ATLAS EXPERIMENT

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Top Precision Measurements and EFT Fits

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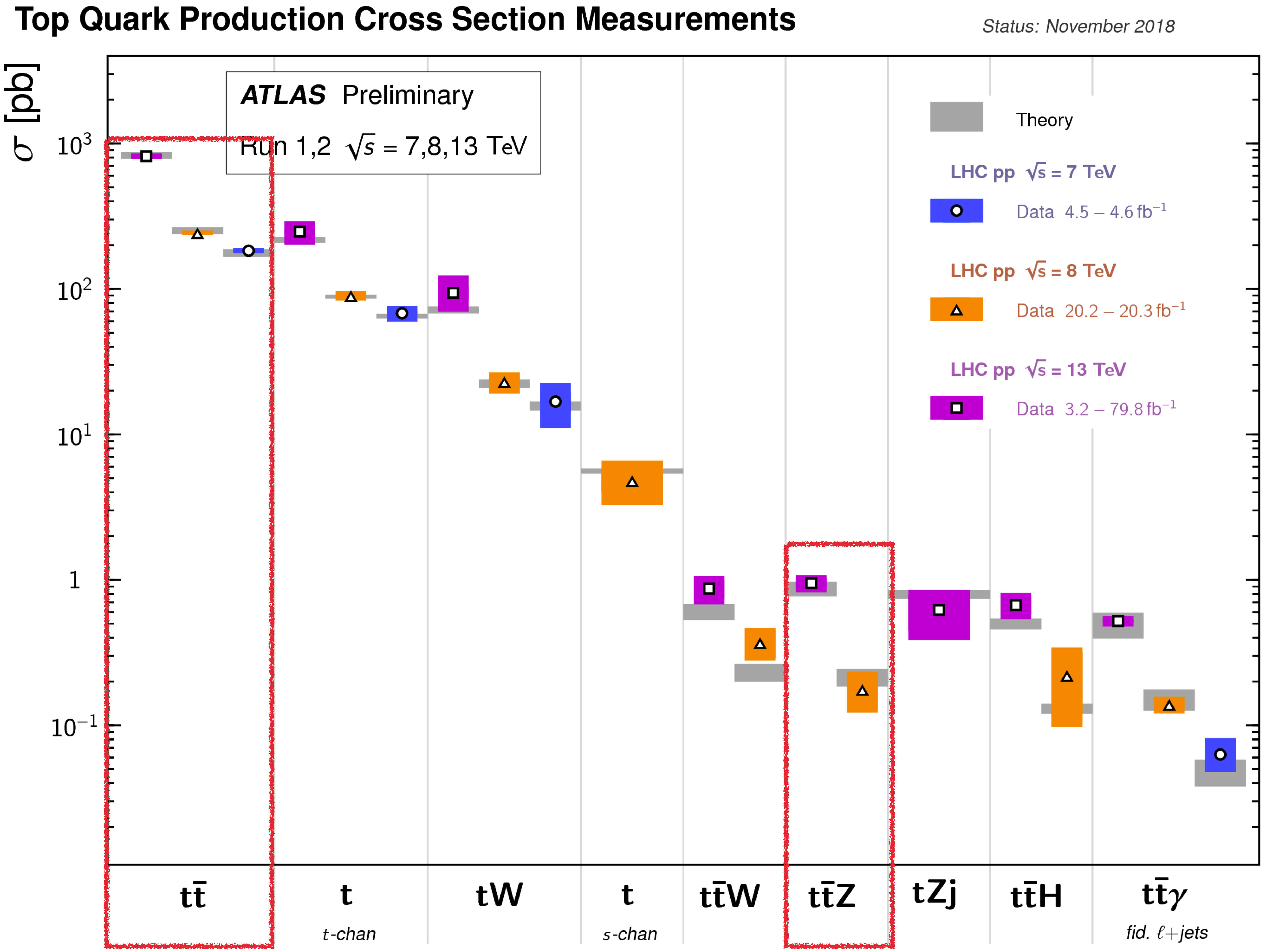
Pushing the Boundaries - Standard Model and Beyond at LHC
IPPP Durham
20 September 2019

Top Measurements at the LHC



- Precision measurements of top quarks at the LHC cover many orders of magnitude
- Due to large top quark mass, close to EW symmetry breaking scale, particle could play special role in SM as well as BSM theories
- Focus on two recent results at both ends of range which include EFT interpretations:
  - tt charge asymmetry
  - ttZ production

EFT Interpretations

- Effective field theory (EFT) framework provides model-independent approach to parametrisation of possible deviation from SM predictions
- BSM physics described by higher order operators
  - dimension six or higher
  - each operator is associated with a Wilson coefficient C_i
  - extended Lagrangian is series expansion in inverse of new physics energy scale

$$\mathscr{L}_{eff} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \ldots$$

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ATLAS-CONF-2019-026

$t\bar{t}$ charge asymmetry

$t\bar{t}$ Charge Asymmetry

- A LO production of top anti-top pairs is symmetric under C
- Higher order QCD contributions, i.e. from ISR/FSR and one-loop diagrams, mean top (anti-top) produced preferentially in direction of incoming quark (anti-quark)
- Though pp collisions at LHC are symmetric, on average valence quarks carry larger fraction of proton momentum than sea quarks
- Result in more forward top quarks and more central anti-top quarks
- Charge asymmetry defined as:

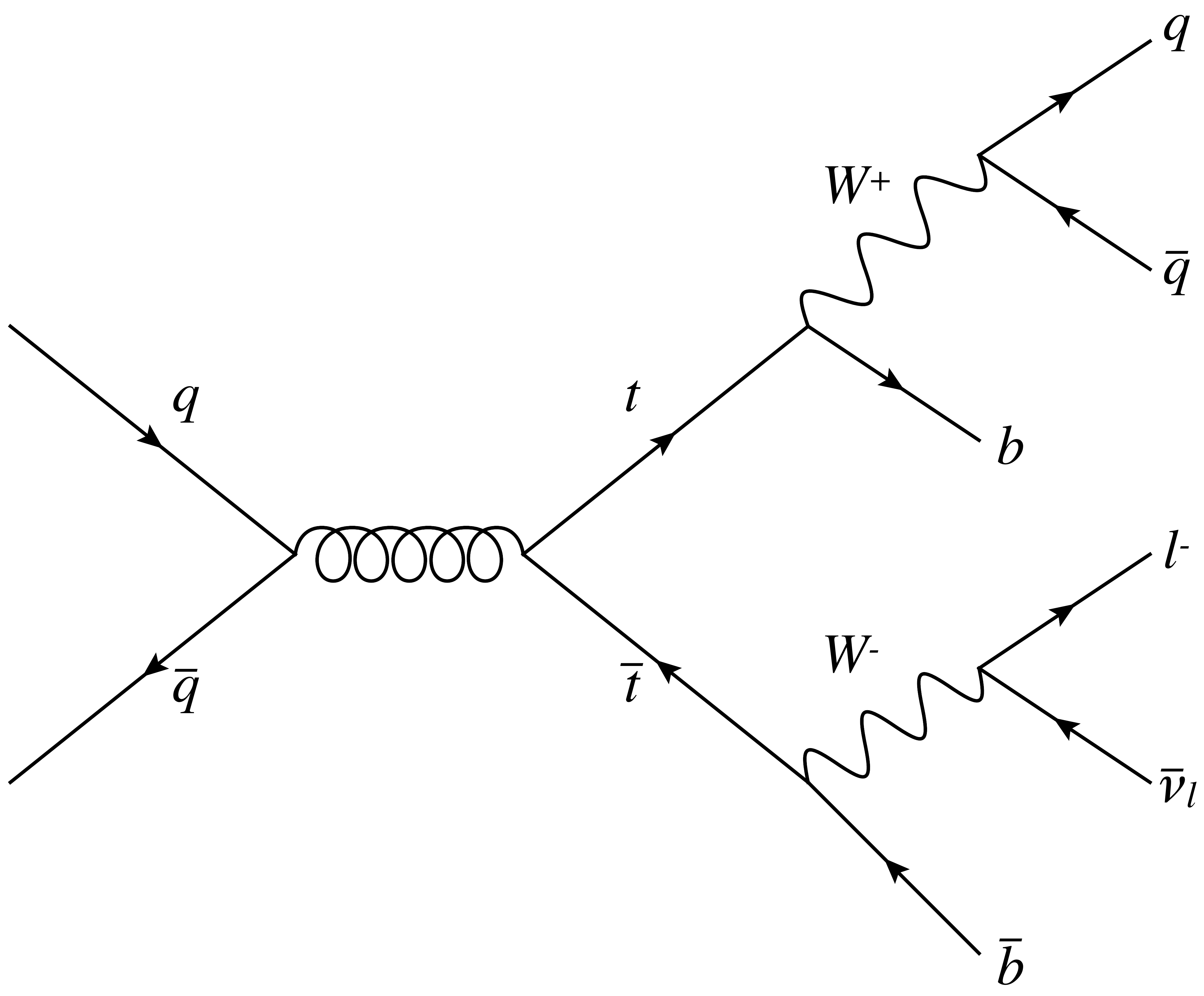
$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

where

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

- Sensitive to BSM processes, e.g. anomalous couplings, heavy bosons, etc.

