Pion-kaon femtoscopy in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

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Ashutosh Kumar Pandey

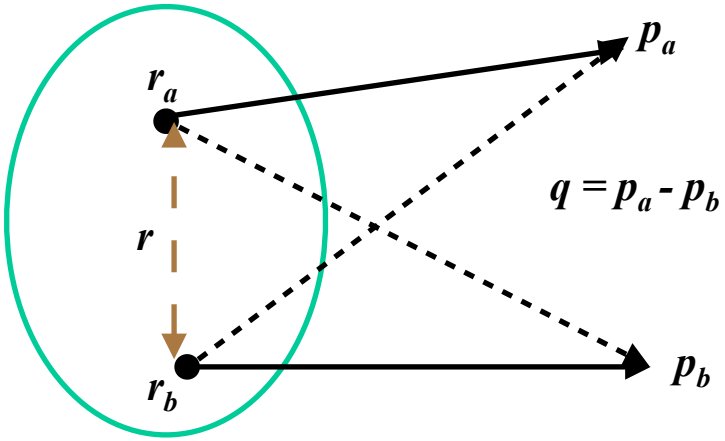
(for the ALICE collaboration)

Introduction

- It is impossible to measure dimensions of fireball directly due to its very small size
- Femtoscopy (or HBT technique) provides a direct tool to measure the source size

Two particle correlation function

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



Koonin-Pratt Equation,

PLB70 (1977) **43**,*S. Pratt et al.*, PRC42 (1990) 2646

$$C(q) = \int dr |\psi(q, r)|^2 S(r)$$

Experimental correlation function

Pair wave function

Source 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

Relevant coordinate system

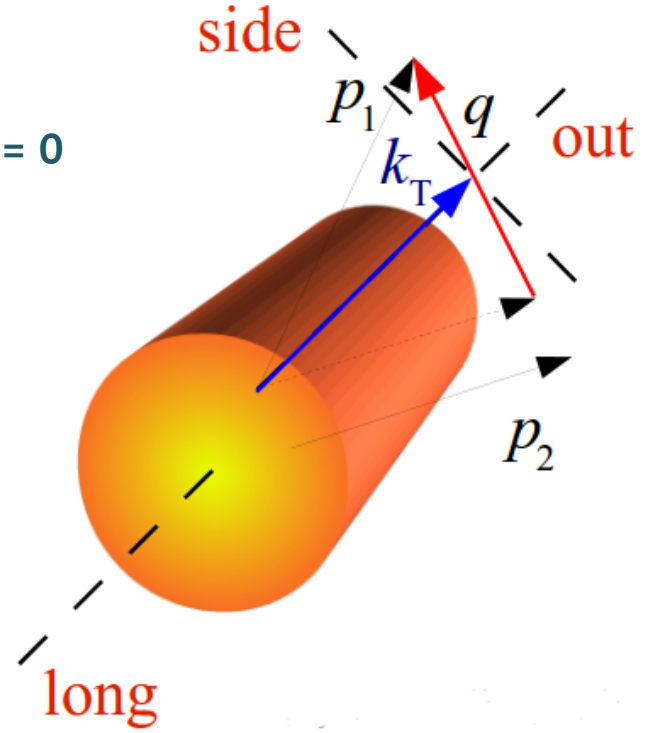
Longitudinal co-moving system (LCMS):

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

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

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

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



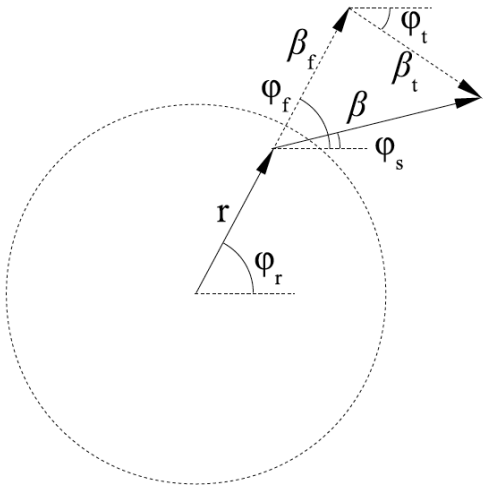
Pair rest frame (PRF):

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

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 ?



Adam Kisiel, *Phy.Rev.C* **81**, 064906 (2010)

$$\beta_{particle} = \beta_f + \beta_t$$

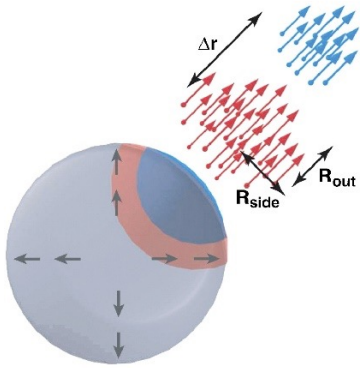
component of mean emission point of a single particle parallel to the velocity

$$\langle x_{out} \rangle = \frac{\langle r\beta_f \rangle}{\left\langle \sqrt{\beta_t^2 + \beta_f^2} \right\rangle} = \frac{r_0 \beta_0 \beta}{\beta_0^2 + T/m_t}$$

assume a Gaussian density profile with radius r_0 and linear transverse velocity profile $\beta_f = \beta_0 r/r_0$

emission asymmetry

$$\mu_{out}^{light,heavy} = \left\langle r_{out}^{light,heavy} \right\rangle = \left\langle x_{out}^{light} - x_{out}^{heavy} \right\rangle$$



