Measurements of **associated top quark** production and searches for **new top-quark phenomena** with the ATLAS detector

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on behalf of the ATLAS Collaboration

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ATLAS EXPERIMENT

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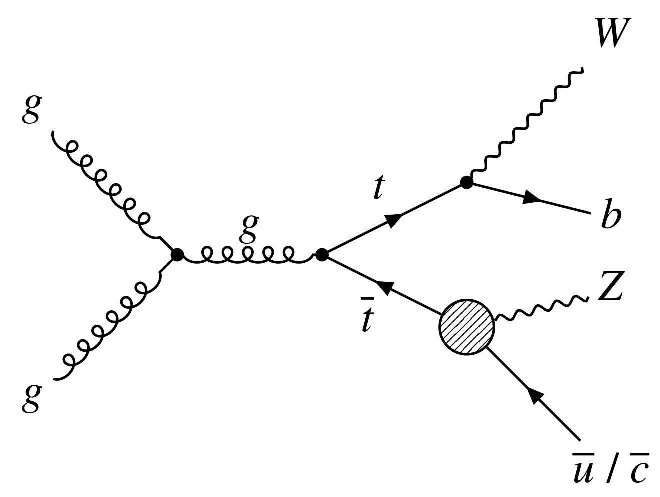
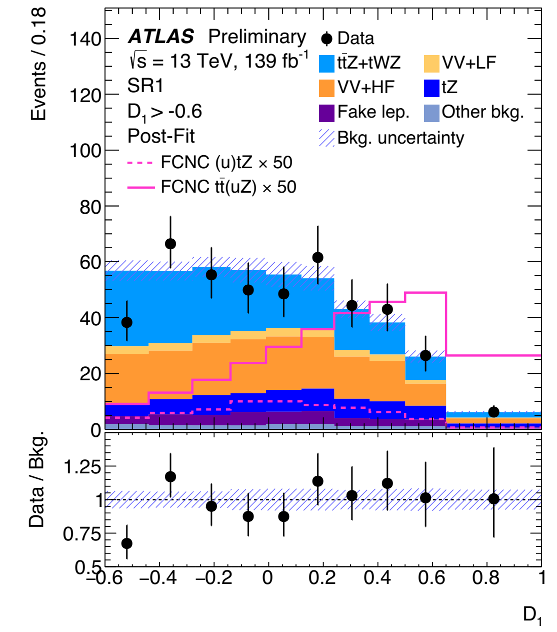
Overview of Top Quark Measurements

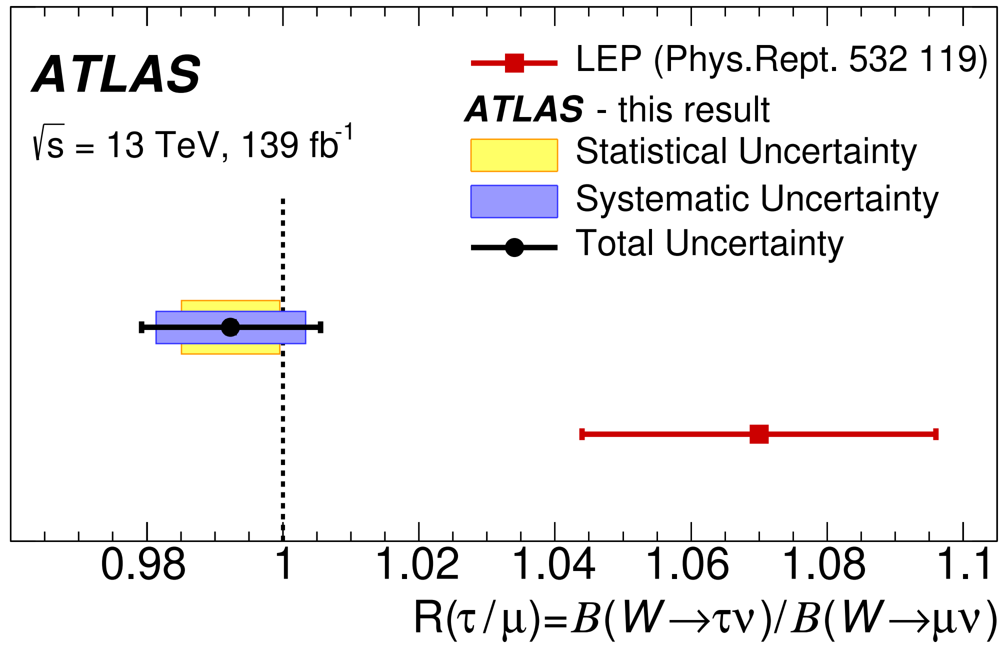
- Top is most massive SM particle
  - Large coupling to Higgs boson
  - Can couple strongly to new physics
    - Interpreted in the SM EFT paradigm
- Run II ATLAS dataset of 139 fb^{-1} maximal sensitivity to rare processes
  - Testing forbidden SM phenomena with $t\bar{t}$ production
  - Measure rare SM $t\bar{t}+X$ processes inclusively and differentially
- Present latest results from ATLAS

Flavor Changing Neutral Currents (FCNC)

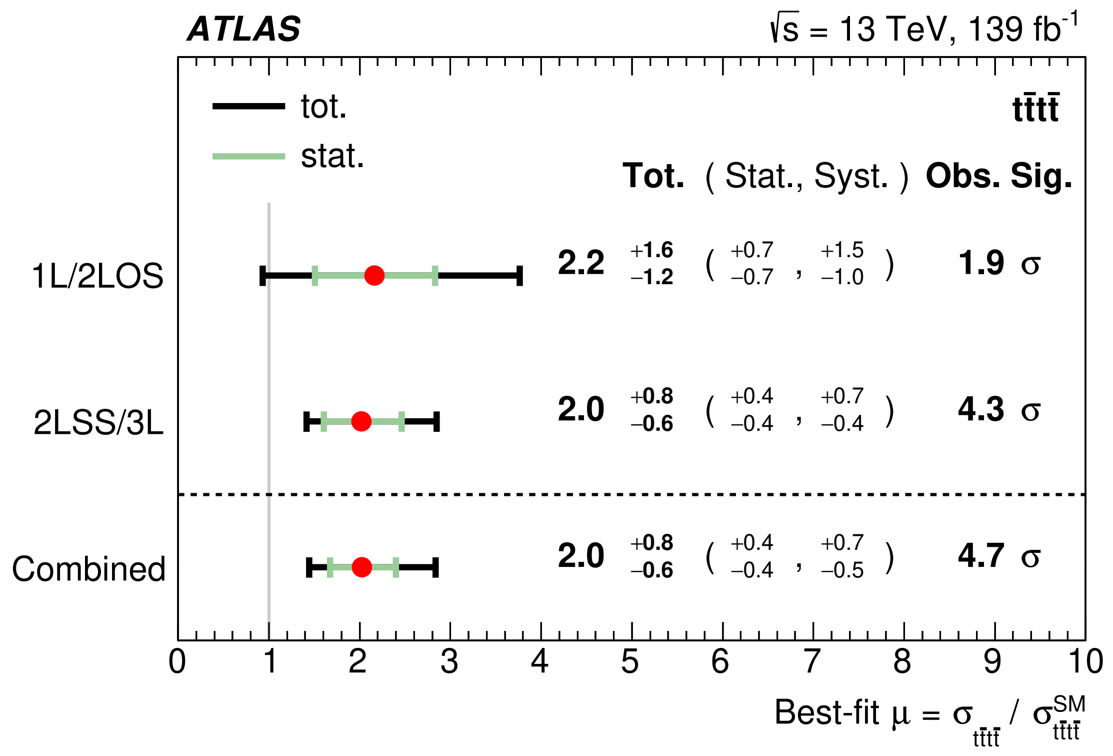




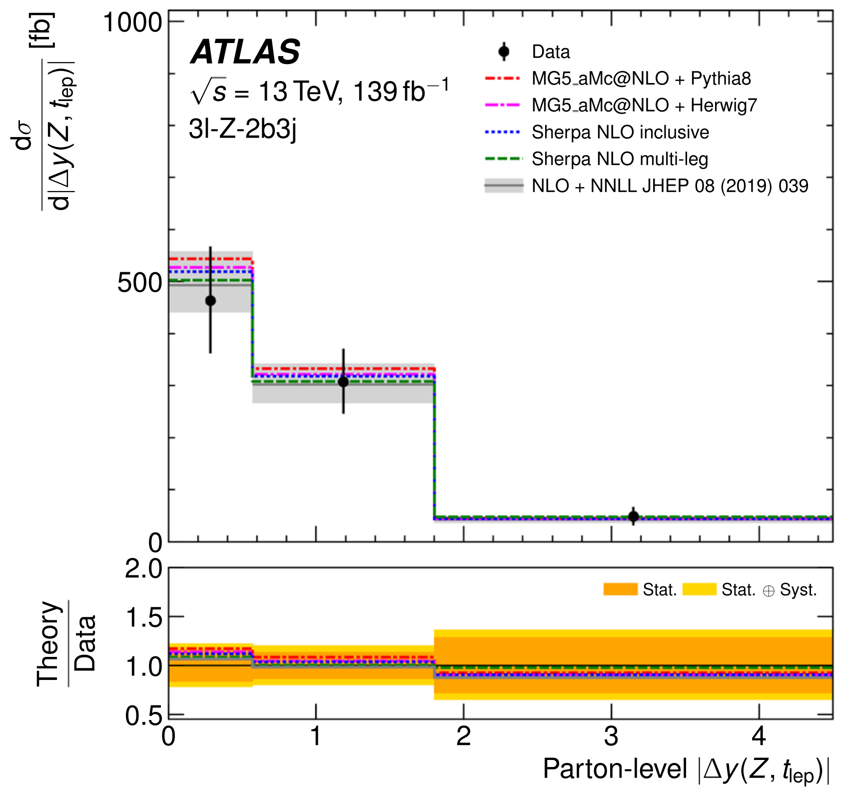
Tests of Lepton-Flavor Universality

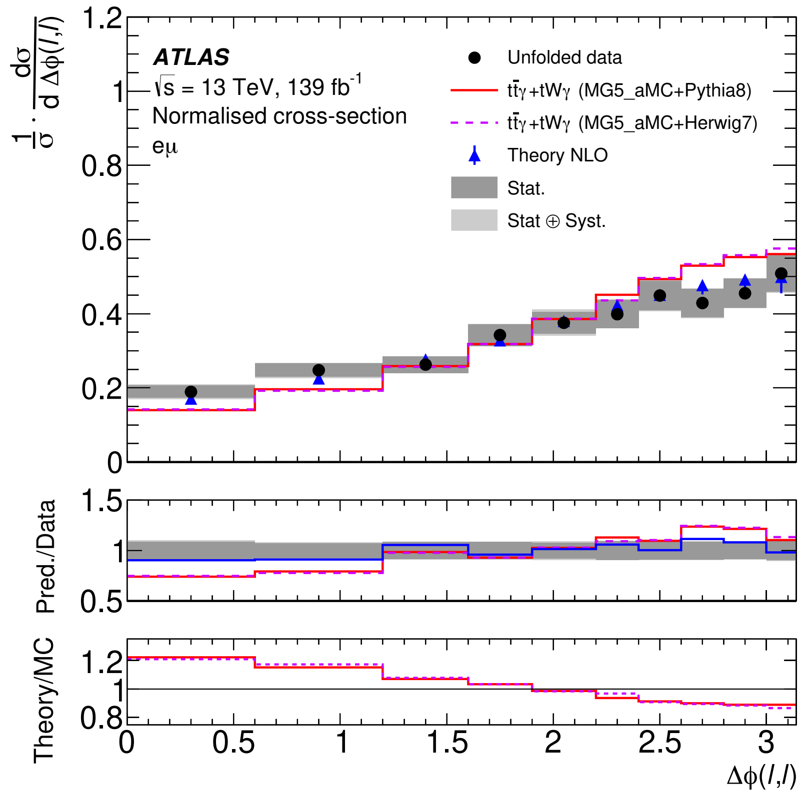


Combined Measurement of $t\bar{t}t\bar{t}$ Cross Section



Inclusive and Differential Cross Section Measurements of $t\bar{t}Z$ and $t\bar{t}\gamma+tW\gamma$

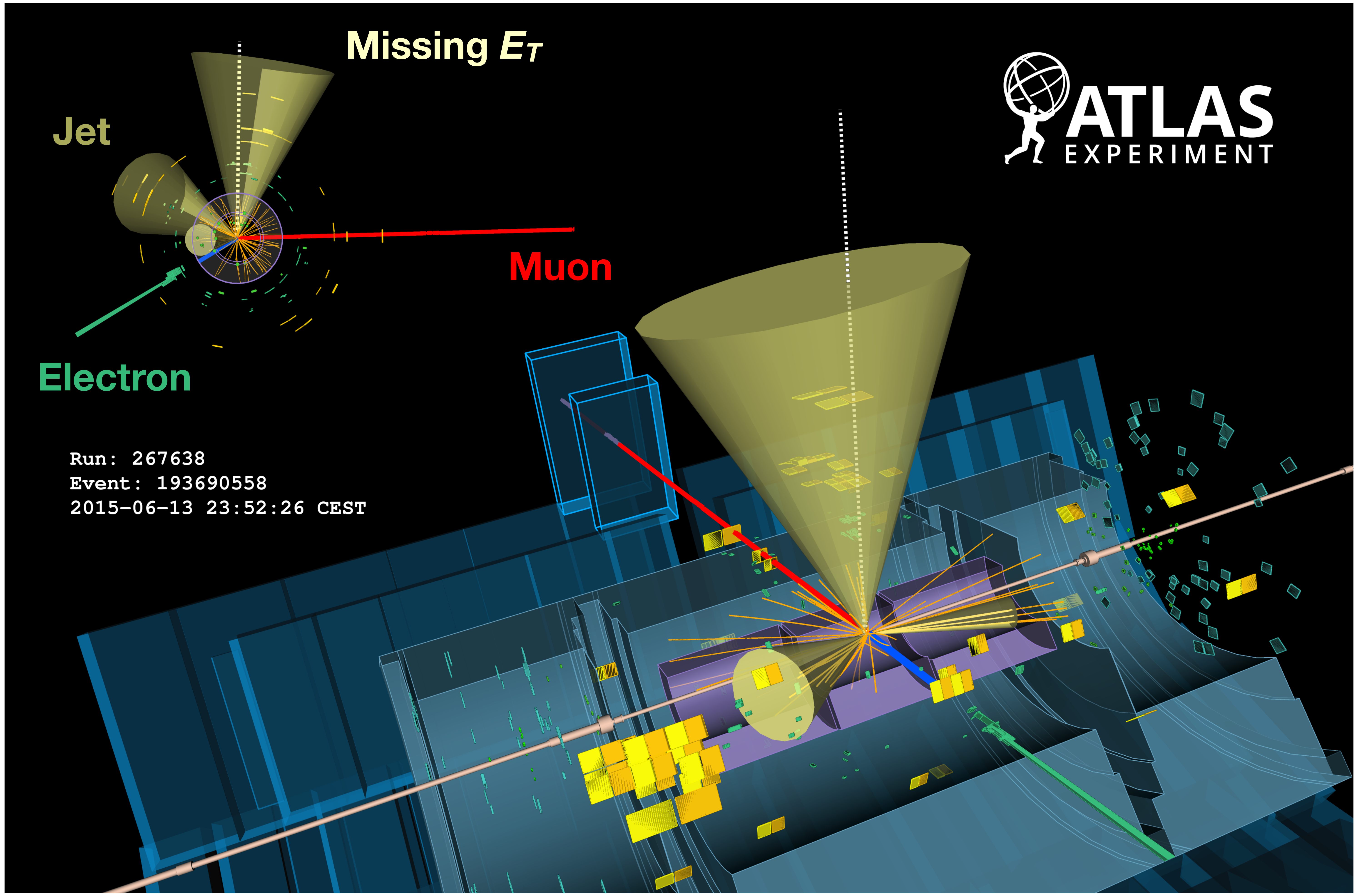




Overview of Top Quark Measurements

- Top quark signatures rely on many reconstructed objects
  - Jets (p_T resolution, scale)
  - Heavy flavor tagging (efficiency)
  - Muons, electrons (trigger, isolation)
  - Missing energy (from ν in t_{lep})
- Similar systematic uncertainties
  - Luminosity, object reconstruction
  - Theory uncertainties of fixed order calculation (μ_R/μ_F variations)
  - Showering/hadronization modeling (varying MC algorithm)

