Studies of top quark properties in ATLAS

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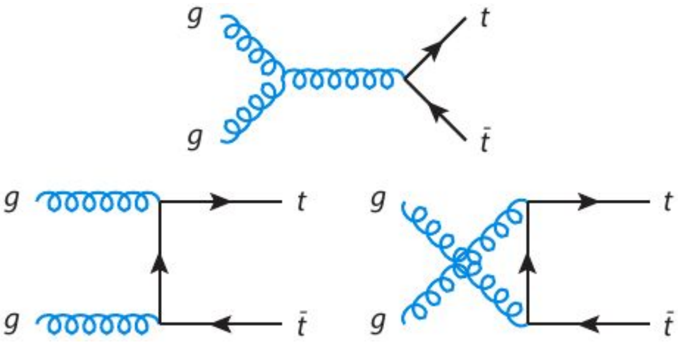
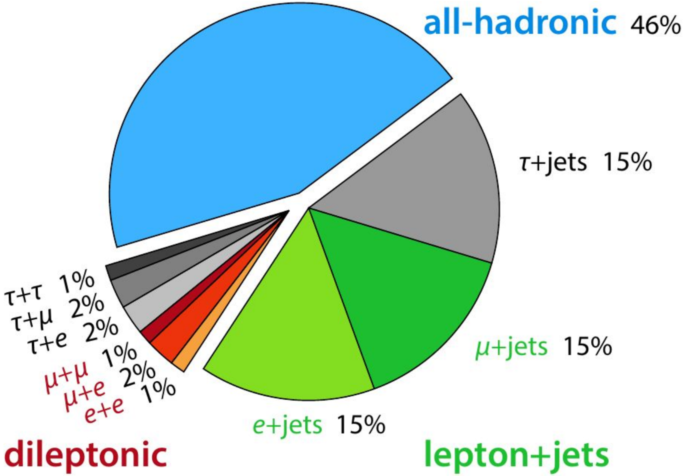
On behalf of the ATLAS Collaboration

TOP 2022, 6th September 2022

Introduction



- Top quarks produced at high energies
  - “Small” coupling strength - allows **precise theory predictions**
- Top quarks are produced abundantly at the LHC
  - **High statistics** analyses



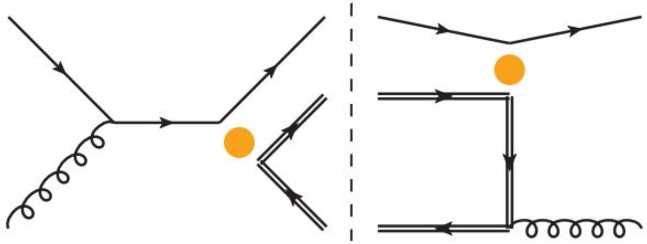
- **Energy asymmetry** in ttbar+jet events
- **Charge asymmetry** in ttbar events
- **Colour reconnection** measurement
- Measurement of **b-fragmentation** in ttbar events

Top-quark spin and polarisation measurements presented today by Miriam

Energy asymmetry in ttbar+jet

[Eur. Phys. J. C 82 (2022) 374]

Energy asymmetry - introduction



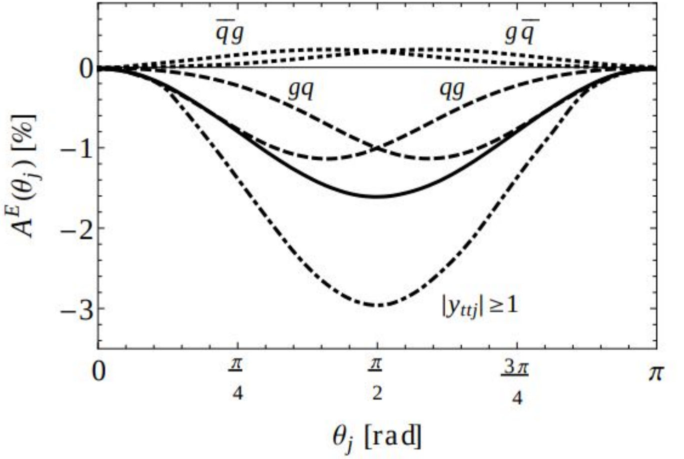
- Asymmetry between the energies of top and anti-top

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

$$\sigma^{\rm opt}(\theta_j) = \sigma(\theta_j|y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j|y_{t\bar{t}j} < 0)$$

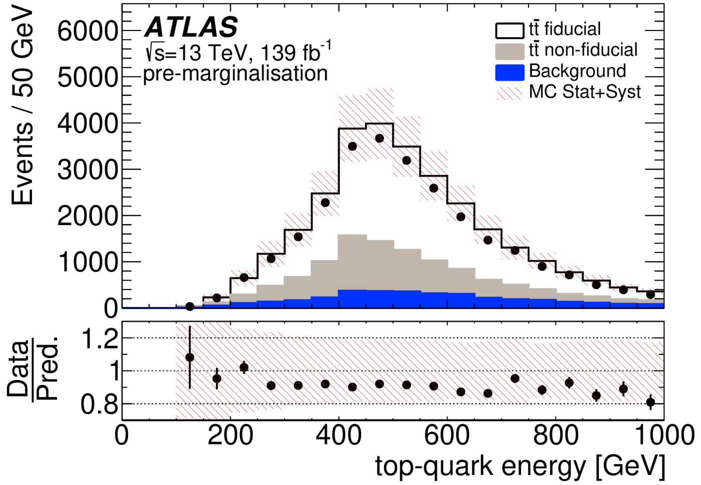
JHEP 07(2013)179

- Using the optimised cross-section
- Measured in **ttj rest-frame**
- Angle between the jet and z-axis
- **Asymmetry increases with increased jet p_T**
- **LO effect** due to the **presence of the extra jet**
- Sensitive to new physics



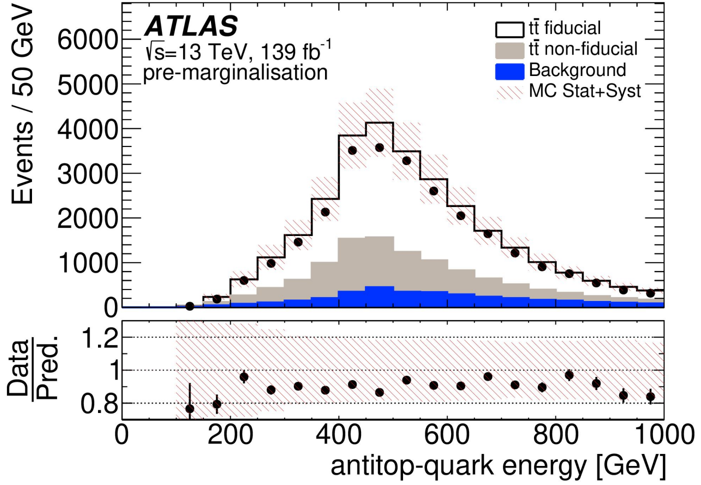
Energy asymmetry - measurement

- One isolated electron or muon (27 GeV)
- **Large-R jet** (delta R = 1.0), 350 GeV, top-tagged with **DNN**
- **Small-R** (delta R = 0.4) close to the lepton
- Associated jet, 100 GeV, isolated from top-candidates
- At least one small-R b-tag
- MET and MWT cuts - to suppress fake leptons

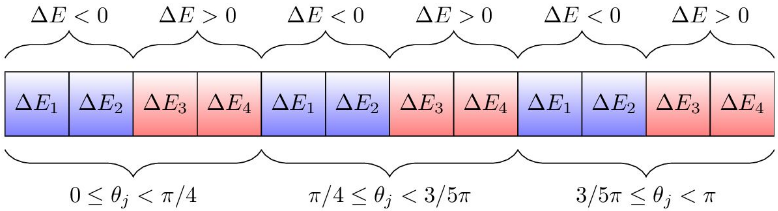


Strategy

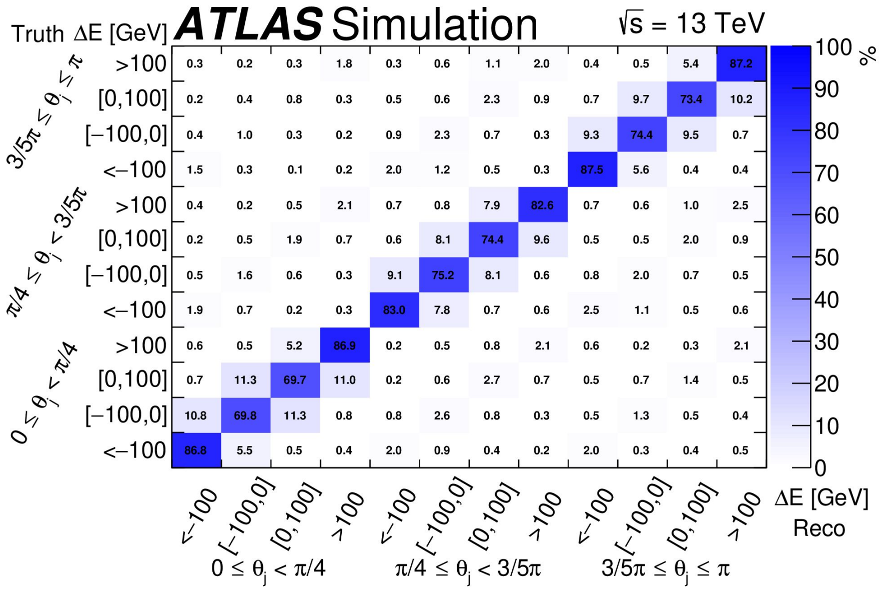
- **Unfold** optimised differential distribution to **particle level**
- Extract the asymmetry from the unfolded distribution

