Recent results on the Higgs Boson Production in Association with Top Quarks

Jelena Jovićević, *TRIUMF - Canada*, on behalf of the **ATLAS collaboration**

LHCP 2018, Bologna, Italy

Observation of the Higgs Boson Production in Association with Top Quarks

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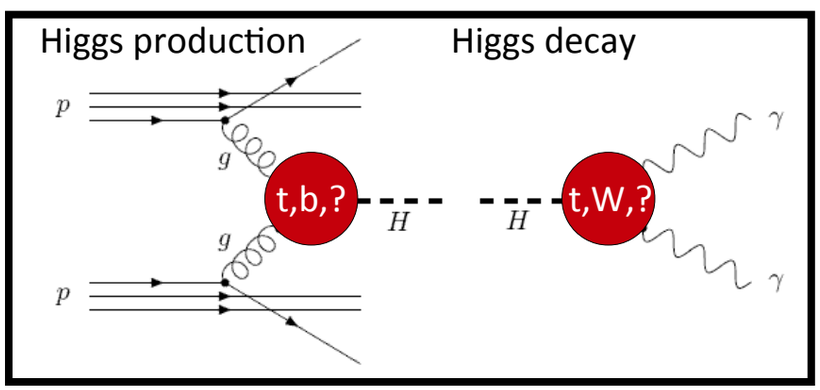
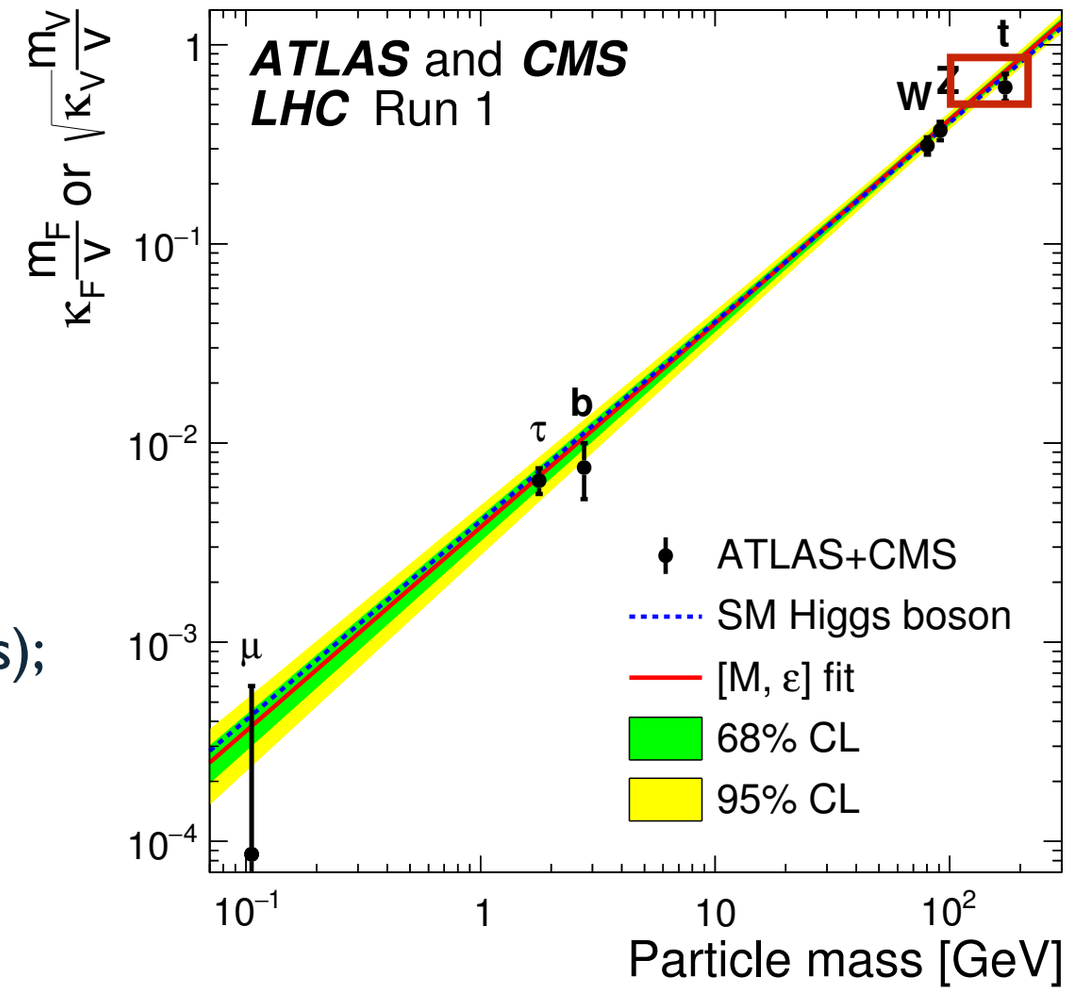
Introduction

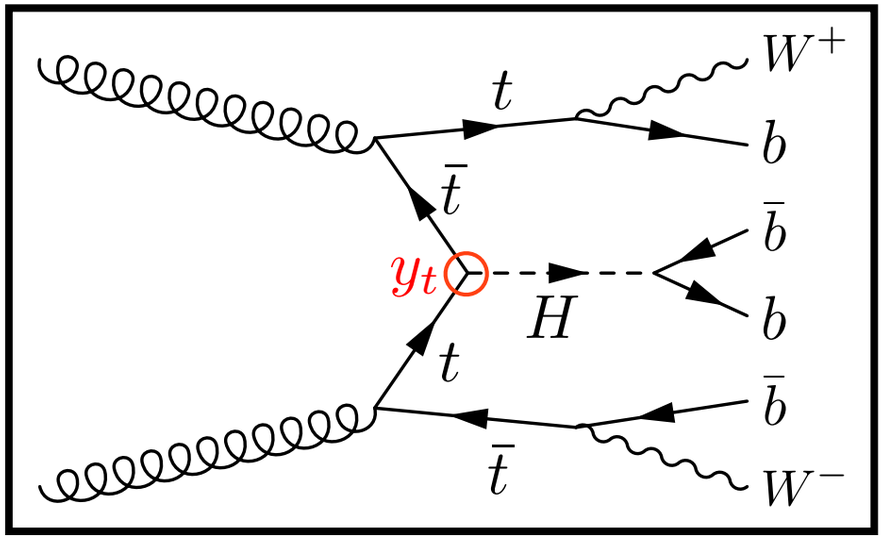
Higgs-top Yukawa coupling

- Largest Yukawa coupling (y_t) in the SM; Sensitive to presence of new physics!
- Measurement of y_t from global "couplings" fit using several prod. & decay modes (ATLAS+CMS Run 1 combination: $\sigma(\kappa_t) \sim 15\%$)
  - Mainly **indirect constraints** from loops in **ggF** & **Hγγ** vertices (assuming no BSM effects);





- **Directly accessible Yt by measuring $t\bar{t}H$ production**



Extensive efforts by ATLAS & CMS to measure $t\bar{t}H$ process during LHC Run 1 and Run 2!

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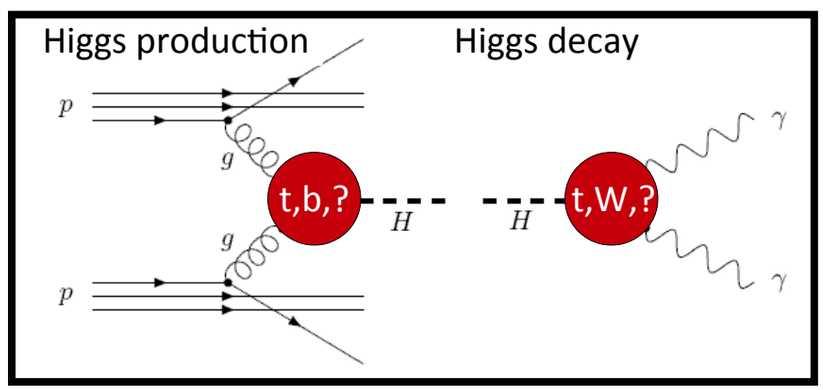
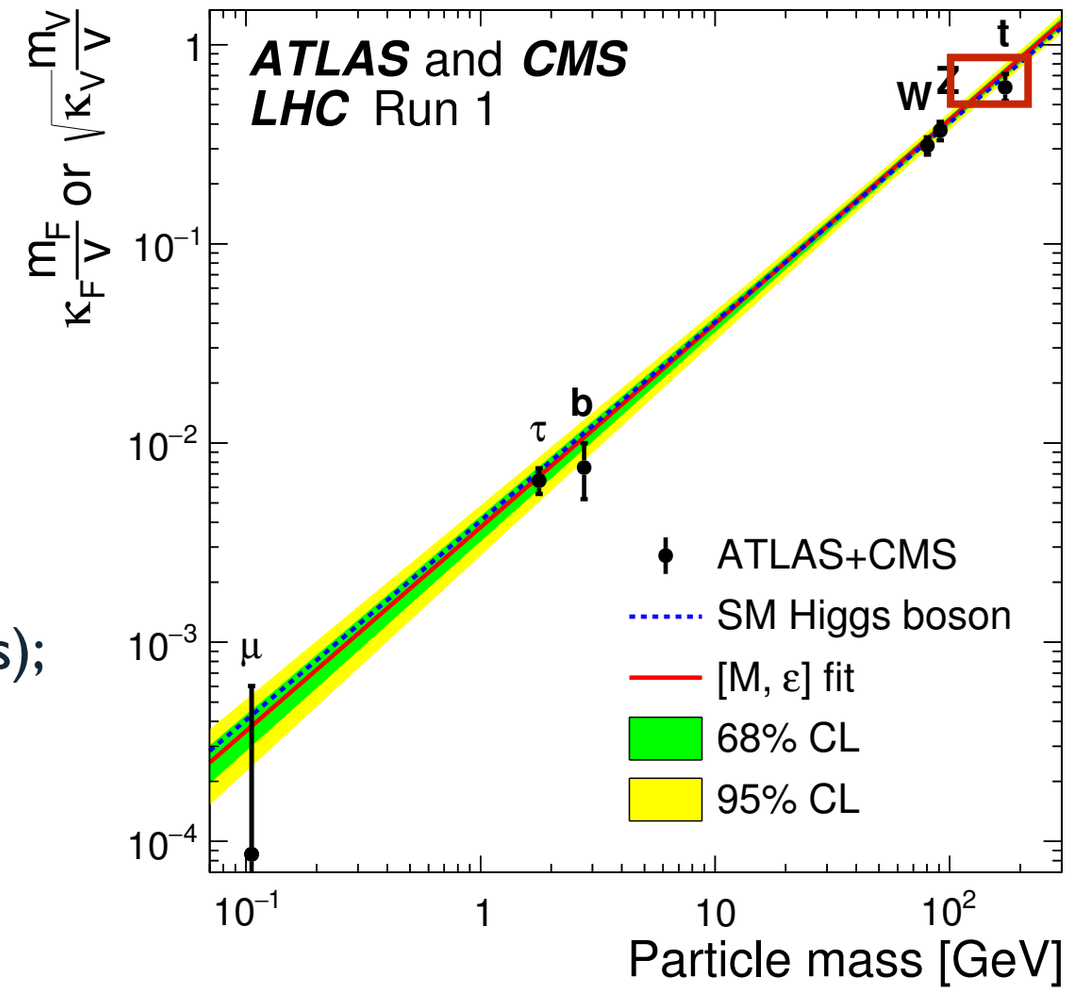
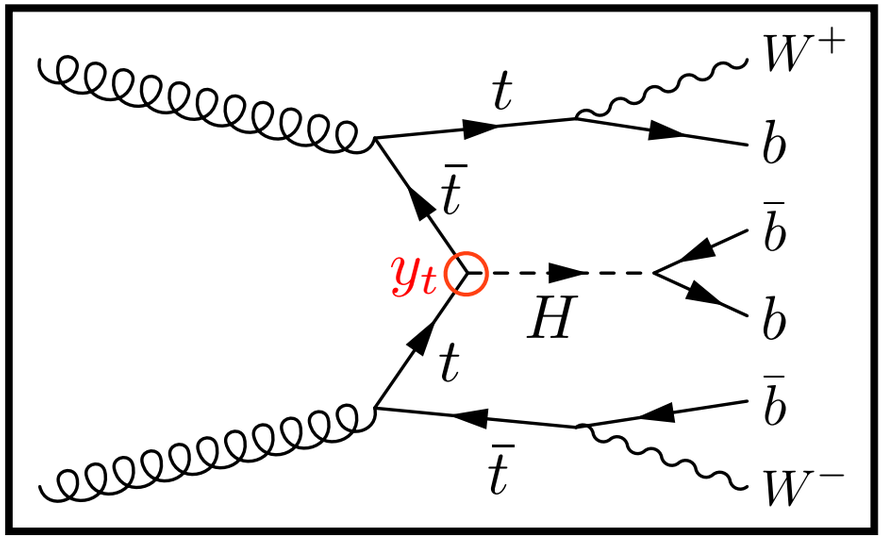




Recent results on direct $t\bar{t}H$ prod. measurement:

ATLAS: Evidence: 4.2σ (3.8σ exp)
(36fb^{-1}@13 TeV)

CMS: Observation: 5.2σ (4.2σ exp)
(5fb^{-1}@7 TeV+20fb^{-1}@8 TeV+36fb^{-1}@13 TeV)



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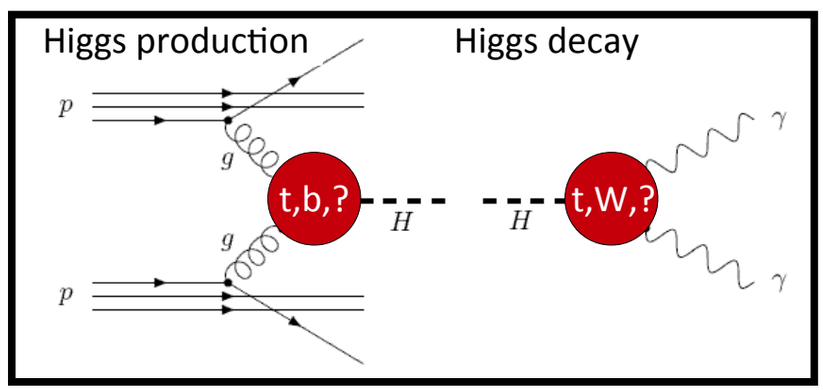

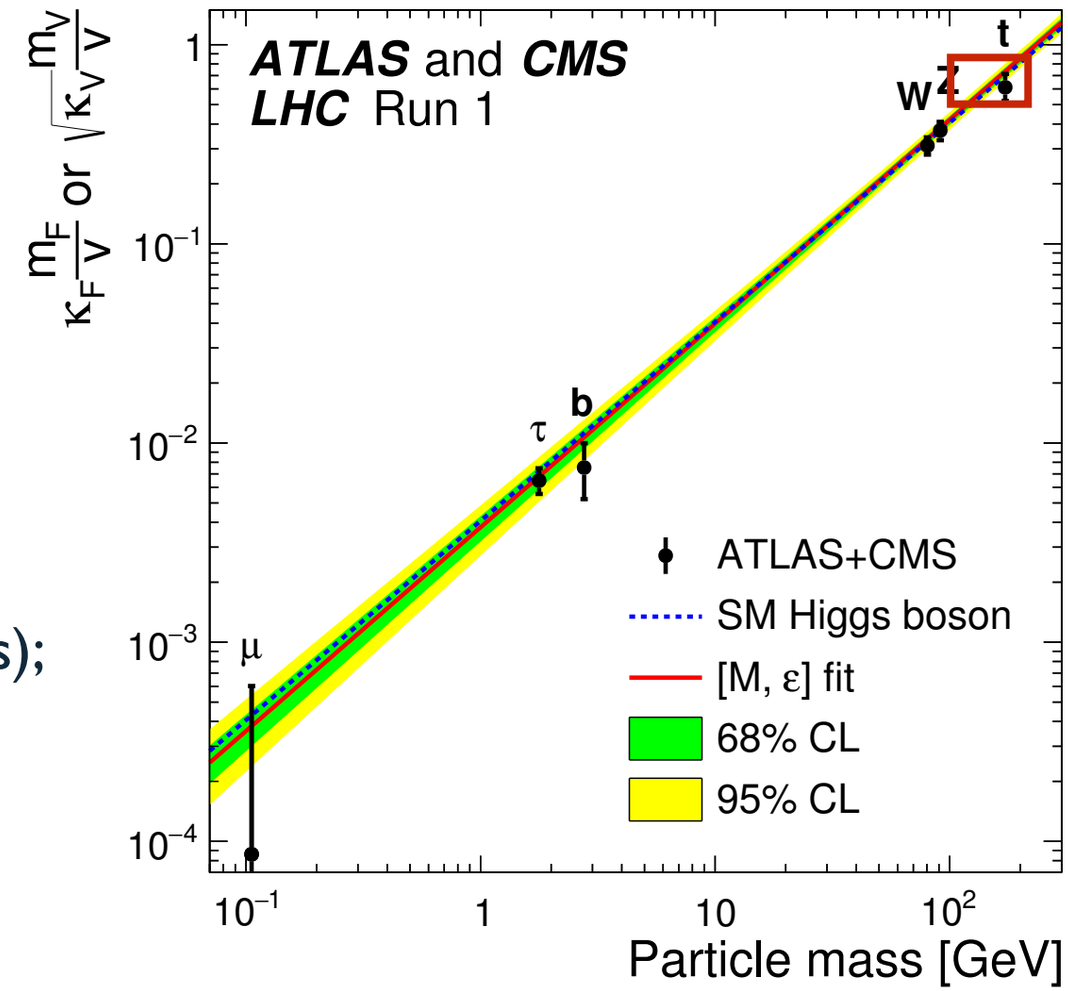

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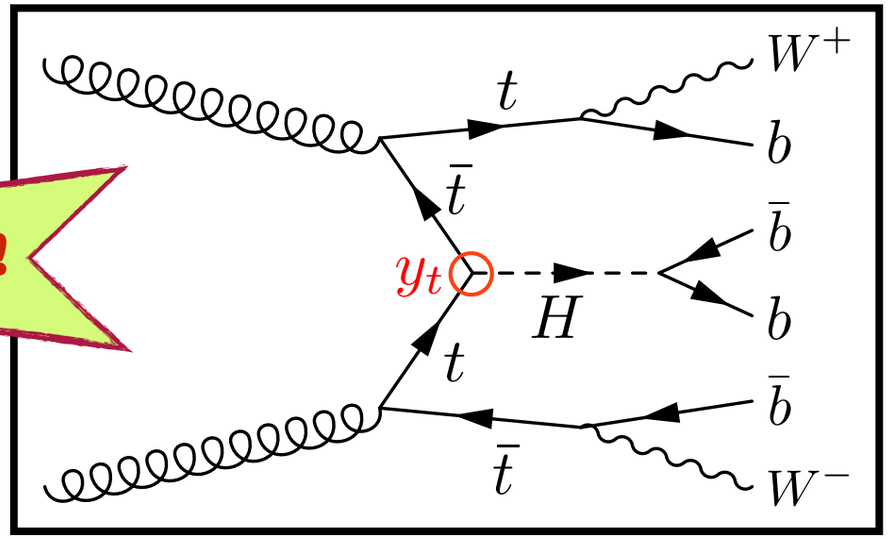
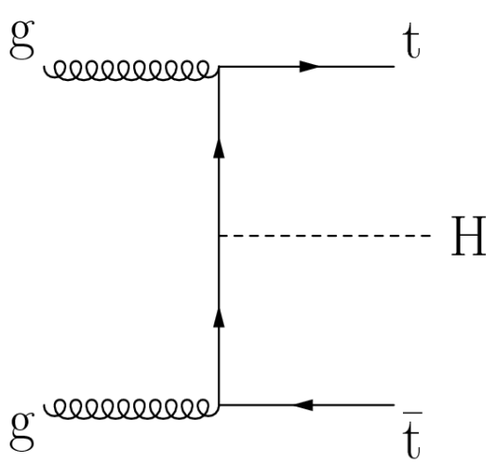
New!



$t\bar{t}H$ - Analysis approach

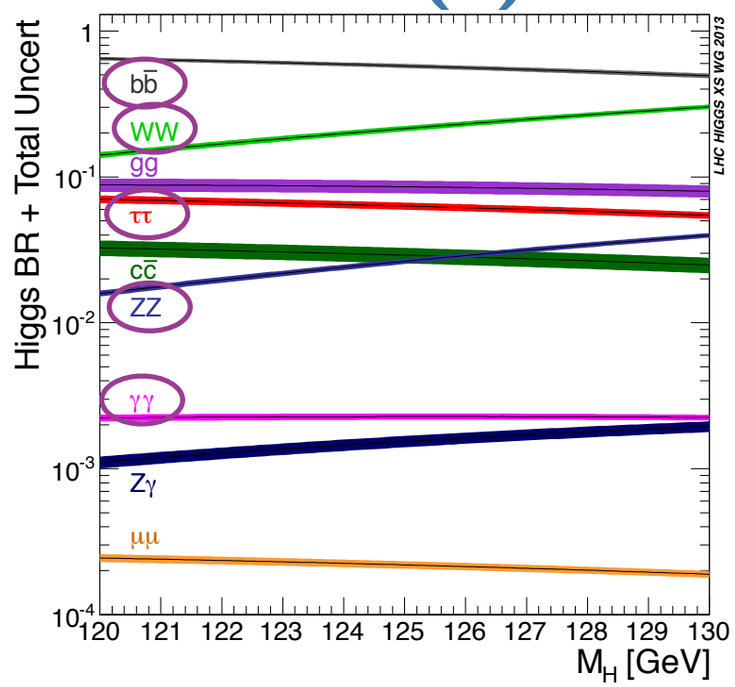
ttH production



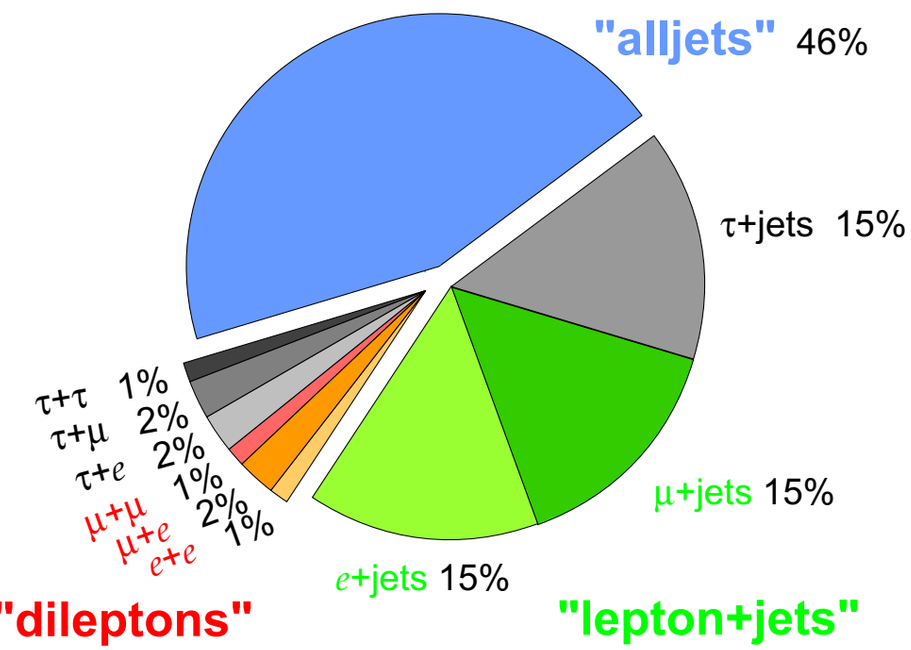
$\sigma(t\bar{t}H) = 507 fb^{-1}$ @ 13TeV

$1\%\sigma(H)$

BR(H)



BR($t\bar{t}$)



Broad spectrum of analyses explored to cover **multiple final states**:

- Large variety of final states - **need good understanding of all reconstructed objects** [e, μ, γ, hadronically decaying τ, jets, *b*-jets, $E_T^{miss.}$].

