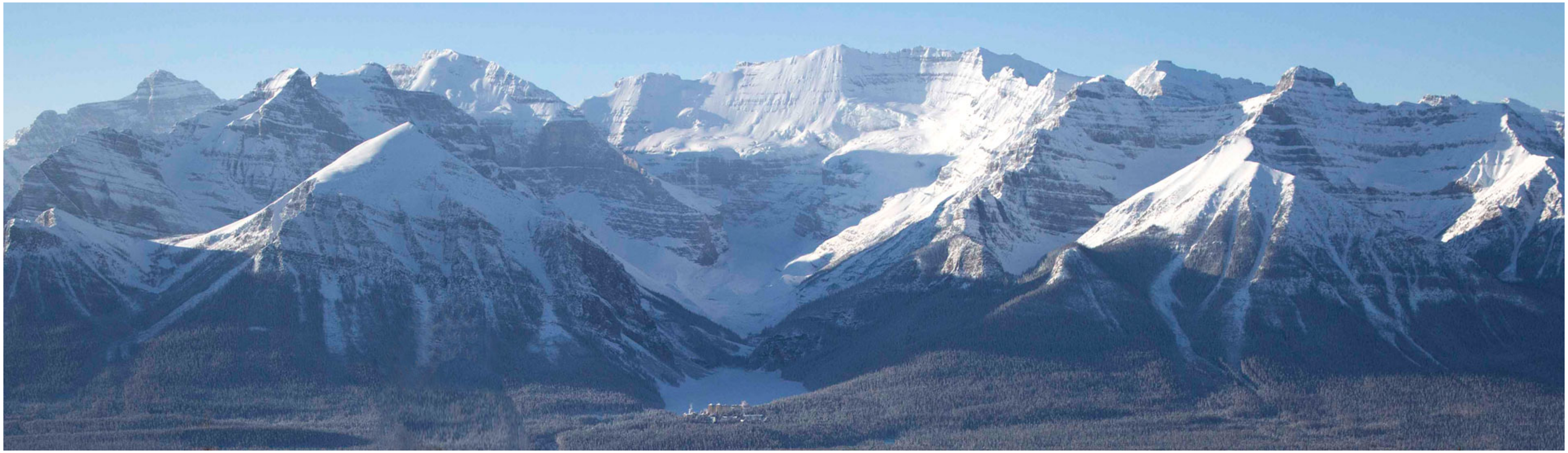
Higgs measurements in ATLAS

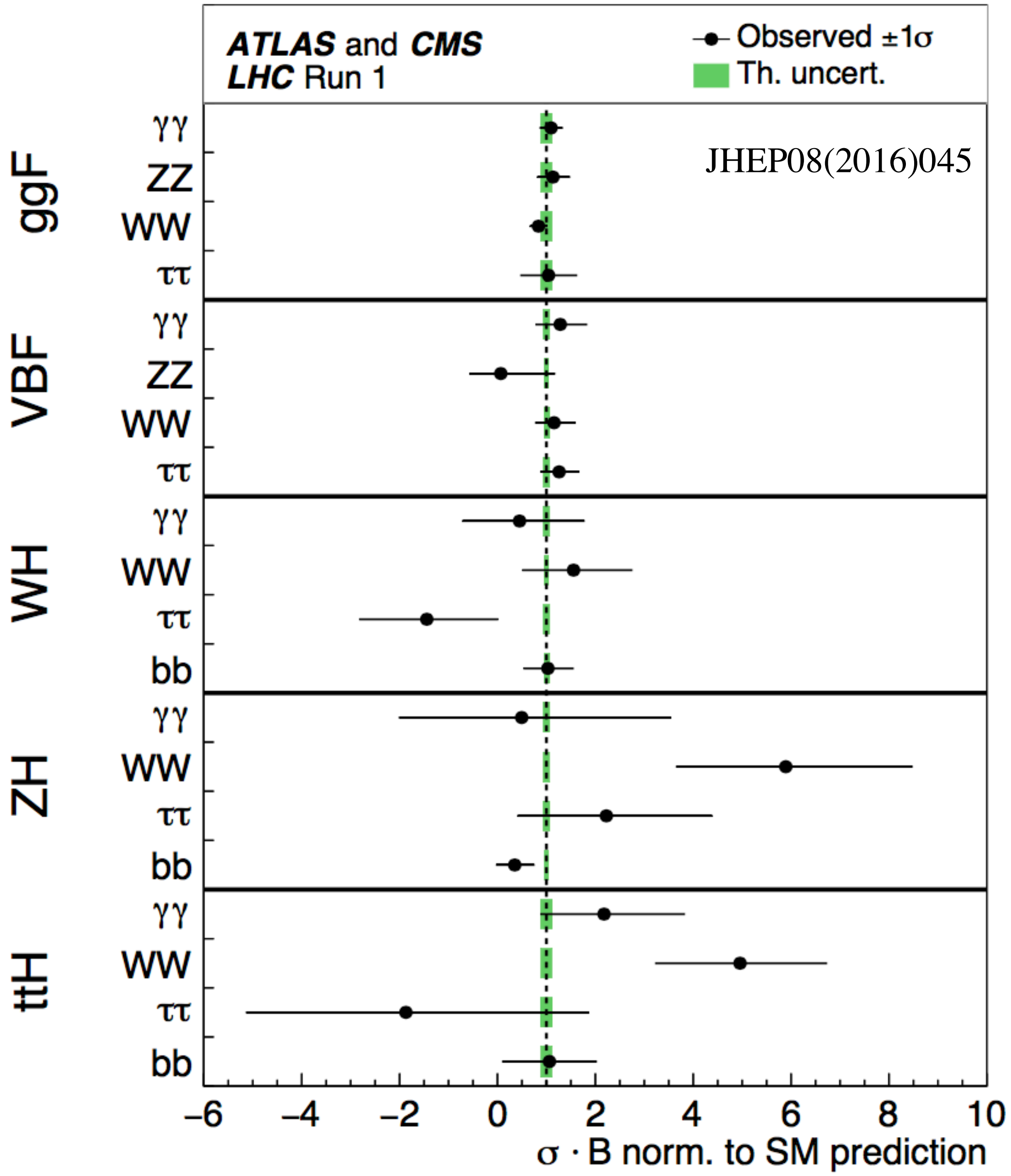


Carlo Pandini (CERN)
on behalf of the ATLAS collaboration

LLWI2018 - 19/02/2016

Introduction and outline

From LHC **Run-1** dataset: **Higgs discovery** and first property measurements



Higgs boson discovery in 2012 from vector bosons decay channels:
H→γγ, H→ZZ, H→WW

Evidence of coupling to fermions: H→$\tau\tau$

Run-1 measured properties SM-like
m_H = 125.09 ± 0.24 GeV, spin-0, CP-even

From LHC **Run-2** dataset:

- establish discovery in remaining decay channels / production modes
- measurement of Higgs boson properties

Focus of this talk on ATLAS Higgs results with first 36fb^{-1} of data collected at 13 TeV

H→γγ

H→4l

couplings
cross-section
differential distributions
mass measurement

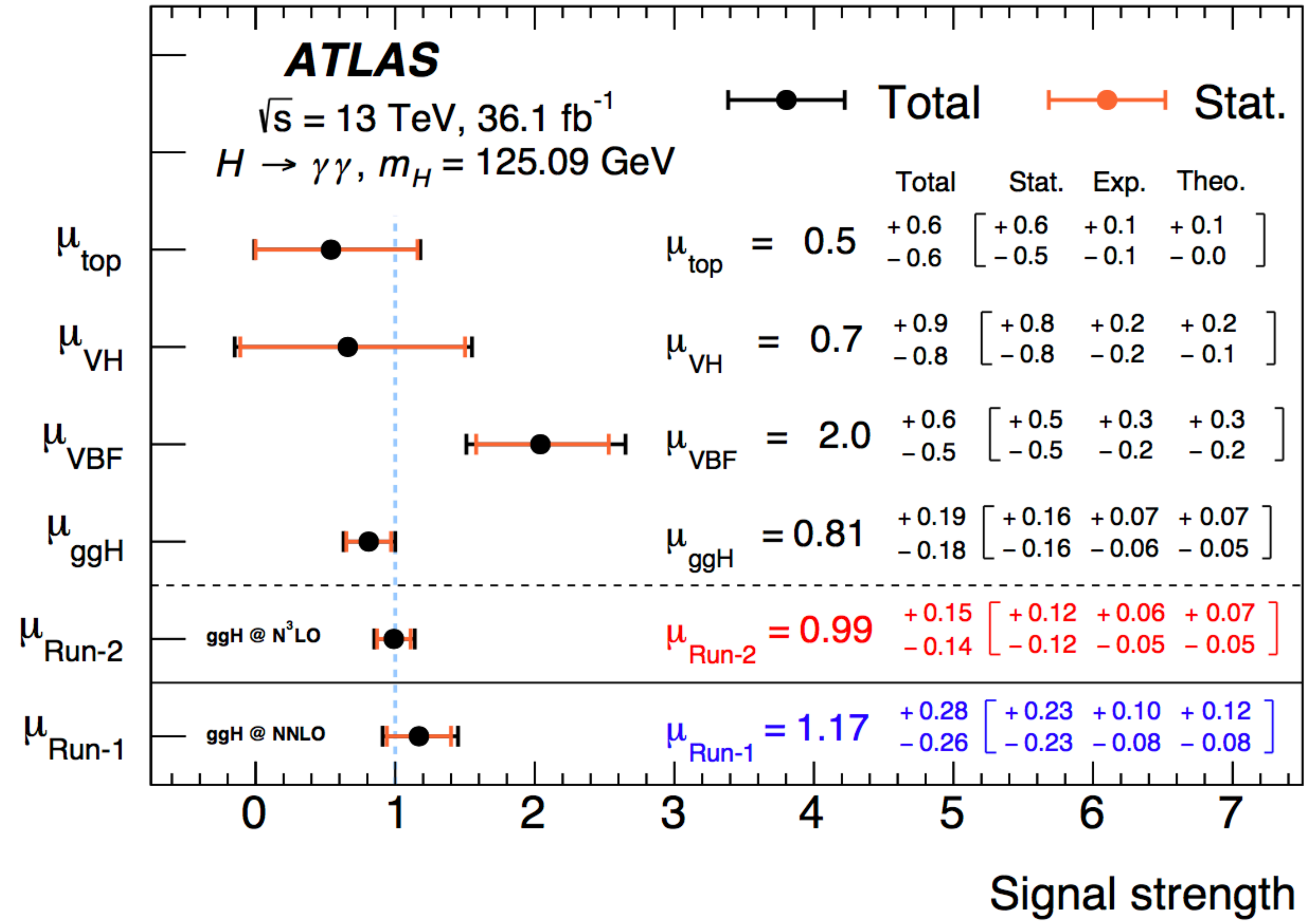
VH→bb

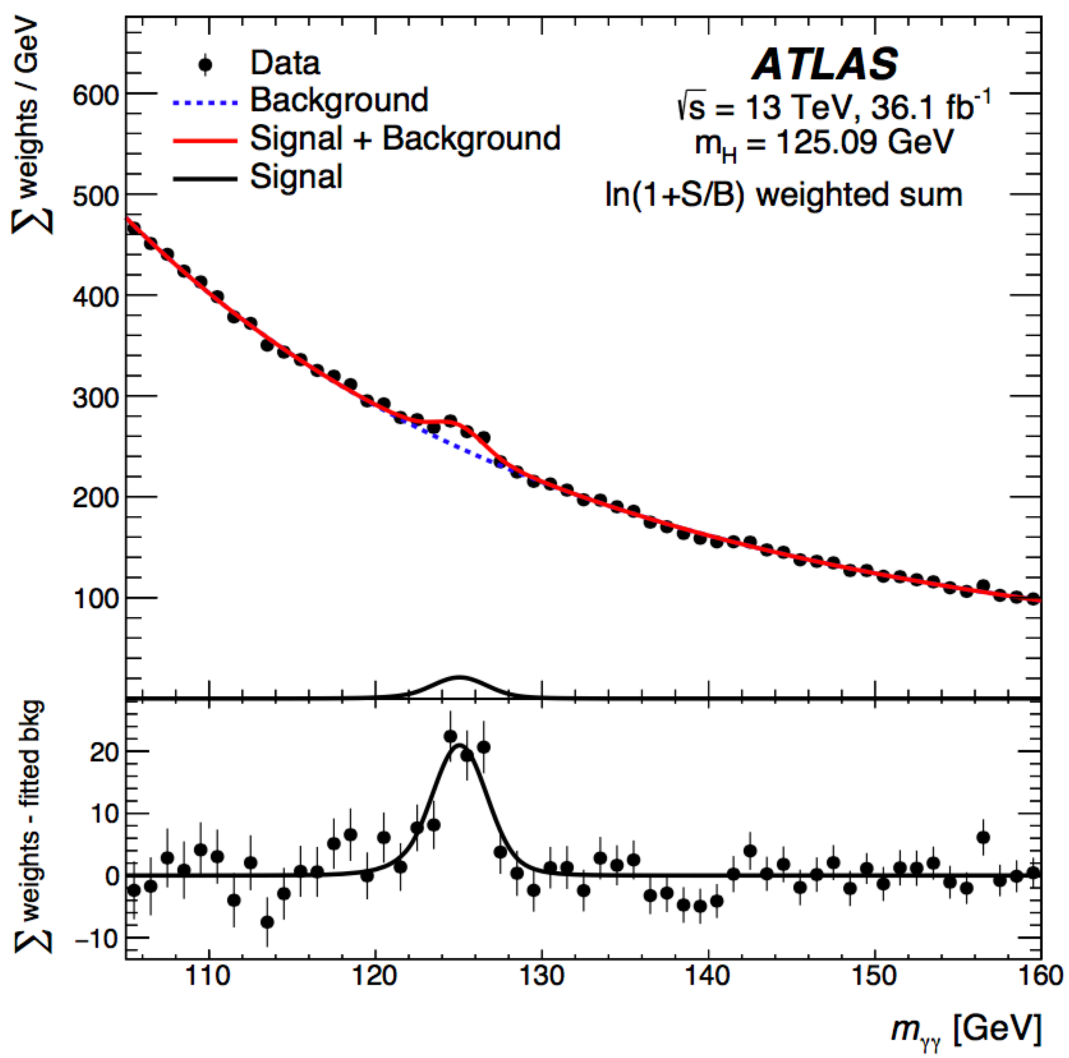
ttH

$H \to \gamma\gamma$ couplings

arxiv 1802.04146
$36.1 fb^{-1}$ @ 13TeV

- clean experimental signature
- analysis **event categorization** targeting H production modes
- signal yield from simultaneous S+B fit of the $m_{\gamma\gamma}$ distribution
  - background function - limiting the potential bias on the fitted signal
  - signal function double-sided Crystal Ball





$\mu_{Run\text{-}2} = 0.99\ ^{+0.12}_{-0.12}(stat.)\ ^{+0.6}_{-0.5}(syst.)\ ^{+0.7}_{-0.5}(TH.)$

Improvement of ~ factor x2 on all uncertainty components with respect to Run-1 results

H→γγ couplings

arxiv 1802.04146
36.1fb⁻¹ @ 13TeV

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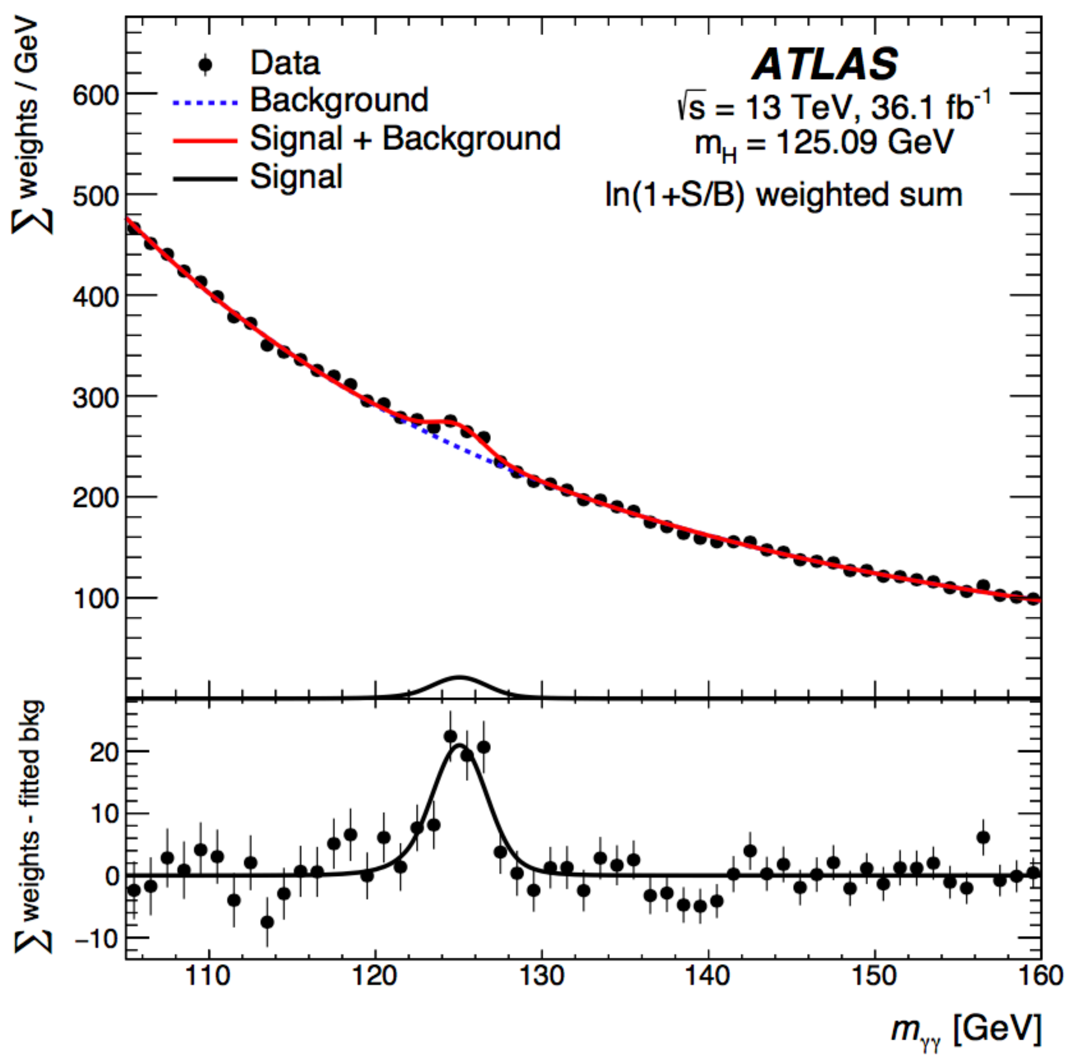
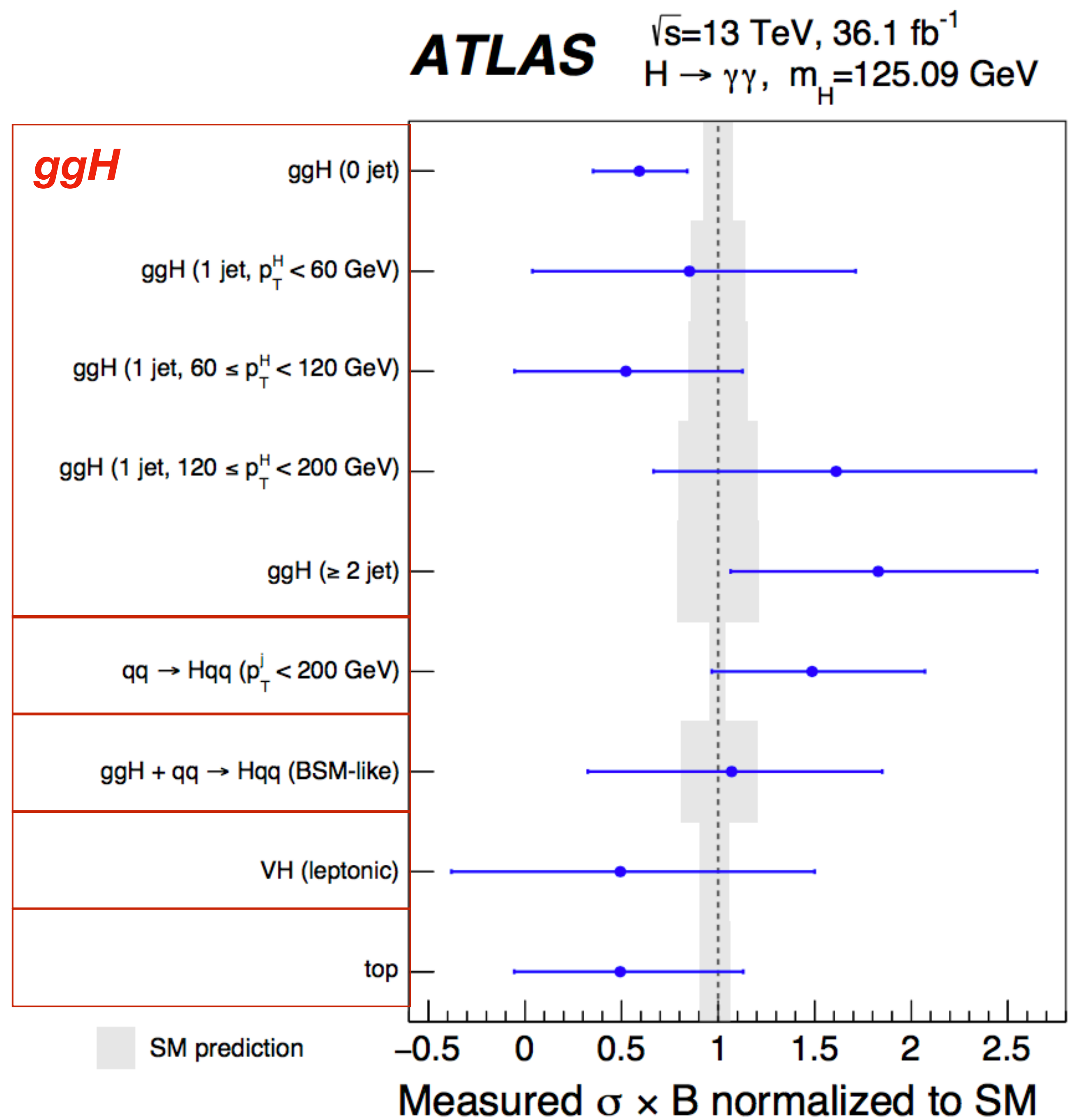


Production mode cross-section x BR(H→γγ)
(rapidity region $|y_H|<2.5$)

Simplified Template Cross-Sections (STXS)

Exclusive regions, reducing theory dependence while maximising experimental sensitivity:



H→γγ fiducial & differential measurements

[arxiv 1802.04146
36.1fb^{-1} @ 13TeV]

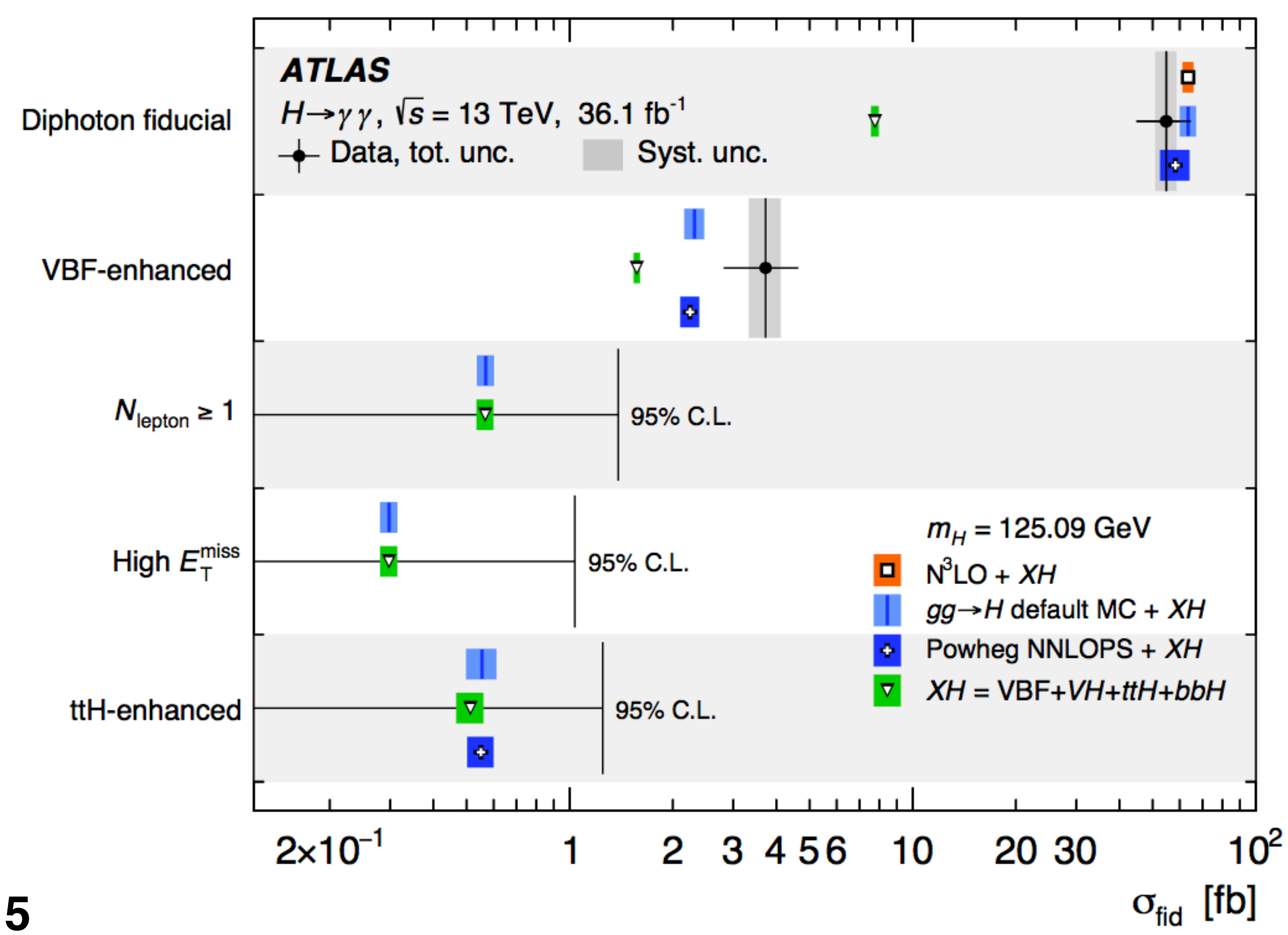
- Differential cross-sections as function of Higgs and jet kinematic variables: pT(γγ), y(γγ), N(jets), ...
- Compared to several state-of-the-art gluon-fusion Higgs TH predictions
- Measurements in several fiducial regions, targeting H prod. mode, or sensitive to BSM effects

XS(pp→H→γγ)

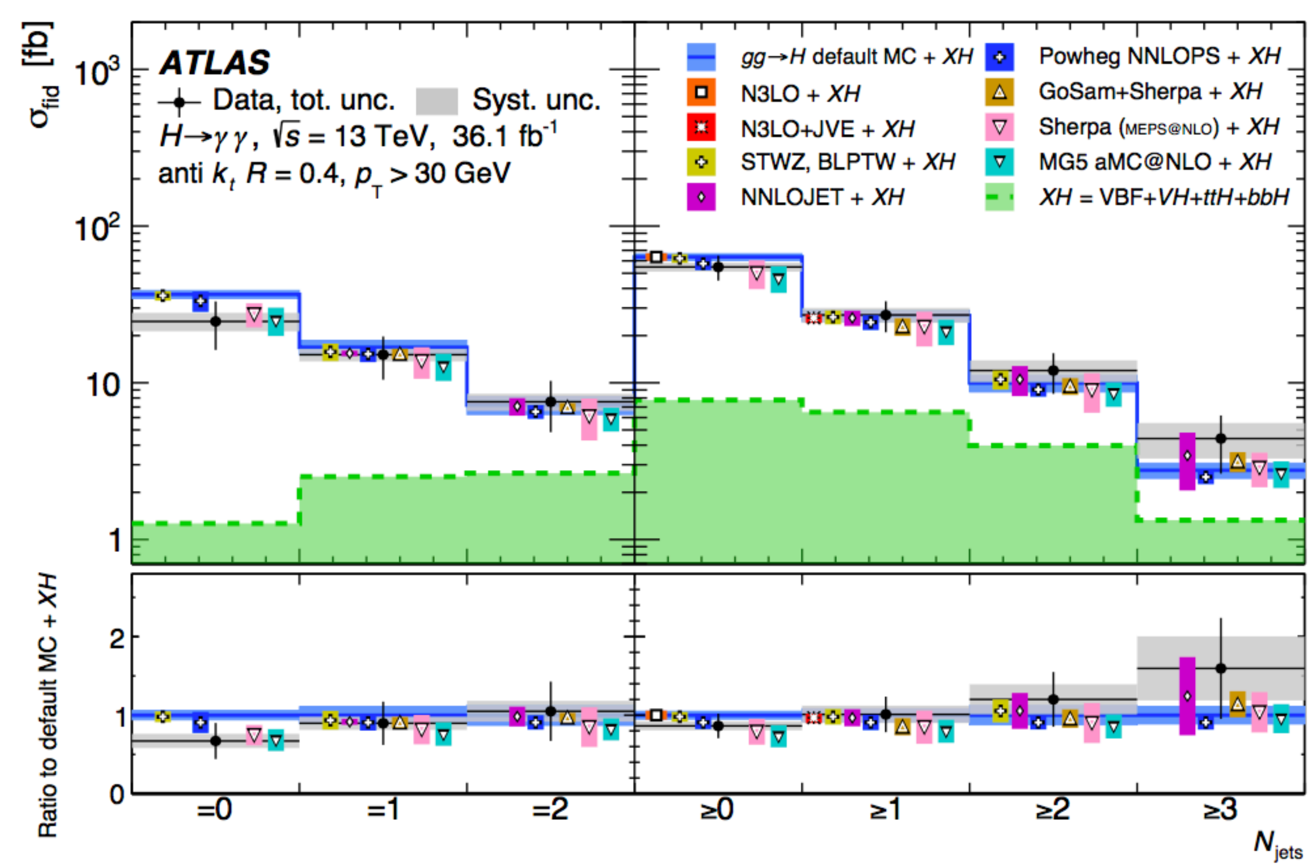
σ^{meas}_{fid} =55 ± 9(stat.) ± 4(exp.) ± 0.1(theo.)fb

σ^{SM}_{fid} =64 ± 2fb

$$\frac{d\sigma_i}{dx} = \frac{N_i^{sig}}{c_i\,\Delta x_i \int L\,dt},$$



jet-exclusive jet-inclusive



H→γγ fiducial & differential measurements

arxiv 1802.04146
36.1fb⁻¹ @ 13TeV

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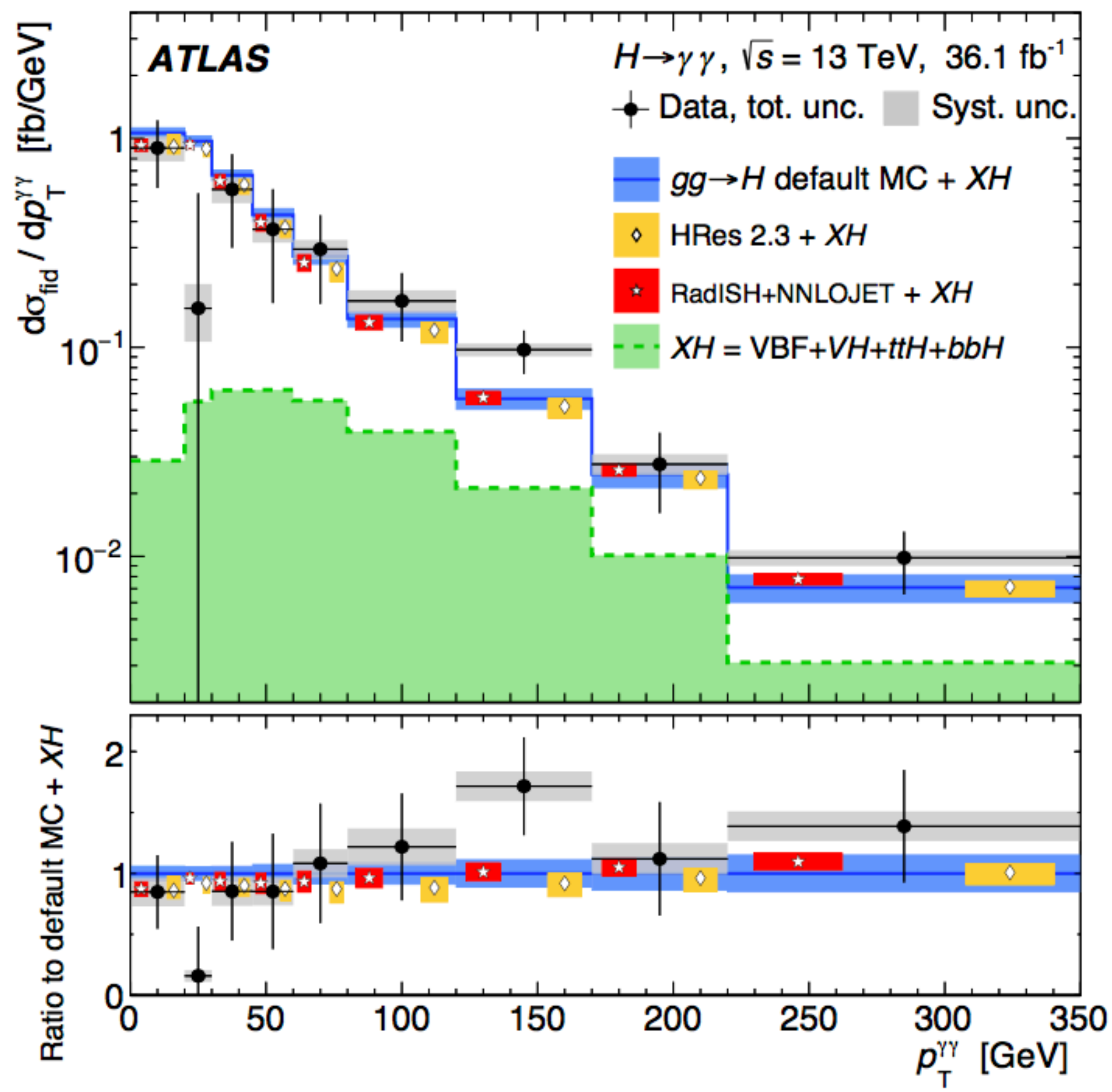
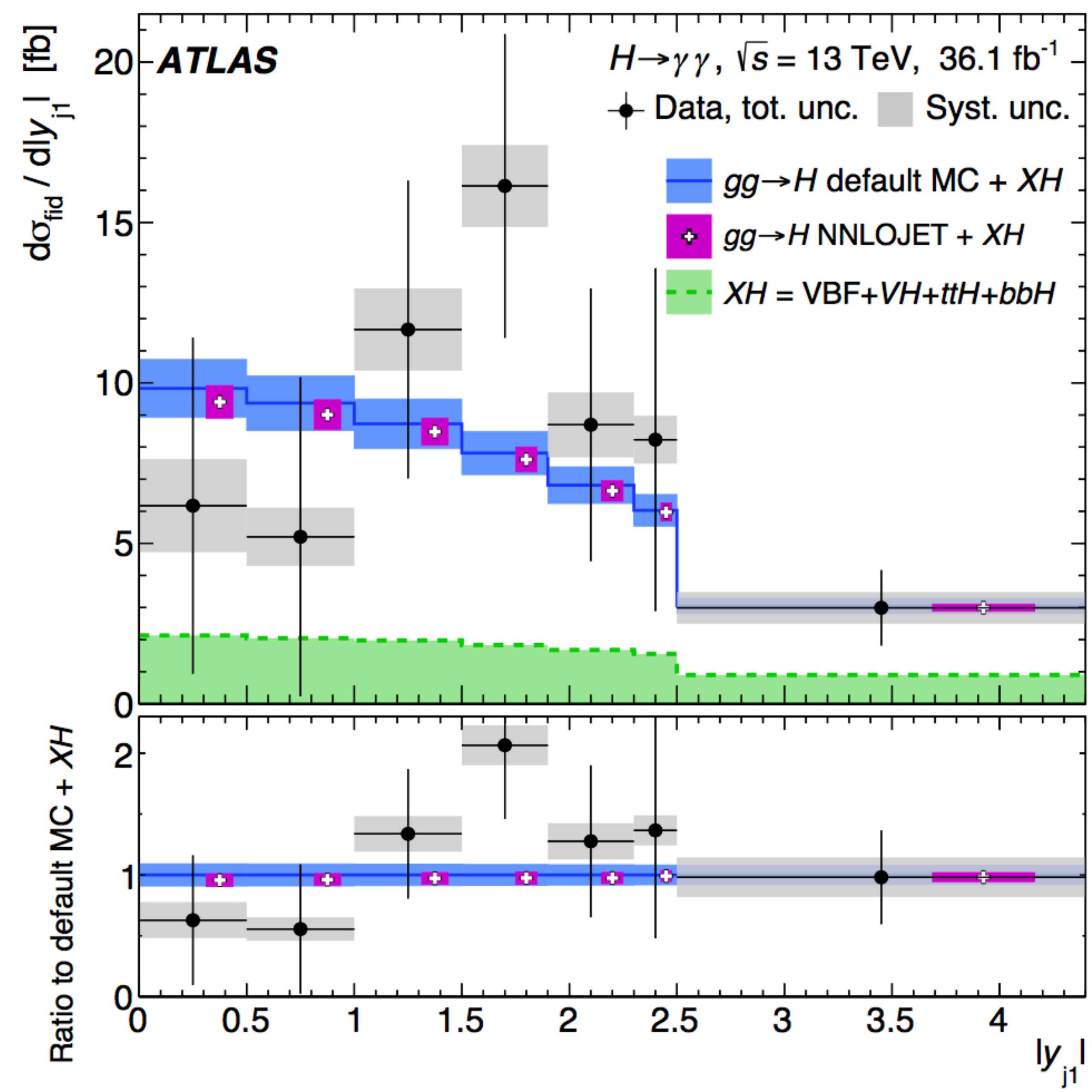




$H\to ZZ^*$ production mode cross-section

arxiv 1712.02304
$36.1 fb^{-1}$ @ 13TeV

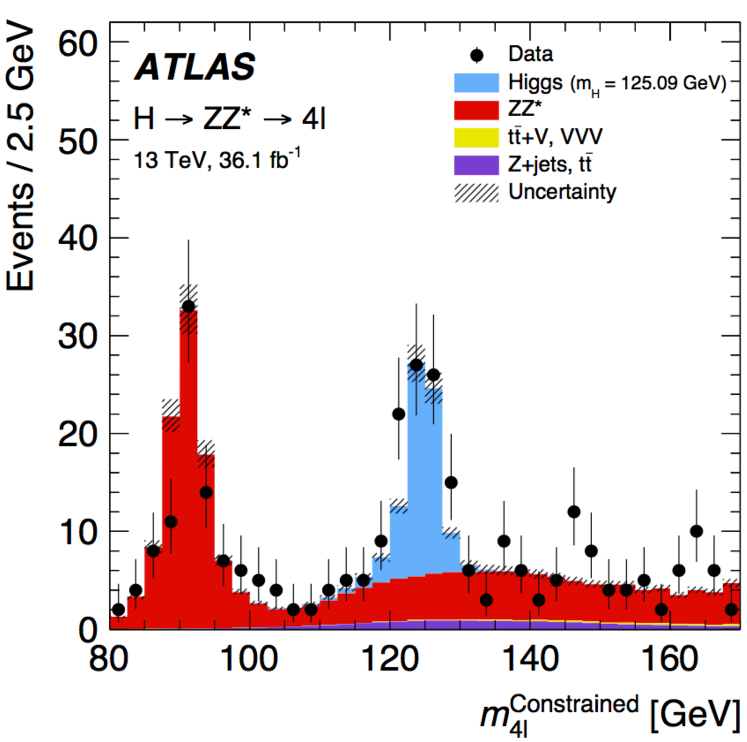
- low branching fraction: $BR(H\to ZZ^*)\sim 2.6\%$
  further reduced by $BR(Z\to ee,\mu\mu)$
- main background: non-resonant ZZ^* production (irreducible)
- reducible background (Z+jets, top) strongly suppressed by selection
- $\sigma^*BR(H\to ZZ^*)$ for different production modes from dedicated $H\to 4l$ event categories

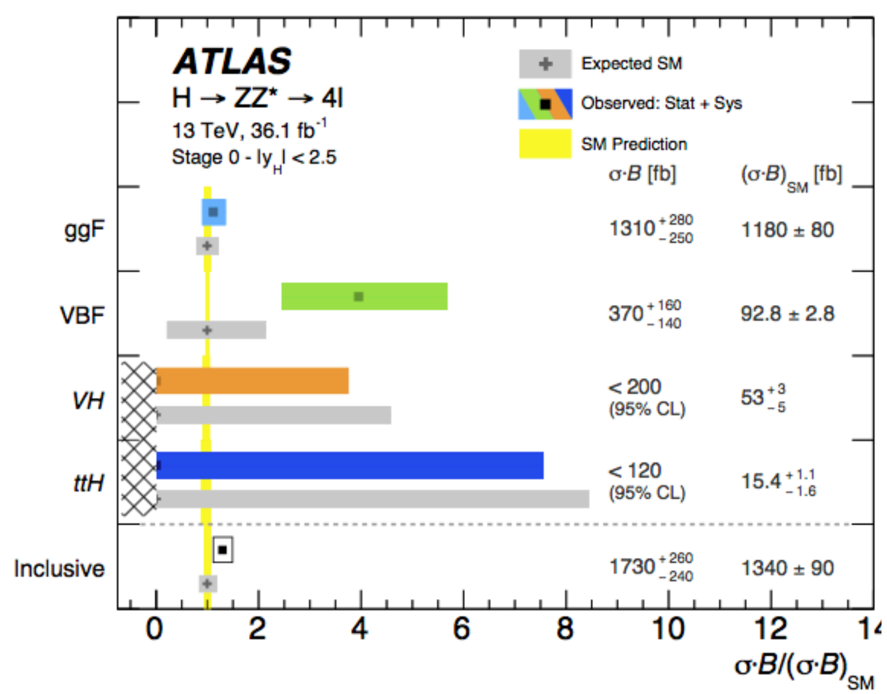
Production cross-section measured inclusively, and in exclusive STXS regions

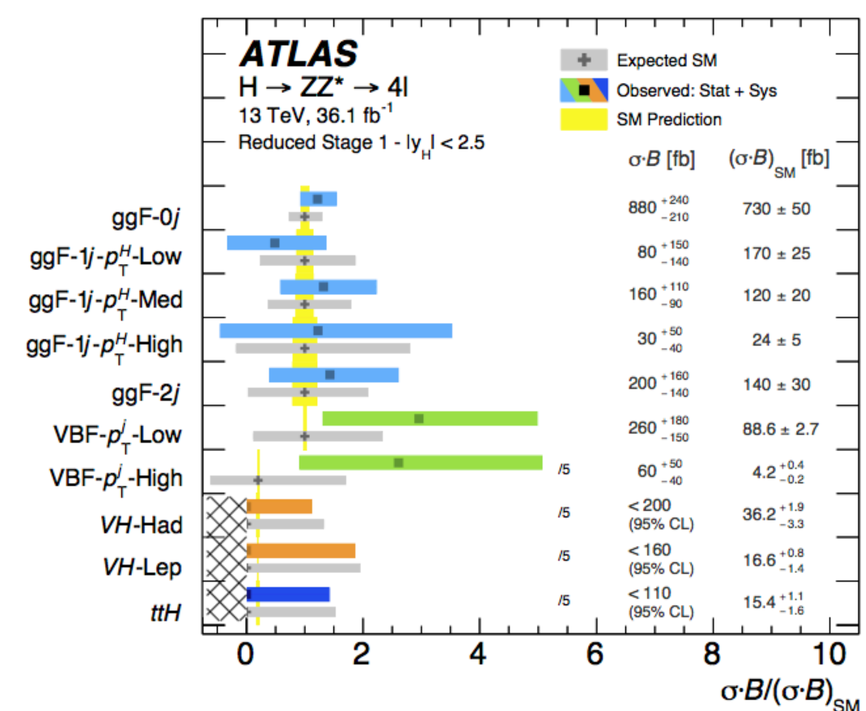
$\sigma_{inclusive}{}^*BR(H\to ZZ^*) = 1.73\ ^{+0.24}_{-0.23}(stat)^{+0.10}_{-0.08}(sys)$ pb

$\sigma^{SM}_{inclusive}{}^*BR(H\to ZZ^*) = 1.34$ fb ± 0.09 pb

$|y_H|<2.5$







4 "stage-0" STXS bins → 10 "stage-1" STXS bins

H→ZZ* fiducial & differential measurements

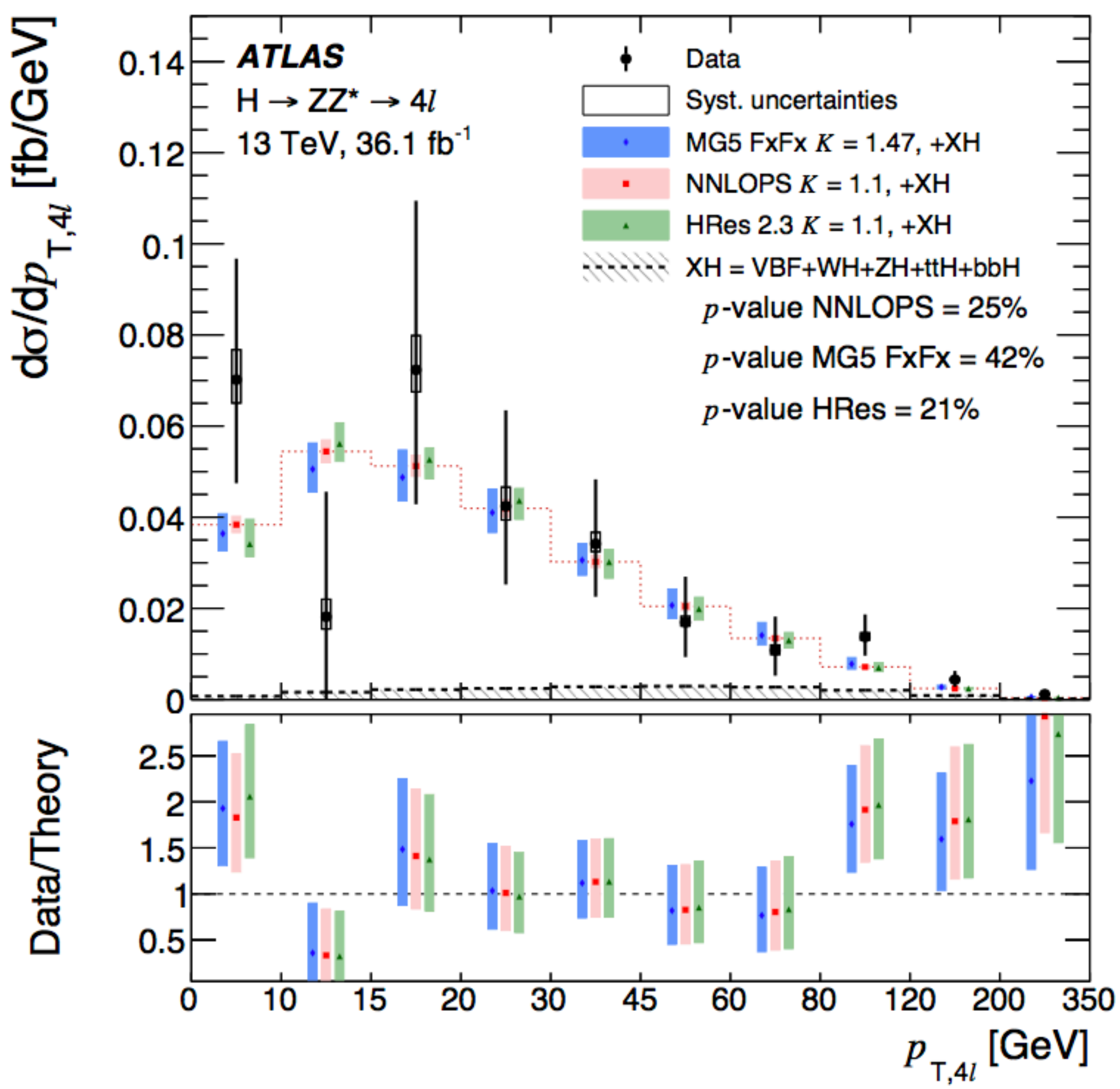
- fiducial cross-section measurement also in good agreement with SM

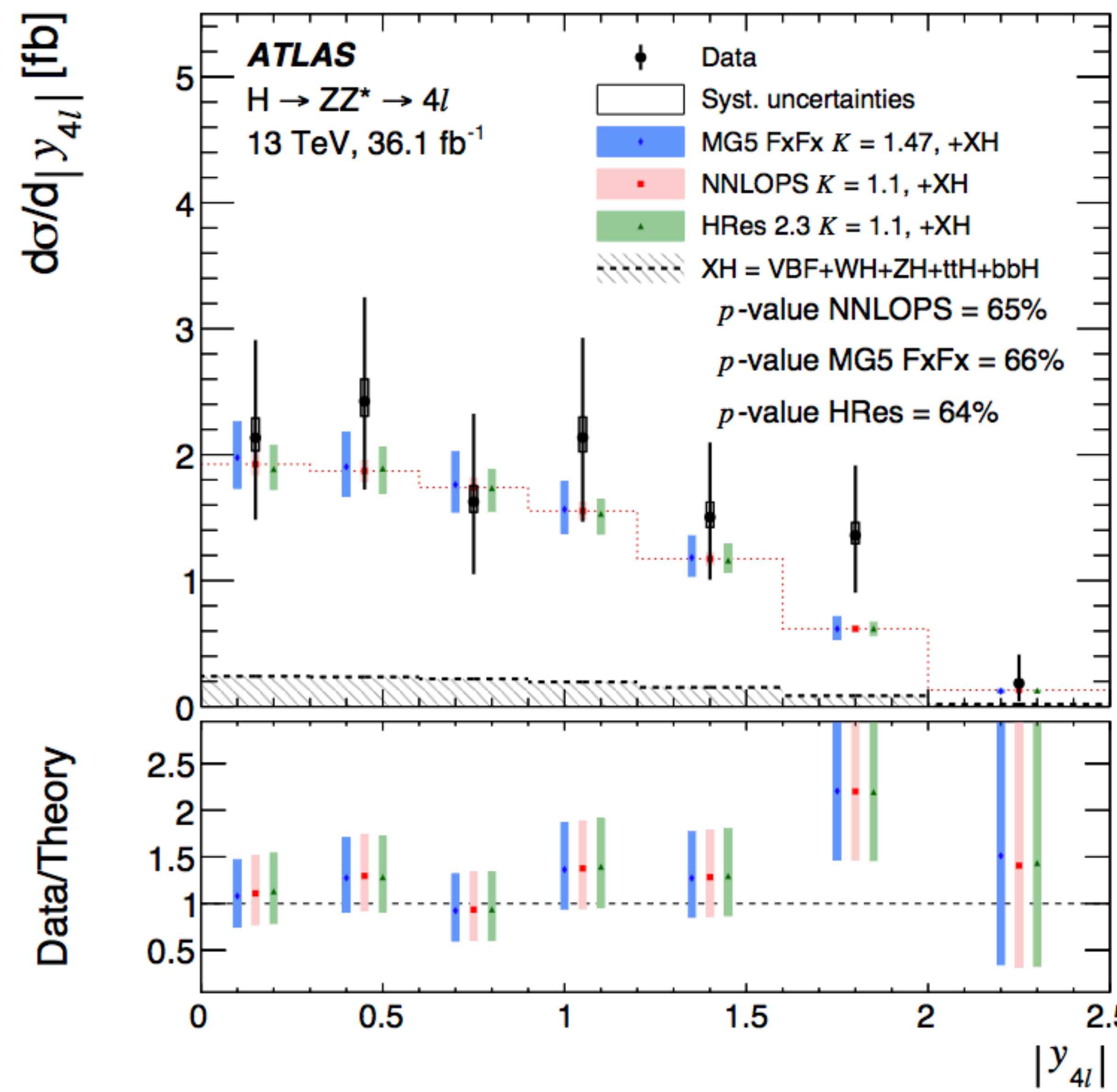
JHEP 10 (2017) 132
36.1fb⁻¹ @ 13TeV

$\sigma^{meas}_{fid} = 3.62 \pm 0.50(stat)^{+0.25}_{-0.20}(sys)$ fb
$\sigma^{SM}_{fid} = 2.91 \pm 0.13$ fb

- single/double-differential cross-section measurements

SM ggH predictions normalized to total ***N3LO*** *cross-section from LHCHXSWG*





Higgs mass measurement

ATLAS-CONF-2017-046
36.1fb^{-1} @ 13TeV

Di-photon and 4-leptons selections inherited from coupling/cross-section measurements

