Recent measurement of underlying events

13 TeV results with leading charged-particles and jets

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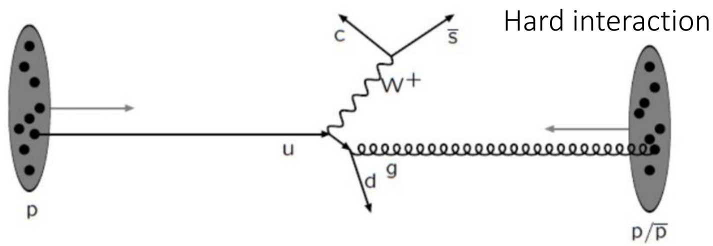
Outline

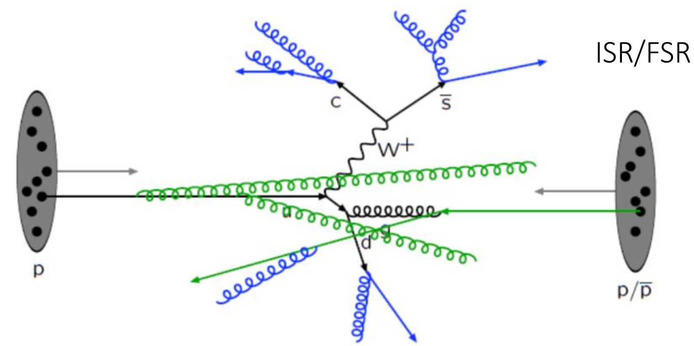
1. Underlying event observables
2. Data/MC samples
3. Event and track selections
4. Data correction
5. Systematic uncertainties
6. Results

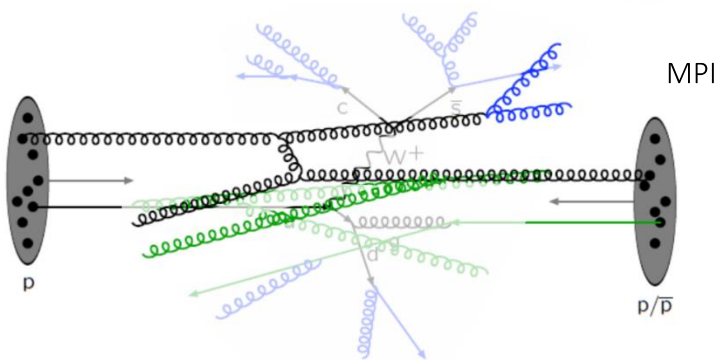
Underlying Event Observables

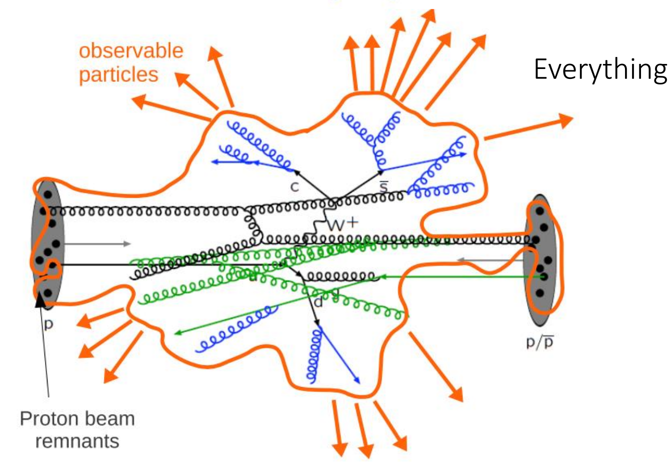
The underlying event:

- Additional activity on top of the hard scattering component of the collision









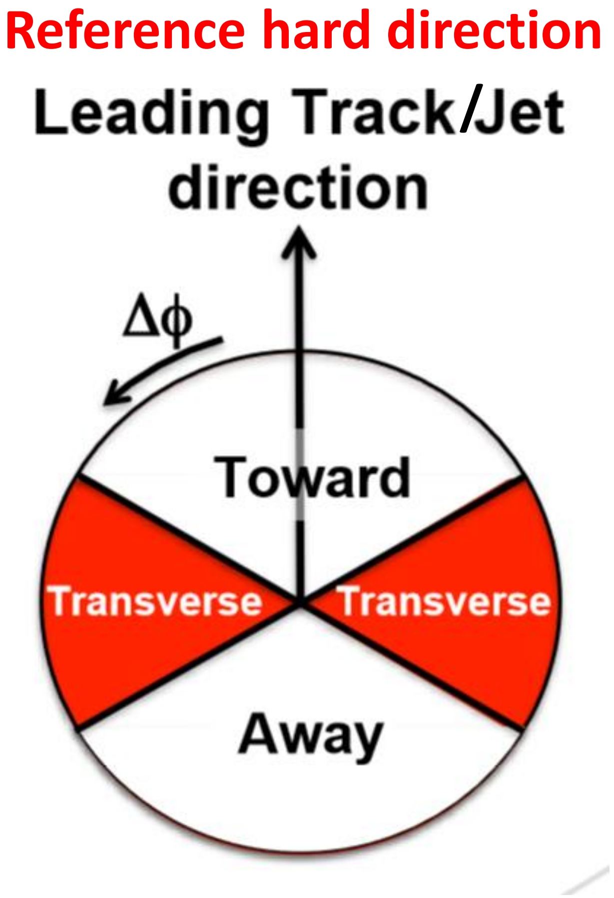
MPI, ISR/FSR, hadronisation, colour reconnections, beam remnants, soft rescattering of beam remnants etc…