- Emission asymmetry only arises in a system where both random (thermal) and correlated (flow) velocities exist and are comparable in magnitude
- Identical particle femtoscopy - source size
- Non-identical particle femtocopy - source size plus emission asymmetry

Experimental Correlation function

$$C(k^*) = \frac{N(k^*)}{D(k^*)}$$

distribution of k^* of pairs from same events

distribution of k^* of pairs from mixed events

where k* : momentum of the first particle (pions) in PRF

Method 1. Cartesian representation (CC)

Measured Correlation functions can be divided into two groups:

- C+ : k* and v aligned (**k***.**v** > 0) i.e. pions are faster
- C- : k* and v anti-aligned (**k***.**v** < 0) i.e. kaons are faster.
- Double ratio C+/C- : sensitive to emission asymmetry (if unity - no asymmetry)

Method 2. Spherical Harmonics representation (SH)

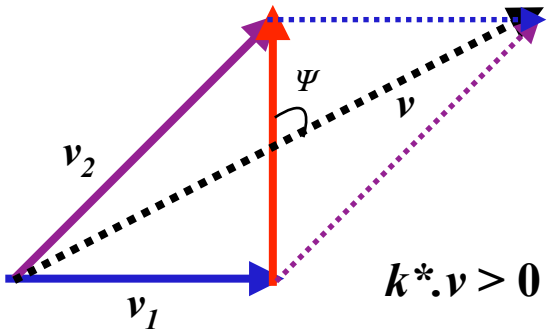
- 3D correlation function converted into infinite set of 1D functions in terms of spherical harmonics (Y_l^m).

  ➡ C_0^0 - reflects the growth of the overall system size;

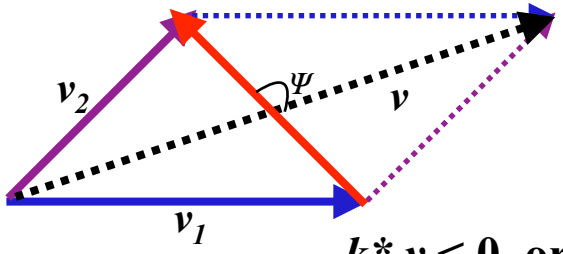
  ➡ Real(C_1^1) - sensitive to emission asymmetry (if zero - no asymmetry)

  ➡ Other terms vanish because of symmetry

Probing space-time asymmetry

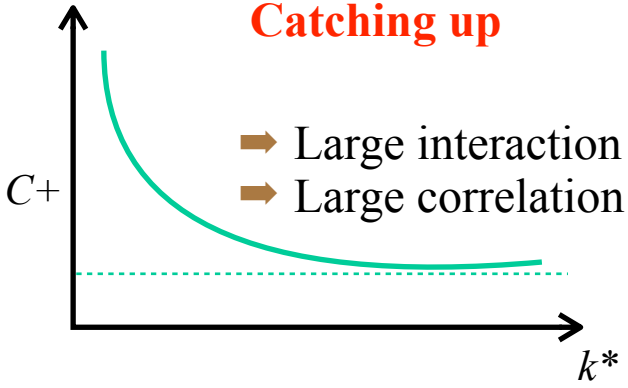


$k^*.v > 0$ or $\cos(\Psi) > 0$



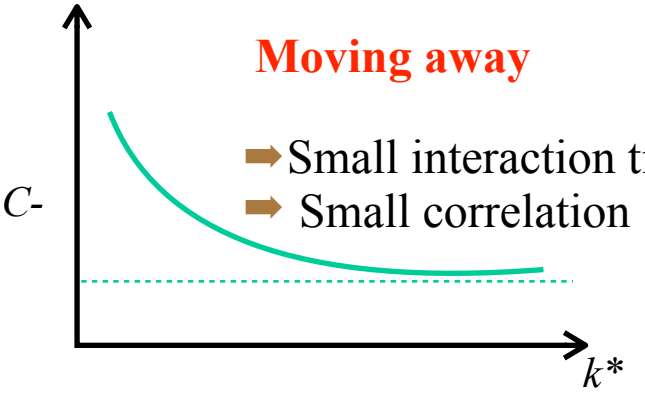
$k^*.v < 0$ or $\cos(\Psi) < 0$

Catching up



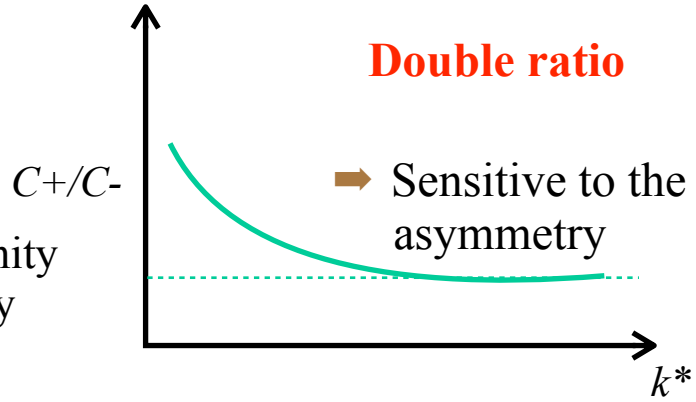
➡ Large interaction time
➡ Large correlation

