Evidence for ttH production at ATLAS

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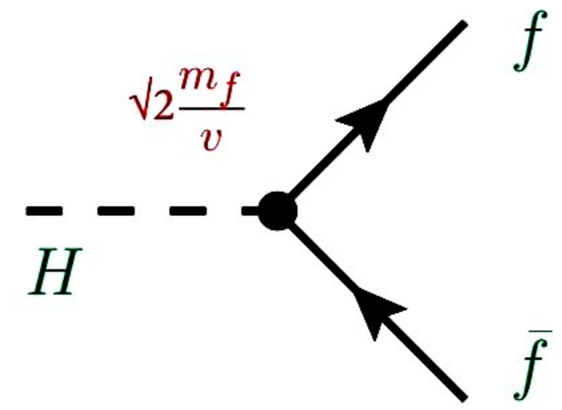
Nov-6-2017, Higgs couplings
Heidelberg

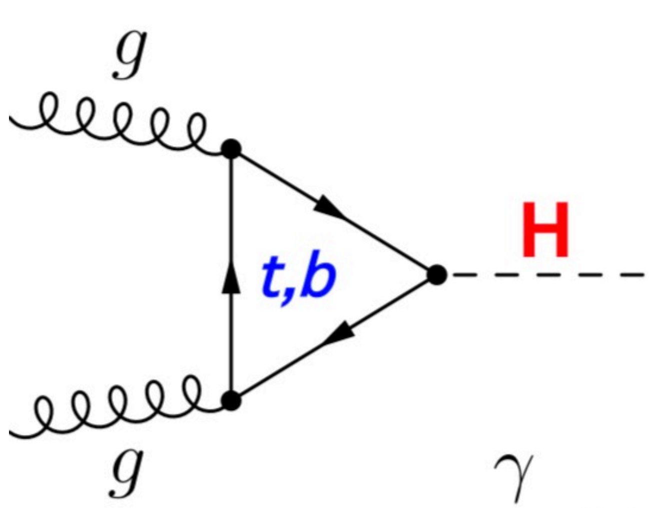
Motivation

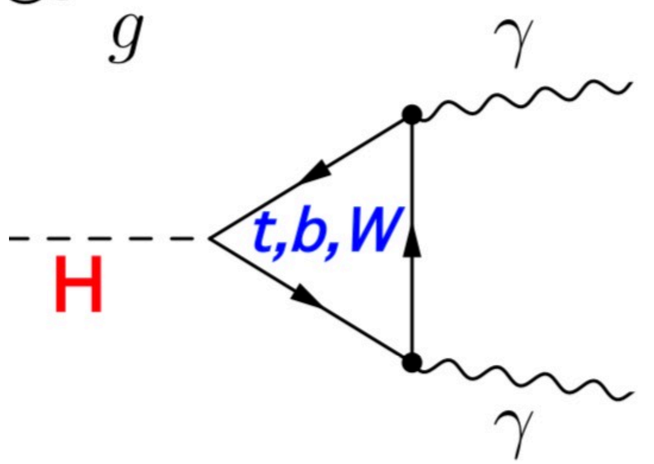
- Fermion masses are generated through Yukawa interaction
- Heaviest SM particle (top) expected to have largest Yukawa coupling to the Higgs field.
- No direct observation yet.



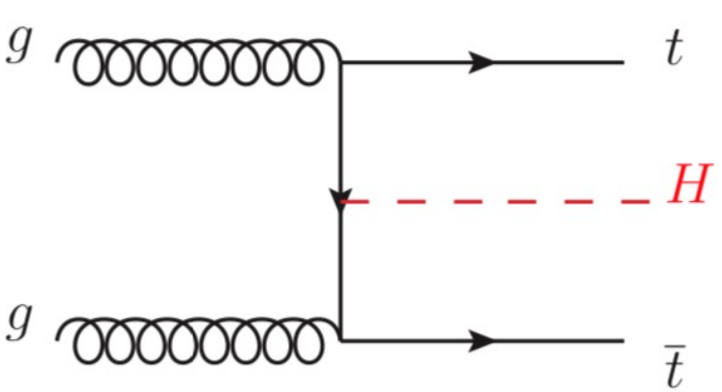
- Indirect constraints on top Yukawa coupling possible through ggH and H->γγ loop processes.
- ATLAS+CMS Run-1 combination of ratio of measured coupling to SM expectation (κ_t)

$$\kappa_t = 0.87 \pm 0.15$$





- Direct measurement of top-Yukawa coupling needed to disentangle any new physics effects.
- ttH production cross-section measurement is one direct way to measure top-Yukawa coupling.

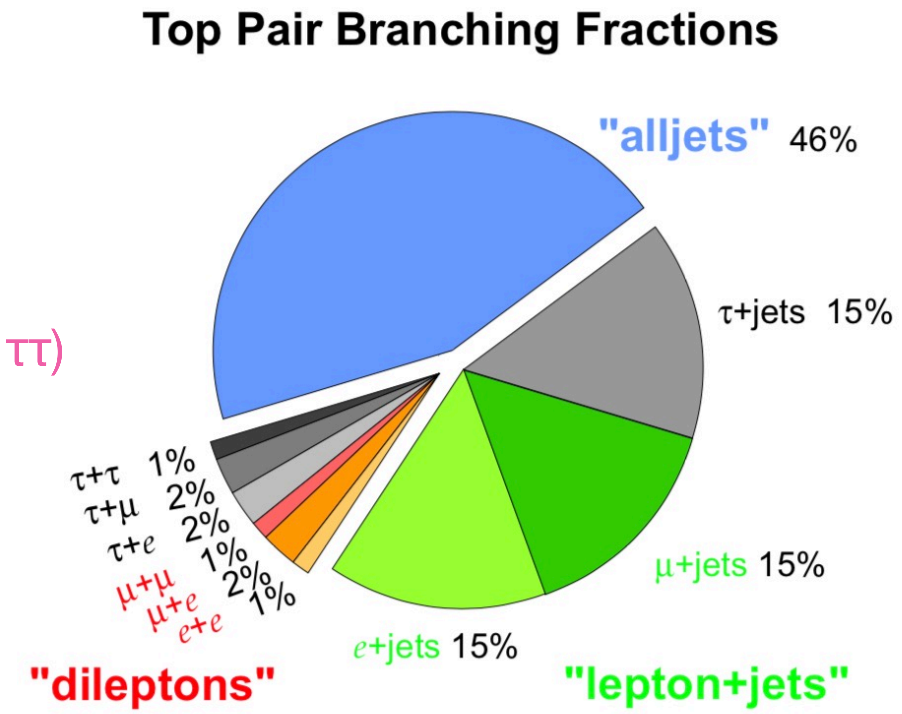


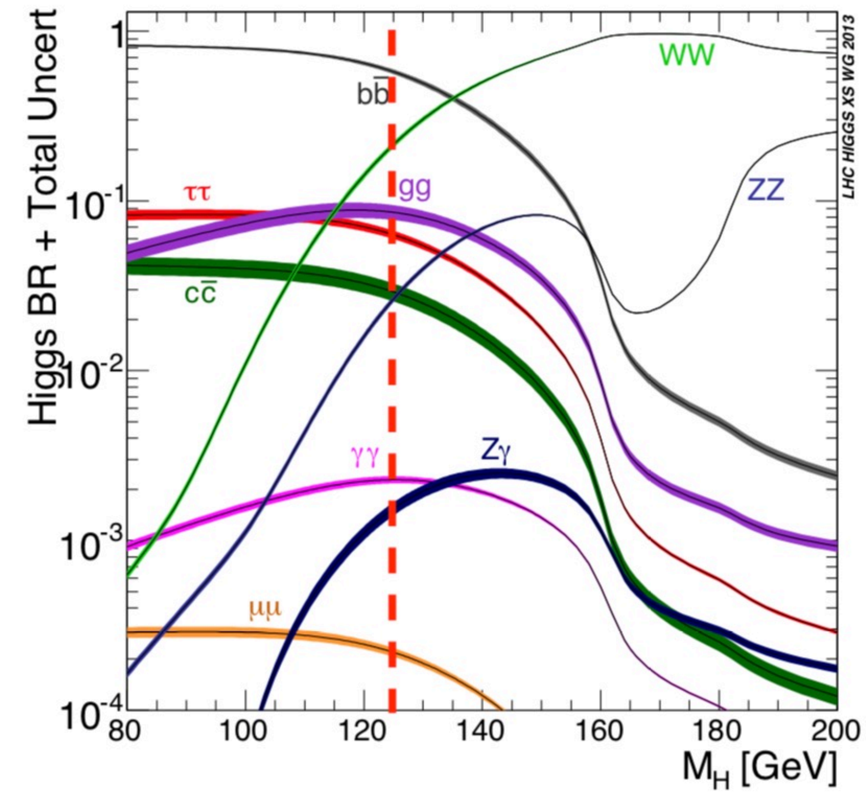
Experimental strategy & challenges

- Production cross section: ~507 fb: About 1% of total Higgs cross-section.

Channels

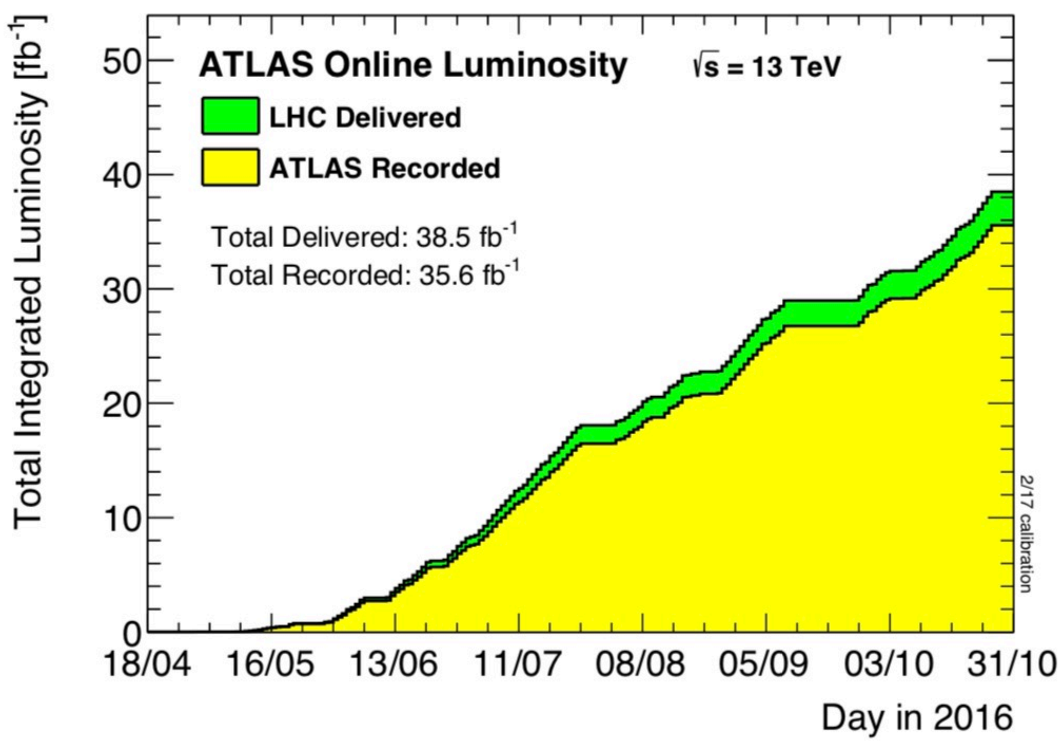
- tt(1-2 e/μ) + H(bb)
- tt(1-2 e/μ/τ-had) + H(WW, ZZ*, ττ)
- tt(0-2 e/μ) + H(ZZ*)
- tt(0-2 e/μ) + H(γγ)

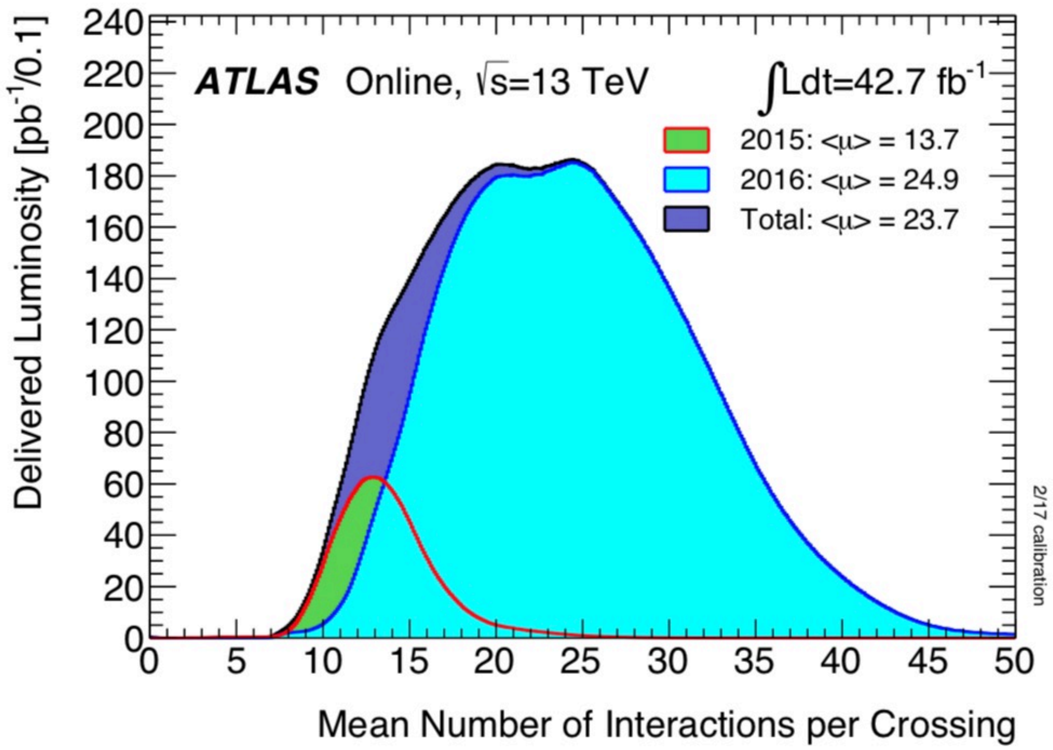




- Object identification and reconstruction among multiple proton collisions
- Many types of objects in the signal signature: γ, e, μ, τ-hadronic, jets, b-jets
  - Combined Identification efficiency decreases
  - High combinatorial background [mainly in ttH(bb)]
  - Identification of prompt and non-prompt leptons [mainly in ttHML]
- Large irreducible background from $t\bar{t}$+HF and $t\bar{t}V$

Data taking





- Data from 2015 and 2016 runs used for this analysis
- After quality requirements 36.1 fb^{-1}

- Peak Luminosity of 1.4 x 10^{34} $cm^{-2}s^{-1}$
- Pile up almost doubled for 2016 runs
- Many efforts to mitigate pileup effects

- ATLAS data acquisition efficiency: 92.1%(2015) – 92.4% (2016)
- Only a few non operational channels in sub detectors: ‰-3.5%

Signal and Background modeling

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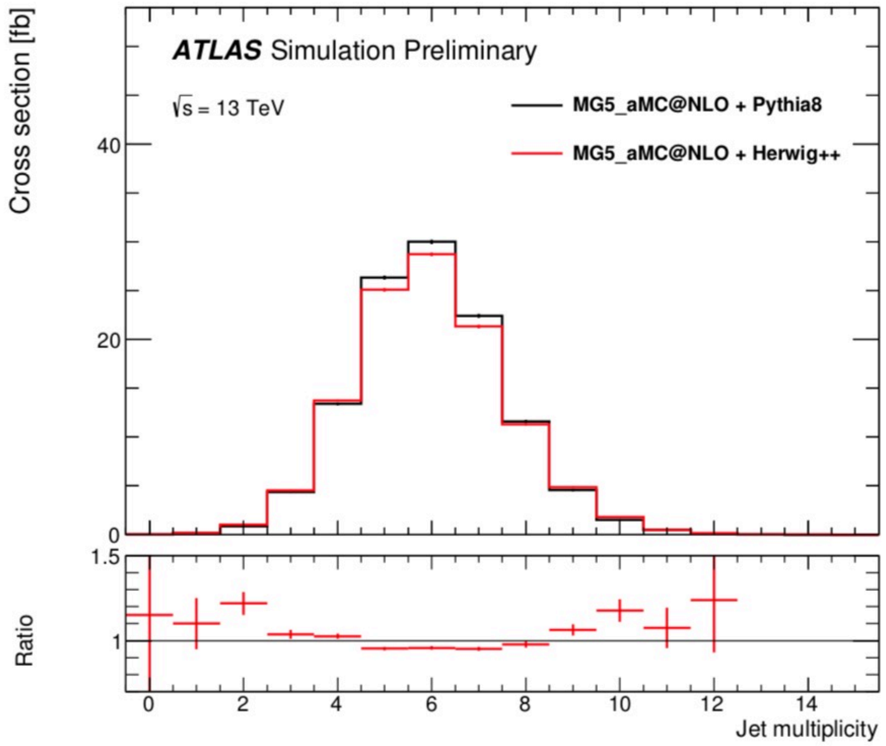
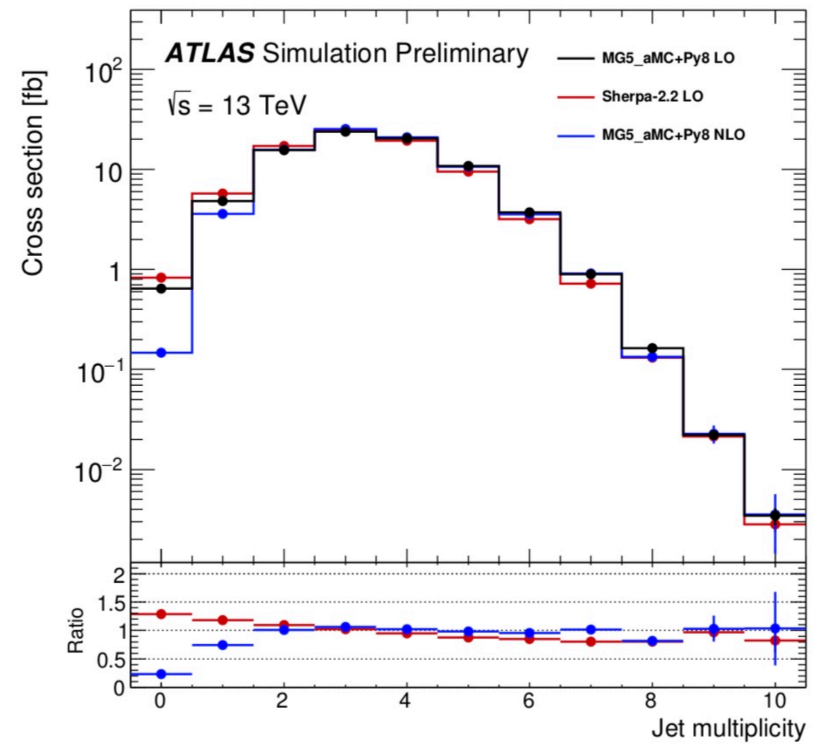
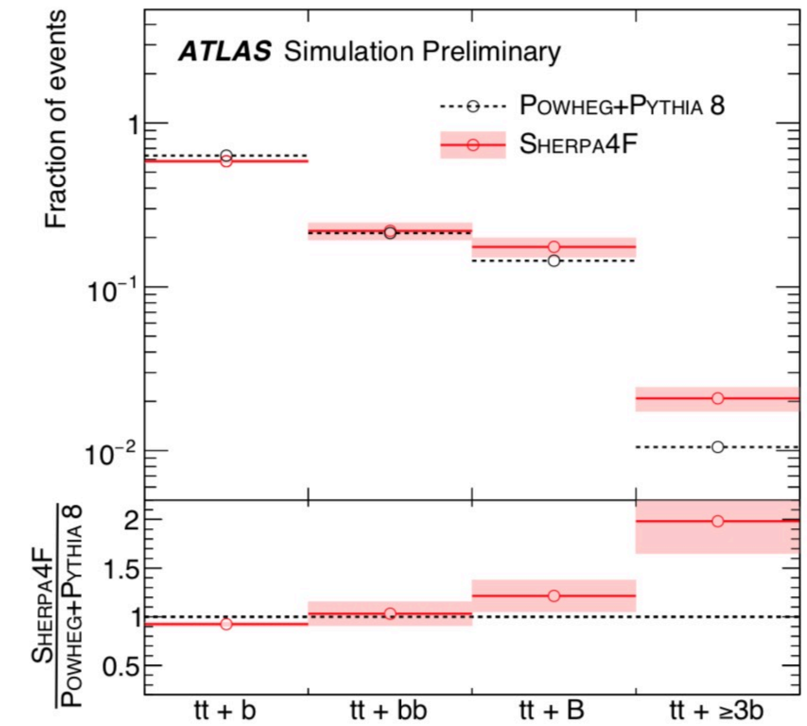


ttH



ttV



ttbar +HF

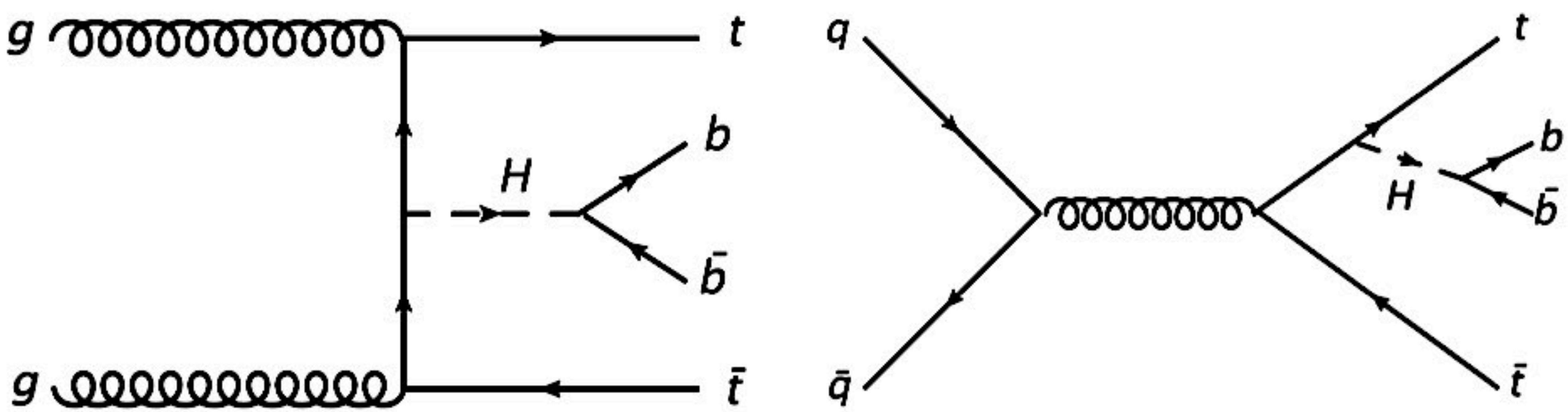
- Nominal: aMC@NLO + Pythia8
- Alternative sample: aMC@NLO + Herwig++

- Nominal aMC@NLO+ Pythia8
- Alternative: Sherpa

- Nominal: Powheg+Pythia8
  - Normalized to NNLO + NNLL cross section predictions
  - tt+ ≥1b reweighed to state of the art Sherpa OpenLoops (4F scheme)
- Alternative: Sherpa5F (ME+PS@NLO), Powheg+Herwig7

- Parton shower, QCD scales and PDF uncertainties are also considered
- Alternative samples used as additional systematics in the fit

ttH(bb)



ttH(bb): Categorization

- Categorized into sub channels to increase sensitivity
- Categorized according to number of leptons, number of jets and b-tag discriminant

- All b-tagging working points used in region definitions
- Rejection : c-jets : 3→35 ; light jets: 30→1500

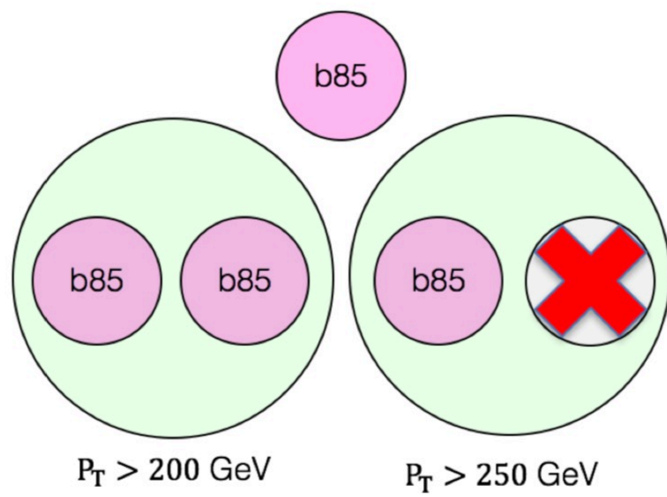
	none	*loose*	*medium*	*tight*	*very-tight*
Efficiency	-	85%	77%	70%	60%
Discriminant value	1	2	3	4	5

Sub channels

$2l$

- Exactly two opposite sign leptons, Veto Z-candidates, No hadronic τ
- Require ≥3 jets and ≥2 medium b-tagged jets