$t\bar{t}$ Charge Asymmetry - Analysis Setup

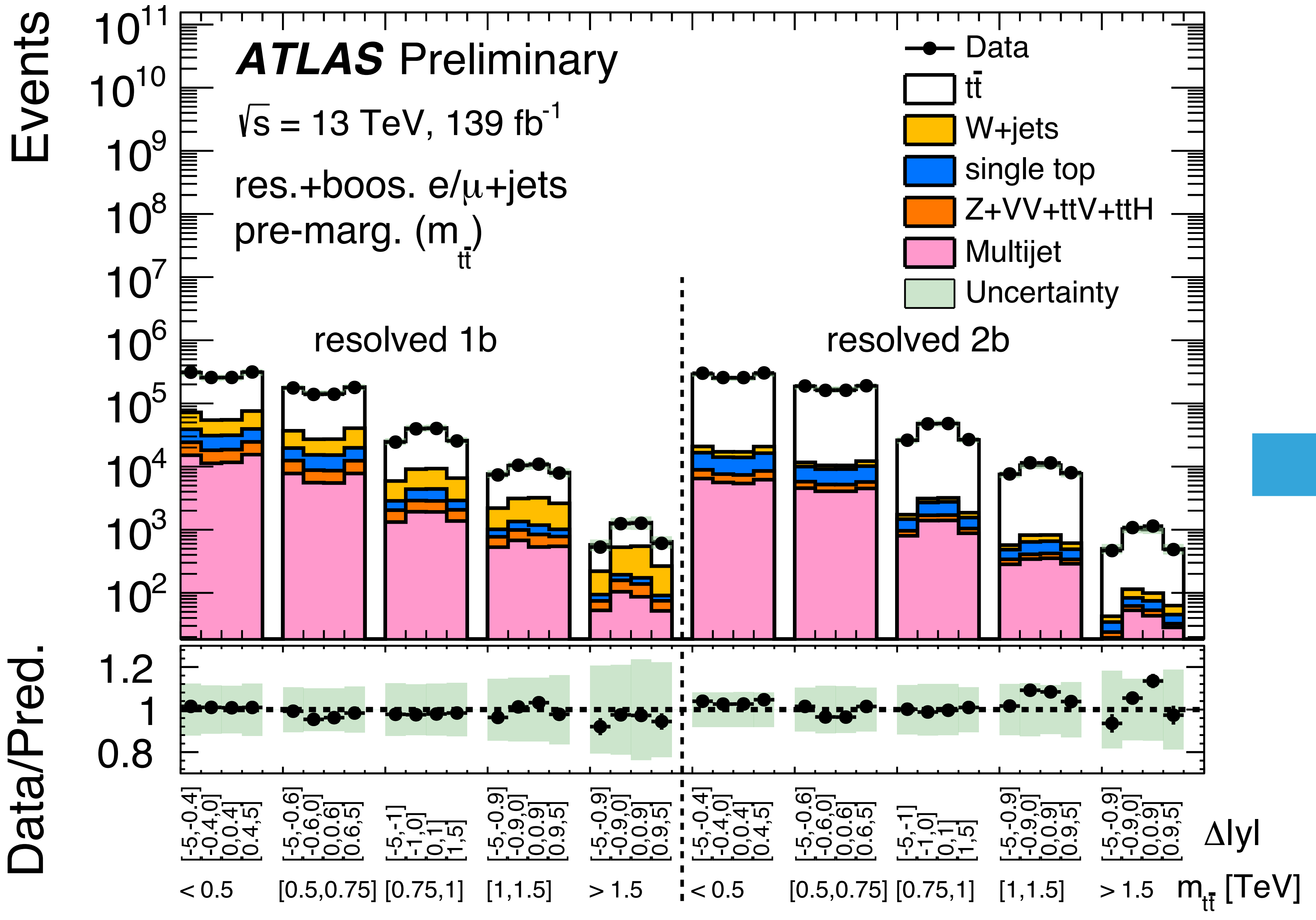


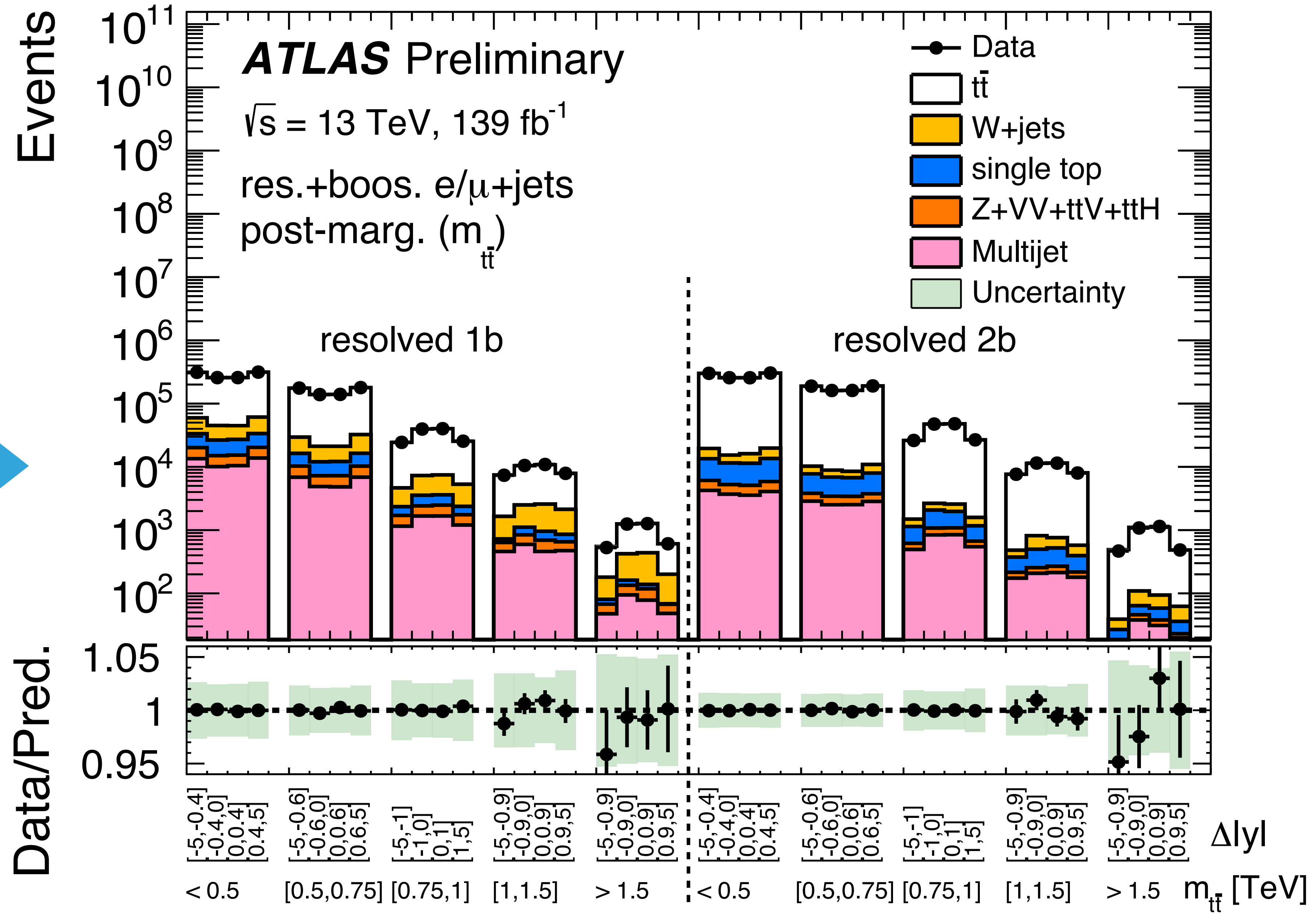
- Analysis uses 139 fb^{-1} dataset at $\sqrt{s}$=13 TeV
- Lepton+jets considered for both resolved and boosted channels
  - Split into categories by:
    - ≡1 or ≥2 b-tags
    - +ve or -ve lepton
- Measurement of $t\bar{t}$ asymmetry inclusively and binned in $t\bar{t}$ mass and velocity in z-direction, β_z
- Dominant backgrounds are single top production, W/Z+jets production, diboson and multijet

