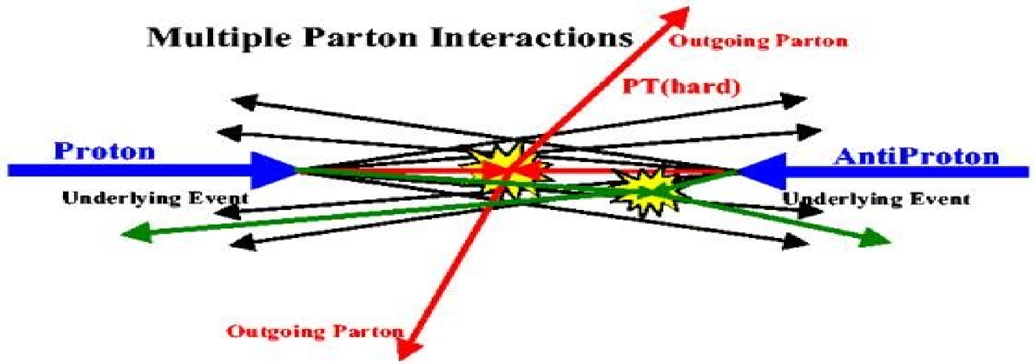

Underlying Event Measurements at CMS

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Outline

- **Introduction**

  1) Soft QCD

  2) Underlying Event (UE)

  3) UE Observables

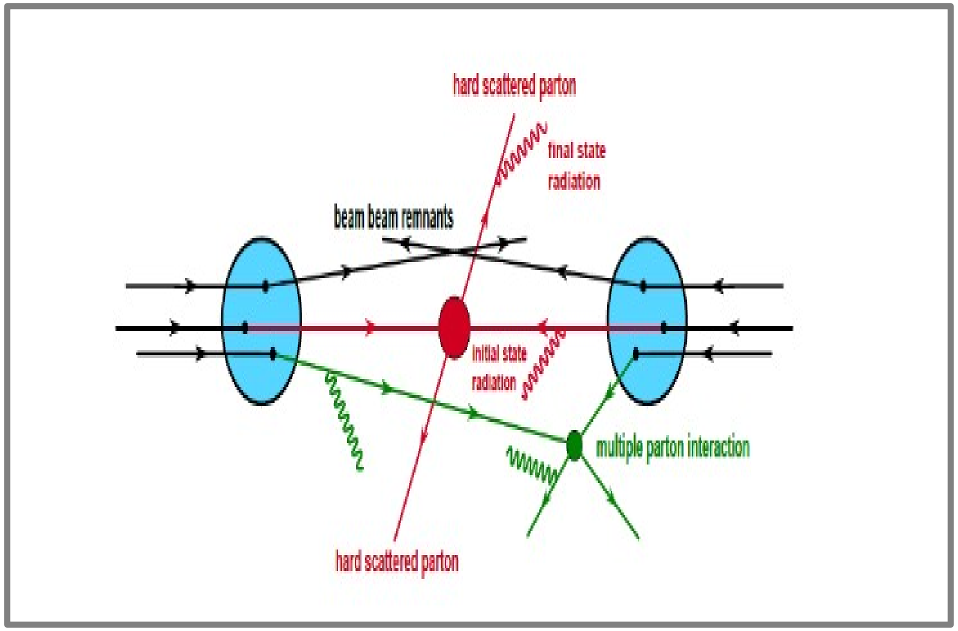
- **UE Measurement at 13 TeV**
- **Results and Summary**

Underlying Event (UE)

- Production of particles in a hadron-hadron collision involves parton-parton scatterings, initial-state radiation (ISR), final-state radiation (FSR), and beam-beam remnants (BBR).

- The large parton densities available in the proton-proton (pp) collisions result in a significant probability of more than one parton-parton scattering in the same pp collision, called multiple parton interactions (MPIs).

- The combination of particle production from MPIs (excluding parton-parton scattering with highest momentum-transfer) and BBR interactions is called underlying event (UE) activity.



Importance of UE

- These processes can't be completely described by perturbative QCD, and require phenomenological models, whose parameters are tuned by means of fits to data.

- Same sign WW production from MPI can mimic final state of same sign dilepton SUSY searches.

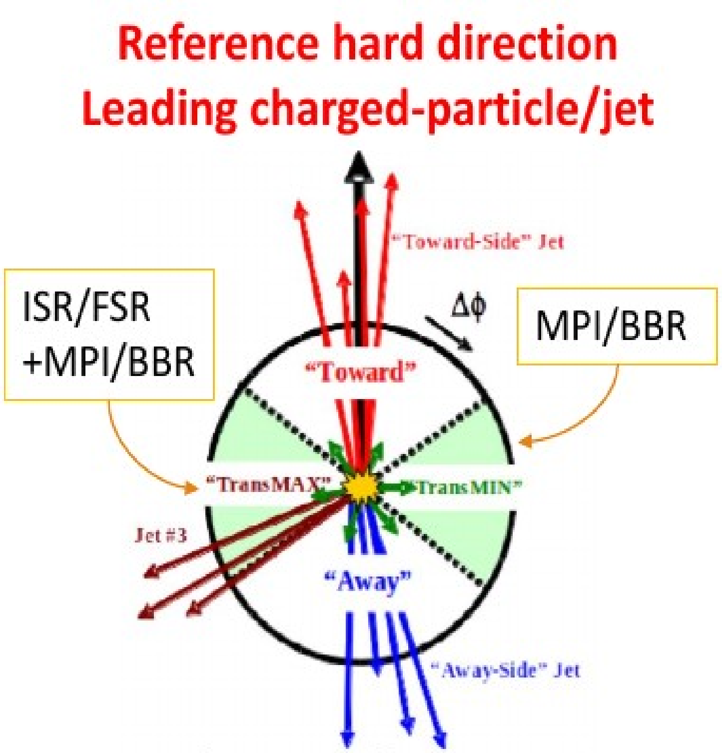
- It can affect isolation criteria aplied to photons and charged leptons.

