Analysis of background effects in identical pion femtoscopic correlations in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV}$

Przemysław Karczmarczyk

Warsaw University of Technology
Faculty of Physics

XVII GDRE, 30.06.2015

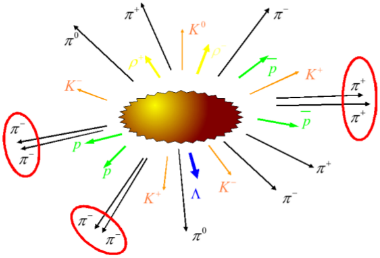
Overview

1. Introduction
2. Motivation
3. Data selection
4. Fitting procedure
5. Results
6. Summary

Overview

Femtoscopy

- Technique developed to study space-time characteristics of the particle emitting sources which are created during particle collisions;
- Measurements of momentum correlations between particle pairs in a collision, i.e. pions;
- From these correlations the source size can be calculated.



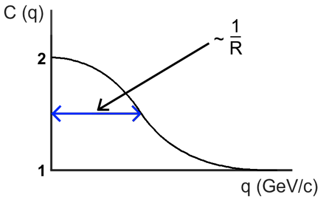
Correlation function

Two particle correlation function

$$C(\vec{q}) = \frac{P(\vec{p_1},\vec{p_2})}{P(\vec{p_1})P(\vec{p_2})} = \frac{S(\vec{q})}{B(\vec{q})}$$

$\vec{q} = \vec{p_1} - \vec{p_2}$ - momentum difference
S - distribution of momentum difference using pairs from the same event (signal)
B - distribution of momentum difference using pairs from different events (background)

- Ideal case for identical bosons:
  - No dependence at large momentum q;
  - Strong dependence at low q;
  - Gives information about size of the emitting source.



Example of 1D correlation function.

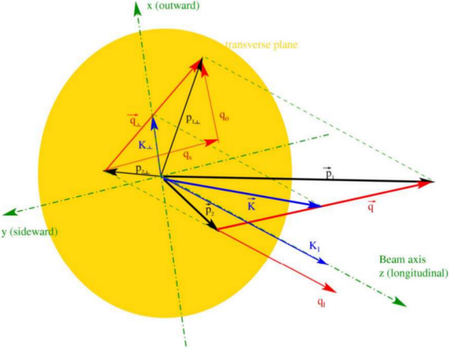
Sources of correlations

- Quantum statistics
    - Bose-Einstein satistics for pions - enhances the probability to find two identical pions in the same quantum state
- Final State Interactions (FSI)
    - Coulomb repulsion
    - Strong force
- Detectors' effects (only in experimental correlation functions)
    - Splitting
    - Merging
    - ...

Frame of reference

- 3-dimensional correlation functions calculated in Longitudinaly Co-Moving System

- LCMS – coordinate system where pair momentum along the beam vanishes
  - z axis: in the beam direction;
  - x axis: parallel to pair transverse momentum $k_{\mathrm{T}} = \frac{1}{2}|\vec{p_{\mathrm{T}_1}} + \vec{p_{\mathrm{T}_2}}|$;
  - y axis: perpendicular to x and z axes;
  - every pair of particles has its own system.



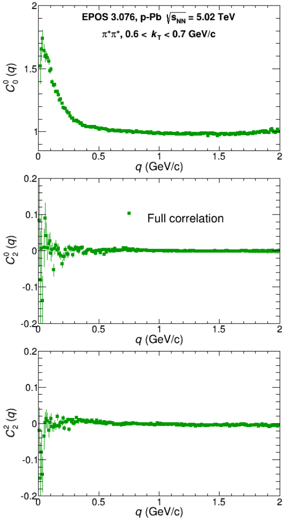
LCMS frame of reference.

Projection of correlation function

- Impossible to visualize 3-dimensional correlation functions (out, side, long axes, and a value of function)
- Solution: Spherical Harmonics decomposition
  - 3D space converted into infinite set of 1-dimensional functions (Y_l^m spherical harmonics functions);
  - For identical pions: pair symmetries make most of them vanish, only three important remains:
    - C_0^0 – the average correlation function;
    - C_2^0 – difference between transverse and long direction;
    - C_2^2 – difference between out and side direction.

Spherical Harmonics example

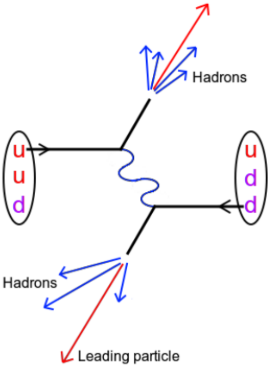
- C_0^0 is not flat at large q!
- Are there other effects?
- Does these effects affect the characteristic femtoscopic structure at low q?



Spherical Harmonics example.

Other effects?

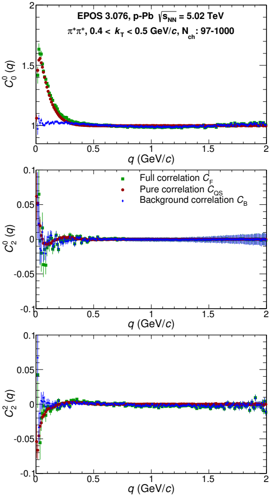
- Energy-momentum conservation effects
- Minijet manifestation
  - Jet – a collimated stream of hadrons produced in a process of parton (quarks and gluons) scattering with a high momentum transfer
  - In the case of multi-parton scattering with low momentum scale, created stream of collimated hadrons is called a minijet



Creation of minijets.

Components of Spherical Harmonics

- Three components:
    1. Pure correlation function C_{QS} – contains “pure” Quantum Statistics and FSI signal;
    2. Background correlation function C_{B} – contains only non-femtoscopic effects;
    3. Full correlation function C_{F} – contains all effects.
- The background correlation sources affect the femtoscopic signal also at low q!



Spherical Harmonics components example.

Overview

1. Introduction
2. **Motivation**
3. Data selection
4. Fitting procedure
5. Results
6. Summary

Motivation

- We can provide the analysis of the source size and shape in collisions in function of multiplicity and pair momentum;
- We know that the non-femtoscopic background is significant in p–Pb collisions, but we have to find a method to describe it properly;
- Our target: propose and validate a method which best describes femtoscopic correlations with taking into account non-femtoscopic effects in the extraction of the femtoscopic information in p–Pb collisions.

Overview

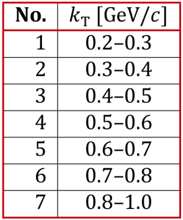
1. Introduction
2. Motivation
3. **Data selection**
4. Fitting procedure
5. Results
6. Summary

EPOS 3.076

- EPOS ver. 3.076 - Monte Carlo (MC) generator
- Why MC generator?
  - In real data – only full correlation function (without division into pure femtoscopic and background effects);
  - MC generator does not include BE correlations → it can be used to estimate the non-femtoscopic background.
- Why EPOS?
  - The only model which has been found to correctly describe the non-femtoscopic background in p–Pb collisions;
  - Provides the freeze-out coordinates (space-time emission points of the particles) → it enables the calculation of BE correlations.

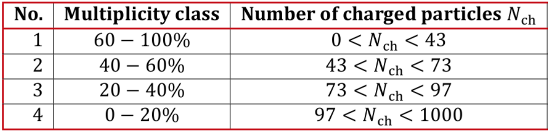
Data selection

- EPOS ver. 3.076, p–Pb@5.02 TeV
- Cut for kinematic range: $p_{\mathrm{T}} > 0.12\ \mathrm{GeV}/c$
- Data ranges:
  - 7 k_{T} ranges;
  - 4 multiplicity ranges counted in number of charged particles N_{ch} (correspond to the mulitplicity classes in collision data, defined as fractions of the analysed event sample sorted by decreasing V0A detector signal);
  - No multiplicity ranges.
- Total analysed events: ∼50 million.



No.	k_{T} [GeV/c]
1	0.2–0.3
2	0.3–0.4
3	0.4–0.5
4	0.5–0.6
5	0.6–0.7
6	0.7–0.8
7	0.8–1.0

k_{T} ranges.



