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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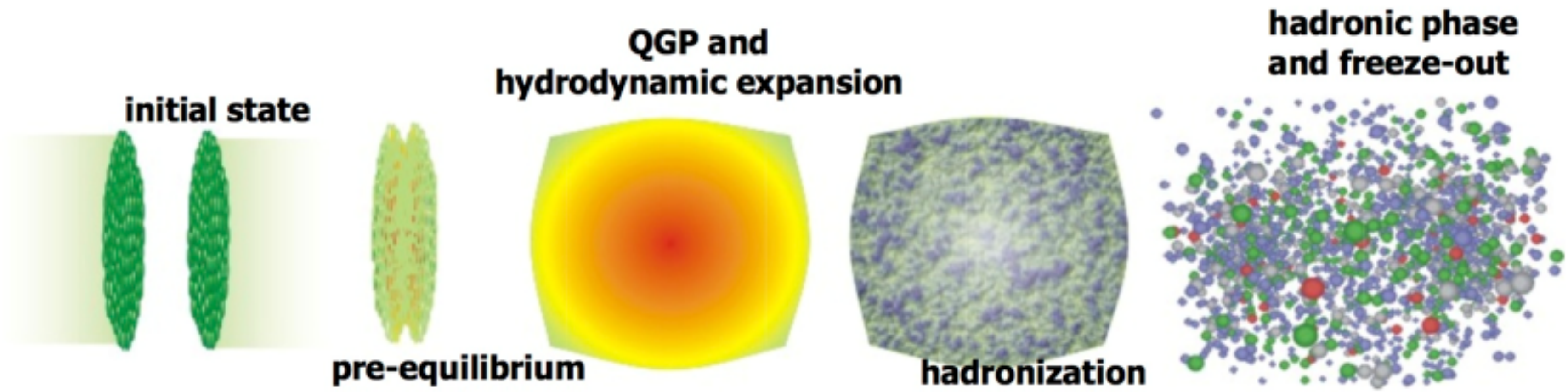
Introduction

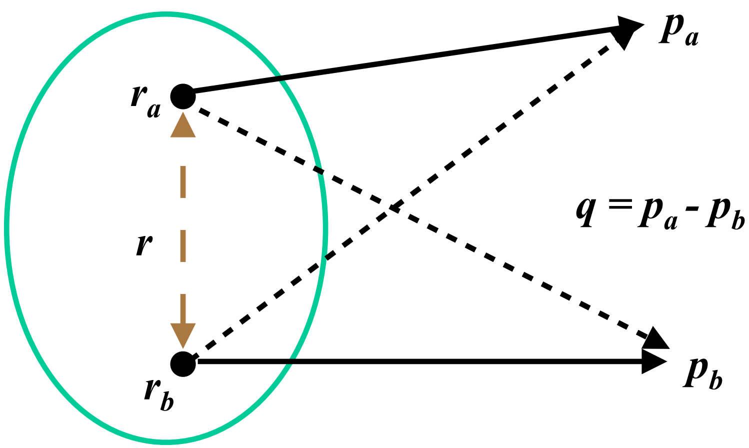
- Big-Bang theory of the universe predicts that matter existed in QGP form after ~1 μs of the universe formation
- Lattice QCD predicts QGP at ~170 MeV temperature



- 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

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



Koonin-Pratt Equation,

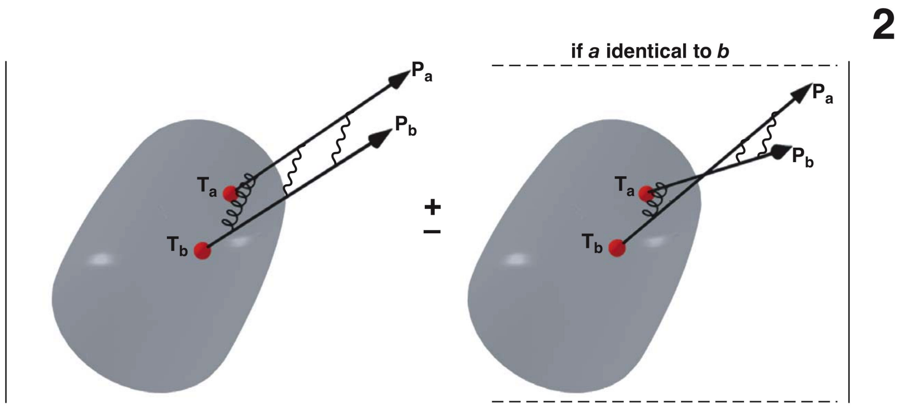
PLB70 (1977) **43**,*S. Pratt et al.*, PRC42 (1990) 2646

Source function

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

Experimental correlation function

Pair wave 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

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

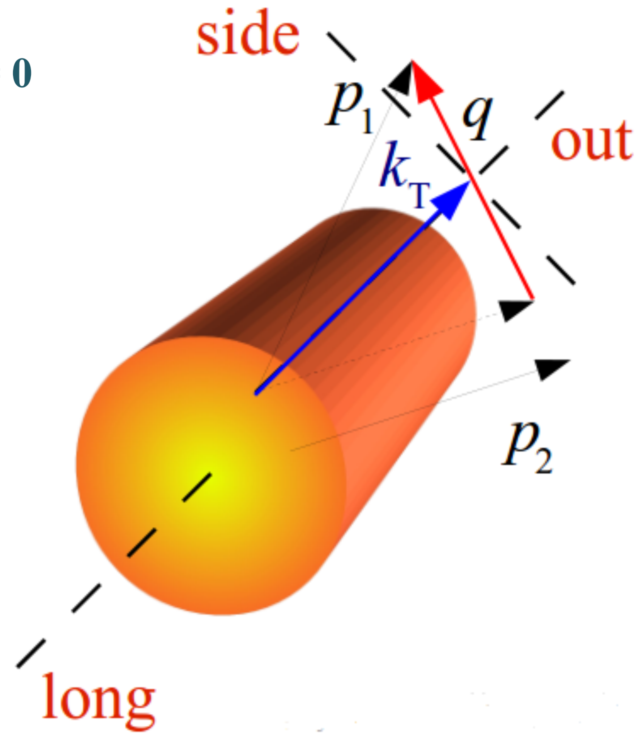
Longitudinal co-moving system (LCMS):

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

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

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

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



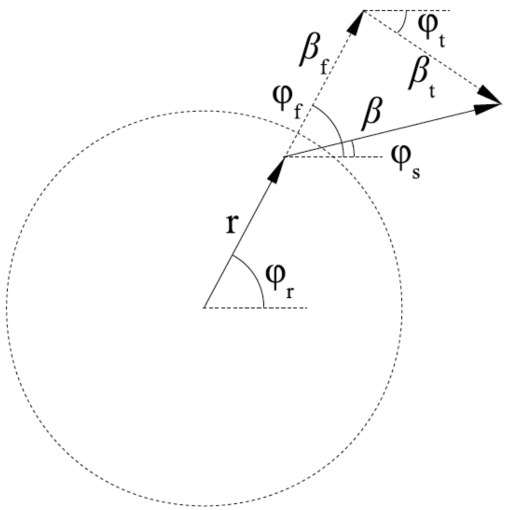
Pair rest frame (PRF):

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

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)

- In a hydrodynamical induced system :

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

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

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

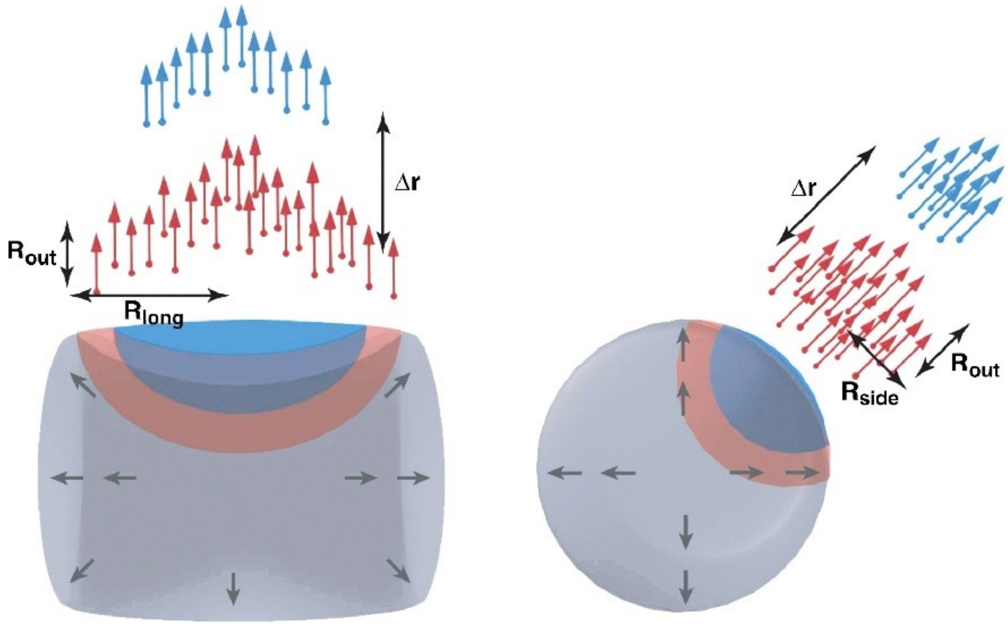
assume a Gaussian density profile with radius r_0 and linear transverse velocity profile $\beta_f = \beta_0 r/r_0$ then we

emission asymmetry

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

- 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.) ?



Lisa MA, et al. 2005.
Annu. Rev. Nucl. Part. Sci. 55:357–402

- 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

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

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

where ***v*** is pair velocity

Double Ratio : C+/C-

$\downarrow$

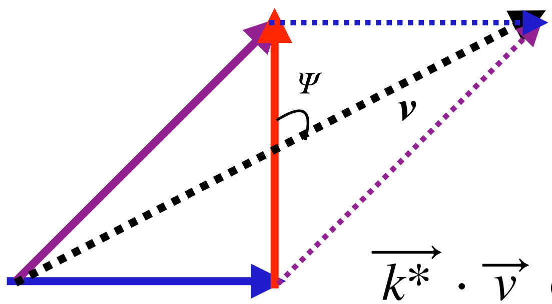
Sensitive to emission asymmetry and equal to unity if asymmetry is absent.

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

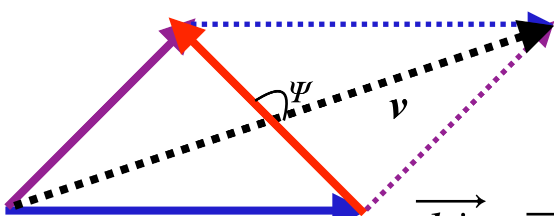
Probing space-time asymmetry

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

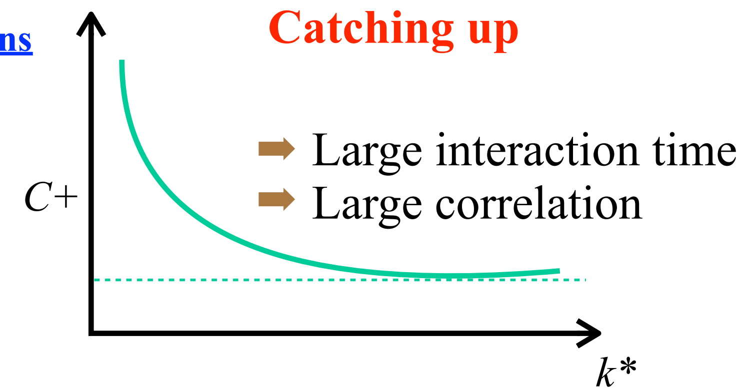


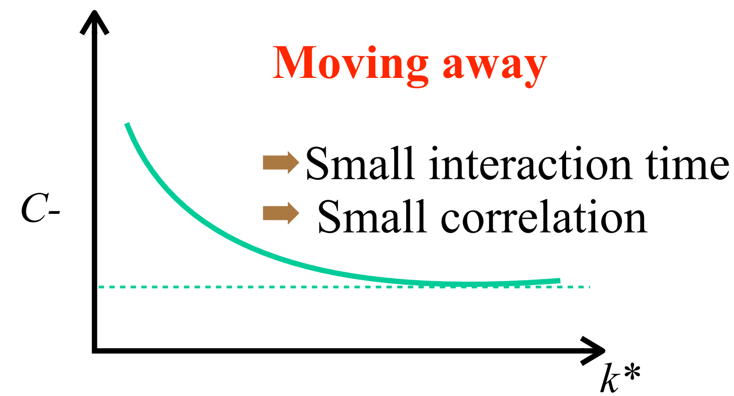
$\vec{k^*} \cdot \vec{v}$ or $\cos(\psi) > 0$