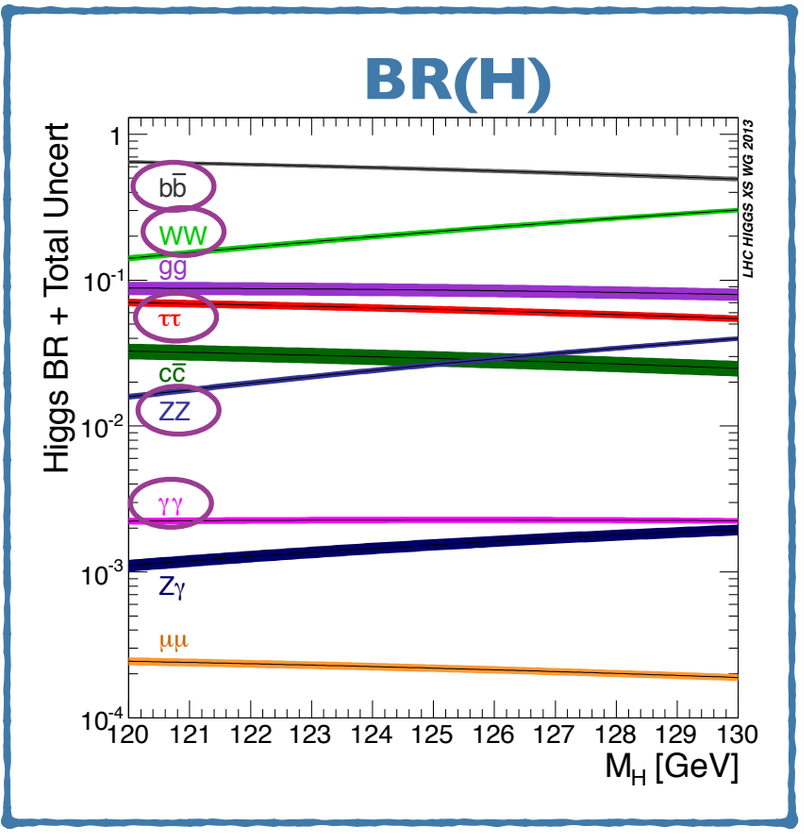
Thanks to excellent detector performance and hard work of object performance groups!

- generally smaller branching ratios correspond to better signal-over-background.

$t\bar{t}H$ - Analysis approach

Categorisation by Higgs boson decay:

Large BR
Large background



Small BR
Purity and precision

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

BR~58%, S/B~1-6%

$t\bar{t}H$ multi-leptons (WW^*,ττ,ZZ^*)

BR = 30%, S/B=4-34%

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

BR = 0.23%, S/B=5-200%

$t\bar{t}H(ZZ^* \rightarrow 4l)$

BR = 0.01%, S/B=50-500%

$t\bar{t}H$ - Analysis approach

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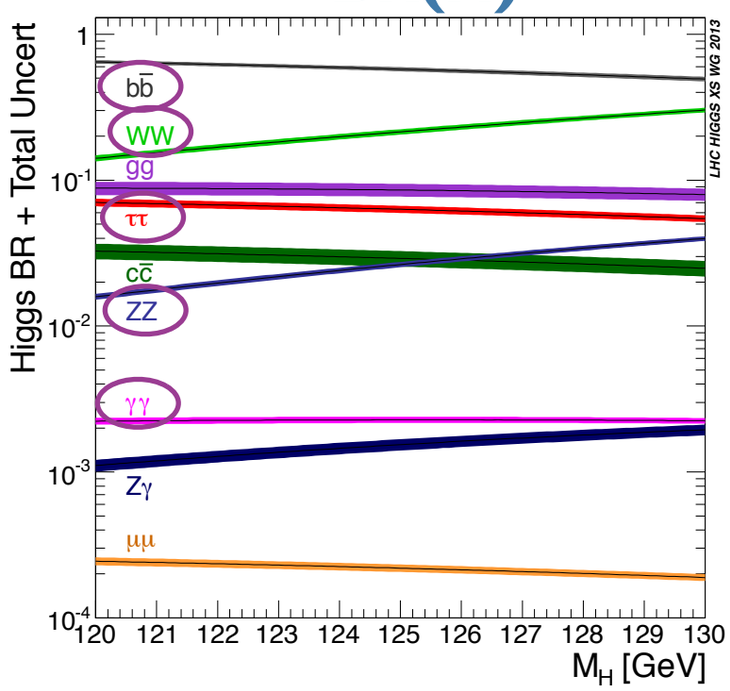
BR(H)



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

Phys. Rev. D 97 (2018) 072016

$t\bar{t}H$ multi-leptons (WW^*,ττ,ZZ^*)

Phys. Rev. D 97 (2018) 072003

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

arXiv:1802.04146

$t\bar{t}H(ZZ^* \rightarrow 4l)$

JHEP 03 (2018) 095

Combined
13TeV
@36.1fb^{-1}
4.2σ (3.8σ exp)

Phys. Rev. D 97 (2018) 072003

$t\bar{t}H$ - Analysis approach

Categorisation by Higgs boson decay:

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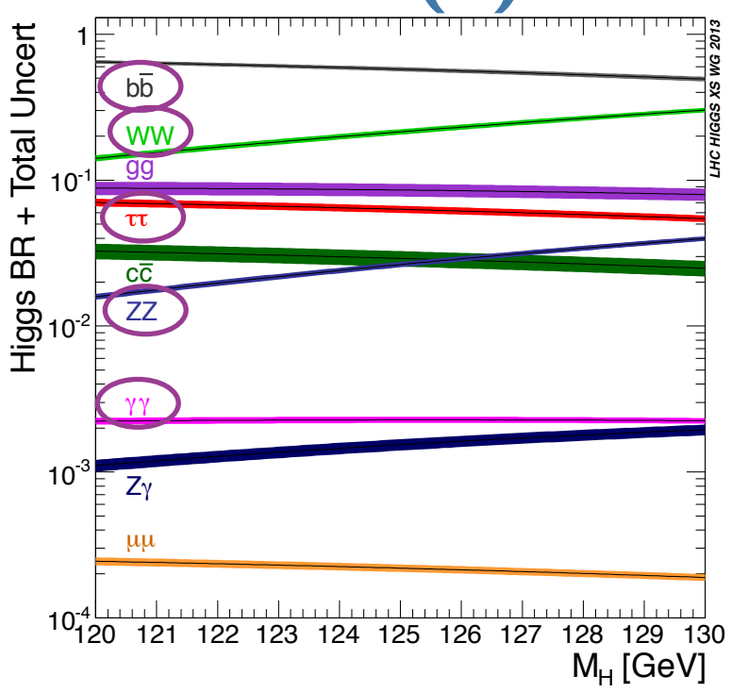
BR(H)



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Phys. Rev. D 97 (2018) 072016

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Phys. Rev. D 97 (2018) 072003

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

arXiv:1806.00425

New! @80fb^{-1}

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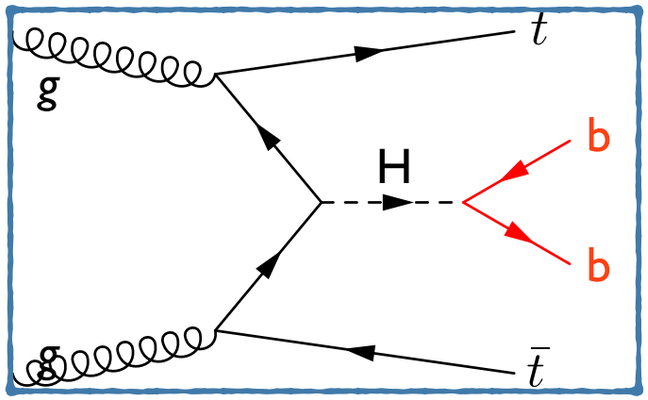
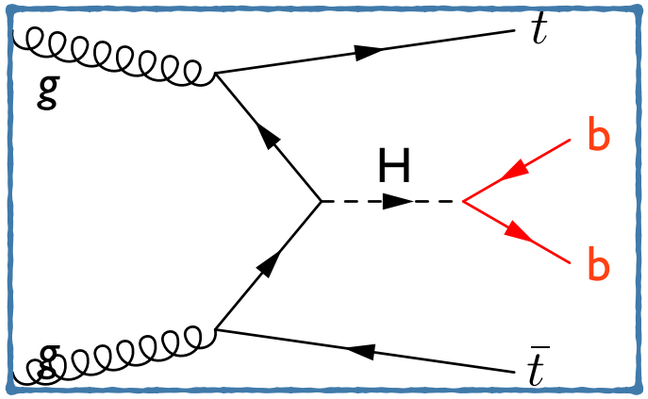


- Fermion-only production and decay;
- Higgs boson reconstruction possible, but challenging due to multiple b-quarks and additional radiation in the final state;
- Irreducible $t\bar{t}+b\bar{b}$ background has large theory uncertainty.

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



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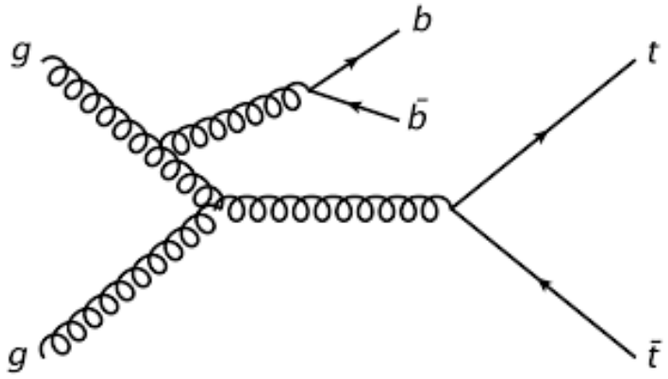
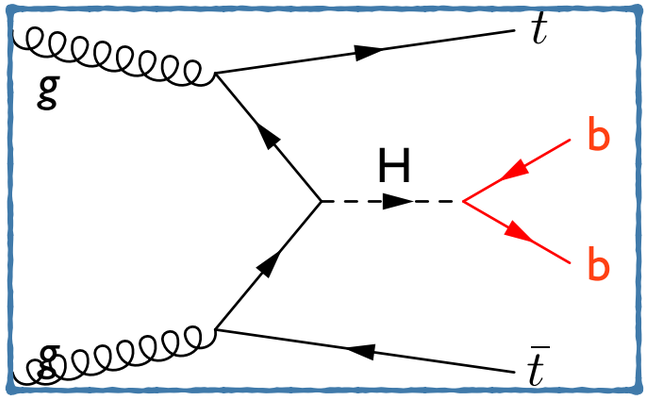
Biggest challenge: good and precise modelling of the **$t\bar{t}$+HF** (**≥1b**, **≥1c**) background



- Nominal sample: 5-flavour scheme;
- Relative contribution of $t\bar{t}$+≥1b subcomponents reweighted to $t\bar{t}+b\bar{b}$ predictions by Sherpa+OpenLoops (4-flavour scheme);

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



- Fermion-only production and decay;
- Higgs boson reconstruction possible, but challenging due to multiple b-quarks and additional radiation in the final state;
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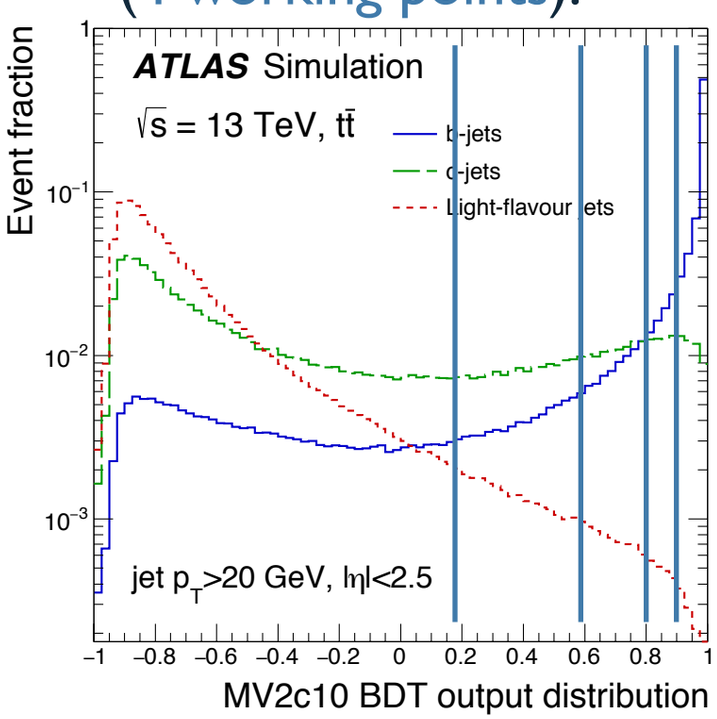
Analysis strategy - cascade of MVAs

Categorisation:

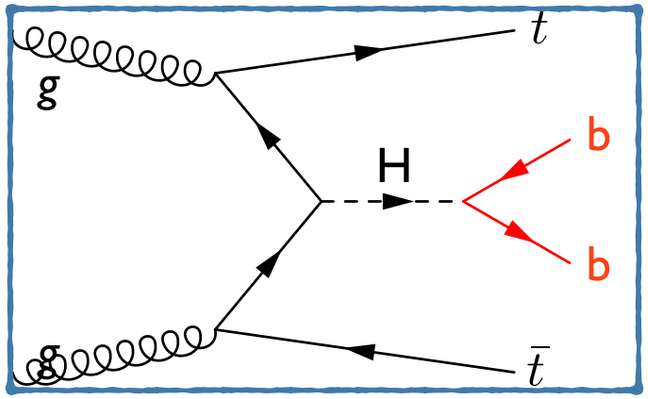
- 1ℓ & 2ℓ (e,μ), # of jets;
- *b*-tag score of jets (4 working points).

Many categories with very different fractions of tt+light, tt+≥1c, tt+1≥b/ttH;
+ Boosted category - events w/ 1 top quark and the H→bb in two large-cone jets



10 CRs
9 SRs

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



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In SRs

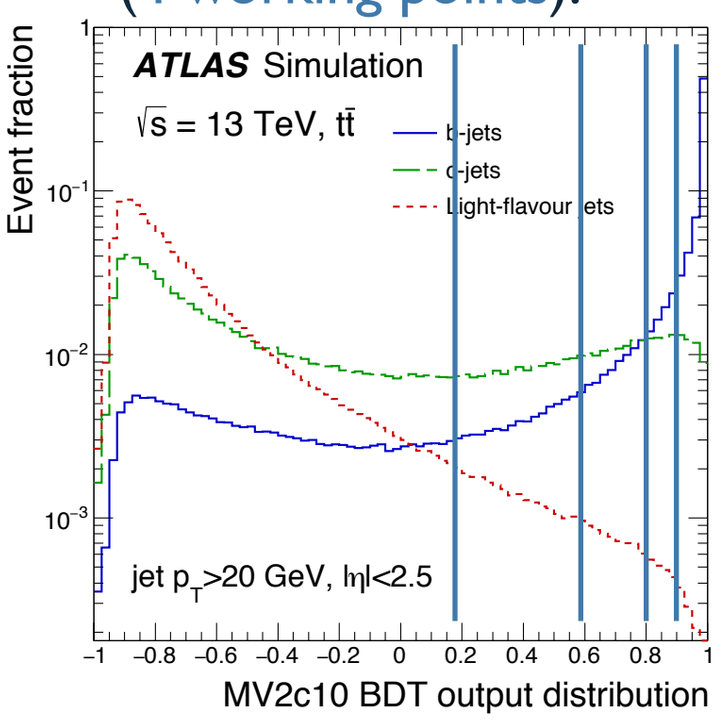
Intermediate:

Reco BDT, matrix element & likelihood discriminants (1ℓ).

+event kinematics, b-tag info

Final:

BDT ttH vs. bkg.



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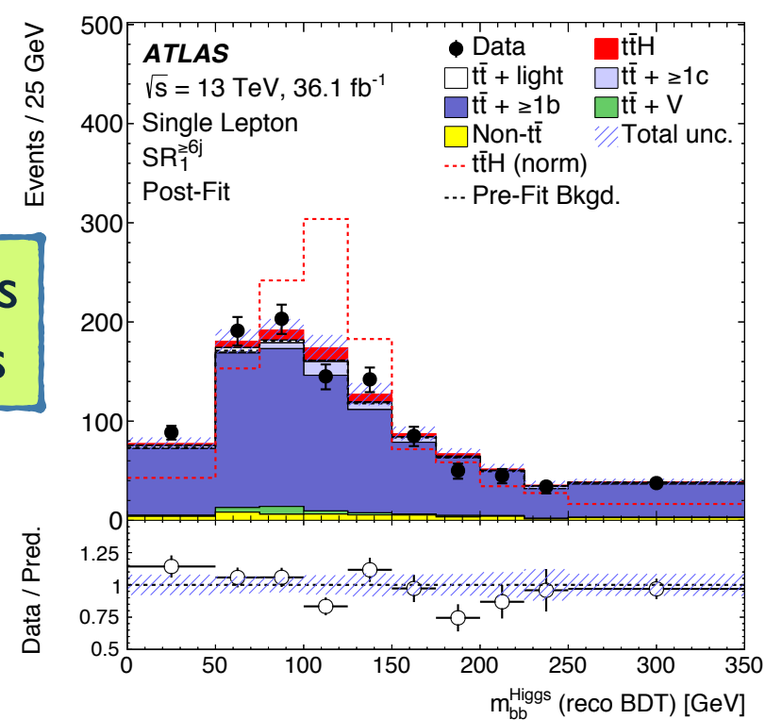
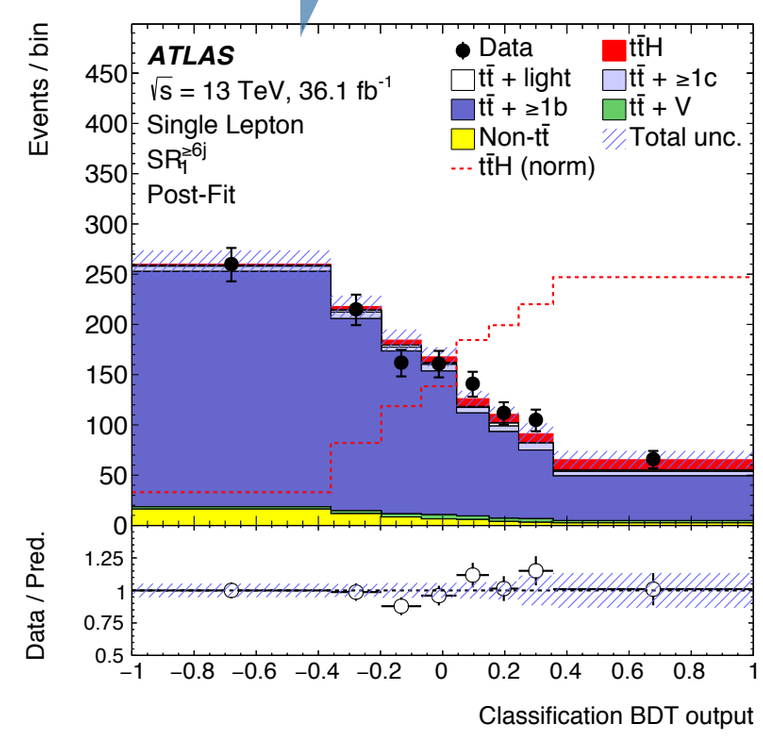
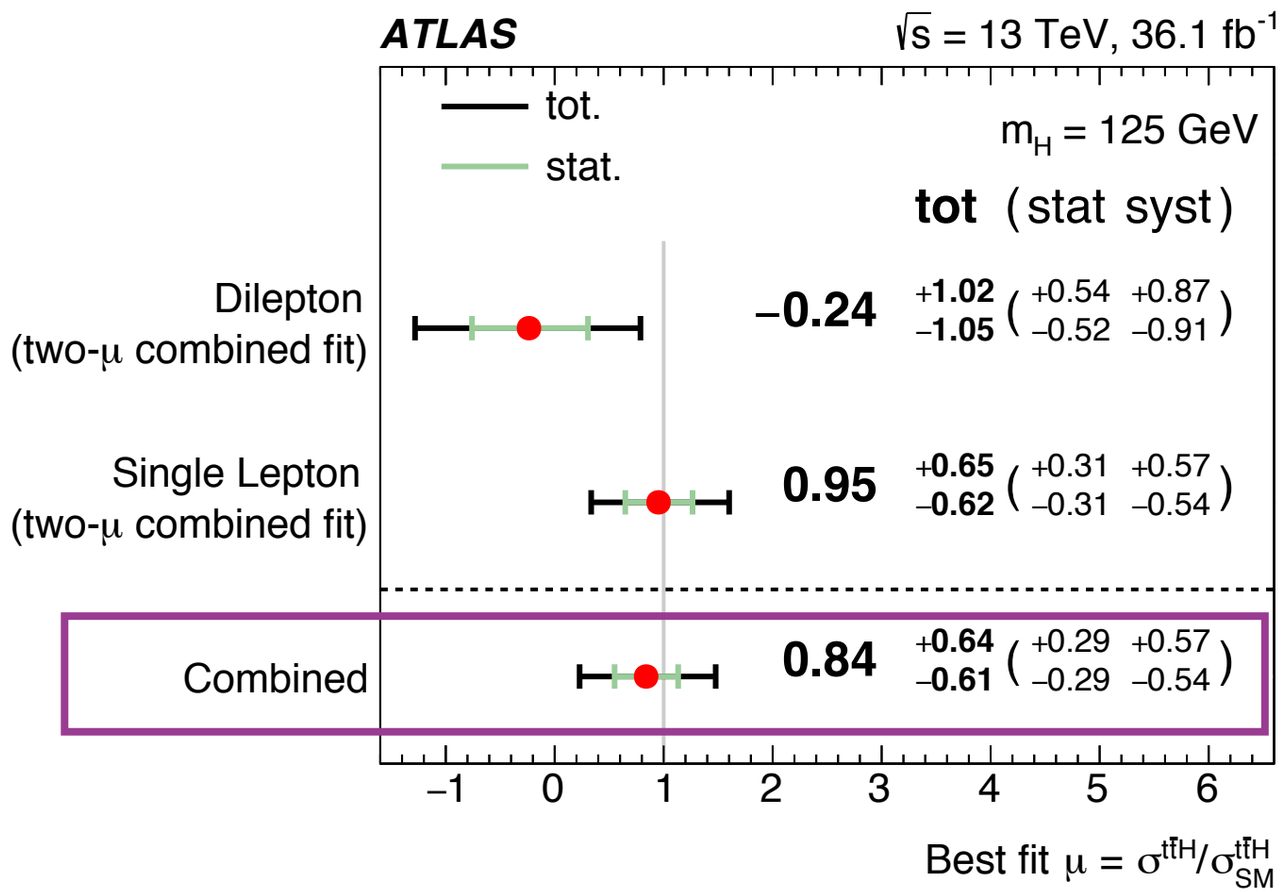




$t\bar{t}H(bb)$ results

Signal extraction: Binned profile likelihood fit to all signal and control regions. Normalisation of $t\bar{t}+\geq 1b$ and $t\bar{t}+\geq 1c$ left free-floating in the fit.

