Recent Results on Soft QCD Topics from ATLAS

Bormio, 55. International Winter Meeting on Nuclear Physics, 25.01.17

Andrey Minaenko, IHEP (Protvino) on behalf of the ATLAS Collaboration
Outline

• The ATLAS detector is designed to investigate very rare high $p_T$ processes in the environment of high luminosities and large number (several tens) of interactions per one bunch crossing

• But ATLAS provides also a window onto important soft QCD processes which have large cross sections and the data for such studies are taken in special low luminosity runs

• These processes have intrinsic interest. They can not be predicted by a perturbative QCD. Various MC models, having a large number of adjustable tuning parameters, are used to describe them

• As well they are needed to understand pile-up and underlying event activity in all LHC measurements

• This presentation concerns the 4 following recent ATLAS soft QCD studies:
  
  I. Charged-particles distributions in $\sqrt{s} = 13$ TeV pp interactions
  
  II. Measurement of charged-particle distributions sensitive to underlying event in $\sqrt{s} = 13$ TeV pp collisions
      ➢ arxive:1701.05390
  
  III. Study of hard double-parton scattering in four jet events in pp collisions at $\sqrt{s} = 7$ TeV
       ➢ JHEP 11 (2016) 110
  
  IV. Measurement of the total cross section from elastic scattering in pp collisions at $\sqrt{s} = 8$ TeV
I-II. Inner Detector

- Studies I and II are based on the reconstructed in the Inner Detector (ID) (Figure above) charged tracks
- ID has full coverage in $\phi$ and covers the pseudorapidity range $|\eta| < 2.5$ and it is placed inside 2T axial magnetic field
- Its barrel (end-cap) part consists of
  - four (three) pixel layers
  - four (nine) double-layers of single-sided silicon microstrips
  - 73 (160) layers of TRT (Transition Radiation Tracker) straws
- A typical track in the barrel part has 4 pixel hits, 8 SCT hits and more than 30 TRT straw hits
- Minimum-bias trigger scintillators (MBTS), covering region $2.07 < |\eta| < 3.86$, are used for triggering. They are mounted at each end of the ID and segmented into 12 sectors each
I-II. Data selection, corrections

- Special low luminosity run with $<\mu> = 0.005$, about 9M events
- Trigger: one or more fired MBTS counters on either side of the ID
- A number of corrections used and their uncertainties included to the corresponding systematic errors
- The corrections account for inefficiencies due to trigger selection, vertex and track reconstruction, background from the secondary interactions
- The trigger efficiency is rather high (next slide) as well as a vertex reconstruction efficiency
I-II. Trigger and Track Reconstruction Efficiency

- The primary track reconstruction efficiency, $\varepsilon_{\text{trk}}(p_T, \eta)$, is determined from the simulation.
- $\varepsilon_{\text{trk}}$ depends on the amount of material in the detector, due to particle interactions that lead to efficiency losses.
- The resulting reconstruction efficiency as a function of $\eta$ and $p_T$ is shown in the above Figures together with its uncertainty.
- The efficiency is lower at $|\eta| > 1$ due to more material in that region.
- The total uncertainty due to imperfect knowledge of the detector material is $\pm 0.7\%$ in the most central region and $\pm 1.5\%$ in the most forward region.
- The Bayesian unfolding is applied to the $p_T$ and multiplicity distributions to correct from the observed track distributions to those for of primary charged particles.
I-II. Monte Carlo generators used

- **PYTHIA8:**
  - includes non-diffractive (ND) processes dominated by t-channel gluon exchange
  - and diffractive processes involving a color-singlet exchange
  - includes multi parton interactions (MPI)
  - for a hard scattering uses perturbative $2 \rightarrow 2$ QCD matrix element with leading logarithmic initial and final state parton showers
  - Lund string hadronization model

- **Herwig:**
  - for a hard scattering uses perturbative $2 \rightarrow 2$ QCD matrix element with leading logarithmic initial and final state parton showers
  - includes MPI (simpler parametrization than in PYTHIA)
  - a cluster-oriented color-disruption mechanism is used in hadronization

- **EPOS:**
  - a specialist softQCD/cosmic-ray air-shower MC generator based on an implementation of parton-based Gribov-Regge theory
  - a QCD inspired effective-field theory describing the hard and soft scattering simultaneously

- **QGSJET-II:**
  - Provides a phenomenological treatment of hadronic and nuclear interactions in the Reggeon field theory framework
I. Mean charged particle density as a function of $\eta$ and $p_T$

