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

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On behalf of the ATLAS collaboration

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Introduction (Multiplicity)

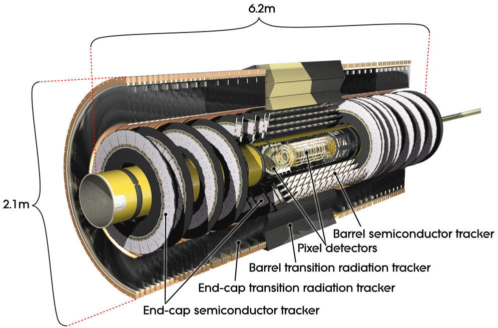
- p+Pb collisions are useful for understanding effects of "cold nuclear matter" on charged particle production
- It's important to have detailed understanding of global observables in these events
- Nuclear modification factor

$$R_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^{\star}) = \frac{1}{\langle T_{\mathrm{Pb}} \rangle} \frac{1/N_{\mathrm{evt}} \mathrm{d}^2 N_{p\mathrm{Pb}}/\mathrm{d}y^{\star}\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma_{pp}/\mathrm{d}y^{\star}\mathrm{d}p_{\mathrm{T}}}$$

  is studied differentially in centrality, transverse momentum (p_{T}), and rapidity ($y^{\star}$)
- $y^{\star}$ 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

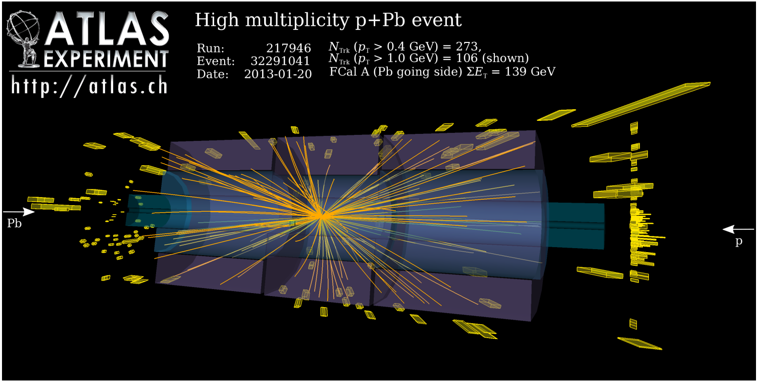
ATLAS inner detector

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



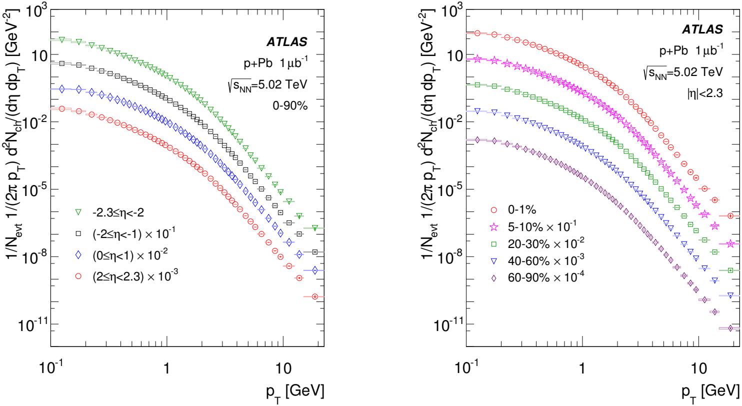
Reconstructed tracks from $|\eta| < 2.5$ at $p_{\mathrm{T}} > 0.1\ \mathrm{GeV}$

Data selection



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

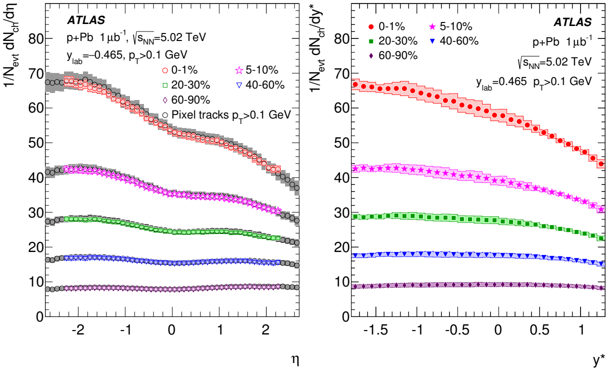
p_{T} spectra



p_{T} spectra in intervals of pseudorapidity η (left) and centrality (right)

see CERN-EP-2016-007

Differential multiplicity



rapidity is calculated with pion mass ($y^\star_{\pi\pi}$), and correction to real $y^\star$ is derived using Hijing

production is enhanced on Pb-going (-z) side of central events.

particle production as a function of η (left) and $y^\star = y - y_{\rm lab}$ (right) in several centrality intervals is shown above.
$y_{\rm lab} = 0.465$ is the nucleon-nucleon centre-of-momentum rapidity in the lab frame.