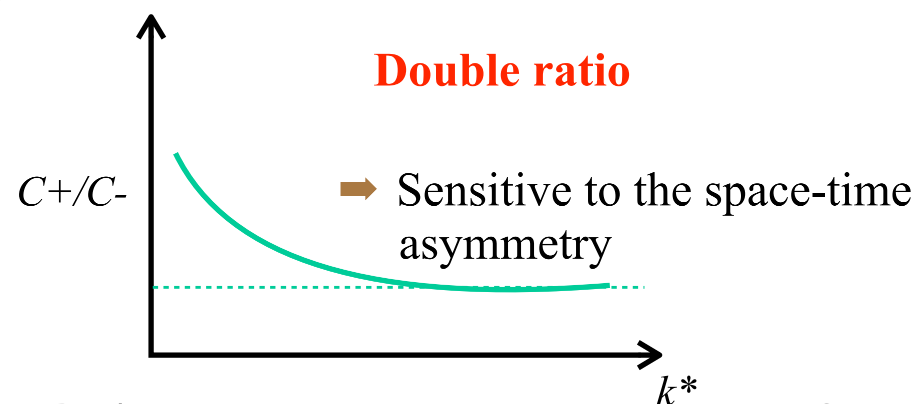
Kaon
Pion



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



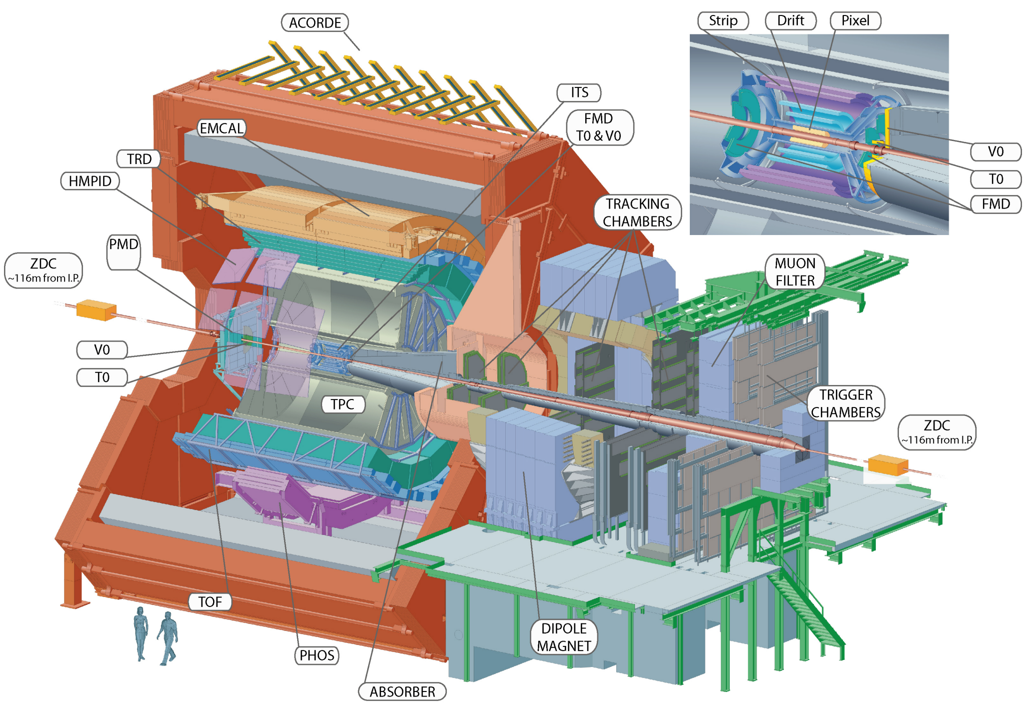


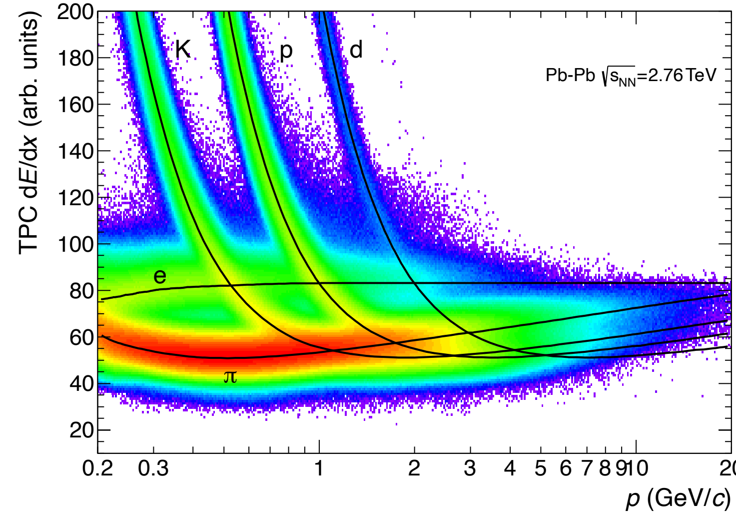


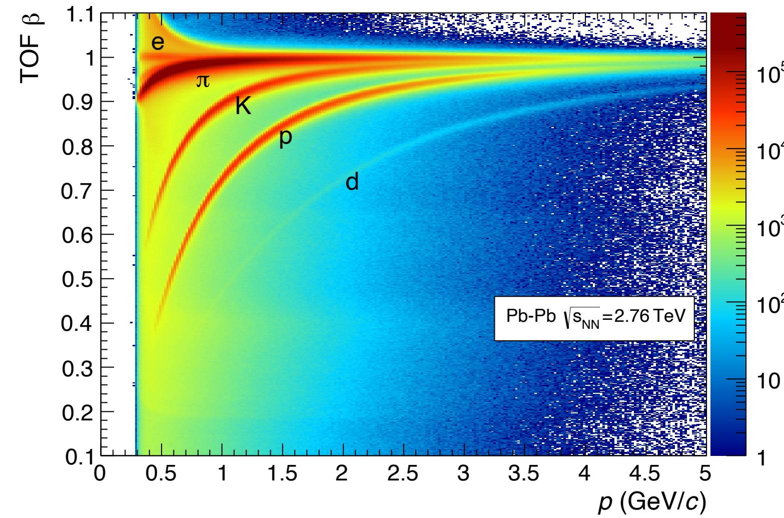
- C+/C- (unlike-sign pairs) : above unity
- C+/C- (like-sign pairs) : below unity

ALICE detector

Dedicated to study hot and dense strongly interacting matter : QGP



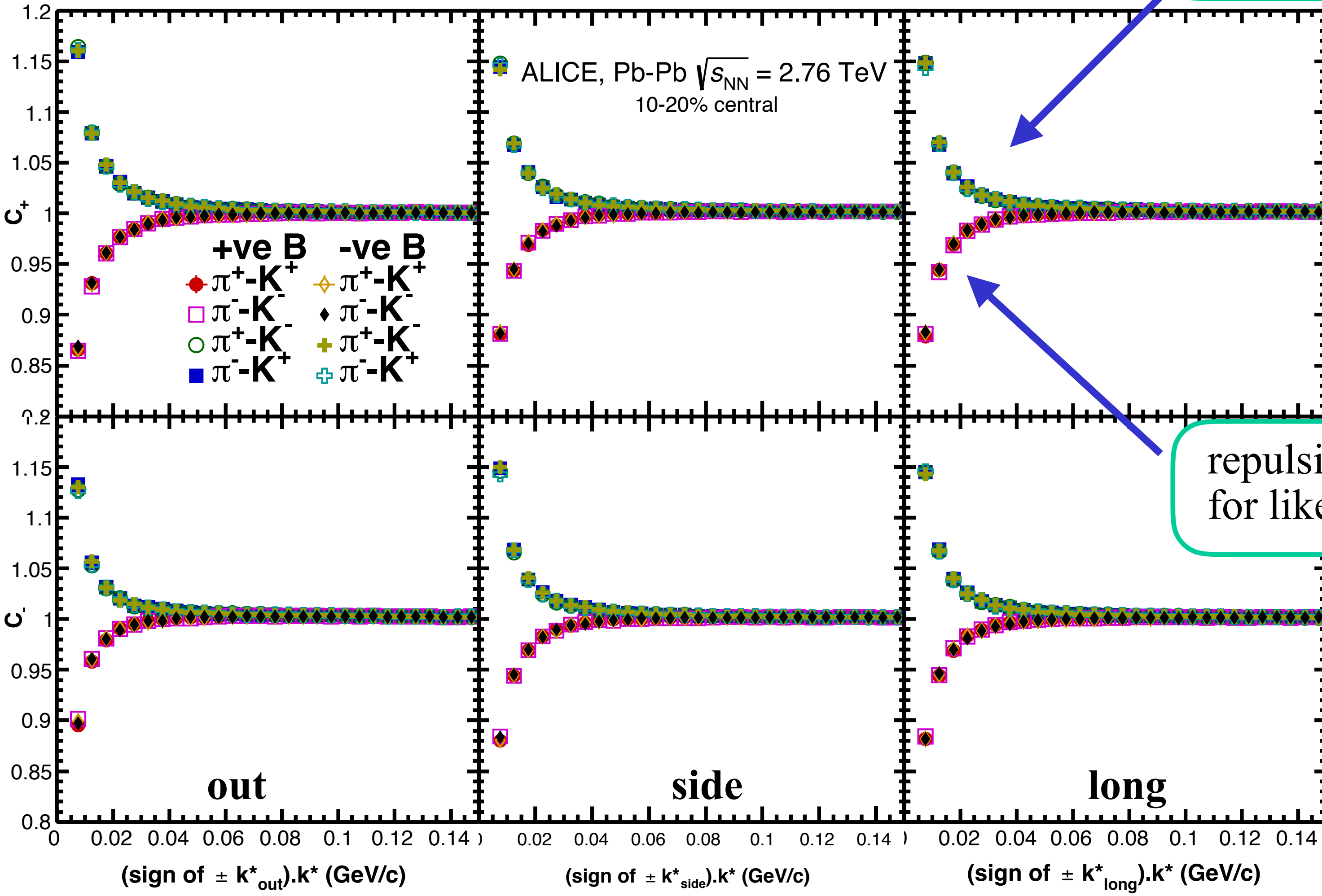




- Excellent tracking by ALICE detector enables us to analyse correlations of particles with low momentum
- TPC was used for track reconstruction
- TPC and TOF are used for particle identification

