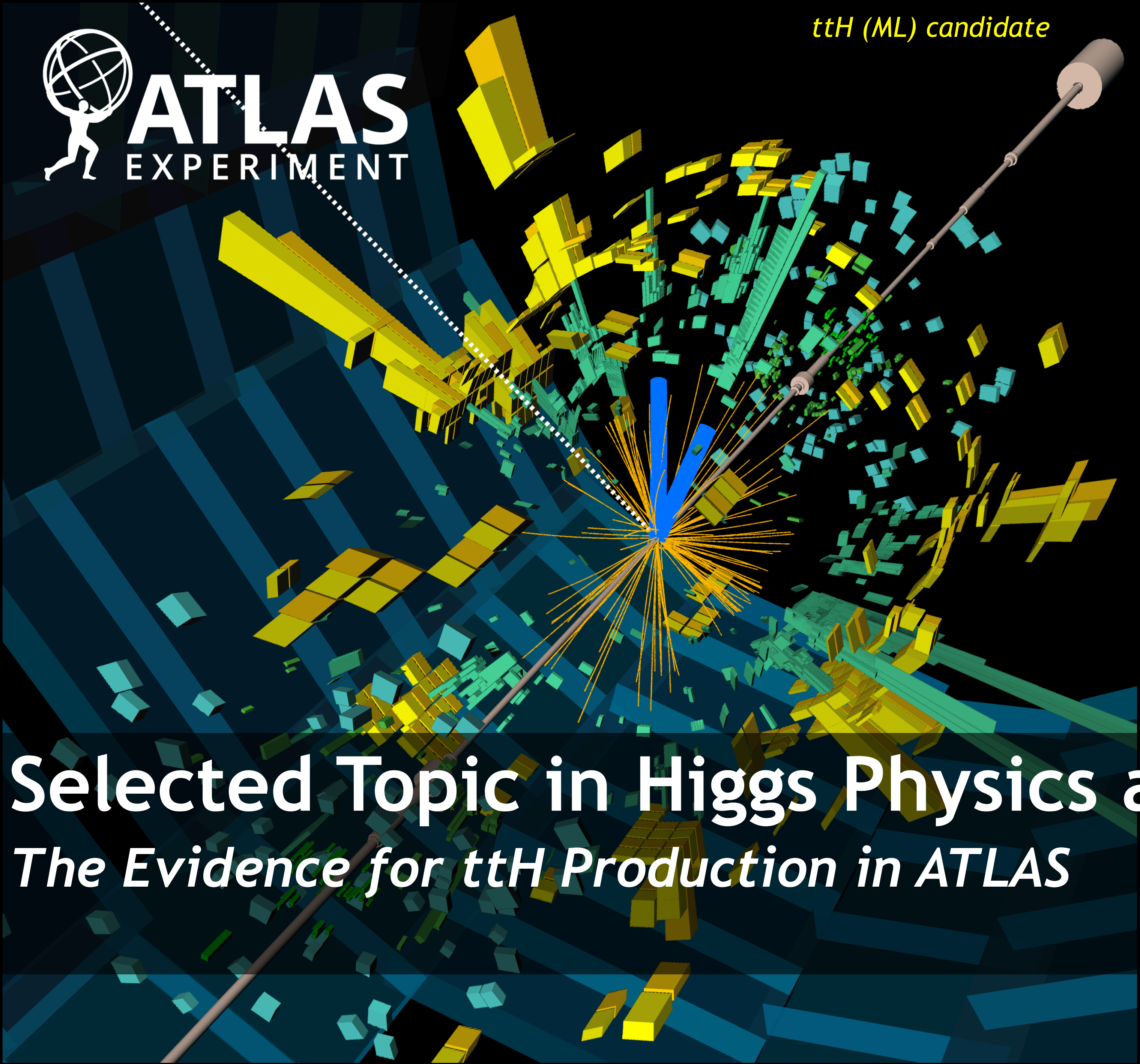


Disclaimer: discuss only Run 2 results: Not all channels have been redone yet (fully hadronic ttH(bb) was done at Run 1)

Selected Topic in Higgs Physics at Run 2

The Evidence for ttH Production in ATLAS

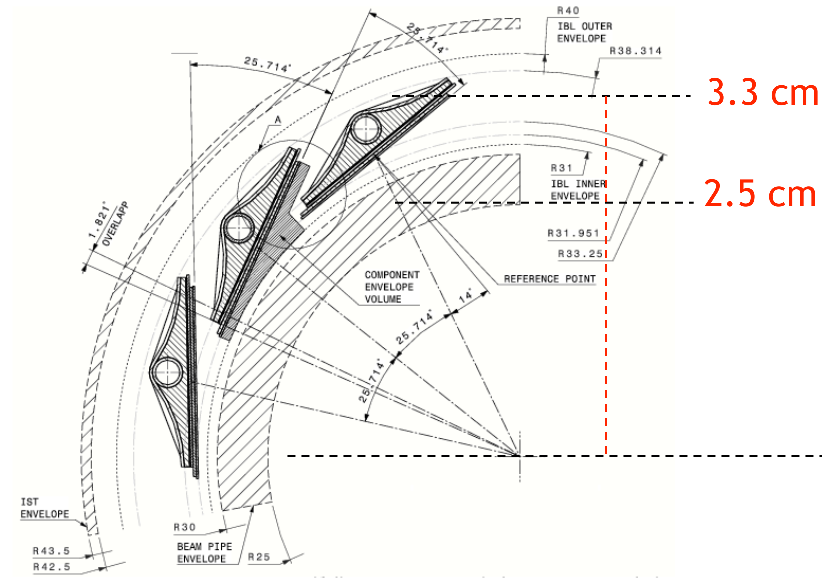
Marumi Kado
LAL, Orsay
Roma La Sapienza

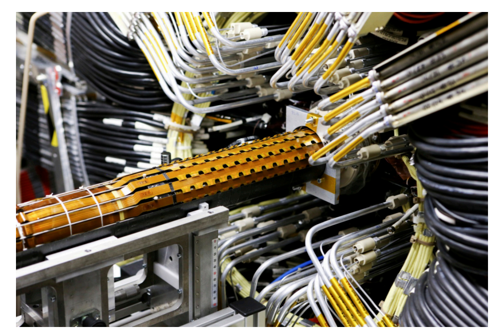
Main ATLAS (phase 0) Detector Improvements

Important changes in all areas of the experiment

ATLAS - Phase 0

- 4th innermost layer of pixels (3.3 cm, 2nd layer at 5.05 cm)
- Consolidation: Complete muon coverage, Luminosity detectors, Repairs (LAr and Tile), Beam Condition. Monitors
- Infrastructure: New Beam Pipe, Magnets and Cryogenic system, Muon Chamber shielding, New pixel services
- Trigger/DAQ: Increase max L1 rate from 75kHz to 100kHz, new Central Trigger Processor, Merge L2 and HLT farms, Additional SFOs for higher output rate.
- Topological L1 triggers
- Fast Track Trigger

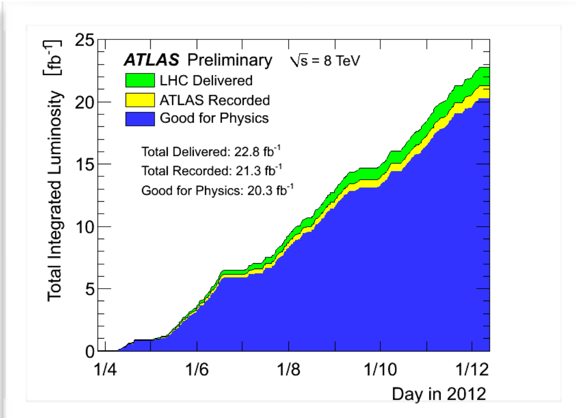




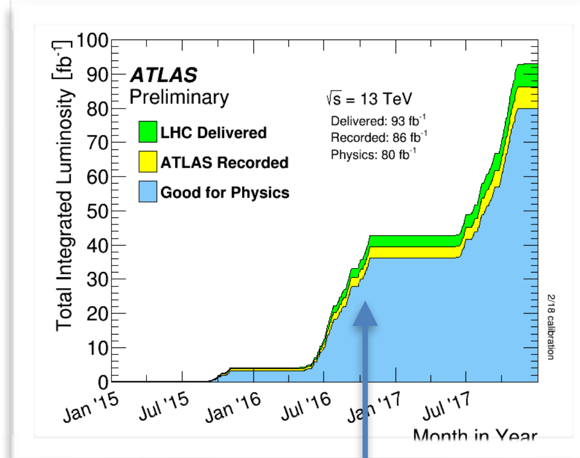
Inserted during LS1

Reconstruction and analysis software are regularly updated, with major update during LS1

Overview of Datasets



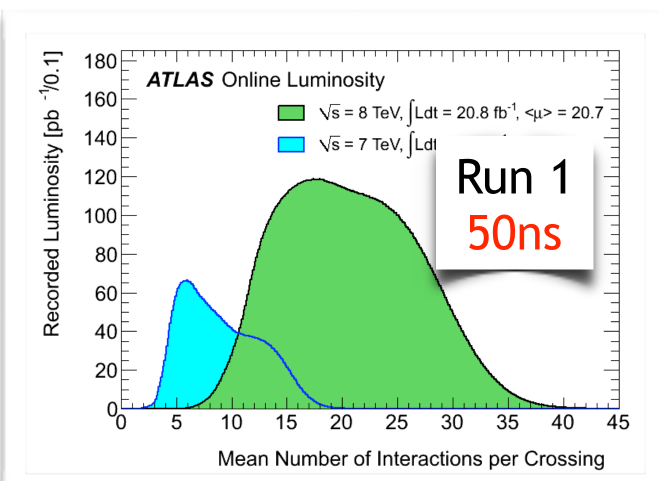
Run 1 dataset~25 fb-1

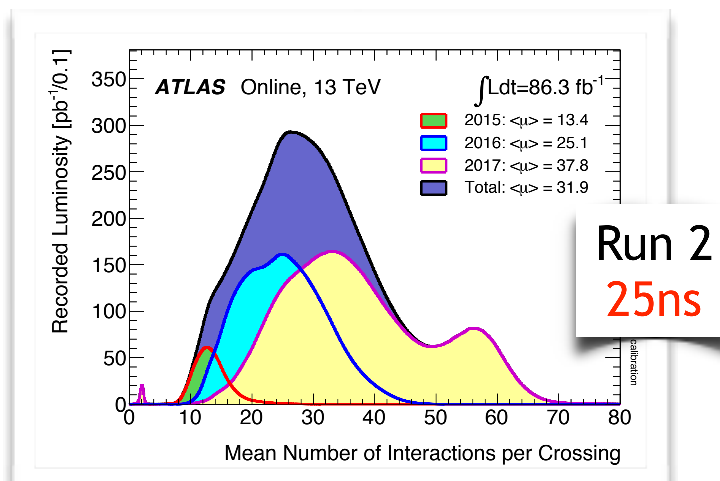


Run 2 dataset
2015-2016: ~35 fb-1

Run 2 dataset
Reached: ~80 fb-1

Turning point: Doubling time of luminosity is now O(1 year)





Higgs physics Landscape

Precision
- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- STXS
- Off Shell couplings and width
- Interferometry

Rare decays
- $Z\gamma$, $\gamma\gamma^*$
- Muons $\mu\mu$
- LFV $\mu\tau$, $e\tau$
- $J/\Psi\gamma$, $Z\Upsilon$, WD
- Phiγ, rhoγ

$$H^0$$

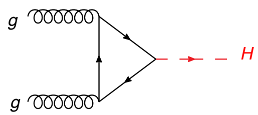
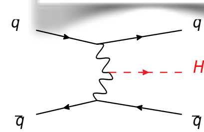
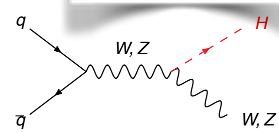
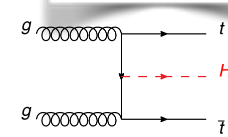
Is the SM minimal?
- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

Rare Production
- tH
- FCNC top decays
- Di-Higgs production (and trilinear couplings)

Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)

Panorama of Main Higgs Analyses at Run 1

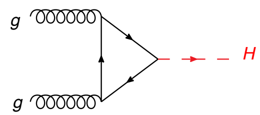
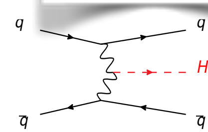
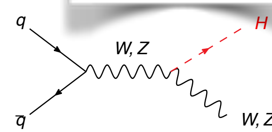
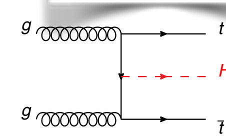
Already impressive harvest of results

Channel categories	ggF 	VBF 5.4σ (4.6σ) 	VH 3.5σ (4.2σ) 	ttH 4.4σ (2.0σ) 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lνlν)	✓	✓	✓	✓
ττ 5.5σ (5.0σ)	✓	✓	✓	✓
bb 2.6σ (3.7σ)		✓	✓	✓
Zγ and γγ*	✓	✓		
μμ and ee	✓	✓		
Invisible	✓ (monojet)	✓	✓	

✓ Run 1 results

Panorama of Run 2 Main Higgs Analyses

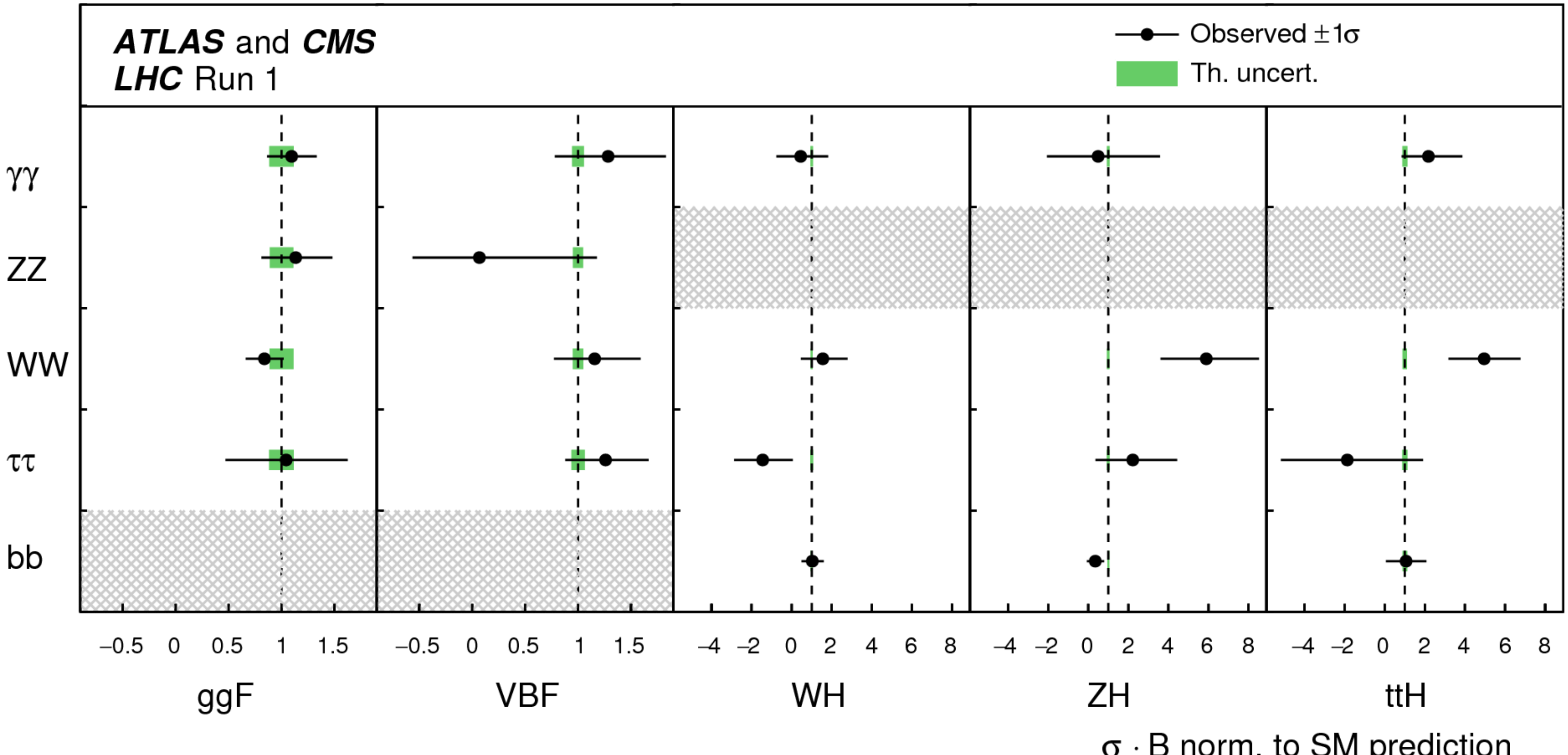
Already impressive harvest of results

Channel categories	ggF 	VBF 5.4σ (4.6σ) 	VH 3.5σ (4.2σ) 	ttH 4.4σ (2.0σ) 
γγ	✔	✔	✔	✔
ZZ (llll)	✔	✔	✔	✔
WW (lνlν)	✔	✔	✓	✔
ττ 5.5σ (5.0σ)	✓	✓	✓	✔
bb 2.6σ (3.7σ)		✔	✔	✔
Zγ and γγ*	✔	✔		
μμ and ee	✔	✔		
Invisible	✓ (monojet)	✓	✓	

