Evidence for ttH production with the ATLAS DETECTOR

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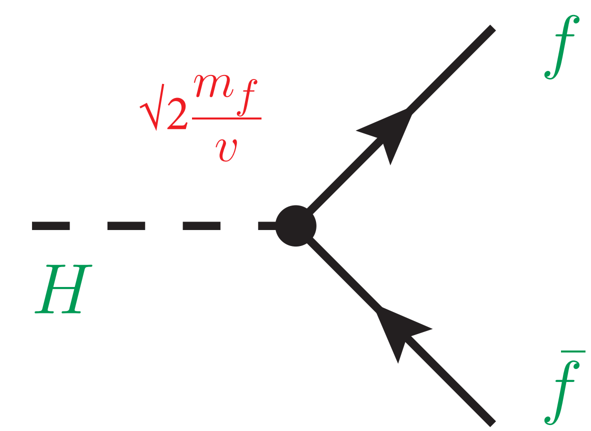
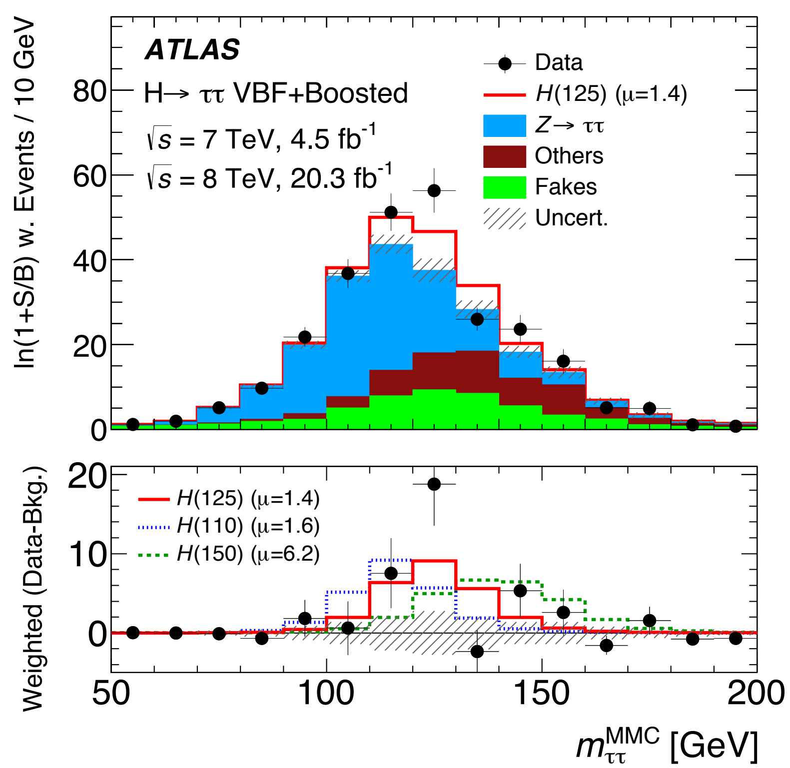
ATLAS EXPERIMENT

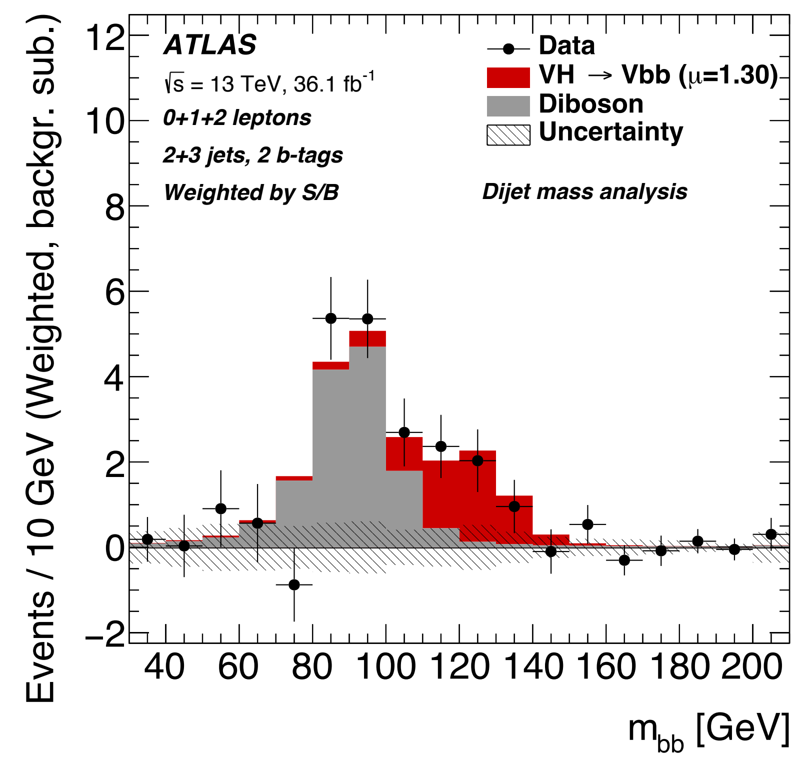
- The measurement of the Higgs properties is the most important challenge after its discovery
- Fermion masses arise in the SM only as consequence of the EWSB through the Yukawa interaction



JHEP 04 (2015) 117



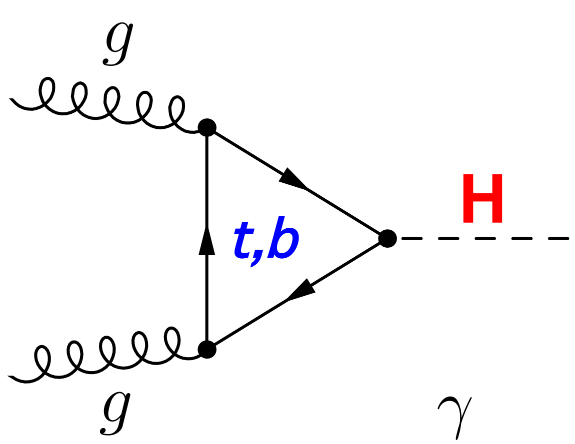
arXiv:1708.03299

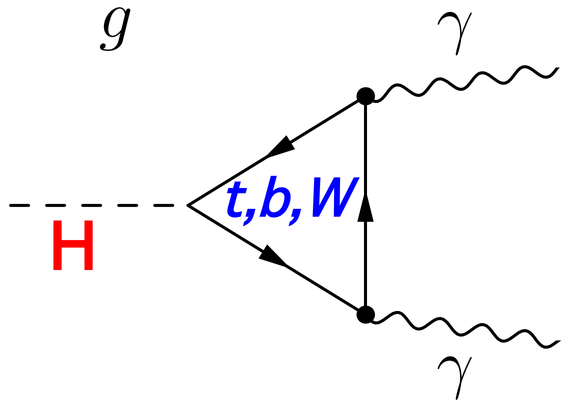


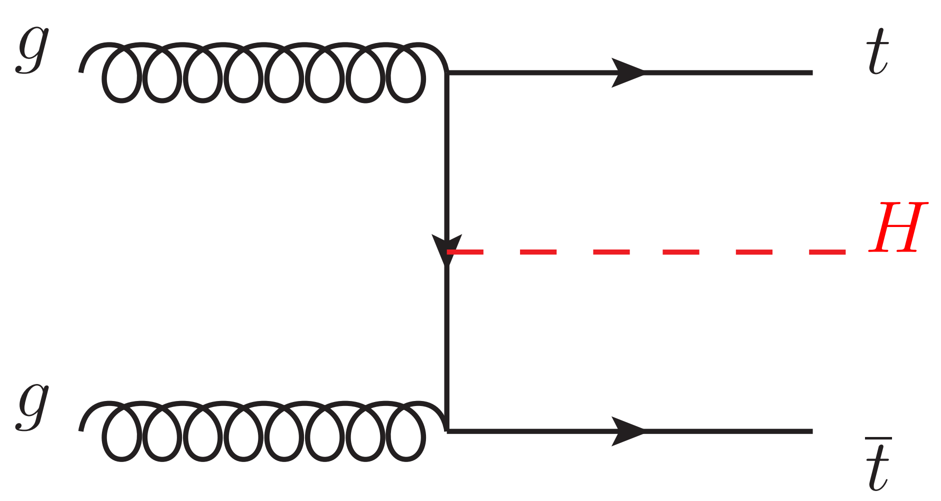
- Experimentally observations:
  - Tau Yukawa coupling observed in H → ττ decays
  - Evidence of bottom-quark Yukawa coupling through H → bb decay

MOTIVATION - Top-quark coupling to Higgs

- Since the top-quark is the heaviest particle in the SM, it has the largest Yukawa coupling → $\lambda_{top} \sim 1$
- Indirect constraints on λ_{top} comes from loops interactions of the Higgs boson:
  - gluon-gluon fusion production (ggF) of the Higgs boson
  - di-photon decay of the Higgs boson







- The production of Higgs boson with a top-quark pair ttH allows the study direct top-quark Yukawa coupling:
  - Leading Order process, cross-section ~ λ_{top}^2

After the direct measurement of λ_{top} one can subtract this term and look for possible BSM contributions in the loop!

LHC RUN1 results for λ_{top}

- Run1 results for the ratio of the measured coupling over the one expected from the SM

JHEP 1608 (2016) 045

Parameter	ATLAS+CMS Measured	ATLAS Measured	CMS Measured
κ_t	$0.87^{+0.15}_{-0.15}$	$0.98^{+0.21}_{-0.20}$	$0.77^{+0.20}_{-0.18}$

- Run1 results for the ratio between the measured cross-section and the one expected from the SM

JHEP 1608 (2016) 045

Production process	ATLAS+CMS	ATLAS	CMS
μ_{ttH}	$2.3\ ^{+0.7}_{-0.6}$	$1.9\ ^{+0.8}_{-0.7}$	$2.9\ ^{+1.0}_{-0.9}$

SM prediction is in good agreement with data observed

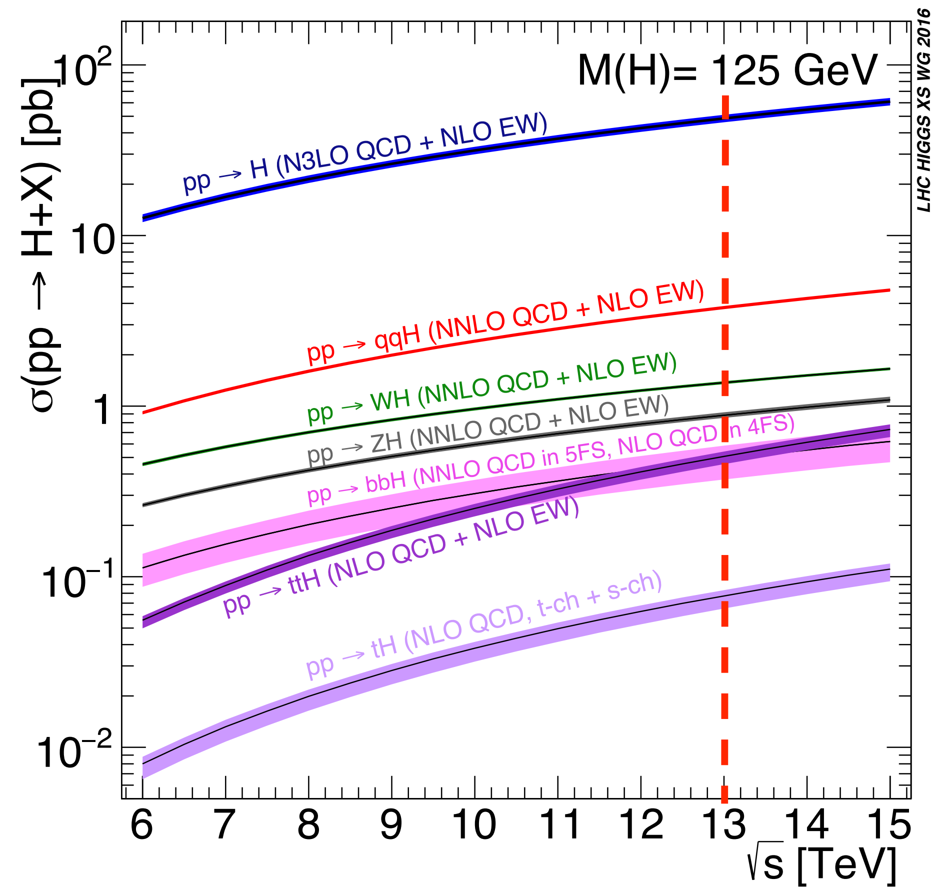
The results of the ttH explorative analysis are expressed in term of the signal-strength defined as:

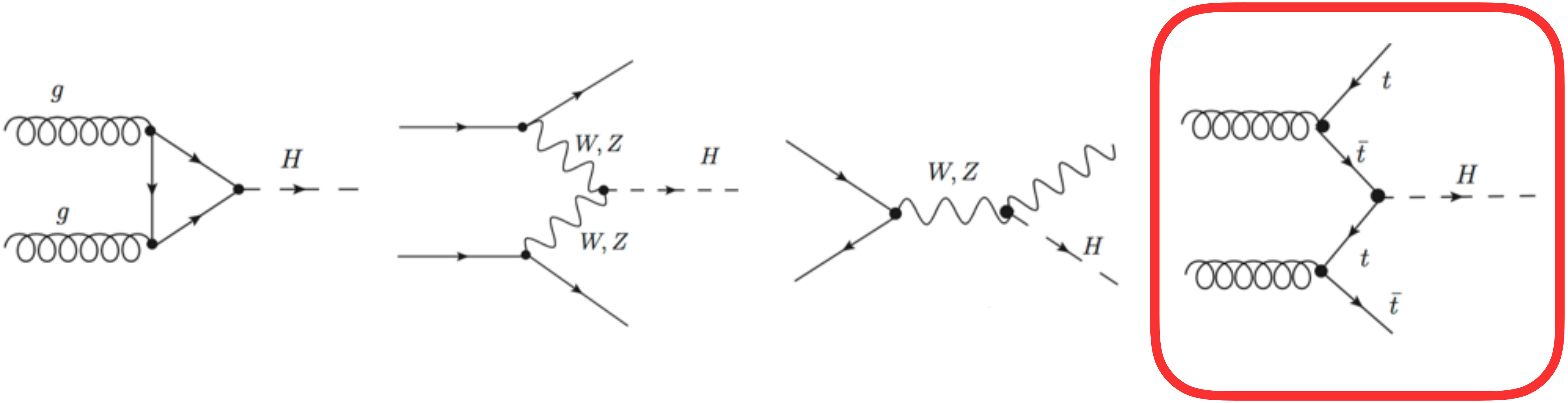
$$\mu = \frac{\sigma_{obs}}{\sigma_{SM}}$$

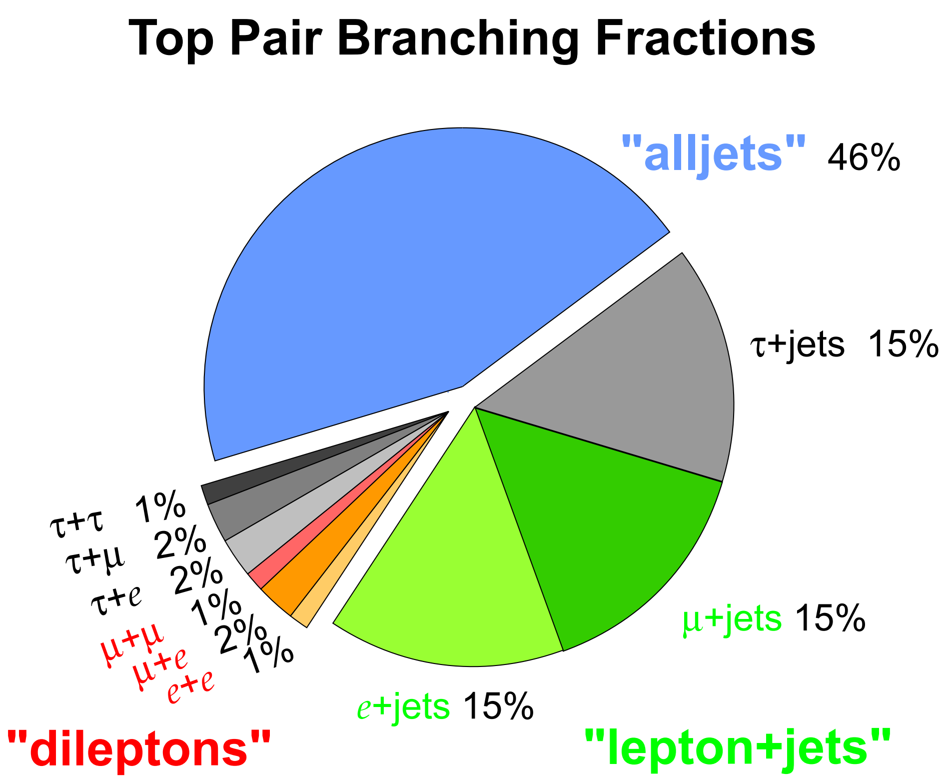
$$\sigma_{obs} = \frac{N_{tot} - N_{bkg}}{\varepsilon \times \int \mathscr{L} dt \times BR(\%)}$$

ttH production at LHC

- ttH production cross-section at 13 TeV represents only the 1% of the total Higgs cross-section
- It is a complex final states involving many objects coming from the decay of both top and Higgs







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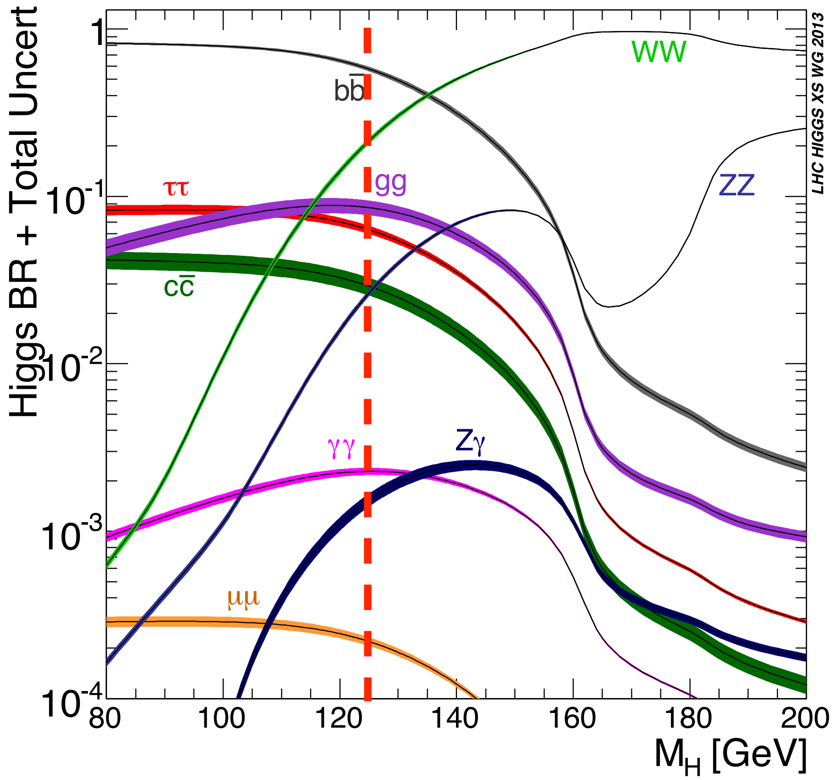


- Since t → Wb with a branching ratio of ~ 100% we define:
  - leptonic decay of top quark the case in which the W boson produced in the top quark decay goes in lepton+neutrino (lν)
  - hadronic decay of the top quark the case in which W → qq'
- So lepton+jets decay of top quark pair is the case in which ttbar → WWbb → (lν)(qq')bb
- The dilepton decays is the case in which ttbar → WWbb → (lν)(lν)bb

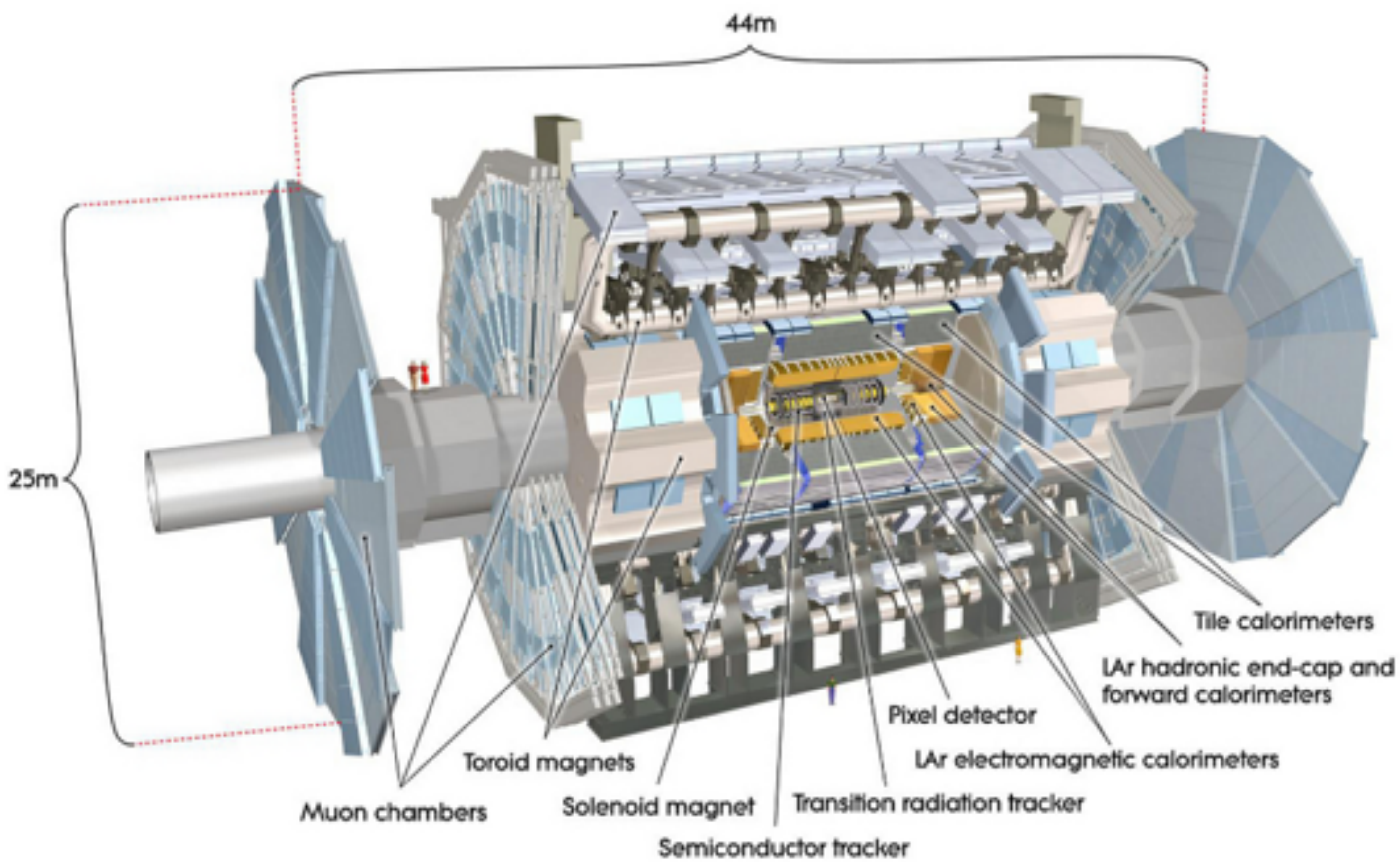
ttH final states

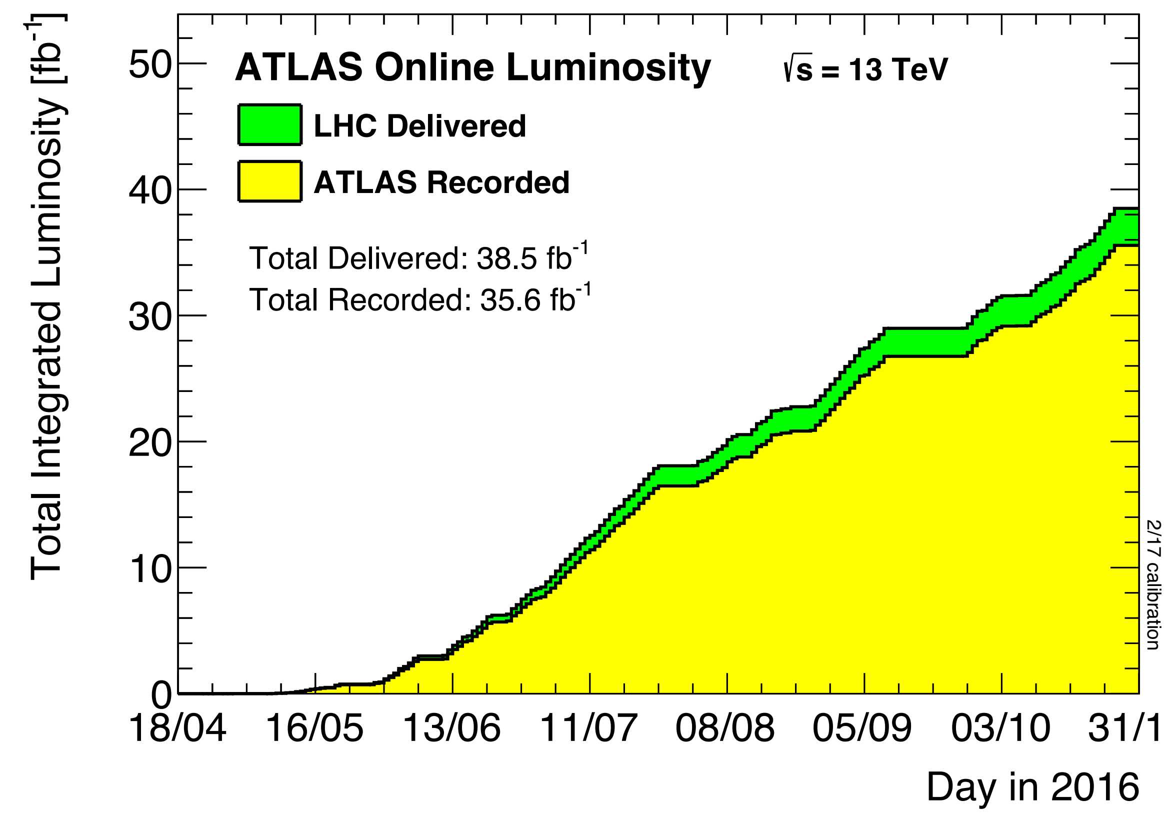
- A complex final states involving many objects:
  - hadronic jets and b-hadron initiated jets (b-tagged jets)
  - light leptons l (electrons and muons)
  - hadronic taus (τ_{had})
  - photons (γ)
- The search analysis are thus characterized depending on the decay modes of the Higgs boson:
  - ttH → tt+ γγ, clear signature but low statistics due to the BR(H →γγ) = 0.2%
  - ttH → tt+bb, high statistics BR(H →bb) = 58% but high uncertainty
  - ttH → leptons + X, where H → WW/ZZ/ττ mainly, called multilepton final state: is a good compromise between the previous two

- Most recent result by ATLAS and CMS (significance is the one on the signal strength μ)

	ATLAS	CMS
Run-1 combination	JHEP **1608** (2016) 045 4.4σ (exp: 2.0σ) $\mu_{t\bar{t}H} = 2.3^{+0.7}_{-0.6}$	
$t\bar{t}H(b\bar{b})$	ATLAS-CONF-2017-076 1.4σ (exp: 1.6σ) μ = 0.8±0.6	CMS-PAS-HIG-16-038 (13 fb^{-1}) $\mu_{t\bar{t}H} = -0.19 \pm 0.8$
$t\bar{t}H$ multilepton	**ATLAS-CONF-2017-077**	CMS-PAS-HIG-17-004 (ℓ only) 3.3σ (exp: 2.5σ) $\mu_{t\bar{t}H} = 1.5 \pm 0.5$ CMS-PAS-HIG-17-003 (τ_{had}) 1.4σ (exp: 1.8σ) $\mu_{t\bar{t}H} = 0.72^{+0.62}_{-0.53}$
$t\bar{t}H(ZZ \to 4\ell)$	ATLAS-CONF-2017-043 $\mu_{t\bar{t}H} < 7.7$	arXiv:1706.09936 $\mu_{t\bar{t}H} < 1.18$
$t\bar{t}H(\gamma\gamma)$	ATLAS-CONF-2017-045 1.0σ (exp: 1.8σ) $\mu_{t\bar{t}H} = 0.5 \pm 0.6$	CMS-PAS-HIG-16-040 3.3σ (exp: 1.5σ) $\mu_{t\bar{t}H} = 2.2^{+0.9}_{-0.8}$

