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: $|\Delta \phi| < 60^\circ$

Away region: $|\Delta \phi| > 120^\circ$

Transverse region: $60^\circ < |\Delta \phi| < 120^\circ$

Reference hard direction
Underlying Event

Towards region: $|\Delta \phi| < 60^\circ$
Away region: $|\Delta \phi| > 120^\circ$
Transverse region: $60^\circ < |\Delta \phi| < 120^\circ$

**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:** $\langle TransMAX + TransMIN \rangle / 2$ 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
- \( \rho \leq 2\text{cm} \) (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
  - $|d_{xy}/\sigma_{d_{xy}}| < 3.0$, $|d_z/\sigma_d| < 3.0$
  - $|\sigma_{p_T}/p_T| < 0.05$
Data Correction

Unfolding

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

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

- “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

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

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