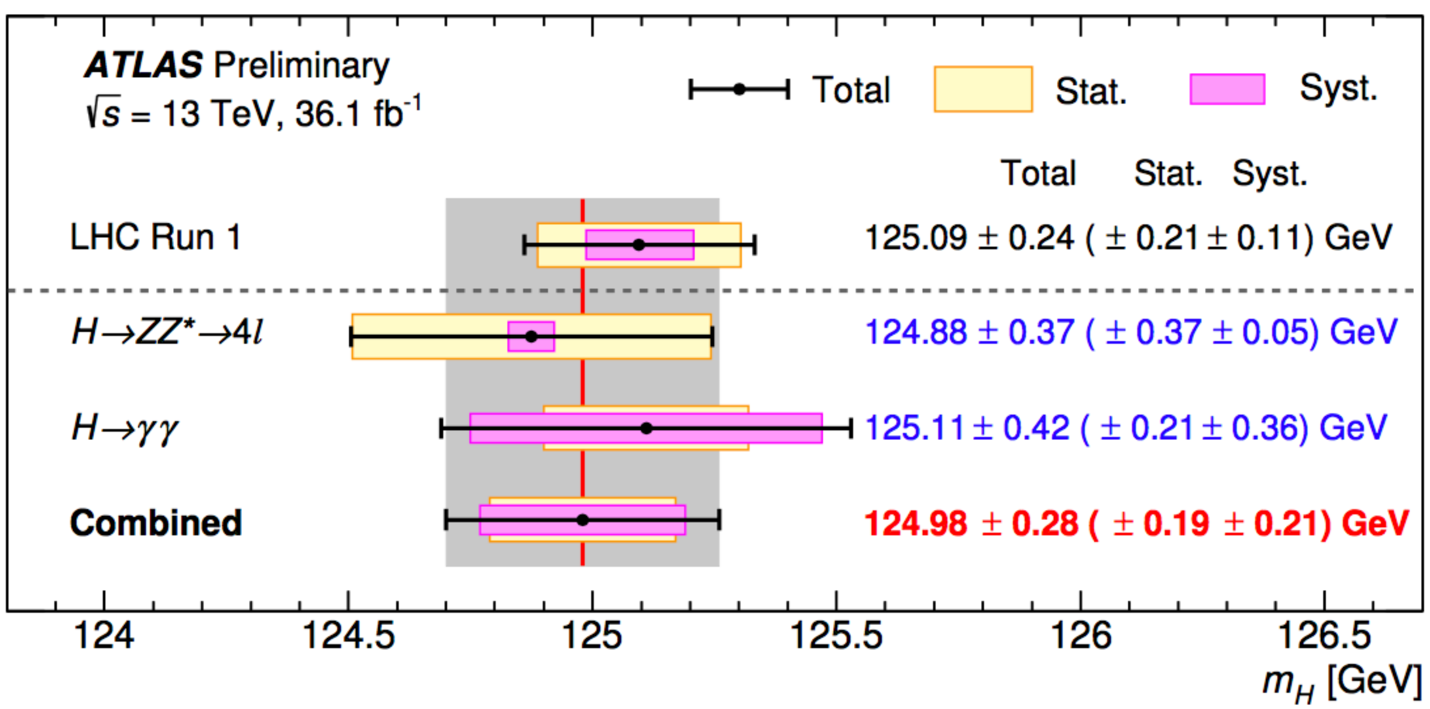
m^{ZZ^*} =124.88 ±**0.37**(stat) ±0.05(syst) GeV

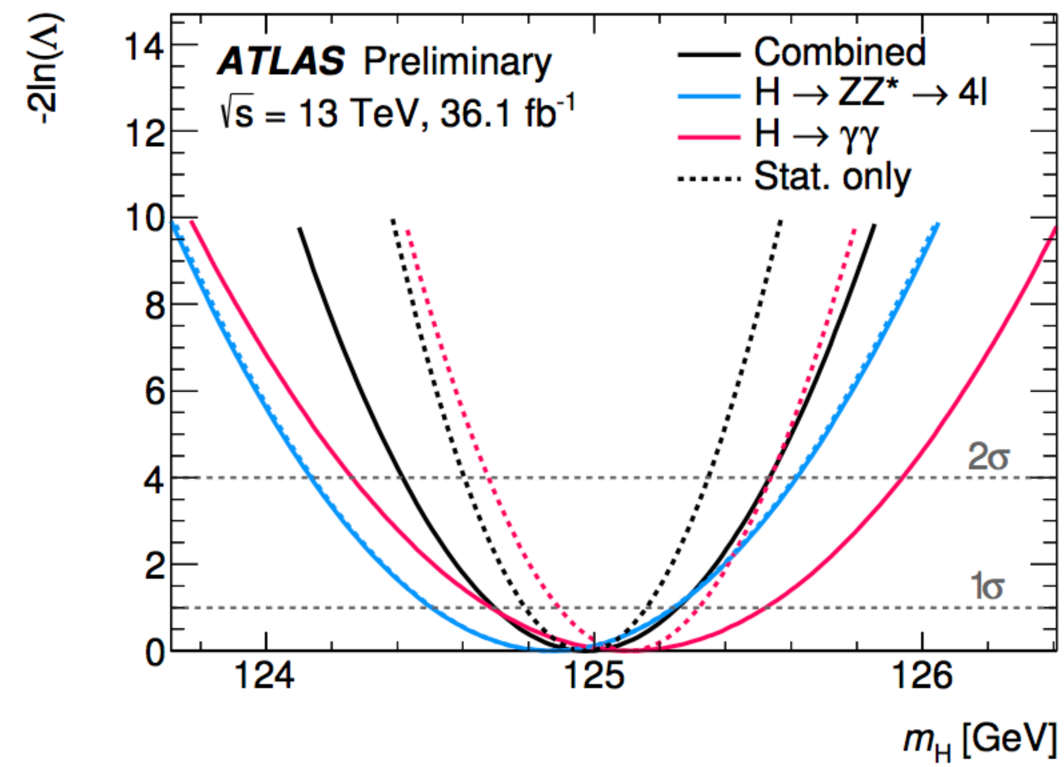
$m^{\gamma\gamma}$ =125.11 ±0.21(stat) ±**0.36**(syst) GeV

H(ZZ) **statistics** limited

H(γγ) **systematics** limited

Δm_H =0.23 ±0.42(stat) ±0.36(syst) GeV





m_H = 124.98 ±0.19(stat) ±0.21(syst) GeV

= 124.98 ±0.28 GeV

(compared to the Run-1 ATLAS⊕CMS result of **m_H** = 125.09 ±0.21(stat) ±0.11(syst) GeV)

VH(H→bb)

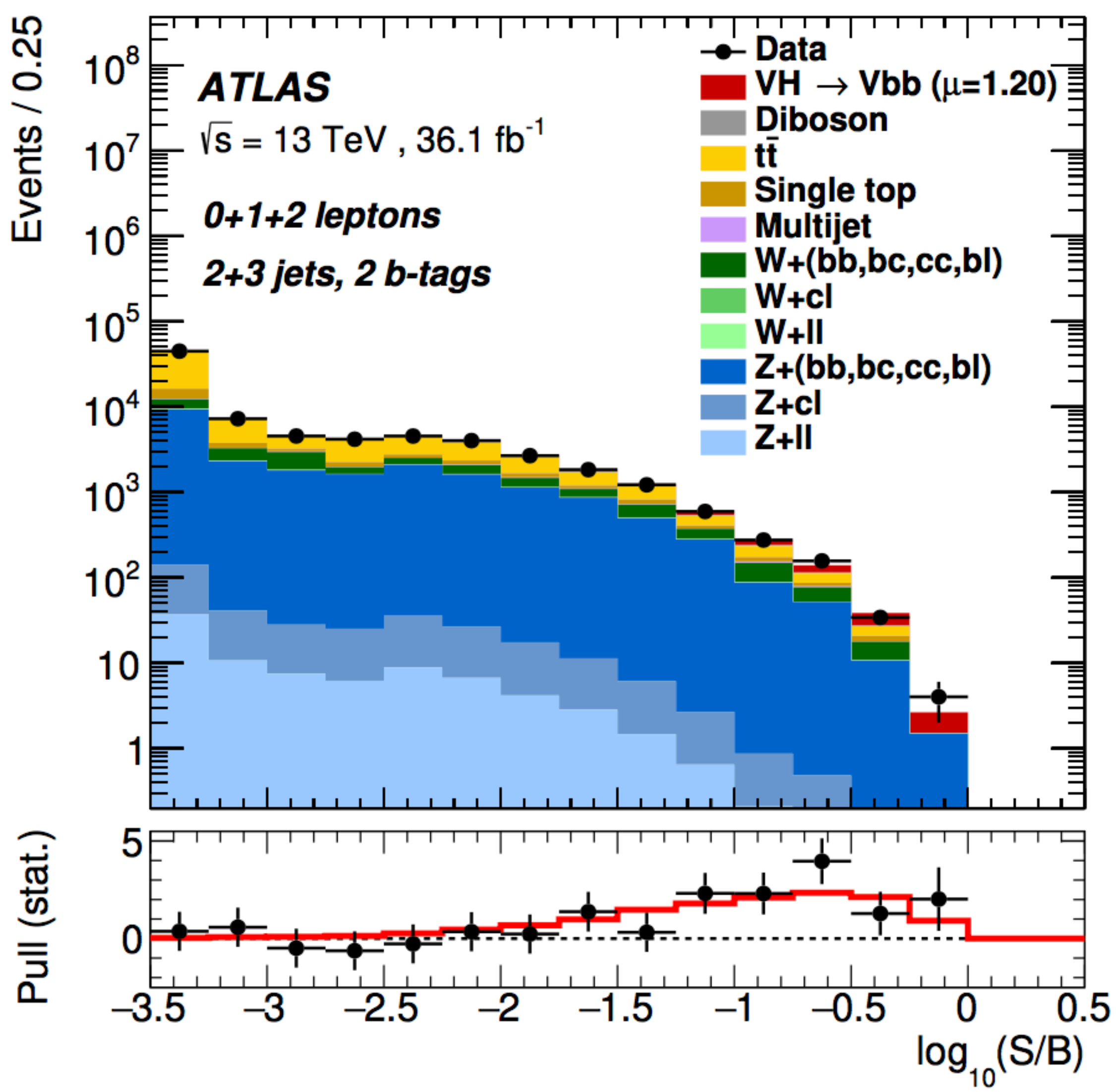
JHEP12(2017)024
$36.1 fb^{-1}$ @ 13TeV

3 main channels: V(→leptons: **ll**, **lv**, **vv**)+H(**bb**)

Standard selection cuts:

- 2 central jets (|η|<2.5) p_T > 20GeV
  reconstruct H(bb) candidate
- nJet ≤ 3 for Z(vv)H and W(lv)H channels
- p_T^V > 150GeV [+75-150GeV for Z(ll)H]
- multivariate approach BDT

Sensitive region relatively boosted: O(150-250)GeV



Systematic > Statistical

Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
E_T^{miss}		0.03
Leptons		0.01
b-tagging	b-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalisations		0.07
Z + jets		0.07
W + jets		0.07
$t\bar{t}$		0.07
Single top quark		0.08
Diboson		0.02
Multijet		0.02
MC statistical		0.13

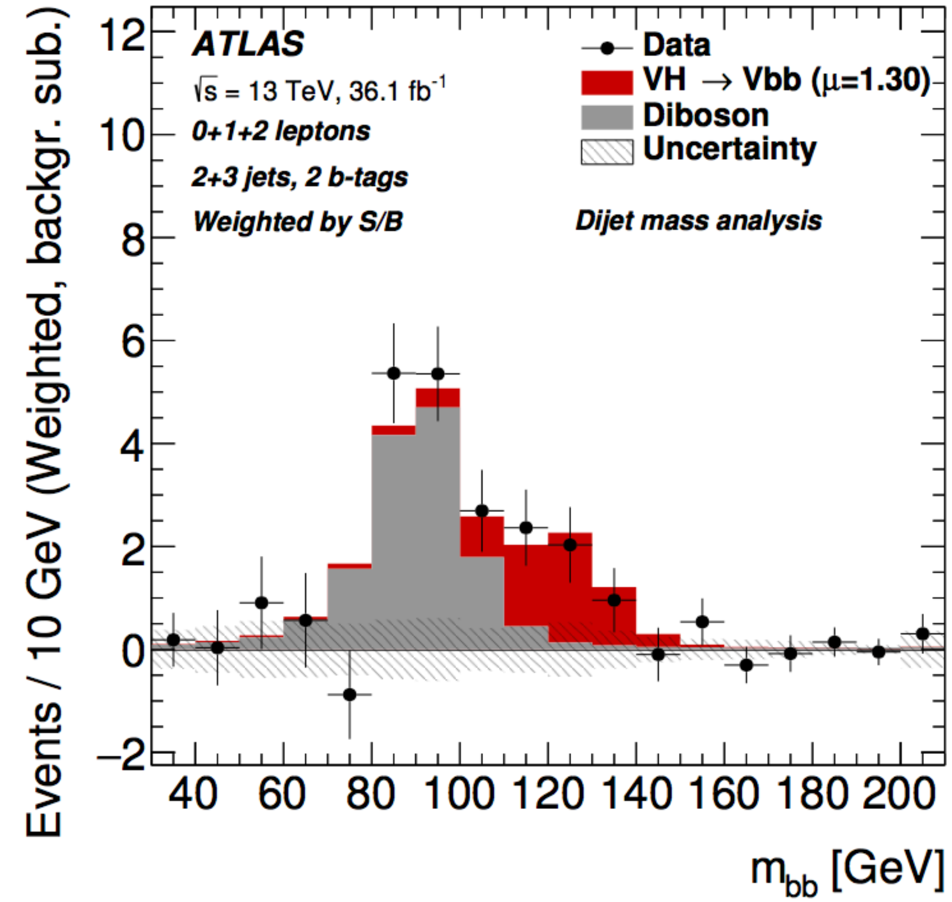
VH(H→bb)

JHEP12(2017)024
$36.1fb^{-1}$ @ 13TeV

Analysis cross-check: measurement of
SM diboson semileptonic VZ(bb)

__VZ__(bb) observed with at 5.8σ sensitivity

$\mu_{VZ} = \mathbf{1.11}\ ^{+0.12}_{-0.11}(stat.)\ ^{+0.22}_{-0.19}(syst.)$



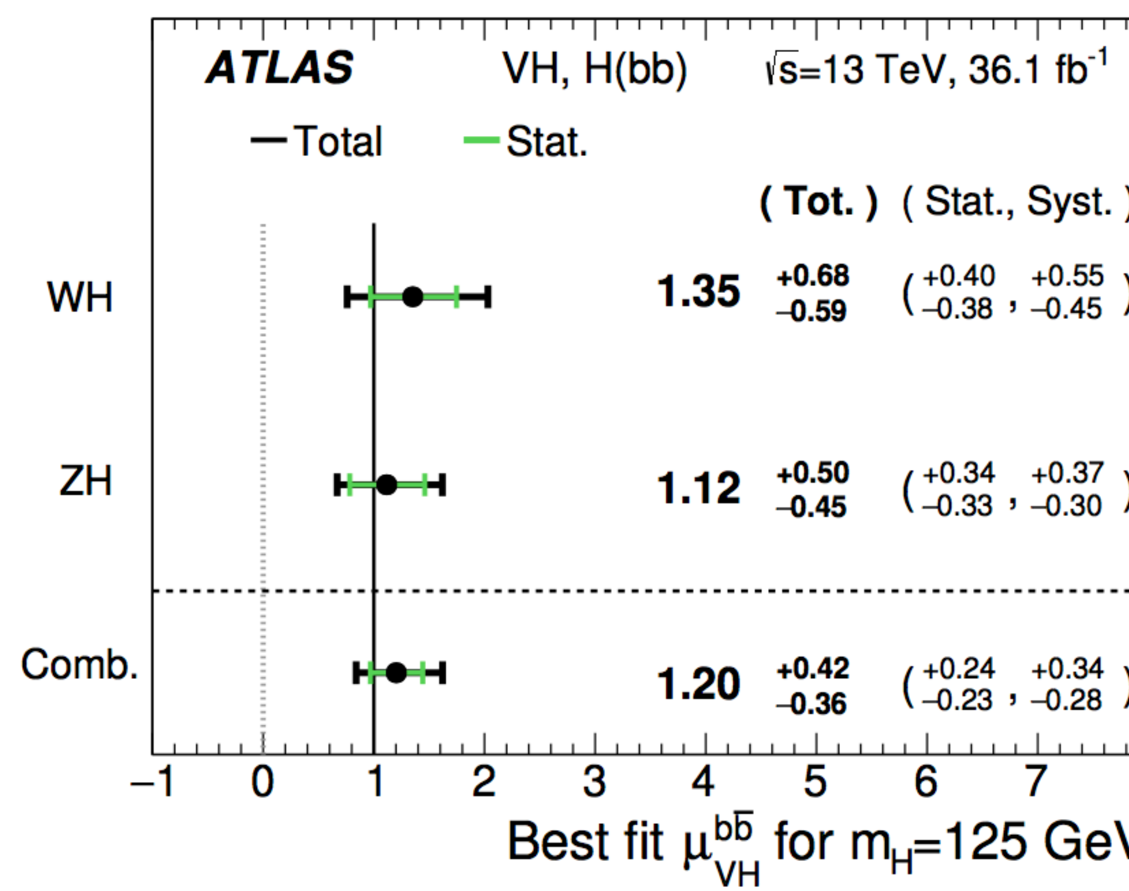
Combining 3 VH(bb) lepton-channels:

VH(bb) signal strength at 13TeV

$\mu_{VH} = \mathbf{1.20}\ ^{+0.24}_{-0.23}(stat.)\ ^{+0.34}_{-0.28}(syst.)$

significance	13TeV	7+8+13TeV
expected	3.0	4.0
observed	**3.5**	**3.6**

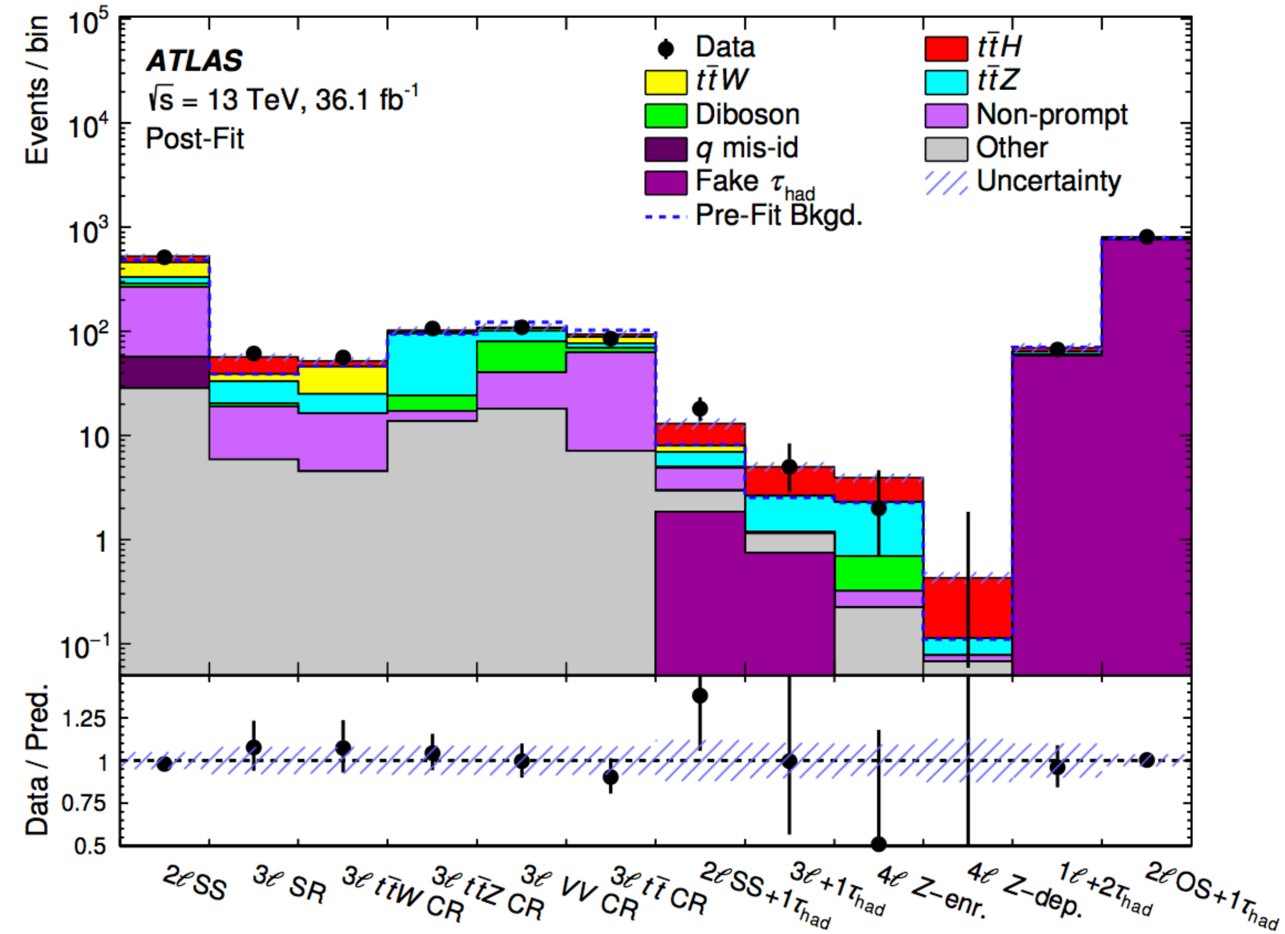
Evidence of VH(bb) above 3σ sensitivity!

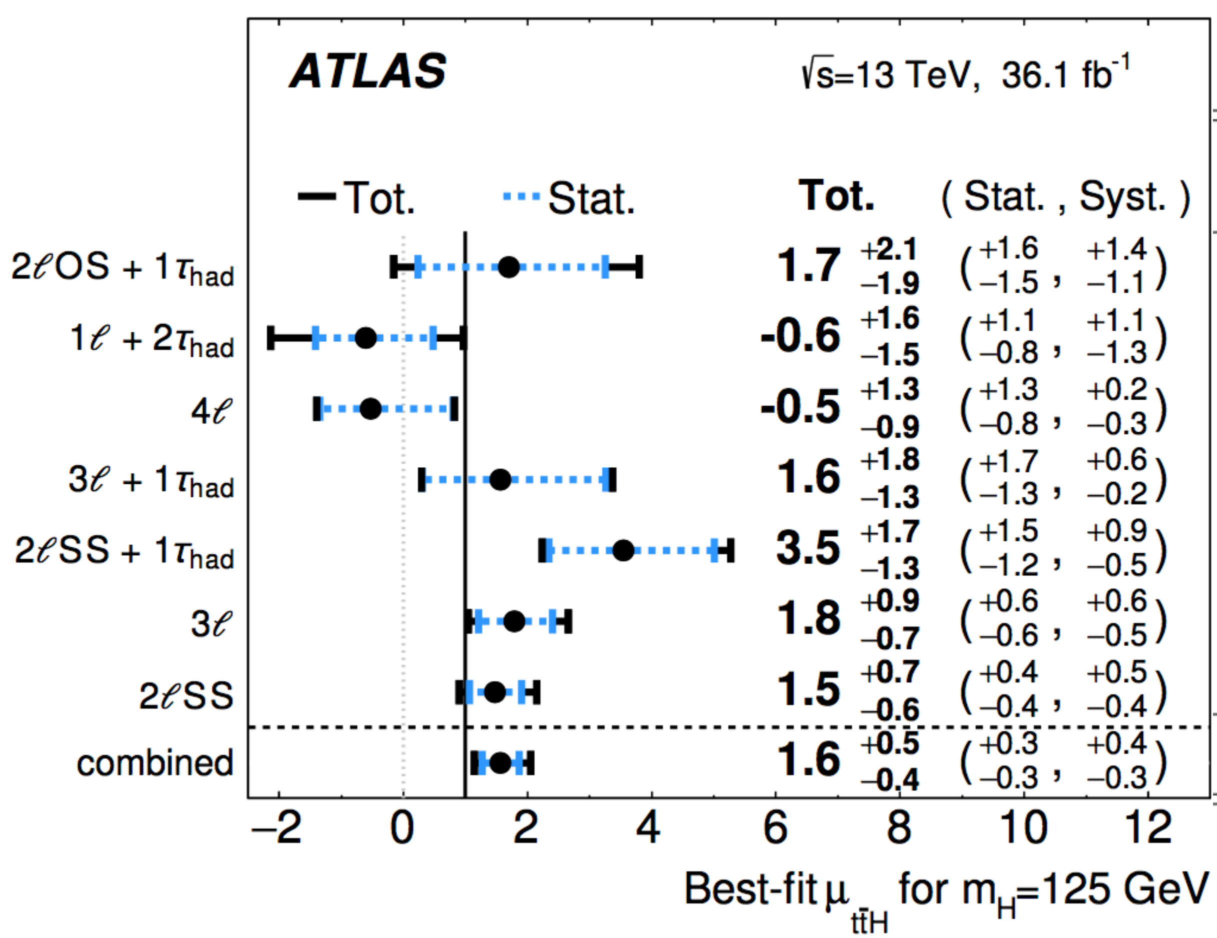


ttH(multilepton)

arxiv 1712.08891
36.1fb^{-1} @ 13TeV

- Sensitive to direct coupling of H to top quarks, targeting **H → WW, H → ττ,** and **H → ZZ** by defining specific categories
- multivariate discriminant (MVA) in signal-enriched regions
- most sensitive regions: 3lepton, 2lepton-SS mainly populated by H → WW decays
- main systematic uncertainties from fake-lepton estimate, jet energy scale/resolution (and signal theory on $\mu_{ttH(ML)}$)





Significance	
Observed	Expected
0.9σ	0.5σ
–	0.6σ
–	0.8σ
1.3σ	0.9σ
3.4σ	1.1σ
2.7σ	1.9σ
2.4σ	1.5σ
4.1σ	2.8σ

Combination of 7 signal regions:

ttH(ML) evidence at 4.1σ observed (2.8σ expected)

$\mu_{ttH(ML)} = 1.6\ ^{+0.3}_{-0.3}(\text{stat.})\ ^{+0.4}_{-0.3}(\text{syst.})$

ttH(bb)

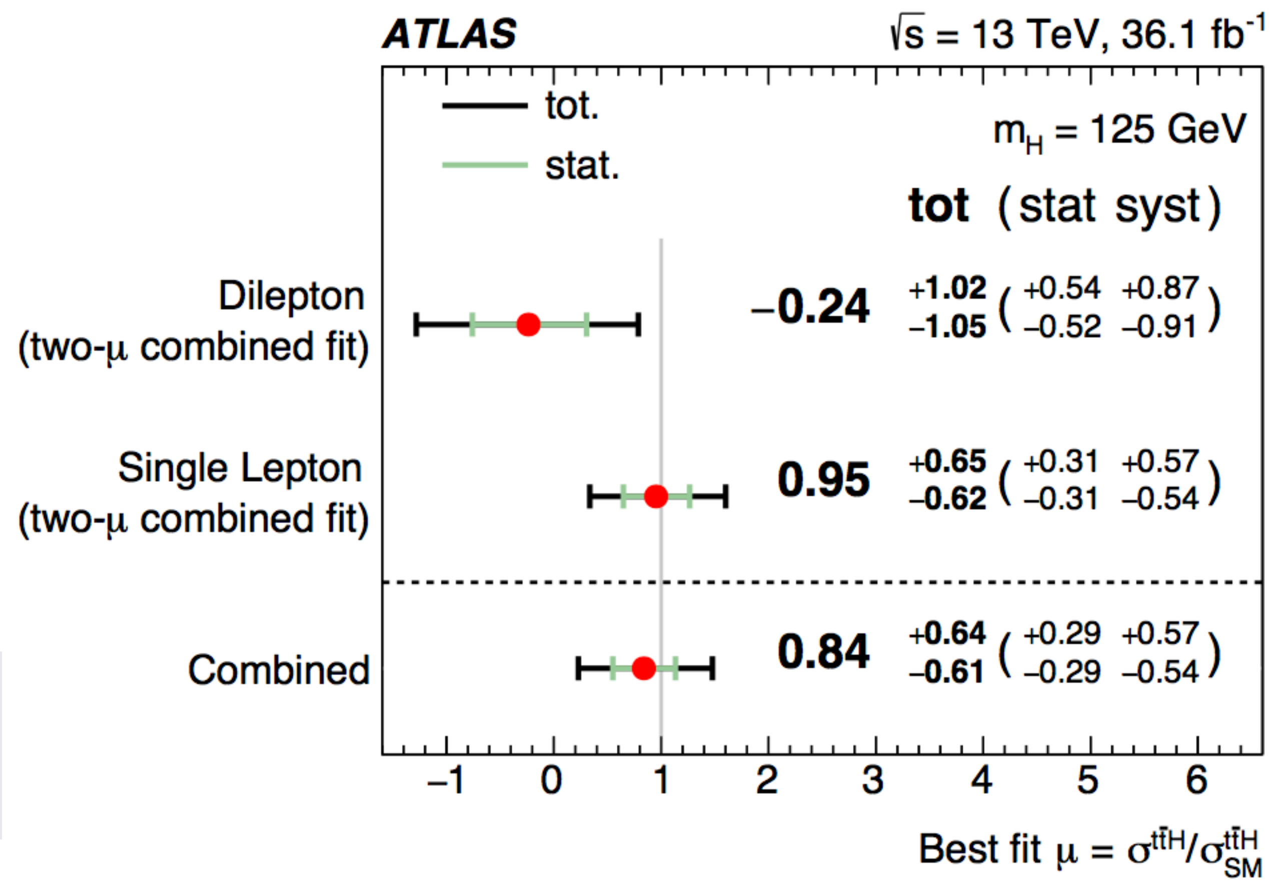
[arxiv 1712.08895](https://arxiv.org/abs/1712.08895)
$36.1 fb^{-1}$ @ 13TeV

- Sensitive to direct coupling of H to top quarks, exploit the **large BR(H→bb)** in combination with **semi-** and **di-leptonic** ttbar channels

- events categorised in signal-enriched and depleted regions based on #jets and #b-tagged jets
- multivariate discriminant (MVA) in signal-enriched regions

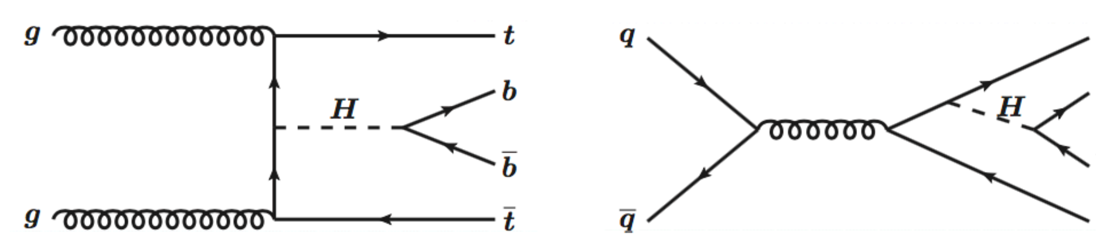
ttH(bb) at 1.4σ observed (1.6σ expected)

$\mu_{ttH(bb)} = 0.84\ ^{+0.29}_{-0.29}(\text{stat.})\ ^{+0.57}_{-0.54}(\text{syst.})$

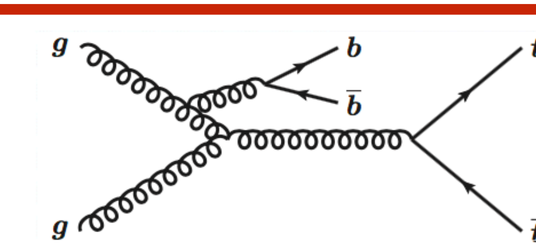


Modeling of **tt+hf** background limiting factor

Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61



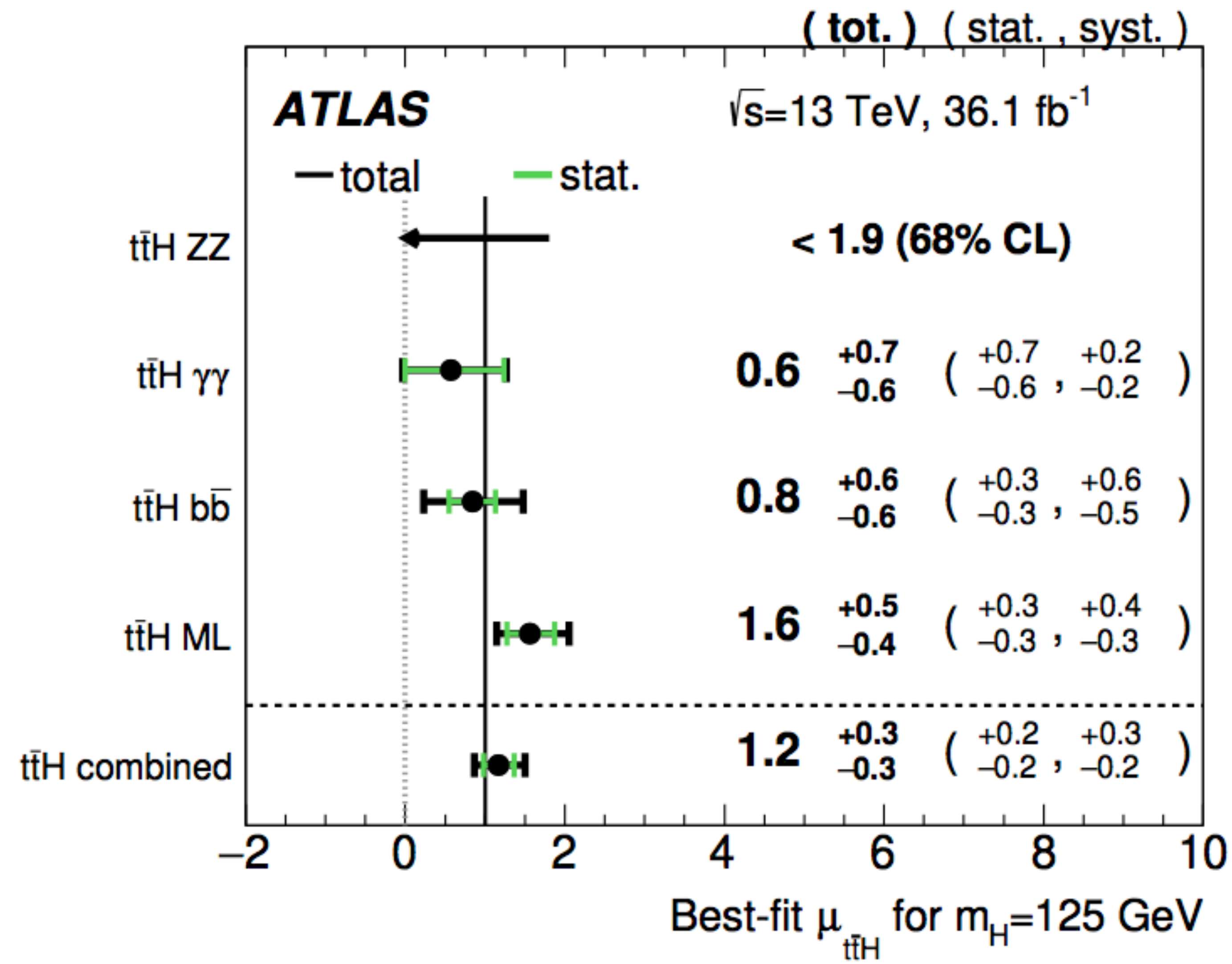
(a) (b)



ttH(ATLAS combination)

arxiv 1712.08891
$36.1fb^{-1}$ @ 13TeV

- ttH(ML)
- ttH(bb)
- ttH(γγ)
- ttH(ZZ)



While ttH(ML) and ttH(bb) have dedicated analyses, the remaining channels come from sub-categories of the main H→γγ and H→ZZ analyses

Evidence of ttH production at 4.2σ observed sensitivity!

Channel	Best-fit μ Observed	Best-fit μ Expected	Significance Observed	Significance Expected
Multilepton	$1.6^{+0.5}_{-0.4}$	$1.0^{+0.4}_{-0.4}$	4.1σ	2.8σ
$H \to b\bar{b}$	$0.8^{+0.6}_{-0.6}$	$1.0^{+0.6}_{-0.6}$	1.4σ	1.6σ
$H \to \gamma\gamma$	$0.6^{+0.7}_{-0.6}$	$1.0^{+0.8}_{-0.6}$	0.9σ	1.7σ
$H \to 4\ell$	< 1.9	$1.0^{+3.2}_{-1.0}$	—	0.6σ
Combined	$1.2^{+0.3}_{-0.3}$	$1.0^{+0.3}_{-0.3}$	4.2σ	3.8σ

Conclusions

Campaign of Higgs measurements ongoing in ATLAS with LHC Run-2 dataset:

results with first 36.1fb^{-1} presented today

- stat. limited measurements will continue to improve throughout Run-2, moving towards a systematics limited regime: understanding of uncertainty sources is critical
- full Run-2: possibility of precision measurements for fermionic channels: towards differential results!
- already recorded 44fb^{-1} more at 13TeV - looking forward to analyzing the new data!

Thanks for your attention!

BACK-UP

(All ATLAS Higgs results are available here)

The Large Hadron Collider (LHC)

Circolar 27 km proton-proton collider, located at **CERN**, on the Franco-Swiss border.

Designed to achieve high centre of mass energy and high luminosity:

- design:

  $\sqrt{s_{pp}}$ = 14 TeV

  L = 1e34 $cm^{-2}s^{-1}$ = 0.01 $pb^{-1}s^{-1}$

  Compared to σ(pp→VH→leptons,bb) = 0.25 pb (m_H = 125 GeV) - O(200) evts/day

- Run-1 (2011-2012) data-taking:

  $\sqrt{s_{pp}}$ = 7-8 TeV
  L_{peak} = 0.35-0.77e34 $cm^{-2}s^{-1}$

→

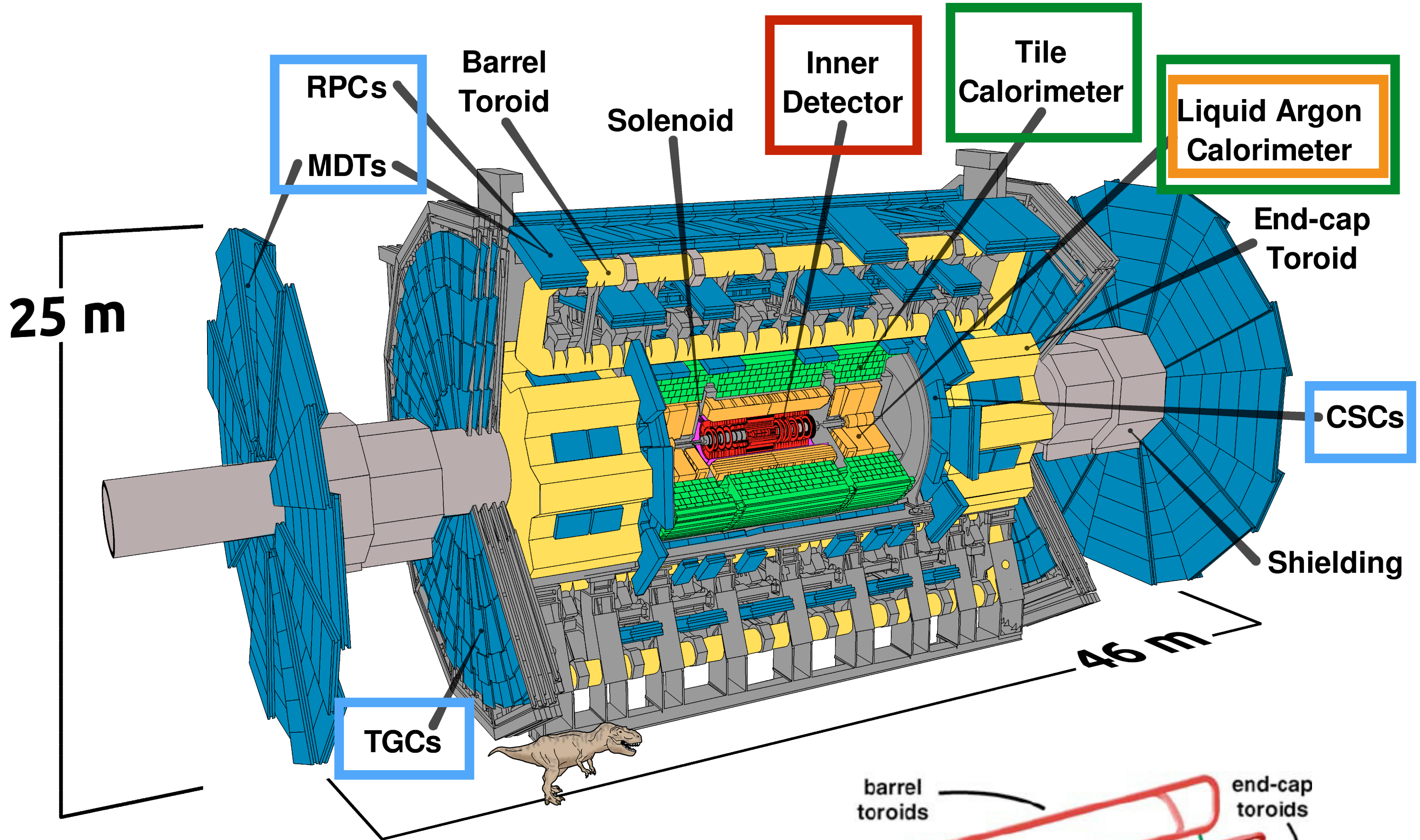
- Run-2 (2015-2016) data-taking:

  $\sqrt{s_{pp}}$ = 13 TeV
  L_{peak} = 1.37e34 $cm^{-2}s^{-1}$

Two main multi-purpose experiments (ATLAS, CMS) designed for precise tests of SM physics, and the search and study of the Higgs boson - along with five experiments targeting specific physics (LHCb, ALICE, LHCf, MoEDAL, TOTEM)

The ATLAS experiment

General-purpose, ~4π detector for multi-TeV *pp* collisions



ID: charged particle tracks, decay vertexes

- |eta| < 2.5
- $\sigma_{p_T}/p_T \sim 0.05\% p_T \oplus 1\%$

ECAL: e/ɣ energy/direction, hadron rejection

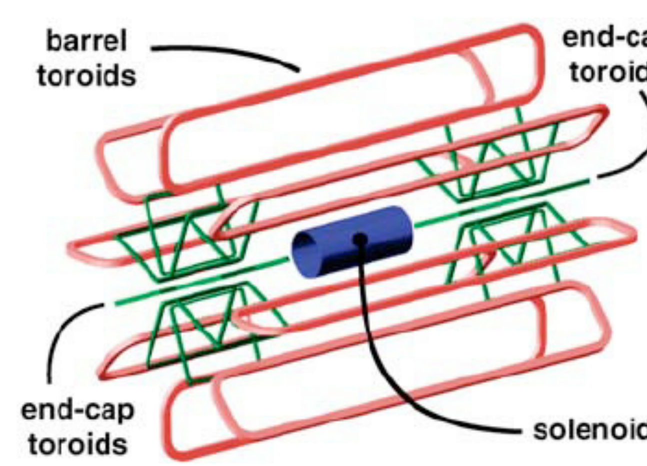
- |η| < 3.2
- $\sigma_E/E \sim 0.05\%\sqrt{E} \oplus 0.7\%$ *(barrel)*

HCAL: hadron(jet) energy/direction

- |η| < 4.9
- $\sigma_E/E \sim 50\%\sqrt{E} \oplus 3\%$ *(barrel)*

MS: muon tracks

- |η| < 2.7
- $\sigma_p/p < 10\%$ up to 1 TeV



Magnetic system: solenoid for the ID (2T), three toroidal magnets for the MS (0.5-1T)

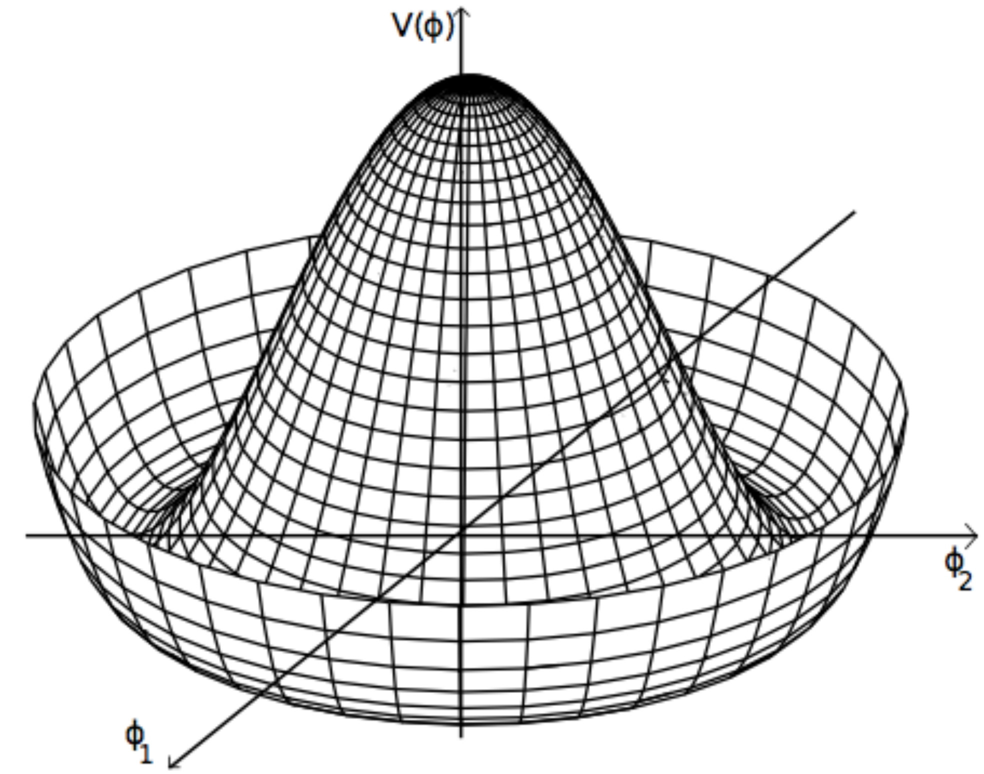
The SM scalar sector: Higgs boson

Brute-force mass terms for fermions and bosons in the SM Lagrangian:

- bosons: $m^2 B_\mu B^\mu$
- fermions: $m(\bar{\phi}_L \phi_R + \bar{\phi}_R \phi_L)$

Gauge invariance of the theory is spoiled:

→ *non-renormalizable theory*
→ *unitarity violation at high-energy scales*



Mass-terms appear in a gauge-invariant way in the Lagrangian when introducing a scalar sector

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi_1 + i\phi_2 \end{pmatrix}$$

Scalar-field potential

complex doublet of scalar fields

$$V(\Phi) \to V(v) = \frac{1}{2}\mu^2|v|^2 + \frac{1}{4}\lambda v^4$$

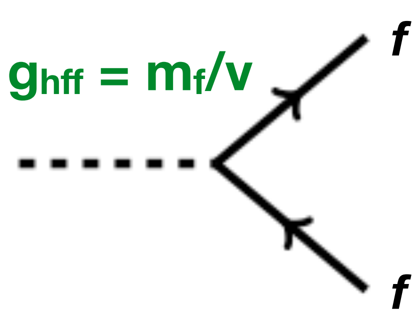
Spontaneous Symmetry Breaking (SSB)

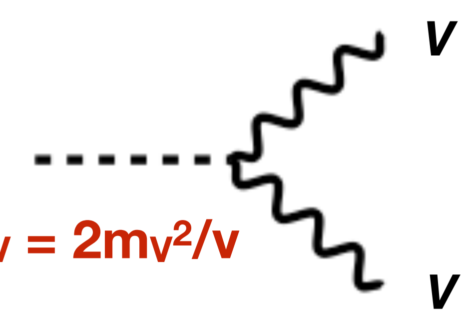
$$L_\Phi + L_{gauge} = \Big(\frac{1}{2}(\partial_\mu\sigma)(\partial^\mu\sigma) + \mu^2\sigma^2 - \lambda v\sigma^3 - \frac{\lambda}{4}\sigma^4 + \\ +(\frac{gv}{2})^2 W^+_\mu W^\mu_- + \frac{1}{2}(\frac{g^2+g'^2}{4})v^2 Z_\mu Z^\mu + \\ + \frac{1}{2}g^2 v W^+_\mu W^\mu_- \sigma + \frac{g^2 v}{2}\frac{1}{2\cos(\theta_W)^2} + Z_\mu Z^\mu \sigma + \\ + \frac{g^2}{4}W^+_\mu W^\mu_- \sigma^2 + \frac{g^2}{4}\frac{1}{2\cos(\theta_W)}Z_\mu Z^\mu \sigma^2 \Big)$$

$$L_{Yukawa} = -Y_u(\bar{Q}_L\tilde{\Phi}u_R + \bar{u}_R\tilde{\Phi}^\dagger Q_L) - Y_d(\bar{Q}_L\Phi d_R + \bar{d}_R\Phi^\dagger Q_L)$$

- *H coupling to gauge boson defined by SSB*
- *H Yukawa coupling to fermions free parameters*

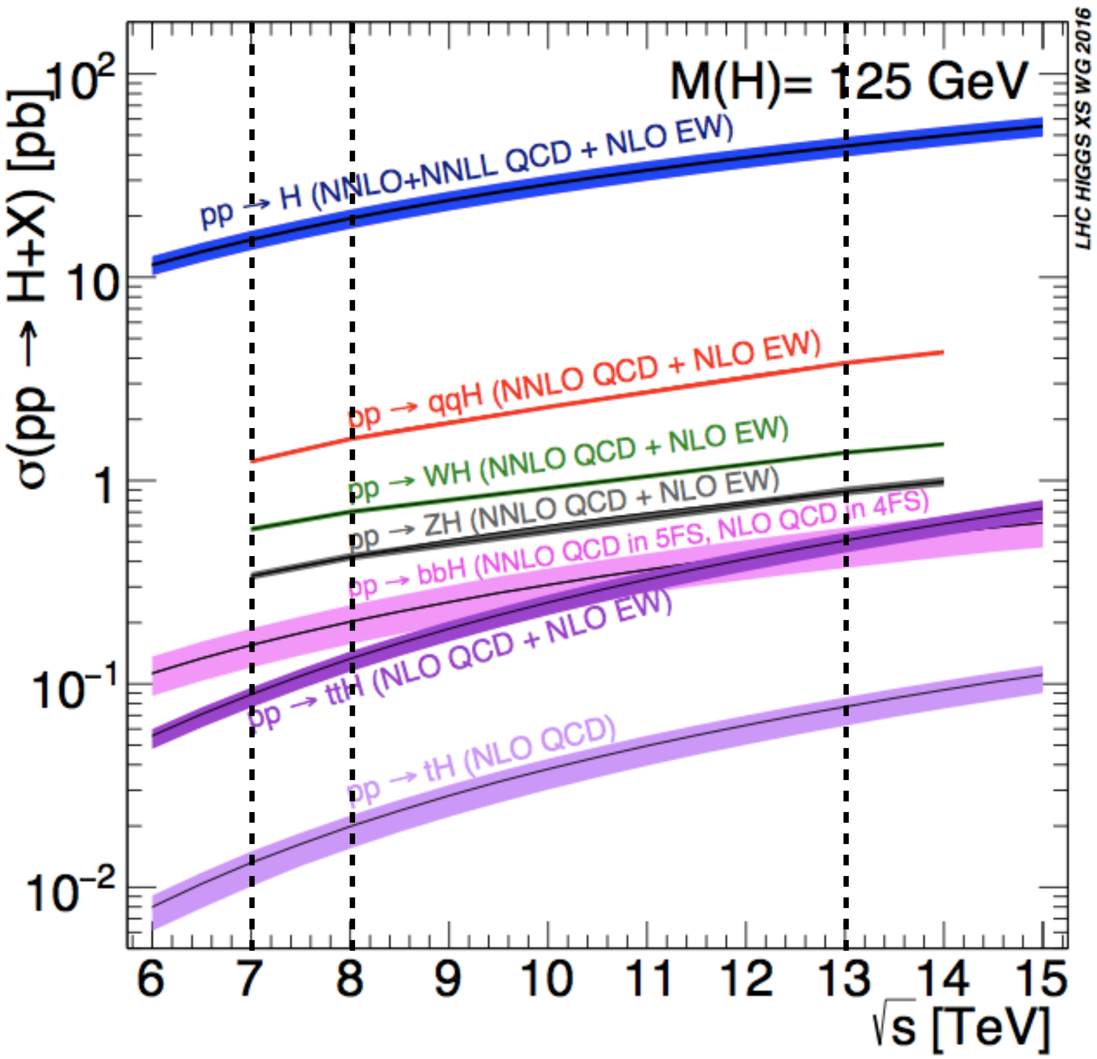
$g_{hff} = m_f/v$

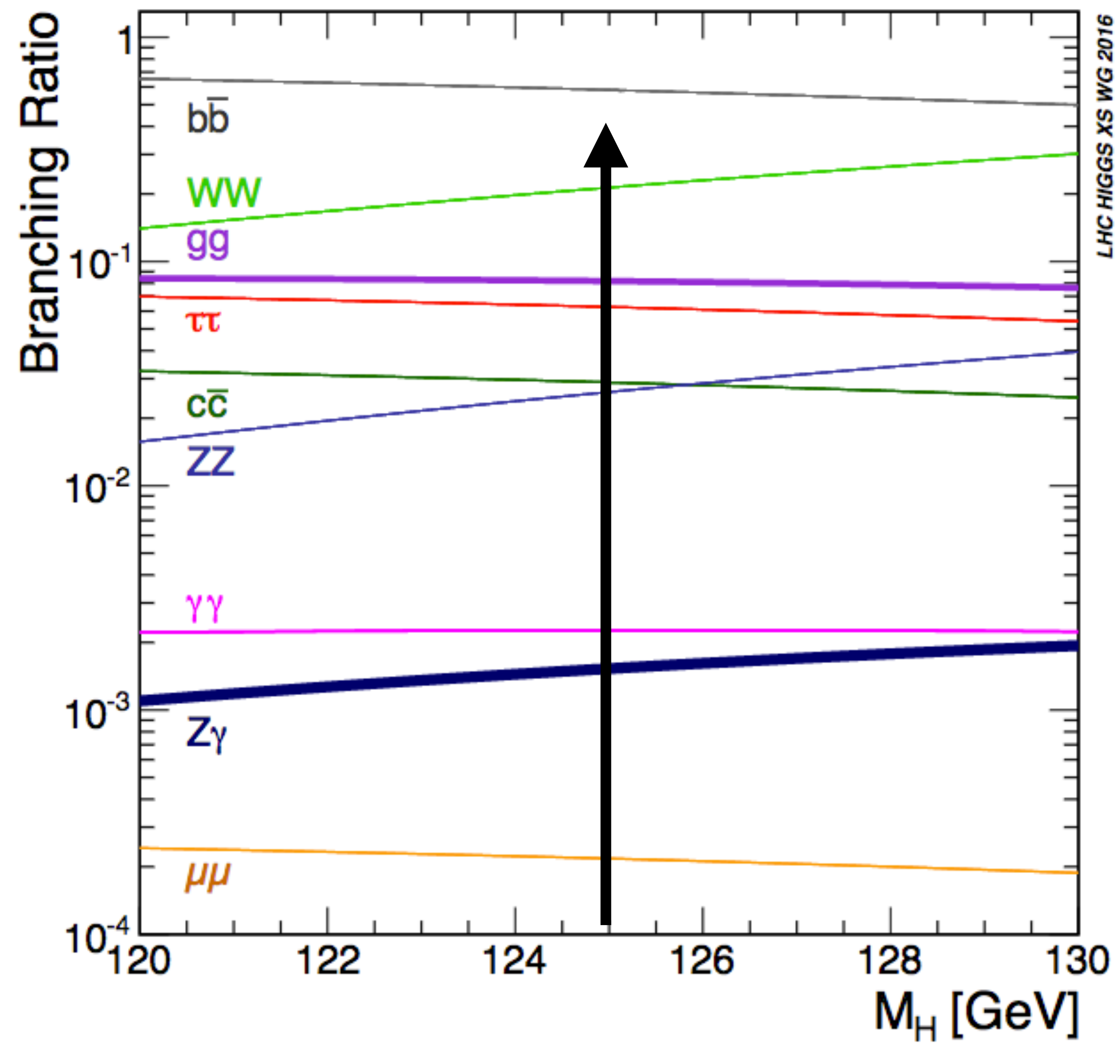


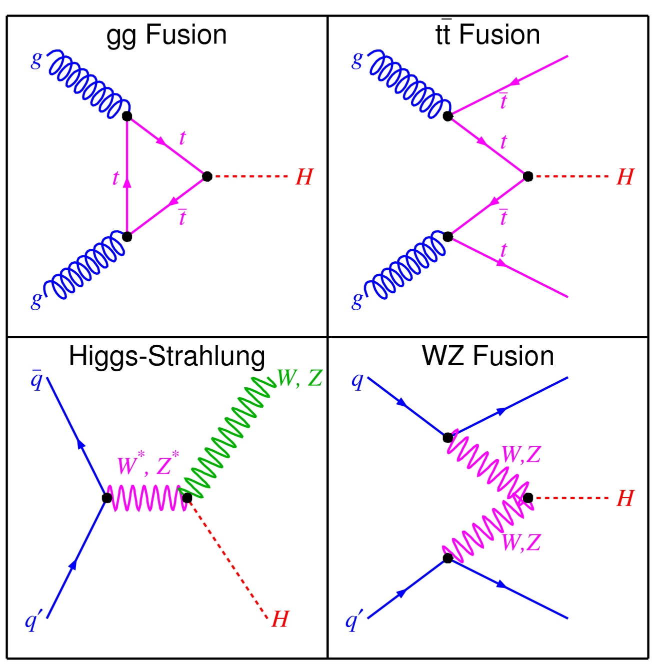


$g_{hVV} = 2m_V^2/v$

Higgs boson physics at the LHC

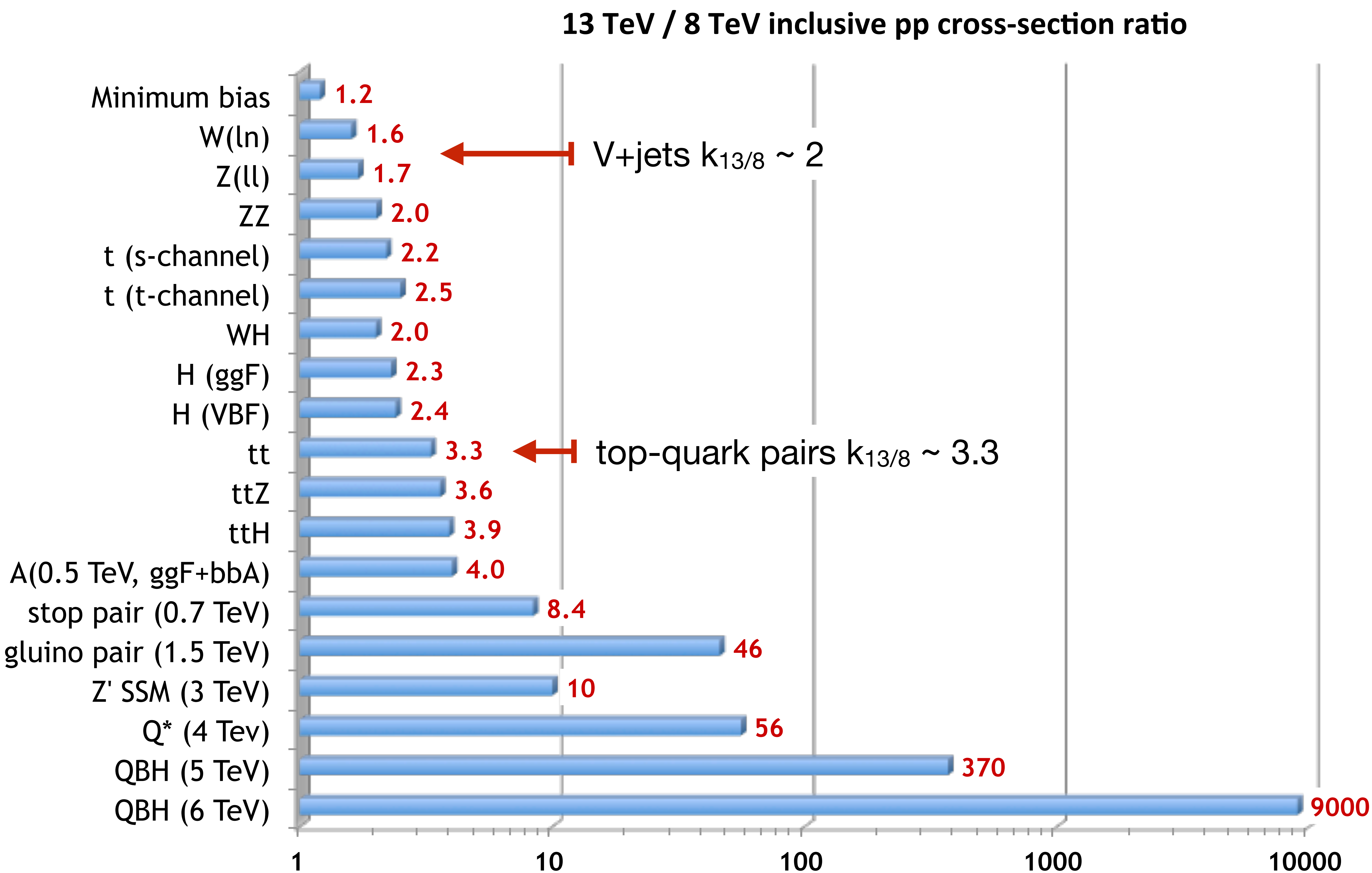






- Main production mechanism at the LHC through gluon-fusion (~via top-quark loop)
- VBF, WH, ZH, bbH and ttH are sub-dominant but can provide interesting experimental signatures

