Evidence for $t\bar{t}H$ production with the ATLAS detector

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on behalf of the ATLAS collaboration

Séminaire à LPNHE-Paris
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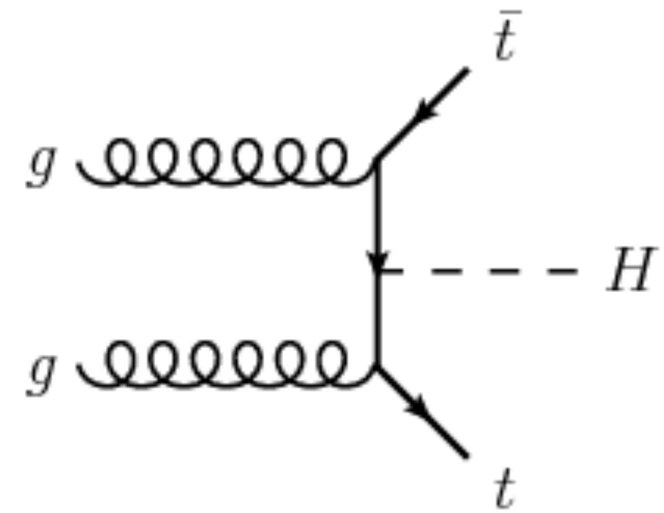
Outline

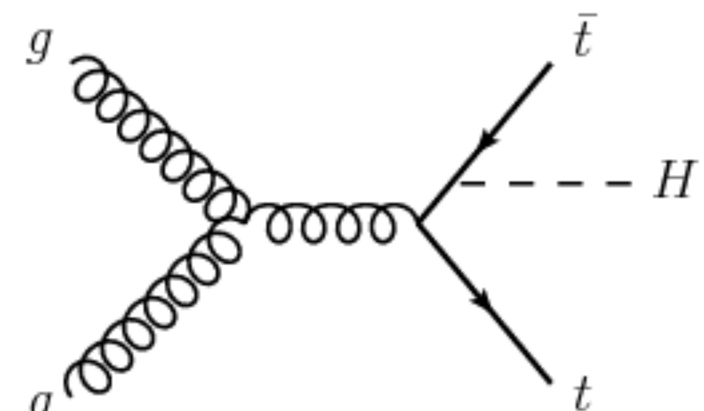
- ttH analysis motivation and complexity
- Search for ttH in four channels
  - with multilepton final states (H → WW*, $\tau\tau$ and partially ZZ*)
  - H → bb
  - H → ZZ* → 4l
  - H → $\gamma\gamma$
- ttH searches combination in ATLAS Run 2
- Summary

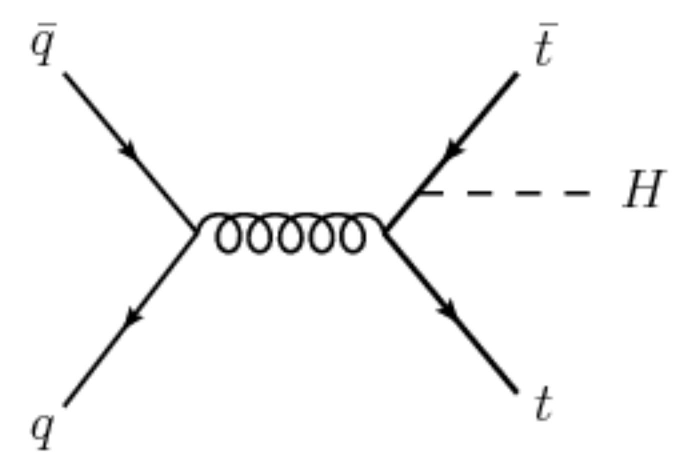
ttH analysis motivation

- ttH allows direct measurement of Higgs-top Yukawa coupling at tree level. Any deviation might be hint for New Physics !
- Indirect constraints on Higgs-top Yukawa coupling possible through ggH and H→$\gamma\gamma$ loop processes.
- ttH as the fifth main Higgs production channel has no 5σ observation yet → ~ 1% of Higgs production in LHC.
- Summary of recent ATLAS and CMS ttH public results:

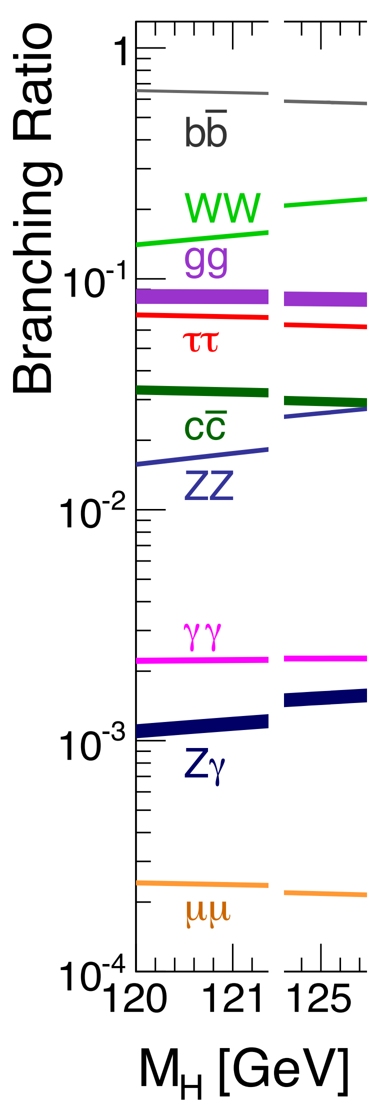
	Signal strength $\mu_{t\bar{t}H}$	Obs. (exp.) significance
Run1 ATLAS+CMS (~25 fb^{-1})	**2.3** +0.7/-0.6	4.4σ (2.2σ)
Run2 ATLAS preliminary (13.2 fb^{-1})	**1.8** ± 0.7	2.8σ (1.8σ)
Run2 CMS preliminary (35.9 fb^{-1})	**1.5** ± 0.5	3.3σ (2.5σ)







ATLAS ttH publications

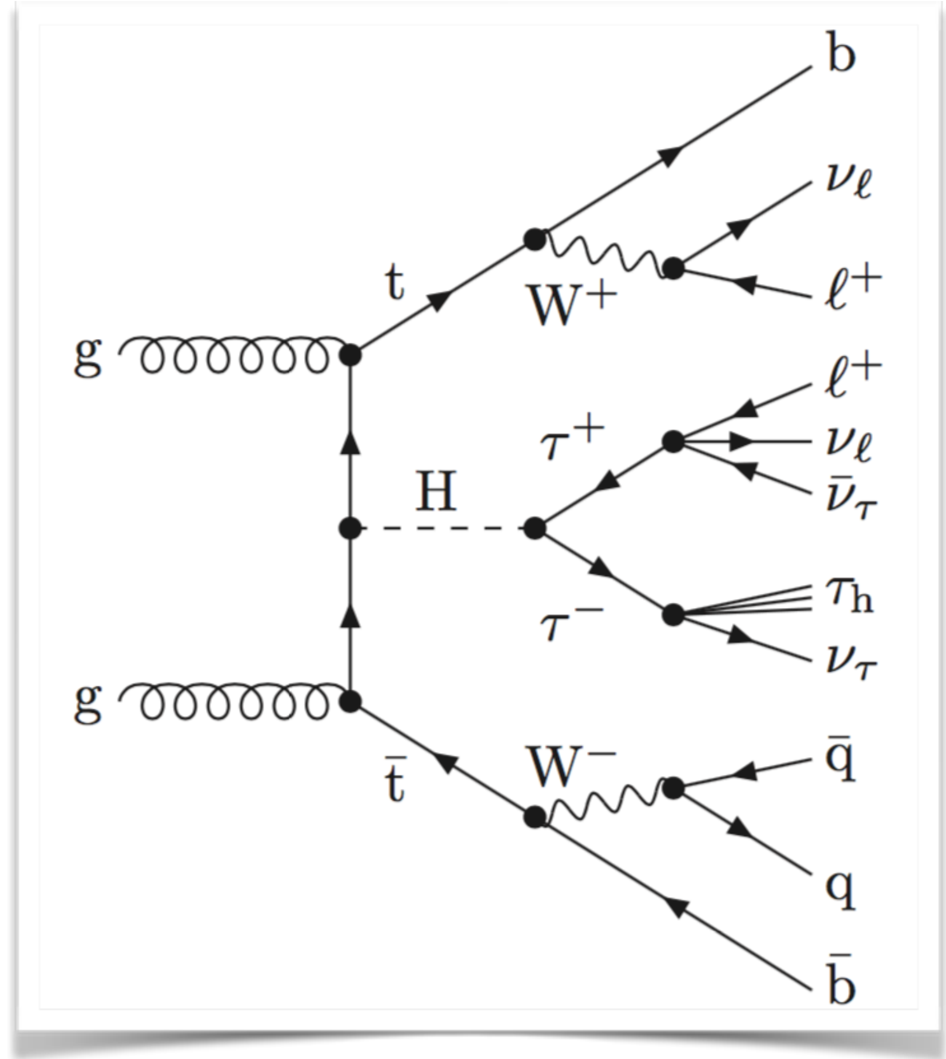


Higgs decay mode	Run 1 (20.3 fb^{-1} / 25 fb^{-1}) (8TeV / 7&8 TeV)	Run 2 (36.1 fb^{-1}) (13 TeV)
H→bb *(leptonic/semileptonic tt)*	Eur. Phys. J. C (2015) 75:349	ATLAS-CONF-2017-076
H→bb *(full hadronic tt)*	JHEP 05 (2016) 160	
Multileptons *(H→WW*, ττ, ZZ*)*	Phys.Lett. B 749 (2015) 519	ATLAS-CONF-2017-077
H→ZZ*→4l	Phys. Rev. D 91, 012006 (2015)	ATLAS-CONF-2017-043
H→γγ	Phys. Lett. B 740 (2015) 222	ATLAS-CONF-2017-045
ttH combination	JHEP 05 (2016) 160	ATLAS-CONF-2017-077

✦ I am going to present those Run 2 analyses on very recent results.

This is an analysis with complex final states

- The analysis is based on ATLAS reconstructed objects of photon, electron, muon, jet, τ-jet (τ_{had}) and b-jet.
- There are massive SM-process productions in ttH favoured phase space.
- Good performance of the ATLAS detector makes this complicated analysis possible



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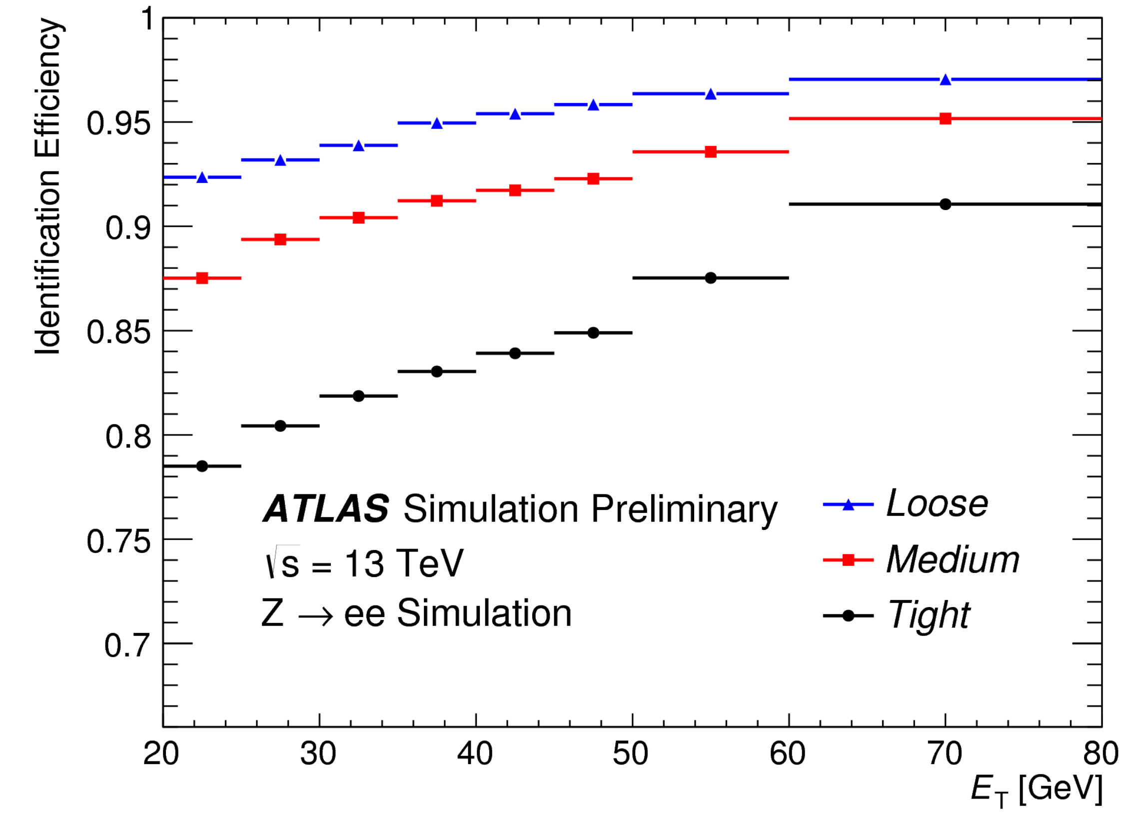

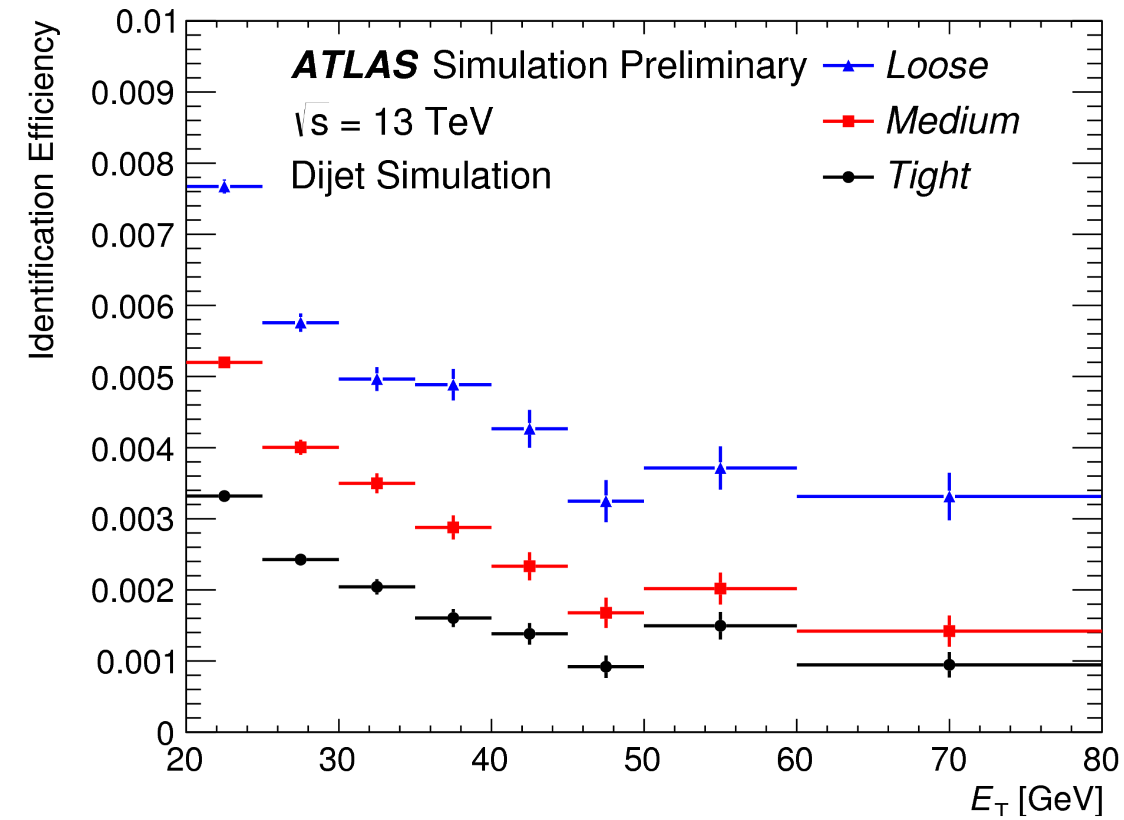

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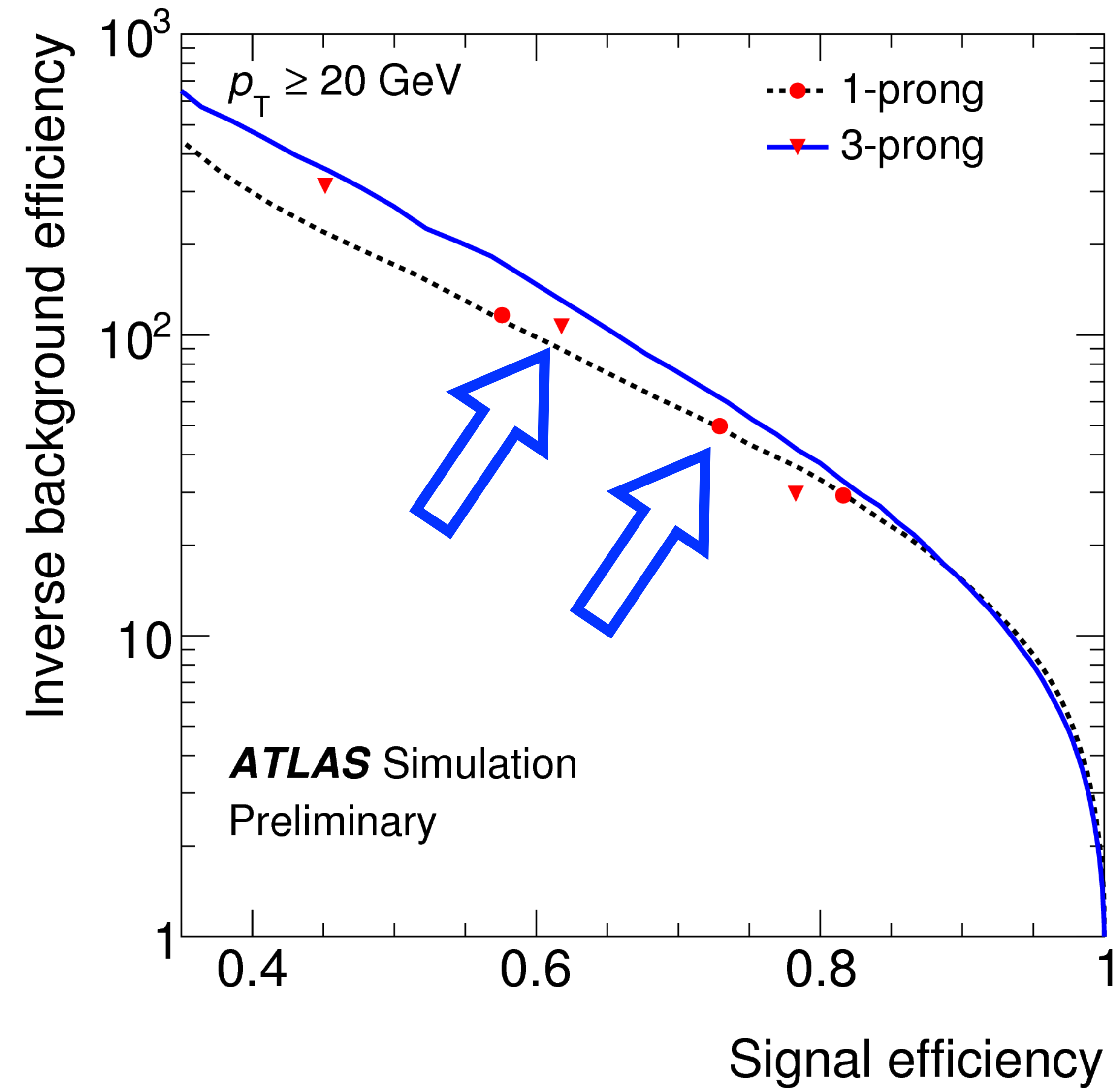

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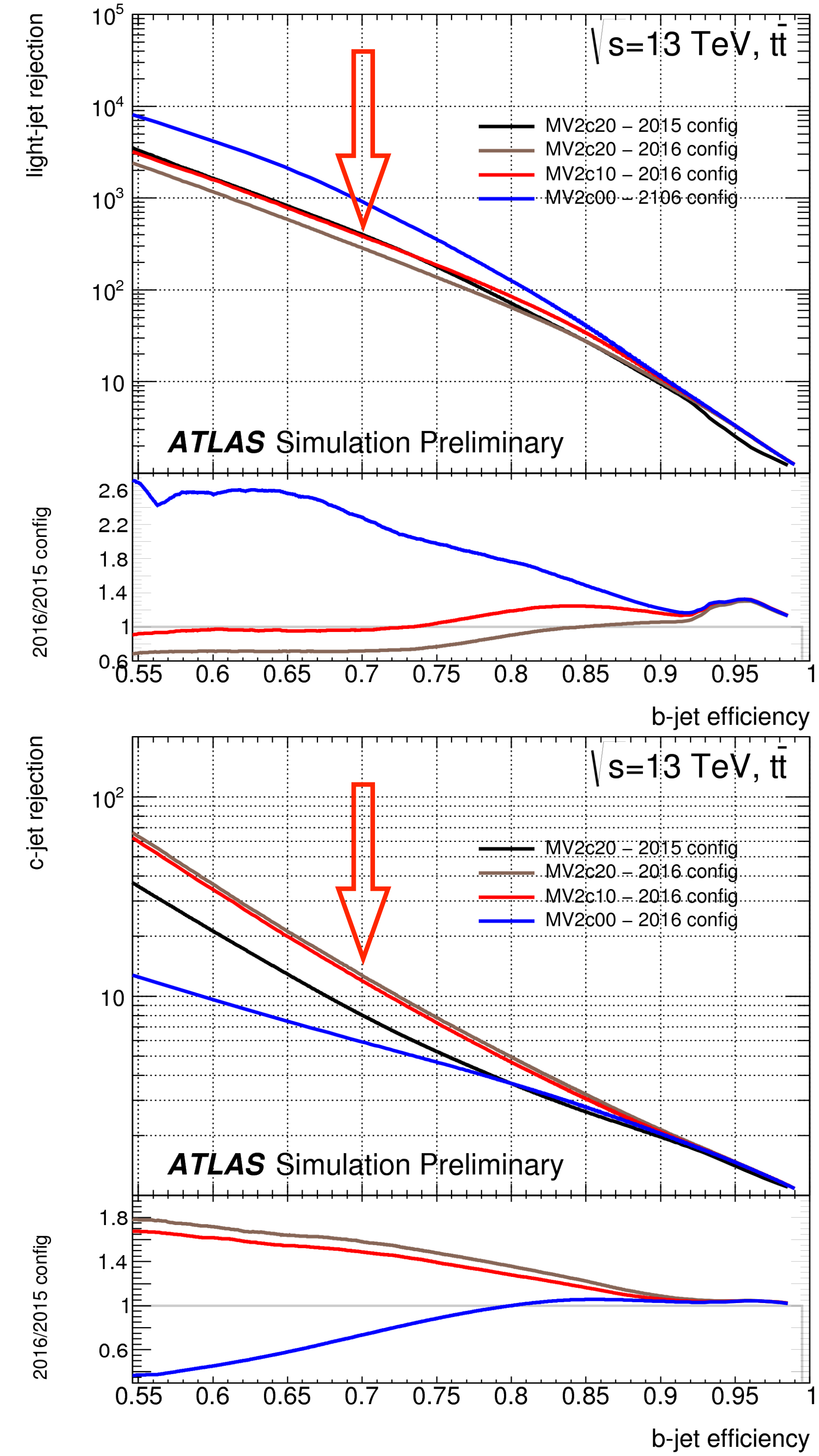

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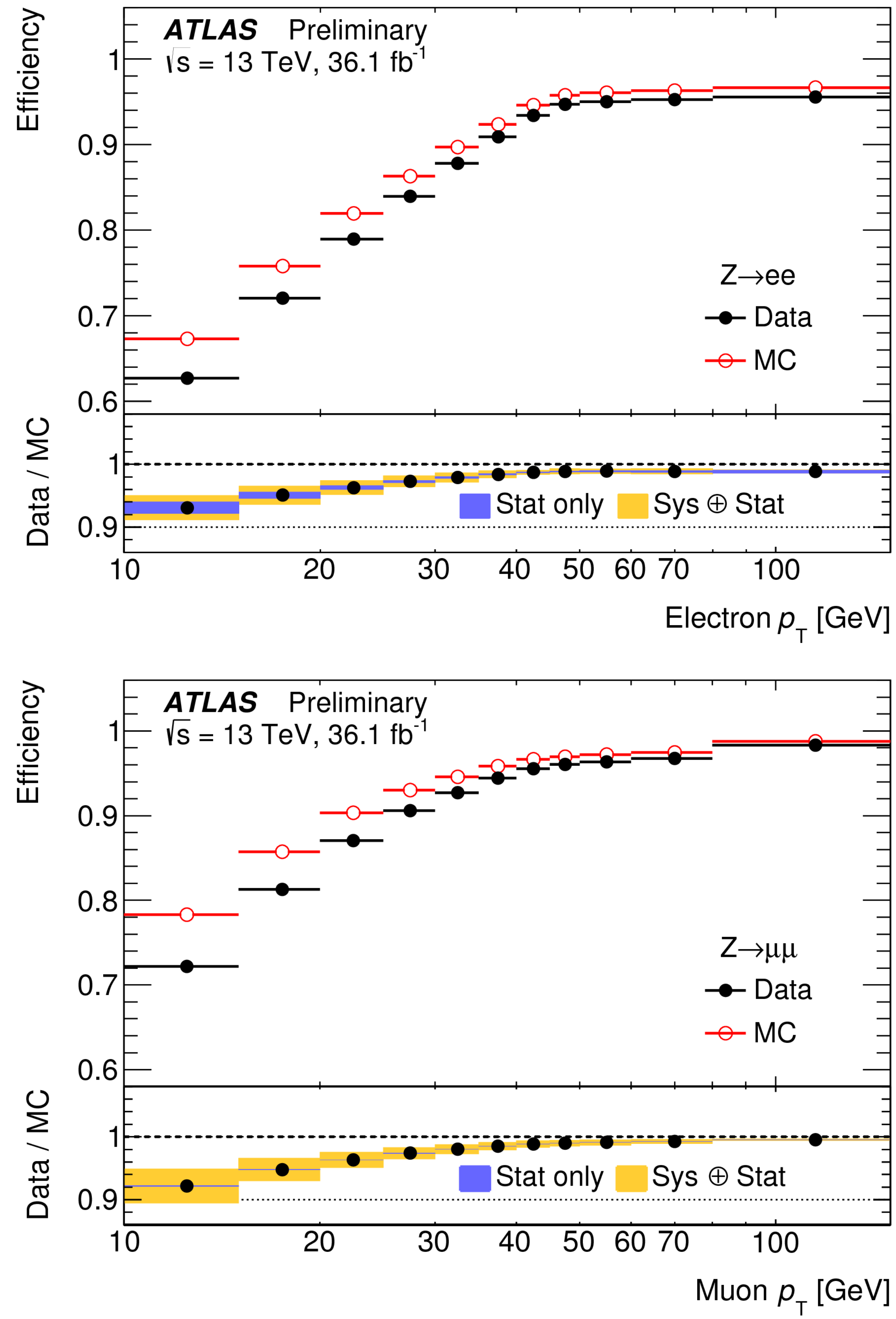
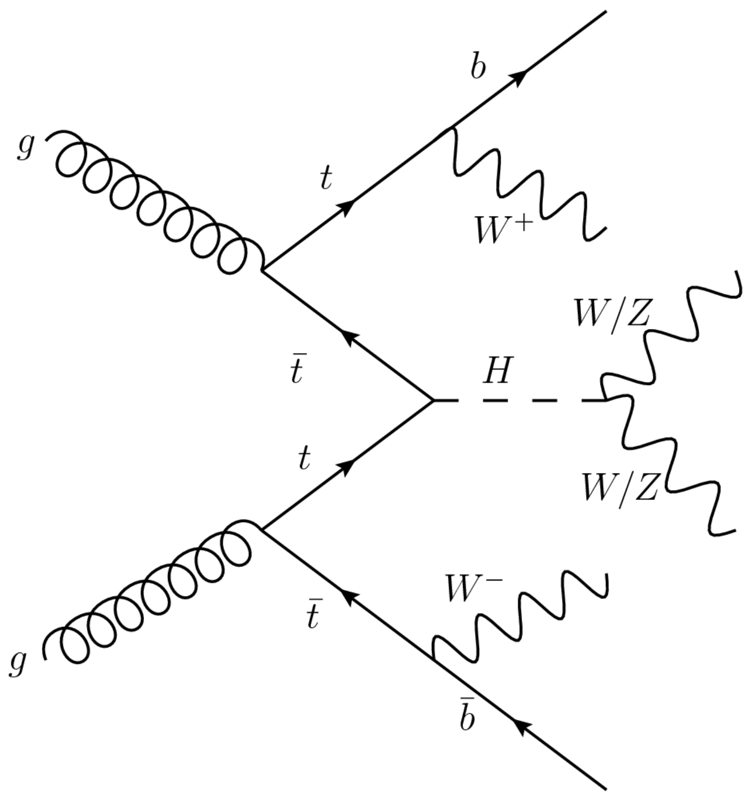
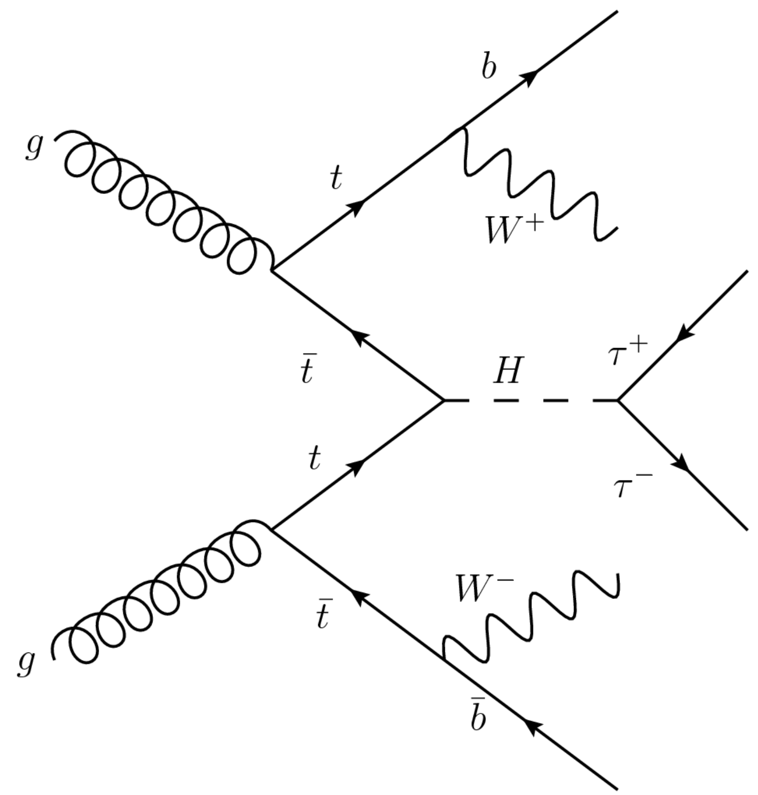
- Good performance of the ATLAS detector makes this complicated analysis possible
  - lepton identification vs light-jets rejection
  - τ_{had} identification vs QCD jets rejection
  - b-jet tagging vs c-jet and light-jet rejection
  - lepton from b-hadron decay (non-prompt lepton) is rejected at O(20) while keeping high efficiency for prompt lepton.



