Rapidity- and azimuthally-dependent femtoscopy with charged pions in p+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with ATLAS

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Introduction

- Signatures of collective behavior are observed in azimuthal harmonics v_n even in small systems (pp and p+Pb).
- Collectivity can be probed by measuring the geometry of particle production (e.g. in collective expansion, the freeze-out size decreases with rising $k_{\rm T}$).
- The freeze-out source can be probed through the 2-particle correlation function

$$C_{\mathbf{k}}(q) = \int d^3r\, S_{\mathbf{k}}(r) \left|\psi_q(r)\right|^2 , \qquad (1)$$

where $k = (p_1 + p_2)/2$ 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*.
- The experimental correlation function is

$$C(q) = [1 - \lambda + \lambda K(q) C_{\rm BE}(q)]\, \Omega(q) , \qquad (2)$$

where K is the Coulomb correction, $C_{\rm BE}$ is the Bose-Einstein correlation, and Ω represents background correlations.

- use "out-side-long" coordinate system
  - $q_{\rm out}$: along $k_{\rm T}$
  - $q_{\rm side}$: other transverse component
  - $q_{\rm long}$: longitudinal component in longitudinal rest frame of pair
- The 3D BE correlation is fit to a function of the form

$$C_{\rm BE}(\mathbf{q}) = 1 + e^{-\|R\mathbf{q}\|} , \qquad (3)$$

where R is a symmetric matrix

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

with $R_{\rm ol} \neq 0$ in the rapidity-dependent analysis and $R_{\rm os} \neq 0$ in the azimuthal analysis.

Pion identification

- The wavefunction in Eqn. 1 has particularly good resolving power if there is BE enhancement.
- Identical pions are identified using ionization energy loss in pixel clusters.

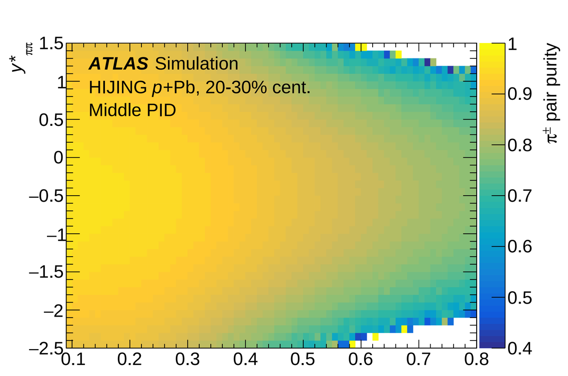

Figure 1: The pion pair purity as a function of $k_{\rm T}$ and rapidity $y^{\star}_{\pi\pi}$.

Jet fragmentation background

- The presence of hard processes in the collisions causes correlations to arise from the mini-jet fragmentation.
- The relationship between same-charge and opposite-charged jet correlations is studied in PYTHIA8.
- The opposite-charge data is used to constrain the same-sign jet contribution.

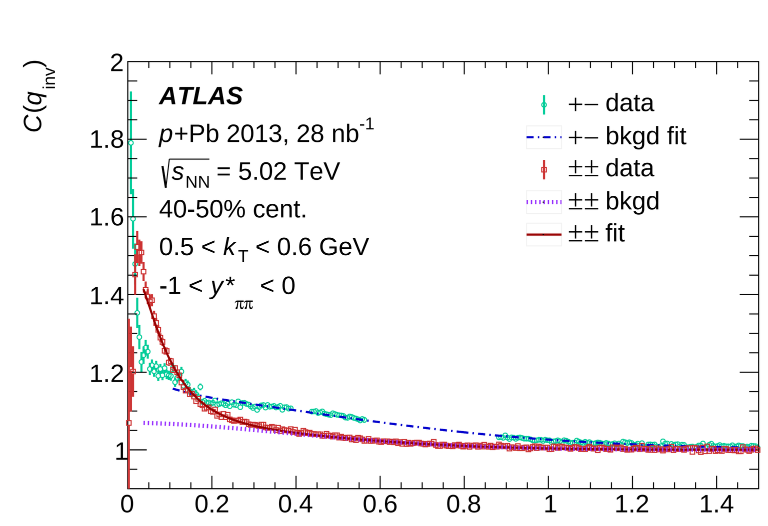

Figure 2: The opposite-charge data (teal) is fit to a function (blue dashed). The parameters of this fit are used to fix the fragmentation description (violet dotted) in the same-charge data (red). The remaining parameters are fit to the same-charge data (dark red line).