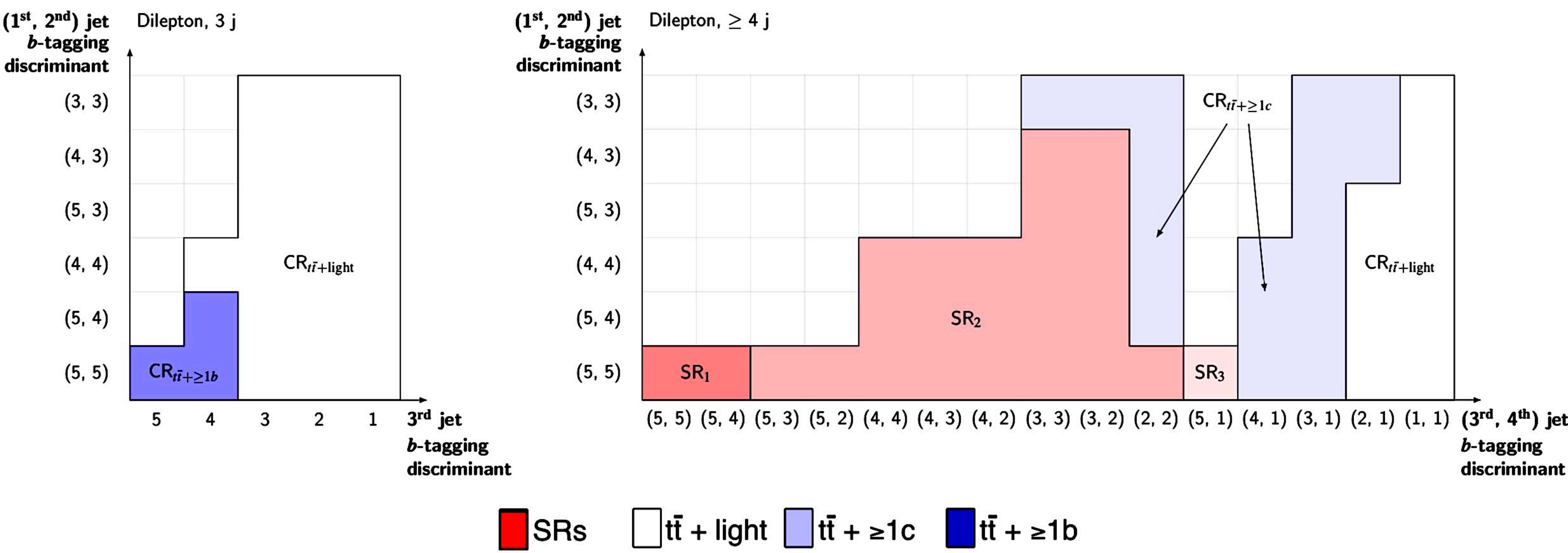
$1l$



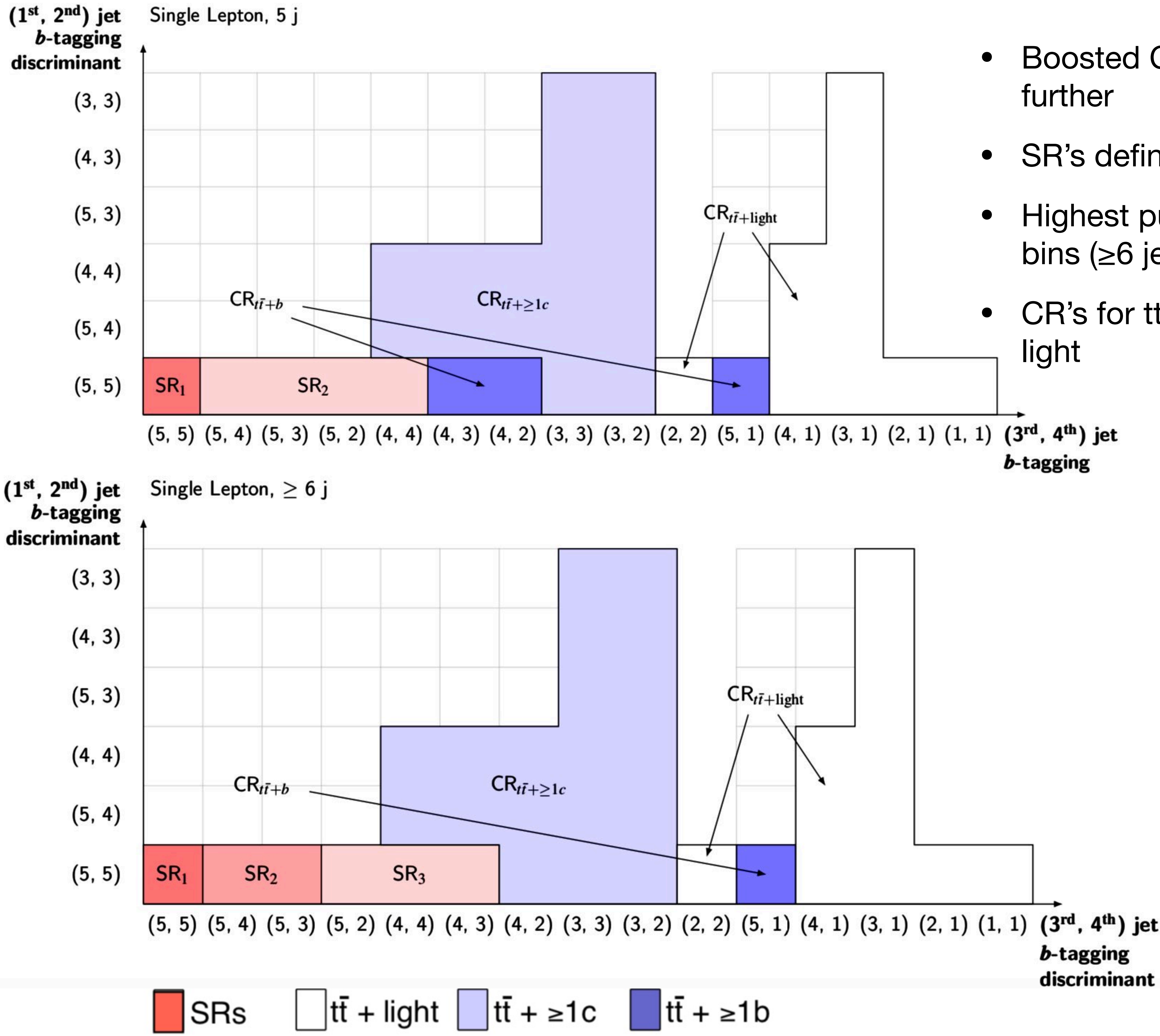
- Exactly 1 lepton.
- Boosted Category:
  - Presence of two R=1.0 reclustered jets (for Higgs and top candidate)
  - Remove jets which have pT < 50GeV and pT>1500 GeV
- Resolved Category: Failing boosted selection
  - Require ≥5 jets and ≥2 very-tight or ≥3 medium b-tagged jets

ttH(bb): 2lepton Regions

- Regions constructed for 3 and ≥4 jets.
    - SR's constructed with high b-tag discriminant
    - Three SR's: purity ranging from 1.8% to 5.4%
    - Highest signal purity in region with 3 very tight and 1 tight b-tag
- CR's for tt+b, tt+c and tt+light to constrain uncertainties, backgrounds,



ttH(bb): 1lepton Regions



- Boosted Channel is not categorized further
- SR's defined for 5 and ≥6 jets
- Highest purity in 4 very tight b-tag bins (≥6 jets)
- CR's for tt+ ≥1b, tt+ ≥1c and tt + light

Multivariate analysis

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- In signal regions, MVA techniques used to further separate signal and background

Reconstruction BDT (2l and 1l resolved SRs)

- Reconstruct ttH(bb) system from jets

Likelihood discriminator (1l resolved SRs only)

- Probability of signal or background based on PDF's for signal and background.

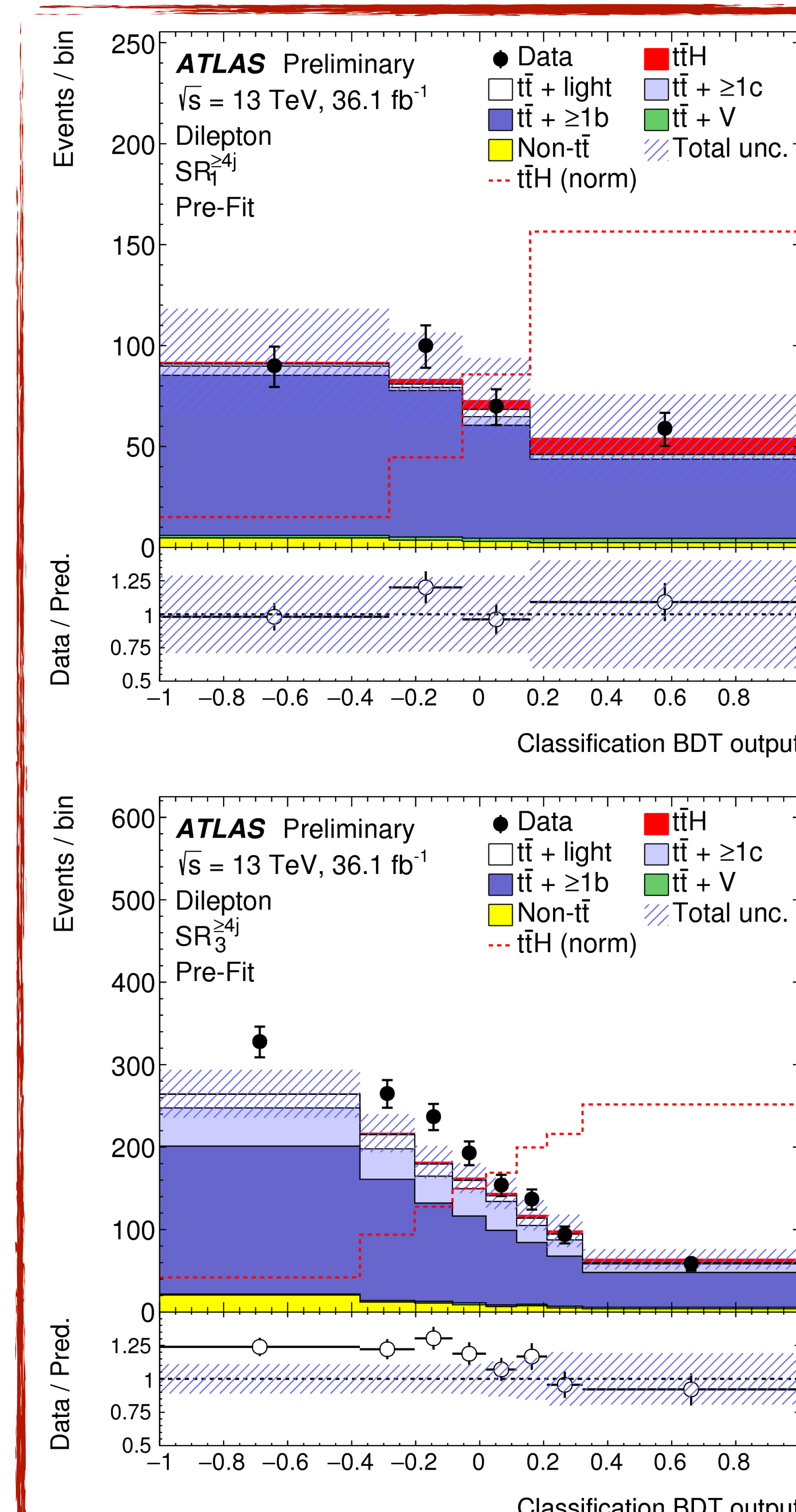
Matrix Element method ($SR^{>=6j}$ only)

- Signal (ttH) background (ttbb) likelihood estimation based on Matrix Element method

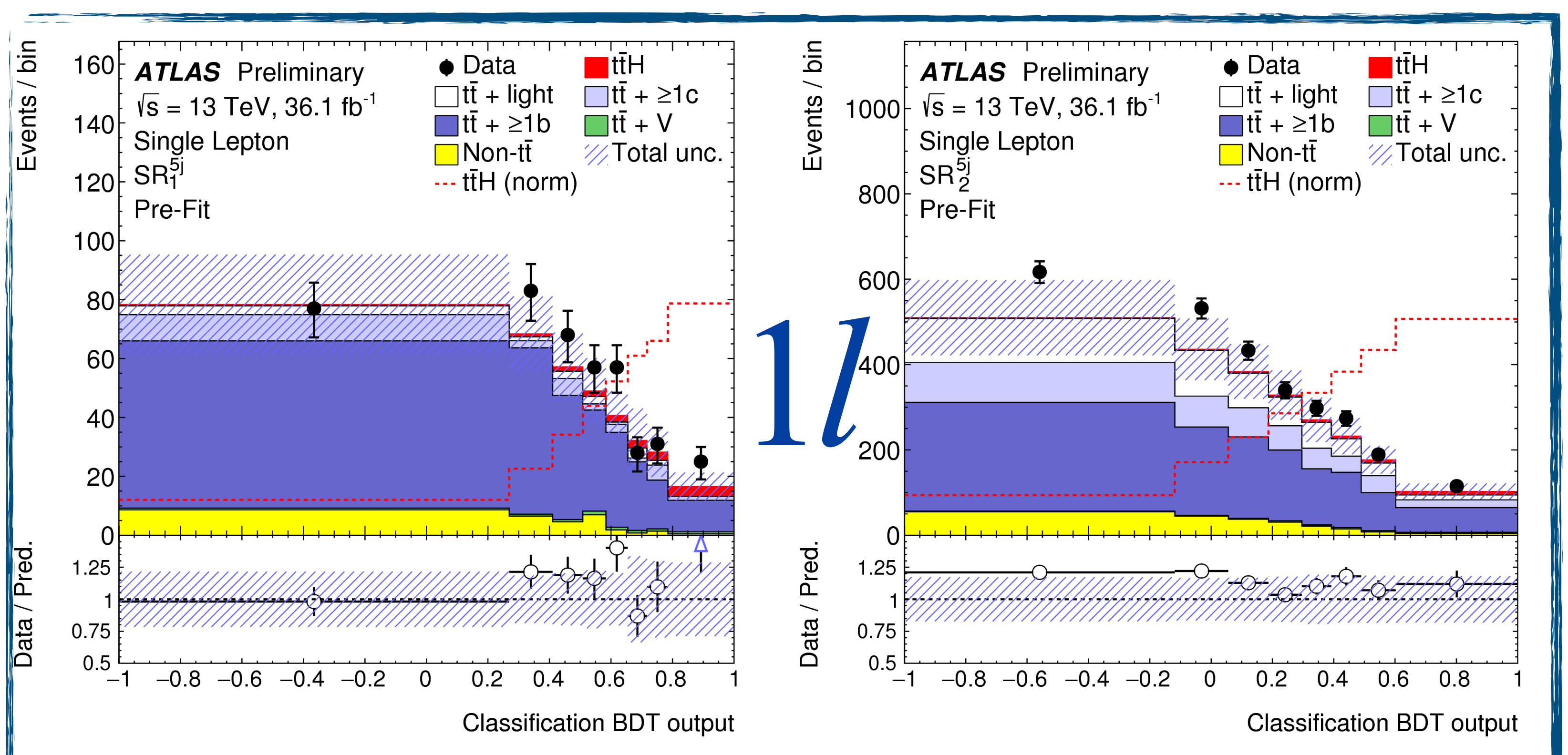
Putting it all together: Classification BDT

- Including kinematic variables
- Trained to separate signal from background

2l



1l

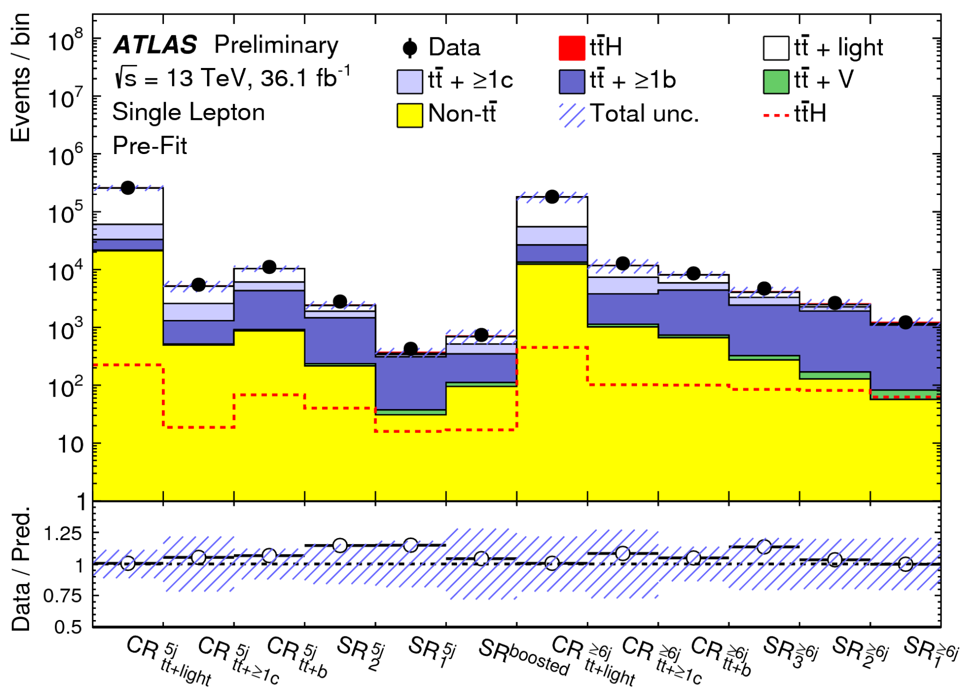


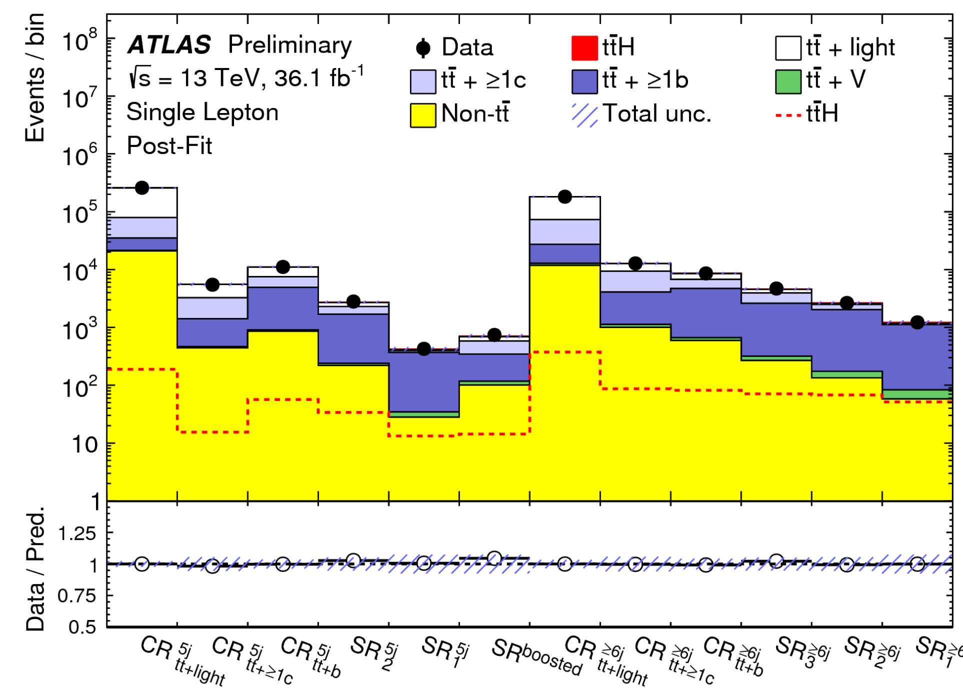
ttH(bb) Fit

- Simultaneous profile likelihood fit to all SR's and CR's
- tt+ ≥1b/c normalization freely floating in the fit
- SR's are binned in BDT discriminant output. Event yields in CR's [except t¯t+≥1c 1l-CRs (binned in HT)

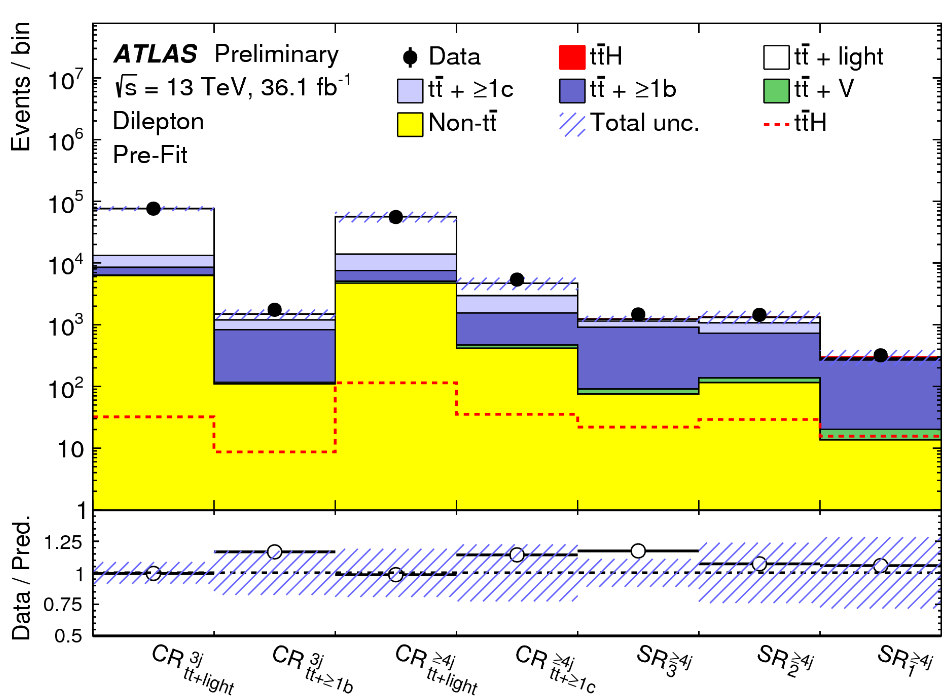
Pre fit **Post fit** ATLAS-CONF-2017-076

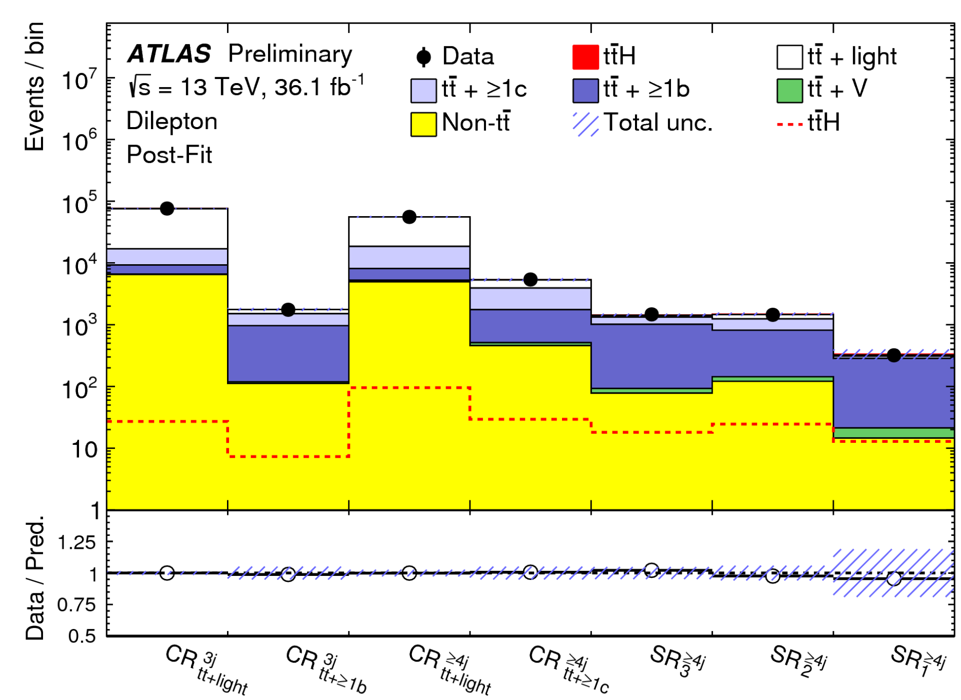
1l





2l





ttH(bb): Systematic Uncertainties

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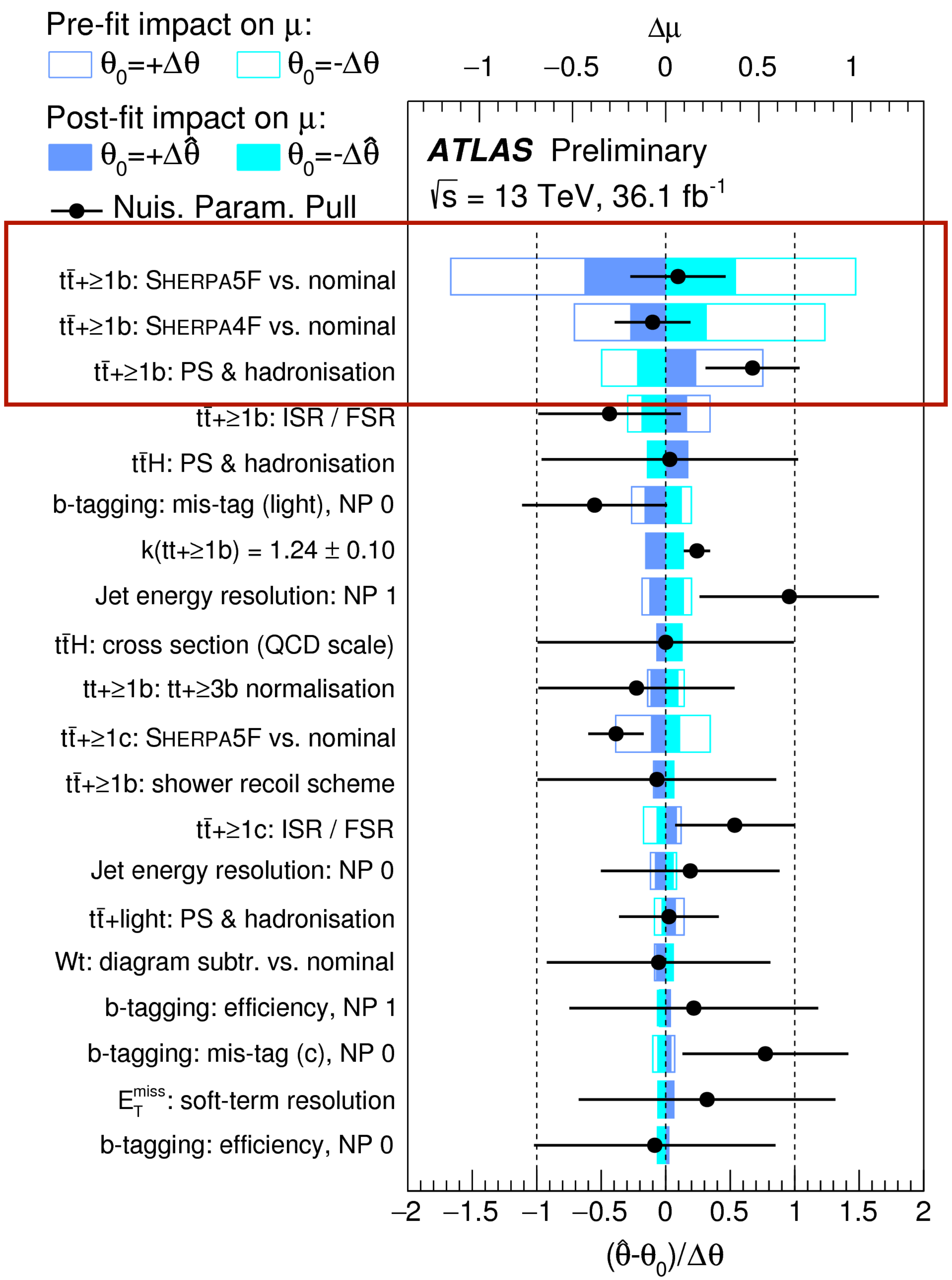

