Particle production and source sizes in $\sqrt{s_{NN}} = 5.02$ TeV $p$-Pb collisions with ATLAS

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Introduction (Multiplicity)

- \( p + Pb \) collisions are useful for understanding effects of “cold nuclear matter” on charged particle production
- It’s important to have detailed understanding of global observables in these events
- Nuclear modification factor

\[
R_{pPb}(p_T, y^*) = \frac{1}{\langle T_{Pb} \rangle} \frac{1/N_{evt} d^2 N_{pPb}/dy^*dp_T}{d^2\sigma_{pp}/dy^*dp_T}
\]

is studied differentially in centrality, transverse momentum (\( p_T \)), and rapidity (\( y^* \))

- \( y^* \) is rapidity in nucleon-nucleon centre-of-momentum frame, needed for fair comparison to \( pp \)
- interpolation between 2.76 and 7 TeV is used for \( pp \) reference
ATLAS inner detector

- Pixel detector - 82 million silicon pixels
- Semiconductor Tracker - 6.2 million silicon microstrips
- Transition Radiation Tracker - 350k drift tubes
- 2 T axial magnetic field

Reconstructed tracks from $|\eta| < 2.5$ at $p_T > 0.1$ GeV
Data selection

- Two separate $p+$Pb runs from the LHC at $\sqrt{s_{NN}} = 5.02$ TeV
- $1 \, \mu b^{-1}$ (multiplicity) / $28 \, nb^{-1}$ (femtoscopy) MinBias data
- Centrality determined from $\sum E_T$ in the Pb-going forward calorimeter at $3.1 < |\eta| < 4.9$
\( p_T \) spectra

\( p_T \) spectra in intervals of pseudorapidity \( \eta \) (left) and centrality (right)

see CERN-EP-2016-007
Differential multiplicity

Particle production as a function of $\eta$ (left) and $y^* = y - y_{lab}$ (right) in several centrality intervals is shown above.

$y_{lab} = 0.465$ is the nucleon-nucleon centre-of-momentum rapidity in the lab frame.

rapidity is calculated with pion mass ($y_{\pi\pi}^*$), and correction to real $y^*$ is derived using Hijing production is enhanced on Pb-going (-z) side of central events.

see CERN-EP-2016-007
Glauber-Gribov colour fluctuations (GGCF)

Number of nucleon participants $N_{\text{part}}$ calculated with:

- Glauber model with constant cross section $\sigma_{\text{NN}}$
- Glauber-Gribov color fluctuation (GGCF) model, which allow $\sigma_{\text{NN}}$ to fluctuate event-by-event

$\omega_\sigma$ parameterizes extent of fluctuations

(above: $N_{\text{part}}$ distributions and corresponding centrality)

Using a model with large fluctuations in the NN cross-section reduces central $R_{pPb}$ significantly. It also increases peripheral $R_{pPb}$ to be more compatible with unity.

see CERN-EP-2016-007
$R_{pPb}$ ($p_T$) in rapidity ($y^*$) intervals

- Low-$p_T$ suppression. Central events have high-$p_T$ enhancement most prominent in Pb-going side.
- Larger GGCF $\omega_\sigma$ brings $R_{pPb}$ closer to unity

see CERN-EP-2016-007
Femtoscopy uses momentum-space correlation functions to infer the source density function:

$$C_k(q) = \int d^3r \ S_k(r) |\psi_q(r)|^2 \ .$$

Here $k = (p_1 + p_2)/2$ is the average pair momentum and $q = (p_1 - p_2)$ is the relative momentum.

$C_k(q)$ is fit to a function to get length scales of $S_k(r)$, which are referred to as the HBT radii.

Bose-Einstein correlations between identical pions give particularly good resolution.
Charged pions are identified using $dE/dx$ measured with charge deposited in pixel hits.

