Kaon femtoscopy correlations in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ =2.76 TeV from the ALICE experiment at LHC

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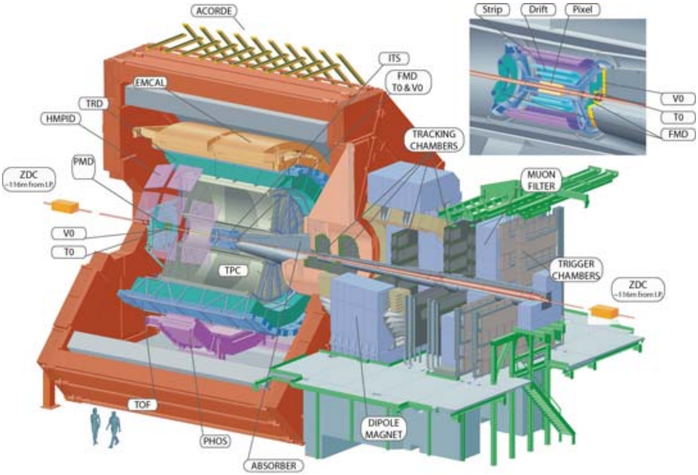
Overview

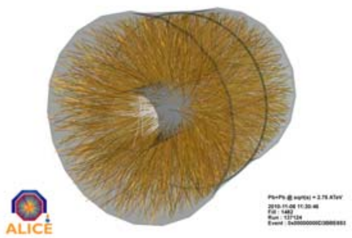
- Introduction: ALICE detector and physics topics
- Femtoscopy: motivation and main results for pions in Pb–Pb at LHC
- Kaon femtoscopy: complementary $K^{\pm}K^{\pm}$ and $K_s^0 K_s^0$ systems and their correlation observables behavior
- m_T dependence of various particles (pions, kaons and protons)
- Results $\&$ Conclusions

A Large Ion Collider Experiment (ALICE): Detector

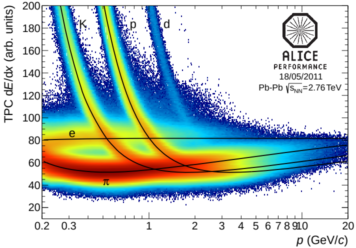


- Main tracking detector: **Time Projection Chamber (TPC)**
- Vertexing and tracking: **Inner Tracker System (ITS)**
- Trigger and centrality: **VZERO**
- Particle identification (PID): **TPC and ITS** (energy loss) & **Time-of-Flight (TOF)**

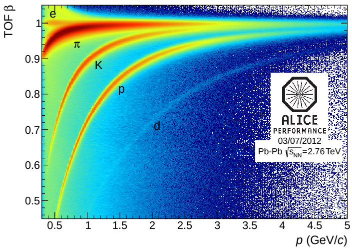
A Large Ion Collider Experiment (ALICE): Particle Selection Quality



- low momentum cut-off ($p_T >$100 MeV/c)
- small material budget
- excellent particle identification (PID) by specific energy loss & time of flight & transition and Cherenkov radiation
- good primary and secondary vertex resolution allows for measurements of strangeness and heavy flavor with low background



$$p_T \text{ range: } \begin{cases} \pi: & 0.2 - 0.7 \\ K: & 0.3 - 0.6 \\ p: & 0.5 - 1.0 \end{cases}, \text{ GeV/c}$$

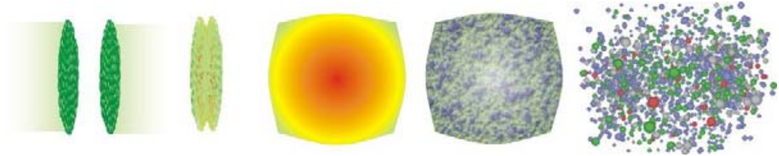


$$p_T \text{ range: } \begin{cases} \pi: & 0.5 - 2.0 \\ K: & 0.5 - 2.0 \\ p: & 0.5 - 2.5 \end{cases}, \text{ GeV/c}$$

