ATLAS EXPERIMENT

Data-driven background estimates in the ATLAS $t\bar{t}H$ multilepton *analysis*

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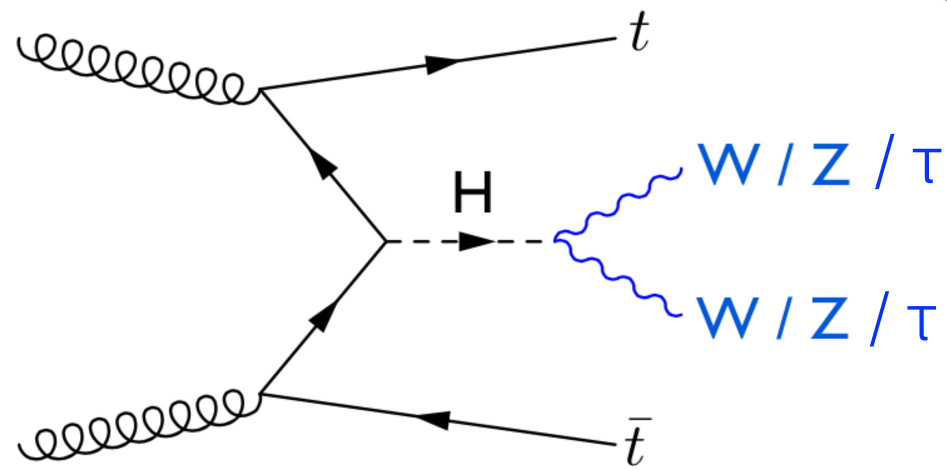
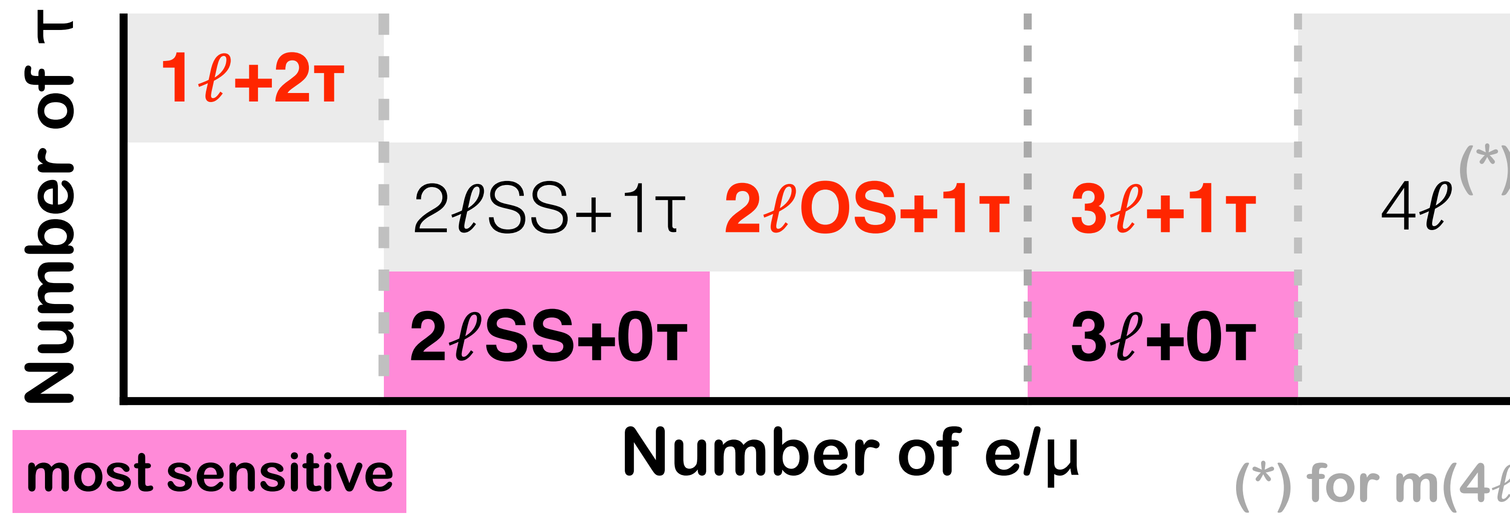
Higgs Toppings workshop
Benasque, Spain - 28/05/18

$t\bar{t}H$ (multileptons): analysis strategy



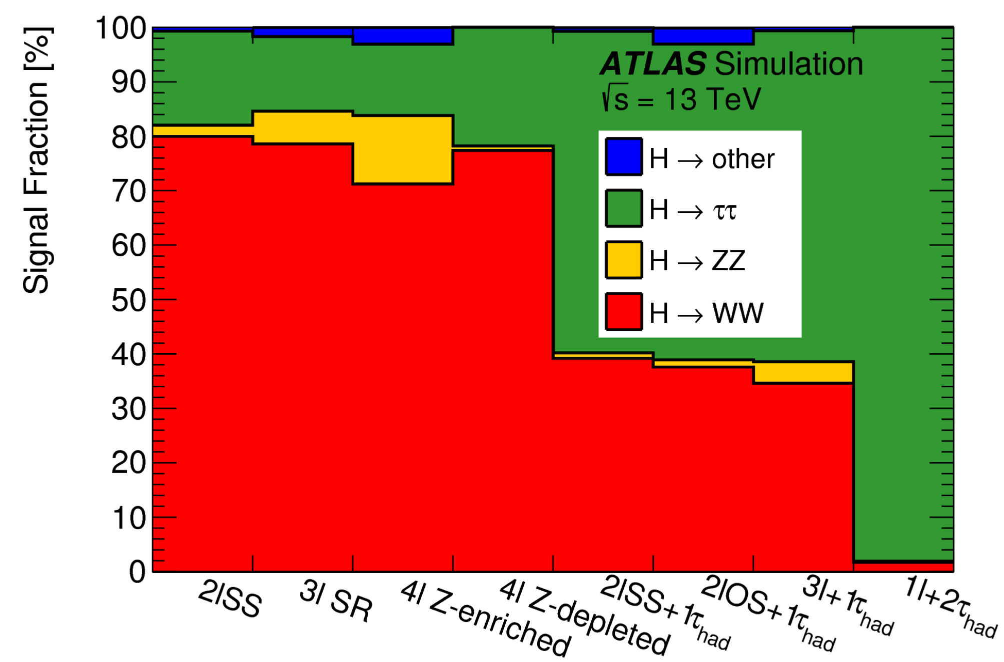
- **Target**: $t\bar{t}H$ with
  - H→WW/ZZ/ττ→≥1ℓ
  - $t\bar{t}$→(ℓ+jets, dilepton)



(*) for m(4ℓ) != Higgs mass window

- **High multiplicity** final state
- **Rare in SM:** same-sign 2ℓ, 3ℓ, 4ℓ
  - Exploit presence of hadronically decaying τ

- Split in categories based on **number of e/μ** and **number of τ**
  - **Loose** lepton definition (no isolation, loose ID)
  - Dilepton and single lepton triggers



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$t\bar{t}H$ (multileptons): background composition

* **Non-prompt** lepton in $t\bar{t}$
  - semileptonic b-decay
  - γ conversions

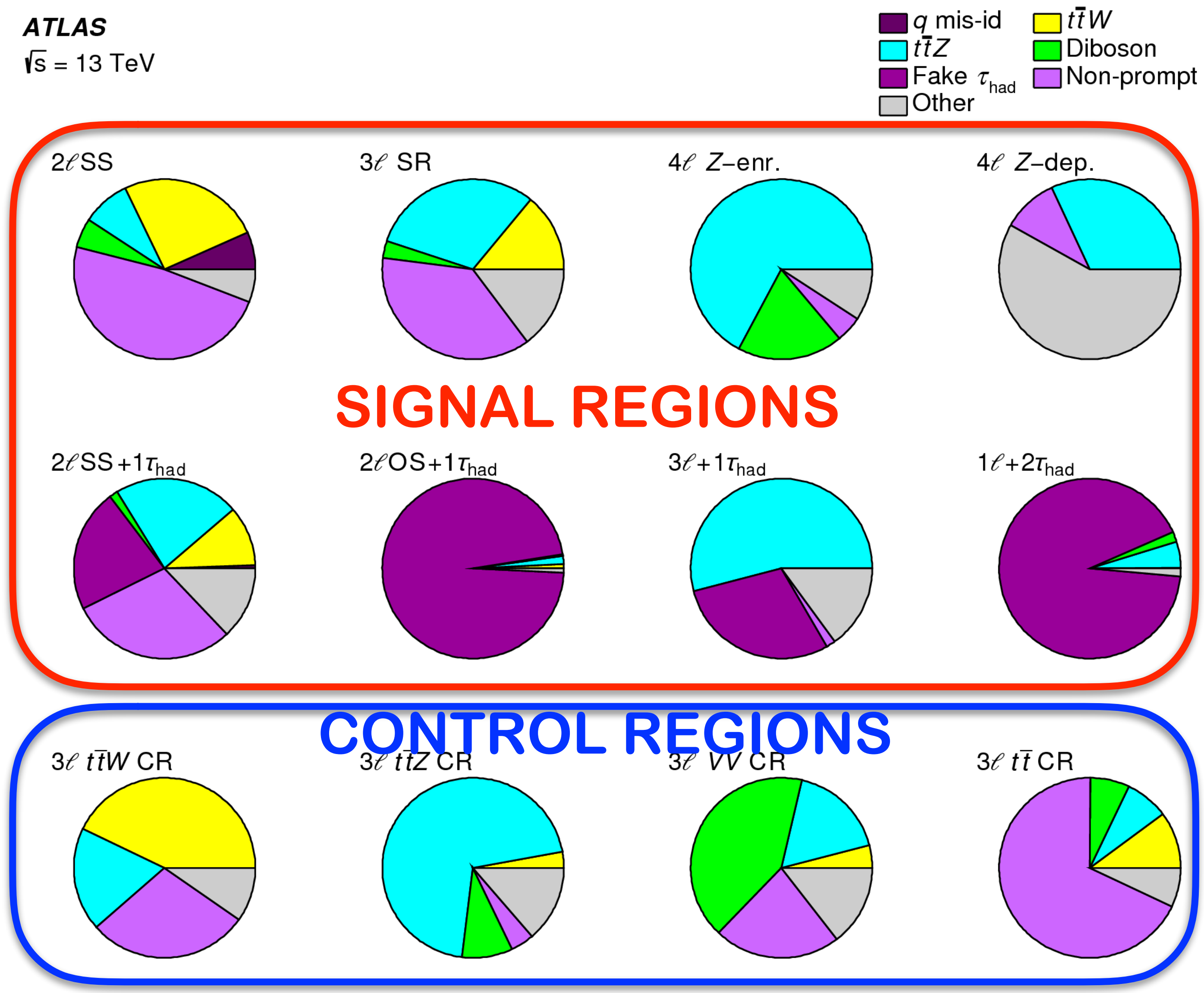
* **Fake τ** from light/b-jets

DATA-DRIVEN (DD): MATRIX METHOD (MM), FAKE FACTOR (FF)

FF ~ matrix method except prompt background is taken from MC

* **Misidentified charge** lepton
  - e.g. trident electrons (Bremsstrahlung)
  - using **3D likelihood method** [pT, η, Tight/Loose]

DATA-DRIVEN (DD): LIKELIHOOD FIT



* **Irreducible backgrounds** with prompt-leptons ($t\bar{t}Z$, $t\bar{t}W$, VV)

MC (cross check: fit to data)

"Other": 4tops, $t\bar{t}WW$, tH, tZ

Important aspects of the ttH-ML analysis

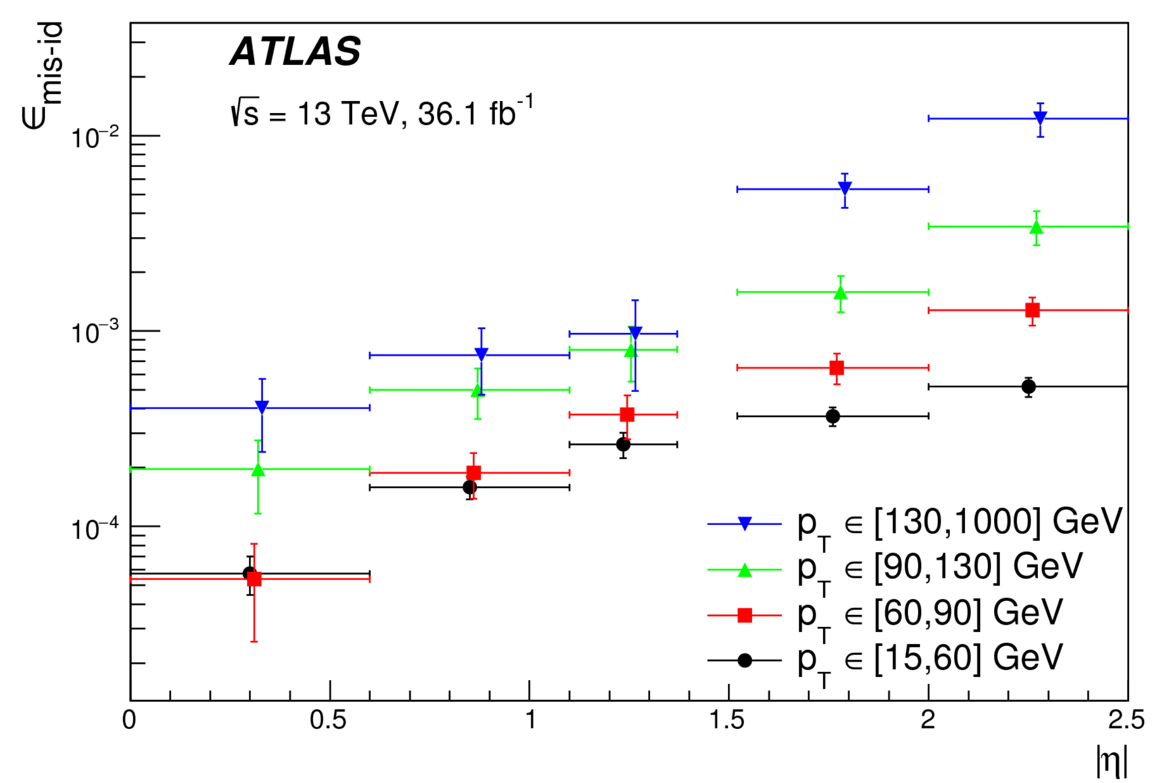
- ... that condition which type of data-driven method we should use and which type of fakes will be most dominant:
  - **Object definition**
    - Lepton MVA-based isolation (PromptLeptonIso) to reject non-prompt ℓ from semileptonic b-decay based on:
      - lepton and overlapping **track jets** properties
      - lepton track/calorimeter **isolation** variables
    - Lepton MVA to reduce charge misidentification background (QMisID) for 2ℓSS and 3ℓ+0τ electron channels
    - These changes the:
      - Composition of the fakes lepton background we need to estimate
  - **Analysis strategy**
    - Event MVA discriminant used in the final fit for the most sensitive channels
    - Need a data-driven method that provides a correct modelling of the shape of the fakes contribution (with complete set of uncertainties!)
- Unavoidable consequence of analysing **more data**
  - Smaller statistical uncertainty in the estimate, but
  - Flaws of assumptions / simplifications in the DD methods become a problem

QMisID estimate

- Estimate QMisID background from data using SS electrons under Z-peak
- Using **3D likelihood method** [p_T, η, Tight/Anti-tight]

high p_T ➜ straighter track ➜ higher chance of QMisID	high η ➜ more material ➜ more trident electrons	needed to provide input to Matrix Method (QMisID subtraction) + increase statistics (consider tight+antitight events)

