Femtoscopy in $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV *p*-Pb collisions with *ATLAS*

ATLAS-CONF-2016-027

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On behalf of the ATLAS collaboration

Hot Quarks 2016
South Padre, Texas, U.S.A.

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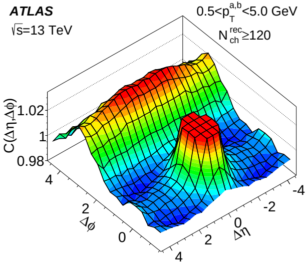
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

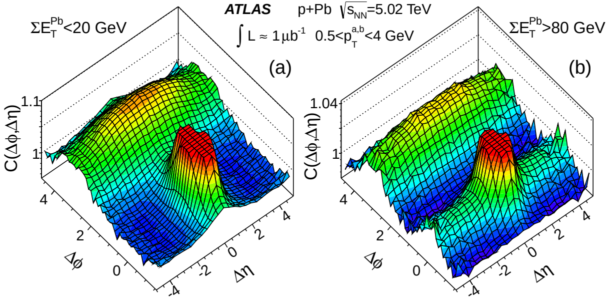
CERN

Motivation



- "ridge" is observed in p+Pb (below) and pp (left) collisions – near-side long-range angular correlation
- predicted by hydrodynamics, but the applicability in small systems is controversial
- want independent handle on spacetime evolution of source

ATLAS-HION-2015-09
ATLAS-HION-2012-13



Introduction

- Momentum-space 2-particle correlation functions,

$$C(\mathbf{p}_1, \mathbf{p}_2) \equiv \frac{\frac{dN_{12}}{d^3p_1 d^3p_2}}{\frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2}} \ ,$$

are sensitive to the 2-particle source density function $S_{\mathbf{k}}(\mathbf{r})$:

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

$\mathbf{r}$ is the displacement between the 2 particles at freezeout, $\mathbf{k} = (\mathbf{p}_1 + \mathbf{p}_2)/2$ is the average pair momentum, and $\mathbf{q} = (\mathbf{p}_1 - \mathbf{p}_2)$ is the relative momentum.

- Background $\frac{dN_1}{dp_1}\frac{dN_2}{dp_2}$ is formed by event-mixing within intervals of centrality and longitudinal position of the collision vertex.

Introduction

- Bose-Einstein correlations between identical pions provide particularly good resolution of the source function.
  - For identical non-interacting bosons, $C_{\mathbf{k}}(\mathbf{q}) = 1 + \mathcal{F}[S_{\mathbf{k}}(\mathbf{r})]$.
- $C_{\mathbf{k}}(\mathbf{q})$ is fit to some function to extract characteristic length scales of $S_{\mathbf{k}}(\mathbf{r})$, which are referred to as the *HBT radii*.
- ATLAS data is described well by 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 Lorentz invariant q_{inv} and of 3 dimensional $\mathbf{q}$, in which case R is a symmetric matrix.

  - In 1D, Cauchy source function: $S_{\mathrm{inv}}(r) \propto \left(1 + R_{\mathrm{inv}}^{-2} r^2\right)^{-1}$

Introduction

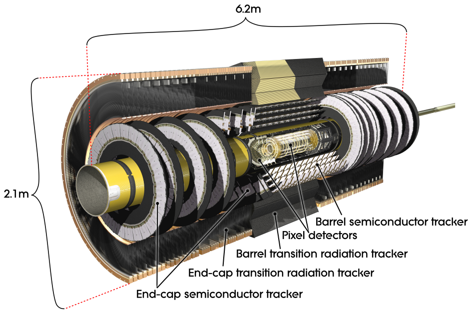
The full experimental correlation function used is the Bowler-Sinyukov form:

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

- $K(q_{\rm inv})$ accounts for Coulomb interactions between the pions
- $\Omega(\mathbf{q})$ represents the non-femtoscopic background features of the correlation function
- λ is a parameter $0 \le \lambda \le 1$ that accounts for mis-identified pions, coherent emission, and long-lived decays ($\lambda = 1$ in an idealized limit)

