Top quark precision measurements at the LHC

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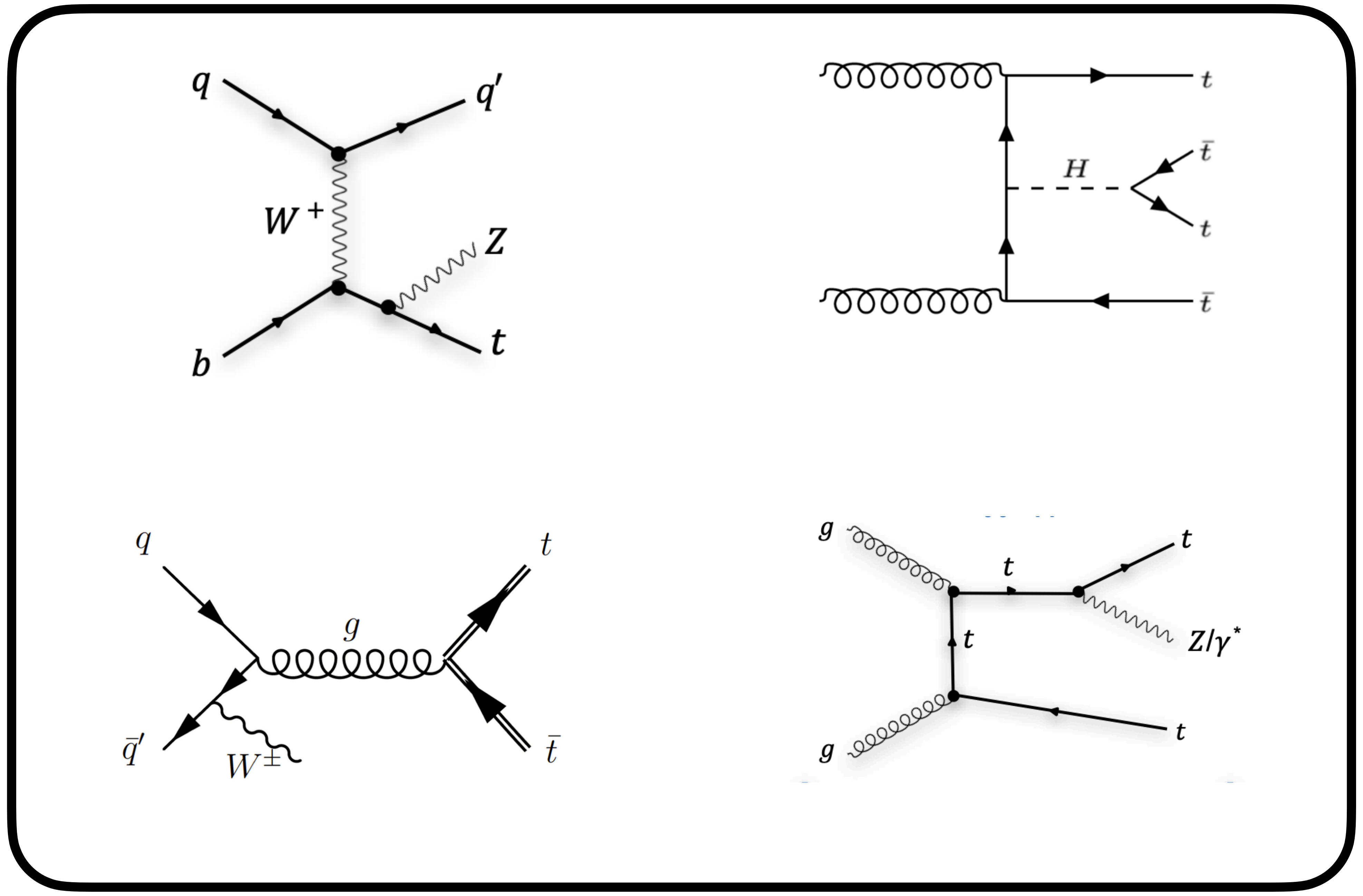
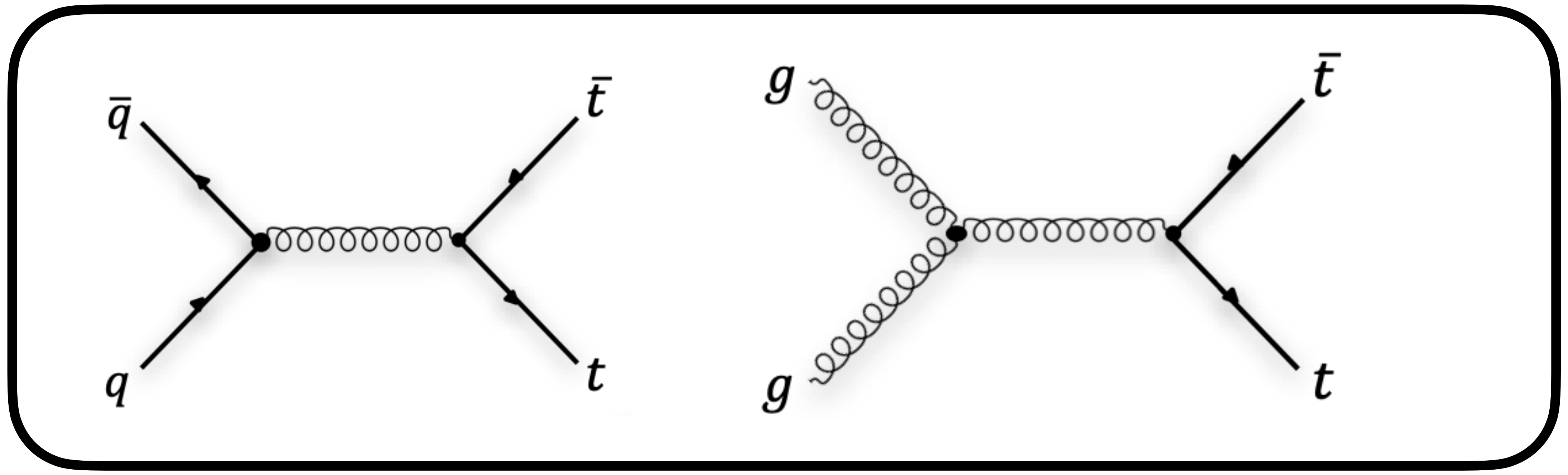
Introduction

- The top quark is the most massive fundamental particle
  - Coupling to Higgs field is ~1
  - Does not hadronize: Decays before hadronization time scale.
- Probe for testing Standard Model and BSM Physics
  - Test pQCD predictions at NNLO precision, Constrain PDF’s
  - Precision SM measurements (top mass, $|V_{tb}|$)

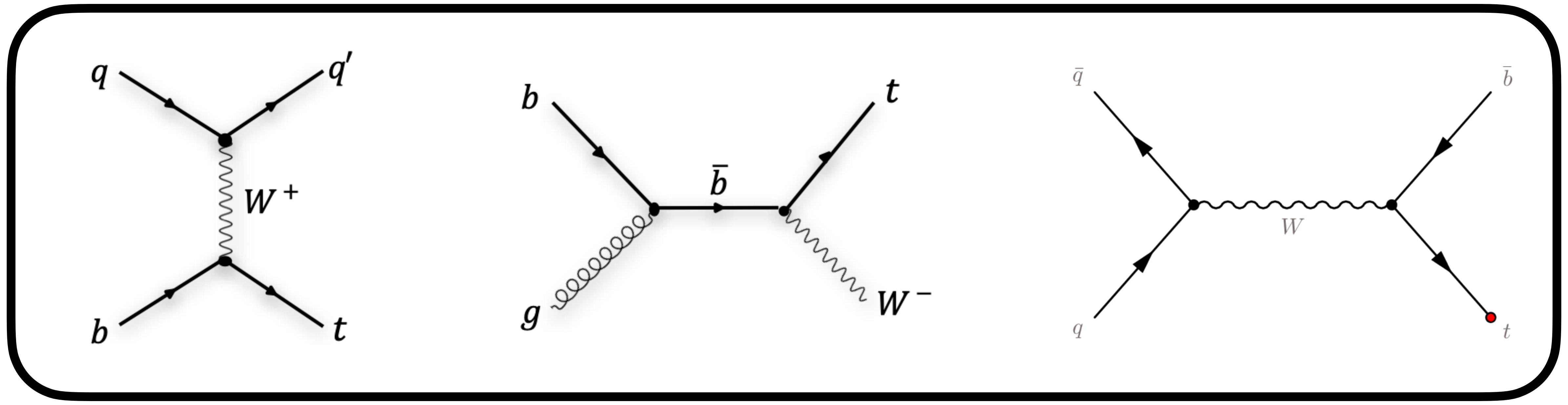
Rare processes



Pair production

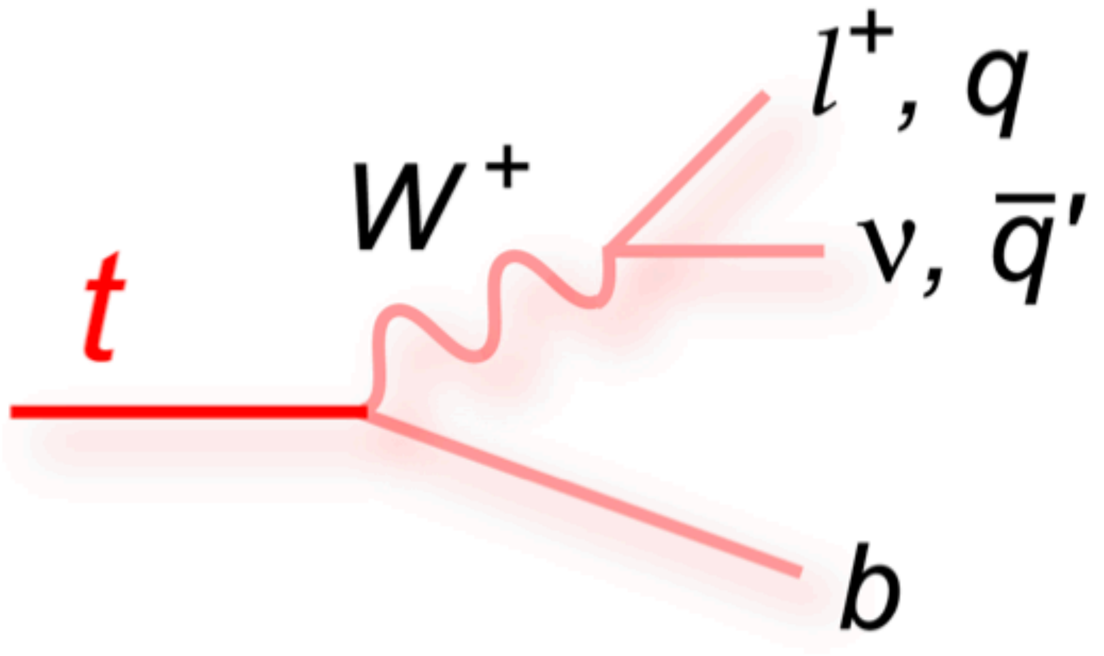


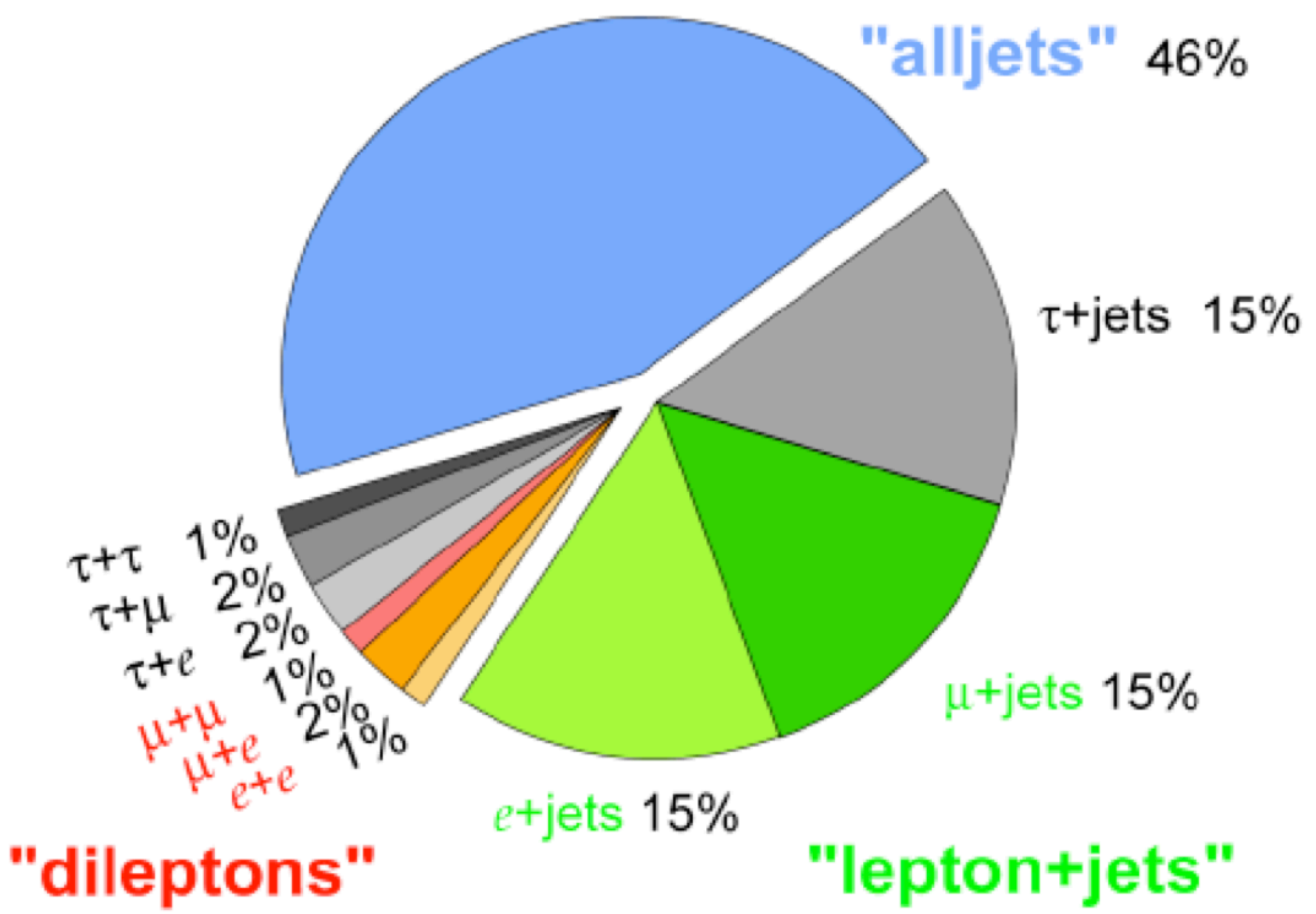
Single top production



$t\bar{t}$ pair production

- Probe boosted top quark topologies
- Background: Dominated by QCD multijet





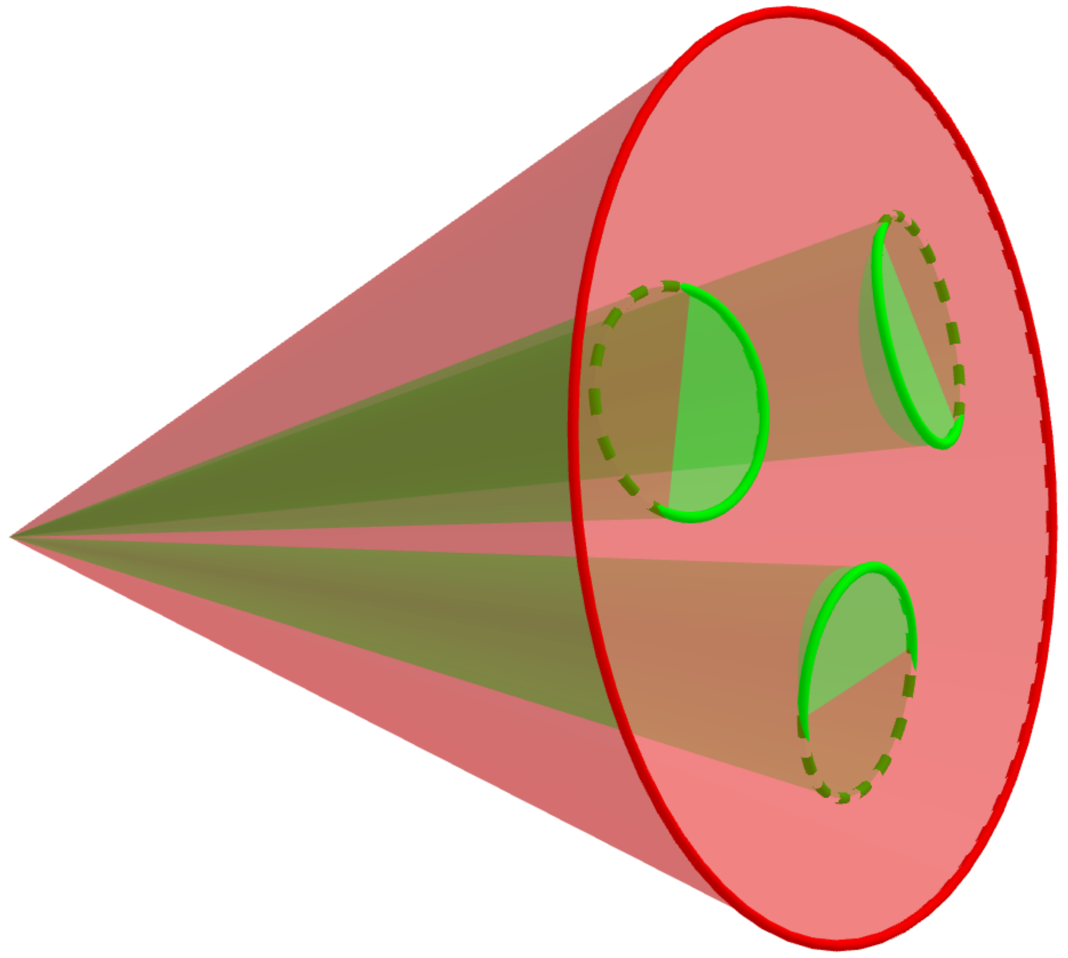
- Presence of 2 neutrinos: Kinematically underconstrained system.
- Background: Wt, di-boson, $Z \to \tau^+\tau^-$

- High statistics
- Backgrounds: W+jets, Multi-jet
- Multiple control regions

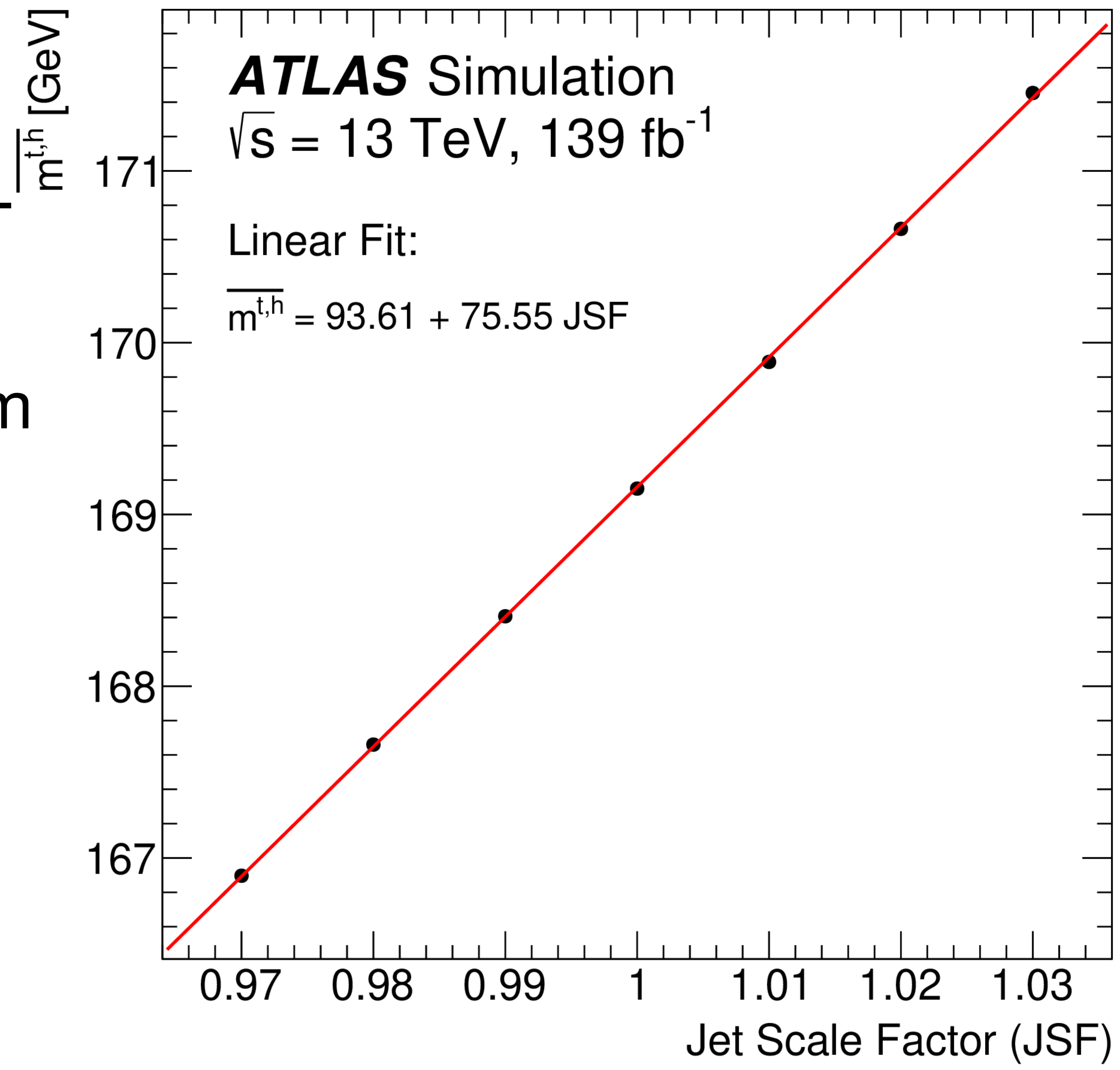
Differential $t\bar{t}$ measurement with boosted tops: $l + jets$

arxiv-202.12134

- The topology consists of a hadronically decaying boosted top quark and a leptonically decaying top ($t\bar{t} \rightarrow WbWb \rightarrow \ell\nu bqq'b$)
- Leading backgrounds (tW, $W + jets$, $t\bar{t}X$ etc.) are estimated from simulated samples.
- The impact of **Jet energy scale** uncertainties are reduced using a dedicated Jet energy scale factor method (JSF)



- Reclustered **Large-R** jet is used as proxy for top-quark
  - Truncated $\overline{m^{t,h}}$ is calculated from 4-vector sum of **small-R** jet
- JSF calculated as a correction for small-R jet energy (based on the precisely known top mass, 172.5 GeV)

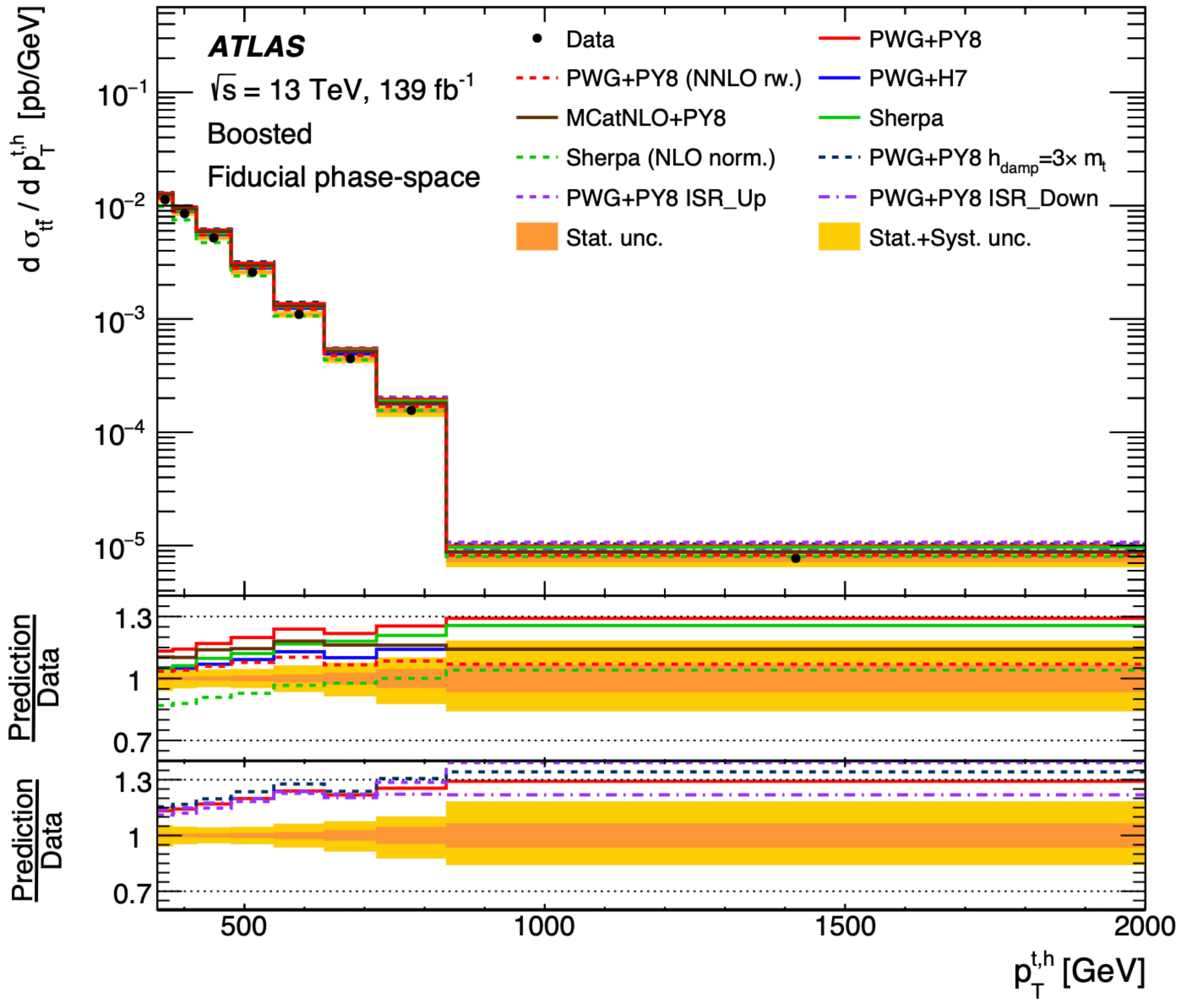


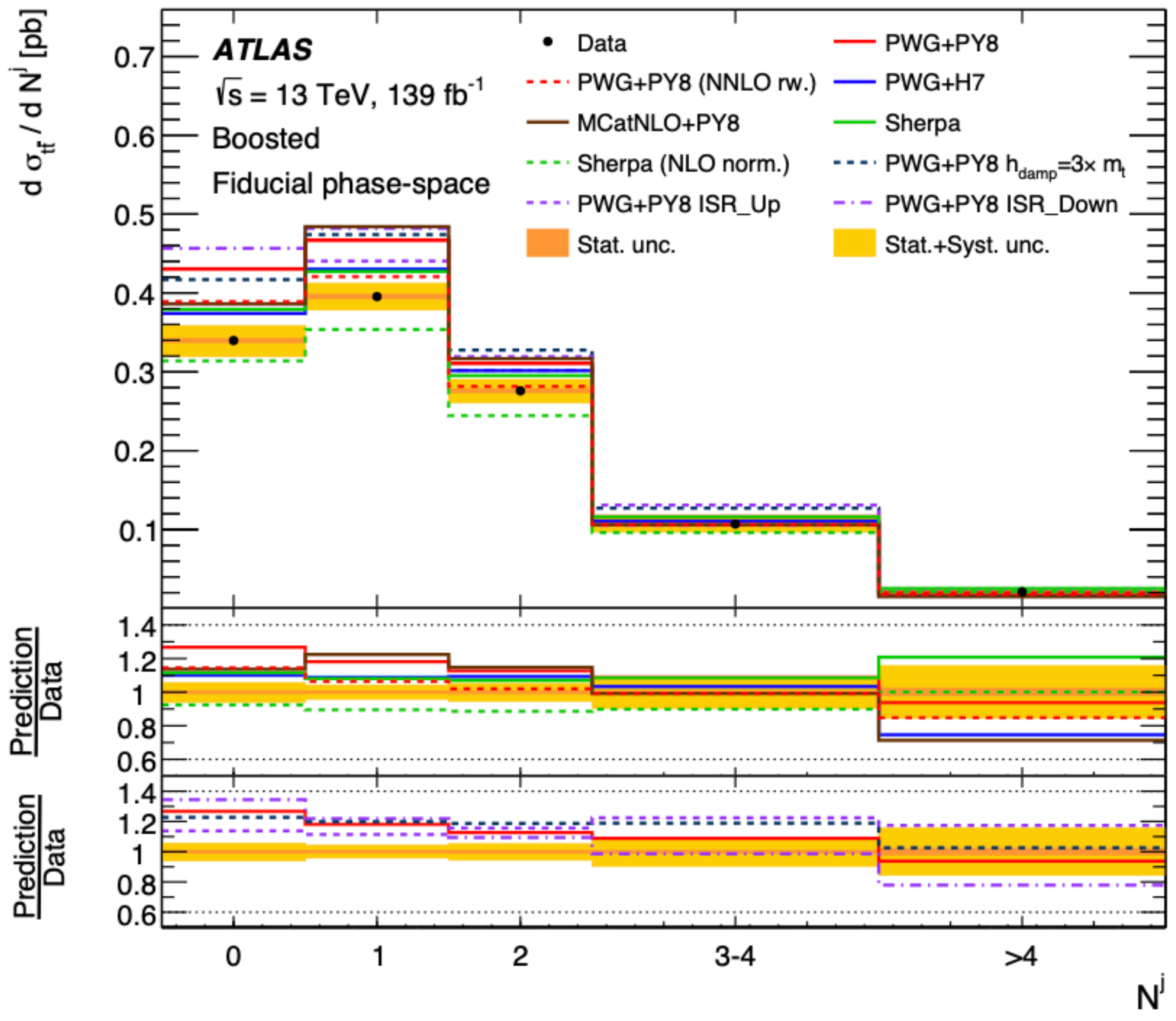
- Relationship between simulated $\overline{m^{t,h}}$ and JSF is linear.
- JSF method reduces total systematic uncertainty by upto 30%.

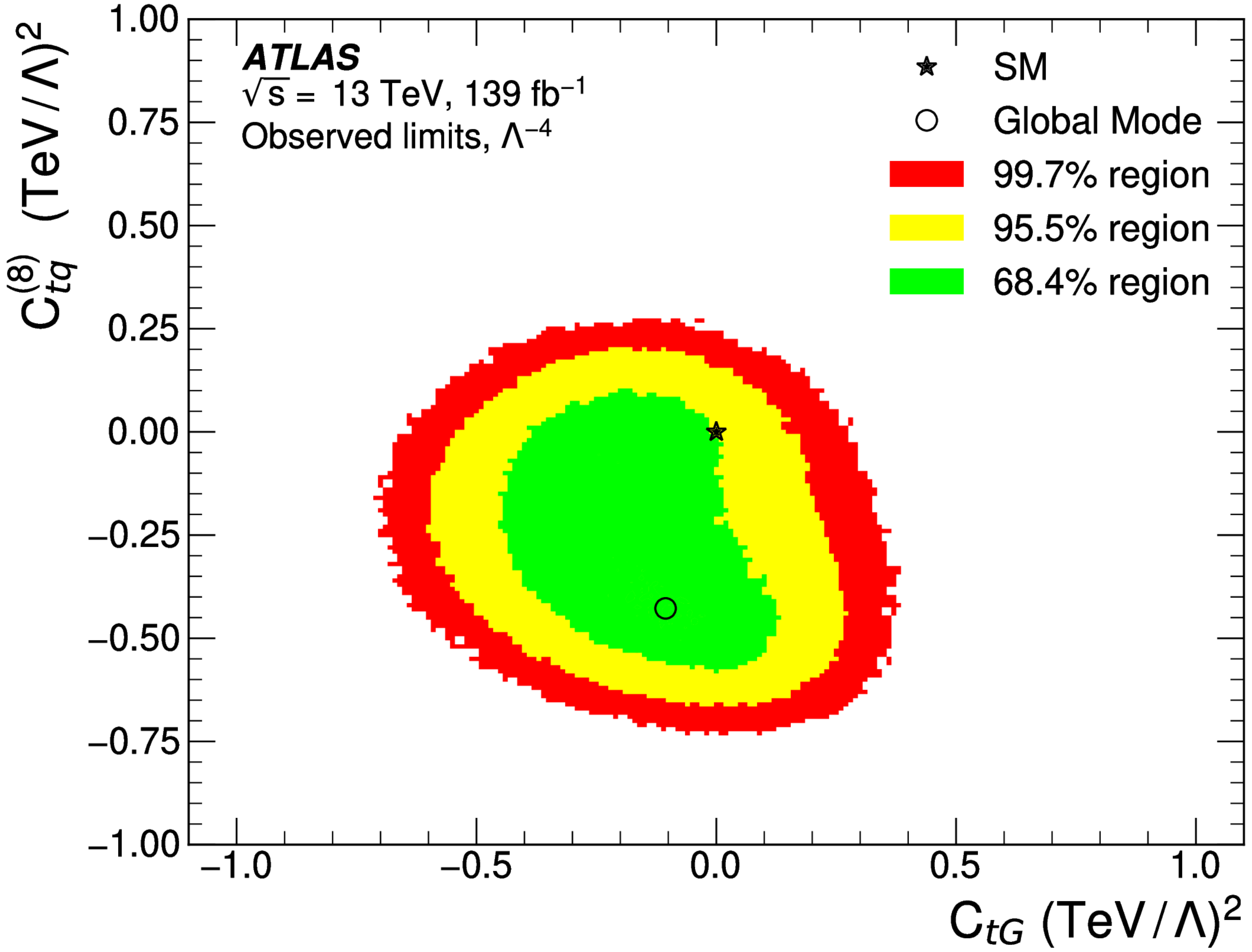
Differential $t\bar{t}$ measurement with boosted tops : $l + jets$

arxiv-2202.12134

- Observables characterizing top quark kinematics as well as those probing additional radiations in the events were probed.
- NNLO corrections relevant: reweighted MC predictions show good agreement with data.
- Leading uncertainty related to top modeling.