- Largest impact from tt+bb generator modeling
- Fit reduces the uncertainty on several systematics
- Systematics which are shifted from their nominal values are checked

ttH(bb):Results

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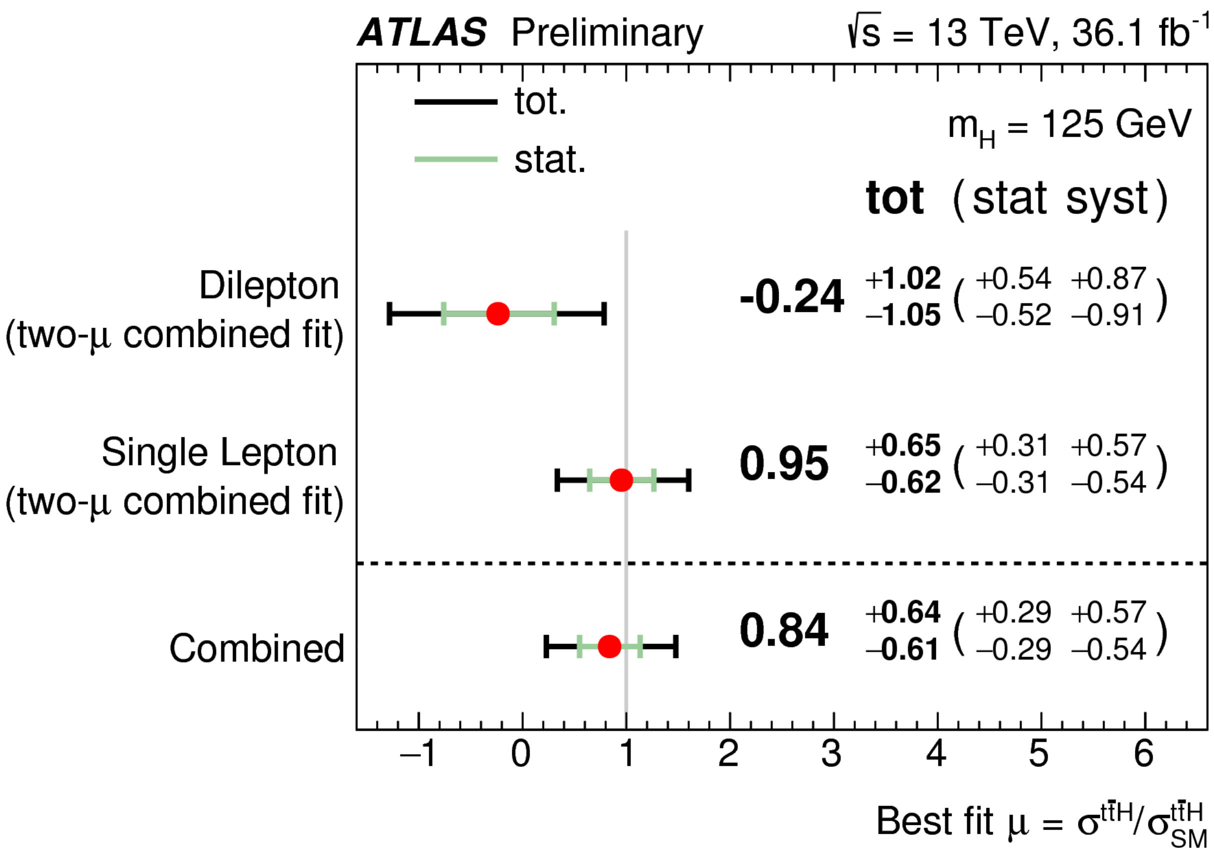
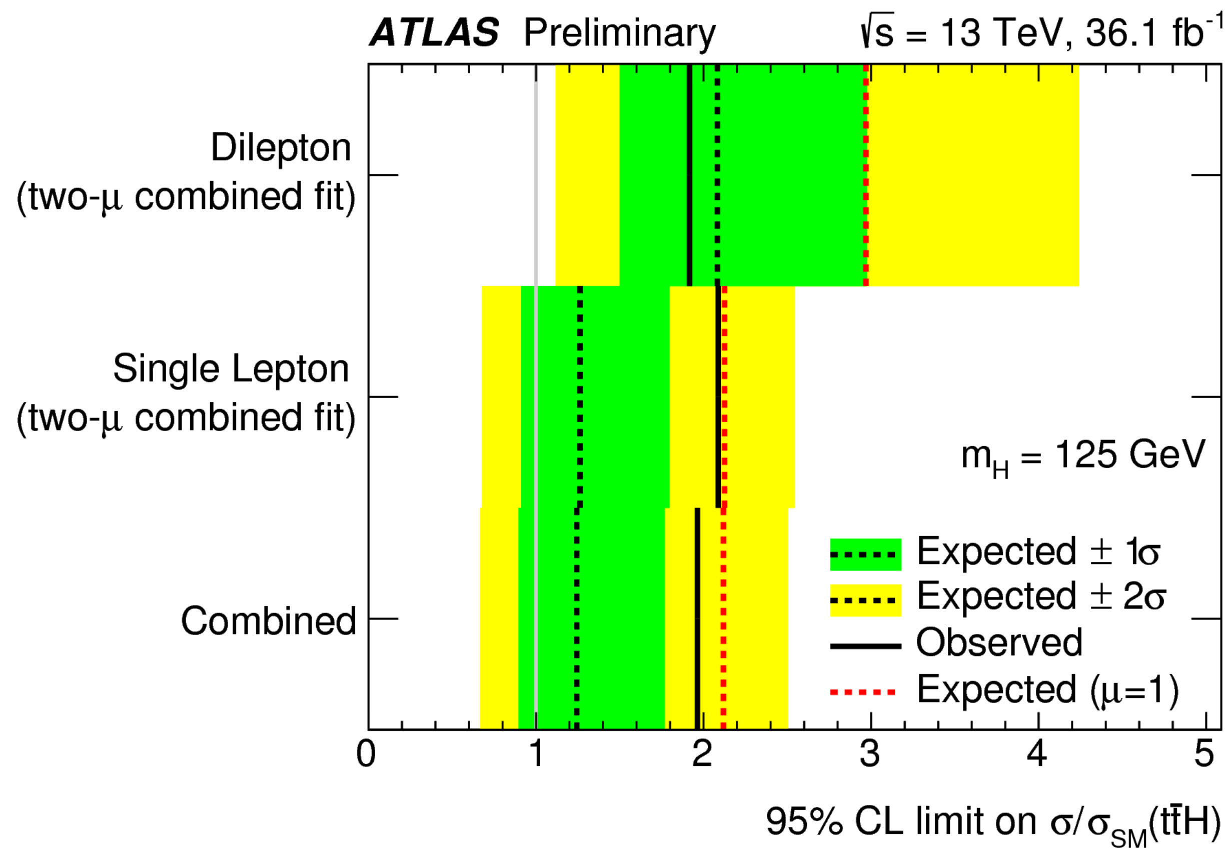
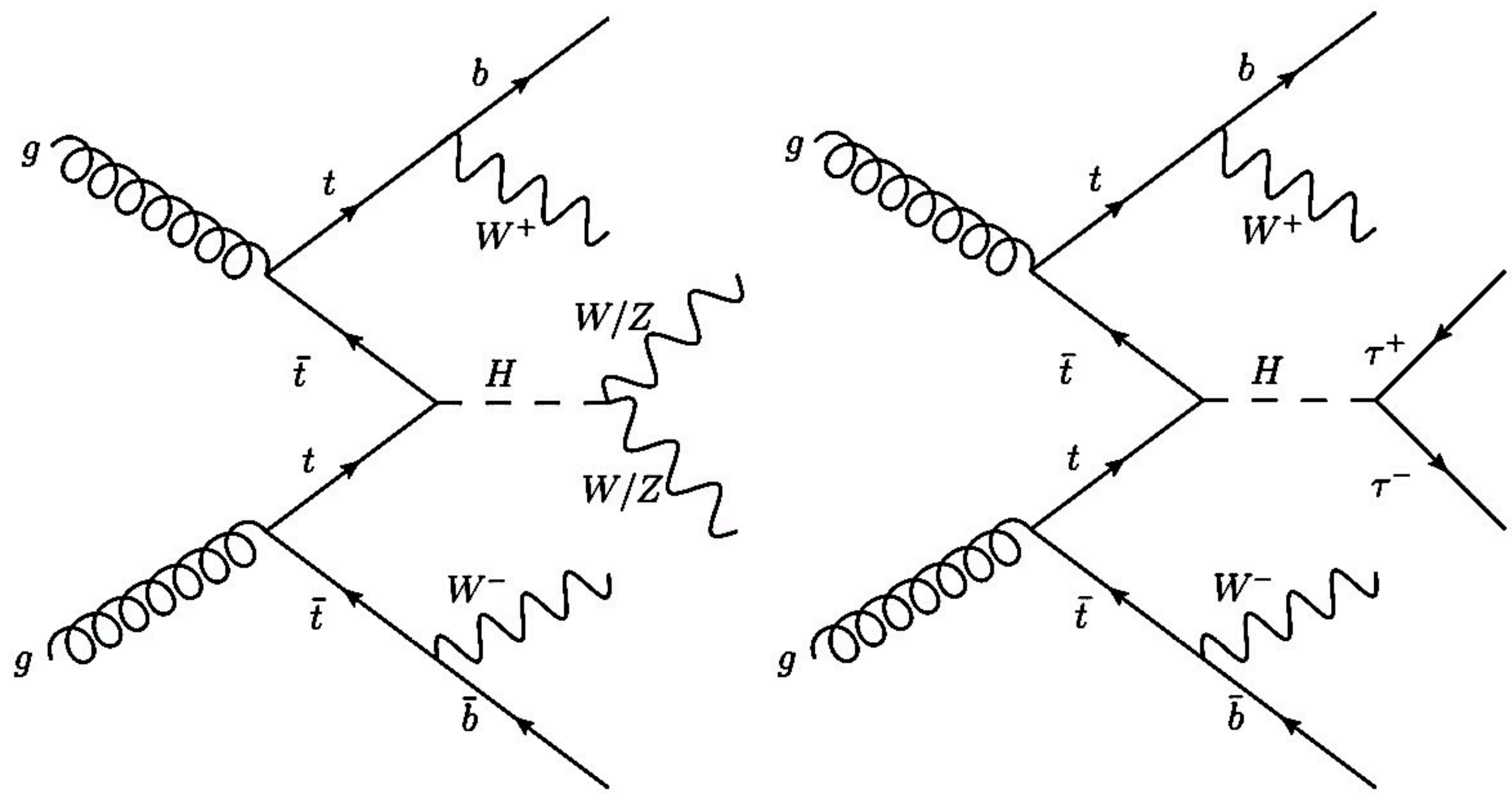




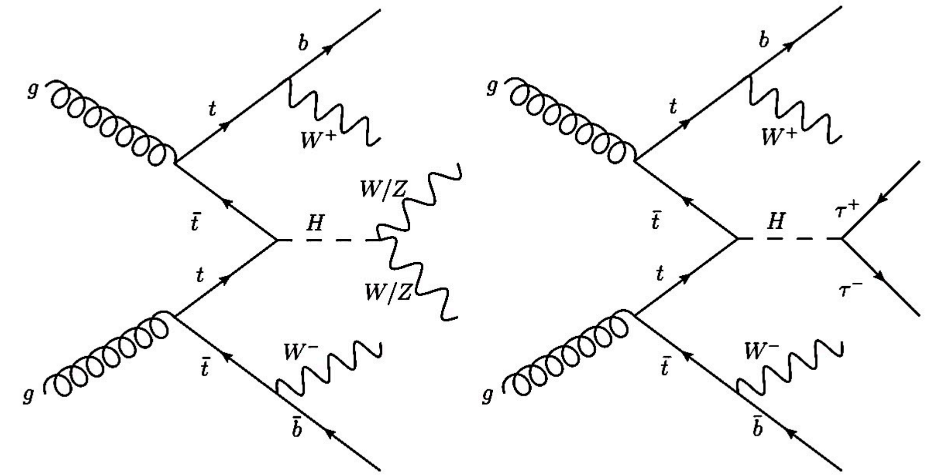
- Measured $\mu = 0.84^{+0.64}_{-0.61}$ with **1.4σ (expected 1.6σ)**
- Excluded **μ > 2.0 at 95% CL**

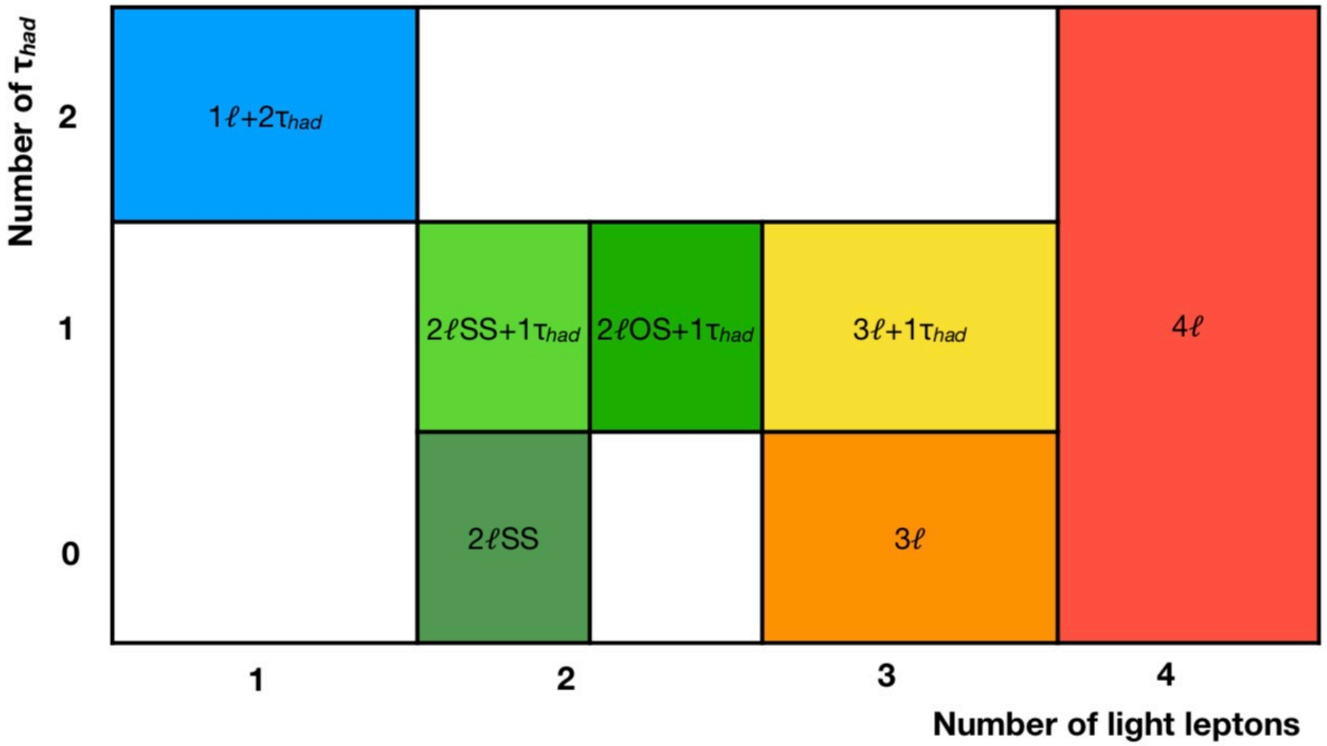
ttH multilepton

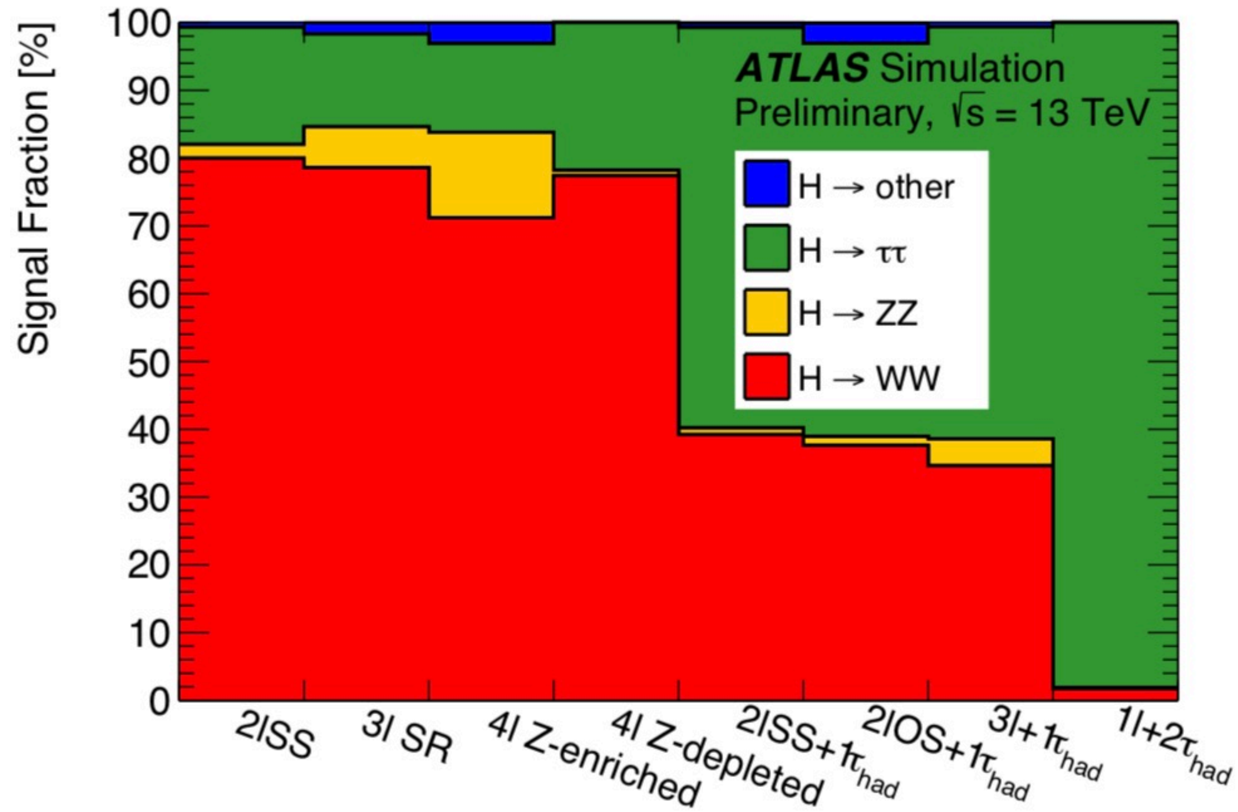


ttHML: Sub channels

- Main background is $t\bar{t}$ (with 1 fake lepton)
- High lepton multiplicity reduces backgrounds
- Analysis divided into 7 orthogonal sub categories according to the multiplicity of hadronic tau and light leptons





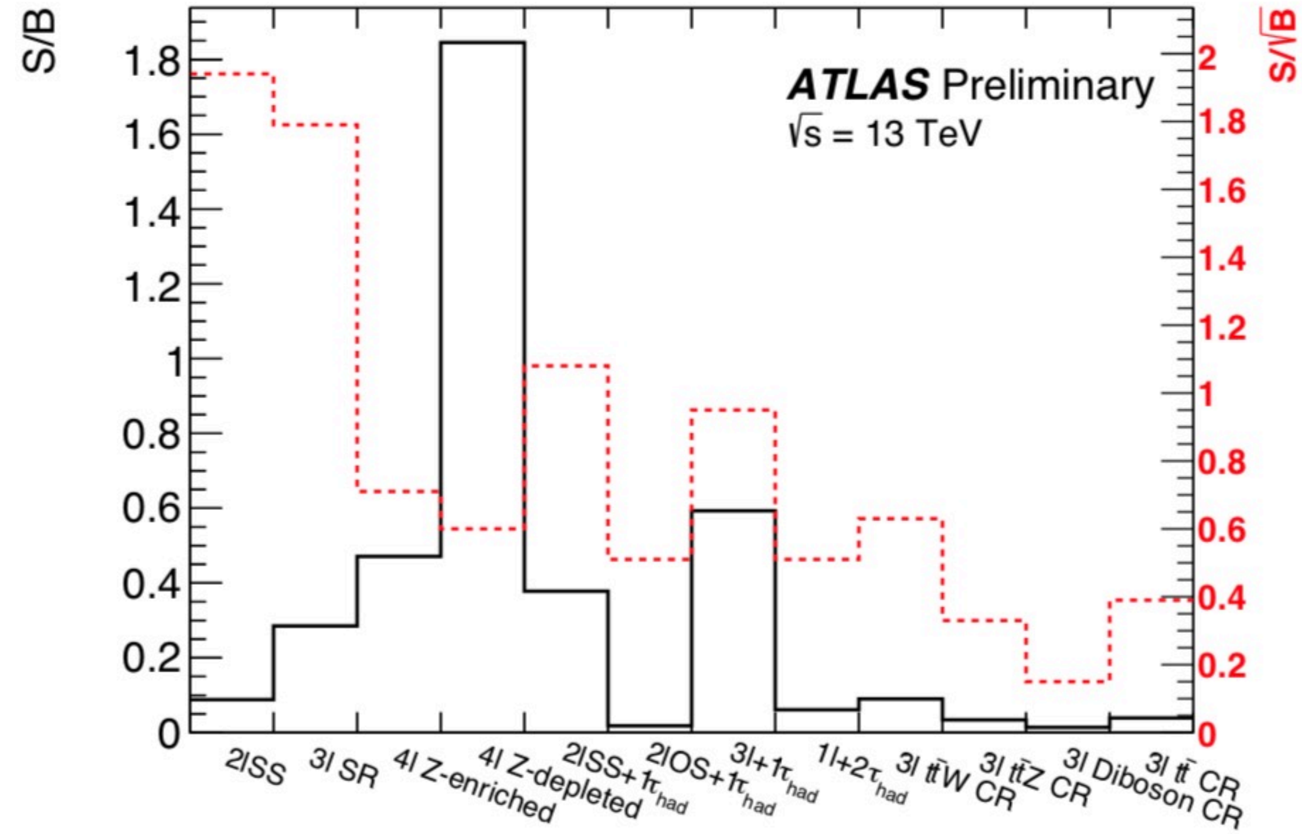


- Common jet selection: $N_{jets} \geq 2$ and $N_{bjets} \geq 1$
- Categorization based on loose lepton definition
- Optimized lepton selection in each category
  - Eg: Nonprompt lepton BDT to suppress fakes from B-hadron decays

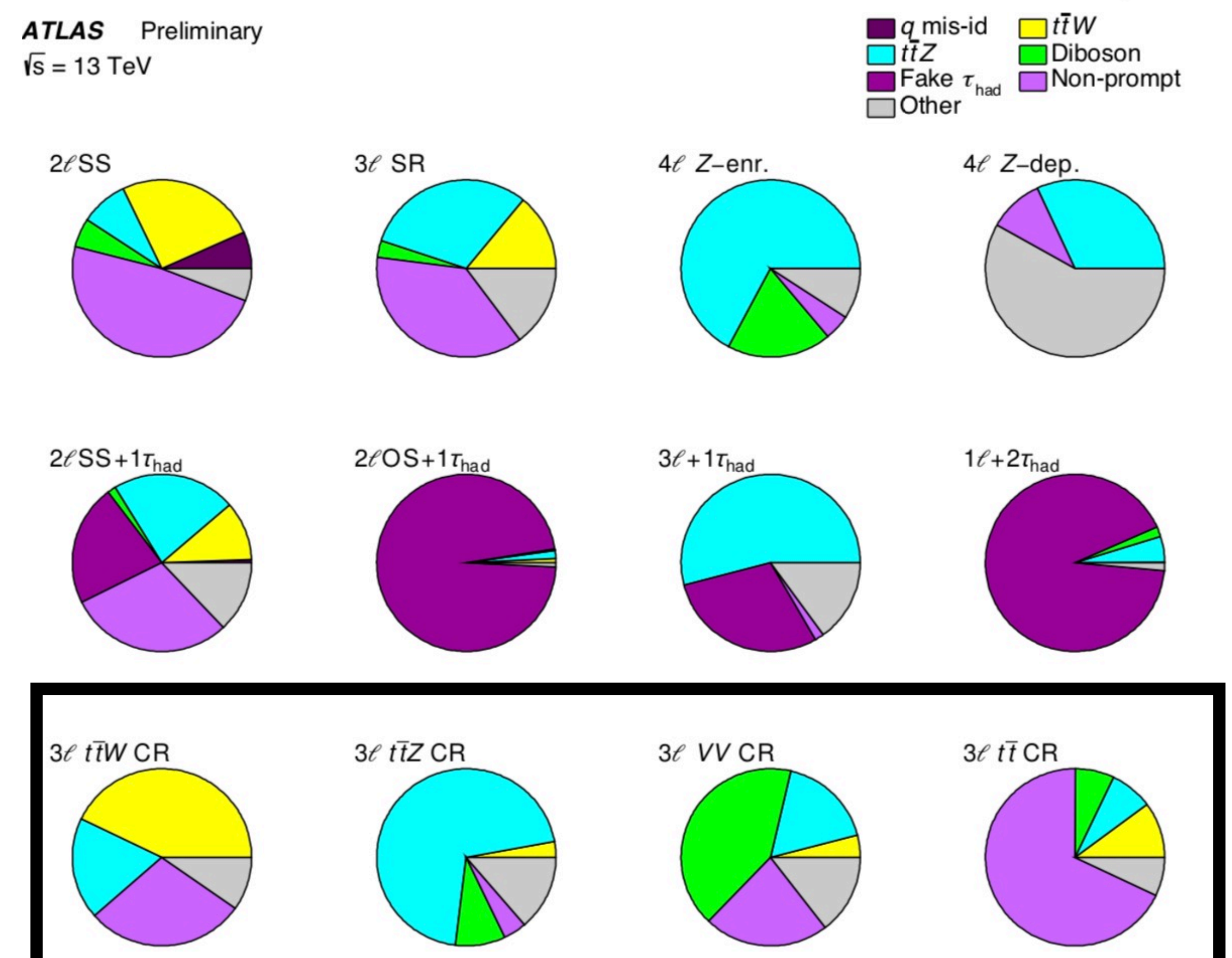
- $H \rightarrow WW^{*}$ mode dominant in light lepton channels.
- $H \rightarrow \tau\bar{\tau}$ dominant in hadronic τ channels

ttHML: Sub channels

- Except for 3l+1τ_{had} all sub channels use MVA techniques to further separate signal from background
  - 2lSS0τ: 2 BDT's: against ttV and ttbar
  - 3l0τ: 5 dimensional multinomial BDT to build categories enriched in ttH, ttW, ttZ, ttbar, diboson
  - 2lss+1τ: 1 BDT against ttbar
  - Cut and count cross check analysis in high sensitivity sub-channels.



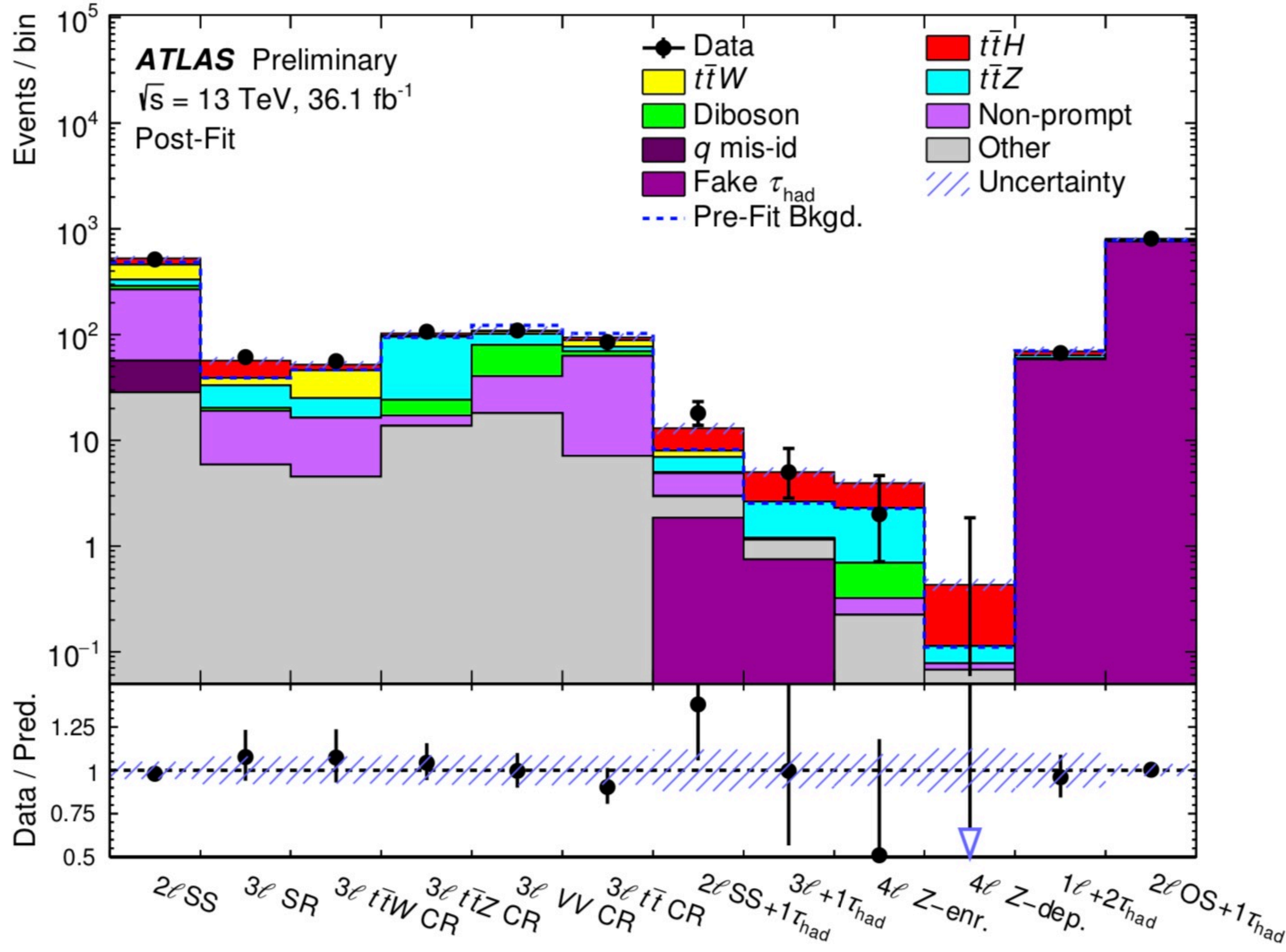
- Different background composition in different sub channels
  - ttW ttZ VV NonPrompt
- Non prompt backgrounds estimated from a low jet multiplicity region using data driven as well as semi-data driven methods.
- Dedicated control regions for constraining irreducible backgrounds →



ttHML: Fit

	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\rm had}$	2ℓSS$+1\tau_{\rm had}$	2ℓOS$+1\tau_{\rm had}$	$3\ell+1\tau_{\rm had}$
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	-	-	-	-	-

- Simultaneous fit in 12 regions (CR+SR)
- Single bin used in 3l CR's as well as low stat SR's
    - 3l+1τ
    - 4l (z-enriched,z-depeleted)
- BDT shape information used in 5 SR's



ttHML: Systematics Uncertainties

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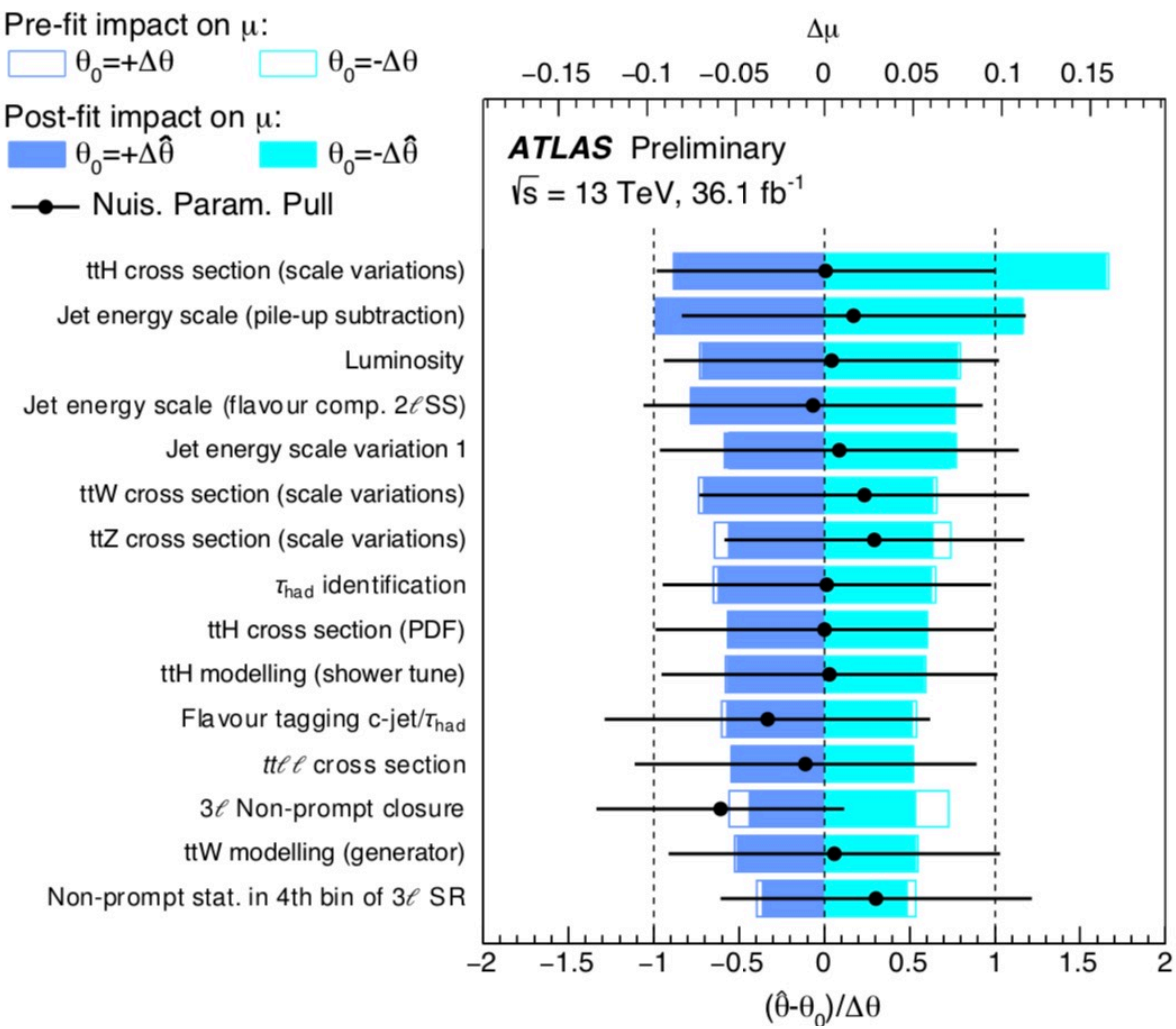

- Highest impact ttH Modeling: Scale uncertainties
- Jet energy scale and resolution
- Non prompt lepton estimation (poor statistics in control regions)
- ttV modeling scale uncertainties

ttHML: Results

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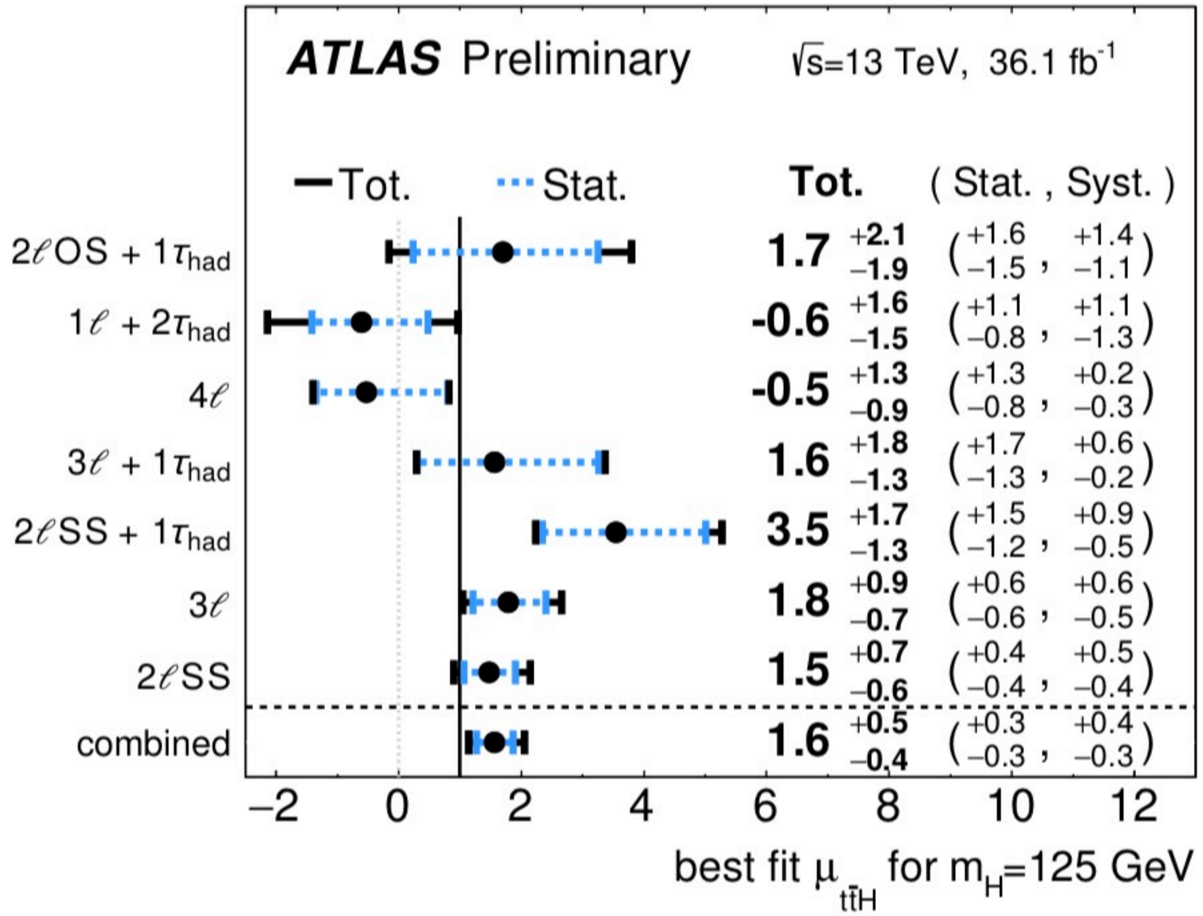

Channel	Significance	
	Observed	Expected
2ℓOS+$1\tau_{\rm had}$	0.9σ	0.5σ
1ℓ+$2\tau_{\rm had}$	-	0.6σ
4ℓ	-	0.8σ
3ℓ+$1\tau_{\rm had}$	1.3σ	0.9σ
2ℓSS+$1\tau_{\rm had}$	3.4σ	1.1σ
3ℓ	2.4σ	1.5σ
2ℓSS	2.7σ	1.9σ
Combined	4.1σ	2.8σ

- Measured $\mu = 1.6^{+0.5}_{-0.4}$ with a significance with respect to background only hypothesis **4.1σ (expct. 2.8σ)**
- Cross section extrapolated to inclusive phase space

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

- Cut and count cross check analysis in most sensitive channels
- Alternate fit model with floating ttV 15% loss in sensitivity μ(ttH)
  - ttV in agreement with SM

$$\mu_{t\bar{t}W} = 0.92 \pm 0.32$$

$$\mu_{t\bar{t}Z} = 1.17^{+0.25}_{-0.22}$$

Combination with ttH(γγ) and ttH(ZZ*)

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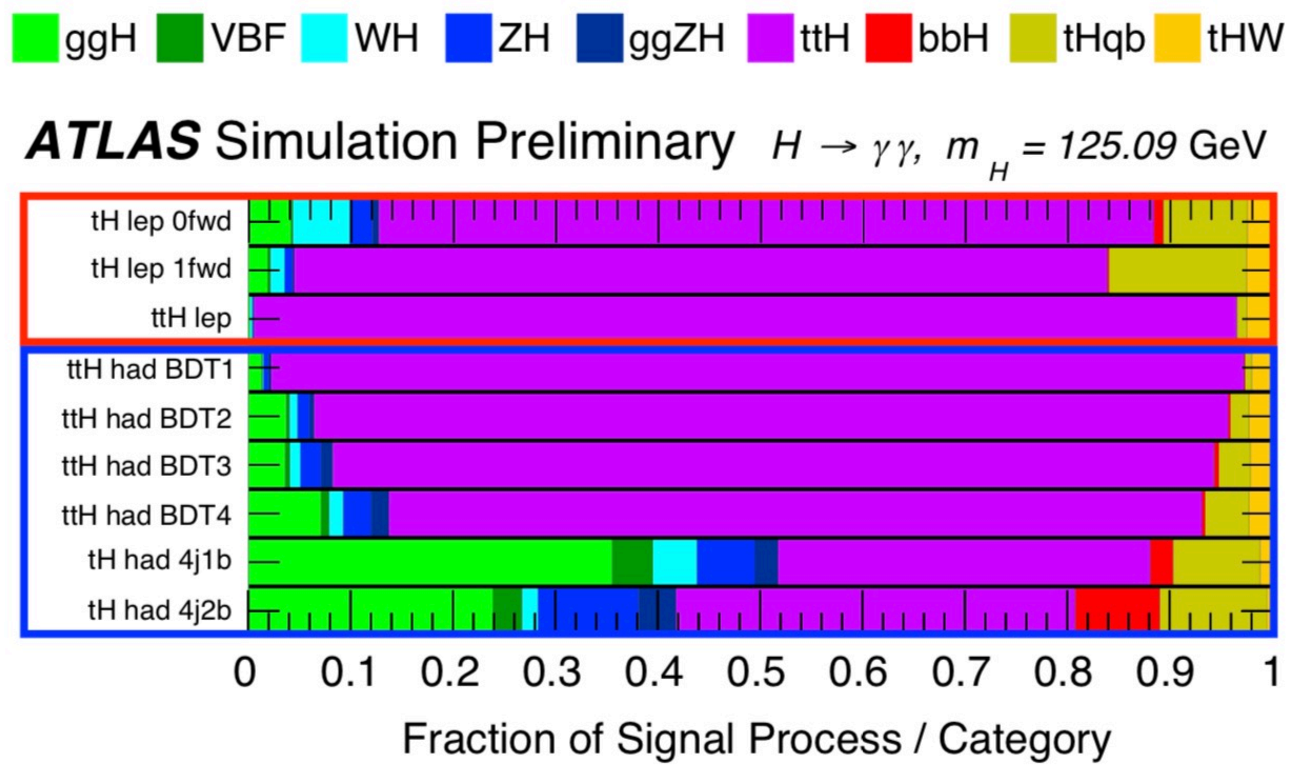
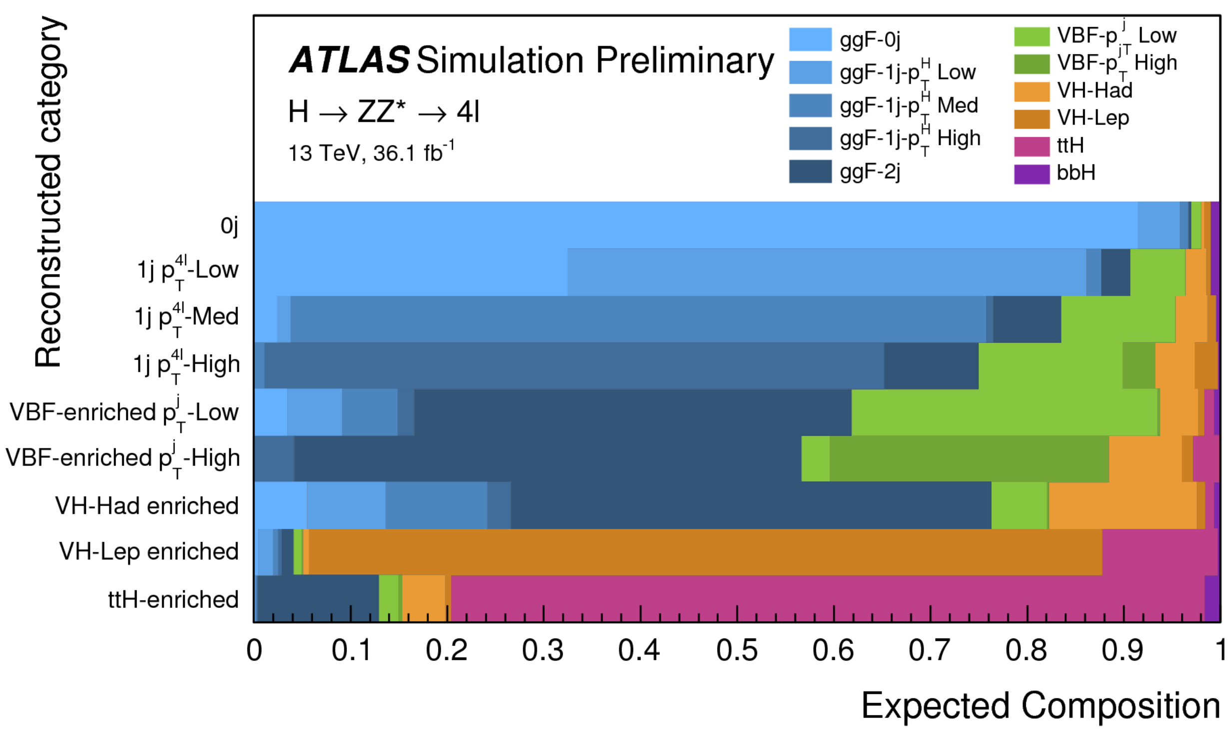
ATLAS-CONF-2017-043





- One ttH and two tH categories in the leptonic channel
- 6 categories in the hadronic channel

- Adding ttH->ZZ* resonant region
- Orthogonal to multilepton 4l category

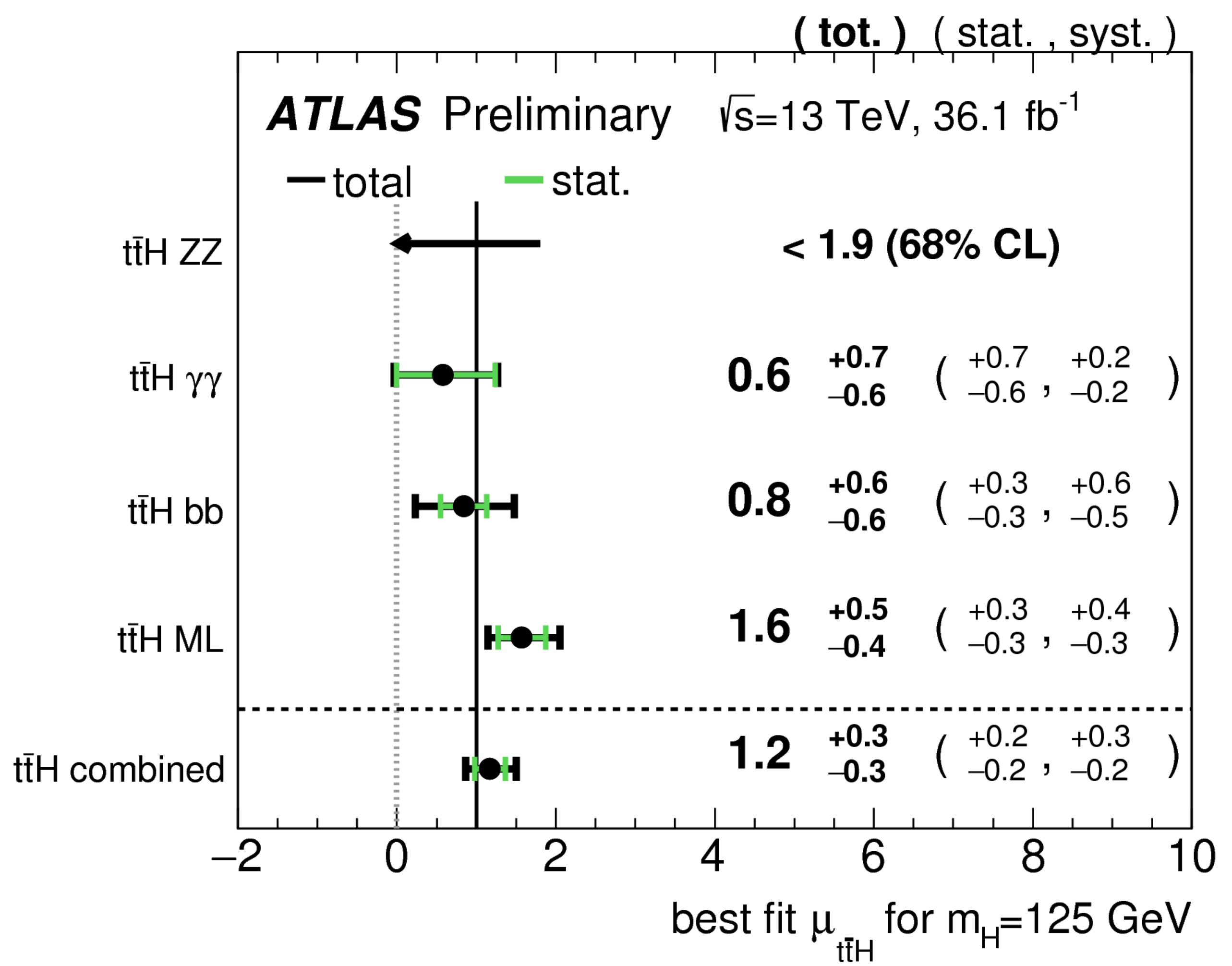
Combination

- Combining multilepton, bb, γγ, ZZ*
- tHjb and tWH treated as background and fixed to SM prediction
- All backgrounds set to SM prediction

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

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

Significance : 4.2σ (expected : 3.8σ)



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

Combination

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- Combining multilepton, bb, γγ, ZZ*
- tHjb and tWH treated as background and fixed to SM prediction
- All backgrounds set to SM prediction

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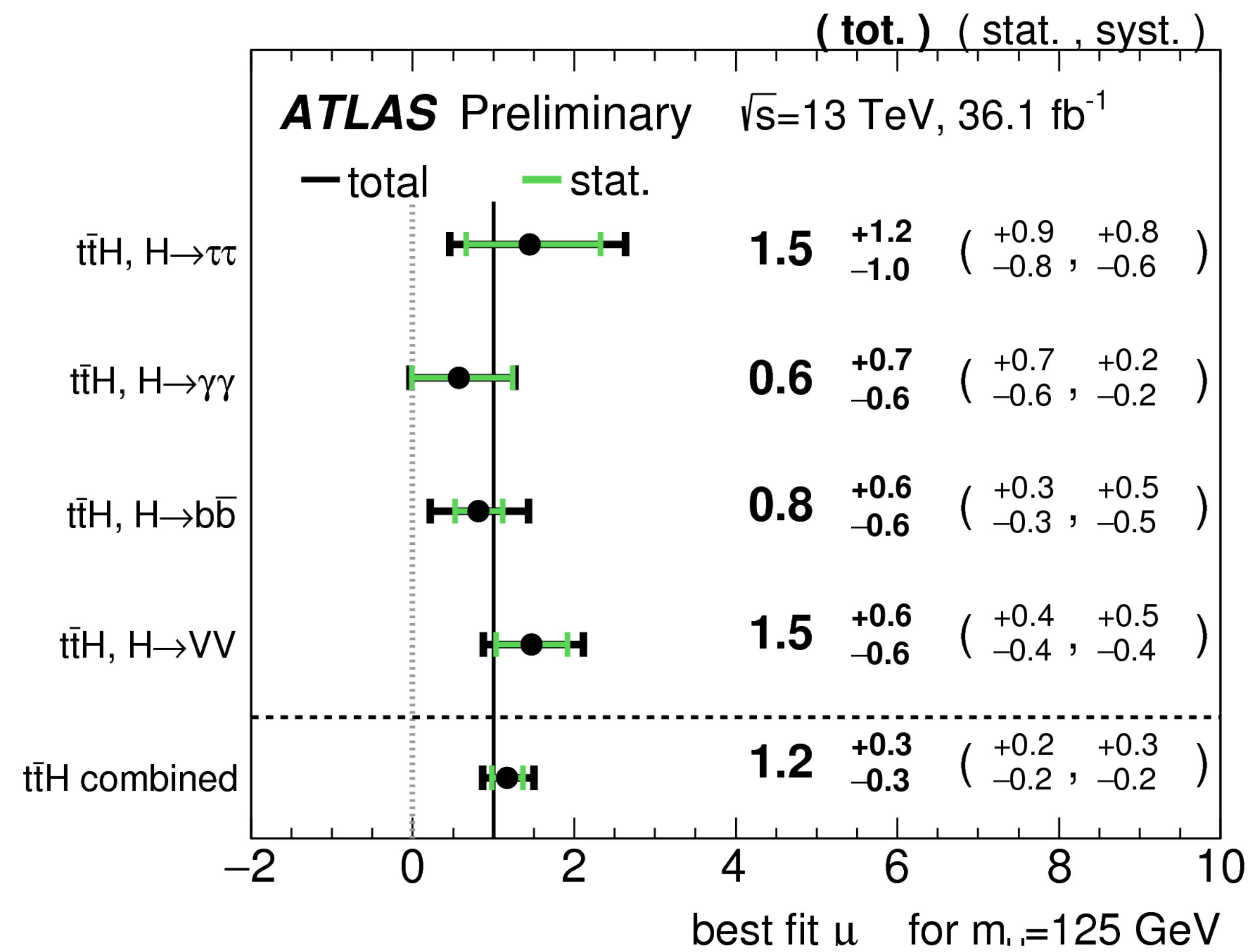
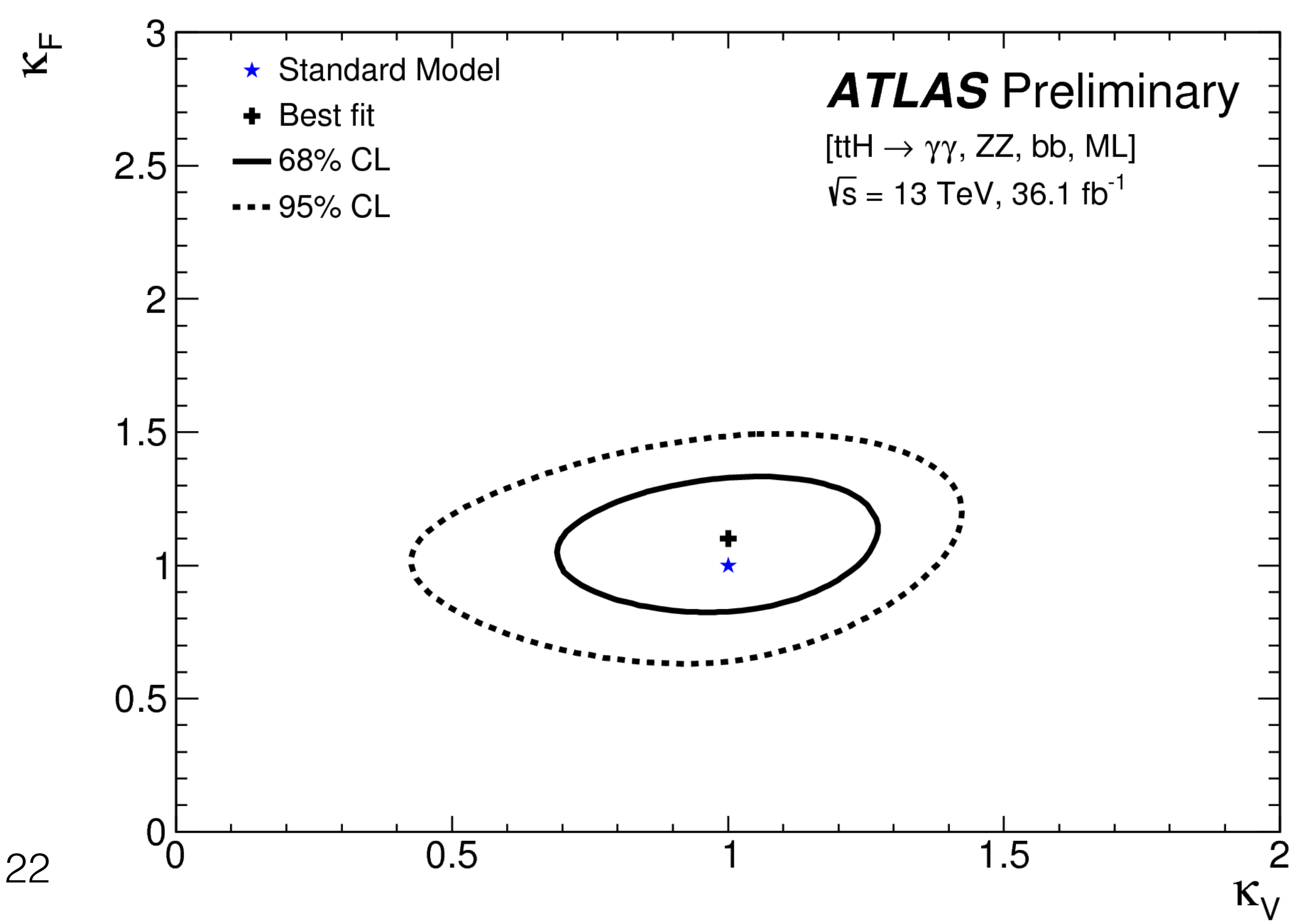




Summary

- Results from the searches for ttH production using 36.1 fb^{-1} ATLAS recorded data shown
- Challenging and complex analysis: Improvement possible due to better background modeling and use of multivariate techniques.
- ttH multilepton: $\mu = 1.6 \pm 0.3(\mathrm{stat})^{+0.4}_{-0.3}(\mathrm{syst})$ 4.1σ (expected 2.8σ)
- ttH(bb): $\mu = 0.84 \pm 0.29(\mathrm{stat})^{+0.57}_{-0.54}(\mathrm{syst})$ 1.4σ (expected 1.6 σ)
- Combination with ttH categories in H(γγ) and H(ZZ*->4l)

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

$$\text{Significance} : 4.2\sigma(\text{expected} : 3.8\sigma) \quad \text{Evidence !!}$$

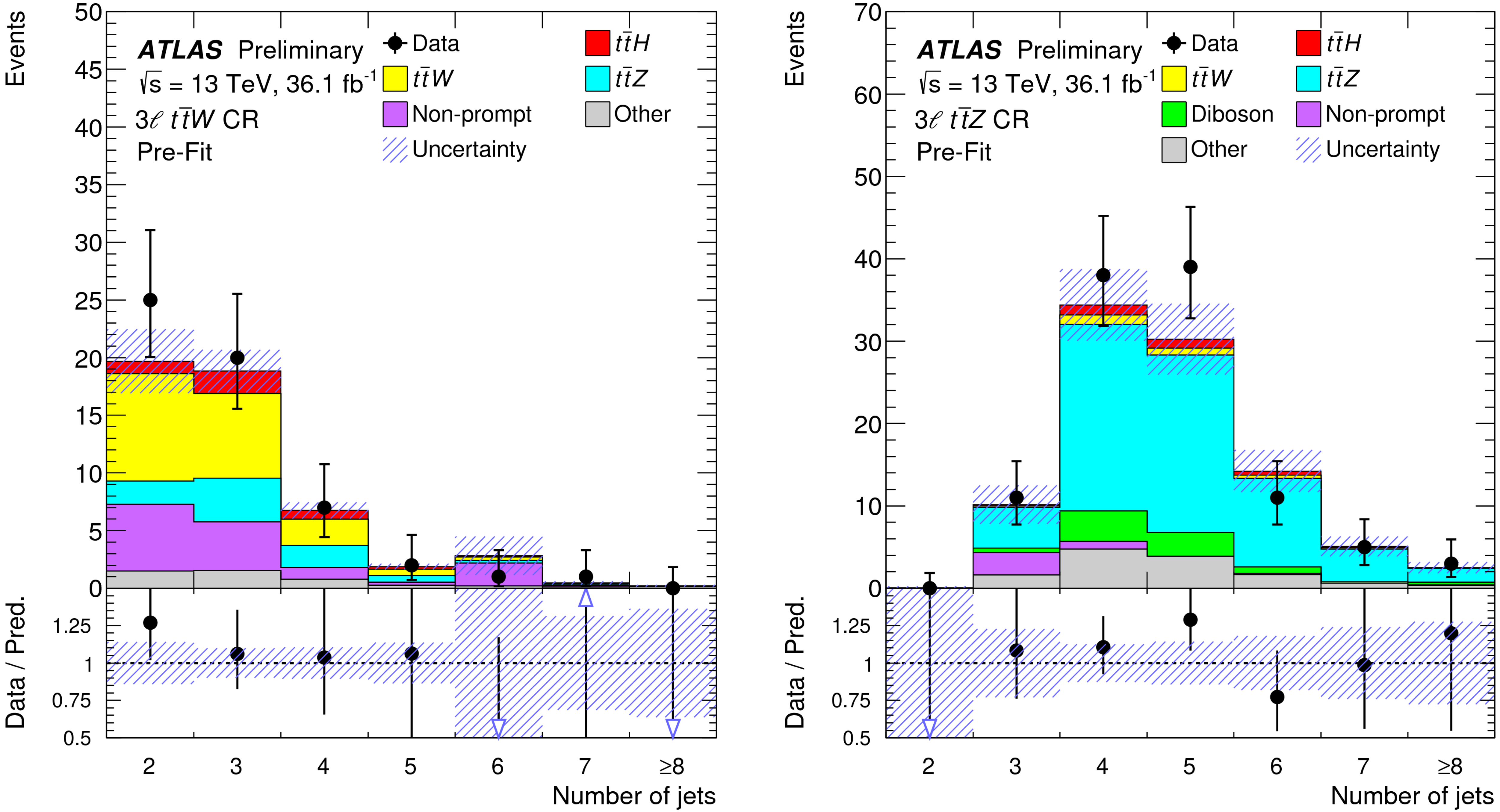
Extrapolated cross section consistent with SM prediction

$$\sigma_{t\bar{t}H} = 590^{+160}_{-150}\,fb \qquad \sigma^{SM}_{t\bar{t}H} = 507^{+35}_{-50}\,fb$$

- Towards observation of top-Yukawa coupling:
- Already recorded 42.7 fb^{-1} of data in 2017

Backup

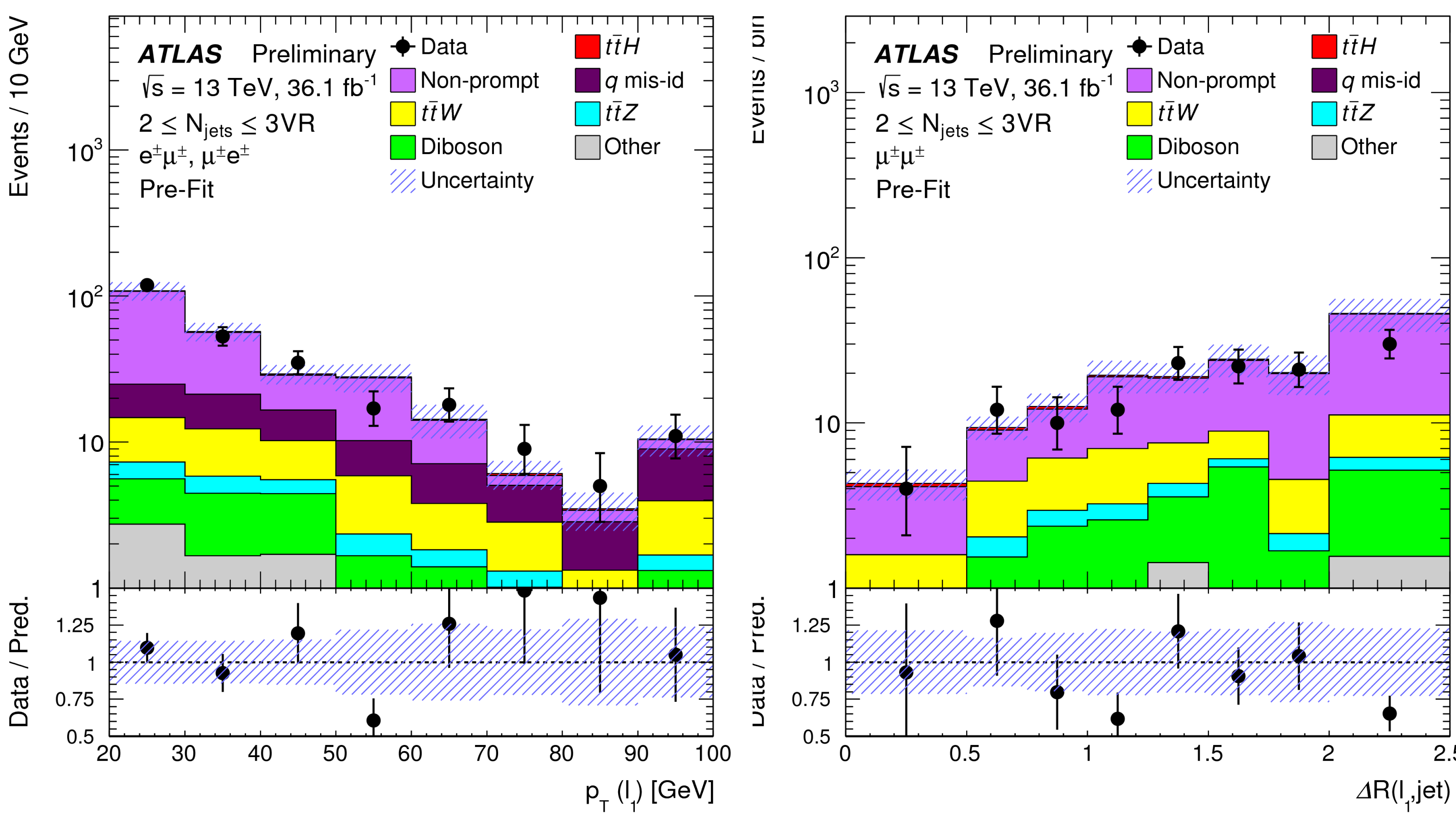
ttHML: ttW/ttZ CR's



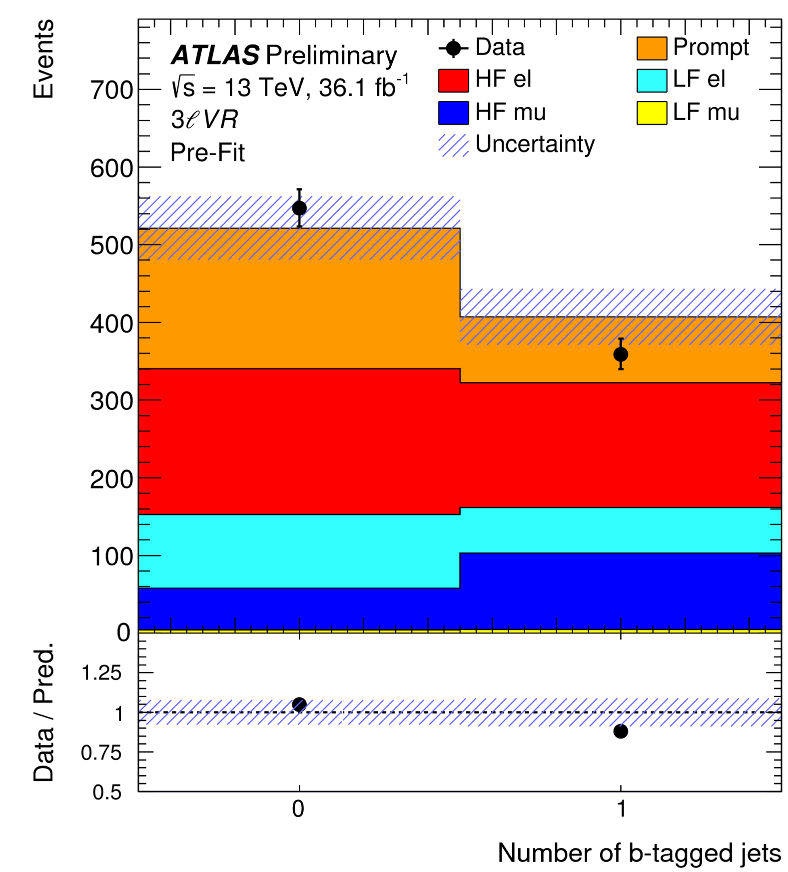
ttHML: light lepton fakes

	2ℓSS	3ℓ	4ℓ	1ℓ+$2\tau_{had}$	2ℓSS+$1\tau_{had}$	2ℓOS+$1\tau_{had}$	3ℓ+$1\tau_{had}$
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)

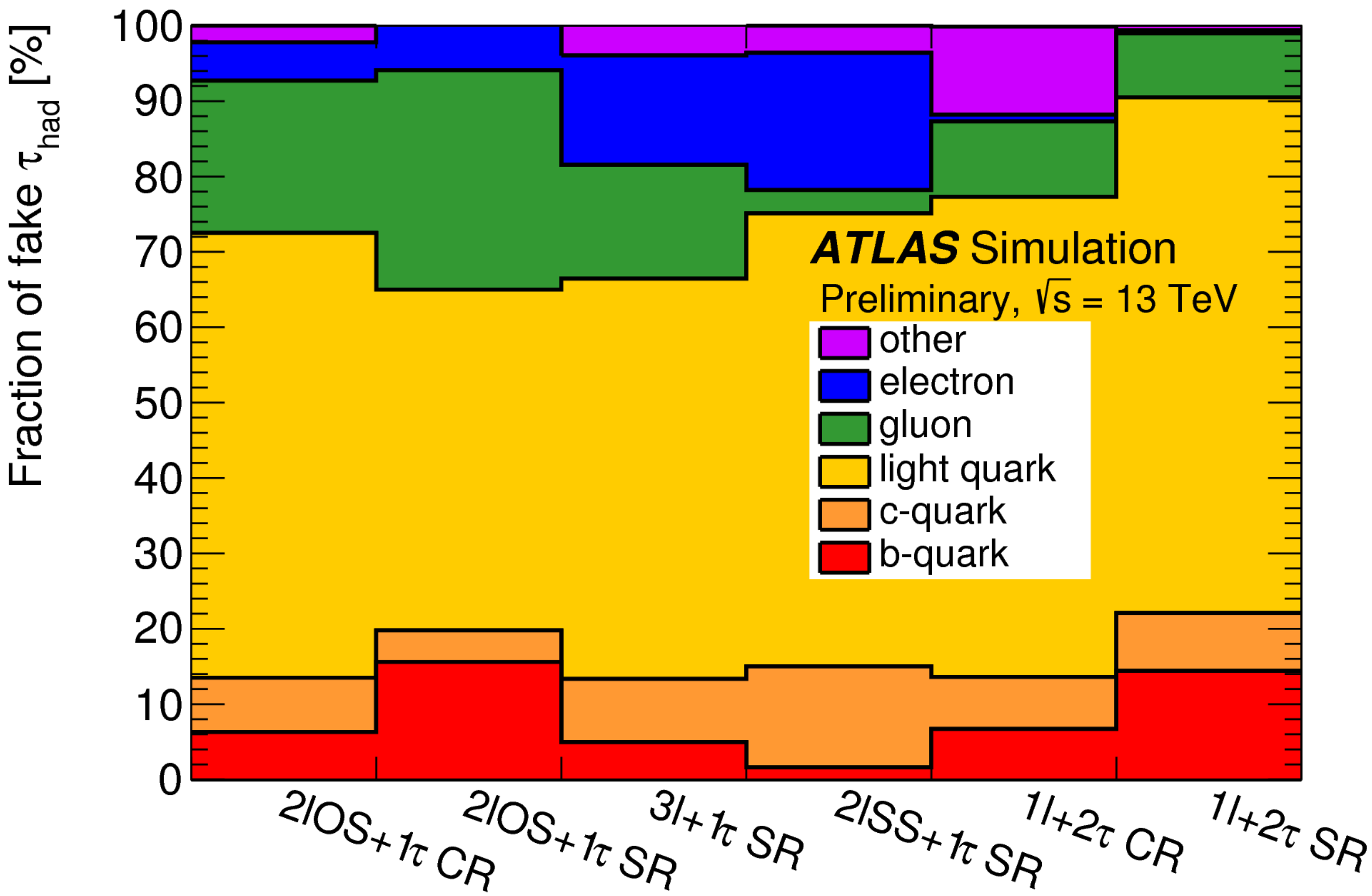
2lSS/3l

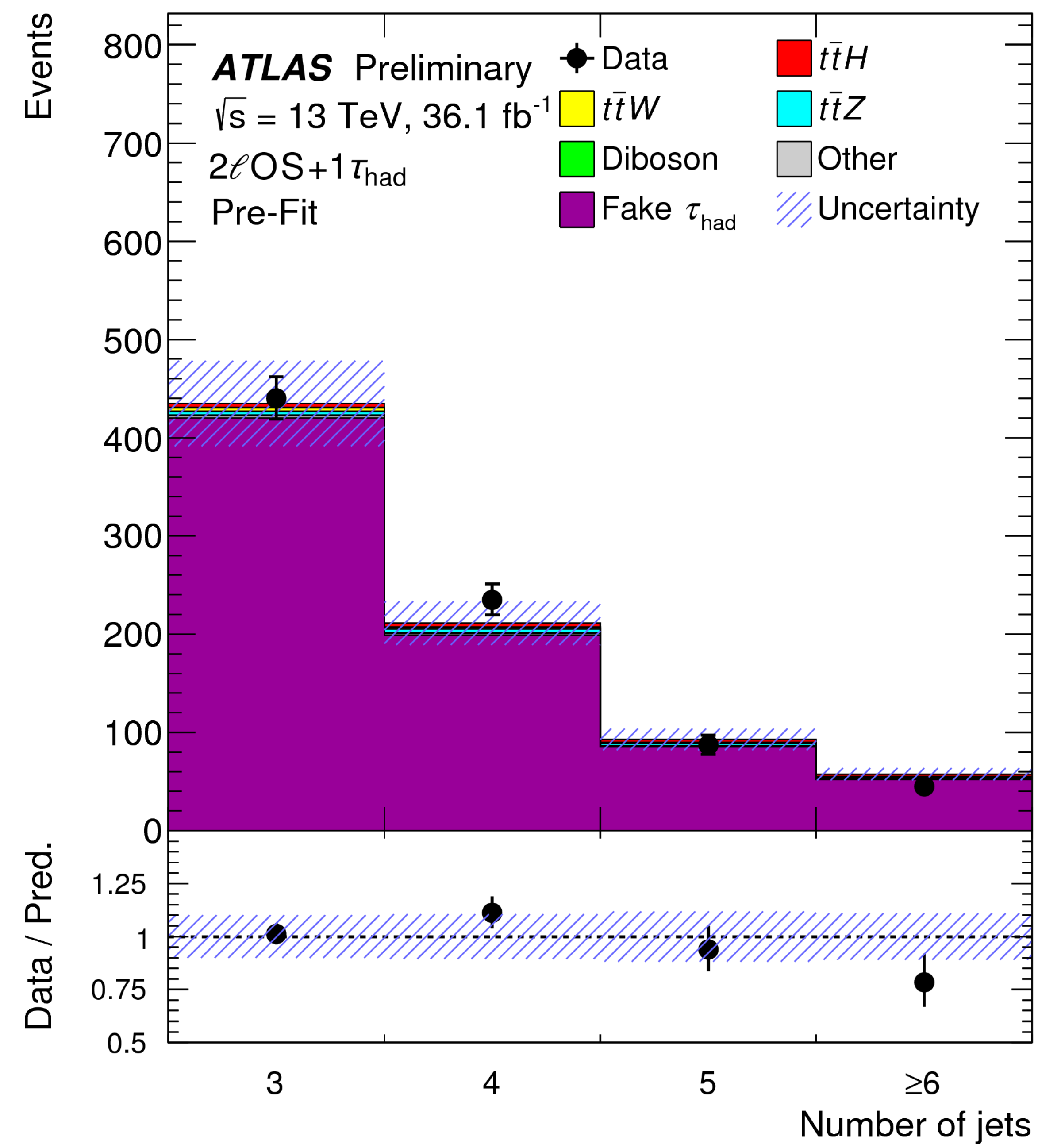


4l



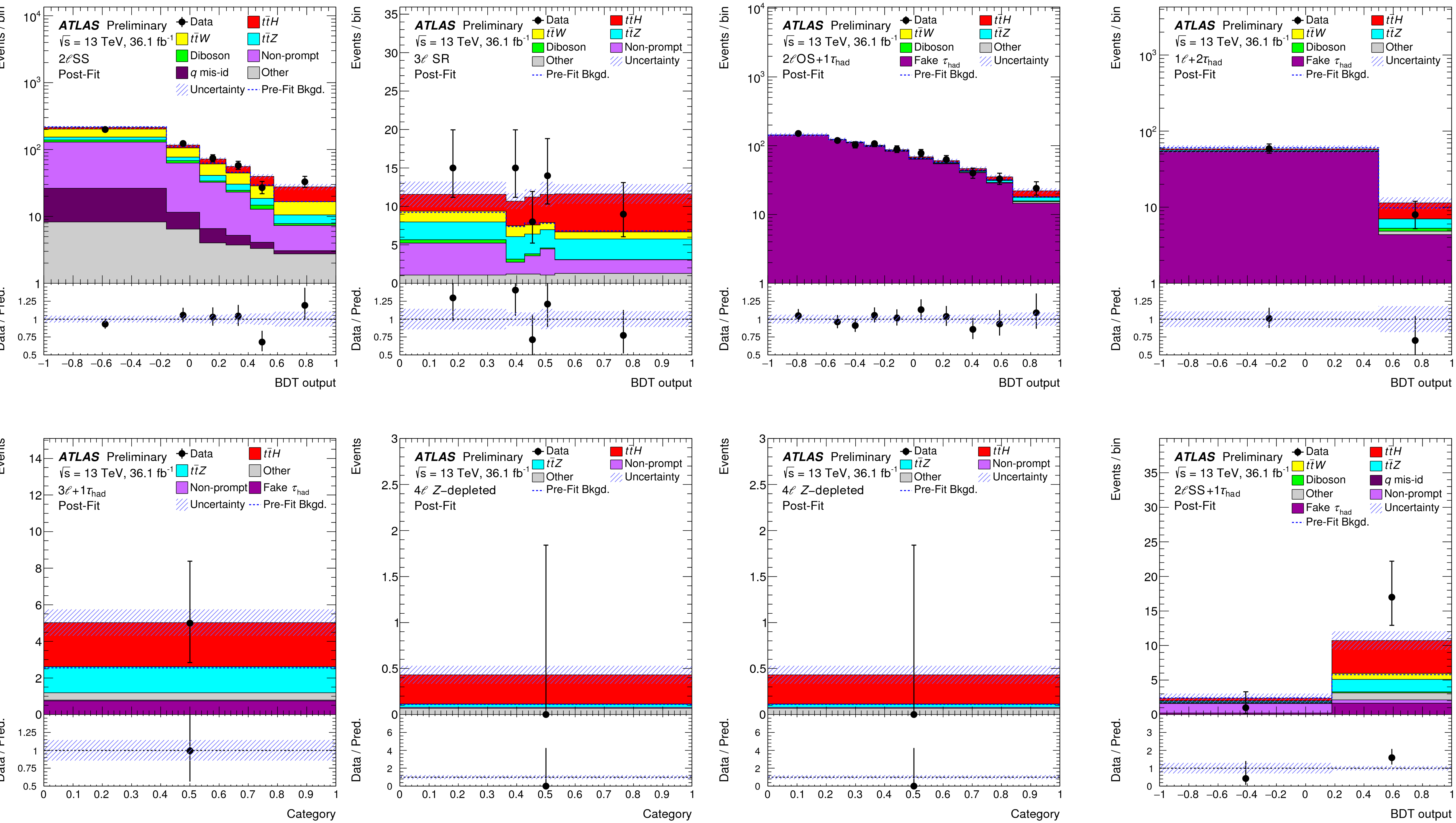
ttHML:Hadronic τ fakes



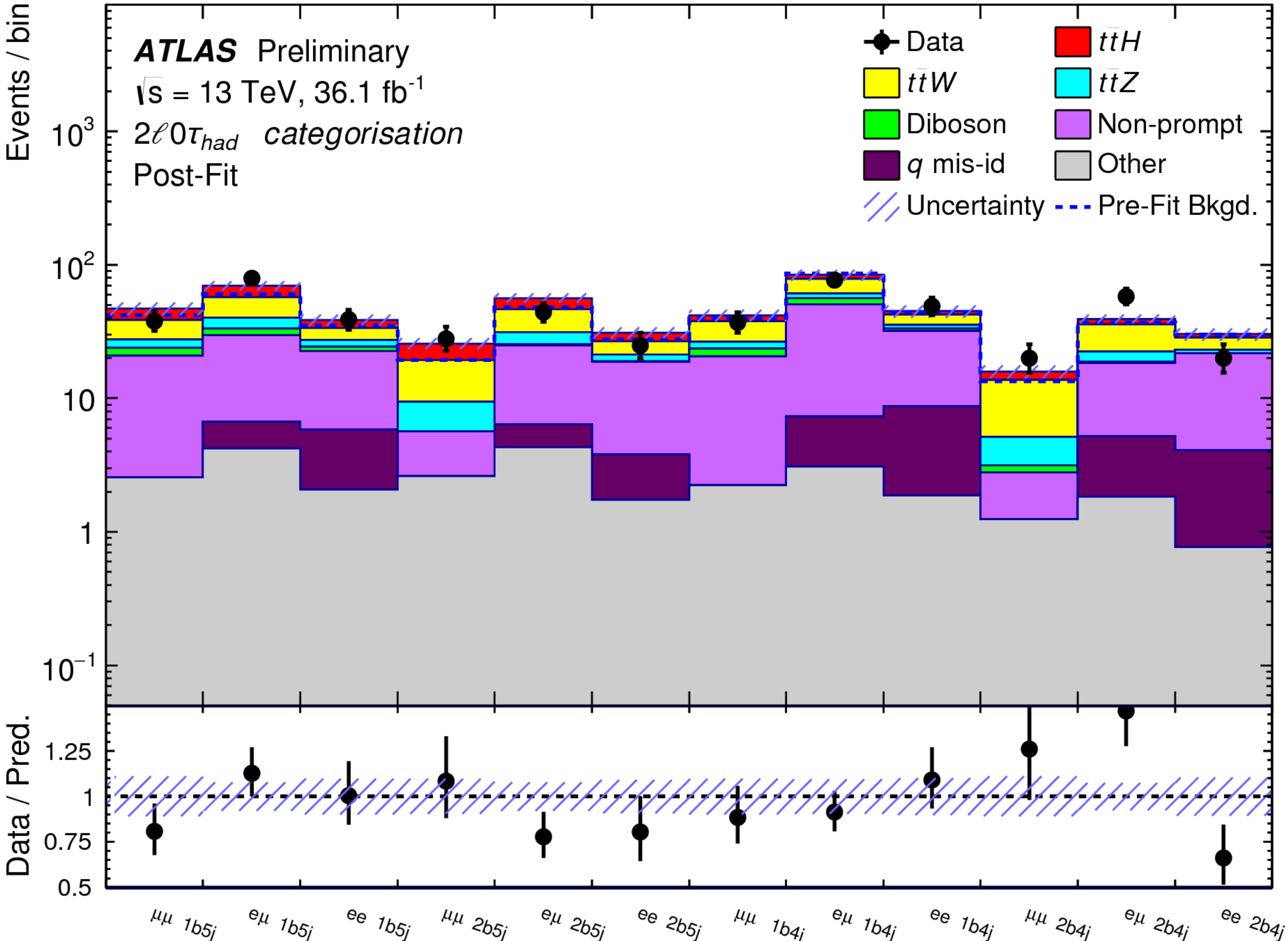


- Fake factor method
    - Fake factors measured in a CR (>=3, b-tag veto), Inverting τ-BDT

