Minimum bias measurement at 13 TeV

Nicola Orlando (for the ATLAS collaboration)

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LHC collisions

Not possible to distinguish the hard process from the rest of the soft QCD interactions on an event by event basis.

Possible to define specific observables sensitive to different mixture of hard process and underlying event (UE).
ATLAS detector
Data taking

- Here focusing on a small fraction of dataset collected in 2015 with special, low luminosity, conditions
- Allows to reduce the effect of pile-up on the measurement

ATLAS pp run: June-August 2015

<table>
<thead>
<tr>
<th>Inner Tracker</th>
<th>Calorimeters</th>
<th>Muon Spectrometer</th>
<th>Magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>LAr</td>
<td>Solenoid</td>
<td>98.5</td>
</tr>
<tr>
<td>SCT</td>
<td>Tile</td>
<td>Toroid</td>
<td>99.7</td>
</tr>
<tr>
<td>TRT</td>
<td>MDT</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>RPC</td>
<td>99.1</td>
<td>99.3</td>
</tr>
<tr>
<td></td>
<td>CSC</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>TGC</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Solenoid</td>
<td>100</td>
<td>99.6</td>
</tr>
<tr>
<td></td>
<td>Toroid</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Luminosity weighted relative detector uptime (in percent) and good quality data delivery during the stable beams in pp collisions at 13 TeV between June-August 2015, corresponding to 173 pb⁻¹ recorded luminosity.
## Introduction

- Here focusing on a few results, most recent

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Reference</th>
<th>Integrated luminosity</th>
<th>Average interactions per</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low $p_T$ analysis</td>
<td>Eur.Phys.J. C76 (2016) no.9, 502</td>
<td>$151 \mu b^{-1}$</td>
<td>0.005 in average</td>
</tr>
<tr>
<td>“Standard” analysis</td>
<td>JHEP 1703 (2017) 157</td>
<td>1.6$nb^{-1}$</td>
<td>0.003-0.03</td>
</tr>
</tbody>
</table>

Extra information on tacking performance can be found here [https://cds.cern.ch/record/2037683](https://cds.cern.ch/record/2037683)
Track reconstruction performance

- Evaluate in early, low pile-up, data
  - Track selection, dataset, trigger strategy similar to the ATLAS 13 TeV minimum bias measurement
- Comparing data and simulation for basic observables entering in the track reconstruction (e.g., silicon hits multiplicity)
- Validation of the passive material description: plays a major role in the UE measurements
- Residual discrepancies covered by uncertainties of passive material description or dead modules emulation in simulation
Analysis strategy

- Low $p_T$ analysis: based on selection of events with at least two tracks with $p_T > 100$ MeV and $|\eta| < 2.5$
  - Observables built out of all tracks with $p_T > 100$ MeV and $|\eta| < 2.5$
- Exclusive analysis: based on selection of events with at least one track with $p_T > 1$ GeV and $|\eta| < 2.5$
  - Observables built out of all tracks with $p_T > 500$ MeV and $|\eta| < 2.5$
- Underlying event (UE) sensitive observables measured in different azimuthal regions defined based on the direction of the leading charged particle
- Measuring observables also in “trans diff” region (event by event difference between trans-max and trans-min) to isolate the contribution from the hard process
Particle level definition and correction

- Particle level definition uses two set of particles
  - Charged prompt particles with lifetime $\tau>300\text{ps}$
  - Charged particles coming form decays of particles with lifetime $\tau<30\text{ps}$
  - Exclude poorly reconstructed charmed baryons (typical reconstruction efficiency below 1%), avoid application of a large efficiency correction

$$w_{\text{trk}}(p_T, \eta) = \frac{1}{\varepsilon_{\text{trk}}(p_T, \eta)} \cdot [1 - f_{\text{fake}}(p_T, \eta) - f_{\text{sb}}(p_T, \eta) - f_{\text{sec}}(p_T, \eta) - f_{\text{okr}}(p_T, \eta)]$$

Tracking efficiency  Fraction of fake tracks  Fraction of strange baryons  Fracking of secondary tracks  Outside-of-kinematic correction

