Non-identical particle femtoscopy in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE detector at the LHC

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Introduction

• Big-Bang theory of the universe predicts that matter existed in QGP form after \( \sim 1\mu s \) of the universe formation

• Lattice QCD predicts QGP at \( \sim 170 \text{ MeV} \) temperature

• Very hot and dense QGP like medium formation in heavy-ion collisions due to inelastic collisions between nuclei and conversion of kinetic energy into heat

• To obtain the equation of state, it is important to know the dimensions of fireball which is impossible to measure directly due to its very small size

• Femtoscopy (or HBT technique) provides a direct tool to measure the source parameters
Two-particle correlation function

\[ C_2 = \frac{P_2(p_a, p_b)}{P_1(p_a)P_1(p_b)} \]

Koonin-Pratt Equation,

\[ C(q) = \int \, d\mathbf{r} \left| \psi(q, \mathbf{r}) \right|^2 S(\mathbf{r}) \]

Experimental correlation function

\[ P_2(p_a,p_b) \] – probability of detection of particles with momenta \( p_a \) and \( p_b \)

\[ P_1(p_i) \] – probability of detection of particle with momentum \( p_i \)

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Relevant coordinate system

*Out-Side-Long* coordinate system is used in femtoscopic analysis.

**Longitudinal co-moving system (LCMS):**

A pair rest frame moving along the beam direction such that $P_z = 0$

$$V_{long} = \frac{(P_0 V_z - P_z V_0)}{M_T}$$

$$V_{side} = \frac{(P_x V_y - P_y V_x)}{P_T}$$

$$V_{out} = \frac{(P_x V_x + P_y V_y)}{P_T}$$

**Pair rest frame (PRF):**

$$V'_{out} = \frac{M_{inv}}{M_T} \frac{(P_x V_x + P_y V_y)}{P_T} - \frac{P_T}{M_T M_{inv}} P \cdot V$$

Where $M_T^2 = P_0^2 - P_z^2$, $P_T^2 = P_x^2 + P_y^2$ and $M_{inv}^2 = P^2$

Pion-kaon femtoscopy analysis has been performed in PRF.
Why non-identical particles?

- In a hydrodynamical induced system:
  \[ \beta_{\text{particle}} = \beta_f + \beta_t \]
  
  component of mean emission point of a single particle parallel to the velocity

  \[ \langle x_{\text{out}} \rangle = \frac{\langle r \beta_f \rangle}{\sqrt{\beta_t^2 + \beta_f^2}} = \frac{r_0 \beta_0 \beta}{\beta_0^2 + T/m_t} \]

  assume a Gaussian density profile with radius \( r_0 \) and linear transverse velocity profile \( \beta_f = \beta_0 r/r_0 \) then we

  \[ \mu_{\text{light, heavy}} = \langle r_{\text{light, heavy}} \rangle = \langle x_{\text{light, heavy}} \rangle \]

- Lighter particles emitted closer to the centre/later than heavier particles

- Emission asymmetry only arises in a system where both random (thermal) and correlated (flow) velocities exist and are comparable in magnitude
Why non-identical particles (cont.)?

- Kaons are heavier than Pions and have more inertia than Pions
- Pions suffer more thermal collisions with other particles inside the system than kaons and hence, spend more time in system and emitted from larger volume
- Kaons leave system earlier than pions and emission asymmetry arises
- Non-identical particle femtoscopy - source size plus emission asymmetry

Experimental correlation function

\[ C(k^*) = \frac{\int N(p_a, p_b) \delta(k^* - \frac{1}{2}(p_a^* - p_b^*)) d^3p_a d^3p_b}{\int D(p_a, p_b) \delta(k^* - \frac{1}{2}(p_a^* - p_b^*)) d^3p_a d^3p_b} = \frac{N(k^*)}{D(k^*)} \]

- \( N(k^*) \) - distribution of \( k^* \) of pairs from same events (signal)
- \( D(k^*) \) - distribution of \( k^* \) of pairs from different events (background)

where \( k^* \) : half of the relative momentum of pair or momentum of the first particle (pions) in PRF

Lighter mass particles are selected as first particle conventionally
Double Ratio : C+/C- 

Measured Correlation functions can be divided into two groups:

- **C+**: $k^*$ and $\nu$ aligned ($\vec{k}^* \cdot \vec{\nu} > 0$) i.e. pions are faster
- **C-**: $k^*$ and $\nu$ anti-aligned ($\vec{k}^* \cdot \vec{\nu} < 0$) i.e. kaons are faster.

where $\nu$ is pair velocity.

