Minimum bias and underlying event measurements with CMS

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on behalf of the CMS collaboration

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Motivation

→ We want to probe **the dynamics** of hadron production ...
... investigate the behavior of its **different components** ...
... as well as their **universality**

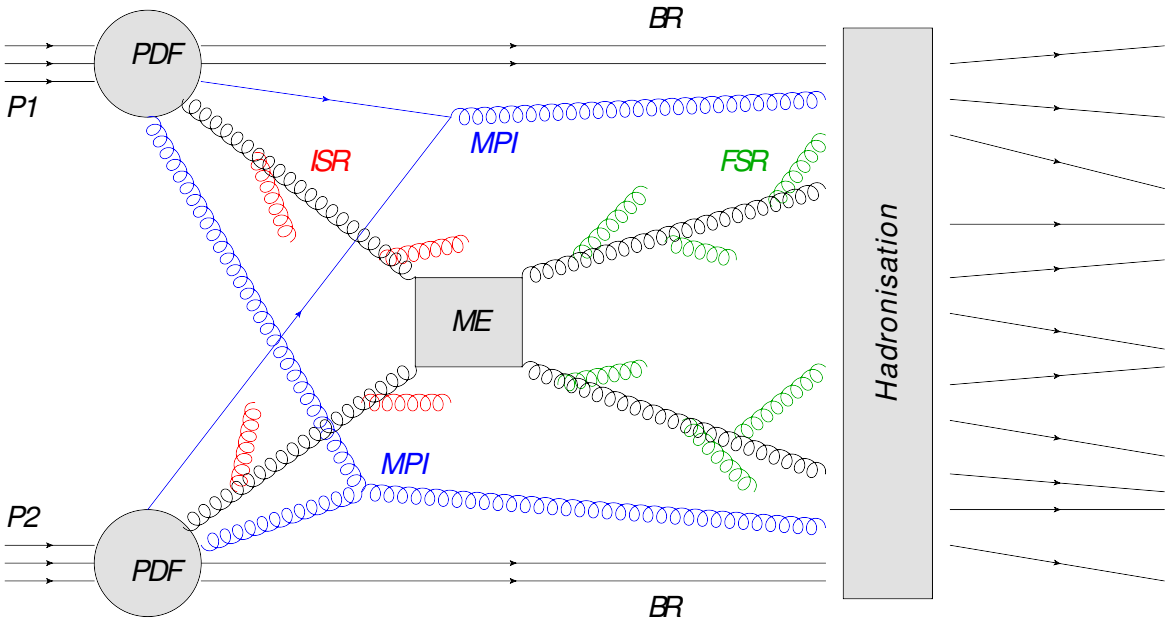
→ We want to get an insight in the **non-perturbative** QCD regime ...
... and in the behavior of QCD at **small-x**

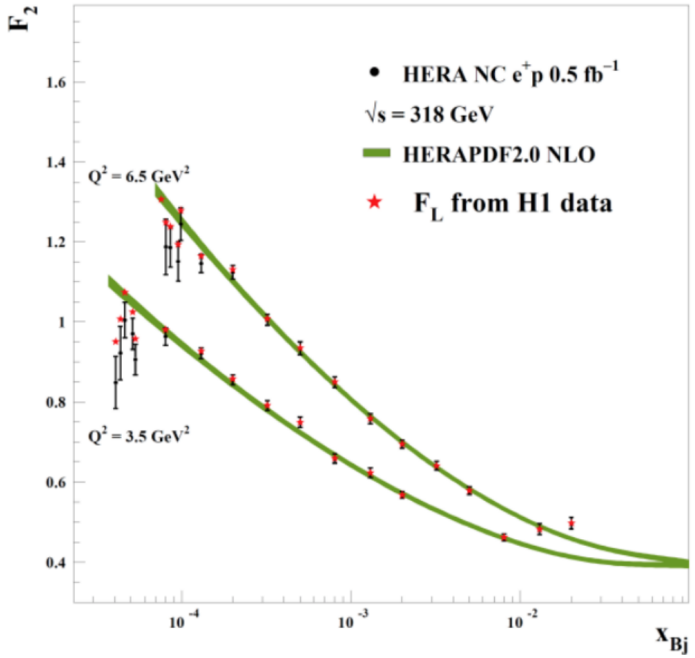
→ We want to probe the **transition scale** between ...
... the perturbative and non-perturbative regions

→ We study **different observables** sensitive ...
... to **specific components** of the hadron production

- inclusive observable: charged particle density in minimum bias events
- differential observables: charged particle and energy densities
  with respect to the direction of the leading object
  in hadronic events and Drell-Yan events

Description of the hadron production





- Parton densities **at small x and small scale**
- **The Hard Scattering** → described by pQCD at fixed order
- **Initial-State Radiation** and **Final-State Radiation**
  → account for higher order emissions
  → described by QCD-evolution-inspired Parton Shower
- **Several Soft to Semi-Hard Scatterings: Multiple Partonic Interactions**
  → described by pQCD-inspired phenomenological models
- **MPI** have their own **ISR** and **FSR**
- Beam Remnants
- Hadronisation

Underlying Event

Tuning of the model parameters based on experimental data

Phenomenology of the low-p_T region

- total $2 \to 2$ **partonic cross section**: $\sigma(p_T) \propto 1/p_T^2$

  is **divergent towards low** p_T and eventually becomes **larger than** σ_{inel}

- At LHC energies: $\sigma(p_T) > \sigma_{inel}$ already for $p_T \sim 5$ GeV

  ⟶ **Cross section needs to be tamed in the low** p_T **region**

- In PYTHIA: the rise of the $2 \to 2$ partonic cross section is controled by:

