Characterization of the underlying event in p-p collisions in CMS

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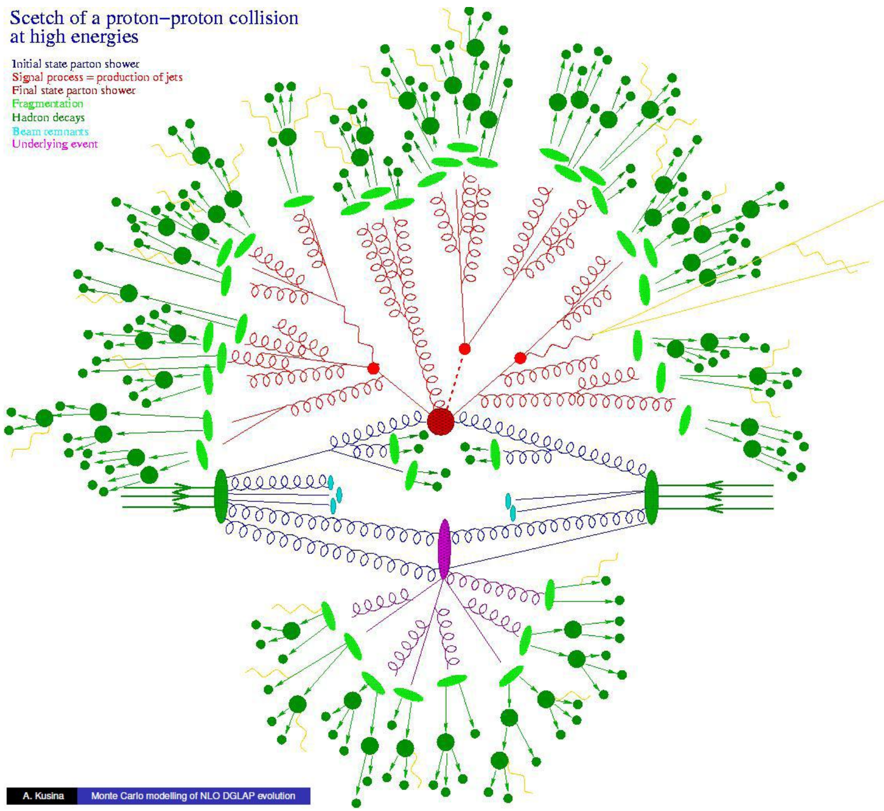
The underlying event in p-p collisions

- The underlying event (UE) is everything except the hard scattering:
  - ➔ Initial state radiation (ISR)
  - ➔ Final state radiation (FSR)
  - ➔ Multiple partonic interactions (MPI)
  - ➔ Beam remnants



- Its understanding is crucial for
  - ➔ precision measurements of the Standard Model processes
  - ➔ the search for new physics

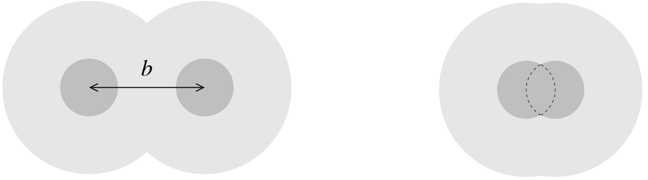
- But its dynamics are not well understood
  - ➔ soft & semi-hard interactions
  - ➔ can not be fully described with perturbative QCD
  - ➔ phenomenological models in MC involve parameters which **must be tuned using data**

- Use LHC data to constrain the existing UE models

Phenomenology of multi-parton interactions

- The number of interactions depends on
  - ➔ the p_T scale of the event
  - ➔ the centre-of-mass energy: increase of particle densities

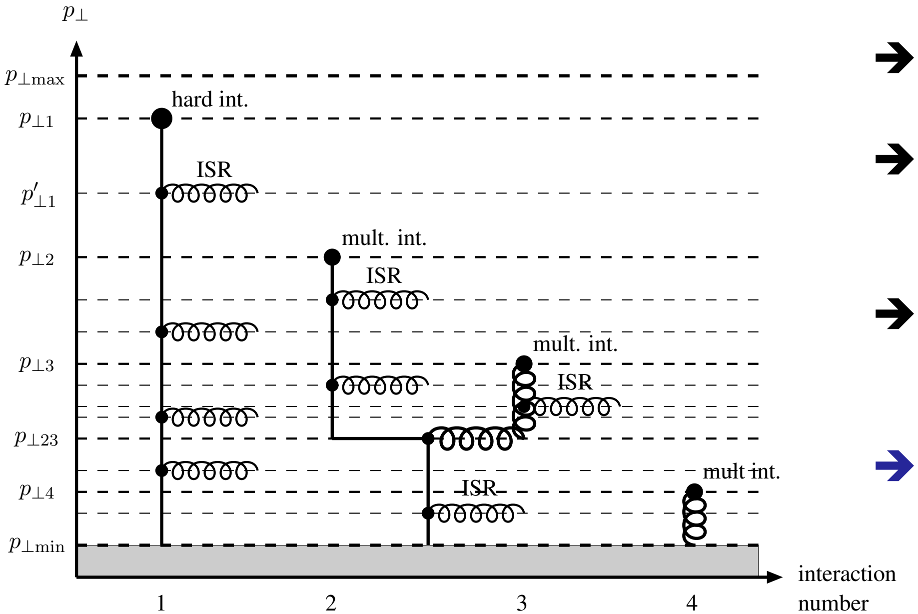
Minimum bias | Hard scale $\hat{p}_T$



Peripheral collision few MPI | Central collision many MPI

[Phys. Rev. D83 (2011) 054012]

- Introduce a MPI model to describe the soft interactions: extend hard scatter cross section to low p_T



[arXiv:hep-ph/0601012]

➔ But divergence: $1/\hat{p}_T^4$ if $\hat{p}_T \to 0$

➔ Introduce regularization:

$$1/\hat{p}_T^4 \to 1/(\hat{p}_T^2 + \hat{p}_{T,0}^2)^2$$

➔ Which is energy dependent:

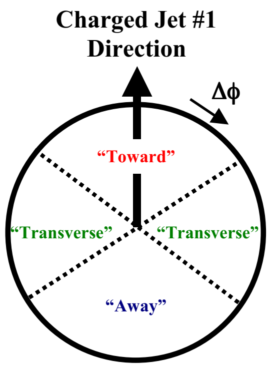
$$\hat{p}_{T,0}(\sqrt{s}) = \hat{p}_{T,0}(\sqrt{s_0}) \cdot (\sqrt{s}/\sqrt{s_0})^{\varepsilon}$$

➔ More MPI activity is predicted for smaller values of $\hat{p}_{T,0}$ and ε

Measurements of the UE

- Study the UE activity as a function of the hard scale of the event, and at different centre-of-mass energies

- Different possibilities
  ➔ <u>at central rapidities</u>



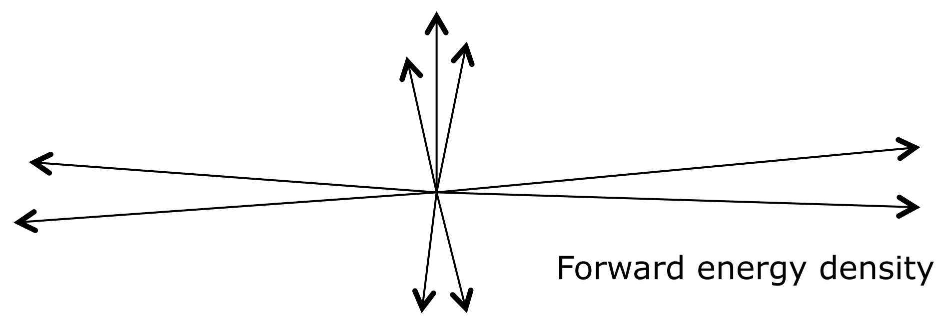
Hard scatter & UE are contained in same η range
➔ divide φ phase space to separate the UE from the hard scatter
➔ look at particle densities, energies in the transverse region
➔ As function of the hard scatter p_T scale
leading jets, **Drell-Yan**

[JHEP 09 (2011) 109]

➔ Use different observables: **jet area/median**
➔ no φ phase space division needed

