Azimuthally-dependent femtoscopy in central p+Pb collisions at 5.02 TeV with the ATLAS detector

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for the ATLAS collaboration

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ATLAS EXPERIMENT

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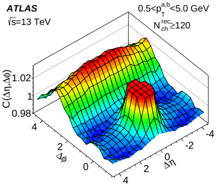
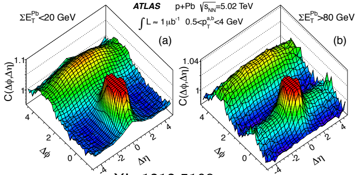
motivation

pp:



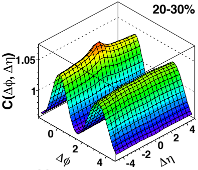
arXiv:1509.04776

p+Pb:



arXiv:1212.5198

Pb+Pb:



arXiv:1203.3087

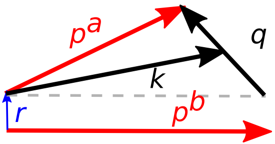
- long-range azimuthal correlations ("ridge") are observed not only in Pb+Pb, but also in p+Pb and pp collisions
- this is reproduced by hydrodynamics, however is it suitable to use hydrodynamics in such small systems?
- we can measure geometry of the source of the outgoing particles using Hanbury Brown & Twiss correlations (HBT)

$\rightarrow$ pairs of identical particles needed

$\Rightarrow$ Bose-Einstein correlations may be observed

introduction

- using relative variables:
  - $q = (p^a - p^b) \qquad q_{inv} = \sqrt{|q^\mu q_\mu|}$
  - $k = (p^a + p^b)/2$
  - r – displacement at freeze-out



- two-particle correlation function:

$$C_k(q) = \frac{A_k(q)}{B_k(q)} = \frac{\mathrm{d}N/\mathrm{d}^3q}{\mathrm{d}N'/\mathrm{d}^3q} \qquad \begin{matrix} \leftarrow \text{pairs from the same event} \\ \leftarrow \text{pairs from different event} \end{matrix}$$

- to account for all real-world effects, Bowler-Sinyukov form is used:

$$C_k(q) = [(1-\lambda) + \lambda K(q) C_{BE}(q)]\,\Omega(q)$$

- the correlation function depends on the two-particle source density function $S_k(r)$:

$$C_{BE}(q) = 1 + \int S_k(r) \underbrace{\left(|\langle q|r\rangle|^2 - 1\right)}_{\cos q\cdot r} \mathrm{d}^3r = 1 + \mathcal{F}[S_k](q)$$

(for non-interacting identical bosons)

introduction

- vectors can be expressed in longitudinal rest frame of each pair (a.k.a. longitudinal co-moving frame, LCMF; $k_z = 0$ and $p_z^a = -p_z^b$):
  - q_{out} – along k_{T} ($k_{\mathrm{T}} = (p_{\mathrm{T}}^a + p_{\mathrm{T}}^b)/2$)
  - q_{side} – other transverse direction
  - q_{long} – longitudinal (was boosted w.r.t. center-of-mass system)
- Bose-Einstein part of the correlation function is a fit to:

$$C_{BE}(q) = 1 + \mathrm{e}^{-R_{inv} q_{inv}} \qquad \text{... 1D fit}$$
$$C_{BE}(q) = 1 + \mathrm{e}^{-|Rq|} \qquad \text{... 3D fit}$$

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

- R_{inv} is *invariant radius*
- R_{out}, R_{side}, and R_{long} are *HBT radii*

} length scales of the source

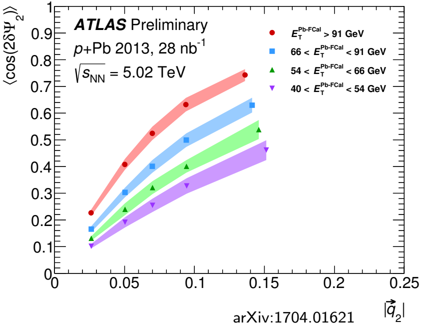
- one of the non-diagonal element has to be zero

azimuthal analysis

- HBT radii are also measured as a function of elliptic flow vector magnitude $|\vec{q}_2|$ and w.r.t event plane Ψ_2
  - $\Psi_2 = \frac{1}{2}\arctan\left(\frac{q_{2,y}}{q_{2,x}}\right)$
  - Ψ_2 measured in Pb-going side ($\eta < -2.5$)
- correlation functions are corrected for the event plane resolution
- results only for the most central events (0–1%, red)
- event planes are aligned in the event mixing
- allowed cross-term to be non-zero is R_{os}
- two Fourier components of HBT radii are extracted:

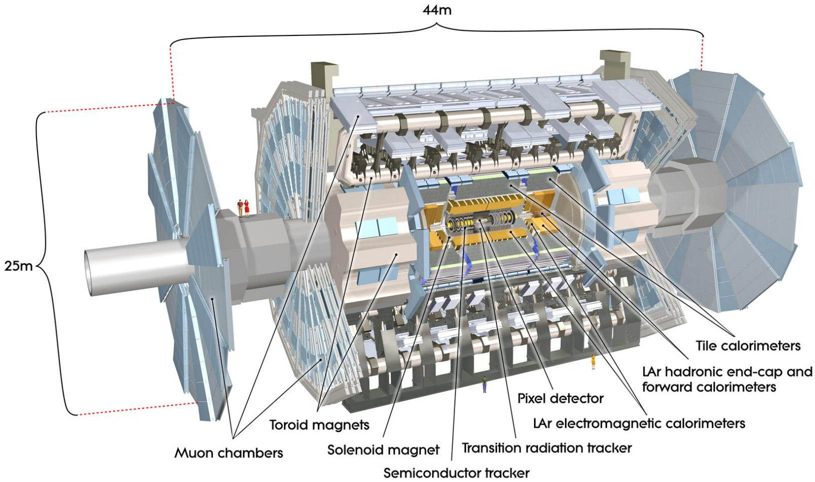
$$R_i = R_{i,0} + 2R_{i,2}\cos[2(\phi_k - \Psi_2)]$$

- ϕ_k – azimuthal angle of k_T



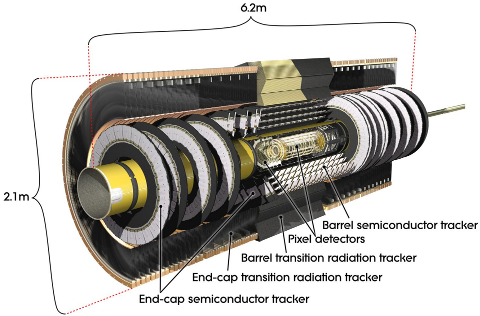
arXiv:1704.01621

ATLAS detector



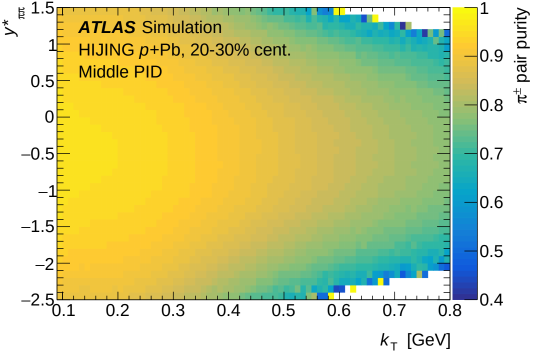
Inner detector & dataset

- 2T magnetic field
- reconstructing tracks with $|\eta| < 2.5$ and $p_{\mathrm{T}} > 0.1$ GeV
- Pixel detector providing deposited charge



- p+Pb data from 2013 with $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$; $L_{\mathrm{int}} = 28\,\mathrm{nb}^{-1}$
- trigger:
  - MBTS signal (minimum bias)
  - high-multiplicity trigger (for azimuthal analysis)
- centrality based on energy deposited in Pb-going side of Forward Calorimeter ($-4.9 < \eta < -3.1$)

pion identification

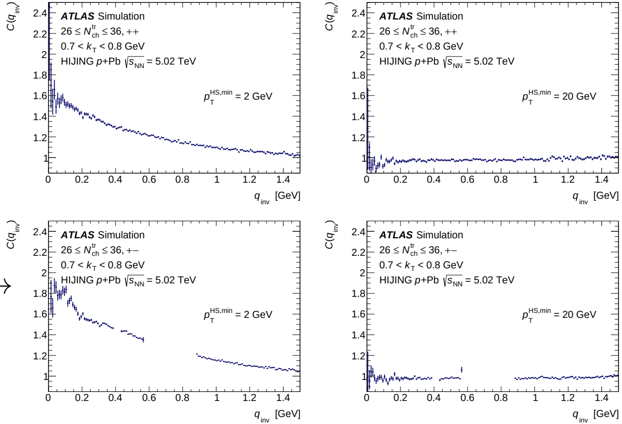


arXiv:1704.01621

- using dE/dx derived from the ionization charge deposit in the Pixel detector
- purity estimated from Hijing; requiring both particles are correctly identified as pions
- $y^\star_{\pi\pi}$ – rapidity of the pair in the center-of-mass frame, assuming masses of pions

hard-process contributions

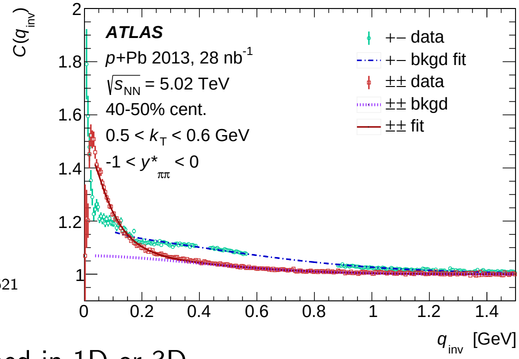
resonance peaks excluded in $(+-)$ $\longrightarrow$



arXiv:1704.01621

- significant contributions from hard processes even in Hijing
- when hard scattering suppressed, the background disappears
- mapping $(+-) \rightarrow (\pm\pm)$ is derived from the simulation to predict the contribution in data
- hard-process contributions measured in opposite-sign data

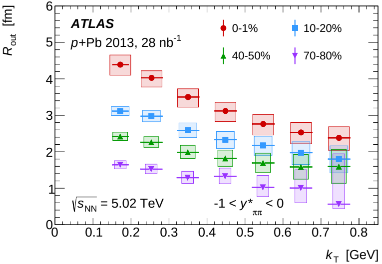
fitting procedure

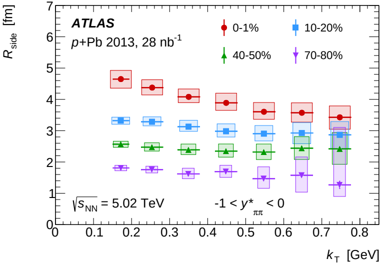


arXiv:1704.01621

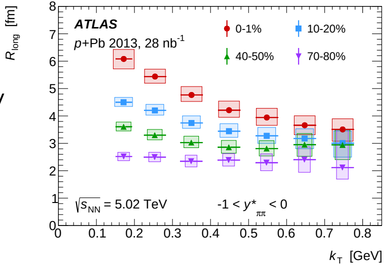
- fit performed in 1D or 3D
- background measured in opposite-sign data (blue)
- used to predict background in same-sign data (violet)
- (same-sign) correlation function fitted (red) while the background is fixed
- HBT radii are extracted from the fit

HBT radii





- decreasing size with k_T indicates collective expansion
  - high-p_T particles are more likely to be created earlier
- pronounced mostly in central collisions
- vanishing in peripheral collisions



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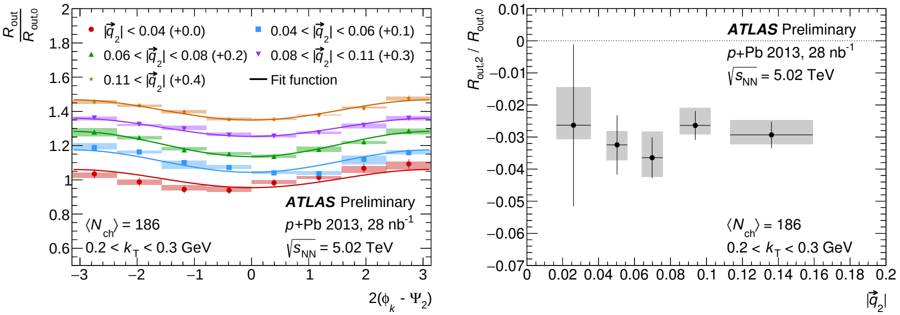

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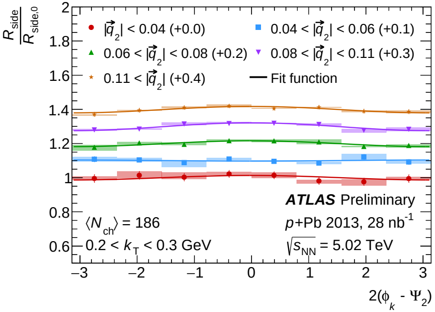
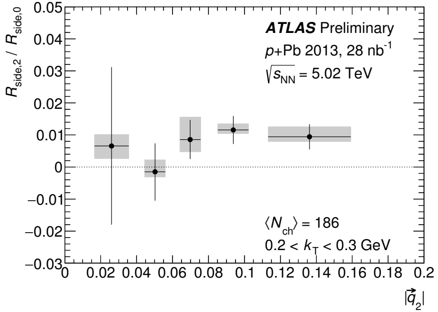
- $0.2 < k_{\mathrm{T}} < 0.3$ GeV, represent late stage of the evolution
- sign of modulation indicates smaller in-plane size
- stronger modulation than other HBT radii
- same orientation as in A+A

azimuthal $R_{side}\,(|\vec{q}_2|)$





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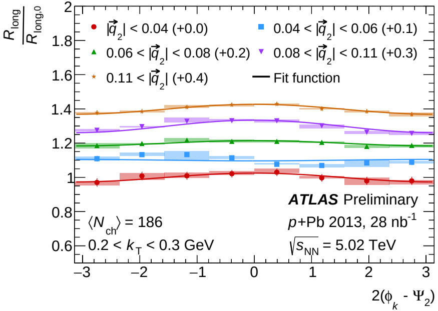
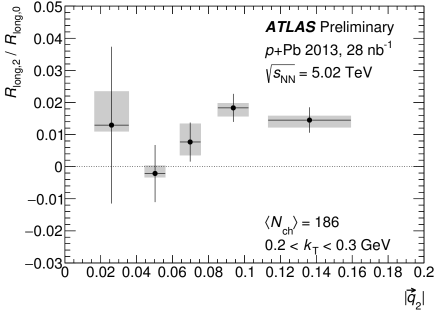
- R_{side} perpendicular to R_{out}
- modulation larger in-plane, thus the source is extended out-of-plane at freeze-out
- compatible with elliptical transverse density with its minor axis aligned with event plane

azimuthal $R_{long}\,(|\vec{q}_2|)$





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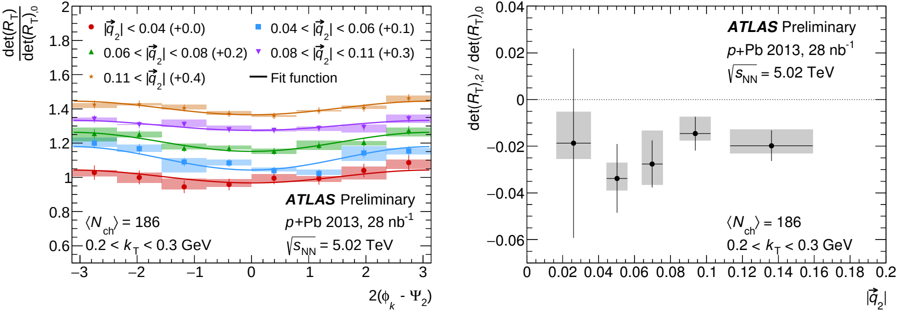
- similar behavior as R_{side}
- source expands longitudinally in-plane

azimuthal $\det(R_{\mathrm{T}})$



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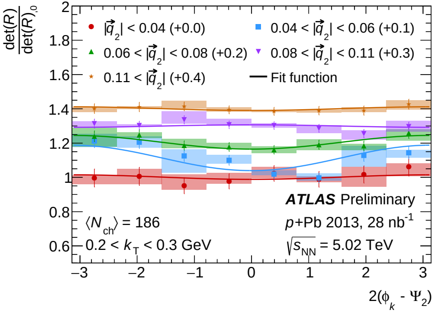
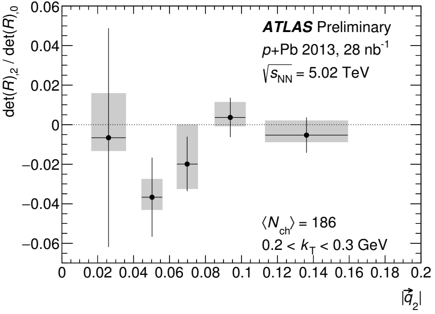
- $\det(R_{\mathrm{T}}) = R_{out} R_{side} - R_{os}^2$
- transverse area is slightly suppressed in-plane

azimuthal det(R)





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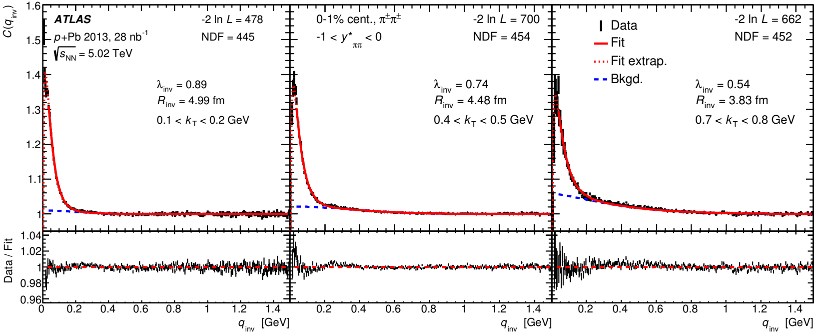
- det(R) – volume scale
- no modulation within uncertainties

conclusion

- HBT radii measured in p+Pb collisions
- they show a decrease with increasing k_{T}; consistent with collective expansion
- azimuthal distributions in the most central collisions are consistent with short-lived hydrodynamic evolution:
  - no significant modulations for small $|\vec{q}_2|$
  - R_{out} and R_{side} modulations suggest in-plane suppression and out-of-plane enhancement
- similar dependence on $(\phi_k - \Psi_2)$ observed in A+A collisions

backup

3D fits


ATLAS
p+Pb 2013, 28 nb-1
√sNN = 5.02 TeV
-2 ln L = 478
NDF = 445
λinv = 0.89
Rinv = 4.99 fm
0.1 < kT < 0.2 GeV
0-1% cent., π±π±
-1 < y*ππ < 0
-2 ln L = 700
NDF = 454
λinv = 0.74
Rinv = 4.48 fm
0.4 < kT < 0.5 GeV
Data
Fit
Fit extrap.
Bkgd.
-2 ln L = 662
NDF = 452
λinv = 0.54
Rinv = 3.83 fm
0.7 < kT < 0.8 GeV
C(qinv)
Data / Fit
qinv [GeV]

systematic uncertainties