Overview of SM Higgs ATLAS and CMS results

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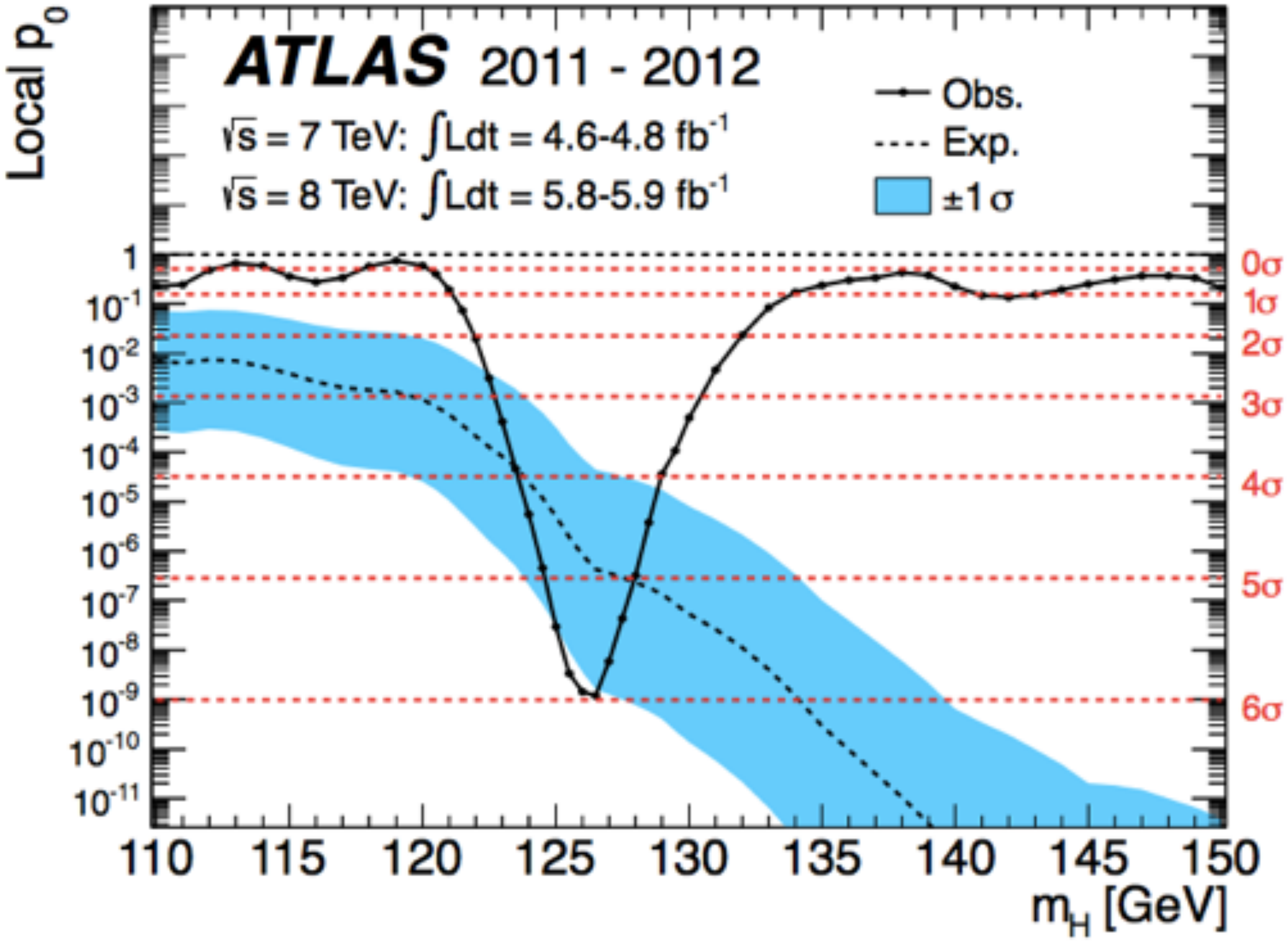
LoopFest 2017

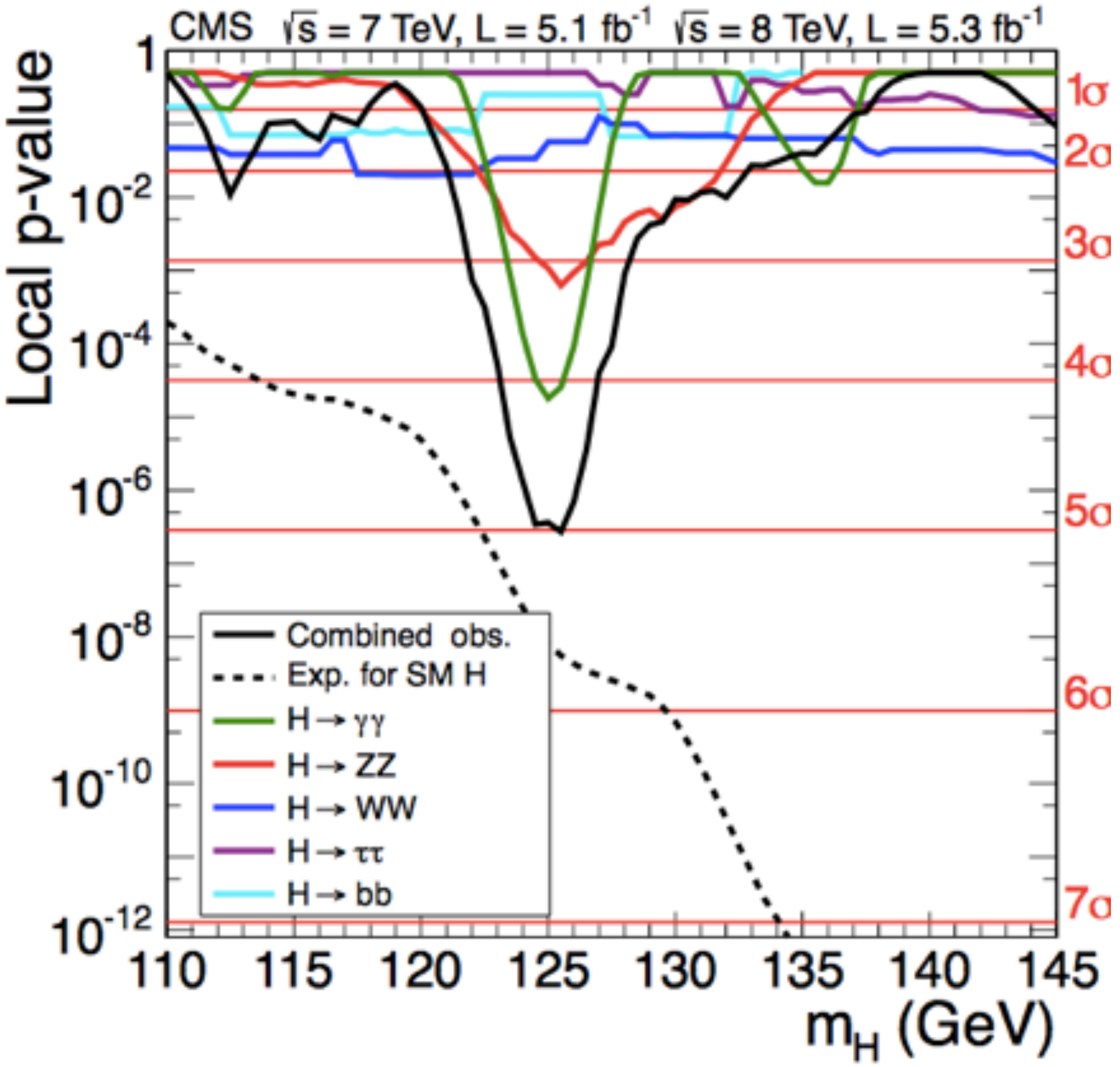
Higgs discovery at the LHC

A scalar boson compatible with the SM Higgs has been discovered in Run1 as shown by the combination of ATLAS and CMS Run1 results

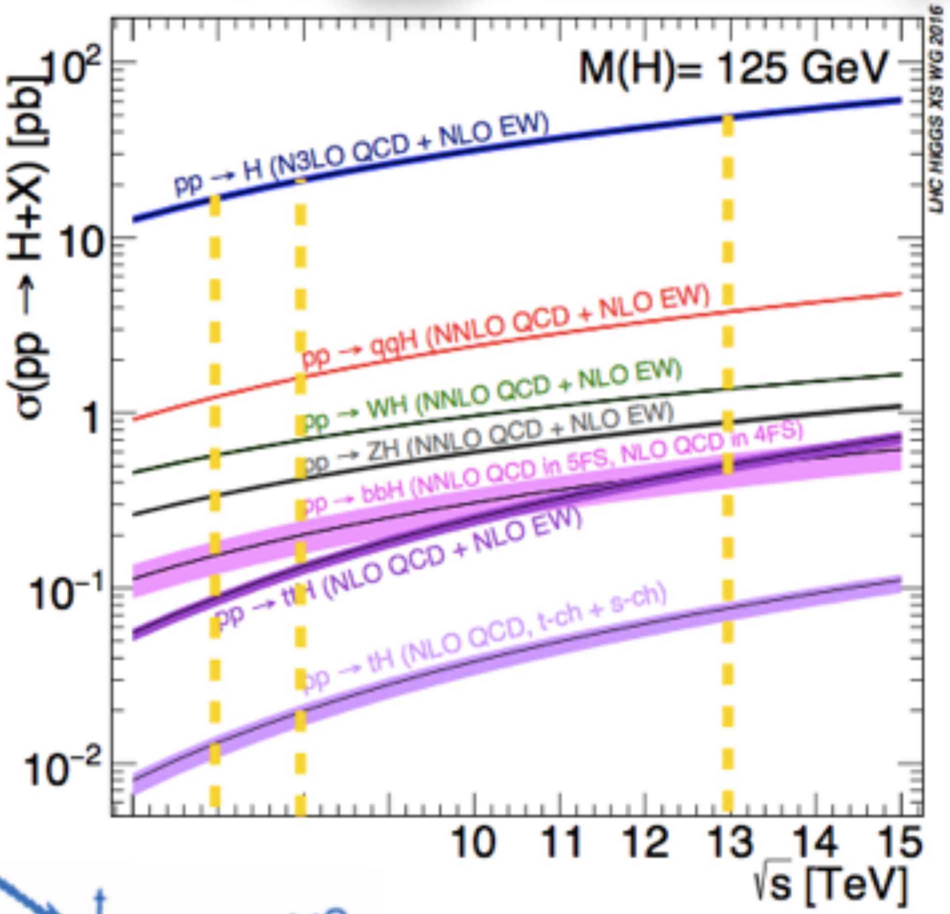
Greatest achievement of Run1

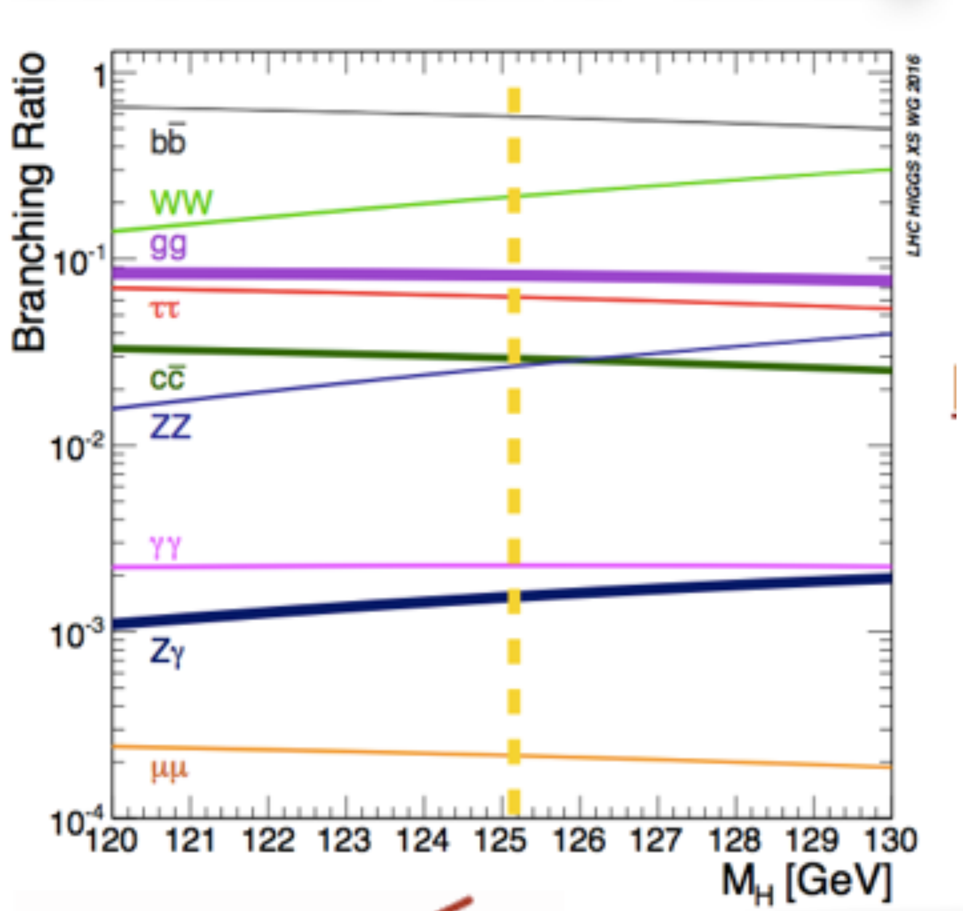
- concentrated effort on its properties:
  - magnitude of couplings
  - mass measurements
  - spin/CP

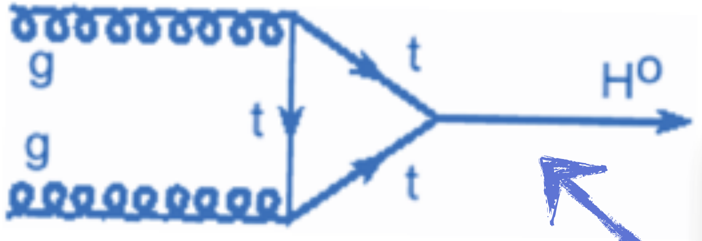




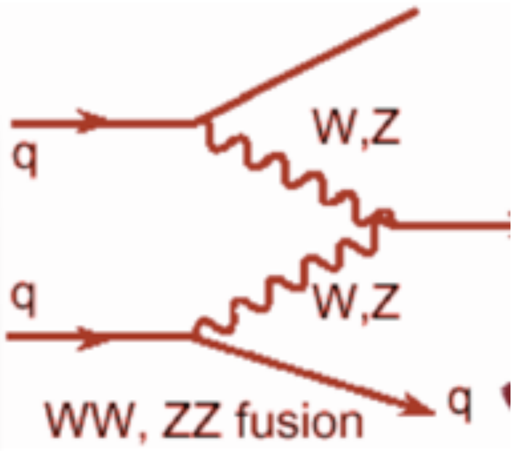
Higgs boson production and decay







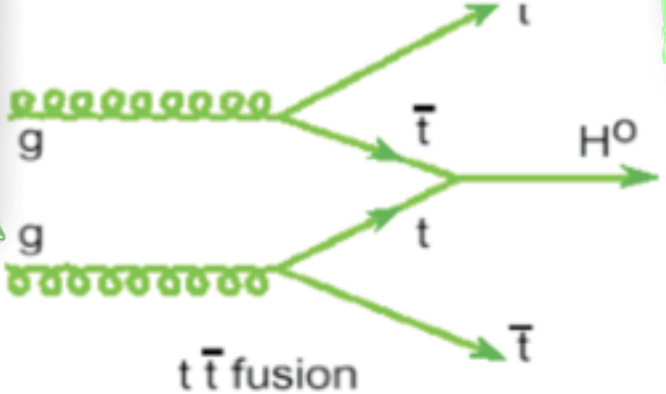
m_H=125.09 GeV	σ(pb)13 TeV
ggF	**49**
VBF	**3.8**
Z(W)H	**0.9(1.4)**
ttH	**0.5**



WW, ZZ fusion

	BR(%)
bb	**57**
WW	**22**
ττ	**6.2**
ZZ	**2.8**
$\gamma\gamma$	**0.23**
$Z\gamma$	**0.15**

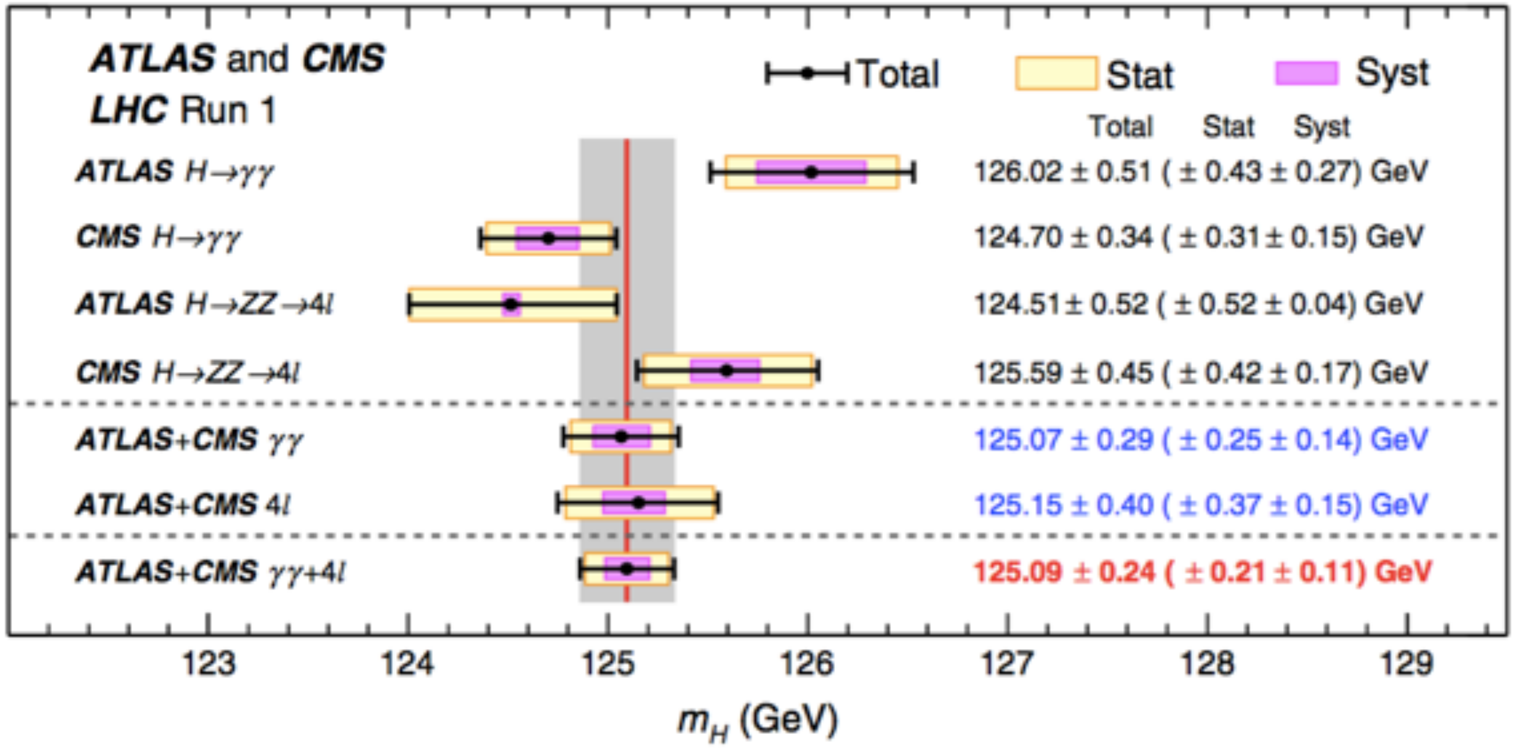
W, Z bremsstrahlung



$t\bar{t}$ fusion

Higgs mass

PRL 114,191803



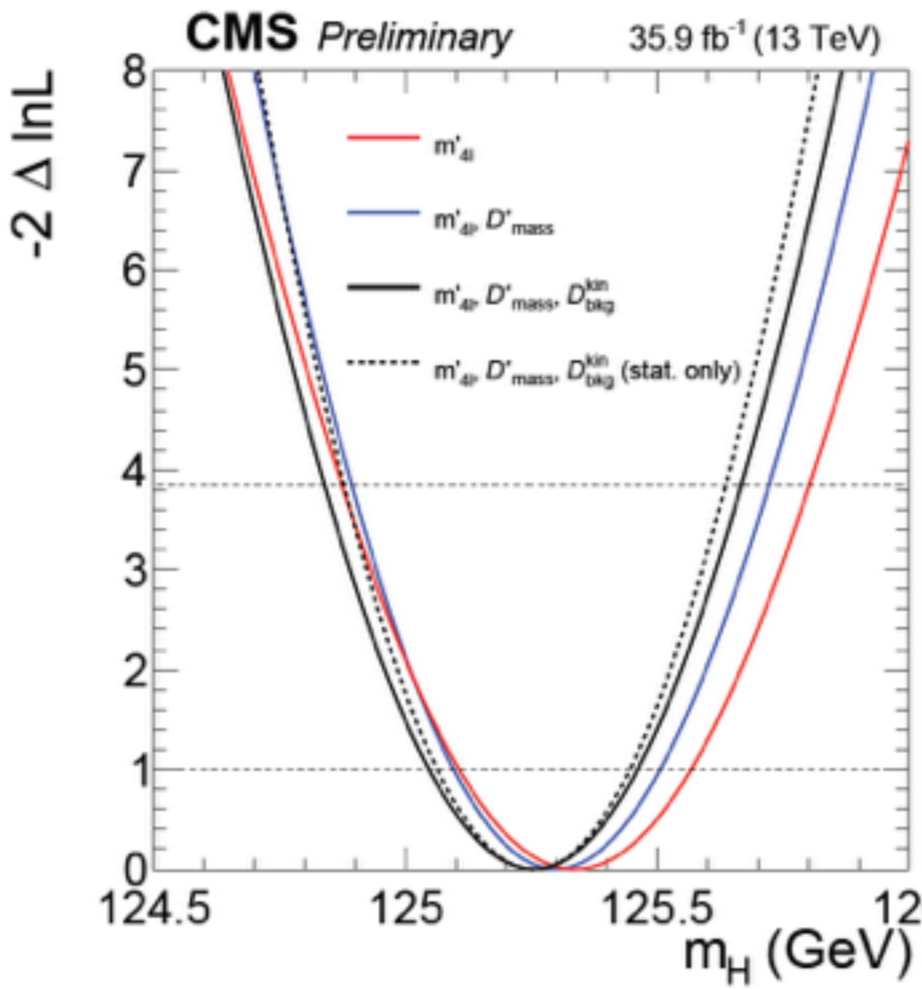
Run1 CMS+ATLAS combination

Measured in γγ and 4l channels:

best mass resolution.

Mass within 0.2% precision.

CMS-PAS-HIG-16-041



Predominantly limited by statistical uncertainty

m_H=125.09±0.21(stat)±0.11(syst) GeV

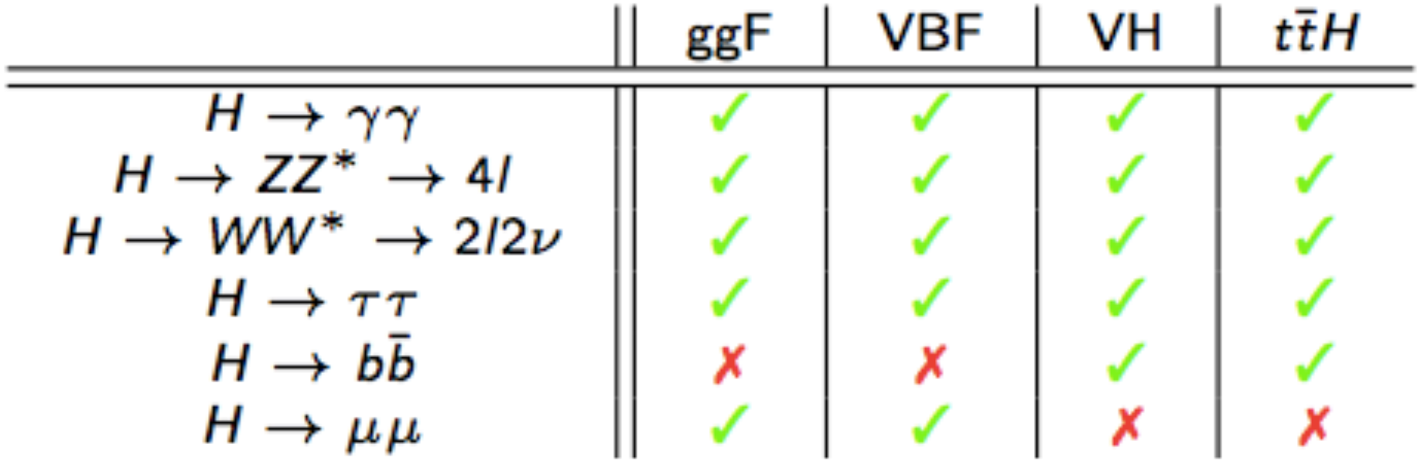
Run2 CMS Measures in 4l channel

with 35.9 fb^{-1} at 13 TeV

m_H=125.26±0.20(stat)±0.08(syst) GeV

comparable with Run1 combination

ATLAS and CMS Run1 combination



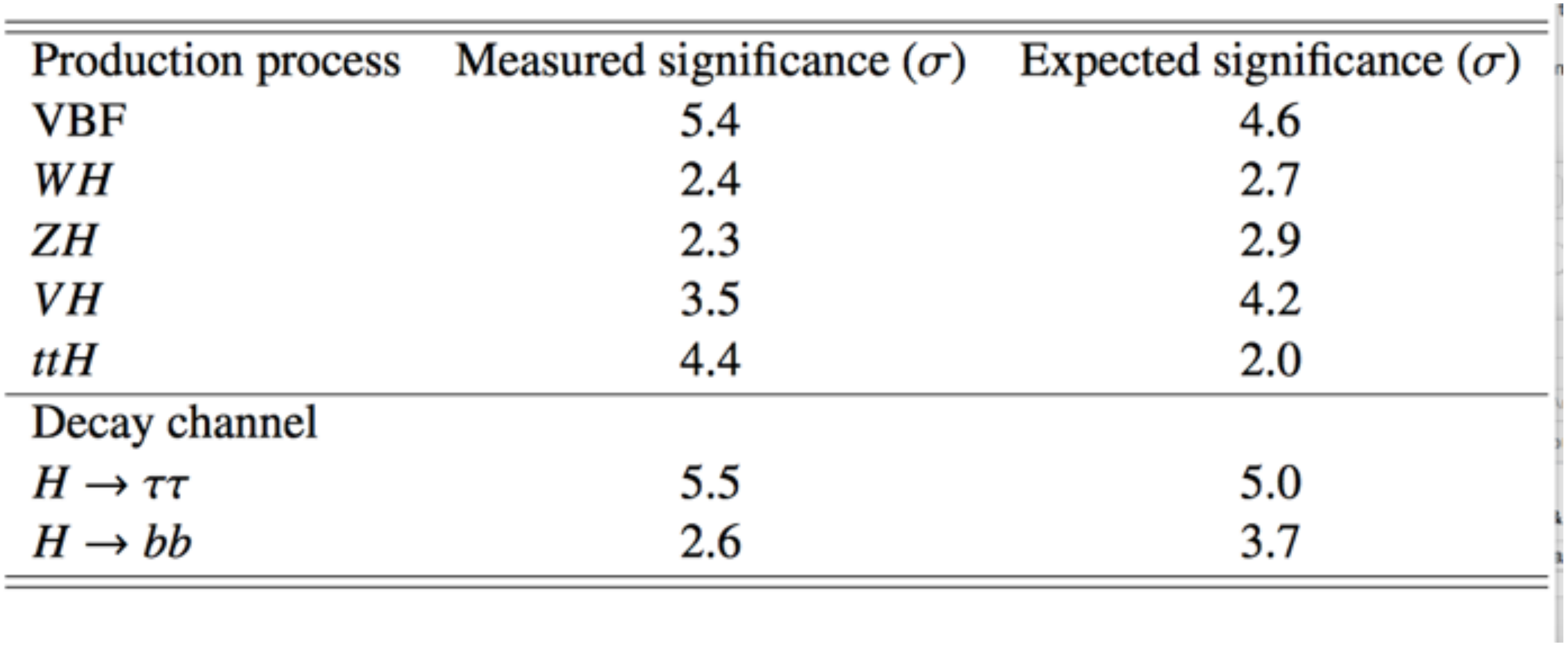
	ggF	VBF	VH	$t\bar{t}H$
$H \to \gamma\gamma$	✓	✓	✓	✓
$H \to ZZ^* \to 4l$	✓	✓	✓	✓
$H \to WW^* \to 2l2\nu$	✓	✓	✓	✓
$H \to \tau\tau$	✓	✓	✓	✓
$H \to b\bar{b}$	✗	✗	✓	✓
$H \to \mu\mu$	✓	✓	✗	✗

Observation of

- ggF,VBF production
- H →γγ, ZZ, WW, ττ decay

Evidence for

- VH, ttH production



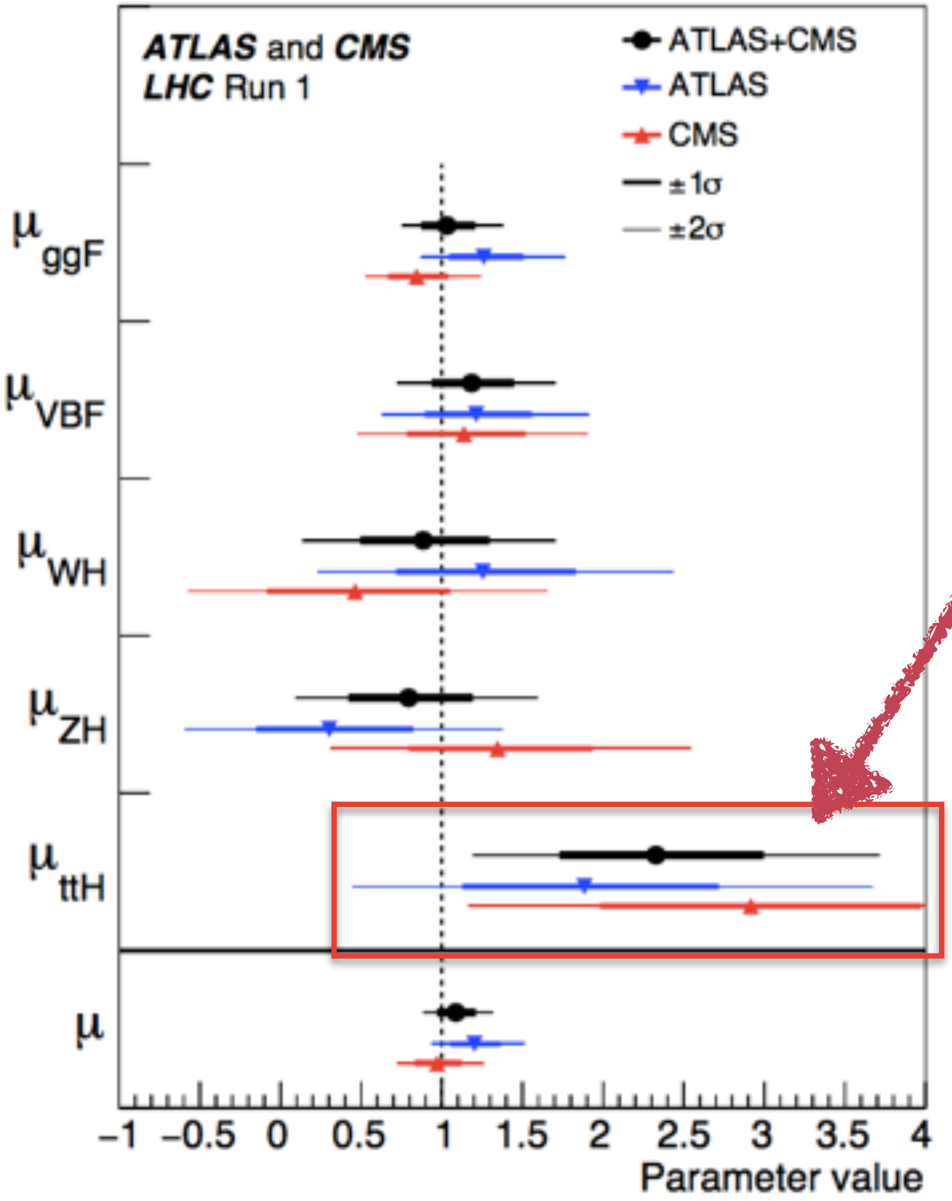
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

ATLAS + CMS

JHEP 08(2016) 045

ATLAS & CMS coupling RunI

Assuming SM BR

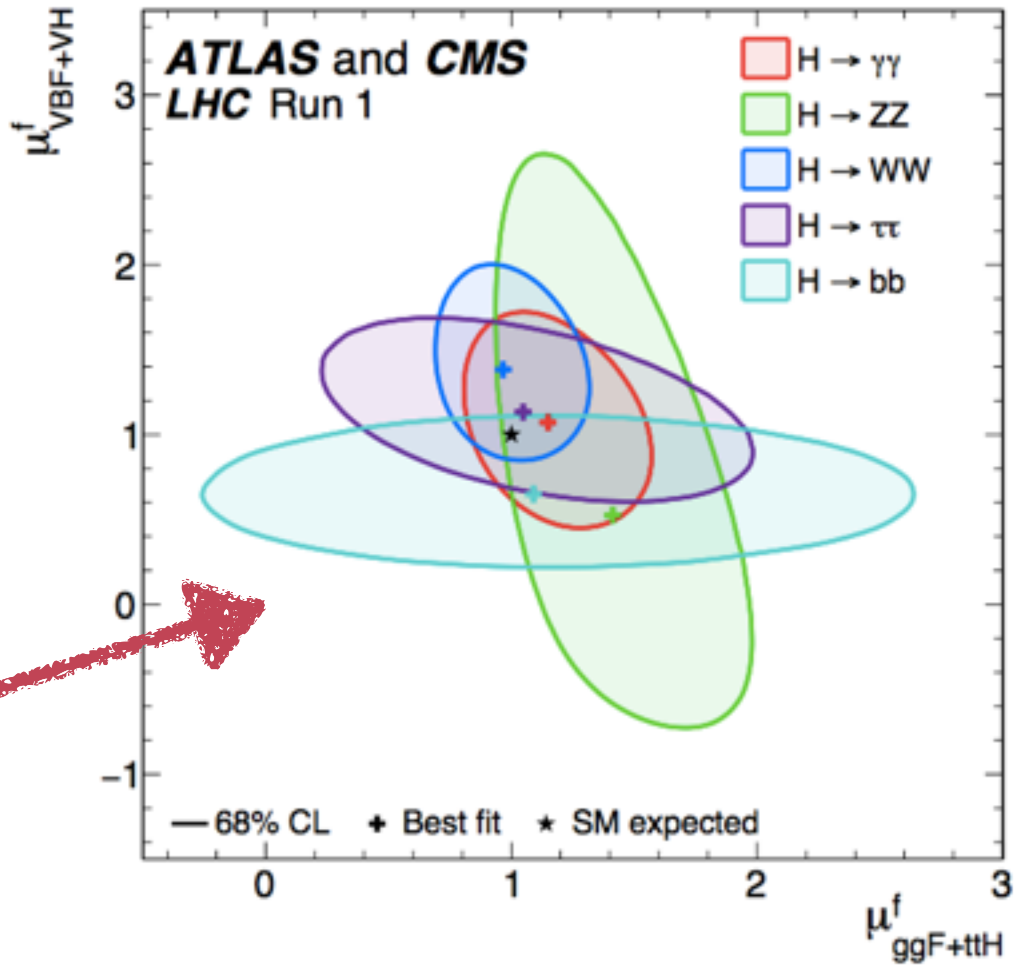


μ=σ BR/(σ BR)$_{SM}$
The signal strength wrt to the SM

Good agreement between all decay channels

All measured processes in agreement with SM within 2 standard deviations
Largest deviation measured in ttH x-section about 3 **σ**.

The p-value of the compatibility between the data and the SM predictions is 75%.



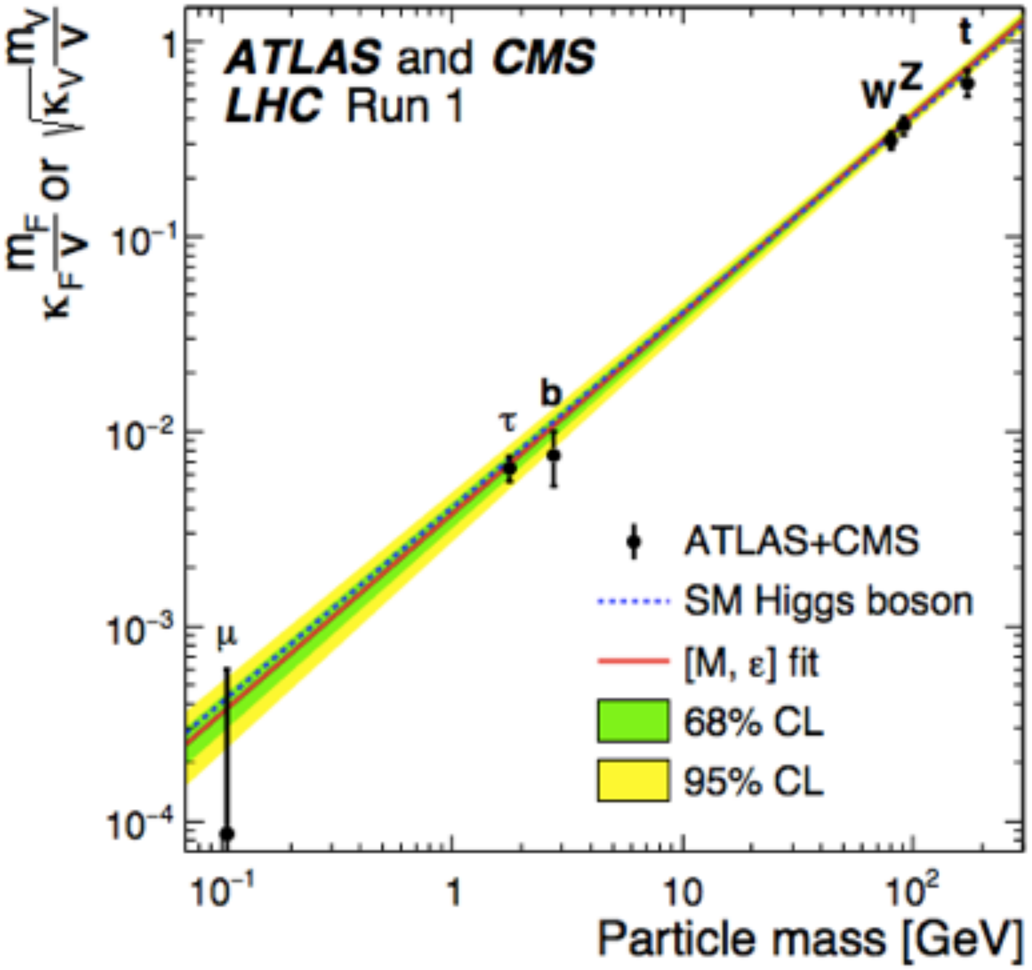
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09 \pm 0.07(\mathrm{stat}) \pm 0.04(\mathrm{expt}) \pm 0.03(\mathrm{th\text{-}bkgd})^{+0.07}_{-0.06}(\mathrm{th\text{-}sig})$$

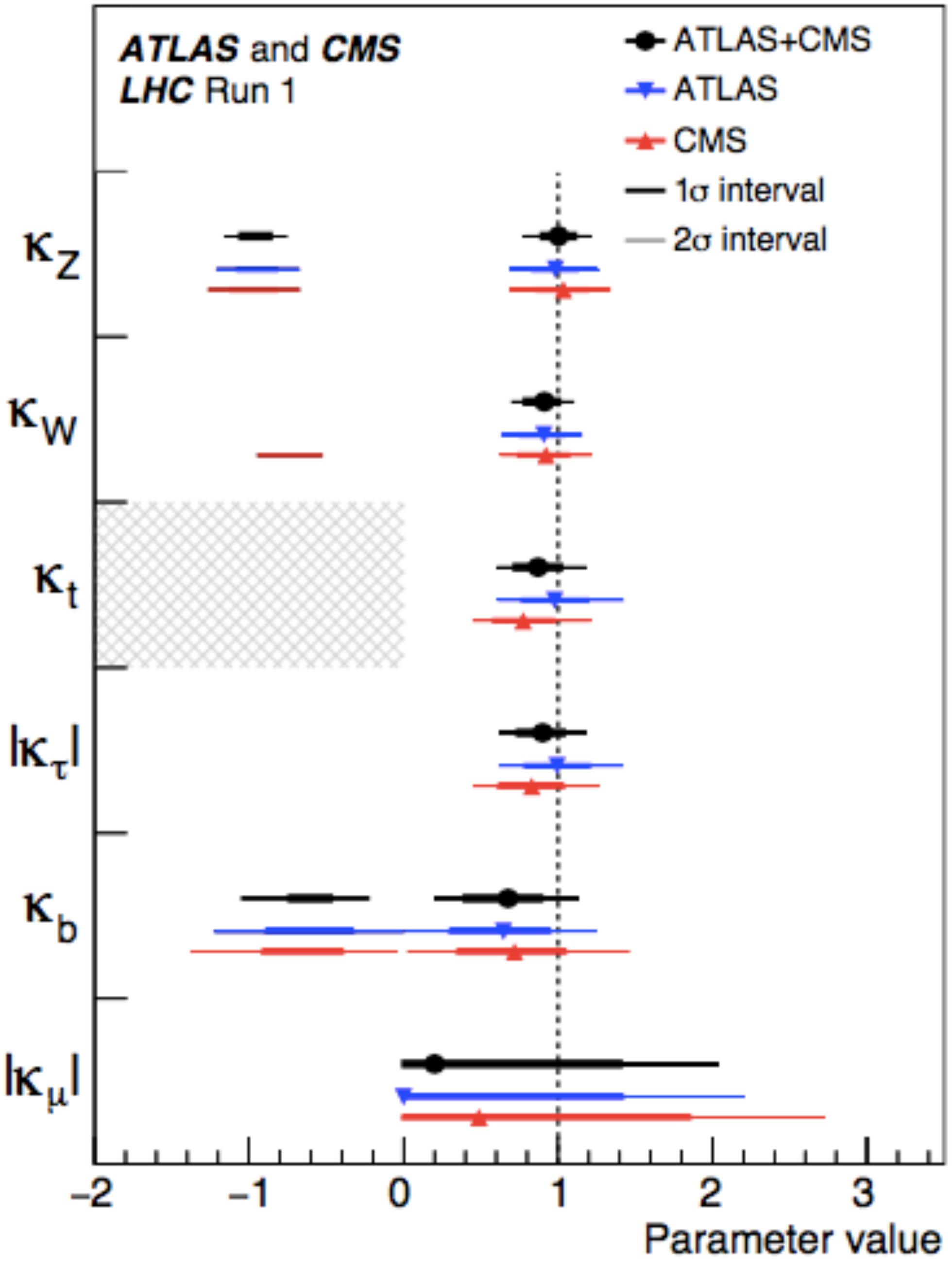
ATLAS &CMS k-framework RunI

Leading-order inspired framework to study couplings, developed by the LHC Higgs Cross Section WG. For a given production process or decay mode (i) a coupling modifier is defined as :

$\kappa_i^2=\sigma_i/\sigma_i^{SM}$ or $\kappa_i^2=\Gamma_i/\Gamma_i^{SM}$

no new particles in the loops entering ggF production and $H \to \gamma\gamma$ decay. No BSM decays.