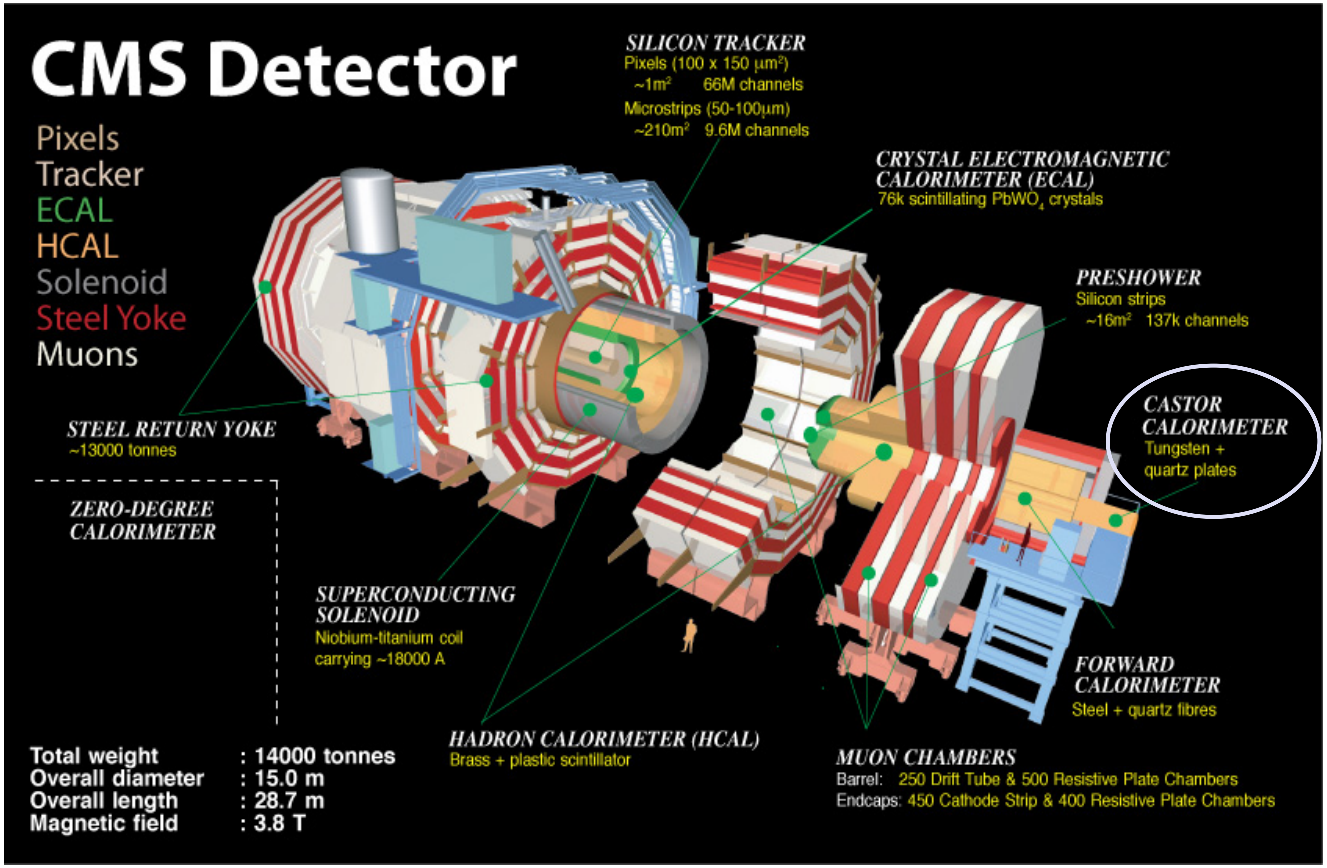
➔ **<u>at forward rapidities</u>**
UE observables separated with large Δη from hard scatter
No division of φ phase space
Possible to study UE φ structure

➔ look at forward energy densities as a function of central leading jets



Measurements with CMS detector at LHC

- CMS has a very good pseudorapidity coverage: $-6.6 < \eta < 5.2$

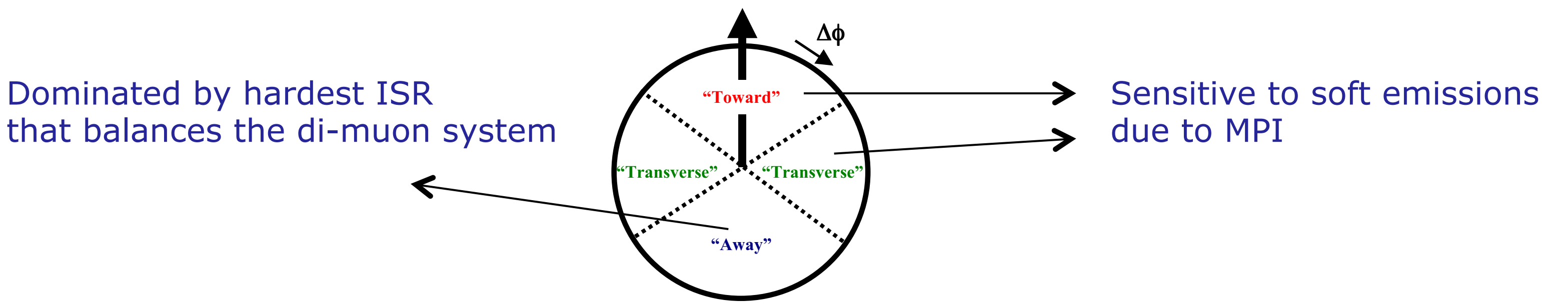


CASTOR calorimeter
$-6.6 < \eta < -5.2$
14m from IP
tungsten/quartz
Čerenkov detector
16 φ segmentations
14 modules in z

UE activity in the Drell-Yan process

- Complementary approach to existing central UE measurements
  ➔ clean separation of the hard interaction from the soft components
  ➔ Drell-Yan: experimentally clean, theory well understood
  ➔ absence of QCD FSR & low probability of photon brehmsstrahlung from muons

- Measure particle & energy densities in central region:
  ➔ average number of primary charged particles
  ➔ average of the scalar sum of p_T of the particles
  ➔ central charged particles: $p_T > 0.5$ GeV/c, $|\eta| < 2$ (muons from DY excluded)



- Study the UE activity as function of ($81 \text{ GeV}/c^2 < M_{\mu\mu} < 101 \text{ GeV}/c^2$)
  ➔ the di-muon p_T: - to minimize background, study dependence in narrow mass window
  - energy scale sufficiently large to saturate MPI
  ➔ **probes ISR spectrum**
  ➔ the di-muon mass: - look at wide $M_{\mu\mu}$ range for di-muon $p_T < 5$ GeV/c
  ➔ **verify MPI saturation**

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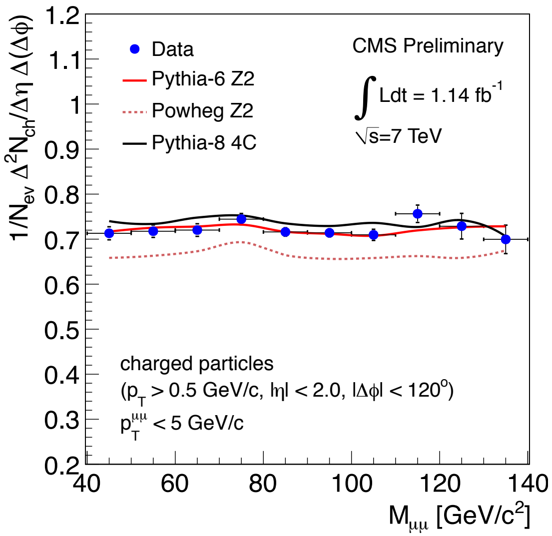
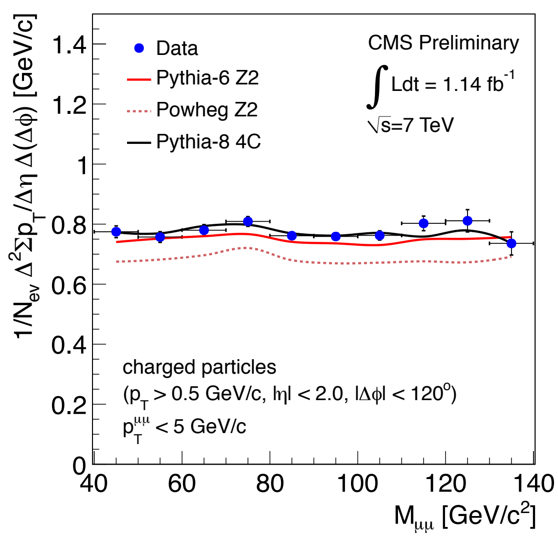
UE activity in the Drell-Yan process (II)

- Drell-Yan event selection:
  ➔ exactly 2 opposite charge isolated muons with $p_T > 20$ GeV/c, $|\eta| < 2.4$ from vertex well centered around the beam-spot

  ➔ charged particles for UE: central high purity tracks from primary vertex $p_T > 0.5$ GeV/c, $|\eta| < 2$, $\sigma(p_T)/p_T < 5\%$

- Study energy scale dependence of MPI as function of $M_{\mu\mu}$:
  ➔ limit ISR: di-muon $p_T < 5$ GeV/c





Look at towards & transverse region: $\Delta\varphi < 120°$

Pythia6 Z2 & Pythia8 4C describe the densities well

Powheg Z2 underestimates by 10-15%

➔ no dependence on $M_{\mu\mu}$ ➔ saturated MPI

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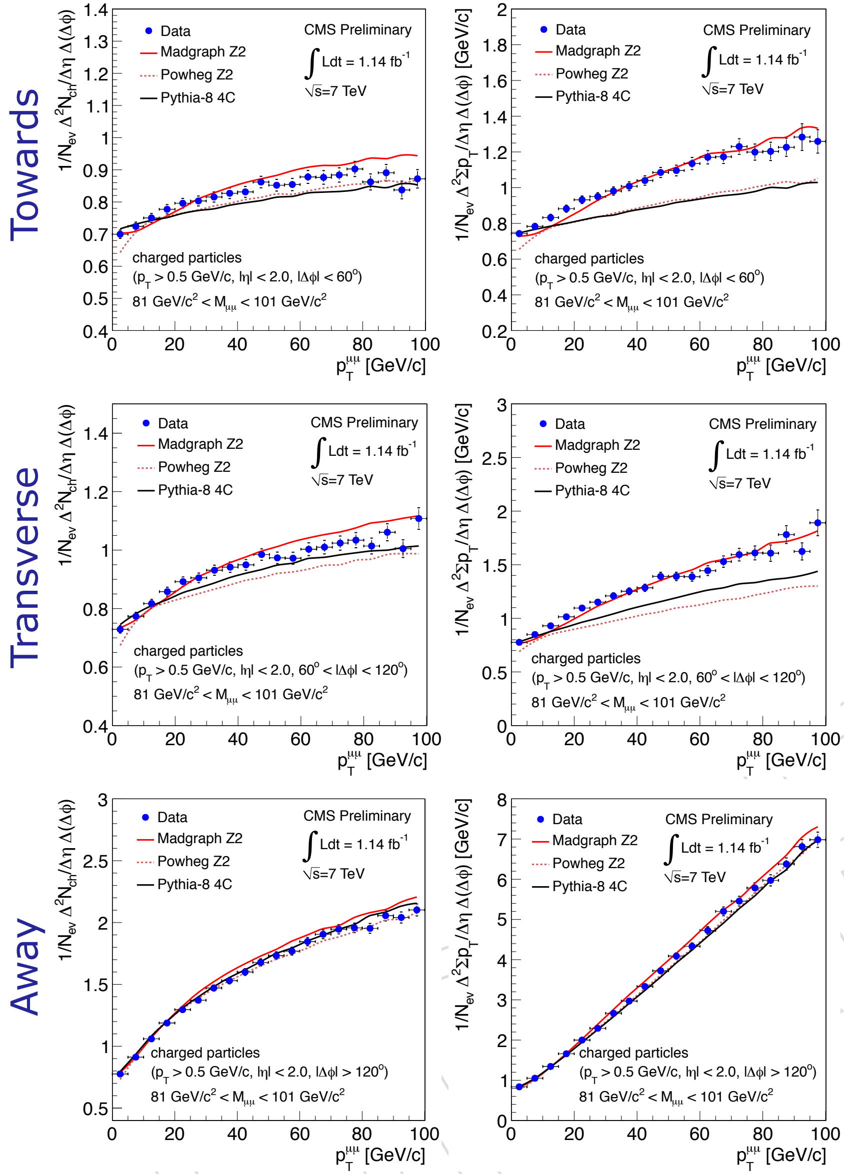
UE activity in the Drell-Yan process (III)



Dependence of UE activity vs di-muon p_T for 81 GeV/c^2 < $M_{\mu\mu}$ < 101 GeV/c^2

At this energy scale ➔ MPI saturated
➔ p_T dependence sensitive to ISR

Towards & transverse region:
➔ slow growth in particle & energy density with increasing di-muon p_T

➔ Madgraph with tune Z2 describes the data well
➔ Powheg Z2 & Pythia8 4C fail to describe the data (but agree at low p_T)

Away region:
mostly sensitive to spectrum of hardest emission
➔ equally well described by all tunes & generators

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UE activity with jet area/median

- Alternative method to study the UE activity at central rapidity
- Measure the soft hadronic activity by calculating the ratio of the jet p_T and the area covered by this jet in the (η,φ) plane for all jets in the event
- Introduce event variable: $\rho = \underset{j \in \text{jets}}{\text{median}} \left[\left\{ \frac{p_{Tj}}{A_j} \right\} \right]$

  ➔ median: robust to outliers in the distribution, these can be hard interactions
  ➔ ρ thus naturally isolates UE contributions assuming that the majority of the event is dominated by soft interactions
  ➔ no geometrical slicing of phase space needed

- Use track-jets reconstructed with k_T algorithm, R = 0.6 within |η| < 1.8
  ➔ input tracks: $p_T > 0.3$ GeV/c, |η| < 2.3
  ➔ on hadron level: stable charged particles with $p_T > 0.3$ GeV/c, |η| < 2.3

- Basic event selection: minimum bias (inclusive) events
  ➔ study the jet area/median observable as a function of the leading track-jet

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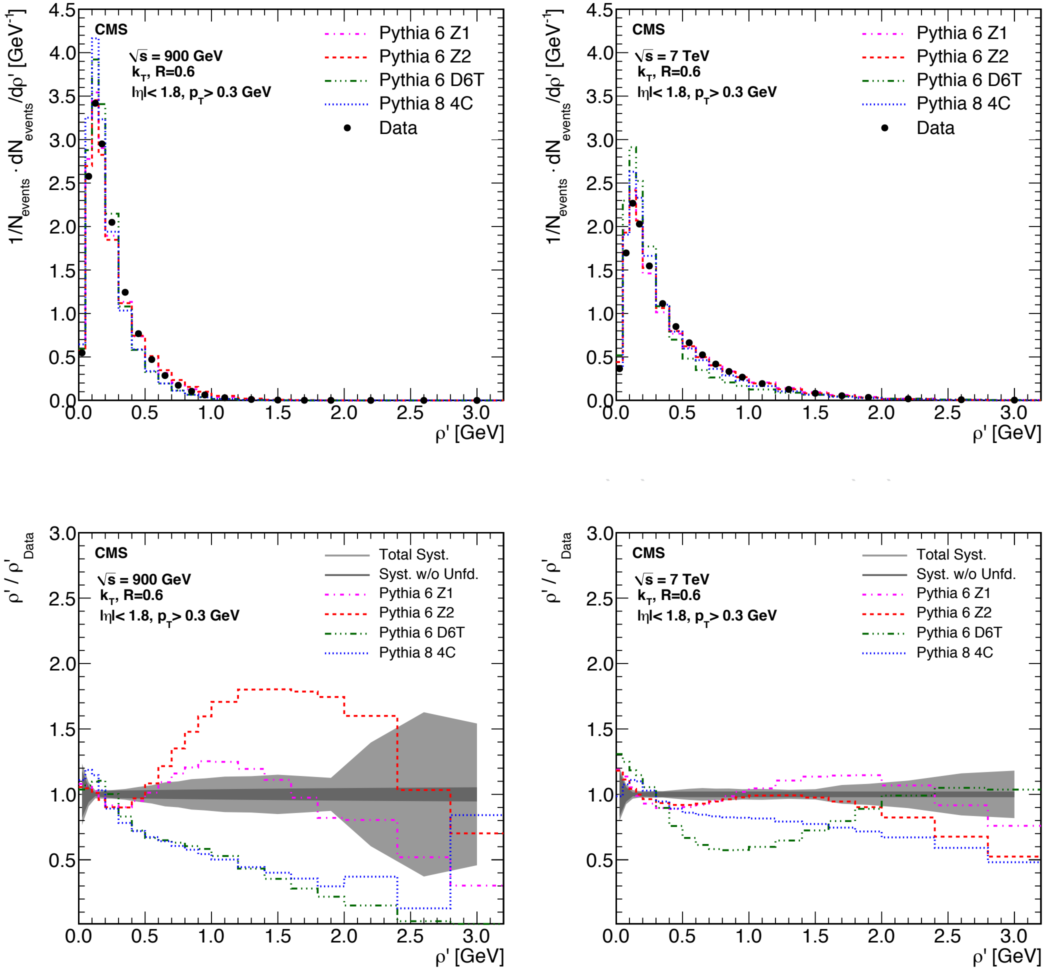
UE activity with jet area/median (II)

- First look at the inclusive event distributions of the jet area/median



At 0.9 and 7 TeV:

➔ Pythia6 Z1 gives reasonable description while other tunes reveal substantial differences with data

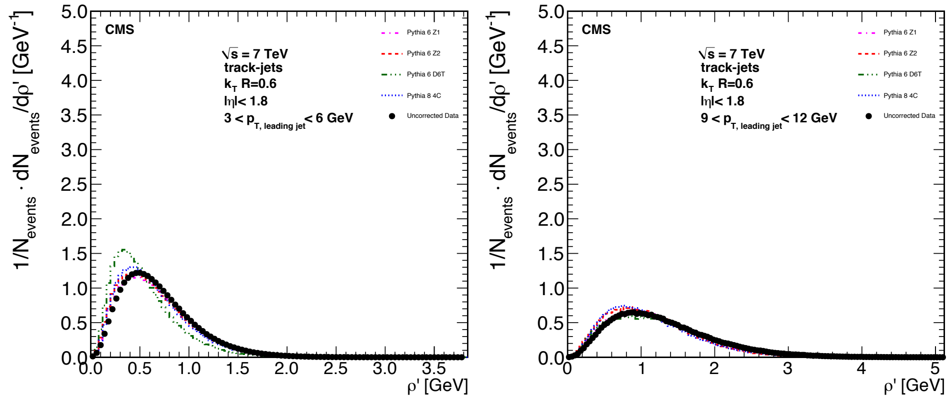
CMS-PAS-QCD-10-021

UE activity with jet area/median (III)

- Event scale dependency: jet area/median distribution vs leading jet

➔ both peak values and widths of the distributions change

➔ increase of UE activity with p_T

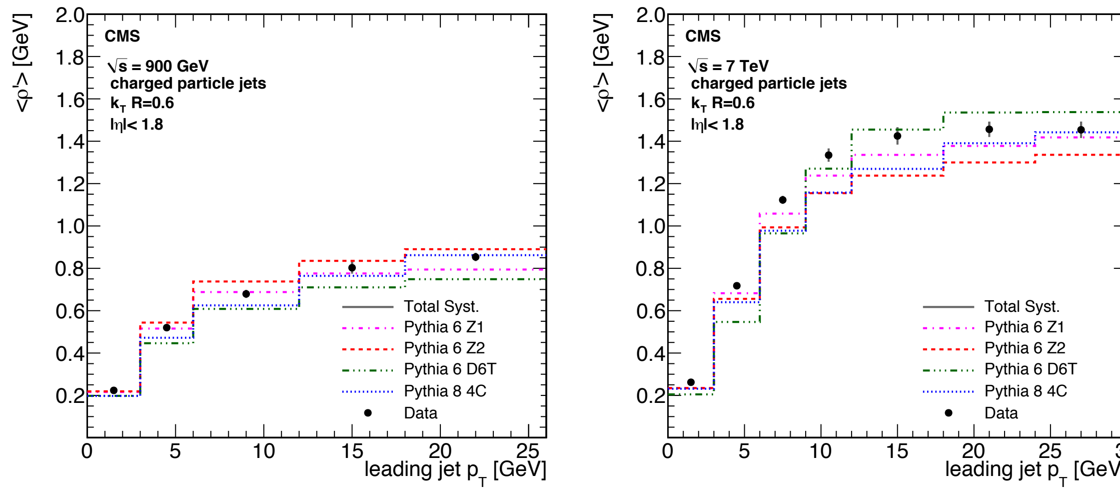


- Characterize UE behavior by plotting the means as a function of leading jet p_T

➔ amount of events with very high activity is underestimated

➔ implications on treatment of jet energy corrections using area-based methods

➔ Tune Z1, Z2, 4C are to low at 7 TeV



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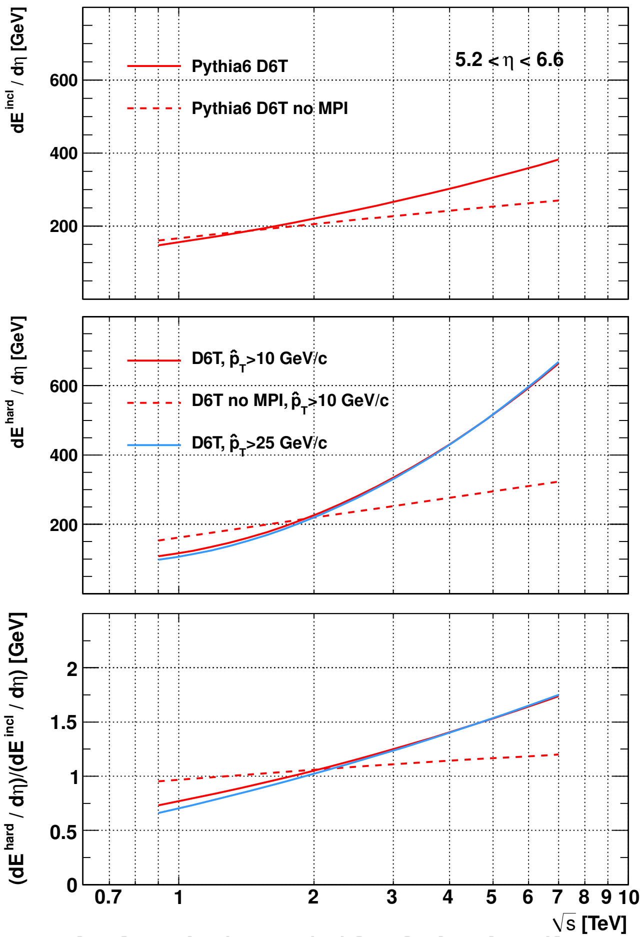
Study of UE activity at forward rapidity

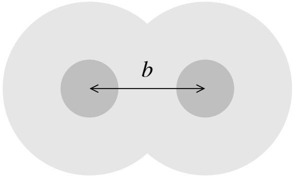
- Measure the Underlying Event (UE) activity by comparing energy density in CASTOR ($-6.6 < \eta < -5.2$) for minimum bias events w.r.t. events with a hard scale present



Minimum bias (inclusive events)

➔ energy density not much affected by MPI

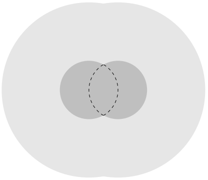
➔ non-diffractive dominated event sample



Hard scale $\hat{p}_T$

➔ energy flow strongly affected by MPI

➔ use the central leading charged jet with $p_T > 1$ GeV/c and $|\eta| < 2$



Compute ratio of energy densities

➔ independent of calibration

➔ minimizes systematic uncertainties

Look at behavior of ratio as function of p_T scale and at relative energy flow as function of $\sqrt{s}$

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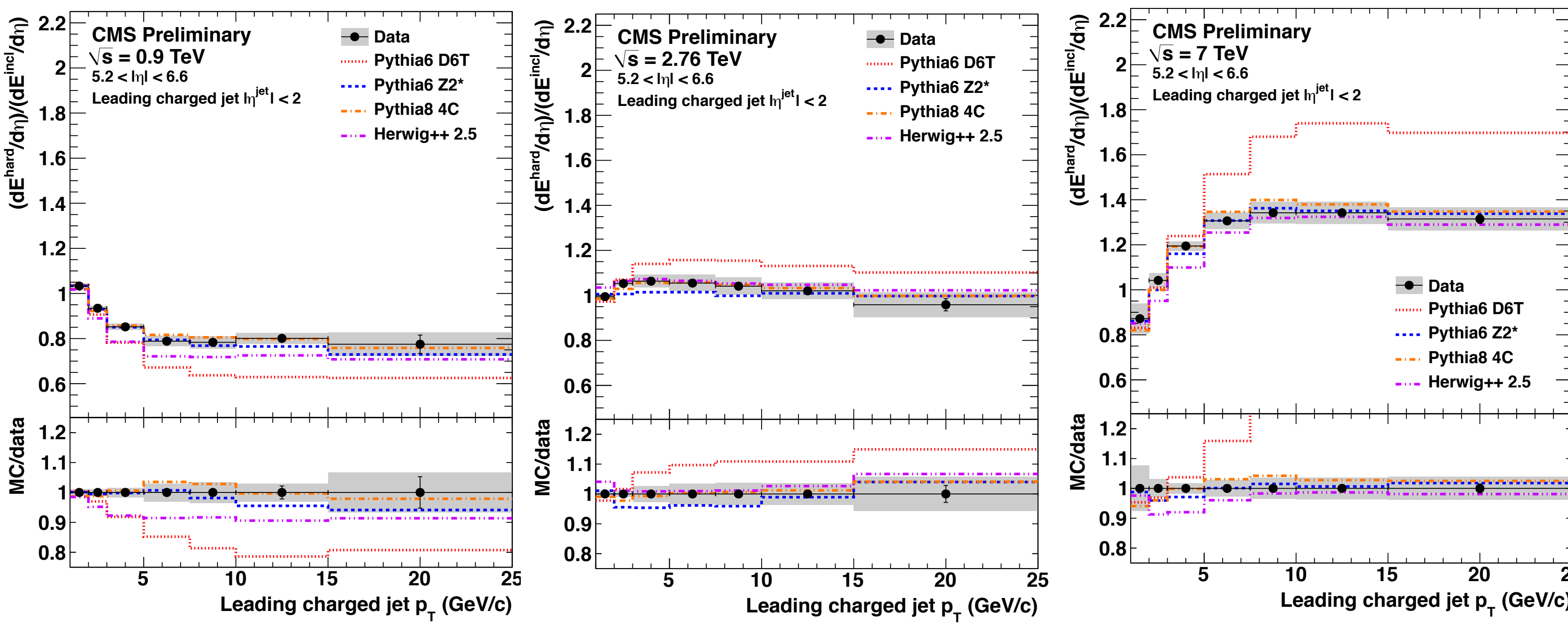
Study of UE activity at forward rapidity (II)

- Hard-to-inclusive ratio vs leading charged jet p_T at $\sqrt{s}$ = 0.9, 2.76, 7 TeV

At 0.9 TeV: ratio below 1
production of central hard jets accompanied with higher UE activity depletes energy of the proton remnant which fragments in CASTOR

At 7 TeV well known UE behaviour: fast increase at low p_T followed by a plateau above p_T=8 GeV/c

At 2.76 TeV the increase of the ratio is much reduced

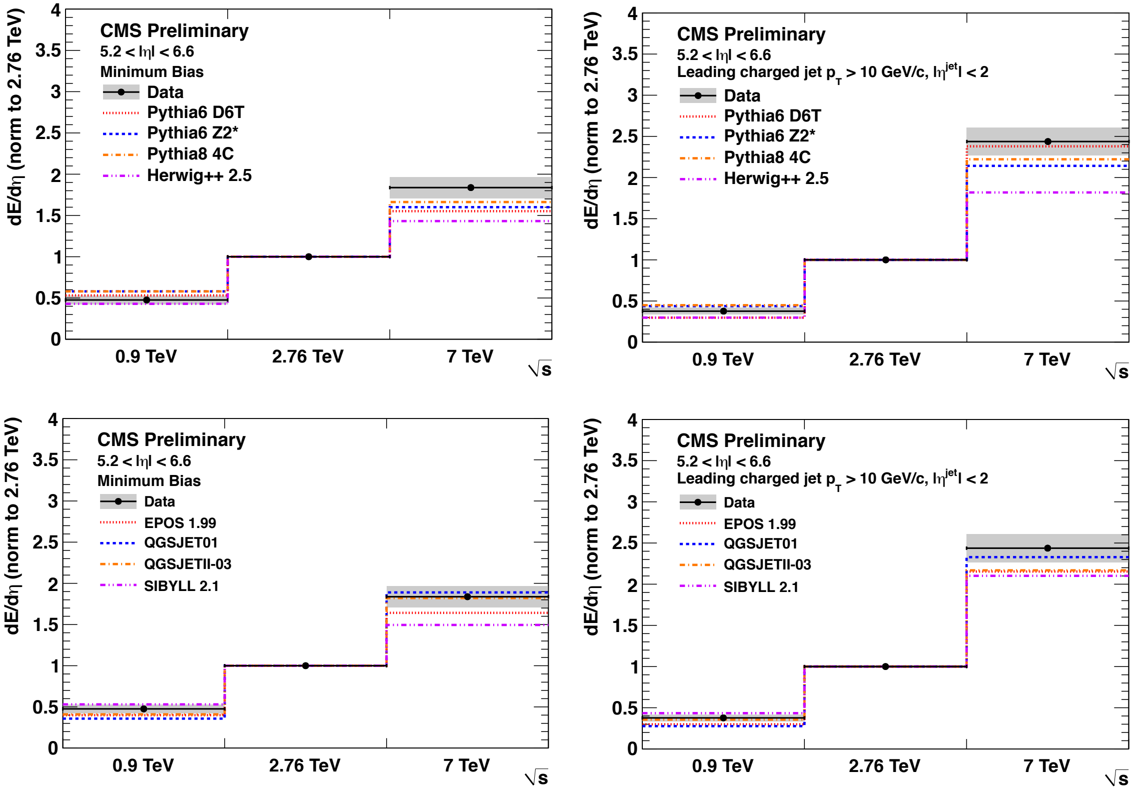


➔ Pythia tunes fitted to LHC (Z2*, 4C) & Herwig 2.5 describe data well
➔ Older tune Pythia6 D6T fails to describe the results

CMS-PAS-FWD-11-003

Study of UE activity at forward rapidity (III)

- Normalized energy density vs √s:
  - ➔ normalized to 2.76 TeV (minimize systematic uncertainties)
  - ➔ for both inclusive and hard scale (leading charged jet, p_T > 10 GeV/c, |η| < 2) events



Energy density increases much faster in events with a hard scale

Inclusive events:
- ➔ None of the Pythia & Herwig models can describe the relative increase at 7 TeV
- ➔ QGSJET describes data, other tunes underestimate

Hard scale:
- ➔ Pythia6 D6T & QGSJET01 close to the data, other tunes underestimate the increase

- Increase of the UE activity with centre-of-mass energy very challenging

CMS-PAS-FWD-11-003

Summary

- Study of the Underlying Event activity is done (ongoing) in many ways in CMS

  ➔ at central rapidity using leading jets and Drell-Yan as hard scales
  to measure particle & energy densities, and novel observables as jet area/median
  ➔ at forward rapidity using leading jets to measure the relative energy densities
  ➔ at 3 different centre-of-mass energies: 0.9, 2.76 and 7 TeV

- Models tuned to LHC data can describe many aspects of the UE

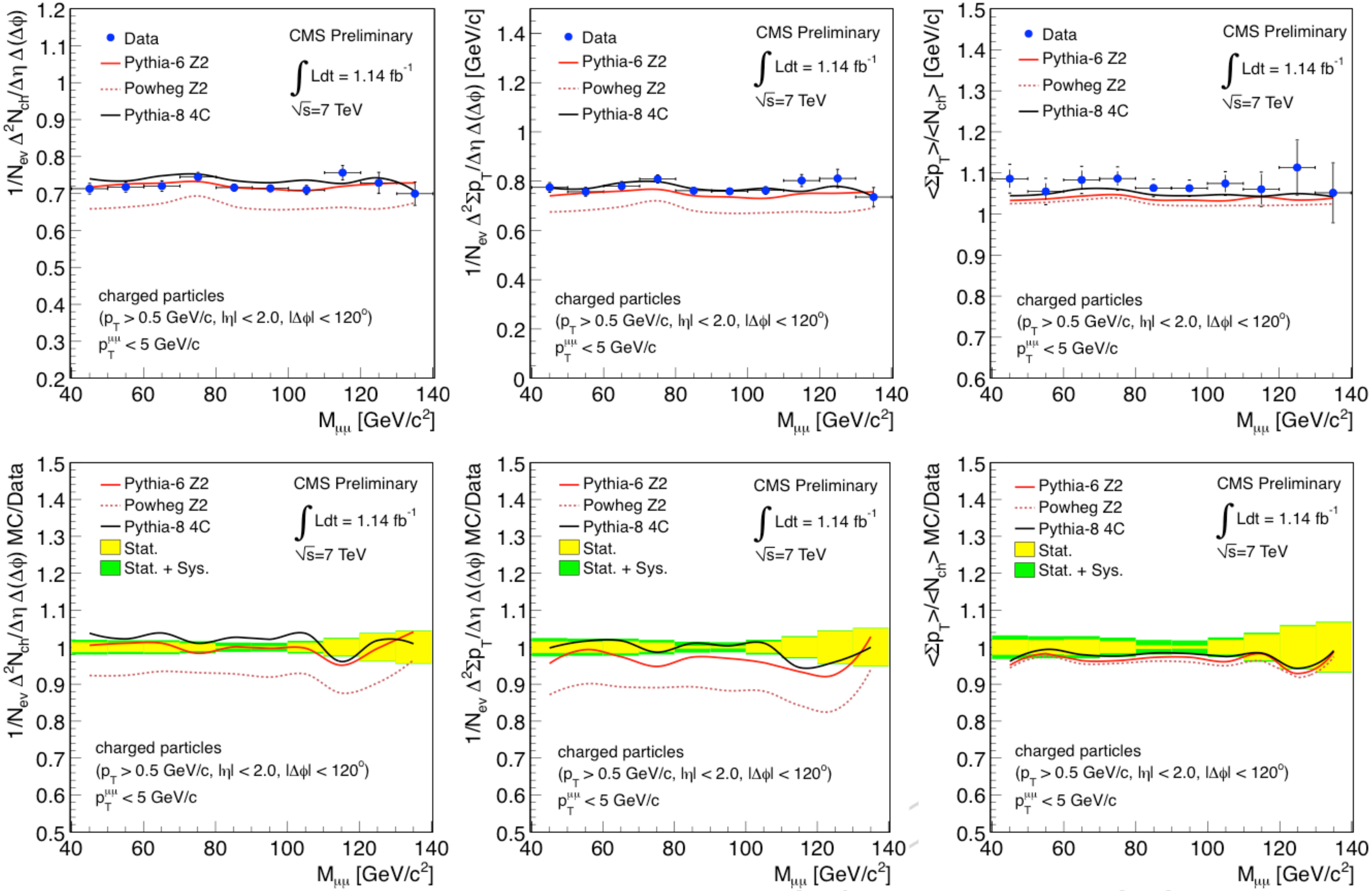
  ➔ evolution of central & forward energy densities as function of the hard scale
  of the event (central leading jets & Drell-Yan process)
  ➔ behavior of the jet area/median as a function of the central leading jet p_T
  ➔ **universality of the UE description**

- Notable discrepancies

  ➔ UE activity in the towards & transverse regions in Drell-Yan at high p_T
  ➔ relative increase of forward energy density in inclusive and hard scale events

Backup slides

UE activity in the Drell-Yan process



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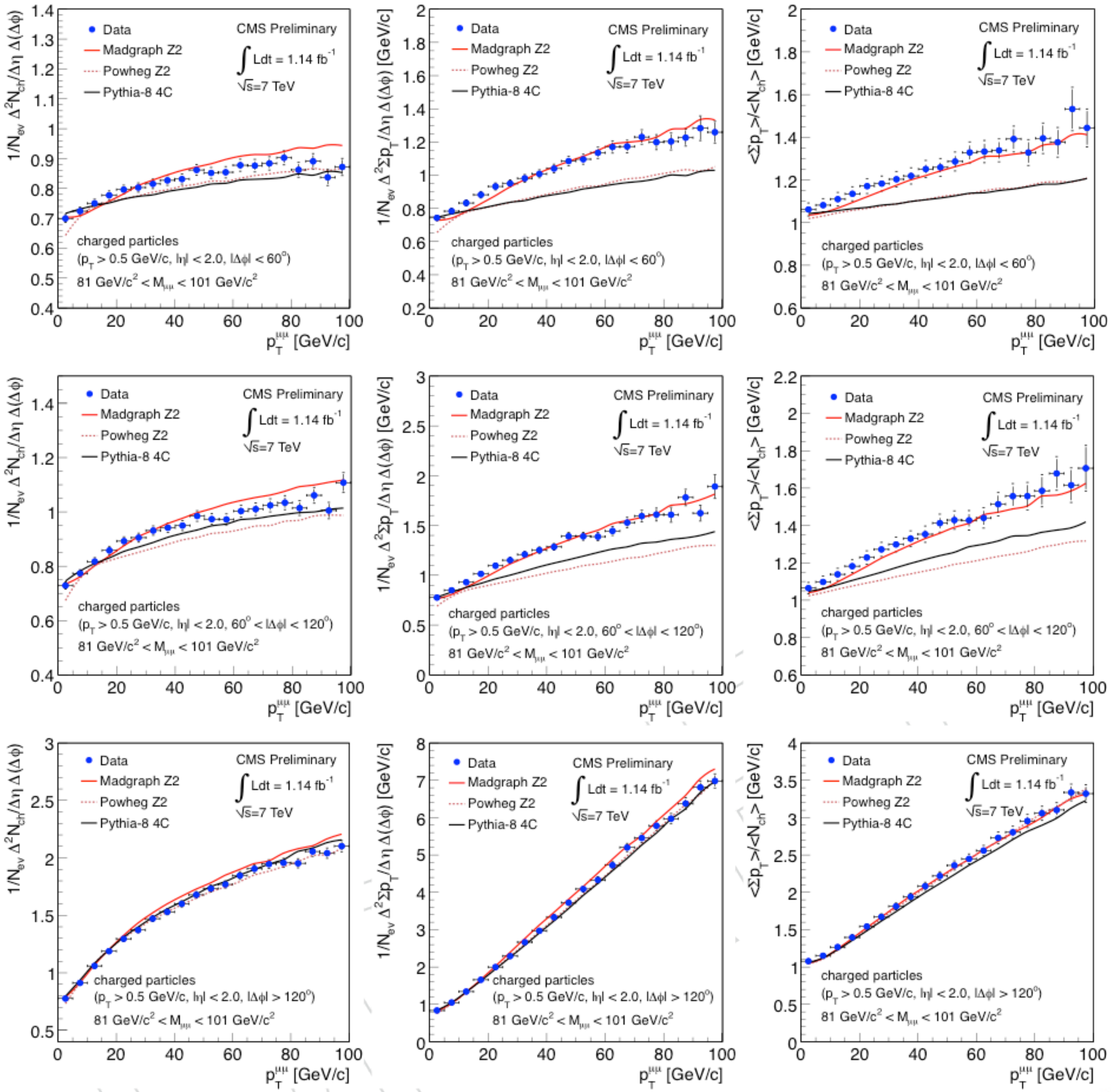

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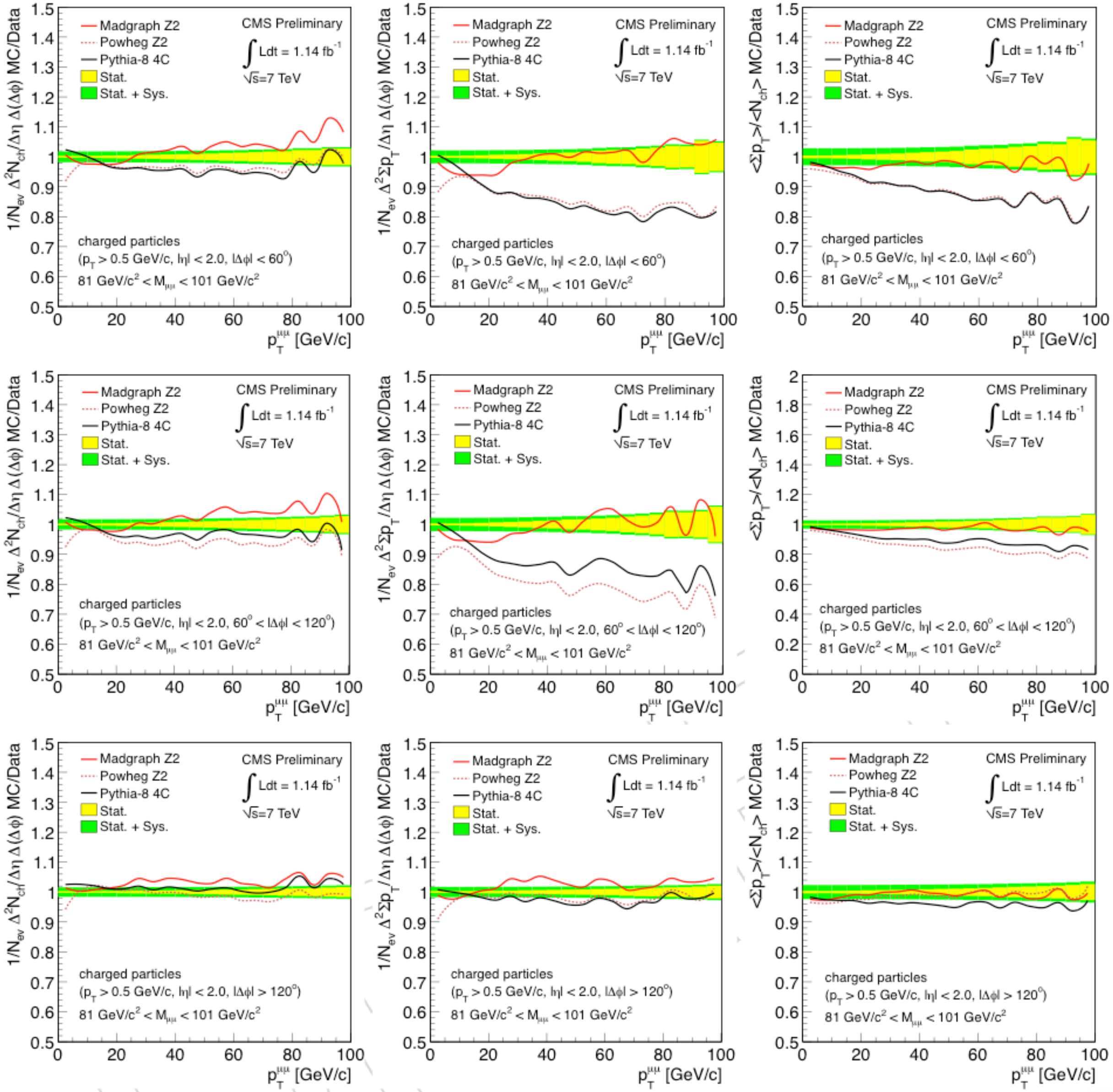