- It can affect the vertex reconstruction efficiency of H → γ γ, where the primary vertex is partly determined from the charged particles originating from the UE

Underlying Event study using Leading Track/Jet:

Spatial Distribution of tracks is categorized by azimuthal separation $\Delta\Phi = \Phi_{track} - \Phi_{leading\ track/jet}$

1. $|\Delta\Phi| > 120^0$ (away)
2. $60^0 < |\Delta\Phi| < 120^0$ (transverse)
3. $|\Delta\Phi| < 60^0$ (towards).



UE observable:

Avg charged particle multiplicity density:

$\langle N_{ch} \rangle / [\Delta\eta\Delta(\Delta\varphi)]$,

Average Scalar sum of transverse momenta

$\langle \Sigma p_T \rangle / [\Delta\eta\Delta(\Delta\varphi)]$

transMAX(TransMIN): activity in maximum (minimum) activity side of transverse region

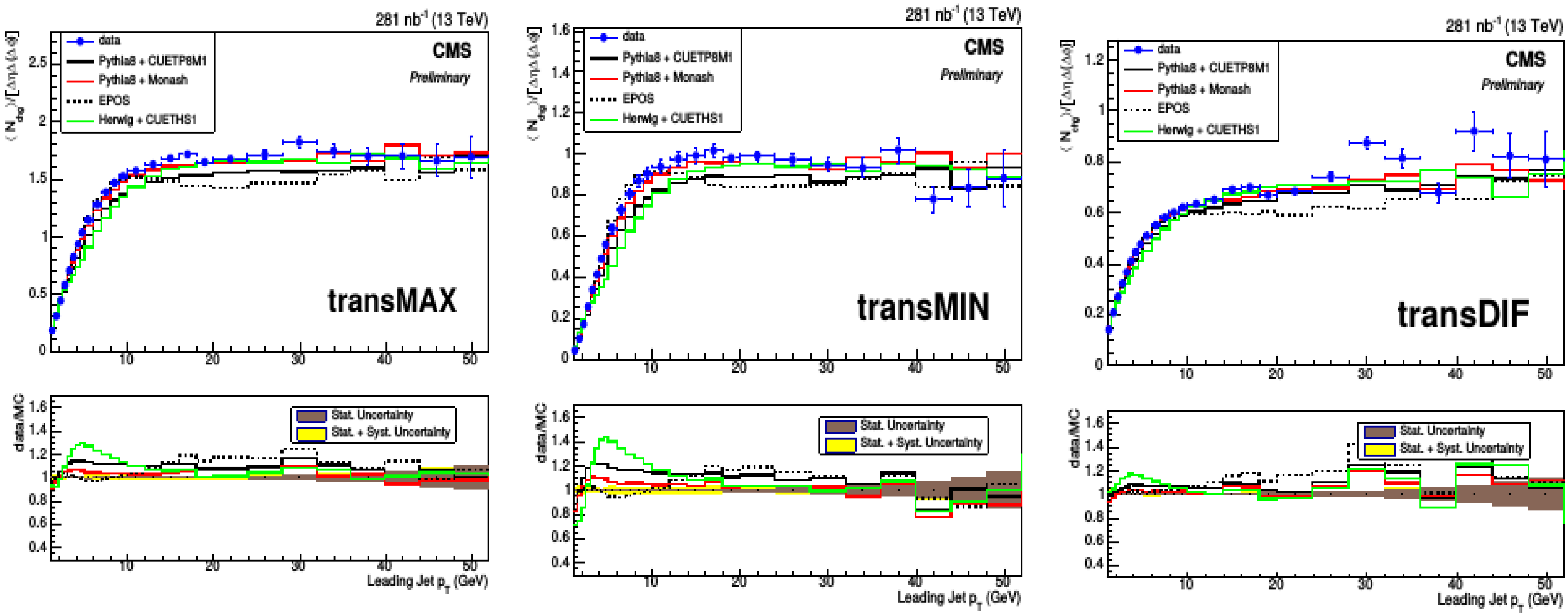
transAVE: (TransMAX+TransMIN)/2

transDIF: (TransMAX-TransMIN)
Sensitive to ISR/FSR

Underlying event with leading particle and Jet @ 13 TeV

CMS-PAS-FSQ-15-007

- Average Particle density vs leading jet p_T for charged particles : p_T > 0.5 GeV and $|\eta|$ < 2.



