Bose-Einstein correlations and results on minimum bias interactions, underlying event and particle production from ATLAS

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on behalf of the ATLAS Collaboration

XLV International Symposium on Multiparticle Dynamics
Wildbad Kreuth, Germany, 4 – 9 October 2015
The focus of ATLAS is high-\(p_T\) physics, and also provides a window onto important \textit{softer} QCD processes. These have intrinsic interest but also the understanding of underpins searches for new physics.

\textbf{Selected topics, often 13 TeV first results.} ► Bose Einstein Correlations ► Charged-particles distributions ► Underlying event ► Particles production

\textbf{ATLAS now has data 0.9 – 13 TeV in the same detector}, allowing scale evolution to be probed.

\textbf{ATLAS Inner Detector (ID) main tracking device:}

Consists of Pixel, Silicon strip (SCT) and drift tube (TRT) detectors. Single hit resolution between 10 \(\mu\)m (Pixel) and 130 \(\mu\)m (TRT).

\textbf{New: Insertable B-Layer (IBL) in the Pixel.}
Bose-Einstein Correlations

Correlations in phase space between two identical bosons from symmetry of wave functions.

- Enhances likelihood of two particles close in phase space
- Allows one to ‘probe’ the source of the bosons in size and shape
- Dependence on particle multiplicity and transverse momentum probes the production mechanism

Correlation function $C_2(Q)$ a ratio of probabilities:

$$C_2(Q) = \frac{\rho(p_1, p_2)}{\rho_0(p_1, p_2)} = C_0 \left(1 + \Omega(\lambda, RQ)\right) \cdot \left(1 + Q\varepsilon\right), \quad Q^2 = -(p_1 - p_2)^2$$

$C_0$ is a normalisation, $\varepsilon$ accounts for long range effects, $R$ is the effective radius parameter of the source, $\lambda$ is the strength of the effect parameter, 0/1 for coherent/chaotic source. Two possible parameterisation: Gaussian and Exponential.

$$C_2(Q) = \frac{N^{++,-,-}(Q)}{N^{ref}(Q)}$$

$\Omega^G(\lambda, RQ) = \lambda e^{-R^2Q^2}$

$\Omega^E(\lambda, RQ) = \lambda e^{-RQ}$

$N_{ref}$ without BEC effect from: unlike-charge particles (UCP), opposite hemispheres, event mixing. Basic Reference: distribution of UCP pairs of non-identical particle taken from the same event.

$$R_2(Q) = \frac{C_{Data}^{++,-,-}(Q)}{C_{MC}^{++,-,-}(Q)} = \frac{\rho^{++,-,-}}{\rho^{MC}^{++,-,-}} \frac{\rho^{MC}(++)}{\rho^{MC}(+-)}$$

The studies are carried out using the double ratio correlation function. The $R_2(Q)$ eliminates problems with energy-momentum conservation, topology, resonances etc. MC without BEC.
Inclusive Double Ratio correlation functions

Studies of one-dimensional BEC effects in pp collisions for $p_T > 100$ MeV and $|\eta| < 2.5$ at centre-of-mass energies of 0.9 and 7 TeV.

Fit to extract strength and source size. **Goldhaber** spherical shape with a Gaussian distribution of the source. **Exponential**, radial Lorentzian distribution of the source -> much better at low Q.

Bump in $\rho$-meson region because **MC overestimates $\rho \to \pi\pi$**, therefore region 0.5 – 0.9 GeV excluded from the fit. Q region is from 0.02 to 2 GeV.

- Lum. ~7 $\mu$b$^{-1}$
  - ~3.6×$10^5$ events with 4.5×$10^6$ tracks

- Lum. ~190 $\mu$b$^{-1}$
  - ~10$^7$ events with 2.1×$10^8$ tracks

- Lum. ~12 $\mu$b$^{-1}$
  - ~1.8×$10^4$ events with 2.7×$10^6$ tracks
Comparison with results of previous experiments

Most of the previous experiments provided \( R \) measurement using the Gaussian fit. The calculation of Gaussian result from the Exponential fit can be done using the scale factor \( \sqrt{\pi} \): 

\[ R^{(G)} = R^{(E)} / \sqrt{\pi} \]

### Energy [GeV] \( n_{ch} \) \( \lambda \) \( R \) [fm]

<table>
<thead>
<tr>
<th>Energy [GeV]</th>
<th>( n_{ch} )</th>
<th>( \lambda )</th>
<th>( R ) [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>≥2</td>
<td>0.74 ± 0.10</td>
<td>1.83 ± 0.25</td>
</tr>
<tr>
<td>7</td>
<td>≥2</td>
<td>0.71 ± 0.07</td>
<td>2.06 ± 0.22</td>
</tr>
<tr>
<td>7 (HM)</td>
<td>≥150</td>
<td>0.74 ± 0.06</td>
<td>2.36 ± 0.30</td>
</tr>
</tbody>
</table>

The results of BEC parameters for Exponential fits of \( R_2 \) used total uncertainties. Statistical uncertainties are below 2–4%.