✓ Run 1 results

Run 1 Status of the Higgs Couplings Measurements

(Simplified or combined*) panorama of Higgs channels used (many more categories are used in each case and two experiments)



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Nano (biased) Summary of the Run 1 Status of Couplings

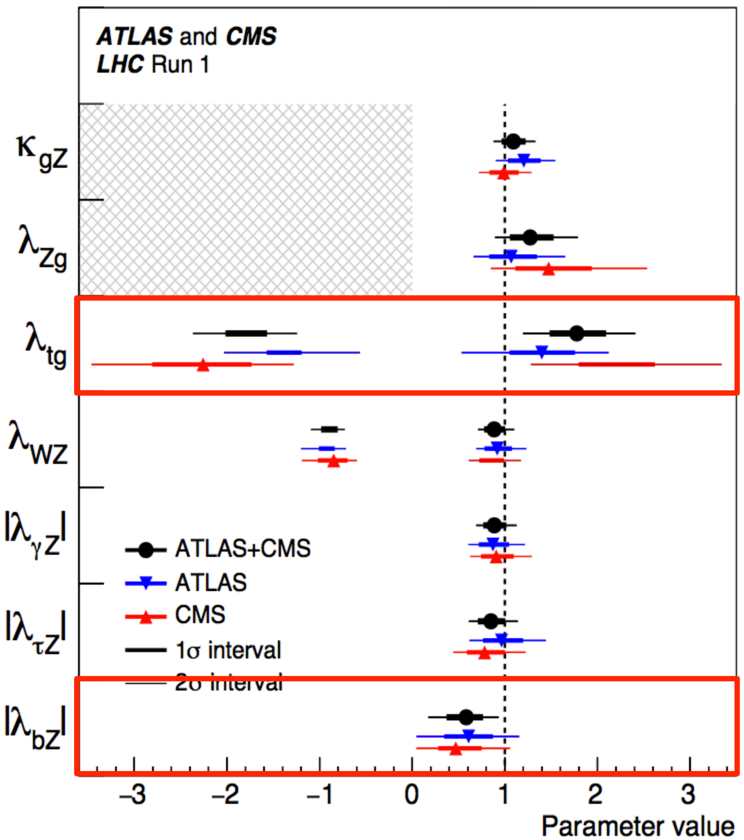
$$\mu = 1.09 \quad \pm 0.11$$
$$(\pm 0.07\,(Stat)$$
$$\pm 0.04\,(Exp)$$
$$\pm 0.03\,(Th.\,bkg)$$
$$\pm 0.07\,(Th.\,sig)\,)$$

Signal strength illustrates the agreement of measurements with the SM and the importance of the TH input.

Very illustrative, but not transparent on the underlying assumptions and relies on the TH input at a given time.

$\Delta\lambda/\lambda$ ~ 30%

$\Delta\lambda/\lambda$ ~ 34%



Direct coupling to the top*
(through ttH production channels)

Direct coupling to b quarks*
(Through mainly VH channels)

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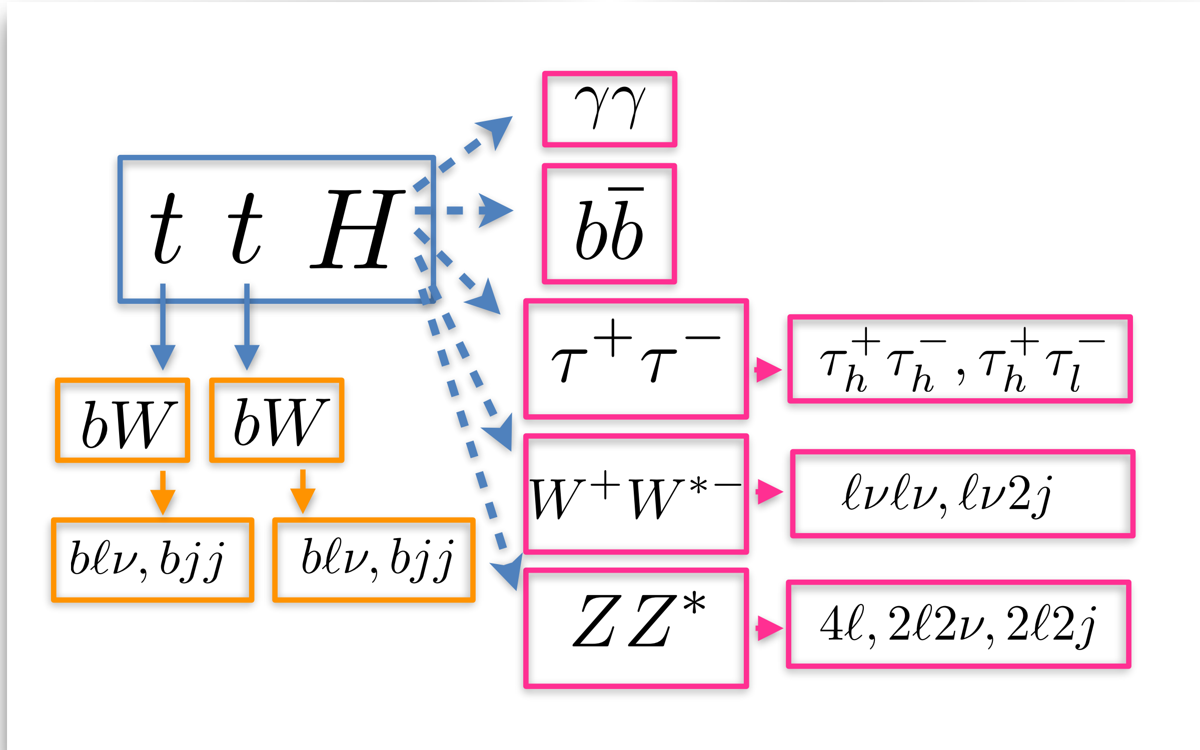
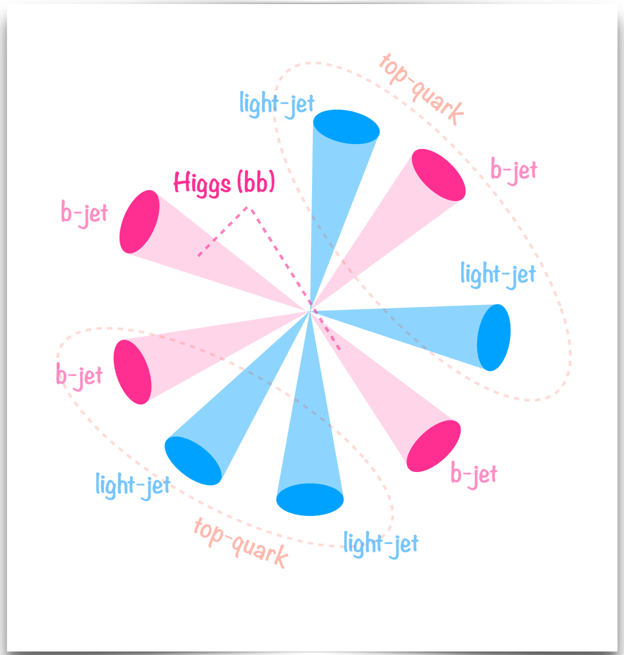
ttH Analyses at LHC: Massively Complex!

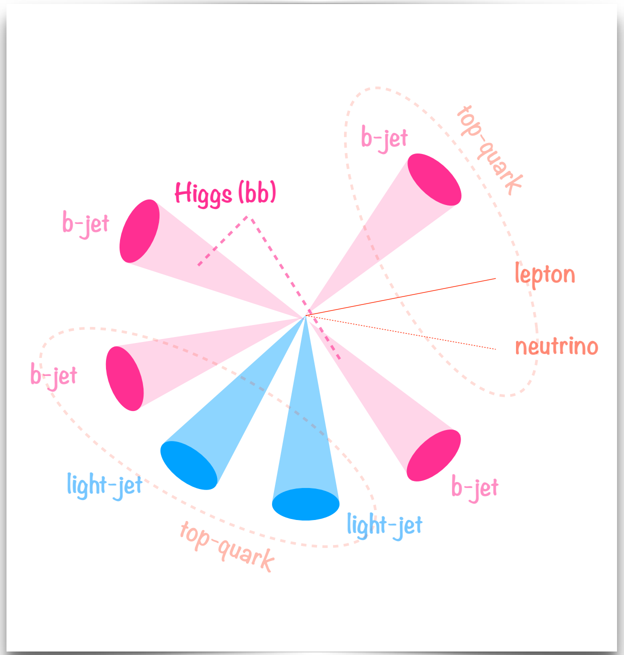


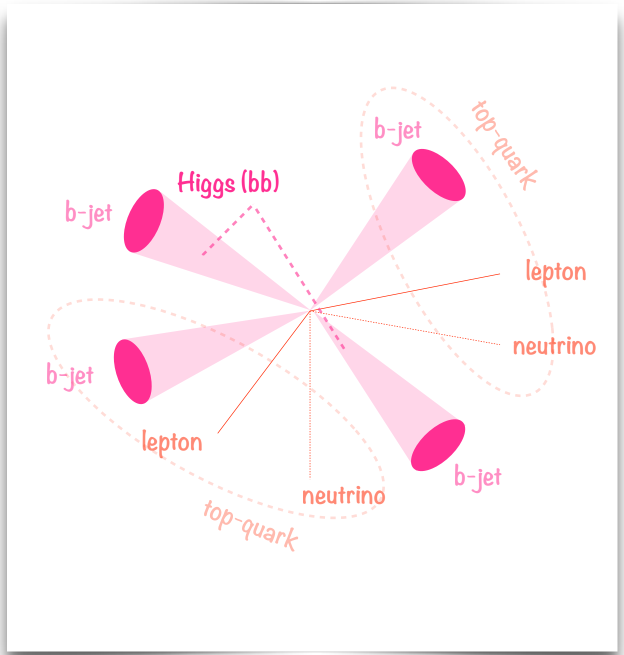
- Five main Higgs decay channels
- Several with possible sub-branches
- Several possible top decay channels
- Giving rise to a very large number of signatures

- Large number of final states which are typically very complex (mixture of b-jets, leptons, taus and photons)
- But, many different channels, also means different backgrounds and different systematic uncertainties and therefore also a strength!
- With the new Run at close to double centre-of-mass energy and increased statistics, changes in leading channels.

ttH(bb)


light-jet
top-quark
b-jet
Higgs (bb)
b-jet
light-jet
b-jet
light-jet
b-jet
top-quark
light-jet


b-jet
top-quark
Higgs (bb)
b-jet
lepton
neutrino
b-jet
light-jet
b-jet
light-jet
top-quark

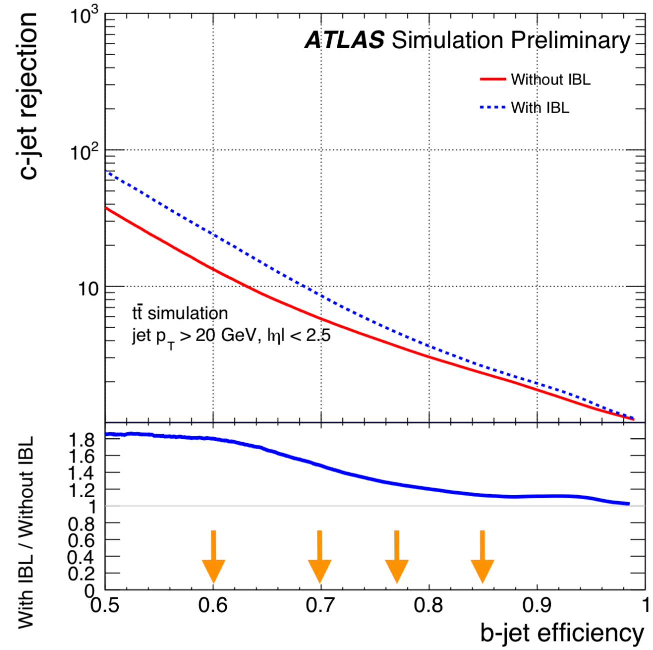

b-jet
top-quark
Higgs (bb)
b-jet
lepton
neutrino
b-jet
lepton
neutrino
b-jet
top-quark

ttH(bb) Relevant Performance Improvements

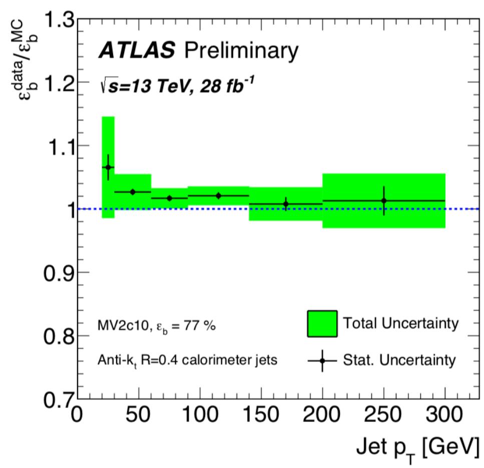
Large improvement in b-tagging performance in Run-2 due both to the insertable b-layer and improved algorithms (b-tagging still improving)

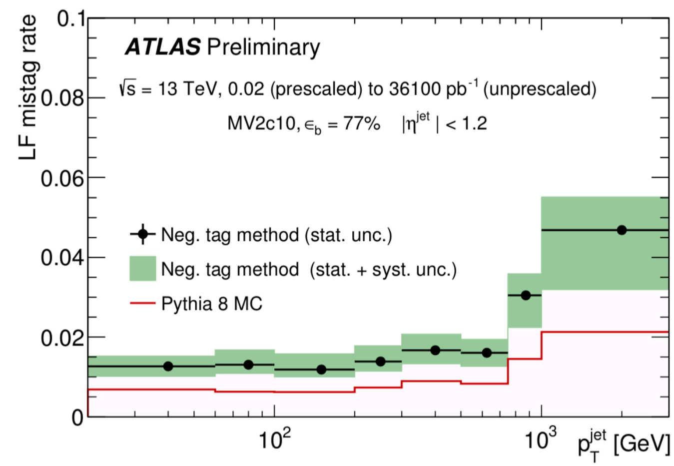
Calibration derived from data:

- b-jet efficiency: dileptonic tt (2-10%)
- c-jet mistag: semileptonic tt (W → cs), W +c (5-20%)
- Light-flavour mistag: dijet events (10-50%)



Four different working points often referred to as pseudo-continuous b-tagging (fully calibrated)