Signal strength: $\mu=\sigma/\sigma_{SM}$



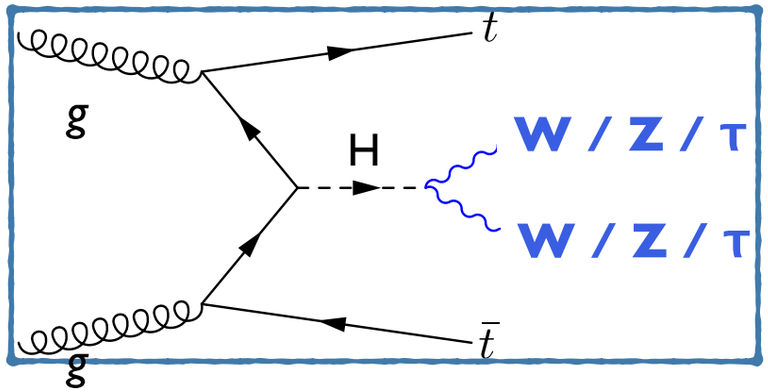
Significance:
1.4 σ (expected 1.6 σ)

Dominant systematics

- **Modelling of $t\bar{t}$ +≥1b (±0.46);**
- Limited MC statistics (±0.30);
- Jet flavour tagging (±0.16);
- Jet energy scale & resolution (±0.16);

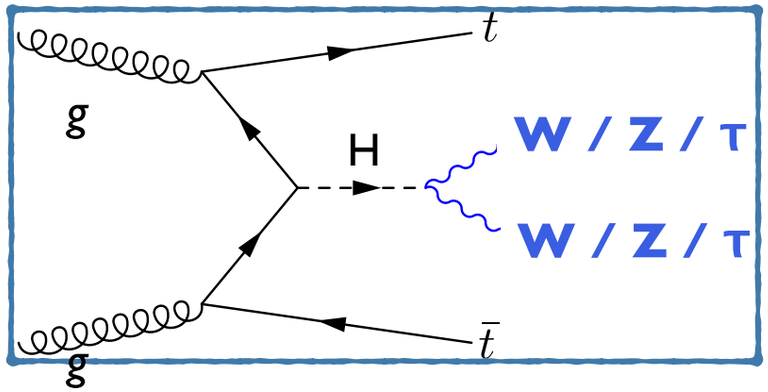
Systematically limited:
Requires improvements from both TH and EX communities!

$t\bar{t}H$(multi-leptons)



- Targeting: **ZZ*, WW*** and **ττ** decays combined with leptonic $t\bar{t}$ decays - distinct multi-lepton signatures*
- Higgs reconstruction is difficult.

$t\bar{t}H$(multi-leptons)



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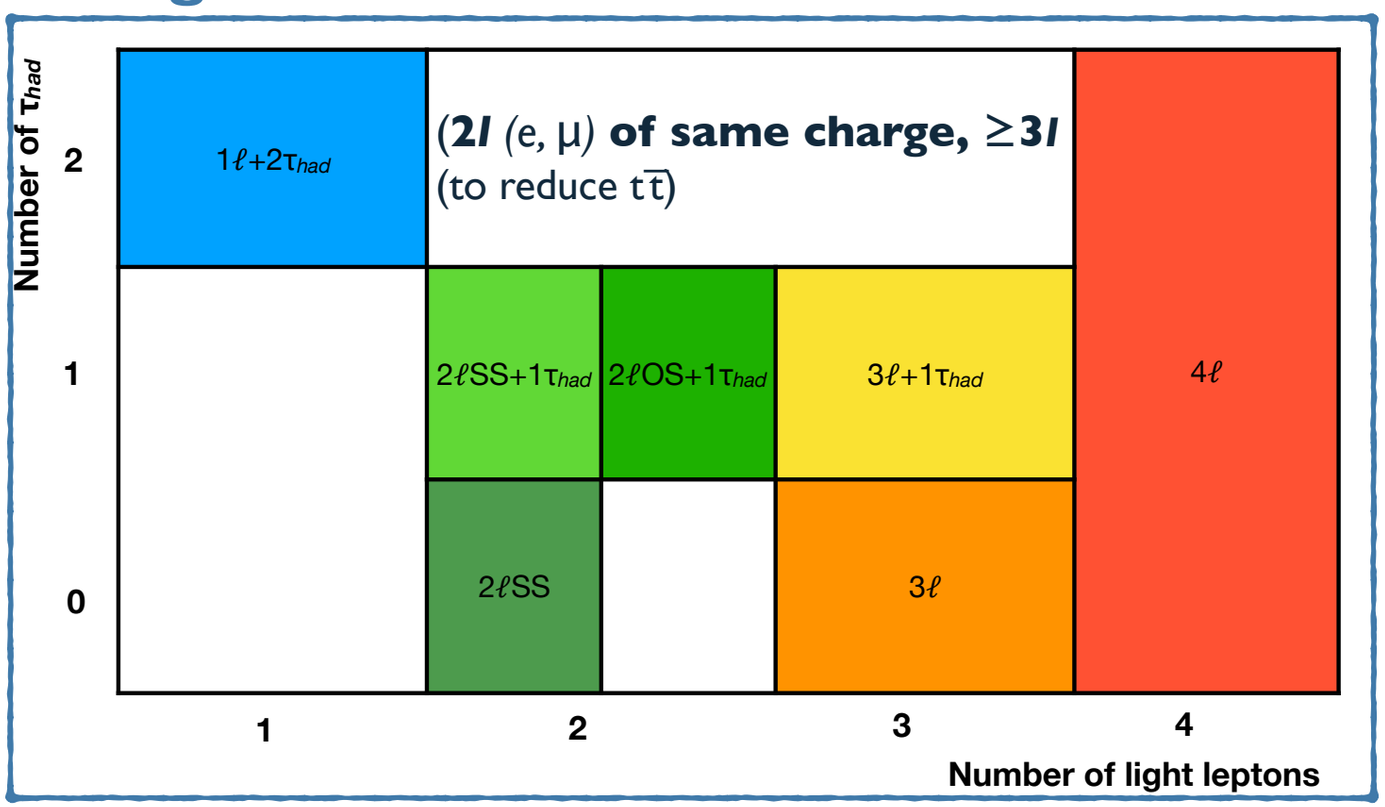
Categorisation:

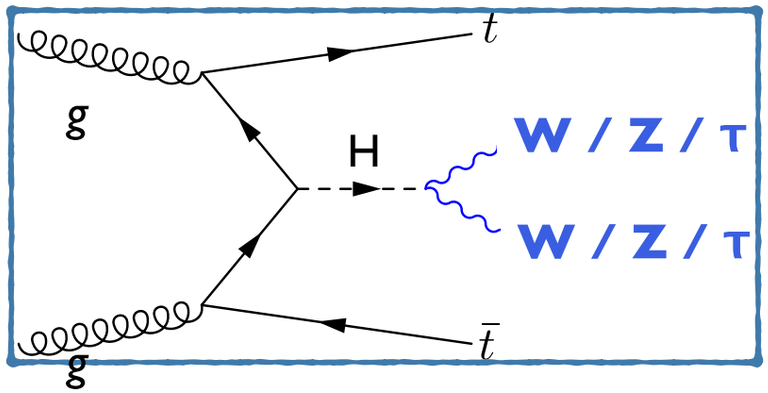


Main backgrounds:

- Irreducible: $t\bar{t}$ +V and VV - estimated from NLO MC & validated in data.
- Reducible: Non-prompt e, μ and hadronic τ: primarily from decays in $t\bar{t}$, and prompt light leptons with misidentified charge - estimated from data;

*Events originating from ttH(ZZ→4ℓ) are analysed within H→ZZ→4ℓ coupling analysis.

$t\bar{t}H$(multi-leptons)



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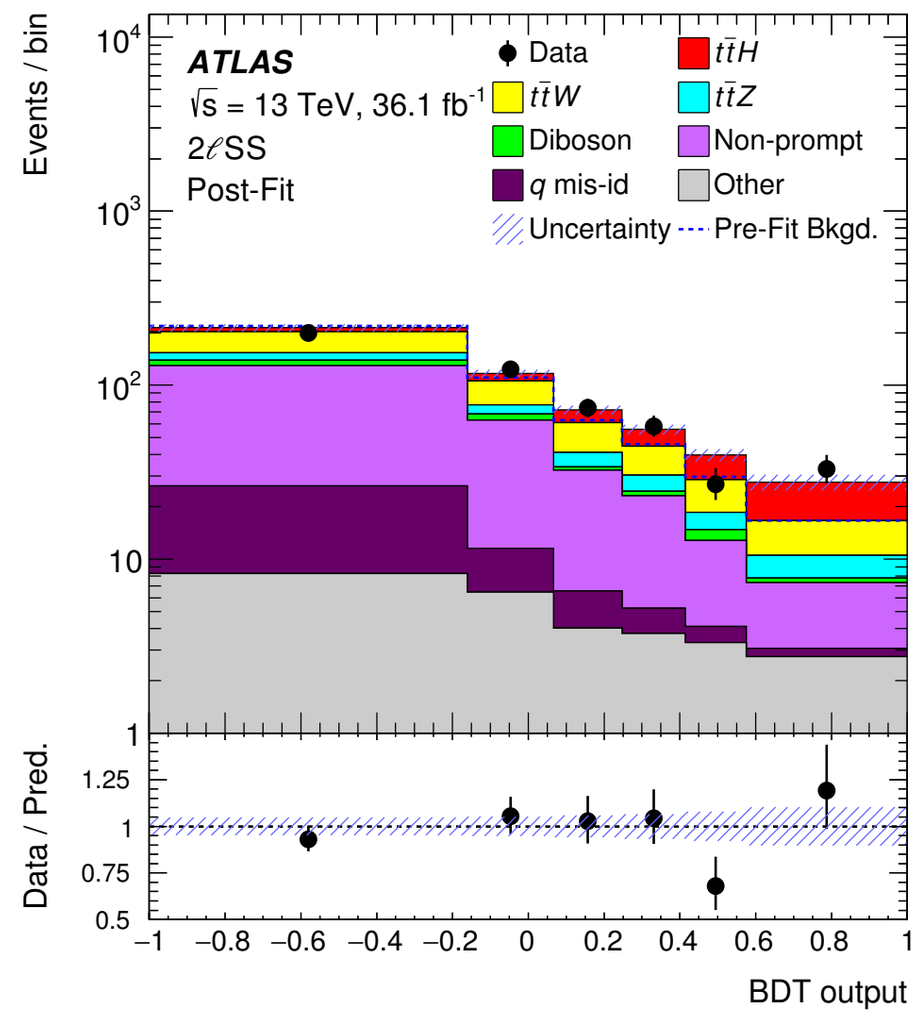
Signal extraction strategy

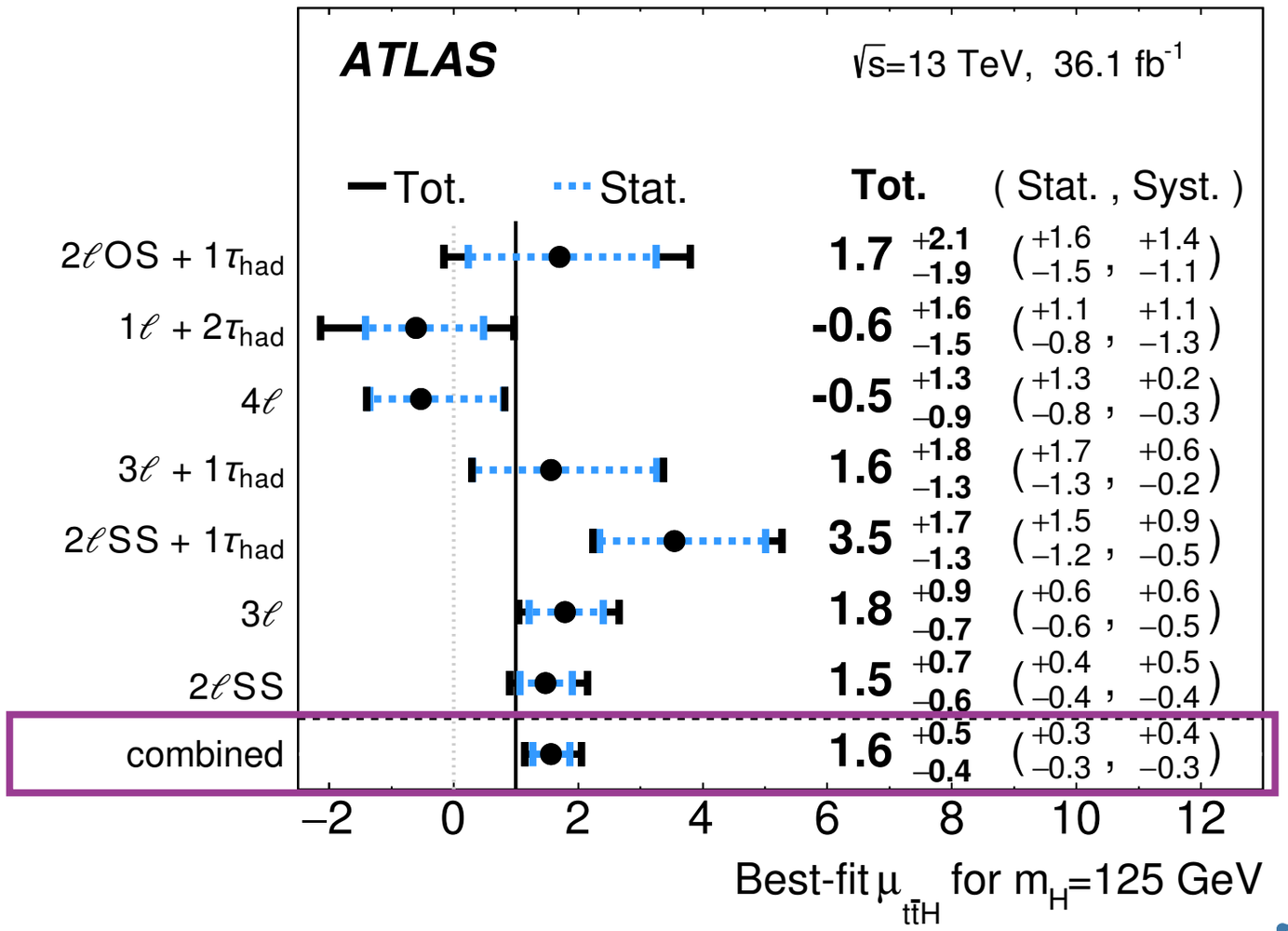
Object level discrimination: Isolation BDT to reduce non-prompt bkg, Charge misID BDT;

Event level discrimination: Fit or cut on BDT output in all categories [except 3ℓ+1τ & 4ℓ].



$t\bar{t}H$(multi-leptons) results

Signal extraction: Binned profile likelihood fit across all categories including main background control regions.



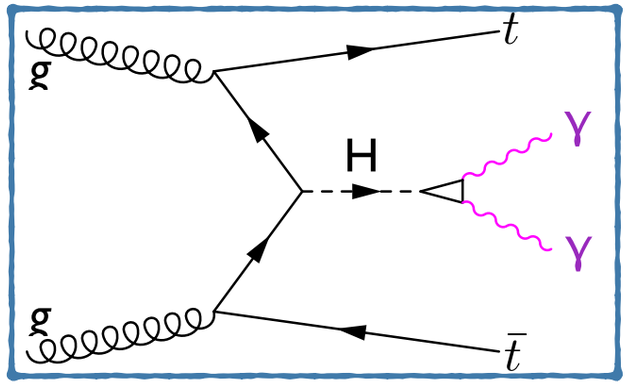
Significance:
4.1 σ (expected 2.8 σ)

Dominant systematics

- $t\bar{t}H$ modelling (+0.20,-0.10);
- Jet energy scale/resolution (±0.17);
- Non-prompt e/μ (±0.14) - large contribution from limited CR stat .

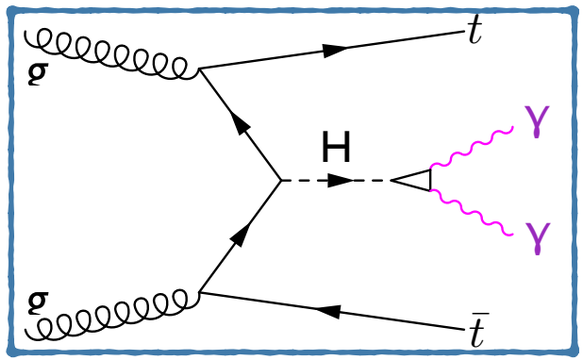
New data will improve the precision on channels that are still stats. limited and help constraining $t\bar{t}Z$ & $t\bar{t}W$ background.

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



- Small rate;
- Higgs boson can be reconstructed as a "narrow" peak; Side-bands can be used to estimate the background.

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



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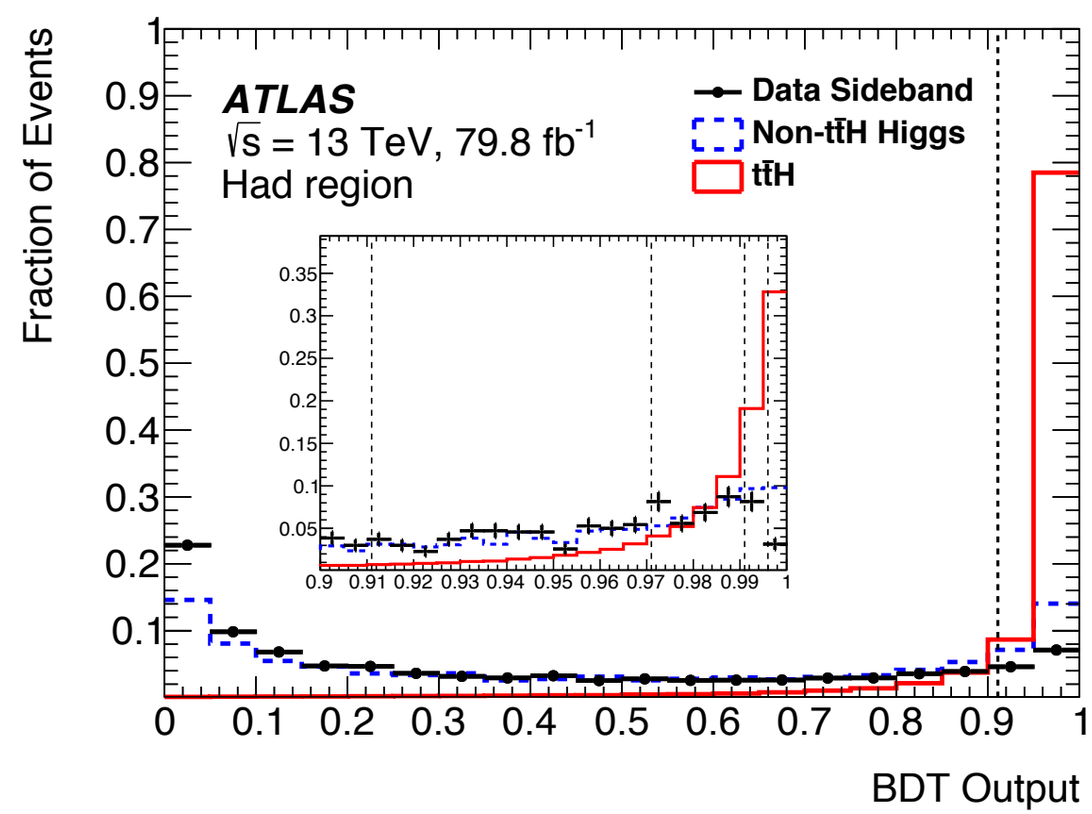
(New) Analysis strategy:

- Categorisation based on $t\bar{t}$ decay - **leptonic** ($\geq 1\ell$) and **hadronic** (0ℓ) category;
- Further categorisation based on **XGBoost BDT** discriminant value - **4 hadronic** and **3 leptonic** categories (events w/ low BDT scores rejected).

- Input vars to XGBoost BDT:
  4-vector information of photons ($p_T/m_{\gamma\gamma}$), jets, E_T^{miss} (both cat), lepton(s) (lep cat), and b-tag (had cat);
- Training $t\bar{t}H$ (from simulation) vs. main background - $\gamma\gamma$, $tt\gamma\gamma$ (from data CRs), other *H* (from simulation).



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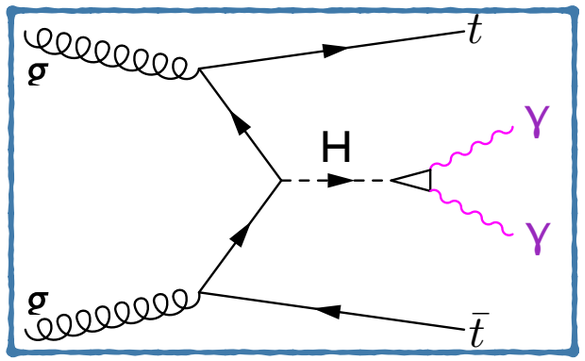

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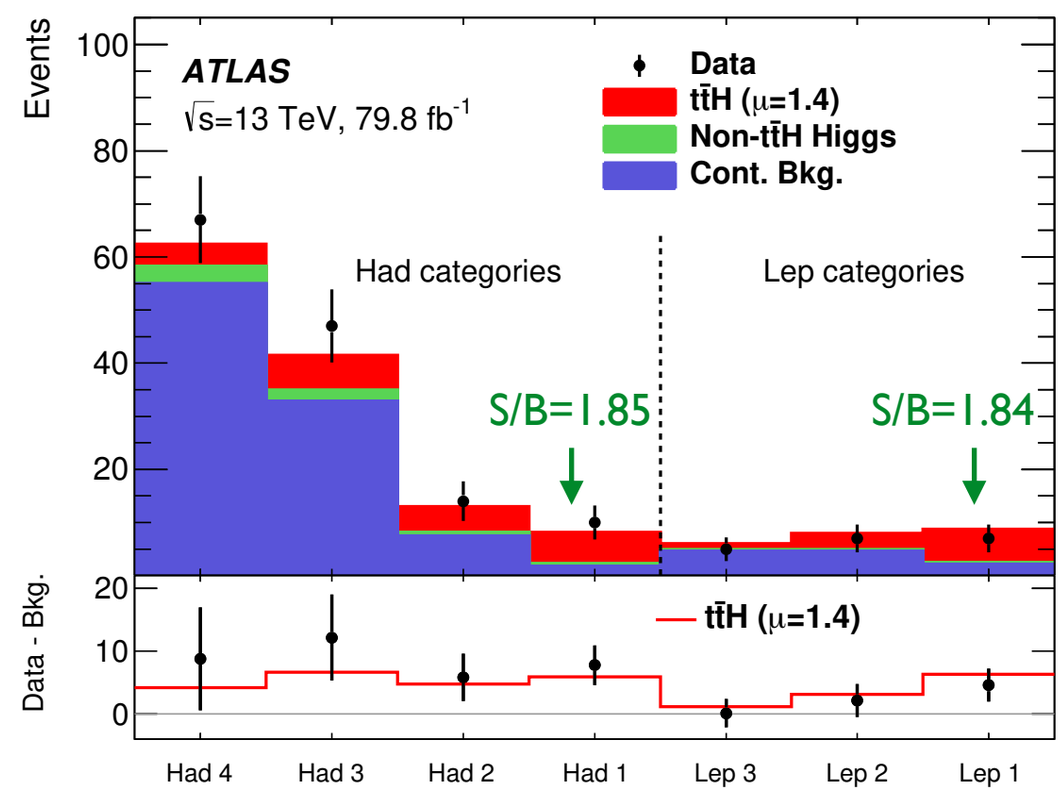

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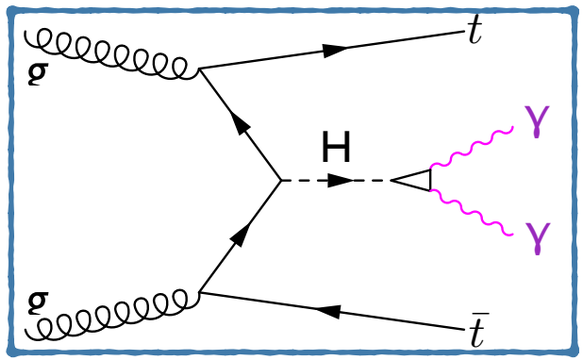

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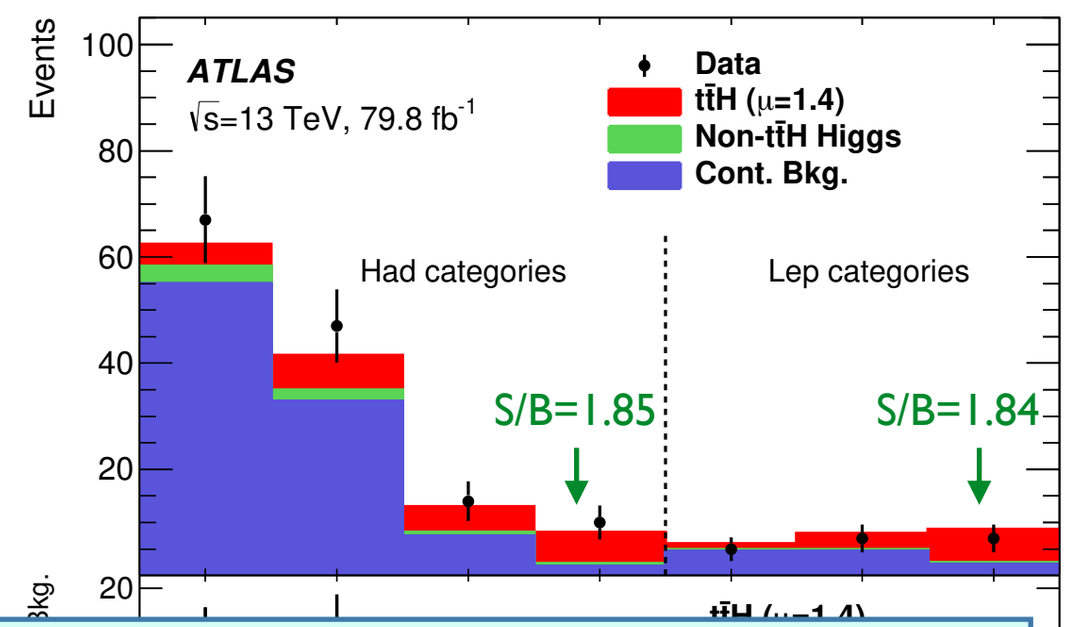
- Categorisation based on $t\bar{t}$ decay - **leptonic** ($\geq 1\ell$) and **hadronic** (0ℓ) category;
- Further categorisation based on **XGBoost BDT** discriminant value - **4 hadronic** and **3 leptonic** categories (events w/ low BDT scores rejected).