Main Physics Topics

- In pp, Pb–Pb, p–Pb (beginning of 2013) collisions:
    - Event characterization (multiplicity, centrality)
    - Particle species and spectra
    - Correlations (femtoscopic measurements)
    - Resonance production
    - Jet physics
    - Photons
    - Dileptons
    - Heavy-quark and quarkonium production
- Physics of ultra-peripheral heavy-ion collisions
- Contribution of ALICE to cosmic-ray physics

Physics Motivation: Femtoscopy



Correlation femtoscopy is a measurement of space-time characteristics R, $c\tau$ ~fm of particle production using particle correlations due to effects of QS and FSI

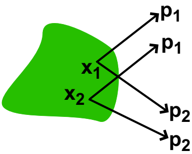
G. Goldhaber, S. Goldhaber, W-Y Lee, A. Pais (Phys.Rev. 120 (1960) 300): first showed the **BE** correlation of identical pions in $p\bar{p}$ collisions

G.I. Kopylov and M.I. Podgoretsky (1971-1975) (review: Phys.Part.Nucl. 20, iss. 3 (1989) 629, in Russian): elaborated basics of correlation femtoscopy

V.G. Grishin, G.I. Kopylov, and M.I. Podgoretsky showed
analogy **(Sov.J.Nucl.Phys. 13 (1971) 638)** and
difference **(G.I. Kopylov and M.I. Podgoretsky, Sov.J.Nucl.Phys. 15 (1972) 219)**
between femtoscopy in particle physics and HBT effect in astronomy **(R. Hanbury-Brown and R.Q. Twiss, Phil.Mag. 45 (1954) 633):**

HBT effect is the change of intensity of the signal received from the particle emission source

Physics Motivation: Identical Boson Femtoscopy

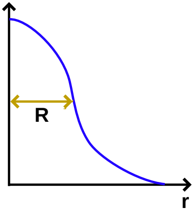


$$U_{x1p1} = U(x_1, p_1),\ V_{x2p2} = V(x_2, p_2)$$

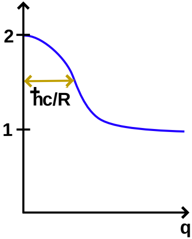
$$A(x_1, x_2; p_1, p_2) \sim U_{x1p1}V_{x2p2} + U_{x1p2}V_{x2p1} \ \rightarrow\ <|A|^2>_{x_1x_2}$$

$$W(p_1, p_2) \sim <|U_{x1p1}|^2><|V_{x2p2}|^2> + <|U_{x1p2}|^2><|V_{x2p1}|^2>$$
$$+ <U_{x1p1}U^*_{x1p2}><V_{x2p2}V^*_{x2p1}> + <U^*_{x1p1}U_{x1p2}><V^*_{x2p2}V_{x2p1}>$$

$$|p_1 - p_2| \gg 0 \ \longrightarrow\ W \sim 2|U|^2|V|^2$$
$$|p_1 - p_2| \sim 0 \ \longrightarrow\ W \sim 4|U|^2|V|^2$$



$\Rightarrow$



two-particle correlation function:

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

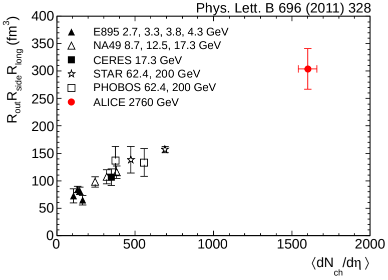
$$\text{experiment}:\ C(q) = \frac{S(q)}{B(q)},\quad q = p_1 - p_2$$

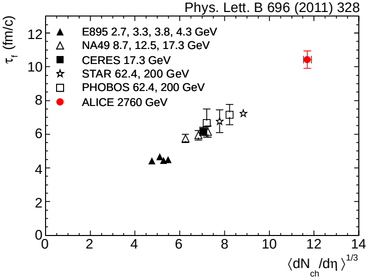
S - distribution of pair momentum difference of particles from the same events
B - reference distribution, built by mixing particles from different events