Correlation Functions

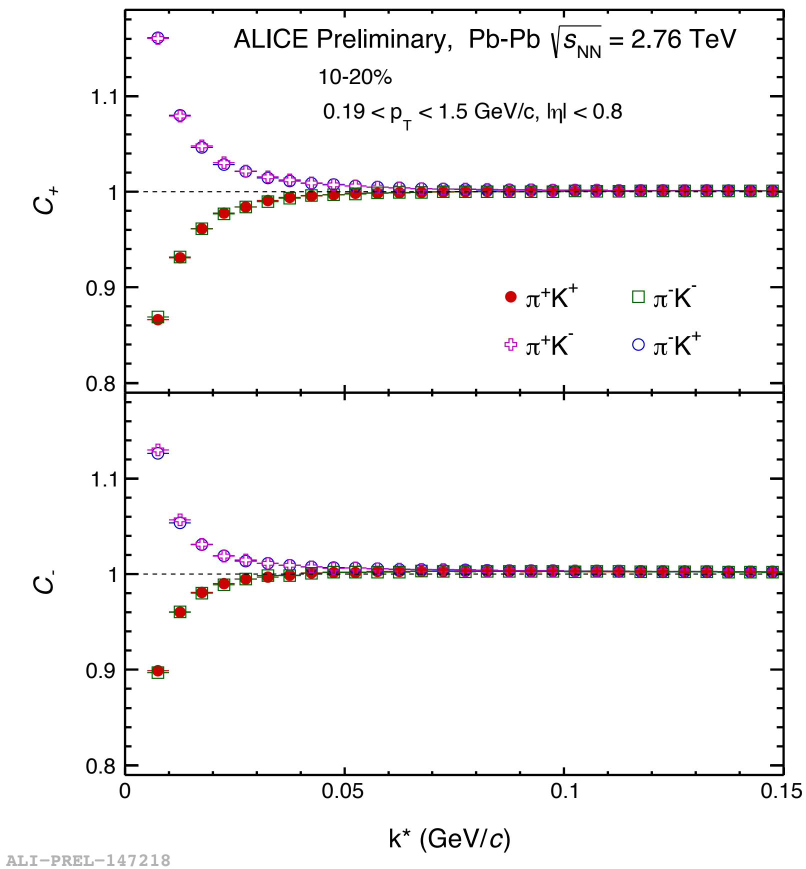
attractive correlation for unlike-sign pairs

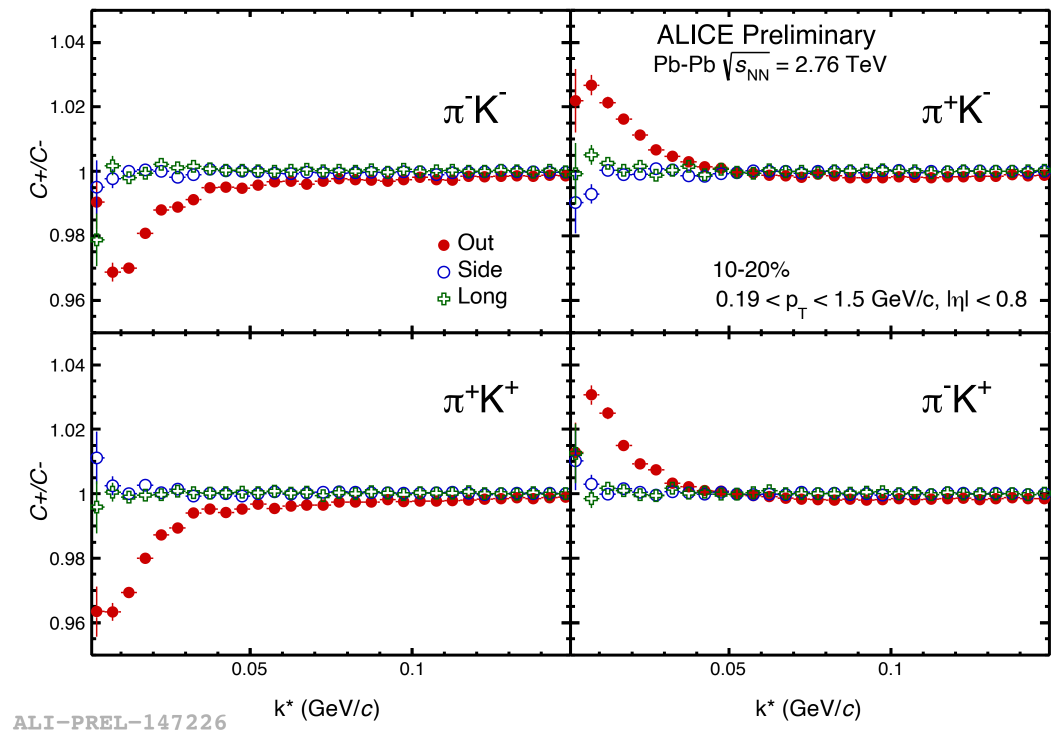


repulsive correlation for like-sign pairs

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

Correlation Functions





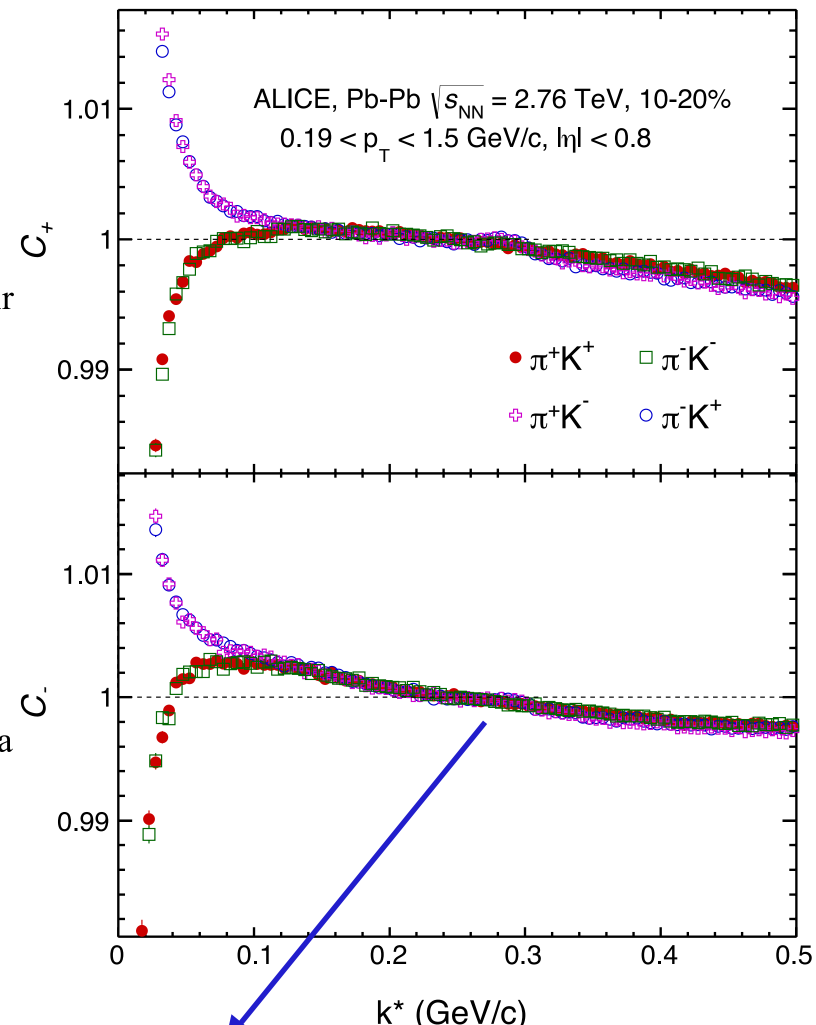
- Double ratio (C_+/C_-) in "out" direction deviates significantly from unity
- On average, pions are emitted closer to the centre/later than kaons
- Double ratio (C_+/C_-) in "side" and "long" directions is consistent with unity (expected from azimuthal and mid-rapidity symmetries)

Non-femtoscopic background

Correlation function contains femtoscopic correlation as well as contributions from:

Elliptic flow (v_2):

- All particles (including pions and kaons) from an events are more likely emitted in a specific direction due to presence of v_2 and their momenta tend to point in 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