Moving away



➡ Small interaction time
➡ Small correlation

Double ratio



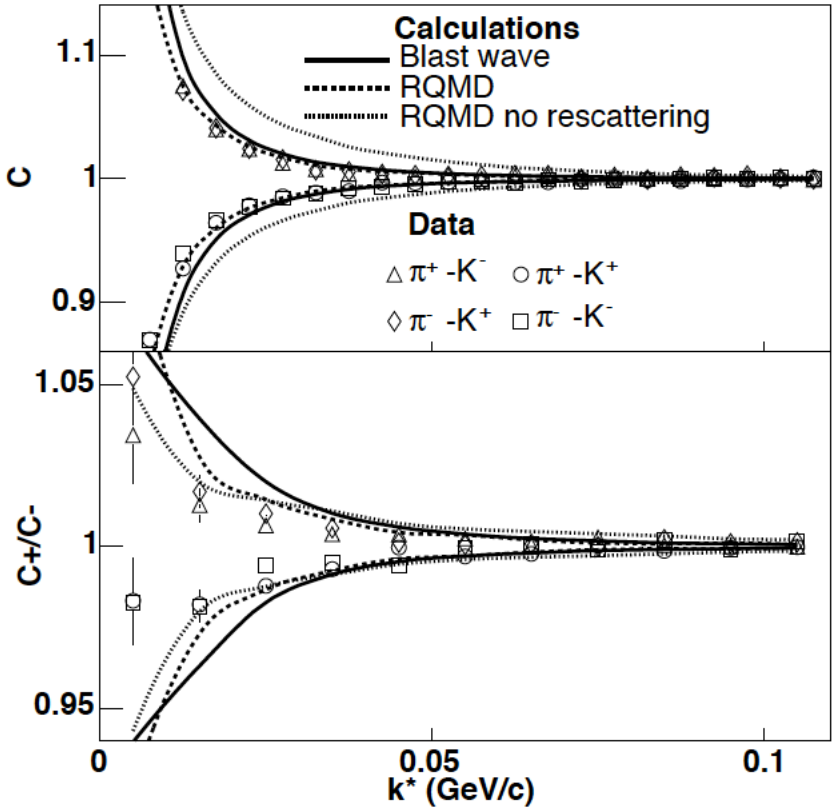
➡ Sensitive to the space-time asymmetry

- C+/C- and Real(C_1^1) (unlike-sign pairs) : above unity
- C+/C- and Real(C_1^1) (like-sign pairs) : below unity

Previous measurement : STAR Au-Au @ 130 GeV

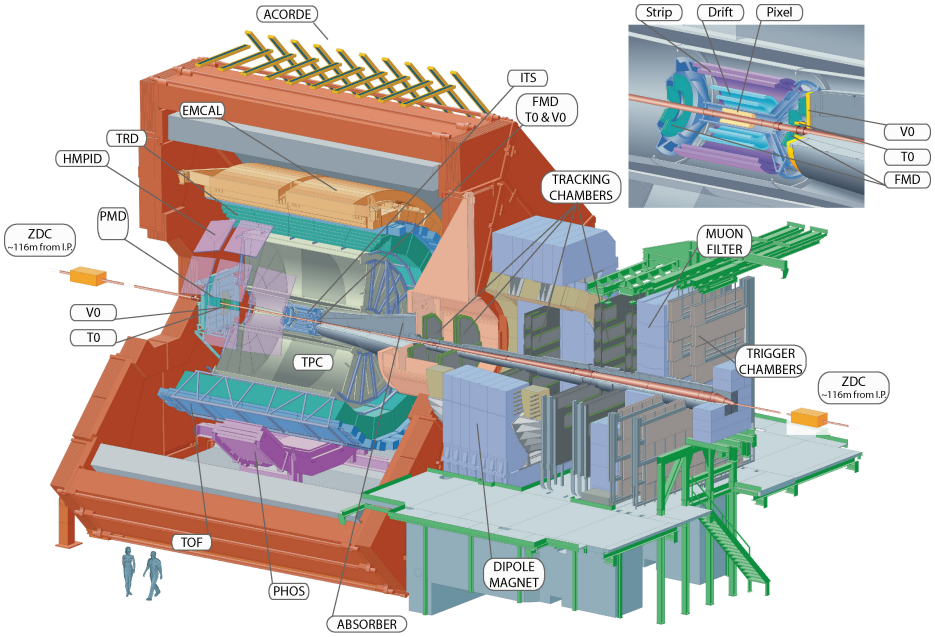
- Emission asymmetry observed between kaons and pions
- On average, pions are emitted closer to the centre/later than kaons

STAR PRL91 262302 (2003)

