Two-pion femtoscopy in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV}$ with *ATLAS*

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On behalf of the ATLAS collaboration
from **ATLAS-CONF-2015-054**
XI Workshop on Particle Correlations and Femtoscopy
Warsaw, Poland

November 4, 2015

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Motivation

- Recent measurements of angular correlations in p+Pb collisions have indicated signs of collective behavior.
- An additional independent handle on the size, shape, and evolution of the particle source is desirable.
- Momentum-space correlation functions ($C(p_1, p_2) \equiv \frac{\frac{dN_{12}}{dp_1 dp_2}}{\frac{dN_1}{dp_1}\frac{dN_2}{dp_2}}$) are sensitive to the source density function $S(r)$:

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

  $k = (p_1 + p_2)/2$ is the average pair momentum and $q = (p_1 - p_2)$ is the relative momentum.
- Background $\frac{dN_1}{dp_1}\frac{dN_2}{dp_2}$ is formed by event-mixing in intervals of centrality and longitudinal position of the collision vertex.

Introduction

- These 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 in 3 dimensions, where R is a diagonal matrix. In 1D, e.g., this implies a Cauchy source function: $S_{\mathrm{inv}}(r) \propto \left(1 + R_{\mathrm{inv}}^{-2} r^2\right)^{-1}$

- With some fraction of pairs λ being composed of pions from a core (not from, e.g., weak decays or long-lived resonances), the full experimental correlation function used is the Bowler-Sinyukov form:

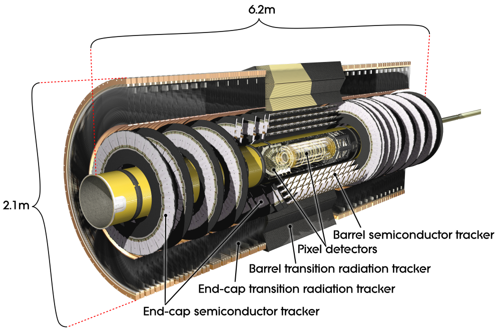
$$C_{\mathrm{exp}}(q) = \left[(1-\lambda) + \lambda K(q_{\mathrm{inv}}) C_{BE}(q)\right] \Omega(q_{\mathrm{inv}}) \ ,$$

where $K(q_{\mathrm{inv}})$ accounts for Coulomb interactions between the pions and $\Omega(q_{\mathrm{inv}})$ represents the non-femtoscopic background features of the correlation function.

- Mis-identified pions, coherent emission contribute to decrease in λ.

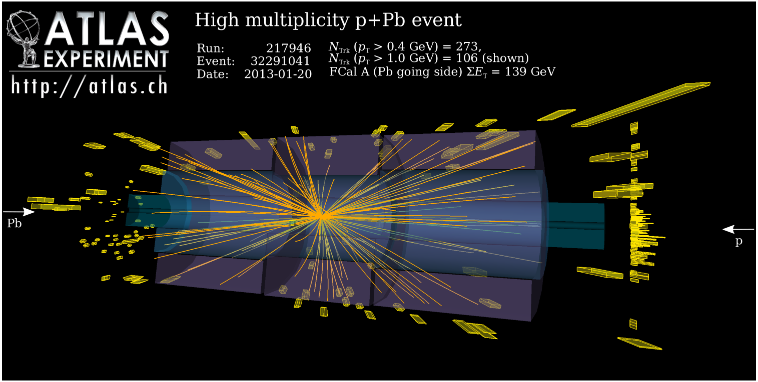
ATLAS inner detector

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



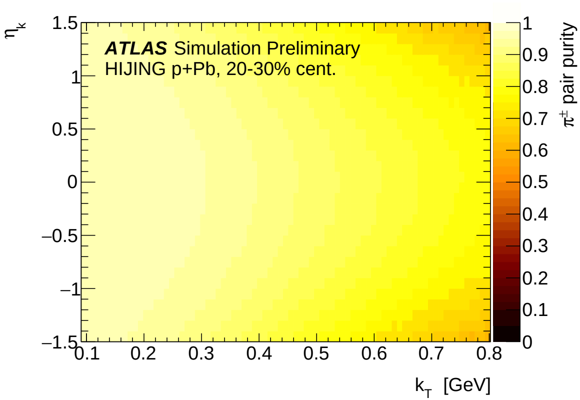
Reconstructed tracks from $|\eta| < 2.5$ at $p_\mathrm{T} > 0.1 \ \mathrm{GeV}$