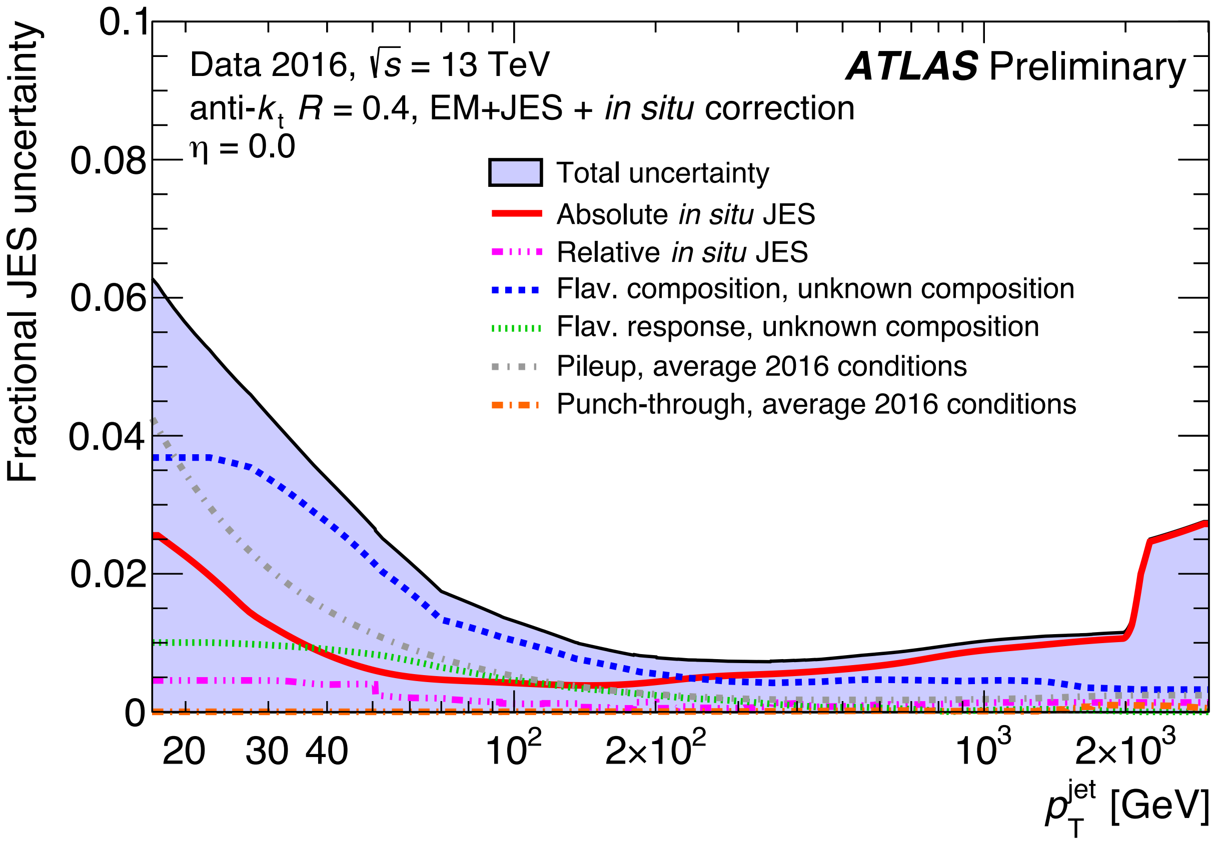
ATLAS EXPERIMENT

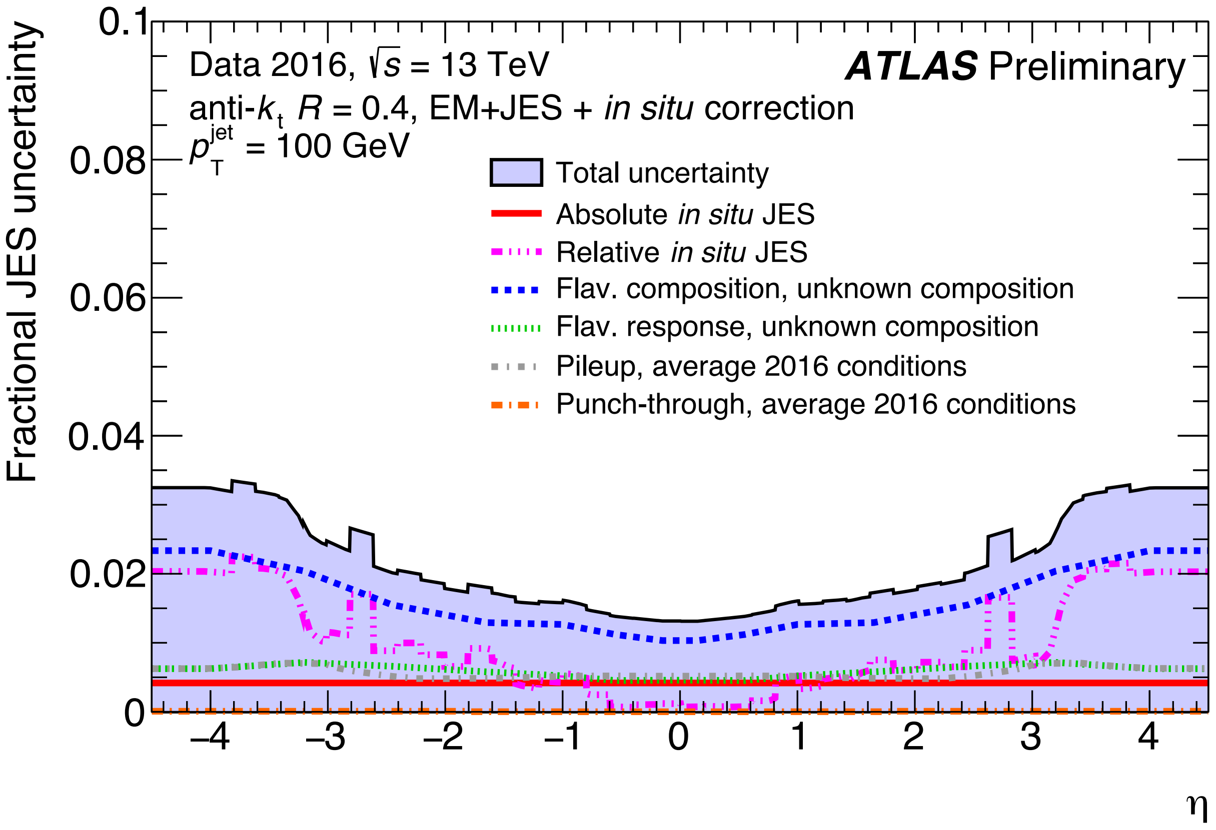




- 2015-2016: more than 36 fb^{-1} of LHC pp collision data recorded in ATLAS after beam and data quality requirements
- ATLAS data acquisition efficiency: 92.1%(2015) – 92.4% (2016)
- Peak luminosity of $1.4\times10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Pile-up of ~25 average (~45 maximum) collisions per crossing ⇒ Up to more than 20-25 pile-up vertices per event!
- more than 40 fb^{-1} of data already collected in 2017, at even higher peak luminosities

Jets reconstruction performance

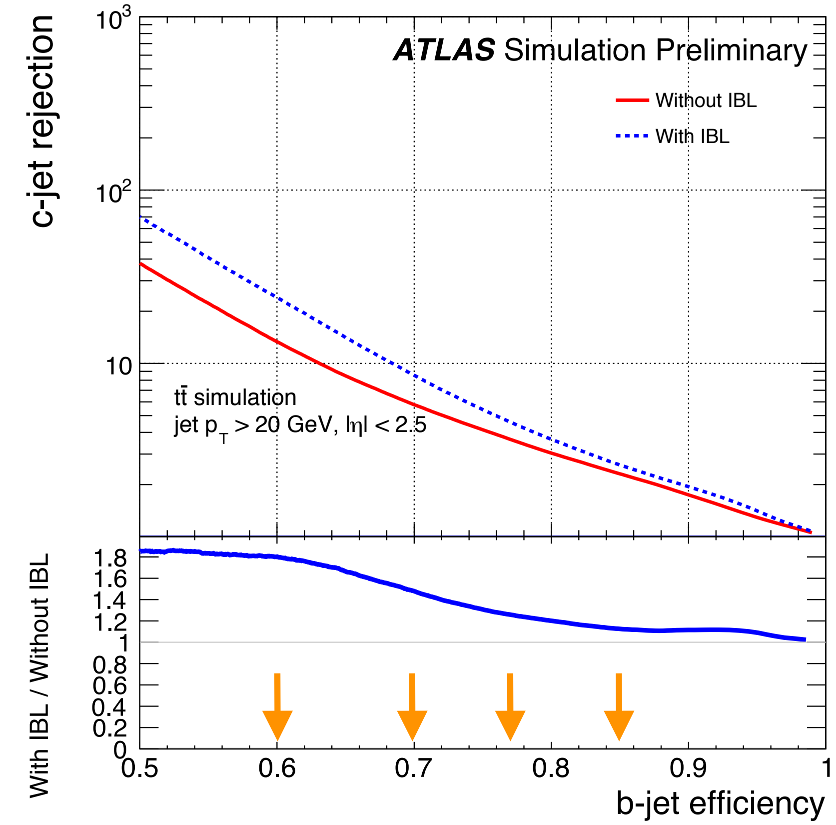


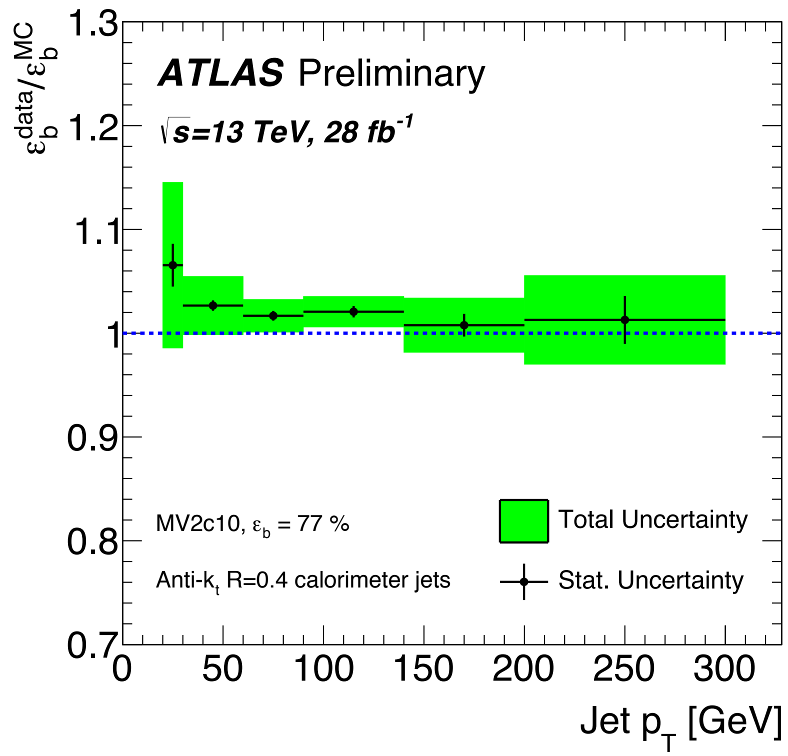


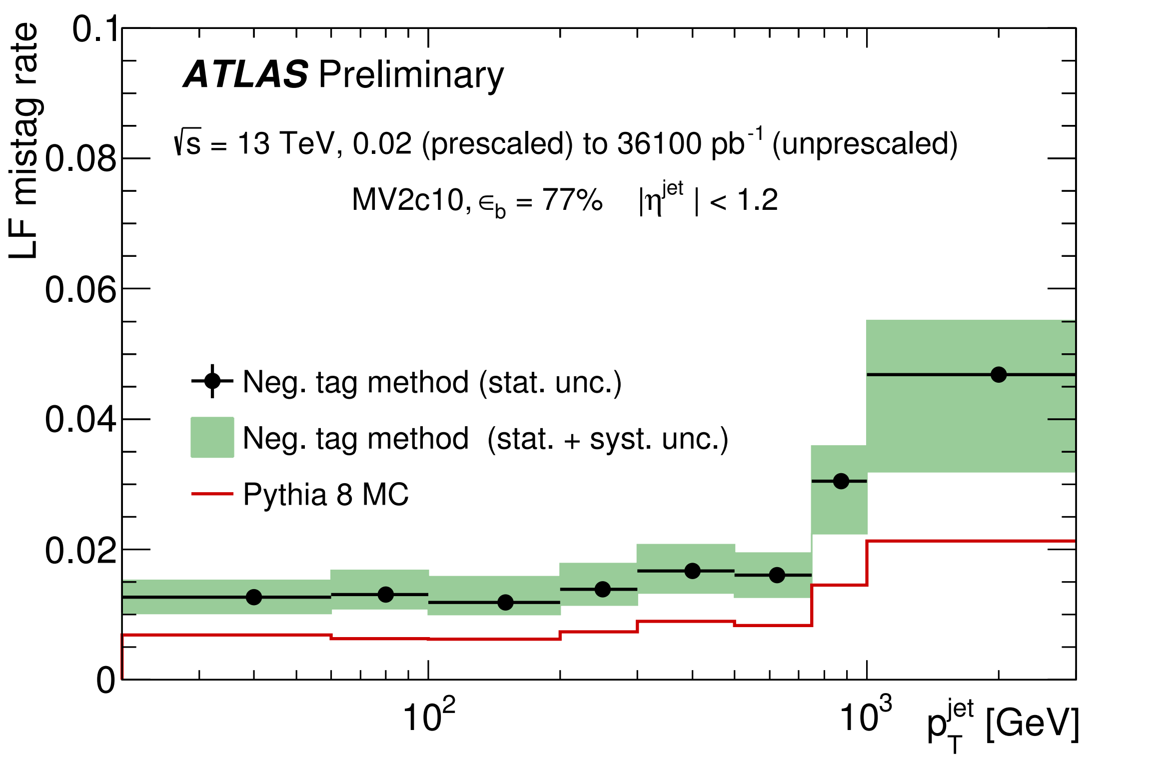
- Jets are reconstructed combining the tracks in the inner detector to clusters of energy deposits in the hadronic calorimeter (anti-kt algorithm)
- Well-understood jet calibration, using γ+jet, Z+jet and multijet data
- Jet energy scale uncertainty:
  - Below 1% for $p_T > 150$ GeV
  - ~5% for $p_T \approx 25$ GeV

b-tagging of jets

- Exploiting their kinematical properties it is possibile to identify jets initiated from b-quark wrt jets initiated from light quark
- Large improvement in b-tagging performance in Run-2 due to the additional Insertable B-Layer (radius: 3.3 cm)
- Calibration derived from data:
  - b-jet efficiency: dileptonic ttbar (2-10% uncert.)
  - c-jet mistag: semileptonic ttbar (W→cs), W +c (5-20% uncert.)
  - Light-flavour mistag: dijet events (10-50% uncert.)

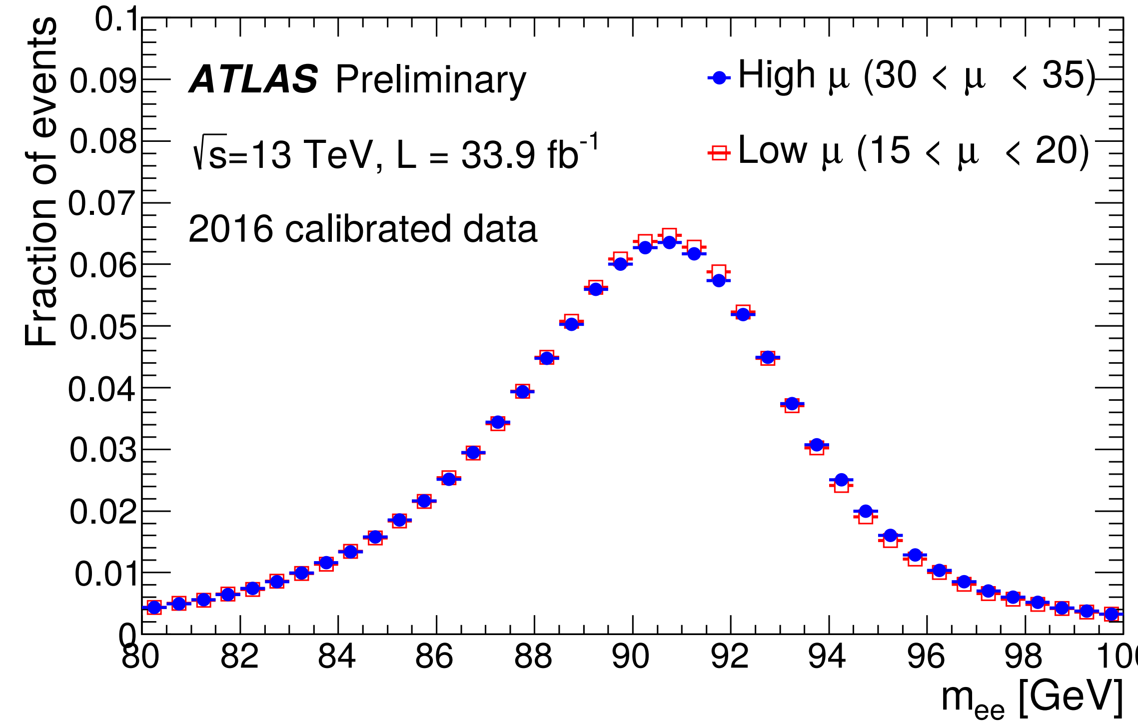




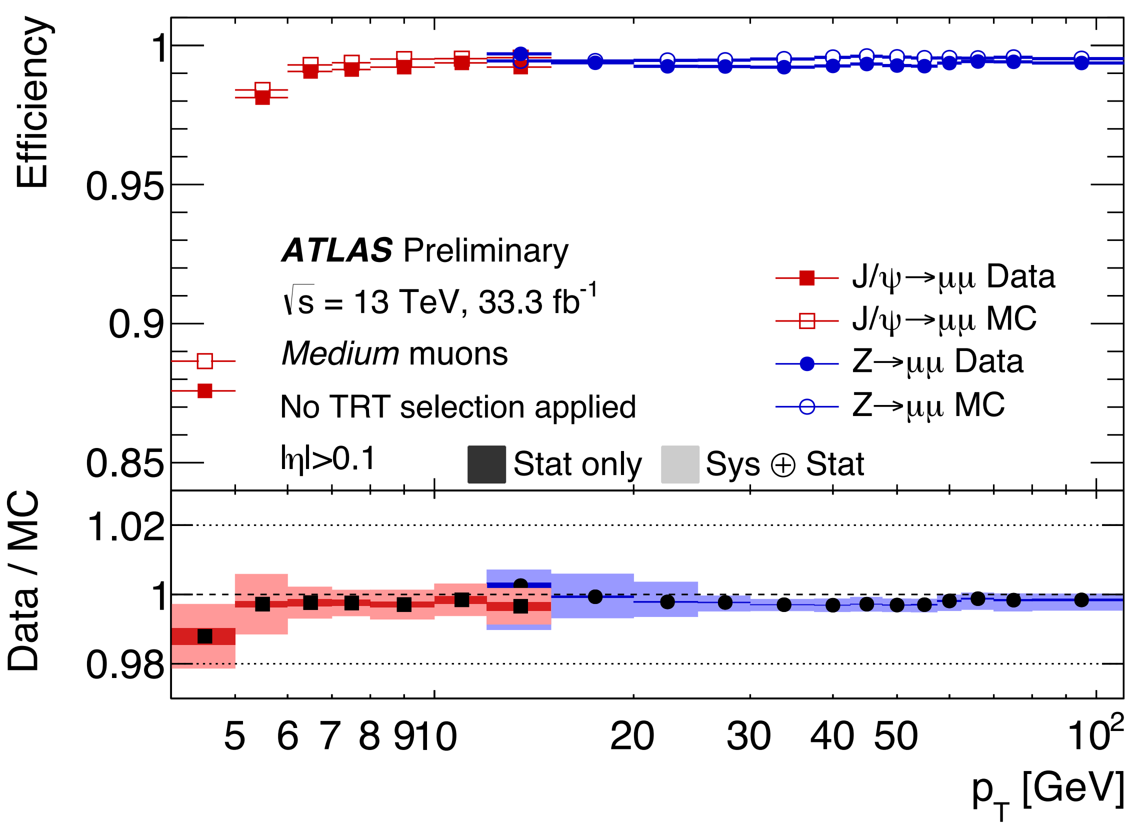


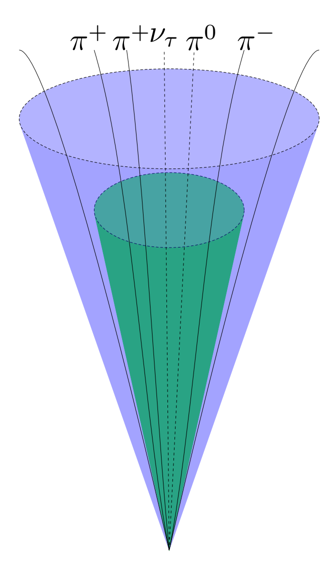
- Electrons are reconstructed combining a track recontruced in the inner tracker with the deposit of energy in the electromagnetic calorimeter
- Muons are reconstructed combining the track on the inner tracker with the one in the muon spectrometer
- Electron/muon reconstruction efficiency accurately measured using Z→ll and J/φ→ ll data down to very low pT
- Well understood energy calibration also at high pileup
- Hadronic taus identification based on a BDT
- Efficiency and energy scale corrections derived in Z → ττ data

$Z \to ee$ mass distribution

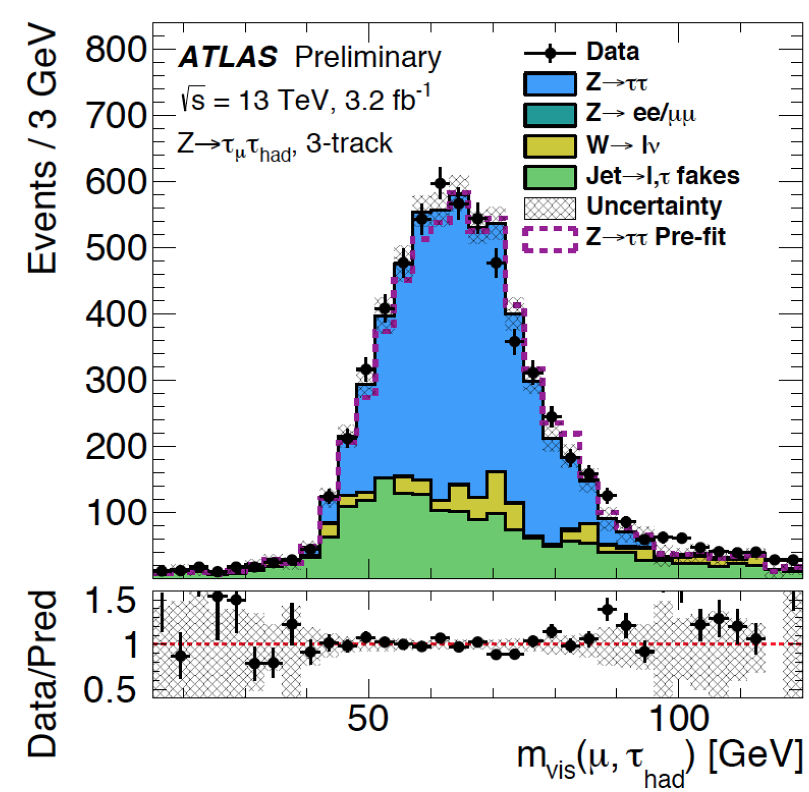


Muon efficiency





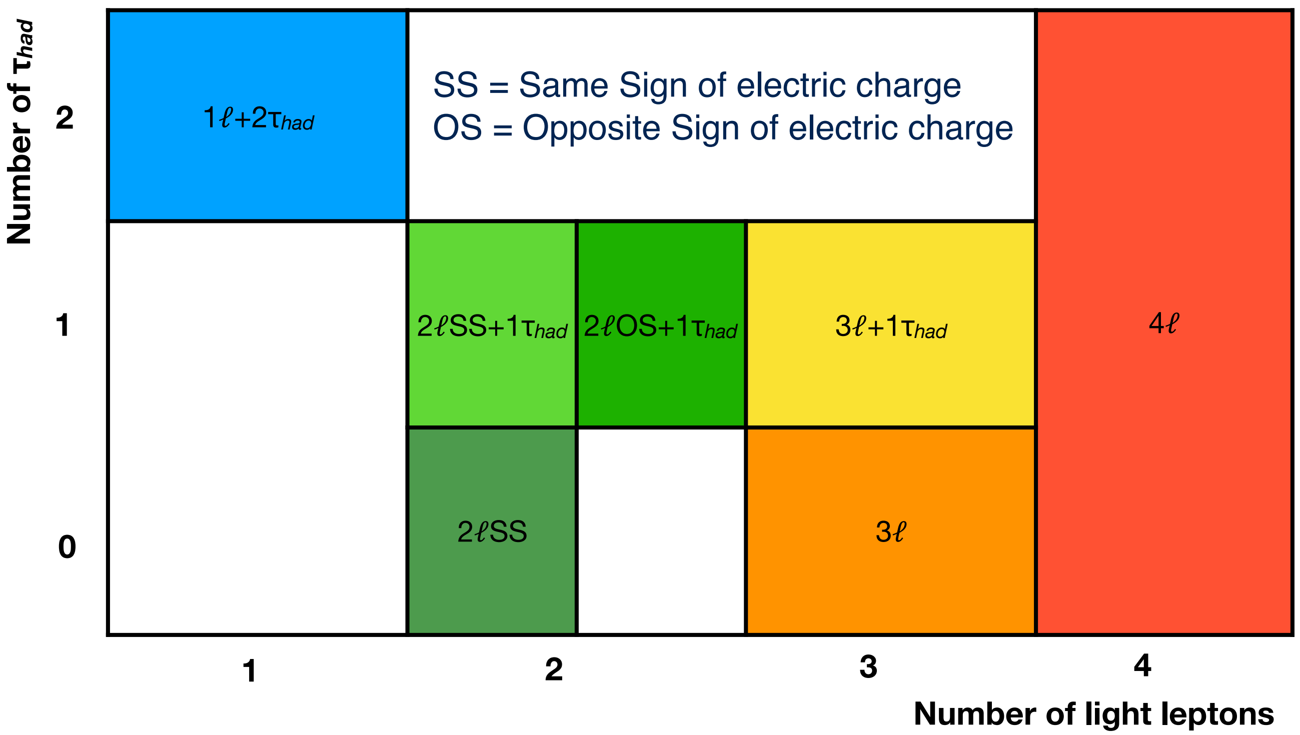
Tau calibration

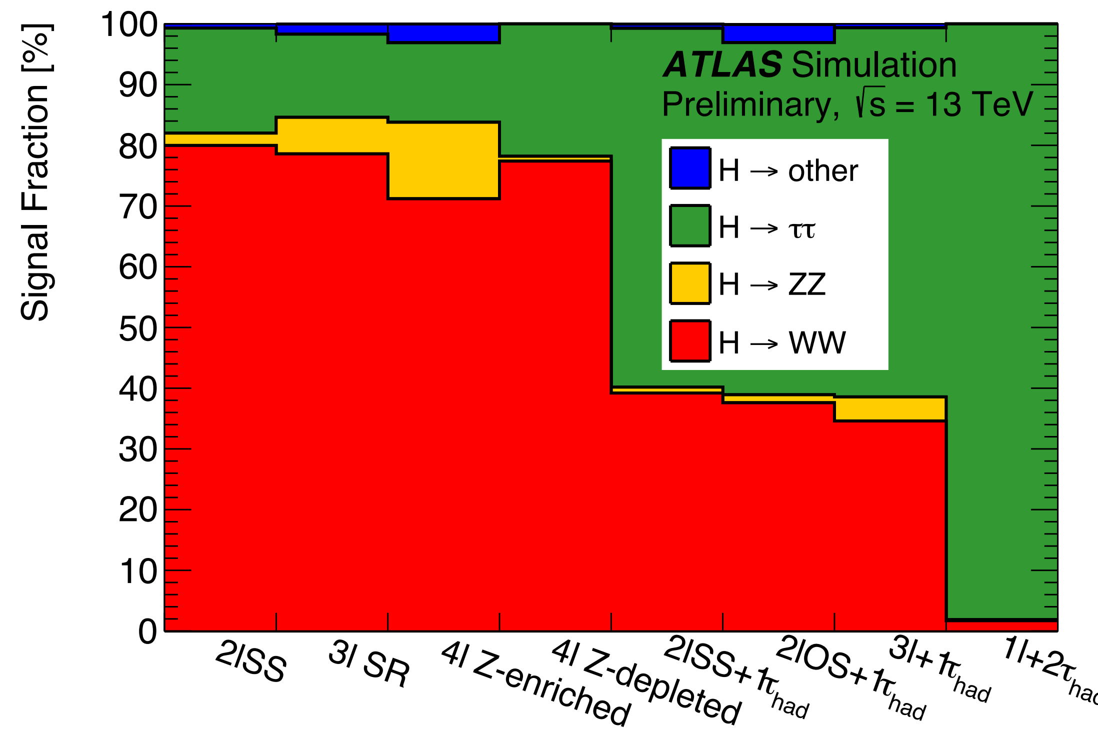


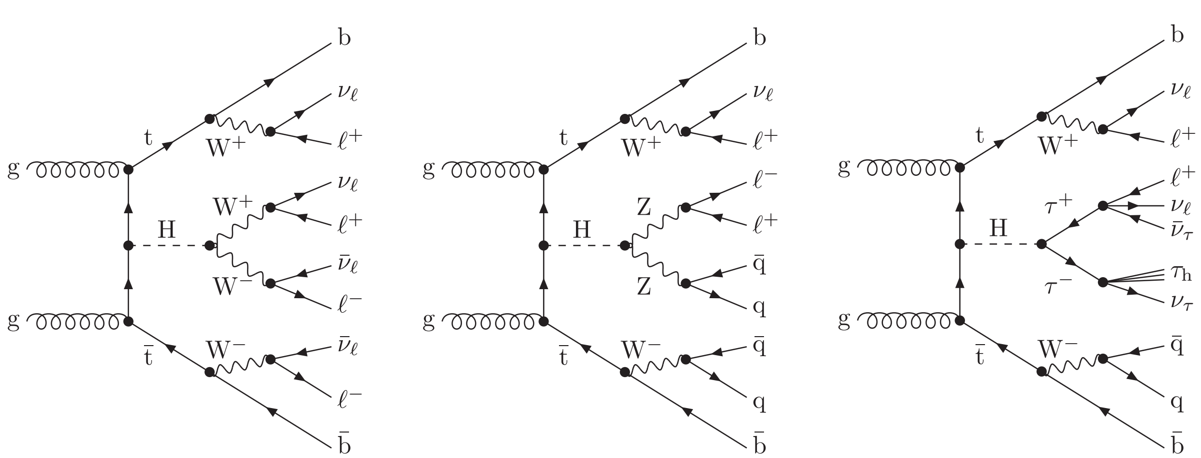
ttH multilepton

ttH multilepton: strategy

- Targeting H → WW, ZZ, ττ decay modes, combined with leptonic decays of the ttbar pair
- Seven different channel depending on the number of light prompt leptons (electrons and muon) and τ_{had}