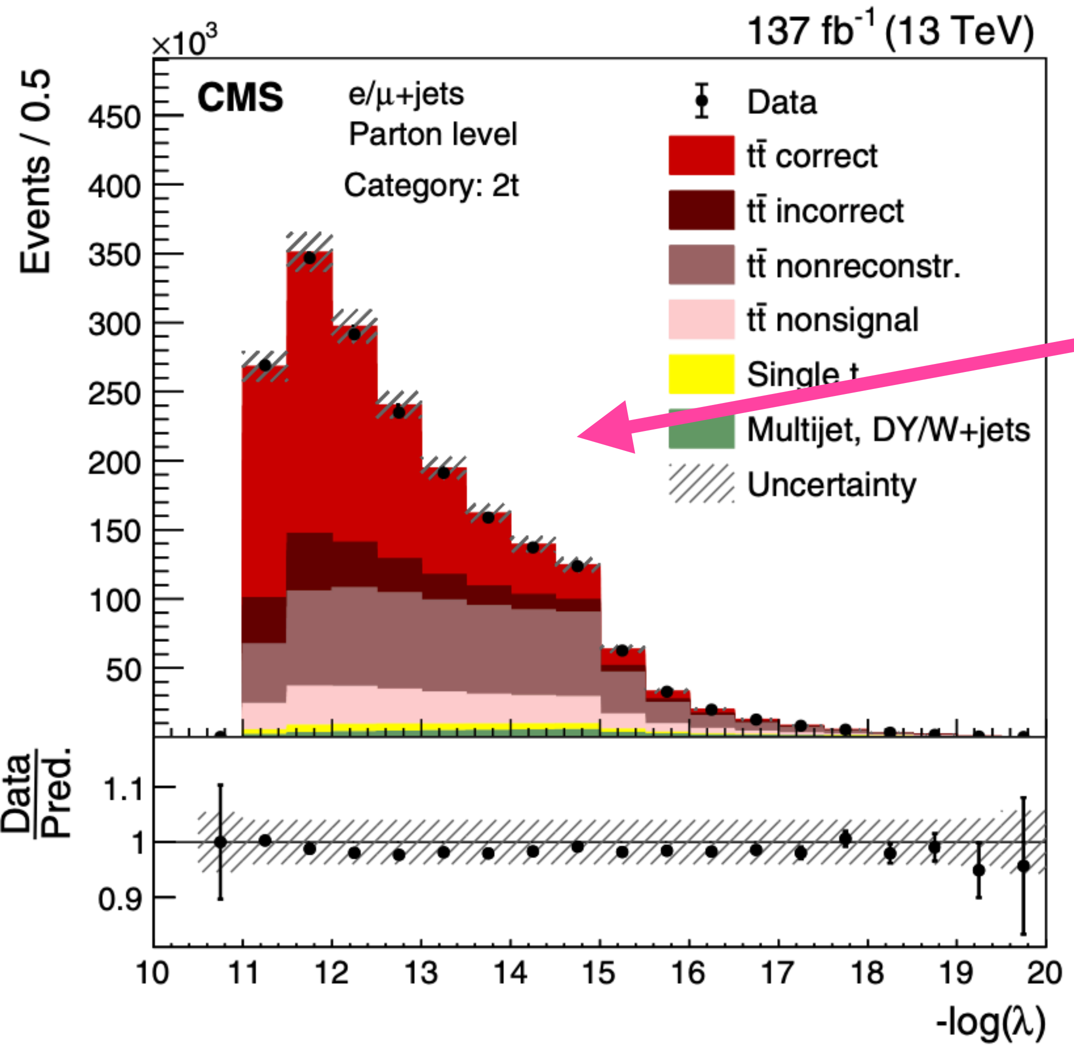


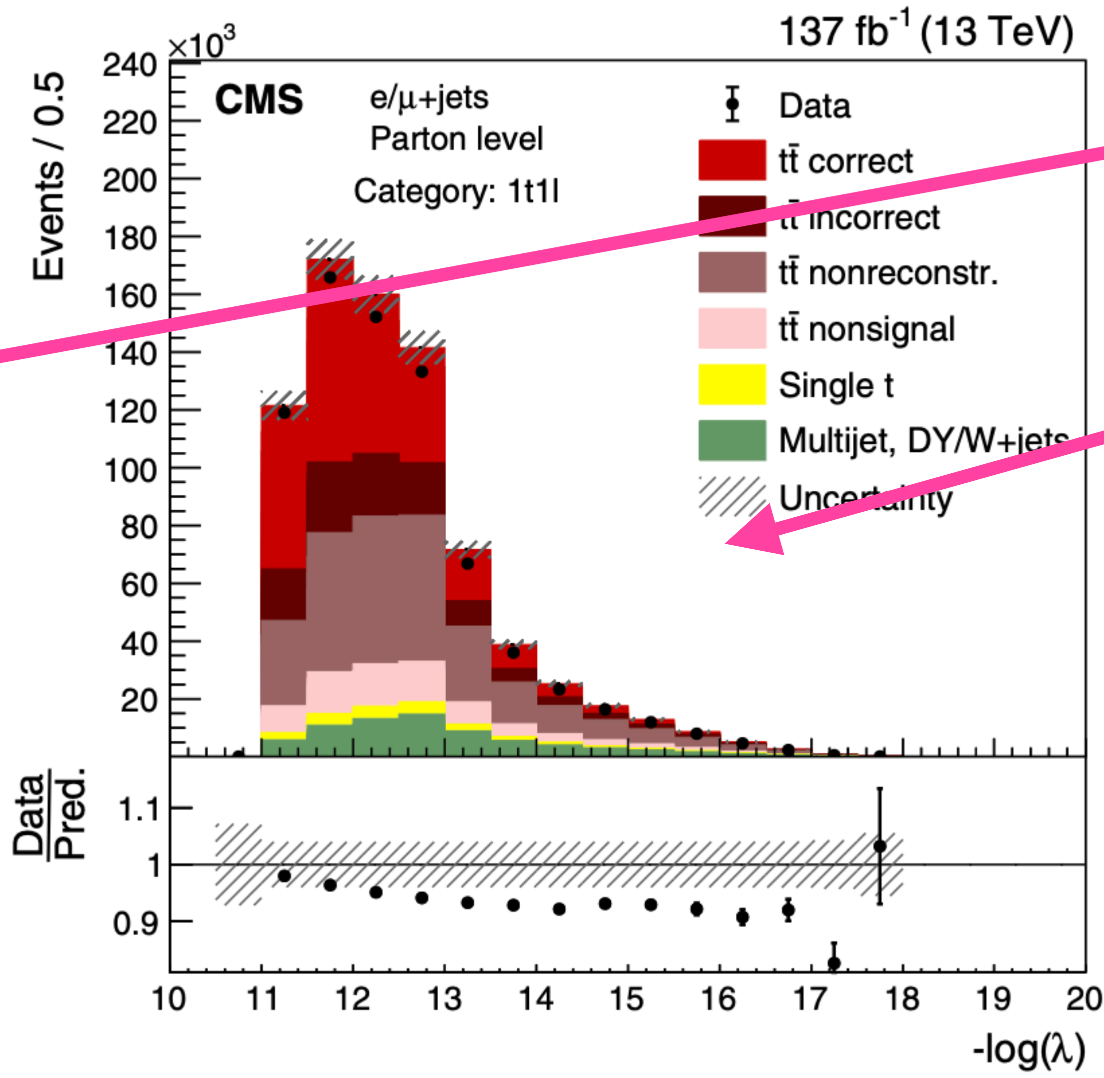
- Sensitivity of the analysis to New physics is probed in terms of dim-6 EFT operators.
- O_{tG} operator changes the overall rate of $t\bar{t}$ production, $O_{tq}^{(8)}$ results in additional $t\bar{t}$ events at high energy.
- $p_T^{top_{had}}$ distribution is chosen to disentangle both operators.

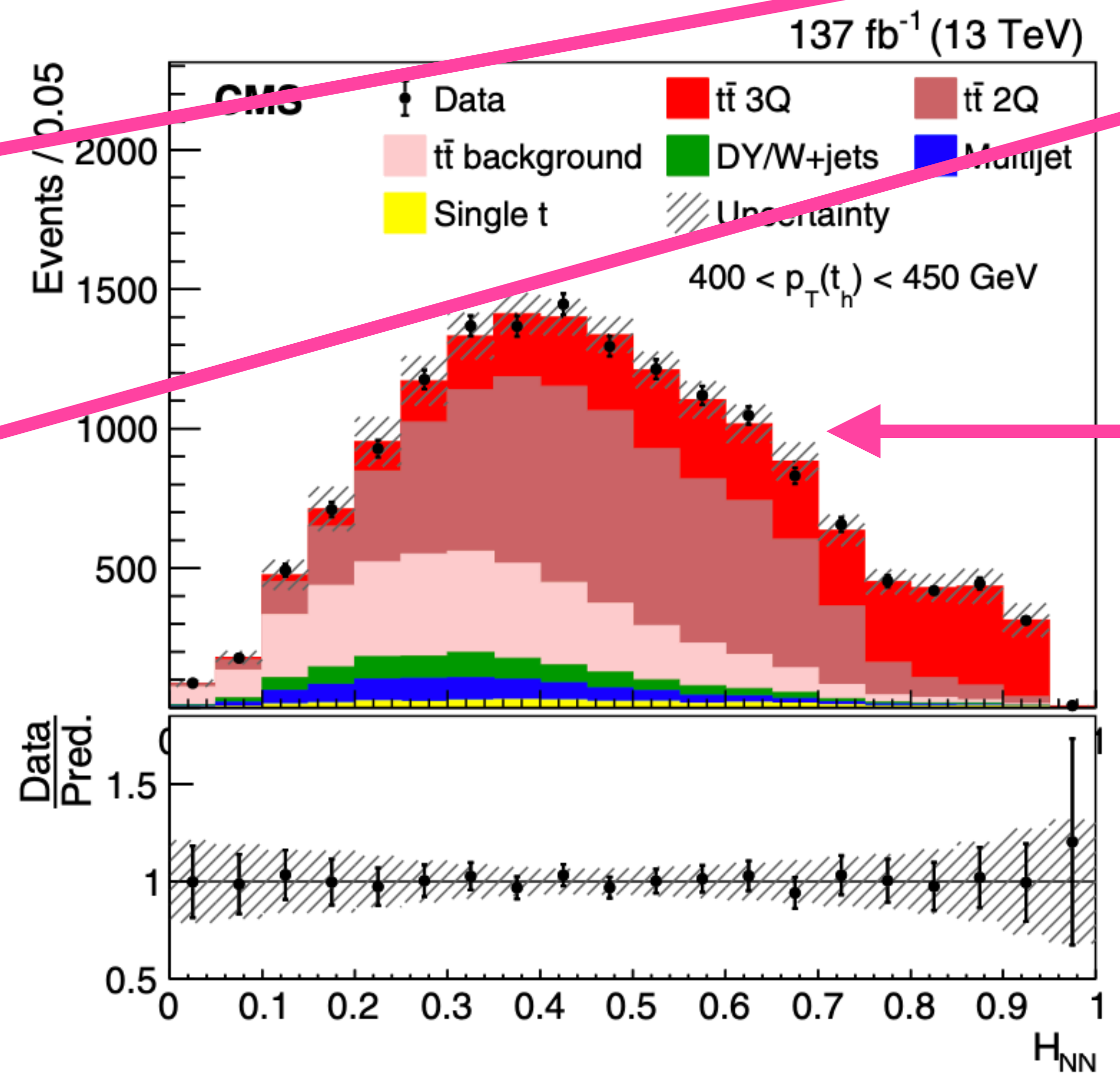
Differential $t\bar{t}$ measurement with (resolved+boosted) tops: $l + jets$

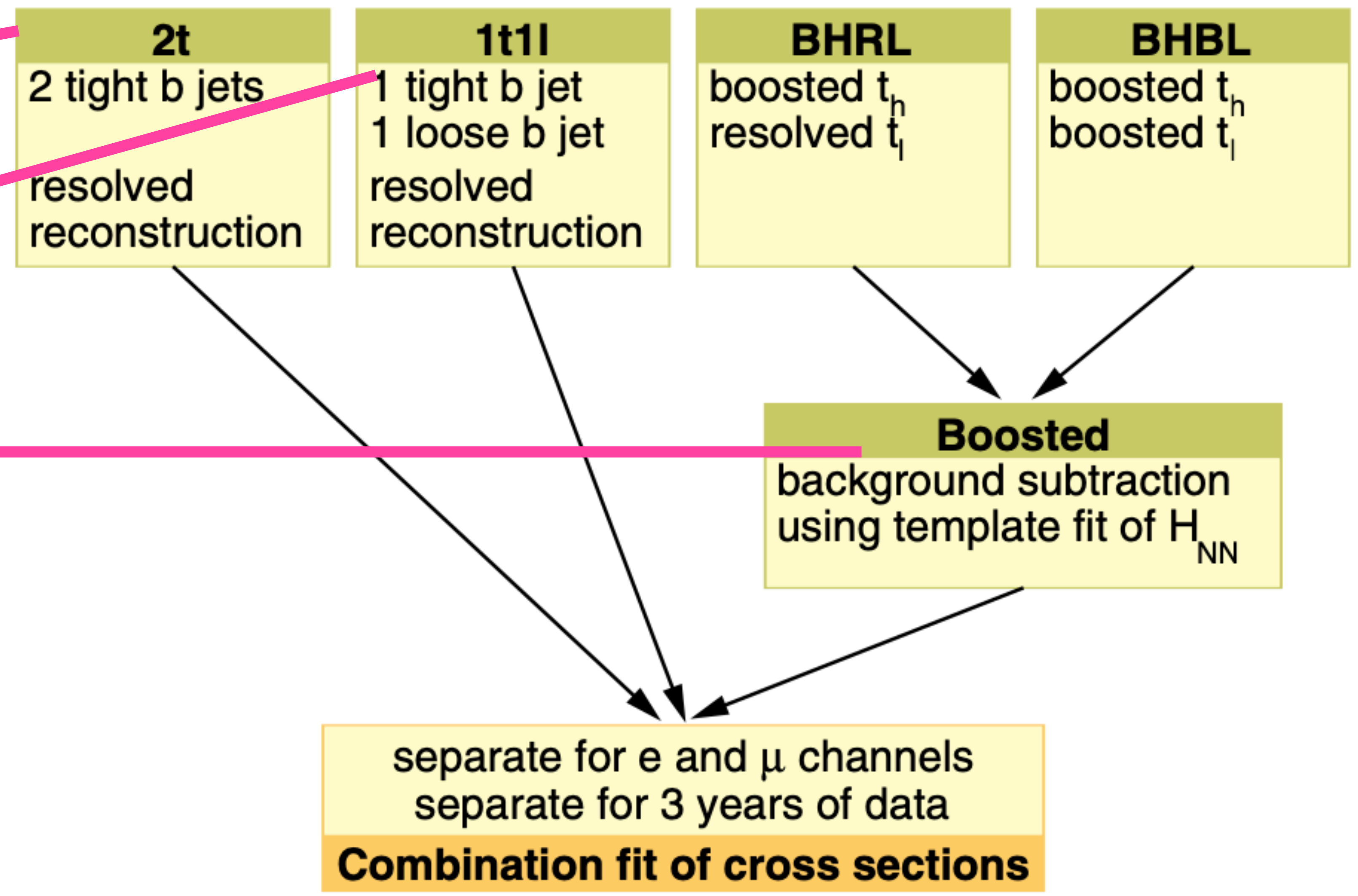
PRD(104)092013 (2021)

- Combined analysis of categories with resolved and boosted signatures.
- Likelihood & NN based association of objects to hadronic top(t_{had}) and leptonic top(t_l) in various resolved and boosted categories

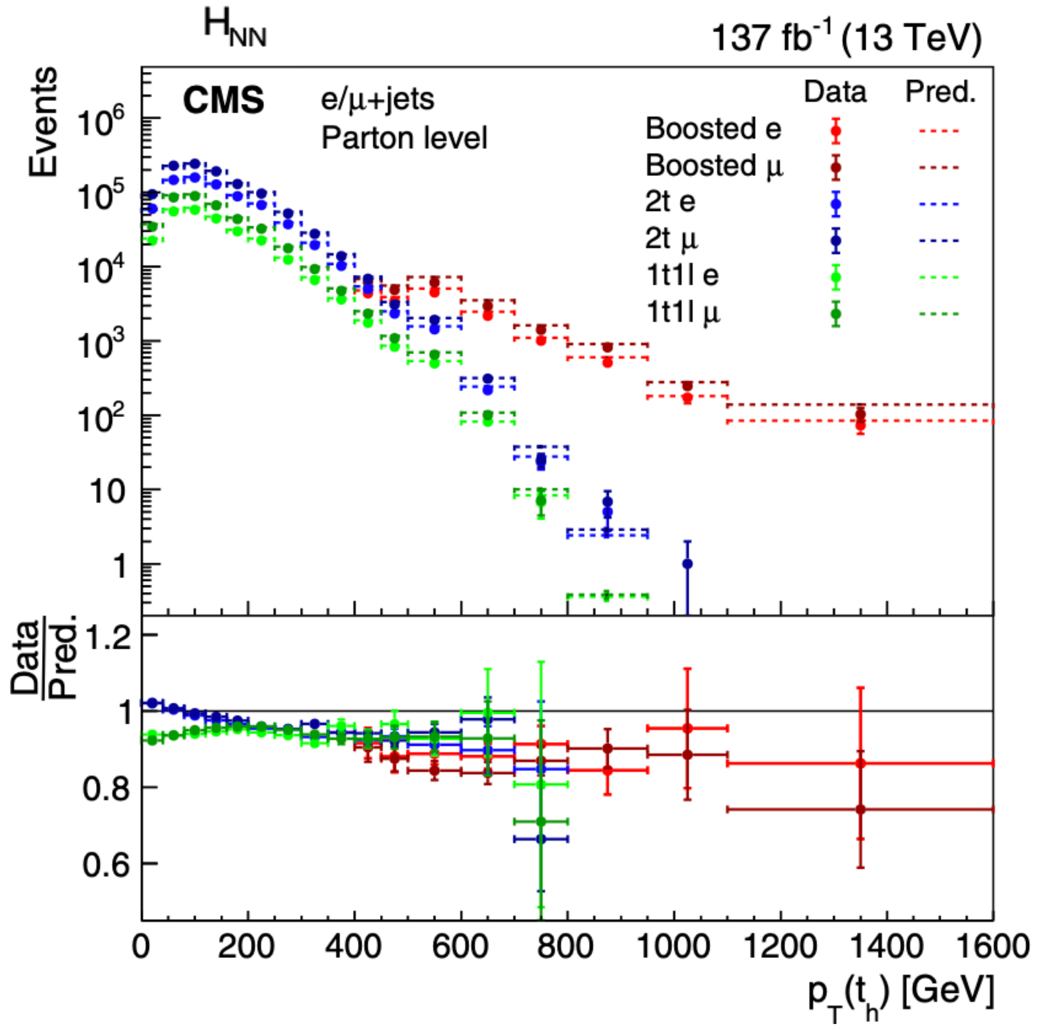


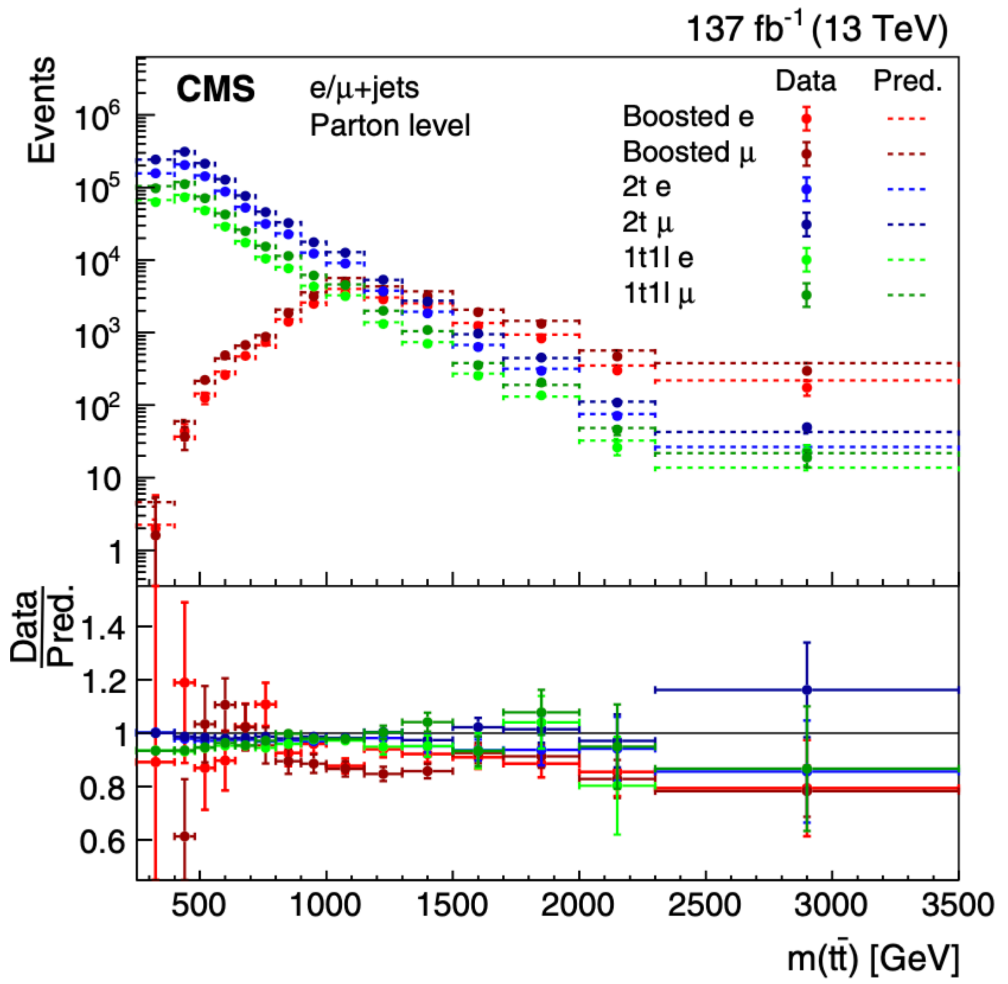






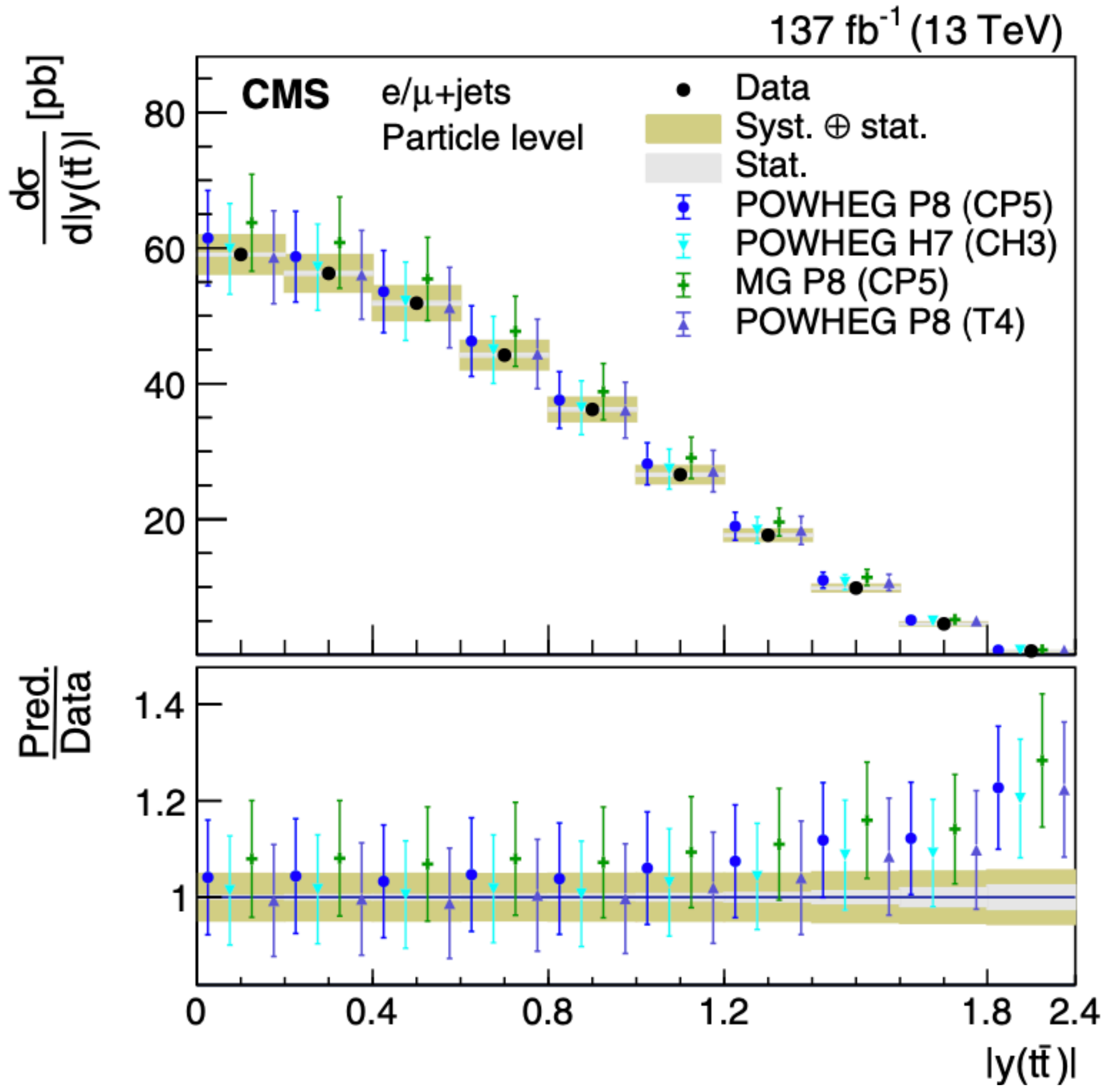
- Background subtraction is performed using a template-based likelihood fit
- Measurement performed both at parton level and particle level.

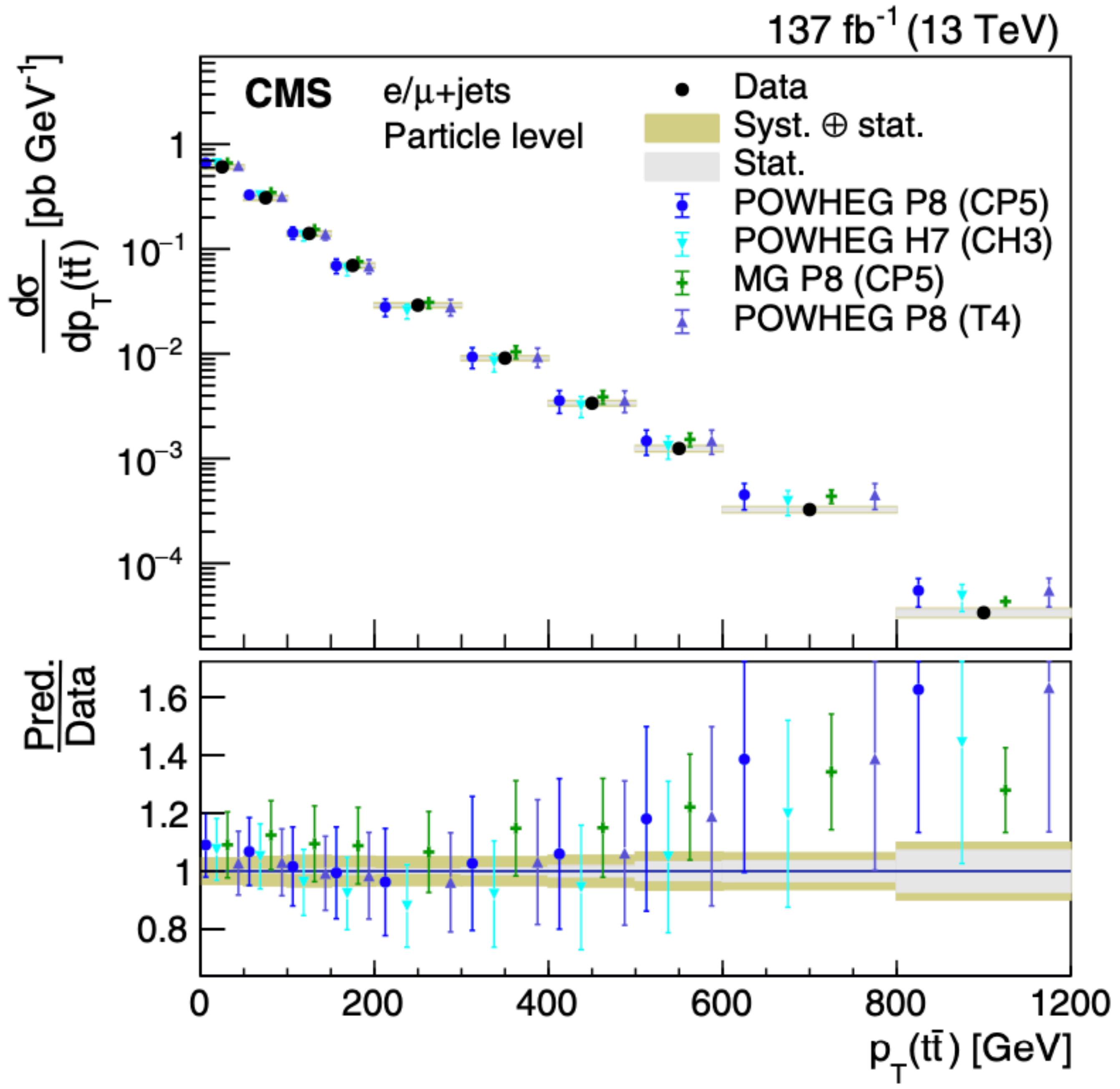


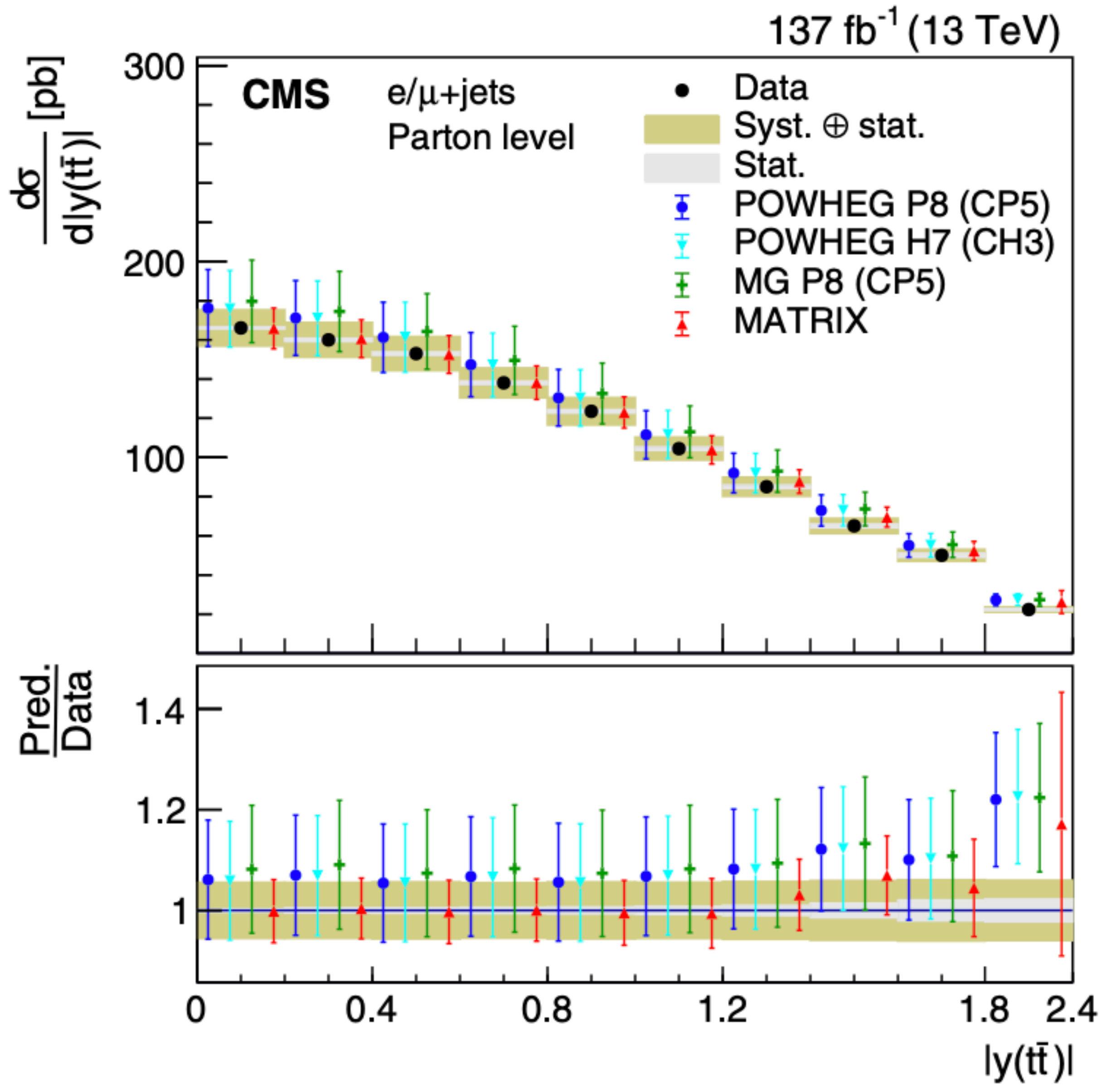


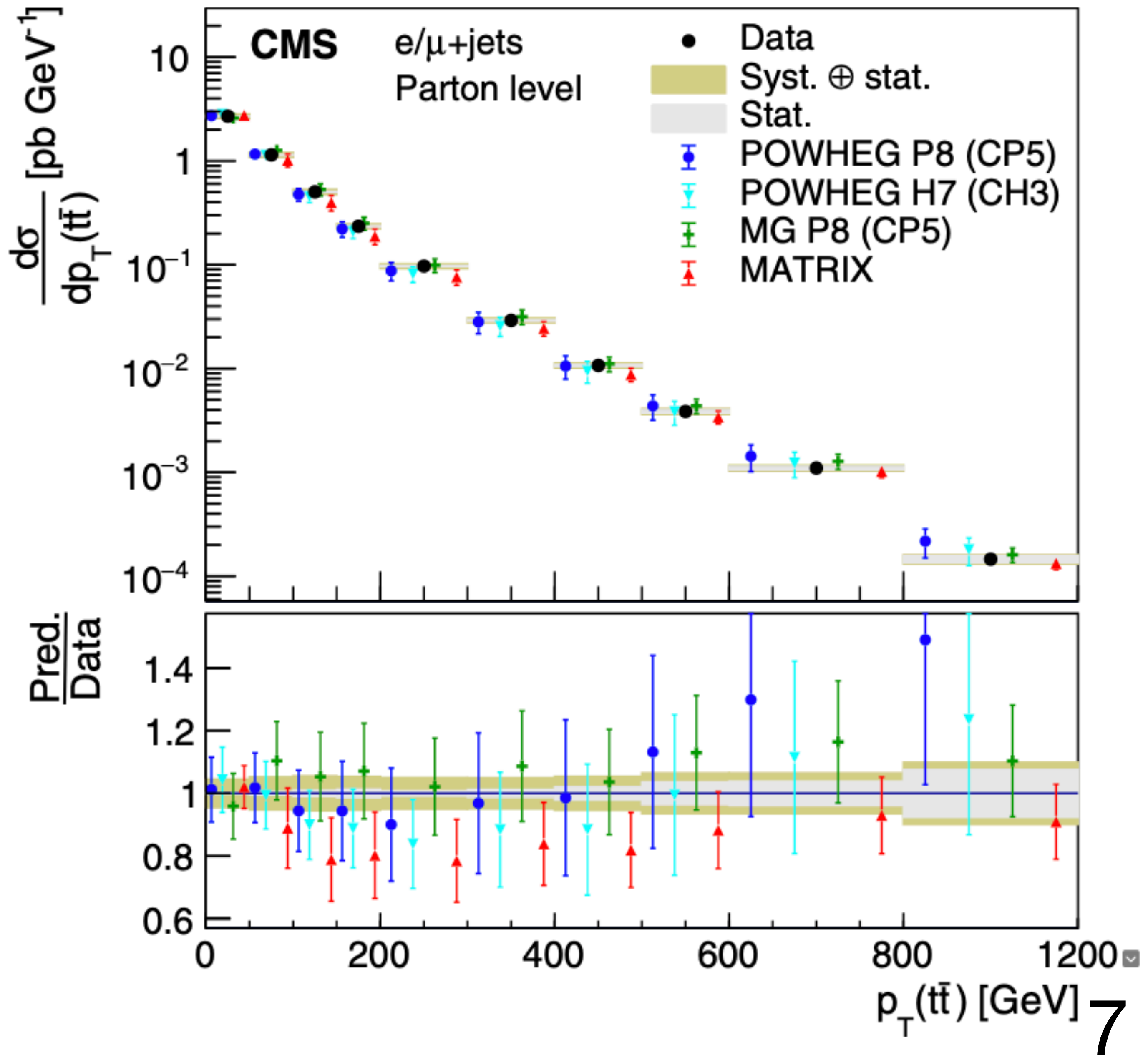
Differential $t\bar{t}$ measurement with (resolved+boosted) tops : $l + jets$

PRD(104)092013 (2021)