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Y. Kulchitsky, ISMD 2015
The error bars – quadratic sum of the statistical and the systematic uncertainties

- \( \lambda \) and \( R \) are energy independent within the uncertainties
- \( \lambda \) exponentially decrease with multiplicity
- \( R \) of the \( \alpha \cdot n_{ch}^{1/3} \) fit for \( n_{ch} \leq 55 \) at 0.9 TeV is \( \alpha = 0.64 \pm 0.07 \) fm, at 7 TeV is \( \alpha = 0.63 \pm 0.05 \) fm
- \( R \) is a Constant for \( n_{ch} > 55 \) at 7 TeV \( R = 2.28 \pm 0.32 \) fm observed for the first time
- Pomeron-based model: Predicted plateau for \( n_{ch} \sim 60-80 \) with \( R = 2.2 \) fm and decreasing of \( R \) to 1 fm for higher multiplicity. PL B703(2011) 288
**K_T DEPENDENCE OF \( \lambda \) AND R PARAMETERS**

\[
k_T = \frac{\vec{p}_{T,1} + \vec{p}_{T,2}}{2}
\]

- \( \lambda \) and R are energy-independent within uncertainties;
- \( \lambda \) and R decrease exponentially with \( k_T \);
- Good agreement with earlier (non-LHC) measurements

\[\begin{align*}
\lambda & \text{ vs } k_T \text{ at } s = 7 \text{ TeV} \\
R & \text{ vs } k_T \text{ at } s = 7 \text{ TeV}
\end{align*}\]

- No \( k_T \) –dependence of \( \lambda \) for different multiplicity intervals
- \( k_T \) –dependence of R shows R increasing with multiplicity interval
Charged-particle distributions at 13 TeV

The composition of inelastic p-p collisions:

Charged-particle multiplicity as a function of \( p_T \) for events with \( n_{ch} \geq 1, p_T > 500 \text{ MeV} \) and \( |\eta| < 2.5 \)

Measurement – do not apply model dependent corrections and allow to tune models to data measured in well defined kinematic range.

Charged-particle multiplicity as a function of \( p_T \) for events with \( n_{ch} \geq 1, p_T > 500 \text{ MeV} \) and \( |\eta| < 2.5 \)

Measurement spans 10 orders of magnitude. EPOS and Pythia 8 Monash give remarkably good predictions.

More details for 13 TeV results on Friday by Hideyuki Oide
Charged-particle events and mean transverse momentum as a functions of multiplicity. The dots represent the data and the curves the predictions from different MC models. The bottom inserts show the ratio of the MC/Data.
Charged-particle multiplicity as a function of $\eta$

The average charged-particle multiplicity per unit of rapidity for $\eta=0$ as a function of the centre-of-mass energy from 0.9 to 13 TeV. The definition of charged-particle includes charged strange baryons.

Analysis is ongoing: Reduced $|\eta|<0.8$ for comparison to the various detectors; Extended for $p_T>0.1$ GeV; High multiplicity events.

The mean number of charged particles increases by a factor of 2.2 from 0.9 TeV to 13 TeV!
The underlying event (UE) is defined as the activity accompanying any hard scattering in a collision event:

- **Partons** not participating in a hard-scattering process (**beam remnants**)
- Multiple parton interactions (**MPI**)
- Initial and final state **gluon** radiation (**ISR, FSR**)

These soft interactions cannot be calculated with perturbative QCD:

- Free parameters to be tuned using data

**Leading object** can be defined variously:

- Leading jet, Z ($p_T$), Leading track in Minimum Bias like events

**Preliminary 13 TeV analysis based on Leading track:**

- Same dataset and same event and track selection as the MB13 analysis with an **additional requirement**: leading track with a $p_T$ of at least 1 GeV
- Results presented at detector level, without any correction (the width of the vertex distribution along the Z axis in MC is reweighted to match the data)
- The tracking efficiency uncertainty is about ≤2%
- No correction for secondary tracks is performed

More details for 13 TeV results on Friday by Hideyuki Oide
Comparison of detector level data and MC predictions for the $|\Delta \phi|$ distributions of average track multiplicity density (left) and average scalar $p_T$ sum density of tracks (right).