Data selection



- 2013 $p+\mathrm{Pb}$ run from the LHC at $\sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV}$
- $28.1\ \mathrm{nb}^{-1}$ minimum-bias data
- centrality determined from $\sum E_{\mathrm{T}}$ in the Pb-going forward calorimeter at $3.1 < |\eta| < 4.9$

Pion identification

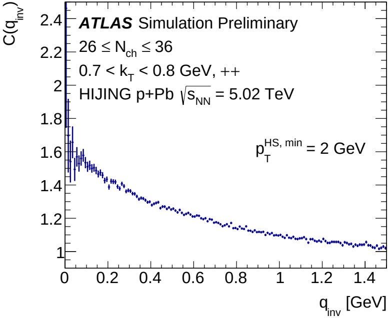


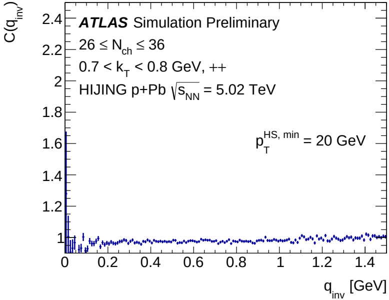
The pair purity for the nominal selection, estimated from simulation, is shown above as a function of pair k_{T} and η_k.

- Pions are identified using an estimation of dE/dx from time-over-threshold of charge deposited in pixel hits.
- Three particle identification (PID) selections are defined; high efficiency, high purity, and one in the middle (nominal).
- The variation is used to estimate systematic uncertainty.

Jet fragmentation correlation

- significant non-femtoscopic contribution observed in the two-particle correlation function
- commonly attributed to mini-jets
- increased hard-scattering p_{T} cutoff in samples generated from HIJING
- lack of hard processes causes the correlation to disappear (right)
- not particularly surprising, but important to verify in order to justify description of this feature in data





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

Jet fragmentation correlation

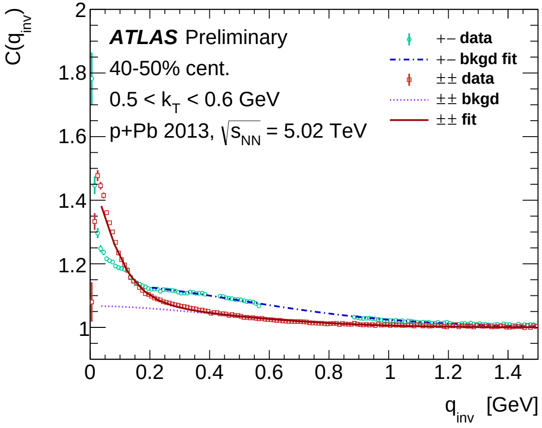
A data-driven method is developed to constrain the effect of hard processes. Fits to the opposite-sign correlation function are used to predict the fragmentation correlation in same-sign. This has its own challenges.

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

The background is modeled as a stretched exponential in q_{inv}:

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

Summary of fitting procedure



1. $\lambda^{+-}_{\rm bkgd}$ and $R^{+-}_{\rm bkgd}$ are fit in opposite-sign correlation function, with worst resonances removed (blue dashed)
2. the results from $+-$ are used to fix $\lambda^{\pm\pm}_{\rm bkgd}$ and $R^{\pm\pm}_{\rm bkgd}$ (violet dotted)
3. the remaining parameters are fit in $\pm\pm$ (dark red) to extract the source radii

Mapping of fragmentation background from opposite- to same-sign

Pythia 8 is used to derive the mapping from opposite-sign parameters to same-sign parameters.

$$\alpha_{\mathrm{bkgd}}^{\pm\pm} = \alpha_{\mathrm{bkgd}}^{+-} = \alpha_{\mathrm{bkgd}}(k_{\mathrm{T}})$$

$\alpha_{\mathrm{bkgd}} = 2$ (Gaussian) works well at $k_{\mathrm{T}} \lesssim 0.4\ \mathrm{GeV}$, but decreases in value at larger k_{T}.