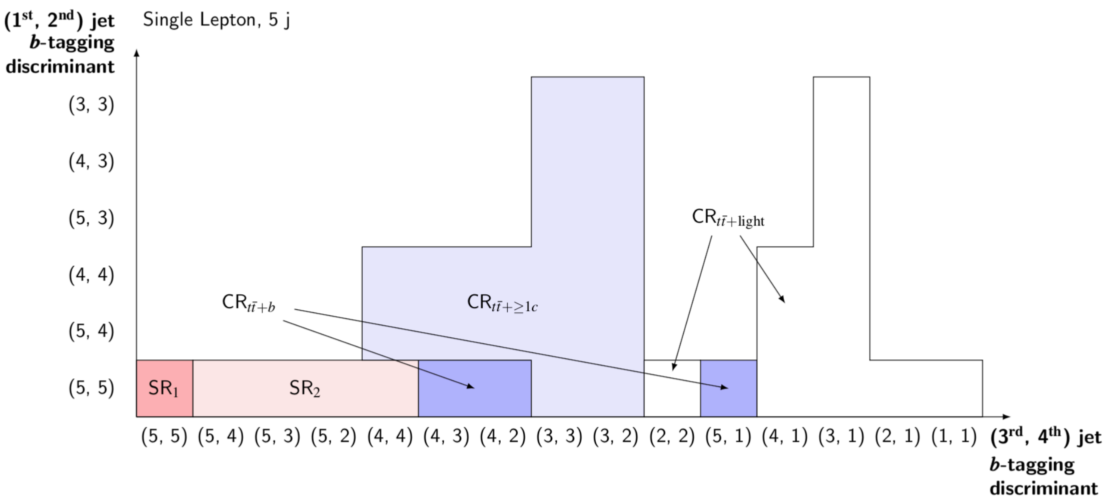
ttH(bb)

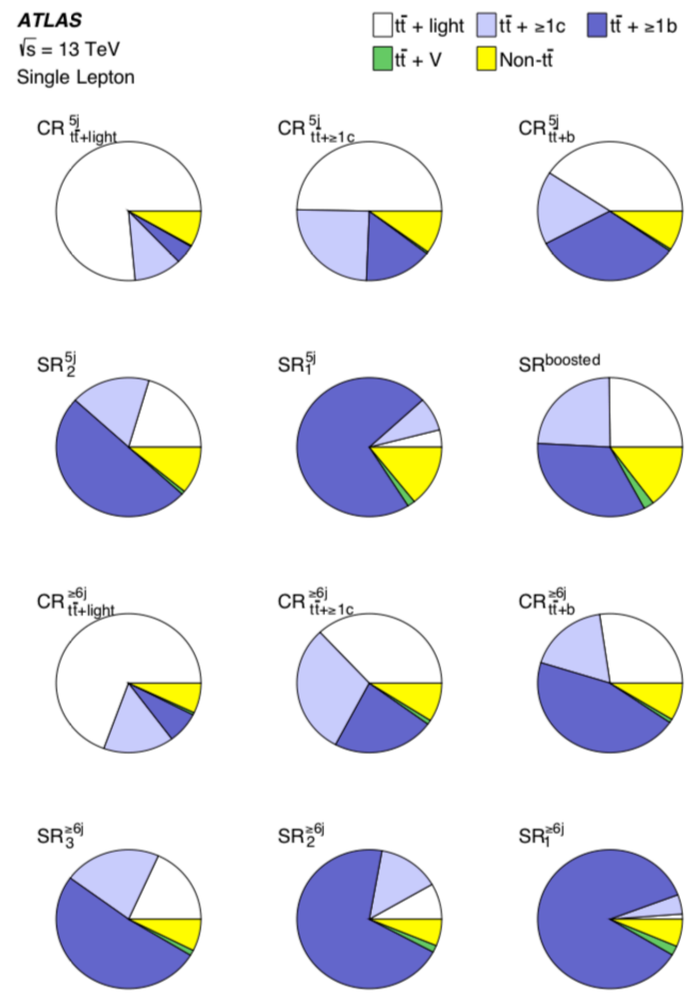
Two main channels based on number of leptons 1l, 2l (here focus on most sensitive channel 1l).

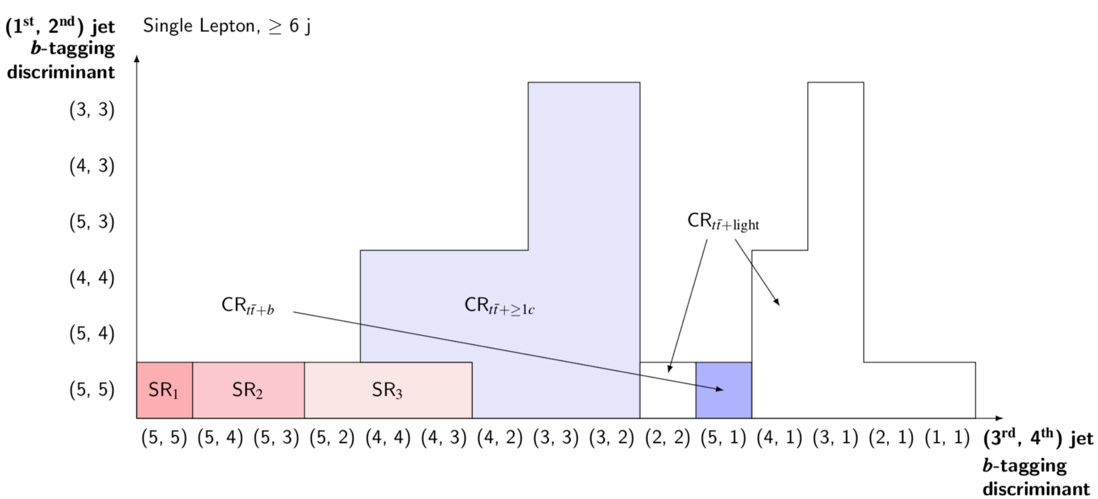
- Require ≥3 jets and ≥2 medium b-tagged jets and 1e or mu with $p_T > 27$ GeV (veto events with ≥2 taus)
- High-pT category:
    - 'Boosted' event: boosted Higgs and top candidates (large-R 1.0 jets, reclustered
      from 0.4 jets), plus a loose b-tagged jet
    - Higgs boson candidate ($p_T > 200$ GeV): two loose b-tagged jets
    - Top candidate ($p_T > 250$ GeV): one loose b-tagged + ≥1 non-b-tagged jets
- If failing the 'boosted' selection → 'Resolved' event Require ≥5 jets and ≥2 very-tight b-tagged jets or ≥3 medium b-tagged jets

ttH(bb)

Categories based on the level of b-tagging based on the 5 categories defined from pseudo continuous definition (see previous slide)

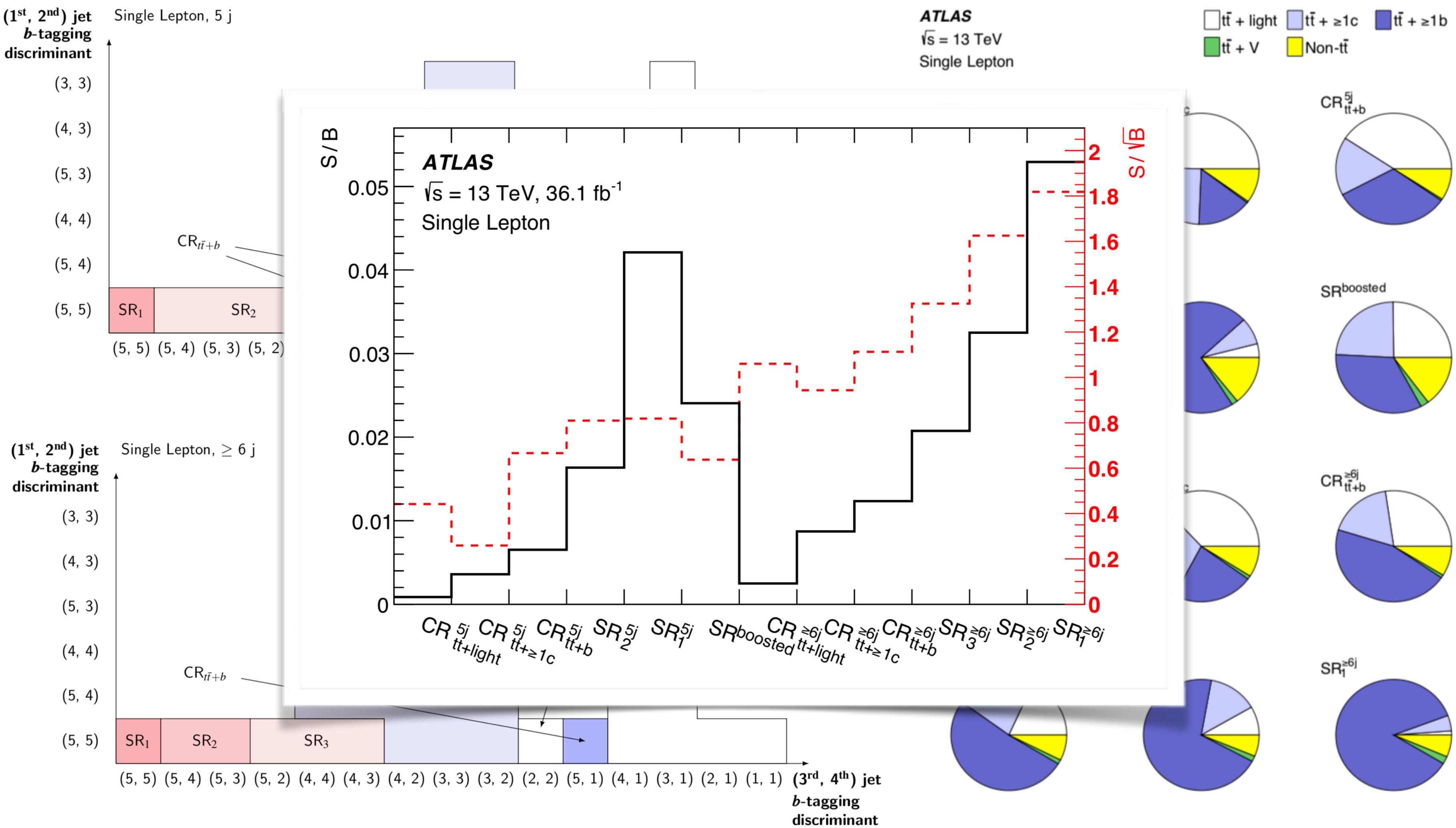






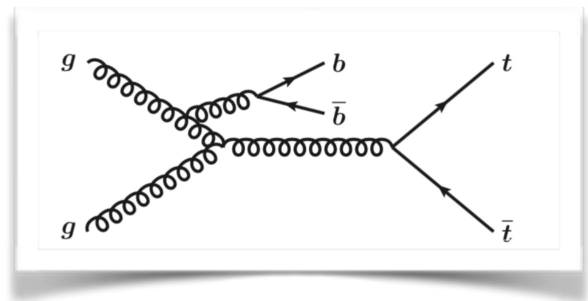
ttH(bb)

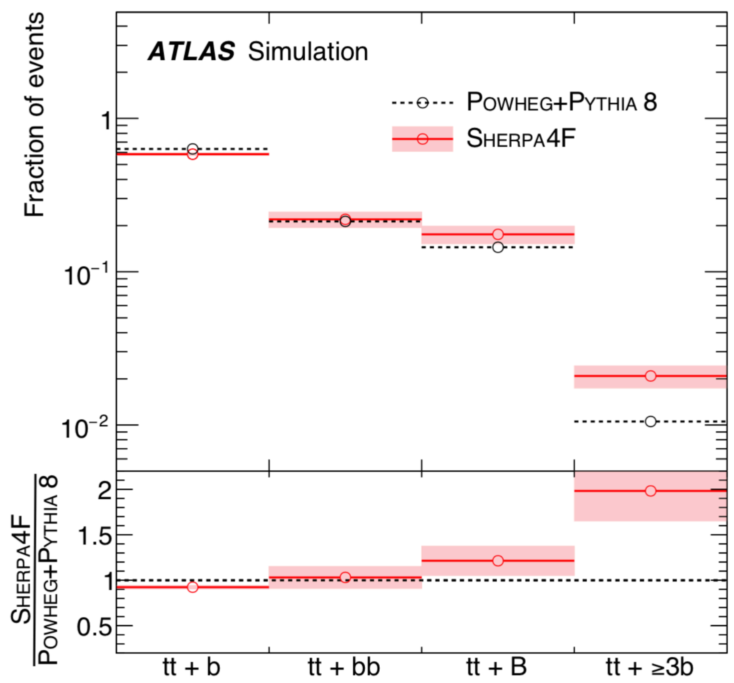
Categories based on the level of b-tagging based on the 5 categories defined from pseudo continuous definition (see previous slide)



The Challenge

- Nominal sample: Powheg+Pythia8, modelling extensively studied with 7/8/13 TeV data (ATL-PHYS-PUB-2014-021, ATL-PHYS-PUB-2016-020)
- Normalized to NNLO+NNLL cross-section
- MC sample split in number of HF jets at particle level
  ◦ $t\bar{t}$+≥1b: jets matched to 1(b) or 2(B) b hadrons ◦ Extra b-jets from MPI or FSR
  ◦ $t\bar{t}$+≥1c: analogous to $t\bar{t}$+≥1b
  ◦ $t\bar{t}$+light
- $t\bar{t}$+≥1b: relative contribution from each sub-component are reweighted to $t\bar{t}b\bar{b}$ predictions by Sherpa+OpenLoops: NLO, 4-flavour scheme (massive b-quarks, g - from ME)
- Additional systematic checks using Sherpa+OpenLoops 5F scheme and Powheg with Herwig 7 (instead of P8).





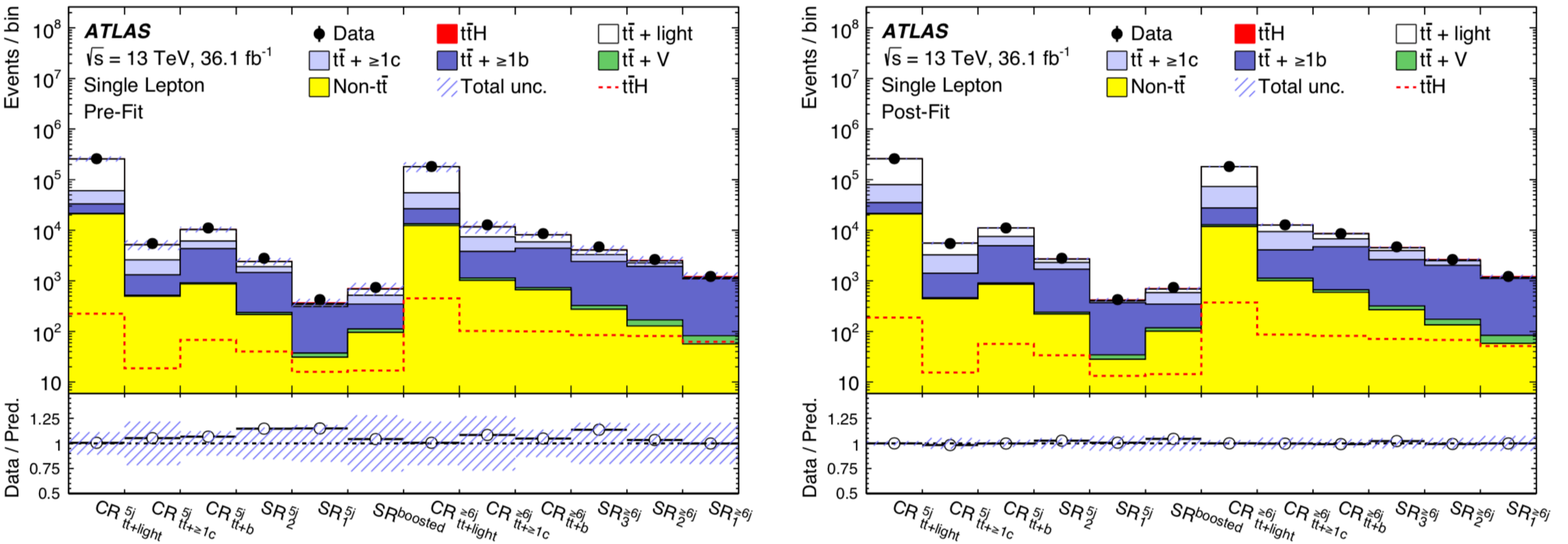
Modelling Systematics Uncertainties

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)

