Underlying Events Measurements @ LHC

Sunil Bansal
UIET, Panjab University

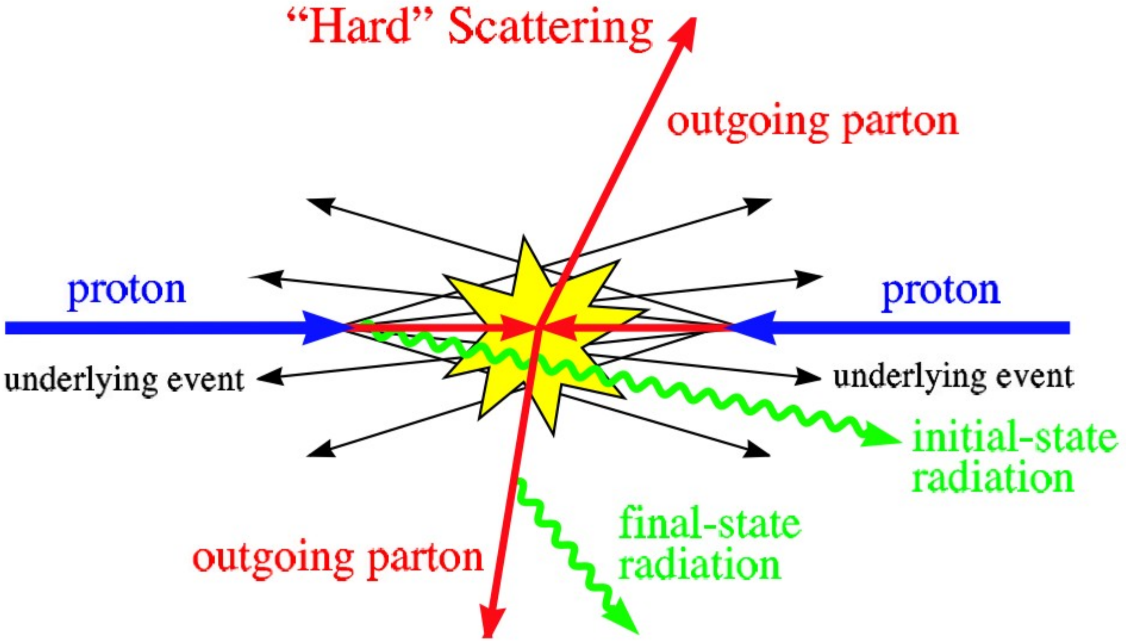
Discussion Meeting on Jets@LHC, 21-28th January, 2017
ICTS, Bengaluru

Outline

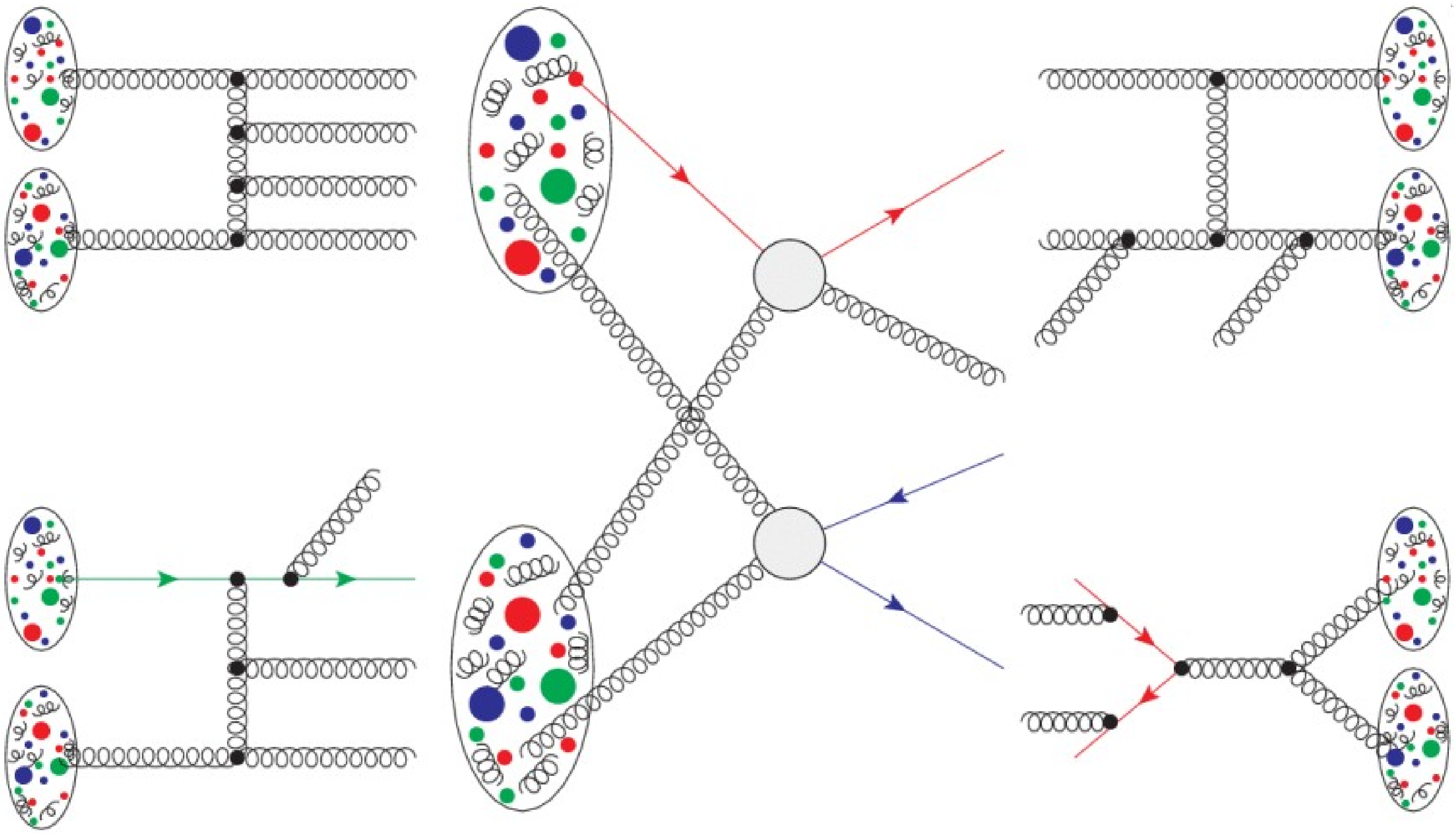
- Description of underlying events
- Experimental results (CMS/ATLAS)
  - leading jet/track
  - Drell-Yan
  - top-quark pair
  - Forward rapidity measurements
- Summary and Outlook in context of jets

Hadron-Hadron Collision

- ✔ parton – parton interactions which produce particles of interest i.e. W/Z, Higgs, species of SUSY jungle. (Hard scattering)
- ✔ Radiation from incoming partons. (ISR)
- ✔ Radiations from outgoing partons. (FSR)
- ✔ Spectator partons. (beam remnants)



Multiple Partons Interaction (MPI)



Large parton densities in proton: significant probability of more than one parton-parton scattering in same pp collision, so called MPI.

MPIs are same as HI, can produce from low pT particles to top-quarks

Underlying Events (UE)

- ✔ MPI, usually produce low p_T particles.
- ✔ Experimentally, not possible to distinguish particles coming from MPI, ISR/FSR and BBR.

- ✔ **UE ≡ MPI + Contribution from (ISR + FSR + BBR)**

Importance of UE

- Hadron sub-structure.
- Vertex identification in processes involving neutral particles in final states i.e. $H \rightarrow \gamma\gamma$.
- Affect isolation of leptons and photon.
- Affect jet energy scale.
- Hard MPI produces possible background processes for new physics searches i.e. same-sign WW
- Need proper modeling of UE in Monte-Carlo event generators.

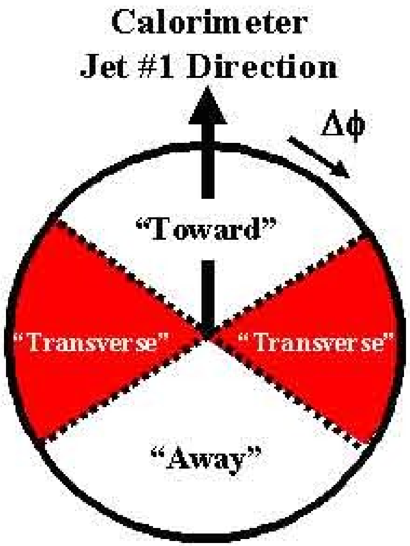
UE dynamics to understand

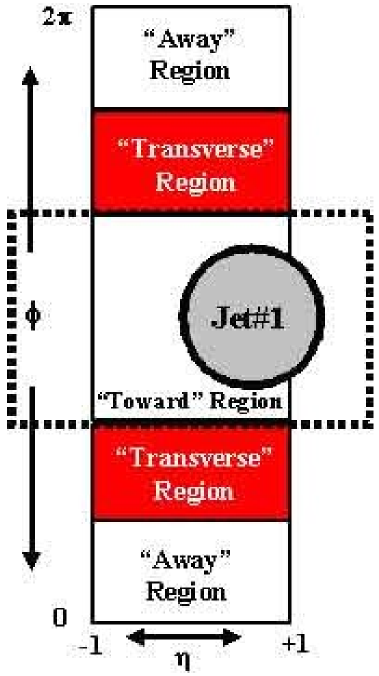
- Quantification of UE: number of particles and their transverse momentum.
- Variation with scale of the hard interaction.
- Variation with collision energy.
- Dependence on the nature of hard interaction.

Need range of UE measurements for proper understanding of these effects and their modeling in MC event generators.

Conventional Method for UE measurements

- Identify process to define hard interaction: leading jet/track, Drell-Yan, top-quark
- Identify regions with higher MPI sensitivity.
- Measure number of charged particles and their p_T as a function of the scale of interaction.

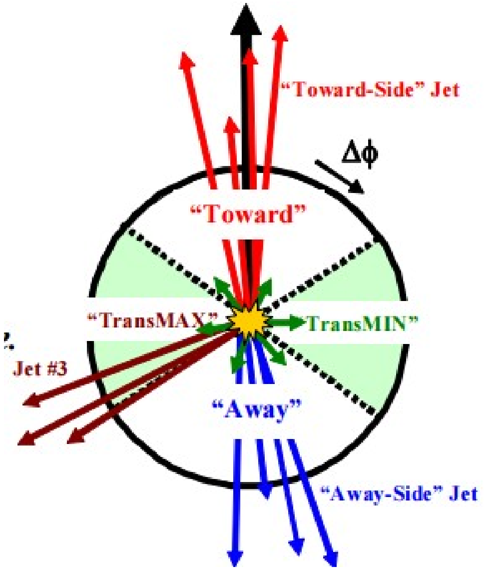


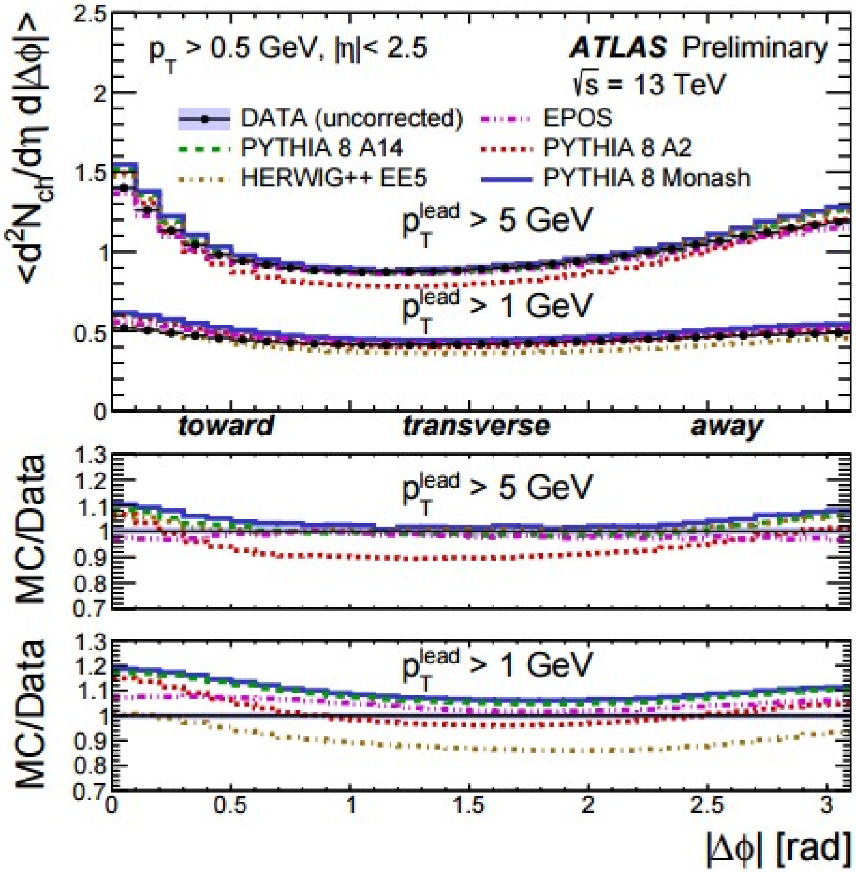


UE measurement with leading jet/track

UE measurement with leading jet/track

- Highest p_T jet / track is used to define scale and reference direction.
- Jet/track p_T defines the scale of event.