  - **an infrared cutoff** p_{T0} **tuned to data:**

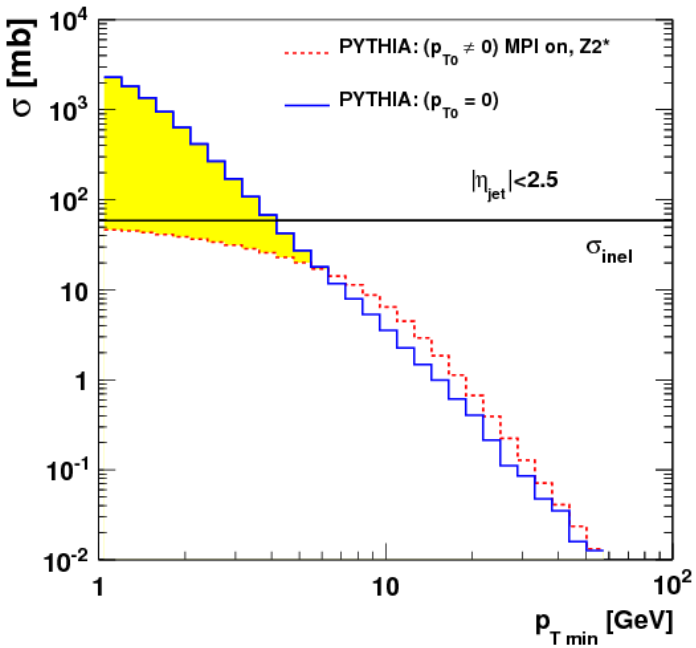
$$\sigma(p_T) \propto \frac{1}{p_T^2 + p_{T0}^2}$$

    energy dependence parametrised by a power law:

$$p_{T0}(\sqrt{s}) = p_{T0}(\sqrt{s_0}) \left(\frac{\sqrt{s}}{\sqrt{s_0}} \right)^{\alpha}$$

  - **multiple partonic interactions (MPI):**

$$< n_{MPI} >= \sigma(p_T)/\sigma_{inel}$$



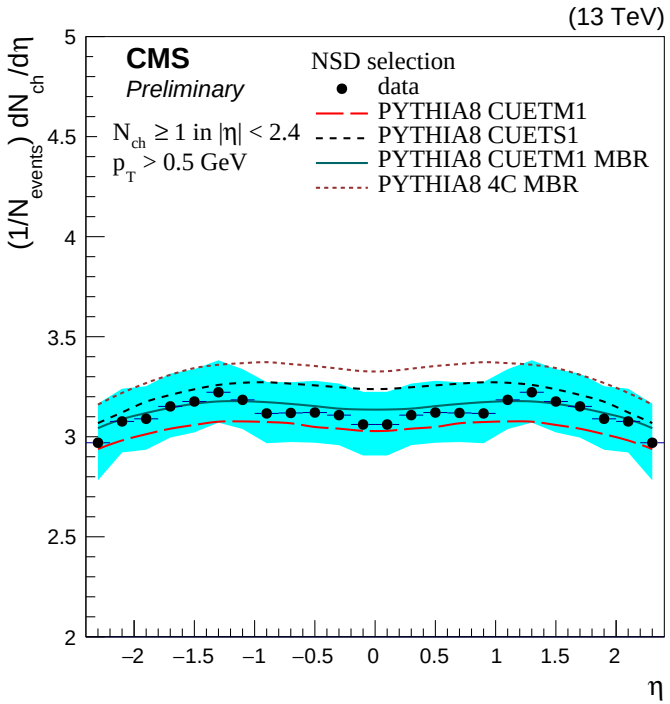
[Phys. Rev. D 86 (2012) 117501]

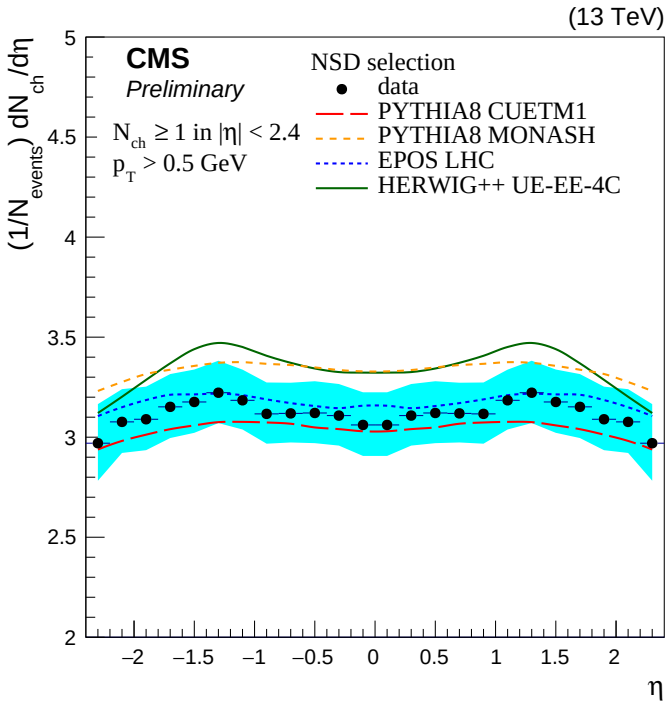
Charged particle pseudorapidity density at 13 TeV - NSD

[CMS-PAS-FSQ-15-008]

- Results corrected to primary charged particles - $N_{ch} \geq 1$ - $p_T > 0.5$ GeV - $|\eta| < 2.4$
- Different event categories based on the **activity in the forward region** $3 < |\eta| < 5$

  At least one particle with $E > 5$ GeV in **both** forward regions $\rightarrow$ **NSD enhanced sample**





→ **PYTHIA8** with different tunes and **EPOS LHC** show similar agreement with the data

