ATLAS Boosted Top Precision Measurements with Jet Substructure

BOOST 23

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ATLAS EXPERIMENT

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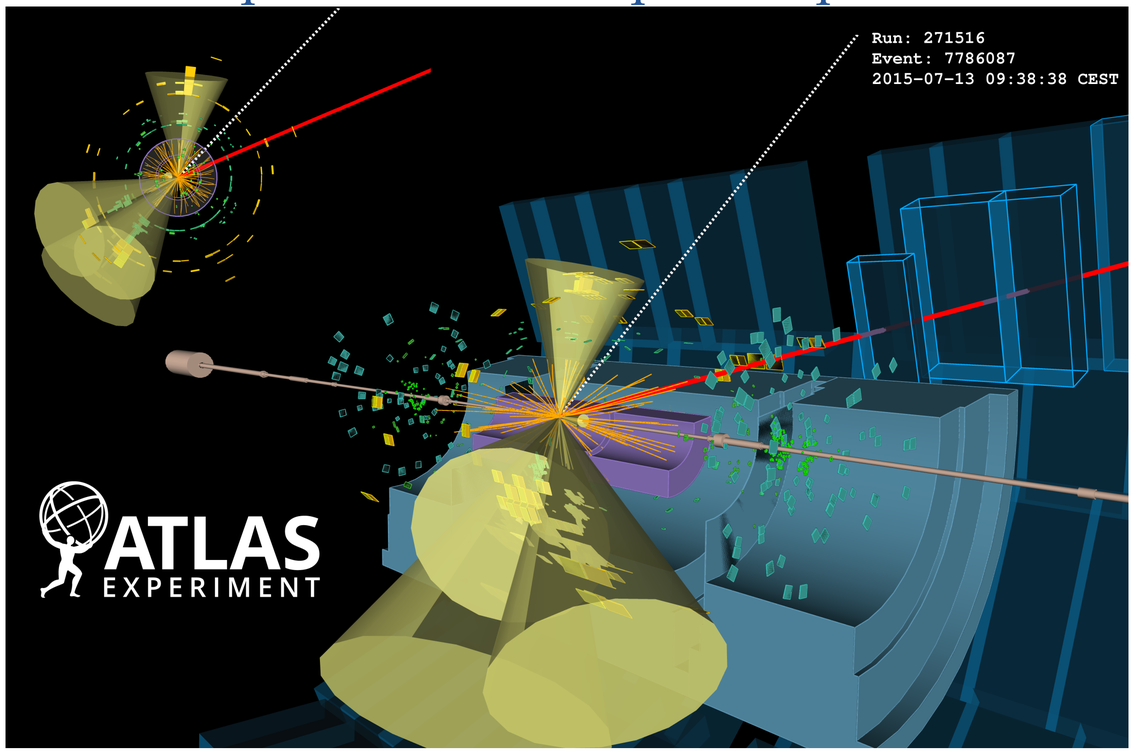
Why do top physics?

- The top quark is the most massive in the SM
  - Largest Higgs coupling
  - Top processes are important for many searches for rare processes and BSM physics
  - The top decays before hadronisation, so may be studied as a bare quark
- The LHC provides abundant top production
- Top processes are sensitive to many QCD parameters
- Properties of the top quark are important as input parameters in the SM

Top quark precision measurements

- Can probe SM with precision greater than NLO
- Precision measurements of top processes allow for tests of Effective Field Theory interpretations
- Compare data agreement across generators —> test SM, EFT interpretation, MC tuning
- Can search for rare processes and probe extreme phase space

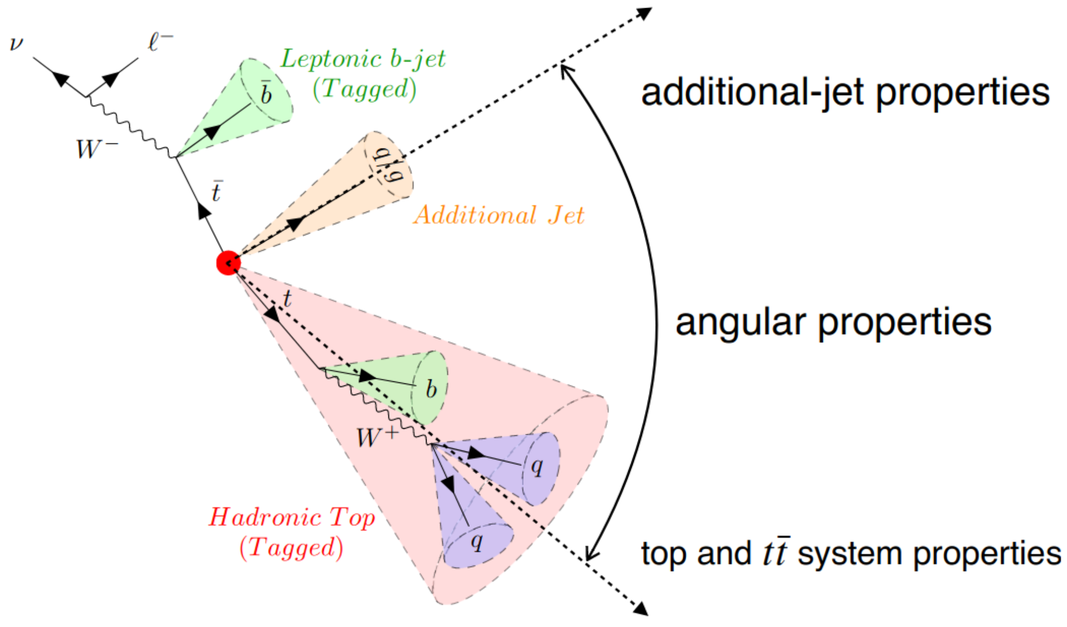


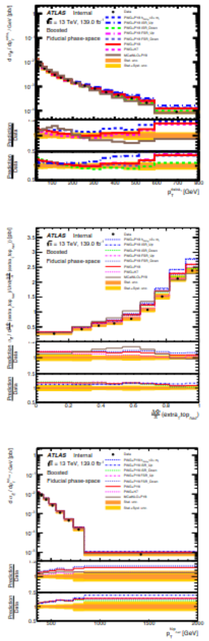
Measurements of differential cross-sections in top-quark pair events with a high transverse momentum top quark and limits on beyond the Standard Model contributions to top-quark pair production with the ATLAS Detector at $\sqrt{s} = 13$ TeV

arXiv:2202.12134

$t\bar{t}$ + jets ℓ+jets Differential Cross-Section: Overview

- Single and double-differential cross section measurement looking at additional jet properties and measuring angular variables
- Avenue to probe QCD in complex phase space encompassing range of scales in an event - important to model for new physics searches
- Distributions unfolded to particle-level, hadronic top p_T distribution used to place limits on EFT Wilson coefficients, C_{tG} and $C_{tq}^{(8)}$
- New Jet Scale Factor (JSF) method used to reduce JES uncertainty