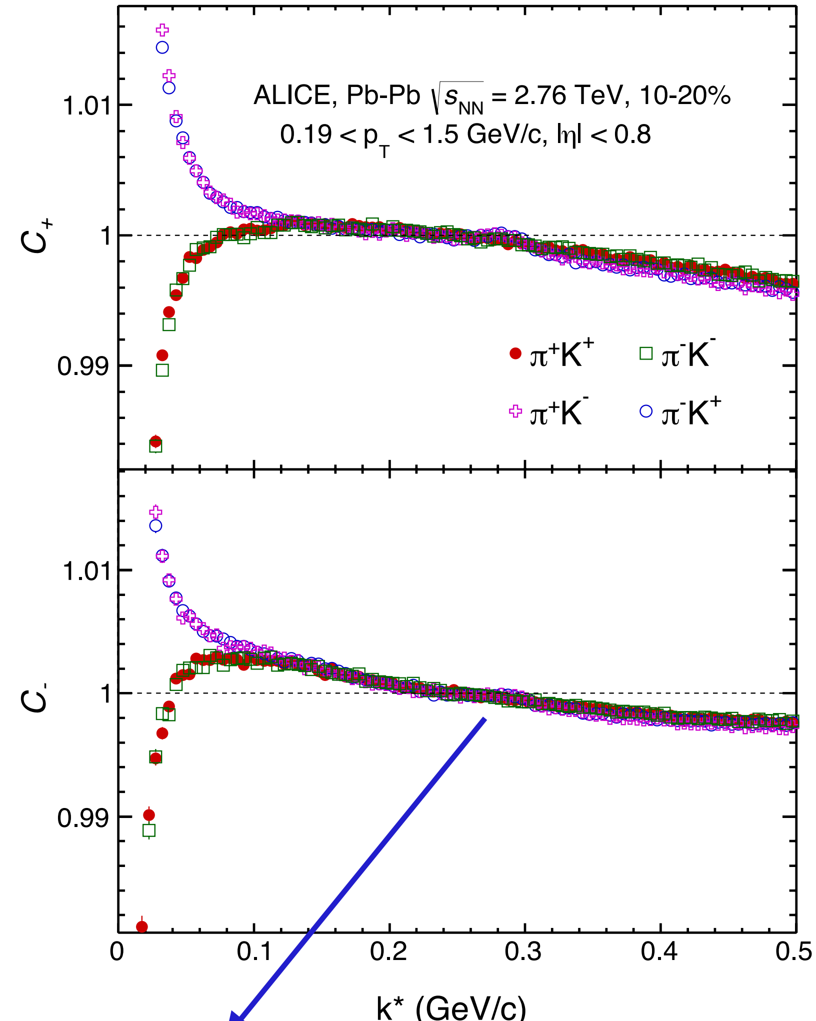
Non-femtoscopic background

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

Non-femtoscopic background correction

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

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

Experimental correlation function

Non-femtoscopic background

real femtoscopic correlation

For Coulomb interaction at a given k*: $C_{SS} = 1/C_{OS}$

With a background "*B*": $$(C_{exp,SS} - B) = \frac{1}{(C_{exp,OS} - B)}$$

Background function "*B*": $$B^{ij} = a_0^{ij} + \sum_{l=1}^{5} a_l x^{(l+1)}$$

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

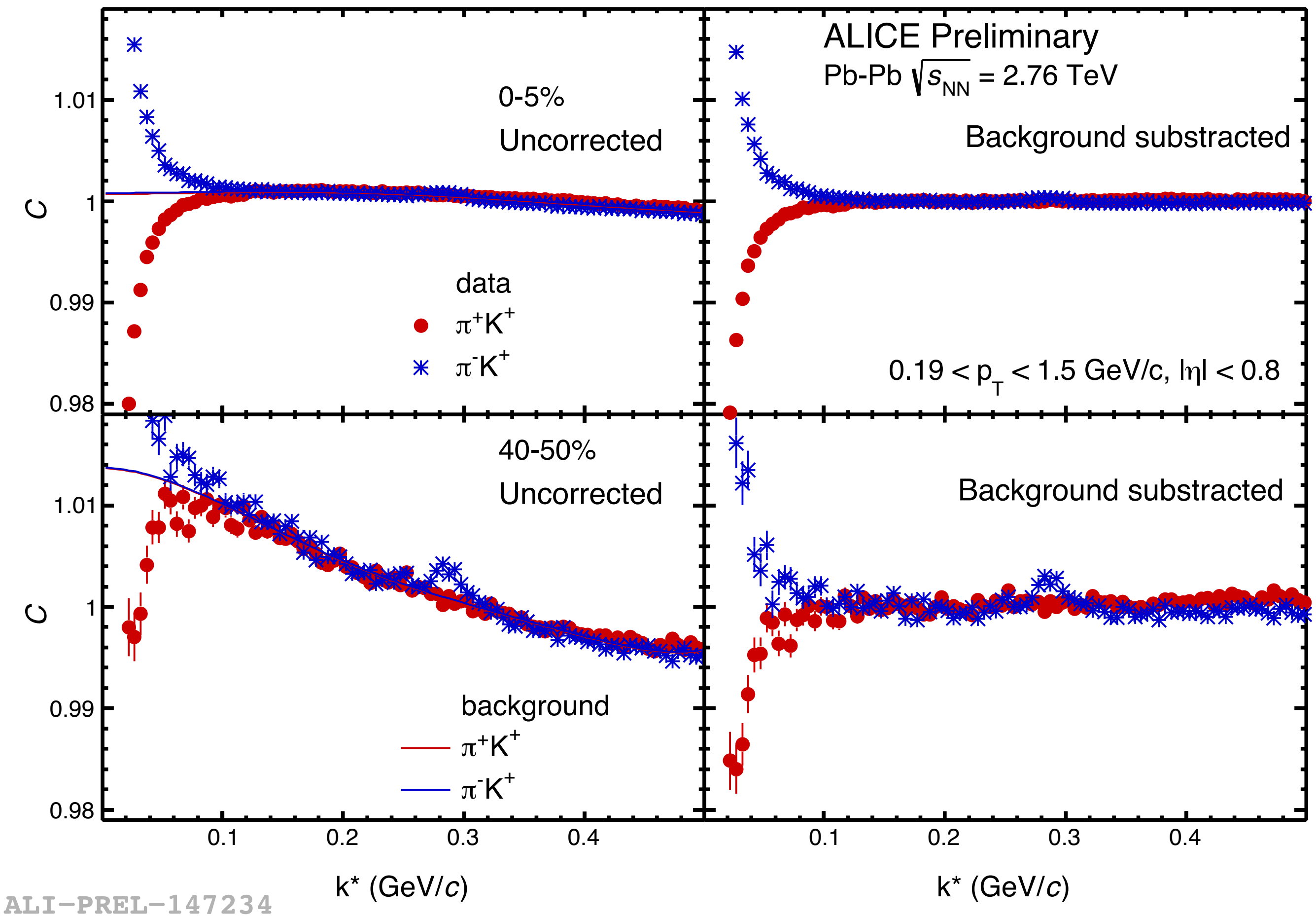
$$\chi^2_{background} = \frac{1}{\sigma^2_{tot}}\left[(C^{++} - B) - \frac{1}{(C^{+-} - B)}\right]^2 + \frac{1}{\sigma^2_{tot}}\left[(C^{--} - B) - \frac{1}{(C^{+-} - B)}\right]^2$$

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

Sum of errors for all pairs at given k*

$$C^{ij}_{real} = C^{ij}_{exp} - B^{ij}$$

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

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

known from experiment

unknown

Pair wave function: (treated as weight)

$$\Psi_{pair} = \Psi_{motion} + \Psi_{FSI}$$

Interaction term

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

Combination of the regular and singular s-wave Coulomb functions

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

Confluent hypergeometric function

Gamow factor

Strong scattering amplitude, modified by the Coulomb interaction

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

Extracting the source size and emission asymmetry

$$\eta = \frac{1}{k^* a_C}$$

a_C → Bohr radius of the pair (248.52 fm for pion-kaon)

$$\zeta = k^* r^* (1 + \cos\theta^*)$$

θ^* → Angle between k* and pair relative position r* in PRF

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

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:

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

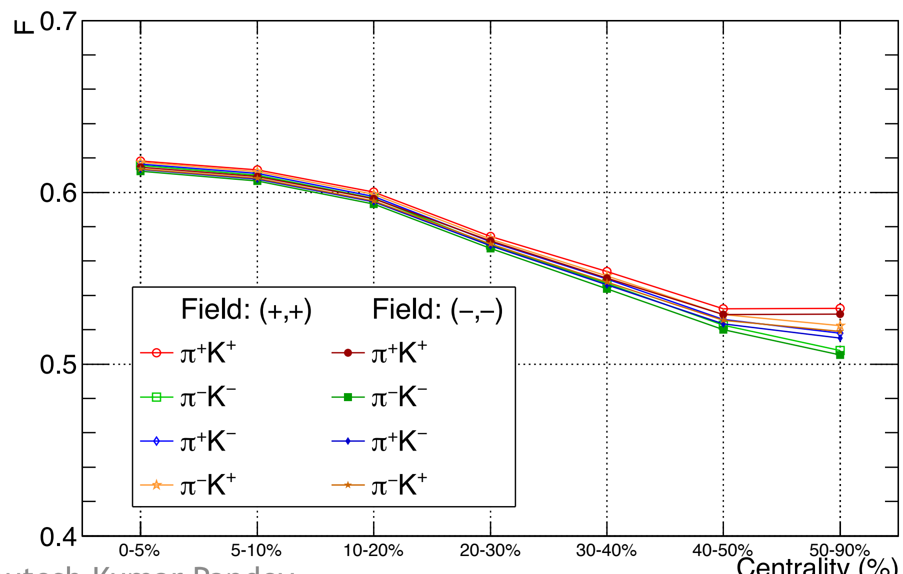
Fitting: using CorrFit package, generate correlation function using Monte-Carlo method

(Adam Kisiel, NUKLEONIKA 2004;49(Supplement 2):S81−S83)

CorrFit Input: Fraction of primary, correctly identified pairs

$$F^s_{\pi^\pm K^\pm}(c) = p^s_\pi(c)\cdot p^s_K(c)\cdot f^s_{\pi^\pm}(c)\cdot f^s_{K^\pm}(c)\cdot g^s(c)$$

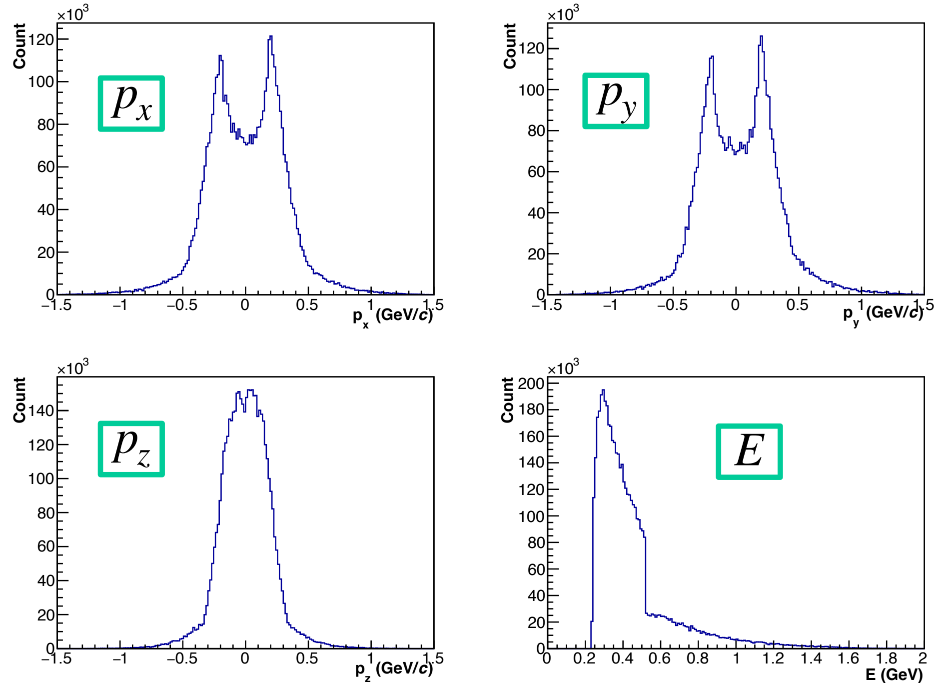
- F is a fraction of primary, correctly identified pairs of particles that fits under the assumed Gaussian profile,
- p is the purity of particles,
- f is the fraction of primary particles,
- g is the fraction of femtoscopically correlated pairs under assumed Gaussian profile,
- c is centrality class, 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)

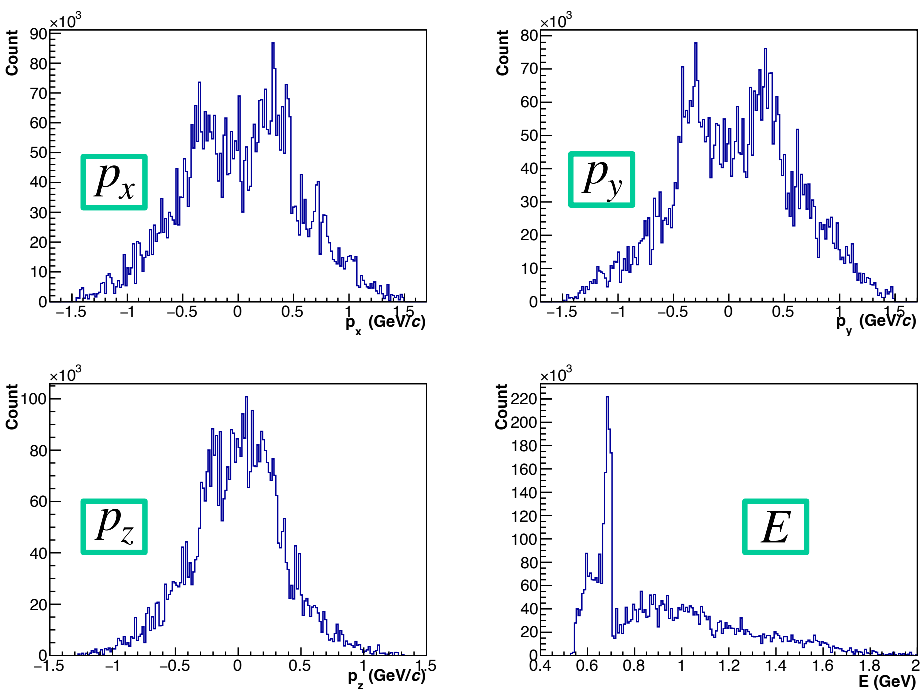


CorrFit Input (cont.)

Ideally, generated correlation function should be able to reproduce momentum distributions and freeze-out conditions of particles, which is very hard