Cross-sections from 8TeV to 13TeV



Simplified Template XS measurements

STXS framework as natural evolution of signal strength measurements:

***maximize** experimental sensitivity while **minimizing** theory dependence folded into the measurement*

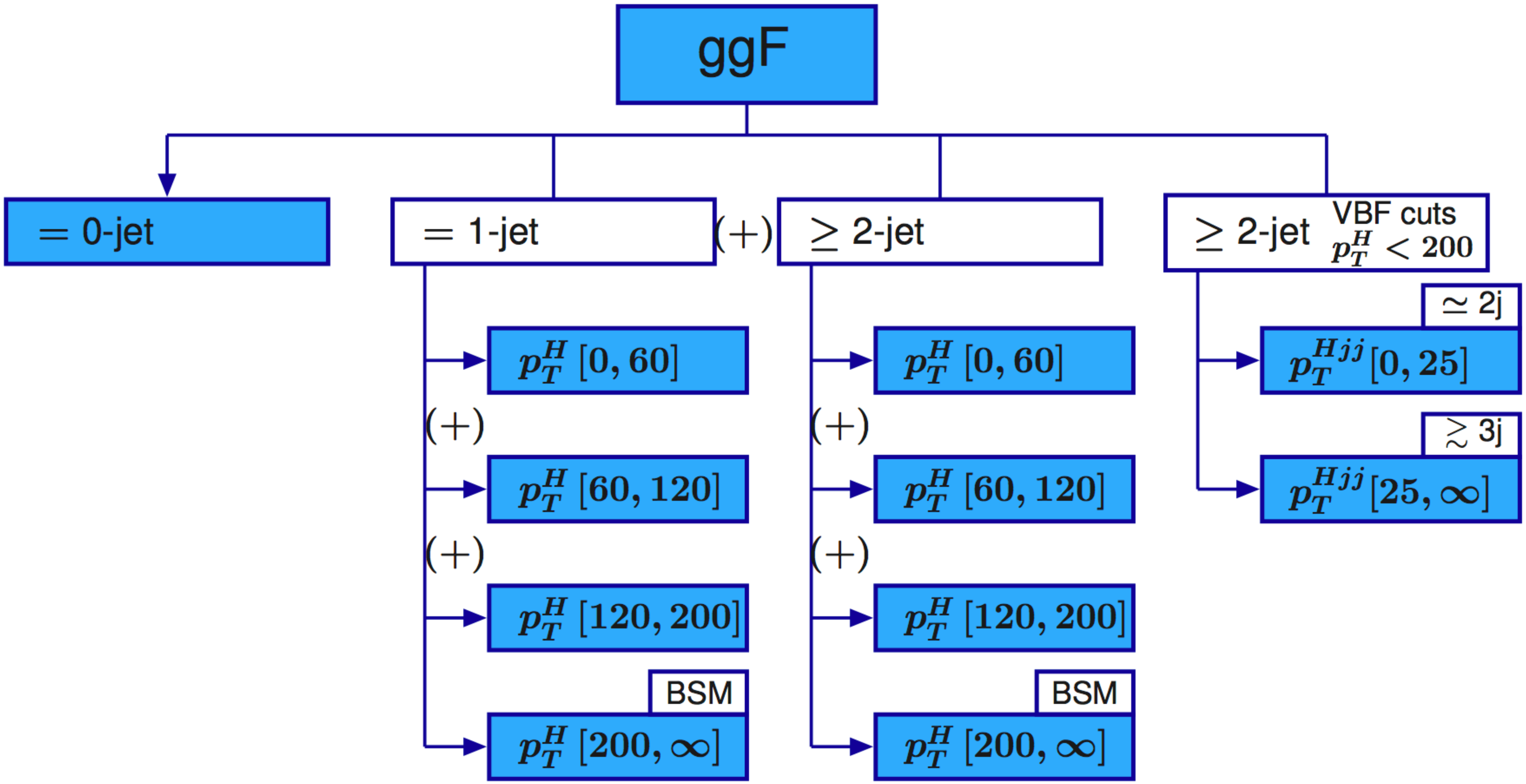
→ *theoretical uncertainties on SM prediction*
underlying theory model (SM or BSM)

- measure **prod. mode cross-sections** in **exclusive regions** (simplified templates), rather than signal strengths
- inclusive in H decay: possibility to combine channels
- allowing for advance analysis techniques (MVA, ...)
- **complementary** to full-fledged fiducial and differential measurements

$$y_j = \sum_i A_{ji} \cdot r_i \cdot (\sigma_i \cdot \mathrm{B}_{4\ell})_{\mathrm{SM}} \cdot r_f \cdot \left(\frac{\mathrm{B}_f}{\mathrm{B}_{4\ell}}\right)_{\mathrm{SM}} \cdot \mathcal{L},$$

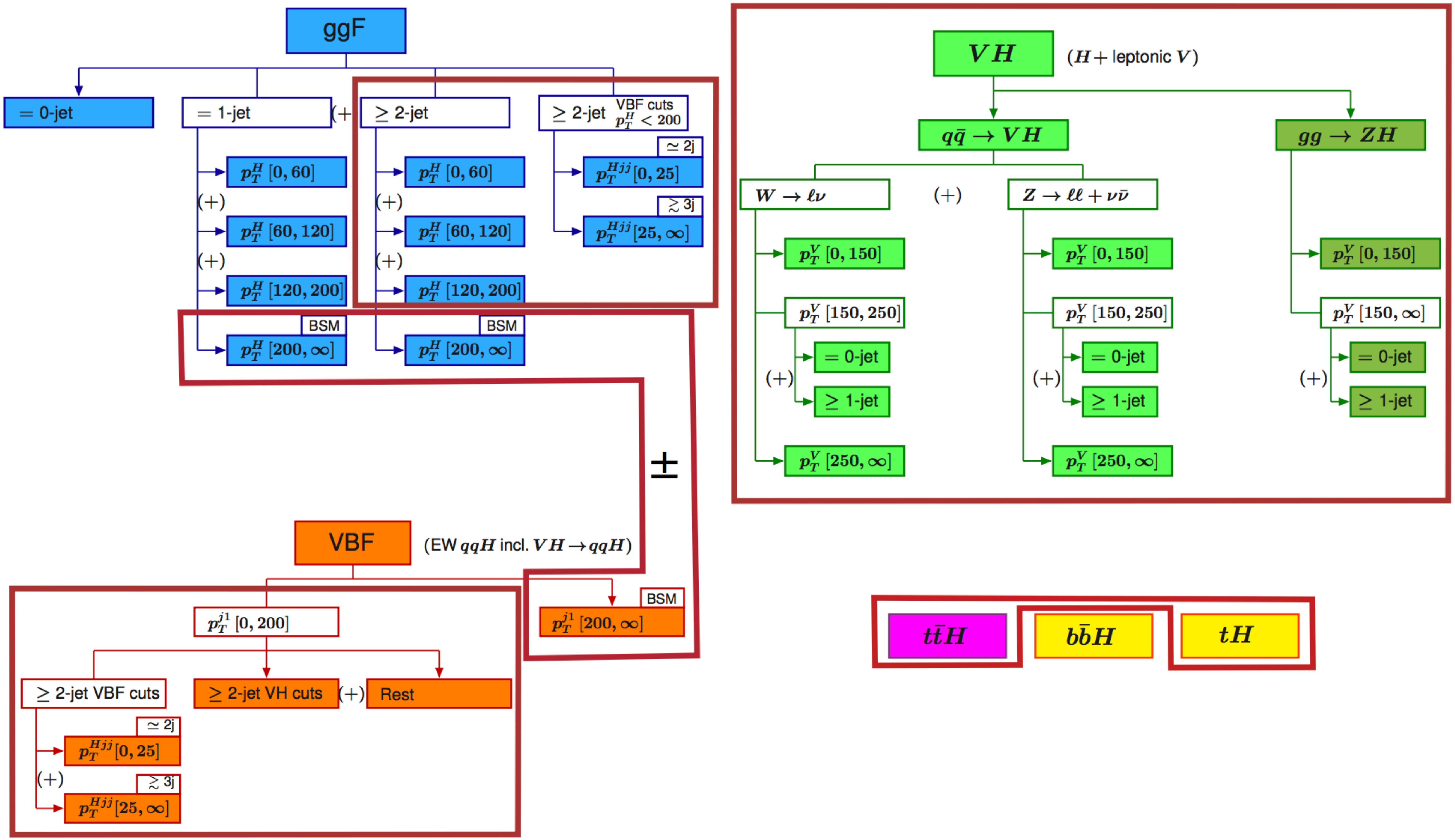
- σ_i = SM template cross-section in the region-i, B = SM branching-ratio
- r_i = multiplicative 'signal-strength-like' factor for the region-i
- A_{ij} = detector acceptance and response matrix between analyses categories and STXS regions

Simplified Template XS measurements



- avoid extrapolation with nontrivial or sizeable theoretical uncertainties
- avoid large variations of exp. acceptance within one bin
- sensitivity to BSM effects (e.g. high-p_T)
- mutually exclusive, and in minimum number

Simplified Template XS measurements

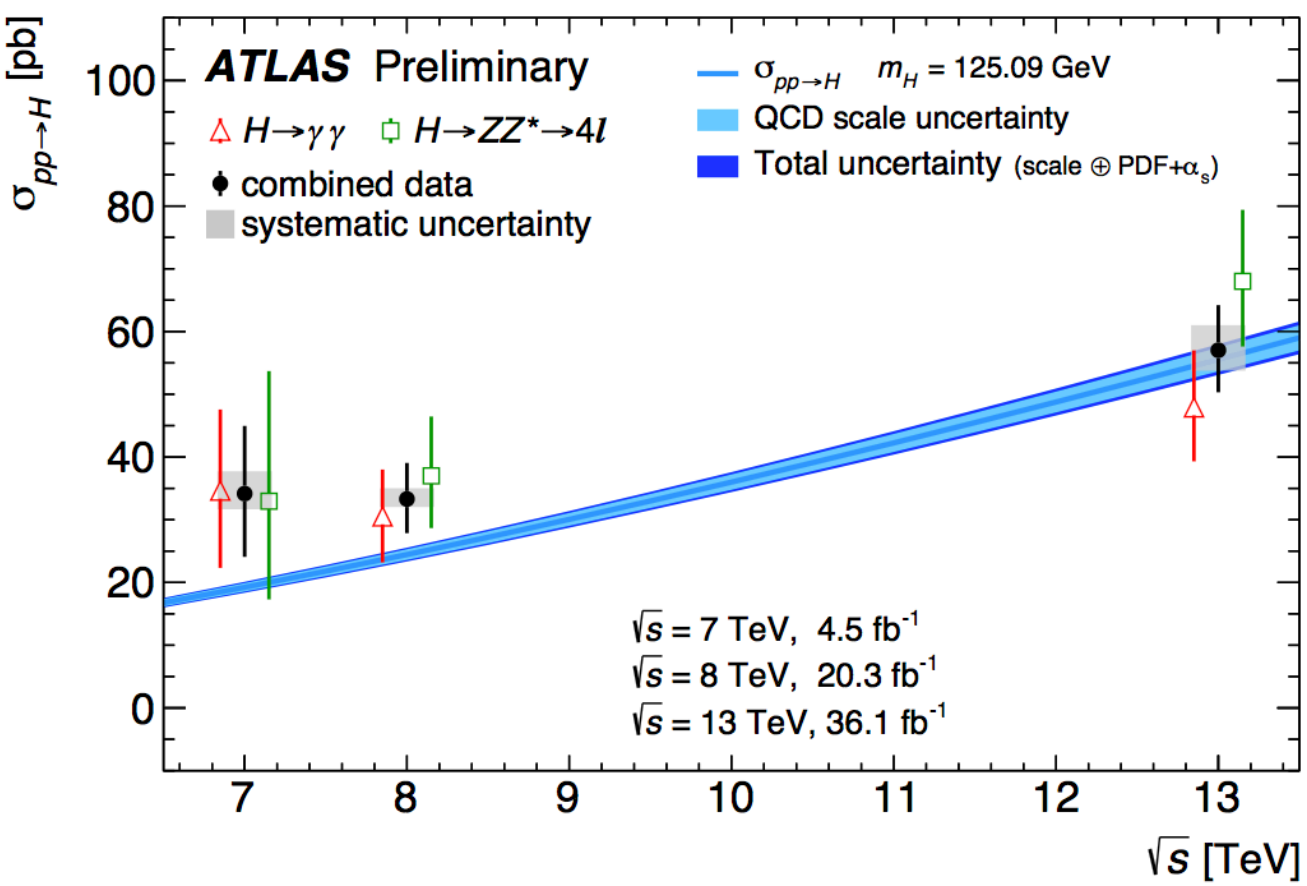


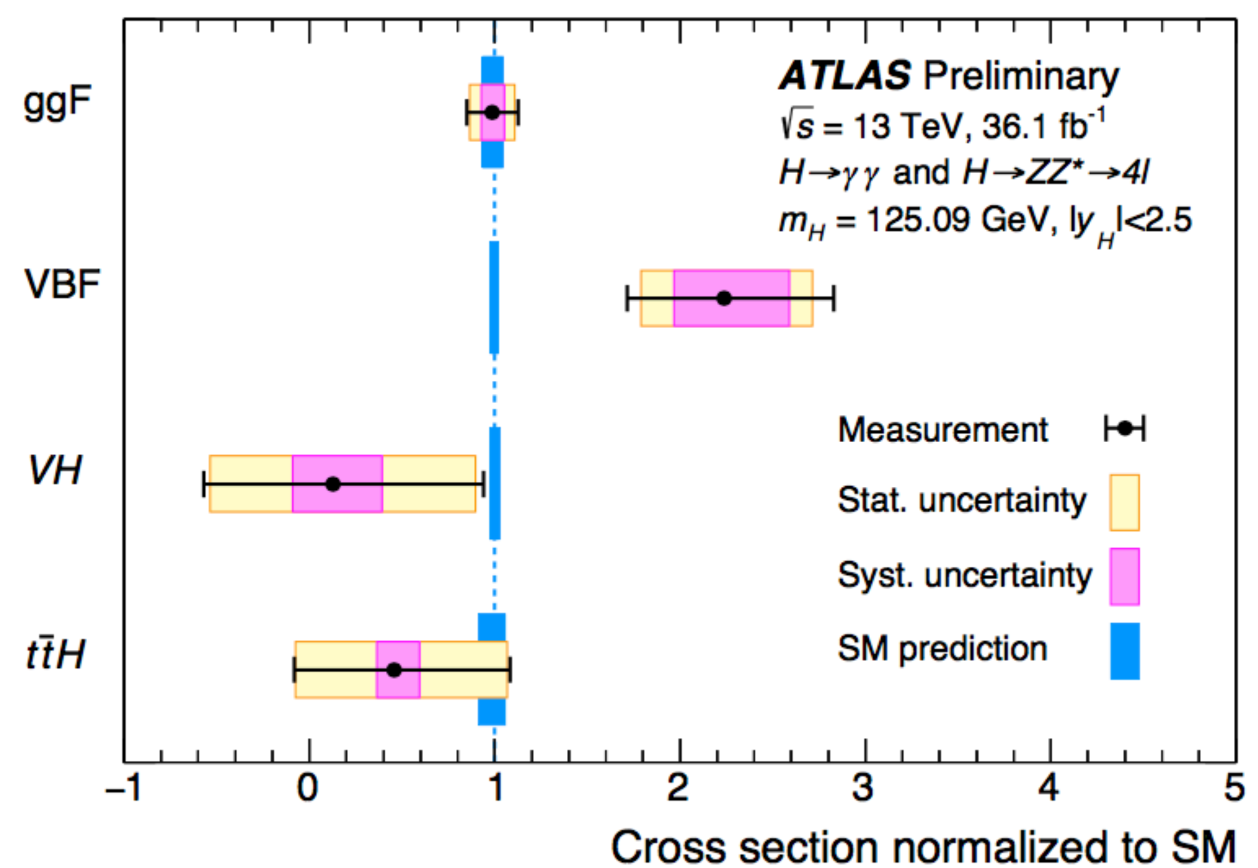
Higgs total cross-section combination

- Cross-section measurements @ 13TeV combined to
  $\sigma(pp \to H+X) = 57\ ^{+6.0}_{-5.9}(stat)^{+4.0}_{-3.3}(sys)$ pb
  $\sigma^{SM}(pp \to H+X) = 55.6\ ^{+2.4}_{-3.4}(stat)$

from combination of the ($H \to \gamma\gamma, ZZ^*$) production cross sections

- measurements @ 7,8TeV from inclusive signal strengths translated to total prod. XS
- direct combination of 13TeV Simplified Template Cross Section "stage-0" results





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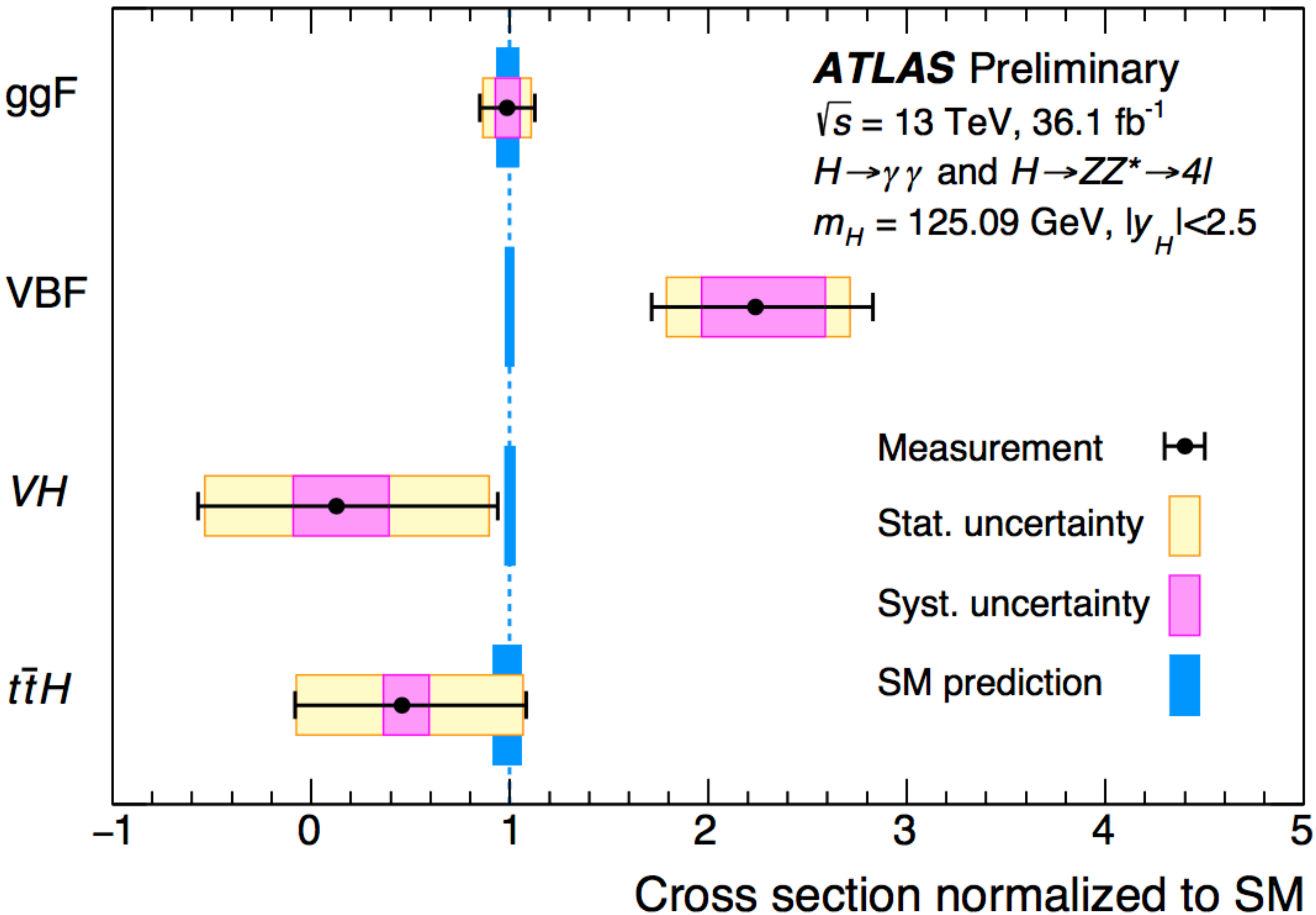
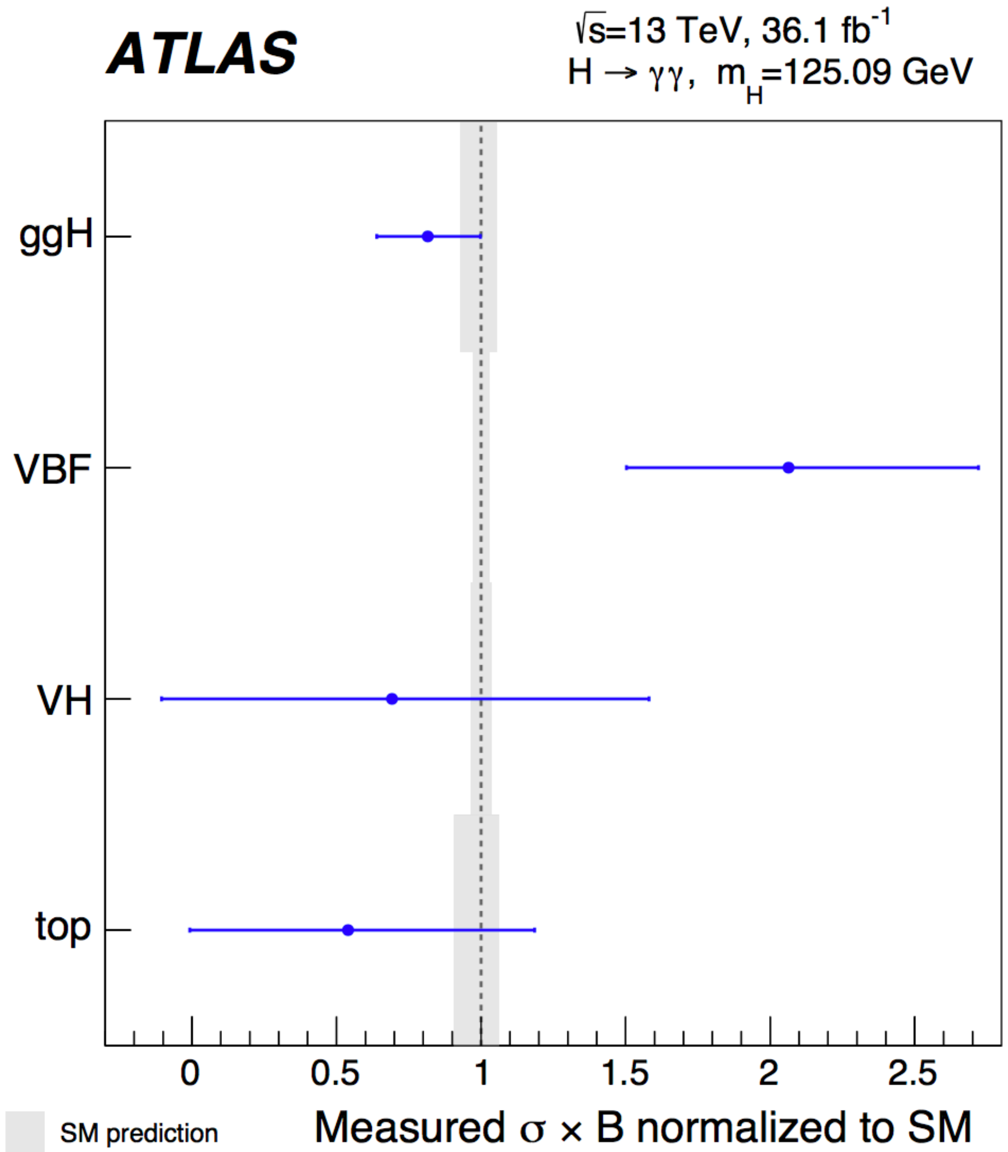
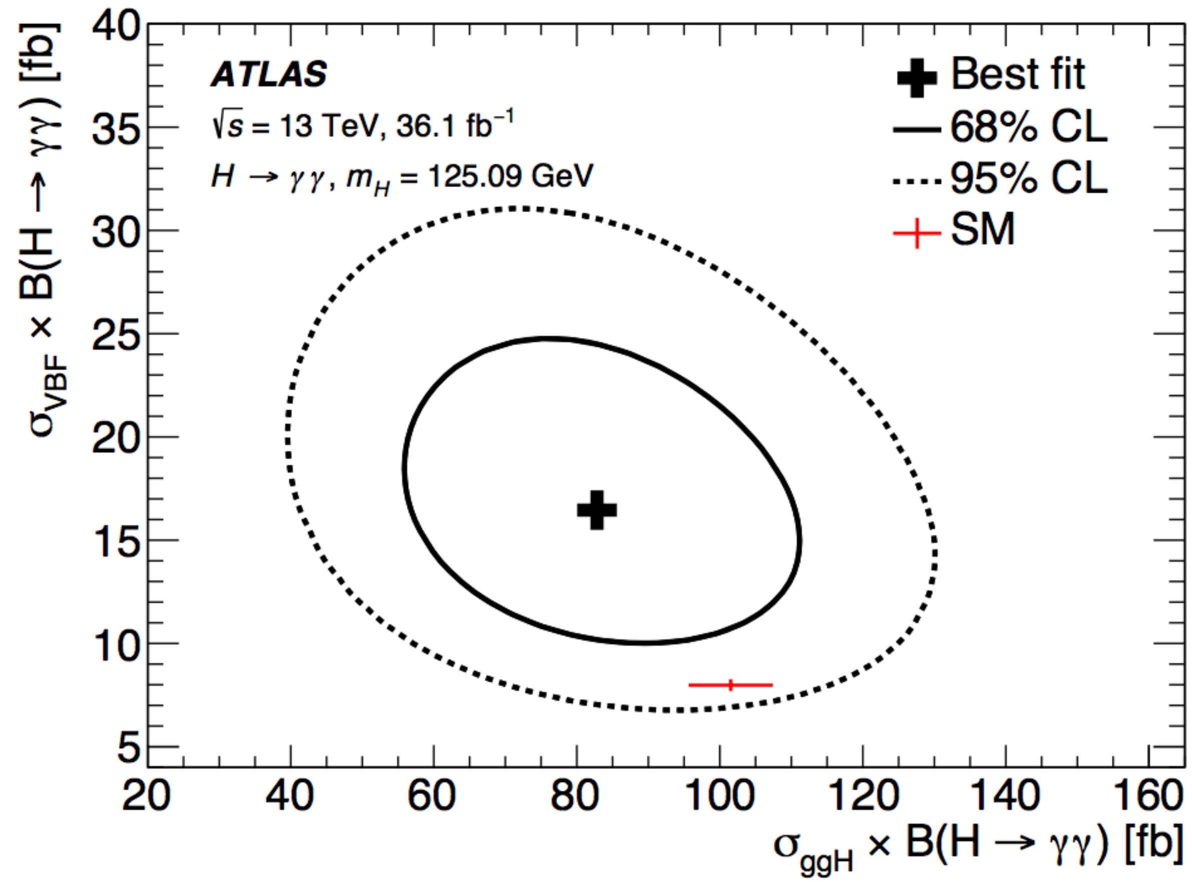


H→γγ production cross-section

Production mode cross-section in the rapidity region $|y_H|<2.5$, multiplied by BR(H→γγ)





Impact of possible deviations in the BR(H→γγ) removed by measuring ratios to ggH cross-section

Process ($\|y_H\| < 2.5$)	Result	Total	Stat.	Exp.	Theo.	SM prediction
		Uncertainty				
$\sigma_{VBF}/\sigma_{ggH}$	0.20	$^{+0.10}_{-0.07}$	$(^{+0.09}_{-0.06}$	$^{+0.04}_{-0.02}$	$^{+0.04}_{-0.02})$	$0.078^{+0.005}_{-0.006}$
σ_{VH}/σ_{ggH}	0.04	$^{+0.06}_{-0.05}$	$(^{+0.06}_{-0.04}$	$^{+0.01}_{-0.01}$	$^{+0.01}_{-0.01})$	$0.045^{+0.004}_{-0.005}$
$\sigma_{top}/\sigma_{ggH}$	0.009	$^{+0.010}_{-0.009}$	$(^{+0.010}_{-0.009}$	$^{+0.002}_{-0.001}$	$^{+0.002}_{-0.001})$	$0.012^{+0.001}_{-0.002}$

H→γγ uncertainties

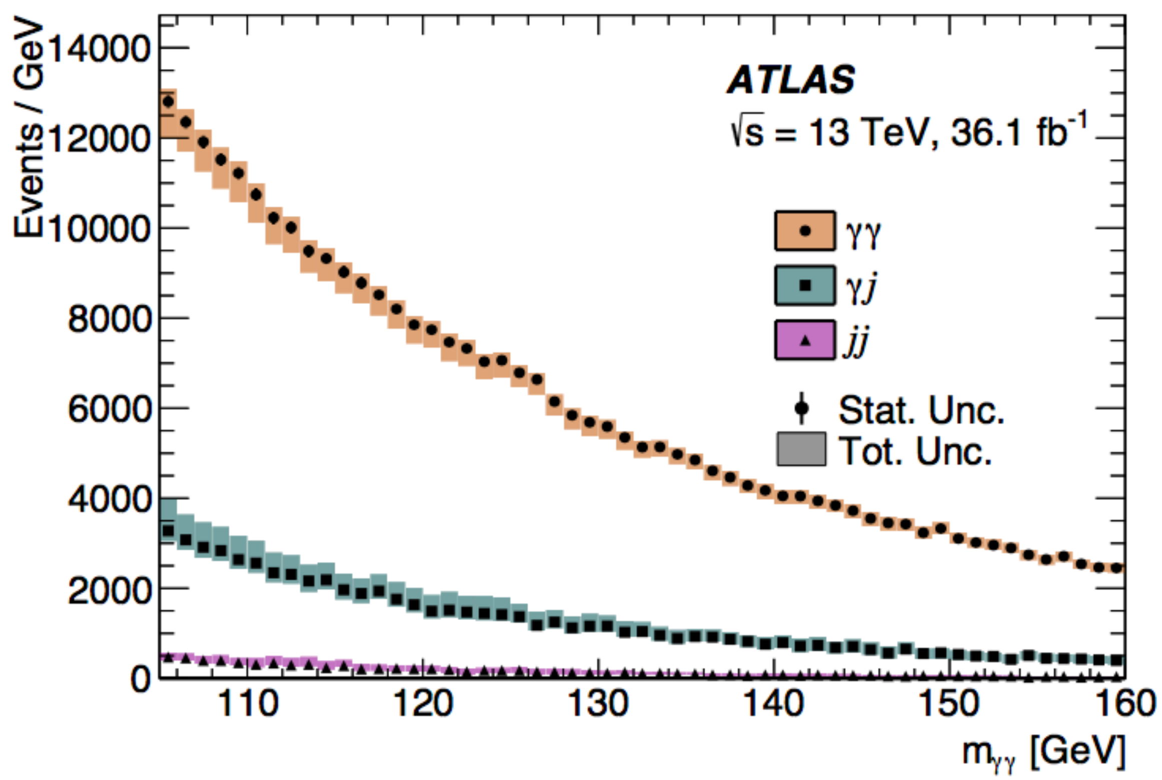
- N3LO ggH
- 4 uncertainties for missing higher order correction: 2 yield unc., 2 jet-bin-migrations
- 3 uncertainties on pTH: 2 pTH migration effects, 1 top-mass
- 2 uncertainties for ggH acceptance in VBF categories, 2 yield in 2-jet and >2-jet bin, 1 on dPhi(jj,γγ)

		Systematic uncertainty source	N_{NP}	Constraint	Category Likelihood	Fiducial Likelihood
Theory		ggH QCD	9	$N_{\text{S}}^{\text{ggH}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		Missing higher orders (non-ggH)	6	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		$B(H\to\gamma\gamma)$	1	$N_{\text{S}}^{\text{tot}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		PDF	30	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		α_{S}	1	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		UE/PS	5	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
Experimental	Yield	Heavy flavor content	1	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		Luminosity	1	$N_{\text{S}}^{\text{tot}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		Trigger	1	$N_{\text{S}}^{\text{tot}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		Photon identification	1	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		Photon isolation	2	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
	Migration	Flavor tagging	14	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		Jet	20	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		Jet flavor composition	7	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		Jet flavor response	7	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		Electron	3	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		Muon	11	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		Missing transverse momentum	3	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		Pileup	1	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
		Photon energy scale	40	$N_{\text{S}}^{\text{p}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	-
Mass		ATLAS-CMS m_H	1	$\mu_{\text{CB}}\ F_{\text{G}}(\sigma_i,\theta_i)$	✓	✓
		Photon energy scale	40	$\mu_{\text{CB}}\ F_{\text{G}}(\sigma_i,\theta_i)$	✓	✓
		Photon energy resolution	9	$\sigma_{\text{CB}}\ F_{\text{LN}}(\sigma_i,\theta_i)$	✓	✓
Background		Spurious signal	Varies	$N_{\text{spur},c}\ \theta_{\text{spur},c}$	✓	✓

Uncertainty Group	$\sigma_{\mu}^{\text{syst.}}$
Theory (QCD)	0.041
Theory ($B(H\to\gamma\gamma)$)	0.028
Theory (PDF+α_S)	0.021
Theory (UE/PS)	0.026
Luminosity	0.031
Experimental (yield)	0.017
Experimental (migrations)	0.015
Mass resolution	0.029
Mass scale	0.006
Background shape	0.027

- photon energy scale - shift in peak position by 0.21%-0.36% of nominal peak position
- photon energy resolution change signal width by 6%-13% of nominal width

H→γγ background functions



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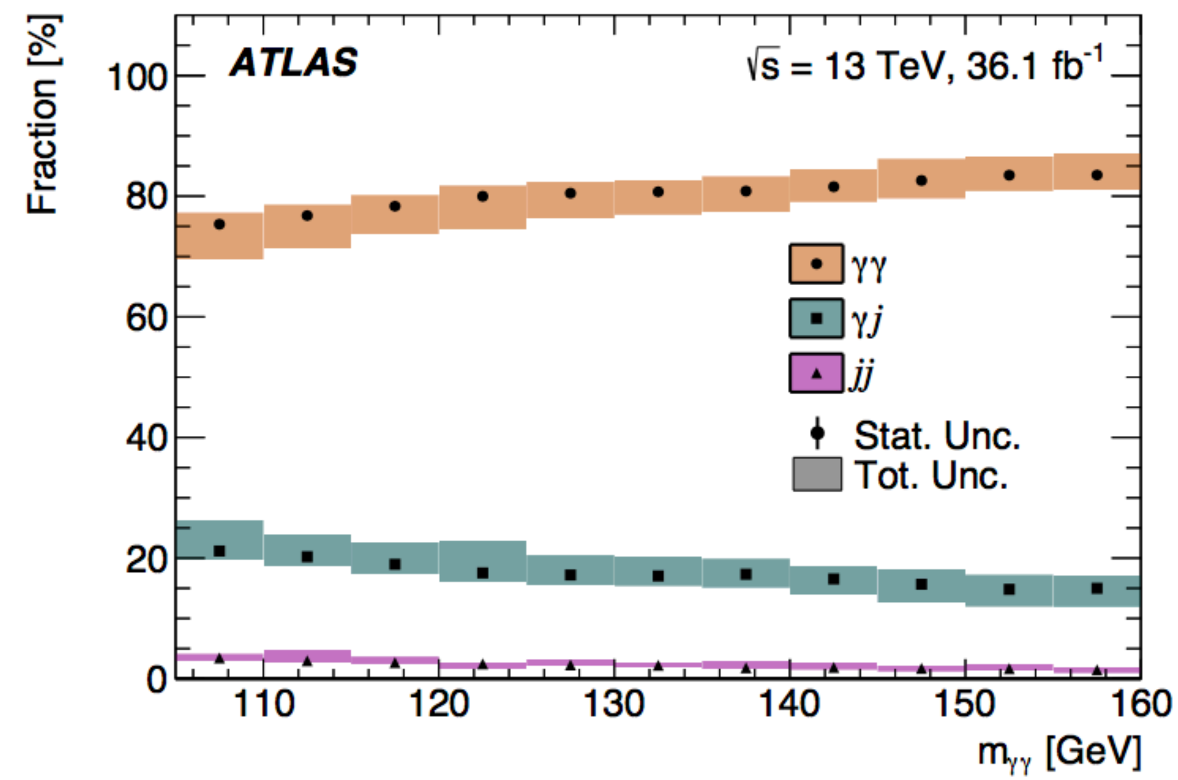

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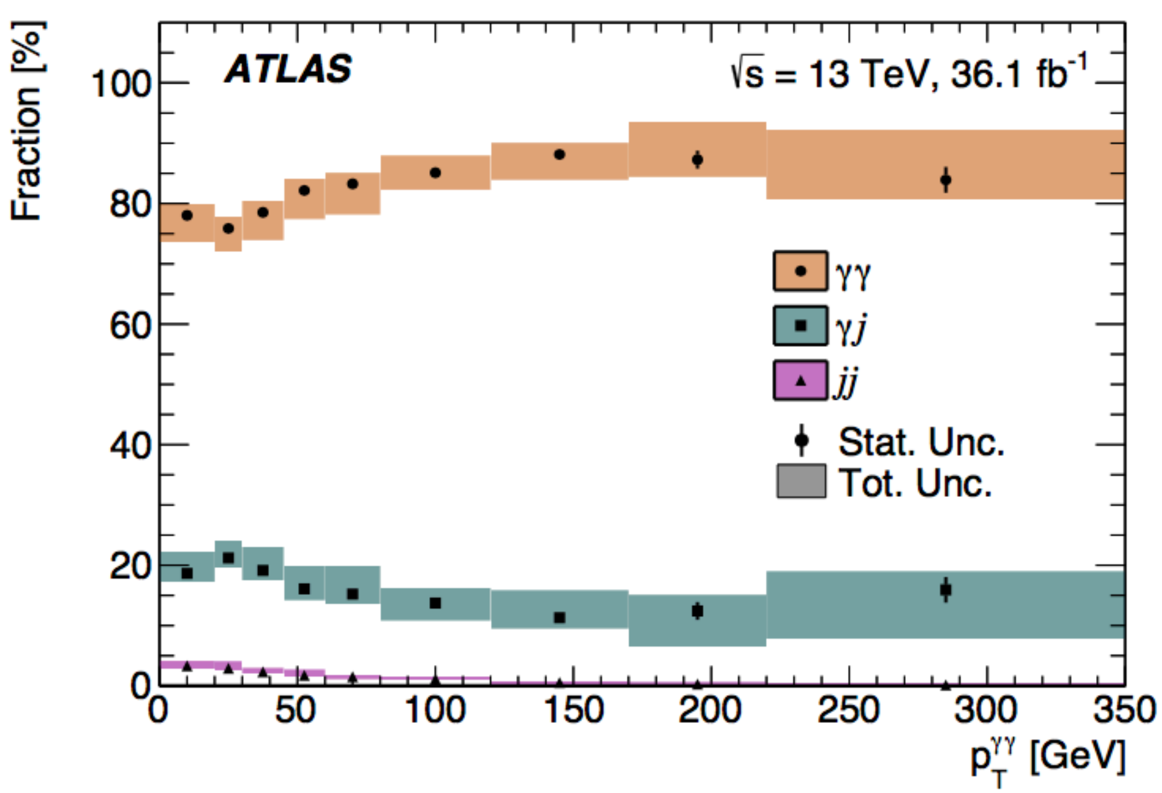
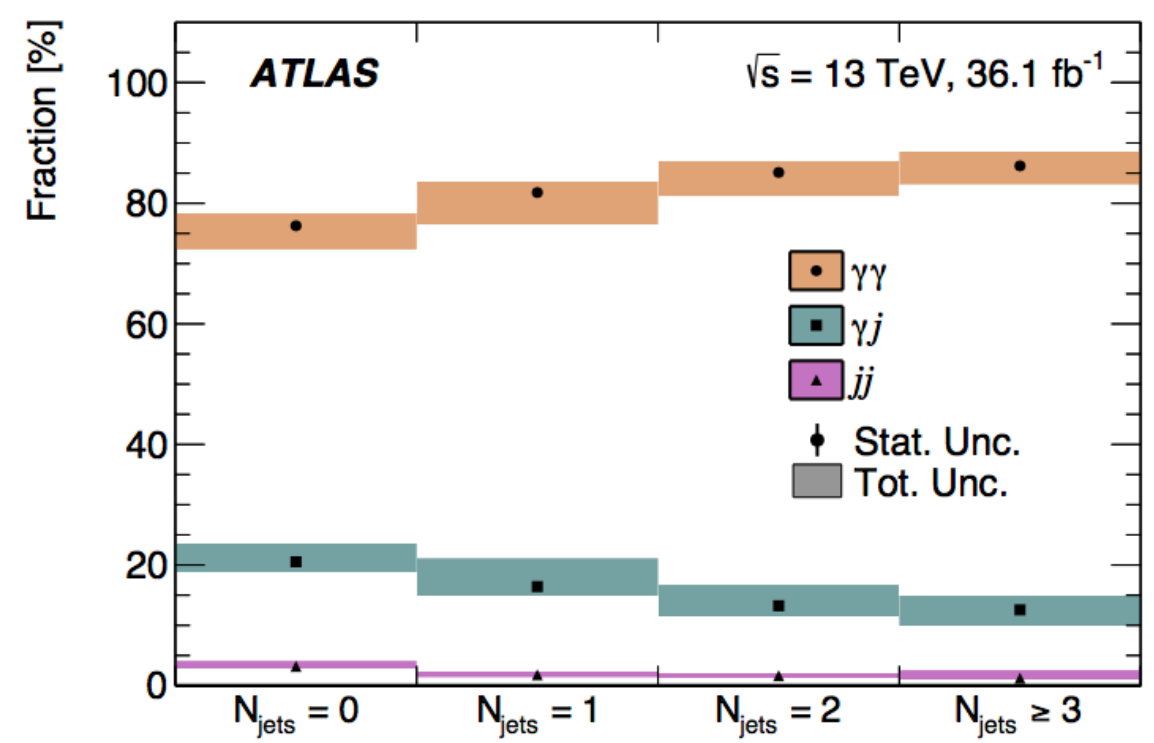
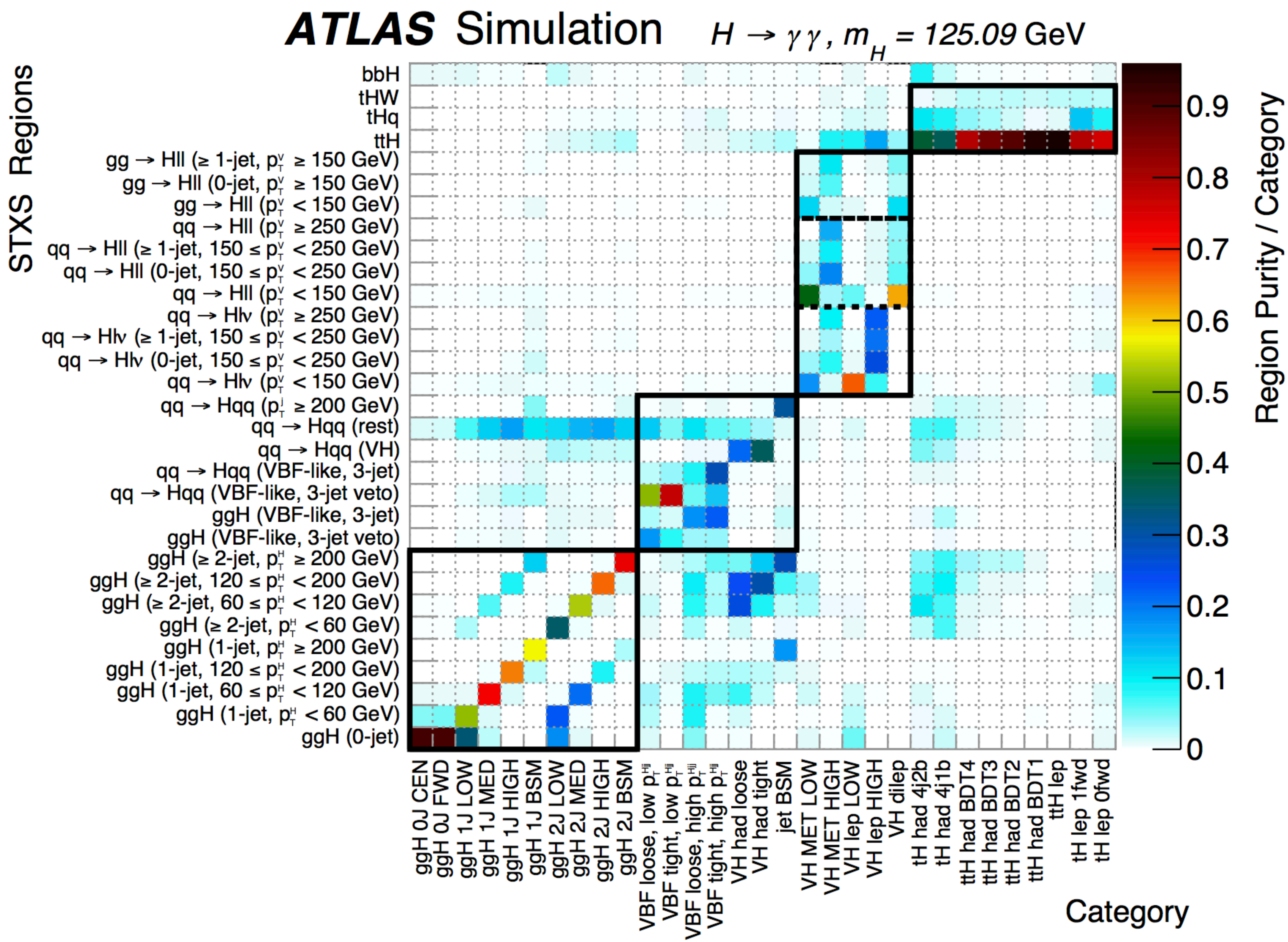