Results

Example fit

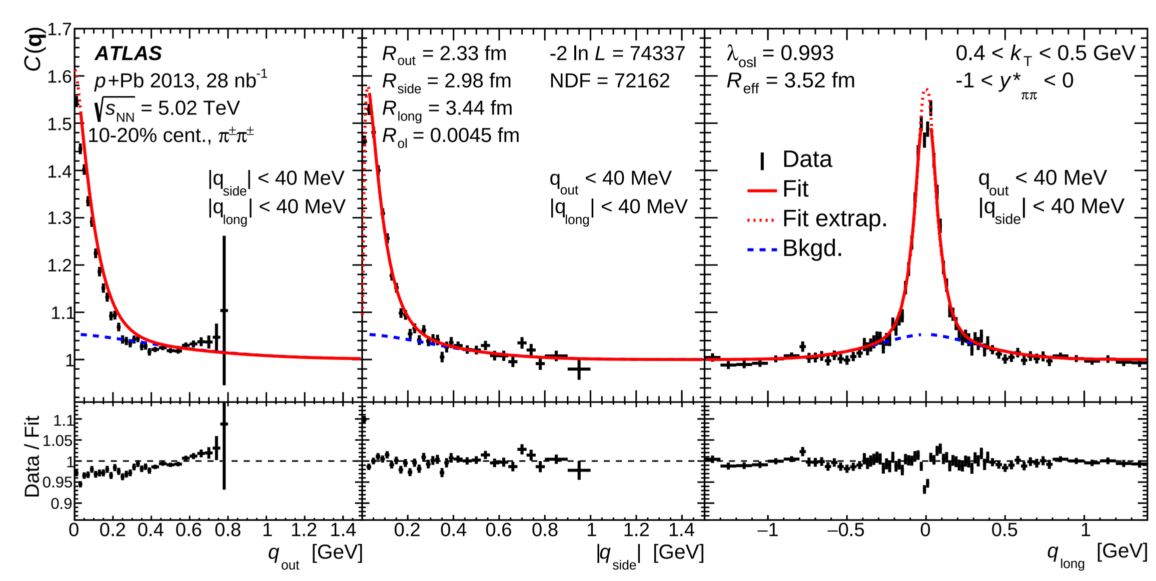

Figure 3: An example 3D fit along each q-axis.

Main HBT radii as function of $k_{\rm T}$, $y^{\star}_{\pi\pi}$, and multiplicity

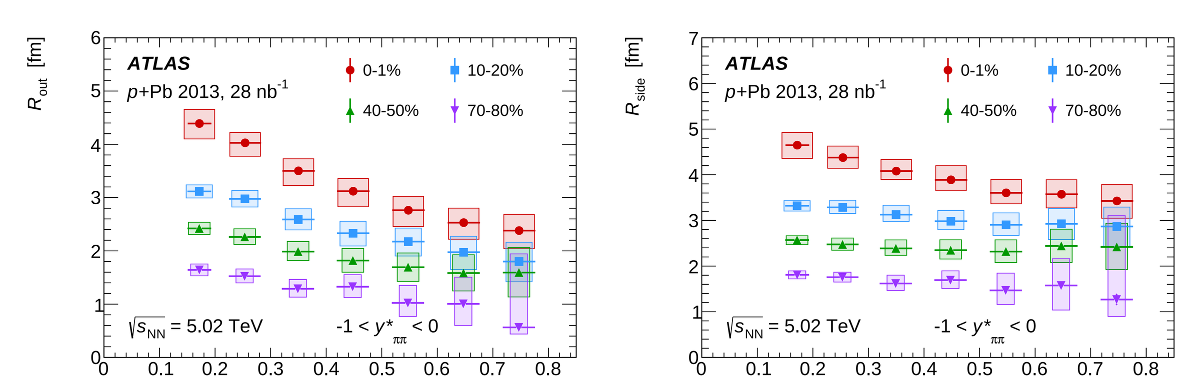

Figure 4: The transverse HBT radii $R_{\rm out}$ (left), $R_{\rm side}$ (right) as a function of pair transverse momentum $k_{\rm T}$.