The mean particle density is approximately constant at 2.9 for $|\eta| < 1$ and decreases at higher $|\eta|$

- EPOS describes the data well for $|\eta| < 1$ but predicts slightly larger multiplicities for larger $|\eta|$
- QGSJET-II and PYTHIA8 Monash predict too large multiplicities (by 15% and 5%)
- PYTHIA8 A2 – by about 3% too low in the central region but is OK in the forward region

The distribution on $p_T$ decreases by about 9 orders of value

- EPOS describes the data well over the entire $p_T$ spectrum
- The PYTHIA 8 tunes describe the data well but are slightly above at large $p_T$
- QGSJET-II gives a poor prediction over the entire spectrum
I. The charged particle multiplicity distribution and $<p_T>$ vs $n_{ch}$

- The charged particle multiplicity distribution decreases by 5 orders. The high $n_{ch}$ region has significant contribution from events with numerous MPI
  - All the models describes the data satisfactory in the region $n_{ch} < 30-50$ but fail at higher $n_{ch}$
  - At high $n_{ch}$ the strongest deviations are for QGSJET-II and PYTHIA8 A2

- $<p_T>$ rises with $n_{ch}$ from 0.8 to 1.2 GeV. The increase is modelled by a color reconnection mechanism in PYTHIA8 or by the hydrodynamical evolution model used in EPOS
  - EPOS predicts slightly lower $<p_T>$, but describes the dependence on $n_{ch}$ well
  - The PYTHIA8 tunes predict a steeper rise of $<p_T>$ with $n_{ch}$ than the data
  - QGSJET-II predicts $<p_T>$ of ~1 GeV, with very little dependence on $n_{ch}$
I. Energy dependence of the charged particles density at $\eta = 0$

- The mean number of primary charged particles in the central region is $2.874 \pm 0.001$ (stat.) $\pm 0.033$ (syst.)
- The value increases by a factor of 2.2 when $\sqrt{s}$ increases by a factor of about 14 from $0.9$ TeV to $13$ TeV
- EPOS and PYTHIA8 A2 describe the dependence very well
- PYTHIA8 Monash and QGSJET-II predict a steeper rise in multiplicity with c.m.s. energy

Conclusions

- Primary-charged-particle multiplicity measurements with the ATLAS detector using pp interactions at $\sqrt{s} = 13$ TeV are presented
- The results highlight clear difference between MC models and the measured distributions
- EPOS reproduces data the best, PYTHIA8 A2 and Monash give reasonable descriptions of the data and QGSJET-II provides the worst description
II. Underlying event with leading pₜ charged particle

- Underlying event is defined as activity accompanying any hard scattering in an event
- It includes
  - Partons not participating in a hard scattering (beam remnants)
  - Multiple parton interactions
  - Initial state gluon radiation (ISR)
- It is impossible to separate the UE from the hard scattering process on an event by event base
- However distributions have been measured which are sensitive to the properties of the UE
- These are the distributions of particles in the transverse regions (Figure)
- The figure illustrates distribution of charged particles in the transverse to the beam plane with respect to the leading pₜ charged particle
- The towards and away regions contain products of the hard scatter mostly
II. Trans-min region

- Trans-min region most sensitive to MPI and hard process contamination is small: the distributions are rather flat above $p_T = 5$ GeV
- EPOS and PYTHIA8 A2 are too low at the plateau region
- Herwig7 gives one of the best descriptions at the plateau but severe undershoots transition region below $p_T = 5$ GeV
II. Trans-max region

- The trans-max region has larger hard process contamination: the rise in the plateau region is stronger and its mean level is noticeably larger.
- In general MC generators describes the data better than for the trans-min.
- EPOS strongly undershoots data at $p_T > 10$ GeV.
- Herwig7 again undershoots $p_T < 5$ GeV.
II. Conclusions

- A number of distributions sensitive to properties of the UE are presented
- Present measurement completes previous ATLAS measurements at lower energies (above figures)
- An increase of UE activity of approximately 20% is observed when going from 7 TeV to 13 TeV pp collisions
- Comparison against prediction from several MC generator tunes indicate that for most observables the models describe UE data to better than 5% accuracy
- EPOS gives the worst predictions
- The data can be used to improve MC tunes
III. Hard double parton scattering in 4-jet events

\[ \hat{\sigma}_{DPS}^{A,B} = \frac{1}{1+\delta_{AB}} \frac{\hat{\sigma}_A \hat{\sigma}_B}{\sigma_{\text{eff}}} , \]

\[ \implies \sigma_{\text{eff}} = \frac{1}{1+\delta_{AB}} \frac{\hat{\sigma}_A \hat{\sigma}_B}{f_{DPS} \cdot \hat{\sigma}_{\text{tot}}^{A,B}} \]