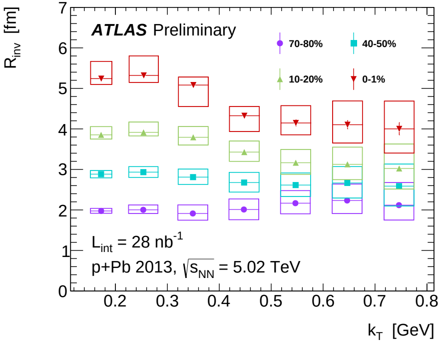
$$R_{\mathrm{bkgd}}^{\pm\pm} = \rho R_{\mathrm{bkgd}}^{+-}$$

proportionality breaks down at low k_{T}, but the contribution from jets is not strong in that region anyway

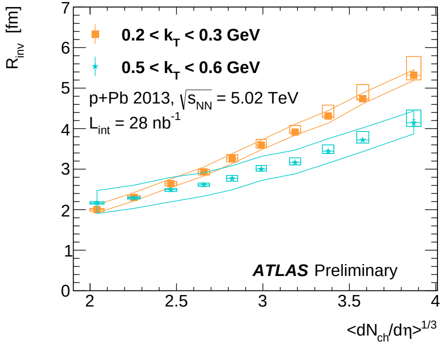
$$\log \lambda_{\mathrm{bkgd}}^{\pm\pm} = \log \mu(k_{\mathrm{T}}) + \nu(k_{\mathrm{T}}) \log \lambda_{\mathrm{bkgd}}^{+-}$$

μ and ν are fit in each k_{T} interval to describe several multiplicities

Invariant fit results



Close-to-linear scaling of R_{inv} with multiplicity, esp. at low k_{T}. At higher k_{T}, radii is less multiplicity-dependent.



Fall-off with increasing k_{T} in central collisions, qualitatively consistent with hydrodynamical description. This feature disappears in peripheral collisions.

NB: Exponential radii typically have larger values than Gaussian.

3D fit results

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

$$q_{\mathrm{out}} \equiv \hat{\mathbf{k}}_{\mathrm{T}} \cdot \mathbf{q}_{\mathrm{T}} \quad (1)$$

$$q_{\mathrm{side}} \equiv (\hat{\mathbf{z}} \times \hat{\mathbf{k}}_{\mathrm{T}}) \cdot \mathbf{q}_{\mathrm{T}} \quad (2)$$

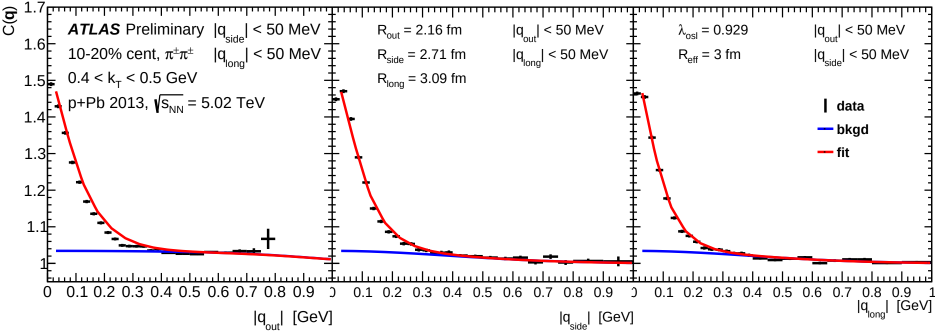
$$q_{\mathrm{long}} \equiv \hat{\mathbf{z}} \cdot \mathbf{q}_{\mathrm{LCMF}} \quad (3)$$

The Bose-Einstein part of the correlation function is fit to an ellipsoidally symmetric exponential.

$$C_{BE}(\mathbf{q}) = 1 + \exp\left(-\sqrt{R_{\mathrm{out}}^2 q_{\mathrm{out}}^2 + R_{\mathrm{side}}^2 q_{\mathrm{side}}^2 + R_{\mathrm{long}}^2 q_{\mathrm{long}}^2}\right)$$

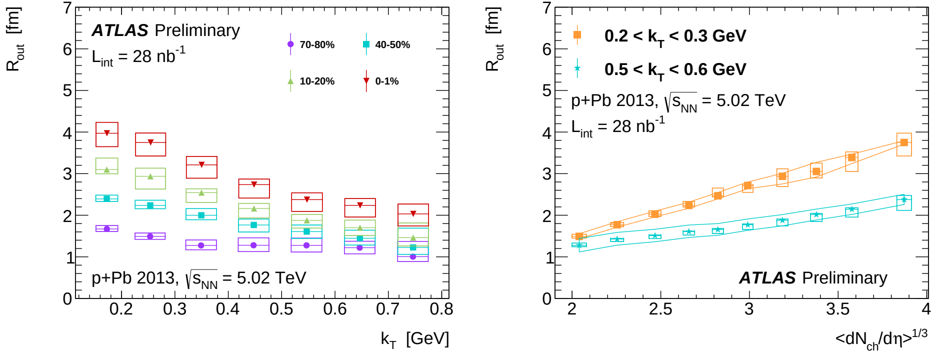
The same fragmentation background model is used as in the 1D fits by contracting $\mathbf{q}$ onto q_{inv} (using the average k_{T} in the interval).