- Input vars to XGBoost BDT:
  4-vector information of photons ($p_T/m_{\gamma\gamma}$), jets, E_T^{miss} (both cat), lepton(s) (lep cat), and b-tag (had cat);
- Training $t\bar{t}H$ (from simulation) vs. main background - $\gamma\gamma$, $tt\gamma\gamma$ (from data CRs), other *H* (from simulation).

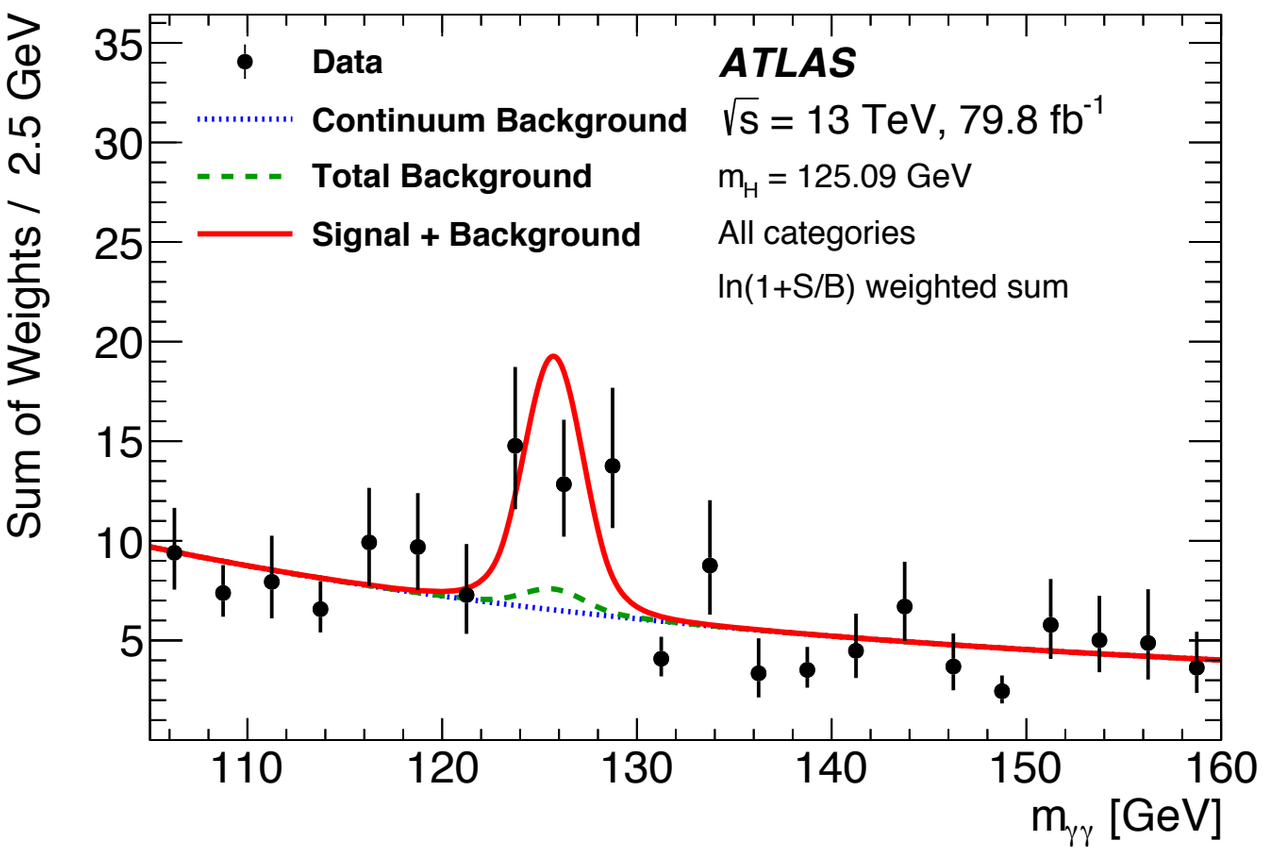


50% improvement in sensitivity:
Changes in analysis strategy + update to the new ATLAS reconstruction software

$t\bar{t}H(\gamma\gamma)$ results

Background estimation and **signal extraction** performed by simultaneous **unbinned fit** of $\mathbf{m_{\gamma\gamma}}$ spectra (105-160 GeV) in all **7 categories**.

- Higgs signal parametrisation: double-sided Crystal Ball function;
- Continuous background parametrisation: smooth function (power-law or exponential)



$t\bar{t}H(\gamma\gamma)$ results

Background estimation and **signal extraction** performed by simultaneous **unbinned fit** of $\mathbf{m_{\gamma\gamma}}$ spectra (105-160 GeV) in all **7 categories**.

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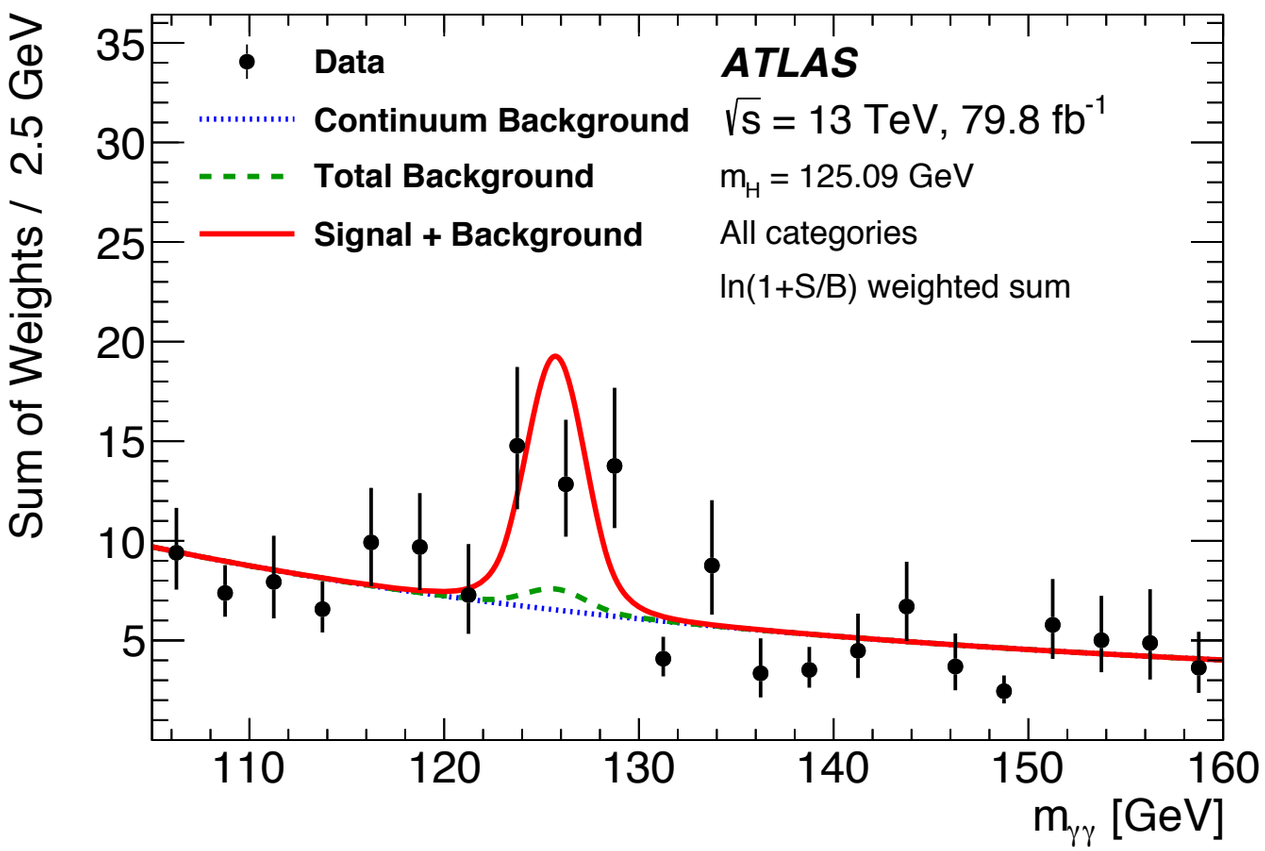
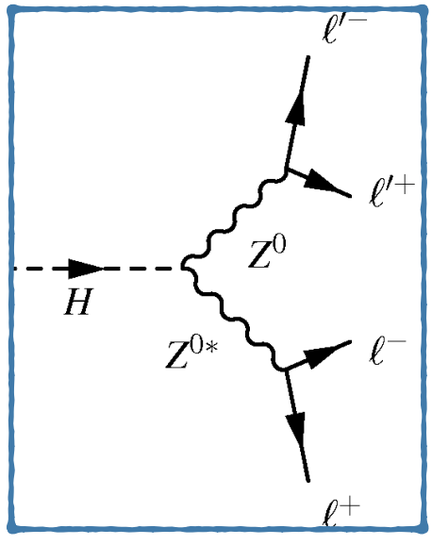


Dominant uncertainties

- Statistical (~29%);
- $t\bar{t}H$ parton shower model (8%);
- photon isolation, energy resolution & scale (8%);
- Jet energy scale & resolution (6%);

Significance: 4.1 σ (expected 3.7 σ)

$t\bar{t}H(ZZ^* \rightarrow 4l)$



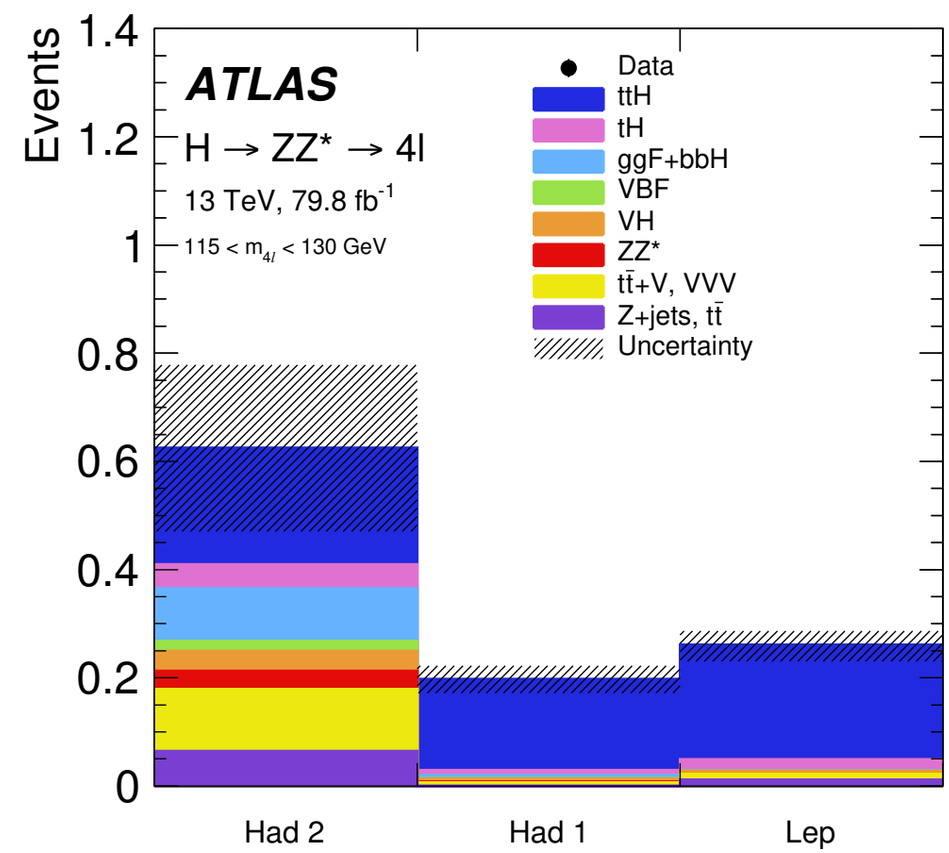
- Extremely low rate.
- Clean final state w/ high S/B.

Categorisation:

Based on $t\bar{t}$ decay

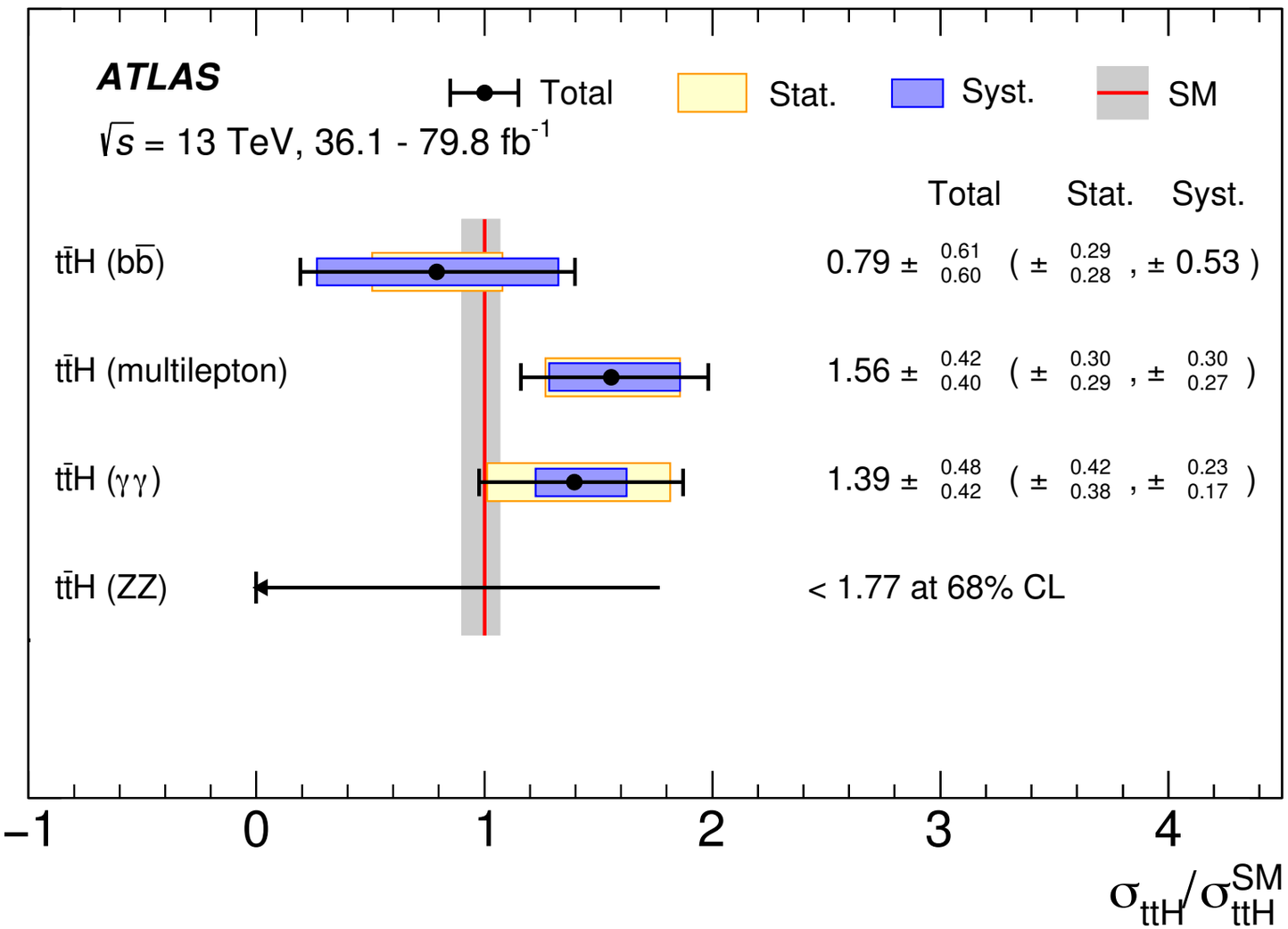
- Hadronic
  - Based on BDT output
    input vars: production and decay kinematics including matrix element discriminant ($t\bar{t}H$ vs. ttV)
    - Tight (Had 1)
    - Loose (Had 2)
- Leptonic

- Simultaneous fit to all categories;



No events observed.
(exp. significance 1.2 σ)
Very statistically limited!

$t\bar{t}H$ combination

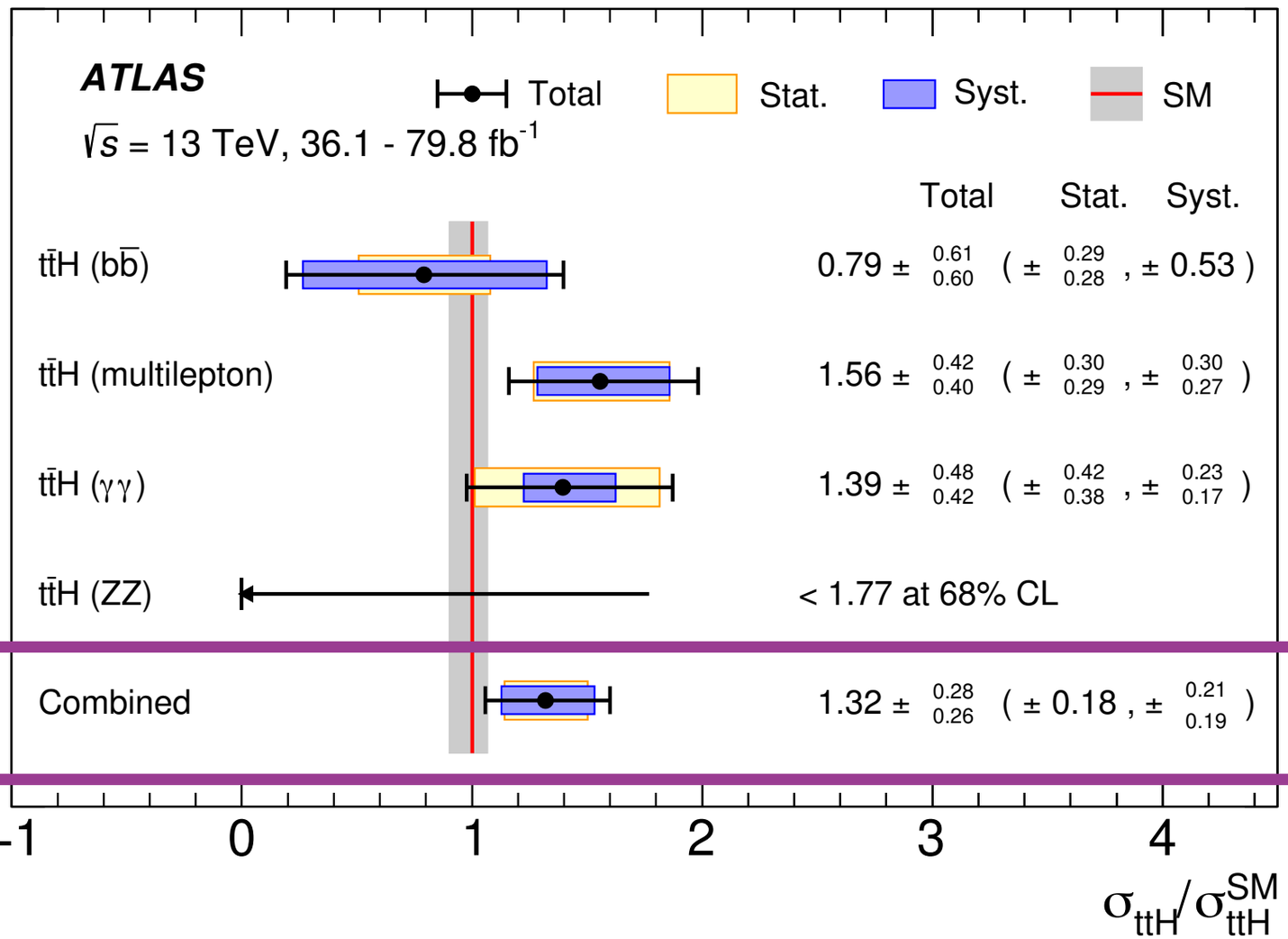


Significance	
obs.	**exp.**
1.6 σ	**1.4 σ**
4.1 σ	**2.8 σ**
4.1 σ	**3.8 σ**
0 σ	**1.2 σ**

Combination

- Contribution from non-$t\bar{t}H$ Higgs production modes fixed to SM prediction;
- Correlation scheme studied in detail.