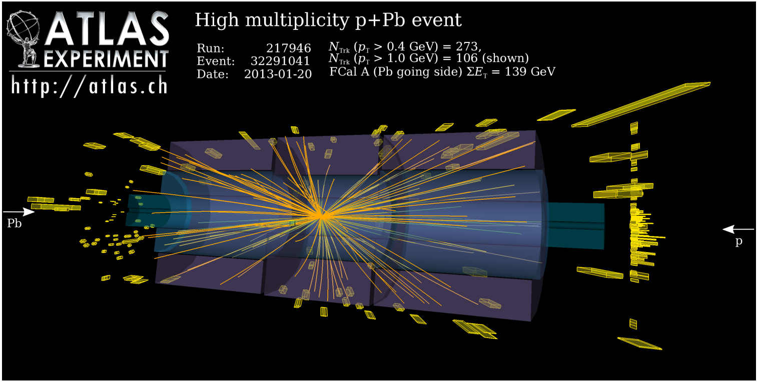
ATLAS inner detector

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



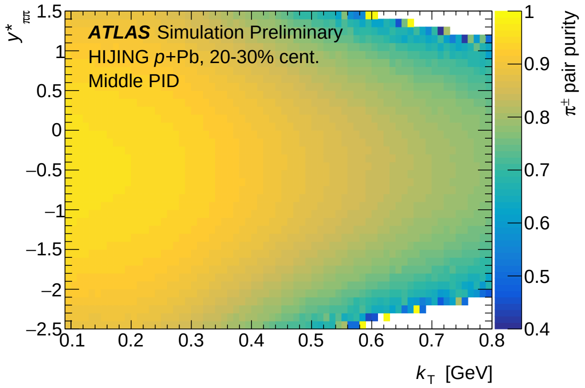
Reconstructed tracks from $|\eta| < 2.5$ and $p_\mathrm{T} > 0.1\ \mathrm{GeV}$

Data selection



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

Pion identification



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

k_{T} is the transverse component of the pair's average momentum.
$y^{\star}_{\pi\pi} = y_{\pi\pi} - 0.465$ is the rapidity in the nucleon-nucleon centre-of-momentum frame.

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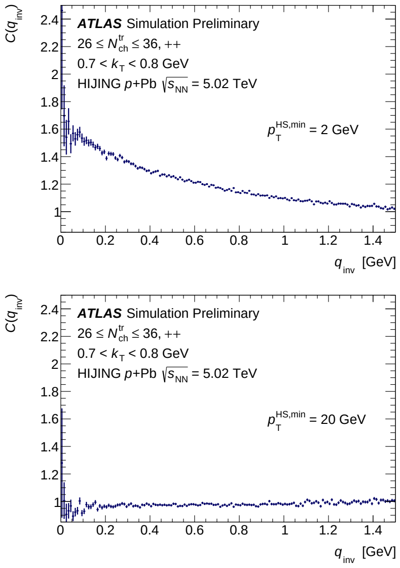
Jet fragmentation correlation

- significant background contribution observed in the two-particle correlation function, even in HIJING which has no femtoscopic signal (top)
- suppressing hard processes in HIJING causes the correlation to disappear (bottom)
- opposite-sign correlations also contain jet fragmentation correlations, but no BE enhancement
- jet fragmentation is measured in opposite-sign and the results are used to predict it in same-sign



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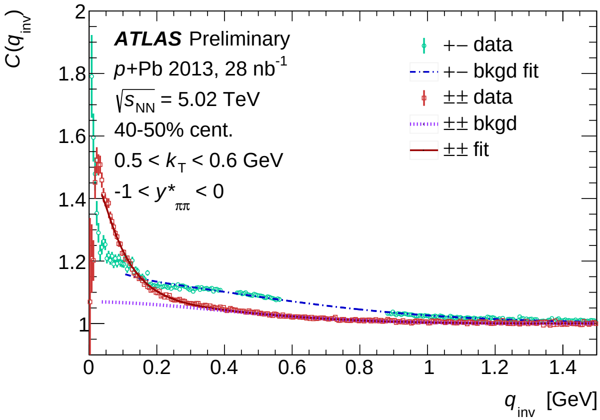
Jet fragmentation correlation

Common methods to account for this background include:

1. Using a double ratio, dividing by correlation function in Monte Carlo simulation: $C(q) = C^{data}(q)/C^{MC}(q)$.
   - MC tends to over-estimate the magnitude of the effect, skewing results significantly
2. Partially describing the background shape using simulation and allowing additional free parameters in the fit.
   - additional free parameters can bias the fits

In this analysis the jet fragmentation is measured in opposite-sign data and a mapping is derived in Pythia 8 to predict the form in same-sign (see backup slides, ATLAS-CONF-2016-027).