3D fit example



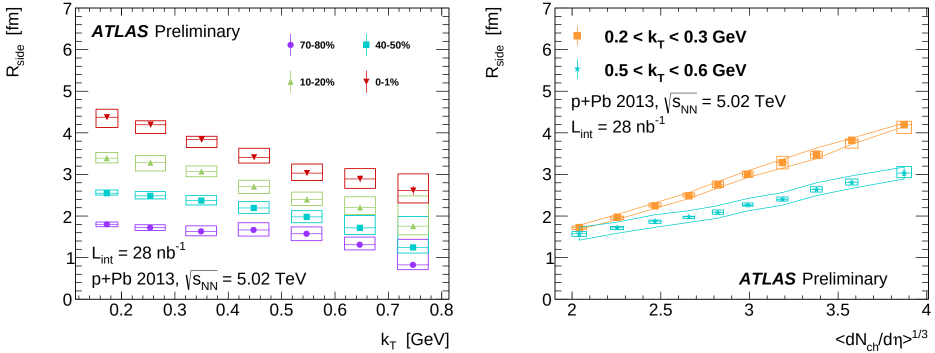
The fit along the q_{out} axis is a worst-case: characteristic of $q_{\text{side}}, q_{\text{long}} \approx 0$.

3D results (R_{out})



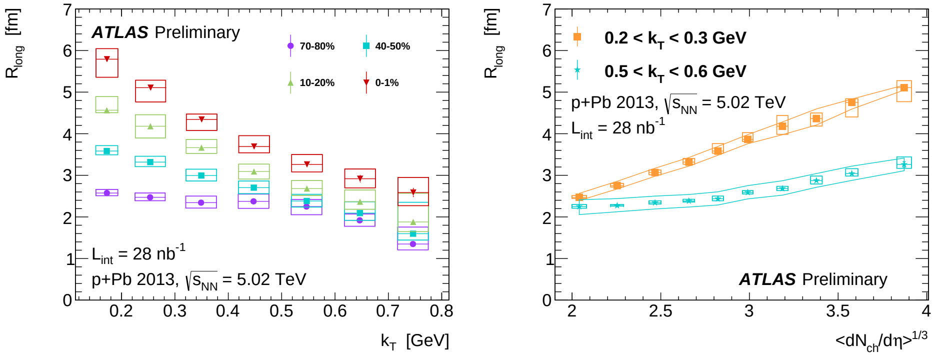
- the smallest radius
- exhibits a trend of decreasing size with increasing k_{T}, which is diminished in peripheral collisions
- consistent with linear scaling vs. $< dN/d\eta >^{1/3}$, suggestive of constant freeze-out density

3D results (R_{side})



Qualitatively similar to R_{out}, but slightly larger.

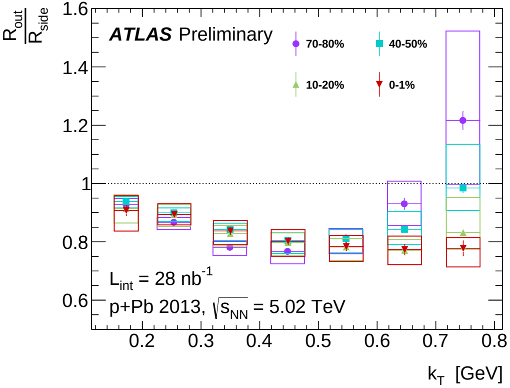
3D results (R_{long})



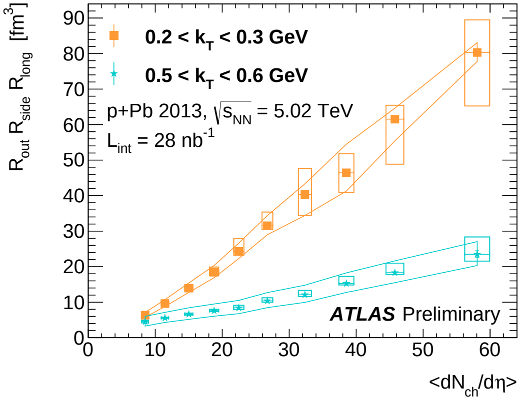
- The largest source radius, with most prominent fall-off with increasing k_{T}
- Linear scaling with $< dN/d\eta >^{1/3}$ starting to break down at higher k_{T}