Pion four momentum distribution



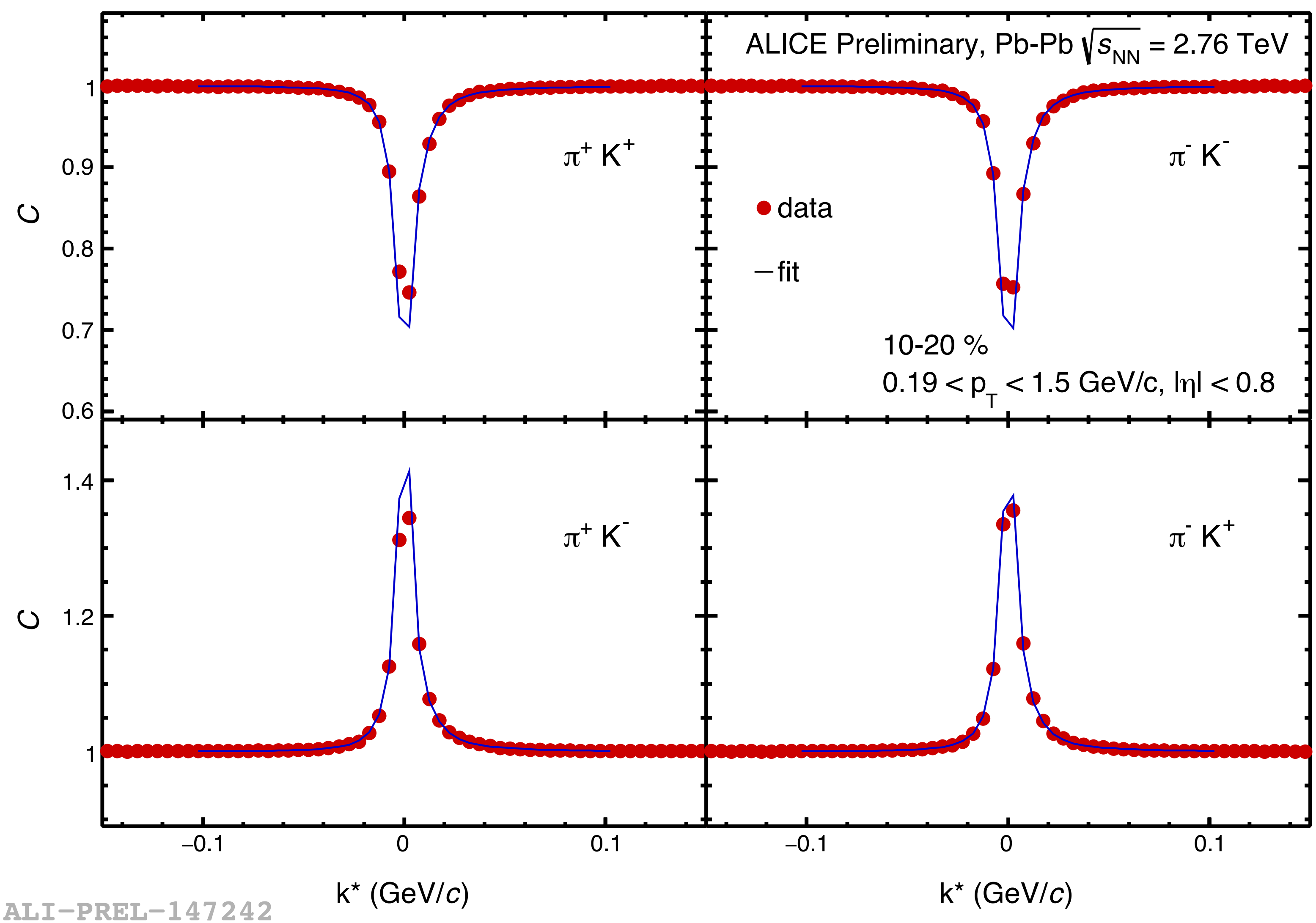


Kaon four momentum distribution

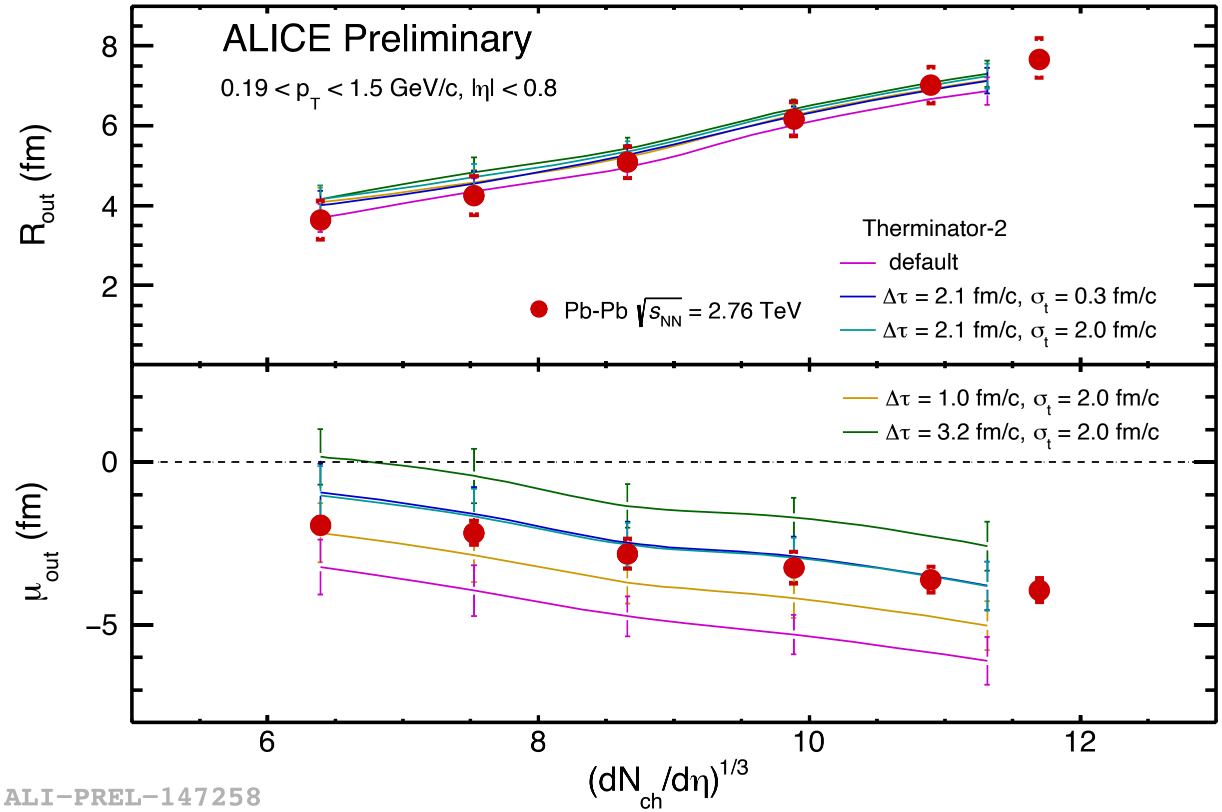
Fitting: CorrFit Input (cont.)

- **CorrelationFitter** = CFFitterNonId
- **SourceModel** = SourceModelGausLCMS
- **Fitting range of R_{out}** : (3.0,12.0) fm
- **Fitting range of μ_{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:



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

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**
- **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

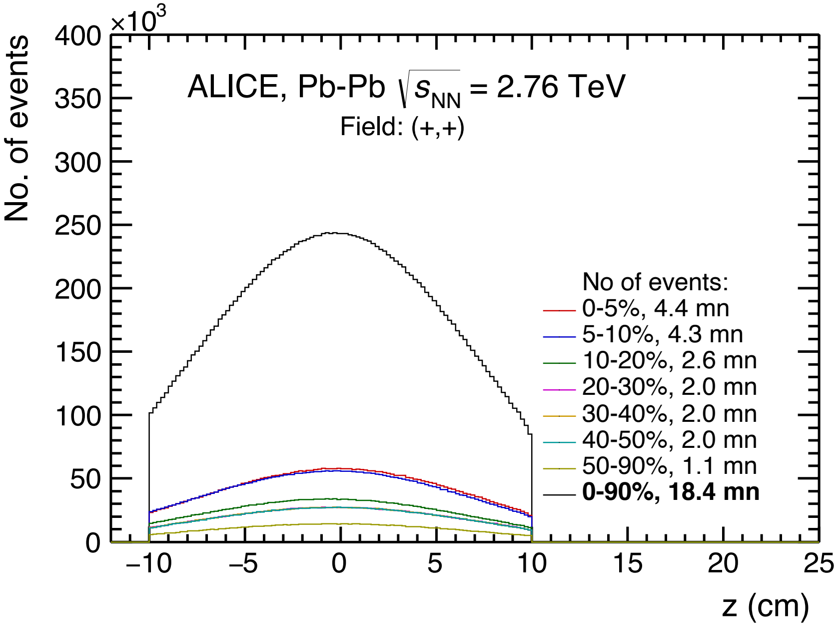
Analysis Details

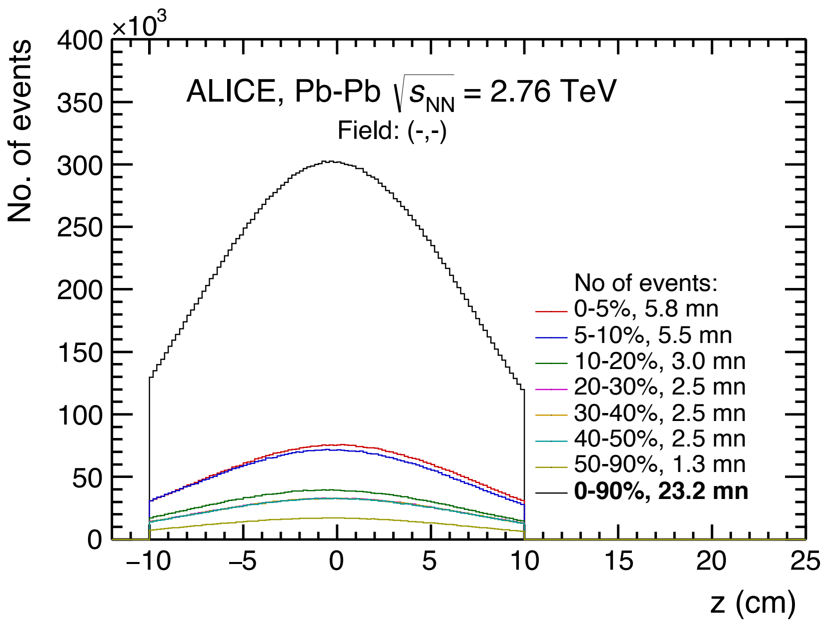
Data set : **Pb-Pb@2.76 TeV :** LHC11h_pass2 (AOD145)

Magnetic field polarity: +ve and -ve

Event Selection: $|V_z| < 10.0$ cm

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

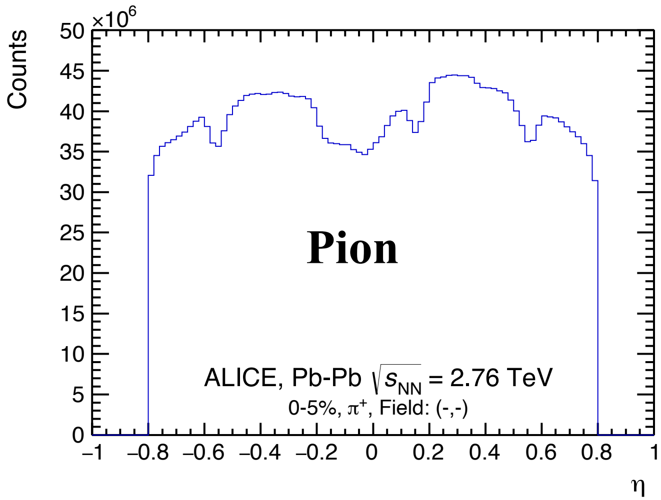


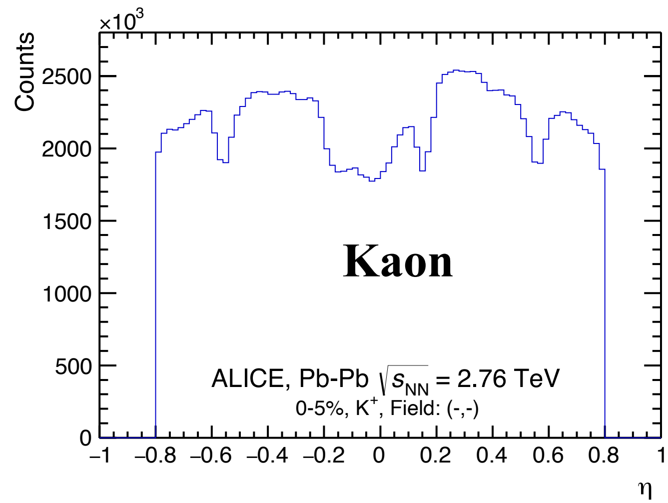


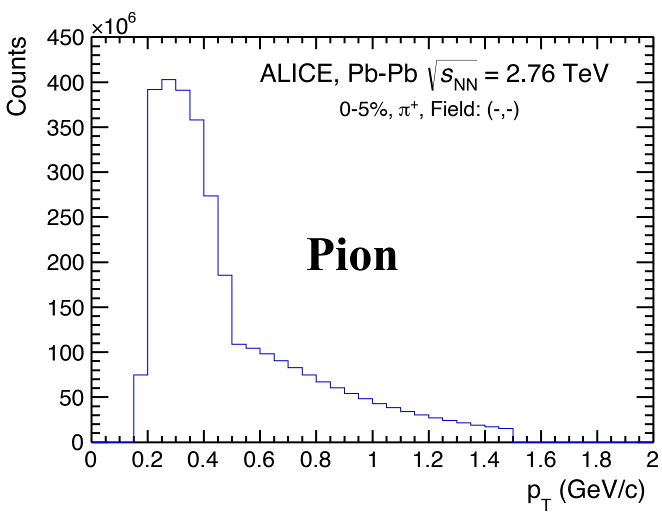
Analysis Details (Cont.)