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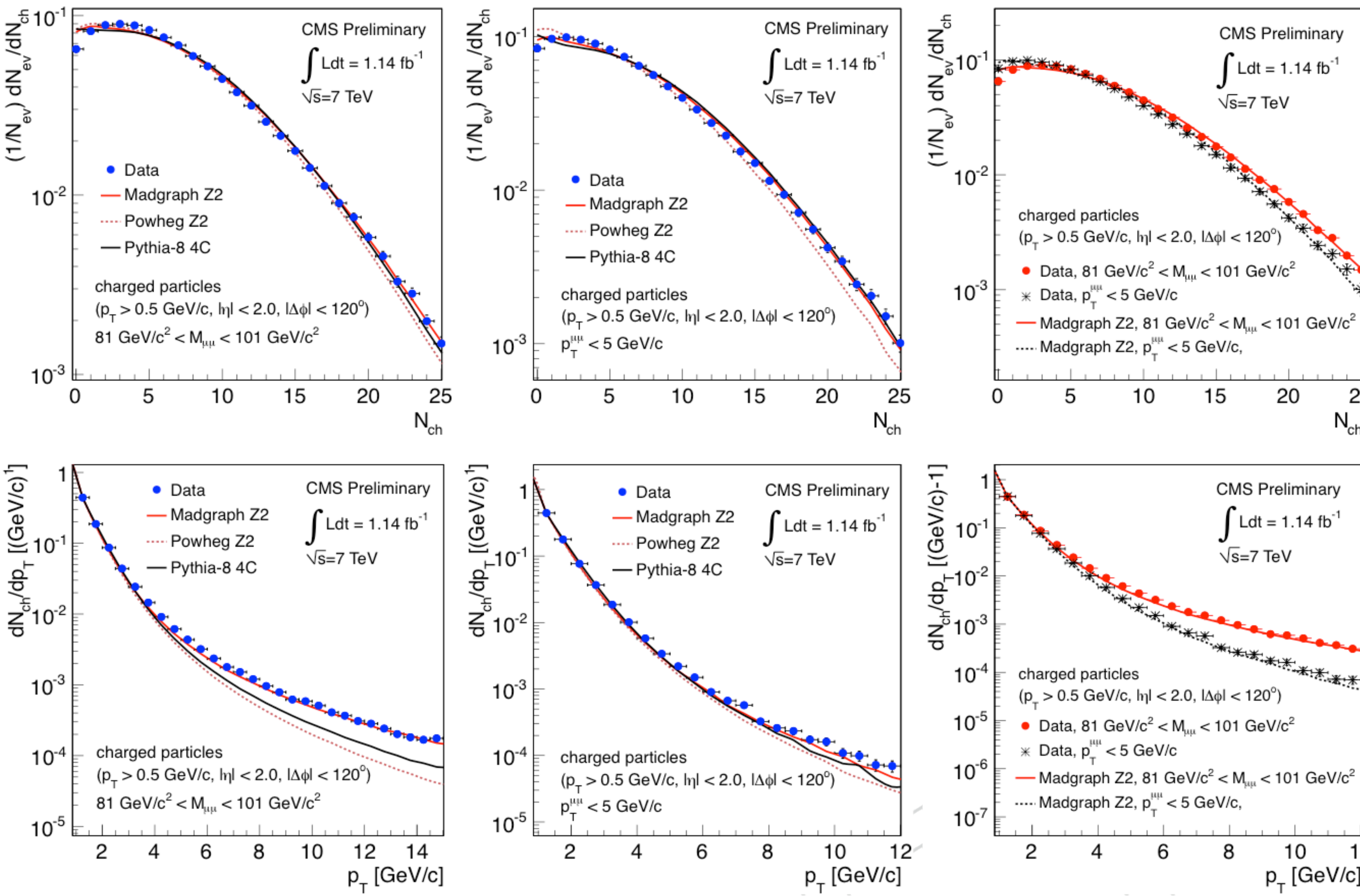

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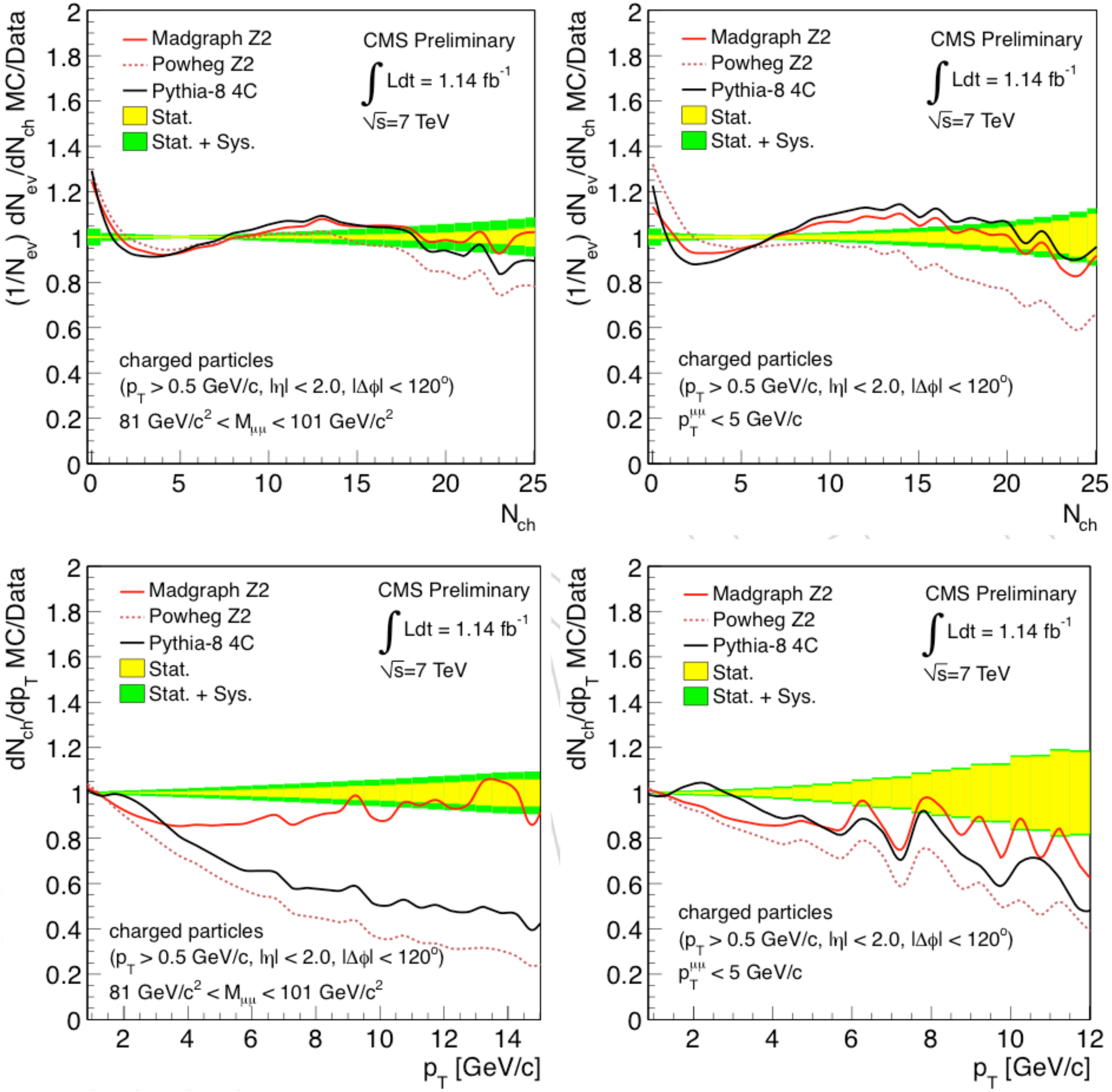
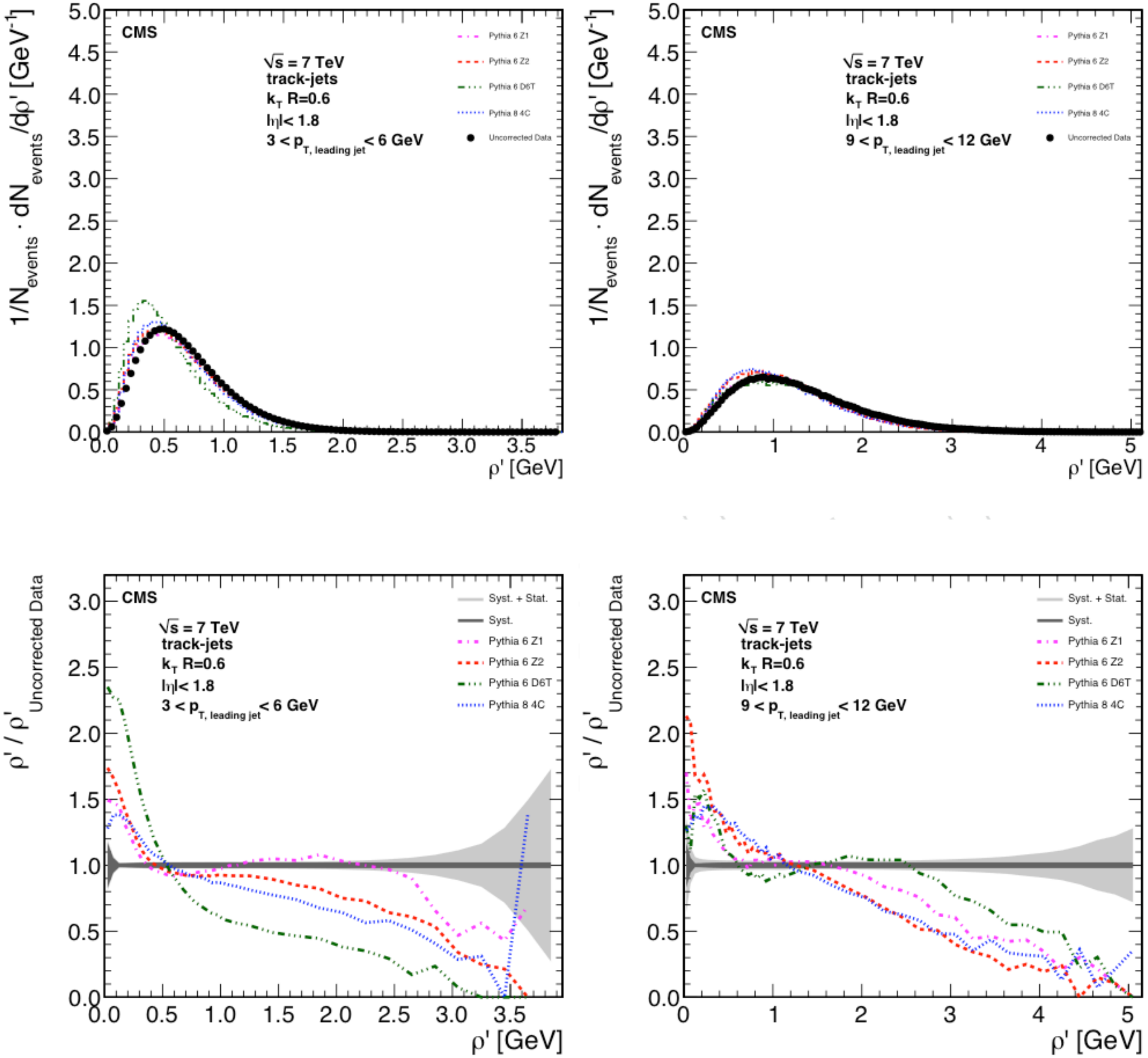