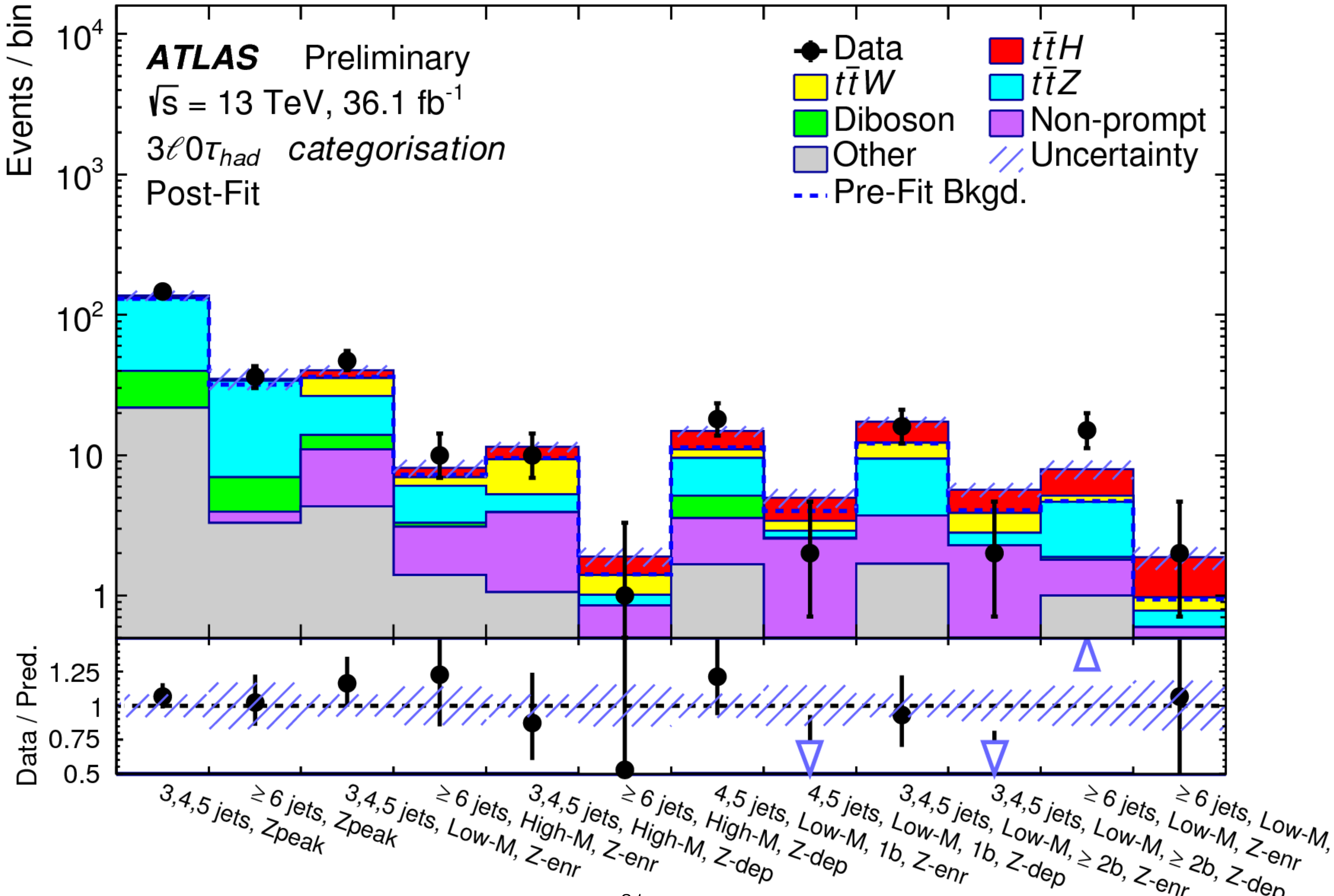
ttHML: fit distributions



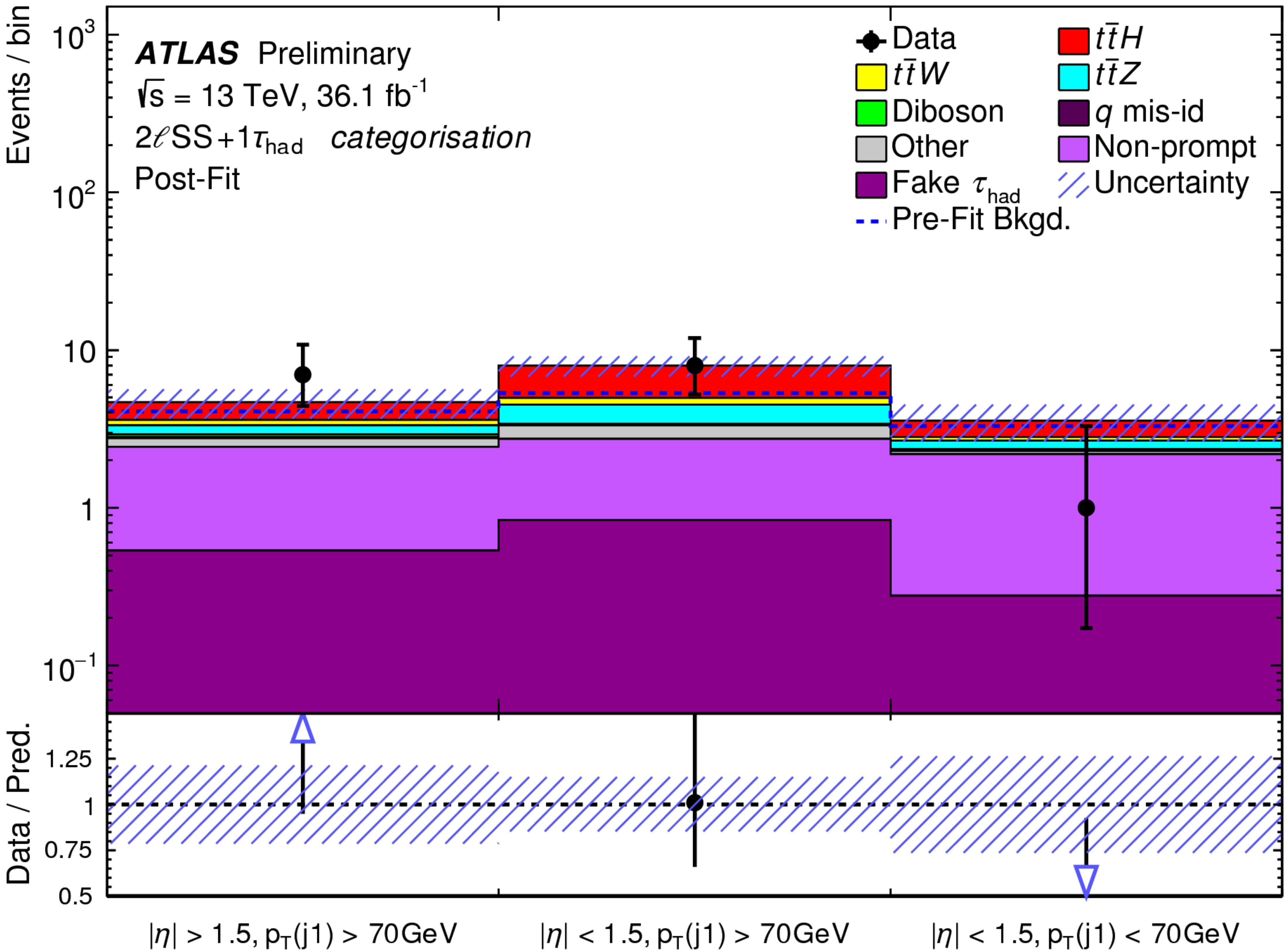
ttHML: Cross-check analysis



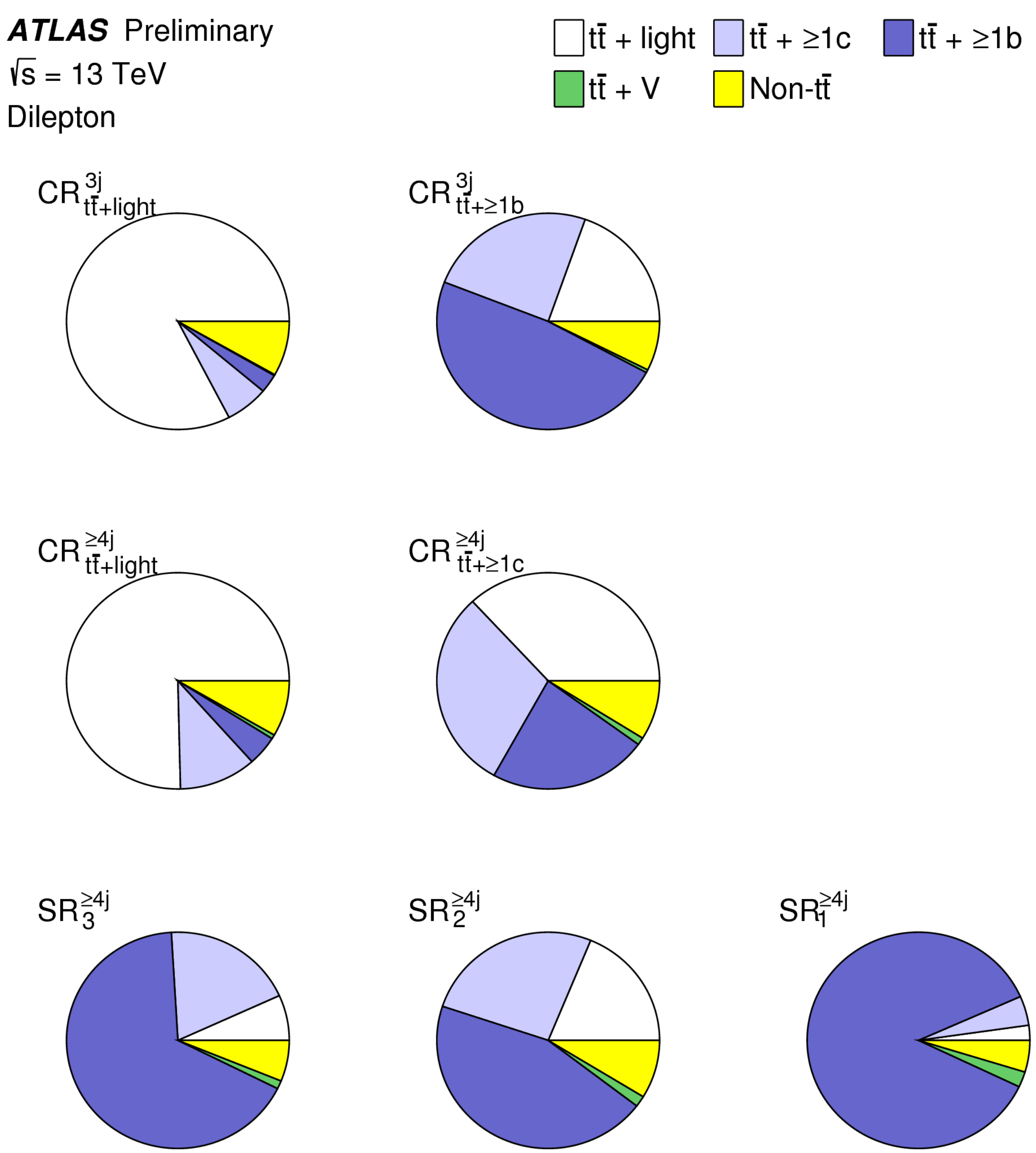
ttHML: Cross-check analysis

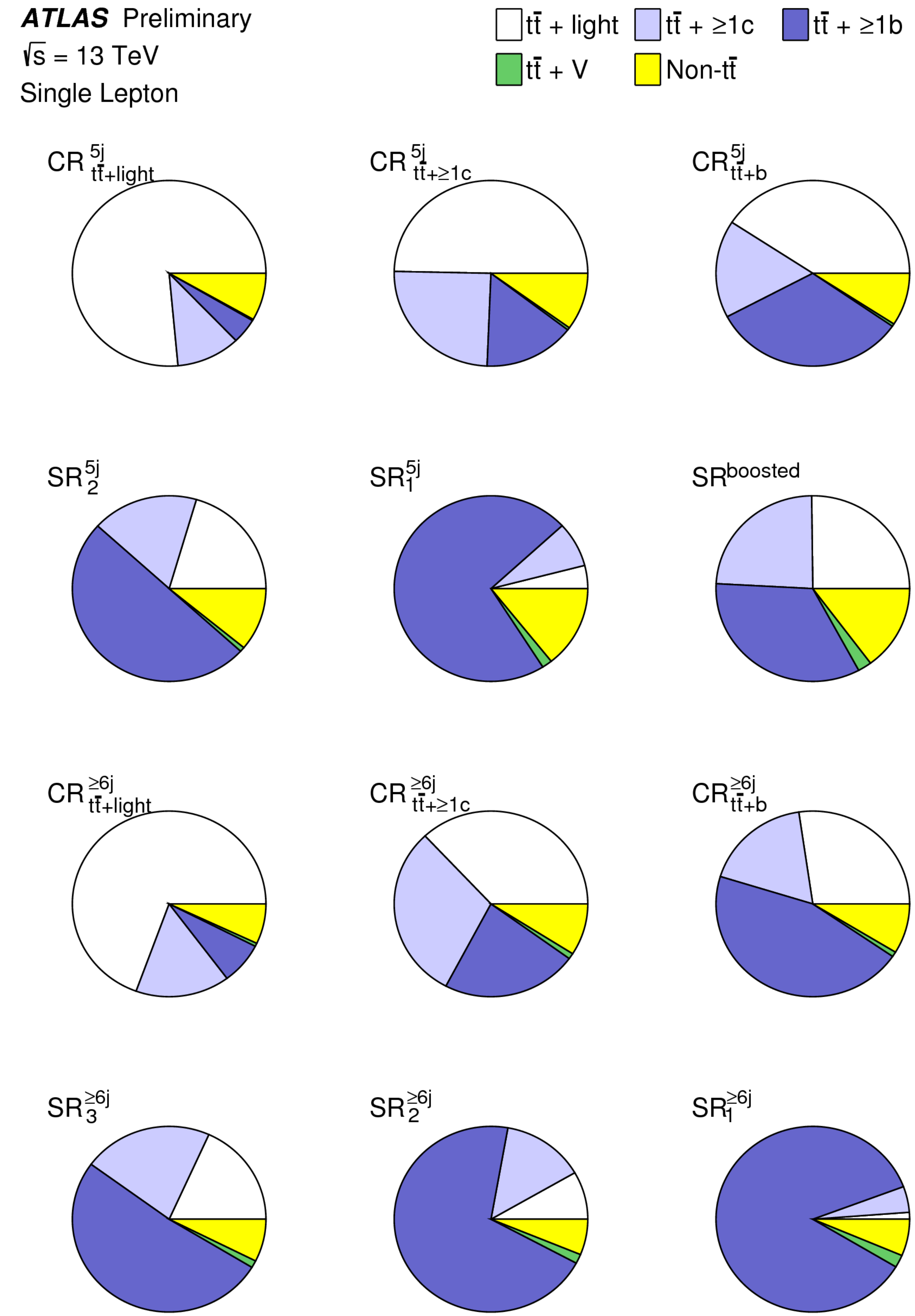


ttHML: Cross-check analysis

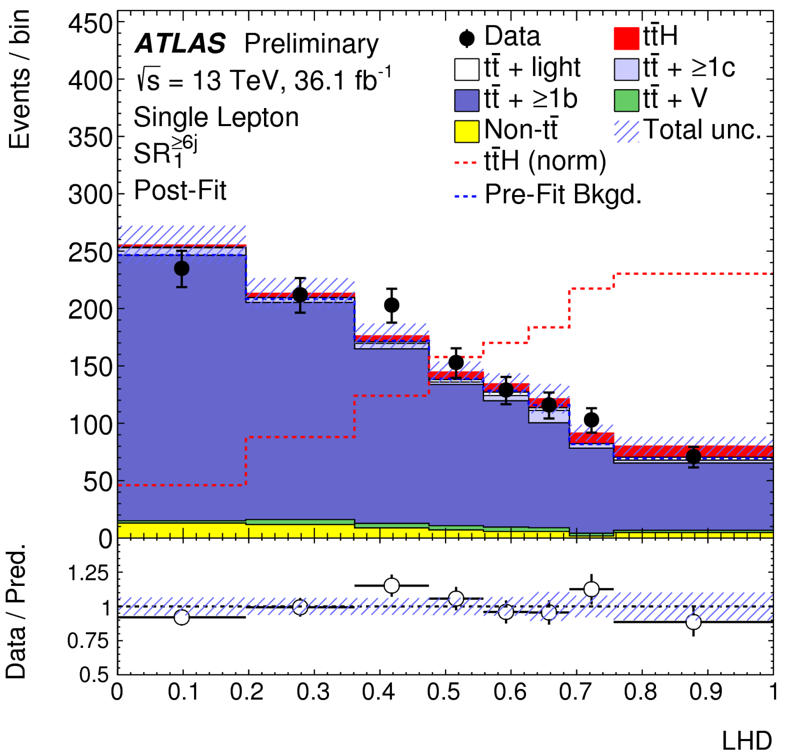


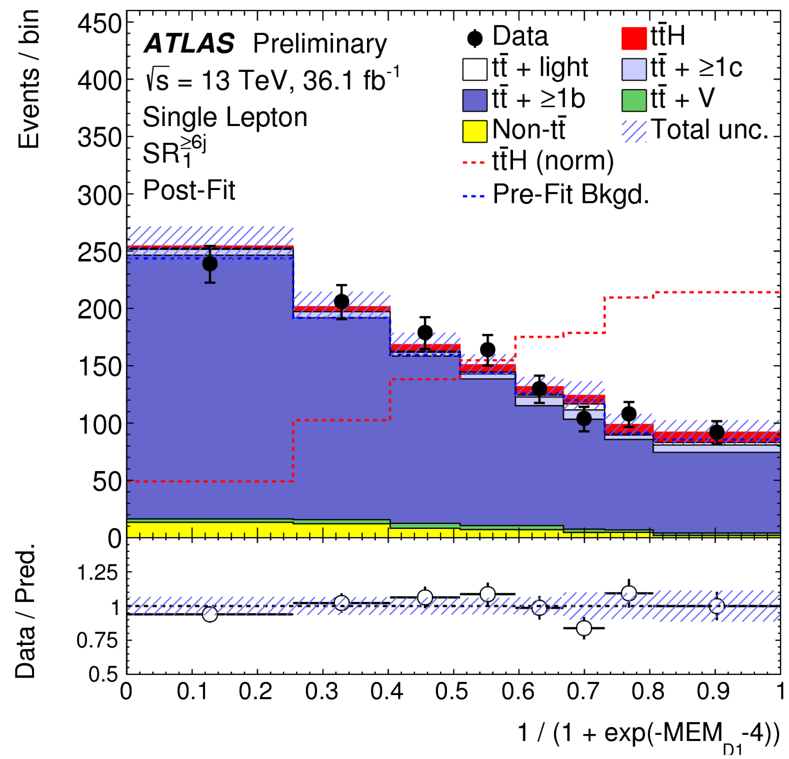
ttH(bb): Background composition

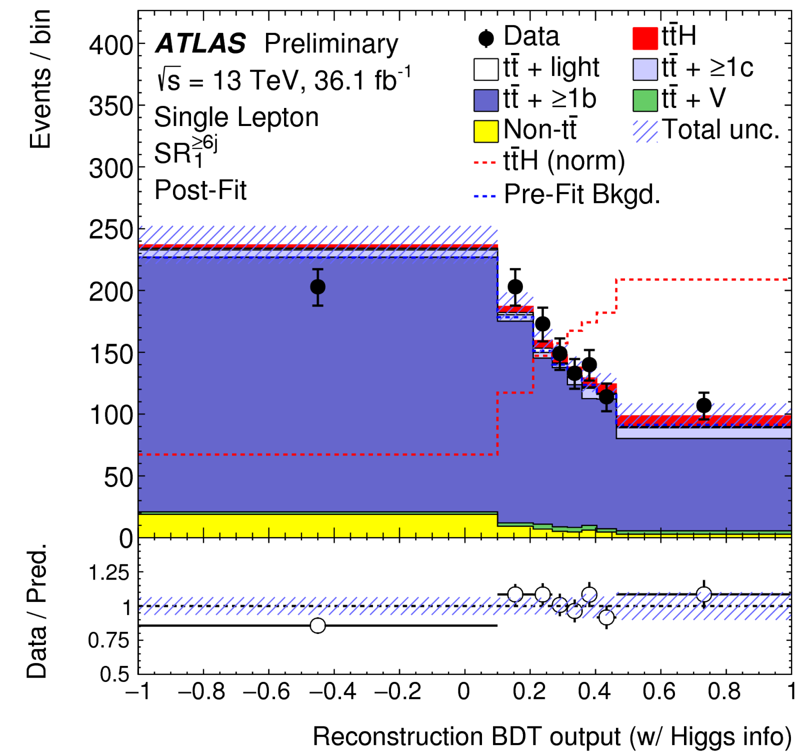


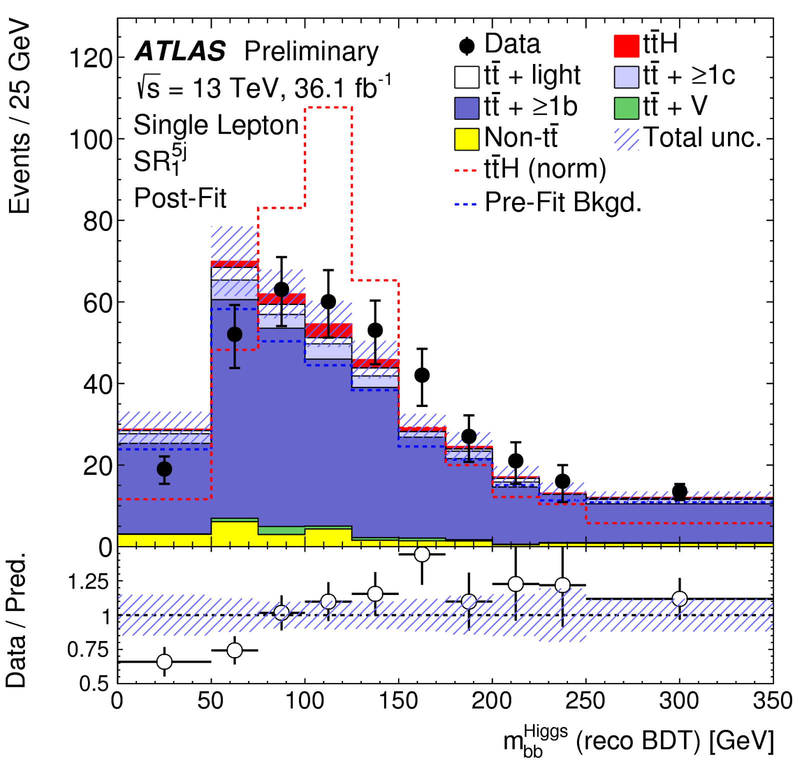


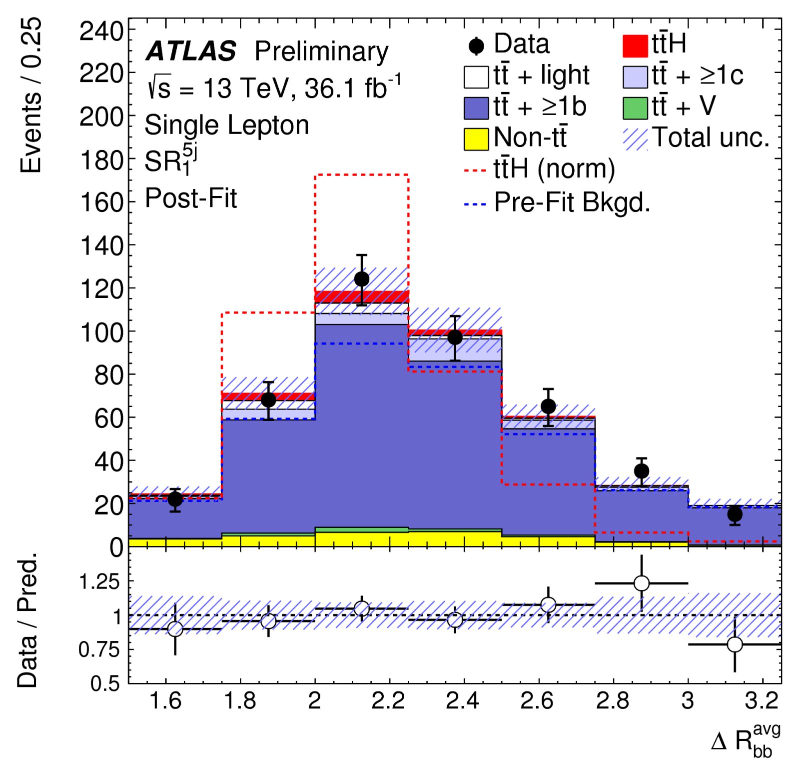
ttH(bb): Classification BDT input



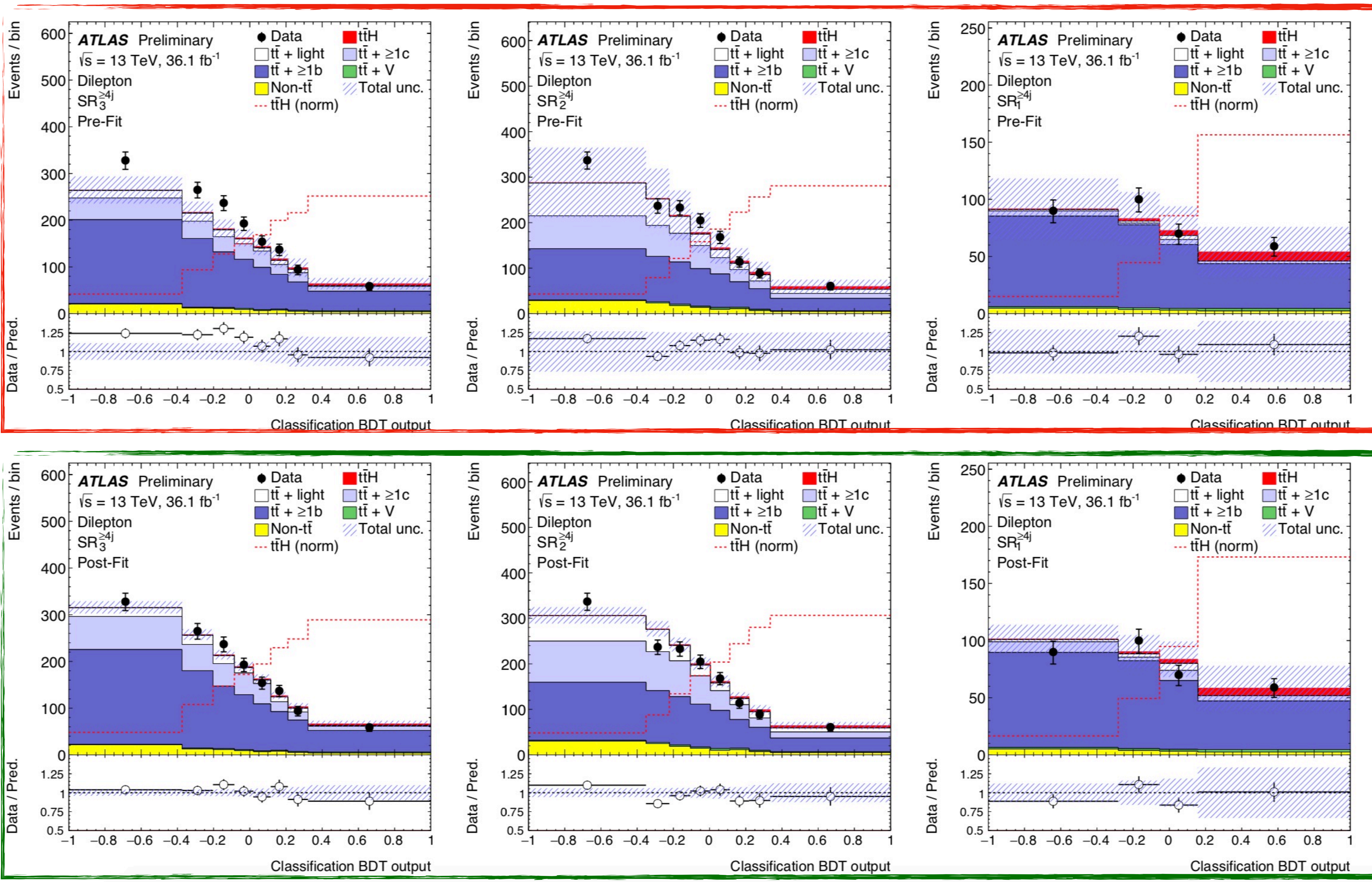




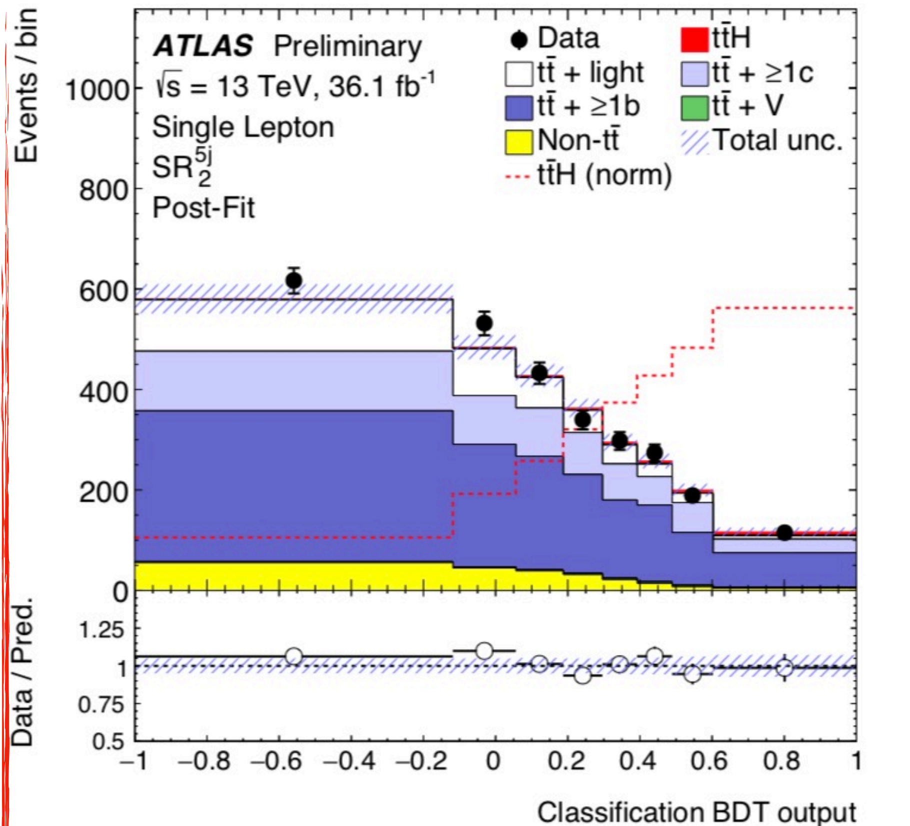


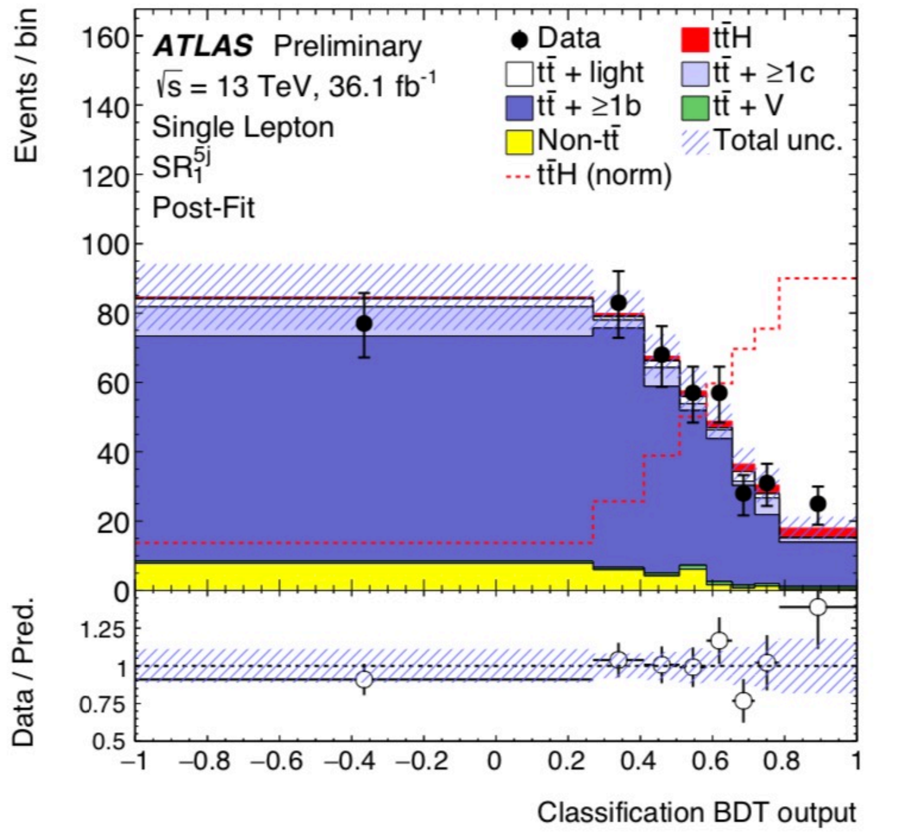


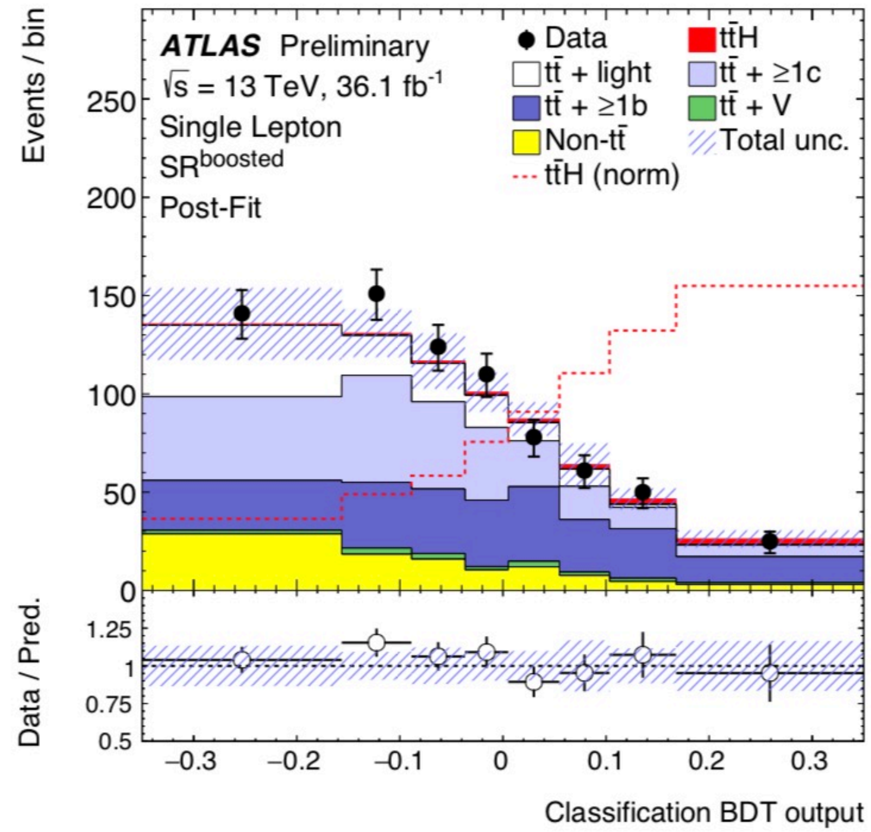
ttH(bb): Prefit-Postfit SR's 2l