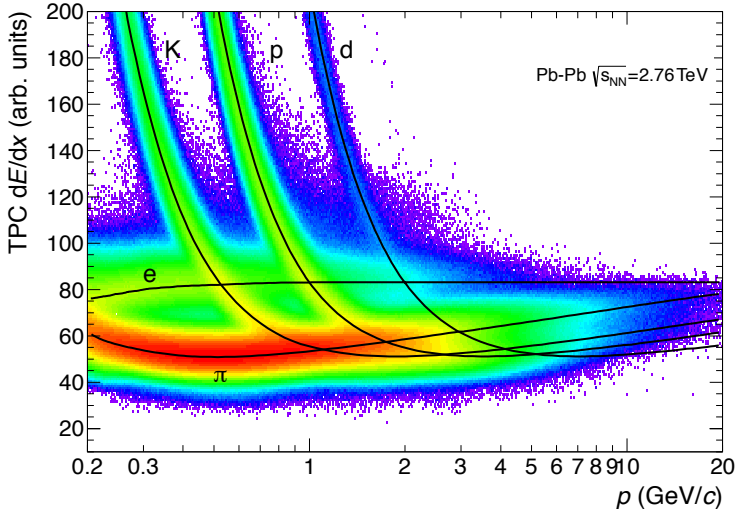


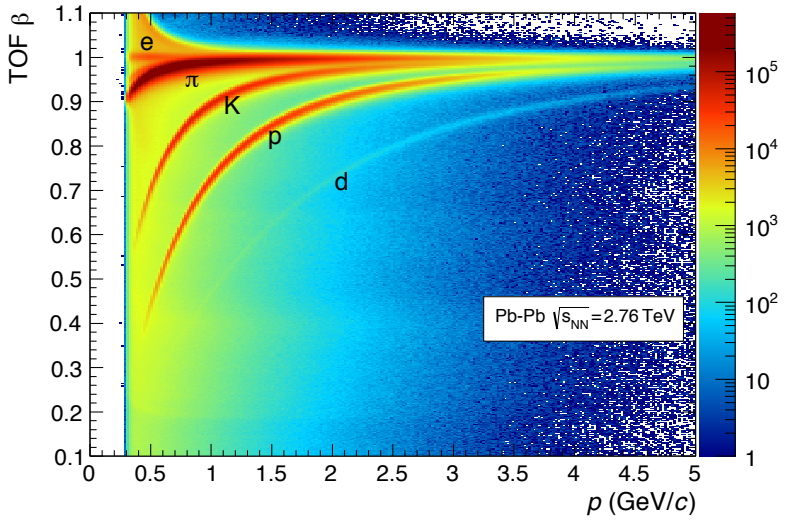
New STAR results : talk by Sebastian Siejka

ALICE detector



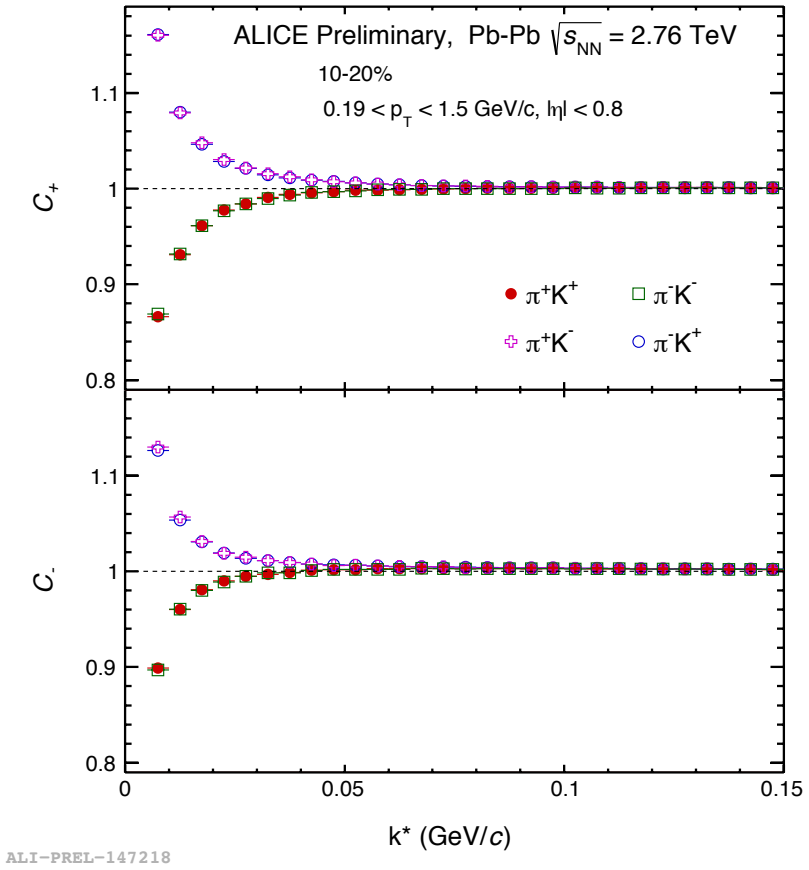
p_T range: 0.19-1.5 GeV/c, $|\eta| < 0.8$