Underlying Event Observables

Towards region: $|\Delta\phi| < 60°$

Away region: $|\Delta\phi| > 120°$

Transverse region: $60° < |\Delta\phi| < 120°$



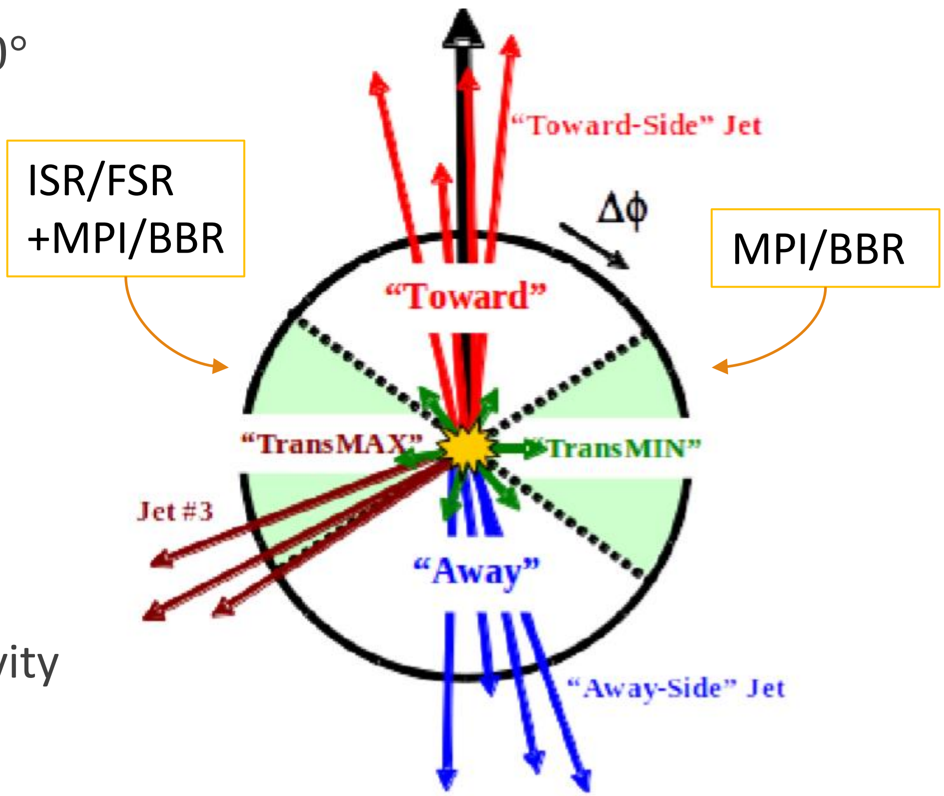
Underlying Event

Towards region: $|\Delta\phi| < 60°$

Away region: $|\Delta\phi| > 120°$

Transverse region: $60° < |\Delta\phi| < 120°$

Reference hard direction
Leading charged-particle/jet



UE observable:

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

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

TransAVE: (*TransMAX+TransMIN)/2* activity

TransDIF: (*TransMAX-TransMIN)* activity
- Sensitive to ISR/FSR

Data/MC samples

Early run 2 data:

- Lumi 281 nb^{-1}
- Pileup of 1.3
- ZeroBias trigger

Monte Carlo samples:

- PYTHIA8 CUETP8M1:
  - validation and correction (with PU 1.3)
  - PU systematic (w/o PU)
- HERWIG++ CUETHS1 and EPOS v1.99: model dependency systematic
- PYTHIA8 Monash and CUETP8S1: comparison with corrected data

Detector response simulated with GEANT4 and events processed as with data

Event selection

ZeroBias triggered event sample with exactly (exclusive) one good vertex.

All good vertex within:

- 10cm of beamspot-z
- ρ <= 2cm (relative to beamspot in xy-plane)
- Vertex dof > 4

Object Selections

Particle level selection

UE/Leading particles:

- $p_T \geq 0.5$ GeV
- $|\eta| \leq 2$

leading objects from most energetic vertex

Leading jet (SisCone, $R = 0.5$):

- Using particles with $|\eta| < 2.5$
- $p_T \geq 1$ GeV
- $|\eta| \leq 2$

Detector level selection

- Same as particle level selection, done on tracks

+

- Track quality cuts:
  - *highPurity*
  - $\left|d_{xy}/\sigma_{d_{xy}}\right| < 3.0$, $\left|d_z/\sigma_{d_z}\right| < 3.0$
  - $\left|\sigma_{p_T}/p_T\right| < 0.05$

Data Correction

Unfolding

- RooUnfold: Iterative ("Bayesian") method
- Methodology:
  - Characterising UE activity as 2D histogram before making a profile

$$\left(X_{Tracks}, p_{T_{Leading\ TrackJet}}\right)_{2D} \xrightarrow{unfold} \left(X_{Particles}, p_{T_{Leading\ GenJet}}\right)_{2D} \xrightarrow{profile} \left(\langle X_{Particles}\rangle, p_{T_{Leading\ GenJet}}\right)_{Profile}$$

  - "Training" the unfolding matrix (using CUETP8M1)
  - Unfolding data iteratively with the "Bayesian" method

Systematic Uncertainties

Efficiency/Fake mismodelling

- Reduction of efficiency by 3.9% and increasing fakes by 50%

Pileup (PU)

- Effect of unfolding (CUETP8M1) with response matrix with and without PU (CUETHS1)

Model dependency of correction

- Effect of correction with different MC generator models
- CUETP8M1 corrected with CUETHS1 or EPOS

Impact parameter variation

- Varying the impact parameter to 2 and 4 (from 3)

Vertex degree of freedom

- Varying the vertex degree of freedom requirement to 2 and 6 (from 4)

Systematic: Summary

Summary of systematics at $p_T = 20$ GeV (plateau)

Ranges given across regions.

- Black: leading track
- Red: leading jet

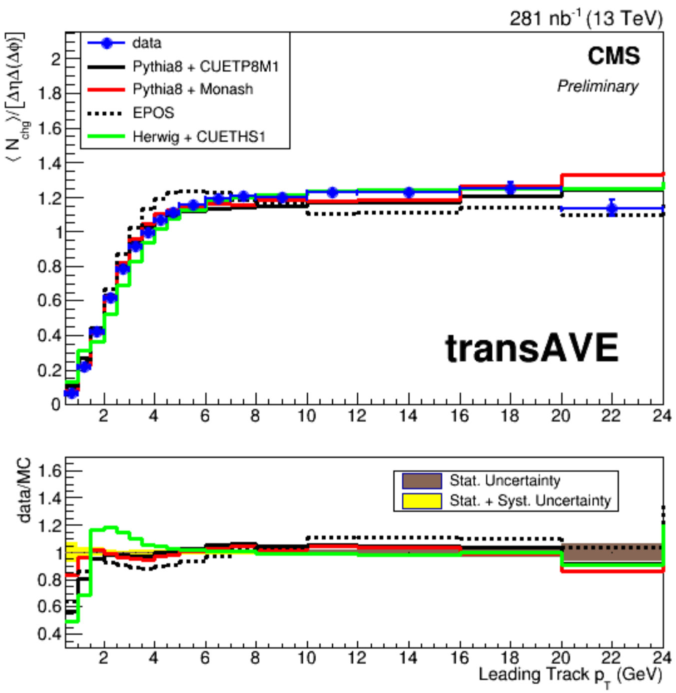
Distribution ($p_T = 20GeV$)	Pileup	Impact Parameter Significance sig<2 (sig<4)	Vertex Sel. Dof>2 (Dof>6)	Efficiency/ Fake mismodelling	Model dependency
$\langle N_{ch} \rangle / [\Delta\eta\Delta(\Delta\phi)]$	1-2% 1-4%	0.4-0.7 (0.1)% 0.2-0.4 (*)%	<0.1 (0.1)% <0.1 (0.3)%	1-2% 1-2%	1-4% 1-4%
$\langle \Sigma p_T \rangle / [\Delta\eta\Delta(\Delta\phi)]$	1-2% 1-4%	0.7-0.8 (0.1)% 0.4-0.5 (0.3-0.5)%	<0.1 (0.1)% <0.1 (0.2-0.3)%	1-2% 1-2%	1-4% 1-4%

