Charged particle production in p+Pb collisions with the ATLAS detector

Martin Spousta
on behalf of ATLAS Collaboration

Charles University
Physics motivation

- Deviations from simple geometrical expectations due to
  - Shadowing (suppression of yields at small $p_T$)
    - modifications of nuclear PDFs
    - parton saturation at low-$x$ (CGC)
  - Cronin effect (enhancement at intermediate $p_T$)
    - $k_T$ broadening due to multiple scattering
    - Possible energy loss in “cold nuclear matter”

- Baseline to understand the role of the nuclear environment in modifying hard scattering rates.

![Graph showing dN/dη]
Observables

- Charged particle $R_{pPb}$

$$R_{pPb}(p_T, y) = \frac{1}{\langle T_{Pb} \rangle} \frac{1/N_{evt} \ d^2N_{p+Pb}/dydp_T}{d^2\sigma_{pp}/dydp_T}$$

- Charged particle $R_{CP}$

$$R_{CP}(p_T, \eta) = \frac{\langle T_{Pb,P} \rangle (1/N_{evt,C})d^2N_{p+Pb,C}/d\eta dp_T}{\langle T_{Pb,C} \rangle (1/N_{evt,P})d^2N_{p+Pb,P}/d\eta dp_T}$$

- Charged particle pseudorapidity distributions

$$dN_{ch}/d\eta \quad (dN_{ch}/d\eta|_{cent.}) / (dN_{ch}/d\eta|_{60-90%})$$
Input data

- 1 $\mu$b$^{-1}$ of **5.02 TeV p+Pb** Minimum Bias events (~ 2.1 x 10$^6$ events after cleaning) collected during September 2012
- 188 $\mu$b$^{-1}$ **7 TeV pp** Minimum Bias events collected during April 2010
- 202 nb$^{-1}$ **2.76 TeV pp** Minimum Bias events collected during March 2011

Interpolation of pp data to get 5.02 TeV reference

Measured rapidity: $y^* = y - y_{CM}$

$E = 1.57$ TeV/N

$\eta < 0$

$\sqrt{s_{NN}} = 5.02$ TeV

$\eta = 0$

$E = 4$ TeV

$\eta > 0$
Event selection

- Events selected using the Minimum Bias Trigger Scintilators (MBTS).
- Pile-up of $\sim 10^{-3}$ reduced $10^{-4}$ by rejecting events with two or more good vertices.
- Diffractive and electromagnetic excitations of proton rejected:
  - rapidity gap analysis (similar to EPJ C72 (2012) 1926)
  - rapidity interval starting from $\eta_{\text{Pb-edge}} = 4.9$ divided into clusters in $\Delta \eta = 0.2$
  - occupied cluster = cluster with $p_T > 200$ MeV
  - events with $\Delta \eta_{\text{gap}} = |\eta_{\text{Pb-edge}} - \eta_{\text{cluster}}| > 2$ rejected
- Total 2.1 M events = 98% ± 2% of inelastic events.
Centrality and $\langle T_{Pb} \rangle$

- Centrality determination
  - Total transverse energy in Pb-going using forward calorimeters (eta < -3.2)
  - Eight centrality bins: 0-1%, 1-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-60%, 60-90%.

- $\langle T_{Pb} \rangle$ determined using Glauber and Glauber+Gribov model
  - Glauber:
    - fixed $\sigma_{NN}$ ($\sigma_{NN} = 70 \pm 5$ mb)
    - incoming proton is off-shell between successive interactions!
  - Glauber+Gribov model:
    - allows for event-by-event fluctuations in $\sigma_{NN}$, $\langle \sigma_{NN} \rangle = 70 \pm 5$ mb
    - fluctuations quantified using parameter $\Omega$
    - two choices for $\Omega$ ($\Omega=0.55$, $\Omega=1.01$) based on extraction from experimental data (see PLB 633 (2006) 245 and PLB 722 (2013) 347)
  - Glauber and Glauber+Gribov model can reproduce the measured centrality distribution => determination of $\langle T_{Pb} \rangle$ or $\langle N_{part} \rangle = \langle T_{Pb} \rangle * \sigma_{NN} + 1$
Example of \( \langle T_{\text{Pb}} \rangle \)