HERWIG++ (version 6.521) UE-EE-4C is not able to describe the measurement

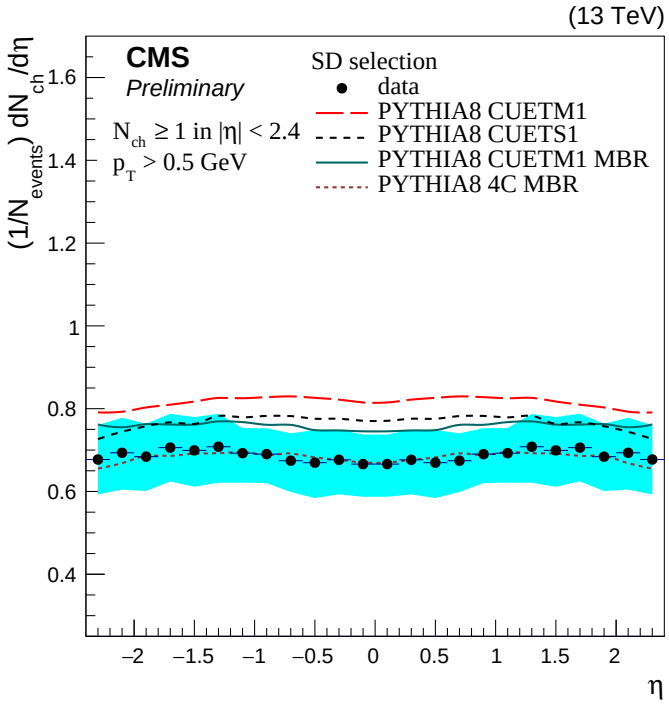
→ difficult to describe **simultaneously** the density in the central and most forward regions

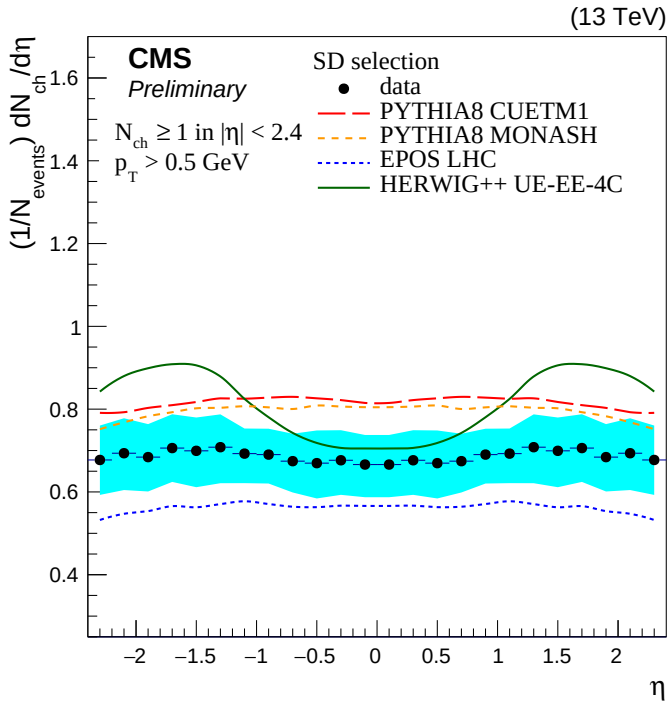
Charged particle pseudorapidity density at 13 TeV - SD

- Results corrected to primary charged particles - $N_{ch} \geq 1$ - $p_T > 0.5$ GeV - $|\eta| < 2.4$

  At least one particle with $E > 5$ GeV in **only one** of the forward regions,

  no activity on the other side $\rightarrow$ **SD enhanced sample**





→ particle density $\sim$ 4 times smaller $\rightarrow$ **correlation** between the central and forward regions

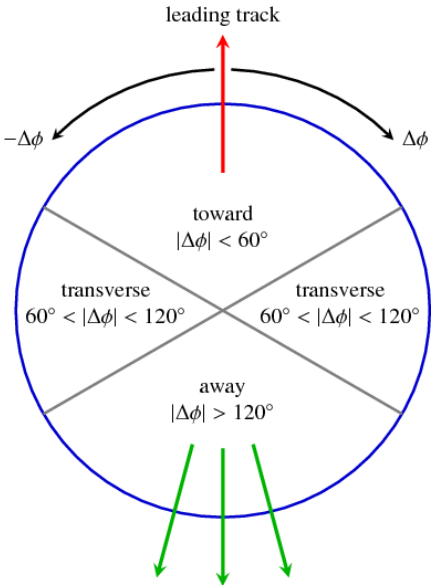
PYTHIA8 4C MBR gives the best description

HERWIG++ (version 6.521) UE-EE-4C has no diffractive component

→ **Larger model dependence not covered by the systematic uncertainties**

Underlying event measurements - strategy

- Underlying Event: activity not attributed to the hardest partonic scattering
  Initial-State Radiation, **Final-State Radiation**, **Multiple Partonic Interactions**, proton remnants
- Experimentally: final-state hadrons can not be identified as coming from one of these processes
  → define 3 regions in φ with respect to the **direction of the leading object**



Towards region ($|\Delta\varphi| < 60°$) and **Away region** ($|\Delta\varphi| > 120°$)

→ dominated by the **leading object** and the **hadronic recoil**

Transverse region ($60° < |\Delta\varphi| < 120°$)