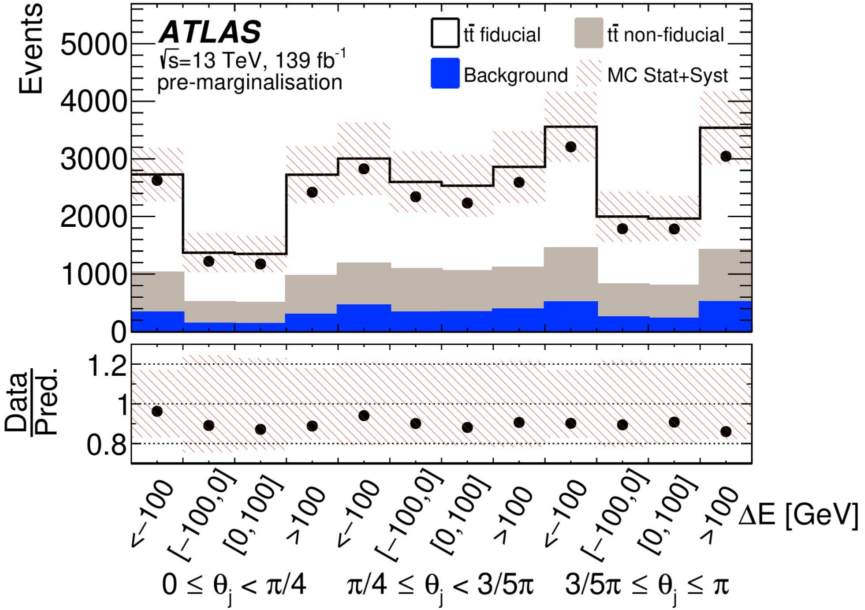


Energy asymmetry - unfolding

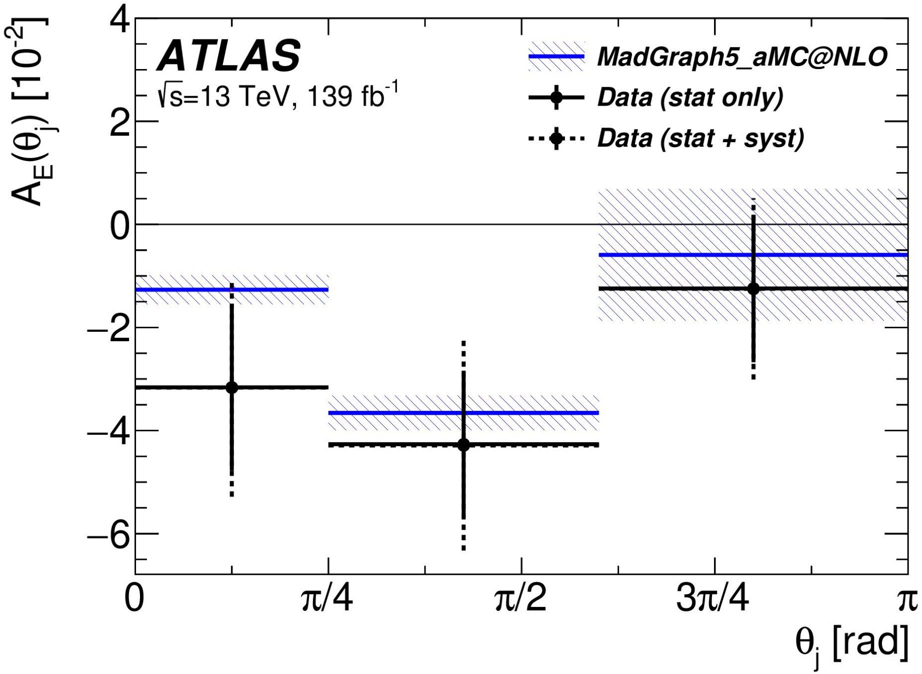


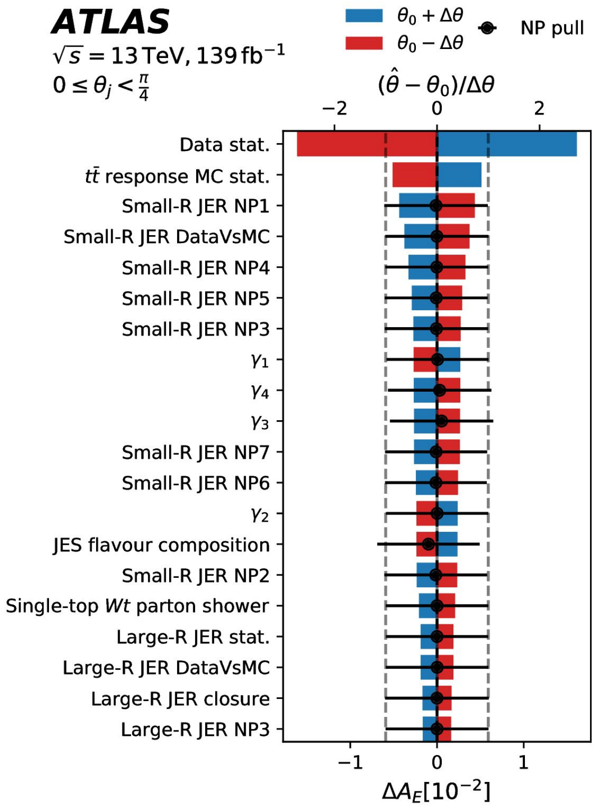
- Using **three regions**, **each** with four **delta energy bins**
- Using **Fully Bayesian Unfolding** to unfold to truth level - see the talk from Barbora
  - Systematic uncertainties included in the likelihood
  - Using MCMC sampling for marginalisation
  - **Full posterior distribution**





Energy asymmetry - results

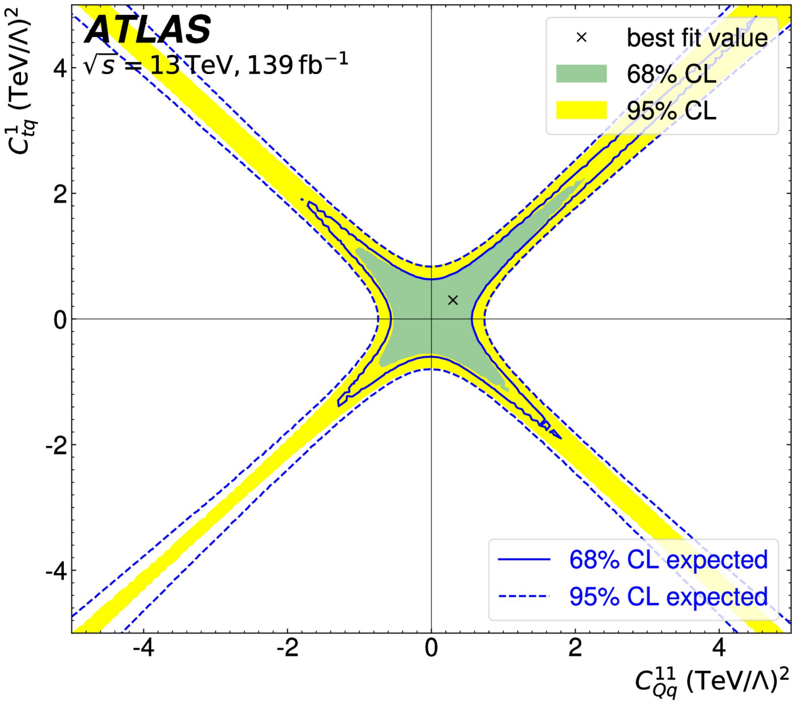


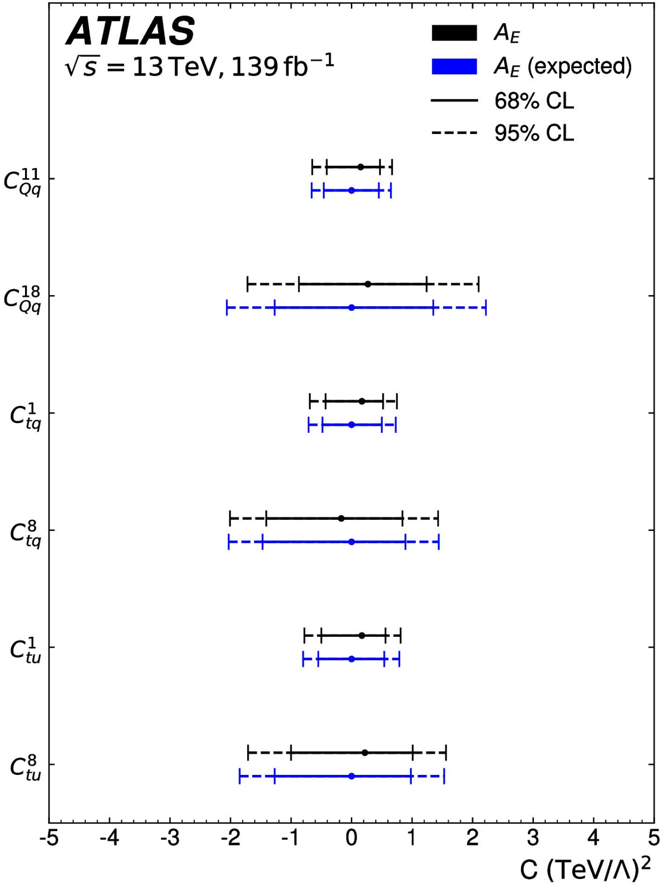


- **Statistically dominated**, dominant **systematics** from **ttbar modelling and JER**
- **In agreement with the SM prediction** from Madgraph

Energy asymmetry - EFT interpretation

- Using **SMEFT** framework





Charge asymmetry in ttbar

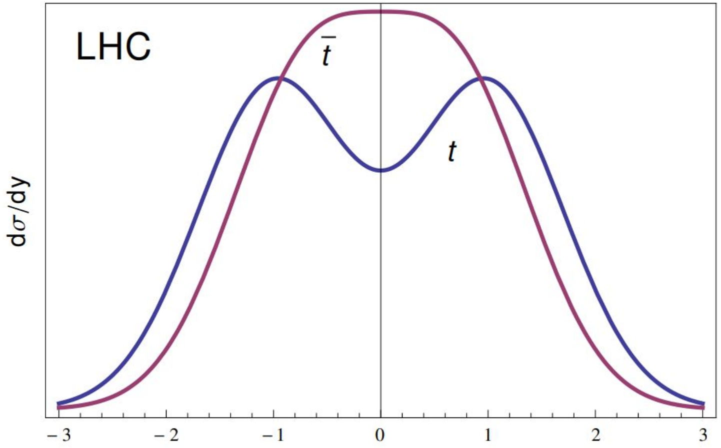
Submitted to JHEP

See the YSF talk from Barbora!