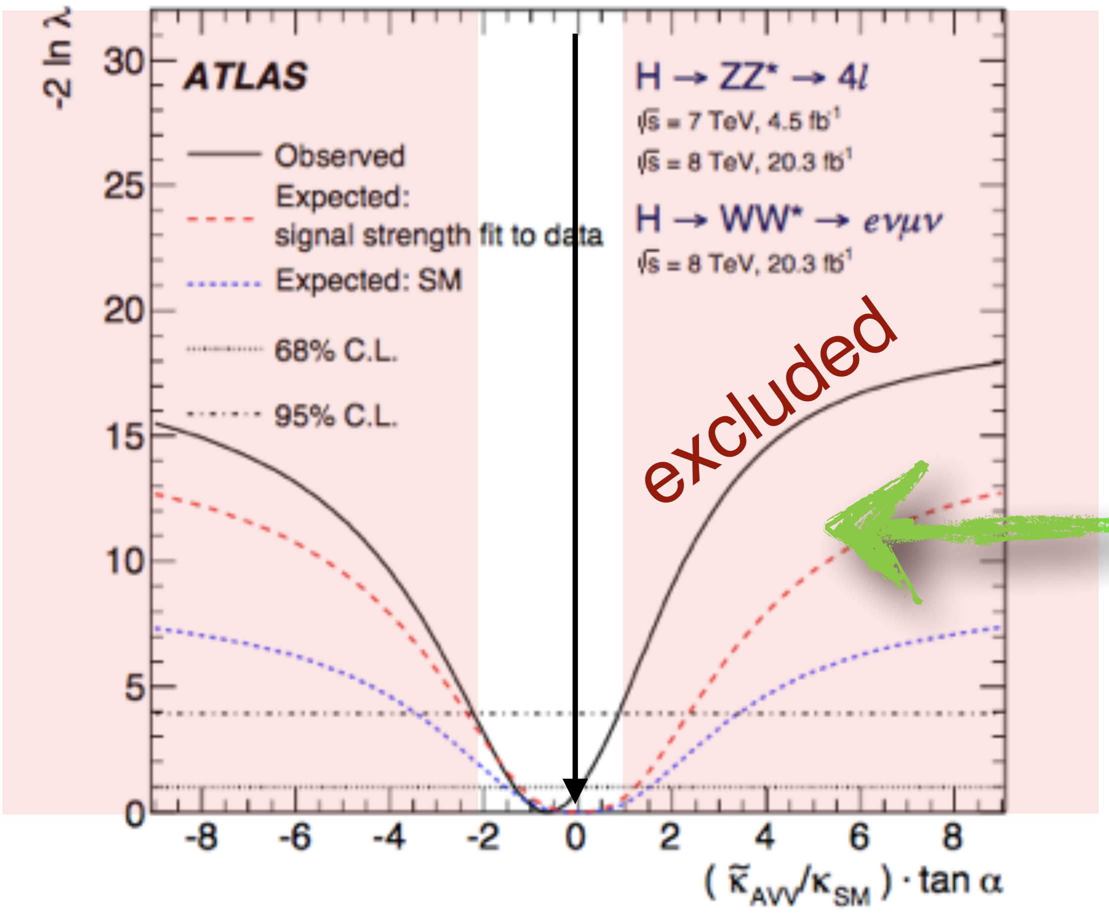


Couplings scale with mass as expected in SM

Spin CP Run I

Spin 1 and 2 excluded at
more than 99% CL
by both collaborations

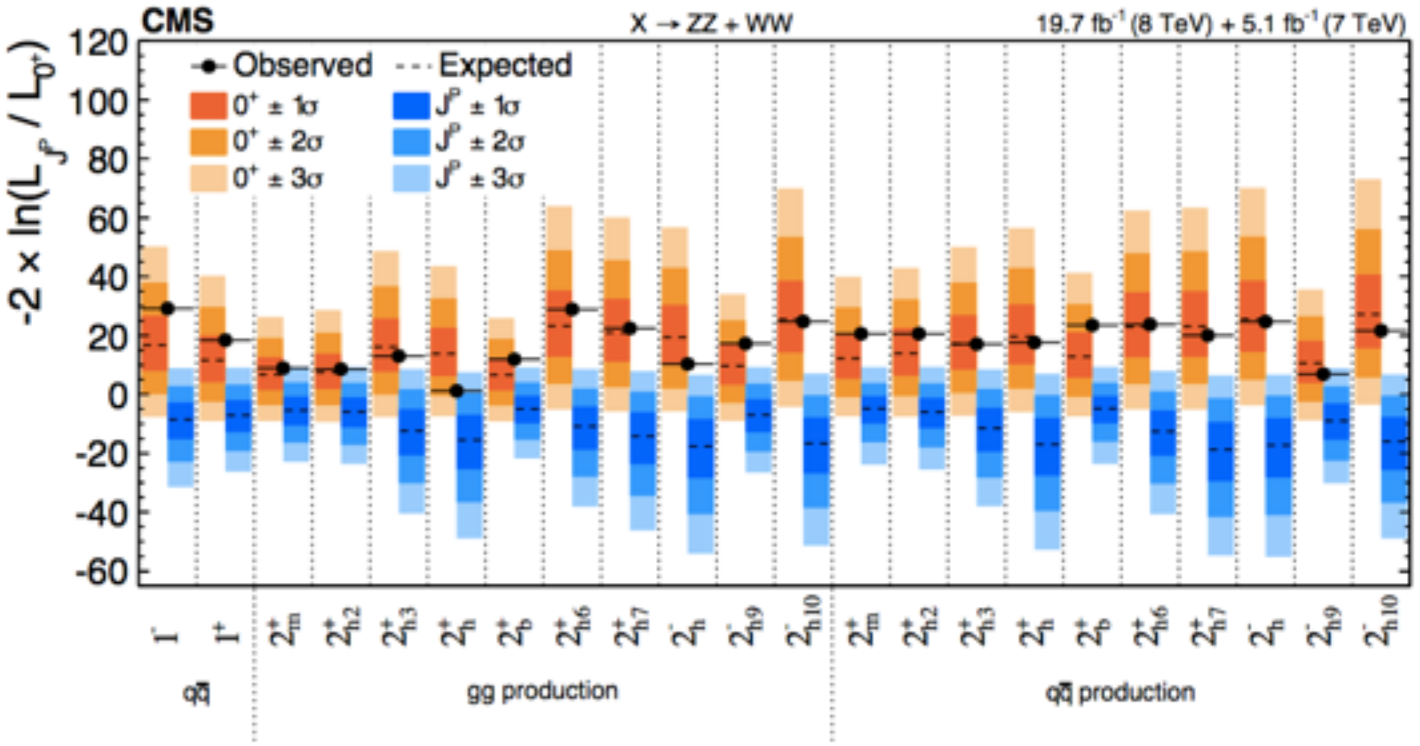
SM case



← CP odd increasing →

Eur. Phys. J. C75 (2015) 476

Phys. Rev. D 92 (2015) 012004



A pure CP even (higher order) and CP odd excluded at > 99.9% CL by both collaborations.

CP mixing also investigated,
large fractions of CP mixing are still allowed <30%

EFT interpretation should still be a priority:

- **combine couplings and CP studies!**

- increase of generality PseudoObservables,
- K-framework limited to rates!

Higgs width

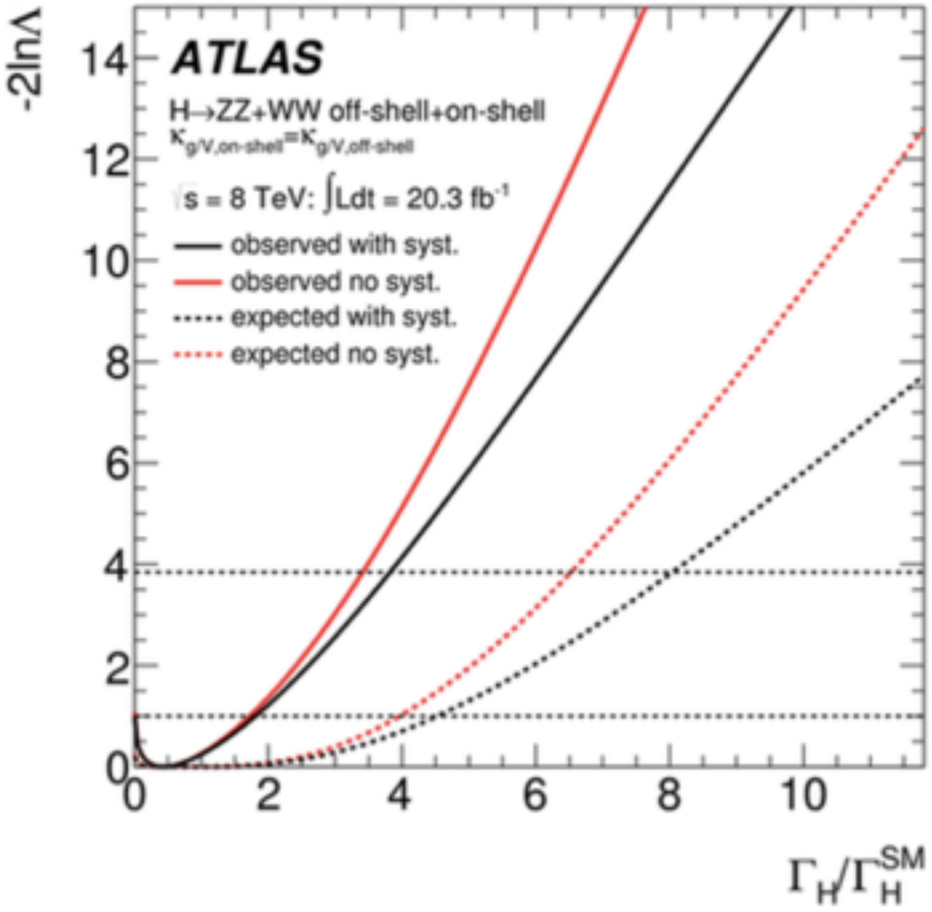
ATLAS Eur. Phys. J. C75,335 (2015)
CMS Phys. Lett. B736, 64 (2014),
JHEP 09, 051 (2016)

EPJC 75(2015)212, PRD 90 052004(2014)

	$H\to\gamma\gamma$	$H\to 4\ell$
ATLAS **GeV**	5.0obs 6.2 exp	2.6 obs 6.2 exp
CMS **GeV**	2.4 obs 3.1 exp	3.4 obs 2.8 exp

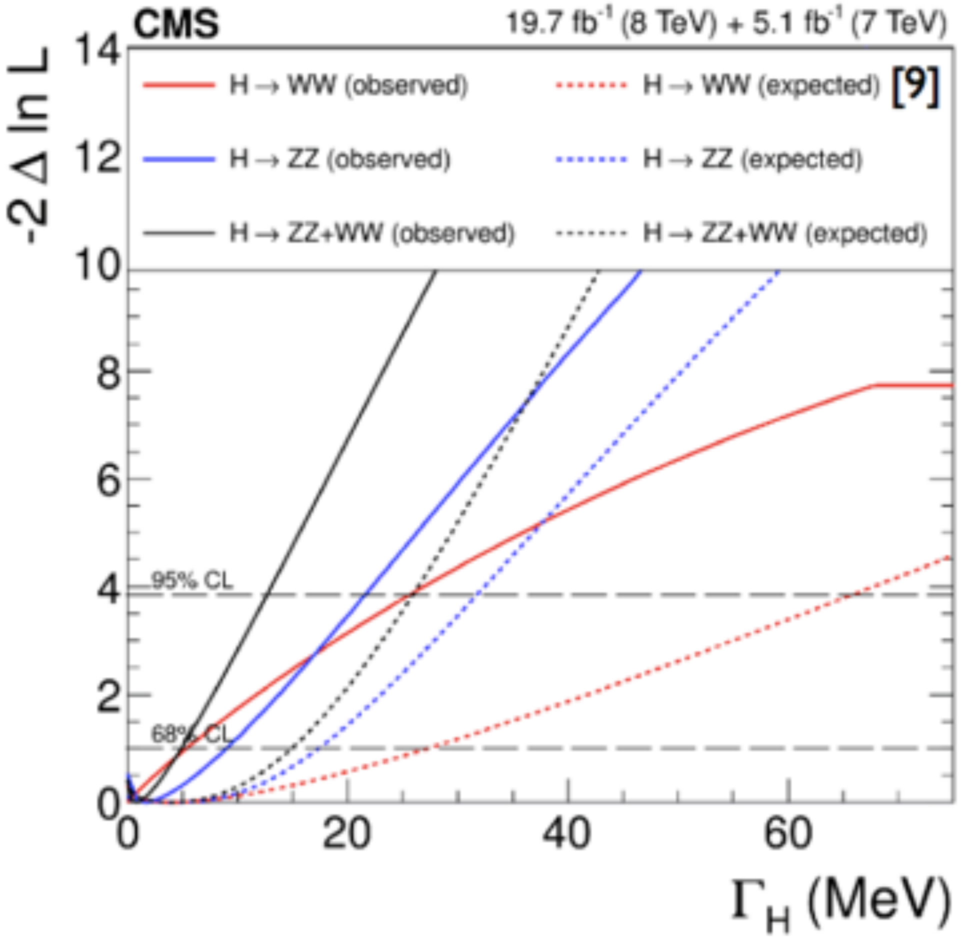
Direct measurement: @95% CL at GeV level.
limited by detector resolution≃1.5 GeV($\Gamma_H^{SM}\simeq 4$ MeV)

Indirect measurement: comparing on-shell and off-shell rates and assuming coupling of
on shell and off shell are the same



$$\sigma^{\text{on-shell}}_{VV\to H\to ZZ}\propto \mu_{VVH}$$

$$\sigma^{\text{off-shell}}_{VV\to H\to ZZ}\propto \mu_{VVH}\,\Gamma_H$$



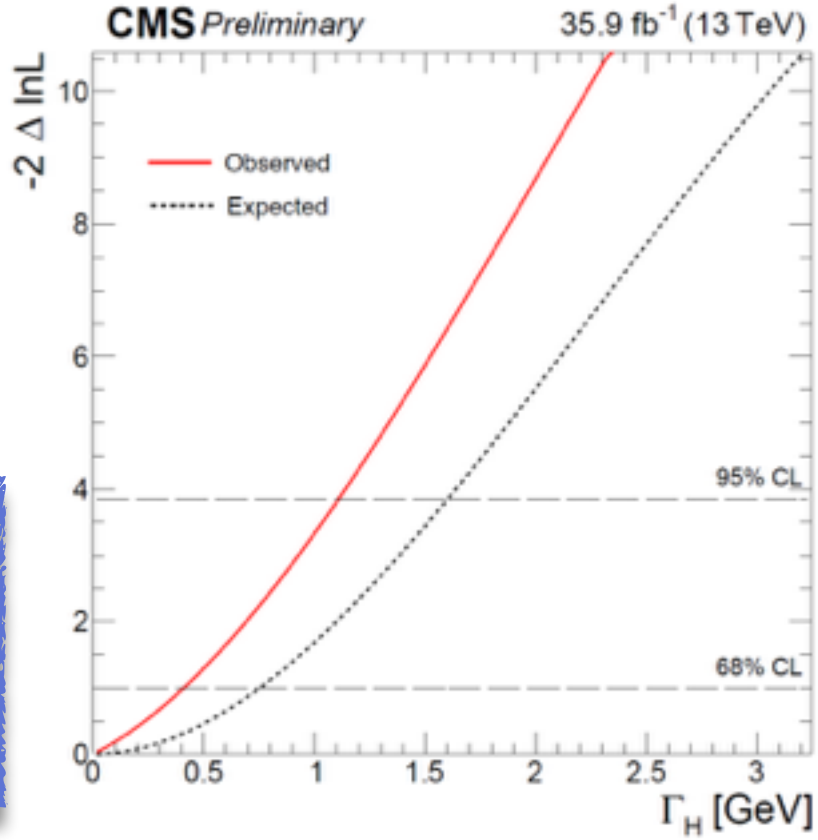
Γ_H < 22.7 MeV (33 MeV expected) @95%CL
NNLO/LO K-factor gg→VV poorly known and assumed to be similar to gg→ H* →VV

Γ_H < 13 MeV (26 MeV expected) @95%CL
assuming μVBF / μggF to be identical for ZZ and WW

Higgs width Run2

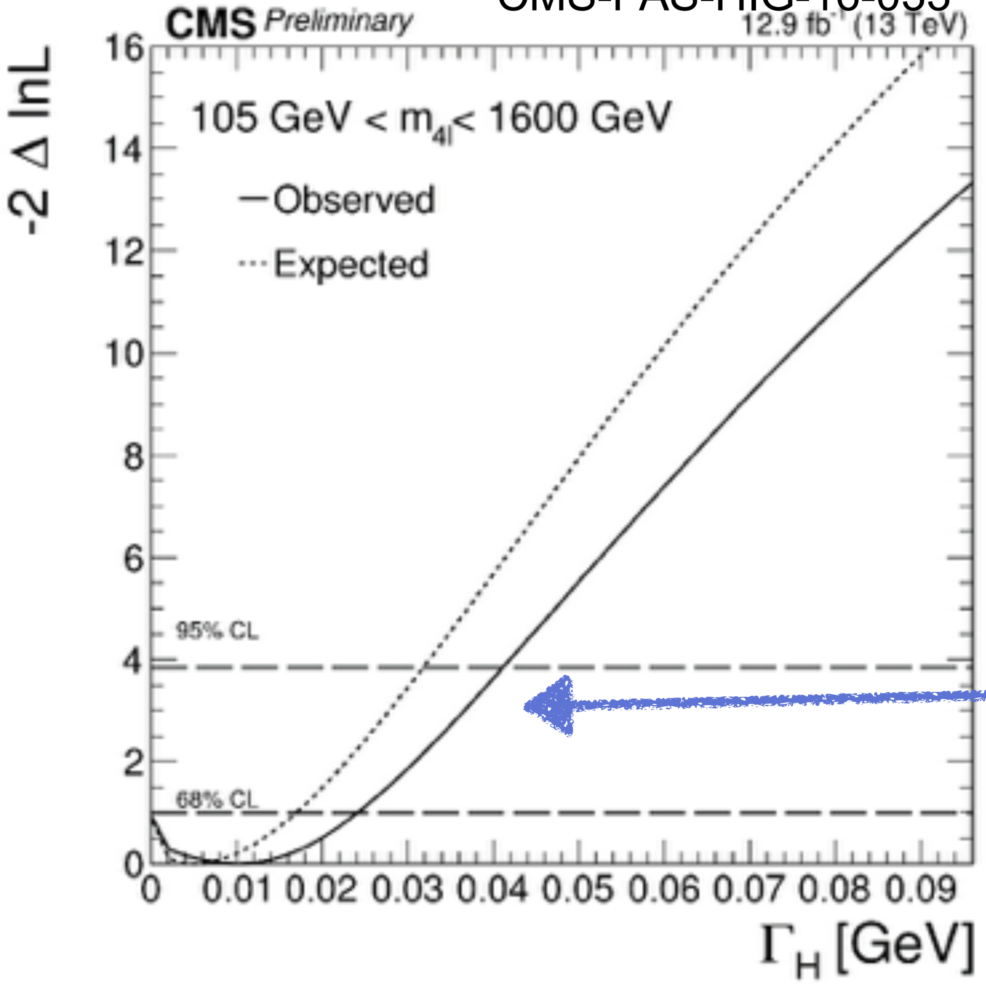
CMS-PAS-HIG-16-041

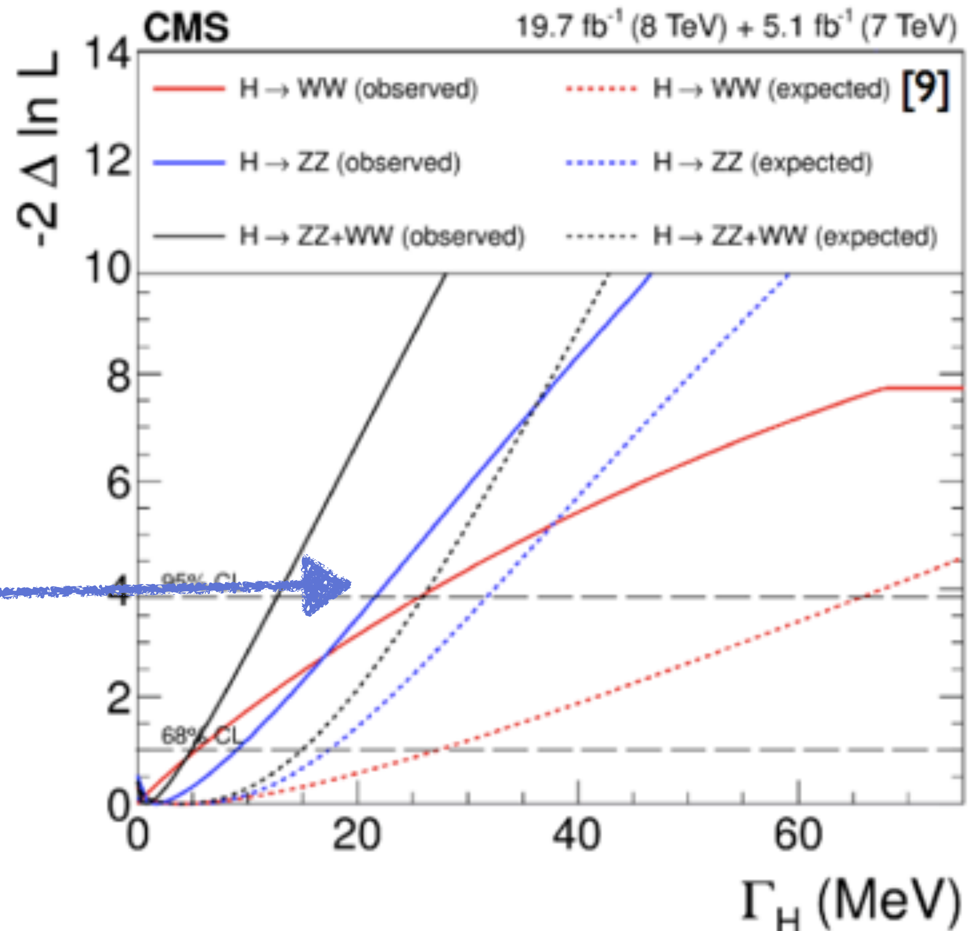
Direct limit: from H→ZZ $\Gamma = 0.00^{+0.41}_{-0.00}$ GeV.
On shell only: Tighter limit than Run1 with 35.9 fb^{-1}
Run2 $\Gamma_H < 1.10$ GeV at 95% CL (105<m4l<140 GeV)
no assumption on BSM
Run1 $\Gamma_H < 3.4$ GeV ZZ (1.7 GeV $\gamma\gamma$+ZZ) @95% CL



Γ <41 MeV (100<m_H<1600GeV) with both on-shell and off-shell and 12.9 fb^{-1}. Assumption for off-shell analysis:
no BSM particles or interactions affect the H boson couplings.

CMS-PAS-HIG-16-033

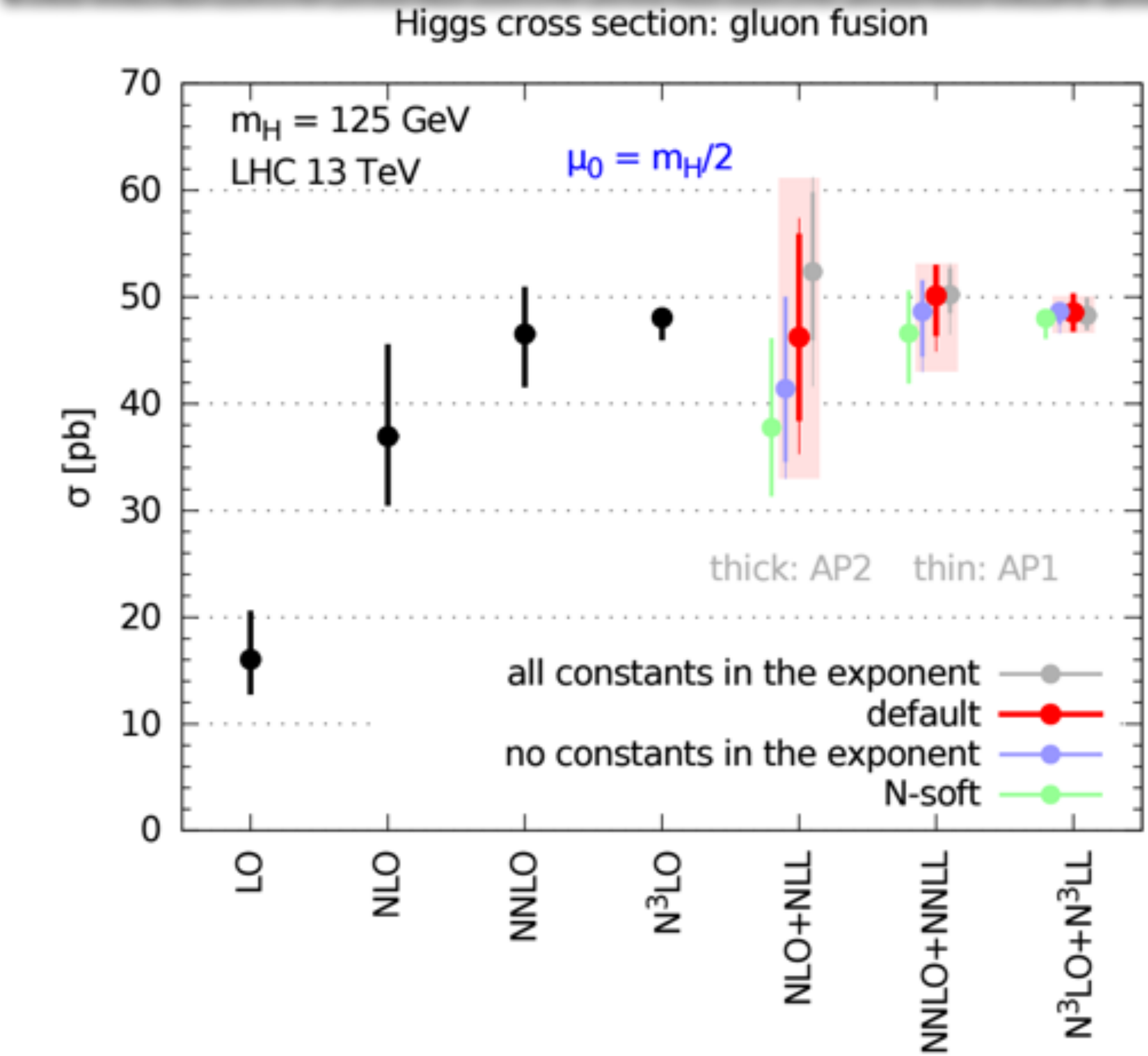


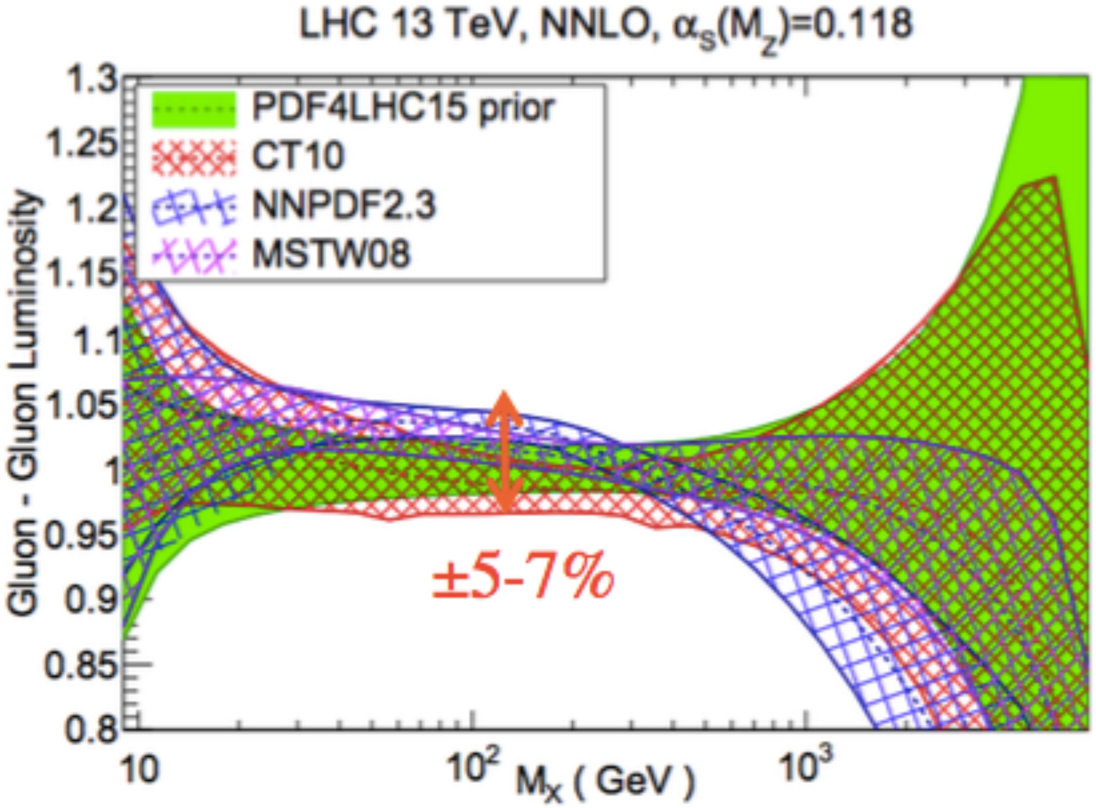


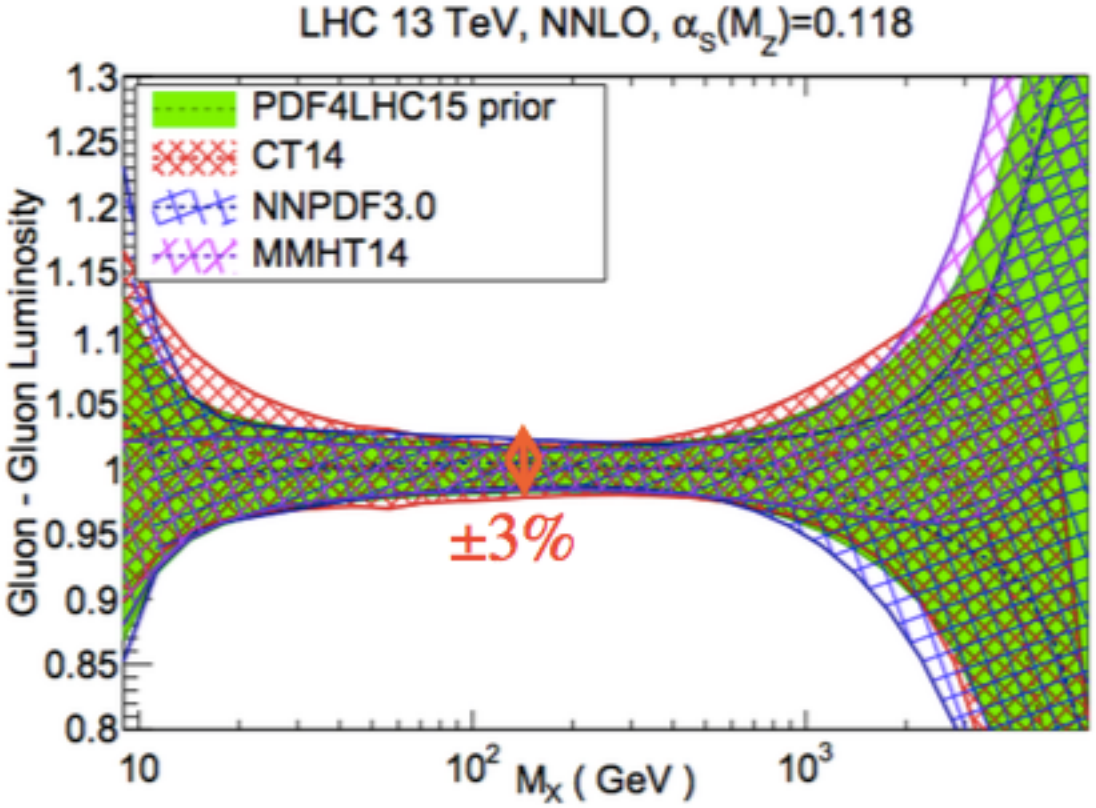
Theory improvements

PDFs: Improvements are due to additional data available, but mainly to improvements in fitting formalism: All PDF are at NNLO

Precision on ggF x-section:
from NNLL to N^{3}LO







see YR4 of LHCHXSWG

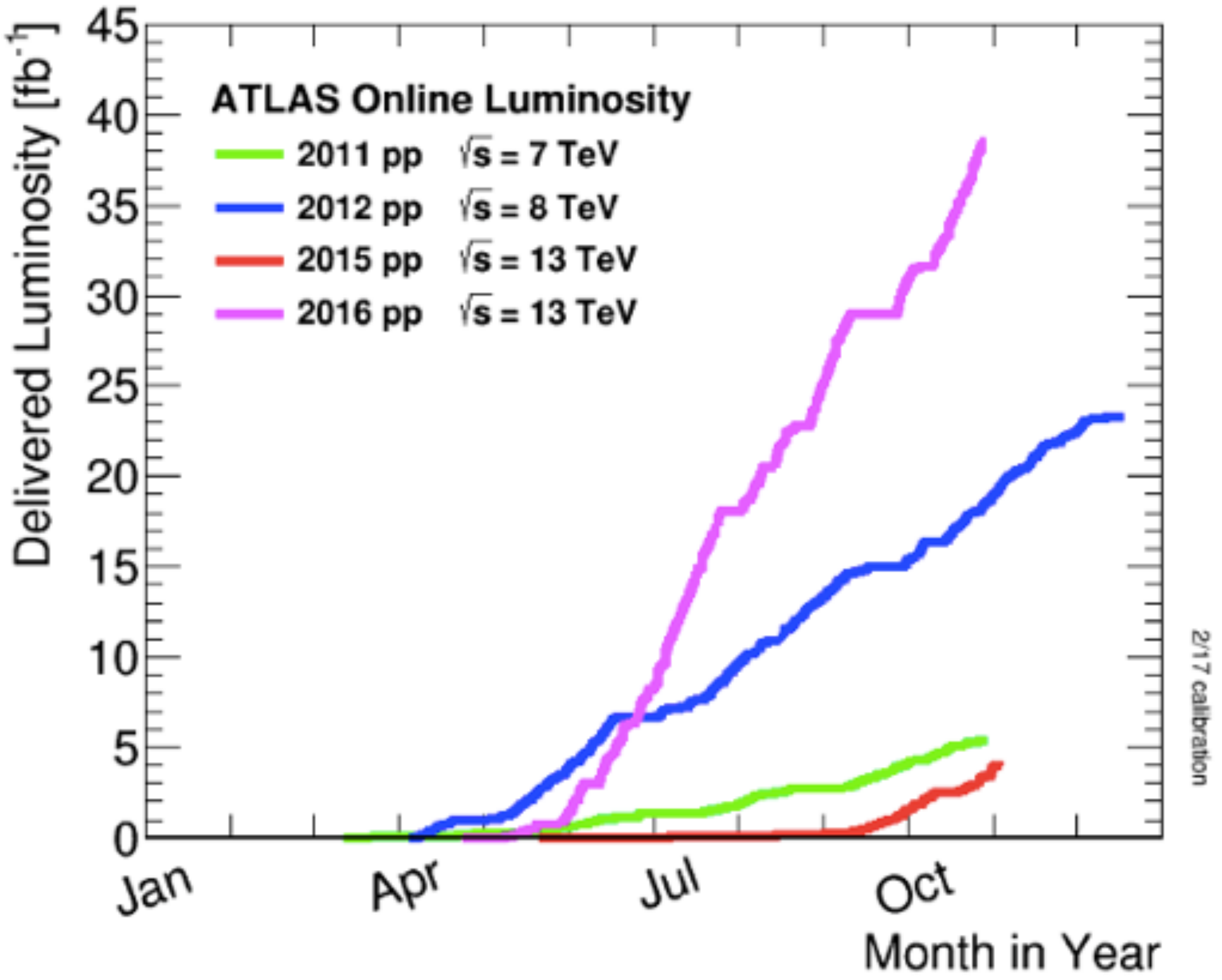
arXiv:1610.07922v2 [hep-ph]

SM Higgs Run2

LHC Run2

Excellent performance in 2016 !

- more data than all previous years
- Peak L = 1.4 10^{34} $cm^{-2}s^{-1}$ (exceeded design)
- higher pileup conditions



	Lumi fb^{-1}	Year
Run1 7 TeV	4.5	2011
Run1 8 TeV	20.3	2012
Run2 13 TeV	3.2	2015
Run2 13 TeV	32.9	2016

Run2 results presented in this talk typically are 2 sets corresponding to

~13 fb^{-1} of Run2 data (summer 2016)
~36 fb^{-1} of Run2 data (winter 2017)

H→γγ

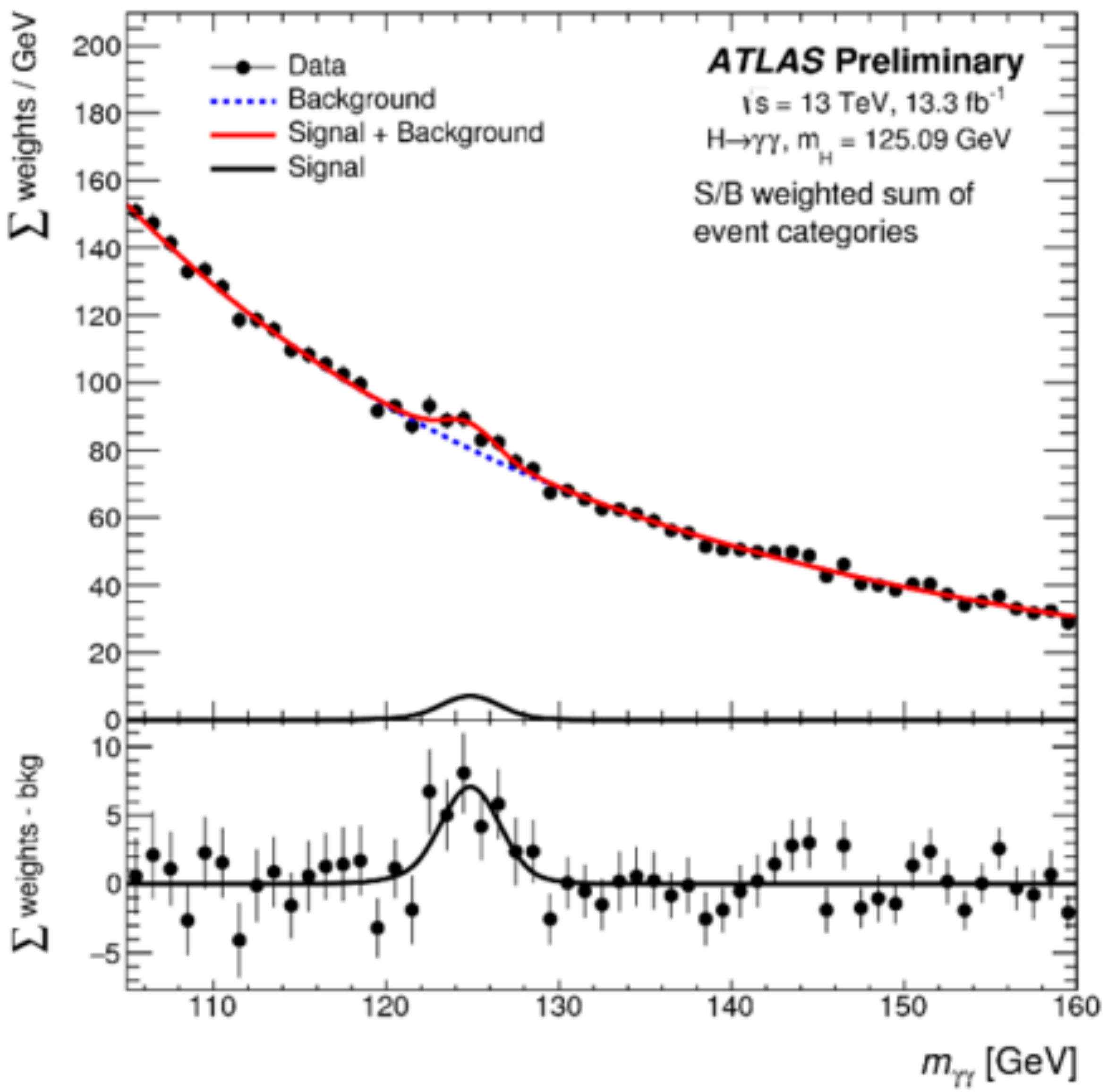
13.3 fb^{-1}

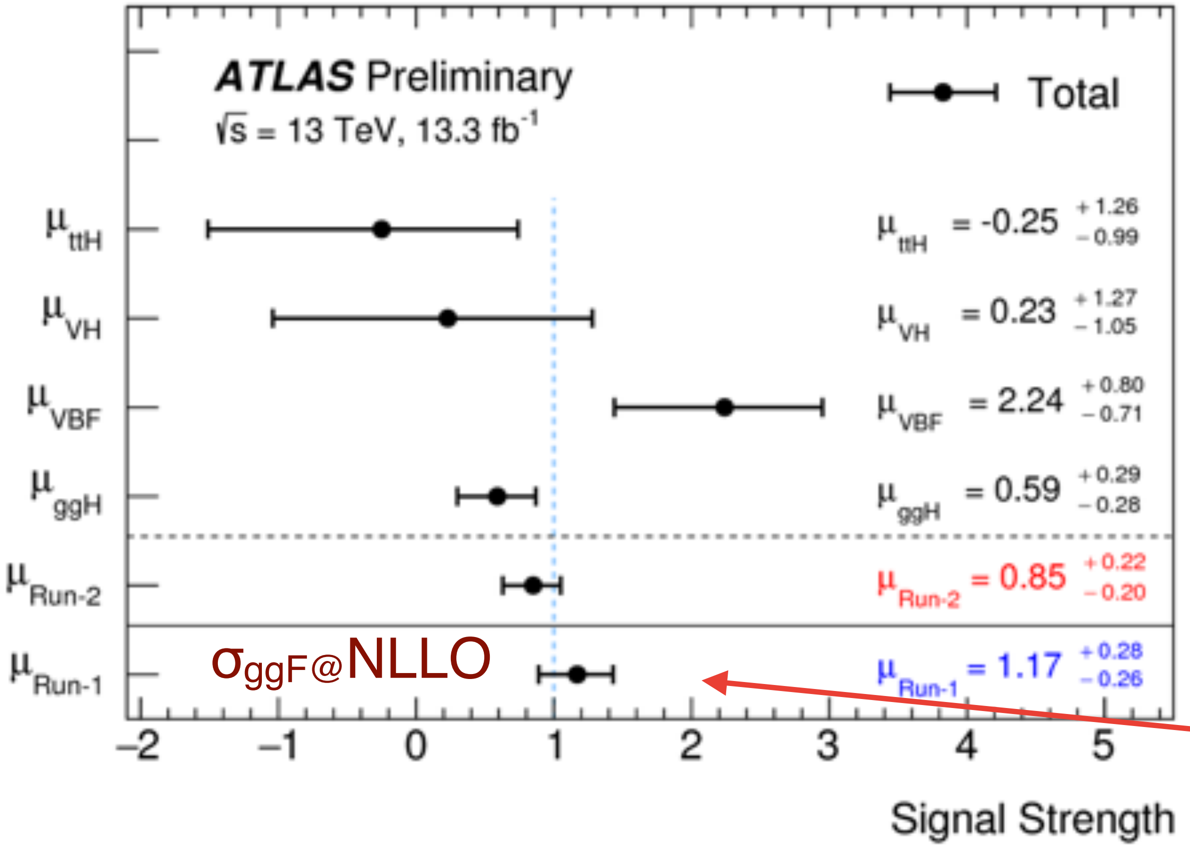
13 categories: final state+production modes
Signal extracted by fit to $m_{\gamma\gamma}$, bkg modeled with polynomials.
Observed significance is 4.7σ

- $\mu = 0.85^{+0.22}_{-0.20}$

No significant deviation from SM

ATLAS-CONF-2016-067





- Run 2 result uses N^{3}LO calculation for ggF.

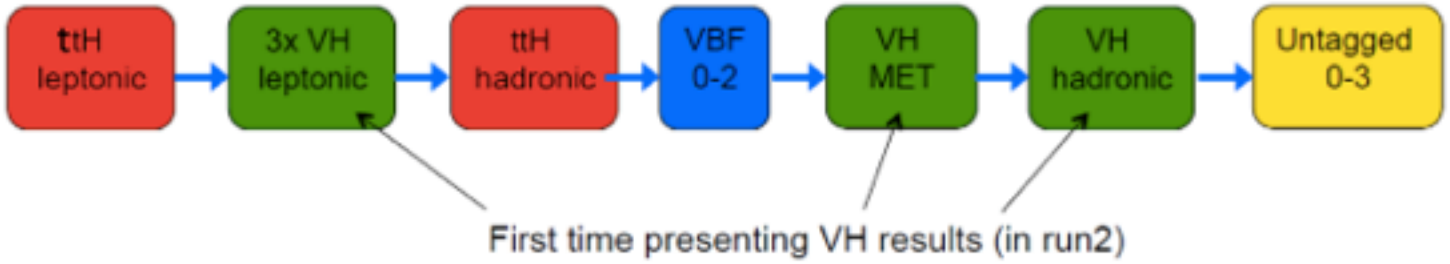
- Better agreement with theory of Run1 result when N^{3}LO calculation is used: σ_{ggF}^{theory} increases by ~10%.

