Hadronic Event Shape Variables in *pp* Collisions at $\sqrt{s} = 13$ TeV

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Outline

- Introduction : QCD & Event Shape Variables
- Data Set and Event Selection
  - Triggers used
  - Phase space selection
  - Basic Distributions
- Unfolding
- Systematic Uncertainty
- Event Shape Variables at the Particle Level
- Results and Conclusion

- Event shape variables (ESV) are defined as ratios of momenta of hadrons or their combinations:
  - sensitive to the energy flow in hadronic final states;
  - important for understanding many perturbative and nonperturbative aspects of QCD, details of parton radiation and hadronization etc.
  - important for validation of Monte Carlo (MC) event generators which use different models for describing these aspects
- Robust and safe from collinear and infrared divergences.
- Many expt. uncertainties are reduced in their distributions.
- May be exploited to determine α_s, search for new physics.

Introduction

- Important suggestion - the theoretical uncertainties are better controlled if the average p_T of the two leading jets is used instead of their individual values.

$$H_{T,2} = (p_{T,jet1} + p_{T,jet2})/2$$

is used instead of p_T of the leading jet for demarcating the phase space of the events.

- This analysis measures four ESVs using jets as inputs - complement of transverse thrust ($\tau_{\perp,C}$), total jet mass (ρ_{tot}), total transverse jet mass (ρ^T_{tot}) and total jet broadening (B_{tot}).

Introduction: Complement of Transverse Thrust

The event thrust in the transverse plane is defined as

$$T_{\perp,C} \equiv \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \vec{n}_T|}{\sum_i p_{T,i}} \tag{1}$$

- $p_{T,i}$ is the transverse momentum of the ith jet.
- $\vec{n}_T$, is the transverse unit vector which maximizes the projection, is the transverse thrust axis.
- C denotes that the ESV is evaluated using objects in the central region of the detector.

$T_{\perp,C}$ is maximal for back-to-back two jet events. Other ESVs studied in this analysis have higher values for multi-jet, spherical events. To keep parity, the complement of $T_{\perp,C}$ is used:

$$\tau_{\perp,C} \equiv 1 - T_{\perp,C}. \tag{2}$$

In a single event one can separate the central region into two parts:
Upper part (U): all particles in U have $\overrightarrow{p_T}.\vec{n}_T > 0$.
Lower part (L): all particles in L have $\overrightarrow{p_T}.\vec{n}_T < 0$.
The pseudorapidities and the azimuthal angles of the axes for the two regions (X = U, L) are

$$\eta_X \equiv \frac{\sum_{i\in\mathcal{C}_X} p_{T,i}\eta_i}{\sum_{i\in\mathcal{C}_X} p_{T,i}}, \quad \phi_X \equiv \frac{\sum_{i\in\mathcal{C}_X} p_{T,i}\phi_i}{\sum_{i\in\mathcal{C}_X} p_{T,i}}$$

The jet broadening variable for each region is defined as

$$B_X \equiv \frac{1}{2\,P_T} \sum_{i\in\mathcal{C}_X} p_{T,i}\sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}\ , \qquad (3)$$

where P_T is the scalar sum of the p_T of all the input objects.
Total jet broadening is then defined as

$$B_{tot} \equiv B_U + B_L. \qquad (4)$$

Event Shape Variables: Jet Masses

The normalized squared invariant mass of the jets in the upper and lower regions of the event:

$$\rho_X \equiv \frac{M_X^2}{P^2}$$

- M_X: invariant mass of the constituents of the jets in X,
- P: scalar sum of $\vec{p}$ of all constituents on both sides.

The total jet mass is:

$$\rho_{tot} \equiv \rho_U + \rho_L. \tag{5}$$

The corresponding quantity in the transverse plane, total transverse jet mass ρ^T_{tot} is similarly calculated using transverse momenta.