Commonly used parametrization: $C(q) = 1 + \lambda \exp^{-R^2q^2}$, λ - correlation strength

Main ALICE Results of the Pion Femtoscopy Analysis in Pb–Pb

"Homogeneity volume" at LHC is bigger by a factor ~ 2 than for the most central events at RHIC $\longrightarrow$





The measured decoupling time τ_f at LHC $\longleftarrow$ is about 40% larger than at RHIC

- Increased homogeneity volume at LHC
- Transverse momentum dependence of the radii $\rightarrow$ strong collective motion of matter
- Strong constraints on timescales and sensitivity to the EOS in dynamic models

Kaon Femtoscopy

- Kaon radii dependence on the transverse momentum $k_T = |\vec{p}_{T,1} + \vec{p}_{T,2}|/2$ and/or mass $m_T = \sqrt{k_T^2 + m^2}$ - study of collective behavior. Kaons suffer from the resonance contributions less than pions $\rightarrow$ clearer signal.

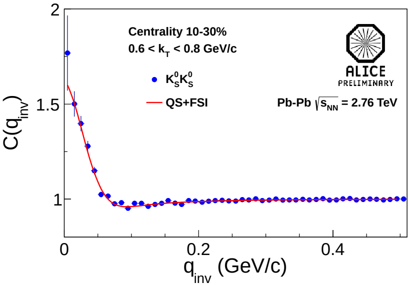
- Study of m_T dependence of correlation radii - m_T scaling - using $K^{\pm}K^{\pm}$ and $K_s^0 K_s^0$.

- First measurements of the charged kaon source size in Pb–Pb collisions at 2.76 TeV.

$K^{\pm}K^{\pm}$ and $K_s^0K_s^0$ in Pb–Pb: Correlation Functions

Neutral kaons:

- PID via $\pi^+\pi^-$ decay channel (purity $\sim$95%) - easily identified up to 2 GeV/c
- Strong FSI and QS lead to femtoscopic effect, both included in the fit (**Lednicky & Lyuboshitz model, Sov.J.Nucl.Phys. 35 (1982) 770**)
- No Coulomb suppression

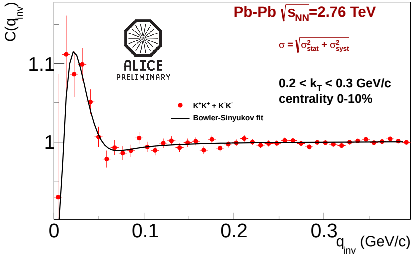


Charged kaons:

- PID: TPC+TOF to extend p_T range (up to 1.5 GeV/c)
- Bowler-Sinyukov fit

$$C(q_{\rm inv}) = (1-\lambda) + \lambda K(q_{\rm inv})\left(1 + e^{-R_{\rm inv}^2 q_{\rm inv}^2}\right)$$

$\boldsymbol{K}$ - Coulomb function, $q_{\rm inv} = \sqrt{\vec{q}^{\,2} - q_0^2}$