$H \to \gamma\gamma$ categories

Category	Selection
tH lep 0fwd	$N_{\text{lep}} = 1$, $N_{\text{jets}}^{\text{cen}} \leq 3$, $N_{b-\text{tag}} \geq 1$, $N_{\text{jets}}^{\text{fwd}} = 0$ ($p_{\text{T}}^{\text{jet}} > 25$ GeV)
tH lep 1fwd	$N_{\text{lep}} = 1$, $N_{\text{jets}}^{\text{cen}} \leq 4$, $N_{b-\text{tag}} \geq 1$, $N_{\text{jets}}^{\text{fwd}} \geq 1$ ($p_{\text{T}}^{\text{jet}} > 25$ GeV)
ttH lep	$N_{\text{lep}} \geq 1$, $N_{\text{jets}}^{\text{cen}} \geq 2$, $N_{b-\text{tag}} \geq 1$, $Z_{\ell\ell}$ veto ($p_{\text{T}}^{\text{jet}} > 25$ GeV)
ttH had BDT1	$N_{\text{lep}} = 0$, $N_{\text{jets}} \geq 3$, $N_{b-\text{tag}} \geq 1$, $\text{BDT}_{\text{ttH}} > 0.92$
ttH had BDT2	$N_{\text{lep}} = 0$, $N_{\text{jets}} \geq 3$, $N_{b-\text{tag}} \geq 1$, $0.83 < \text{BDT}_{\text{ttH}} < 0.92$
ttH had BDT3	$N_{\text{lep}} = 0$, $N_{\text{jets}} \geq 3$, $N_{b-\text{tag}} \geq 1$, $0.79 < \text{BDT}_{\text{ttH}} < 0.83$
ttH had BDT4	$N_{\text{lep}} = 0$, $N_{\text{jets}} \geq 3$, $N_{b-\text{tag}} \geq 1$, $0.52 < \text{BDT}_{\text{ttH}} < 0.79$
tH had 4j1b	$N_{\text{lep}} = 0$, $N_{\text{jets}}^{\text{cen}} = 4$, $N_{b-\text{tag}} = 1$ ($p_{\text{T}}^{\text{jet}} > 25$ GeV)
tH had 4j2b	$N_{\text{lep}} = 0$, $N_{\text{jets}}^{\text{cen}} = 4$, $N_{b-\text{tag}} \geq 2$ ($p_{\text{T}}^{\text{jet}} > 25$ GeV)
VH dilep	$N_{\text{lep}} \geq 2$, $70\text{ GeV} \leq m_{\ell\ell} \leq 110\text{ GeV}$
VH lep High	$N_{\text{lep}} = 1$, $\lvert m_{e\gamma} - 89\text{ GeV}\rvert > 5$ GeV, $p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} > 150$ GeV
VH lep Low	$N_{\text{lep}} = 1$, $\lvert m_{e\gamma} - 89\text{ GeV}\rvert > 5$ GeV, $p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} < 150$ GeV, $E_{\text{T}}^{\text{miss}}$ significance > 1
VH MET High	$150\text{ GeV} < E_{\text{T}}^{\text{miss}} < 250$ GeV, $E_{\text{T}}^{\text{miss}}$ significance > 9 or $E_{\text{T}}^{\text{miss}} > 250$ GeV
VH MET Low	$80\text{ GeV} < E_{\text{T}}^{\text{miss}} < 150$ GeV, $E_{\text{T}}^{\text{miss}}$ significance > 8
jet BSM	$p_{\text{T,j1}} > 200$ GeV
VH had tight	$60\text{ GeV} < m_{\text{jj}} < 120$ GeV, $\text{BDT}_{\text{VH}} > 0.78$
VH had loose	$60\text{ GeV} < m_{\text{jj}} < 120$ GeV, $0.35 < \text{BDT}_{\text{VH}} < 0.78$
VBF tight, high p_{T}^{Hjj}	$\lvert\Delta\eta_{jj}\rvert > 2$, $\lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5$, $p_{\text{T}}^{Hjj} > 25$ GeV, $\text{BDT}_{\text{VBF}} > 0.47$
VBF loose, high p_{T}^{Hjj}	$\lvert\Delta\eta_{jj}\rvert > 2$, $\lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5$, $p_{\text{T}}^{Hjj} > 25$ GeV, $-0.32 < \text{BDT}_{\text{VBF}} < 0.47$
VBF tight, low p_{T}^{Hjj}	$\lvert\Delta\eta_{jj}\rvert > 2$, $\lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5$, $p_{\text{T}}^{Hjj} < 25$ GeV, $\text{BDT}_{\text{VBF}} > 0.87$
VBF loose, low p_{T}^{Hjj}	$\lvert\Delta\eta_{jj}\rvert > 2$, $\lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5$, $p_{\text{T}}^{Hjj} < 25$ GeV, $0.26 < \text{BDT}_{\text{VBF}} < 0.87$
ggH 2J BSM	≥ 2 jets, $p_{\text{T}}^{\gamma\gamma} \geq 200$ GeV
ggH 2J High	≥ 2 jets, $p_{\text{T}}^{\gamma\gamma} \in [120, 200]$ GeV
ggH 2J Med	≥ 2 jets, $p_{\text{T}}^{\gamma\gamma} \in [60, 120]$ GeV
ggH 2J Low	≥ 2 jets, $p_{\text{T}}^{\gamma\gamma} \in [0, 60]$ GeV
ggH 1J BSM	$= 1$ jet, $p_{\text{T}}^{\gamma\gamma} \geq 200$ GeV
ggH 1J High	$= 1$ jet, $p_{\text{T}}^{\gamma\gamma} \in [120, 200]$ GeV
ggH 1J Med	$= 1$ jet, $p_{\text{T}}^{\gamma\gamma} \in [60, 120]$ GeV
ggH 1J Low	$= 1$ jet, $p_{\text{T}}^{\gamma\gamma} \in [0, 60]$ GeV
ggH 0J Fwd	$= 0$ jets, one photon with $\lvert\eta\rvert > 0.95$
ggH 0J Cen	$= 0$ jets, two photons with $\lvert\eta\rvert \leq 0.95$

H→γγ STXS to categories



$H \to \gamma\gamma$ STXS

Process	Measurement region	Particle-level stage-1 region
ggH + $gg \to Z(\to qq)H$	0-jet	0-jet
	1-jet, $p_T^H < 60$ GeV	1-jet, $p_T^H < 60$ GeV
	1-jet, $60 \le p_T^H < 120$ GeV	1-jet, $60 \le p_T^H < 120$ GeV
	1-jet, $120 \le p_T^H < 200$ GeV	1-jet, $120 \le p_T^H < 200$ GeV
	$\ge$ 1-jet, $p_T^H > 200$ GeV	1-jet, $p_T^H > 200$ GeV
		$\ge$ 2-jet, $p_T^H > 200$ GeV
	$\ge$ 2-jet, $p_T^H < 200$ GeVor VBF-like	$\ge$ 2-jet, $p_T^H < 60$ GeV
		$\ge$ 2-jet, $60 \le p_T^H < 120$ GeV
		$\ge$ 2-jet, $120 \le p_T^H < 200$ GeV
		VBF-like, $p_T^{Hjj} < 25$ GeV
		VBF-like, $p_T^{Hjj} \ge 25$ GeV
$qq' \to Hqq'$ (VBF + VH)	$p_T^j < 200$ GeV	$p_T^j < 200$ GeV, VBF-like, $p_T^{Hjj} < 25$ GeV
		$p_T^j < 200$ GeV, VBF-like, $p_T^{Hjj} \ge 25$ GeV
		$p_T^j < 200$ GeV, VH-like
		$p_T^j < 200$ GeV, Rest
	$p_T^j > 200$ GeV	$p_T^j > 200$ GeV
VH (leptonic decays)	VH leptonic	$q\bar{q} \to ZH$, $p_T^Z < 150$ GeV
		$q\bar{q} \to ZH$, $150 < p_T^Z < 250$ GeV, 0-jet
		$q\bar{q} \to ZH$, $150 < p_T^Z < 250$ GeV, $\ge$ 1-jet
		$q\bar{q} \to ZH$, $p_T^Z > 250$ GeV
		$q\bar{q} \to WH$, $p_T^W < 150$ GeV
		$q\bar{q} \to WH$, $150 < p_T^W < 250$ GeV, 0-jet
		$q\bar{q} \to WH$, $150 < p_T^W < 250$ GeV, $\ge$ 1-jet
		$q\bar{q} \to WH$, $p_T^W > 250$ GeV
		$gg \to ZH$, $p_T^Z < 150$ GeV
		$gg \to ZH$, $p_T^Z > 150$ GeV, 0-jet
		$gg \to ZH$, $p_T^Z > 150$ GeV, $\ge$ 1-jet
Top-associated production	top	$t\bar{t}H$
		W-associated $tH(tHW)$
		t-channel $tH(tHq)$
$b\bar{b}H$	merged w/ ggH	$b\bar{b}H$

H→γγ additional results

Measurement	Exp. Z_0	Obs. Z_0
μ_{VBF}	2.6 σ	4.9 σ
μ_{VH}	1.4 σ	0.8 σ
μ_{top}	1.8 σ	1.0 σ

$$\mu_{\text{ggH}} = 0.81\,^{+0.19}_{-0.18} = 0.81\,\pm 0.16\,(\text{stat.})\,^{+0.07}_{-0.06}\,(\text{exp.})\,^{+0.07}_{-0.05}\,(\text{theo.})$$

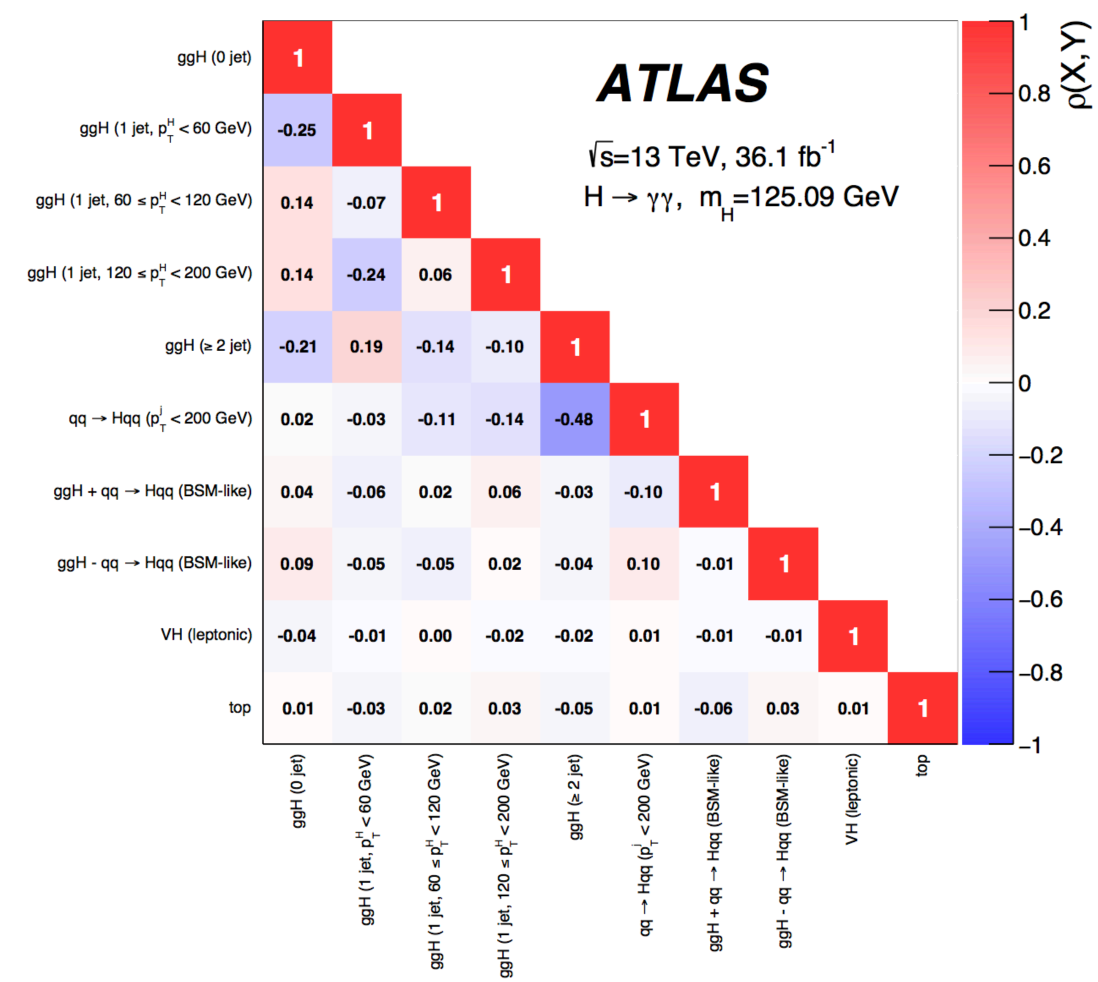
$$\mu_{\text{VBF}} = 2.0\,^{+0.6}_{-0.5} = 2.0\,\pm 0.5\,(\text{stat.})\,^{+0.3}_{-0.2}\,(\text{exp.})\,^{+0.3}_{-0.2}\,(\text{theo.})$$

$$\mu_{\text{VH}} = 0.7\,^{+0.9}_{-0.8} = 0.7\,\pm 0.8\,(\text{stat.})\,^{+0.2}_{-0.2}\,(\text{exp.})\,^{+0.2}_{-0.1}\,(\text{theo.})$$

$$\mu_{\text{top}} = 0.5\,^{+0.6}_{-0.6} = 0.5\,^{+0.6}_{-0.5}\,(\text{stat.})\,^{+0.1}_{-0.1}\,(\text{exp.})\,^{+0.1}_{-0.0}\,(\text{theo.})$$

Measurement	Observed	Exp. Limit ($\mu_i = 1$)	Exp. Limit ($\mu_i = 0$)	$+2\sigma$	$+1\sigma$	-1σ	-2σ
μ_{VH}	2.3	2.5	1.5	3.1	2.2	1.1	0.8
μ_{top}	1.7	2.3	1.2	2.6	1.8	0.9	0.6

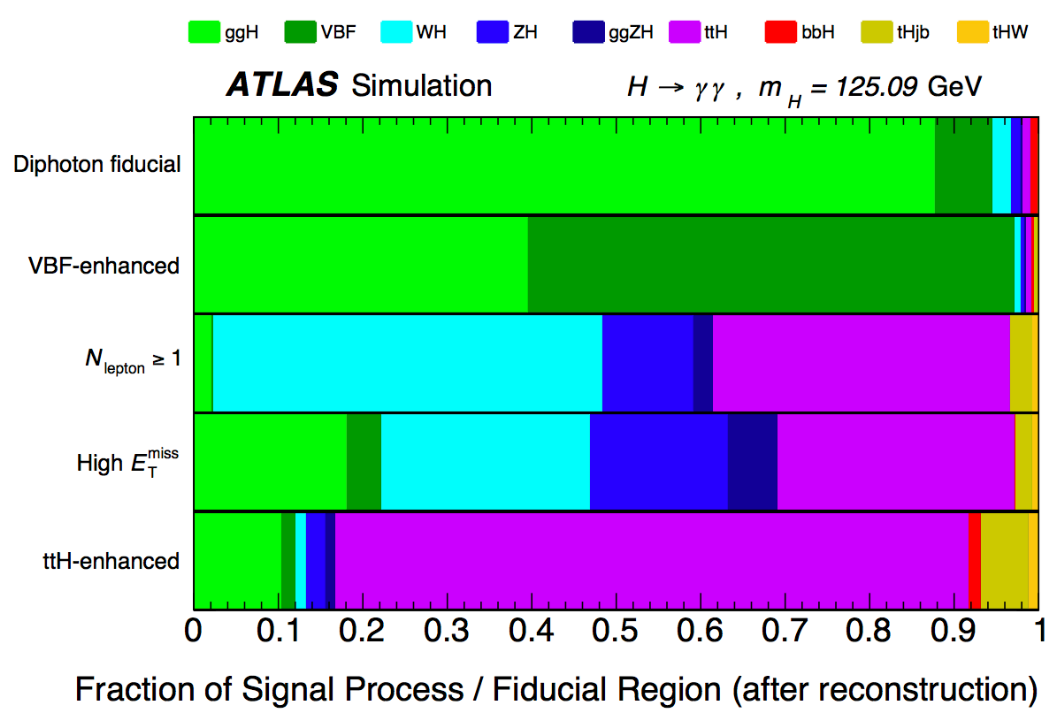
Process ($\lvert y_H \rvert < 2.5$)	Result [fb]	Uncertainty [fb] Total	Stat.	Exp.	Theo.	SM prediction [fb]
ggH	82	$^{+19}_{-18}$	± 16	$^{+7}_{-6}$	$^{+5}_{-4}$	102^{+5}_{-7}
VBF	16	$^{+5}_{-4}$	± 4	± 2	$^{+3}_{-2}$	8.0 ± 0.2
VH	3	± 4	$^{+4}_{-3}$	± 1	$^{+1}_{-0}$	4.5 ± 0.2
Top	0.7	$^{+0.9}_{-0.7}$	$^{+0.8}_{-0.7}$	$^{+0.2}_{-0.1}$	$^{+0.2}_{-0.0}$	1.3 ± 0.1



H→γγ fiducial phase-space

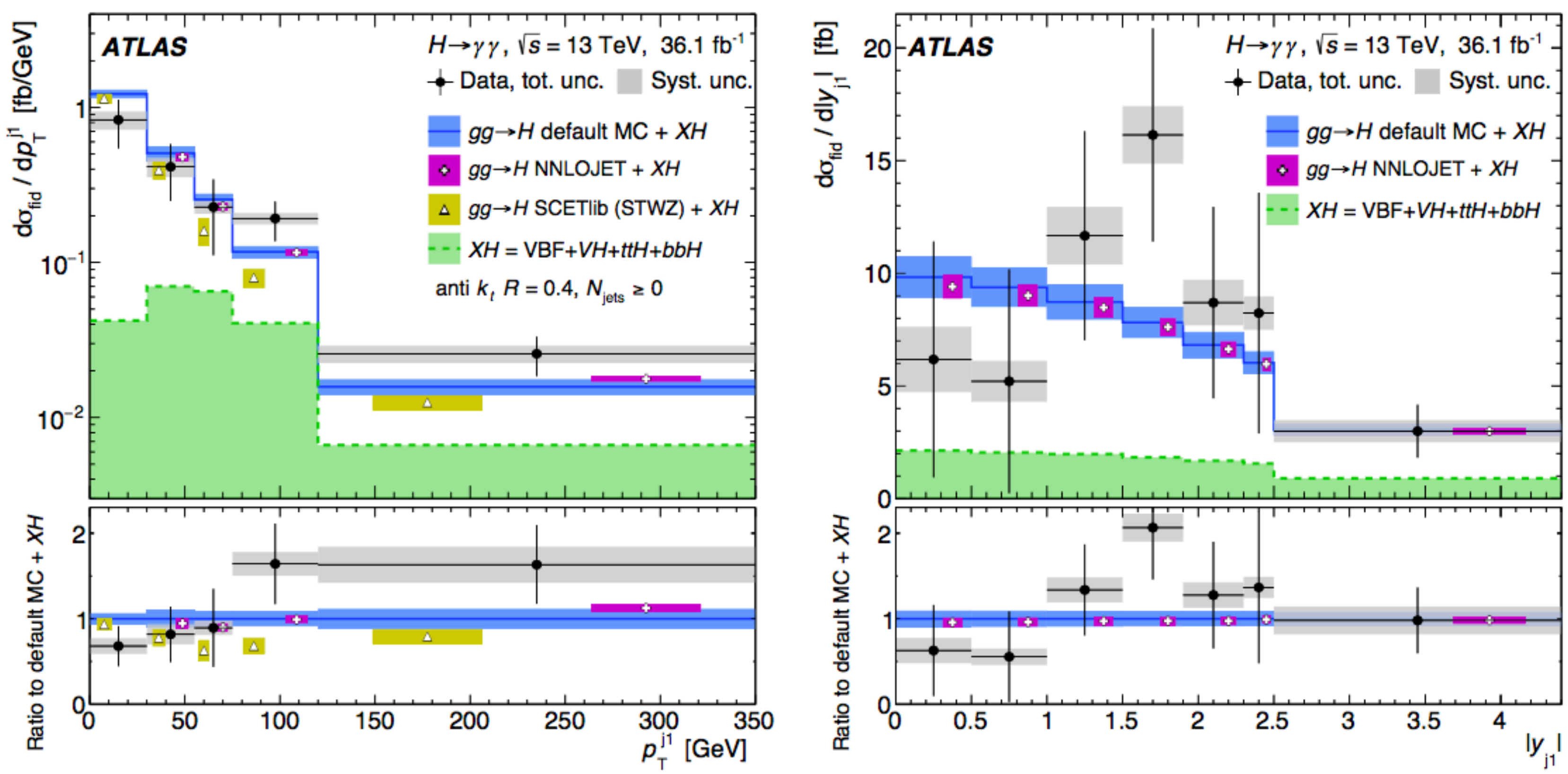
Objects	Definition
Photons	$|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$, $p_T^{iso,0.2}/p_T^{\gamma} < 0.05$
Jets	anti-k_t, $R = 0.4$, $p_T > 30$ GeV, $|y| < 4.4$
Leptons, ℓ	e or μ, $p_T > 15$ GeV, $|\eta| < 2.47$ for e (excluding $1.37 < |\eta| < 1.52$) and $|\eta| < 2.7$ for μ
Fiducial region	**Definition**
Diphoton fiducial	$N_\gamma \geq 2$, $p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma} = 43.8$ GeV, $p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma} = 31.3$ GeV
VBF-enhanced	Diphoton fiducial, $N_j \geq 2$ with $p_T^{jet} > 25$ GeV, $m_{jj} > 400$ GeV, $|\Delta y_{jj}| > 2.8$, $|\Delta\phi_{\gamma\gamma,jj}| > 2.6$
$N_{lepton} \geq 1$	Diphoton fiducial, $N_\ell \geq 1$
High E_T^{miss}	Diphoton fiducial, $E_T^{miss} > 80$ GeV, $p_T^{\gamma\gamma} > 80$ GeV
$t\bar{t}H$-enhanced	Diphoton fiducial, $(N_j \geq 4,\ N_{b\text{-jets}} \geq 1)$ or $(N_j \geq 3,\ N_{b\text{-jets}} \geq 1, N_\ell \geq 1)$

$$\sigma_i = \frac{N_i^{sig}}{c_i \int L\,dt} \quad \text{and} \quad \frac{d\sigma_i}{dx} = \frac{N_i^{sig}}{c_i\, \Delta x_i \int L\,dt},$$

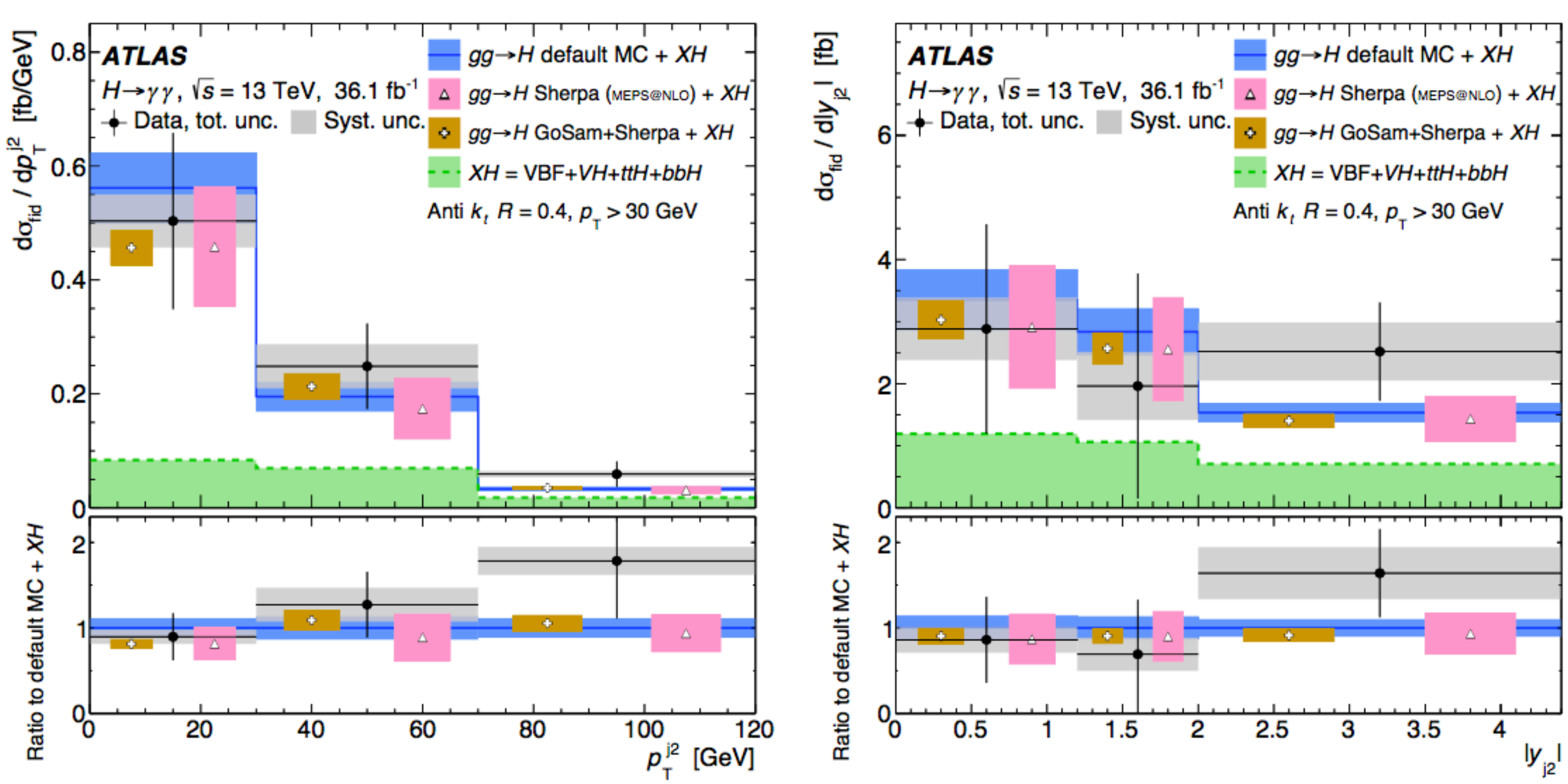


- VBF-enhanced:
  m(jj)>400GeV; $\Delta y_{jj} > 2.8$; $|\Delta\phi_{\gamma\gamma,jj}| > 2.6$
  [32%ggH]
- VH-enhanced:
  1-el or 1-muon, pT(lep)>15GeV
- high-MET:
  MET>80GeV; pT(γγ)>80GeV
- ttH-enhanced:
  1lepton+3jet, or 0lepton+4jet
  at least 1-bottom-jet

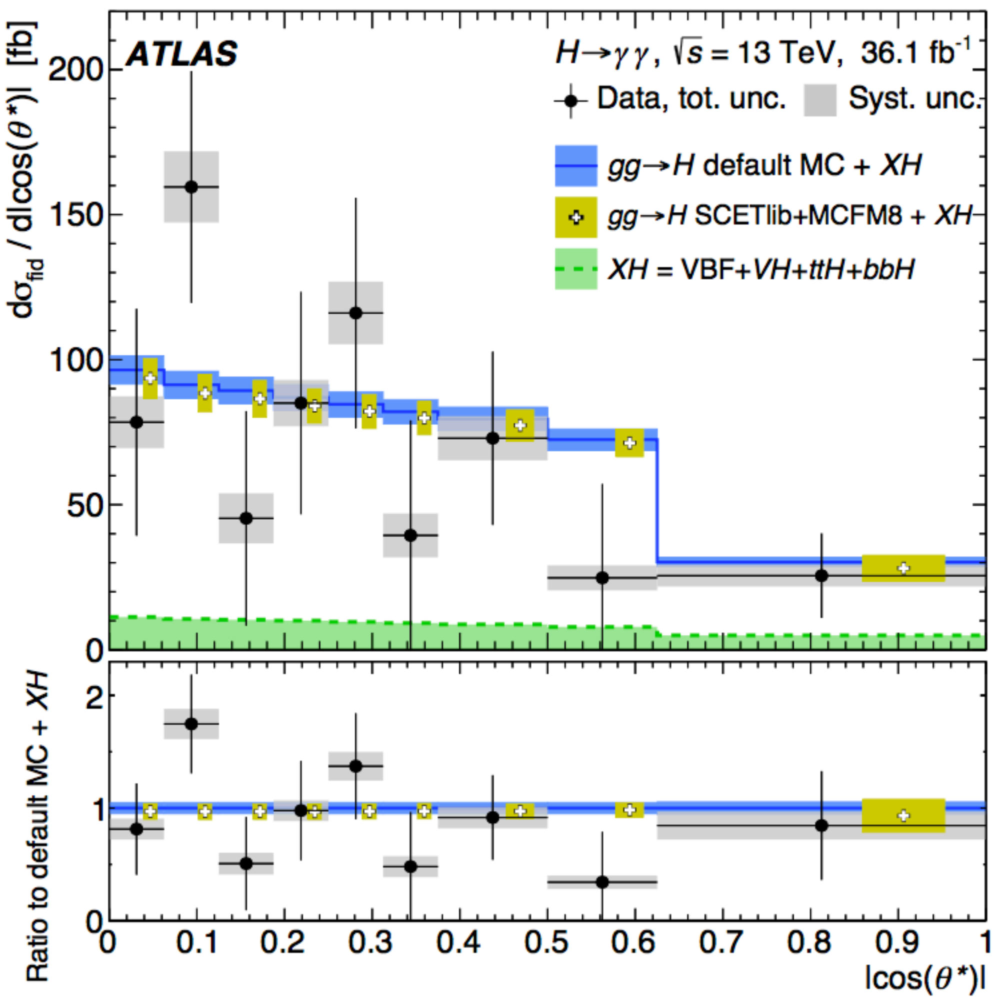
H→γγ differential

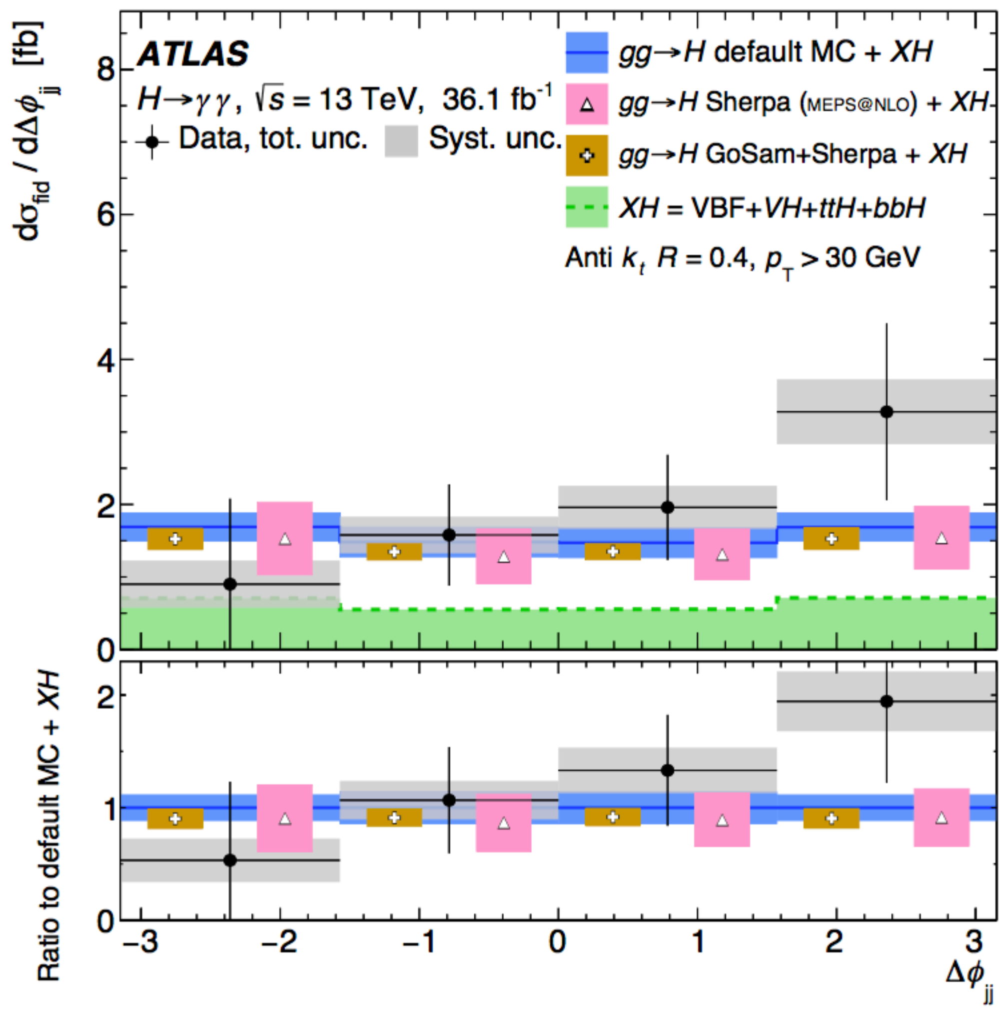


(a) (b)

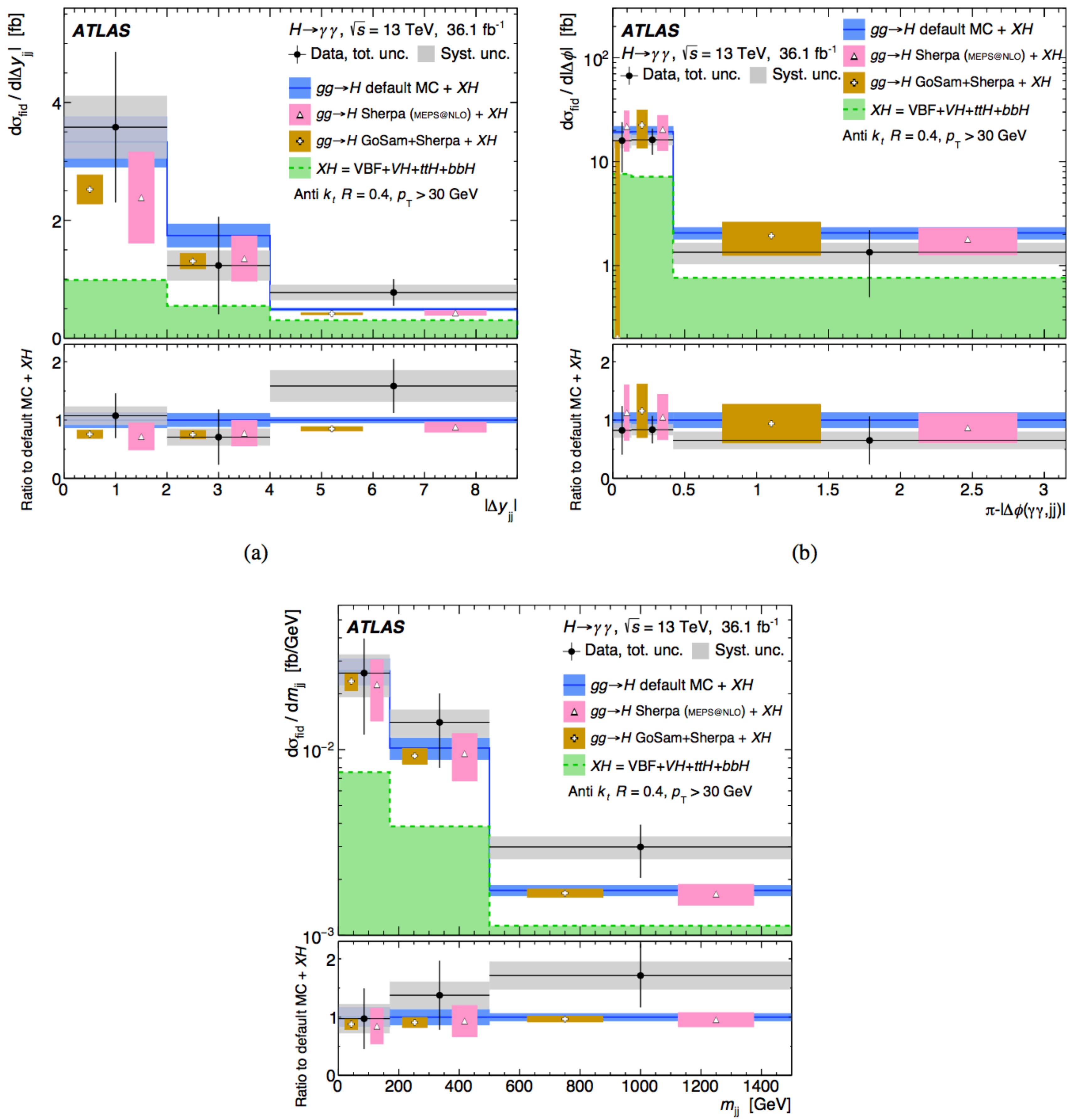


H→γγ differential





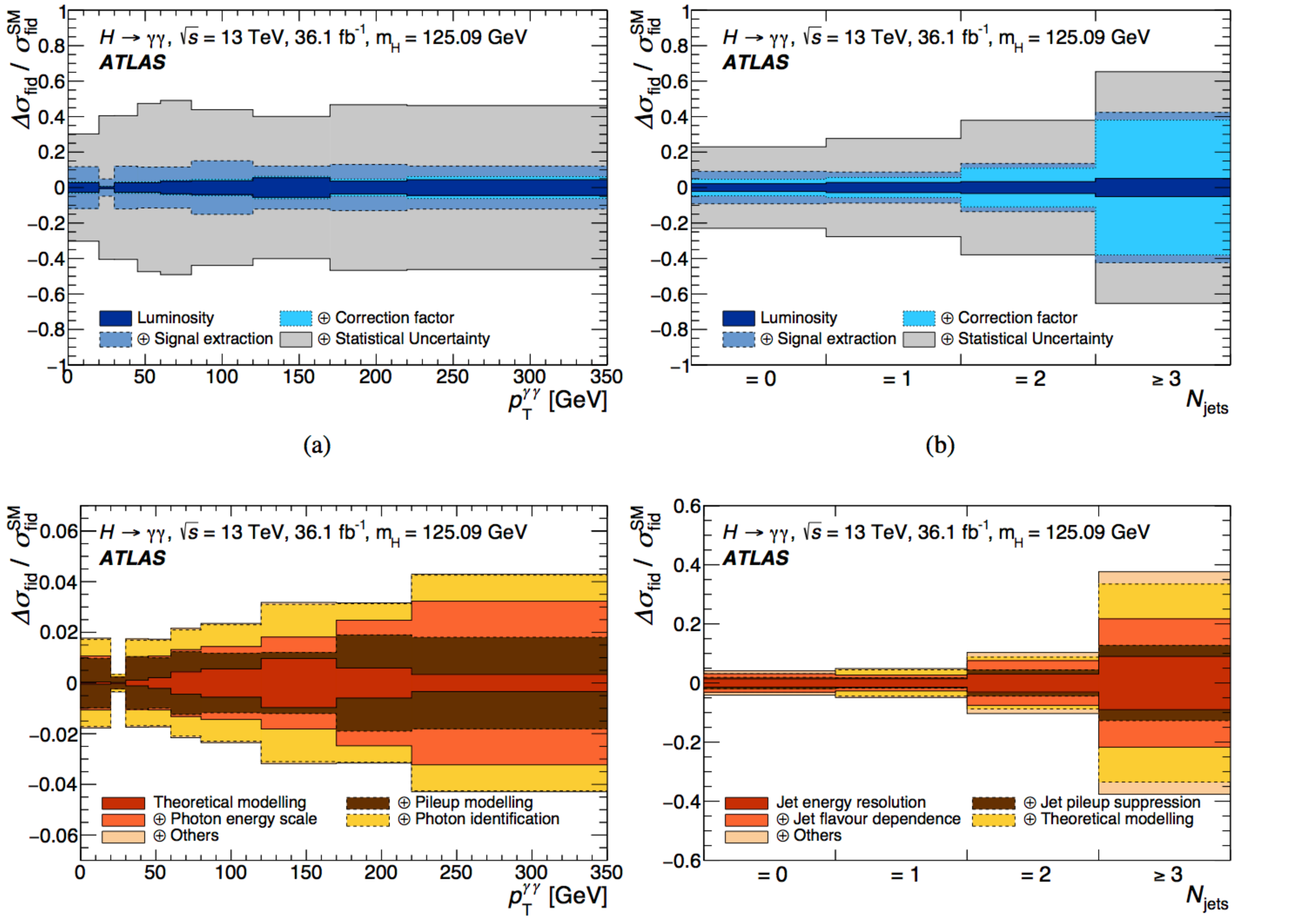
H→γγ differential



$H \rightarrow \gamma\gamma$ differential uncertainties

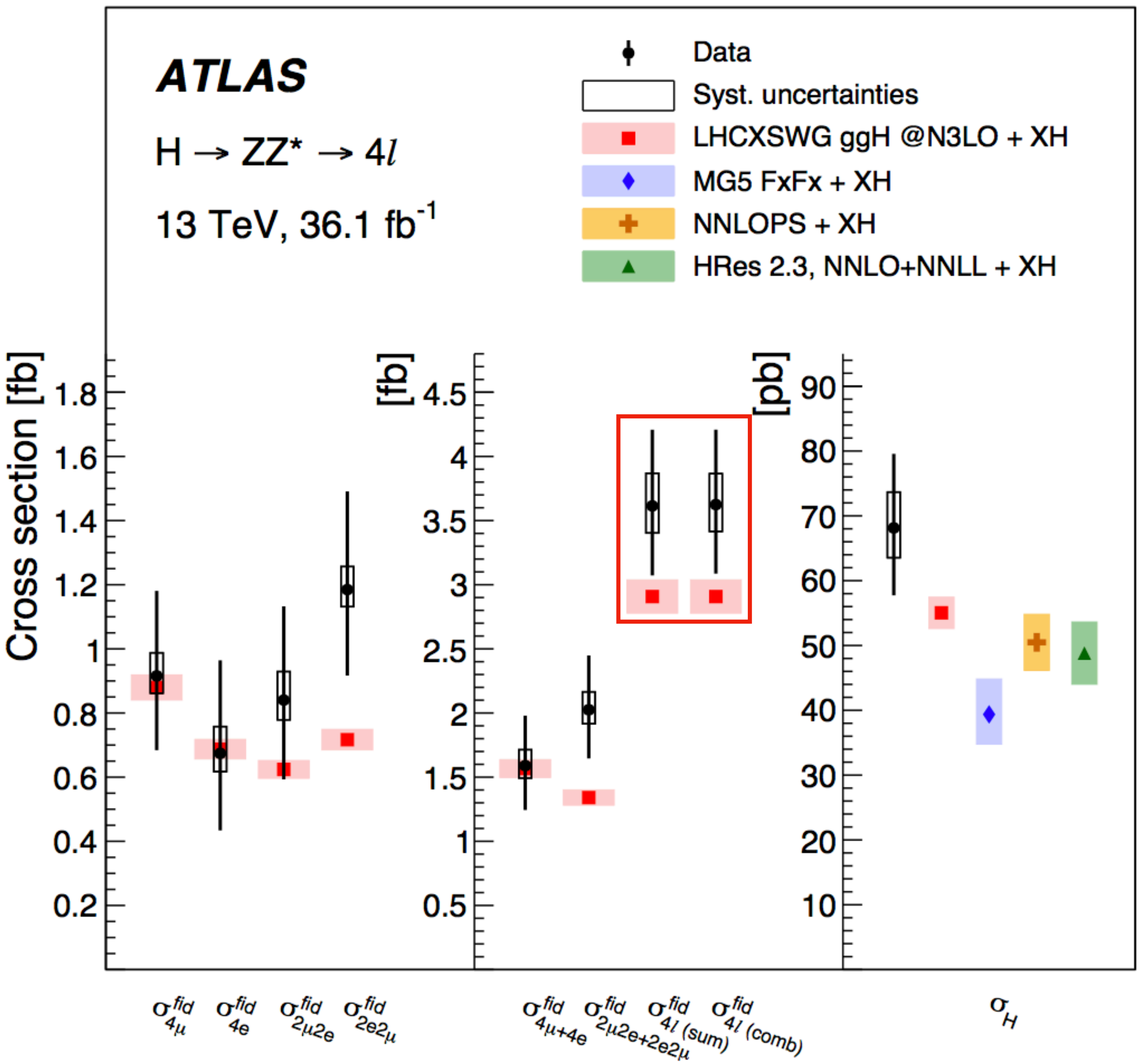
Source	Uncertainty in fiducial cross section				
	Diphoton	VBF-enhanced	$N_{\mathrm{lepton}} \geq 1$	$t\bar{t}H$-enhanced	High $E_{\mathrm{T}}^{\mathrm{miss}}$
Fit (stat.)	17%	22%	72%	176%	53%
Fit (syst.)	6%	9%	27%	138%	13%
Photon energy scale & resolution	4.3%	3.5%	3.1%	10%	4.1%
Background modelling	4.2%	7.8%	26.7%	138%	12.2%
Photon efficiency	1.8%	1.8%	1.8%	1.8%	1.9%
Jet energy scale/resolution	-	8.9%	-	4.5%	6.9%
b-jet flavor tagging	-	-	-	3%	-
Lepton selection	-	-	0.7%	0.2%	-
Pileup	1.1%	2.9%	1.3%	2.5%	2.5%
Theoretical modeling	0.1%	4.5%	4.0%	8.1%	31%
Signal composition	0.1%	4.5%	3.1%	8.1%	25%
Higgs boson p_{T}^{H} & $\lvert y_H \rvert$	0.1%	0.9%	0.2%	0.7%	0.1%
UE/PS	-	0.3%	0.7%	1.1%	31%
Luminosity	3.2%	3.2%	3.2%	3.2%	3.2%
Total	18%	26%	77%	224%	63%

H→γγ differential uncertainties



H→ZZ* fiducial & differential measurements

JHEP 10 (2017) 132
$36.1 fb^{-1}$ @ 13TeV

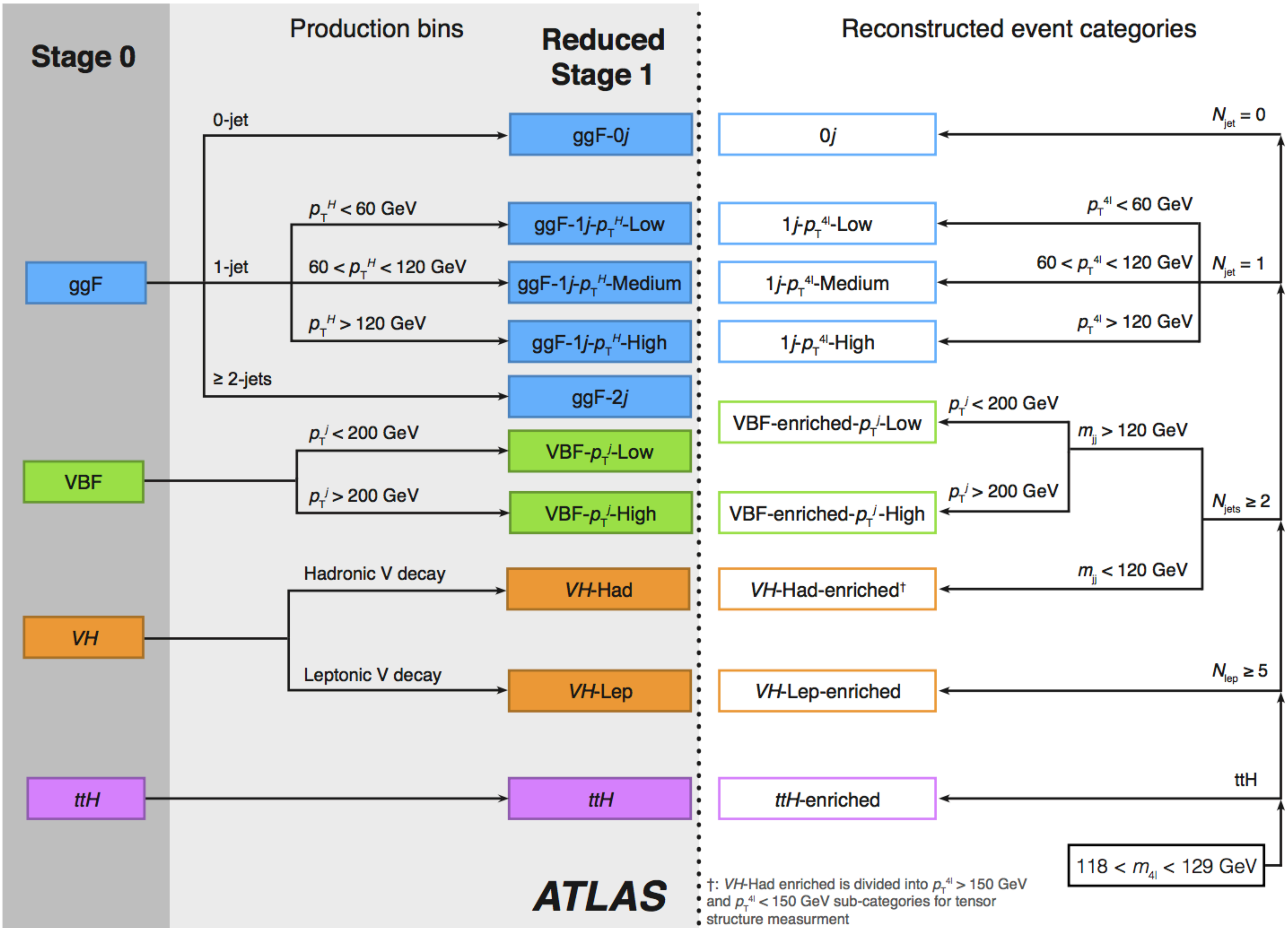


- fiducial cross-section from $115 < m_{4l} < 130$ GeV phase space in fair agreement with SM prediction
- Fiducial cross-section separately in each lepton sub-channel, and combined

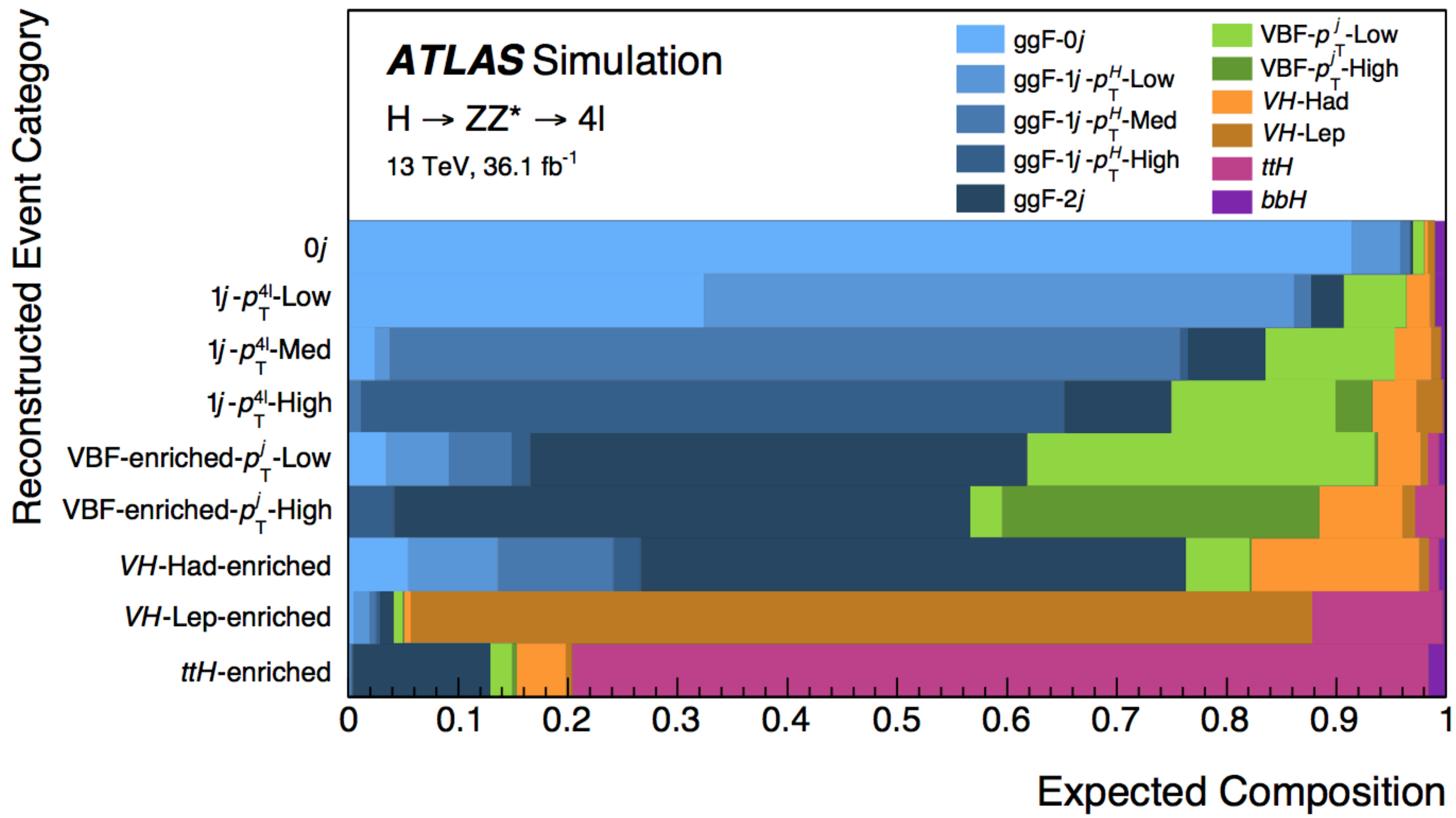
$\sigma^{meas}_{fid} = 3.62 \pm 0.50(stat)^{+0.25}_{-0.20}(sys)$ fb
$\sigma^{SM}_{fid} = 2.91 \pm 0.13$ fb

- Fiducial results also extrapolated to the total phase space (right box)

H→ZZ* STXS to categories



H→ZZ*



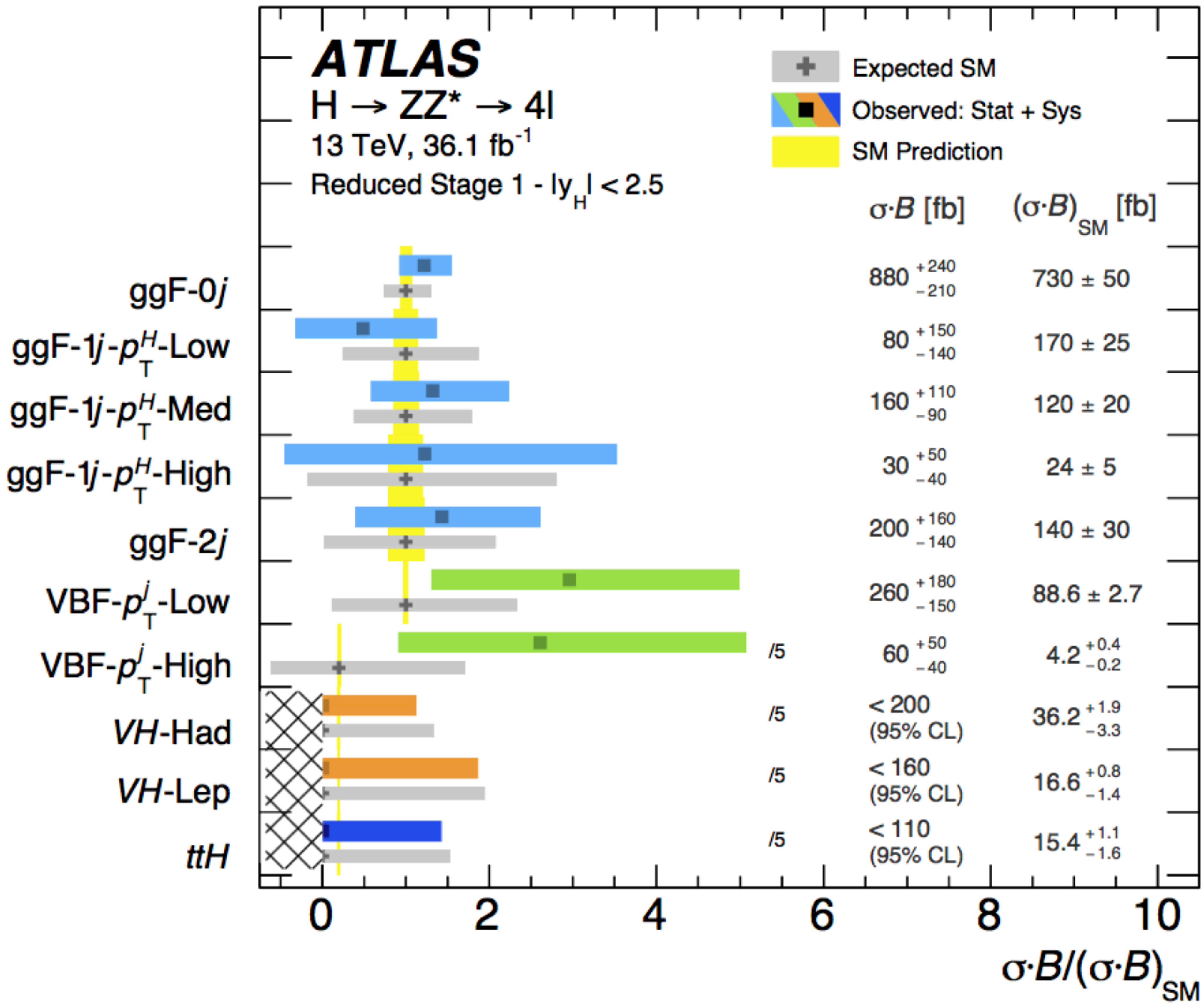
Reconstructed event category	BDT discriminant	Input variables
$0j$	$\mathrm{BDT}_{\mathrm{ggF}}$	$p_T^{4\ell}, \eta_{4\ell}, D_{ZZ^*}$
$1j$-$p_T^{4\ell}$-Low	$\mathrm{BDT}_{\mathrm{VBF}}^{1j\text{-}p_T^{4\ell}\text{-Low}}$	$p_T^j, \eta_j, \Delta R(j, 4\ell)$
$1j$-$p_T^{4\ell}$-Med	$\mathrm{BDT}_{\mathrm{VBF}}^{1j\text{-}p_T^{4\ell}\text{-Med}}$	$p_T^j, \eta_j, \Delta R(j, 4\ell)$
$1j$-$p_T^{4\ell}$-High	-	-
VBF-enriched-p_T^j-Low	$\mathrm{BDT}_{\mathrm{VBF}}$	$m_{jj}, \Delta\eta_{jj}, p_T^{j1}, p_T^{j2}, \eta_{4\ell}^*, \Delta R_{jZ}^{\min}, (p_T^{4\ell jj})_{\mathrm{constrained}}$
VBF-enriched-p_T^j-High	-	-
VH-Had-enriched	$\mathrm{BDT}_{VH\text{-Had}}$	$m_{jj}, \Delta\eta_{jj}, p_T^{j1}, p_T^{j2}, \eta_{4\ell}^*, \Delta R_{jZ}^{\min}, \eta_{j1}$
VH-Lep-enriched	-	-
ttH-enriched	-	-