- The four ESVs are designed to have higher values for multi-jet, spherical events and lower values for back-to-back two-jet events.
- Complement of Transverse Thrust ($\tau_{\perp,C}$) is more dependent on the hard scattering process - sensitive to the modelling of two-jet and multi-jet topologies. Here 'multijet' refers to 'more-than-two jets'.
- In the limit of a perfectly balanced two-jet event, $\tau_{\perp,C} = 0$, while in isotropic, multi-jet events $\tau_{\perp,C} = (1 - 2/\pi)$.
- Jet masses ρ_{tot}, ρ^{T}_{tot} and jet broadening B_{tot} depend more on the details of QCD (fragmentation, hadronization) which control the evolution of the partons into hadrons.

Together the four ESVs can test models of QCD implemented in the different MC event generators.

Event Selection

- Reconstruction with anti-kt 4: PFchs Jets
- Jets are selected with $p_T > 30$ GeV/c and $|\eta| < 2.4$, i.e., within the coverage of the tracker.
- An event must have at least two jets.
- The jets with highest and second highest p_T are selected.
- A third jet is selected from the other jets with the highest recoil term. The recoil term for jet k is

$$\mathcal{R}_{\perp,k} = \sqrt{(\sum Px)^2 + (\sum Py)^2}/(\sum P_T)$$

An iterative approach, based on D' Agostini' theorem (Bayes) is used as default unfolding method, correct to particle level.

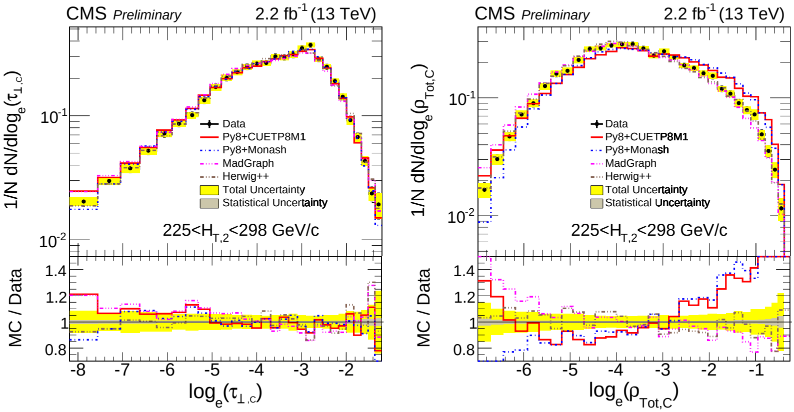
Experimental Uncertainties

- JES: 26 JES uncertainty sources are considered from Summer15_25nsV5_DATA_Uncertainty_AK4PFchs.txt file
- JER: Varied resolution scaling factor as recommended by JetMet
- PDF: To estimate the uncertainty due to PDF, 100 sets of NNPDF3 replicas used
- Unfolding:
  - Detector level distribution of Pythia8 is unfolded with MadGraph response matrix and compared with detector level distribution of Pythia8. The difference between particle level and unfolded distributions contributes to the systematic uncertainty.
  - This is repeated for MadGraph with Pythia8 and HERWIG++ response matrices and for HERWIG++ with Pythia8 and MadGraph response matrices.
  - Out of these six differences for each bin the largest is taken as the systematic uncertainty.

Result

Comparison of particle level distributions in data and MC:

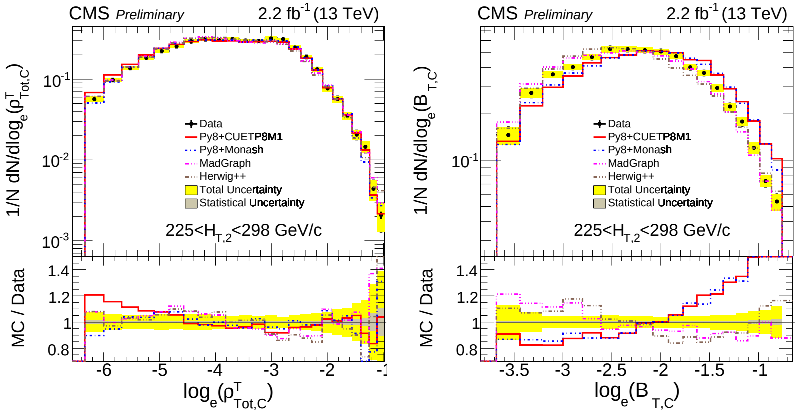
$\tau_{\perp,C}$, ρ_{tot}, $225 < H_{T,2} < 298$ GeV/c