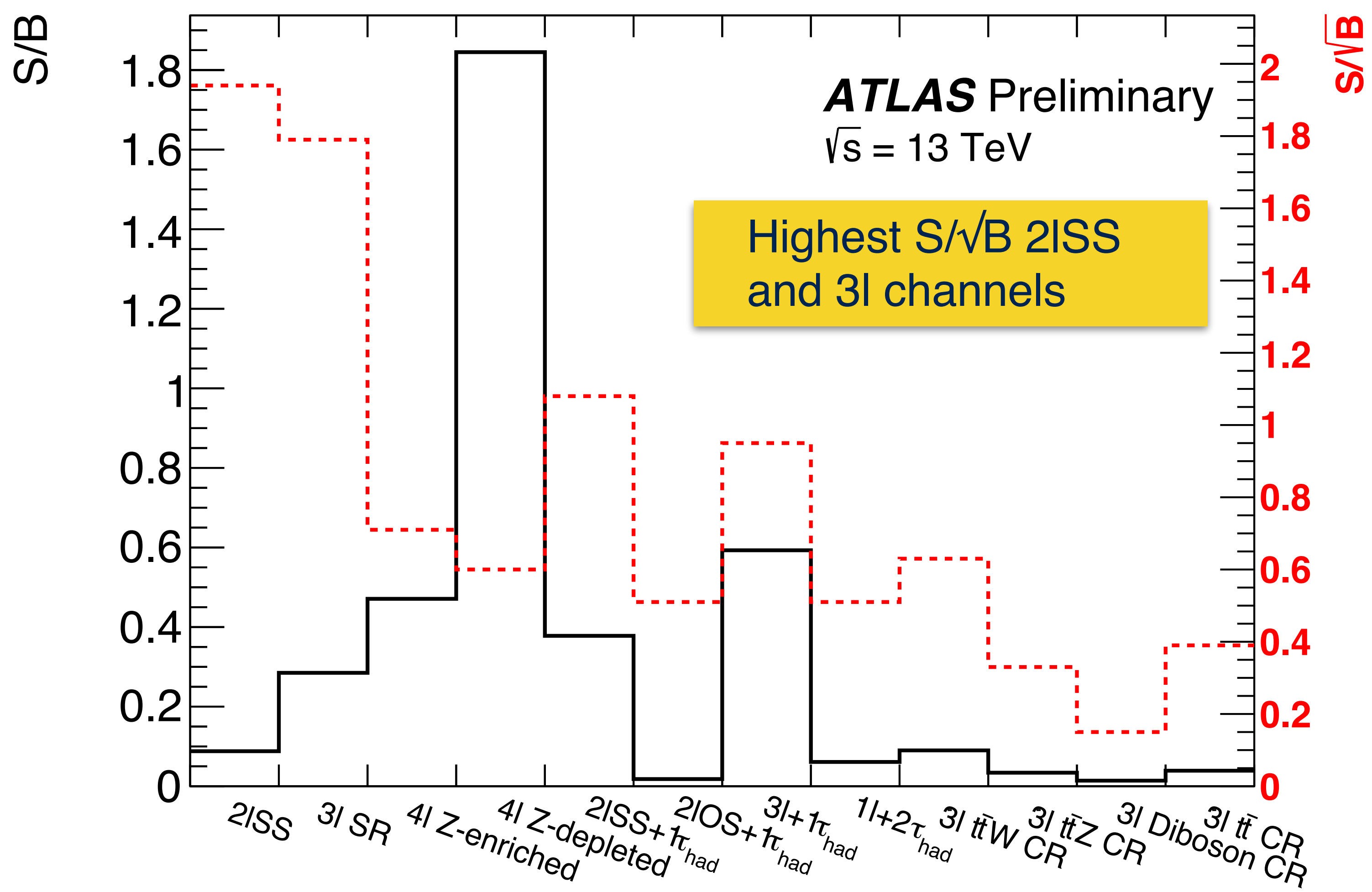
- Each channel's signal region (SR) is given by selections on event level variables
- These SRs are orthogonal between the different channels in order to make the final combination easier

complete set of cuts for each channel

ttH multilepton: strategy

MVA techniques to increase the sensitivity of each channel!

- 2lSS uses the combination od two BDTs (ttH vs ttbar, ttH vs ttV)
- 3l uses 5-dimensional multinomial BDTs mappe to 5 categories (ttH, ttW, ttZ, ttbar, VV)
- 4l (Z-enriched) uses BDT of ttH vs tty
- 2lSS+1 τ_{had}, 2lOS+1 τ_{had}, 1l+2 τ_{had} uses BDT of ttH vs ttbar

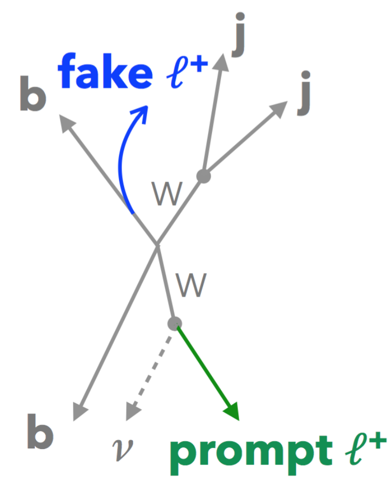


ttH multilepton: background processes

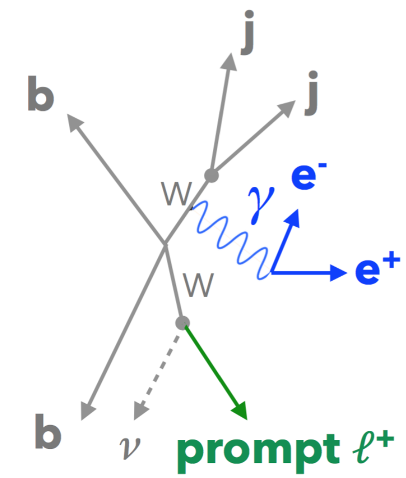
Main background processes are:

- Prompt leptons same experimental signature as signal → irreducible
  - these processes have real prompt leptons and τ_{had}
  - estimated from Monte Carlo simulation
- Electron charge mis-identification
  - estimated from data events using mis-id rates from the Z → e+e-
- Non-prompt and fake leptons: leptons not coming from the primary interaction or jets mis-identified as leptons
  - Mainly coming from the semileptonic decay of heavy quarks hadrons
  - sizable contribution also from photon conversion
  - estimated from data events
- Fake tau leptons:
  - mainly from light flavor jets or electrons mis-identified as τ_{had}

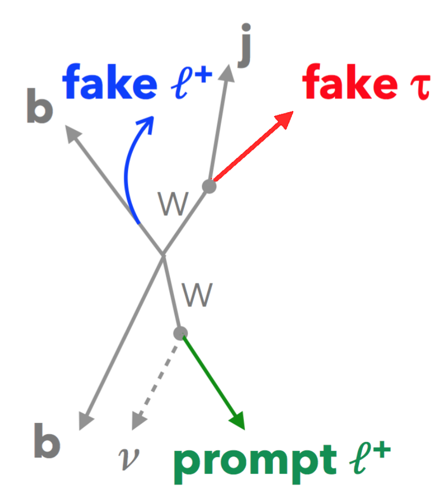
Semileptonic b-decay



Photon conversions



Non-prompt lepton & fake τ



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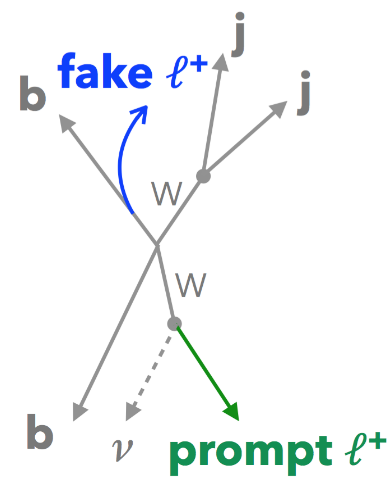

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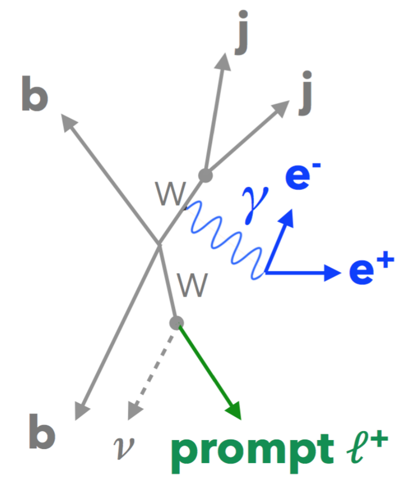

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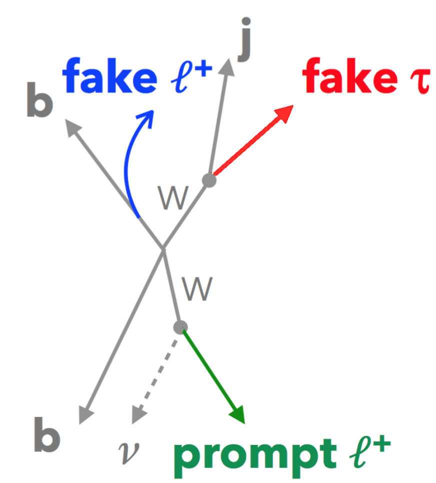
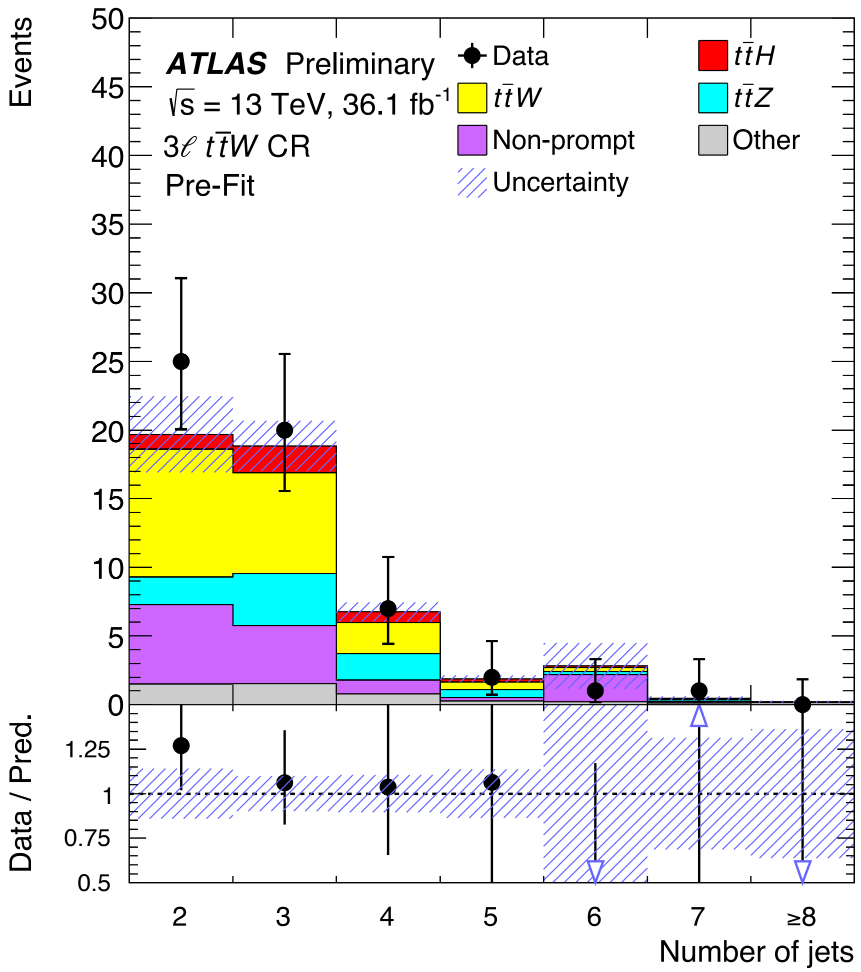
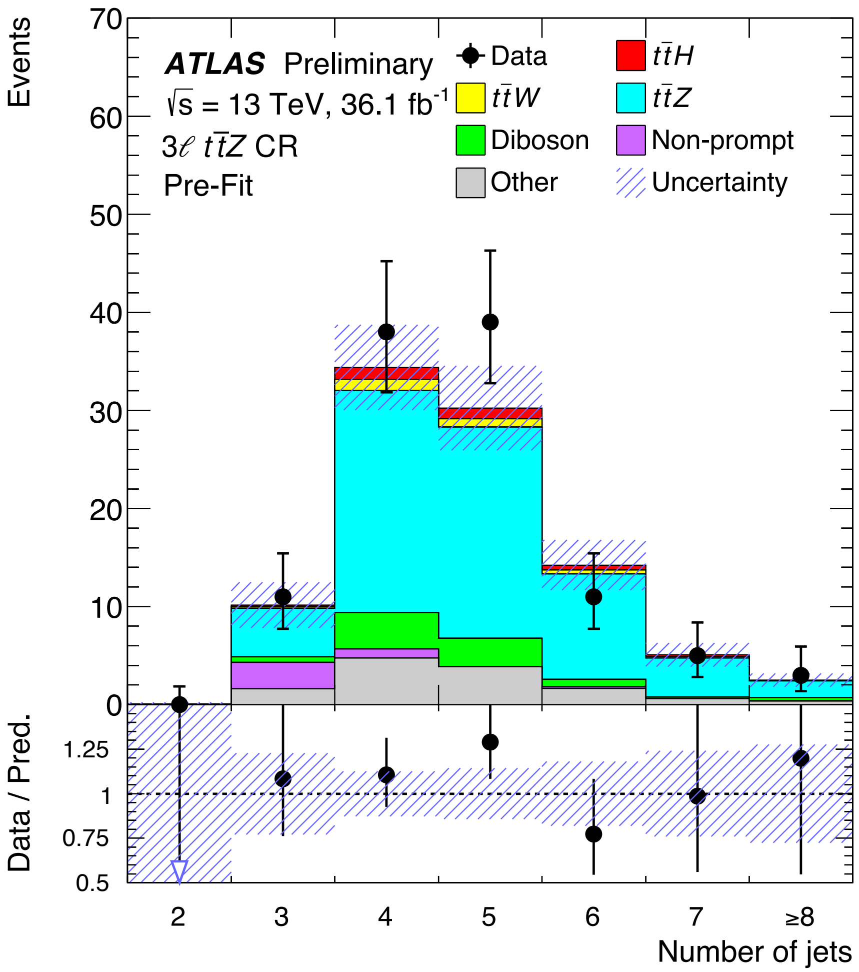


Background estimation: prompt leptons

- Largest irreducible backgrounds: ttW, ttZ, diboson
- Estimated using NLO MC samples, with theory/modelling uncertainties:
  - Cross-section uncertainties
  - Scale variations
  - Generator comparisons
- Validated in several regions enriched by these processes
- Rare SM processes also included: 4tops, 3tops, tZ, tWZ, ttWW, rare top radiative decays t → Wbγ*(ll)





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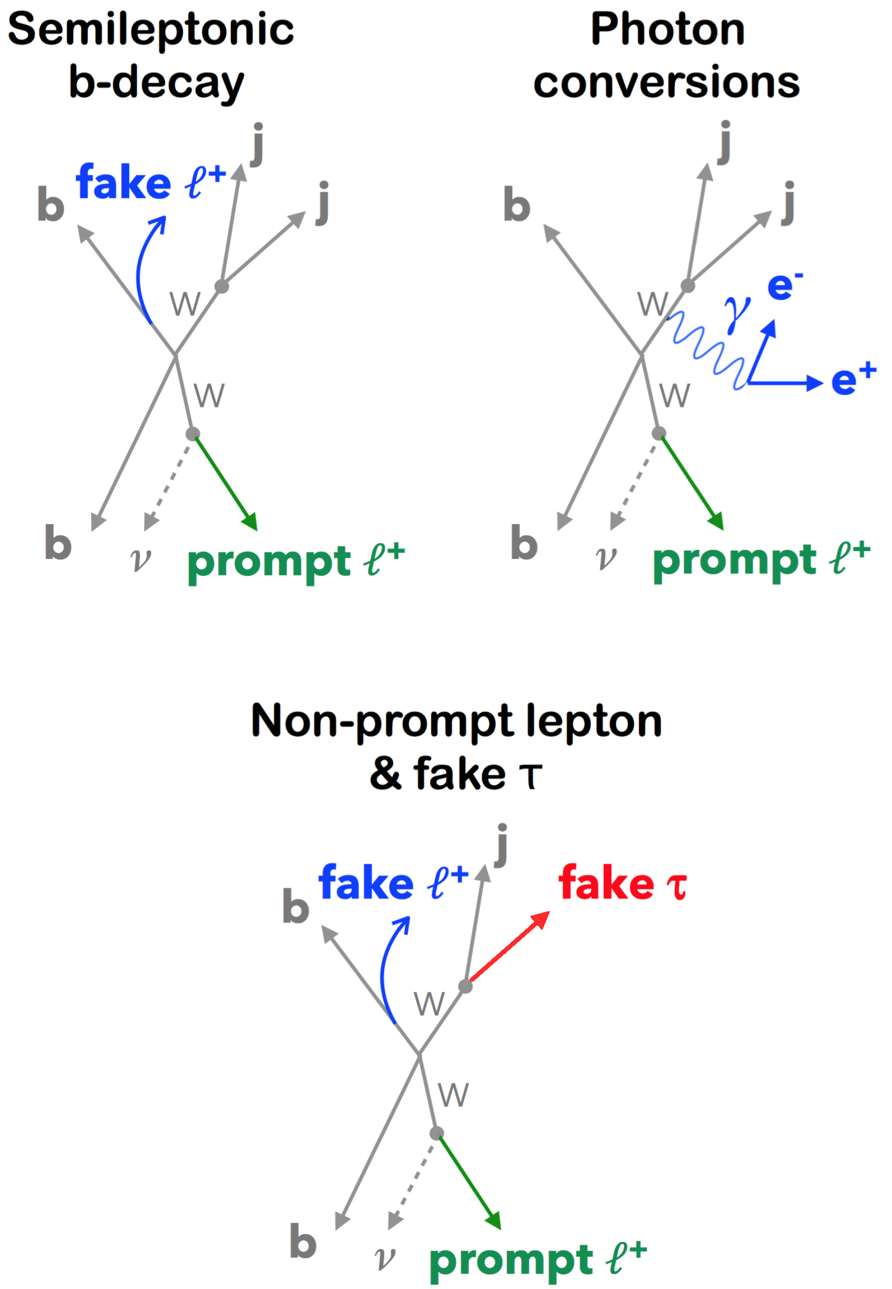
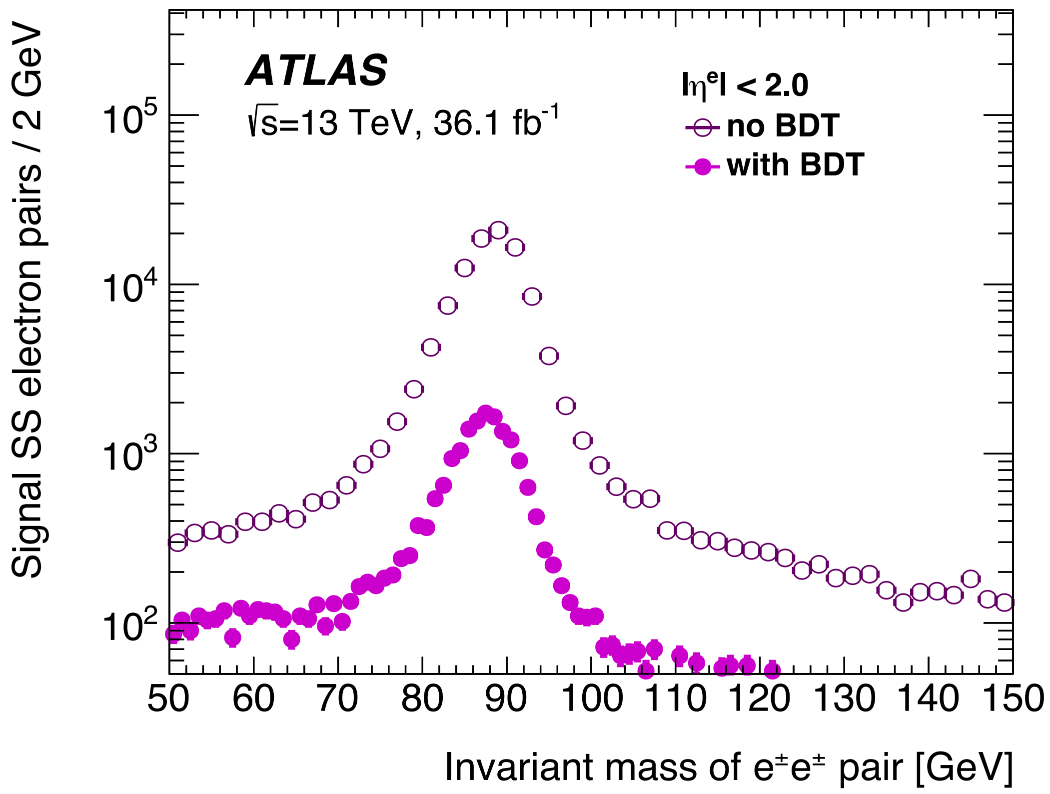
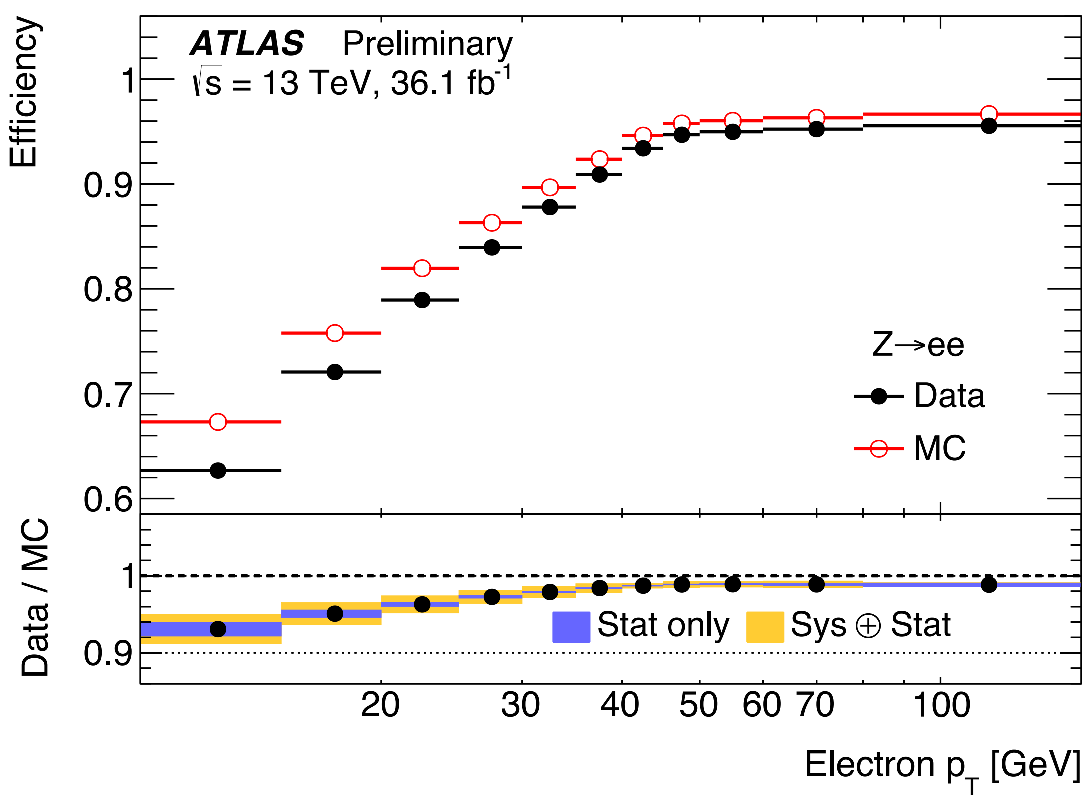


Ad-hoc improvements for ttH multilepton

- Important improvements on the performance of leptons reconstruction have been introduced in ttH analysis
- BDT to reduce the electron charge mis-identification
  - Using electron calorimeter and track variables
  - Factor 17 rejection for 95% efficiency



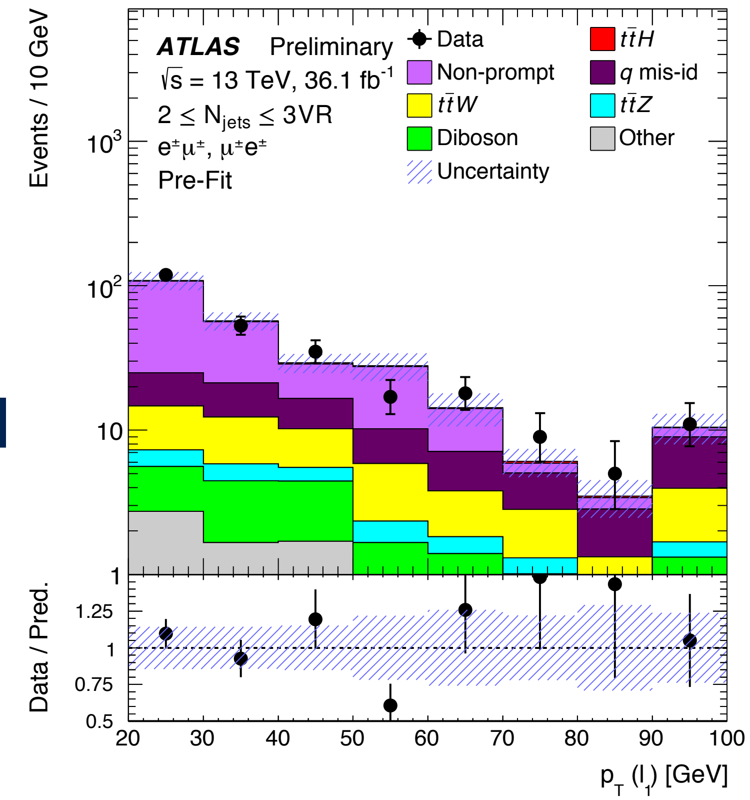


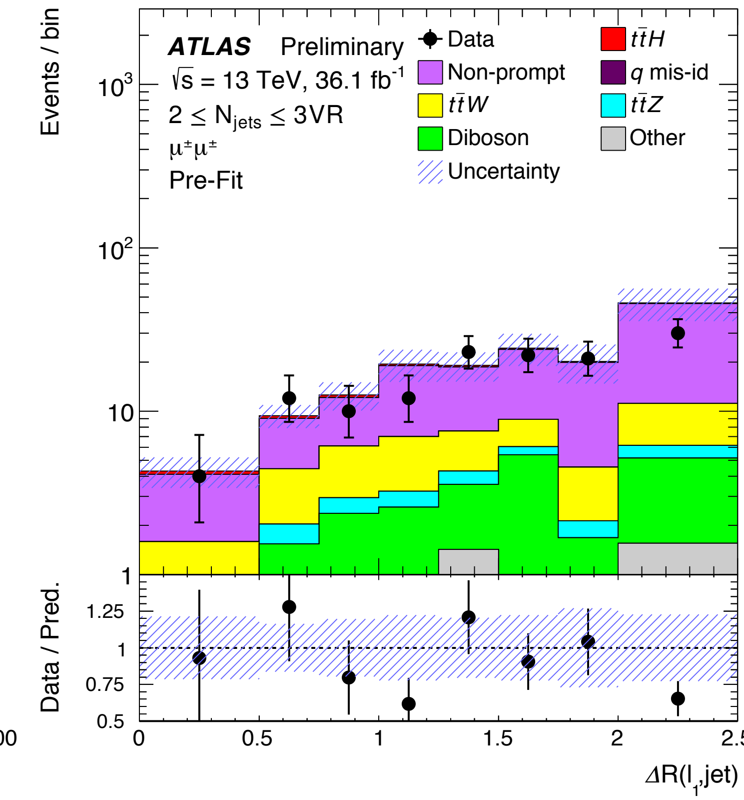
- BDT to reduce non prompt e/μ
  - Input variables: isolation variables, jet reco and b-tag algorithms using tracks around leptons
  - Factor 20 rejection for leptons originating from b-hadrons
  - Efficiency for prompt e/μ: ~70% (60%) at low p_T, >95% at high p_T
  - Calibration performed in Z→ll events