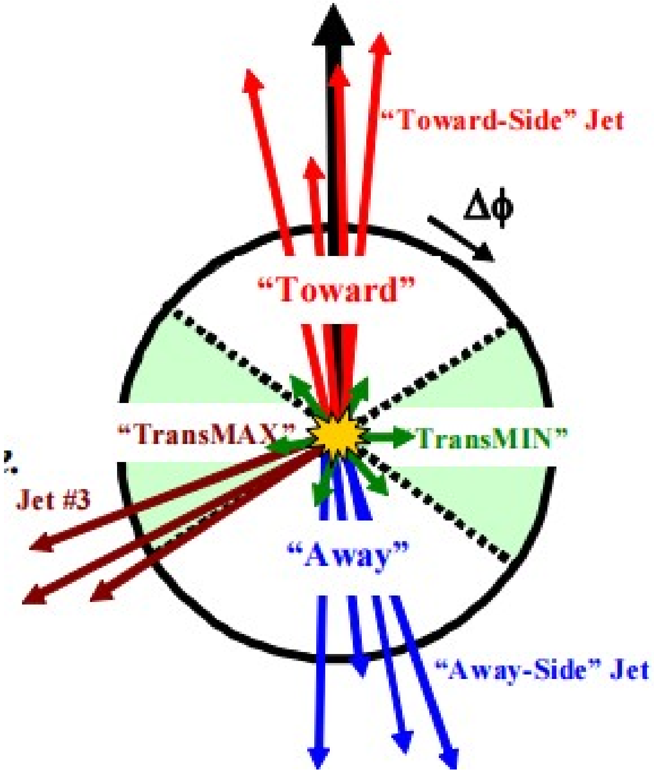
- **Away region:** dominated by recoiled hadronic activity.
- **Towards region:** dominated by leading jet/track
- **Transverse region:** spill-over contribution from away side jet and hard jet in case of 3 jet events

UE measurement with leading jet/track

- For 3-jet events: transMin and transMax region

  transMin: sensitive to MPI + BBR

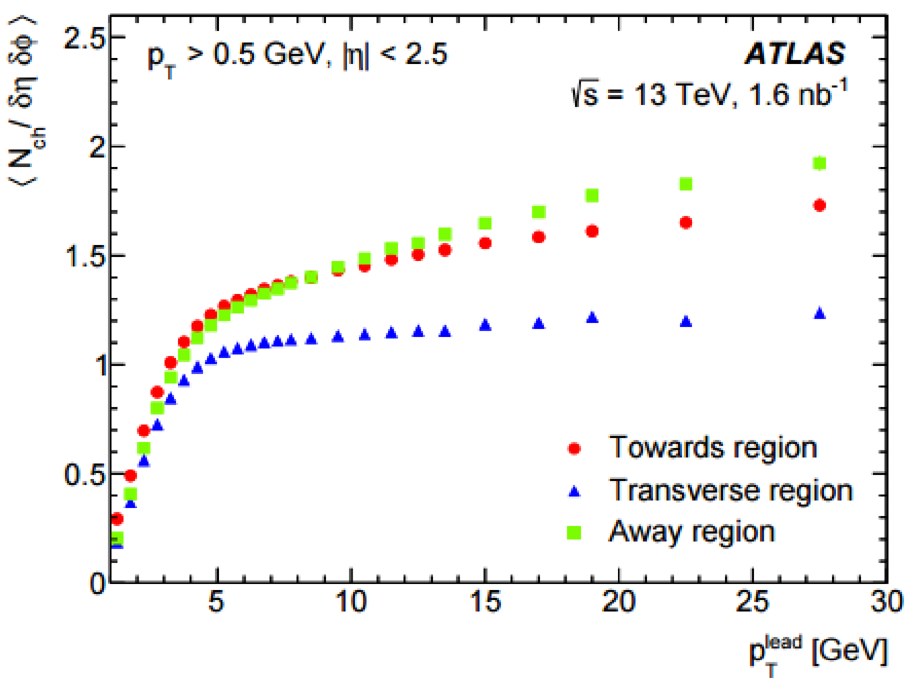
  transMax-transMin: sensitive to ISR & FSR

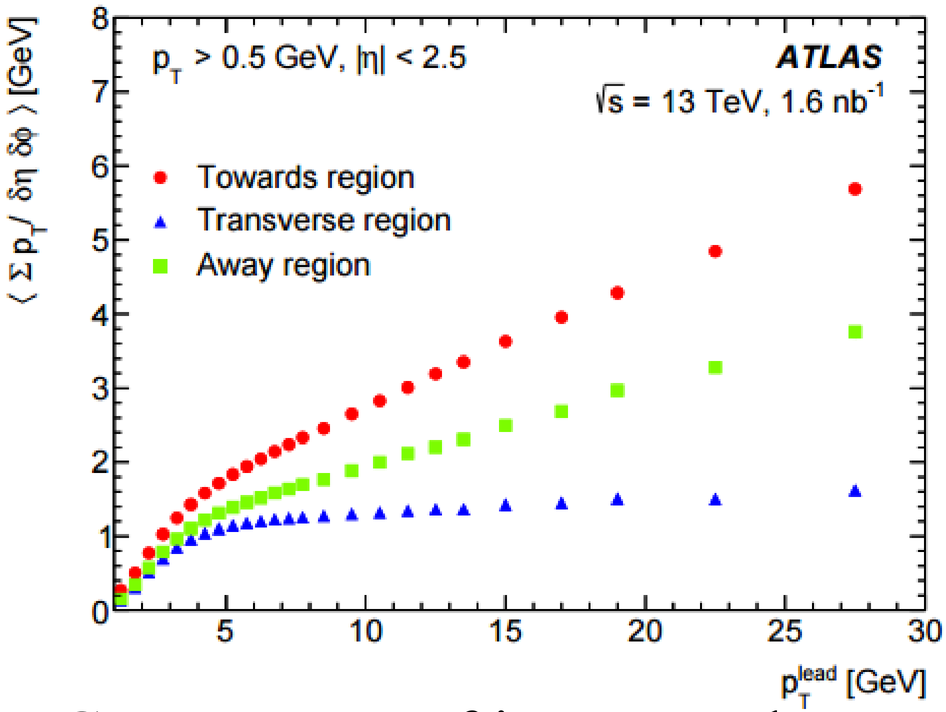


- Particle production is measured in away, towards, transDiff, and transAvg region.

UE as a function of leading jet/track pT

- ✔ Faster rise in towards and away region as compared to transverse region.

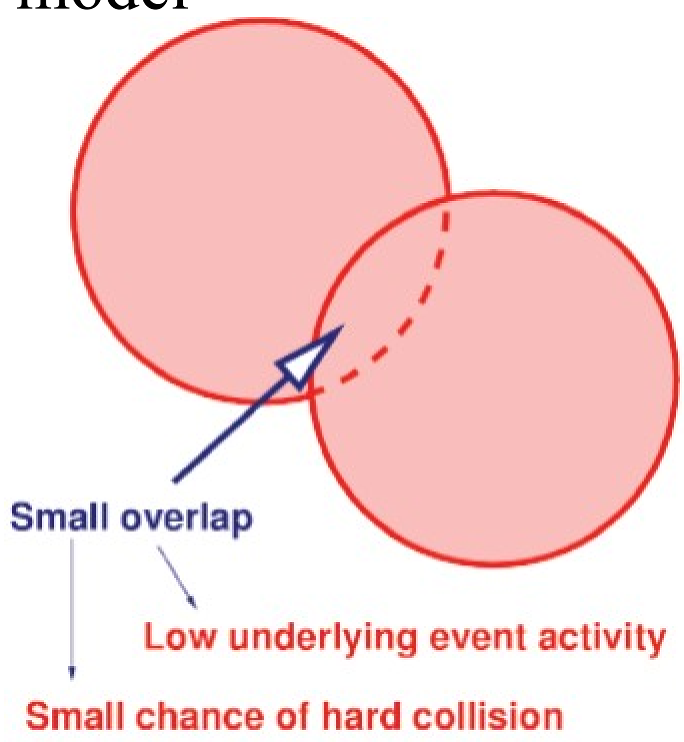


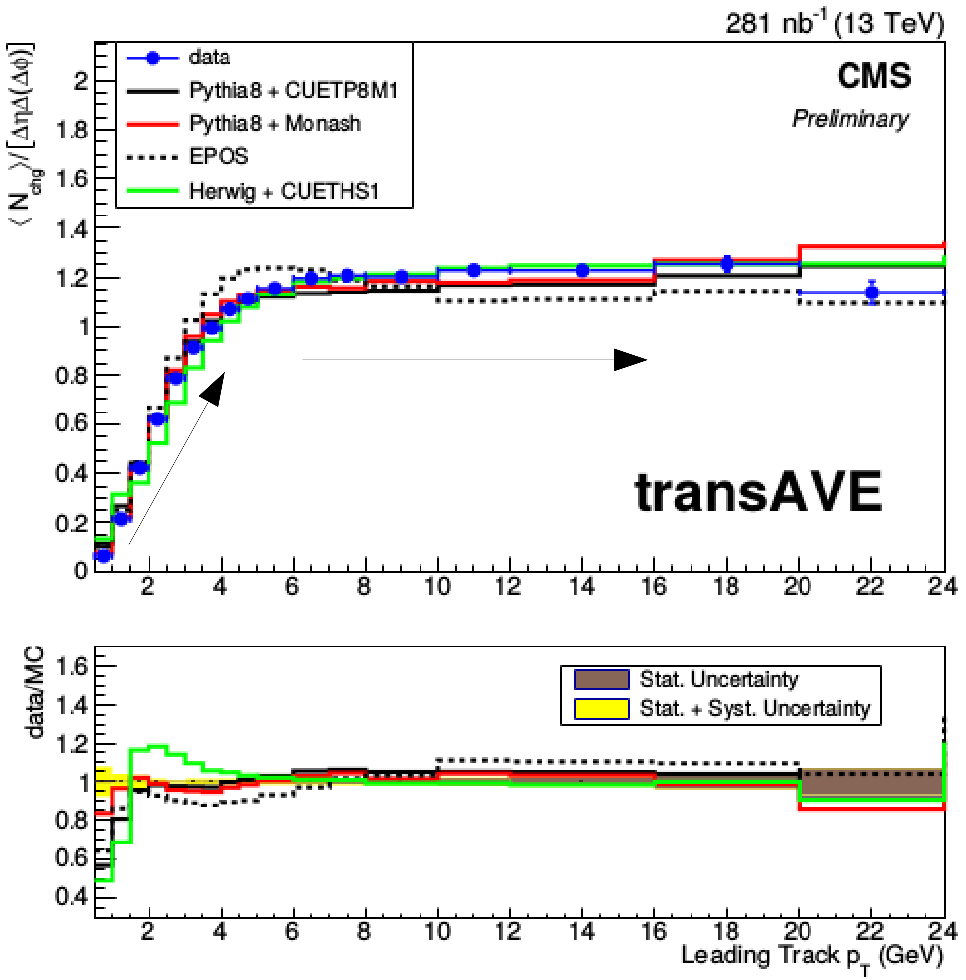


- ✔ Rate of increase changes about 4-5 GeV; source of increase changes from MPI → radiation
- ✔ Interestingly, away region has higher particle multiplicity ($p_T > 7$ GeV) despite not containing highest p_T particle.