MadGraph and Herwig++ good agreement with data for ρ_{tot}, but both tunes of Pythia8 CUETP8M1 and MONASH are not

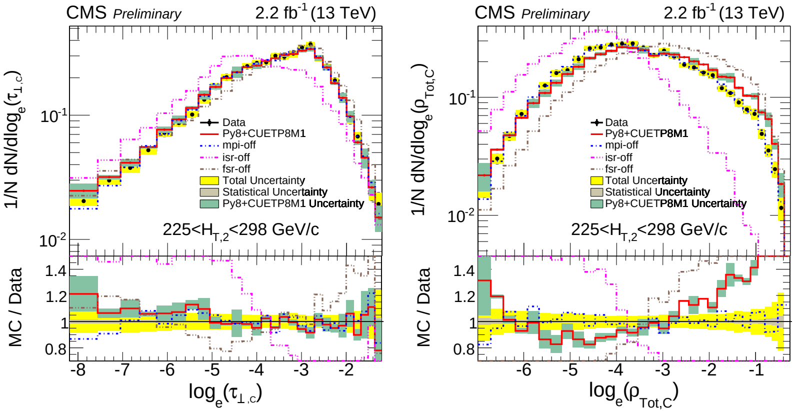
Comparison of particle level distributions in data and MC:

ρ^T_{tot}, B_{tot}, $225 < H_{T,2} < 298$ GeV/c



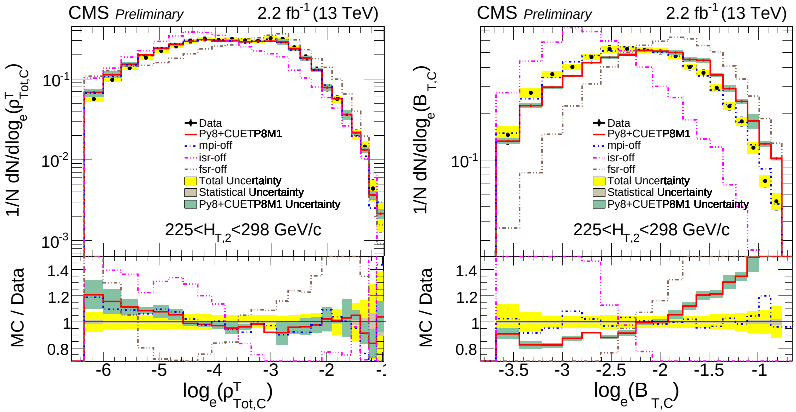
Treatment of the energy flow in the transverse plane is done reasonably well by both Pythia8 CUETP8M1 and MONASH tunes

The effect of switching OFF MPI, ISR and FSR



ISR is very large effect for both ESVs and FSR is small for ρ_{tot}

The effect of switching OFF MPI, ISR and FSR



For 3D-plane variables the ISR widely effect, we can find the better ISR, FSR model for pythia8

Summary

- Four event shape variables, complement of transverse thrust ($\tau_{\perp,C}$), total jet mass (ρ_{tot}), total transverse jet mass (ρ^{T}_{tot}) and total jet broadening (B_{tot}) are measured in pp collisions at $\sqrt{s} = 13$ TeV.
- Pythia8 : CUETP8M1 and MONASH tunes of agree well among themselves as well as data for $\tau_{\perp,C}$ and ρ^{T}_{tot}. overestimates for ρ_{tot} and B_{tot}.
  Treatment of the energy flow in the transverse plane is done reasonably well by both
- Herwig++ : Good agreement with data for the four ESVs; better than Pythia8 CUETP8M1 in predicting ρ_{tot} and B_{tot}; agreement with data is stable for the higher $H_{T,2}$ bins.
- MadGraph : Better than Pythia8 CUETP8M1; comparable with Pythia8 MONASH tune