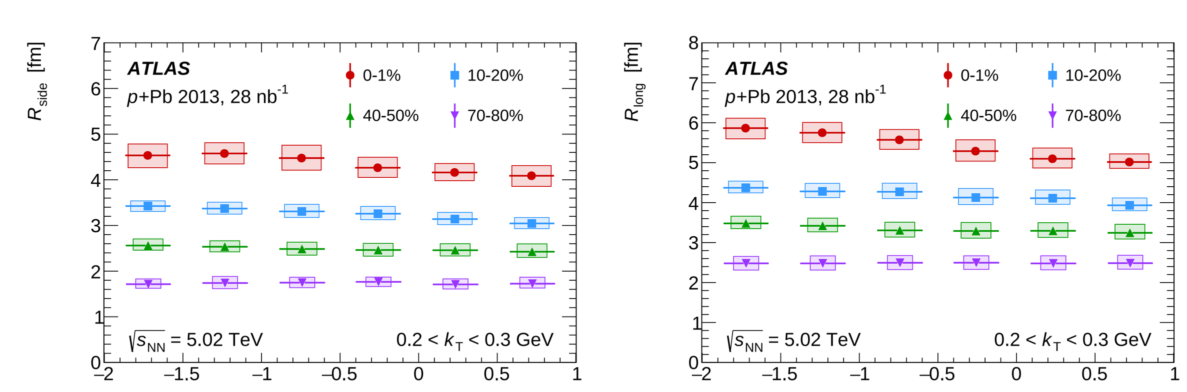

Figure 5: The HBT radii $R_{\rm side}$ (left), and $R_{\rm long}$ (right) as a function of pair rapidity $y^{\star}_{\pi\pi}$.

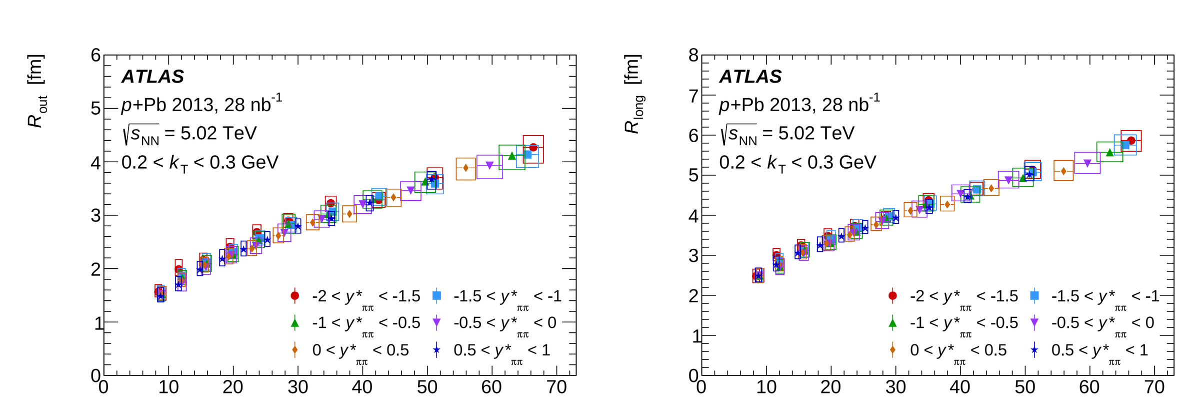

Figure 6: The HBT radii $R_{\rm out}$ (left) and $R_{\rm long}$ (right) as a function of local multiplicity $dN_{\rm ch}/dy^{\star}$.