→ **most sensitive to the UE activity**

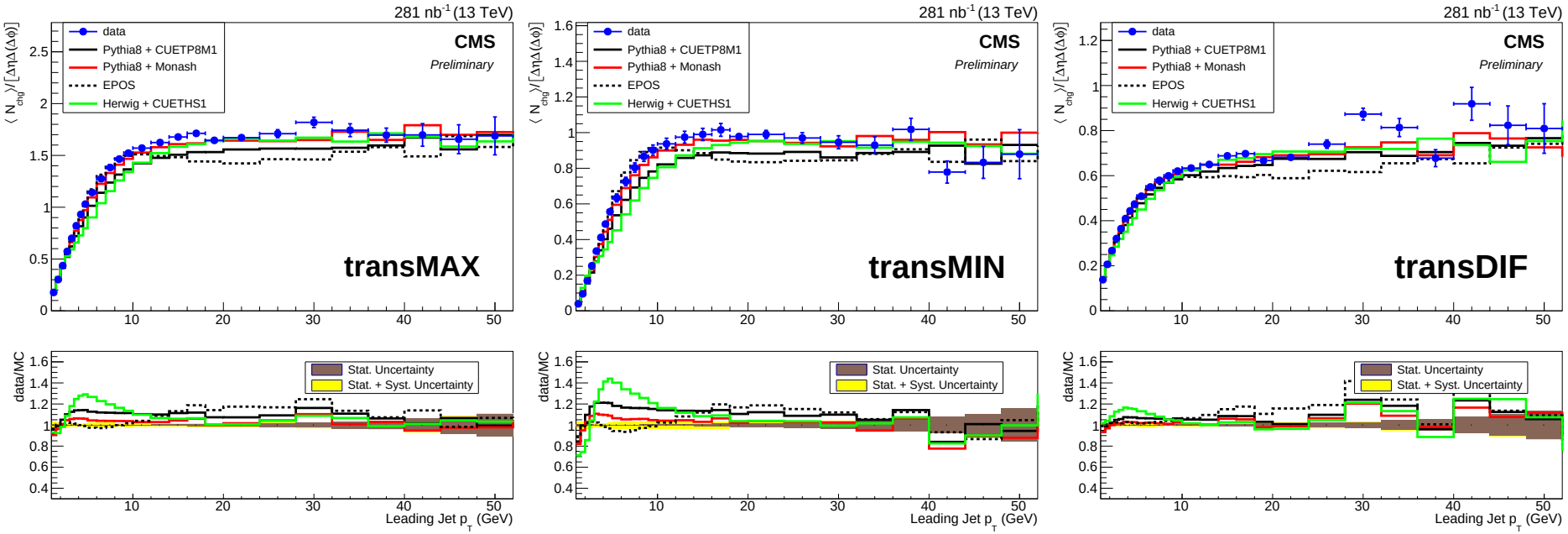
Separate activity from **Radiation** and **Multiple Partonic Interactions**

- **TransMIN:** transverse region with the **lowest** activity → **MPI**
- **TransMAX:** transverse region with the **highest** activity → **MPI** + **Radiation**
- **TransDIF:** difference between TransMAX and TransMIN → **Radiation**
- **TransAVE:** average between TransMAX and TransMIN

Underlying event with leading particles and jets at 13 TeV

[CMS-PAS-FSQ-15-007]

- **Average particle density** versus **leading jet** p_T for charged particles - $p_T > 0.5$ GeV - $|\eta| < 2$



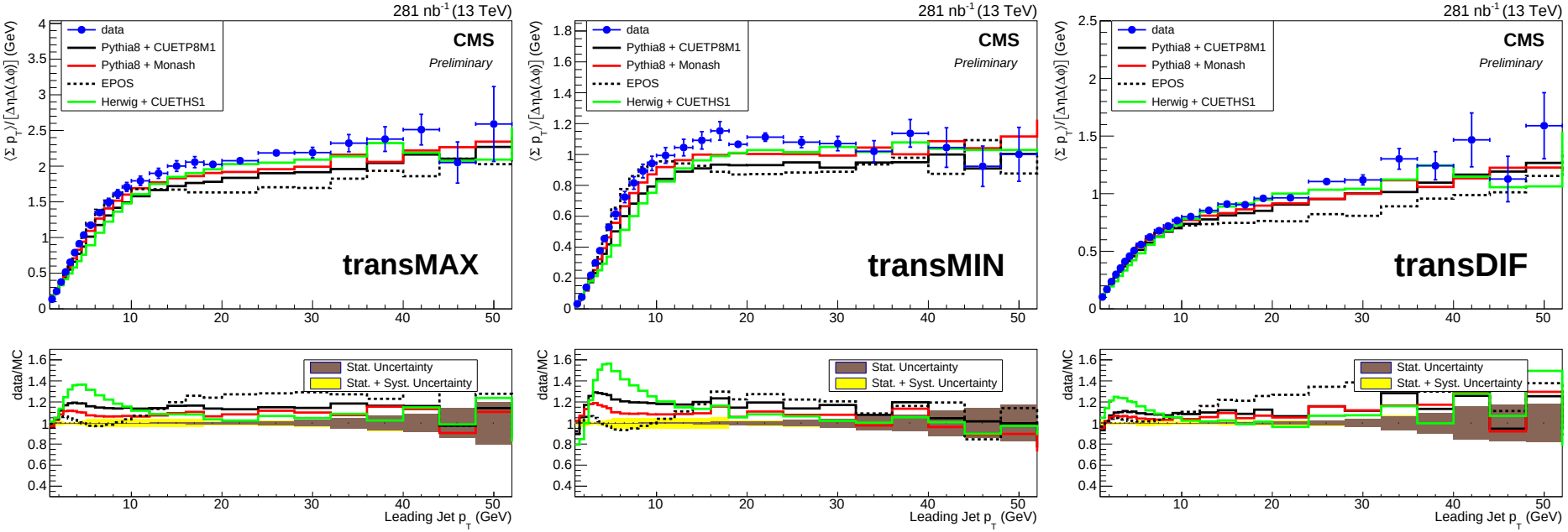
2 different regimes:

- at low p_T: sharp rise due to the increase of the **MPI** activity
- at higher p_T: **MPI** activity saturates, slow increase due to the **ISR** and **FSR** contributions