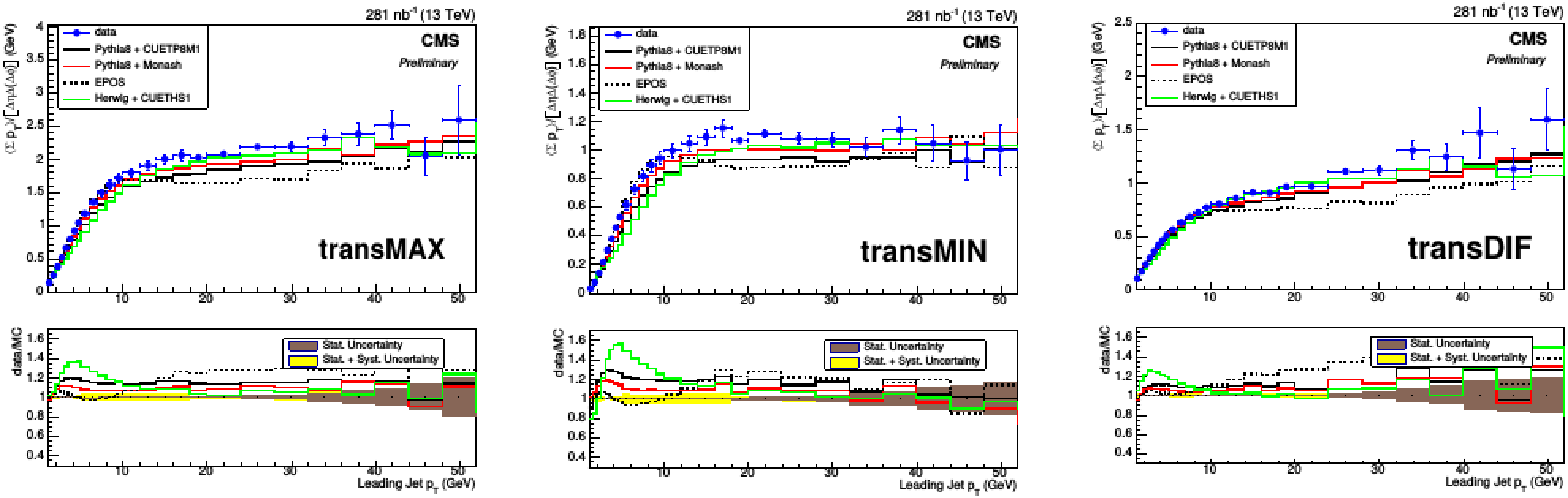
two different regimes:

- At low p_T : sharp rise due to increase of the MPI activity.
- At higer p_T : MPI activity saturates, slow increase due to the ISR and FSR contributions.

TransMIN flatter at higher p_T (MPI saturated) than transMAX and transDIF (ISR/FSR increase)

Underlying event with leading particle and Jet @ 13 TeV

- Average p_T sum vs leading jet p_T for charged particles – p_T > 0.5 GeV and $|\eta| < 2$.



Qualitative behavior described by the simulations:

- Level of agreement is 10-20% in the plateau region.
- Larger difference between models in the low p_T regions.

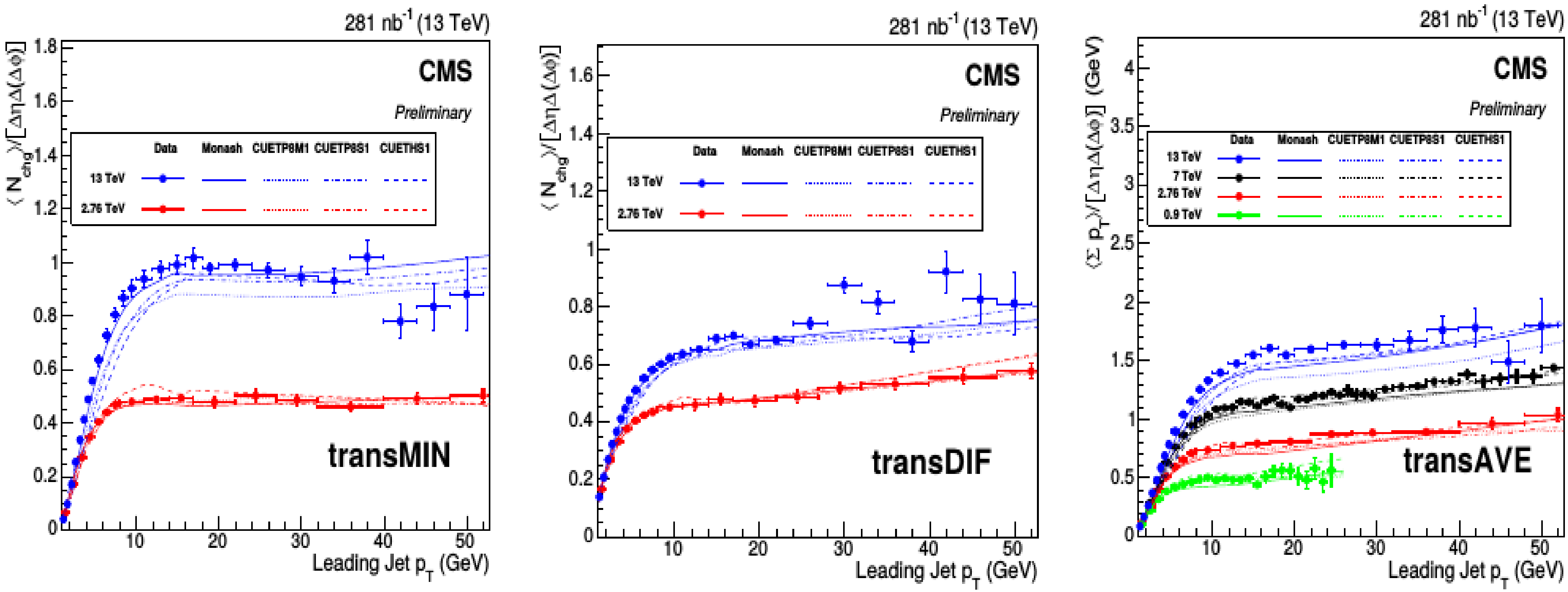
→ Data better described by Pythia8 Monash and CUETP8M1

HERWIG + CUETHS1 fails in the low p_T region (lack of diffractive events)

EPOS describes the rising part but fails to describe the plateau.