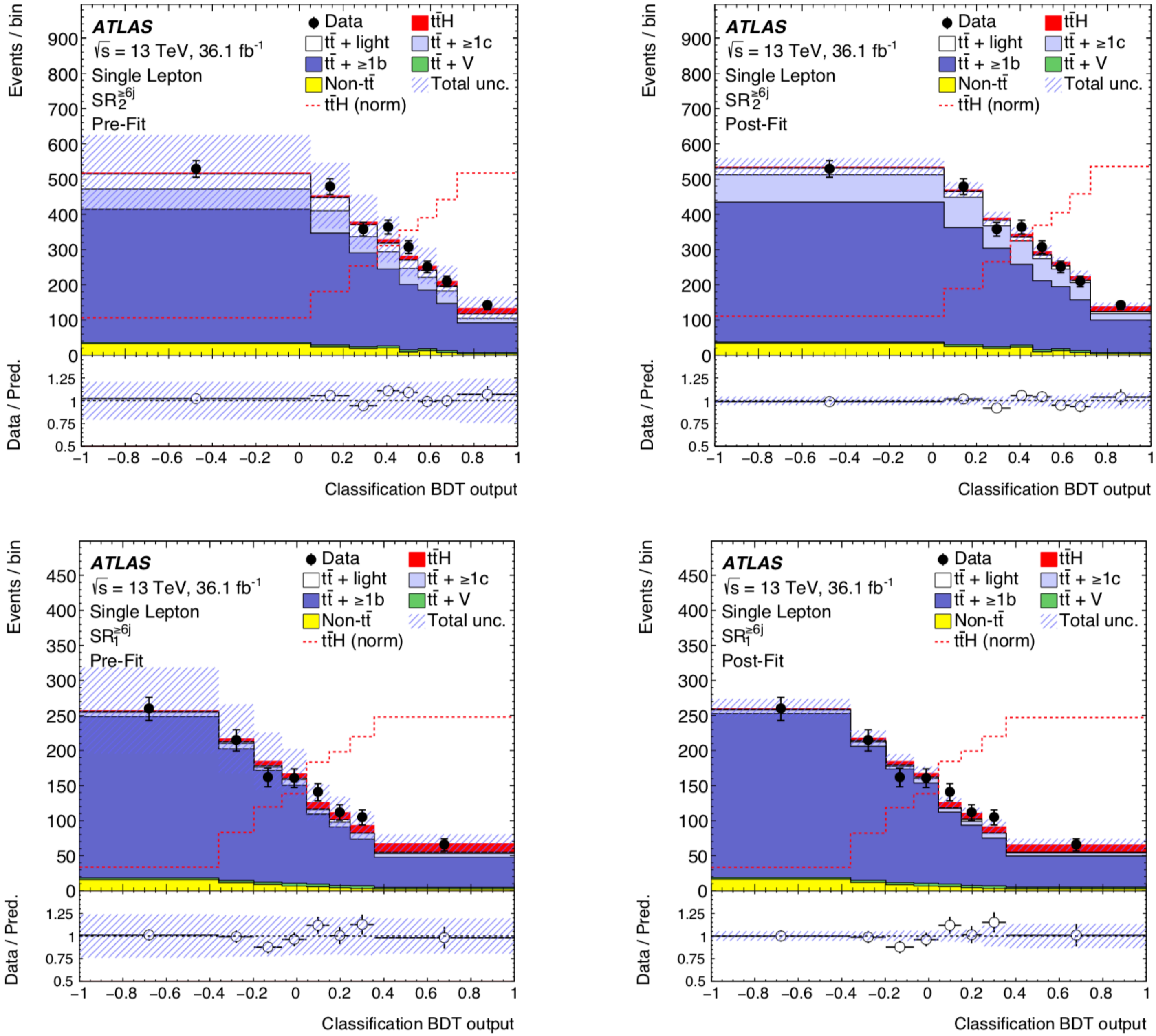
Normalisations and the profiling at work

Log scale misleading to represent non top backgrounds

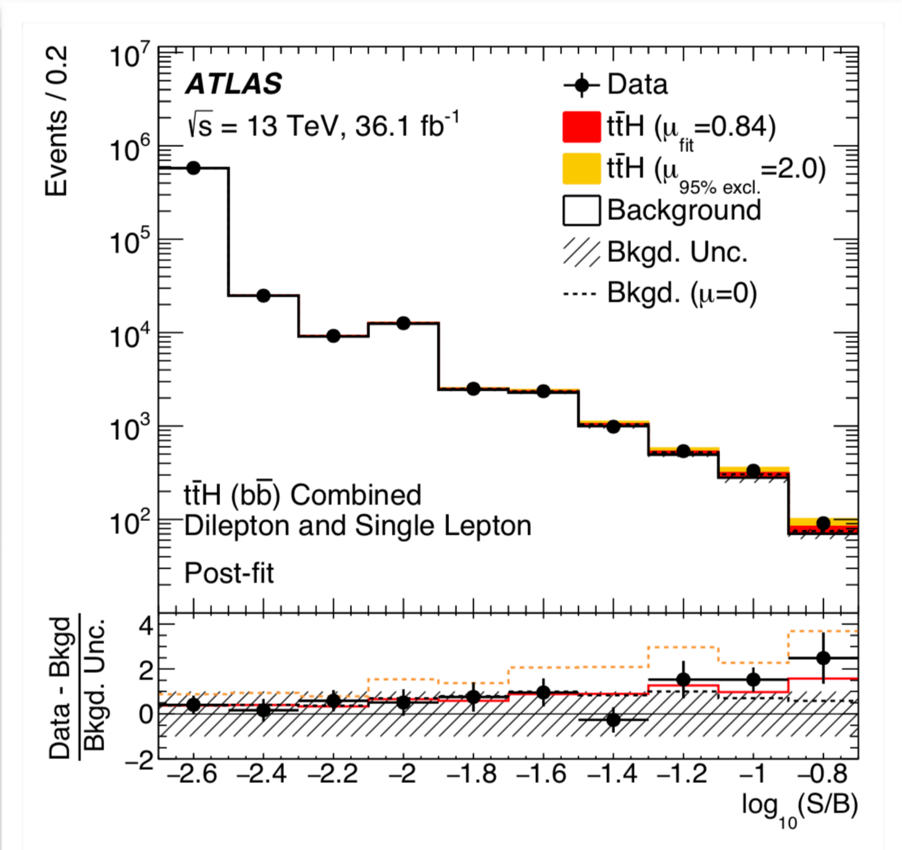


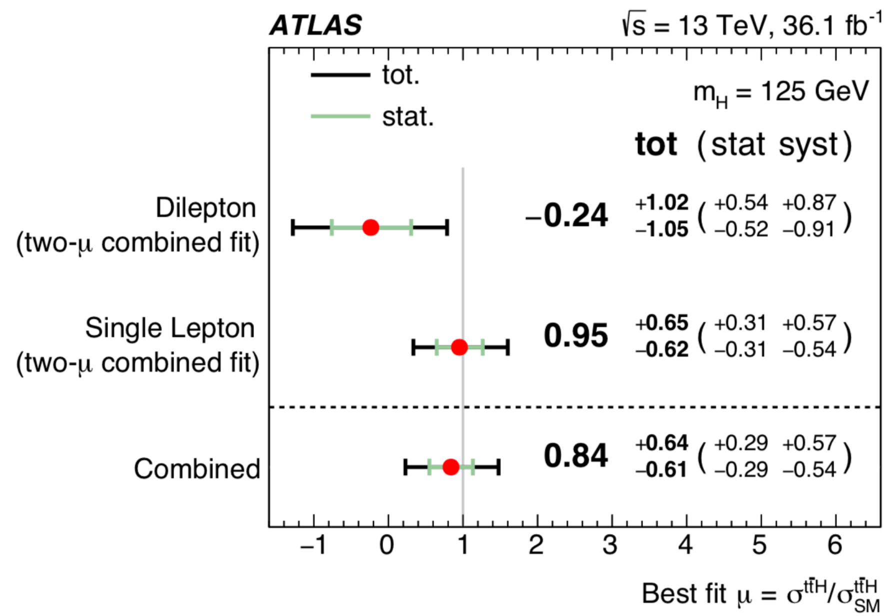
- Profiling of systematic uncertainties plays a very important role in this analysis it can be seen already in the overall rates.
- Also very much visible in the discriminant distributions in each channel

Shapes and the profiling at work



Results (incl. dilepton channel)

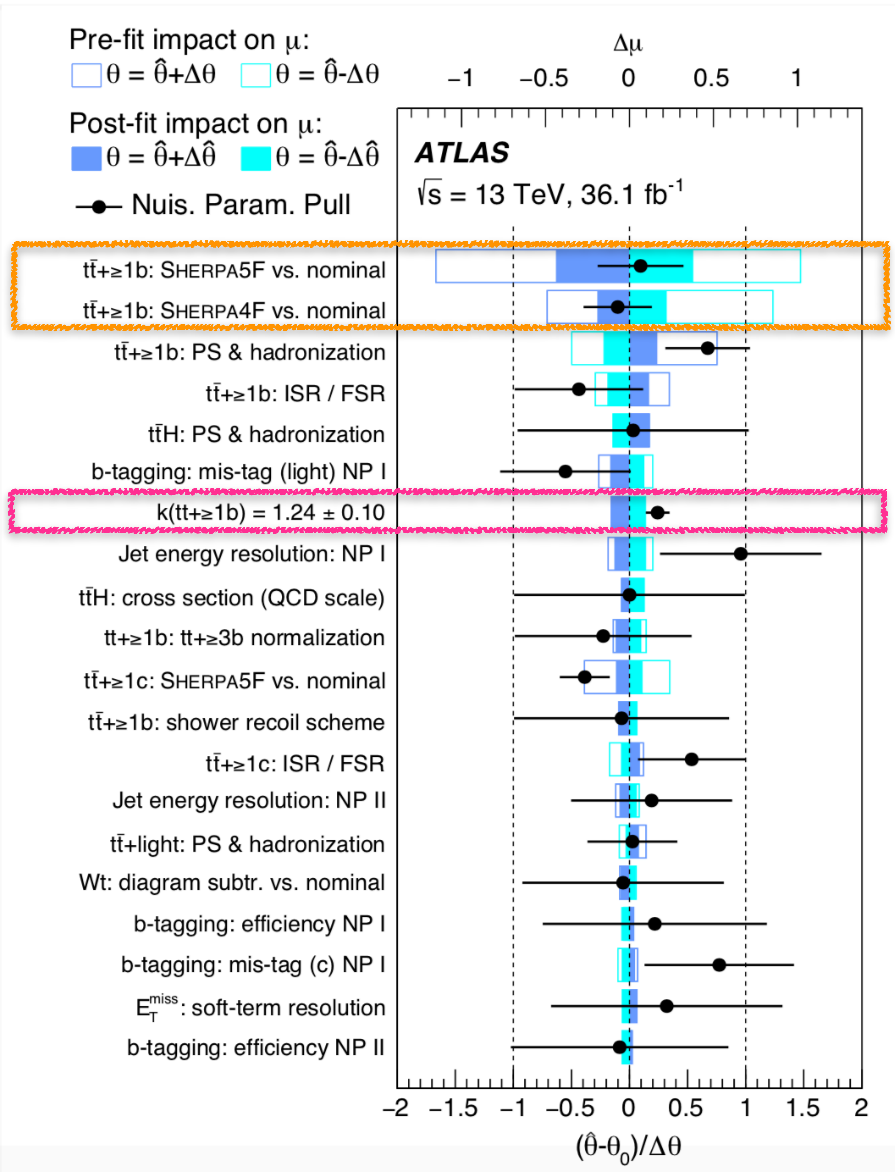




$$\mu = 0.84 \pm 0.29\,(stat)^{+0.57}_{-0.54}\,(syst)$$

80% Dominated by systematic uncertainties

The Profiling Paradigm



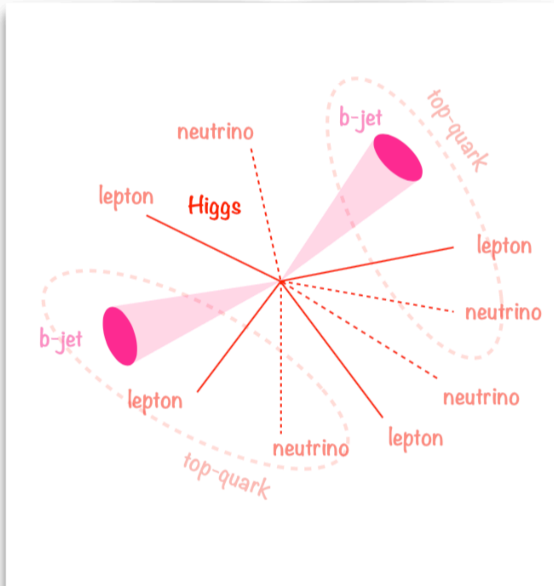
- Pulls w.r.t. to postfit error bars do not necessarily mean a tension between data and auxiliary measurement (or pre-fit uncertainty).
- Interpretation of two point systematic uncertainties with log-normal is highly not straightforward.
- Distribution of pulls do not give a good representation of the goodness of fit.
- Normalisations are not so high in the ranking (shapes do play quite an important role).
- Should an excluded model still serve to estimate a systematic uncertainty? ATLAS current choice: yes.

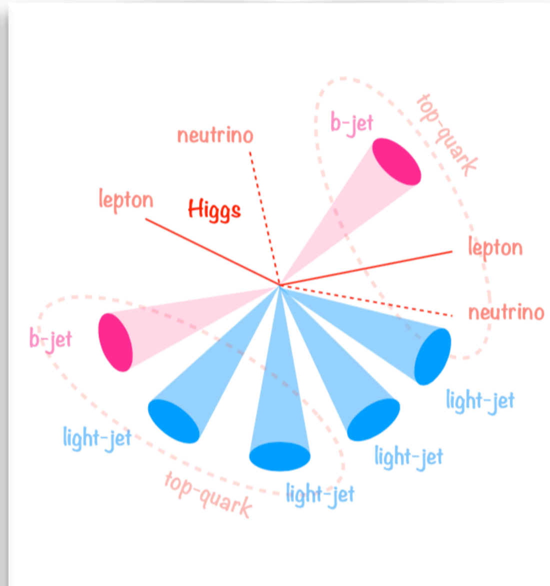
ttH(bb)

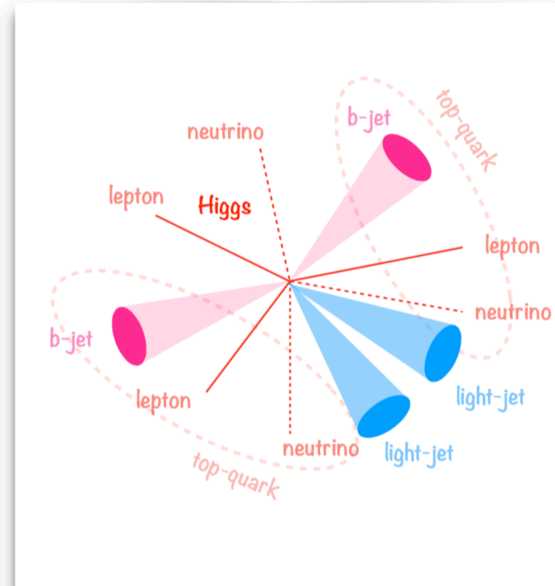
Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t} + \geq 1c$ modeling	+0.09	−0.11
JVT, pileup modeling	+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

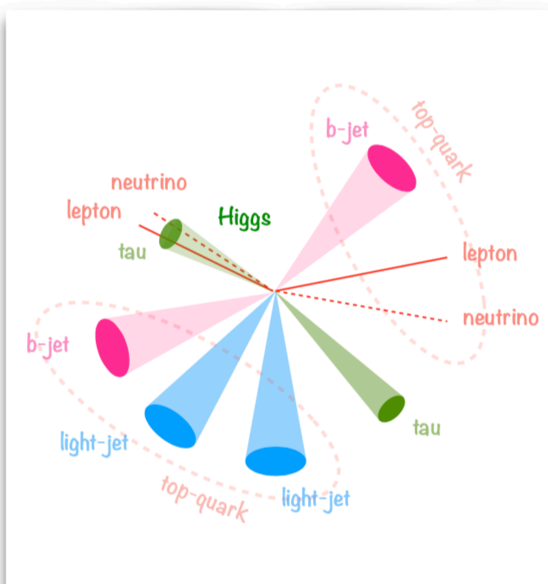
After modelling systematics, come modelling statistics!