TransMIN flatter at high p_T (MPI saturated) than TransMAX and TransDIF (radiative increase)

Underlying event with leading particles and jets at 13 TeV

- **Average energy density** versus **leading jet** p_T for charged particles - $p_T > 0.5$ GeV - $|\eta| < 2$



qualitative behavior described by the predictions:

- level of agreement of 10 - 20% in the plateau region
- **larger difference** between models in the **low** p_T region

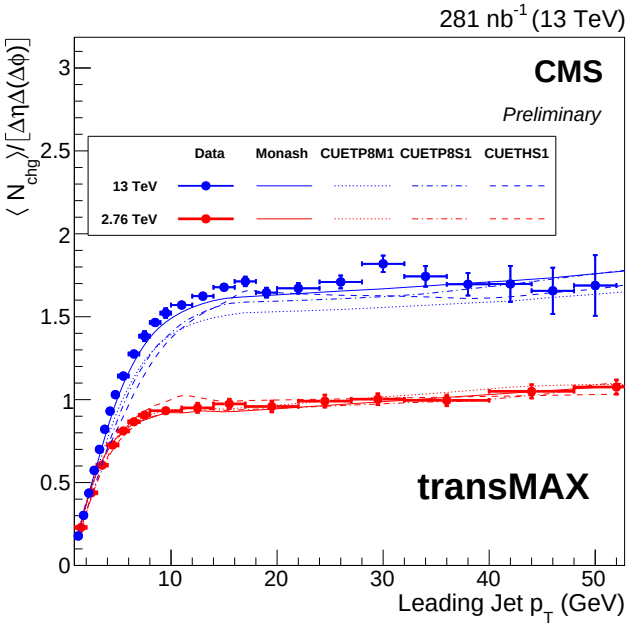
→ data better described by **PYTHIA8 Monash and CUETP8M1**

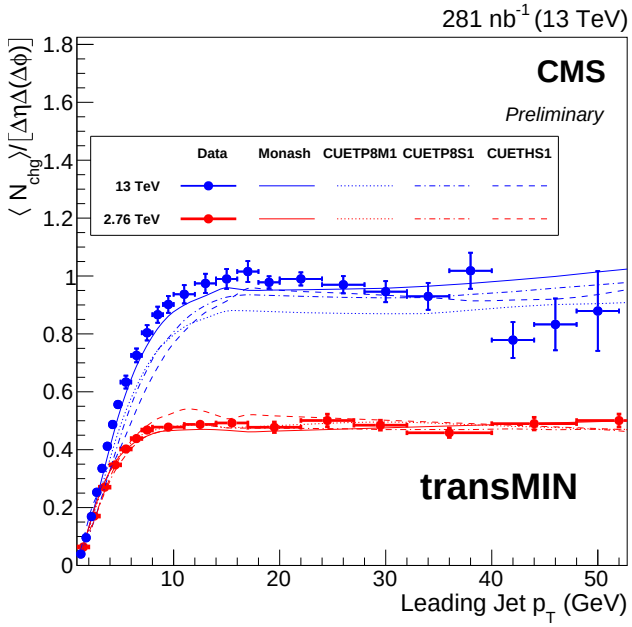
HERWIG CUETHS1 fails in the low p_T region (lack of diffractive events)

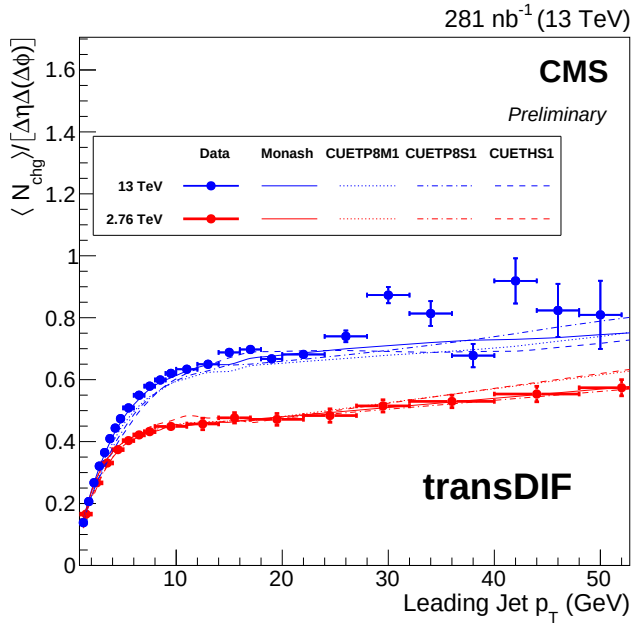
EPOS describes the rising part but fails to describe the plateau

Underlying event with leading particles and jets at 13 TeV

- **Average particle density** versus **leading jet p_T** - **energy dependence 2.76 TeV $\rightarrow$ 13 TeV**







strong energy dependence well reproduced by the different models

$\rightarrow$ **increase** of the parton densities at **smaller** momentum fraction

TransMIN shows a stronger rise than TransDIF

$\rightarrow$ MPI activity grows faster with $\sqrt{s}$ than activity from ISR and FSR

Underlying event in Drell-Yan events at 13 TeV

New results!