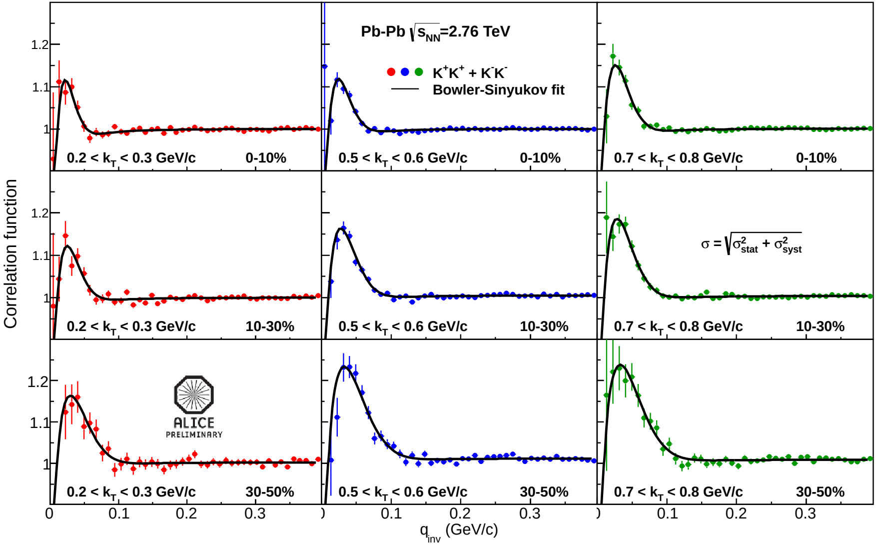


3 centrality bins: 0-10, 10-30, 30-50**%**

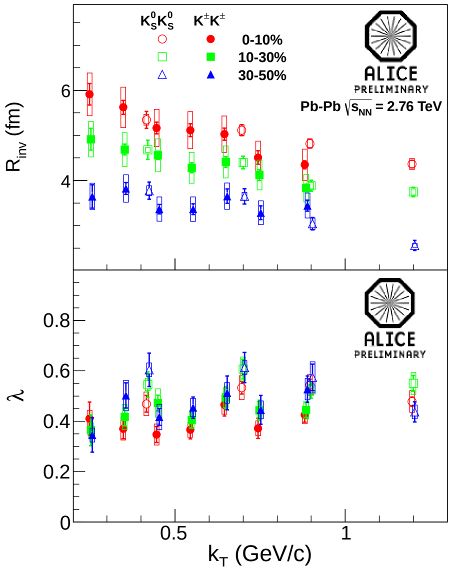
k_T **bins: 4 (neutral kaons)** - 0.2-0.6, 0.6-0.8, 0.8-1.0, 1.0-1.5 **GeV/c**

7 (charged kaons) - 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 **GeV/c**

$K^{\pm}K^{\pm}$ and $K_s^0K_s^0$ in Pb–Pb: Correlation Functions of $K^{\pm}K^{\pm}$

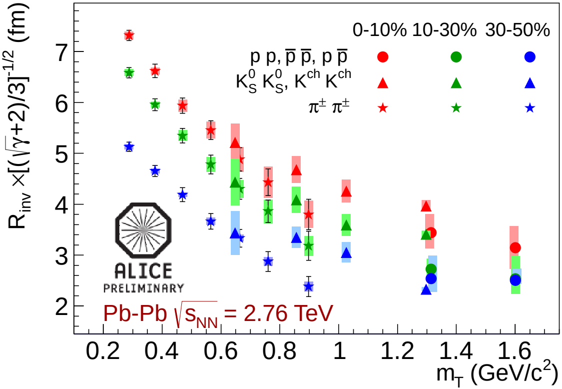


$K^{\pm}K^{\pm}$ and $K_s^0K_s^0$ in Pb–Pb: R_{inv}



- $K_s^0K_s^0$ and $K^{\pm}K^{\pm}$ consistent
- R_{inv} decreases with k_T
- R_{inv} increases with $< dN_{ch}/d\eta >$
- $\lambda \sim 0.5$ in agreement with chemical model estimates

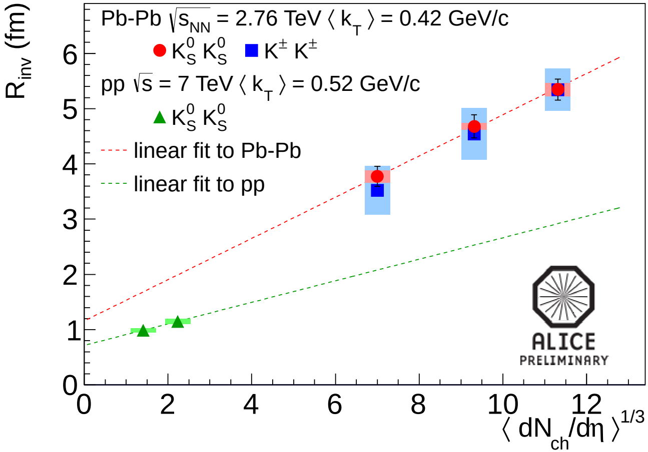
m_T Scaling with Different Masses



Approximate m_T scaling after taking into account kinematics.