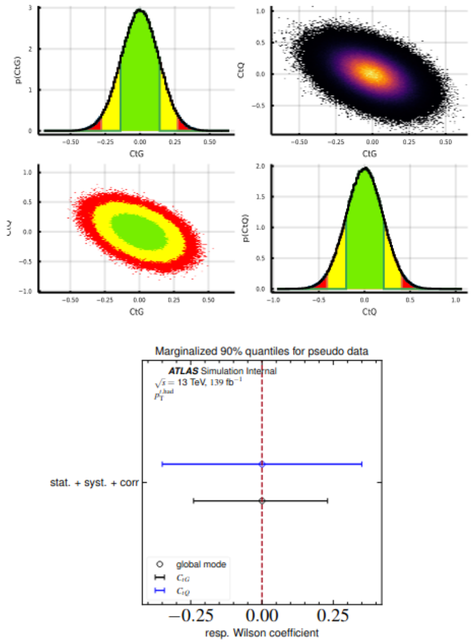
$p_T^{\text{extra}_1}$

$\frac{\Delta\phi}{\pi}(\text{extra}_1, \text{top}_{had})$

$p_T^{\text{top}_{had}}$

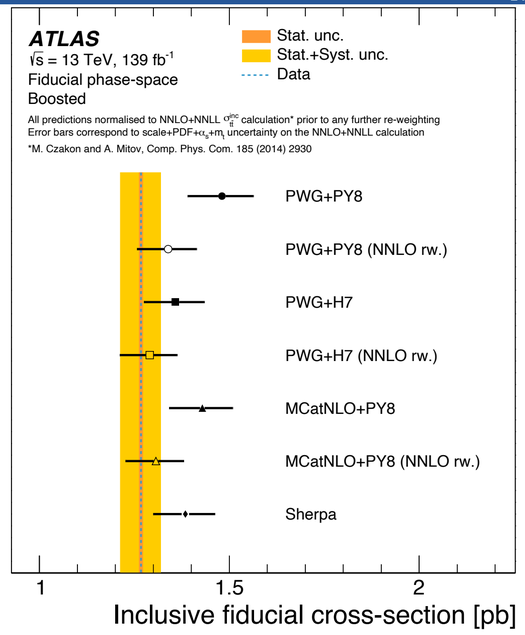
EFT*fitter*

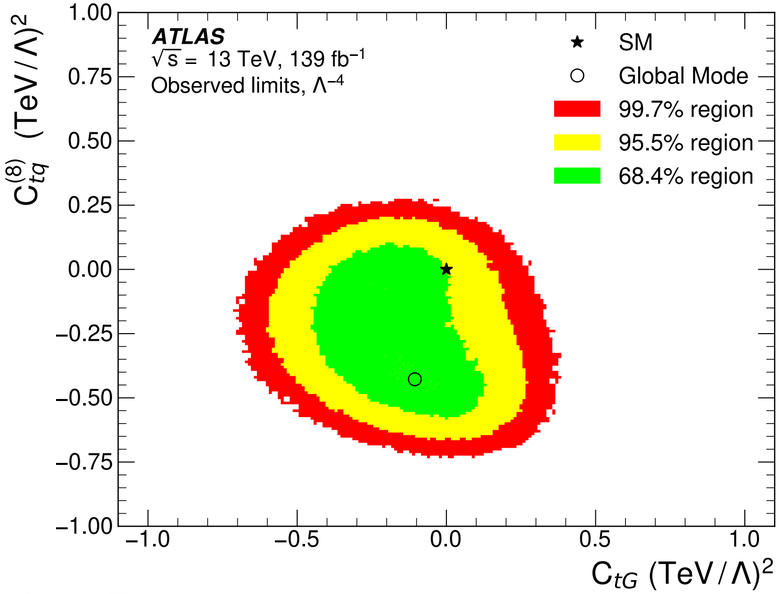
EFT model function
$\sigma_i^J(C_{tG}, C_{tq}^{(8)})$

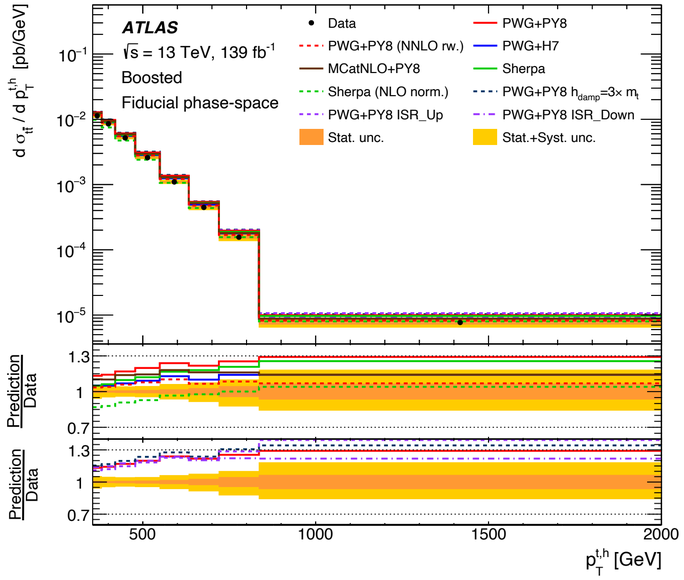


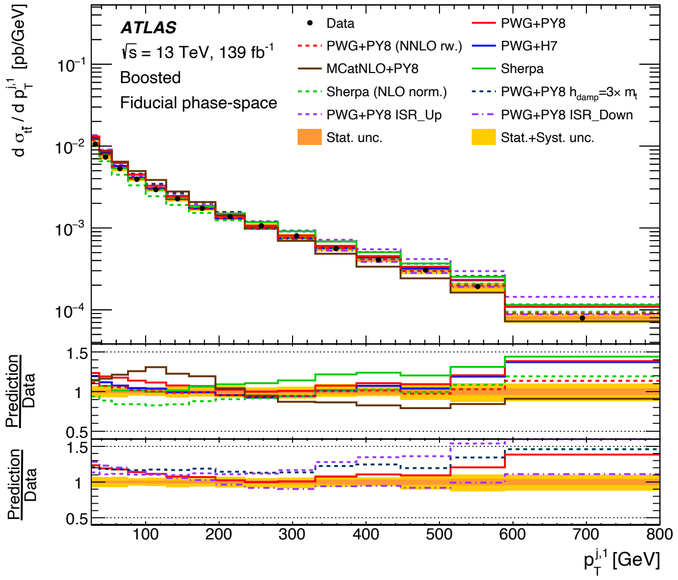
$t\bar{t}$ + jets ℓ+jets Differential Cross-Section: Results

- Systematics greatly reduced compared to previous measurements
- No one MC seen to predict well all of the distributions measured
- Parton-level reweighting improves agreement for all generators
- EFT limits from fit to $p_{\mathrm{T}}^{t,h}$ distribution competitive with global fit







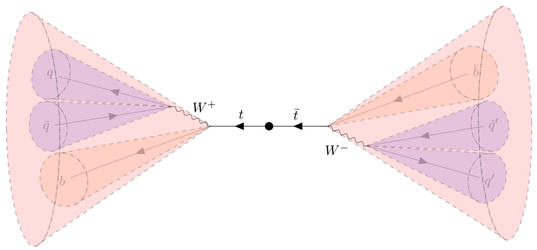


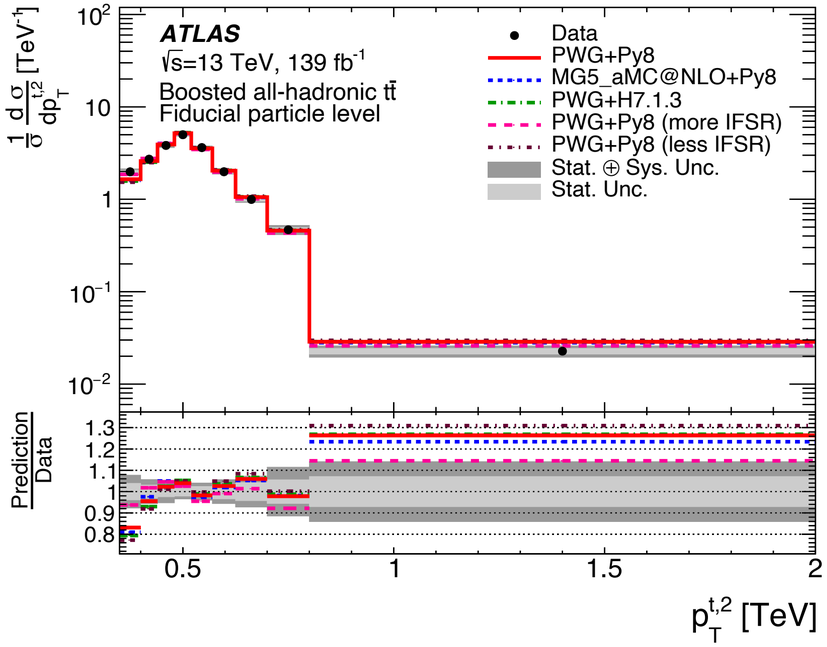
Differential $t\bar{t}$ cross-section measurements using boosted top quarks in the all-hadronic final state with 139 fb^{-1} of ATLAS data