The leading track is defined to be at $\Delta \phi = 0$, and excluded from the distributions.

- Good Data/MC agreement with Minimum-Bias tune (A2) at $p_T^{\text{lead}} > 1$ GeV
- Good Data/MC agreement with UE tunes (Herwig++, Monash, A14) at $p_T^{\text{lead}} > 5$ GeV
Comparison of detector level data and MC predictions for **average track multiplicity density values** (left column) and **average scalar $p_T$ sum density of tracks** (right column) as a function of track $p_T^{lead}$ in the transverse (top row) and toward (bottom row) regions.

- These detector level distributions show discriminating power between different MC models.
- However, none of the models are very discrepant from data, building confidence in MPI energy extrapolation model used in these generators.
- From 10 GeV: good description for the UE tunes. The EPOS 15% off in the plateau.
Comparison of detector level data and MC predictions for **average scalar $p_T$ sum density of tracks** (top row) and **average track multiplicity density values** (bottom row) as a function of $Z$ (left column) and leading jet (right column) transverse momentum.

- For Jets: **Not perfect agreement** between data and simulation Herwig better than Pythia6
- For $Z$-boson: Good description given by Sherpa, followed by PYTHIA 8, ALPGEN and POWHEG
Charged particle multiplicity average values (left row) and scalar $p_T$ sum density average values (right row) compared between leading charged particle (MB), leading jet and Z boson events, respectively as functions of leading track $p_T$, leading jet $p_T$ and Z boson $p_T$.

- Data are compatible between the different definitions
- Transition between leading track and jet
- In the track density distribution, Z-bosons and jets agree well at high $p_T$
The $\Lambda$ transverse polarization measured by ATLAS compared to lower energy experiments.

$P_\Lambda = -0.010 \pm 0.005\text{ (stat)} \pm 0.004\text{ (syst)}$

$P_{\bar{\Lambda}} = 0.002 \pm 0.006\text{ (stat)} \pm 0.004\text{ (syst)}$

$0.8 < p_T < 15\text{ GeV}; |\eta| < 2.5; 5 \times 10^{-5} < x_F < 0.01,$

$1100\text{ MeV} < m_{p\pi} < 1127\text{ MeV}$

Polarizations in $p_T$ and $x_F$ bins: less than 2% (consistent with zero within estimated uncertainty).

Polarization of anti-$\Lambda$ was measured consistent with zero by all the previous experiments.

Transverse polarization of $\Lambda$ and anti-$\Lambda$ hyperons as a function of $p_T$.

Some energy dependence could be introduced → about 50% of $\Lambda$ in ATLAS are produced in decays (Pythia). Assume: polarization of the original baryons diluted in the decay → Measured polarization expected to be consistent with or smaller than the extrapolation.
\( pp \rightarrow \phi + X, \ \phi \rightarrow K^+K^- \)

\( K^\pm \) are identified by \( dE/dx \) in the Pixel detector.

Fiducial volume: \( 500 < p_T(\phi) < 1200 \) MeV, \( |y(\phi)| < 0.8, p_T(K^\pm) > 230 \) MeV, \( p(K^\pm) < 800 \) MeV

Sensitive to \( s \)-quark and low-\( x \) gluon densities. Also constrains fragmentation models.

The \( \phi(1020) \)-meson cross section vs. \( p_{T,\phi} \), extrapolated using PYTHIA6 to the kinematic region with \( 0.5 < p_{T,\phi} < 1.2 \) GeV and \( |y(\phi)| < 0.5 \), is compared to the ALICE.

The fiducial cross section: \( \sigma \cdot \text{Br}(\phi \rightarrow K^+K^-) = 570 \pm 8_{\text{stat}} \pm 66_{\text{syst}} \pm 20_{\text{lumi}} \) \( \mu b \)
Bose-Einstein correlations at 0.9 & 7 TeV: for the first time a saturation effect in the multiplicity dependence of the extracted BEC radius parameter is observed: $R=2.28\pm0.32$ fm for $n_{ch}>55$. The $k_T$ dependence of $R$ is obtained to increase with increase of multiplicity.