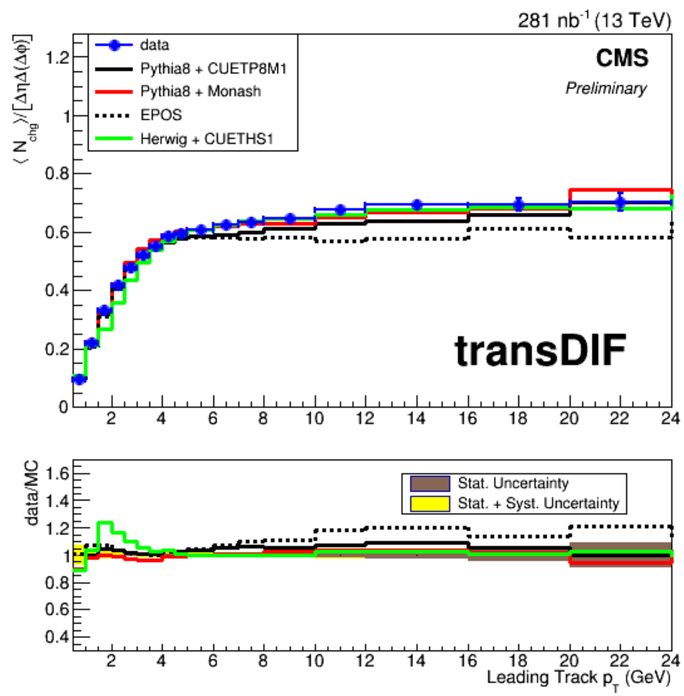
Results

Particle densities:Leading track

TransAVE/transDIF: Comparison with PYTHIA8 (Monash, CUETP8M1, EPOS), HERWIG++ (CUETHS1)

Best performing: Monash and CUETP8M1

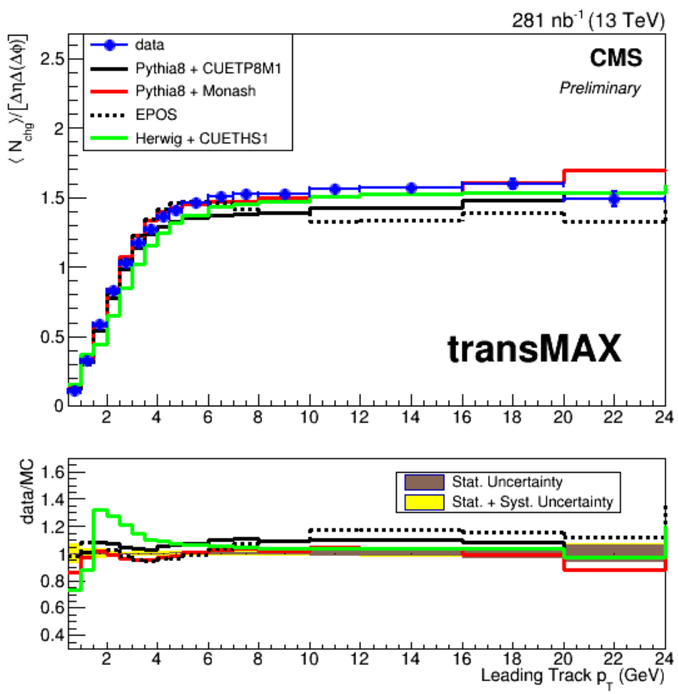


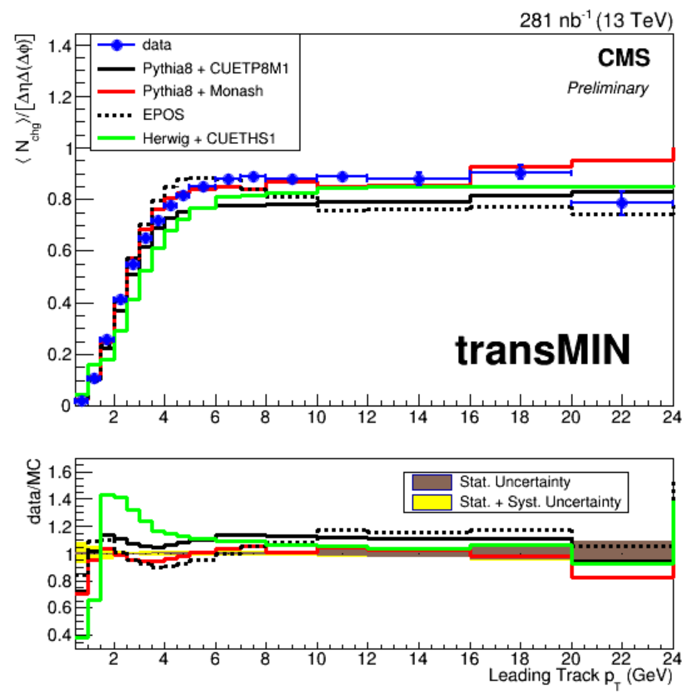


Particle densities:Leading track

TransMAX/transMIN: Comparison with PYTHIA8 (Monash, CUETP8M1, EPOS), HERWIG++ (CUETHS1)

Best performing: Monash

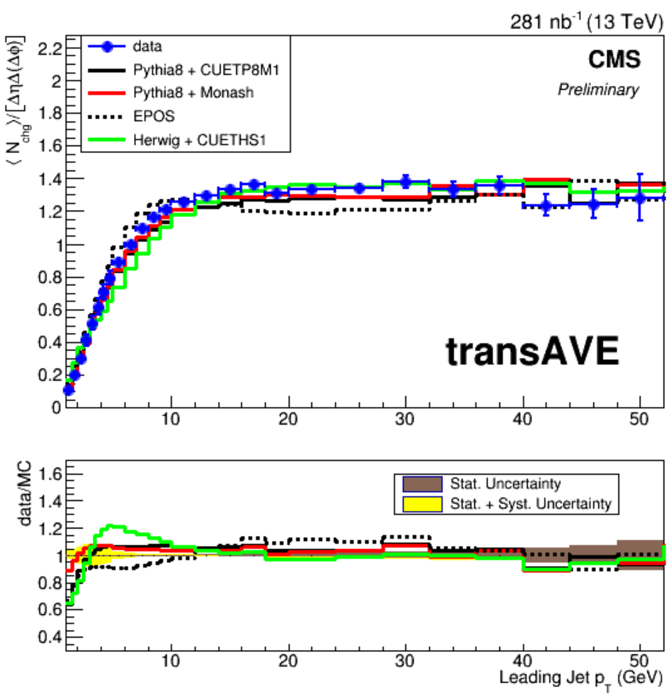


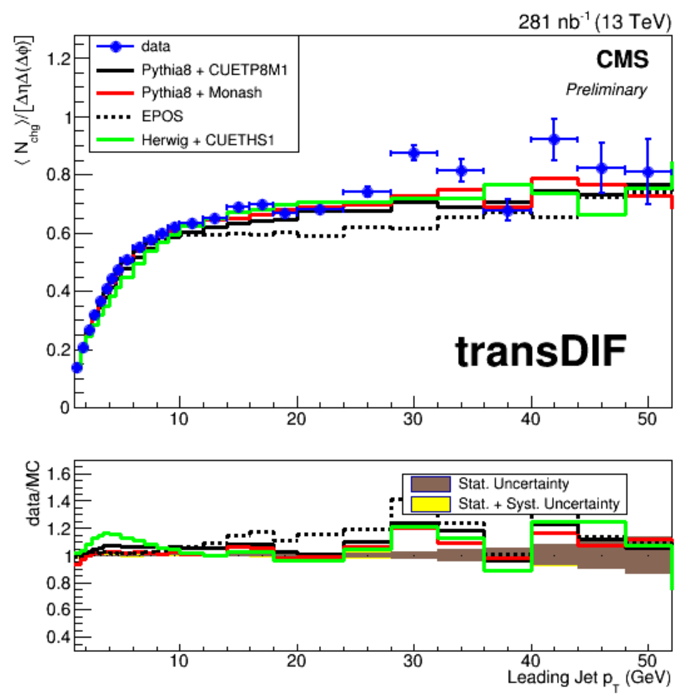


EPOS describes the rising region but drops in the plateau region and seems to flatten again