An additional correction used per event basis to remove vertex reconstruction and trigger efficiencies

$$w_{\text{ev}}(n_{\text{sel}}^{\text{no-z}}, \Delta z_{\text{tracks}}) = \frac{1}{\varepsilon_{\text{trig}}(n_{\text{sel}}^{\text{no-z}})} \cdot \frac{1}{\varepsilon_{\text{vtx}}(n_{\text{sel}}^{\text{no-z}}, \Delta z_{\text{tracks}})}$$
**Backgrounds**

- **Fake tracks** due to random silicon hits combinations
  - Low $p_T$ analysis: checked in simulation and data, found to be less than 1%
  - Standard analysis: fully negligible, checked on simulation

- **Strange baryons**, not included in the measurements definition, are subtracted using EPOS which provides the best description of ALICE strange baryon data
  - Up to 3% for tracks of 20 GeV $p_T$, deceasing with $p_T$ down to 0.01% on average for the low $p_T$ analysis

- **Non collision backgrounds** checked in simulation, found to be negligible

**Secondary particles** due to hadronic interaction with the detector material and photon conversion

Used sidebands of the transverse impact parameter distribution to estimate it to be $2.3\% \pm 0.7\%$
Monte Carlo predictions

<table>
<thead>
<tr>
<th>Generator (version)</th>
<th>Tune</th>
<th>PDF</th>
<th>Tune features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pythia8</td>
<td>A2</td>
<td>MSTW2008LO</td>
<td>Built on top of Pythia8 C4 tune, used ATLAS minimum bias 7 TeV data for MPI</td>
</tr>
<tr>
<td>Pythia8</td>
<td>A14</td>
<td>NNPDF2.3LO</td>
<td>ATLAS tune on UE and high $p_T$ measurements (jets, Drell-Yan, top-quark pair cross sections)</td>
</tr>
<tr>
<td>Pythia8</td>
<td>Monash</td>
<td>NNPDF2.3LO</td>
<td>Includes ATLAS Drell-Yan and UE data, plus CMS, SPS, Tevatron data</td>
</tr>
<tr>
<td>Herwig7</td>
<td>UE-MMHT</td>
<td>MMHT2014LO</td>
<td>Based on LHC and Tevatron UE as well as MPI data</td>
</tr>
<tr>
<td>EPOS</td>
<td>LHC</td>
<td>-</td>
<td>Based on LHC data, including Totem cross section measurement</td>
</tr>
</tbody>
</table>
Low $p_T$ analysis: systematic uncertainties

- Track reconstruction efficiency studied in simulation as a function of $p_T$ and $\eta$
- Main uncertainty due to description of passive material: from 1% to 10% (depending on $\eta$) per track
- Other components due to track selection efficiency, resolution, alignment
- Other minor uncertainties due to background estimation, track $p_T$ modeling, model dependence on the unfolding (non-closure)

| Distribution | $1/N_{ev} \cdot dN_{ch}/d|\eta|$ | $1/N_{ev} \cdot d^2N_{ch}/d\eta dp_T$ | $1/N_{ev} \cdot dN_{ev}/dn_{ch}$ | $\langle p_T \rangle$ vs. $n_{ch}$ |
|--------------|-------------------------------|-----------------------------------|---------------------------------|----------------|
| Range        | 0–2.5                         | 0.1–50 GeV                        | 2–250                           | 0–160 GeV      |
| Track
reconstruction | 1%–7%                         | 1%–6%                            | 0%–+38%–20%                     | 0%–0.7%        |
| Track
background | 0.5%                          | 0.5%–1%                          | 0%–+7%–1%                       | 0%–0.1%        |
| $p_T$

spectrum | –                             | –                                | 0%–+3%–9%                       | 0%–+0.3%–0.1% |
| Non-closure | 0.4%–1%                       | 1%–3%                            | 0%–4%                           | 0.5%–2%        |
Low $p_T$ analysis: selection and observables

- Targeting events with at least two tracks of $p_T$ greater than 100 MeV
- Special track reconstruction to cope with the low $p_T$ region
  - Requiring at least five silicon hits (instead of seven as in the default reconstruction)
  - Other set of cuts (e.g. impact parameter cuts) applied to suppress secondary tracks
- Events with more than a reconstructed vertex are vetoed
- Trigger based on random L1 items and, HLT requiring at least one track with $p_T>$200 MeV, typical efficiency above 95% for all selected events

