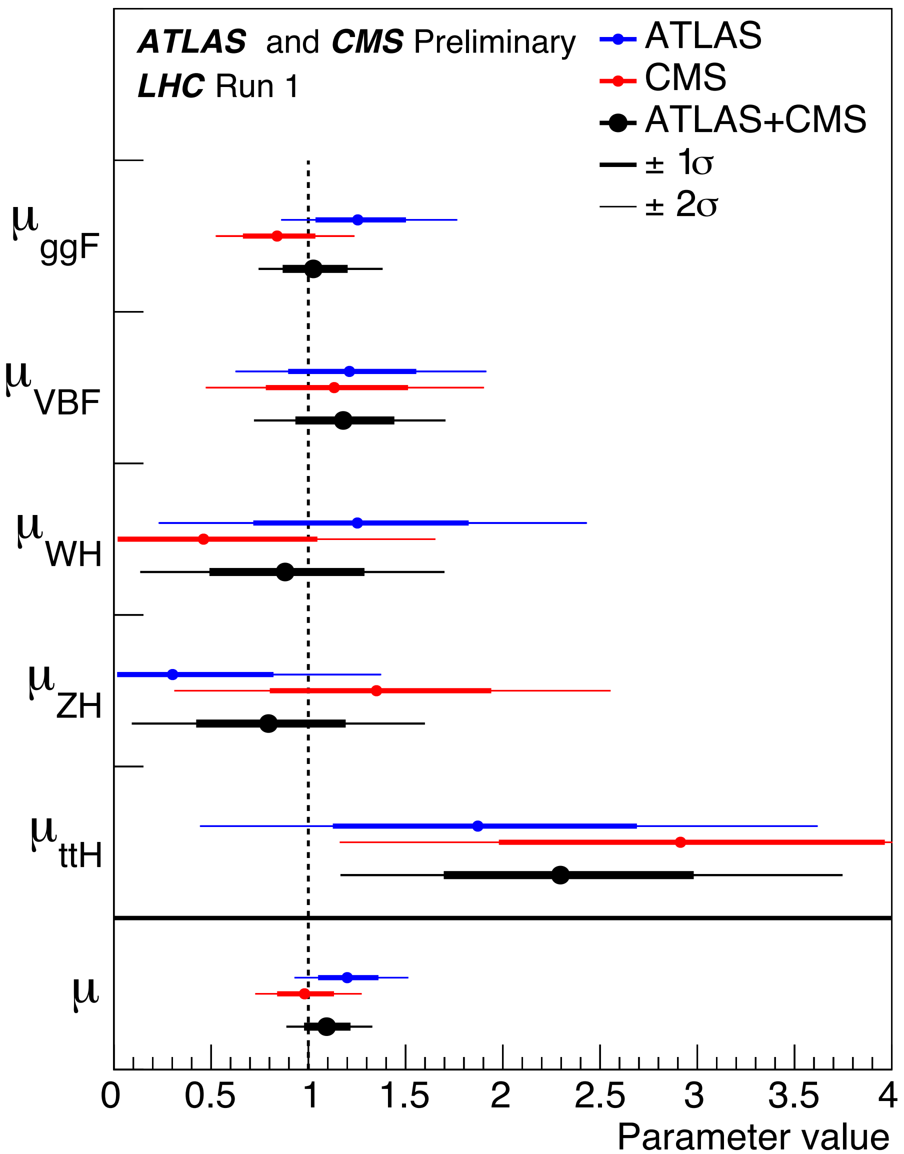
- The combination of the various analyses is achieved by building a combined Likelihood function
- Combined **Likelihood encodes correlation** among uncertainties :
  - Most important correlated uncertainties:
    - Theoretical uncertainties on **signal modeling: BR, PDF, QCD, UE, PS**
    - Some theoretical uncertainties on background modeling
      - e.g. in cases were the models rely solely on simulation (ZZ continuum, ..)
    - LHC luminosity
  - Many other uncertainties treated uncorrelated across experiments:
    - Detector related uncertainties
    - Background modeling uncertainties in significantly different phase-space regions
  - Many crosschecks to ensure a reasonable and non-aggressive choice of the correlation model
- Final Likelihood contains a product over all bins in all signal and control regions
  - it depends on:
    - the **parameters of interest α_i** describing the individual signal strengths
    - and the **nuisance parameters θ_j** parametrizing the uncertainties
  - About **575 categories**, and about **4200 nuisance parameters**

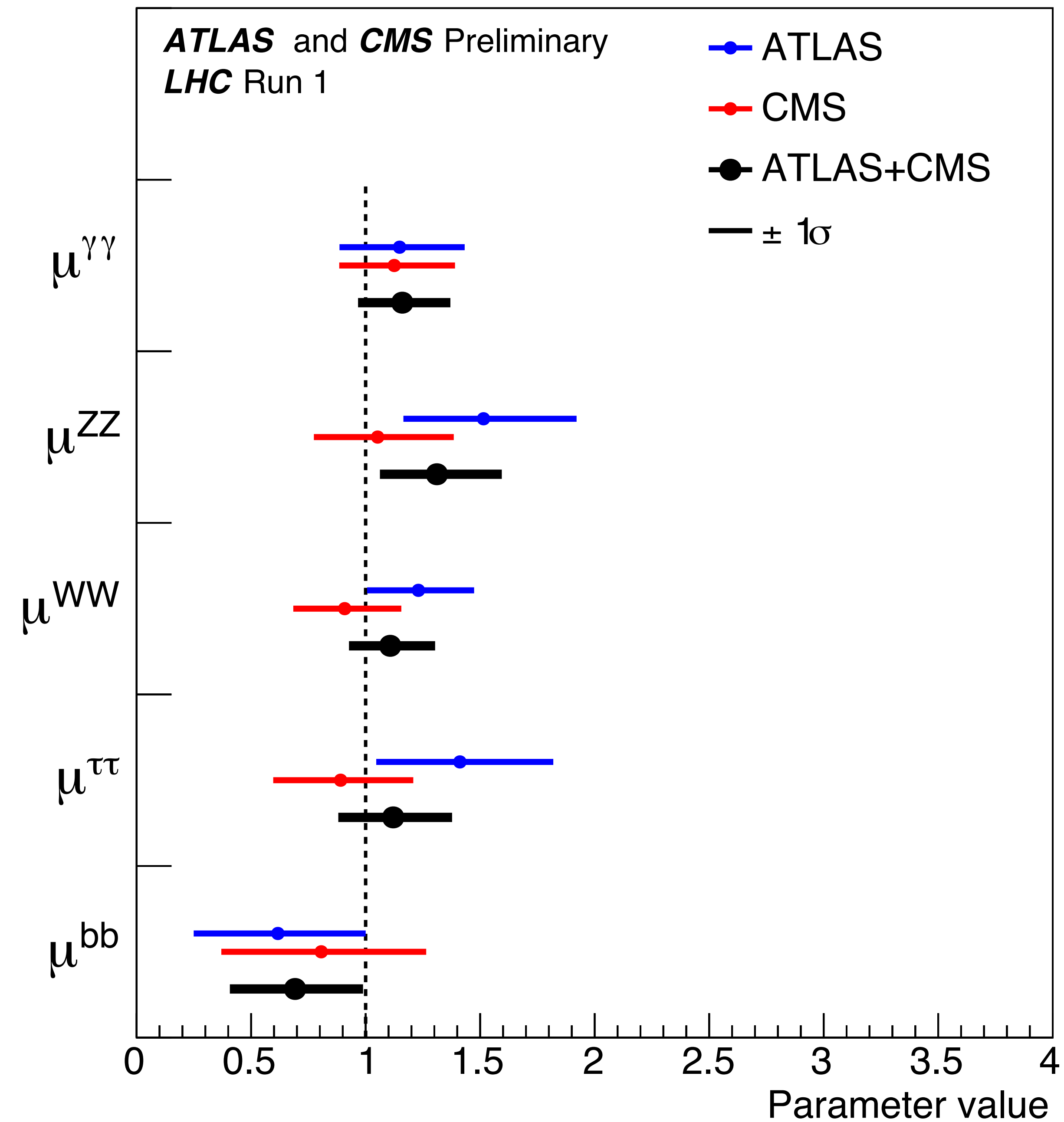
$$\mathcal{L}(\vec{\alpha}, \vec{\theta} | \vec{N})$$

-> Choose different **signal parameterizations** depending on the underlying question

Signal strength parametrization

- Signal strength parametrization closely reflecting results of the individual analyses
- Grouping either **production or decay** modes - and **assuming the other to be SM-like**
- Good agreement with the SM expectation with **p-values : 24% / 60%**
  - VBF production and $H \to \tau\tau$ decay both above the 5 σ significance level
- Most restrictive parametrization uses a single signal strength parameter
- Combined precision of 10 %
  - **μ = 1.09 +- 0.11**

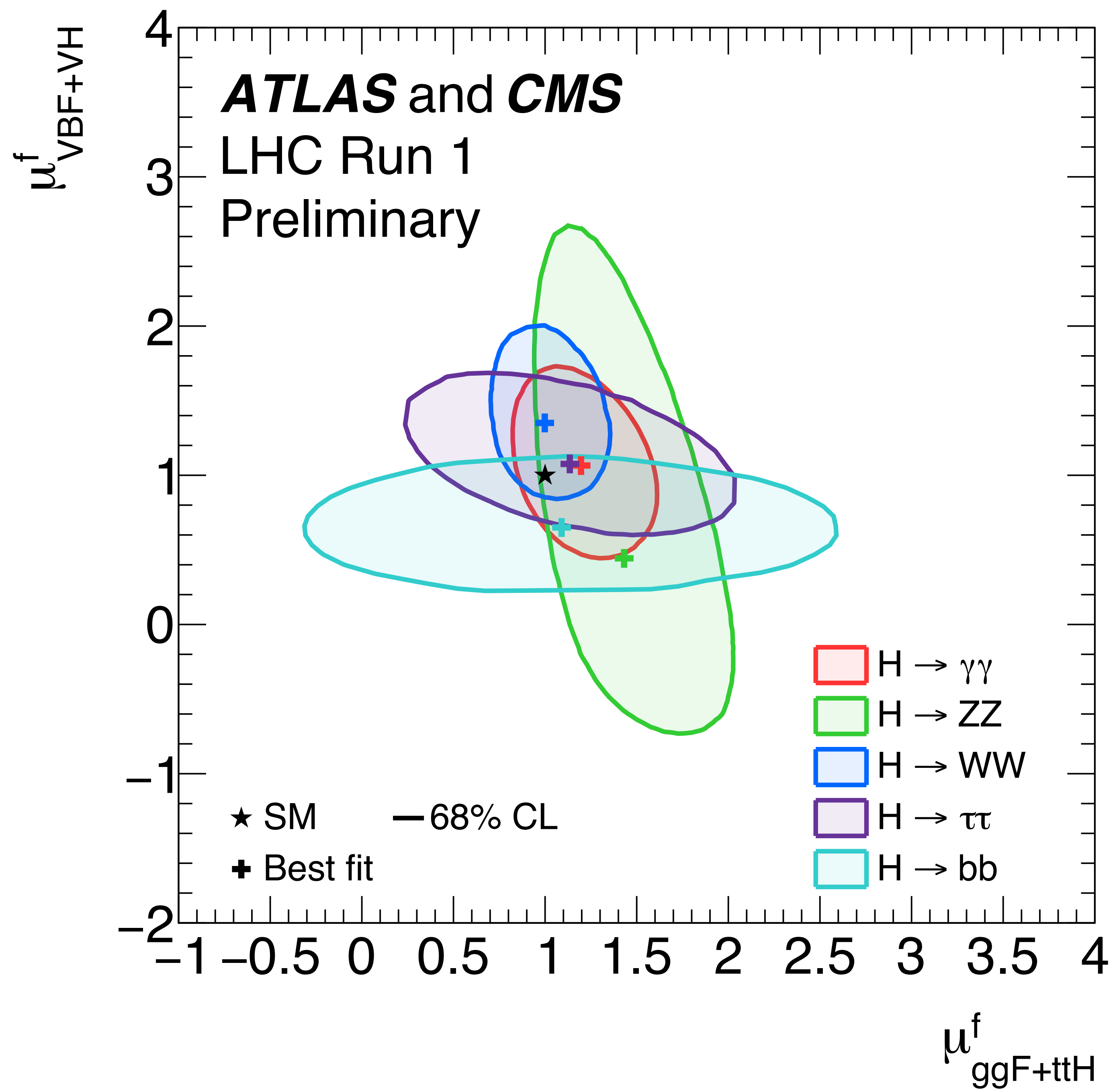




Fermionic & Bosonic production

- Compare bosonic (μ_V) to fermionic (μ_F) production modes in all decay modes
- Branching ratio and many uncertainties cancel in the ratio (μ_V / μ_F)
- Can either fit all decay modes separately
  - Or fit a **combined ratio** along with separate fermion strengths

Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty
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}	$1.08^{+0.22}_{-0.19}$	$^{+0.19}_{-0.17}$
$\mu_F^{\tau\tau}$	$1.07^{+0.35}_{-0.28}$	$^{+0.32}_{-0.27}$
μ_F^{bb}	$0.65^{+0.37}_{-0.28}$	$^{+0.45}_{-0.34}$