Underlying event with leading particle and Jet @ 13 TeV

- p_T sum density vs leading jet p_T : energy dependence 2.76 TeV ⟶ 13 TeV



Strong energy dependence well reproduced by the different models

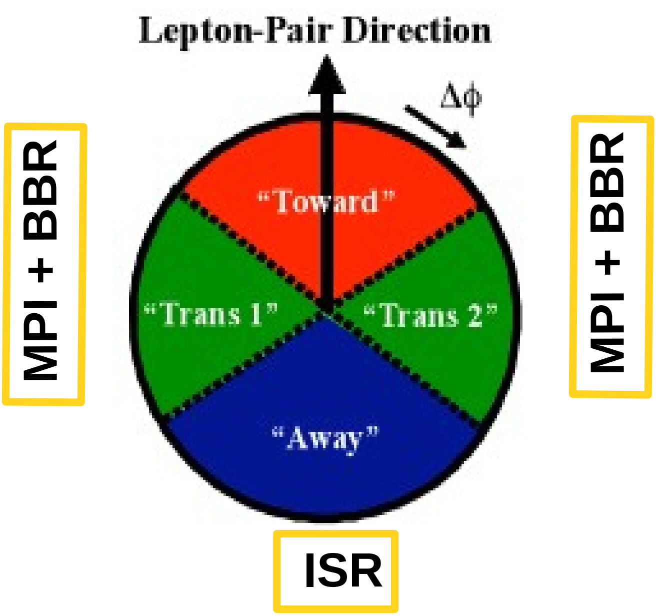
- Increase of the parton densities at smaller momentum fraction.
- transMIN shows a stronger rise than transDIF

⟶ MPI activity grows faster with CM energy than activity from ISR and FSR.

Underlying Event (UE) Observables

Underlying event using Drell-Yan process with muonic final state:

- Experimentally clean, theoretically well understood and no final state radiation
- Possible to study both UE (MPI + BBR) and radiation contribution separately



- **Not possible to separate UE from hard component of the interaction. Topological structure of hard collisions : used to define physics observables sensitive to the UE.**

Spatial Distribution of tracks is categorized by azimuthal separation $\Delta\Phi = \Phi_{track} - \Phi_{\mu\mu}$

1. $|\Delta\Phi| > 120^0$ (away) region dominated by hardest ISR emission.
2. $60^0 < |\Delta\Phi| < 120^0$ (transverse) and $|\Delta\Phi| < 60^0$ (towards) region are more sensitive to soft emissions (MPI).

1. average charged particle density $1/N_{ev}\ \Delta^2 N_{ch}/\Delta\eta\Delta(\Delta\varphi)$
2. average scalar sum of the transverse momenta of tracks, $1/N_{ev}\ \Delta^2\Sigma p_T/\Delta\eta\Delta(\Delta\varphi)$

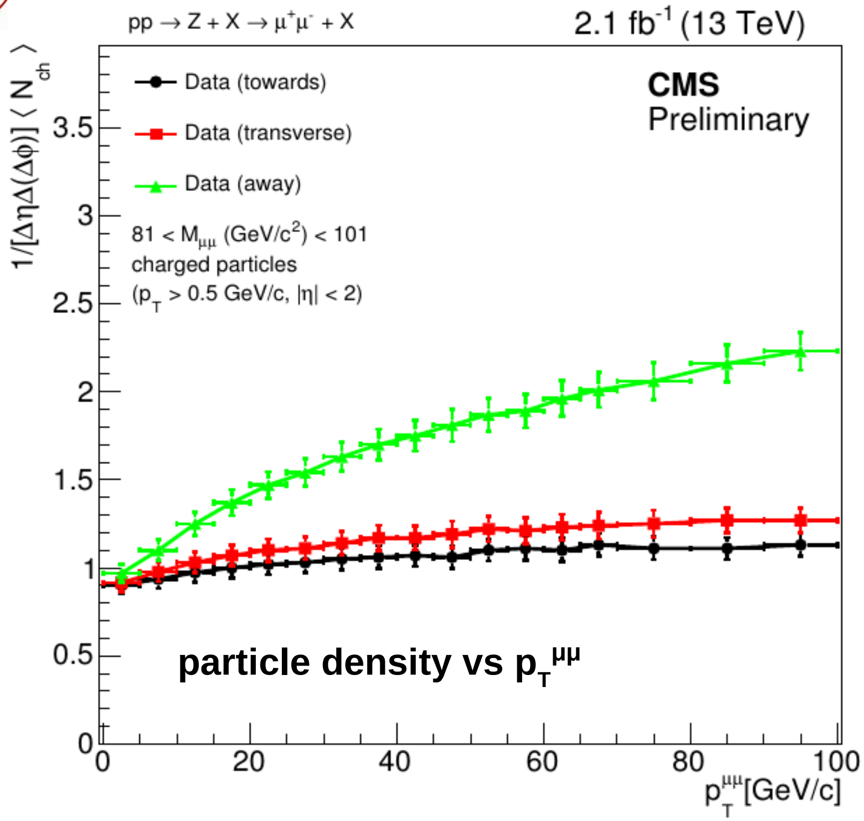
These observables are studied as a function of $p_T^{\mu\mu}$ in narrow mass window (around Z resonance i.e 81-101 GeV), in away, towards and transverse regions.