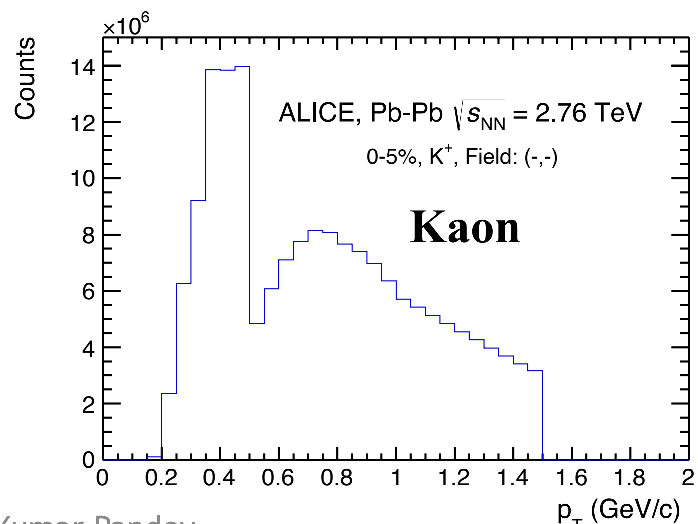
Track Selection: Filter Bit 7 (TPC only track)

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









Analysis Details (Cont.)

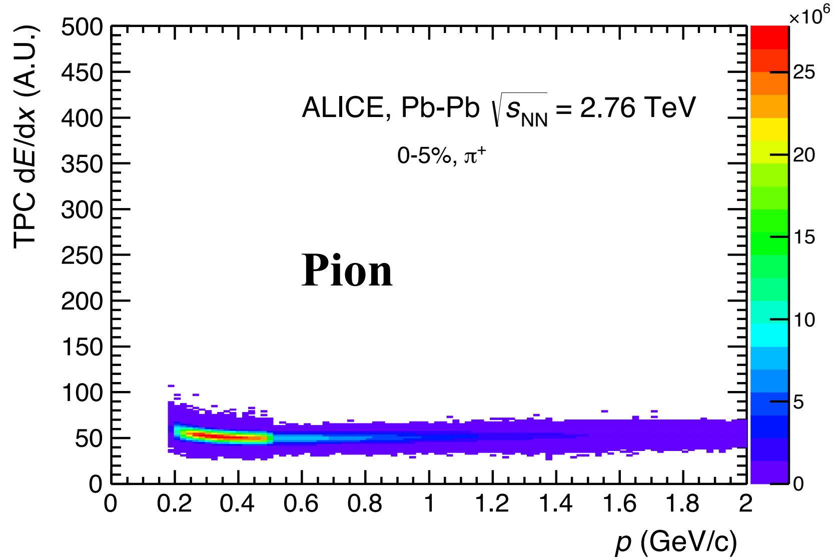
PID cuts for Pions:

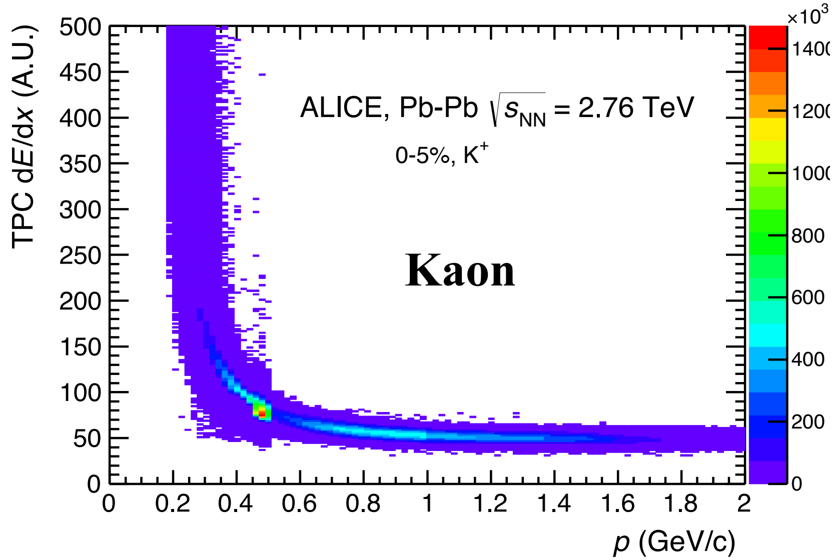
- $|n\sigma_{TPC}| < 3.0 \longrightarrow |p| < 500\ MeV/c,$
- $\sqrt{(\mathrm{n}\sigma_{\mathrm{TPC}}{}^2 + \mathrm{n}\sigma_{\mathrm{TOF}}{}^2)} < 3.0 \longrightarrow |\mathrm{p}| > 500\ \mathrm{MeV/c}$

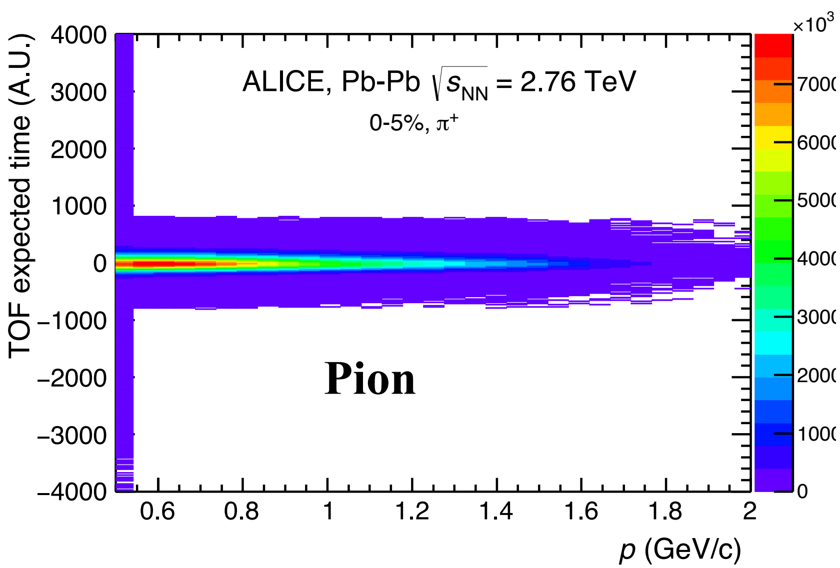
PID cuts for Kaons:

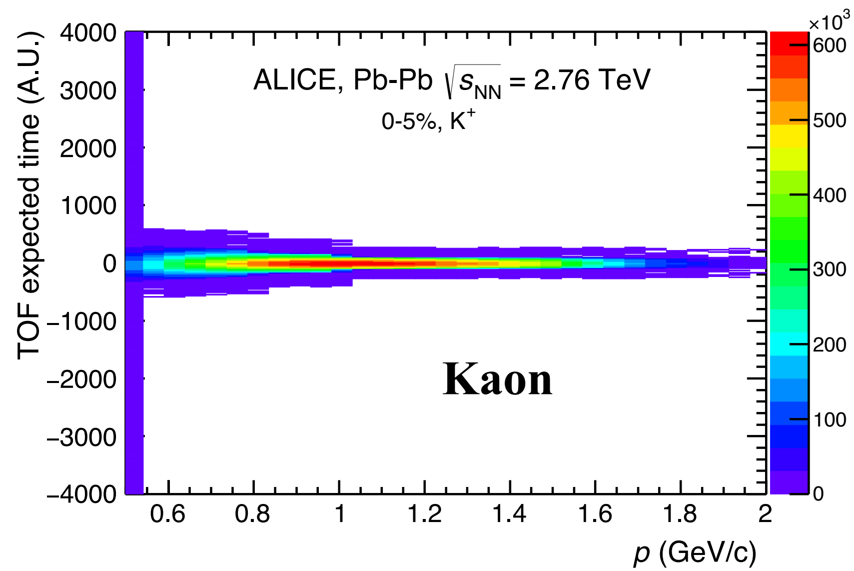
- $|n\sigma_{TPC}| < 2.0 \longrightarrow |p| < 400\ MeV/c,$
- $|n\sigma_{TPC}| < 1.0 \longrightarrow 400\ MeV < |p| < 450\ MeV/c,$
- $|n\sigma_{TPC}| < 3.0$ *and* $|n\sigma_{TOF}| < 2.0 \longrightarrow 450\ MeV < |p| < 800\ MeV/c,$
- $|n\sigma_{TPC}| < 3.0$ *and* $|n\sigma_{TOF}| < 1.5 \longrightarrow 800\ MeV < |p| < 1000\ MeV/c,$
- $|n\sigma_{TPC}| < 3.0$ *and* $|n\sigma_{TOF}| < 1.0 \longrightarrow |p| > 1000\ MeV/c$

Basic distributions









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^- $M_{inv} = 0.002$ GeV;

$$\mathbf{M_{inv} = 2m_e^2 + 2(E_1E_2 - \overrightarrow{p_1} \cdot \overrightarrow{p_2})}$$

- 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 ($MF = \mathbf{N_{pass}/N_{total}}$): 0.01 (Unlike sign pairs)
  0.07 (Like sign pairs)

where, N_{pass} is number of points for distance between track < d in R range,
N_{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: $0.0 \leq k^* \leq 0.2$ GeV/c

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

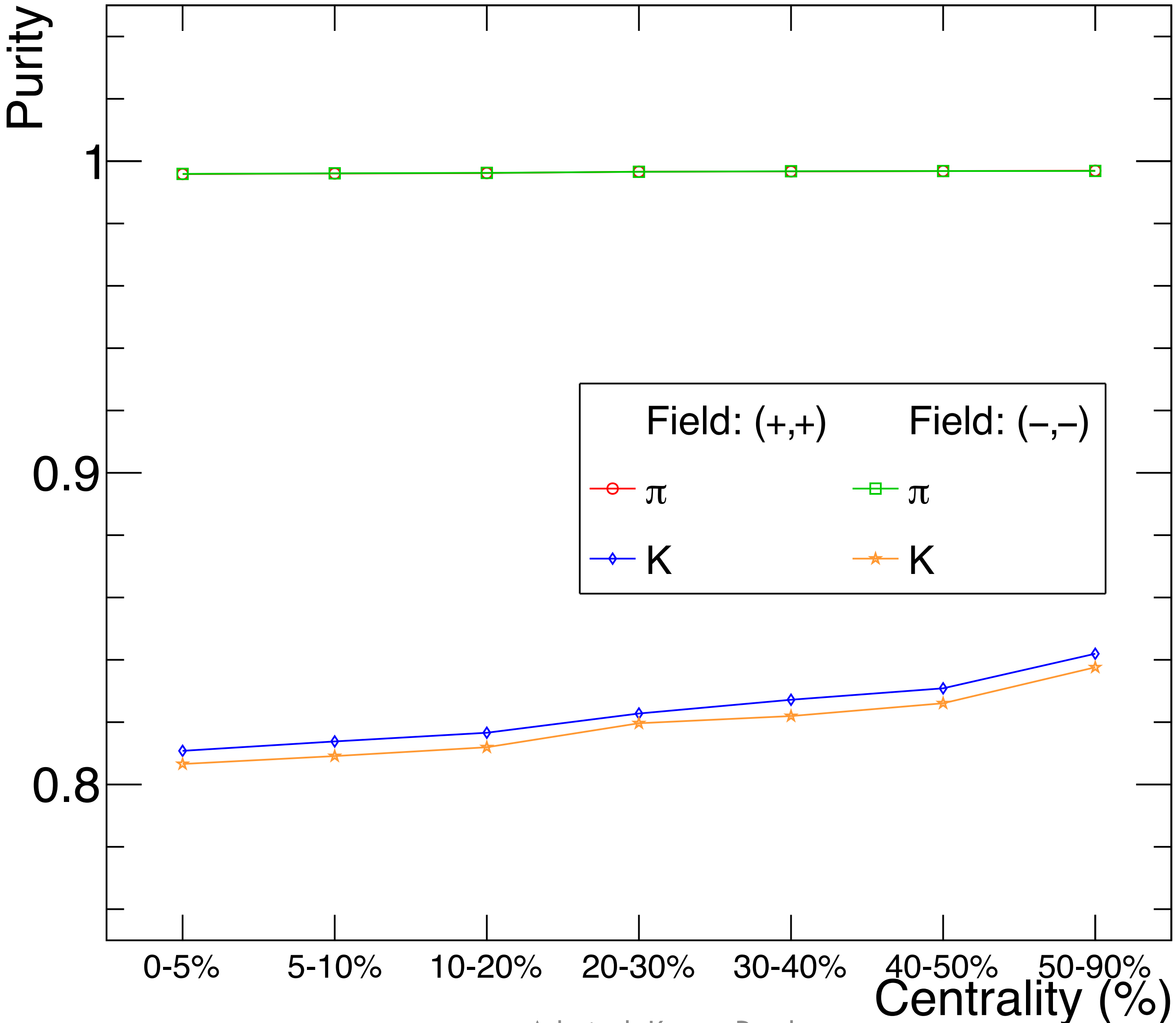
Like sign pairs:

Pair	Magnetic Field	χ^2/ndf for no paircut	χ^2/ndf for 1% MF cut	χ^2/ndf for 3% MF cut	χ^2/ndf for 7% MF cut
π^+K^+	+ve	5.4976	2.4188	2.4310	2.2936
π^-K^-	+ve	6.2763	2.3971	2.4165	2.4859
π^+K^+	-ve	6.9418	1.9611	1.8666	1.8129
π^-K^-	-ve	7.4470	2.2219	2.2031	2.1611
Average		6.5407	2.2497	2.2293	2.1883

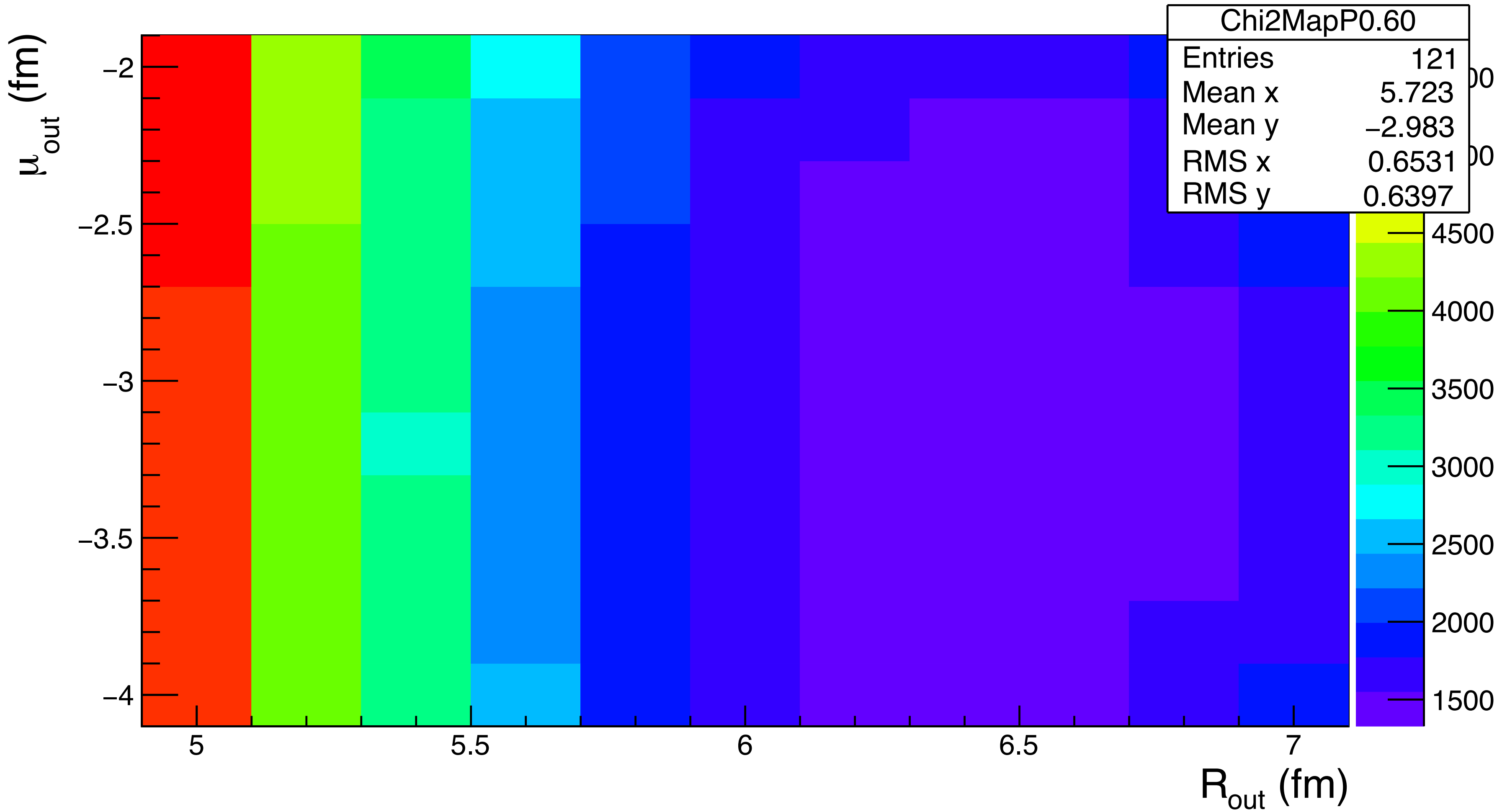
Un-like sign pairs:

Pair	Magnetic Field	χ^2/ndf for no paircut	χ^2/ndf for 1% MF cut	χ^2/ndf for 3% MF cut	χ^2/ndf for 7% MF cut
π^-K^+	+ve	1.3168	1.0588	1.2069	1.2820
π^+K^-	+ve	2.8674	2.1149	2.1333	2.3948
π^-K^+	-ve	1.7220	1.2660	1.2785	1.1984
π^+K^-	-ve	2.2667	1.7491	1.6335	1.7308
Average		2.0432	1.5472	1.5630	1.6515

Particle purity



Chi2Map

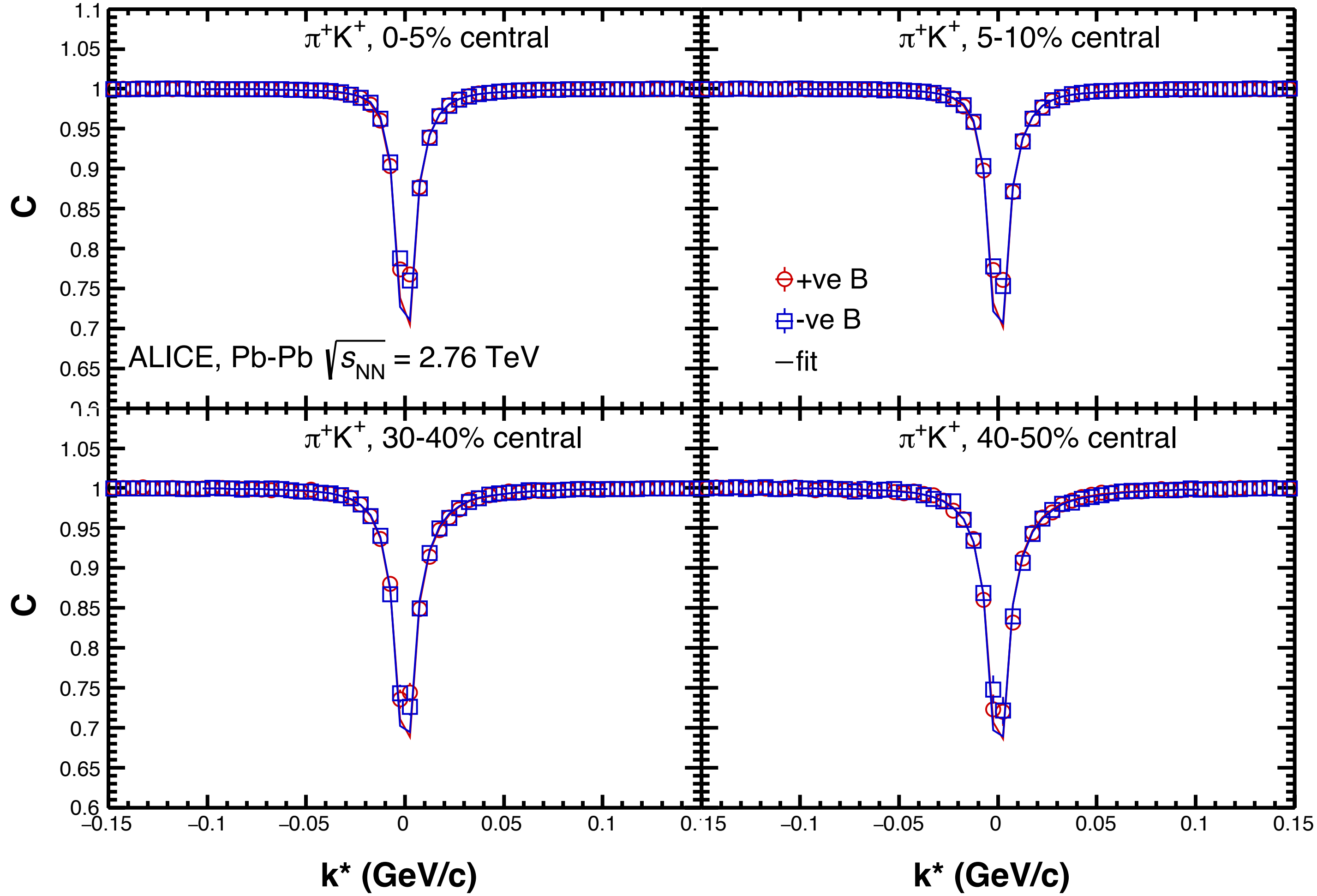


Chi2MapP0.60
Entries 121
Mean x 5.723
Mean y −2.983
RMS x 0.6531
RMS y 0.6397
−2
−2.5
−3
−3.5
−4
5
5.5
6
6.5
7
4500
4000
3500
3000
2500
2000
1500
μ_{out} (fm)
R_{out} (fm)

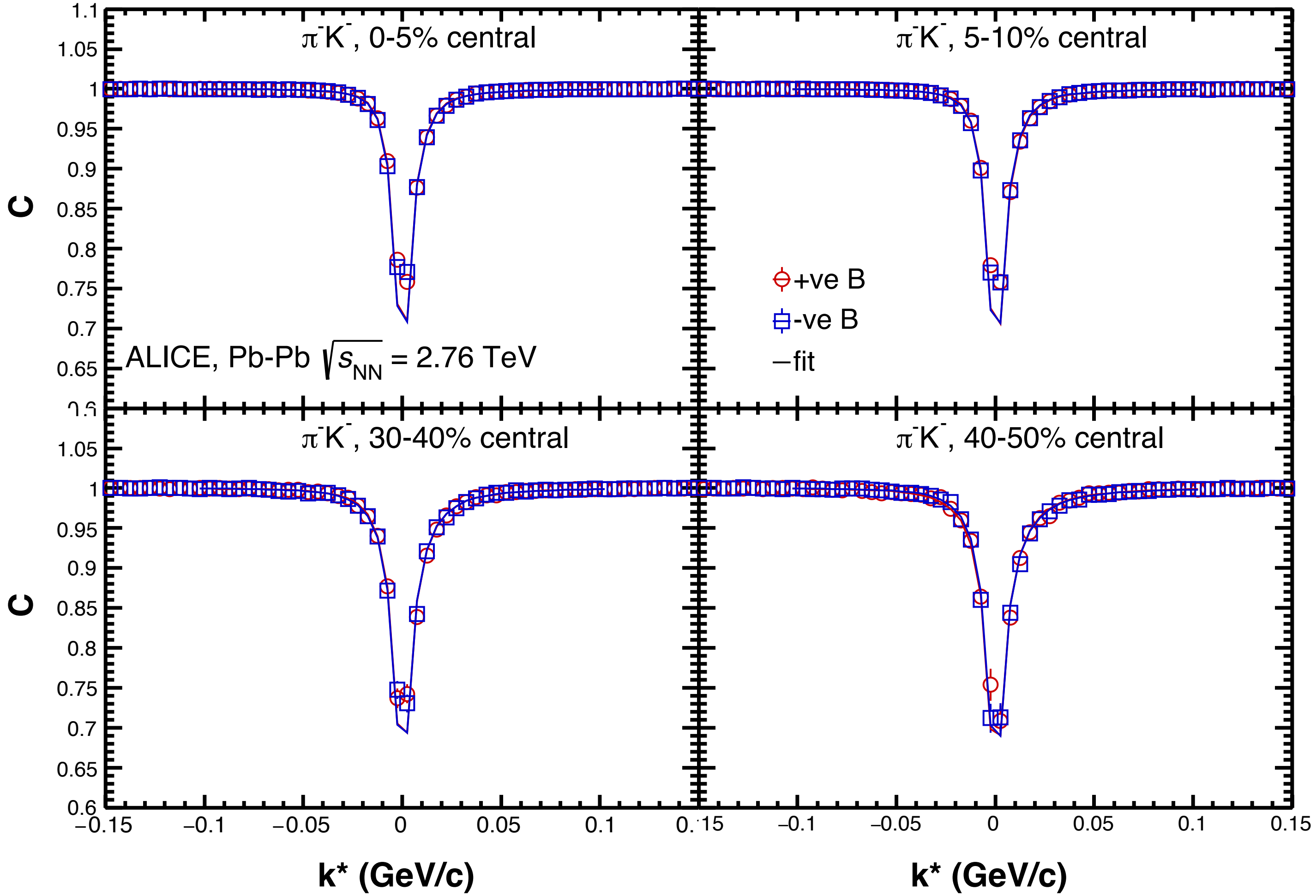
Systematic studies :