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Glauber</th>
<th>Glauber-Gribov</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Omega = 0.55 )</td>
<td>( \Omega = 1.01 )</td>
</tr>
<tr>
<td>60-90%</td>
<td>( 42.3^{+2.8}_{-4} ) (+7%) (-10%)</td>
<td>( 36.6^{+2.7}_{-2.2} ) (+7%) (-6%)</td>
</tr>
<tr>
<td></td>
<td>( 34.4^{+4}_{-2.1} ) (+11%) (-6%)</td>
<td>( 377^{+12}_{-60} ) (+3.2%) (-16%)</td>
</tr>
<tr>
<td>0-1%</td>
<td>( 245^{+37}_{-7} ) (+15%) (-2.7%)</td>
<td>( 330^{+15}_{-23} ) (+5%) (-7%)</td>
</tr>
<tr>
<td></td>
<td>( 377^{+12}_{-60} ) (+3.2%) (-16%)</td>
<td>( 108.5^{+4}_{-2.4} ) (+4%) (-2.2%)</td>
</tr>
<tr>
<td>0-90%</td>
<td>( 106.3^{+4}_{-2.7} ) (+4%) (-2.5%)</td>
<td>( 107.3^{+4}_{-2.6} ) (+4%) (-2.4%)</td>
</tr>
</tbody>
</table>

\[ \langle T_{\text{Pb}} \rangle \rightarrow [b^{-1}] \]

\[ \frac{\langle T_{\text{Pb}} \rangle_{\text{cent}}}{\langle T_{\text{Pb}} \rangle_{60-90}} \]

Uncertainties:
- central collisions: model + pp cross-section
- peripheral collisions: model + pp cross-section + event selection
Corrections

\[
\frac{1}{2\pi p_T} \frac{dN_{ch}}{dp_T d\eta} = \frac{1}{2\pi p_T N_{evt} \Delta \eta} \frac{N_{ch}(p_T, \eta)}{\Delta p_T} \frac{\mathcal{P}(p_T, \eta)}{\varepsilon_{trk}(p_T, \eta)}
\]

\[
\frac{1}{2\pi p_T} \frac{dN_{ch}}{dp_T dy^*} = \frac{1}{2\pi p_T N_{evt} \Delta y^*_\pi} \frac{N_{ch}(p_T, y^*_\pi)}{\Delta p_T} \frac{\mathcal{P}(p_T, y^*_\pi) \mathcal{A}(p_T, y^*_\pi)}{\varepsilon_{trk}(p_T, y^*_\pi)}
\]

\[\varepsilon_{trk}(p_T, y^*_\pi) \quad \text{... tracking efficiency}\]

\[\mathcal{P}(p_T, y^*_\pi) \quad \text{... purity (to remove fakes and residual secondary tracks)}\]

\[\mathcal{A}(p_T, y^*_\pi) \quad \text{... to correct } N(y^*_\pi) \text{ to } N(y^*) \text{ since } \eta \rightarrow y^*_\pi \text{ (no particle ID)}\]
Tracking efficiency

\[ \epsilon_{\text{trk}}(p_T, \eta) = \frac{N_{\text{Rec}}^{\text{Primary}}(p_T^{\text{Rec}}, \eta)}{N_{\text{Gen}}(p_T^{\text{Gen}}, \eta)} \]

\[ \epsilon_{\text{trk}}(p_T, y_{\pi}^*) = \frac{N_{\text{Rec}}^{\text{Primary}}(p_T^{\text{Rec}}, y_{\pi}^*)}{N_{\text{Gen}}(p_T^{\text{Gen}}, y_{\pi}^*)} \]
Reference spectra from pp collisions

**pp@2.76 TeV**

**pp@7 TeV**
Reference spectra from pp collisions

... pp reference at $\sqrt{s} = 5.02$ TeV does not exist => existing pp measurements at 7 TeV and 2.76 TeV interpolated using linear and logarithmic dependence on $\sqrt{s}$.
Systematic uncertainties for $R_{pPb}$ and $R_{CP}$ measurement

