Centrality dependence of charged particle production in proton-lead collisions measured by ATLAS
(based on ATLAS-CONF-2013-096)

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Introduction

p/d+A collisions at the LHC and RHIC provide an opportunity to study the physics of the initial-state of ultra-relativistic A+A collisions without of thermalization and collective evolution

• p/d+A measurements can shed insight on the:
  • impact of an extended nuclear target
  • the dynamics of soft and hard scattering processes
  • subsequent particle production

• $dN_{ch}/d\eta$ vs $\eta$ is the most basic experimental probe which as a function of centrality can provide understanding of p+A interactions
RHIC energies

- Centrality dependence of the charged particle production @ RHIC
- Scaling with $N_{\text{part}}$ have been previously observed

PHOBOS

PHYSICAL REVIEW C 72, 031901(R) (2005)
Existing results

- ALICE measured MB (non-singly diffractive) $dN_{ch}/d\eta$ vs $\eta$.
- The centrality dependence is important and it is not yet measured.

![Graph showing $dN_{ch}/d\eta$ vs $\eta$ for p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.](image)
Centrality dependence of charged particle production in proton-lead collisions measured by ATLAS.
p+Pb @ LHC and ATLAS

Centrality dependence of charged particle production in proton-lead collisions measured by ATLAS
p+Pb @ LHC and ATLAS

Minimum Bias Scintillators used for the event selection
2.1<|η|<3.9 (not shown here)
Centrality dependence of charged particle production in proton-lead collisions measured by ATLAS

All calorimeters are used for the diffraction contribution studies $|\eta|<4.9$
p+Pb @ LHC and ATLAS

Centrality dependence of charged particle production in proton-lead collisions measured by ATLAS
Event selection

2012 p+Pb pilot run is used for the measurements
Integrated Luminosity: 1μb⁻¹

1. Two scintillator signals in the MBTS:
2. Good timing |Δt|<10ns
3. Reconstructed vertex with at least two tracks of pₜ>100 MeV.
4. Pileup during data taking was at the level of 10⁻³
5. Events with two good vertices were rejected, residual pile-up 10⁻⁴
6. A pseudorapidity gap on the lead going side of Δη^{Pb}≤2.0

Sample used in the analysis: 2,131,219 events.
This sample corresponds to 98±2% of the inelastic events.
Removal of events with large $\eta$ gaps

- $pPb$ interactions produce an additional coherent and photo-nuclear component of events consistent with the excitation of the proton.

- Full coverage $|\eta| < 4.9$ divided into $\Delta\eta = 0.2$ intervals.

- Occupied interval, contains reconstructed tracks or calorimeter clusters with $p_T > 200$ MeV.

- $\Delta\eta_{\text{Pb gap}} = \Sigma \Delta\eta_{\text{Pb gap}}$ Empty interval.

- Electromagnetic or diffractive excitation of the proton typically produce $\Delta\eta_{\text{Pb gap}} > 2$ ($f_{\text{gap}} = 6\%$).
Centrality definition

• Pb-going FCal (side “A”) is used to characterize event centrality, it is more sensitive to nuclear geometry

• FCal $\Sigma E_{T}^{\text{Pb}}$ is divided into centrality intervals: 0-1%, 1-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-60%, 60-90%

• 90-100% is excluded due to larger systematic uncertainties on event composition and reconstruction efficiency
Glauber and Glauber-Gribov models

To model Npart distribution we used:

- standard Glauber with \( \sigma_{NN} \) cross section = 70±5mb
- Glauber-Gribov color fluctuation models, with \( \langle \sigma_{NN} \rangle \) cross section = 70±5mb

In Glauber-Gribov model:

- \( \sigma_{tot} \) is considered frozen for each event
- parameter \( \Omega \) controls the amount of fluctuations
- \( \Omega \) is extracted from experimental data: 0.55 [PLB633 (2006) 245–252] and 1.01 [PLB 722 (2013) 347–354]

\[
P_h(\sigma_{tot}) = \rho \frac{\sigma_{tot}}{\sigma_{tot} + \sigma_0} \exp \left\{ -\frac{(\sigma_{tot}/\sigma_0 - 1)^2}{\Omega^2} \right\}.
\]

\[
P_H(\sigma_{NN}) = \frac{1}{\lambda} P(\sigma_{NN}/\lambda)
\]
Constructing FCal $\Sigma E_T^{\text{Pb}}$ response

$E_T$ distribution modeled by PYTHIA simulated taking into account FCal response in $p+\text{Pb}$ configuration and were approximated by Gamma($k,\theta$) distributions

Convolution of $N_{\text{part}}$ Gamma($k,\theta$) was taken as Gamma($k(N_{\text{part}}),\theta(N_{\text{part}})$)