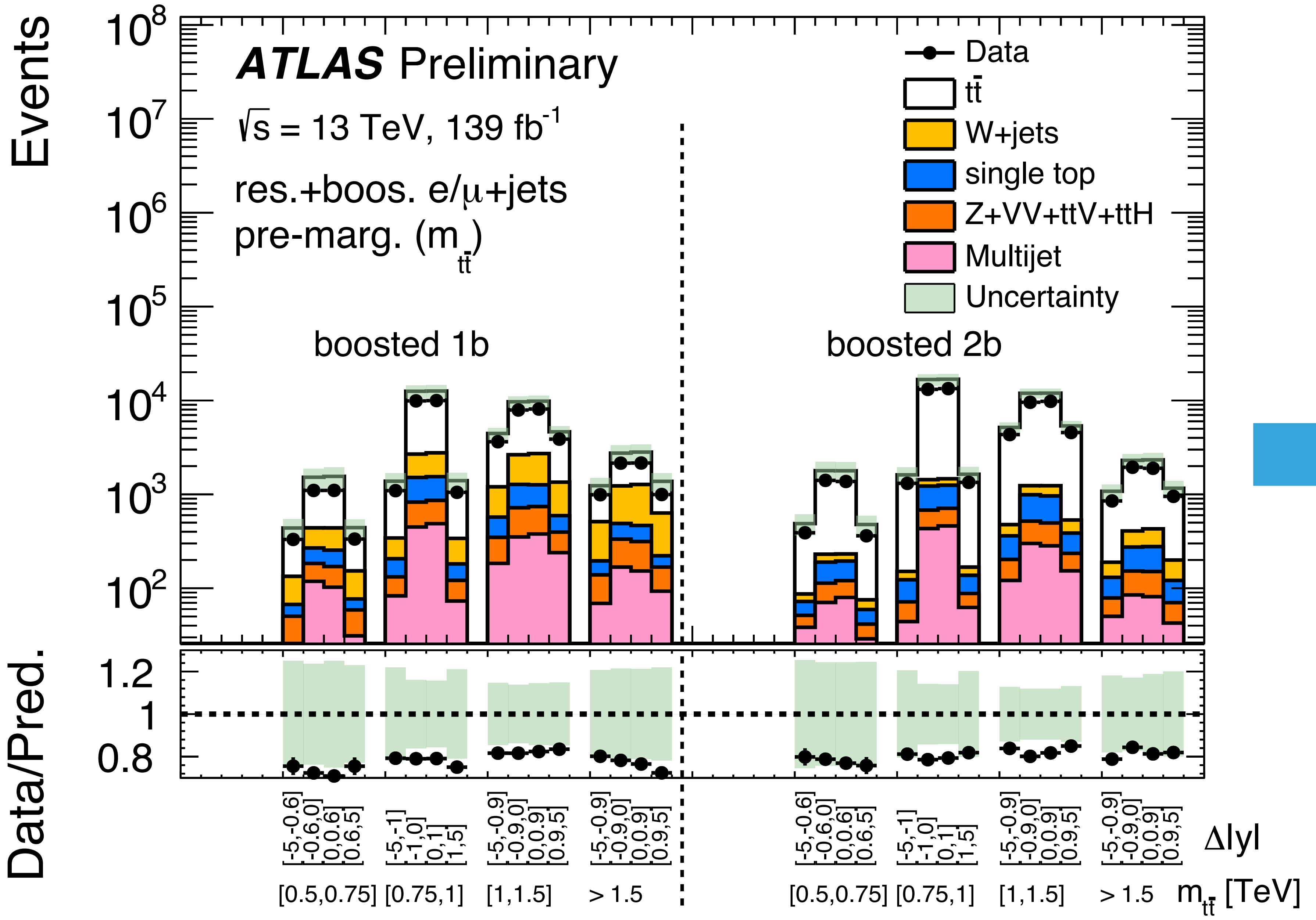
$t\bar{t}$ Charge Asymmetry - Unfolding

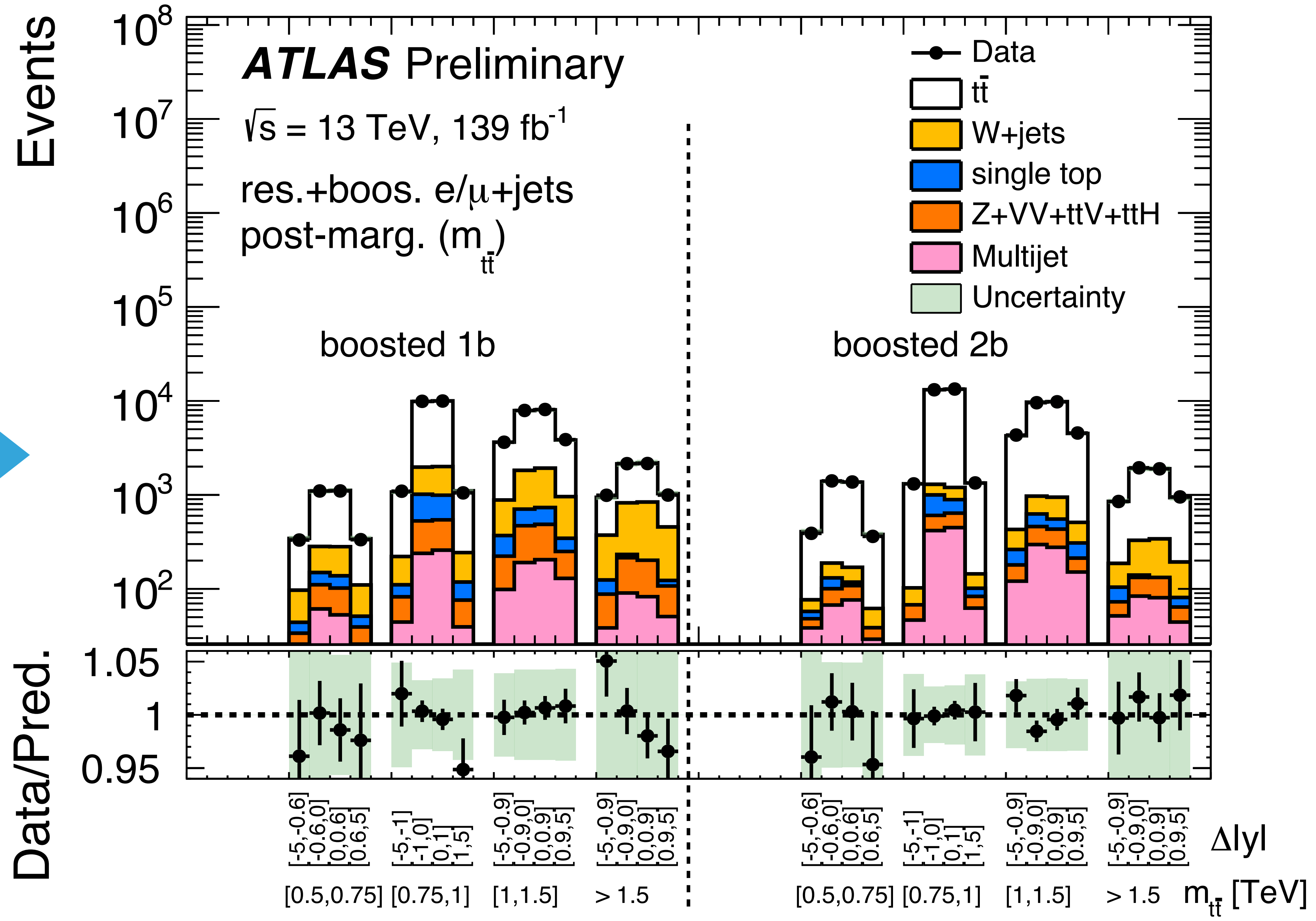
- Analysis uses fully Bayesian Unfolding (FBU) to estimate “true” Δ|y| distribution from measured distribution, which is smeared by acceptance and detector resolution effects
  - arXiv:1201.4612
  - Allows for combined unfolding of all channels
  - Also marginalises the systematics to reduce their values
- Posterior probability of true distribution is proportional to likelihood function (observed data **D** given truth) multiplied by prior probability density for true distribution **T** (uniform prior is chosen)
- Systematics included by extending likelihood to include nuisance parameters
- Likelihood sampled around minimum using Markov-Chain Monte Carlo based method to estimate posterior probability for all parameters of interest