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$p$+Pb</th>
<th>$pp$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track selection</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Particle composition</td>
<td>1-6%</td>
<td>2%</td>
</tr>
<tr>
<td>Material budget</td>
<td>1-7%</td>
<td></td>
</tr>
<tr>
<td>$p_T$ reweighting</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>Rapidity transformation</td>
<td>0-8%</td>
<td></td>
</tr>
<tr>
<td>Centrality selection</td>
<td>1-6%</td>
<td>n/a</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>n/a</td>
<td>0.5%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>n/a</td>
<td>2.7% (2%)</td>
</tr>
<tr>
<td>$\sqrt{s}$ interpolation</td>
<td>n/a</td>
<td>3-9%</td>
</tr>
<tr>
<td>Vertex reconstruction</td>
<td>n/a</td>
<td>1%</td>
</tr>
</tbody>
</table>

+ Uncertainties on $\langle T_{Pb} \rangle$
Measured spectra: left inclusive in pseudorapidity, right inclusive in centrality.
Spectra in $y^*$

Measured spectra: left inclusive in rapidity, right inclusive in centrality. Full line $\langle T_{Pb} \rangle$ scale pp cross-section.
Increase between 0.1-2 GeV, decrease up to ~8 GeV, flattening above 8 GeV.

Three different geometrical models used to extract $\langle T_{\text{Pb}} \rangle$

$\rightarrow$ very different magnitude $\times$ ratio of Cronin region to plateau stays similar
$R_{CP}$

ATLAS Preliminary
$p+Pb \; L_{int}=1\mu b^{-1}$
$\sqrt{s_{NN}}=5.02$ TeV
$|\eta|<2.5$

Glauber
Glauber-Gribov $\Omega=0.55$
Glauber-Gribov $\Omega=1.01$

Systematics without $\delta(\langle T_{Pb} \rangle)$
All systematics

Hard Probes 2013  Martin Spousta for ATLAS Collaboration
\( R_{pPb} \) more differentially
$R_{pPb}$ more differentially

$p$-going side

$\eta < 0$

$\eta = 0$

$\eta > 0$

Pb-going side

$y^* = -0.465$
Inclusive $R_{pPb}$

... Good agreement among $R_{pPb}$ obtained using different models when evaluated inclusively in centrality.
Inclusive $R_{pPb}$

... Good agreement of $R_{pPb}$ with ALICE.
Charged particle multiplicity

Multiplicities as a function of pseudorapidity (left) and their central to peripheral ratio along with the fit by second order polynomial (right).
Charged particle multiplicity

Charged particle multiplicity per participant pair … sensitivity to the choice of the model to extract $\langle N_{\text{part}} \rangle$:

- Glauber case: strong increase with centrality
- Glauber+Gribov: only weak centrality dependence

... $N_{\text{part}}$ scaling observed previously
Summary and conclusions

• Nuclear modification factors in p+Pb collisions
  – measured for $p_T = 0.1–22$ GeV, $\eta = -2.5–2.5$, $y^* = -2–2.5$
  – trends: increase between 0.1–2 GeV, decrease up to 8 GeV, then plateau
  – magnitude of the peak (at $\sim$3 GeV) increases with centrality and from p-going to Pb-going direction
  – magnitude of the peak strongly depends on the choice of geometric model

• Charged particle multiplicity in p+Pb collisions
  – measured for $|\eta|<2.7$
  – almost symmetric shape in peripheral $\rightarrow$ highly asymmetric shape in central
  – central to peripheral ratio linear with a slope strongly dependent on centrality
  – multiplicity per participant pair strongly depends on the geometric model

• These data should provide an input for:
  – understanding the modifications of gluon distributions in the Pb-target
  – discrimination among different saturation scenarios
  – understanding the fluctuating nature of nucleon-nucleon collisions and geometry of the initial state
Summary and conclusions

- Details can be found in:
  - ATLAS-CONF-2013-107
  - ATLAS-CONF-2013-096
Backup
Multiplicity, extrapolation to 0 MeV

\[ \text{dN}_{\text{ch}}/\text{dhn} \]