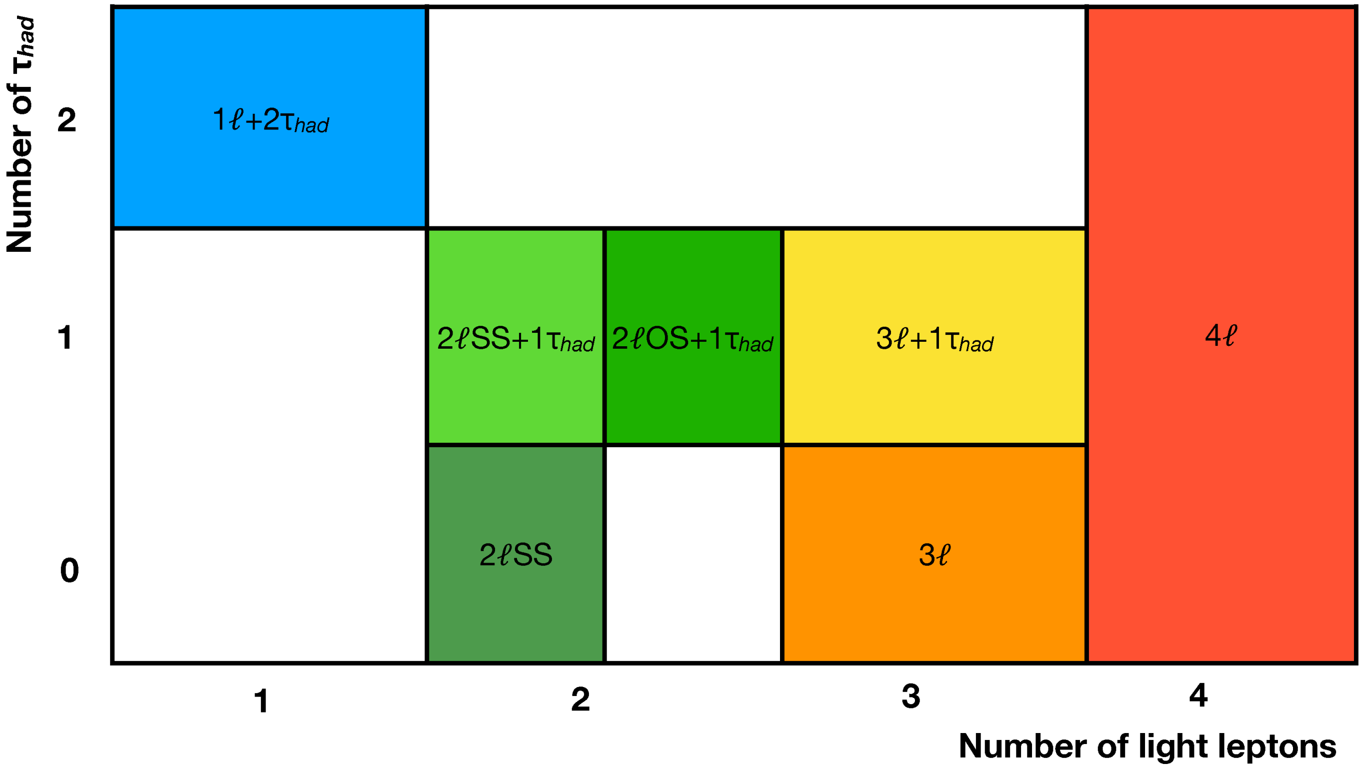
Search for ttH in multilepton final states

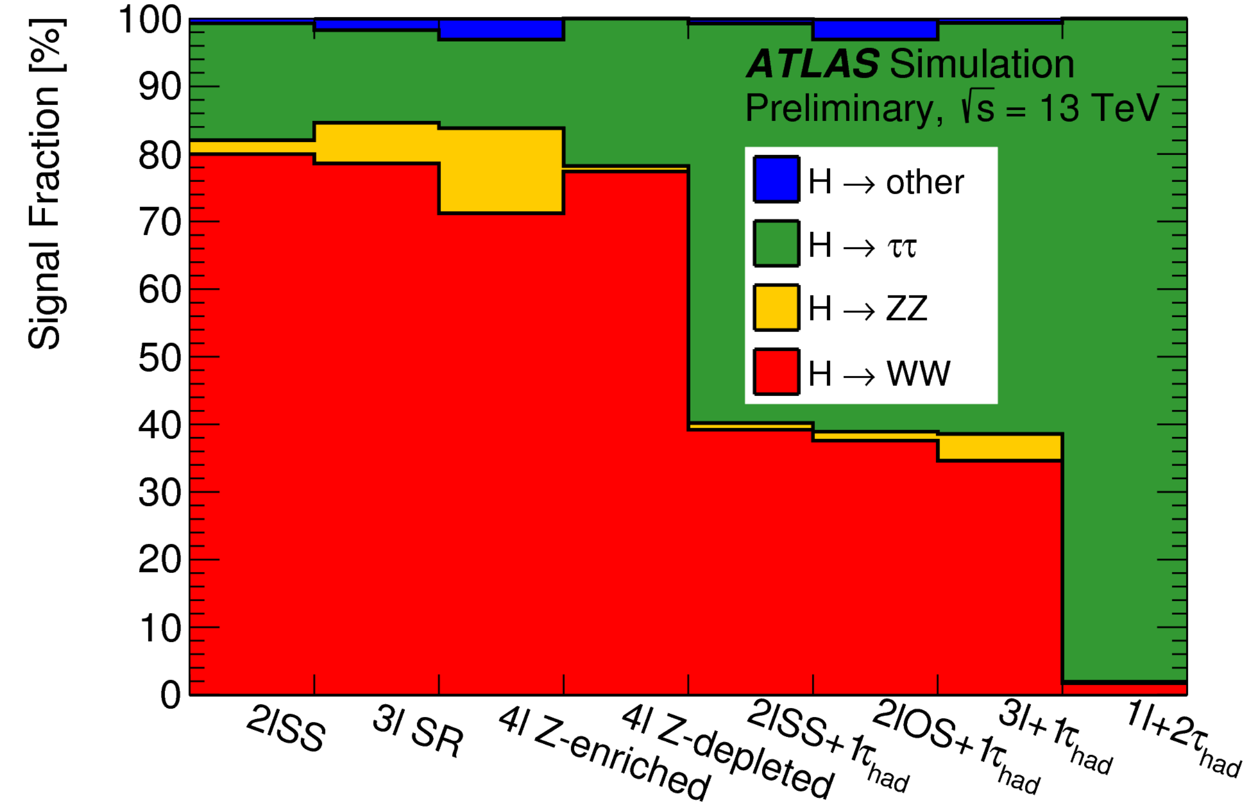
Higgs decays to WW*, **ττ** and partially ZZ* (veto on H→ZZ*→ 4l)





Event selection and classification





≥ 2 jets and ≥ 1 of them being b-tagged jet.

- 7 orthogonal analysis channels (8 signal regions), according to number and flavour of charged leptons, with and without τ_{had}.
- 91 expected ttH events after selection → 0.50% of all expected ttH events.
- ~ 300k background events dominated by
  - ttV (ttW, ttZ) : similar event topologies as ttH signal
  - tt : “extra” non-prompt lepton mainly from b-hadron decay
- 4 control regions in 3l are defined for ttW, ttZ, di-boson and tt processes.

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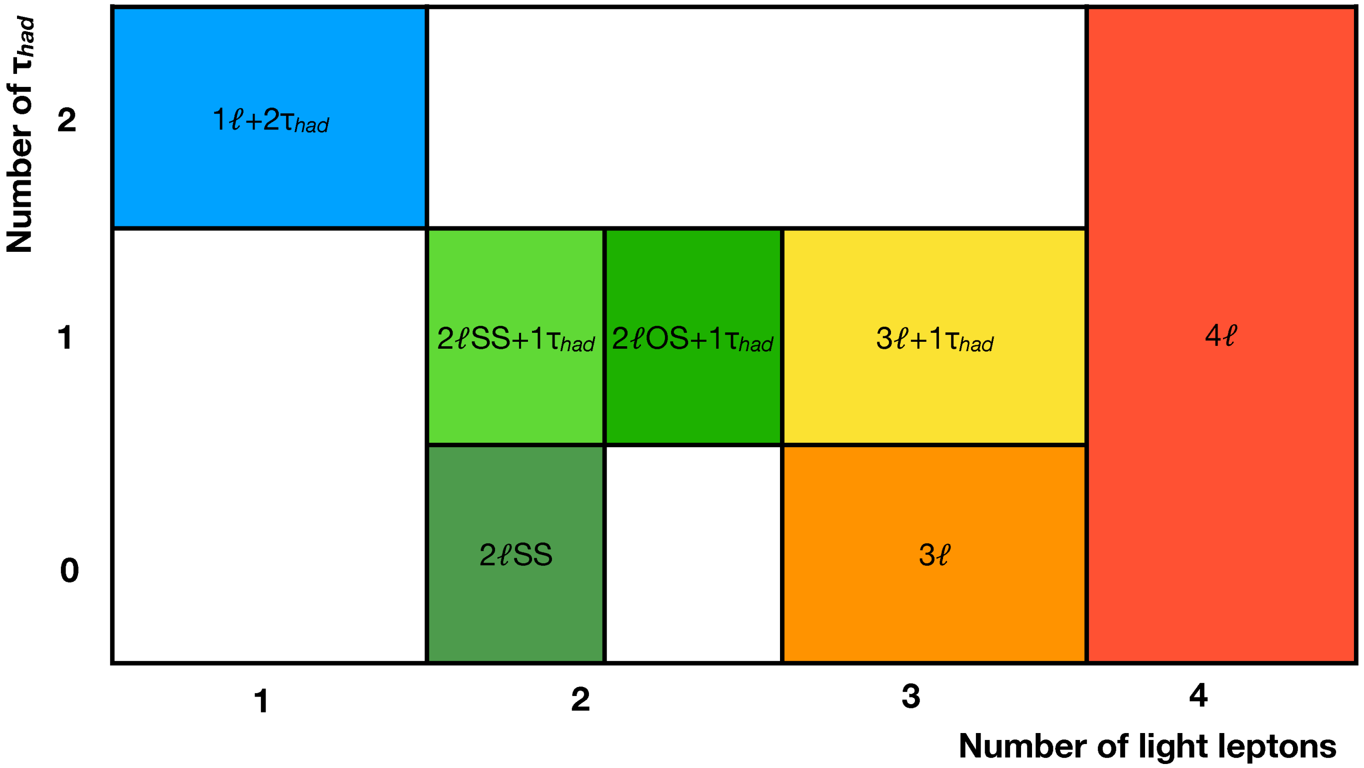

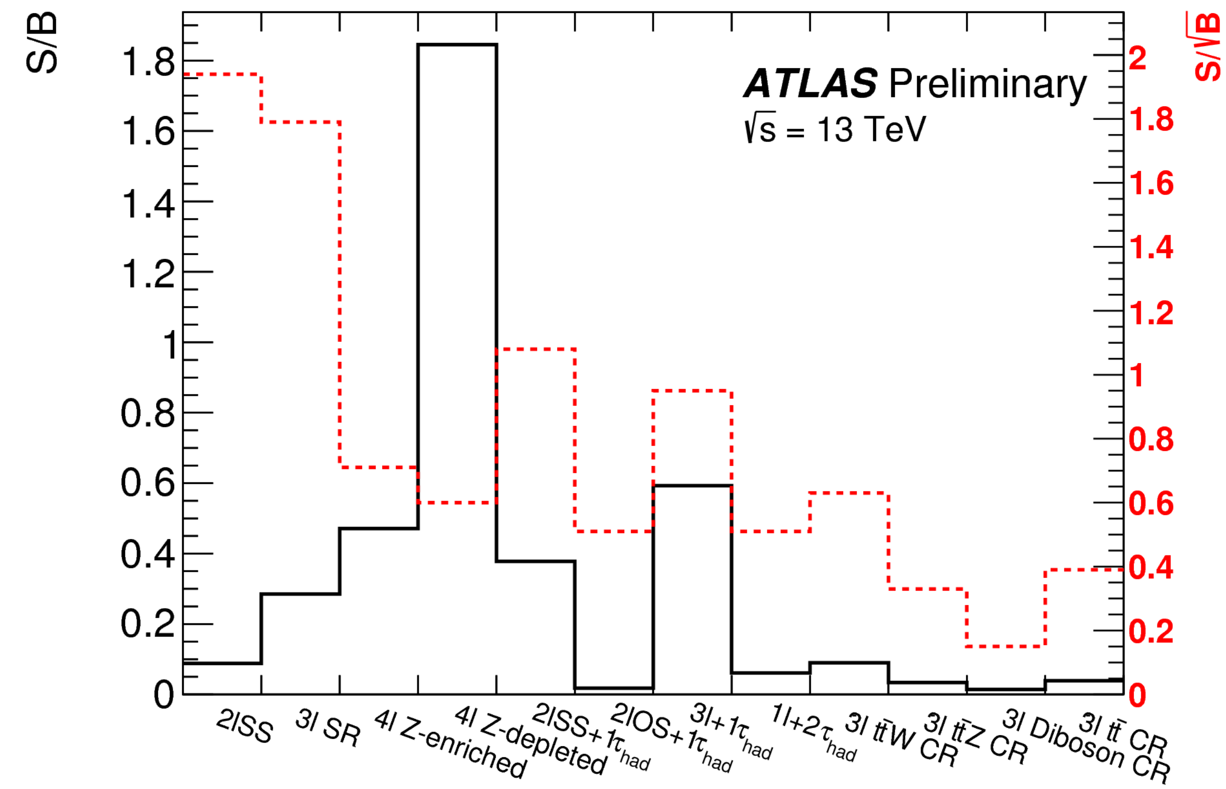

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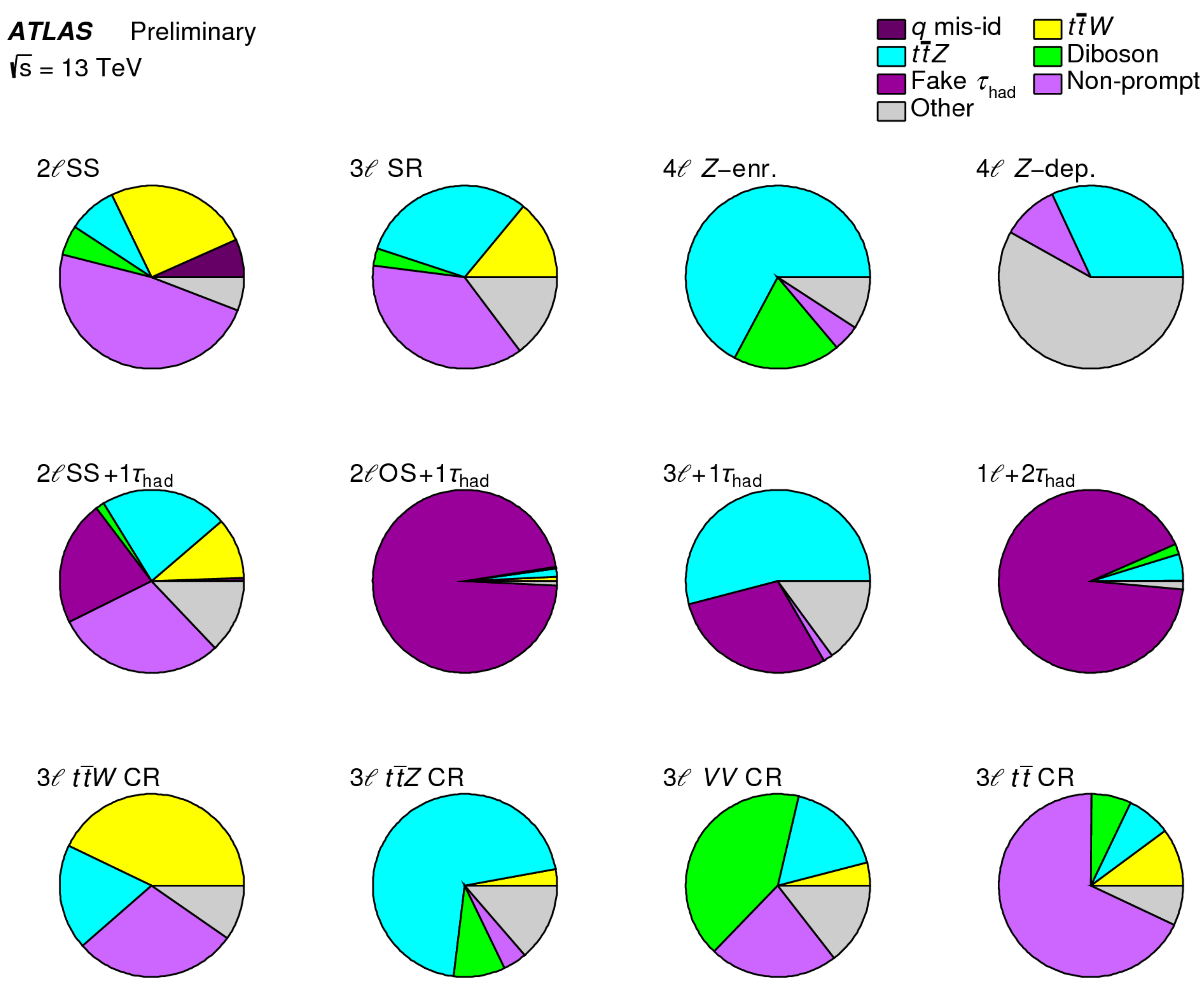
Background compositions

The fractional contributions of each bkg. to the total:



SR → signal region ; CR → control region

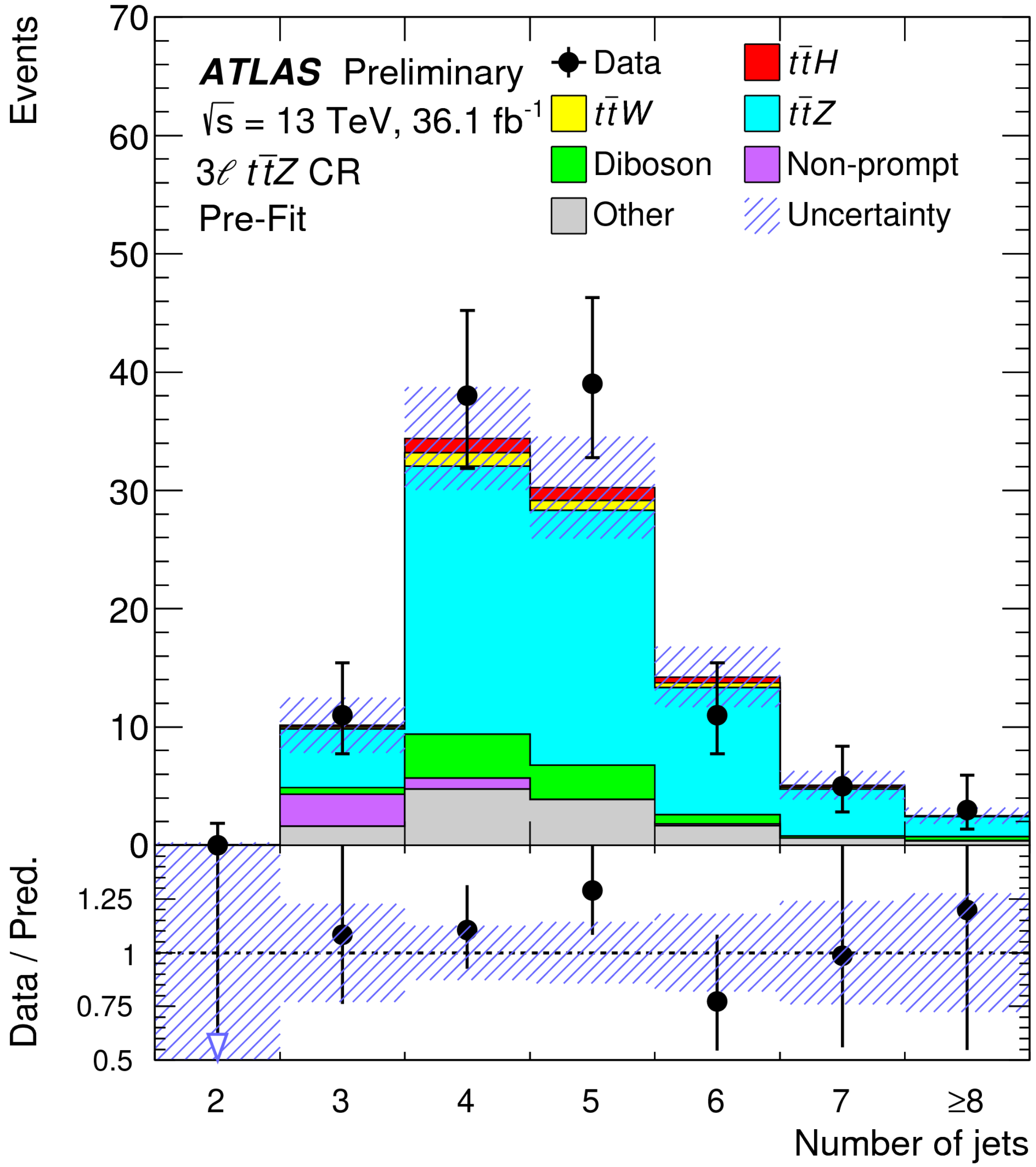
- "Non-prompt" bkg. arises from tt process with non-prompt lepton mainly from b-hadron decay.
- "q mis-id" bkg. arises from tt and Z+jets with electron charge being mis-assigned → only visible in 2lSS channel.
- "Fake τ_{had}" includes any other objects mis-tagged as τ_{had}.
- "Other" includes many rare processes, i.e tZ, tW, tWZ, tH, ttWW, triboson, ttt and tttt.

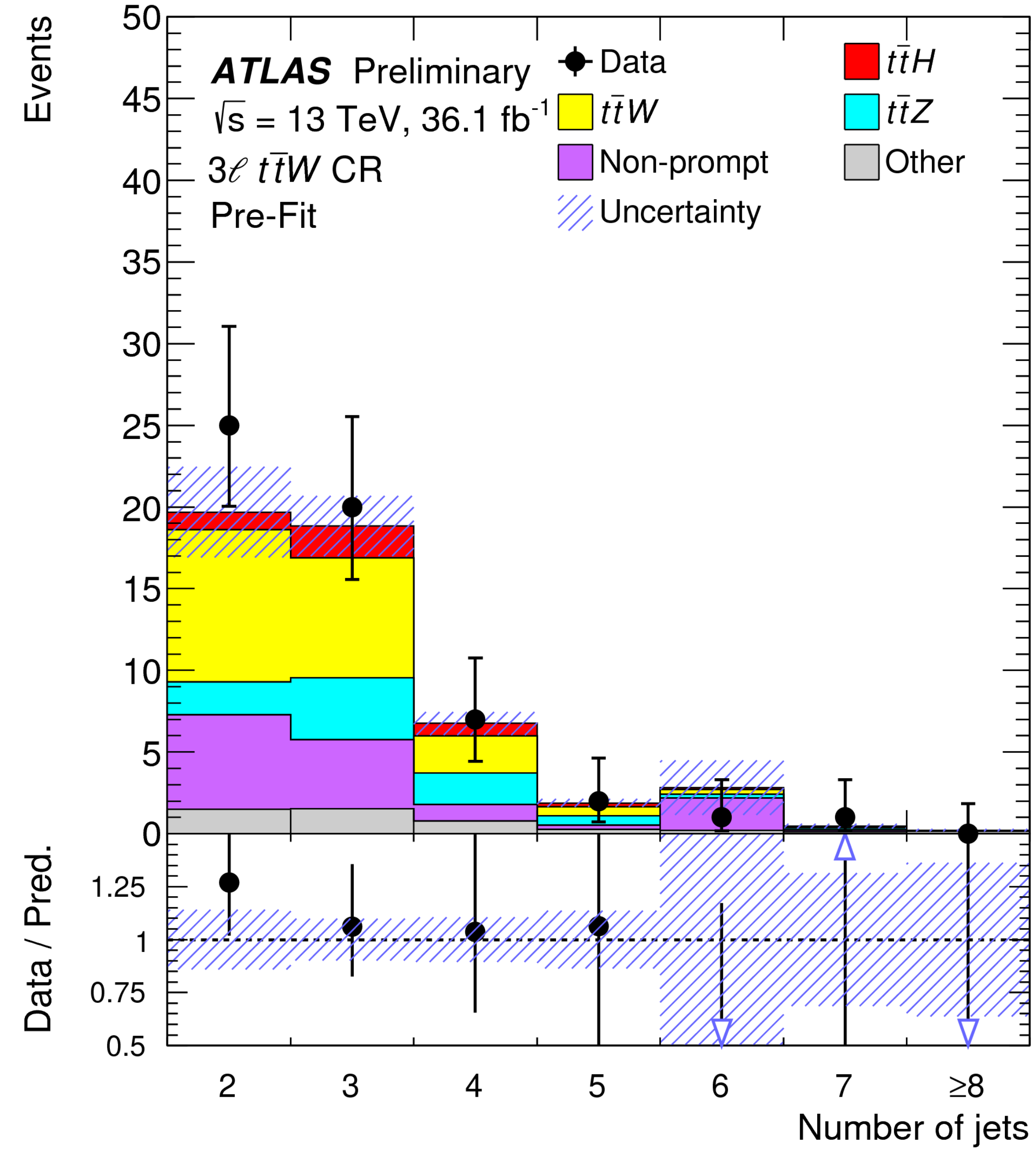
➡ **Irruducible bkg.** (ttW, ttZ, VV and rare) estimates rely on simulation, whose modelling are validated in data control regions.