We allowed:

\[ k(N_{\text{part}}) = k_0 + k_1 \times (N_{\text{part}} - 2); \quad \theta(N_{\text{part}}) = \theta_0 + \theta_1 \times \log(N_{\text{part}} - 1); \]

In WN:

\[ k(N_{\text{part}}) = k \times N_{\text{part}}; \quad \theta(N_{\text{part}}) = \theta; \]

$E_T$ response for $N_{\text{part}}$ was weighted according to Glauber or Glauber-Gribov model and fitted to the data
FCal $E_T$ distribution fits

- $dN_{\text{evt}}/dE_T$ obtained by summing the gamma distributions over different $N_{\text{part}}$ values weighted by $P(N_{\text{part}})$

Fits to the measured $E^{\text{Pb}}_T$ distributions show reasonable agreement over 3 orders of magnitude in $E_T$ distribution.
Centrality dependence of charged particle production in proton-lead collisions measured by ATLAS

- Results produced with models are different
- Standard Glauber has highest fluctuations of produced $E_T$ per participant
- Glauber-Gribov $\Omega=1.01$ has less $E_T$ fluctuation and therefore gives highest $N_{\text{part}}$
$dN_{ch}/d\eta$ measurement
Multiplicity Analysis

- Use Pixel detector only to have largest acceptance at low $p_T$ of registered particles

- Three analysis methods used in parallel to control combinatorial background
  - Standard pixel tracks: lower acceptance, low fakes
  - Tracklet method 1: largest acceptance, some fakes
  - Tracklet method 2: large acceptance, more fakes, with fake rate estimate
Three Analysis Methods

Pixel tracks:
- $|\eta| < 2.5$
- provide $p_T$ of the particle
- used to reweight HIJING -> Data
Two Tracklet Methods

Method 1

tracklet = Vertex + 2 hits/clusters

• only one tracklet for a given cluster on the first pixel layer.
• for multiple clusters on the second pixel layer, two tracklets merged into a single
• method limits but do not suppress fake tracks

\[ |\Delta \eta| < 0.015, \quad |\Delta \varphi| < 0.1, \quad |\Delta \eta| < |\Delta \varphi| \]

The primary event vertex and clusters on an inner pixel layer define a search region for clusters in the outer layers.
Two Tracklet Methods

Method 2
- reconstructed tracklets for all combinations of clusters in only two pixel layers
- fake tracklets arising from random combinations of clusters, obtained with inverting the X and Y positions of all clusters on the second layer with respect to the primary vertex

\[ |\Delta \eta| < 0.015, \quad |\Delta \varphi| < 0.1, \quad |\Delta \eta| < |\Delta \varphi| \]
Two Tracklet Methods

Method 2
• reconstructed tracklets for all combinations of clusters in only two pixel layers
• fake tracklets arising from random combinations of clusters, obtained with inverting the X and Y positions of all clusters on the second layer with respect to the primary vertex

\[ |\Delta \eta| < 0.015, \quad |\Delta \varphi| < 0.1, \quad |\Delta \eta| < |\Delta \varphi| \]
Fake tracklets estimation

- Method 2 has the largest contribution of fakes
- The results are in good agreement with each other -> fake rejection and the correction procedure are well understood
Corrections provided by three methods

- Method 1 is chosen as the default result for $dN_{ch}/d\eta$
- Method 2 is used for systematic uncertainties
- Pixel track method is used primarily as a consistency test
- The correction factor is evaluated as a function of occupancy (O), event vertex ($z_{vtx}$), and $\eta$ as:

$$C(O, z_{vtx}, \eta) \equiv \frac{N_{pr}(O, z_{vtx}, \eta)}{N_{rec}(O, z_{vtx}, \eta)}.$$ 

$$\frac{dN_{ch}}{d\eta} = \frac{1}{N_{evt}} \sum_{\eta} \frac{\Delta N_{raw}(O, z_{vtx}, \eta)C(O, z_{vtx}, \eta)}{\Delta \eta},$$

$\eta$-3 -2 -1 0 1 2 3
$1/N_{evt}$ $dN_{ch}/d\eta$

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ATLAS Simulation Preliminary
p+Pb $\sqrt{s_{NN}} = 5.02$ TeV $y_{cm} = -0.465$
0 - 10 %

- generated primary
- Method 1
- Method 2
- pixel tracks method

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ATLAS Preliminary
p+Pb $L_{int} = 1\mu b^{-1}$
$\sqrt{s_{NN}} = 5.02$ TeV $y_{cm} = -0.465$
0 - 10 %

- Method 1 raw
- Method 2 raw
- pixel tracks method raw
- Method 1 corrected
- Method 2 corrected
- pixel tracks method corrected
Systematic Uncertainties

Sources of uncertainties:
- inaccuracies of detector description in simulations
- sensitivity to selection criteria, including fakes and secondaries
- differences between data and MC

