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

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Phenomenology of the low-\(p_T\) region

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

  is **divergent towards low** \(p_T\) and eventually becomes **larger than** \(\sigma_{inel}\)

- 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 → 2 partonic cross section is controlled 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):**
    \[
    \langle n_{MPI} \rangle = \sigma(p_T)/\sigma_{inel}
    \]

Charged particle pseudorapidity density at 13 TeV - NSD

- 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
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

\[
\begin{align*}
\eta/\text{d}N_{\text{events}} (1/N) & \geq 1 \text{ in } |\eta| < 2.4 \\
p_T > 0.5 \text{ GeV} & \geq \text{ch} \text{ N} > 0.5 \text{ GeV} \\
\text{CMS Preliminary} & \text{ SD selection} \\
\text{PYTHIA8 CUETM1} & \text{data} \\
\text{PYTHIA8 CUETS1} & \text{PYTHIA8 CUETM1 MBR} \\
\text{HERWIG++ UE-EE-4C} & \text{PYTHIA8 4C MBR}
\end{align*}
\]

\( \eta \)

particle density \( \sim 4 \) times smaller \( \rightarrow \) correlation between the central and forward regions

\text{PYTHIA8 4C MBR} gives the best description

\text{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 $\varphi$ with respect to the direction of the leading object

  **Towards region** ($|\Delta \varphi| < 60^\circ$) and **Away region** ($|\Delta \varphi| > 120^\circ$)
  → dominated by the **leading object** and the **hadronic recoil**

  **Transverse region** ($60^\circ < |\Delta \varphi| < 120^\circ$)
  → 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

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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

- **increase** of the parton densities at **smaller** momentum fraction

TransMIN shows a stronger rise than TransDIF

- **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

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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
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
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
- 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.