$t\bar{t}H$ combination



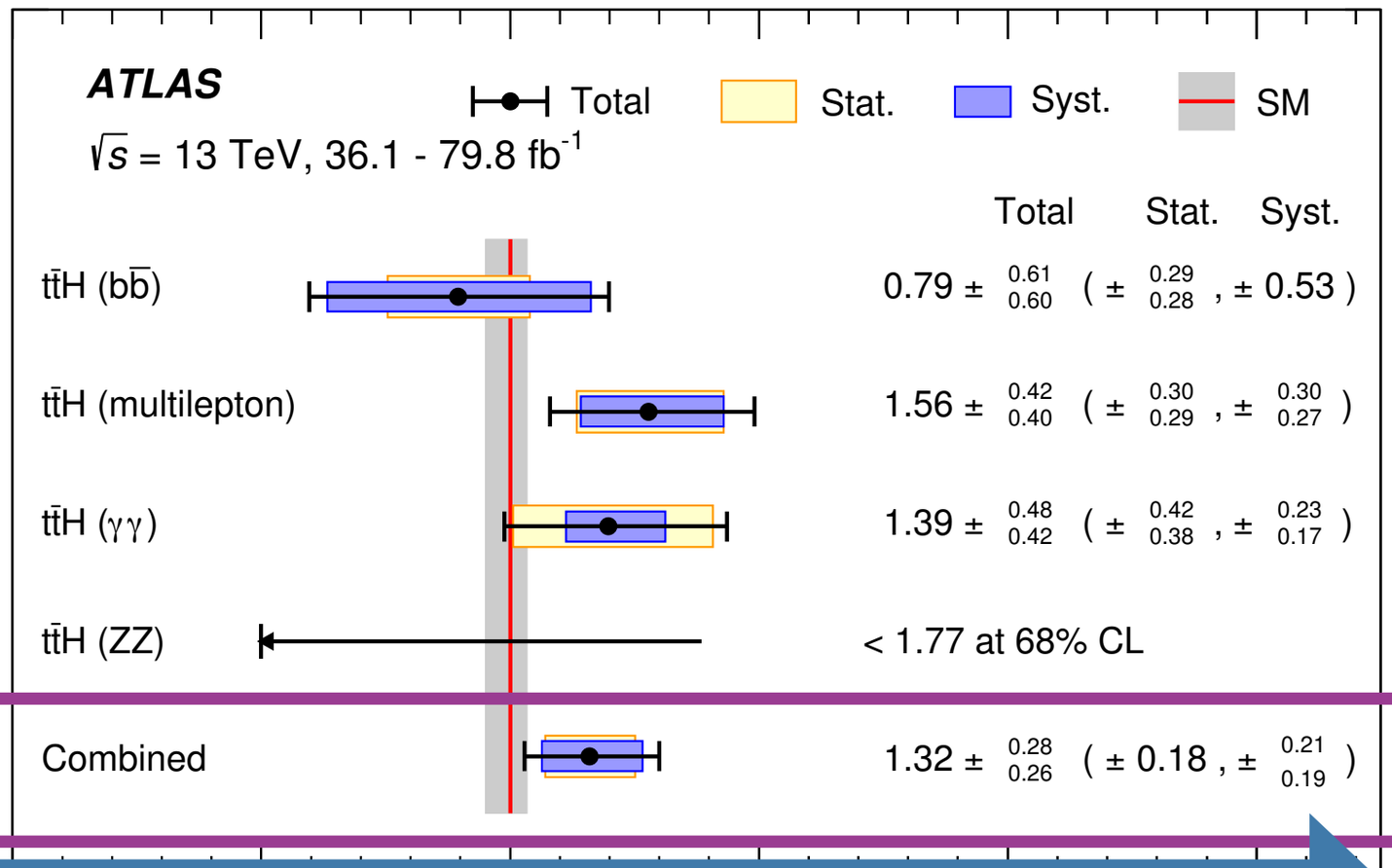
Significance	
obs.	**exp.**
1.6 σ	**1.4 σ**
4.1 σ	**2.8 σ**
4.1 σ	**3.8 σ**
0 σ	**1.2 σ**
5.8 σ	**4.9 σ**

Combination

Observation of $t\bar{t}H$ production at 13TeV alone!

- Correlation scheme studied in detail.

$t\bar{t}H$ combination



	Significance obs.	Significance exp.
$t\bar{t}H$ ($b\bar{b}$)	1.6 σ	1.4 σ
$t\bar{t}H$ (multilepton)	4.1 σ	2.8 σ
$t\bar{t}H$ ($\gamma\gamma$)	4.1 σ	3.8 σ
$t\bar{t}H$ (ZZ)	0 σ	1.2 σ
Combined	5.8 σ	4.9 σ

Combination with measurements @7TeV (4.5fb^{-1}) and @8TeV (20.3fb^{-1})*

6.3 σ 5.1 σ

*Eur. Phys. J. C 76 (2016) 6

Including Run 1 data improves the sensitivity!
Observation of $t\bar{t}H$ production!

$t\bar{t}H$ cross-section

Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]
$H \to \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)
$H \to$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)
$H \to b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)
$H \to ZZ^* \to 4\ell$	79.8	<900 (68% CL)

combined

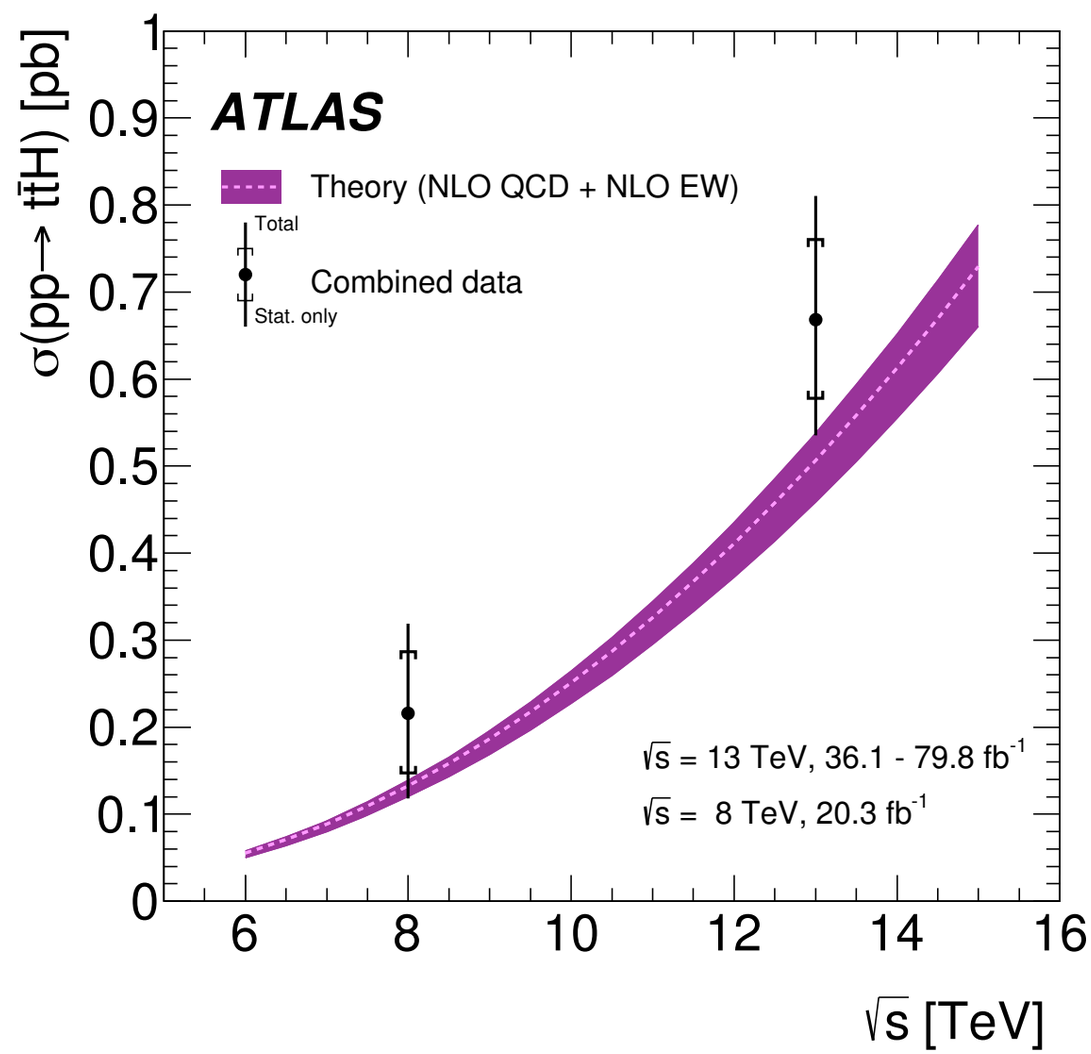
$$\sigma_{t\bar{t}H}(13TeV) = 670 \pm 90(stat)^{+110}_{-100}(sys)\text{fb}$$

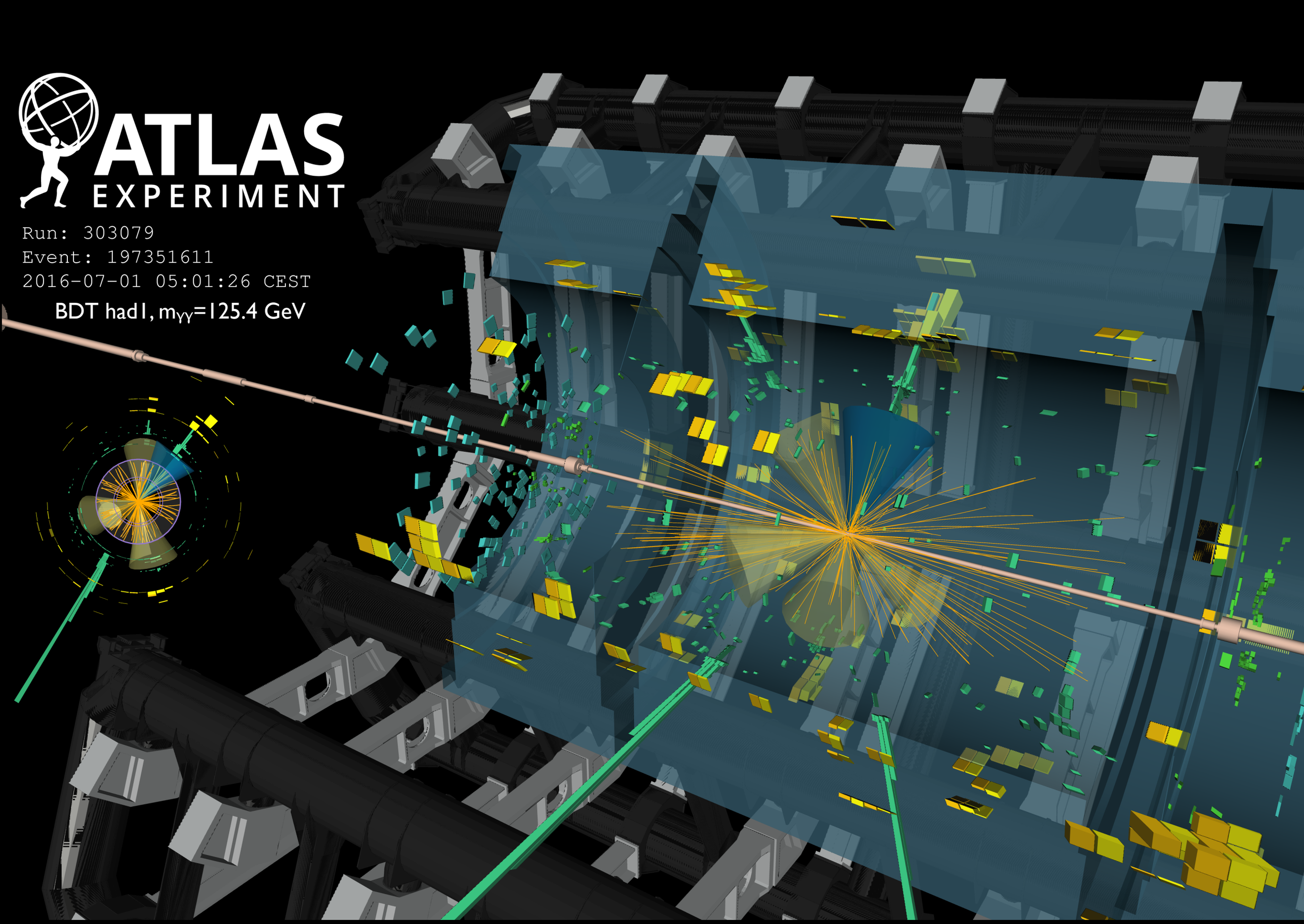
$$\sigma_{t\bar{t}H,SM}(13TeV) = 507^{+35}_{-50}\text{fb}$$

Compatible with the SM prediction

Dominant systematics

- $t\bar{t}$+heavy flavour modelling (9.9%);
- $t\bar{t}H$ modelling (6%);
- Non-prompt leptons (5.2%).



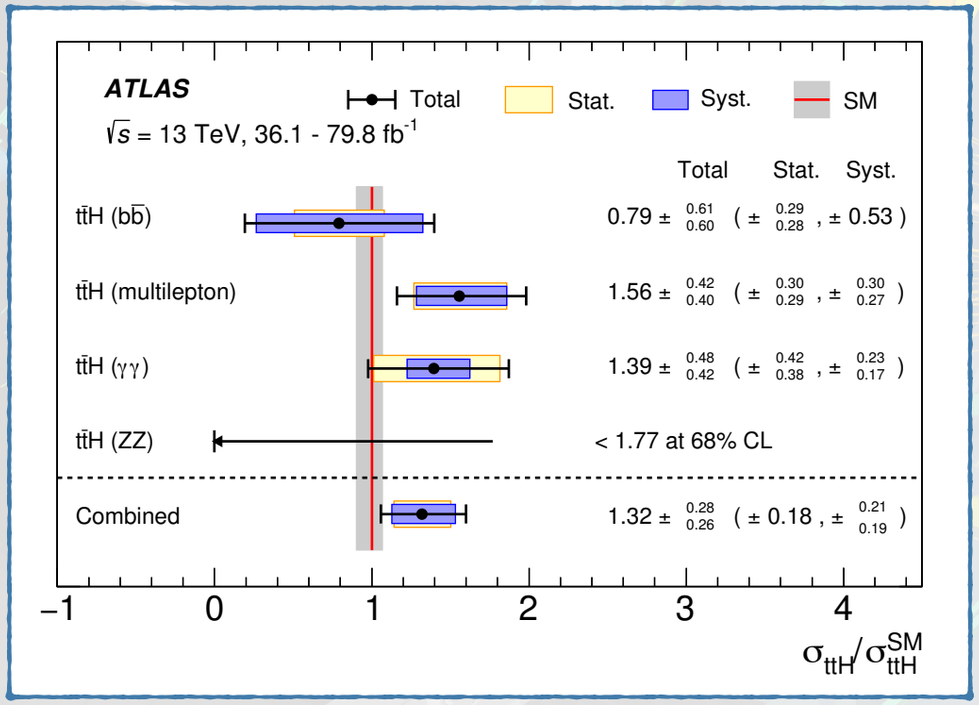

ATLAS
EXPERIMENT
Run: 303079
Event: 197351611
2016-07-01 05:01:26 CEST
BDT had1, $m_{\gamma\gamma}$=125.4 GeV

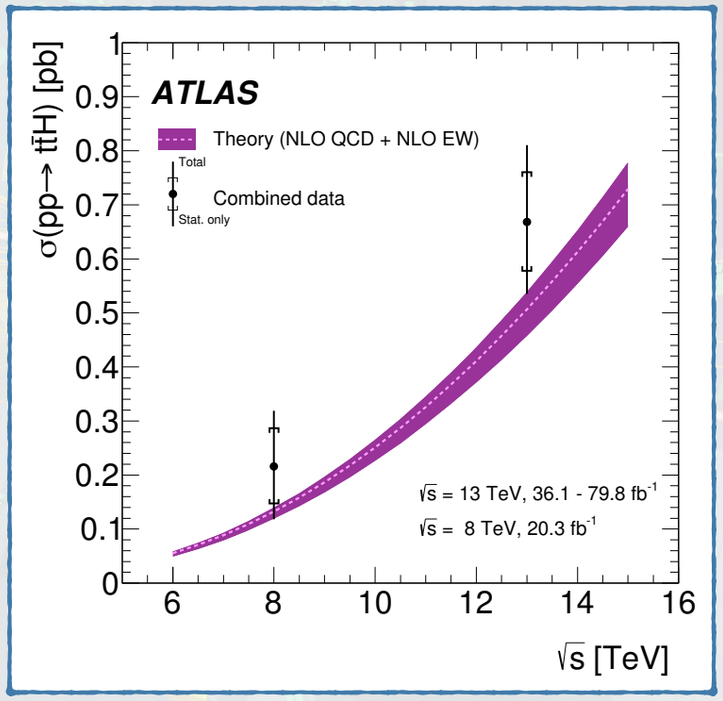
Summary

Observation of $t\bar{t}H$ production with a significance of **6.3 σ** (expected **5.1 σ**)

Cross-section at 13 TeV: $670 \pm 90\ (\text{stat})\ ^{+110}_{-100}\ (\text{sys})$ fb

Compatible with the SM prediction.





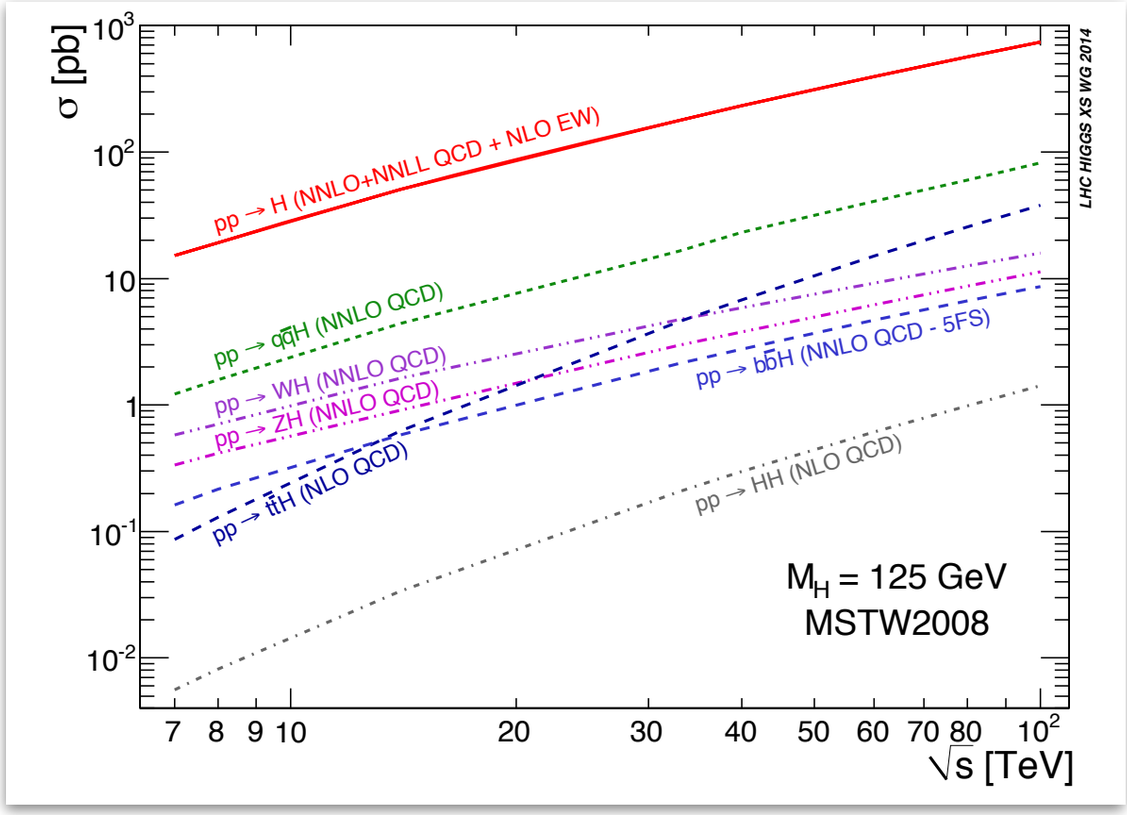
Thank you!

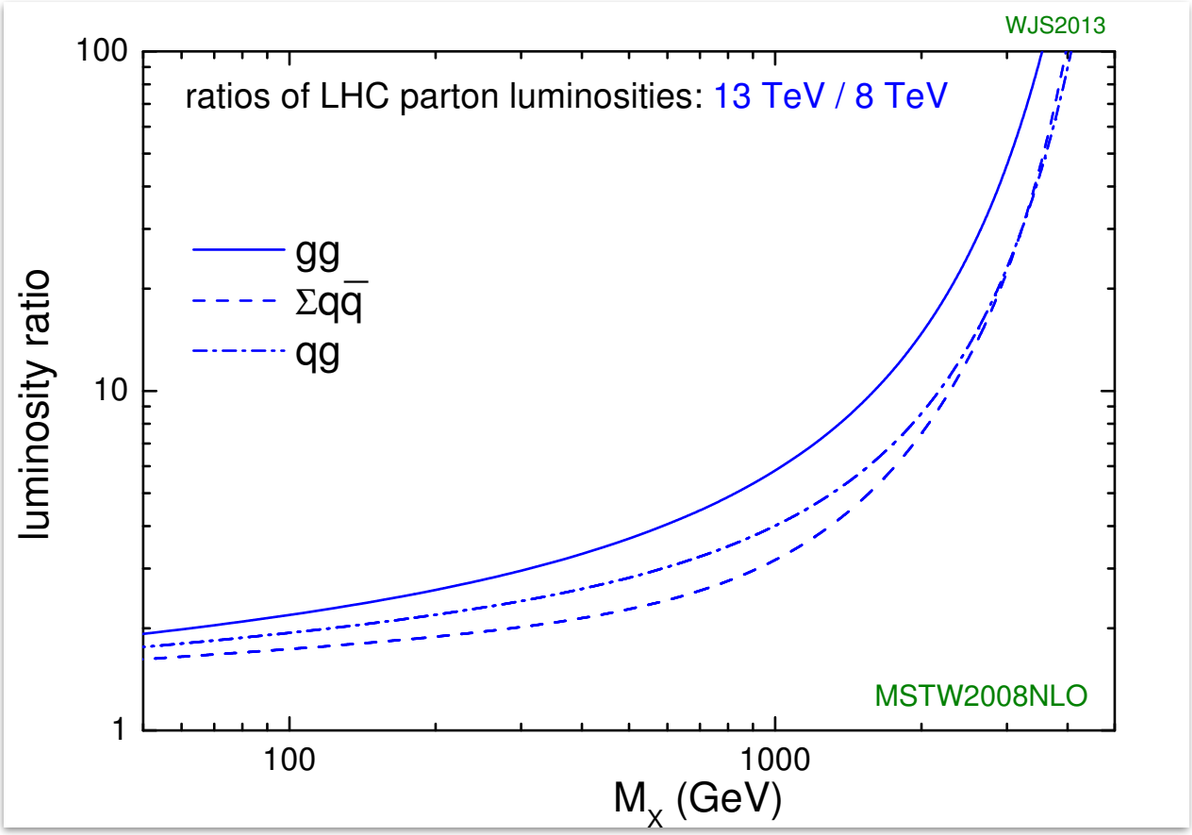
Backup

ttH production

$$\sigma_{t\bar{t}H}(13TeV) \sim 4 \times \sigma_{t\bar{t}H}(8TeV)$$

Phase space opening
+
$M_X = 2M_t + M_H$ in gg





	σ(13 TeV) / σ(8 TeV)
gg→H	~**2.3** (M_X=M_H)
qq→H	~**2.4** (probes high M_X)
qq→VH	~**2.0** (M_X=M_V+M_H)
qq→ttH	~**3.9** (phase space + M_X)
tt	~**3.3** (gg→tt dominates)

Hunting the Higgs-top Yukawa coupling

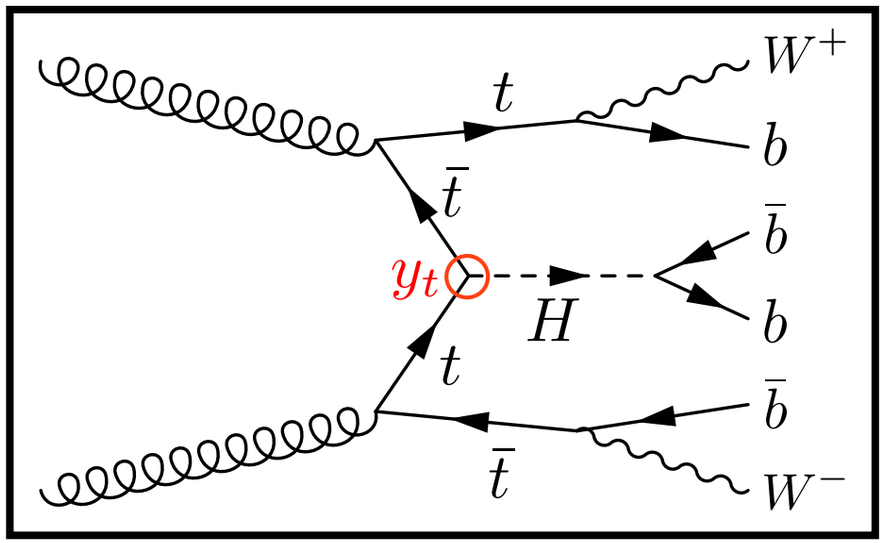
Direct measurement

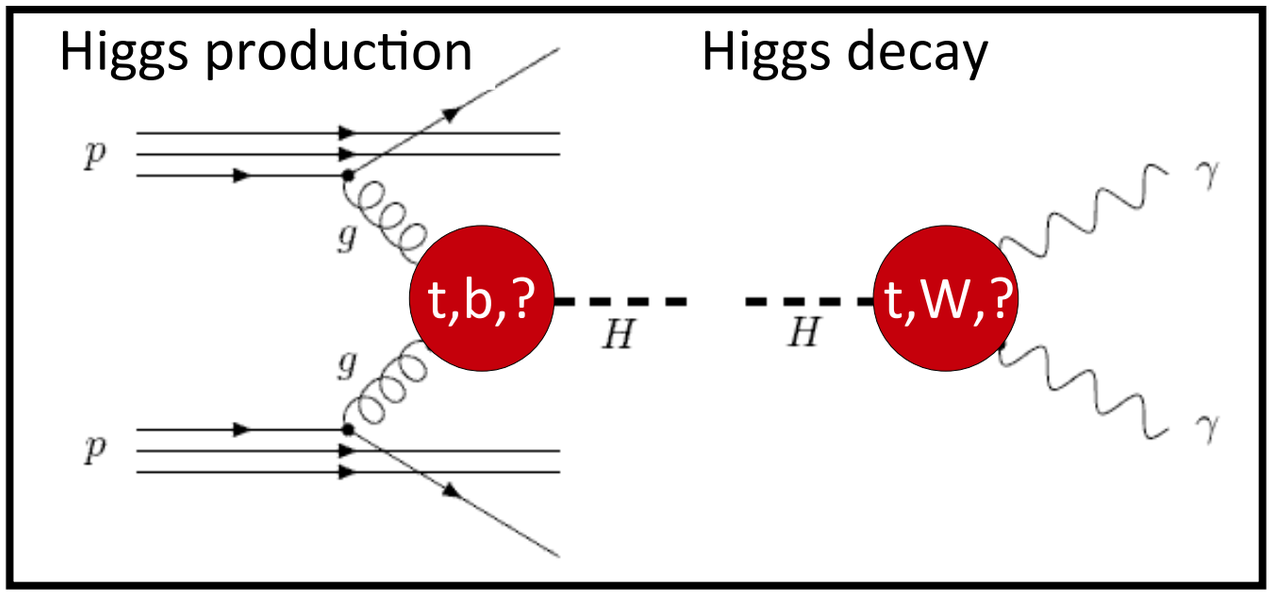
- **Direct** measurement **in $t\bar{t}H$** production

Indirect constraints:

- loops in **ggF** and **H → γγ** vertices;
  - assuming only SM particles contributing to the loops.