Particle densities: Leading jet

TransAVE/transDIF: Comparison with PYTHIA8 (Monash, CUETP8M1, EPOS), HERWIG++ (CUETHS1)
Best performing: Monash and CUETP8M1

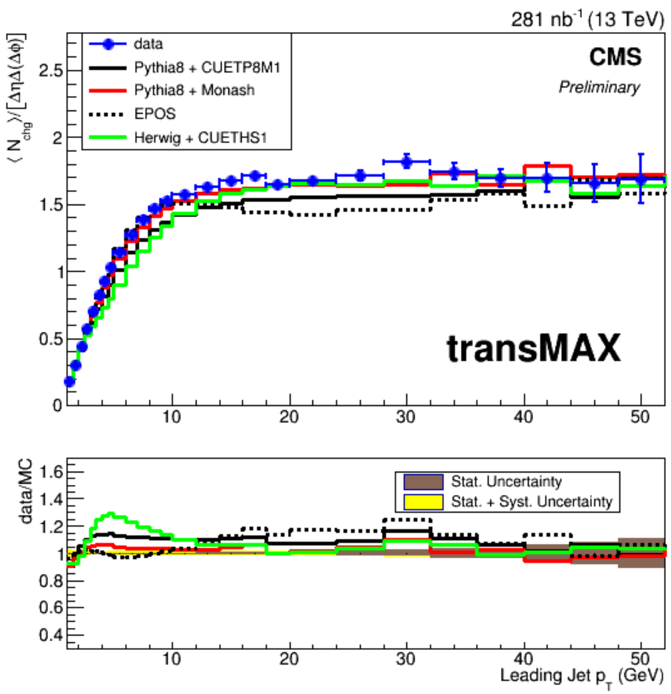


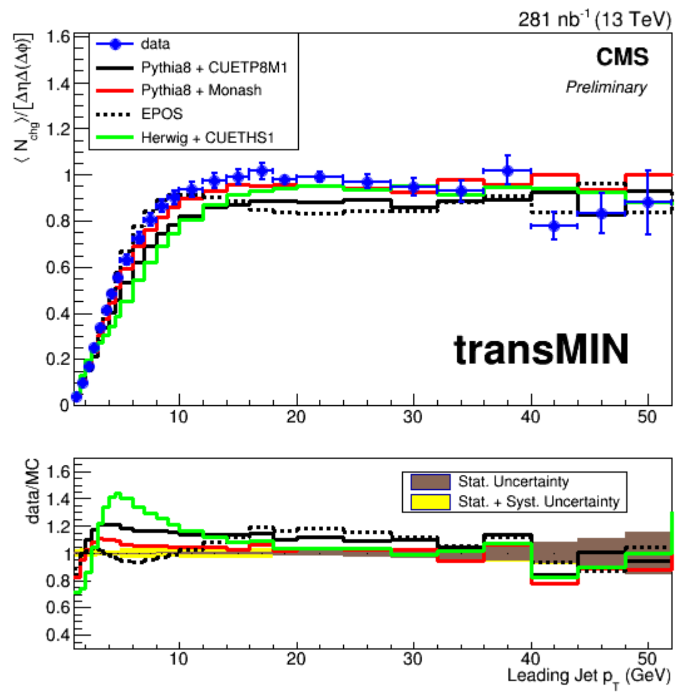


UE densities plateaus with a higher activity as a function of leading jet p_T

Particle densities: Leading jet

TransMAX/transMIN: Comparison with PYTHIA8 (Monash, CUETP8M1, EPOS), HERWIG++ (CUETHS1)
Best performing: Monash

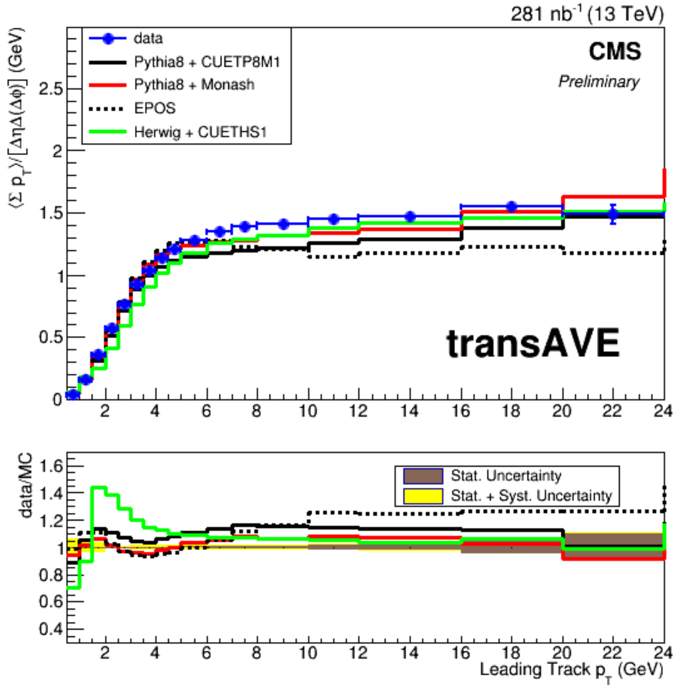


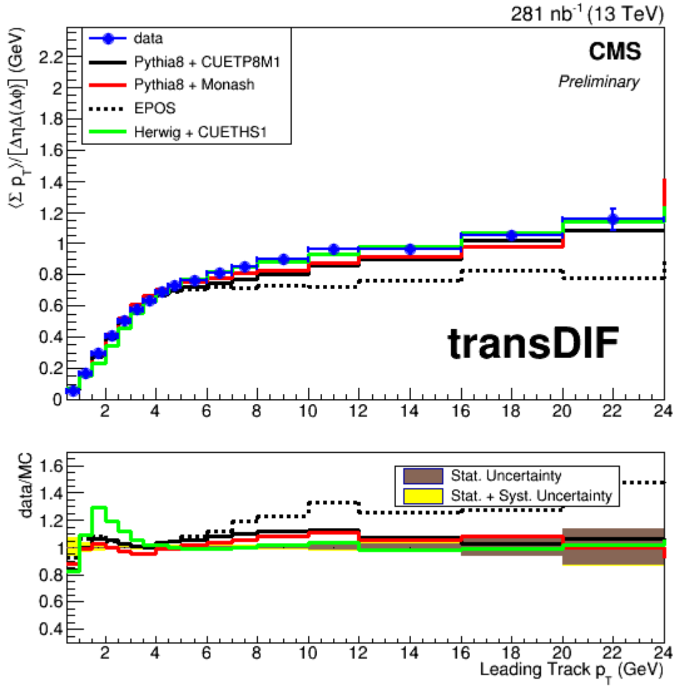


Energy densities: Leading track

TransAVE/transDIF: Comparison with PYTHIA8 (Monash, CUETP8M1, EPOS), HERWIG++ (CUETHS1)