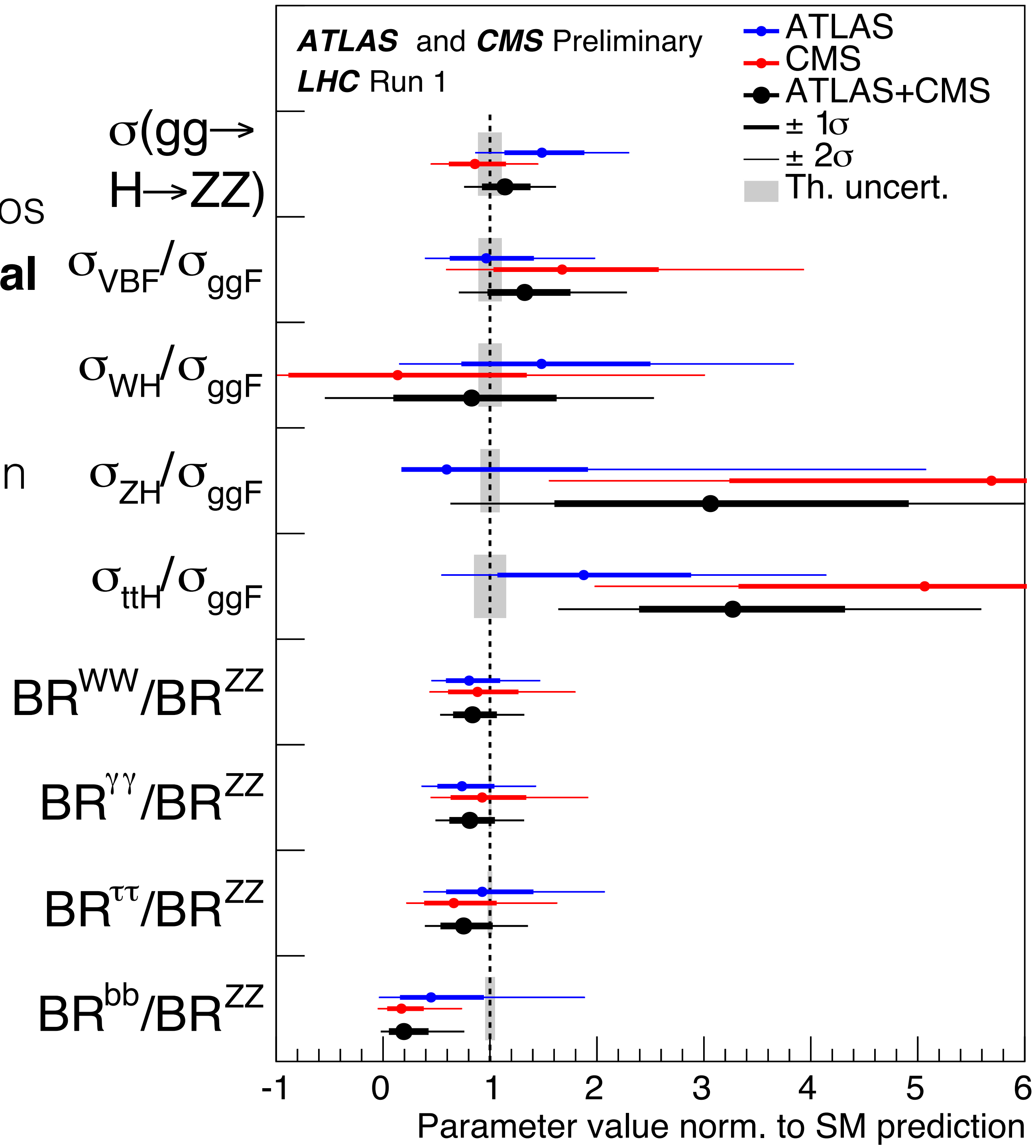


- Excellent agreement with SM expectation

Generic parametrization

- Only measuring product of cross-sections and branching ratios
- Cannot determine them independently
- Use ratios of cross-sections and branching ratios
  - Relative to gg→H→ZZ
  - **Independent of the Higgs width**
  - Main theoretical uncertainties cancel in the ratios
  - **Results remain valid as (inclusive) theoretical predictions progress**
- Overall good compatibility with the SM expectation
  - **p-value 16%**
- Largest deviations occur in:
  - BR^{bb}/BR^{ZZ} (~2.4 sigma)
  - $\sigma_{ttH}/\sigma_{ggH}$, σ_{ZH}/σ_{ggH}
- Individual measurements slightly correlated
  - due to common denominator

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



The *Kappa Framework*

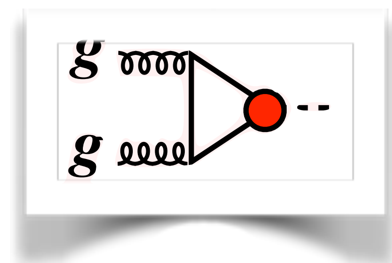
- Instead of signal strengths can use *coupling modifiers* to parametrize the signal contribution

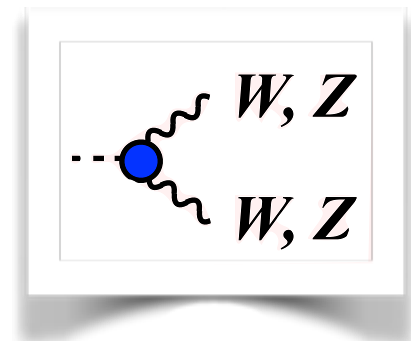
$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_\mathrm{H}}$$

$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}}$$

$$\kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$$

Example: Various choices to scale gg→H→WW :





$$\mu_{gg}^{WW} \quad , \quad \frac{\kappa_g^2 \kappa_W^2}{\kappa_H^2} \quad , \quad \frac{\kappa_g(\kappa_t, \kappa_b)^2 \kappa_W^2}{\kappa_H(\vec{\kappa})^2}$$

Higgs width enters here!

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

- Describe loops by effective parameters **or** use expected SM interference

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

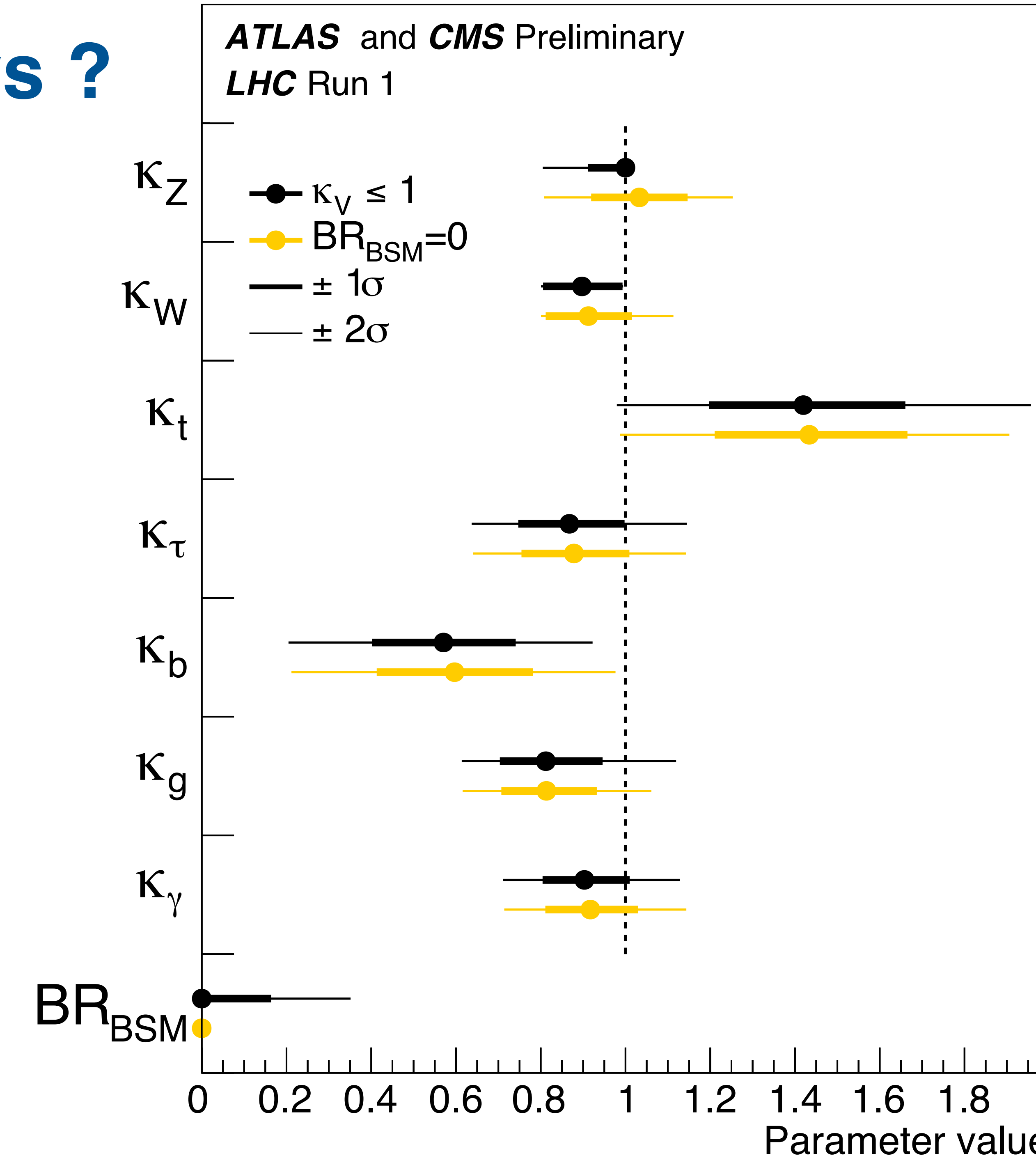
$$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$$

- Assumes SM like coupling structure - **only accounts for rates** !
- Useful quantities as long as overall picture is SM-like

BSM physics in loops or decays ?

- Making assumptions about Higgs Boson width allows to extract coupling modifiers

- Assume either:
  a) $\kappa_V < 1$
  b) No BSM decays

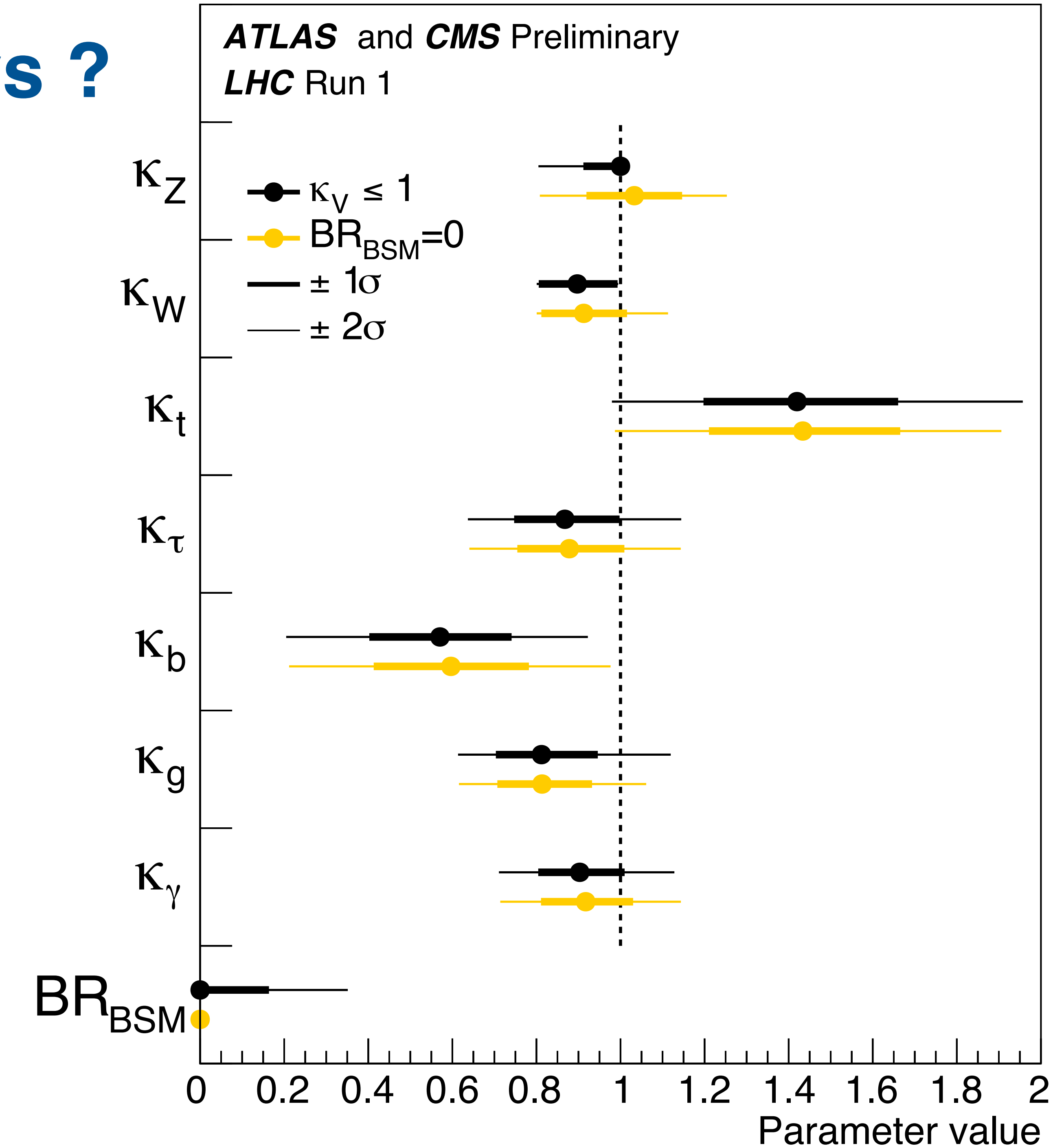


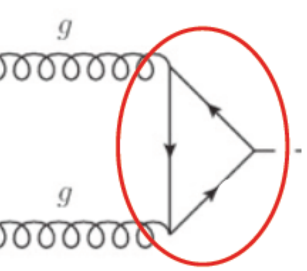
- Under assumption a):
  - Extract a limit on **$BR_{BSM} < 0.34$**

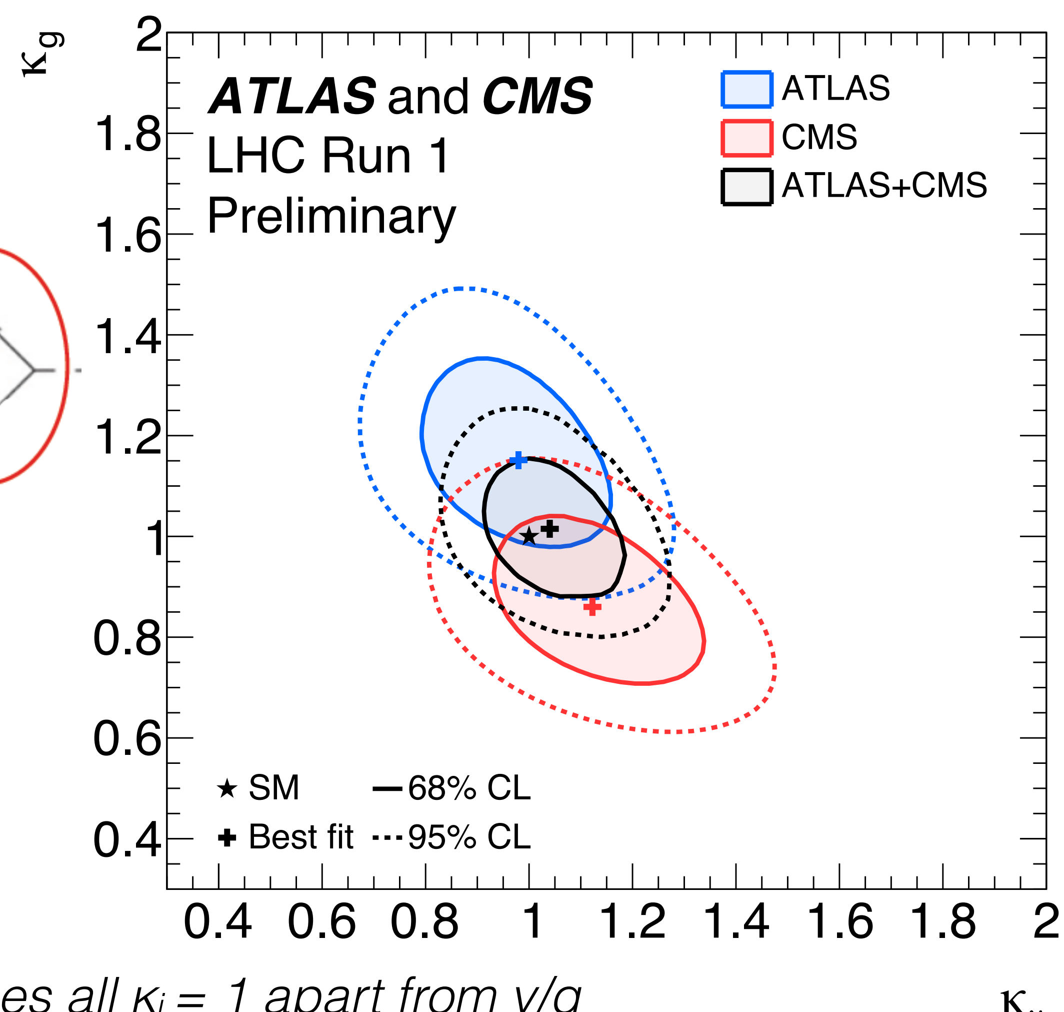
Direct limits on VBF H → inv.:
BR_{inv} < 28% (31%) (ATLAS)
BR_{inv} < 57% (40%) (CMS)

BSM physics in loops or decays ?

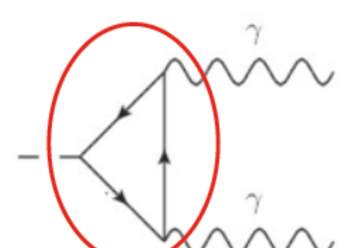
- Making assumptions about Higgs Boson width allows to extract coupling modifiers
- Assume either:
  - a) $\kappa_V < 1$
  - b) No BSM decays
- **Test for BSM contributions in loops**
  - Fitting effective photon and gluon couplings
  - Assuming all other couplings are SM-like







Assumes all $\kappa_i = 1$ apart from y/g



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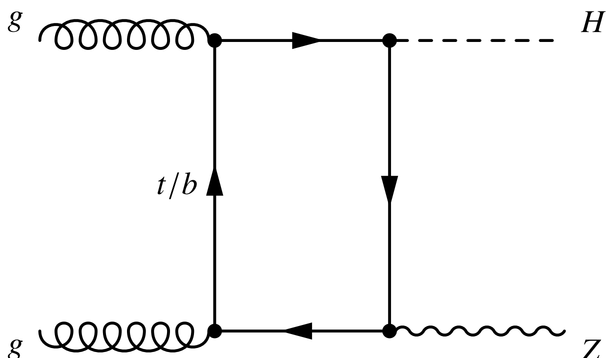
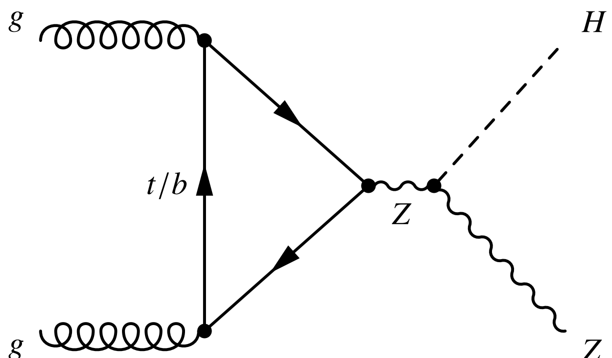
Resolving interferences - tH and gg→ZH

- Interference terms carry information about the relative sign between couplings

Production	Loops	Interference	Multiplicative factor
$\sigma(gg \to ZH)$	✓	$Z - t$	$\sim \quad 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(qb \to tHq')$	–	$W - t$	$\sim \quad 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$



(b)



(c)

- Large negative interference suppresses the cross section of tH production SM
  - Not observing it as an excess in ttH analyses therefore constrains the sign

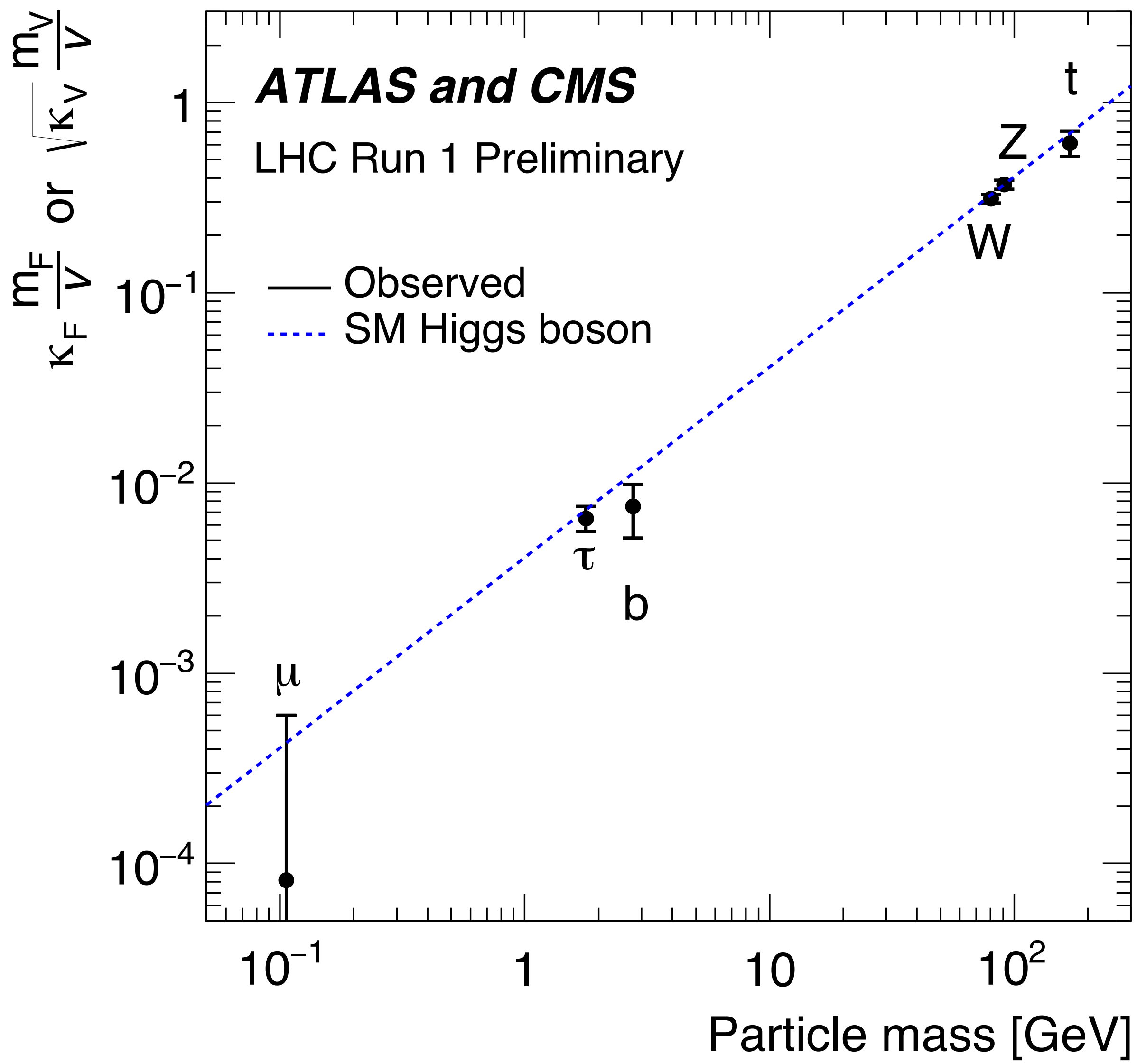
- Similarly the process gg→ZH involves an interference term between Z and top couplings
- gg→ZH features a harder p_T spectrum than the qq initiated process
- But small overall cross section

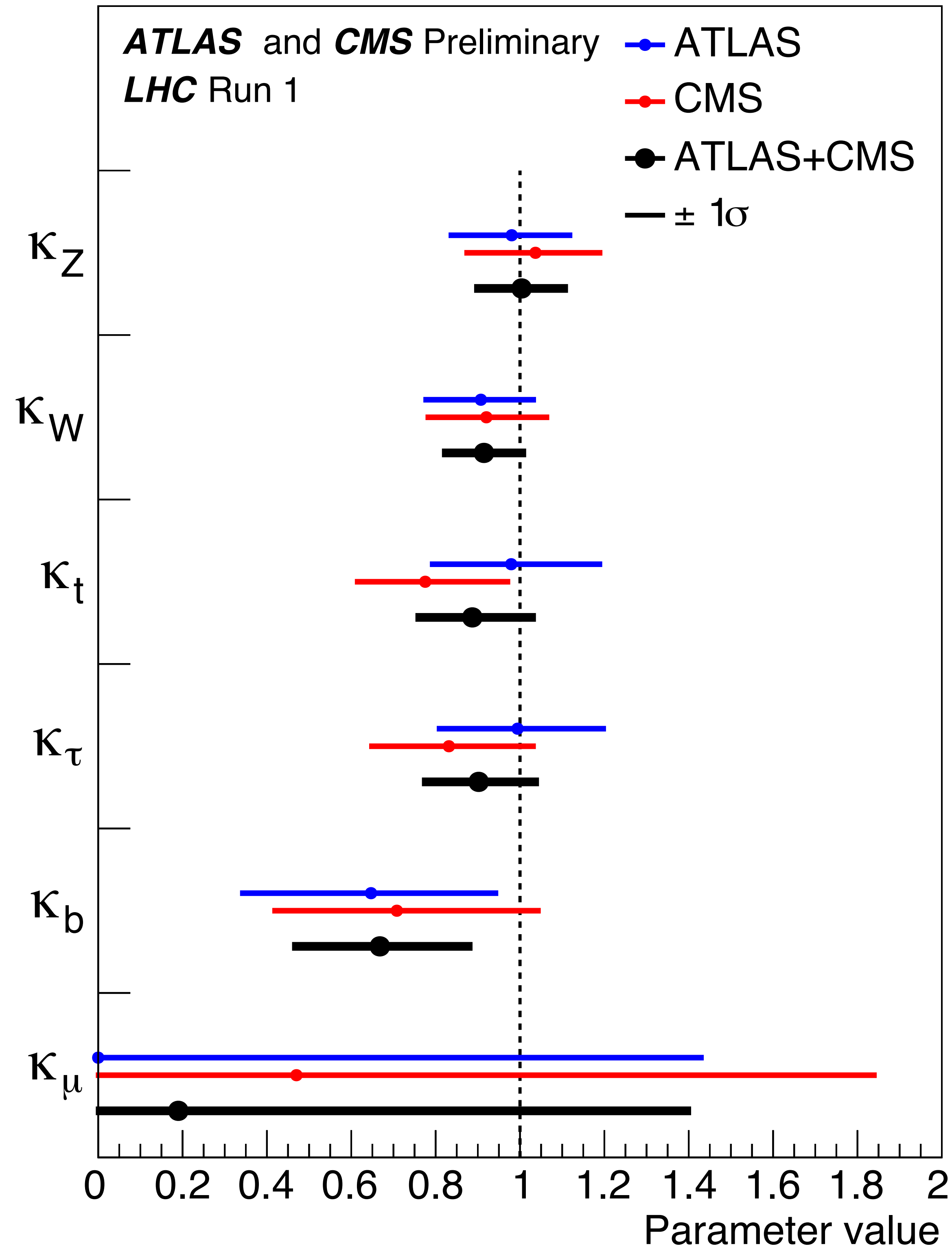
- Much smaller interference effect than in the case of tH
  - Little constraining power concerning the sign of κ_Z