[CMS-PAS-FSQ-16-008]

- 2 muons from Z leptonic decay with $p_T > 10$ and 20 GeV, $|\eta| < 2.4$ and $81 < M_{\mu\mu} < 101$ GeV

  average particle and energy densities for charged particles with $p_T > 0.5$ GeV and $|\eta| < 2$

  in the towards, transverse and away regions

- test the **process universality** of the underlying event activity

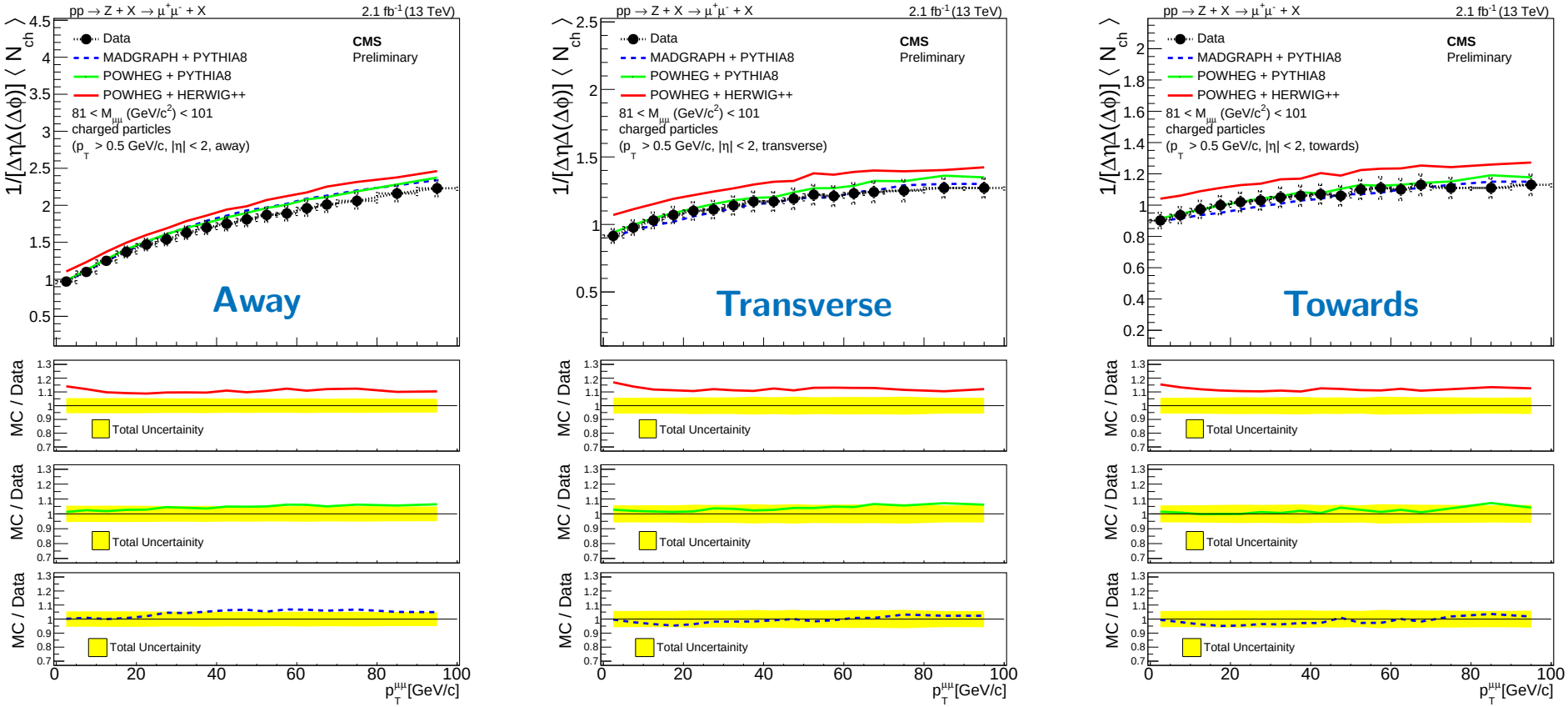
  test the underlying event activity at **higher scale**

  no **Final-State Radiation** $\rightarrow$ more direct access to **Initial-State Radiation** and **MPI**

  test the **universality of the tunes** interfaced with different event generators

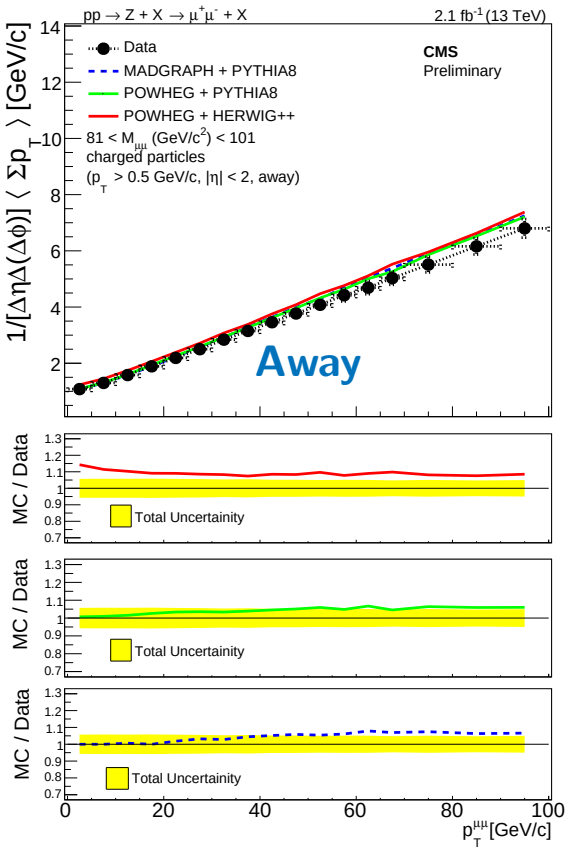
  - MADGRAPH (Z + up to 4 partons at LO) + PYTHIA8 CUETP8M1
  - POWHEG (Z + up to 2 partons at NLO) + PYTHIA8 CUETP8M1
  - POWHEG + HERWIG++ EE5C