Error source	**variation**	**Error (in %) $\mathbf{R}_{Out}$, μ_{Out}**
Track	Hybrid track (FilterBit8)	13, 17
Pair cuts	$\pm$ 2 % MF cut	0.18, 0.5
Strict PID cut	**Pion:** $n\sigma_{TPC} < 2.5$ for $\|p\| < 500$ MeV/c, $\sqrt{(n\sigma_{TPC}^2 + n\sigma_{TOF}^2)} < 2.5$ for $\|p\| > 500$ MeV/c **Kaon:** $n\sigma_{TPC} < 2.0$ for $\|p\| < 400$ MeV/c, $n\sigma_{TPC} < 1.0$ for 400 MeV/c $< \|p\| <$ 450 MeV/c, $n\sigma_{TPC} < 2.0$ and $n\sigma_{TOF} < 2.0$ for 450 MeV/c $< \|p\| <$ 800 MeV/c, $n\sigma_{TPC} < 2.0$ and $n\sigma_{TOF} < 1.5$ for 800 MeV/c $< \|p\| <$ 1000 MeV/c, $n\sigma_{TPC} < 2.0$ and $n\sigma_{TOF} < 1.0$ for $\|p\| > 1000$ MeV/c	Combined error from strict and loose PID: 6, 15
Looser PID cut	**Pion:** $n\sigma_{TPC} < 3.0$ for $\|p\| < 500$ MeV/c, $\sqrt{(n\sigma_{TPC}^2 + n\sigma_{TOF}^2)} < 3.0$ for $\|p\| > 500$ MeV/c **Kaon:** $n\sigma_{TPC} < 2.5$ for $\|p\| < 400$ MeV/c, $n\sigma_{TPC} < 2.0$ for 400 MeV/c $< \|p\| <$ 450 MeV/c, $n\sigma_{TPC} < 3.0$ and $n\sigma_{TOF} < 2.5$ for 450 MeV/c $< \|p\| <$ 500 MeV/c, $n\sigma_{TPC} < 3.0$ and $n\sigma_{TOF} < 3.0$ for 500 MeV/c $< \|p\| <$ 800 MeV/c, $n\sigma_{TPC} < 3.0$ and $n\sigma_{TOF} < 2.5$ for 800 MeV/c $< \|p\| <$ 1000 MeV/c, $n\sigma_{TPC} < 3.0$ and $n\sigma_{TOF} < 2.0$ for $\|p\| > 1000$ MeV/c	
Normalization range	k* : (0.1,0.12), (0.12,0.17), (0.18,0.25) GeV/c	0.6, 0.9
Fit range	k* = (0.,0.08),(0.,0.12),(0.,0.15), (0.005, 0.1), (0.01,0.1) GeV/c	9, 19
Primary fraction (purity)	$\pm$ 10%	10,16

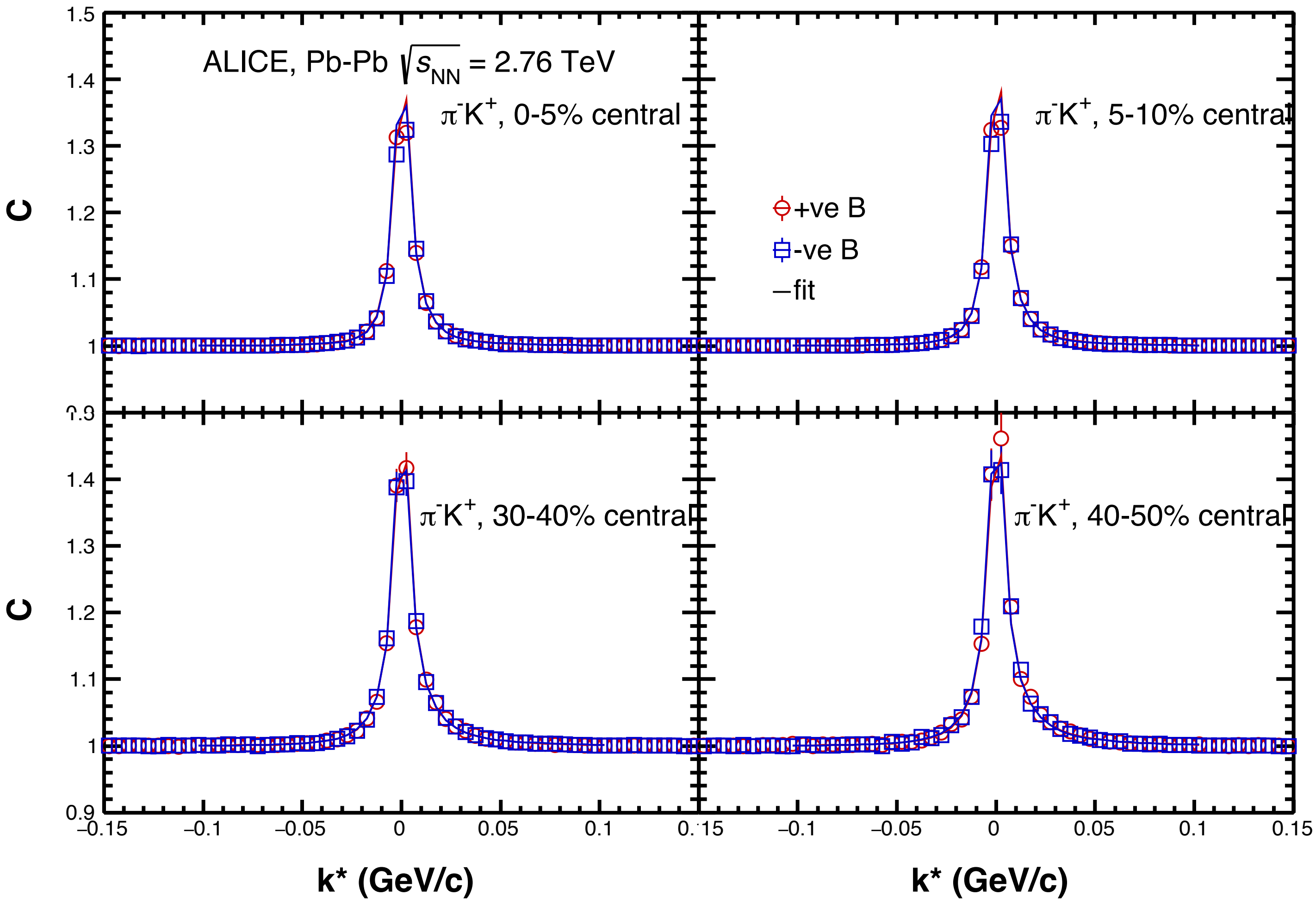
Correlation function (like sign)



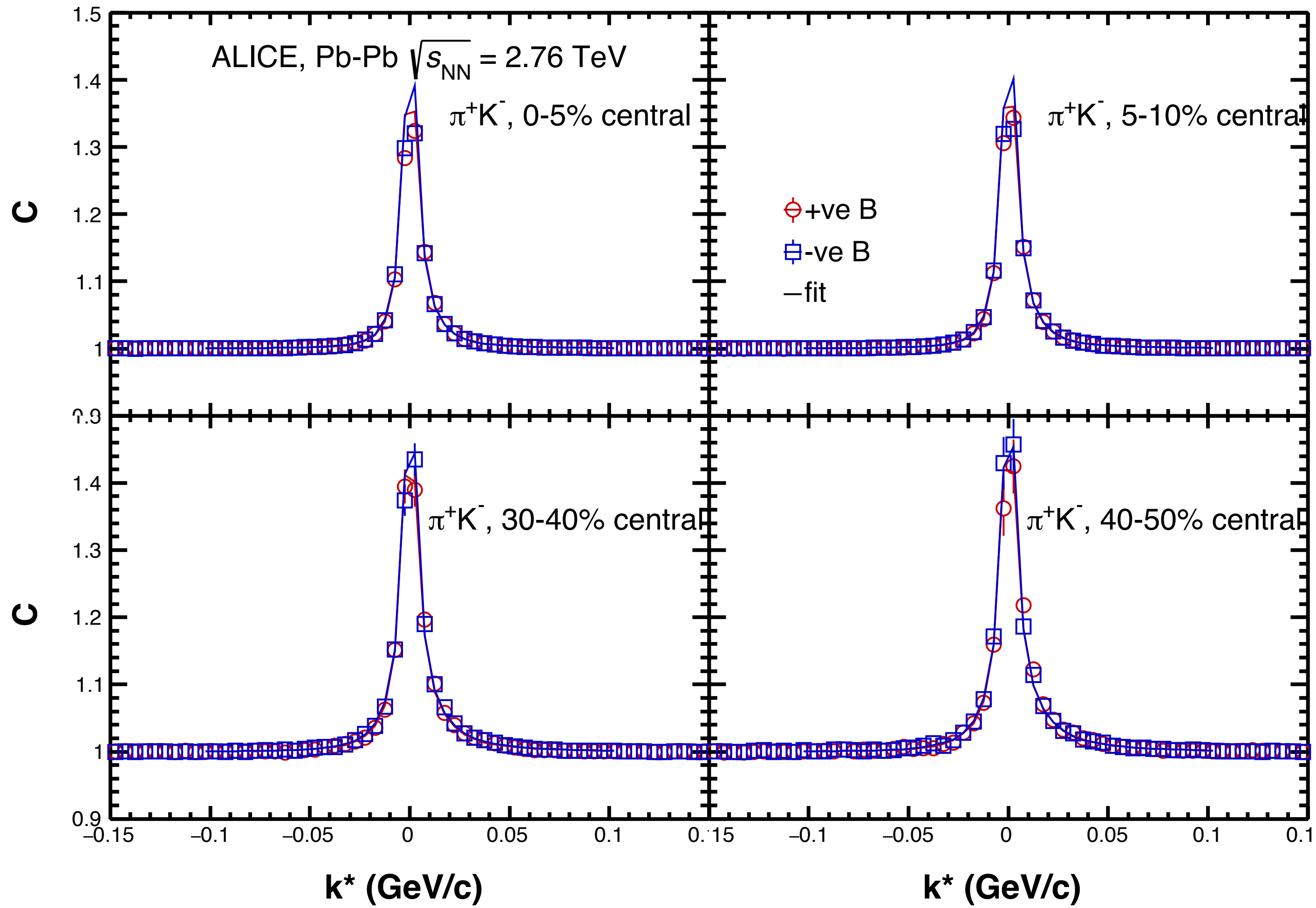
Correlation function (like sign)



Correlation function (unlike sign)



Correlation function (unlike sign)



Reason for large statistical errors

One expects larger errors for μ 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 μ. 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