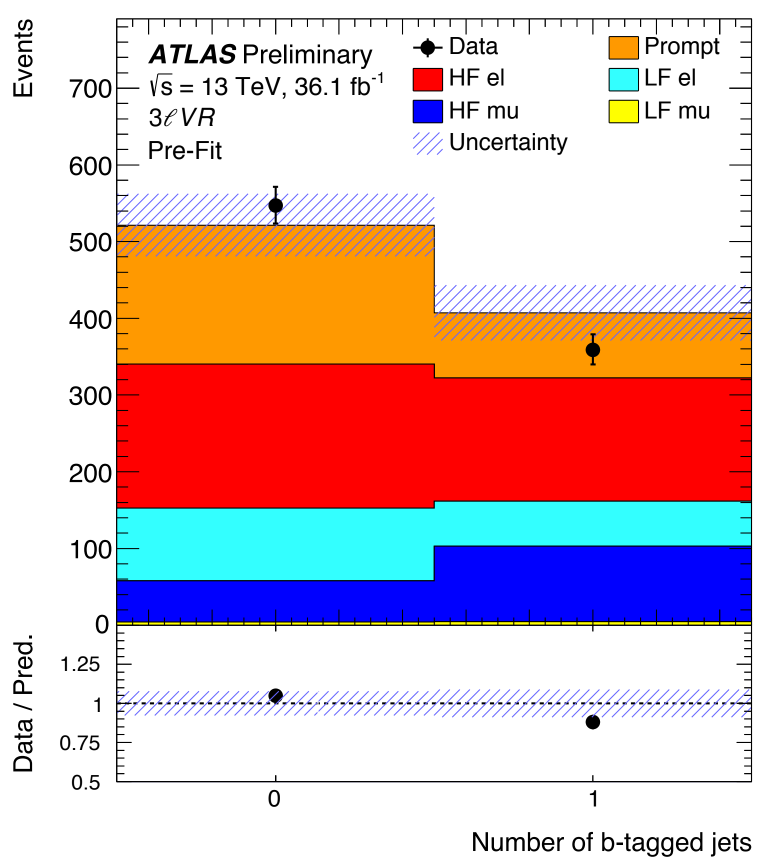
Background estimation: Fake/non-prompt leptons

2lss/3l channels:

- Fully data-drive estimate with a loose-to-tight matrix method
- Real and fake efficiencies measured in data
- Validated in various regions







4l channels:

- Semi data-driven method
- MC split between prompt, heavy and light flavor
- Normalization in factors for each component determined in 3l low jet multiplicity CR, then applied to MC predictions for 4l

ttH multilepton: background processes

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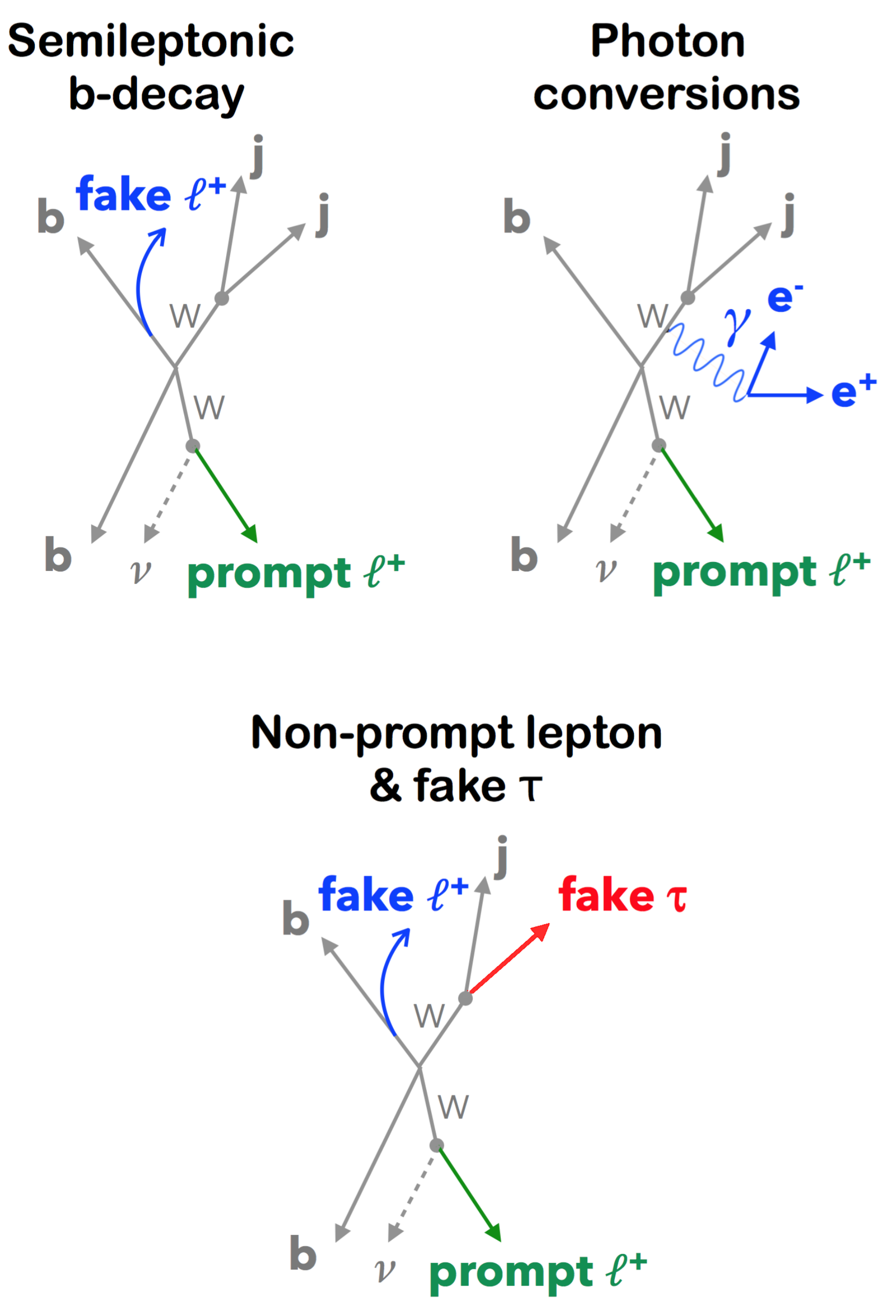


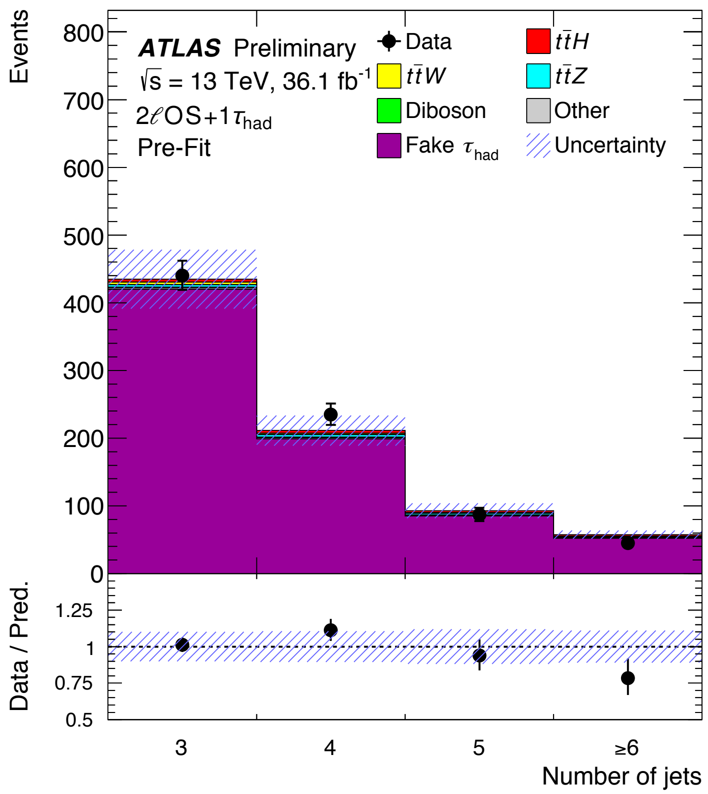
- Fake τ_{had} background from ttbar or ttV relevant for all SRs including τ_{had}
- Negligible fake/non-prompt l, expects for 2lSS+1 τ_{had}

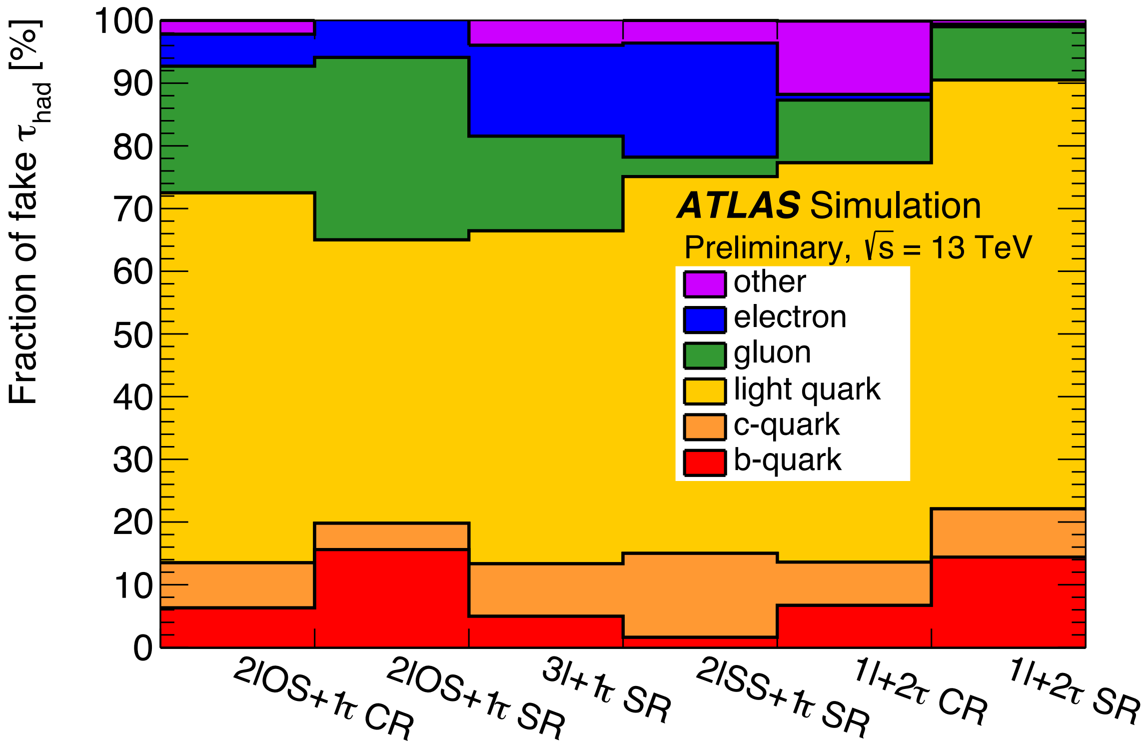
1l+2τ_{had} channel:

- Using CR with two same-sign τ_{had} extrapolated to SR using MC

2lOS+1τ_{had} channel:

- Fake factors measured in a CR, inverting part of the τ_{had} identification requirements

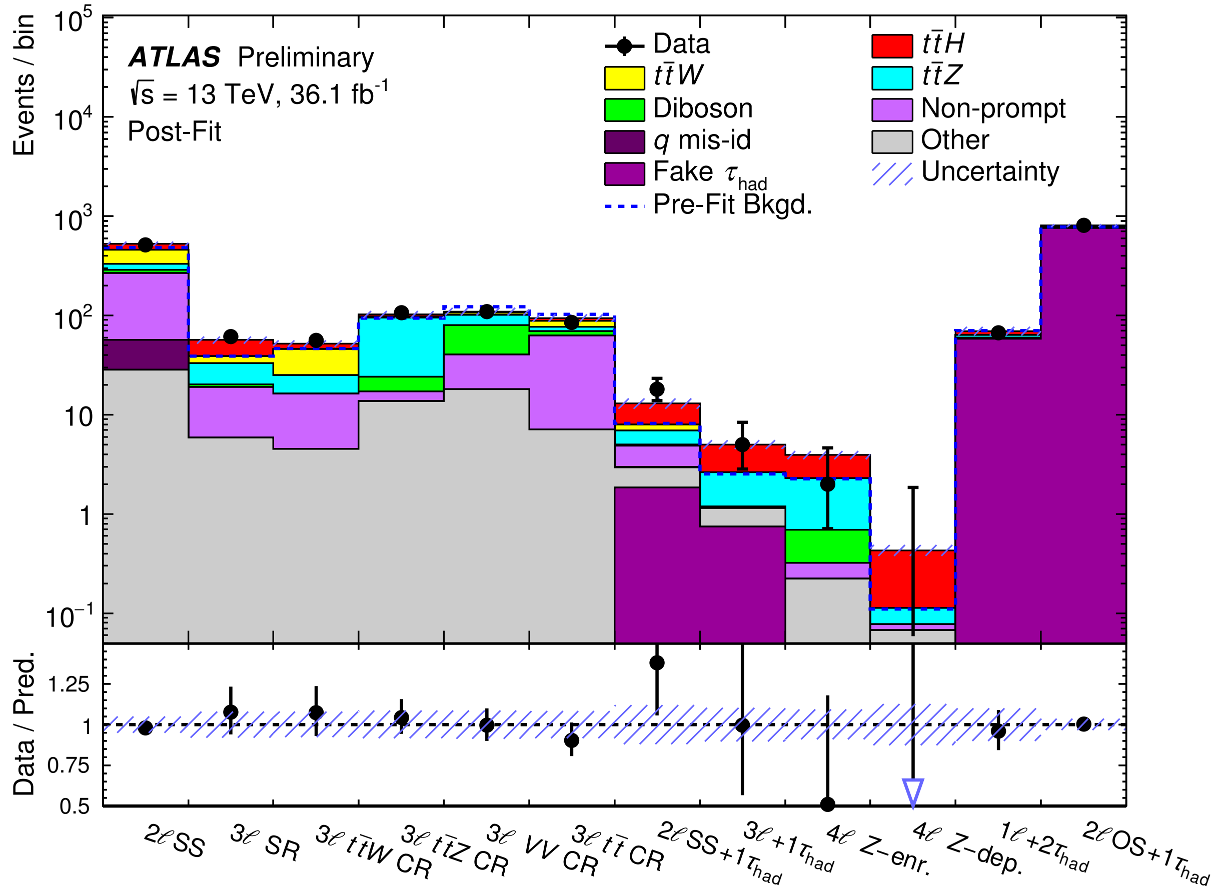




- Good data agreement for 2lOS+1τ_{had}
- Very similar fake τ_{had} origin in the 2lOS/2lSS/3l+1τ_{had}
- Use data-driven estimates from 2lOS+1τ_{had} as correction factor for the fake τ_{had} +prompt l MC in 2lSS/3l+1τ_{had}
- Fake l in 2lSS+1τ_{had}: estimated from data using fake factor method

Fit setup

- Maximum-likelihood fit to extract ttH signal strength μ
- Statistical analysis of the data uses a binned likelihood function which is constructed from a product of Poisson probability terms to estimate μ
- Simultaneous fit to the 12 SR and CR
- BDT shape used as discriminate in 5 of the SRs
- Single bin used for SRs with lower statistics: 4l and /3l+1τ_{had}
- Single bin also used for the 3l CRs



	2ℓSS	3ℓ	4ℓ	1ℓ+2τ_{had}	2ℓSS+1τ_{had}	2ℓOS+1τ_{had}	3ℓ+1τ_{had}
BDT trained against	Fakes and $t\bar{t}V$	$t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, VV	$t\bar{t}Z$ / -	$t\bar{t}$	all	$t\bar{t}$	-
Discriminant	2×1D BDT	5D BDT	Event count	BDT	BDT	BDT	Event count
Number of bins	6	5	1 / 1	2	2	10	1
Control regions	-	4	-	-	-	-	-

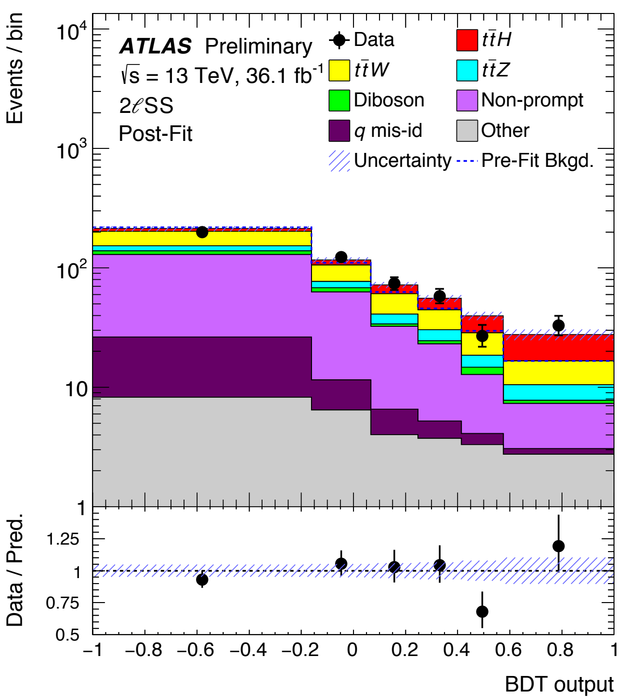
- The test statistic q_μ is constructed from the profile log-likelihood ratio

$$q_\mu = -2\ln\Lambda_\mu = -2\ln\mathcal{L}(\mu,\hat{\hat{\vec{\theta}}})/\mathcal{L}(\hat{\mu},\hat{\vec{\theta}})$$

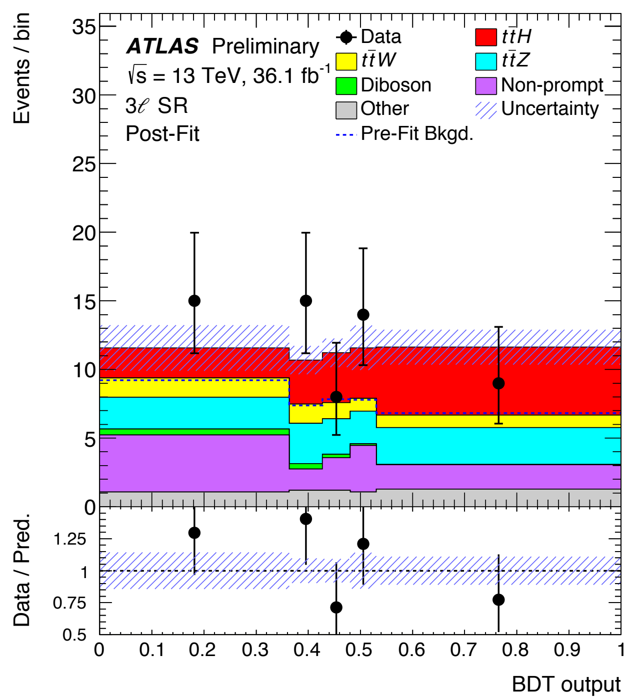
- where θ are nuisance parameter that carry the impact of systematics (Gaussian distributed)

Signal Region distributions

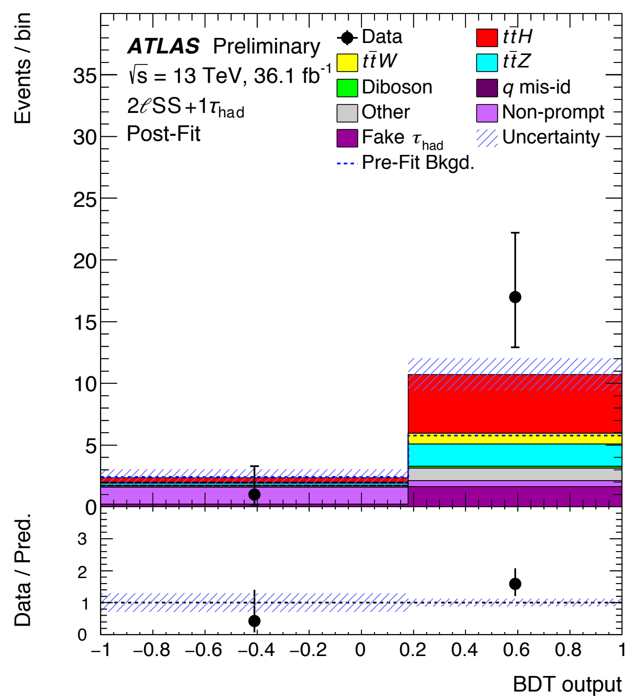
2ℓSS



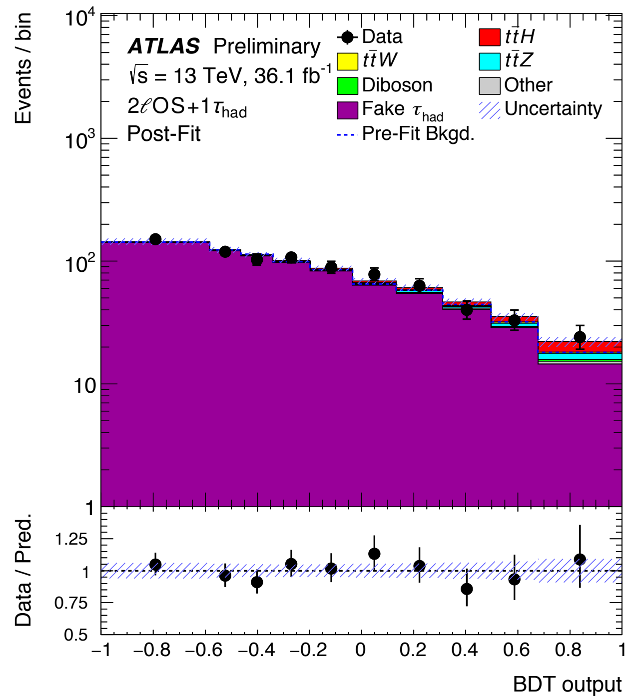
3ℓ



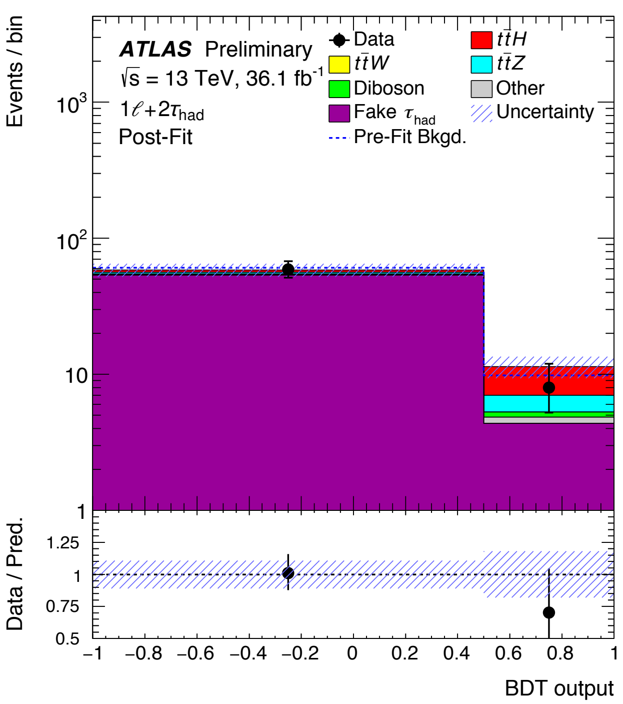
2ℓSS$+1\tau_{\rm had}$



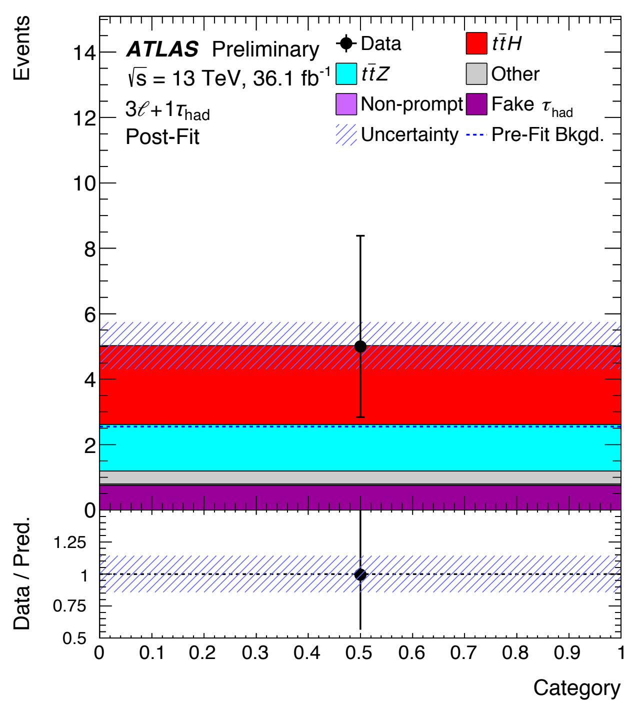
2ℓOS$+1\tau_{\rm had}$



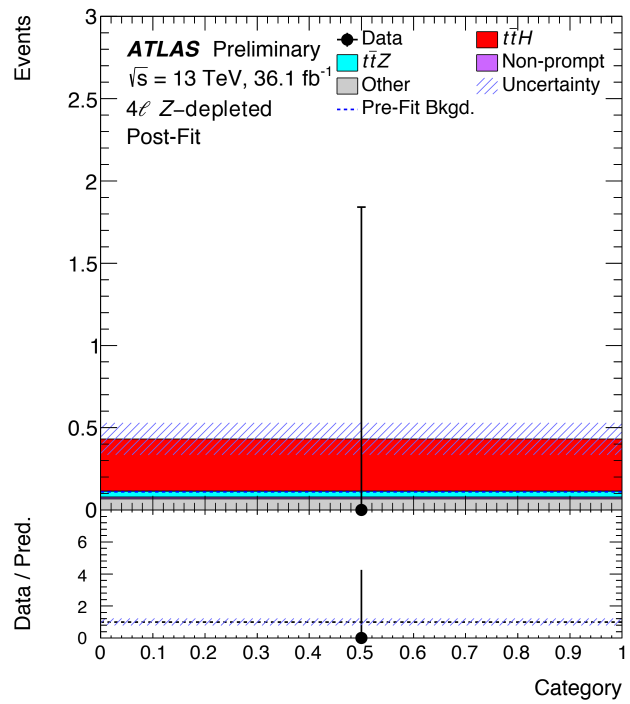
$1\ell+2\tau_{\rm had}$



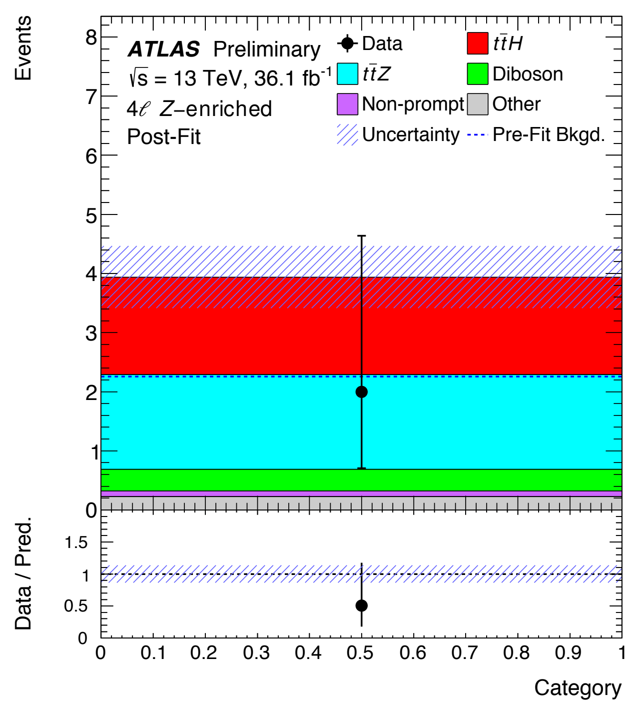
$3\ell+1\tau_{\rm had}$



4ℓ (Z-dep.)

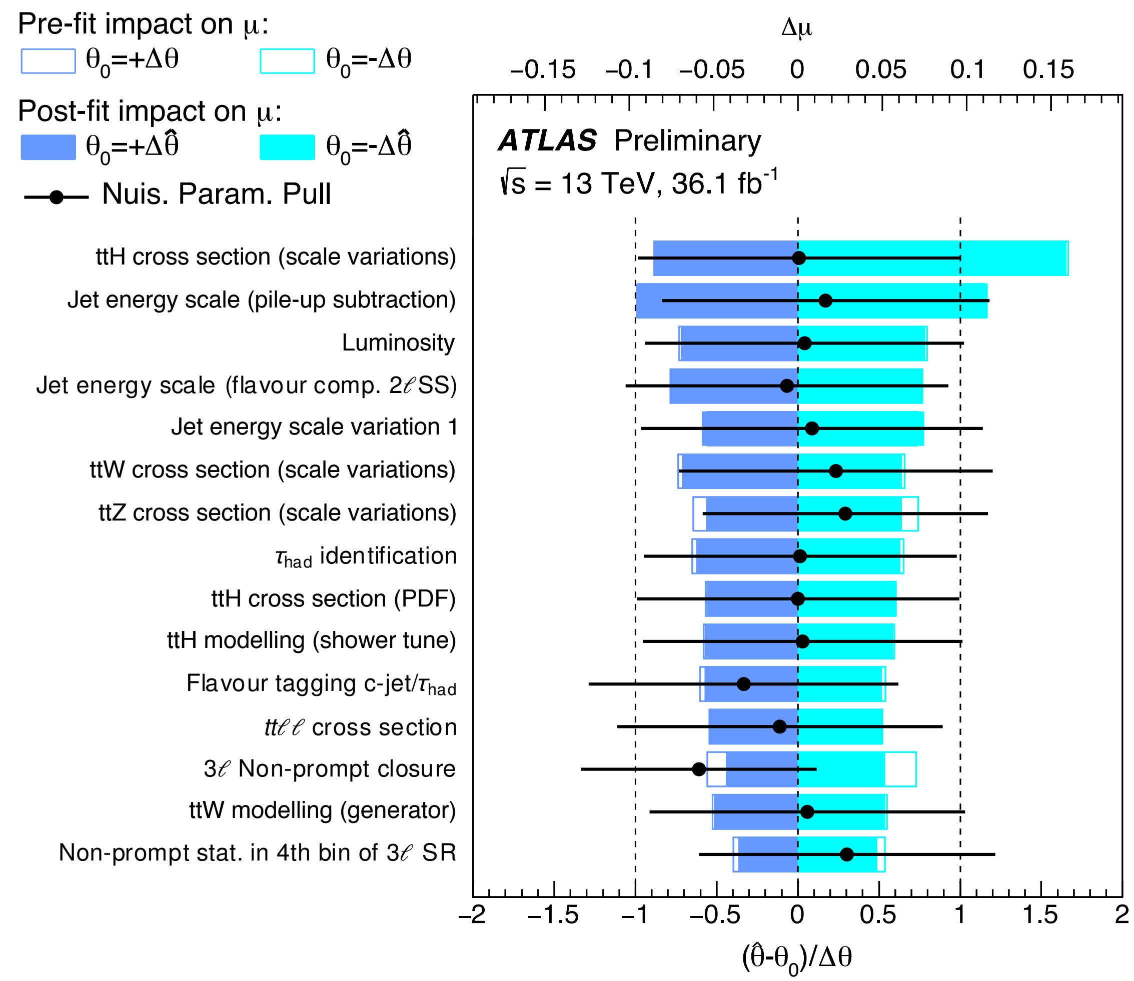


4ℓ (Z-enr.)