No.	**Multiplicity class**	**Number of charged particles N_{ch}**
1	60 – 100%	$0 < N_{\mathrm{ch}} < 43$
2	40 – 60%	$43 < N_{\mathrm{ch}} < 73$
3	20 – 40%	$73 < N_{\mathrm{ch}} < 97$
4	0 – 20%	$97 < N_{\mathrm{ch}} < 1000$

Multiplicity ranges.

Overview

1. Introduction
2. Motivation
3. Data selection
4. **Fitting procedure**
5. Results
6. Summary

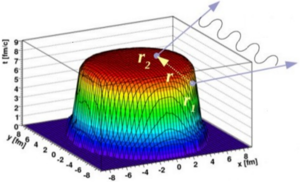
Fitting procedure

Koonin-Pratt formula (space-time characteristics of the source)

$$C(\vec{q}) = \int S(r,\vec{q})|\Psi(r,\vec{q})|^2 d^4 r$$

$S(r,\vec{q})$ – source emission function (probability to emit a particle pair from a given set of emission points with given momenta)
$\Psi(r,\vec{q})$ – pair wave function
r – pair separation four-vector

- Source emission function:
  - Parametrization in heavy-ion collisions at RHIC and LHC:
    $$S(r) \approx \exp\left(-\frac{r_{\mathrm{out}}^2}{4{R_{\mathrm{out}}^G}^2} - \frac{r_{\mathrm{side}}^2}{4{R_{\mathrm{side}}^G}^2} - \frac{r_{\mathrm{long}}^2}{4{R_{\mathrm{long}}^G}^2}\right)$$
  - The best parametrization for pp@7TeV:
    $$S(r) \approx \frac{1}{r_{\mathrm{out}}^2 + {R_{\mathrm{out}}^{\mathrm{E}}}^2} \exp\left(-\frac{r_{\mathrm{side}}^2}{4{R_{\mathrm{side}}^G}^2}\right) \frac{1}{r_{\mathrm{long}}^2 + {R_{\mathrm{long}}^E}^2}$$



Pair separation vector definition.

Fitting procedure

Pure correlation function parametrization

GGG (Gaussian form):

$$C_{\mathrm{qs}}(\mathbf{q}) = (1-\lambda) + \lambda K_{\mathrm{C}} \left[1 + e^{\left(-{R^{G}_{\mathrm{out}}}^{2} q^{2}_{\mathrm{out}} - {R^{G}_{\mathrm{side}}}^{2} q^{2}_{\mathrm{side}} - {R^{G}_{\mathrm{long}}}^{2} q^{2}_{\mathrm{long}}\right)}\right]$$

EGE (Exponential-Gaussian-Exponential form):

$$C_{\mathrm{qs}}(\mathbf{q}) = (1-\lambda) + \lambda K_{\mathrm{C}} \left[1 + e^{\left(-\sqrt{{R^{E}_{\mathrm{out}}}^{2} q^{2}_{\mathrm{out}}} - {R^{G}_{\mathrm{side}}}^{2} q^{2}_{\mathrm{side}} - \sqrt{{R^{E}_{\mathrm{long}}}^{2} q^{2}_{\mathrm{long}}}\right)}\right]$$

K_{C} – Coulomb part of the 2-pion wave function

λ – correlation strength

Strong interaction is small – neglected

Fitting procedure

Background correlation function parametrization

No theoretical prediction about the shape of non-femtoscopic structures.

Three 1D functions were proposed:

$$\Omega_0^0(q) = N_0^0\left[1 + a_0^0 \exp\left(-\frac{q^2}{2(\sigma_0^0)^2}\right)\right]$$

$$\Omega_2^0(q) = a_2^0 \exp\left(-\frac{q^2}{2(\sigma_2^0)^2}\right)$$

$$\Omega_2^2(q) = a_2^2 \exp\left(-\frac{q^2}{2(\sigma_2^2)^2}\right) + \alpha_2^2 \cdot q + \beta_2^2$$

a_0^0 – the magnitude of the correlation
σ_0^0 – the width of the correlation
N_0^0 – the overall normalisation
a_2^0, a_2^2, σ_2^0, σ_2^2 – describe the Gaussian part of Ω_2^0 and Ω_2^2 components
α_2^2, β_2^2 – describe the linear shift of the Ω_2^2 function

Fitting procedure

Full correlation function parametrization

$$C_{\mathrm{f}}(\mathbf{q}) = N C_{\mathrm{qs}}(\mathbf{q}) \Omega(\mathbf{q})$$

N – overall normalisation factor

Method A

$$C^0_{\mathrm{f}0}(q) = N \cdot C^0_{\mathrm{qs}0}(q) \cdot \Omega^0_0(q)$$
$$C^0_{\mathrm{f}2}(q) = N \cdot [C^0_{\mathrm{qs}2}(q) \cdot \Omega^0_0(q) + \Omega^0_2(q)] + \gamma^0_2$$
$$C^2_{\mathrm{f}2}(q) = N \cdot [C^2_{\mathrm{qs}2}(q) \cdot \Omega^0_0(q) + \Omega^2_2(q)] + \gamma^2_2$$

Method B

$$C^0_{\mathrm{f}0}(q) = N \cdot C^0_{\mathrm{qs}0}(q) \cdot \Omega^0_0(q)$$
$$C^0_{\mathrm{f}2}(q) = N \cdot C^0_{\mathrm{qs}2}(q) \cdot \Omega^0_0(q) + \gamma^0_2$$
$$C^2_{\mathrm{f}2}(q) = N \cdot C^2_{\mathrm{qs}2}(q) \cdot \Omega^0_0(q) + \gamma^2_2$$

γ^0_2, γ^2_2 – parameters describing the vertical shift of the function

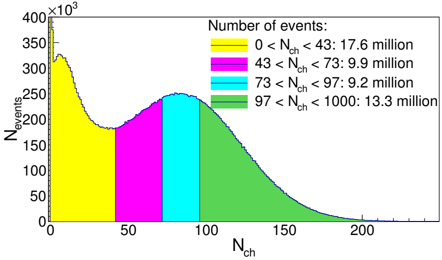
Methods

- In total 8 combinations of methods which differ in:
  - source parametrization: EGE or GGG;
  - shape of the non-femtoscopic correlation function: method A (asymmetric) or method B (spherically symmetric);
  - background parameters changeability: fixed or free during fitting the full correlation function.

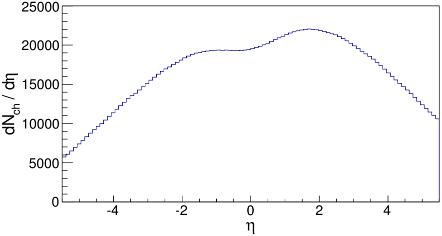
No.	Method	Parametrisation	Background
1	Method A	GGG	Fixed
2			Free
3		EGE	Fixed
4			Free
5	Method B	GGG	Fixed
6			Free
7		EGE	Fixed
8			Free

Overview

Basic distributions



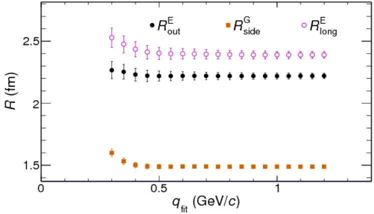
Distribution of the number of charged particles.



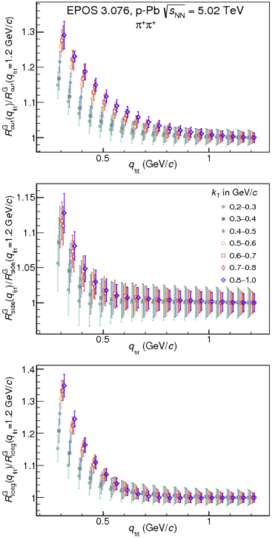
Distribution of the pseudorapidity.

Fitting range

- All fits were performed in $0 < q < 1\ \mathrm{GeV}/c$ range;
- This range is good enough to get the stable fitting results in:
    - all directions (out, side, long);
    - all k_T ranges;
    - both functional forms of the fit – EGE and GGG.

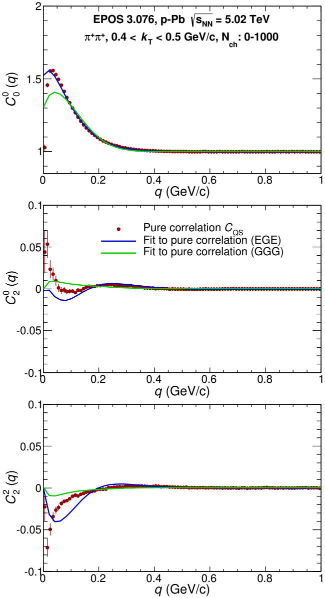


Results for EGE, all directions.



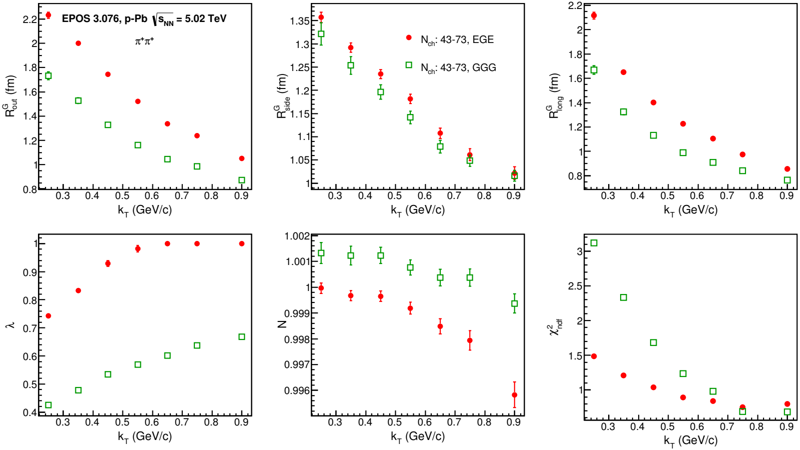
Results for EGE, k_T dependence.

Pure correlation function results and fit



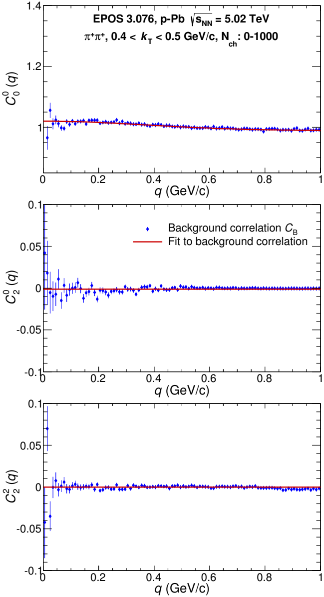
- First three non-vanishing components of the SH representation of the $\pi^+\pi^+$ pure femtoscopic effect
- Example for EGE and GGG parametrization
- In further analysis: used as the reference method

Parameters results example



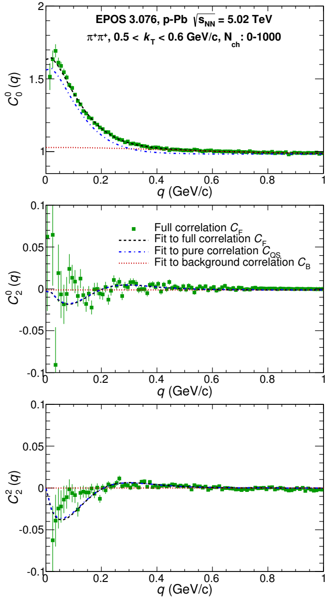
Obtained values for reference method for multiplicity range $43 < N_{\mathrm{ch}} < 73$.

Background correlation function results and fit



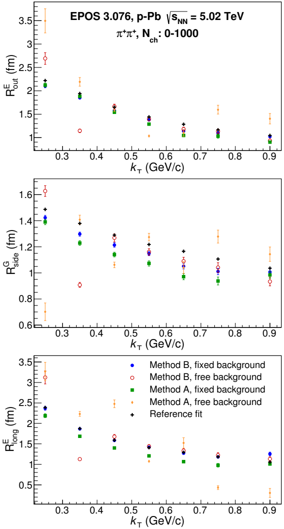
- First three non-vanishing components of the SH representation of the $\pi^+\pi^+$ background correlation function
- In further analysis: used to fit the full correlation function