Coupling modifiers - no BSM in loops nor decays

- Effective photon and gluon couplings compatible with SM
- No sign for BSM decays

➡ Extract coupling modifiers assuming SM loop structure and no BSM decays



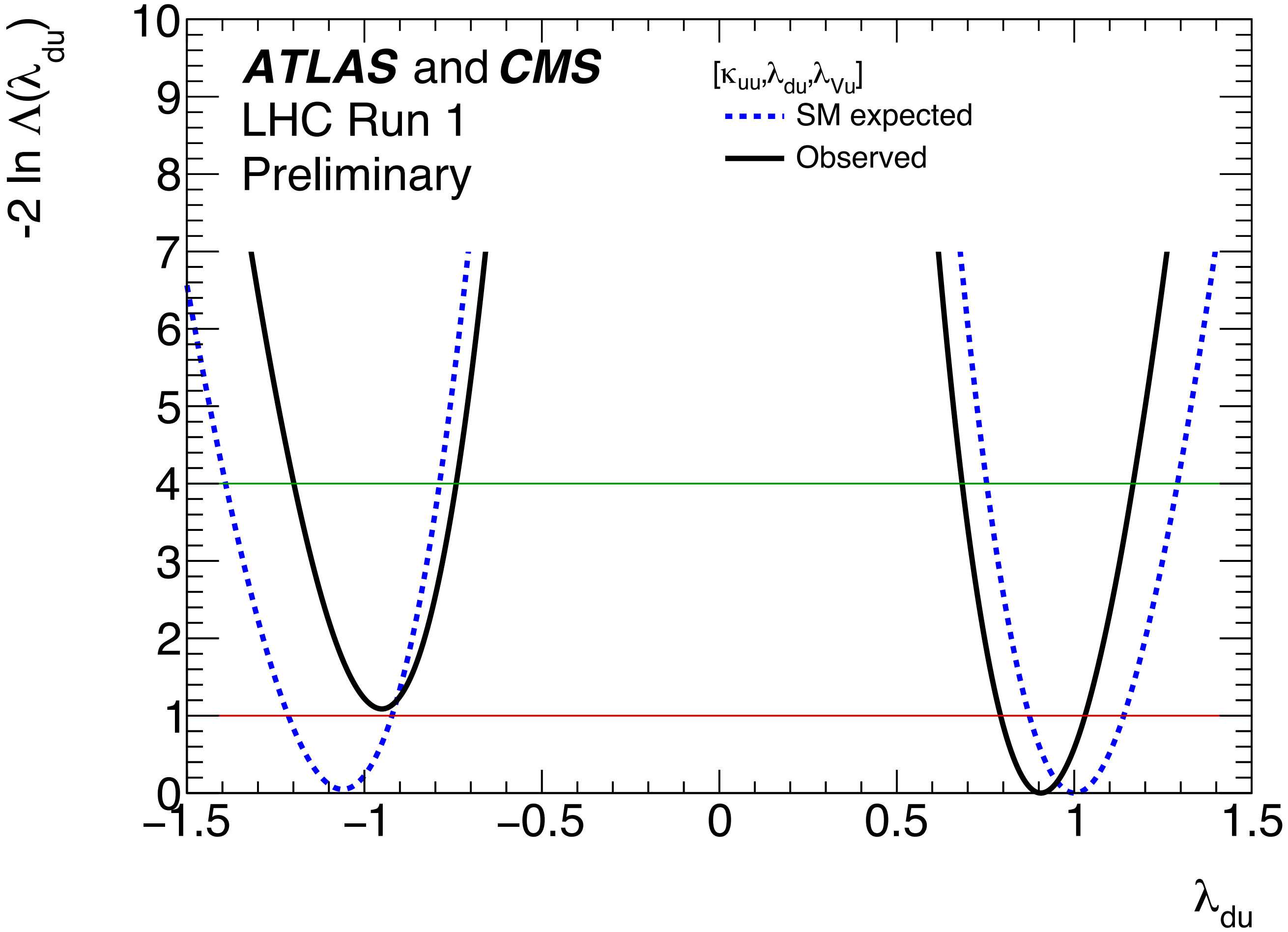


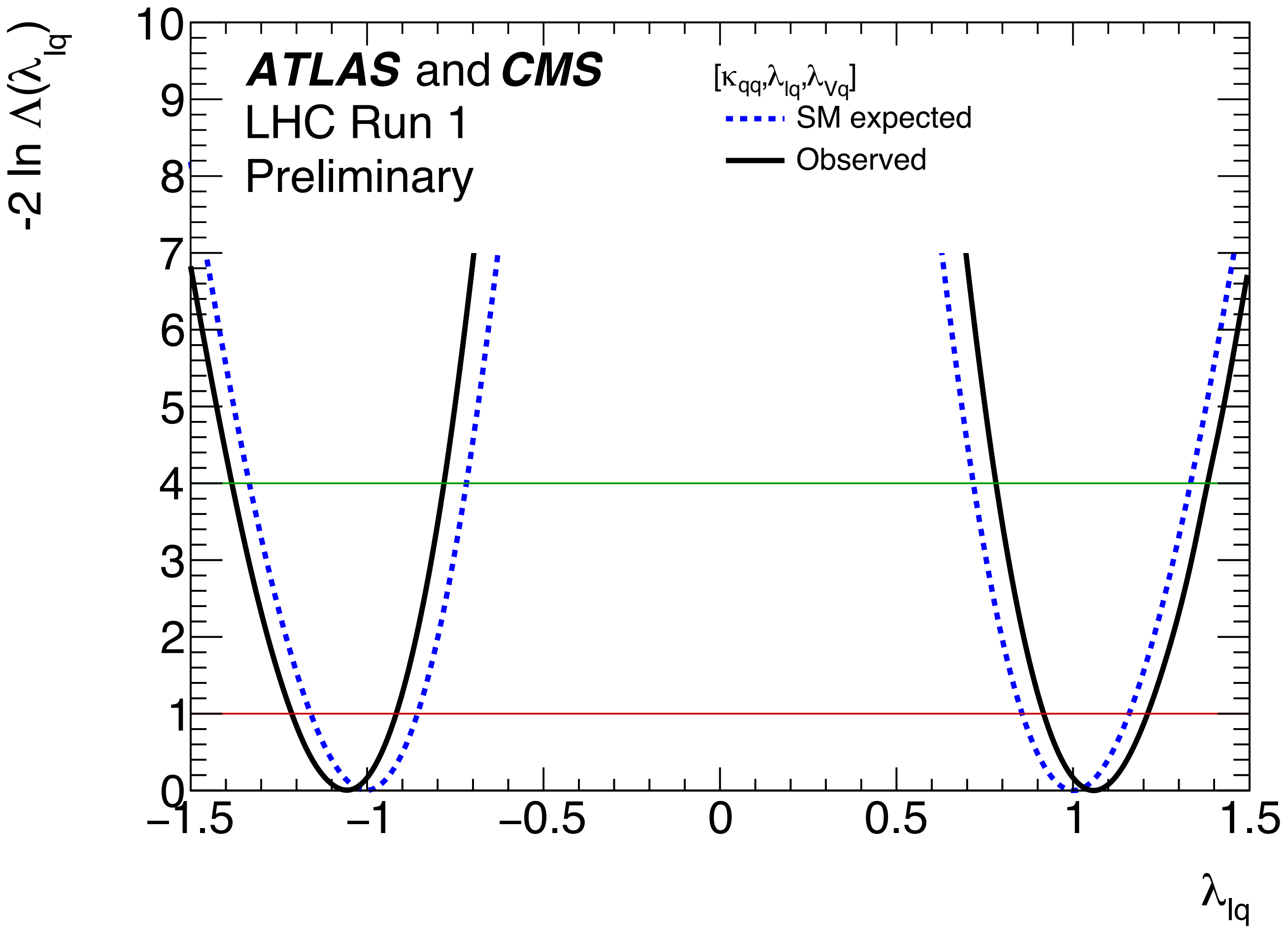
- **Nice demonstration of correlation between couplings and masses**

Zooming in on Fermion Couplings

- Several BSM theories predict different coupling structures for **up**- and **down**-type fermion
- .. or for **lepton** and **quarks**
- Assuming the SM loop structure can extract information on all those

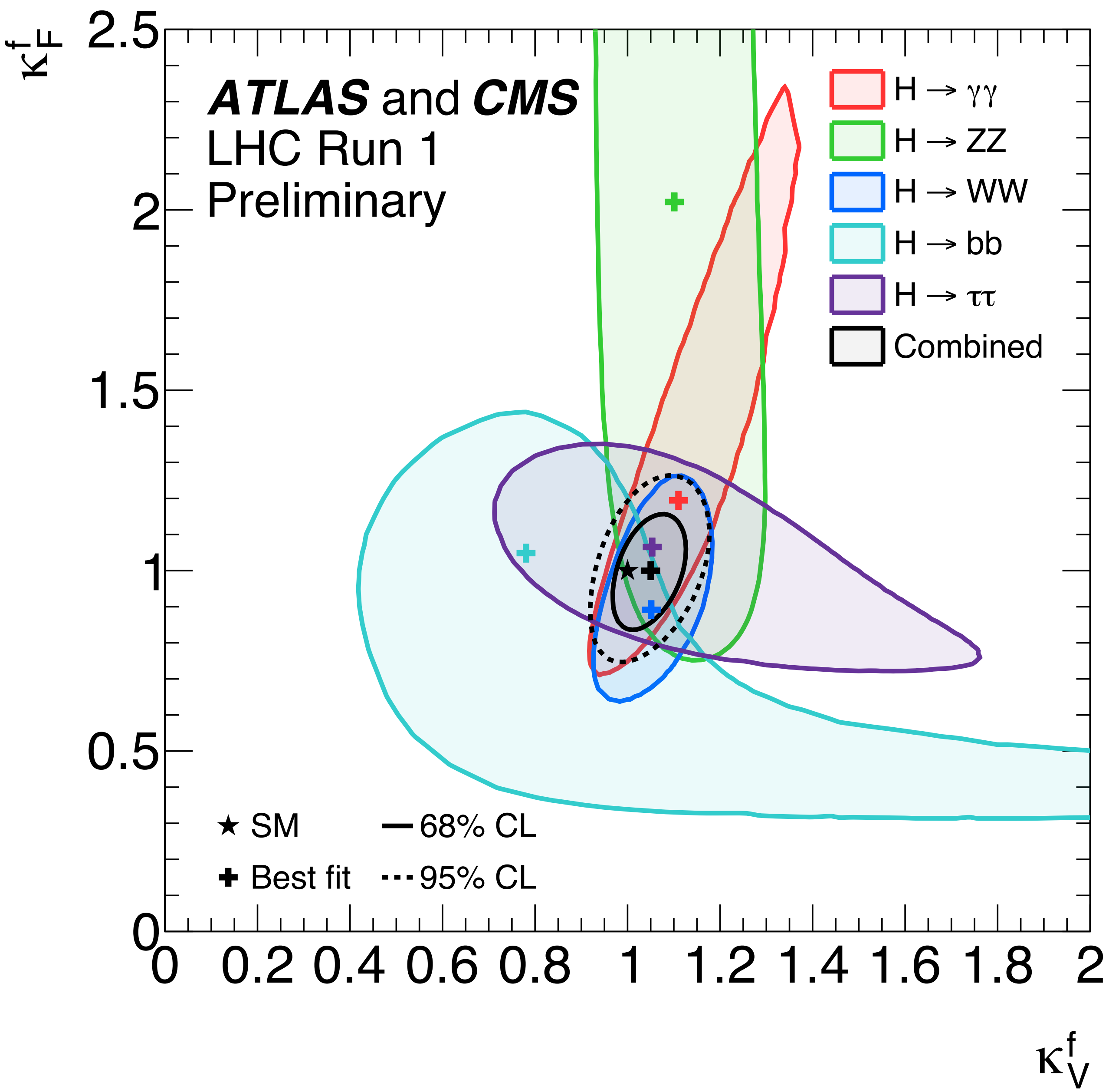
- Check the ratio of these couplings, while assuming:
  - $\kappa_W = \kappa_Z$
  - No BSM in loops

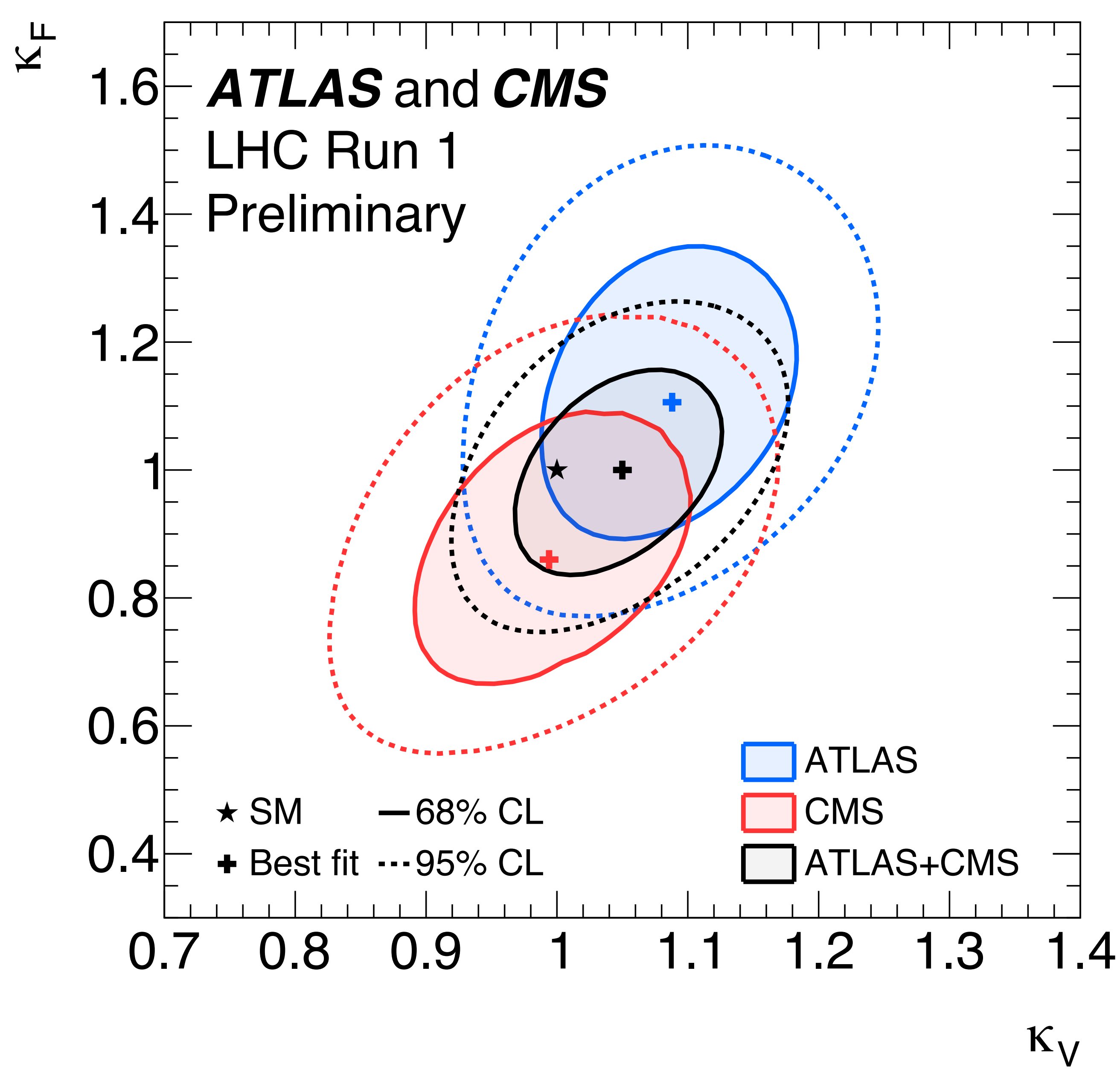




Fermion vs Boson Couplings

- Yukawa sector and Bosonic Higgs Boson couplings are of a different origin and structure !
- Therefore comparing boson to fermion couplings is a crucial test of the SM
- Good agreement with the SM expectation
- Nicely demonstrates the power of combining all analyses

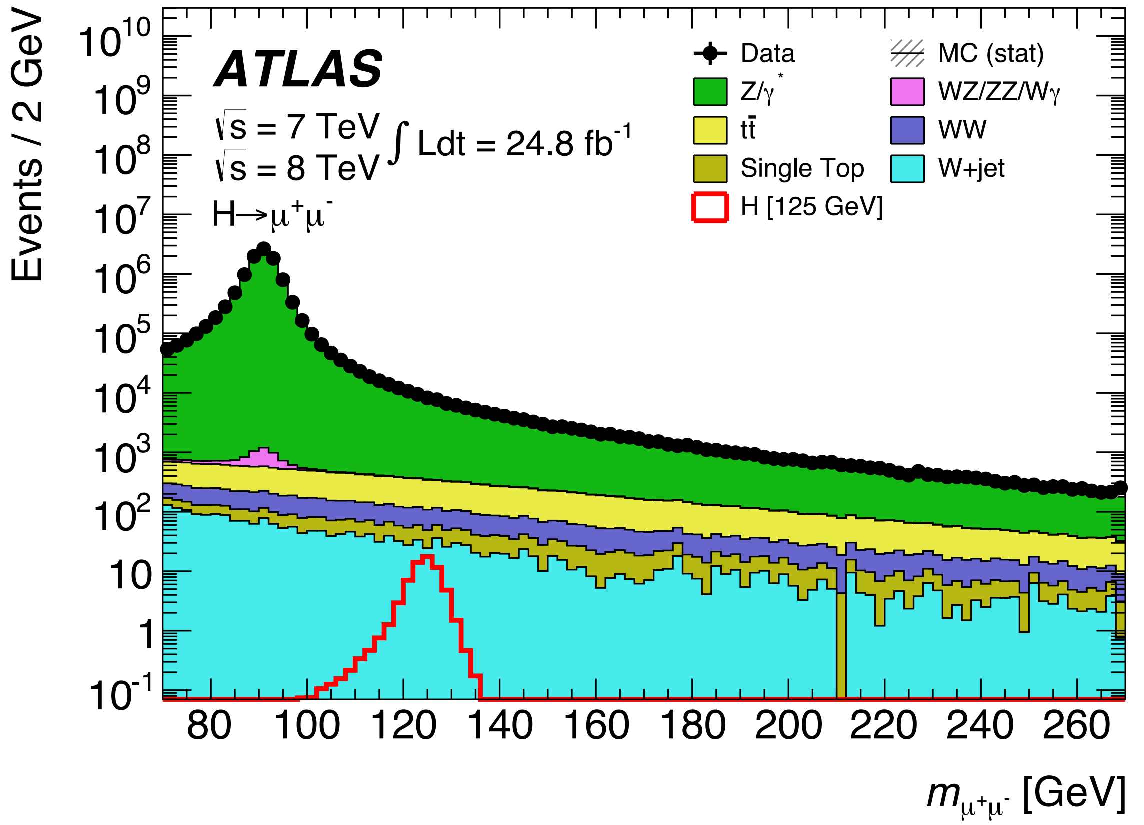


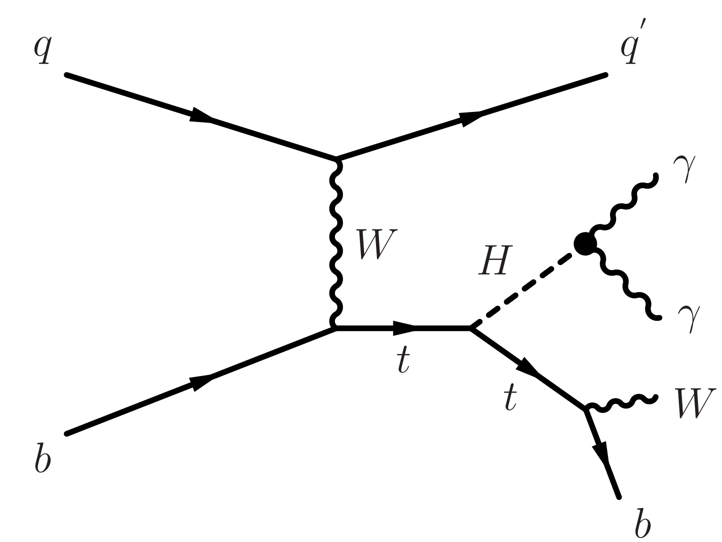


Limits on rare decay and production modes

- Besides the dominant decay and production modes many limits were set on rarer modes
- They complement the coupling measurements and are highly sensitive to BSM physics

Process	obs. (exp.) limits on μ (95% CL) ATLAS / CMS	
H→μμ	7 (7) / 7.4 (6.5)	Phys. Lett. B 738 (2014), 68-86 PLB 744 (2015) 184
H→ee	- / 3 * 10^5	PLB 744 (2015) 184
H→Zγ	11 (9) / 9 (10)	PLB 726 (2013) 587 Phys. Lett. B 732C (2014), 8-27
H→γ Z/γ*	- / 7.7 (6.4)	1507.03031
H→J/ψγ	540 / 540	Phys. Rev. Lett. 114 (2015) 121801 1507.03031
tH→t(WW/ττ)	- / 6.7 (5.0) on c_t=-1	CMS-PAS-HIG-14-026
tH→t(γγ)	- / 4.1 (4.1) on c_t=-1	CMS-PAS-HIG-14-001
BR VBF H→ inv.	28% (31%) / 57% (40%)	1508.07869 Eur. Phys. J. C 74 (2014) 2980





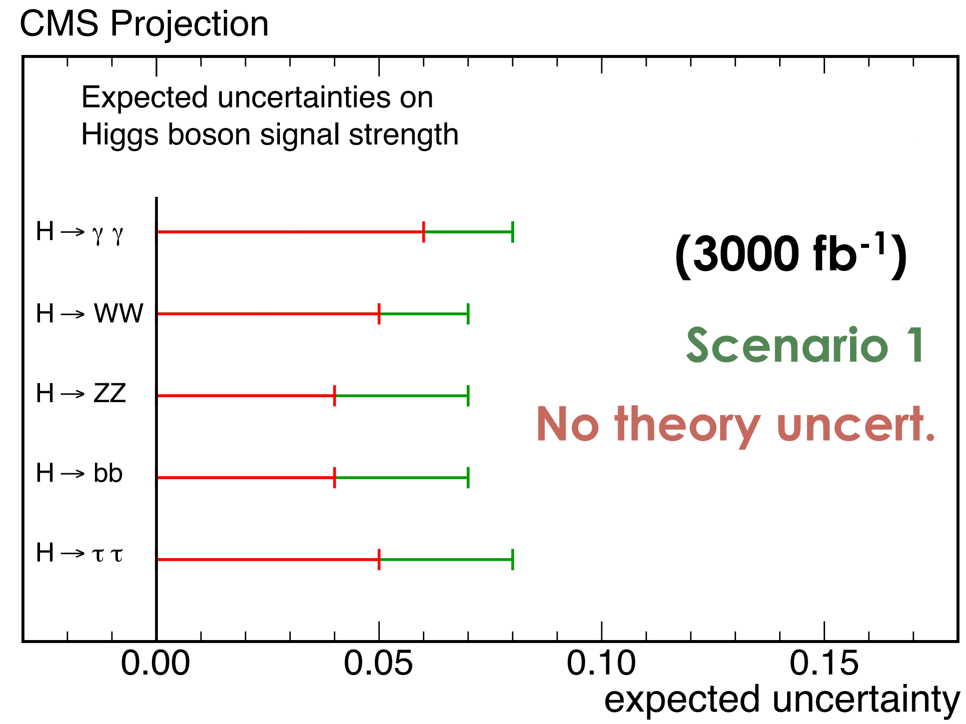
Summary

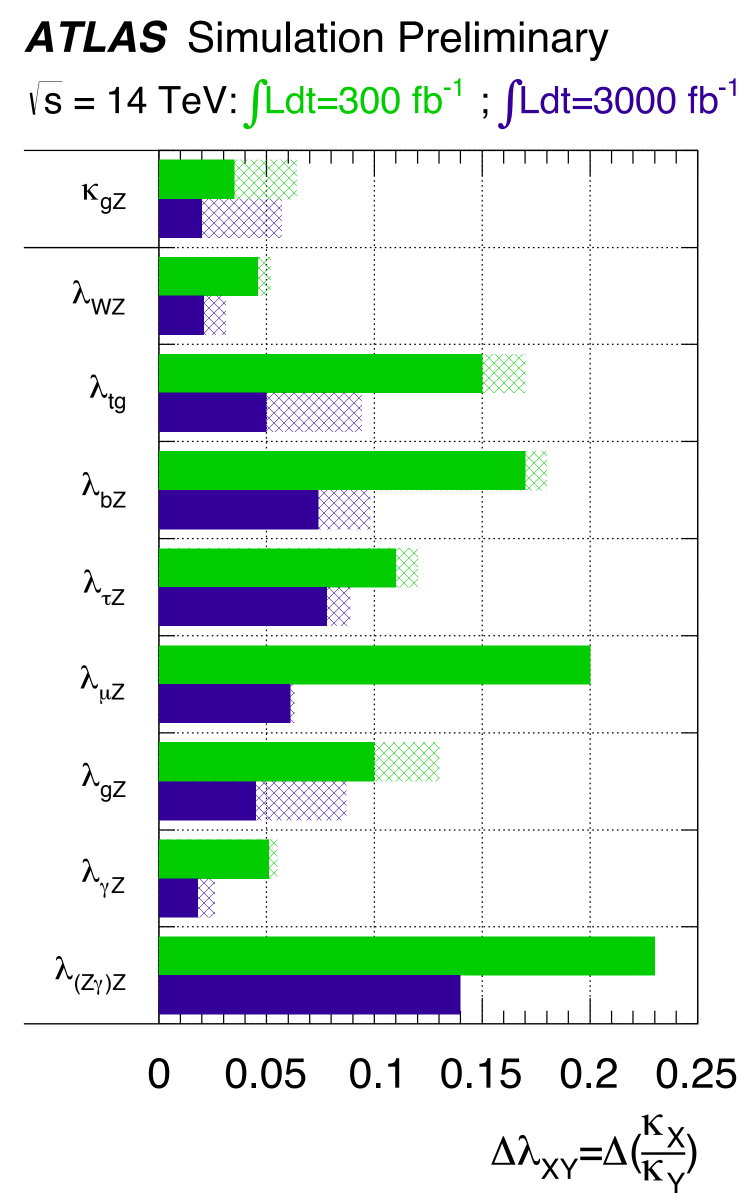
- Presented an overview over Higgs Boson coupling measurements after LHC Run 1
- Two word summary: No surprises !

- Many tests of the SM consistency from very different points view:
  - Bosons vs Fermions
  - Differences between up/down type fermions
  - Differences between leptons/quarks
  - Loop structure
  - Invisible decays
- Overall precision reaching up to 10% in the combination
- and up to ~30-50% in some the individual channels

- The future of Higgs Boson coupling measurements at the LHC has just begun !

- Targeting **O(%) precision** which is needed for sensitivity to many BSM scenarios





BACKUP

Production processes

Production process	Event generator	
	ATLAS	CMS
ggF	POWHEG [29–33]	POWHEG
VBF	POWHEG	POWHEG
WH	PYTHIA8 [34]	PYTHIA6.4 [35]
ZH ($qq \to ZH$ or $qg \to ZH$)	PYTHIA8	PYTHIA6.4
$ggZH$ ($gg \to ZH$)	POWHEG	See text
ttH	POWHEL [43]	PYTHIA6.4
tHq ($qb \to tHq$)	MADGRAPH [45]	aMC@NLO [28]
tHW ($gb \to tHW$)	aMC@NLO	aMC@NLO
bbH	PYTHIA8	PYTHIA6, aMC@NLO

Production process	Cross section [pb]		Order of calculation
	$\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV	
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)
[$gg \to ZH$	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	

- ggF p_T distribution reweighted to match HRES 2.1 (NNLO + NNLL)
  - ggF + 2 Jets reweighted to MiNLO

Theoretical uncertainty correlations

- PDF uncertainties:
  - Correlated across exp. for same channel but decorrelated across channels
  - WH & ZH correlated
  - ggF & ttH anticorrelated (from theoretical point of view expect about 60% anticorr.)
- QCD & UEPS correlated across experiments but decorrelated across channels
- Effect of BR uncertainty correlations mostly negligible

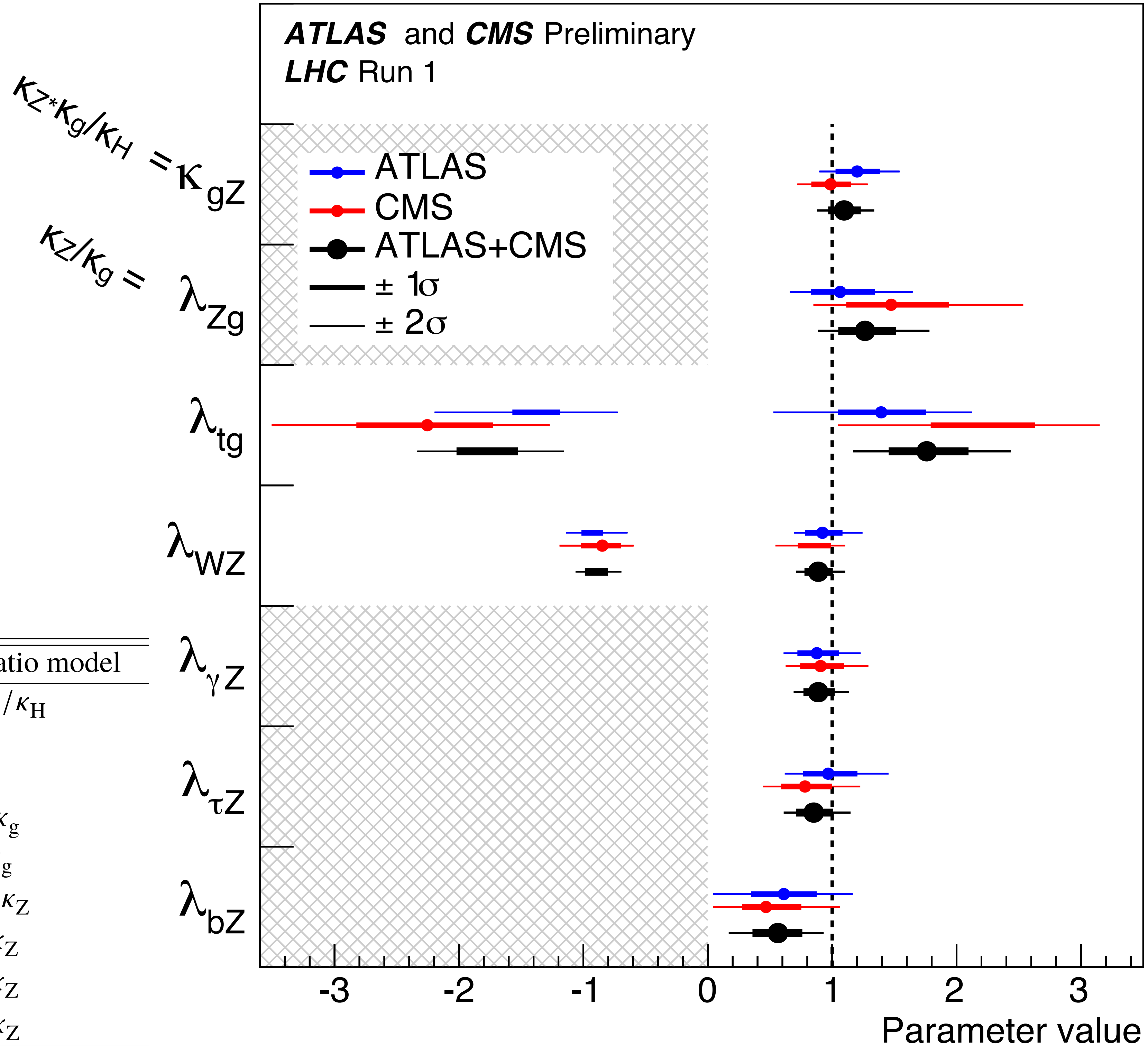
- Backgrounds:
  - Correlated theory uncertainties across experiments for
    - ZZ continuum (4l)
    - ttW & ttZ backgrounds (ttH)

Signal parametrization

Production	Loops	Interference	Multiplicative factor
$\sigma(\text{ggF})$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(q\bar{q} \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq')$	–	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
Partial decay width			
$\Gamma_{b\bar{b}}$	–	–	$\sim \kappa_b^2$
Γ_{WW}	–	–	$\sim \kappa_W^2$
Γ_{ZZ}	–	–	$\sim \kappa_Z^2$
$\Gamma_{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
Total width for $\text{BR}_{\text{BSM}} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Ratios of coupling modifiers

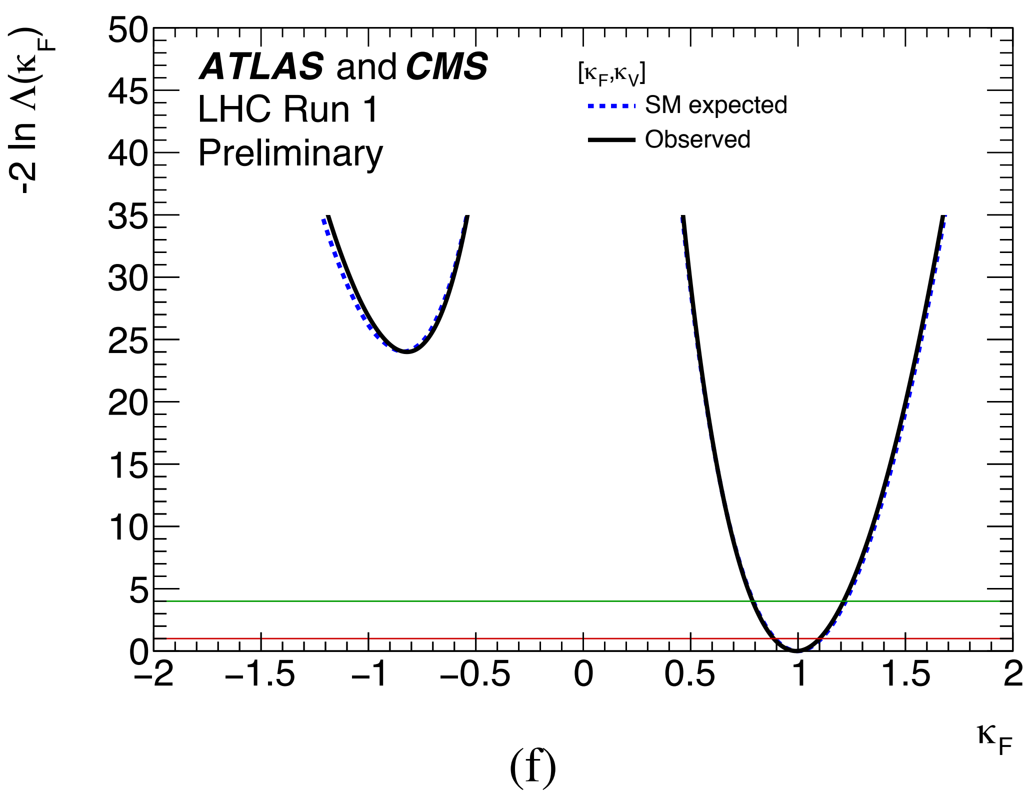
- An alternative generic parametrisation
- Measurement of ratio sof coupling modifiers

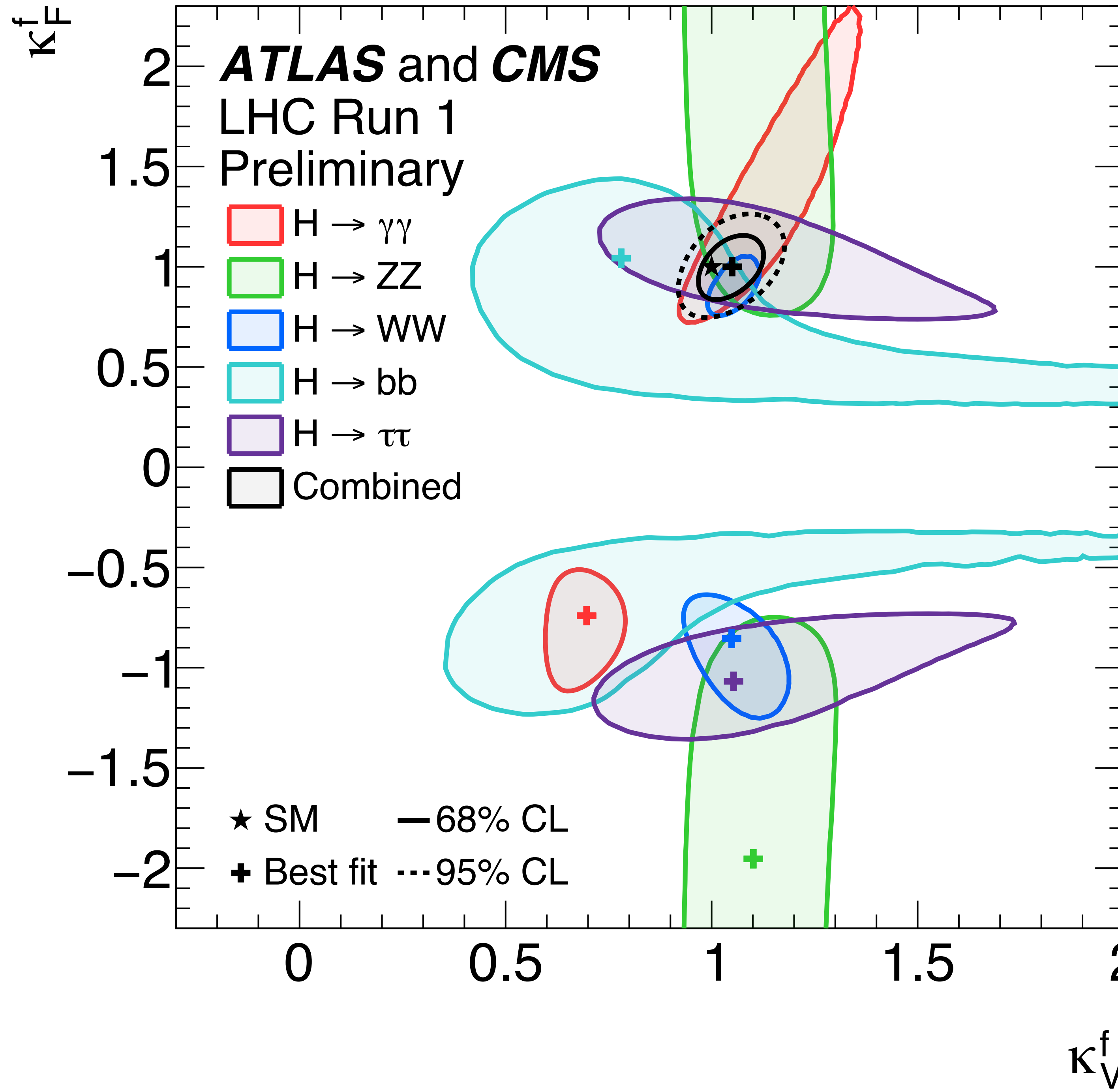


σ and BR ratio model	Coupling-strength ratio model
$\sigma(gg \to H \to ZZ)$	$\kappa_{gZ} = \kappa_g \cdot \kappa_Z/\kappa_H$
$\sigma_{VBF}/\sigma_{ggF}$	
σ_{WH}/σ_{ggF}	
σ_{ZH}/σ_{ggF}	$\lambda_{Zg} = \kappa_Z/\kappa_g$
$\sigma_{ttH}/\sigma_{ggF}$	$\lambda_{tg} = \kappa_t/\kappa_g$
BR^{WW}/BR^{ZZ}	$\lambda_{WZ}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

Fermion vs Boson Couplings

- Allowing for a relative sign between fermionic and bosonic couplings
  - disfavoured nearly at the 5 σ level

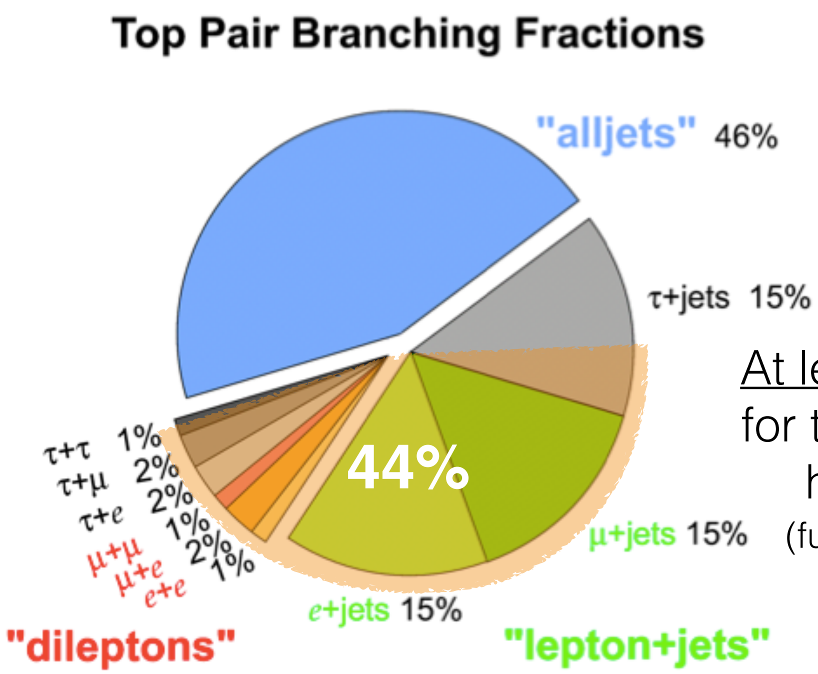




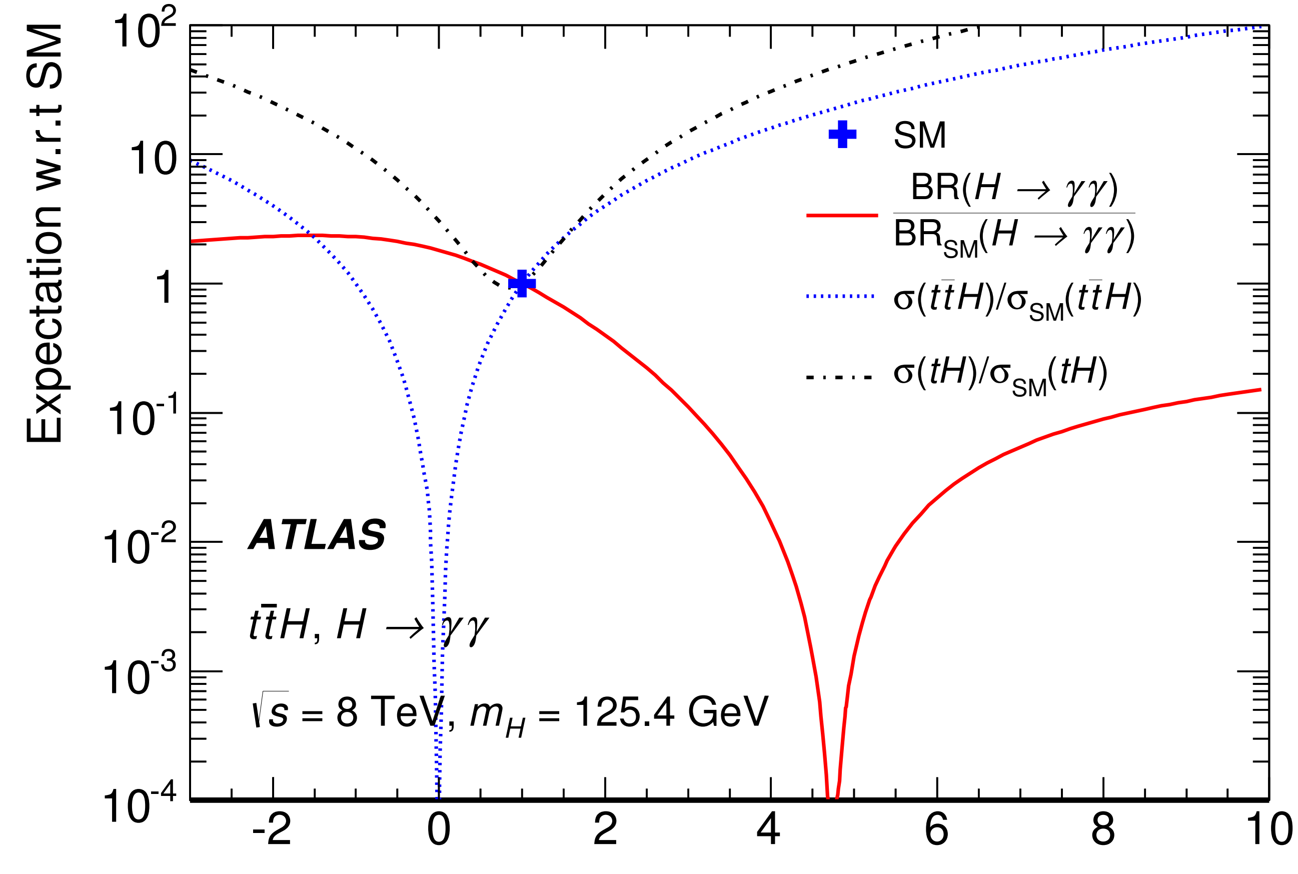
Compatibility with the SM

Model	p-value	DoF	Parameters
Global signal strength	34%	1	μ
Production processes	24%	5	$\mu_{\rm ggF}, \mu_{\rm VBF}, \mu_{WH}, \mu_{ZH}, \mu_{ttH}$
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	$\sigma(gg \to H \to ZZ)$, $\sigma_{\rm VBF}/\sigma_{\rm ggF}$, $\sigma_{WH}/\sigma_{\rm ggF}$, $\sigma_{ZH}/\sigma_{\rm ggF}$, $\sigma_{ttH}/\sigma_{\rm ggF}$, ${\rm BR}^{WW}/{\rm BR}^{ZZ}$, ${\rm BR}^{\gamma\gamma}/{\rm BR}^{ZZ}$, ${\rm BR}^{\tau\tau}/{\rm BR}^{ZZ}$, ${\rm BR}^{b\bar{b}}/{\rm BR}^{ZZ}$
Ratios of σ and BR relative to $\sigma(gg \to H \to WW)$	16%	9	$\sigma(gg \to H \to WW)$, $\sigma_{\rm VBF}/\sigma_{\rm ggF}$, $\sigma_{WH}/\sigma_{\rm ggF}$, $\sigma_{ZH}/\sigma_{\rm ggF}$, $\sigma_{ttH}/\sigma_{\rm ggF}$, ${\rm BR}^{ZZ}/{\rm BR}^{WW}$, ${\rm BR}^{\gamma\gamma}/{\rm BR}^{WW}$, ${\rm BR}^{\tau\tau}/{\rm BR}^{WW}$, ${\rm BR}^{b\bar{b}}/{\rm BR}^{WW}$
Coupling ratios	13%	7	$\kappa_{gZ}, \lambda_{Zg}, \lambda_{tg}, \lambda_{WZ}, \lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{bZ}$
Couplings, SM loops	65%	5	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b$
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

ttH



At least one lepton required for triggering and to reduce hadronic background
(full hadronic only with H→$\gamma\gamma$ to maximise acceptance)



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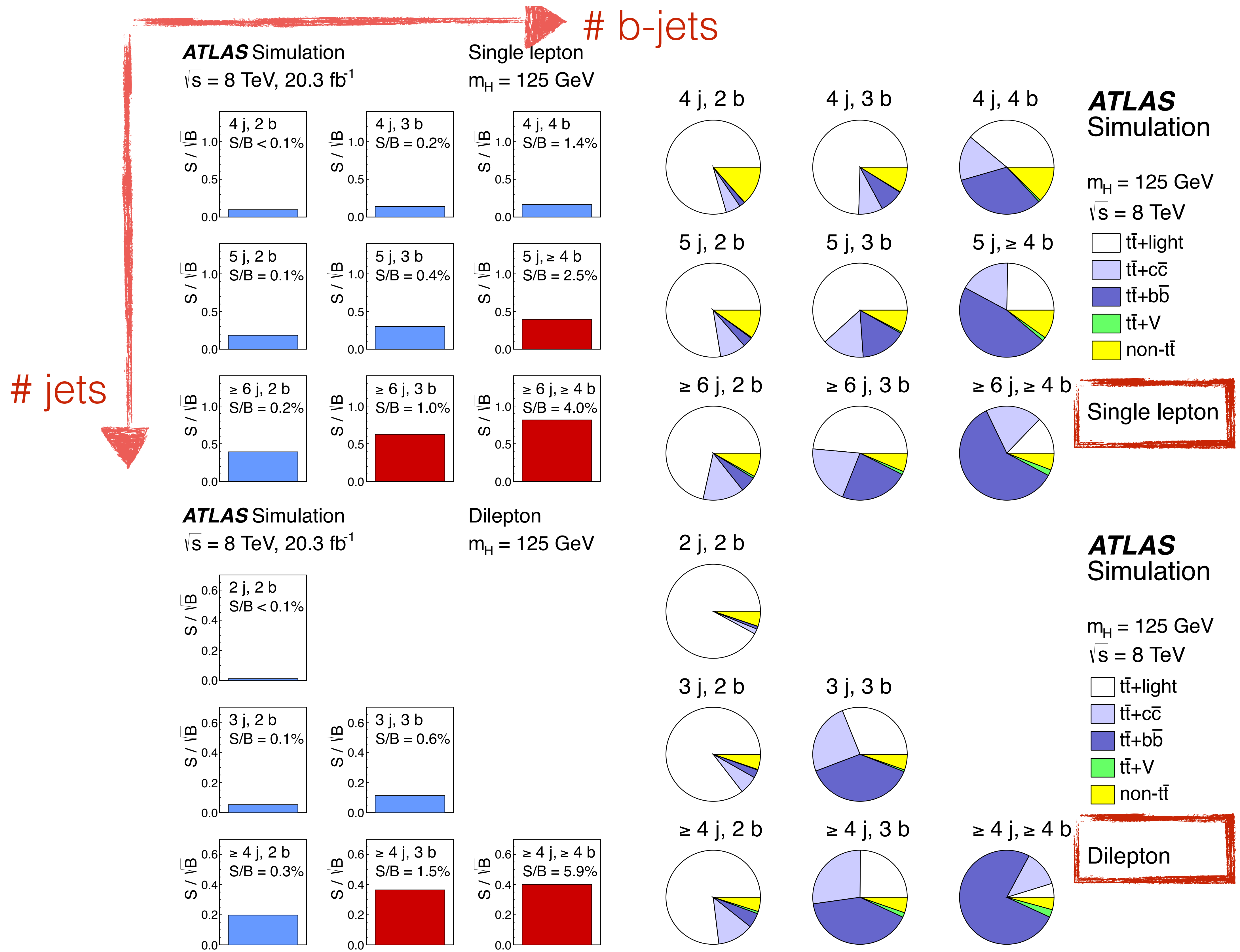
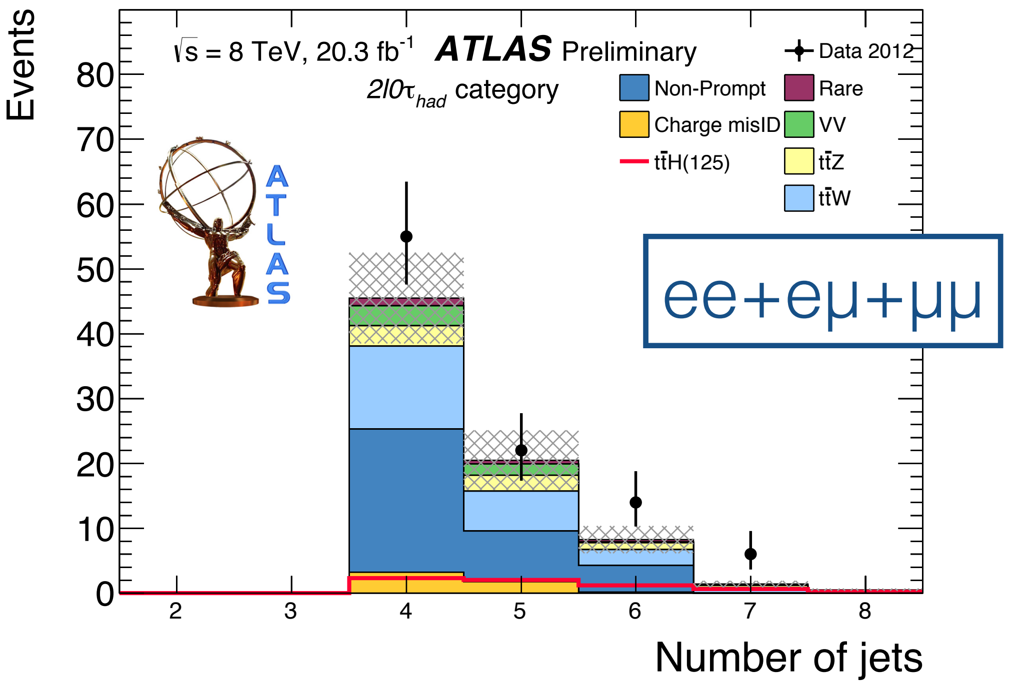
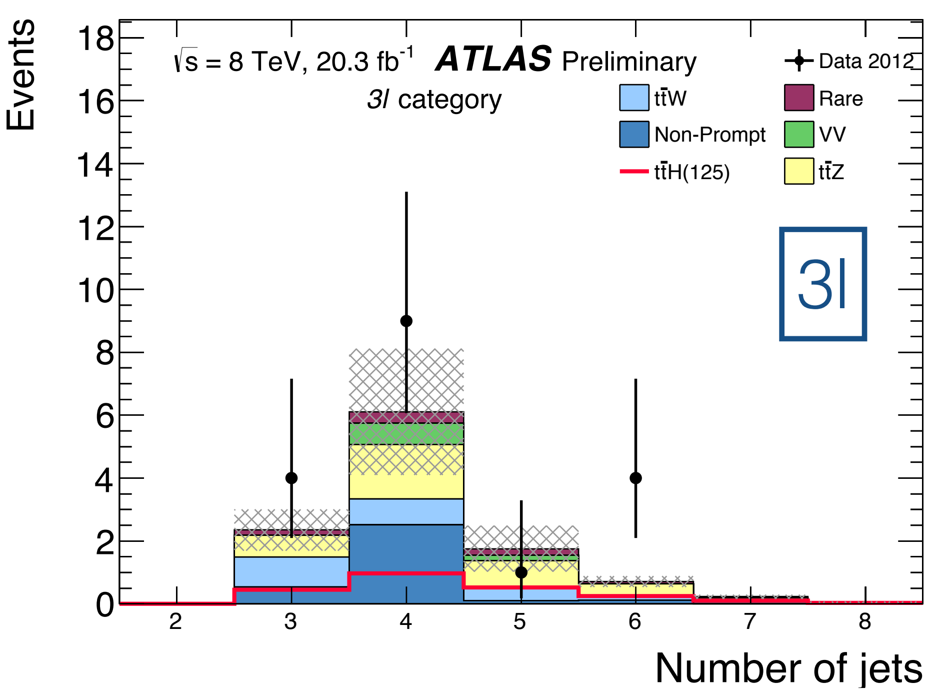
- Very complex channel
- Many final states need to be combined in order to gain sensitivity
- top quark Yukawa coupling has direct influence on SM expectation of ggF production mechanism