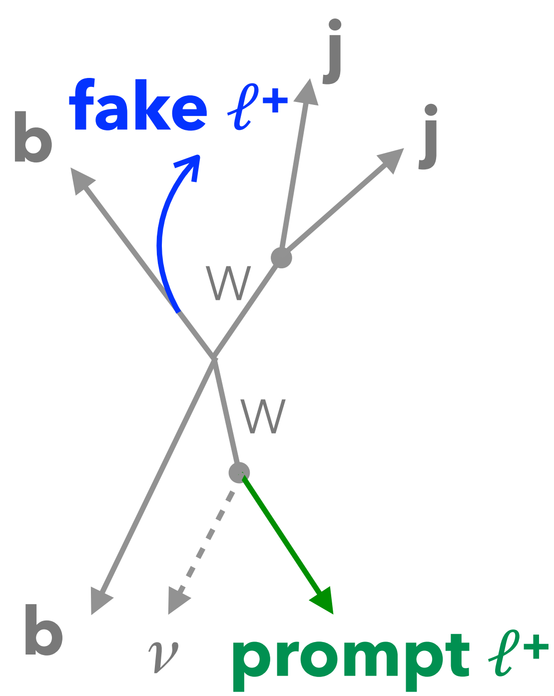
- Obtain QMisID rates $\varepsilon_{mis\text{-}id}$ by minimising a global likelihood function in a sample of Z➜ee events reconstructed as SS or OS pairs
  - The background is subtracted using a sideband method
- Scale OS data events by this rate
- Total systematic uncertainty **~30 %**
  - Dominated by closure test uncertainty at low p_T and by statistical uncertainties at high p_T



Non-prompt light ℓ

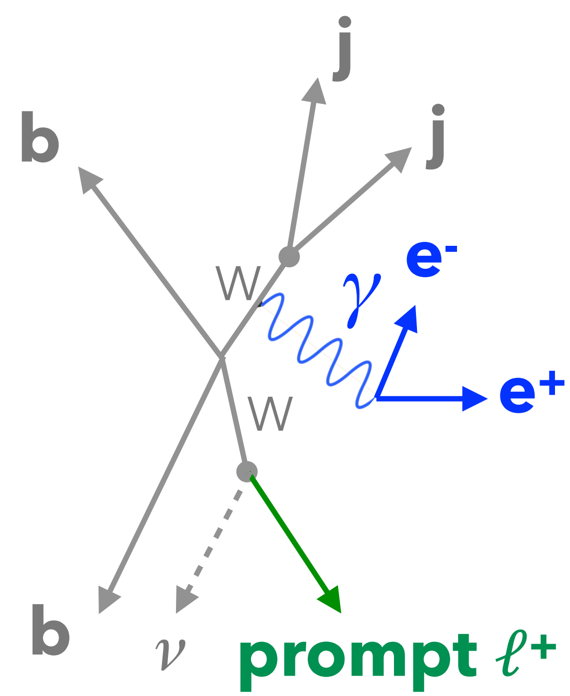
Method [parametr.]	2ℓSS+0τ			3ℓ+0τ	4ℓ	2ℓSS+1τ	Other τ channels
Non-prompt lepton	**DD (MM)** el: [p_T, NBjets] μ: [p_T, dR(μ,j)]				pseudo-DD (Fake SF)	**DD (FF)** el/μ: [p_T]	**MC** (very small)
DD/MC	ee: 2.0±0.5	eμ: 1.7±0.4	μμ: 1.5 ±0.5	SR: 1.8 ± 0.8			

Semileptonic b-decay



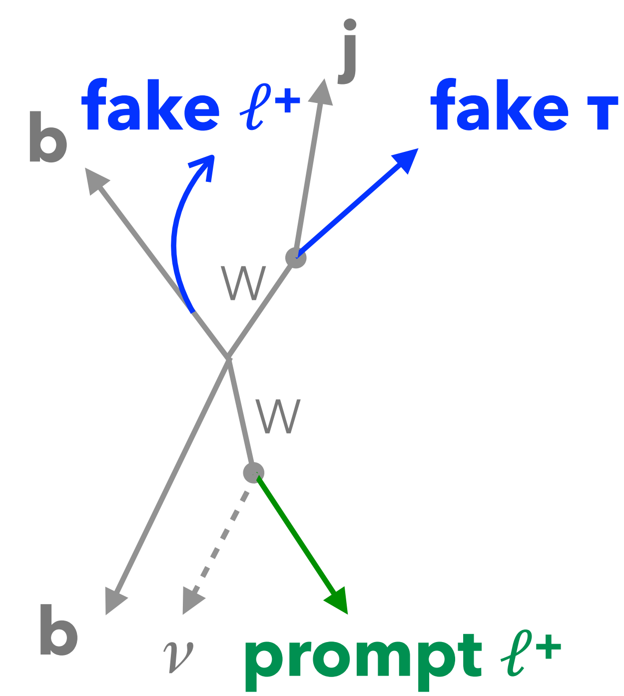
strongly reduced with PLI

Photon conversions



50% of the "fakes" in 3ℓ!

Non-prompt lepton & fake τ



70% from $t\bar{t}$ in 2ℓSS+1τ

Non-prompt light ℓ: Matrix Method

2ℓSS/3ℓ+0τ: Matrix Method

events in pre-MVA signal region with SS **loose** leptons
(in 3ℓ, lep_0 (OS to SS pair) is prompt in 98% of the times)

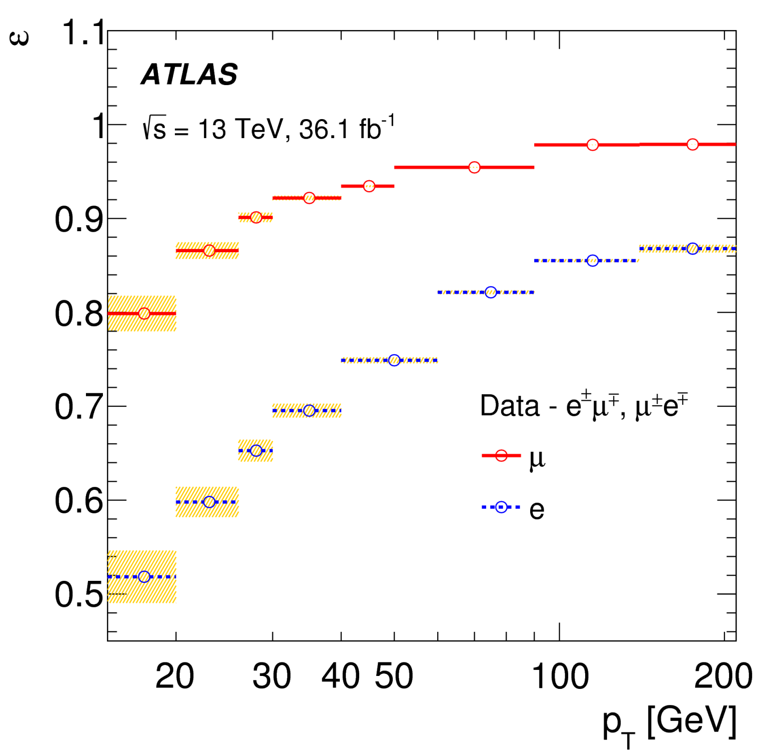
$$N^{f}_{TT} = w_{TT}N^{TT} + w_{\not{T}T}N^{\not{T}T} + w_{T\not{T}}N^{T\not{T}} + w_{\not{T}\not{T}}N^{\not{T}\not{T}}$$

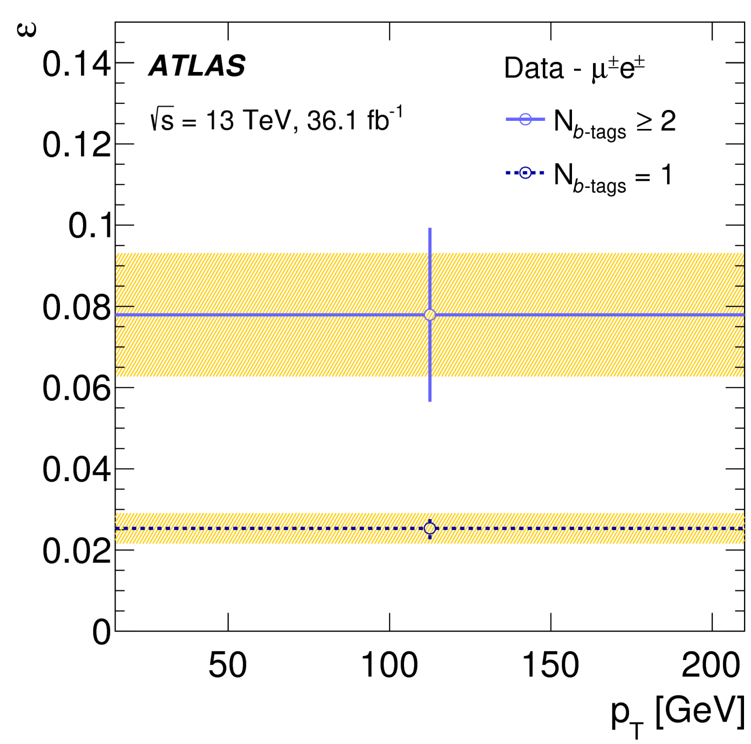
f(ε$_r$, ε$_f$)
via tag&probe method in $t\bar{t}$ events

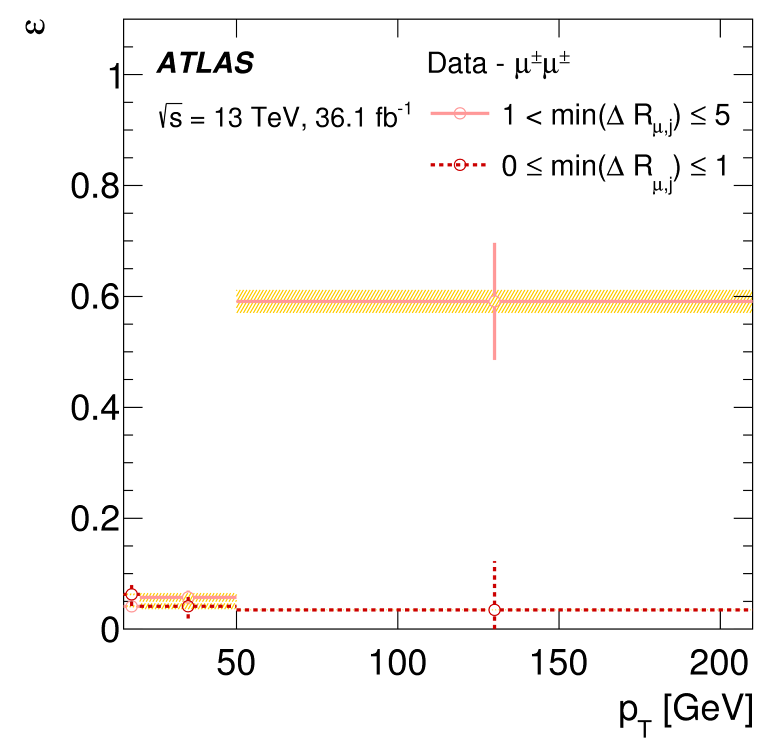
Channel	Region	Selection criteria
2ℓSS		$2 \leq N_{\text{jets}} \leq 3$ and $N_{b\text{-jets}} \geq 1$
(3ℓ)		One very tight, one loose light lepton with $p_T > 20$ (15) GeV
		Zero τ_{had} candidates
	ϵ_{real}	Opposite charge; opposite flavour
	ϵ_{fake}	Same charge; opposite flavour or $\mu\mu$

- **electrons and muons ε$_r$:** 1D (p_T) parametrisation

- **electrons ε$_f$:** 2D ($N_{b\text{-tags}}$, p_T) parametrisation
- **muons ε$_f$:** 2D (minΔR(μ,j), p_T) parametrisation



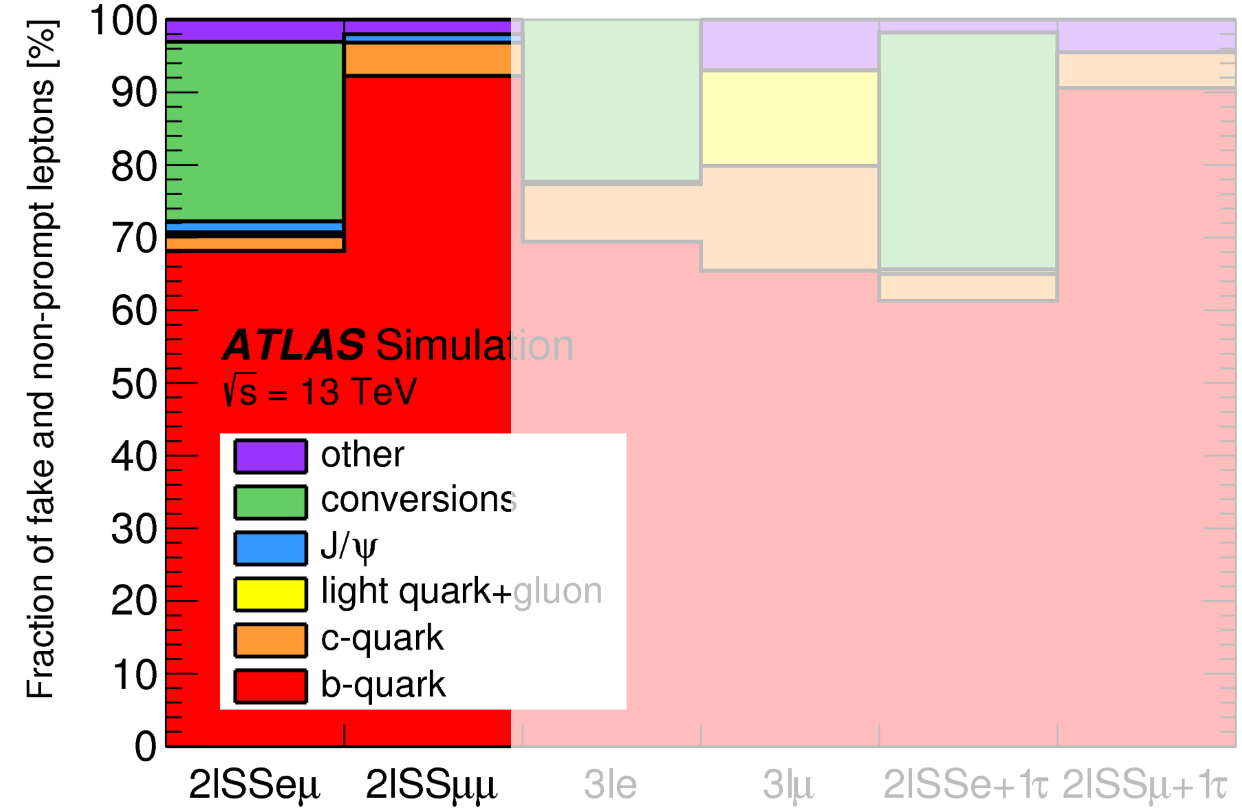




Non-prompt light ℓ: Matrix Method (II)

Treatment of conversions

- $\varepsilon_{f,\gamma}$ significantly higher than $\varepsilon_{f,hf}$
- Account for the change of photon conversion fraction between the CR and SR from simulation
- Use to correct ε_f



- **Systematic uncertainties: 40%**
  - 15% from modelling of conversions in MC
  - 20% from measurement of $t\bar{t}\gamma$
  - 50% from modelling of semileptonic b-decays

Non-closure

- Apply Matrix Method on $t\bar{t}$ MC, compare to $t\bar{t}$ MC prediction
- (11 ± 8)% and (9 ± 18)% non-closure in 2ℓSS and 3ℓ, respectively
- Include non-closure as systematic uncertainty source