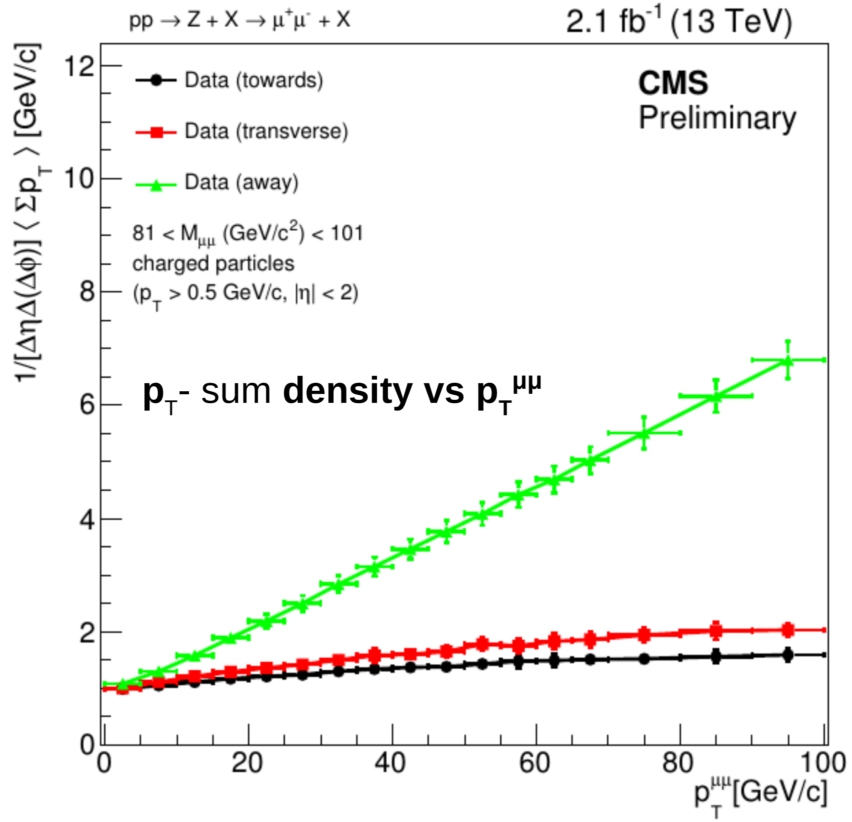
Underlying Event (UE) in Drell-Yan Process

CMS-PAS-FSQ-16-008

- 2 muons from Z leptonic decay with p_T > 10 & 20 GeV, $|\eta| < 2.4$ & $81 < M_{\mu\mu} < 101$ GeV
- Average particle and p_T sum density for charged particles with $p_T > 0.5$ GeV & $|\eta| < 2$ in the towards, transverse and away region.
- Test the process universality of the underlying event activity.
- Test the underlying event activity at higher scale
- No Final-State Radiation → more direct access to MPI and Initial-State Radiation
- Test the universality of the tunes interfaced with different event generators:
  - MADGRAPH (Z + upto 4 partons at LO) + PYTHIA8 CUETP8M1
  - POWHEG (Z + upto 2 partons at NLO) + PYTHIA8 CUETP8M1
  - POWHEG (Z + upto 2 partons at NLO) + HERWIG++ EE5c