The pair purity estimated from simulation is shown (left) as a function of pair $k_T$ and $y^*_{\pi\pi}$.
Jet fragmentation correlation

- significant background contribution observed in the two-particle correlation function (top right)
- suppressing hard processes in HIJING causes the correlation to disappear (bottom right)
- since correlations come from jet fragmentation, they appear in opposite-sign pairs as well
- jet fragmentation is measured in opposite-sign and the results are used to infer contribution to same-sign
Summary of fitting procedure

1. amplitude and width of opposite-sign correlation function are measured, with resonances removed by mass cuts (blue dashed)

2. the results from $\pm\pm$ are used to fix $\pm\pm$ background (violet dotted)

3. full correlation function $\pm\pm$ (dark red) is fit on top of jet background to extract the source radii

ATLAS-CONF-2016-027
Invariant fit results

Decrease with rising $k_T$ in central collisions, suggestive of collective behavior. This feature disappears in peripheral collisions.

Radii increase in Pb-going direction of central events. Peripheral are flat across rapidity.

N.B. Widths of boxes in these plots vary only for visibility purposes.
Invariant fit results

Scaling of $R_{\text{inv}}$ with the cube root of average multiplicity curves slightly upward.

Across centrality and rapidity intervals, the source size is tightly correlated with the local multiplicity.
3D fit results

In three dimensions, the Bertsch-Pratt ("out-side-long") coordinate system is used. It is boosted to the longitudinal co-moving frame (LCMF) of each pair.

- $q_{\text{out}}$: along $k_T$
- $q_{\text{side}}$: other transverse direction
- $q_{\text{long}}$: longitudinal (boosted to LCMF)

The Bose-Einstein part of the correlation function is fit to an quasi-ellipsoid exponential:

$$C_{BE}(q) = 1 + \exp \left( - \| R q \| \right)$$

$$R = \begin{pmatrix}
R_{\text{out}} & 0 & R_{\text{ol}} \\
0 & R_{\text{side}} & 0 \\
R_{\text{ol}} & 0 & R_{\text{long}}
\end{pmatrix}.$$
3D radii vs. $k_T$ and $y_{\pi\pi}^*$

- Decreasing size with rising $k_T$ in central events; trend is diminished in peripheral.
- Radii vs. $y_{\pi\pi}^*$ are flat in peripheral, and larger on Pb-going side of central.
- Typically $R_{\text{out}} < R_{\text{side}} < R_{\text{long}}$

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3D radii vs. multiplicity (global and local)

scaling vs. $<dN/d\eta>^{1/3}$ shown on left

three-dimensional radii also tightly correlated with local multiplicity (right)

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Ratio of $R_{\text{out}} / R_{\text{side}}$

- $R_{\text{out}}$ couples to the lifetime directly where $R_{\text{side}}$ does not
- small ratio $R_{\text{out}} / R_{\text{side}}$ is indicative of “explosive” event
- steadily decreases with rising $k_T$ and is constant over rapidity
- marginally larger in central events

ATLAS-CONF-2016-027
At low $k_T$, the transverse area element $R_{\text{out}} R_{\text{side}}$ scales linearly with multiplicity. The volume element $\det(R)$ scales linearly with multiplicity at higher $k_T$. 
Volume scaling with $N_{\text{part}}$ including color fluctuations is more modest when fluctuations in the proton's size are accounted for.

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In central events on the forward side, there is strong evidence of a positive $R_{0\pi}$ (4.8σ combined significance in 0–1% centrality)

- demonstrates breaking of boost invariance: z-asymmetry is manifest in proton-going side.
- requires both longitudinal and transverse expansion in hydrodynamic models
Conclusion