➡ **Non-prompt and fake τ_{had} bkg.** are estimated from collision data.

Irreducible background validation in CRs

- Data and predictions are in good agreements for ttZ (left) and for ttW (right).

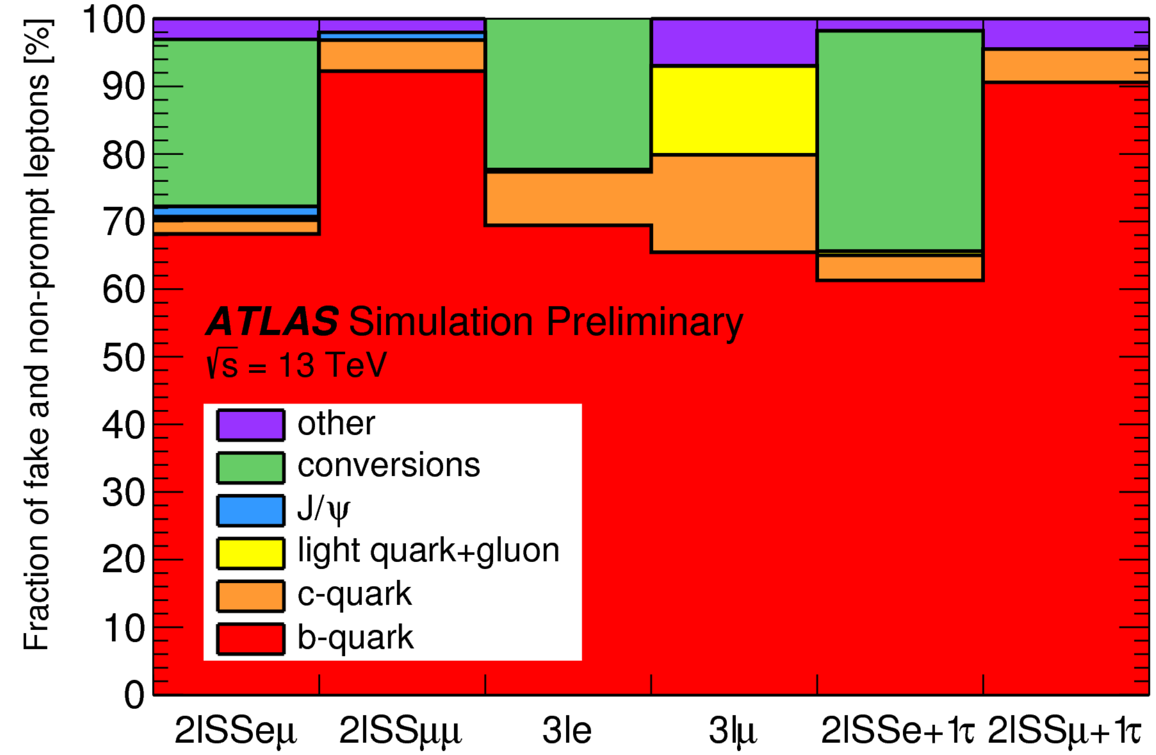




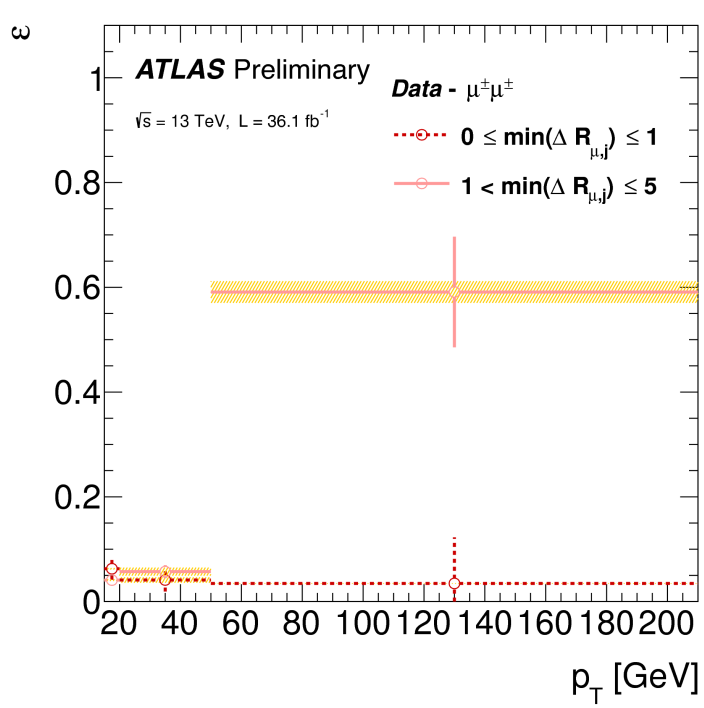
- CR definitions are orthogonal and close to signal regions → in backup slide 50.
- A list of all MC samples is in backup slide 51.

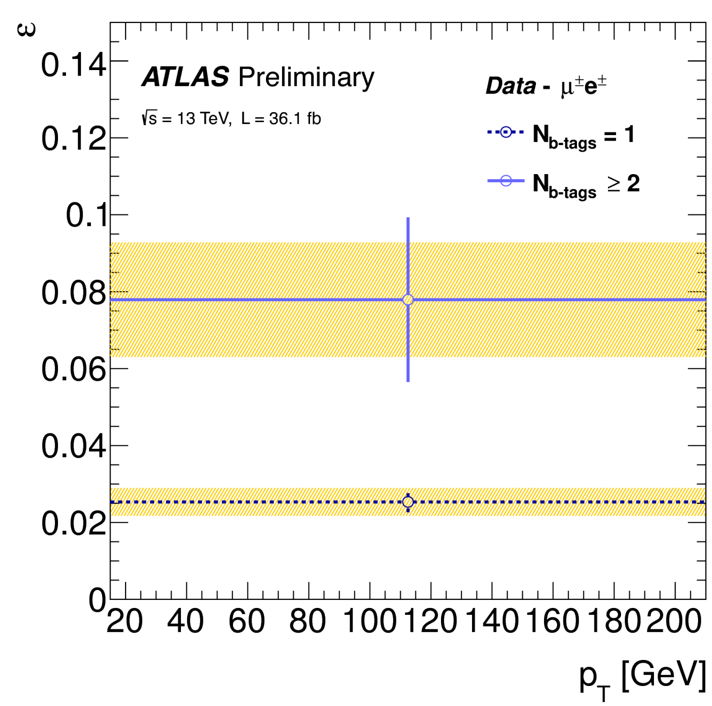
Non-prompt lepton background estimates - I

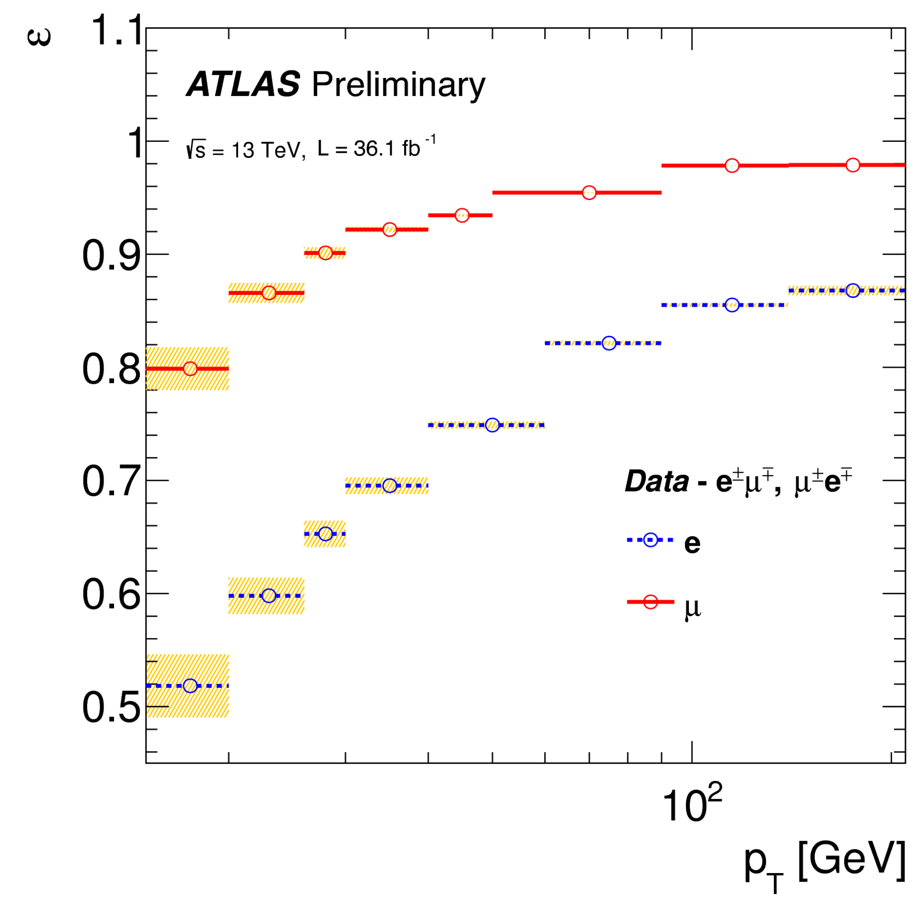
- Arising from $t\bar{t}$ production with non-prompt leptons mainly from b-hadron decay, and photon to electron conversions.
- Polluting 2lSS, 3l and 2lSS+ τ_{had} channels.
- The estimation counts number of events passing loose selection (loosen lepton's identification and isolation requirements), which is weighted by the probabilities for loose prompt and non-prompt leptons passing tighter requirements.



- The probabilities for non-prompt and prompt leptons:

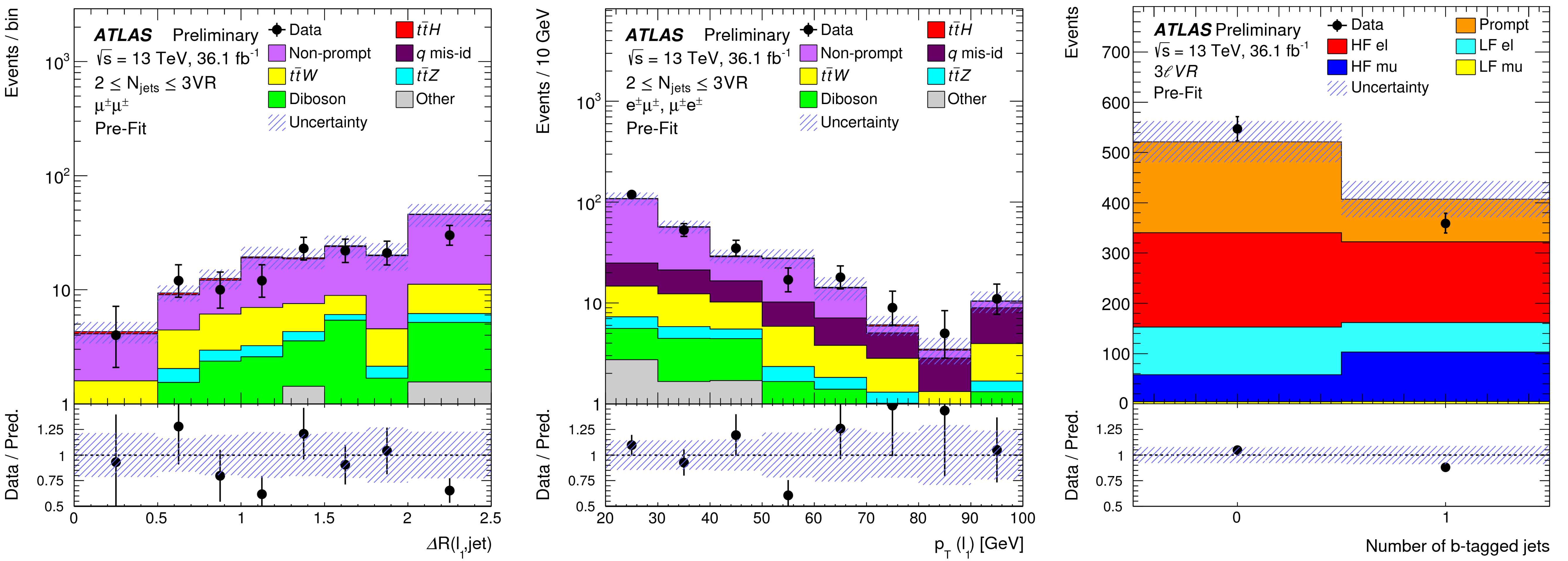






Non-prompt lepton background estimates - II

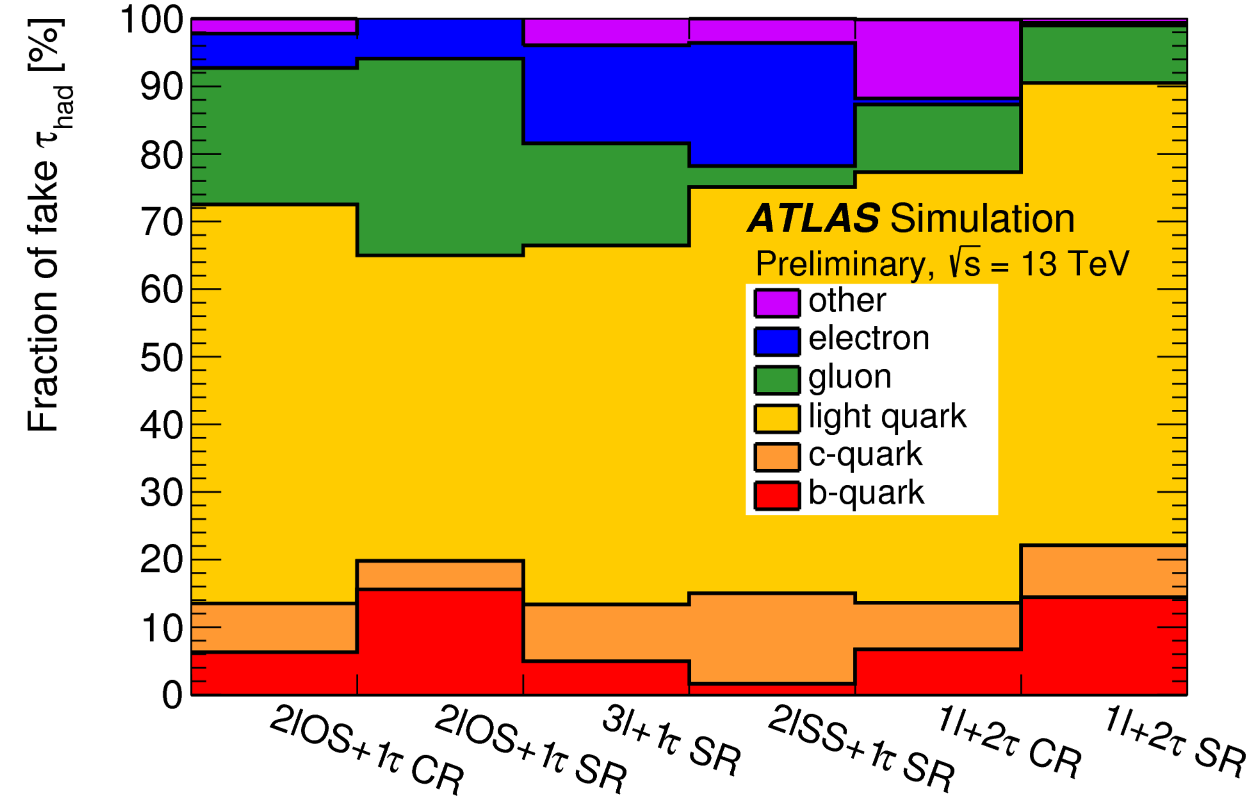
- Closure test is performed using simulated tt events. Non-closure of (11± 8)% for 2lSS and (9±18)% for 3l are taken as systematic uncertainties.
- The estimates procedure is validated in data regions enriched by non-prompt leptons:

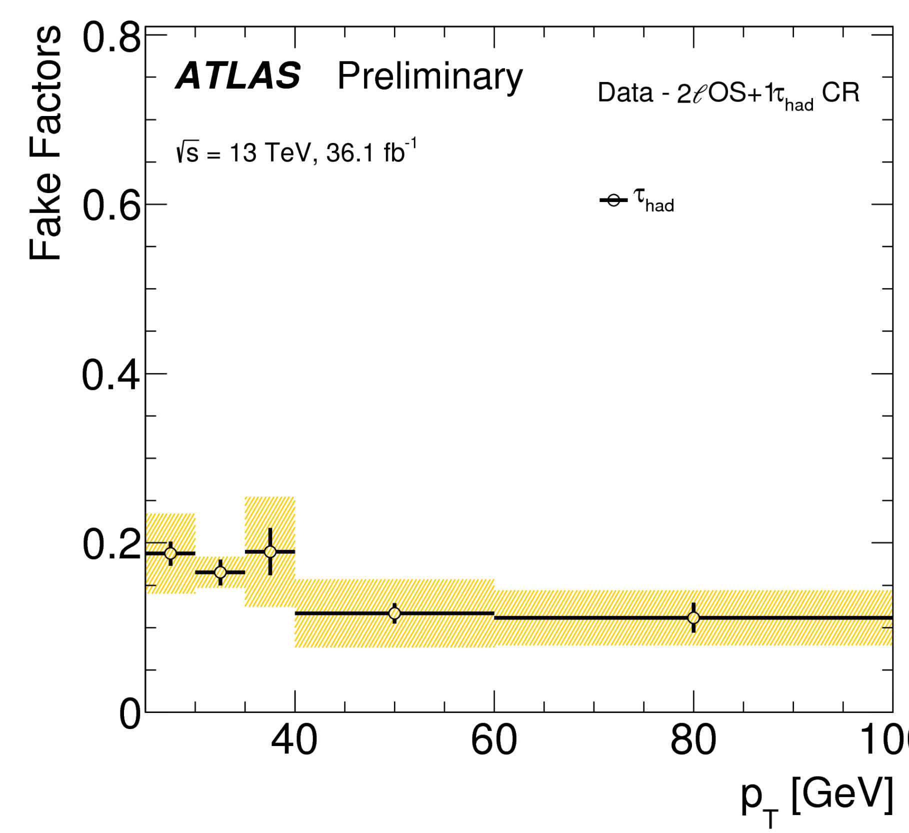


- The total uncertainty of non-prompt background estimation varies from 20% to 30% in 2lSS and 3l channels, and about 55% in 2lSS+1τ_{had} channel.

Fake τ_{had} background estimates in τ_{had} channels

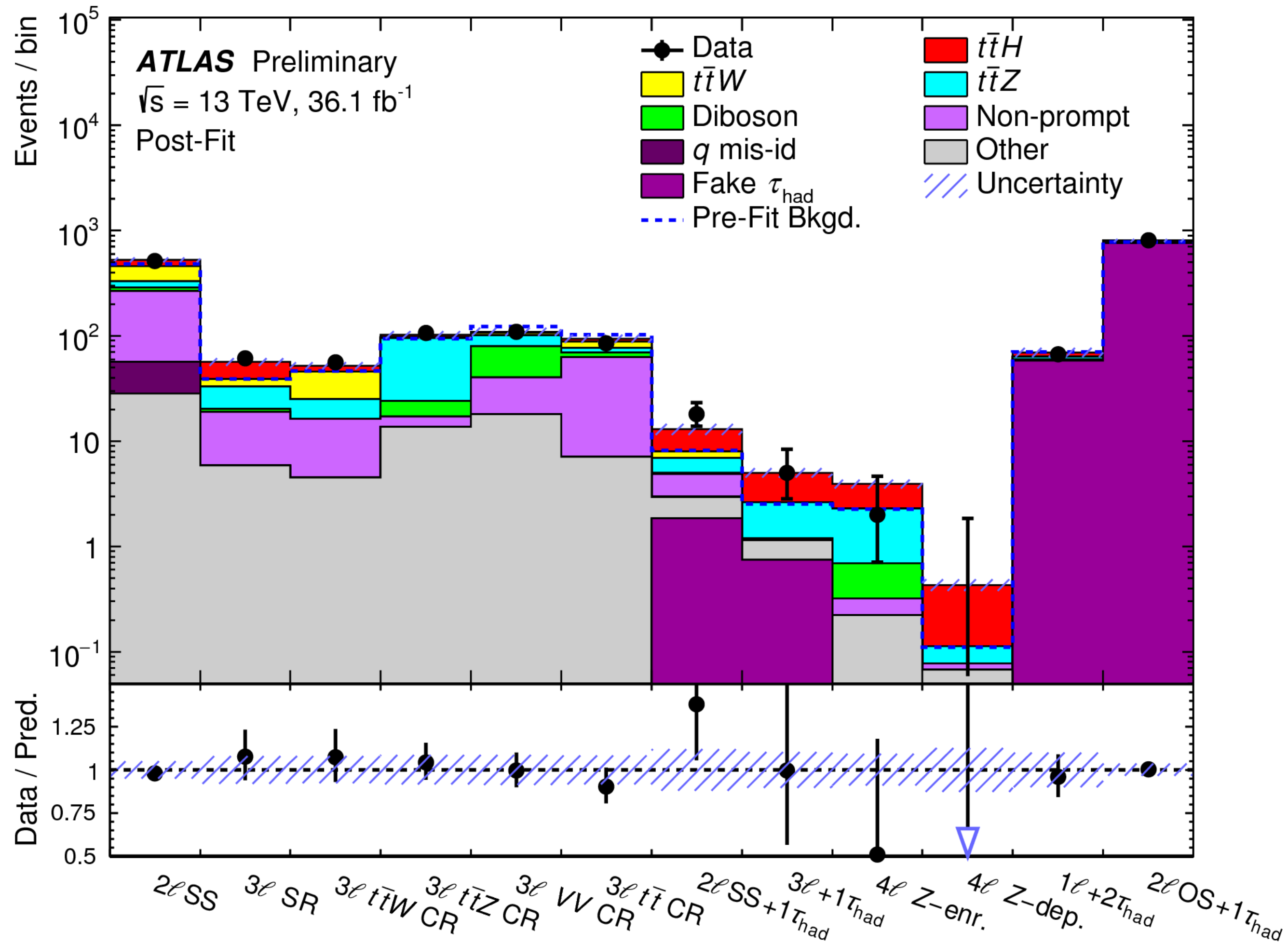
- Arising from tt and ttV production with mis-reconstructed τ_{had} candidate.
- Fake τ_{had} factor (ratio of fake τ_{had} passing tight to those passing loose but failing tight) are measured in CR (close to 2lOS+τ_{had} SR).
- In 2lOS+τ_{had} channel, systematic uncertainty of fake τ_{had} background is 11%.
- In 3l+τ_{had} 2lSS+τ_{had} channels, a scale factor 1.36±0.16 is used to correct MC prediction for fake τ_{had} component.
- In 1l+2τ_{had} channel, fake τ_{had} background is estimated in control region identical to the signal region but with same charge τ_{had} pair. In total, 30% systematic uncertainty mainly comes from method non-closure.

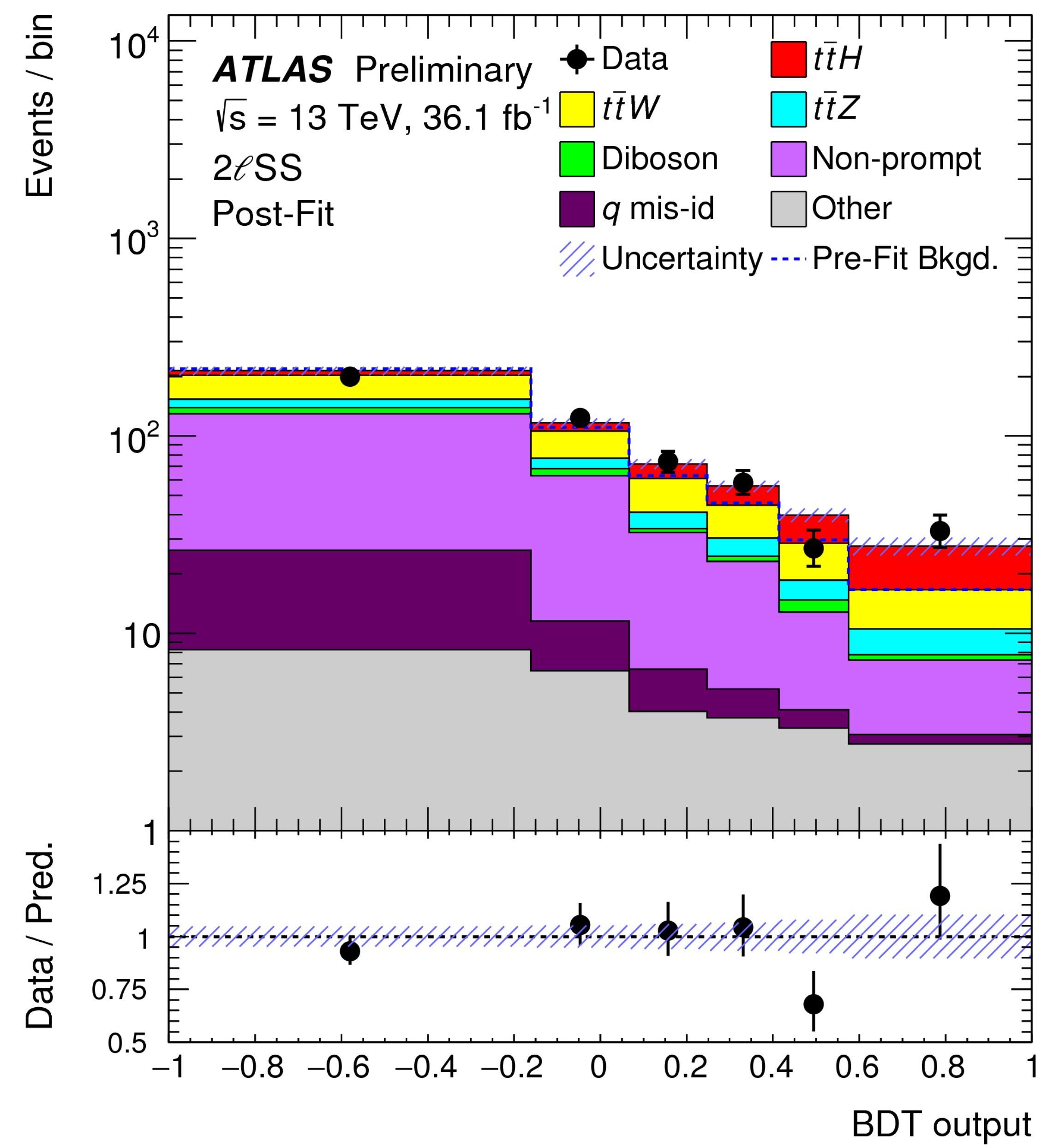




Comparison between data and estimates - I

- A fit of predictions to data is performed simultaneously on various discriminants over all 12 regions (in total 32 bins). The ttH signal strength ($\mu_{t\bar{t}H}$) is the parameter of interest.
- Post-fit predictions are in good agreement with data.