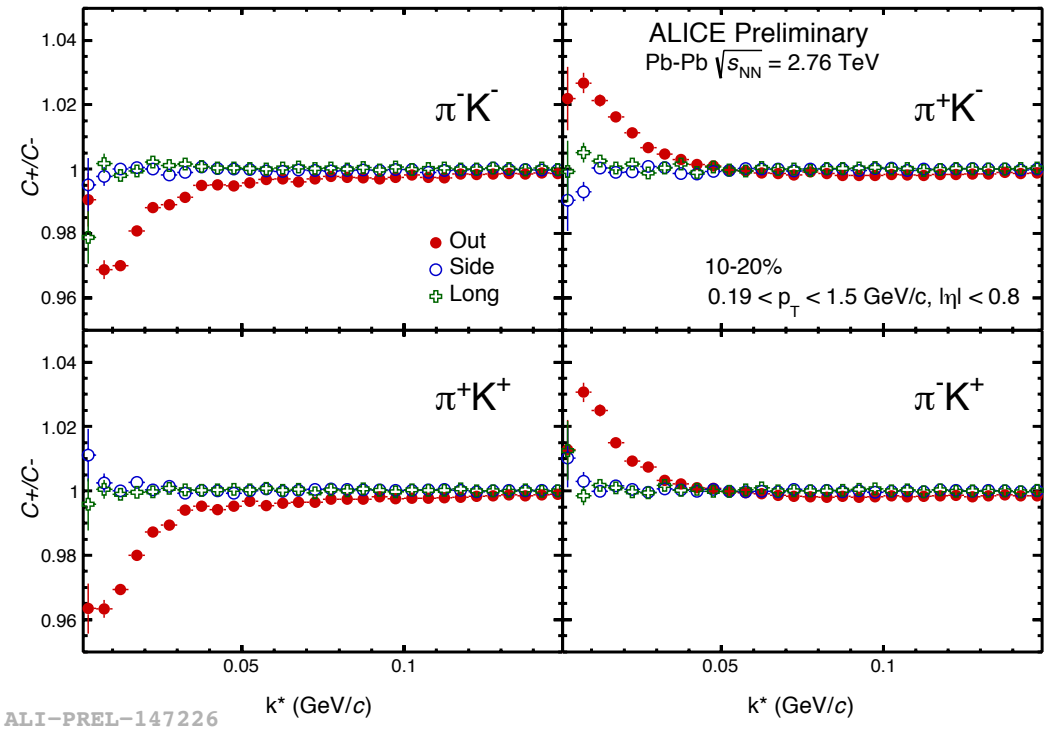




- Excellent tracking by ALICE detector enables us to analyse correlations of particles with low momentum
- TPC was used for track reconstruction
- TPC and TOF are used for particle identification

Correlation Functions (Cartesian representation)





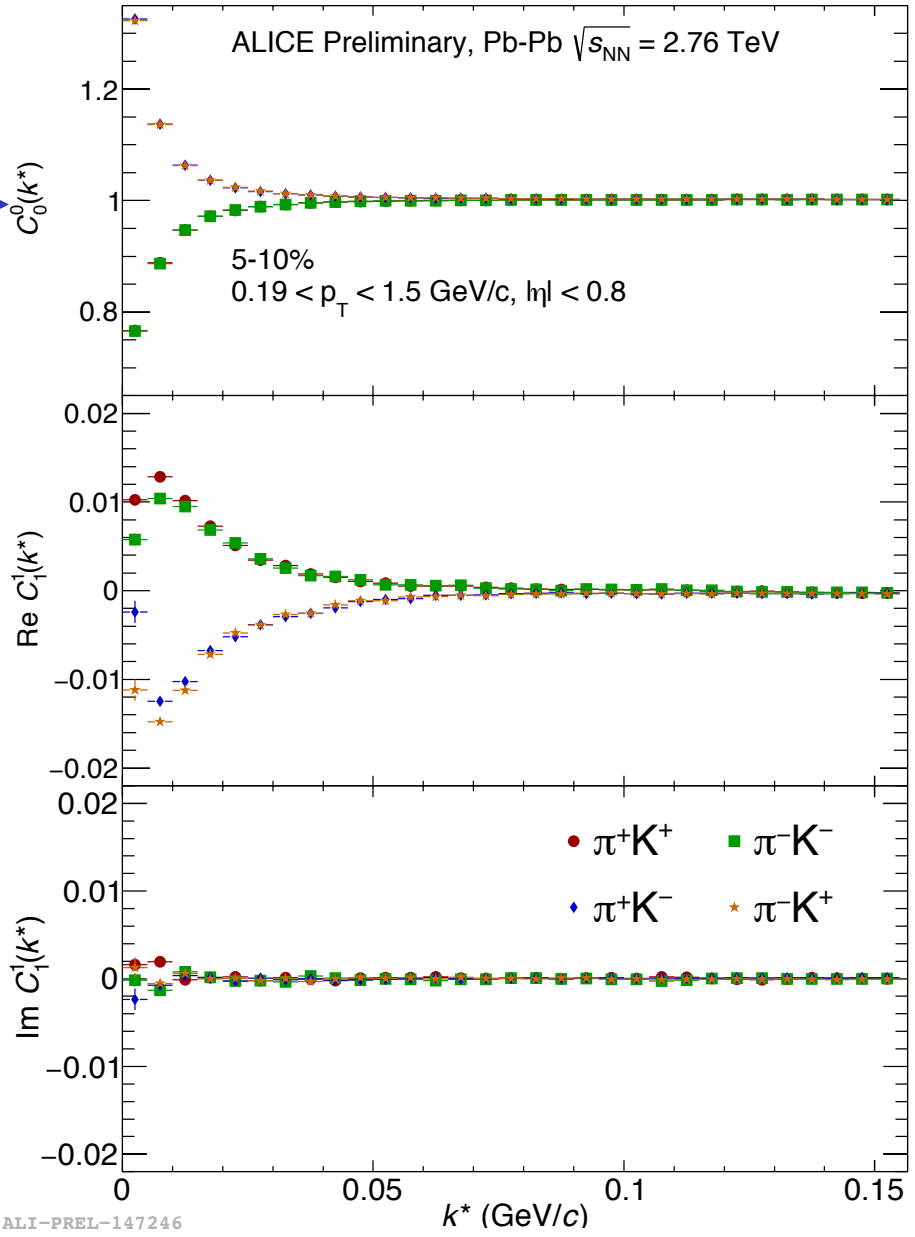
- Double ratio (C_+/C_-) in "out" direction deviates significantly from unity
- On average, pions are emitted closer to the centre/later than kaons
- Double ratio (C_+/C_-) in "side" and "long" directions is consistent with unity