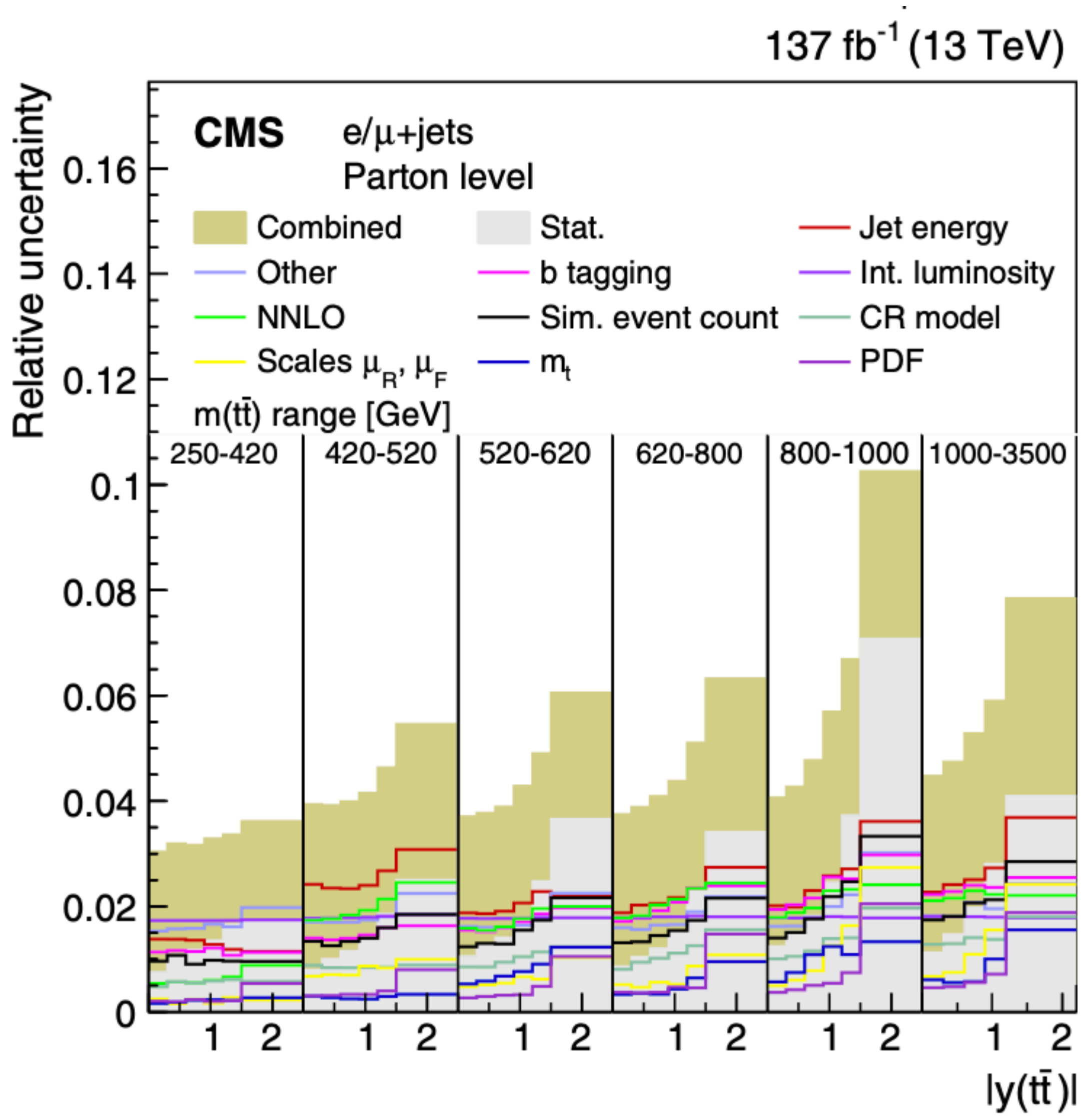


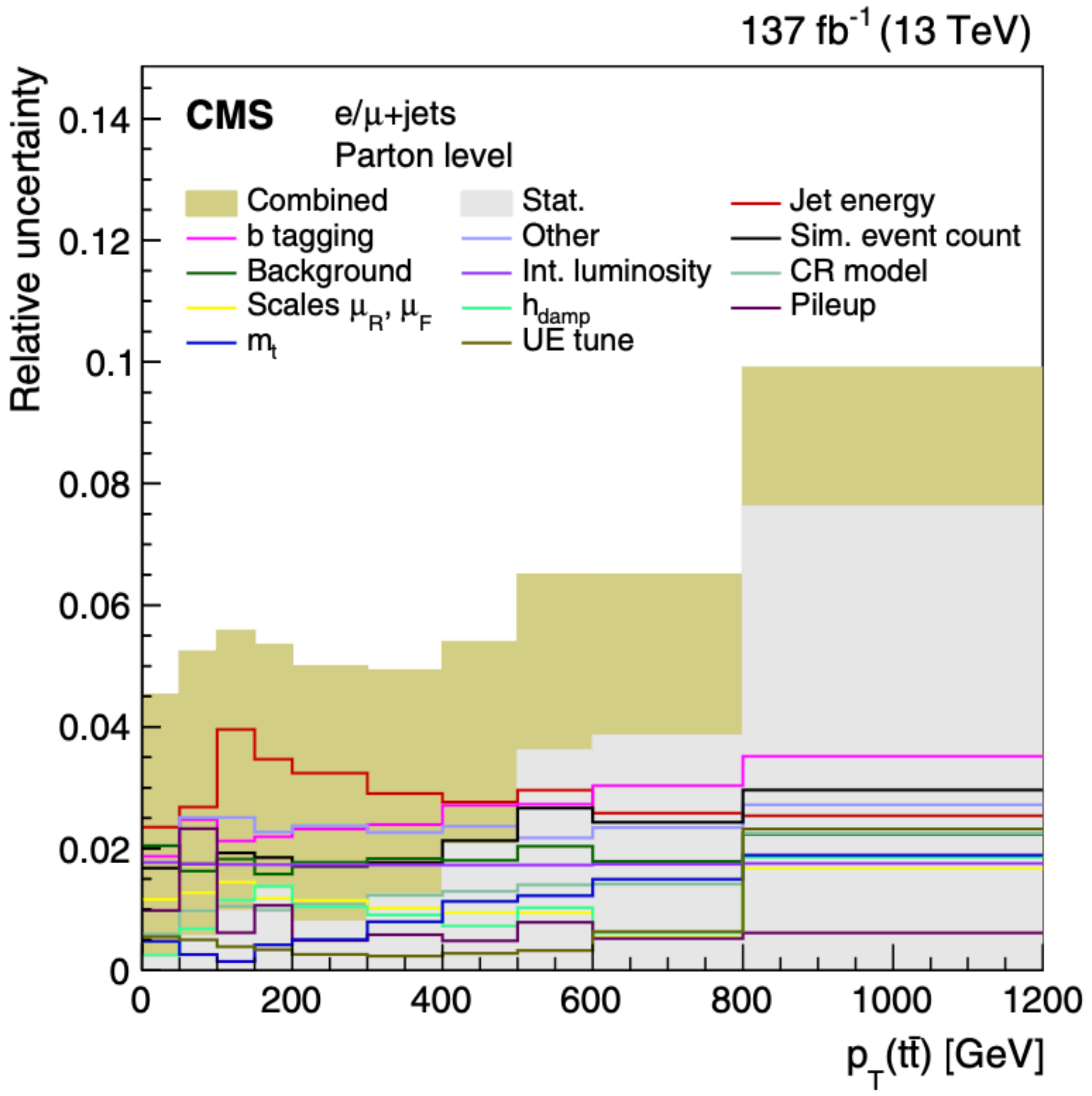






- Overall, the measurement agrees with predictions.
  - A small modulation was observed in $p_T(t\bar{t})$ system
  - A small discrepancy was observed in high rapidity distributions.
- More pronounced in particle-level distributions.
- Leading systematics are related to jet energy scale and b-tagging.





Uncertainties

Differential $t\bar{t}$ measurement with boosted tops: all hadronic

ATLAS-CONF-2021-050

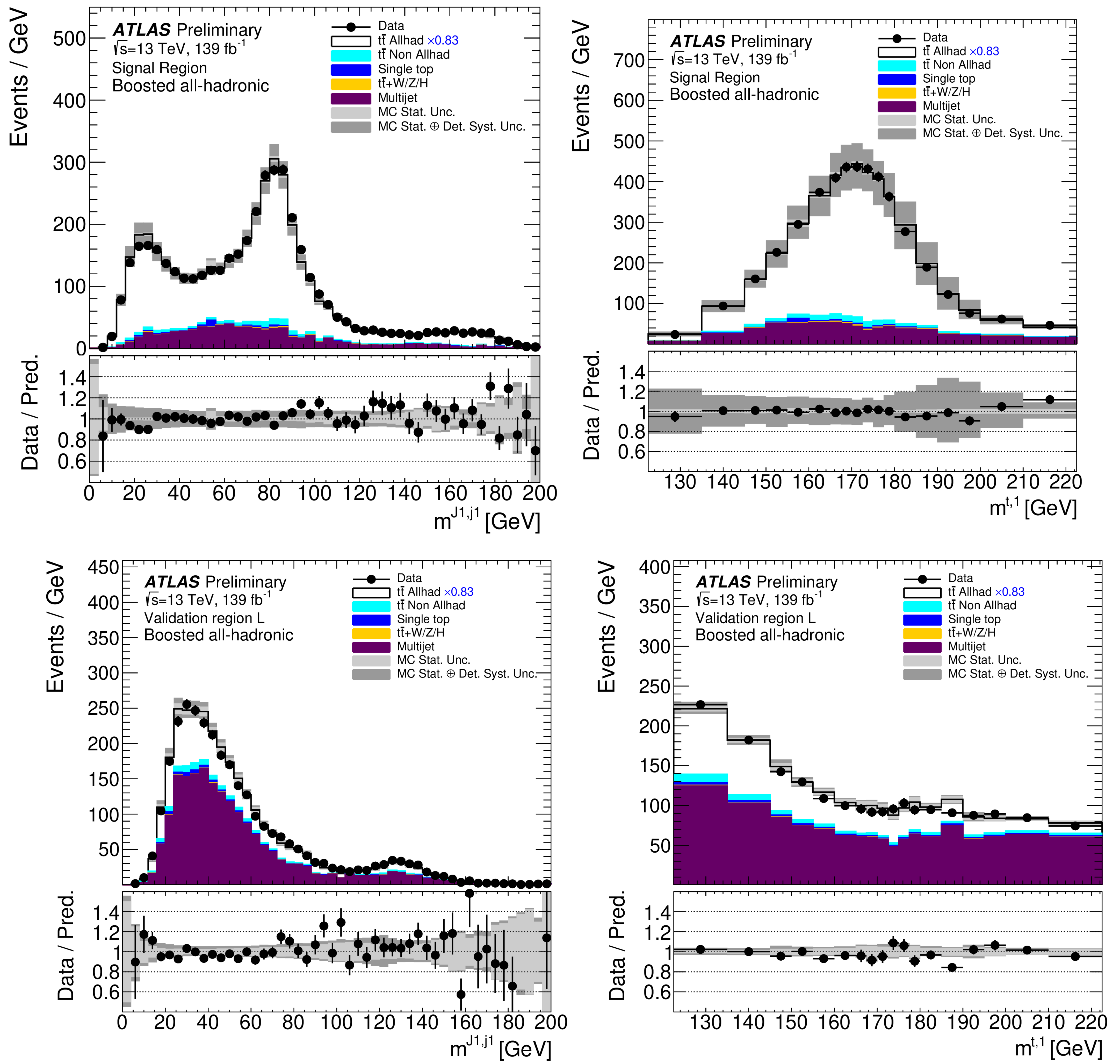
- Observed through the hadronic decay of top quarks, via reconstruction of large-R jets.
  - Jet substructure observables used in a DNN based top-tagging algorithm.
  - Leading top quark jet $p_T^{t1} > 500$ GeV and subleading top quark jet $p_T^{t2} > 350$ GeV.
- QCD multijet process is a major background. Estimated through a data-driven procedure ("ABCD") method.
  - Other backgrounds derived from simulations.

Signal | Validation | Control

2nd large-R jet				
1t1b	J (7.0%)	K (25%)	L (39%)	S
0t1b	B (1.2%)	D (5.0%)	H (9.0%)	N (47%)
1t0b	E (0.5%)	F (2.3%)	G (4.9%)	M (31%)
0t0b	A (0.09%)	C (0.5%)	I (1.1%)	O (9.0%)
	0t0b	1t0b	0t1b	1t1b

Leading large-R jet

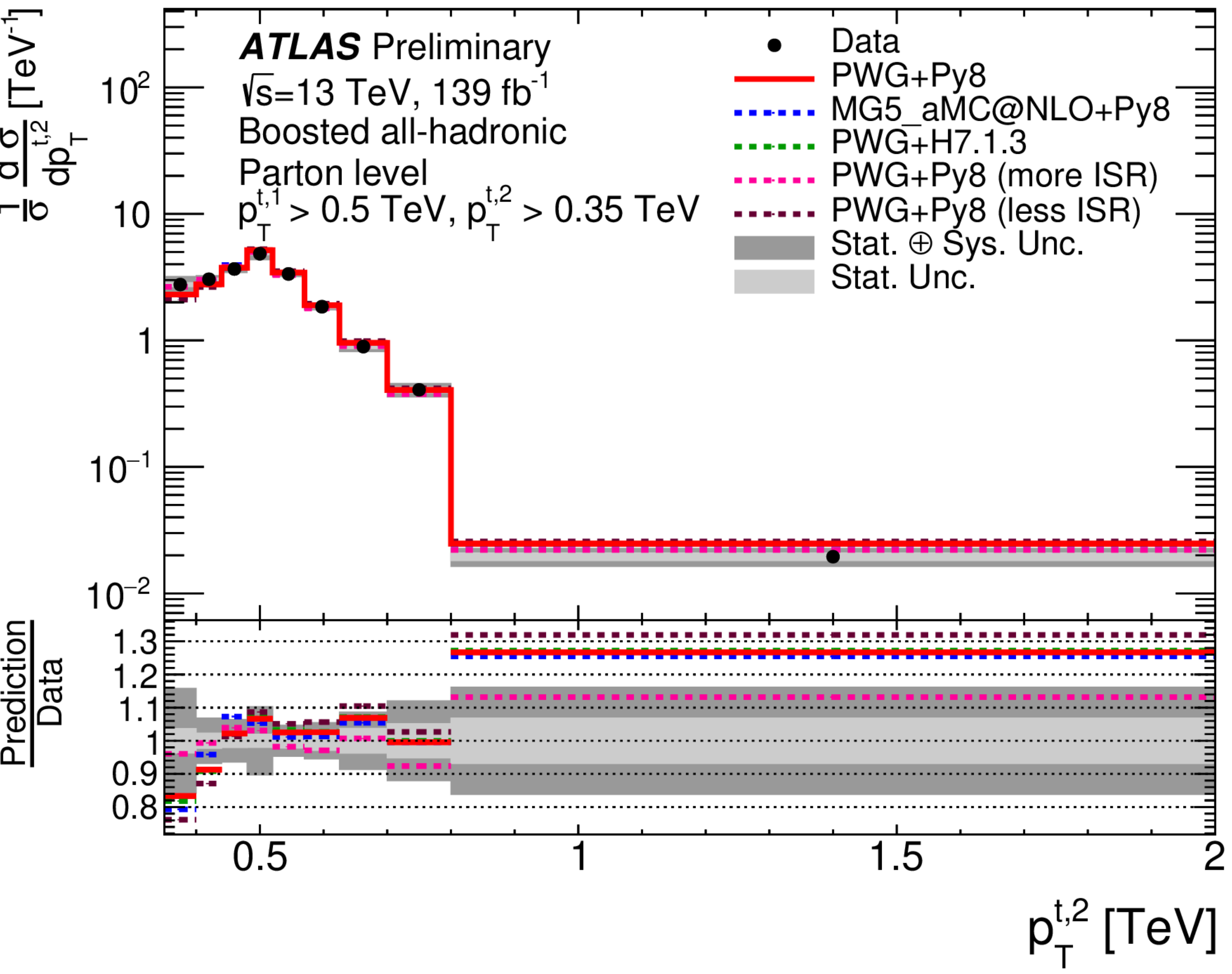
$$S = \frac{J \times O}{A} \cdot \frac{D \times A}{B \times C} \cdot \frac{G \times A}{E \times I} \cdot \frac{F \times A}{E \times C} \cdot \frac{H \times A}{B \times I}$$

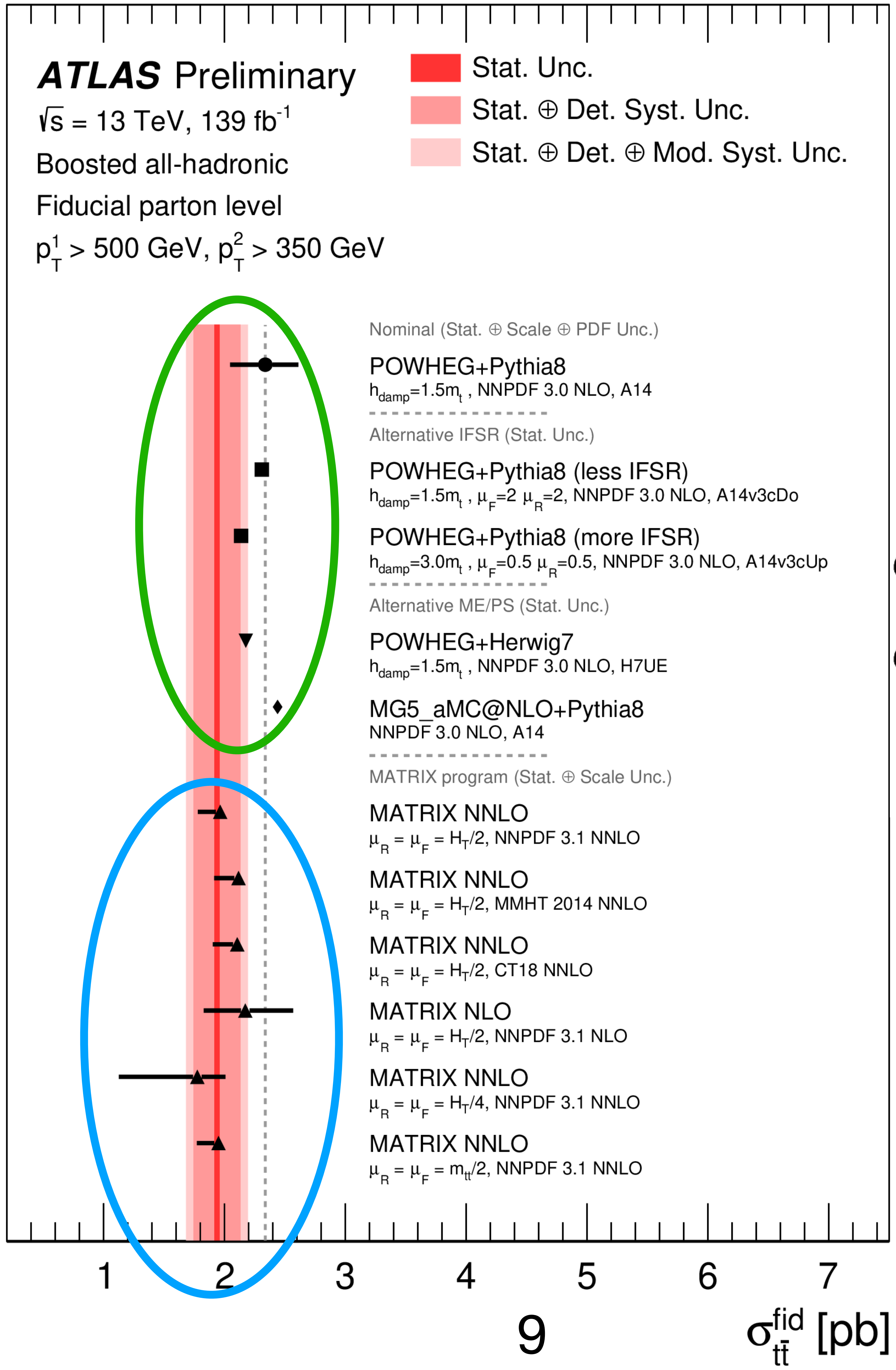


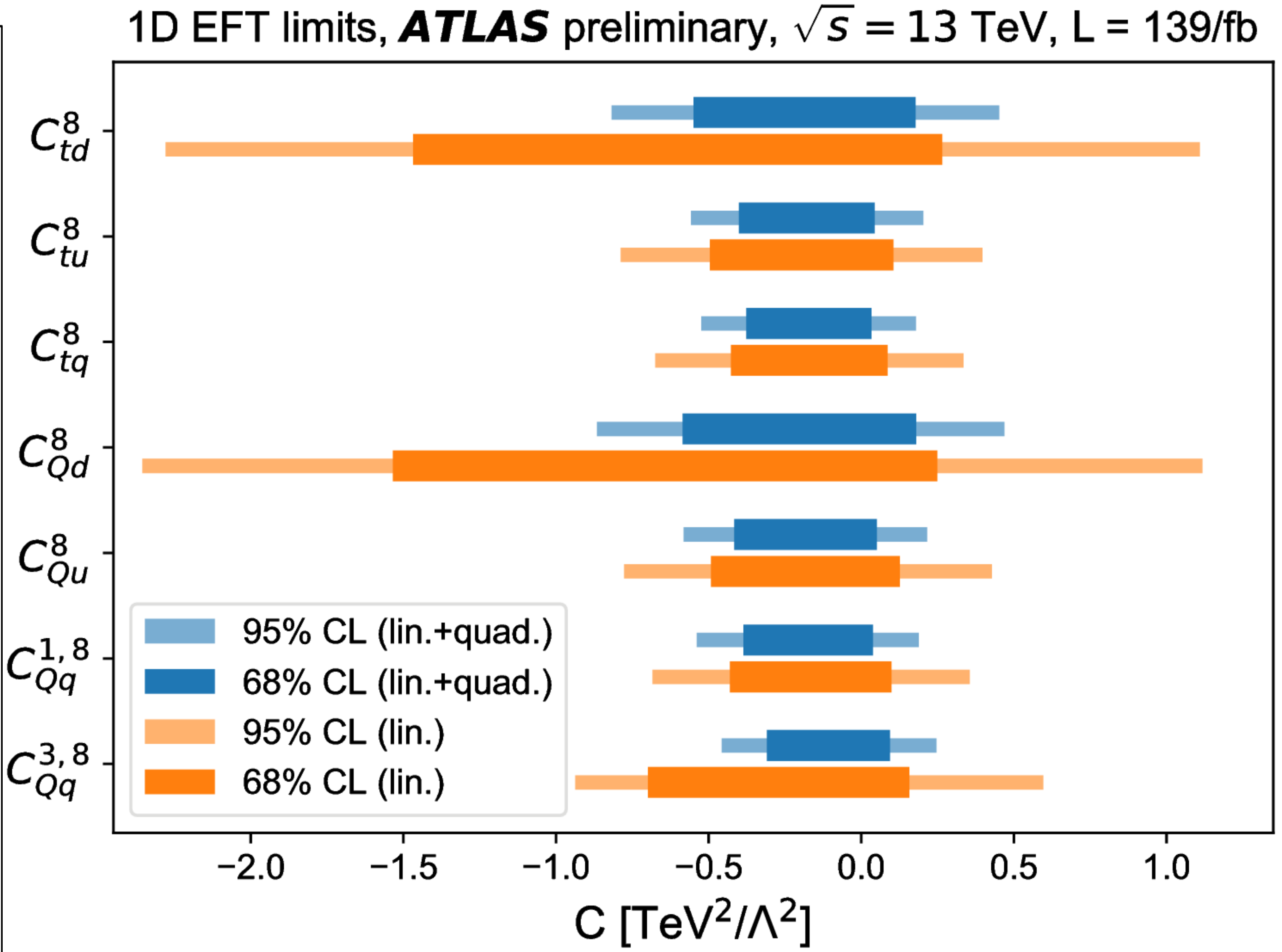
Differential $t\bar{t}$ measurement with boosted tops: all hadronic

ATLAS-CONF-2021-050

- Several single, double and triple differential cross-section measurements were performed.
  - Both at particle level as well as parton level







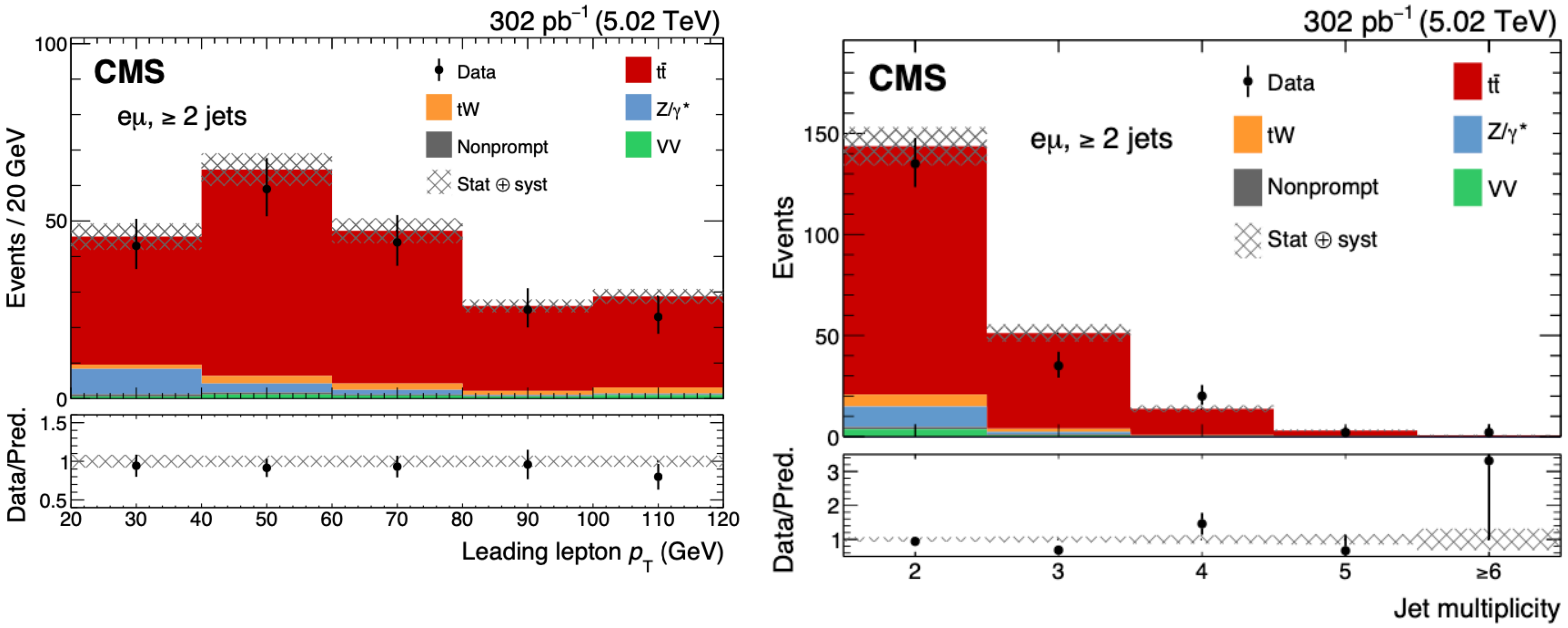
- Data softer than predictions for p_T of the second leading top quark.
- Agreement with NNLO predictions better than NLO + PS
- Leading systematics related top-tagging and jets.

- EFT interpretation is performed with differential cross-section in the leading top-quark p_T.
  - Limits set on 4-quark operators.
- Competitive to currently available limits on individual operators in global fits [JHEP 04(2019) 100]

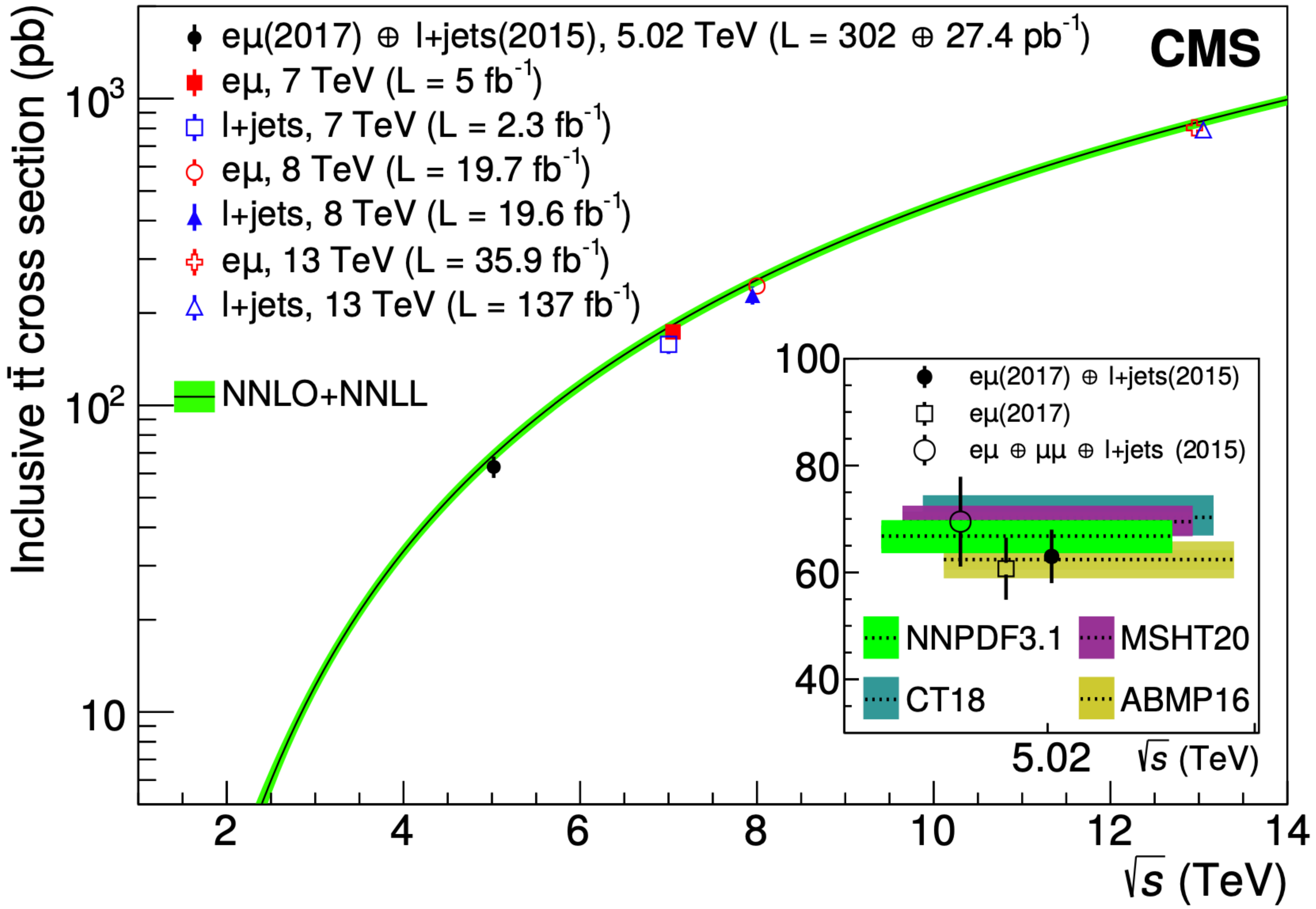
Inclusive $t\bar{t}$ measurement at $\sqrt{s} = 5.02$ TeV

arxiv-2112.09114

- Based on $302\ pb^{-1}$ data collected in a special low-intensity low-energy LHC run.
- Events with opposite sign $e\mu$ pairs are selected for the analysis.



$$\sigma_{t\bar{t}} = 60.7 \pm 5.0\,(\text{stat}) \pm 2.8\,(\text{syst}) \pm 1.1\,(\text{lumi})\ \text{pb}.$$

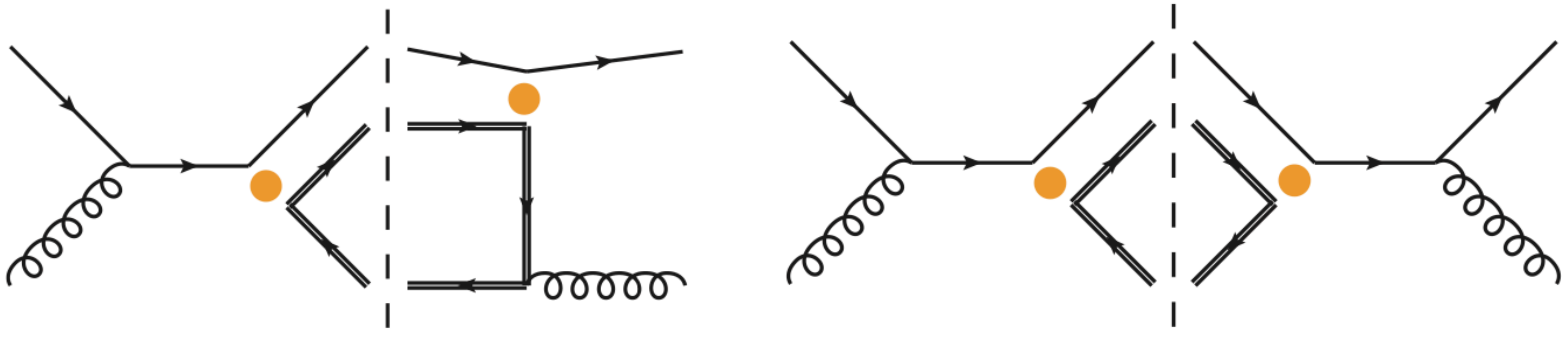


- Leading systematic uncertainties are related to lepton efficiencies and trigger efficiencies.

$t\bar{t}j$ Energy asymmetry: EFT interpretation

arxiv-2110.05453

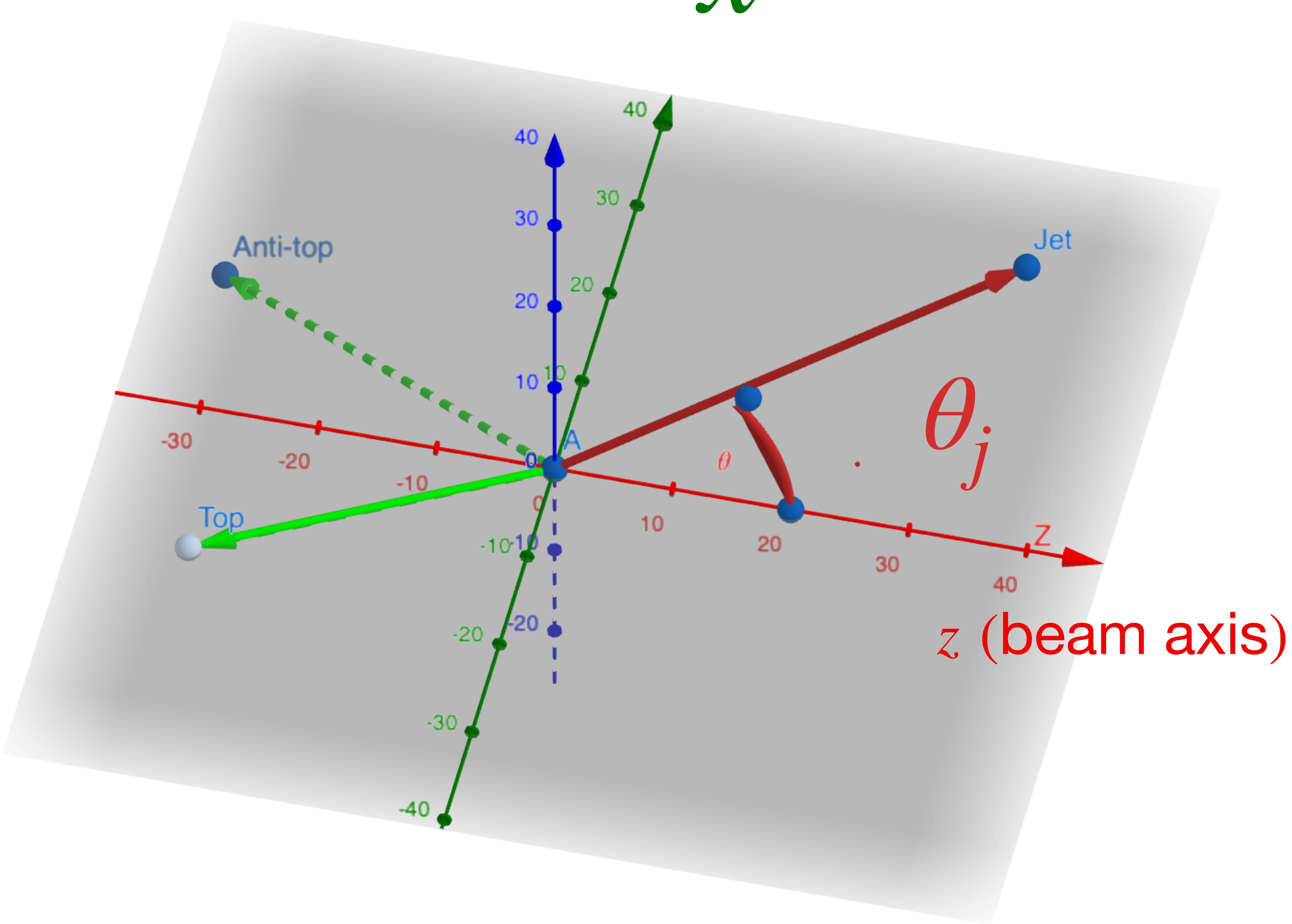
- Charge asymmetry can be measured as rapidity asymmetry as well as energy asymmetry in the $t\bar{t}j$ the system.
    - Complementary phase space.