$35.9\ \text{fb}^{-1}$

$H \rightarrow \gamma\gamma$

CMS-PAS-HIG-16-040

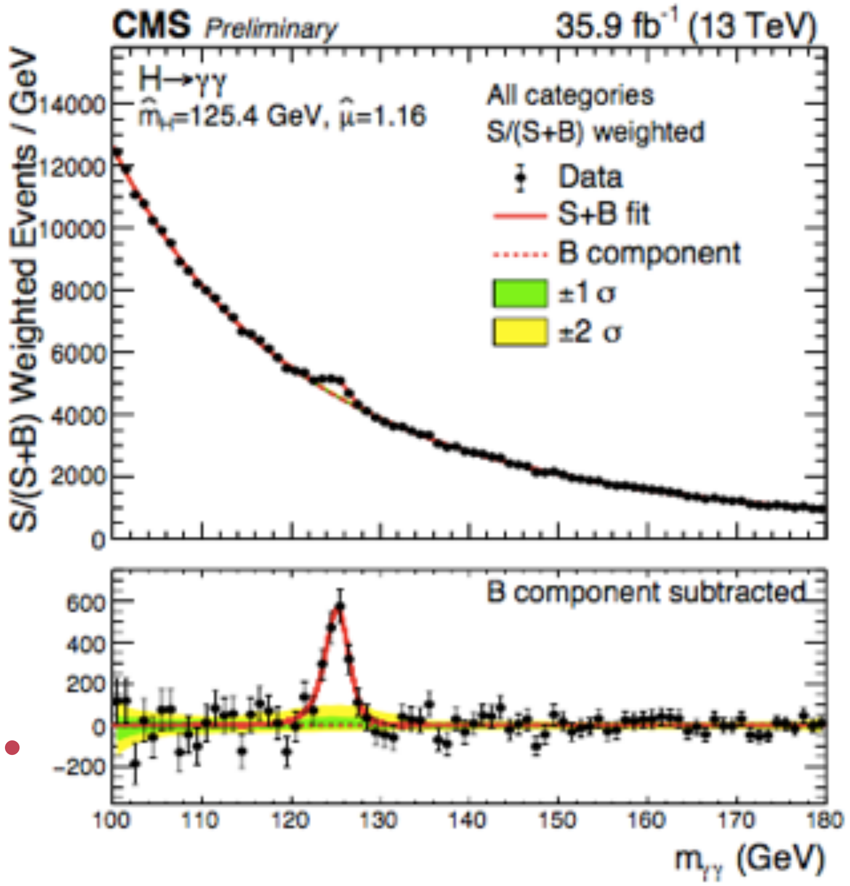
Events are sorted into 14 categories depending on Higgs production modes and kinematics, to improve the analysis sensitivity



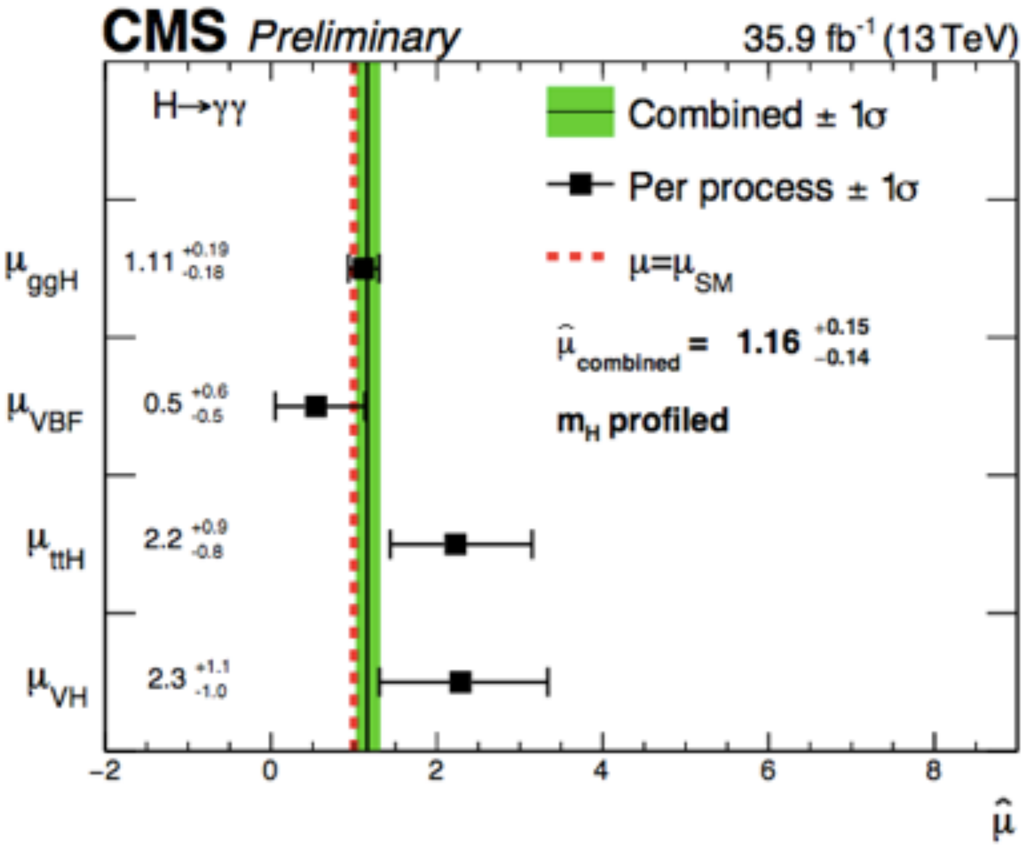
First time presenting VH results (in run2)

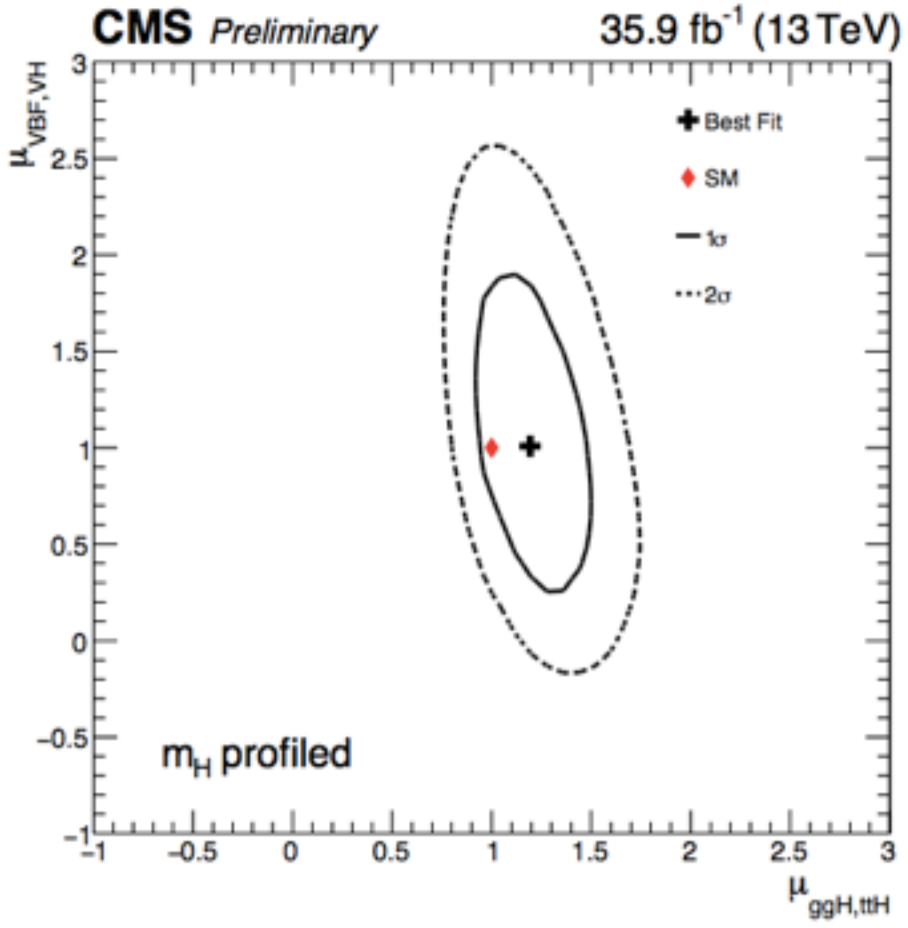
$$\hat{\mu} = 1.16^{+0.15}_{-0.14} = 1.16^{+0.11}_{-0.10}\ (\text{stat.})\ ^{+0.09}_{-0.08}\ (\text{syst.})\ ^{+0.06}_{-0.05}\ (\text{theo.})$$

New!



Significance
Observed(Expected)
VBF 1.1σ(1.9σ)
ttH 3.3σ (1.5σ)
VH 2.4σ (1.2 σ)



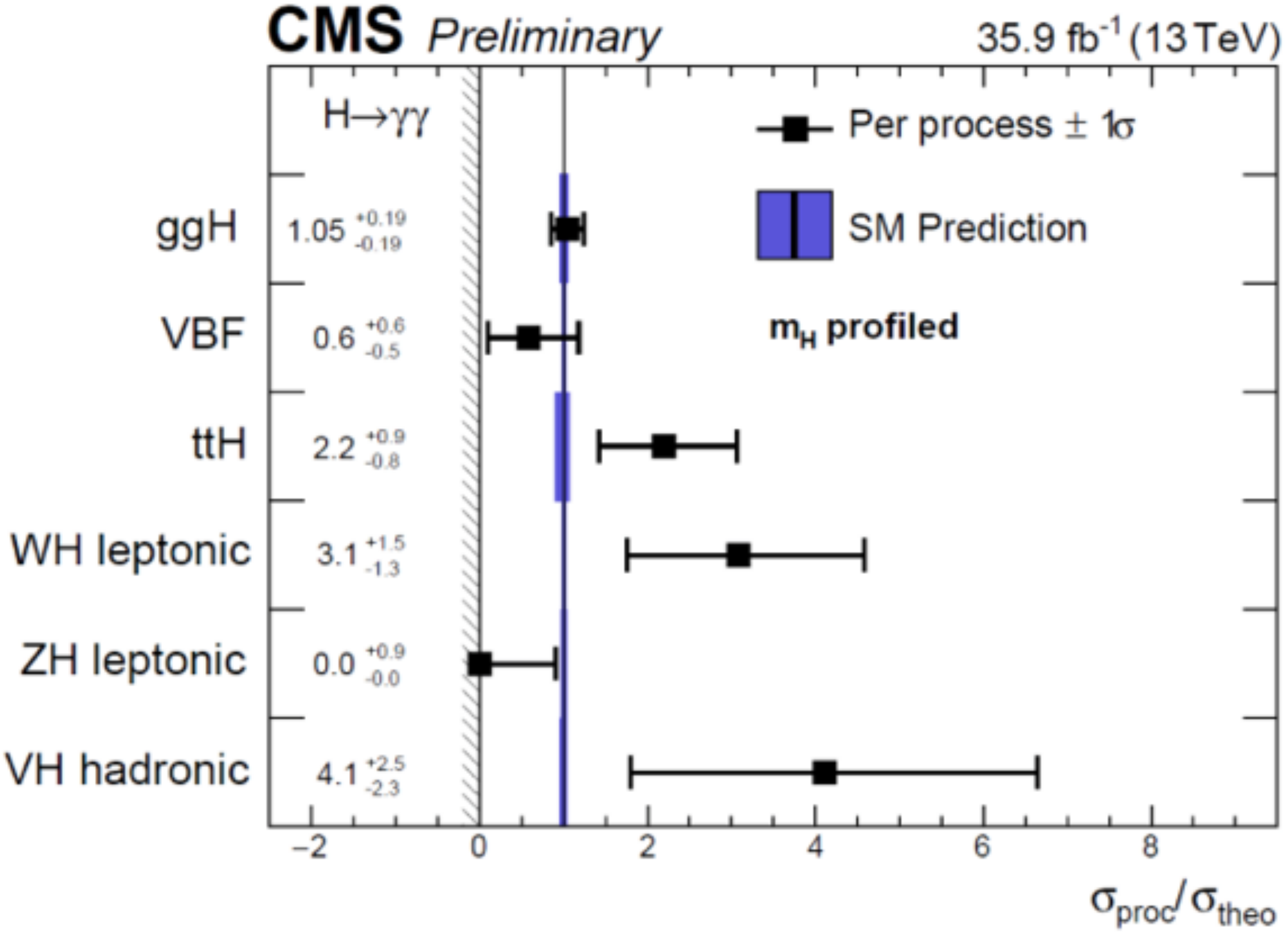


35.9 fb^{-1}

$H \to \gamma\gamma$

CMS-PAS-HIG-16-040

Cross-sections at stage 0 of the simplified Template cross-section framework $|y_H|<2.5$ profiled m_H to render the measurement as independent as possible from any mass hypothesis.



$H\rightarrow\gamma\gamma$ Differential

35.9 fb^{-1} CMS-HIG-17-015

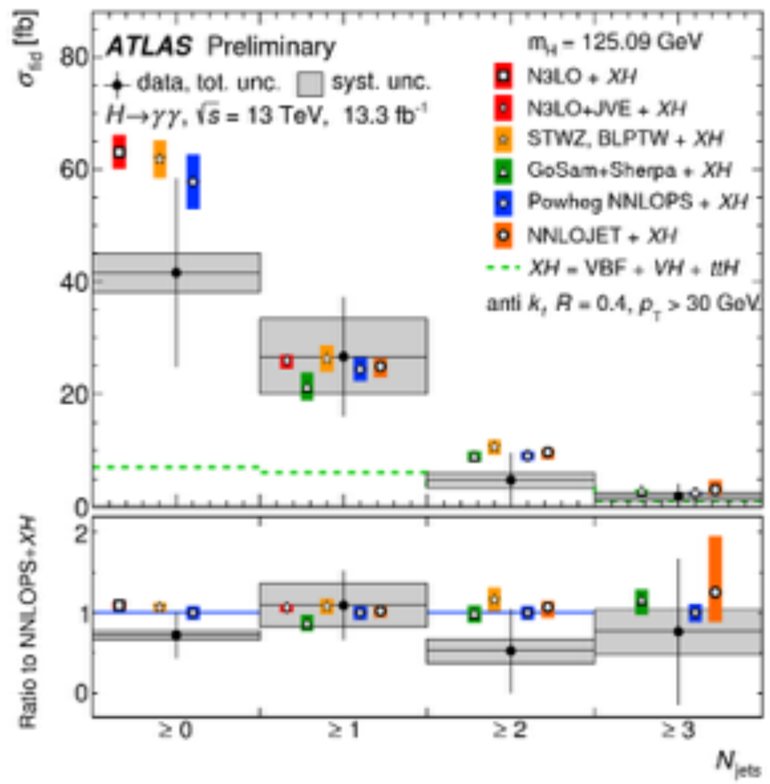
13.3 fb^{-1} ATLAS-CONF-2016-067

Fiducial phase space defined to closely match experimental acceptance to reduce systematic uncertainty associated with underlying model.

*calorimeter crack region excluded

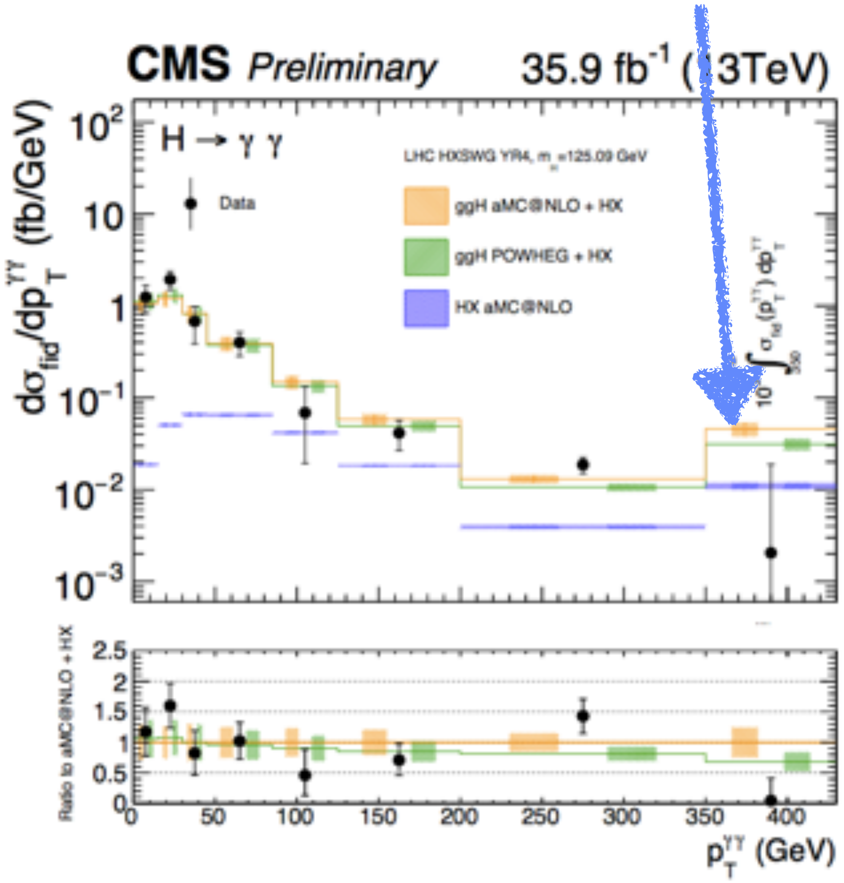
HX= (VBF+VH+ttH) non ggF production mode.

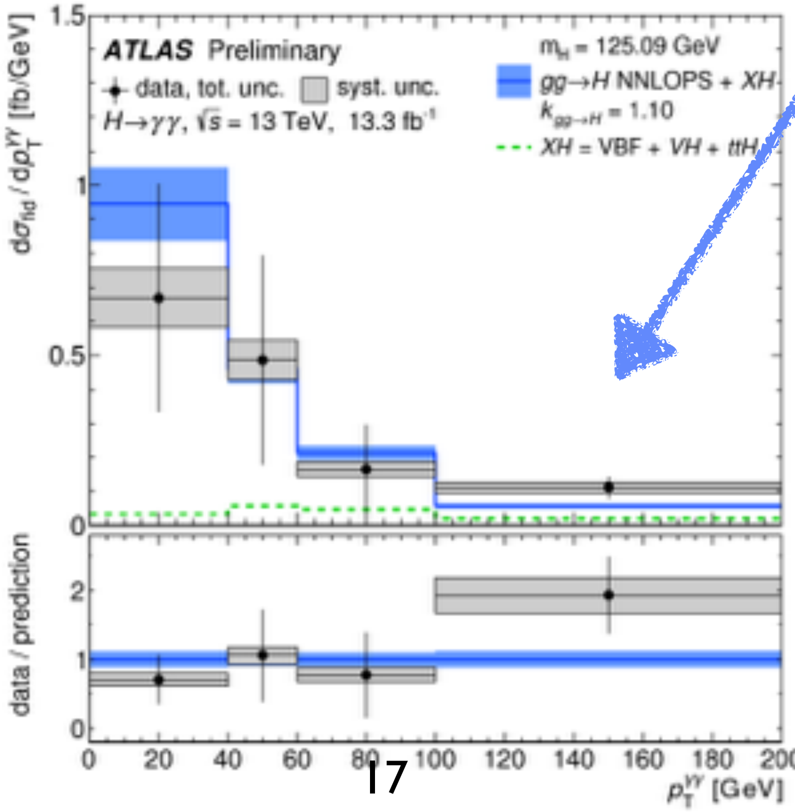
	Definition	**σ_{fid} (fb)**	**σ^{SM}_{fid} (fb)**
CMS	$\lvert\eta_\gamma\rvert^* < 2.5$, iso < 10GeV ($\Delta R = 0.3$) and $p_{T1(2)}/m_{\gamma\gamma} > 1/3$ (1/4)	84 ± 11(stat) ± 7(sys)	75±4
ATLAS	$\lvert\eta_\gamma\rvert^* < 2.37$, and $p_{T1(2)}/m_{\gamma\gamma} > 0.35$ (0.25)	43.2 ± 14.9(stat) ± 4.9(sys)	$62.8^{+3.4}_{-4.4}$

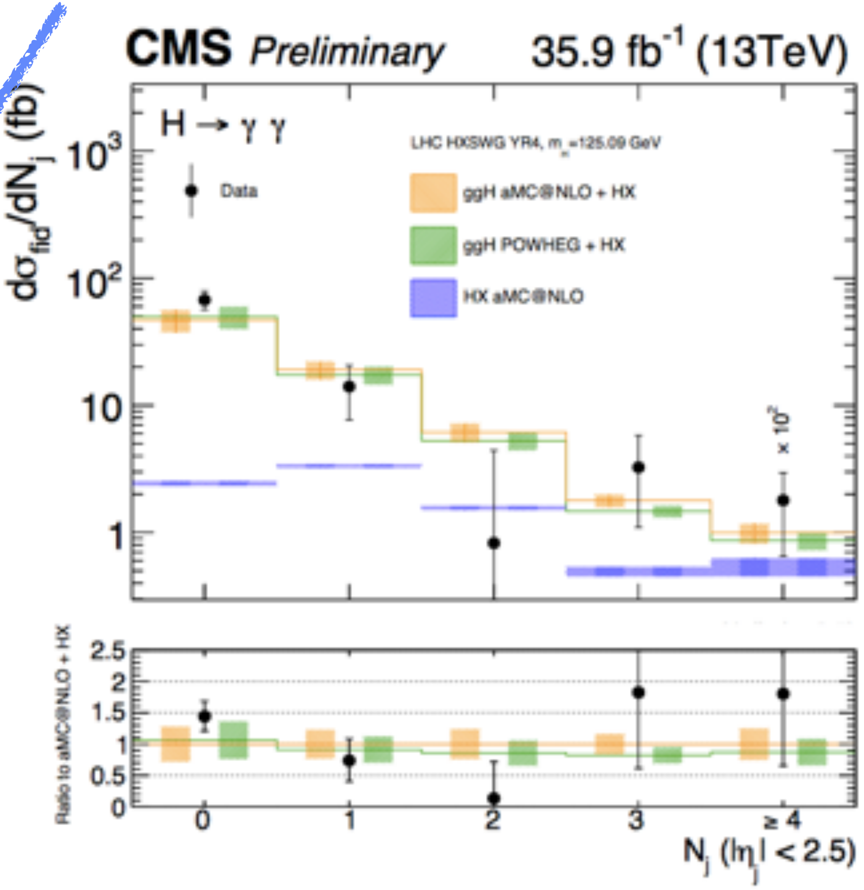


substantial increase in p_T coverage: $p_T > 2m_{top}$

Data slightly undershoot (overshoot) theory prediction at low (high) p_T



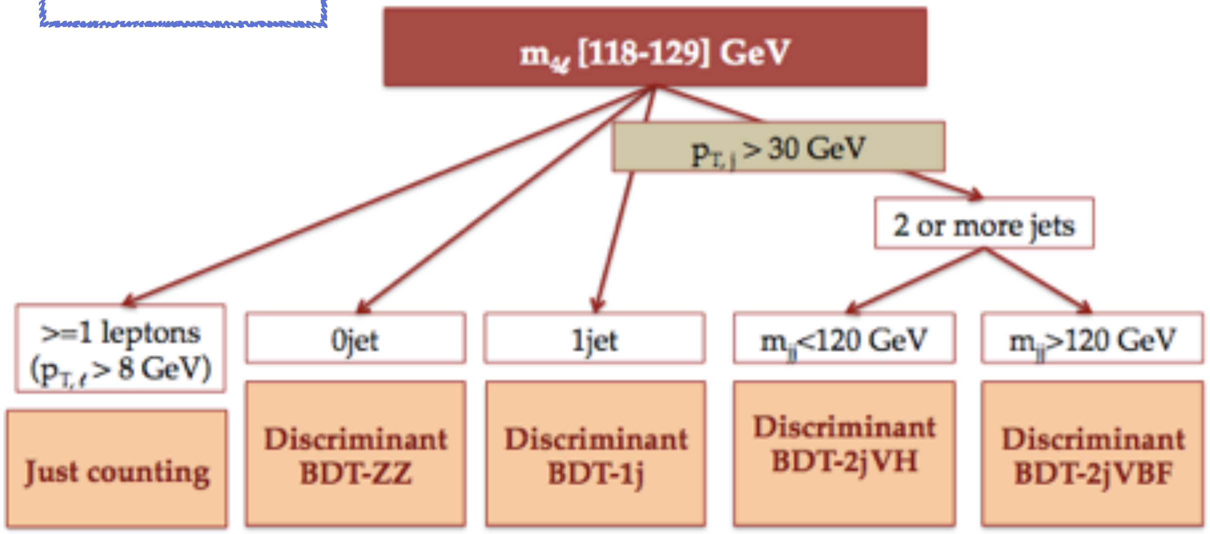




14.8 fb^{-1}

H→ZZ*→4l,l=e,μ

ATLAS-CONF-2016-079



$m_{4\ell}$ [118-129] GeV

$p_{T,j} > 30$ GeV

2 or more jets

>=1 leptons ($p_{T,\ell} > 8$ GeV)

0jet

1jet

m_{jj}<120 GeV

m_{jj}>120 GeV

Just counting

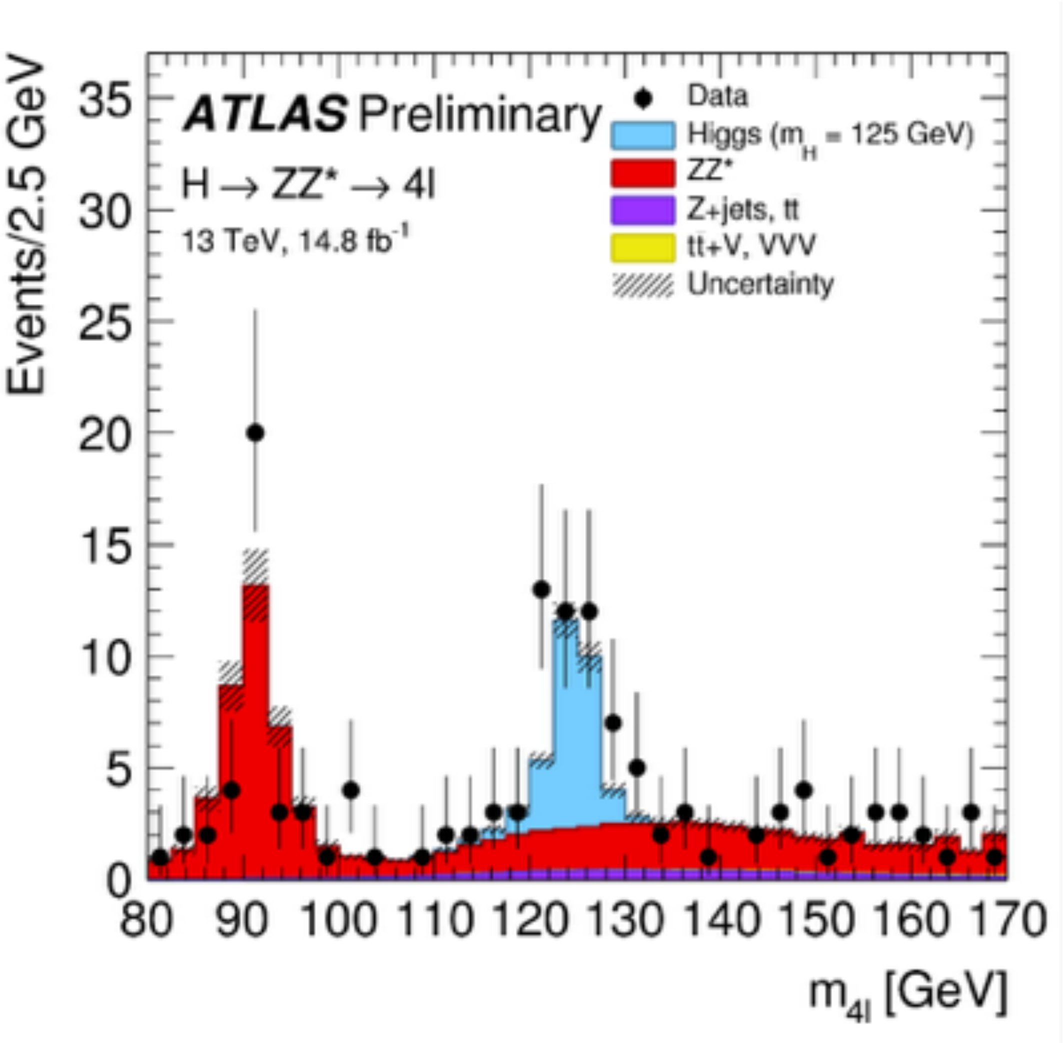
Discriminant BDT-ZZ

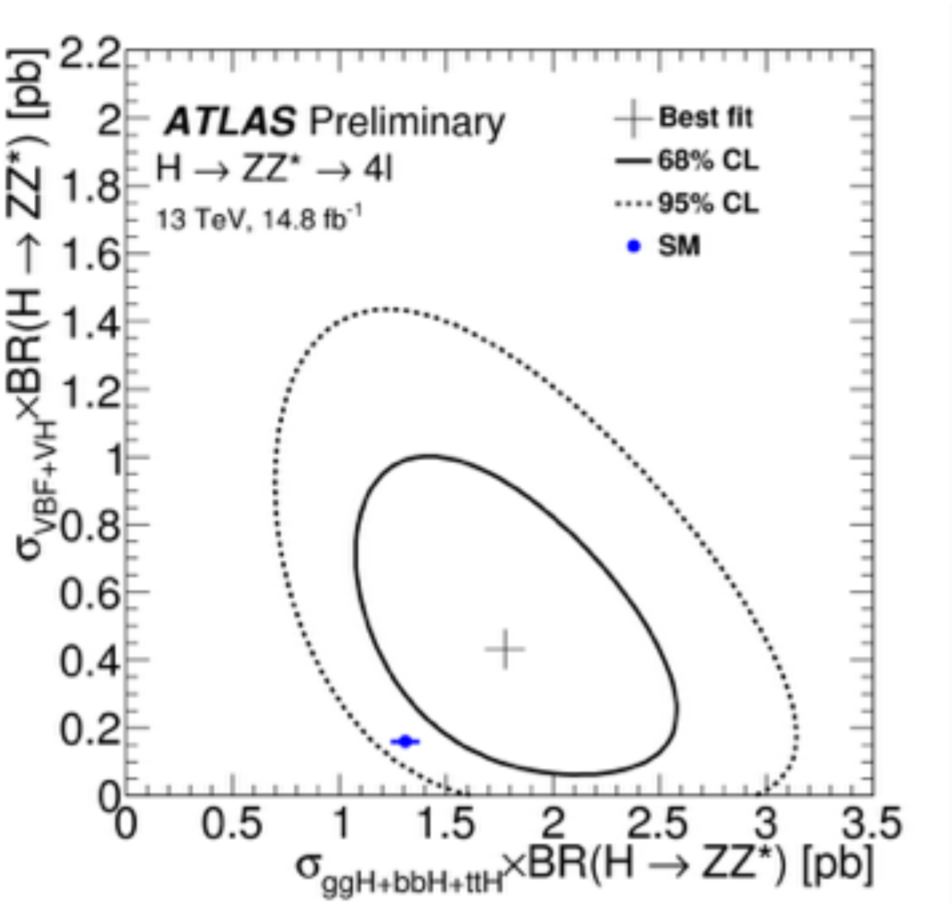
Discriminant BDT-1j

Discriminant BDT-2jVH

Discriminant BDT-2jVBF

High S/B≥2, but low statistics.
Event categorization to measure cross section per production mode and jet multiplicity. Extract signal by fitting the shape of discriminants in each category.





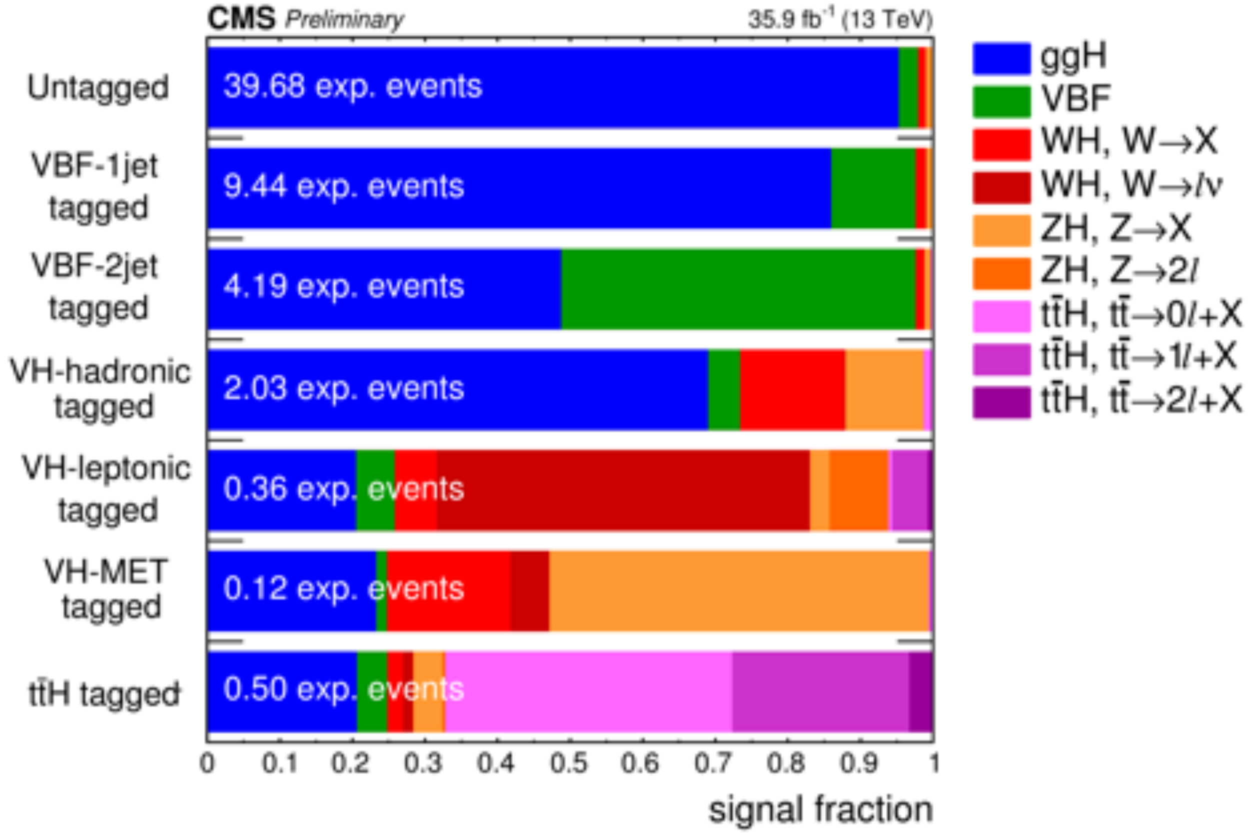
Measured cross sections and couplings are consistent with the SM expectations within 2σ.

- Mass is fixed to m_H=125.09 GeV.
- No undetected or invisible decays are assumed to exist

35.9 fb^{-1}

$H \rightarrow ZZ^* \rightarrow 4l, l=e,\mu$

CMS-PAS-HIG-16-041



4 isolated leptons (e,μ) : two pairs of same flavour opposite sign leptons

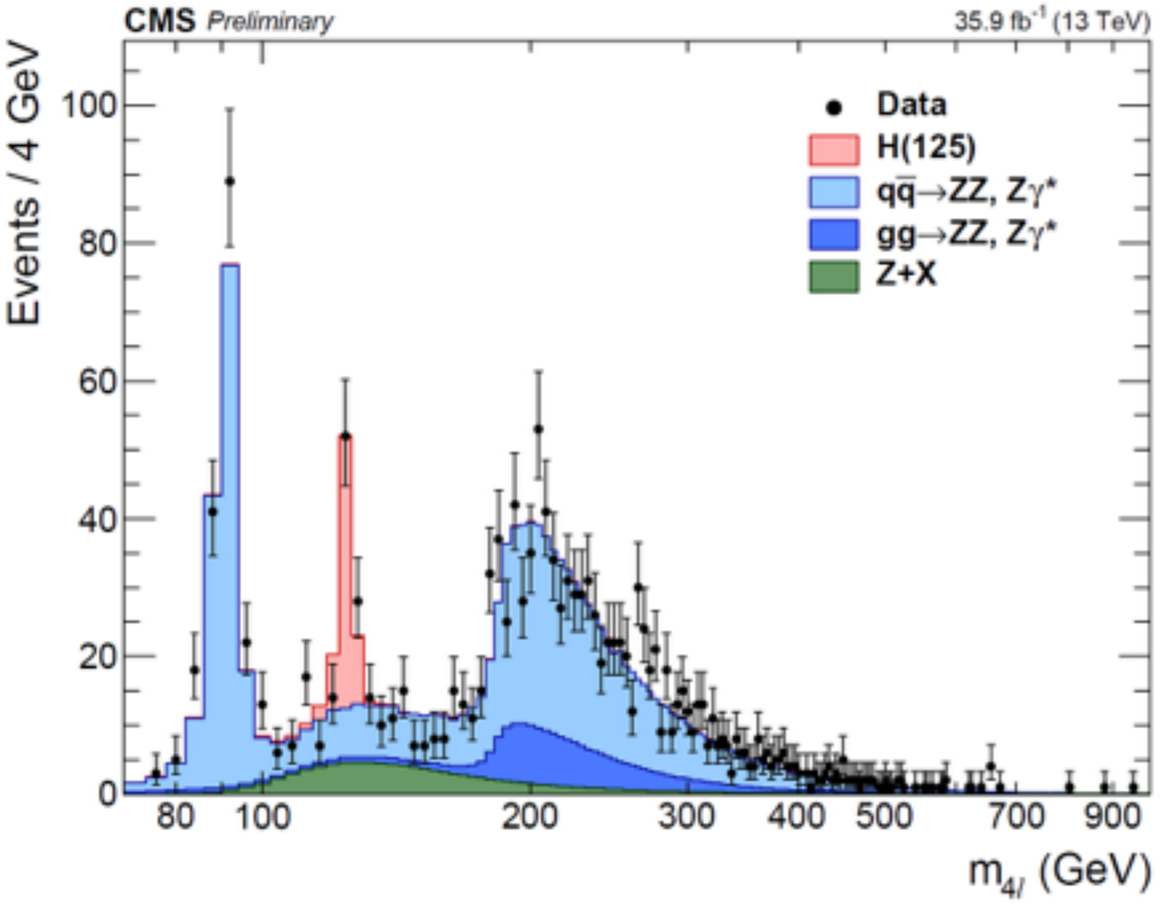
(4e, 4μ, 2e2μ or 2μ2e)

p_T >7(5)GeV,|η|<2.5(2.4) for e(μ)

Probing ggH, VBF, VH, ttH production modes with 7 event categories based on number of leptons jets, b-jets, MET. Kinematic discriminants using ME.

Assuming m_H=125.09 GeV

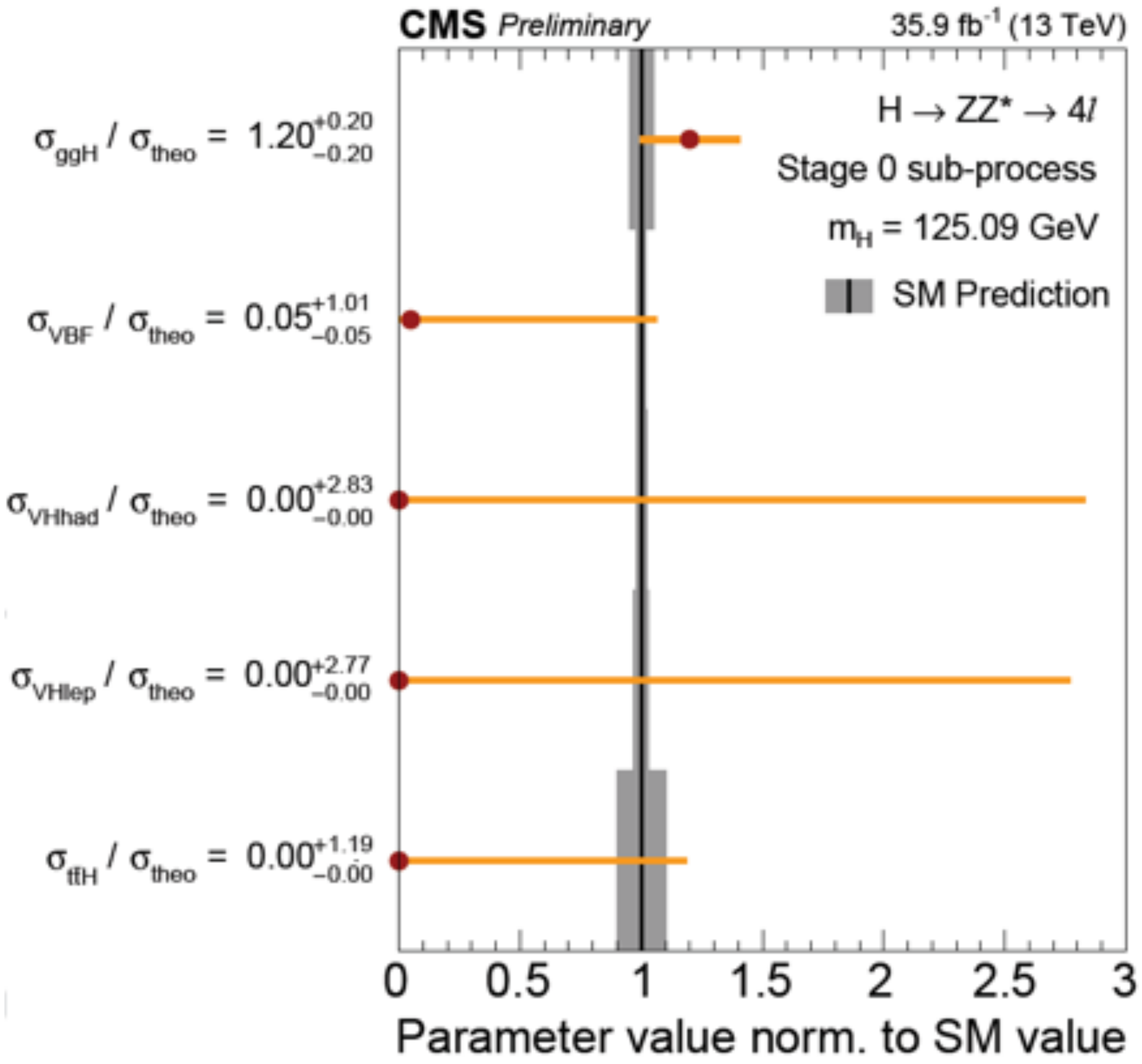
$$\mu = \frac{\sigma}{\sigma_{SM}} = 1.05^{+0.15}_{-0.14}(stat.)^{+0.11}_{-0.09}(sys.)$$

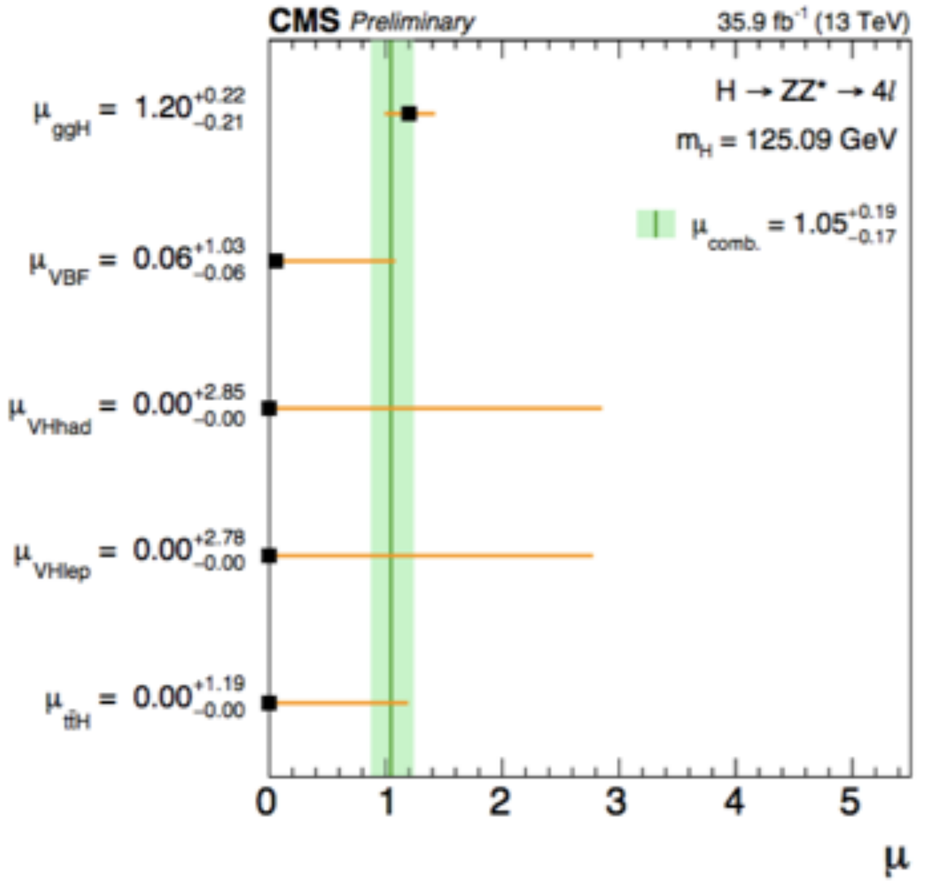


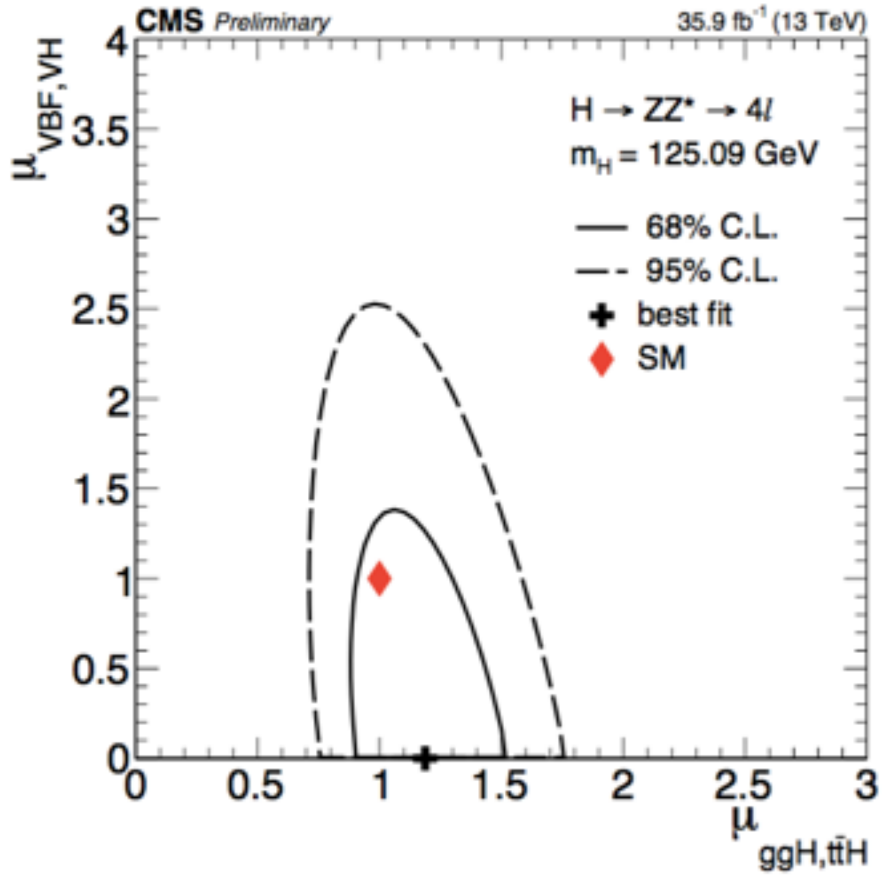
H→ZZ*→4l,l=e,μ

CMS-PAS-HIG-16-041

$35.9\ \mathrm{fb}^{-1}$







- Simplified cross sections for $|y_H|<2.5$

CMS H→ZZ*→4l Differential fiducial

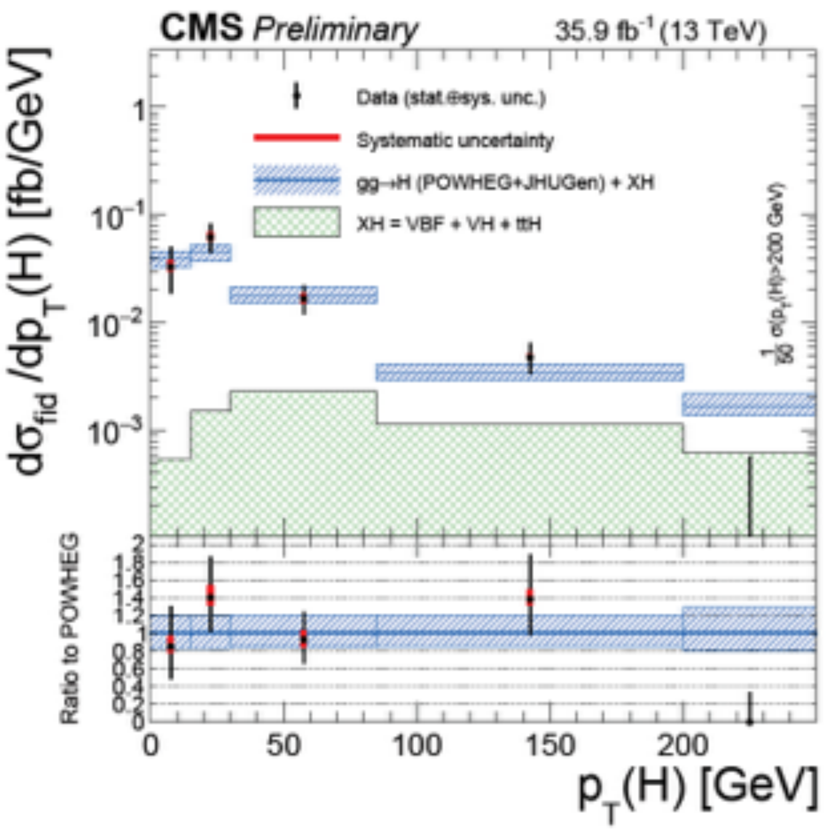
CMS-PAS-HIG-16-041

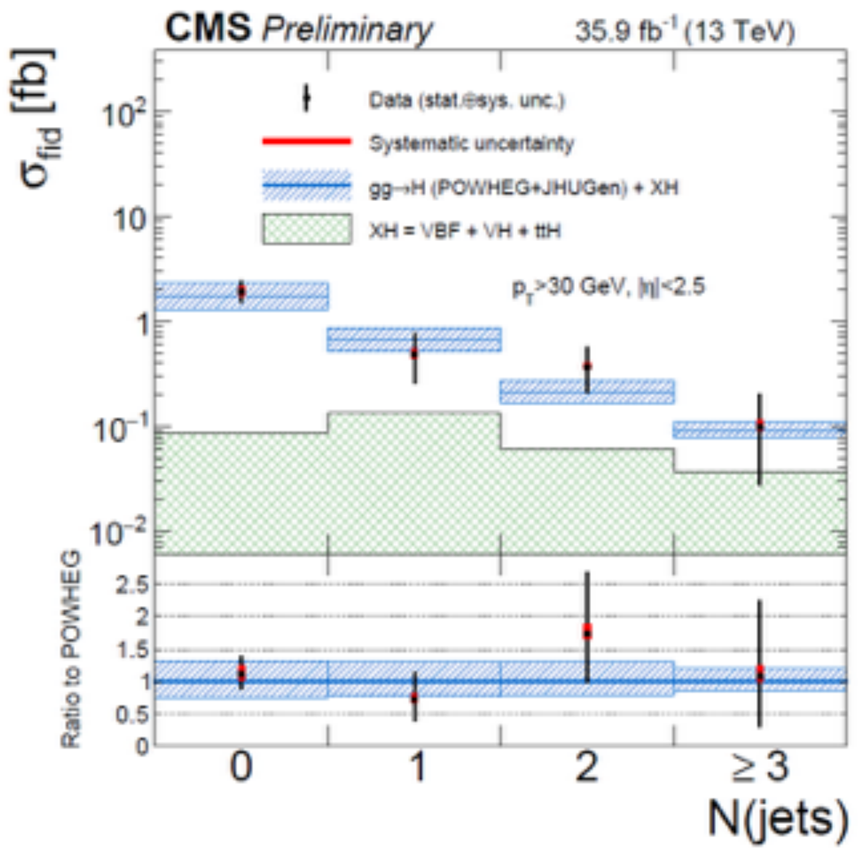
Fiducial phase space defined to closely match the experimental acceptance to reduce systematic uncertainty associated with the underlying model. Maximum likelihood fit to the m_{4l} distribution to extract the σ_{fid}. Detector level bin-by-bin correction applied.

$$\sigma_{fid} = 2.90^{+0.48}_{-0.44}(stat)^{+0.27}_{-0.22}(syst)\,fb$$

$$\sigma^{SM}_{fid} = 2.72 \pm 0.14\,fb$$

Consistent with SM expectations within uncertainties, statistically dominated.





35.9 fb^{-1}

New!

$H \rightarrow ZZ^* \rightarrow 4l$ Differential

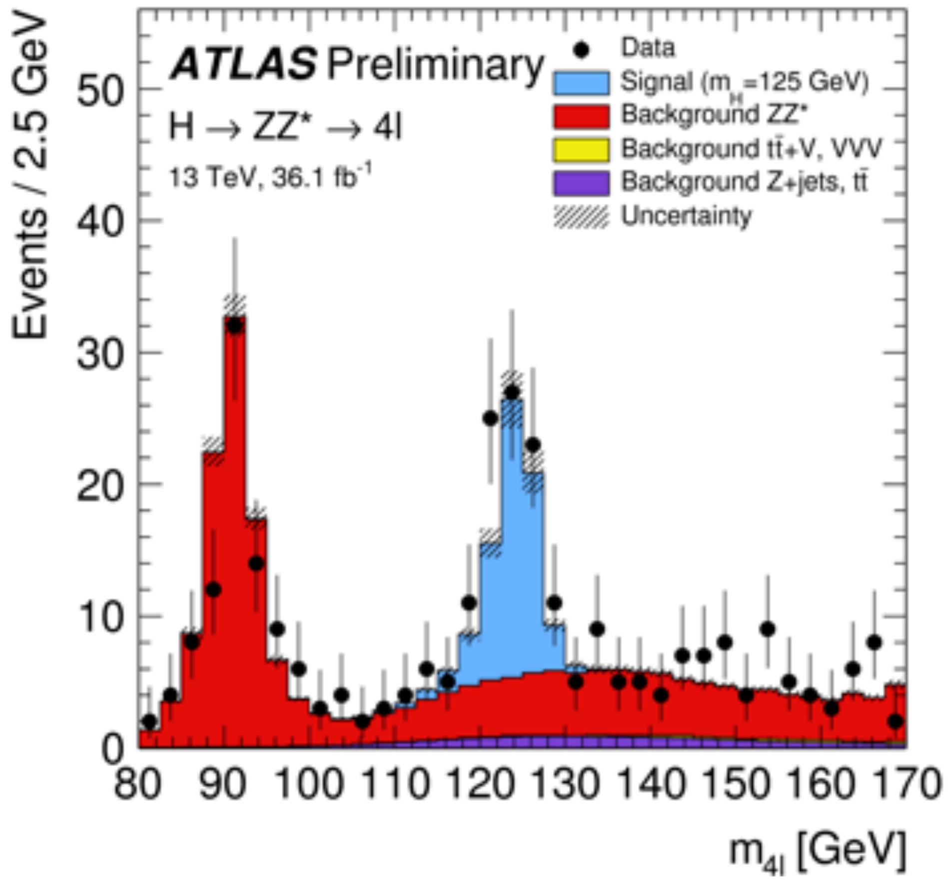
ATLAS-CONF-2017-032

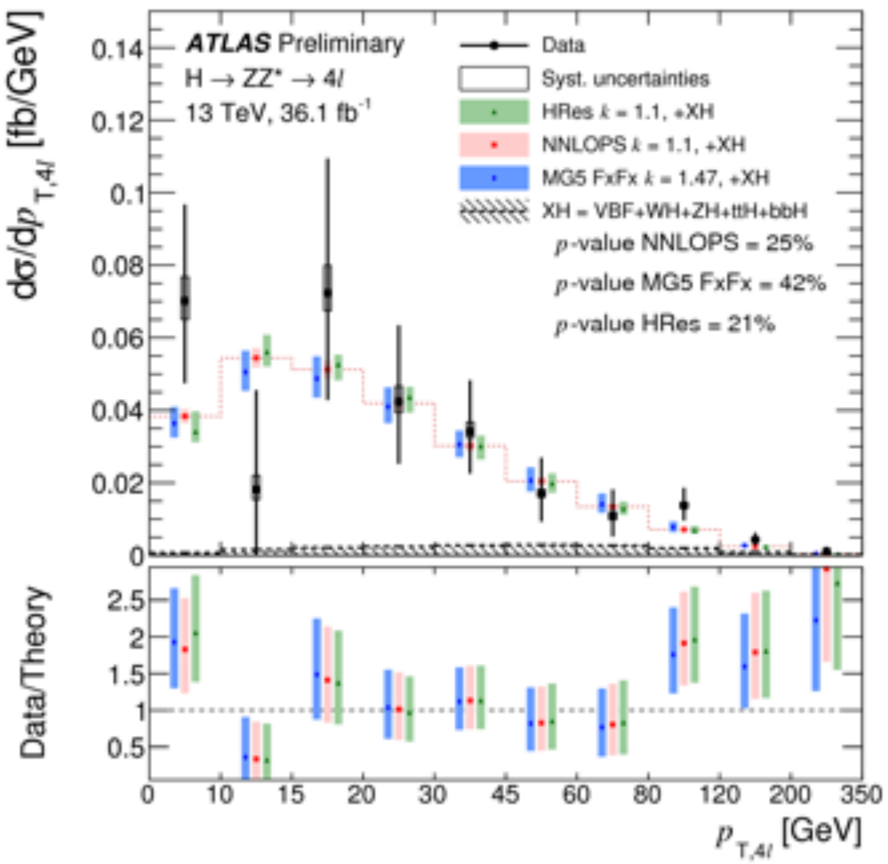
Two isolated-lepton pairs
p_T>5/7 GeV for muons/electrons loose lepton identification criteria

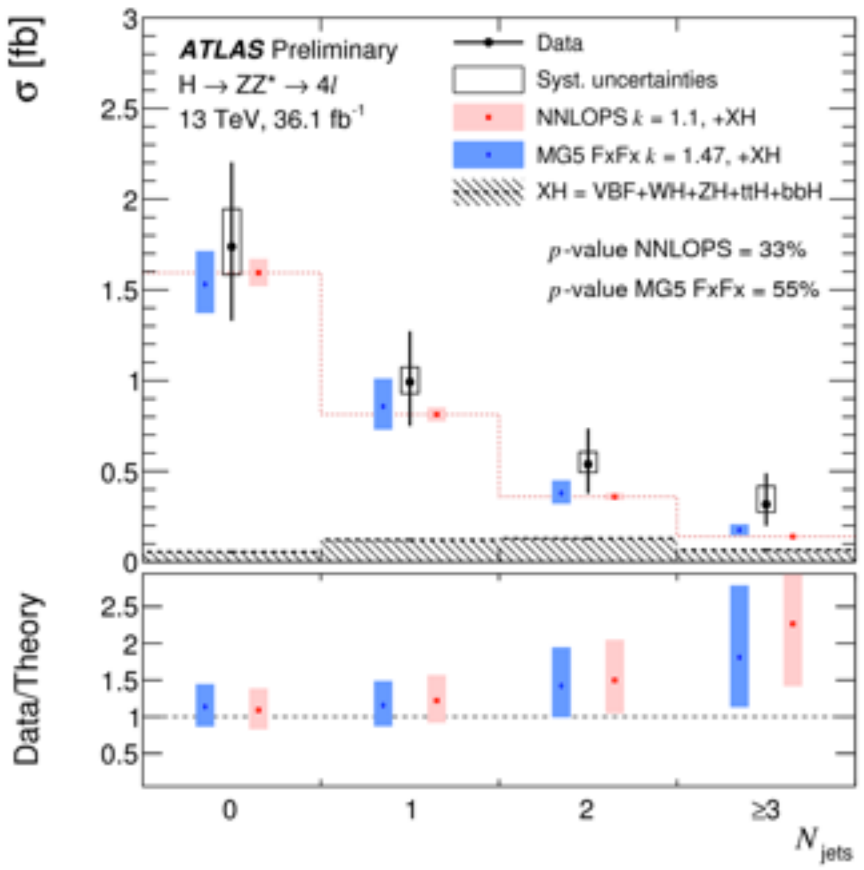
Profile likelihood ratio fit to the m_{4l} distribution to extract the σ_{fid}.

Probe kinematics [p_T, y], spin/parity sensitive variables [cosθ*, $\Delta\phi_{jj}$] and production-mechanism sensitive observables [N_{jets}, m_{jj}, p_{Tj1}]

36.1 fb^{-1}



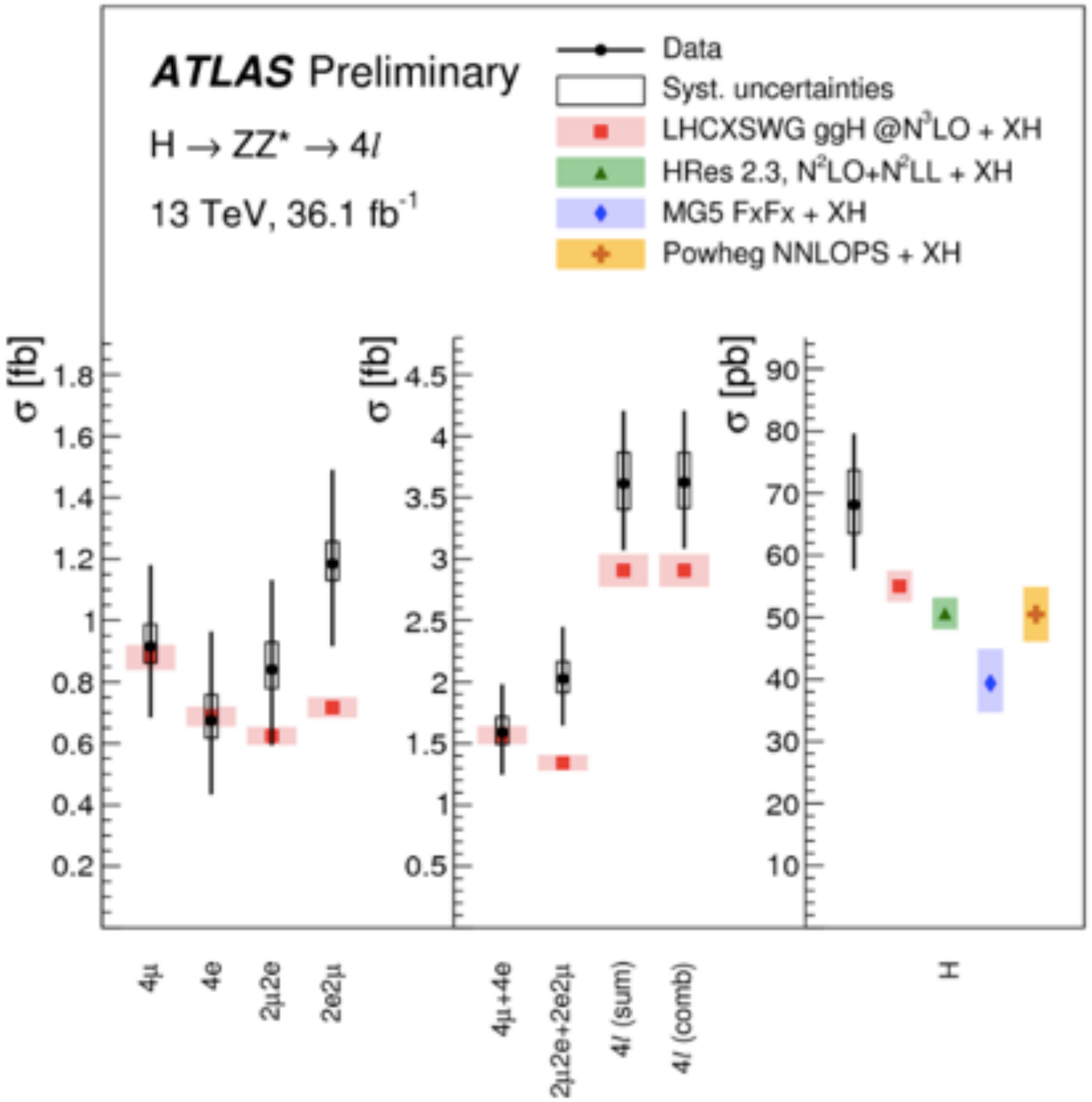




36.1 fb^{-1}

ATLAS H→ZZ*→4l fiducial

ATLAS-CONF-2017-032



- 2e2μ and 2μ2e channels fiducial x-sections larger than expected.
- Agreement of combined fiducial x-section and prediction within 1.5 σ
- Statistically dominated. Larges systematics: lepton uncertainties+Luminosity.

$$\sigma_{i,\mathrm{fid}} = \sigma_i \times A_i \times \mathrm{BR} = \frac{N_{i,\mathrm{fit}}}{\mathcal{L} \times C_i},$$

$$C_i = \frac{N_{i,\mathrm{reco}}}{N_{i,\mathrm{part}}},$$

- Ai=Acceptance in fiducial volume
- Ci= correction factor for events in fiducial volume to be reconstructed and selected
- Ni,fit is the number of extracted signal events in data

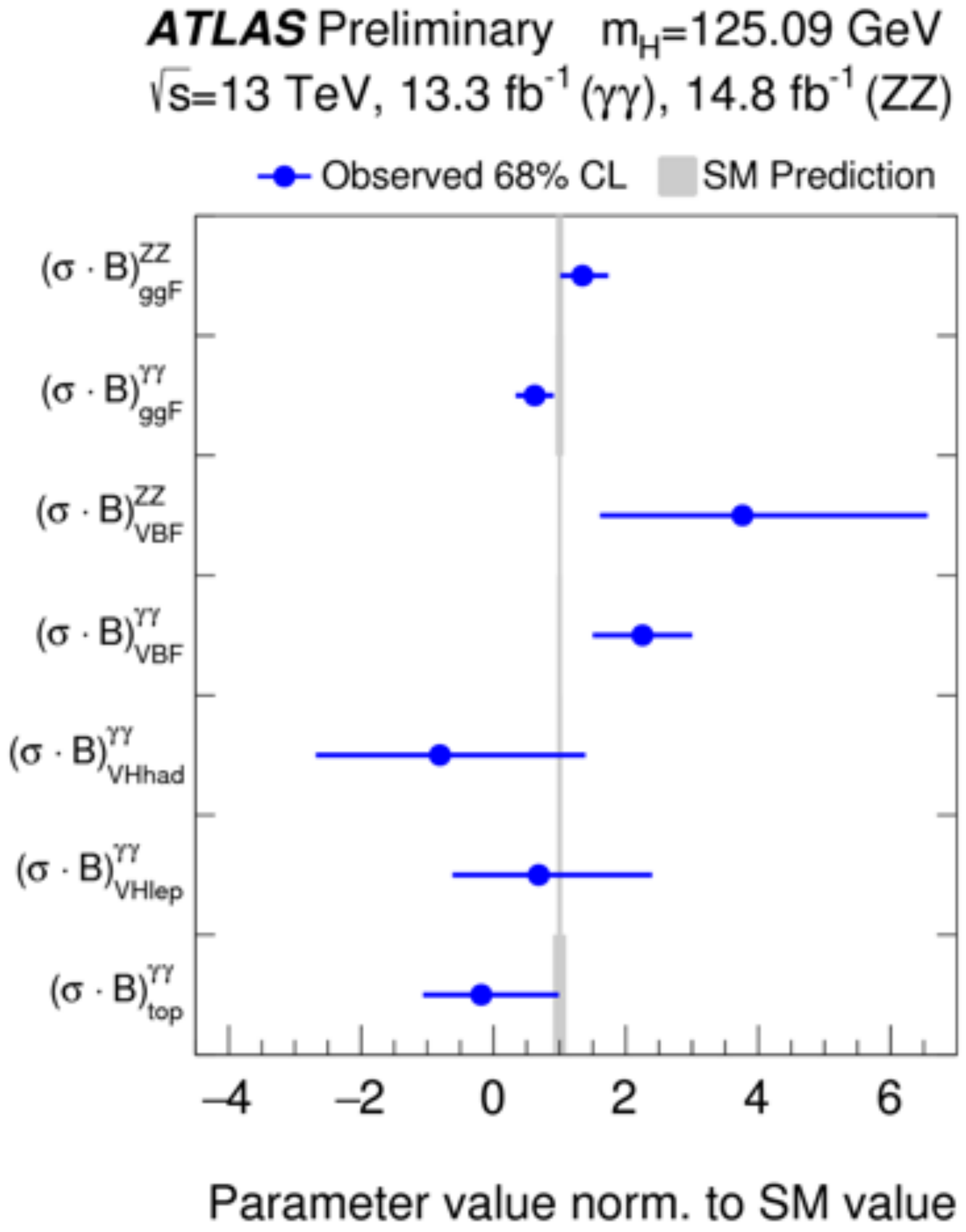
Cross section	Data (± (stat) ± (sys))	LHCXSWG prediction	p-value [%]
$\sigma_{4\mu}$ [fb]	$0.92\,^{+0.25}_{-0.23}\,^{+0.07}_{-0.05}$	0.880 ± 0.039	88
σ_{4e} [fb]	$0.67\,^{+0.28}_{-0.23}\,^{+0.08}_{-0.06}$	0.688 ± 0.031	96
$\sigma_{2\mu 2e}$ [fb]	$0.84\,^{+0.28}_{-0.24}\,^{+0.09}_{-0.06}$	0.625 ± 0.028	39
$\sigma_{2e2\mu}$ [fb]	$1.18\,^{+0.30}_{-0.26}\,^{+0.07}_{-0.05}$	0.717 ± 0.032	7
$\sigma_{4\mu+4e}$ [fb]	$1.59\,^{+0.37}_{-0.33}\,^{+0.12}_{-0.10}$	1.57 ± 0.07	65
$\sigma_{2\mu 2e+2e2\mu}$ [fb]	$2.02\,^{+0.40}_{-0.36}\,^{+0.14}_{-0.11}$	1.34 ± 0.06	6
σ_{sum} [fb]	$3.61\,^{+0.54}_{-0.50}\,^{+0.26}_{-0.21}$	2.91 ± 0.13	19
σ_{comb} [fb]	$3.62\,^{+0.53}_{-0.50}\,^{+0.25}_{-0.20}$	2.91 ± 0.13	18
σ_{tot} [pb]	$69\,^{+10}_{-9}\,\pm 5$	55.6 ± 2.5	19

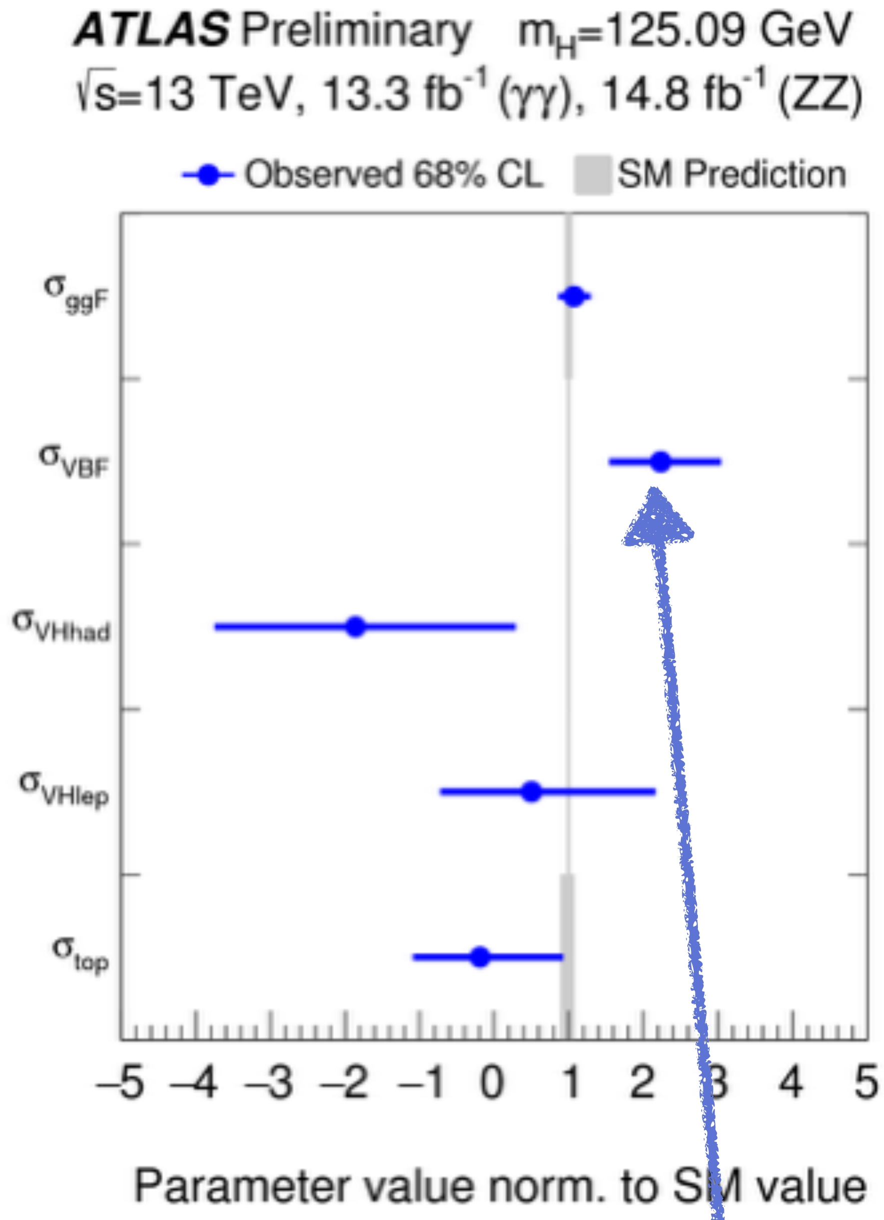
ZZ* and $\gamma\gamma$ ATLAS combination

Products of Higgs boson production cross sections of process i (σ_i) and branching ratios to the final states are reported for $|y_H| < 2.5$ ("stage-0" simplified template cross sections)

SM decays are assumed

13.3 fb^{-1}





No significant deviation from SM, 4σ significance of VBF production in Run 2 (1.9σ exp)

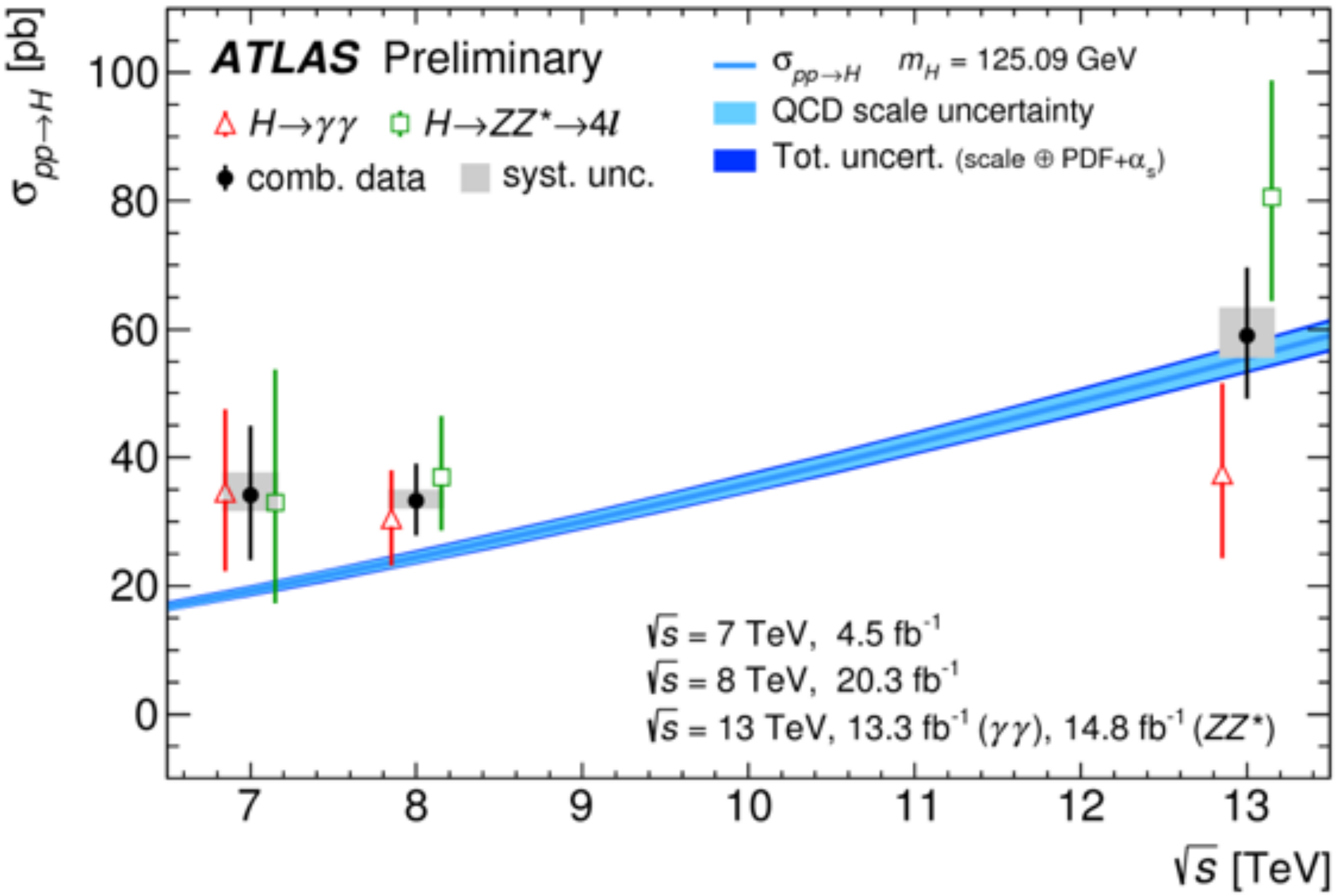
ZZ* and $\gamma\gamma$ ATLAS combination

Signal strength $\mu = 1.13^{+0.18}_{-0.17}$

$\gamma\gamma$ 13.3 fb^{-1}

ZZ 14.8 fb^{-1}

σ(pp → H+X) in the full phase space obtained from fiducial cross section



$$\sigma(pp \rightarrow H+X) = 59.0^{+9.7}_{-9.2}(stat)^{+4.4}_{-3.5}(syst)\ pb$$

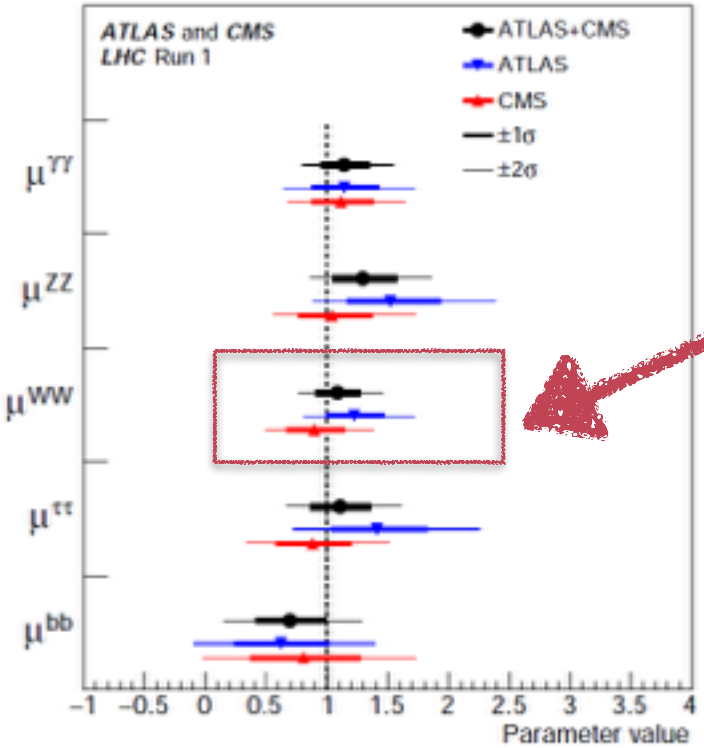
good agreement with
N3LO QCD + NLO EW

$$\sigma(pp \rightarrow H+X) = 55.5^{+2.4}_{-3.4}\ pb$$

H→WW*

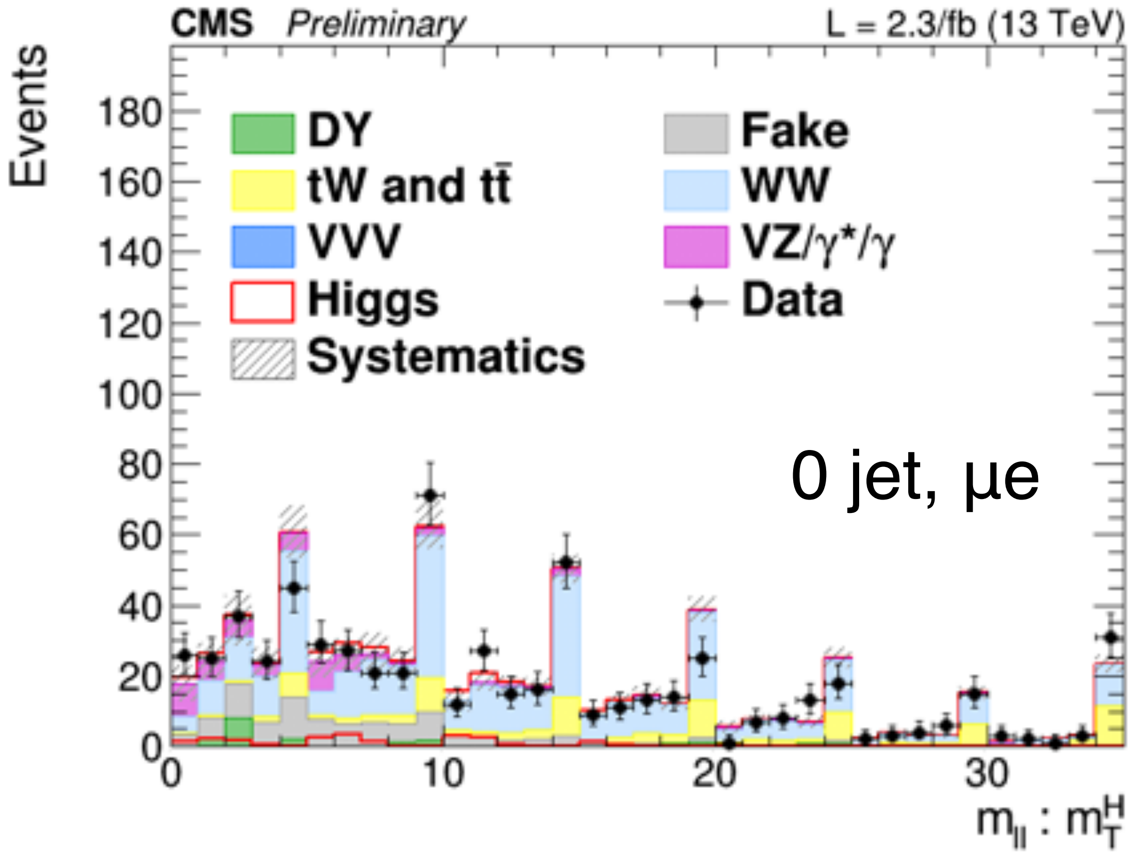
$2.3\ \text{fb}^{-1}$
$5.81\ \text{fb}^{-1}$

CMS-PAS-HIG-15-003
ATLAS-CONF-2016-112



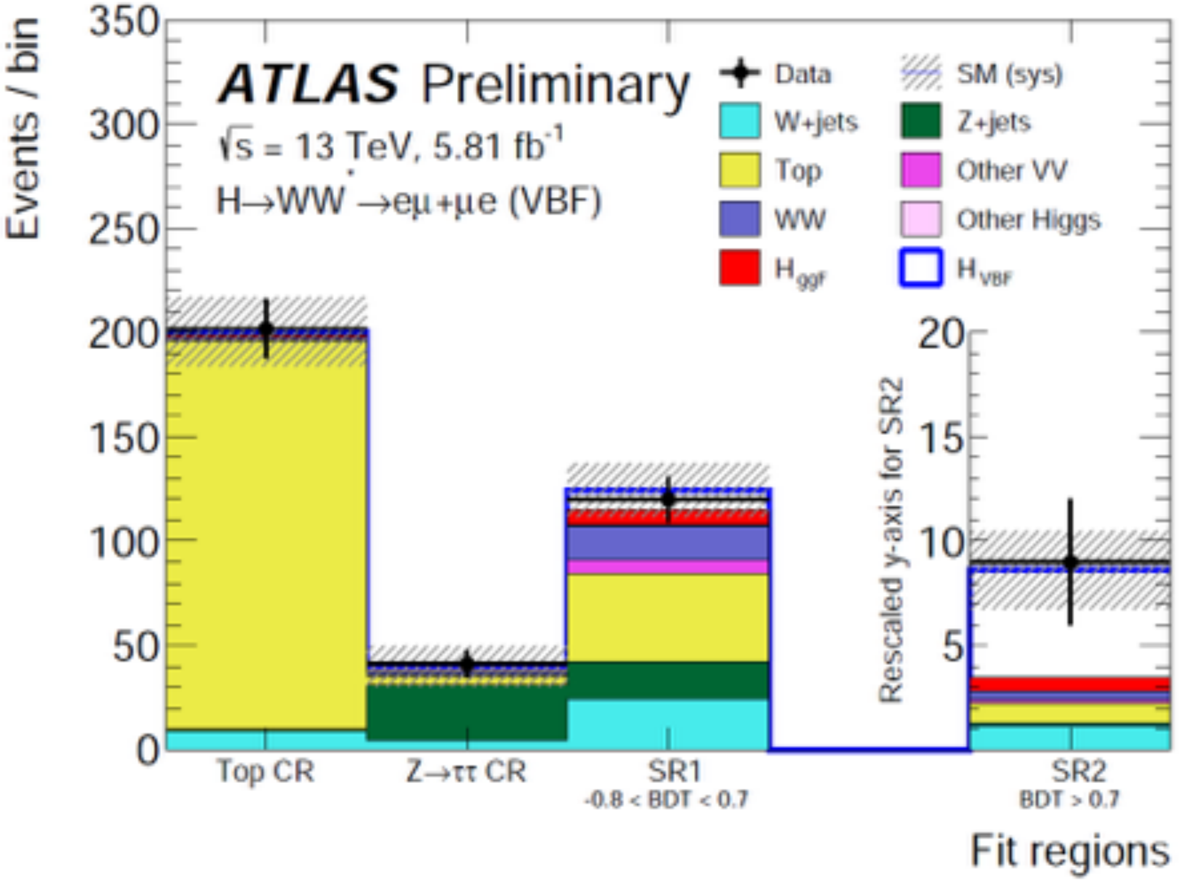
Gave most precise signal strength in Run1.

CMS ggF only: Categorization: 0,1 jet, eμ,μe (p_T ordered)
Binned fit of unrolled 2D histograms m_{ll}, m_T^H



$\mu_{ggF} = 0.3 \pm 0.5\ \sigma = 0.7 (2\sigma\ \text{expected})$

only $2.3\ \text{fb}^{-1}$ run II still limited by stat uncertainty!