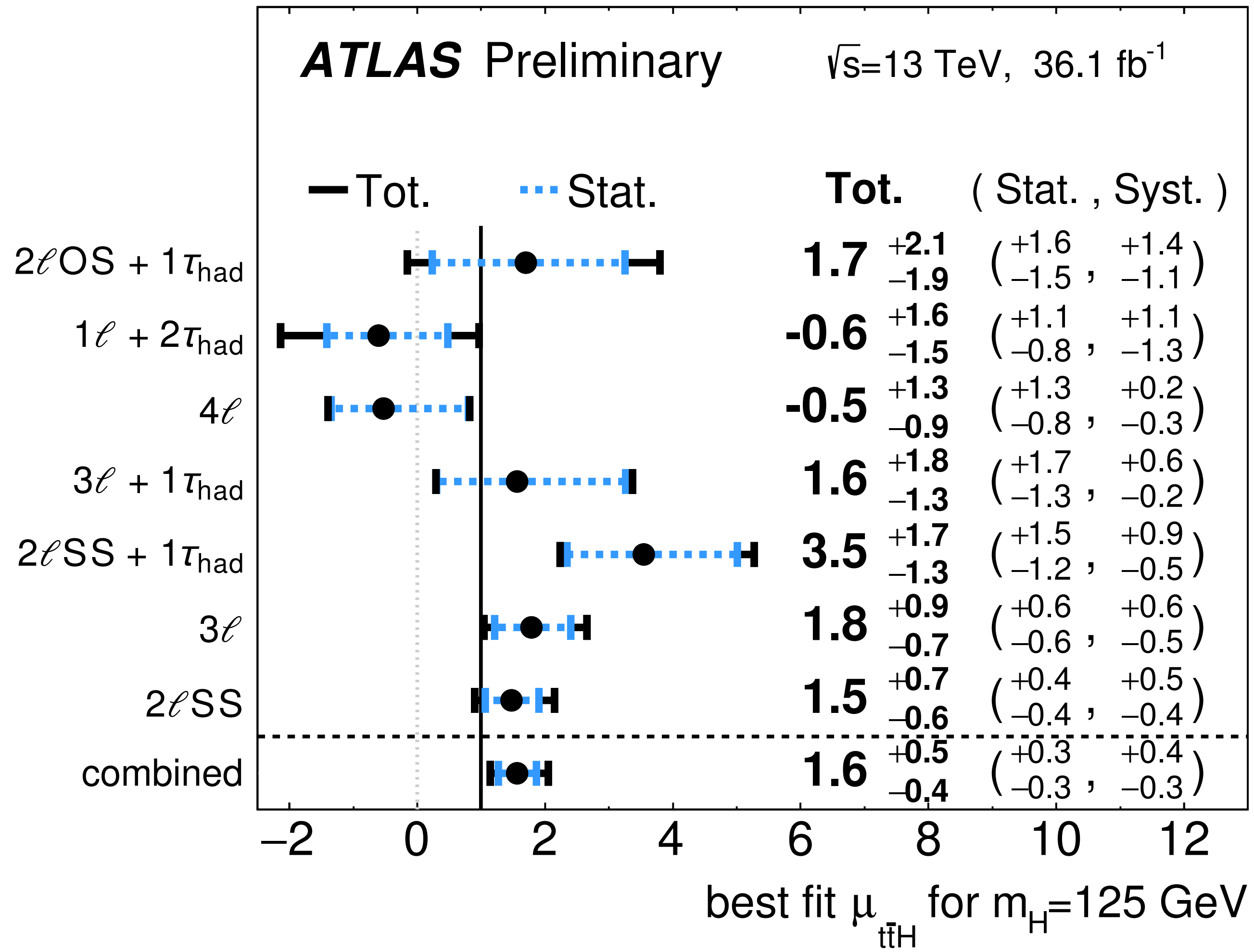


Uncertainties

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



- Most relevant uncertainties on the signal strength:
  - Signal modelling (dominated by scale uncertainties)
  - Jet energy scale and resolution
  - Non-prompt l estimation (with large contribution from limited CR statistics)
- Very small nuisance parameters constraints
  - Largest pull: 3l fake method non-closure (slight deficit in 3l ttbar CR)



Channel	Significance Observed	Expected
2ℓOS+$1\tau_{\text{had}}$	0.9σ	0.5σ
1ℓ+$2\tau_{\text{had}}$	-	0.6σ
4ℓ	-	0.8σ
3ℓ+$1\tau_{\text{had}}$	1.3σ	0.9σ
2ℓSS+$1\tau_{\text{had}}$	3.4σ	1.1σ
3ℓ	2.4σ	1.5σ
2ℓSS	2.7σ	1.9σ
Combined	4.1σ	2.8σ

- Significance wrt background-only hypothesis: 4.1σ(expected: 2.8σ)
- Cross-section extrapolated to the inclusive phase space:
- Cross-checks performed:
  - Consistency of the fitted signal strengths between the seven channels is 34%
  - 2lSS, 3l and 2lSS+1τ_{had} cross checked with simpler cut & count analyses
  - Cross-check with ttV free floating:
    - 15% loss in sensitivity on signal strength
    - ttV in agreement with SM $\mu_{t\bar{t}W}$=0.92±0.32, $\mu_{t\bar{t}Z} = 1.17^{+0.25}_{-0.22}$

4.1σ (exp: 2.8σ)

$\boldsymbol{\sigma(t\bar{t}H) = 790 \pm 150(\text{stat.})^{+170}_{-150}(\text{syst.})\ \text{fb}}$

expected: $\sigma(t\bar{t}H) = 507^{+35}_{-50}$ fb

CMS multilepton status

CMS ttH multilepton: strategy

- CMS performed an explorative analysis of 2015+2016 data searching for ttH in a multilepton final state (presented during Moriond2017)
- Cut & count + MVA technique to enhance the sensitivity
- Separate analyses for the tau channels

Multilepton channel (tau veto)

2l channel

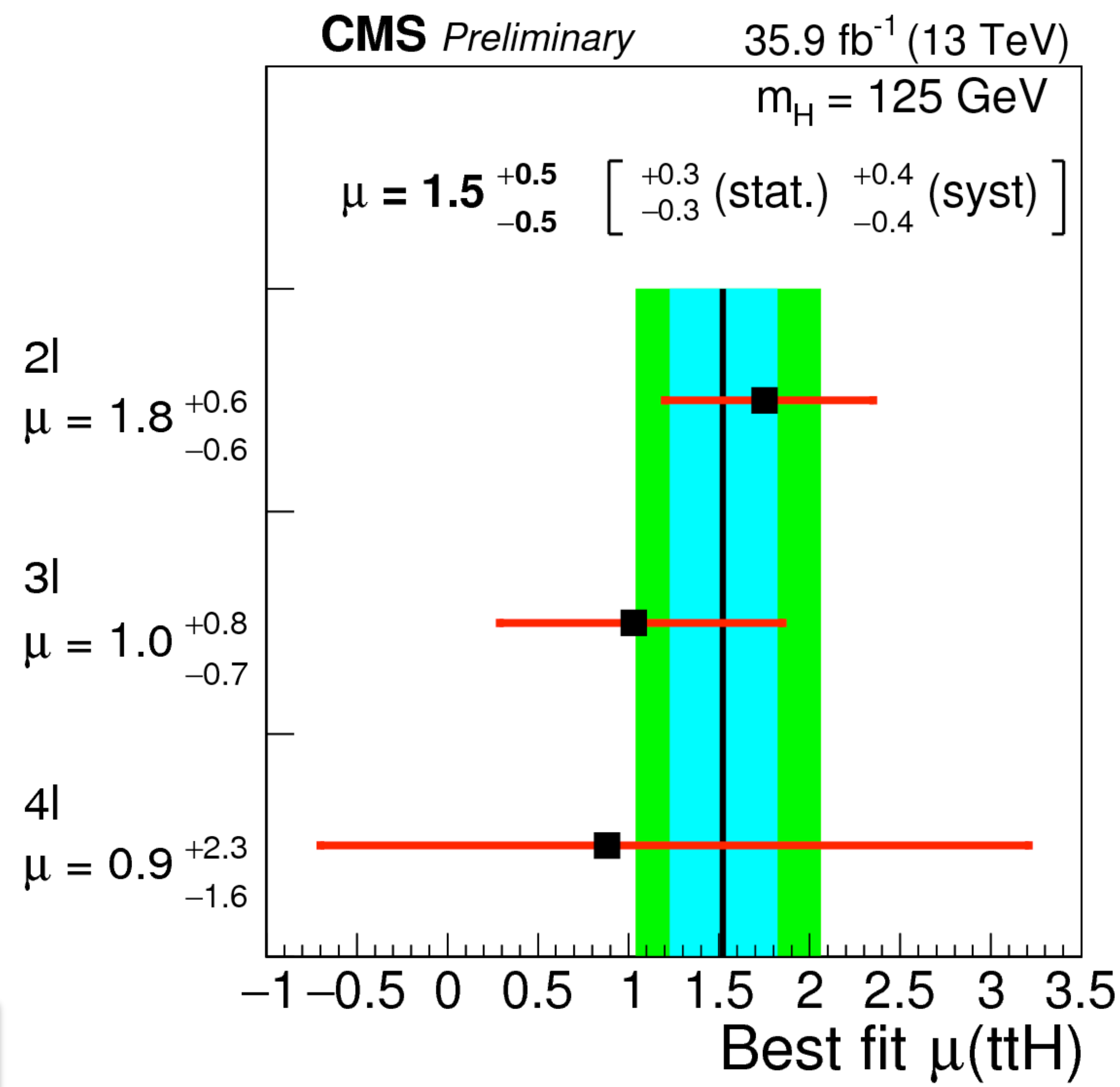
- BDT inputs from hadronic top tagging (vs ttbar) and "jets from Higgs" tagging (vs ttV)

3l channel

- BDT vs ttV uses likelihood ratio from Matrix Element computation for ttH, ttW, ttZ

4l channel

- counting experiment



CMS-PAS-HIG-17-004

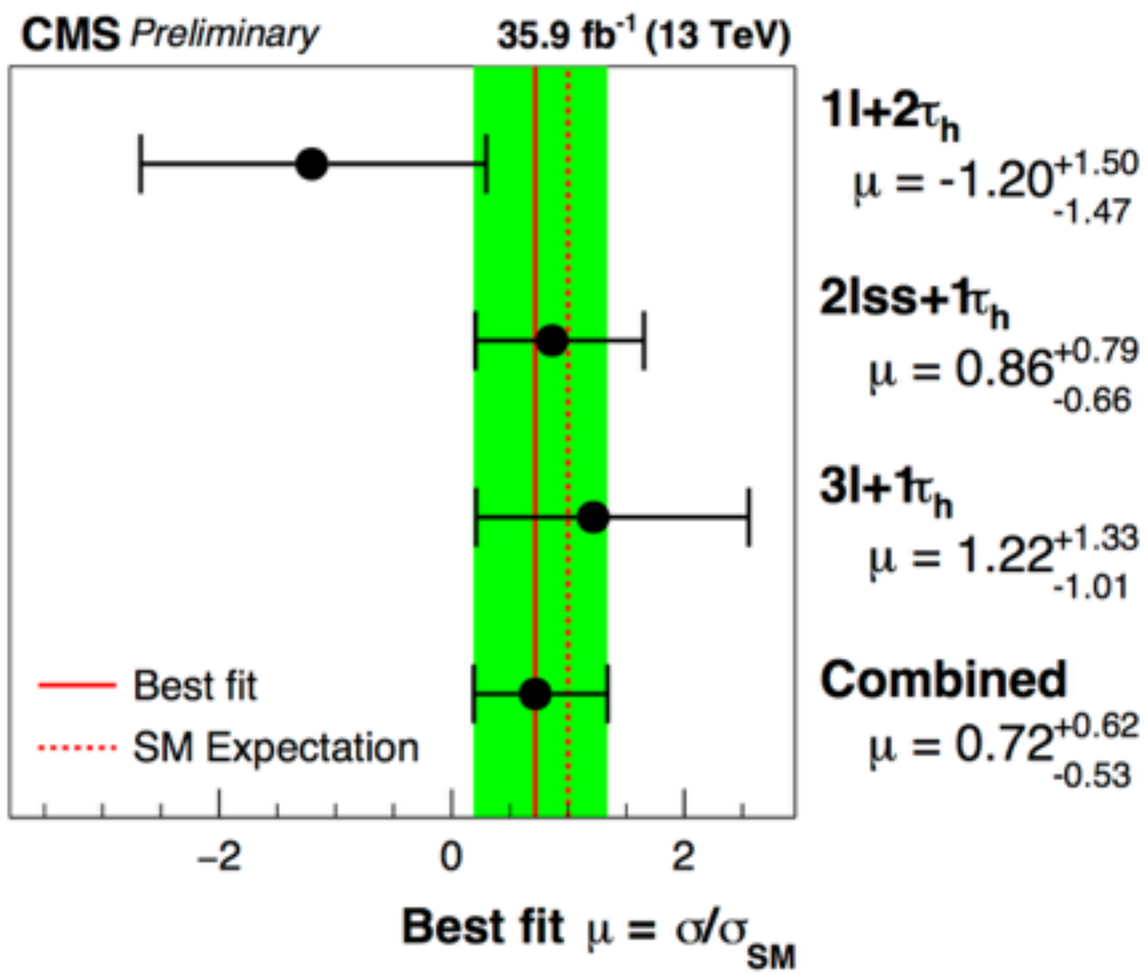
Significance wrt bkg only 3.3σ (exp: 2.5σ)

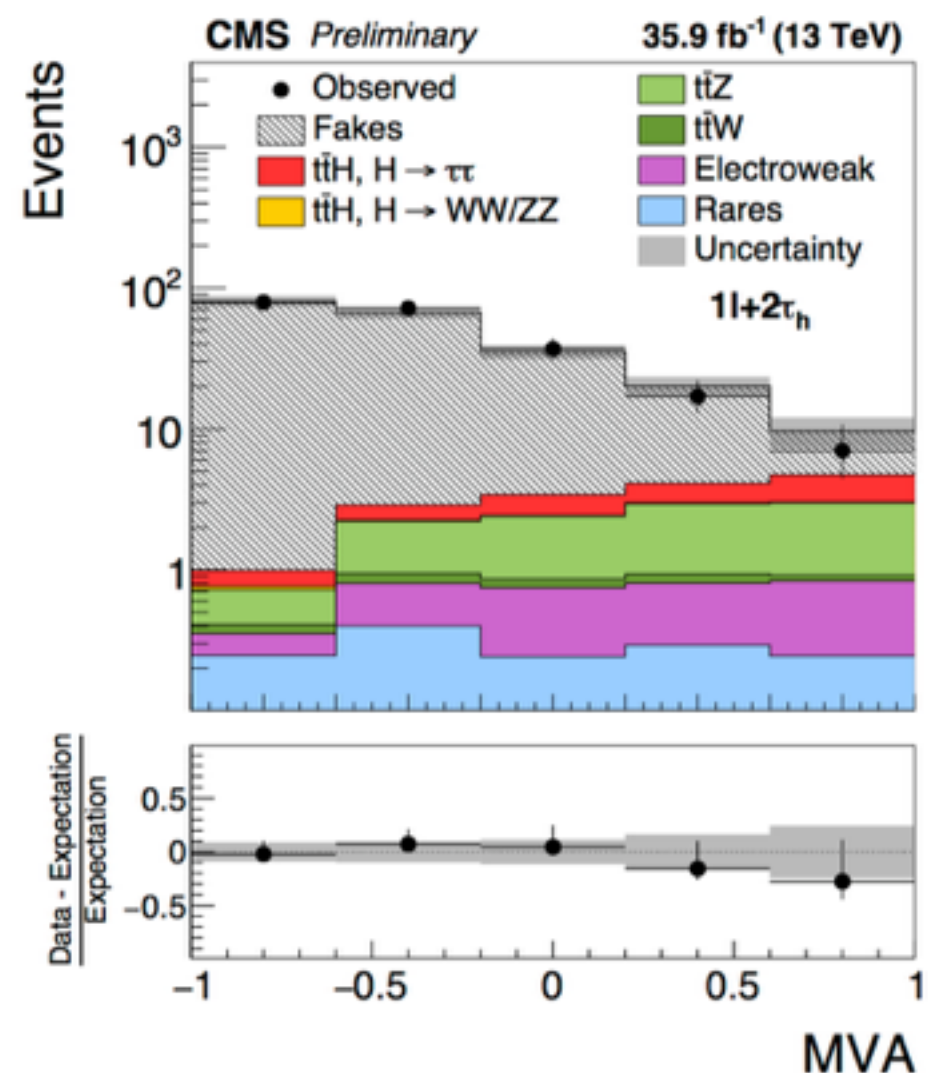
CMS ttH multilepton: uncertainties

- ttH modeling +5/-9%
- ttW/Z theoretical uncert. on cross section 12% and 10%
- VV backgrounds:
  - statistical uncertainty due to the limited sample size in the control region (30%)
  - the residual background in the control region (20%)
  - the uncertainties on the b-tagging rate (between 10–40%) (WZ enters in the SR if high mis-tag rate not well known)
  - from the knowledge of PDFs and the theoretical uncertainties of the extrapolation (up to 10%)
- Non-prompt leptons estimates:
  - from the statistical uncertainty in the measurement of the tight-to-loose ratios, and from a systematical uncertainty derived by comparing alternative methods of subtracting prompt lepton backgrounds and from testing the closure of the method in simulated background events (20-40%)

CMS ttH multilepton: strategy tau channels

- Tau channel same as ATLAS (no 2l0S+1tau)
- Uncert. on charge mis-measurement in 2lSS+1tau 30% (mainly stat.)
- ttW and ttZ background are 12% and 11% respectively
- Rate of WZ+jets background is assigned uncert. up to 100% depending on the categories
- Rate of small irreducible background 50%
- b-tagging efficiency 3-10%

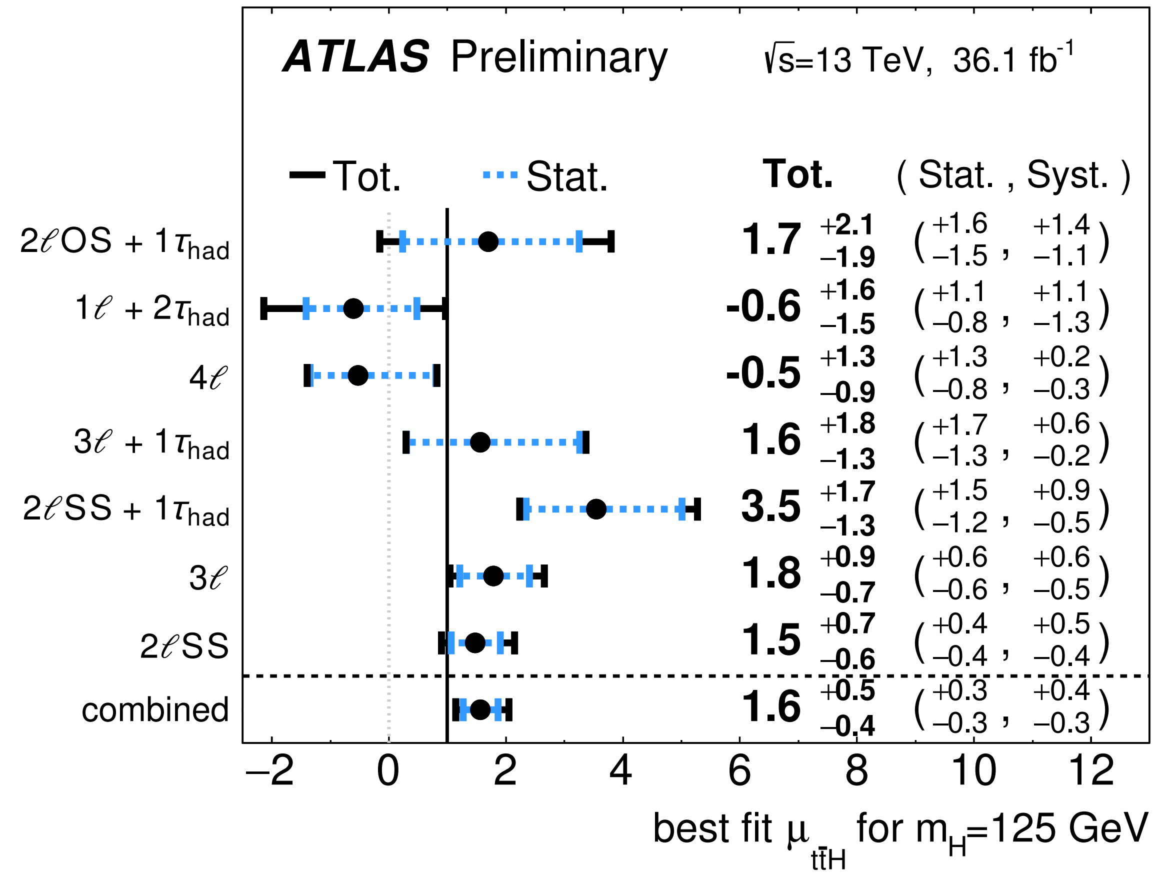




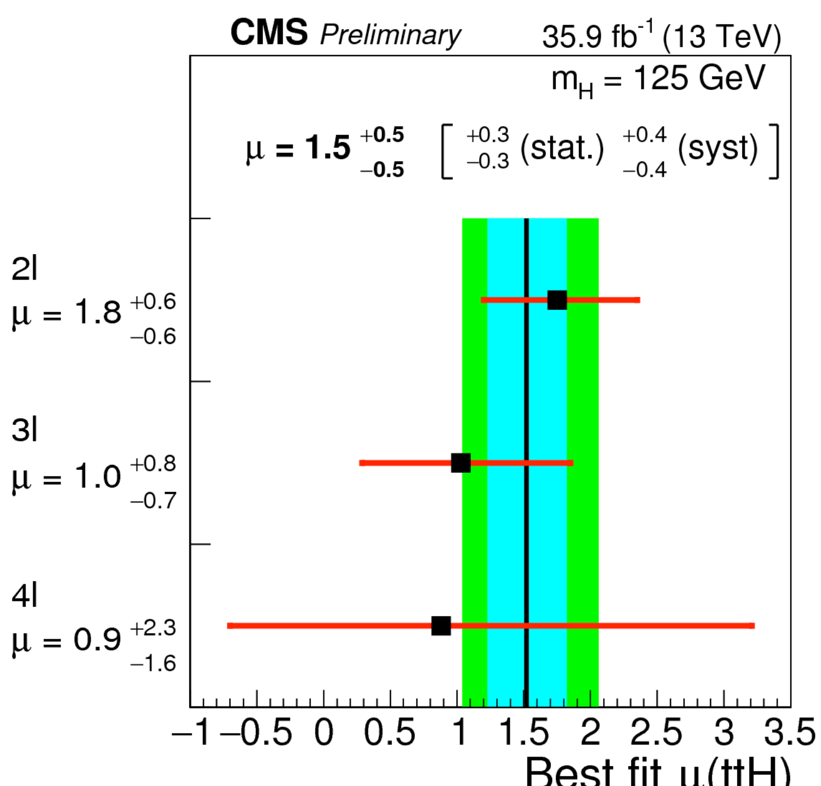
Significance wrt bkg only 1.4σ (exp: 1.8σ)

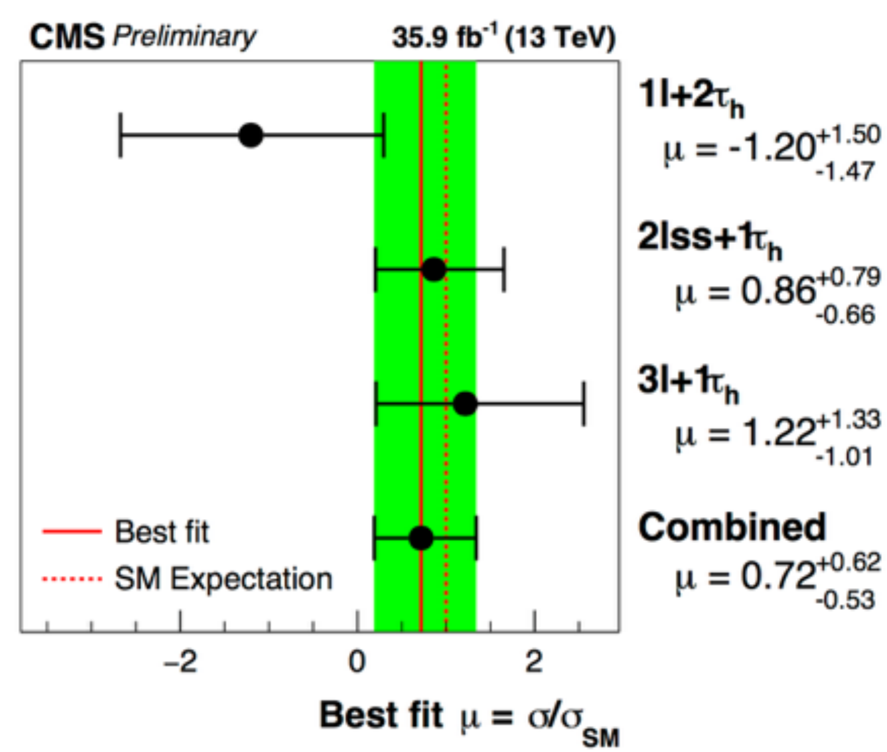
CMS-PAS-HIG-17-003

ATLAS and CMS results: comparison



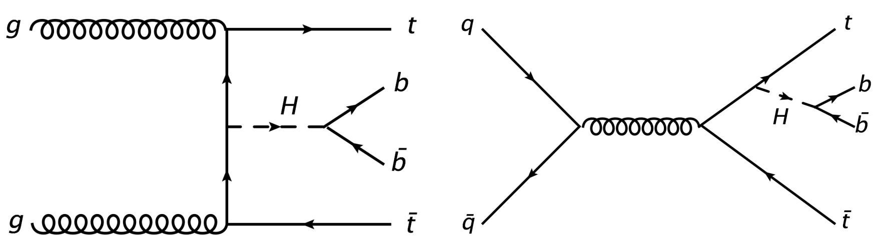
Channel	Significance	
	Observed	Expected
$2\ell OS+1\tau_{had}$	0.9σ	0.5σ
$1\ell+2\tau_{had}$	-	0.6σ
4ℓ	-	0.8σ
$3\ell+1\tau_{had}$	1.3σ	0.9σ
$2\ell SS+1\tau_{had}$	3.4σ	1.1σ
3ℓ	2.4σ	1.5σ
$2\ell SS$	2.7σ	1.9σ
Combined	4.1σ	2.8σ





ttH(bb)