Best performing: Monash and CUETP8M1 (transDIF)



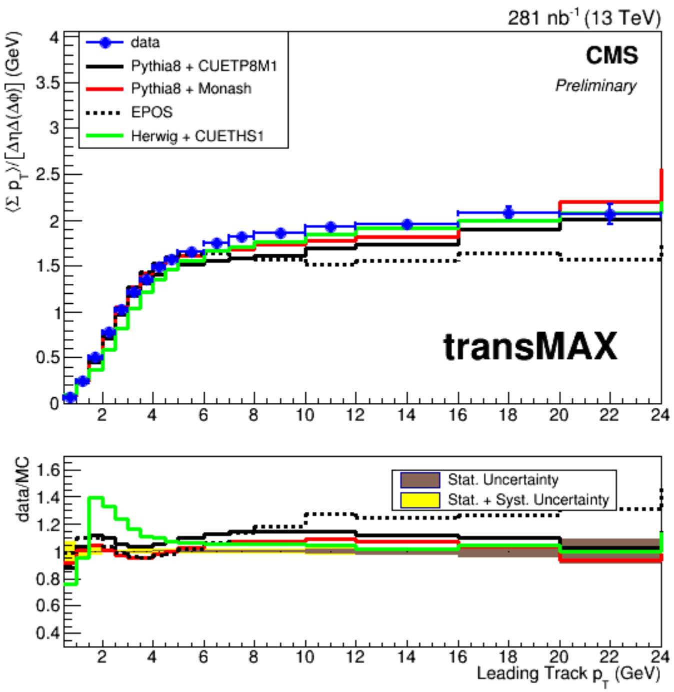


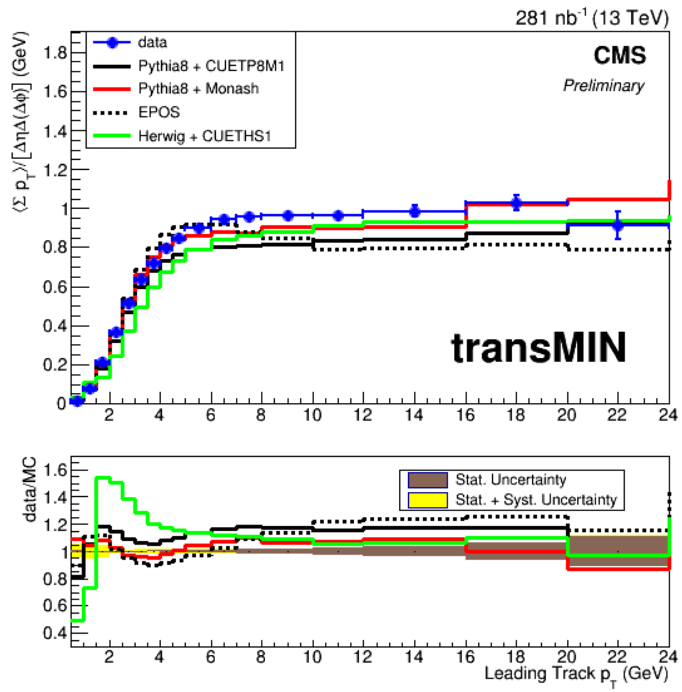
CUETP8M1 overestimates transAVE energy densities at high leading track p_T

Energy densities: Leading track

TransMAX/transMIN: Comparison with PYTHIA8 (Monash, CUETP8M1, EPOS), HERWIG++ (CUETHS1)

Best performing: Monash and CUETP8M1



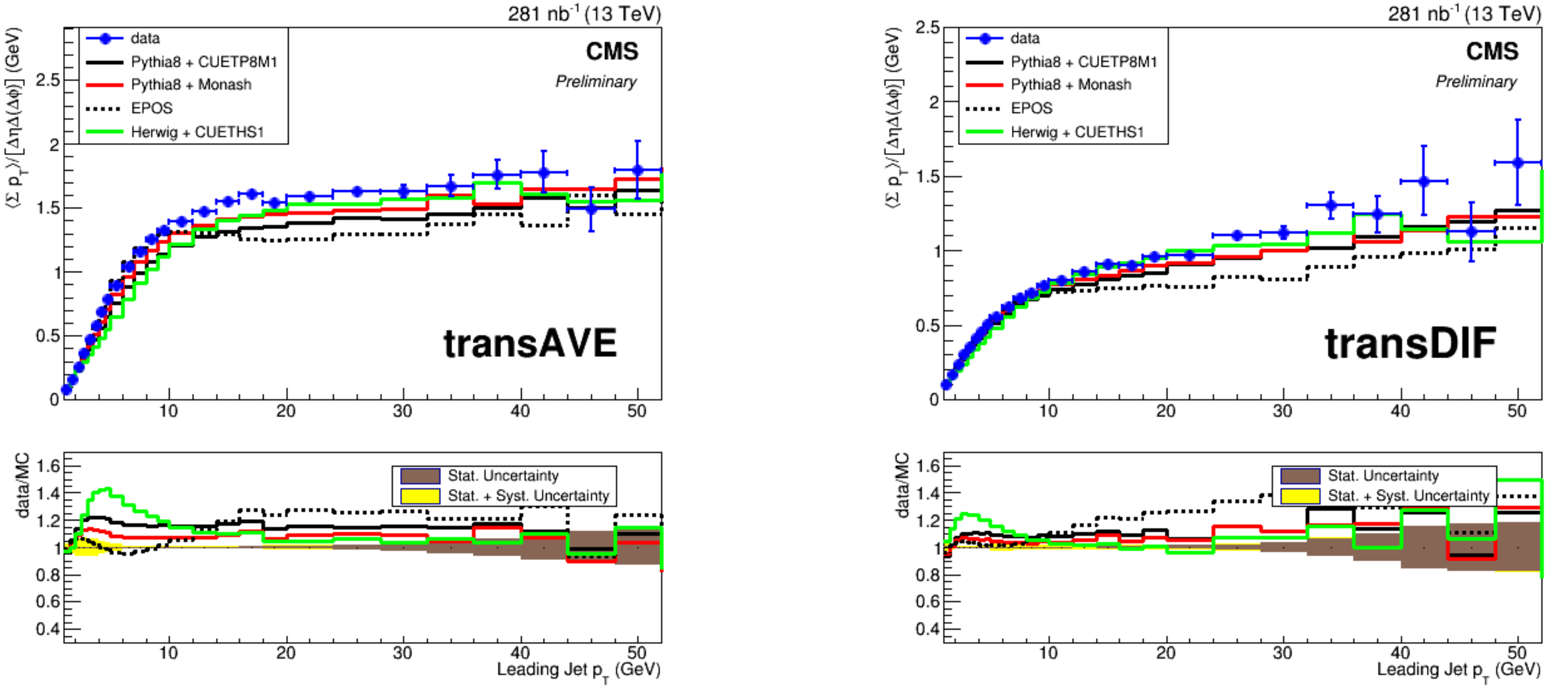


CUETP8M1 tends to overestimate energy densities at high leading track p_T

Energy densities: Leading jet

TransAVE/transDIF: Comparison with PYTHIA8 (Monash, CUETP8M1, EPOS), HERWIG++ (CUETHS1)