Comparison between data and estimates - II

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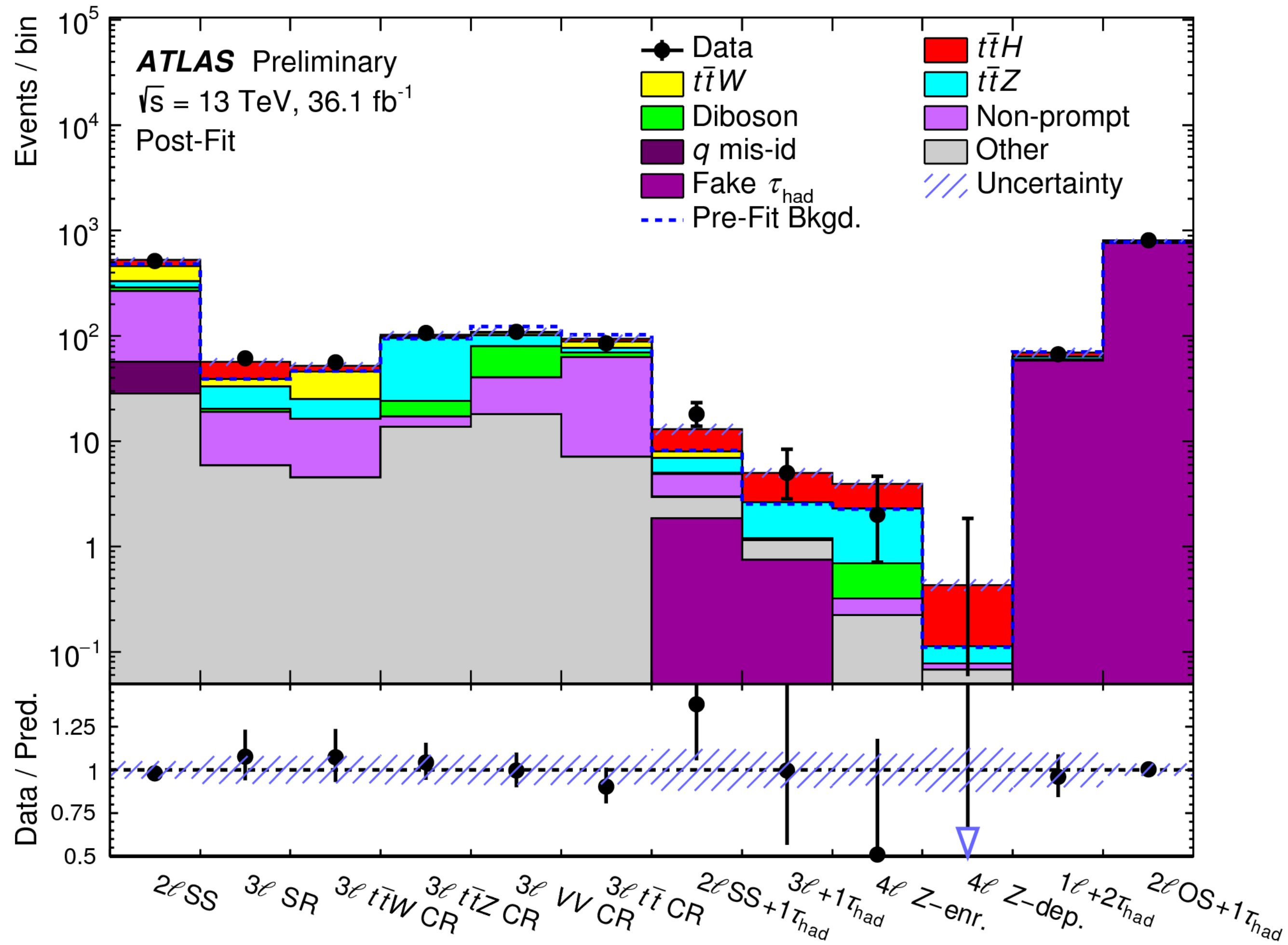

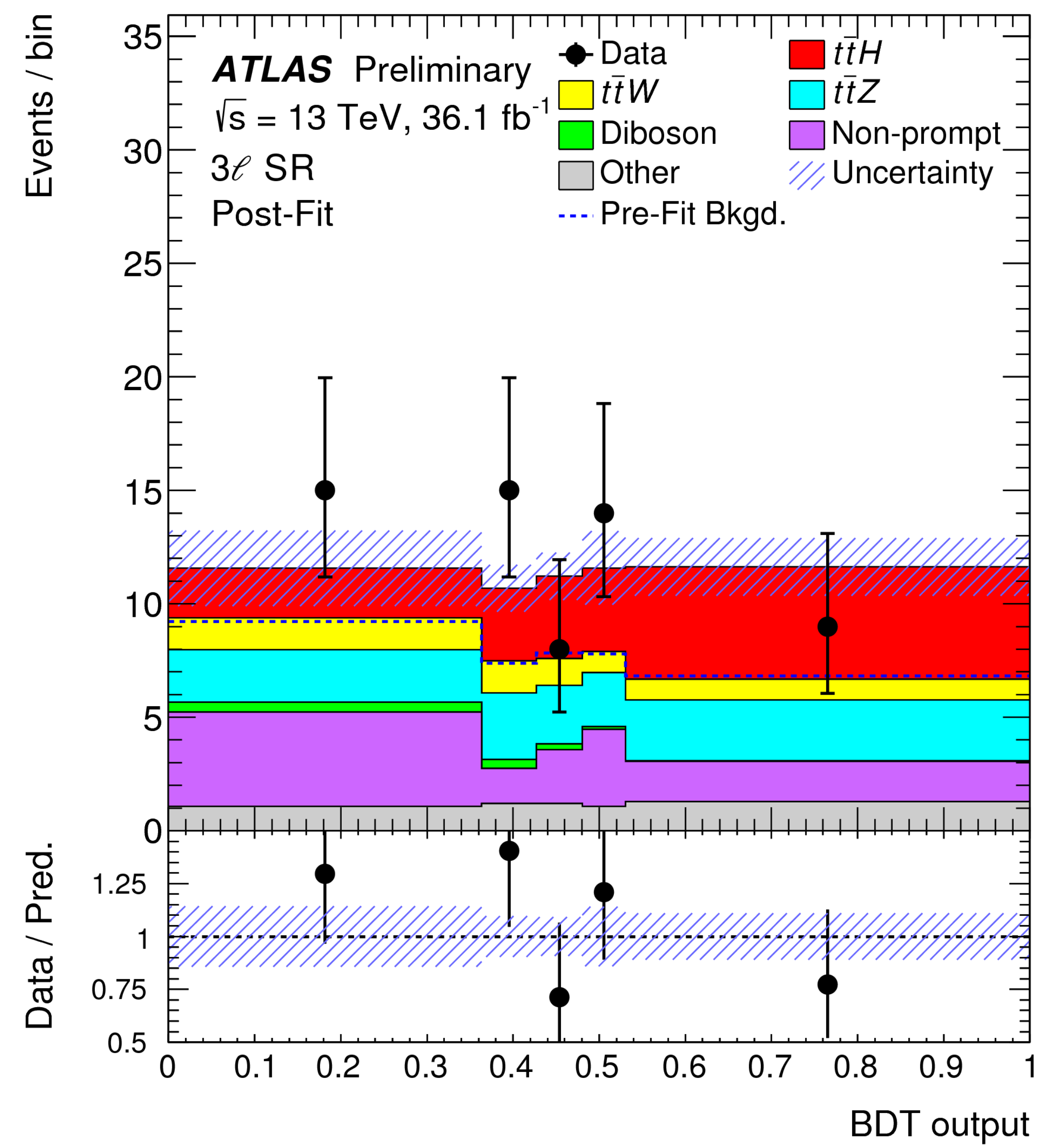

Comparison between data and estimates - III

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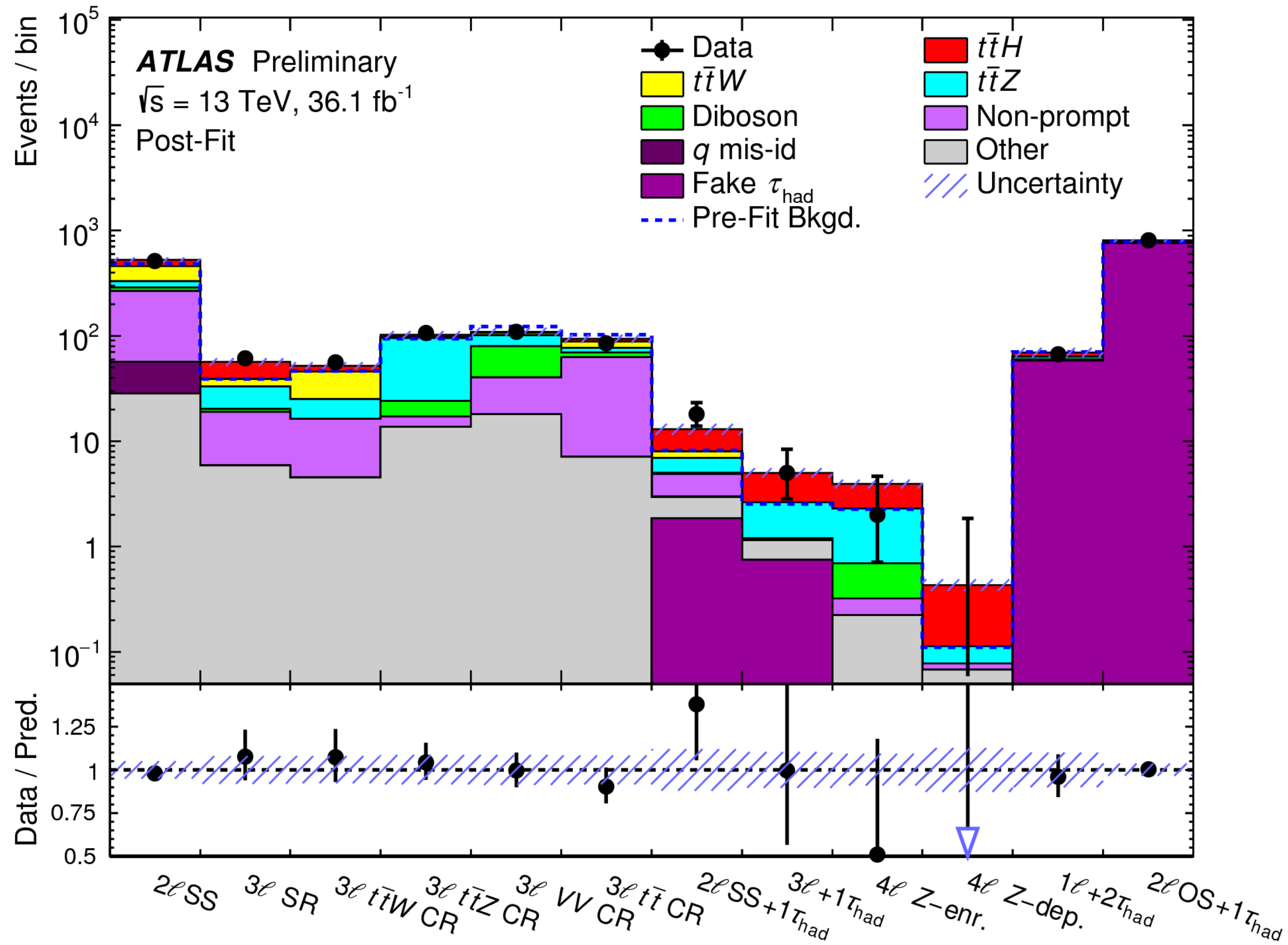

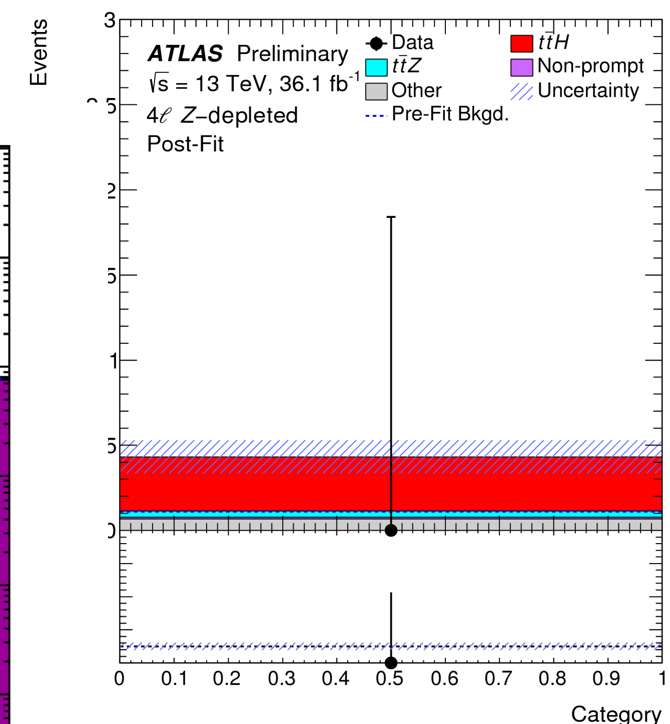

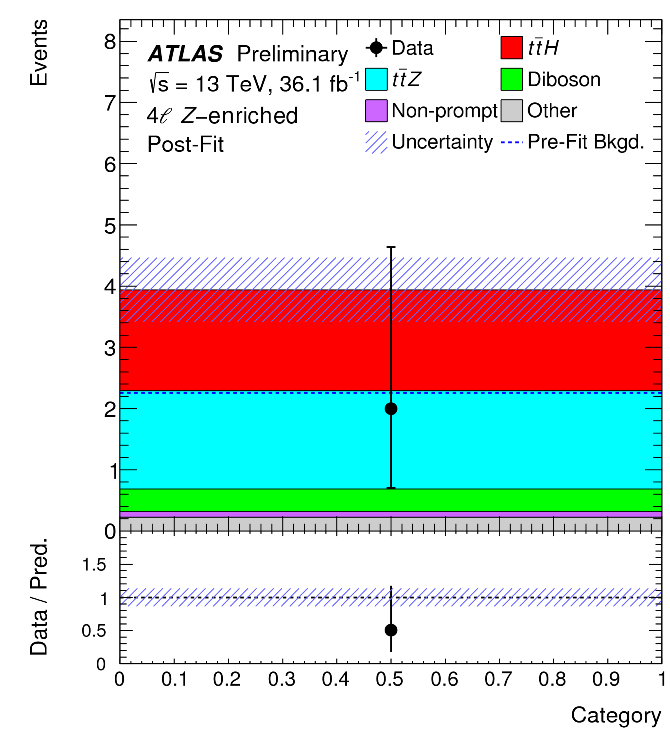

Comparison between data and estimates - IV

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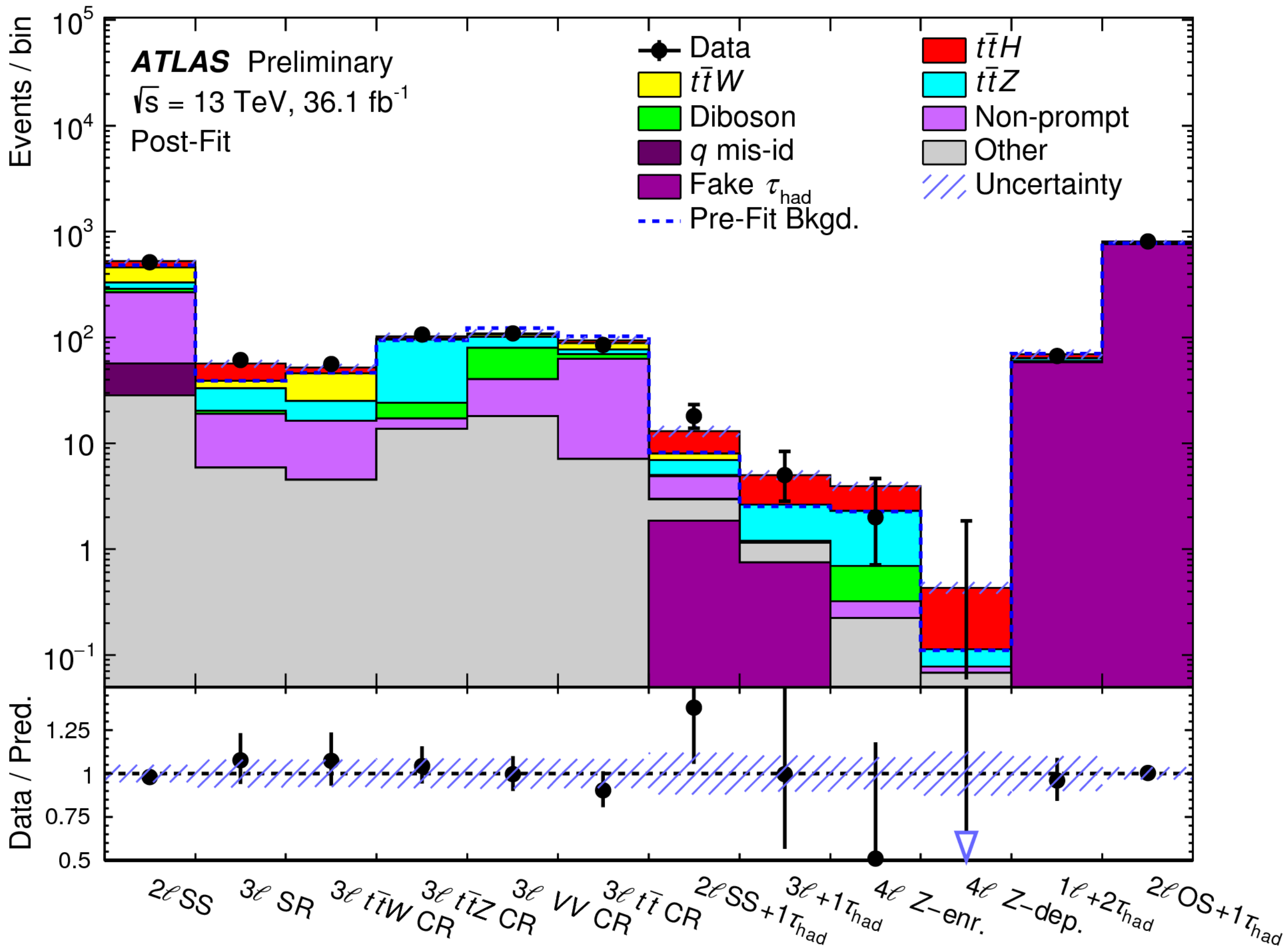
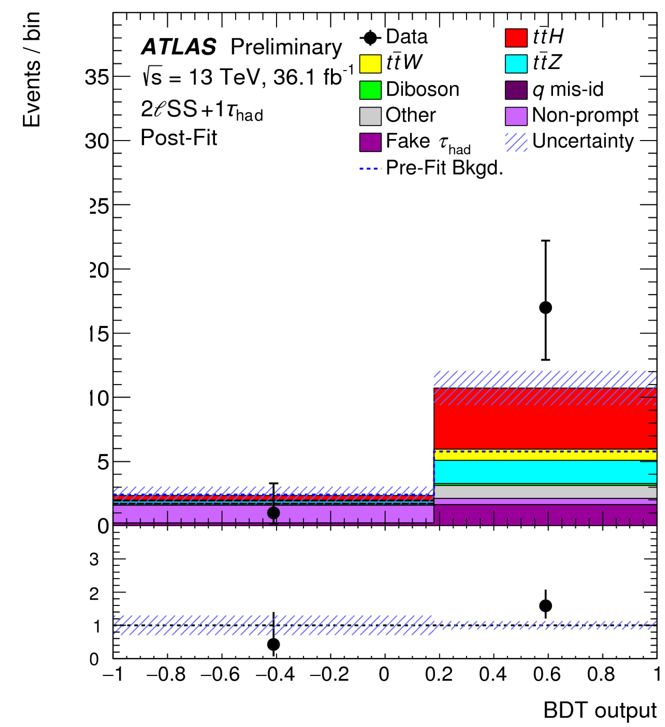
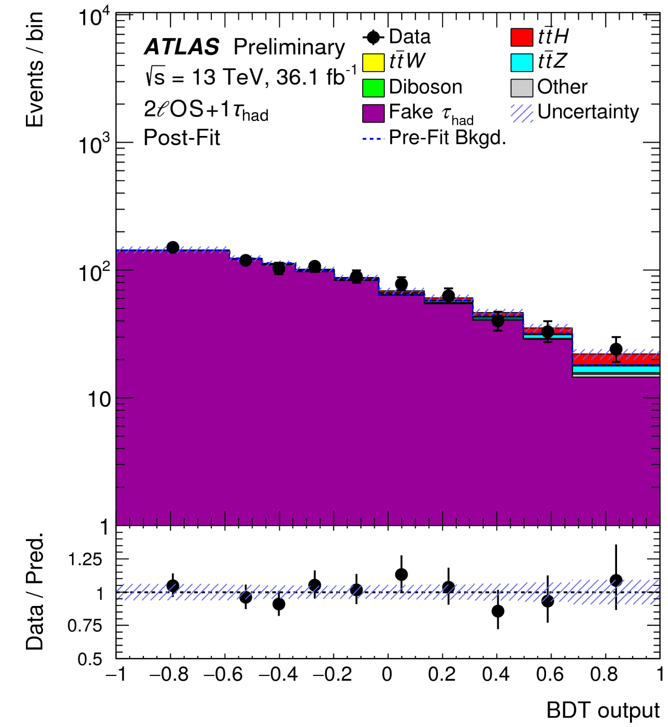
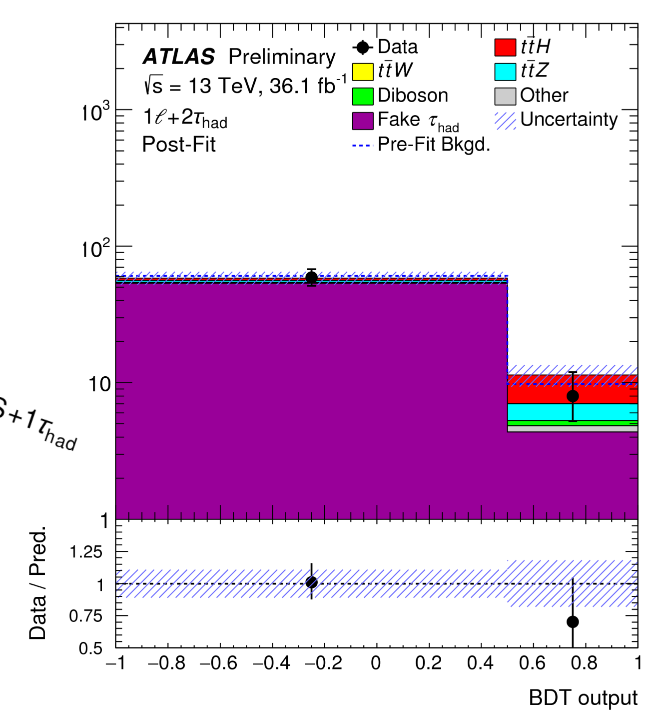
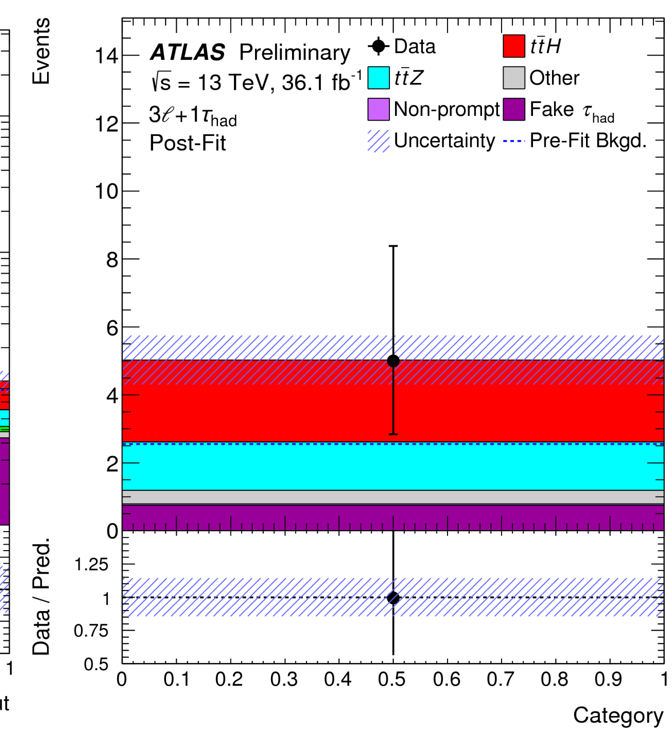