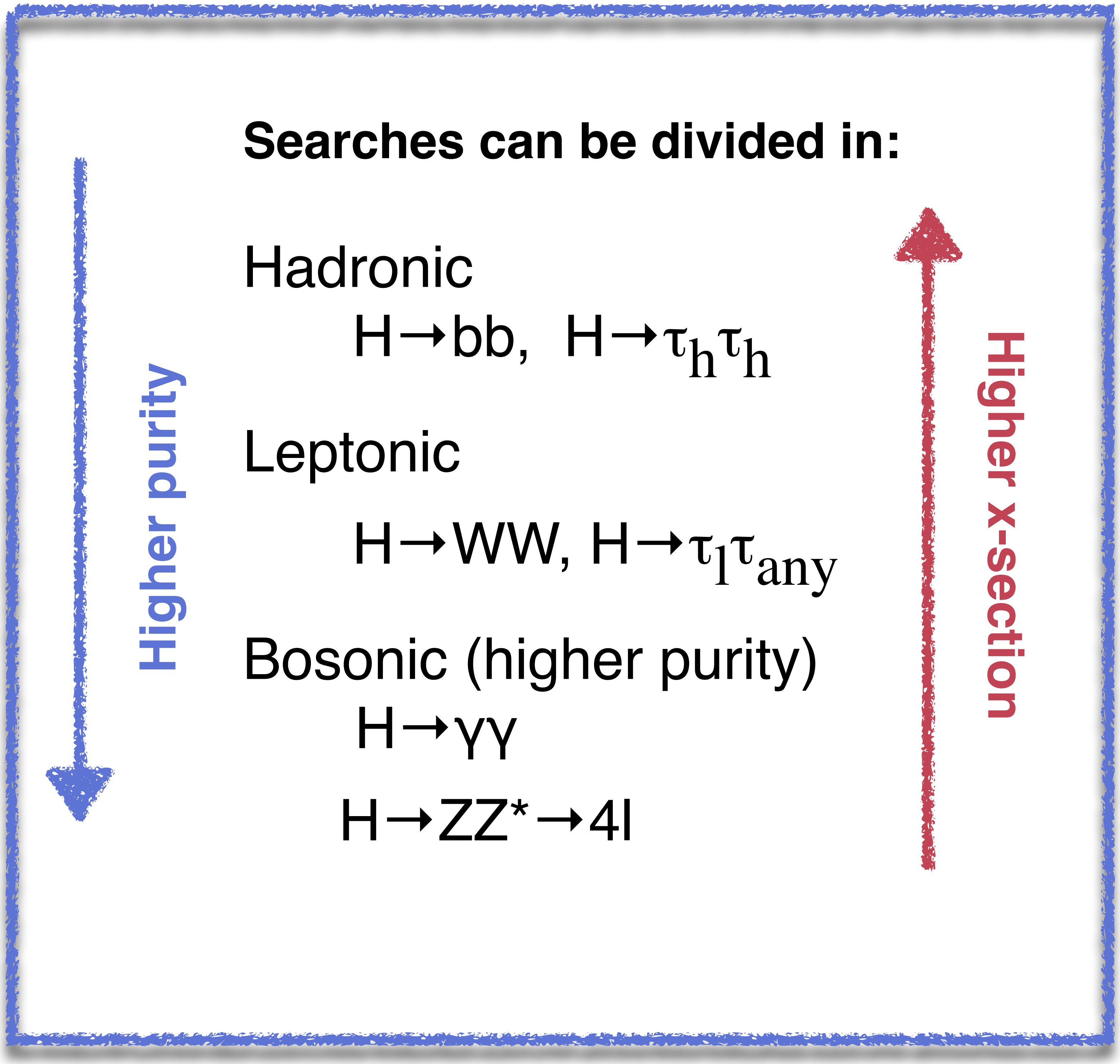


ATLAS: VBF and WH production modes studied.
Categorization in jet and lepton multiplicities.
Consistent with SM

$\mu_{VBF} = 1.7^{+0.10}_{-0.08}(\text{stat})^{+0.6}_{-0.4}(\text{syst})$

$\mu_{WH} = 3.2^{+3.7}_{-3.2}\ (\text{stat})+^{2.3}_{-2.7}(\text{syst})$

ttH



Searches can be divided in:

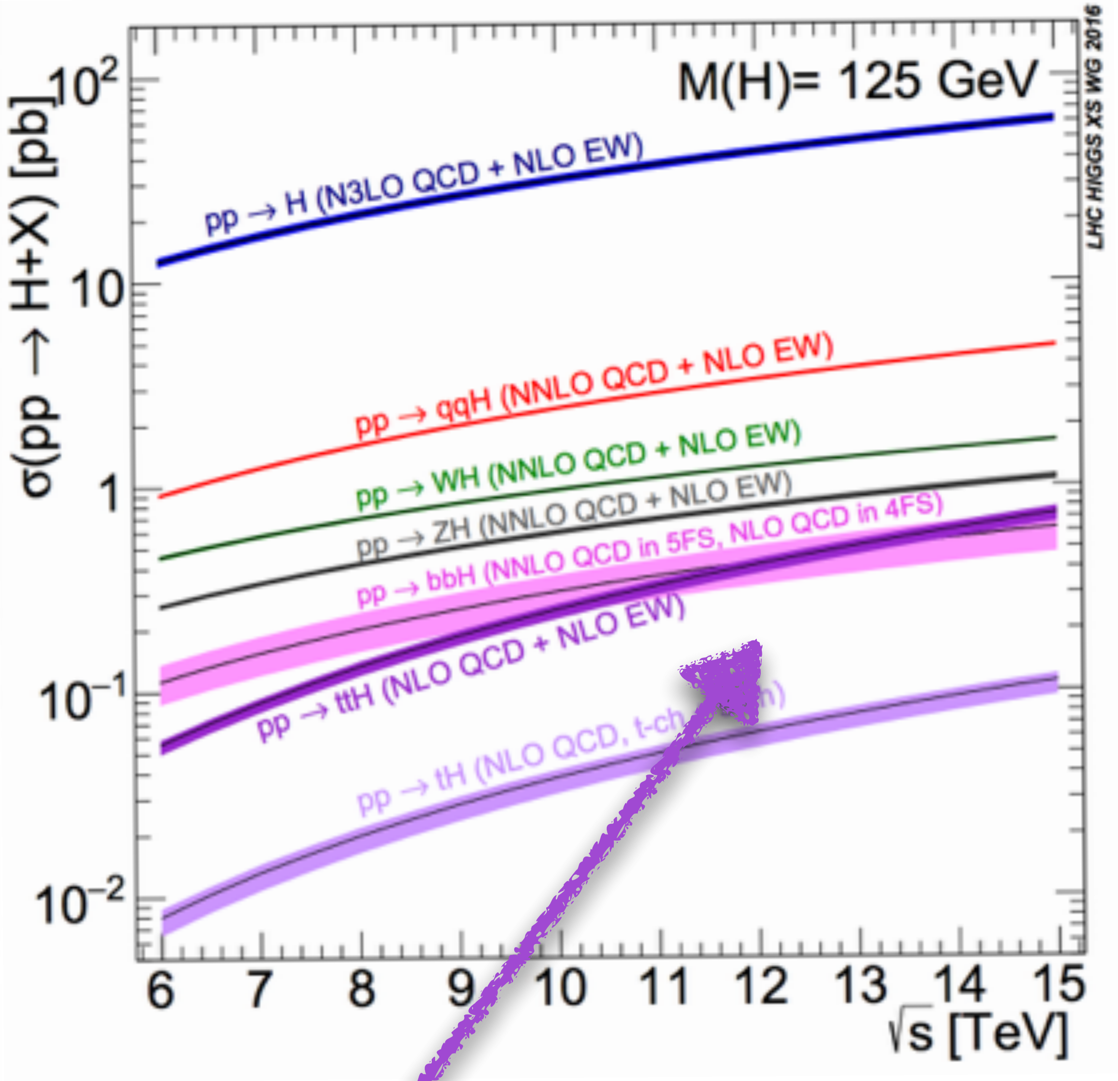
Higher purity

Higher x-section

Hadronic
$H \to bb$, $H \to \tau_h \tau_h$

Leptonic
$H \to WW$, $H \to \tau_l \tau_{any}$

Bosonic (higher purity)
$H \to \gamma\gamma$
$H \to ZZ^* \to 4l$



ttH x-sec increases 2 times faster than other modes

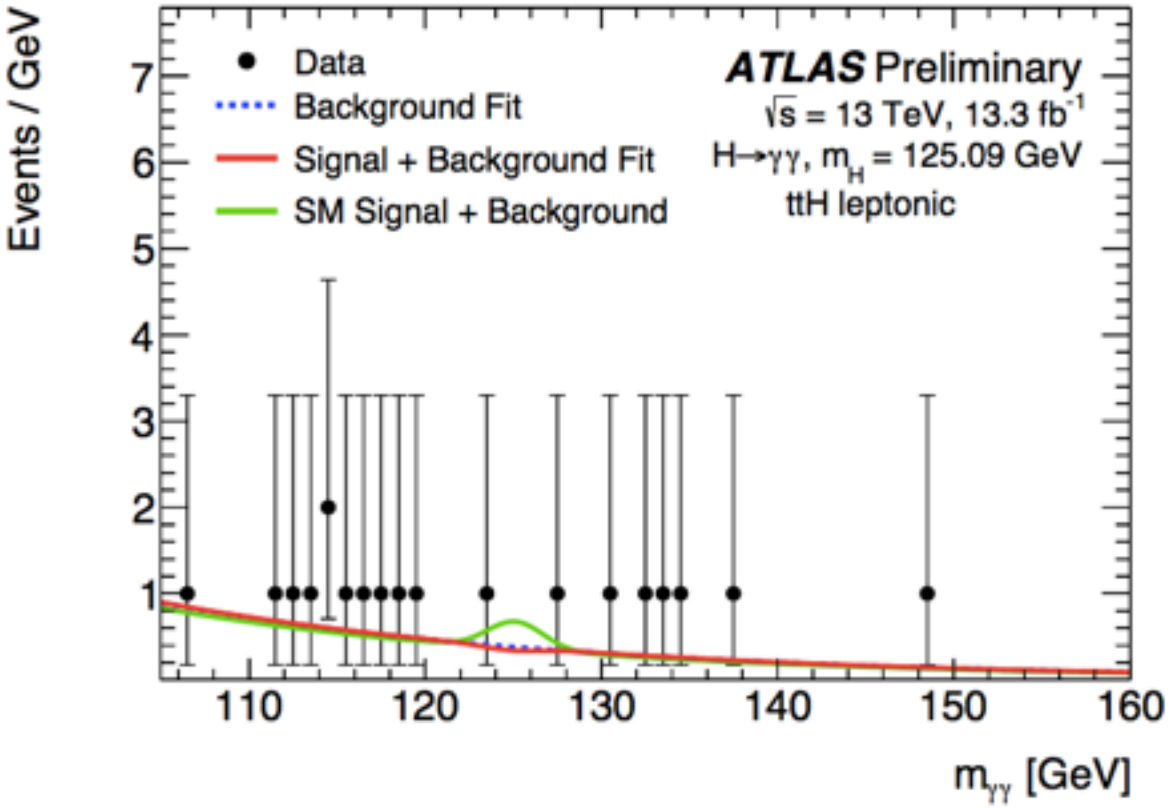
ttH→γγ

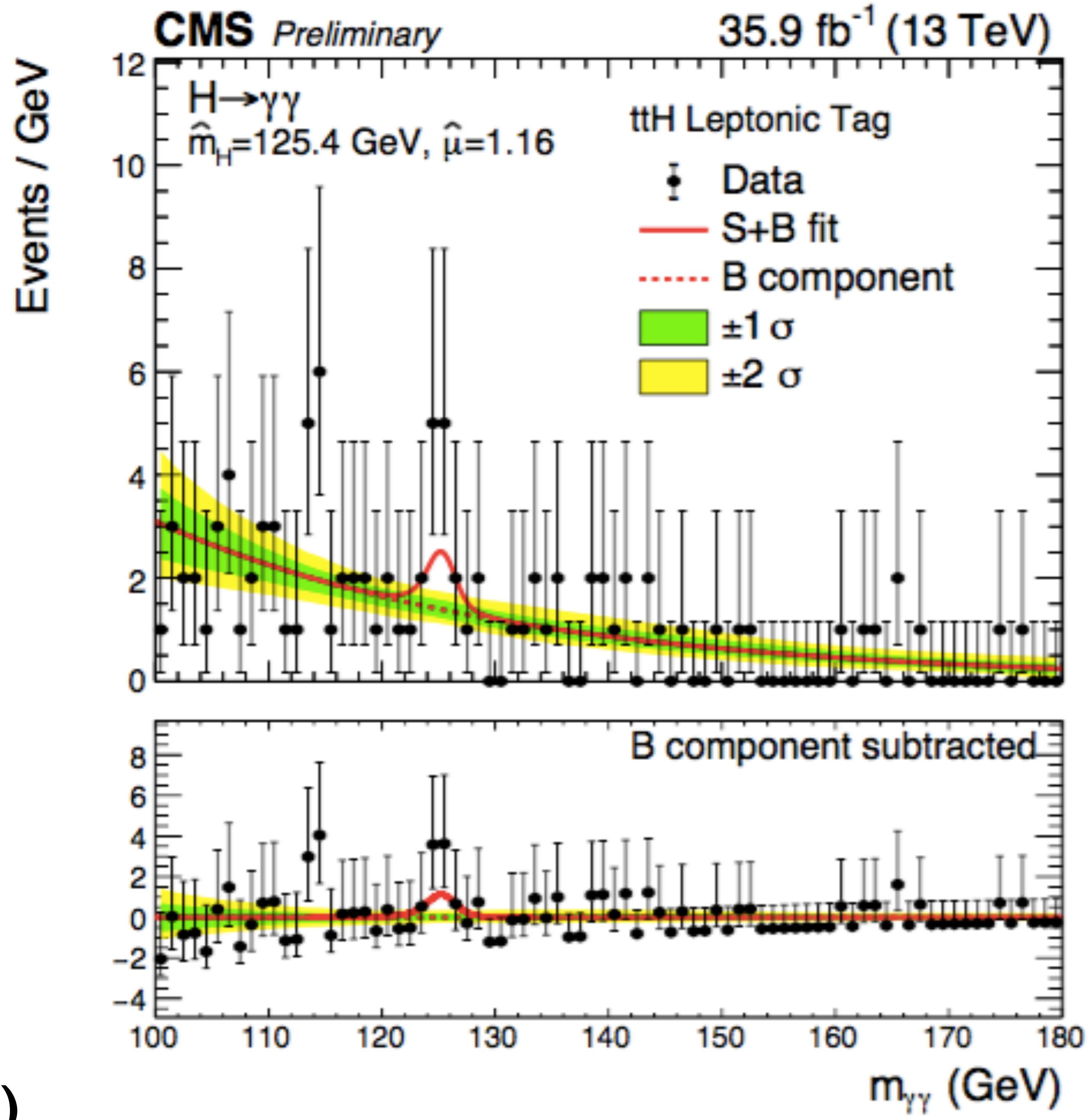
CONF-2016-067 13.3 fb^{-1}
PAS HIG-16-040 35.9 fb^{-1}

Both ATLAS and CMS use hadronic and semi-leptonic decays of top
Background estimated from CR where ≥ 1 **γ**

- fails tight identification
- fails isolation criteria

BDT for S vs Bkg separation in both cases





		σ(stat)	σ(syst)
ATLAS	$\mu=-0.25^{1.2}_{-1.0}$	1.2 -1.0	0.2 -0.2
CMS	$\mu=2.2^{+0.9}_{-0.8}$		

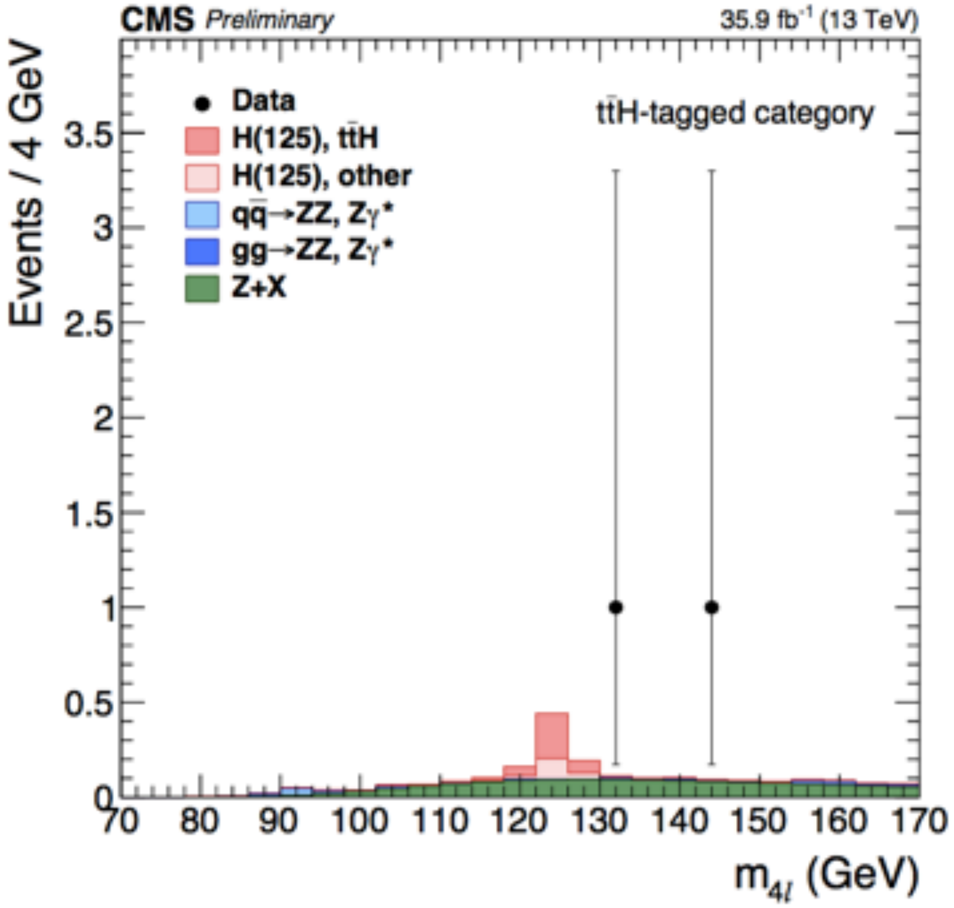
statistically limited
CMS observed 3.3σ (exp1.5σ)
compatible with SM at 1.6σ

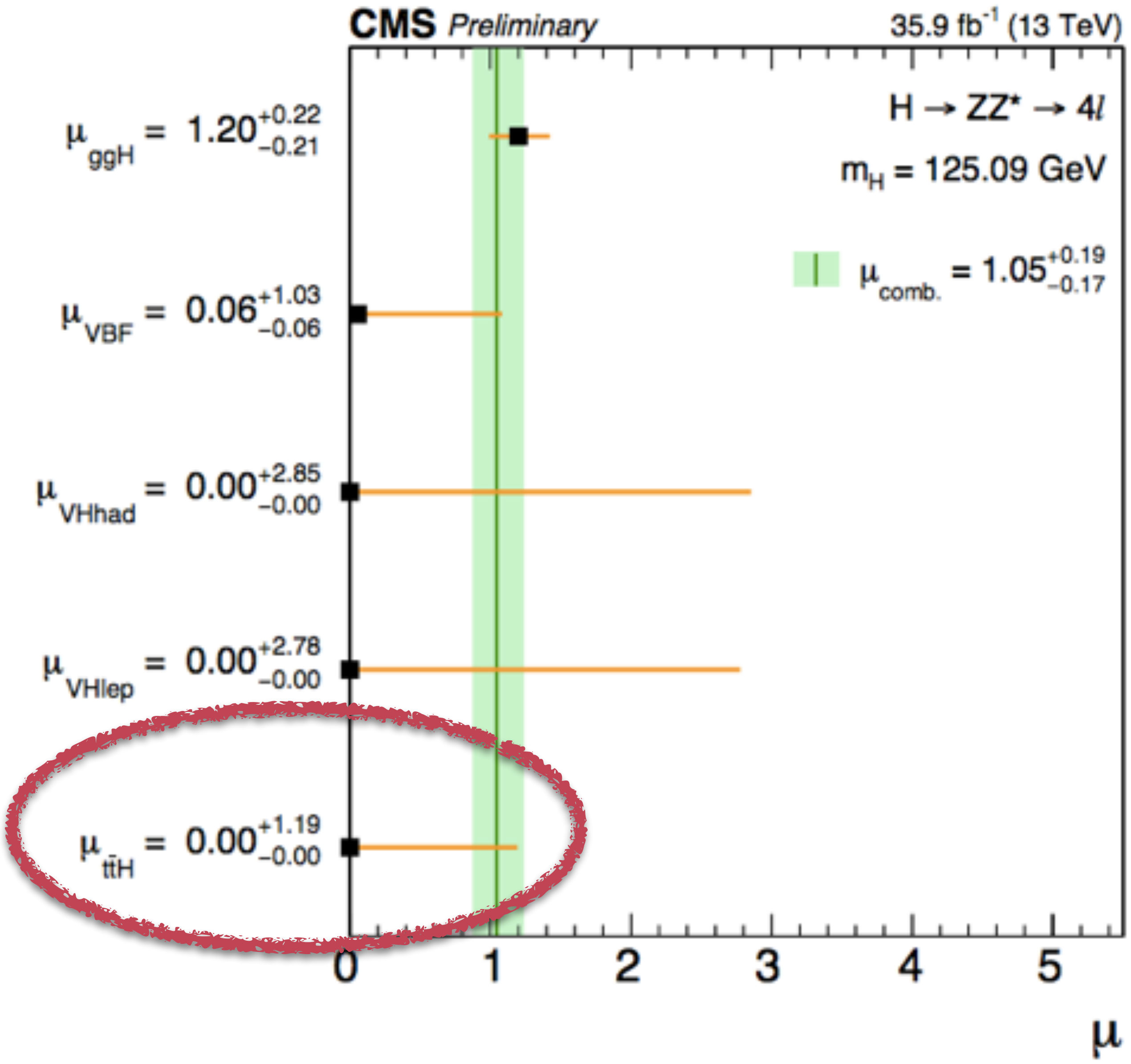
ttH→4l

CMS PAS HIG-16-041

Full 13 TeV statistics.
Strategy: Measure inclusive production cross section of H → ZZ → 4l, tag production mode and extract ttH

$35.9\ \text{fb}^{-1}$





Statistically limited, both 4l and $\gamma\gamma$ will profit in near future from more data

ttH→bb

ATLAS-CONF-2016-080 13.2 fb^{-1}

CMS PAS HIG-16-038 12.9 fb^{-1}

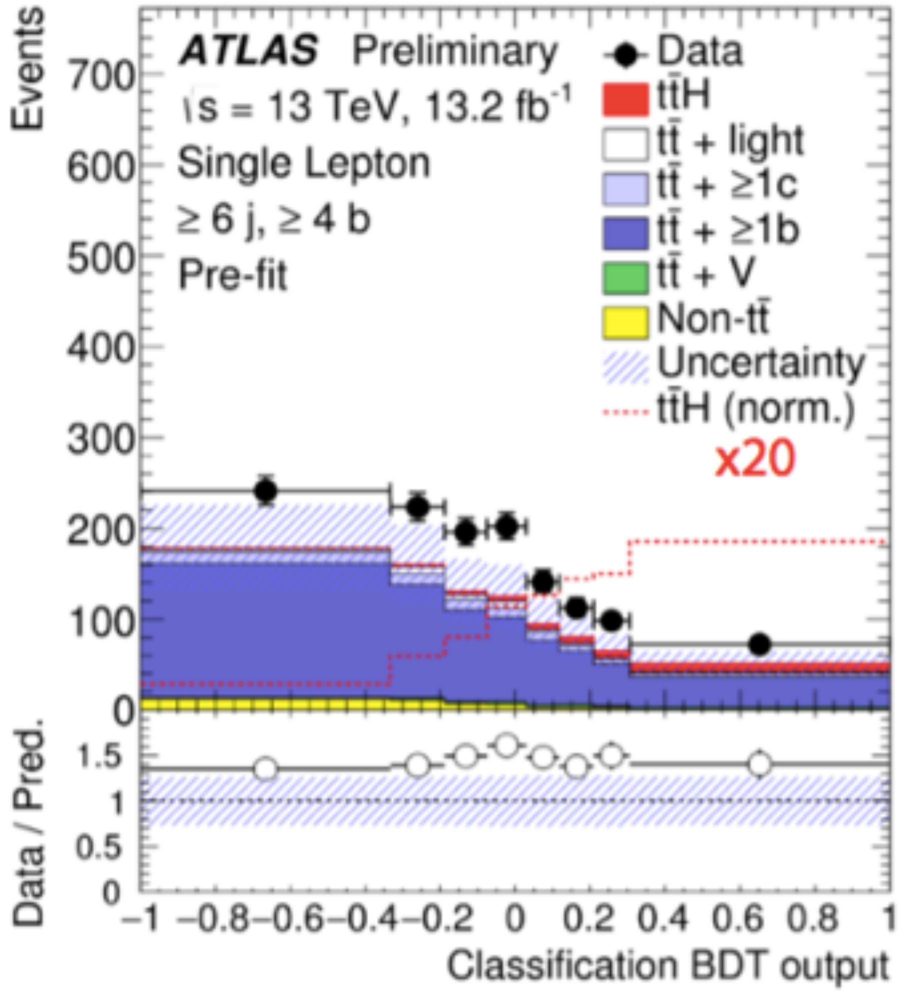
Select semi-leptonic and di-leptonic tt decays

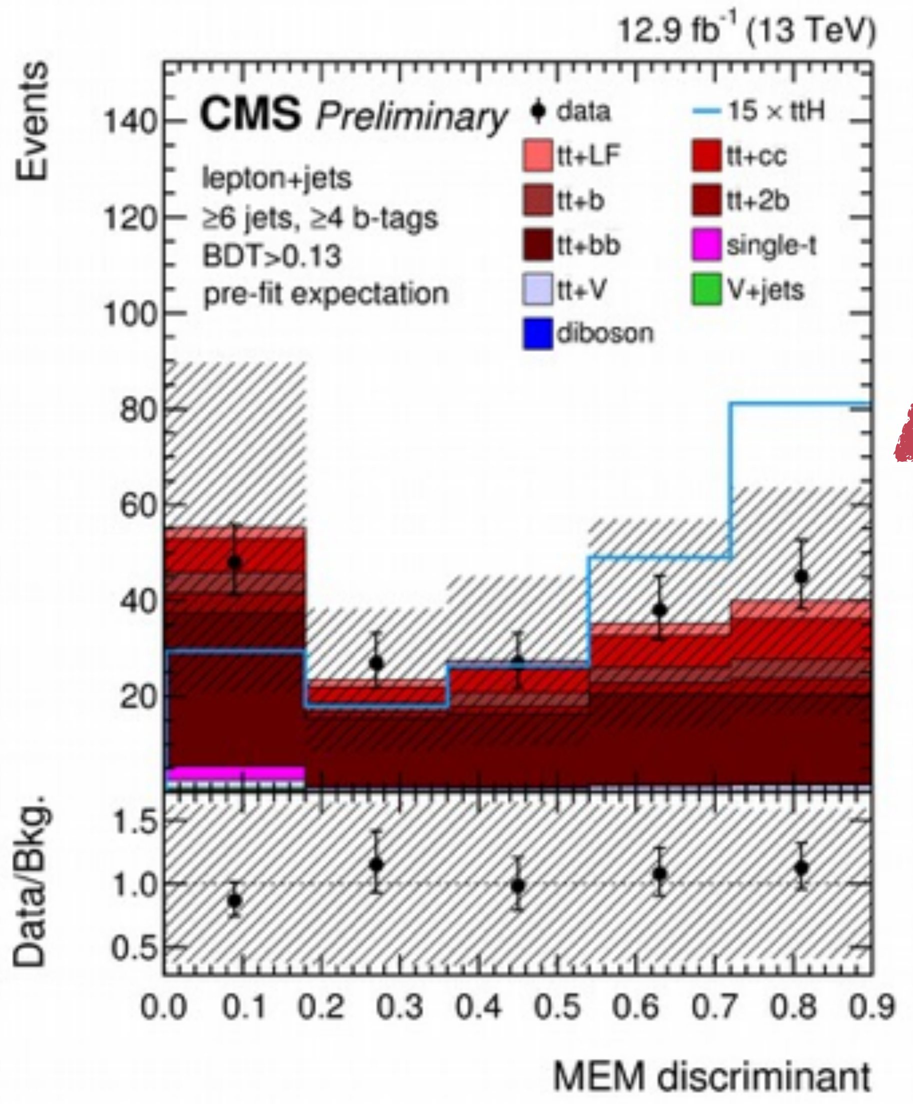
(fully hadronic ATLAS Run1)

- Leptonic, (6 quarks, 4b)
- Dileptonic (4 quarks, all b)

Both ATLAS & CMS use N_{jets} and N_b categories

ATLAS:1 BDT to reconstruct events+ 2nd BDT to disentangle S and B (HT fitted in CR)

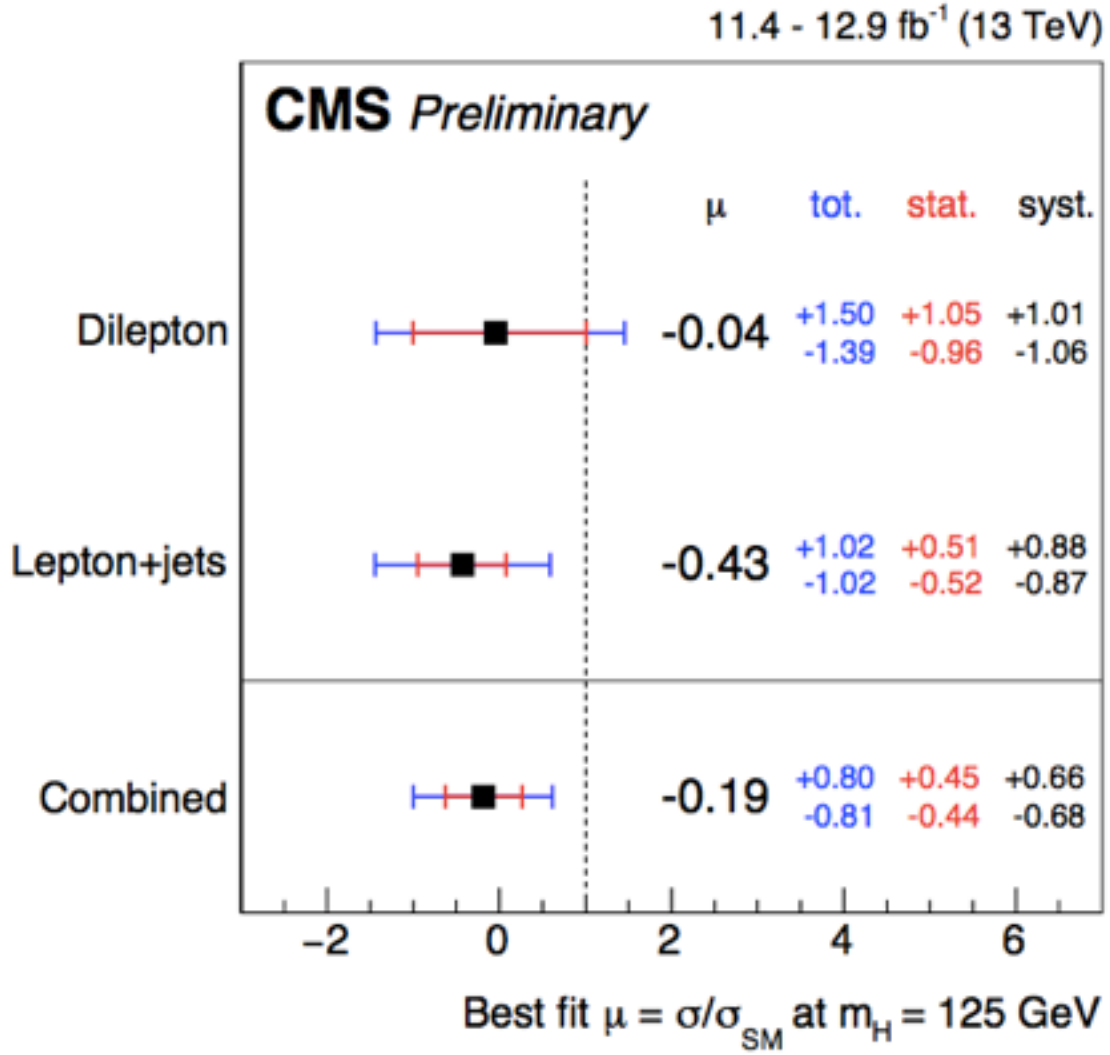


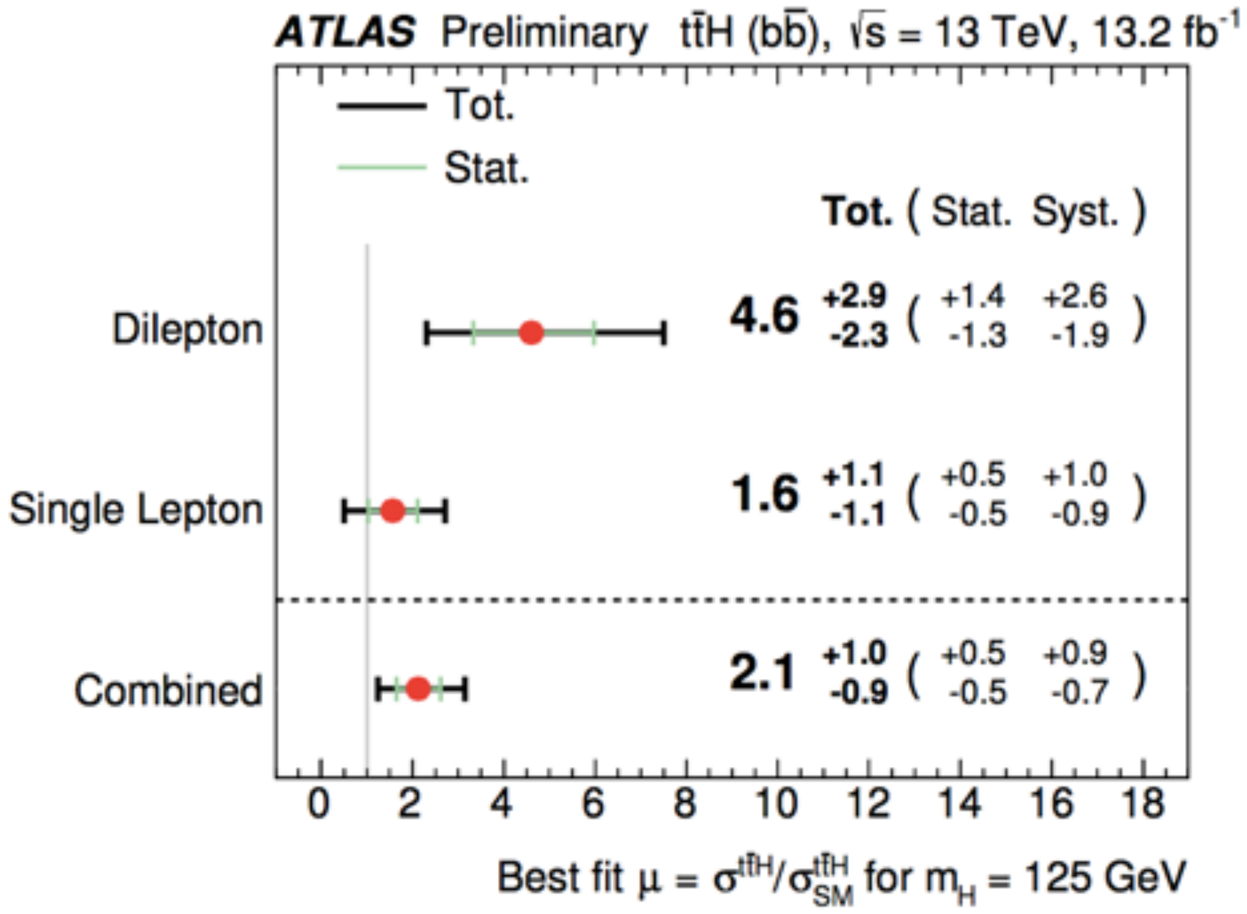


pre-fit= before fit to data of SR and CR

CMS: BDT inputs are kinematics, event shapes, b-tag discriminant. Then after BDT use Matrix Element Method (MEM) discriminant optimized to separate ttH(bb) signal from irreducible ttbb background (MEM most useful in high BDT part)

ttH→bb





limited by systematics

notably on the theoretical modeling the tt+bjets background,

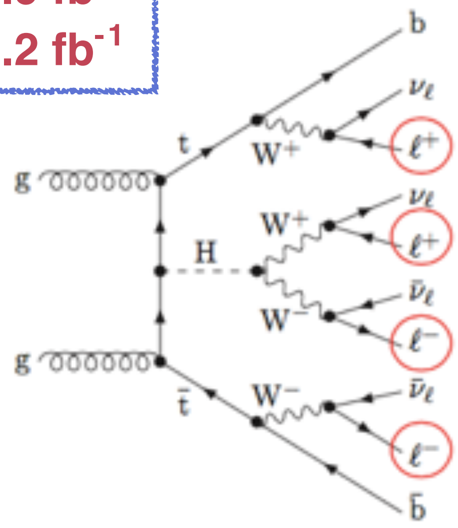
and on the experimental side flavor tagging.

CMS PAS HIG-17-004
ATLAS-CONF-2016-058

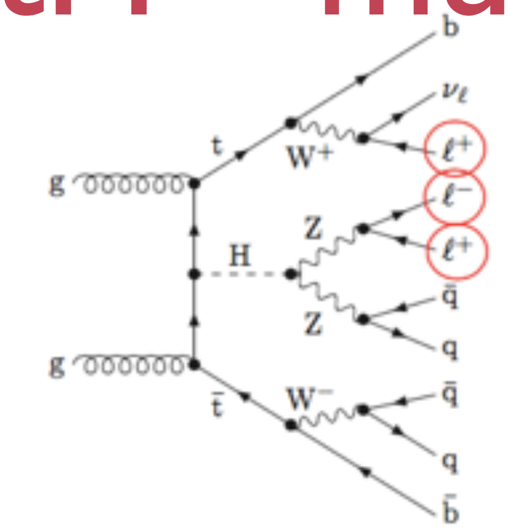
35.9 fb^{-1}
13.2 fb^{-1}

ttH→multilepton

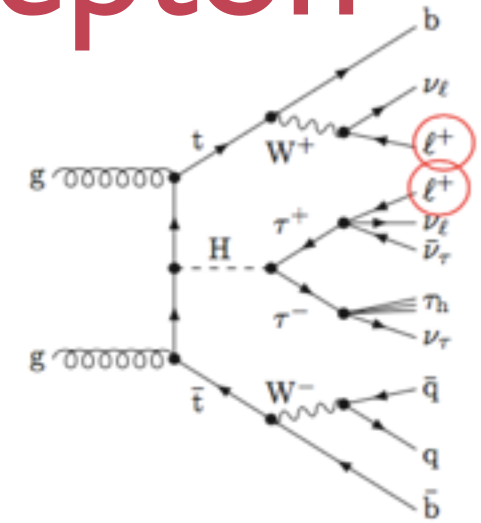
H->WW,ZZ,$\tau\tau$



4ℓ



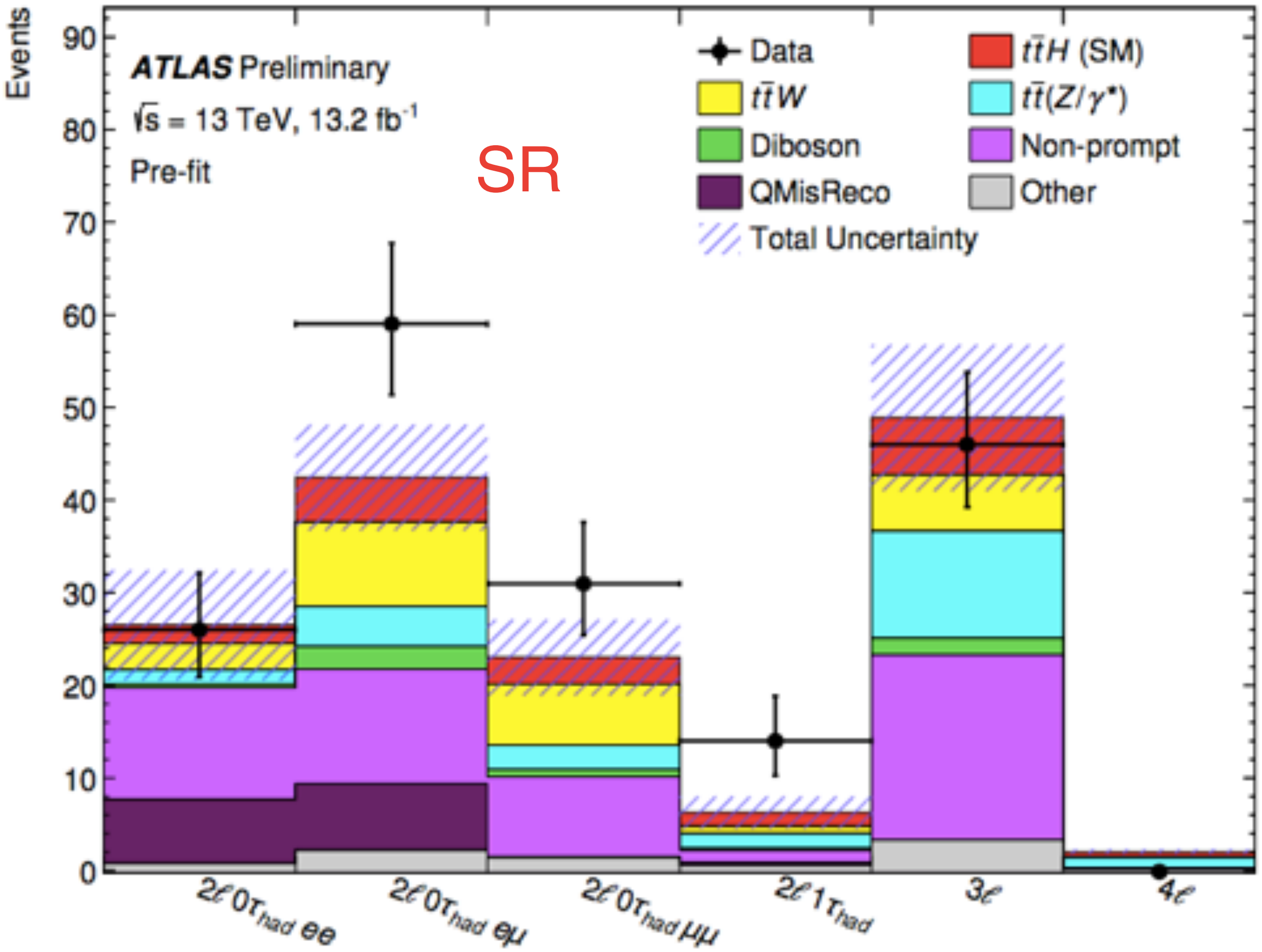
3ℓ

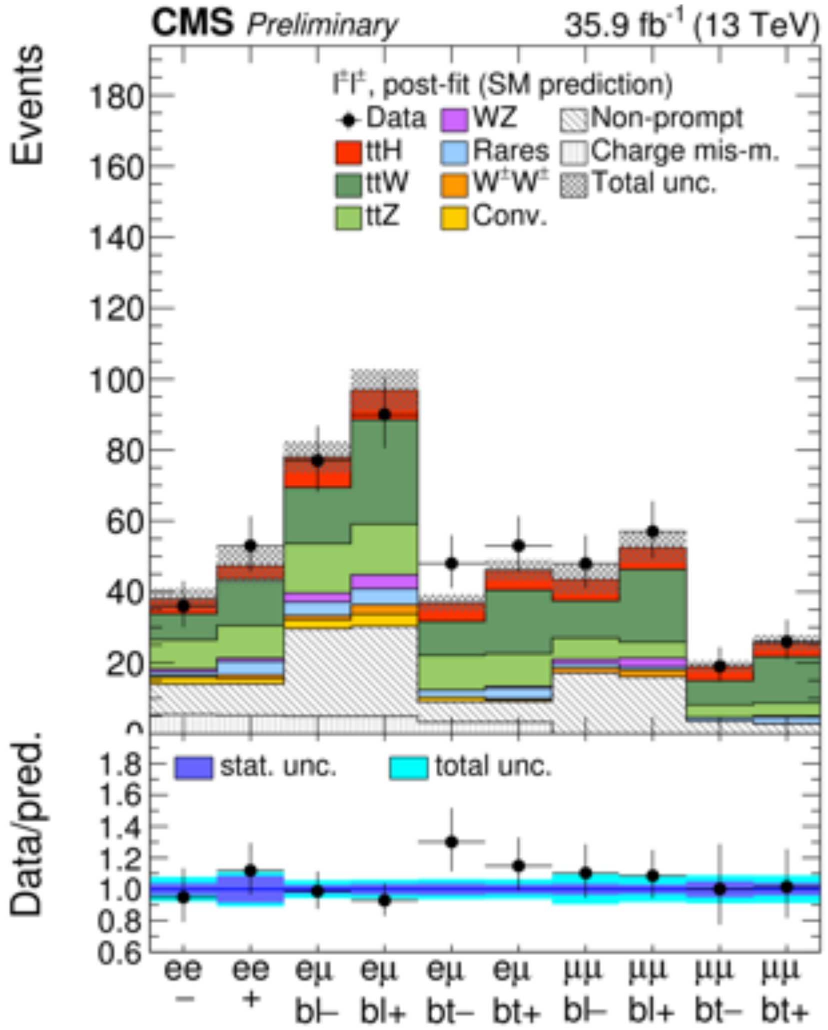


2ℓ

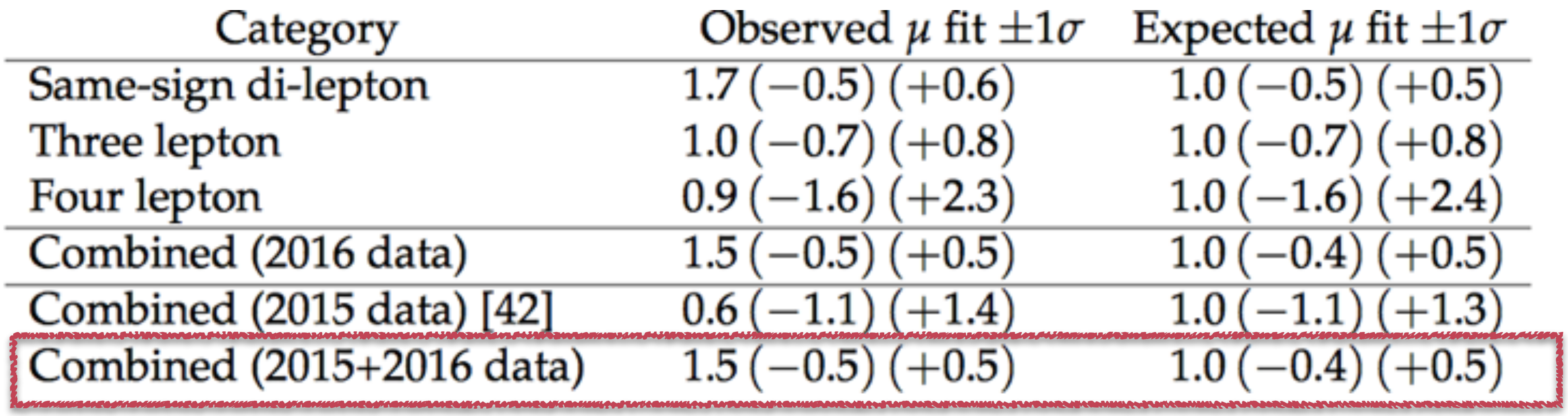
ATLAS: 4 categories, 2ℓSS 0τ_{HAD}, 2ℓSS 1τ_{HAD}, 3ℓ nτ_{HAD},4ℓ nτ_{HAD}. Uses counting experiment in all final states

CMS has full 2016 stat:2ℓSS 0τ_{HAD}, 2ℓSS 1τ_{HAD} moved to tt$\bar{H}$, H→ττ, 3ℓ 0τ_{HAD},4ℓ 0τ_{HAD} . Uses 2BDTs for 2 ℓ and 3 ℓ final states against tt and ttV bkg. Counting for 4 ℓ.





ttH→multilepton



Category	Observed μ fit $\pm1\sigma$	Expected μ fit $\pm1\sigma$
Same-sign di-lepton	1.7 (−0.5) (+0.6)	1.0 (−0.5) (+0.5)
Three lepton	1.0 (−0.7) (+0.8)	1.0 (−0.7) (+0.8)
Four lepton	0.9 (−1.6) (+2.3)	1.0 (−1.6) (+2.4)
Combined (2016 data)	1.5 (−0.5) (+0.5)	1.0 (−0.4) (+0.5)
Combined (2015 data) [42]	0.6 (−1.1) (+1.4)	1.0 (−1.1) (+1.3)
Combined (2015+2016 data)	1.5 (−0.5) (+0.5)	1.0 (−0.4) (+0.5)

CMS

35.9 fb^{-1}

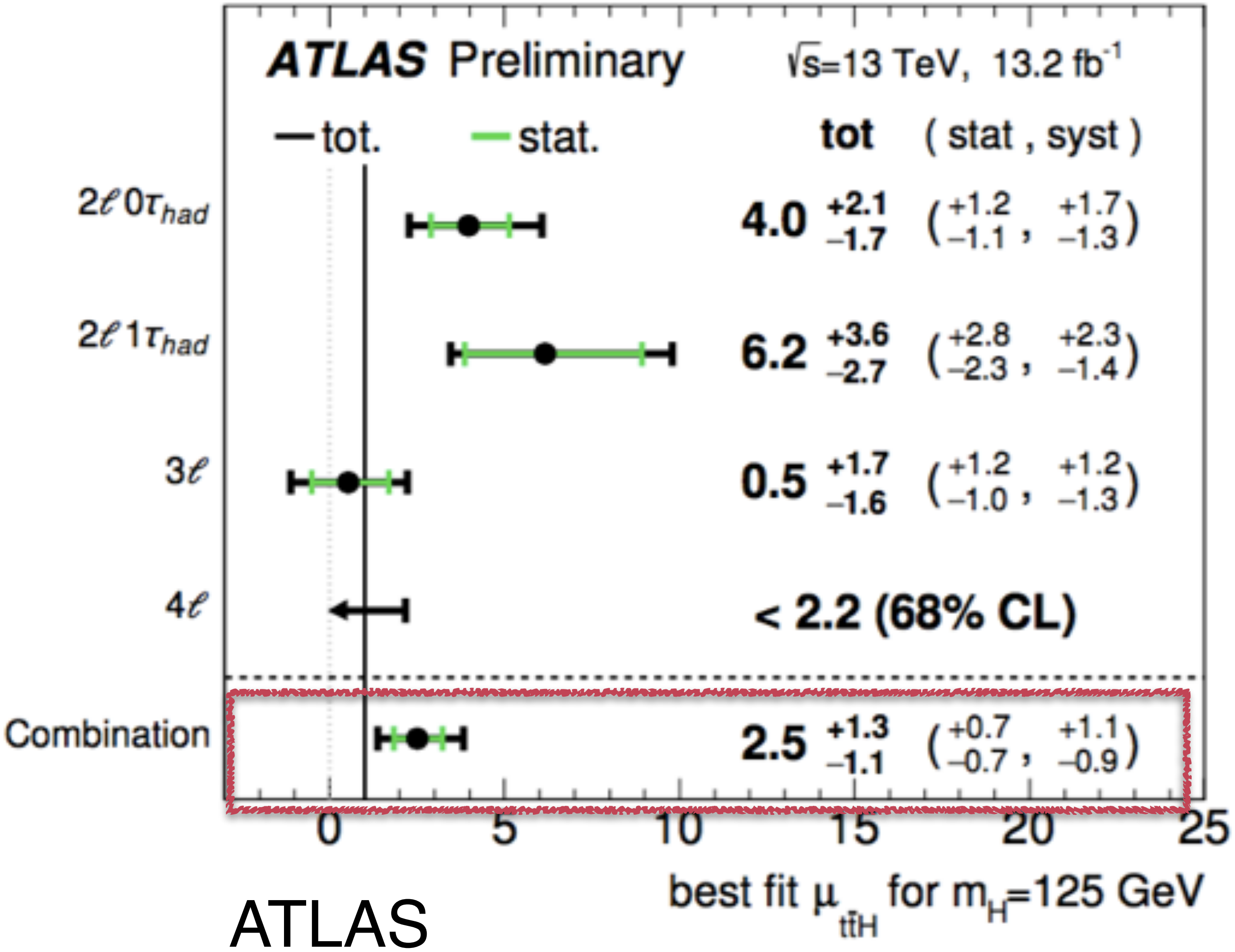
Results compatible with SM at 1/2σ level

ATLAS significance 2.2σ_{obs} (1σ_{exp})

CMS significance 3.3σ_{obs} (2.5σ_{exp})

This channel will profit of increased statistics, better understanding of backgrounds. Main systematics in both analyses fake (non-prompt) lepton.