In principle, we can have two scenarios of particle emission in real data:

1. pions are emitted closer to center of source (or later) than kaons
2. kaons are emitted closer to center of source (or later) than pions
Probing space-time asymmetry

**Pions** are emitted closer to center of source (or later) than **kaons**

\[ \vec{k}^* \cdot \vec{v} \text{ or } \cos (\psi) > 0 \]

**Catching up**
- Large interaction time
- Large correlation

\[ \vec{k}^* \cdot \vec{v} \text{ or } \cos (\psi) < 0 \]

**Moving away**
- Small interaction time
- Small correlation

**Double ratio**
- Sensitive to the space-time asymmetry

- \( \frac{C_+}{C_-} \) (unlike-sign pairs) : above unity
- \( \frac{C_+}{C_-} \) (like-sign pairs) : below unity
ALICE detector

Dedicated to study hot and dense strongly interacting matter: QGP

- Excellent tracking by ALICE detector enables us to analyse correlations of particles with low momentum
- TPC was used for track reconstruction
- TPC and TOF are used for particle identification

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Correlation Functions

![Graph showing correlation functions]

- Correlation functions show similar trend in all direction and for both magnetic field polarity

\[\text{ALICE, Pb-Pb } \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \]

10-20% central

- Attractive correlation for unlike-sign pairs
- Repulsive correlation for like-sign pairs

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**Observation:**

- Correlation functions exhibit a consistent trend across different directions and magnetic field polarities.
Double ratio \((C_+/C_-)\) in “out” direction deviates significantly from unity

On average, pions are emitted closer to the centre/later than kaons

Double ratio \((C_+/C_-)\) in “side” and “long” directions is consistent with unity (expected from azimuthal and mid-rapidity symmetries)
Non-femtososcopic background

Correlation function contains femtososcopic correlation as well as contributions from:

**Elliptic flow ($v_2$):**

- All particles (including pions and kaons) from an event are more likely emitted in a specific direction due to presence of $v_2$ and their momenta tend to point in the same direction, hence their relative momenta will be low.

- For particles from different events, collimation effect doesn’t exist since they have different event plane and hence, pair will make more combinations with larger relative momenta.

- Which means, probability of finding a pair of low relative momenta is more for same event pairs and vice-versa.

- The background shape is above unity for low relative momentum and below unity for high relative momentum.

Same negative slope for all pairs: global event-wide correlation are producing it.

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Non-femtoscopic background

Correlation function contains femtoscopic correlation as well as contributions from:

**Resonance decay correlations:**
- Resonance particles travel some distance with common flow velocity before they decay
- Decay products have two velocity component: common velocity equal to resonance particle velocity and random component of decay momenta
- If decay momentum will large w.r.t. daughter’s mass, emission of them will be randomised
- It may produce similar correlation/asymmetry like collective flow which will depend on relative production of resonance and their daughters

**Residual correlations** (remnants of the femtoscopic correlations from weakly decaying particles): parent particles should be treated as femtoscopically correlated

Same negative slope for all pairs : global event-wide correlation are producing it

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Non-femtoscopic background correction

\[ C^{ij}_{\text{exp}} = B^{ij} + |\psi^{ij}|^2 \]
where \( i,j \) are +,- (pion-kaon)

Experimental correlation function
real femtoscopic correlation
Non-femtoscopic background

For Coulomb interaction at a given \( k^* \):
\[ C_{SS} = 1/C_{OS} \]

With a background “\( B \)”: \[
(C_{\text{exp},SS} - B) = \frac{1}{(C_{\text{exp},OS} - B)}
\]

Background function “\( B \)”: \[
B^{ij} = a^{ij}_0 + \sum_{l=1}^5 a_l x^{(l+1)}
\]

\[ \chi^2_{\text{background}} = \frac{1}{\sigma^2_{\text{tot}}} \left[ (C^{++} - B) - \frac{1}{(C^{+} - B)} \right]^2 + \frac{1}{\sigma^2_{\text{tot}}} \left[ (C^{--} - B) - \frac{1}{(C^{+} - B)} \right]^2 \]
\[ + \frac{1}{\sigma^2_{\text{tot}}} \left[ (C^{++} - B) - \frac{1}{(C^{+} - B)} \right]^2 + \frac{1}{\sigma^2_{\text{tot}}} \left[ (C^{--} - B) - \frac{1}{(C^{+} - B)} \right]^2 \]

\[ C^{ij}_{\text{real}} = C^{ij}_{\text{exp}} - B^{ij} \]

Sum of errors for all pairs at given \( k^* \)


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Non-femtoscopic background contribution in the data

- Non-femtoscopic background function shape changes from central to peripheral collisions
Extracting the source size and emission asymmetry

\[ C(k^*) = \int dr' |\psi(k^*, r')|^2 S(r') \]

*known from experiment* \*unknown*

**Pair wave function:** (treated as weight)

\[ \psi_{pair} = \psi_{motion} + \psi_{FSI} \]

**Motion of pair as whole (plane wave: exponential function, only additional phase)**

\[ \Psi(k^*, r') = \sqrt{A_C(\eta)} \left[ e^{-i \vec{k}^* . \vec{r}^*} F(-i\eta, 1, i\zeta) + f_C(\vec{k}^*) \frac{\tilde{G}(\rho, \eta)}{r^*} \right] \]

*Gamow factor*

**Confluent hypergeometric function**

**Strong scattering amplitude, modified by the Coulomb interaction**


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Extracting the source size and emission asymmetry

\[ \eta = \frac{1}{k^*a_C} \]  
Bohr radius of the pair (248.52 fm for pion-kaon)

\[ \zeta = k^*r^*(1 + \cos \theta^*) \]
Angle between \( k^* \) and pair relative position \( r^* \) in PRF

\[ f_C(\vec{k}^*) = \left[ \frac{1}{f_0} + \frac{1}{2}d_0 k^*^2 - \frac{2}{a_C}h(\vec{k}^*a_C) - i \vec{k}^*A_C(\vec{k}^*) \right]^{-1} \]

where \( f_0 = 0.137 \) fm for like-sign pair of pion-kaon, -0.071 fm for unlike-sign pair of pion-kaon, \( d_0 \) is the effective radius (taken to 0 for small \( k^* \) where \( 1/f_0 \) term dominates).

\[ F(\alpha,1,z) = 1 + \alpha z + \alpha(\alpha + 1)z^2/2!^2 + \ldots \]
Extracting the source size and emission asymmetry

Source emission function:

\[ S(r) = \exp \left( -\frac{(r_{\text{out}} - \mu_{\text{out}})^2}{R_{\text{out}}^2} - \frac{r_{\text{side}}^2}{R_{\text{side}}^2} - \frac{r_{\text{long}}^2}{R_{\text{long}}^2} \right) \]

Fitting: using CorrFit package, generate correlation function using Monte-Carlo method
(Adam Kisiel, NUKLEONIKA 2004;49(Supplement 2):S81–S83)

CorrFit Input: Fraction of primary, correctly identified pairs

\[ F_{\pi^\pm K^\pm}(c) = p_{\pi}(c) \cdot p_{K}(c) \cdot f_{\pi^\pm}(c) \cdot f_{K^\pm}(c) \cdot g_s(c) \]

- F is a fraction of primary, correctly identified pairs of particles that fits under the assumed Gaussian profile,
- p is the purity of particles,
- f is the fraction of primary particles,
- g is the fraction of femtoscopically correlated pairs under assumed Gaussian profile,
- c is centrality class, and
- s is the magnetic field polarity.
- The value of g is estimated using the results obtained in Adam Kisiel, Phy.Rev.C 81, 064906 (2010)
Ideally, generated correlation function should be able to reproduce momentum distributions and freeze-out conditions of particles, which is very hard.
Fitting: CorrFit Input (cont.)

- **CorrelationFitter** = CFFitterNonId
- **SourceModel** = SourceModelGausLCMS
- **Fitting range of** $R_{out}$ : (3.0, 12.0) fm
- **Fitting range of** $\mu_{out}$ : (-8.0, 0.0) fm
- **$R_{side}$ multiplier** : 1.0
- **$R_{long}$ multiplier** : 1.3
- **Interactions**: Strong, Coulomb
- **Fitting range (in k*)** : (0.0, 0.1) GeV/c
- **Normalisation Range (in k*)** : (0.15, 0.20) GeV/c
Fitted correlation function:

\( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

Data and fit for the correlation functions of \( \pi^+ K^+ \) and \( \pi^- K^- \) in the ALICE Preliminary Pb-Pb experiment. The data points are represented by red dots, and the fit is shown as a blue line.

- **\( \pi^+ K^+ \)**
- **\( \pi^- K^- \)**

Conditions:
- 10-20% centrality
- \( 0.19 < p_T < 1.5 \text{ GeV/c} \)
- \( |\eta| < 0.8 \)
### Results: source size and emission asymmetry

Finite emission asymmetry between pion and kaon is observed which increases with centrality.

- Source size increases from peripheral to central collisions
- Default Therminator overestimate asymmetry


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ALICE Preliminary

0.19 < p_T < 1.5 GeV/c, |h| < 0.8

Therminator-2

- Default
- $\Delta t = 2.1$ fm/c, $\sigma_t = 0.3$ fm/c
- $\Delta t = 2.1$ fm/c, $\sigma_t = 2.0$ fm/c

- $\Delta t = 1.0$ fm/c, $\sigma_t = 2.0$ fm/c
- $\Delta t = 3.2$ fm/c, $\sigma_t = 2.0$ fm/c

ALICE Preliminary | < 0.8
dN_{ch}/d\eta (dN_{ch}/d\eta)^{1/3}

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**ALI-PREL-147258**
Summary

- First measurement of emission asymmetry at the LHC in Pb-Pb collisions at 2.76 TeV

- Finite emission asymmetry observed between pions and kaons which shows pions are emitted later than kaons

- It is expected in a system with strong collectivity which includes flow of resonances (consistent with model predictions, e.g. Therminator2 coupled with viscous hydrodynamics)

- Source size and emission asymmetry increase from peripheral to central collisions

- Results may suggest a 2.1 fm/c delay in emission time which means different particle species freeze-out at different times

- Results have been shown in QM2018 talk and ICHEP 2018, paper is under IRC review
Thank you
Backup
**Analysis Details**

Data set: **Pb-Pb@2.76 TeV**: LHC11h_pass2 (AOD145)

Magnetic field polarity: +ve and -ve

Event Selection: $|V_z| < 10.0$ cm

Centrality Percentile Bins: (0, 5, 10, 20, 30, 40, 50, 90)

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**ALICE, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV**

Field: (+,+)

No of events:
- 0-5%, 4.4 mn
- 5-10%, 4.3 mn
- 10-20%, 2.6 mn
- 20-30%, 2.0 mn
- 30-40%, 2.0 mn
- 40-50%, 2.0 mn
- 50-90%, 1.1 mn
- 0-90%, 18.4 mn

**ALICE, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV**

Field: (-,-)

No of events:
- 0-5%, 5.8 mn
- 5-10%, 5.5 mn
- 10-20%, 3.0 mn
- 20-30%, 2.5 mn
- 30-40%, 2.5 mn
- 40-50%, 2.5 mn
- 50-90%, 1.3 mn
- 0-90%, 23.2 mn

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**Analysis Details (Cont.)**

**Track Selection:** Filter Bit 7 (TPC only track)

\[ p_T \text{ range: } 0.19-1.5 \text{ GeV/c, } |\eta| <0.8 \]

---

**Pion**

ALICE, Pb-Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

0-5%, \( \pi^* \), Field: (-,-)

---

**Kaon**

ALICE, Pb-Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

0-5%, \( K^* \), Field: (-,-)

---

**Pion**

ALICE, Pb-Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

0-5%, \( \pi^* \), Field: (-,-)

---

**Kaon**

ALICE, Pb-Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

0-5%, \( K^* \), Field: (-,-)
Analysis Details (Cont.)

PID cuts for Pions:

- $|n\sigma_{TPC}| < 3.0 \rightarrow |p| < 500 \text{ MeV}/c,$
- $\sqrt{(n\sigma_{TPC}^2 + n\sigma_{TOF}^2)} < 3.0 \rightarrow |p| > 500 \text{ MeV}/c$

PID cuts for Kaons:

- $|n\sigma_{TPC}| < 2.0 \rightarrow |p| < 400 \text{ MeV}/c,$
- $|n\sigma_{TPC}| < 1.0 \rightarrow 400 \text{ MeV} < |p| < 450 \text{ MeV}/c,$
- $|n\sigma_{TPC}| < 3.0 \text{ and } |n\sigma_{TOF}| < 2.0 \rightarrow 450 \text{ MeV} < |p| < 800 \text{ MeV}/c,$
- $|n\sigma_{TPC}| < 3.0 \text{ and } |n\sigma_{TOF}| < 1.5 \rightarrow 800 \text{ MeV} < |p| < 1000 \text{ MeV}/c,$
- $|n\sigma_{TPC}| < 3.0 \text{ and } |n\sigma_{TOF}| < 1.0 \rightarrow |p| > 1000 \text{ MeV}/c$
Analysis Details (Cont.)

Number of Events to Mix: 5

Pairs considered: Pion-Kaon (all ± charge combinations)

Pair cuts: to optimise merging effect/detector resolution effect
  
  Cut for Fraction of shared cluster: remove pairs of particles which share more than 5% of their overall numbers of registered hits in TPC

Anti-gamma cut: to remove $e^+e^-$ conversion pairs coming from photons
  
  ▶ Minimum allowed $e^+e^-$ $M_{\text{inv}} = 0.002$ GeV;

  \[ M_{\text{inv}} = 2m_e^2 + 2(E_1E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2) \]
  
  ▶ Minimum polar angle difference: 0.008 rad.

Merged fraction cut (MF cut):
  
  ▶ Radius range: $R = (0.8, 2.5)$ m, $|\Delta \eta| < 0.01$,
  
  ▶ Maximum allowed distance between tracks: $d = 3.0$ cm,
  
  ▶ Fraction of merged clusters (MF = $N_{\text{pass}}/N_{\text{total}}$): 0.01 (Unlike sign pairs)
    0.07 (Like sign pairs)

  where, $N_{\text{pass}}$ is number of points for distance between track < d in R range,
  $N_{\text{total}}$ is total number of points in R range (step size = 1.0 cm)

Remove tracks if their MF is more than selected value
MF cut selection

MF cut selection method: $0.0 \leq k^* \leq 0.2 \text{ GeV/c}$

$$\chi^2_{n,\text{ndf}(\text{Side})} = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{(C^+/C^-)_{\text{Side}}(k^*_i) - 1}{\sigma_i(\text{Side})} \right)^2$$

Like sign pairs:

<table>
<thead>
<tr>
<th>Pair</th>
<th>Magnetic Field</th>
<th>$\chi^2$/ndf for no paircut</th>
<th>$\chi^2$/ndf for 1% MF cut</th>
<th>$\chi^2$/ndf for 3% MF cut</th>
<th>$\chi^2$/ndf for 7% MF cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+K^+$</td>
<td>+ve</td>
<td>5.4976</td>
<td>2.4188</td>
<td>2.4310</td>
<td>2.2936</td>
</tr>
<tr>
<td>$\pi^-K^-$</td>
<td>+ve</td>
<td>6.2763</td>
<td>2.3971</td>
<td>2.4165</td>
<td>2.4859</td>
</tr>
<tr>
<td>$\pi^+K^+$</td>
<td>-ve</td>
<td>6.9418</td>
<td>1.9611</td>
<td>1.8666</td>
<td>1.8129</td>
</tr>
<tr>
<td>$\pi^-K^-$</td>
<td>-ve</td>
<td>7.4470</td>
<td>2.2219</td>
<td>2.2031</td>
<td>2.1611</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>6.5407</td>
<td>2.2497</td>
<td>2.2293</td>
<td>2.1883</td>
</tr>
</tbody>
</table>

Un-like sign pairs:

<table>
<thead>
<tr>
<th>Pair</th>
<th>Magnetic Field</th>
<th>$\chi^2$/ndf for no paircut</th>
<th>$\chi^2$/ndf for 1% MF cut</th>
<th>$\chi^2$/ndf for 3% MF cut</th>
<th>$\chi^2$/ndf for 7% MF cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^-K^+$</td>
<td>+ve</td>
<td>1.3168</td>
<td>1.0588</td>
<td>1.2069</td>
<td>1.2820</td>
</tr>
<tr>
<td>$\pi^+K^-$</td>
<td>+ve</td>
<td>2.8674</td>
<td>2.1149</td>
<td>2.1333</td>
<td>2.3948</td>
</tr>
<tr>
<td>$\pi^-K^+$</td>
<td>-ve</td>
<td>1.7220</td>
<td>1.2660</td>
<td>1.2785</td>
<td>1.1984</td>
</tr>
<tr>
<td>$\pi^+K^-$</td>
<td>-ve</td>
<td>2.2667</td>
<td>1.7491</td>
<td>1.6335</td>
<td>1.7308</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>2.0432</td>
<td>1.5472</td>
<td>1.5630</td>
<td>1.6515</td>
</tr>
</tbody>
</table>
Particle purity