Charged-particle multiplicity measurements at 13 TeV using pp-collisions are presented. Of the models considered EPOS reproduces the data the best, PYTHIA 8 A2 and MONASH give reasonable descriptions.

Underlying event analysis with 13 TeV data are shown: reasonable agreement of tunes used in Atlas MC with new data. Diverse studies done at 7 TeV: Z, leading jet and leading track. Needed for tuning of the soft part of Monte Carlo simulation.

Transverse polarisation of $\Lambda$ and anti-$\Lambda$ hyperons at 7 TeV consistent with 0 at low $x_F$ confirming the behaviour of previous experiments showing a decrease of polarization as function of $x_F$.

The measurement of $\phi(1020)$ differential cross section at 7 TeV can provide useful input for turning and development of phenomenological models in order to improve MC generators.

THANKS A LOT TO ATLAS COLLEAGUES!
MANY THANKS TO YOU FOR ATTENTION!
Publications

New 13 TeV results:

- Charged-particle distributions in $\sqrt{s} = 13$ TeV pp interactions measured with the ATLAS detector at the LHC (ATLAS-CONF-2015-028)
- Leading Track Underlying Event at 13 TeV (ATL-PHYS-PUB-2015-019)

New 7 TeV results:

- Two-particle Bose-Einstein correlations in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV measured with the ATLAS detector (Eur.Phys.J. C75 (2015) 3644)
- Measurement of the transverse polarization of $\Lambda$ and anti-$\Lambda$ hyperons produced in proton-proton collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector (Phys. Rev. D 91 (2015) 032004)
- The differential production cross section of the $\phi$ (1020) meson in $\sqrt{s} = 7$ TeV pp collisions measured with the ATLAS Detector (Eur.Phys.J. C74 (2014) 2895)
32 independent wedge-shaped plastic scintillators (16 per side) read out by PMTs, $2.09<|\eta|<3.84^*$

* Pseudorapidity is defined as $\eta = -\frac{1}{2} \ln (\tan (\theta/2))$, $\theta$ is the polar angle with respect to the beam.

- Designed for triggering on min bias events, >99% efficiency
- MBTS timing used to veto halo and beam gas events
- Also being used as gap trigger for various diffractive subjects
Minimum-bias Event selection criteria

Events pass the data quality criteria (“good events”: all ID sub-systems nominal cond., stable beam, defined beam spot)

- Accept on signal-arm Minimum Bias Trigger scintillator
- Primary vertex (2 tracks with $p_T>$100 MeV),
- Veto to any additional vertices with ≥4 tracks.
- At least 2 tracks with $p_T>$100 MeV, $|\eta|<$2.5
- At least 1 first Pixel layer hit & 2, 4, or 6 SCT hits for $p_T>$100, 200, 300 MeV respectively.
- IBL hit required if expected (if not expected, next to innermost hit required if expected)
- Cuts on the transverse impact parameter: $|d_0^{BL}|<$1.5 mm (w.r.t beam line)
- Cuts on the longitudinal impact parameter: $|\Delta z_0 \sin \Theta|<$1.5 mm ($\Delta z_0$ is difference between tracks $z_0$ and vertex $z$ position)
- Track fit $\chi^2$ probability >0.01 for tracks with $p_T>$10 GeV

Correct distributions for detector effects:
- where possible the data used to reduce the MC dependencies
- Monte Carlo derived corrections for tracking
The systematic uncertainties of the inclusive fit parameters, $R$ and $\lambda$, of the exponential model are summarized in Table 1. The systematic uncertainties are combined by adding them in quadrature and the resulting values are given in the bottom row of Table 1. The same sources of uncertainty are considered for the differential measurements in $n_{\text{ch}}$ and the average transverse momentum $k_T$ of a pair, and their impact on the fit parameters is found to be similar in size.

**Table 1.** Systematic uncertainties on $\lambda$ and $R$ for the exponential fit of the two-particle double-ratio correlation function $R_2(Q)$ in the full kinematic region at $\sqrt{s} = 0.9$ and 7 TeV for minimum-bias and high-multiplicity (HM) events.