$t\bar{t}$ Charge Asymmetry - Unfolding

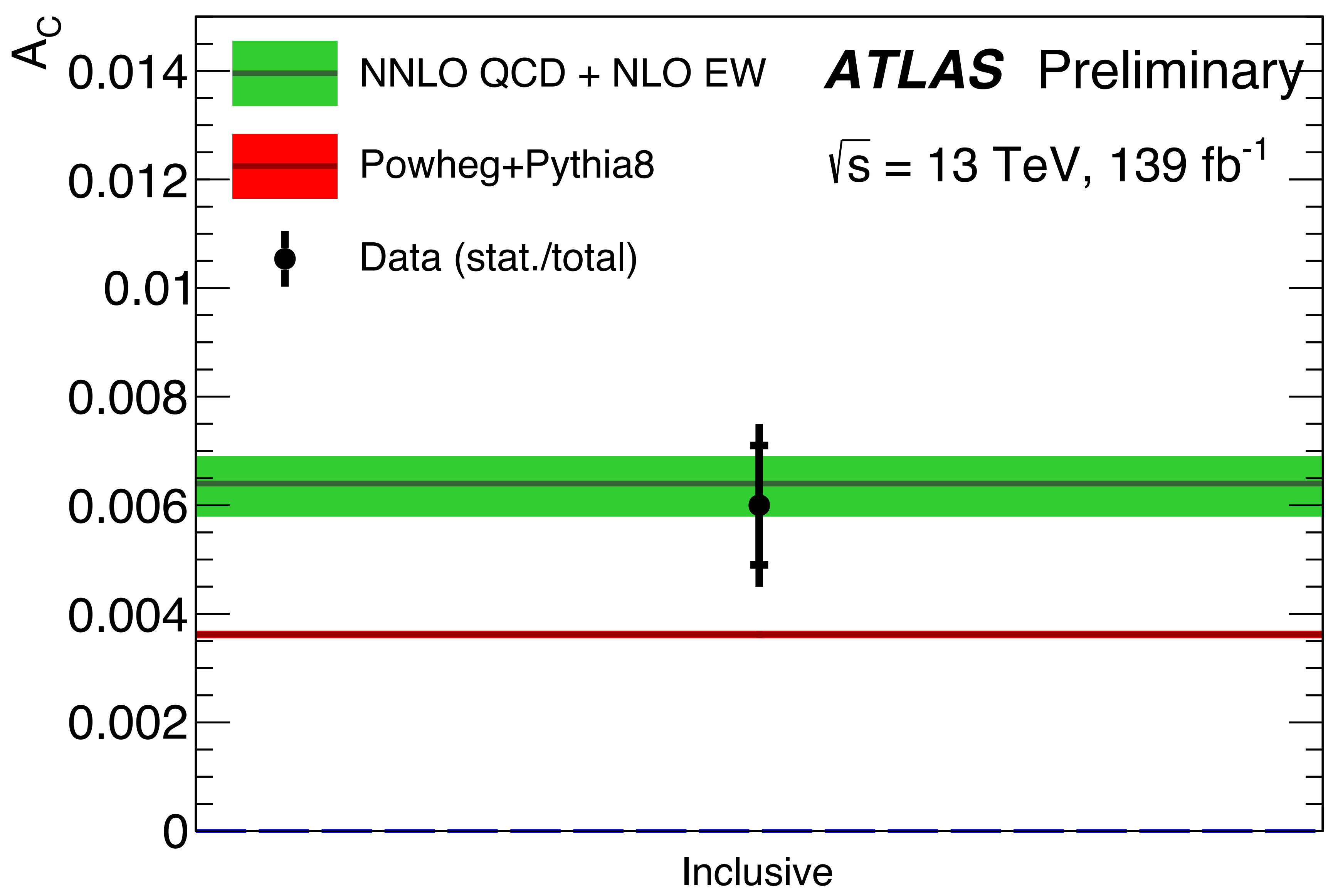


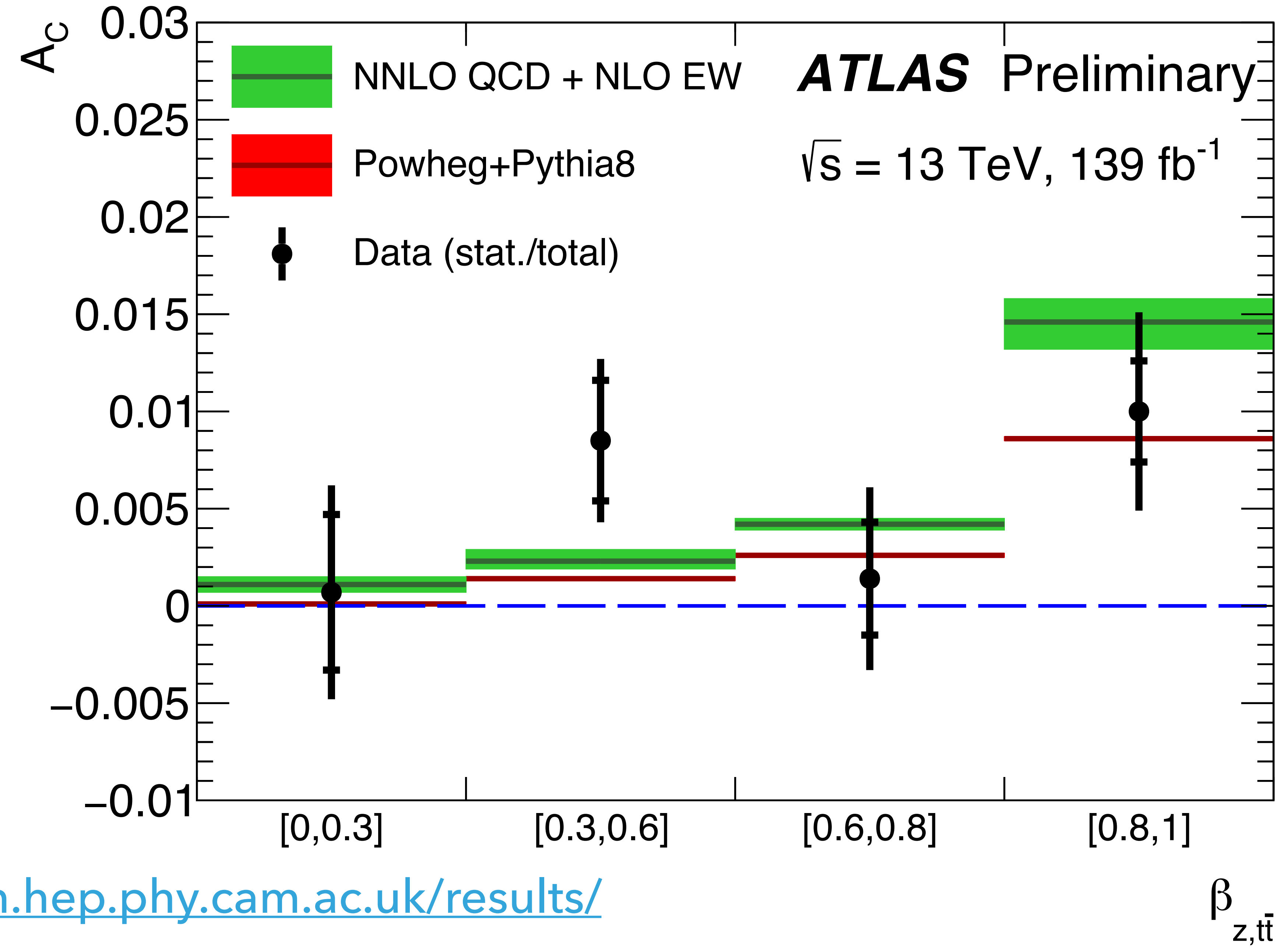




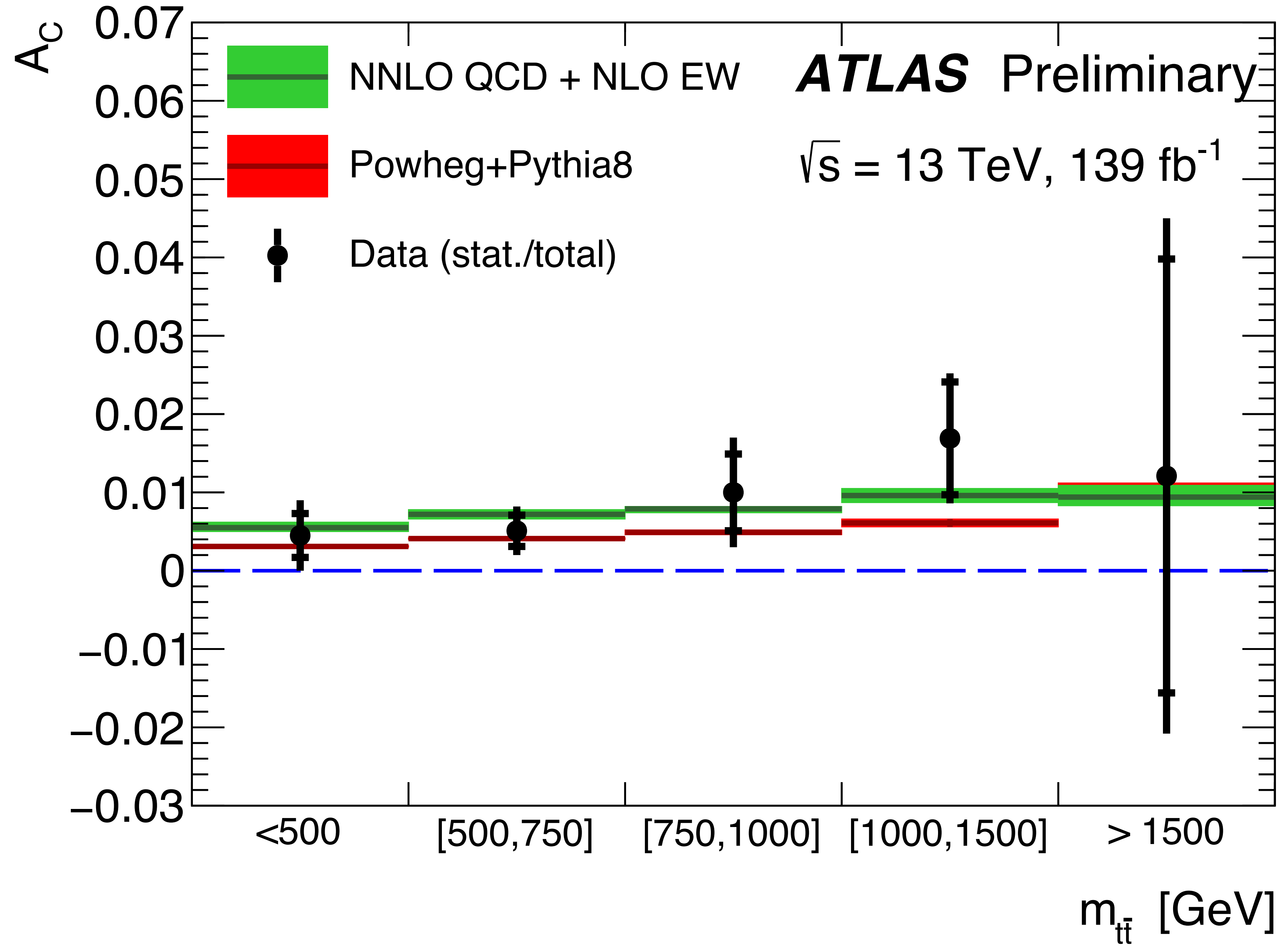


$t\bar{t}$ Charge Asymmetry - Results





Green Bands: http://www.precision.hep.phy.cam.ac.uk/results/



		Data 139 fb^{-1}						SM prediction
		A_C	Stat.	Syst.	MC stat.	Bias	Total unc.	
Inclusive		0.0060	0.0011	0.0009	0.0005	0.0001	0.0015	$0.0064^{+0.0005}_{-0.0006}$
$m_{t\bar{t}}$	< 500 GeV	0.0045	0.0028	0.0034	0.0013	0.0001	0.0045	$0.0055^{+0.0007}_{-0.0005}$
	500-750 GeV	0.0051	0.0020	0.0021	0.0009	<0.0001	0.0031	$0.0072^{+0.0006}_{-0.0006}$
	750-1000 GeV	0.0100	0.0049	0.0046	0.0021	0.0001	0.0070	$0.0079^{+0.0003}_{-0.0005}$
	1000-1500 GeV	0.0169	0.0072	0.0027	0.0029	0.0004	0.0083	$0.0096^{+0.0009}_{-0.0009}$
	> 1500 GeV	0.0121	0.0277	0.0150	0.0092	0.0005	0.0329	$0.0094^{+0.0015}_{-0.0011}$
$\beta_{z,t\bar{t}}$	0-0.3	0.0007	0.0040	0.0032	0.0020	0.0001	0.0055	$0.0011^{+0.0004}_{-0.0004}$
	0.3-0.6	0.0085	0.0031	0.0025	0.0013	0.0003	0.0042	$0.0023^{+0.0006}_{-0.0004}$
	0.6-0.8	0.0014	0.0029	0.0033	0.0015	0.0004	0.0047	$0.0042^{+0.0003}_{-0.0003}$
	0.8-1.0	0.0100	0.0026	0.0042	0.0013	0.0007	0.0051	$0.0146^{+0.0012}_{-0.0014}$

$t\bar{t}$ Charge Asymmetry - EFT Operators

- Warsaw basis comprises complete set of dimension-six operators
  - Charge asymmetry at LHC sensitive to seven four-fermion operators
  - Reduced to four by using flavour-specific linear combination:

$$C_u^1 = C_{qq}^{(8,1)} + C_{qq}^{(8,3)} + C_{ut}^{(8)}$$

$$C_u^2 = C_{qu}^{(1)} + C_{qt}^{(1)}$$

$$C_d^1 = C_{qq}^{(8,1)} - C_{qq}^{(8,3)} + C_{dt}^{(8)}$$

$$C_d^2 = C_{qd}^{(1)} + C_{qt}^{(1)}$$

- Number of combinations further reduced by making assumption of equal couplings to up- and down-type quarks:

$$C_u^1 = C_d^1 = C^1 \qquad C_u^2 = C_d^2 = C^2$$

$t\bar{t}$ Charge Asymmetry - EFT Fit Results

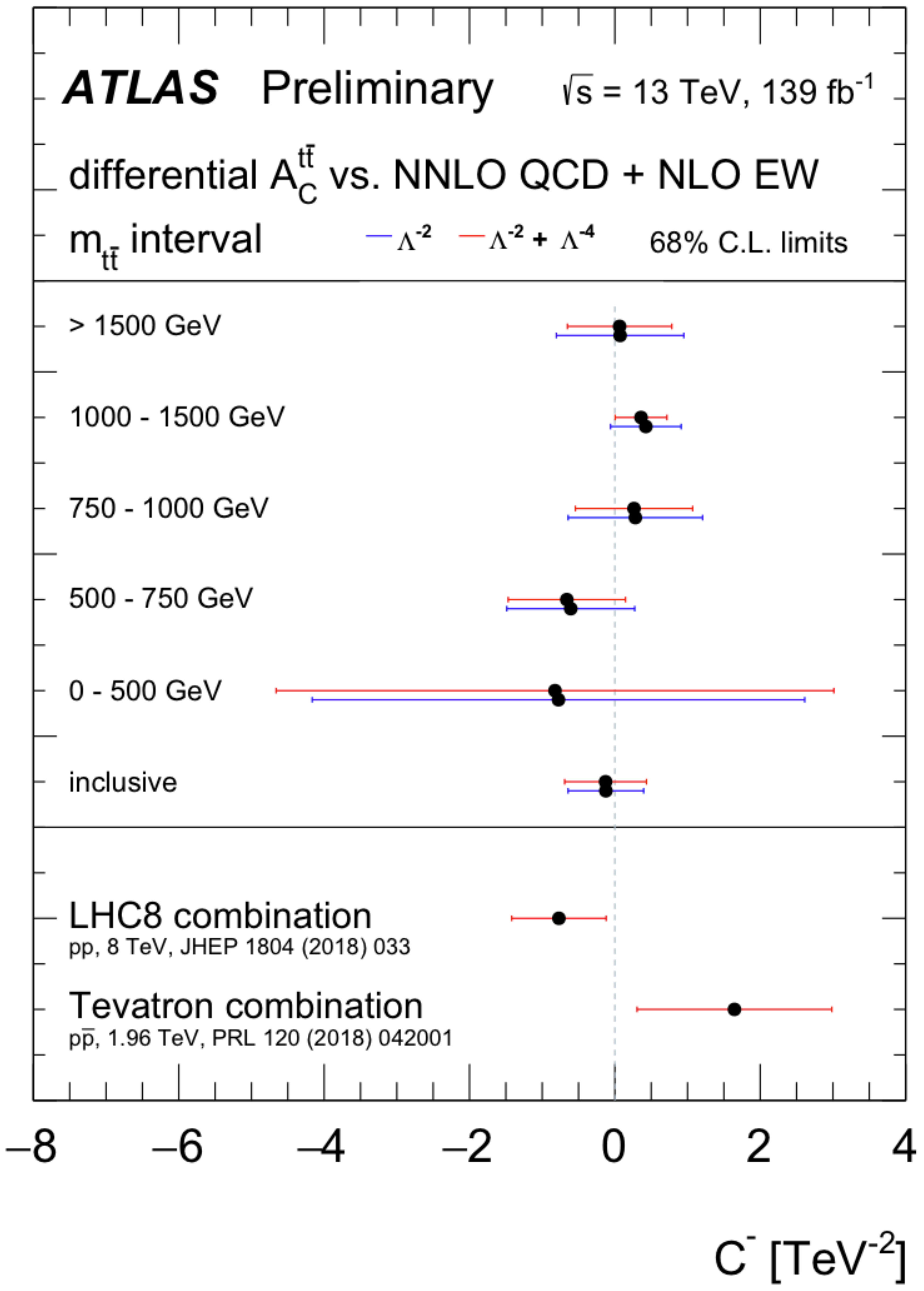
- At LHC tt charge asymmetry is sensitive to difference

$$C^{-} = C^{1} - C^{2}$$

- Can be recast as bound on coupling and massive of massive new states in variety of models.
  - e.g.

$$C^{-}/\Lambda^{2} = -4g_s^2/m_A^2$$

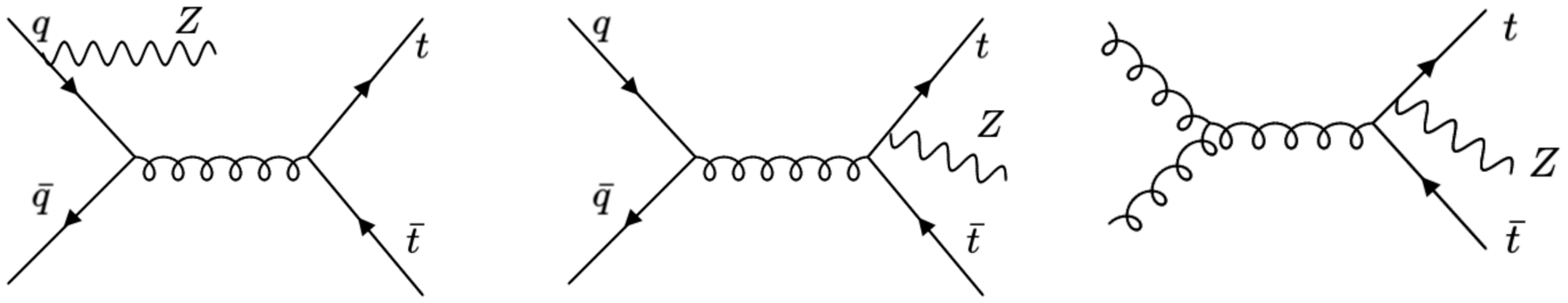
- Bounds on C^{-}/Λ^{2} derived from inclusive measurement and differential $m_{t\bar{t}}$ bins (right)
  - Small total uncertainty on inclusive measurement yields tight bound
  - Tevatron result and ATLAS & CMS combination at √s=8 TeV result are included for comparison



PhysRevD.99.072009

$t\bar{t}Z$

$t\bar{t}Z$ - Production at LHC



- Rare SM process - provides important test of the SM

$$\sigma_{t\bar{t}Z}^{NLO+NNLL} = 811^{+11.0\%}_{-9.6\%}(\text{scale})^{+2.4\%}_{-2.4\%}(\text{PDF} + \alpha_S)\ \text{fb}$$ [1907.04343]

- Main contribution from gg ~70%, qq contribution ~30%
- Cross-section is sensitive to the $t\bar{t}Z$ coupling in case of Z originating from FSR
- Important background for $t\bar{t}H$ and some SUSY searches

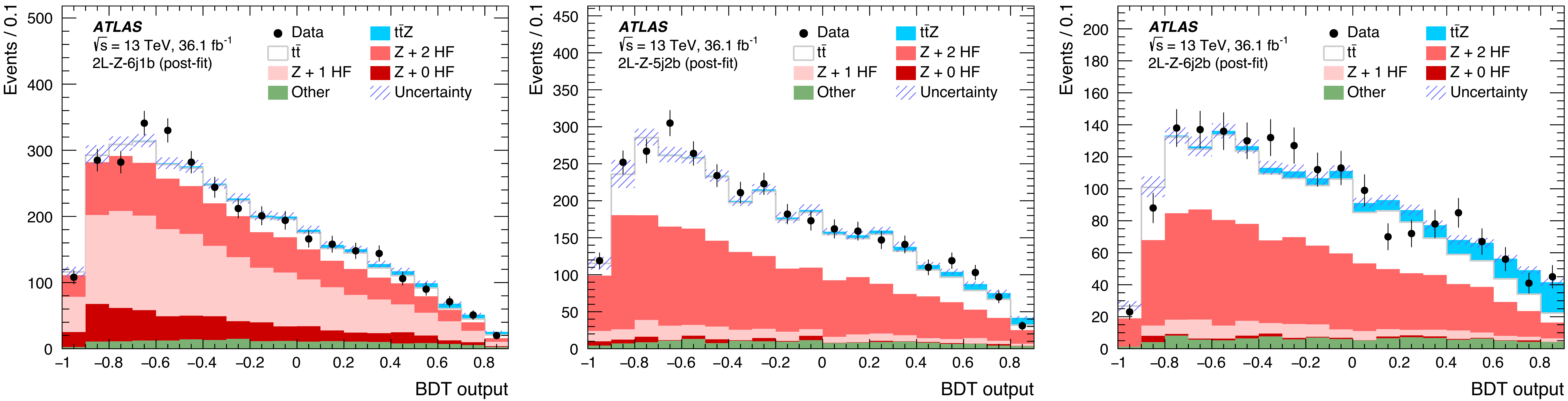
$t\bar{t}V$ - 13 TeV Measurement

- ATLAS result based on full 2015+2016 dataset of 13 TeV collision (36.1 fb-1)
- Different final states, with varying S/B and dominant backgrounds
- Measurement uses l=e,μ only
- Will focus on $t\bar{t}Z$ as this is used for EFT interpretations

Process	$t\bar{t}$ decay	V decay	Channel	Dominant Backgrounds
$t\bar{t}W$	$(l^{\pm}\nu b)(q\bar{q}b)$	$l^{\pm}\nu$	SS di-lepton	Non-prompt
	$(l^{\pm}\nu b)(l^{\pm}\nu b)$	$l^{\pm}\nu$	tri-lepton	Non-prompt, $t\bar{t}X$
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$	$l^{+}l^{-}$	OS di-lepton	Z+jets $t\bar{t}$
	$(q\bar{q}b)(l^{\pm}\nu b)$	$l^{+}l^{-}$	tri-lepton	WZ+jets rare
	$(l^{\pm}\nu b)(l^{\pm}\nu b)$	$l^{+}l^{-}$	tetra-lepton	ZZ+jets rare