Event display for dileptonic $t\bar{t}$ candidate recorded by ATLAS



Tests of SM with Top Quarks

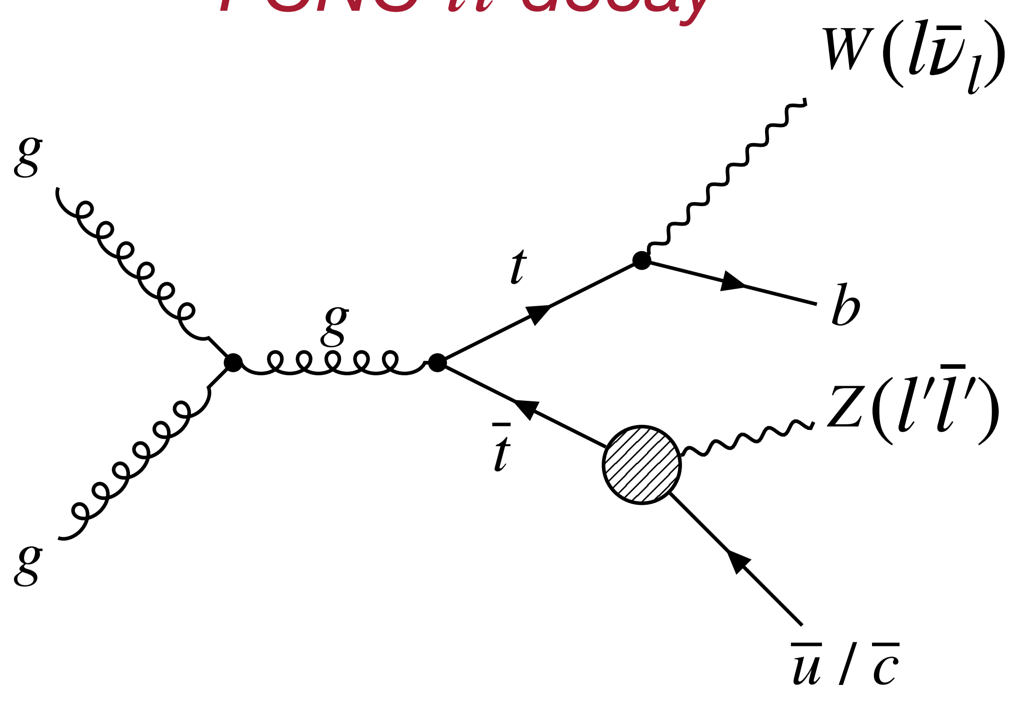
Motivation and Event Selection

- FCNC forbidden at tree level and suppressed at loop level in SM
  - Top decays via FCNC ~10^{-14}, can be 10^{-7} - 10^{-4} in BSM (SUSY, 2HDM)
  - Interpret rates of FCNC top decays in an EFT extension of SM:

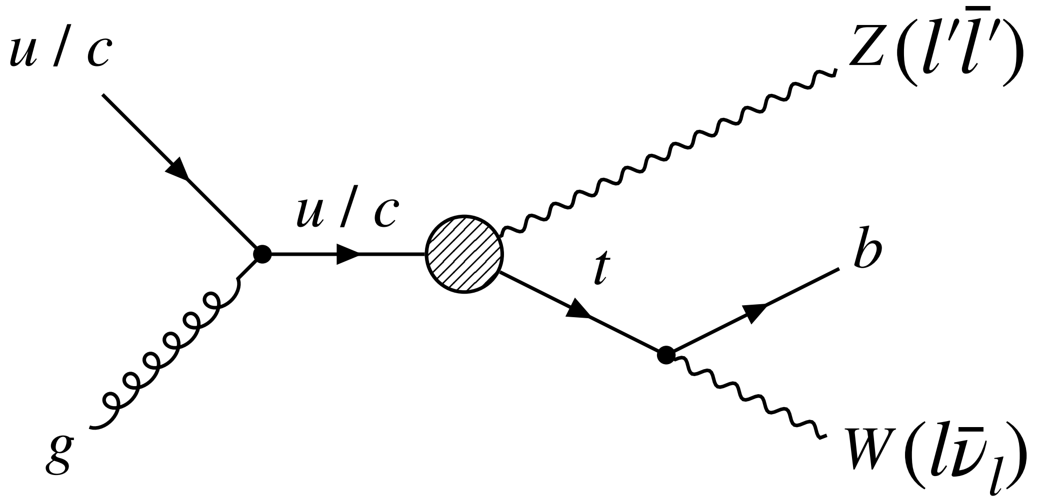
$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \frac{1}{\Lambda_{NP}^2}\sum_k C_k \mathcal{O}_k$$

  - Search for $t \to Zq$ $(q = u, c)$, sensitive to tZu and tZc couplings through C_{qB}, C_{qW}
- Improvement on previous ATLAS measurement using only 36 fb^{-1}
  - Include single-top FCNC production
  - Use MVA to better isolate FCNC signal

FCNC $t\bar{t}$ decay



FCNC tZ production



- *Require exactly* ***3 leptons*** *(cleaner than hadronic channel)*
- *Exactly* ***1 b-tagged jet*** *(DL1r MVA tagger @ 70% eff OP)*
- *Missing energy from escaping neutrino*
- *Define two (2) signal regions (SR1, SR2) targeting $t\bar{t}$ and tZ*

t_{SM} candidates reconstructed using χ^2 minimization with M_t and M_W constraint

$m_T(l_W, \nu)$ cut to reject non-prompt leptons

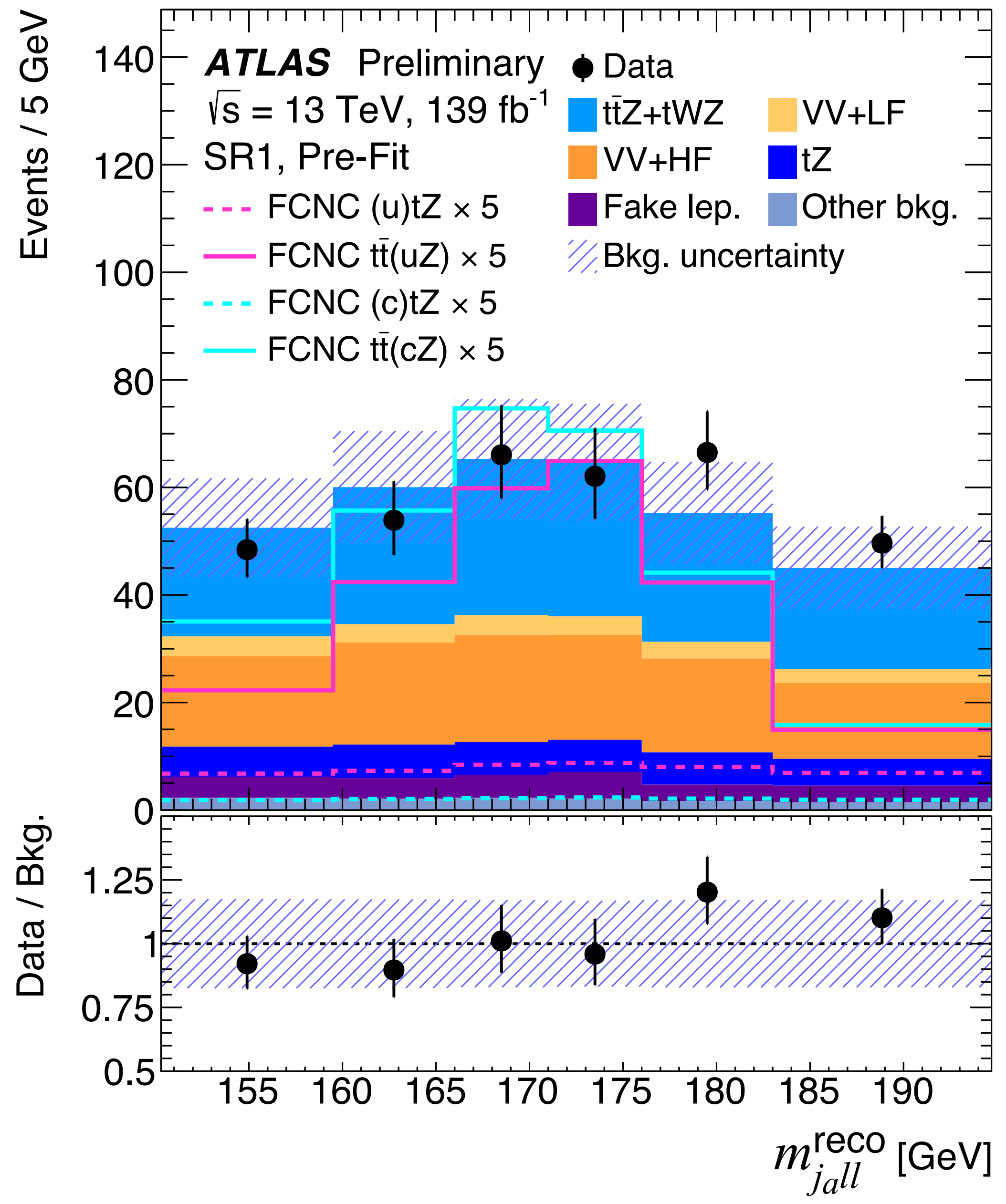
Remove overlap, favor SR1 for t_{FCNC} candidates

Common selections		
Exactly 3 leptons with $p_T(\ell_1) > 27$ GeV ≥ 1 OSSF pair, with $\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV		
SR1	SR2	
≥ 2 jets 1 b-jet	1 jet 1 b-jet	2 jets 1 b-jet
–	$m_T(\ell_W, \nu) > 40$ GeV	$m_T(\ell_W, \nu) > 40$ GeV
$\lvert m^{reco}_{j_a\ell\ell} - m_t\rvert < 2\sigma_{t_{FCNC}}$	–	$\lvert m^{reco}_{j_a\ell\ell} - m_t\rvert > 2\sigma_{t_{FCNC}}$
–	$\lvert m^{reco}_{j_b\ell_W\nu} - m_t\rvert < 2\sigma_{t_{SM}}$	$\lvert m^{reco}_{j_b\ell_W\nu} - m_t\rvert < 2\sigma_{t_{SM}}$

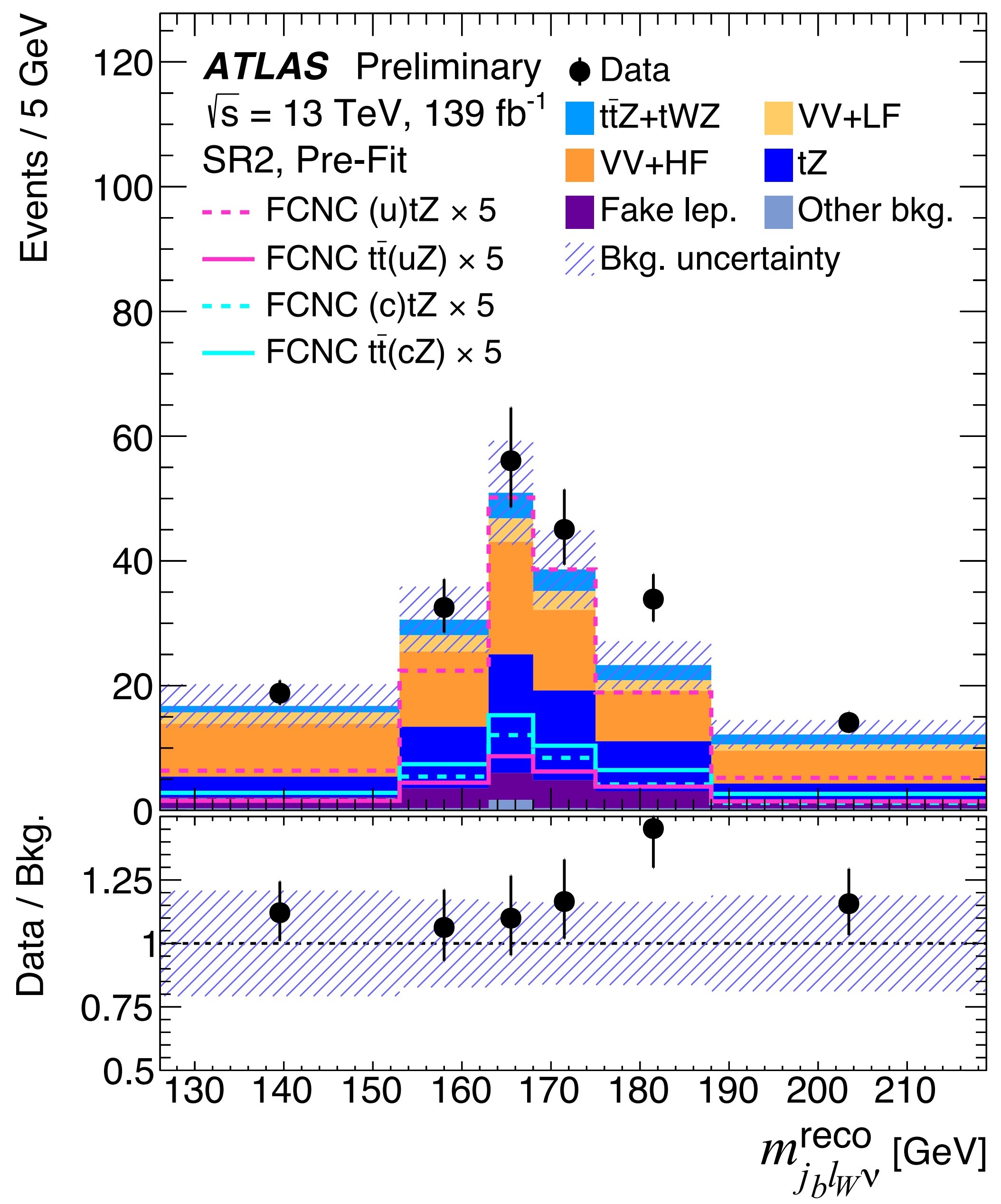
Background Estimation

- Backgrounds from prompt lepton production are dominant
  - SR1: *VV*+HF and $t\bar{t}Z$ (65% total bkg)
  - SR2: *VV*+HF and tZ (70% total bkg)
- Non-prompt leptons from *VV* and associated top production are small
- Define four control regions (CR)
  - $t\bar{t}$ CR selecting OSOF leptons
  - $t\bar{t}Z$ CR selecting 2 b-jets
  - CR1(2) defined by SR1(2) mass sidebands of $t_{FCNC(SM)}$; cut on $m_T(l_W, \nu)$ in CR2 to suppress non-prompt backgrounds