- Nuclear modification factor, as well as one- and three-dimensional HBT radii, are measured in proton-lead collisions at 5 TeV.
- These measurements are presented differentially in centrality, transverse momentum, and rapidity.
- Accounting for fluctuations in the nucleon-nucleon cross section is seen to significantly affect the behavior of both the nuclear modification factors and the source size.
- HBT Radii in central events show a decrease with increasing $k_T$, which is qualitatively consistent with collective expansion. This trend is diminished in peripheral events.
- Variation of source over rapidity follows local multiplicity.
- Evidence for non-zero (positive) $R_{o1}$ on the proton-going side of central events is observed.
BACKUP SLIDES
Comparison of $R_{p\text{Pb}}$ with other collaborations

\begin{center}
\includegraphics[width=\textwidth]{comparison_graph.png}
\end{center}

see CERN-EP-2016-007
$R_{pPb}$ as function of rapidity
Choice of initial geometry model does not significantly affect results inclusive in centrality

see CERN-EP-2016-007
modest value of $\omega_\sigma = 0.11$ gives consistent high-$p_T$ production across centralities

see CERN-EP-2016-007
$R_{CP}$ as function of rapidity

Central-to-peripheral ratio as function of rapidity, as low and high $p_T$
Introduction (Femtoscopy)

- Recent observations of angular correlations in $p+Pb$ collisions indicate signs of collective behavior – the so-called “ridge”.
- Femtoscopy is used to provide additional handles on the size, shape, and evolution of the particle source.
- *Femtoscopy* uses the sensitivity of the momentum-space correlation function to the source density function:

\[
C_k(q) - 1 = \int_{\partial \Sigma} d^3 r \, S_k(r) \left( |\langle q| r \rangle|^2 - 1 \right).
\]

Here $k = (p_1 + p_2)/2$ is the average pair momentum and $q = (p_1 - p_2)$ is the relative momentum, and $\partial \Sigma$ is the freeze-out hypersurface of the source.

- $C(q)$ is fit to a function and results are used to infer the length scales of $S_k(r)$, which are referred to as the *HBT radii*.
- For identical non-interacting bosons, $C_k(q) - 1$ is the Fourier transform of the source density. These results use charged pions.
Introduction (Femtoscopy)

- Results will focus on exponential fits to the Bose-Einstein part of two-pion correlation functions $C_{BE}$:

$$C_{BE}(q) = 1 + e^{-\|Rq\|}.$$  

The analysis is done as a function of $q_{\text{inv}}$ or with 3-dimensional $q$, where $R$ is a symmetric matrix.

- The full experimental correlation function is the Bowler-Sinyukov form:

$$C_{\text{exp}}(q) = [(1 - \lambda) + \lambda K(q_{\text{inv}})C_{BE}(q)] \Omega(q),$$

where $\lambda$ is a free parameter, $K(q_{\text{inv}})$ accounts for Coulomb interactions between the pions and $\Omega(q)$ represents the non-femtoscopic background features of the correlation function.

- Mis-identified pions, coherent emission, weak decays contribute to decrease in $\lambda$. 
Three PID selection criteria are defined, and a variation from the nominal selection to a looser and tighter definition is used as a systematic variation.
Wide correlation disappears in opposite-sign too when turning off hard processes
Jet fragmentation correlation

Common methods to account for this background include:

1. Using a double ratio $C(q) = C_{data}(q) / C_{MC}(q)$.
   - Monte Carlo tends to over-estimate the magnitude of the effect, which can skew the results significantly

2. Partially describing the background shape using simulation and allowing additional free parameters in the fit.
   - one might worry about additional free parameters biasing the fits

Here we measure the jet fragmentation in opposite-sign and use a mapping derived in Pythia to predict the form in same-sign.
Jet fragmentation correlation

A data-driven method is developed to constrain the effect of hard processes. Fits to the opposite-sign correlation function are used to predict the fragmentation correlation in same-sign. This has its own challenges.