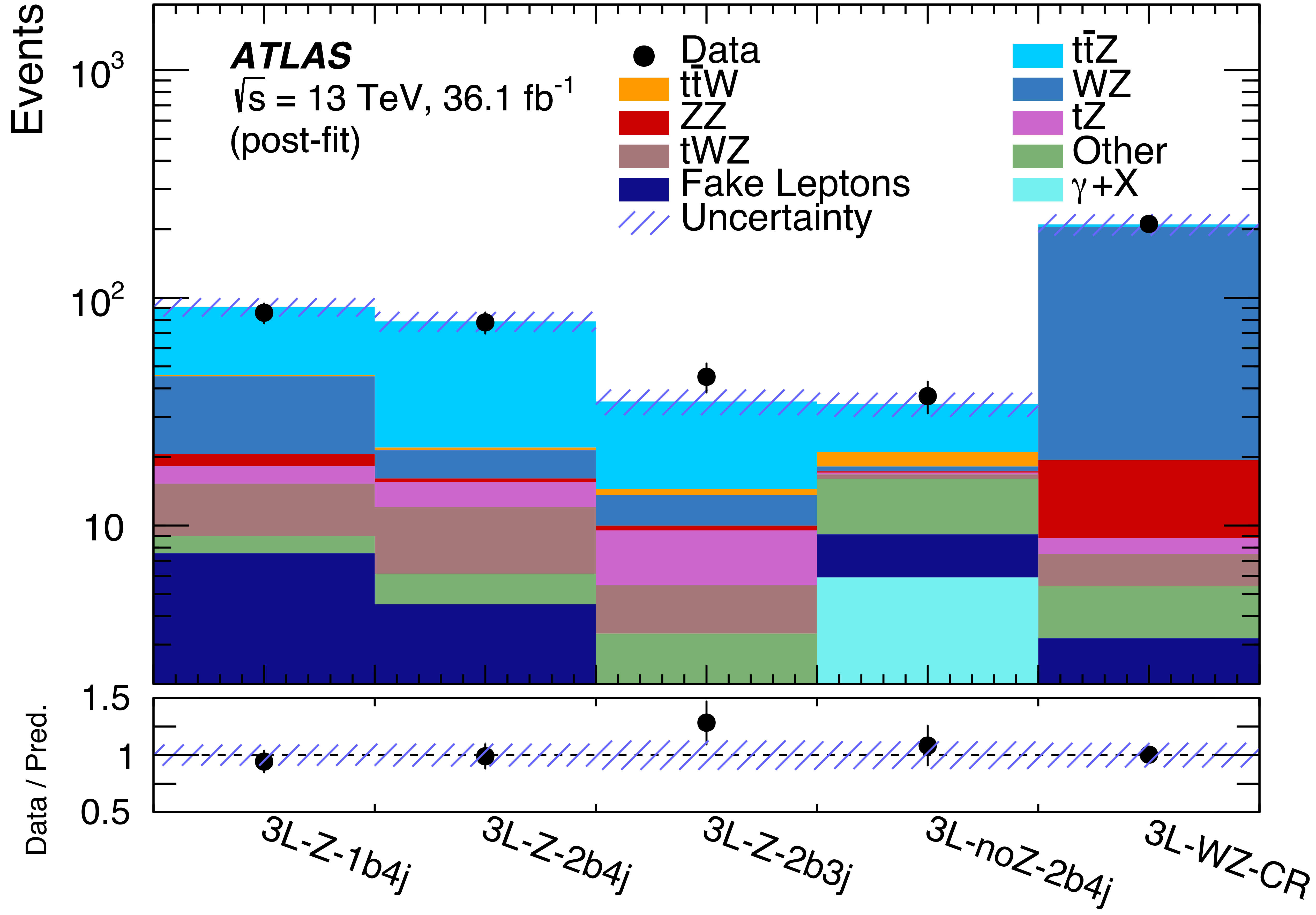
tt̄Z - OS Dilepton Channel

- Overwhelming Z+jets and tt̄ backgrounds:
  - Use a BDT to increase sensitivity
- Three signal regions with different S/B:
  - 2l-Z-6j1b, 2l-Z-5j2b, 2l-Z-6j2b
- Data-driven estimate of tt̄ from an eμ control region
- Z+heavy flavour normalisation from data (low BDT values)

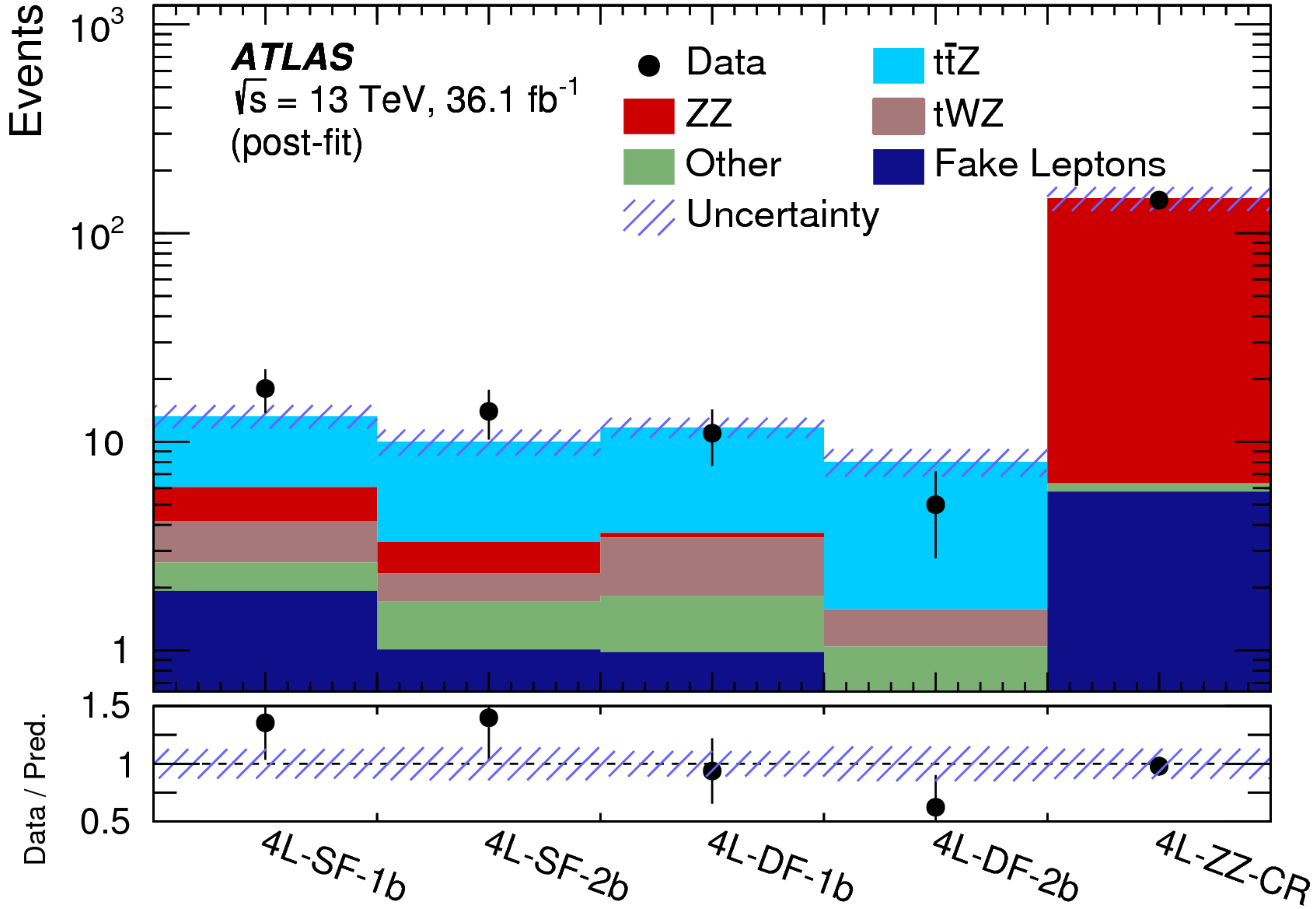


$t\bar{t}Z$ - Trilepton Channel

- Most sensitive regions for $t\bar{t}Z$
- Signal regions defined by (b-)jet multiplicities:
  - 3l-Z-1b4j, 3l-Z-2b3j, 3l-Z-2b4j, 3l-noZ-2b4j
- Dominant backgrounds: WZ+jets, non-prompt leptons and rare SM processes (tZ, tWZ, ttH, etc.)
- Control region for WZ+jets defined using ≡3 jets and ≡0 b-tags
- Additional uncertainties included for WZ+HF and extrapolation to the SR



$t\bar{t}Z$ - Tetralepton Channel



- Regions with excellent S/B, but relatively low yields due to small BR
- Always require a Z-like OSSF pair
- Four SRs, depending on the whether the other two flavours are the same (SF) or different (DF) and the number of b-jets:
  - 4l-DF-1b, 4l-DF-2b, 4l-SF-1b, 4l-SF-2b
- Dominant backgrounds are ZZ+jets and rare SM processes (tWZ, $t\bar{t}X$)
- Dedicated control regions for ZZ+jets, where two OSSF pairs consistent with a Z boson are required

$t\bar{t}V$ - Results

- Combined fit in all signal regions to simultaneously extract $\sigma_{t\bar{t}Z}$ and $\sigma_{t\bar{t}W}$
  - Values from individual fits compatible within uncertainties
  - Dominated by signal & diboson background modelling and flavour-tagging uncertainties

$$\sigma_{t\bar{t}Z} = 0.95 \pm 0.08_{\text{stat.}} \pm 0.10_{\text{syst.}}\ \text{pb}$$

$$\sigma_{t\bar{t}W} = 0.87 \pm 0.13_{\text{stat.}} \pm 0.14_{\text{syst.}}\ \text{pb}$$

Fit configuration	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$
Combined	1.08 ± 0.14	1.44 ± 0.32
2ℓ-OS	0.73 ± 0.28	–
3ℓ $t\bar{t}Z$	1.08 ± 0.18	–
2ℓ-SS and 3ℓ $t\bar{t}W$	–	1.41 ± 0.33
4ℓ	1.21 ± 0.29	–

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.9%	4.5%
Simulated sample statistics	2.0%	5.3%
Data-driven background statistics	2.5%	6.3%
JES/JER	1.9%	4.1%
Flavor tagging	4.2%	3.7%
Other object-related	3.7%	2.5%
Data-driven background normalization	3.2%	3.9%
Modeling of backgrounds from simulation	5.3%	2.6%
Background cross sections	2.3%	4.9%
Fake leptons and charge misID	1.8%	5.7%
$t\bar{t}Z$ modeling	4.9%	0.7%
$t\bar{t}W$ modeling	0.3%	8.5%
Total systematic	10%	16%
Statistical	8.4%	15%
Total	13%	22%

$t\bar{t}Z$ - EFT Interpretation

- $t\bar{t}Z$ measurement is sensitive to a number of EFT couplings:
  - 59 independent, gauge-invariant and baryon- & lepton- number conserving EFT operators in total at dimension six
  - Consider subset of these that modify ttV production
    - Some of these can modify the top coupling to the gluon or the gluon self-couplings as well as the ttZ vertex
    - Some of these, e.g. $O_{tG} \equiv y_t g_s \left(\bar{Q}\sigma^{\mu\nu}T^A t\right) \tilde{\phi} G^A_{\mu\nu}$, can be constrained more precisely from other measurements (e.g. $t\bar{t}$ cross-section)
  - aMC@NLO used to perform EFT computation

$t\bar{t}Z$ - EFT Operators

- Consider 5 operators only affecting $t\bar{t}Z$
  - Uses the NLO model of arXiv:1601.08193
  - Direct relationship can be made with anomalous-coupling approach, Bylund et al [arXiv:1601.08193]