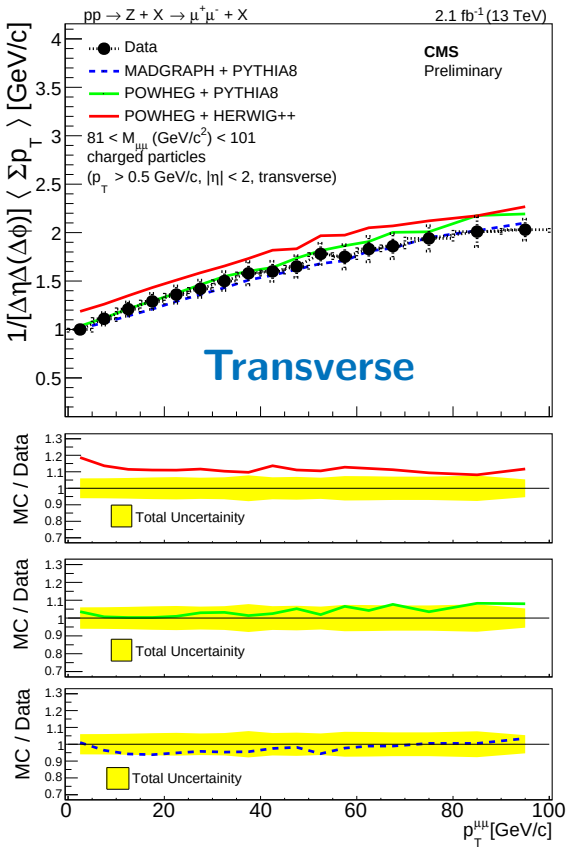
UE in DY - average particle density versus dimuon p_T

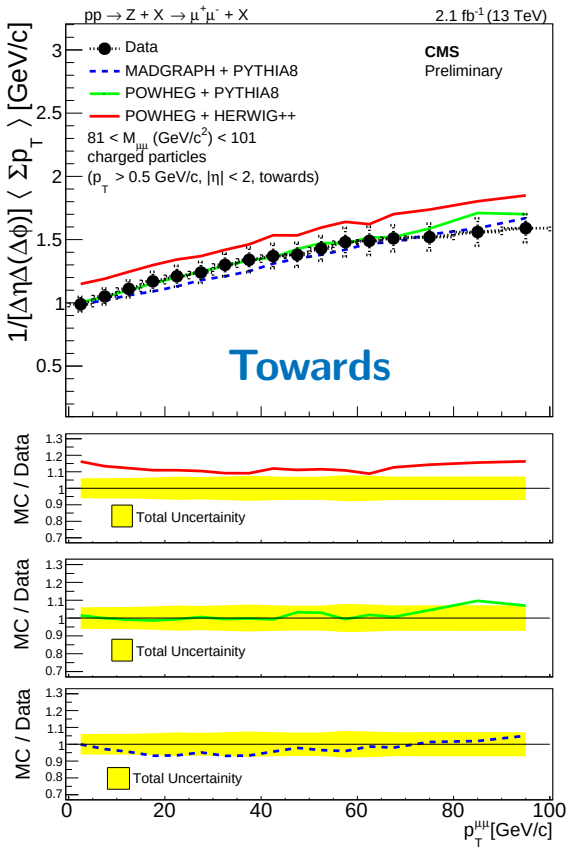


- at low p_T: no sharp rise, **MPI activity already saturated** (hard scale $M_{\mu\mu}$)
- at higher p_T: **slow increase** of the **ISR activity** in the transverse and towards regions
  sharp increase of the **ISR activity** in the away region (recoiling hadronic activity)
- similar activities in the 3 regions as dimuon $p_T \to 0$
  $\to$ similar MPI activities in the 3 regions $\to$ **different behaviors due to varying ISR**

UE in DY - average energy density versus dimuon p_T







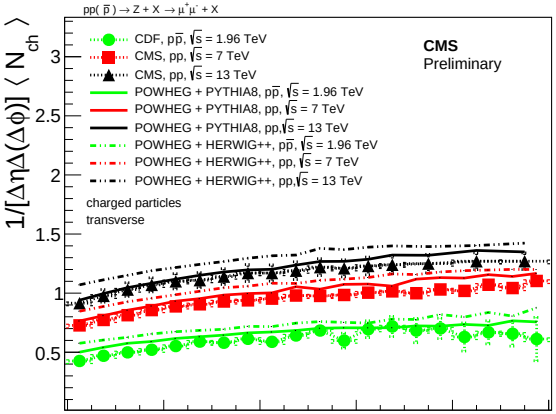
→ **POWHEG + HERWIG++ EE5C** overestimates the activity by 10-15% in all regions

POWHEG + CUETP8M1 describes the data within 5%

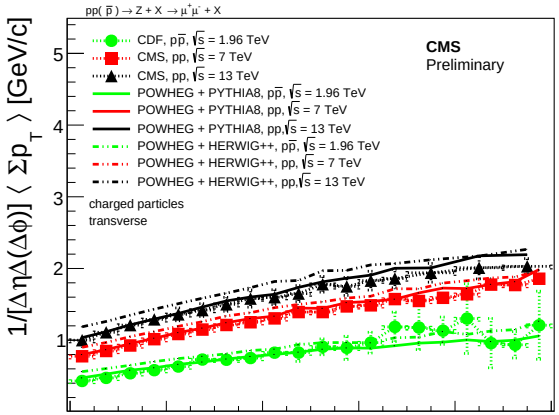
MADGRAPH + CUETP8M1 gives the best description