**ATLAS** Preliminary

\[ p+\text{Pb} \quad L_{\text{int}} = 1 \mu\text{b}^{-1} \]

\[ \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \]

\[ y_{\text{cm}} = -0.465 \]
Multiplicity compared to ALICE

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

- ATLAS 0-90\% scaled by 7.9/8.44

\[
dN_{\text{ch}}/d\eta
\]
Multiplicity for different models

\[ \frac{dN_{ch}}{d\eta}/\langle (N_{part})/2 \rangle \]

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

Glauber

Glauber-Gribov \( \Omega = 0.55 \)

Glauber-Gribov \( \Omega = 1.01 \)
Estimates of $\Omega$ based on data at 1.8, 9, and 14 TeV $\Rightarrow$ interpolation to 5 TeV $\Rightarrow \Omega=0.55$, corresponding $\sigma_0 = 78.6$ mb

New results from diffractive analysis from LHC $\Rightarrow \Omega=1.01$, $\sigma_0 = 72.5$ mb

For each choice of $\Omega$ and $\sigma_0$, $\lambda$ chosen to produce $\sigma_{NN} = 70$ mb.

... constant inelastic cross section
Glauber-Gribov analysis

- For fixed $N_{\text{part}}$, $\Sigma E_T^{\text{Pb}} \sim N_{\text{part}}$-fold convolution of $\Sigma E_T^{\text{pp}}$
- $\Sigma E_T^{\text{pp}} \sim$ gamma function:

$$\text{gamma}(x; k, \theta) = \frac{1}{\Gamma(k)} \frac{1}{\theta} \left( \frac{x}{\theta} \right)^{k-1} e^{-x/\theta}$$

=> can fit the measured $\Sigma E_T^{\text{Pb}} \times$ unsatisfactory result
=> generalized WN-model:

$$k(N_{\text{part}}) = k_0 + k_1 (N_{\text{part}} - 2),$$
$$\theta(N_{\text{part}}) = \theta_0 + \theta_1 \log(N_{\text{part}} - 1)$$

... e.g. allows for possible variation in effective acceptance of FCal due to Npart-dependent backward shift
Glauber-Gribov analysis

**PYTHIA 8**

![Graph showing data for PYTHIA 8 with a fit to a gamma function: $k_0 = 1.402$, $\theta_0 = 3.414$.]

**PYTHIA 6**

![Graph showing data for PYTHIA 6 with a fit to a gamma function: $k_0 = 1.231$, $\theta_0 = 2.677$.]
Glauber-Gribov analysis

\[ \langle N_{\text{part}} \rangle \]

**ATLAS Simulation Preliminary**

p+Pb, \( \sqrt{s_{NN}} = 5.02 \) TeV

\( L_{\text{int}} = 1 \mu b^{-1} \)

- Glauber
- Glauber-Gribov \( \Omega = 0.55 \)
- Glauber-Gribov \( \Omega = 1.01 \)

Centrality vs. \( \langle N_{\text{part}} \rangle \)
“Mass correction”

\[ \mathcal{A}(p_T, y^*_\pi) = \frac{N_{Gen}(m, p_T, y^*_\pi)}{N_{Gen}(m_\pi, p_T, y^*_\pi)} \bigg|_{y^*_\pi = y^*_\pi} \]

Pion acceptance limitations
Uncertainties for the multiplicity measurement

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty 60-90%</th>
<th></th>
<th>Uncertainty 0-1%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>barrel</td>
<td>endcap</td>
<td>barrel</td>
</tr>
<tr>
<td>MC detector description</td>
<td>1.7%</td>
<td></td>
<td>1.7%</td>
</tr>
<tr>
<td>Extra material</td>
<td>1%</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>Tracklet selection</td>
<td>0.5%</td>
<td>1.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$p_T$ re-weighting</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Extrapolation to $p_T=0$</td>
<td>1%</td>
<td>2.5%</td>
<td>1%</td>
</tr>
<tr>
<td>Particle composition</td>
<td>1%</td>
<td></td>
<td>1%</td>
</tr>
<tr>
<td>Analysis method</td>
<td>1.5%</td>
<td>2.0%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Event selection</td>
<td>5.0%</td>
<td>6.0%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>
Centrality
Two methods for tracklet reconstruction