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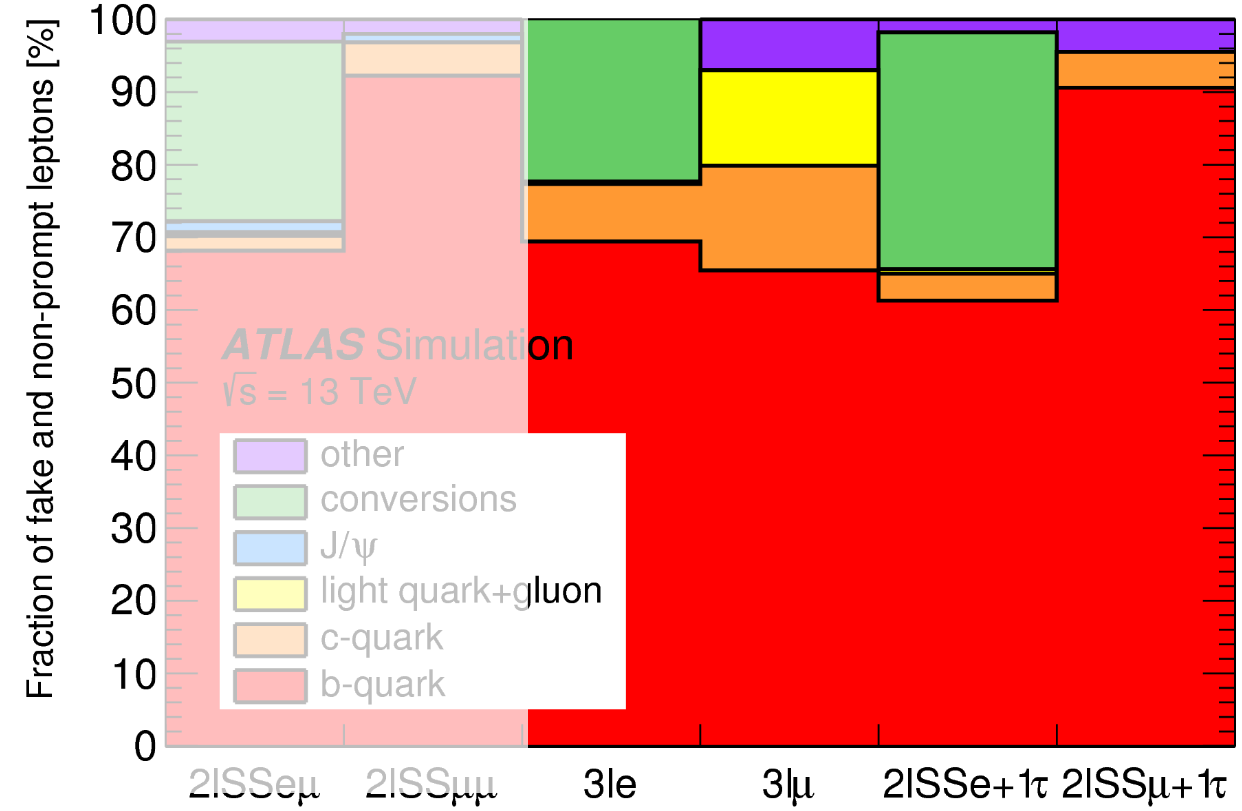
4ℓ and $2\ell SS1\tau$ (light ℓ) fakes estimate

4ℓ

- **Semi data-driven technique**
- Correction factors for MC (λ^{hf}_e, λ^{lf}_e, and λ_μ) measured in dedicated 3ℓ CR (loose leptons, 1-2 jets) split into 4 lepton-flavour categories, from a fit to the leading jet p_T distribution

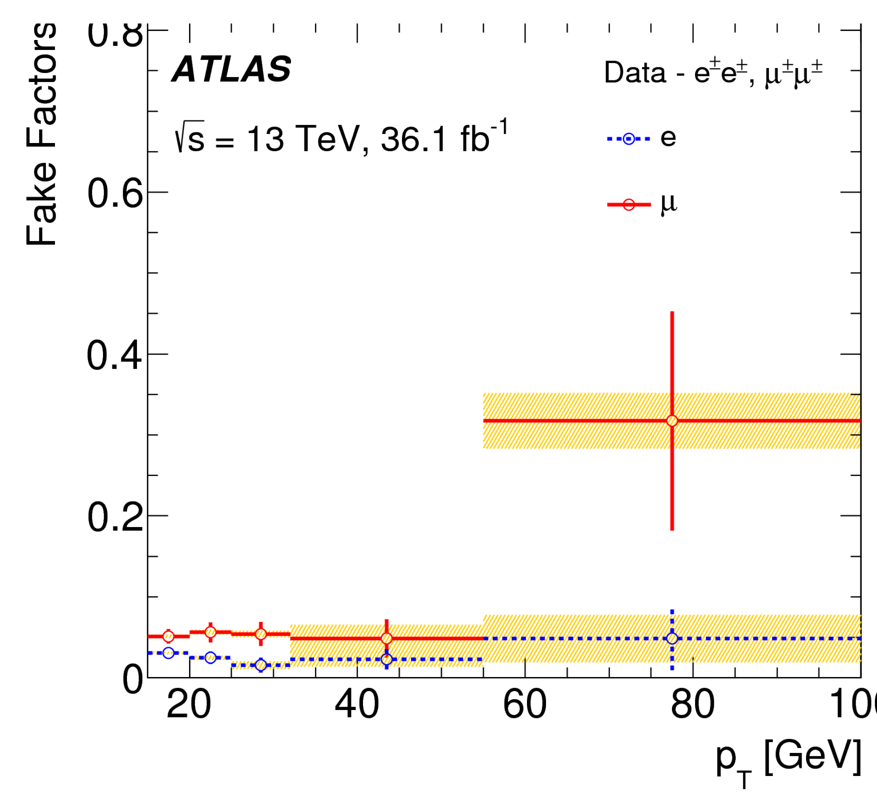
$\lambda^{\mu} = 0.66 \pm 0.19$ $\quad$ $\lambda^{e}_{\text{heavy}} = 1.48 \pm 0.22$

$\lambda^{e}_{\text{light}} = 0.72 \pm 0.53$



$2\ell SS1\tau$

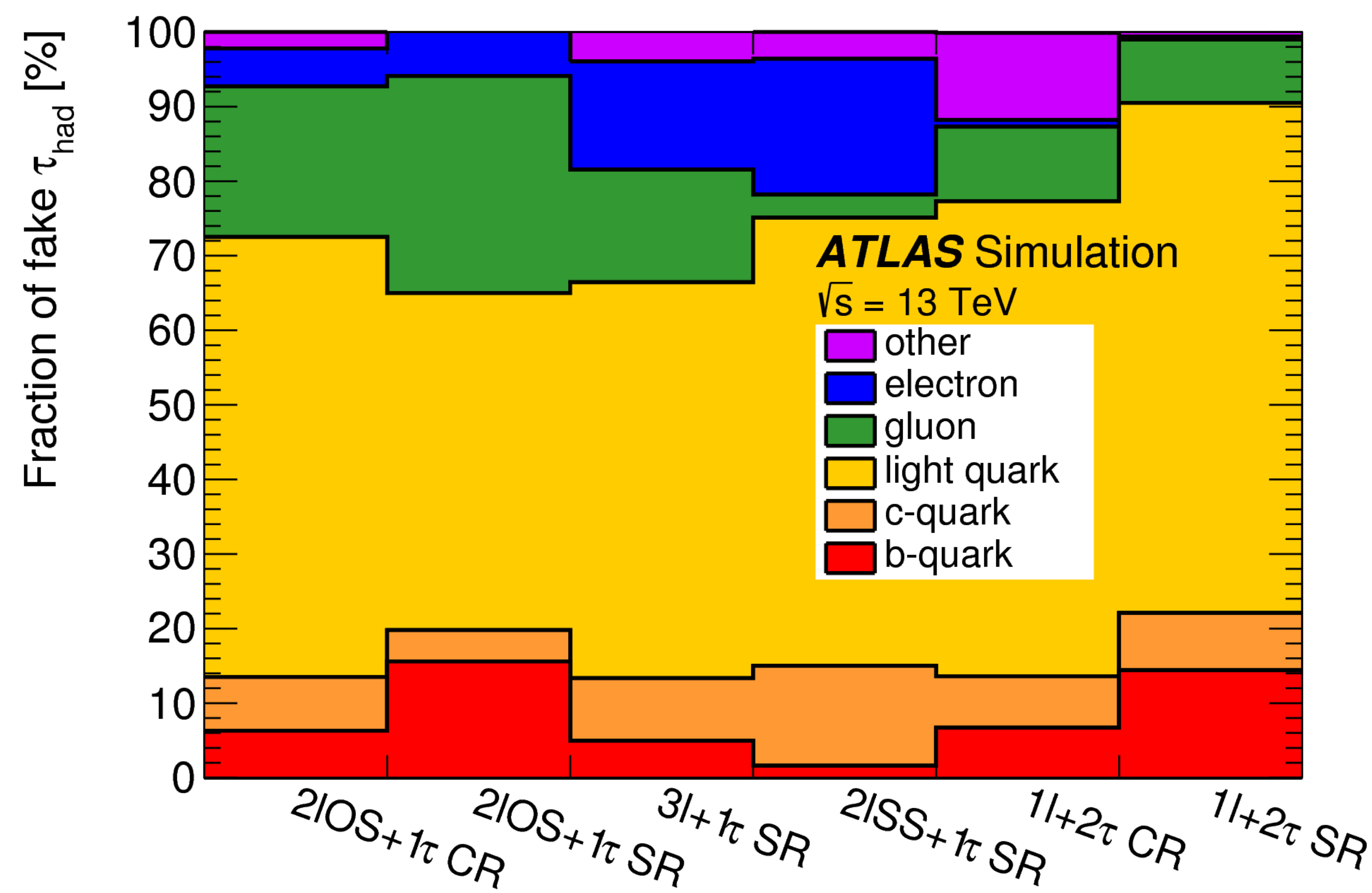
- **Fake-factor method** to estimate background from events containing non-prompt light leptons (and a real or fake tau)
- FF derived from CR differing from SR by **looser lepton requirements and lower jet multiplicity**
- Total systematic uncertainty = 55%, dominated by statistical uncertainty in the closure test on simulation



Fake tau background

Estimate method [parametrisation]	1ℓ+2τ	2ℓOS+1τ	2ℓSS+1τ	3ℓ+1τ
Fake tau	DD (SS data)	DD (FF) [p_T]	pseudo-DD (MC correction with 2ℓOS+1τ DD SF)	

- **1ℓ+2τ:** mostly $t\bar{t}$ with 1 or 2 fake τ
  - Estimated from data in CR with same definition as SR but SS taus
  - Closure uncertainty < 30%
- **2ℓOS+1τ:** fake factor
  - Mainly $t\bar{t}$ with jet faking τ
  - Fake rates parametrised in τ pT
- **2ℓSS+1τ and 3ℓ+1τ:** MC correction with SF derived from **{DD(2ℓOS+1τ) / MC}**
  - Harmonised 1-fake-τ estimate for all channels, profit from large statistics from 2ℓOS+1τ
  - Final SF = 1.36 ± 0.16



Data-driven fake estimate uncertainties

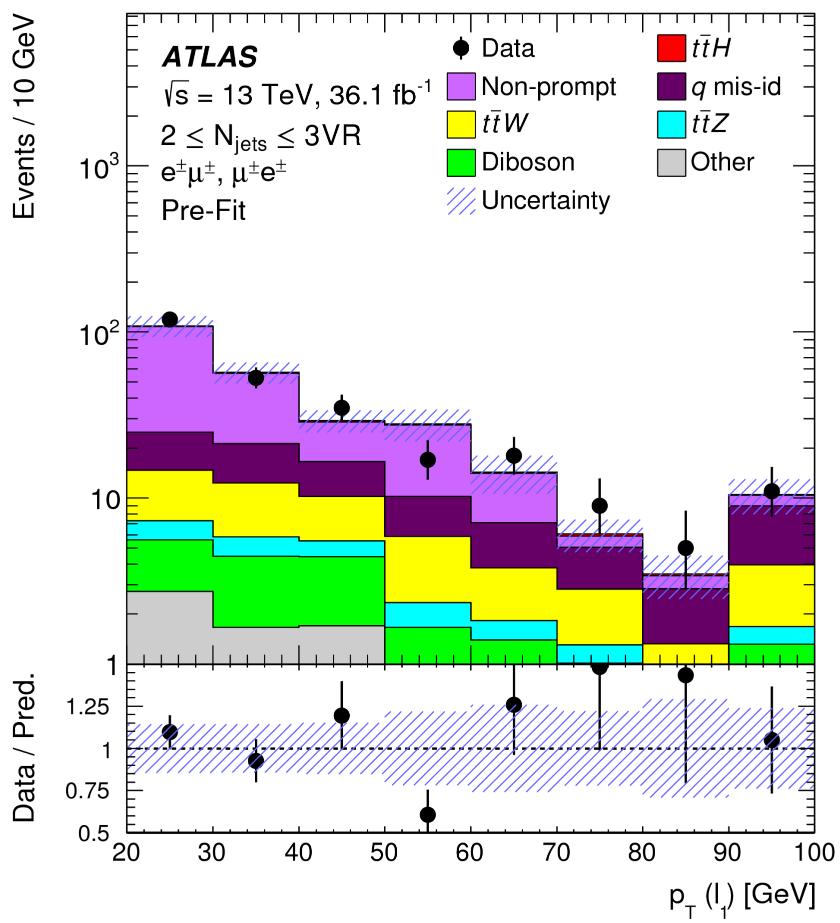
Data-driven non-prompt/fake leptons and charge misassignment		
Control region statistics	SN	38
Light-lepton efficiencies	SN	22
Non-prompt light-lepton estimates: non-closure	N	5
γ-conversion fraction	N	5
Fake τ_{had} estimates	N/SN	12
Electron charge misassignment	SN	1
Total (Data-driven reducible background)	–	83

- **Light lepton efficiencies:**
  - real eff (1), fake eff (6 μ, 2 el, 3 prompt background subtraction theory uncertainties), 4ℓ fake rate (1), 2ℓSS1τ (10)
- **γ conversion fraction and non-closure uncertainties:**
  - Uncorrelated across channels (ee, eμ, Xee, Xeμ, 2ℓSS1τ), affecting only normalisation
- **Electron charge miss assignment:**
  - Anti-correlated among background in SR and subtraction from fake rate calculation

Fakes/non-prompt ℓ validation

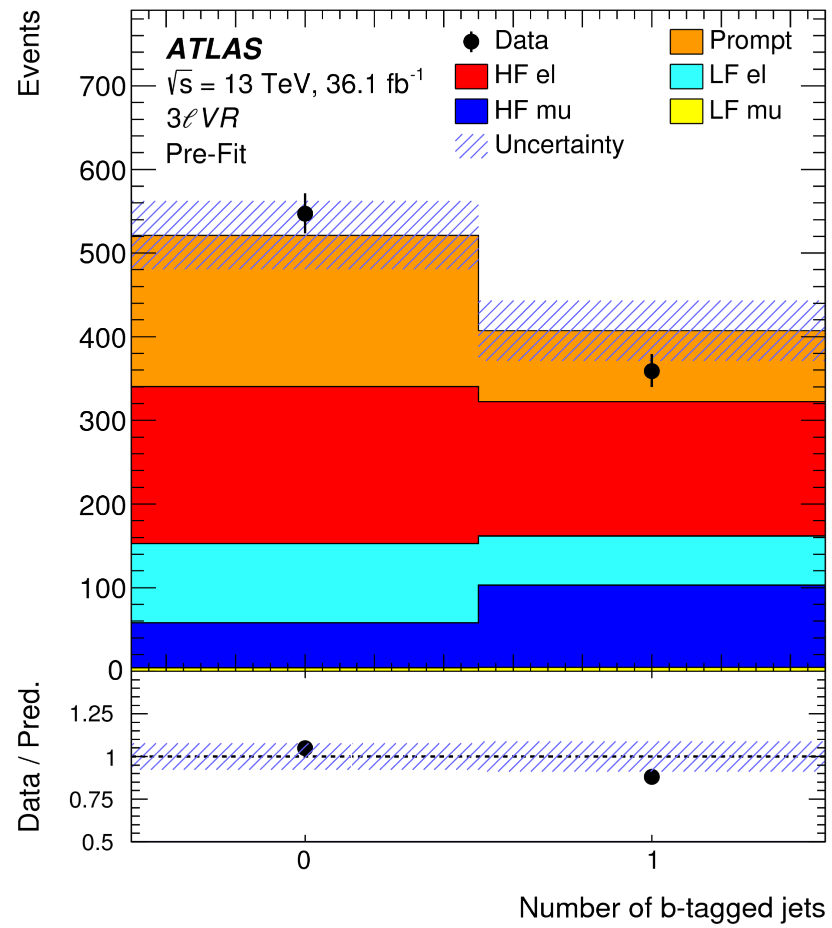
- Overall **reasonable data/prediction agreement** with estimates fakes in VRs