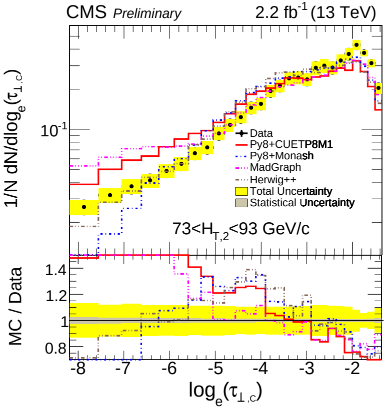
Summary

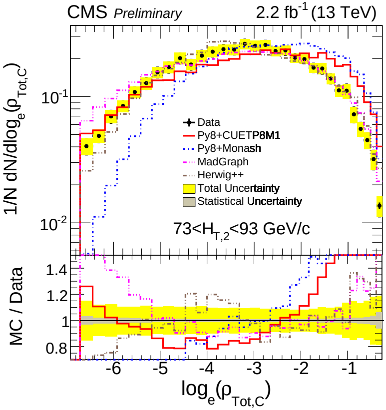
- Correct understanding of initial state radiation, final state radiation and MPI are important aspects for the QCD models. Pythia8 CUETP8M1, the popular generator is studied for these aspects.
- The effect of switching off ISR is very large shifting the ESVs to lower values, i.e reducing the spherical multi-jet nature of the events
- Effect of switching off FSR is relatively small while that of MPI is even smaller.

Back Up Slides

Comparison of unfolded data and MC: $\tau_{\perp,C}$ and ρ_{tot}

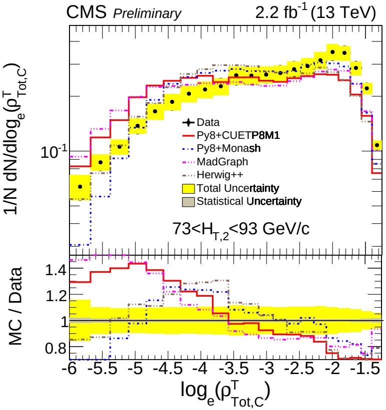
$73 < H_{T,2} < 93$ GeV/c

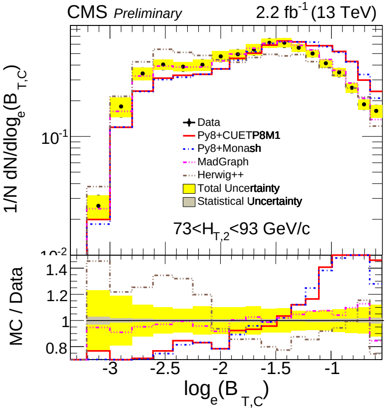




Comparison of unfolded data and MC: ρ^T_{tot} and B_{tot}

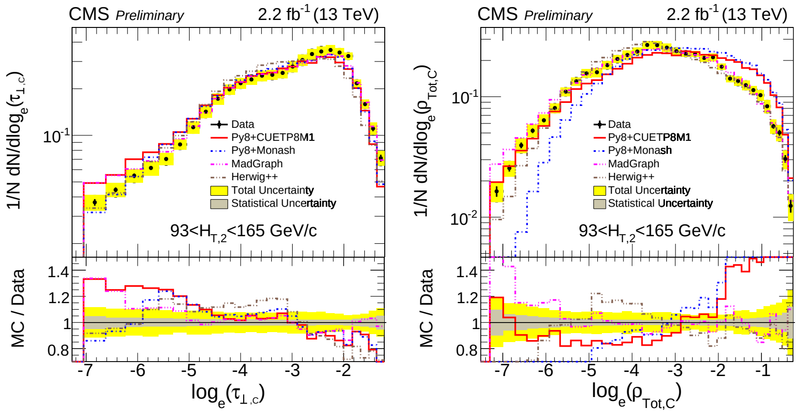
$$73 < H_{T,2} < 93 \text{ GeV}/c$$





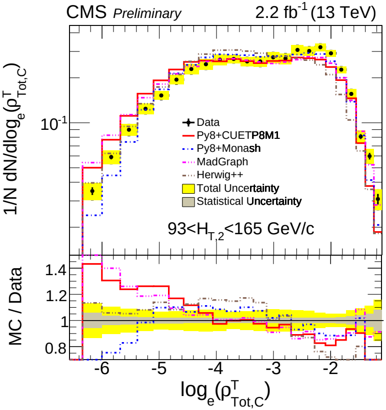
Comparison of unfolded data and MC: $\tau_{\perp,C}$ and ρ_{tot}