UE as a function of leading jet/track p_T

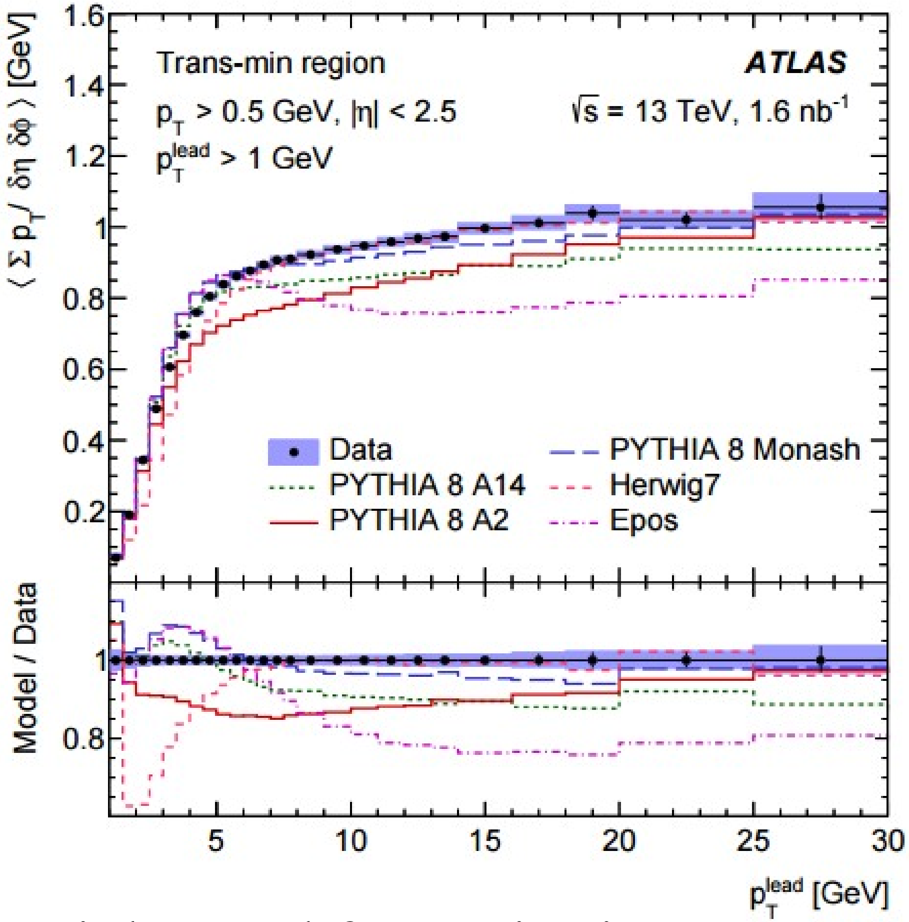
- ✔ Activity increases sharply first then reaches a plateau.
- ✔ Explained on the basis of overlap model



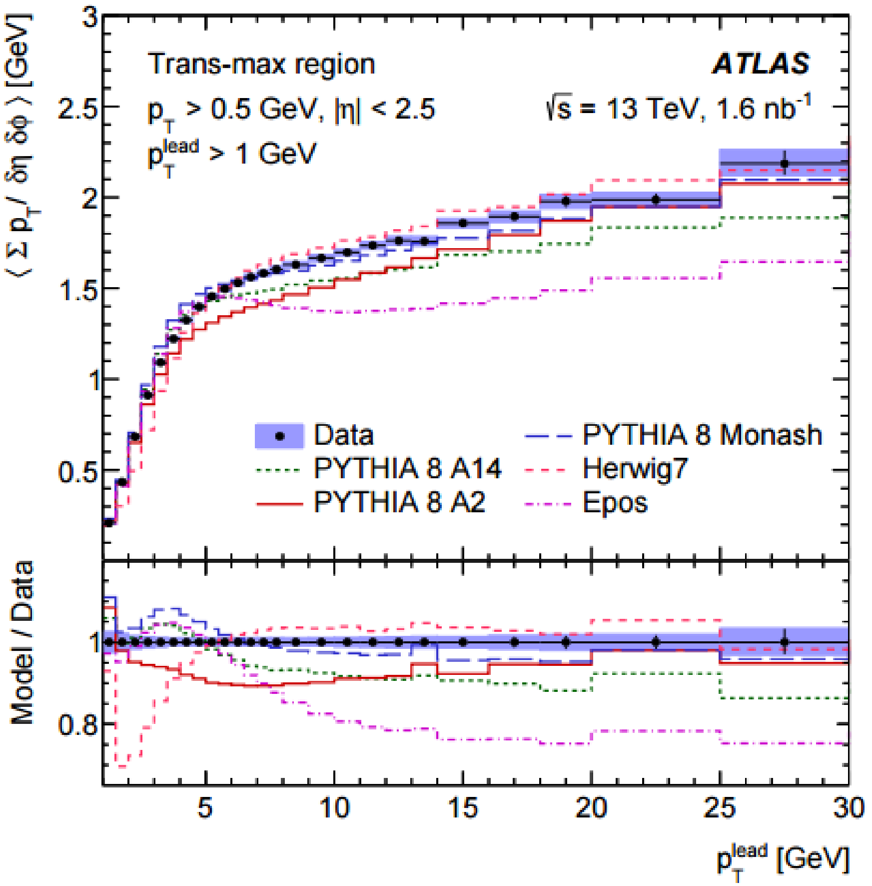


UE as a function of leading jet/track p_T (Σp_T density)

transMin



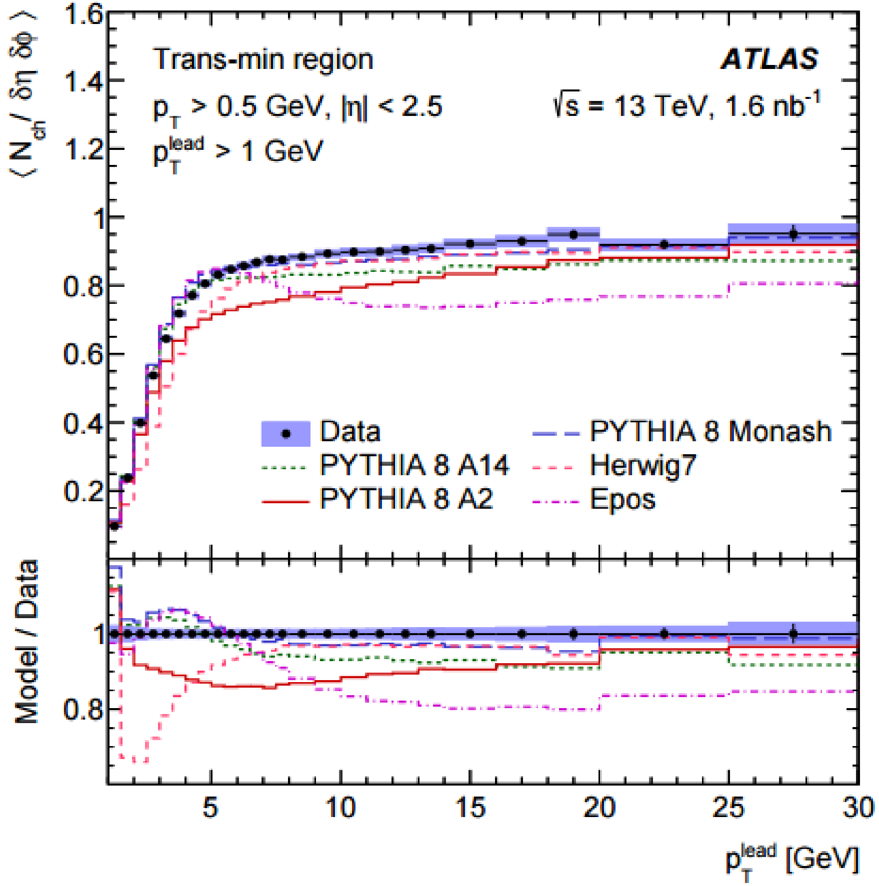
transMax



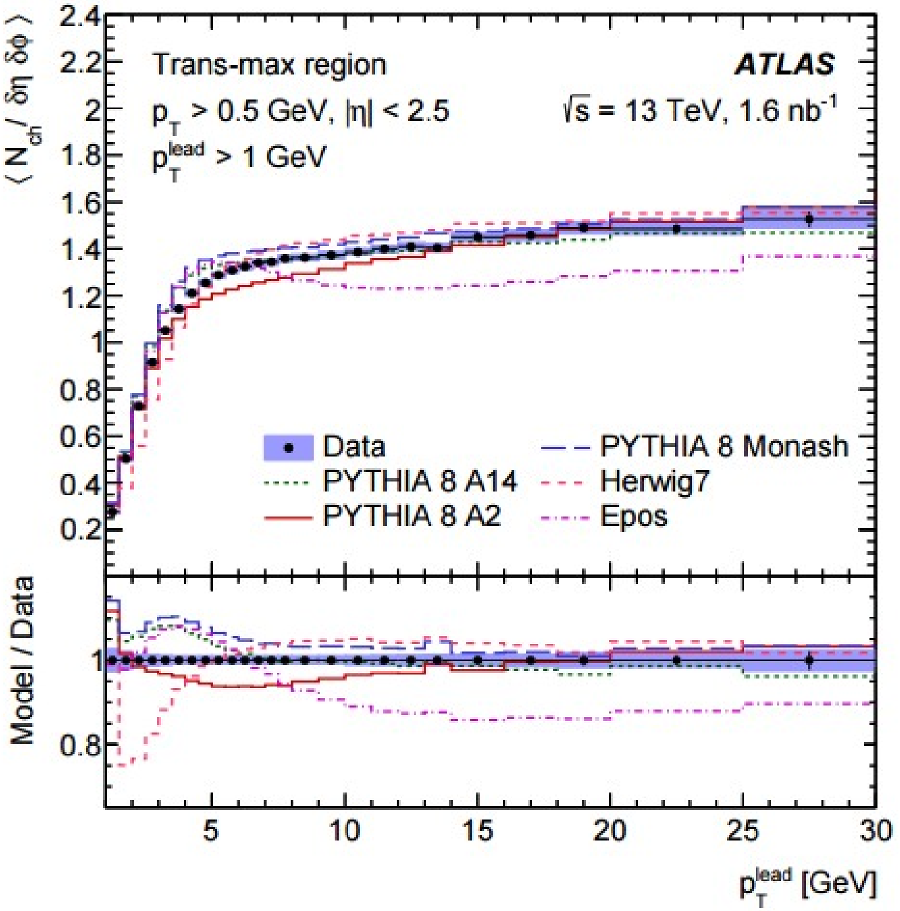
- Higher and faster rise in transMax region.
- Monash tune doing a good job, EPOS fails at higher p_T, Herwig7 fails at low p_T. Need further tuning of model parameters.