<table>
<thead>
<tr>
<th>Source</th>
<th>0.9 TeV</th>
<th>7 TeV</th>
<th>7 TeV (HM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda$</td>
<td>$R$</td>
<td>$\lambda$</td>
</tr>
<tr>
<td>Track reconstruction efficiency</td>
<td>0.6%</td>
<td>0.7%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Track splitting and merging</td>
<td>negligible</td>
<td></td>
<td>negligible</td>
</tr>
<tr>
<td>Monte Carlo samples</td>
<td>14.5%</td>
<td>12.9%</td>
<td>7.6%</td>
</tr>
<tr>
<td>Coulomb correction</td>
<td>2.6%</td>
<td>0.1%</td>
<td>5.5%</td>
</tr>
<tr>
<td>Fitted range of $Q$</td>
<td>1.0%</td>
<td>1.6%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Starting value of $Q$</td>
<td>0.4%</td>
<td>0.3%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Bin size</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Exclusion interval</td>
<td>0.2%</td>
<td>0.2%</td>
<td>1%</td>
</tr>
<tr>
<td>Total</td>
<td>14.8%</td>
<td>13.0%</td>
<td>9.6%</td>
</tr>
</tbody>
</table>
## Systematic uncertainties for UE Jets & Z

Table 3 Summary of systematic uncertainties for inclusive jet and exclusive dijet profiles vs. $p_T^{lead}$. The “efficiency” uncertainties include material uncertainties in the tracker and calorimeter geometry modelling. The “JES” uncertainty source for jets refers to the jet energy scale calibration procedure [49]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Inclusive jets</th>
<th>Exclusive dijets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pile-up and merged vertices</td>
<td>Pile-up and merged vertices</td>
</tr>
<tr>
<td>All observables</td>
<td>1–3 %</td>
<td>1–5 %</td>
</tr>
<tr>
<td>Charged tracks</td>
<td>Unfolding Efficiency</td>
<td>Unfolding Efficiency</td>
</tr>
<tr>
<td>$\sum p_T$</td>
<td>3 % 1–7 %</td>
<td>3–13 % 2–7 %</td>
</tr>
<tr>
<td>$N_{ch}$</td>
<td>1–2 % 3–4 %</td>
<td>3–22 % 3–7 %</td>
</tr>
<tr>
<td>mean $p_T$</td>
<td>1 % 0–4 %</td>
<td>1–9 % 1 %</td>
</tr>
<tr>
<td>Calo clusters</td>
<td>Unfolding Efficiency</td>
<td>Unfolding Efficiency</td>
</tr>
<tr>
<td>$\sum E_T,</td>
<td>\eta</td>
<td>&lt; 4.8$</td>
</tr>
<tr>
<td>$\sum E_T,</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>Jets</td>
<td>Energy resolution JES Efficiency</td>
<td>Energy resolution JES Efficiency</td>
</tr>
<tr>
<td>$p_T^{lead}$</td>
<td>0.3–1 % 1–4 % 0.1–2 %</td>
<td>0.4–3 % 1–3 % 0.3–3 %</td>
</tr>
</tbody>
</table>

Table 3 Typical contributions to the systematic uncertainties (in %) on the unfolded and corrected distributions of interest in the toward and transverse regions for the profile distributions. The range of values in the columns 3–5 indicate the variations as a function of $N_{ch}$. The column labelled Correlation indicates whether the errors are treated as correlated or not between the electron and muon channels.
### MC models for Minimum bias and underlying event at 13 TeV

<table>
<thead>
<tr>
<th>Generator</th>
<th>Version</th>
<th>Tune</th>
<th>PDF</th>
<th>7 TeV data MB</th>
<th>UE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYTHIA 8</td>
<td>8.185</td>
<td>A2</td>
<td>MSTW2008LO [19]</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>PYTHIA 8</td>
<td>8.186</td>
<td>MONASH</td>
<td>NNPDF2.3LO [20]</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>HERWIG++</td>
<td>2.7.1</td>
<td>UE-EE-5-CTEQ6L1</td>
<td>CTEQ6L1 [21]</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>EPOS</td>
<td>3.1</td>
<td>LHC</td>
<td>N/A</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>QGSJET-II</td>
<td>II-04</td>
<td>default</td>
<td>N/A</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Pythia8</td>
<td>8.186</td>
<td>A14</td>
<td>NNPDF2.3LO</td>
<td>UE/Shower</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Summary of MC tunes used to compare to the corrected data. The generator and its version are given in the first two columns, the tune name and the PDF used are given in the next two columns and the last two columns indicate whether the data used in the tune included 7 TeV minimum bias (MB) and/or underlying event (UE) data.