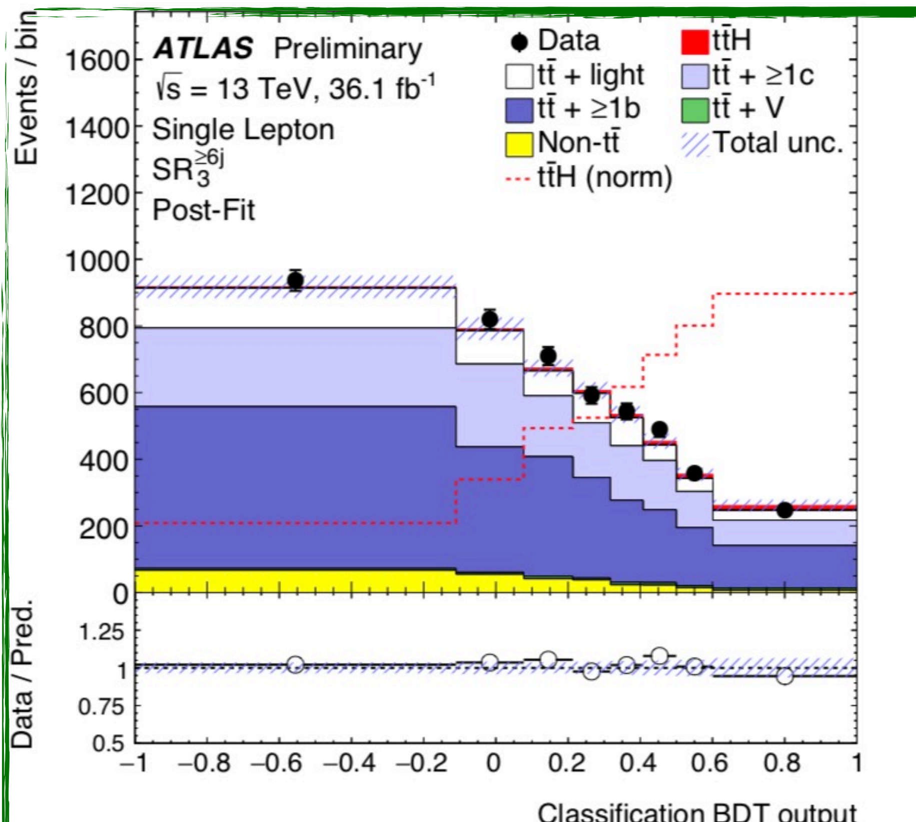


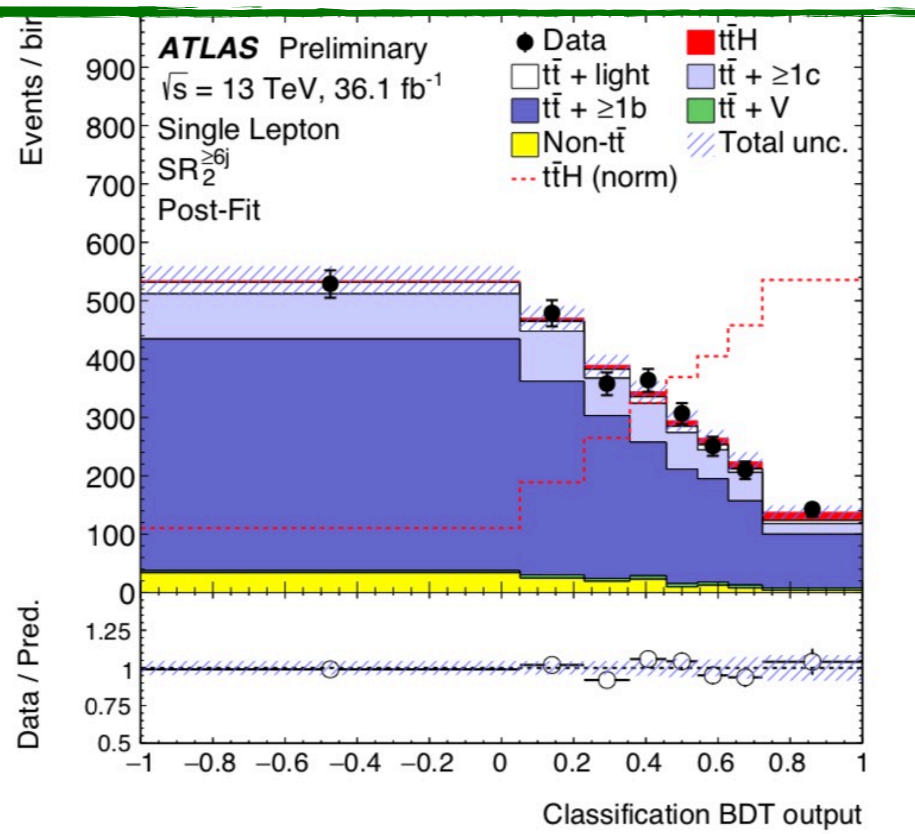
ttH(bb): Prefit-Postfit SR’s 1l

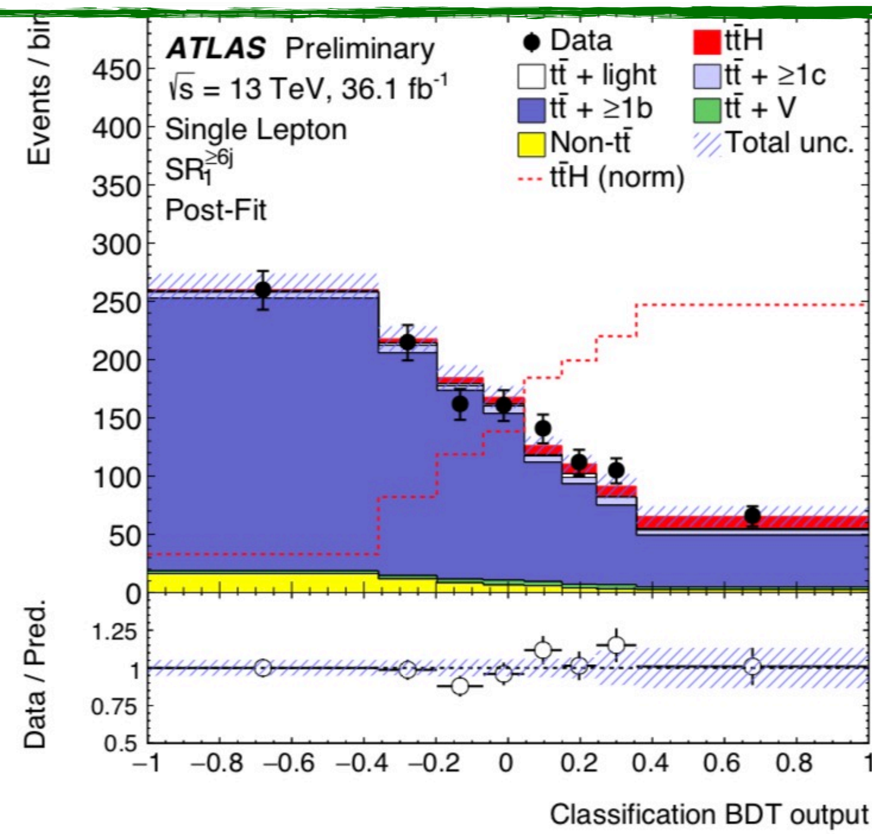






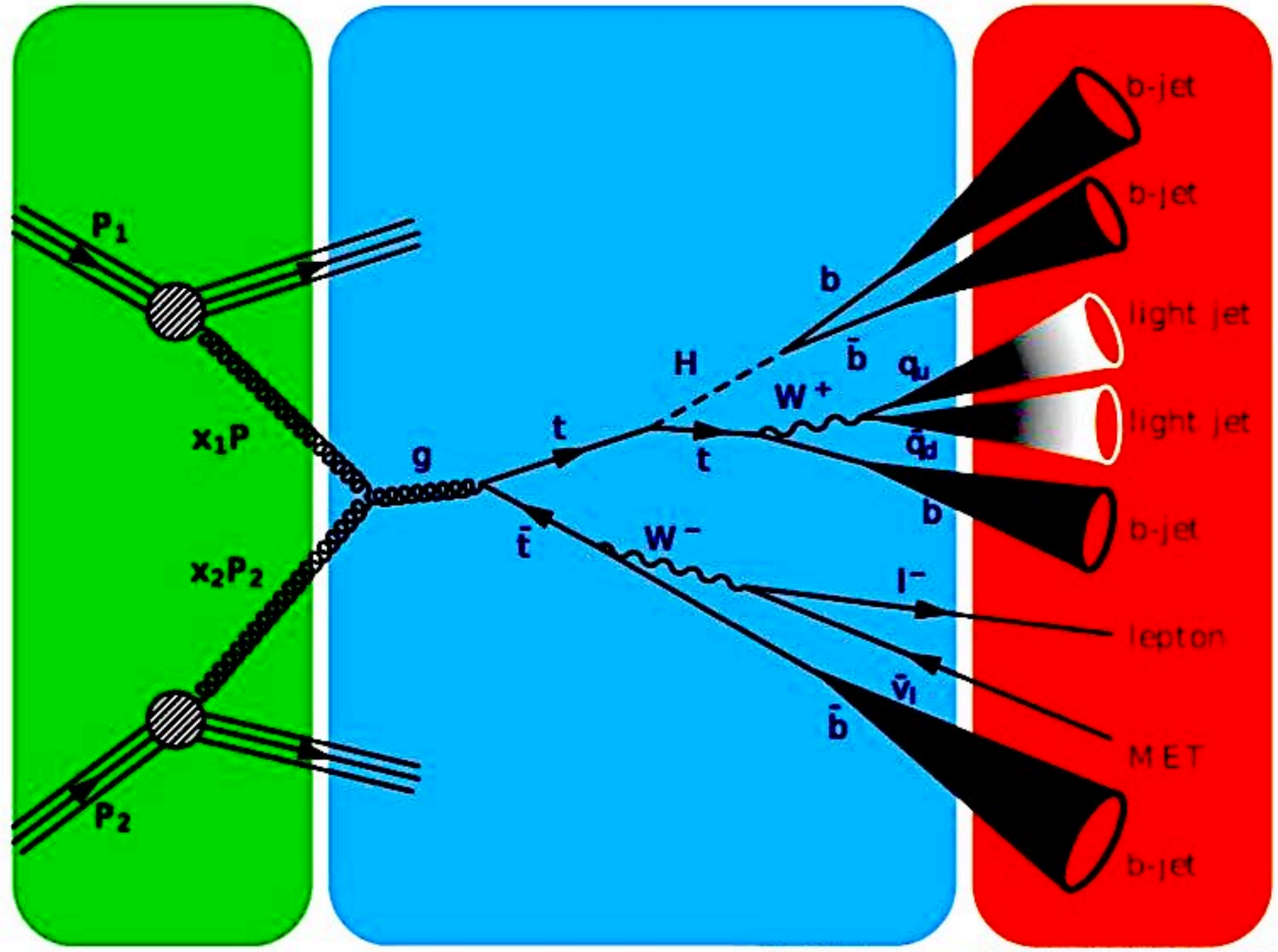






ttH(bb): Matrix Element method

- Calculate the likelihood of each event to originate from ttH or tt + bb
- Used in most powerful signal region 6j SR1



Olaf Nackenhorst, CERN-THESIS-2015-186

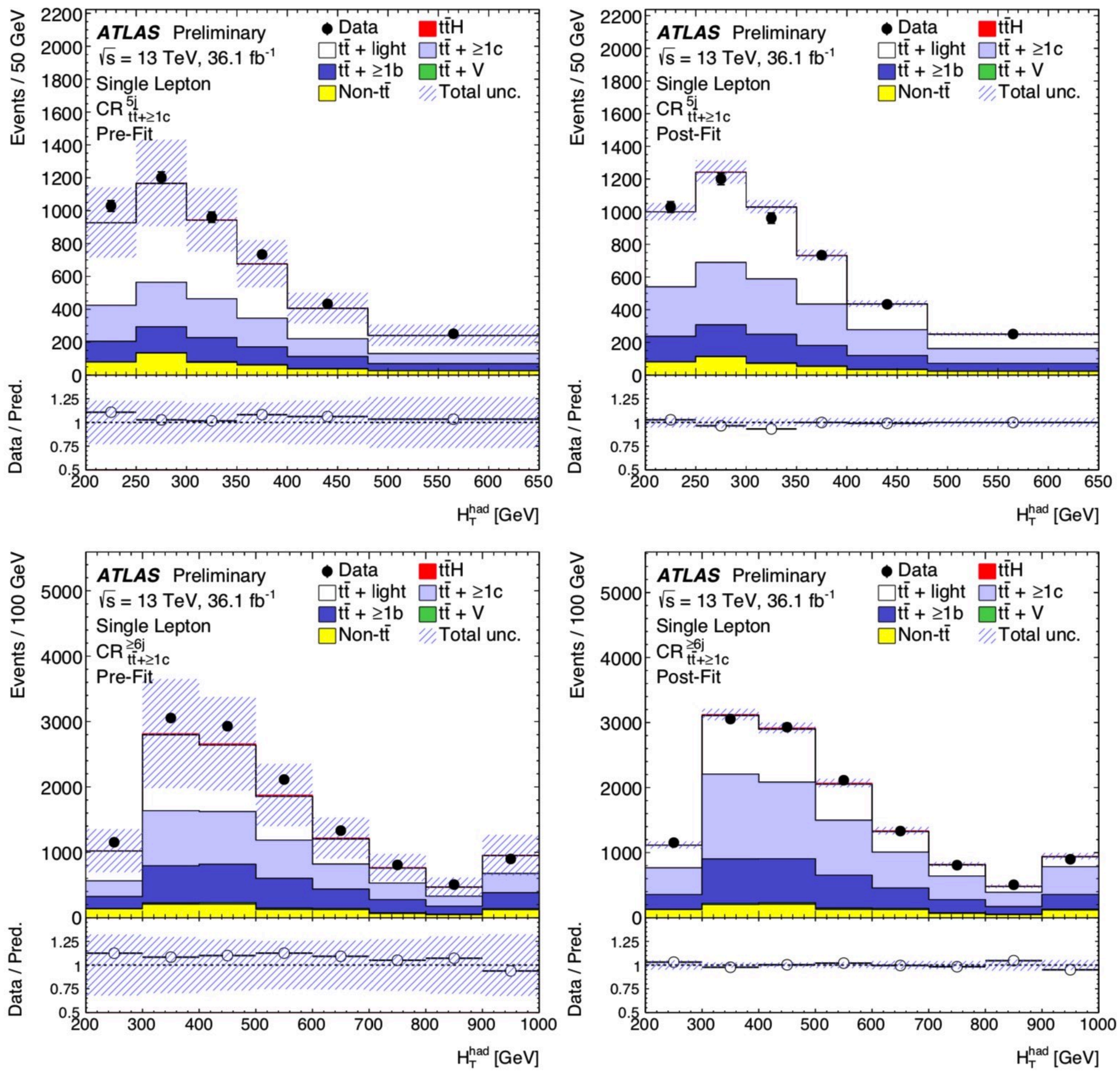
parton distribution function
accounts for production mechanism

transfer function
maps detector response to diagram

$$L_i = \sum_{\text{flavor}} \int \frac{f_1\left(x_1, Q^2\right) f_2\left(x_2, Q^2\right)}{|\vec{q}_1|\,|\vec{q}_2|} \left|\mathcal{M}_i\left(\mathbf{Y}\right)\right|^2 T(\mathbf{X};\mathbf{Y}) \mathrm{d}\Phi_n \mathrm{d}\mathbf{Y}$$