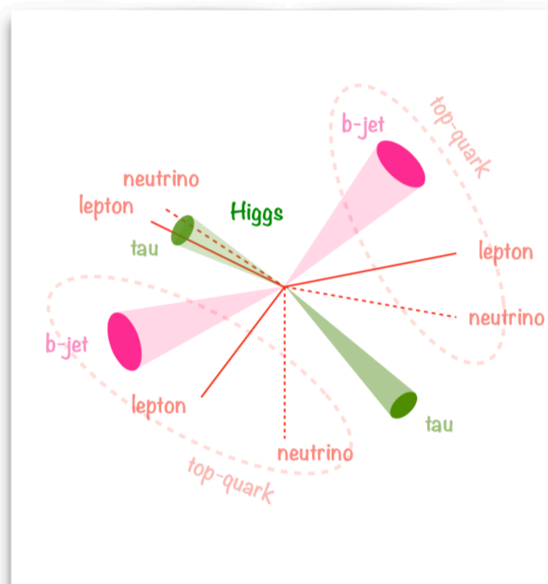
ttH (Multi-Lepton)









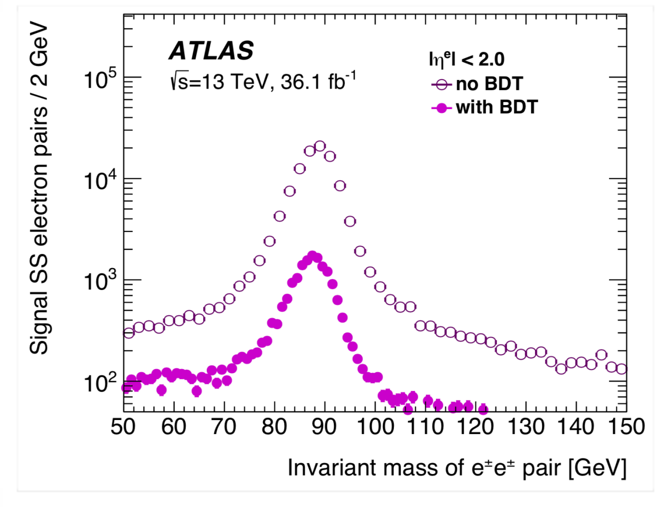


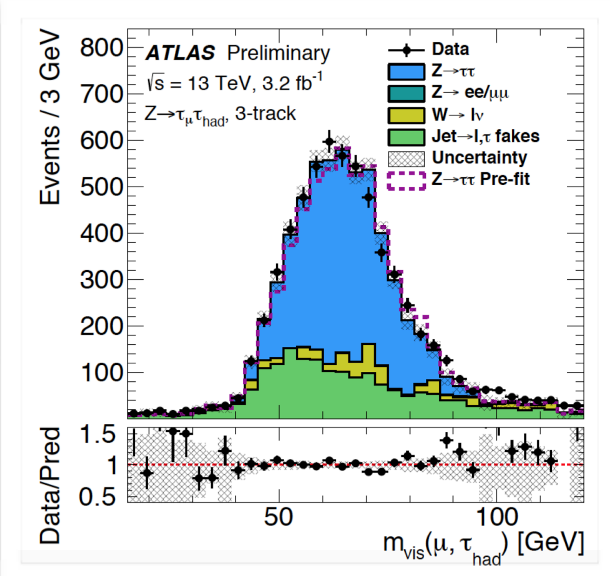
ttH(ML) Relevant Performance Improvements

- BDT to reduce charge mis-identification
    - Uses calorimeter and track variables
    - A rejection of order O(20) for 95% efficiency
- Improved isolation with BDT aimed at reducing non-prompt e/μ (taking into account correlations between IP and isolation):
    - Inputs: isolation variables, jet reconstruction and b-tagging algorithms using tracks around the leptons
    - Factor O(20) rejection for leptons originating from b-hadrons
    - Efficiency for prompt e/μ: ~70% (60%) at low pT, ≥95% at high pT
    - Calibration performed in Z → ll events

Implication changing the nature of the fake lepton backgrounds

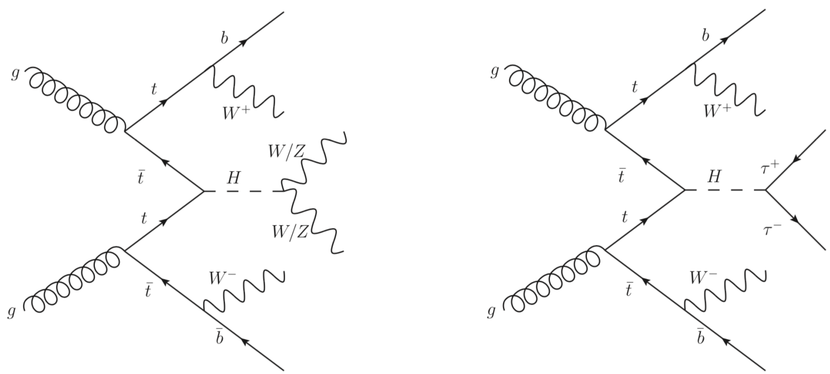
- Taus reconstructed using a BDT (improved tau reconstruction using PF algorithm not yet used)



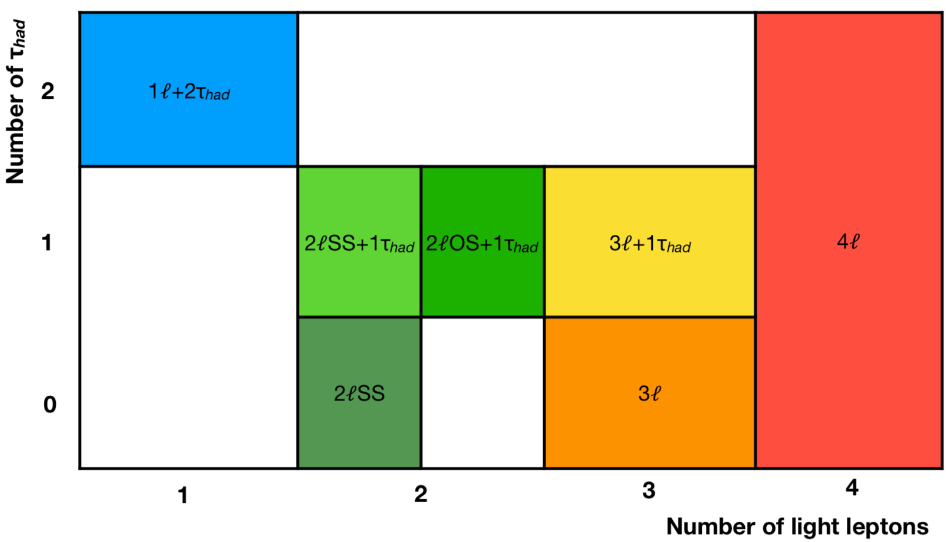


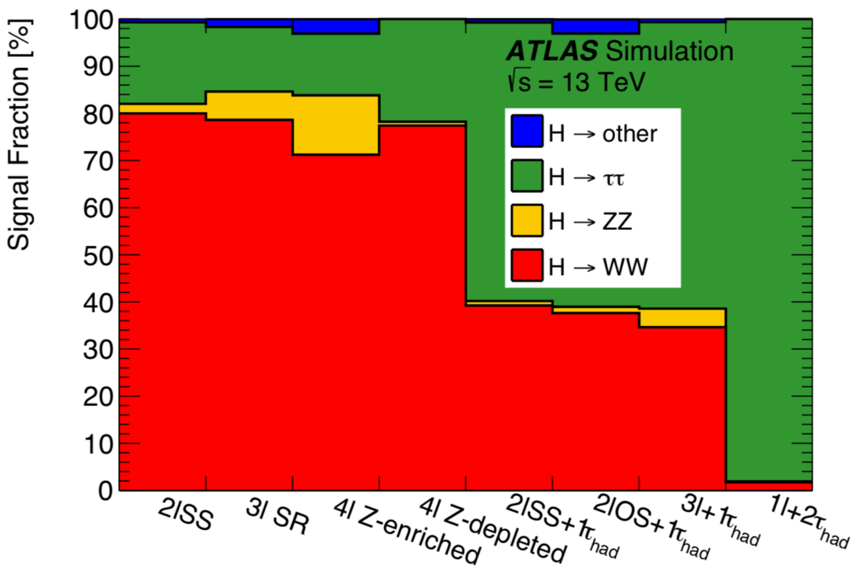
ttH (Multi-Lepton)

- Main targets of the channel WW, ZZ (with subsequent decays to electrons, electrons and taus) and tautau

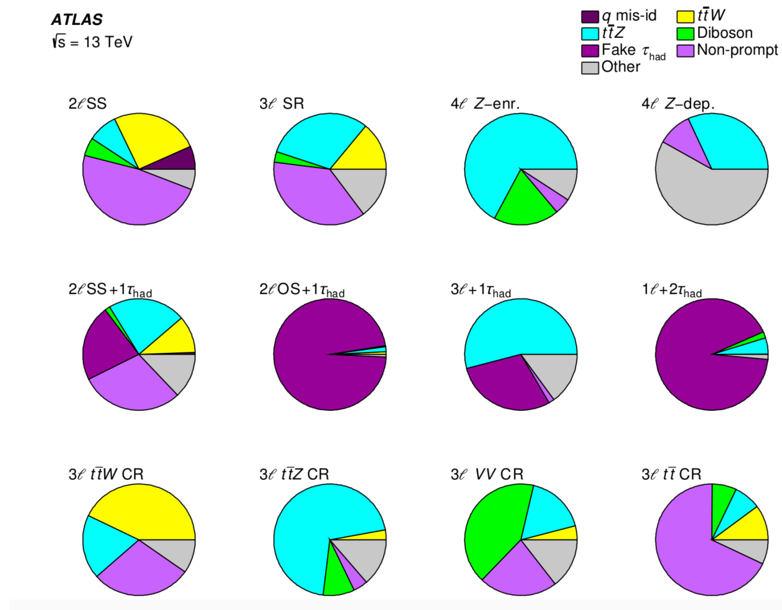


- Channel with sizeable excess at Run 1.
- A lot of attention was paid to the control of backgrounds, in particular the most difficult one to constrain: fakes!





ttH (Multi-Lepton)

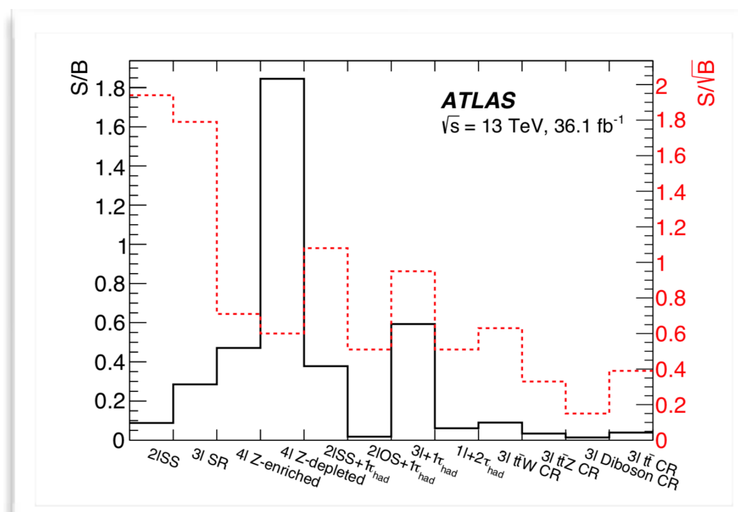


Jet and b tagging requirements:

- Njets ≥ 2, Nb-jets ≥ 1
- 2lSS, 2lSS+1τhad: Njets ≥ 4
- 2lOS+1τhad, 1l+2τhad: Njets ≥ 3

Multivariate analysis to enhance performance:

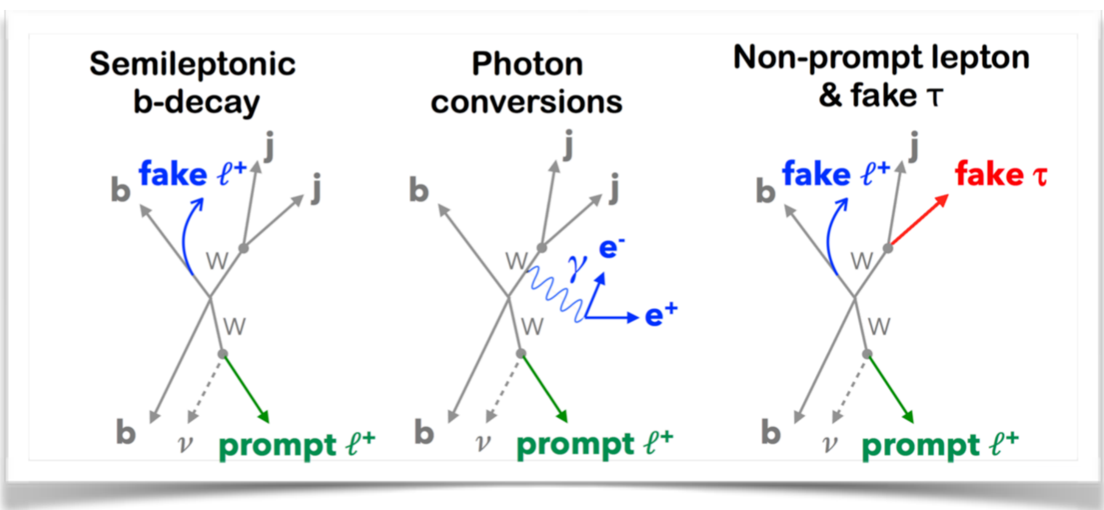
- 2LSS: two BDTs against tt and ttV
- 3L: 5-dim. multiclass BDT mapping 5 categories simultaneously (ttH, ttW, ttZ, tt, VV)
- 4l: BDT ttH against ttZ
- 2LSS-1Tau and other channels: BDT ttH against tt.