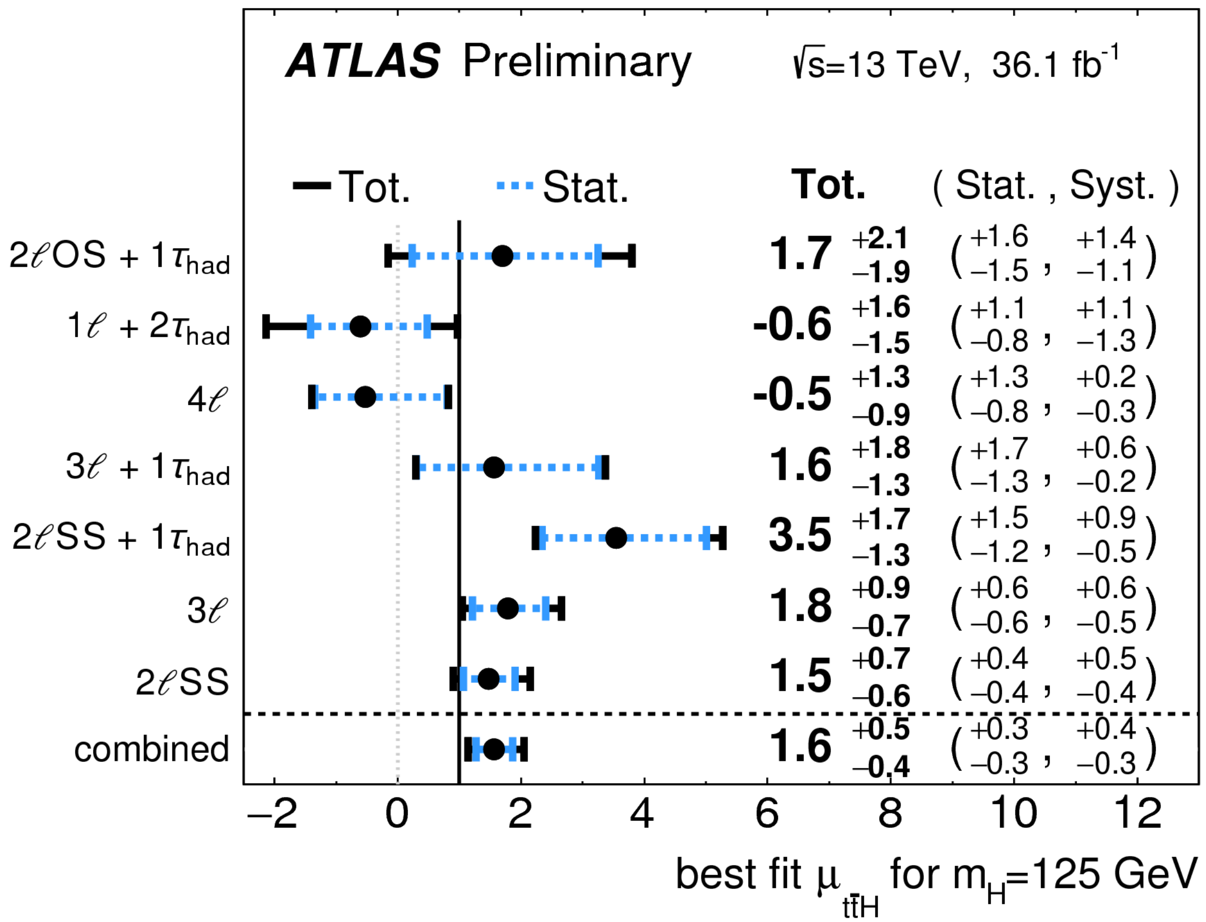




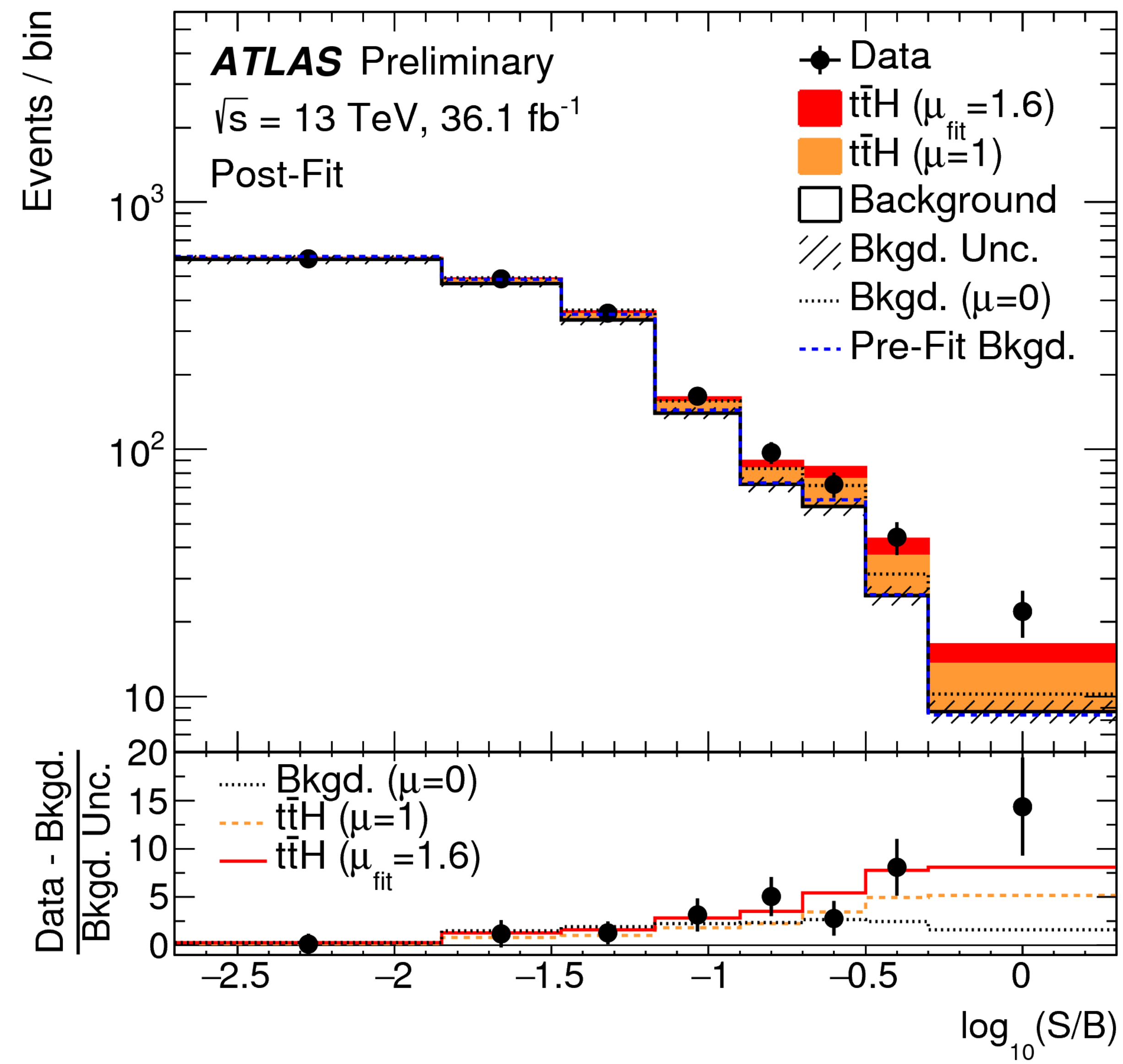


Results in ttH-multileptons analysis

The best-fit values of the ttH signal strength



Event yields as a function of $\log_{10}(S/B)$

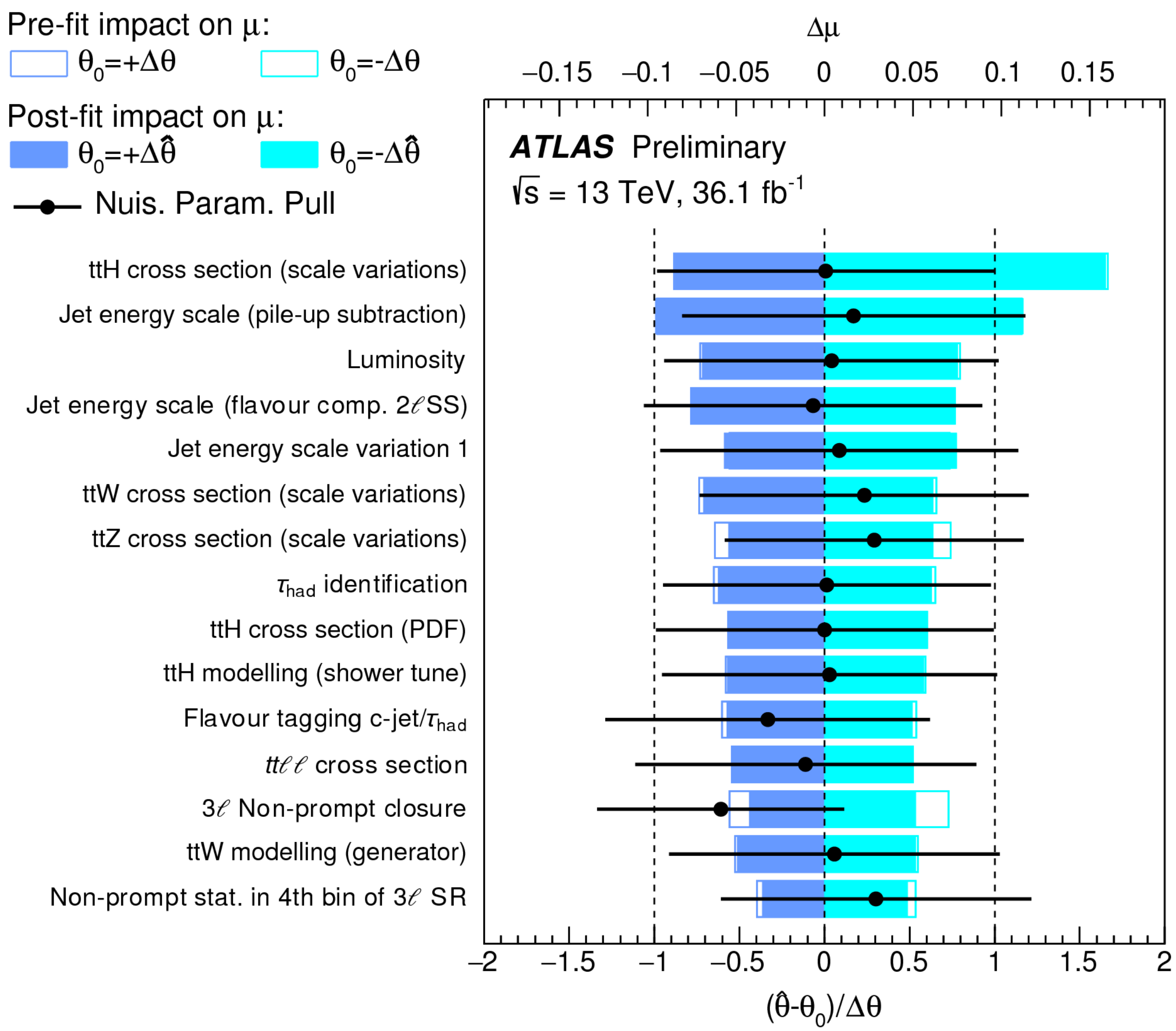


- ✦ The combined signal strength is $1.6^{+0.5}_{-0.4}$, which corresponds to 4.1**σ** (2.8**σ**) observed (expected) significance.
- ✦ The measured ttH cross section is $\sigma(t\bar{t}H) = 790^{+230}_{-210}$ fb (the SM prediction 507^{+35}_{-50} fb).
- ✦ Cutting&count analyses in 2lSS, 3l and 2lSS+1$\tau_{\rm had}$ observe compatible results.
- ✦ Sensitive to cross section modifier for ttW 0.92±0.32 and for ttZ 1.17±0.25.

Summary of systematic uncertainties

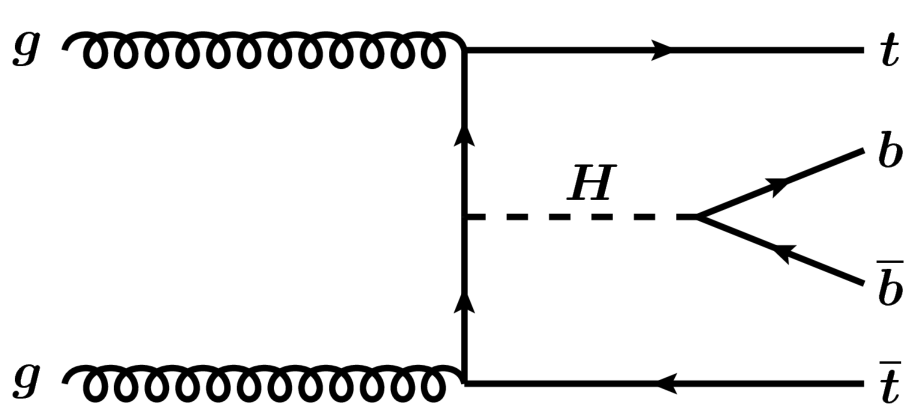
- Left: summary of the effects of the most important groups of systematic uncertainties.
- Right: the impact of systematic uncertainties in the fitted signal strength.

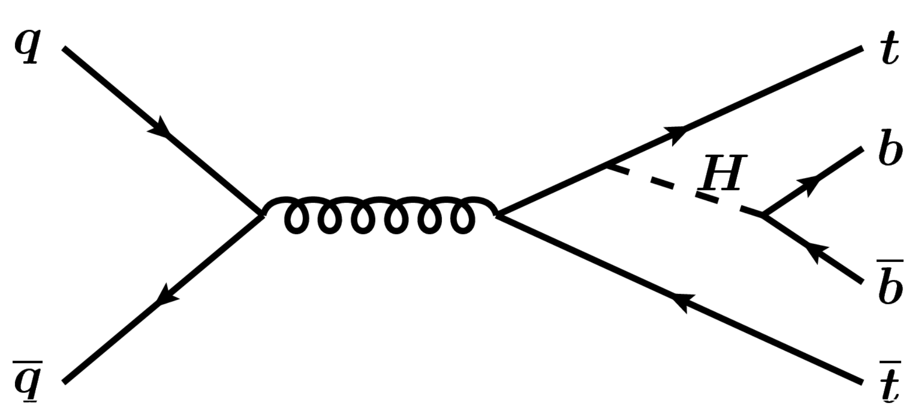
Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modelling (cross section)	+0.20	−0.09
Jet energy scale and resolution	+0.18	−0.15
Non-prompt light-lepton estimates	+0.15	−0.13
Jet flavour tagging and τ_{had} identification	+0.11	−0.09
$t\bar{t}W$ modelling	+0.10	−0.09
$t\bar{t}Z$ modelling	+0.08	−0.07
Other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

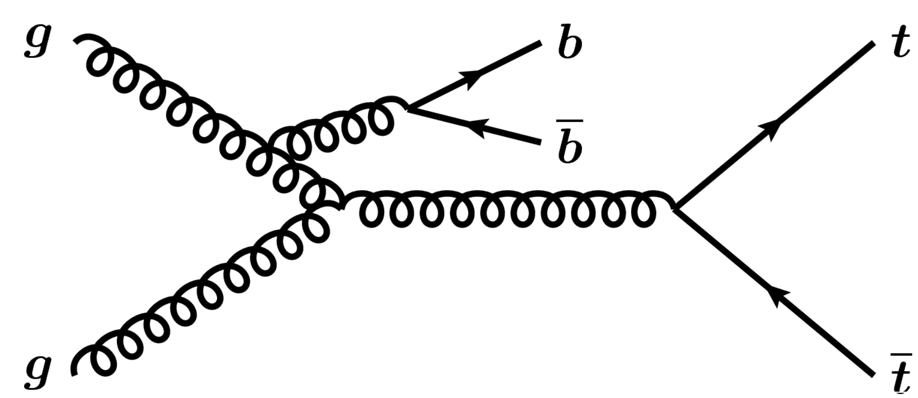


Search for ttH, Higgs decays to bb

the W bosons from one or both top quarks decay leptonically

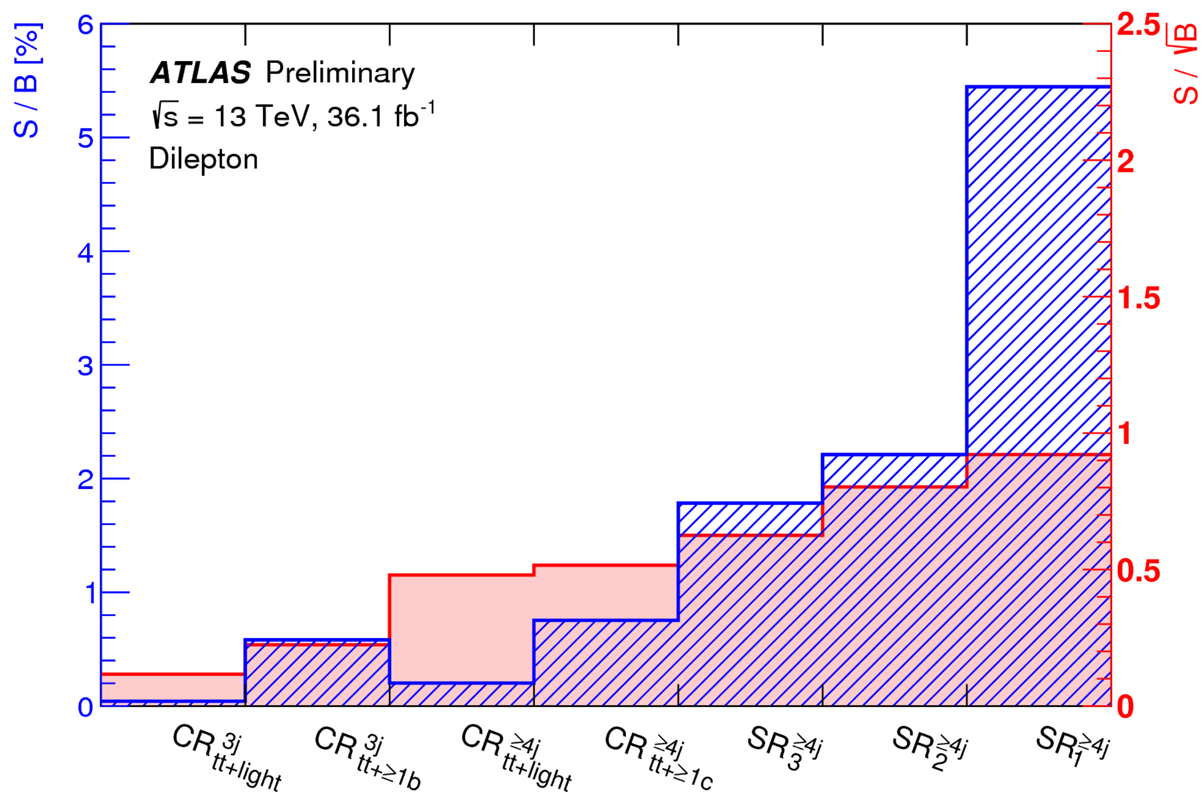


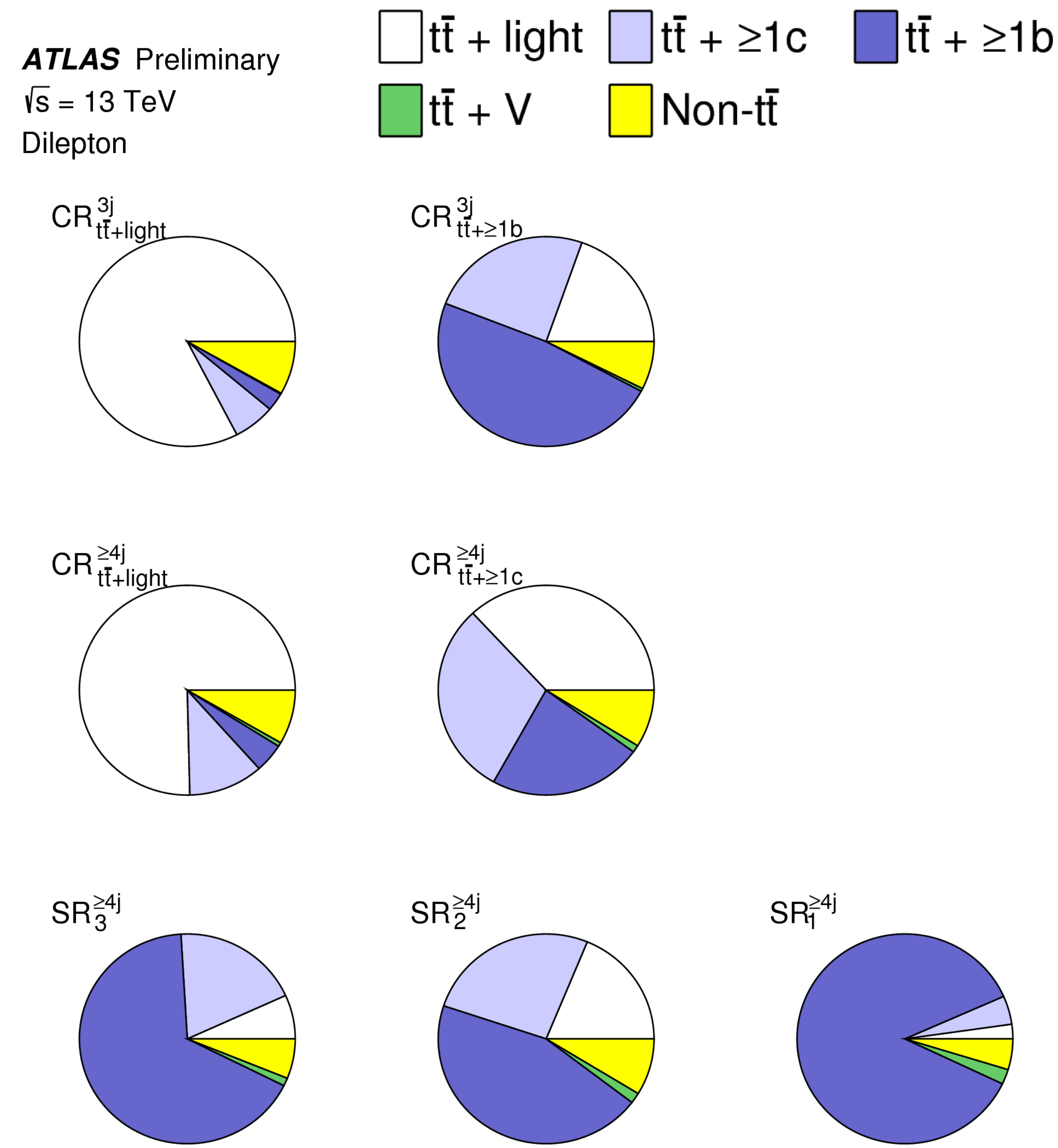




Event selection and classification - I

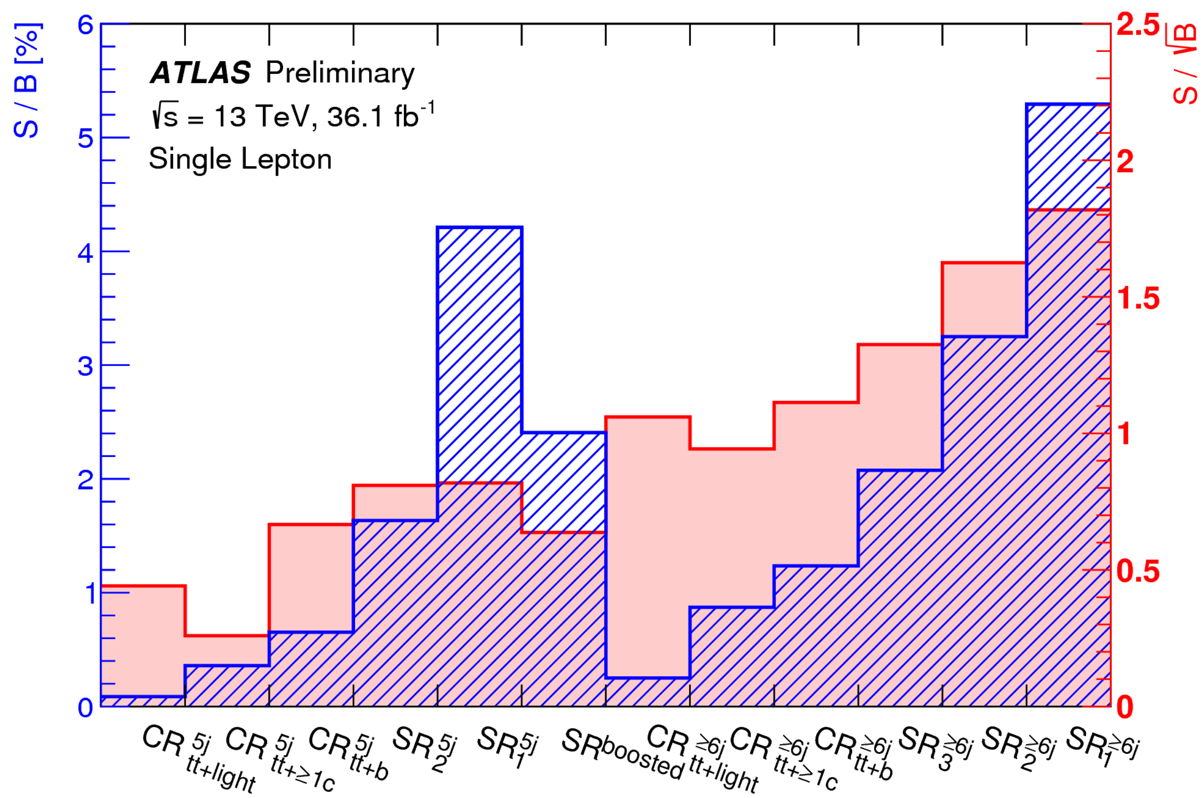
- **Di-lepton channel** (tt leptonic decay, categorisation on jets and b-jets multiplicity)
  - at least 4 jets : 3 SRs + 2 CRs
  - exactly 3 jets : 2 CRs
- **Event reconstruction** employs multivariate techniques (BDT, LHD, MEM), achieving **49% (32%) of tt̄H signal being correctly reconstructed** with (without) Higgs boson kinematics included.

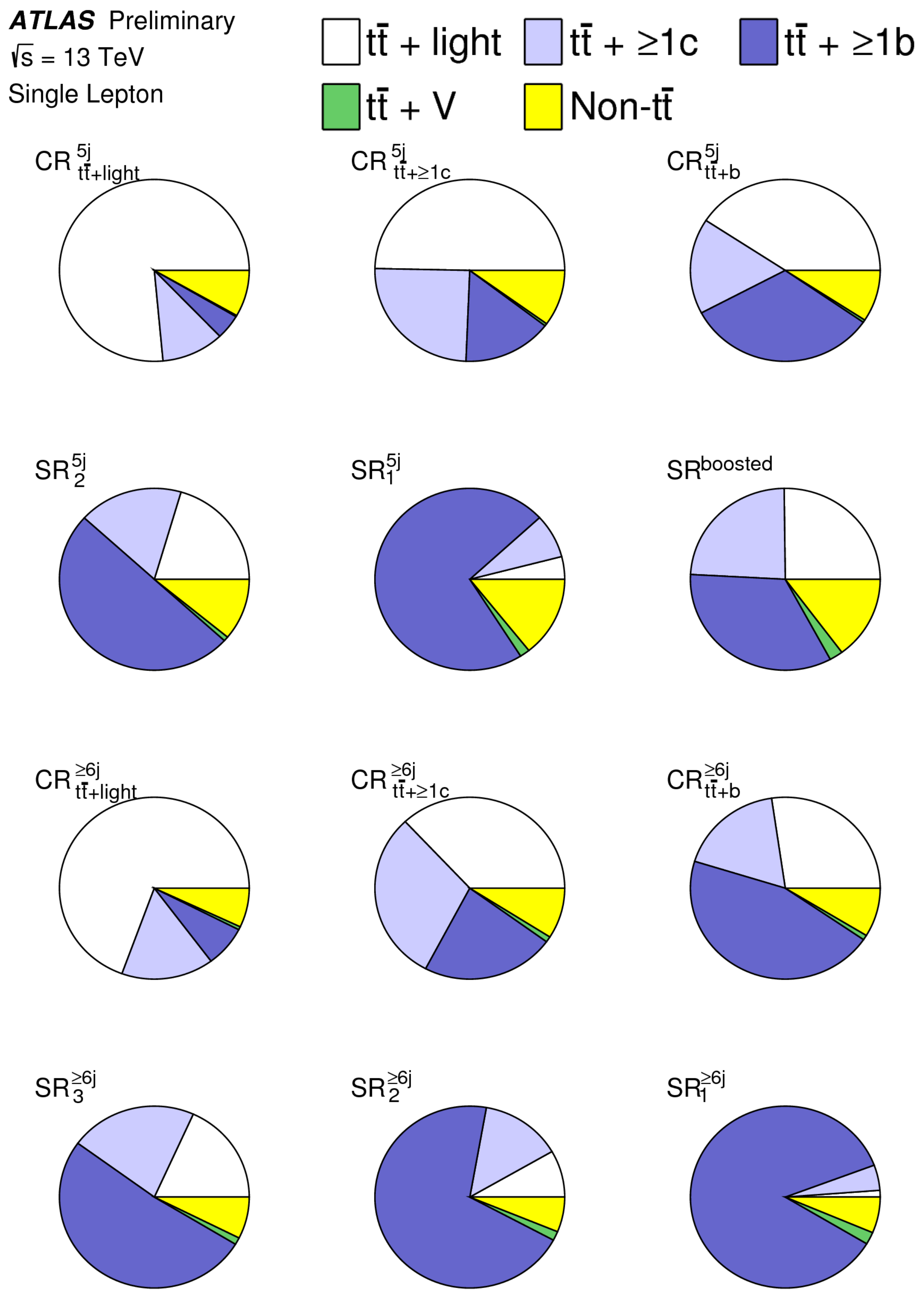




Event selection and classification - II

- **Single lepton channel**
  - exactly 5 jets : 2 SRs + 3 CRs
  - at least 6 jets : 3 SRs + 3 CRs
  - boosted SR: large-R jet with p_T > 200 GeV
- **Event reconstruction achieves 48% (32%) of ttH signal being correctly reconstructed** with (without) Higgs boson kinematics included.





tt+jets background modelling

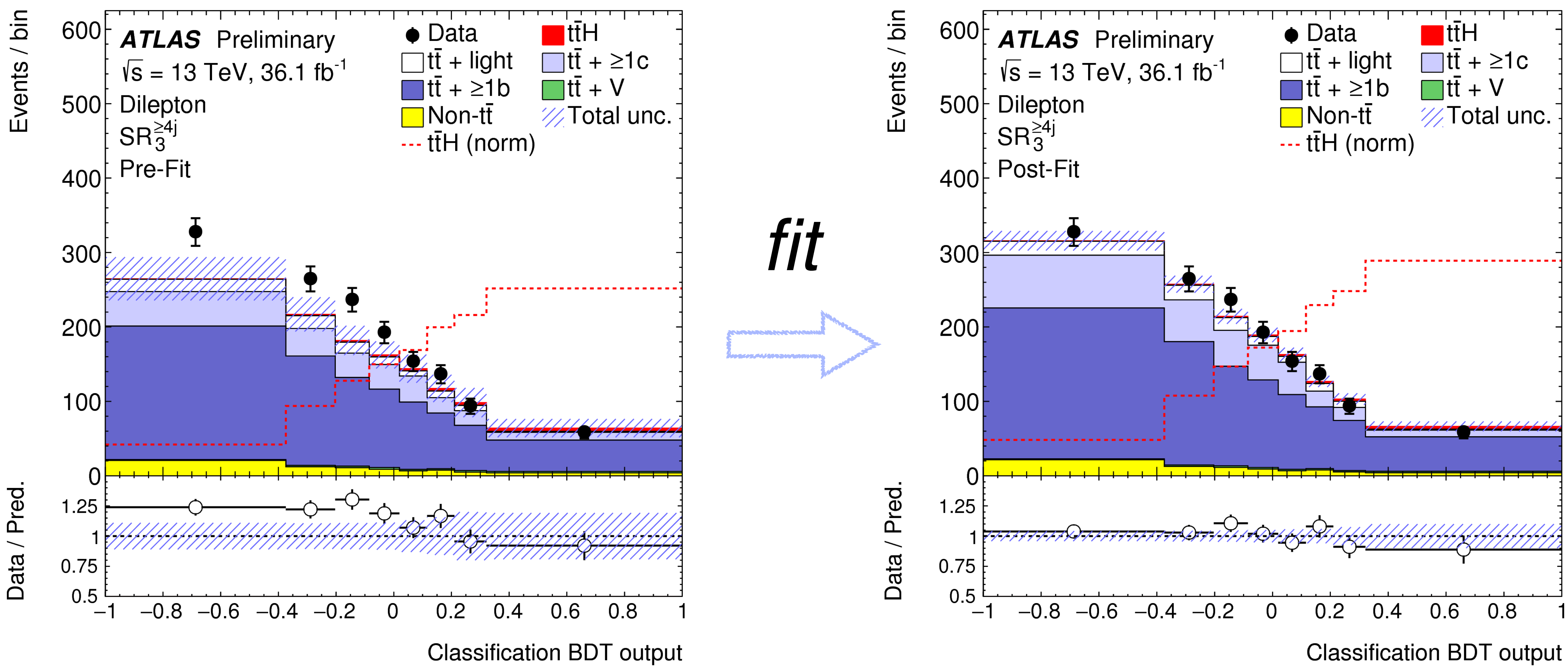
- tt+heavy-flavour jets modelling relies on Powheg+Pythia8 simulation. The cross section is normalised to NNLO+NNLL prediction 832^{+46}_{-51} pb.
- A set of systematic uncertainties are evaluated, account for various variations.