Charge asymmetry ttbar - introduction

- Central-forward asymmetry at LHC
  - Proton-proton collider
- **Pure NLO effect**
  - Sensitive to new physics effects

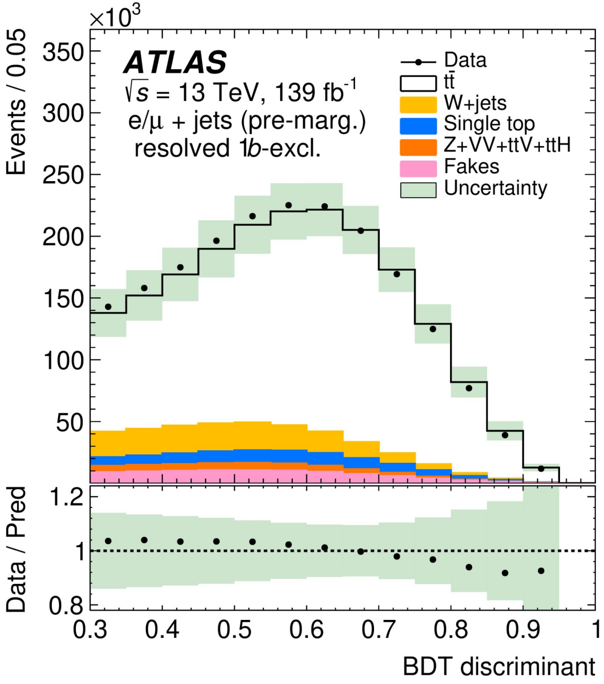
$$A_C^{t\bar{t}} = \frac{N(\Delta|y_{t\bar{t}}| > 0) - N(\Delta|y_{t\bar{t}}| < 0)}{N(\Delta|y_{t\bar{t}}| > 0) + N(\Delta|y_{t\bar{t}}| < 0)}$$



- Predicted inclusive asymmetry: 0.6% - Phys. Rev. D 98, 014003 (2018)
  - Calculated at NNLO (QCD) with NLO EW corrections
- **Increased asymmetry in differential bins**

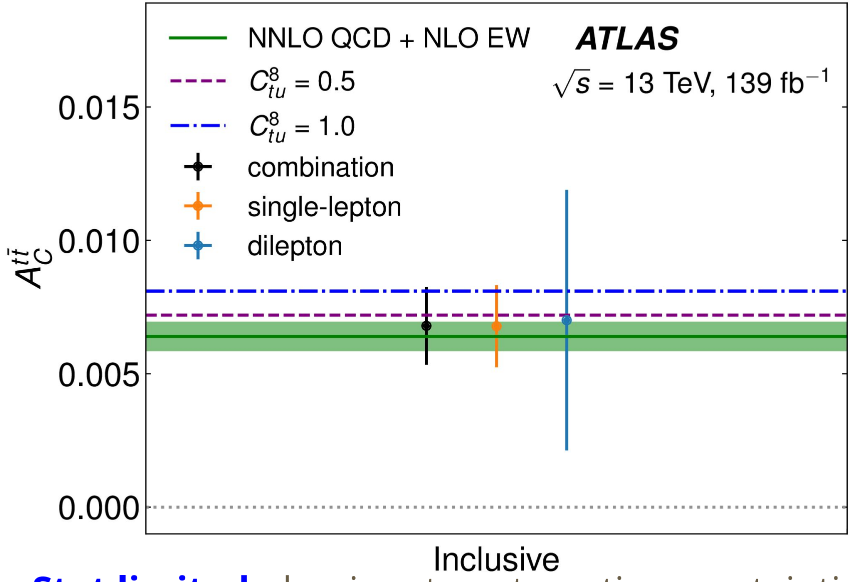
Charge asymmetry ttbar - measurement

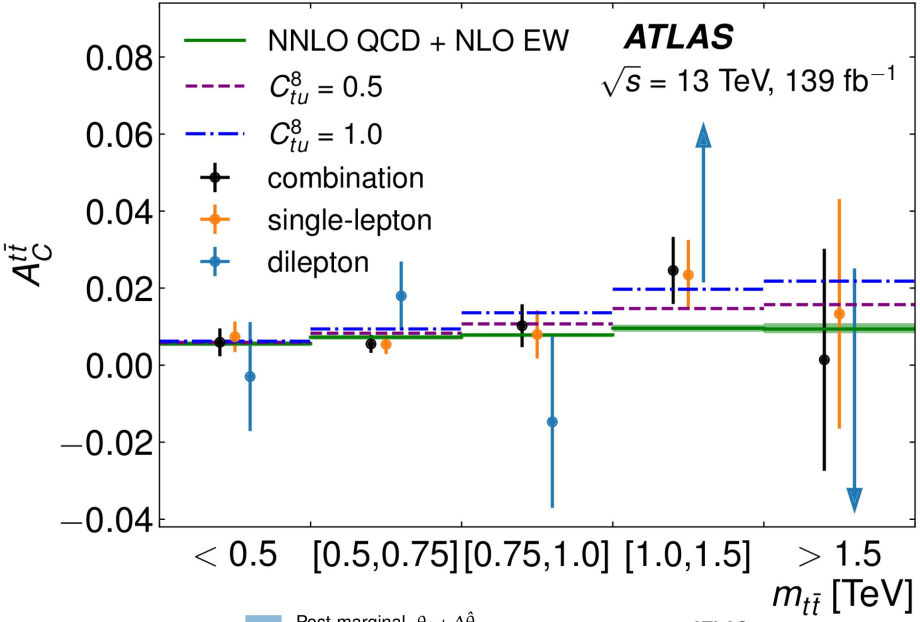
- **Lepton+jets** **resolved**, lepton+jets **boosted**
  - One lepton, 28 GeV
  - At least one b-tagged small-R jet, 25 GeV
  - **At least 4 jets** (resolved), **large-R jet** (boosted) >350 GeV
  - **Kinematic reconstruction**
    - **Permutational BDT**
- **Dilepton**
  - Two leptons, 25(28) GeV
  - At least two **small-R jets,** 25 GeV
  - Z boson veto
  - At least one b-tagged jet
  - **Kinematic reconstruction using Neutrino Weighting**

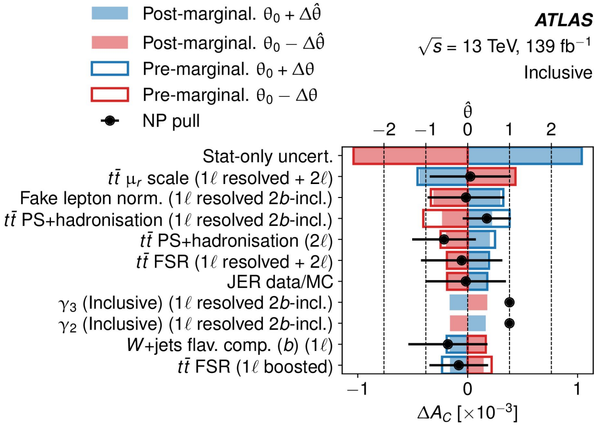


Charge asymmetry ttbar

- Using **Fully Bayesian Unfolding** to unfold to parton level
- ***A_{tt}* = 0.0068 ± 0.0015(stat+syst.).**
  - <u>4.7 sigma from zero asymmetry</u>