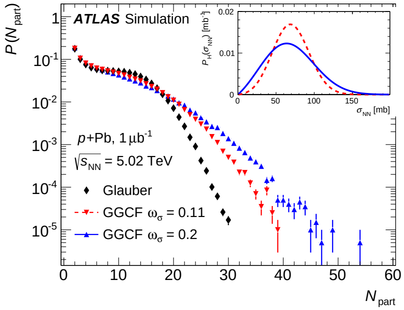
see CERN-EP-2016-007

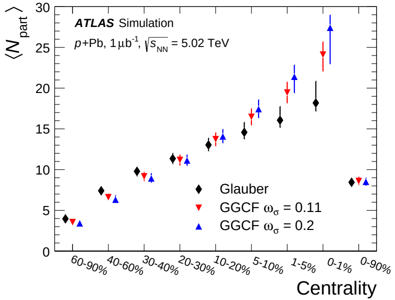
Glauber-Gribov colour fluctuations (GGCF)

Number of nucleon participants N_{part} calculated with:

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

ω_σ parameterizes extent of fluctuations

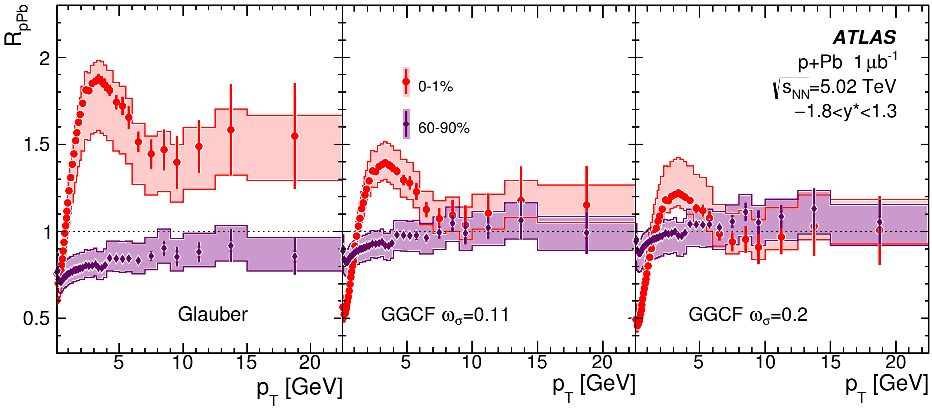




(above: N_{part} distributions and corresponding centrality)

see Eur. Phys. J. C (2016) 76:199

$R_{p\mathrm{Pb}}$



Using a model with large fluctuations in the NN cross-section reduces central $R_{p\mathrm{Pb}}$ significantly.

It also increases peripheral $R_{p\mathrm{Pb}}$ to be more compatible with unity.

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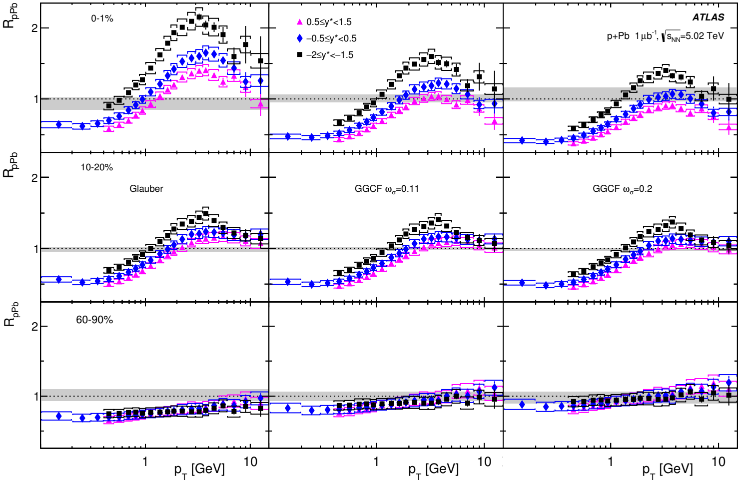
$R_{p\mathrm{Pb}}$ (p_T) in rapidity ($y^\star$) intervals



- Low-p_T suppression. Central events have high-p_T enhancement most prominent in Pb-going side.
- larger GGCF ω_σ brings $R_{p\mathrm{Pb}}$ closer to unity

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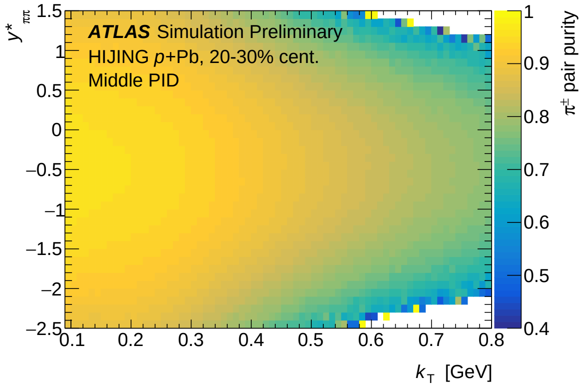
Introduction (Femtoscopy)

- Femtoscopy uses momentum-space correlation functions to infer the source density function:

$$C_{\mathbf{k}}(q) = \int d^3r \, S_{\mathbf{k}}(r) \left|\psi_q(r)\right|^2 \ .$$

  Here $k = (p_1 + p_2)/2$ is the average pair momentum and $q = (p_1 - p_2)$ is the relative momentum.
- $C_{\mathbf{k}}(q)$ is fit to a function to get length scales of $S_{\mathbf{k}}(r)$, which are referred to as the *HBT radii*.
- Bose-Einstein correlations between identical pions give particularly good resolution.