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 $t\bar{t} + \geq 1c$ normalisation	$t\bar{t} + \geq 1c$
$k(t\bar{t} + \geq 1b)$	Free-floating $t\bar{t} + \geq 1b$ normalisation	$t\bar{t} + \geq 1b$
Sherpa5F vs. nominal	Related to the choice of the NLO generator	All, uncorrelated
PS & hadronisation	Powheg-Box+Herwig 7 vs. Powheg-Box+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-Box+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 $H_{\mathrm{T}}/2$ 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 tunable parameters for the underlying event	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ MPI	Up or down by 50%	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 3b$ normalisation	Up or down by 50%	$t\bar{t} + \geq 1b$

- tt+ ≥1b, tt+ ≥1c normalisations are determined in data from the fit.

Discriminants in signal regions

- Classification BDT is built by combining event reconstruction outputs with kinematic variables and b-tagging discriminants.



- The fit is done simultaneously in all SRs+CRs in single- and di-lepton channels.

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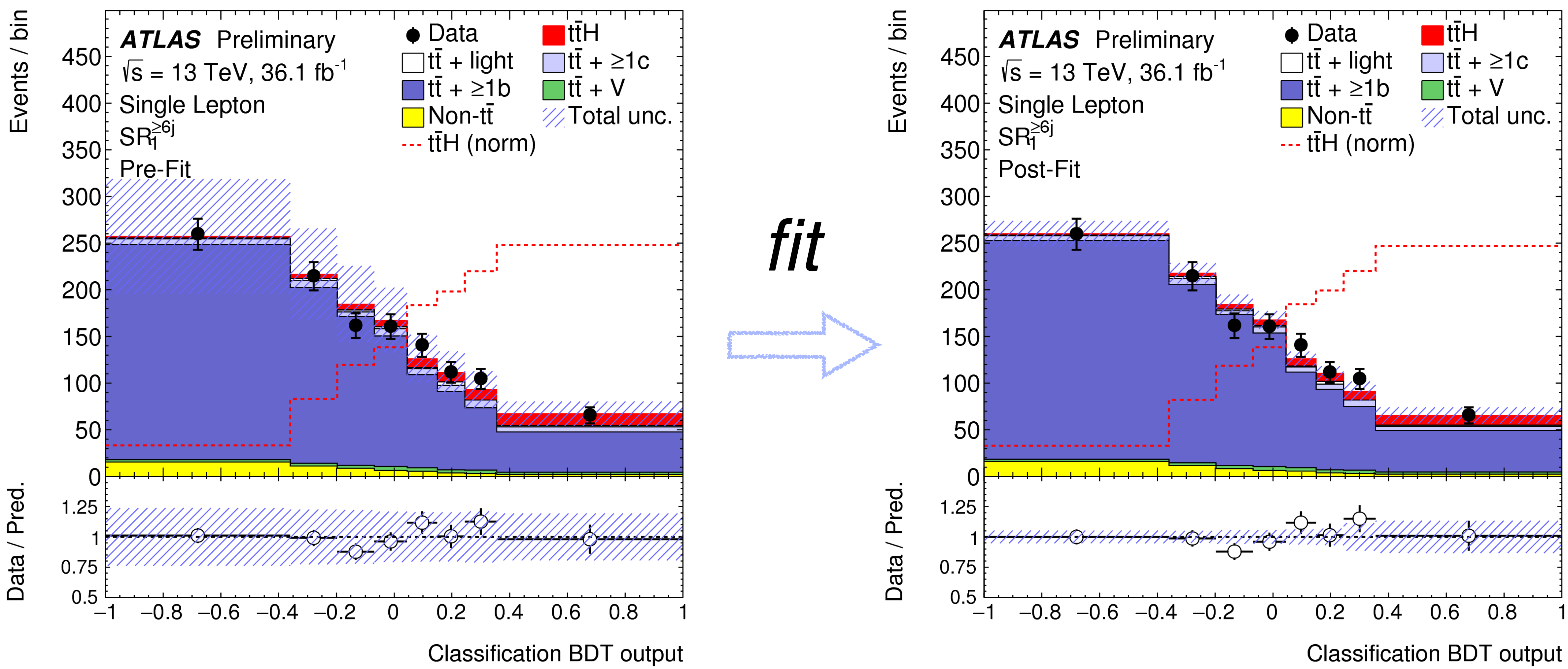
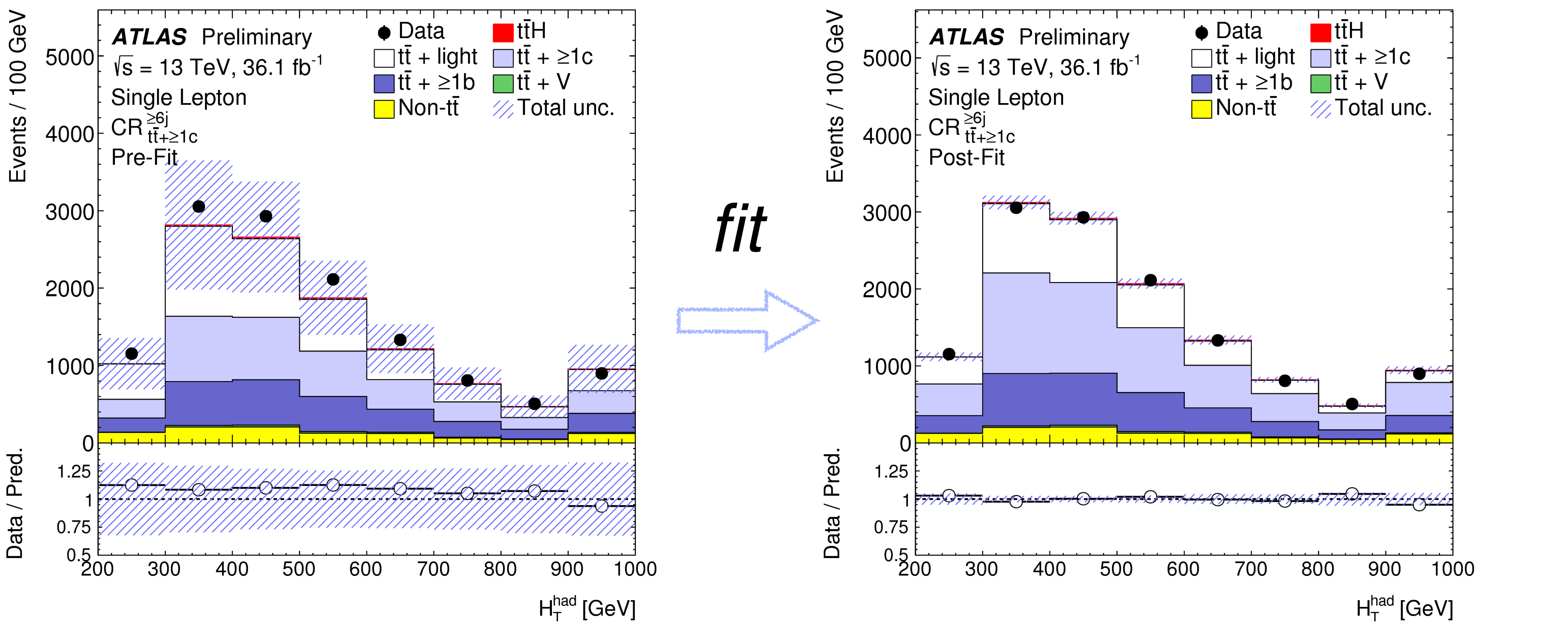


✦ The fit is done simultaneously in all SRs+CRs in single- and di-lepton channels.

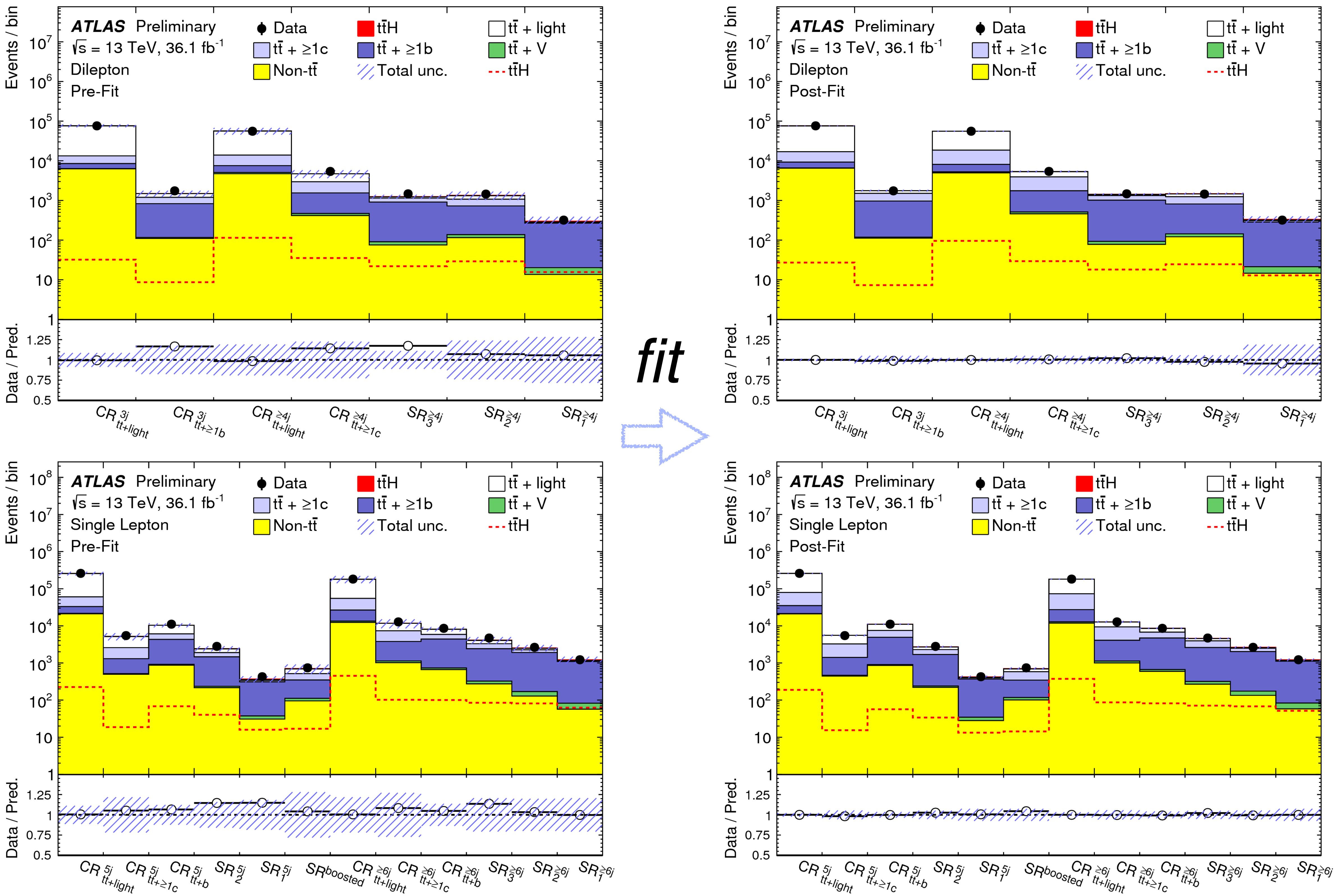
Discriminant in tt+ ≥1c control region

- The scalar sum of the p_T of all jets (H_T^{had}) is used as discriminant in tt+ ≥1c control region.



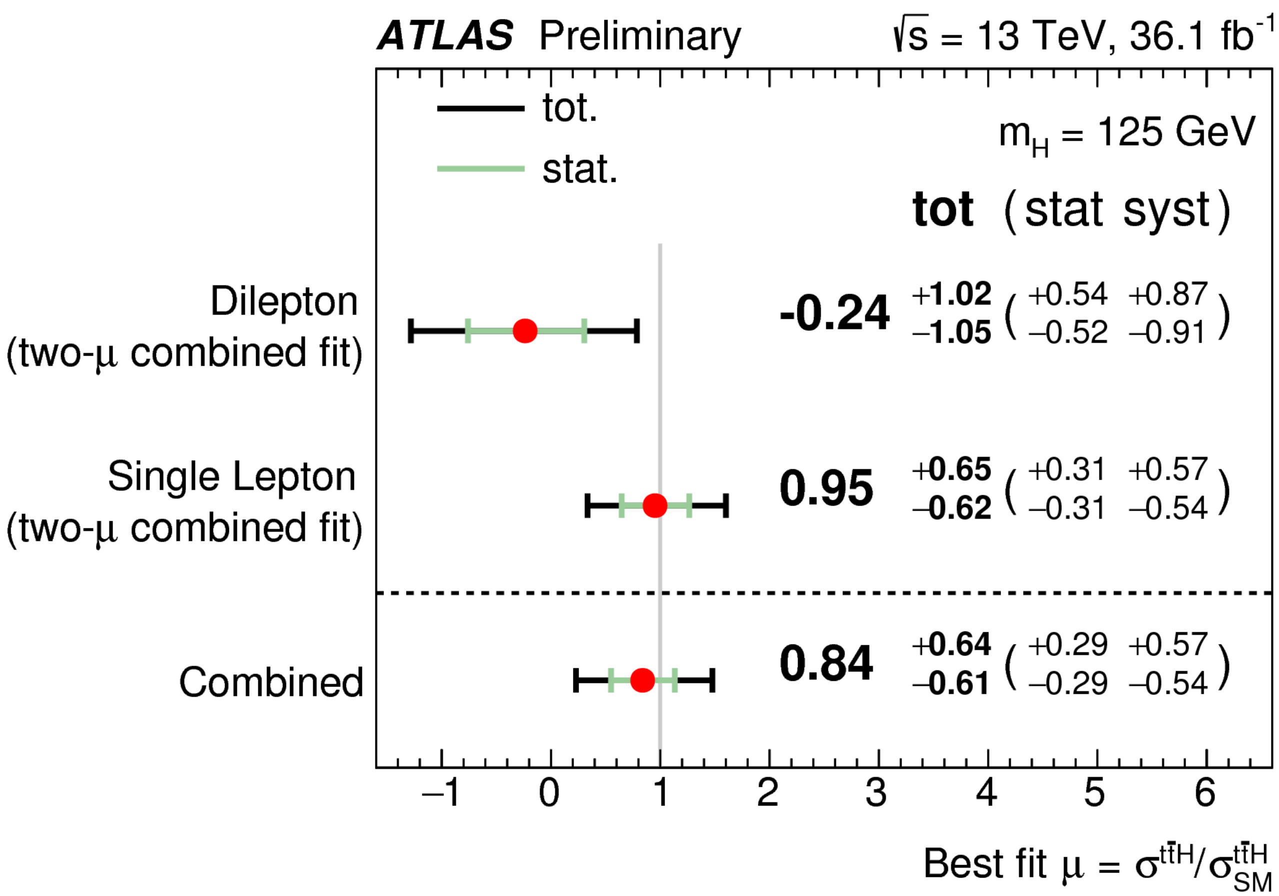
- The fit is done simultaneously in all SRs+CRs in single- and di-lepton channels.

All other regions are taken as bins in the fit

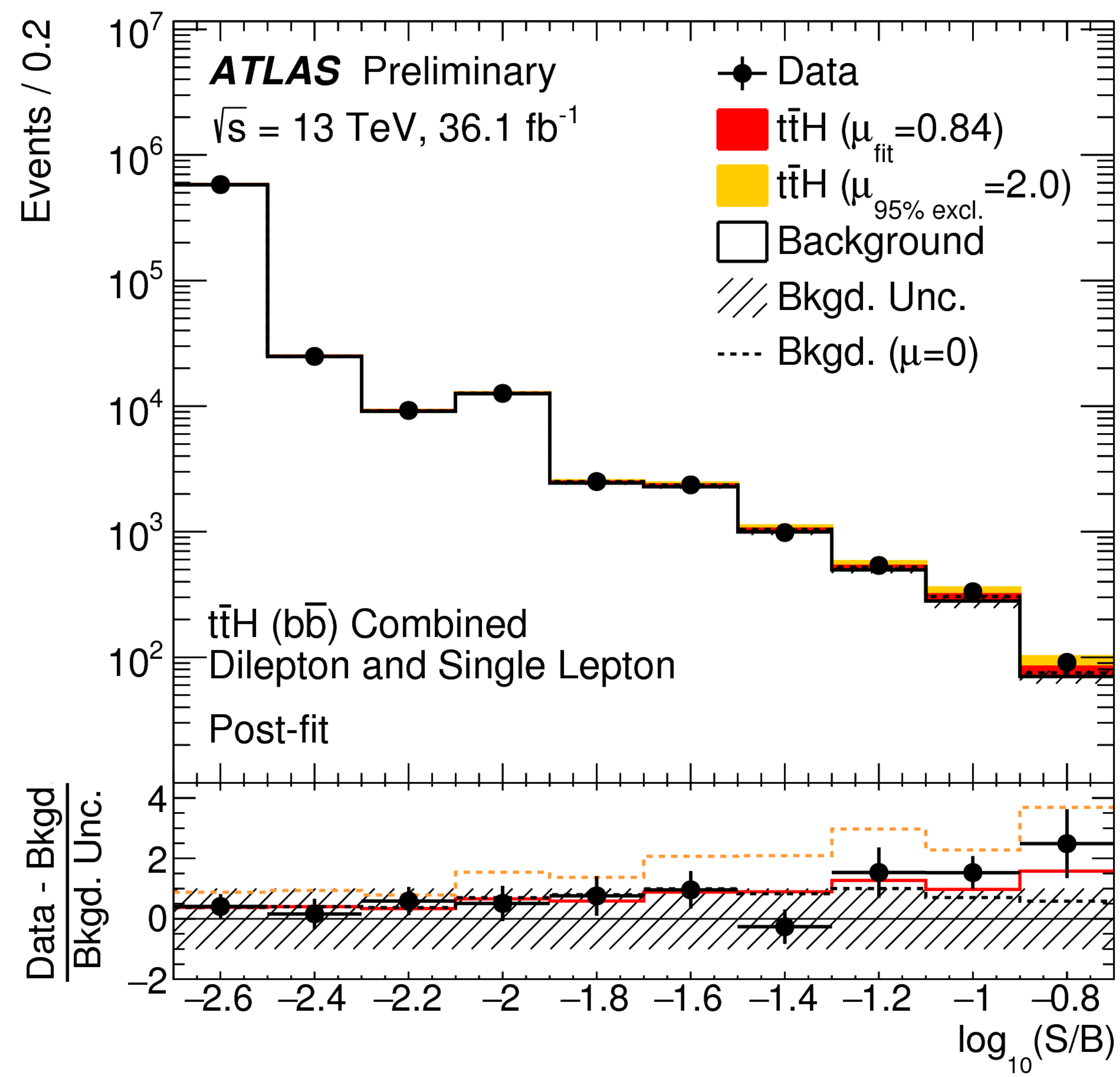


Results in ttH-bb analysis

The best-fit values of the ttH signal strength



Event yields as a function of $\log_{10}$(S/B)

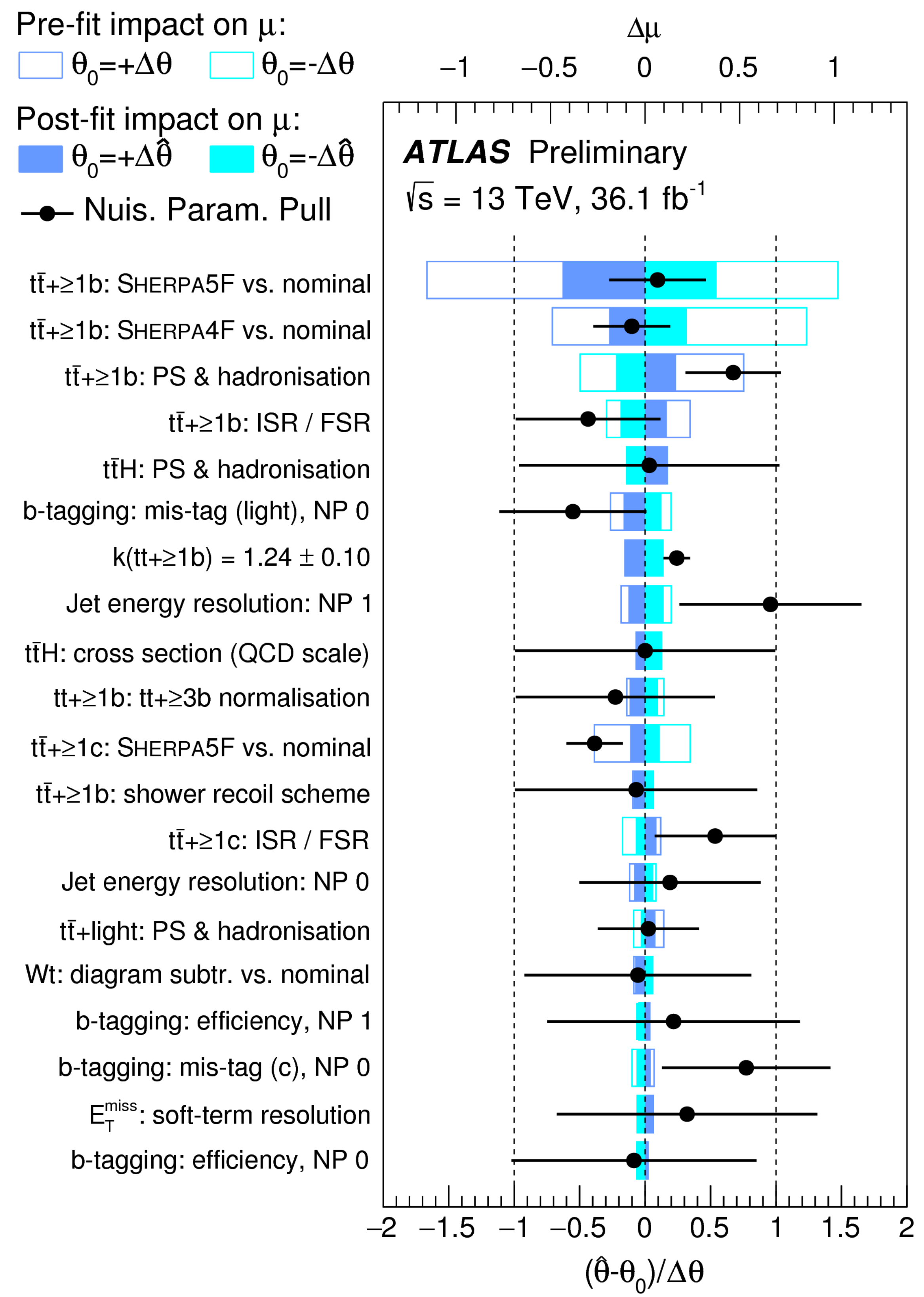


- ✦ The combined signal strength is $0.84^{+0.64}_{-0.61}$, which corresponds to 1.4**σ** (1.6**σ**) observed (expected) significance.
- ✦ The best-fit values of tt+ ≥1b, tt+ ≥1c normalisation factors are 1.24±0.10 and 1.63±0.23.

