Narodowe Centrum Nauki

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Emission time delays from Pion-Kaon femtoscopy as a probe of hadronic rescattering

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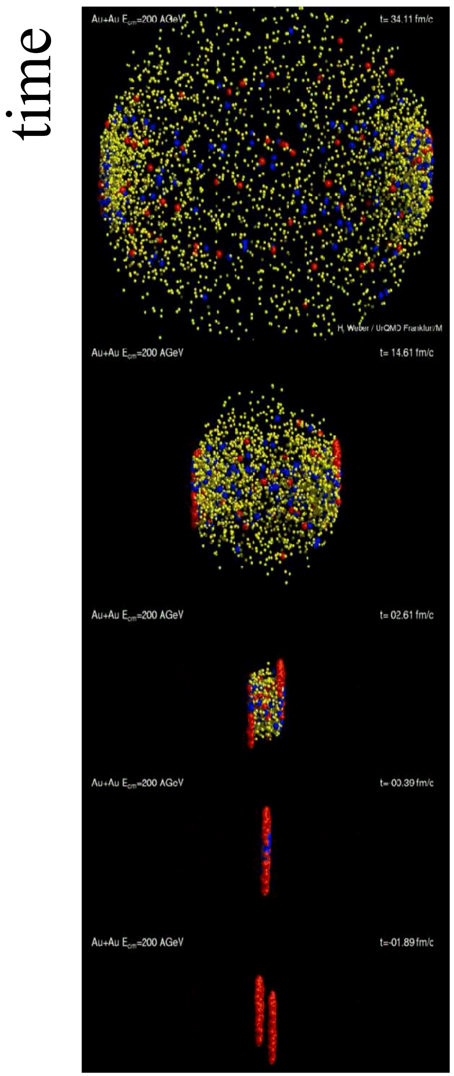
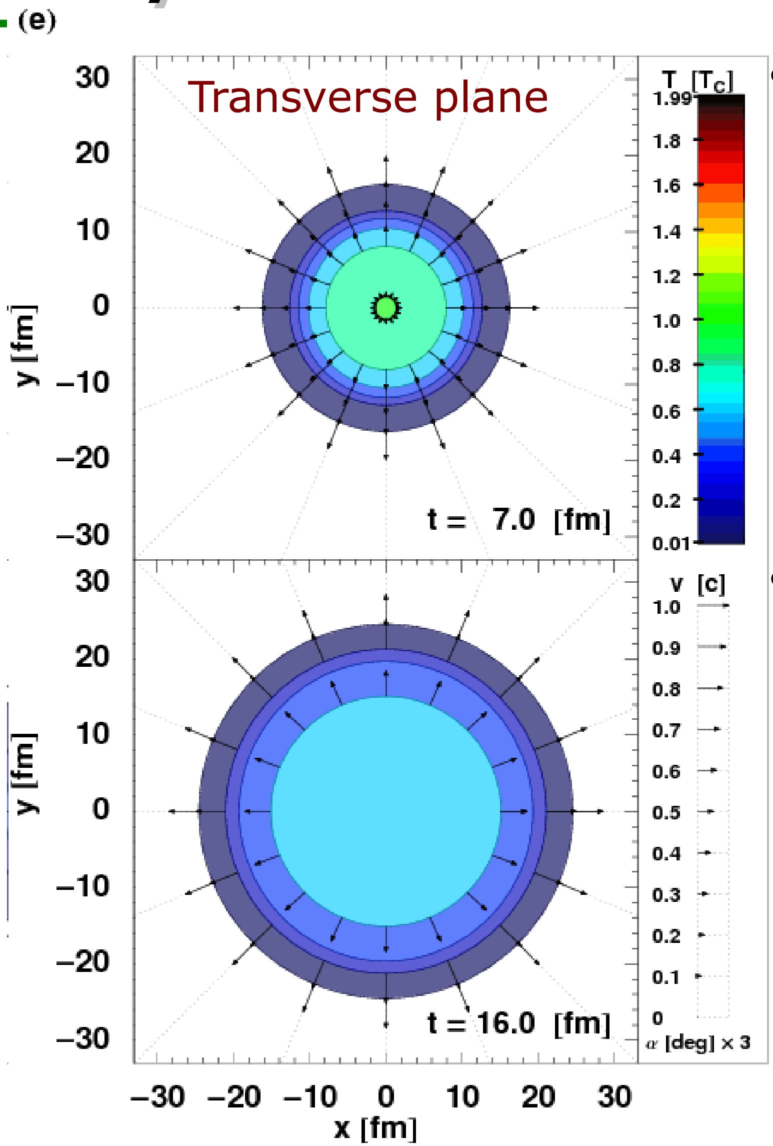
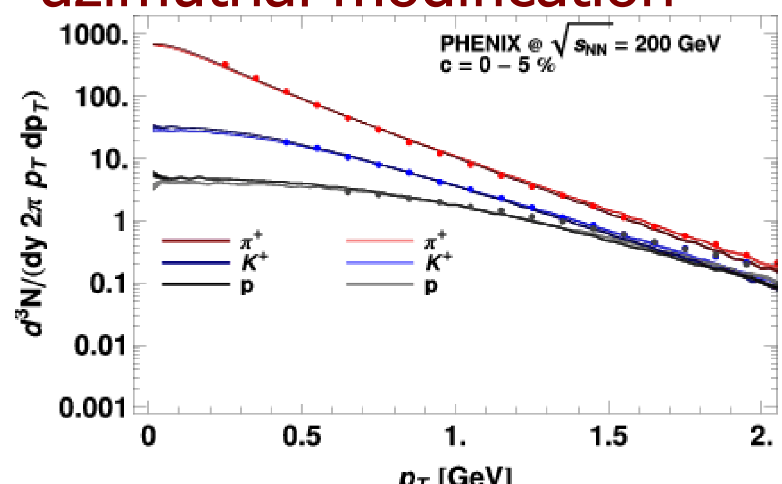
Heavy-ion collision evolution