$H \rightarrow ZZ^*$

Decay channel	Signal (full mass range)	Signal	ZZ^* background	Other backgrounds	Total expected	Observed
4μ	21.0 ± 1.7	19.7 ± 1.6	7.5 ± 0.6	1.00 ± 0.21	28.1 ± 1.7	32
$2e2\mu$	15.0 ± 1.2	13.5 ± 1.0	5.4 ± 0.4	0.78 ± 0.17	19.7 ± 1.1	30
$2\mu 2e$	11.4 ± 1.1	10.4 ± 1.0	3.57 ± 0.35	1.09 ± 0.19	15.1 ± 1.0	18
$4e$	11.3 ± 1.1	9.9 ± 1.0	3.35 ± 0.32	1.01 ± 0.17	14.3 ± 1.0	15
Total	59 ± 5	54 ± 4	19.7 ± 1.5	3.9 ± 0.5	77 ± 4	95

	Experimental uncertainties [%]					Theory uncertainties [%]			
Production bin	Lumi	e, μ, pile-up	Jets, flavour tagging	Higgs mass	Reducible backgr.	ZZ^* backgr.	Signal theory PDF	Signal theory QCD scale	Signal theory Shower
Inclusive cross section									
	4.1	3.1	0.7	0.8	0.9	1.9	0.3	0.8	1.2
Stage-0 production bin cross sections									
ggF	4.3	3.4	1.1	1.2	1.1	1.8	0.5	1.8	1.4
VBF	2.6	2.7	10	1.3	0.9	2.2	1.6	11	5.3
VH	3.0	2.7	11	1.6	1.7	5.9	2.1	12	3.7
ttH	3.6	2.9	19	< 0.1	2.4	1.9	3.3	7.9	2.1

H→ZZ*


ATLAS
H → ZZ* → 4l
13 TeV, 36.1 fb-1
Reduced Stage 1 - |y_H| < 2.5
Expected SM
Observed: Stat + Sys
SM Prediction
σ·B [fb]
(σ·B)_SM [fb]
ggF-0j
ggF-1j-pT^H-Low
ggF-1j-pT^H-Med
ggF-1j-pT^H-High
ggF-2j
VBF-pT^j-Low
VBF-pT^j-High
VH-Had
VH-Lep
ttH
880 +240 −210
730 ± 50
80 +150 −140
170 ± 25
160 +110 −90
120 ± 20
30 +50 −40
24 ± 5
200 +160 −140
140 ± 30
260 +180 −150
88.6 ± 2.7
/5
60 +50 −40
4.2 +0.4 −0.2
/5
< 200 (95% CL)
36.2 +1.9 −3.3
/5
< 160 (95% CL)
16.6 +0.8 −1.4
/5
< 110 (95% CL)
15.4 +1.1 −1.6
0
2
4
6
8
10
σ·B/(σ·B)_SM

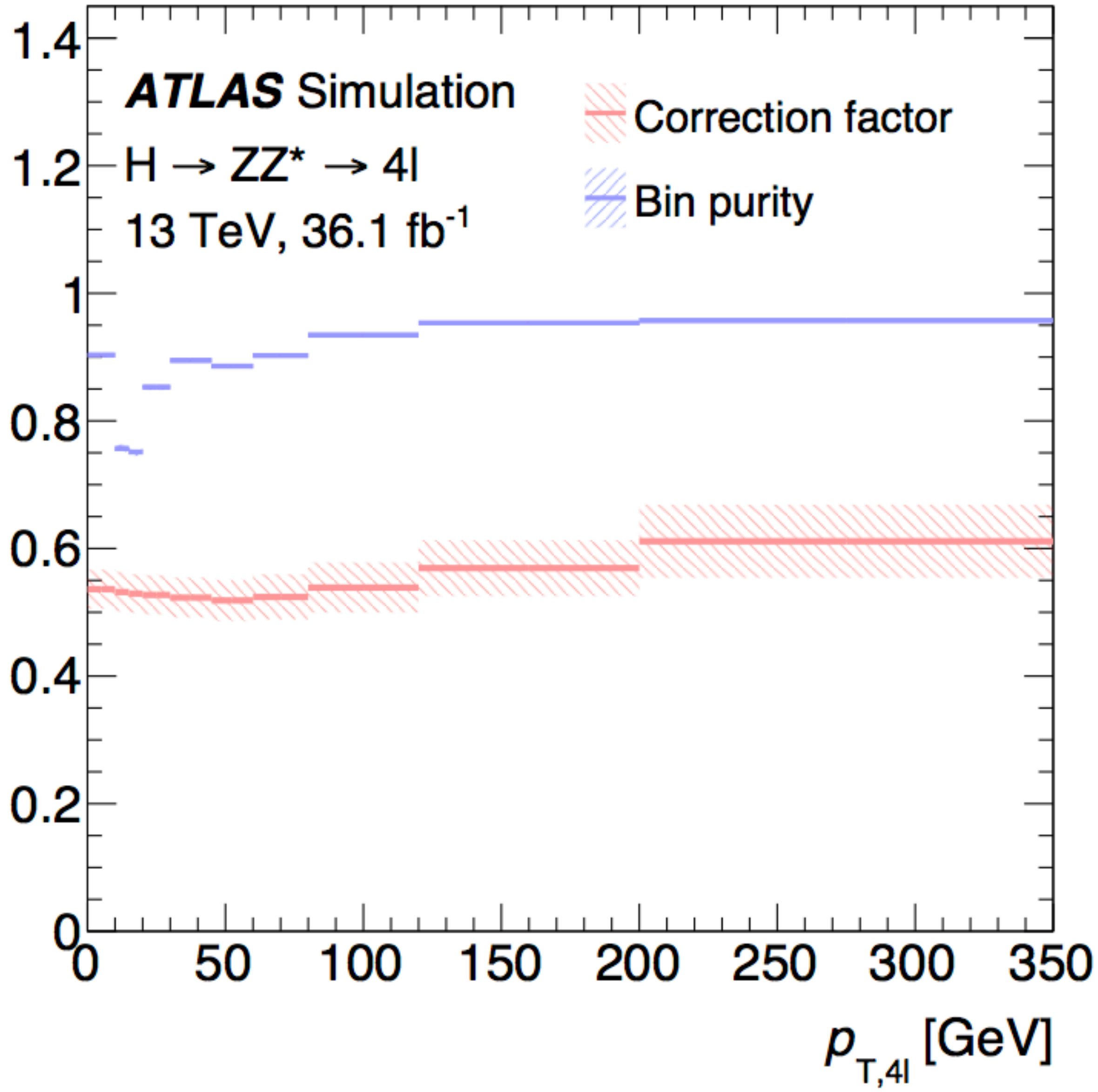
$H\rightarrow ZZ^*$ fiducial & differential measurements

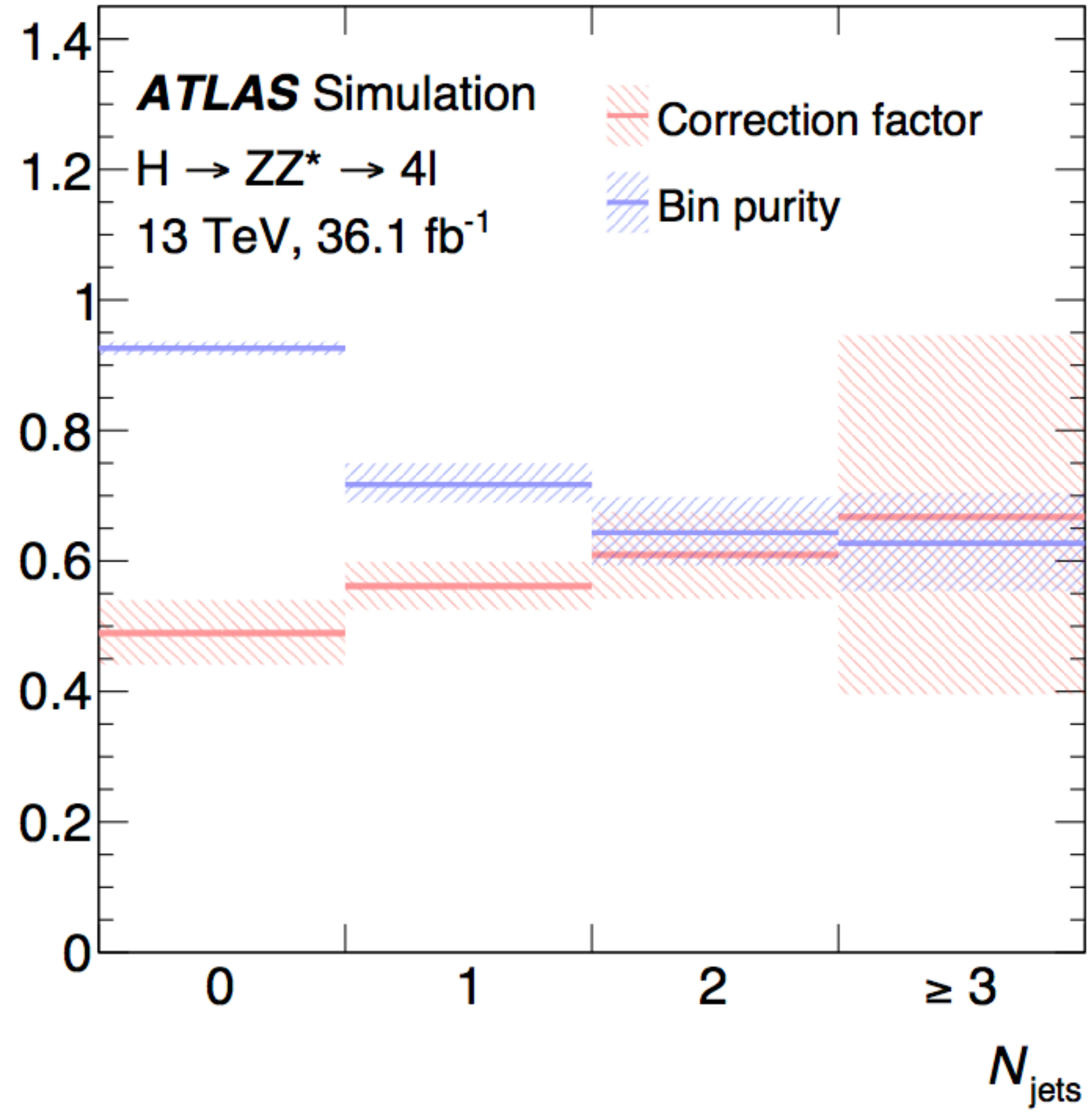
Leptons and jets	
Muons:	$p_T > 5$ GeV, $\|\eta\| < 2.7$
Electrons:	$p_T > 7$ GeV, $\|\eta\| < 2.47$
Jets:	$p_T > 30$ GeV, $\|y\| < 4.4$
Jet–lepton overlap removal:	$\Delta R(\text{jet}, \ell) > 0.1$ (0.2) for muons (electrons)
Lepton selection and pairing	
Lepton kinematics:	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12}):	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34}):	remaining SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection (at most one quadruplet per channel)	
Mass requirements:	50 GeV$< m_{12} <$ 106 GeV and 12 GeV$< m_{34} <$ 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 GeV$< m_{4\ell} <$ 130 GeV

Final state	SM Higgs	ZZ^*	Z + jets, $t\bar{t}$ WZ, ttV, VVV	Expected	Observed
4μ	20.1 ± 1.6	9.8 ± 0.8	1.3 ± 0.3	31.2 ± 1.8	33
$4e$	10.6 ± 1.0	4.4 ± 0.4	1.3 ± 0.2	16.3 ± 1.1	16
$2e2\mu$	14.2 ± 1.1	7.1 ± 0.5	1.0 ± 0.2	22.3 ± 1.2	32
$2\mu2e$	10.8 ± 1.0	4.6 ± 0.5	1.4 ± 0.3	16.8 ± 1.1	21
Total	56 ± 4	25.9 ± 2.0	5.0 ± 0.7	87 ± 5	102

$$\sigma_{i,\text{fid}} = \sigma_i \times A_i \times \mathcal{B} = \frac{N_{i,\text{fit}}}{\mathcal{L} \times C_i}, \quad C_i = \frac{N_{i,\text{reco}}}{N_{i,\text{part}}},$$

$H \rightarrow ZZ^*$ fiducial & differential measurements



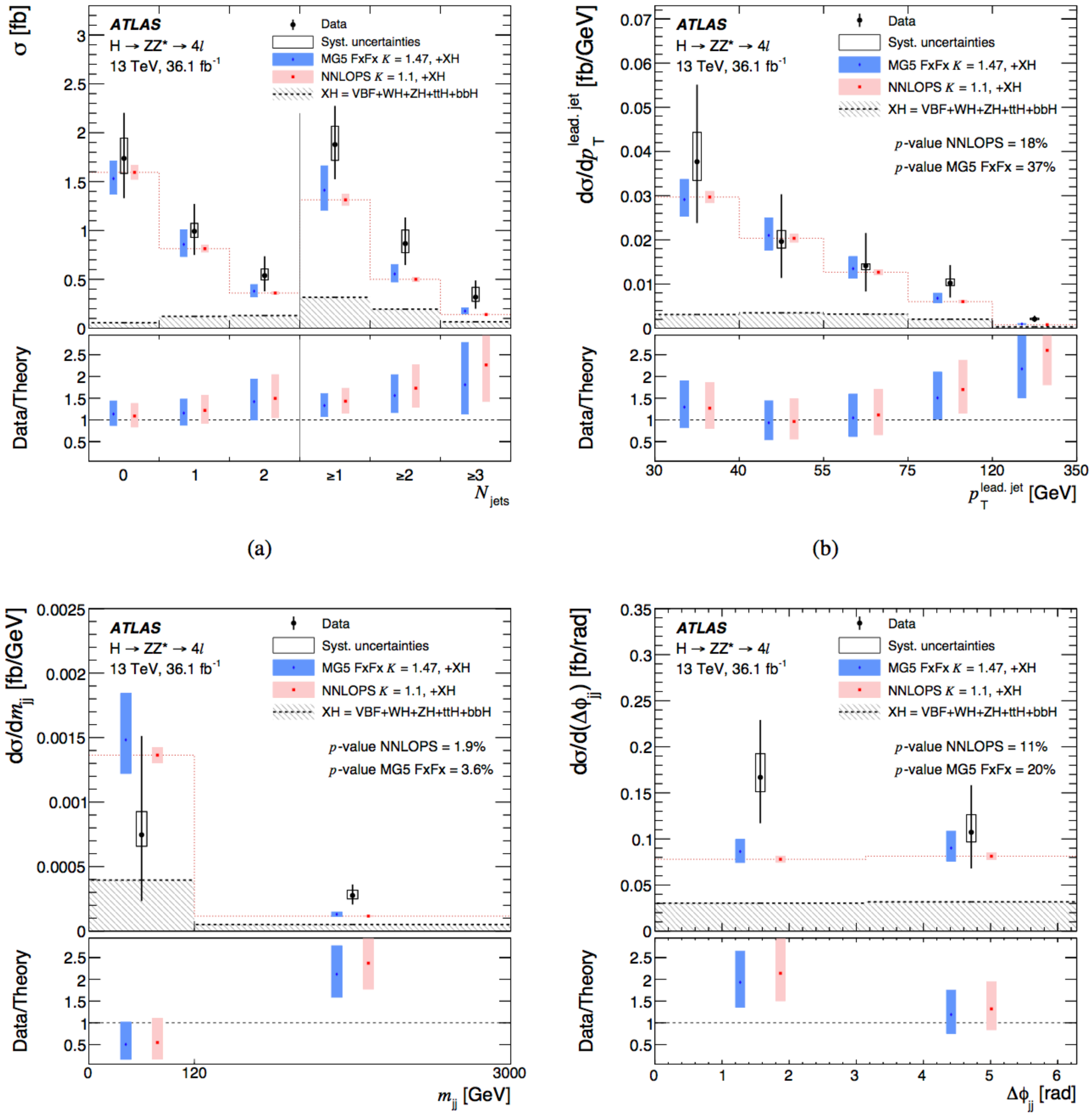


$$\sigma_{i,\text{fid}} = \sigma_i \times A_i \times \mathcal{B} = \frac{N_{i,\text{fit}}}{\mathcal{L} \times C_i}, \quad C_i = \frac{N_{i,\text{reco}}}{N_{i,\text{part}}},$$

$H \rightarrow ZZ^*$ fiducial & differential measurements

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

H→ZZ* fiducial & differential measurements



Higgs mass measurement

Higgs mass - only free parameter of the SM Higgs sector

ATLAS-CONF-2017-046

$36.1 fb^{-1}$ @ 13TeV

- clear and narrow m_H peak over smooth background provides minimal model dependence in $H \to \gamma\gamma$ and $H \to ZZ^*$ channels
- stat. uncertainty depending on mass resolution and number of events
- syst. uncertainty from momentum/energy scale resolution of e/γ/μ

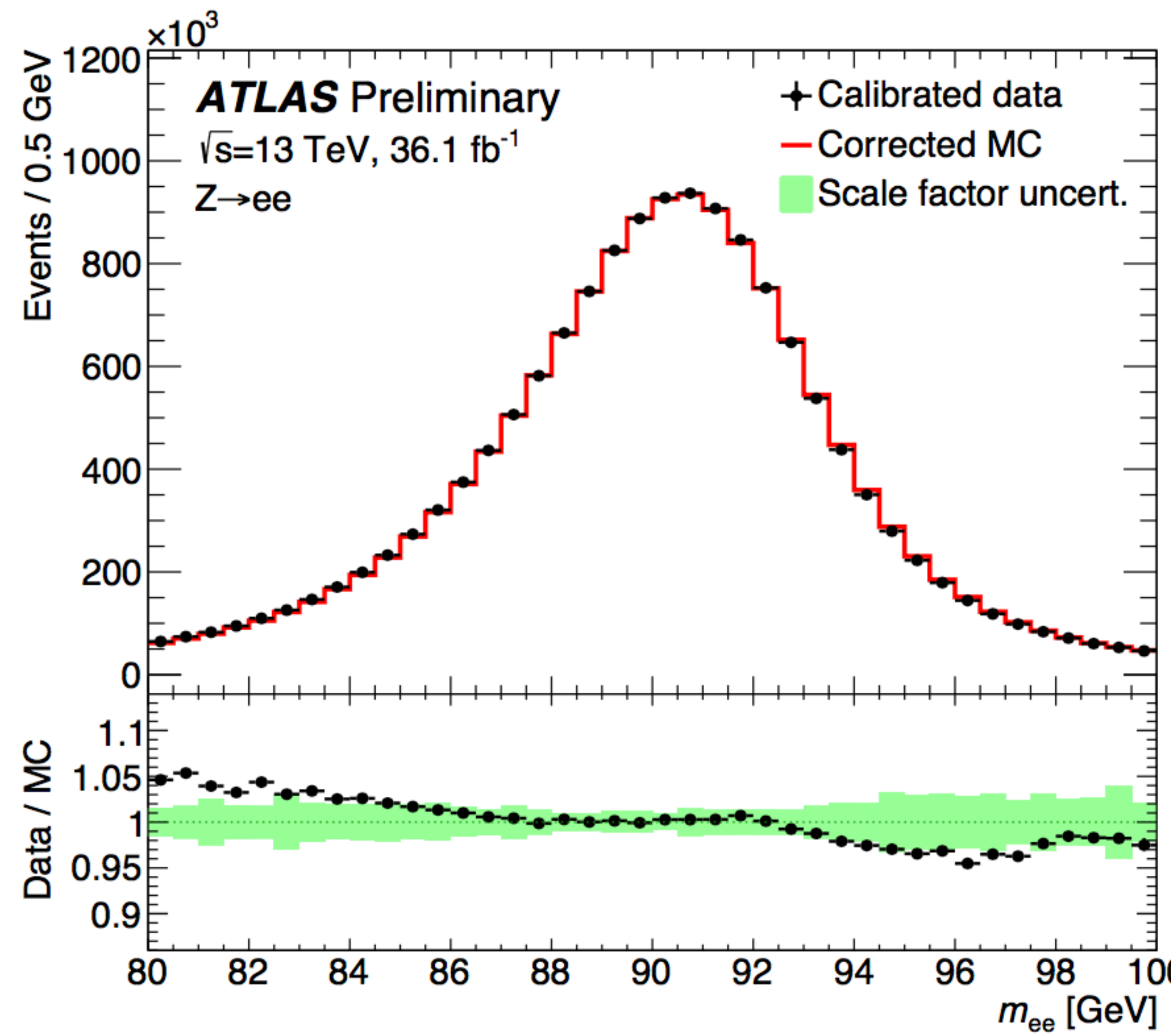
Electrons / photons

- **reconstruction** seeded by EM cluster
  electron: matching track from primary vertex
  converted γ: 1- or 2-track secondary vertex
  unconverted γ
- **calibration** based on $Z \to ee$ data/MC

  Separately for electrons, unconverted photons, converted photons - with BDT technique

Muons

- **combined track-fit** from ID and MS
- calibration based on $J/\psi \to \mu\mu$ and $Z \to \mu\mu$
- especially critical for $H \to 4l$ low-pT events



Higgs mass measurement - H→4l

4-lepton selection: $l^-_1 l^+_1 l^-_2 l^+_2$

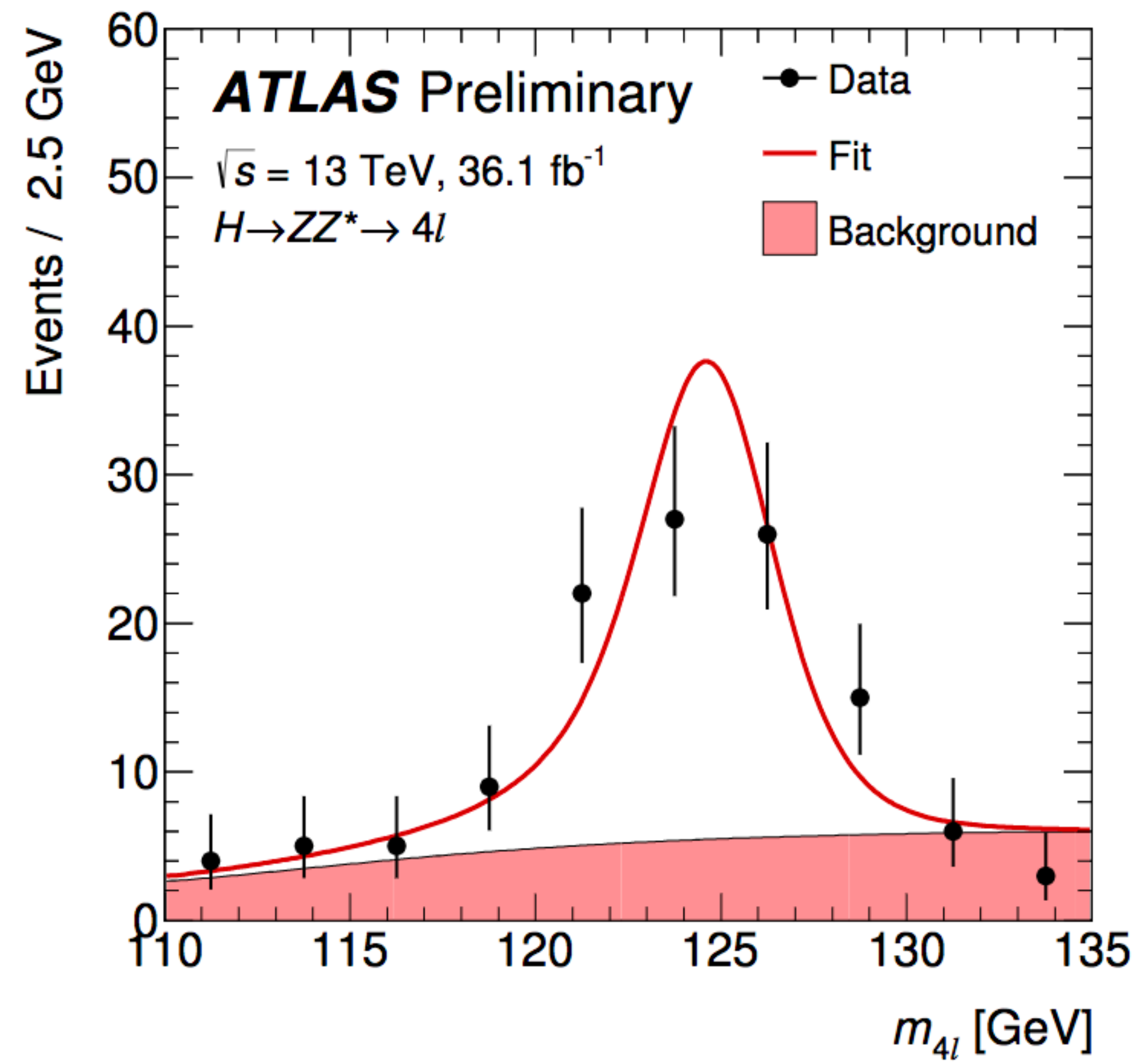
- 50 < $\mathbf{m_{lead}(ll)}$ < 106 GeV
  constrain to m_Z brings
  15% resolution improvement
- $\mathbf{m_{sub\text{-}lead}(ll)}$ > 12 GeV
- 110 < $\mathbf{m_{4\text{-}lepton}}$ < 135 GeV

Classified in **16-categories**

- 4 lepton-pair channels
  4e, 4μ, 2e2μ, 2μ2e
- 4 multivariate BDT regions

Per-event invariant mass PDF as convolution of the 4 leptons energy response functions (depending on lepton flavor, η, p_T)

inclusive



Systematic effect	Uncertainty on $m_H^{ZZ^*}$ [MeV]
Muon momentum scale	40
Electron energy scale	20
Background modelling	10
Simulation statistics	8

Higgs mass measurement - H→4l

4-lepton selection: $l^-_1 l^+_1 l^-_2 l^+_2$

- 50 < $\mathbf{m_{lead}(ll)}$ < 106 GeV
  constrain to m_Z brings
  15% resolution improvement
- $\mathbf{m_{sub\text{-}lead}(ll)}$ > 12 GeV
- 110 < $\mathbf{m_{4\text{-}lepton}}$ < 135 GeV

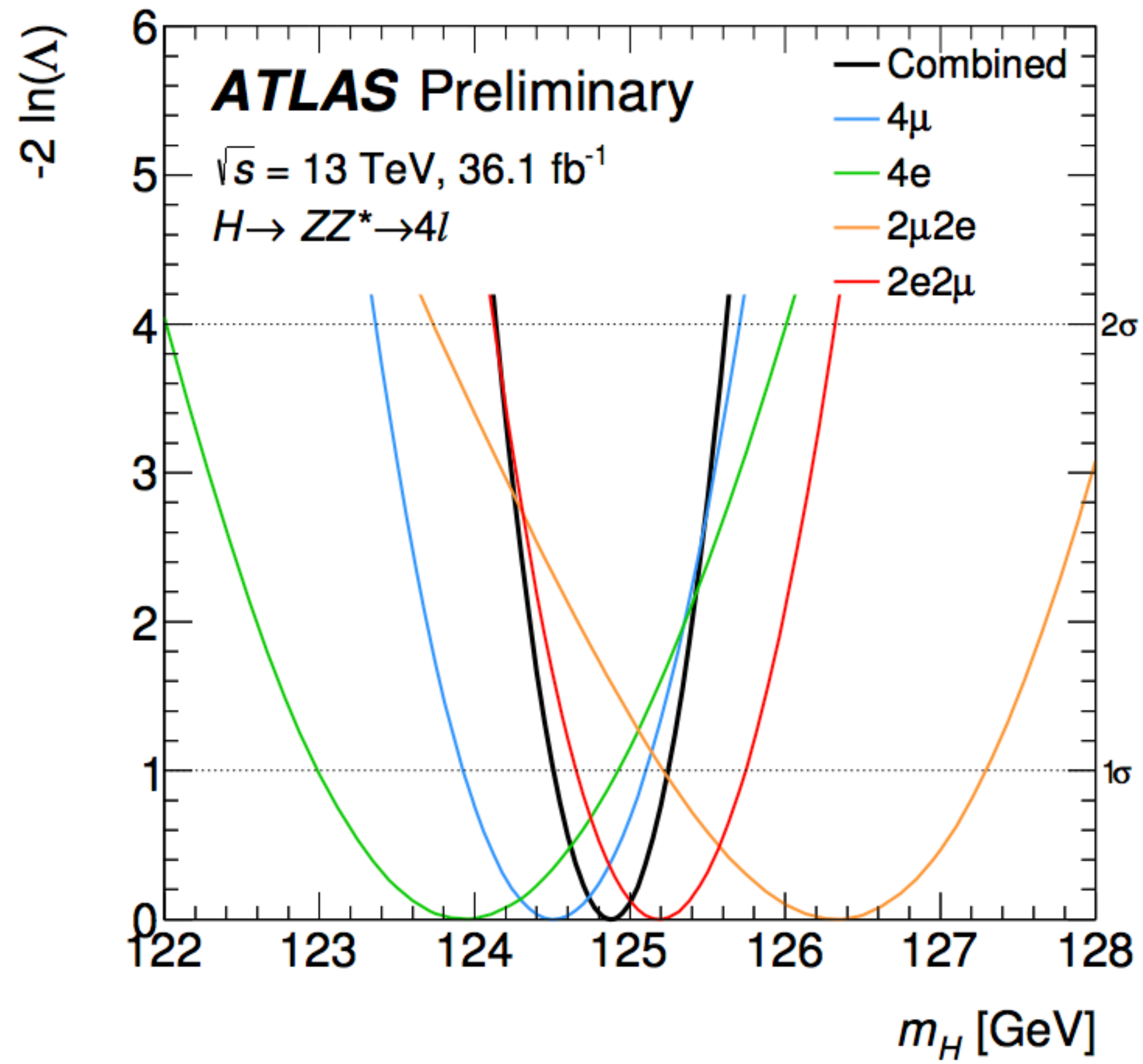
Classified in **16-categories**

- 4 lepton-pair channels
  4e, 4μ, 2e2μ, 2μ2e
- 4 multivariate BDT regions

Dominant channels are 4μ and 2e2μ, where the sub-leading lepton pair is **μμ**

m^{ZZ^*} =124.88 ±0.37(stat) ±0.05(syst) GeV
=124.88 ±0.37 GeV

(clearly stat. dominated)

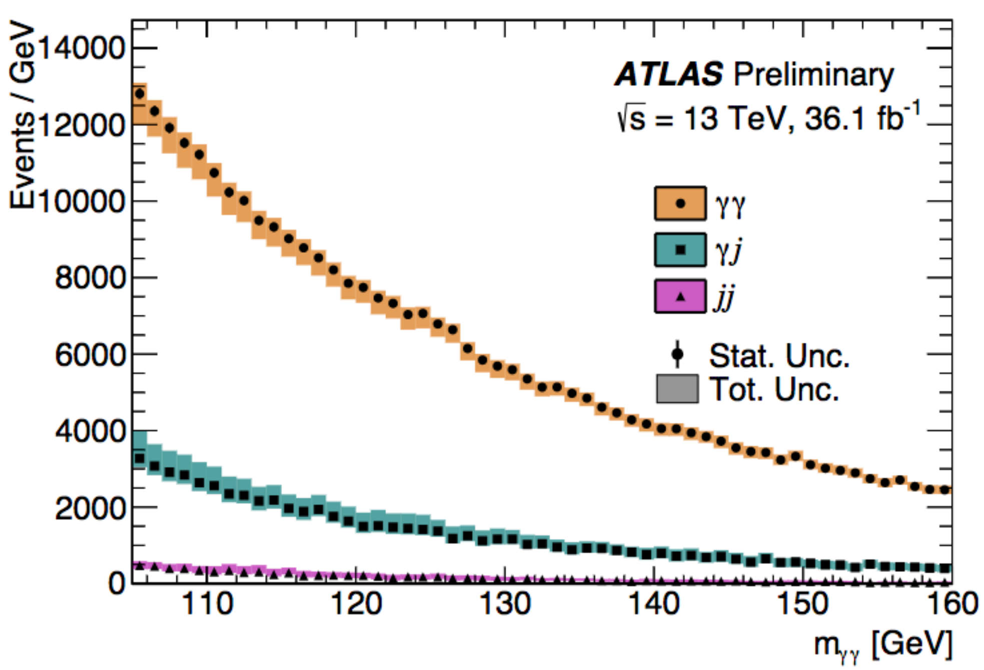


Systematic effect	Uncertainty on $m_H^{ZZ^*}$ [MeV]
Muon momentum scale	40
Electron energy scale	20
Background modelling	10
Simulation statistics	8

Higgs mass measurement - H→γγ

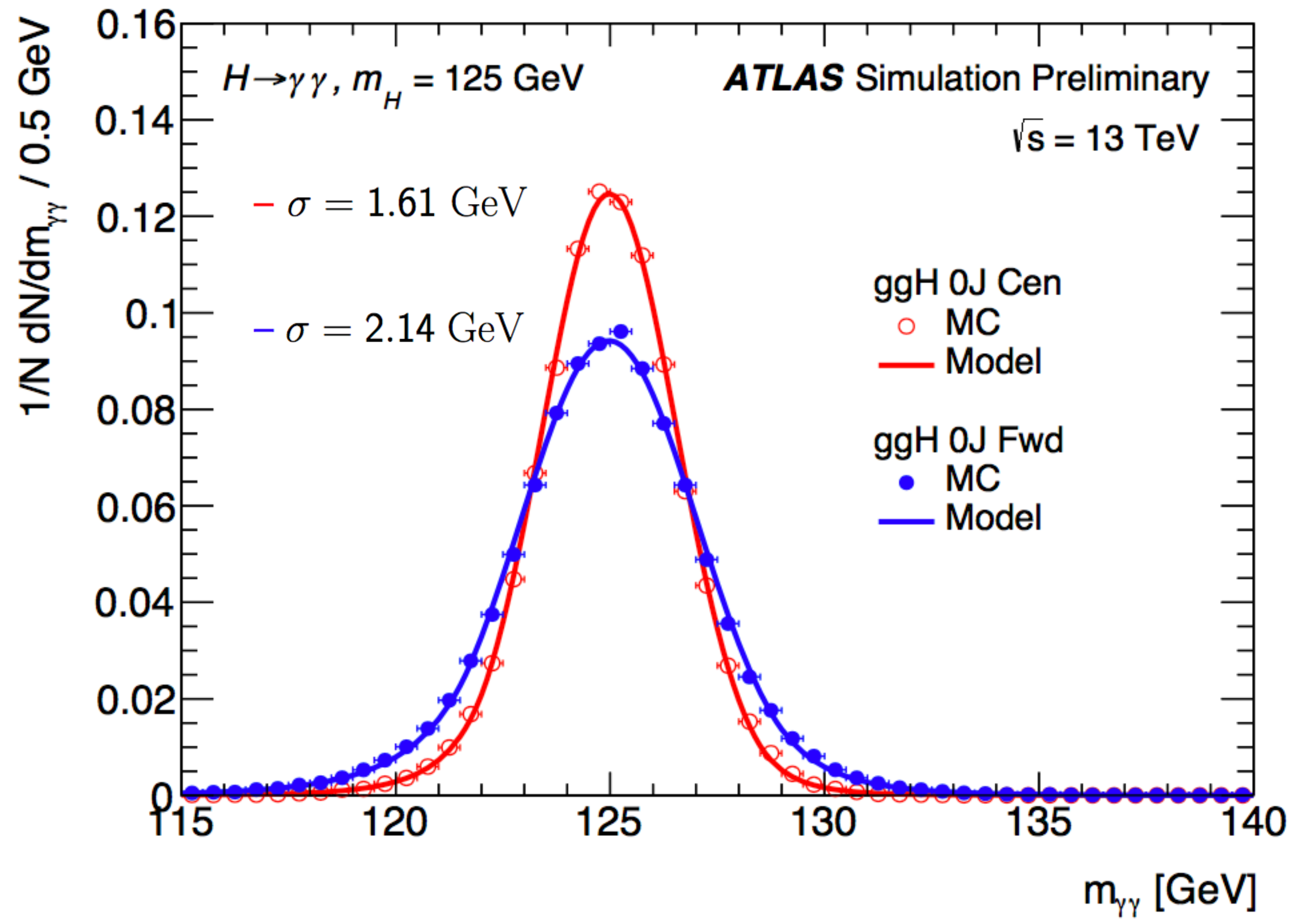
Analysis strongly inherited from coupling / cross-section selection

- 31-categories (STXS stage-1) optimising sensitivity to prod. modes
- 1 signal-model per category, different Gaussian resolution, different non-Gaussian tails
- signal PDF($m_{\gamma\gamma}$) 2-sided Crystal Ball
- background model from empirical analytical functions



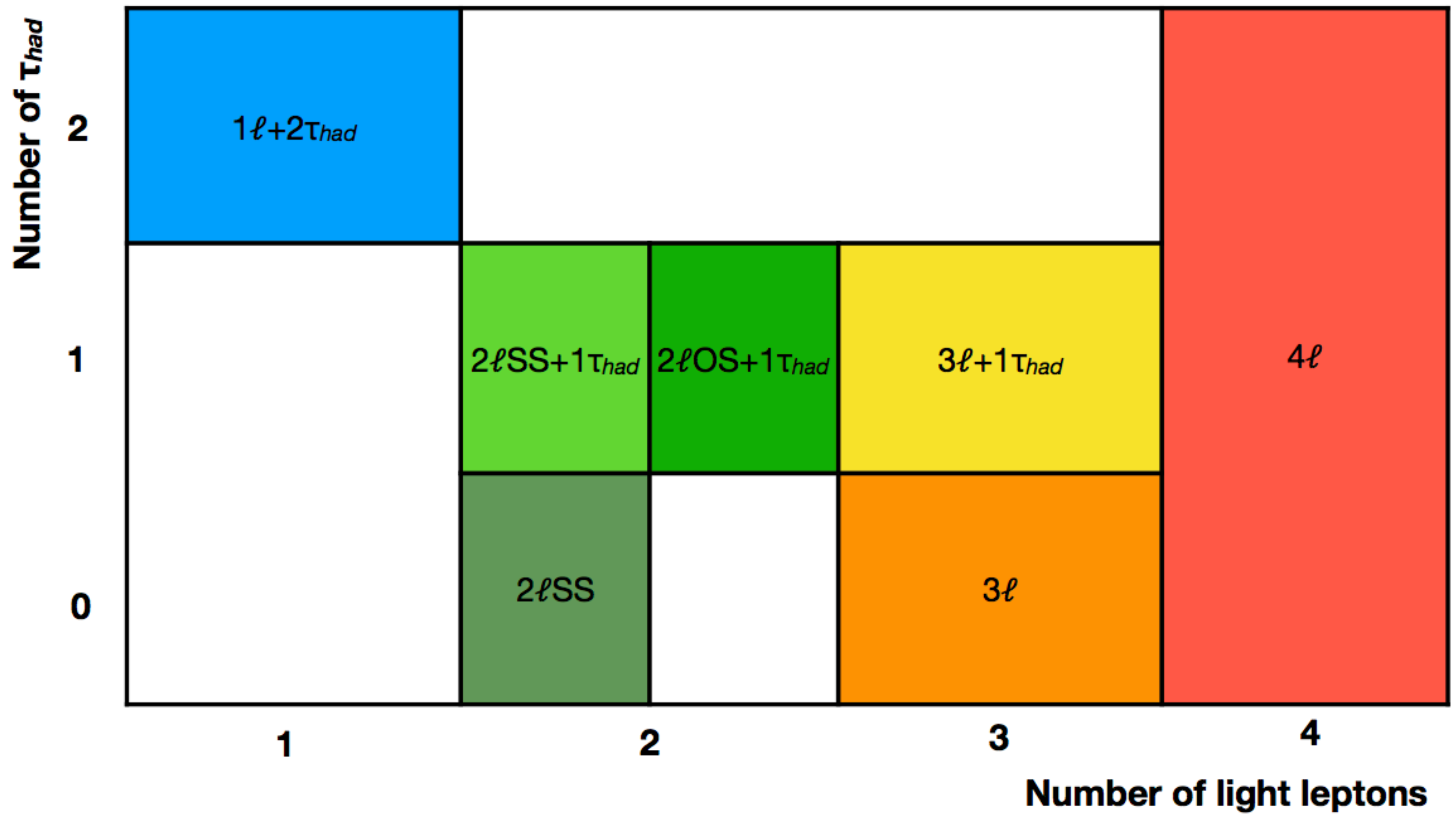
$m^{\gamma\gamma}$ =125.11 ±0.21(stat) ±0.36(syst) GeV

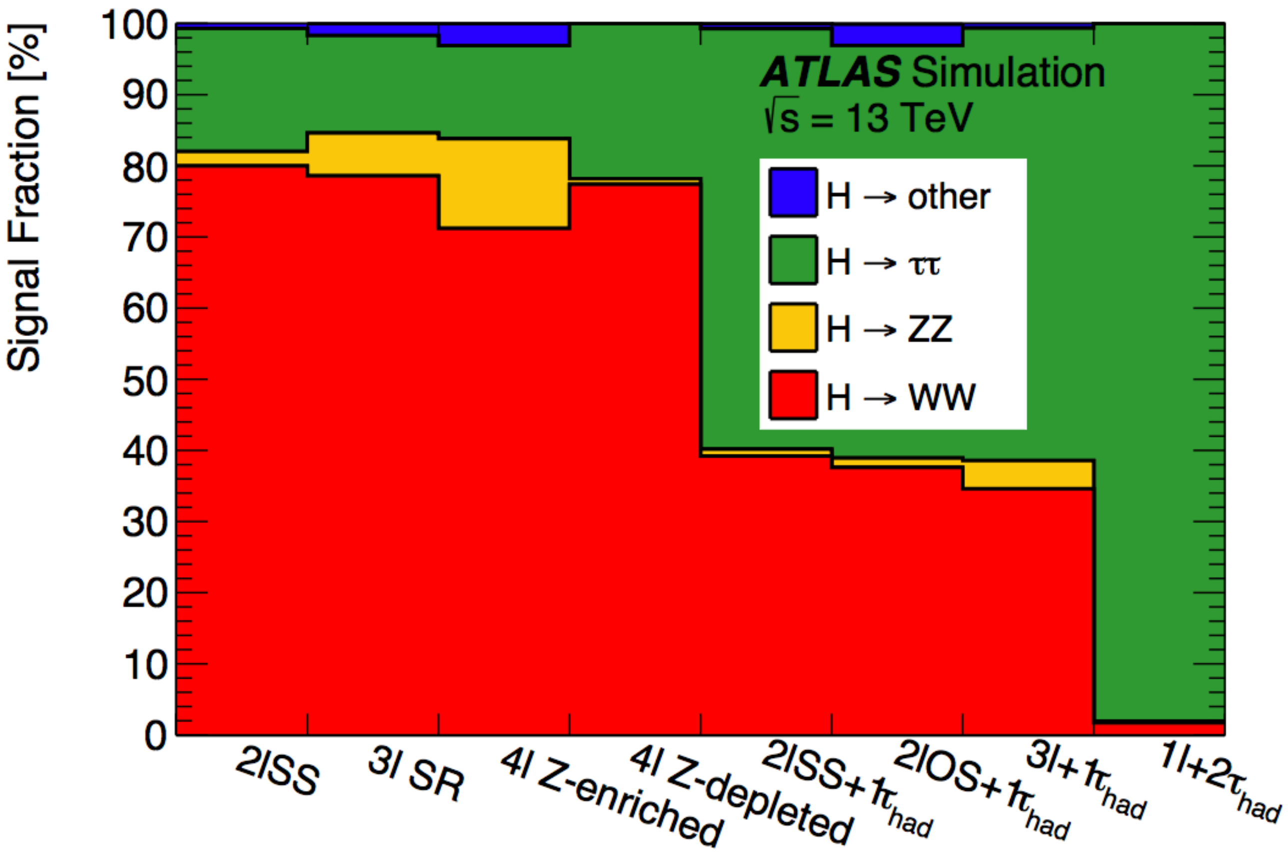
(syst. dominated)

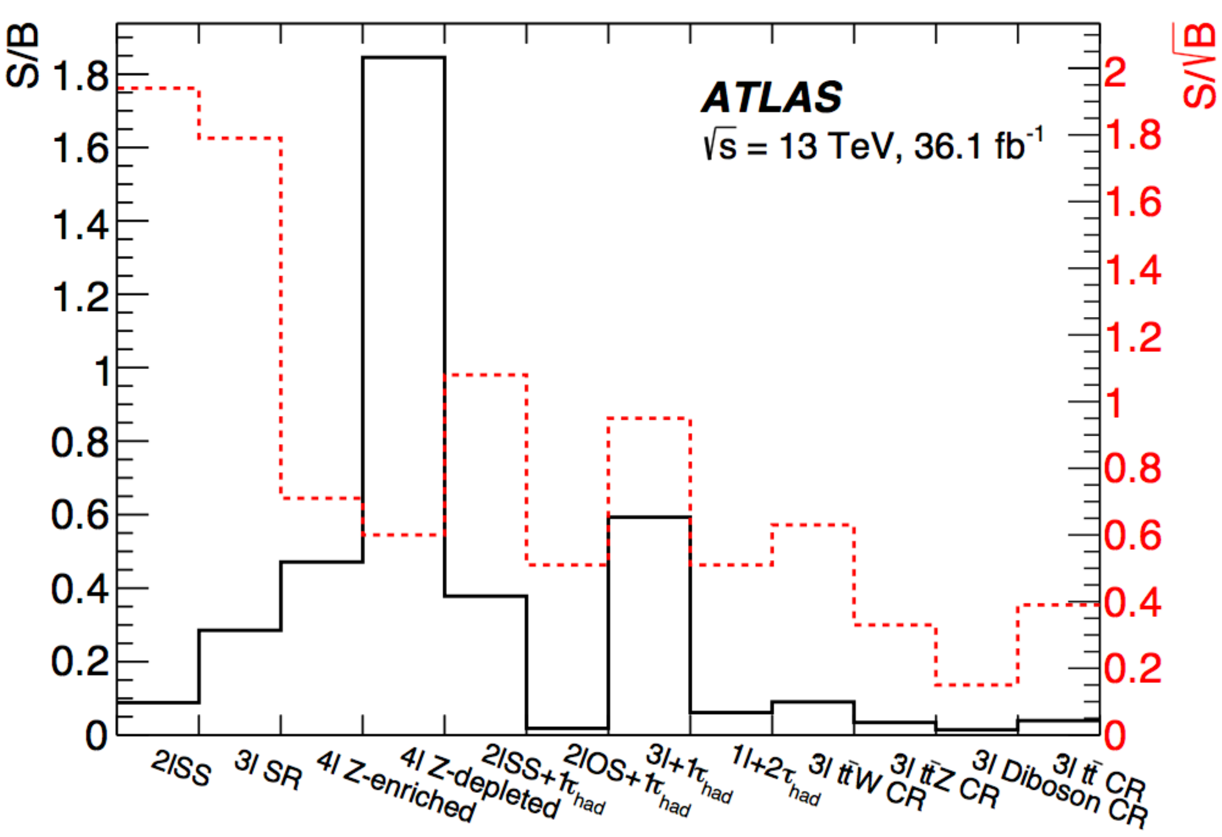


Source	Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]
LAr cell non-linearity	±200
LAr layer calibration	±190
Non-ID material	±120
Lateral shower shape	±110
ID material	±110
Conversion reconstruction	±50
$Z \to ee$ calibration	±50
Background model	±50
Primary vertex effect on mass scale	±40
Resolution	$^{+20}_{-30}$
Signal model	±20

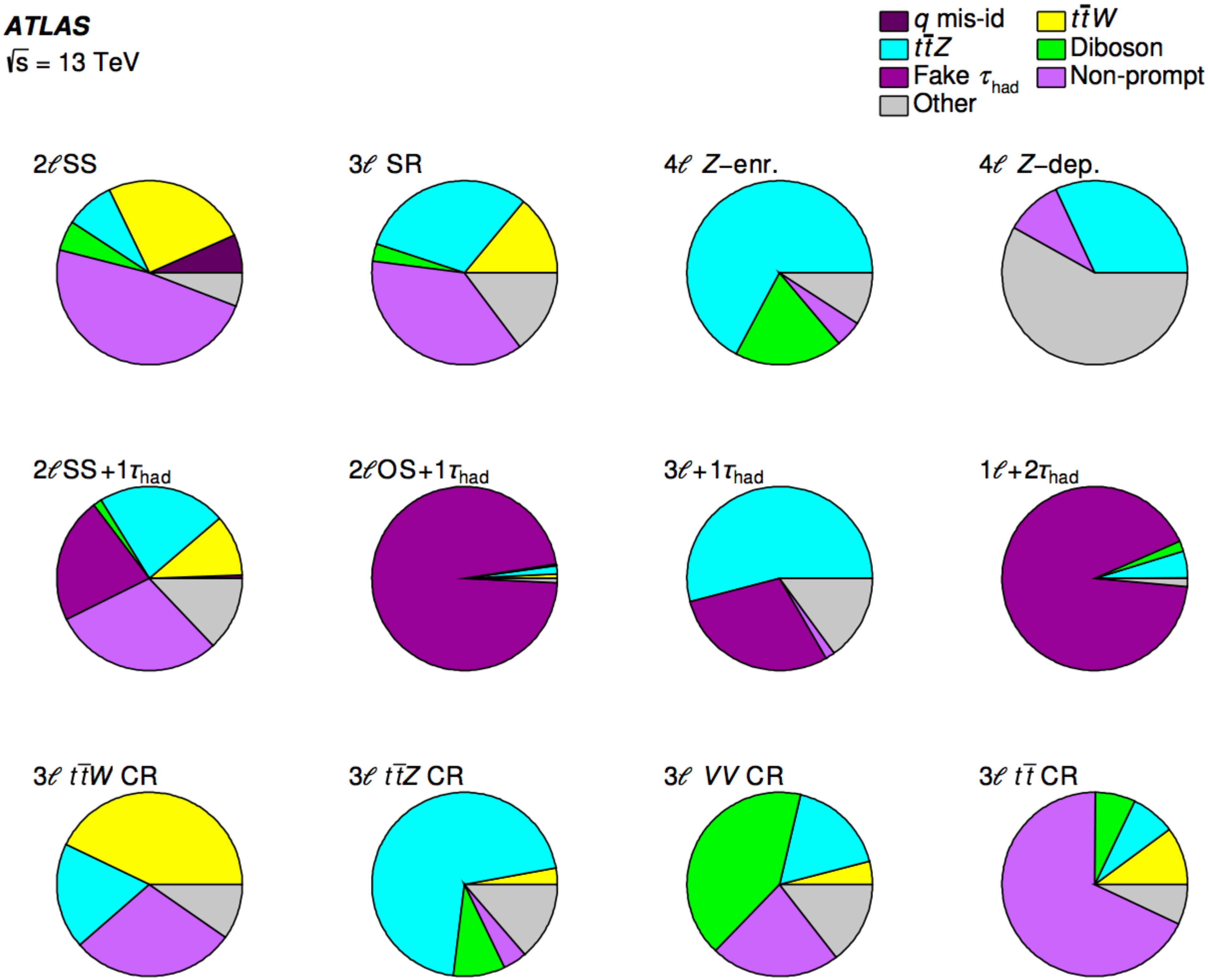
ttH(multilepton categories)







ttH(multilepton categories)