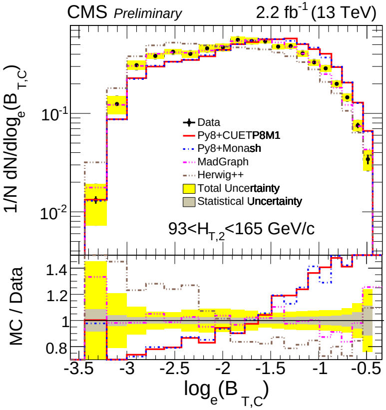
$$93 < H_{T,2} < 165 \text{ GeV/c}$$



Comparison of unfolded data and MC: ρ^{T}_{tot} and B_{tot}

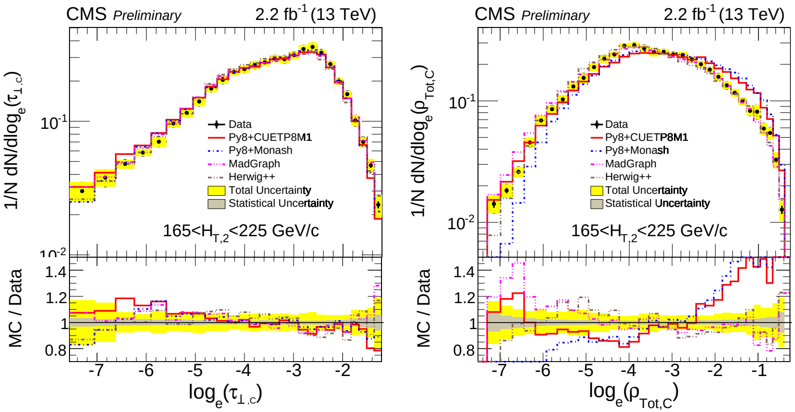
$$93 < H_{T,2} < 165\ \mathrm{GeV/c}$$





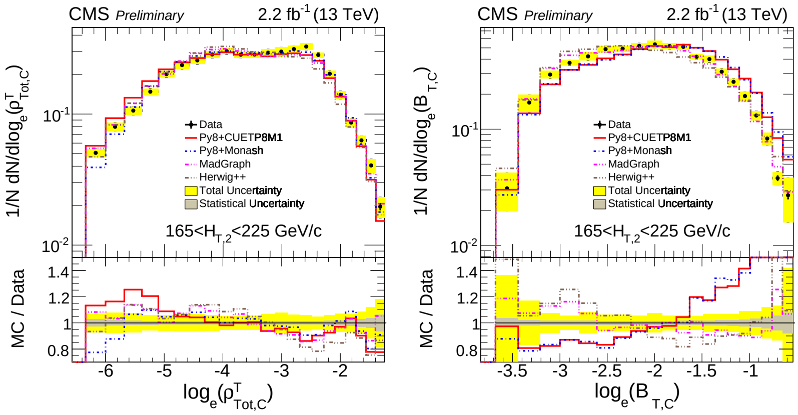
Comparison of unfolded data and MC: $\tau_{\perp,C}$ and ρ_{tot}

$$165 < H_{T,2} < 225 \text{ GeV/c}$$



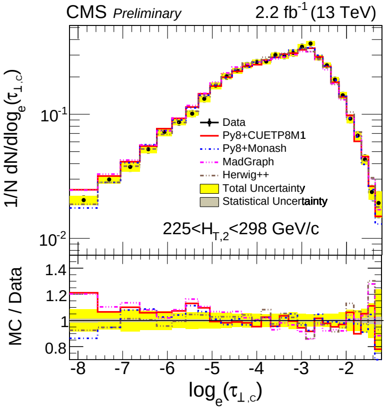
Comparison of unfolded data and MC: ρ^T_{tot} and B_{tot}