Sensitive to y_t^2



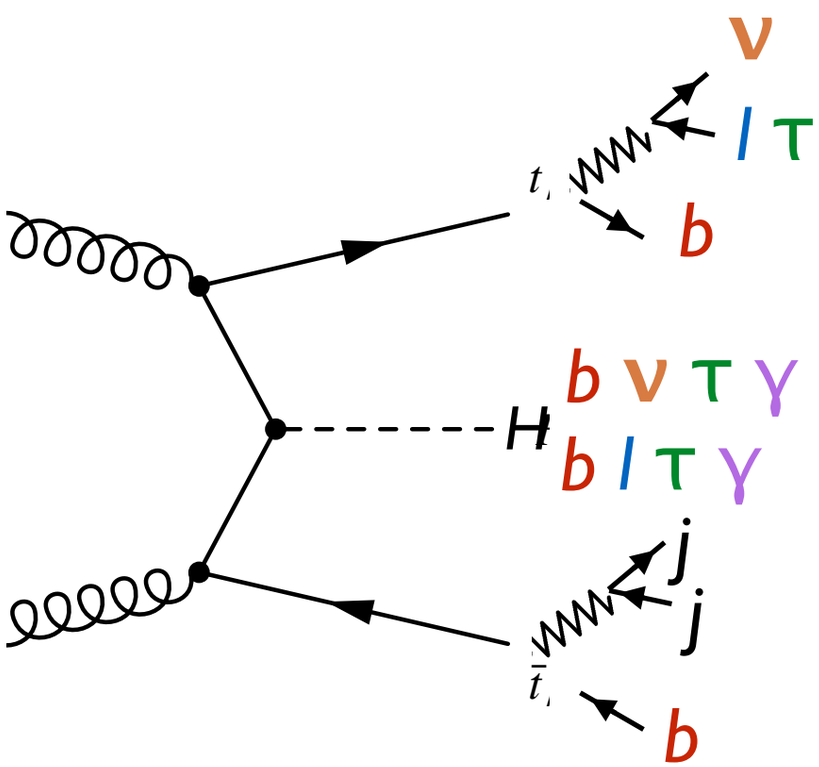


- **tH production**: interference between top-mediated and W-mediated diagrams;
- **H → γγ**: interference between top quark and W boson in the loop;
- **ZH production and H->Zγ**: interference between top quark and W-boson contribution in the loop.

Sensitive to y_t

Experimental challenges

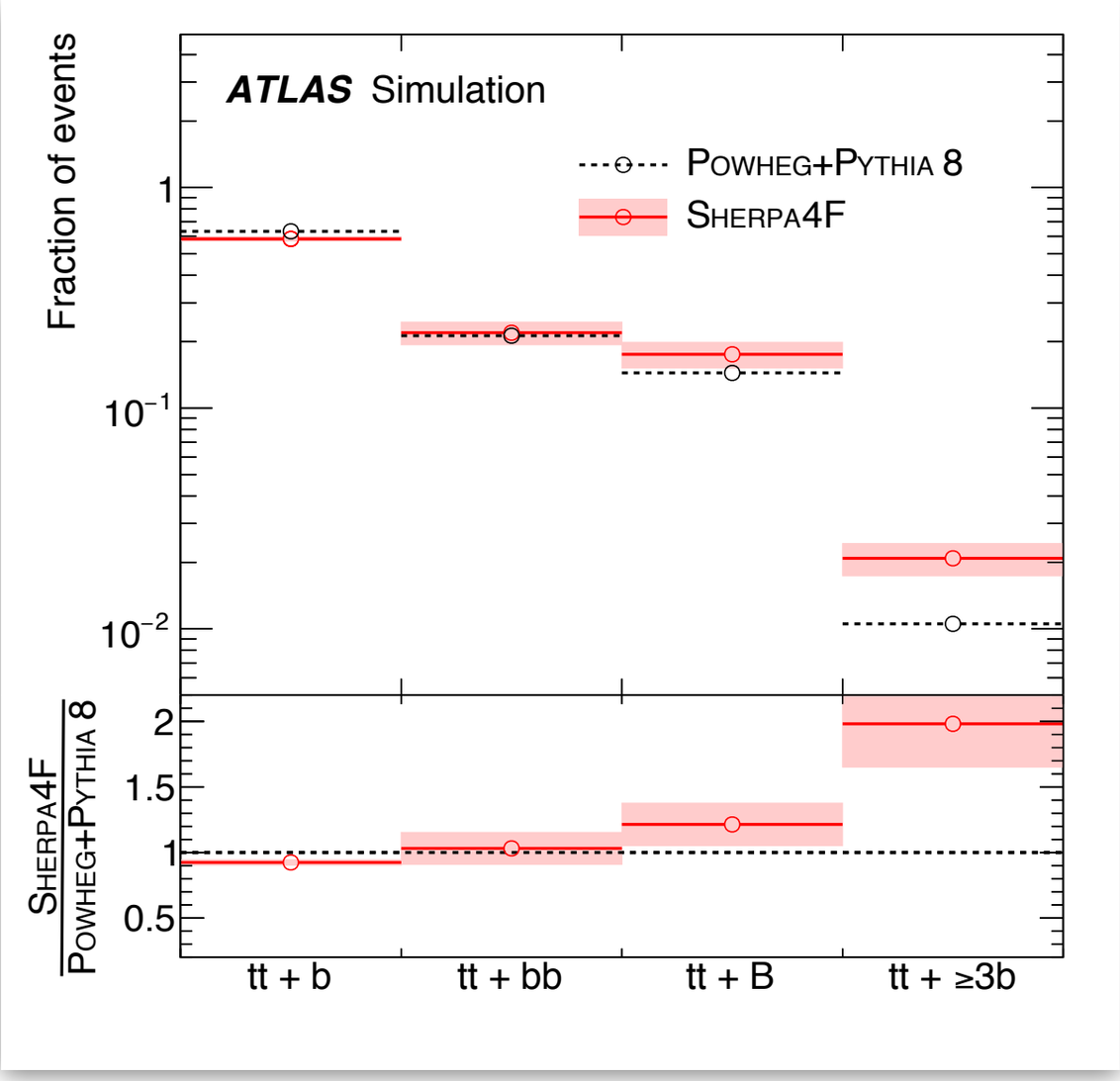
Large variety of final states - good understanding of all reconstructed objects



- **electrons / muons**: precise (sub % level) energy / momentum calibration, understanding of identification efficiency, trigger rate;
- **hadronically decaying taus**: energy calibration, controlling rate from misidentified jets and electrons.
- **photons**: energy calibration, precise identification, direction determination (pointing).
- **jets**: precise calibration (% level), stability in presence of large pile-up.
- **missing transverse energy**: stability in presence of large pile-up
- **b-jets** Good understanding of signal efficiency and misidentification rate.

$t\bar{t}$+jets background in $t\bar{t}H(bb)$

- Powheg+Pythia8 normalised to NNLO prediction;
- $t\bar{t}$ +b, $t\bar{t}$ +bb, $t\bar{t}$ +≥3b and $t\bar{t}$ +B corrected to Sherpa+OpenLoops NLO calculation 4FS (massive *b*-quarks, g→bb from ME);
- normalisation for $t\bar{t}$ +≥1b and $t\bar{t}$ +≥1c free floating in the fit.



CMS 13 TeV $t\bar{t}$ +bb measurement CMS-PAS-TOP-16-010:
ATLAS 8 TeV $t\bar{t}$ +bb measurement: Eur. Phys. J. C (2016) 76:11

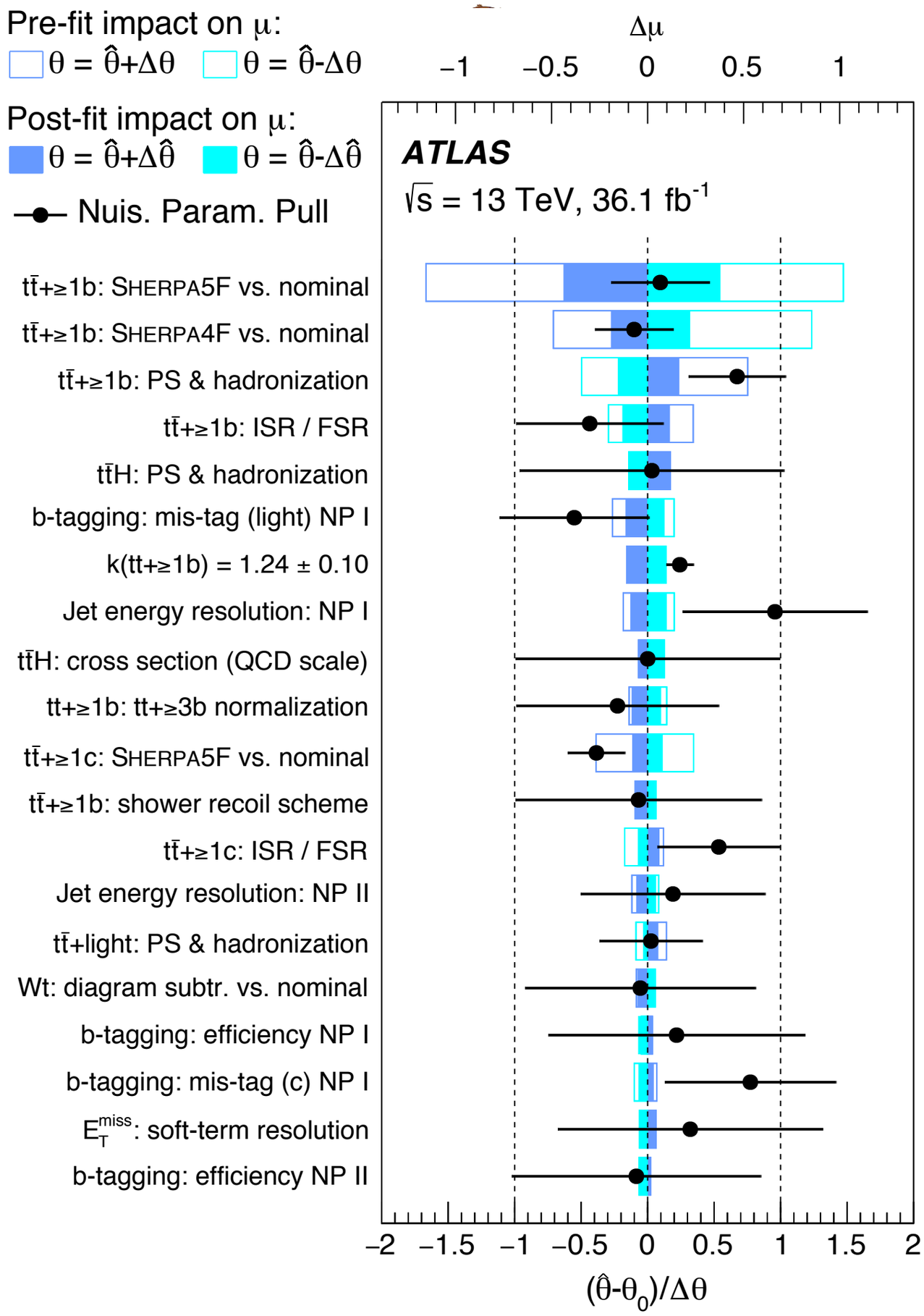
$t\bar{t}H(bb)$ uncertainties

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

$t\bar{t}H(bb)$ systematics

$NF(t\bar{t}+\geq 1b) = 1.24 \pm 0.10$

$NF(t\bar{t}+\geq 1c) = 1.63 \pm 0.23$



$t\bar{t}H(bb)$ theory modelling

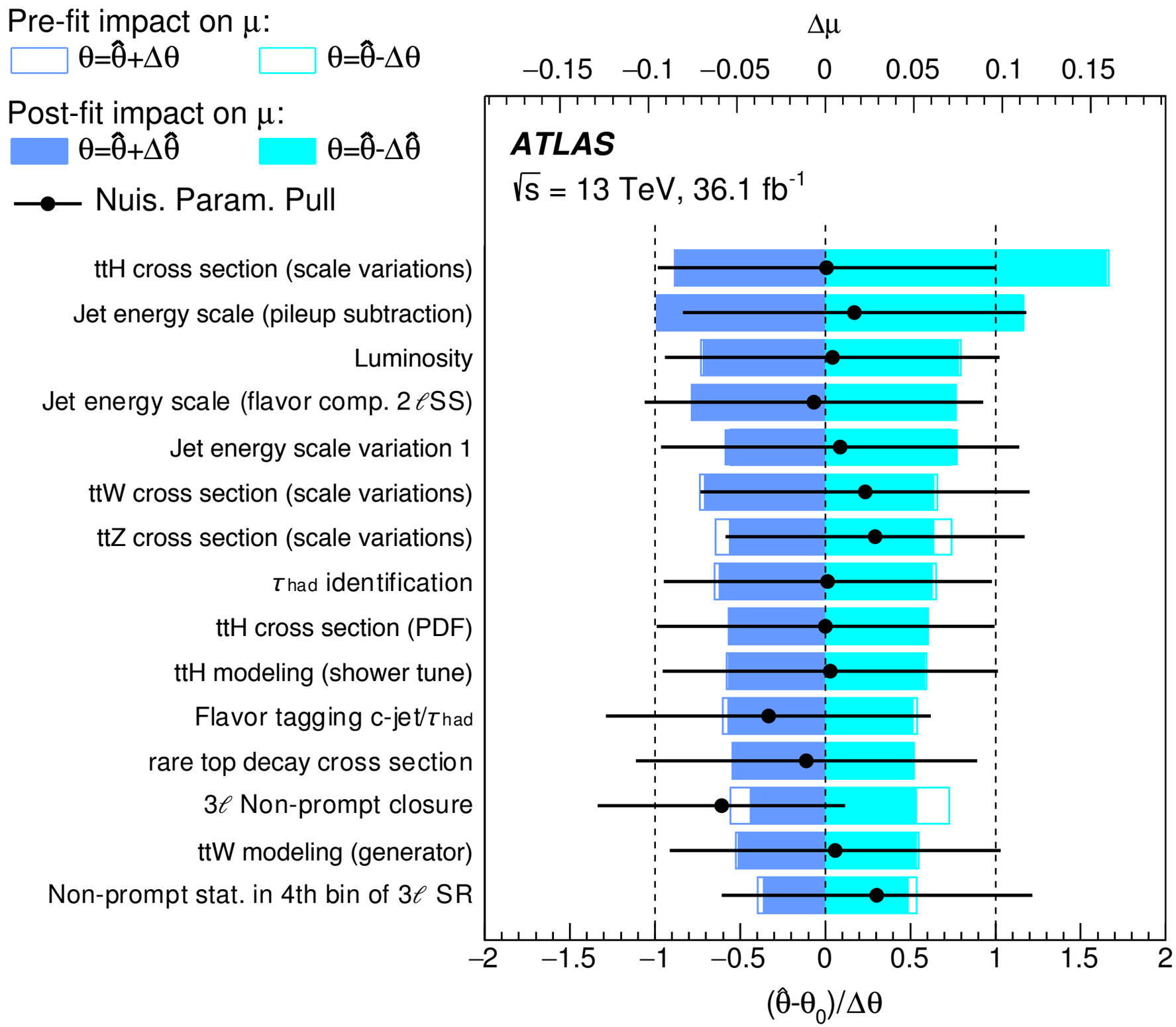
Systematic source	Description	$t\bar{t}$ categories
$t\bar{t}$ cross-section	Up or down by 6%	All, correlated
$k(t\bar{t}+\geq 1c)$	Free-floating $t\bar{t}+\geq 1c$ normalization	$t\bar{t}+\geq 1c$
$k(t\bar{t}+\geq 1b)$	Free-floating $t\bar{t}+\geq 1b$ normalization	$t\bar{t}+\geq 1b$
SHERPA5F vs. nominal	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)	$t\bar{t}+\geq 1b$
$tt+\geq 1b$ renorm. scale	Up or down by a factor of two	$tt+\geq 1b$
$t\bar{t}+\geq 1b$ resumm. scale	Vary μ_{Q} from $H_{\mathrm{T}}/2$ 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%	$t\bar{t}+\geq 1b$

- Four leading systematics from theory modeling of $t\bar{t}$ +bb background; - very little guidance how to model additional g→bb.
- Tested various models with different predictions: g→bb from PS, ME, mix - all give compatible results within uncertainties → confidence in signal extration.

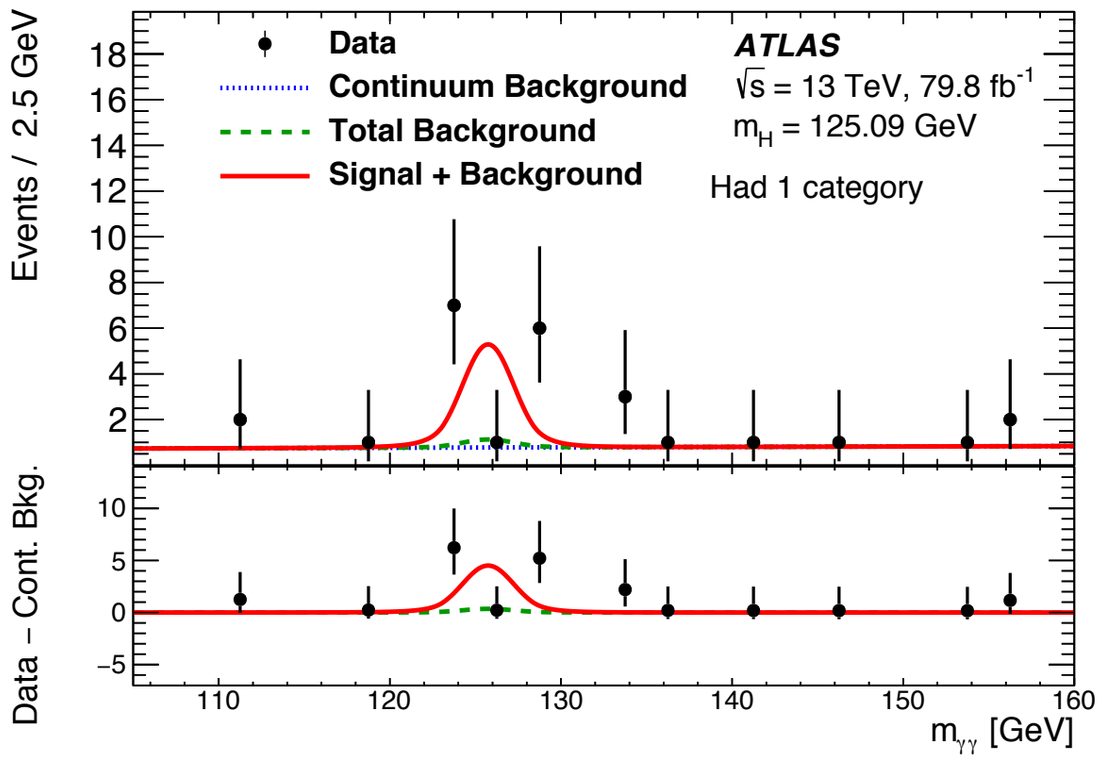
$t\bar{t}H$(multi-leptons) systematics

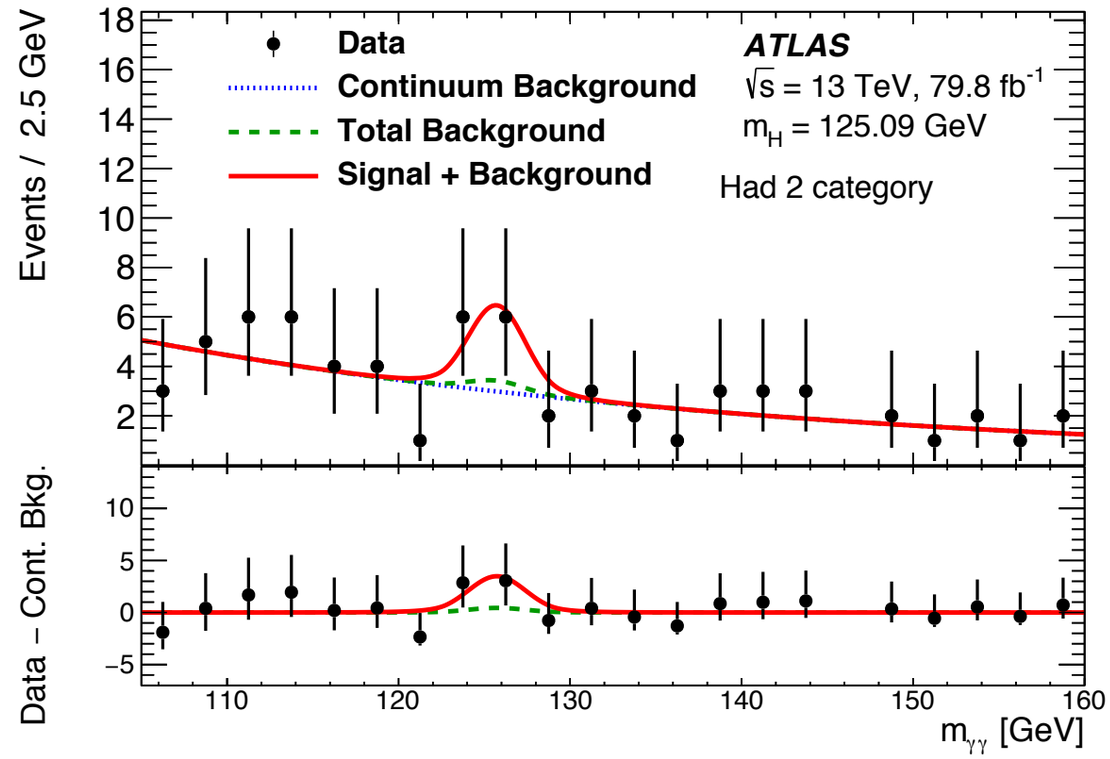
Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	$+0.20$	-0.09
Jet energy scale and resolution	$+0.18$	-0.15
Non-prompt light-lepton estimates	$+0.15$	-0.13
Jet flavor tagging and τ_{had} identification	$+0.11$	-0.09
$t\bar{t}W$ modeling	$+0.10$	-0.09
$t\bar{t}Z$ modeling	$+0.08$	-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