Correlation Functions (Spherical Harmonics)

attractive correlation for unlike-sign pairs & repulsive for like-sign pairs

Significantly deviates from unity - asymmetry exists

Required to vanish due to symmetries



Non-femtoscopic background

Correlation function contains femtoscopic correlation as well as contributions from:

- elliptic flow v_2
- global energy and momentum conservation
- resonance decay correlations
- residual correlations (remnants of the femtoscopic correlations from weakly decaying particles)

Background correction :

$$C_{exp}^{ij} = B^{ij} + |\psi^{ij}|^2$$

where i,j are +,- (pion-kaon)

Experimental correlation function

Non-femtoscopic background

real femtoscopic correlation

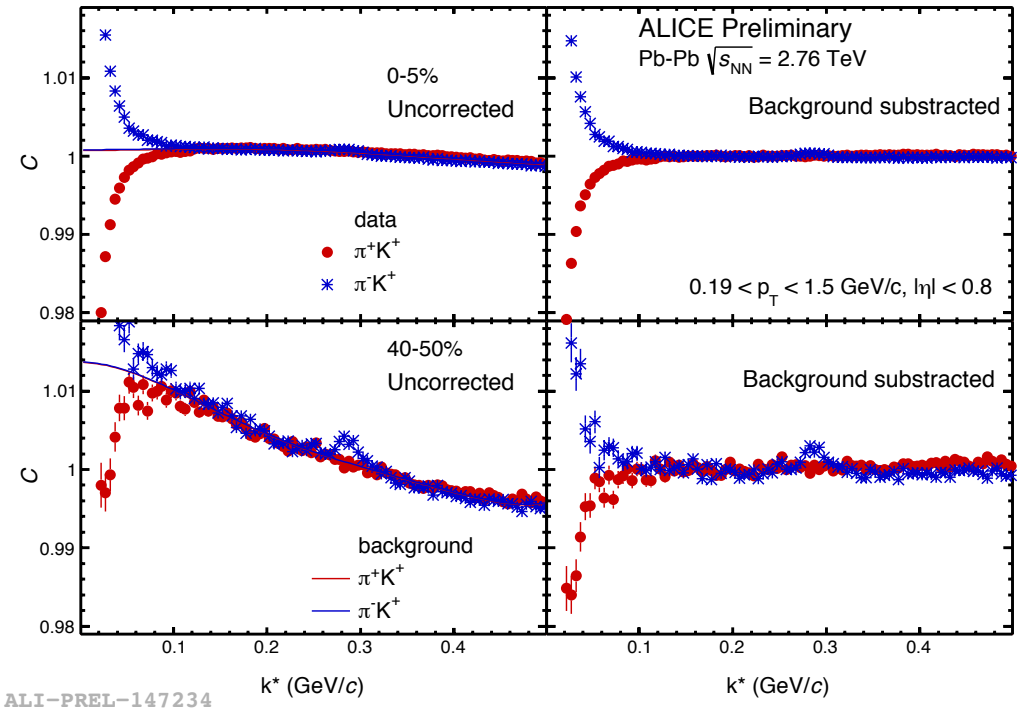
$$B^{ij} = a_0^{ij} + \sum_{l=1}^{5} a_l x^{(l+1)}$$

Adam Kisiel, ACTA PHYSICA POLONICA B, Vol. 48 (2017)

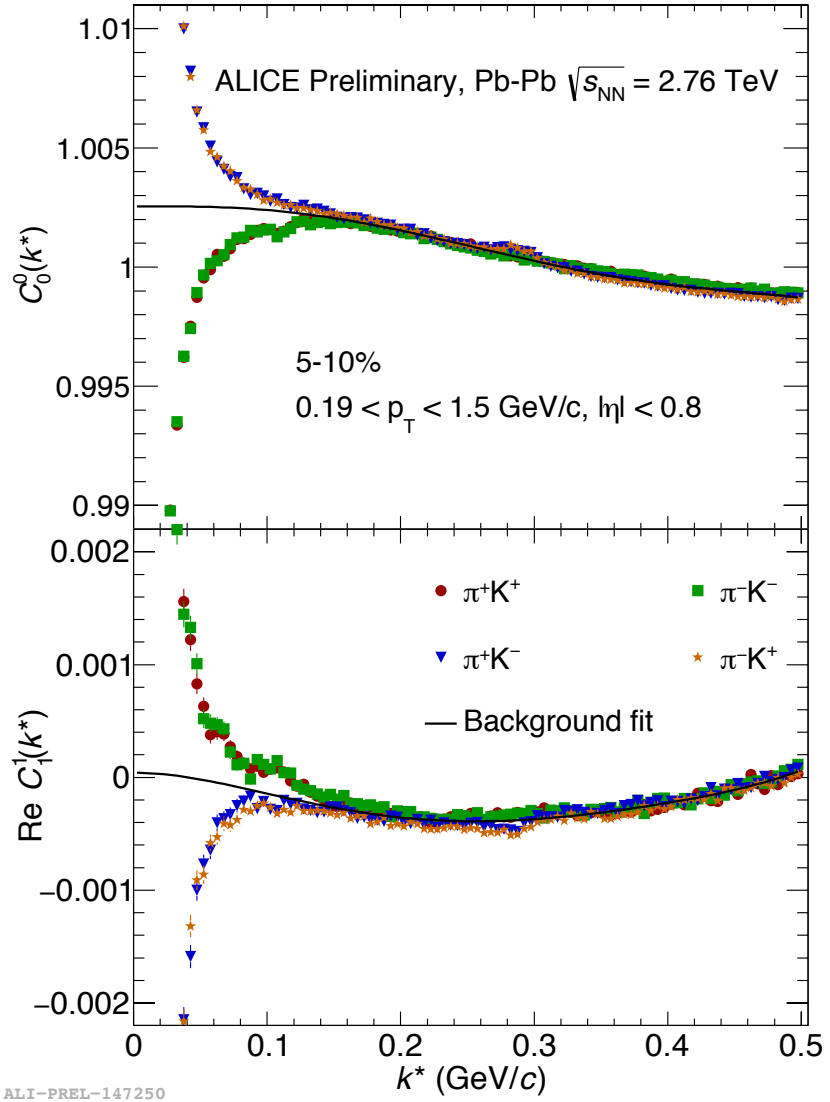
$$C_{real}^{ij} = C_{exp}^{ij} - B^{ij}$$

