Femtoscopy of identified particles in Pb-Pb collisions with ALICE at the LHC

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Overview

- Introduction
- Motivation
- ALICE at LHC
- Analysis details
- Results
  - 1D analysis of $\pi^\pm\pi^\pm$, $K^\pm K^\pm$, $K^0_s K^0_s$, $pp$ and $\bar{pp}$
  - 3D analysis of $\pi^\pm\pi^\pm$, $K^\pm K^\pm$
- Summary
Introduction

Correlation femtoscopy: measurement of space-time characteristics $R, c\tau \sim \text{fm}$ of particle production using particle correlations due to the effects of quantum statistics (QS) and final state interactions (FSI).

- Two particle Correlation Function (CF):
  - Theory: $\mathcal{C}(q) = \frac{N_2(p_1, p_2)}{N_1(p_1) \cdot N_2(p_1)}, \mathcal{C}(\infty) = 1$
  - Experiment: $\mathcal{C}(q) = \frac{S(q)}{B(q)}, q = p_1 - p_2$
    - $S(q)$ – pairs from same event
    - $B(q)$ – pairs from different event

- Parametrization:
  - 1D: $\mathcal{C}(q_{\text{inv}}) = 1 + \lambda \exp(-R^2 q_{\text{inv}}^2), R$ Gaussian radius in Pair Rest Frame (PRF), $\lambda$ correlation strength parameter
  - 3D: $\mathcal{C}(q_{\text{out}}, q_{\text{side}}, q_{\text{long}}) = 1 + \lambda \exp(-R^2_{\text{out}} q_{\text{out}}^2 - R^2_{\text{side}} q_{\text{side}}^2 - R^2_{\text{long}} q_{\text{long}}^2)$

where both $R$ and $q$ are in Longitudinally Co-Moving Frame (LCMS) long $\parallel$ beam; out $\parallel$ transverse pair velocity $v_T$; side normal to out,long
Femtoscopy
- Measure the spatial & temporal characteristics of the particle emitting regions
- Study collective dynamics, radial flow
- Put constraints on system evolution models, e.g. timescales & scattering parameters

Femtoscopy of heavier particles - complement to ππ
- Strong constraints for hydrodynamic models predictions: they should work for heavier mesons and baryons.
- Check for $m_T$ dependence -> determine freeze-out conditions
- Possibility to distinguish between different model scenario
Motivation: $m_T$-dependence of correlation radii

- "$m_T$-scaling": $R \sim m_T^a$, $m_T = \sqrt{m^2 + p_T^2}$

  - Negligible transverse flow
  - Longitudinal boost invariance
  - Common freeze-out

- Approximate "$m_T$-scaling" for different particle species for $R_{\text{long}}, R_{\text{side}}, R_{\text{out}}$ with different $a$ was predicted in (A. Kisiel, M. Galazyn, P. Bozek, Phys. Rev. C 90 (2014) 064914)
  - Indication of flow dominated freeze-out scenario

- Strong violation of "$m_T$-scaling" was predicted in (V.M. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov, Nucl. Phys. A 929 (2014) 1.) due to:
  - Strong transverse flow & resonance decays influence & rescattering phase
  - "$k_T$-scaling" was predicted instead

- Extraction of emission time from fit $R_{\text{long}}^2(m_T)$ using formula generalized for any strong transverse flow (Yu. Sinyukov, V. Shapoval, V. Naboka, arxiv:1508.01812),
  - Once more indication on importance of rescattering phase
ALICE detector

- **Main tracking detector:** Time Projection Chamber (TPC)
- **Vertexing and tracking:** Inner Tracking System (ITS)
- **Centrality determination:** V0
- **Particle identification (PID):**
  - TPC (energy loss)
  - Time-of-Flight (TOF)
\( K^\pm \) and \( K^0_s \) CFs

Results from ArXiv.org:1506.07884

- Example \( K^\pm K^\pm \) & \( K^0_s K^0_s \) CFs are shown
- CFs corrected for momentum resolution and purity
- Bose-Einstein enhancement seen for both
- Coulomb FSI seen in drop at low \( q \) in \( K^\pm K^\pm \)
- Strong FSI seen in dip below \( C=1 \) in \( K^0_s K^0_s \)

Curves corresponds to best fit:

\[ K^\pm K^\pm : \text{Bowler-Sinyukov formula:} \]

\[ C(q) = N \left[ 1 - \lambda + \lambda K(q) \left( 1 + \exp \left( -R_{inv}^2 q^2 \right) \right) \right], \]

\( N \) norm. factor, \( \lambda \) correlation strength, \( K(q) \) symmetrized Coulomb factor

\[ K^0_s K^0_s : \text{ } C(q) = N \left[ 1 - \lambda + \lambda C'(q) \right], \]

\[ C'(q) = 1 + \exp \left( -R_{inv}^2 q^2 \right) + C_{\text{strongFSI}}(q, R) \]

Strong FSI due to resonances \( f_0(980) \) and \( a_0(980) \)
Results from ArXiv.org:1506.07884

- Example \(pp\) CF is shown
- CF corrected for momentum resolution and purity
- Coulomb FSI seen in drop at low \(q\)
- Strong FSI seen in maximum at \(q\sim40\) MeV/c
- Curves correspond to best fit:

\[
C_{\text{meas}}(q_{pp}) = 1 + \lambda_{pp}(C_{pp}(q_{pp}; R) - 1) + \lambda_{p\Lambda}(C_{p\Lambda}(q_{pp}; R) - 1),
\]

- QS, Coulomb and Strong FSI are included in the fit; residual \(p\Lambda\) correlations are taken into account

- \(0.7<p_T<4.0\) GeV/c, \(|\eta|<0.8\), TPC and TOF\((p>0.8\text{GeV/c})\) nσ PID \((n<3)\)
- Purity >95%
$R_{inv}$ radii vs $m_T$ for $\pi^\pm\pi^\pm$, $K^\pm K^\pm$, $K^0_s K^0_s$, pp and $p\bar{p}$

Results from ArXiv.org:1506.07884

- $R_{inv}$ and $\lambda$ for $\pi^\pm\pi^\pm$, $K^\pm K^\pm$, $K^0_s K^0_s$, pp and $p\bar{p}$ vs $m_T$ for several centralities
- Radii decrease with $m_T \to$ radial flow
- Increase size with increasing centrality $\to$ simple geometric picture of the collisions.
- $R_{\pi} > R_{K}$ due to pion Lorentz factor
- $R_p$ compatible with $R_K$ at same $m_T$

- All $\lambda$ lie mostly in 0.3-0.7 due to long-lived resonances, non-Gaussian shape.
- No significant centrality dependence
- $\lambda_{\pi}$ are lower than $\lambda_K$ due to the stronger influence of resonances
$K^\pm K^\pm$ and $K^0_s K^0_s$ in Pb-Pb: HKM model

Results from ArXiv.org:1506.07884

- $R$ and $\lambda$ for $\pi^\pm \pi^\pm$, $K^\pm K^\pm$, $K^0_s K^0_s$, pp for 0-5% centrality
- Radii for kaons show good agreement with HKM predictions for $K^\pm K^\pm$
  (Nucl.Phys.A929 (2014))

- $\lambda$ decreases with $k_T$, both data and HKM
- HKM prediction for $\lambda$ slightly overpredicts the data
- $\lambda_\pi$ are lower $\lambda_K$ due to the stronger influence of resonances
$R_{\text{side}}$ shows approximate $m_T$ scaling;

$R_{\text{out}}$, $R_{\text{long}}$ of K are larger than those of $\pi \rightarrow m_T$ scaling is broken;

This difference increases for more central collisions;

The effect is more important for $R_{\text{long}}$.
Radii scale better with $k_T$ than with $m_T$ according with HKM predictions
Similar observations were reported by PHENIX at RHIC (arxiv:1504.05168).
\( R_{\text{out}} / R_{\text{side}} \) vs \( m_T \) for \( K^\pm K^\pm \) & \( \pi \pi \)

Pion results from ArXiv.org:1507.06842

\[ R_{\text{out}} / R_{\text{side}} (\pi) \sim 1 \text{ for low } k_T; \text{ slowly decreasing with } k_T \]

\[ R_{\text{out}} / R_{\text{side}} (\pi) \text{ smaller than at RHIC (1.1) } \rightarrow \text{ stronger radial flow (x:p correlations)} \]


Indication: \( R_{\text{out}} / R_{\text{side}} (K) > R_{\text{out}} / R_{\text{side}} (\pi) \) → different x:p correlations for pions and kaons

Similar observations were reported by PHENIX at RHIC (arxiv:1504.05168).
Comparison with (3+1)D Hydro+THERMINATOR2


Good description of pion radii vs. $m_T$

Underestimation of kaon radii

Model demonstrates approximate $R \sim m_T^a$ scaling for $\pi$ & $K$, with “a” being different for $R_{\text{out}}, R_{\text{side}}, R_{\text{long}}$. (A. Kisiel, M. Galazyn, P. Bozek, Phys.Rev. C90 (2014) 064914)
Comparison with HKM for 0-5% centrality


HKM model w/o re-scatterings demonstrates approximate $m_T$ scaling for π & K, but does not describe ALICE π & K data.


HKM model slightly underestimates $R_{\text{side}}$ → overestimates $R_{\text{out}} / R_{\text{side}}$ ratio for π.
Extraction of emission time from fit $R_{\text{long}}^2(m_T)$

The new formula for extraction of the maximal emission time for the case of strong transverse flow was used (Yu. Sinyukov, V.Shapoval, V.Naboka, arxiv:1508.01812)

The parameters of freeze-out: $T$ and “intensity of transverse flow”, $\alpha$ were fixed by fitting $\pi$ and $K$ spectra (arxiv:1508.01812)

Indication: $\tau_\pi < \tau_K$. Possible explanations (arxiv:1508.01812): HKM includes re-scatterings (UrQMD cascade): e.g. $K\pi \rightarrow K^*(892) \rightarrow K\pi$, $KN \rightarrow K^*(892)X$; ($K^*(892)$ lifetime 4-5 fm/c) $[\pi N \rightarrow N^*(\Delta)X$, $N^*(\Delta) \rightarrow \pi X$ ($N^*$(s(Δs))- short lifetime)]

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Summary

1D $\pi^\pm\pi^\pm, K^\pm K^\pm$, $K_0^s K_0^s, \bar{p}p, \bar{p}p$ and 3D $\pi^\pm\pi^\pm, K^\pm K^\pm$
femtoscopic radii were measured for several centrality and $m_T$ bins in Pb-Pb collisions at 2.76 TeV.

The study performed by ALICE Collaboration on the femtoscopic correlations of heavy particles is a good compliment to the pion femtoscopy as it allows one to distinguish between different model scenarios.

Importance of hadronic rescattering phase for explanation of breaking of $m_T$-scaling was shown.
Additional slides
$K^\pm$ and $K^0_s$ PID (ArXiv.org: 1506.07884)

**K$^\pm$:** $0.15 < p_T < 1.5$ GeV/c, $|\eta| < 0.8$, TCP and TOF ($p > 0.5$ GeV/c) $N\sigma$ PID ($N < 3$)

- Single and pair purity: main contamination ($0.4 < p < 0.5$ GeV/c) comes from $e^\pm$

**$K^0_s$:** $\rightarrow \pi^+\pi^-$ ($c\tau = 2.7$ cm)

- Daughter $\pi$: $p_T > 0.15$ GeV/c, $|\eta| < 0.8$
- TPC and TOF ($p > 0.8$ GeV/c) $N\sigma$ PID
- $K^0_s$: $|\eta| < 0.8$, $\pi^+\pi^-$ DCA $< 0.3$ cm,
- DCA to prim. vertex $< 0.3$ cm
- decay length $< 30$ cm, $\cos$ (point. angle) $> 0.99$
- $0.48 < m_{\pi\pi} < 0.515$ GeV/c$^2$; Purity $> 95%$

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