3D results ($R_{\rm out}/R_{\rm side}$)

- ratio of $R_{\rm out}/\ R_{\rm side}$ ("explosiveness") is not strongly dependent on centrality
- decrease with larger $k_{\rm T}$ suggests that higher $p_{\rm T}$ particles are emitted at earlier times
- caveat: these are exponential radii

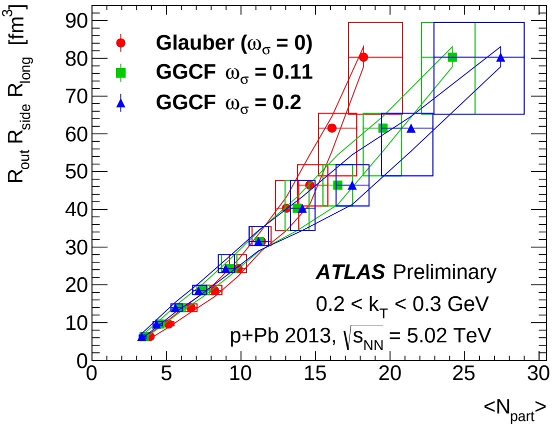


3D results (volume scaling)



- at low k_T, volume element scales linearly with multiplicity. size of homogeneity region approaches zero where multiplicity is still positive.
- at larger k_T, slight convexity: volume beginning to saturate at low multiplicity

3D results (volume scaling with N_{part})



Volume scaling with N_{part} is qualitatively different depending on whether one uses an initial-geometry model that includes color fluctuations in the size of the nucleons (see backup).

Conclusion

- Charged pion correlations are used to take measurements of the freeze-out source dimensions in proton-lead collisions at $|\eta_k| < 1.5$ and $0.1 < k_\mathrm{T} < 0.8\ \mathrm{GeV}$, in 12 centrality intervals from 0–98%
- A data-driven method is employed to describe the correlations from jet fragmentation, which contributed a dominant systematic in small-systems femtoscopy. *No free parameters in background description.*
- Radii in central events show a decrease with increasing k_T, which is qualitatively consistent with collective expansion. This trend becomes less pronounced in peripheral events.
- Linear scaling of volume with multiplicity indicates constant freeze-out density (esp. at low k_T)
- Evolution of volume as function of N_part is dependent on color fluctuations in model

Thank you!

BACKUP SLIDES

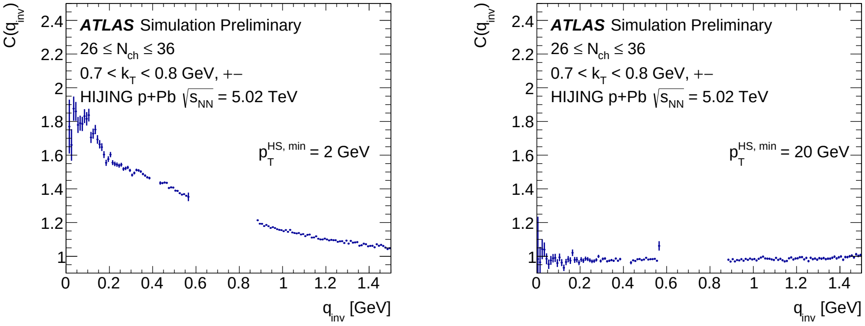
Other ATLAS results regarding collective behavior in small systems:

- azimuthal correlations in proton-lead: Phys. Rev. C 90, 044906
- ridge in proton-proton: CERN-PH-EP-2015-251

See also:

- Bose-Einstein correlations in proton-proton: Eur. Phys. J C75:466

Jet fragmentation contribution (opposite-sign)



Glauber-Gribov colour fluctuations

Spatial extent of color fields inside nucleon fluctuate event-by-event. The color fluctuation parameter ω_σ parameterizes the width of the corresponding fluctuations in the nucleon-nucleon cross-section,

$$\omega_\sigma = \frac{\langle \sigma_{pj} \sigma_{pj'} \rangle_I}{\bar{\sigma}^2} - 1 \,,$$

where j and j' are two different target nucleons and $\langle \rangle_I$ indicates an average over internal configurations.

Further info (links):

Phys. Rev. Lett. 67, 2946

Phys. Rev. D 47, 2761

Phys. Lett. B722 347