Operator	Expression
$O_{\varphi Q}^{(3)}$	$\frac{i}{2} y_t^2 (\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi)(\bar{Q}\gamma^\mu \tau^I Q)$
$O_{\varphi Q}^{(1)}$	$\frac{i}{2} y_t^2 (\varphi^\dagger \overleftrightarrow{Q}_\mu \varphi)(\bar{Q}\gamma^\mu Q)$
$O_{\varphi t}$	$\frac{i}{2} y_t^2 (\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$
O_{tW}	$y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$
O_{tB}	$y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$

Anomalous coupling parametrisation of the ttZ vertex:

$$\mathscr{L}_{t\bar{t}Z} = e\bar{u}(p_t)\left[\gamma^\mu\left(C^Z_{1,V} + \gamma_5 C^Z_{1,A}\right) + \frac{i\sigma^{\mu\nu}q_\nu}{m_Z}\left(C^Z_{2,V} + i\gamma_5 C^Z_{2,A}\right)\right] v(p_{\bar{t}})Z_\mu$$

where the relationships between anomalous couplings and Wilson coefficients are:

$$C^Z_{1,V} = \frac{1}{2}\left(C^{(3)}_{\varphi Q} - C^{(1)}_{\varphi Q} - C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W}$$

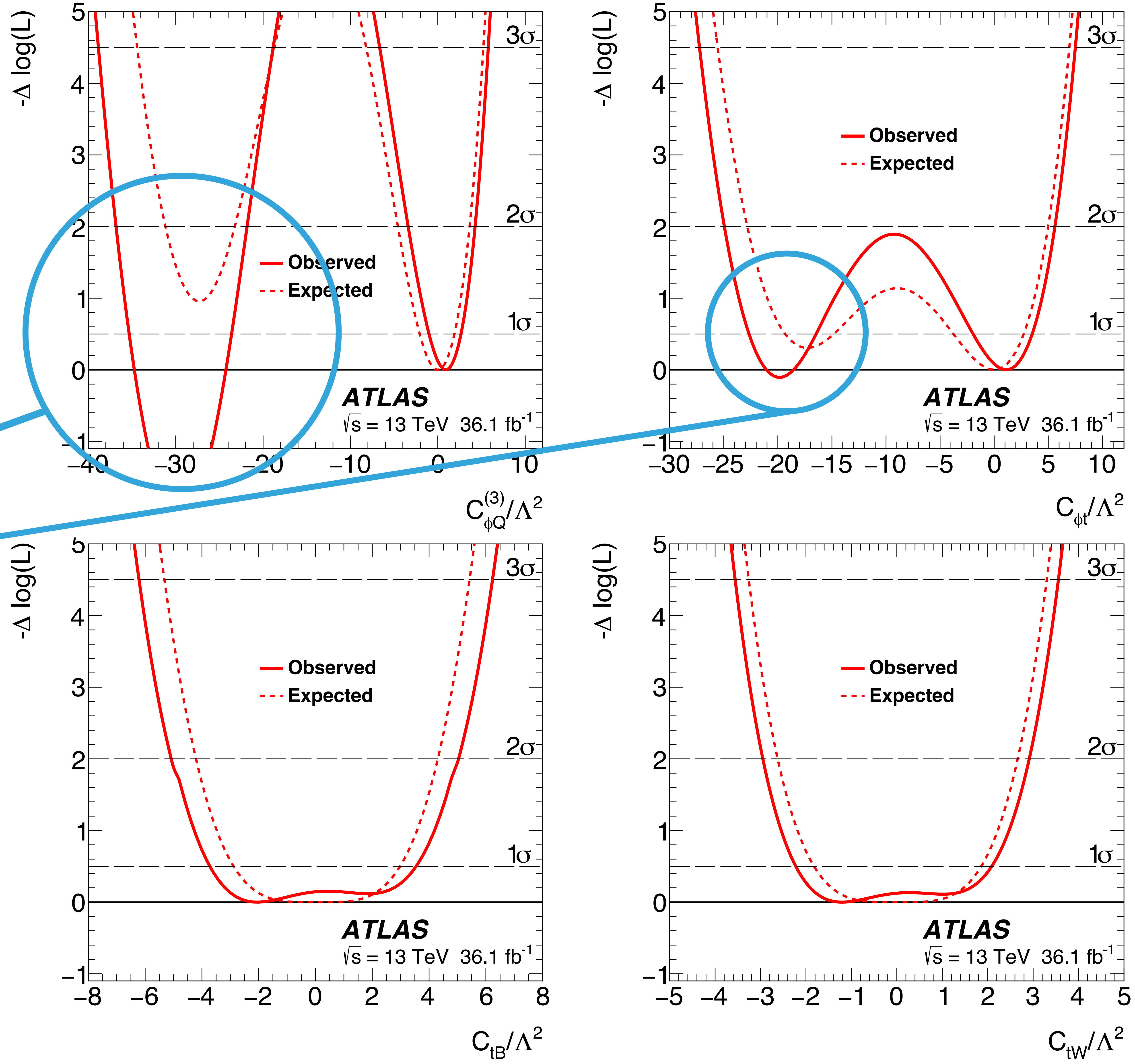
$$C^Z_{1,A} = \frac{1}{2}\left(-C^{(3)}_{\varphi Q} + C^{(1)}_{\varphi Q} - C_{\varphi t}\right)\frac{m_t}{\Lambda^2 s_W c_W}$$

$$C^Z_{2,V} = \left(C_{tW}c_W^2 - C_{tB}s_W^2\right)\frac{2m_t m_Z}{\Lambda^2 s_W c_W}$$

$$C^Z_{2,A} = 0$$

$t\bar{t}Z$ - EFT Fit Results

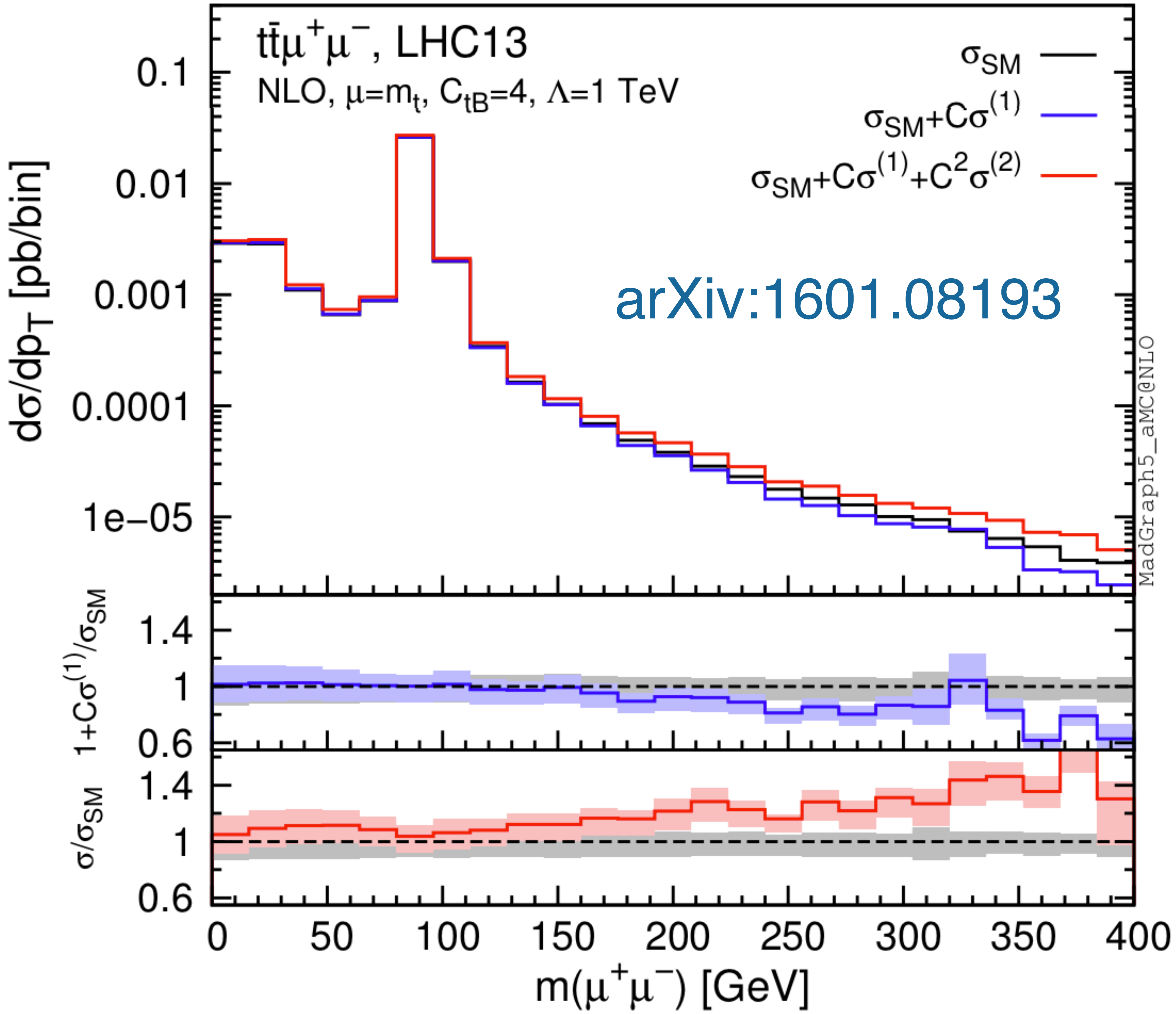
- EFT fit performed using the trilepton and tetralepton signal regions
  - Dilepton is discarded due to low purity



Excluded by previous constraints

Coefficients	$\mathcal{C}^{(3)}_{\phi Q}/\Lambda^2$	$\mathcal{C}_{\phi t}/\Lambda^2$
Previous indirect constraints at 68% CL	[−4.7, 0.7]	[−0.1, 3.7]
Previous direct constraints at 95% CL	[−1.3, 1.3]	[−9.7, 8.3]

$t\bar{t}Z$ - Future Directions



- New possibilities open up with the full Run 2 dataset
- Additional sensitivity to EFT operators from the tails of differential distributions
- Could consider combinations with other measurements sensitive to the same coupling, e.g. $t\bar{t}\gamma$, $t\bar{t}H$

Summary

- ATLAS Top precision measurements cover many orders of magnitude
- EFT framework provides model-independent approach to parametrisation of possible deviation from SM predictions
- Measurements of various top quark productions sensitive to EFT operators
- Presented two recent top quark production measurement with EFT interpretations:
  - $t\bar{t}$ Charge Asymmetry
  - $t\bar{t}Z$ production