1. Resonances appear in the opposite-sign correlation functions
   ▶ mass cuts around $\rho$, $K_S$, and $\phi$
   ▶ cut off opposite-sign fit below 0.2 GeV

2. Fragmentation has different effect on the opposite-sign correlation function than on the same-sign
   ▶ a mapping is derived from opposite- to same-sign using simulation
   ▶ opposite-sign fit results in the data are used to fix the background description in the same-sign
Jet fragmentation correlation

The jet fragmentation is modeled as a stretched exponential in $q_{\text{inv}}$:

$$\Omega(q_{\text{inv}}) = 1 + \lambda_{\text{bkgd}}^{\text{inv}} e^{-|R_{\text{bkgd}}^{\text{inv}} q_{\text{inv}}|^{\alpha_{\text{bkgd}}^{\text{inv}}}}$$

In 3D it is factorized into components parallel and perpendicular to jet axis

$$\Omega(q) = 1 + \lambda_{\text{bkgd}}^{\text{osl}} e^{-|R_{\text{bkgd}}^{\text{out}} q_{\text{out}}|^{\alpha_{\text{bkgd}}^{\text{out}}}} - |R_{\text{bkgd}}^{\text{sl}} q_{\text{sl}}|^{\alpha_{\text{bkgd}}^{\text{sl}}},$$

with $q_{\text{sl}} = \sqrt{q_{\text{side}}^2 + q_{\text{long}}^2}$.

These parameters are studied in Pythia, and a mapping from opposite-sign to same-sign values is derived.
Jet fragmentation mapping

model $R_{\text{inv}}^{\pm \pm}$ as proportional to $R_{\text{inv}}^{+-}$ (right). Then with constant fixed, do $k_T$-dependent comparison of background amplitude in $\pm \pm$ and $+-$ (left). Does not work perfectly but does increasingly well at high $k_T$, where the effect is relevant.
$R_{\text{inv}}^{\pm \pm}$ is modelled as proportional to $R_{\text{inv}}^{+-}$ (right). Then with constant fixed, do $k_T$-dependent comparison of background amplitude in $\pm \pm$ and $+-$ (left). Does not work perfectly but does increasingly well at high $k_T$, where the effect is relevant.
Example fit to invariant correlation function

\[ C(q_{inv}) \]

\begin{align*}
\text{ATLAS Preliminary} & \quad -2 \ln L = 921 \\
p+Pb 2013, 28 \text{ nb}^{-1} & \quad \text{NDF} = 445 \\
\sqrt{s_{NN}} = 5.02 \text{ TeV} & \\
\lambda_{inv} = 0.842 & \\
R_{inv} = 3.37 \text{ fm} & \\
0.1 < k_T < 0.2 \text{ GeV} & \\
\text{20-30\% cent., } \pi^+\pi^- & \quad -2 \ln L = 1412 \\
-1 < y^*_\pi < 0 & \quad \text{NDF} = 454 \\
\lambda_{inv} = 0.660 & \\
R_{inv} = 3.17 \text{ fm} & \\
0.4 < k_T < 0.5 \text{ GeV} & \\
\text{Data} & \quad -2 \ln L = 559 \\
\text{Fit} & \quad \text{NDF} = 452 \\
\text{Bkgd} & \\
\lambda_{inv} = 0.543 & \\
R_{inv} = 2.88 \text{ fm} & \\
0.7 < k_T < 0.8 \text{ GeV} &
\end{align*}
Fit appears poor along $q_{\text{out}}$ axis, but works well globally. Note that the $q_{\text{out}}$ axis is right where the tracks have the same outgoing angle. Moving just 1 or 2 bins away helps significantly.
The above plots show the contributions of each systematic uncertainty on $R_{\text{inv}}$ as a function of $k_T$ and $N_{\text{part}}$. 

**ATLAS Preliminary**

$p+\text{Pb} 2013, 28 \text{ nb}^{-1}$

$\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$
Systematics example \( (\lambda_{\text{inv}}) \)

The above plots show the contributions of each systematic uncertainty on \( \lambda_{\text{inv}} \) as a function of \( k_T \) and \( N_{\text{part}} \).