"Low N_{jets}"
$2 \leq N_{jets} \leq 3$, $N_{jets} \geq 1$



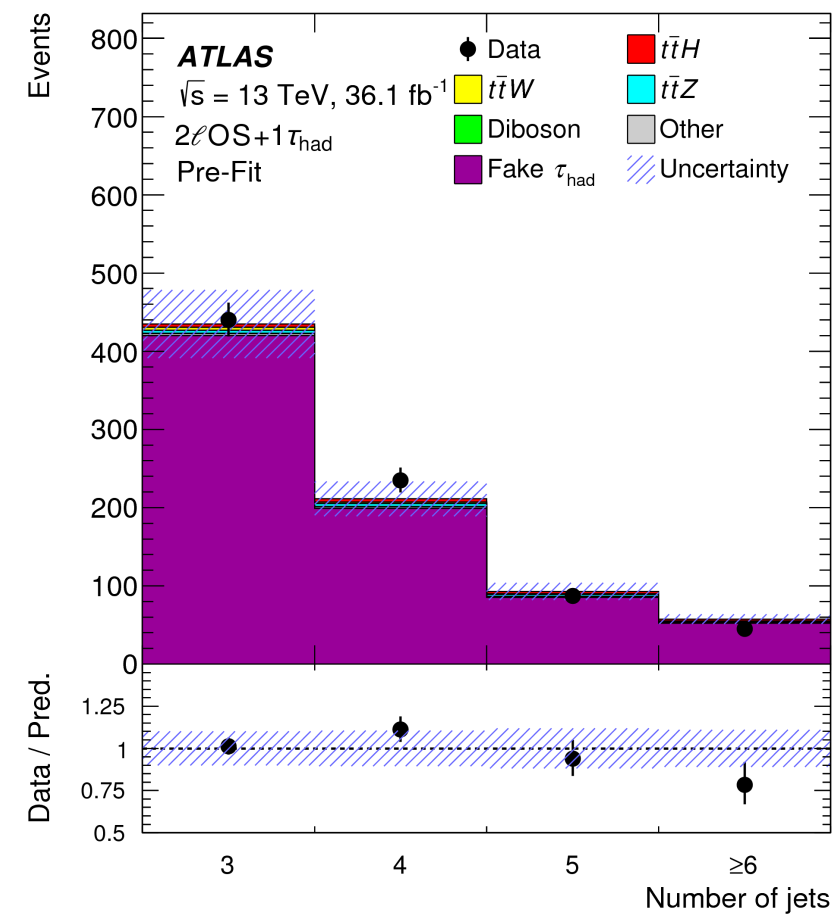
2ℓSS+0τ fake ℓ

"3 loose light ℓ"
$N_{jets} \geq 3$



4ℓ fake ℓ

"Pre-selection"
$N_{jets} \geq 3$



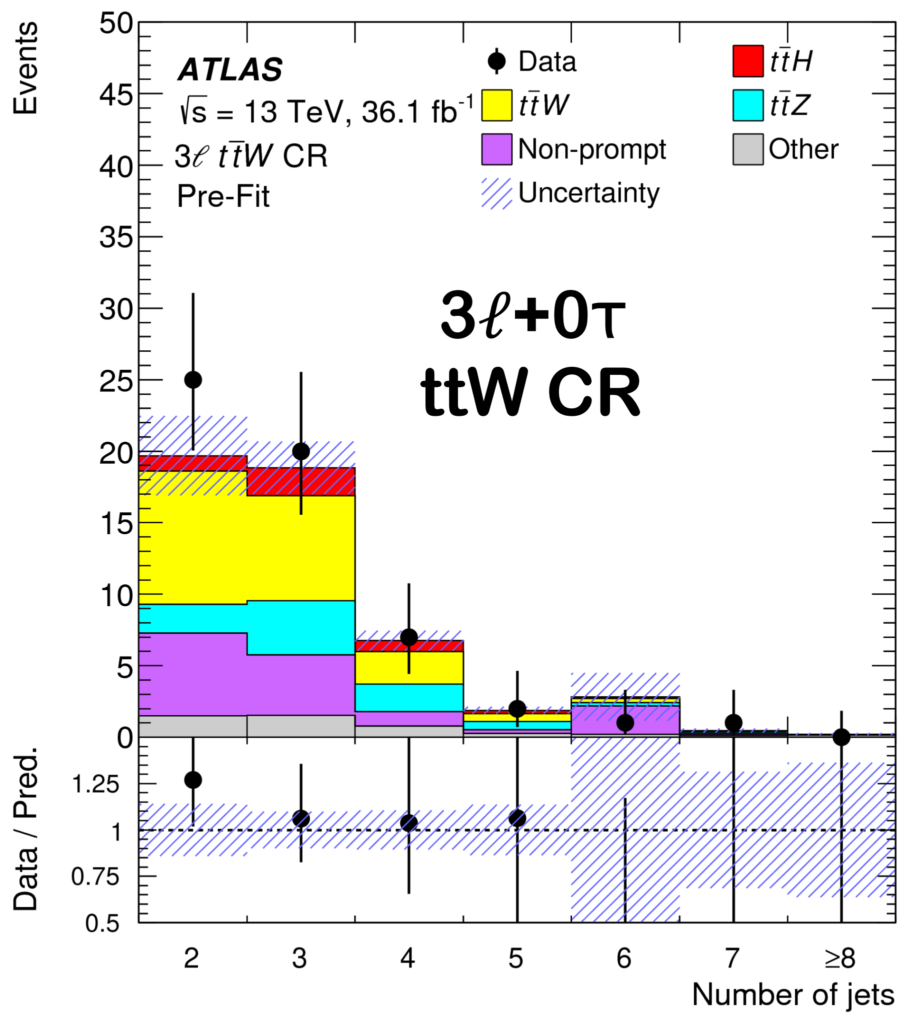
2ℓOS+1τ fake τ

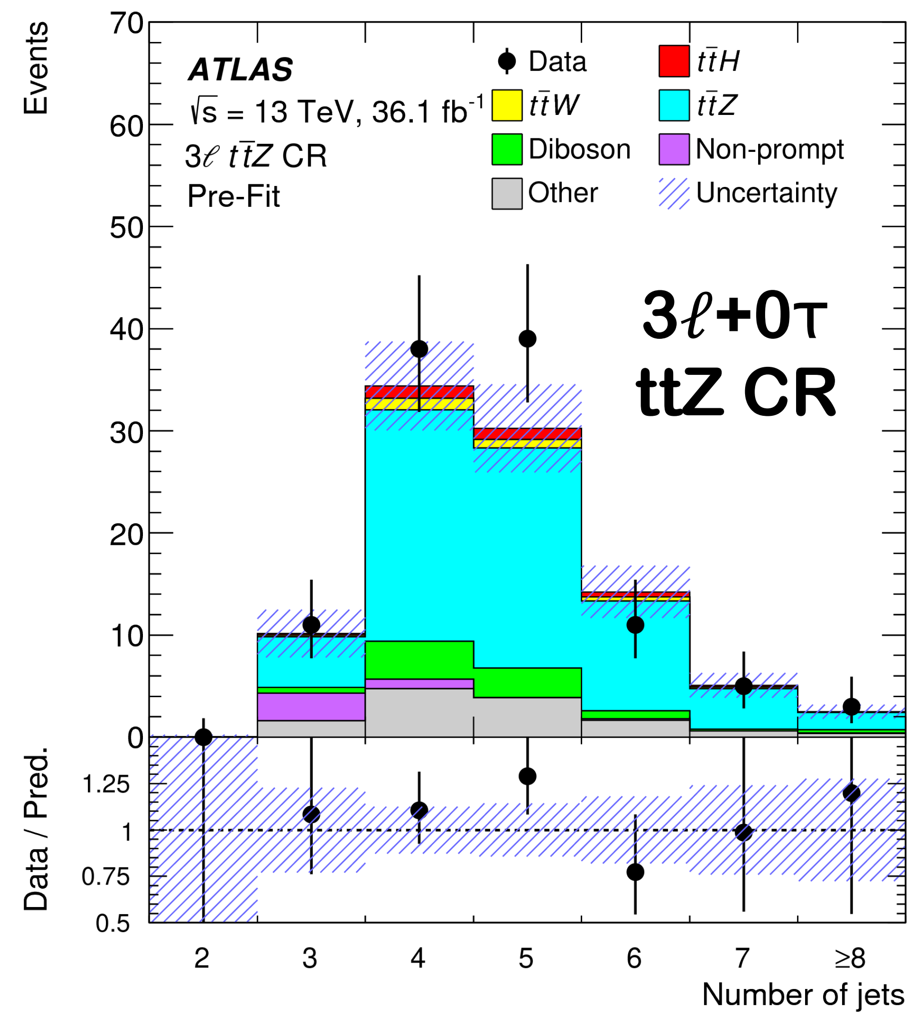
$t\bar{t}V$ background modelling

- The $t\bar{t}W$ and $t\bar{t}Z$ processed have only recently been observed
  - Their properties are not yet fully understood
  - Nor its behaviour in **higher jet multiplicity final states** such as $t\bar{t}H$ SR
- When possible, **design CRs** enriched in this background
  - Difficult to have ttV-enriched CR in the high Njet region but with low signal contamination!
- In the last result:
  - **3ℓ CRs** enriched in $t\bar{t}Z$ (~70% purity) and in $t\bar{t}W$ (~45% purity) included in the fit
    - 5-dimensional multinominal BDTs mapped to 5 categories ($t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$, VV)
  - **Alternative-fit**: $t\bar{t}Z$ and $t\bar{t}W$ normalisation free-floating
    - 15% loss in sensitivity: $\mu(t\bar{t}H) = 1.57^{+0.57}_{-0.50}$
    - $\mu(t\bar{t}Z/W)$ in agreement with SM: $\mu_{t\bar{t}W} = 0.92 \pm 0.32$; $\mu_{t\bar{t}Z} = 1.17^{+0.25}_{-0.22}$

Prompt ℓ background validation

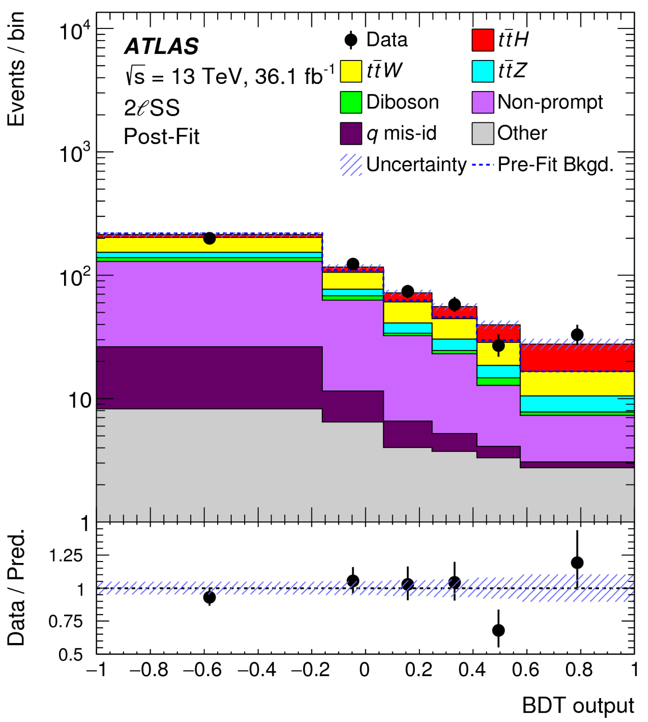
- Overall **good data/prediction agreement** in $t\bar{t}V$-enriched CRs using MC simulation
  - Also good agreement in cut-based VRs



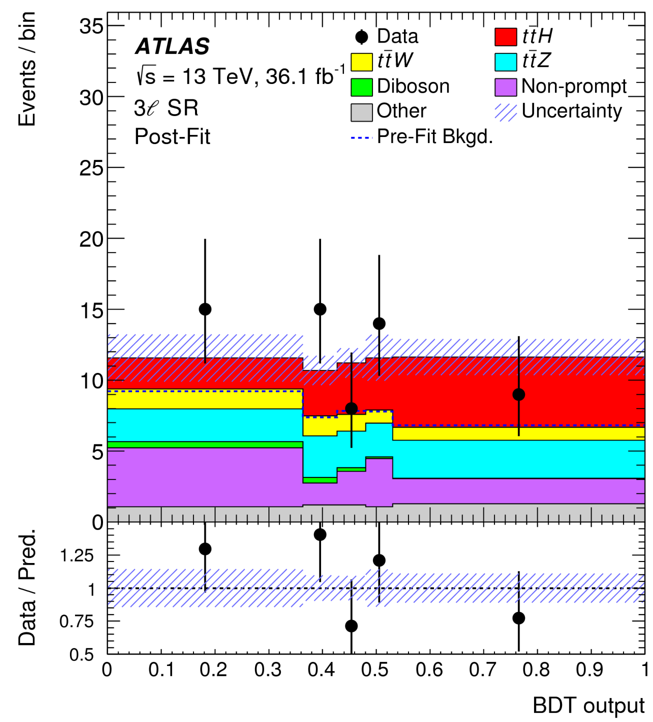


Post-fit signal regions

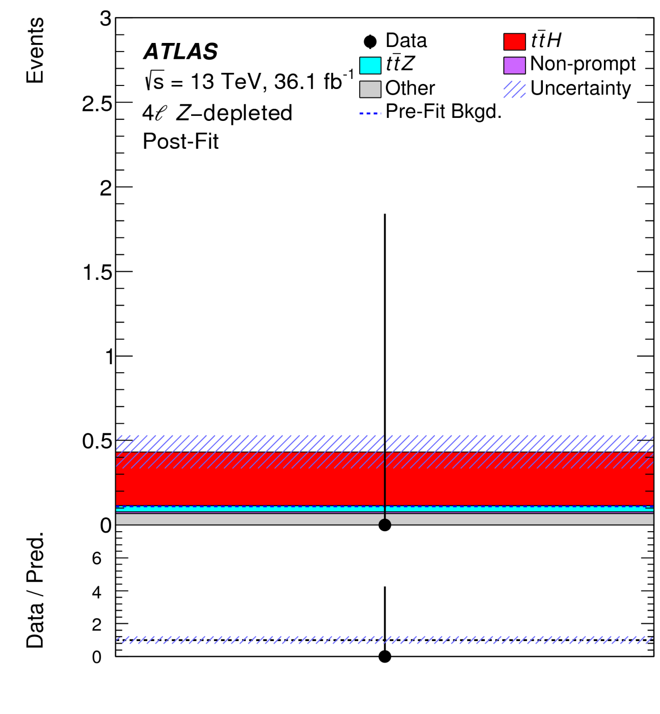
2ℓSS+0τ



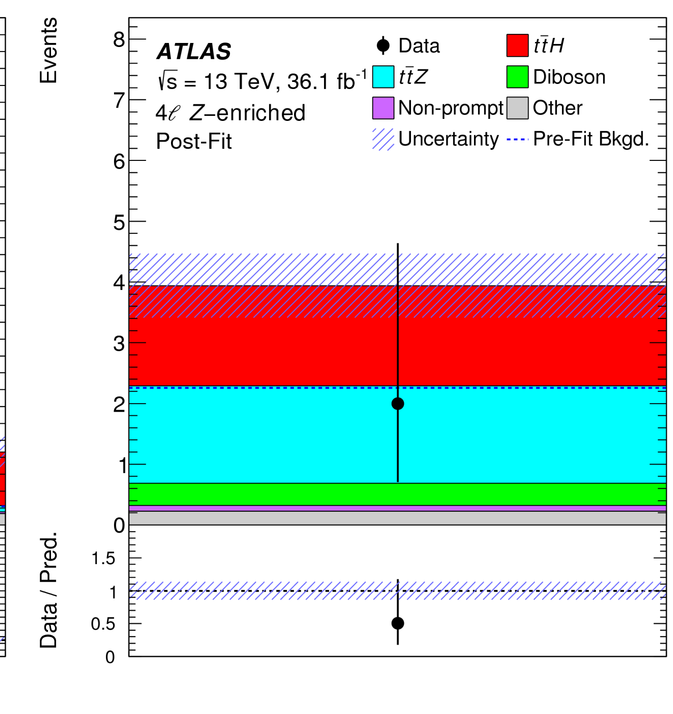
3ℓ+0τ



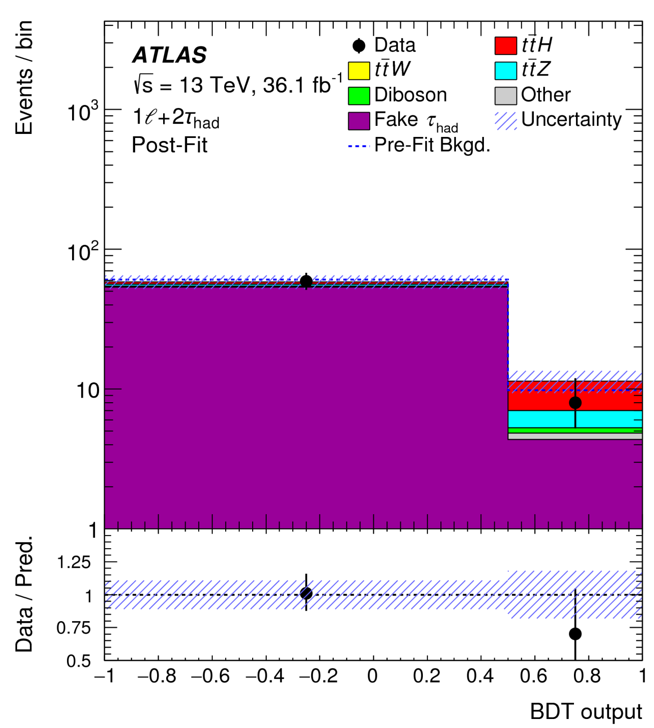
4ℓ (Z-depleted)