Pion identification



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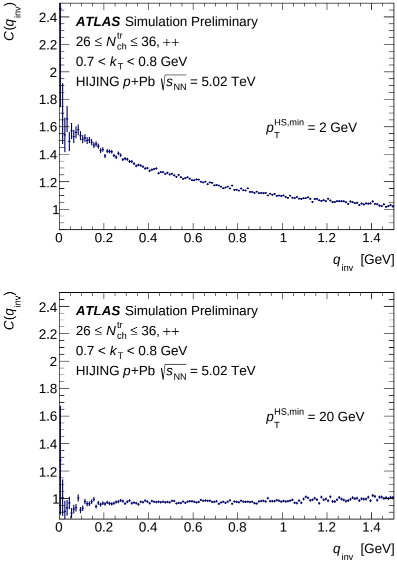
- Charged pions are identified using dE/dx measured with charge deposited in pixel hits.
- The pair purity estimated from simulation is shown (left) as a function of pair k_T and $y^\star_{\pi\pi}$.

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



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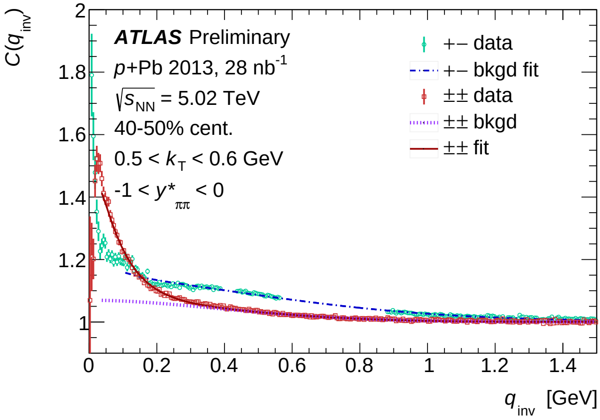
Summary of fitting procedure



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

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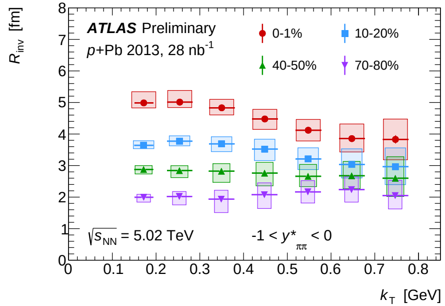
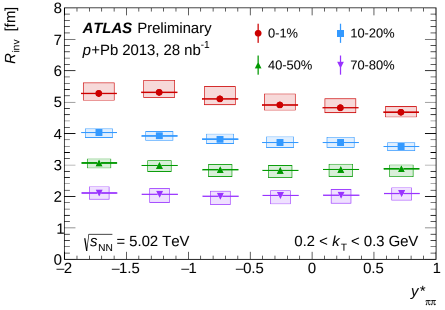
Invariant fit results





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.

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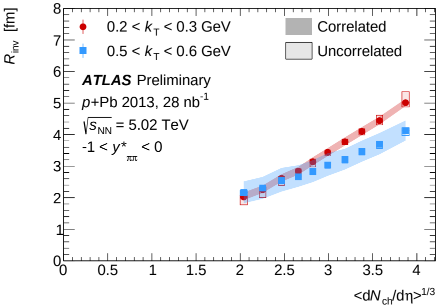
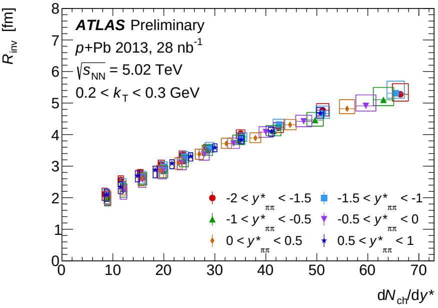
Invariant fit results





Scaling of $R_{\rm inv}$ 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.