Systematics are limiting factor



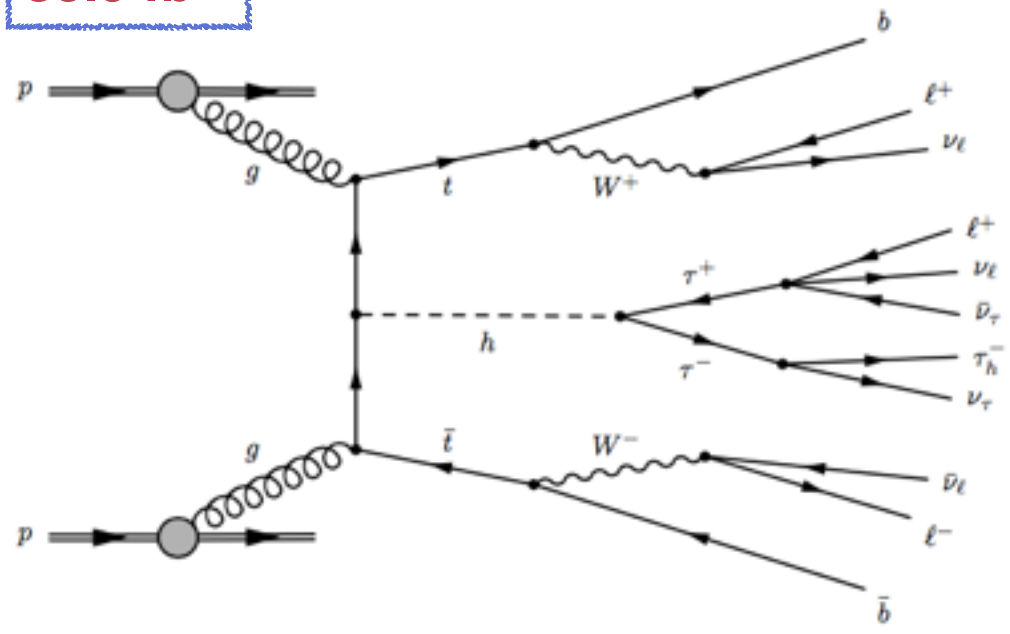
ATLAS

13.2 fb^{-1}

35.9 fb^{-1}

$t\bar{t}H \rightarrow \tau\tau$

CMS-PAS-HIG-17-003



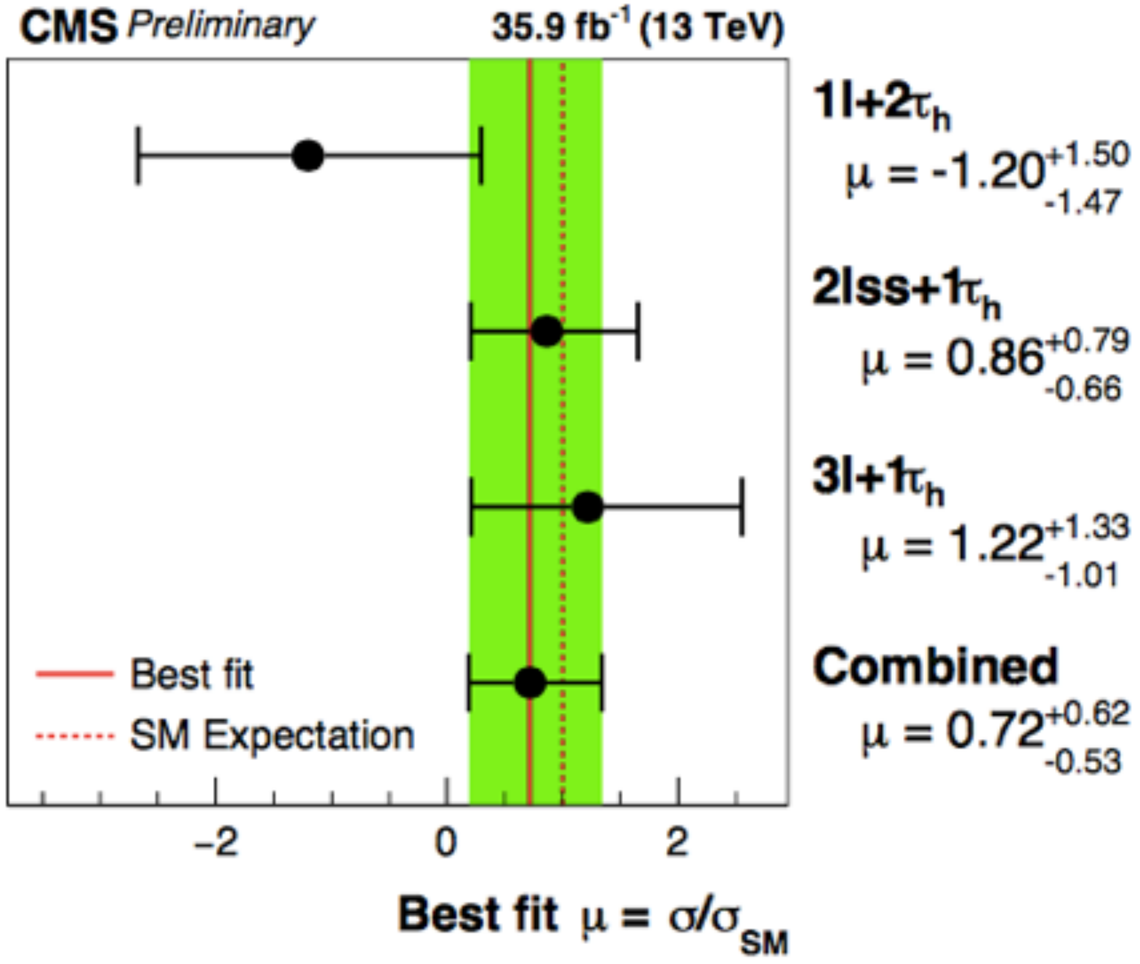
Full run II statistics,

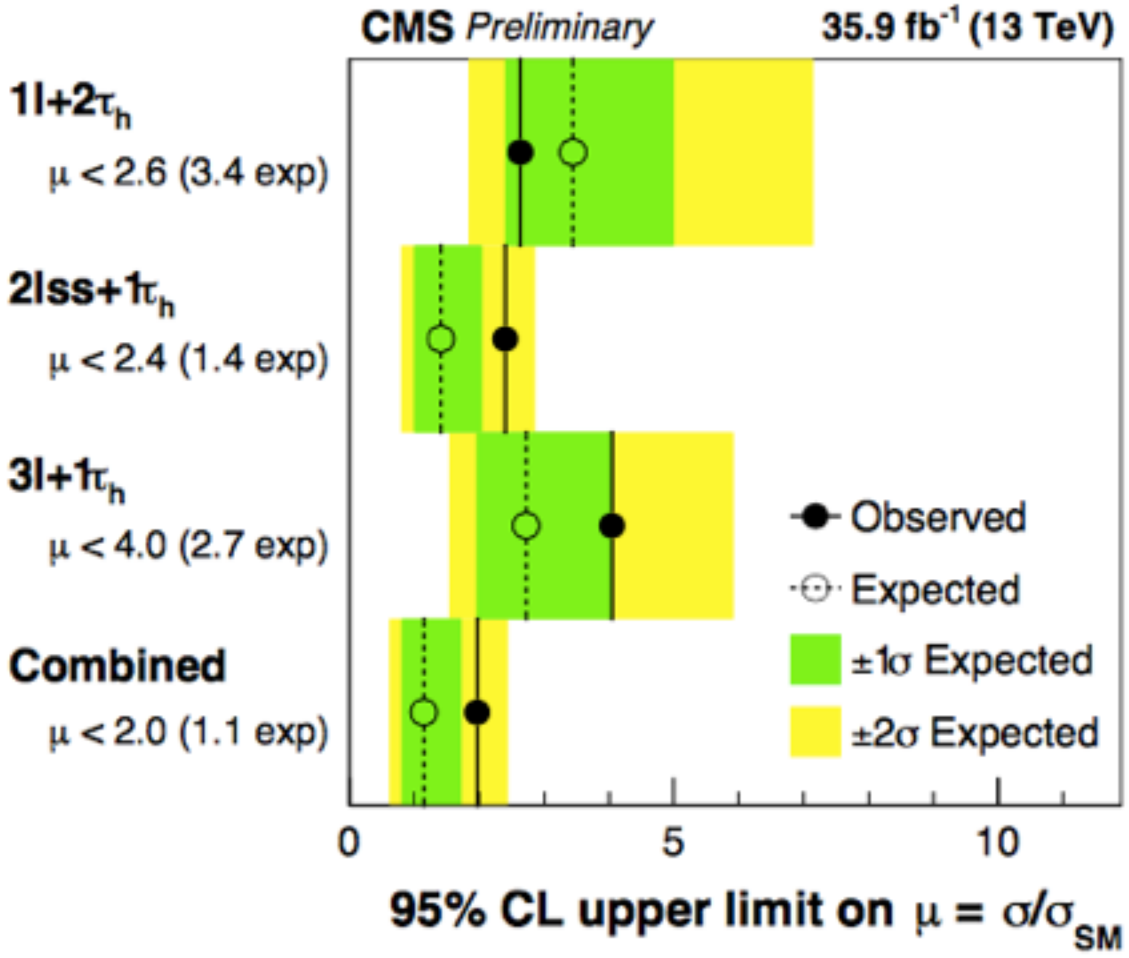
orthogonal categories wrt multi lepton analysis

Similar strategies for bkg treatment

- -1ℓ 2τ_{had}, ≥3 jets, ≥1 b-tag
- -2ℓ SS 1τ_{had}, ≥3 jets, ≥1 b-tag
- -3ℓ τ_{had}, ≥2 jets, ≥1 b-tag

Main systematics: tight lepton selection, τ_{had} id and jets faking τ_{had}

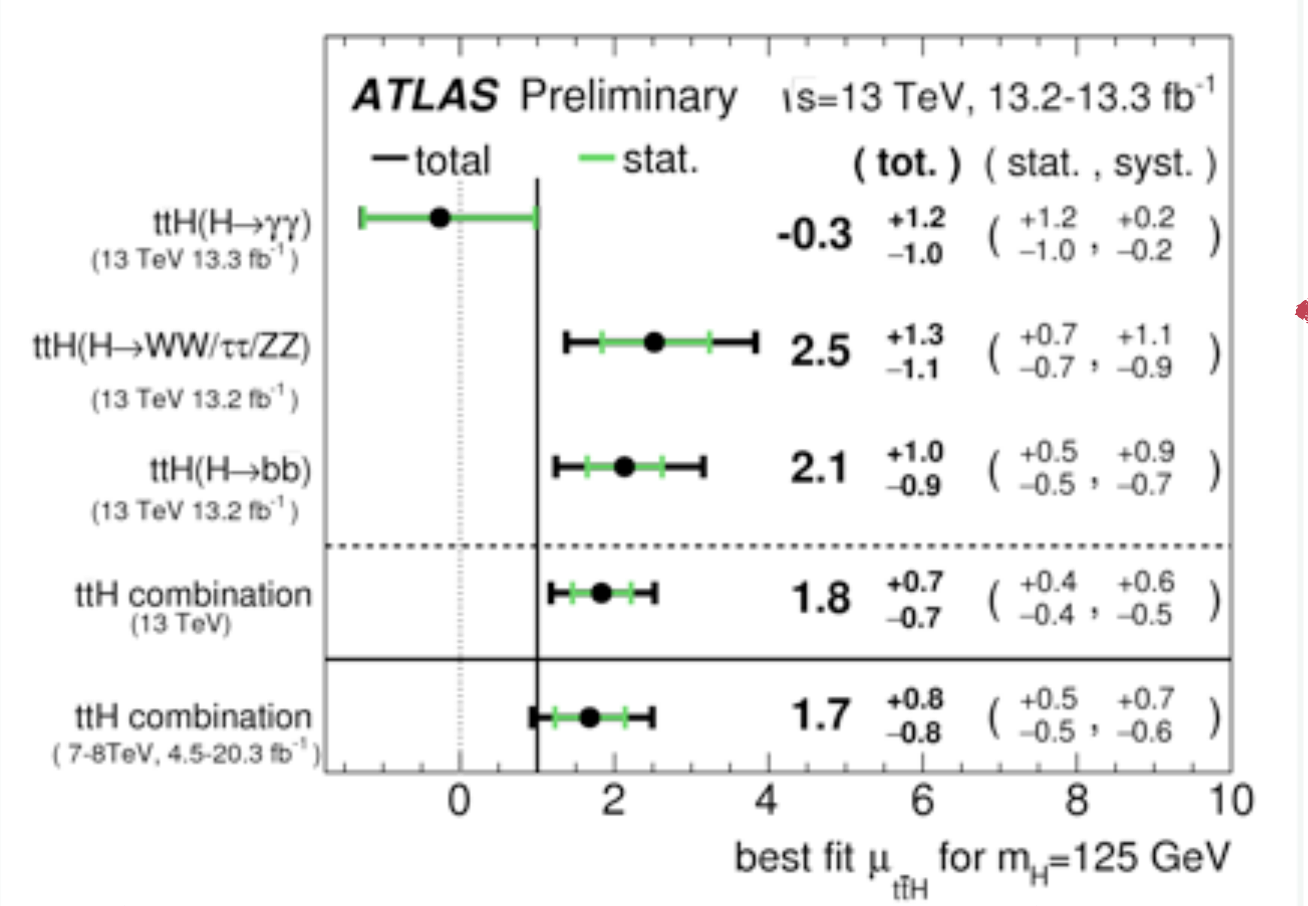




most sensitive easier to model 2ℓ SS 1τ_{had}

ttH ATLAS combination+CMS Summary

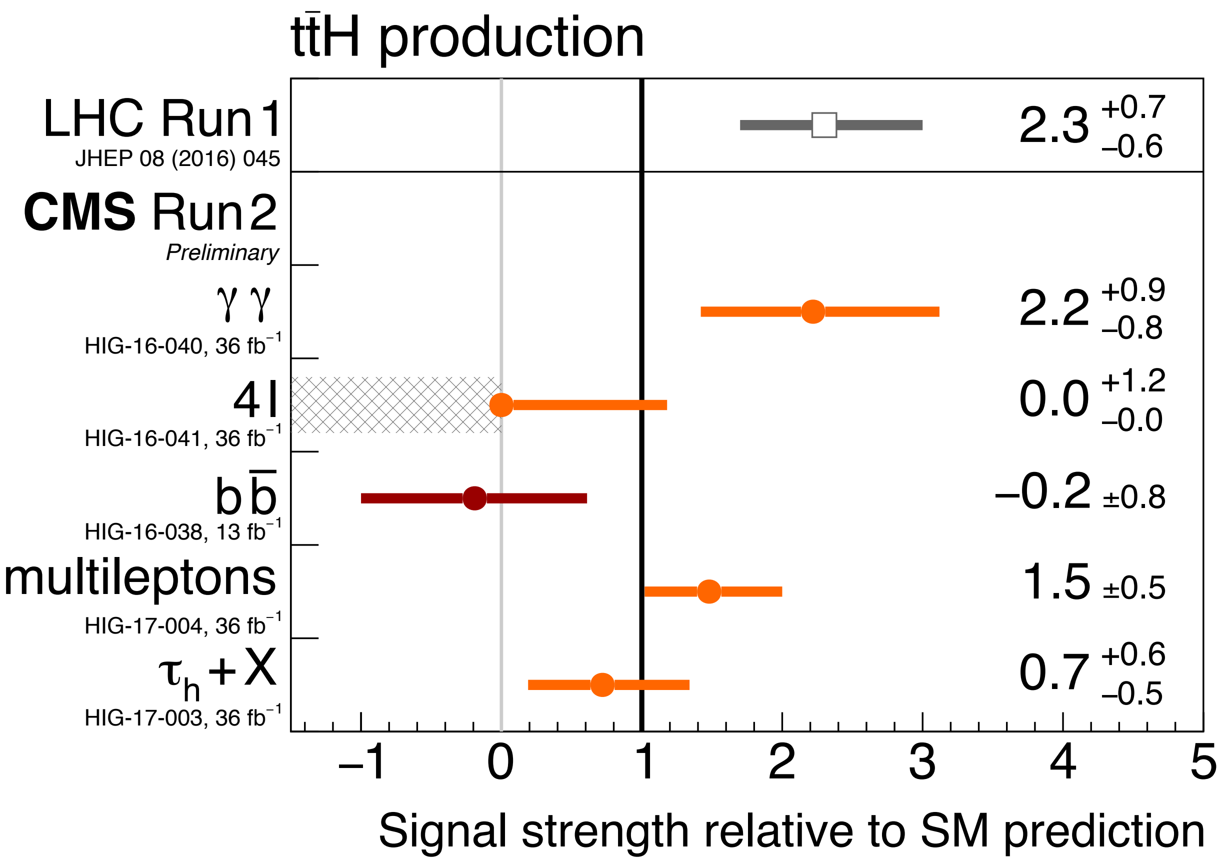
ATLAS-CONF-2016-068



2.8σ observed
(1.8 expected)
already exceeds Run1

Problem for future is systematics,
adding hadronic decays or
exploiting boosted analyses might help.

The bb and multi lepton final states are already systematically dominated.



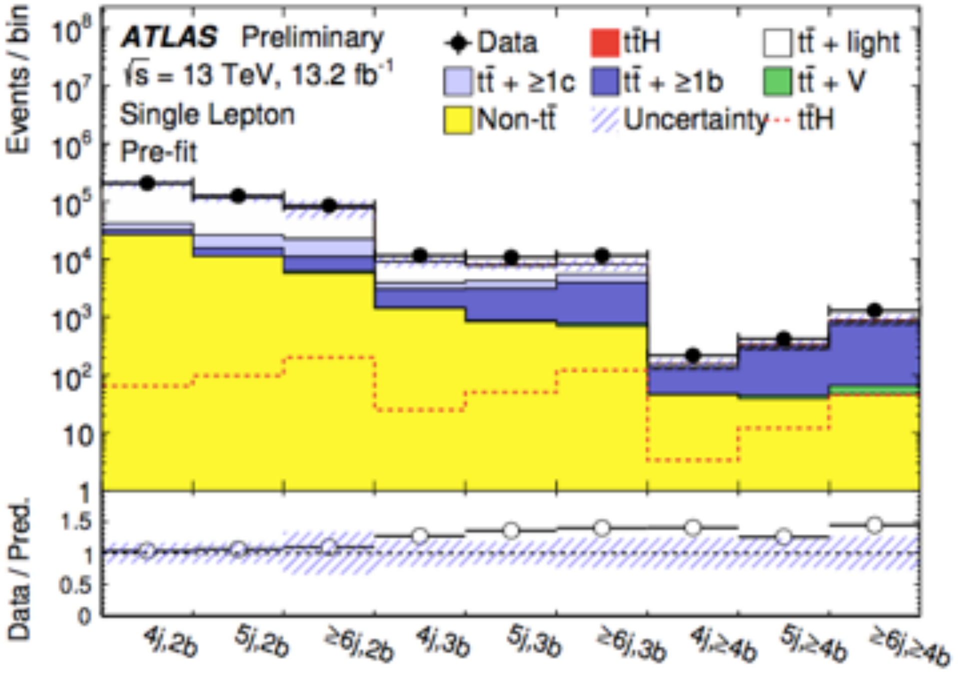
ttH→bb (tt bkg mismodelling)

Both Atlas and CMS use powheg v2 to simulate tt+HF

- ATLAS fits overall b,c,l classes (ttbb and ttcc cross-section predictions were not used)
- CMS fits each with 50% uncertainty (10% degradation due to this)

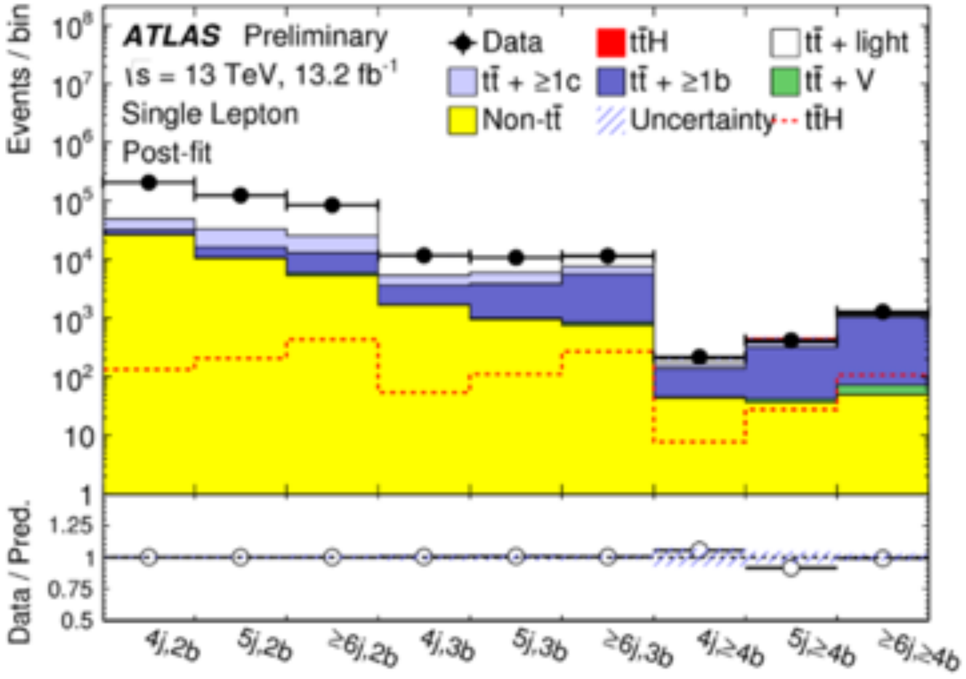
Data overshoots expectation in all regions with important tt+HF contribution. The results are compatible with theoretical errors.

ATLAS 6j4b about a factor 1.5 mismodelling of event numbers
Using NNLO tt calculations of shapes & uncertainties
pre-fit ttbb normalized to NLO Sherpa+OL,(NLO +massive b's)



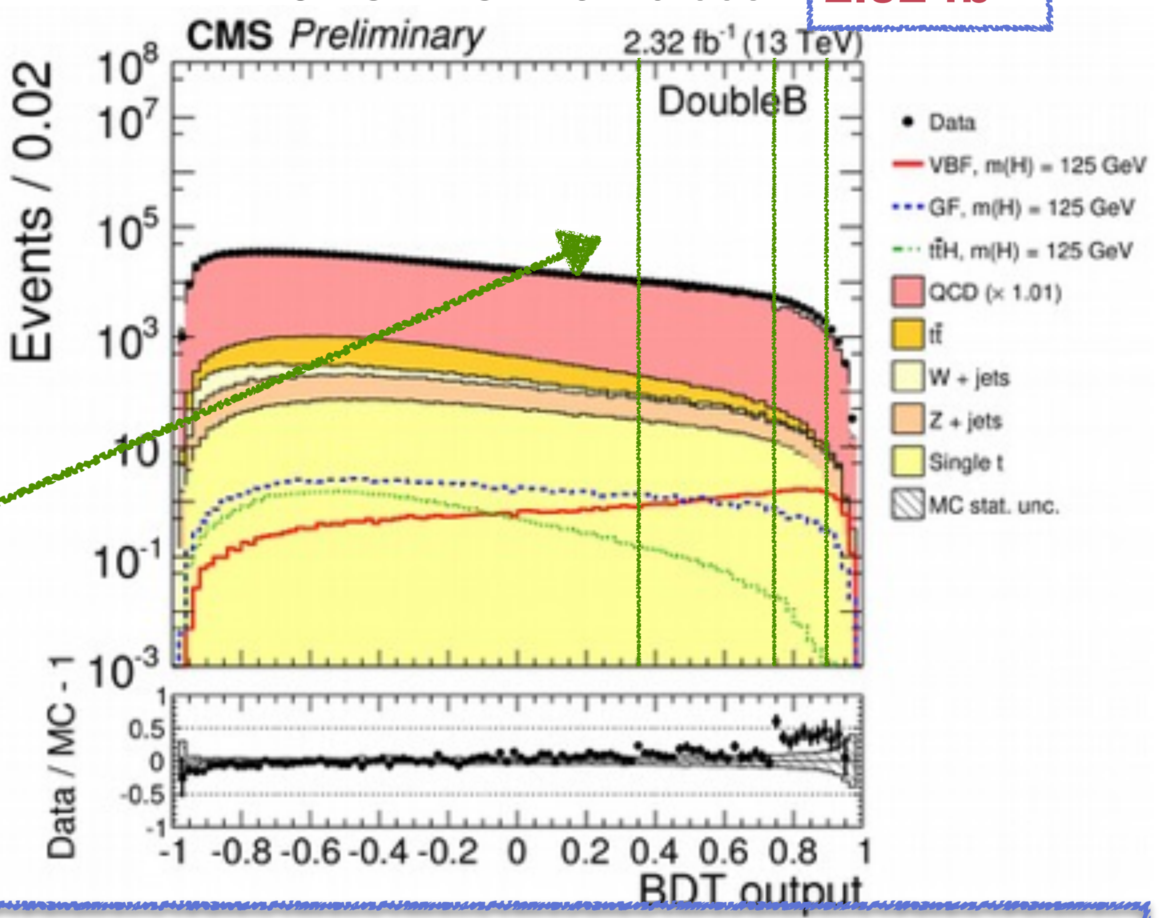
Post-fit shows good agreement

This channel will profit in the future from better understanding of tt+bb and interaction with theory.
SM ttbb measurements see similar features see for example CMS-TOP-16-010.



VBF h→bb

CMS-PAS-HIG-16-003 **2.32 fb^{-1}**



2.3 fb^{-1} CMS looks for pure VBF channel. Trigger is critical: 4jets (1 or 2 b's -> 6.2% or 3.9% efficiency), mass of non b-jets >460,200 GeV

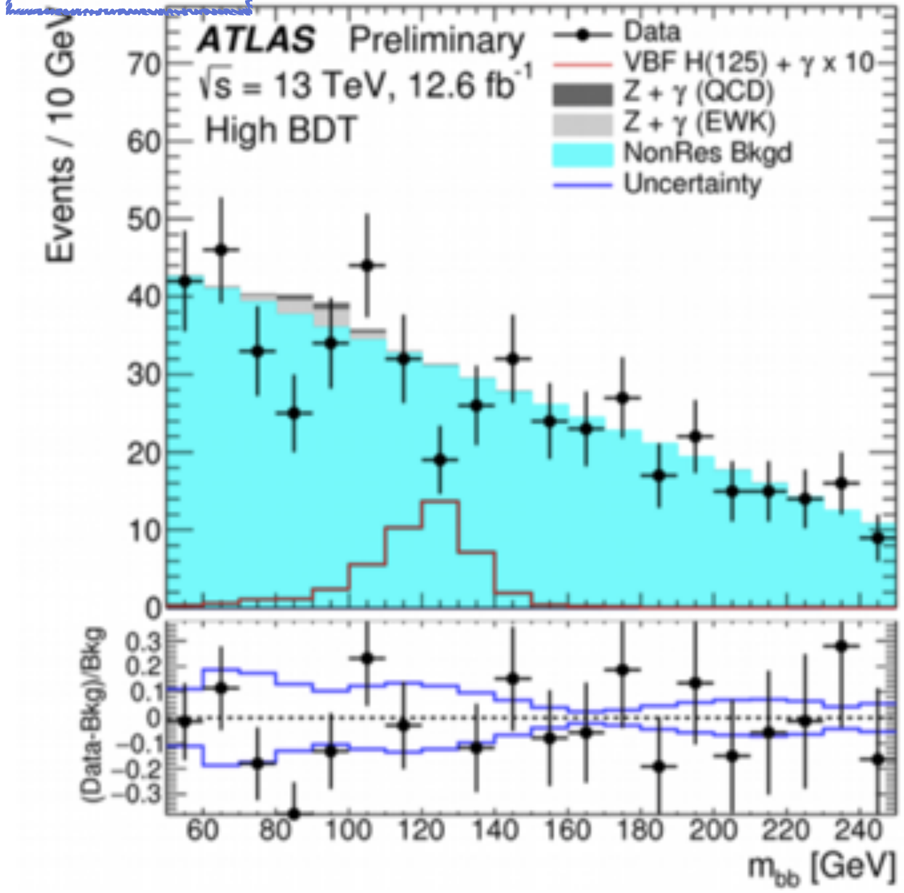
Main background is multi jets (98%)

BDT used to distinguish H from bkgs: multiple signal regions (4 SR for 1 b and 3 SR for 2b).

Fit to m_{bb}. Combined with 8 TeV result.

Dominant statistical uncertainty/ QCD modelling.

12.6 fb^{-1} ATLAS-CONF-2016-063

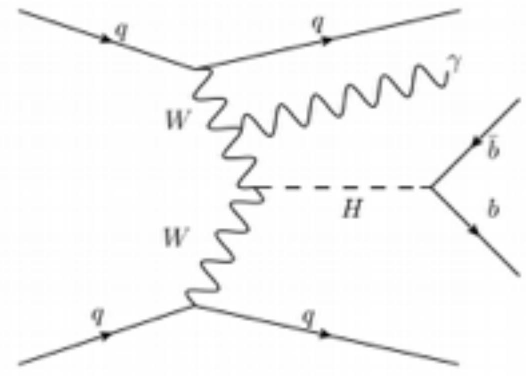


ATLAS VBF Hγ 12.6 fb^{-1} (larger stat):

Trigger is simpler: γ, 4j, mjj>700 GeV

Similar BDT as CMS to distinguish H from bkgs: m_{bb} fit in 3 BDT regions.

Statistically limited



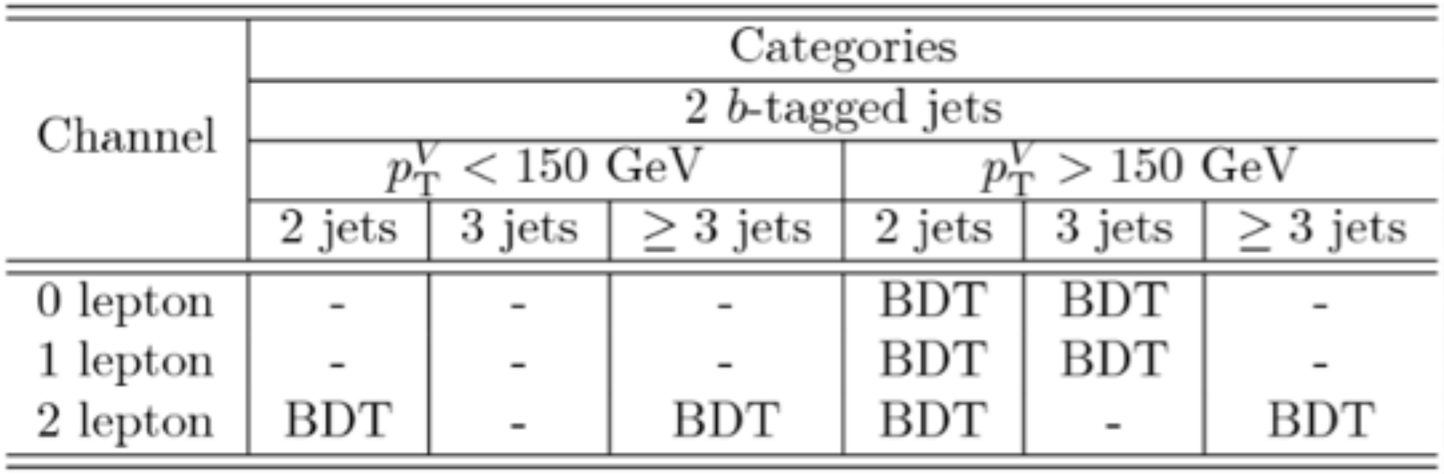
4xSM →

	ATLAS	CMS
13TeV	$\mu=3.9^{+2.8}_{-2.7}$	$\mu=3.7^{+2.4}_{-2.5}$
13+8 TeV		$\mu=1.3^{+1.2}_{-1.1}$

13.2 fb^{-1}

VH h→bb

ATLAS-CONF-2016-091



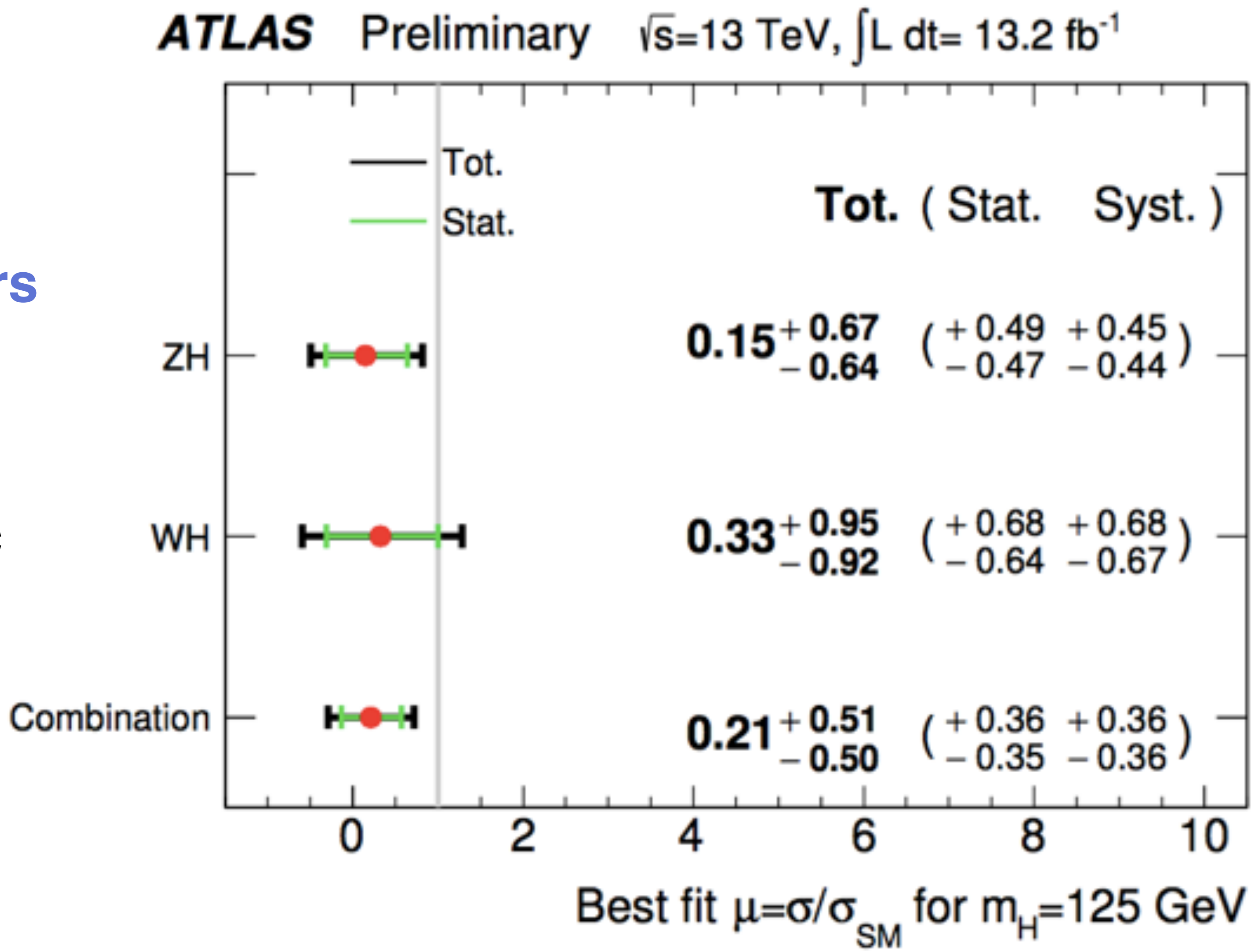
Channel	Categories					
	2 b-tagged jets					
	$p_T^V < 150$ GeV			$p_T^V > 150$ GeV		
	2 jets	3 jets	≥ 3 jets	2 jets	3 jets	≥ 3 jets
0 lepton	-	-	-	BDT	BDT	-
1 lepton	-	-	-	BDT	BDT	-
2 lepton	BDT	-	BDT	BDT	-	BDT

BDT used in various categories using kinematic variables as input.

ZH→llbb, (vvbb) /WH→ lvbb

Statistical and systematics errors are comparable

Highest systematics are due to b/c tag and Z+HF normalization

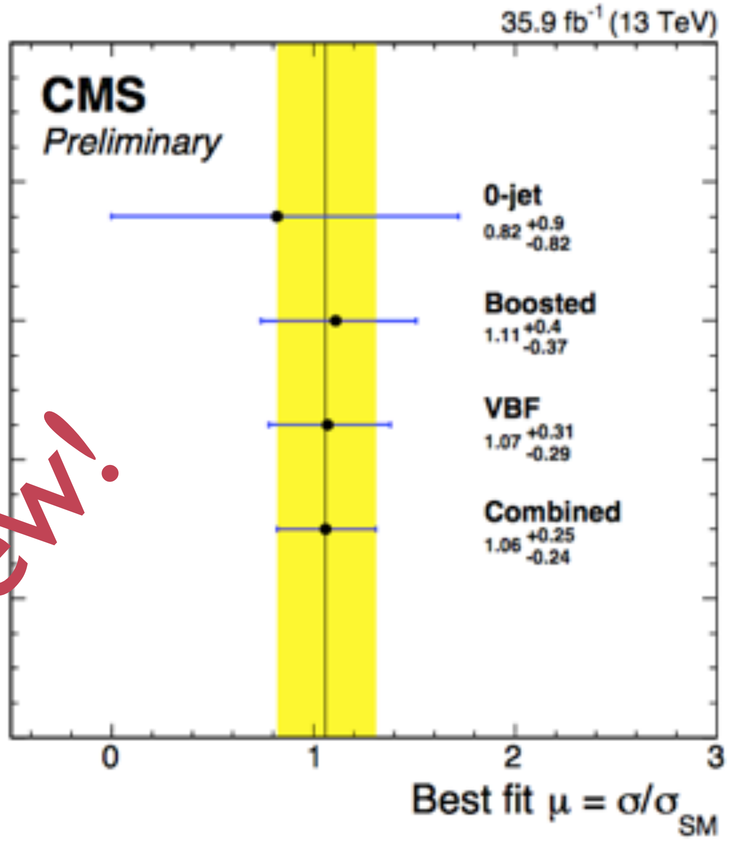


Run I result @7+8 TeV(4.7+20.3 fb–1): 0.52 ± 0.32(stat.) ± 0.24(syst.)

35.9 fb^{-1}

Higgs→ττ

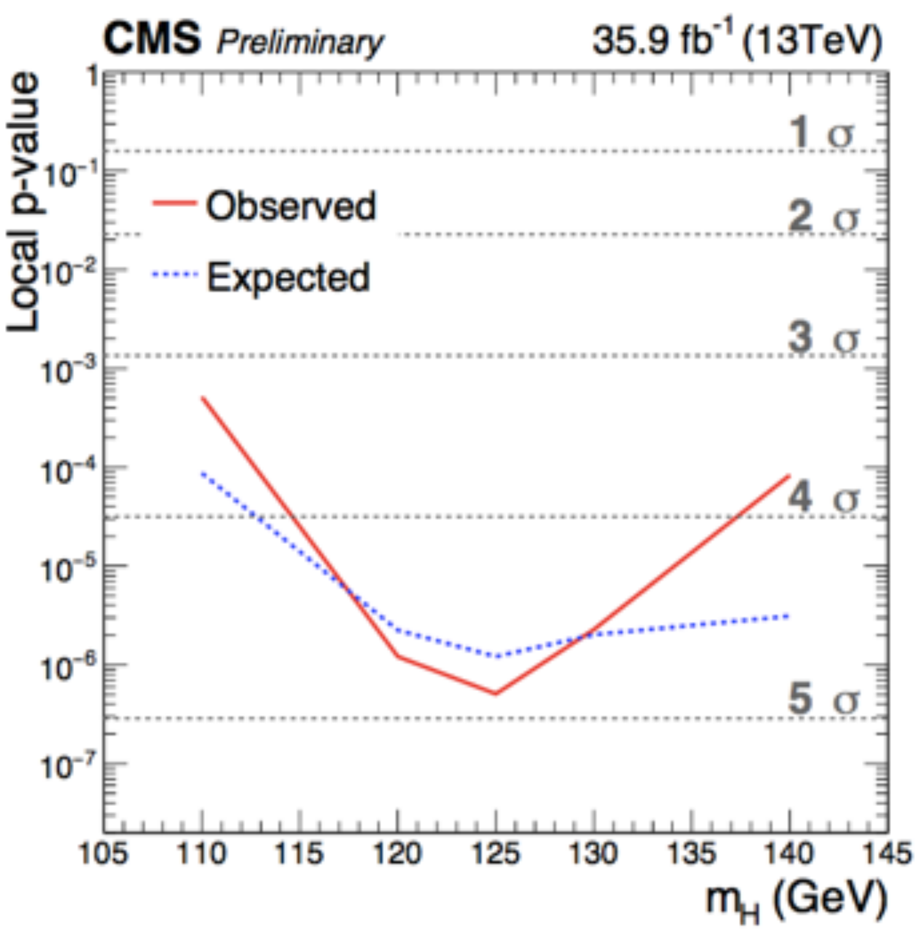
CMS-PAS-HIG-16-043



New!

H→ττ studying the Yukawa couplings to Fermions. Higher event rate than leptonic decays and lesser background than H->bb

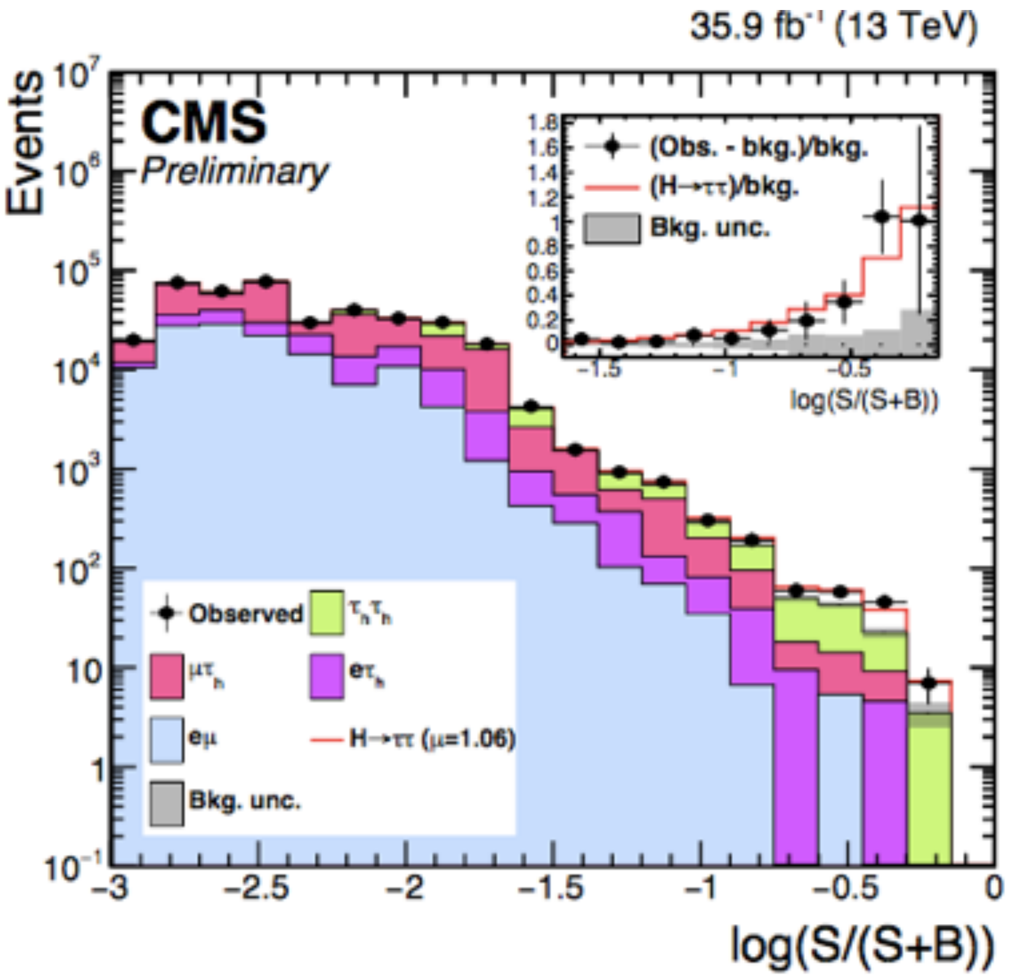
- eτ, μτ, eμ, ττ decay channels
- 3 categories, 0-jet, VBF, boosted
- Main background from Z→ττ
- 2D fit on different quantities depending on category (m_{jj} or $p_T^{\tau\tau}$,$m_{\tau\tau}$.)



μ =1.06 ± 0.25

For m_H=125 GeV
4.9σ observed
(4.7 expected)

Standalone Observation!