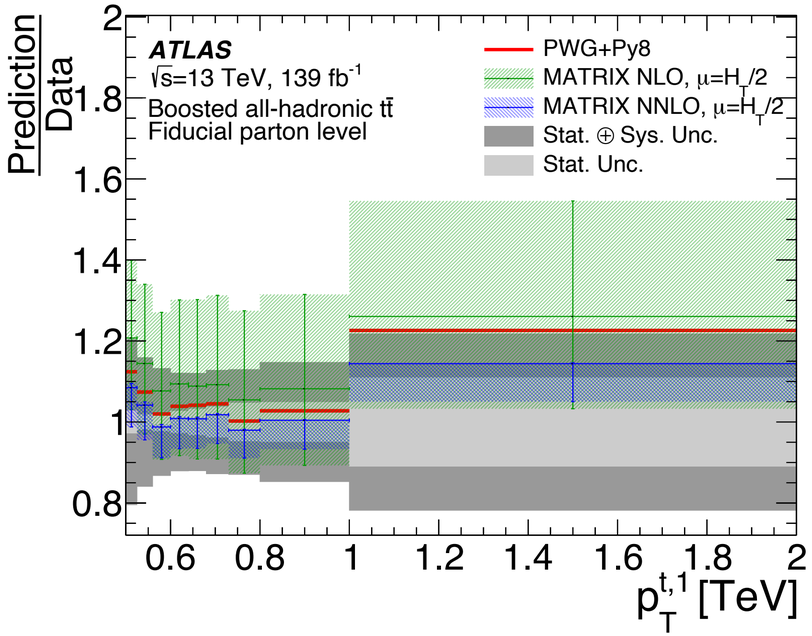
arXiv:2205.02817

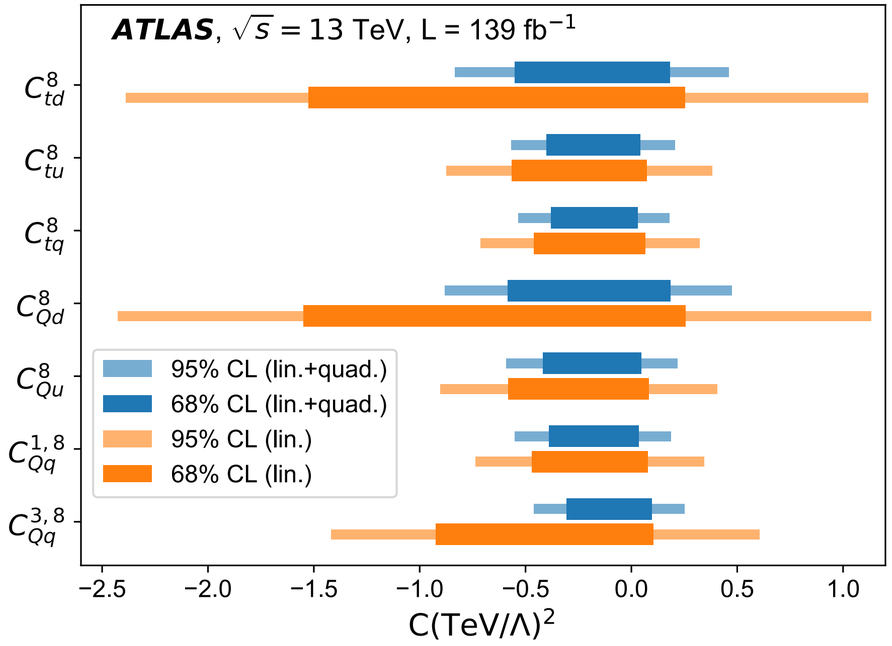
$t\bar{t}$ + jets All-Hadronic Differential Cross-Section

- Measurement in boosted region - leading top jet with $p_T > 500$ GeV, second-leading top jet with $p_T > 350$ GeV; single-, double-, and triple-differential cross-sections measured and unfolded
- Uncertainties around 10-20% providing reasonable agreement with NLO+PS predictions, though some tension at high-p_T tails for second-leading jet
- Agreement with data at parton-level improved by NNLO predictions
- Limits also derived on selected Wilson coefficients in EFT interpretation







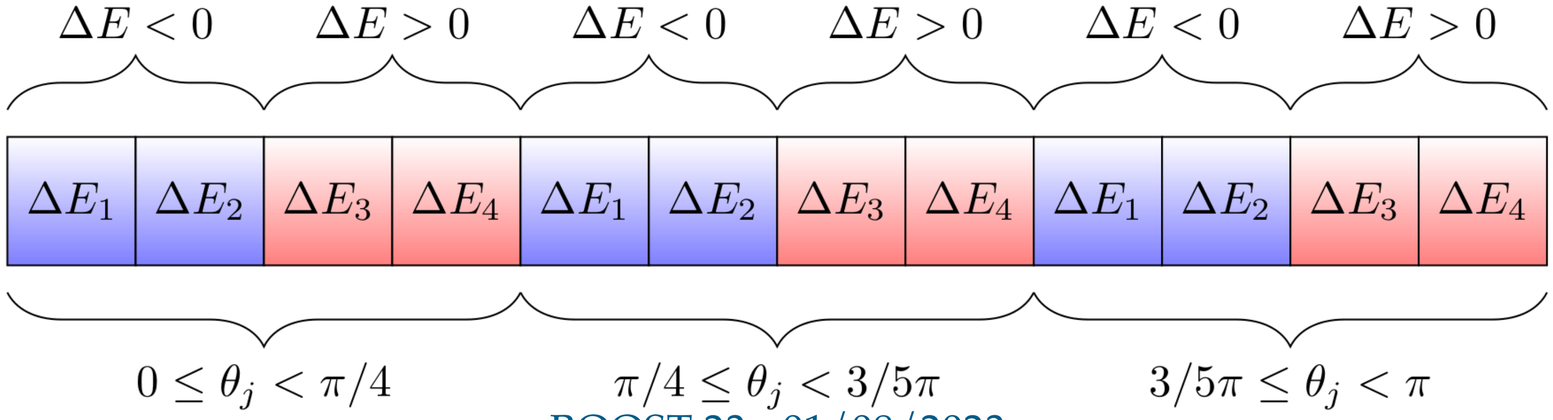


Measurement of the energy asymmetry in $t\bar{t}j$ production at 13 TeV with the ATLAS Experiment and interpretation in SMEFT