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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_{out}: along k_{T}

q_{side}: other transverse direction

q_{long}: longitudinal (boosted to LCMF)

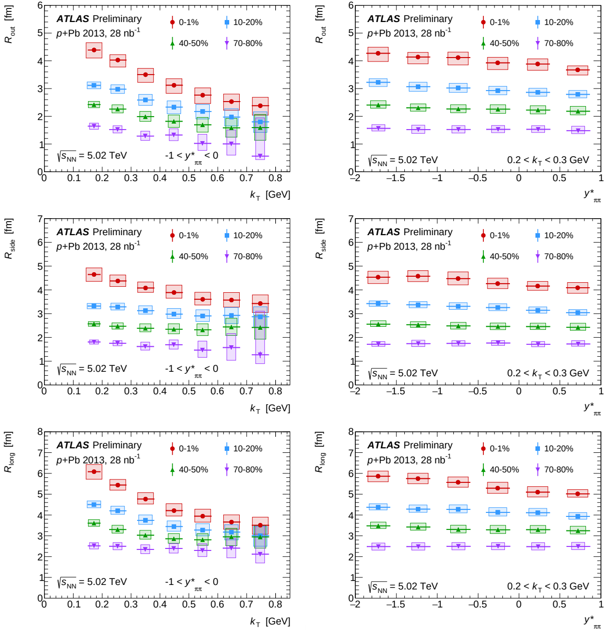
The Bose-Einstein part of the correlation function is fit to an quasi-ellipsoid exponential:

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

$$R = \begin{pmatrix} R_{\mathrm{out}} & 0 & R_{\mathrm{ol}} \\ 0 & R_{\mathrm{side}} & 0 \\ R_{\mathrm{ol}} & 0 & R_{\mathrm{long}} \end{pmatrix} .$$

3D radii vs. k_T and $y^\star_{\pi\pi}$

- decreasing size with rising k_T in central events; trend is diminished in peripheral.
- radii vs. $y^\star_{\pi\pi}$ 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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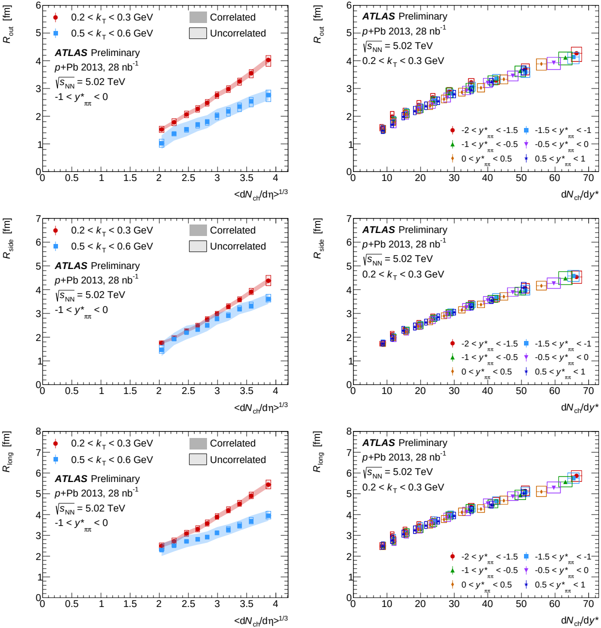
3D radii vs. multiplicity (global and local)



- scaling vs. $< dN/d\eta >^{1/3}$ shown on left
- three-dimensional radii also tightly correlated with local multiplicity (right)

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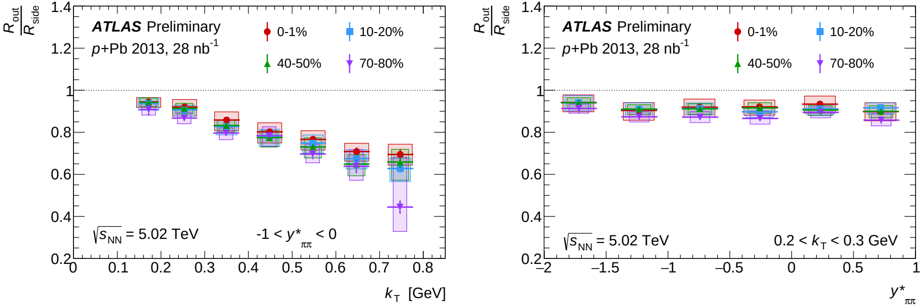
Ratio of $R_{\mathrm{out}}/R_{\mathrm{side}}$



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

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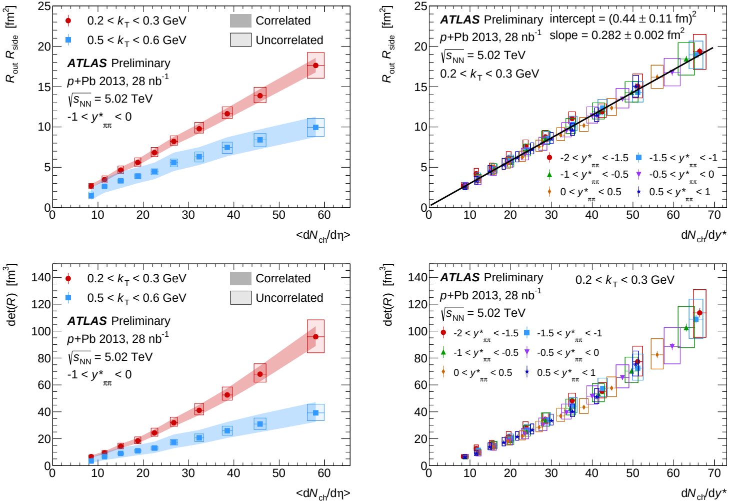
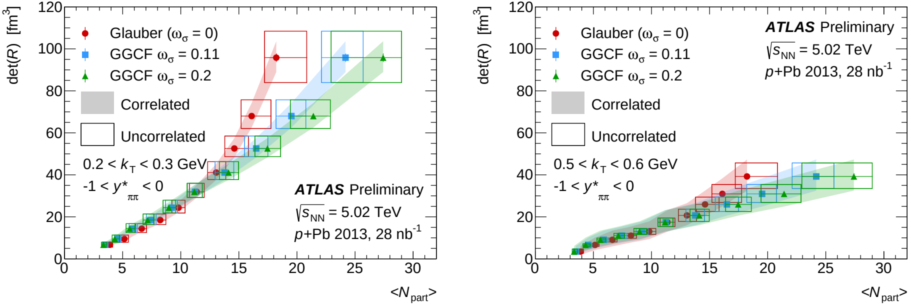
Transverse area and volume elements