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. source radii are extracted by fitting full correlation function $\pm\pm$ (dark red) while including jet background

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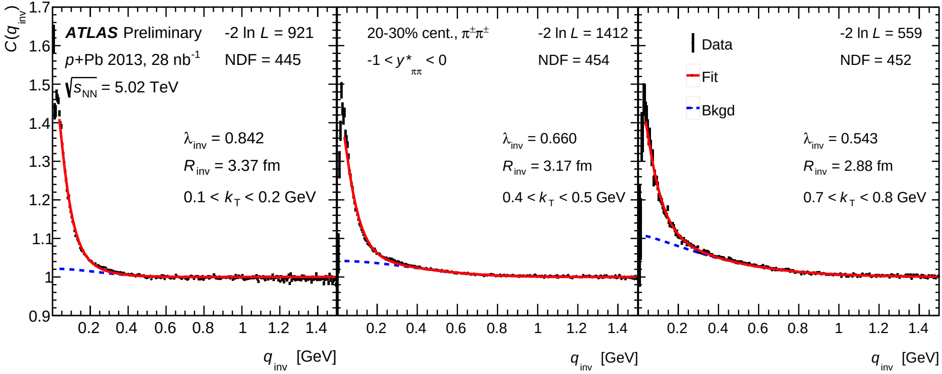
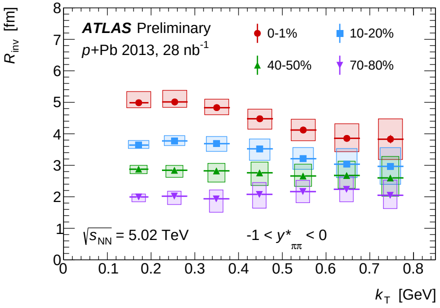
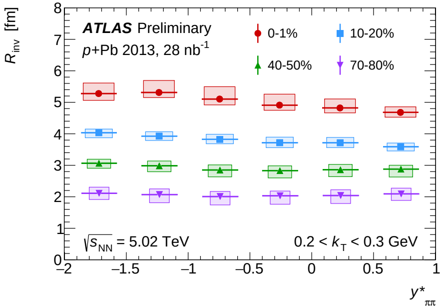
Example fit to invariant correlation function



fit and background estimation typically describe $C(q_{\text{inv}})$ quite well

Results for invariant radius R_{inv}





Decrease with rising k_T in central collisions, consistent with collective behavior. This feature disappears in peripheral collisions.

Radii increase in Pb-going direction of central events. Peripheral are constant with rapidity.

N.B. Widths of boxes in these plots vary only for visual clarity.

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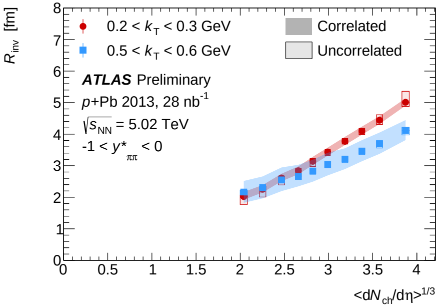
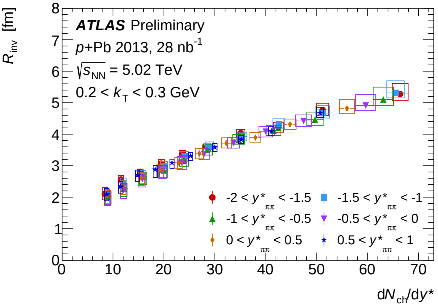
Results for invariant radius $R_{\rm inv}$



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.
- First such observation

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3D fit results

In 3D, the Bertsch-Pratt coordinate system is used. It is boosted to the longitudinal co-moving frame (LCMF) of each pair.

R_{out}: along k_{T}

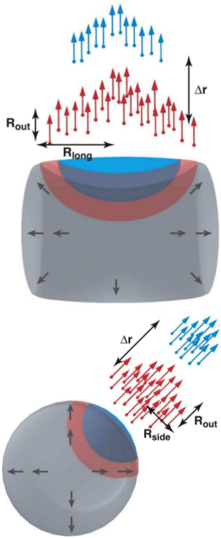
R_{side}: other transverse direction

R_{long}: longitudinal (boosted to LCMF)