Full correlation function results and fit

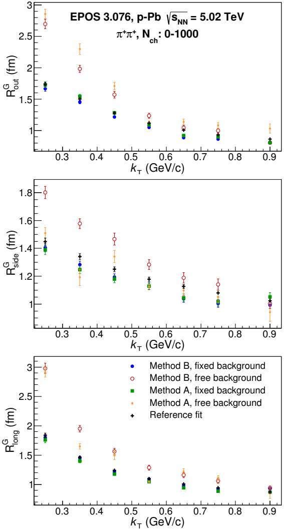


- First three non-vanishing components of the SH representation of the $\pi^+\pi^+$ full correlation function
- Example for method B with EGE parametrization and fixed background

Source sizes



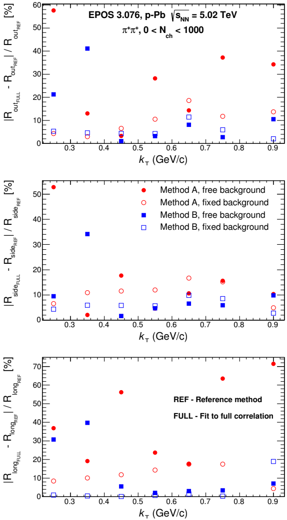
EGE parametrization.



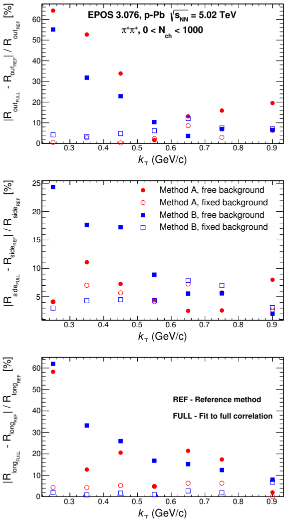
GGG parametrization.

- Obtained radii values for each full correlation function fitting method and reference method
- Results for EGE (left plot) and GGG (right plot) parametrization

Methods validation



EGE parametrization.



GGG parametrization.

- Absolute percentage difference between values of radii obtained from reference fit and other methods
- Results for EGE (left plot) and GGG (right plot) parametrization

Main observations

- Methods with fixed parameters works a lot better, because:
    - they are more stable;
    - their quality does not depend on pair transverse momentum range;
    - their disagreement with the reference method does not exceed 10-20%.
- Methods with free background parameters are unstable for low and high q range
- Methods A and B for GGG parametrization are similar
- Method B with EGE parametrization is slightly better than method A

Overview

Summary

- Femtoscopic analysis of pairs of identical pions was performed using data from EPOS 3.076 Monte Carlo generator
- Several fitting methods which take into account non-femtoscopic effects were proposed, performed, analysed, and compared
- Obtained values of the source emitting size seem right and they correspond to the predicted size pretty well
- Conclusion: proposed methods can correctly extract the values of the radii

References

- P. Karczmarczyk
  Numerical analysis of background effects in identical pion femtoscopic correlations in the ALICE experiment
  Engineer thesis, 2015

- Ł.K. Graczykowski, A. Kisiel, M.A. Janik, P. Karczmarczyk
  Extracting femtoscopic radii in the presence of significant additional correlation sources
  Acta Physica Polonica, vol. B45, pp. 1993-2009, 2014

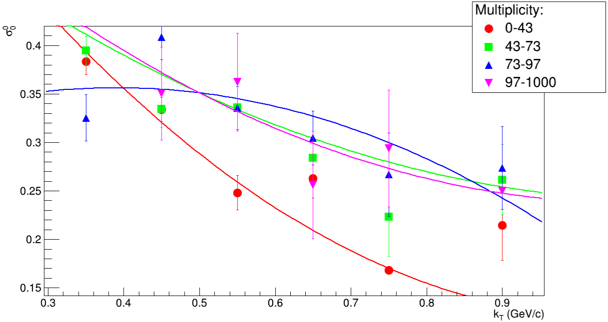
Thank you!

Backup

Background parameters fitting example

Fitting equation

$$y(k_{\mathrm{T}}) = ak_{\mathrm{T}}^2 + bk_{\mathrm{T}} + c$$



Example of the values and its fits of the σ_0^0 parameter for the full multiplicity range.