At low k_T, the transverse area element $R_{out} R_{side}$ scales linearly with multiplicity. The volume element $\det(R)$ scales linearly with multiplicity at higher k_T.

Volume scaling with N_{part} including color fluctuations



Volume scaling curvature with N_{part} is more modest when fluctuations in the proton's size are accounted for.

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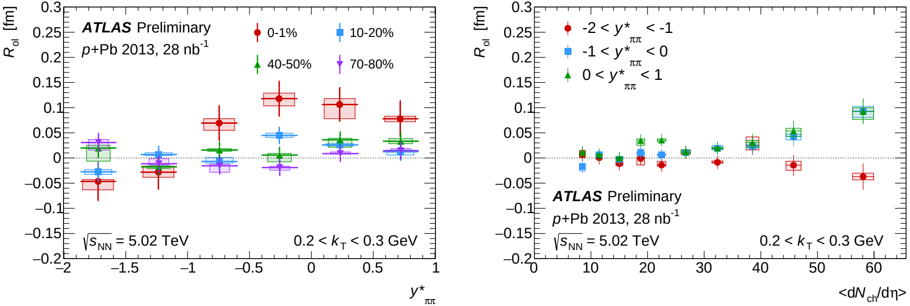
R_{ol} cross term



In *central events* on the *forward* side, there is strong evidence of a positive R_{ol} (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

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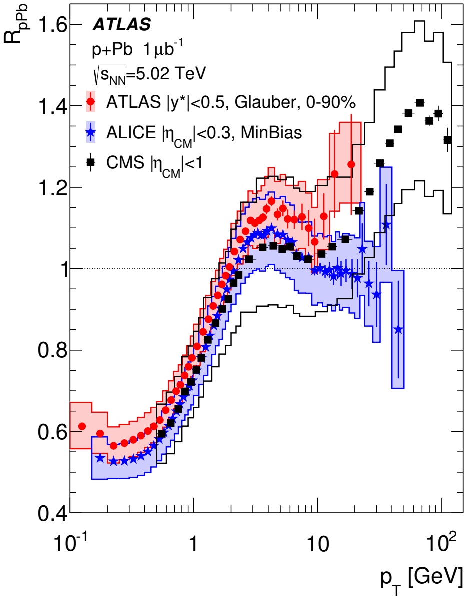
Conclusion

- 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_{ol} on the proton-going side of central events is observed.

BACKUP SLIDES

Comparison of $R_{p\mathrm{Pb}}$ with other collaborations



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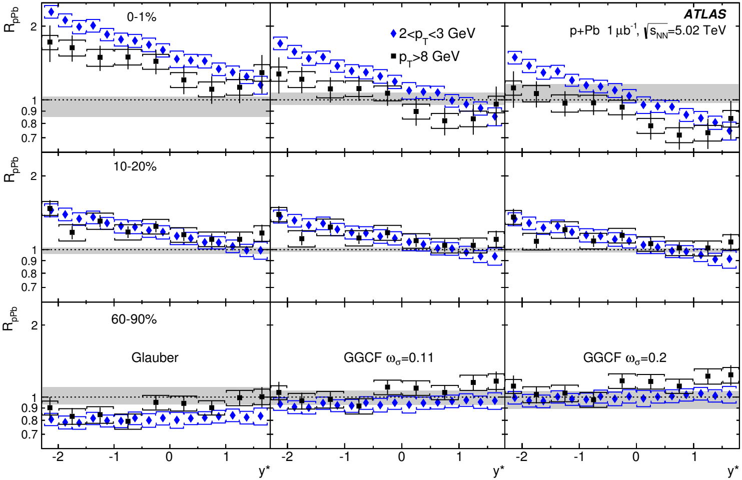
$R_{p\mathrm{Pb}}$ as function of rapidity



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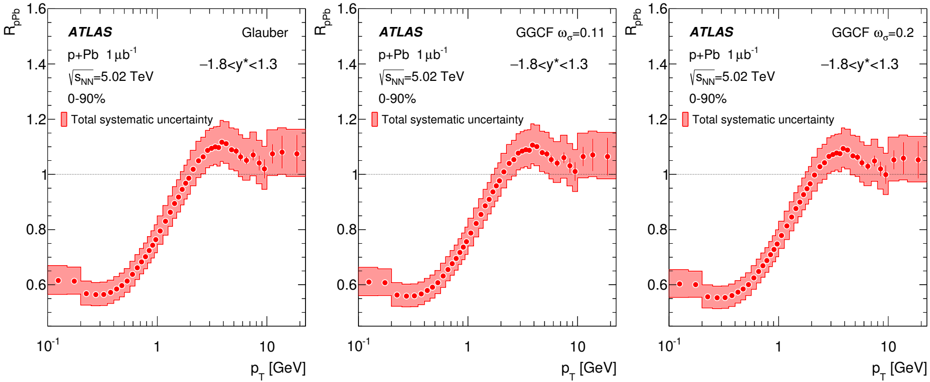
$R_{p\mathrm{Pb}}$ inclusive in centrality



Choice of initial geometry model does not significantly affect results inclusive in centrality

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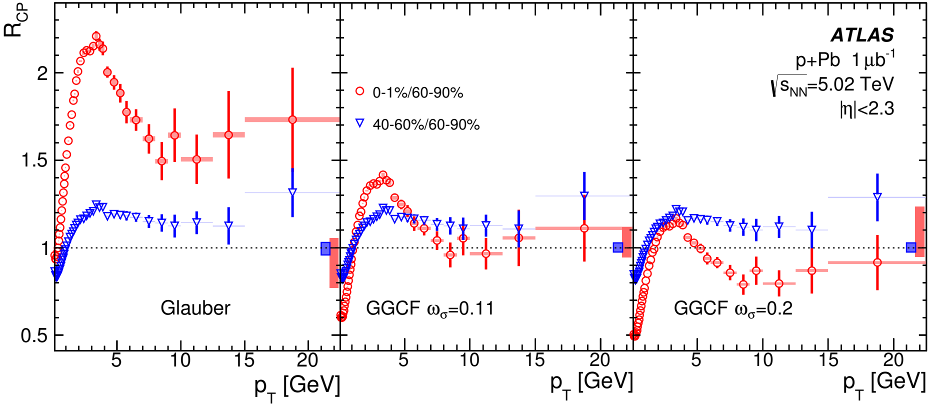
R_{CP} central to peripheral ratio



modest value of $\omega_\sigma = 0.11$ gives consistent high-p_T production across centralities

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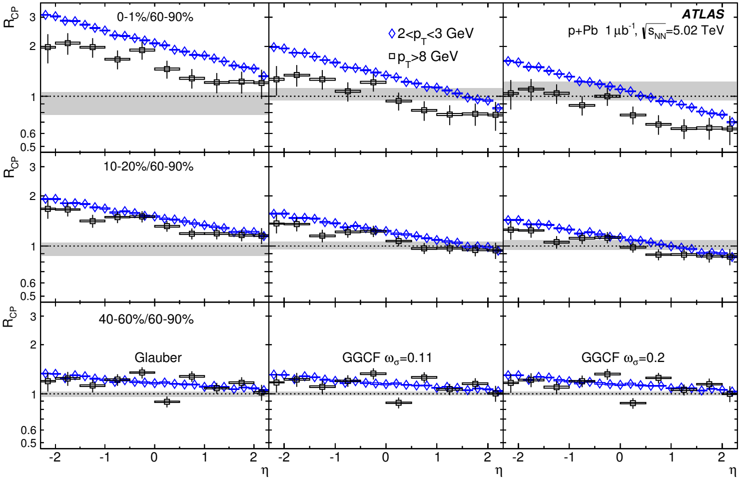
R_{CP} as function of rapidity



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:

$$C_{\mathbf{k}}(q) - 1 = \int_{\partial\Sigma} d^3 r\, S_{\mathbf{k}}(r) \left(|\langle q | r \rangle|^2 - 1 \right) \ .$$

  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 $S_{\mathbf{k}}(r)$, which are referred to as the *HBT radii*.
- For identical non-interacting bosons, $C_{\mathbf{k}}(q) - 1$ 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_{inv} or with 3-dimensional $\mathbf{q}$, where R is a symmetric matrix.

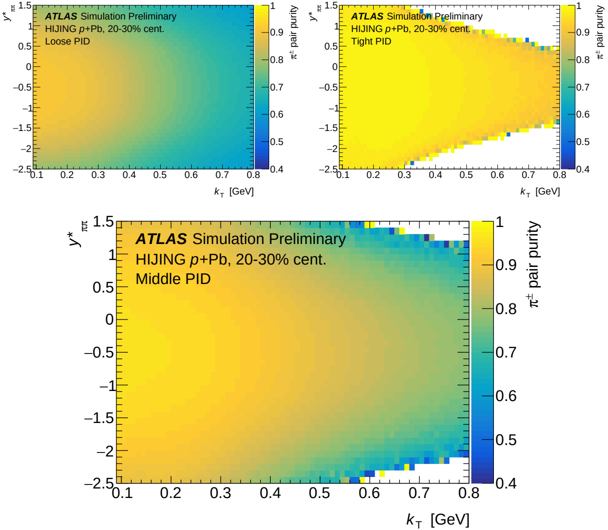
- The full experimental correlation function is the Bowler-Sinyukov form:

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

where λ is a free parameter, $K(q_{\mathrm{inv}})$ 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 λ.