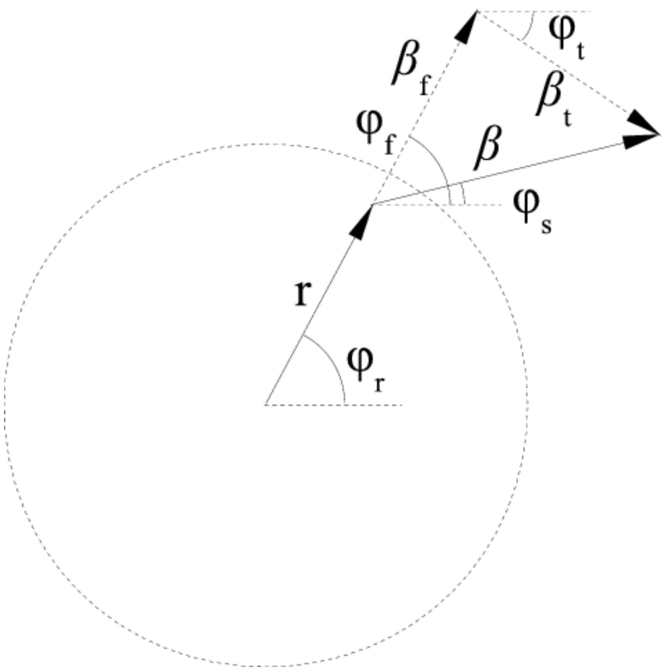


M. Chojnacki, W. Florkowski, PRC 74 (2006) 034905

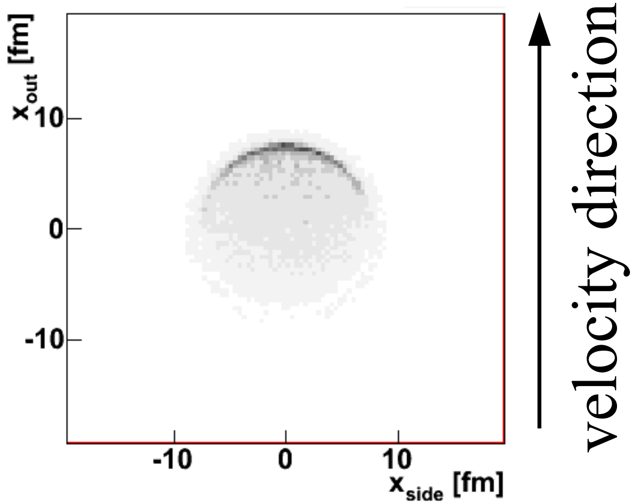
- HIC is expected to go through a QGP phase, where matter is strongly interacting – resulting in the development of collective motion
- Radial flow dominates, with elliptic flow as azimuthal modification