UE as a function of leading jet/track p_T (particle density)

transMin



transMax



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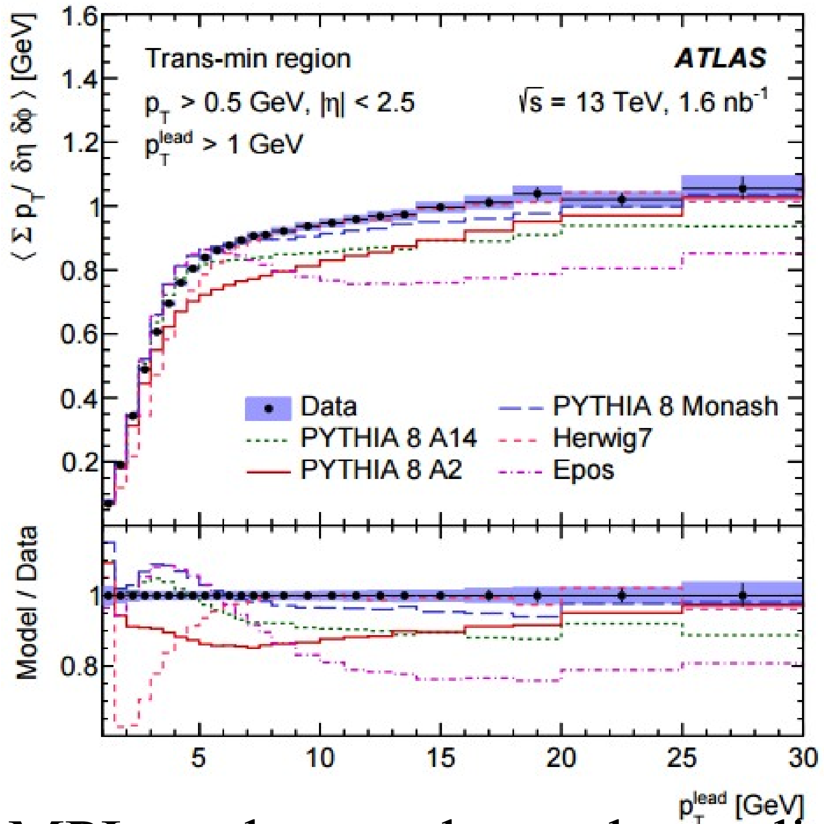
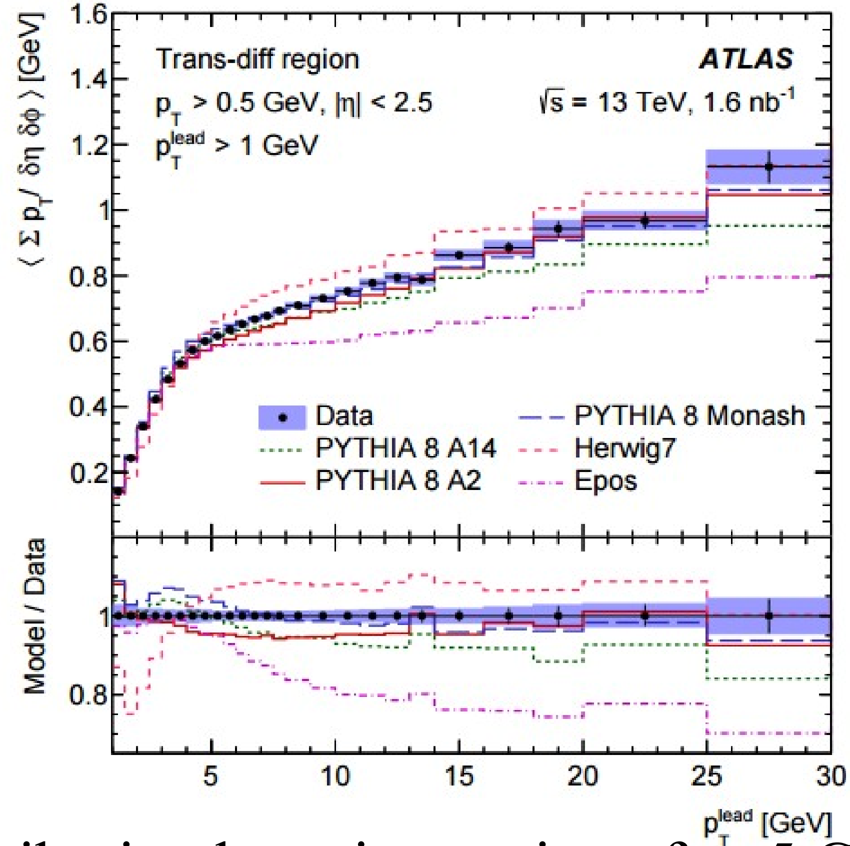
UE as a function of leading jet/track p_T (Σp_T density)

transMin

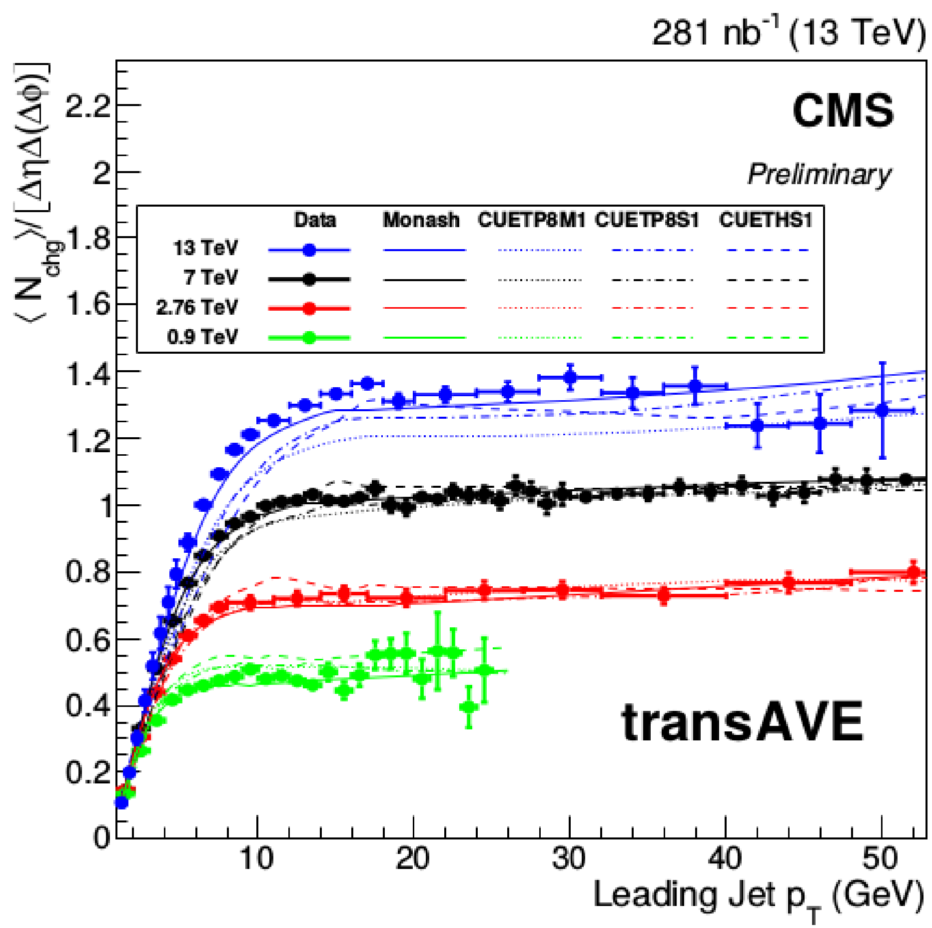


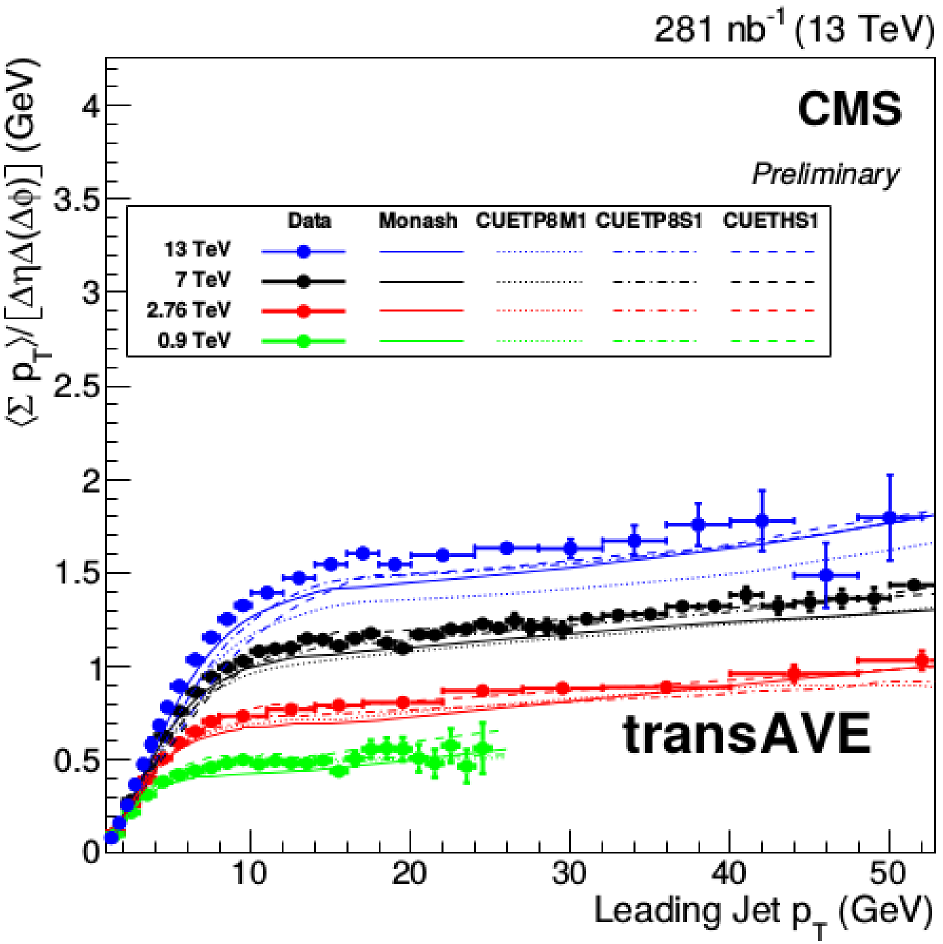
TransMax-transMin



- MPI reaches at plateau but radiation contribution keep increasing after 5 GeV. Below 5 GeV, MPI rise is faster than radiation.
- Monash tune doing a good job, EPOS fails at higher p_T, Herwig fails at low p_T.
- Need further tuning of model parameters.

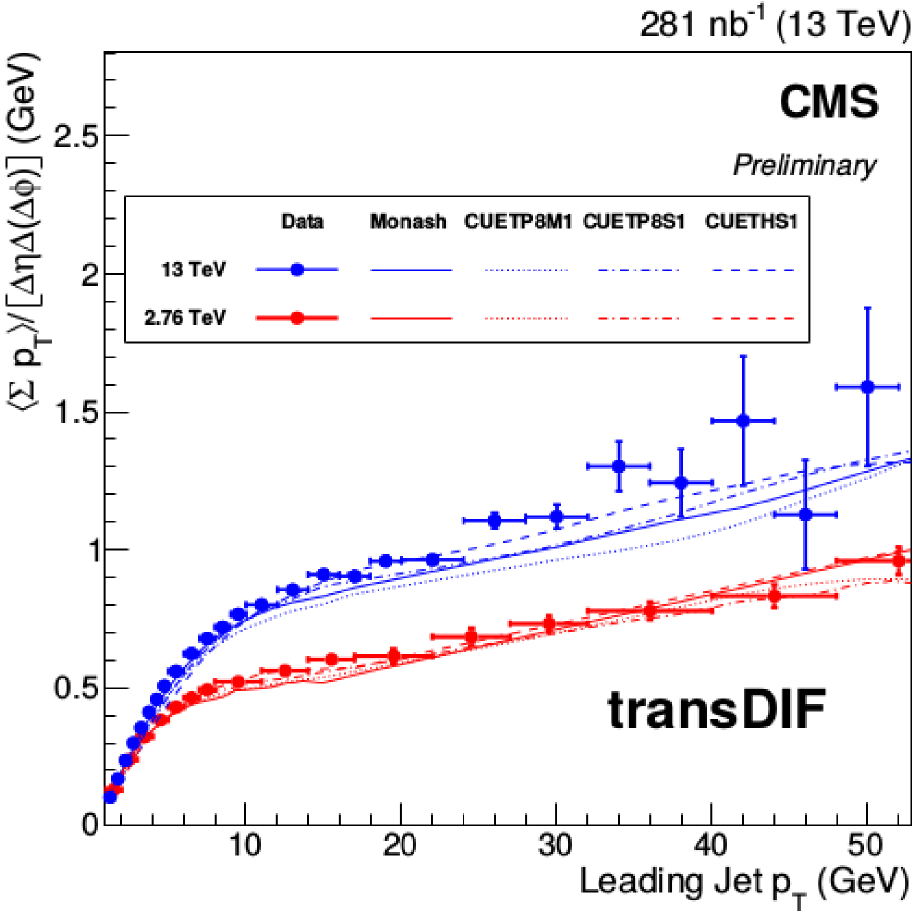
UE as a function of leading jet/track p_T (collision energy dependence)