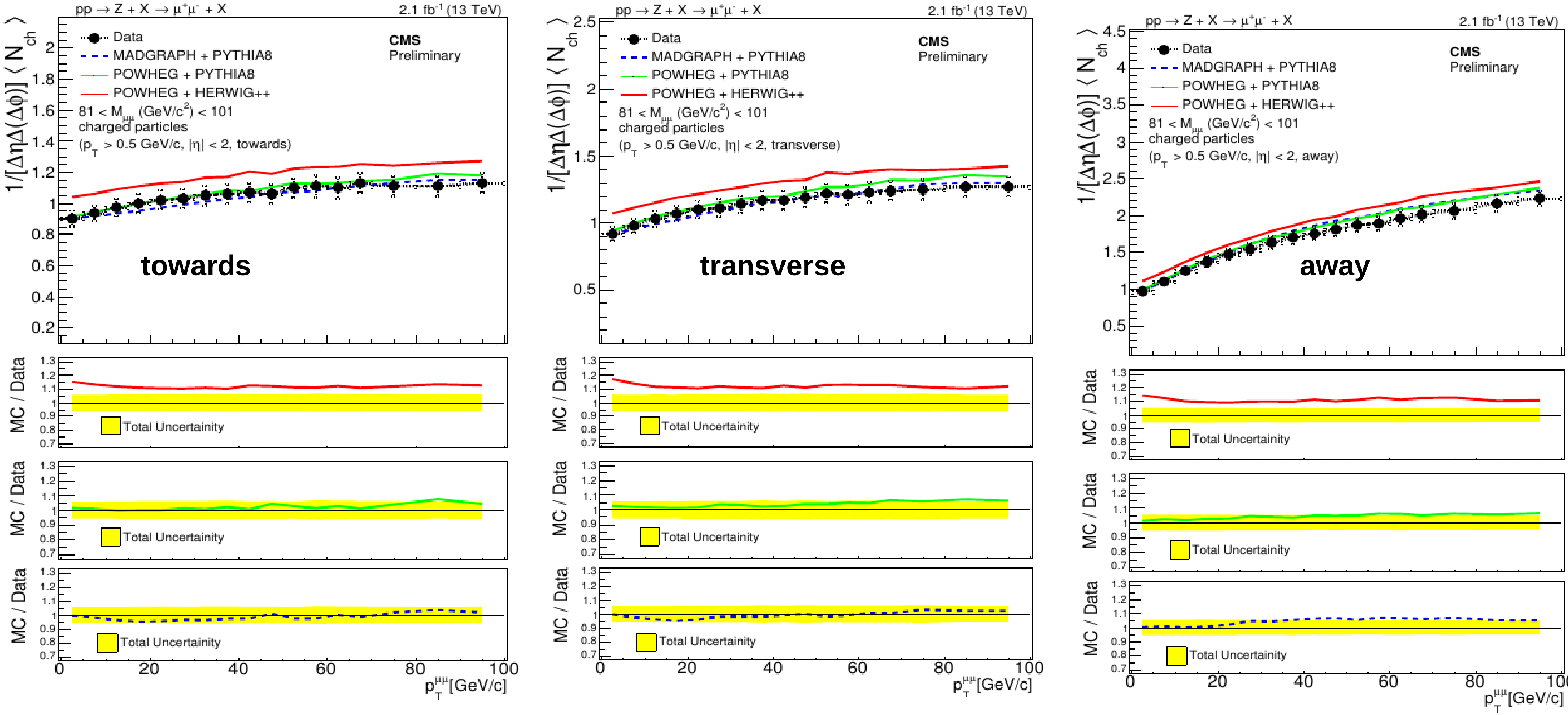
Results





- Away : fast rise in UE activity due to recoiling hadronic activity (ISR).
- Towards and transverse : slow growth (due to large spatial separation).
- All activities equal as $p_T^{\mu\mu} \rightarrow 0$: difference in UE activity for different regions is due to varying radiation contribution.
- UE activity does not start from zero due to hard scale set by event around Z resonance (MPI activity already saturated)

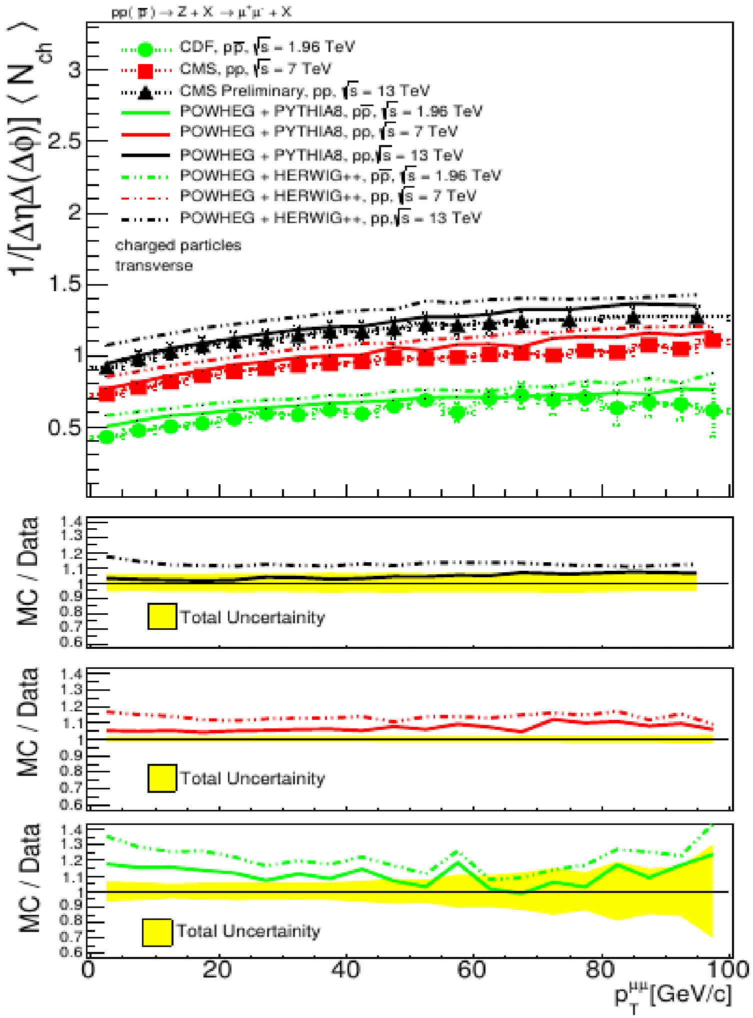
UE in DY – avg particle density vs dimuon p_T

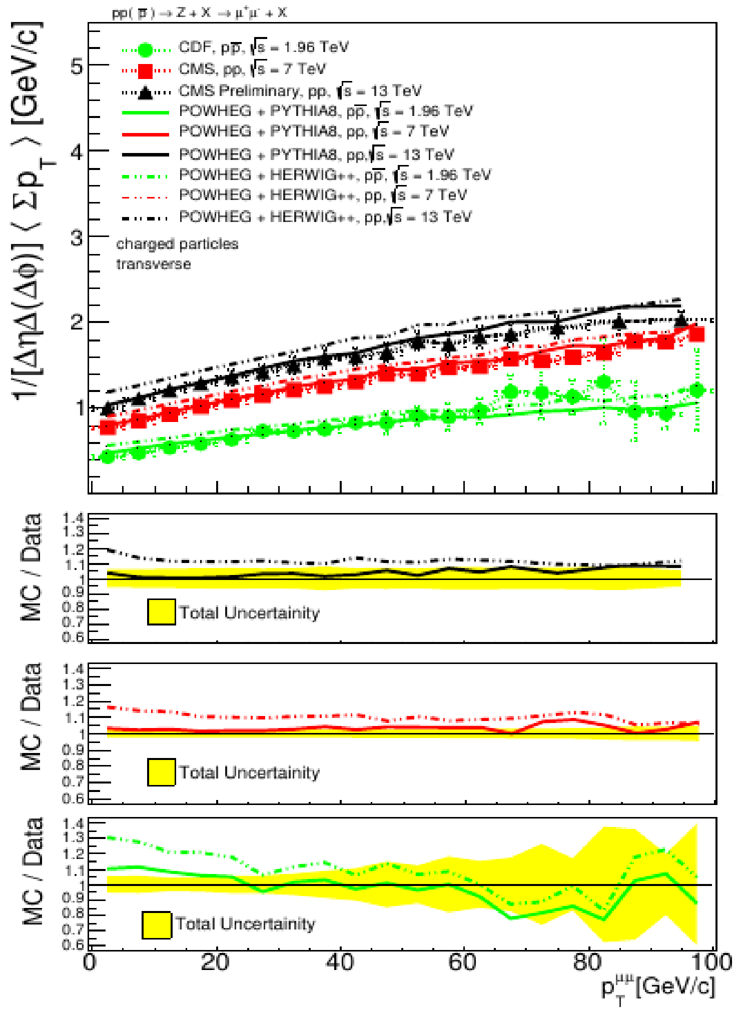


- POWHEG + HERWIG++ EE5c: overestimates UE activity by 10-15% in all regions
- POWHEG + PHYTHIA8 CUETP8M1: describes the data within 5%
- MADGRAPH + PYTHIA8 CUETP8M1: gives the best description