Coefficient $\left(\frac{\sqrt{\gamma}+2}{3}\right)^{-1/2}$ has been matched to recover m_T scaling with R_{inv} (see THERMINATOR: **A. Kisiel, T. Taluc, W. Broniowski, W. Florkowski: Comput.Phys.Commun. 174 (2006) 669-687**; and also Maciej Szymanski's QM2012 talk "Meson and baryon femtoscopy in heavy-ion collisions at ALICE").

Kaon Femtoscopy: pp vs. Pb–Pb



Linear fit is used for Pb–Pb and is assumed for pp (as it is for pions in pp).

Linear scaling of radii in pp and Pb–Pb gives significantly different slopes and offsets.

Femtoscopy Results by ALICE

Quark Matter 2012:

- **Plenary Talk: Particle Correlations from ALICE: Latest Results** (Andrew Marshall Adare)
- **Contributed Conference Presentation: Meson and Baryon Femtoscopy in Heavy-Ion Collisions at ALICE** (Maciej Pawel Szymanski)
- **Poster: Identical Kaon Femtoscopic Correlations in Proton–Proton and Heavy-Ion Collisions at the LHC** (Matthew Donald Steinpreis)
- **Poster: Two-Baryon Correlations in Heavy-Ion Collisions at the LHC** (Jai Salzwedel)
- Poster: Source Chaoticity in Heavy-Ion Collisions at the LHC (Dhevan Raja Gangadharan)
- Poster: Photon-Hadron Correlations in pp Collisions with ALICE (Meidana Huang)

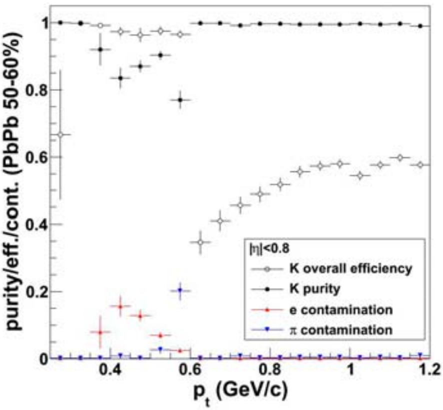
Publications:

- $K_s^0 K_s^0$ Correlations in pp Collisions at $\sqrt{s}$=7 TeV from the LHC ALICE Experiment.
  CERN-PH-EP-2012-160, arXiv:1206.2056 [hep-ex]
- Femtoscopy of pp Collisions at $\sqrt{s}$=0.9 and 7 TeV at the LHC with Two-Pion Bose-Einstein Correlations.
  CERN-PH-EP-2010-083, Phys.Rev. D84 (2011) 112004 (DOI: 10.1103/PhysRevD.84.112004), arXiv:1101.3665 [hep-ex]
- Two-Pion Bose-Einstein Correlations in Central Pb-Pb Collisions at $\sqrt{s_{\mathrm{NN}}}$= 2.76 TeV.
  CERN-PH-EP-ALICE-2010-006, Phys.Lett. B696 (2011) 328-337 (DOI: 10.1016/j.physletb.2010.12.053), arXiv:1012.4035 [nucl-ex]
- Two-Pion Bose-Einstein Correlations in pp Collisions at $\sqrt{s}$=900 GeV.
  Phys.Rev. D82 (2010) 052001 (DOI: 10.1103/PhysRevD.82.052001), arXiv:1007.0516 [hep-th]