BACKUP

$t\bar{t}Z$ signal regions

OS Dilepton

Variable	2ℓ-Z-6j1b	2ℓ-Z-5j2b	2ℓ-Z-6j2b
Leptons	$= 2$, same flavor and opposite sign		
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV		
p_{T} (leading lepton)	>30 GeV		
p_{T} (subleading lepton)	>15 GeV		
$n_{b\text{-tags}}$	1	≥ 2	≥ 2
n_{jets}	≥ 6	5	≥ 6

Trilepton

Variable	3ℓ-Z-1b4j	3ℓ-Z-2b3j	3ℓ-Z-2b4j	3ℓ-noZ-2b4j
Leading lepton	$p_{\mathrm{T}} > 27$ GeV			
Other leptons	$p_{\mathrm{T}} > 20$ GeV			
Sum of lepton charges	± 1			
Z requirement (OSSF pair)	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV			$\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV
n_{jets}	≥ 4	3	≥ 4	≥ 4
$n_{b\text{-tags}}$	1	≥ 2	≥ 2	≥ 2

Tetralepton

Region	Z_2 leptons	$p_{\mathrm{T}4}$	$p_{\mathrm{T}34}$	$\lvert m_{Z_2} - m_Z \rvert$	$E_{\mathrm{T}}^{\text{miss}}$	$n_{b\text{-tags}}$
4ℓ-DF-1b	$e^{\pm}\mu^{\mp}$	–	> 35 GeV	–	–	1
4ℓ-DF-2b	$e^{\pm}\mu^{\mp}$	> 10 GeV	–	–	–	≥ 2
4ℓ-SF-1b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	–	> 25 GeV	> 10 GeV	> 40 GeV	1
				< 10 GeV	> 80 GeV	
4ℓ-SF-2b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	> 10 GeV	–	> 10 GeV	-	≥ 2
				< 10 GeV	> 40 GeV	

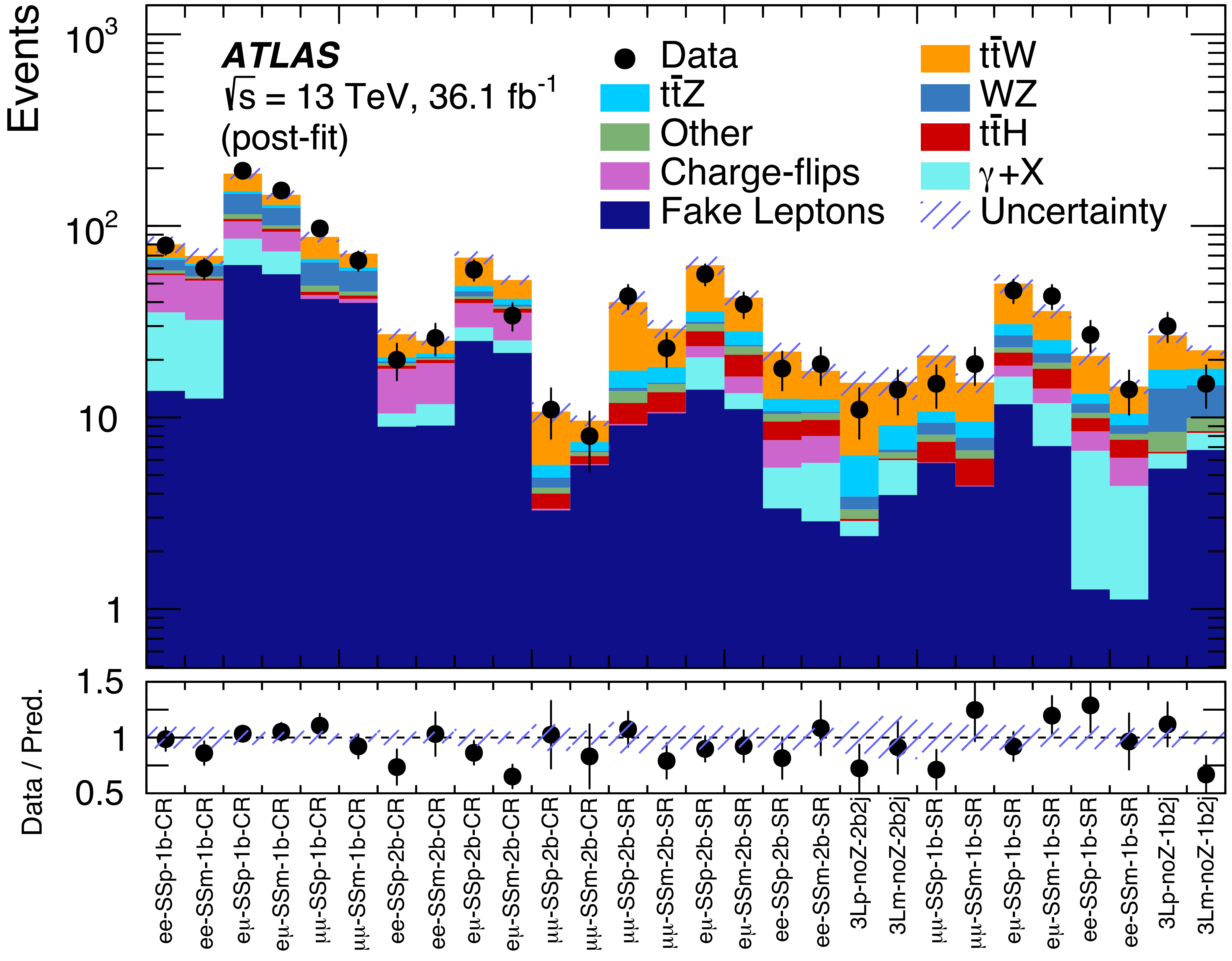
$t\bar{t}W$ signal regions

SS Dilepton

Requirement	2ℓ-SS(p,m)-1b	$2e$-SS(p,m)-2b	$e\mu$-SS(p,m)-2b	2μ-SS(p,m)-2b
$n_{b\text{-tags}}$	$=1$	≥ 2	≥ 2	≥ 2
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 40 GeV	> 40 GeV	> 40 GeV	> 20 GeV
H_{T}	> 240 GeV			
p_{T} (leading lepton)	> 27 GeV			
p_{T} (subleading lepton)	> 27 GeV			
n_{jets}	≥ 4	≥ 4	≥ 4	≥ 2
Z veto	$\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV in the $2e$ and 2μ regions			

Trilepton

Variable	3ℓp-noZ-2b2j	3ℓm-noZ-2b2j	3ℓp-noZ-1b2j	3ℓm-noZ-1b2j
All leptons	$p_{\mathrm{T}} > 27$ GeV			
Z veto (OSSF pair)	$\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV			
n_{jets}	2 or 3			
H_{T}	–		> 240 GeV	
Sum of lepton charges	$+1$	-1	$+1$	-1
$n_{b\text{-tags}}$	≥ 2	≥ 2	1	1



$t\bar{t}Z$ EFT Results

Coefficients	$\mathcal{C}_{\phi Q}^{(3)}/\Lambda^2$	$\mathcal{C}_{\phi t}/\Lambda^2$	$\mathcal{C}_{tB}/\Lambda^2$	$\mathcal{C}_{tW}/\Lambda^2$
Previous indirect constraints at 68% CL	[–4.7, 0.7]	[–0.1, 3.7]	[–0.5, 10]	[–1.6, 0.8]
Previous direct constraints at 95% CL	[–1.3, 1.3]	[–9.7, 8.3]	[–6.9, 4.6]	[–0.2, 0.7]
Expected limit at 68% CL	[–2.1, 1.9]	[–3.8, 2.7]	[–2.9, 3.0]	[–1.8, 1.9]
Expected limit at 95% CL	[–4.5, 3.6]	[–23, 4.9]	[–4.2, 4.3]	[–2.6, 2.6]
Observed limit at 68% CL	[–1.0, 2.7]	[–2.0, 3.5]	[–3.7, 3.5]	[–2.2, 2.1]
Observed limit at 95% CL	[–3.3, 4.2]	[–25, 5.5]	[–5.0, 5.0]	[–2.9, 2.9]
Expected limit at 68% CL (linear)	[–1.9, 2.0]	[–3.0, 3.2]	–	–
Expected limit at 95% CL (linear)	[–3.7, 4.0]	[–5.8, 6.3]	–	–
Observed limit at 68% CL (linear)	[–1.0, 2.9]	[–1.8, 4.4]	–	–
Observed limit at 95% CL (linear)	[–2.9, 4.9]	[–4.8, 7.5]	–	–

$t\bar{t}$ Charge Asymmetry signal regions

- Resolved and Boosted:
  - Exactly one lepton, $p_T > 28$ GeV
  - Electron: $E_T^{miss} > 30$ GeV, $m_T^W > 30$ GeV
  - Muon: $E_T^{miss} + m_T^W > 60$ GeV
  - $\equiv 1$ or ≥ 2 b-tagged jets
- Resolved:
  - ≥ 4 small-R jets with $p_T > 25$ GeV
  - no boosted jets
  - $t\bar{t}$ system reconstructed with BDT (cut > 0.3)
- Boosted:
  - ≥ 1 small-R jet(s) with $p_T > 25$ GeV
  - $\geq$ large-R jet(s) top-tagged with $p_T > 350$ GeV and $|\eta| < 2$
  - $m_{t\bar{t}} > 500$ GeV

$t\bar{t}$ Charge Asymmetry event yields

Process:	Resolved		Boosted	
	$1b$-excl.	$2b$-incl.	$1b$-excl	$2b$-incl.
$t\bar{t}$	1520000±120000	1840000±150000	50000± 7000	74000±10000
Single top	89000± 12000	49000± 8000	3600± 1200	3000± 1200
W + jets	200000± 23000	23000± 14000	10000± 5000	1800± 1000
$Z + VV + t\bar{t}X$	52000± 28000	15000± 8000	2600± 1300	1400± 800
Multijet	90000± 40000	47000± 23000	3000± 1500	2300± 1200
Total Prediction	1950000±200000	1980000±160000	69000±11000	83000±11000
Data (139 fb^{-1})	1945037	2009526	54710	66582

Table 1: Event yields split by topology (resolved, boosted) and b-tag multiplicity (1-excl., 2-incl.). Total pre-marginalisation uncertainty is shown.