Very different background contributions and analyses with large s/b (typically less sensitivity - taking systematics into account)

Fake Backgrounds

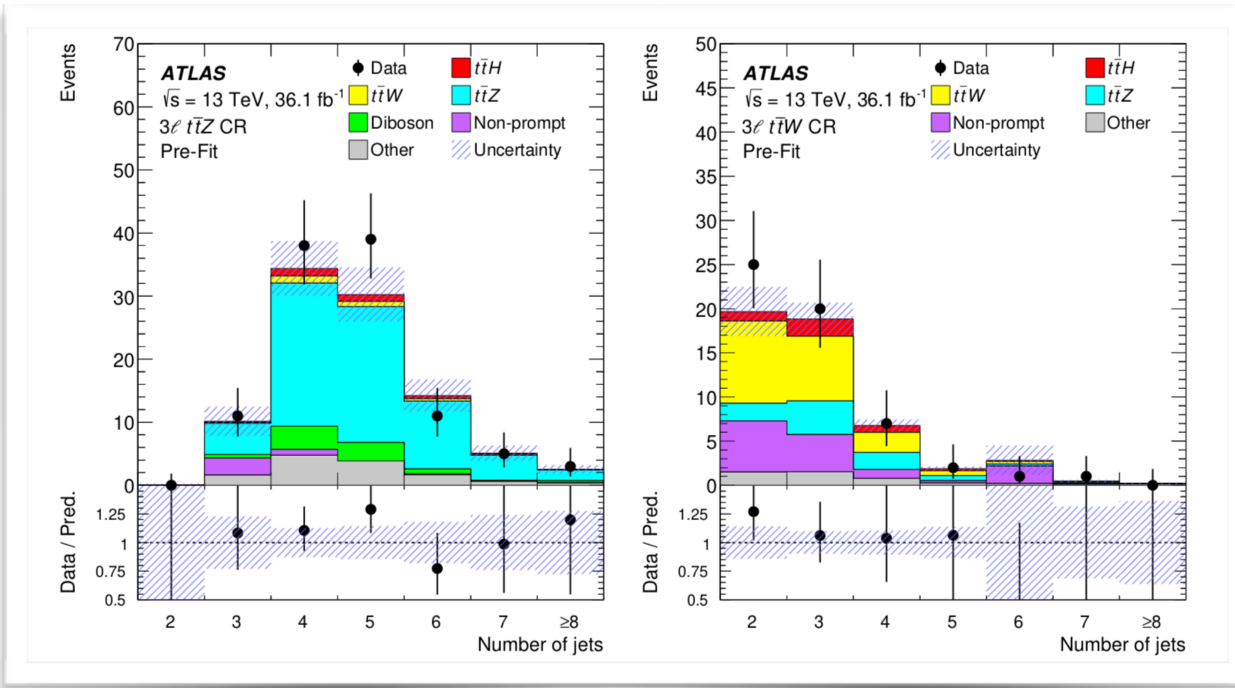
- Main channels fake backgrounds (2LSS and 3L) from fake electrons and muons: using the Matrix method (cross checked with fake factor method).
- Improved isolation criteria enhances the contribution of photon conversions as source of fakes.
- Fake taus are estimated with MC and data driven fake factors
- Electron charge mis-identification for 2lSS and 2lSS+1τhad: Estimated from data using charge mis-id rates measured in $Z \rightarrow e^+e^-/e^\pm e^\pm$ (small)



From X. Poveda (CERN Seminar)

Control of Irreducible Backgrounds

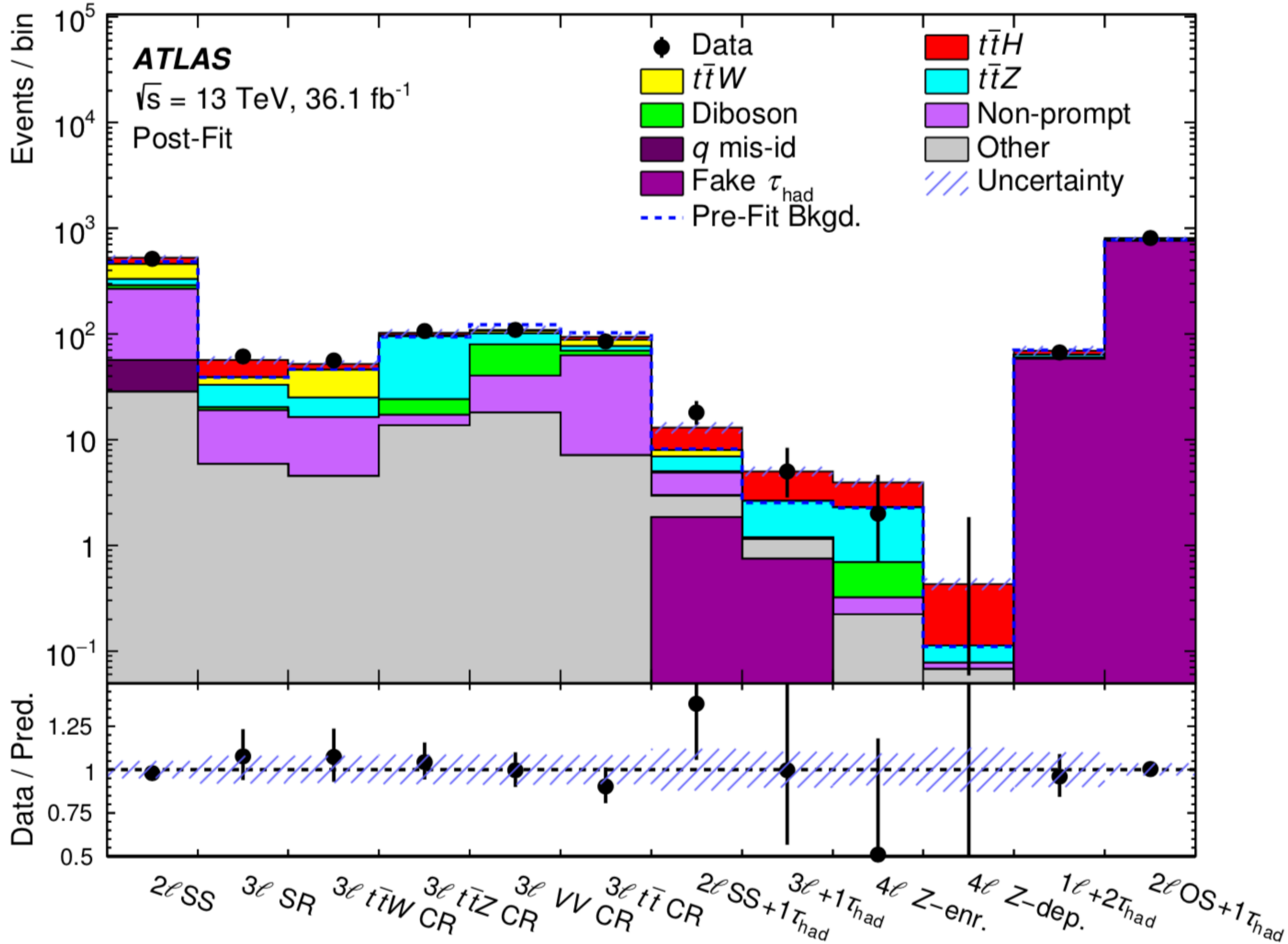
- Main irreducible backgrounds: ttW, ttZ
- Estimated using NLO MC samples (MG5_aMC@NLO - systematic checks using Sherpa 2.1.1 LO), with theory/modelling uncertainties
- Validated in several regions, eg: 3l ttW /Z CRs



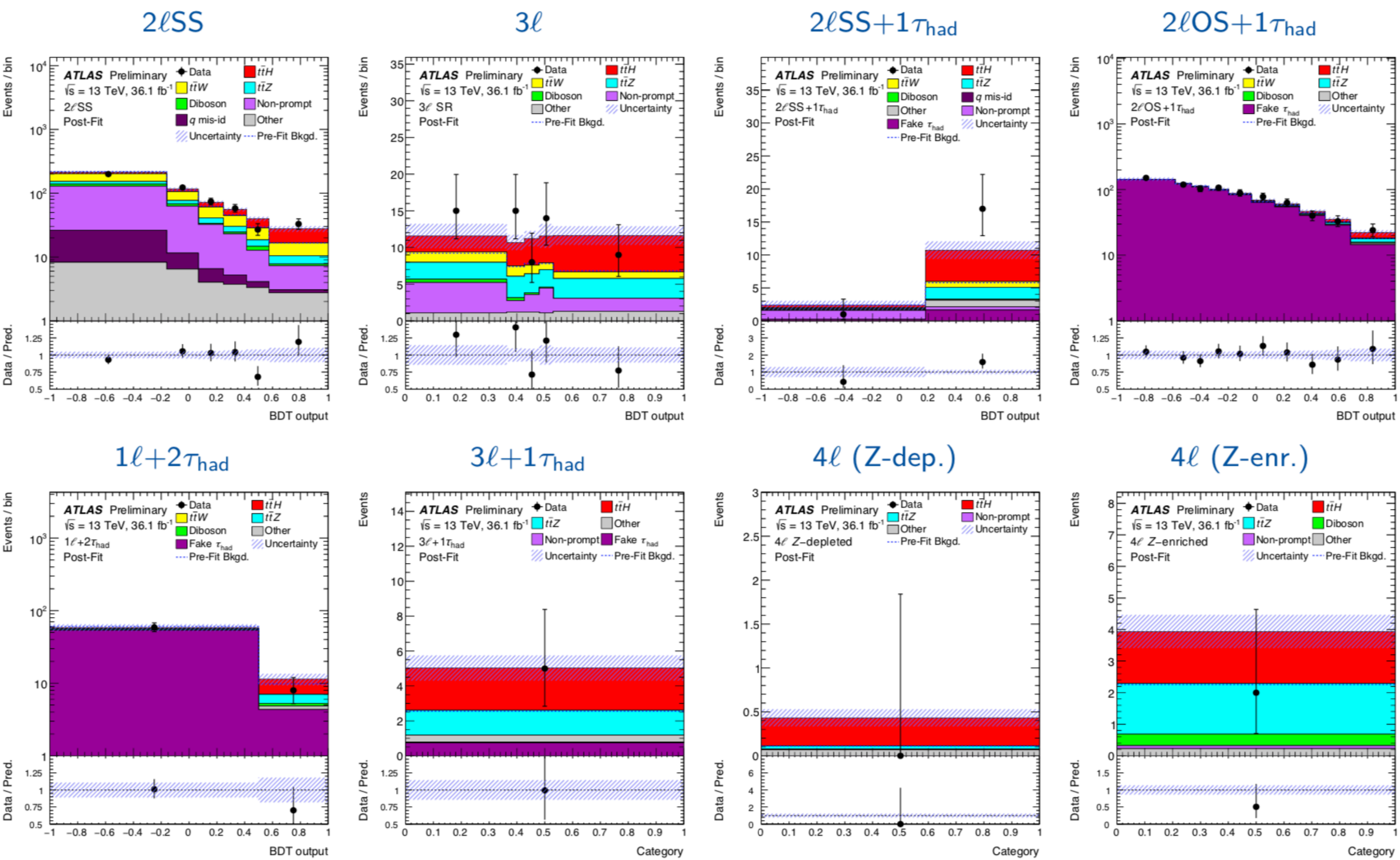
- ttW background in 2lSS: in the signal region needs additional radiation to compensate for the missing W
- ttZ background in 3l and 2lSS-1tau: fairly well represented

ttH (Multi-Lepton)

Overview of normalisations

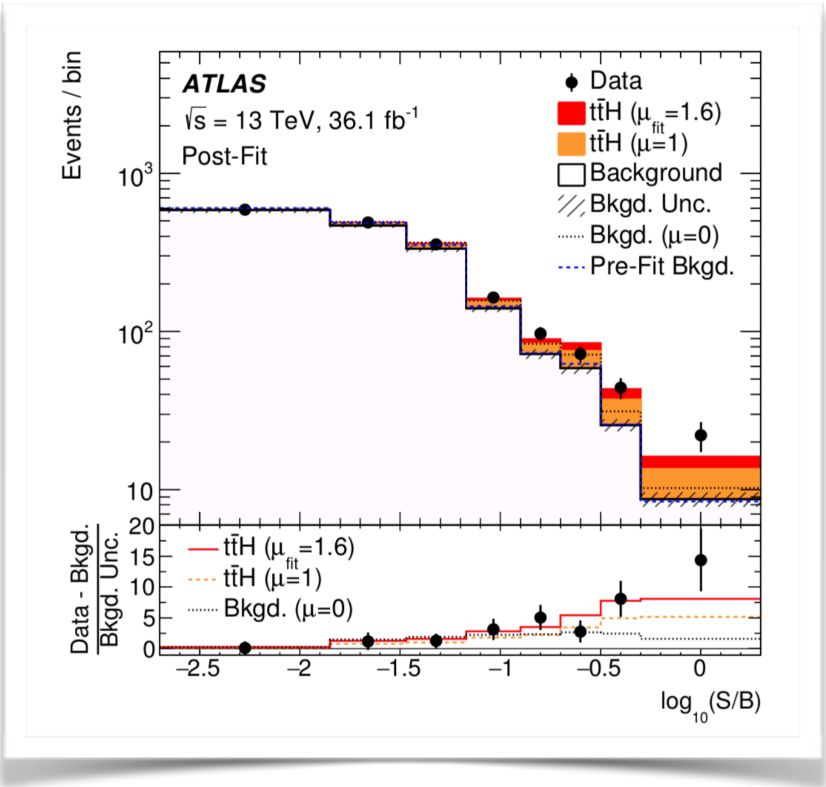


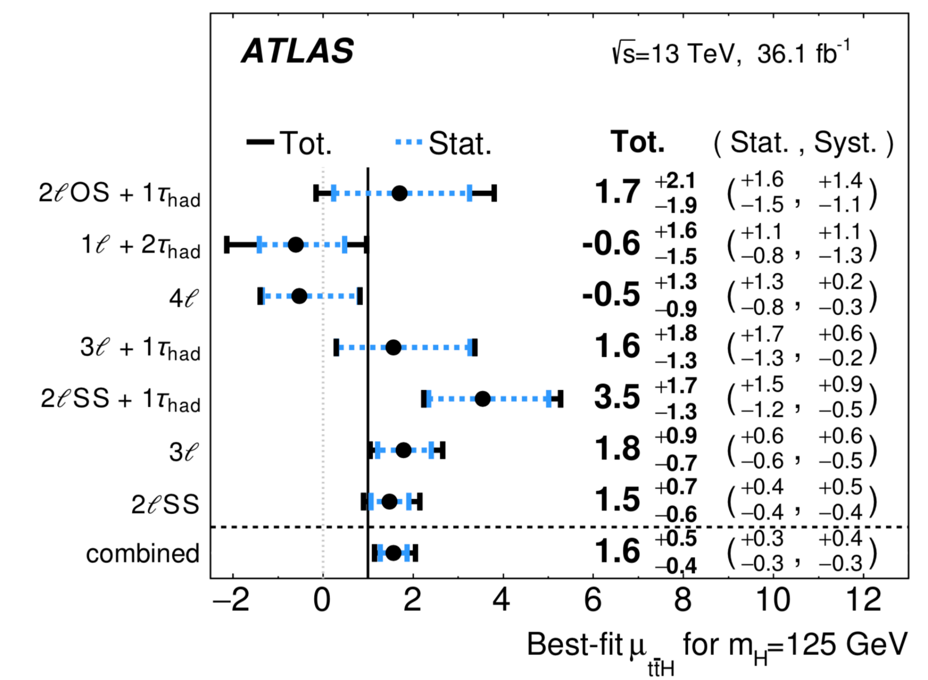
ttH (Multi-Lepton)



From X. Poveda (CERN Seminar)

ttH (Multi-Lepton)



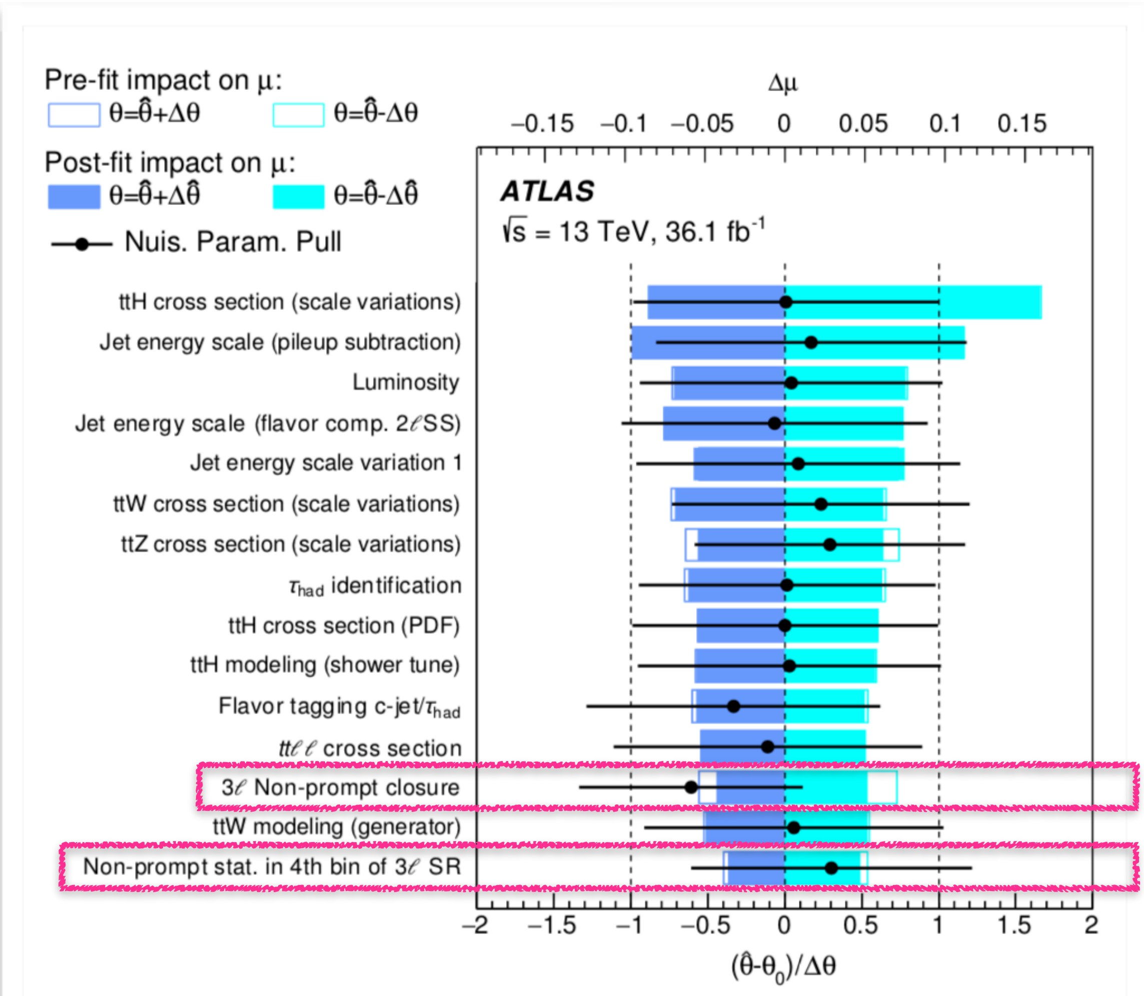


$$\mu = 1.6^{+0.4}_{-0.3}\,(stat)^{+0.3}_{-0.3}\,(syst)$$

40% sub-dominant systematic uncertainties

Result checked allowing ttW and ttZ to vary freely uncertainty moves from 0.5 to 0.6 (same central value)

ttH (Multi-Lepton)



- Impact is an absolute variation: having a somewhat larger mu value implies a larger impact from signal uncertainties.
- Large impact of luminosity due to normalisation of both signal and some of the main backgrounds from MC (although luminosity uncertainty is 2.1%).
- Uncertainties related to fakes: not a single dominant but many fairly small.
- There is no large constraints or pulls.