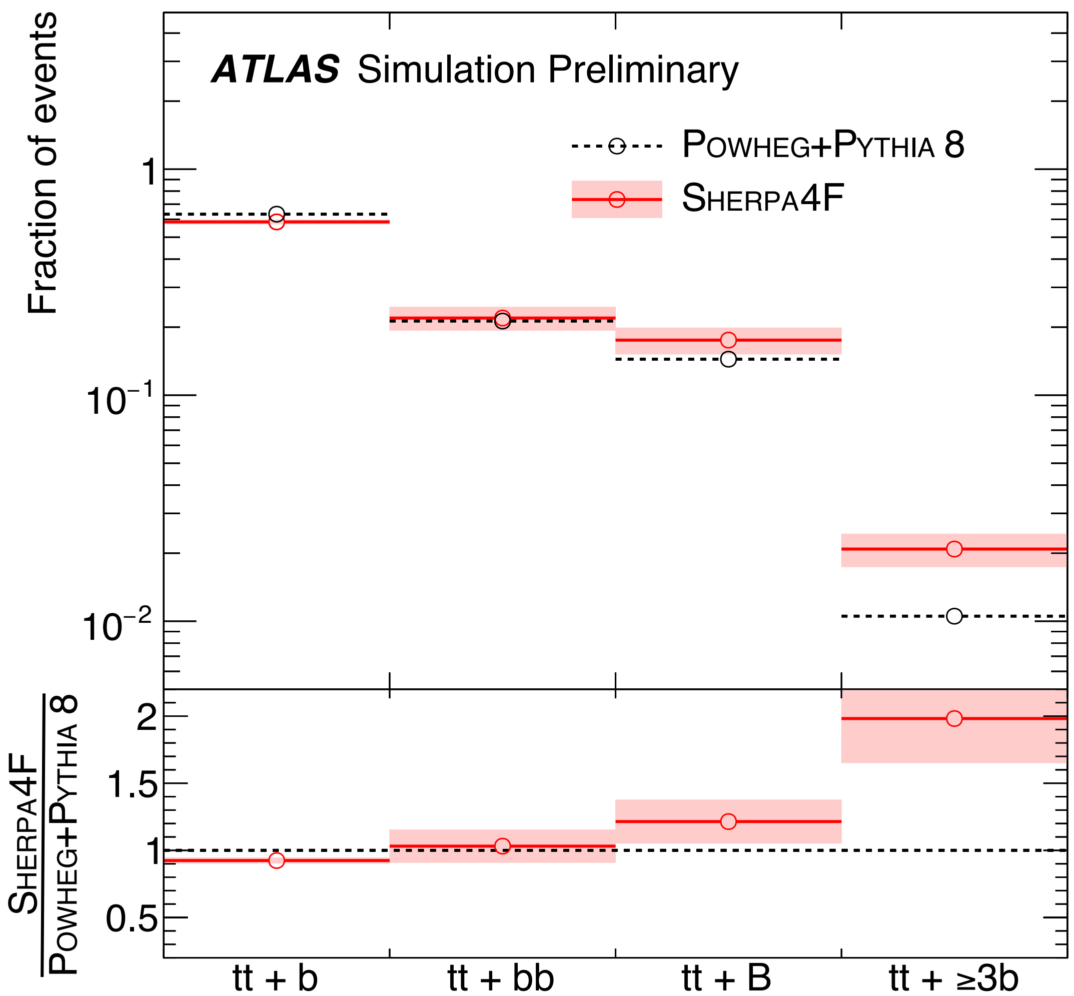
ttH(bb): strategy



- Benefiting from large H → bb branching ratio (58%) and leptonic top decays 🙂
- Large irreducible background from tt+heavy flavor (HF) production ☹️
- Low combined efficiency to reconstruct and identify all final-state objects ☹️
- combinatorial ambiguity from the many b-tagged jets: difficult to reconstruct Higgs mass ☹️

tt+HF modeling:

- MC simulation is NLO, its modeling studied at 7/8/13 TeV
- Normalized to NNLO+NNLL cross-section
- MC sample split in number of HF jets at particle level
  - tt+≥1b: jet matched to 1(b) or 2(B) b-hadrons
  - Extra b-jets from MPI or FSR
  - tt+≥1c: analogous to tt+≥1b
  - tt+light
- tt+≥1b: relative contribution from each sub-component are reweighed to ttbb predictions by Sherpa+OpenLoops: NLO, 4-flavours scheme (massive b-quarks, g→bb from ME)



b-tagging:

- Considering 4 working points: loose, medium, tight, very-tight
- Efficiency from b-jets: 85% to 60%
- Rejection factor for c-jets (light jets): 3 to 35 (30 to 1500)

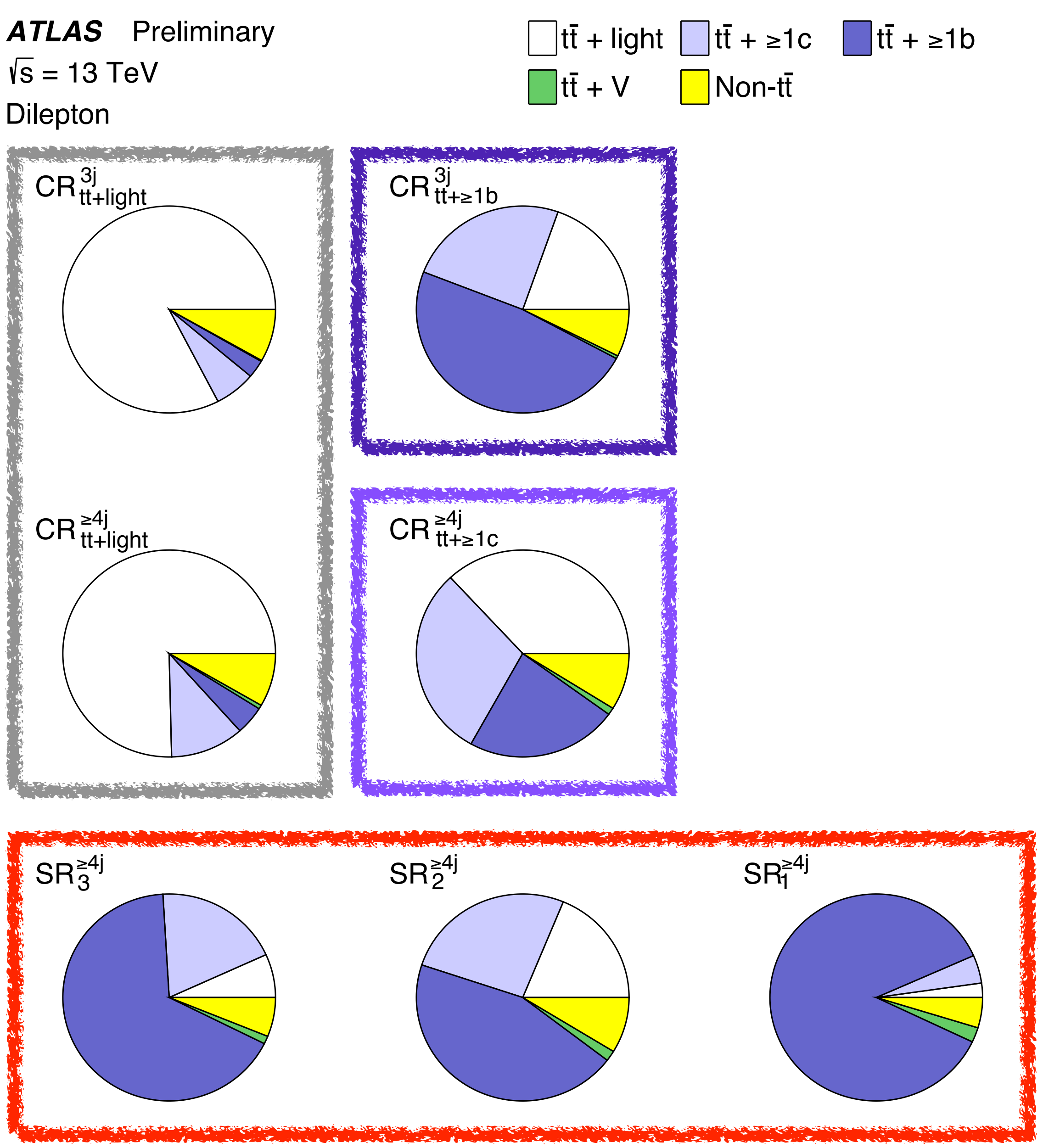
	none	*loose*	*medium*	*tight*	*very-tight*
Efficiency	-	85%	77%	70%	60%
Discriminant value	1	2	3	4	5

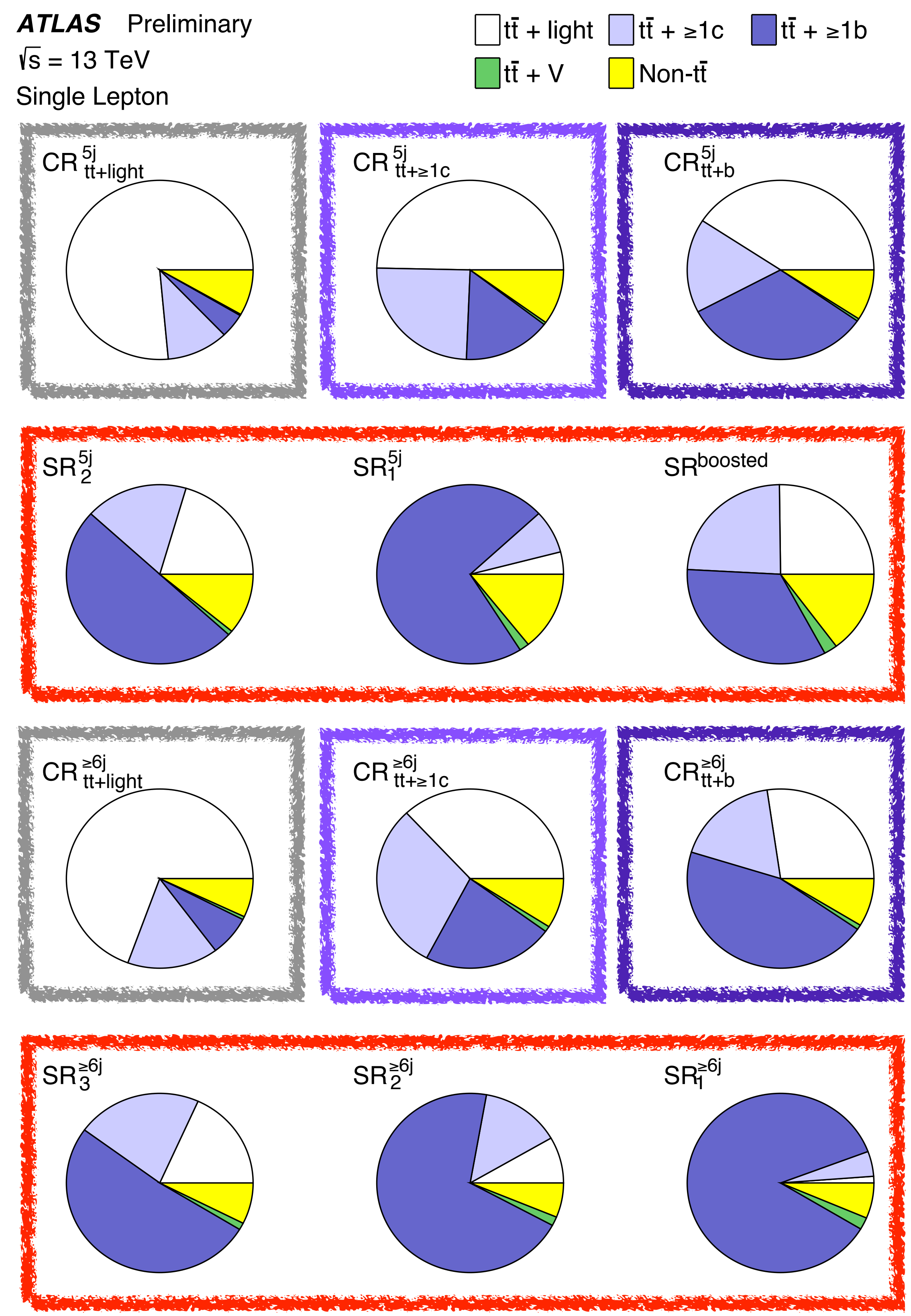
Channel classification:

- Two separate channels depending on the number of light leptons (e/μ): 1l, 2l
- 2l opposite-sign (OS) with p_T > 27, 25 GeV (fraction of total ttH(bb) = 2.5%)
  - at least 3 jets of which at least two medium b-tagged
  - veto mll~mZ and events with τ_{had}
- 1l with p_T>27 GeV
  - veto events with $\geq 2\tau_{had}$
  - Boosted high pT category (fraction of total ttH(bb) = 0.1%):
    - boosted Higgs and top candidates (large R jets, reclustered from R = 0.4 jets), plus a loose b-tagged jet
  - Resolved (if failing boosted selections, fraction of total ttH(bb) = 8.7%)
    - Require ≥ 5 jets and ≥ 2 very tight b-tagged jets or ≥ 3 medium b-tagged jets

Background composition

- Three 2ℓ SR ($\geq$4j)
- Six 1ℓ SR (boosted, 5j, $\geq$6j)
- Ten CRs for the different $t\bar{t}$+HF components

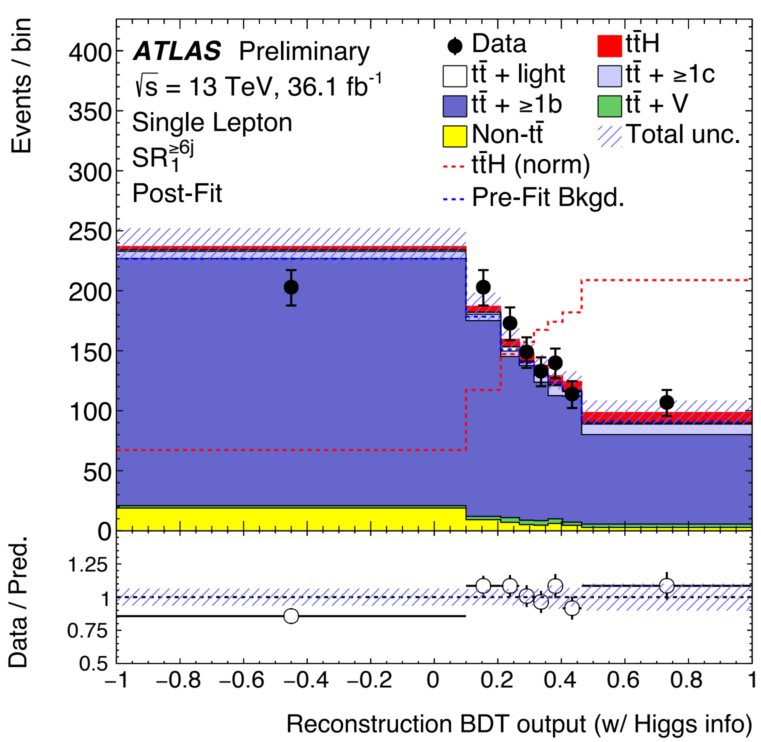




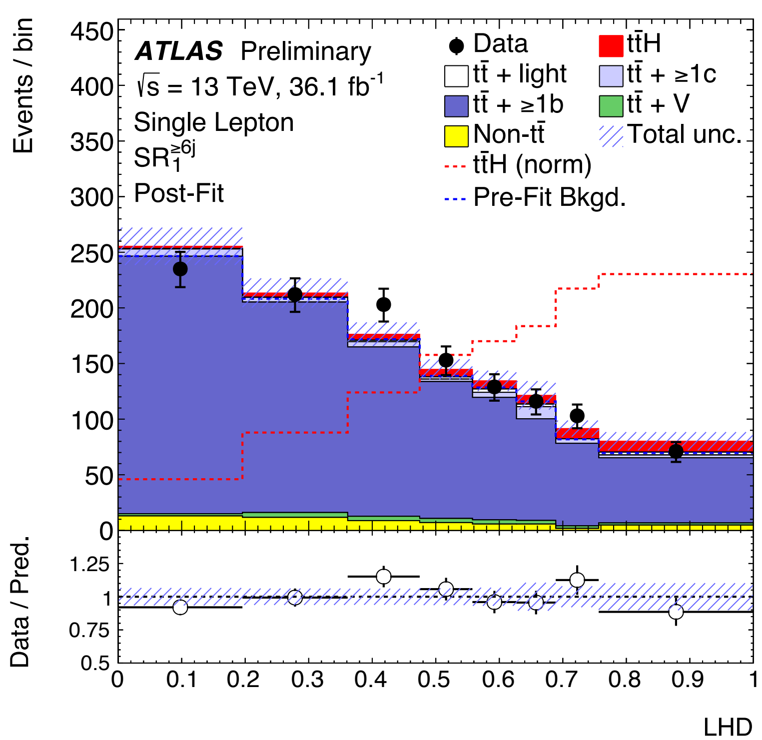
MVA analysis

- Sensitivity enhanced using multivariate techniques to discriminate signal from backgrounds
- 'Reconstruction' BDT (all resolved SRs):
  - Combination of jets as originating from H/top decays to reconstruct the $t\bar{t}H(b\bar{b})$ system
- Likelihood discriminator (LHD) (1ℓ resolved SRs only):
  - Probability for signal/background ($t\bar{t}+\geq 2b$, $t\bar{t}+1b$) hypotheses using 1D distributions of discriminating variables (invariant mass, angular distributions, etc.)
- Matrix Element Method (MEM) ($\mathrm{SR}_1^{\geq 6j}$ only):
  - Signal/background probability using matrix element calculations at parton level

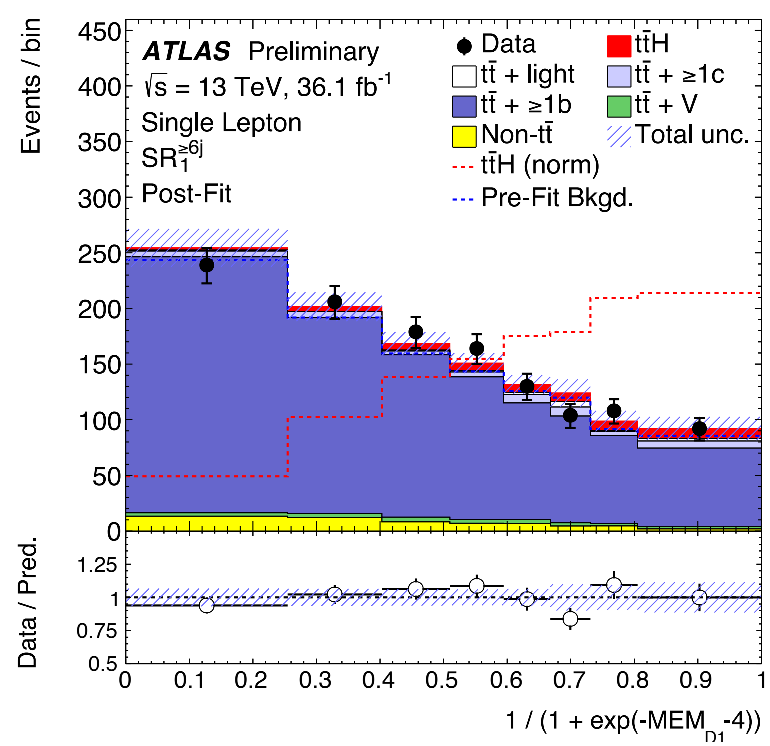
Reconstuction BDT



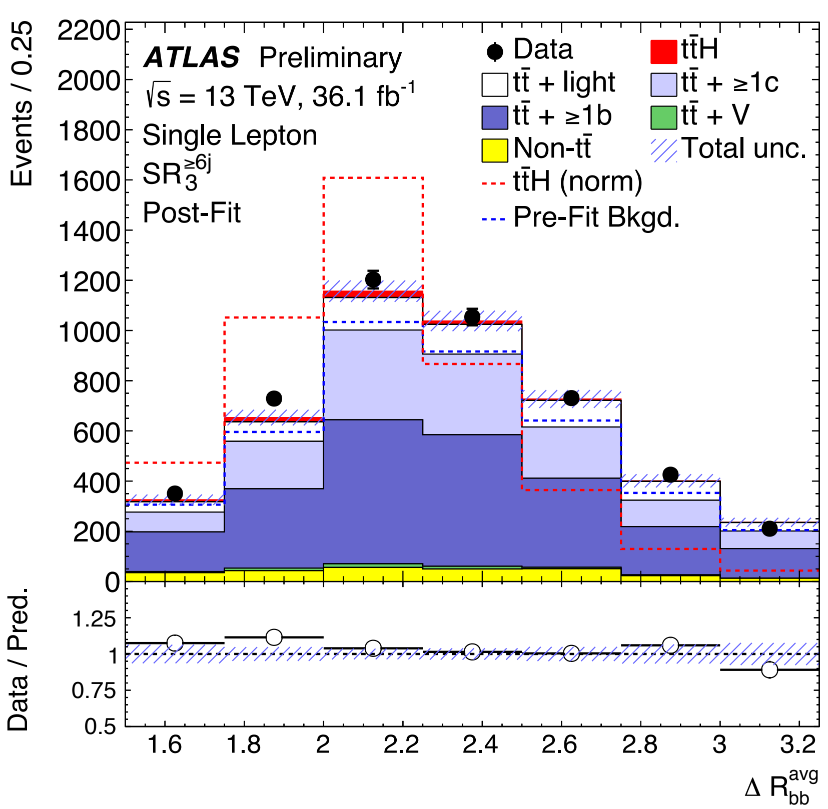
Likelihood discriminant

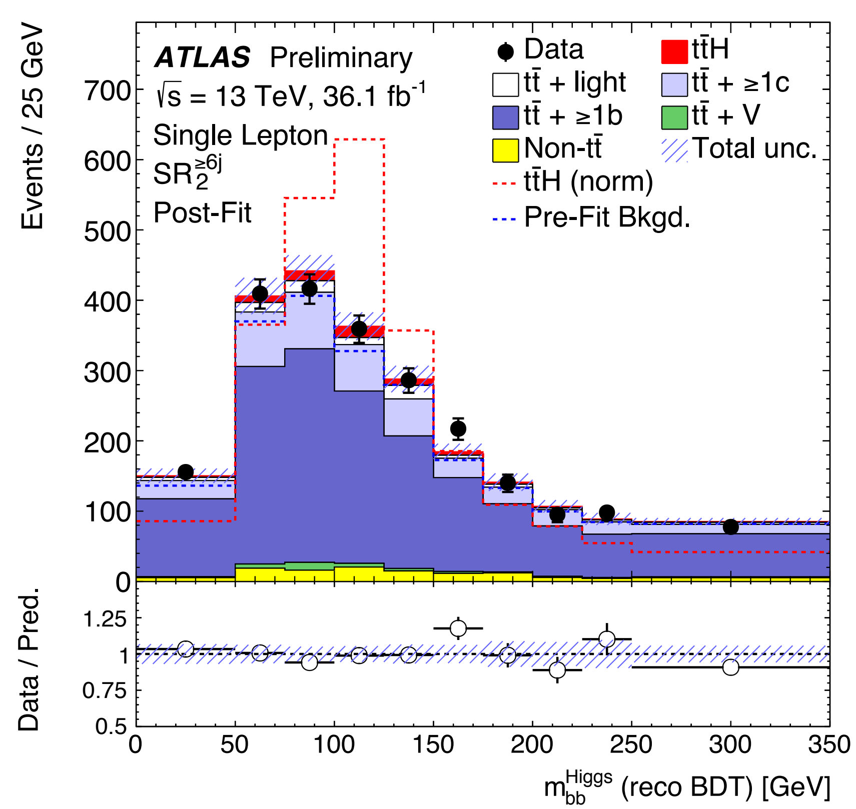


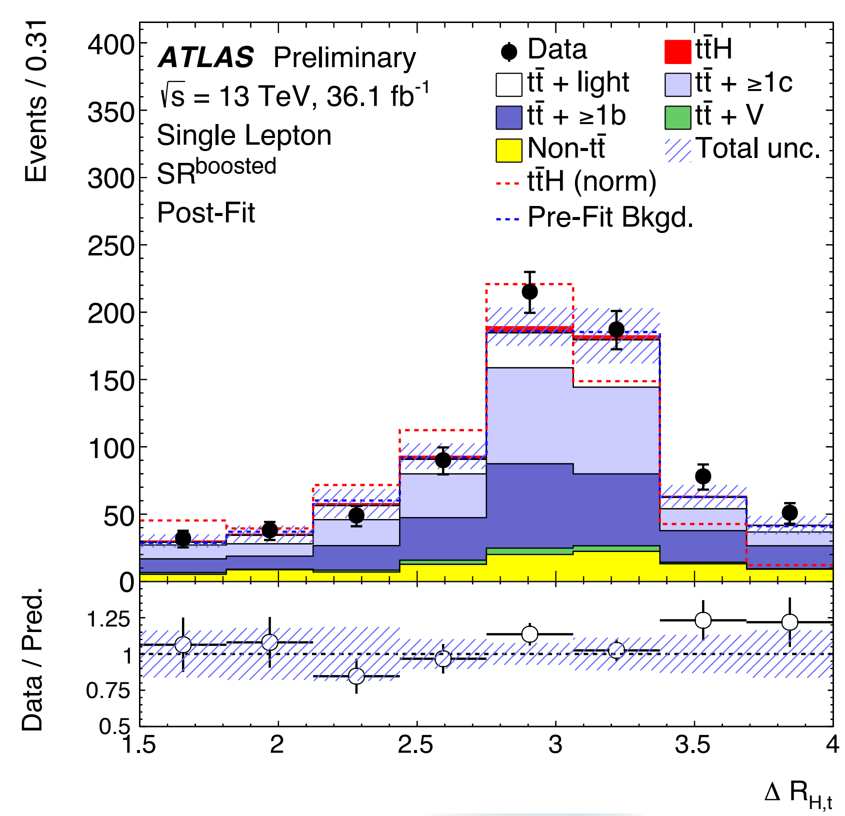
MEM discriminant



- Final discriminant: **'Classification BDT'**
  - Trained to separate signal from background
  - Only variables with good modelling in the MC are considered
- Input variables:
  - General kinematic variables
  - Discrete *b*-tagging discriminant
  - 'Reconstruction BDT' output (resolved SRs only), and variables associated to its *H*/top candidates
  - Likelihood and Matrix Element Methods discriminants (where available)
  - Boosted SR: Properties of the large-*R* jets and their sub-jets



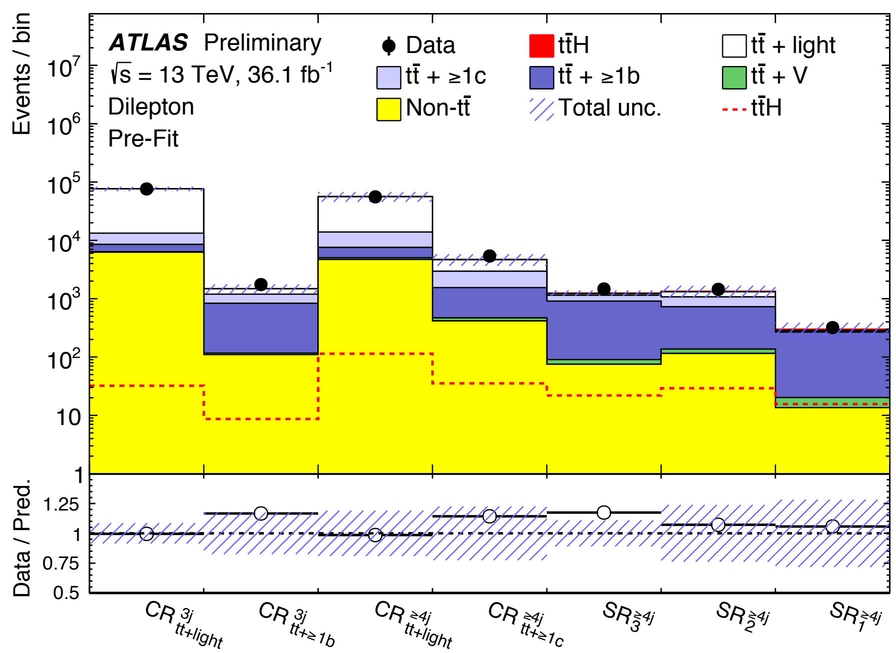




- Simultaneous profile likelihood fit to all SRs and CRs
  - SRs binned in ‘classification BDT’
  - CRs: single bin, except $t\bar{t}+\geq 1c$ 1ℓ-CRs (binned in $H_T = \sum_{\text{jet}} p_T^{\text{jet}}$)

Pre-fit **Post-fit**

2ℓ



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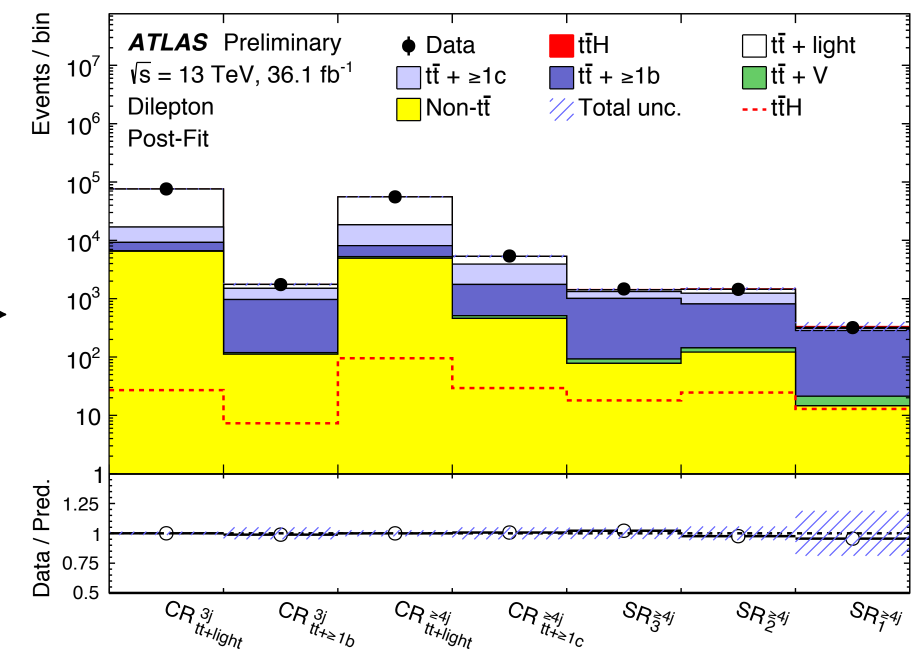
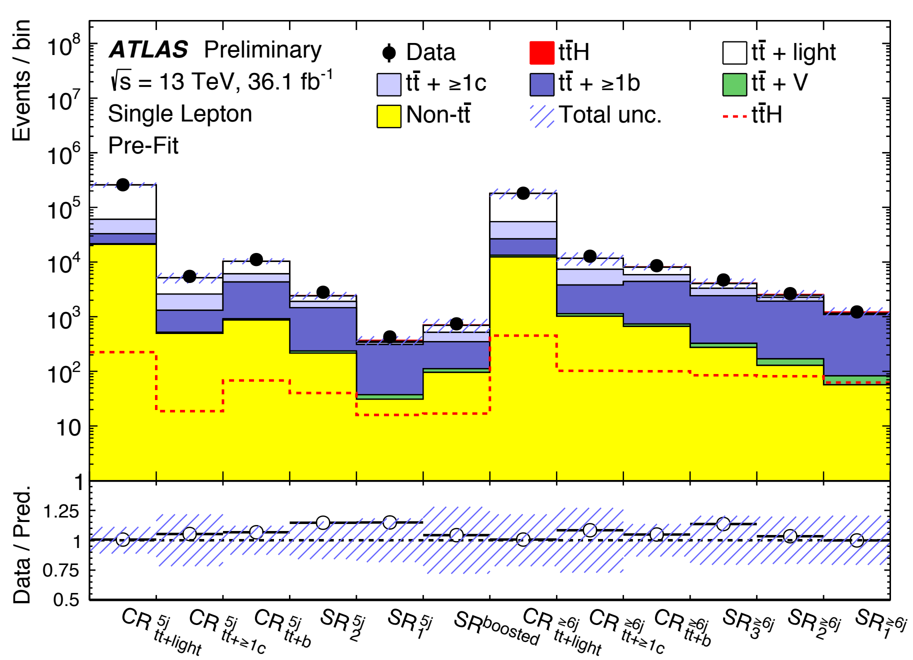