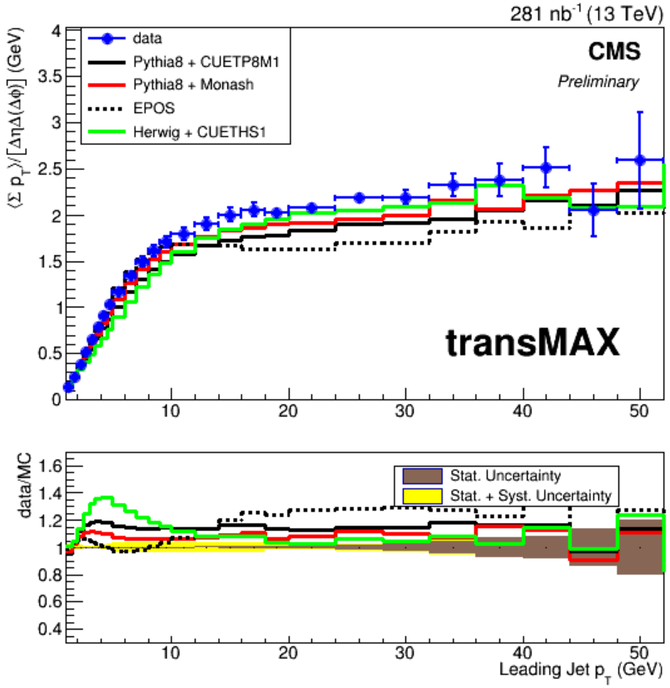
Best performing: Monash

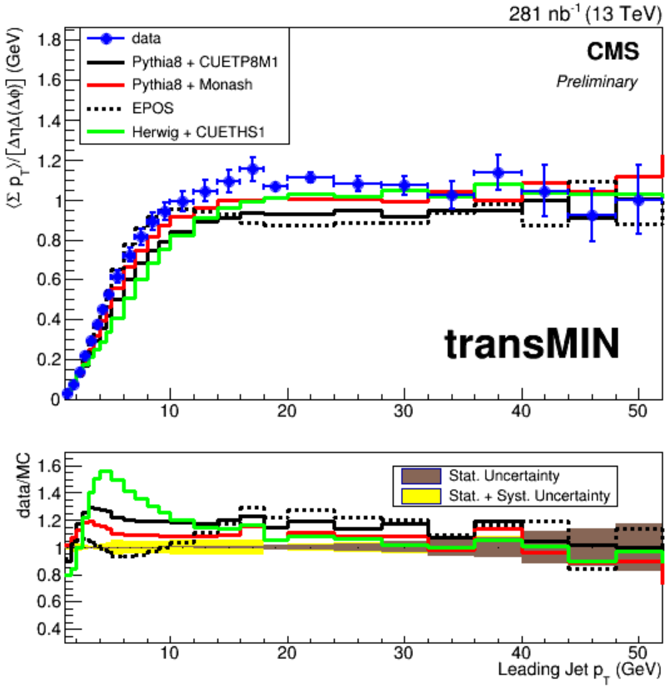


Energy densities: Leading jet

TransMAX/transMIN: Comparison with PYTHIA8 (Monash, CUETP8M1, EPOS), HERWIG++ (CUETHS1)

Best performing: Monash





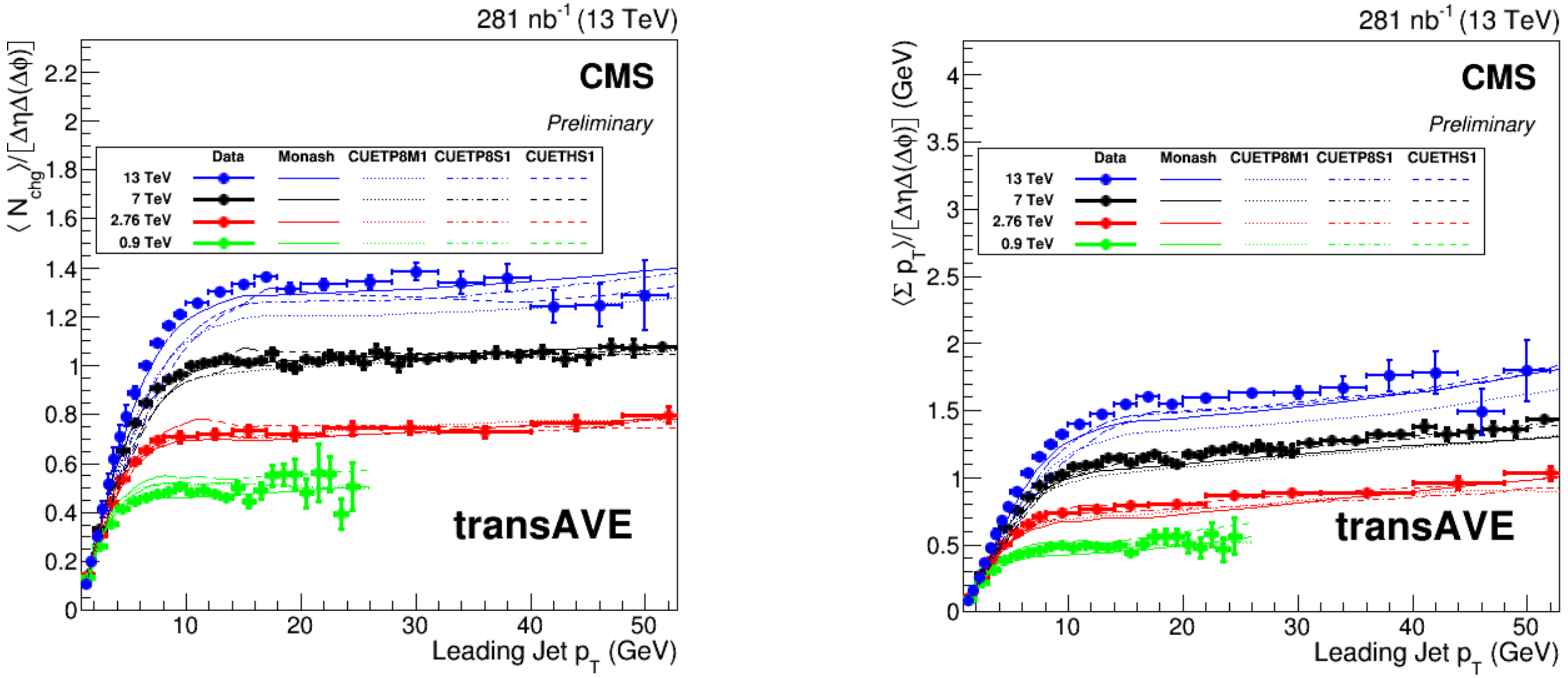
Tunes generally describe UE densities as function of leading track p_T better

Energy dependence

Particle/energy density center-of-mass energy dependence at 0.9, 2.76, 7, and 13 TeV for transAVE activity compared with:

- PYTHIA8 (Monash, CUETP8M1, CUETP8S1), HERWIG++ (CUETHS1)

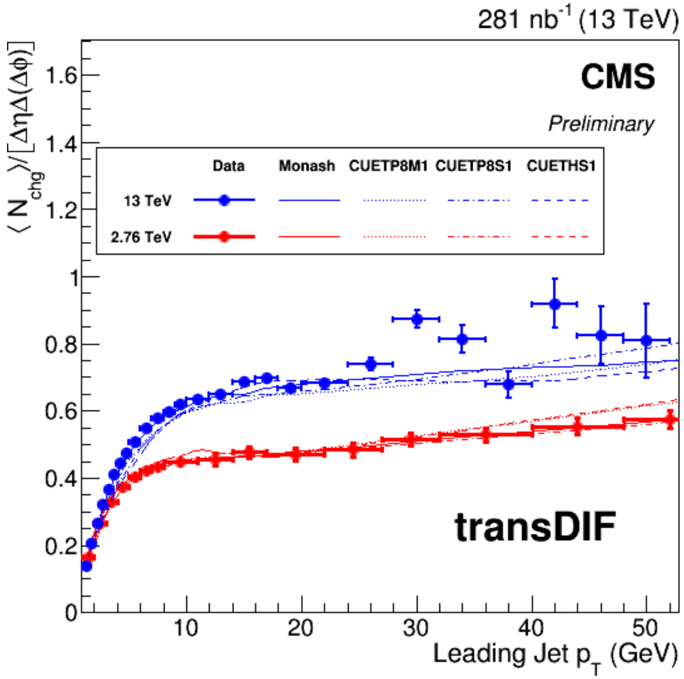
Monash predicts a better centre-of-mass energy dependence

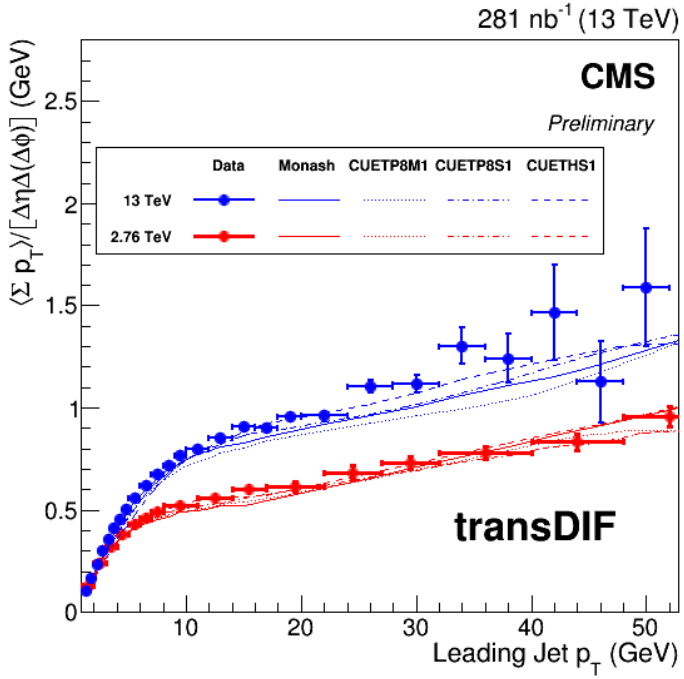


Energy dependence

Particle/energy density at 2.76 and 13 TeV for transMAX/ transMIN/ transDIF activity

All tunes describe transDIF densities better

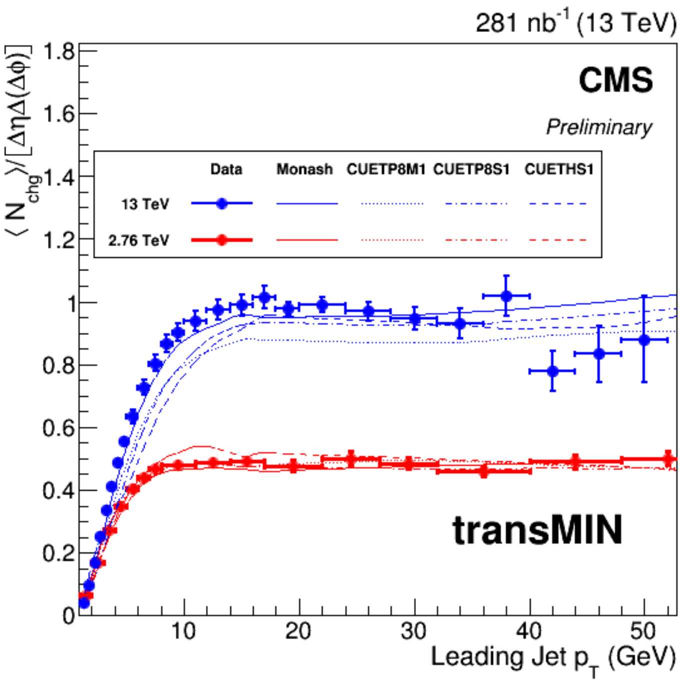


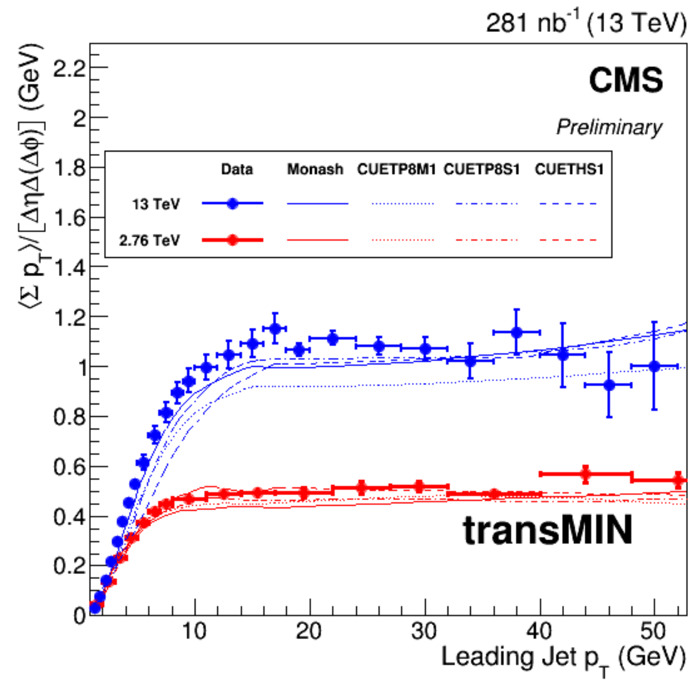


Energy dependence

Particle/energy density at 2.76 and 13 TeV for transMAX/ transMIN/ transDIF activity