Non-femtoscopic background contribution in the data

Cartesian representation



Spherical Harmonics



- Non-femtoscopic background function shape changes from central to peripheral collisions

Extracting the source size and emission asymmetry

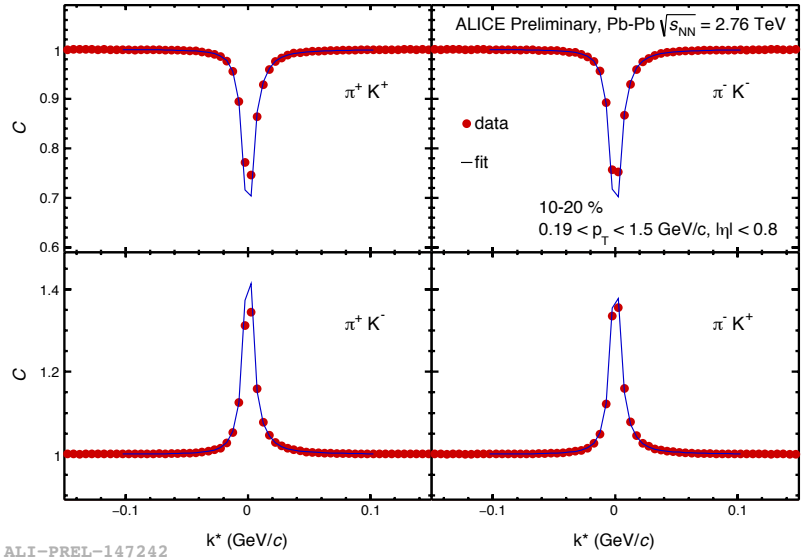
$$\mathbf{C(k^*) = \int dr' |\psi(k^*, r')|^2 S(r')}$$

known unknown

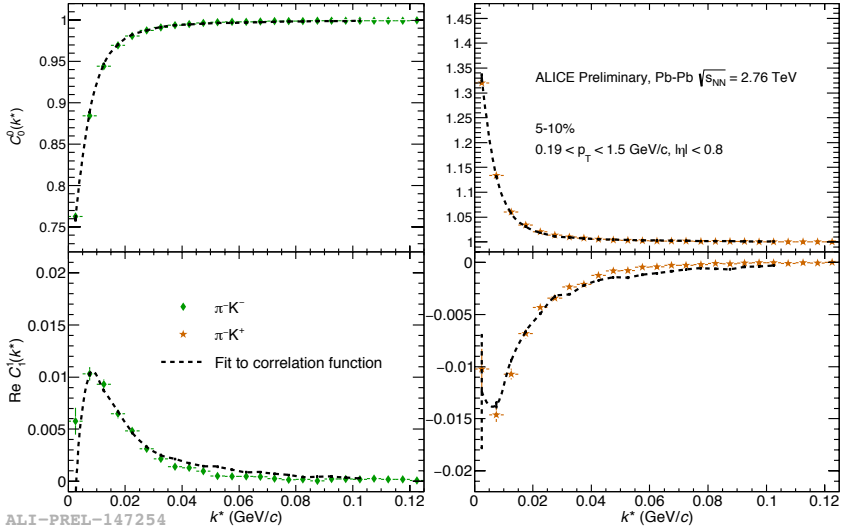
$$S(\mathbf{r}) = exp\left(-\frac{(r_{out}-\mu_{out})^2}{R_{out}^2} - \frac{r_{side}^2}{R_{side}^2} - \frac{r_{long}^2}{R_{long}^2}\right)$$

- $R_{side} = \alpha R_{out}$, $R_{long} = \gamma R_{out}$, α is fixed to 1, γ is fixed to 1.3 based on identical pion femtoscopic measurements
- Can't measure R_{out}, R_{side}, R_{long} and μ_{out} together (too many free parameters), need more statistics to measure C_0^0, C_1^1, C_0^2 and C_2^2 components for it