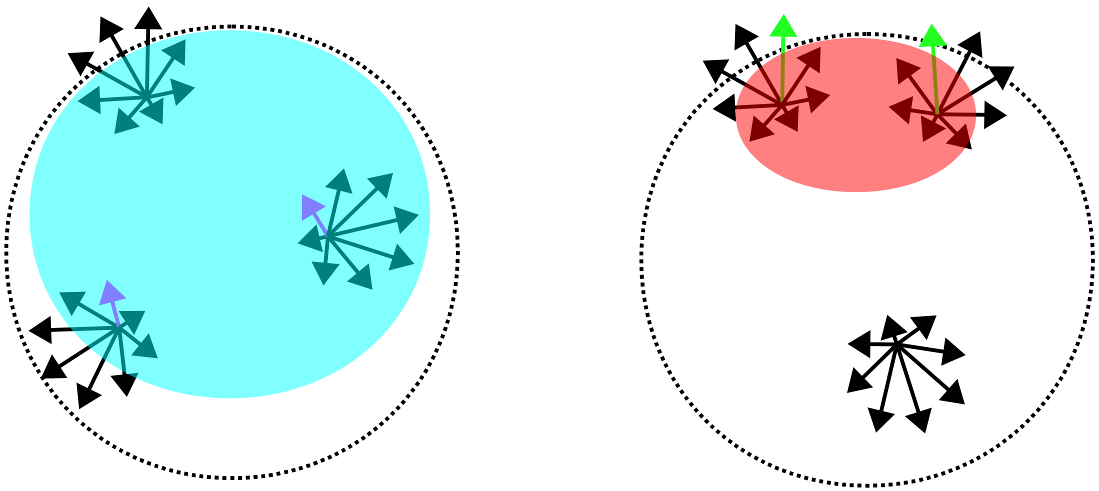


Thermal emission from collective medium



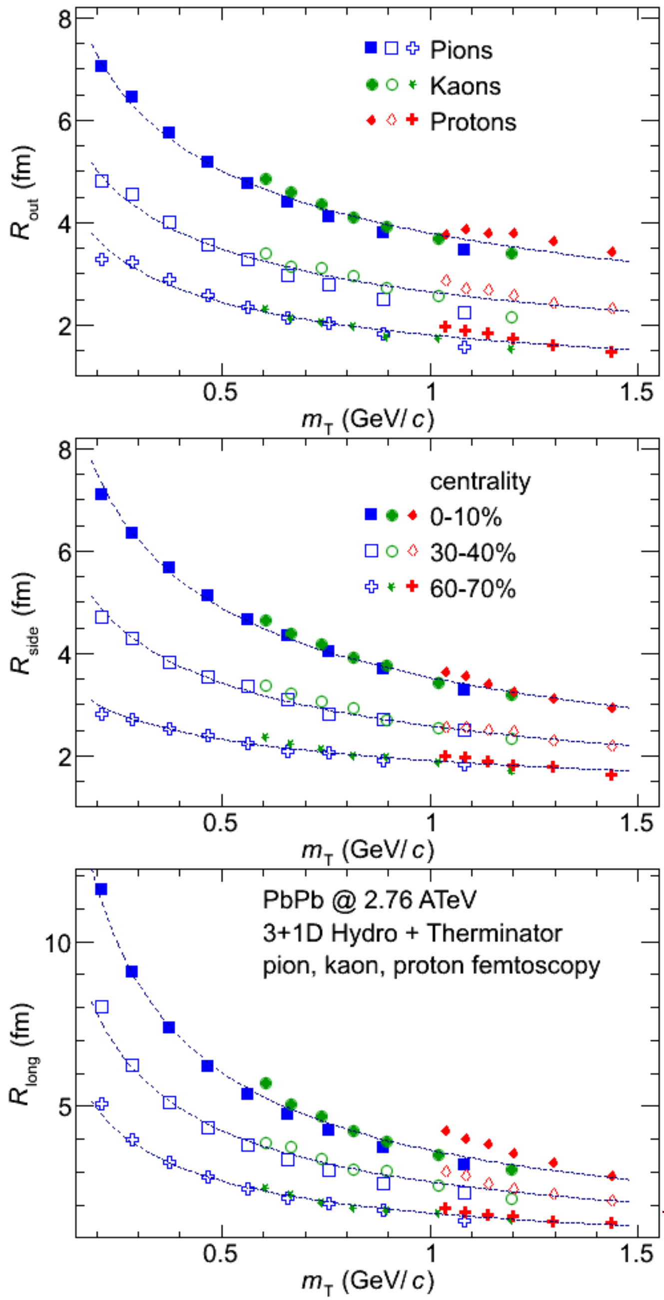
- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source