To extract uncertainties for each source, one of the parameters used in the analysis, such as tracklets selection criteria, simulated particle composition, etc. was altered within acceptable limits.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty 60-90% barrel</th>
<th>Uncertainty 60-90% endcap</th>
<th>Uncertainty 0-1% barrel</th>
<th>Uncertainty 0-1% endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC detector description</td>
<td>1.7%</td>
<td></td>
<td>1.7%</td>
<td></td>
</tr>
<tr>
<td>Extra material</td>
<td>1%</td>
<td>2%</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>Tracklet selection</td>
<td>0.5%</td>
<td>1.5%</td>
<td>0.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>$p_T$ re-weighting</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Extrapolation to $p_T=0$</td>
<td>1%</td>
<td>2.5%</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>Particle composition</td>
<td>1%</td>
<td></td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>Analysis method</td>
<td>1.5%</td>
<td>2.0%</td>
<td>1.5%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Event selection</td>
<td>5.0%</td>
<td>6.0%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>
\( \frac{dN}{d\eta} \) for different centralities

- \( \frac{dN}{d\eta} \) is measured for \( |\eta| < 2.7 \) in eight centrality intervals
- 60-90\% - double-peak structure similar to pp
- Forward backward asymmetry between p and Pb going directions grows with centrality
dN/dη for different centralities

- dN_{ch}/dη ratios to 60-90% is measured for |η| < 2.7 in seven centrality intervals
- Almost linear distributions fitted with 2-nd order polynomial
- double-peak structure disappears as it have been provided by kinematics of the events
- 0-1% grows ~2 times from p- to Pb-going direction
Centrality dependence of $<dN_{ch}/d\eta>$

- $<dN_{ch}/d\eta>$ per pair of participants vs $N_{\text{part}}$ for five $\eta$ intervals

- Results are dependent on Glauber implementation

- Standard Glauber, used up to now shows increase with $<N_{\text{part}}>$

- Glauber-Gribov with $\Omega=0.55$ is almost flat with $\Omega=1.01$ even decreases
Glauber models comparison

- $dN_{\text{ch}}/d\eta$ per pair of participants for two centrality bins and three Glauber models
- Strong correlation of the results with the model
- These results point to the importance of understanding not just the initial state of the nuclear wave function, but also the fluctuating nature of nucleon-nucleon collisions themselves
Conclusion

- ATLAS measurements of the centrality dependence of the charged particle pseudorapidity distribution, $dN_{ch}/d\eta$ in $p+$Pb collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV over the $|\eta|<2.7$ range with a $\gamma_{c.m.s.}=-0.465$ are presented for 8 centrality classes and for the 90% most central $p+$Pb collisions

- Collision centrality definition performed using a forward calorimeter covering $3.2 < \eta < 4.9$ in the lead-going direction

- Performed the average number of participants in each centrality interval, $<N_{part}>$, estimated using a Monte Carlo Glauber model as well as in a Glauber-Gribov approach

- It have been shown that centrality dependence of $dN_{ch}/d\eta/(<N_{part}>/2)$ is sensitive to the Glauber modeling

- Performed results point to the importance of understanding not just the initial state of the nuclear wave function, but also the fluctuating nature of nucleon-nucleon collisions themselves.
Thank you for attention!
High multiplicity p+Pb event

Run: 217946 \( N_{\text{Trk}} (p_T > 0.4 \text{ GeV}) = 273, \)
Event: 32291041 \( N_{\text{Trk}} (p_T > 1.0 \text{ GeV}) = 106 \) (shown)
Date: 2013-01-20 \( \Sigma E_T = 139 \text{ GeV} \)
Removal of events with large $\eta$ gaps

- Additional diffraction component (coherent and photo-nuclear) consistent with the diffractive excitation of the proton have to be subtracted.

- Estimation of the additional diffraction component relies on previous pp studies.

- Full coverage $|\eta| < 4.9$ divided into $\Delta\eta = 0.2$.

- $\Delta\eta_{\text{Pb \ gap}}$ edge-gap - distance between the detector edge on the Pb-going side and the nearest occupied interval, containing reconstructed tracks or calorimeter clusters with $p_T > 200$ MeV.