Cartesian representation

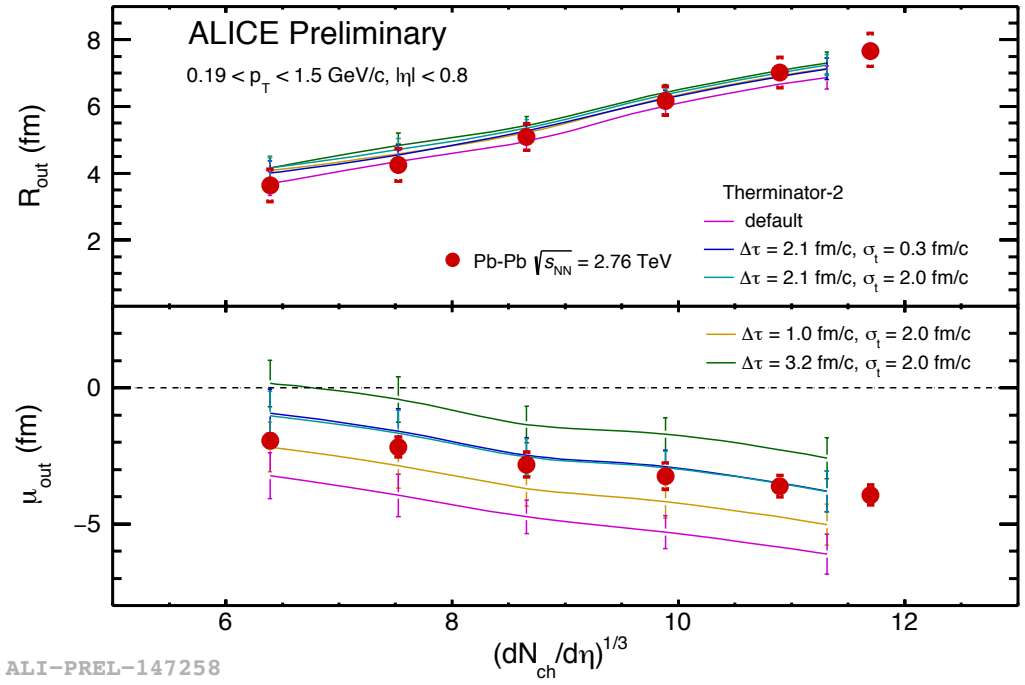


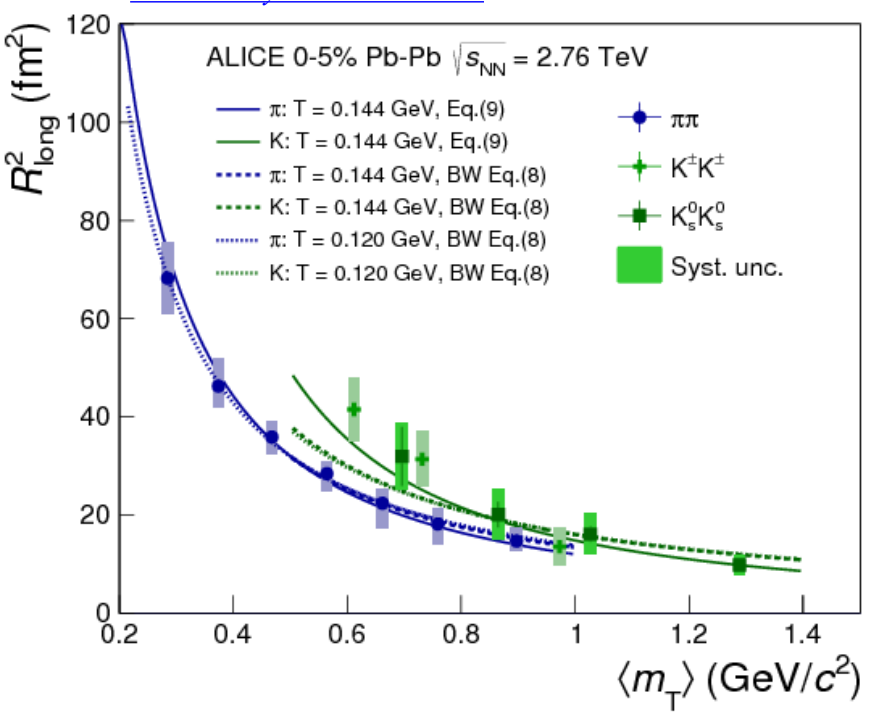
Spherical Harmonics



Extraction using CorrFit package (Adam Kisiel, NUKLEONIKA 2004;49(Supplement 2):S81−S83)

Results: source size and emission asymmetry





- Significant pion-kaon emission asymmetry is observed which increases with centrality.
- Source size increases from peripheral to central collisions
- Blast-wave fits of ALICE identical pion and kaon data show 2.1 fm/*c* delay between pion and kaon average emission time.
- The pion-kaon data is consistent with such delay. It is independent and possibly more precise measurement of such delay

Therminator-2 results : Adam Kisiel, *arXiv:1804.06781*

Summary

- First measurement of emission asymmetry at the LHC in Pb-Pb collisions at 2.76 TeV
- Results indicate that “pions emitted closer to the centre/later than kaons”
- It is expected in a system with strong collectivity which includes flow of resonances (consistent with model predictions, e.g. Therminator2)
- Source size increases 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

THANK YOU