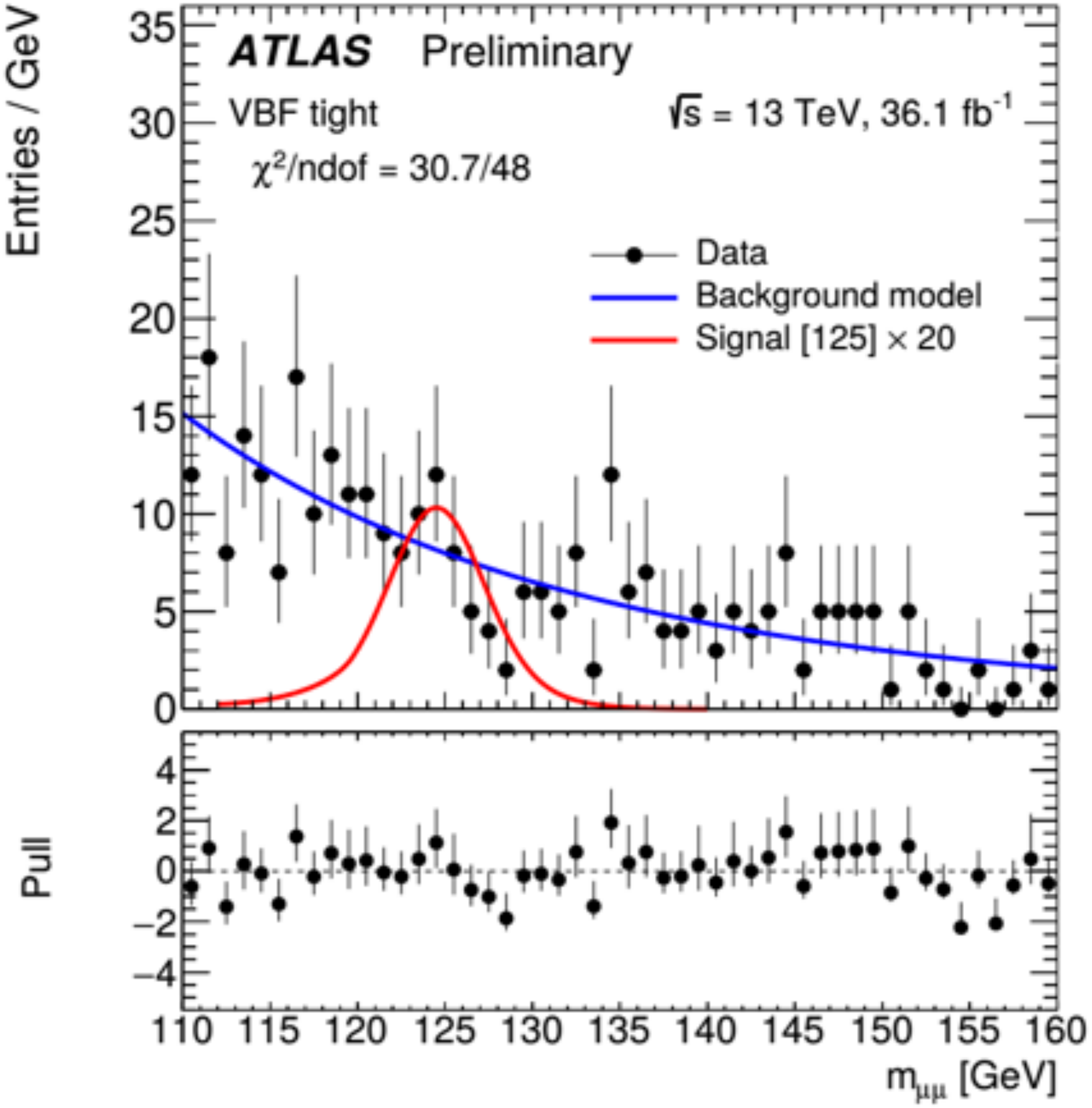


36.1 fb^{-1}

Higgs→μμ

ATLAS-CONF-2017-014

Measure Higgs couplings to second generation fermions



- Clean signature, small BR ~2.18 x10^{-4}
- Dominant background Drell Yan $Z/\gamma^* \to \mu\mu$

Using both ggF and VBF production, but orthogonal selection.

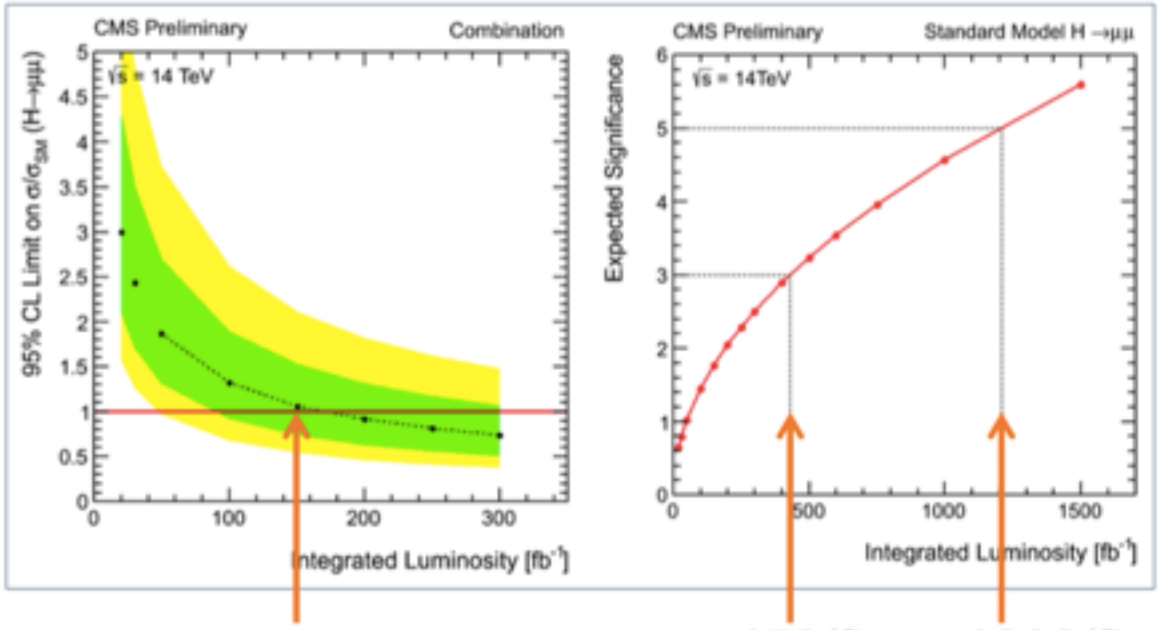
- VBF uses BDT against bkg, ggF uses categories binned in η and $p^T_{\mu\mu}$.

	13TeV	**7+8+13TeV**
μ	-0.07 ±1.5	-0.13 ±1.4
95% CL limit **σ/σ_{SM}**	< 3.0 obs (3.1 exp)	< 2.8 obs (2.9 exp)

CMS projection scaled from Run1

Full Run2: ~2σ

HL-LHC: >5σ



150/fb

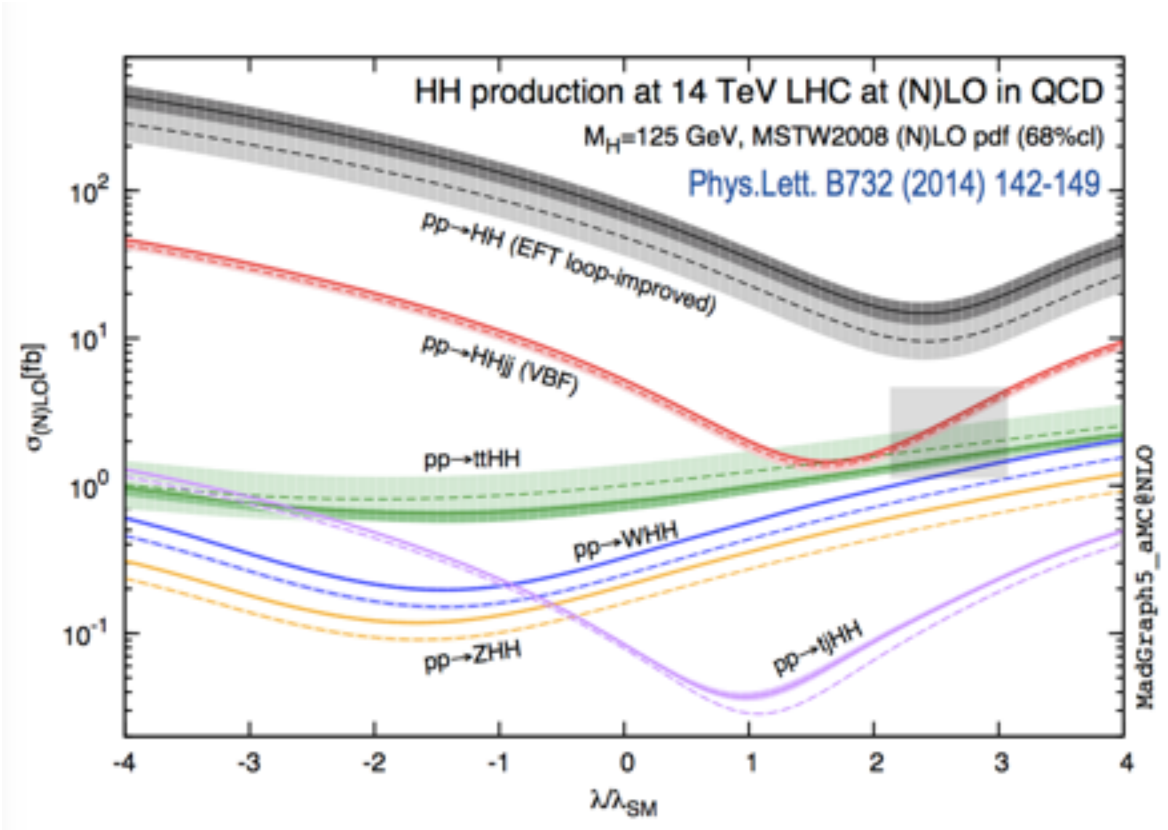
450/fb

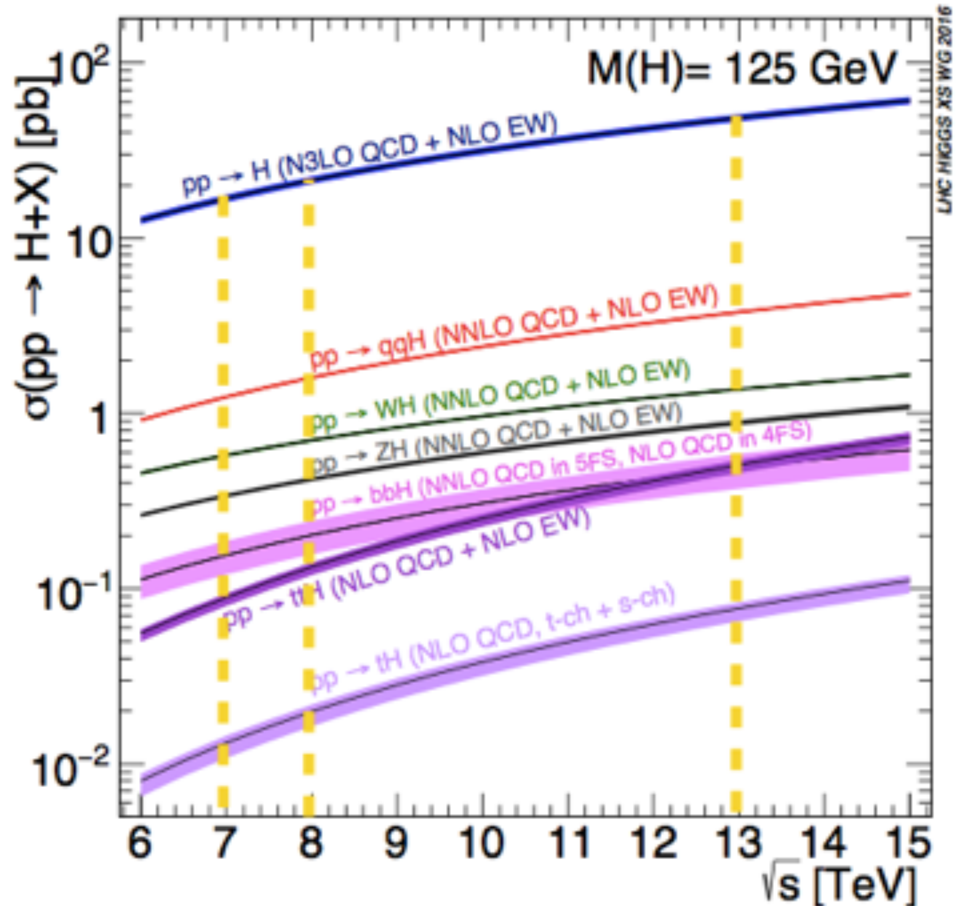
1200/fb

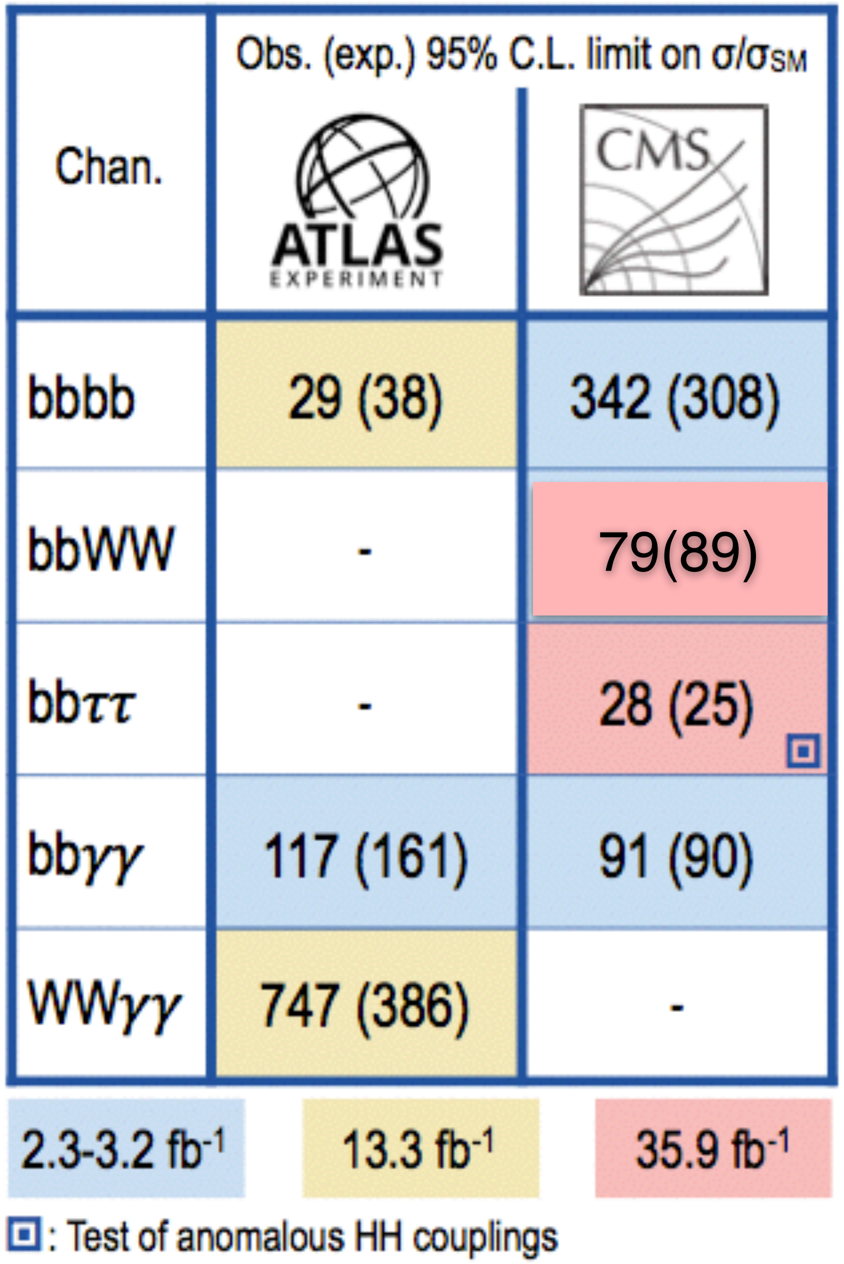
Scaled from run-1 result: CMS-PAS-HIG-13-007
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13007TWiki#Expected_Performance_at_s_14_TeV

Self coupling

Double Higgs production much smaller than single higgs







Chan.	Obs. (exp.) 95% C.L. limit on σ/σ_{SM}	
	ATLAS EXPERIMENT	CMS
bbbb	29 (38)	342 (308)
bbWW	-	79(89)
$bb\tau\tau$	-	28 (25) ▣
$bb\gamma\gamma$	117 (161)	91 (90)
$WW\gamma\gamma$	747 (386)	-

2.3-3.2 fb^{-1} 13.3 fb^{-1} 35.9 fb^{-1}

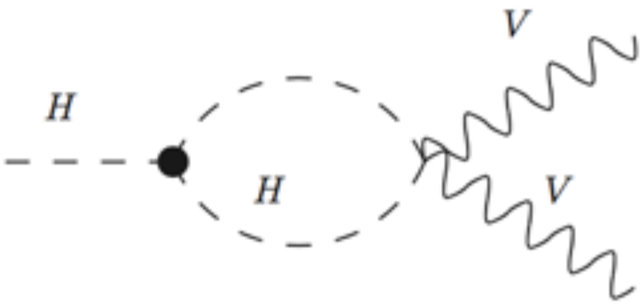
▣: Test of anomalous HH couplings

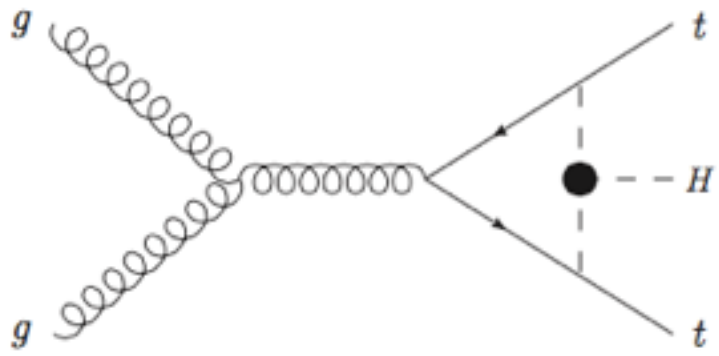
Used to measure Higgs trilinear couplings,

However difficult due to small expected rates, mild dependence of x-section on trilinear couplings and difficult signal separation from backgrounds.

Self coupling (indirect)

Single Higgs couplings can be used to infer constraints on trilinear couplings and are possibly competitive with di-Higgs constraints.





Single Higgs production is affected both in production and decay by triple Higgs couplings via weak loops, e.g. at NLO in the EW interactions.

Distinctive pattern of deformations of the SM rates are obtained that can be compared with data.

F.Maltoni et al, arXiv:1607.04251

Use of single Higgs inclusive data suffers of degeneracies.

Differential distributions and di-Higgs results should be included.

C.Grojean et al, arXiv:1704.01953

Summary

The particle discovered in 2012 is well compatible with the SM Higgs.

Its mass is measured to be: m_H=125.26±0.20(stat)±0.08(syst) GeV (Run2)

The couplings Run1 combination by ATLAS and CMS is well in agreement with SM

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09 \pm 0.07(\text{stat}) \pm 0.04(\text{expt}) \pm 0.03(\text{th-bkgd})^{+0.07}_{-0.06}(\text{th-sig})$$

Run2

- H→γγ, 4l analyses have many results in Run2 that already exceed Run1 precision
- ttH precision already exceeds the Run1 precision. The systematic uncertainties are becoming the limiting factor (some channels need still to be updated with full statistics
- H→ ττ at 4.9 σ : standalone observation by CMS
- H→WW and VH,H→bb need a bit more time but new results will be available soon.

All measured processes in agreement with SM within 2 standard deviations

The next steps in terms of precision measurements of the Higgs properties are:

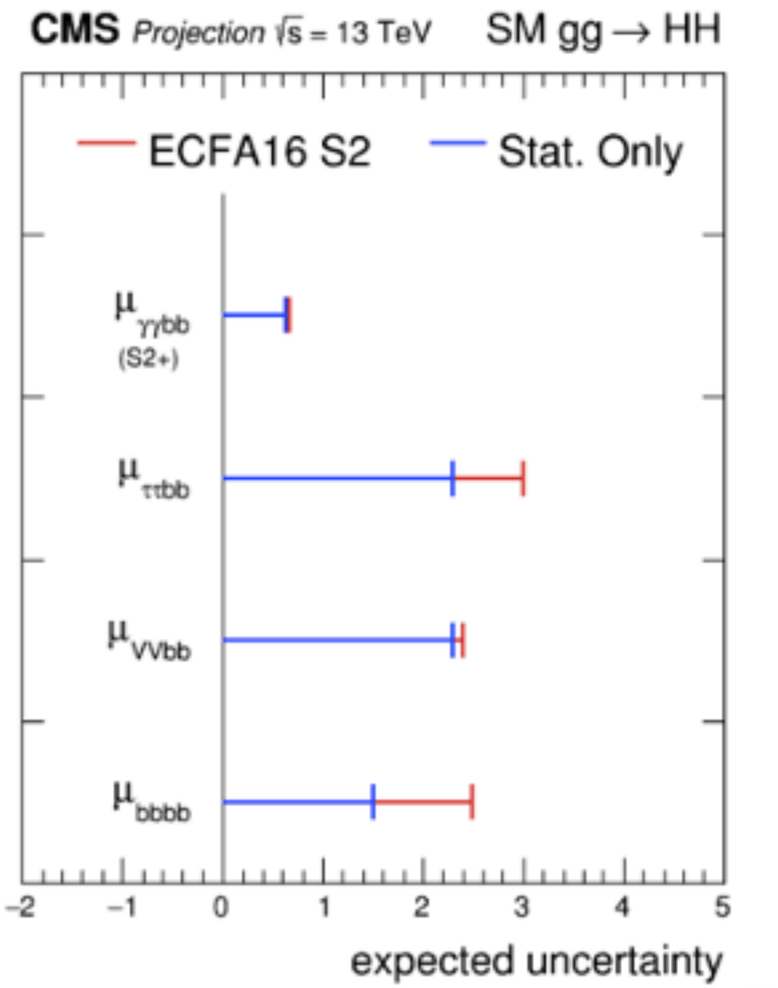
- increase Higgs measurement precision to few percent level (exclude most BSM models)
- study of longitudinally polarized WW scattering

Outlook

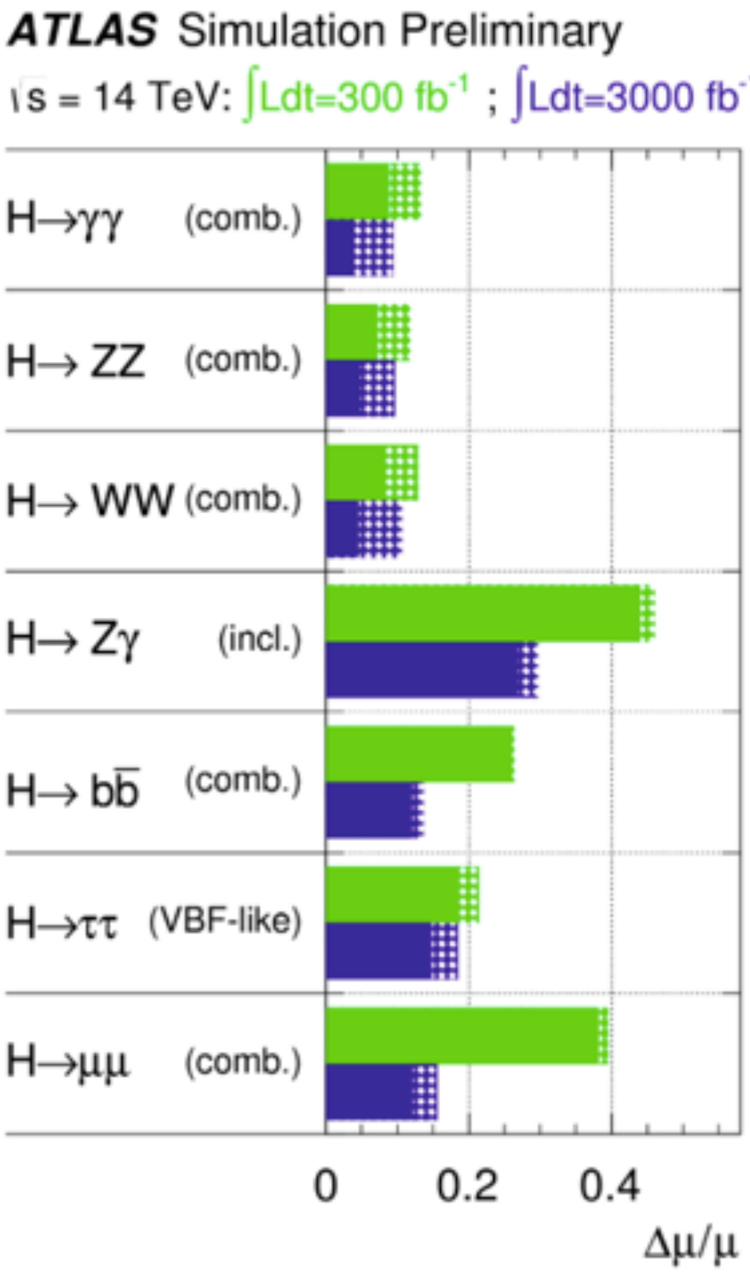
3000 fb^{-1} :

- Search Higgs couplings structure, di-higgs boson production 1.3-1.6 sigma sigma per experiment hh→bb$\gamma\gamma$
- Couplings: precision on main channel 4-5%, 10-40% on other.

CMS-DP-2016-064



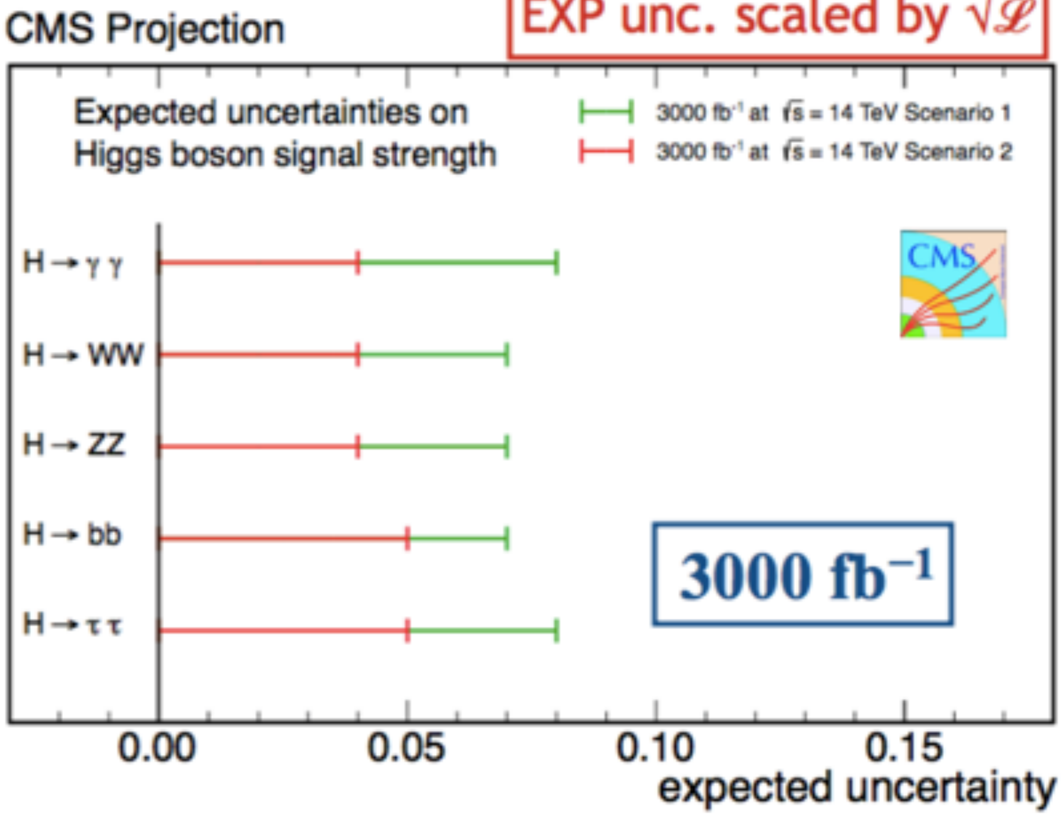
Exp	Significance
bb$\gamma\gamma$	1.6σ
bb$\tau\tau$	0.39σ
bbVV	0.45σ
bbbb	0.39σ



ATL-PHYS-PUB-2014-016,

CERN-LHCC-2015-020

Scenario 2:
TH unc. scaled by 1/2
EXP unc. scaled by $\sqrt{\mathscr{L}}$



Back-up

H->ZZ fiducial phase space

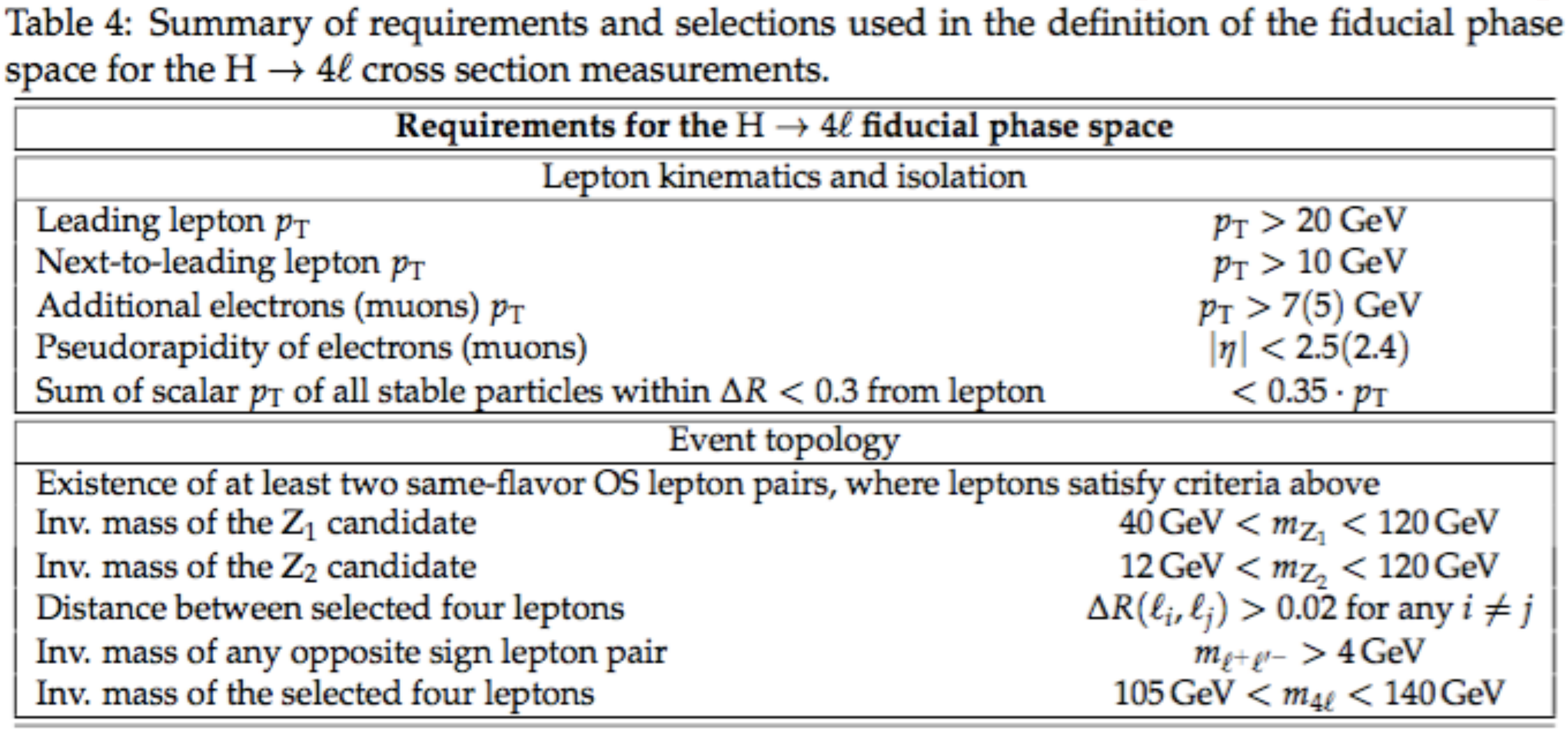


Table 4: Summary of requirements and selections used in the definition of the fiducial phase space for the H $\rightarrow 4\ell$ cross section measurements.

Requirements for the H $\rightarrow 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Next-to-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5(2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 \cdot p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40\,\mathrm{GeV} < m_{Z_1} < 120\,\mathrm{GeV}$
Inv. mass of the Z_2 candidate	$12\,\mathrm{GeV} < m_{Z_2} < 120\,\mathrm{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\mathrm{GeV}$
Inv. mass of the selected four leptons	$105\,\mathrm{GeV} < m_{4\ell} < 140\,\mathrm{GeV}$

CMS

The fiducial cross-sections are defined at particle level.

Leptons dressed DR<0.3

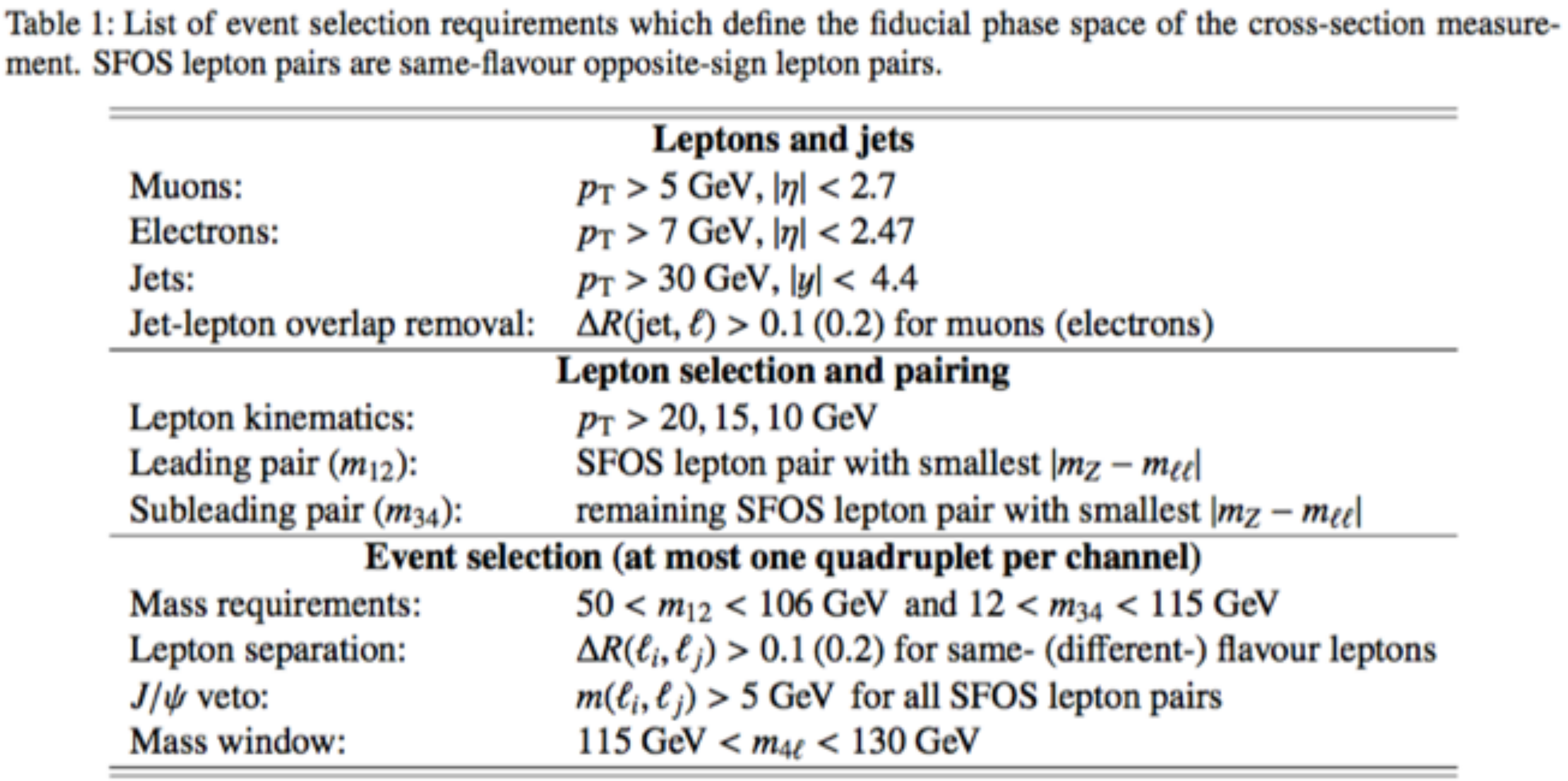


Table 1: List of event selection requirements which define the fiducial phase space of the cross-section measurement. SFOS lepton pairs are same-flavour opposite-sign lepton pairs.

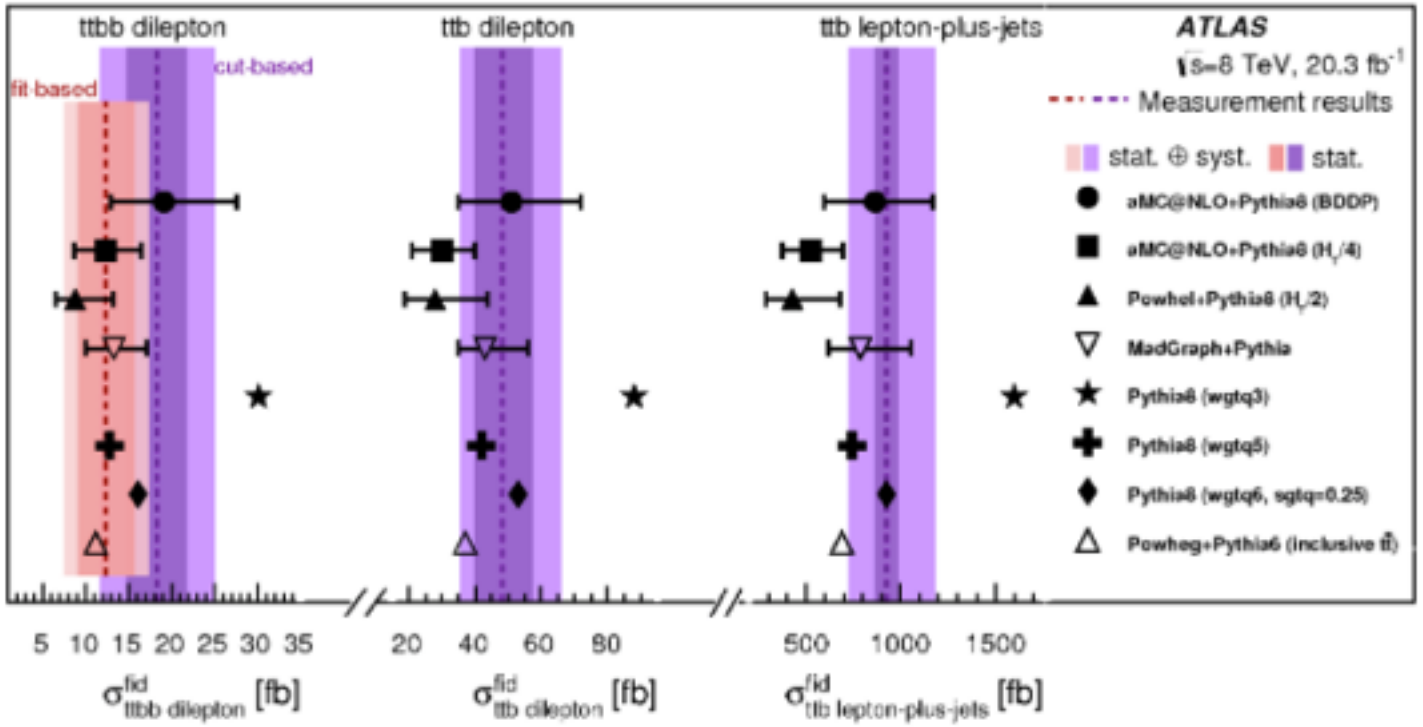
Leptons and jets	
Muons:	$p_T > 5$ GeV, $\lvert\eta\rvert < 2.7$
Electrons:	$p_T > 7$ GeV, $\lvert\eta\rvert < 2.47$
Jets:	$p_T > 30$ GeV, $\lvert y\rvert < 4.4$
Jet-lepton overlap removal:	$\Delta R(\text{jet}, \ell) > 0.1\ (0.2)$ for muons (electrons)
Lepton selection and pairing	
Lepton kinematics:	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12}):	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34}):	remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one quadruplet per channel)	
Mass requirements:	$50 < m_{12} < 106$ GeV and $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1\ (0.2)$ for same- (different-) flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$115\ \mathrm{GeV} < m_{4\ell} < 130$ GeV

ATLAS

The fiducial selection is applied to final-state e and muons "dressed", i.e. the transverse momenta of photons within a cone of ΔR = 0.1 are added to each lepton.

Top physics: Exp. & SM – 1

- Measurement of *ttbb*/*ttjj* figure: HF higher in data than prediction in both ATLAS/CMS
- Single-top differential measurements at 10% level
- Top quark measurements give valuable input to constrain PDF



- ? Do ATLAS and CMS diff. X-section measurements agree? Can they be quantitatively compared?
- ? Do data and predictions of diff. X-section measurements agree? How can we make progress towards “improving” the MC generators?
- ? Diff. NNLO seems to agree with parton-level data, conspiracy of various effects?

Higgs production in single top

CMS-PAS-HIG-019

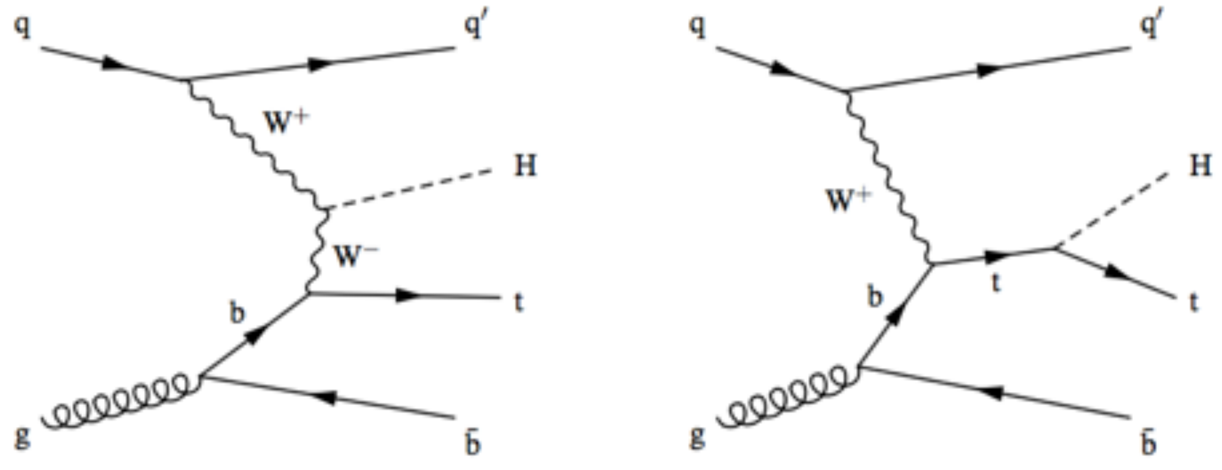
In SM diagrams interfere destructively,

More important for BSM

small x-section

CMS analysis, 2.3 fb-1

Search for H → bb in association with a single top (t → b eν/b μν).

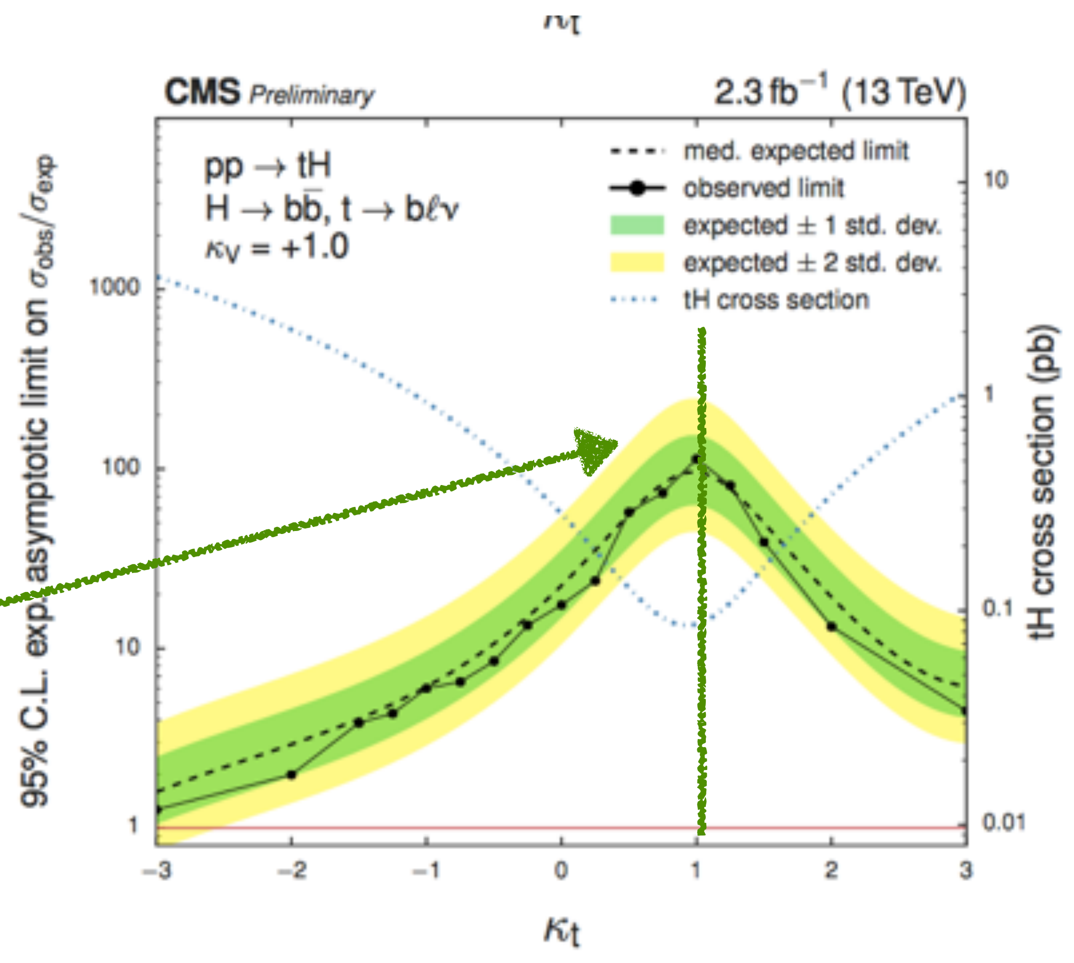


Final state e/m + 3/4 b-jets, 1 non b-tag jet

MVA used against tt bkg.