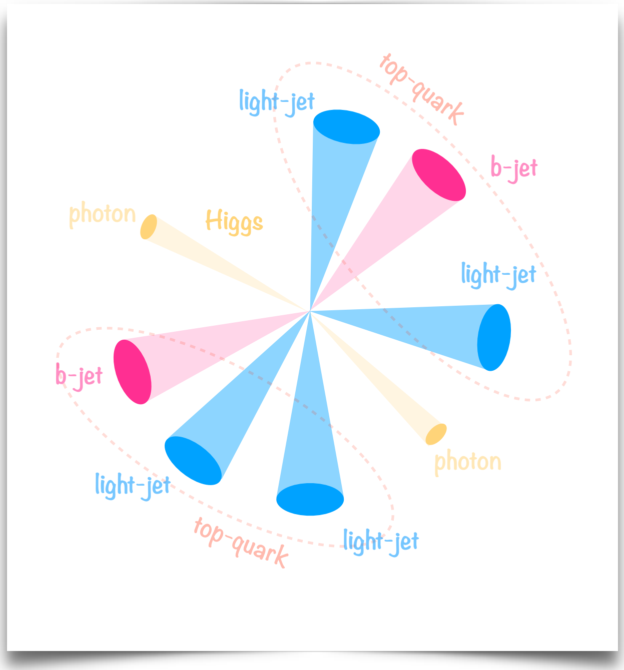
ttH (Multi-Lepton)

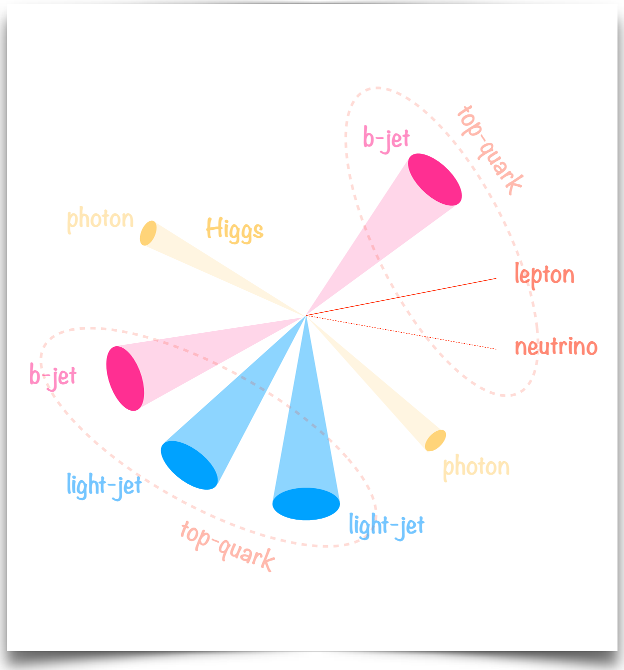
Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	+0.20	−0.09
Jet energy scale and resolution	+0.18	−0.15
Non-prompt light-lepton estimates	+0.15	−0.13
Jet flavor tagging and τ_{had} identification	+0.11	−0.09
$t\bar{t}W$ modeling	+0.10	−0.09
$t\bar{t}Z$ modeling	+0.08	−0.07
Other 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

Somewhat reassuring (but MC stats affect fake backgrounds through closure uncertainties)

- Importance of experimental systematics.
- Non-prompt uncertainties.

ttH (diphoton)

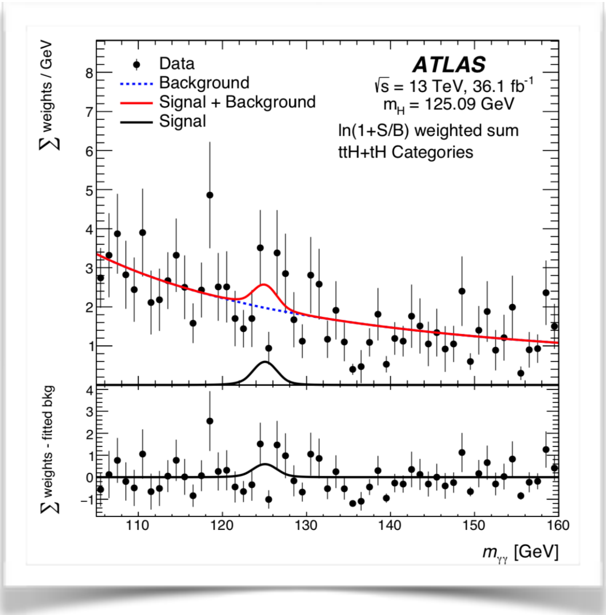


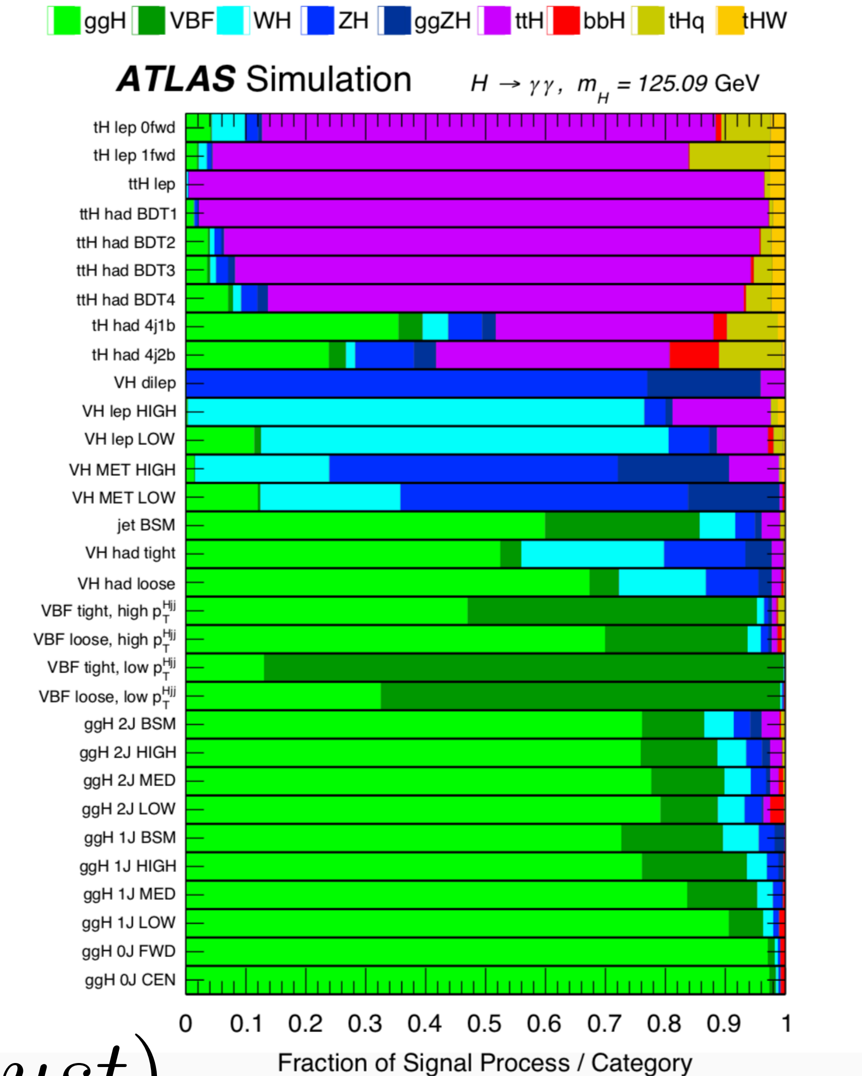


ttH (diphoton)

9 Categories optimised for ttH, tH and tHW, with 0L and 1L channels only

- Leptonic channel (using forward jets for tH)
- Hadronic channel (using BDT to identify ttH against ggH and multijet backgrounds - based on jet variables only)

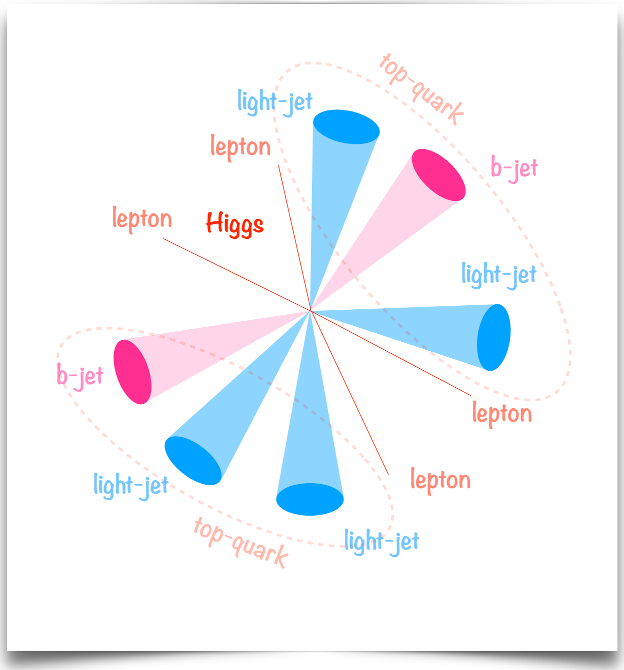


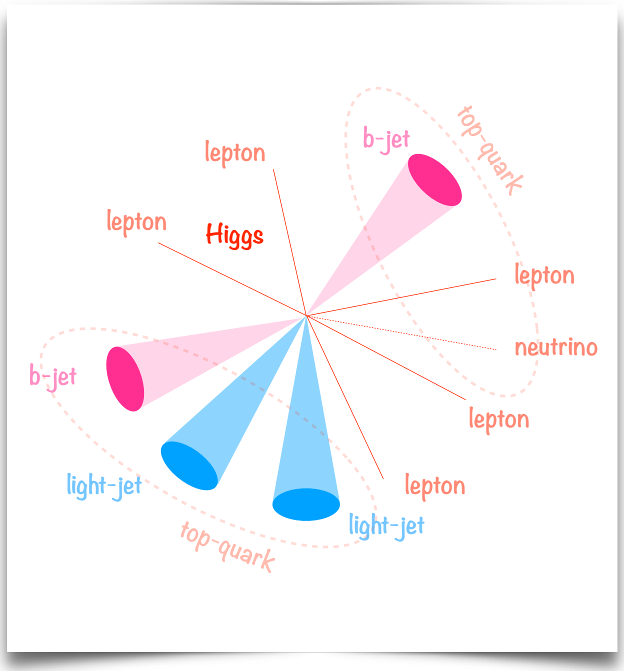


$$\mu = 0.6^{+0.7}_{-0.6}\,(stat)^{+0.2}_{-0.2}\,(syst)$$

92% dominated by systematic uncertainties

ttH (4 leptons)



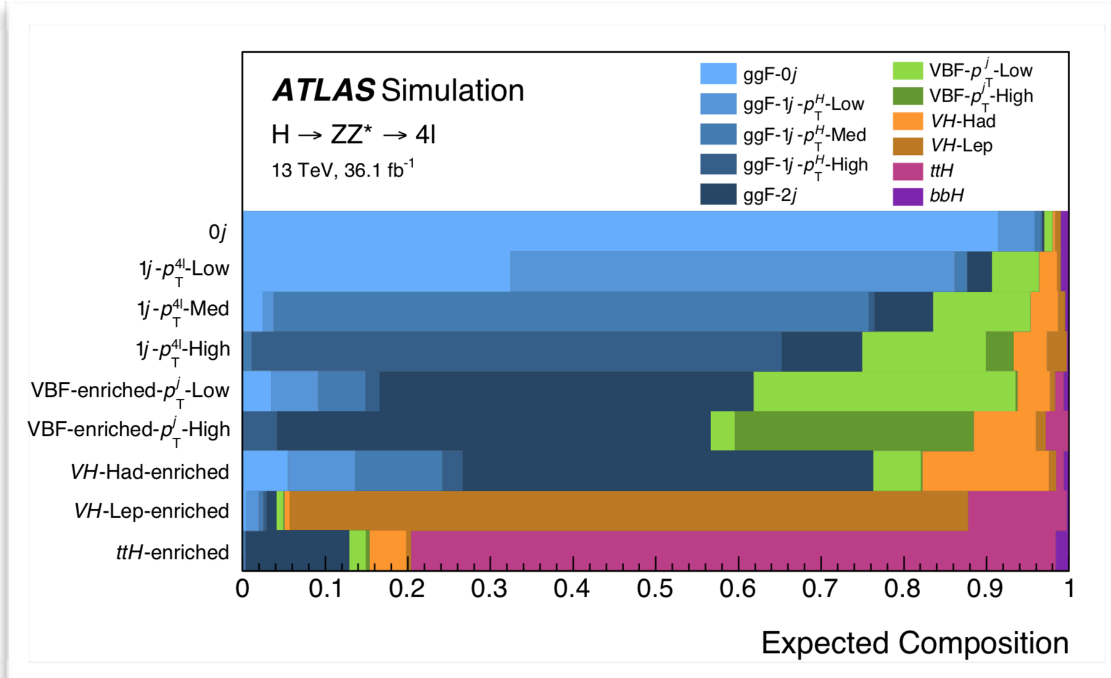


ttH (4 leptons)

Only one ttH category based on OR of 0L and 1L with a simple selection:

- ≥1 b-tagged jet
- ≥4 jets or 1l+≥2 jets

No events were observed!