Kroneker \( \delta = 1 \), if \( A \) and \( B \) the same

Fraction of DPS events

\[ \sigma_{\text{eff}} = \frac{1}{1+\delta_{AB}} \frac{1}{f_{DPS}} \cdot \frac{\sigma_{\text{2j}}^{A} \sigma_{\text{2j}}^{B}}{\sigma_{\text{4j}}} \]

• \( \sigma_{\text{eff}} \) is an effective cross section (to be found)
  
  – phenomenological parameter describing the effective overlap between the interacting hadrons
  
  – determines the overall size of DPS cross section
  
  – Assumed to be process and cut independent

• Data taken in pp collisions at \( \sqrt{s} = 7 \text{ TeV} \) during 2010, \( \langle \mu \rangle = 0.41 \), integrated luminosity 37.3 pb\(^{-1}\)
III. Event selection, templates

• Single vertex events only
• Use anti-\(k_T\) jets with \(R = 0.6\) found in calorimeters at \(|\eta| < 4.4\)
• 4-jet event selection: \(N_{\text{jet}} \geq 4, \ p_T^1 > 42.5\text{ GeV}, \ p_T^{2,3,4} > 20\text{ GeV}\)
• Di-jet samples \(N_{\text{jet}} \geq 2, \ A: p_T^{1,2} > 20\text{ GeV}; \ B: p_T^1 > 42.5\text{ GeV}, p_T^2 > 20\text{ GeV}\)
• 4-jet and B samples are subsamples of sample A
• AHJ MC: Alpgen (2 \(\rightarrow\) n, n up to 5) + Jimmi (MPI) + Herwig (hadronization)
• Event record of AHJ is used to distinguish between (2 \(\rightarrow\) 4) and (two 2 \(\rightarrow\) 2) processes
• Sample SPS: all 4 jets from one hard scatter, based on AHJ MC
• Sample complete DPS (cDPS): 2 jets from 1\(^{\text{st}}\) hard scatter, 2 jets from 2\(^{\text{nd}}\) one. Obtained by overlaying two di-jet data events
• Sample semi DPS (sDPS): 3 jets from 1\(^{\text{st}}\) hard scatter, 1 jet from 2\(^{\text{nd}}\) one. Obtained by overlaying two di-jet data events
• Template fit is used to determine \(f_{\text{DPS}} = f_{\text{cDPS}} + f_{\text{sDPS}}\)
III. Discriminating variables

- 21 discriminating variables are used to classify events as belonging to SPS ($\xi_{\text{SPS}}$), cDPS ($\xi_{\text{cDPS}}$), or sDPS ($\xi_{\text{sDPS}}$): $\xi_{\text{SPS}} + \xi_{\text{cDPS}} + \xi_{\text{sDPS}} = 1$
- Neural network is used for event classification

$$\Delta_{ij}^{\text{PT}} = \frac{|\vec{p}_T^i + \vec{p}_T^j|}{p_T^i + p_T^j}; \quad \Delta\phi_{ij} = |\phi_i - \phi_j|; \quad \Delta y_{ij} = |y_i - y_j|;$$

$$|\phi_{1+2} - \phi_{3+4}|; \quad |\phi_{1+3} - \phi_{2+4}|; \quad |\phi_{1+4} - \phi_{2+3}|;$$
III. NN output for test samples
III. Results

- $\chi^2$ minimization with Minuit to find $f_{cDPS}$ and $f_{sDPS}$
- $D = (1 - f_{cDPS} - f_{sDPS}) M_{SPS} + f_{cDPS} M_{cDPS} + f_{sDPS} M_{sDPS}$
- Here $D$ is ternary data distribution
- $M_{SPS}$, $M_{cDPS}$ and $M_{sDPS}$ are ternary distributions in test samples normalized to measured 4-jet cross section
- Different sources of systematic uncertainties were taken into account and propagated to the final results
- The dominating source is jet energy scale (JES) uncertainty: about 4.5% in the central region and rising to about 10% in the forward one. It gives about 30% uncertainty in the final results

$$f_{DPS} = 0.092 ^{+0.005}_{-0.011} \text{ (stat.)} ^{+0.033}_{-0.037} \text{ (syst.),}$$

$$\sigma_{\text{eff}} = 14.9 ^{+1.2}_{-1.0} \text{ (stat.)} ^{+5.1}_{-3.8} \text{ (syst.) mb}$$
III. Results overview