1ℓ



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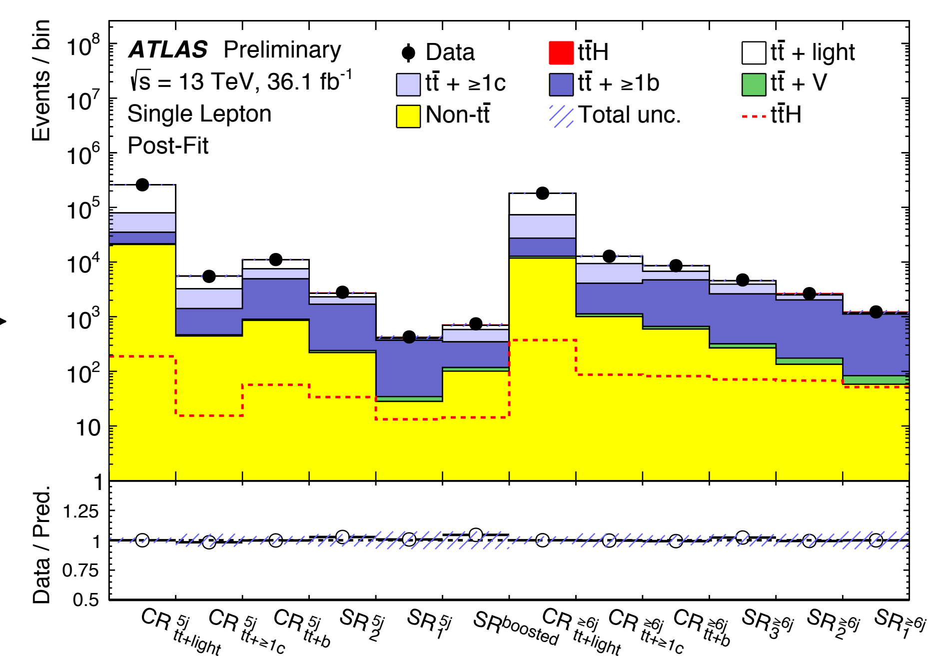
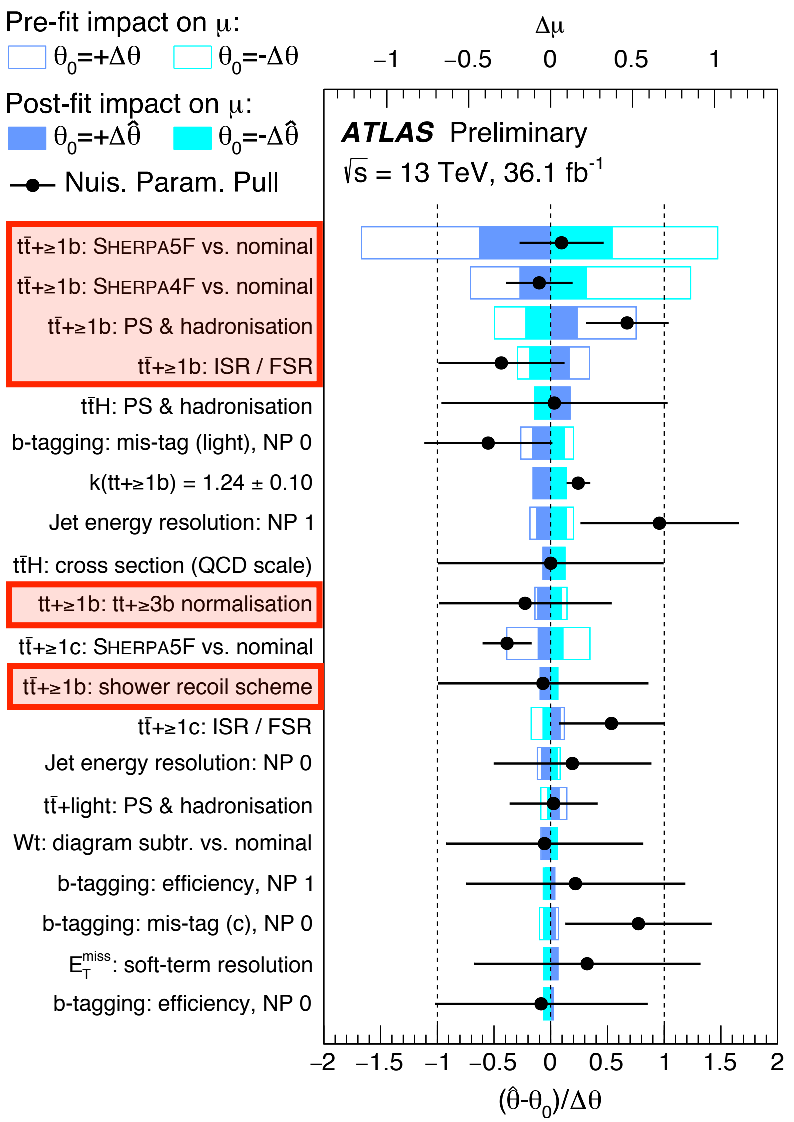
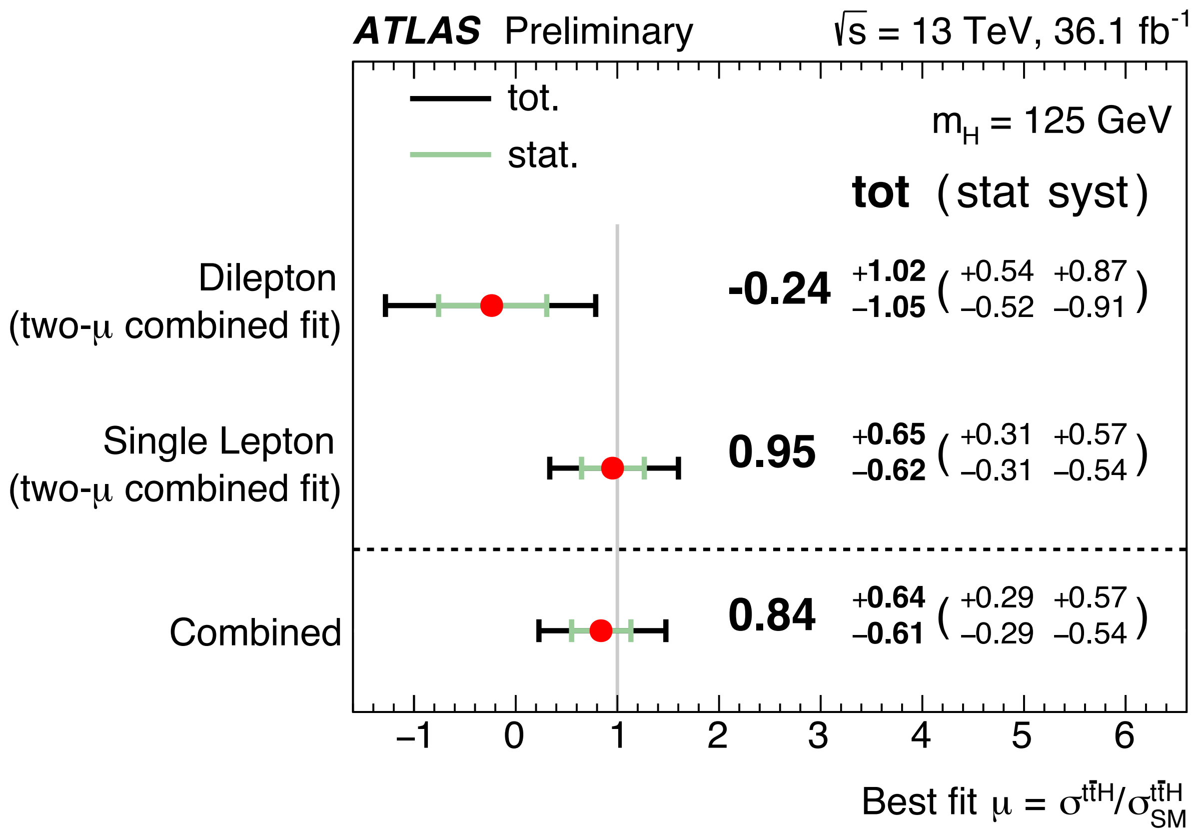


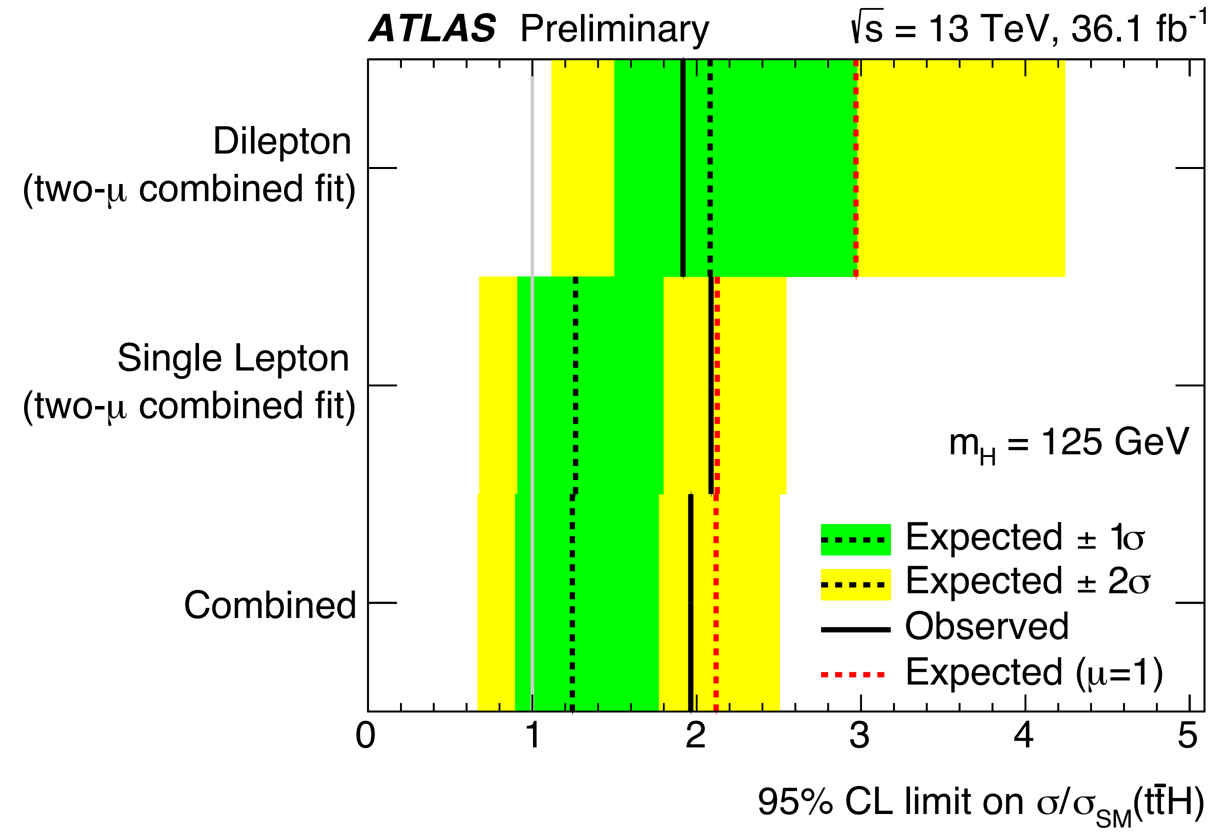
- Normalization factors for $t\bar{t}+\geq1b/\geq1c$ constrained in the fit, no prior uncertainty:
  - $t\bar{t}+\geq1b$: 1.24 ± 0.10
  - $t\bar{t}+\geq1c$: 1.63 ± 0.23
- Analysis already dominated by systematics
- Most relevant uncertainties:
  - $t\bar{t}+\geq1b$ background modelling
  - Limited MC statistics
  - b-tagging uncertainties
  - Jet uncertainties

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq1b$ modelling	+0.46	−0.46
Background model statistics	+0.29	−0.31
Jet flavour tagging	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modelling	+0.22	−0.05
$t\bar{t}+\geq1c$ modelling	+0.09	−0.11
Jet-vertex association, 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
$t\bar{t}+\geq1b$ normalisation	+0.09	−0.10
$t\bar{t}+\geq1c$ normalisation	+0.02	−0.03
Statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61



ttH bb - Results





- Signal strength: $\boldsymbol{\mu_{t\bar{t}H} = 0.84^{+0.64}_{-0.61}}$
  - Sensitivity dominated by the single lepton channel
- Significance w.r.t background-only hypothesis: $\boldsymbol{1.4\sigma}$ (exp: 1.6σ)
- Can exclude $\mu_{t\bar{t}H} > 2.0$ at 95% CL

Combination

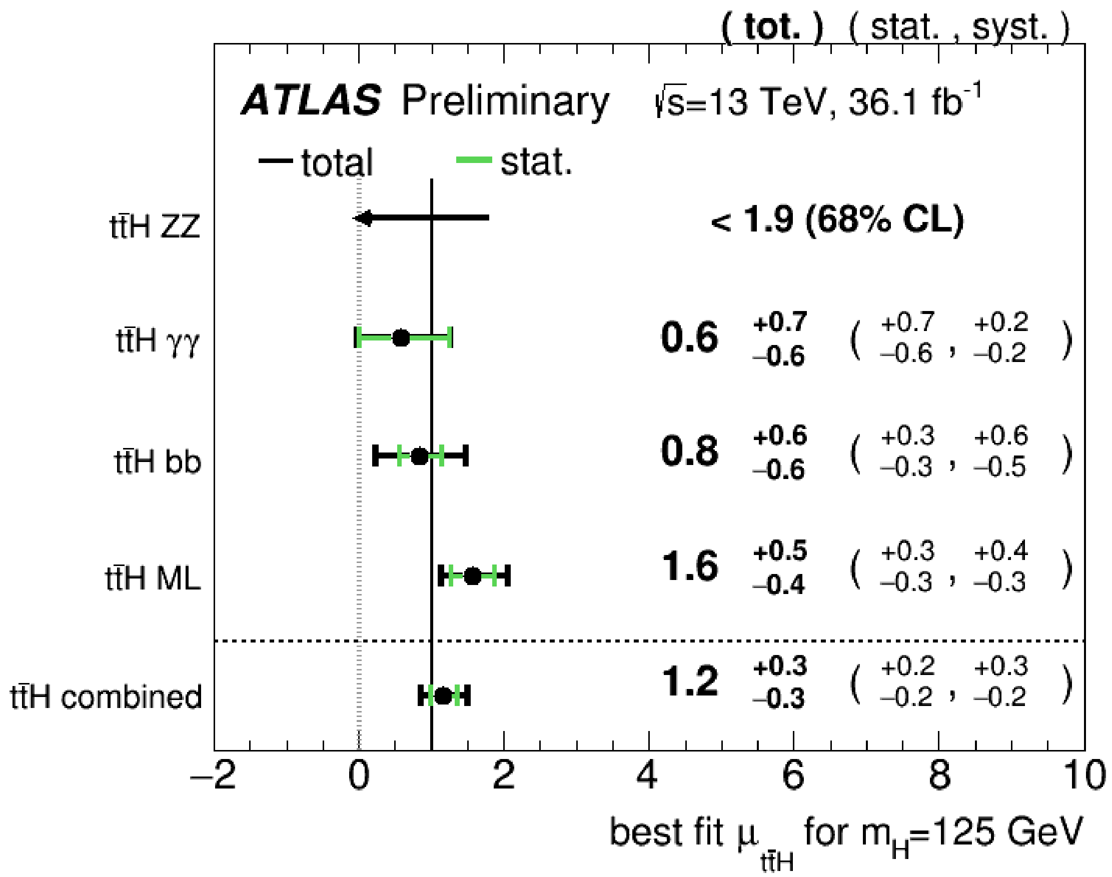
Combination

- Combining $b\bar{b}$, multilepton, $\gamma\gamma$ and $ZZ \to 4\ell$ channels
  - Only $t\bar{t}H$ enhanced categories in $\gamma\gamma$ and 4ℓ included
- $tHjb$ and tWH treated as backgrounds and fixed to the SM prediction
- Non-$t\bar{t}H$ production mechanisms also fixed to the SM predictions
- Correlating almost all signal, background and detector uncertainties
- Best-fit value:

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

$$\sigma_{t\bar{t}H} = 590^{+160}_{-150} \text{ fb}$$

- Significance: **4.2σ (exp: 3.8σ)**



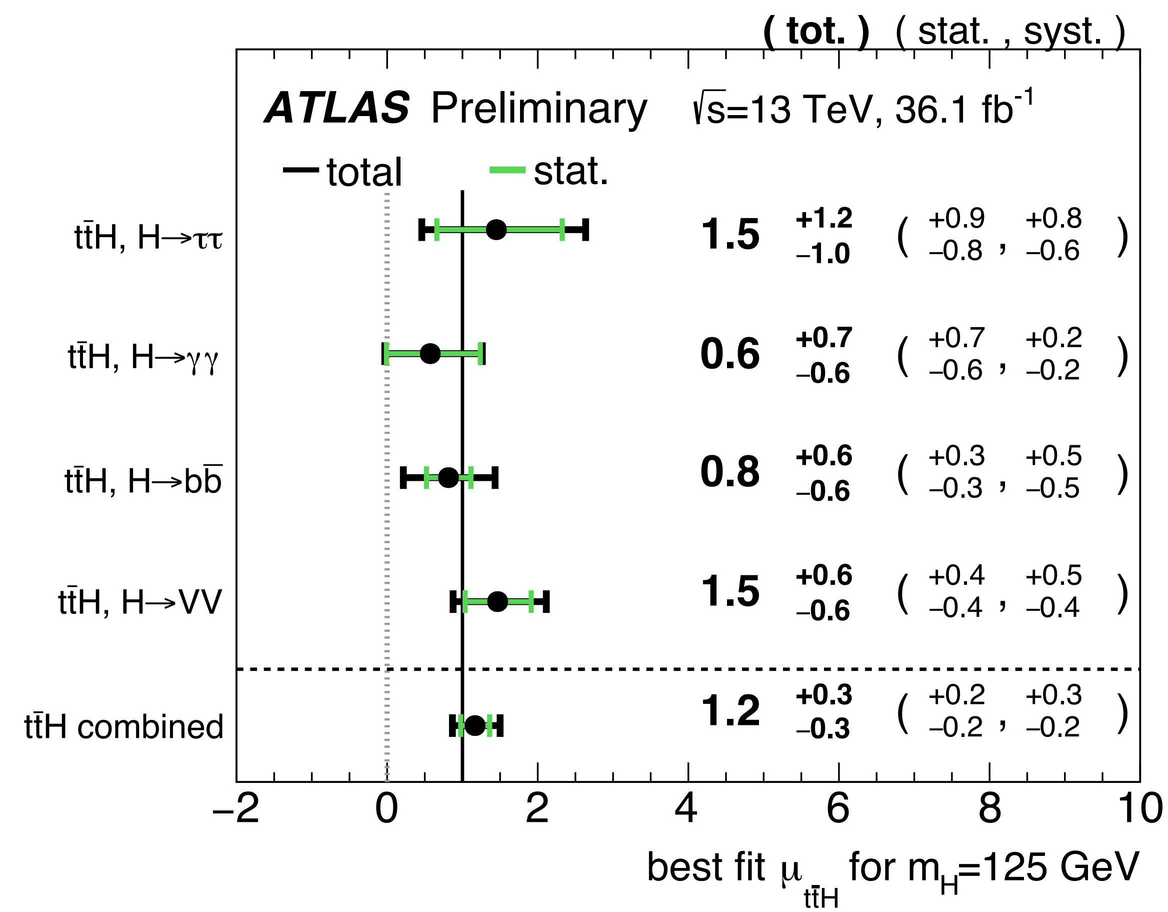
Channel	Significance	
	Observed	Expected
Multilepton	4.1σ	2.8σ
$H \to b\bar{b}$	1.4σ	1.6σ
$H \to \gamma\gamma$	0.9σ	1.7σ
$H \to 4\ell$	—	0.6σ
Combined	4.2σ	3.8σ

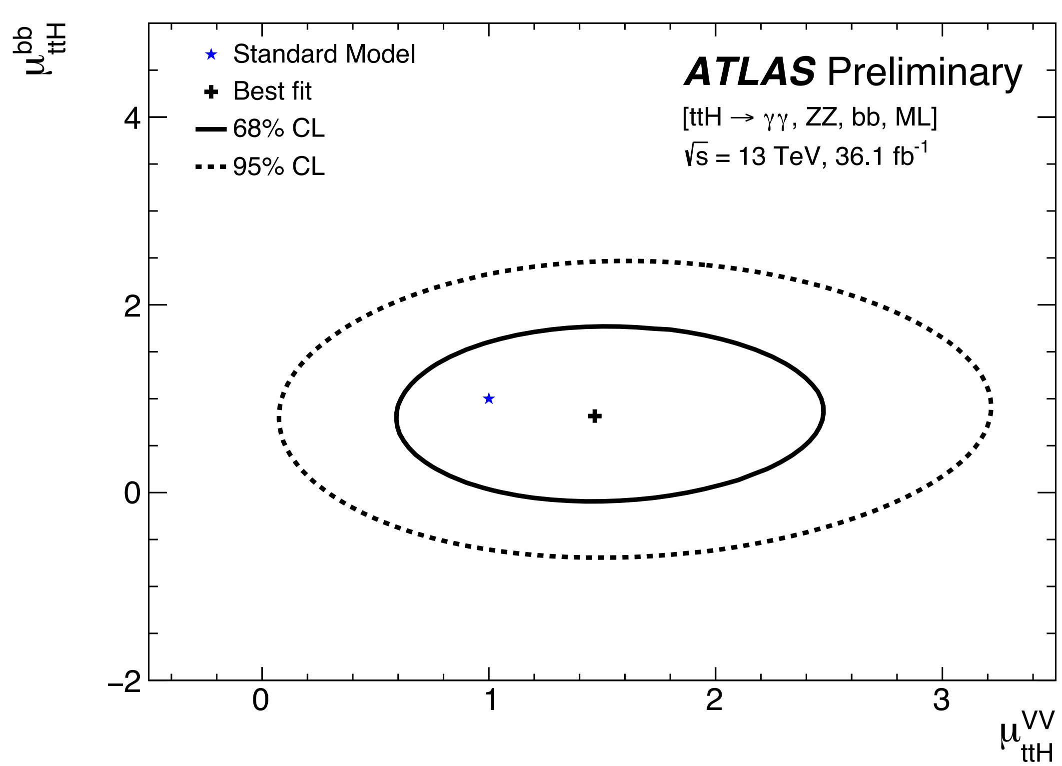
Combination uncertainties

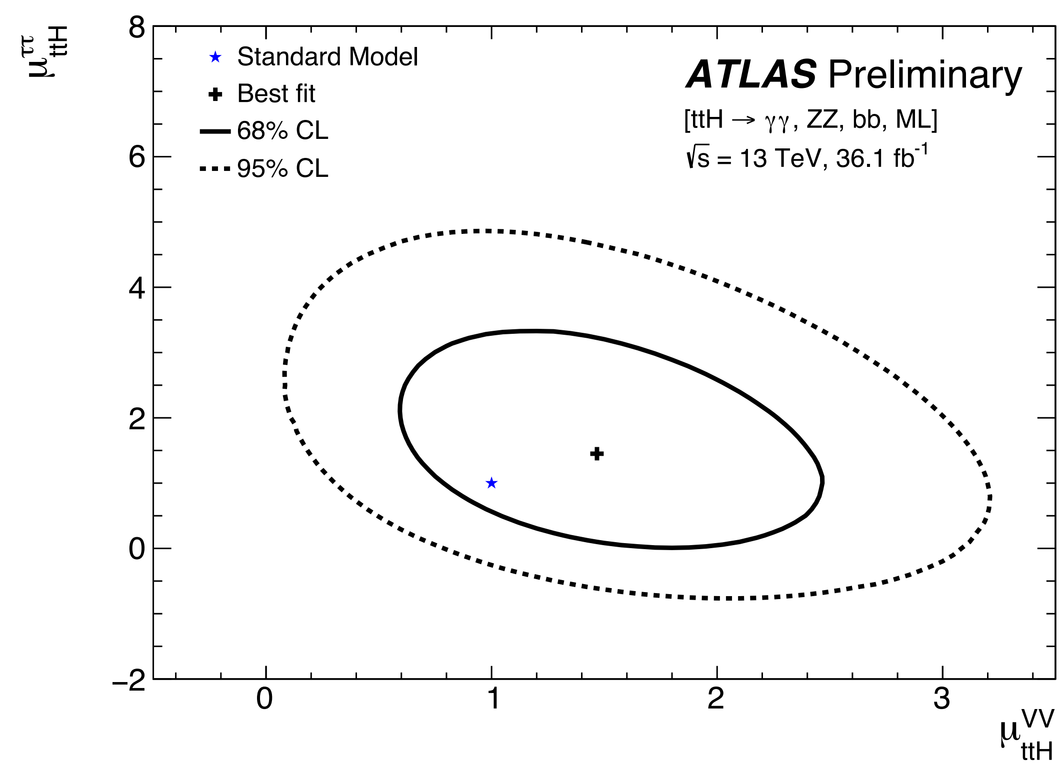
- Compatibility between μ from the individual analyses and combination: 38%
- Dominant systematic uncertainties:
  - $t\bar{t}$ modelling systematics in $t\bar{t}H(b\bar{b})$
  - $t\bar{t}H$ signal modelling
  - Fake/non-prompt ℓ/τ_{had} from $t\bar{t}H$ multilepton

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

- Measuring $\mu_{t\bar{t}H}$ for different decays
  - $H \to WW, \tau\tau$ contribution to $0/\geq 1\tau_{\text{had}}$ categories in multilepton
  - $H \to b\bar{b}, \gamma\gamma$ dominated by their dedicated analyses
  - WW/ZZ ratio set to the SM prediction
- Results in agreement with the SM predictions





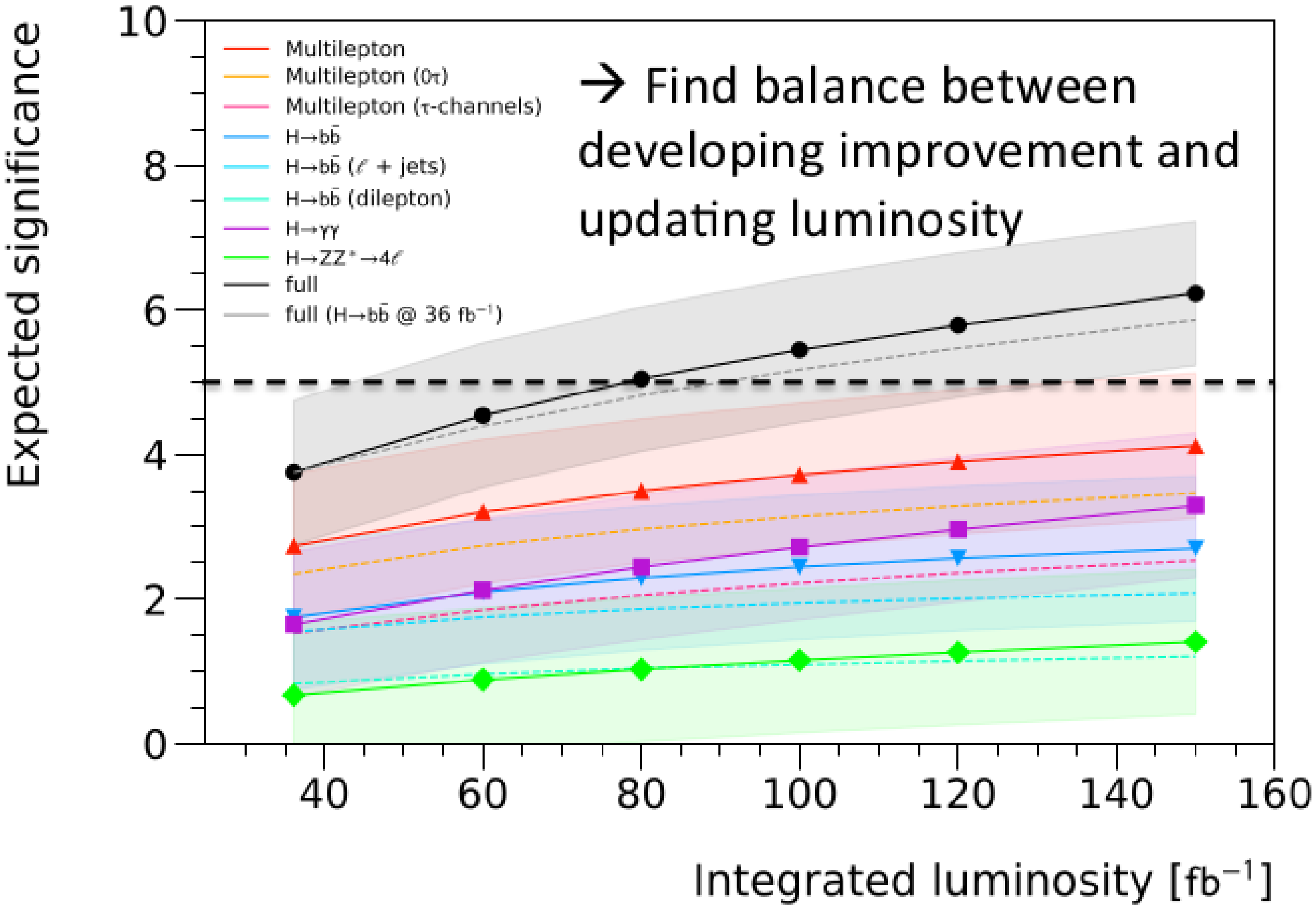


Summary

- Results from search fro ttH in multilepton final state using ATLAS 2015+2016 data @ 13 TeV
- Very challenging and complex analysis that uses multivariate analysis techniques
- Found evidence for ttH production with a leading contribution from the multilepton channel
- SM prediction is consistent with the extrapolated cross section
- ATLAS and CMS analyses very similar
- STAY TUNED FOR THE RESULTS FROM THE FULL RUN2 ANALYSIS

What's next?