R. Lednicky, Phys. Atom. Nucl.67, 73 (2004)
AK, Phys.Rev. C81 (2010) 064906

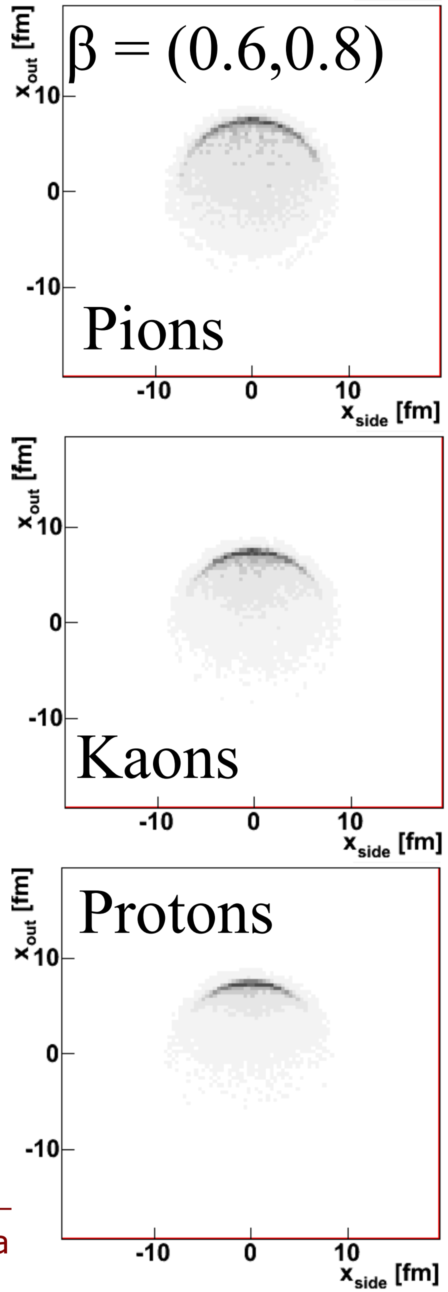
Consequences of flow



- "Collective" flow should apply to all particles
  - Ideal 1D hydro → m_T scaling for all particles
  - "Real" 3+1D hydro + viscosity (no rescattering) → approximate scaling in LCMS
  - Heavier/faster particles give smaller size of the system
- System size decrease – change of the second moment (width) of the emission function
- Measurement of the first moment (average emission position) not possible for identical particles

AK, M.Gałażyn, P.Bożek; Phys.Rev.C90 (2014) 6, 064914

Collectivity and emission asymmetry



- As particle mass (or p_T) grows, average emission point moves more "outwards" - origin of this "emission asymmetry" the same as m_T scaling

- Average emission points for primordial particles with same velocity but different mass:

Pions $\langle x^{\pi}_{out} \rangle$	Kaons $\langle x^{K}_{out} \rangle$	Protons $\langle x^{p}_{out} \rangle$
2.83 fm	4.47 fm	5.61 fm