UE in DY : transverse activity at different energies

particle density vs $p_T^{\mu\mu}$



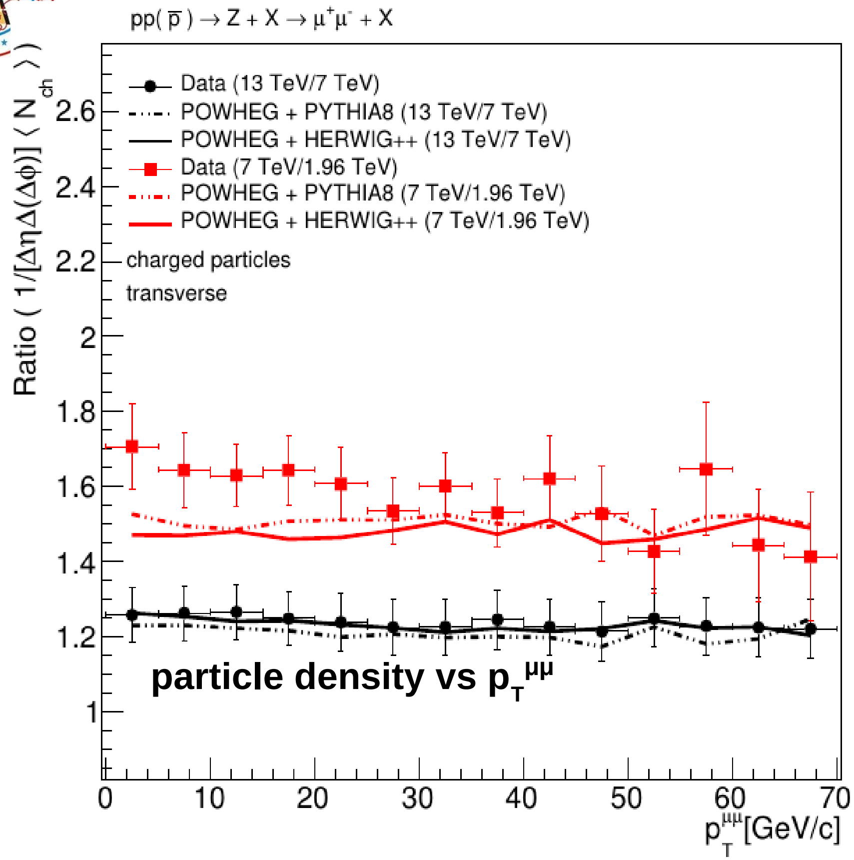


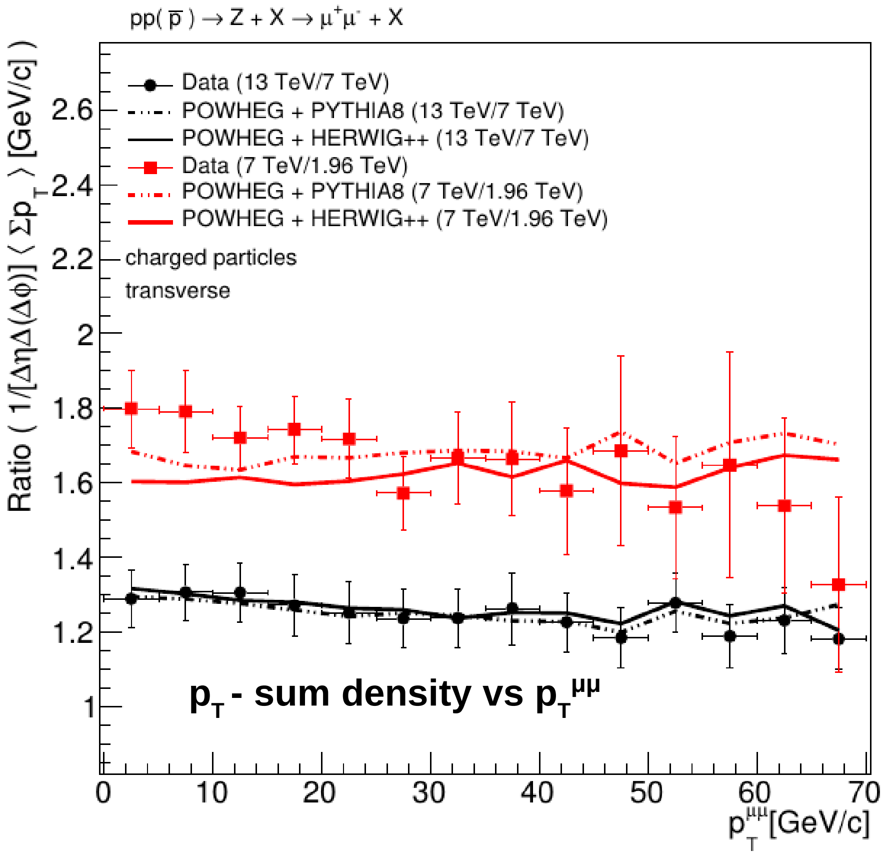
p_T - sum density vs $p_T^{\mu\mu}$

Comparison of UE activity at 13 TeV with Measurement at 7 and 1.96 TeV in transverse Region.