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

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

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



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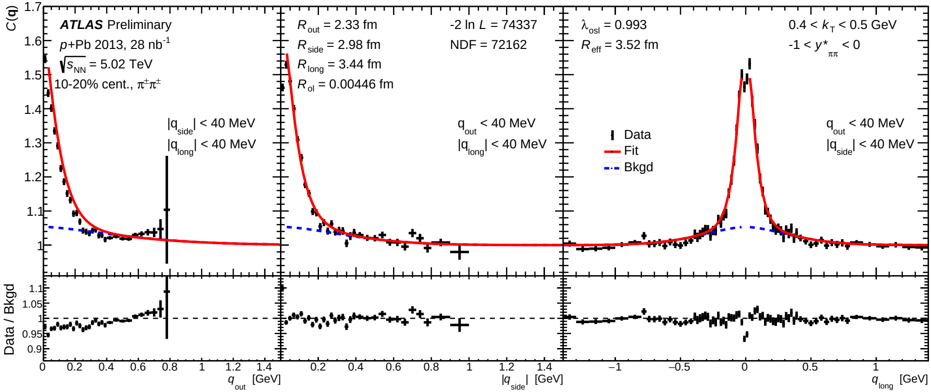
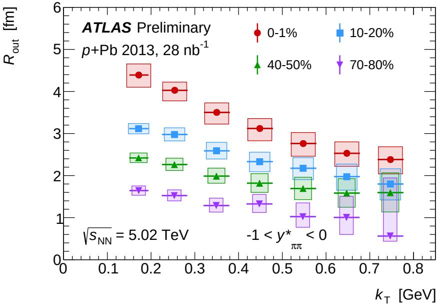
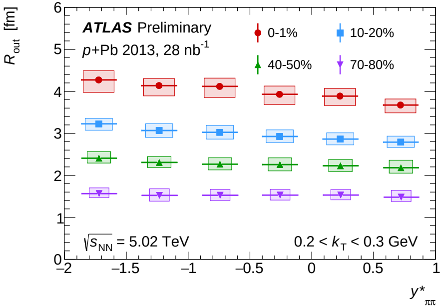
Example fit to 3D correlation function



Fit works well globally ($\chi^2/\mathrm{d.o.f.} = 1.03$) but appears poor along q_{out} axis, where the tracks have the same outgoing angle. Moving just 1 or 2 bins along q_{side} or q_{long} helps significantly.

R_{out} 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

R_{out} is typically the smallest HBT radius

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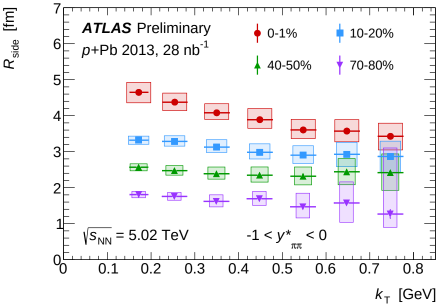
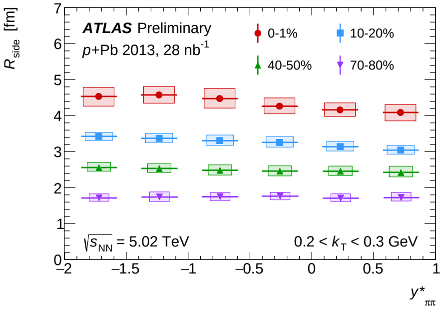
R_{side} vs. k_{T} and $y^{\star}_{\pi\pi}$



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

R_{side} is typically in between R_{out} and R_{long}

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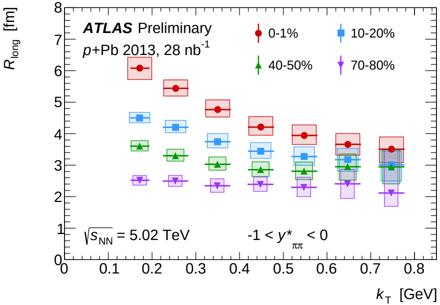
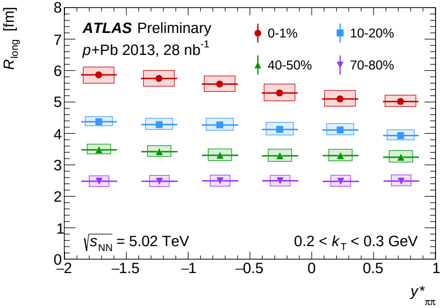
$R_{\rm long}$ vs. $k_{\rm T}$ and $y^\star_{\pi\pi}$



decreasing size with rising $k_{\rm T}$ 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