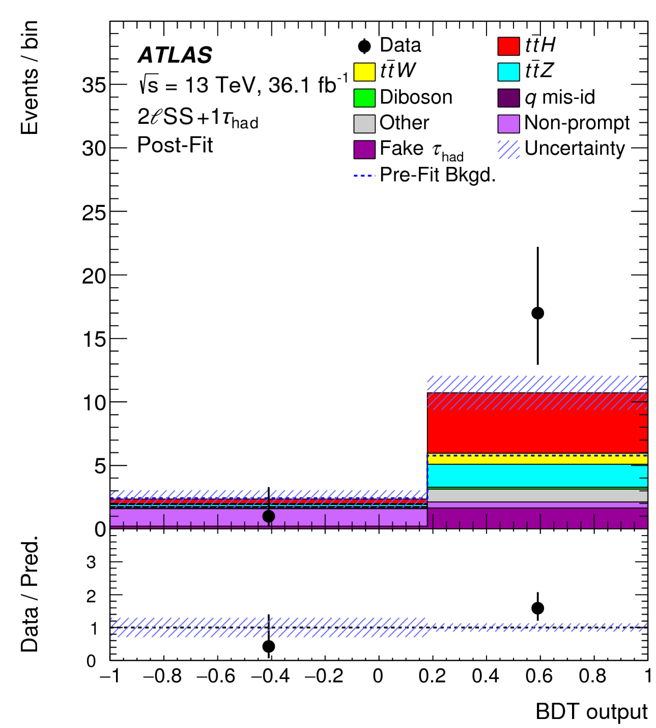
4ℓ (Z-enriched)



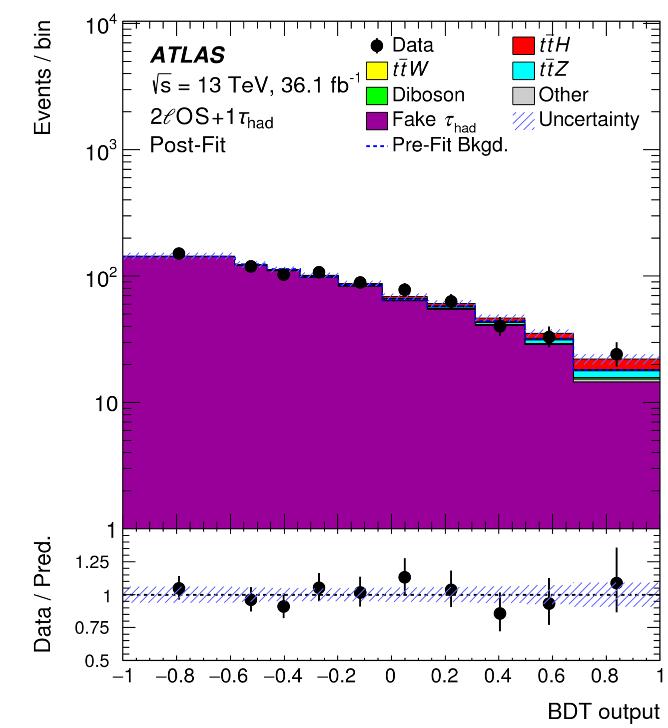
1ℓ+2τ



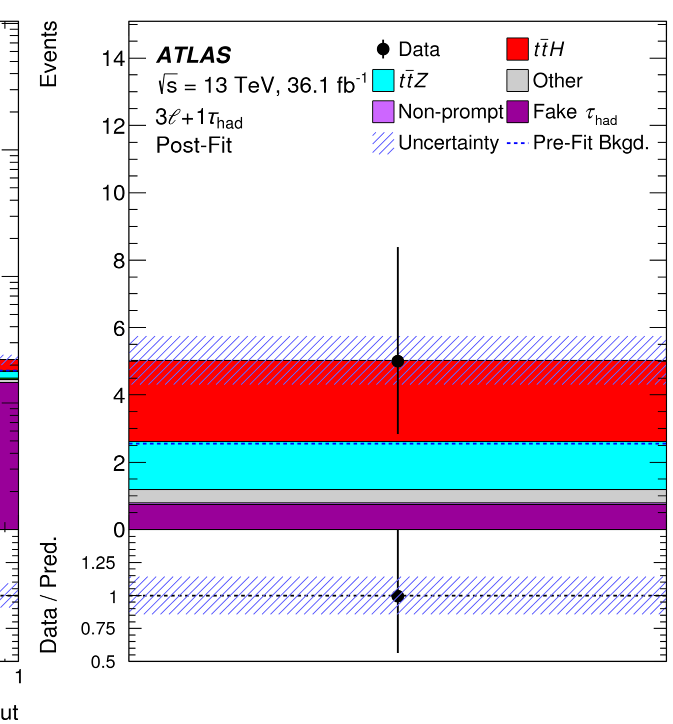
2ℓSS+1τ



2ℓOS+1τ



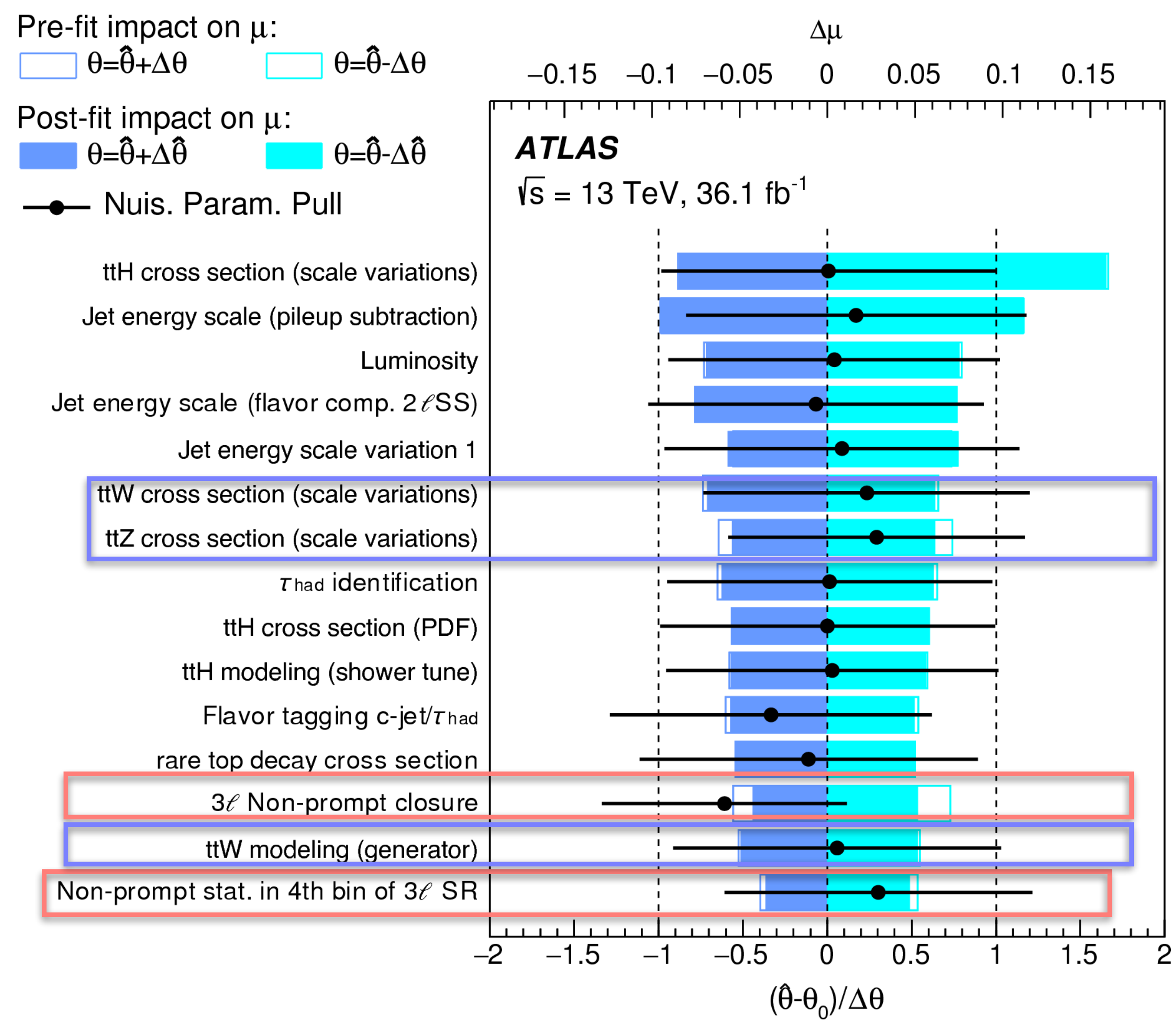
3ℓ+1τ



Impact of DD systematic uncertainties

- **Non-prompt light ℓ estimates uncertainties** ranked as **3rd** group of systematics with the largest impact on the signal strength measurement
- $t\bar{t}W$ and $t\bar{t}Z$ **theory** modelling uncertainties also have an important impact on the signal strength
- **No major constraints or pulls** of nuisance parameters

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



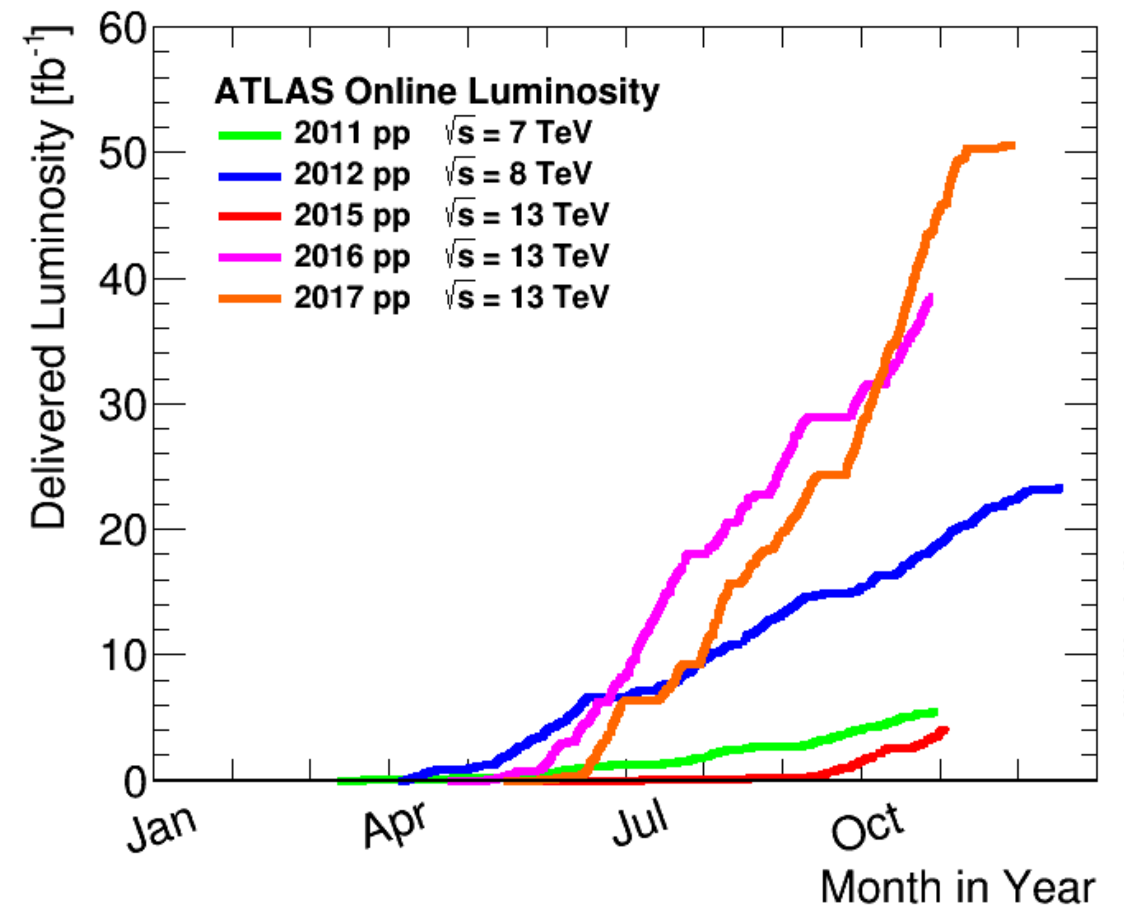
Questions to CMS

- why did the light lepton fake estimate go down by ~30% in the updated version of the results?
- how do you exactly use the FF method to provide an MVA-shape-dependent estimate in each SR? How do you treat correlations between bins?
- what is the DD/MC ratio in each channel for fake light lepton estimates? (CMS DD estimates are in general significantly lower than ATLAS' per channel)
- is the conversion type in the CR similar to the SR?
  - " The small remaining background is modelled using the MC simulation. The validity of the simulation has been verified in control regions (CRs) in data."
- fake taus taken from MC without any correction? where do you validate this assumption?
- provide ranking of nuisance parameters impact on the signal strength measurement
- provide plots with pulls and constraints of nuisance parameters

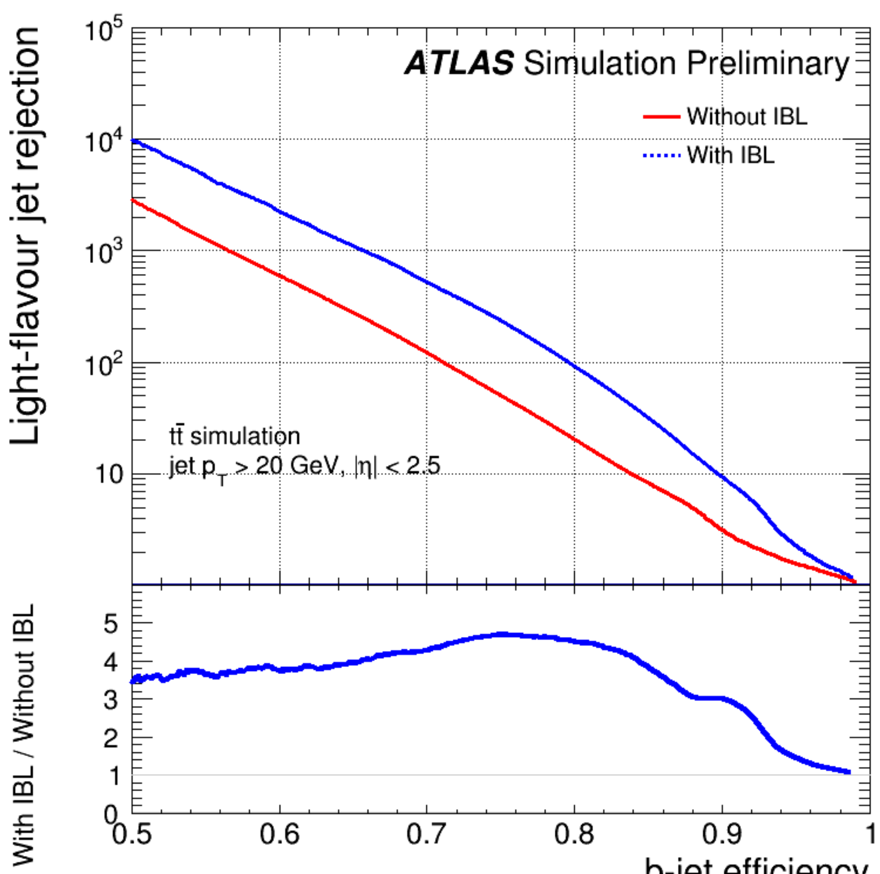
Back-up slides

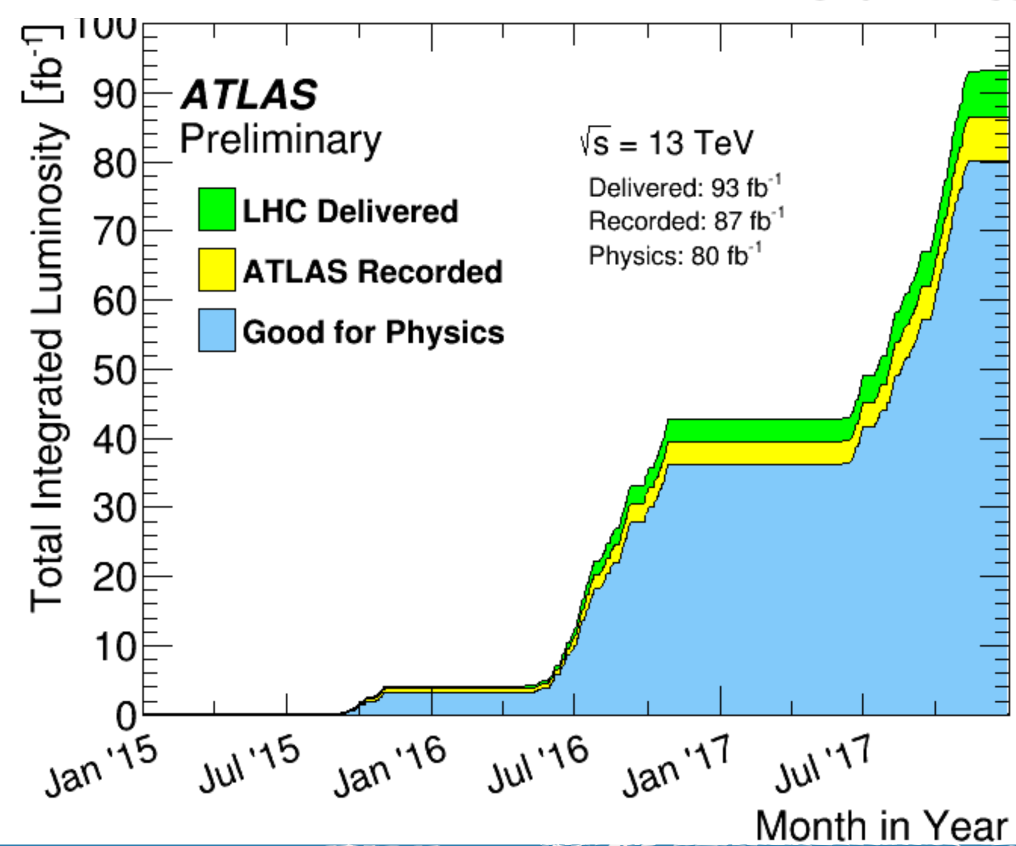
Detector performance (I)

- **Excellent performance of LHC and ATLAS in Run 2 so far**:
  - Record instantaneous luminosity for pp interactions in 2017: 2.06×10^{34} cm^{-2}s^{-1}
    - **double** the LHC design!
  - 80 fb^{-1} good for physics from 87 fb^{-1} recorded by ATLAS



- **Improved b-tagging** performance with the inclusion of **IBL (Insertable B-Layer)** for Run 2

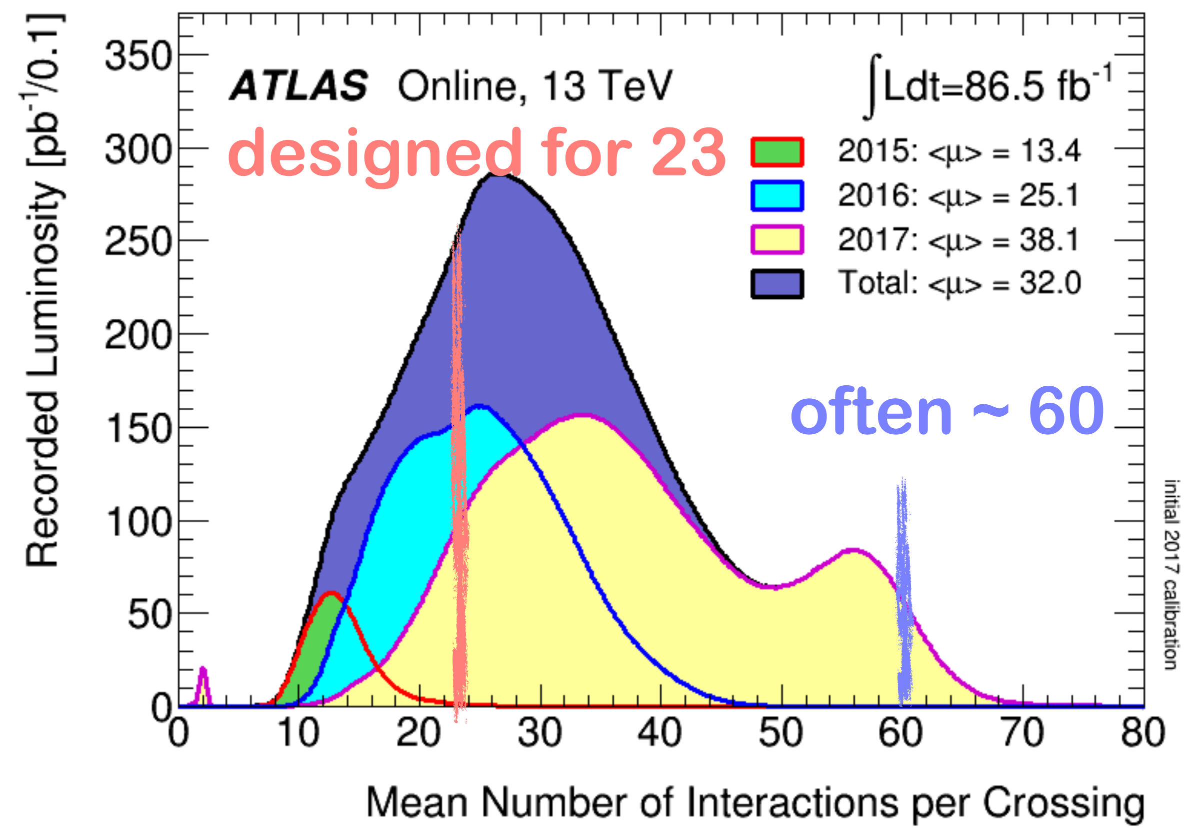




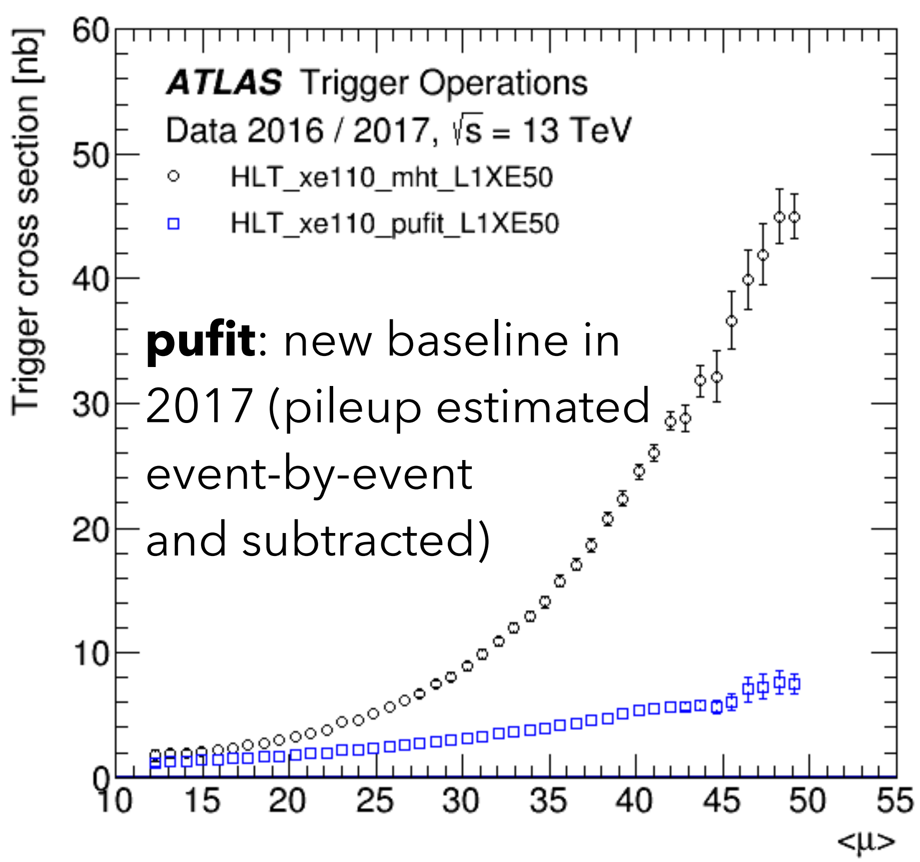
http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/FTAG-2017-005/

Detector performance (II)

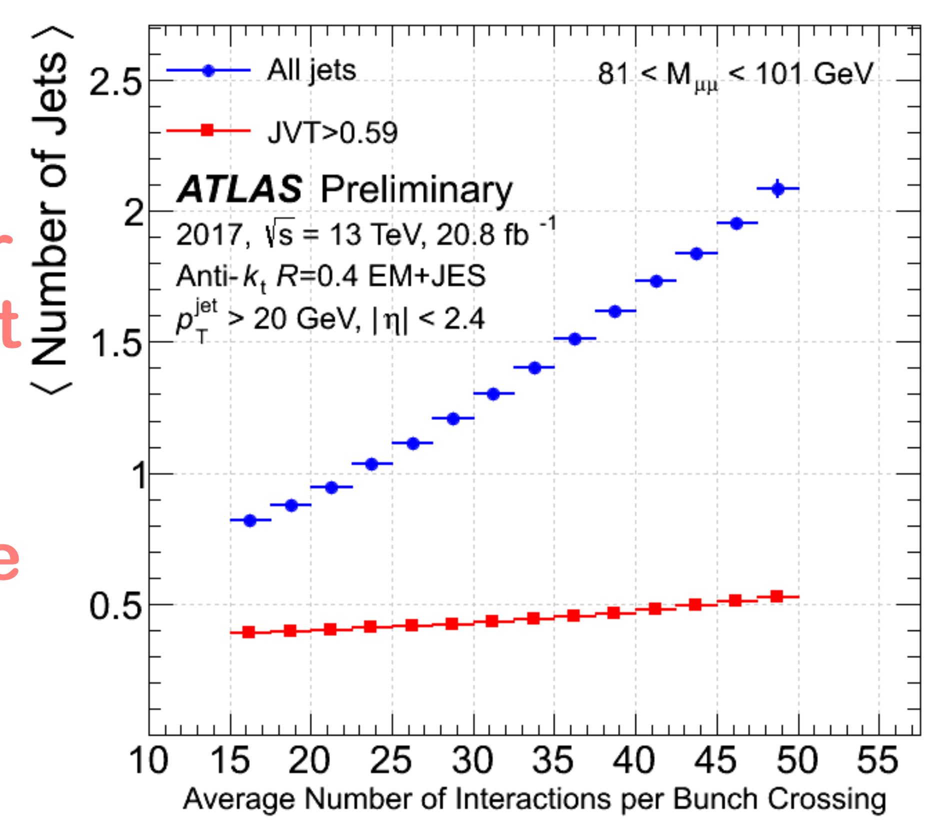
- **Biggest challenge**: robustness against pile-up
  - Controlling trigger rates at high interaction per bunch crossing
  - Online and offline reconstruction performance maintained even at the highest pile-up



improved HLT algorithms to suppress dependence of E_T^{miss} trigger rates on pile-up

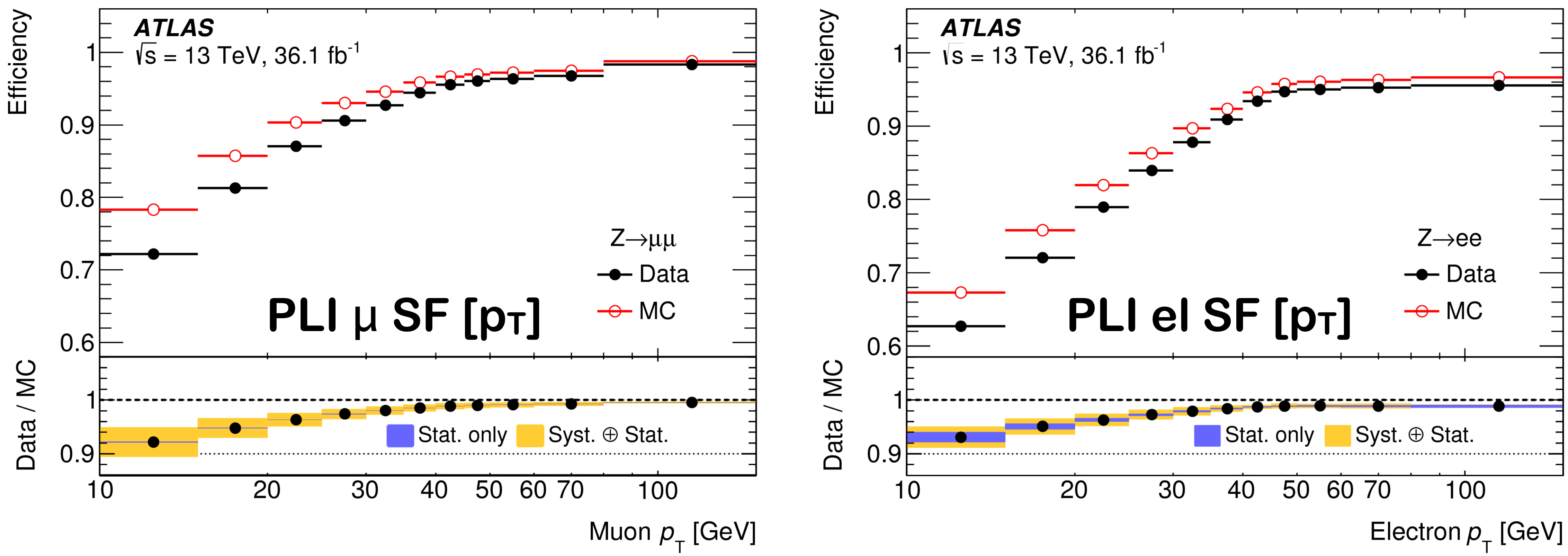


Jet Vertex Tagger (JVT) requirement applied to jets with $20<p_T<60$ GeV to reduce the fake jet rate