FCNC $t\bar{t}$ enriched SR1



FCNC tZ enriched SR2



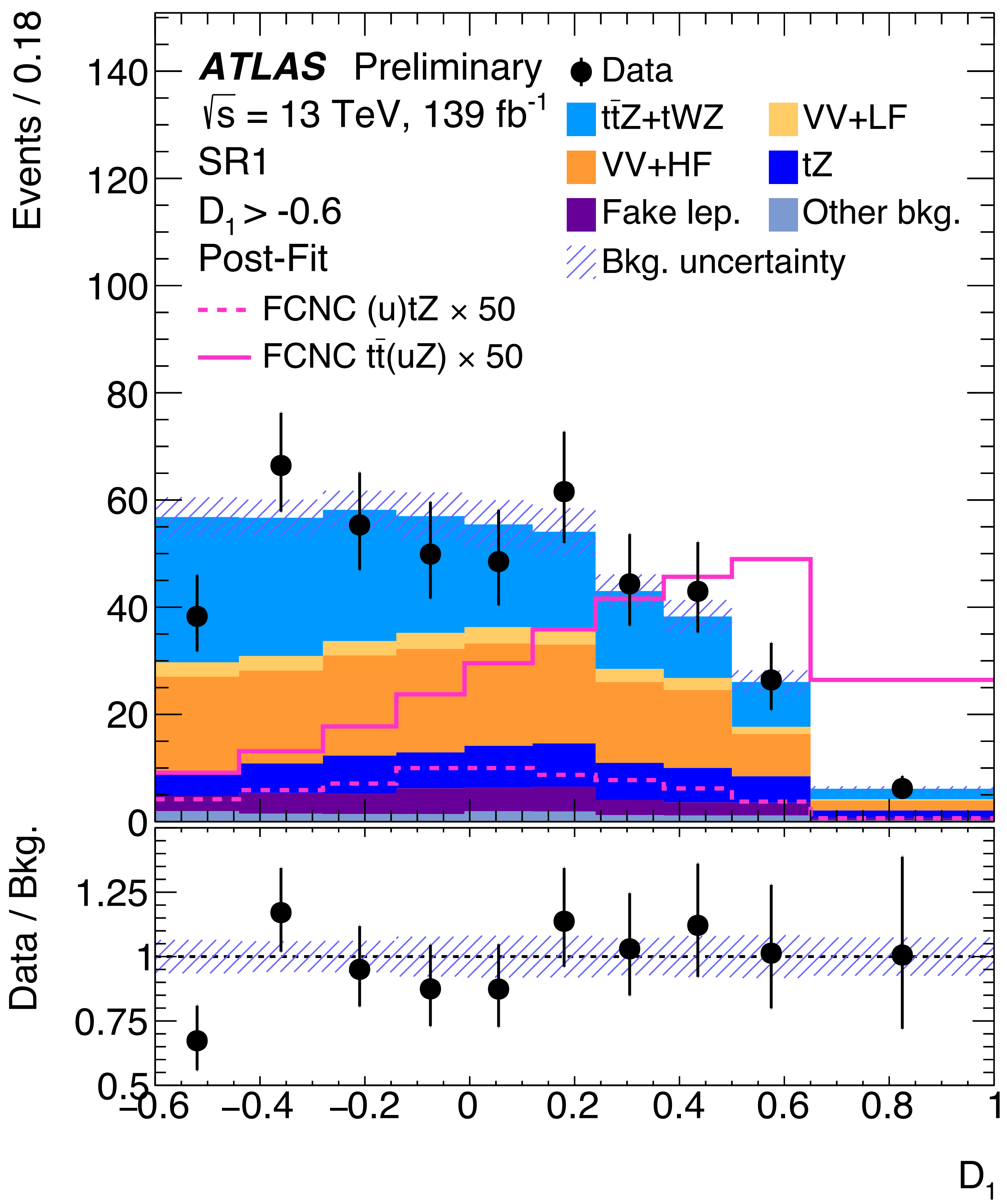
Common selections			
Exactly 3 leptons with $p_T(\ell_1) > 27$ GeV			
$t\bar{t}$ CR	$t\bar{t}Z$ CR	Side-band CR1	Side-band CR2
≥ 1 OS pair, no OSSF	≥ 1 OSSF pair with $\lvert m_{\ell\ell} - m_Z \rvert < 15$ GeV	≥ 1 OSSF pair with $\lvert m_{\ell\ell} - m_Z \rvert < 15$ GeV	≥ 1 OSSF pair with $\lvert m_{\ell\ell} - m_Z \rvert < 15$ GeV
–	–	–	$m_T(\ell_W, \nu) > 40$ GeV
≥ 1 jet	≥ 4 jets	≥ 2 jets	1 jet
1 *b*-jet	2 *b*-jets	1 *b*-jet	1 *b*-jet
–	–	$\lvert m^{\text{reco}}_{j_a\ell\ell} - m_t \rvert > 2\sigma_{t_{\text{FCNC}}}$	–
–	–	$\lvert m^{\text{reco}}_{j_b\ell_W\nu} - m_t \rvert > 2\sigma_{t_{\text{SM}}}$	$\lvert m^{\text{reco}}_{j_b\ell_W\nu} - m_t \rvert > 2\sigma_{t_{\text{SM}}}$

Statistical Analysis

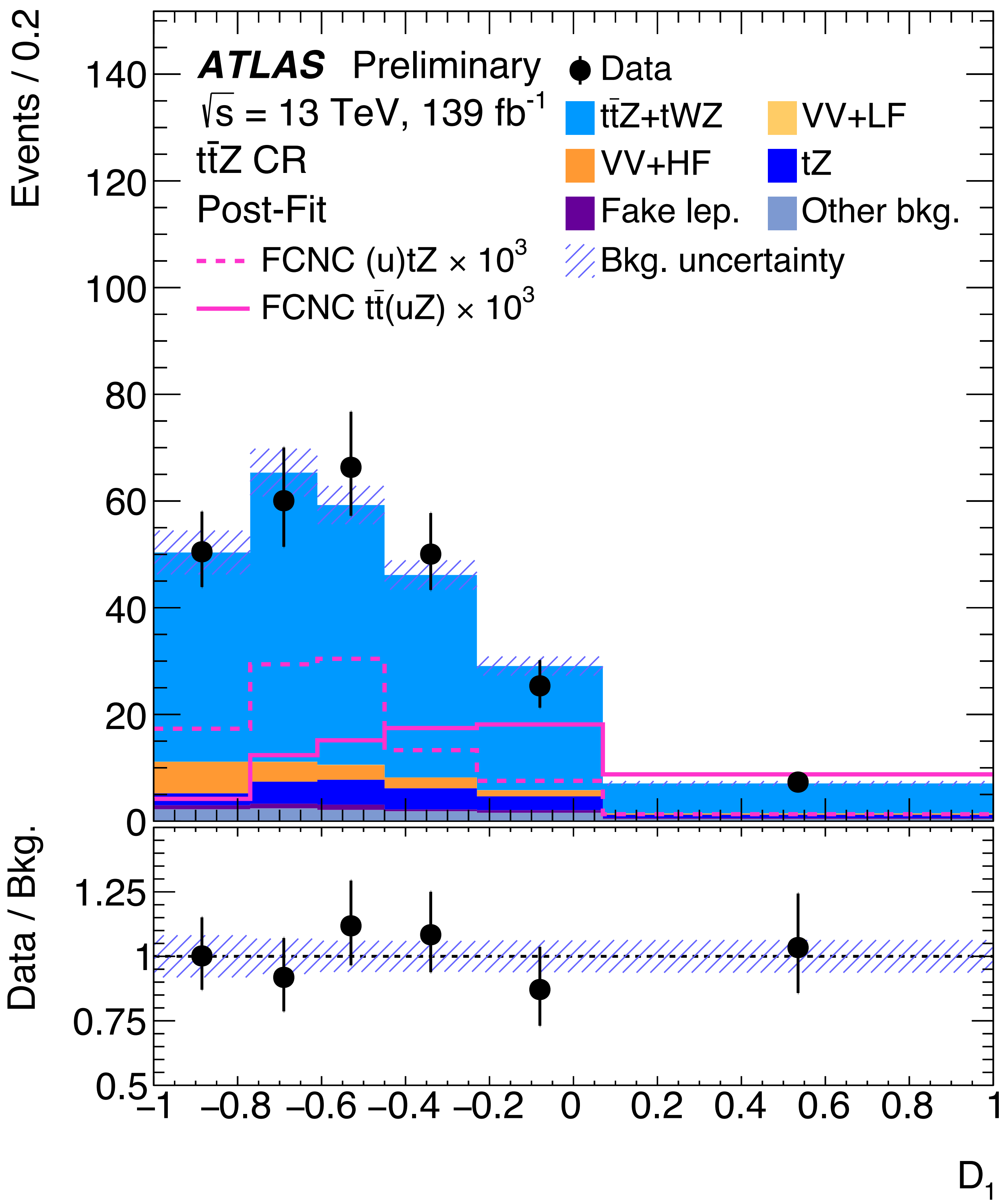
- Purity SR1 and SR2 using MVA (GBDT) trained on well-separating observables
  - SR1: D_1 built for FCNC *tZu* and *tZc*
  - SR2: D_2^u built for *tZu* single-top FCNC, D_2^c built for *tZc* inclusively
  - Use $m(t_{reco})$, dR(tt), N_{jets}, χ^2, …
- Set CL_s limits in different fits for each LH/RH *tZu* and *tZc* coupling
  - Largest uncertainty is $t\bar{t}$ cross section
- Limits obtained on FCNC branching fractions and EFT coefficients:
  - $B(t \to Zu) < 6.2 \times 10^{-5}$
  - $B(t \to Zc) < 13 \times 10^{-5}$

Post-fit results for FCNC tZu LH coupling limits

SR1 enriched in FCNC $t\bar{t}$



$t\bar{t}Z$ Control Region

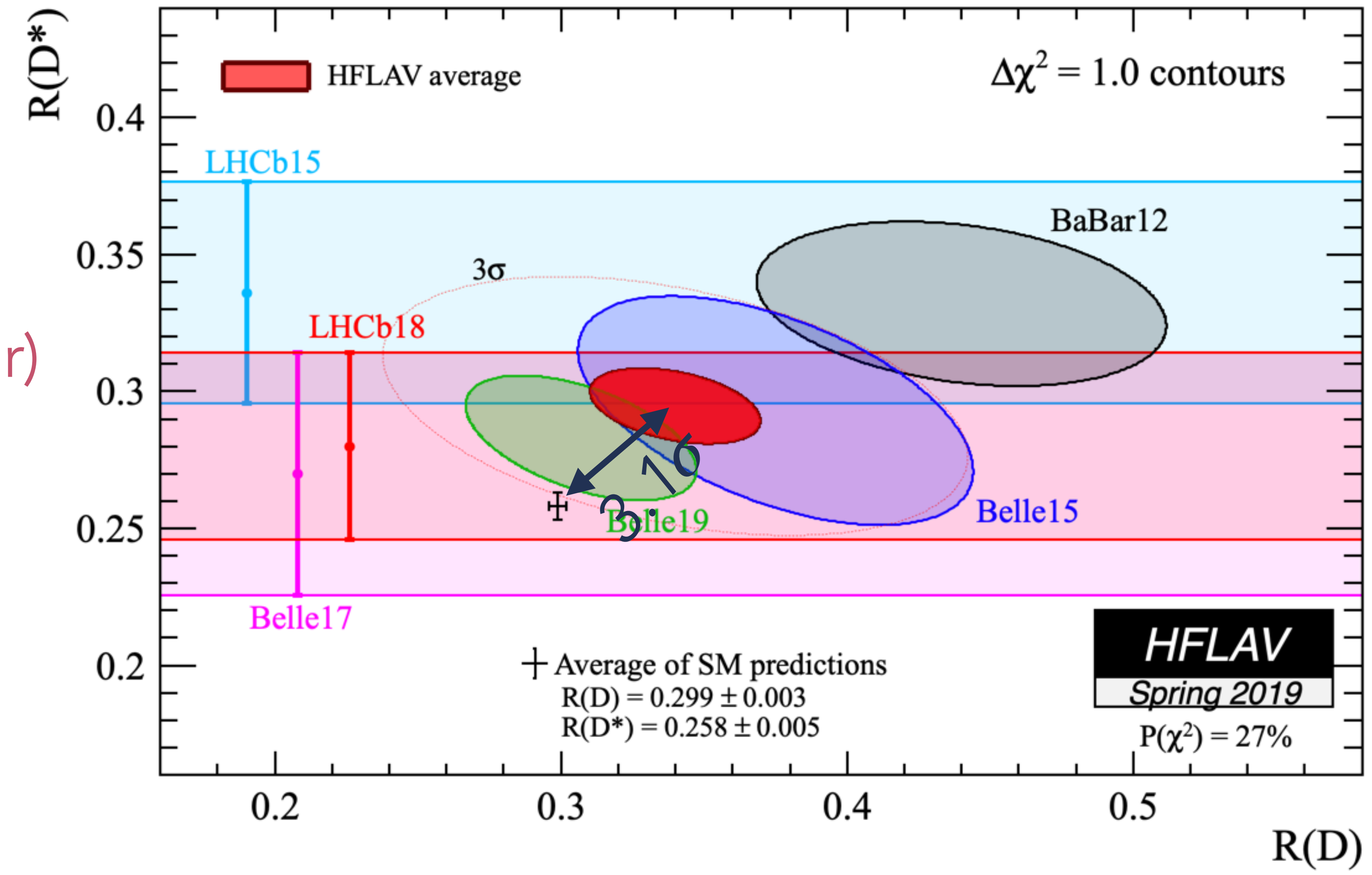


Motivation and Strategy

- Axiom of SM is universal couplings to charged leptons universally in flavors
  - LEP measured $R(\tau/\mu) = 1.070 \pm 0.026$, expected to be very close to unity (2.7σ)
  - Results by LHCb and others show tension with lepton flavor universality $R(D^{(*)})$
- Exploit large number of $t\bar{t}$ events seen by ATLAS, large sample of $W \rightarrow \mu\nu_\mu/\tau\nu_\tau$
  - Measure rates of $W \rightarrow \mu\nu_\mu$, $W \rightarrow \tau(\mu\nu_\mu\nu_\tau)\nu_\tau$
  - Relies on differences in reconstructed muon impact parameter d_0 and p_T
- Select dileptonic $t\bar{t}$ events, with at least one decay in muon channel

2007.14040

$R(D^{(*)})$ combination (LHCb, Belle, BaBar)