$R_{\rm long}$ is typically the largest HBT radius

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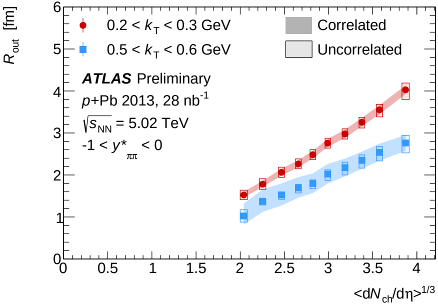
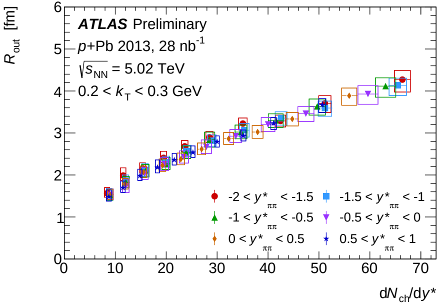
3D radii vs. multiplicity (global and local)





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

three-dimensional radii are also tightly correlated with local multiplicity

$R_{\rm side}$ and $R_{\rm long}$ exhibit same qualitative behavior as $R_{\rm out}$ (backup)

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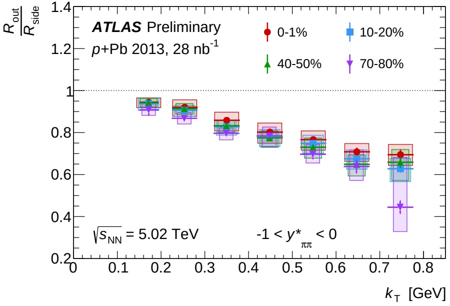
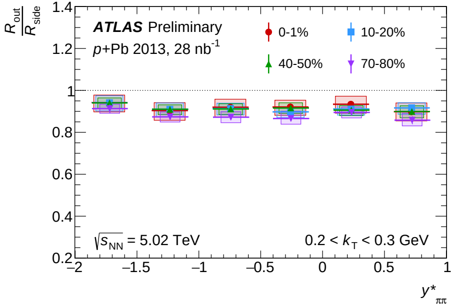
Ratio of $R_{\mathrm{out}} / R_{\mathrm{side}}$

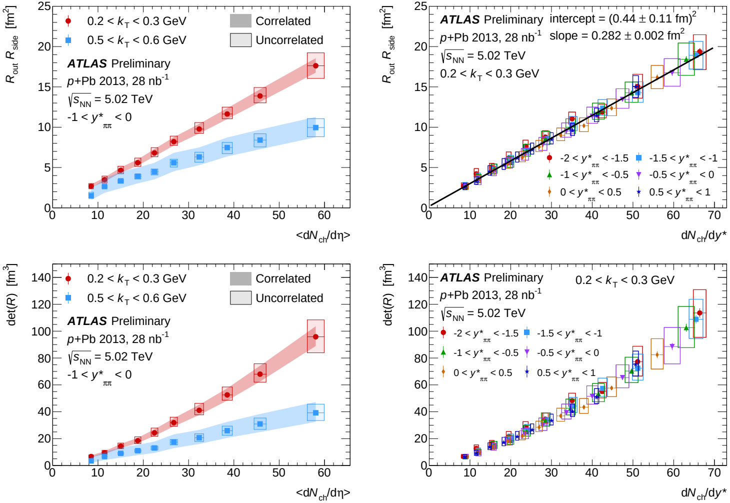




- R_{out} couples to the lifetime directly where R_{side} does not
- small ratio $R_{\mathrm{out}}/R_{\mathrm{side}}$ is indicative of “explosive” event
- steadily decreases with rising k_{T} and is constant over rapidity
- marginally larger in central events

discussion in Ann. Rev. Nucl. Part. Sci. 55 (2005) 357
plots from ATLAS-CONF-2016-027

Transverse area and volume elements



At low k_{T}, the transverse area element $R_{\mathrm{out}} R_{\mathrm{side}}$ scales linearly with multiplicity, indicating constant transverse areal density

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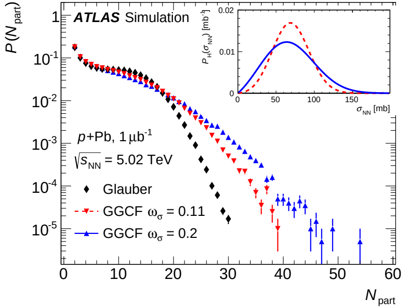
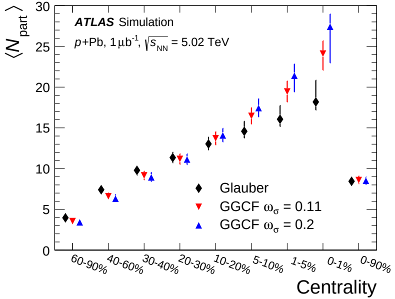
Aside: Glauber-Gribov colour fluctuations (GGCF)