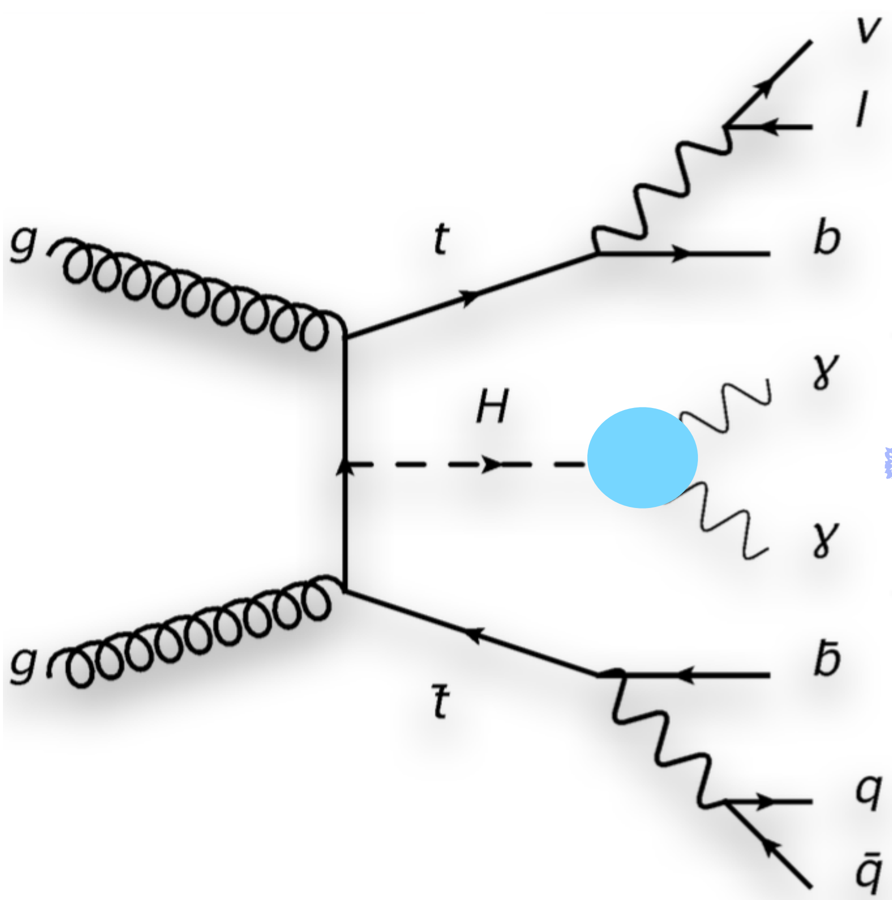
Summary of systematic uncertainties

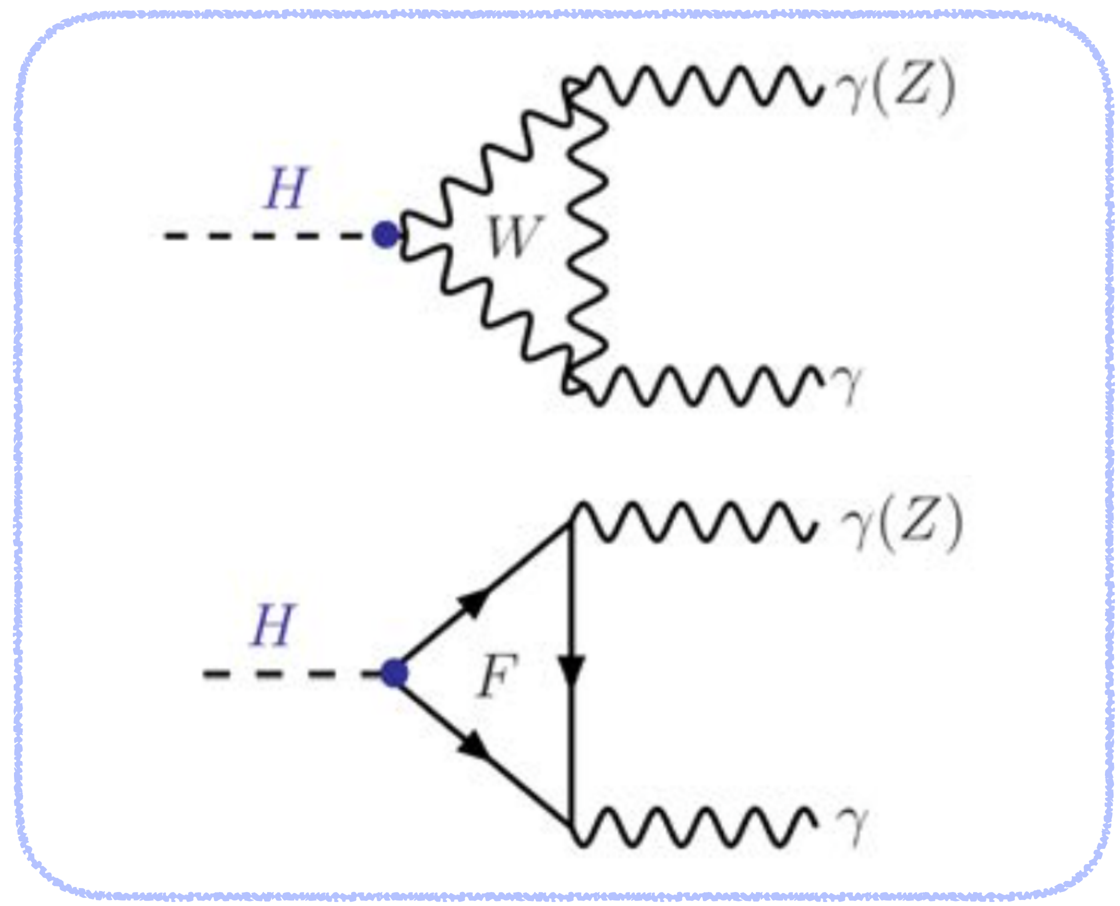
- Left: summary of the effects of the most important groups of systematic uncertainties.
- Right: the impact of systematic uncertainties in the fitted signal strength.

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.46	−0.46
Background model statistics	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modelling	+0.22	−0.05
$t\bar{t}+\geq 1c$ modelling	+0.09	−0.11
JVT, pileup modelling	+0.03	−0.05
Other background modelling	+0.08	−0.08
$t\bar{t}+$light modelling	+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
$t\bar{t}+\geq 1b$ normalisation	+0.09	−0.10
$t\bar{t}+\geq 1c$ normalisation	+0.02	−0.03
Intrinsic statistical uncertainty	+0.21	−0.20
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61



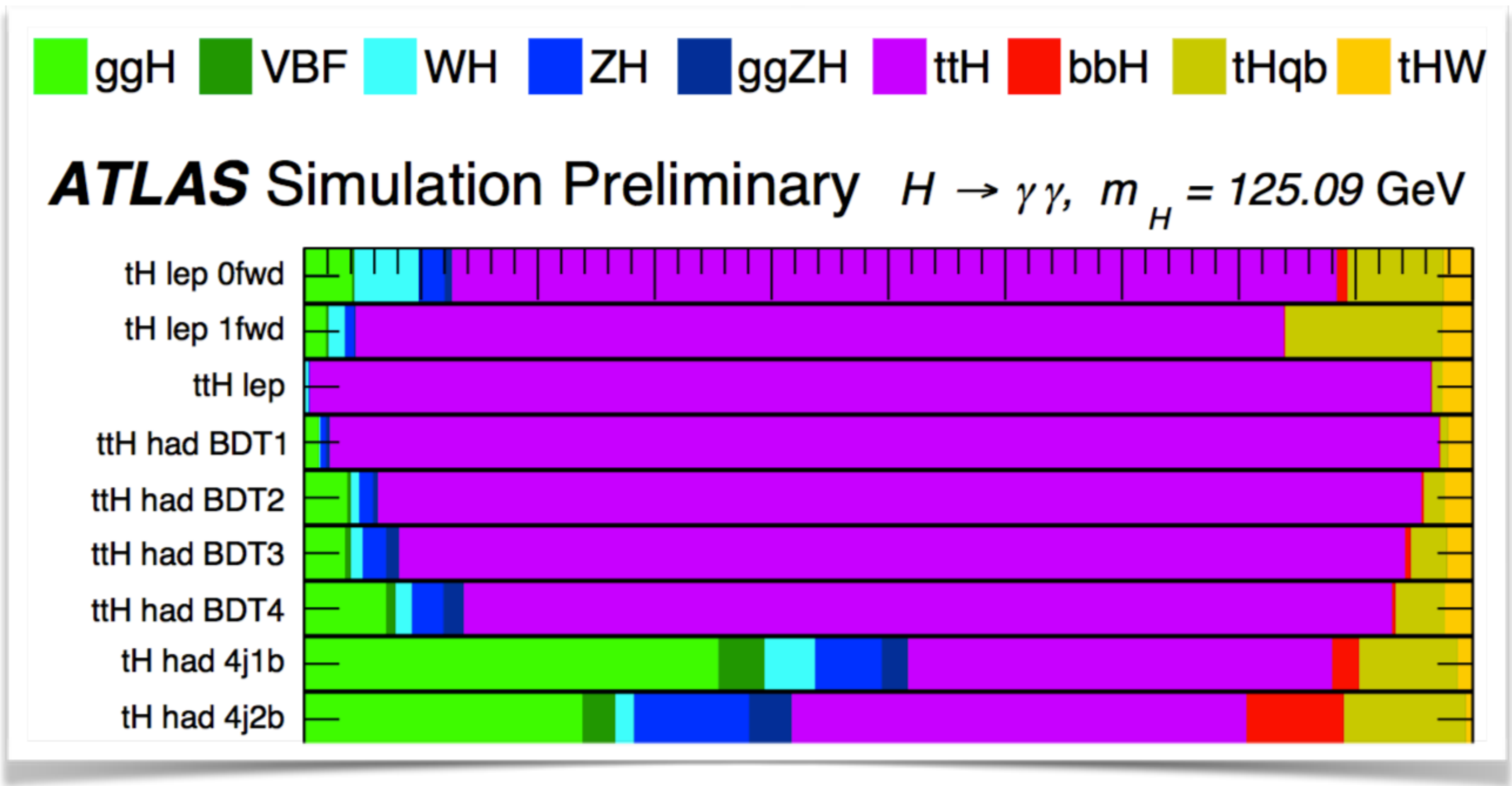
Search for ttH, Higgs decays to photon pair





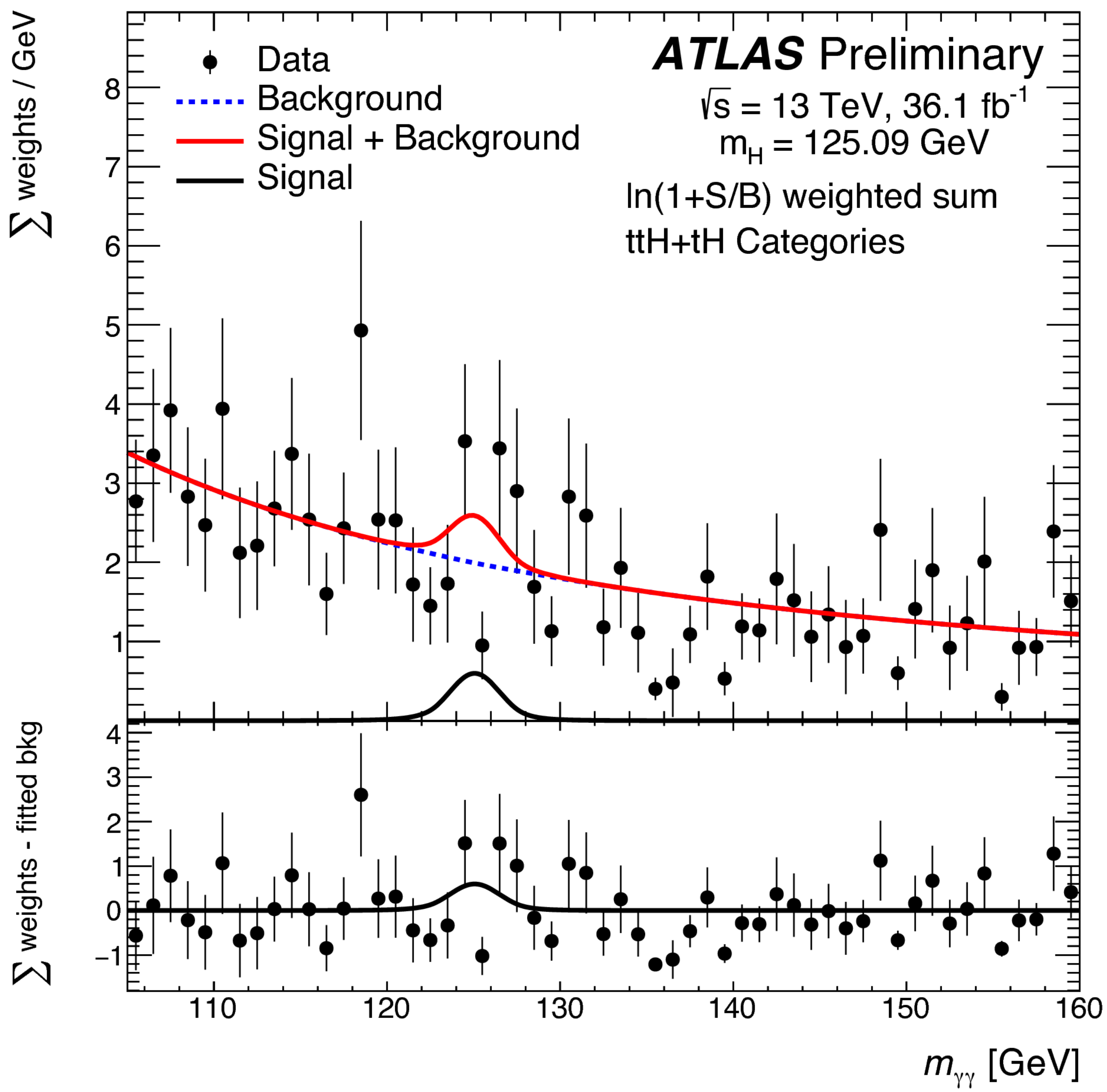
Event selection and classification

- Searching for a resonance on failing down background spectrum on $m_{\gamma\gamma}$.
- 14 ttH events and 95 backgrounds are expected after selection, under $m_{\gamma\gamma}$ peak.
- ttH and tH are classified in leptonic and hadronic categories according to tt (t) decay:
  - leptonic channel (≥ 1 lepton, ≥ 1 b-jet)
    - tH categories (==1 lepton): ≤ 3 jets, no forward jet; ≤ 4 jets + ≥ 1 forward jet
    - ttH category: ≥ 2 central jets, veto on Z boson mass window.
  - hadronic channel (≥ 3 jets, ≥ 1 b-jet)
    - ttH category employs BDT : ttH vs ggH and multijets
    - tH category requires exactly 4 jets with exactly 1 or 2 b-jets



Background estimation

- Background ($\gamma\gamma$+X, γ+jet+X, di-jet+X) distribution is modelled by exponential function, whose parameter is determined by fitting on $m_{\gamma\gamma}$ in data side-band region.

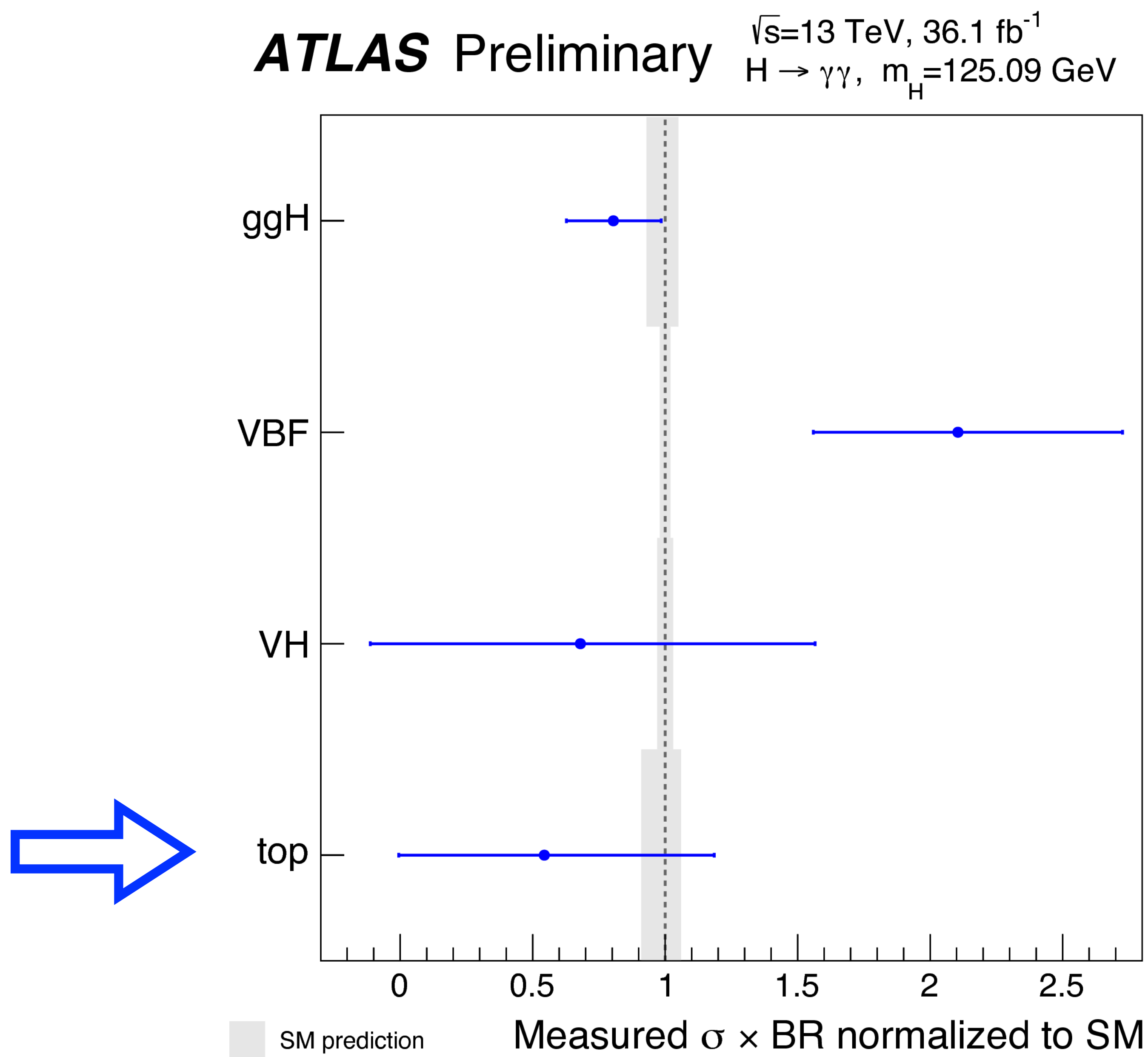


Expected yields of backgrounds and the SM signal in $m_{\gamma\gamma}$ region covering 90% of signal :

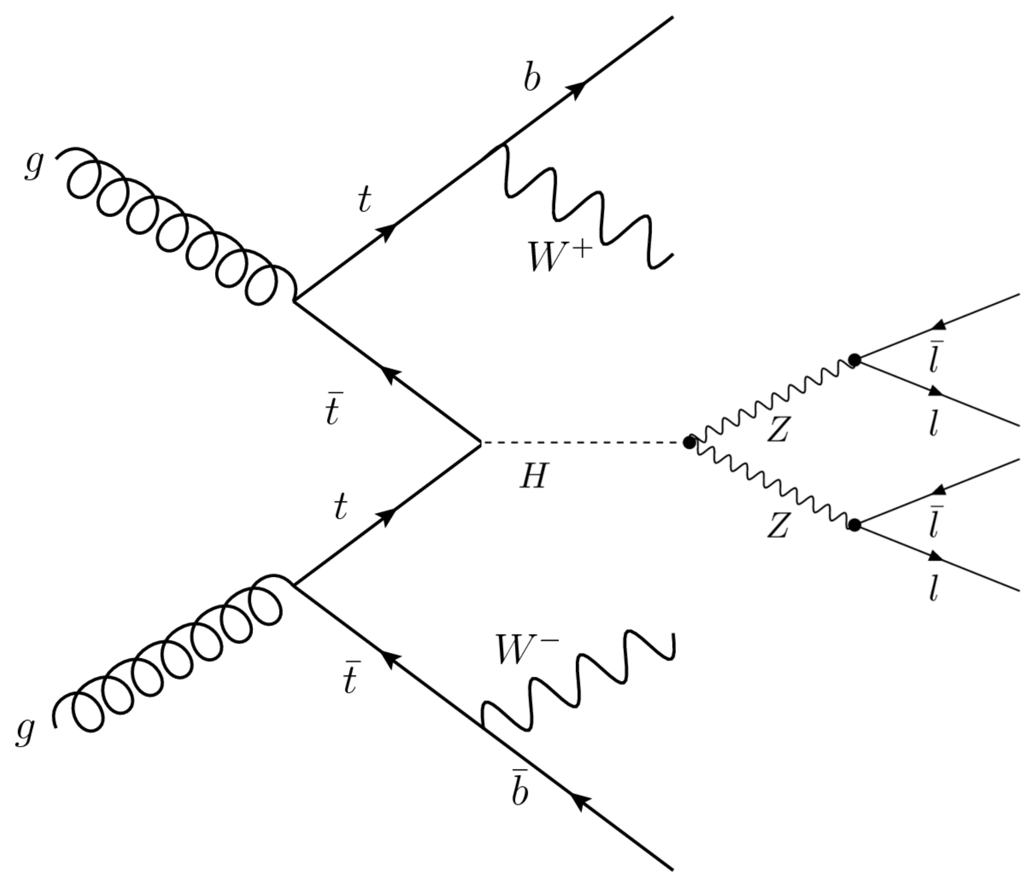
Category	B_{90}	S_{90}	f_{90}	Z_{90}
tHhad_4j2b	6.8	0.56	0.08	0.2
tHhad_4j1b	48	2.3	0.05	0.3
ttHhad_BDT4	14	2.3	0.14	0.6
ttHhad_BDT3	2.3	0.55	0.19	0.4
ttHhad_BDT2	3.9	1.6	0.29	0.8
ttHhad_BDT1	2.0	1.3	0.40	0.9
ttHlep	2.7	2.2	0.44	1.2
tHlep_1fwd	1.9	1.0	0.35	0.7
tHlep_0fwd	3.6	0.92	0.20	0.5

Results in ttH-$\gamma\gamma$ analysis

✦ The measured ttH signal strength is $\mu_{top} = 0.5\,^{+0.6}_{-0.6} = 0.5\,^{+0.6}_{-0.5}\,\text{(stat.)}\,^{+0.1}_{-0.1}\,\text{(exp.)}\,^{+0.1}_{-0.0}\,\text{(theory)}$. which corresponds to 1.0**σ** (1.8**σ**) observed (expected) significance.

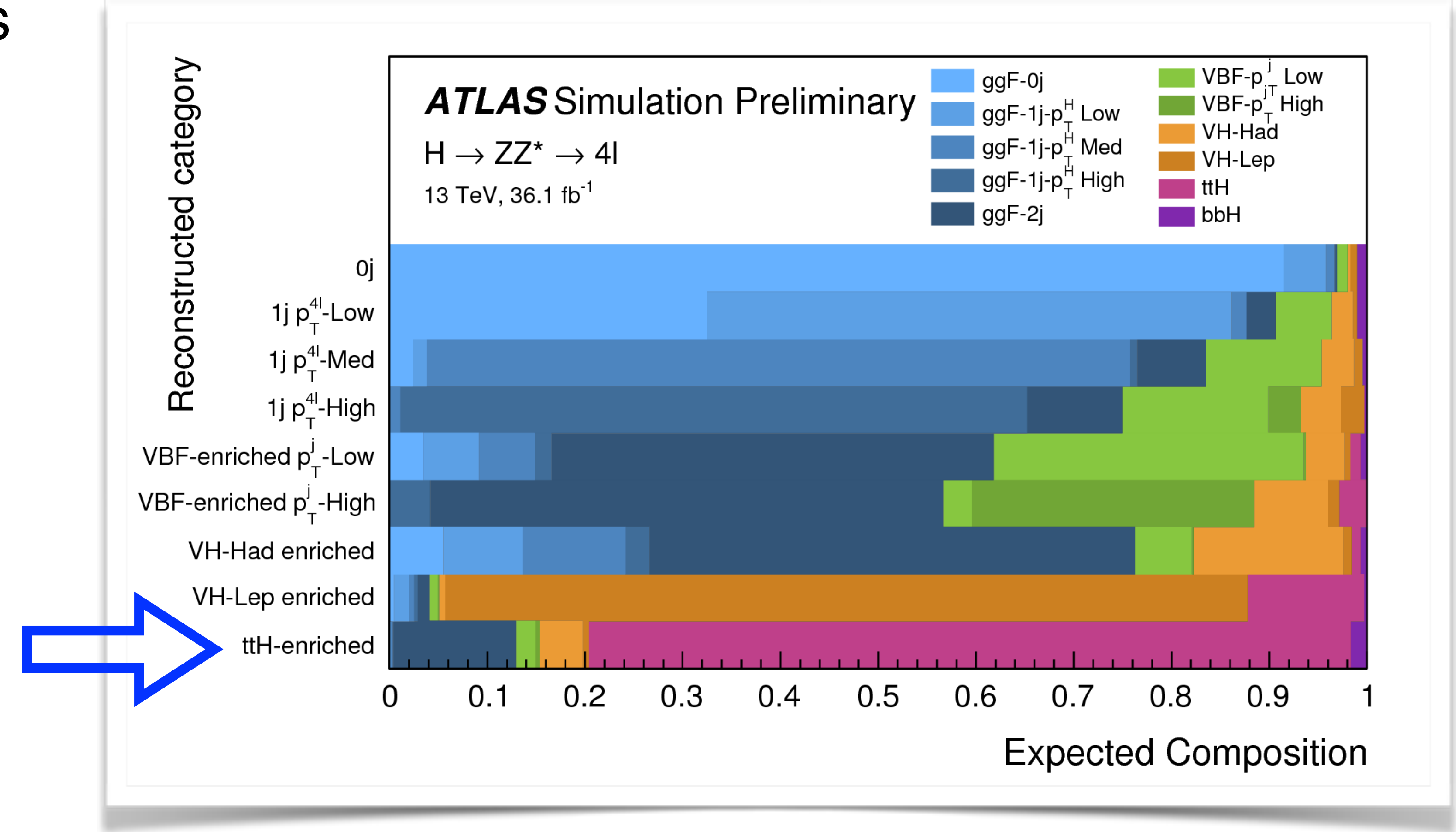


Search for ttH, Higgs decays to ZZ*→4l



Rare decay channel, but very clean

- Higgs candidate within m_{4l} mass window [118,129] GeV, and ≥ 1 b-jet + ≥ 4 jets (or 1l + ≥ 2 jets).
- There are 0.39 ttH (0.08 bkg.) events expected in ttH category.
- No event is observed in data.
- Upper limit on the ttH signal strength is 1.9 at 68% C.L.