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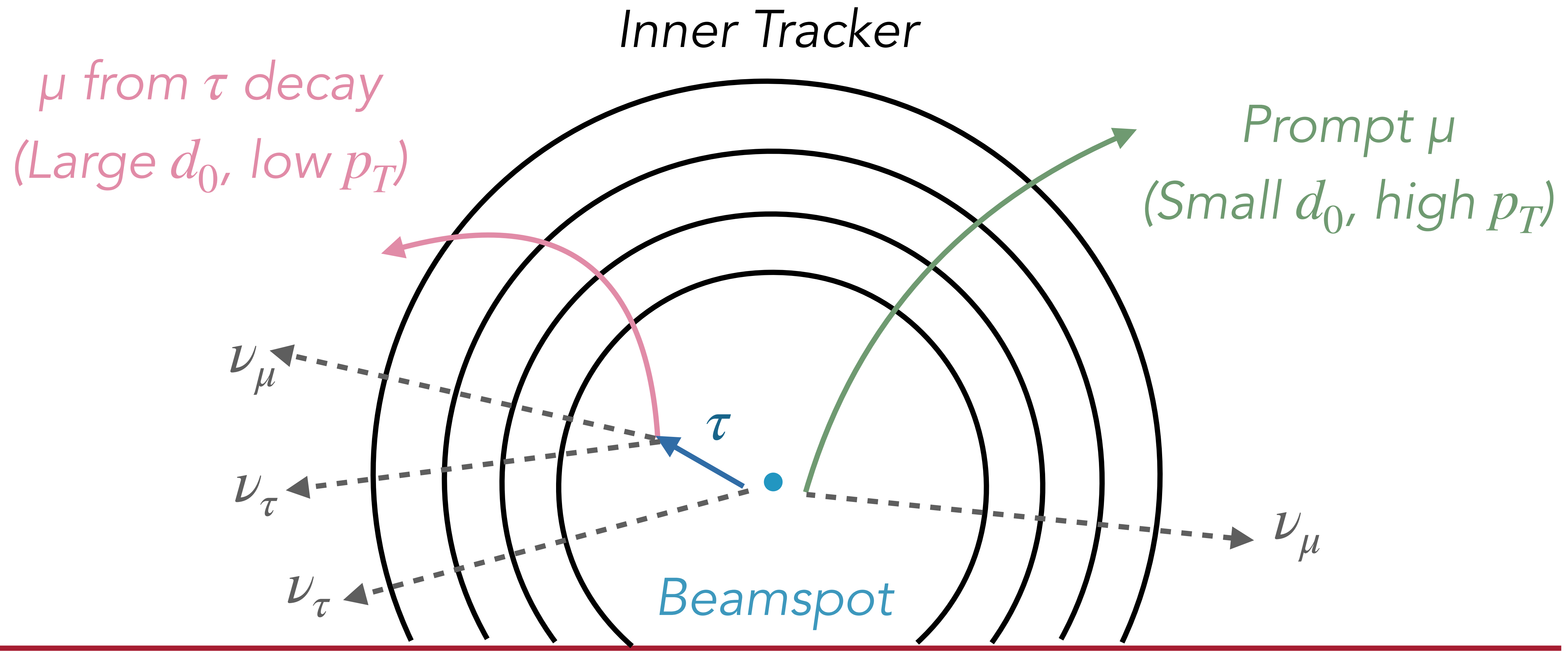
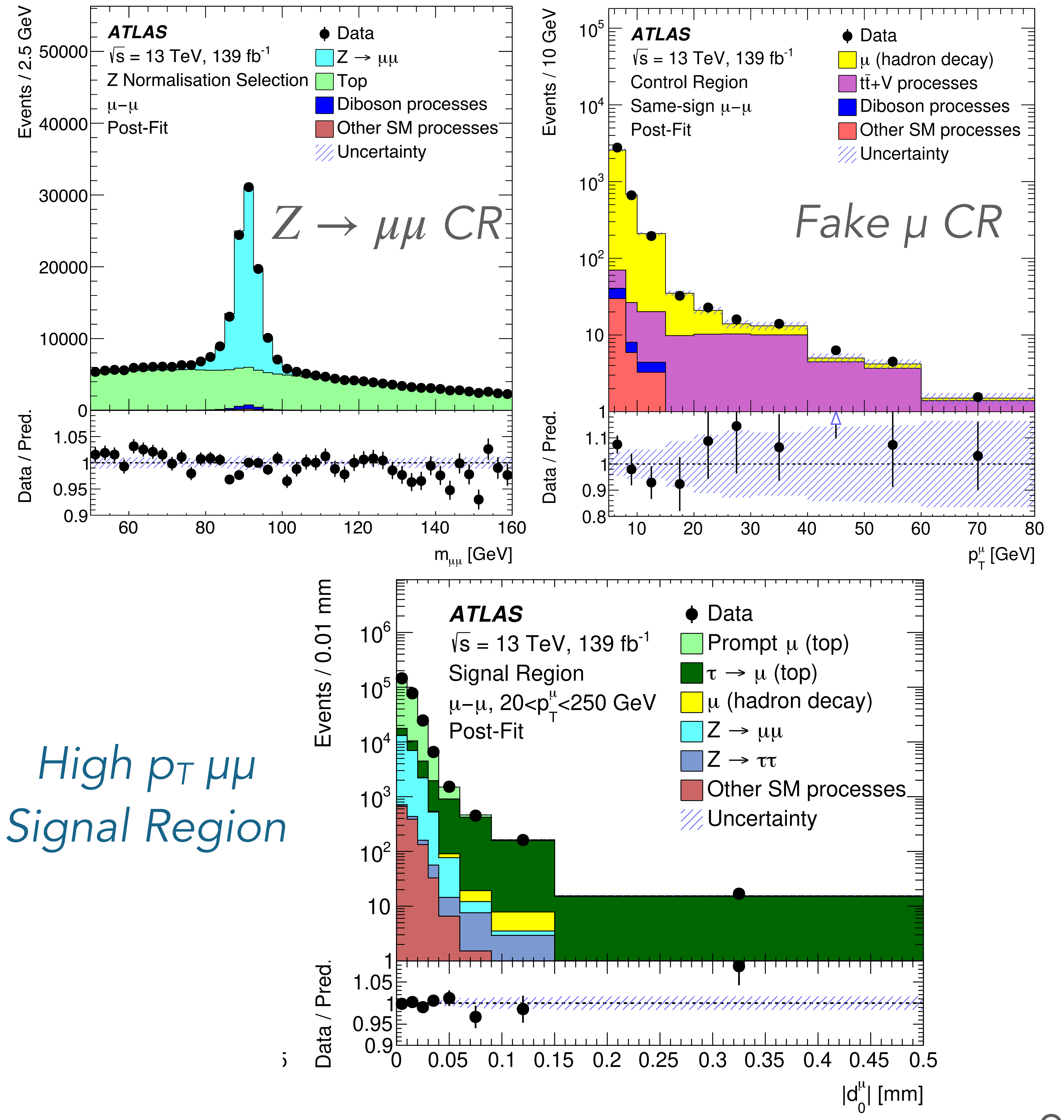
Select events with ***tag*** leptons, test origin of ***probe*** muon

Calibrate modeling of d_0 to data using $Z \rightarrow \mu\mu$



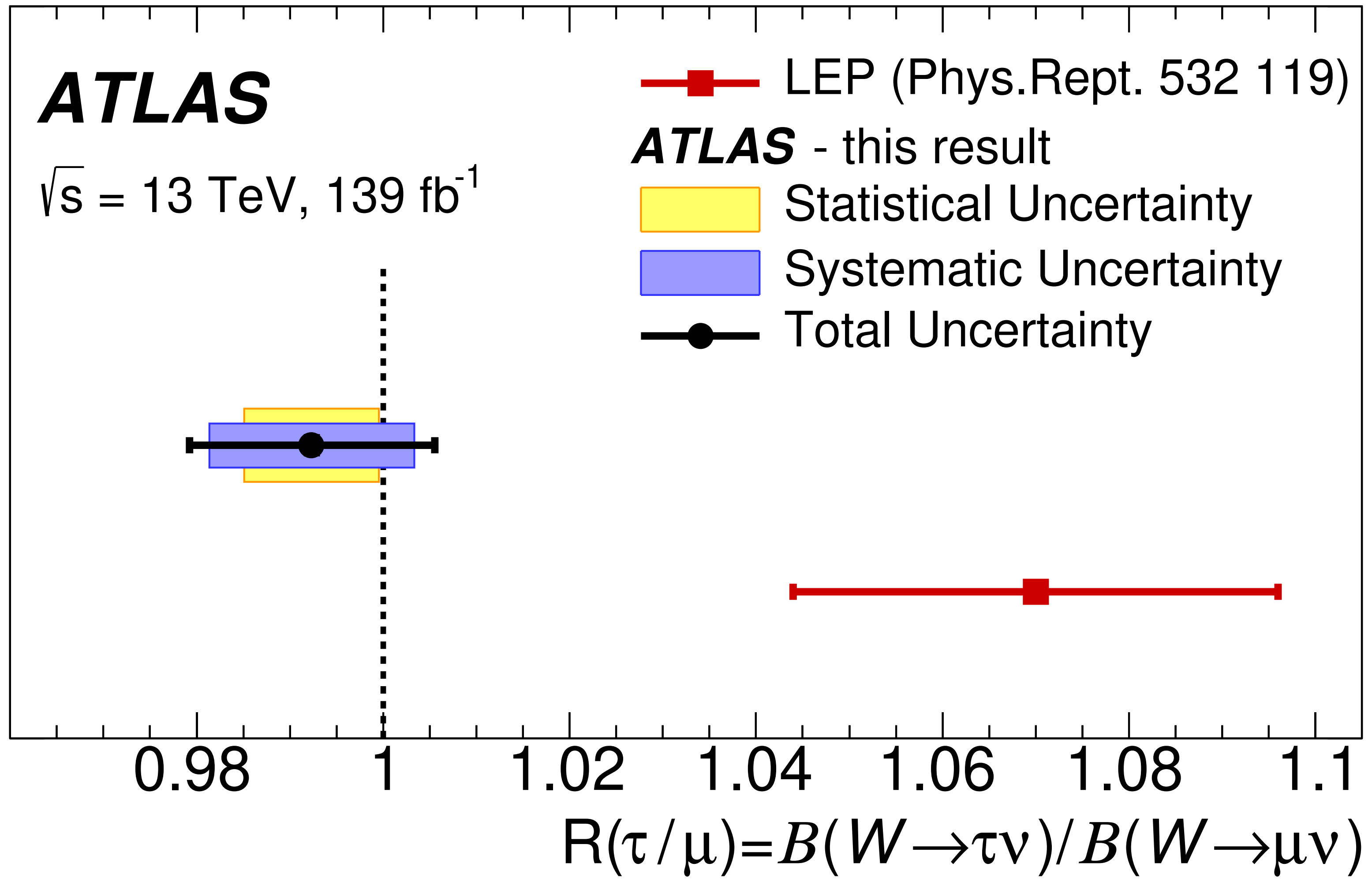
Background Estimation

- Dedicated control regions constrain large normalization of backgrounds
  - $Z \to \mu\mu$+*jets* CR, includes Z mass window (small values of $|d_0|$)
  - Non-prompt *probe* muon from b- and c-hadron decay from semi-leptonic $t\bar{t}$, select SS leptons (large values of $|d_0|$)
- Six SR binned in $p_T, |d_0|$, split by eμ/μμ
  - Modeling of *Z(μμ)+jets* background affects μμ SR only
  - Other SM backgrounds are prompt, high p_T, normalization taken from MC



Extraction of $R(\tau/\mu)$

- Systematics dominated by:
  - Calibration of high-$|d_0|$ region of prompt-μ templates (application of $Z(\mu\mu)$ calibrations to $t\bar{t}$)
  - Uncertainties due to parton showering (affecting N_{jets})
  - Muon instrumental uncertainties
  - Limited statistics of μ_{had} CR and MC $t\bar{t}$ generator

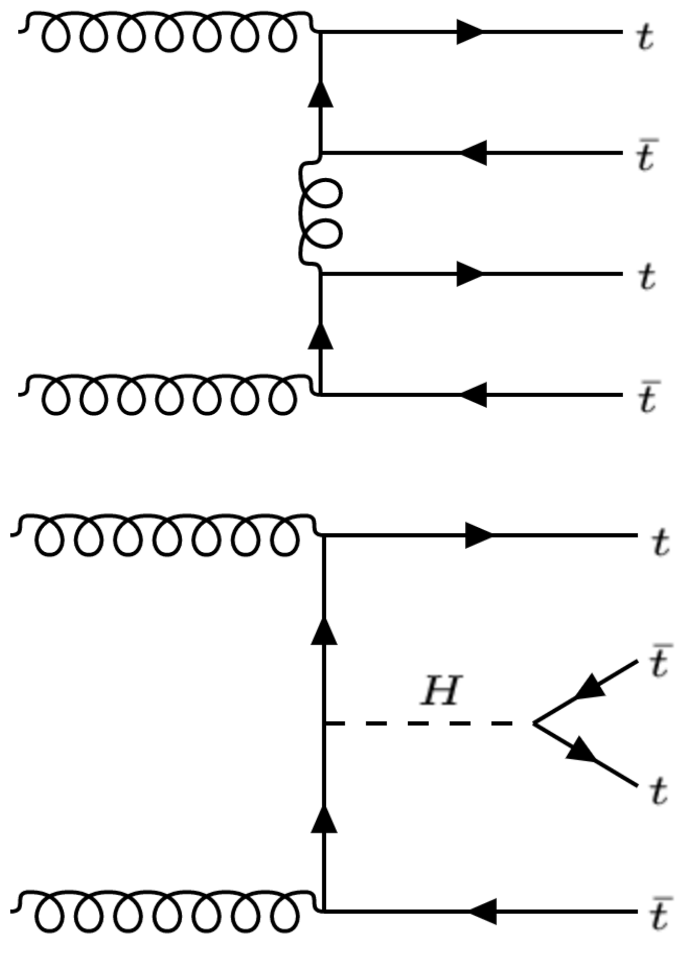


Source	Impact on $R(\tau/\mu)$
Prompt d_0^μ templates	0.0038
μ_{prompt} and $\mu_{\tau(\to\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
μ_{had} normalisation	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_T spectum variation	0.0026
μ_{had} parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{\tau(\to\mu)}$ and μ_{had} d_0^μ shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau \to \mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**