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 width of fluctuations

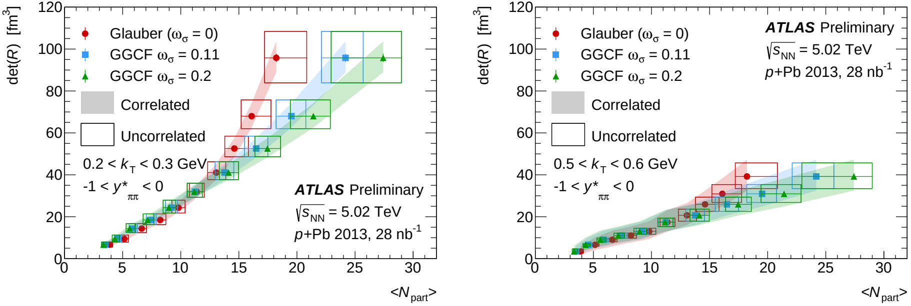




(above: N_{part} distributions and corresponding centrality)

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

Volume–N_{part} scaling including color fluctuations



- volume scaling curvature with N_{part} is more modest when fluctuations in the proton's size are accounted for
- exact linear scaling not necessary, but extreme deviations are difficult to explain
- shows that fluctuations in the nucleon-nucleon cross-section are crucial for understanding initial geometry of p+Pb collisions

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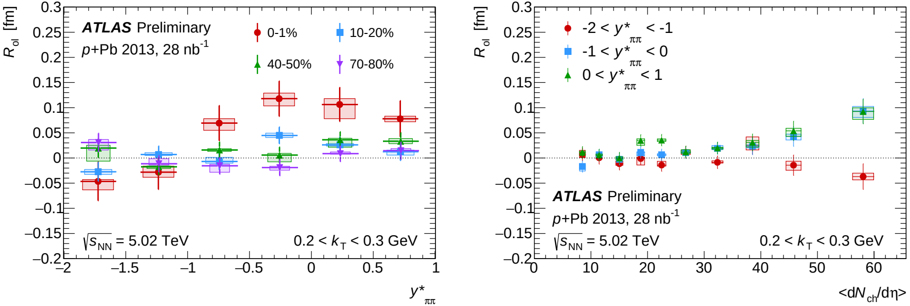
out-long cross term: R_{ol}



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

\- First time this has been observed in p+Pb

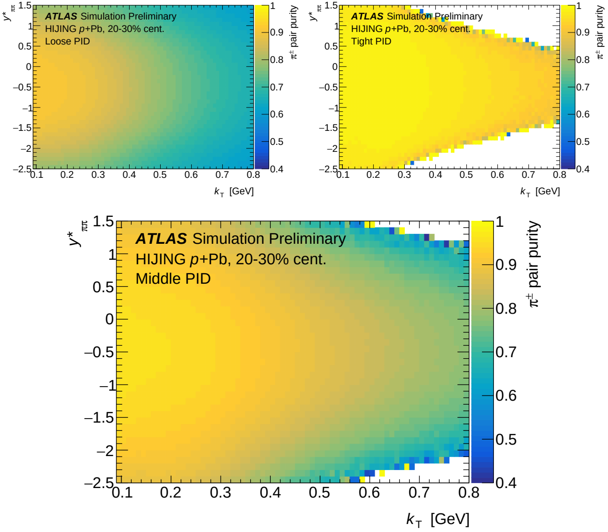
Conclusion

- 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.
- 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.
- Accounting for fluctuations in the nucleon-nucleon cross section is seen to significantly affect the scaling of the source size with initial geometry N_{part}.
- First observation that the source size is tightly correlated with local (rapidity-differential) multiplicity.
- First evidence for non-zero (positive) R_{ol} on the proton-going side of central events is observed.

Thank you!