<table>
<thead>
<tr>
<th>Observable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d\eta}$</td>
<td>Charged particle multiplicity vs $\eta$</td>
</tr>
<tr>
<td>$\frac{1}{N_{ev}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2 N_{ch}}{d\eta d p_T}$</td>
<td>Charged particle multiplicity vs $\eta$ and $p_T$</td>
</tr>
<tr>
<td>$\frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}}$</td>
<td>Charged particle multiplicity</td>
</tr>
<tr>
<td>$\langle p_T \rangle$ vs. $n_{ch}$</td>
<td>Average $p_T$ vs charged particle multiplicity</td>
</tr>
</tbody>
</table>
Low $p_T$ analysis: results

$\eta / dN_{\text{ch}} / d\eta$

$\frac{1}{N_{\text{ev}}} \cdot \frac{dN_{\text{ch}}}{d\eta}$

$\frac{1}{N_{\text{ev}}} \cdot \frac{d^2N_{\text{ch}}}{dp_T d\eta}$

$\eta \geq 2$, $p_T > 100$ MeV, $|\eta| < 2.5$

$\tau > 300$ ps

$\sqrt{s} = 13$ TeV

ATLAS

Data

PYTHIA 8 A2

PYTHIA 8 Monash

EPOS LHC

QGSJET II-04

MC / Data
Low $p_T$ analysis: results

$\tau > 300 \text{ ps}$

ATLAS $\sqrt{s} = 13 \text{ TeV}$
Energy evolution

Extrapolating the measurement to include strange baryons contribution and averaging in $|\eta|<0.2$ to compare with previous results.

At low $p_T$ the A2 tune of Pythia8 and QGSJET II-04 don’t describe the data well.
Standard analysis

- MBTS used for trigger, efficiency above 99%
- Pile-up suppressed by vetoing events with two vertices
- Same background estimation for the low-p_T analysis

<table>
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<th>Observable</th>
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</tr>
</thead>
<tbody>
<tr>
<td>( p_{\text{lead}} )</td>
<td>pT of the leading charged particle</td>
</tr>
<tr>
<td>( N_{\text{ch}}(\text{transverse}) )</td>
<td>Number of charged particles in the transverse regions</td>
</tr>
<tr>
<td>(</td>
<td>\Delta\phi</td>
</tr>
<tr>
<td>( \langle N_{\text{ch}}/\delta\eta\delta\phi \rangle )</td>
<td>Mean number of charged particles per ( \eta-\phi )</td>
</tr>
<tr>
<td>( \langle \Sigma p_T/\delta\eta\delta\phi \rangle )</td>
<td>Mean scalar ( p_T ) sum of charged particles per ( \eta-\phi )</td>
</tr>
<tr>
<td>( \langle \text{mean } p_T \rangle )</td>
<td>Mean per event average ( p_T ) of charged particles</td>
</tr>
</tbody>
</table>
Two different selections illustrate the transition between isotropic particle distribution, minimum-bias like, hard scattering.
Standard analysis

- Similar scaling of all regions at low $p_T$, transition at about 5 GeV
  
- Then the distributions in the transverse regions flatten, indicating UE dominance in those regions
  
- The hard process dominated regions show a clear $p_T$ dependence also at high $p_T$
Standard analysis

- No generator is able to describe well the data
- UE+hard scattering are collectively well described by all generators (but EPOS) for $p_T>10\text{GeV}$
- Trans-diff region for $p_T>10\text{GeV}$ is well described only by EPOS
Standard analysis

- Sensitive to the energy distribution in the UE
- No generator describes the data well in all regions, data typically described within 10% by all generators
- Monash tune performs best across the Pythia8 tunings

Trans-min region

Trans-max region

Trans-diff region
Summary

• New 13 TeV measurement of underlying event sensitive observables performed by the ATLAS collaboration

• The description of the data is typically good within a few percent but clear evidence of room for improvement from several observables

• Data have percent level precision and offer constraining power for generator tuning