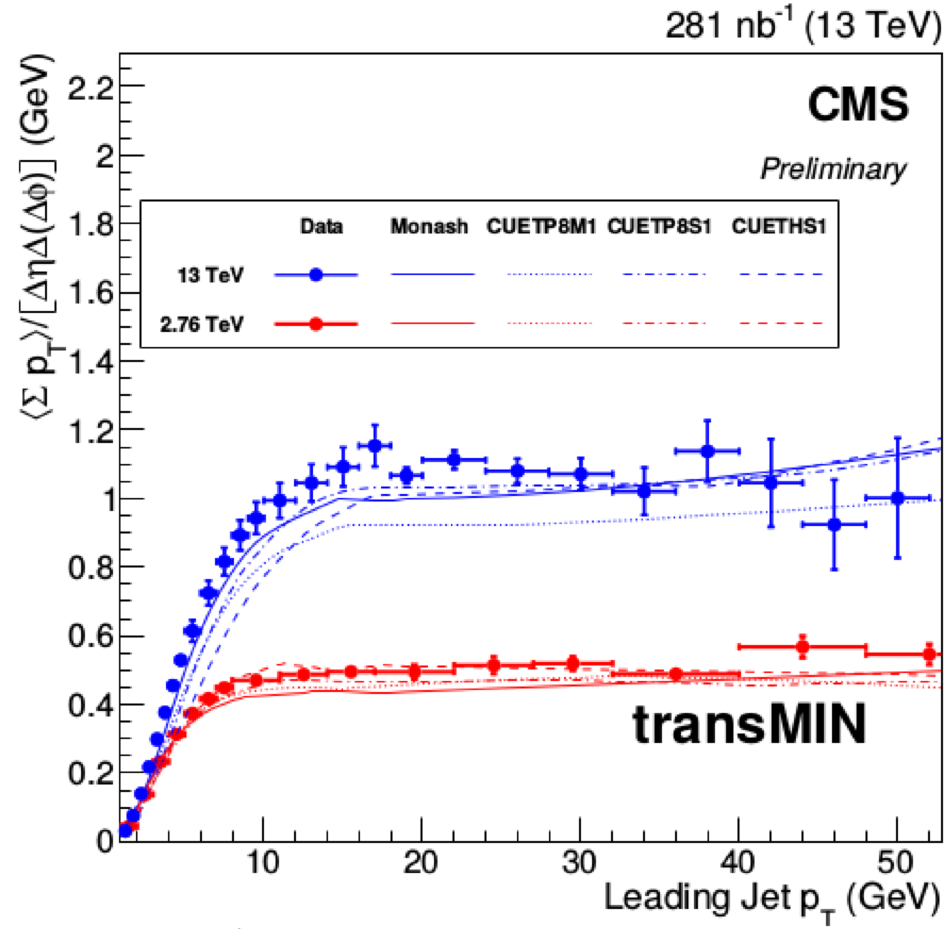




- 3-5 times increase in activity as collision energy increases from 0.9 to 13 TeV.
- Monash tune doing good job in reproducing collision energy dependence.

UE as a function of leading jet/track p_T (collision energy dependence)



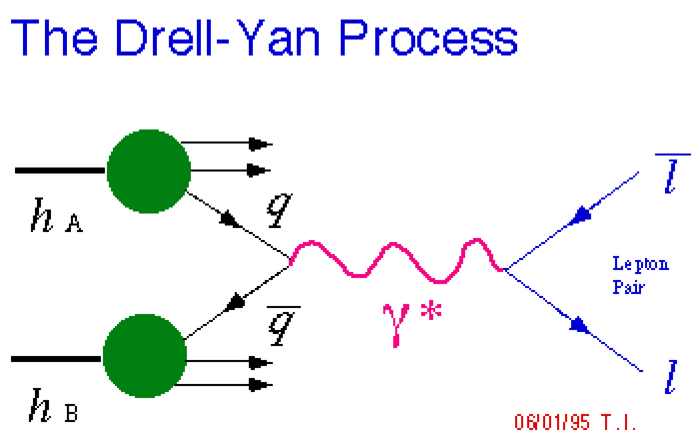


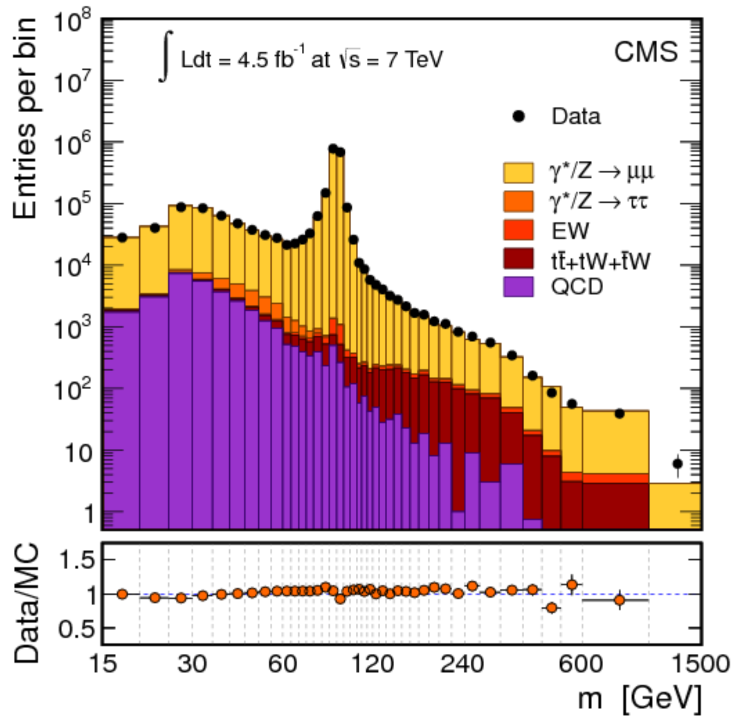
- Faster rise in radiation contribution with event scale.
- Increase in MPI is more than radiation contribution with collision energy.
- Energy dependence of radiation contribution is better described by MCs but that for MPI need further optimization.

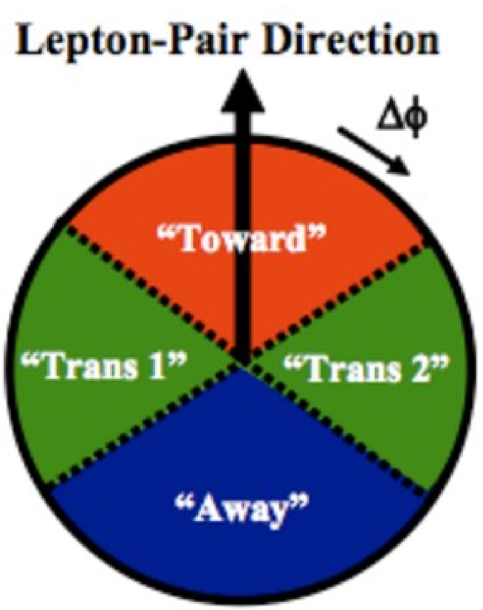
UE measurements with Drell – Yan

UE in Drell - Yan

- Theoretically understood and experimentally clean process.
- No final state radiation.
- Possibility of partial separation of MPI from radiations.
- Negligible backgrounds.
- Leptons are excluded while constructing UE observables.

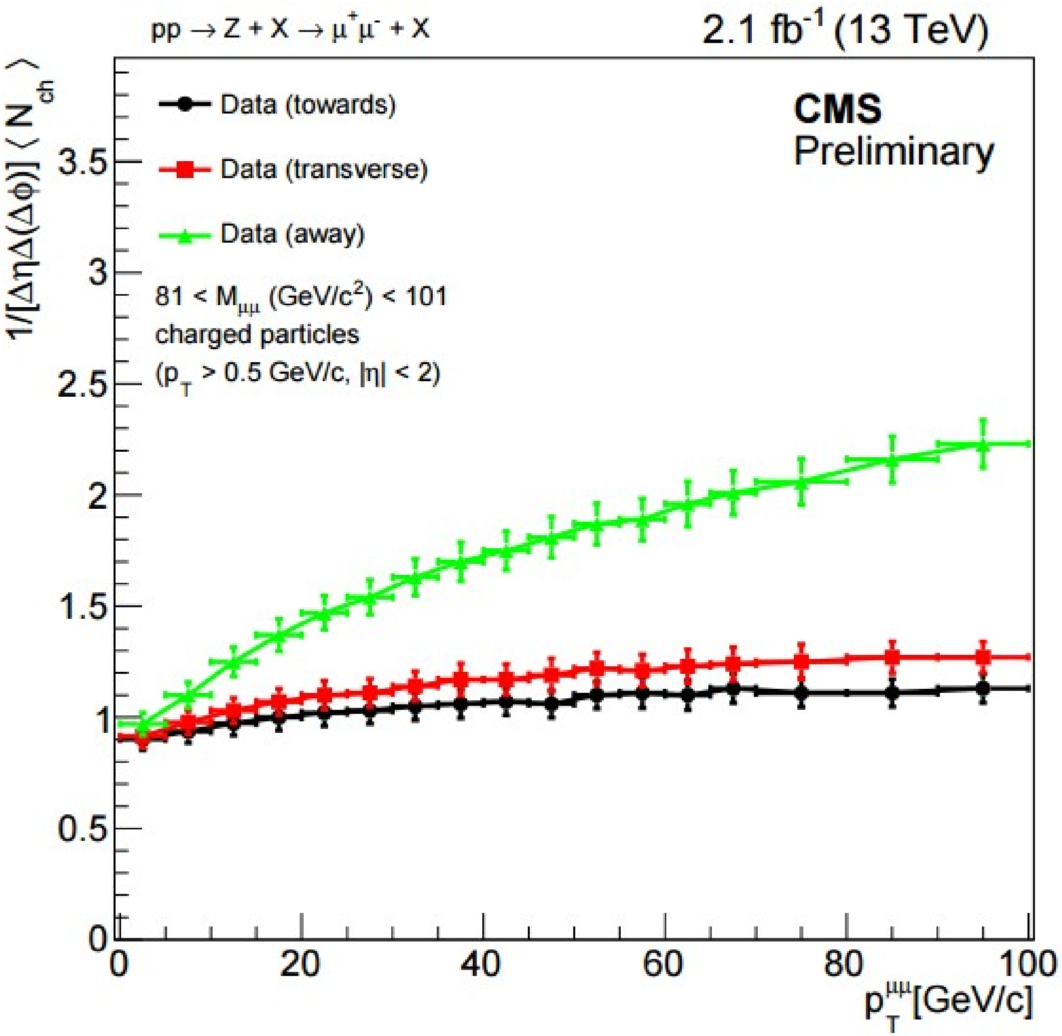






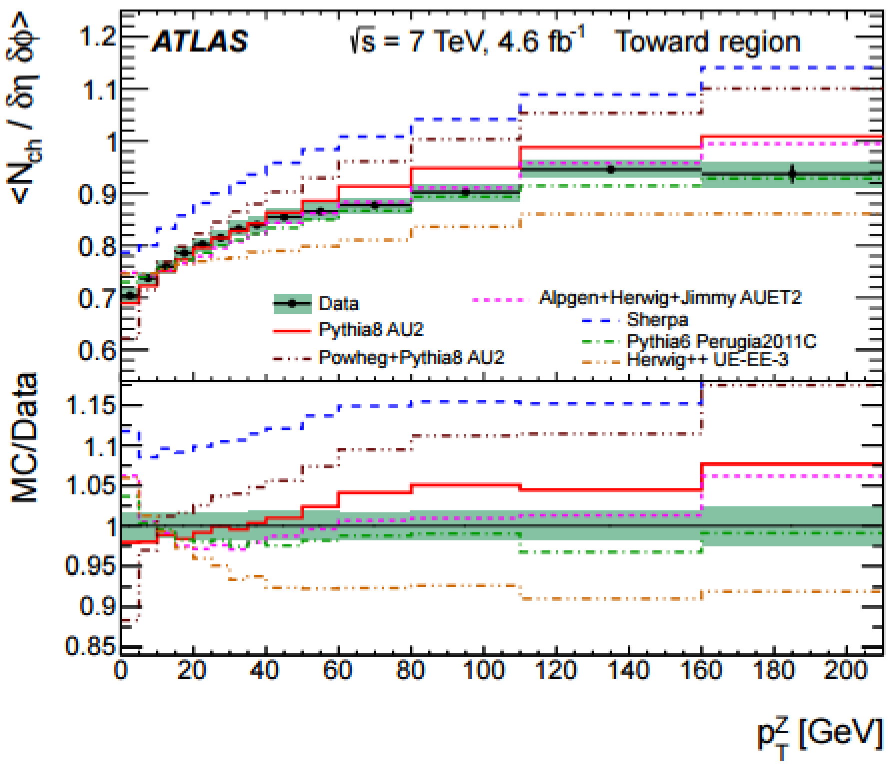
UE as a function of $p_T^{\mu\mu}$

- ✔ Unlike leading jet/track, UE do not start from 0, as initial scale is set by invariant mass.
- ✔ Activity sharply increases with $p_T^{\mu\mu}$ in away region: recoiled hadronic activity.
- ✔ Transverse region get spill-over contribution from recoiled hadronic activity.
- ✔ Unlike leading jet/track, towards region also sensitive to MPI.
- ✔ $p_T^{\mu\mu} \rightarrow 0$, all regions have same activity.