BACKUP SLIDES

Pion identification



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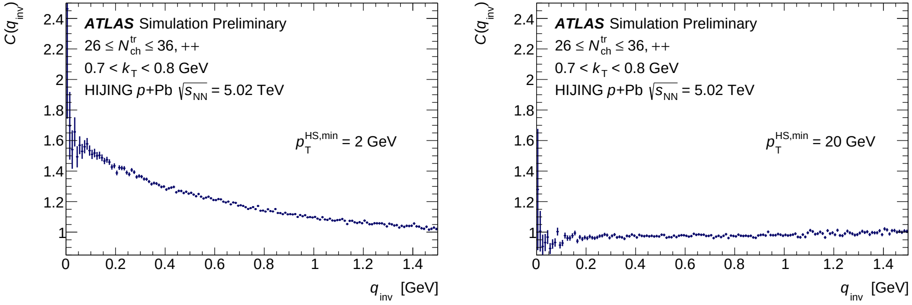
Three PID selection criteria are defined, and a variation from the nominal selection to a looser and tigher definition is used as a systematic variation.

(Jet fragmentation in opposite-sign Hijing)



Wide correlation disappears in opposite-sign too when turning off hard processes

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}:

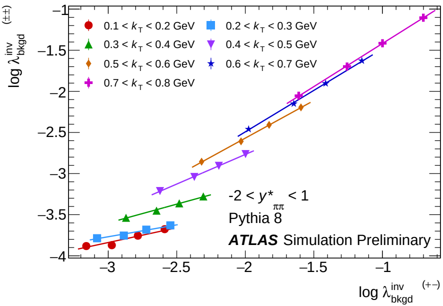
$$\Omega(q_{\mathrm{inv}}) = 1 + \lambda_{\mathrm{bkgd}}^{\mathrm{inv}} e^{-|R_{\mathrm{bkgd}}^{\mathrm{inv}} q_{\mathrm{inv}}|^{\alpha_{\mathrm{bkgd}}^{\mathrm{inv}}}}$$

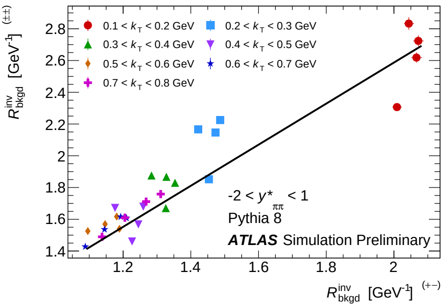
In 3D it is factorized into components parallel and perpendicular to jet axis

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

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

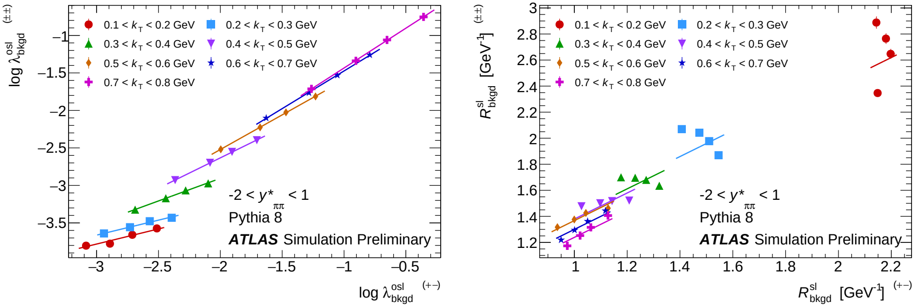
Jet fragmentation mapping (invariant)



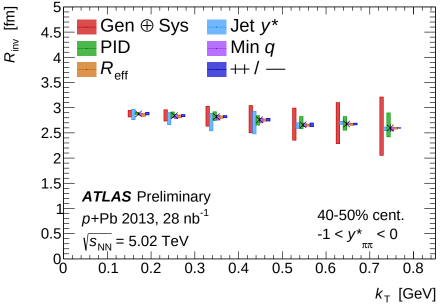


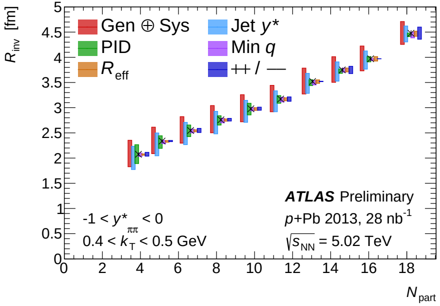
model $R^{\pm\pm}_{\rm inv}$ as proportional to $R^{+-}_{\rm inv}$ (right). Then with constant fixed, do $k_{\rm T}$-dependent comparison of background amplitude in $\pm\pm$ and $+-$ (left). Does not work perfectly but does increasingly well at high $k_{\rm T}$, where the effect is relevant.