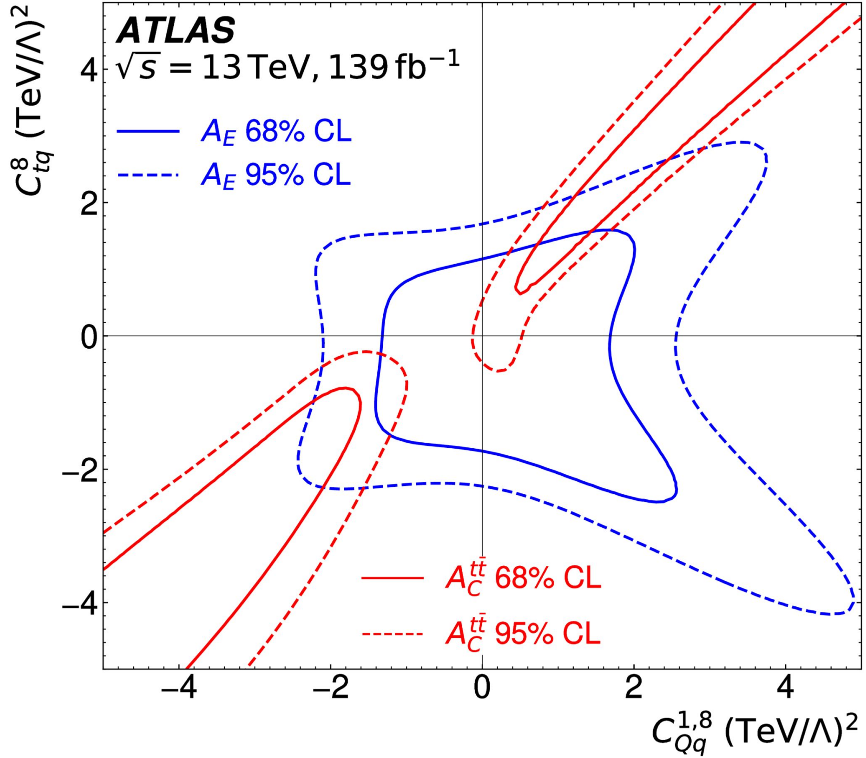


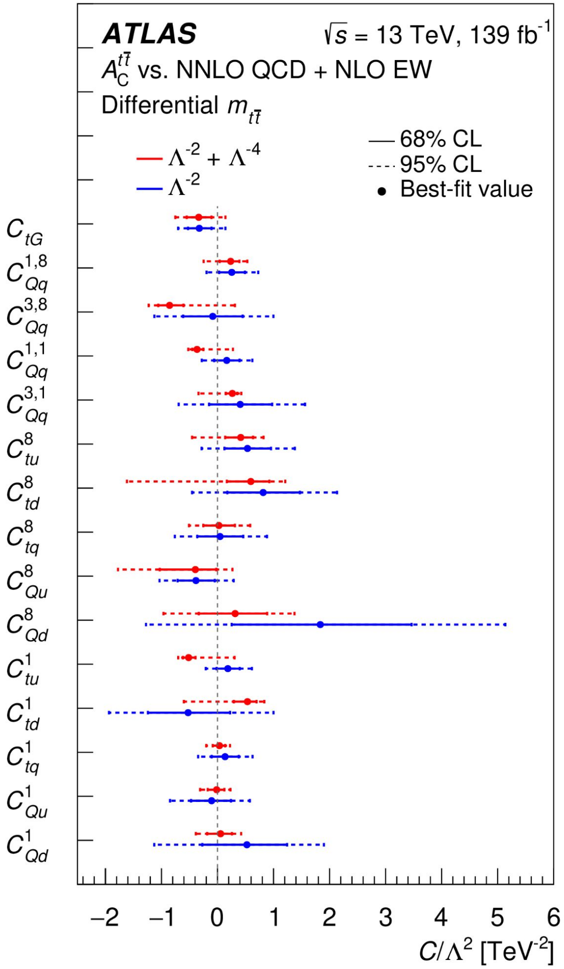


Stat limited, dominant systematic uncertainties from ttbar modelling

Charge asymmetry ttbar - EFT

- **SMEFT** framework
- **Sensitive to blind directions from energy asymmetry**

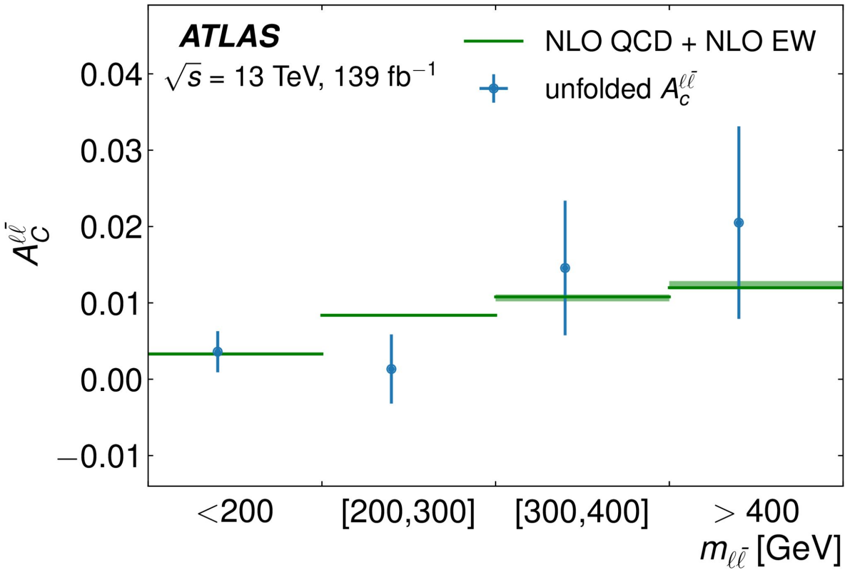


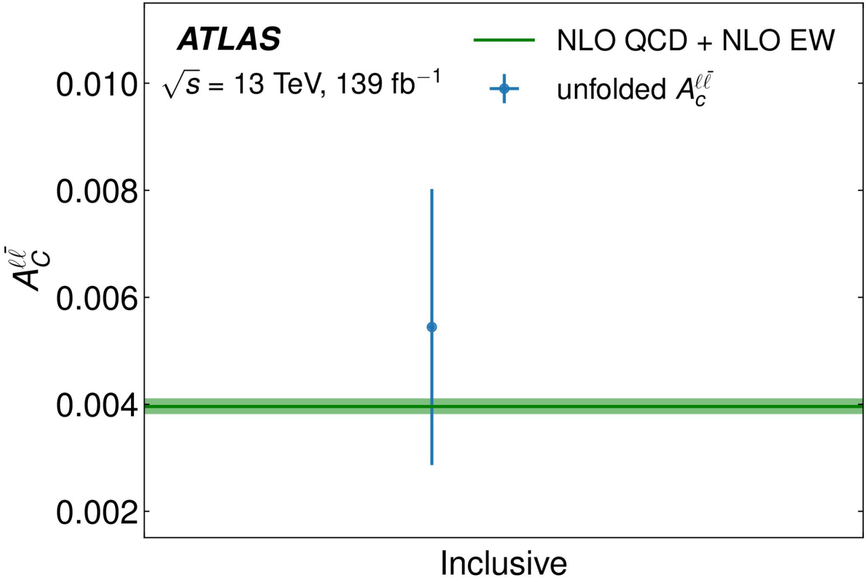


Charge asymmetry ttbar - lepton asymmetry

- Based on **rapidity of charged leptons**
  - **Only dilepton channel**

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



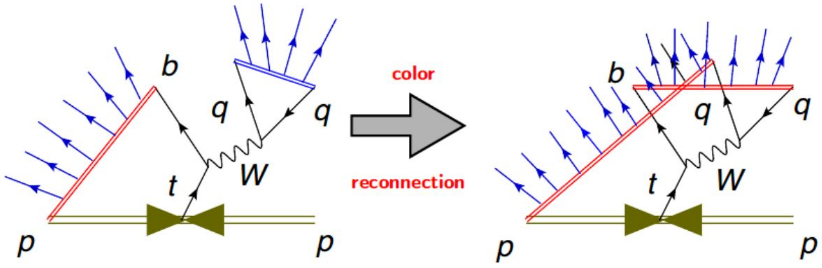


Measurement of colour reconnection in ttbar events

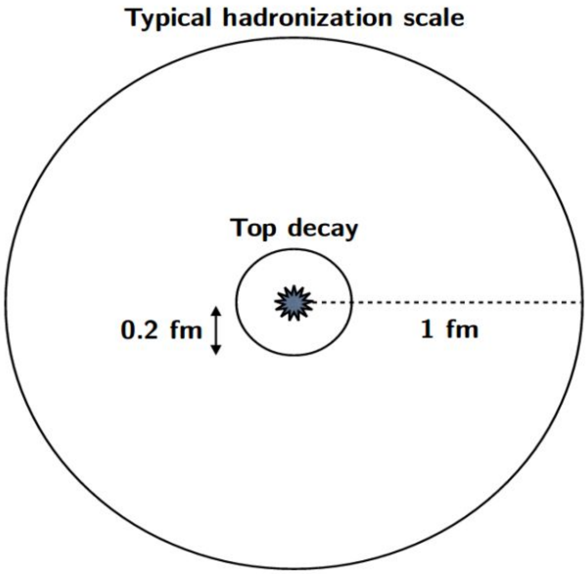
Available soon

See the YSF talk from Shayma

Colour reconnection - introduction

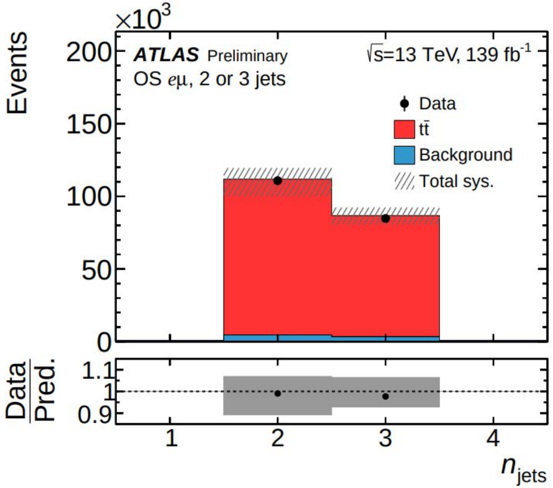


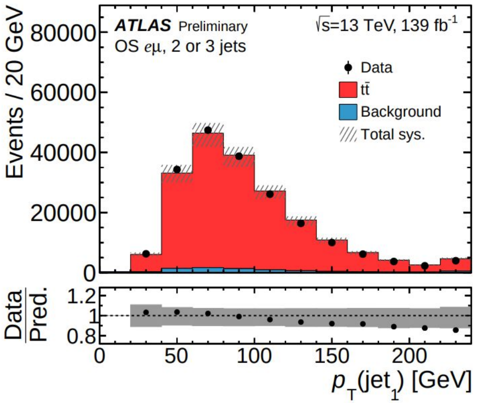
- Important phenomenon for MC generators
- Not simulated from first principles
  - MC: leading-colour approximation
  - Different **colour reconnection models**
    - Mechanism for **re-assigning colour connections** between partons
    - Less energy to create particles
      - Larger energy of particles
      - Different particle multiplicities
  - Pythia, Herwig and Sherpa have different models
  - **Models need to be constrained from data**
- Top quarks
  - Current models include CR before top decays
  - Short lifetime -> **top quarks can interact with final state colour fields**
  - E.g. top mass uncertainty from CR: 0.2-0.4 (8 TeV l+jets)



Colour reconnection - measurement

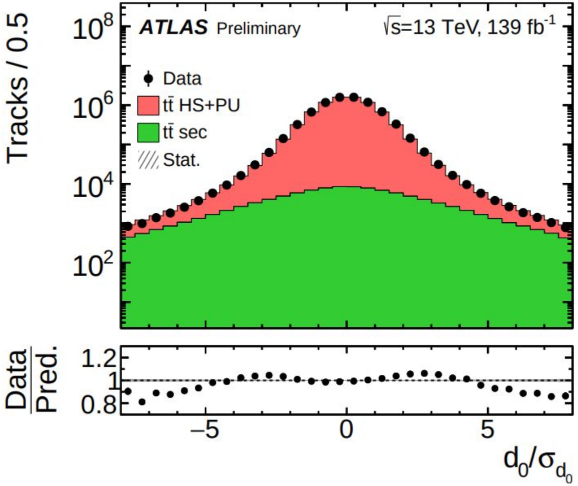
- **Selection**
  - emu ttbar events
  - Two b-tagged jets @70%
  - Tight track multiplicity: < 100 tracks
- **Strategy**
  - **Unfolding to particle level (IBU)**
  - Sensitive distributions
    - Charged-particle multiplicity - n_{ch}
    - Scalar sum of charged particle p_T
    - Scalar sum of charged particle p_T in n_{ch} bins
  - Objects
    - **Tracks outside of jet**
      - Both on detector and particle level
      - Identified to be most sensitive