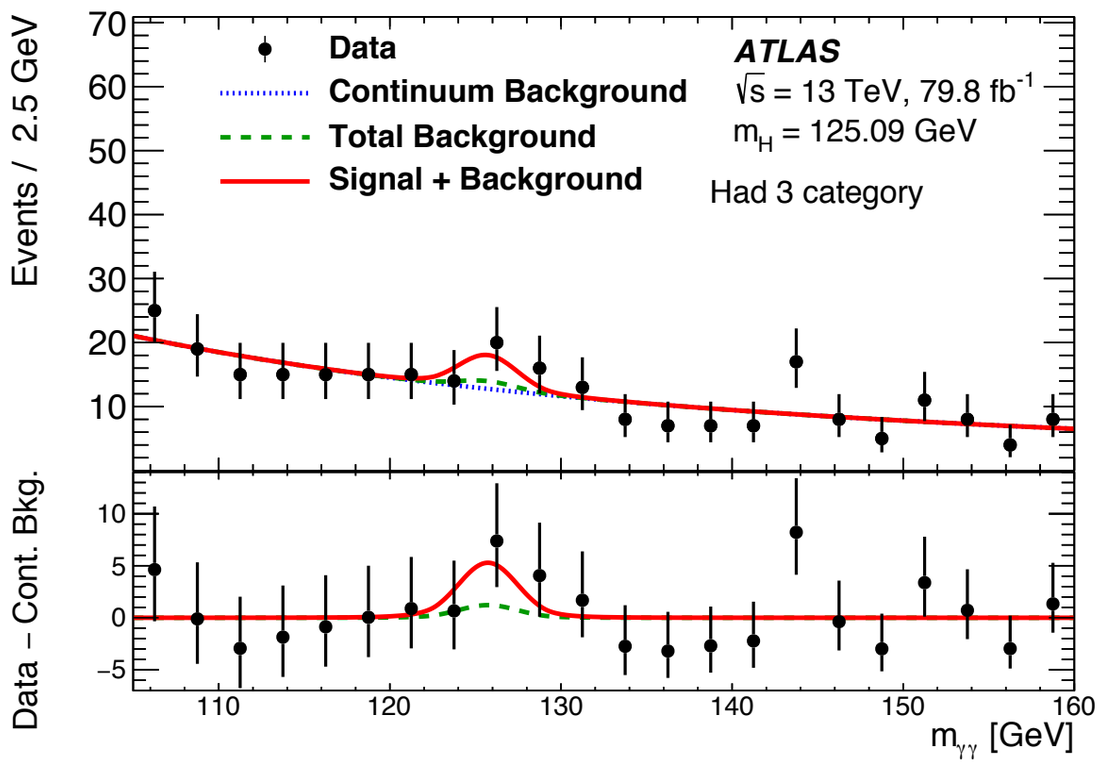
$t\bar{t}H$(multi-leptons) systematics

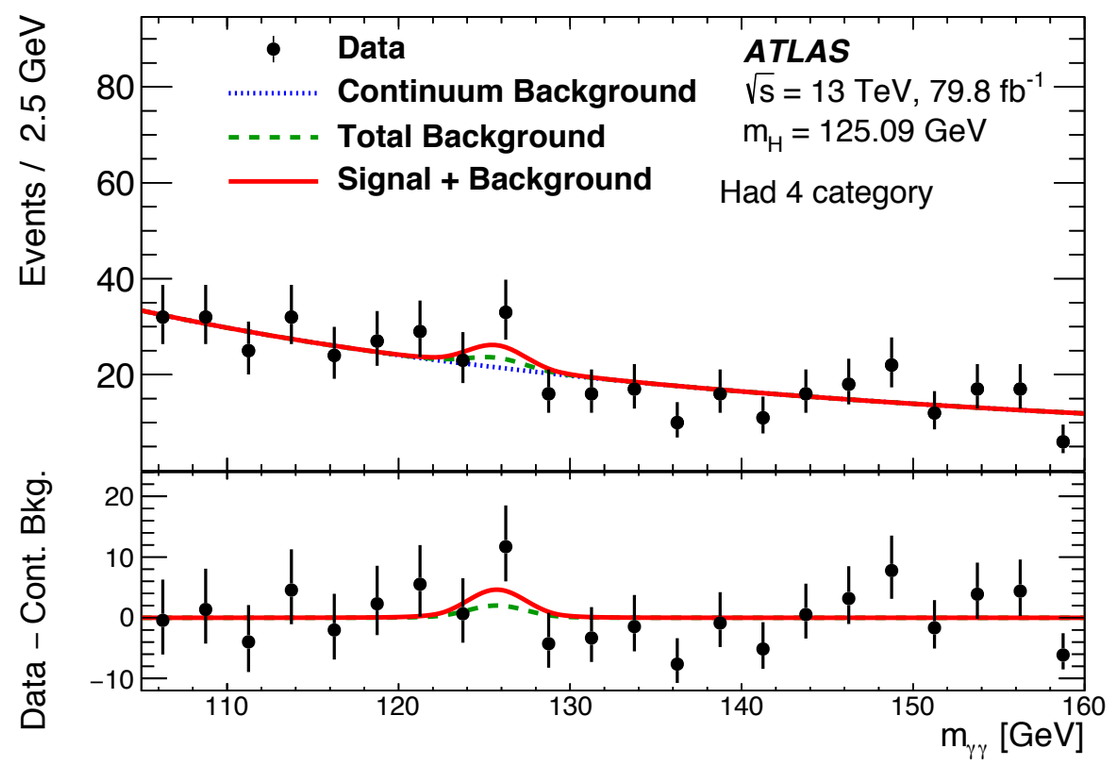


$m_{(\gamma\gamma)}$ - Had categories

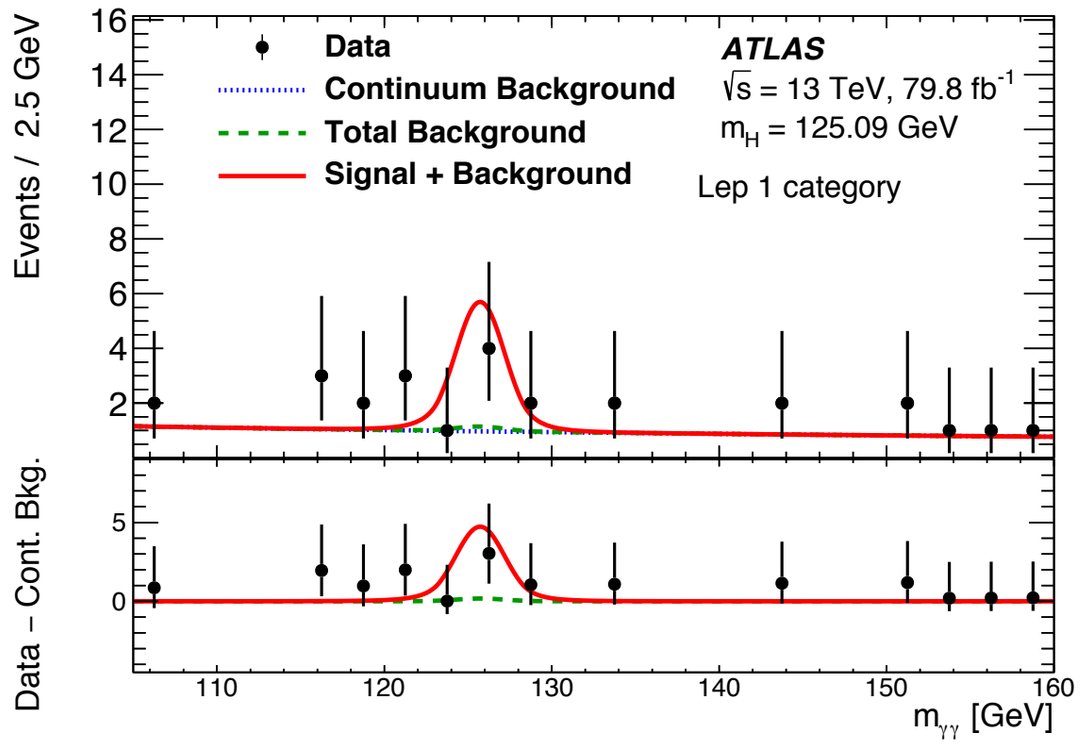


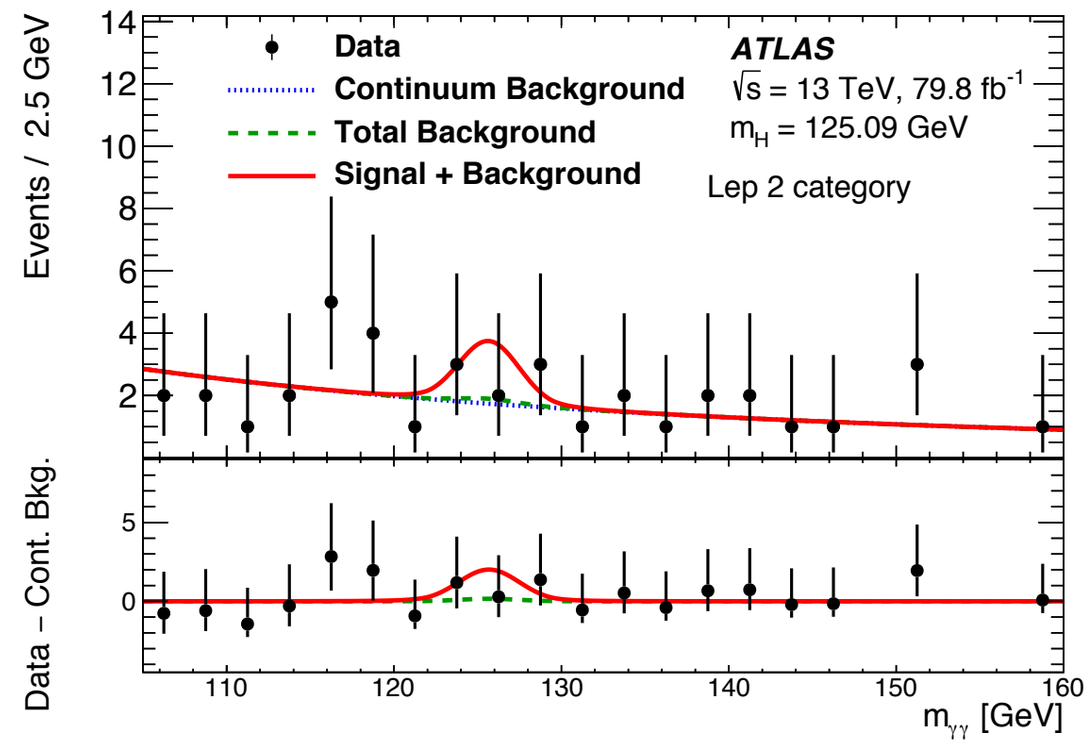


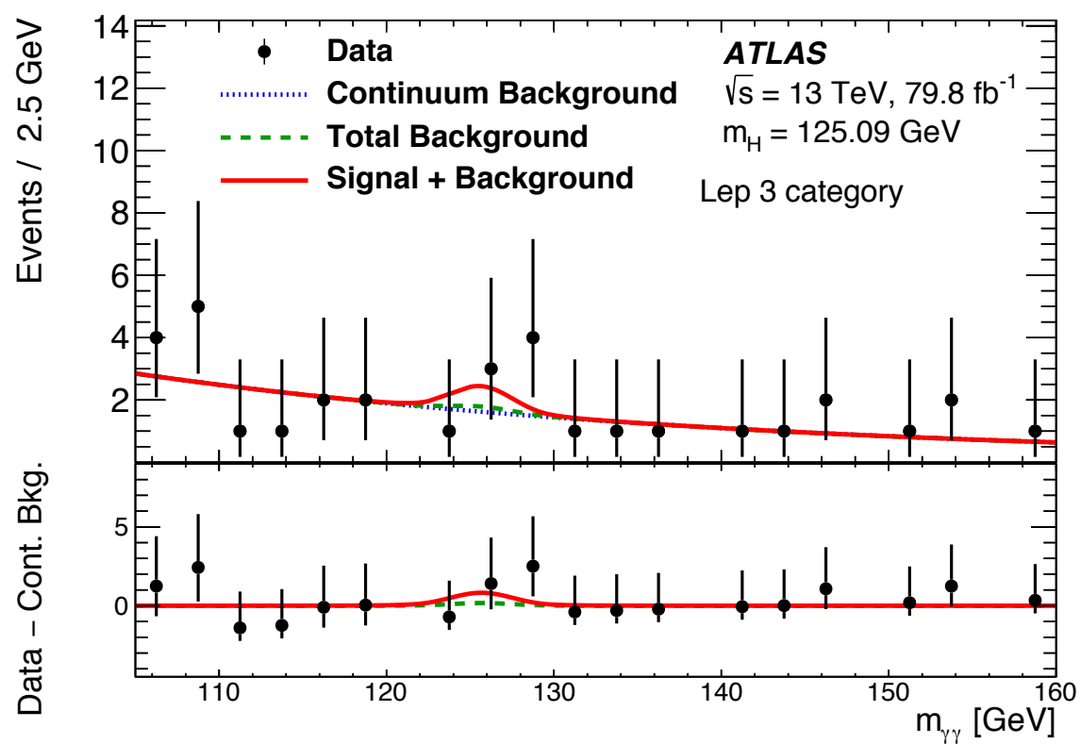




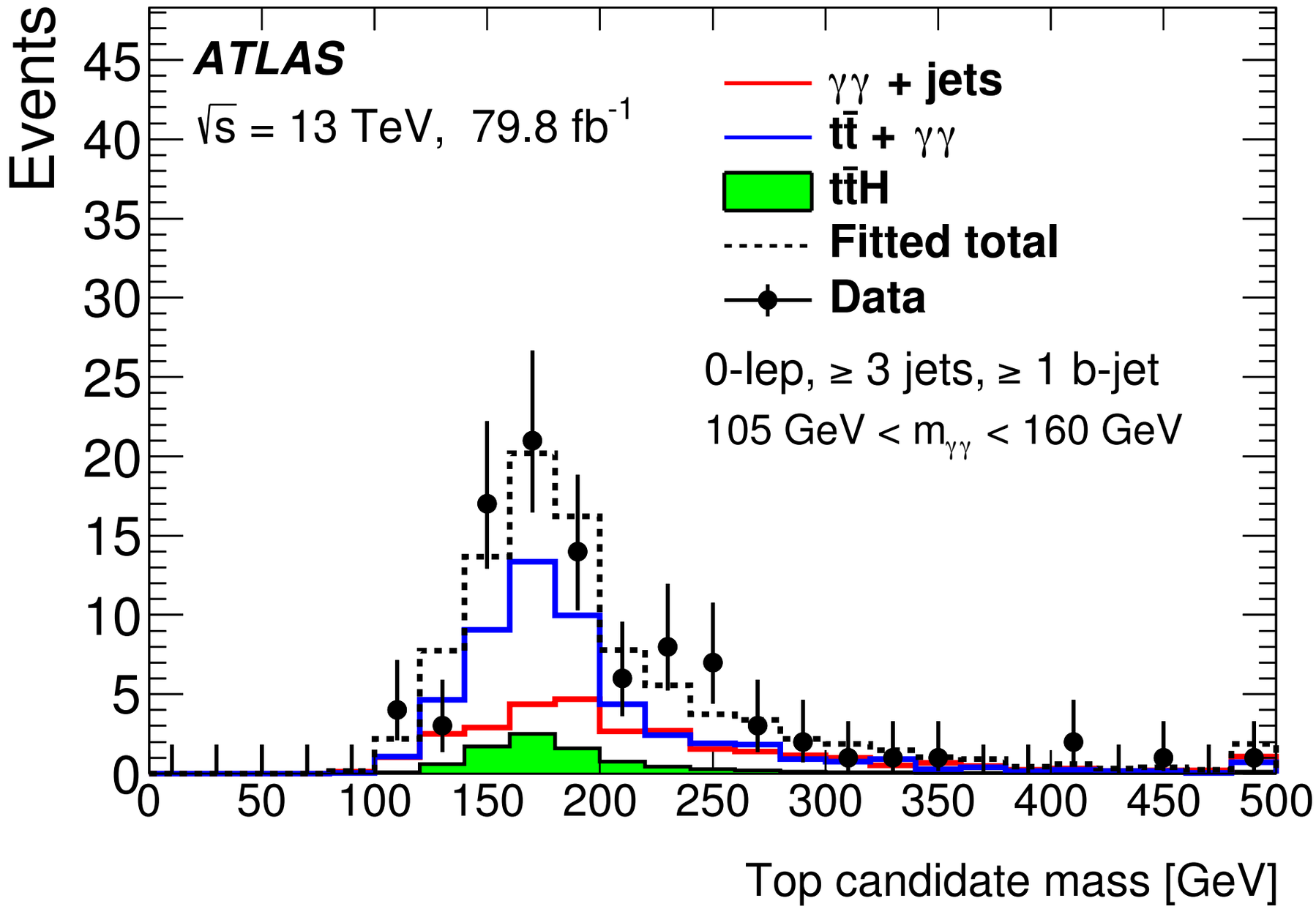
$m_{(\gamma\gamma)}$ - Lep categories







$t\bar{t}H(\gamma\gamma)$ top candidate

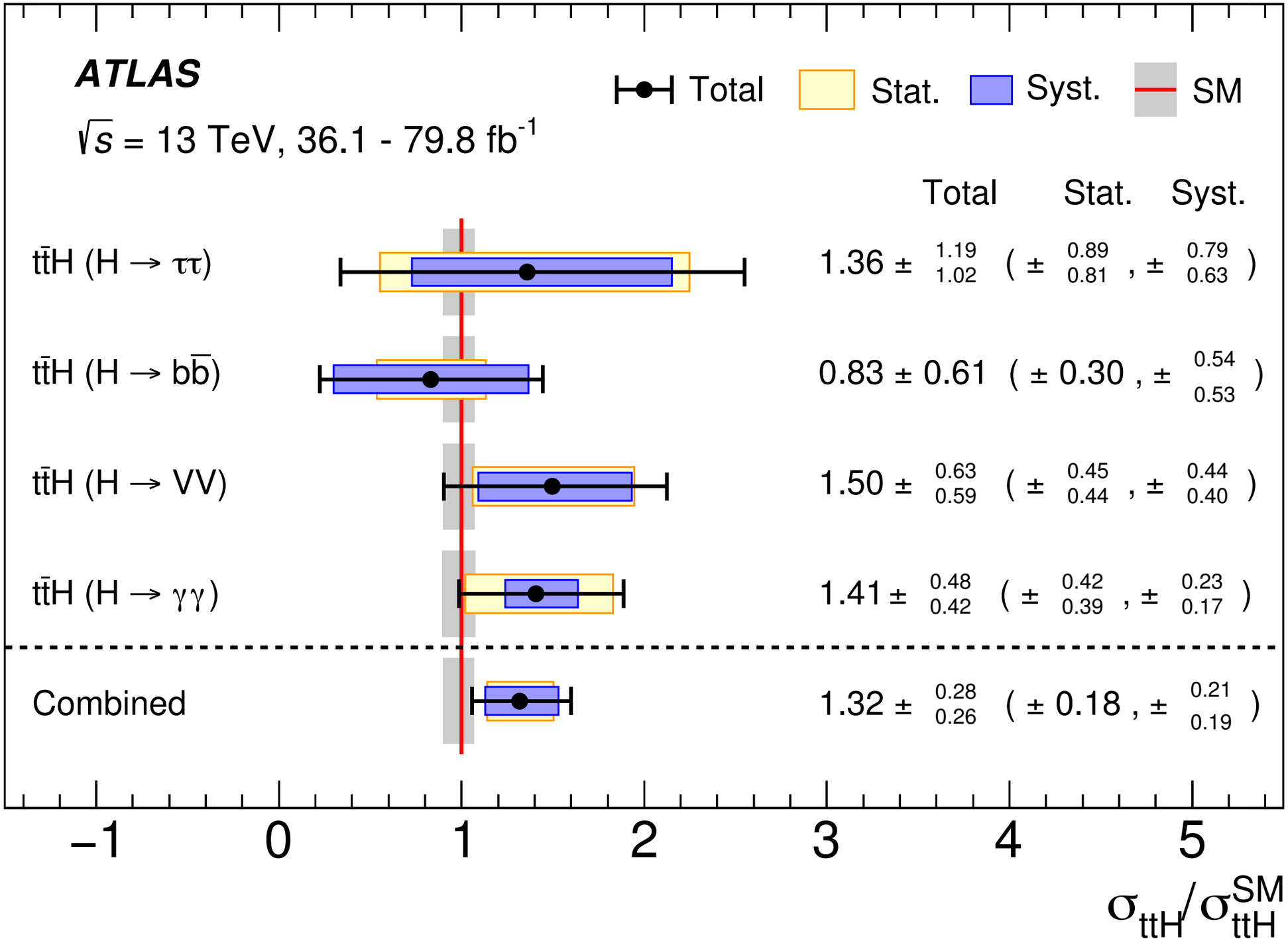


Dedicated BDT trained to find jets originating from the same top decay.