$t\bar{t}H$ (multileptons): tight lepton definition

- **Common main/important background**: non-prompt leptons from semileptonic b-decay
- **New MVA lepton isolation (PromptLeptonIso=PLI)** to reject non-prompt ℓ based on:
  - lepton and overlapping **track jets** properties
  - lepton track/calorimeter **isolation** variables



- **SF values ~ 0.90 - 0.98**
- SF systematic uncertainties small (max ~3% @ low pT), w/ negligible impact in the analysis
- Factor $\mathcal{O}(20)$ rejection for leptons originating from b-hadrons

- **New MVA cut to reduce QMIsID** for 2ℓSS and $3\ell+0\tau$
  - Factor $\mathcal{O}(17)$ background rejection for a 95% signal efficiency

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$t\bar{t}H$ (multileptons): object definition summary

- Several "Loose" and "Tight" lepton definitions to optimise the event selection in each multilepton channel

	e					μ		
	L	L†	L*	T	T*	L	L†	L*/T/T*
Isolation	No	Yes				No	Yes	
Non-prompt lepton BDT	No		Yes			No		Yes
Identification	Loose			Tight		Loose		
Charge misassignment veto BDT	No				Yes	No		
Transverse impact parameter significance, $\lvert d_0\rvert/\sigma_{d_0}$	< 5					< 3		
Longitudinal impact parameter, $\lvert z_0 \sin\theta\rvert$	< 0.5 mm							

L = Loose
L† = + Loose isolated
L* = + PLI isolated
T = Tight (PLI isolated)
T* = + QMisID MVA veto (el only)

τ_{had}
Medium BDT ID to reject jets (1M, 1T in $1\ell+2\tau$)
$p_T > 25$ GeV
BDT to reject el faking τ
τ-μ overlap removal
b-jet veto
τ_{had} vertex is PV

Jets $p_T > 25$ GeV
BJets MV2c10 70% WP

- Minimum jet requirements: $N_{jets} \geq 2$; $N_{b\text{-}jets} \geq 1$

	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{had}$	2ℓSS$+1\tau_{had}$	2ℓOS$+1\tau_{had}$	$3\ell+1\tau_{had}$
Light lepton	2T*	1L*, 2T*	2L, 2T	1T	2T*	2L†	1L†, 2T
τ_{had}	0M	0M	–	1T, 1M	1M	1M	1M
N_{jets}, N_{b-jets}	$\geq 4, =1,2$	$\geq 2, \geq 1$	$\geq 2, \geq 1$	$\geq 3, \geq 1$	$\geq 4, \geq 1$	$\geq 3, \geq 1$	$\geq 2, \geq 1$

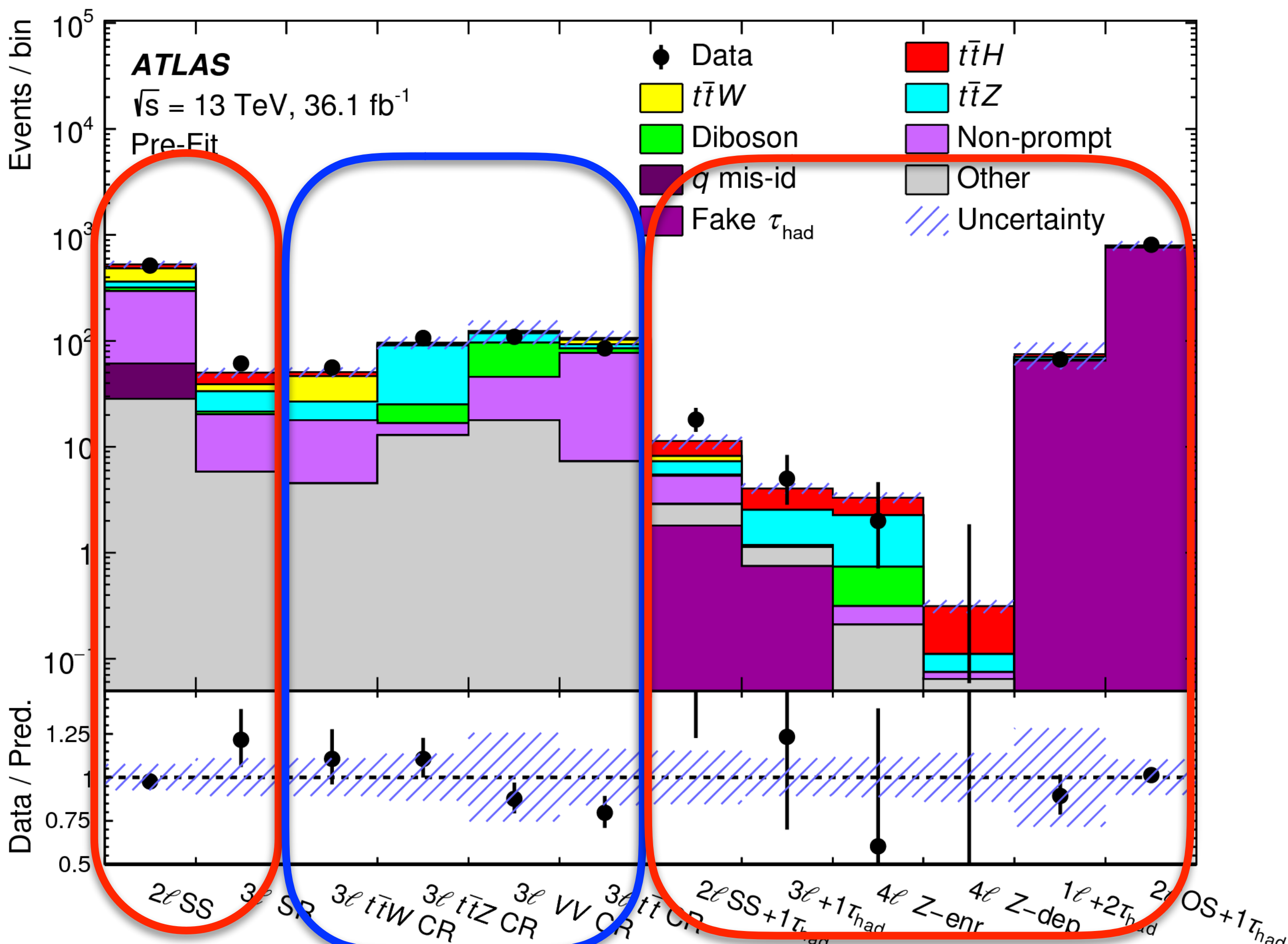
$t\bar{t}H$ (multileptons): multivariate analysis strategy

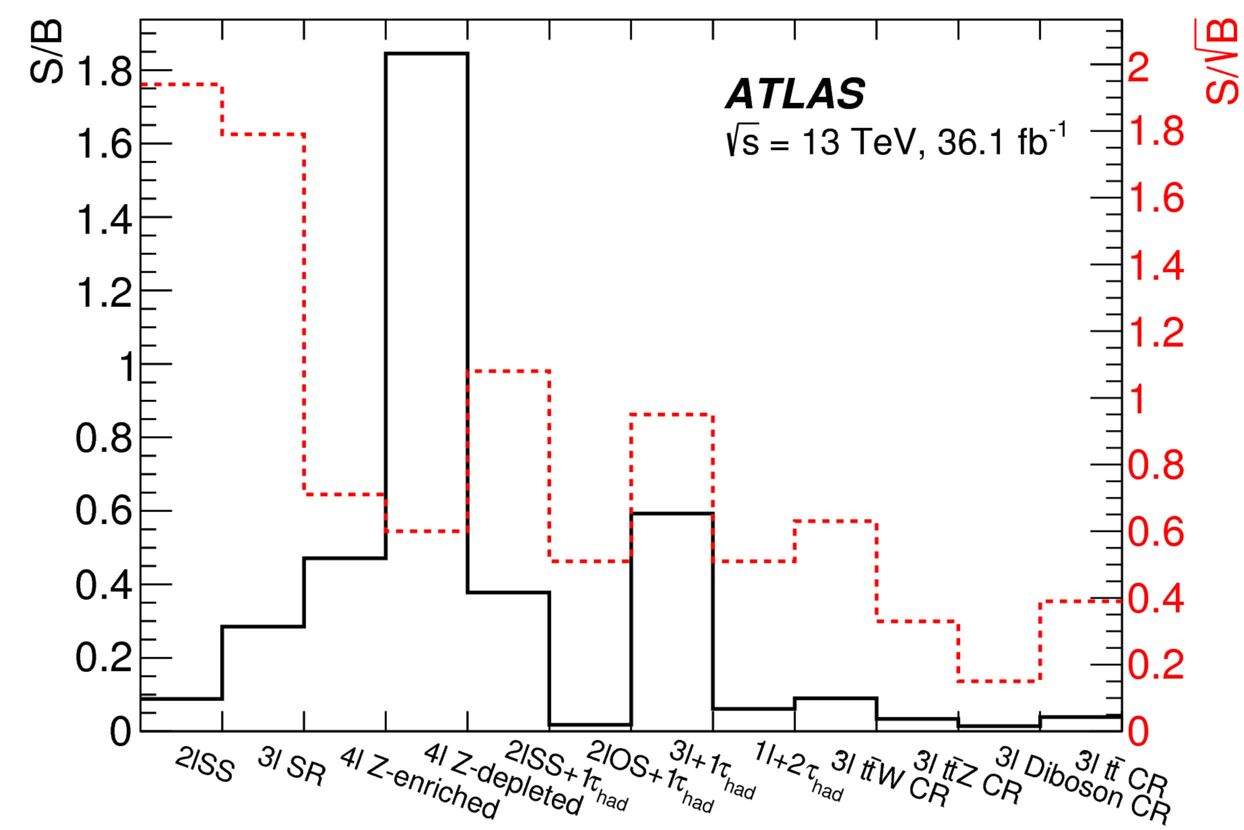
- **Signal extraction**: fit or cut on **BDTs (boosted decision tree)** to discriminate signal against the main background processes [except in 3ℓ+1τ]
- **Pre-MVA region**: loose selection per channel to train MVA
  - **Input variables**: system reconstruction, pseudo-continuous b-tagging, kinematics *[full list in back-up]*
- **Final selection** per channel:
  - Either pre-MVA selection (e.g. 2ℓSS+0τ), tighter selection (e.g. 2ℓSS+1τ), or split pre-MVA region in categories (e.g. 3ℓ+0τ)
  - **2ℓSS0τ**: combination of two BDTs ($t\bar{t}H$ vs. $t\bar{t}$; $t\bar{t}H$ vs. $t\bar{t}V$)
  - **3ℓ0τ**: 5-dimensional multinominal BDTs mapped to 5 categories ($t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$, VV)
  - **4ℓ (Z-enriched)**: $t\bar{t}H$ vs. $t\bar{t}Z$
  - **2ℓSS+1τ, 2ℓOS+1τ, 1ℓ+2τ**: $t\bar{t}H$ vs. $t\bar{t}$ (with fake τ)

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

$t\bar{t}H$ (multileptons): pre-fit summary

- **Most statistically sensitive** to $t\bar{t}H$: $2\ell SS+0\tau$ and $3\ell+0\tau$
- **Purest** but lowest statistics: 4ℓ
- **Largest pre-fit excess** per fit category: $2\ell SS+1\tau$





CONTROL REGIONS

SIGNAL REGIONS

"Other": 4tops, $t\bar{t}WW$, tH, tZ

Fake 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 flavor
	ϵ_{fake}	Same charge; opposite flavor 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, $m_{\text{T}} < 50$ 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, opposite in 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 satisfy tight identification criteria
2ℓOS+$1\tau_{\text{had}}$		Two loose and isolated light leptons, with $p_{\text{T}} > 25$, 15 GeV
		One loose τ_{had} candidate
		$\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV and $m(\ell^+\ell^-) > 12$ GeV
		$N_{\text{jets}} \geq 3$ and $N_{b\text{-jets}} = 0$

MC samples

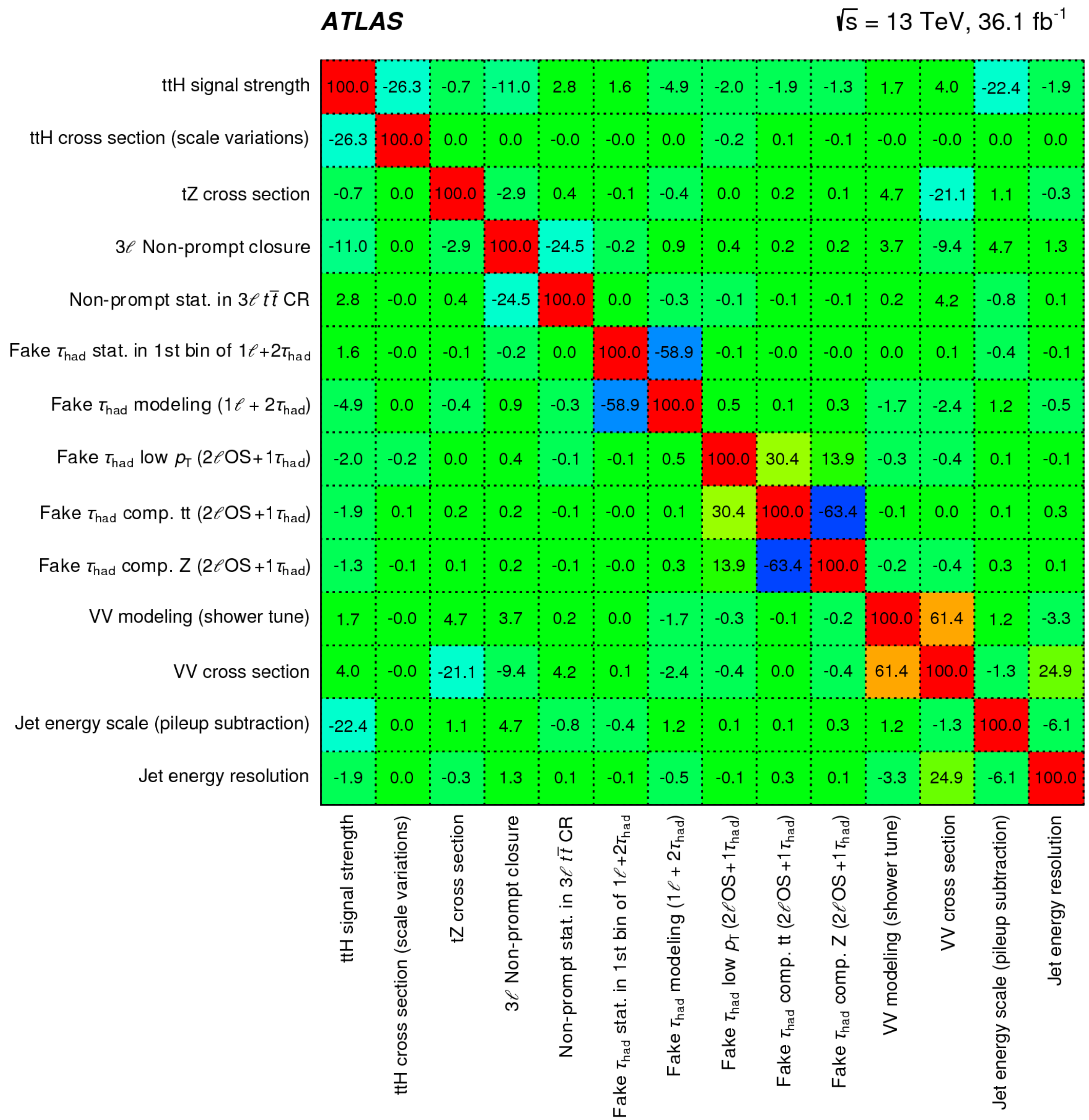
Process	Event generator	ME order	Parton Shower	PDF	Tune
$t\bar{t}H$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO [71]	A14
	(MG5_aMC)	(NLO)	(Herwig++)	(CT10 [72])	(UE-EE-5)
$tHqb$	MG5_aMC	LO	Pythia 8	CT10	A14
tHW	MG5_aMC	NLO	Herwig++	CT10	UE-EE-5
$t\bar{t}W$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO	A14
	(Sherpa 2.1.1)	(LO multileg)	(Sherpa)	(NNPDF 3.0 NLO)	(Sherpa default)
$t\bar{t}(Z/\gamma^* \to ll)$	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 [74,75,76]	NLO	Pythia 6	CT10	Perugia2012
$VV(\to llXX)$, $qqVV$, VVV	Sherpa 2.1.1	MEPS NLO	Sherpa	CT10	Sherpa default
$Z \to l^+l^-$	Sherpa 2.2.1	MEPS NLO	Sherpa	NNPDF 3.0 NLO	Sherpa default

Input variables for MVA

	Variable	$2\ell SS$	3ℓ	4ℓ	$1\ell+2\tau_{had}$	$2\ell SS+1\tau_{had}$	$2\ell OS+1\tau_{had}$
Lepton properties	Leading lepton p_T		×				
	Second leading lepton p_T	×	×			×	
	Third lepton p_T		×				
	Dilepton invariant mass (all combinations)	×	×*				×
	Three-lepton invariant mass		×				
	Four-lepton invariant mass			×			
	Best Z-candidate dilepton invariant mass			×			
	Other Z-candidate dilepton invariant mass			×			
	Scalar sum of all leptons p_T			×			×
	Second leading lepton track isolation					×	
	Maximum $\lvert\eta\rvert$ (lepton 0, lepton 1)	×				×*	
	Lepton flavor	×*	×*				
	Lepton charge		×				
Jet properties	Number of jets	×*	×*		×	×	×
	Number of b-tagged jets	×*	×*		×	×	×
	Leading jet p_T						×
	Second leading jet p_T		×			×*	
	Leading b-tagged jet p_T		×				
	Scalar sum of all jets p_T		×		×	×	×
	Scalar sum of all b-tagged jets p_T						×
	Has leading jet highest b-tagging weight?		×				
	b-tagging weight of leading jet		×				
	b-tagging weight of second leading jet		×			×	
	b-tagging weight of third leading jet					×	
	Pseudorapidity of fourth leading jet					×	
τ_{had}	Leading τ_{had} p_T				×		×
	Second leading τ_{had} p_T				×		
	Di-τ_{had} invariant mass				×		
	Invariant mass τ_{had}–furthest lepton					×	
Angular distances	ΔR(lepton 0, lepton 1)		×				
	ΔR(lepton 0, lepton 2)		×				
	ΔR(lepton 0, closest jet)	×	×				
	ΔR(lepton 0, leading jet)		×			×	
	ΔR(lepton 0, closest b-jet)		×				
	ΔR(lepton 1, closest jet)	×	×				
	ΔR(lepton 2, closest jet)		×				
	Smallest ΔR(lepton, jet)		×				×
	Smallest ΔR(lepton, b-tagged jet)						×
	Smallest ΔR(non-tagged jet, b-tagged jet)						×
	ΔR(lepton 0, τ_{had})						×
	ΔR(lepton 1, τ_{had})						×
	Minimum ΔR between all jets				×		
	ΔR between two leading jets					×	
$\vec{p}_T^{\,miss}$	Missing transverse momentum E_T^{miss}	×		×			
	Azimuthal separation $\Delta\phi$(leading jet, $\vec{p}_T^{\,miss}$)		×				
	Transverse mass leptons (H/Z decay) - $\vec{p}_T^{\,miss}$			×			
	Pseudo-Matrix-Element			×			

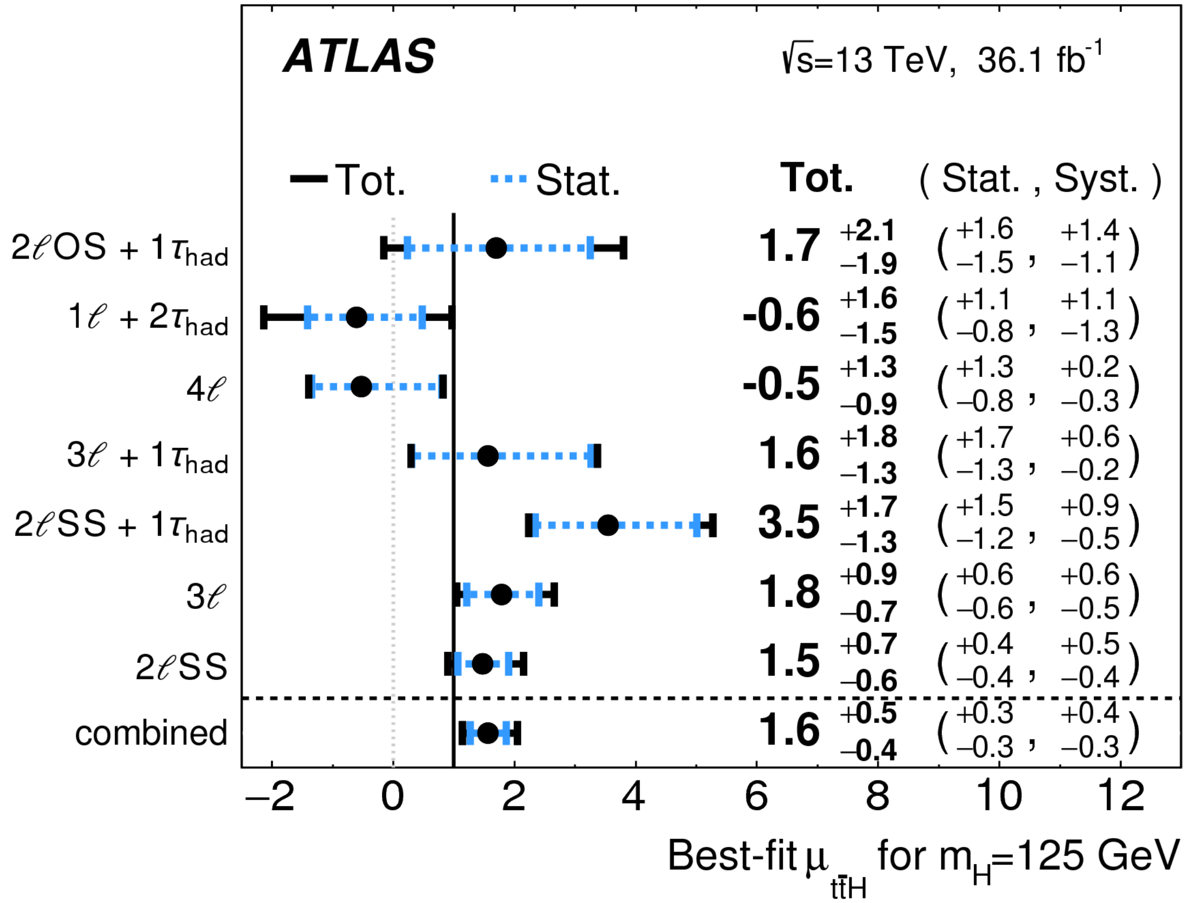
The variables used in cross-check analyses are indicated by a $*$

Correlation NPs



Correlation min threshold = 20%

$t\bar{t}H$ (multileptons): fit results (II)



Channel	Significance Observed	Significance 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

- Cross-section extrapolated to the inclusive phase space:
  - **$\sigma(ttH)=790 \pm 150$ (stat.) $^{+170}_{-150}$ (syst.) fb**
- Significance with respect to background-only hypothesis = **4.1 σ (2.8 σ) obs (exp)**
- Compatible with SM (within 1.4σ)
- Compatibility (7 chan.) = 34%
- **Alternative fit**: $t\bar{t}Z$ and $t\bar{t}W$ normalisation free-floating
  - 15% loss in sensitivity: $\mu(t\bar{t}H) = 1.57^{+0.57}_{-0.50}$
  - $\mu(t\bar{t}Z/W)$ in agreement with SM: $\mu_{t\bar{t}W} = 0.92 \pm 0.32$; $\mu_{t\bar{t}Z} = 1.17^{+0.25}_{-0.22}$

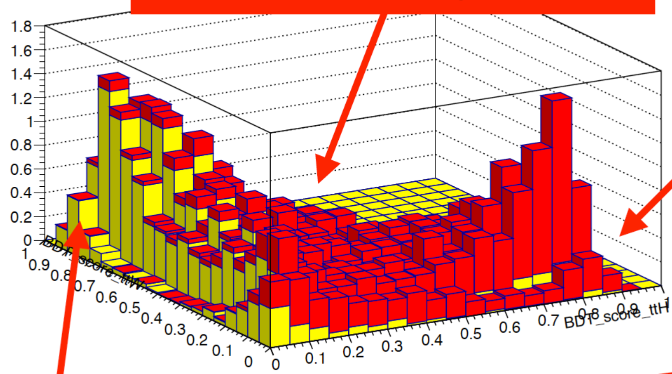
(*) for m(4ℓ) != Higgs mass window

Multinomial classification

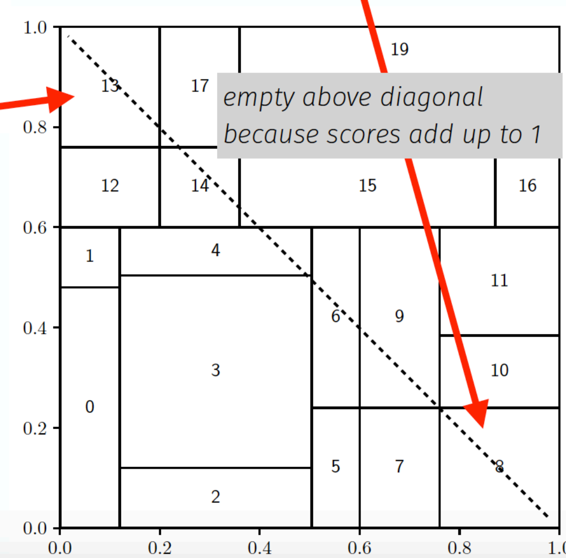
* Explore multinomial classifiers to simultaneously define signal and control regions
  * Processes are separated in the space of a multiD observable
  * Define CRs and VRs with a topology similar to the SR

"Rest" (not ttW, not ttH)

ttH like



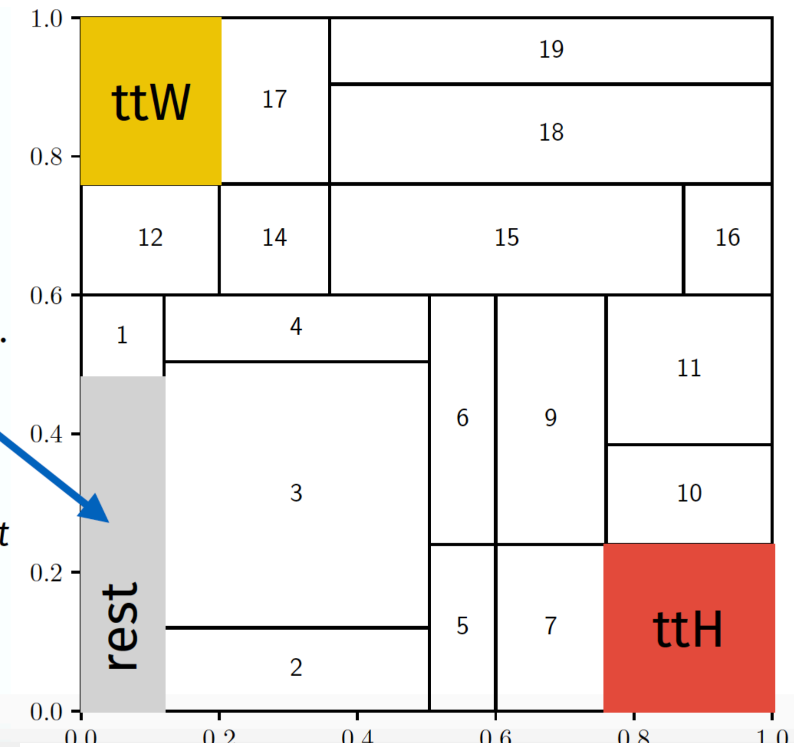
ttW like

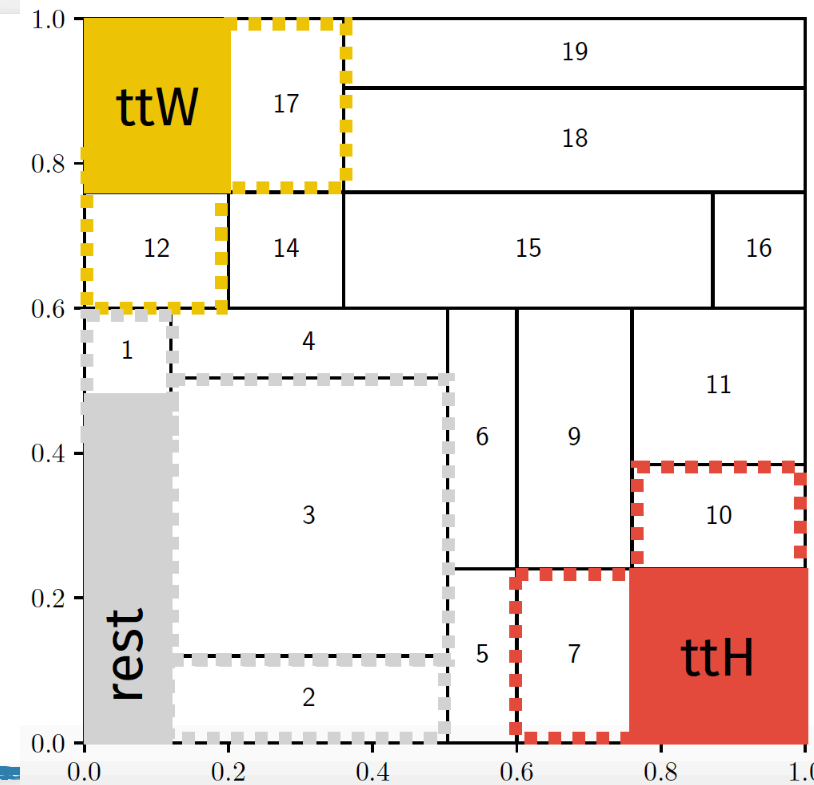


- Approximate the n-dimensional space of the BDT output scores by bins of variable size
- In practice, start with 1 large bin and split it according to the density

"rare" processes, etc.

Rest groups bins that do not contribute to ttH and ttW and speeds up the algorithm





- Clustering: add a single neighbouring bin to the seed and compute analytically the significance again; add the cell giving the largest improvement

$t\bar{t}H$ (multileptons): fake tau (II)

2ℓOS+1τ: fake factor

FF method	τ	anti-τ
apply in B:	**A**	B
extract FF:	C	D

		nJets	nBJets	Z cut	Used for
A, B	2LOS+tau selection	≥ 3	≥ 1	$\|M_{ee/\mu\mu} - M_Z\| > 10$ GeV	to be estimated
C, D	ZVeto 3j0b	≥ 3	0	$\|M_{ee/\mu\mu} - M_Z\| > 10$ GeV	nominal FF
C, D	OnZ 3j0b	≥ 3	0	$\|M_{ee/\mu\mu} - M_Z\| < 10$ GeV	systematics (Z+jets enriched)
C, D	exc2j1b	2	≥ 1	$\|M_{ee/\mu\mu} - M_Z\| > 10$ GeV	systematics (ttbar enriched)

- τ/anti-τ definition based on BDT score of jet-vs-τ
- Reasonable agreement of yield and shape of DD estimate with data

2ℓSS+1τ and 3ℓ+1τ: MC correction with SF derived from **{DD(2ℓOS+1τ) / MC}**

- Harmonised 1-fake-τ estimate for all channels, profit from large statistics from 2ℓOS+1τ, composition uncertainties to cover wide range of b-faking-τ content
- Final SF = 1.36 ± 0.16

Pre- and post-fit yields

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
$1\ell+2\tau_{had}$	–	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$+1\tau_{had}$	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$+1\tau_{had}$	–	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
$3\ell+1\tau_{had}$	–	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
$1\ell+2\tau_{had}$	–	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$+1\tau_{had}$	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$+1\tau_{had}$	–	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
$3\ell+1\tau_{had}$	–	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