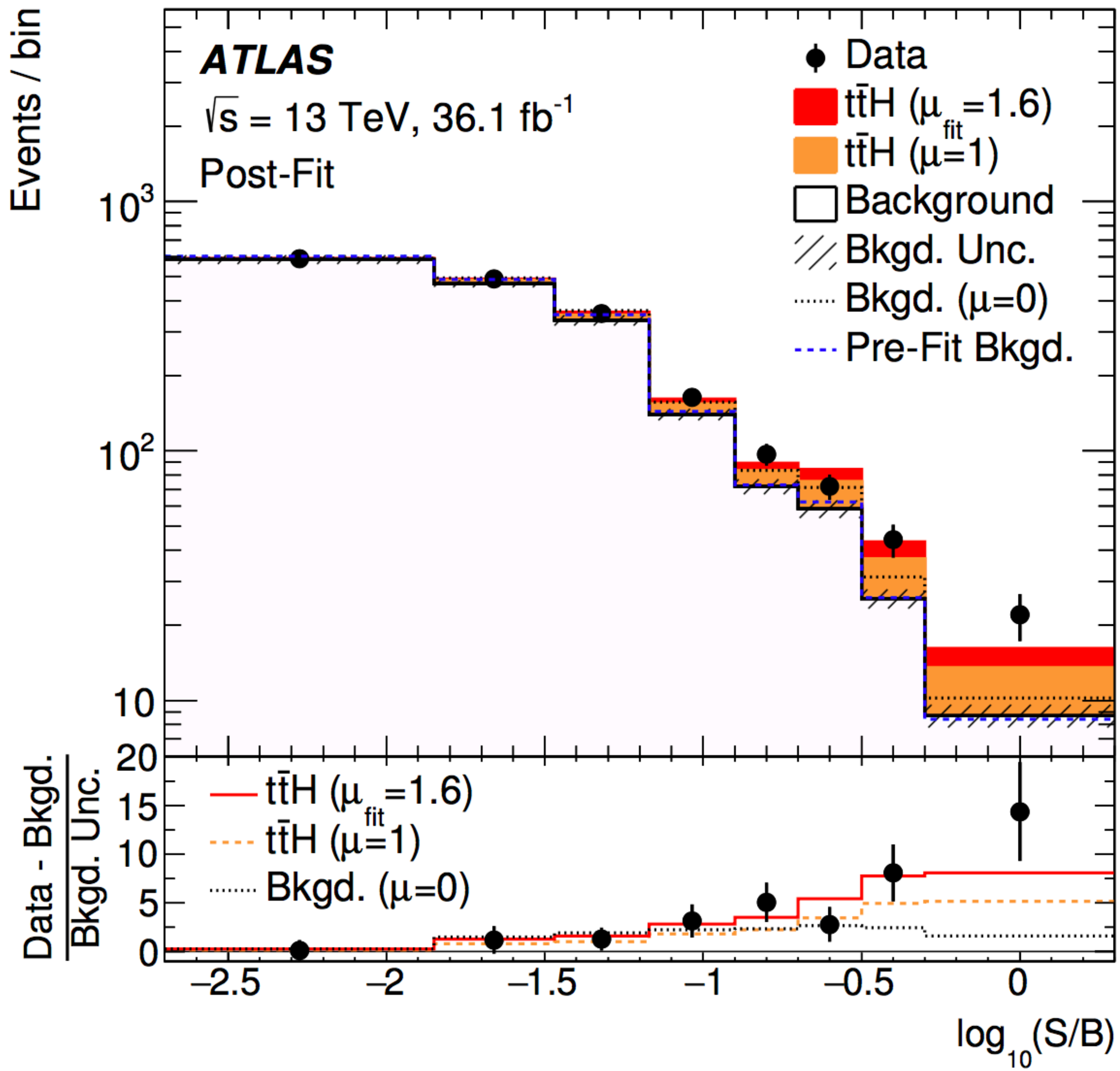


ttH(multilepton categories)

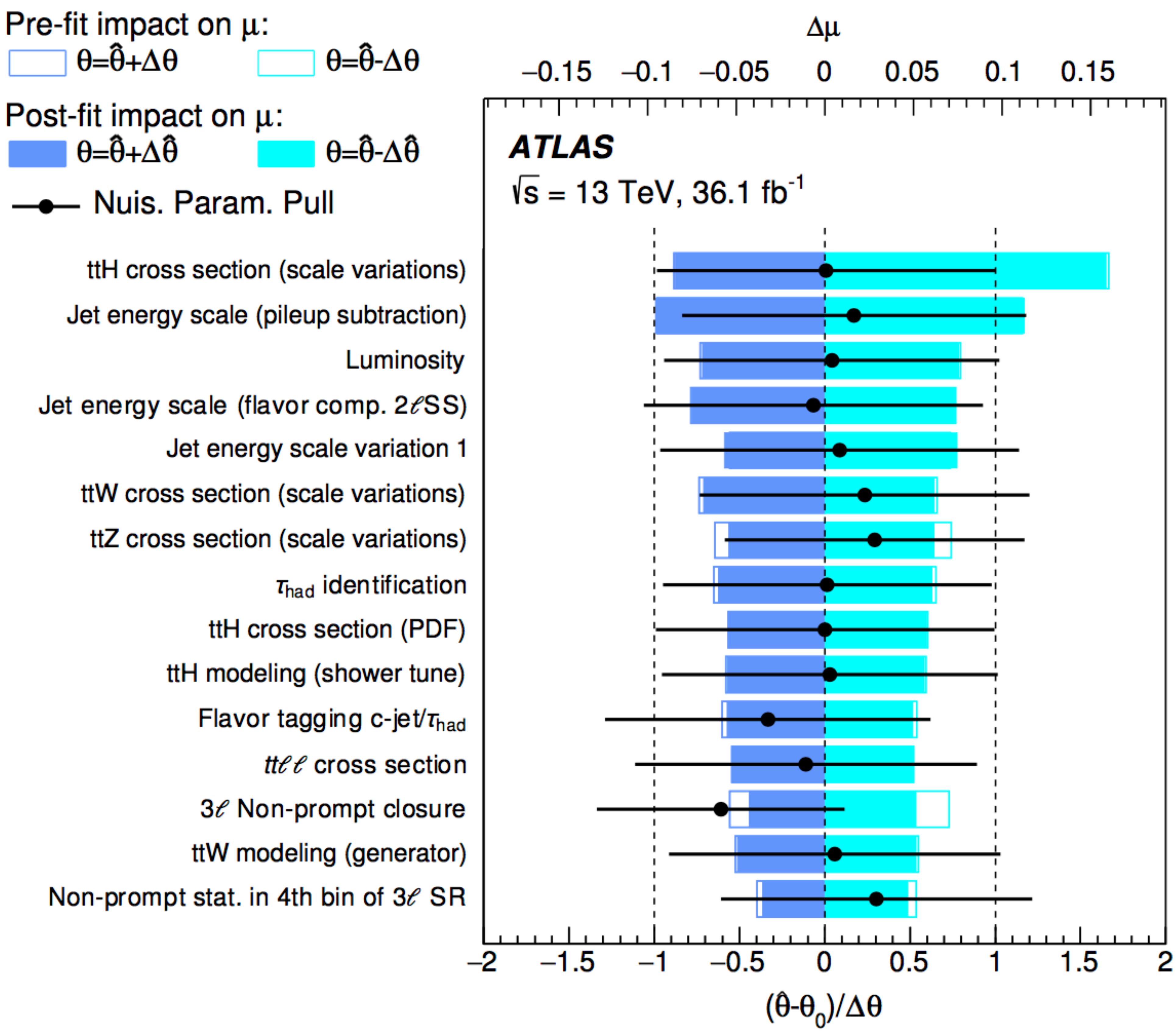
	2ℓSS	3ℓ	4ℓ	1ℓ+$2\tau_{had}$	2ℓSS+$1\tau_{had}$	2ℓOS+$1\tau_{had}$	3ℓ+$1\tau_{had}$
Light lepton	2T*	1L*, 2T*	2L, 2T	1T	2T*	2L†	1L†, 2T
τ_{had}	0M	0M	–	1T, 1M	1M	1M	1M
N_{jets}, $N_{b\text{-}jets}$	$\geq 4, = 1, 2$	$\geq 2, \geq 1$	$\geq 2, \geq 1$	$\geq 3, \geq 1$	$\geq 4, \geq 1$	$\geq 3, \geq 1$	$\geq 2, \geq 1$

Channel	Selection criteria
Common	$N_{jets} \geq 2$ and $N_{b\text{-}jets} \geq 1$
2ℓSS	Two very tight light leptons with $p_T > 20$ GeV Same-charge light leptons Zero medium τ_{had} candidates $N_{jets} \geq 4$ and $N_{b\text{-}jets} < 3$
3ℓ	Three light leptons with $p_T > 10$ GeV; sum of light-lepton charges ± 1 Two same-charge leptons must be very tight and have $p_T > 15$ GeV The opposite-charge lepton must be loose, isolated and pass the non-prompt BDT Zero medium τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2 \text{ GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(3\ell) - 91.2 \text{ GeV}\rvert > 10$ GeV
4ℓ	Four light leptons; sum of light-lepton charges 0 Third and fourth leading leptons must be tight $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2 \text{ GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(4\ell) - 125 \text{ GeV}\rvert > 5$ GeV Split 2 categories: Z-depleted (0 SFOC pairs) and Z-enriched (2 or 4 SFOC pairs)
1ℓ+$2\tau_{had}$	One tight light lepton with $p_T > 27$ GeV Two medium τ_{had} candidates of opposite charge, at least one being tight $N_{jets} \geq 3$
2ℓSS+$1\tau_{had}$	Two very tight light leptons with $p_T > 15$ GeV Same-charge light leptons One medium τ_{had} candidate, with charge opposite to that of the light leptons $N_{jets} \geq 4$ $\lvert m(ee) - 91.2 \text{ GeV}\rvert > 10$ GeV for ee events
2ℓOS+$1\tau_{had}$	Two loose and isolated light leptons with $p_T > 25, 15$ GeV One medium τ_{had} candidate Opposite-charge light leptons One medium τ_{had} candidate $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2 \text{ GeV}\rvert > 10$ GeV for the SFOC pair $N_{jets} \geq 3$
3ℓ+$1\tau_{had}$	3ℓ selection, except: One medium τ_{had} candidate, with charge opposite to the total charge of the light leptons The two same-charge light leptons must be tight and have $p_T > 10$ GeV The opposite-charge light lepton must be loose and isolated

ttH(multilepton)



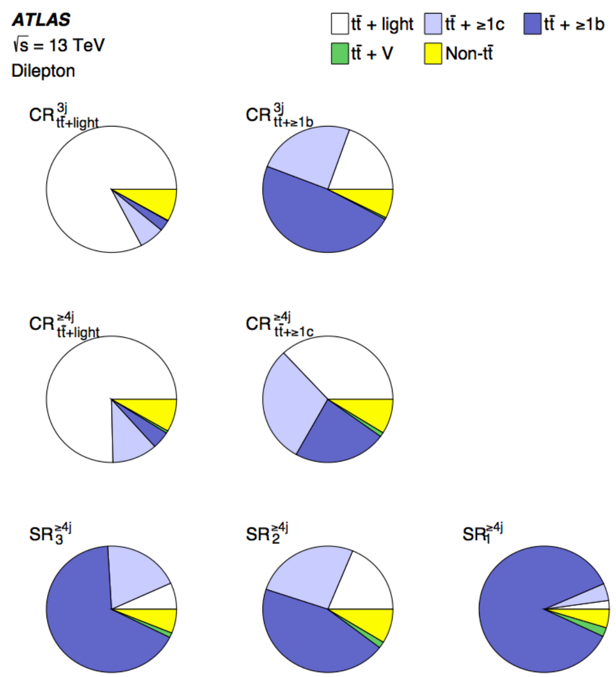
ttH(multilepton)

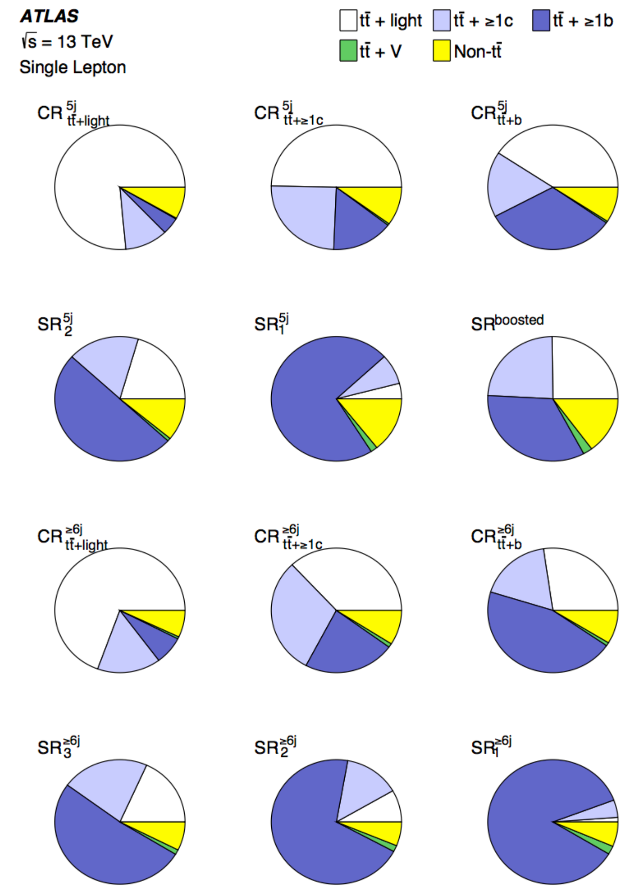


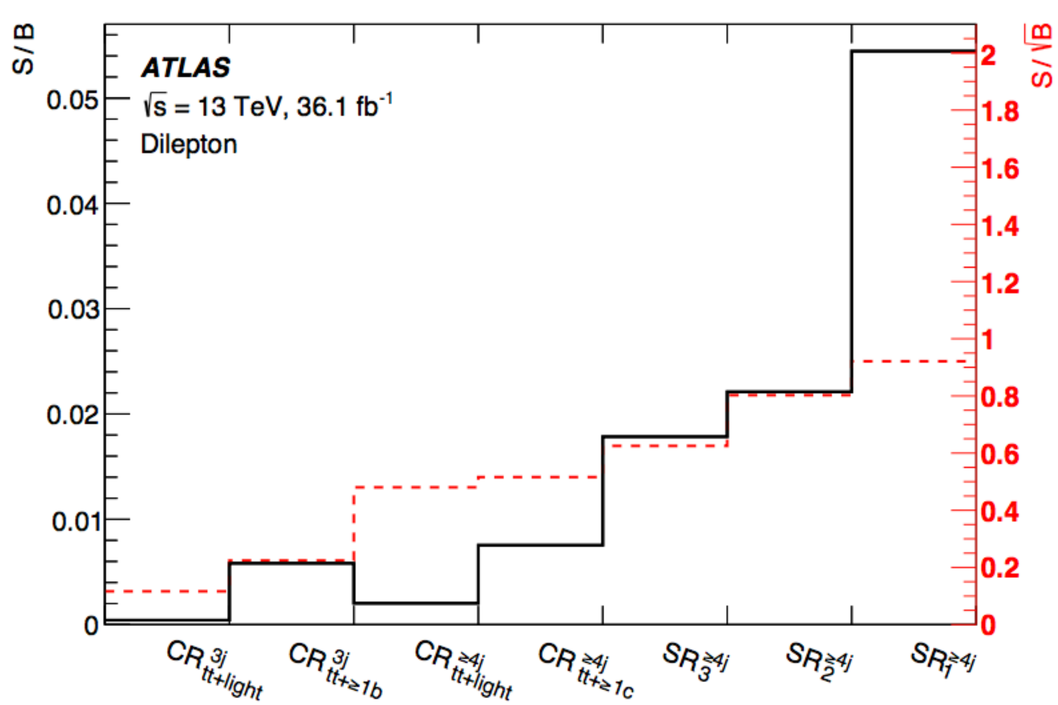
ttH(multilepton)

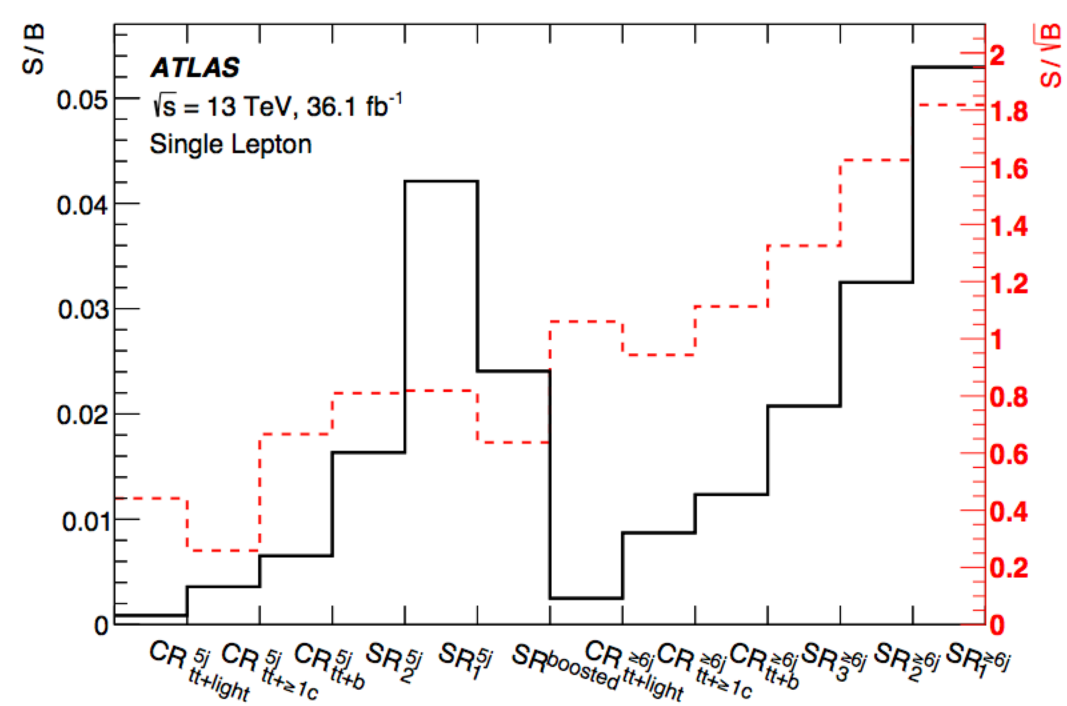
Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	+0.20	−0.09
Jet energy scale and resolution	+0.18	−0.15
Non-prompt light-lepton estimates	+0.15	−0.13
Jet flavor tagging and τ_{had} identification	+0.11	−0.09
$t\bar{t}W$ modeling	+0.10	−0.09
$t\bar{t}Z$ modeling	+0.08	−0.07
Other background modeling	+0.08	−0.07
Luminosity	+0.08	−0.06
$t\bar{t}H$ modeling (acceptance)	+0.08	−0.04
Fake τ_{had} estimates	+0.07	−0.07
Other experimental uncertainties	+0.05	−0.04
Simulation sample size	+0.04	−0.04
Charge misassignment	+0.01	−0.01
Total systematic uncertainty	+0.39	−0.30

ttH(bb)

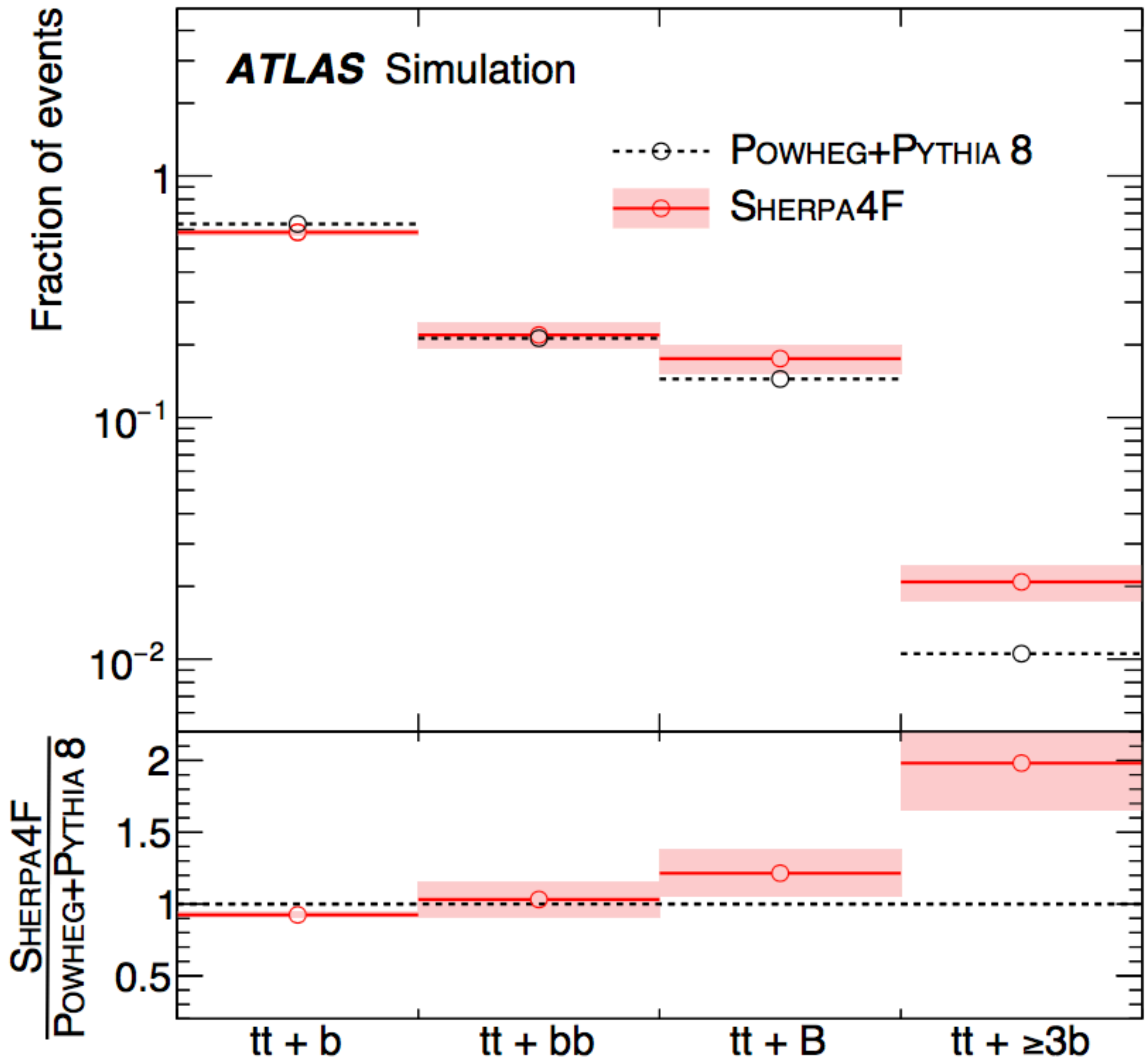

ATLAS
√s = 13 TeV
Dilepton
tt̄ + light
tt̄ + ≥1c
tt̄ + ≥1b
tt̄ + V
Non-tt̄


ATLAS
√s = 13 TeV
Single Lepton
tt̄ + light
tt̄ + ≥1c
tt̄ + ≥1b
tt̄ + V
Non-tt̄


ATLAS
√s = 13 TeV, 36.1 fb-1
Dilepton
S / B
S/√B


ATLAS
√s = 13 TeV, 36.1 fb-1
Single Lepton
S / B
S/√B

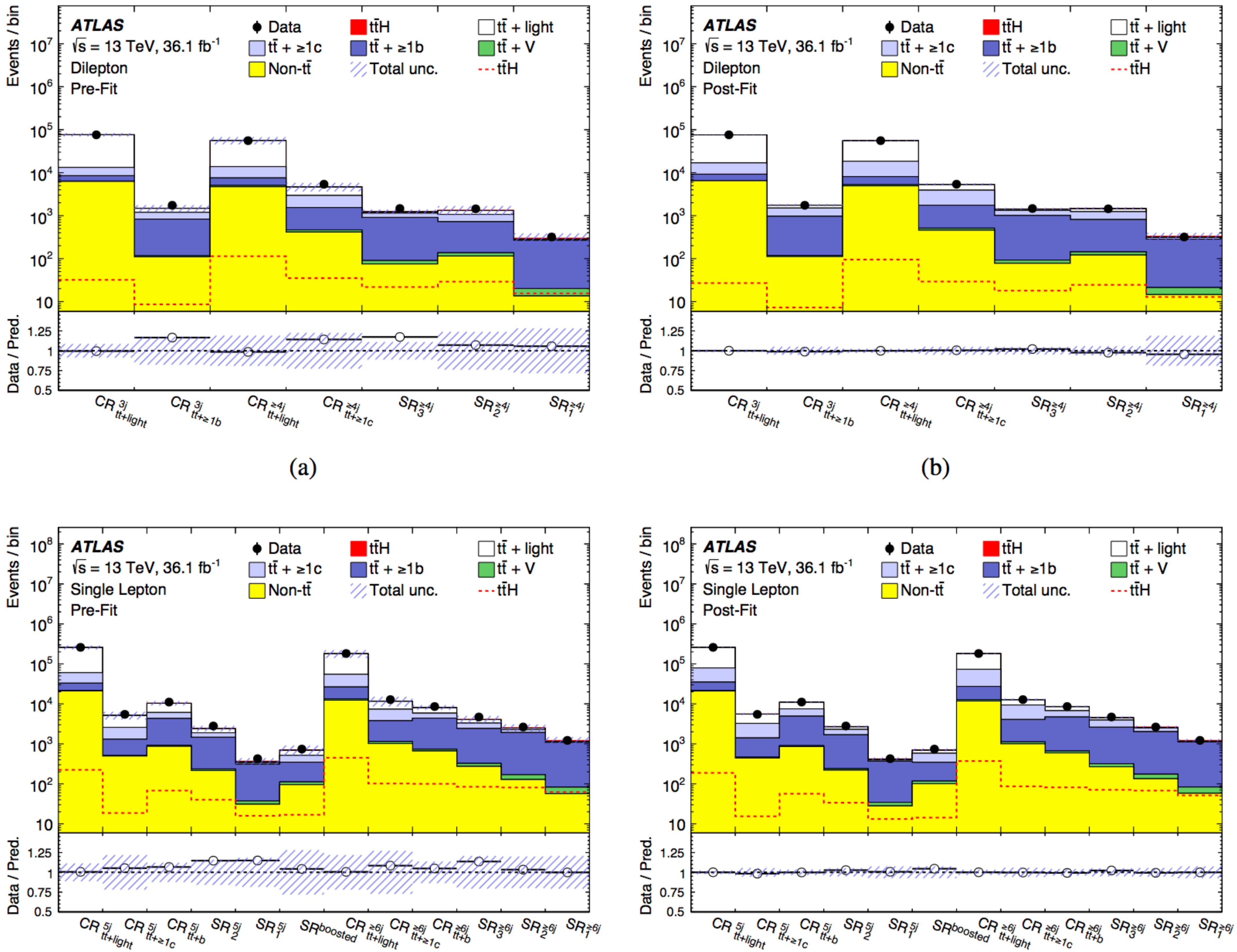
ttH(bb)


ATLAS Simulation
Powheg+Pythia 8
Sherpa4F
Fraction of events
1
10^{-1}
10^{-2}
Sherpa4F / Powheg+Pythia 8
2
1.5
1
0.5
tt + b
tt + bb
tt + B
tt + ≥3b

ttH(bb)

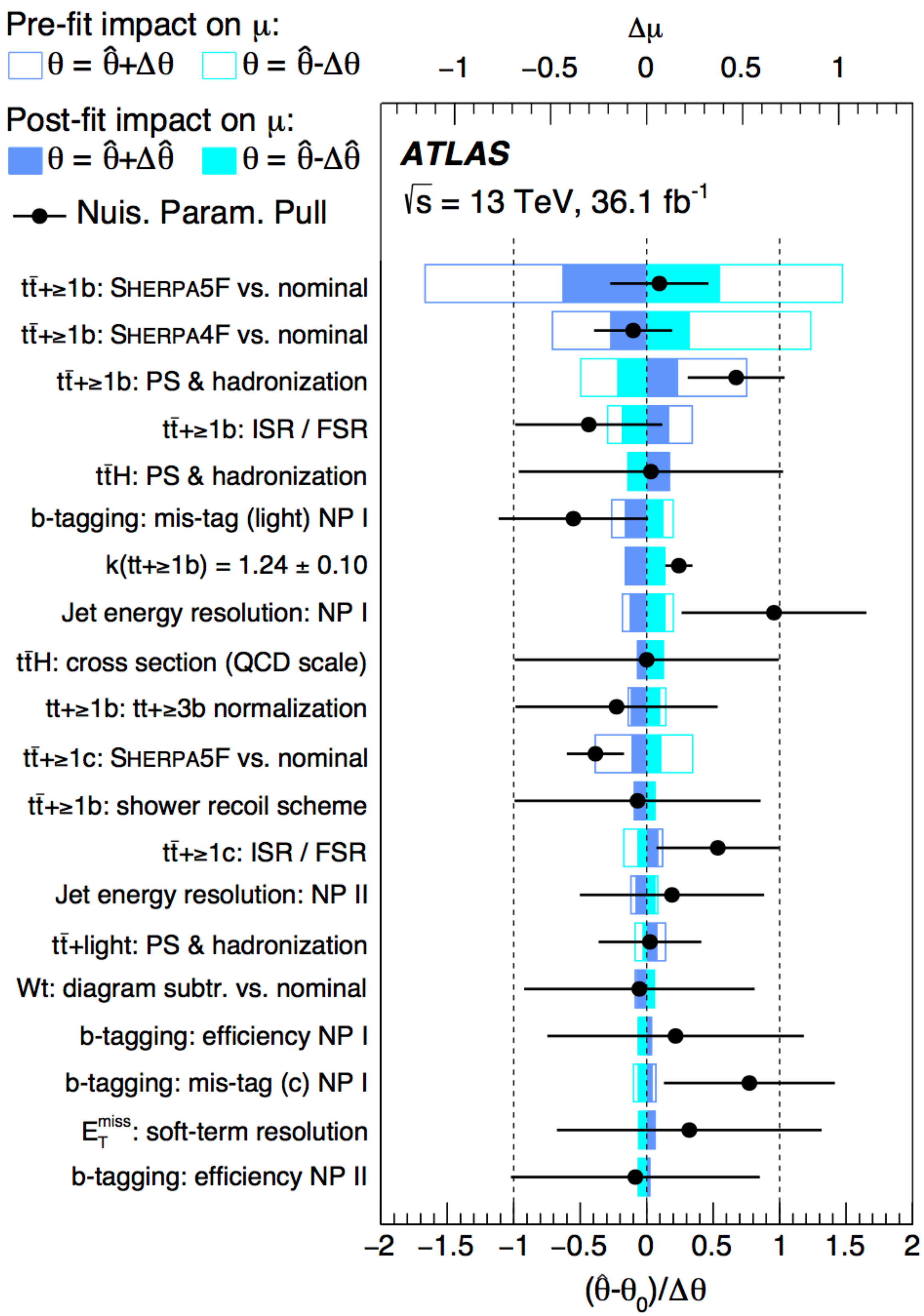
Systematic source	Description	$t\bar{t}$ categories
$t\bar{t}$ cross-section	Up or down by 6%	All, correlated
$k(t\bar{t} + \geq 1c)$	Free-floating $t\bar{t} + \geq 1c$ normalization	$t\bar{t} + \geq 1c$
$k(t\bar{t} + \geq 1b)$	Free-floating $t\bar{t} + \geq 1b$ normalization	$t\bar{t} + \geq 1b$
SHERPA5F vs. nominal	Related to the choice of NLO event generator	All, uncorrelated
PS & hadronization	POWHEG+HERWIG 7 vs. POWHEG+PYTHIA 8	All, uncorrelated
ISR / FSR	Variations of μ_R, μ_F, h_{damp} and A14 Var3c parameters	All, uncorrelated
$t\bar{t} + \geq 1c$ ME vs. inclusive	MG5_aMC@NLO+HERWIG++: ME prediction (3F) vs. incl. (5F)	$t\bar{t} + \geq 1c$
$t\bar{t} + \geq 1b$ SHERPA4F vs. nominal	Comparison of $t\bar{t} + b\bar{b}$ NLO (4F) vs. POWHEG+PYTHIA 8 (5F)	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ renorm. scale	Up or down by a factor of two	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ resumm. scale	Vary μ_Q from $H_T/2$ to μ_{CMMPS}	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ global scales	Set μ_Q, μ_R, and μ_F to μ_{CMMPS}	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ shower recoil scheme	Alternative model scheme	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ PDF (MSTW)	MSTW vs. CT10	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ PDF (NNPDF)	NNPDF vs. CT10	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ UE	Alternative set of tuned parameters for the underlying event	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ MPI	Up or down by 50%	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 3b$ normalization	Up or down by 50%	$t\bar{t} + \geq 1b$

ttH(bb)



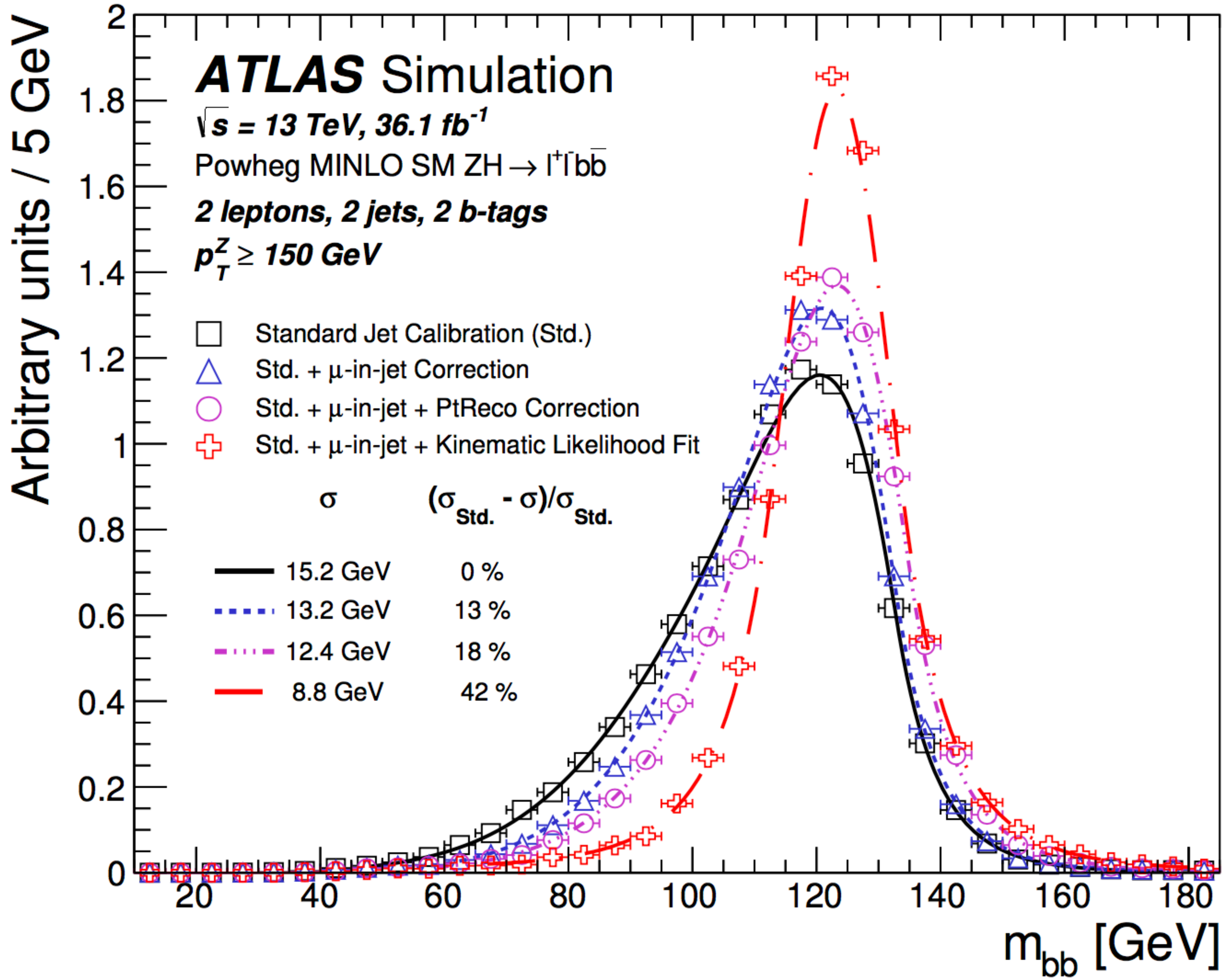
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Dilepton
Pre-Fit
Post-Fit
Single Lepton
Data
tt̄H
tt̄ + light
tt̄ + ≥1c
tt̄ + ≥1b
tt̄ + V
Non-tt̄
Total unc.
Events / bin
Data / Pred.
(a)
(b)

ttH(bb)



Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t} + \geq 1c$ modeling	+0.09	−0.11
JVT, pileup modeling	+0.03	−0.05
Other background modeling	+0.08	−0.08
$t\bar{t}$ + light modeling	+0.06	−0.03
Luminosity	+0.03	−0.02
Light lepton (e, μ) id., isolation, trigger	+0.03	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t} + \geq 1b$ normalization	+0.09	−0.10
$t\bar{t} + \geq 1c$ normalization	+0.02	−0.03
Intrinsic statistical uncertainty	+0.21	−0.20
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

VH(bb)



ATLAS Simulation
√s = 13 TeV, 36.1 fb⁻¹
Powheg MINLO SM ZH → l⁺l⁻bb̄
2 leptons, 2 jets, 2 b-tags
p_T^Z ≥ 150 GeV
Standard Jet Calibration (Std.)
Std. + μ-in-jet Correction
Std. + μ-in-jet + PtReco Correction
Std. + μ-in-jet + Kinematic Likelihood Fit
σ
(σ_Std. - σ)/σ_Std.
15.2 GeV 0 %
13.2 GeV 13 %
12.4 GeV 18 %
8.8 GeV 42 %
Arbitrary units / 5 GeV
m_bb [GeV]

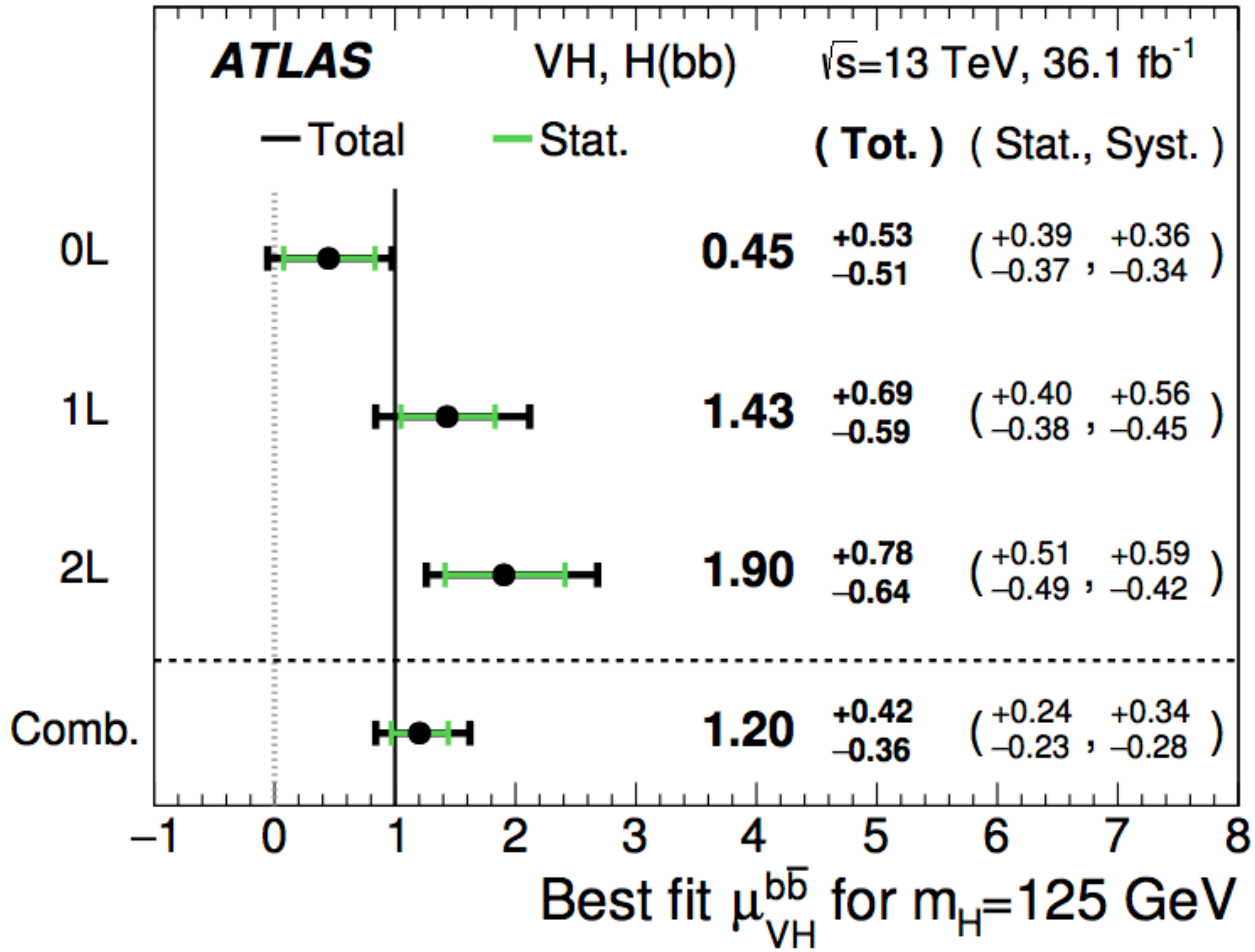
VH(bb)

Z + jets	
$Z+ll$ normalisation	18%
$Z+cl$ normalisation	23%
$Z+bb$ normalisation	Floating (2-jet, 3-jet)
$Z+bc$-to-$Z+bb$ ratio	30 – 40%
$Z+cc$-to-$Z+bb$ ratio	13 – 15%
$Z+bl$-to-$Z+bb$ ratio	20 – 25%
0-to-2 lepton ratio	7%
m_{bb}, p_T^V	S
W + jets	
$W+ll$ normalisation	32%
$W+cl$ normalisation	37%
$W+bb$ normalisation	Floating (2-jet, 3-jet)
$W+bl$-to-$W+bb$ ratio	26% (0-lepton) and 23% (1-lepton)
$W+bc$-to-$W+bb$ ratio	15% (0-lepton) and 30% (1-lepton)
$W+cc$-to-$W+bb$ ratio	10% (0-lepton) and 30% (1-lepton)
0-to-1 lepton ratio	5%
W + HF CR to SR ratio	10% (1-lepton)
m_{bb}, p_T^V	S
$t\bar{t}$ (all are uncorrelated between the 0+1 and 2-lepton channels)	
$t\bar{t}$ normalisation	Floating (0+1 lepton, 2-lepton 2-jet, 2-lepton 3-jet)
0-to-1 lepton ratio	8%
2-to-3-jet ratio	9% (0+1 lepton only)
W + HF CR to SR ratio	25%
m_{bb}, p_T^V	S
Single top quark	
Cross-section	4.6% (s-channel), 4.4% (t-channel), 6.2% (Wt)
Acceptance 2-jet	17% (t-channel), 35% (Wt)
Acceptance 3-jet	20% (t-channel), 41% (Wt)
m_{bb}, p_T^V	S (t-channel, Wt)
Multi-jet (1-lepton)	
Normalisation	60 – 100% (2-jet), 100 – 400% (3-jet)
BDT template	S

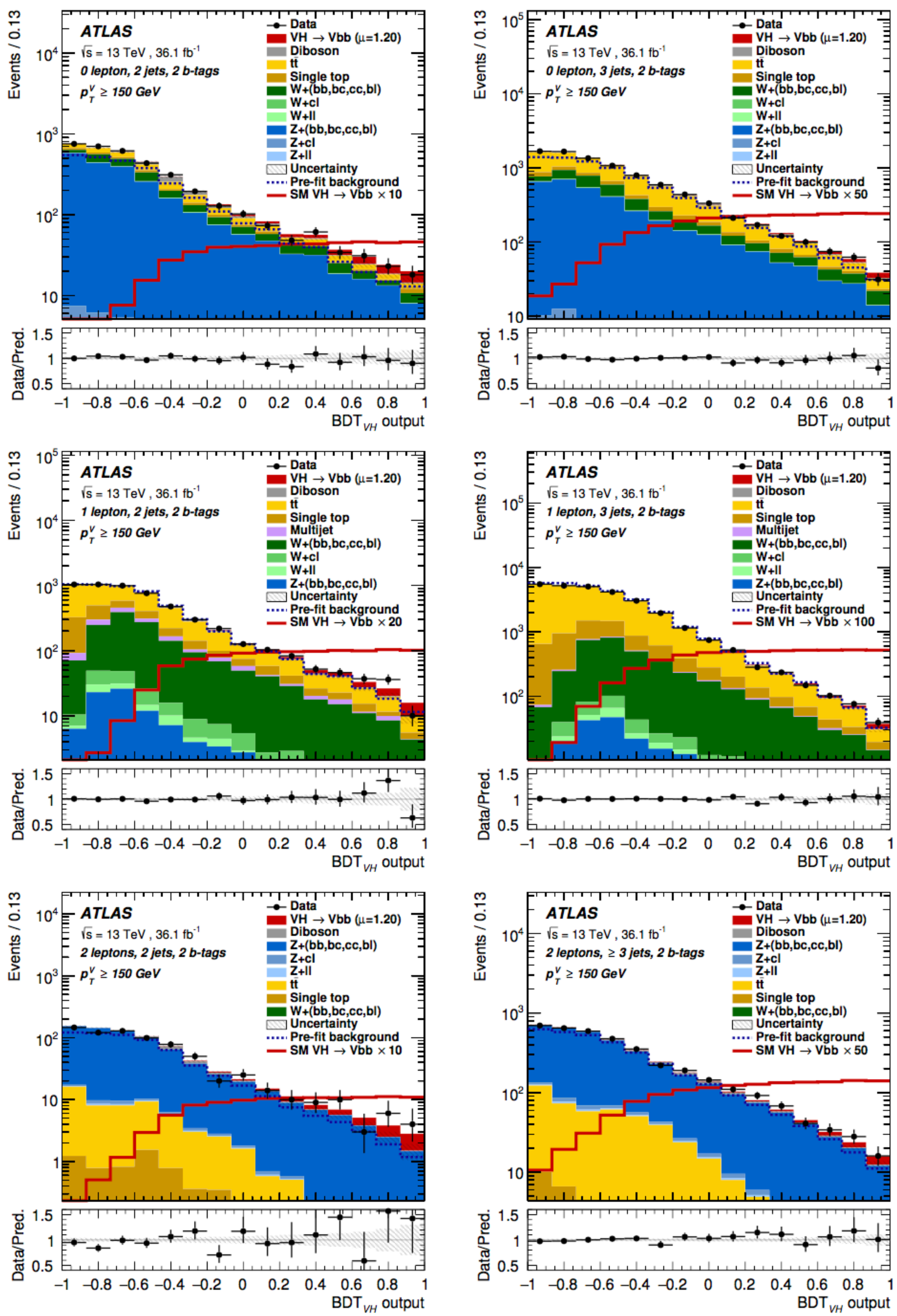
Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.90 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	0.97 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	1.04 ± 0.06
W + HF 2-jet	1.22 ± 0.14
W + HF 3-jet	1.27 ± 0.14
Z + HF 2-jet	1.30 ± 0.10
Z + HF 3-jet	1.22 ± 0.09

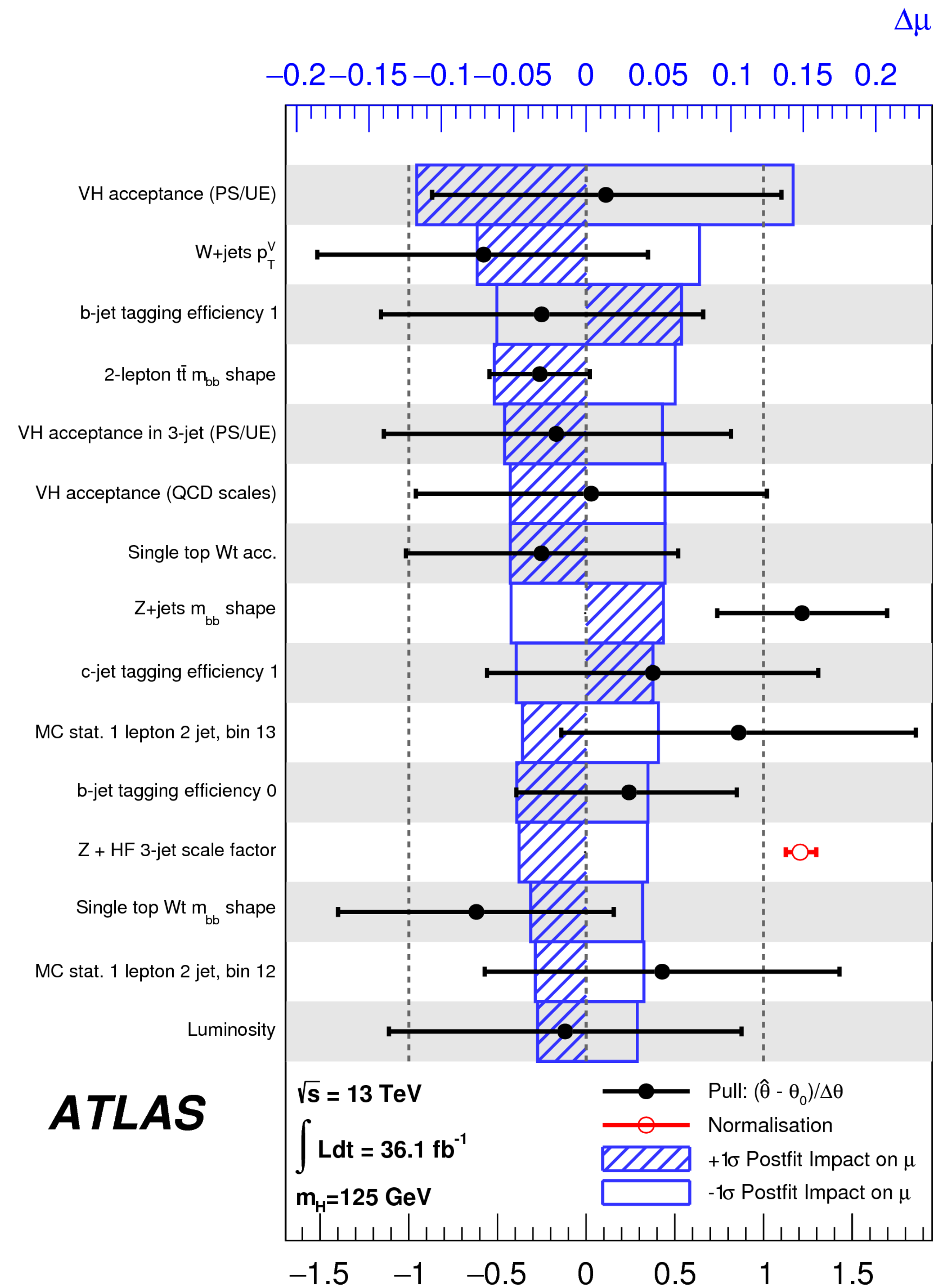
Channel	SR/CR	Categories			
		75 GeV $< p_T^V <$ 150 GeV		$p_T^V >$ 150 GeV	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	—	—	BDT	BDT
1-lepton	SR	—	—	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	—	—	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

VH(bb)


ATLAS
VH, H(bb)
√s=13 TeV, 36.1 fb-1
Total
Stat.
(Tot.) (Stat., Syst.)
0L
0.45 +0.53 −0.51 (+0.39 −0.37 , +0.36 −0.34)
1L
1.43 +0.69 −0.59 (+0.40 −0.38 , +0.56 −0.45)
2L
1.90 +0.78 −0.64 (+0.51 −0.49 , +0.59 −0.42)
Comb.
1.20 +0.42 −0.36 (+0.24 −0.23 , +0.34 −0.28)
−1 0 1 2 3 4 5 6 7 8
Best fit μ VH bb̄ for mH=125 GeV

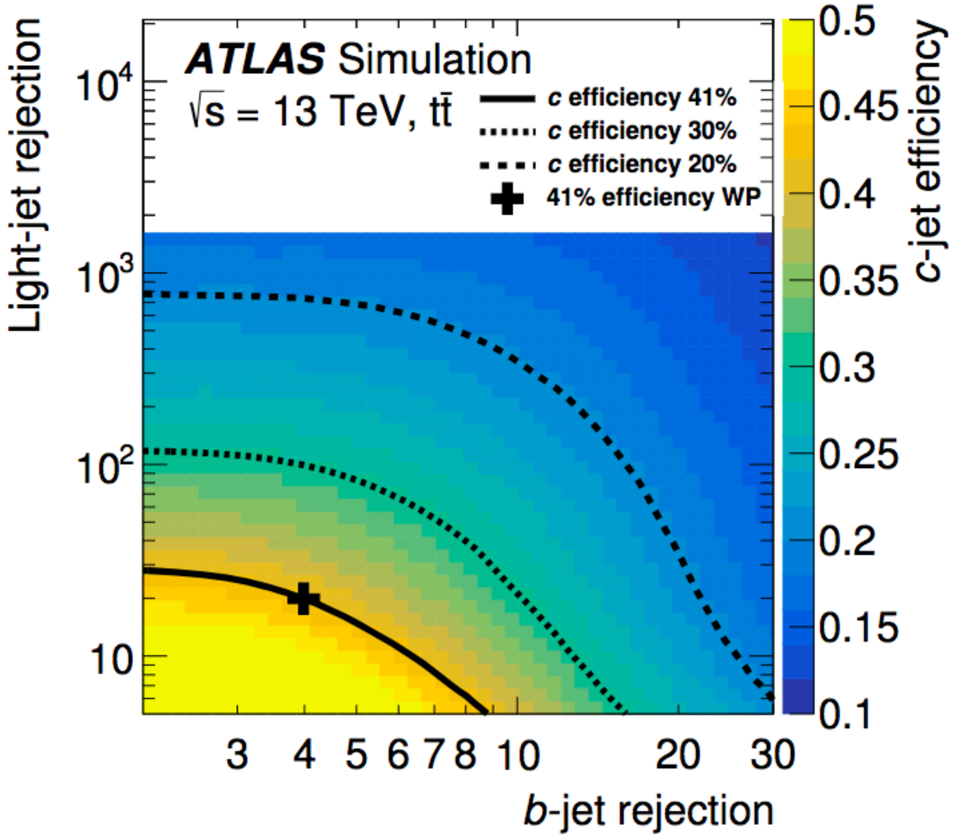
VH(bb)


ATLAS
√s = 13 TeV , 36.1 fb⁻¹
0 lepton, 2 jets, 2 b-tags
0 lepton, 3 jets, 2 b-tags
1 lepton, 2 jets, 2 b-tags
1 lepton, 3 jets, 2 b-tags
2 leptons, 2 jets, 2 b-tags
2 leptons, ≥ 3 jets, 2 b-tags
p_T^V ≥ 150 GeV
Data
VH → Vbb (μ=1.20)
Diboson
tt
Single top
Multijet
W+(bb,bc,cc,bl)
W+cl
W+ll
Z+(bb,bc,cc,bl)
Z+cl
Z+ll
Uncertainty
Pre-fit background
SM VH → Vbb × 10
SM VH → Vbb × 50
SM VH → Vbb × 20
SM VH → Vbb × 100
Events / 0.13
Data/Pred.
BDT_{VH} output


Δμ
VH acceptance (PS/UE)
W+jets p_T^V
b-jet tagging efficiency 1
2-lepton tt̄ m_{bb} shape
VH acceptance in 3-jet (PS/UE)
VH acceptance (QCD scales)
Single top Wt acc.
Z+jets m_{bb} shape
c-jet tagging efficiency 1
MC stat. 1 lepton 2 jet, bin 13
b-jet tagging efficiency 0
Z + HF 3-jet scale factor
Single top Wt m_{bb} shape
MC stat. 1 lepton 2 jet, bin 12
Luminosity
ATLAS
√s = 13 TeV
∫Ldt = 36.1 fb⁻¹
m_H=125 GeV
Pull: $(\hat{\theta} - \theta_0)/\Delta\theta$
Normalisation
+1σ Postfit Impact on μ
-1σ Postfit Impact on μ