Pion identification



Three PID selection criteria are defined, and a variation from the nominal selection to a looser and tigher definition is used as a systematic variation.

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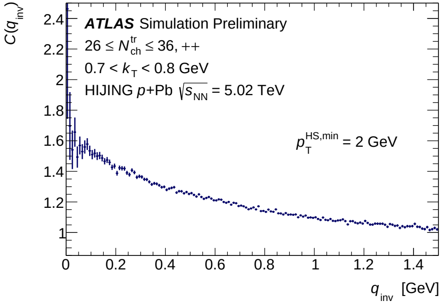
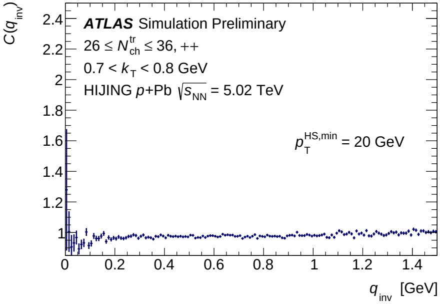
(Jet fragmentation in opposite-sign Hijing)





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 ρ, K_S, and ϕ
   - 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_{inv}:

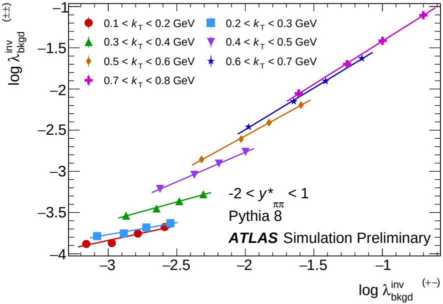
$$\Omega(q_{\mathrm{inv}}) = 1 + \lambda^{\mathrm{inv}}_{\mathrm{bkgd}} e^{-|R^{\mathrm{inv}}_{\mathrm{bkgd}} q_{\mathrm{inv}}|^{\alpha^{\mathrm{inv}}_{\mathrm{bkgd}}}}$$

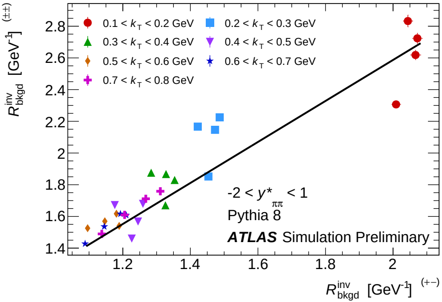
In 3D it is factorized into components parallel and perpendicular to jet axis

$$\Omega(\mathbf{q}) = 1 + \lambda^{\mathrm{osl}}_{\mathrm{bkgd}} e^{-|R^{\mathrm{out}}_{\mathrm{bkgd}} q_{\mathrm{out}}|^{\alpha^{\mathrm{out}}_{\mathrm{bkgd}}} - |R^{\mathrm{sl}}_{\mathrm{bkgd}} q_{\mathrm{sl}}|^{\alpha^{\mathrm{sl}}_{\mathrm{bkgd}}}}$$

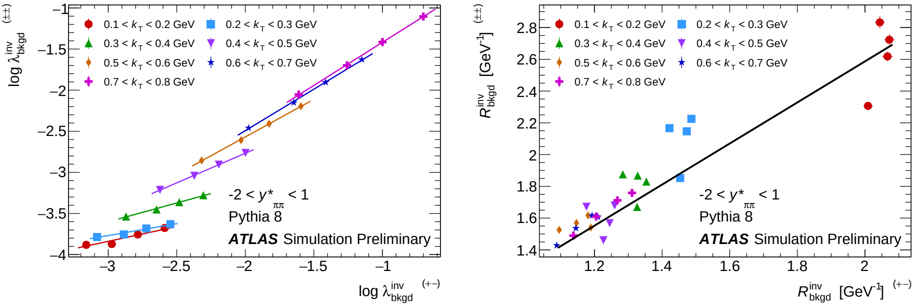
with $q_{\mathrm{sl}} = \sqrt{q^2_{\mathrm{side}} + q^2_{\mathrm{long}}}$.
These parameters are studied in Pythia, and a mapping from opposite-sign to same-sign values is derived.