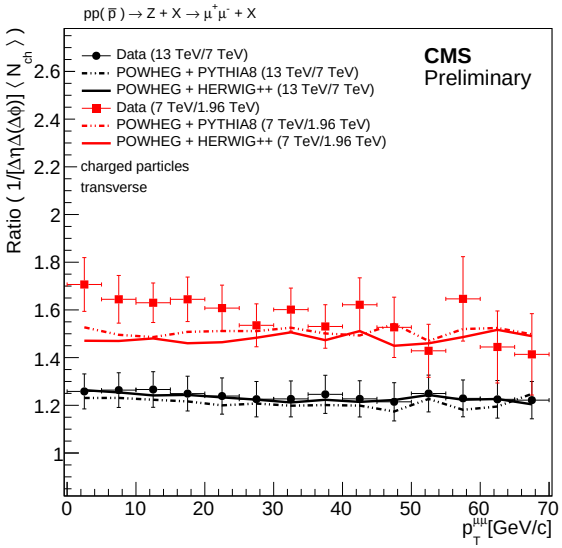
UE in DY - transverse activity at different energies

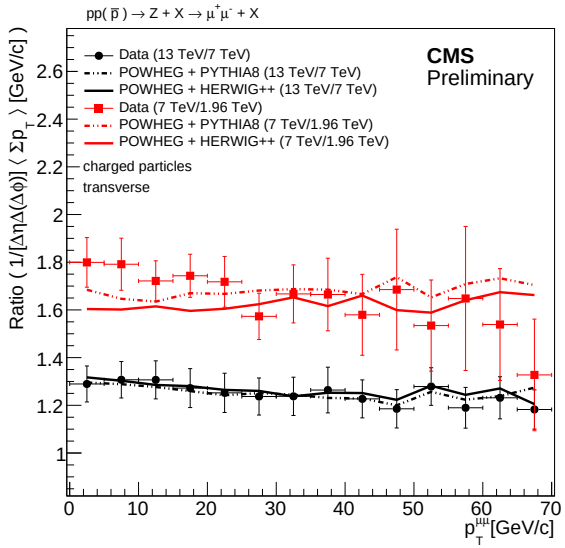
average particle density



average energy density







1.96 TeV → 7 TeV → 13 TeV

POWHEG + HERWIG++ EE5C
overestimates data by 40 to 10%

POWHEG + CUETP8M1
describes data within 10 to 5%

increase in densities

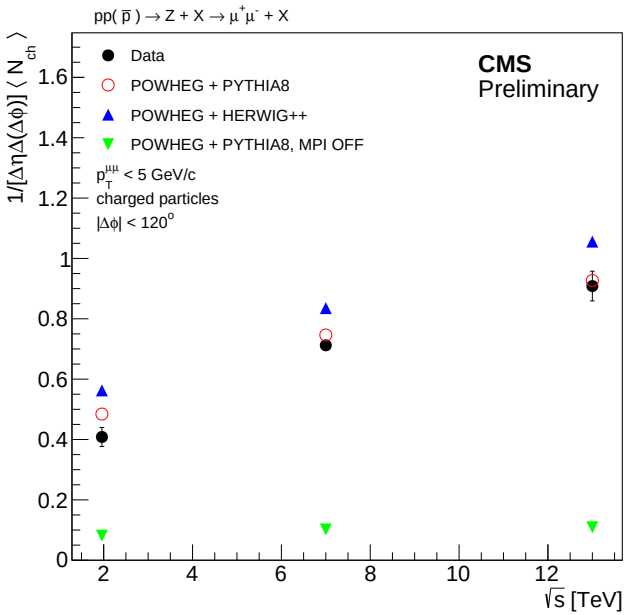
25-30% from 7 to 13 TeV
models in good agreement

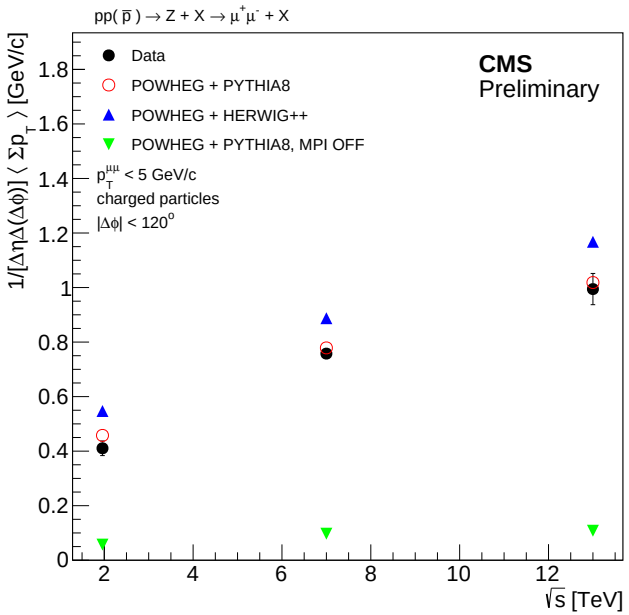
60-80% from 1.96 to 7 TeV
models predict lower increase
particularly at low p_T

UE in DY - MPI activity at different energies

at low dimuon p_T: underlying event activity dominated by **MPI** contributions and **similar** in transverse and towards regions

→ **average particle and energy densities for dimuon $p_T < 5$ GeV versus $\sqrt{s}$** in the combined transverse and towards regions





POWHEG + PYTHIA8 without MPI → contributions from radiation very small

increase of MPI activity well reproduced by **POWHEG + CUETP8M1**

overestimated by **POWHEG + HERWIG++ EE5C**

Conclusion

- Minimum bias and 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 Partonic 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

Thanks for your attention!

Back up

CMS publications

- Underlying Event Measurements with Leading Particles and Jets in proton-proton collisions at $\sqrt{s} = 13$ TeV, CMS-PAS-FSQ-15-007.
- Measurement of the underlying event using the Drell-Yan process in proton-proton collisions at $\sqrt{s} = 13$ TeV, CMS-PAS-FSQ-16-008.
- Measurement of pseudorapidity distributions of charged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV by the CMS experiment, CMS-PAS-FSQ-15-008.