- Considering all current analyses and same level of systematics without any improvements : **5σ discovery with ~80 fb^{-1}** !



→ Find balance between developing improvement and updating luminosity

Other possible scenarios:

- 5σ@~100 fb^{-1} if no bb update with lumi (keep 36 fb^{-1})
- 5σ@~70 fb^{-1} if keep bb with 36 fb^{-1} and improve γγ analysis sensitivity by *30-40%*
- 5σ@~60 fb^{-1} if all systematics are cut in half

Remarks:

- *1σ error on the projections lead to* ***80 ± 40 fb^{-1}***

BACK UP

ttH multilepton: channels definition

Table 3: Selection criteria applied in all channels. Same-flavour, opposite-charge lepton pairs are referred to as SFOC pairs. The common selection criteria for all channels is listed in the first line under the title “Common”.

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

Matrix method fro non-prompt leptons

- The matrix method estimates the number of non-prompt leptons in the SR by selecting events passing all selection requirements expect the tight-lepton and splitting the events into four categories (tight-tight, loose but not tight-tight…)
- The probabilities for loose prompt and non-prompt leptons to be tight are measured in CR independent from the SR

$$f_{SR} = w_{TT} N^{TT} + w_{\bar{T}T} N^{\bar{T}T} + w_{T\bar{T}} N^{T\bar{T}} + w_{\bar{T}\bar{T}} N^{\bar{T}\bar{T}}$$

- where w weighted depend on the measured prompt and non-prompt lepton efficiencies
- defined CRs to measure the prompt (ε_{real}) and non-prompt (ε_{fake}) leptons efficiencies
    - electrons from conversion have higher efficiency than electron from HF
    - non-prompt muons mainly come from HF semileptonic decay

	2ℓSS	3ℓ	4ℓ	1ℓ+$2\tau_{\text{had}}$	2ℓSS+$1\tau_{\text{had}}$	2ℓOS+$1\tau_{\text{had}}$	3ℓ+$1\tau_{\text{had}}$
Non-prompt lepton strategy	DD (MM)	DD (MM)	semi-DD (SF)	MC	DD (FF)	MC	MC
Fake tau strategy	–	–	–	DD (SS data)	semi-DD (SF)	DD (FF)	semi-DD (SF)
Control Region Selection							
Light lepton	1T*, 1L		3L	1T	1T*, 1L	2L†	–
τ_{had}	0M			1T, 1M	$\leq$ 1M	1L	–
N_{jets}	$2 \leq N_{\text{jets}} \leq 3$		$1 \leq N_{\text{jets}} \leq 2$	≥ 3	$2 \leq N_{\text{jets}} \leq 3$	≥ 3	–
$N_{b-\text{jets}}$	≥ 1					$= 0$	–

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
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

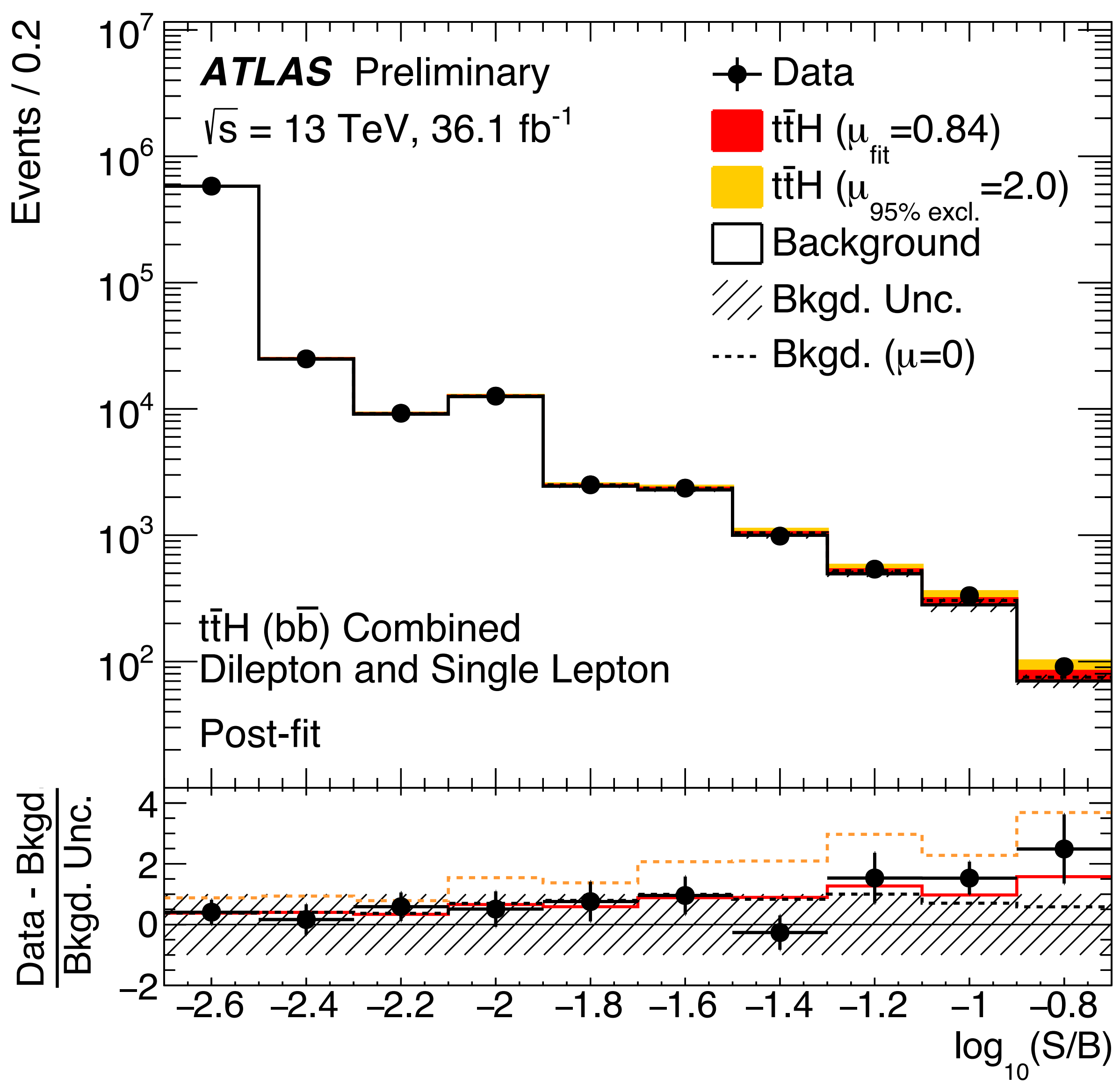
ttH multilepton: systematics

Systematic uncertainty	Type	Components
Luminosity	N	1
Pile-Up reweighting	SN	1
Physics Objects		
Electron	SN	6
Muon	SN	15
Tau	SN	10
Jet energy scale and resolution	SN	28
Jet vertex fraction	SN	1
Jet flavour tagging	SN	126
$E_{\mathrm{T}}^{\mathrm{miss}}$	SN	3
Total (Experimental)	–	191
Data-driven non-prompt/fake leptons and charge misassignment		
Control region statistics	SN	38
Light-lepton efficiencies	SN	22
Non-prompt light-lepton estimates: non-closure	N	5
γ-conversion fraction	N	5
Fake τ_{had} estimates	N/SN	12
Electron charge misassignment	SN	1
Total (Data-driven reducible background)	–	83

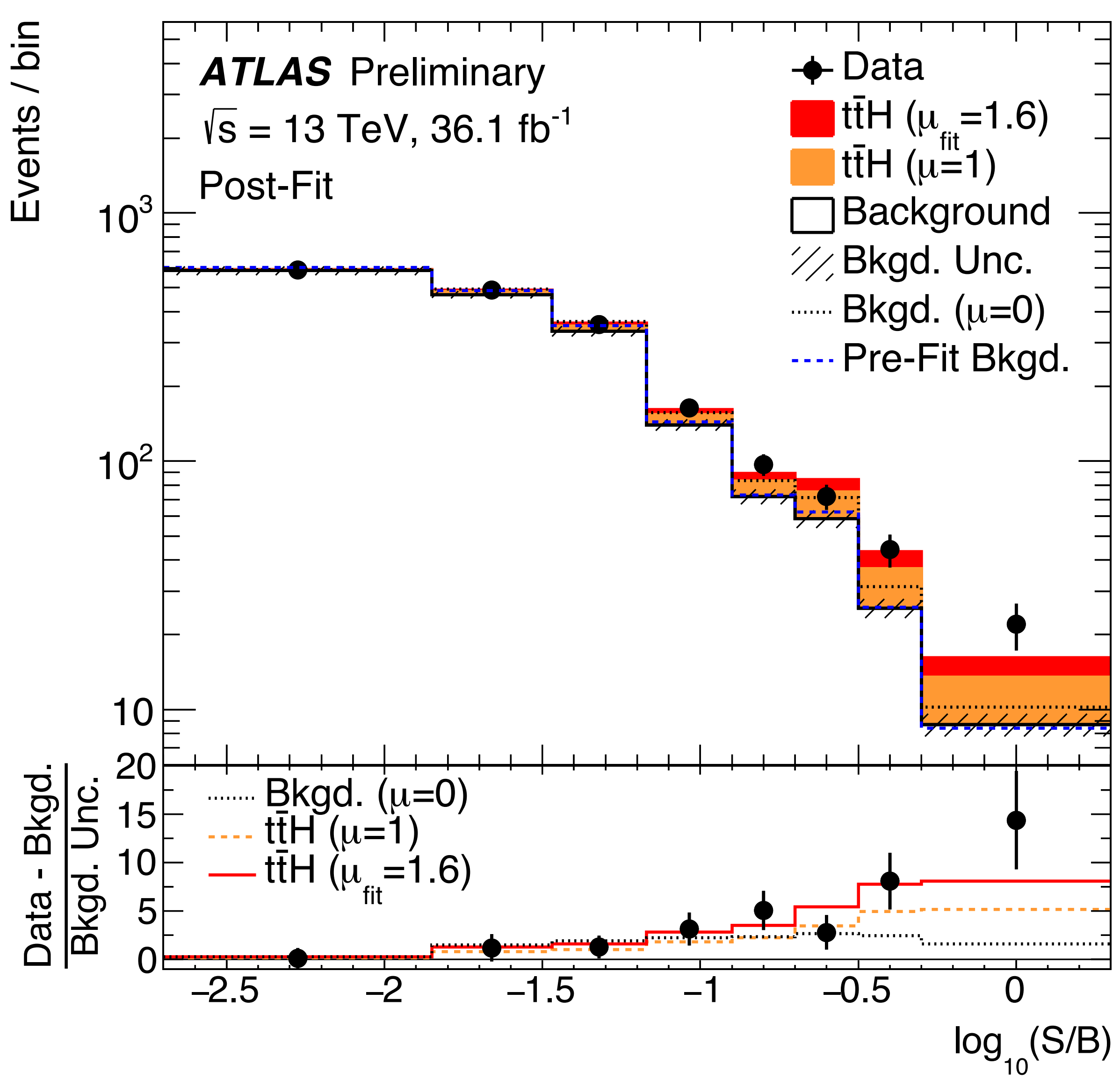
$t\bar{t}H$ modelling		
Cross section	N	2
Renormalisation and factorisation scales	S	3
Parton shower and hadronisation model	SN	1
Higgs boson branching ratio	N	4
Shower tune	SN	1
$t\bar{t}W$ modelling		
Cross section	N	2
Renormalisation and factorisation scales	S	3
Matrix-element MC generator	SN	1
Shower tune	SN	1
$t\bar{t}Z$ modelling		
Cross section	N	2
QCD scale	S	3
Matrix-element MC generator	SN	1
Shower tune	SN	1
Other background modelling		
Cross section	N	15
Shower tune	SN	1
Total (Signal and background modelling)	–	41
Total (Overall)	–	315

Event yields

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



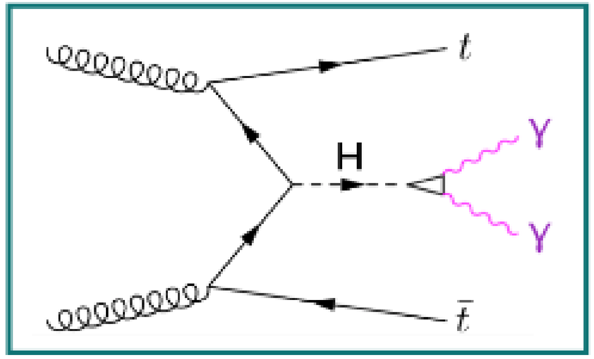
$t\bar{t}H$ multilepton

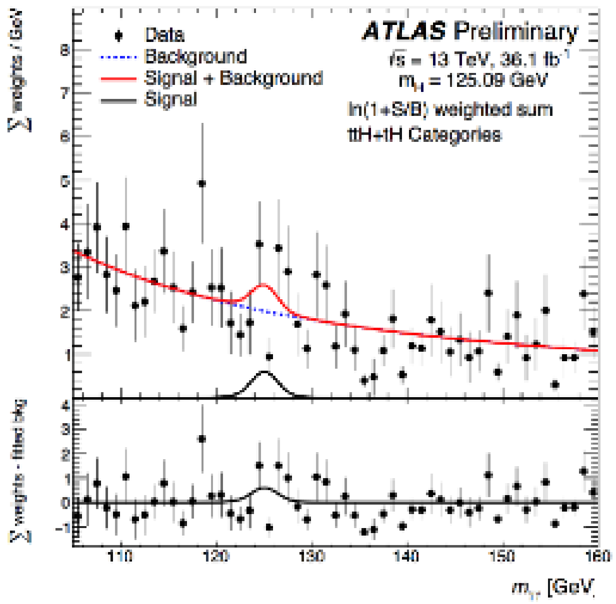


2 channels studied:

(included in the H->γγ analysis)

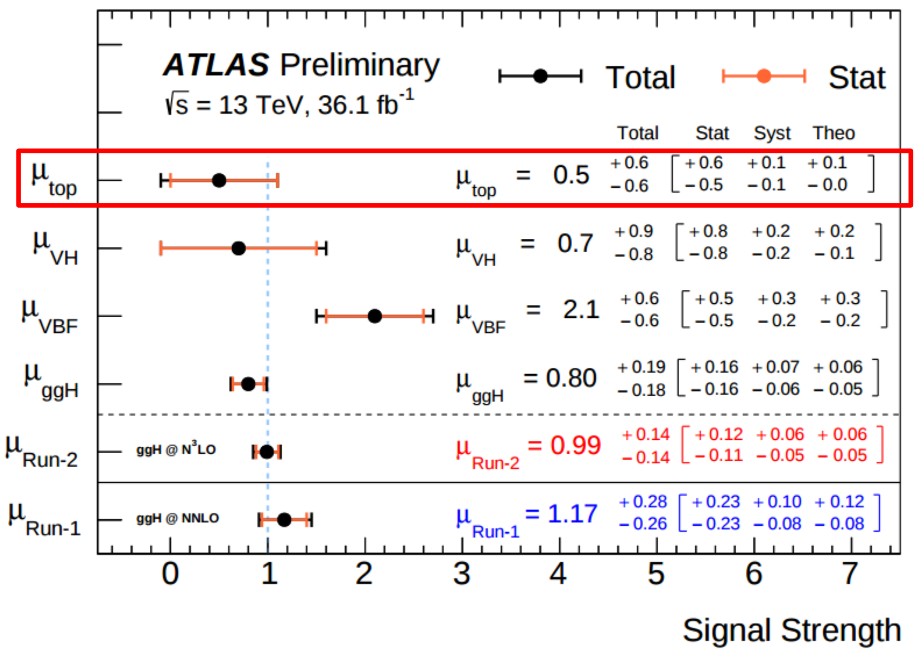
- **leptonic**: 2 isolated γ, ≥ 1 lepton, ≥ 2 jets, ≥ 1 b-tags (@70%)
- **hadronic**: 4 categories depending on the BDT score and two thresholds in order to maximise the significance (in Run1 was cut-based!).

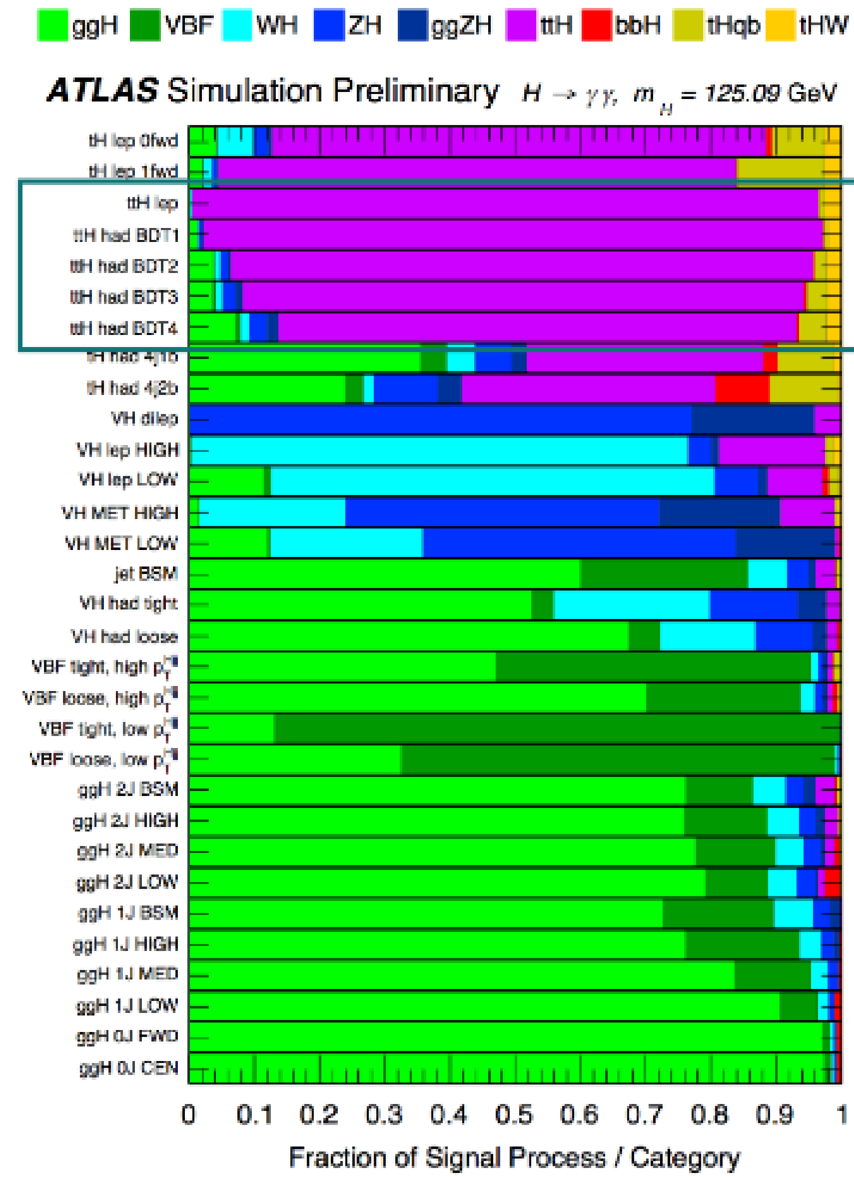




Systematic model:

- signal and background modelling unc.;
- all the detector uncertainties considered;
- spurious signal for ttH/tH has significant impact: 2 control regions for the data-driven technique (dependent on the choice of the background parametrisation in all the SRs).





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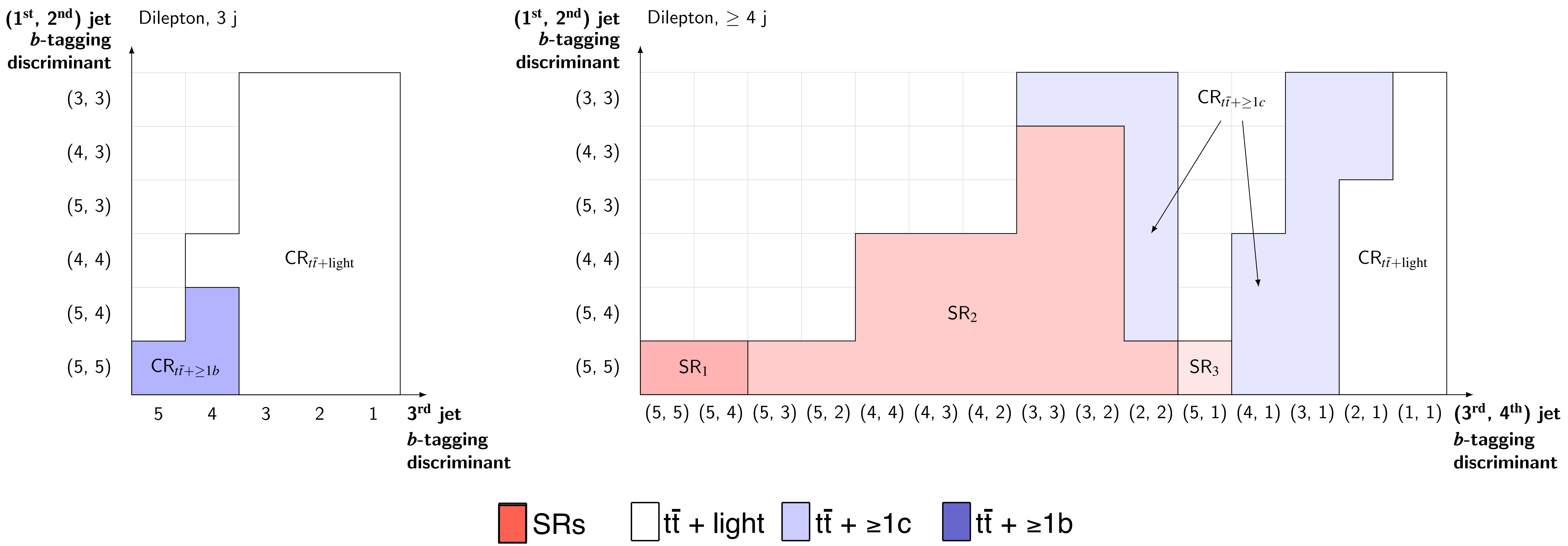
+ 4 tH categories (2 lep & 2 had) considered for the ttH final combination

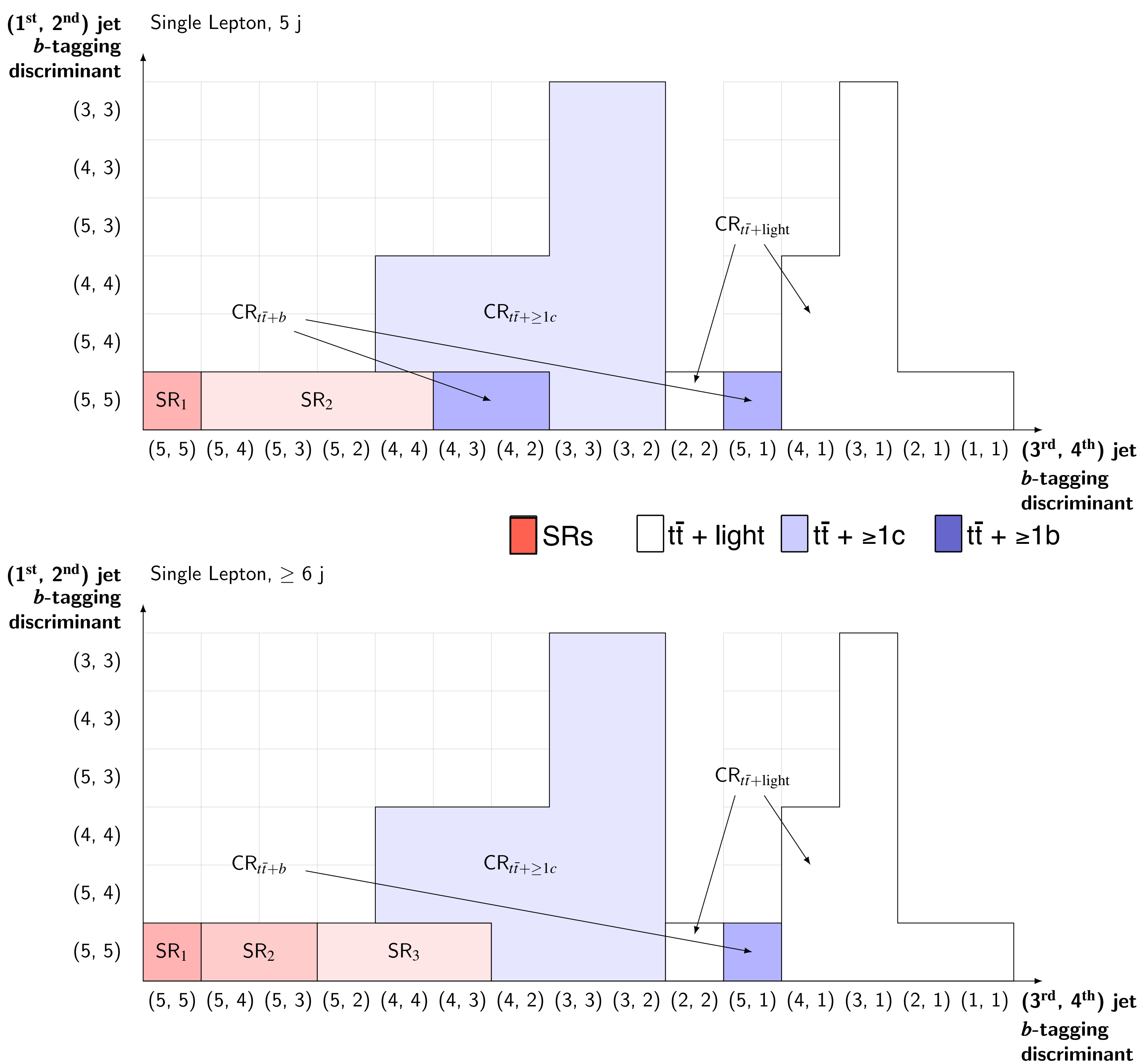
Statistically dominated analysis

Signal/Control regions for 2l channel

- Signal and control regions defined varying the requirements on the b-tagging discriminate
- Three separate SRs defined with 2l+ ≥4 jets:
  - ttH signal purity: 1.8%-5.4%
- Separate CRs for tt+ ≥1b, tt+ ≥1c and tt+light built with looser b-tagging requirements



Signal/Control regions for 1l channel



- Events with high-pT category are not classified
- Events in the resolved category are classified in SR/CR similarly to the 2l channel
- Five SRs defined with 1l+5/≥6 jets:
  - ttH signal purity: 1.6%-5.3%
  - Highest purity (SR1≥6jets) 4 very-tight b-tags
- CRs defined for tt+b, tt+≥1c and tt +lighr separatey for 5/≥6 jets loosening the b-tagging requirements

$t\bar{t}$ modelling 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 $t\bar{t}+\geq 1c$ 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 $H_T/2$ 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	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 3b$ normalisation	Up or down by 50%	$t\bar{t}+\geq 1b$

- Many sources of modelling uncertainty considered:
  - Generator: Powheg+Pythia8 vs. Sherpa (5F)
  - Parton shower: Powheg+Pythia8 vs. Powheg+Herwig7
  - 5F vs. 4F in Sherpa+OpenLoops
  - Scale variations in Sherpa+OpenLoops
- All $t\bar{t}$+jets modelling uncertainties uncorrelated between $t\bar{t}+\geq 1b/\geq 1c$/light
- Scale variation uncertainties correlated across each $t\bar{t}+\geq 1b$ sub-component