Reconstructed category	Signal	ZZ^*	Other backgrounds	Total expected	Observed
ttH-enriched	0.39 ± 0.04	0.014 ± 0.006	0.07 ± 0.04	0.47 ± 0.05	0

ttH searches combination

combining analyses using 36.1 fb^{-1} collision data collected in ATLAS Run 2

ttH analyses combination in ATLAS Run 2

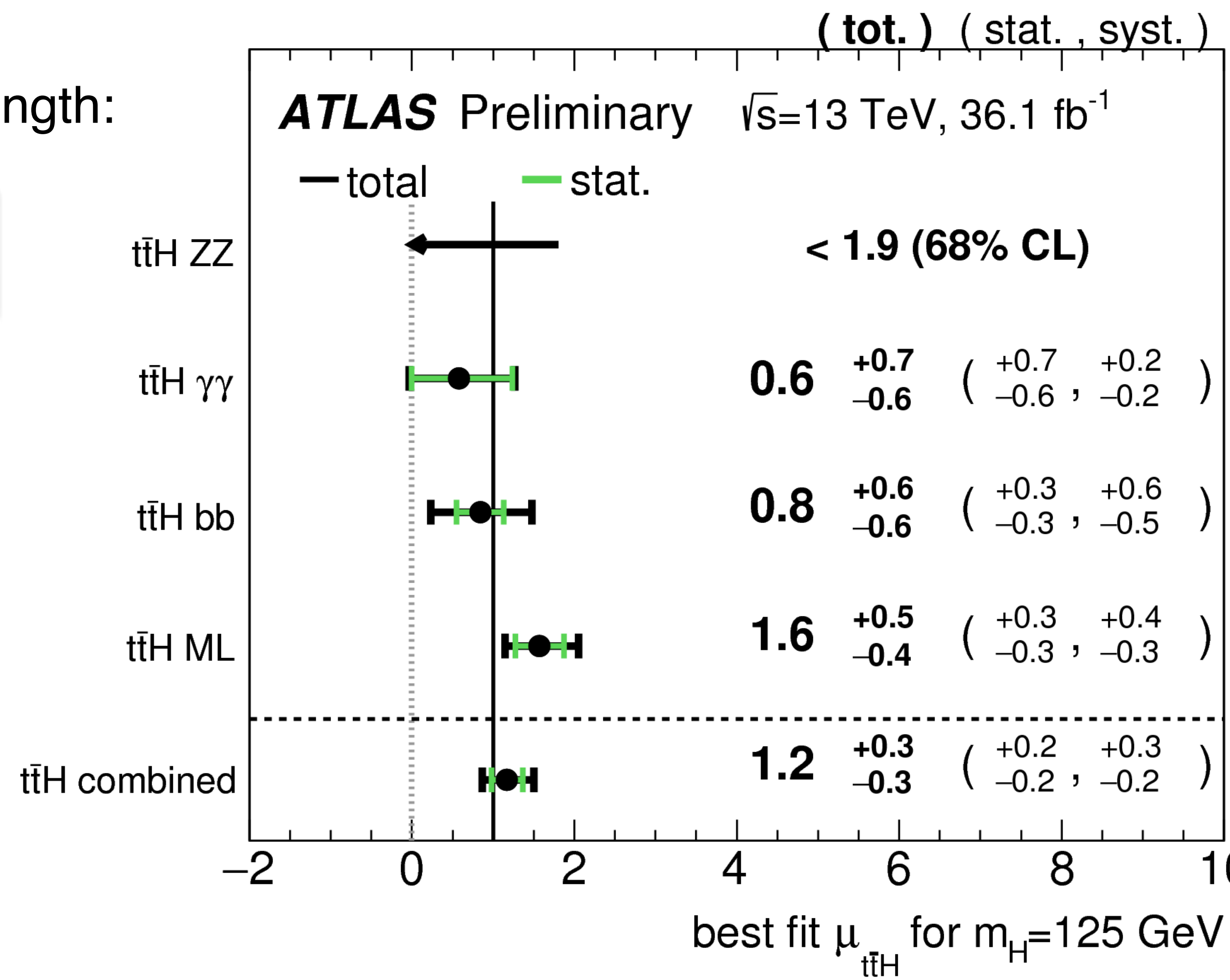
- Combination of the four ATLAS Run 2 analyses: multileptons, bb, $\gamma\gamma$ and ZZ→4l
  - all results are based on 36.1 fb^{-1} data collected at $\sqrt{s}$ = 13 TeV
  - ttH signal strength is the only parameter of interest (tH as background)

- Combination on the ttH signal strength:

$$\mu = 1.17 \pm 0.19\,(\text{stat})\,^{+0.27}_{-0.23}\,(\text{syst})$$

- The background-only hypothesis is excluded at 4.2σ, with an expectation of 3.8σ in the case of a SM signal !

- The measured ttH cross section is $590\,^{+160}_{-150}$ fb, in good agreement with the SM prediction $507\,^{+35}_{-50}$ fb.



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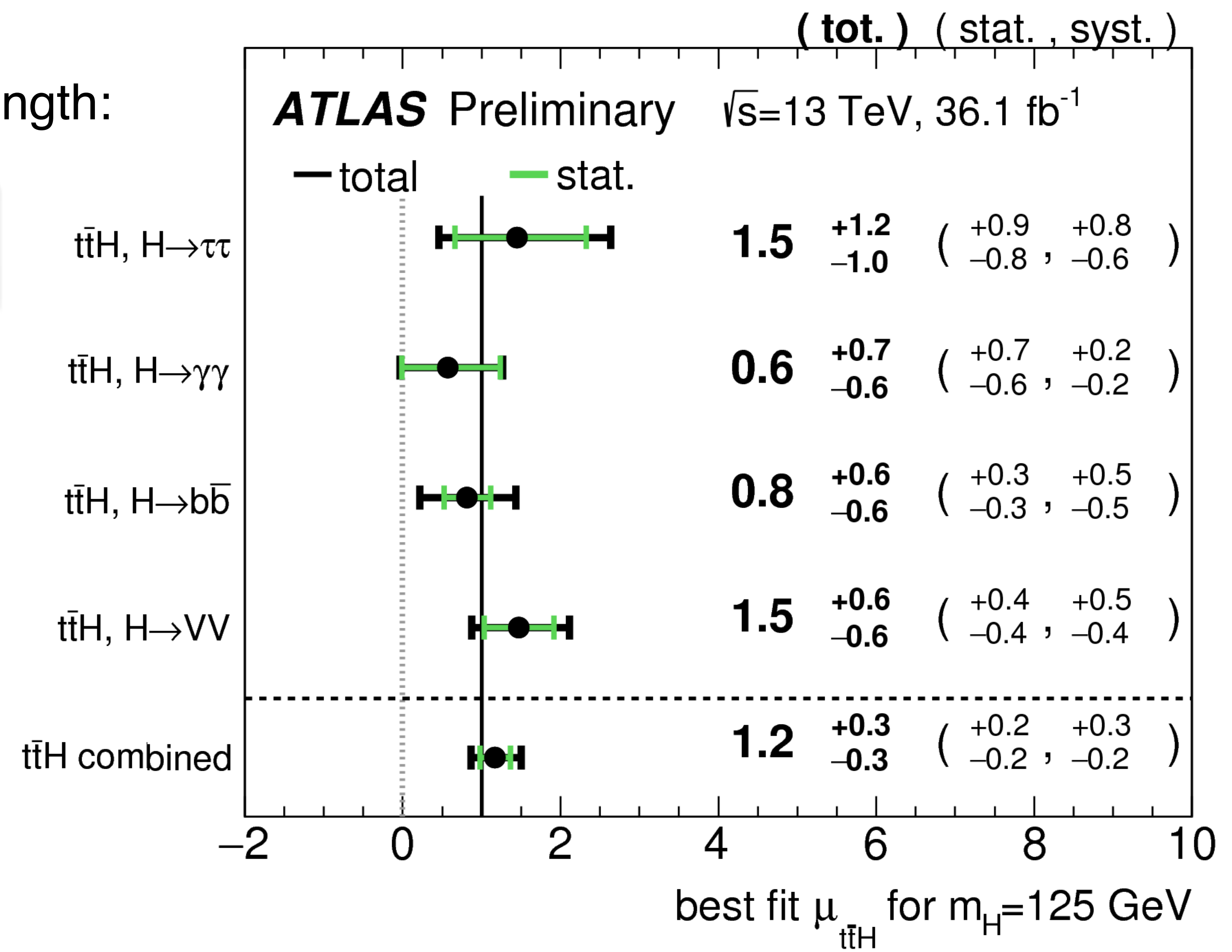


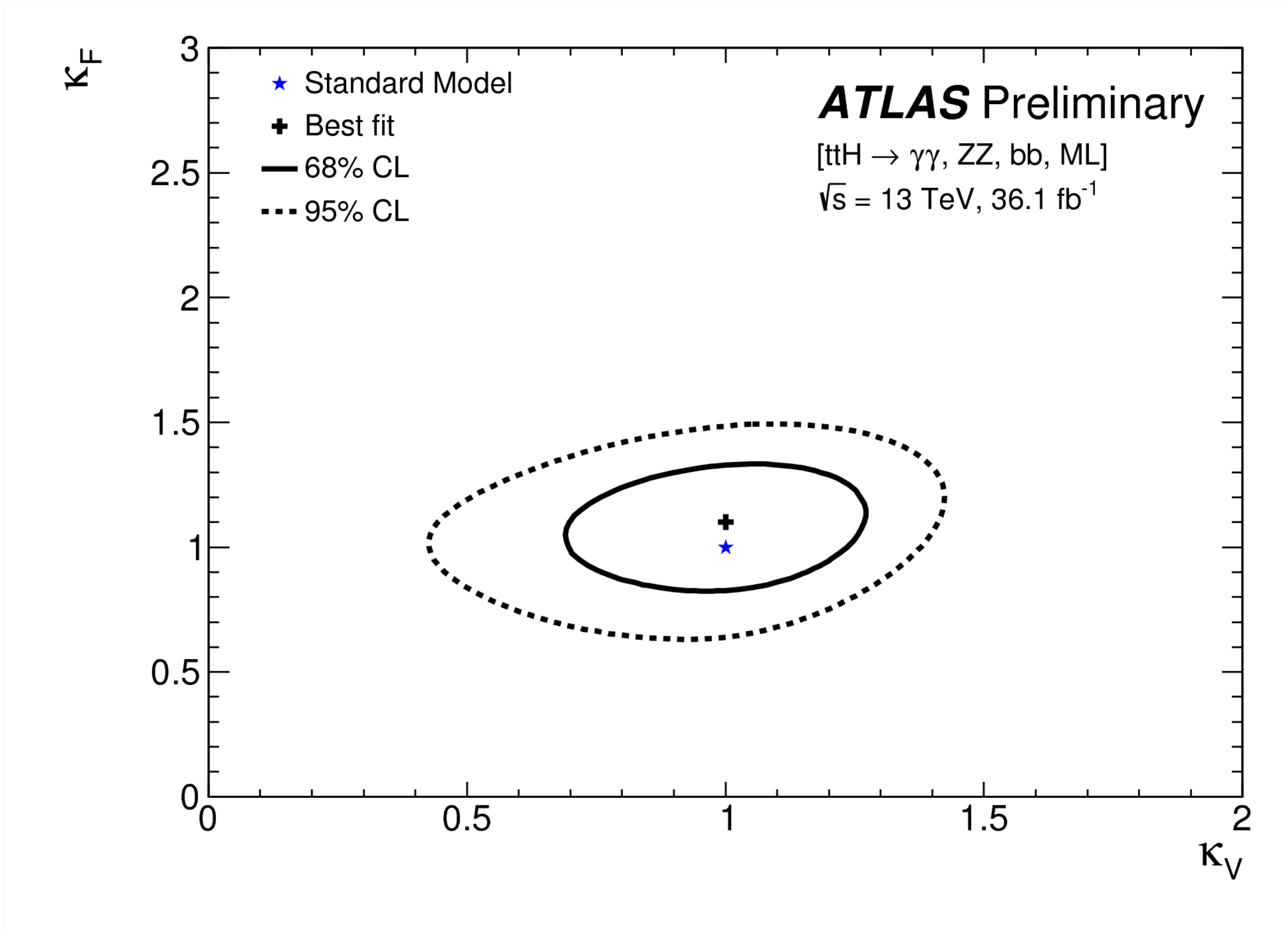
ttH combination uncertainties

- The impact of systematic uncertainties in the fitted signal strength.

Uncertainty Source	$\Delta\mu$	
$t\bar{t}$ modelling in $H \to bb$ analysis	+0.15	−0.14
$t\bar{t}H$ modelling (cross section)	+0.13	−0.06
Non-prompt light-lepton and fake τ_{had} estimates	+0.09	−0.09
Simulation statistics	+0.08	−0.08
Jet energy scale and resolution	+0.08	−0.07
$t\bar{t}V$ modelling	+0.07	−0.07
$t\bar{t}H$ modelling (acceptance)	+0.07	−0.04
Other non-Higgs boson backgrounds	+0.06	−0.05
Other experimental uncertainties	+0.05	−0.05
Luminosity	+0.05	−0.04
Jet flavour tagging	+0.03	−0.02
Modelling of other Higgs boson production modes	+0.01	−0.01
Total systematic uncertainty	+0.27	−0.23
Statistical uncertainty	+0.19	−0.19
Total uncertainty	+0.34	−0.30

Result interpretation in κ-parametrisation

- κ is a linear scale factor to Higgs coupling parameter.
- ttH analyses are sensitive to Higgs coupling to fermions (κ_F) and to bosons (κ_V).



- The measurement is in good agreement with the SM prediction.

Summary

- Search for ttH production has been performed in ATLAS using 36.1 fb^{-1} dataset at $\sqrt{s}$ = 13 TeV, in final states of multilpetons, bb, $\gamma\gamma$ and $ZZ^* \rightarrow 4l$.
- The background-only hypothesis is excluded at 4.2σ, with an expectation of 3.8σ in the case of a SM signal. This constitutes evidence for ttH production !
- For a Higgs boson at 125 GeV, the measured signal strength is

$$\mu = 1.17 \pm 0.19\,(\text{stat})\,^{+0.27}_{-0.23}\,(\text{syst})$$

- The measured cross section is $590\,^{+160}_{-150}$ fb , which is in good agreement with the SM prediction.


ttH evidence

Backup

Selection criteria in multilepton signal regions - I

Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b-\text{jets}} \geq 1$
2ℓSS	Two very tight light leptons with $p_{\text{T}} > 20$ GeV Same charge light leptons Zero medium τ_{had} candidates $N_{\text{jets}} \geq 4$; $N_{b-\text{jets}} < 3$
3ℓ	Three light leptons with $p_{\text{T}} > 10$ GeV; sum of light lepton charges ± 1 Two same-charge leptons must be very tight and have $p_{\text{T}} > 15$ 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)

Selection criteria in multilepton signal regions - II

$1\ell+2\tau_{\rm had}$	One tight light lepton, with $p_{\rm T} > 27$ GeV Two medium $\tau_{\rm had}$ candidates of opposite charge, at least one being tight $N_{\rm jets} \geq 3$
$2\ell{\rm SS}+1\tau_{\rm had}$	Two very tight light leptons with $p_{\rm T} > 15$ GeV Same charge light leptons One medium $\tau_{\rm had}$ candidate, of opposite charge to that of the light leptons $N_{\rm jets} \geq 4$ $\lvert m(ee) - 91.2\ {\rm GeV}\rvert > 10$ GeV for ee events
$2\ell{\rm OS}+1\tau_{\rm had}$	Two loose and isolated light leptons, with $p_{\rm T} > 25$, 15 GeV One medium $\tau_{\rm had}$ candidate Opposite charge light leptons One medium $\tau_{\rm had}$ candidate $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\ {\rm GeV}\rvert > 10$ GeV for all SFOC pairs $N_{\rm jets} \geq 3$
$3\ell+1\tau_{\rm had}$	3ℓ selection, except: One medium $\tau_{\rm had}$ candidate, of opposite charge to the total charge of the light leptons The two same-charge leptons must be tight and have $p_{\rm T} > 10$ GeV The opposite-charge lepton must be loose and isolated

Selection criteria in multilepton control regions

Channel	Region	Selection criteria
2ℓSS		$2 \leq N_{\text{jets}} \leq 3$ and $N_{b-\text{jets}} \geq 1$
(3ℓ)		One very tight, one loose light lepton with $p_{\text{T}} > 20$ (15) GeV
		Zero τ_{had} candidates
	ϵ_{real}	Opposite charge; opposite flavour
	ϵ_{fake}	Same charge; opposite flavour or $\mu\mu$
4ℓ		$1 \leq N_{\text{jets}} \leq 2$
		Three loose light leptons; sum of light lepton charges ± 1
		Subleading same-charge lepton must be tight
		Veto on 3ℓ selection
	Either	One SFOC pair with $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert < 10$ GeV
		$E_{\text{T}}^{\text{miss}} < 50$ GeV, $m_T < 50$ GeV
	or	No SFOC pair
		Subleading jet $p_{\text{T}} > 30$ GeV
2ℓSS+$1\tau_{\text{had}}$		$2 \leq N_{\text{jets}} \leq 3$ and $N_{b-\text{jets}} \geq 1$
		One very tight, one loose light lepton with $p_{\text{T}} > 15$ GeV
		A SFSC pair
		$\lvert m(ee) - 91.2\text{ GeV}\rvert > 10$ GeV
		Zero or one medium τ_{had} candidate, of opposite charge to the light leptons
1ℓ+$2\tau_{\text{had}}$		$N_{\text{jets}} \geq 3$ and $N_{b-\text{jets}} \geq 1$
		One tight light lepton, with $p_{\text{T}} > 27$ GeV
		Two τ_{had} candidates of same charge
		At least one τ_{had} candidate has to pass tight identification criteria
2ℓOS+$1\tau_{\text{had}}$		Two loose and isolated light leptons, with $p_{\text{T}} > 25$, 15 GeV
		$\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV and $m(\ell^+\ell^-) > 12$ GeV
		$N_{\text{jets}} \geq 3$ and $N_{b-\text{jets}} = 0$

The MC configurations in multileptons analysis

Process	Generator	ME order	Parton Shower	PDF	Tune
$t\bar{t}H$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO [71]	A14
	(MG5_aMC)	(NLO)	(Herwig++)	(CT10 [72])	(UE-EE-5)
$tHqb$	MG5_aMC	LO	Pythia 8	CT10	A14
tHW	MG5_aMC	NLO	Herwig++	CT10	UE-EE-5
$t\bar{t}W$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO	A14
	(Sherpa 2.1.1)	(LO multileg)	(Sherpa)	(NNPDF 3.0 NLO)	(Sherpa default)
$t\bar{t}(Z/\gamma^* \to \ell\ell)$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO	A14
	(Sherpa 2.1.1)	(LO multileg)	(Sherpa)	(NNPDF 3.0 NLO)	(Sherpa default)
tZ	MG5_aMC	LO	Pythia 6	CTEQ6L1	Perugia2012
tWZ	MG5_aMC	NLO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}t$, $t\bar{t}t\bar{t}$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}W^+W^-$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}$	Powheg-BOX v2 [73]	NLO	Pythia 8	NNPDF 3.0 NLO	A14
$t\bar{t}\gamma$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
s-, t-channel, Wt single top	Powheg-BOX v1 [74,75]	NLO	Pythia 6	CT10	Perugia2012
$VV(\to \ell\ell XX)$, $qqVV$, VVV	Sherpa 2.1.1	MEPS NLO	Sherpa	CT10	Sherpa default
$Z \to \ell^+\ell^-$	Sherpa 2.2	MEPS NLO	Sherpa	NNPDF 3.0 NLO	Sherpa default

The cross sections used in MC samples

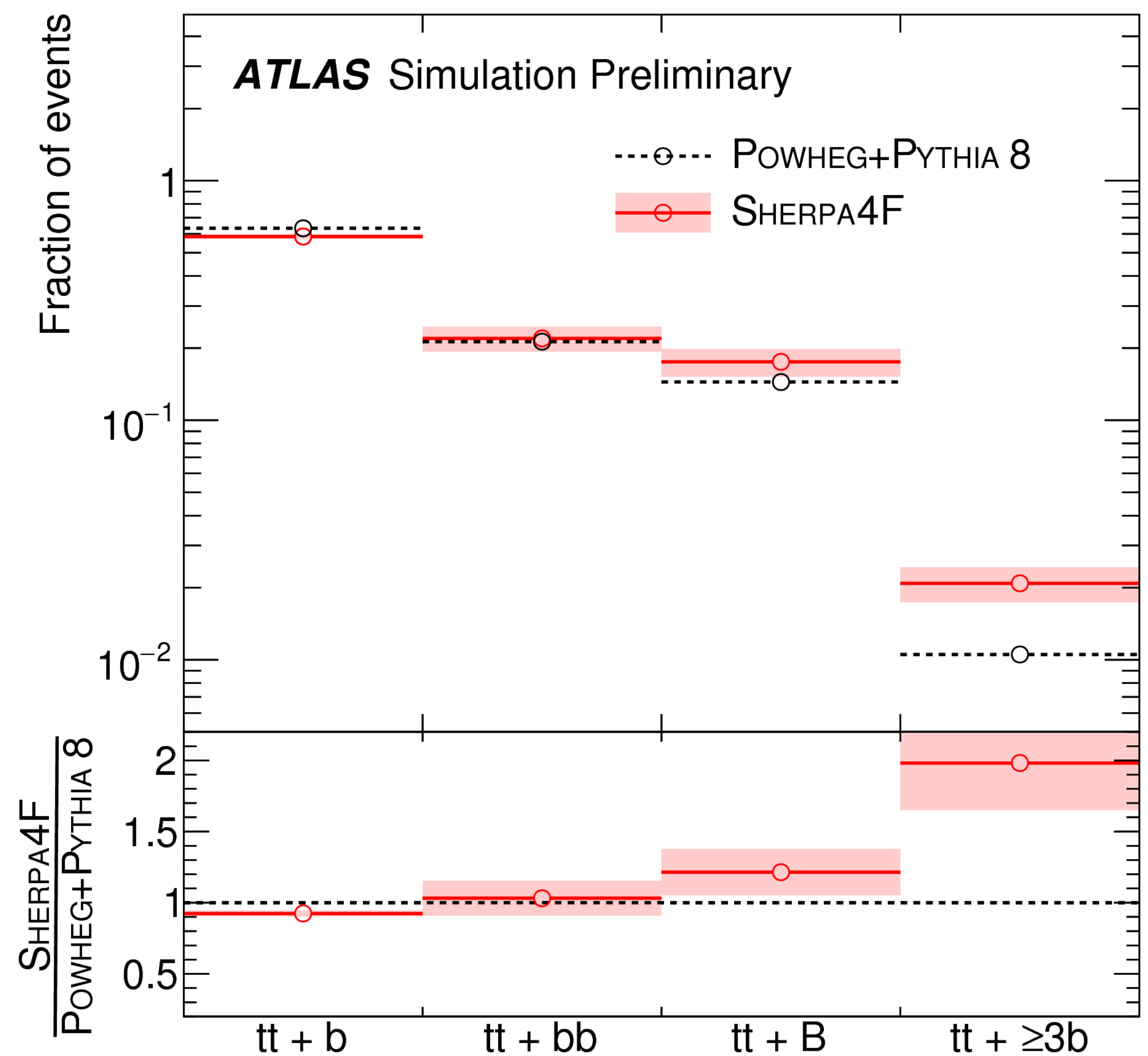
Process	Cross section [pb]	QCD scale [%]	PDF+α_S [%]	Order
$t\bar{t}H$	0.51	$^{+5.8}_{-9.2}$	± 3.6	NLO QCD+EWK
$tHqb$	0.074	$^{+6.5}_{-14.7}$	± 3.7	NLO QCD
tHW	0.015	$^{+4.9}_{-6.7}$	± 6.3	NLO QCD
$t\bar{t}W$	0.60	$^{+12.9}_{-11.5}$	± 3.4	NLO QCD+EWK
$t\bar{t}(Z/\gamma^* \to \ell\ell)$	0.12	$^{+9.6}_{-11.3}$	± 4.0	NLO QCD+EWK
$t\bar{t}t\bar{t}$	0.0092	$^{+30.8}_{-25.6}$	$^{+5.5}_{-5.9}$	NLO QCD
$t\bar{t}W^+W^-$	0.0099	$^{+10.9}_{-11.8}$	± 2.1	NLO QCD
$t\bar{t}$	832	$^{+2.4}_{-3.5}$	± 4.2	NNLO QCD + NNLL
$t\bar{t}\gamma$	5.7	± 50		NLO QCD
tZ	0.61	± 50		LO QCD
tWZ	0.16	± 50		NLO QCD
s-, t-channel,	10, 217	± 4		NLO QCD
Wt single top	72	± 5		NLO QCD + NNLL
$VV(\to \ell\ell XX)$	37	± 50		NLO QCD
$Z \to \ell^+\ell^-$	2070	± 5		NNLO QCD

Background, signal and observed yields in the 12 multileptons analysis channels

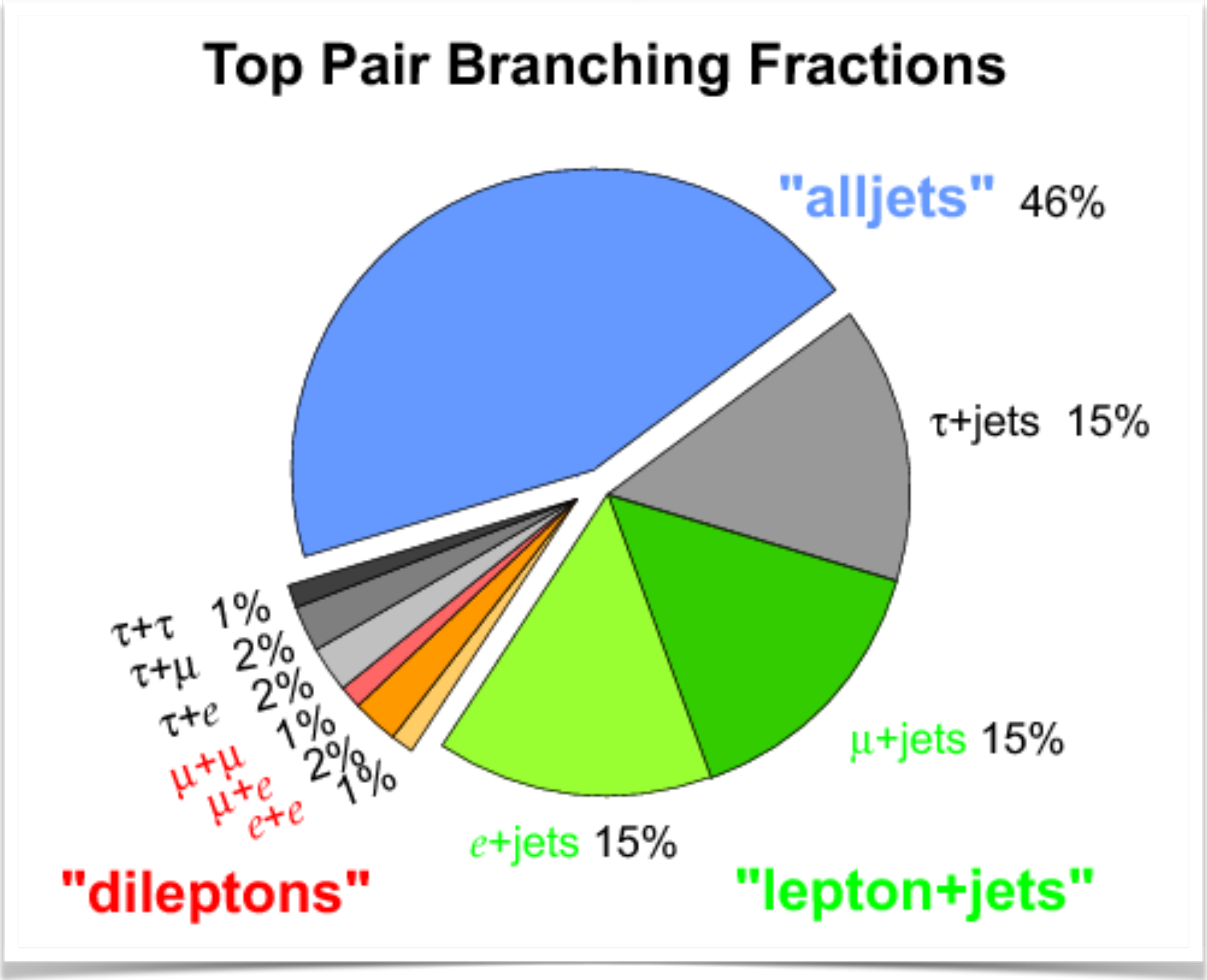
Category	Non-prompt	Fake τ_{had}	q mis-id	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Other	Total Bkgd.	$t\bar{t}H$	Observed
					Pre-fit yields					
2ℓSS	233 ± 39	–	33 ± 11	123 ± 18	41.4 ± 5.6	25 ± 15	28.4 ± 5.9	484 ± 38	42.6 ± 4.2	514
3ℓ SR	14.5 ± 4.3	–	–	5.5 ± 1.2	12.0 ± 1.8	1.2 ± 1.2	5.8 ± 1.4	39.1 ± 5.2	11.2 ± 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
$1\ell+2\tau_{\text{had}}$	–	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
$3\ell+1\tau_{\text{had}}$	–	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
$1\ell+2\tau_{\text{had}}$	–	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
$3\ell+1\tau_{\text{had}}$	–	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

tt+ ≥1b backgrounds sub-categories re-weight

✦ The relevant contributions of sub-categories, tt+≥3b, tt+bb, tt+B and tt+b, in Powheg+Pythia8 are scaled to match the predictions of an NLO tt + bb sample including Parton shower and hadronisation, generated with Sherpa+OpenLoops. The sample is produced with Sherpa version 2.1 and the CT10 four-flavour scheme PDF set.



Top pair decay branching fractions



Reconstructed m_{bb}