- Electromagnetic or diffractive excitation of the proton typically produce $\Delta\eta_{\text{Pb \ gap}} > 2$ ($f_{\text{gap}} = 6\%$)

Δη and Δφ distributions for tracklets

- All three methods rely on the MC to correct for secondary particles
- Method 1 and the pixel track method rely on the MC to correct for fakes
pol2 fit parameters

<table>
<thead>
<tr>
<th>Centrality ratio</th>
<th>c</th>
<th>b</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1% / 60 - 90%</td>
<td>6.78±0.28</td>
<td>0.77±0.05</td>
<td>-0.033±0.006</td>
</tr>
<tr>
<td>1 - 5% / 60 - 90%</td>
<td>5.35±0.22</td>
<td>0.515±0.031</td>
<td>-0.030±0.005</td>
</tr>
<tr>
<td>5 - 10% / 60 - 90%</td>
<td>4.49±0.18</td>
<td>0.377±0.021</td>
<td>-0.0218±0.0035</td>
</tr>
<tr>
<td>10 - 20% / 60 - 90%</td>
<td>3.77±0.14</td>
<td>0.269±0.014</td>
<td>-0.0169±0.0025</td>
</tr>
<tr>
<td>20 - 30% / 60 - 90%</td>
<td>3.11±0.11</td>
<td>0.182±0.010</td>
<td>-0.0113±0.0020</td>
</tr>
<tr>
<td>30 - 40% / 60 - 90%</td>
<td>2.61±0.08</td>
<td>0.122±0.006</td>
<td>-0.0076±0.0016</td>
</tr>
<tr>
<td>40 - 60% / 60 - 90%</td>
<td>1.95±0.06</td>
<td>0.0595±0.0031</td>
<td>-0.0037±0.0011</td>
</tr>
</tbody>
</table>
### $N_{\text{part}}$ values

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Glauber</th>
<th>Glauber-Gribov $\Omega = 0.55$</th>
<th>Glauber-Gribov $\Omega = 1.01$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60-90%</td>
<td>3.96±0.20 (+5%)</td>
<td>3.56±0.19 (+5%)</td>
<td>3.41±0.26 (+8%)</td>
</tr>
<tr>
<td>40-60%</td>
<td>7.4±0.4 (+6%)</td>
<td>6.6±0.4 (+6%)</td>
<td>6.31±0.5 (+8%)</td>
</tr>
<tr>
<td>30-40%</td>
<td>9.8±0.6 (+6%)</td>
<td>9.2±0.5 (+6%)</td>
<td>8.9±0.6 (+7%)</td>
</tr>
<tr>
<td>20-30%</td>
<td>11.4±0.6 (+6%)</td>
<td>11.2±0.6 (+6%)</td>
<td>11.1±0.7 (+6%)</td>
</tr>
<tr>
<td>10-20%</td>
<td>13.0±0.8 (+6%)</td>
<td>13.7±0.8 (+6%)</td>
<td>14.1±0.9 (+6%)</td>
</tr>
<tr>
<td>5-10%</td>
<td>14.6±1.2 (+8%)</td>
<td>16.5±1.0 (+6%)</td>
<td>17.4±1.1 (+7%)</td>
</tr>
<tr>
<td>1-5%</td>
<td>16.1±1.7 (+11%)</td>
<td>19.5±1.3 (+7%)</td>
<td>21.4±1.4 (+7%)</td>
</tr>
<tr>
<td>0-1%</td>
<td>18.2±2.7 (+15%)</td>
<td>24.1±1.6 (+7%)</td>
<td>27.4±1.6 (+6%)</td>
</tr>
<tr>
<td>0-90%</td>
<td>8.4±0.5 (+6%)</td>
<td>8.5±0.5 (+6%)</td>
<td>8.6±0.5 (+6%)</td>
</tr>
</tbody>
</table>

Other variations for which the complete analysis was repeated are: the PYTHIA6 event generator, alternative models for Glauber-Gribov geometries including Glauber results using alternative parameter values. The analysis described in this section and the comparison to the data in Figure 3 and listed in Table 4.

The resulting asymmetric uncertainties are indicated by the error bars on the points in Figure 3. Using the results of the fits to the measured NN-dE/dx distributions, the average number of participants $N_{\text{part}}$ in each centrality interval, was calculated to be twice the PYTHIA8-PYTHIA6 difference. For the maximum positive and negative fractional variation in the acceptance, new centrality intervals were chosen assuming a total e-uncertainty.
ATLAS Results:

dN/d\eta p-Pb ATLAS (0-90%) vs ALICE (MinBias)

- ALICE MinBias:
  0-98% N_{part} = 7.9 (±7.6%)
- ATLAS:
  0-90% N_{part} = 8.44 (+5.6%, -4.9%)
- ATLAS points are scaled by the ratio
- ALICE makes no gap cleaning and have a statement of non diffractive events

\textit{ATLAS} Preliminary

p+Pb L_{int} = 1 \mu b^{-1}
\sqrt{s_{NN}} = 5.02 \text{ TeV}
y_{cm} = -0.465

\textbullet{} ATLAS 0-90% scaled by 7.9/8.44
\square{} ALICE [Phys. Rev. Lett. 110, 032301 (2013)]
Motivation to study p-Pb collisions:

- Disentangle initial and final state effects.
- Probe nuclear wave function at small $x$.
- Investigate QCD at high gluon density: shadowing and gluon saturation.
- Study diffractive and photo-nuclear excitations

Elements of both pp and heavy ion collisions: