Pion and kaon femtoscopy in Pb–Pb collisions at 2.76 TeV in comparison with the EPOS 3 model prediction

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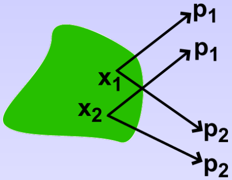
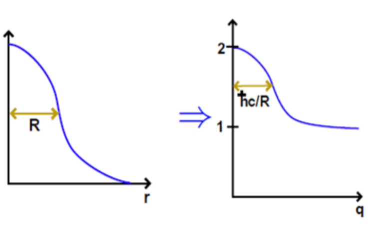
Motivation: Femtoscopy



Correlation femtoscopy: measurement of space-time characteristics R, $c\tau$ ∼fm$=10^{-15}$ m of particle production source using particle correlations due to the effects of quantum statistics (QS) and final state interactions (FSI).

Two-particle correlation function (CF):



$$\text{theory}: C(q) = \frac{N_2(p_1, p_2)}{N_1(p_1)N_2(p_2)}, \quad C(\infty) = 1$$

$$\text{experiment}: C(q) = \frac{S(q)}{B(q)}, \quad q = p_1 - p_2$$

$S(q)$ - pairs from the same event
$B(q)$ - pairs from different events

1D analysis, spherical source of size R: $C_{\text{fit}}(\boldsymbol{q}_{\text{inv}}) \sim 1 + \lambda \exp\left(-R^2 \boldsymbol{q}^2_{\text{inv}}\right)$

3D analysis, arbitrary shape source of size $(R_{\text{out}}, R_{\text{side}}, R_{\text{long}})$:

$$C_{\text{fit}}(\boldsymbol{q}) \sim 1 + \lambda \exp\left(-R^2_{\text{out}} q^2_{\text{out}} - R^2_{\text{side}} q^2_{\text{side}} - R^2_{\text{long}} q^2_{\text{long}}\right)$$

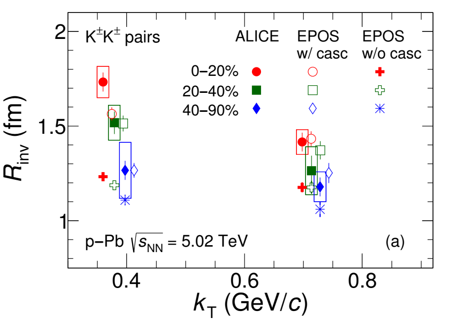
λ - correlation strength

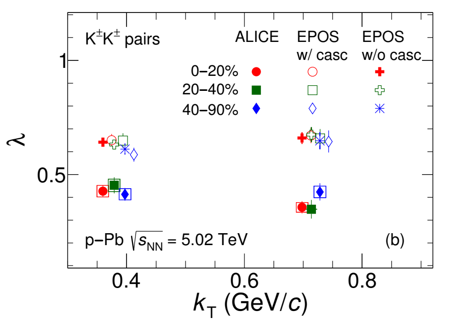
Motivation: Kaon femtoscopy

- Compare EPOS 3 predictions [Phys. Rev. C 89 (2014) 6, 064903; Phys. Rev. C 92 (2015) 054908] for kaons with experimental femtoscopic data.
- Momentum correlations ($K^{\pm}K^{\pm}$ – QS+Coulomb FSI, strong FSI is negligible, $K^0_S K^0_S$ – QS+strong FSI) $\rightarrow$ space-time characteristic of production process from two experimentally independent analyses.
- Different physics and experimental analyses for $K^{\pm}K^{\pm}$ and $K^0_S K^0_S$ $\rightarrow$ cross-check of the femtoscopic method.
- Kaons are less influenced by resonance decays than pions $\rightarrow$ clearer signal.
- Study of collective dynamics (collective flow) using $k_{\mathrm{T}} = |\boldsymbol{p}_{\mathrm{T},1} + \boldsymbol{p}_{\mathrm{T},2}|/2$ ($m_{\mathrm{T}} = \sqrt{k_{\mathrm{T}}^2 + m_{\pi,K}^2}$) dependence of correlation radii for different particle species.
- **Pb–Pb** vs **p–Pb** $\rightarrow$ different influence of collectivity in EPOS 3.

1D kaon analysis: p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- Experimental data [Phys. Rev. C 100 (2019) 2, 024002]: ∼55M events
- EPOS 3.111 [Phys. Rev. C 89 (2014) 6, 064903; Phys. Lett. B 728 (2014) 25-38]: ∼10M events
- **Centrality bins, %:** 0–20, 20–40, 40–90
- **k_T bins, GeV/c:** 0.2–0.5, 0.5–1.0
- Select kaons with $|\eta| < 0.8$, $0.14 < p_T < 1.5$ GeV/c
- EPOS 3 pure QS calculations are fit with $C_{fit}(\boldsymbol{q}_{inv}) = N\left(1 + \lambda \exp\left(-R^2 \boldsymbol{q}_{inv}^2\right)\right)$, N - normalization coefficient





Good agreement of the EPOS 3 w/ UrQMD calculations with the data.

Data are systematically less than the EPOS 3 results.

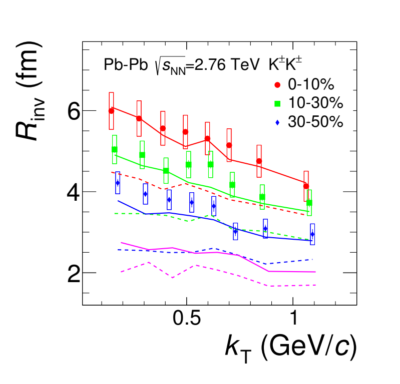
EPOS 3 w/o UrQMD radii are significantly smaller than the experimental ones.

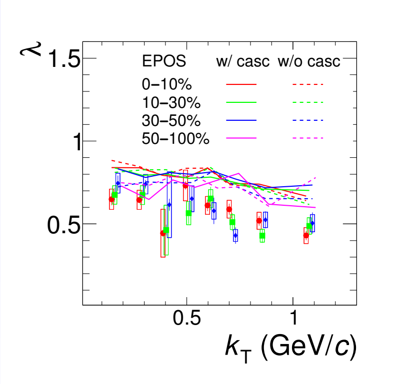
1D kaon analysis: Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, I

- Experimental data: [Phys. Rev. C 92 (2015) 054908] ∼40M events
- EPOS 3.107*:
  - UrQMD is ON (6.3e+5 minimum bias events)
  - UrQMD is OFF (1.8e+5 minimum bias events)
- **Centrality bins, %:** 0–10, 10–30, 30–50
- **k_{T} bins, GeV/c:** 0.1–0.2, 0.2–0.3, 0.3–0.4, 0.4–0.5, 0.5–0.6, 0.6–0.7, 0.7–0.8, 0.8–1.0, 1.0–1.2
- Select kaons with $|\eta| < 0.8$, $0.14 < p_{\mathrm{T}} < 1.5$ GeV/c
- EPOS 3 pure QS calculations are fit with $C_{\mathrm{fit}}(\boldsymbol{q}_{\mathrm{inv}}) = N\left(1 + \lambda \exp\left(-R^2 \boldsymbol{q}_{\mathrm{inv}}^2\right)\right)$, N - normalization coefficient

*The speaker acknowledges Christina Markert and Anders Knospe and the Texas Advanced Computing Center (TACC) at the University of Texas at Austin for providing computing resources that have contributed to the research results reported within this talk [URL: http://www.tacc.utexas.edu].

1D kaon analysis: Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, II





- EPOS 3 w/ UrQMD radii are in excellent agreement with the experimental data.
- EPOS 3 λ are very close to the data.
- Radii from EPOS 3 w/o UrQMD are significantly smaller than the experimental ones and show noticeably flatter k_T dependence.
- EPOS 3 w/o UrQMD λ are slightly larger than they are w/ UrQMD.
- Hadron cascade is crucial to describe the data.
- The most peripheral collisions' 50–100% range in EPOS 3 is presented for completeness to see how femtoscopic parameters change from central to very peripheral collisions.

3D pion and kaon analysis: Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

- Pions ([Phys. Rev. C 93 (2016) 024905] ∼4M events):
  - Centrality bins, %: 0–10, 10–30, 30–50
  - k_{T} bins, GeV/c: 0.2–0.3, 0.3–0.4, 0.4–0.5, 0.5–0.6, 0.6–0.7, 0.7–0.8, 0.8–1.0
  - Select pions with $|\eta| < 0.8$, $0.14 < p_{\mathrm{T}} < 2.0$ GeV/c
- Kaons ([Phys. Rev. C 96 (2017) 064613] ∼40M events):
  - Centrality bins, %: 0–10, 10–30, 30–50
  - k_{T} bins, GeV/c: 0.2–0.4, 0.4–0.6, 0.6–1.3
  - Select kaons with $|\eta| < 0.8$, $0.14 < p_{\mathrm{T}} < 1.5$ GeV/c
- EPOS 3.107*:
  - UrQMD is ON (6.3e+5 minimum bias events)
  - UrQMD is OFF (1.8e+5 minimum bias events)
- EPOS 3 pure QS calculations are fit with

$$C(\boldsymbol{q}) = N\left(1 + \lambda \exp\left(-R^2_{\mathrm{out}} q^2_{\mathrm{out}} - R^2_{\mathrm{side}} q^2_{\mathrm{side}} - R^2_{\mathrm{long}} q^2_{\mathrm{long}}\right)\right)$$

$\boldsymbol{q} = (q_{\mathrm{out}}, q_{\mathrm{side}}, q_{\mathrm{long}})$, N - normalization coefficient

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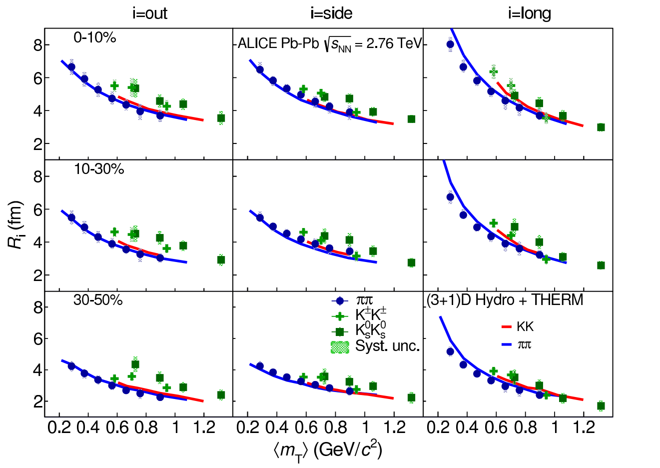
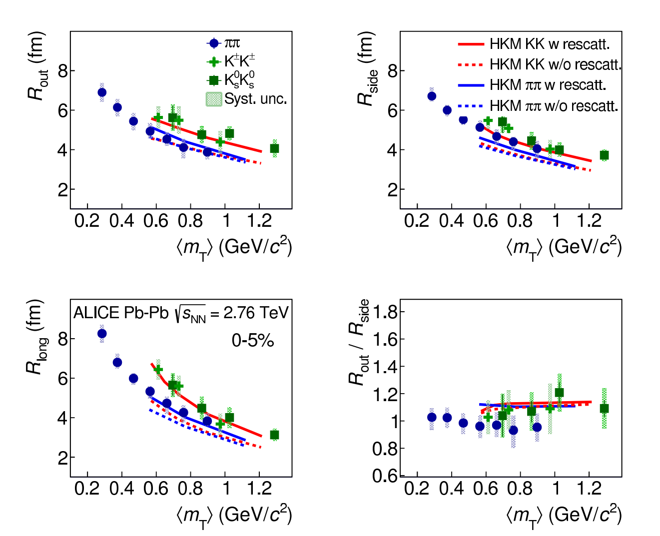
3D pion and kaon analysis:
Experiment vs (3+1)D Hydro + THERMINATOR 2



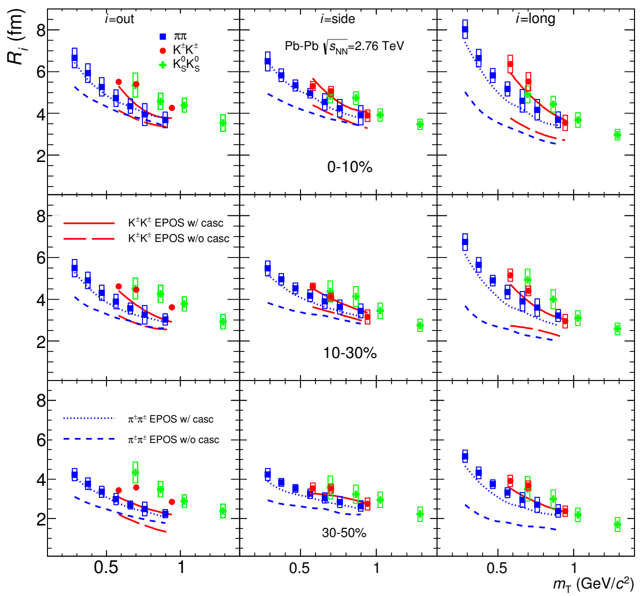
- (3+1)D Hydro + THERMINATOR 2 model [Phys. Rev. C 90 (2014) 064914] includes hydrodynamic evolution and resonance decays.
- Pion radii are very well described.
- Kaon radii are noticeably underestimated.
- Model demonstrates an approximate $R \sim m_T^a$ scaling where a is different for R_{out}, R_{side}, R_{long}.

3D pion and kaon analysis: Experiment vs HKM



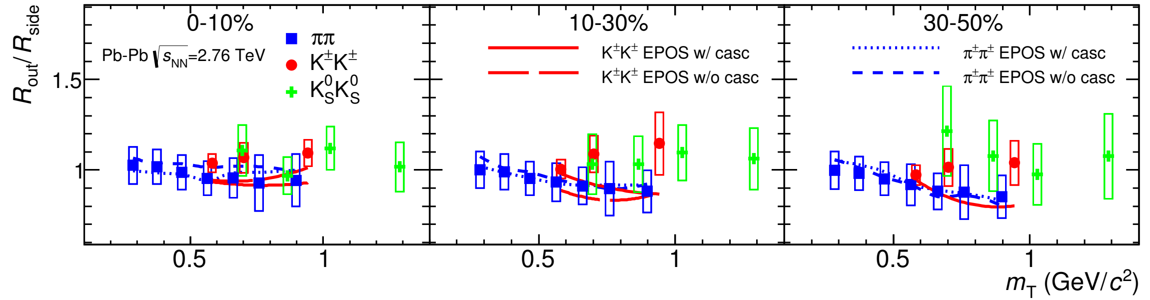
- Hydro-Kinetic Model (HKM) [Nucl. Phys. A 929 (2014) 1].
- HKM model w/o rescatterings demonstrates an approximate m_{T} scaling for pions and kaons and does not describe the experimental data.
- HKM model w/ rescatterings describes experimental data better and explains the observed deviation from the m_{T} scaling.

3D pion and kaon analysis: Experiment vs EPOS 3, I



- EPOS 3 w/ UrQMD describes fairly well the experimental data except out projection for kaons, long projection is a bit underestimated for pions.
- Hadron cascade is very important both for pions and for kaons.
- EPOS 3 w/o UrQMD radii show noticeably flatter m_T dependence.
- UrQMD effect is more pronounced for kaons than for pions and for more peripheral events.
- Unlike THERMINATOR 2 and HKM w/o rescatterings, EPOS 3 w/o UrQMD does not predict m_T scaling for pions and kaons.
- *Not enough data w/o UrQMD available for kaon analysis at 30–50%

3D pion and kaon analysis: Experiment vs EPOS 3, II



- $(R_{out}/R_{side})_{\text{PION}} \leqslant 1$
- EPOS 3 describes well experimental pion R_{out}/R_{side}.
- $(R_{out}/R_{side})_{\text{KAON}} \approx 1$
- EPOS 3 underestimates experimental kaon R_{out}/R_{side} (following bad R_{out} description).
- EPOS 3 predicts $(R_{out}/R_{side})_{\text{KAON}} < (R_{out}/R_{side})_{\text{PION}}$ while in experiment $(R_{out}/R_{side})_{\text{KAON}} > (R_{out}/R_{side})_{\text{PION}}$.
- Theoretical explanation: [Phys. Lett. B 688 (2010) 50].
- Not enough data w/o UrQMD available for kaon analysis at 30–50%.

Conclusion

- EPOS 3 femtoscopic calculations were compared with the ALICE experimental data in p–Pb collisions at 5.02 TeV and in Pb–Pb collisions at 2.76 TeV.

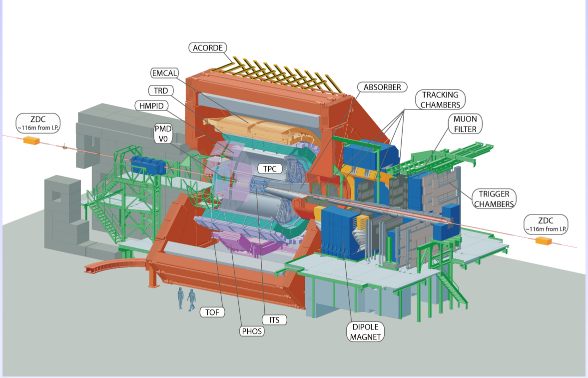
- Good agreement of EPOS 3 w/ UrQMD 1D radii with the data in p–Pb was observed.
- λ for p–Pb data are systematically smaller than the EPOS 3 ones.
- Excellent agreement of EPOS 3 w/ UrQMD 1D radii and λ with the data in Pb–Pb was observed.
- EPOS 3 w/o UrQMD radii are significantly smaller than the data both in p–Pb and Pb–Pb collisions.

- 3D EPOS 3 w/ UrQMD pion radii are in good agreement with the data for out and side directions, long projection is underestimated.
- 3D EPOS 3 w/ UrQMD kaon radii are in good agreement with the data for side and long directions, out projection is slightly underestimated.
- $R_{\mathrm{out}}/R_{\mathrm{side}}$ ratio is well described by EPOS 3 for pions and is underestimated for kaons.

- Hadron cascade is very important to describe femtoscopic radii.

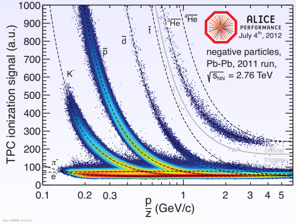
THANK YOU FOR YOUR ATTENTION!

ALICE

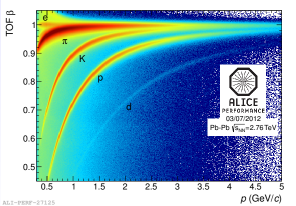


- Tracking and vertex:
  - Time Projection Chamber (TPC)
  - Inner Tracking System (ITS)
- Particle identification:
  - TPC
  - Time-of-Flight (TOF)
- Centrality determination:
  - V0

TPC PID:



TOF PID:



Longitudinally Co-Moving System

1D CF is parametrized in terms of Gaussian correlation radius R:

$$C(\boldsymbol{q}_{\mathrm{inv}}) = 1 + \lambda \exp\left(-R^2 \boldsymbol{q}_{\mathrm{inv}}^2\right),$$

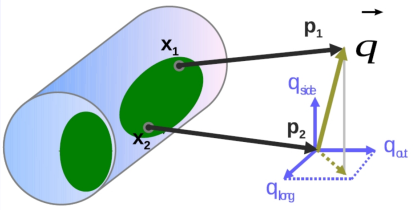
where R is defined in the Pair Rest Frame. 1D analysis gives the source size averaged over all directions. Correlation strength λ represents a fraction of correlating particles emitted by independent emission sources.

3D CF:

$$C(q_{\mathrm{out}}, q_{\mathrm{side}}, q_{\mathrm{long}}) = 1 + \lambda \exp\left(-R_{\mathrm{out}}^2 q_{\mathrm{out}}^2 - R_{\mathrm{side}}^2 q_{\mathrm{side}}^2 - R_{\mathrm{long}}^2 q_{\mathrm{long}}^2\right),$$

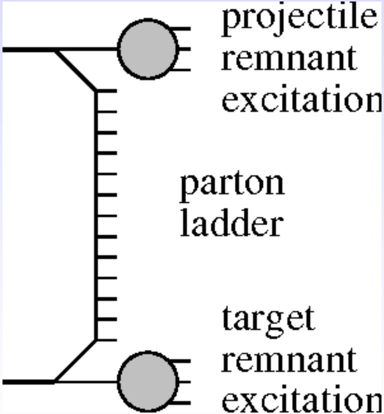
where $R_{\mathrm{out,side,long}}$ is defined in the `Longitudinally Co-Moving System`:

long $\parallel$ beam direction
out $\parallel$ transverse pair momentum k_{T}
side $\perp$ (out,long)
$p_{\mathrm{long},1} + p_{\mathrm{long},2} = 0$



EPOS 3 [Phys. Rev. C82 (2010) 044904]
UrQMD [Phys. Rev. C93, 1 (2016) 014911]

Elementary parton-parton scattering: the hard scattering in the middle is preceded by parton emissions attached to remnants. The remnants are an important source of particle production.



- Monte-Carlo event generator for minimum bias hadronic interactions.
- Parton model, with many binary parton-parton interactions, each one creating a parton ladder.
- Includes heavy quark production in pQCD calculations.
- Full 3D hydrodynamical simulation and parton energy loss in QGP/followed by the hadronic cascade.