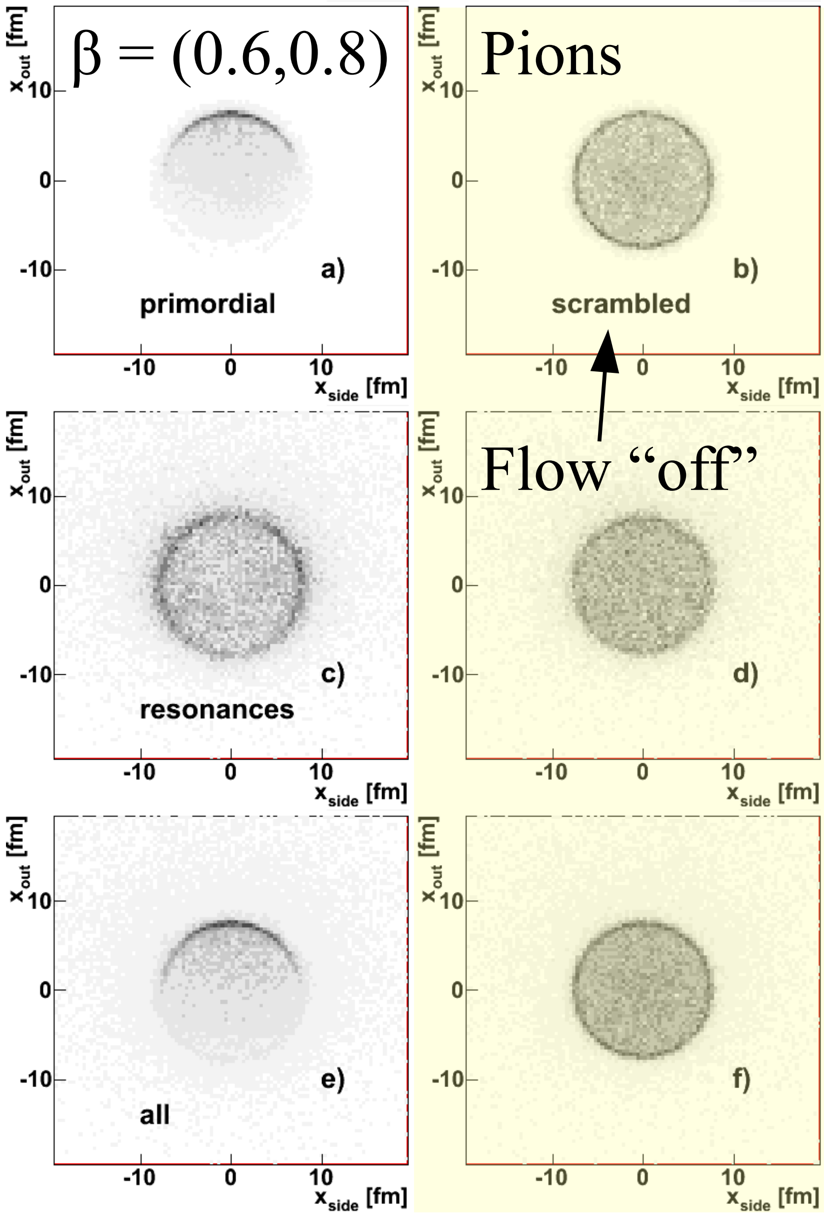
Asymmetry: $\langle r^{\pi K}_{out} \rangle \approx \langle x^{\pi}_{out} \rangle - \langle x^{K}_{out} \rangle$

- Heavier particles (resonances) are pushed even further out

- Significant difference between particles' average emission points at same velocity, different mass