### MC models for underlying event at 7 TeV

<table>
<thead>
<tr>
<th>Generator</th>
<th>Type</th>
<th>Version</th>
<th>PDF</th>
<th>Tune</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYTHIA 8</td>
<td>LO PS</td>
<td>8.165</td>
<td>CTEQ6L1</td>
<td>AU2 [31]</td>
</tr>
<tr>
<td>HERWIG++</td>
<td>LO PS</td>
<td>2.5.1</td>
<td>MRST LO** [32]</td>
<td>UE-EE-3 [33]</td>
</tr>
<tr>
<td>Sherpa</td>
<td>LO multi-leg</td>
<td>1.4.0</td>
<td>CT10 [34]</td>
<td>Default</td>
</tr>
<tr>
<td></td>
<td>ME + PS</td>
<td>/1.3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALPGEN</td>
<td>LO multi-leg ME</td>
<td>2.14</td>
<td>CTEQ6L1</td>
<td></td>
</tr>
<tr>
<td>+ HERWIG</td>
<td>+ PS</td>
<td>6.520</td>
<td>MRST**</td>
<td>AUET2 [35]</td>
</tr>
<tr>
<td>+ JIMMY</td>
<td>(adds MPI)</td>
<td>4.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>POWHEG</td>
<td>NLO ME</td>
<td>–</td>
<td>CT10</td>
<td></td>
</tr>
<tr>
<td>+ PYTHIA 8</td>
<td>+ PS</td>
<td>8.165</td>
<td>CT10</td>
<td>AU2</td>
</tr>
</tbody>
</table>

Table 2: Main features of the Monte-Carlo models used. The abbreviations ME, PS, MPI, LO and NLO respectively stand for matrix element, parton shower, multiple parton interactions, leading order and next to leading order in QCD.
**Table 2** Details of the MC models used in this paper. It should be noted that all tunes use data from different experiments for constraining different processes, but for brevity only the data which had most weight in each tune is listed. A “main data” value of “LHC” indicates data taken at $\sqrt{s} = 7$ TeV, although $\sqrt{s} = 900$ GeV data were also included with much smaller weight in the ATLAS tunes. Some tunes are focused on describing the minimum bias (MB) distributions better, while the rest are tuned to describe the underlying event (UE) distributions, as indicated in “focus”. The detector-simulated MC configurations used for data correction are separated from those used in the results comparison plots, for clarity. For the POWHEG+PYTHIA 6 entry, separate parton distribution functions (PDFs) were used for the matrix element and parton shower/multiple scattering aspects of the modelling, indicated with “ME” and “PS/MPI” respectively.

<table>
<thead>
<tr>
<th>Generator</th>
<th>Version</th>
<th>Tune</th>
<th>PDF</th>
<th>Focus</th>
<th>Main data</th>
<th>Used for</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYTHIA 8</td>
<td>8.157</td>
<td>AU2 [28]</td>
<td>CT10 [29]</td>
<td>UE</td>
<td>LHC</td>
<td>MC/data comparison</td>
</tr>
<tr>
<td>PYTHIA 6</td>
<td>6.421</td>
<td>DW [32]</td>
<td>CTEQ5L</td>
<td>UE</td>
<td>Tevatron</td>
<td>MC/data comparison</td>
</tr>
<tr>
<td>HERWIG++</td>
<td>2.5.1</td>
<td>UE7-2 [33]</td>
<td>MRST LO** [34]</td>
<td>UE</td>
<td>LHC</td>
<td>MC/data comparison</td>
</tr>
<tr>
<td>HERWIG+JIMMY</td>
<td>6.510</td>
<td>AUET2 [35]</td>
<td>MRST LO**</td>
<td>UE</td>
<td>LHC</td>
<td>MC/data comparison</td>
</tr>
<tr>
<td>POWHEG+PYTHIA 6</td>
<td>r2169 + 6.425</td>
<td>Perugia 2011</td>
<td>CT10 (ME) + CTEQ5L (PS/MPI)</td>
<td>UE</td>
<td>LHC</td>
<td>MC/data comparison</td>
</tr>
<tr>
<td>PYTHIA 6</td>
<td>6.425</td>
<td>AMBT1 [37]</td>
<td>MRST LO* [38]</td>
<td>MB</td>
<td>Early LHC</td>
<td>Data correction</td>
</tr>
<tr>
<td>HERWIG++</td>
<td>2.5.0</td>
<td>LO*_JETS [39]</td>
<td>MRST LO*</td>
<td>UE</td>
<td>Tevatron</td>
<td>Correction systematics</td>
</tr>
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</table>
Strange baryons