transMIN densities have a stronger energy evolution to transDIF

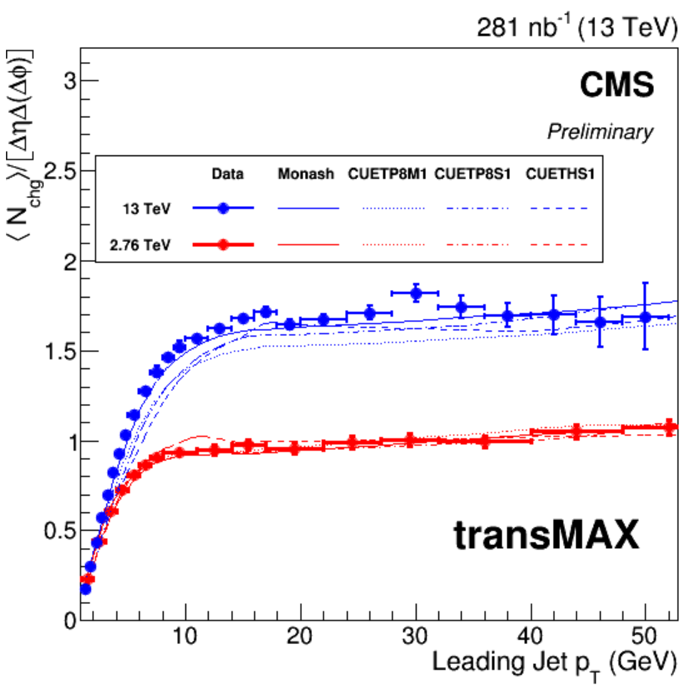


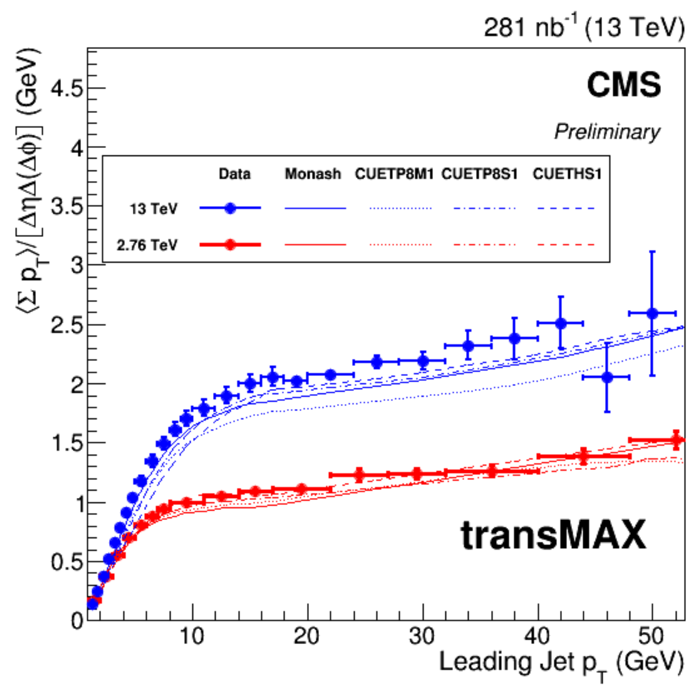


Energy dependence

Particle/energy density at 2.76 and 13 TeV for transMAX/ transMIN/ transDIF activity

Monash describes well for all transverse densites but generally not as well for average energy density.





Summary

UE @ 13 TeV has been measured and fully corrected for detector effects and selection efficiencies for the *transAVE*, *transMIN*, *transMAX* and *transDIF* densities

Results are compared to various PYTHIA8, HERWIG++ tunes, and EPOS

Comparison is made with UE @ 0.9, 2.76, 7 TeV

- For tuning of energy dependence of the MC

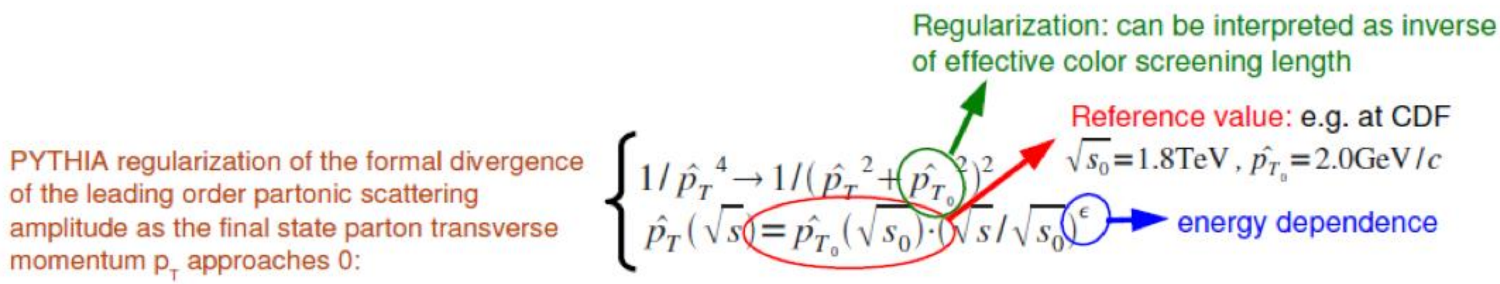
END

Thank you for your attention!

Appendix

MC regularisation of soft MPI cross section

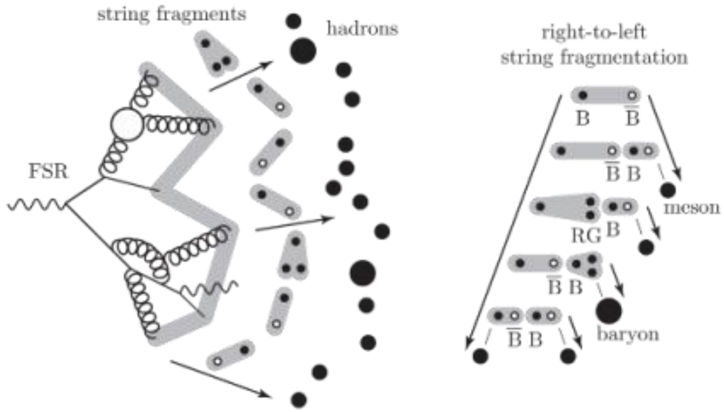
PYTHIA8 energy dependence follows the following prescription:



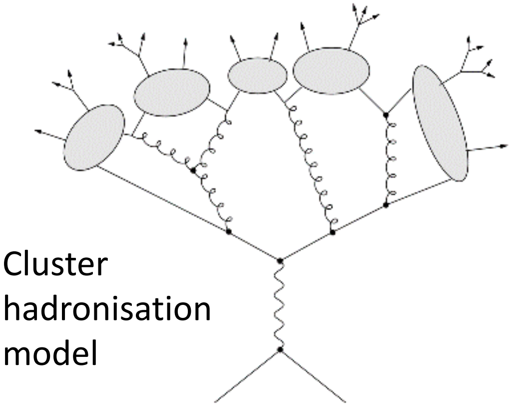
HERWIG++ follows a similar prescription

Monte Carlo models

String hadronisation model



Cluster hadronisation model



PYTHIA/HERWIG differences (same PDF, CTEQ6L1):

- Details of interleaving between ISR/FSR/MPI
- p_T-ordered/angular-ordered evolution
- Lund string/cluster hadronisation
- Tunable parameters in all MC are optimised with different datasets

EPOS describes soft-parton dynamics by Gribov-Regge theory with the exchange of virtual quasi-states with multi-pomeron exchanges. Hard-pomeron scattering is included to simulate hard-parton processes.

String hadronisation is implemented in EPOS