matrix element
describes signal or background process

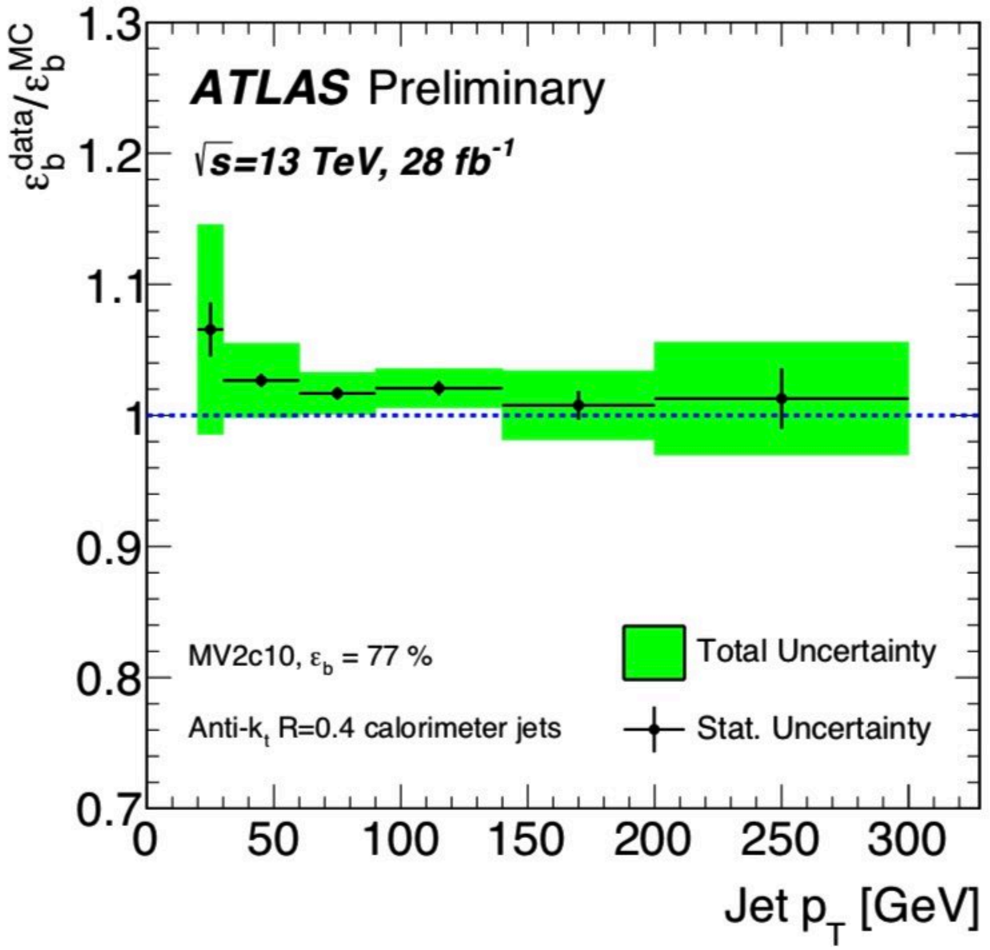
ttH(bb): CR disturbutions

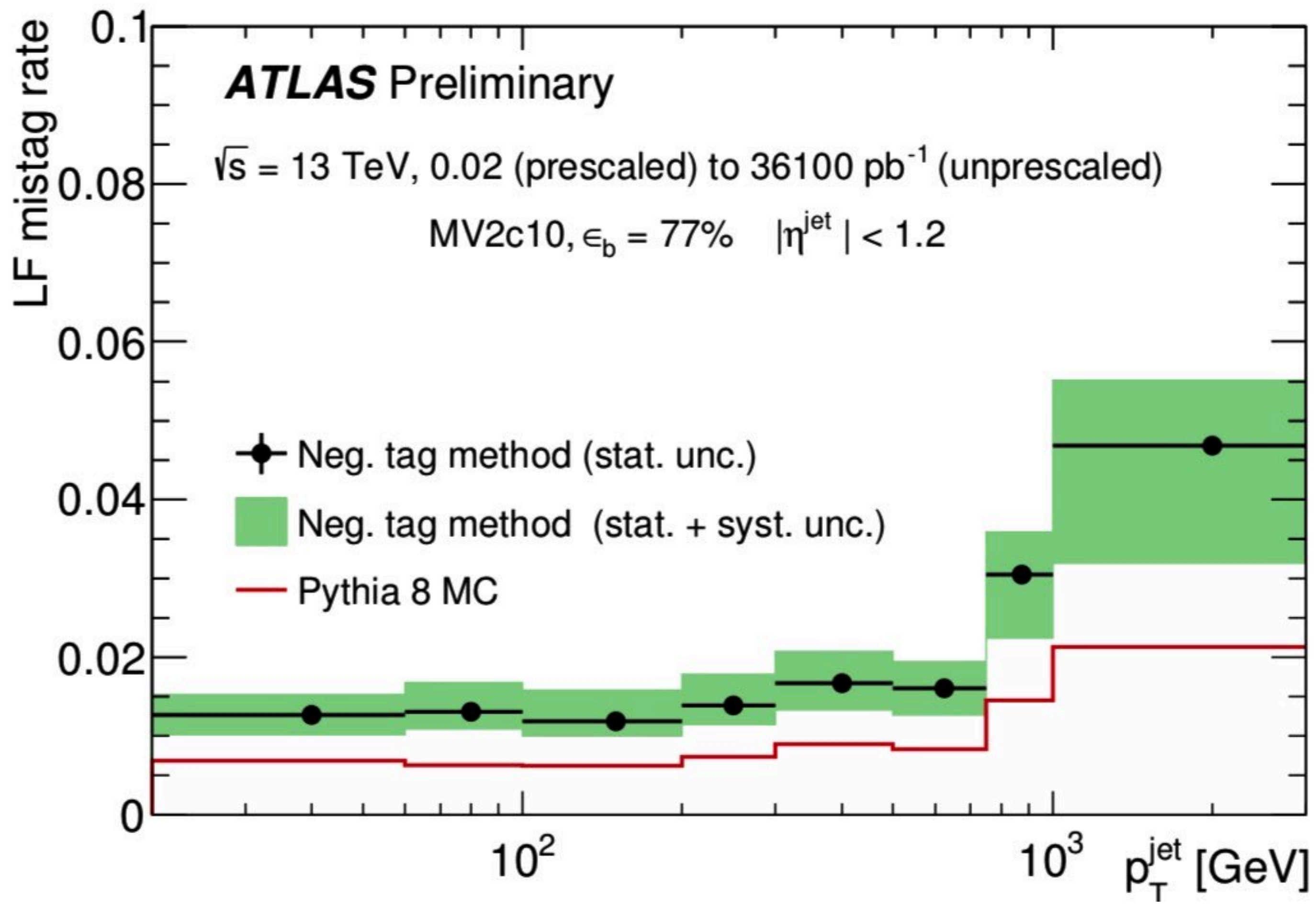


ttbar + HF modeling

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%	$t\bar{t}+\geq 1b$

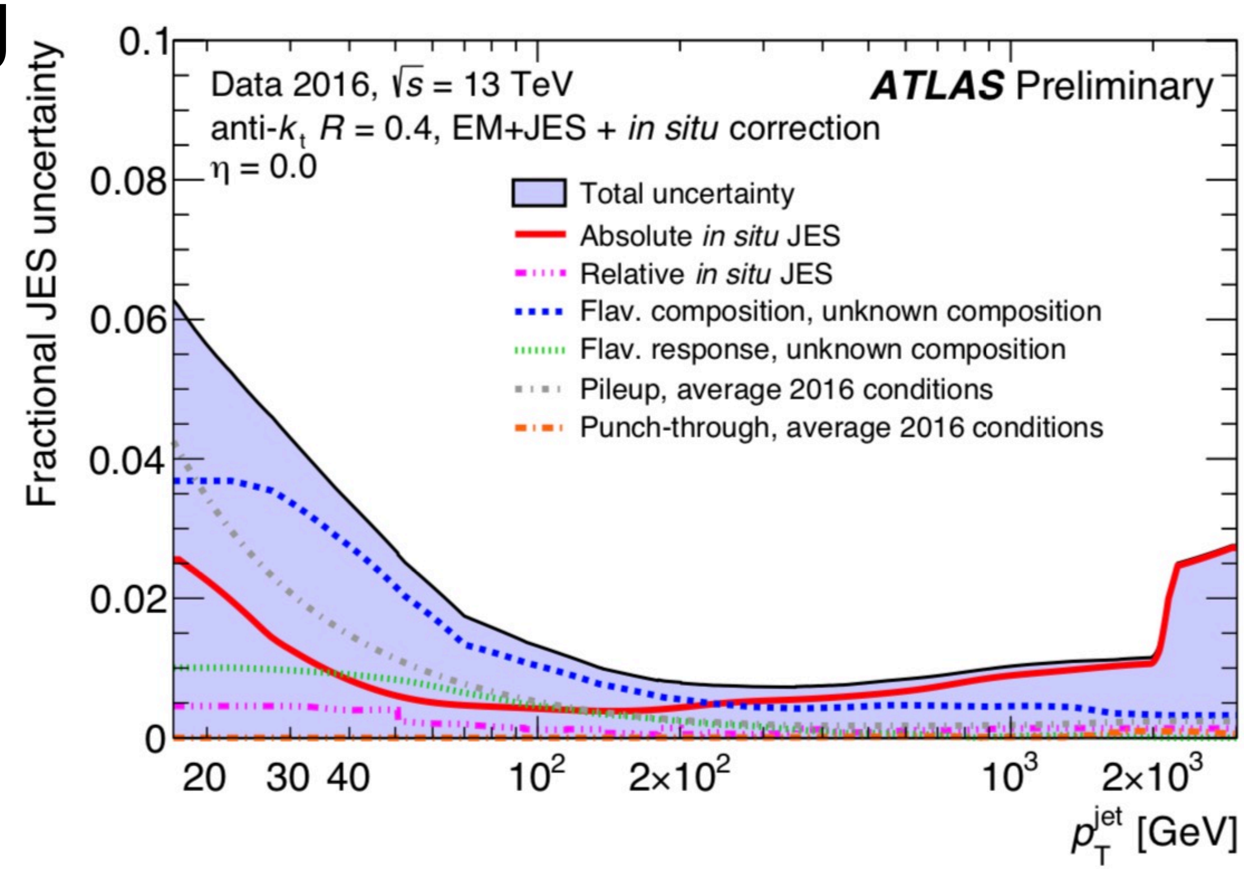
B-tagging Charm rejection and Efficiency scale factor





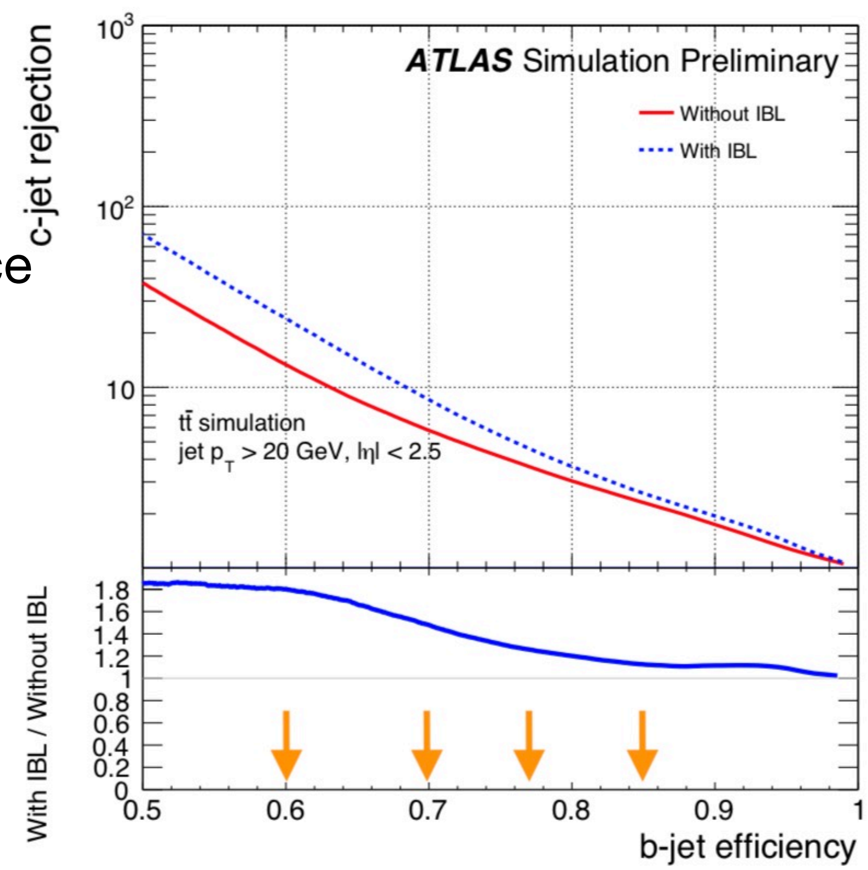
Performance: Jets & b-tagging

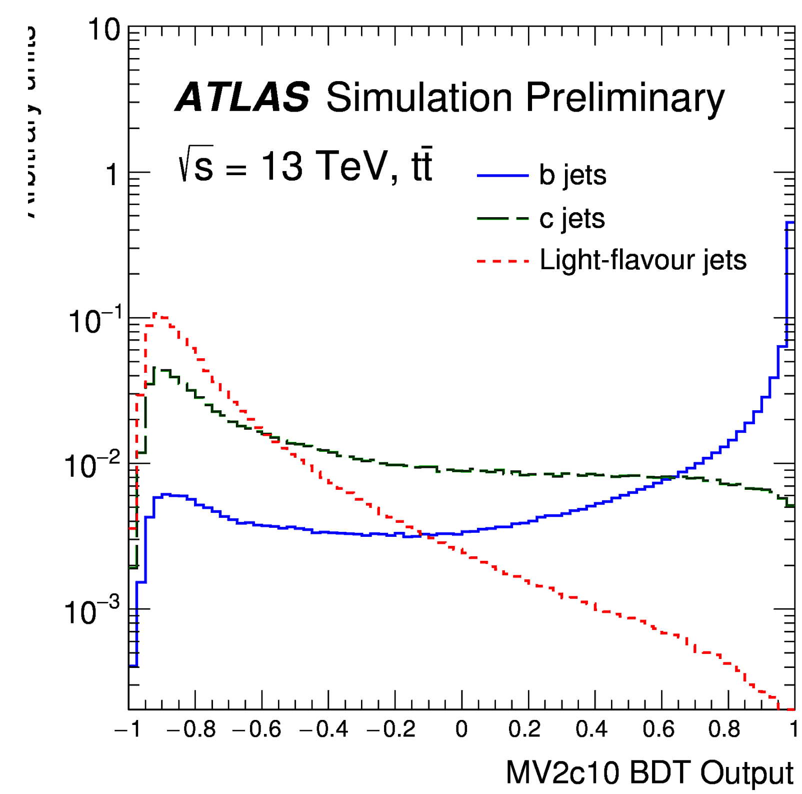
- Jets reconstructed with Anti-kT (R=0.4 jets) from calorimeter clusters calibrated to EM scale
- Particle level calibration by applying JES correction
- Dedicated efforts to mitigate pile up effects
- JES uncertainty about 1-2% above 60 GeV



B-tagging

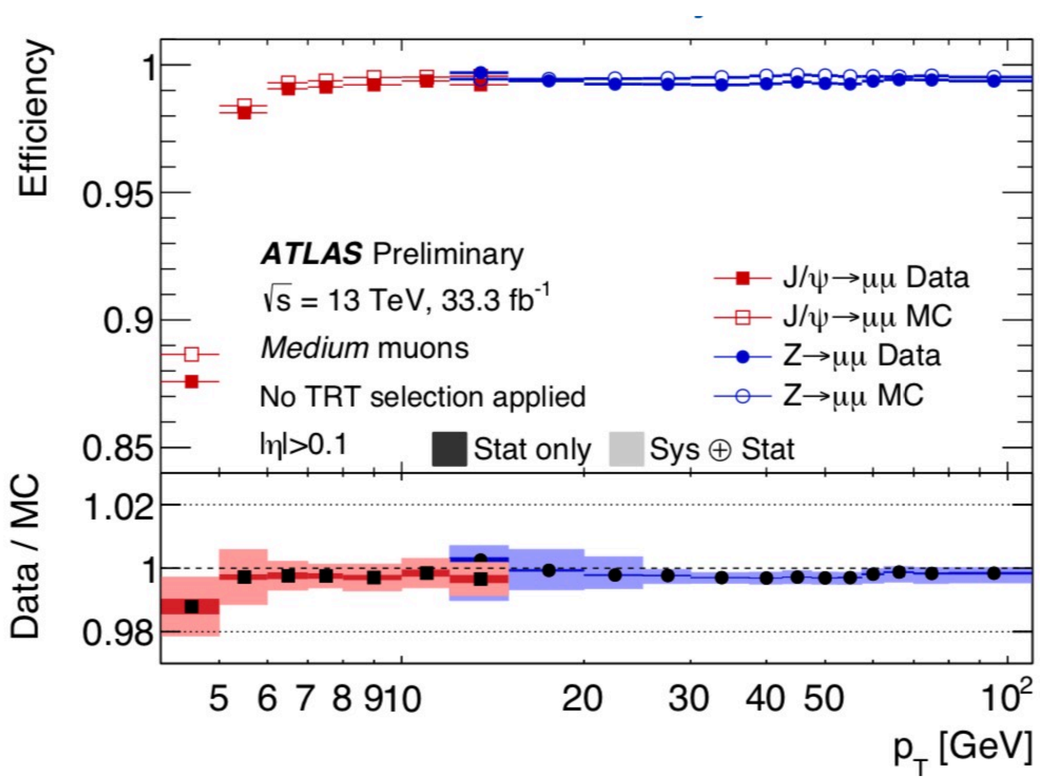
- Run2 improvement: New inner most pixel layer IBL
  - Significantly improves performance
- MVA algorithm exploits B-decay topologies
- Four calibrated working points with different tagging efficiencies
- b-tag efficiency: 2-10% uncert.
- c-jet mistag rate: 5-20% uncert.
- light-jet mistag rate: 10-50% uncert.

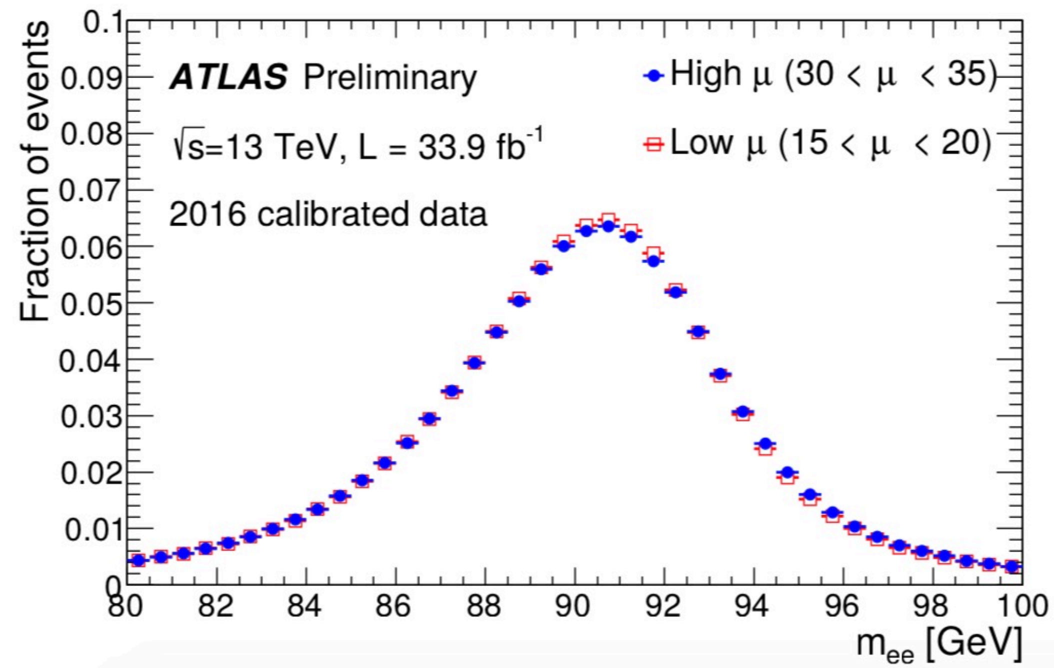




Performance: Leptons

- Leptons reconstructed using calorimeter as well as tracking information



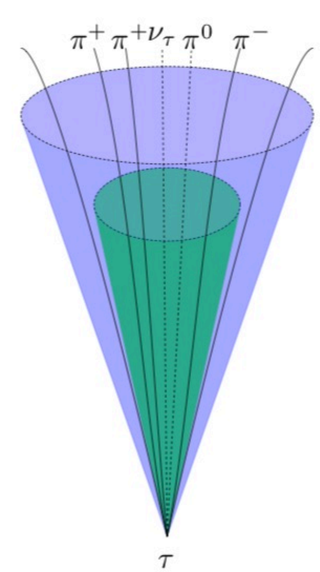


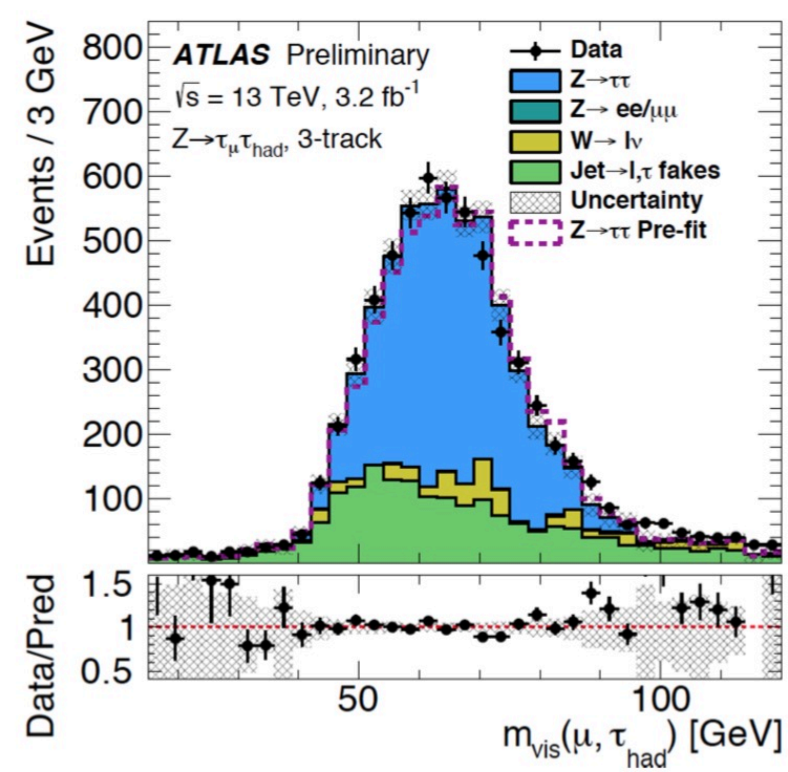
- Calibrated leptons robust to pileup

- Identification efficiency of e/μ measured in $Z \rightarrow l^+l^-$ and $J/\Psi \rightarrow l^+l^-$ in data.

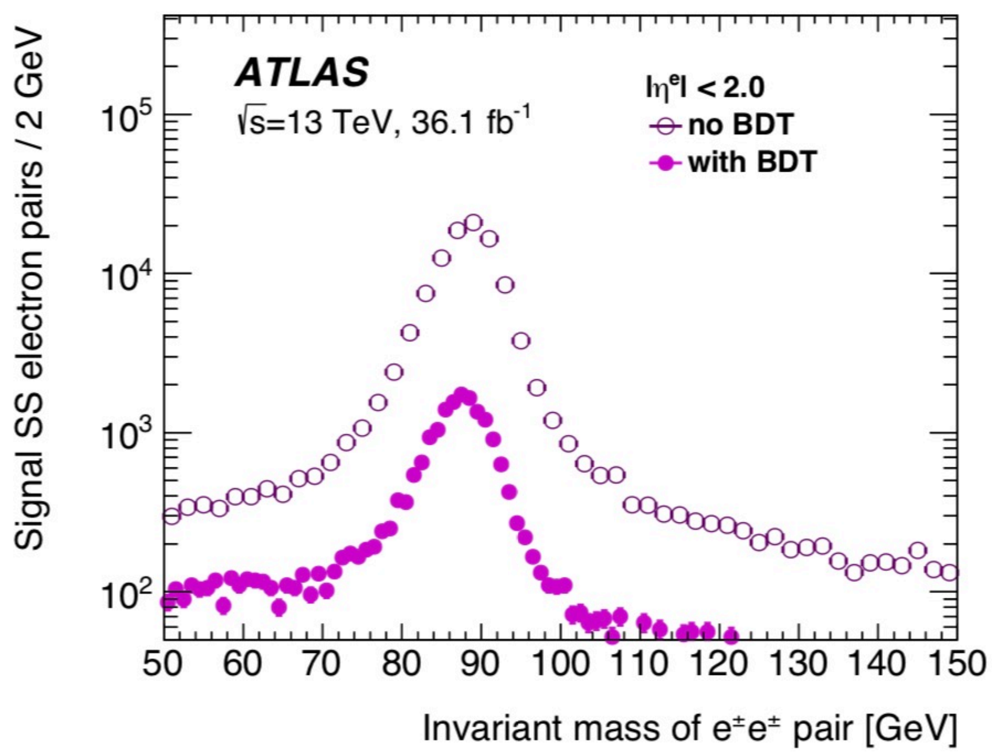
- Hadronic τ are reconstructed from calorimeter cluster and tracking variables.

- Identified using a Boosted decision tree algorithm (BDT)



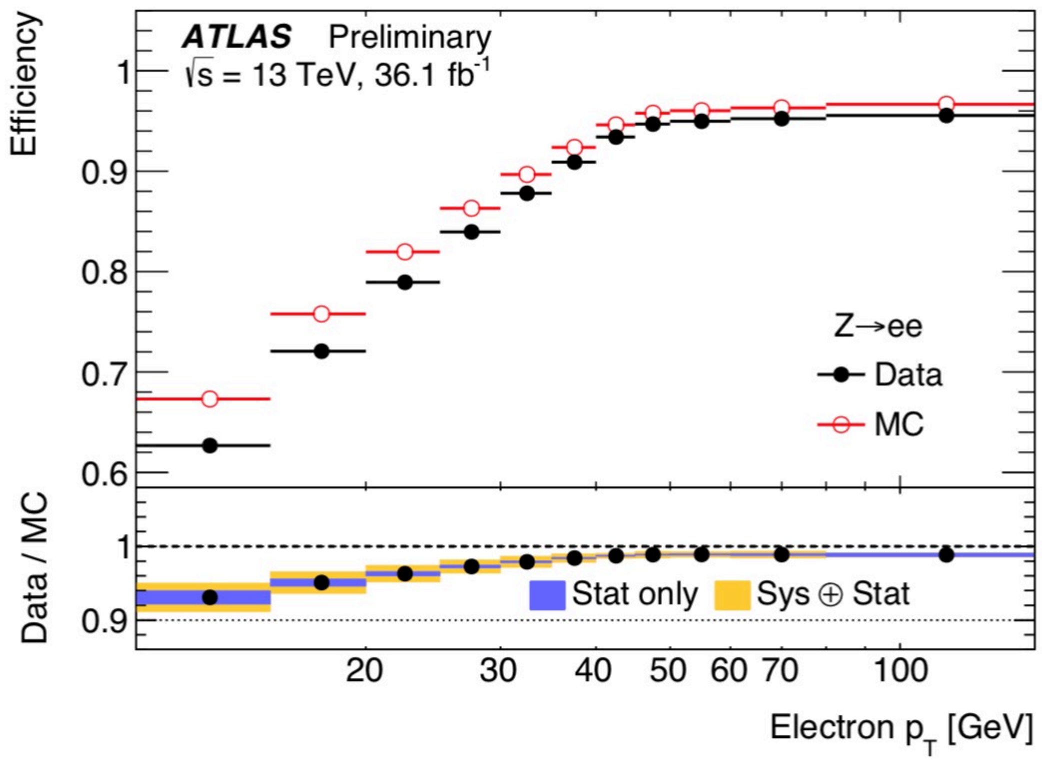


Performance: Leptons



Charge mis-assignment BDT

- Uses calorimeter and track variables associated to electrons
- Factor of 17 reduction in charge flip processes at 95% efficiency



Non prompt lepton BDT

- For electrons and muons
- Uses isolation variables as well as track jet variables (b-tagging algorithms)
- Reduces lepton fraction from B-hadron decays by a factor of 20
- Calibrated in $Z \to l^+ l^-$ events

- These BDT's are only used in multilepton channels