VH(cc)

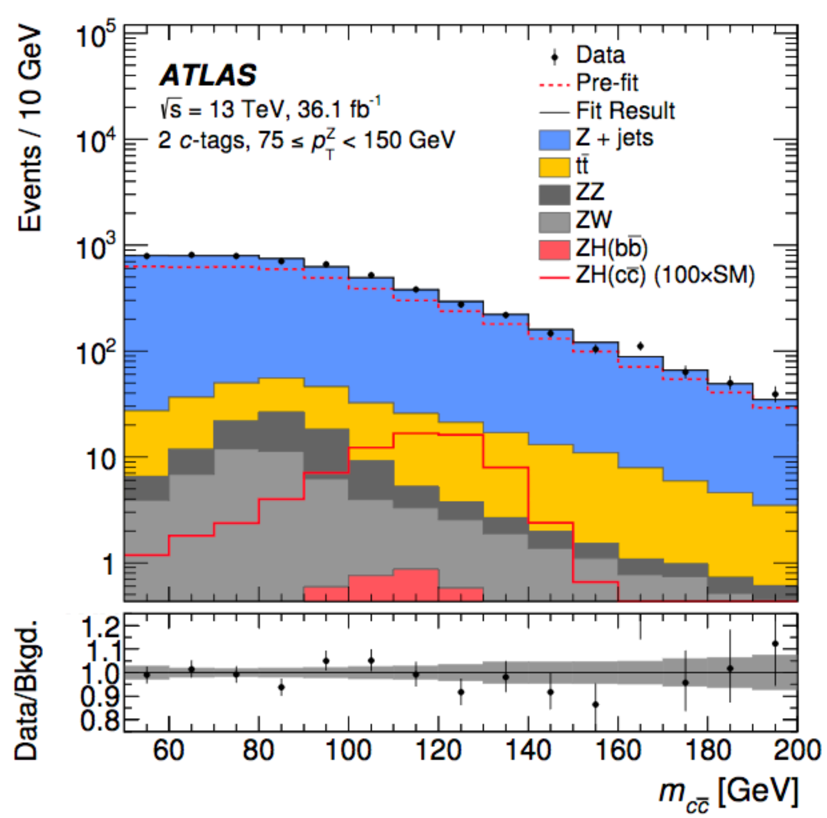
https://arxiv.org/pdf/1802.04329.pdf

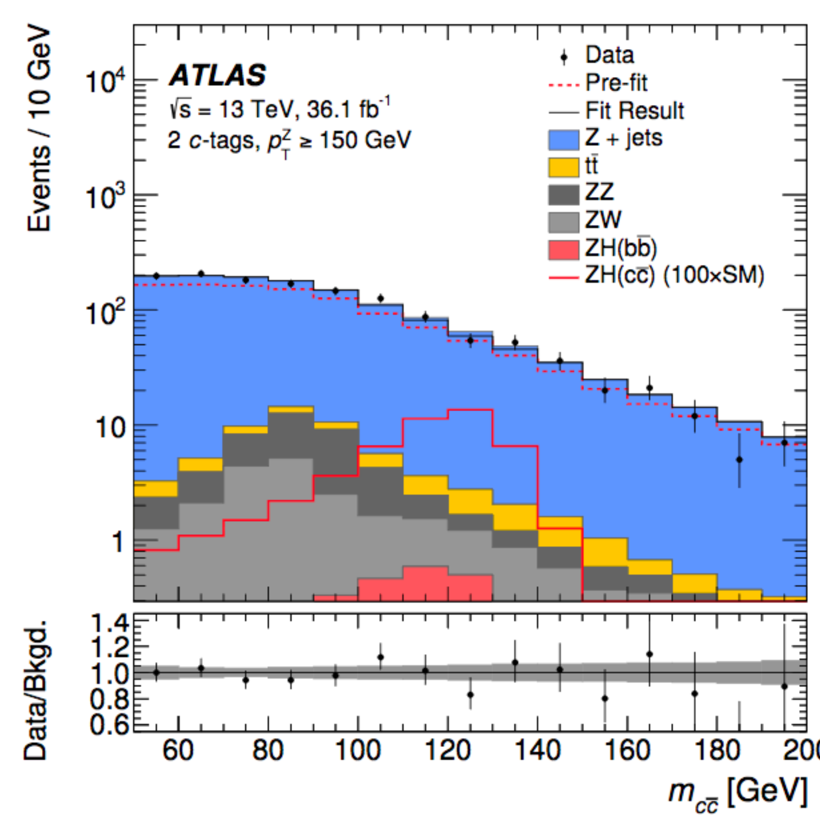


Sample	Yield, 50 GeV < $m_{c\bar{c}}$ < 200 GeV			
	1 c-tag		2 c-tags	
	$75 \leq p_T^Z < 150$ GeV	$p_T^Z \geq 150$ GeV	$75 \leq p_T^Z < 150$ GeV	$p_T^Z \geq 150$ GeV
Z + jets	69400 ± 500	15650 ± 180	5320 ± 100	1280 ± 40
ZW	750 ± 130	290 ± 50	53 ± 13	20 ± 5
ZZ	490 ± 70	180 ± 28	55 ± 18	26 ± 8
$t\bar{t}$	2020 ± 280	130 ± 50	240 ± 40	13 ± 6
$ZH(b\bar{b})$	32 ± 2	19.5 ± 1.5	4.1 ± 0.4	2.7 ± 0.2
$ZH(c\bar{c})$ (SM)	-143 ± 170 (2.4)	-84 ± 100 (1.4)	-30 ± 40 (0.7)	-20 ± 29 (0.5)
Total	72500 ± 320	16180 ± 140	5650 ± 80	1320 ± 40
Data	72504	16181	5648	1320

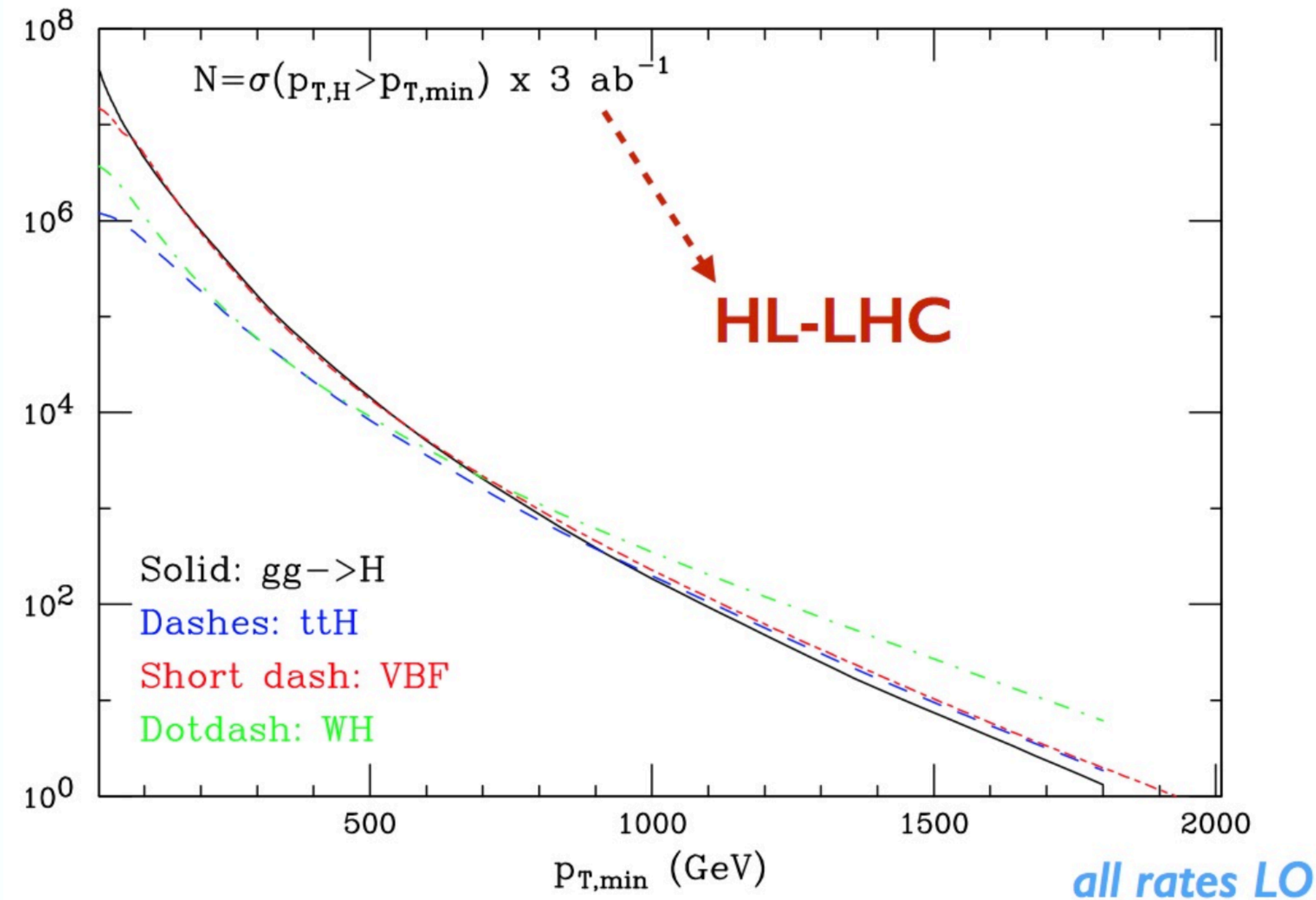
The observed upper limit on σ(pp→ZH)×B(H→c̄c) is 2.7 pb at the 95% CL (expected 3.9 pb)

observed(expected) upper limit on μ at the 95% CL of 110 (150+80−40)





Boosted Higgs rates



Careful: large corrections (in different directions)

ggH cross-section

Using these input parameters, our current best prediction for the production cross section of a Higgs boson with a mass $m_H = 125$ GeV at the LHC with a centre-of-mass energy of 13 TeV is

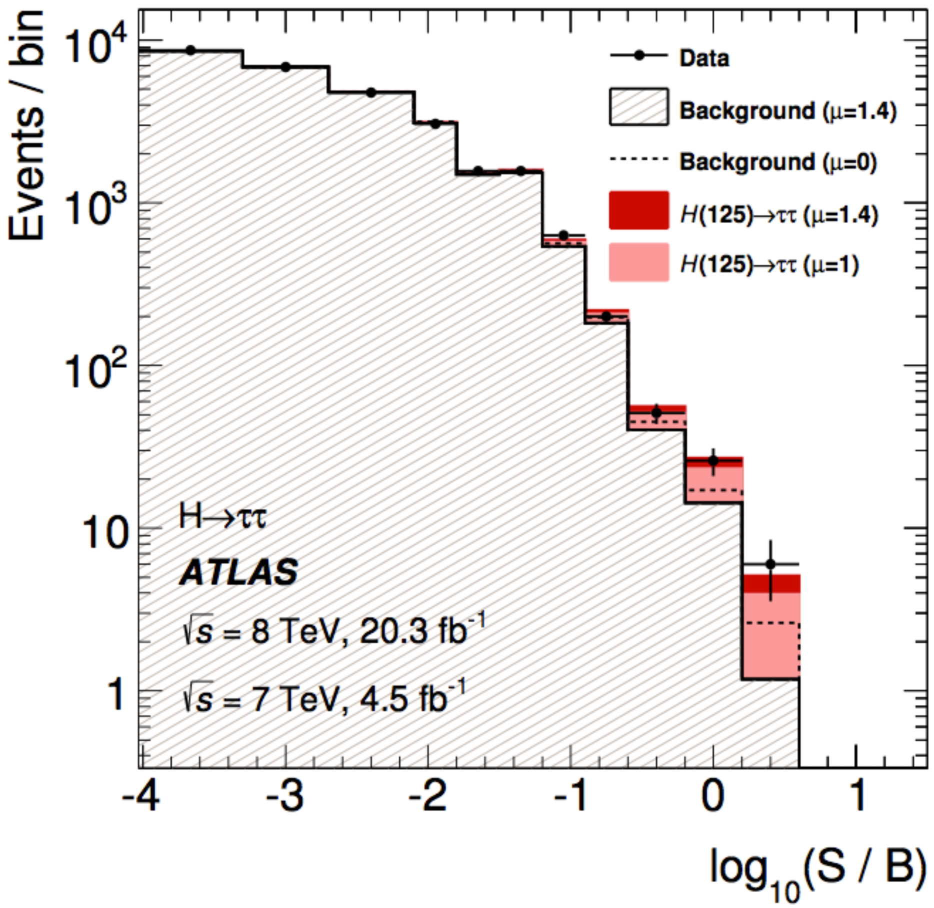
$$\boxed{\sigma = 48.58\,\mathrm{pb}^{+2.22\,\mathrm{pb}\,(+4.56\%)}_{-3.27\,\mathrm{pb}\,(-6.72\%)}\,(\mathrm{theory}) \pm 1.56\,\mathrm{pb}\,(3.20\%)\,(\mathrm{PDF}{+}\alpha_s)\,.} \quad (\mathrm{I.4.3})$$

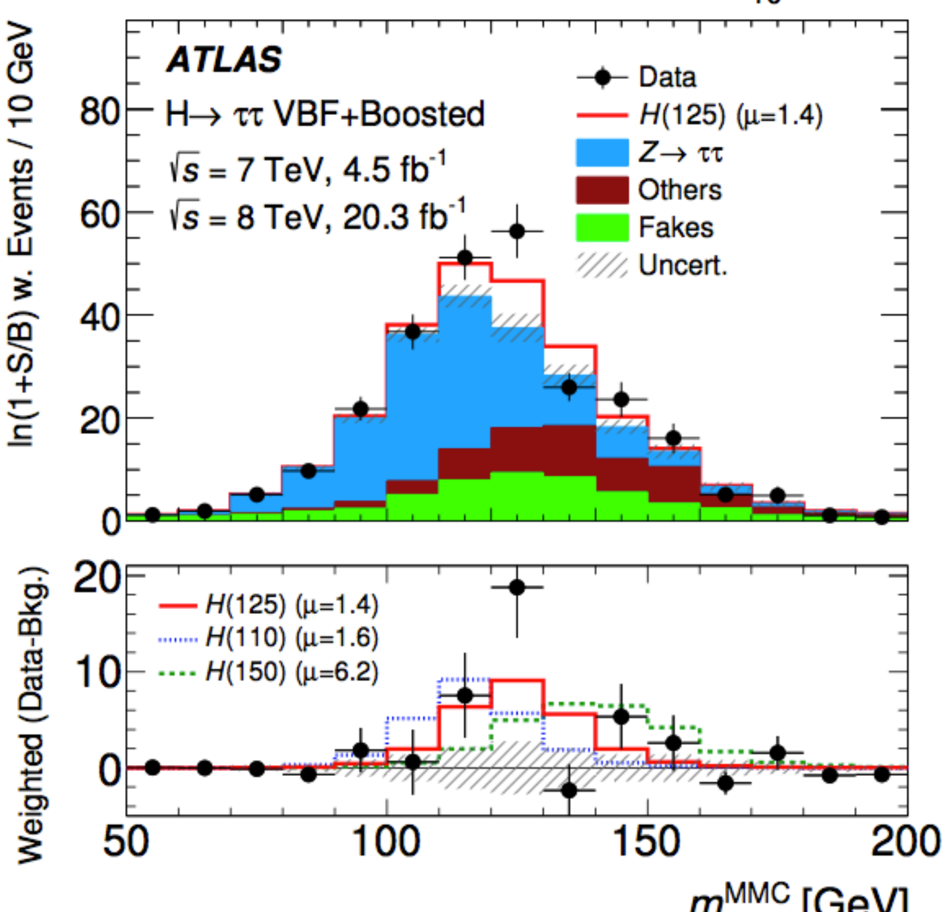
The central value in eq. (I.4.3), computed at the central scale $\mu_F = \mu_R = m_H/2$, is the combination of all the effects considered in eq. (I.4.1). The breakdown of the different effects is:

$$\begin{aligned}
48.58\,\mathrm{pb} = \;& 16.00\,\mathrm{pb} & (+32.9\%) && (\mathrm{LO,\ rEFT}) \\
& +20.84\,\mathrm{pb} & (+42.9\%) && (\mathrm{NLO,\ rEFT}) \\
& -\;\;2.05\,\mathrm{pb} & (-4.2\%) && ((t,b,c),\ \mathrm{exact\ NLO}) \\
& +\;\;9.56\,\mathrm{pb} & (+19.7\%) && (\mathrm{NNLO,\ rEFT}) \\
& +\;\;0.34\,\mathrm{pb} & (+0.7\%) && (\mathrm{NNLO},\ 1/m_t) \\
& +\;\;2.40\,\mathrm{pb} & (+4.9\%) && (\mathrm{EW,\ QCD\text{-}EW}) \\
& +\;\;1.49\,\mathrm{pb} & (+3.1\%) && (\mathrm{N^3LO,\ rEFT})
\end{aligned} \quad (\mathrm{I.4.4})$$

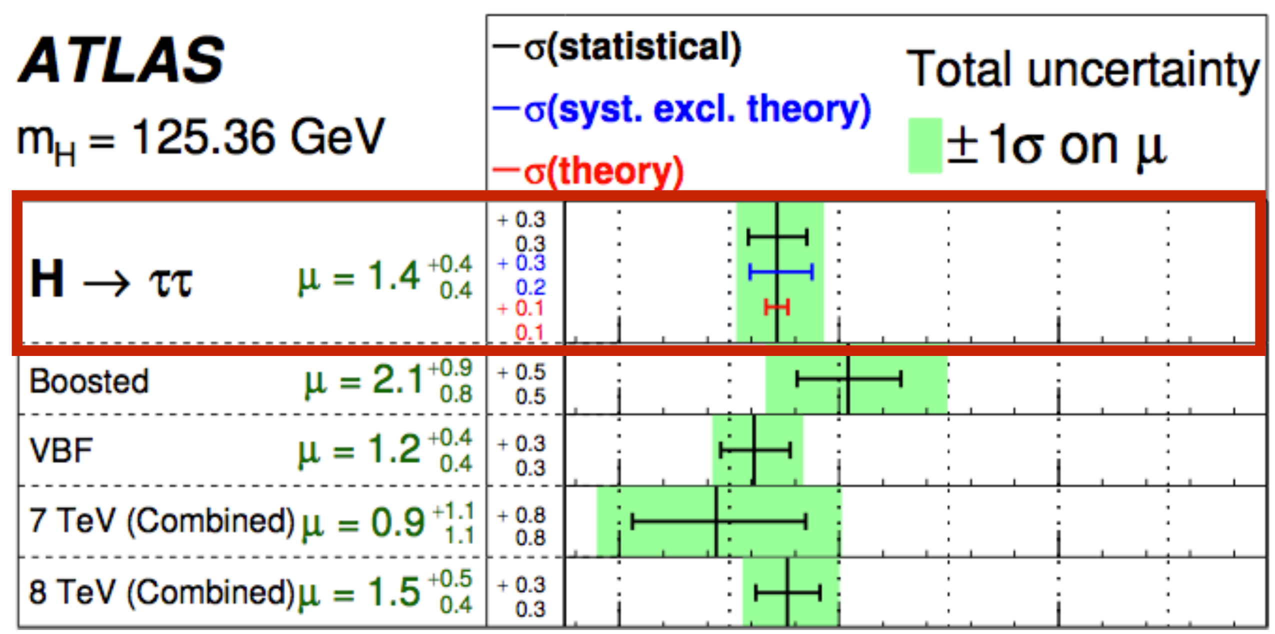
δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
+0.10 pb −1.15 pb	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
+0.21% −2.37%	±0.37%	±1.16%	±1%	±0.83%	±1%

H→ττ



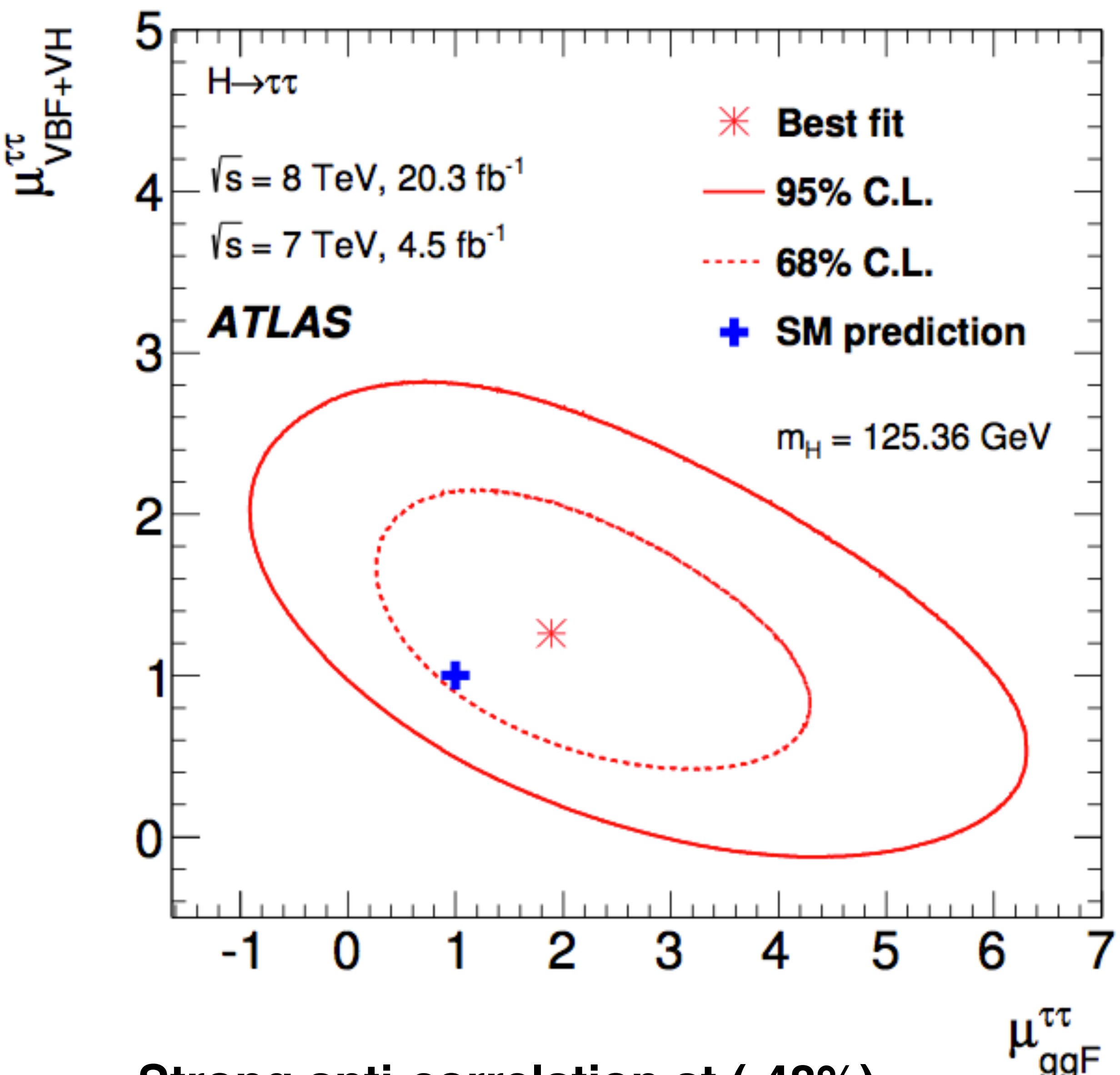


- **second largest BR(fermions):** lower than H(bb) but cleaner signature
- **3 analysis channels: $\tau_{lep}\tau_{lep}$ + $\tau_{lep}\tau_{had}$ + $\tau_{had}\tau_{had}$**
- events categorised in jet-multiplicity and $p_T(\tau\tau)$, **VBF-like and ggF-like categories**
- **Fit of multivariate discriminant (MVA) distribution**
- **main challenges of the ττ channel**
  - invariant mass reconstruction & resolution
  - background control: Z(→ττ) & fake-τ_{had} estimate



Signal Strength μ	$\mu = 1.43\ ^{+0.27}_{-0.26}(\text{stat.})\ ^{+0.32}_{-0.25}(\text{syst.})\ \pm 0.09(\text{theory syst.})$
Significance σ	$\sigma_{observed} = 4.5$ $\sigma_{expected} = 3.4$

$H \to \tau\tau$ - production modes



Strong anti-correlation at (-48%)

Main $H \to \tau\tau$ search interpreted in [ggF] vs [VH+VBF] production modes couplings

VBF-enriched region:

- 2 high p_T jets with large pseudo-rapidity separation

ggF-enriched (boosted) region:

- $p_T(\tau\tau) \sim p_T(H) > 100$ GeV

Two dimensional fit of the Higgs signal strength separating the ggF from VH+VBF production modes

Prod. mode	Significance σ	
ggF	$\sigma_{observed} = 1.74$	$\sigma_{expected} = 0.95$
VH+VBF	$\sigma_{observed} = 2.25$	$\sigma_{expected} = 1.72$

$$\mu^{\tau\tau}_{ggF} = 2.0 \ \pm 0.8(\text{stat.}) \ ^{+1.2}_{-0.8}(\text{syst.}) \ \pm 0.3(\text{theory syst.})$$

$$\mu^{\tau\tau}_{\text{VBF}+VH} = 1.24 \ ^{+0.49}_{-0.45}(\text{stat.}) \ ^{+0.31}_{-0.29}(\text{syst.}) \ \pm 0.08(\text{theory syst.})$$

H→ττ - CP invariance

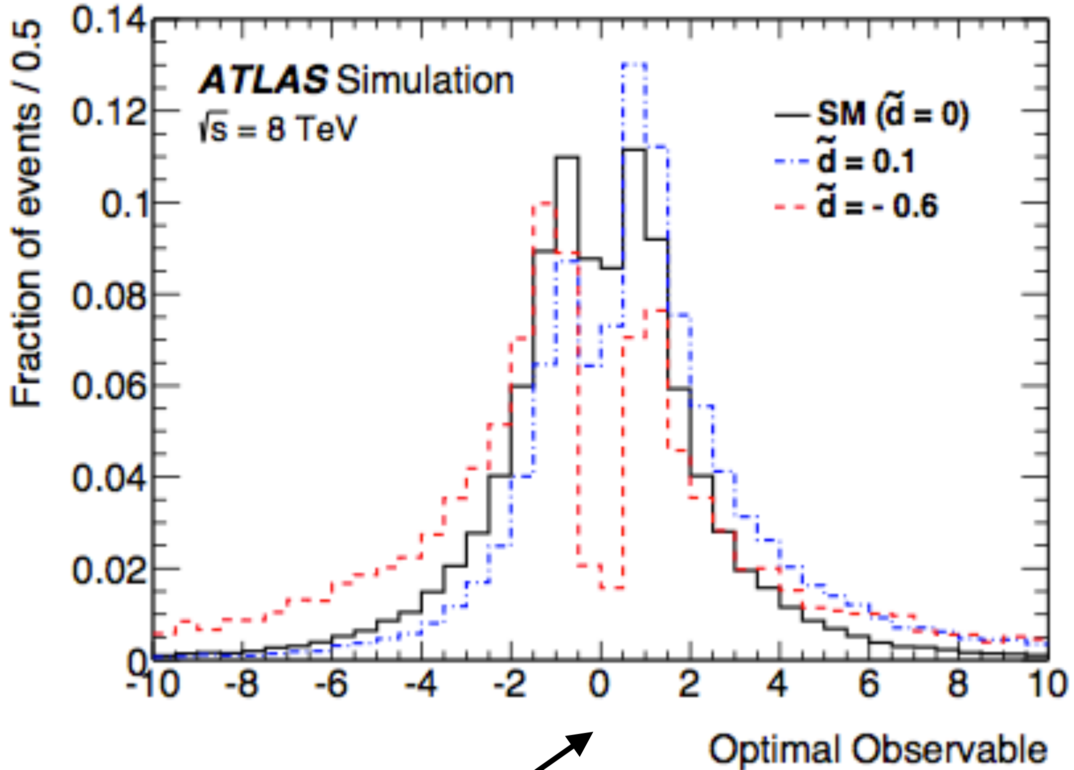
- **HVV couplings as a test of CP-violation / CP-invariance**

HWW, HZZ decays and Hɣɣ differential cross-section:
no deviations from Run1 data

Direct test through VBF production (H→ττ)

- **CP-odd observable:**
sensitive to interference between SM and CP-odd contributions

- **Optimal observable:** combine multi-dimensional information in a single variable from the VBF production LO matrix-element [independent from H decay mode]



$$OO = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

most sensitive for smallest values

Results interpreted in the Effective Field Theory framework:
CP-violating effects from dim≤6 operators on HVV: $\tilde{d}$ parameter

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \tilde{g}_{HAA} H\tilde{A}_{\mu\nu}A^{\mu\nu} + \tilde{g}_{HAZ} H\tilde{A}_{\mu\nu}Z^{\mu\nu} + \tilde{g}_{HZZ} H\tilde{Z}_{\mu\nu}Z^{\mu\nu} + \tilde{g}_{HWW} H\tilde{W}^{+}_{\mu\nu}W^{-\mu\nu}$$

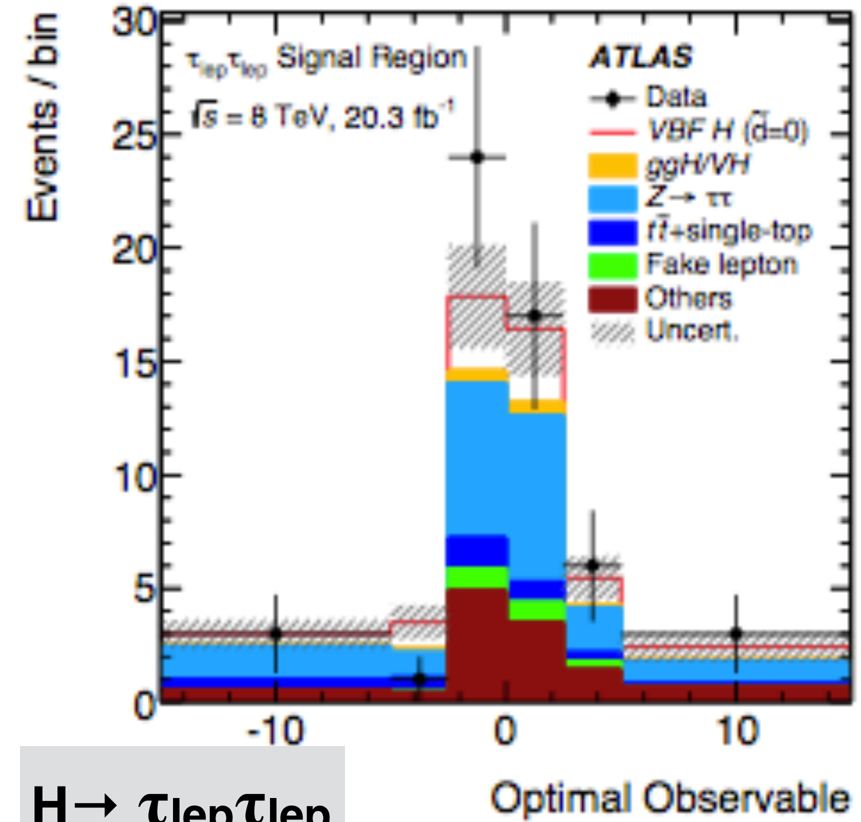
Couplings parametrisation:

$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W) \qquad \tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$

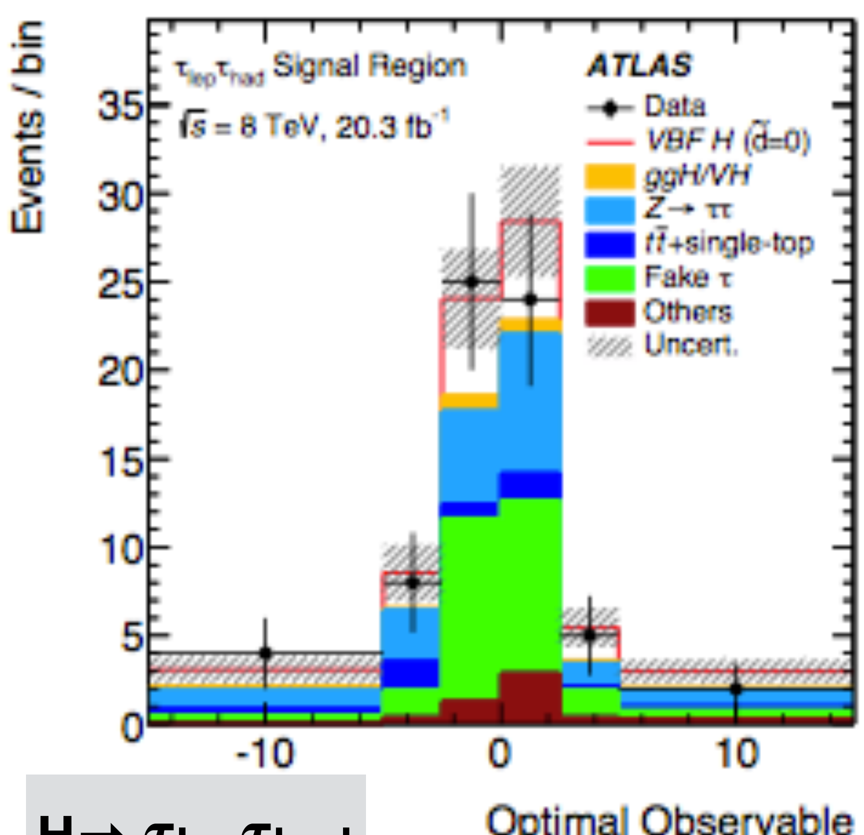
$$\tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W) \qquad \tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d}\,.$$

$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}$$

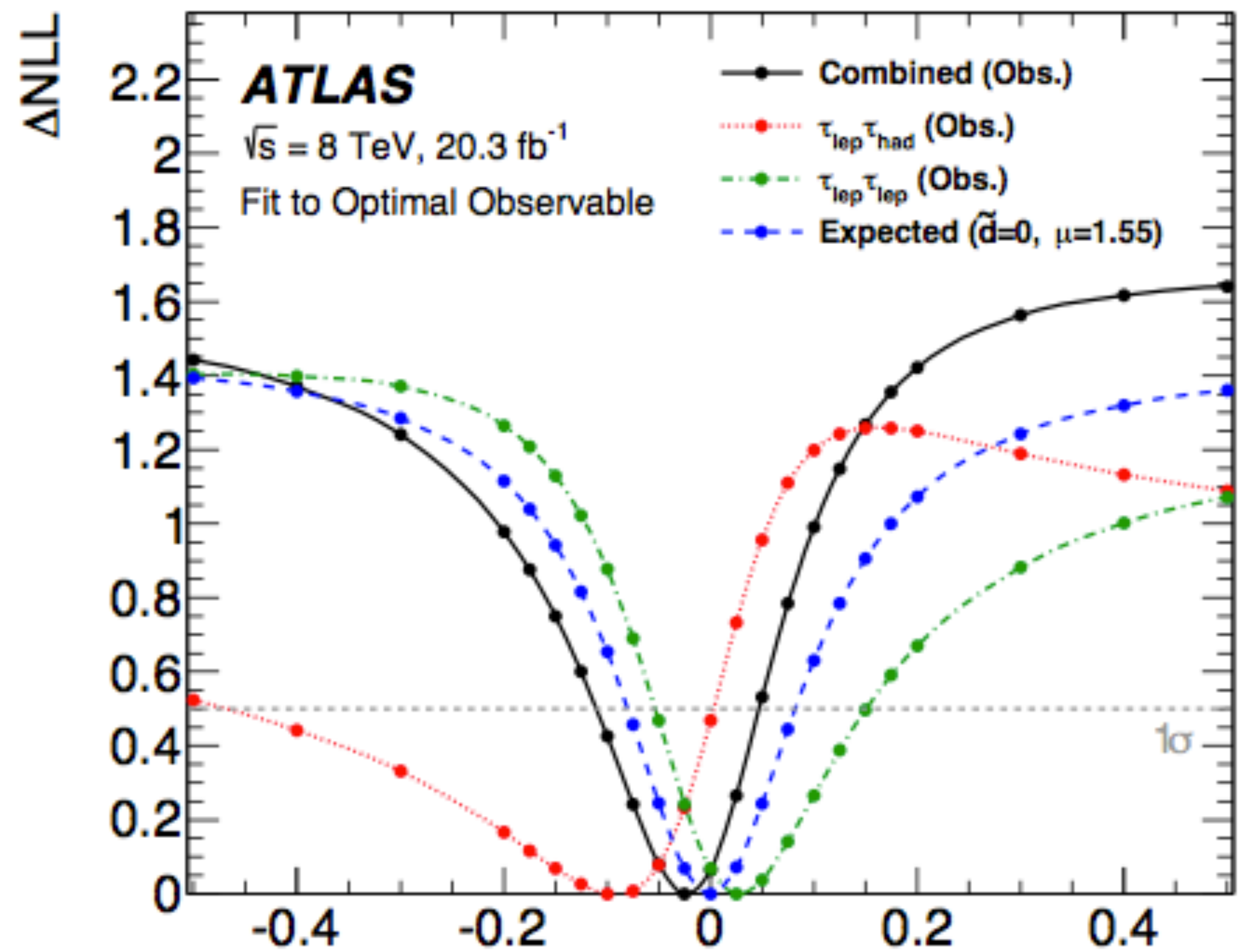
H→ττ - CP invariance



H→ $\tau_{lep}\tau_{lep}$



H→ $\tau_{lep}\tau_{had}$



No CP-violation ('background-only') minimum at 0 $\tilde{d}$

- [$\bar{d}$ < -0.11] & [$\bar{d}$ > 0.05] excluded at 68% CL
  [10x improvement over same limit from HWW, HZZ]
- same limit-setting with $\Delta\Phi^{sign}$(jj) shows worse results
  [azimuthal angle between VBF-tagging jets]

Channel	Fitted value of $\bar{d}$
$\tau_{lep}\tau_{lep}$	0.3 ± 0.5
$\tau_{lep}\tau_{had}$	-0.3 ± 0.4

ATLAS Run-1 Higgs combination

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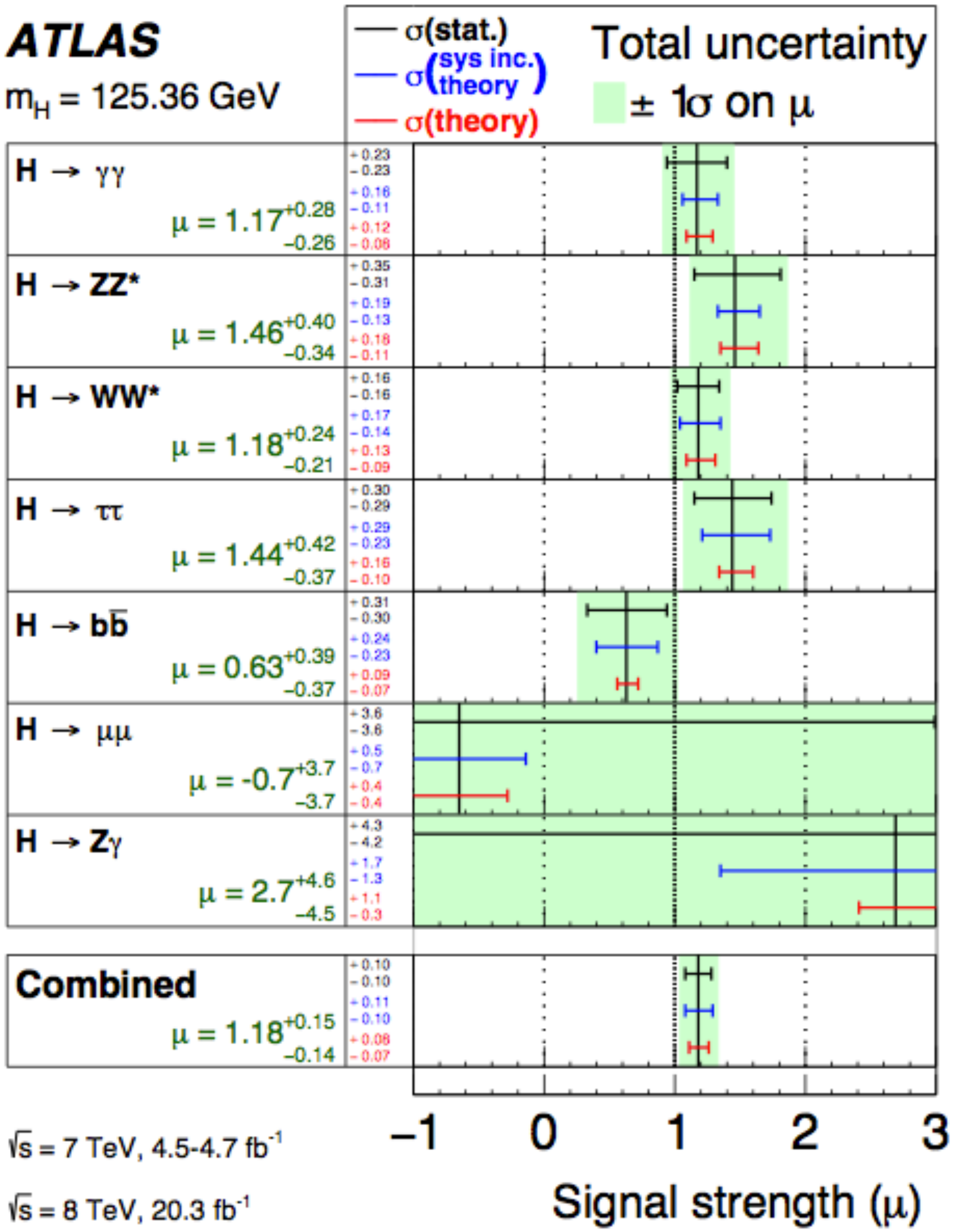
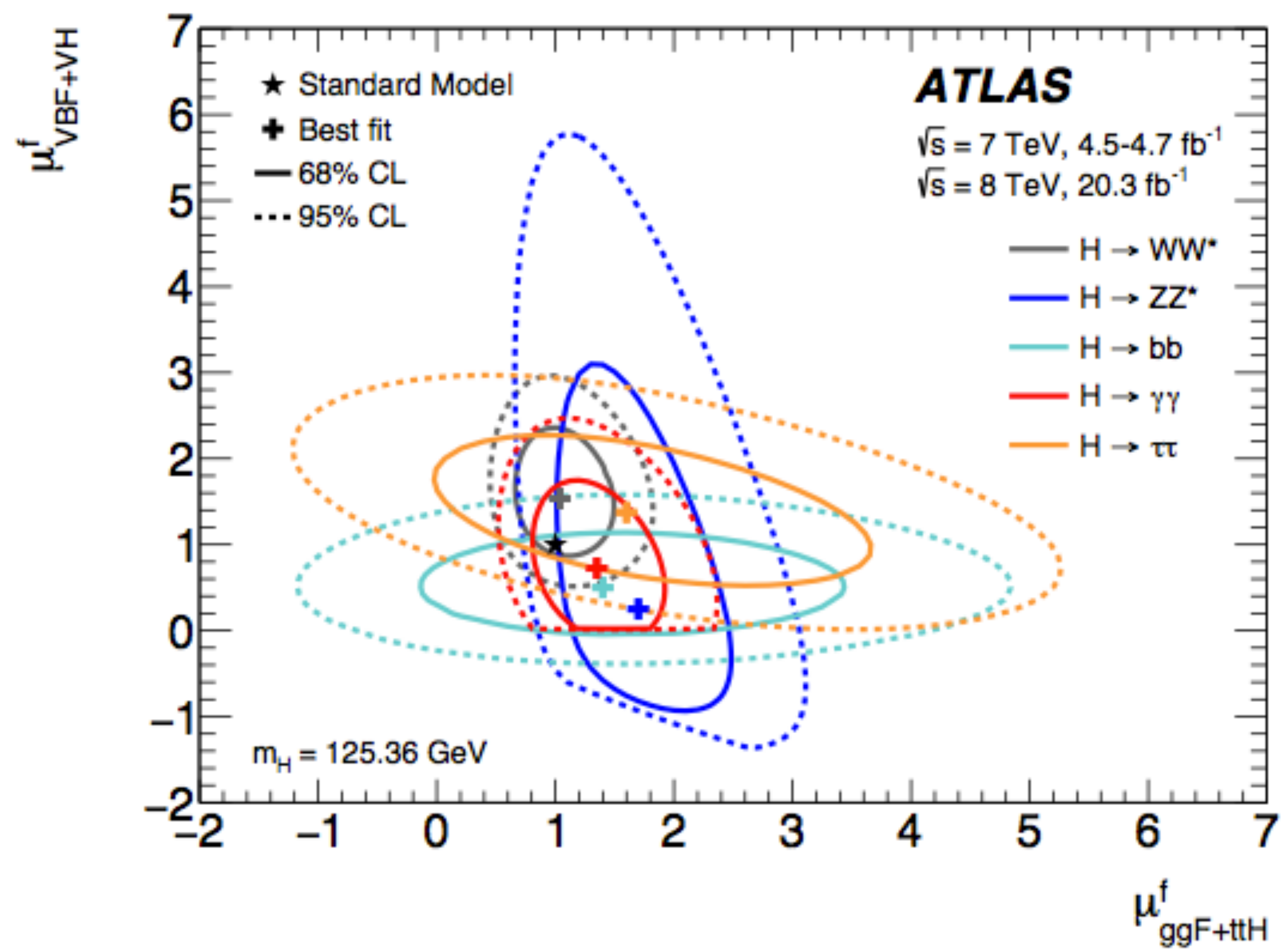
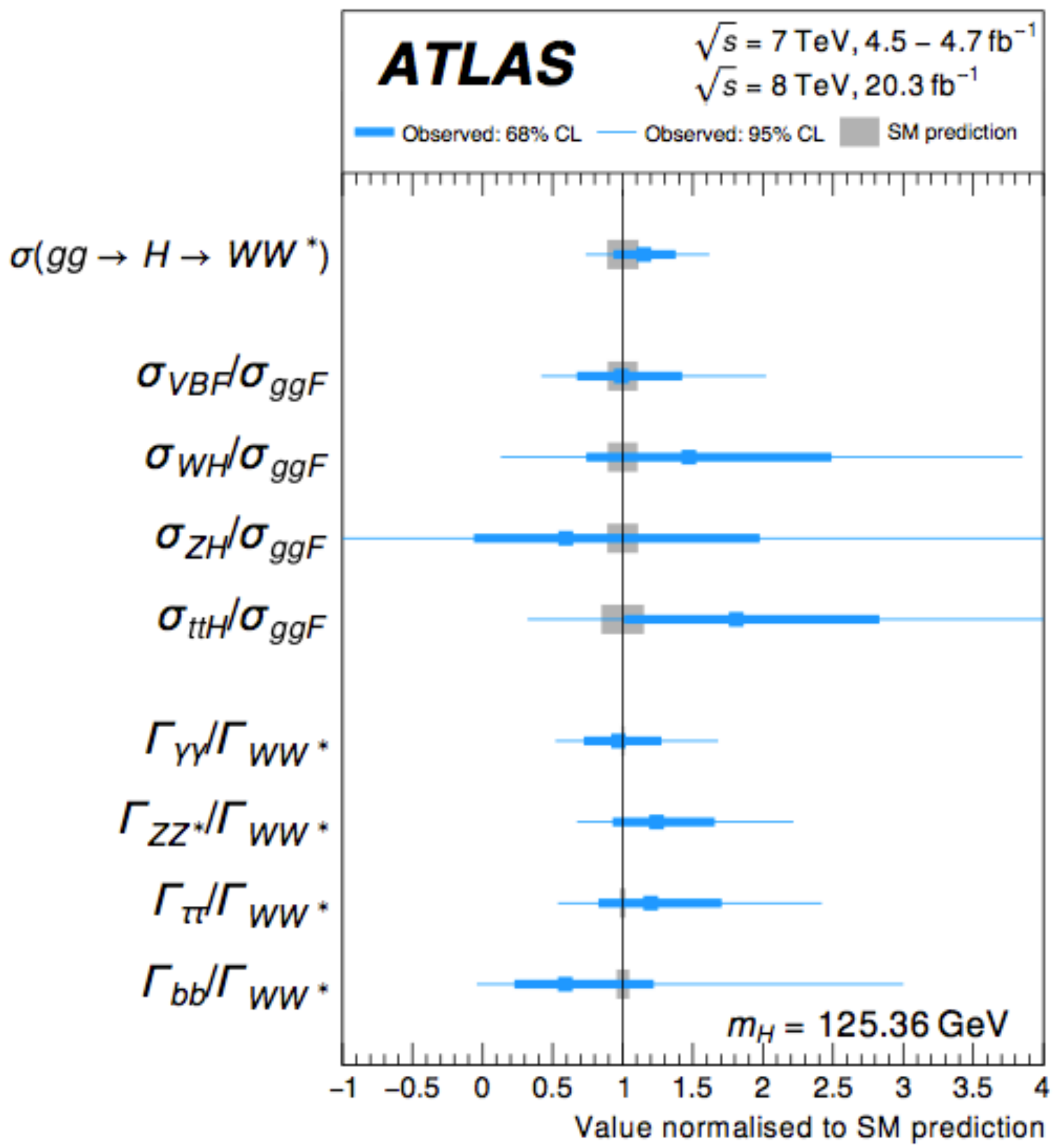
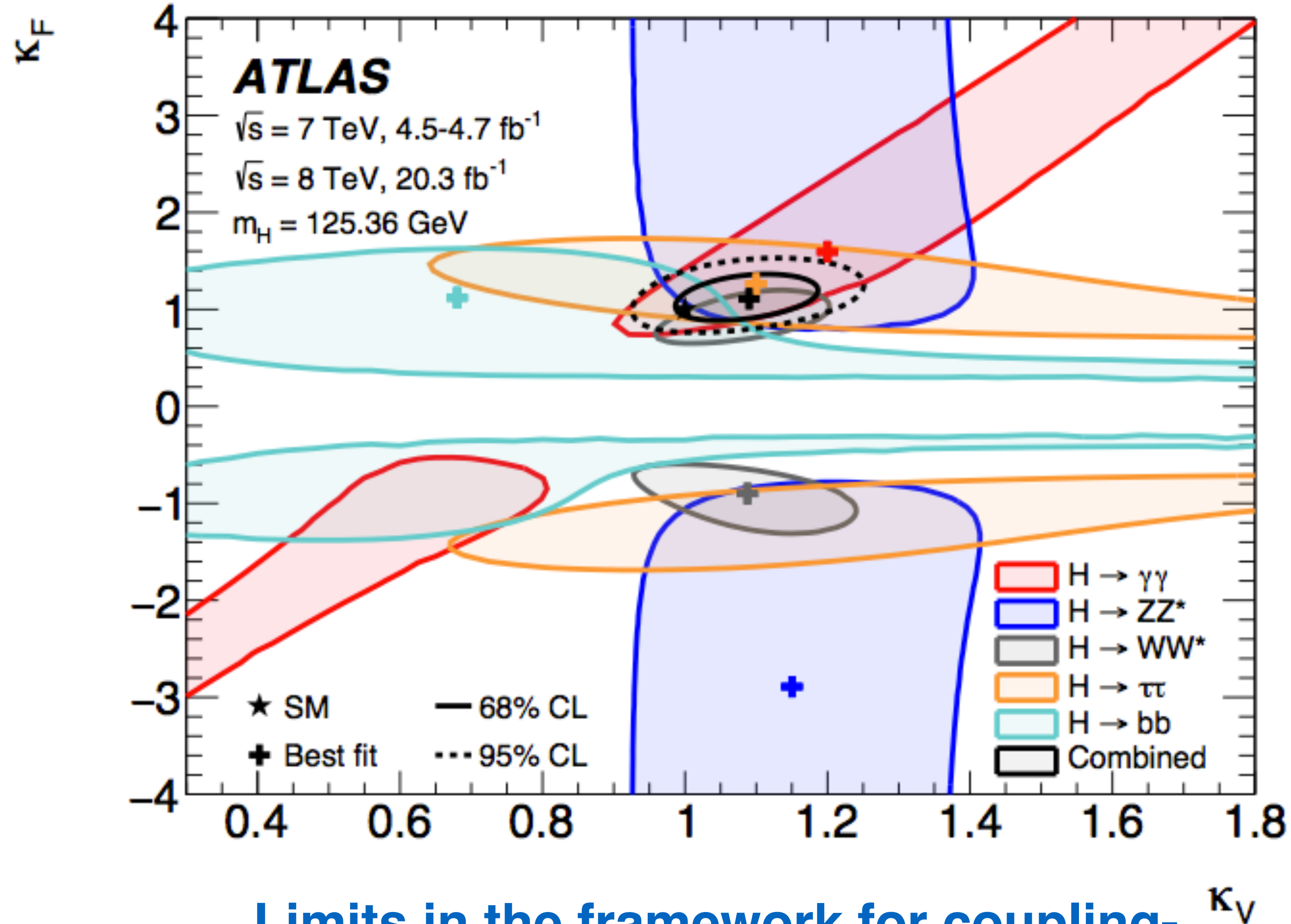