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(energy, final state, year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>(√s = 7 TeV, 4 jets, 2016)</td>
</tr>
<tr>
<td>CDF</td>
<td>(√s = 1.8 TeV, 4 jets, 1993)</td>
</tr>
<tr>
<td>UA2</td>
<td>(√s = 630 GeV, 4 jets, 1991)</td>
</tr>
<tr>
<td>AFS</td>
<td>(√s = 63 GeV, 4 jets, 1986)</td>
</tr>
<tr>
<td>DØ</td>
<td>(√s = 1.96 TeV, 2γ + 2 jets, 2016)</td>
</tr>
<tr>
<td>DØ</td>
<td>(√s = 1.96 TeV, γ + 3 jets, 2014)</td>
</tr>
<tr>
<td>DØ</td>
<td>(√s = 1.96 TeV, γ + b/c + 2 jets, 2014)</td>
</tr>
<tr>
<td>DØ</td>
<td>(√s = 1.96 TeV, γ + 3 jets, 2010)</td>
</tr>
<tr>
<td>CDF</td>
<td>(√s = 1.8 TeV, γ + 3 jets, 1997)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>(√s = 8 TeV, Z + J/ψ, 2015)</td>
</tr>
<tr>
<td>CMS</td>
<td>(√s = 7 TeV, W + 2 jets, 2014)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>(√s = 7 TeV, W + 2 jets, 2013)</td>
</tr>
<tr>
<td>DØ</td>
<td>(√s = 1.96 TeV, J/ψ + Ψ, 2016)</td>
</tr>
<tr>
<td>LHCb</td>
<td>(√s = 7 &amp; 8 TeV, Ψ(1S)D0⁺, 2015)</td>
</tr>
<tr>
<td>DØ</td>
<td>(√s = 1.96 TeV, J/ψ + J/ψ, 2014)</td>
</tr>
<tr>
<td>LHCb</td>
<td>(√s = 7 TeV, J/ψΛc⁺, 2012)</td>
</tr>
<tr>
<td>LHCb</td>
<td>(√s = 7 TeV, J/ψD_s⁺, 2012)</td>
</tr>
<tr>
<td>LHCb</td>
<td>(√s = 7 TeV, J/ψD⁺, 2012)</td>
</tr>
<tr>
<td>LHCb</td>
<td>(√s = 7 TeV, J/ψD0⁺, 2012)</td>
</tr>
</tbody>
</table>

σ eff [mb]
IV. Total and elastic cross sections

- Optical theorem relates total pp cross section to the elastic-scattering amplitude extrapolated to the forward direction
  \[ \sigma_{\text{tot}} = 4\pi \cdot \text{Im}(f_{\text{el}})_{t \to 0} \]

- ATLAS uses optical theorem and luminosity-dependent method of the total cross section extraction. With this method
  \[ \sigma_{\text{tot}}^2 = \frac{16\pi(hc)^2}{1 + \rho^2} \frac{d\sigma_{\text{el}}}{dt}\bigg|_{t \to 0} \]

- Where \( \rho = 0.1362 \) represents a small correction arising from the ratio of the real to the imaginary part of the elastic-scattering amplitude
IV. ALFA detector, data taking

- ALFA detector is used to record elastic-scattering data
- Consists of Roman Pot (RP) tracking detector stations placed at 237 m (inner) and 241 m (outer) on either side of the ATLAS IP
- Each station houses two scintillating fibre detectors with a spatial resolution of about 35 μm
- The detectors are supplemented with trigger counters consisting of plain scintillator tiles
- The data recorded in a single low luminosity run with special high β* optics for pp interactions at $\sqrt{s} = 8$ TeV
- 3.8 M selected elastic events
- Measure elastic track positions at ALFA to get the scattering angle $\Theta$ and thereby the t-spectrum $d\sigma/dt$
- To calculate $\Theta$ from the measured tracks the transport matrix elements of the beam optics are used
IV. ALFA detector
IV. Analysis of elastic data