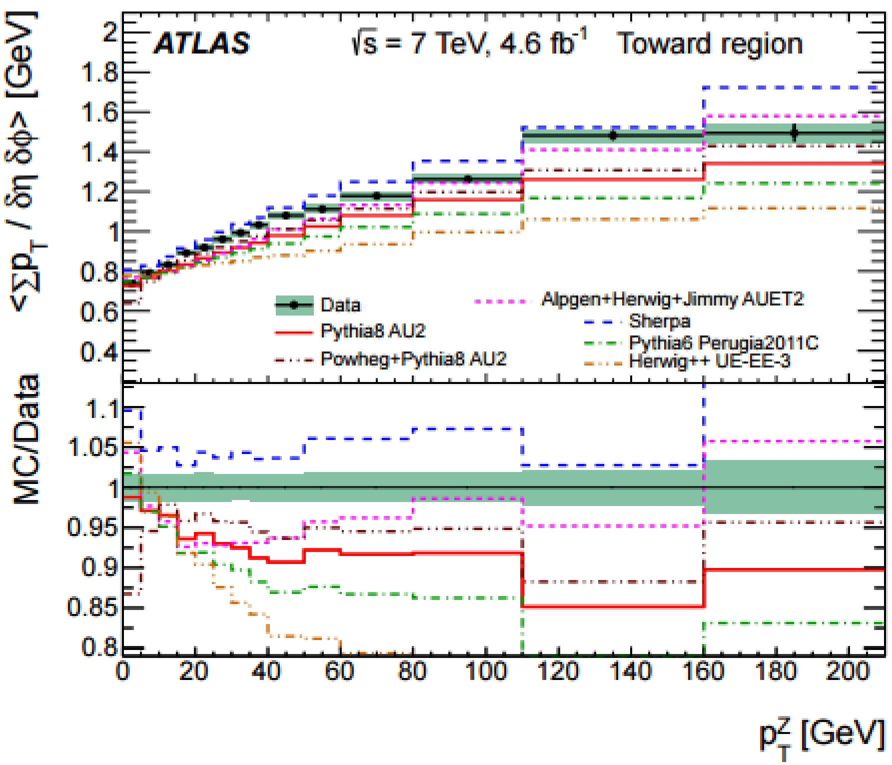


UE as a function of $p_T^{\mu\mu}$

Particle density

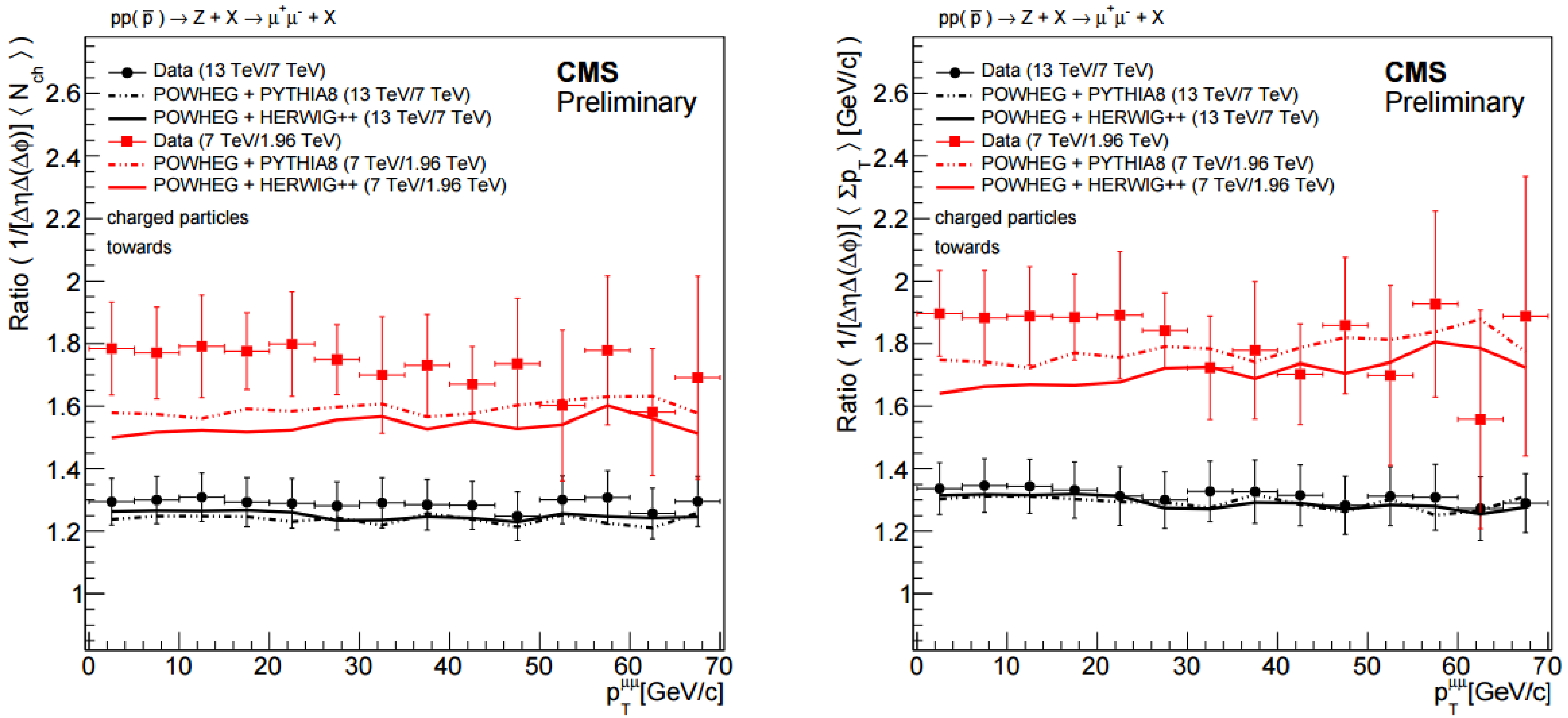


Σp_T density



- Strain in different generators and tunes, measurements will be useful in further tuning.

UE as a function of $p_T^{\mu\mu}$ (collision energy dependence)

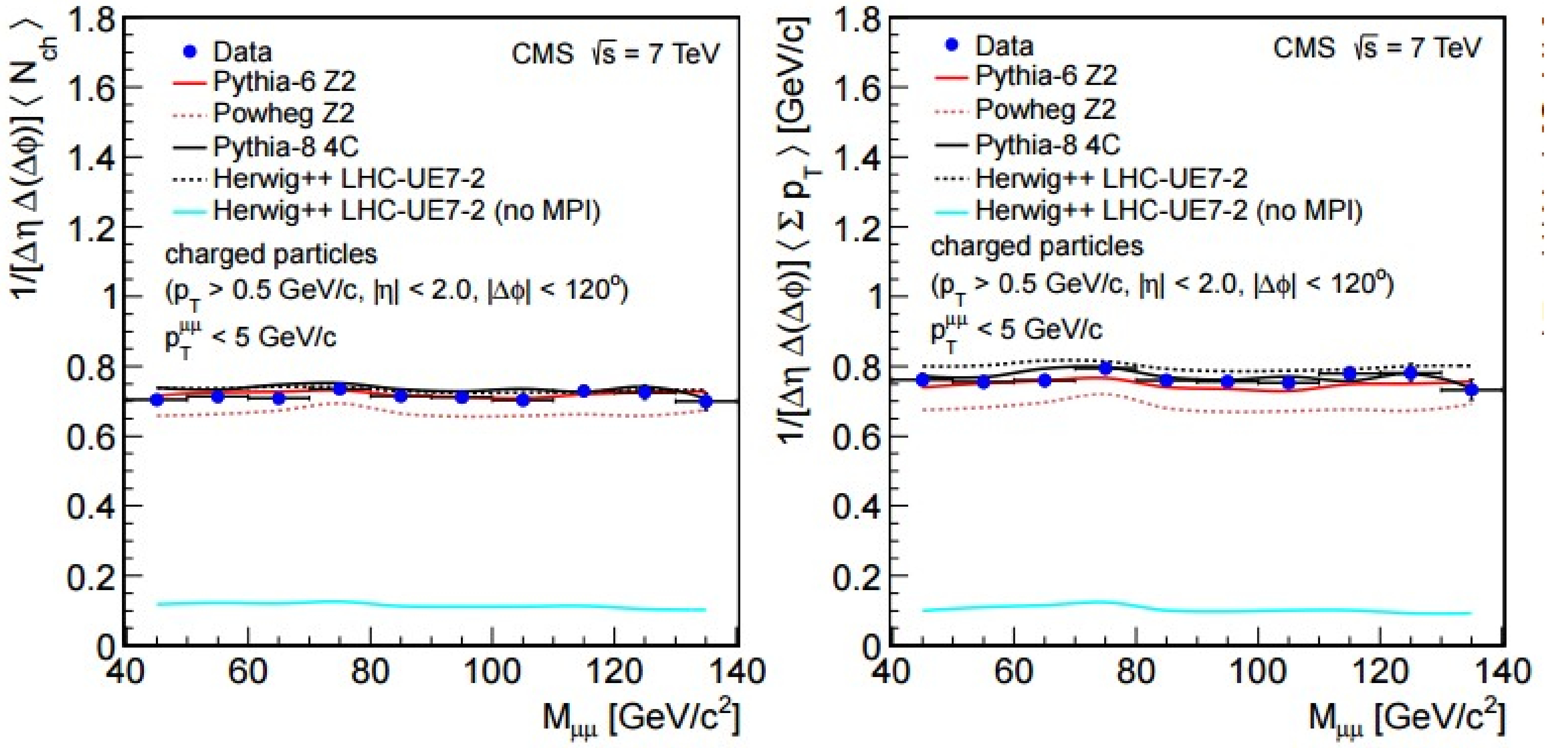


- **To quantify increase in UE : $(UE)_{13\ TeV}$ / $(UE\ activity)_{7\ TeV}$ & $(UE\ activity)_{7TeV}$ /$(UE\ activity)_{1.96\ TeV}$ for both simulation and data.**
- **From 7 TeV to 13 TeV : 20-25% rise in particle and p_T - sum density described by POWHEG + PYTHIA8, POWHEG + HERWIG++ .**
- **From 1.96 TeV to 7 TeV : 60-80% rise for both particle and $p_{T\_}$ sum density.**
- **Simulation predicts slower rise, but agreement better at higher $p_T^{\mu\mu}$**

UE as a function of $M_{\mu\mu}$

- With $p_T^{\mu\mu} < 5$ GeV, particle production is flat as a function of $M_{\mu\mu}$.
- About 80% contribution of MPI + BBR.

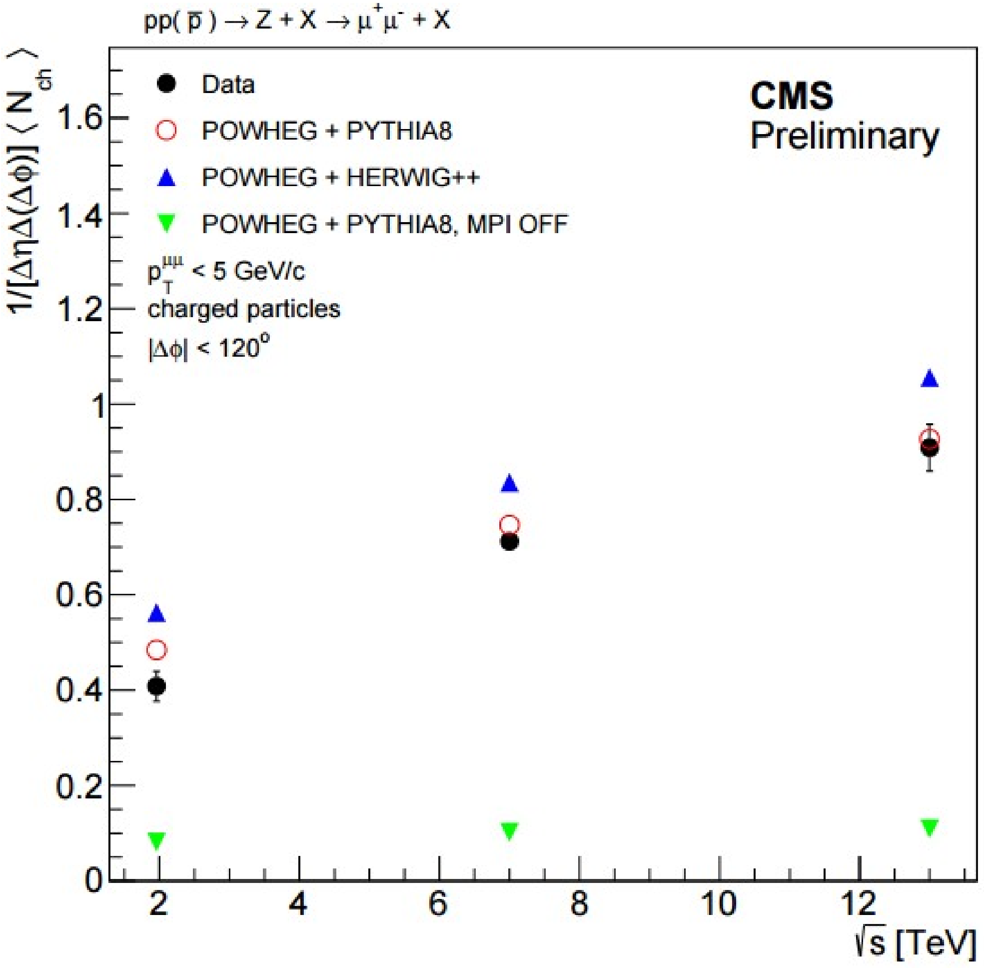
particle density   energy density



- Corroborates UE universality

Collision energy dependence

- **Comparison of POWHEG with and without MPI shows : there is only 17% contribution from radiation after requiring dimuon $p_T < 5$ at 1.96 TeV, which decreases to about 12% at 13 TeV.**
- **Logarithmic increase in UE activity with CM energy, which is qualitatively reproduced by MC.**
- **2.1 times increase in data, 1.91 times increase in POWHEG + PYTHIA8, 1.87 times increase in POWHEG + HERWIG++, as CM energy is increased from 1.96 TeV to 13 TeV.**
- **POWHEG + PYTHIA8 shows better agreement with measurements at all collision energies.**
- **POWHEG + HERWIG++ is describing data within 37% at 1.96 TeV, within 17% at 7 TeV and 21% at 13 TeV.**

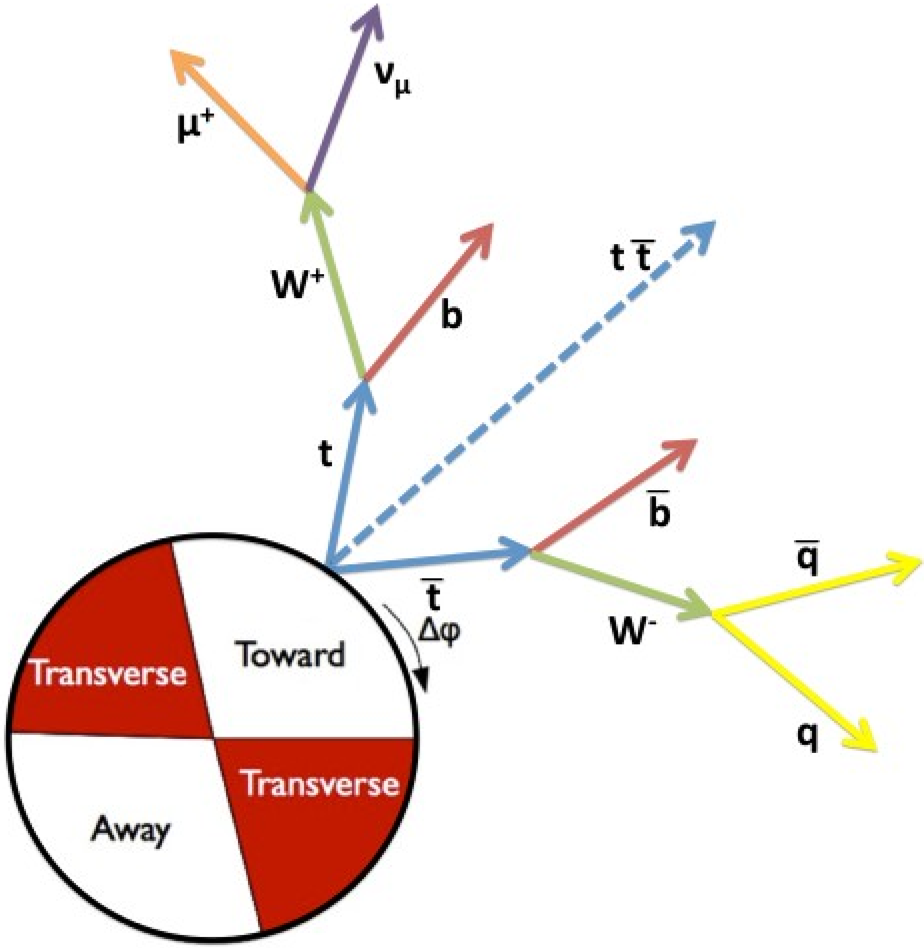


UE measurements for top-pair events

UE measurements for top-pair events

Motivation:

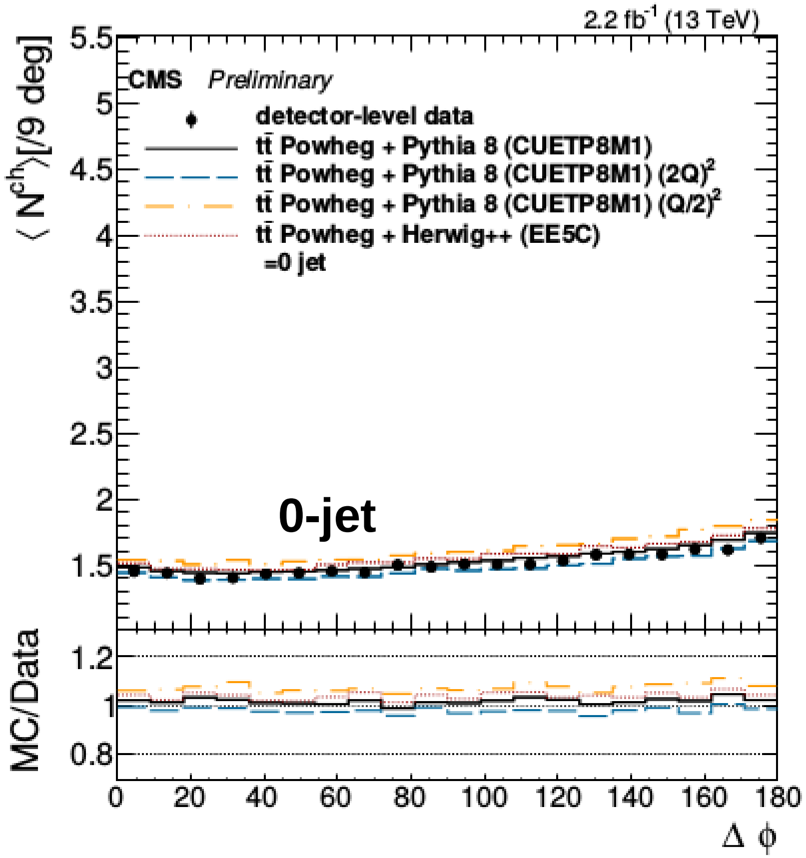
- Highest event scale explored for UE measurements.
- First UE results involving heavy-quark, description of b quark fragmentation and hadronization.
- UE universality..

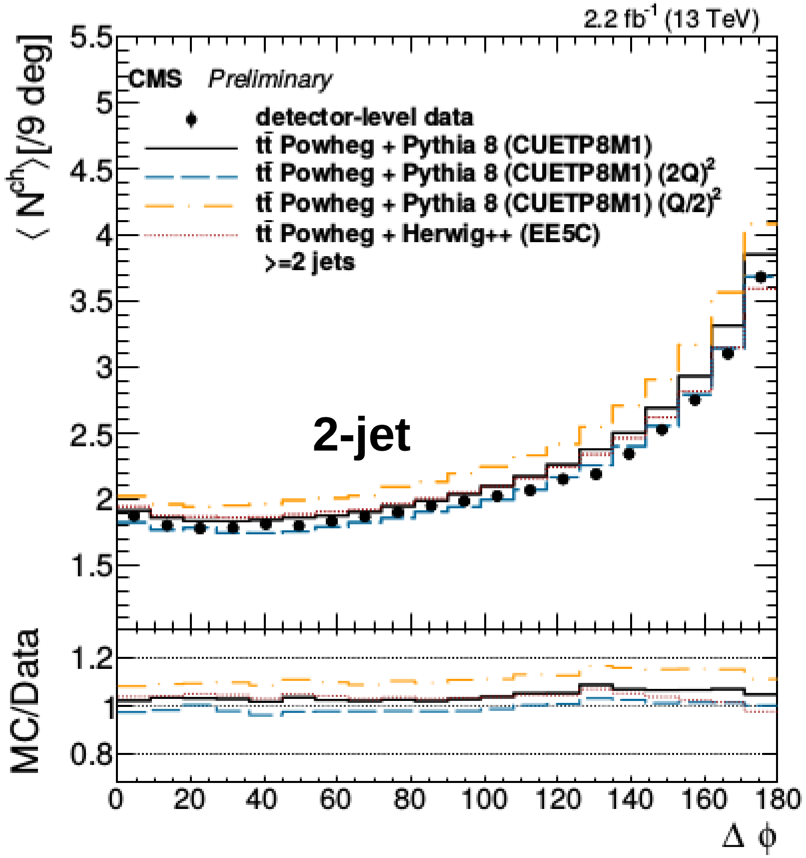


✔ 1 μ + atleast 4 jets (2 b jets)

✔ p_T (ttbar) = p_T^{μ} + p_T (jets) + MET

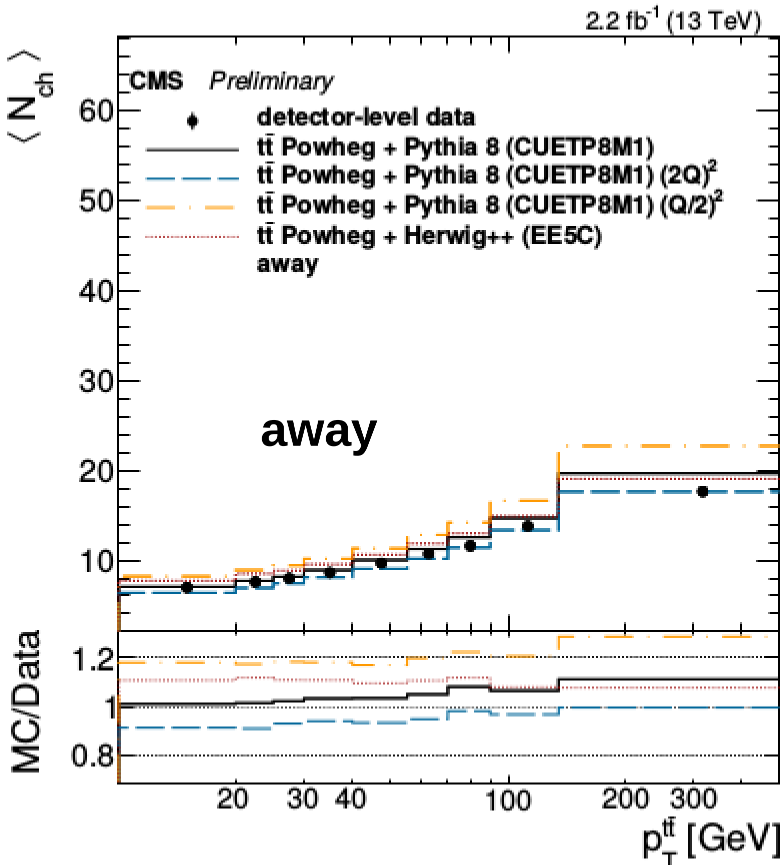
Azimuthal distribution for top-pair events

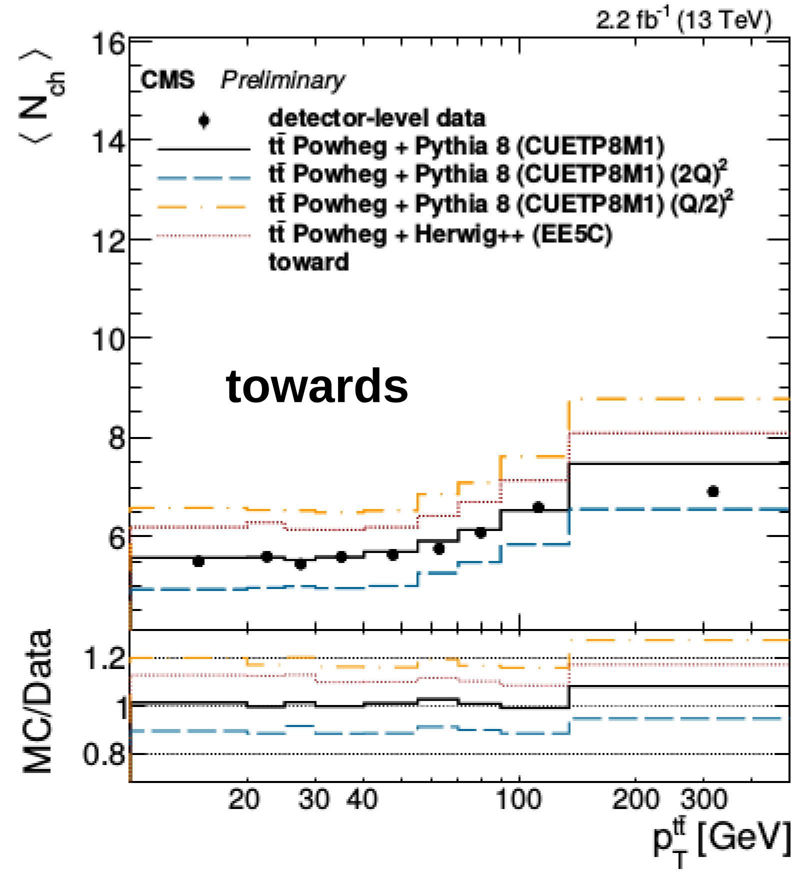




- ✔ Flatter distribution for 0-jet events.
- ✔ Smaller sensitivity to matching scale variation.
- ✔ Good descriptions by Powheg + Py8 and Powheg + HerwigPP

UE activity as a function p_T(tt)



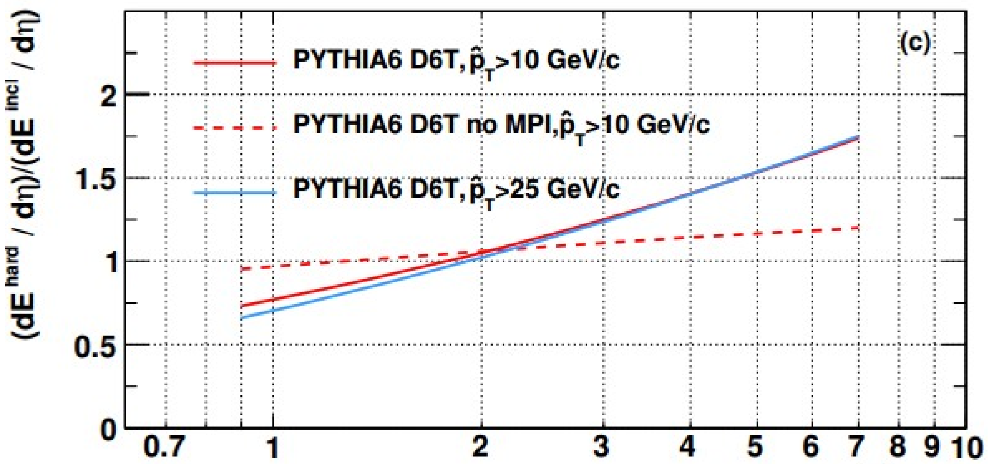


- ✔ Faster rise in away region.
- ✔ Powheg + Py8 gives better agreement. No need to have separate tune for events with heavy quarks
- ✔ Dependence on the scale variation, can be used to optimize the matching scale.

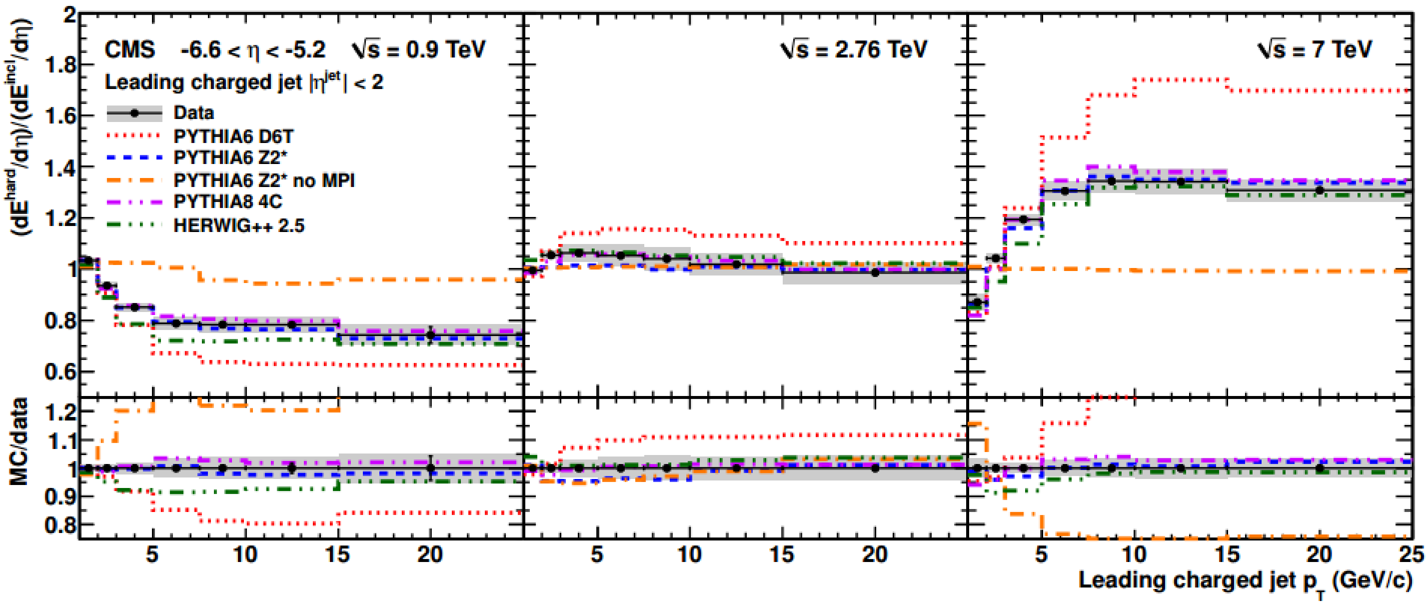
UE in forward rapidity using CASTOR detector

UE in forward rapidity

Compare energy density in forward calorimeter ($-6.6 < \eta < -5.2$, using CASTOR) for events with a central leading charged jet ($p_T > 1$ GeV and $|\eta|<2$) w.r.t. minimum bias events at $\sqrt{s} = 0.9$, 2.76 and 7 TeV. Sensitive to MPI

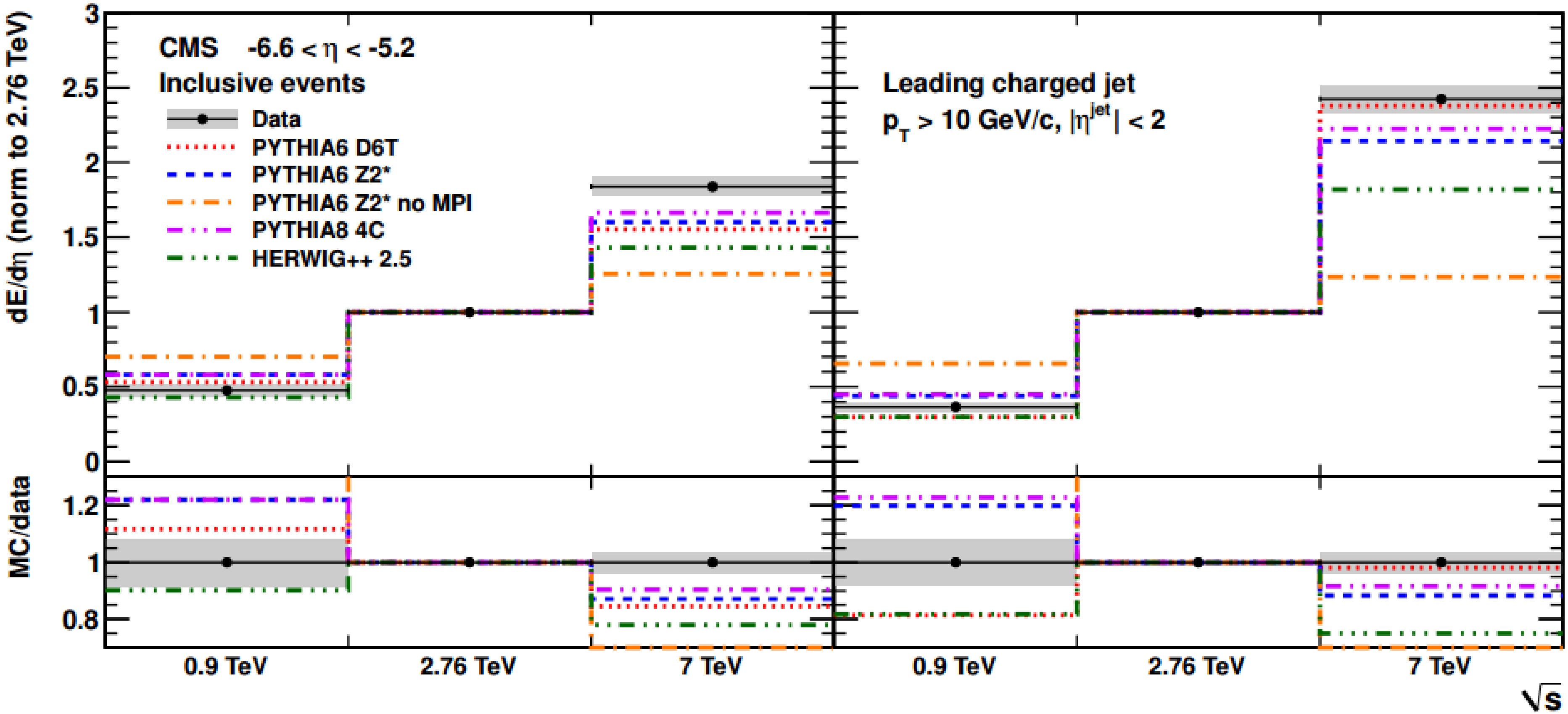


At 0.9 TeV Central jets with high UE activity depletes energy of the proton remnant



At 2.76 and 7 TeV well know UE behavior : fast increase at low pT followed by a plateau

UE in forward rapidity (collision energy dependence)



- ✔ Energy density increase 2 times as collision energy increases from 2.76 TeV and get reduced by 50% at 0.9 TeV.
- ✔ Energy dependence of forward particle production need further tuning.

Summary

- LHC measurements of underlying event observables in Jets, Z-boson, and tt production, and in minimum bias, provide stringent tests of the MPI model.
- Measurements are sensitive to MPI models and to other nonperturbative QCD parameters, and can be used to tune the MC generators.
- Interplay between MPI parameters and PDF, but still much work to do to develop frameworks for fitting together soft QCD parameters and PDF.
- Collision energy dependence, MC need further tuning.
- UE universality is corroborated

UE in Jet Reconstruction

- How much UE contribute in a jet ?
- At what stage of JEC, UE contribution is subtracted? Or we do not need it?
- If yes data driven or tuned MC will be good enough?
- Process, jet flavor, p_T dependence?