ATLAS Run-1 Higgs combination

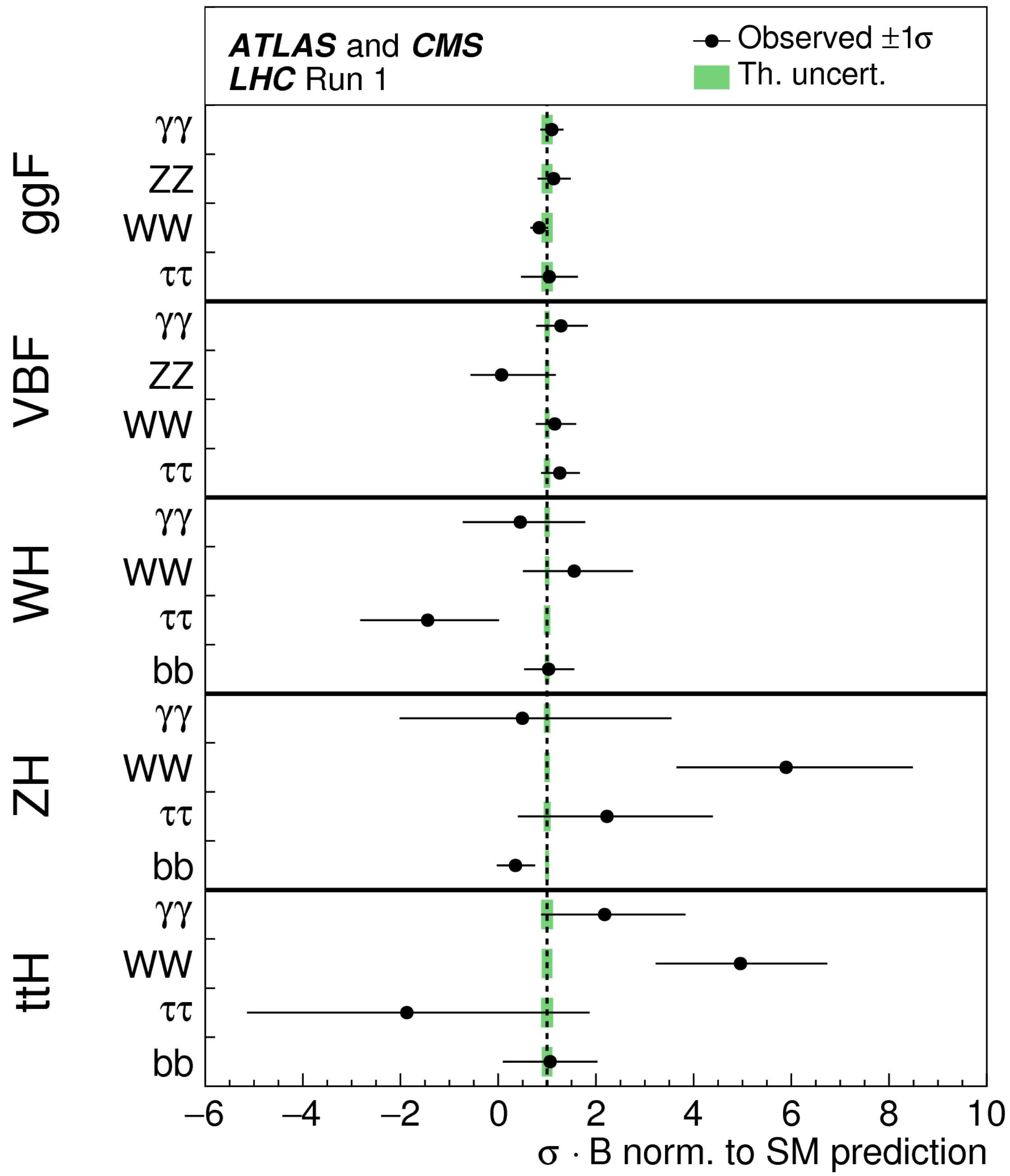


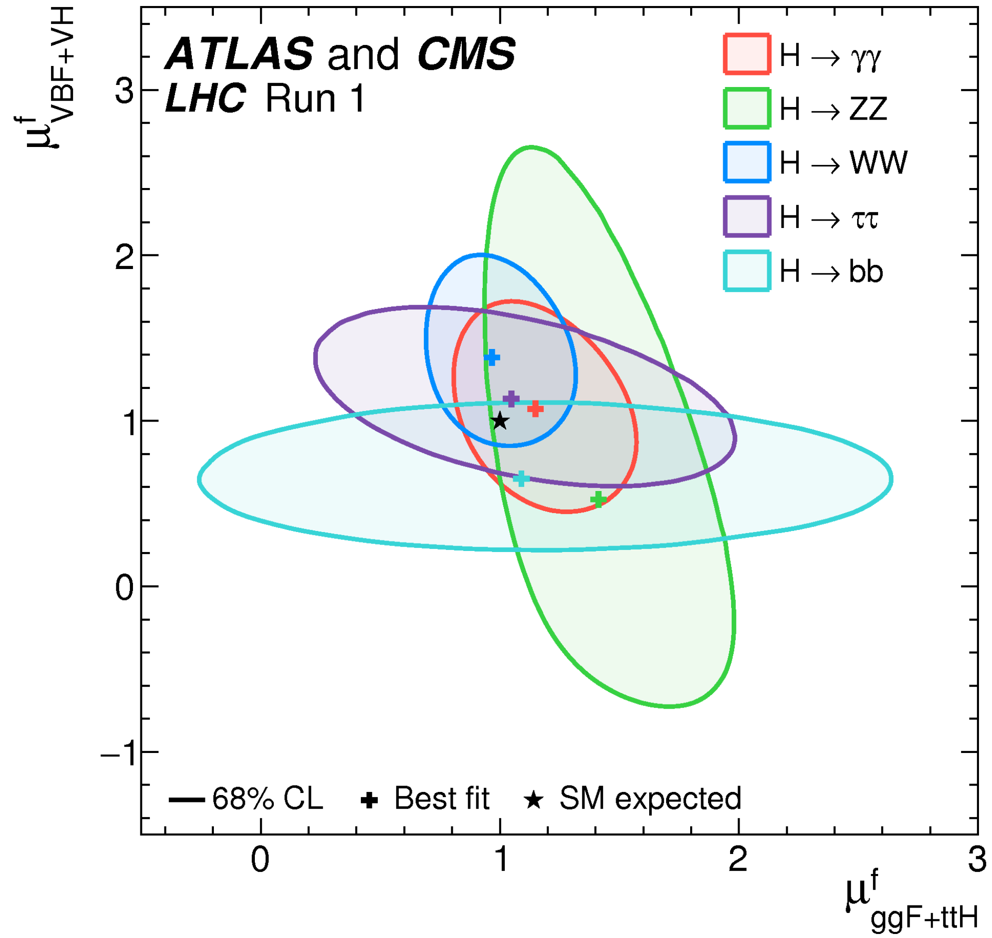


Limits in the framework for coupling-strength measurements

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

ATLAS+CMS Run-1 Higgs combination



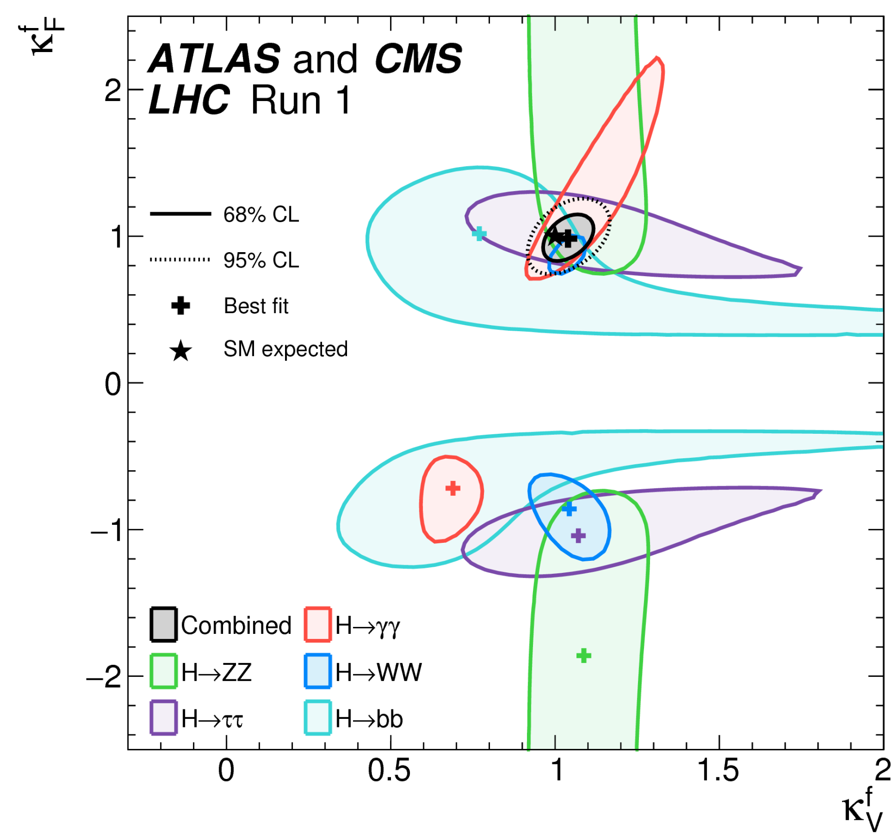


μ_{VH+VBF}

vs

$\mu_{ggF+ttH}$

Limits in the coupling-strength measurement framework

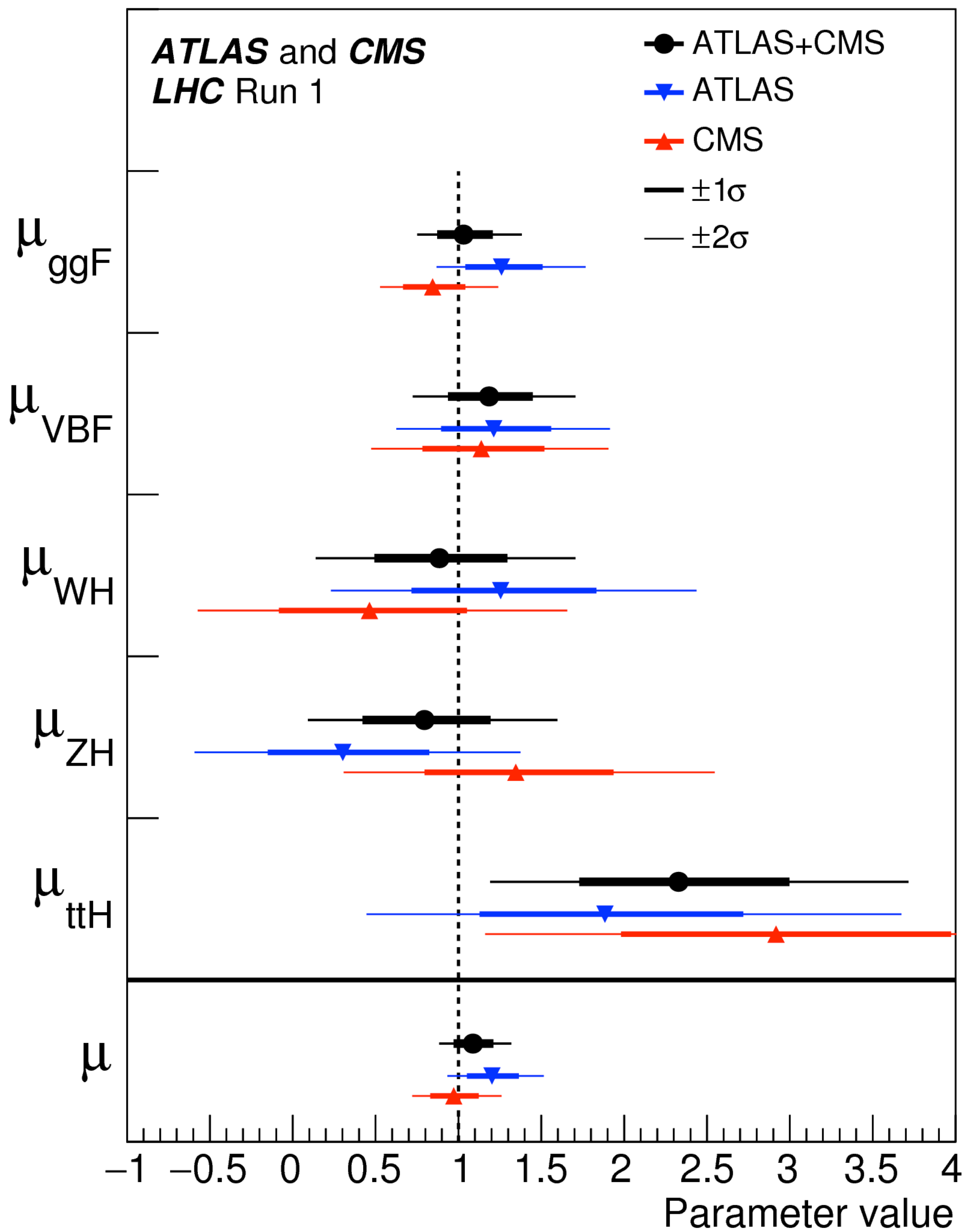


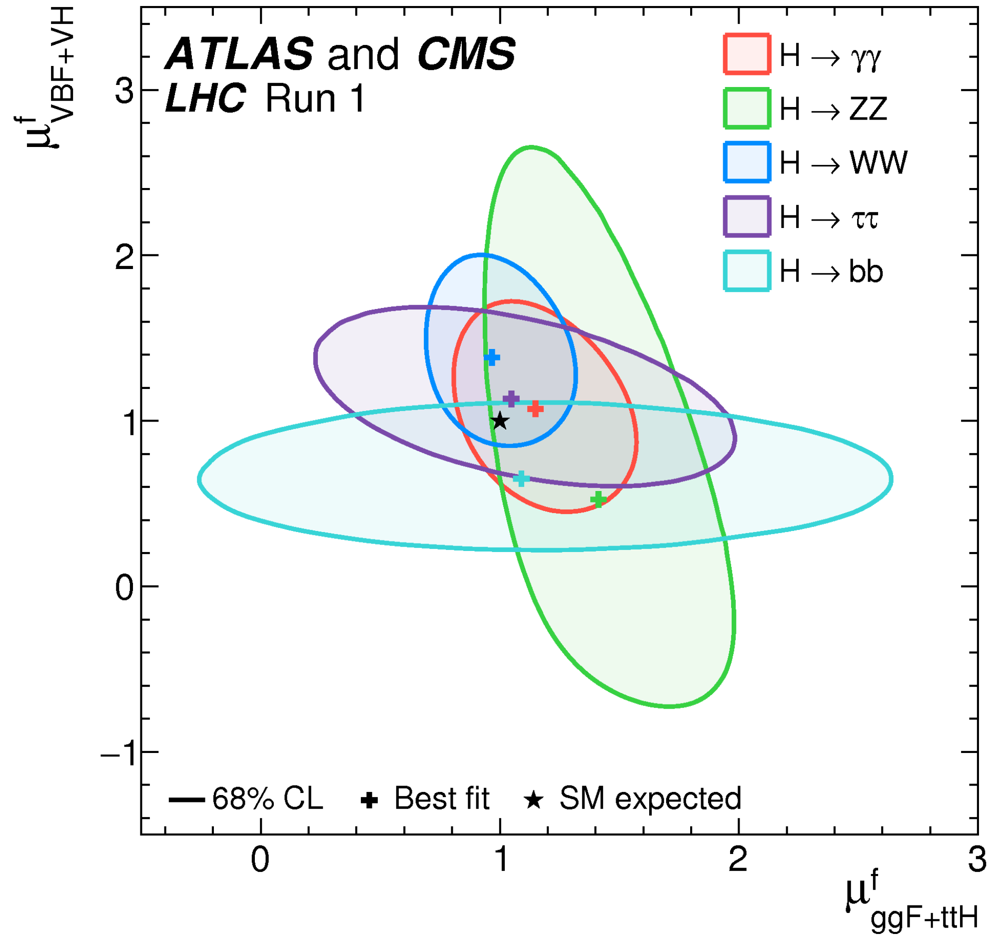
Fermionic decays (together with ttH) **offer a direct probe of k_F coupling**

(accessible only from loop contributions in bosonic channels)

Direct exploration of the Higgs Yukawa mechanism

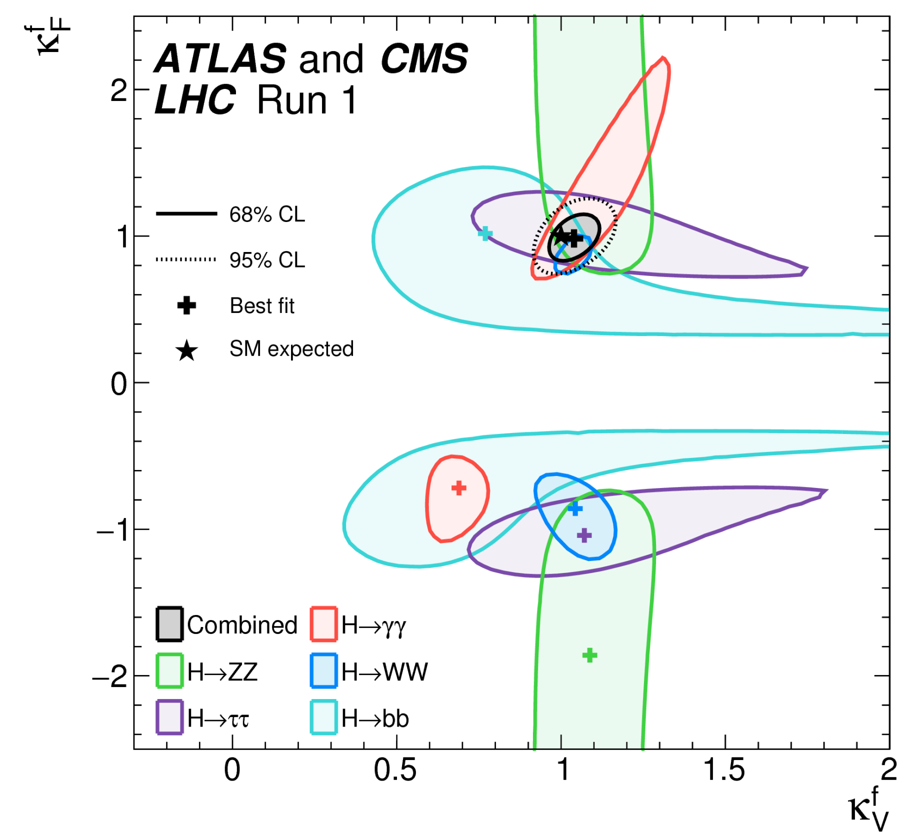
ATLAS+CMS Run-1 Higgs combination





μ_{VH+VBF} vs $\mu_{ggF+ttH}$

Limits in the coupling-strength measurement framework



Fermionic decays (together with ttH) **offer a direct probe of k_F coupling**

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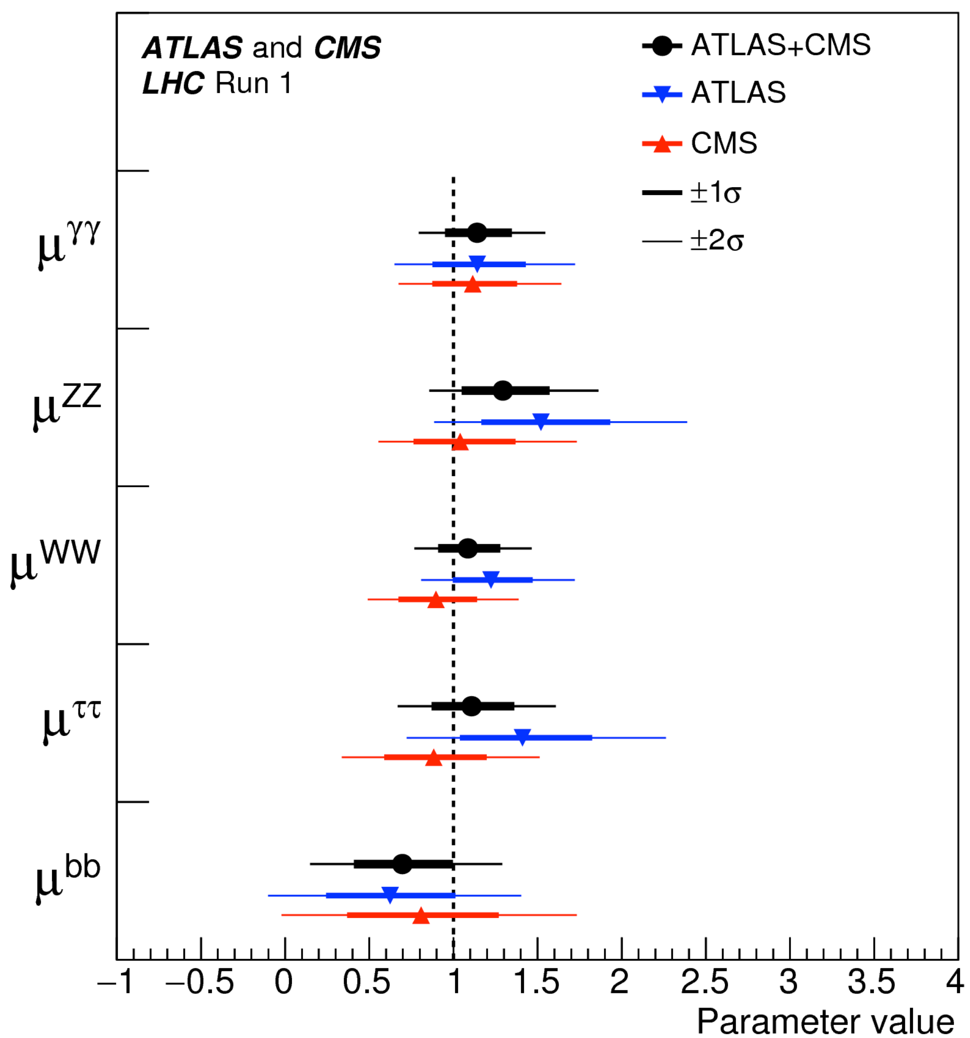

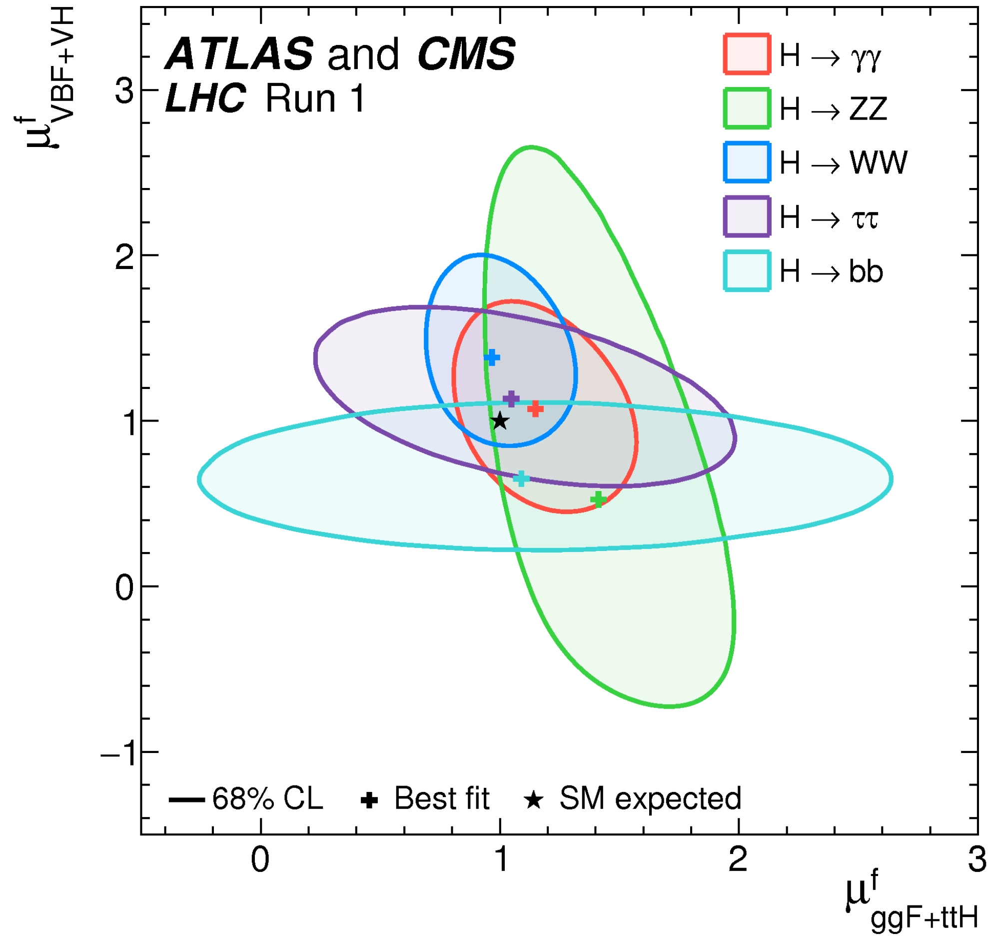

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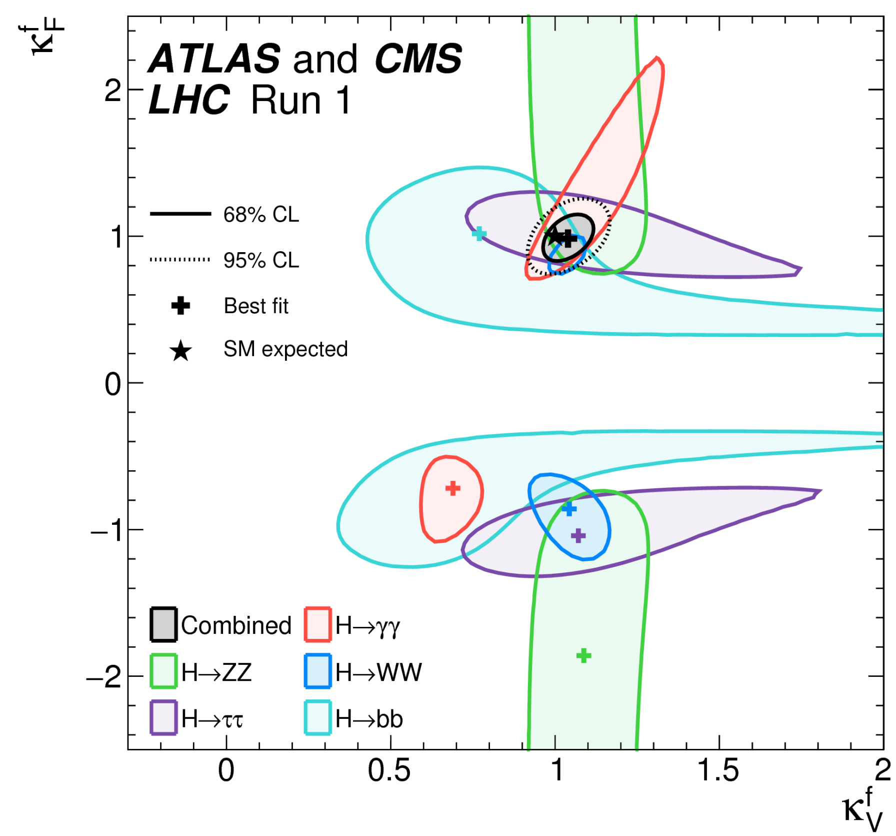

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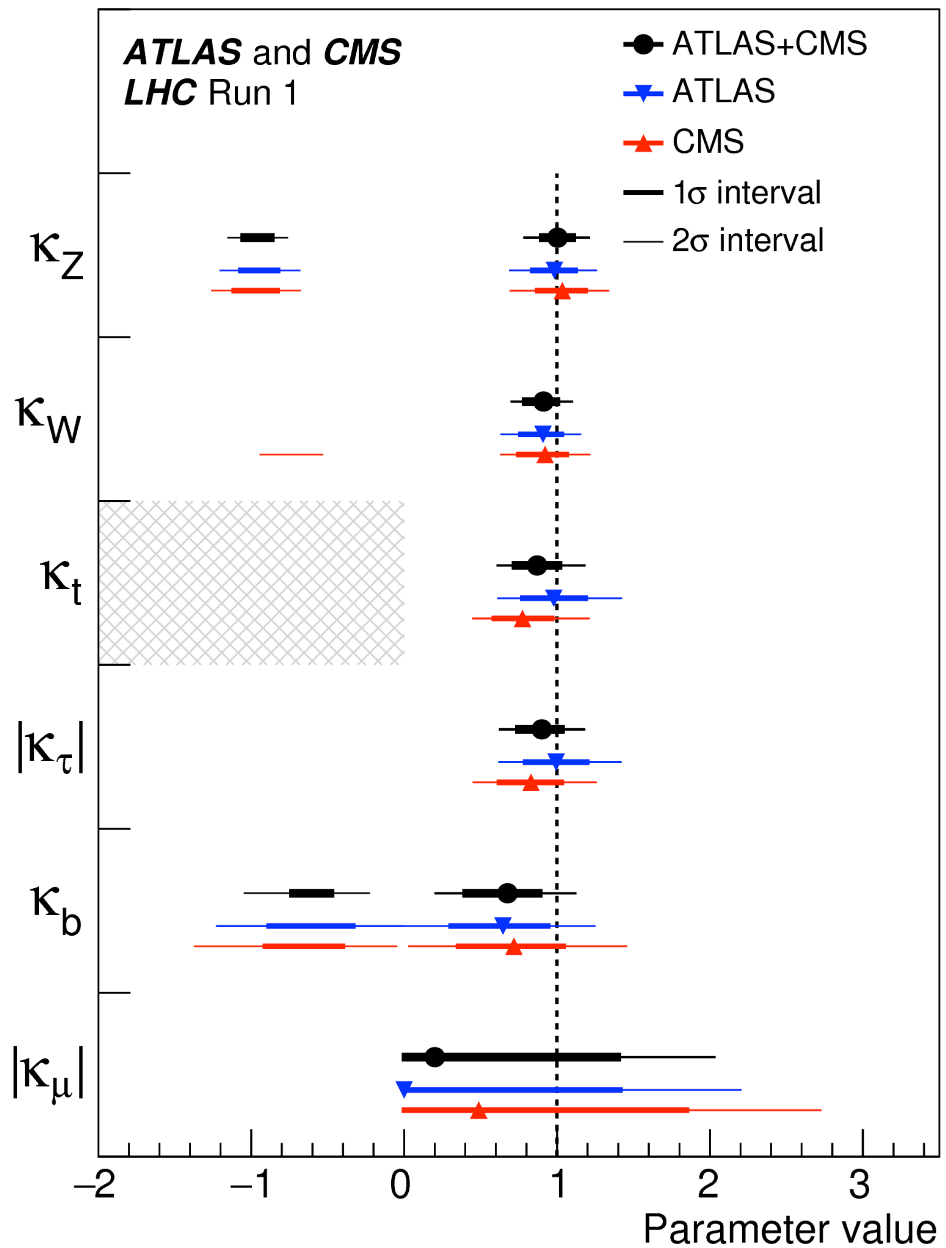

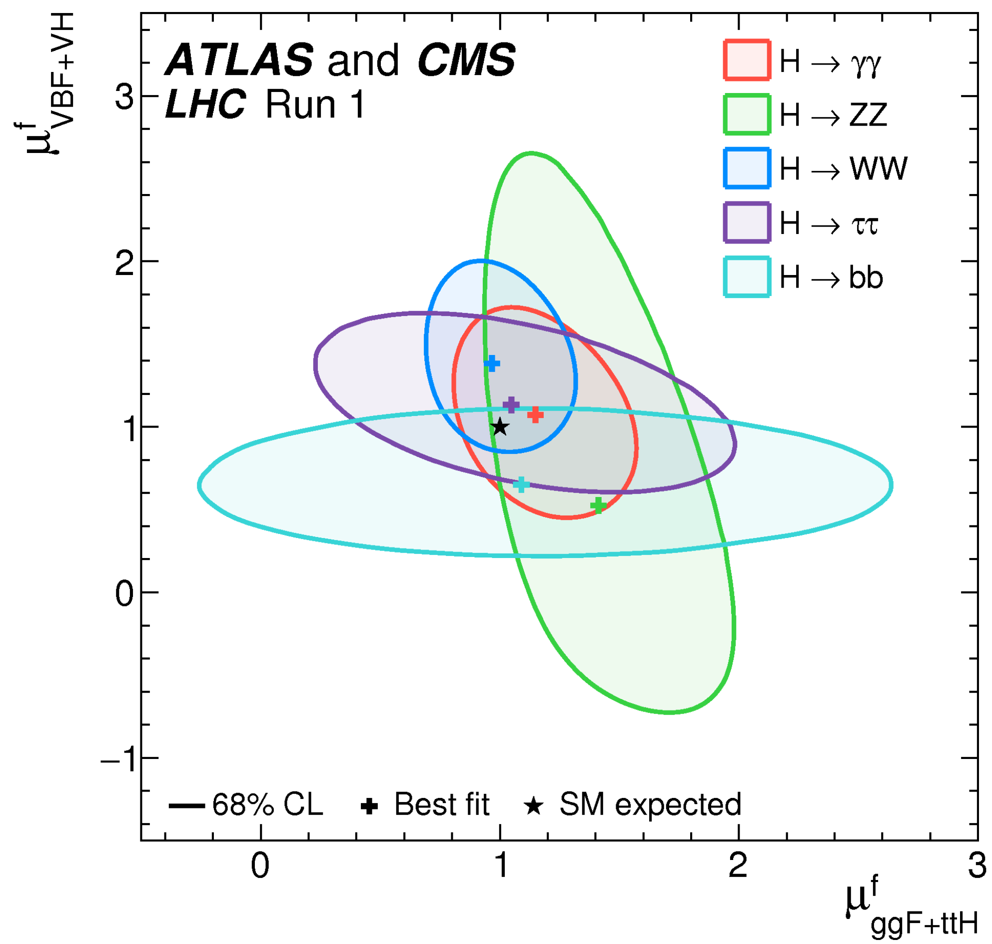

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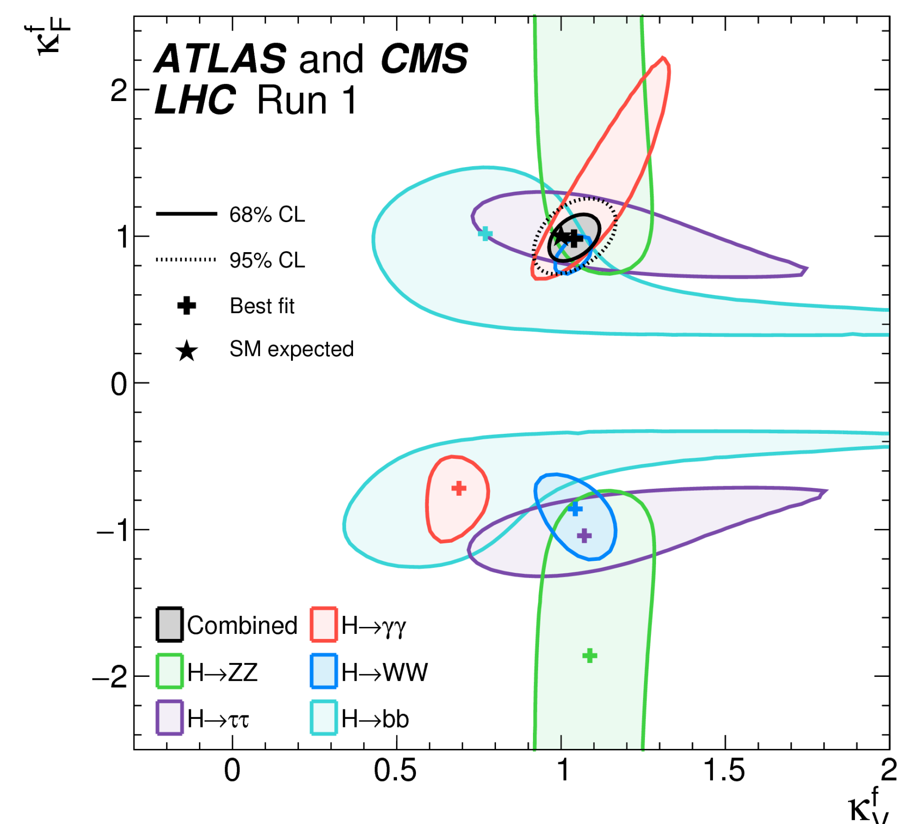

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Direct exploration of the Higgs Yukawa mechanism

Projections for future accelerators

NLO rates

R(E) = σ(E TeV)/σ(14 TeV)

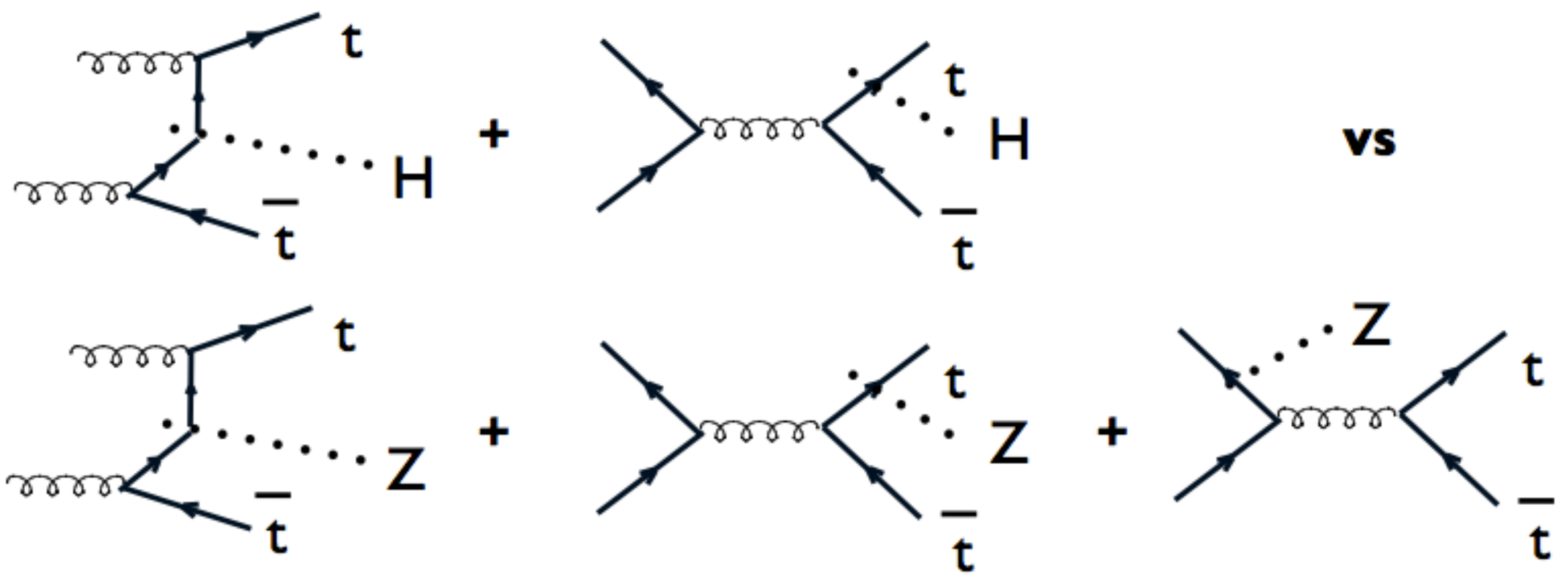
	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

Projections for future accelerators

Coupling	LHC	CepC	FCC-ee	ILC	CLIC	FCC-hh
$\sqrt{s}$ (TeV)→	14	0.24	0.24 +0.35	0.25+0.5	0.38+1.4+3	100
L (fb^{-1}) →	3000(1 expt)	5000	13000	6000	4000	40000
K_W	2-5	1.2	0.19	0.4	0.9	
K_Z	2-4	0.26	0.15	0.3	0.8	
K_g	3-5	1.5	0.8	1.0	1.2	
K_γ	2-5	4.7	1.5	3.4	3.2	< 1
K_μ	~8	8.6	6.2	9.2	5.6	~ 2
K_c	--	1.7	0.7	1.2	1.1	
K_τ	2-5	1.4	0.5	0.9	1.5	
K_b	4-7	1.3	0.4	0.7	0.9	
$K_{Z\gamma}$	10-12	n.a.	n.a.	n.a.	n.a.	
Γ_h	n.a.	2.8	1%	1.8	3.4	
BR_{invis}	<10	<0.28	<0.19%	<0.29	<1%	
K_t	7-10	--	13% ind. tt scan	6.3	<4	~ 1 ?
K_{HH}	?	35% from K_Z model-dep	20% from K_Z model-dep	27	11	5-10

Coupling to top-quarks

y_{top} from $pp \to tt\ H / pp \to tt\ Z$



To the extent that the qqbar → tt Z/H contributions are subdominant:

- **Identical production dynamics:**

  o correlated QCD corrections, correlated scale dependence
  o correlated α_S systematics

- **$m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:**

  o correlated PDF systematics
  o correlated m_{top} systematics

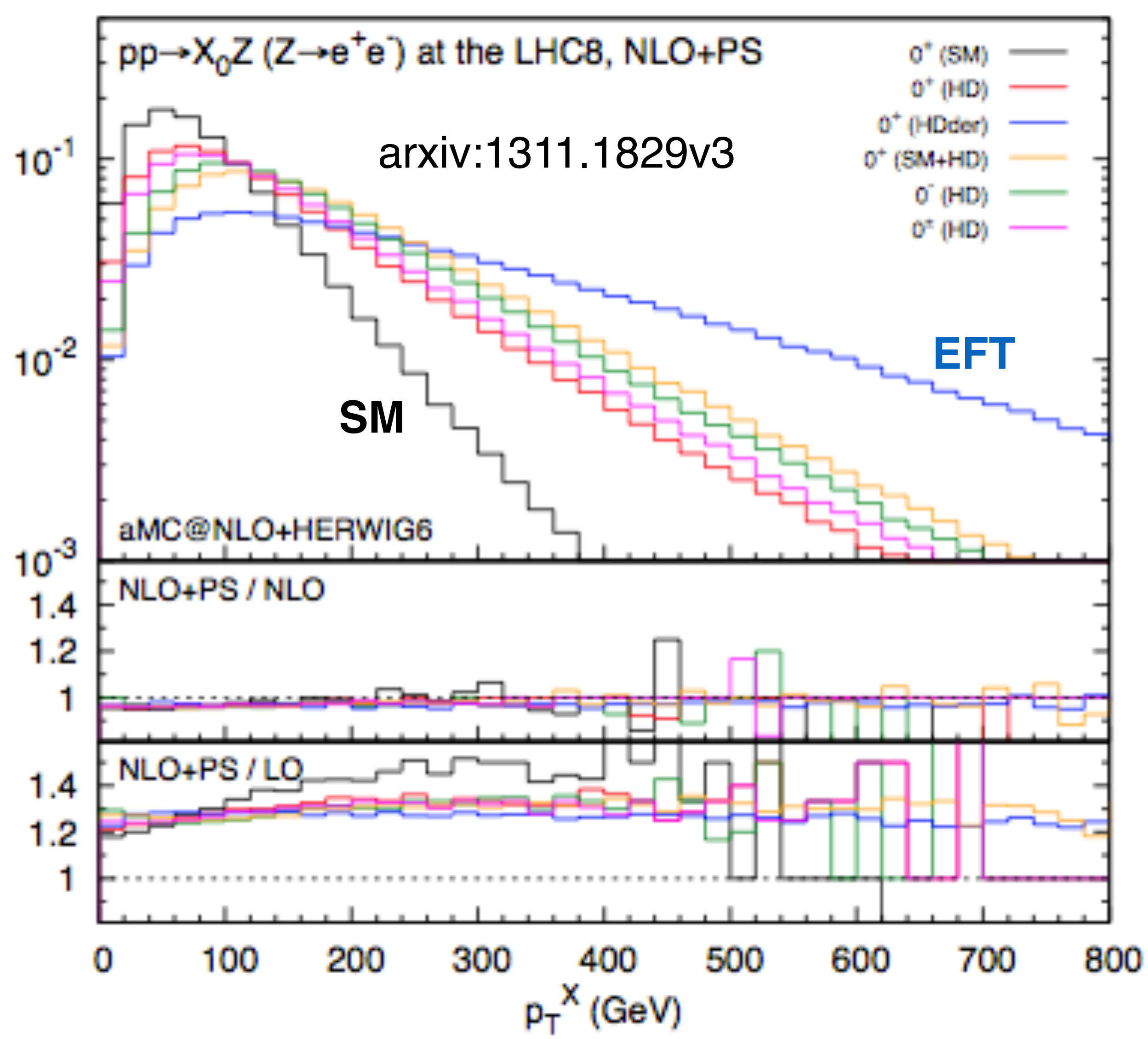
For a given y_{top}, we expect $\sigma(ttH)/\sigma(ttZ)$ to be predicted with great precision

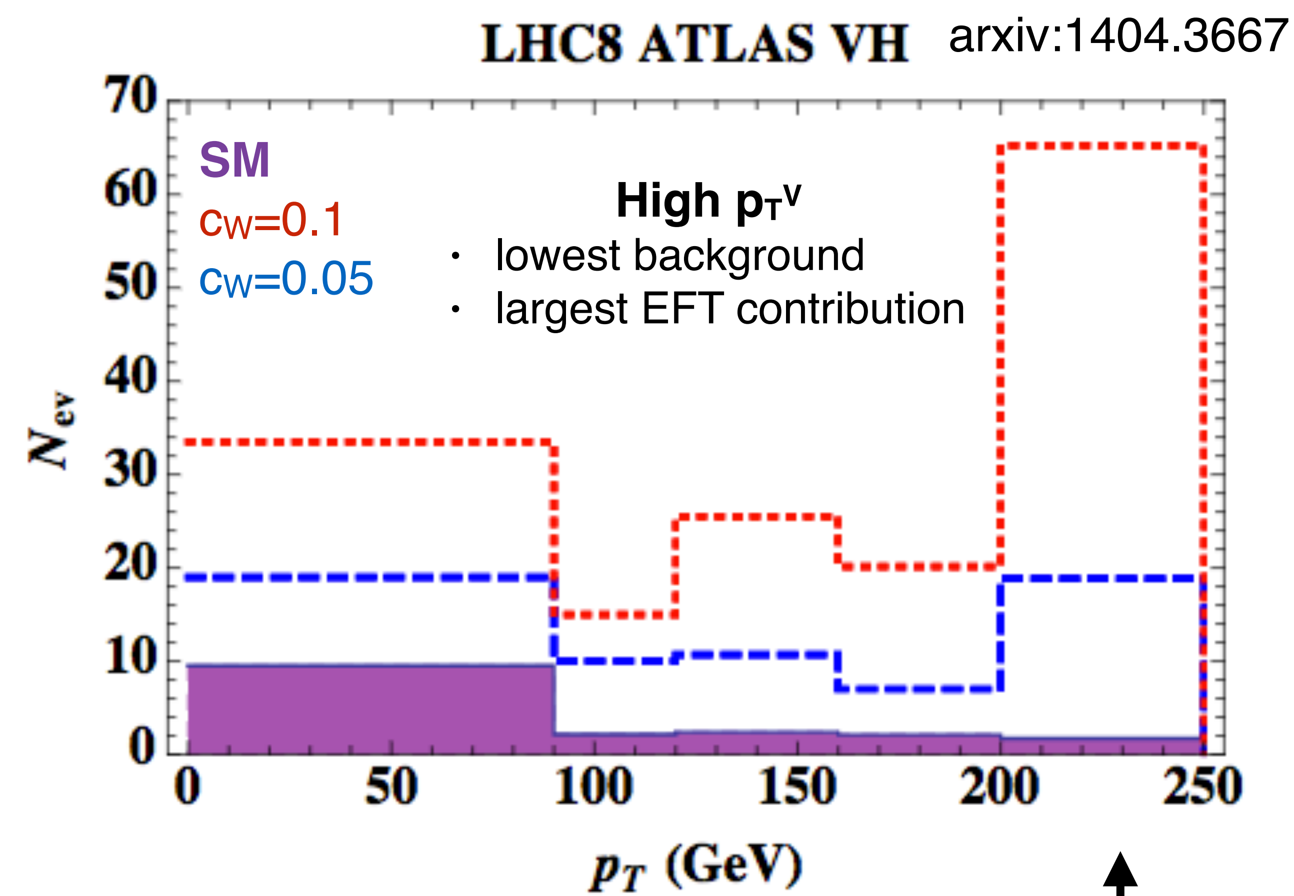
VH - EFT interpretation

The VHbb channel is able to constrain some **combination of parameters** related to the dim-6 operators used to build the **EFT Lagrangian** (see arxiv:1404.3667 Ellis, Sanz, You)

EFT samples already under study in ATLAS:
mg5_aMC *Higgs Characterization Model*

MonteCarlo generation at NLO(QCD)+PS

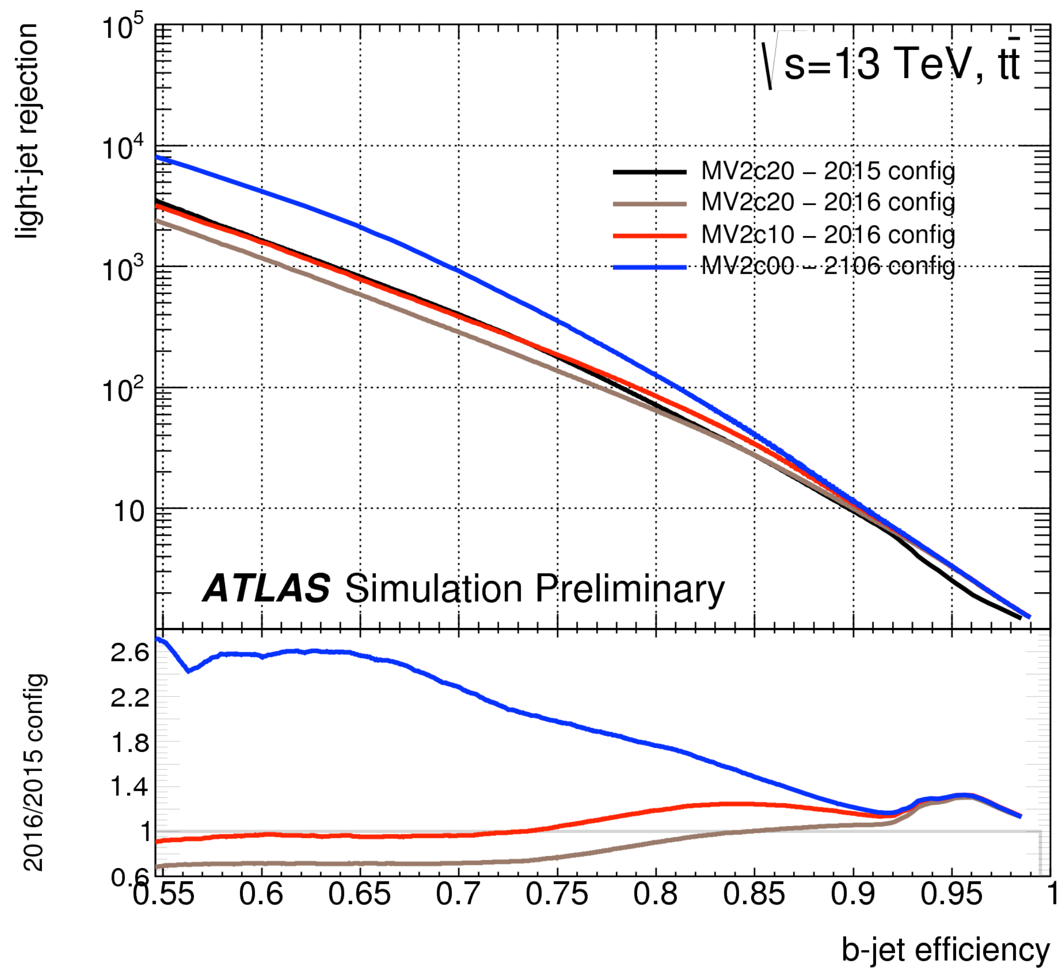


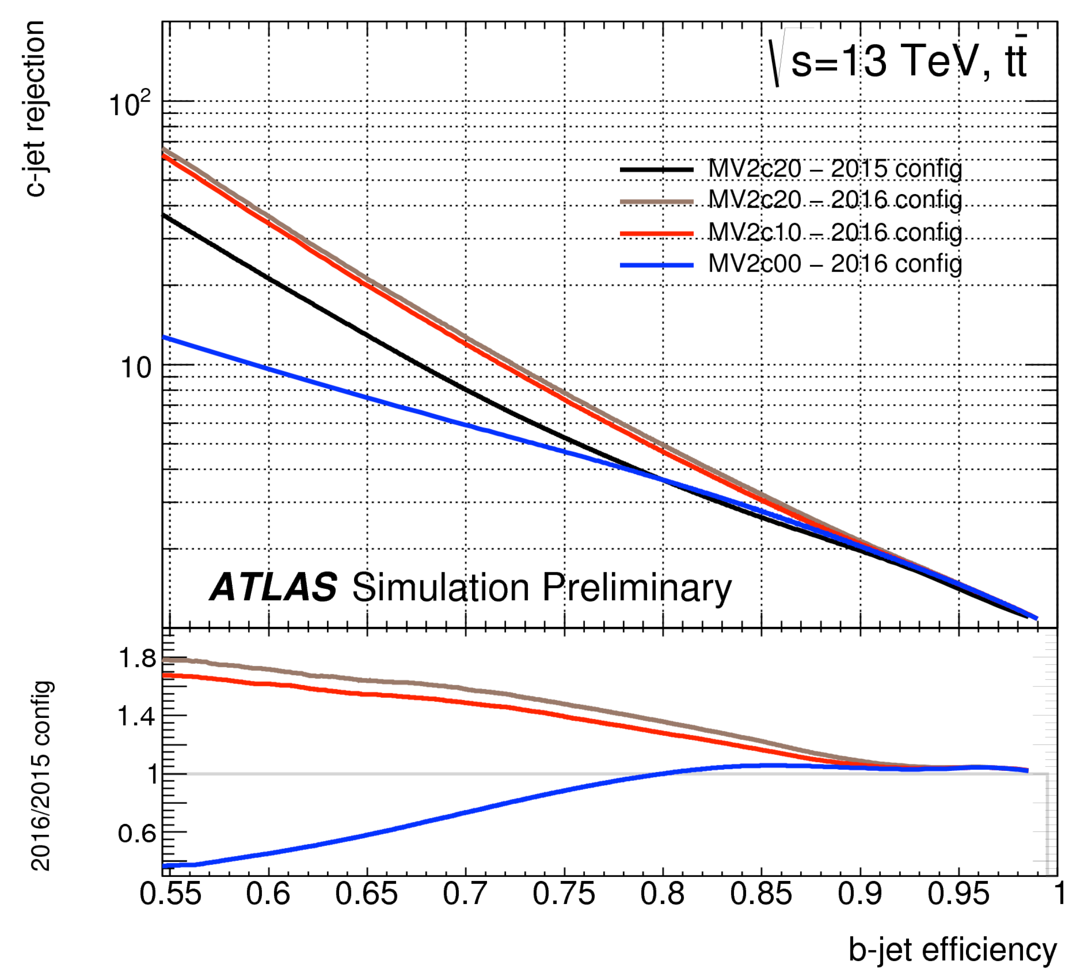


$$\mathcal{L} \supset \; - \; \frac{1}{4} g^{(1)}_{HZZ} Z_{\mu\nu} Z^{\mu\nu} h - g^{(2)}_{HZZ} Z_\nu \partial_\mu Z^{\mu\nu} h$$
$$- \; \frac{1}{2} g^{(1)}_{HWW} W^{\mu\nu} W^\dagger_{\mu\nu} h - \left[g^{(2)}_{HWW} W^\nu \partial^\mu W^\dagger_{\mu\nu} h + \text{h.c.} \right]$$

EFT Lagrangian with VH anomalous couplings
(mass basis, unitary gauge)

B-tagging in ATLAS: Run-1 and Run-2





b-efficiency 70%	MV1c	MV2c20 (2015)	MV2c10
c-rejection	5	8	12
light-rejection	136	400	380