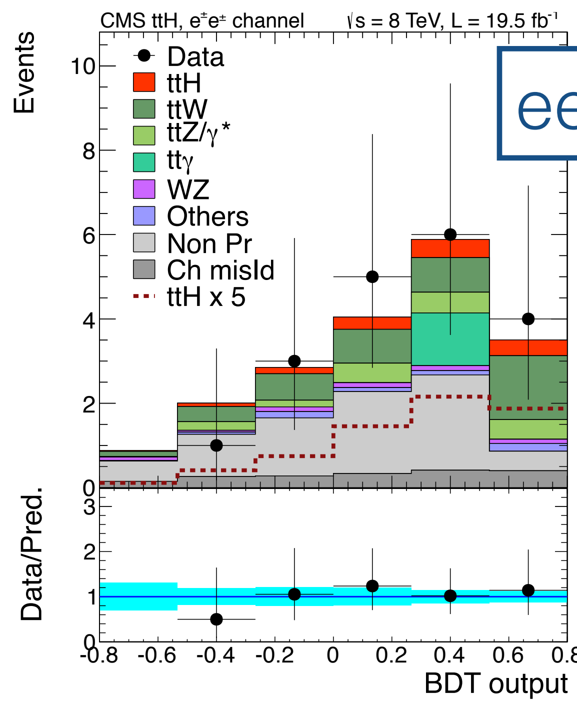
Background composition, example ttH(->bb)

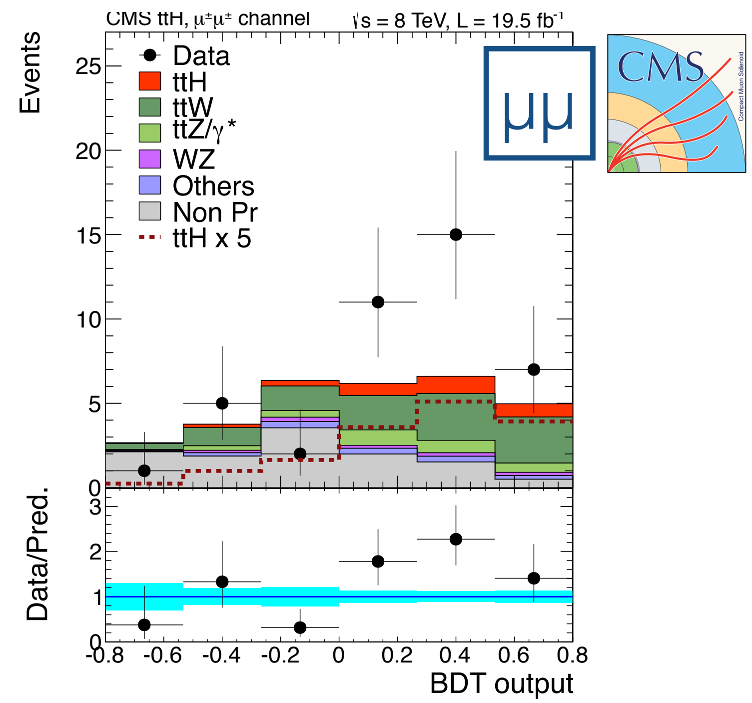


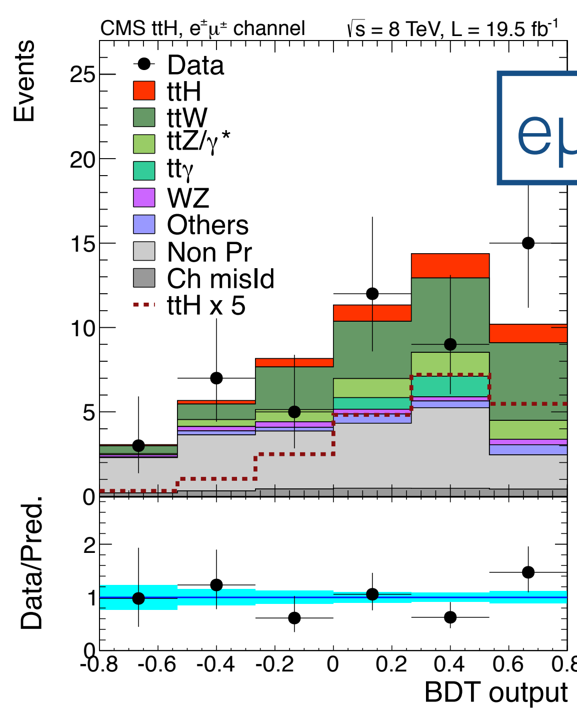
ttH (->leptons)

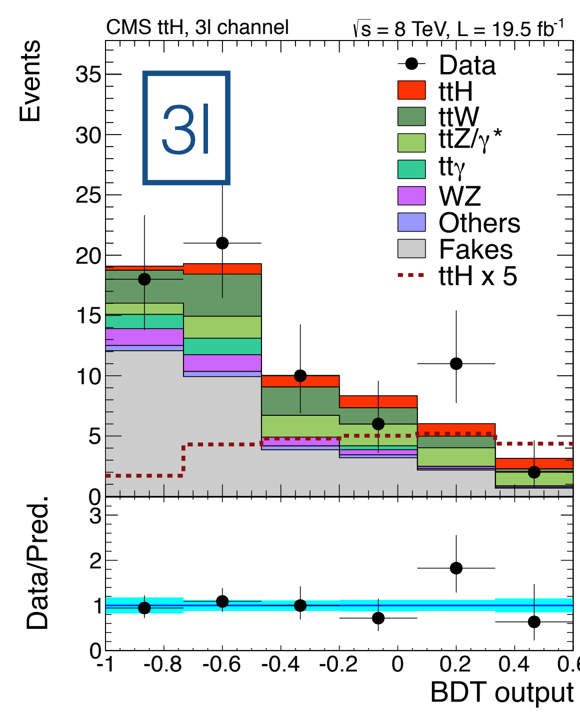

√s = 8 TeV, 20.3 fb⁻¹ ATLAS Preliminary
2l0τhad category
Data 2012
Non-Prompt
Rare
Charge misID
VV
tt̄H(125)
tt̄Z
tt̄W
ee+eμ+μμ
Events
Number of jets


√s = 8 TeV, 20.3 fb⁻¹ ATLAS Preliminary
3l category
Data 2012
tt̄W
Rare
Non-Prompt
VV
tt̄H(125)
tt̄Z
3l
Events
Number of jets

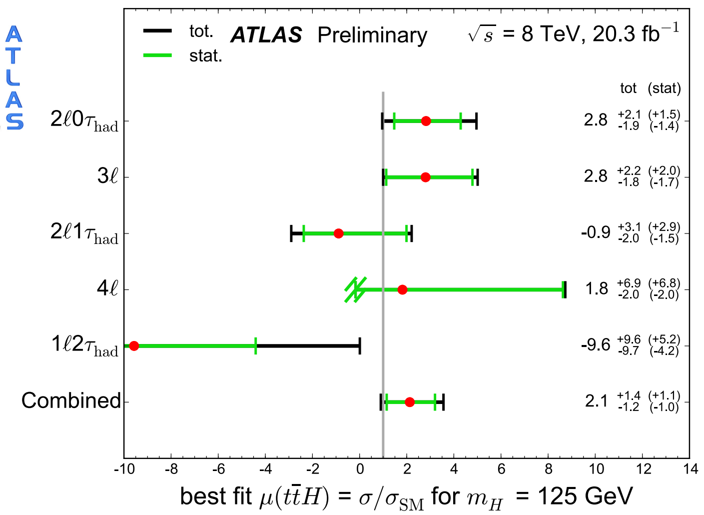

CMS ttH, e±e± channel
√s = 8 TeV, L = 19.5 fb⁻¹
Data
ttH
ttW
ttZ/γ*
ttγ
WZ
Others
Non Pr
Ch misId
ttH x 5
ee
Events
Data/Pred.
BDT output

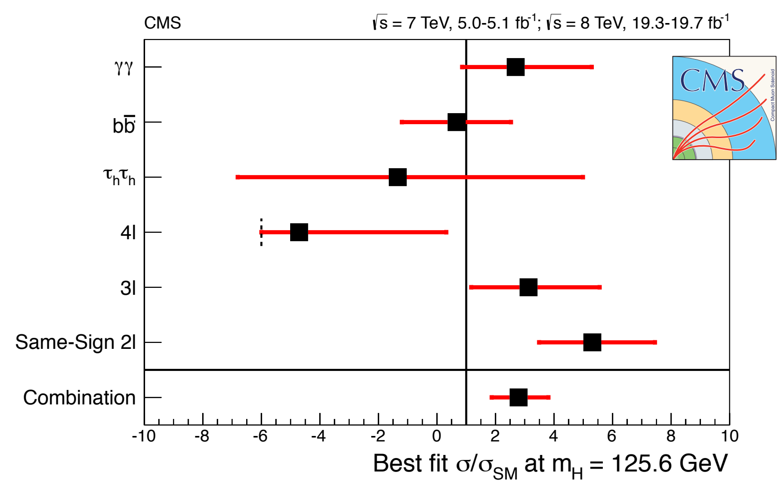

CMS ttH, μ±μ± channel
√s = 8 TeV, L = 19.5 fb⁻¹
Data
ttH
ttW
ttZ/γ*
WZ
Others
Non Pr
ttH x 5
μμ
Events
Data/Pred.
BDT output


CMS ttH, e±μ± channel
√s = 8 TeV, L = 19.5 fb⁻¹
Data
ttH
ttW
ttZ/γ*
ttγ
WZ
Others
Non Pr
Ch misId
ttH x 5
eμ
Events
Data/Pred.
BDT output


CMS ttH, 3l channel
√s = 8 TeV, L = 19.5 fb⁻¹
Data
ttH
ttW
ttZ/γ*
ttγ
WZ
Others
Fakes
ttH x 5
3l
Events
Data/Pred.
BDT output

ttH (->leptons)





Category	Higgs boson decay mode WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{had}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell 1\tau_{had}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell 2\tau_{had}$	4%	93%	0%	3%

Category	Signature	Trigger	Signature
H → Leptons H → WW H → ττ H → ZZ	Same-Sign Dilepton ($t\bar{t}H \to \ell^{\pm}\nu\ell^{\pm}[\nu]jjj[j]bb$)	Dilepton	2 e/μ, $p_T > 20$ GeV ≥4 jets + ≥1 b-tags, $p_T > 25$ GeV
	3 Lepton ($t\bar{t}H \to \ell\nu\ell[\nu]\ell[\nu]j[j]bb$)	Dilepton, Trielectron	1 e/μ, $p_T > 20$ GeV 1 e/μ, $p_T > 10$ GeV 1 e(μ), $p_T > 7(5)$ GeV ≥2 jets + ≥1 b-tags, $p_T > 25$ GeV
	4 Lepton ($t\bar{t}H \to \ell\nu\ell\nu\ell[\nu]\ell[\nu]bb$)	Dilepton, Trielectron	1 e/μ, $p_T > 20$ GeV 1 e/μ, $p_T > 10$ GeV 2 e(μ), $p_T > 7(5)$ GeV ≥2 jets + ≥1 b-tags, $p_T > 25$ GeV

Dominant Backgrounds
Non-prompt and charge-flip from ttbar, ttV
Non-prompt from ttbar, ttV, WZ
ttV, ZZ