UE activity with the jet area/median approach



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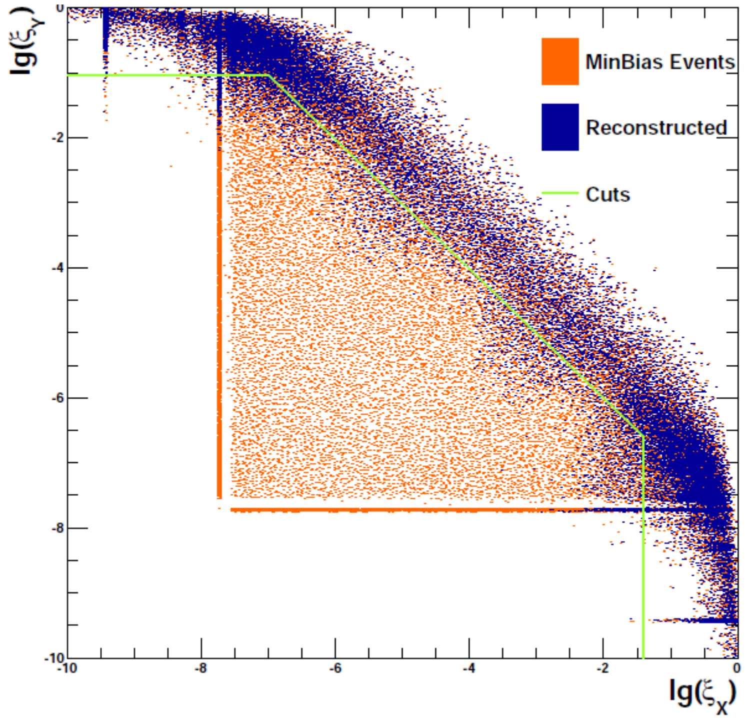

$$\xi_X = \frac{M_X^2}{s}, \qquad \xi_Y = \frac{M_Y^2}{s}, \qquad \xi_{DD} = \frac{M_X^2 M_Y^2}{m_p^2\, s}$$

$\sqrt{s}$ (TeV)	ξ_X^{min}	ξ_Y^{min}	ξ_{DD}^{min}
0.9	0.1	0.4	0.5
2.76	0.07	0.2	0.5
7	0.04	0.1	0.5

Study of UE activity at forward rapidity

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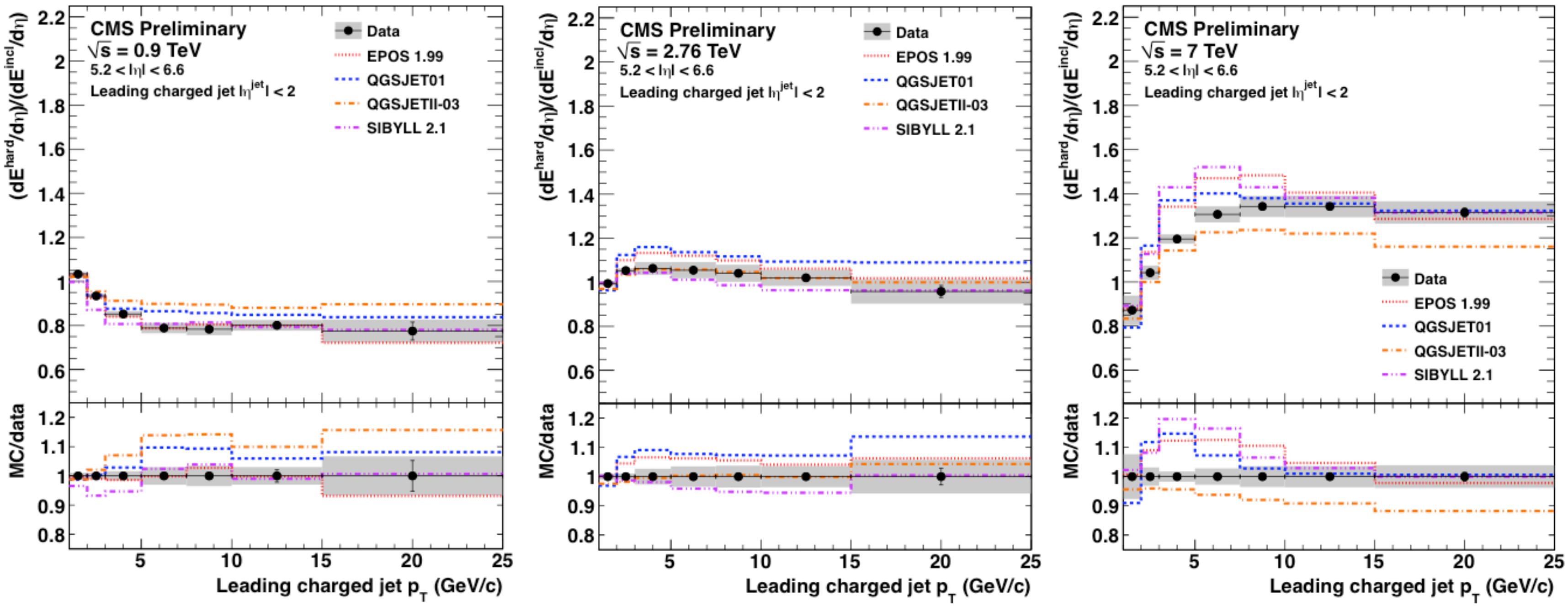

➔ Cosmic ray models are not tuned to LHC
➔ None of the tunes can fully describe the data

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