Measurements of Associated Top Production

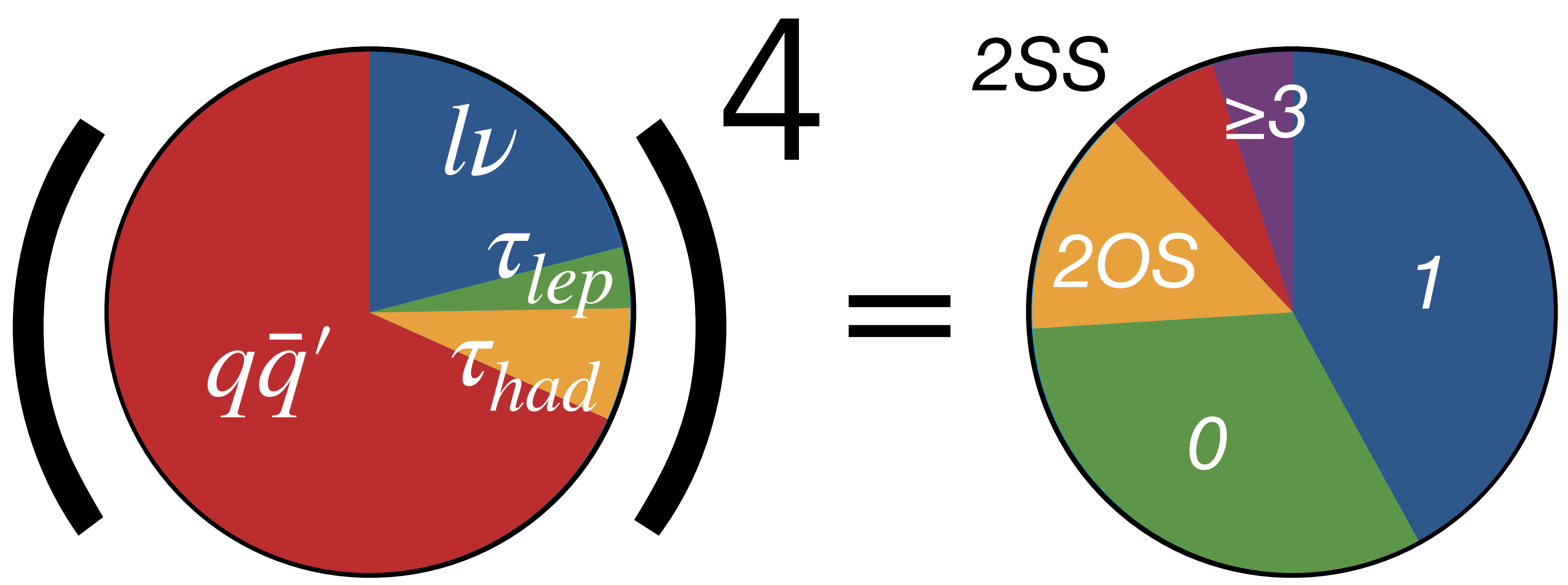
Motivation and Strategy

- SM $t\bar{t}t\bar{t}$ production is sensitive to many BSM effects and 4-fermion EFT operator
  - 2HDM H/A, gluinos, top-philic BSM fields
- Cross section at 13 TeV is 11.97 fb at NLO in QCD and QED (1711.02116)
- Split into separate analysis channels
  - 2lSS/3l: 12% of $t\bar{t}t\bar{t}$, cleaner channel (2007.14858), observed 4.3σ significance
  - 2OS/1l: 56% of $t\bar{t}t\bar{t}$, dominated by $t\bar{t}b\bar{b}$ background (highlighted in this talk)
- Events with many jets, b-jets, large-R jets, pseudo-continuous b-tagging

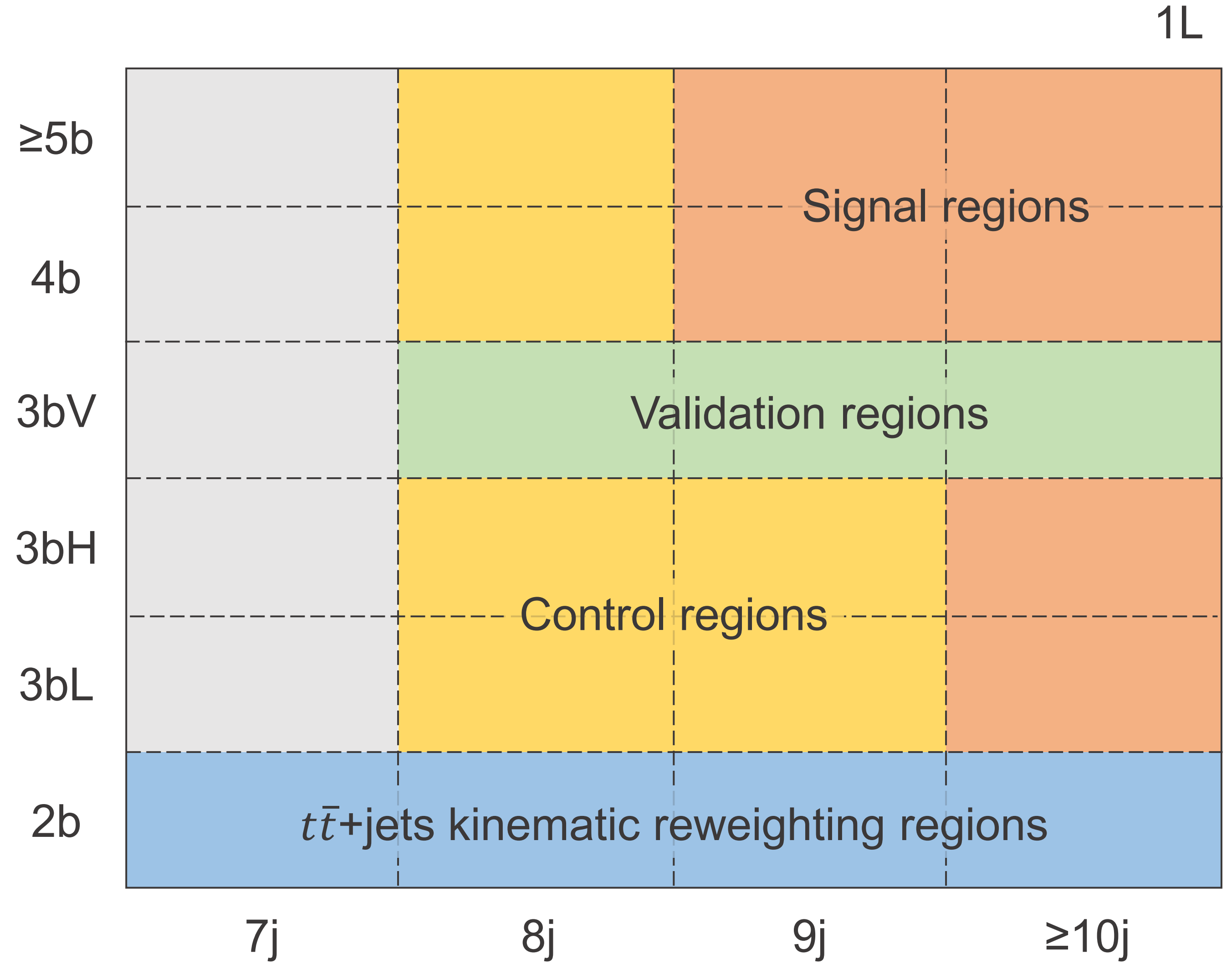


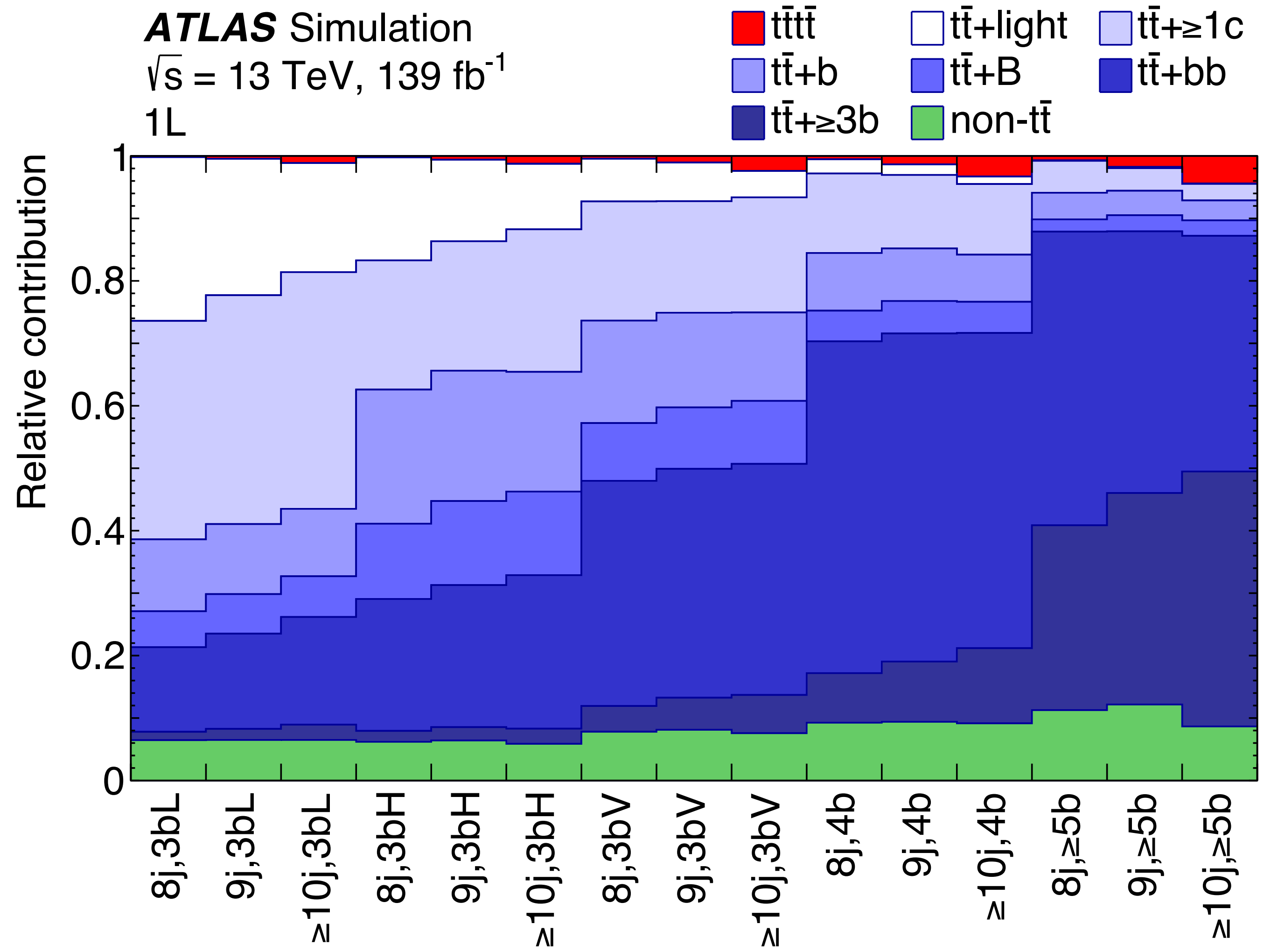
$B(t \to Wb)$ ~ 100%, channels determined by W decays

$t\bar{t}t\bar{t}$ Channels (# of leptons)



Regions in 1L Channel

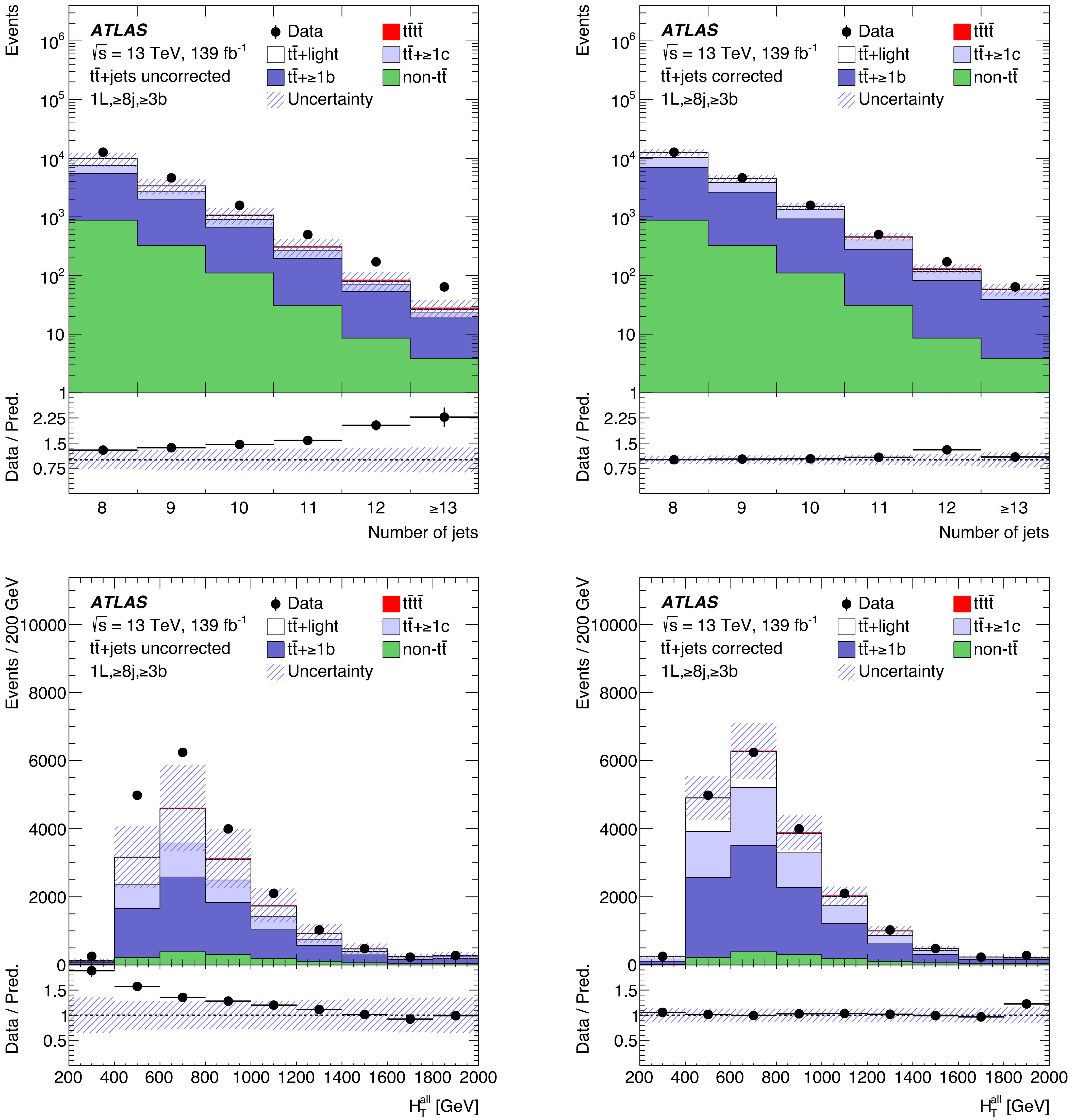




Sequential Reweighting

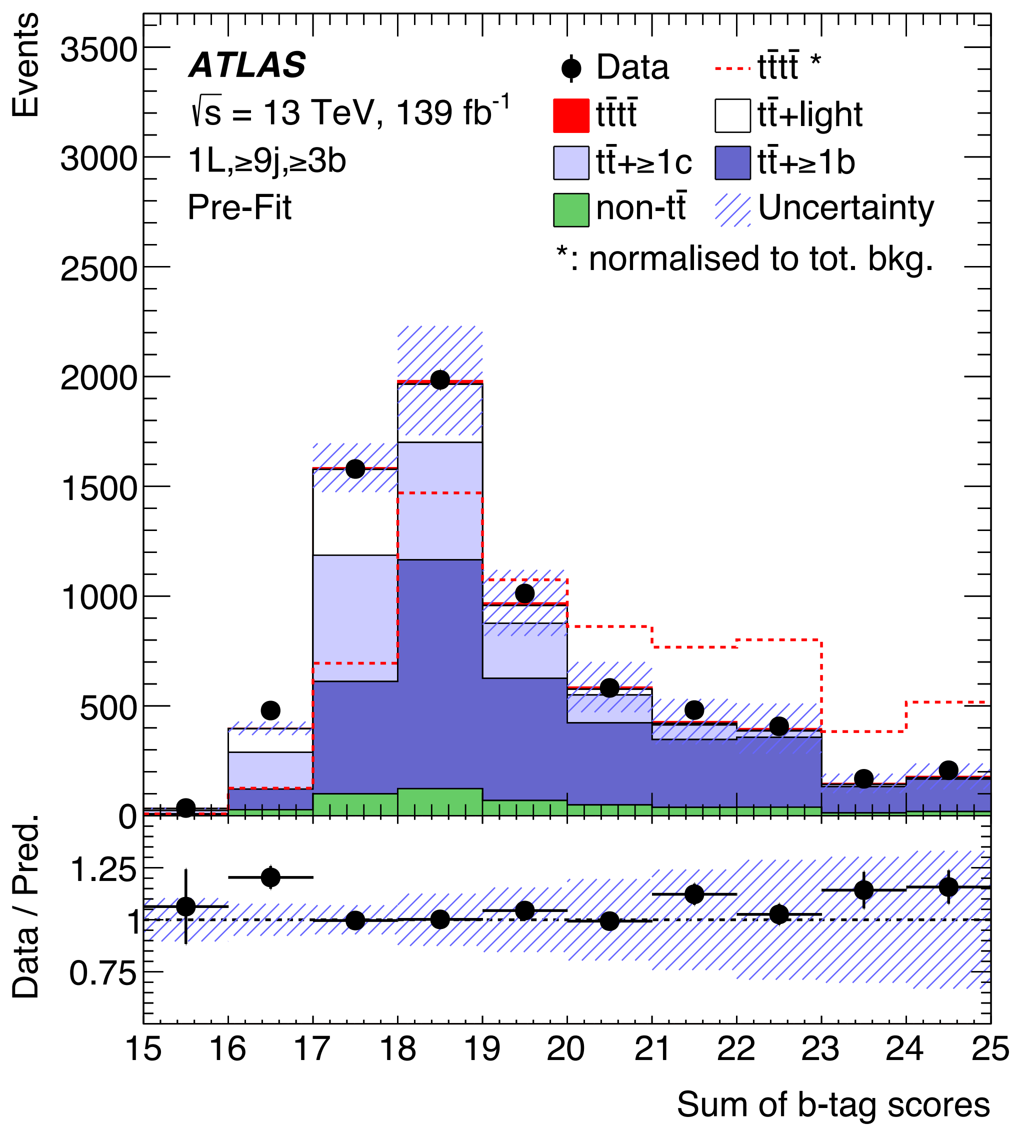
- Modeling in high N_{jets} relies heavily on PS but is not reliable - needs correction
- $t\bar{t}$+jets rescaled by flavor in dedicated fit
  - *$t\bar{t}$+light/c/b rescaled by 0.99, 1.58, 1.33*
- Correct modeling of $t\bar{t}$+jets N_{jets} in 1L/2LOS SRs using 2 *b*-jet region
  - Reweight in (N_{jets}, $N_{LR\text{-}jets}$), H_T, and ΔR^{jj}_{avg}
- Reweighting procedure **significantly improves modeling** at high multiplicities

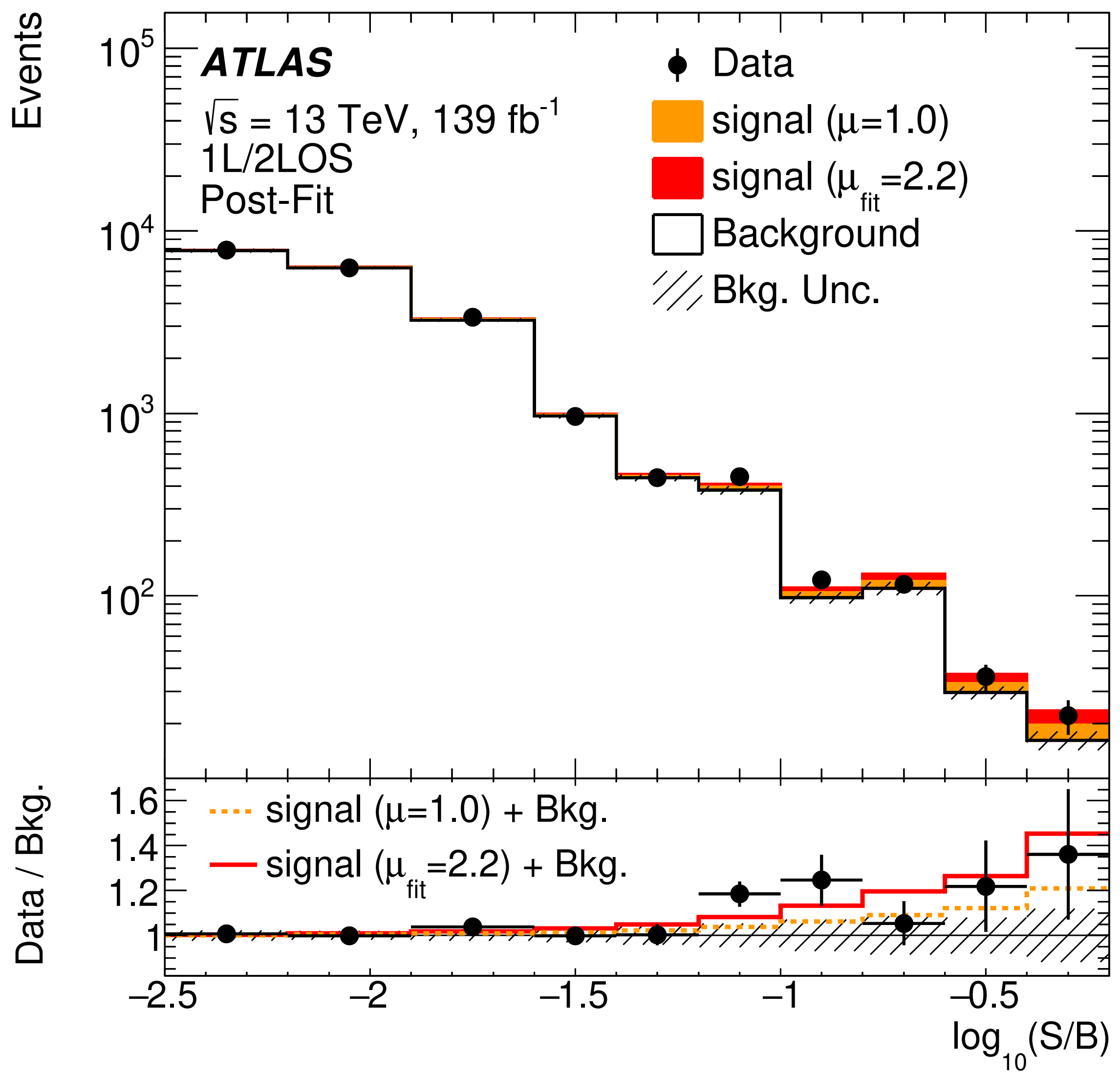
Before Reweighting | *After Reweighting*

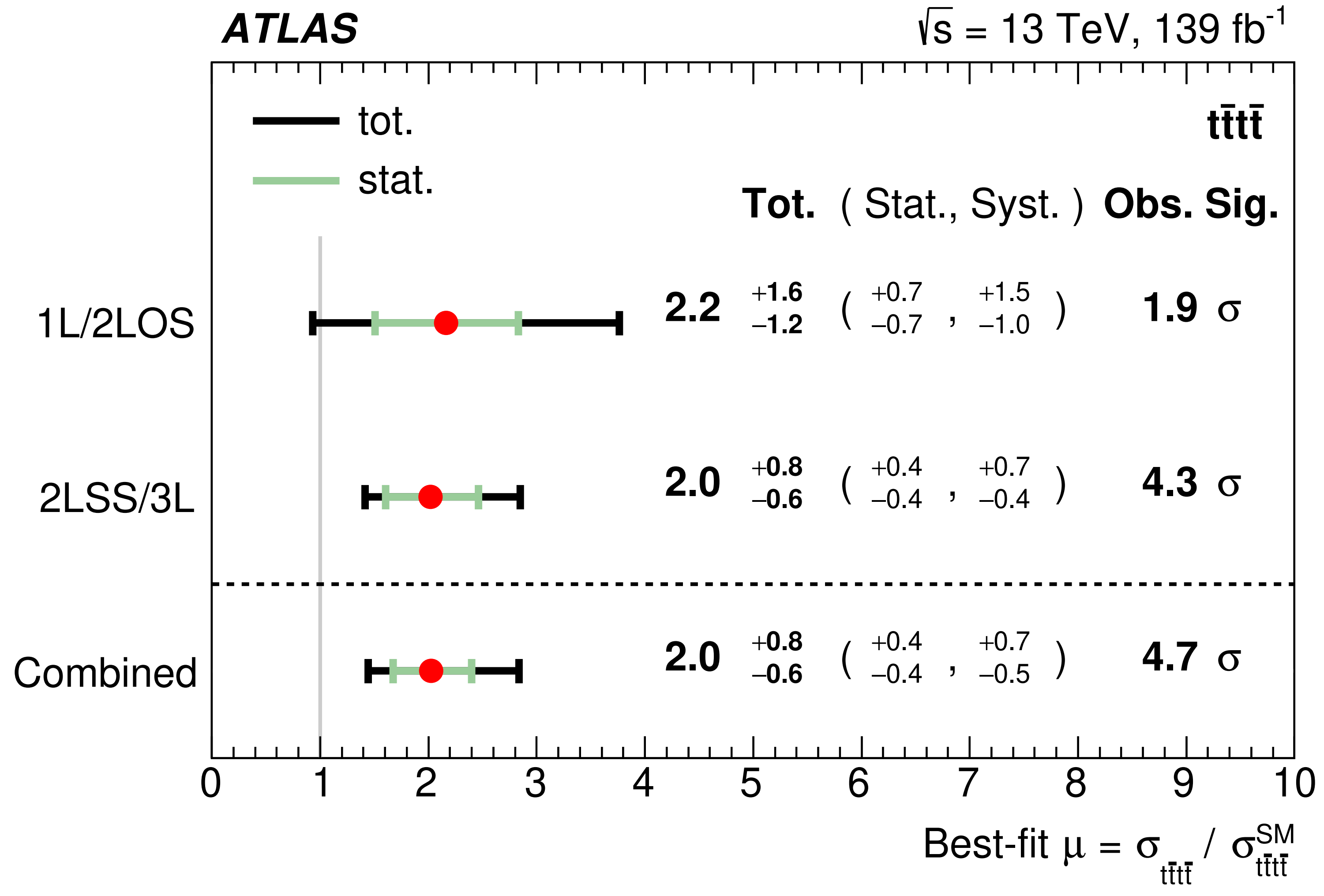


Fit and Results

- Train BDTs in each SR, most powerful variables are H_T and sum of pseudo-continuous b-tagging scores of leading 6 jets
- PL fit is performed in BDT score and H_T
- Dominant systematics due to modeling
  - Parton shower evaluated using alternate algorithm
  - Modeling of large $t\bar{t}b\bar{b}$ background (5FS/4FS)
- 1L/2LOS measurement combined with earlier multi-lepton channels, 4.7σ observed significance
  - Cross section measured 24^{+7}_{-6} fb within 2 standard deviations of SM prediction 12.0 ± 2.4 fb

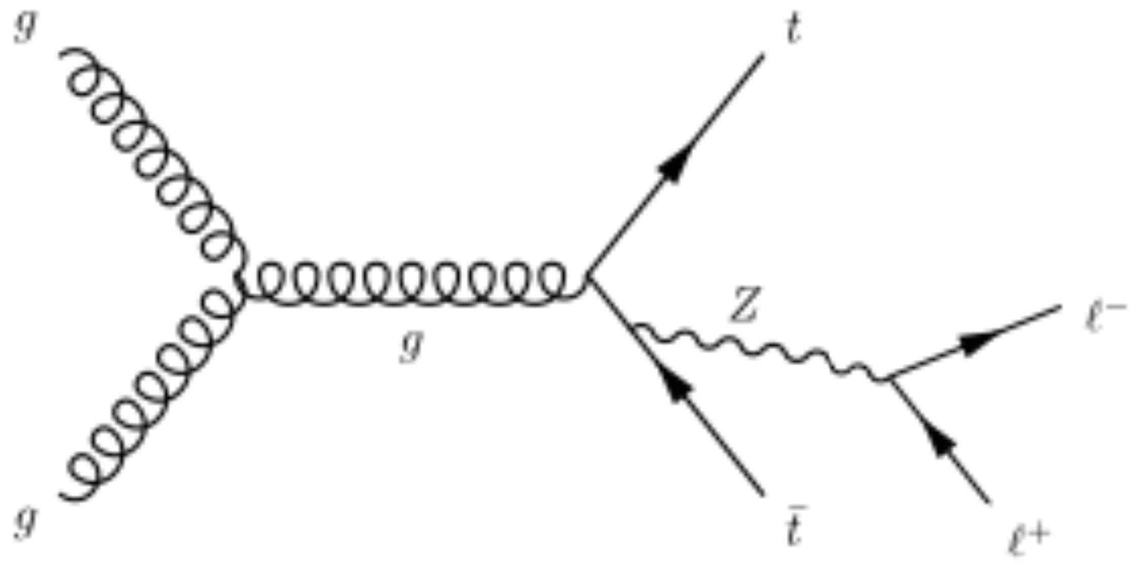






Motivation and Selections

- Measurements of $t\bar{t}Z$ sensitive to tZ EW coupling
  - Differential measurement useful for theoretical predictions from MC generators
- Inclusive cross section performed at parton level
- Differential cross sections at parton/particle level
  - No kinematic selections applied at parton level
  - Similar selections at particle level to detector level
- $t\bar{t}Z$ modeled at NLO+NNLL in QCD with EW corrections, normalized to full off-shell cross section



Split into two regions based on the $t\bar{t}$ decay

Trilepton: semi-leptonic

Tetralepton: dileptonic

Trilepton Region

Inclusive

≥4j, =1b @60%	≥3j, ≥2b @70%

Differential

≥3j, ≥2b @80%

- Split Inclusive regions to **isolate WZ background** (few b-jets expected)
- Single differential region to **boost statistics**

Tetralepton Region (Inclusive and Differential)

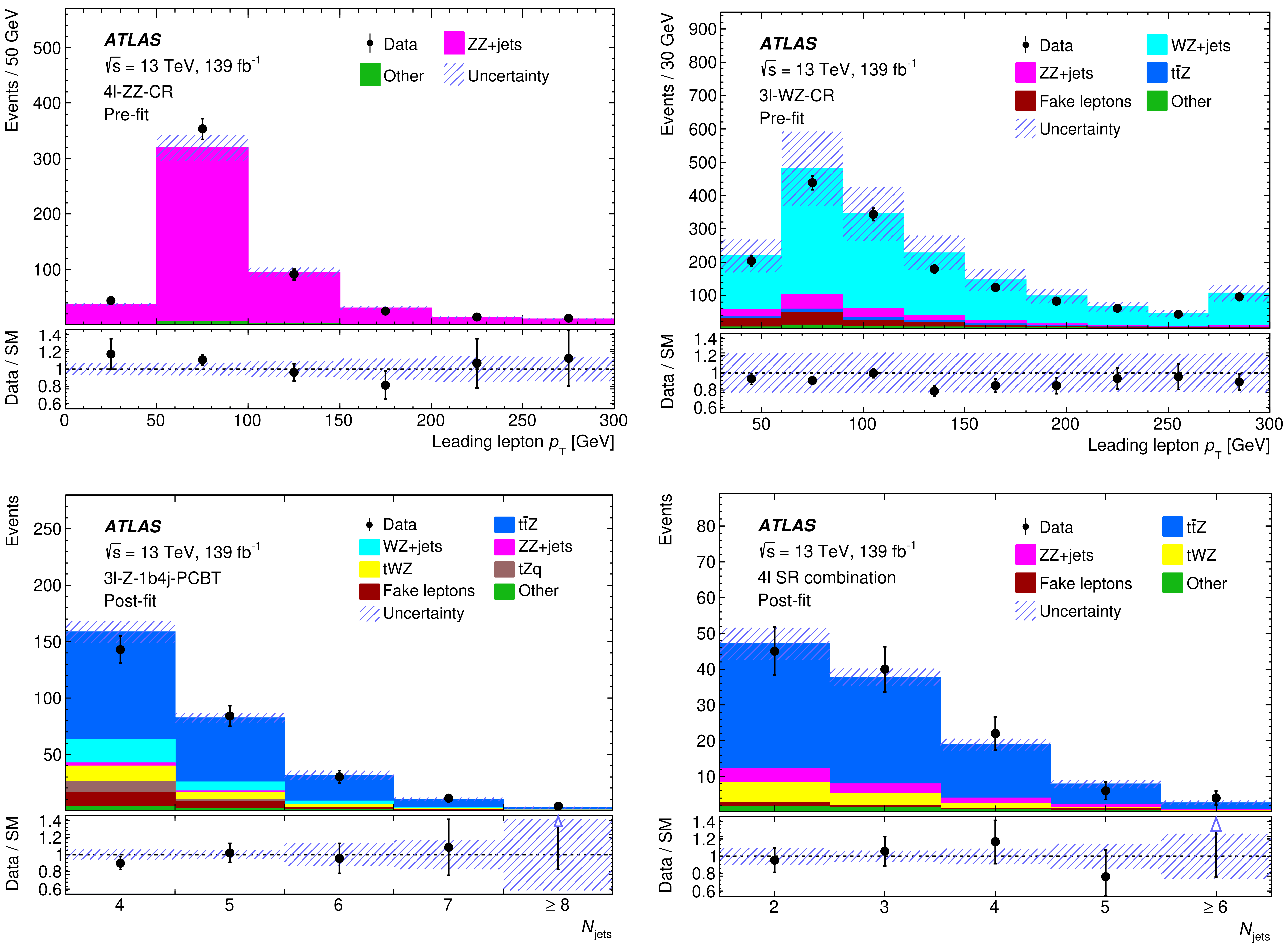
ee+μμ, =1b @ 85%	ee+μμ, ≥2b @ 85%
eμ+μe, =1b @ 85%	eμ+μe, ≥2b @ 85%

- Split channels based on the flavor of the non-Z candidate lepton pair to **isolate ZZ background**

Background Estimation

- Control regions for WZ (b-jet veto) and ZZ + jets (require 2 OSOF lepton pairs)
- Largest uncertainties are *ttZ* parton shower, *tWZ* modeling, and b-tagging
- Check compatibility through fits with either or both of 3l and 4l regions
- Good agreement with NLO+NNLL prediction:
  - $\sigma_{t\bar{t}Z} = 0.99 \pm 0.05$ (stat) $\pm\, 0.08$ (syst) pb
  - $\sigma_{t\bar{t}Z}^{NLO+NNLL} = 0.86 \pm {}^{+0.07}_{-0.08}$ (scale) $\pm\, 0.02$ (PDF) (2001.03031)

Channel	$\mu_{t\bar{t}Z}$
Trilepton	1.17 ± 0.07 (stat.) ${}^{+0.12}_{-0.11}$ (syst.)
Tetralepton	1.21 ± 0.15 (stat.) ${}^{+0.11}_{-0.10}$ (syst.)
Combination ($3\ell + 4\ell$)	1.19 ± 0.06 (stat.) $\pm\, 0.10$ (syst.)



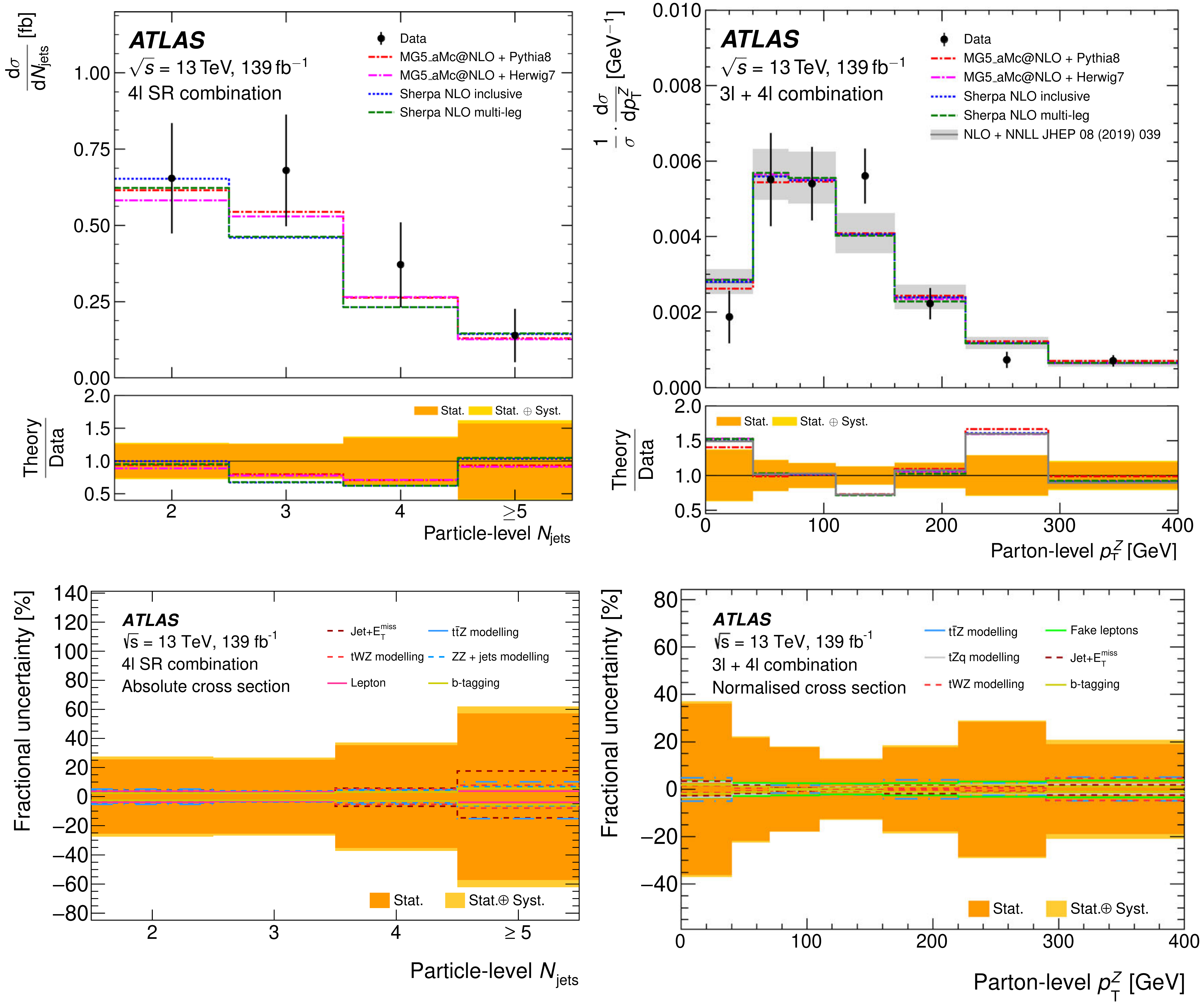
Unfolded Observables

Eur. Phys. J. C (2021) 81:737

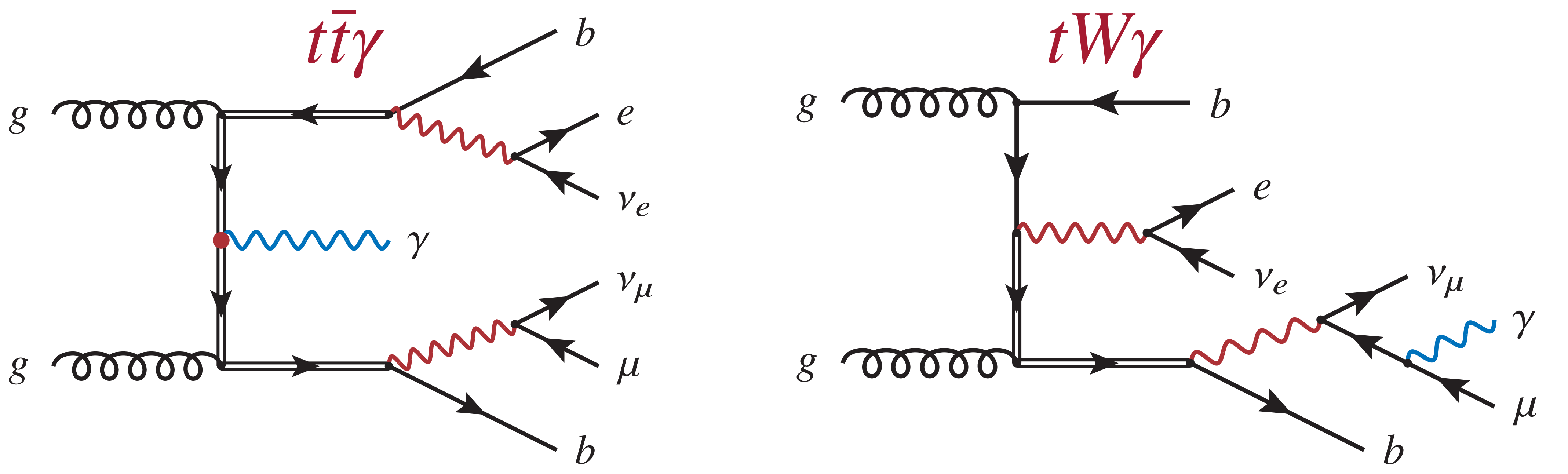
- Differential results dominated by statistical uncertainties, signal modeling and b-tagging

- Observables sensitive to tZ coupling, $t\bar{t}$ spin correlations, and MC generator modeling

- Generally good agreement between unfolded distributions and MC/theory predictions

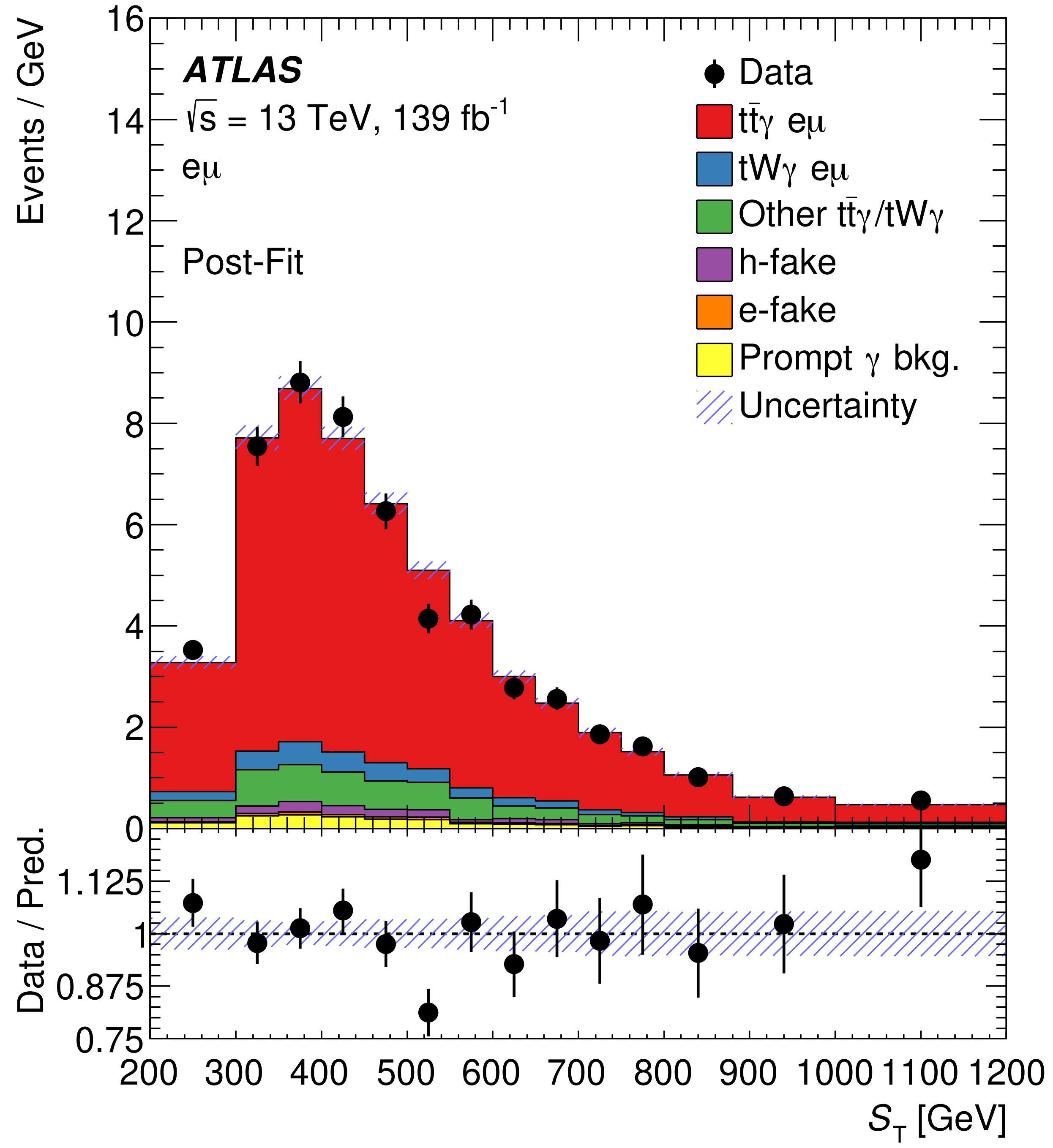


Motivation and Strategy



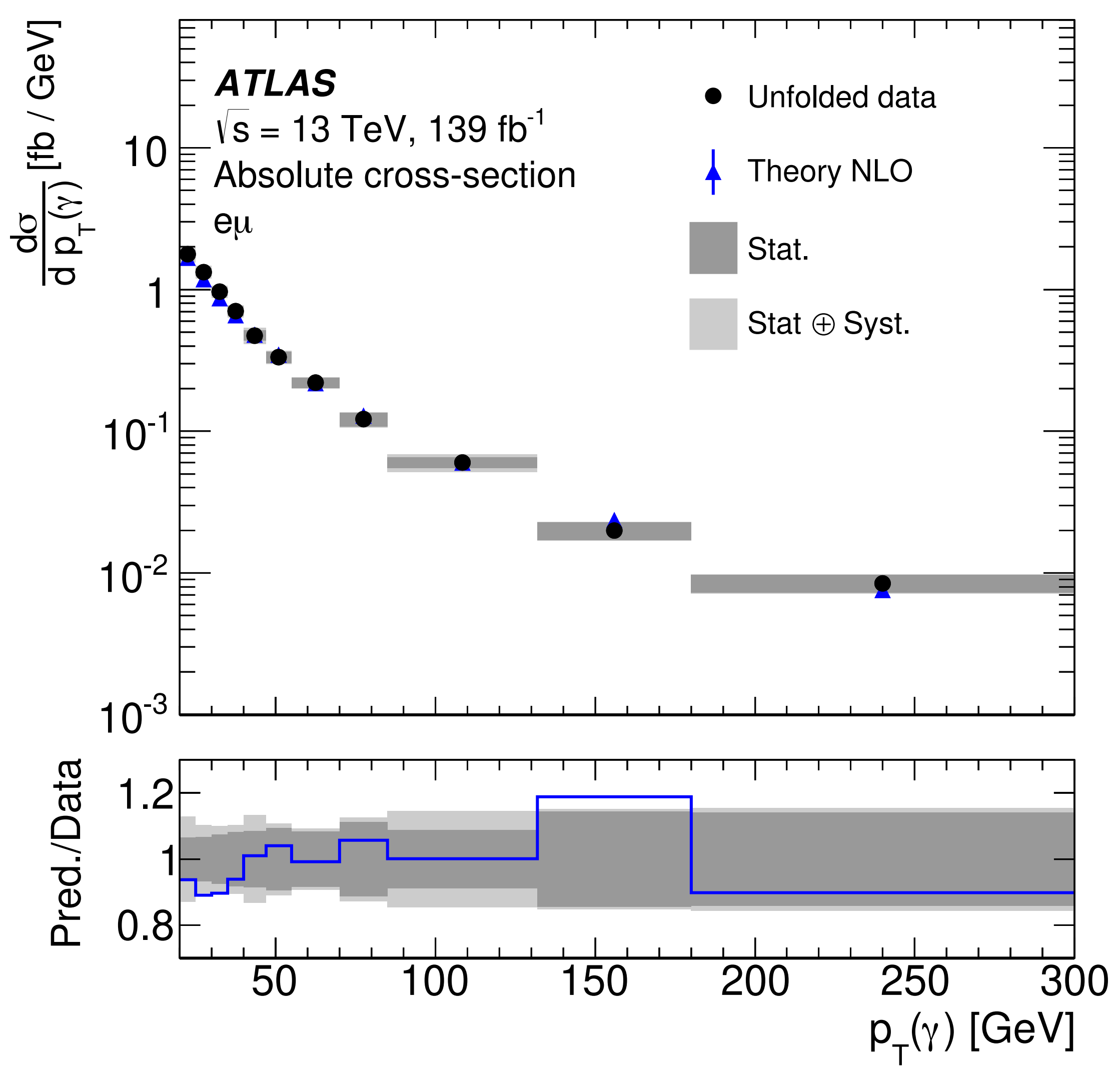
- Production of $t\bar{t}\gamma$ sensitive to $t\gamma$-coupling
  - Differential cross sections sensitive to BSM effects via anomalous top quark dipole moment
- Full fixed-order calculation with non-resonant diagrams and interference
  - Measure jointly $t\bar{t}\gamma$ and non-resonant $tW\gamma$
- Select events in eμ channel with hard photon, fit to S_T = sum of all transverse momenta
- Measured and theoretical fiducial cross section:
  - $\sigma^{fid}(t\bar{t}\gamma \to e\mu) =$ 39.6 ± 0.8 (stat) $^{+2.6}_{-2.2}$ (syst) fb
  - σ^{fid}_{NLO} = 38.50 ± $^{+0.56}_{-2.18}$ (scale) $^{+1.04}_{-1.18}$ (PDF) fb (1803.09916, 1809.08562)

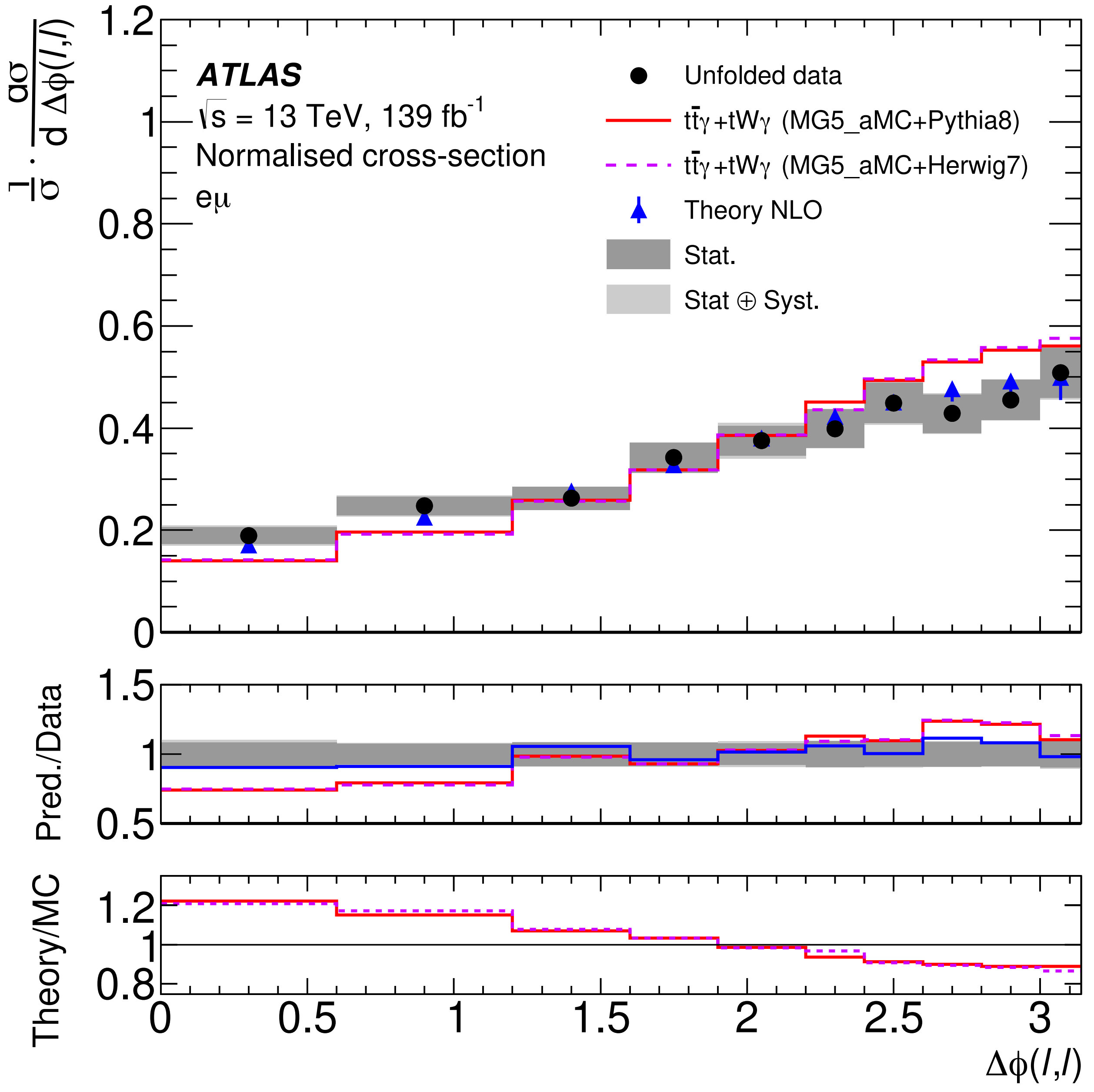
- *OS eμ, both p_T > 25 GeV; M_{ll} >15 GeV*
- *≥ 2 jets, ≥1 b-tagged with 85% efficiency WP*
- *Exactly 1 photon with p_T > 20 GeV*

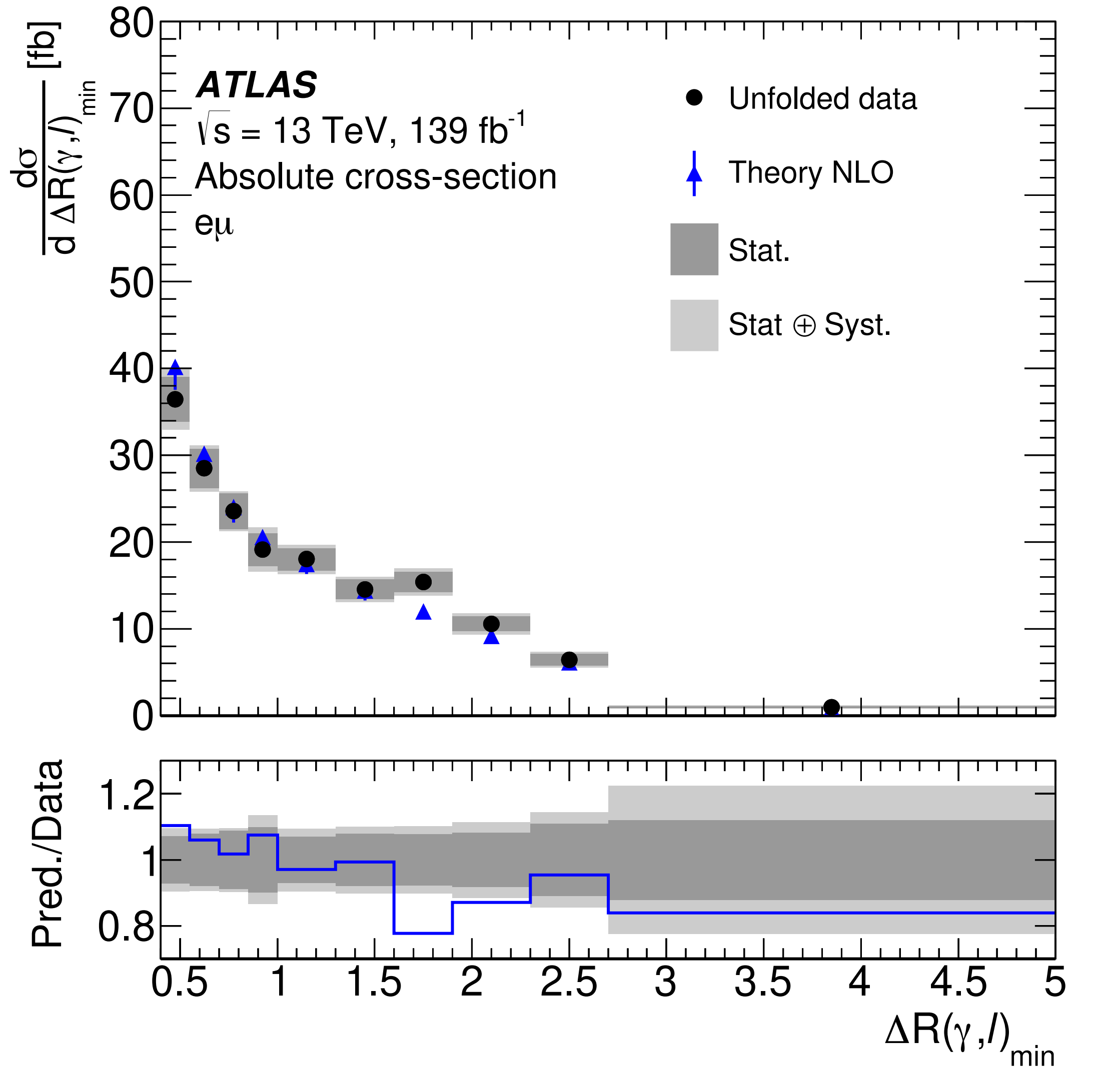


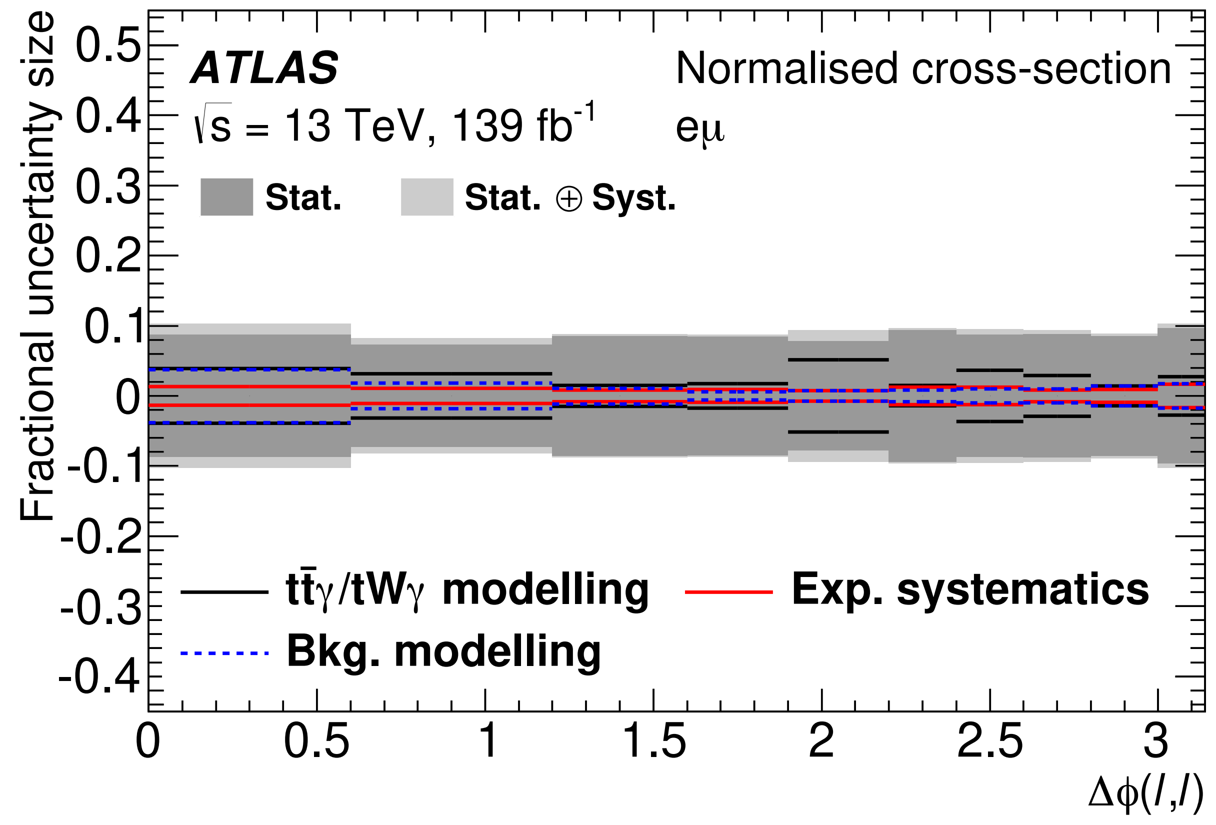
Unfolded Observables

- Unfolded to parton level, compare to fixed-order NLO theory and LO+PS MC simulation
  - Photon p_T and rapidity; angular separation of leptons and between photon and nearest lepton
- Theory in good agreement with data, mostly good agreement with MC
- LO+PS MC simulation unable to fully describe angular observables $\Delta\phi(ll)$, $\Delta R(\gamma l)_{min}$
- Largest systematic uncertainties from signal and background modeling, fully reliant on MC









Summary

- Presented latest results from ATLAS Experiment on precision tests of Standard Model
  - Search for FCNC provide **most stringent limits to date** on $t \to Zq$ FCNC decays
  - Measurement of $R(\tau/\mu)$ exceed precision of LEP and **resolves tension in $R(\tau/\mu)$** measurement with SM
- Presented latest measurements of associated top production measured by ATLAS
  - Measurement of $t\bar{t}t\bar{t}$ in 1L/OS channels; combined with multi-lepton channels, observe **4.7σ significance**
  - **First measurement of $t\bar{t}Z$ differential cross section** at using full LHC Run II dataset in observables sensitive to BSM physics affecting *tZ* coupling
  - Perform differential cross section measurement of $t\bar{t}\gamma + tW\gamma$; **compare with first ever full calculation** of $t\bar{t}$ in association with a hard photon including non-resonant/off-shell effects at NLO QCD

Thank you for your attention!

Backup