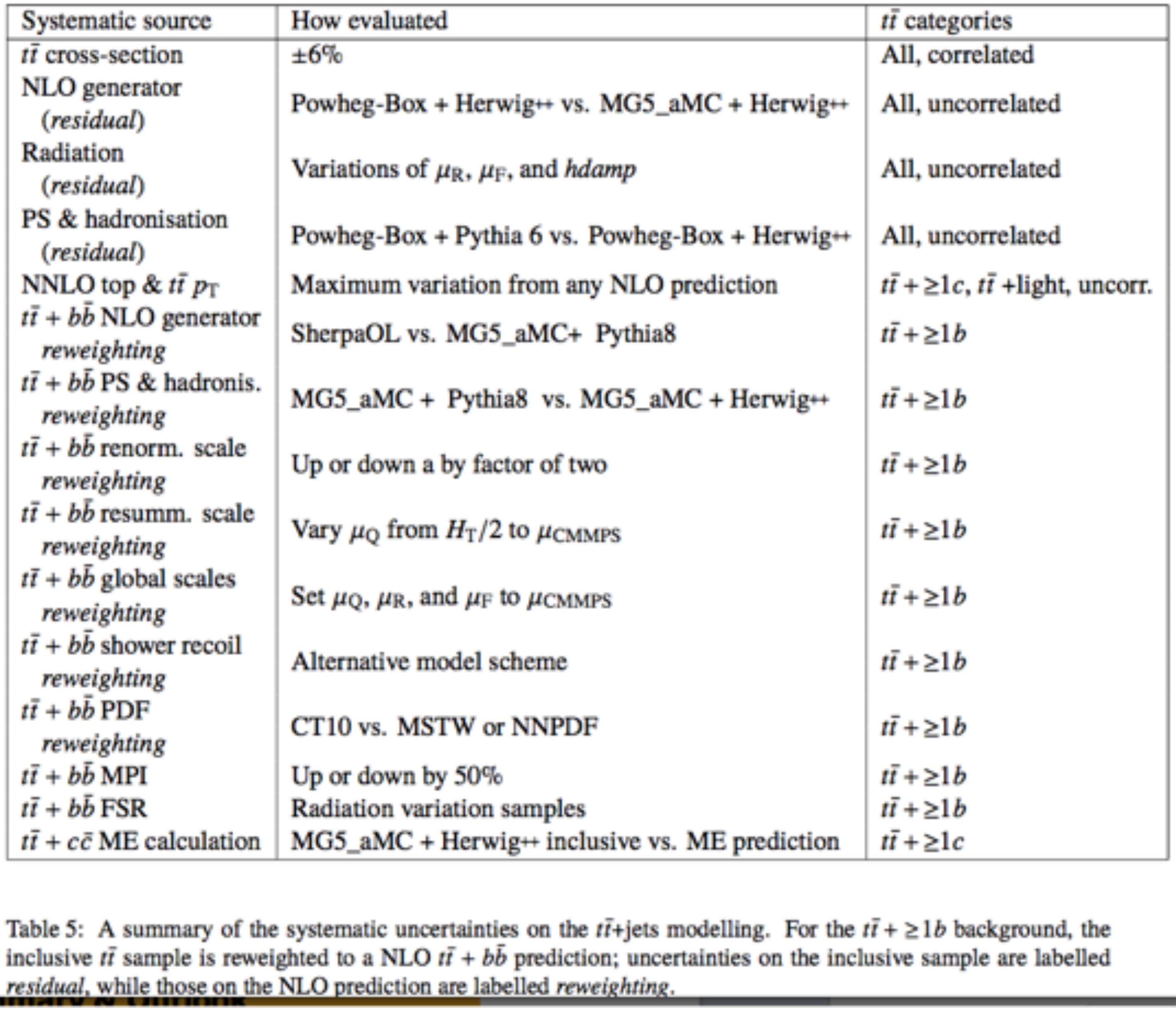
Final discriminant MV classifier.

95% CL limit on SM x-section 113.7xSM



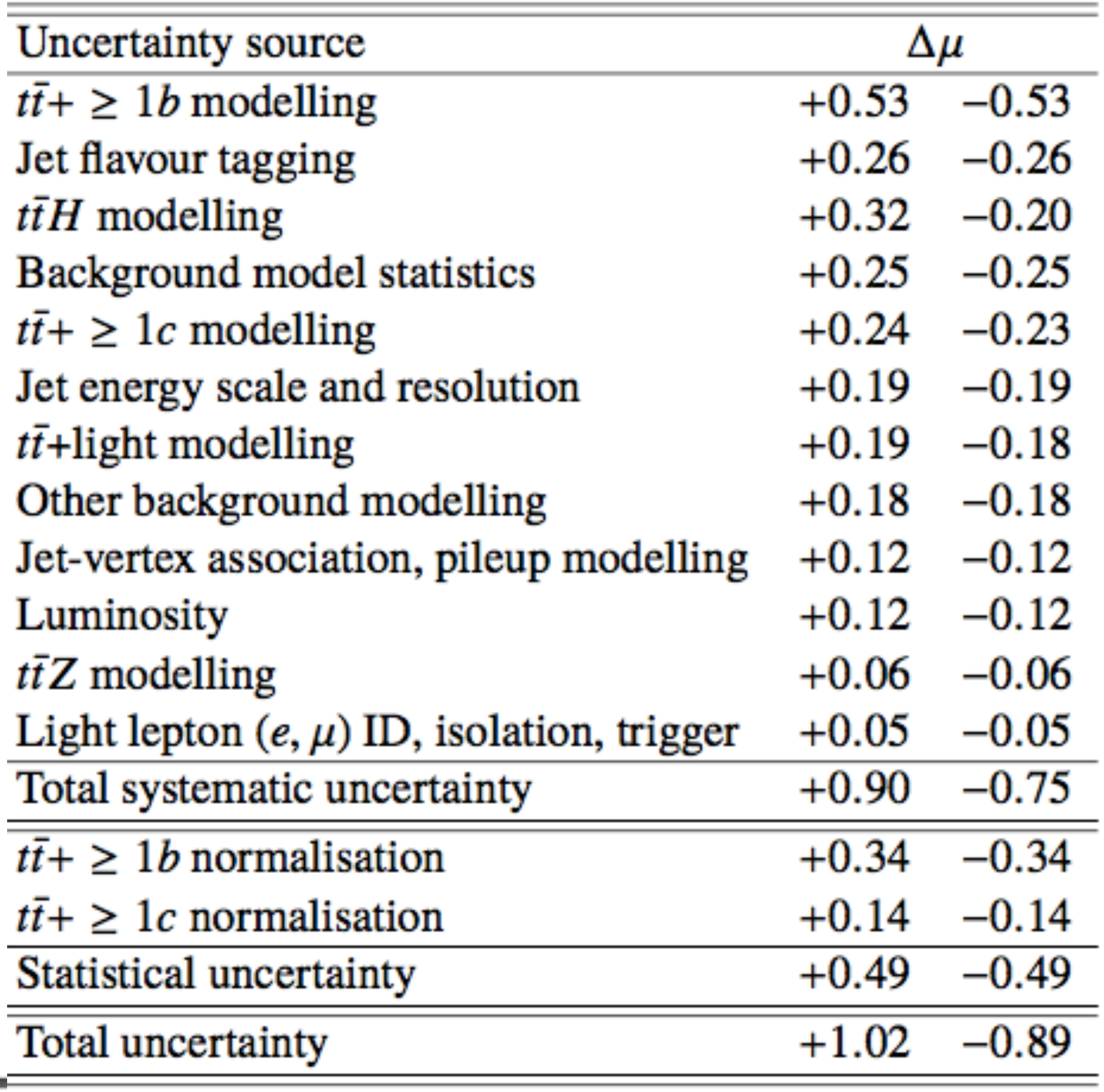
ttH tt modelling

effect on mu



Systematic source	How evaluated	$t\bar{t}$ categories
$t\bar{t}$ cross-section	±6%	All, correlated
NLO generator (*residual*)	Powheg-Box + Herwig++ vs. MG5_aMC + Herwig++	All, uncorrelated
Radiation (*residual*)	Variations of μ_R, μ_F, and *hdamp*	All, uncorrelated
PS & hadronisation (*residual*)	Powheg-Box + Pythia 6 vs. Powheg-Box + Herwig++	All, uncorrelated
NNLO top & $t\bar{t}$ p_T	Maximum variation from any NLO prediction	$t\bar{t}+\geq 1c$, $t\bar{t}$ +light, uncorr.
$t\bar{t}+b\bar{b}$ NLO generator *reweighting*	SherpaOL vs. MG5_aMC+ Pythia8	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PS & hadronis. *reweighting*	MG5_aMC + Pythia8 vs. MG5_aMC + Herwig++	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ renorm. scale *reweighting*	Up or down a by factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ resumm. scale *reweighting*	Vary μ_Q from $H_T/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ global scales *reweighting*	Set μ_Q, μ_R, and μ_F to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ shower recoil *reweighting*	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PDF *reweighting*	CT10 vs. MSTW or NNPDF	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ FSR	Radiation variation samples	$t\bar{t}+\geq 1b$
$t\bar{t}+c\bar{c}$ ME calculation	MG5_aMC + Herwig++ inclusive vs. ME prediction	$t\bar{t}+\geq 1c$

Table 5: A summary of the systematic uncertainties on the $t\bar{t}$+jets modelling. For the $t\bar{t}+\geq 1b$ background, the inclusive $t\bar{t}$ sample is reweighted to a NLO $t\bar{t}+b\bar{b}$ prediction; uncertainties on the inclusive sample are labelled *residual*, while those on the NLO prediction are labelled *reweighting*.



Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e, μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89

ttH tt modelling

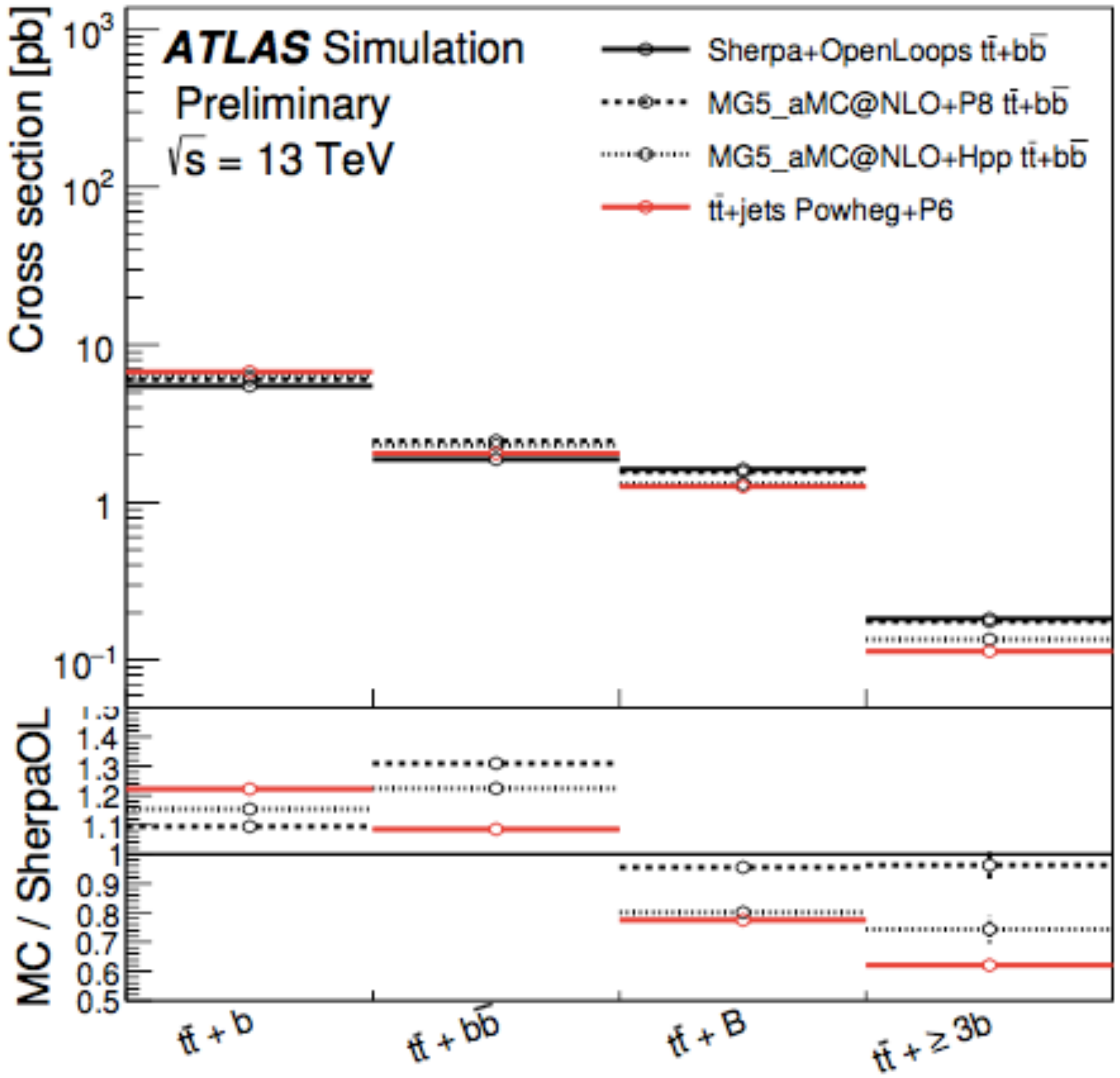


Figure 9: The predicted cross-sections for the $t\bar{t}+\geq 1b$ sub-categories. The inclusive Powheg+Pythia 6 prediction is compared to four-flavour $t\bar{t}+b\bar{b}$ calculations from SherpaOL and MG5_aMC with different parton showers. The reweighting from Powheg+Pythia 6 to SherpaOL has not been applied.

SM $t\bar{t}$ modelling

CMS PAS TOP-16-010

2.3 fb^{-1} of integrated luminosity

σttbb/σttjj = 0.024 ± 0.003 (stat) ± 0.007 (syst) visiblae phase space

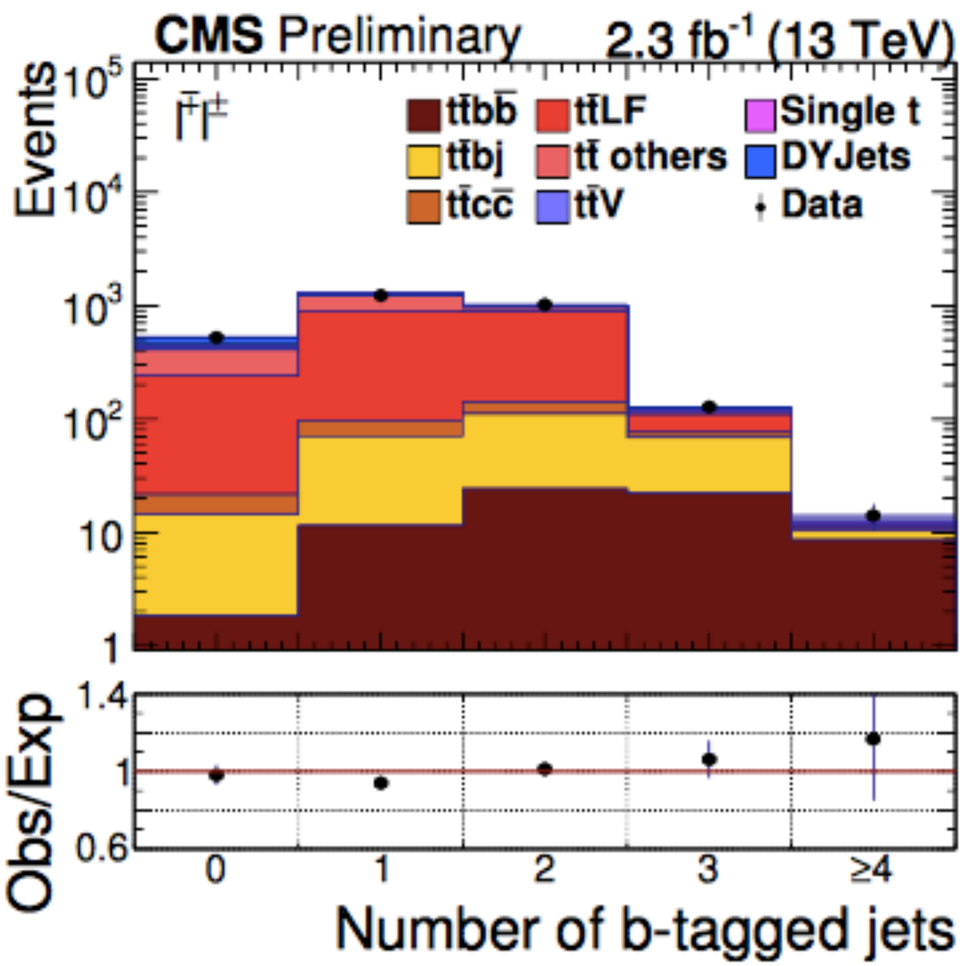
σttbb/σttjj = 0.022 ± 0.003 (stat) ± 0.006 (syst) full phase space

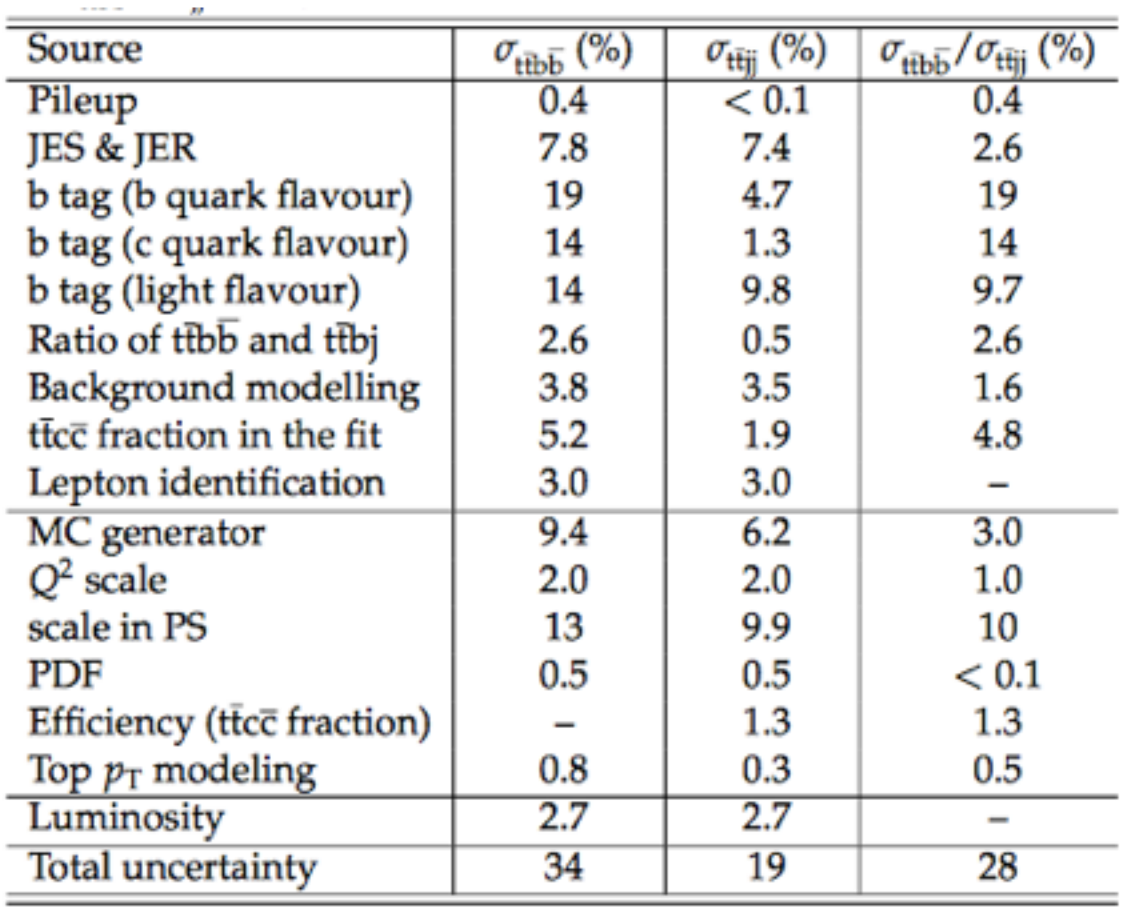
particle-level jets p_T >20 GeV.

POWHEG simulation (interfaced with PYTHIA) gives:

0.014 ± 0.001 for the visible phase space

0.012 ± 0.001 for full phase space.





Source	$\sigma_{t\bar{t}b\bar{b}}$ (%)	$\sigma_{t\bar{t}jj}$ (%)	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ (%)
Pileup	0.4	< 0.1	0.4
JES & JER	7.8	7.4	2.6
b tag (b quark flavour)	19	4.7	19
b tag (c quark flavour)	14	1.3	14
b tag (light flavour)	14	9.8	9.7
Ratio of $t\bar{t}b\bar{b}$ and $t\bar{t}bj$	2.6	0.5	2.6
Background modelling	3.8	3.5	1.6
$t\bar{t}c\bar{c}$ fraction in the fit	5.2	1.9	4.8
Lepton identification	3.0	3.0	–
MC generator	9.4	6.2	3.0
Q^2 scale	2.0	2.0	1.0
scale in PS	13	9.9	10
PDF	0.5	0.5	< 0.1
Efficiency ($t\bar{t}c\bar{c}$ fraction)	–	1.3	1.3
Top p_T modeling	0.8	0.3	0.5
Luminosity	2.7	2.7	–
Total uncertainty	34	19	28

Pseudo-Observables/Template Method

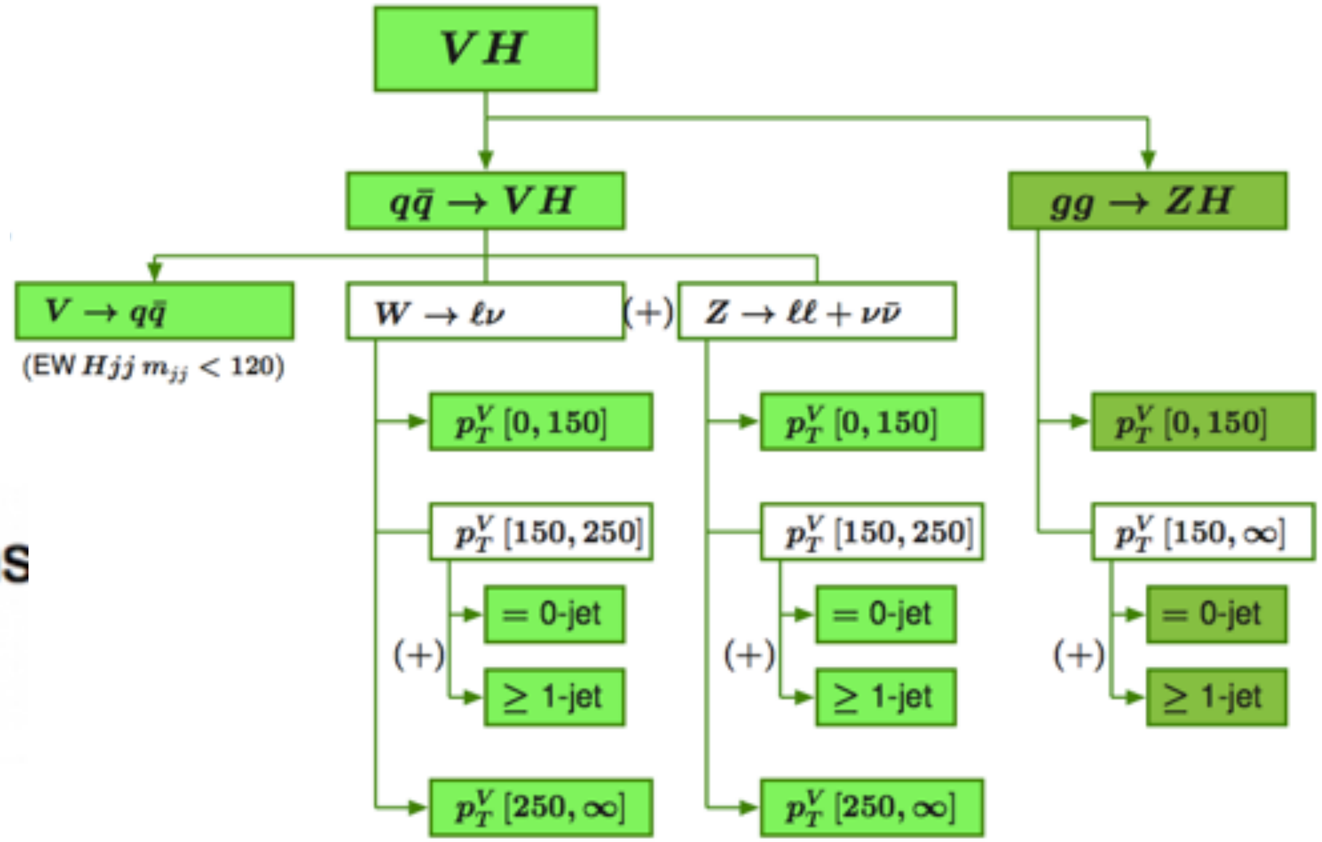
$$\sigma_1^{\rm meas} = A_{1a}^{ggH}\times\sigma_{ggH}^a + A_{1b}^{ggH}\times\sigma_{ggH}^b + A_{1c}^{\rm VBF}\sigma_{\rm VBF}^c + \cdots$$

$$\sigma_2^{\rm meas} = A_{2a}^{ggH}\times\sigma_{ggH}^a + A_{2b}^{ggH}\times\sigma_{ggH}^b + A_{2c}^{\rm VBF}\sigma_{\rm VBF}^c + \cdots$$

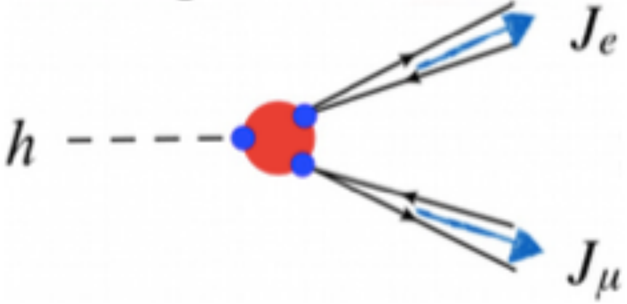
$$\sigma_3^{\rm meas} = \cdots$$

Separately fit bin cross sections σ_{ggH}^a, σ_{ggH}^b, $\sigma_{\rm VBF}^c$, ...

- Template cross sections: Fit cross sections in different bins inclusive of Higgs decays.
- Calculate in favorite model and compare.



$$\mathcal{A} = i\frac{2m_Z^2}{v_F}(\bar e\gamma_\alpha e)(\bar\mu\gamma_\beta\mu)\times \left[F_L^{e\mu}(q_1^2,q_2^2)g^{\alpha\beta} + F_T^{e\mu}(q_1^2,q_2^2)\frac{q_1\cdot q_2\; g^{\alpha\beta} - q_2{}^{\alpha} q_1{}^{\beta}}{m_Z^2} + F_{\rm CP}^{e\mu}(q_1^2,q_2^2)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$



$$F_X(q_1^2, q_2^2) = \sum_V \frac{({\rm const})_{2V}}{(q_1^2 - m_V^2)(q_2^2 - m_V^2)} + \frac{({\rm const})_{1V}}{(q_{1,2}^2 - m_V^2)} + ({\rm const}) + f_{\rm reg}(q_1^2, q$$

2 poles *1 pole* *no poles*

- Pseudo-Observables: Systematic way to encode experimental information for on-shell Higgs decays.
- Pseudo-Observables are the residues of physical poles in the decay amplitude.
- Can systematically include more information as statistics increase.

Template x-sections

The primary goals of the simplified template cross section framework are to maximize the sensitivity of the measurements while at the same time to minimize their theory dependence. This means in particular

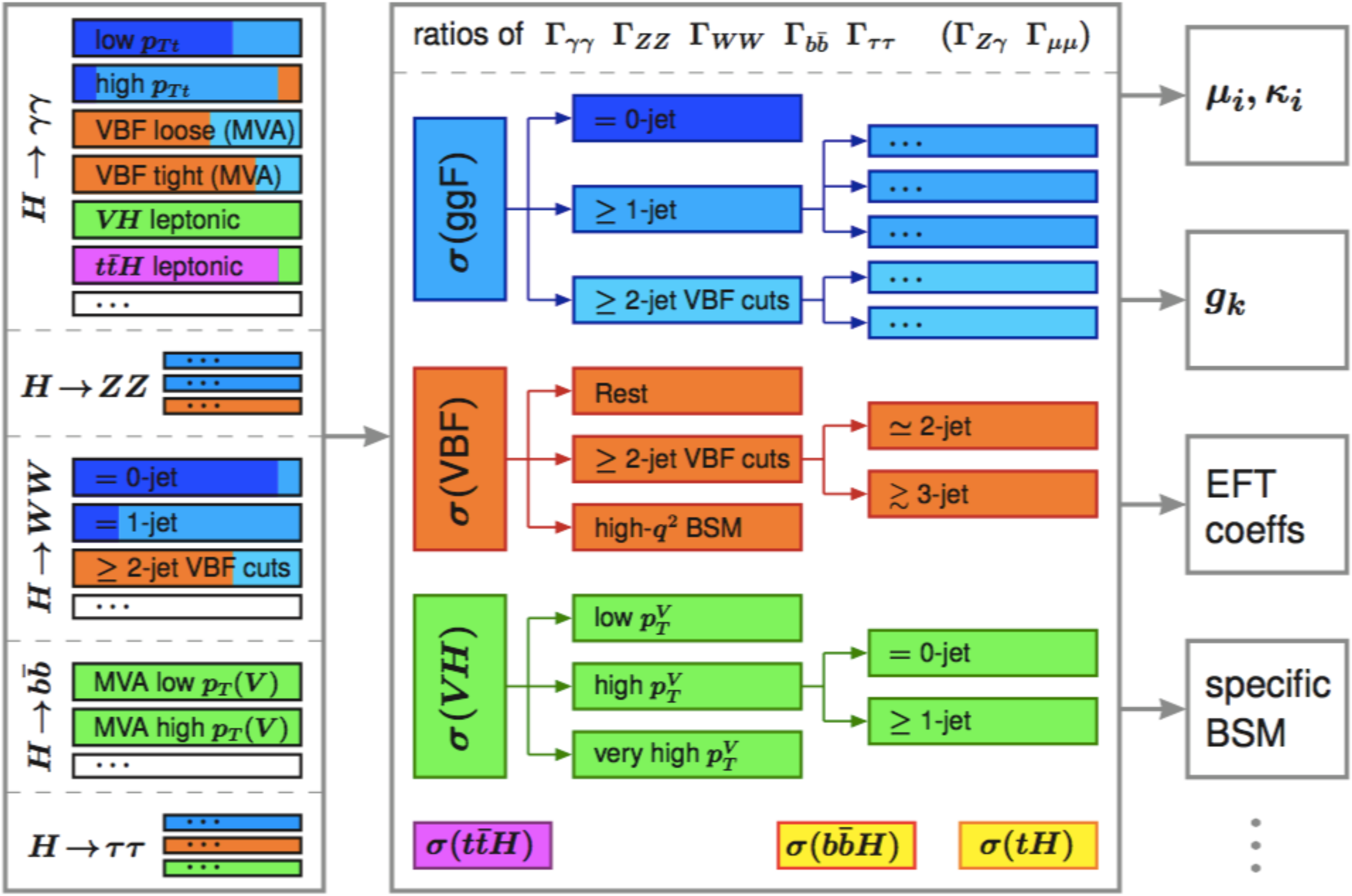
- combination of all decay channels
- measurement of cross sections instead of signal strengths, in mutually exclusive regions of phase space cross sections are measured for specific production modes
- measurements are performed in abstracted/simplified fiducial volumes allow the use of advanced analysis techniques such as event categorization, multivariate techniques, etc.

The measured exclusive regions of phase space, called “bins” for simplicity, are specific to the different production modes. Their definitions are motivated by minimizing the dependence on theoretical uncertainties that are directly folded into the measurements

- maximizing experimental sensitivity
- isolation of possible BSM effects
- minimizing the number of bins without loss of experimental sensitivity

The theory systematics do not have to be considered anymore apart from the ones having to deal with bin migrations.

Template x-sections



$H \to \gamma\gamma$

low p_{Tt}

high p_{Tt}

VBF loose (MVA)

VBF tight (MVA)

VH leptonic

$t\bar{t}H$ leptonic

…

$H \to ZZ$

…

…

…

$H \to WW$

= 0-jet

= 1-jet

≥ 2-jet VBF cuts

…

$H \to b\bar{b}$

MVA low $p_T(V)$

MVA high $p_T(V)$

…

$H \to \tau\tau$

…

…

…

ratios of $\Gamma_{\gamma\gamma}$ Γ_{ZZ} Γ_{WW} $\Gamma_{b\bar{b}}$ $\Gamma_{\tau\tau}$ $(\Gamma_{Z\gamma}$ $\Gamma_{\mu\mu})$

σ(ggF)

= 0-jet

≥ 1-jet

≥ 2-jet VBF cuts

…

…

…

…

…

σ(VBF)

Rest

≥ 2-jet VBF cuts

high-q^2 BSM

≃ 2-jet

≳ 3-jet

$\sigma(VH)$

low p_T^V

high p_T^V

very high p_T^V

= 0-jet

≥ 1-jet

$\sigma(t\bar{t}H)$

$\sigma(b\bar{b}H)$

$\sigma(tH)$

μ_i, κ_i

g_k

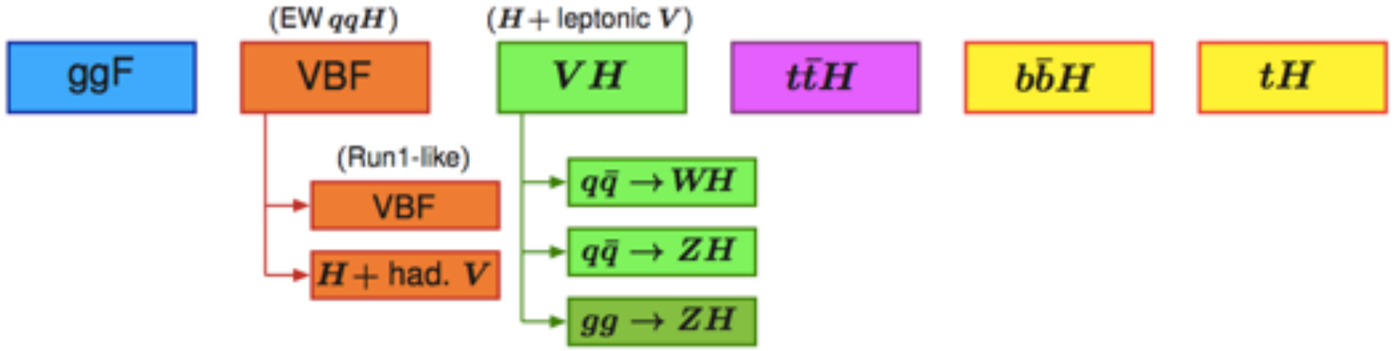
EFT coeffs

specific BSM

⋮

Stages Template x-sections

Stage 0 Corresponds to mu measurements in run I. Inclusive gluon fusion cross section within |YH | < 2.5. Should the measurements start to have acceptance beyond 2.5, an additional bin for |YH | > 2.5 can be included.



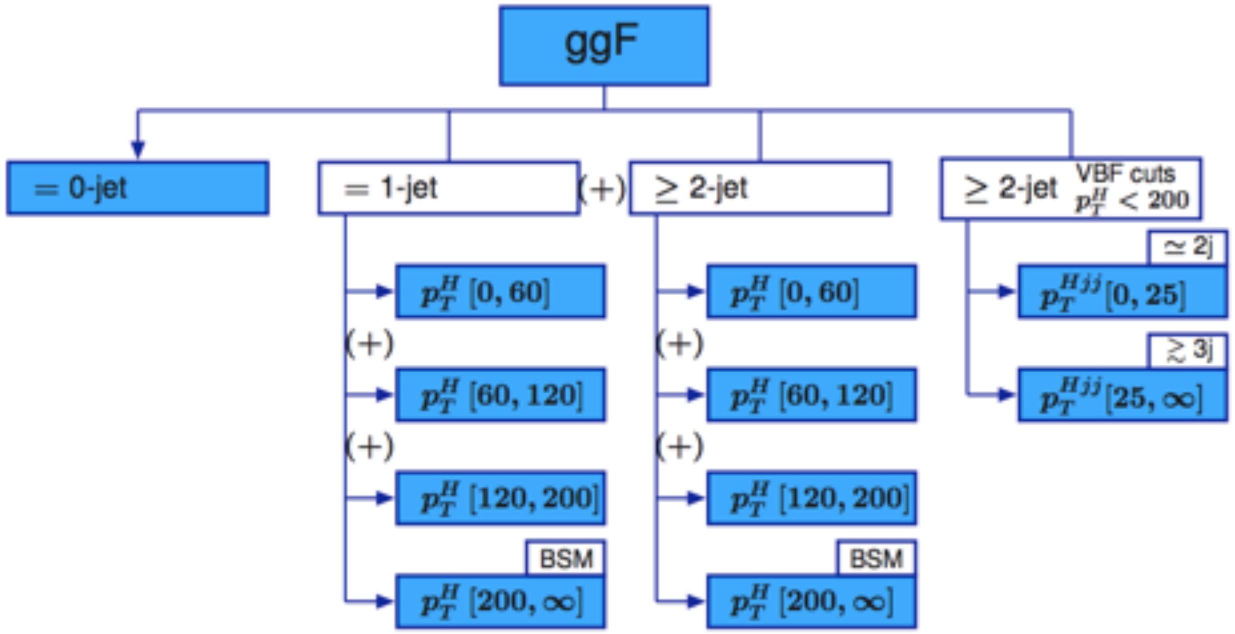


Figure 219: Stage 1 binning for gluon fusion production.

Pseudo-observables

The idea of PO has been formalized the first time in the context of electroweak observables around the Z pole. The basic idea is to identify a set of quantities that are

I. experimentally accessible,
II. well-defined from the point of view of QFT,

and capture all relevant New Physics (NP) effects (or all relevant deformations from the SM) without losing information and with minimum theoretical bias..

The independence from NP models can not be fulfilled in complete generality. However, it can be fulfilled under very general assumptions. In particular, the PO should

III. capture all relevant NP effects in the limit of no new (non-SM) particles propagating on-shell (in the amplitudes considered) in the kinematical range where the decomposition is assumed to be valid.

Under this additional hypothesis, the PO provide a bridge between the fiducial cross-section measurements and the determination of NP couplings in explicit NP frameworks.

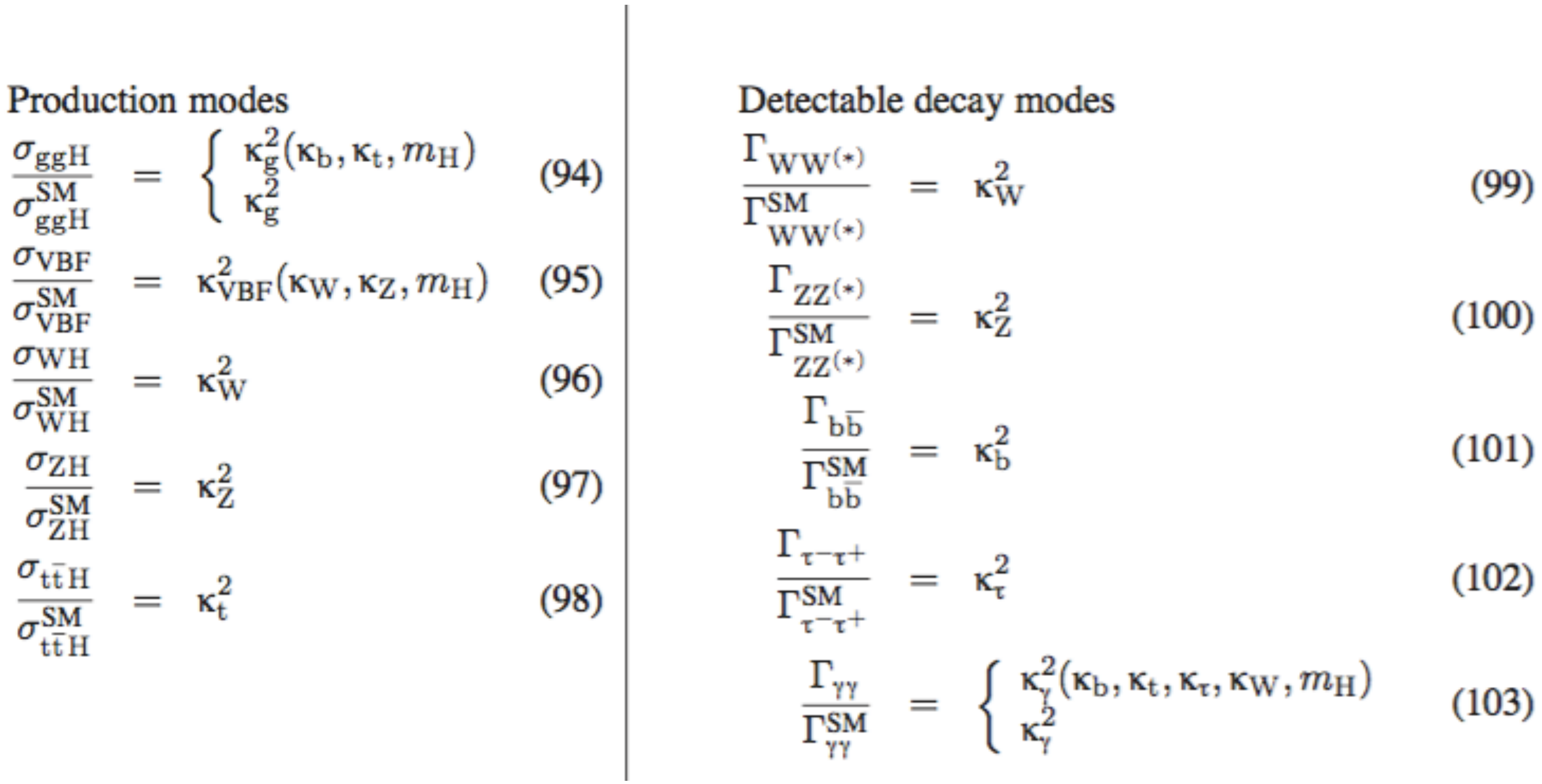
k-framework

The old κ framework satisfied the conditions I and II, but not the condition III, since the framework was not general enough to describe modifications in (n > 2)-body Higgs boson decays resulting in non-SM kinematics. Similarly, the old κ framework could not describe modifications of the Higgs-cross sections that cannot be reabsorbed into a simple overall re-scaling with respect to the SM.

k-framework assumptions:

- narrow resonance
- Only modifications of couplings strengths, i.e. of absolute values of couplings, are taken into ac- count, while the tensor structure of the couplings is assumed to be the same as in the SM prediction. This means in particular that the observed state is assumed to be a CP-even scalar.
- By definition, the currently best available SM predictions for all σ · BR are recovered when all κi = 1. In general, this means that for κi/= 1 higher-order accuracy is lost. Nonetheless, NLO QCD corrections essentially factorize with respect to coupling rescaling, and are accounted for wherever possible. This approach ensures that for a true SM Higgs boson no artificial deviations (caused by ignored NLO corrections) are found from what is considered the SM Higgs boson hypothesis. The functions : κ2 (κW,κZ,mH), κg2(κb,κt,mH), κγ2(κb,κt,κτ,κW,mH), κ2 (κb,κt,κτ,κW,mH) and κ2 (κi,mH) VBF (Zγ) H are used for cases where there is a non-trivial relationship between scale factors κi and cross sections or (partial) decay widths, and are calculated to NLO QCD accuracy.

k-framework



Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \left\{ \begin{array}{l} \kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa_{\mathrm{g}}^2 \end{array} \right. \quad (94)$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}}) \quad (95)$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2 \quad (96)$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2 \quad (97)$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma_{\mathrm{t\bar{t}H}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^2 \quad (98)$$

Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma_{\mathrm{WW}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2 \quad (99)$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma_{\mathrm{ZZ}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2 \quad (100)$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_{\mathrm{b\bar{b}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^2 \quad (101)$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{\mathrm{SM}}} = \kappa_{\tau}^2 \quad (102)$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \left\{ \begin{array}{l} \kappa_{\gamma}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{\gamma}^2 \end{array} \right. \quad (103)$$

the notation in terms of the partial widths $\Gamma_{WW(*)}$ and $\Gamma_{ZZ($ is meant for illustration only.

In the experimental analysis the 4-fermion partial decay widths are taken into account.