Jet fragmentation mapping (3D)



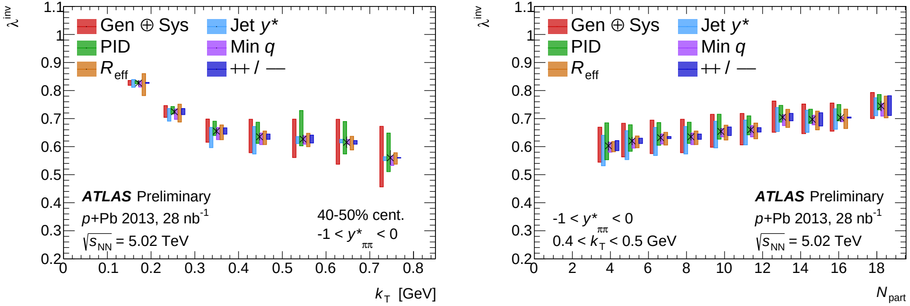
Systematics example (R_{inv})





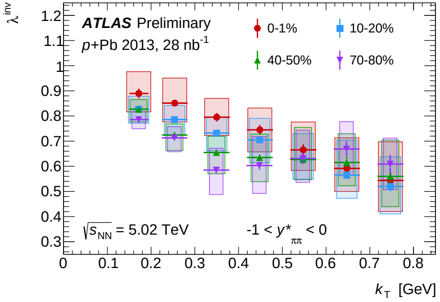
The above plots show the contributions of each systematic uncertainty on R_{inv} as a function of k_{T} and N_{part}.

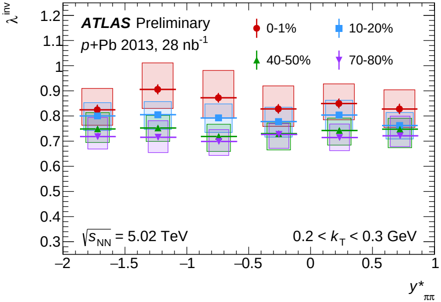
Systematics example (λ_{inv})



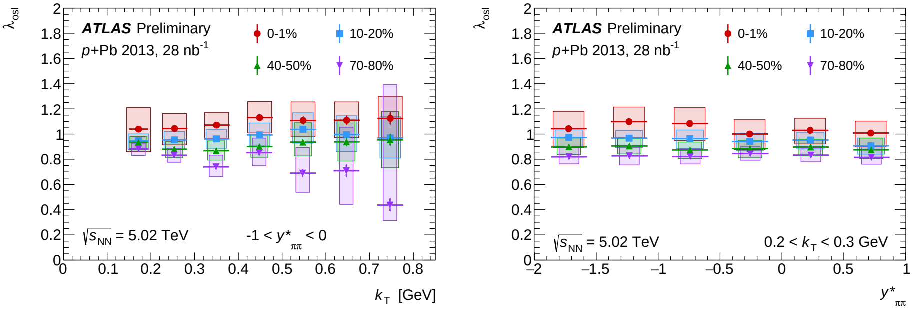
The above plots show the contributions of each systematic uncertainty on λ_{inv} as a function of k_{T} and N_{part}.

Invariant λ

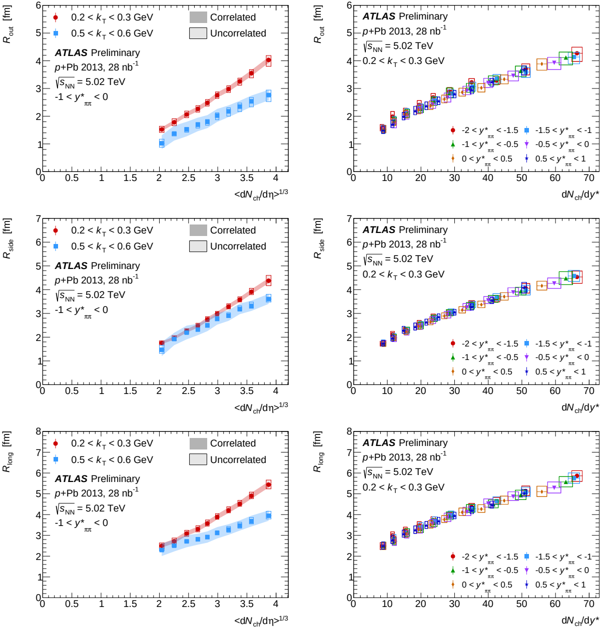




3D λ


ATLAS Preliminary
p+Pb 2013, 28 nb-1
0-1%
10-20%
40-50%
70-80%
√sNN = 5.02 TeV
-1 < y*ππ < 0
λosl
kT [GeV]
0.2 < kT < 0.3 GeV
y*ππ

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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