Jet fragmentation mapping



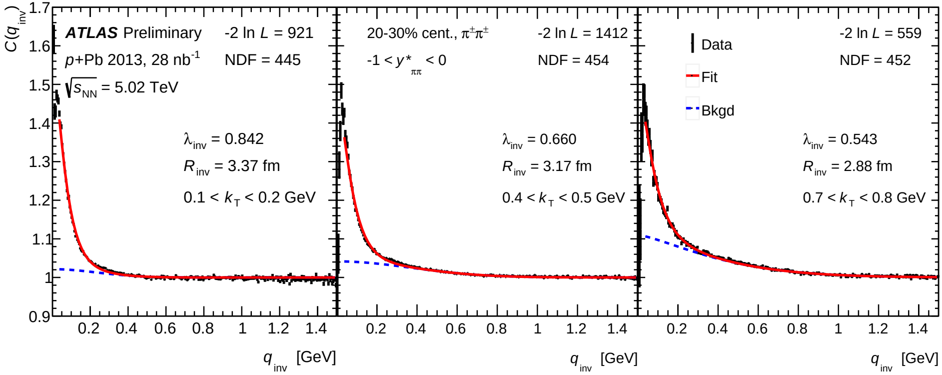


model $R_{\text{inv}}^{\pm\pm}$ as proportional to R_{inv}^{+-} (right). Then with constant fixed, do k_{T}-dependent comparison of background amplitude in $\pm\pm$ and $+-$ (left). Does not work perfectly but does increasingly well at high k_{T}, where the effect is relevant.

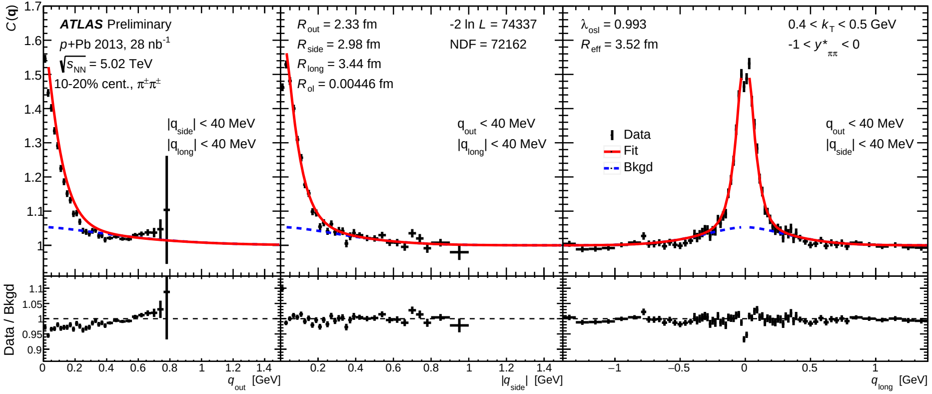


$R_{\text{inv}}^{\pm\pm}$ is modelled as proportional to R_{inv}^{+-} (right). Then with constant fixed, do k_{T}-dependent comparison of background amplitude in $\pm\pm$ and $+-$ (left). Does not work perfectly but does increasingly well at high k_{T}, where the effect is relevant.

Example fit to invariant correlation function

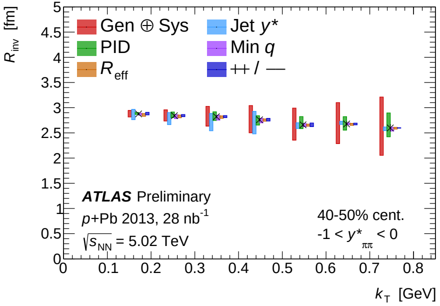


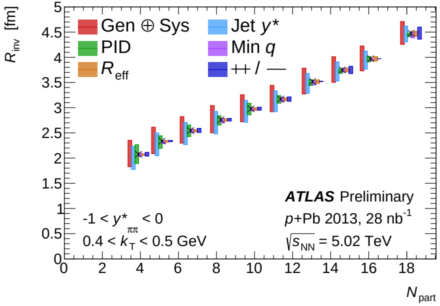
Example fit to 3D correlation function



Fit appears poor along q_{out} axis, but works well globally. Note that the q_{out} axis is right where the tracks have the same outgoing angle. Moving just 1 or 2 bins away helps significantly.

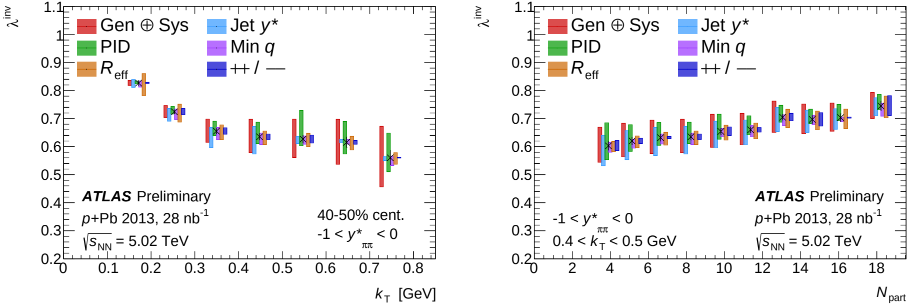
Systematics example (R_{inv})





The above plots show the contributions of each systematic uncertainty on R_{inv} as a function of k_{T} and N_{part}.

Systematics example (λ_{inv})



The above plots show the contributions of each systematic uncertainty on λ_{inv} as a function of k_{T} and N_{part}.