arXiv:2110.05453

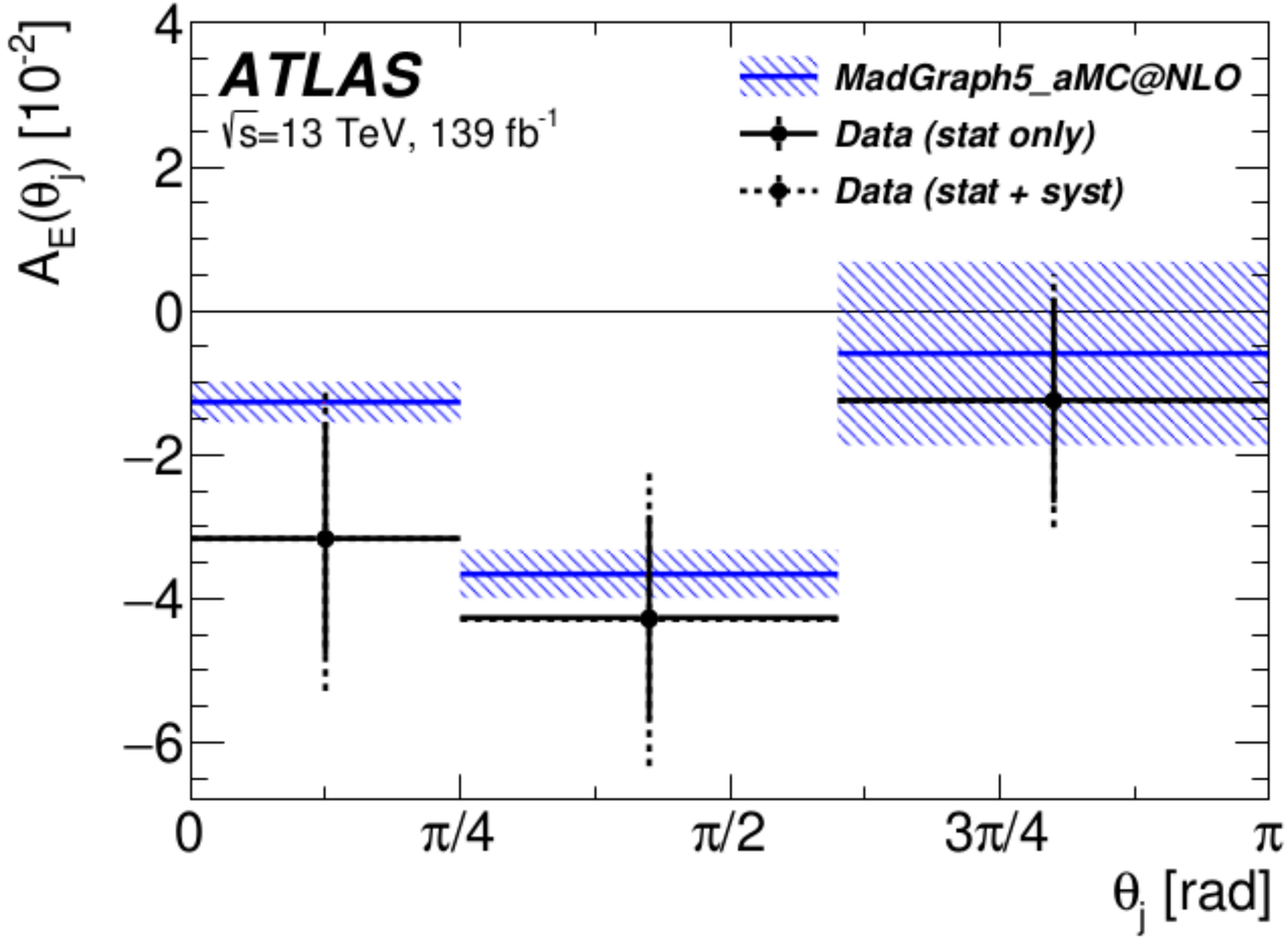
Energy Asymmetry in $t\bar{t}j$: Overview

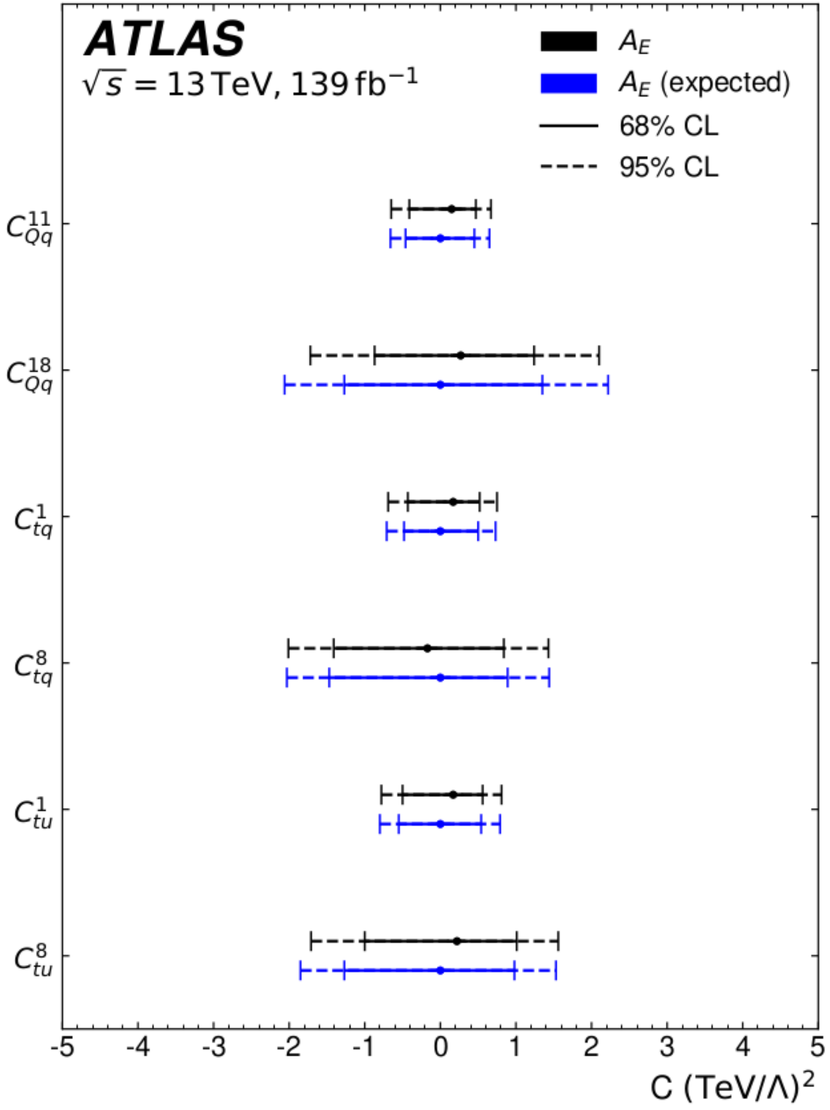
- Charge asymmetry in top pair production particularly sensitive to new physics
- Can measure charge asymmetry as an energy asymmetry when top pairs are produced in association with a high-p_{T} additional jet
- Measurement in boosted lepton+jets $t\bar{t}$ using full Run-2 dataset
- Data unfolded to particle-level and used to obtain EFT limits
- Define asymmetry observable $A_E\left(\theta_j\right) \equiv \dfrac{\sigma^{\mathrm{opt}}\left(\theta_j \mid \Delta E > 0\right) - \sigma^{\mathrm{opt}}\left(\theta_j \mid \Delta E < 0\right)}{\sigma^{\mathrm{opt}}\left(\theta_j \mid \Delta E > 0\right) + \sigma^{\mathrm{opt}}\left(\theta_j \mid \Delta E < 0\right)}$, where $\Delta E = E_t - E_{\bar{t}}$ is measured in bins of θ_j, the angle of the additional jet relative to the beamline



Energy Asymmetry in $t\bar{t}j$: Measurement

- Constraints on Wilson coefficients from energy asymmetry complementary to those from other top observables such as charge asymmetry



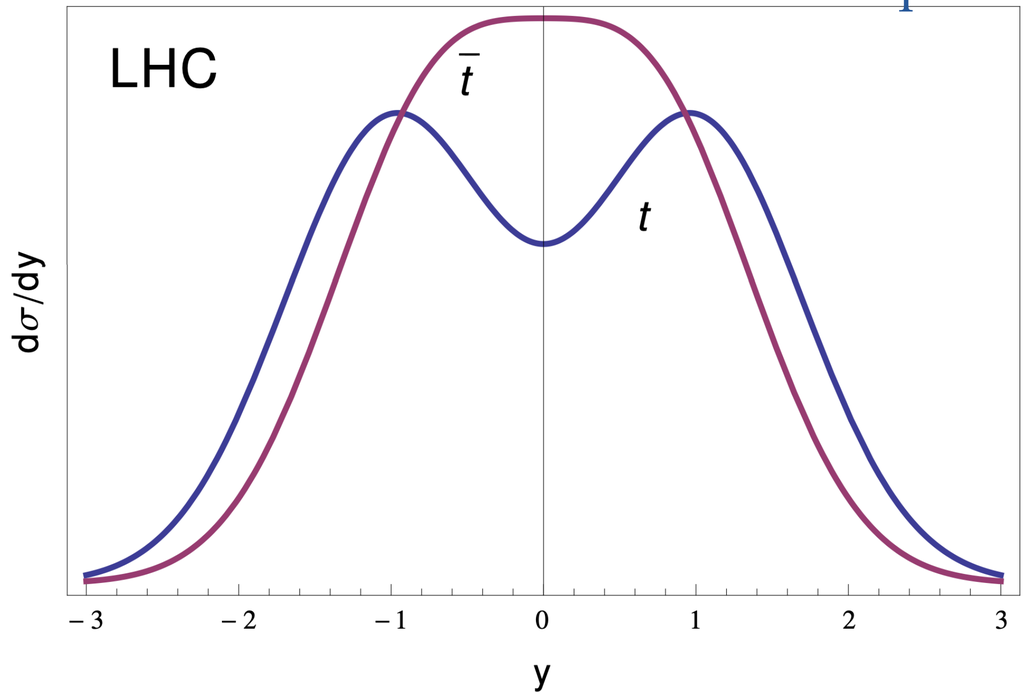


Evidence for the charge asymmetry in $pp \to t\bar{t}$ production at $\sqrt{s} = 13$ TeV with the ATLAS Detector

arXiv:2208.12095

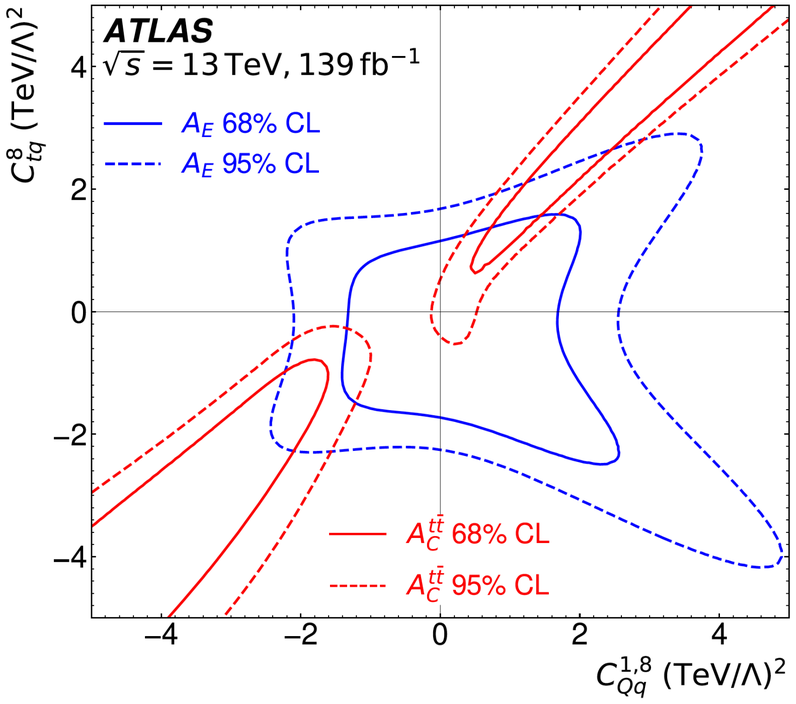
Charge Asymmetry in $t\bar{t}$: Overview

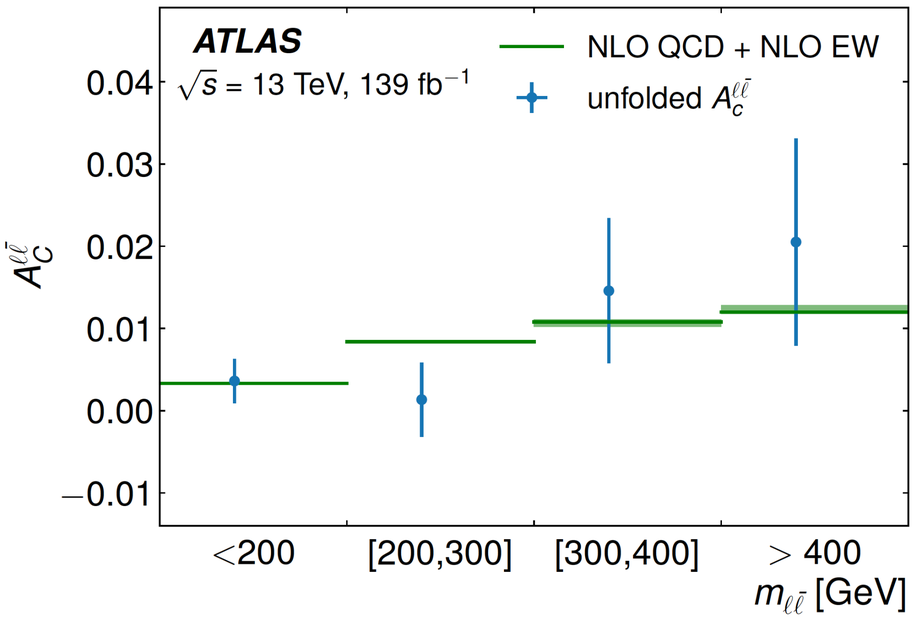
- Asymmetry arising from $q\bar{q}$ and qg initial states, diluted at LHC by $gg \to t\bar{t}$ process
- $A_C^{t\bar{t}}$ and $A_C^{\ell\bar{\ell}}$ measured differentially as function of $m_{t\bar{t}}/m_{\ell\bar{\ell}}$, $p_{\mathrm{T},t\bar{t}}/p_{\mathrm{T},\ell\bar{\ell}}$, and $\beta_{z,t\bar{t}}/\beta_{z,\ell\bar{\ell}}$ using full Run-2 dataset in lepton+jets and resolved channels
- Asymmetries sensitive to many BSM effects, with previous measurement statistically limited, consistent with SM
- EFT interpretation to place limits on Wilson coefficients of operators affecting top production

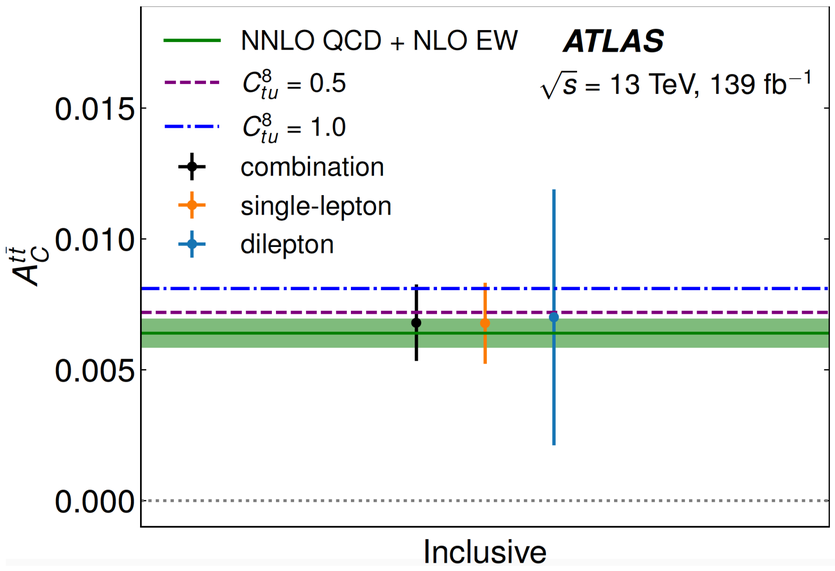


Charge Asymmetry in $t\bar{t}$: Results

- SM prediction gives $A_C^{t\bar{t}} = 0.0064^{+0.0005}_{-0.0006}$, measured here to be $A_C^{t\bar{t}} = 0.0068 \pm 0.0015$, compatible with SM and 4.7σ from zero
- SM prediction gives $A_C^{\ell\bar{\ell}} = 0.0040^{+0.0002}_{-0.0001}$, measured here to be $A_C^{\ell\bar{\ell}} = 0.0054 \pm 0.0026$, compatible with SM
- Improved bounds on Wilson coefficients, complementary to constraints from $t\bar{t}j$ energy asymmetry measurement





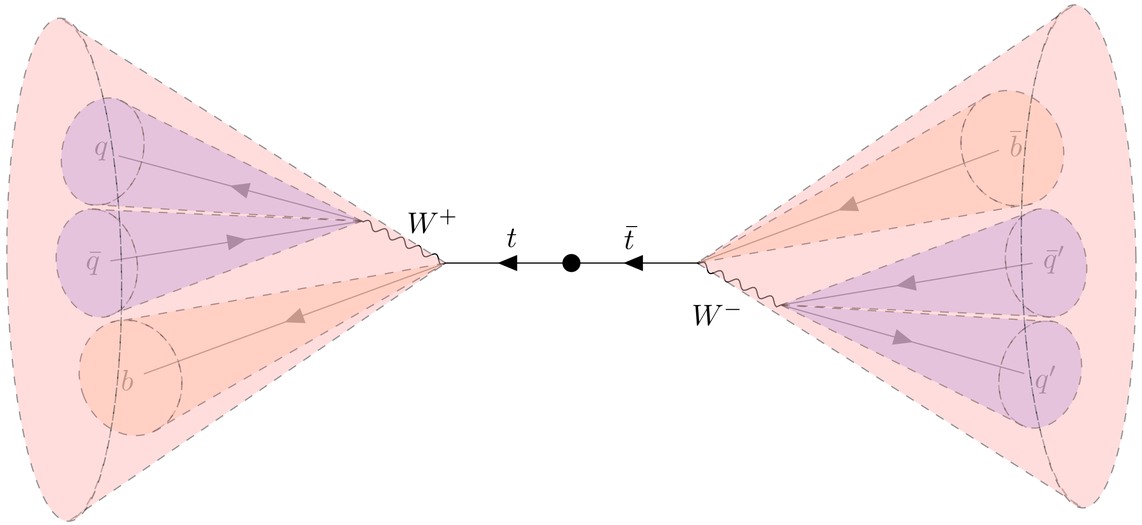


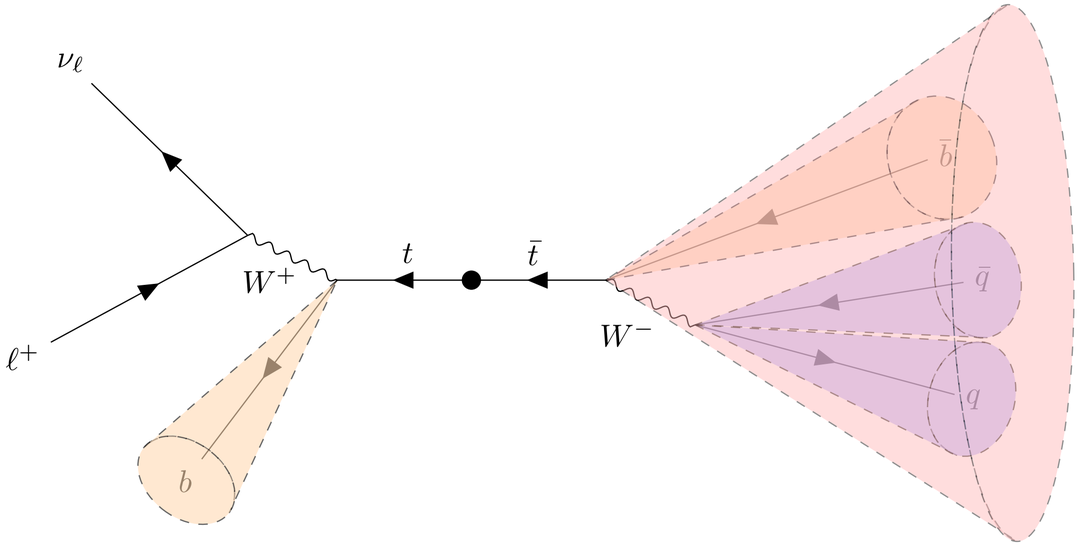
Measurement of jet substructure in boosted $t\bar{t}$ events with the ATLAS detector using 140 fb^{-1} of 13 TeV pp collisions

ATLAS-CONF-2023-027

Jet Substructure in $t\bar{t}$: Overview

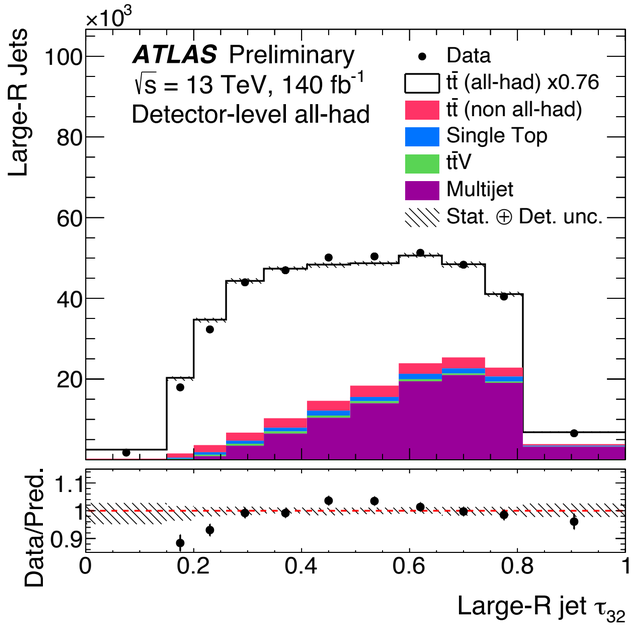
- Measurement of jet substructure observables in boosted $t\bar{t}$ in both lepton+jets and all-hadronic channels, using full Run-2 dataset
- Jet tagging algorithms make use of jet substructure observables
- Substructure distributions sensitive to certain MC parameters
- An analytic description of jet substructure is challenging
- BSM physics may manifest as modification to jet substructure

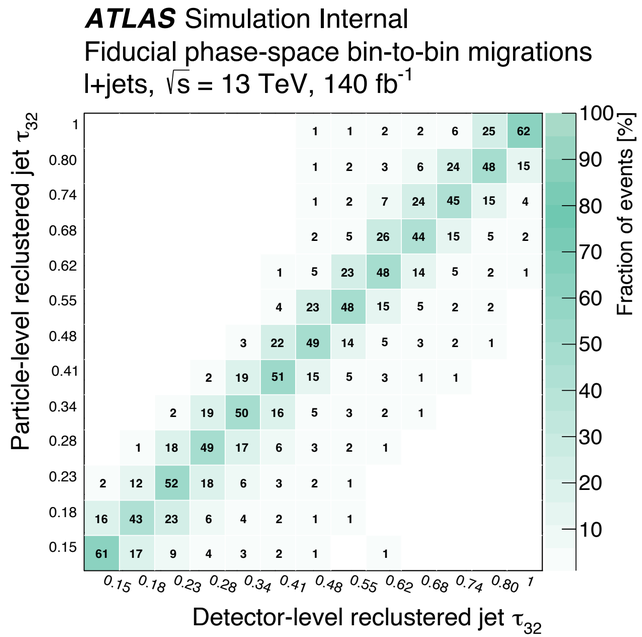




Jet Substructure in $t\bar{t}$: Measurement

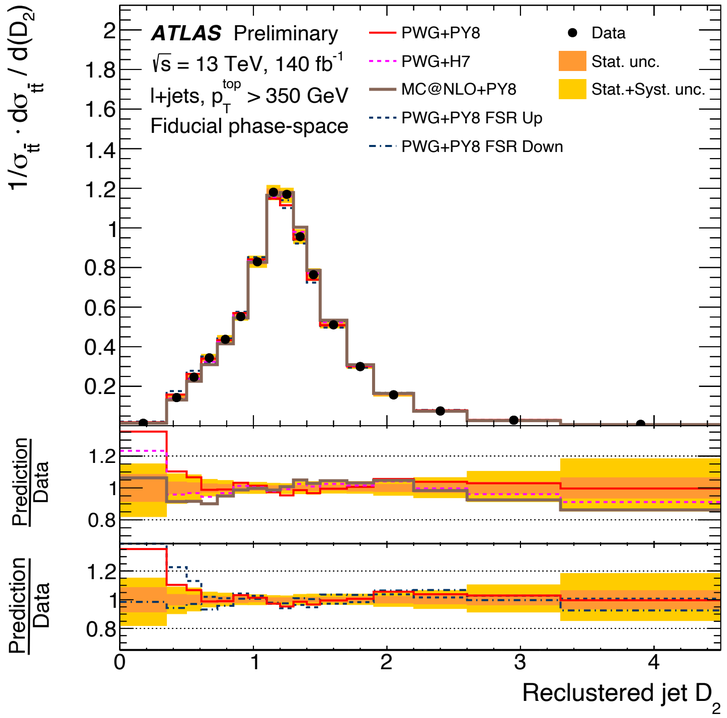
- Eight substructure observables selected for measurement, based on Energy Correlation Functions, $\mathcal{N}$-subjettiness, and Generalised Angularities
- Observables measured in large-R jets using ghost-associated tracks
- Single and double-differential cross-sections measured
- "Double tag-n-probe" method in all-hadronic channel used to improve stats
- $m_{\ell b}$ cut used in lepton+jets channel to reduce bias from tagging and reduce backgrounds
- Distributions unfolded to particle-level and compared to several NLOME+PS predictions

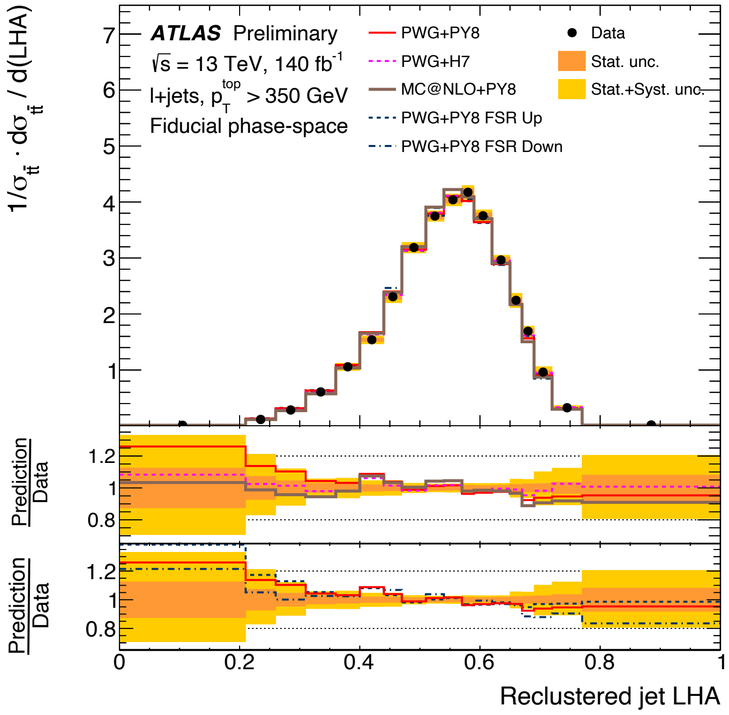


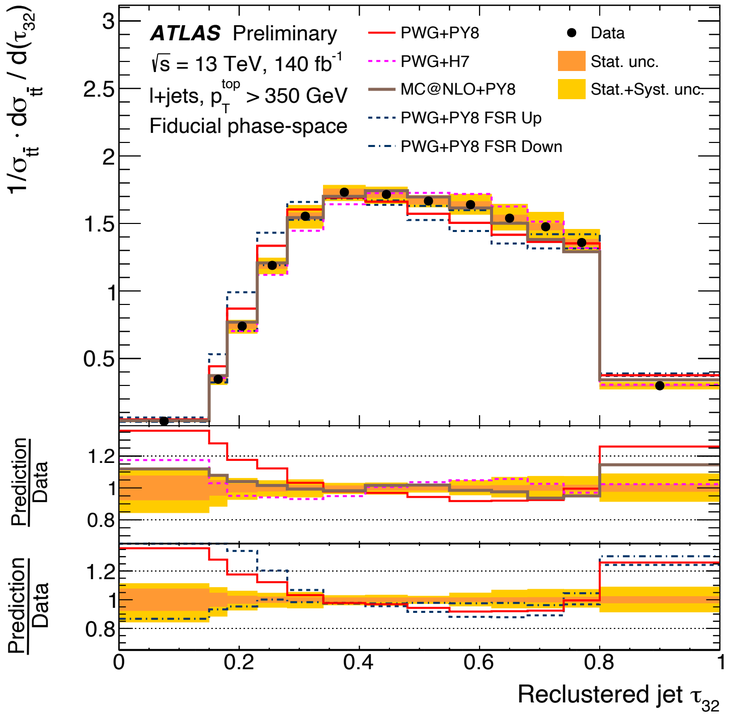


Jet Substructure in $t\bar{t}$: Results

- Some observables described better than others: two-pronged observables generally better described than three-pronged observables
- Nominal Powheg+Pythia8 prediction generally outperformed by Powheg+Herwig7, as well as by the FSR-down variation of PP8 - the data prefers above-nominal value of α_S
- Uncertainties reduced considerably as compared to previous measurements