• Data-driven method to calculate the reconstruction efficiency of about 90%
• Tuning of the beam optics model with ALFA constrains → effective optics
• Trigger efficiency is very high ~99.9%; determined from data stream with looser conditions
• Dedicated luminosity determination resulting in a small uncertainty of 1.5%

\[
\left( \frac{d\sigma}{dt} \right)_i = \frac{1}{t_i} \cdot \frac{M^{-1}[N_i - B_i]}{A_i \cdot \varepsilon_{\text{reco}} \cdot \varepsilon_{\text{trig}} \cdot \varepsilon_{\text{DAQ}} \cdot L_{\text{int}}}
\]

• \( \Delta t_i \): the width of the bins in \( t \)
• \( A \): acceptance(\( t \))
• \( M^{-1} \): symbolizes the unfolding procedure applied to the background subtracted number of events \( N_i - B_i \)
• \( \varepsilon_{\text{reco}} \): event reconstruction efficiency
• \( \varepsilon_{\text{trig}} \): trigger efficiency
• \( \varepsilon_{\text{DAQ}} \): the dead time correction
• \( L_{\text{int}} \): the integrated luminosity
IV. Fitting formula for $d\sigma/dt$

- The theoretical prediction used to fit the elastic data consists of the Coulomb term, the Coulomb-Nuclear-Interference term and the dominant Nuclear term.

\[
\frac{d\sigma}{dt} = \frac{4\pi\alpha^2(\hbar c)^2}{|t|^2} \cdot G^4(t) + \sigma_{tot} \cdot \frac{\alpha G^2(t)}{|t|} \left[ \sin(\alpha\phi(t)) + \rho \cos(\alpha\phi(t)) \right] \cdot \exp\left(\frac{-B |t|}{2}\right) + \sigma_{tot}^2 \frac{1 + \rho^2}{16\pi(\hbar c)^2} \cdot \exp(-B |t|) 
\]

- Coulomb
- CNI
- Nuc.

\[
G(t) = \left( \frac{\Lambda}{\Lambda + |t|} \right)^2, \quad \text{Proton dipole form factor}
\]

\[
\phi(t) = -\ln \frac{B|t|}{2} - \phi_C, \quad \text{Coulomb phase}
\]

\[
\begin{array}{c|c|c}
\rho & 0.1362 \\
\Lambda & 0.71 \text{ GeV}^2 \\
\phi_C & 0.577
\end{array}
\]
Fit results

- The fit includes experimental systematic uncertainties in the $\chi^2$
- Main systematics
  - t-independent: luminosity ±1.5%
  - t-dependent: beam energy ±0.65%
- The fit range is set to $-t[0.014, 0.1]$ GeV$^2$, where possible deviations from exponential form of the nuclear amplitude are expected to be small
- The extrapolation uncertainty is evaluated by a variation of the fit range

\[ \sigma_{\text{tot}} = 96.07 \pm 0.18(\text{stat.}) \pm 0.85(\text{exp.}) \pm 0.31(\text{extr.}) \]
\[ B = 19.74 \pm 0.05(\text{stat.}) \pm 0.16(\text{exp.}) \pm 0.15(\text{extr.}) \]
IV. Energy evolution

- Comparison with COMPETE model Chin.Phys. C, 38, 090001 (2014) for the evolution of the total cross section. High accuracy of the ATLAS data due to precise luminosity measurement

- Comparison with a model from Schegelsky and Ryskin Phys.Rev. D85, 094024 (2012) for the evolution of the nuclear slope
Summary

• Primary-charged-particle multiplicity measurements with the ATLAS detector using pp interactions at $\sqrt{s} = 13$ TeV were done

• The results highlight clear difference between MC models and the measured distributions

• EPOS reproduces data the best, PYTHIA8 A2 and Monash give reasonable descriptions of the data and QGSJET-II provides the worst description

• A number of distributions sensitive to properties of the UE are presented for pp interactions at $\sqrt{s} = 13$ TeV

• EPOS fails to describe the data properly contrary to the minimum bias event description, for which EPOS is the best

• Comparison against prediction from several other MC generator tunes indicate that for most observables the models describe UE data to better than 5% accuracy

• Hard double parton scattering in 4-jet events is investigated in pp interactions at $\sqrt{s} = 7$ TeV

• The phenomenological DPI parameter $\sigma_{\text{eff}}$ is extracted

• Distribution $d\sigma/dt$ for proton-proton elastic scattering at $\sqrt{s} = 8$ TeV is measured and used to estimate $\sigma_{\text{tot}} = 96.07 \pm 0.18(\text{stat.}) \pm 0.85(\text{exp.}) \pm 0.31(\text{extr.})$