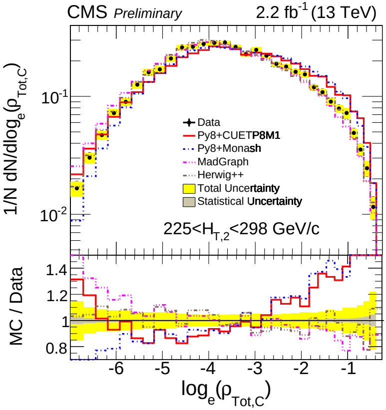
$$165 < H_{T,2} < 225 \text{ GeV/c}$$



Comparison of unfolded data and MC: $\tau_{\perp,C}$ and ρ_{tot}

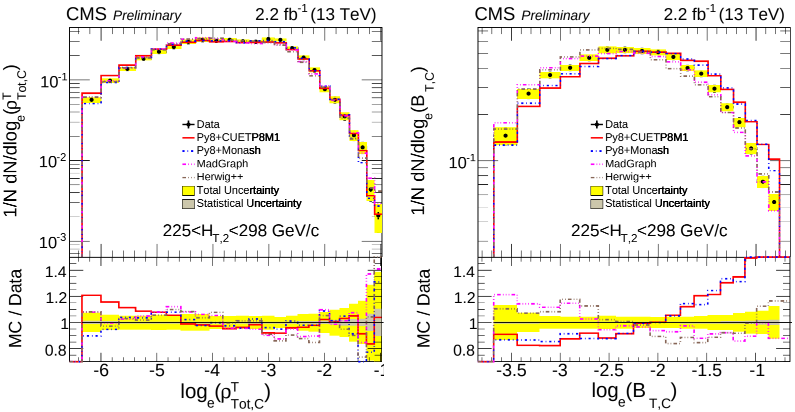
$225 < H_{T,2} < 298$ GeV/c



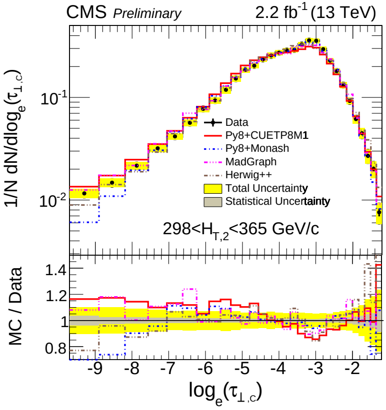


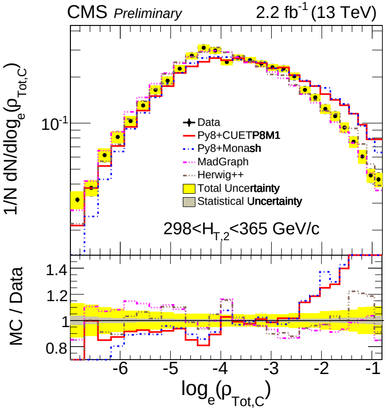
Comparison of unfolded data and MC: ρ^T_{tot} and B_{tot}