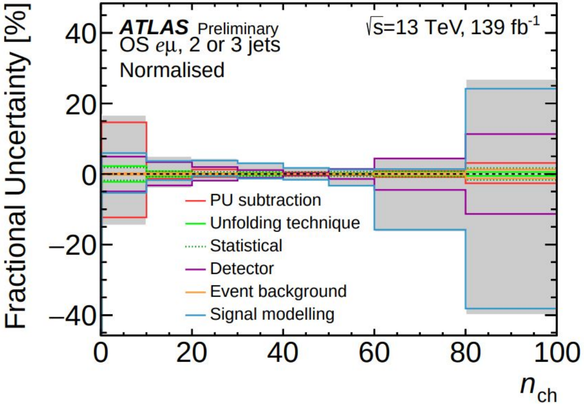


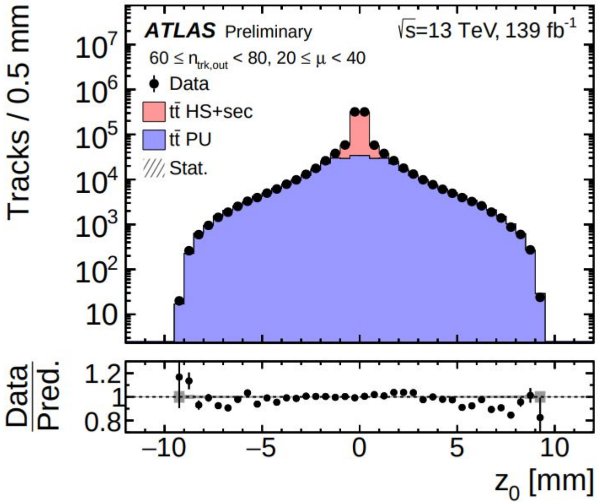


Colour reconnection - backgrounds

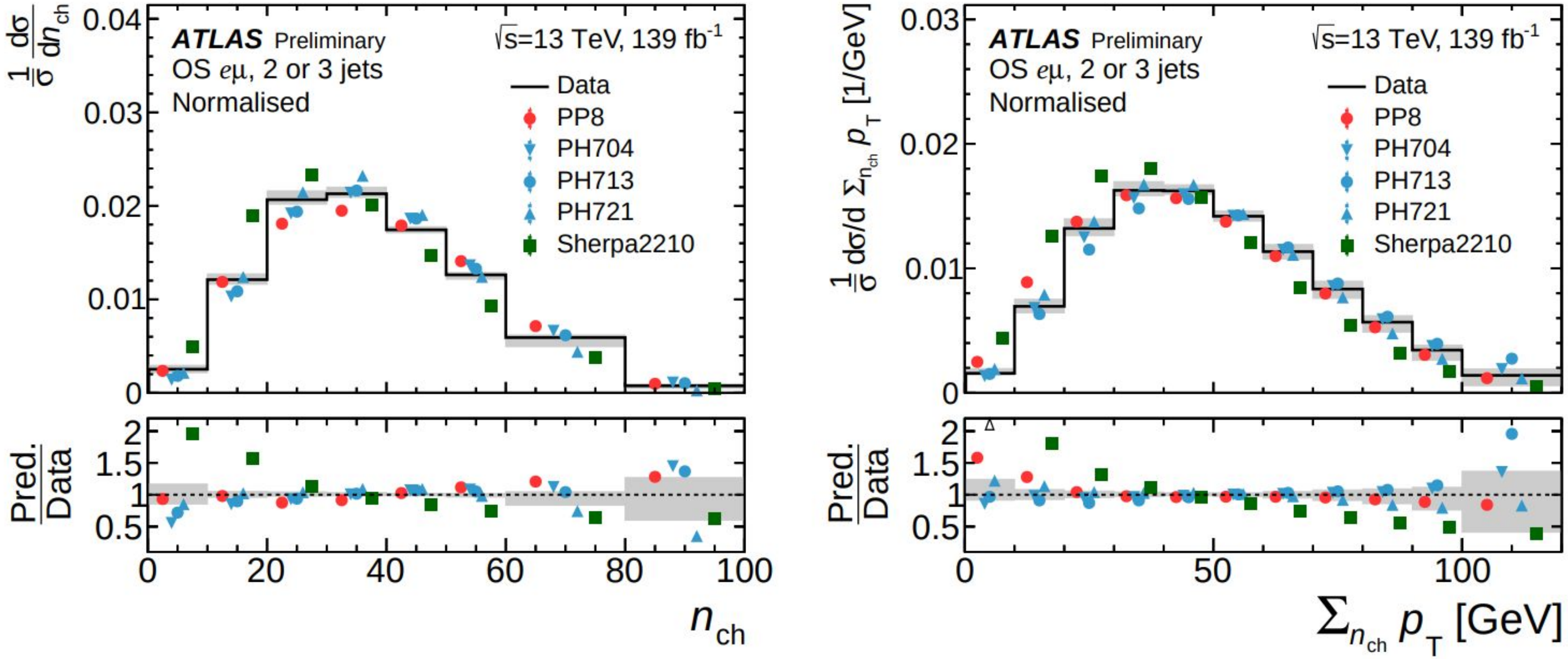
- Standard event-based backgrounds estimated
- **Track-based backgrounds**
  - Pile-up and sec. vertex subtracted stochastically
- **Correction to pileup simulation**
  - Based on impact parameter comparison in MC and data
  - A function of number of interactions and number of tracks
  - Range between 0.9 and 1.4
- **Track reconstruction corrections**
  - Correct for efficiency in track reconstruction





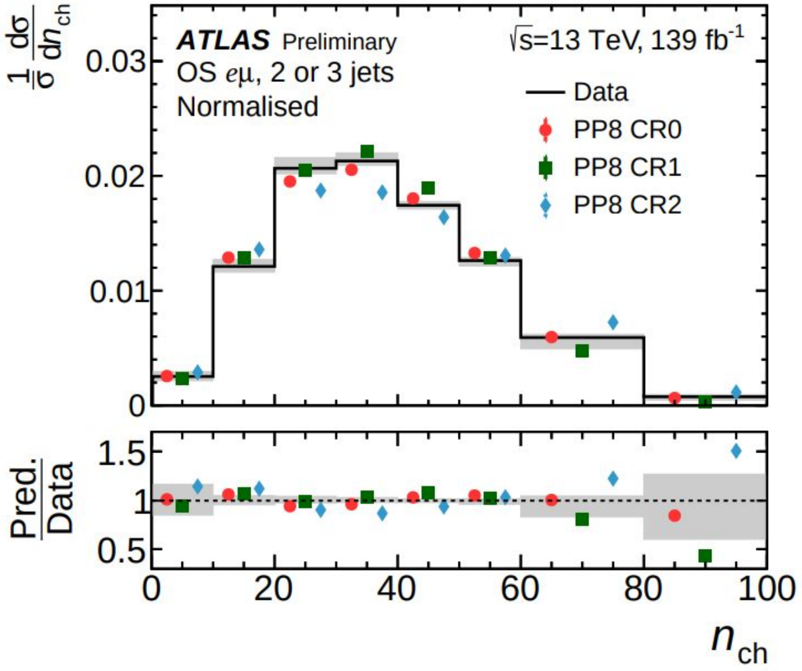


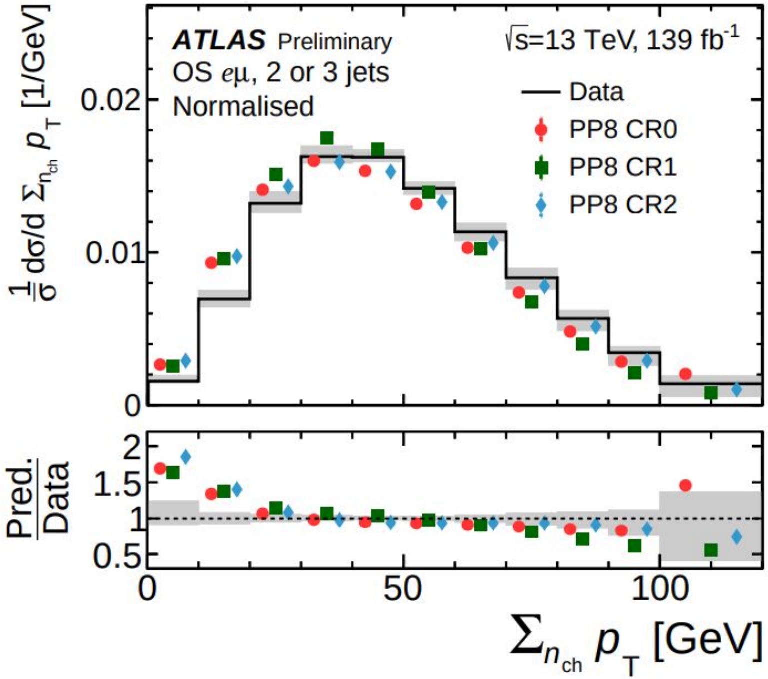
Colour reconnection - results 1



- **Reasonable agreement for Pythia and Herwig**
- **Sherpa predicts softer spectrum and more low multiplicities than seen in data**
    - **Sherpa CR model assumes no colour reconnection**

Colour reconnection - results 2





- CR0 model agrees better, **none of the models describe data perfectly**
- **Important to check Underlying Event modelling simultaneously with CR models**

Measurement of b-fragmentation in ttbar events

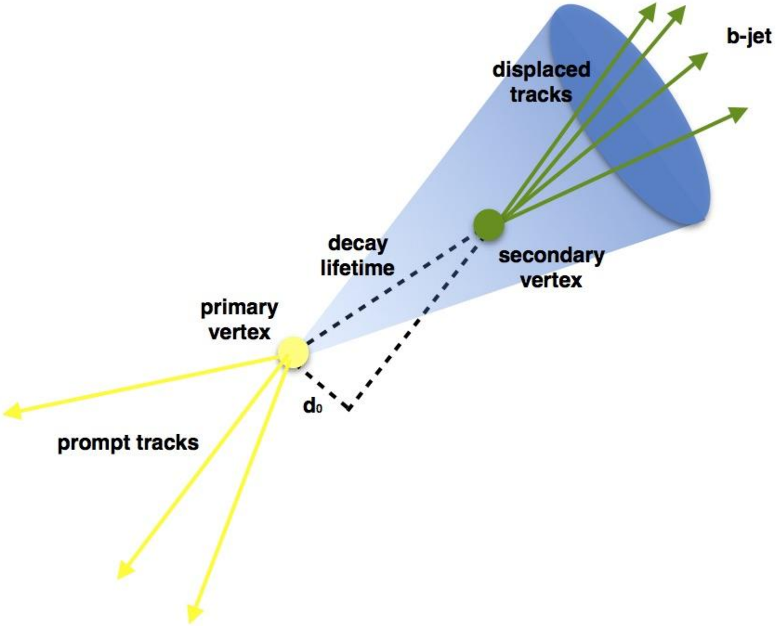
Phys. Rev. D 106 (2022) 032008

b-fragmentation - introduction

- Important for many processes
    - E.g. **top mass using soft muons**
- b-jets provide clear experimental signature - identified via secondary vertices
- Using ttbar emu events to measure b-fragmentation
    - Cannot access quarks - **using b-hadrons**
    - **Only charged particles**/tracks used for b-jets
    - **Lepton p_T** as a proxy for top quark p_T
        - Initial energy not known, unlike in LEP
- Different observables sensitive to b-fragmentation

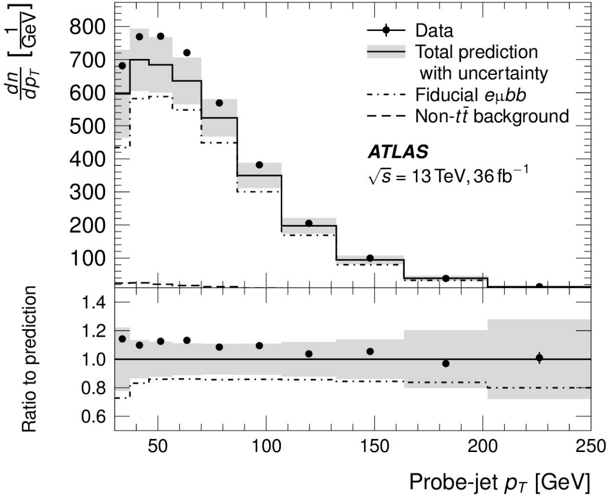
$$z^{ch}_{T,b} = \frac{p^{ch}_{T,b}}{p^{ch}_{T,jet}} \quad z^{ch}_{L,b} = \frac{\vec{p}^{\,ch}_{b} \cdot \vec{p}^{\,ch}_{jet}}{|p^{ch}_{jet}|^2} \quad \rho = \frac{2p^{ch}_{T,b}}{p^{e}_{T} + p^{\mu}_{T}}$$

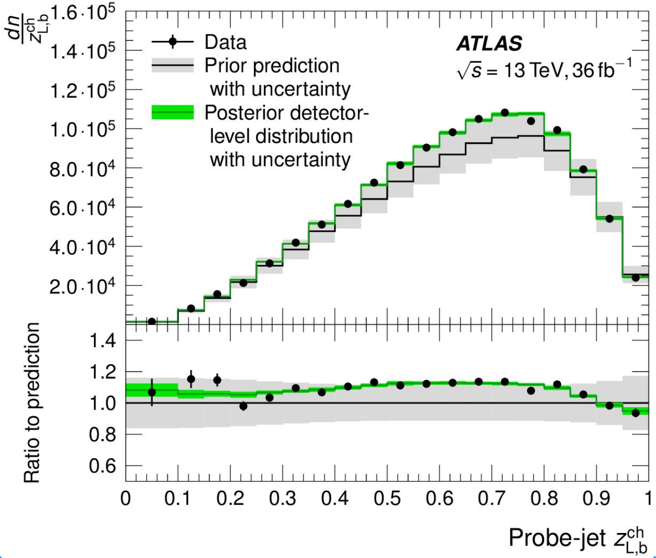
- Unfolding to stable particle (tracks) level
    - Using FBU

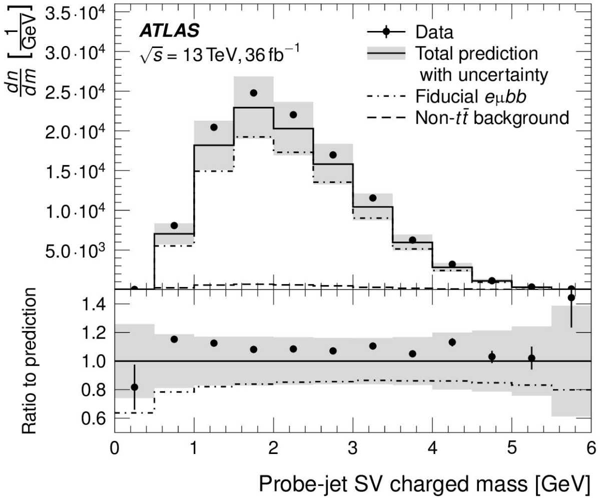


b-fragmentation - selection

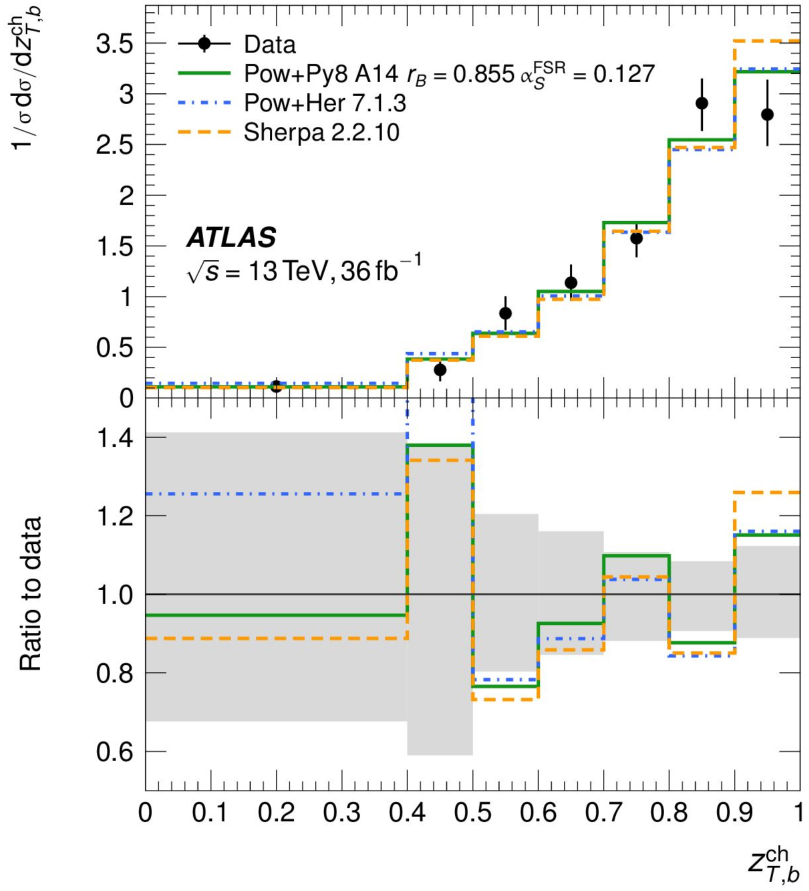
- Electron and muon OS pair, 25(27) GeV
- Exactly two jets, 25 GeV, separated by Delta R > 0.5
- At least one b-tagged jet @70% WP
- **b-hadron reconstruction**
  - Tight tracks matched to jet
  - **Tracks matched to a secondary vertex**

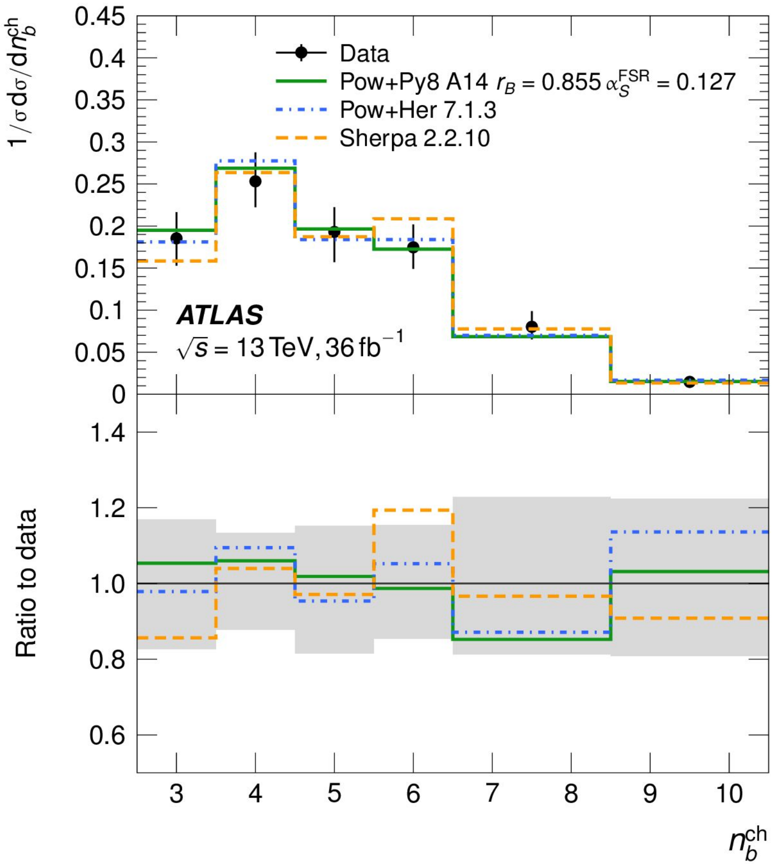




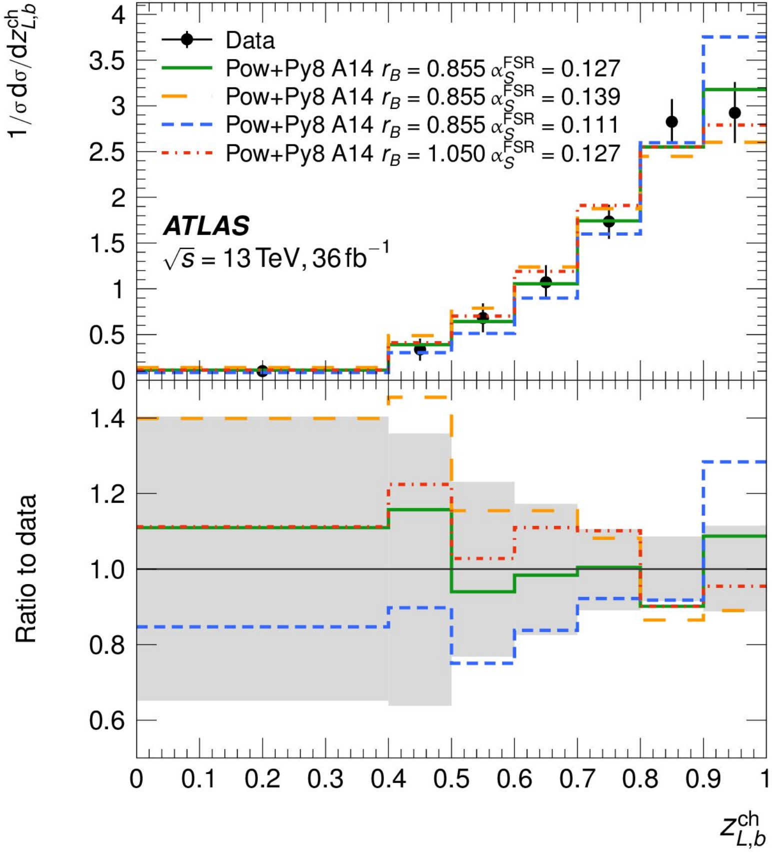


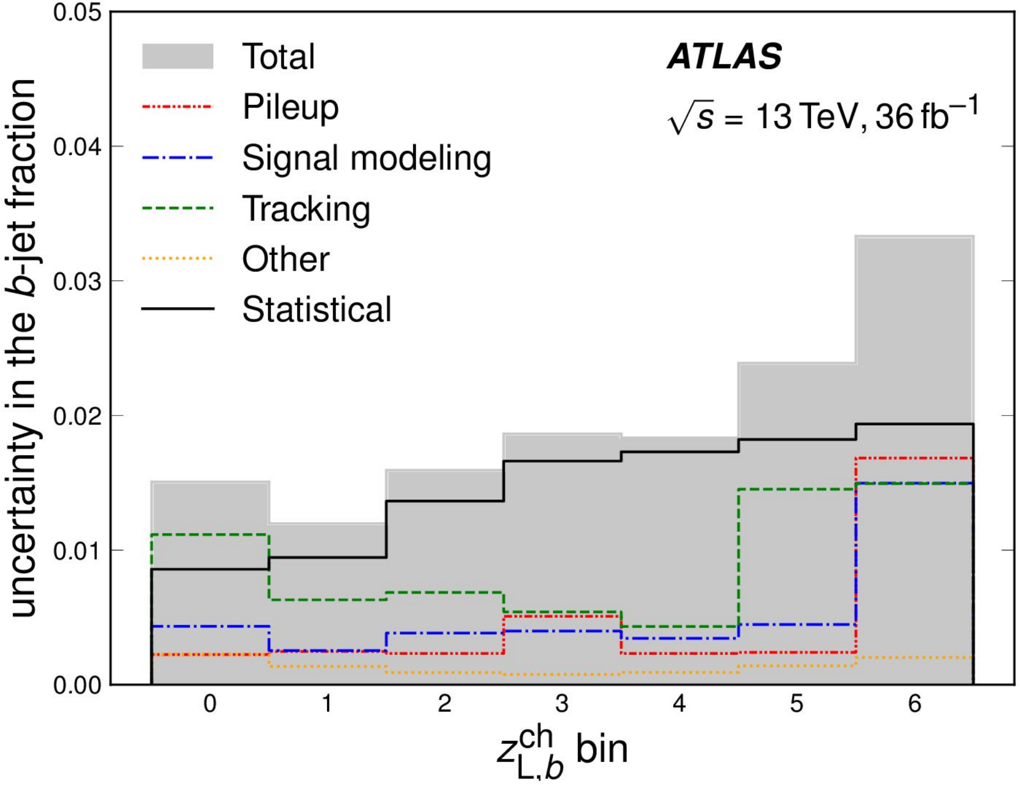
b-fragmentation - results





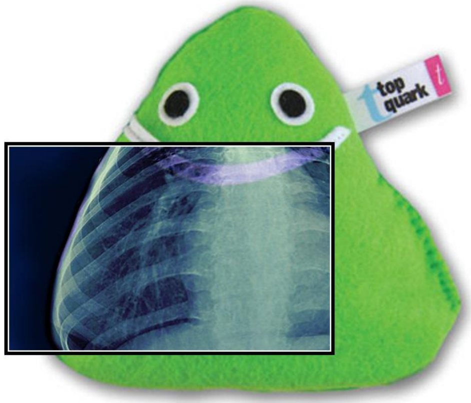
b-fragmentation - results 2





Reasonable agreement between data and prediction

Summary



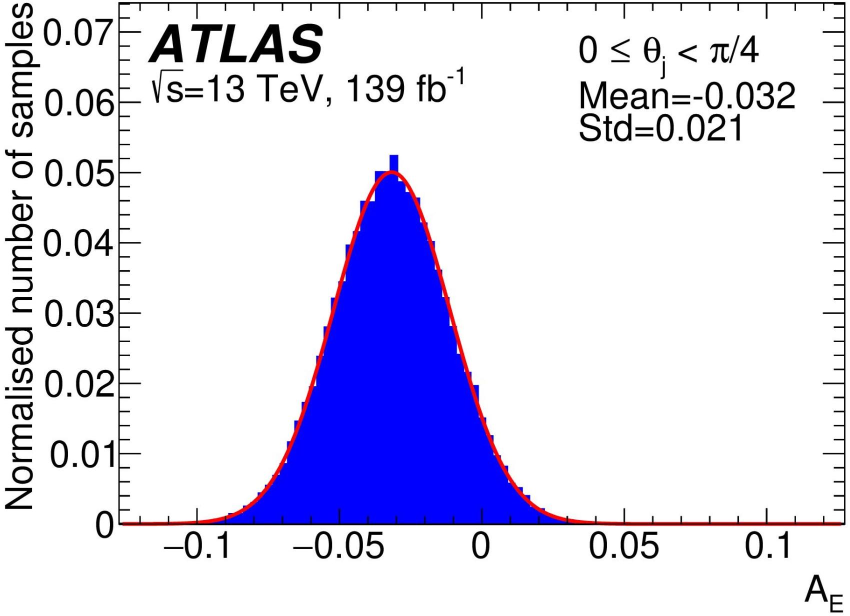
- Large LHC dataset allows to measure top-quarks properties precisely
- **Energy and asymmetry measurements in ttbar**
    - Still **statistically limited!**
        - Run 3 dataset can significantly improve the precision
    - **EFT interpretations**
- **Colour reconnection and b-fragmentation**
    - Help with better understanding of the MC generators
    - **Possibility to improve future hadronisation models**
        - Crucial for improving modelling uncertainties that limit many measurements

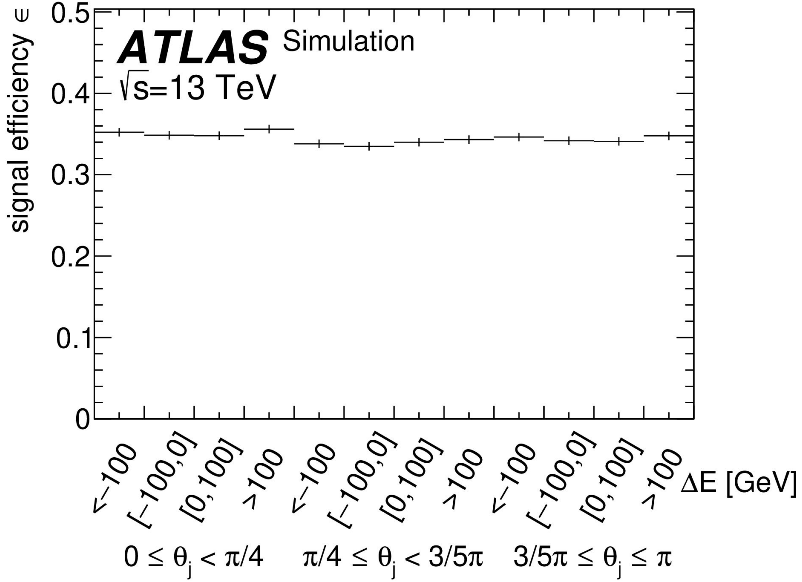
Check the YSF talks about charge asymmetry and colour reconnection later today!

BACKUP

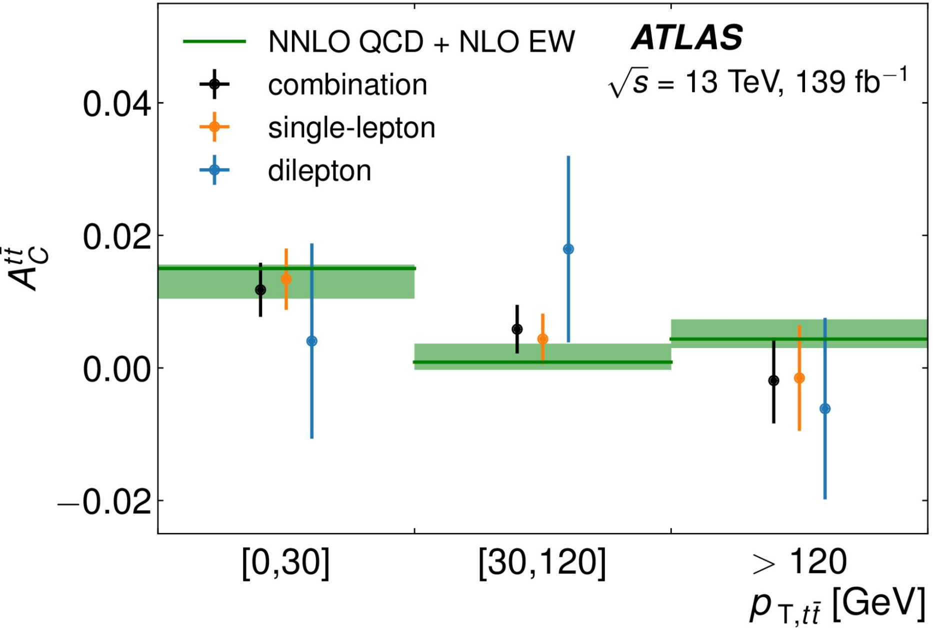
Energy asymmetry

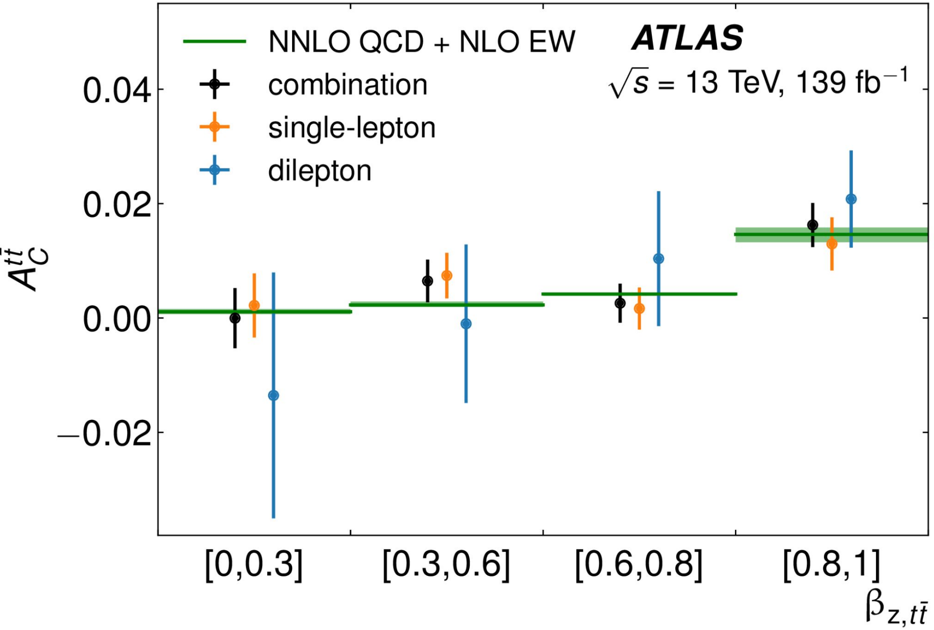
$C\,(\text{TeV}/\Lambda)^2$	$A_E\ (\Lambda^{-4})$ 68% CL	$A_E\ (\Lambda^{-4})$ 95% CL	$A_E\ (\Lambda^{-2})$ 68% CL	$A_E\ (\Lambda^{-2})$ 95% CL
C_{Qq}^{11}	$[-0.41, 0.47]$	$[-0.65, 0.67]$	$[-0.68, 4.06]$	$[-3.36, 6.16]$
C_{Qq}^{18}	$[-0.87, 1.24]$	$[-1.72, 2.10]$	$[-1.26, 4.76]$	$[-3.24, 9.64]$
C_{tq}^{1}	$[-0.43, 0.52]$	$[-0.69, 0.75]$	$[-0.60, 5.76]$	$[-3.42, 9.36]$
C_{tq}^{8}	$[-1.41, 0.84]$	$[-2.01, 1.43]$	$[-1.86, 1.70]$	$[-3.30, 3.98]$
C_{tu}^{1}	$[-0.50, 0.56]$	$[-0.78, 0.81]$	$[-0.96, 5.82]$	$[-4.72, 8.88]$
C_{tu}^{8}	$[-1.00, 1.01]$	$[-1.71, 1.56]$	$[-1.30, 2.52]$	$[-3.02, 4.66]$



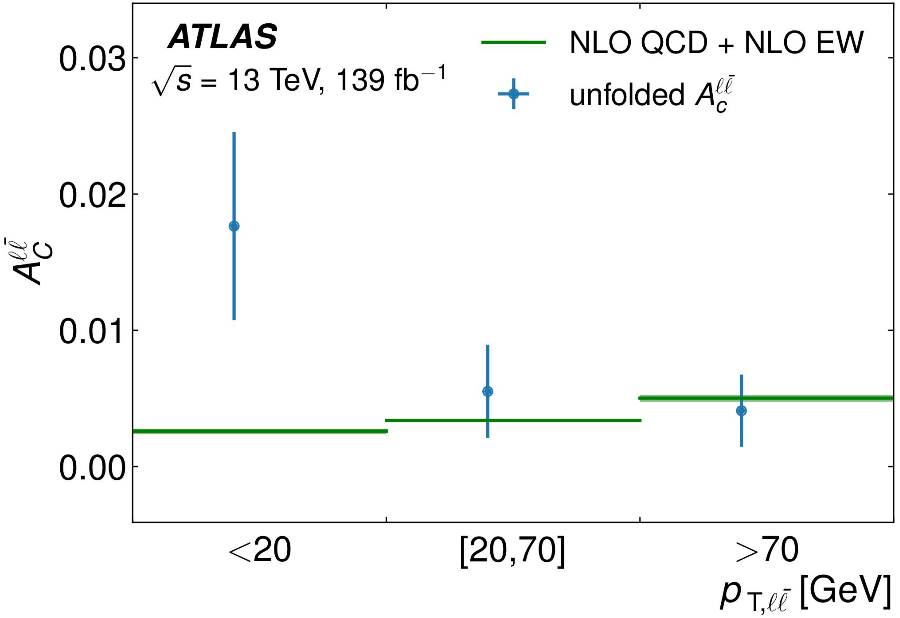


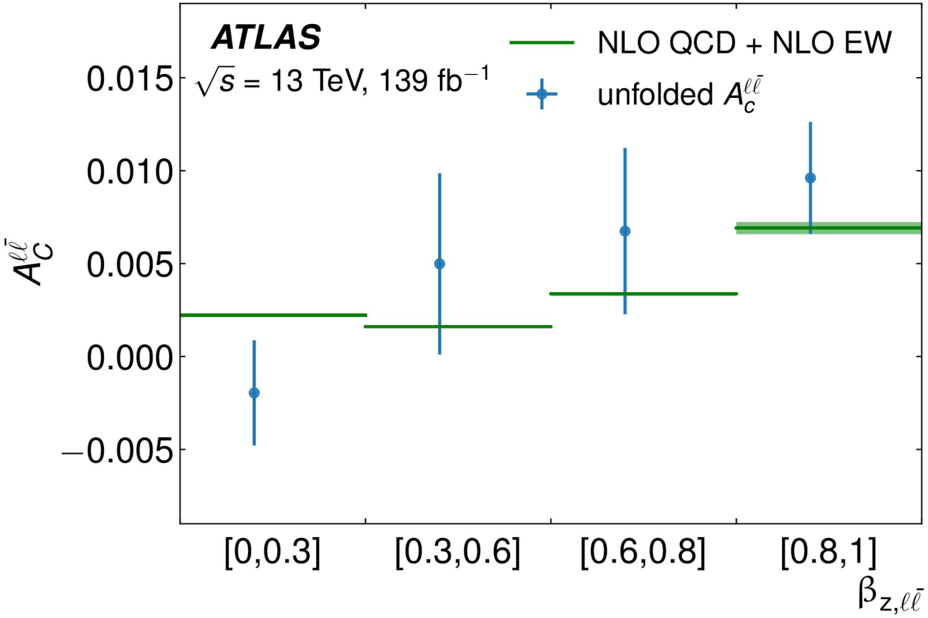
Charge asymmetry ttbar



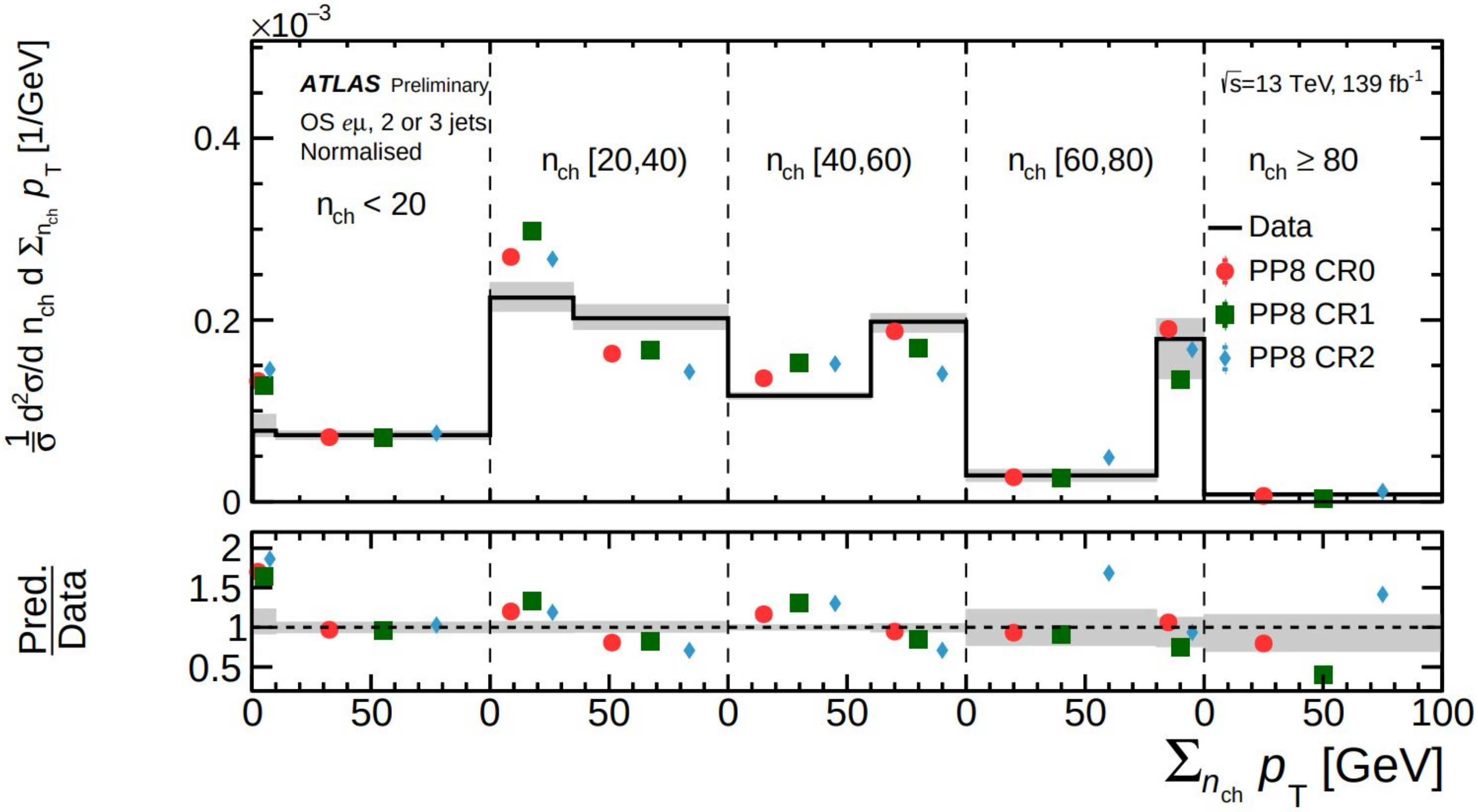


Charge asymmetry ttbar





Colour reconnection



b-fragmentation

Generator configuration	$z^{\mathrm{ch}}_{\mathrm{T},b}$ p-value	$z^{\mathrm{ch}}_{\mathrm{L},b}$ p-value	ρ p-value	n^{ch}_{b} p-value
POWHEG+PYTHIA8 A14	0.24	0.85	0.19	0.98
POWHEG+PYTHIA8 A14 $\alpha_s^{\mathrm{FSR}} = 0.139$	0.09	0.33	0.28	0.98
POWHEG+PYTHIA8 A14 $\alpha_s^{\mathrm{FSR}} = 0.111$	0.04	0.32	0.07	0.98
POWHEG+PYTHIA8 A14 $r_B = 1.05$	0.09	0.48	0.28	0.98
aMC@NLO+PYTHIA 8 A14	0.29	0.92	0.21	0.98
POWHEG+PYTHIA8 Monash	0.13	0.57	0.32	0.97
POWHEG+PYTHIA8 Monash Peterson	0.01	0.02	0.10	0.96
POWHEG+HERWIG 7.0.4	0.16	0.46	0.11	0.98
POWHEG+HERWIG 7.1.3	0.23	0.71	0.16	0.96
SHERPA 2.2.1	0.08	0.42	0.53	0.01
SHERPA 2.2.8 ($Z + b\bar{b}$ tune)	0.0005	0.005	0.19	0.48
SHERPA 2.2.8	0.10	0.47	0.11	0.61
SHERPA 2.2.10	0.07	0.53	0.07	0.40