Event yields in γγ and ZZ channels

Bin	Expected $t\bar{t}H$ (signal)	Non-$t\bar{t}H$ Higgs	Non-Higgs	Total	Observed Total
		$H \to \gamma\gamma$			
Had 1	4.2(11)	0.49(33)	1.76(55)	6.4(13)	10
Had 2	3.41(74)	0.69(56)	7.5(11)	11.6(15)	14
Had 3	4.70(88)	2.0(17)	32.9(22)	39.6(32)	47
Had 4	3.00(55)	3.2(31)	55.0(28)	61.3(47)	67
Lep 1	4.5(10)	0.25(9)	2.19(59)	6.9(12)	7
Lep 2	2.23(39)	0.27(10)	4.59(91)	7.1(10)	7
Lep 3	0.82(18)	0.30(13)	4.58(91)	5.70(88)	5
		$H \to ZZ^* \to 4\ell$			
Had 1	0.169(31)	0.021(7)	0.008(8)	0.198(33)	0
Had 2	0.216(32)	0.20(9)	0.22(12)	0.63(16)	0
Lep	0.212(31)	0.0256(23)	0.015(13)	0.253(34)	0

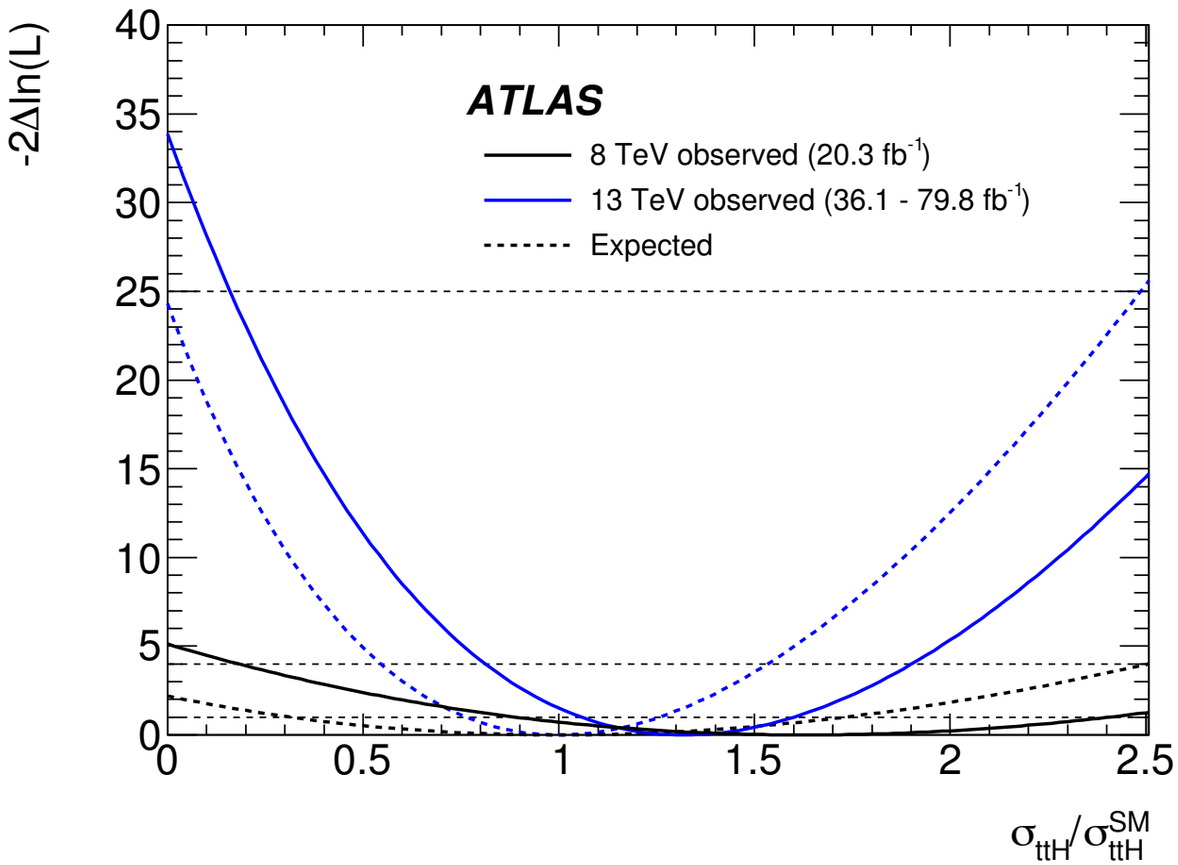
$t\bar{t}H$ signal strength per decay

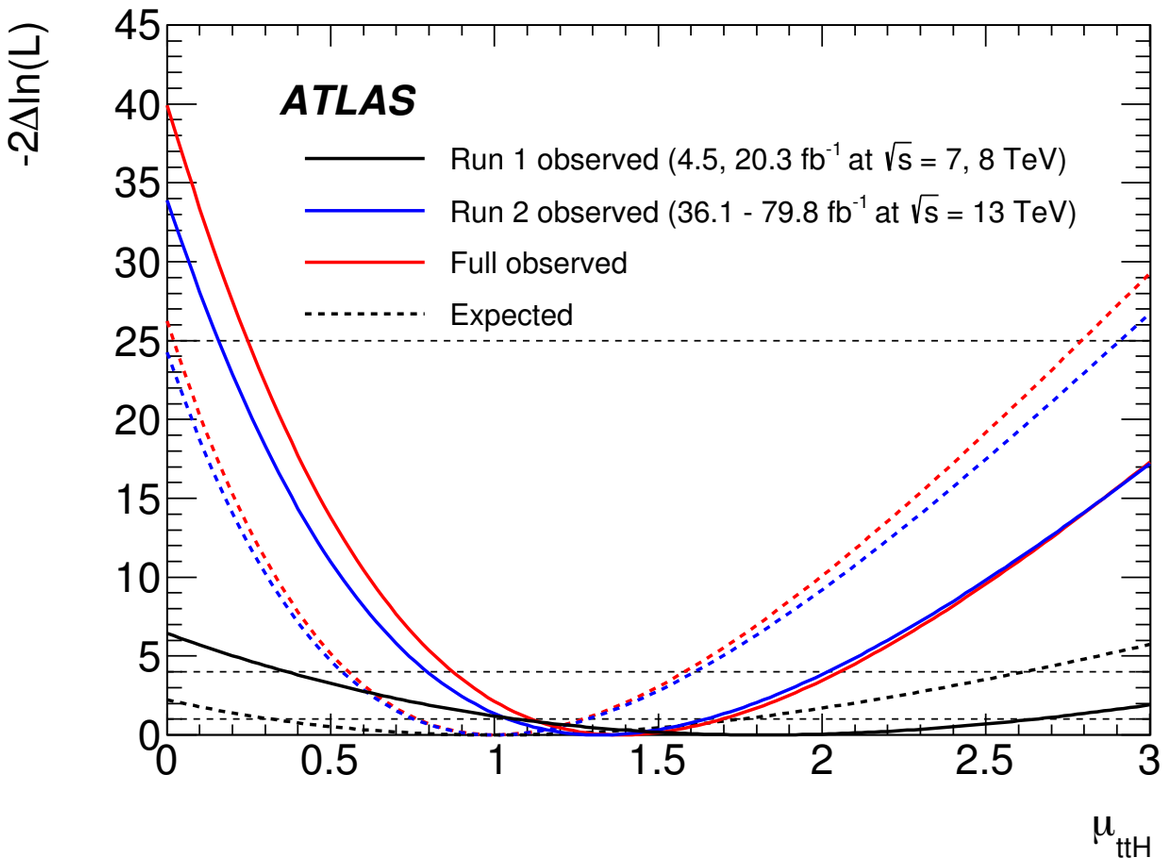


$t\bar{t}H$ cross-section uncertainties

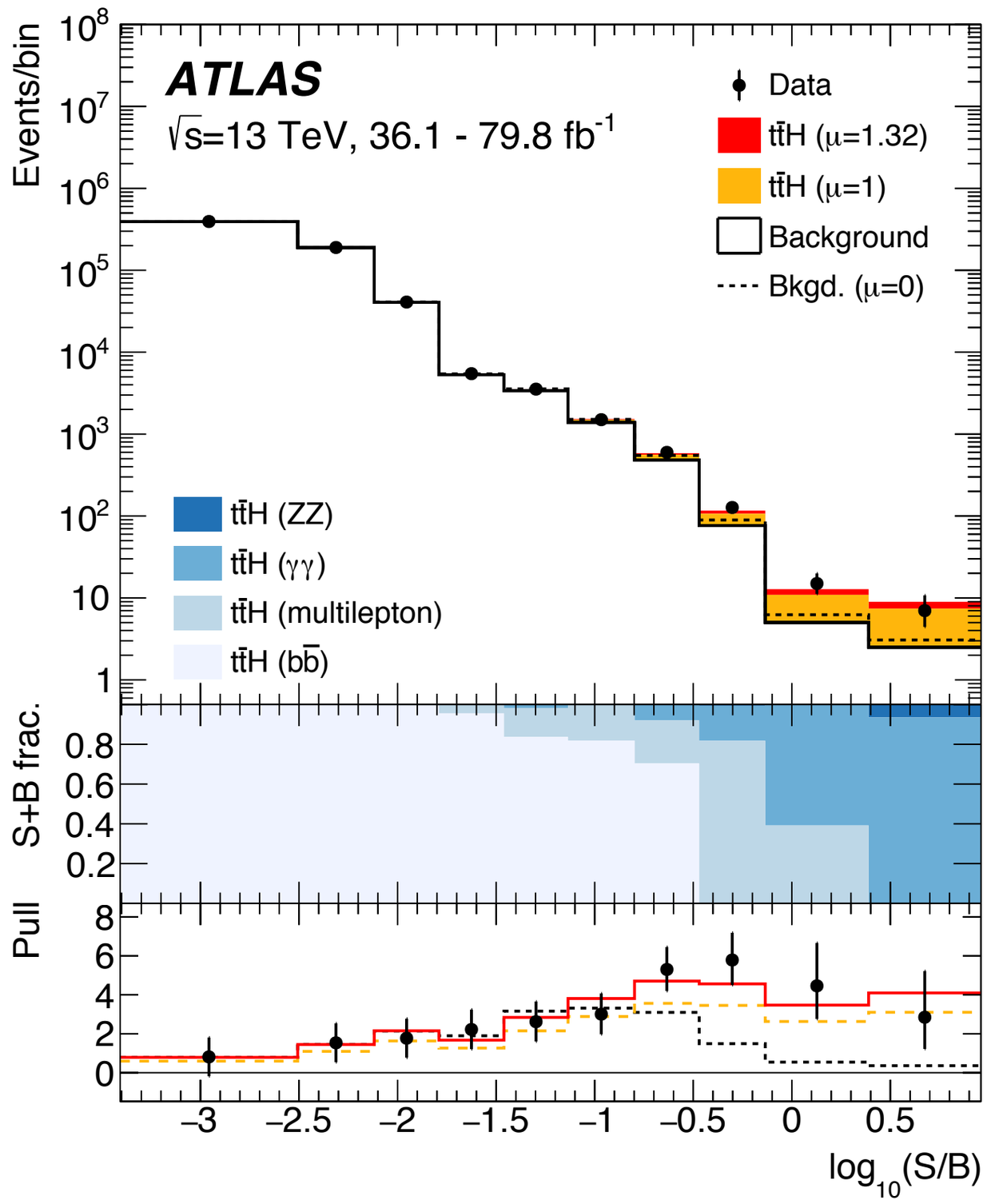
Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production modes	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-lepton	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4

$t\bar{t}H$ likelihood curves

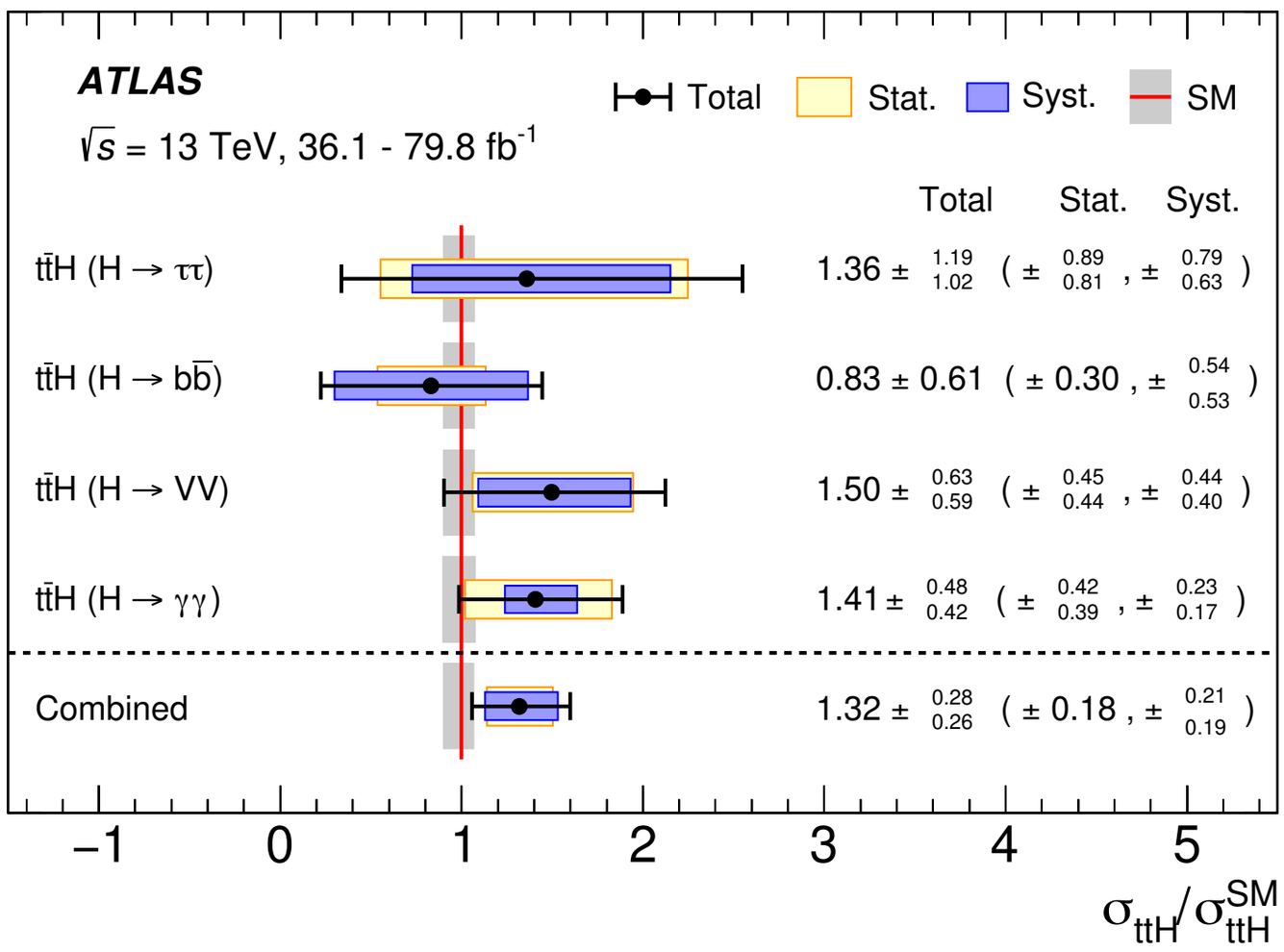


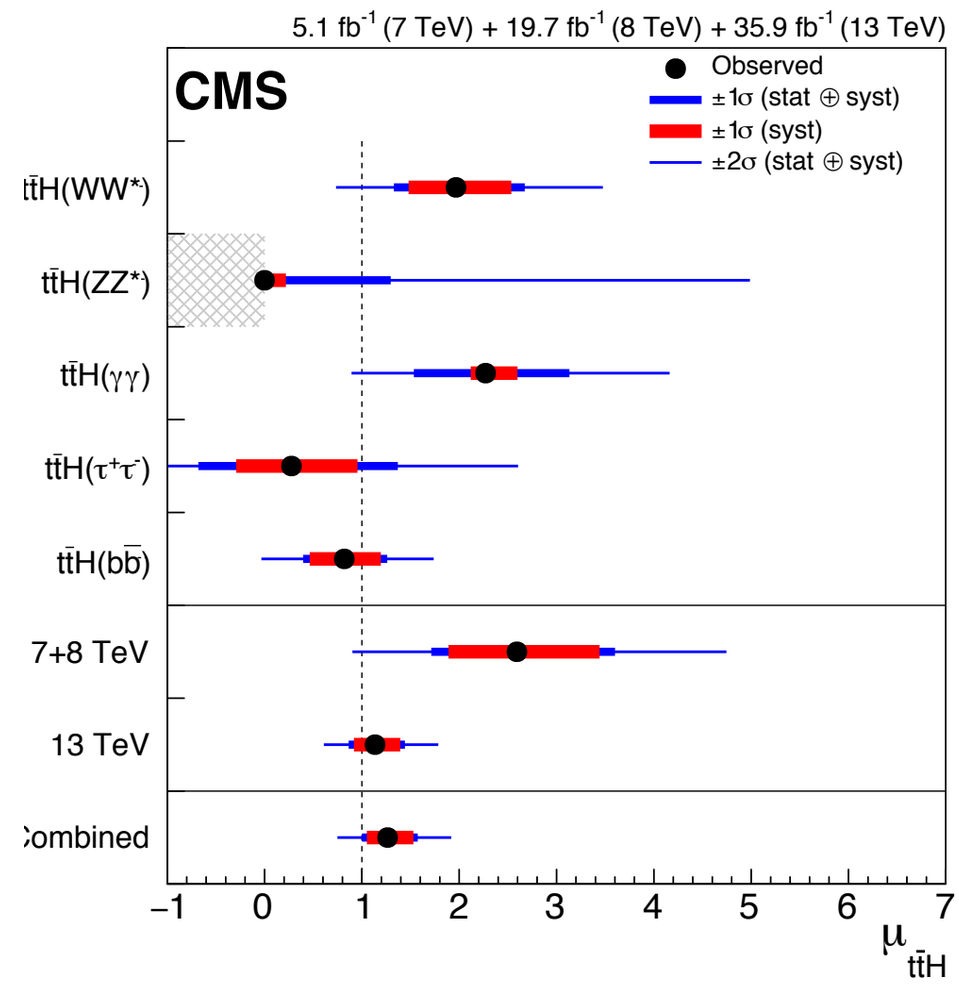


$t\bar{t}H$ SR yields



ATLAS vs CMS





arXiv:1804.02610

ATLAS Run I result

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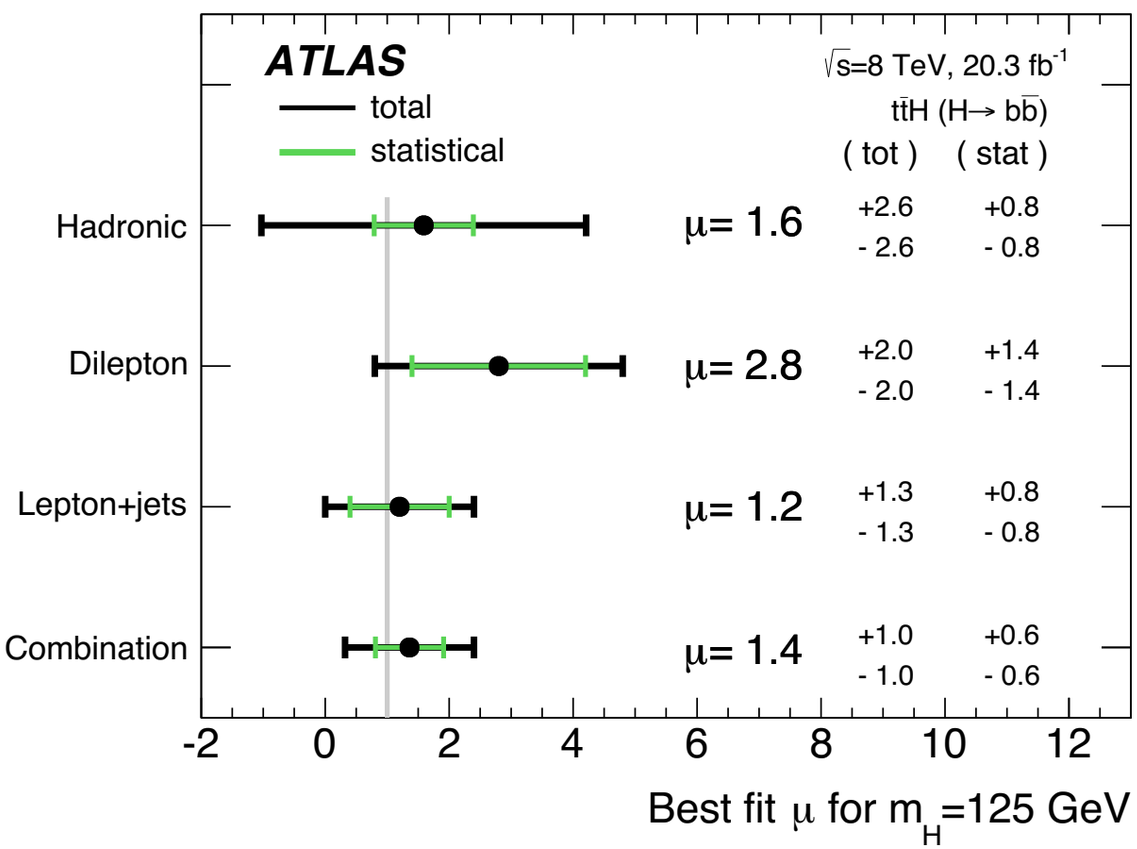

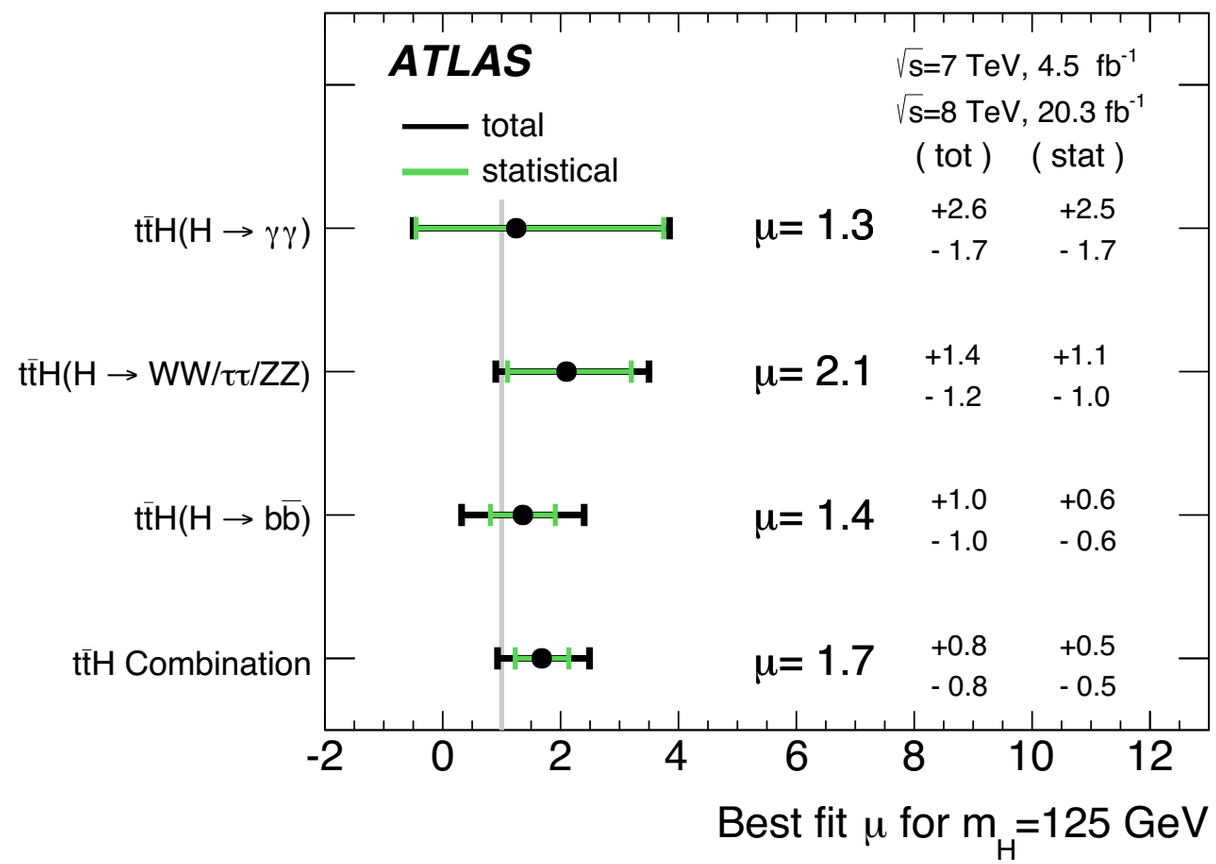

Combined significance:

2.33σ (1.53σ)