- Particles with lifetime $30 \text{ ps} < \tau < 300 \text{ ps}$ are no longer considered primary particles in the analysis, decay products are treated like secondary particles.
- All of these particles were **strange baryons**: with low reconstruction efficiency (<0.1%) and large variations in predicted rates lead to a model dependence.
- Primary particles have $\tau > 300 \text{ ps}$

The fraction of strange baryons in generated particles as a function of particle $p_T$ as predicted by various generators.

The fraction of reconstructed tracks coming from strange baryons as a function of track $p_T$ as predicted by PYTHIA8 A2.
Charged-particle multiplicities as a function of the pseudorapidity for events with $n_{ch} \geq 1$, $p_T > 500$ MeV and $|\eta| < 2.5$ at $\sqrt{s} = 0.9$ (a), 2.36 (b) and 7 TeV (c). The dots represent the data and the curves the predictions from different MC models. The vertical bars represent the statistical uncertainties, while the shaded areas show statistical and systematic uncertainties added in quadrature. The bottom inserts show the ratio of the MC over the data.
Charged-particle multiplicities as a function of the transverse momentum for events with $n_{ch} \geq 1$, $p_T > 500$ MeV and $|\eta| < 2.5$ at $\sqrt{s} = 0.9$ (a), 2.36 (b) and 7 TeV (c). The dots represent the data and the curves the predictions from different MC models. The vertical bars represent the statistical uncertainties, while the shaded areas show statistical and systematic uncertainties added in quadrature. The bottom inserts show the ratio of the MC over the data.
Charged-particle multiplicities distribution for events with $n_{ch} \geq 1$, $p_T > 500$ MeV and $|\eta| < 2.5$ at $\sqrt{s} = 0.9$ (a), 2.36 (b) and 7 TeV (c). The dots represent the data and the curves the predictions from different MC models. The vertical bars represent the statistical uncertainties, while the shaded areas show statistical and systematic uncertainties added in quadrature. The bottom inserts show the ratio of the MC over the data.
Average transverse momentum as a function of the number of charged particles in the event for events with $n_{ch} \geq 1$, $p_T > 500$ MeV and $|\eta| < 2.5$ at $\sqrt{s} = 0.9$ (a) and 7 (b). The dots represent the data and the curves the predictions from different MC models. The vertical bars represent the statistical uncertainties, while the shaded areas show statistical and systematic uncertainties added in quadrature. The bottom inserts show the ratio of the MC over the data.
The Λ hyperons are spin-1/2 particles and their polarization is characterized by a polarization vector \( P \). Its component transverse to the Λ momentum is of interest since for hyperons produced via the strong interaction parity conservation requires that the parallel component is zero. Huge Λ sample allows to measure Λ polarization \( P \) by measuring the decay angle \( \cos \theta^* \) between the decay proton and Λ flight directions.

Probability distribution of \( \theta^* \) is

\[
g(t; p) = \frac{1}{2}(1 + \alpha p t) \cos \theta^* + \text{PEE Edt} \cos \theta^* + \text{PEE Edt} \cos \theta^*
\]

were \( \alpha = 0.642 \pm 0.013 \) is world average of the \( P \)-violating decay asymmetry for Λ.

From previous experiments:

- polarization measured only in experiment with fixed target up to 40 GeV in the cms system and \( t \) up to 62 GeV at ISR.
- the magnitude of the Λ polarization increases with \( p_T \) until it saturates at about 1 GeV.
- the magnitude of the Λ polarization decreases with decreasing \( |x_F| \).
- the Λ polarization does not depend strongly on the center of mass energy, tested up to 40 GeV.
The truncated mean for the energy loss per track as a function of signed momentum for tracks.

Examples of invariant $K+K^-$ mass distributions in the data (dots) compared to results of the fits (solid lines), as described in the text, for a the lowest $p_{T,\phi}$ bin, b one of the middle $p_{T,\phi}$ bins, c the most central $|y_{\phi}|$ bin and d most forward $|y_{\phi}|$ bin. The dashed curves show the background contribution and the dotted red curves demonstrate the signal contributions, with parameters listed in the legend.