(a) (b)

- The energy asymmetry is sensitive to the chiral and color structure of four-quark operators.

$t\bar{t}j$ – Rest frame



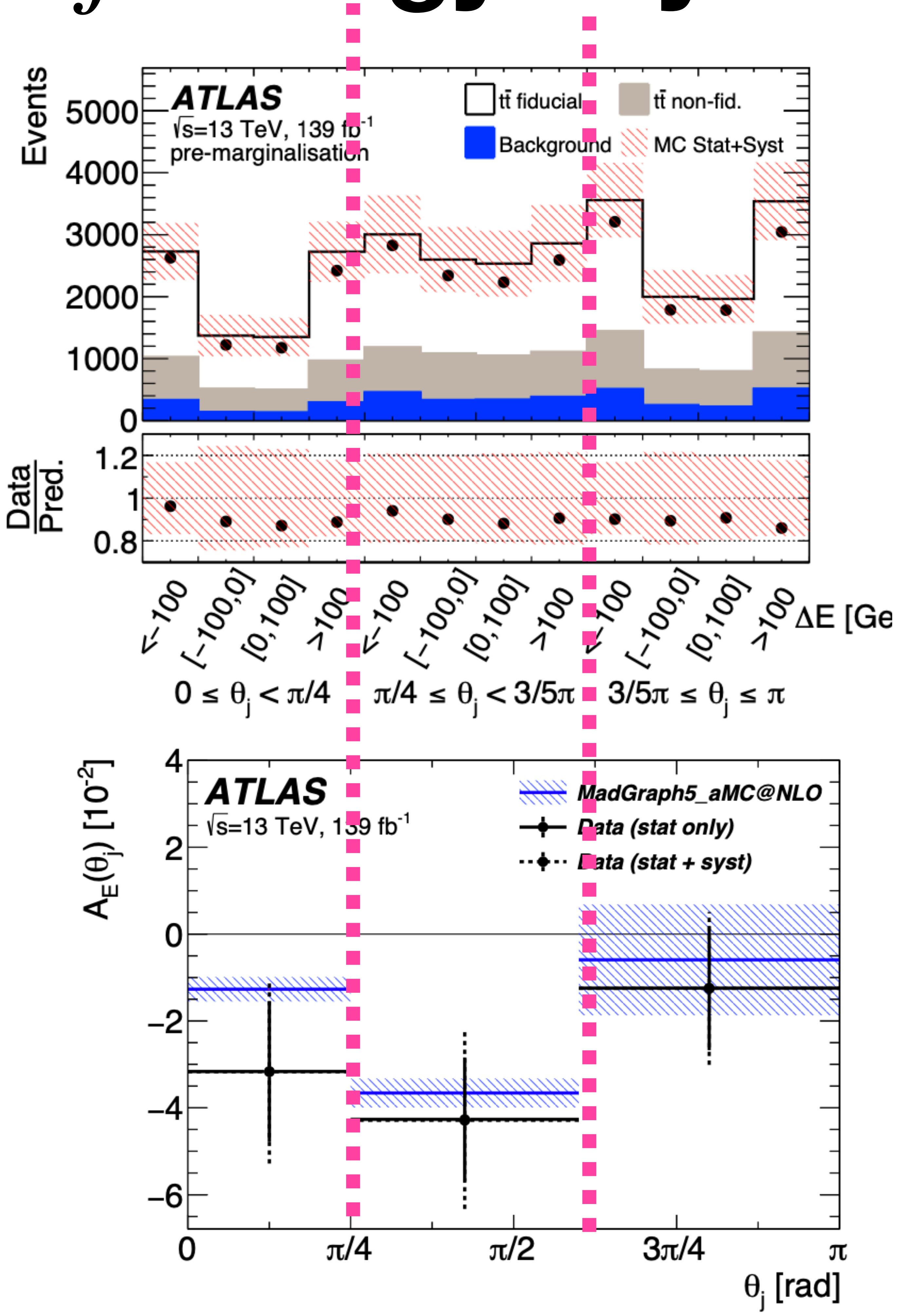
$$\sigma^{\text{opt}}(\theta_j) = \sigma(\theta_j | y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j | y_{t\bar{t}j} < 0)\,, \qquad \theta_j \in [0, \pi]$$

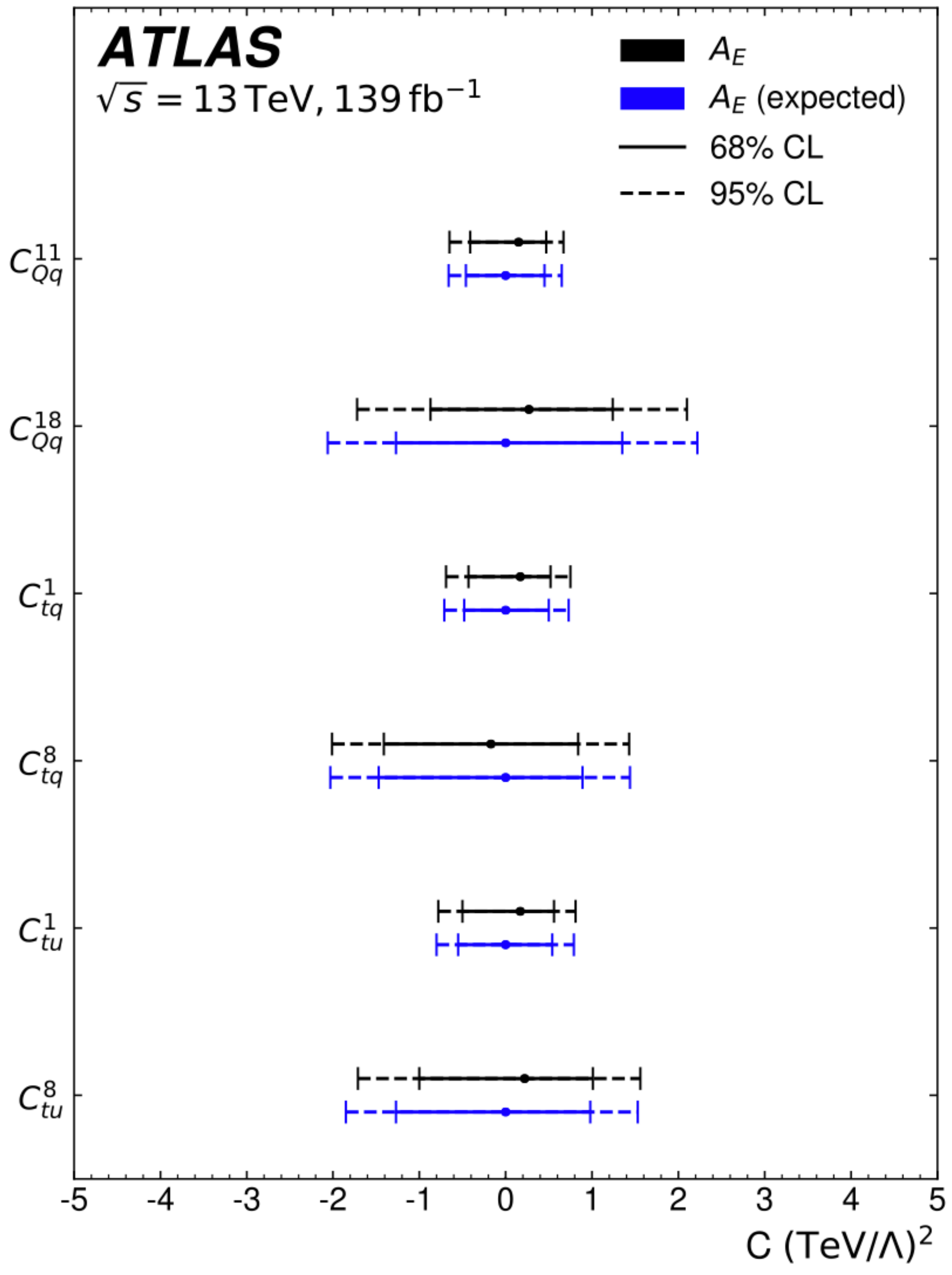
- $\Delta E = E_t - E_{\bar{t}}$

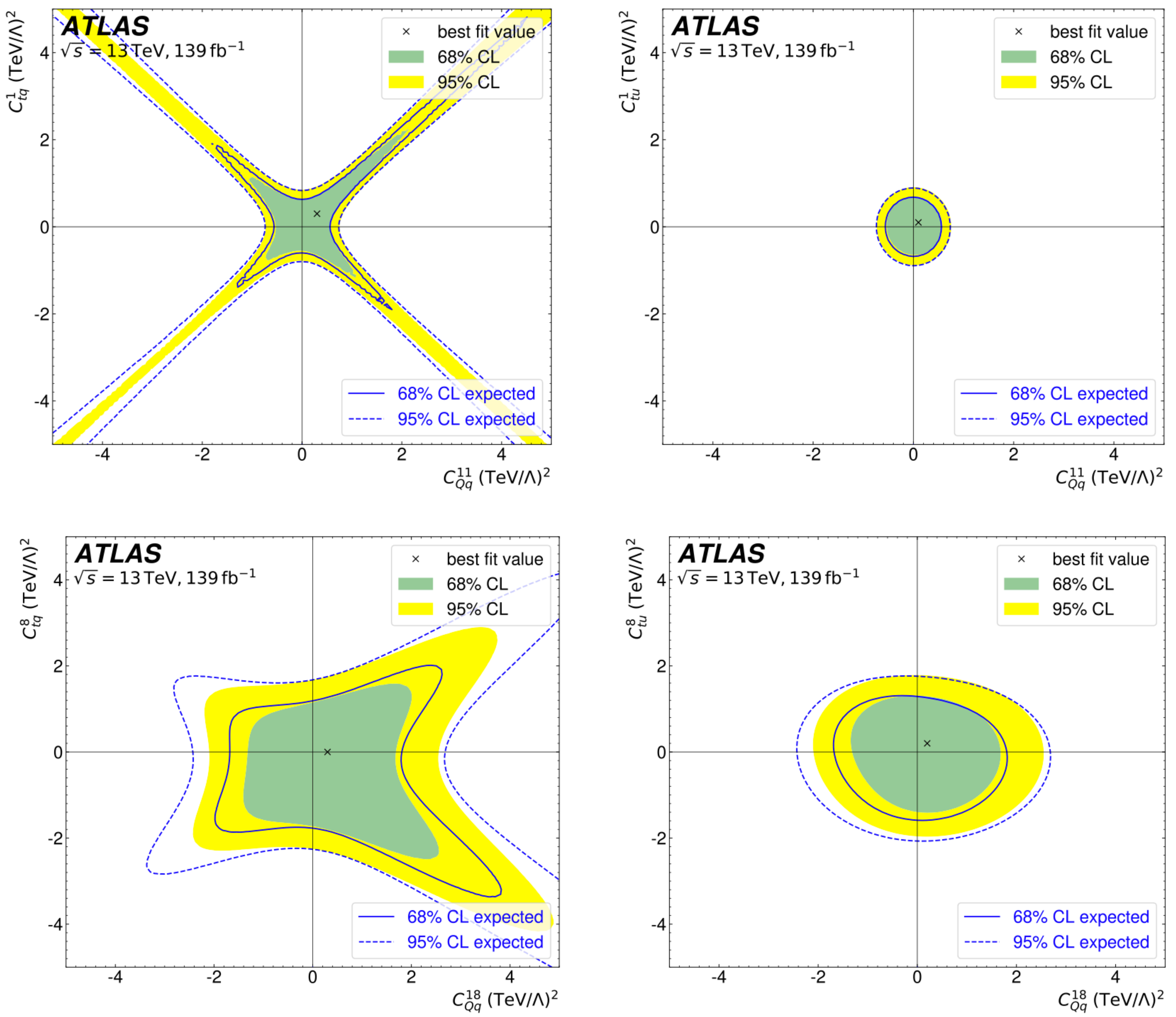
$$A_E(\theta_j) \equiv \frac{\sigma^{\text{opt}}(\theta_j | \Delta E > 0) - \sigma^{\text{opt}}(\theta_j | \Delta E < 0)}{\sigma^{\text{opt}}(\theta_j | \Delta E > 0) + \sigma^{\text{opt}}(\theta_j | \Delta E < 0)}\,,$$

$t\bar{t}j$ Energy asymmetry: EFT interpretation

arxiv-2110.05453



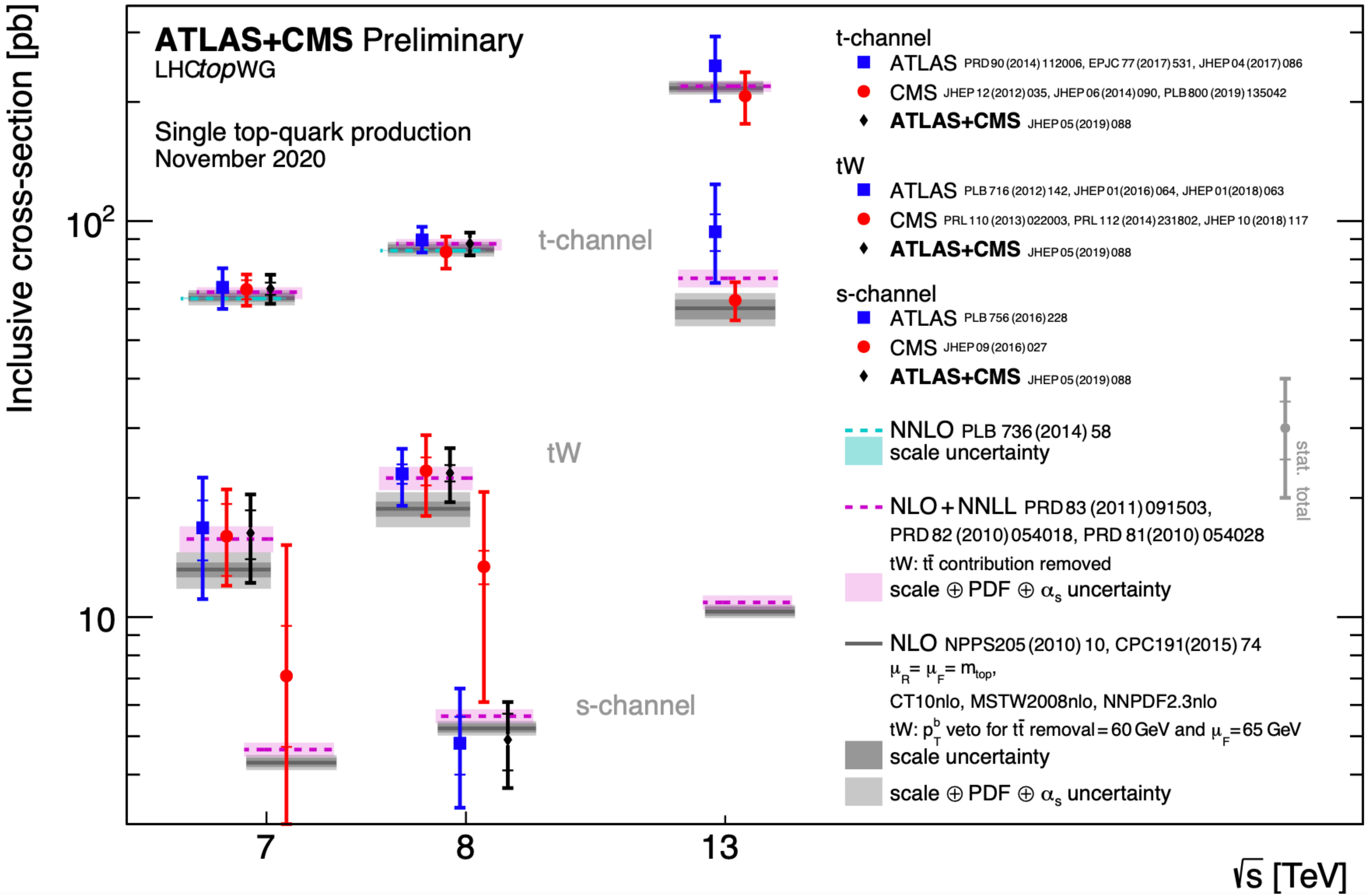


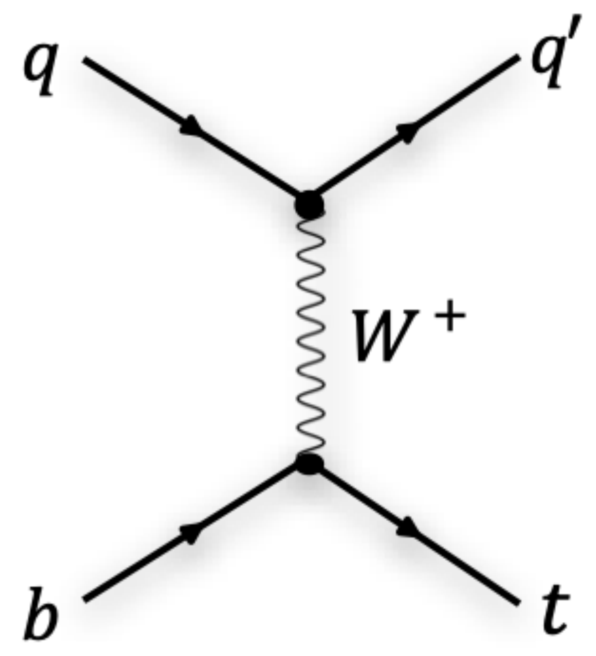


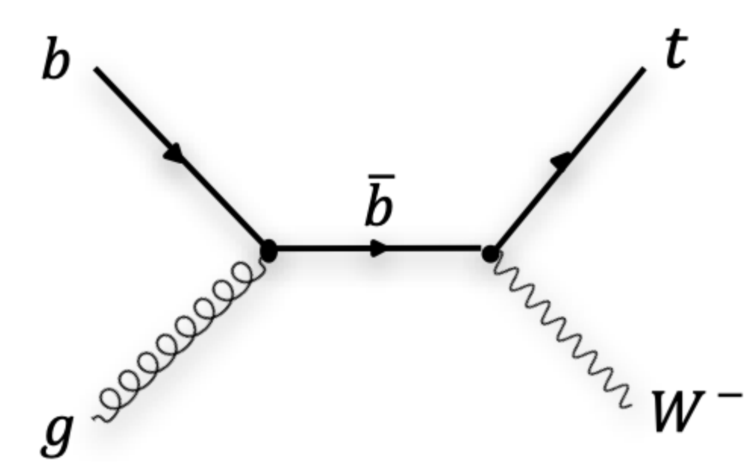
- The measured asymmetry in all θ_j bins are consistent with NLO QCD predictions.
- The bounds for color singlet operators are stronger than color octet operators.
    - SMEFT interpretation probes new directions in the dim-6 parameter space.
    - The analysis is limited by available data statistics and $t\bar{t}$ FSR modelling.

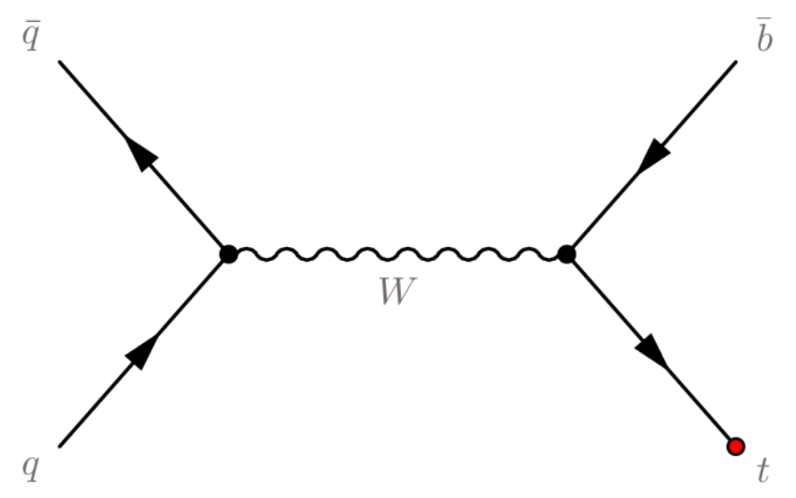
Single top production

LHC-topWG









- Several measurements performed by ATLAS & CMS at 7, 8 & 13 TeV.
- Theory predictions in good agreement with measurement

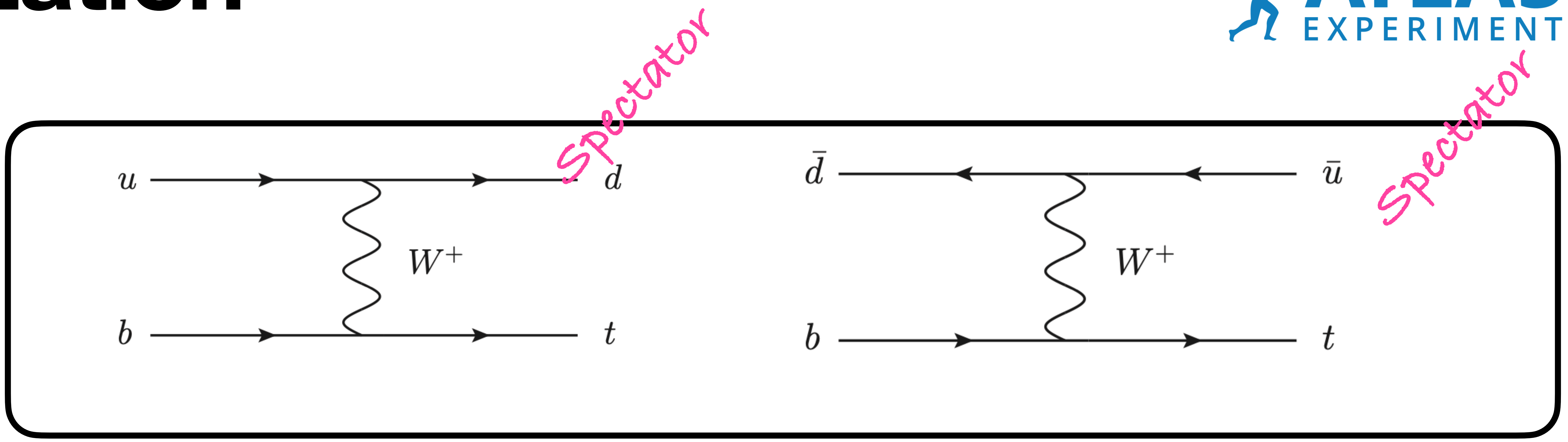
Single top: t-Channel, Polarization

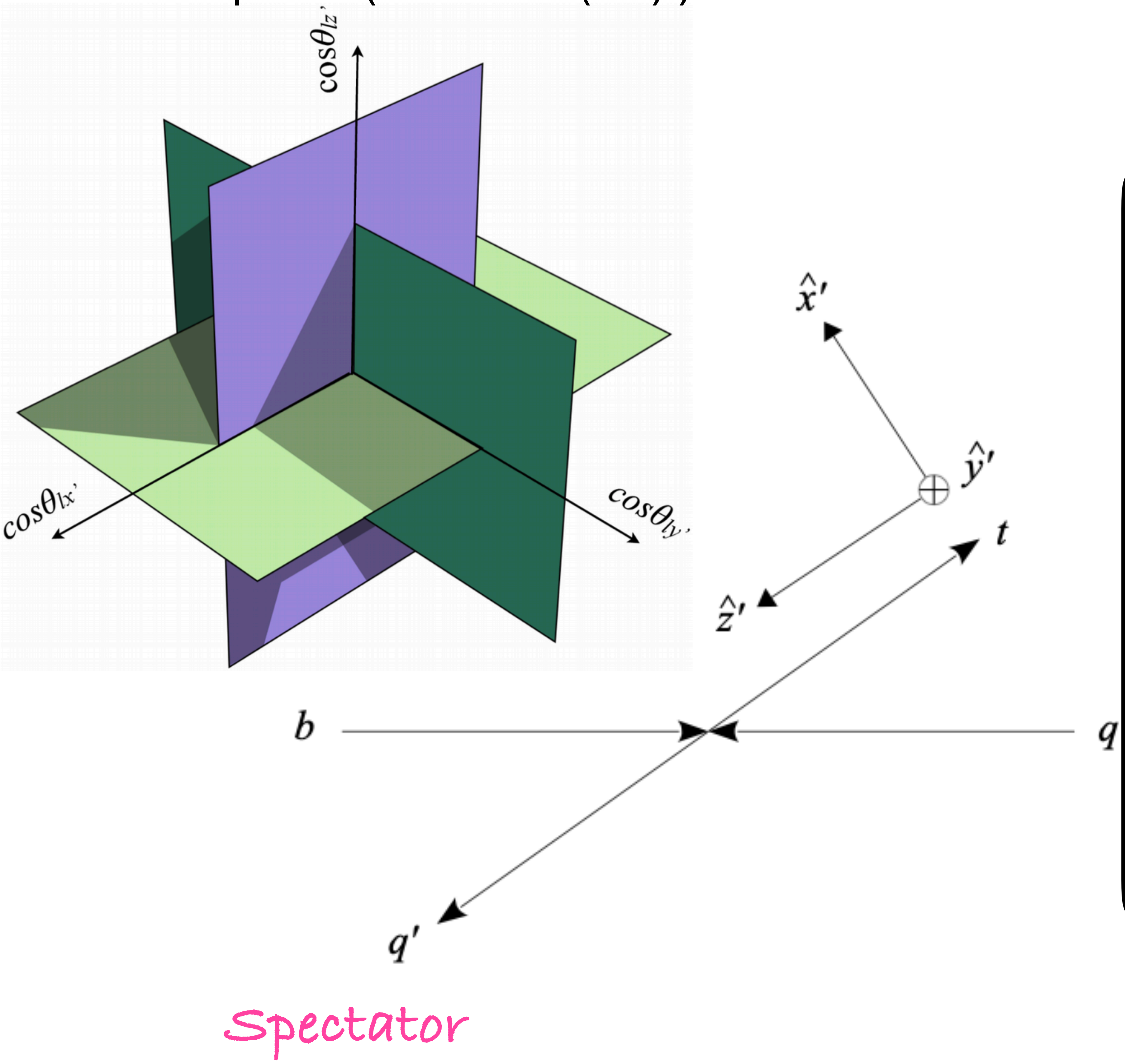
arxiv-2202.11382

ATLAS EXPERIMENT

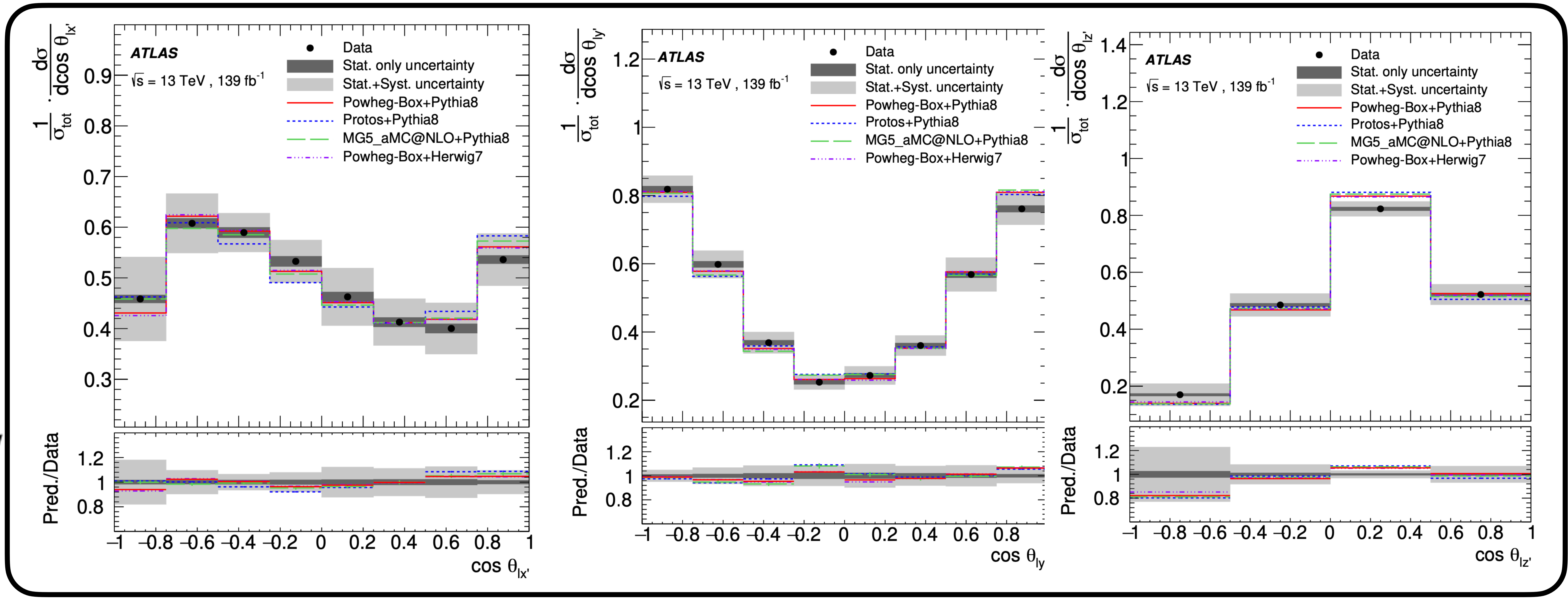
Production

- Top quark in t-channel single top production is polarized.
- Polarization vector is extracted as a function of $cos\theta_{\ell j}$
  - Analysis based on angular distribution of charge lepton. ($t \rightarrow bW(\ell\nu)$)





Unfolded direction cosines



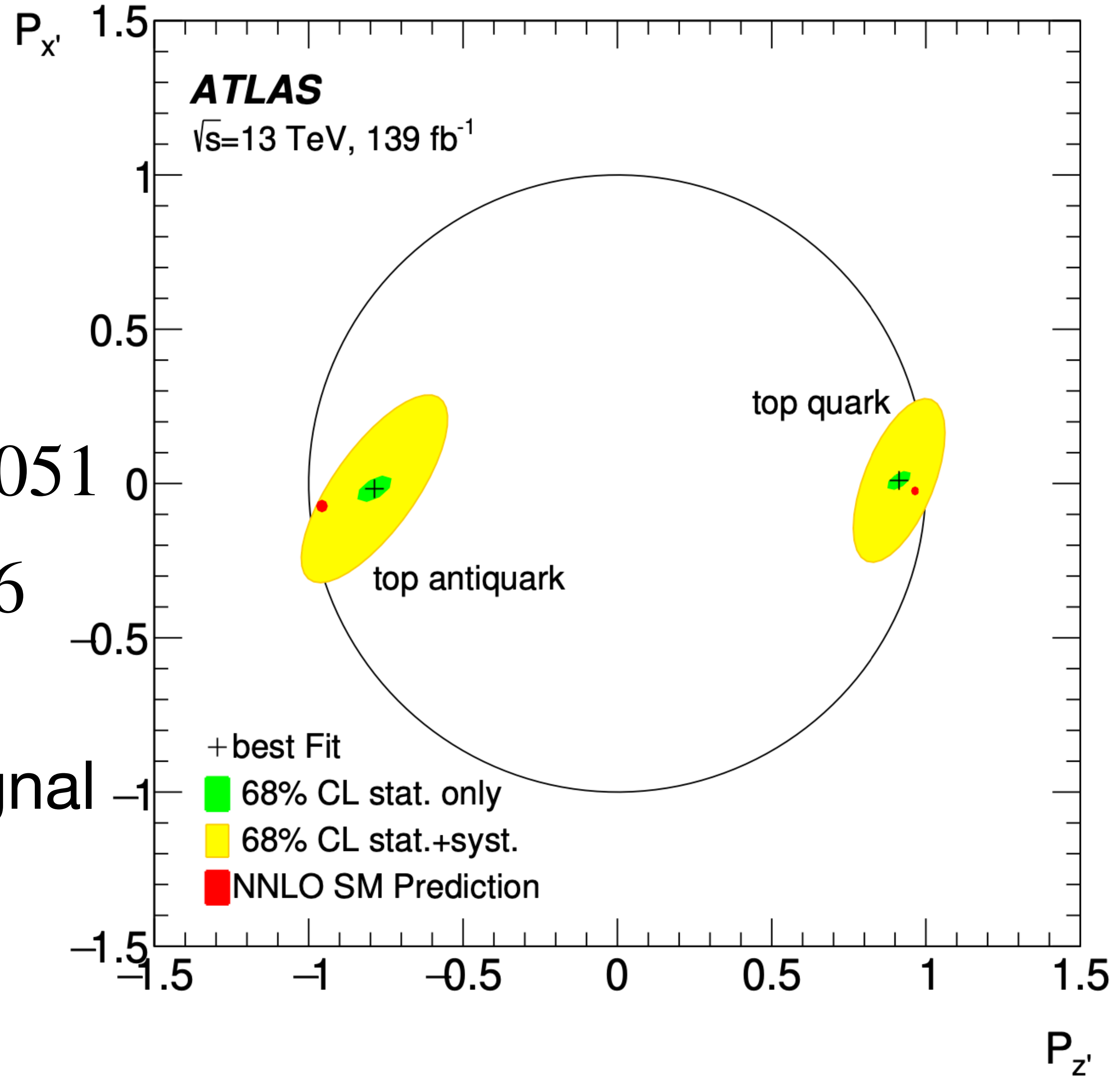
arxiv-2202.11382

Single top: t-Channel, Polarization

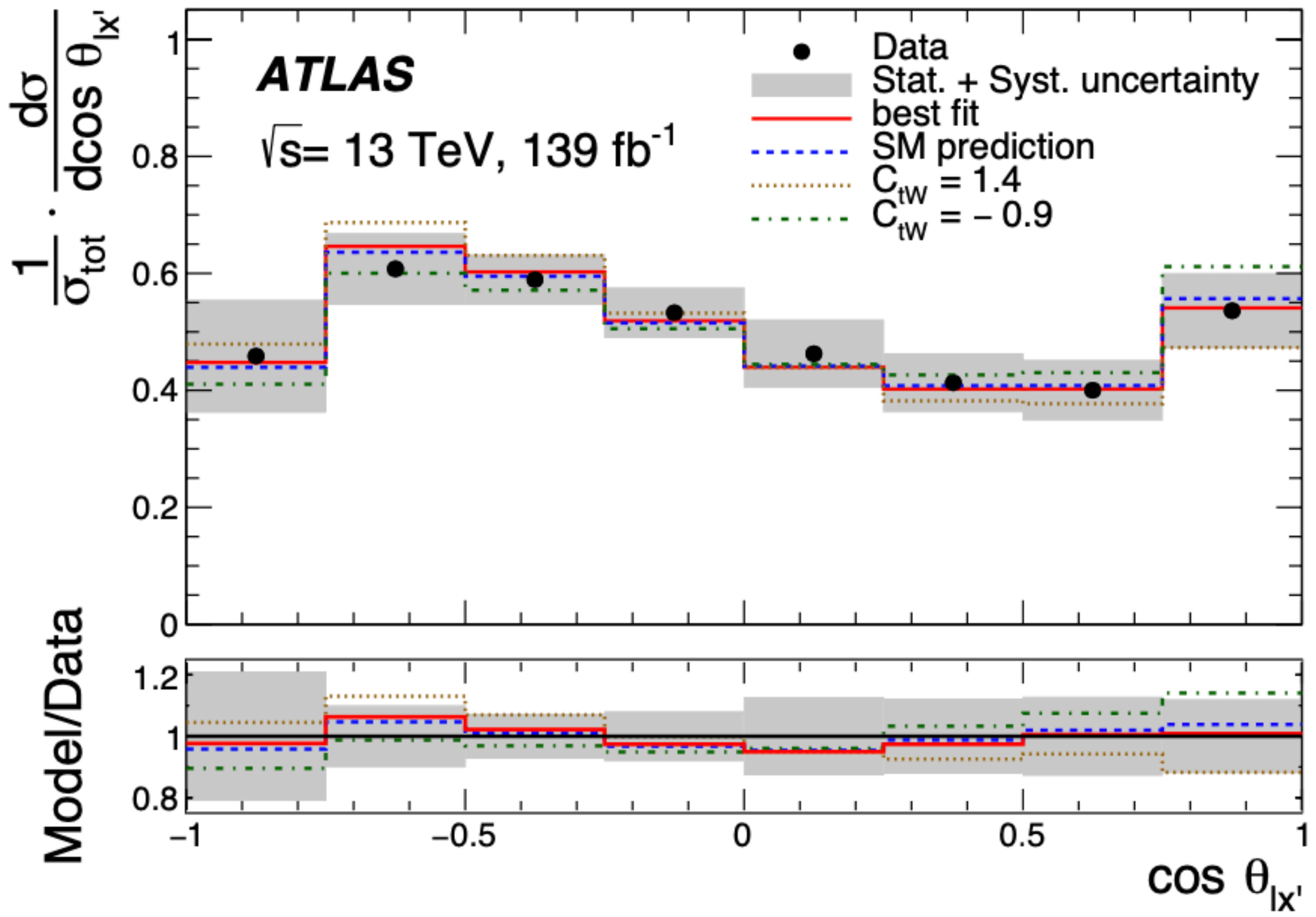
- Best fit polarization measurement values.

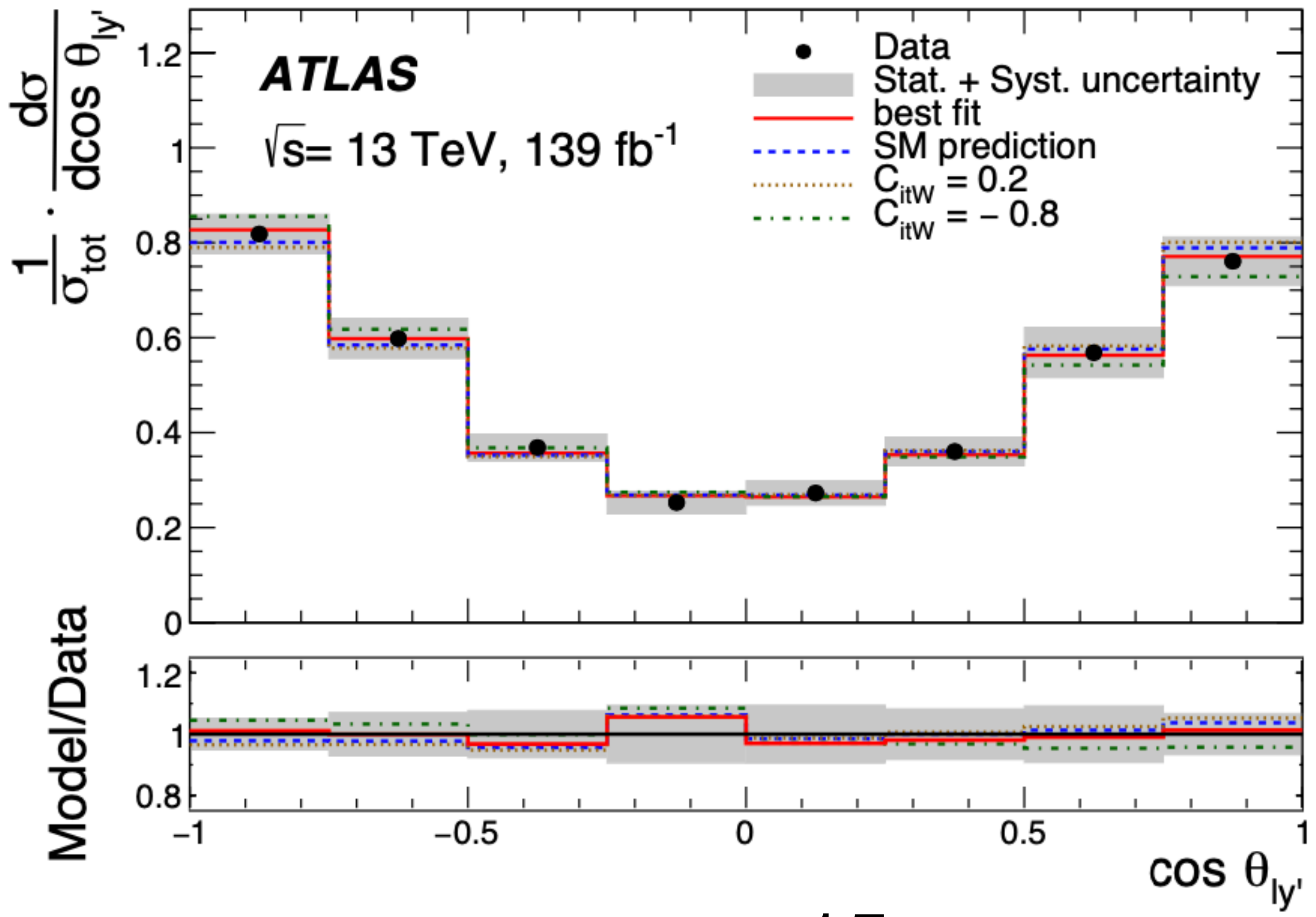
- Top quarks
  - $P_{x'} = 0.01 \pm 0.18$
  - $P_{y'} = -0.029 \pm 0.027$
  - $P_{z'} = 0.91 \pm 0.10$
- Top Anti quarks
  - $P_{x'} = -0.2 \pm 0.20$
  - $P_{y'} = -0.007 \pm 0.051$
  - $P_{z'} = -0.79 \pm 0.16$

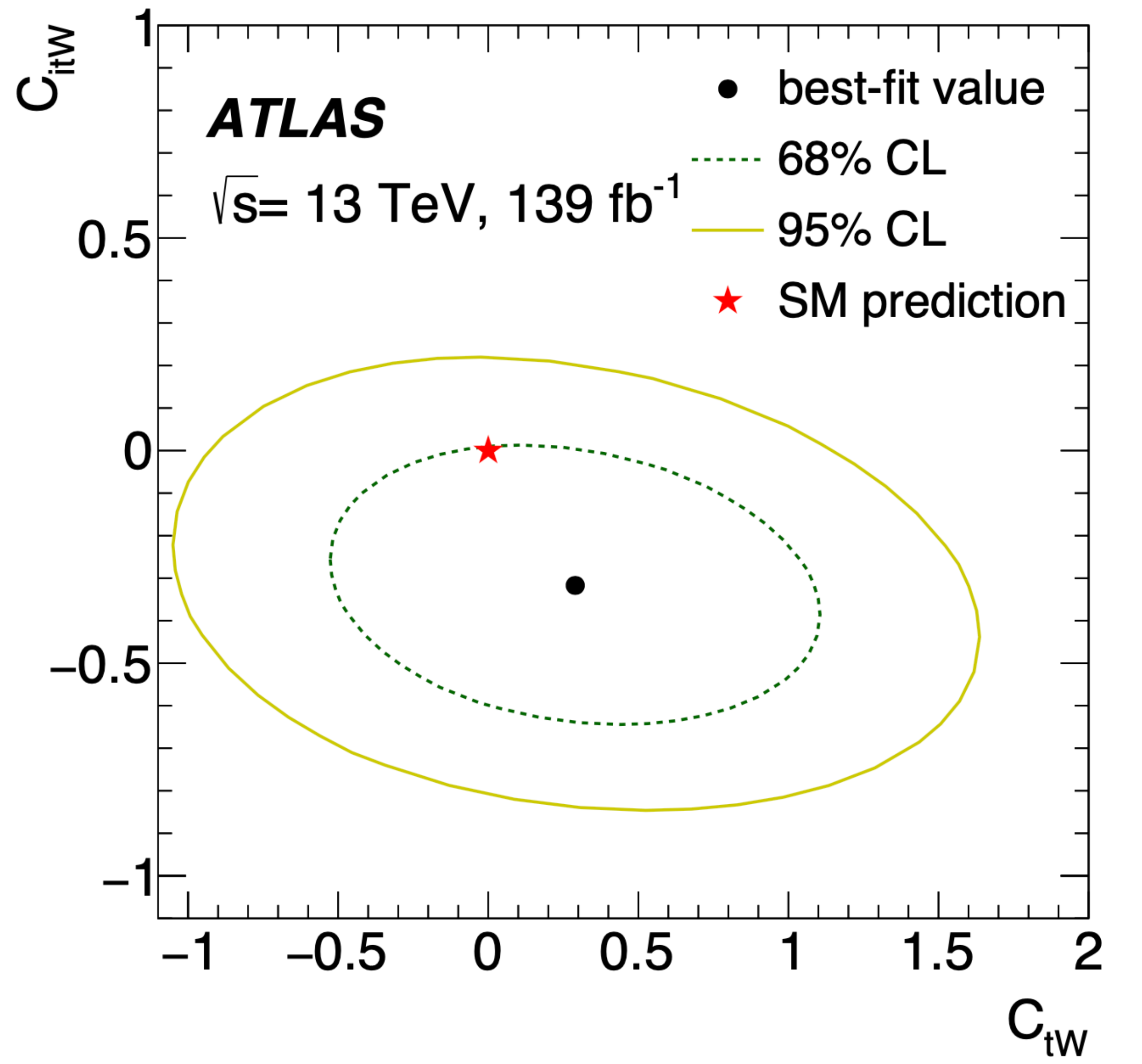
- Leading uncertainties: JER followed by JES and signal modelling.



- EFT interpretation
- Angular measurement used to derive bounds on the complex Wilson coefficients of dim-6 operator $\mathcal{O}_{tW}$



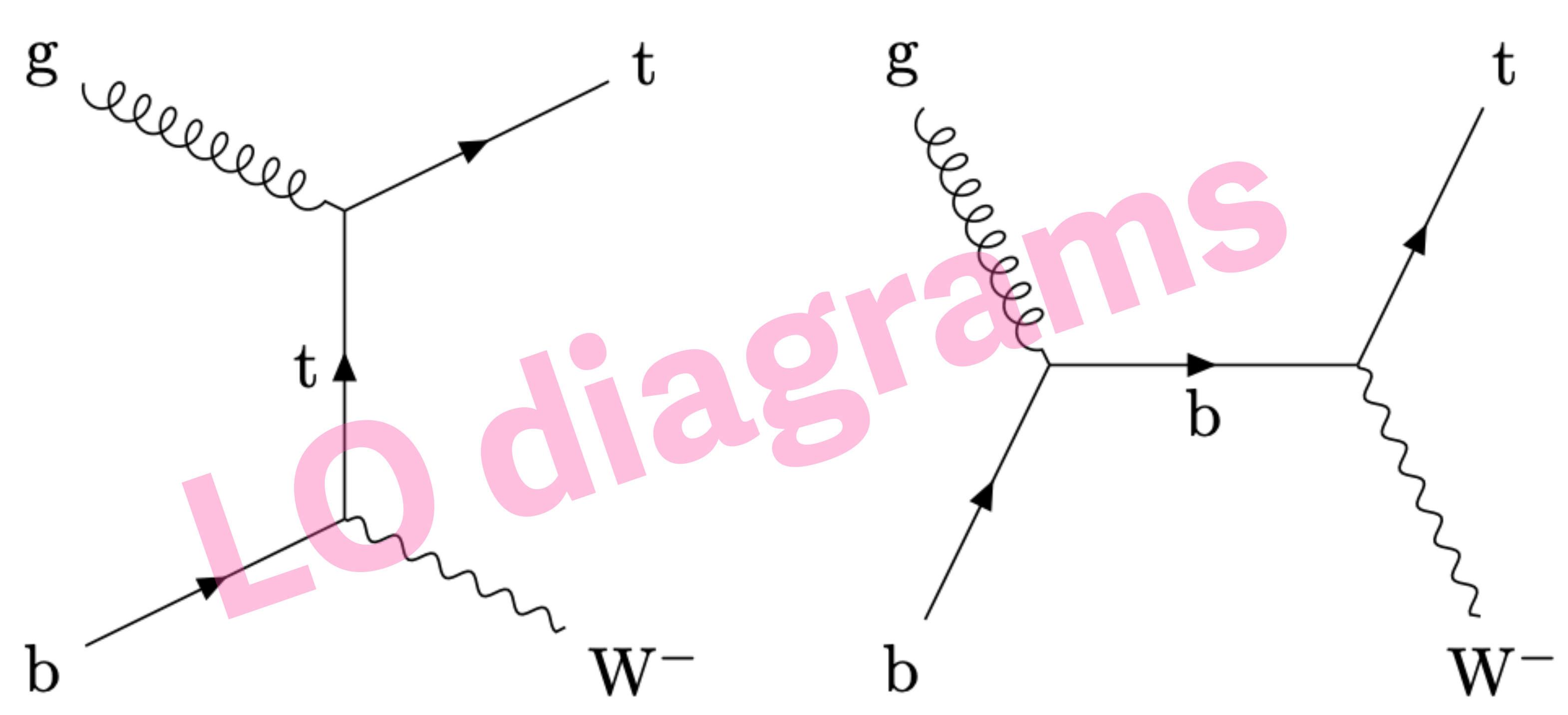




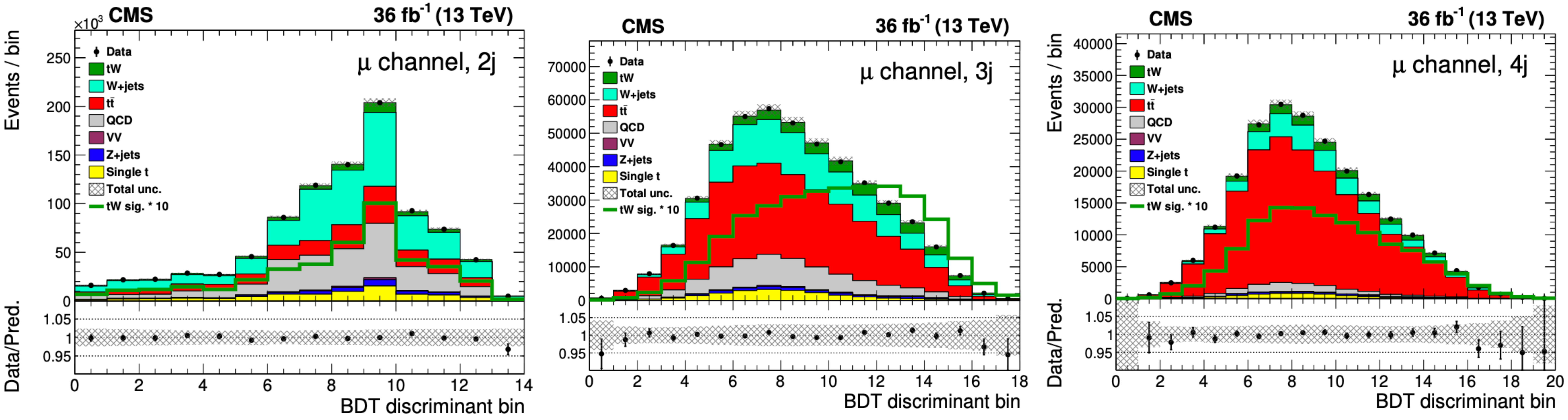
JHEP11(2021)111

Single top: tW production

- Sensitive to the CKM matrix element $|V_{tb}|$
- Interference with $t\bar{t}$ production at NLO
  - Diagram removal scheme adopted for signal modleling



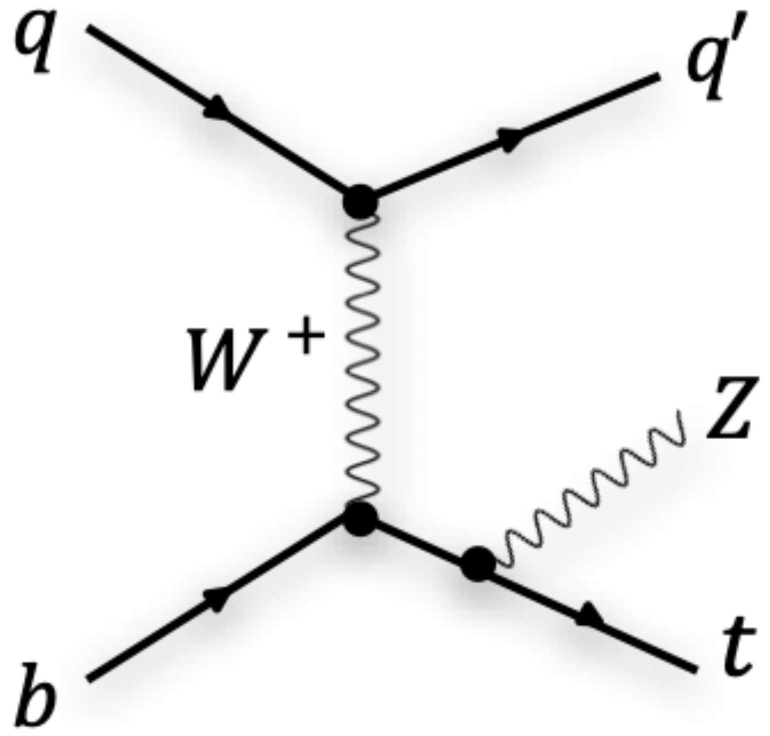
- BDT is trained to separate tW from $t\bar{t}$ background.
- Leading backgrounds: W+jets, QCD multijets & $t\bar{t}$ process
  - W+jets template from simulation and normalization derived from fit to data
  - QCD multijet, both template and normalization derived from data.



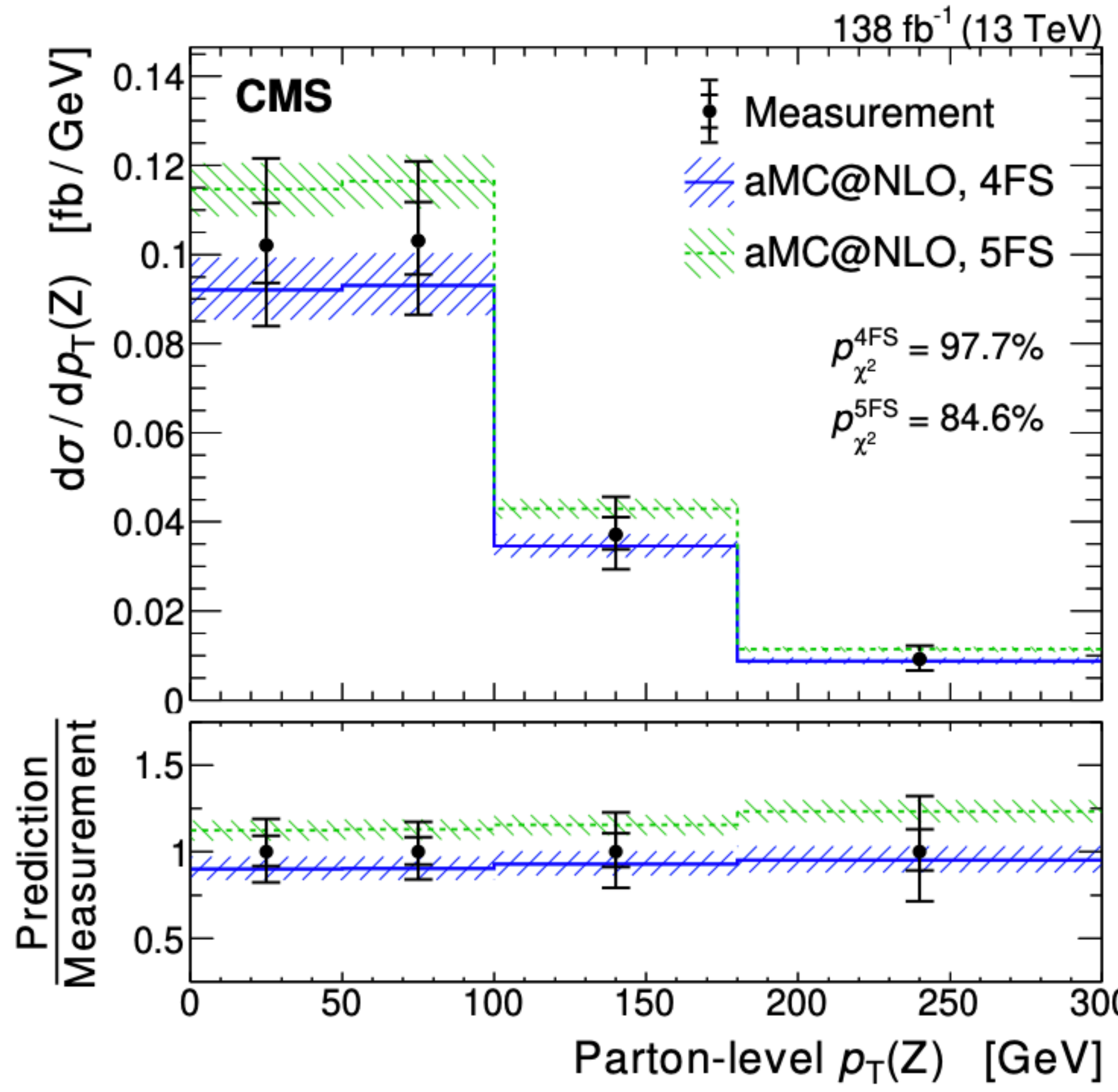
- Cross-section extracted via binned likelihood fit on the BDT discriminant for e, μ channel across jet-multiplicity bins simultaneously.
- Observed cross-section: $89 \pm 4(stat) \pm 12(syst)$ pb (consistent with SM prediction
- Leading systematics: Jet energy scale, b-tagging efficiency, luminosity

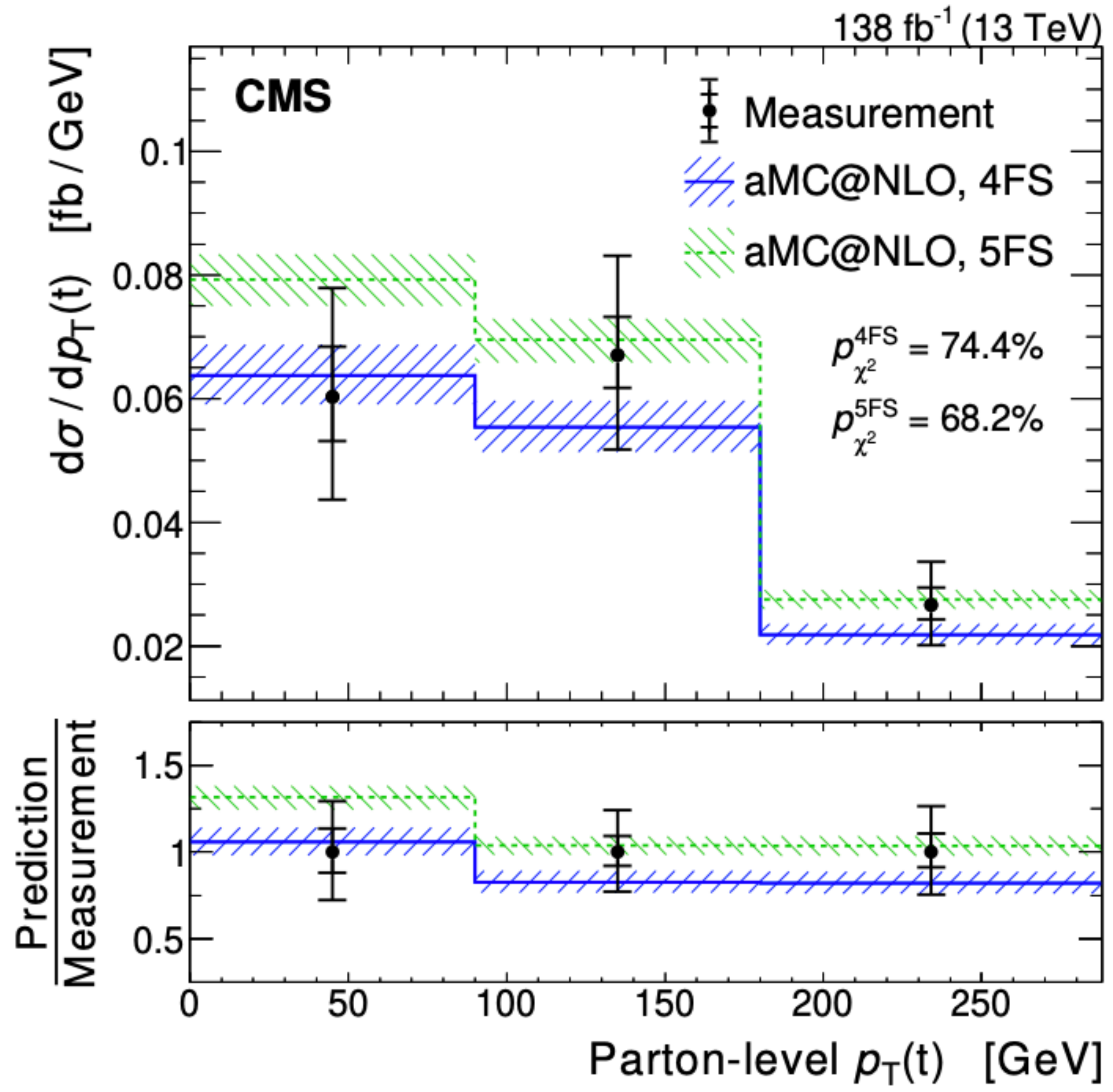
JHEP02(2022)107

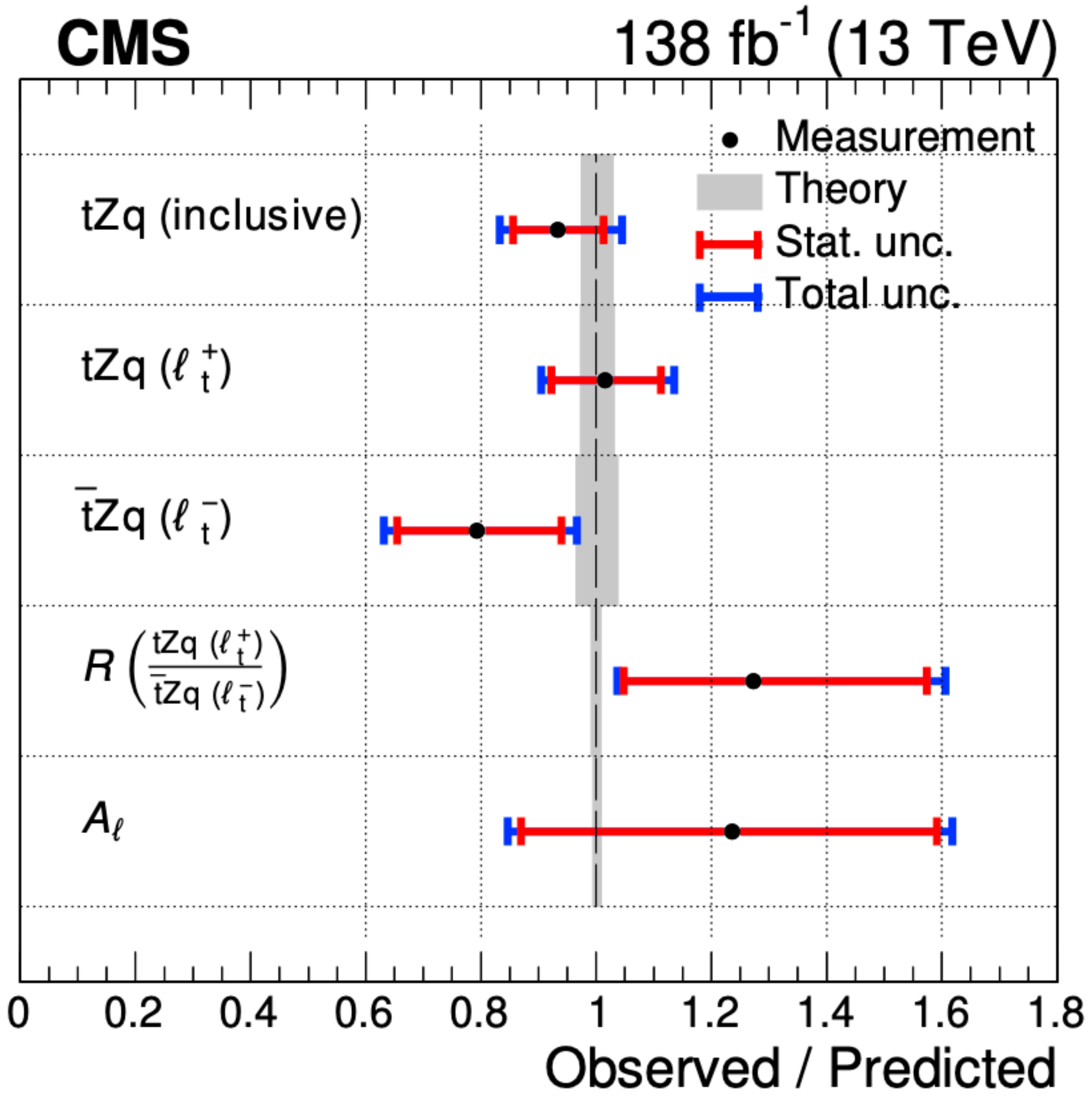
tZq: Differential and inclusive measurement



- Only small QCD corrections. Precise tZ coupling measurement possible







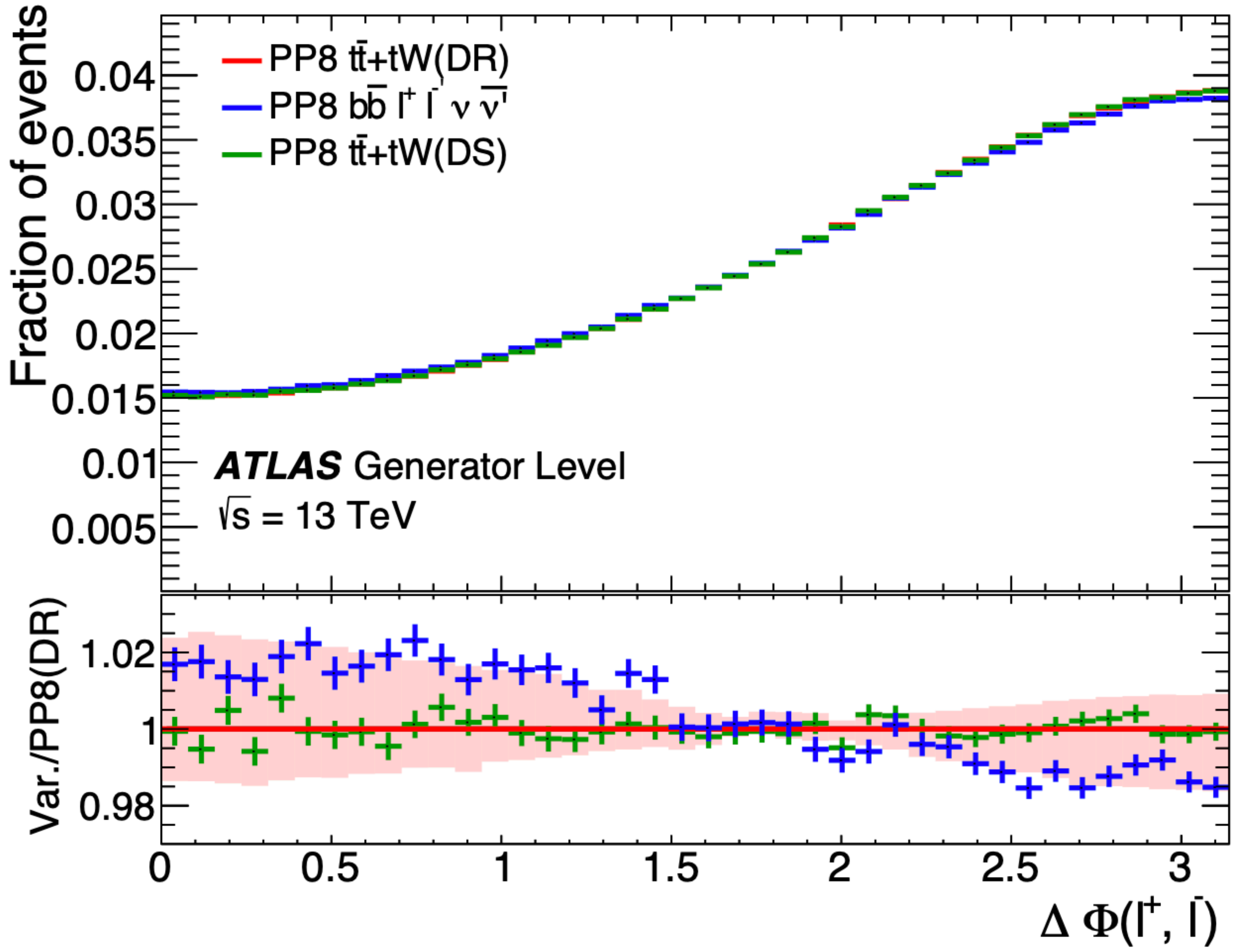
- Systematics are dominated by signal and $t\bar{t}Z$ scale variations.