Reconstructed event category	Signal	ZZ^* background	Other backgrounds	Total expected	Observed
$0j$ (s/b=0.6)	26.8 ± 2.5	13.7 ± 1.0	2.23 ± 0.31	42.7 ± 2.7	49
ttH-enriched (s/b~6)	0.39 ± 0.04	0.014 ± 0.006	0.07 ± 0.04	0.47 ± 0.05	0

$$\mu < 1.9\,(95\%\,CL)$$

… no need to comment on the statistical component

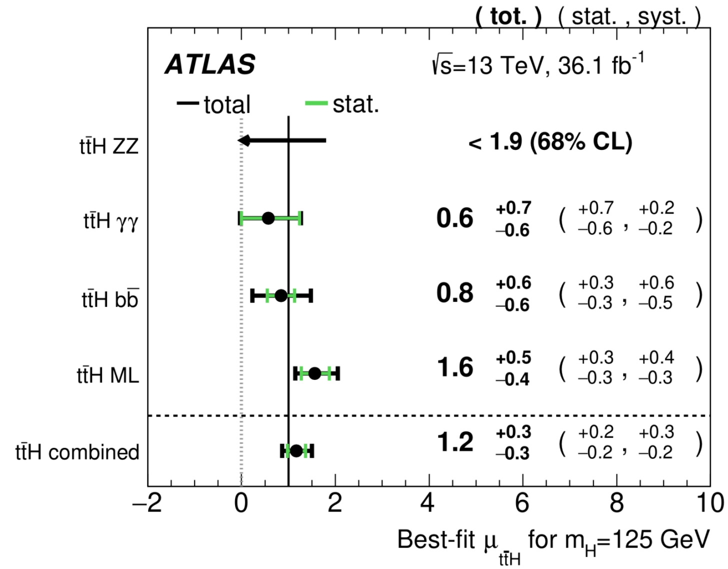
Combination

ttH Combining all channels with ttH enriched diphoton and 4-leptons categories (only)

Assuming tH and all other Higgs production mechanisms as backgrounds

Channel	Significance	
	Observed	Expected
Multilepton	4.1σ	2.8σ
$H \to b\bar{b}$	1.4σ	1.6σ
$H \to \gamma\gamma$	0.9σ	1.7σ
$H \to 4\ell$	—	0.6σ
Combined	4.2σ	3.8σ

4.2σ (3.8σ exp)



ATLAS only combination of all channels:

$$\mu = 1.2 \pm 0.2\,(stat)^{+0.3}_{-0.2}\,(syst)$$

70% dominated by systematic uncertainties

Uncertainty Source	$\Delta\mu$	
$t\bar{t}$ modeling in $H \to b\bar{b}$ analysis	+0.15	−0.14
$t\bar{t}H$ modeling (cross section)	+0.13	−0.06
Non-prompt light-lepton and fake $\tau_{\rm had}$ estimates	+0.09	−0.09
Simulation statistics	+0.08	−0.08
Jet energy scale and resolution	+0.08	−0.07

Still dominant impact from the tt(bb) modelling!

Overall Summary of ttH Results

Overview of channels Run 1 and Run 2 for both ATLAS and CMS

	$\gamma\gamma$	bb	ML	ZZ
ATLAS Run 1	1.2 ± 2.6	1.4 ± 0.6 (stat) ± 0.8 (syst)	2.1 ± 1.1 (stat) ± 0.9 (syst)	-
CMS Run 1	2.7 ± 2.6	0.7 ± 1.9	3.3 ± 1.4	-
ATLAS Run 2	0.6 ± 0.6	0.8 ± 0.3 (stat) ± 0.6 (syst)	1.6 ± 0.3 (stat) ± 0.4 (syst)	<1.9 (68% CL)
CMS Run 2	$2.2^{+0.9}_{-0.8}$	0.72 ± 0.45	1.23 ± 0.43	0.0 ± 1.2

ttH back of the envelope combination is tempting, but should at this point already refrain, given that individual experiments combined results are already dominated by systematics.

However **ttH** combination is highly non trivial especially since the dominant systematic is modelling and it is somewhat correlated across experiments.

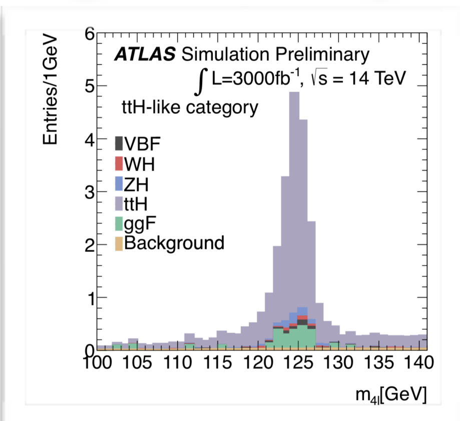
ATLAS and CMS differences w.r.t. modelling:

- Similar baseline models for top production (Powheg-P8)
- Different systematic alternatives (use of Sherpa-OpenLoops in ATLAS)
- Different model of systematics (different NP implementation - e.g. free normalisations for some critical processes)

HL-LHC Projections

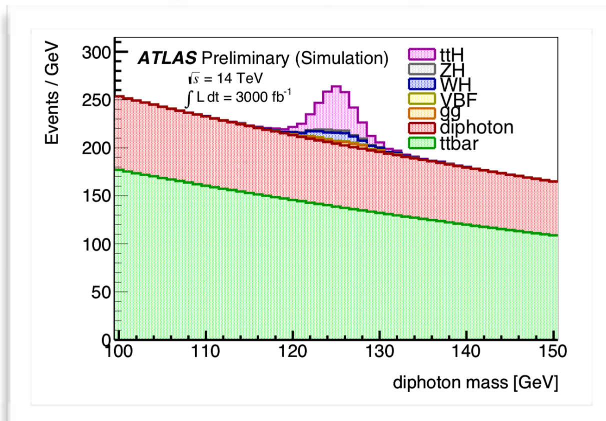
Projections are still incomplete (in terms of channels)

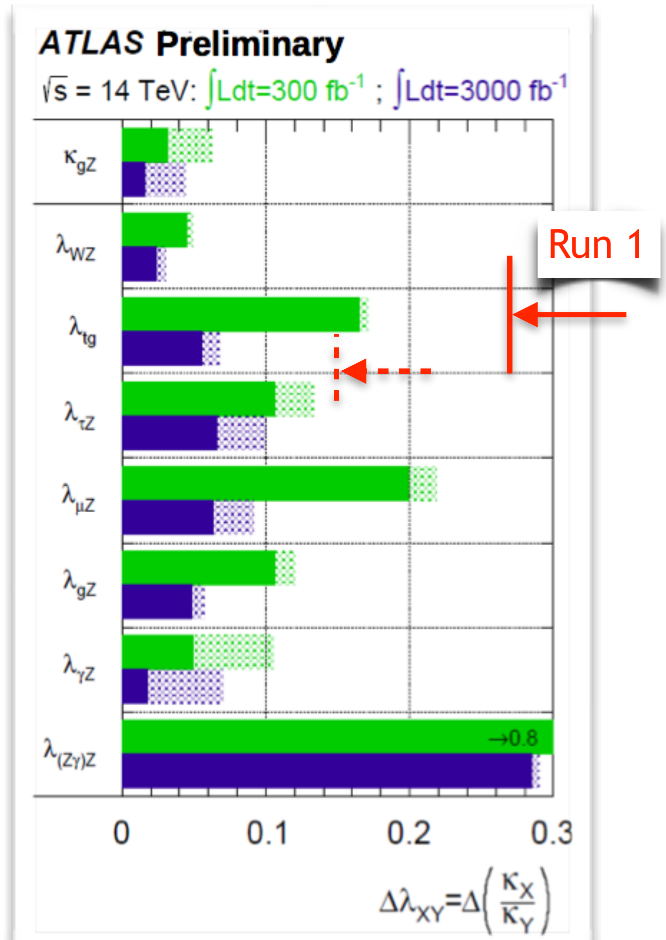
0L - 2L (s/b~20)

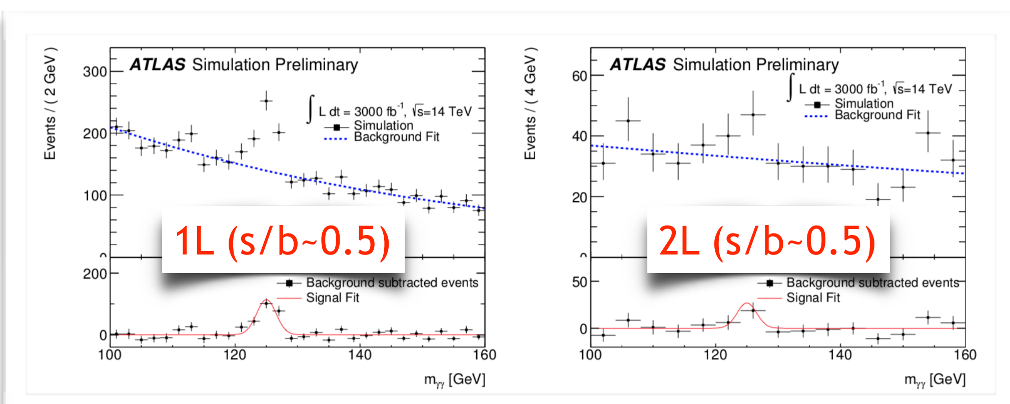


s~30 and b~1.6

1L (s/b~0.2)







Conclusions

With approximately 1/3 of the Run 2 data and 1% of the full LHC statistics:

First evidence for ttH production (by both ATLAS and CMS - independently)

Combination dominated by systematic uncertainties (of the ugly kind - two point tt-HF modelling)

For the near future:

- Both experiments are aiming at a stronger result with the additional data (potentially sufficient for an observation).

- What would be an observation in the presence of complex modelling systematic uncertainties? How should the ttH(bb) channel be approached?

- Unambiguous channels such as diphoton should soon become dominant.

- The MC statistics are a very significant component of the systematic uncertainties: not trivial at all to avoid (more CPU expensive, fast simulation - how fast? filtering or slicing algorithms, not trivial either) not obvious also for NLO generators (generation times can be extremely long and impact of negative weights).

Outlook

Pursuit of precision at LHC an overarching and pressing theme - at this point in the LHC program with much longer doubling time of luminosity!

How to best take advantage of the statistics?

- Find robust regions of phase space (for the difficult channels) - e.g. boosted channel in ttH(bb).

- Find the right ratios to avoid specific systematic uncertainties - e.g. ratio to ttV.

- Work together with TH community to improve modelling (with ancillary measurements) - extremely important top production measurements and e.g. gluon splitting to b quarks measurements.

Bibliography

- Full Run 1 ATLAS and CMS couplings combination
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2015-07/
- ttH All hadronic channel at Run 1
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2015-05/
- Diphoton couplings (including ttH) at Run 2
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-21/
- 4-leptons couplings (including ttH) at Run 2
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-22/
- ttH(bb) at Run 2
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2017-03/
- ttH Multilepton and combination at Run 2
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2017-02/

Backup

ttH (Multi-Lepton)

Category	Non-prompt	Fake τ_{had}	q mis-id	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Other	Total Bkgd.	$t\bar{t}H$	Observed
					Pre-fit yields					
2ℓSS	233 ± 39	–	33 ± 11	123 ± 18	41.4 ± 5.6	25 ± 15	28.4 ± 5.9	484 ± 38	42.6 ± 4.2	514
3ℓ SR	14.5 ± 4.3	–	–	5.5 ± 1.2	12.0 ± 1.8	1.2 ± 1.2	5.8 ± 1.4	39.1 ± 5.2	11.2 ± 1.6	61
3ℓ $t\bar{t}W$ CR	13.3 ± 4.3	–	–	19.9 ± 3.1	8.7 ± 1.1	$<$ 0.2	4.53 ± 0.92	46.5 ± 5.4	4.18 ± 0.46	56
3ℓ $t\bar{t}Z$ CR	3.9 ± 2.5	–	–	2.71 ± 0.56	66 ± 11	8.4 ± 5.3	12.9 ± 4.2	93 ± 13	3.17 ± 0.41	107
3ℓ VV CR	27.7 ± 8.7	–	–	4.9 ± 1.0	21.3 ± 3.4	51 ± 30	17.9 ± 6.1	123 ± 32	1.67 ± 0.25	109
3ℓ $t\bar{t}$ CR	70 ± 17	–	–	10.5 ± 1.5	7.9 ± 1.1	7.2 ± 4.8	7.3 ± 1.9	103 ± 17	4.00 ± 0.49	85
4ℓ Z-enr.	0.11 ± 0.07	–	–	$<$ 0.01	1.52 ± 0.23	0.43 ± 0.23	0.21 ± 0.09	2.26 ± 0.34	1.06 ± 0.14	2
4ℓ Z-dep.	0.01 ± 0.01	–	–	$<$ 0.01	0.04 ± 0.02	$<$ 0.01	0.06 ± 0.03	0.11 ± 0.03	0.20 ± 0.03	0
1ℓ+$2\tau_{\text{had}}$	–	65 ± 21	–	0.09 ± 0.09	3.3 ± 1.0	1.3 ± 1.0	0.98 ± 0.35	71 ± 21	4.3 ± 1.0	67
2ℓSS+$1\tau_{\text{had}}$	2.4 ± 1.4	1.80 ± 0.30	0.05 ± 0.02	0.88 ± 0.24	1.83 ± 0.37	0.12 ± 0.18	1.06 ± 0.24	8.2 ± 1.6	3.09 ± 0.46	18
2ℓOS+$1\tau_{\text{had}}$	–	756 ± 80	–	6.5 ± 1.3	11.4 ± 1.9	2.0 ± 1.3	5.8 ± 1.5	782 ± 81	14.2 ± 2.0	807
3ℓ+$1\tau_{\text{had}}$	–	0.75 ± 0.15	–	0.04 ± 0.04	1.38 ± 0.24	0.002 ± 0.002	0.38 ± 0.10	2.55 ± 0.32	1.51 ± 0.23	5
					Post-fit yields					
2ℓSS	211 ± 26	–	28.3 ± 9.4	127 ± 18	42.9 ± 5.4	20.0 ± 6.3	28.5 ± 5.7	459 ± 24	67 ± 18	514
3ℓ SR	13.2 ± 3.1	–	–	5.8 ± 1.2	12.9 ± 1.6	1.2 ± 1.1	5.9 ± 1.3	39.0 ± 4.0	17.7 ± 4.9	61
3ℓ $t\bar{t}W$ CR	11.7 ± 3.0	–	–	20.4 ± 3.0	8.9 ± 1.0	$<$ 0.2	4.54 ± 0.88	45.6 ± 4.0	6.6 ± 1.9	56
3ℓ $t\bar{t}Z$ CR	3.5 ± 2.1	–	–	2.82 ± 0.56	70.4 ± 8.6	7.1 ± 3.0	13.6 ± 4.2	97.4 ± 8.6	5.1 ± 1.4	107
3ℓ VV CR	22.4 ± 5.7	–	–	5.05 ± 0.94	22.0 ± 3.0	39 ± 11	18.1 ± 5.9	106.8 ± 9.4	2.61 ± 0.82	109
3ℓ $t\bar{t}$ CR	56.0 ± 8.1	–	–	10.7 ± 1.4	8.1 ± 1.0	5.9 ± 2.7	7.1 ± 1.8	87.8 ± 7.9	6.3 ± 1.8	85
4ℓ Z-enr.	0.10 ± 0.07	–	–	$<$ 0.01	1.60 ± 0.22	0.37 ± 0.15	0.22 ± 0.10	2.29 ± 0.28	1.65 ± 0.47	2
4ℓ Z-dep.	0.01 ± 0.01	–	–	$<$ 0.01	0.04 ± 0.02	$<$ 0.01	0.07 ± 0.03	0.11 ± 0.03	0.32 ± 0.09	0
1ℓ+$2\tau_{\text{had}}$	–	58.0 ± 6.8	–	0.11 ± 0.11	3.31 ± 0.90	0.98 ± 0.75	0.98 ± 0.33	63.4 ± 6.7	6.5 ± 2.0	67
2ℓSS+$1\tau_{\text{had}}$	1.86 ± 0.91	1.86 ± 0.27	0.05 ± 0.02	0.97 ± 0.26	1.96 ± 0.37	0.15 ± 0.20	1.09 ± 0.24	7.9 ± 1.2	5.1 ± 1.3	18
2ℓOS+$1\tau_{\text{had}}$	–	756 ± 28	–	6.6 ± 1.3	11.5 ± 1.7	1.64 ± 0.92	6.1 ± 1.5	782 ± 27	21.7 ± 5.9	807
3ℓ+$1\tau_{\text{had}}$	–	0.75 ± 0.14	–	0.04 ± 0.04	1.42 ± 0.22	0.002 ± 0.002	0.40 ± 0.10	2.61 ± 0.30	2.41 ± 0.68	5