Combinations and off-diagonal radii

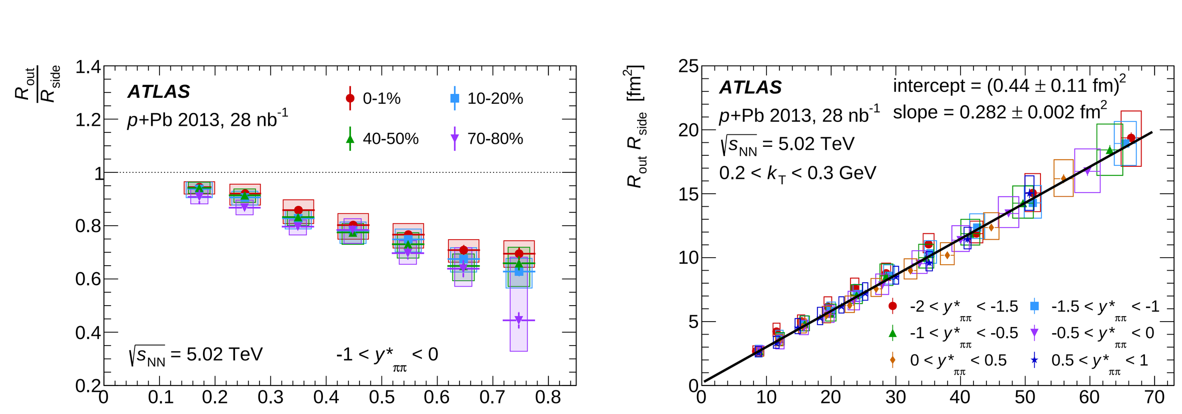

Figure 7: The ratio $R_{\rm out}/R_{\rm side}$ (left) indicates the explosiveness of the event, because $R_{\rm out}$ couples directly to the lifetime while $R_{\rm side}$ does not. At low $k_{\rm T}$ the transverse area element $R_{\rm out}R_{\rm side}$ (right) scales linearly with multiplicity, indicating constant transverse area density.

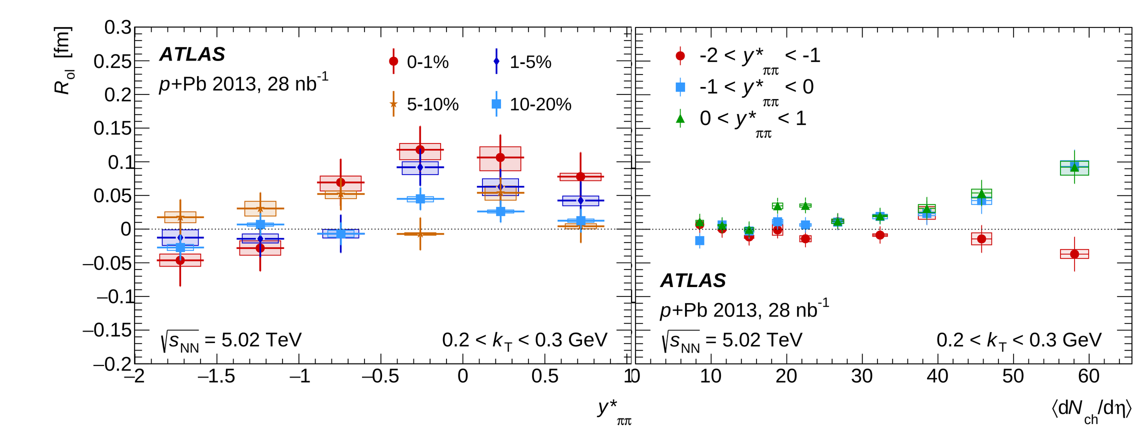

Figure 8: The cross-term $R_{\rm ol}$ is observed to be distinct from 0 in the proton-going side of central events, with a combined significance of 5.1σ at $-1 < y^{\star}_{\pi\pi}$ in the 0–1% centrality interval. This indicates longitudinal and transverse expansion and a breaking of boost invariance.

Azimuthal dependence

The correlation functions are measured in intervals of azimuthal angle ϕ_k with respect to the 2nd-order event plane Ψ_2. The main-diagonal HBT radii are fit to a function which allows extraction of their 2nd-order Fourier coefficients,