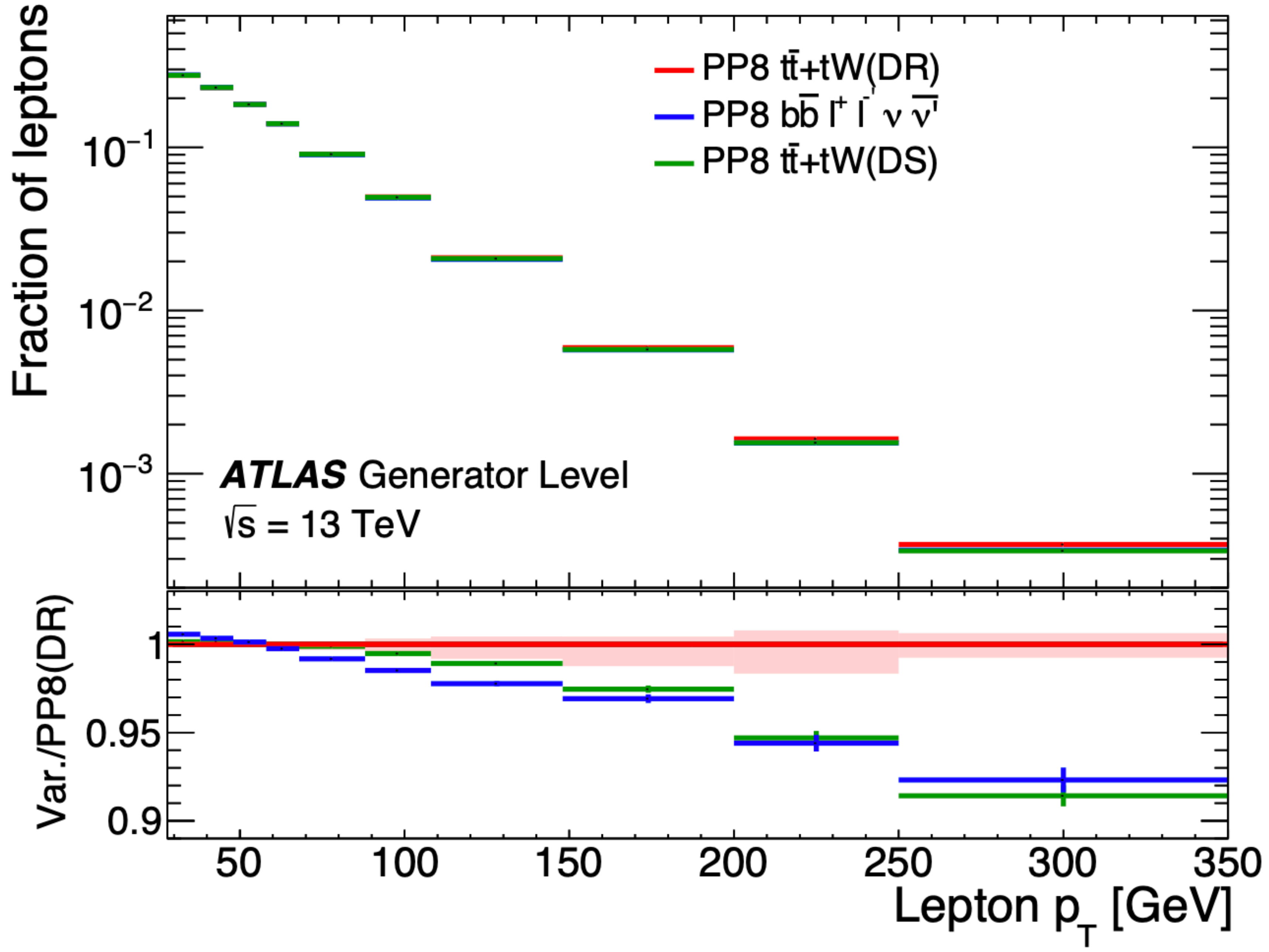
- 5FS predicts larger cross-section wrt 4FS. However the calculations are compatible within uncertainties.
- Inclusive measurement from ATLAS: J. High Energ. Phys. 2020, 124 (2020)

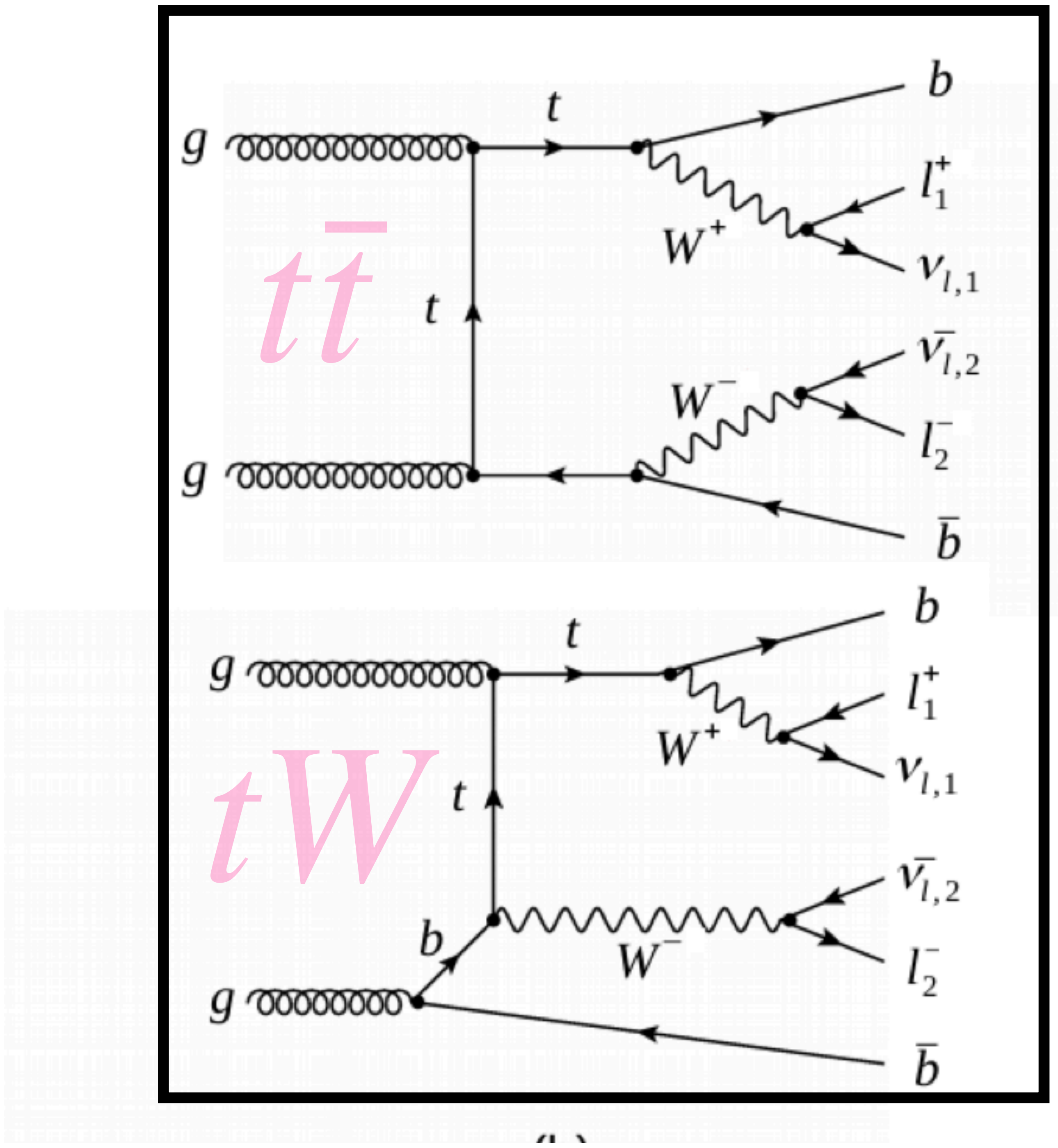
Study of $t\bar{t}/tW$ interference using $pp \to bbl\nu l'\nu'$ simulation

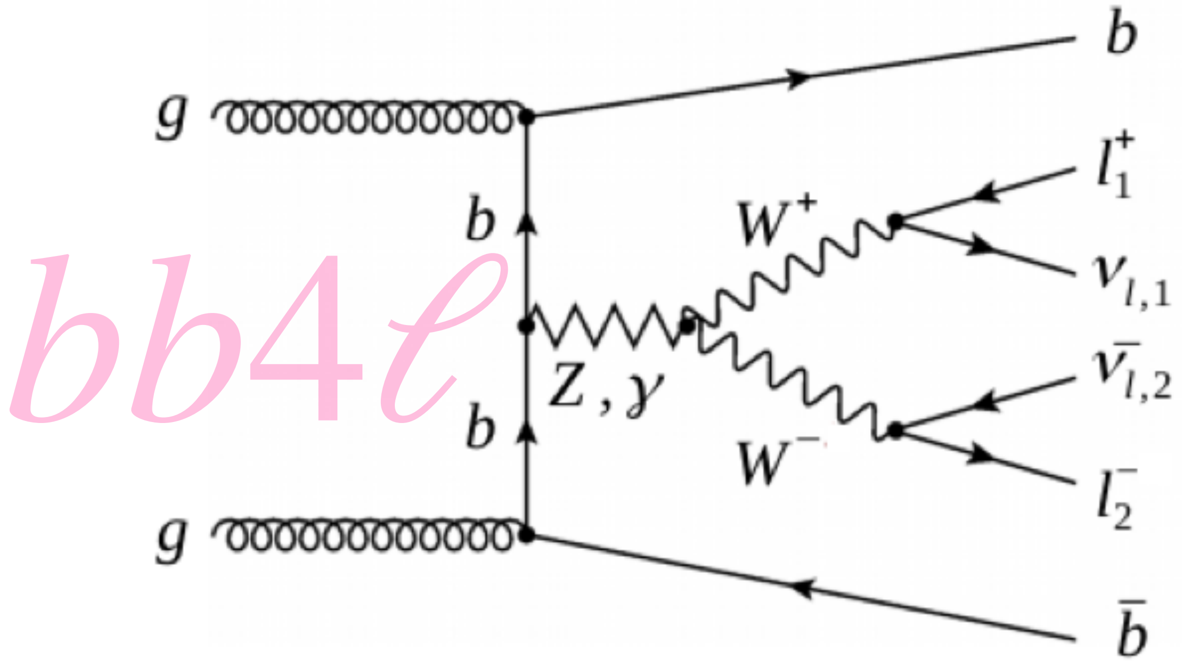
ATL-PHYS-PUB-2021-042

- Interference between $t\bar{t}$ and tW production is handled through various diagram removal (DR) or diagram subtraction (DS) schemes.
- $bb4\ell$ implemented in Powheg-Box-Res framework takes into account overlap between these processes





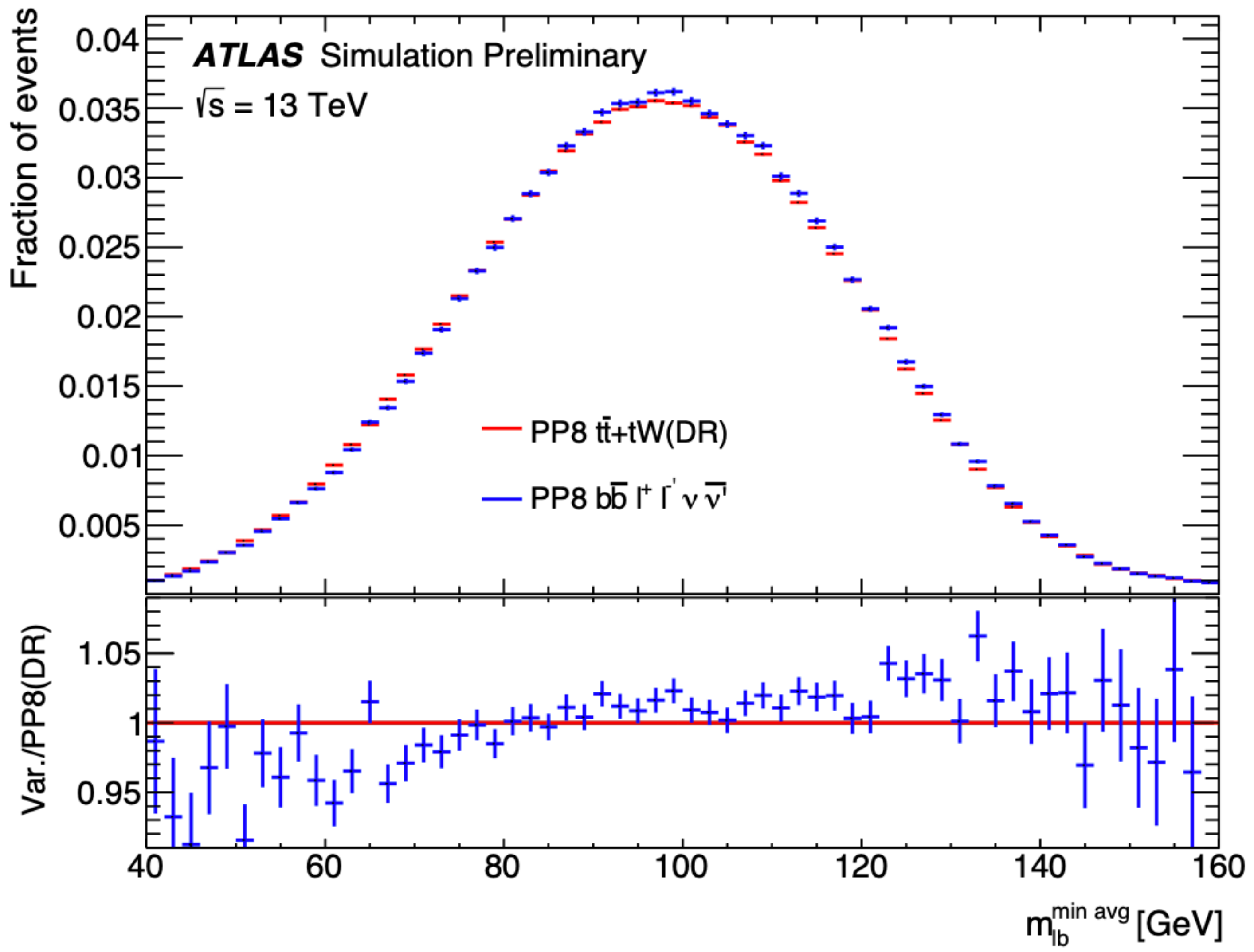




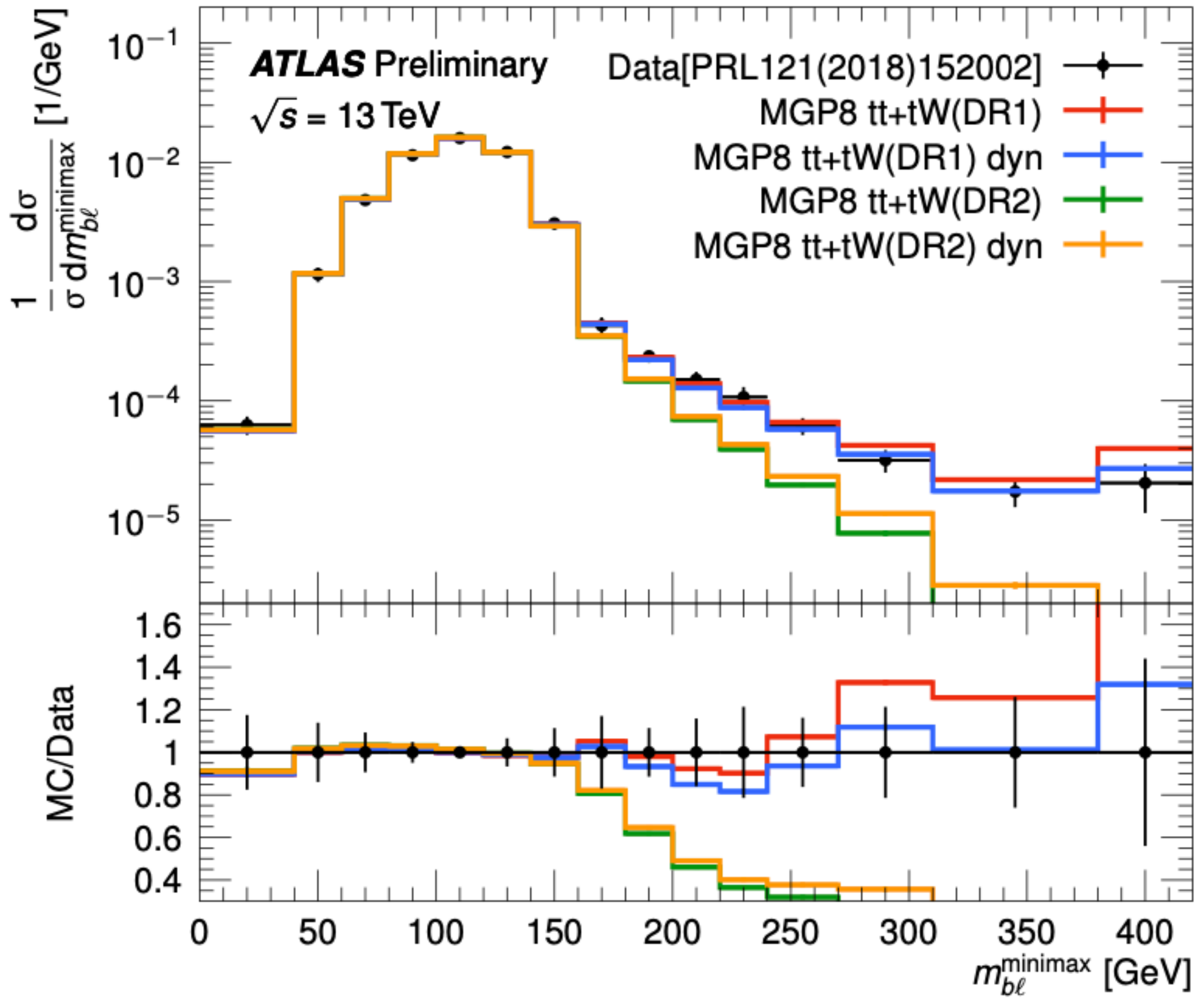
- Some kinematic distributions show similarity between different schemes, while some others don’t.

Study of $t\bar{t}/tW$ interference using $pp \to bbl\nu l'\nu'$ simulation

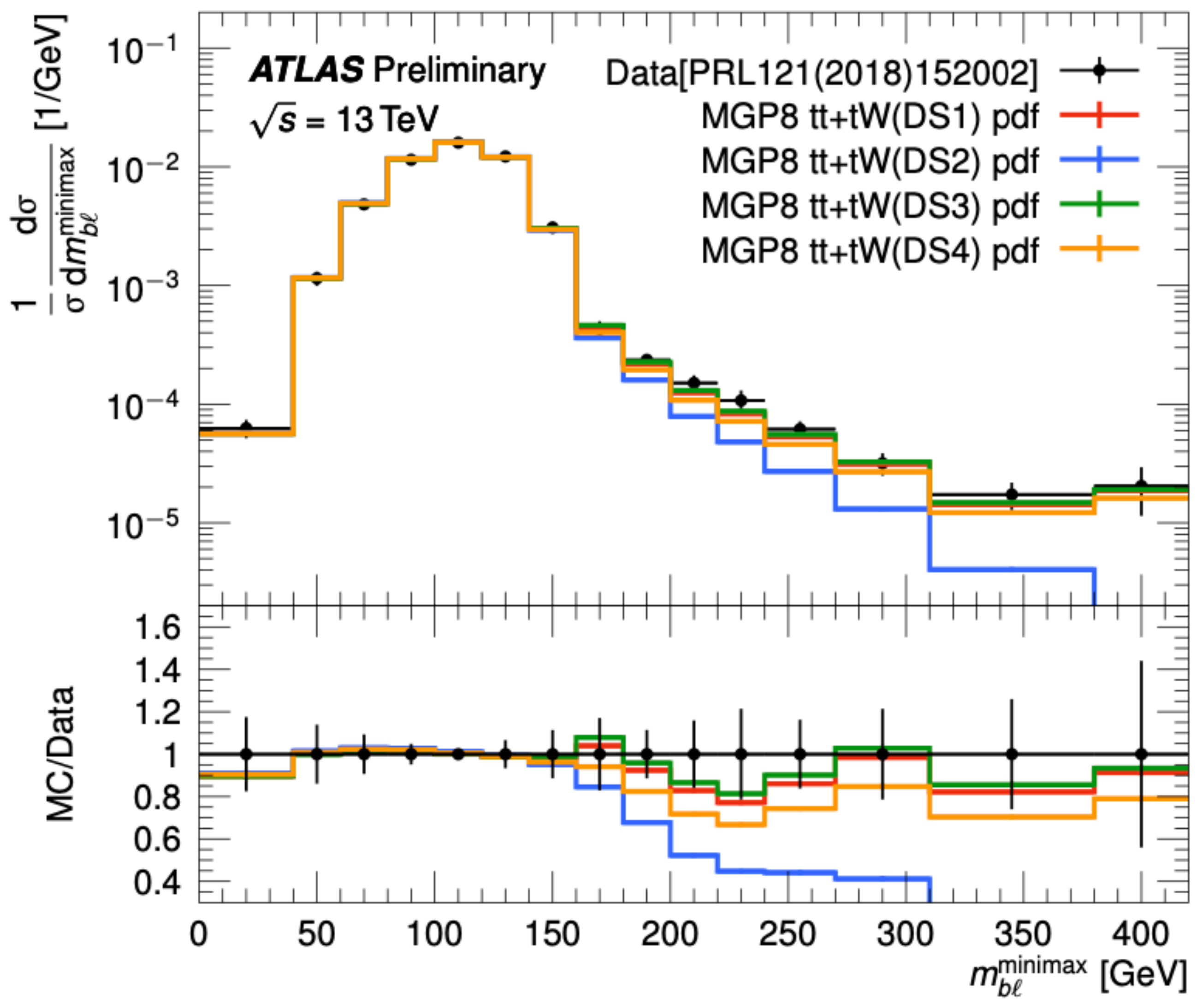
ATL-PHYS-PUB-2021-042

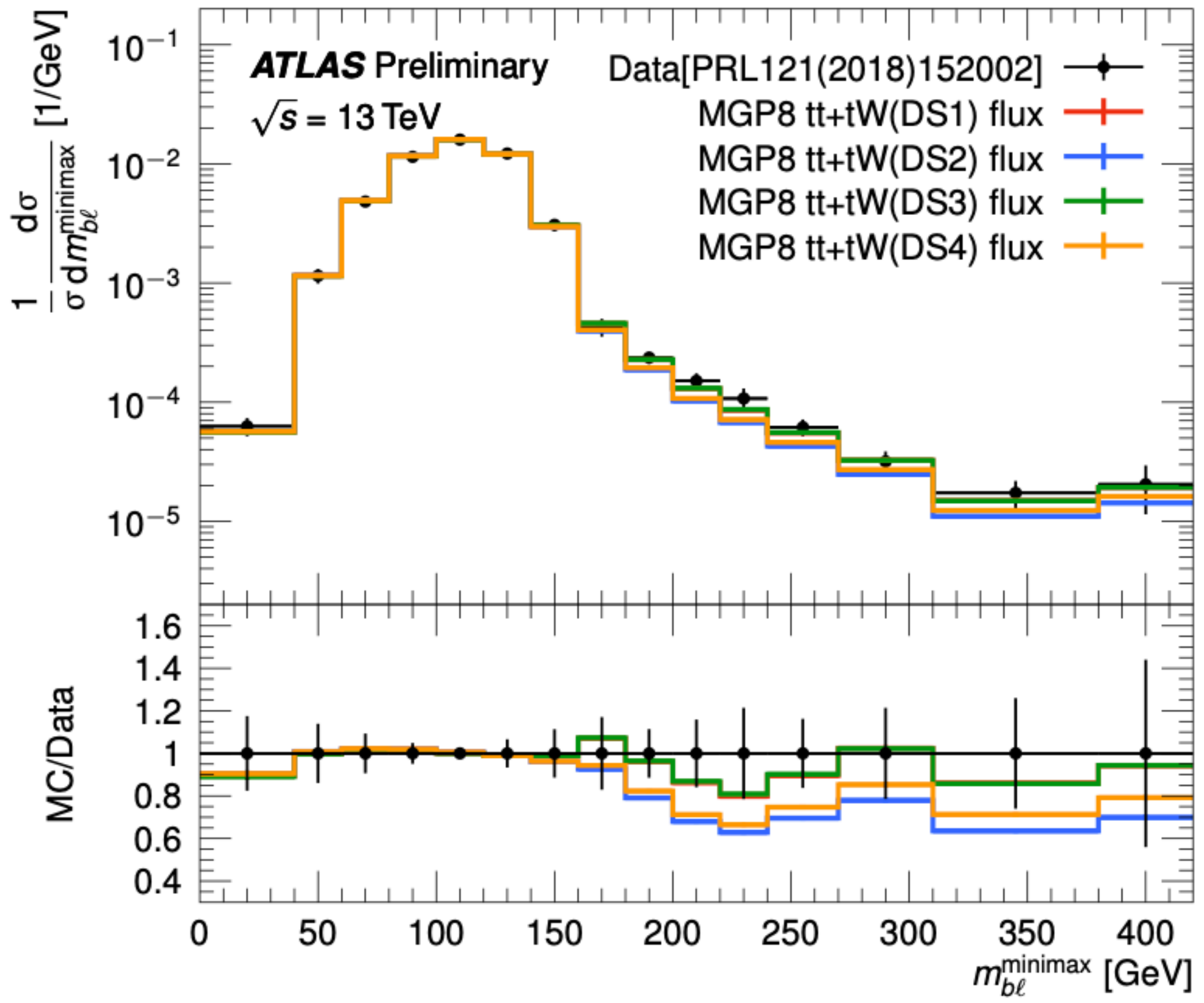


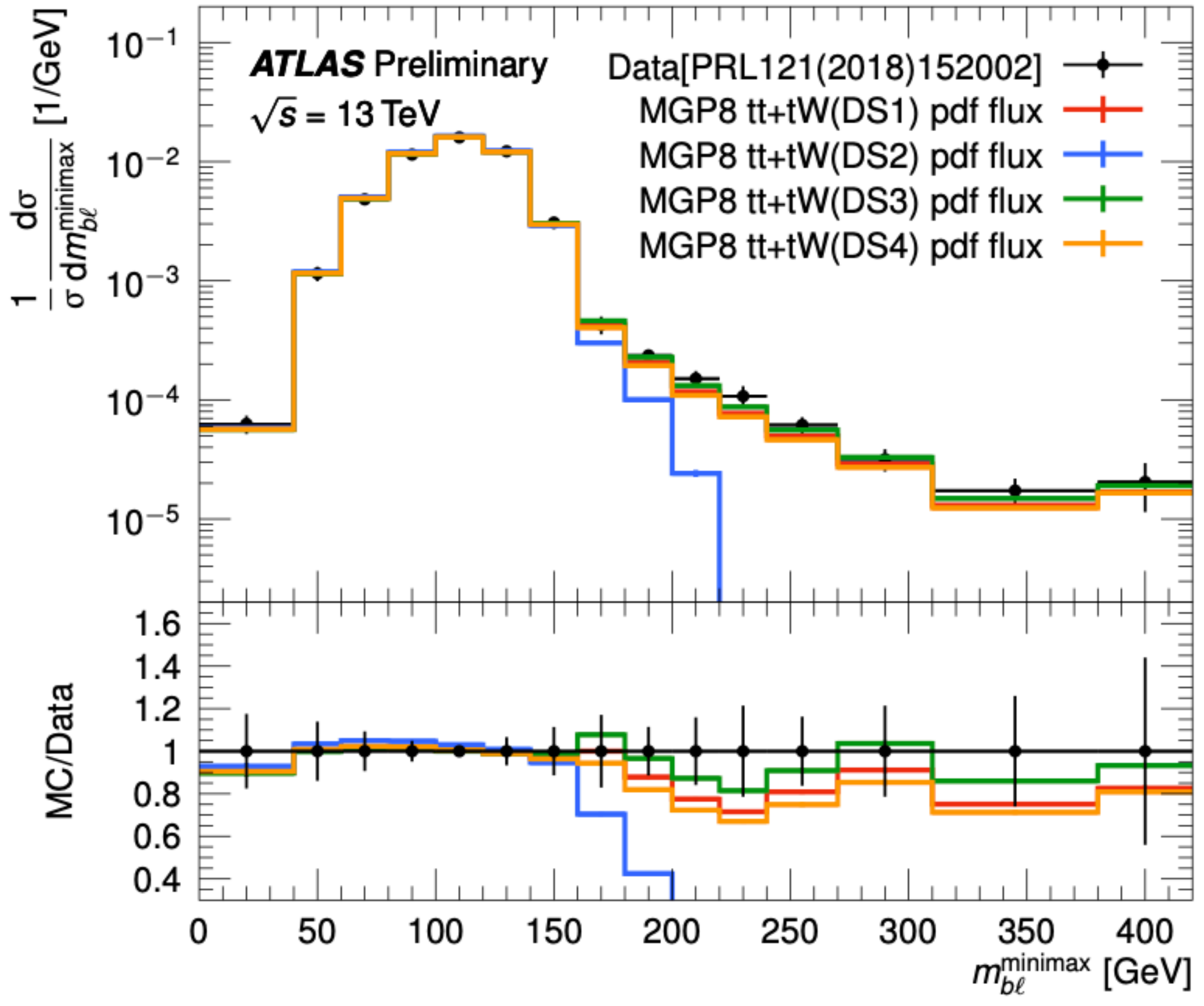
- The impact of "$bb4\ell$" is assessed with a template fit of the top mass
- A difference of 0.36 ± 0.08 GeV is observed
  - Similar size as the total signal modelling uncertainty in the current ATLAS measurement (ATL-PHYS-PUB-2021-015)



- DR2 scheme deviates from the observed data and can be excluded
- Dynamic scale choice of DR1 scheme improves its agreement with data.





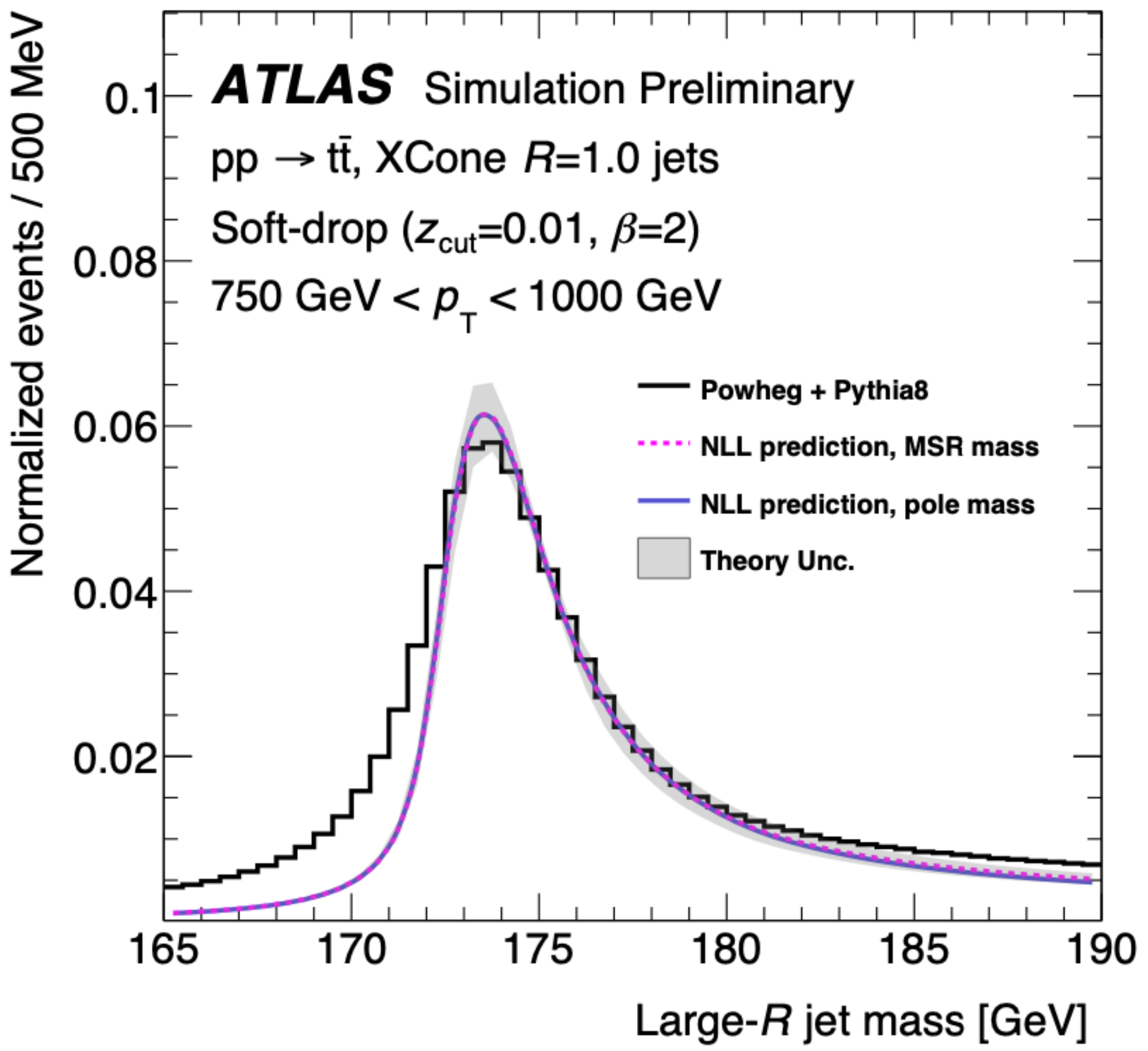


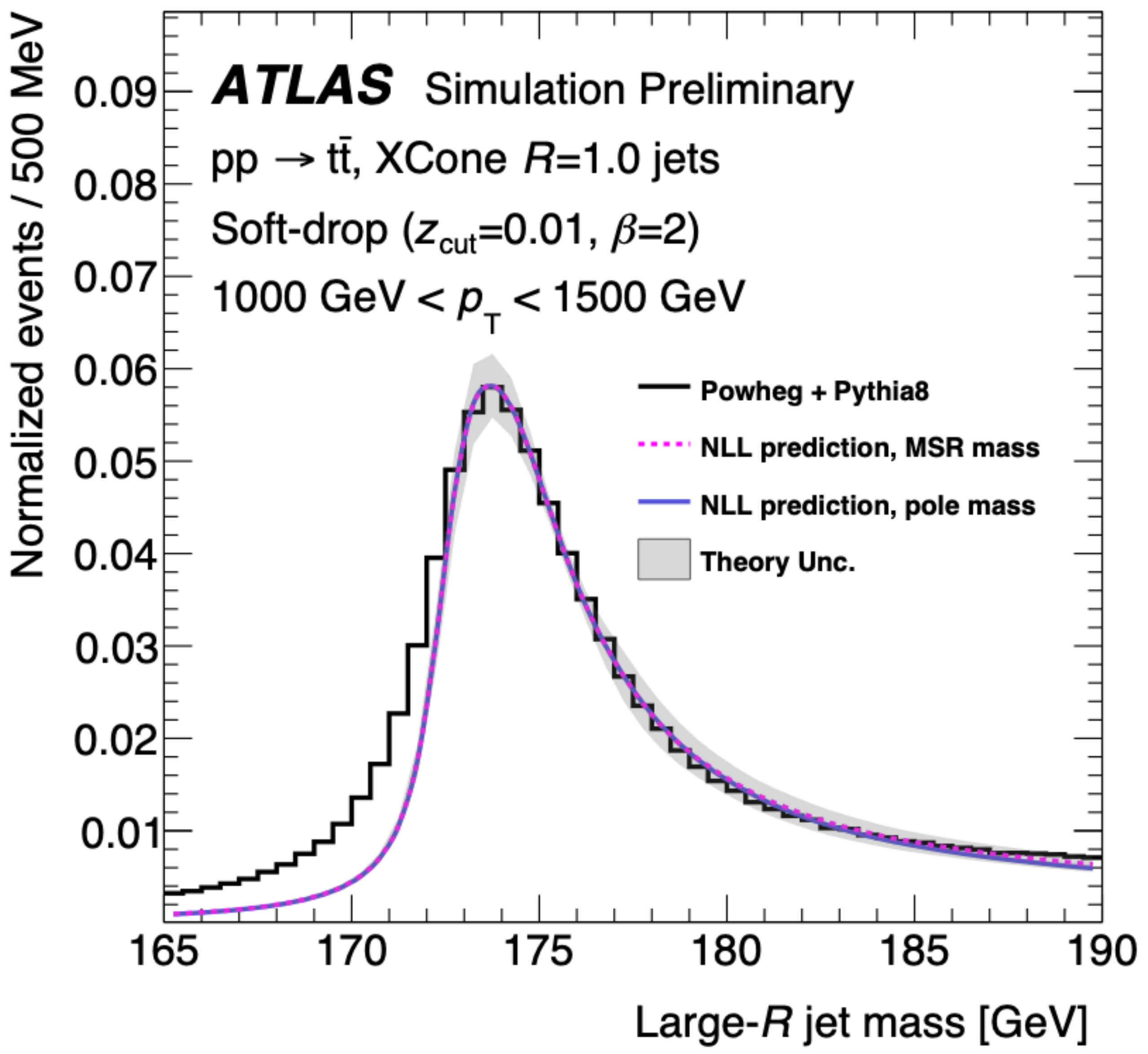
- "PDF" and "flux" parameters are only relevant for DS2 scheme.