Summary

- Consistency of $K^{\pm}K^{\pm}$ and $K_s^0 K_s^0$ analyses
- R_{inv} decreases with increasing transverse momentum k_T/mass m_T and for more peripheral collisions - consistency with hydrodynamics
- m_T scaling for pions, kaons and protons works after scaling R_{inv} by a factor related to kinematics
- No common scaling for pp and Pb–Pb

Backup Slides: Purity



- Contamination comes mainly from e+/e- which is maximal (∼20%) at 0.4< p_T <0.6 GeV/c and from pions which is maximal (∼20%) at 0.5< p_T <0.6 GeV/c
- Purity of $K^{\pm}$ is ∼80% at 0.4< p_T <0.6 GeV/c and ∼100% outside this region
- Purity of $K^{\pm}K^{\pm}$ pairs is ∼64% at 0.4< p_T <0.6 GeV/c and ∼100% outside this region
- Purity correction CFcorr=(CFraw-1+p)/p changes only λ parameter and doesn't influence radii and, therefore, has not been applied in the analysis

Backup Slides: Systematic Errors

- Strong FSI $\longrightarrow$ CF calculated with the scattering length taken from the lattice QCD (Phys. Rev. D 77, 094507): $\sim 4\%$
- Splitting-merging effects, use of $\eta - \varphi^*$ cuts: $< 3\%$
- Coulomb function fit (change the radius of the source by ± 1 fm): $R_{\text{inv}} \longrightarrow \sim 4\%$, $\lambda \longrightarrow \sim 2\%$
- Misidentified particles: $R_{\text{inv}} \longrightarrow \sim 2\%$, $\lambda \longrightarrow \sim 10\%$ in the range $0.4 < p_T < 0.6$, $< 5\%$ elsewhere
- Non-flat background: $< 3\%$

Maximal total systematic error: $R_{\text{inv}} \longrightarrow$ **$\sim 8\%$**, $\lambda \longrightarrow$ **$\sim 12\%$** in the range $0.4 < k_T < 0.6$

Backup Slides: Details of Analysis

$K^{\pm}K^{\pm}$

- **Event selection**
  - Events were selected using minimum bias trigger
  - Reconstructed vertex must be within 8 cm from the center of the TPC along the beam direction
  - At least one particle must be reconstructed and identified as a kaon
- **Single track cuts**
  - $|\eta| < 0.8$ & $0.14 < p_T < 1.5$ GeV/c
  - TPC inner tracks SetMaxTPCChiNdof(4.0);
  - SetMaxImpactXY(0.20); SetMaxImpactZ(0.15);
- **Double track cuts**
  - remove pairs sharing more than 5% of clusters in the TPC - anti-splitting cut
  - remove pairs separated by less than 3 cm at the entrance of the TPC – anti-merging cut

$\sim$ 19.2M events, 2010h run

$K_s^0 K_s^0$

- **Event selection**
  - |Z-vertex| < 10 cm
  - Mix events in bins of 5% centrality and 2 cm z-vertex
  - Must have two good K_s^0
- **Single track cuts**
  - **Daughter cuts**
    - p_T > 0.15 GeV/c
    - $|\ \eta\ |<0.8$
    - DCA pion-pion < 0.3 cm
    - DCA pion-primary vertex > 0.4 cm
    - TPC $\sigma < 3.0$
    - TOF $\sigma < 3.0$ ($0.8 <$ p < 2.1)
  - **K_s^0 cuts**
    - DCA K_s^0-primary vertex < 0.3 cm
    - Decay length < 30 cm
    - $|\ \eta\ |<0.8$
    - Cosine of pointing angle > 0.99
    - .480 $<$ mass $<$ .515 (GeV/c^2)
- **Pair cuts**
  - No daughters with shared IDs
  - Average separation of same-sign daughter throughout TPC > 5 cm (splitting/merging)

$\sim$ 47M events, 2010h&2011h runs