- With increase in CM energy from 1.96 TeV → 7 TeV → 13 TeV, behavior is as follows:
- POWHEG + HERWIG++ EE5c: overestimates data by 40 to 10%.
- POWHEG + PHYTHIA 8 CUETP8M1: describes data within 10 to 5%.

UE in DY : transverse activity at different energies

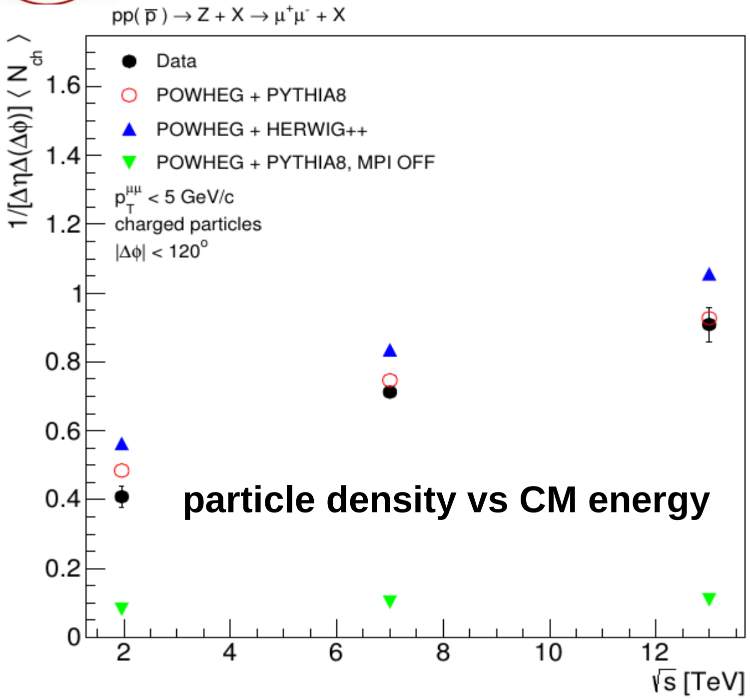


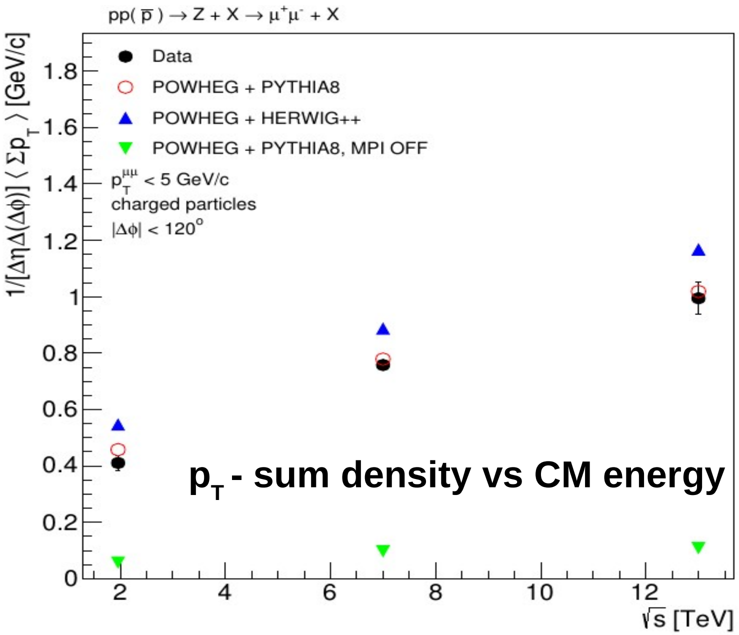


Ratio Particle density (left) and p_T - sum density(right) (13TeV/7TeV, 7 TeV/ 1.96 TeV) as function of $p_T^{\mu\mu}$ In transverse region for data and various simulations.

- To quantify increase in UE : ratios are calulated $(\text{UE})_{13\,\text{TeV}}$ / $(\text{UE activity})_{7\,\text{TeV}}$ & $(\text{UE activity})_{7\text{TeV}}$ /$(\text{UE activity})_{1.96\,\text{TeV}}$ for both simulation and data.
- 25-30% rise from 7 to 13 TeV , models in good agreement.
- 60-80% rise from 1.96 TeV to 7 TeV, models predict lower increase particularly at lower p_T

UE in DY : MPI activity at different energies





- At low dimuon p_T : underlying event activity dominated by MPI contributions.
- And similar in towards and transverse regions.
- Average particle and energy density for dimuon p_T as a function of CM energy in the combined towards and transverse region.

- POWHEG + PYTHIA8 Without MPI : contribution from radiation very small.
- Increase of MPI activity well reproduced by POWHEG + PYTHIA8.
- Overestimated by POWHEG + HERWIG++.

Particle and p_T sum density (with $p_T^{\mu\mu}$ < 5 GeV) as a function of CM energy for data and various simulations.

Conclusion

- Measurement of UE activity at 13 TeV using inclusive Z Boson event and leading jet/track at 13 TeV is presented.

- Underlying event measurements
  - ✓ Probe the dynamics of hadron production with increasing precision.

- Sensitivity to the parton densities at small x and small scale, Initial State Radiation, Final state radiation and Multiple Parton Interactions

- Various observables enable to measure these different components independently from each other.

- Results are valuable inputs to further constrain phenomenological models used to describe the particle production at low $p_{T.}$


Thank You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CMS Publications

- **Underlying Event Measurements with Leading Particles and Jets in proton-proton collisions at s= 13 TeV, CMS-PAS-FSQ-15-007.**
- **Measurement of the underlying event using the Drell-Yan process in proton-proton collisions at s = 13 TeV, CMS-PAS-FSQ-16-008**