![Graph showing particle purity vs. centrality]

- Field: $\pi^+, \pi^-$
- Field: $K^+, K^-$

Centrality (%)

- 0-5%
- 5-10%
- 10-20%
- 20-30%
- 30-40%
- 40-50%
- 50-90%

Purity
## Systematic studies:

<table>
<thead>
<tr>
<th>Error source</th>
<th>variation</th>
<th>Error (in %) $R_{Out}$, $\mu_{Out}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track</td>
<td>Hybrid track (FilterBit8)</td>
<td>13, 17</td>
</tr>
<tr>
<td>Pair cuts</td>
<td>± 2 % MF cut</td>
<td>0.18, 0.5</td>
</tr>
<tr>
<td><strong>Strict PID cut</strong></td>
<td><strong>Pion:</strong> $n\sigma_{TPC} &lt; 2.5$ for $</td>
<td>p</td>
</tr>
<tr>
<td></td>
<td><strong>Kaon:</strong> $n\sigma_{TPC} &lt; 2.0$ for $</td>
<td>p</td>
</tr>
<tr>
<td><strong>Looser PID cut</strong></td>
<td><strong>Pion:</strong> $n\sigma_{TPC} &lt; 3.0$ for $</td>
<td>p</td>
</tr>
<tr>
<td></td>
<td><strong>Kaon:</strong> $n\sigma_{TPC} &lt; 2.5$ for $</td>
<td>p</td>
</tr>
<tr>
<td>Normalization range</td>
<td>$k^* : (0.1,0.12), (0.12,0.17), (0.18,0.25)$ GeV/c</td>
<td>0.6, 0.9</td>
</tr>
<tr>
<td>Fit range</td>
<td>$k^* = (0.,0.08),(0.,0.12),(0.,0.15), (0.005, 0.1), (0.01,0.1)$ GeV/c</td>
<td>9, 19</td>
</tr>
<tr>
<td>Primary fraction (purity)</td>
<td>± 10%</td>
<td>10,16</td>
</tr>
</tbody>
</table>
Correlation function (like sign)

ALICE, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

$\pi^{+}K^{+}$, 0-5% central

$\pi^{+}K^{+}$, 5-10% central

$\pi^{+}K^{+}$, 30-40% central

$\pi^{+}K^{+}$, 40-50% central

C

$C = 2.76$ TeV

$k^*$ (GeV/c)
Correlation function (like sign)

ALICE, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

$\pi K^-$, 0-5% central

$\pi K^-$, 5-10% central

$\pi K^-$, 30-40% central

$\pi K^-$, 40-50% central

C

$0.6$ $0.65$ $0.7$ $0.75$ $0.8$ $0.85$ $0.9$ $0.95$ $1$ $1.05$

$k^*$ (GeV/c)

$-0.15$ $-0.1$ $-0.05$ $0$ $0.05$ $0.1$ $0.15$

$+ve$ B

$-ve$ B

-fit
Correlation function (unlike sign)

ALICE, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

$\pi K^+$, 0-5% central

$\pi K^+$, 5-10% central

$\pi K^+$, 30-40% central

$\pi K^+$, 40-50% central

$C = 2.76$ TeV

$K^+$, 0-5% central

$K^-$, 5-10% central

$K^+$, 30-40% central

$K^-$, 40-50% central

$K^+$, fit

$+ve B$

$-ve B$

$k^*$ (GeV/c)
Correlation function (unlike sign)

ALICE, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

$\pi^+K^-$, 0-5% central

$\pi^+K^-$, 5-10% central

$\pi^+K^-$, 30-40% central

$\pi^+K^-$, 40-50% central

C

k* (GeV/c)
Reason for large statistical errors

One expects larger errors for $\mu$ in Cartesian coordinates. The reason is the following.

- In CC, we divide pairs in 2 groups to create $C^+$ and $C^-$. The division is not equal. There will be higher statistics in one of them and lower in the second one. Thus the statistical significance is not equal.

- The statistical error for $R$ is dominated by the statistics from the component which has higher statistics (best case scenario).

- The opposite situation happens for emission asymmetry $\mu$. In that case the statistical error is dominated by the statistics from the component with lower statistics (worst case scenario).
Comparison of results from CC and SH methods