$225 < H_{T,2} < 298$ GeV/c



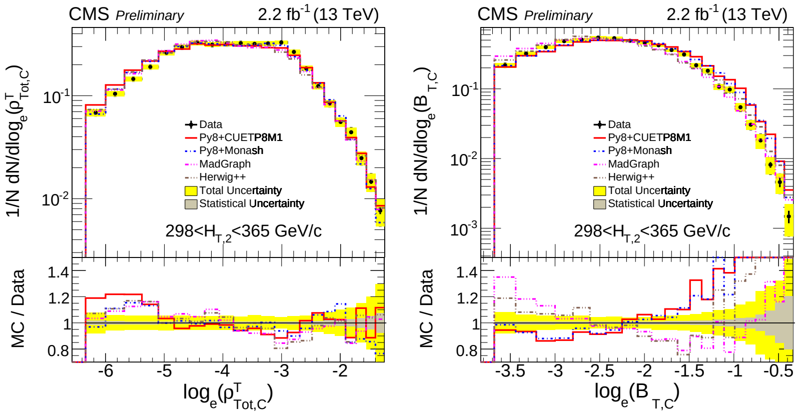
$298 < H_{T,2} < 365$ GeV/c





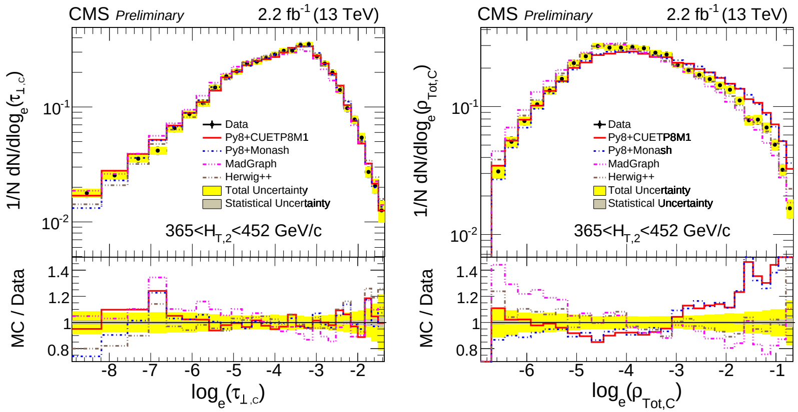
Comparison of unfolded data and MC: ρ^T_{tot} and B_{tot}

$$298 < H_{T,2} < 365 \text{ GeV/c}$$



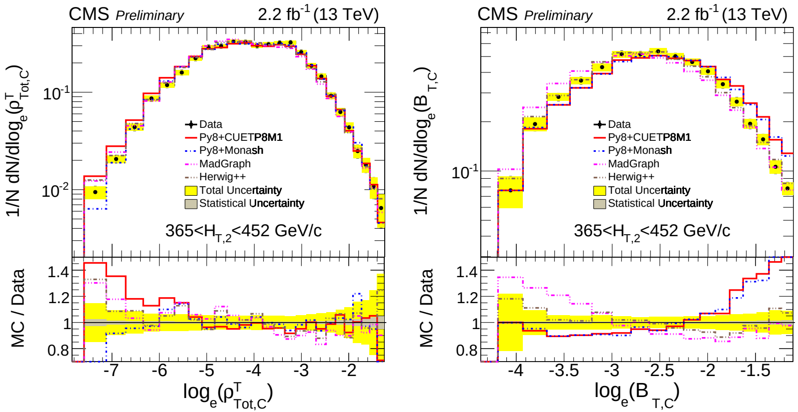
Comparison of unfolded data and MC: $\tau_{\perp,C}$ and ρ_{tot}

$$365 < H_{T,2} < 452 \text{ GeV/c}$$



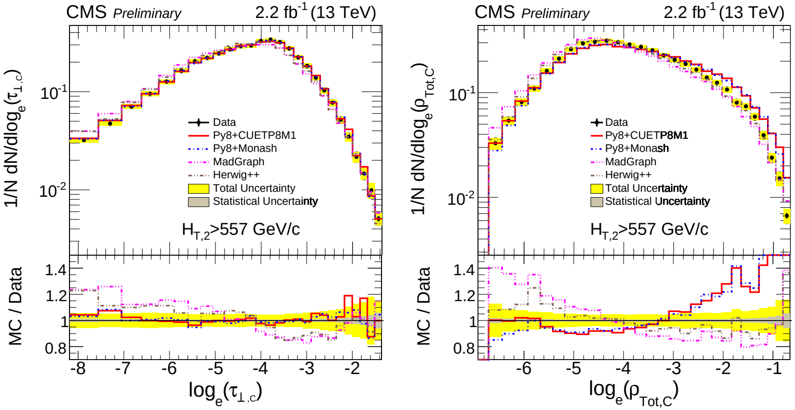
Comparison of unfolded data and MC: ρ^T_{tot} and B_{tot}

$$365 < H_{T,2} < 452 \text{ GeV/c}$$



Comparison of unfolded data and MC: $\tau_{\perp,C}$ and ρ_{tot}

$$H_{T,2} > 557 \text{ GeV/c}$$



Comparison of unfolded data and MC: ρ^T_{tot} and B_{tot}

$$H_{T,2} > 557 \text{ GeV}/c$$