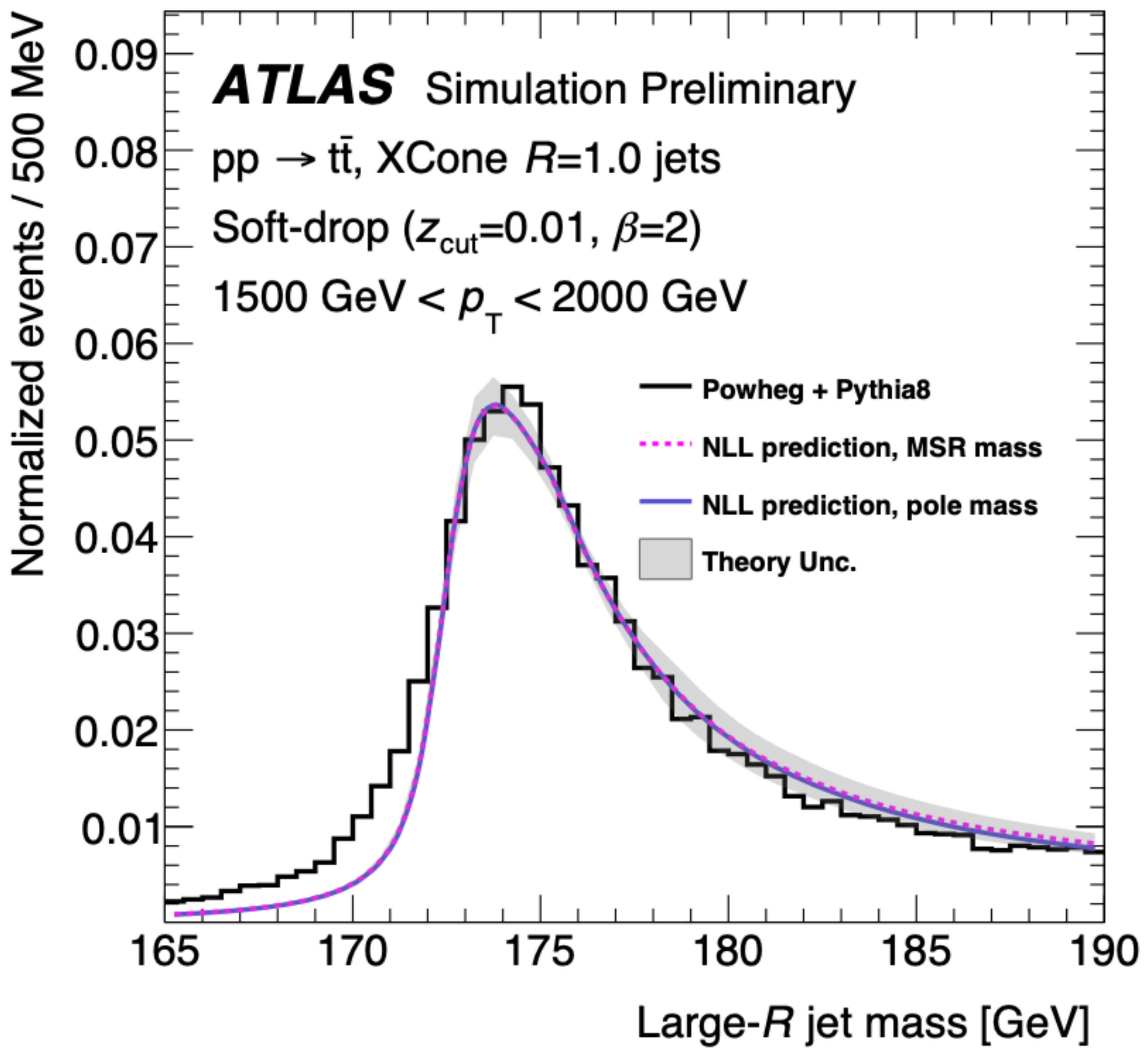
Top quark mass interpretation in ATLAS MC

ATL-PHYS-PUB-2021-034

- Direct top-quark mass measurement analyses uses MC templates with varying m_t^{MC}
- Differences between m_t^{pole} and m_t^{MC} can be larger than current precision on top quark mass measurements.
- NLL templates with varying parameters are fitted to the MC jet Mass distribution in order to extract the best fit $m_t^{(MSR)}$
  - Method described in arxiv-1608.01318 & arxiv-1708.02586







$$m_t^{\text{MC}} = m_t^{\text{MSR}}(1\text{ GeV}) + 80^{+350}_{-410}\text{ MeV}$$

Uncertainties

Source	Size [MeV]	Comment
Theory (higher-order corrections)	+230/−310	Envelope of NLL scale variations
Fit methodology	±190	Choice of fit range, p_T bins
Underlying Event model	±155	A14 eigentune variations, CR models
Total Systematic	**+340/−340**	
Statistical Uncertainty	±100	
Total Uncertainty	**+350/−410**	

Conclusion

- With LHC delivering millions of top quark events, top physics is in the **precision measurement** era.
  - ATLAS + CMS performed many precision measurements.

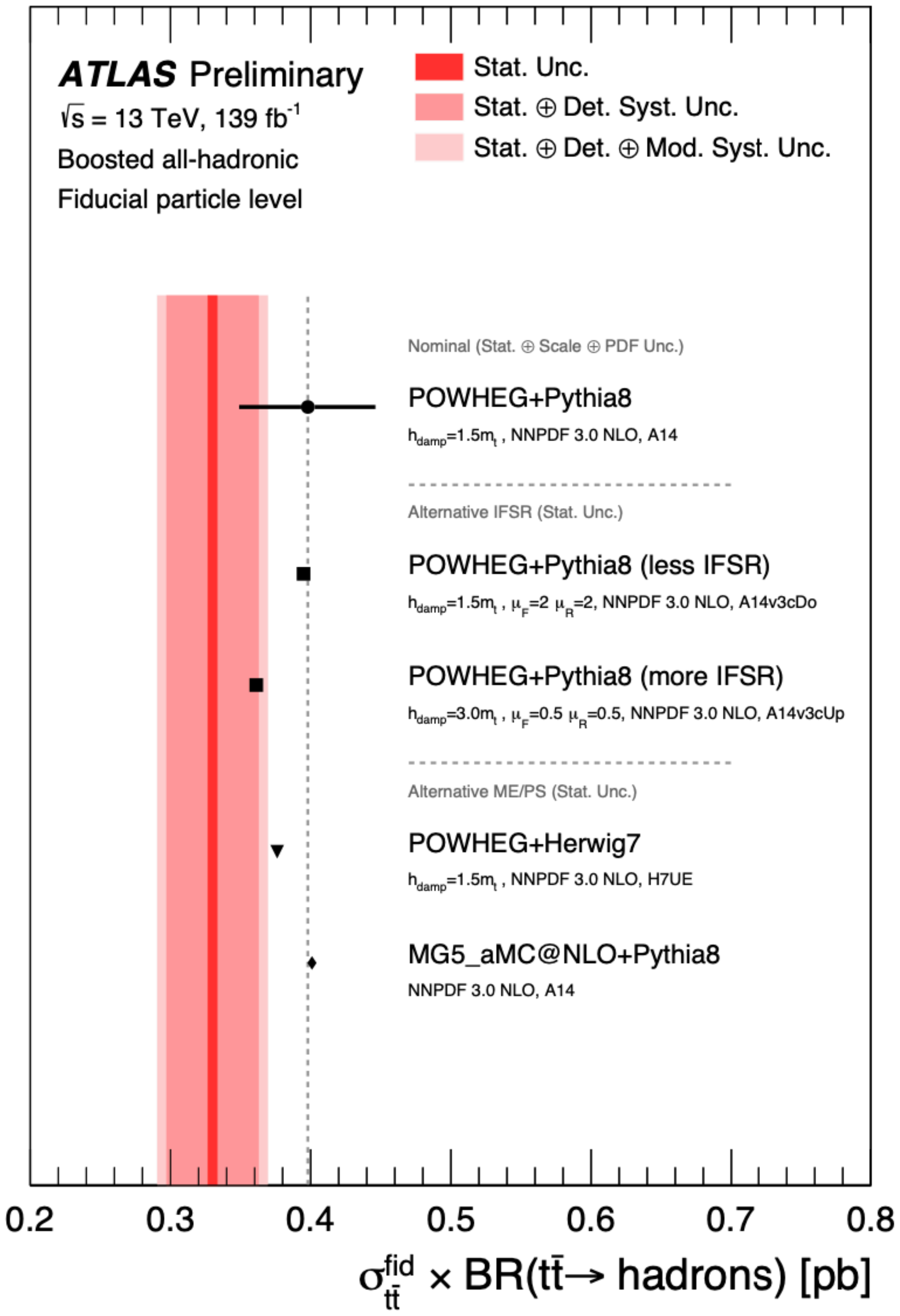
- Recent measurements agree with the Standard Model quite well.
  - More precise and differential measurements.
  - Many EFT interpretations and constraints on Wilson coefficients.

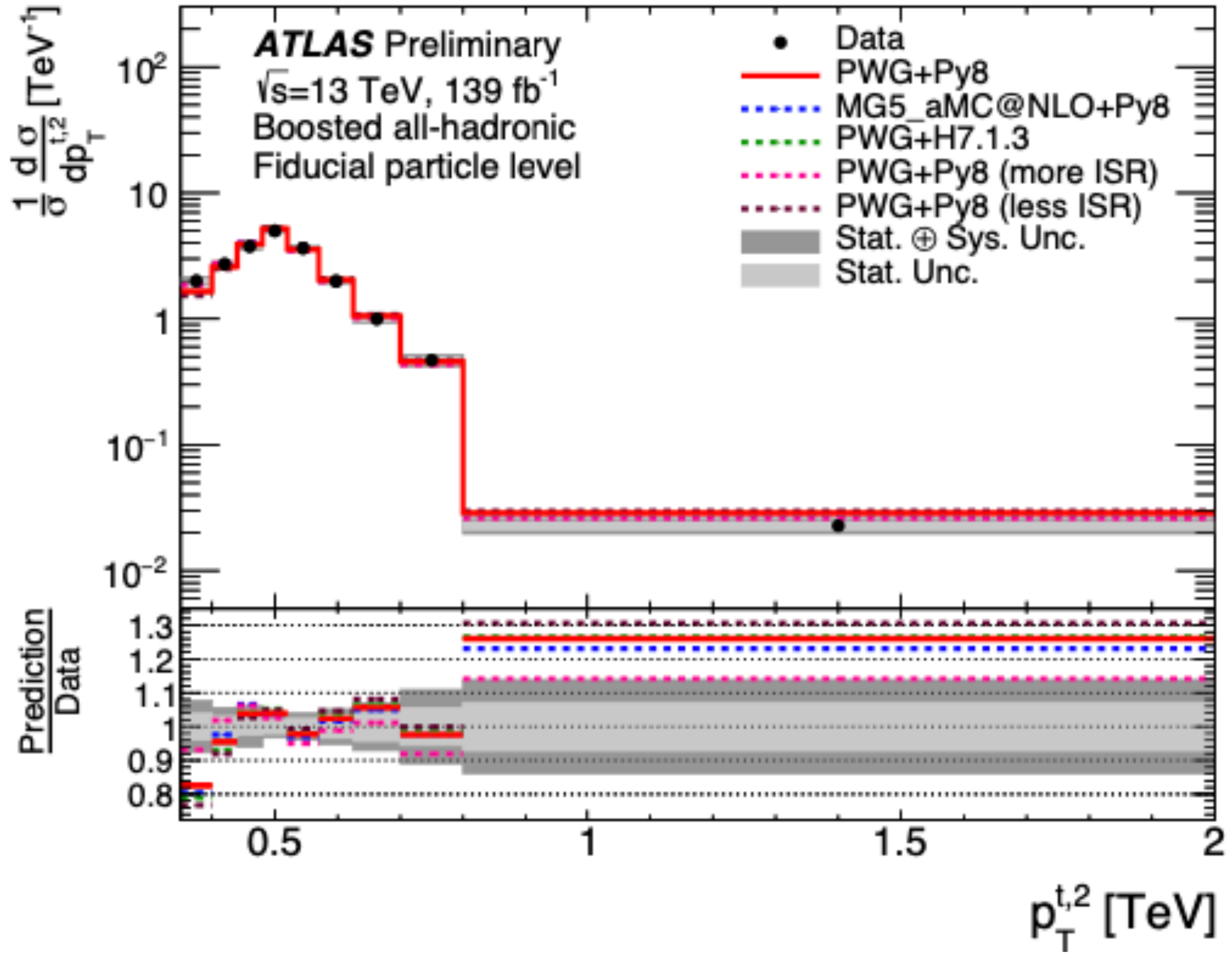
- Understanding of detector and physics modeling.
  - Largest experimental uncertainty from JES, JER and b-tagging.
  - Theory uncertainty limited by modeling of parton shower and hadronization.

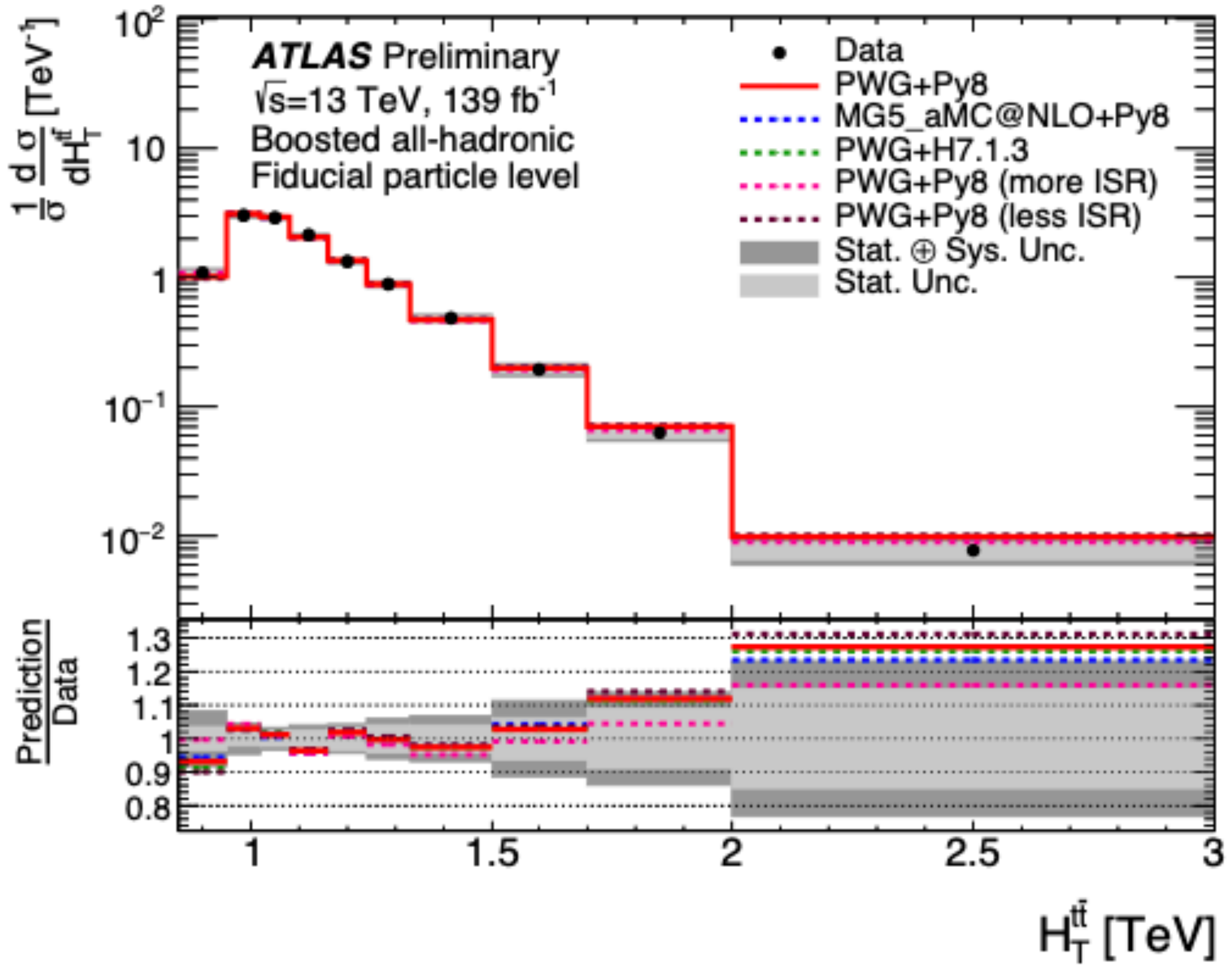
- Monte Carlo studies for future precision measurements.
  - Potential improvements in top quark mass measurement as well as other observables.

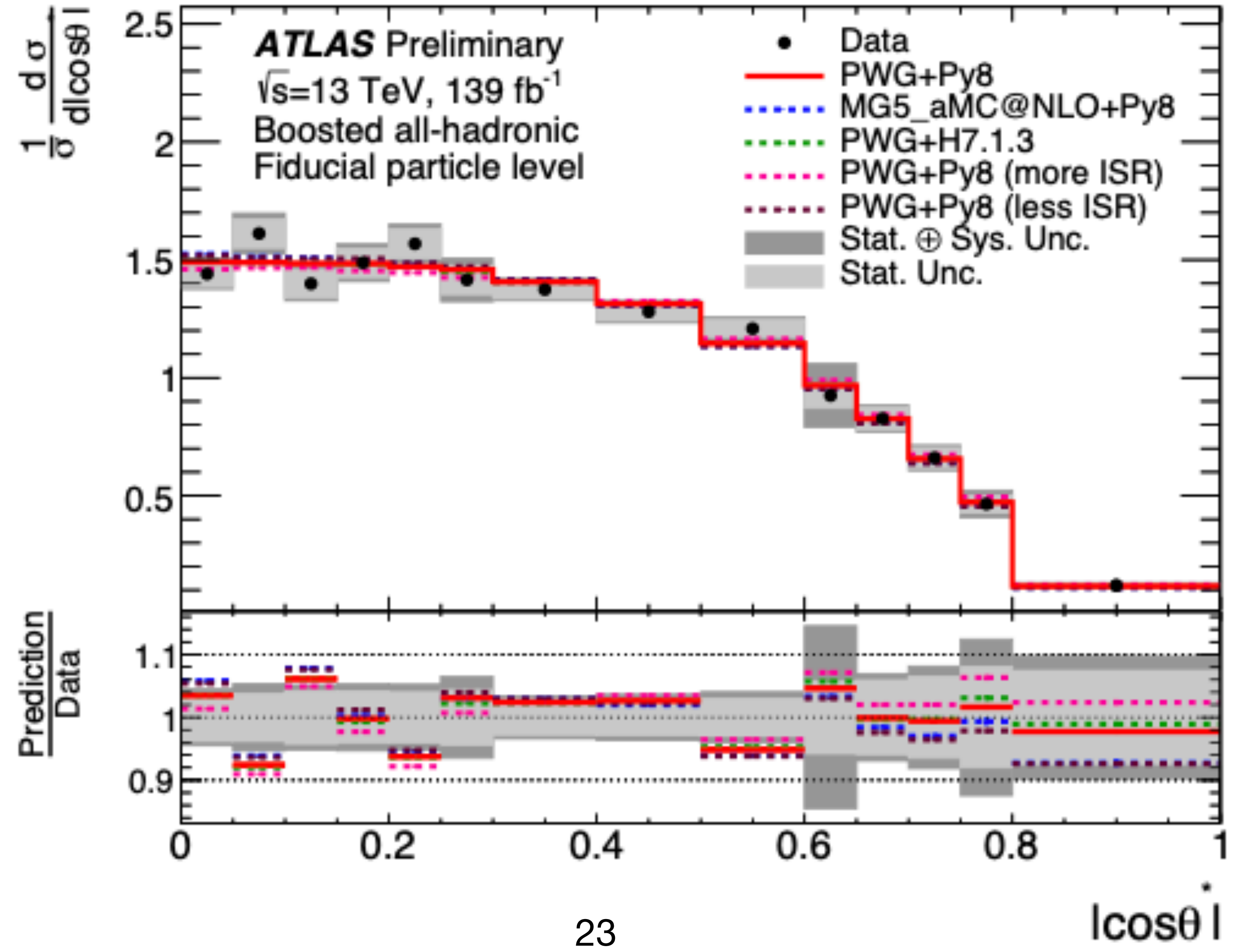
Backup

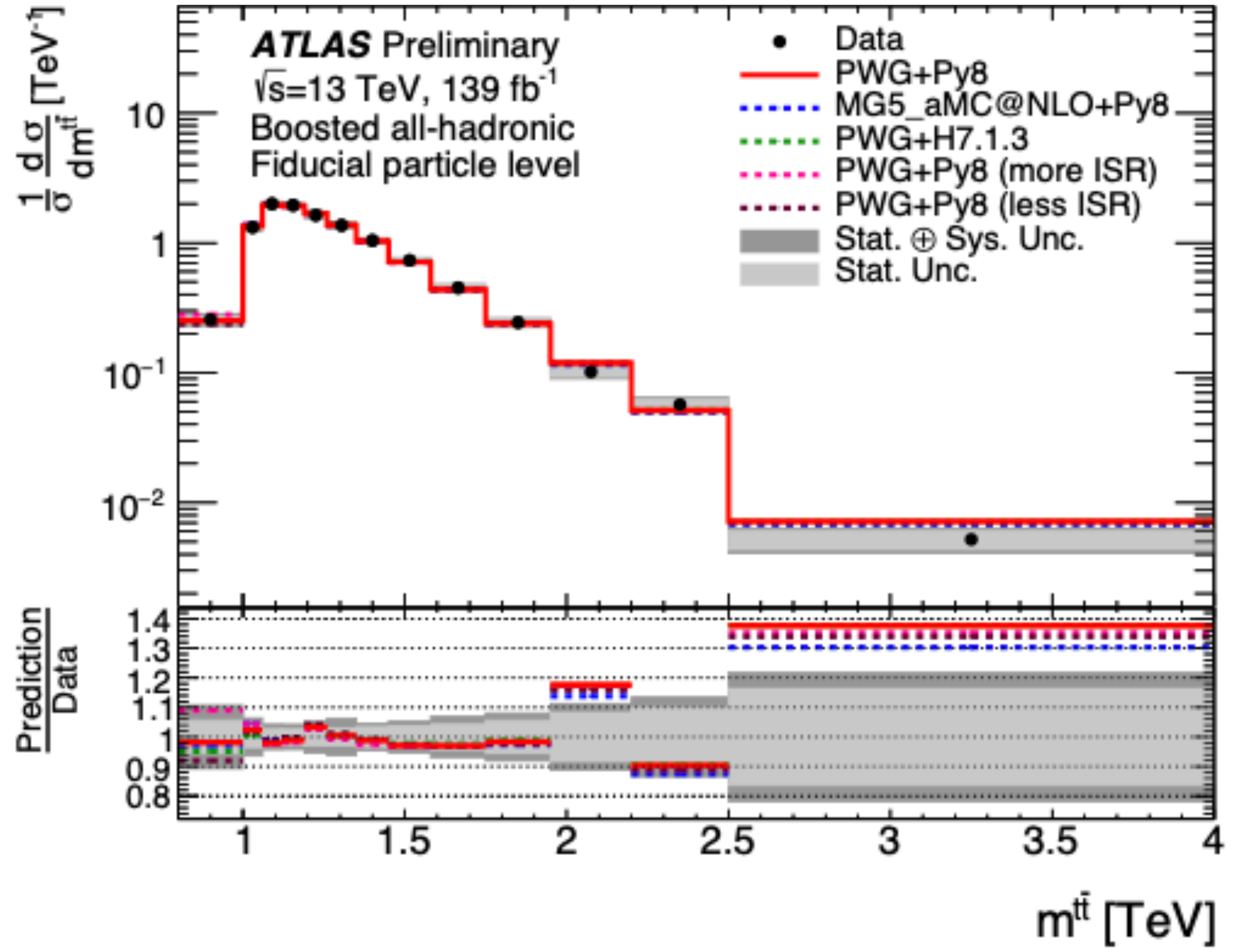
$t\bar{t}$ allhadronic measurements: Particle level







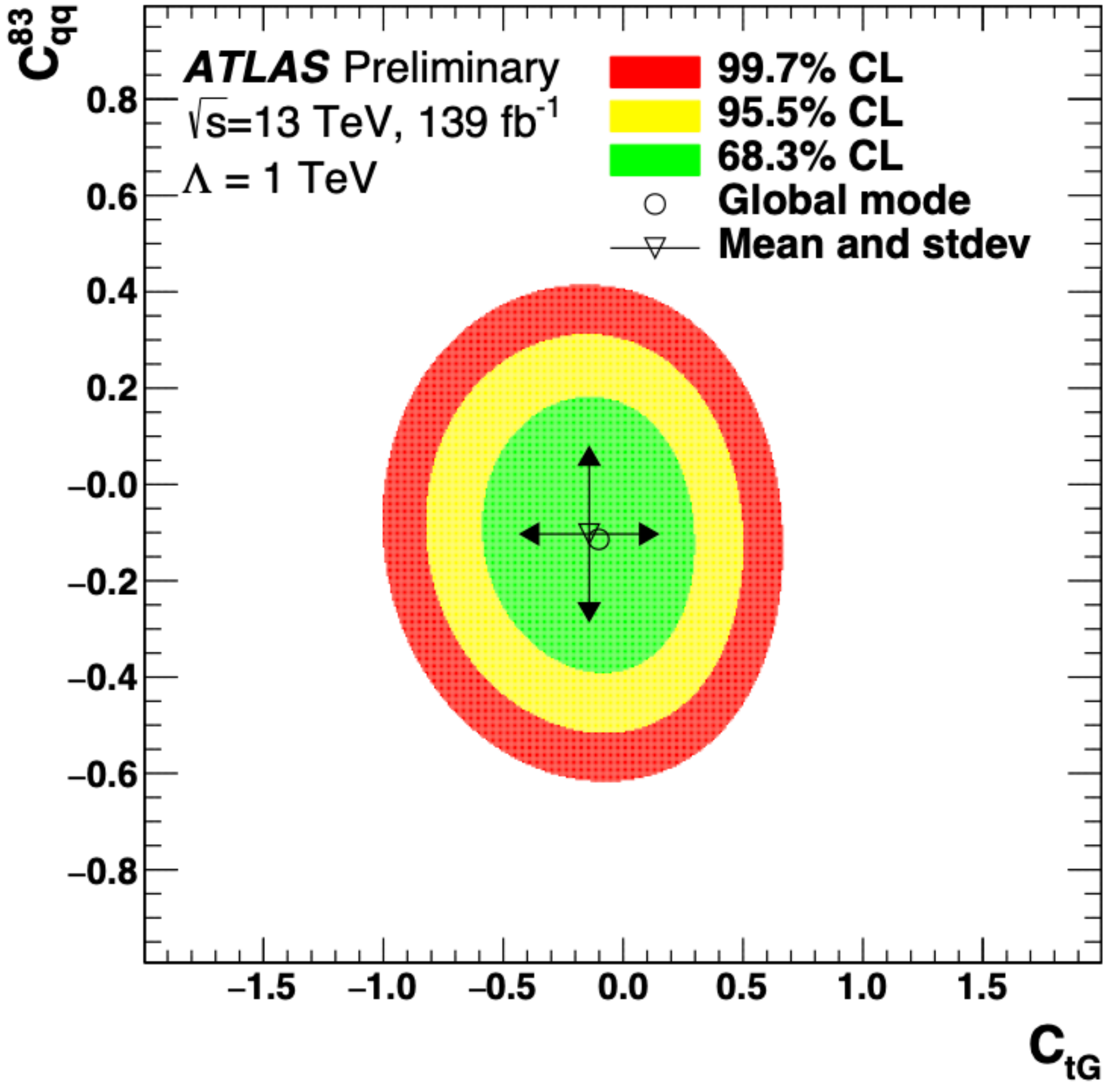


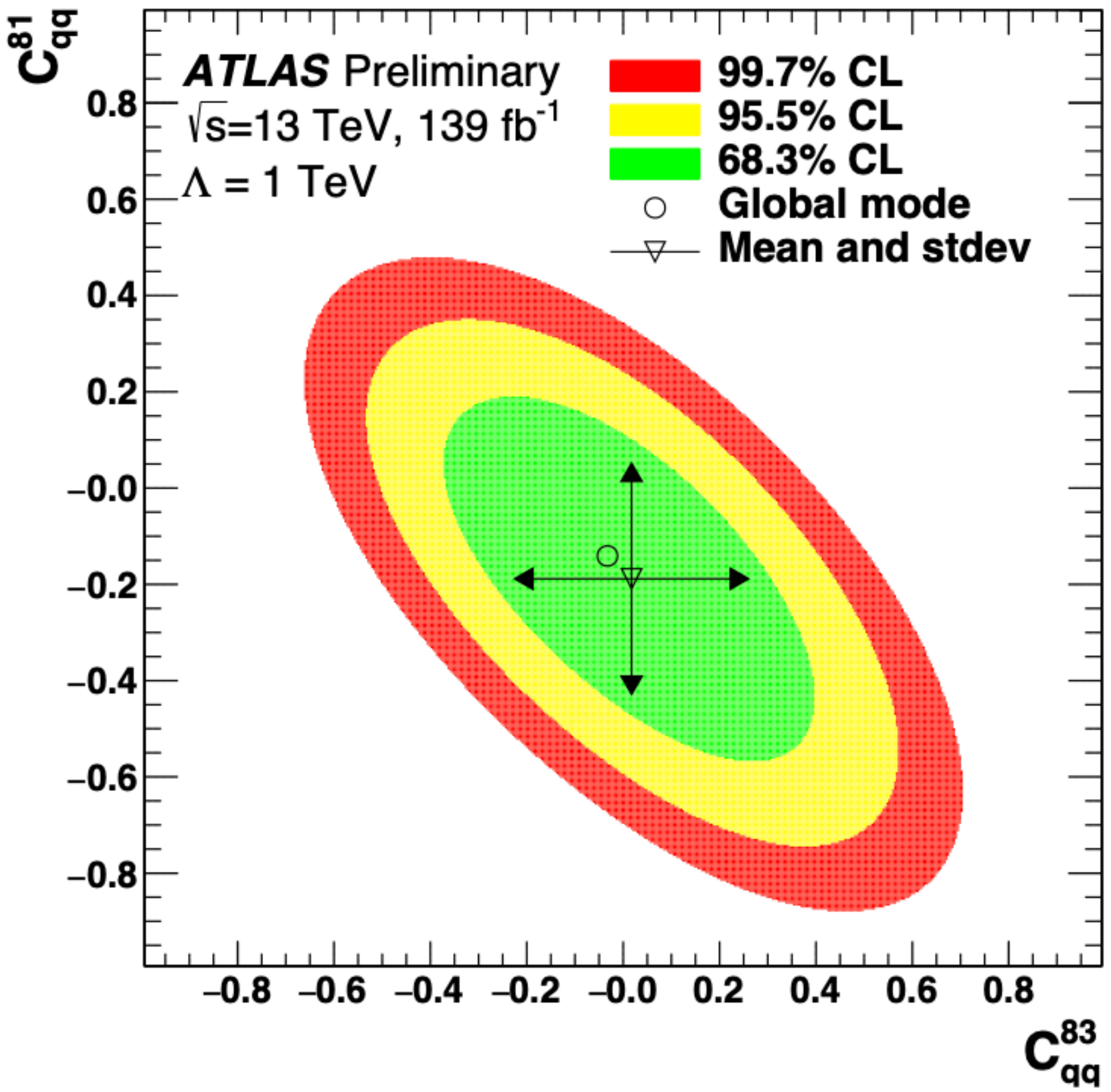


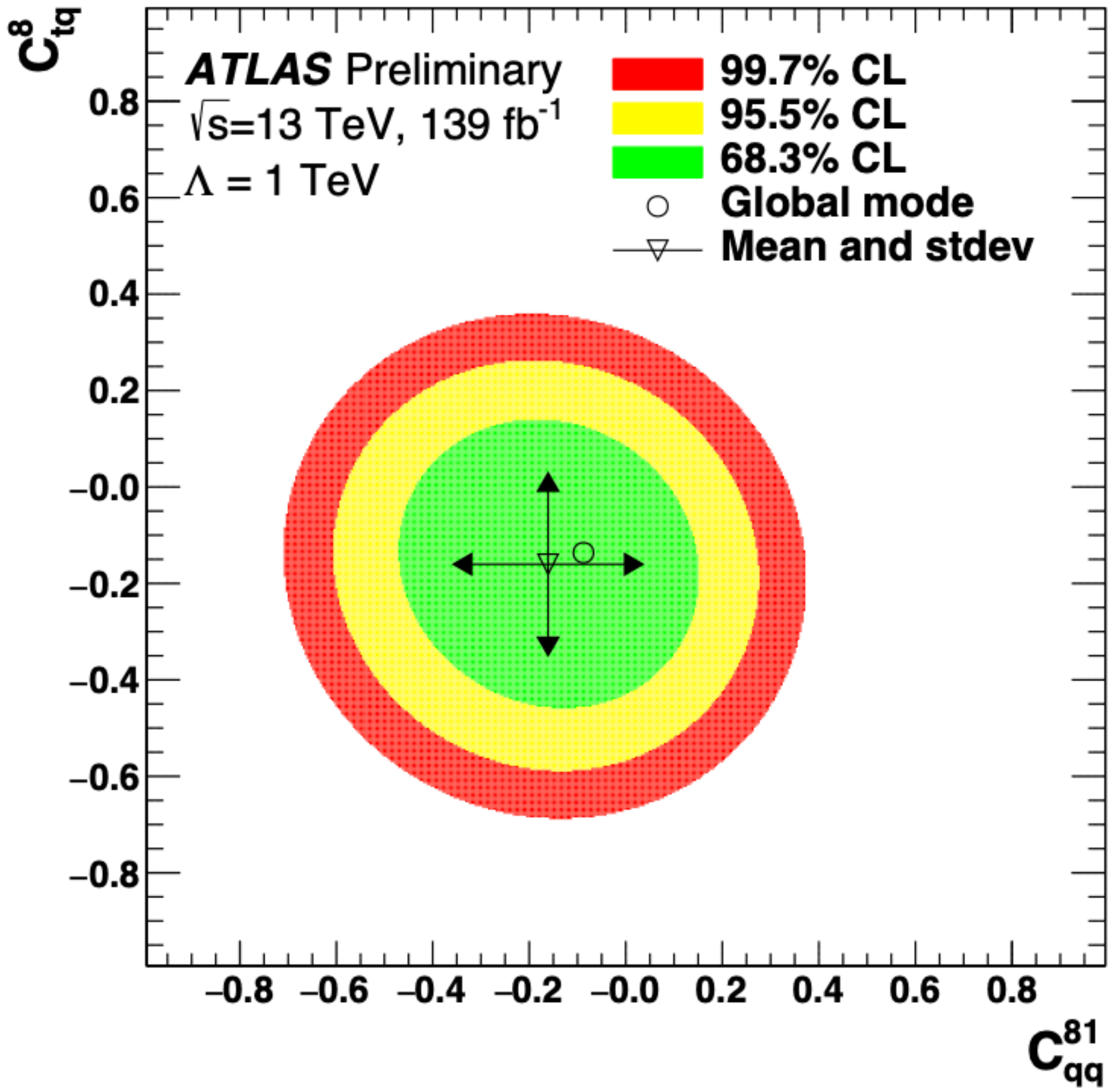
$t\bar{t}$ allhadronic measurements: EFT

$$
\begin{aligned}
\sigma(C_i) \sim |M|^2 &= \sigma_{SM} + \sigma_{SM-EFT} + \sigma_{EFT-EFT} \\
&= \sigma_{SM} + \frac{1}{\Lambda^2}\sum_i \alpha_i C_i + \frac{1}{\Lambda^4}\sum_i \beta_i C_i^2 + \frac{1}{\Lambda^4}\sum_{i,j,i<j} \tilde{\beta}_{ij} C_i C_j,
\end{aligned}
$$

$t\bar{t}$ allhadronic EFT intepretation







- 2D limits on various EFT coefficients in allhadronic measurement.

Source	Relative Uncertainty [%]
Top-tagging	±7.8
JES ⊕ JER	±4.2
JMS ⊕ JMR	±1.1
Flavor tagging	±2.9
Alternative hard-scattering model	±0.9
Alternative parton-shower model	±4.3
ISR/FSR + scale	±4.9
PDF	±0.8
Luminosity	±1.7
Monte Carlo sample statistics	±0.5
Systematics	±11.6
Statistics	±1.0
Total Uncertainty	±11.7

$t\bar{t}$ allhadronic: Uncertanties

Source	Relative Uncertainty [%]
Top-tagging	± 7.8
JES $\oplus$ JER	± 4.2
JMS $\oplus$ JMR	± 1.1
Flavor tagging	± 2.9
Alternative hard-scattering model	± 0.9
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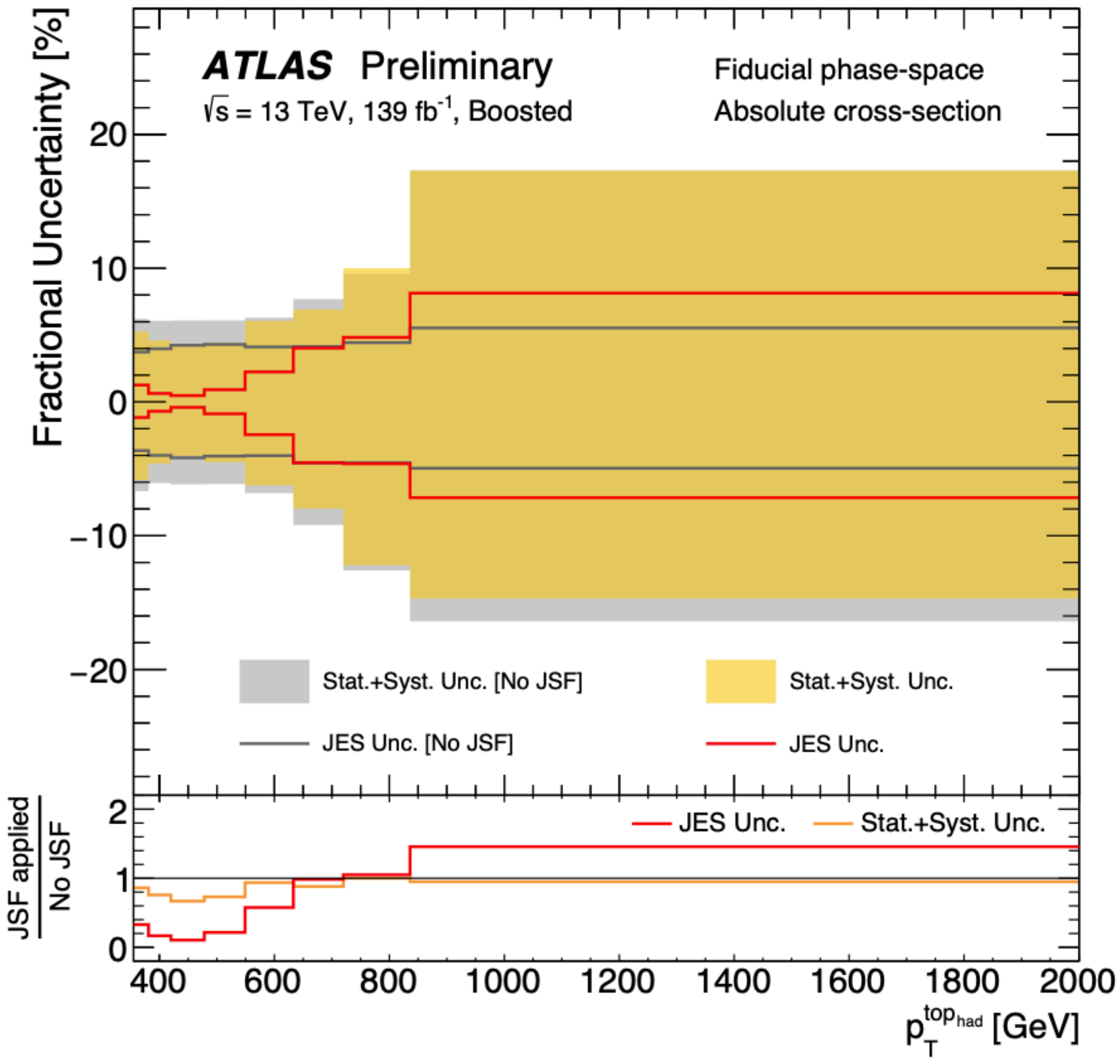
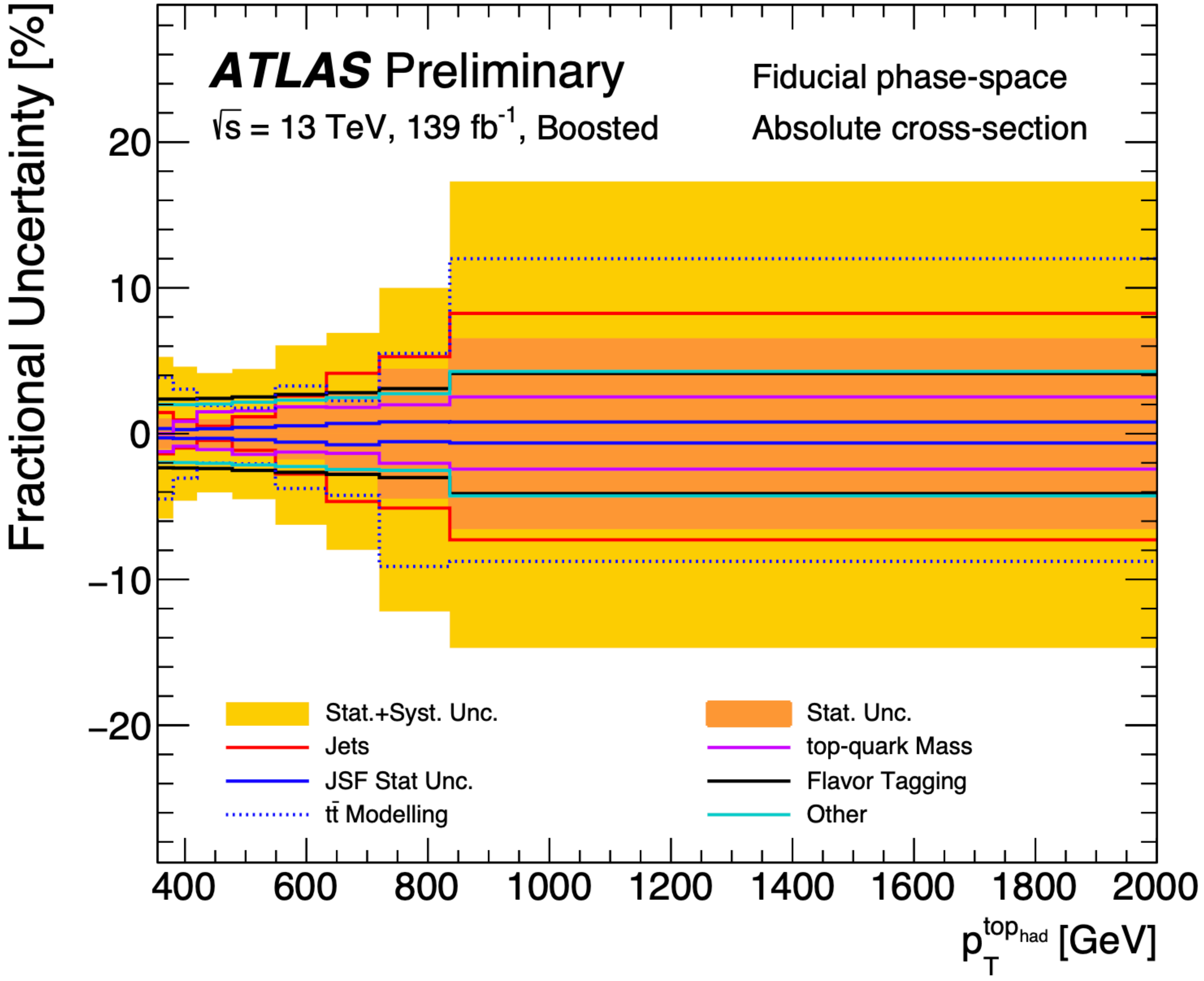
ISR/FSR + scale	± 4.9
PDF	± 0.8
Luminosity	± 1.7
Monte Carlo sample statistics	± 0.5
Systematics	± 11.6
Statistics	± 1.0
Total Uncertainty	± 11.7

$t\bar{t}$ Differential: JSF-1



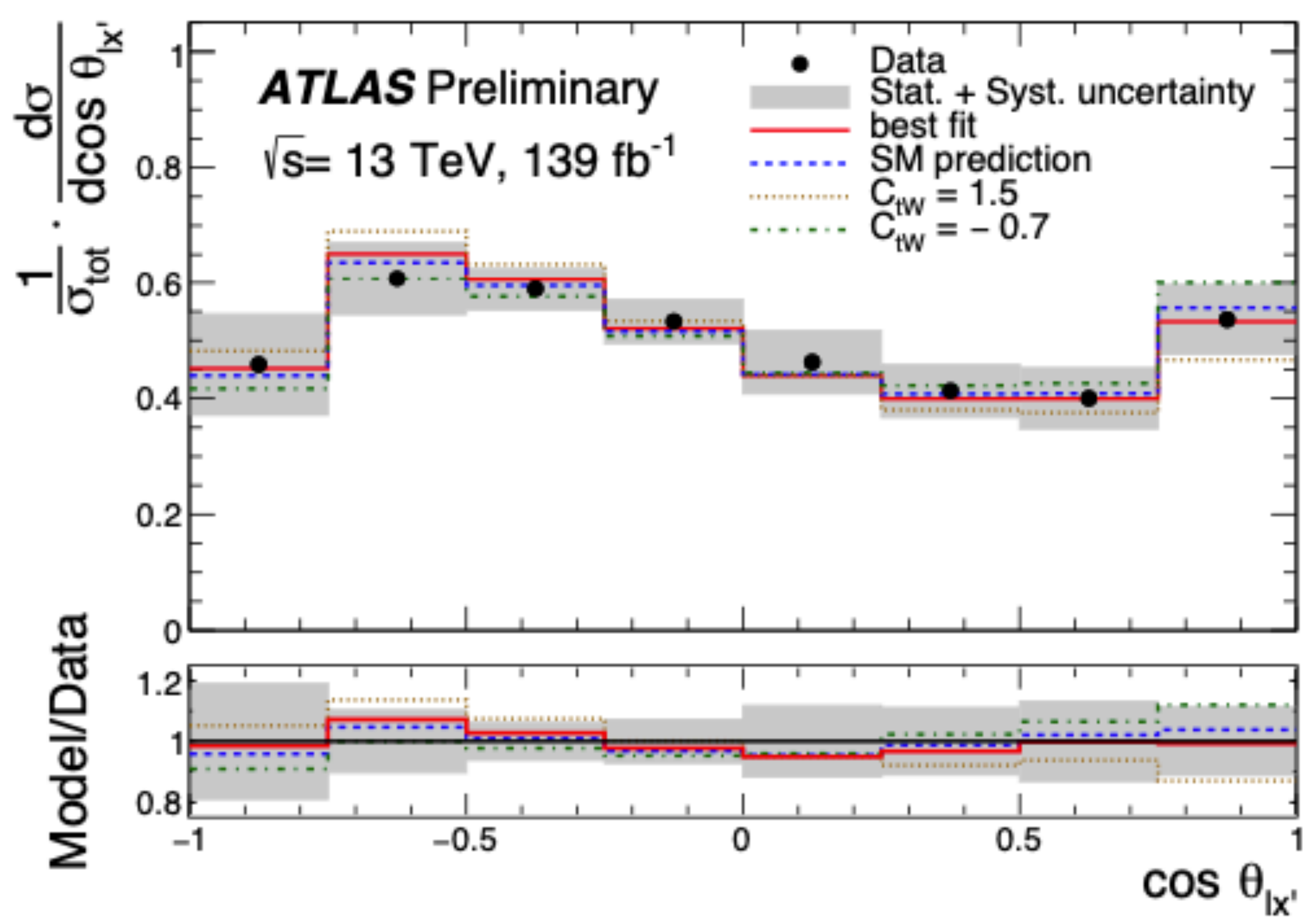


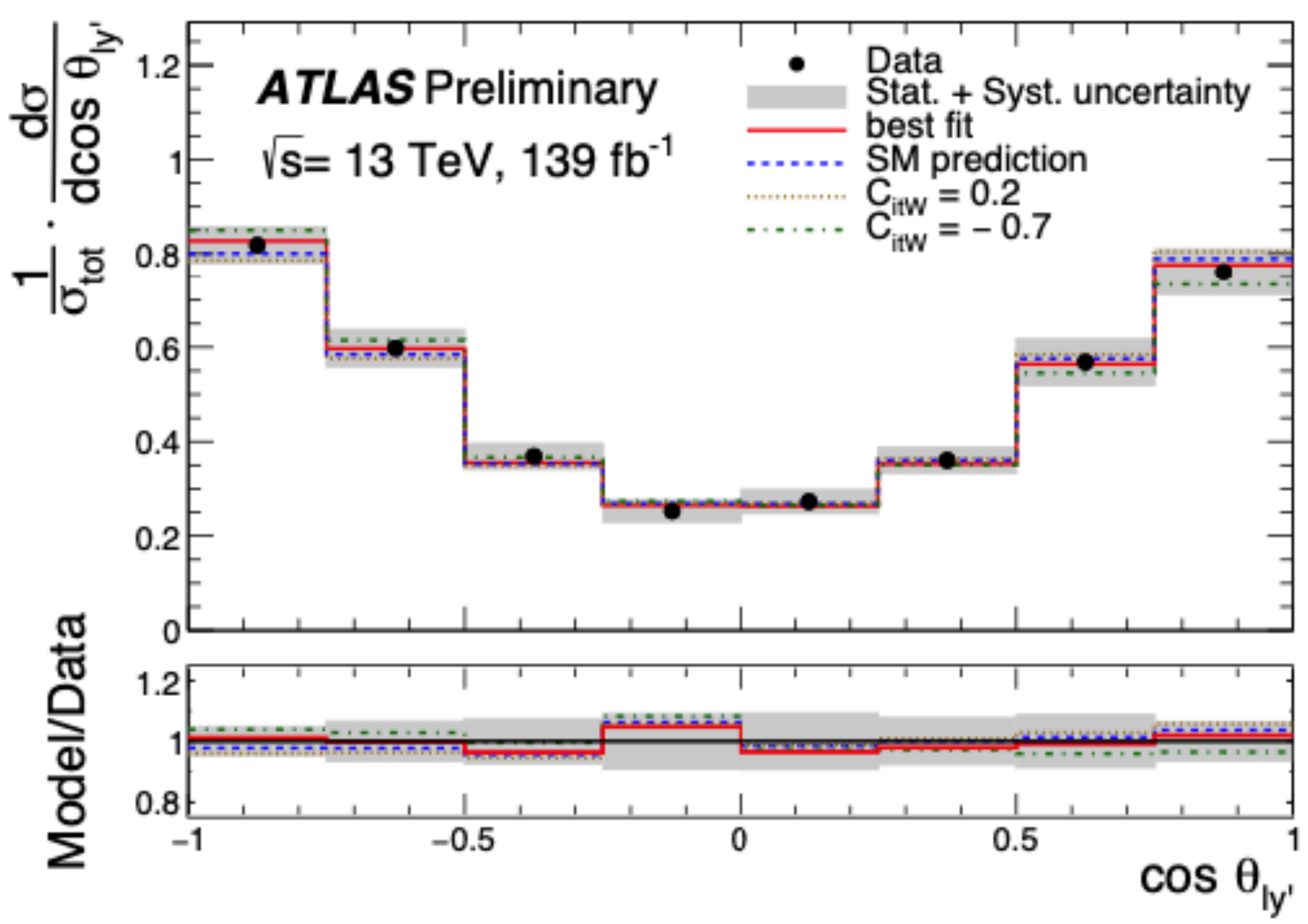
$t\bar{t}$ Differential: JSF-2

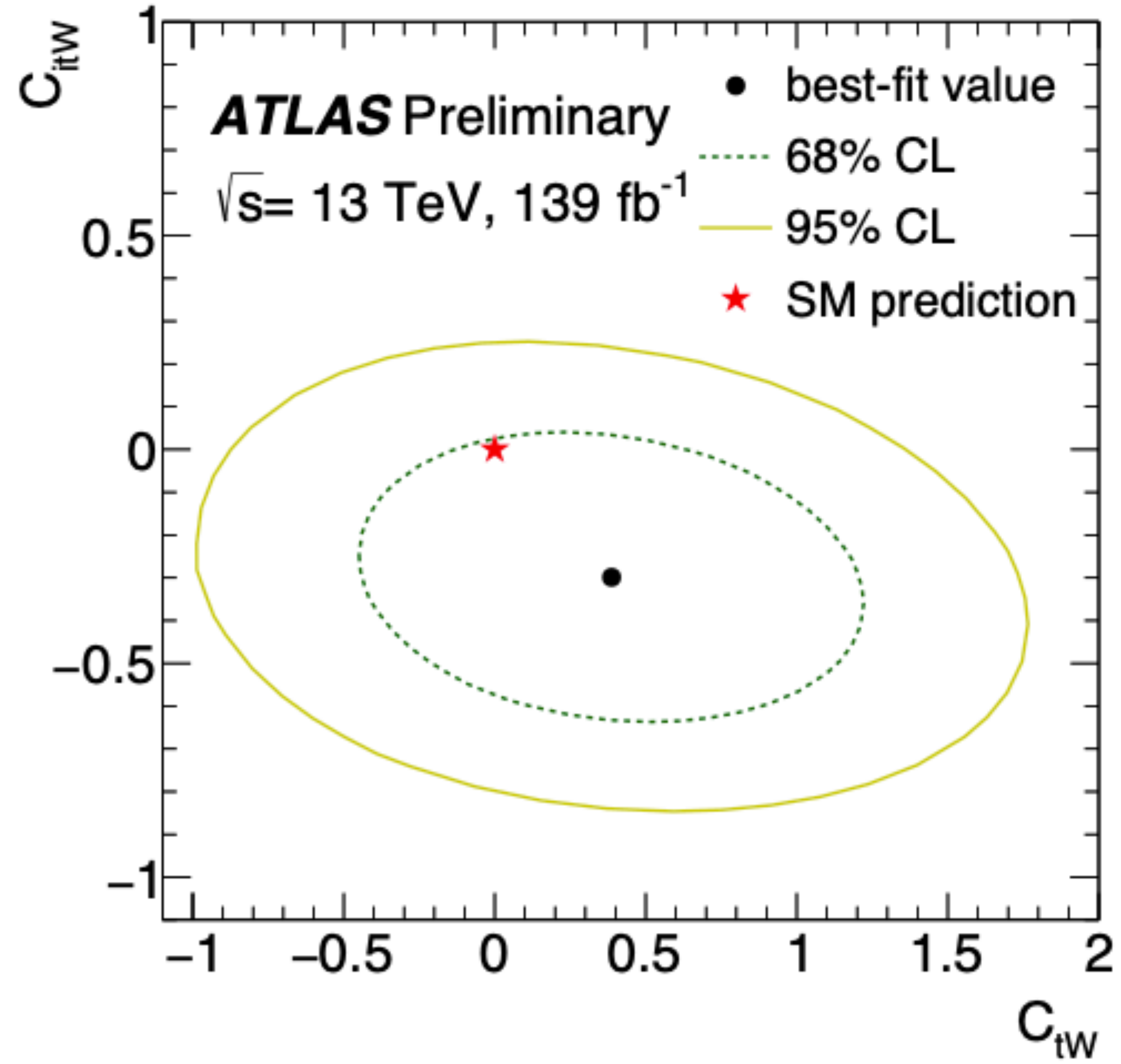
Source	Uncertainty [%]	Uncertainty [%] (no JSF)
Statistical (data)	±0.4	±0.4
JSF statistical (data)	±0.4	—
Statistical (MC)	±0.2	±0.1
Hard scatter	±0.5	±0.8
Hadronisation	±2.0	±1.8
Radiation (ISR/FSR + h_{damp})	$^{+1.0}_{-1.6}$	$^{+1.4}_{-2.3}$
PDF	±0.1	±0.1
Top-quark mass	$^{+0.8}_{-1.1}$	±0.1
Jets	±0.7	±4.2
b-tagging	±2.4	±2.4
Leptons	±0.8	±0.8
$E_{\mathrm{T}}^{\mathrm{miss}}$	±0.1	±0.1
Pile-up	±0.4	±0.0
Luminosity	±1.8	±1.8
Background modelling	±0.6	±0.6
Total systematic uncertainty	$^{+4.1}_{-4.3}$	$^{+5.8}_{-6.0}$
Total	$^{+4.1}_{-4.3}$	$^{+5.8}_{-6.0}$

Single top: EFT interpretation

- The solid line corresponds to the EFT prediction using the best-fit values for the Wilson coefficients $C_{tw} = 0.4$ and $C_{itW} = 0.3$

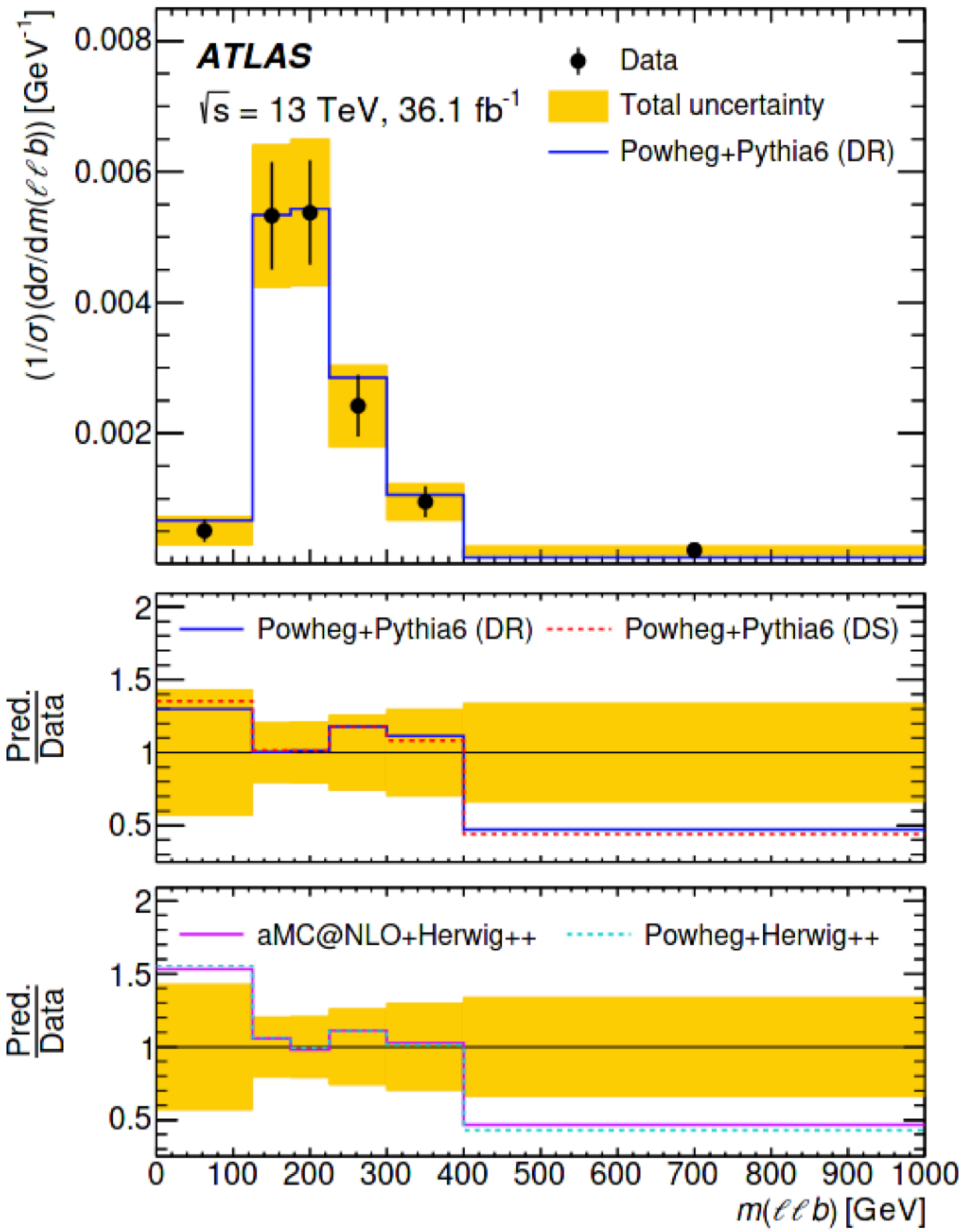


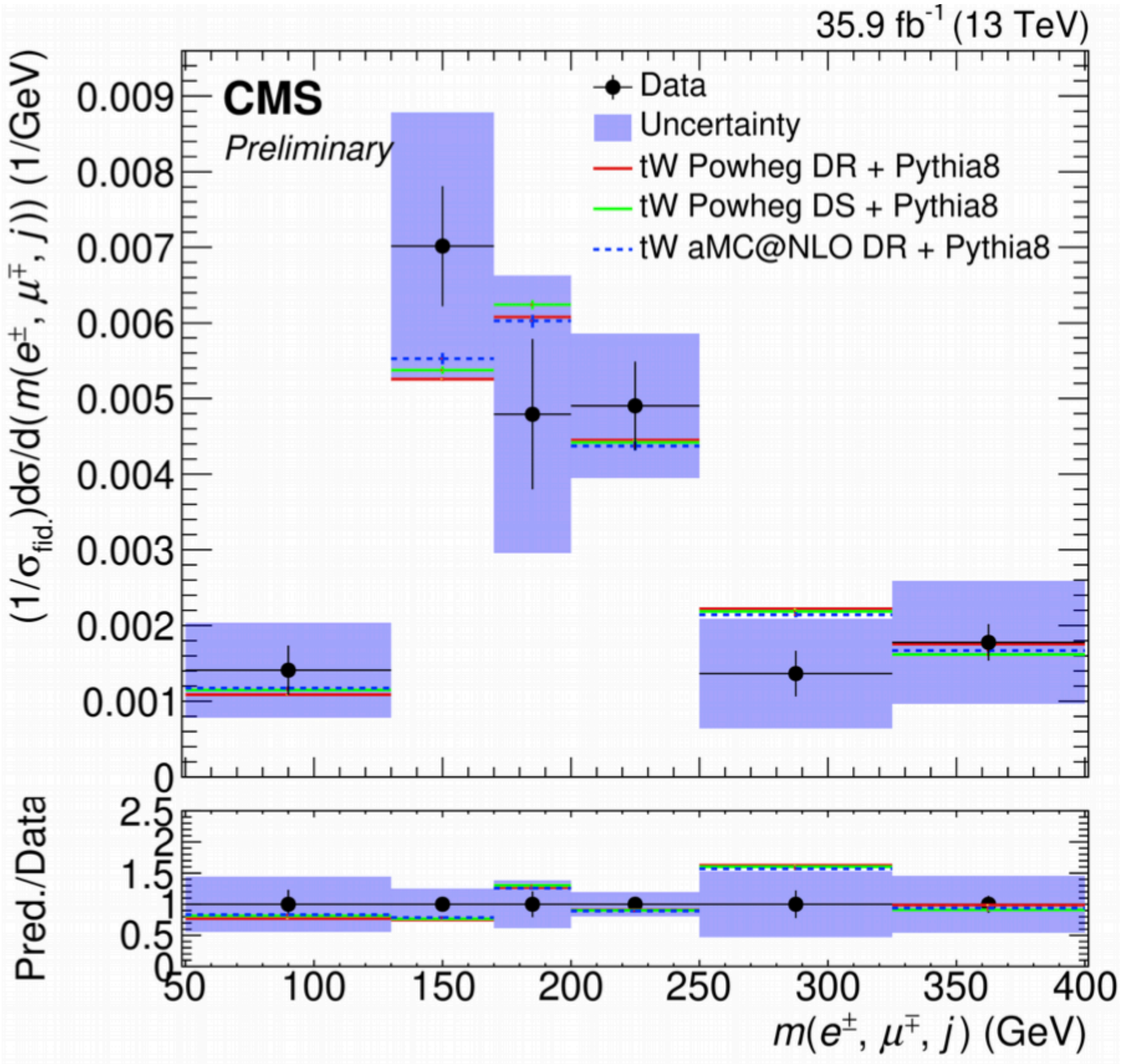




Single top production: Differential

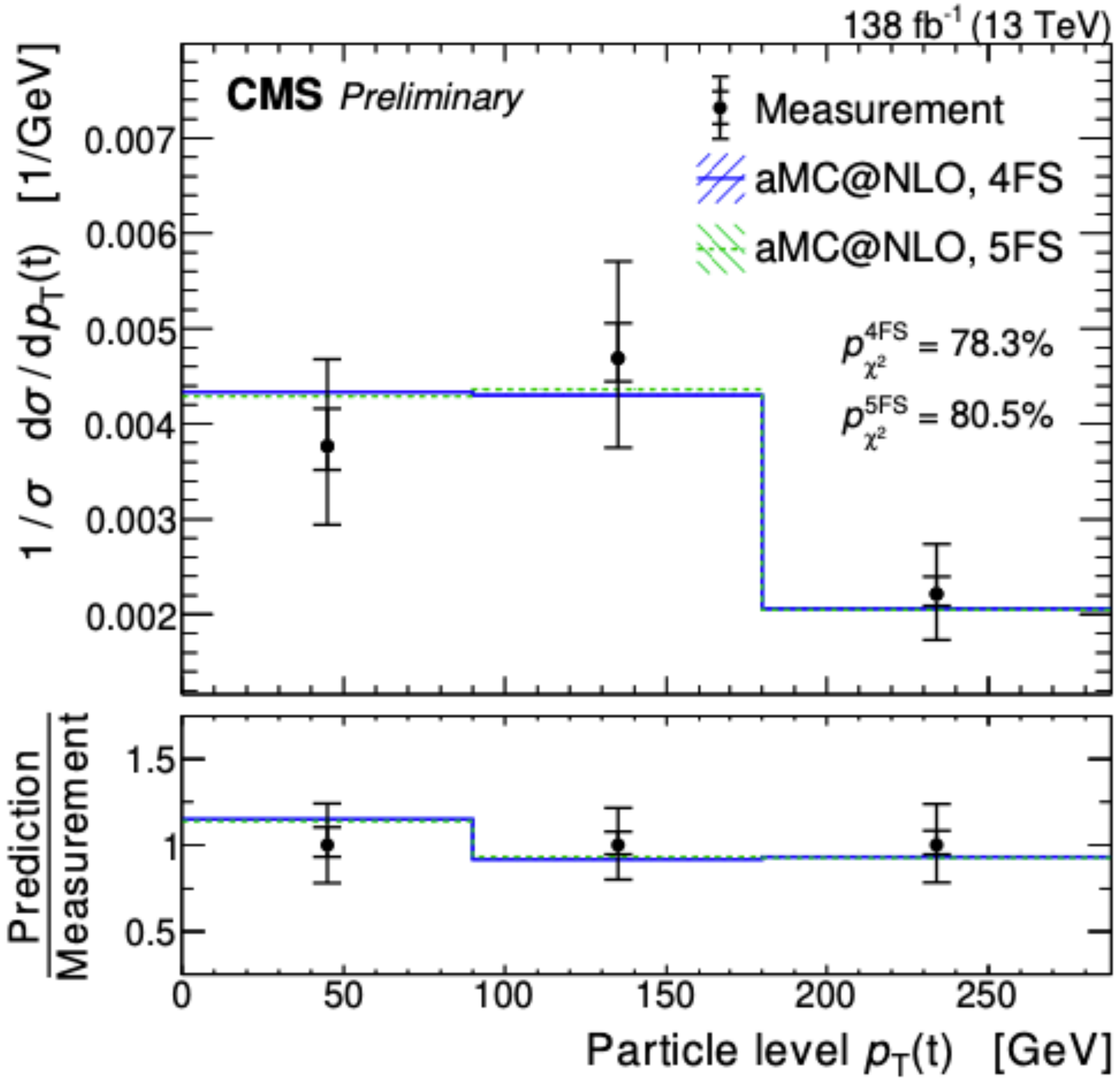
- Showing differential measurement of tW production in dileptonic channel

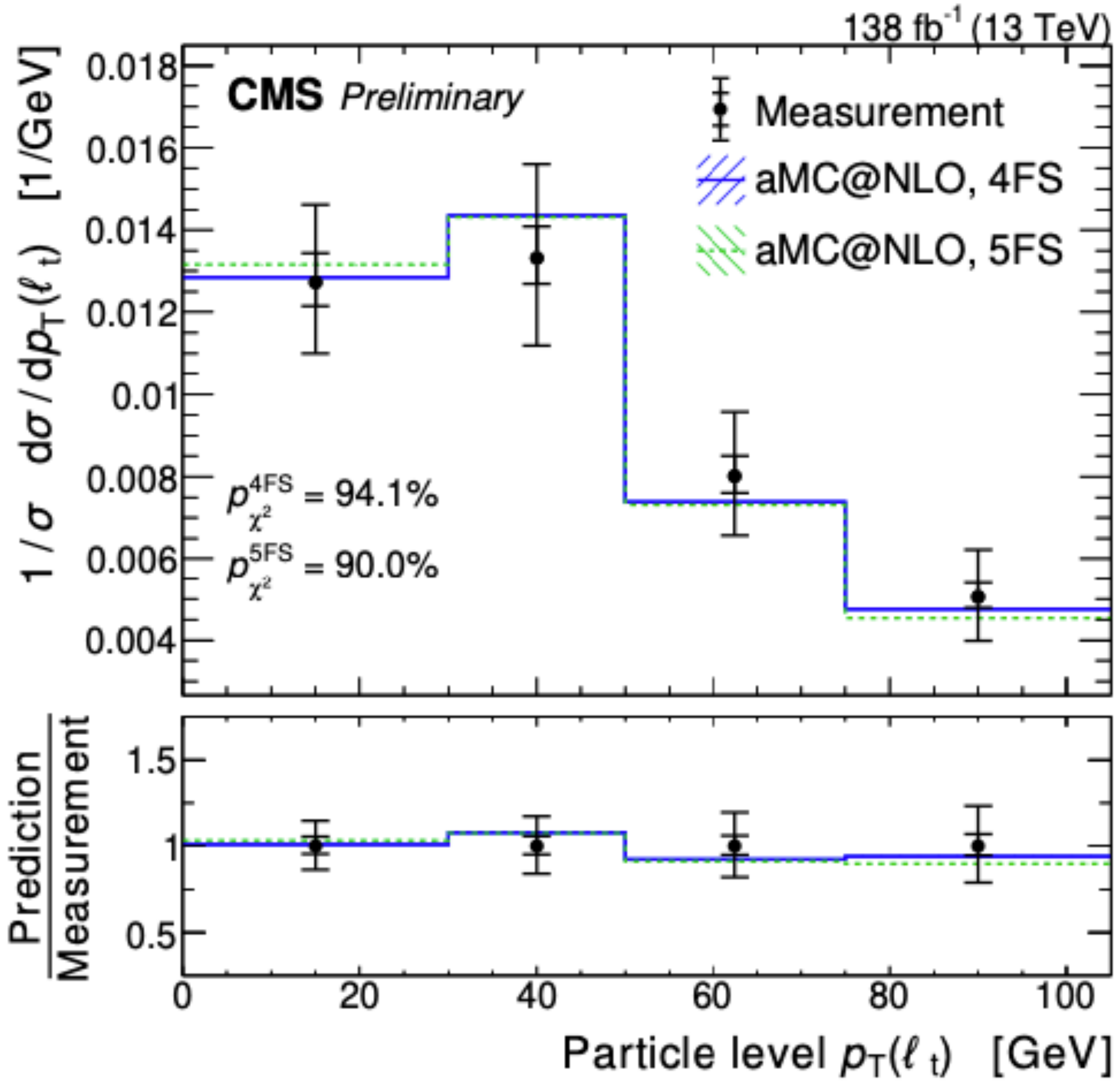




tZq: Differential and inclusive measurement

CMS-PAS-TOP-20-010





- Absolute normalized differential distributions

$bb4l$: More distributions.