$$R_i = R_{i,0} + 2R_{i,2}\cos[2(\phi_k - \Psi_2)] . \qquad (4)$$

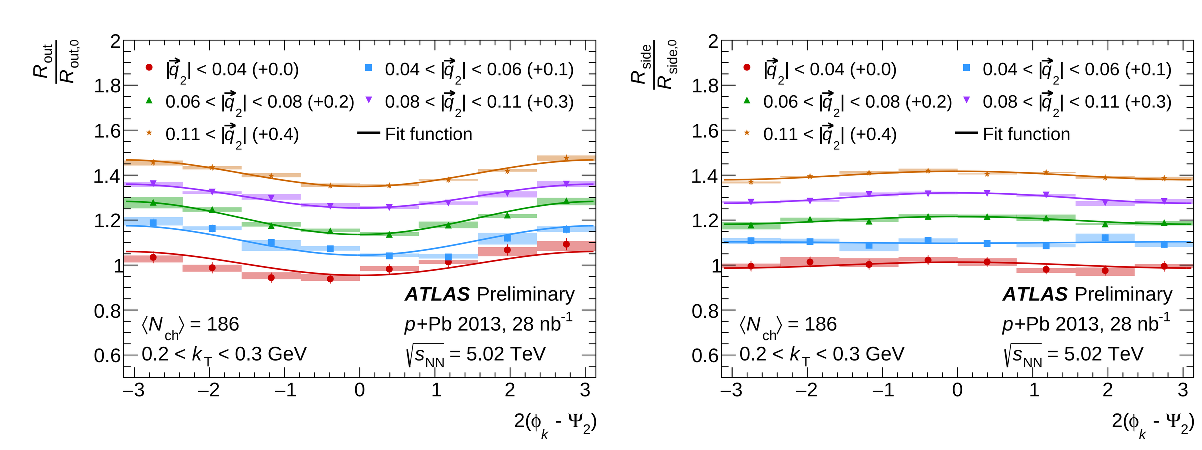

Figure 9: The transverse radii $R_{\rm out}$ (left) and $R_{\rm side}$ (right) as a function of azimuthal angle with respect to the 2nd-order event plane Ψ_2.

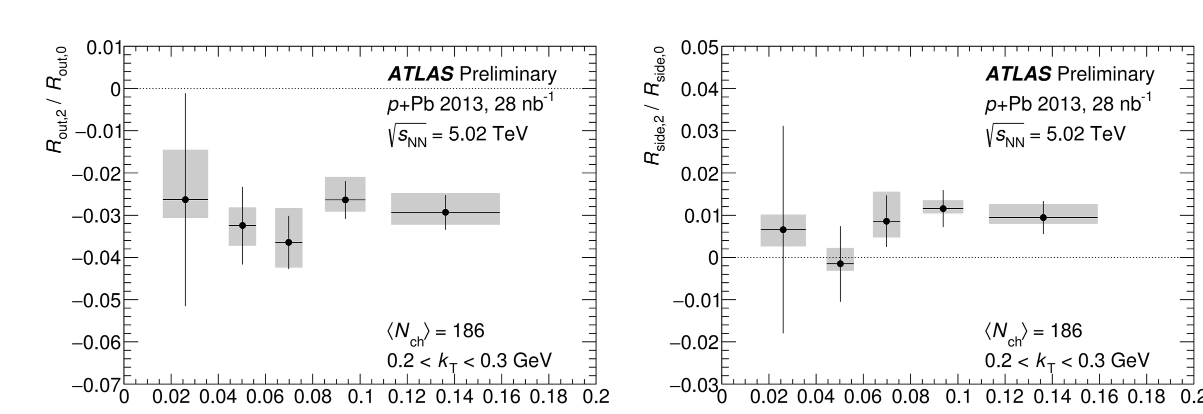

Figure 10: The normalized 2nd-order cosine Fourier components of the transverse radii $R_{\rm out}$ (left) and $R_{\rm side}$ (right) as a function of flow vector magnitude $|\vec{q}_2|$.

Highlighted observations

- Radii in central events show a decrease with rising $k_{\rm T}$, which is qualitatively consistent with collective expansion. This trend is diminished in peripheral events.
- Within uncertainties, each HBT radius depends only on the local multiplicity $dN_{\rm ch}/dy^{\star}$.
- Evidence for a non-zero (positive) $R_{\rm ol}$ is observed on the proton-going side of central events.
- The transverse shape of the freeze-out surface is consistent with short-lived hydrodynamic expansion in central events.

References

ATLAS Collaboration, *Femtoscopy with identified charged pions in proton-lead collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with ATLAS*, Phys. Rev. C **96**, (2017) 064908

ATLAS Collaboration, *Azimuthal femtoscopy in central proton-lead collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with ATLAS*, ATLAS-CONF-2017-008, http://cdsweb.cern.ch/record/2244818