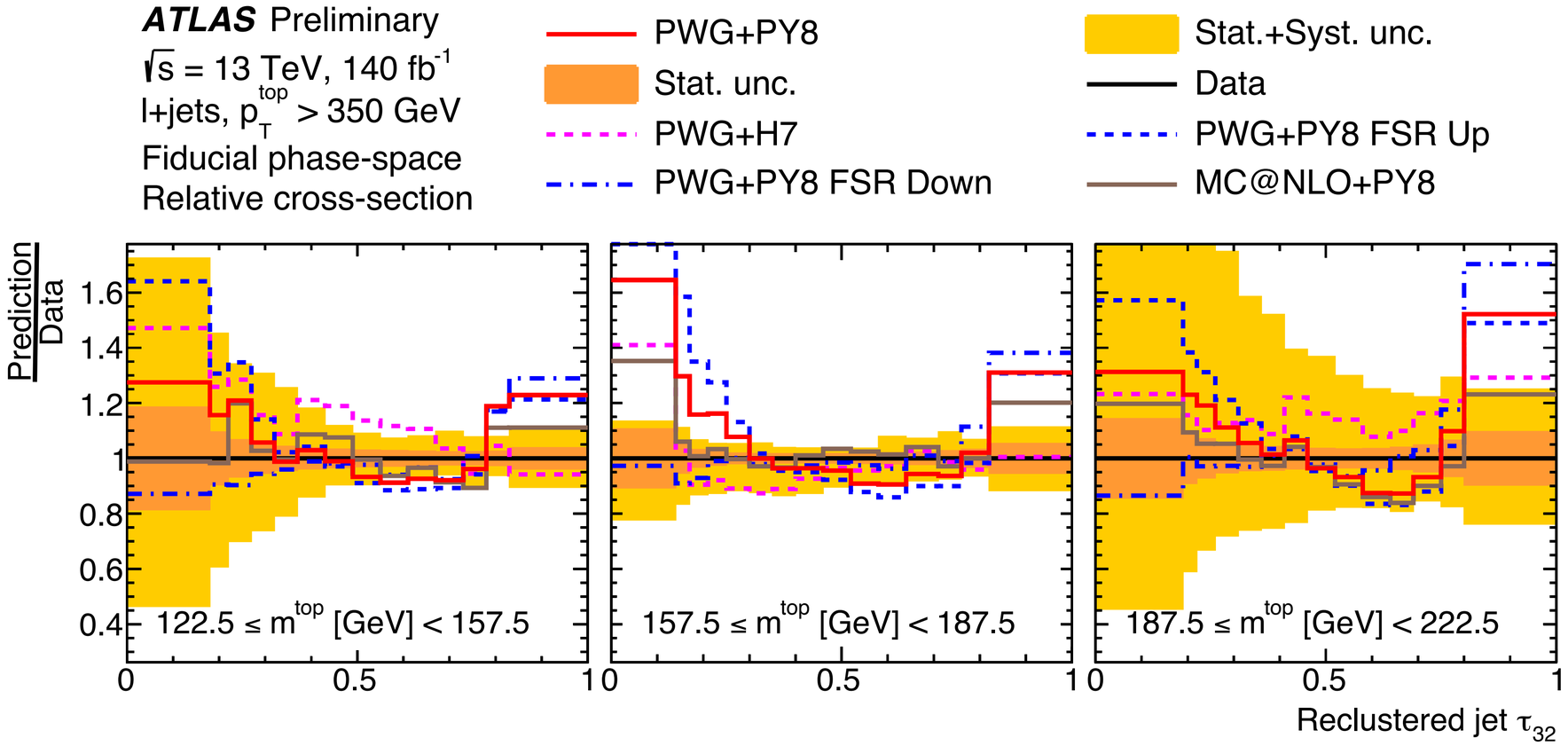






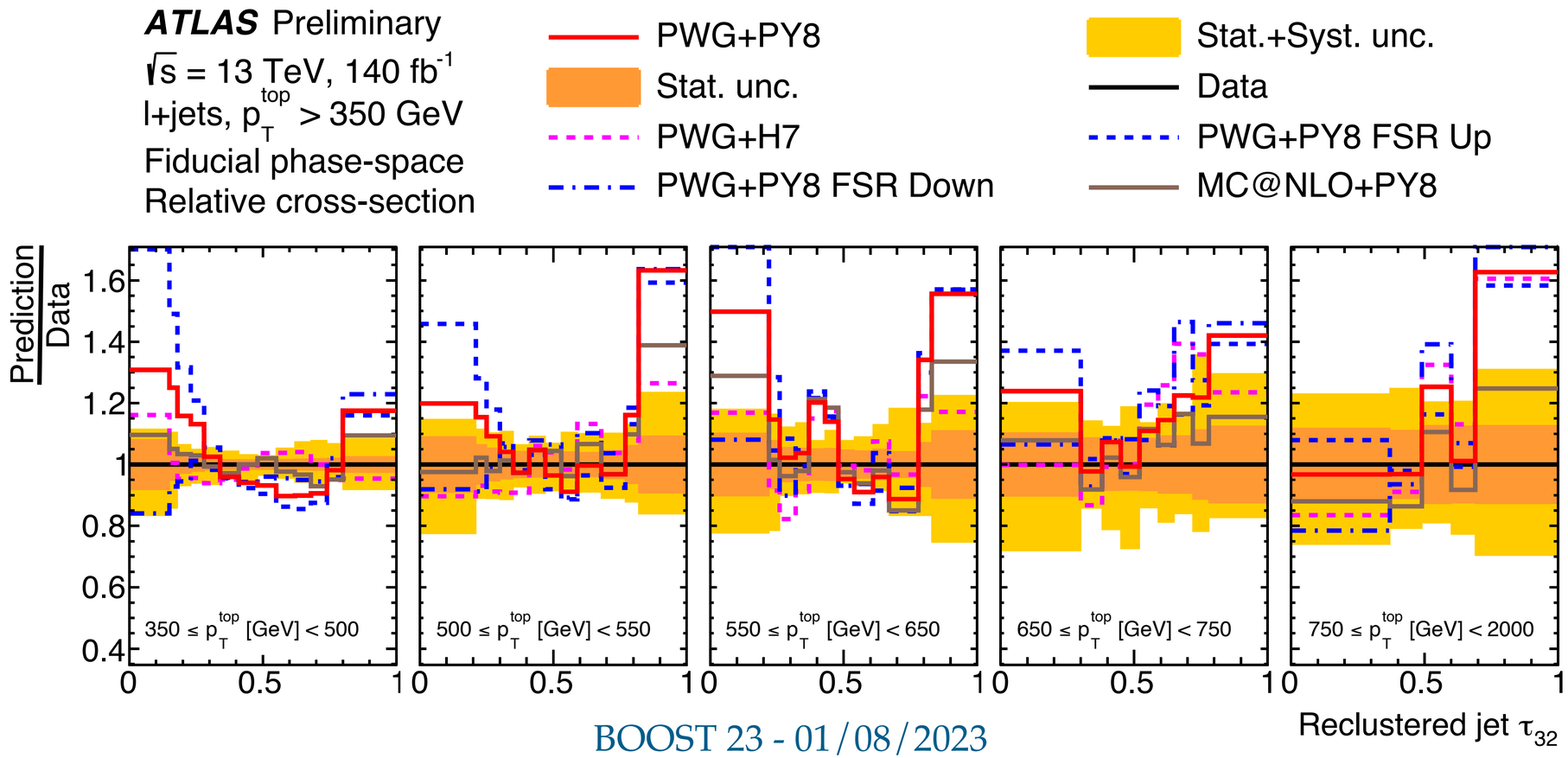
Jet Substructure in $t\bar{t}$: Results

- Correlation of τ_{32} and D_2 observables with mass and p_T of the jet are generally poorly described
- Most significant modelling uncertainties come from PS, hadronisation
- Most significant detector uncertainties come from JES/JER and tracks



Jet Substructure in $t\bar{t}$: Results

- Correlation of τ_{32} and D_2 observables with mass and p_T of the jet are generally poorly described
- Most significant modelling uncertainties come from parton shower, hadronisation
- Most significant detector uncertainties come from JES/JER and tracks



Conclusion

- Lepton + jets with additional jets differential cross-section measured with improved precision and placing constraints on EFT operators competitive with global fit
- All-hadronic differential cross-section shows reasonable agreement with NLO+PS predictions, agreement at parton-level improved with NNLO predictions
- Strong evidence of charge asymmetry in $t\bar{t}$ (4.7σ from zero), placing constraints on EFT Wilson coefficients complementary to those from measurement of energy asymmetry in $t\bar{t}j$
- Measurement of substructure observables with improved resolution, sensitive to variations in NLOME+PS and FSR, favouring higher α_S
- Selected highlights shown, full list of results shown on ATLAS Top Working Group public site
- Constraints on EFT operators shown in these results complement many more from other ATLAS top measurements, shown in the EFT Summary Plots

BACKUP