AK, PRC 81 (2010) 064906

Resonances and pion emission

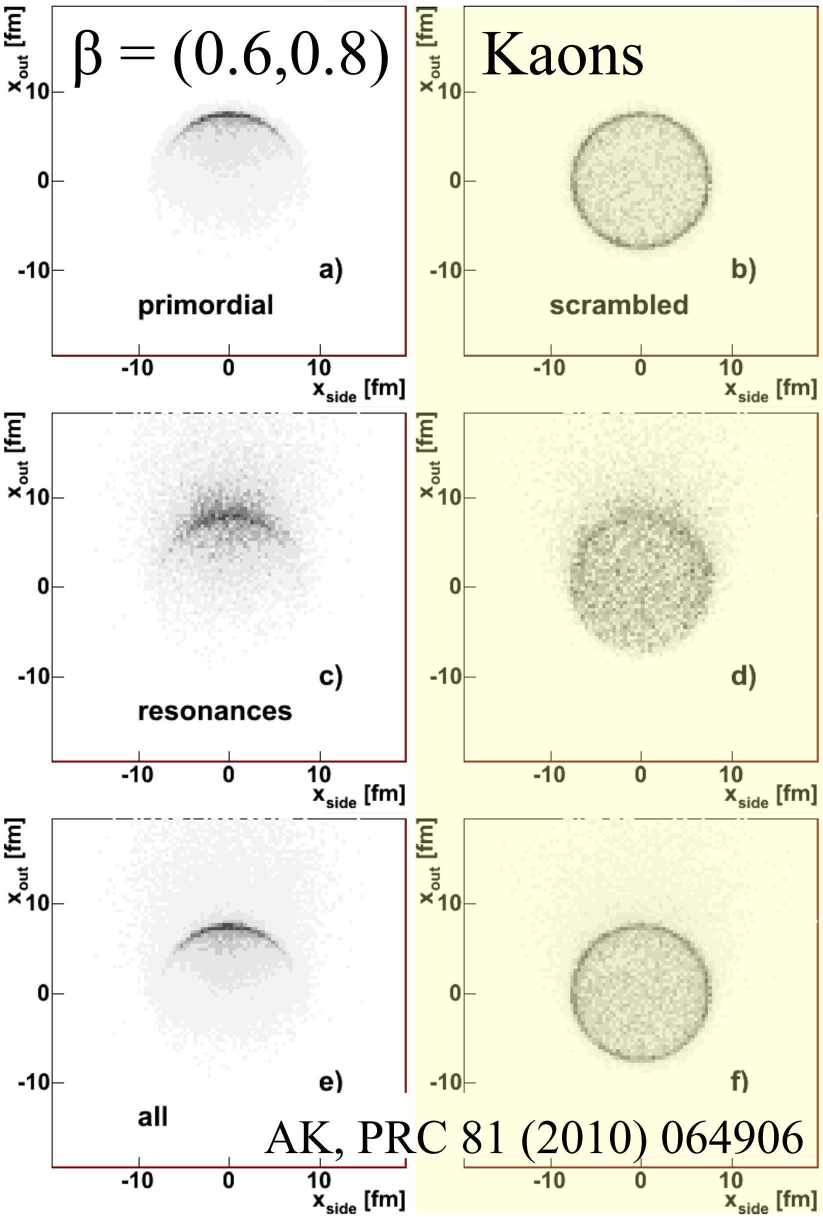


- Flow is "off" (space-momentum correlation "off") → no emission shift
- Pions → decay momentum of most resonances larger than pion mass. Decay acts similarly to thermal smearing with large temperature.
- Emission points of pions from resonances strongly randomized – average very close to system center.
- Overall average emission point of pions closer to the center than just flow.

Pions $\langle x^{\pi}_{out} \rangle$	primodial	all
	2.83 fm	2.00 fm

AK, PRC 81 (2010) 064906

Resonances and kaon emission



AK, PRC 81 (2010) 064906

- Kaons → decay momentum of most resonances smaller than Kaon mass. Kaons retain the shift of the heavy (shifted more!) resonances.
- Emission points of kaons from resonances strongly pushed by flow – average far from system center.

Kaons $\langle x^K_{out} \rangle$	primodial	all
	4.47 fm	5.54 fm

- Overall: resonances **enhance** flow-induced difference between pion and kaon average emission points.

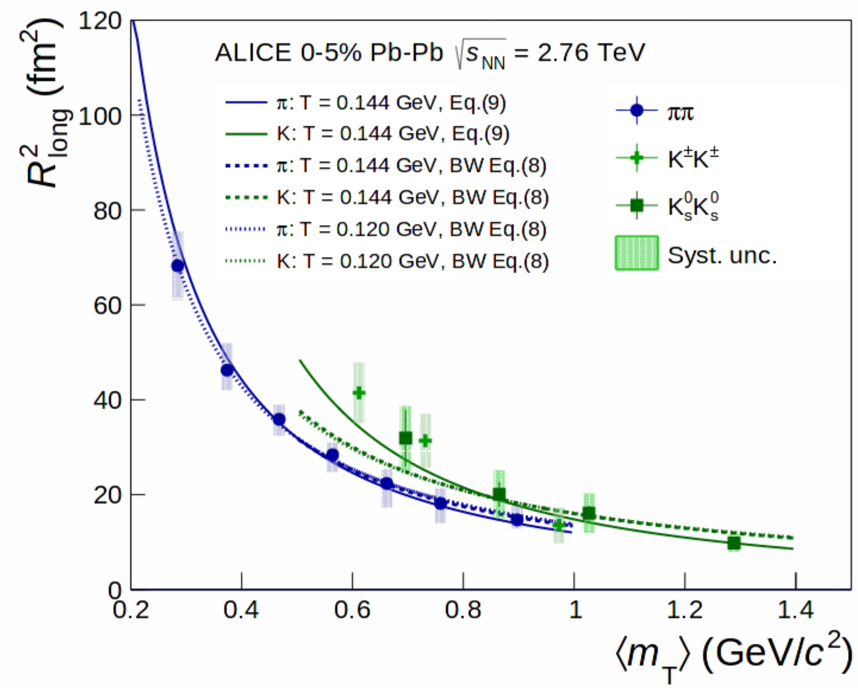
Difference in emission time

- Hydrodynamics predicts emission of higher p_T particles earlier (on average) than low p_T.
- This would mean that at the same velocity pions are emitted later than kaons.
- This effect goes in the same direction as emission asymmetry from flow
- In addition pions are more abundantly produced from resonances, which naturally introduce emission delay
- This again produces later emission of pions – in the same direction as flow
- Estimates show both time differences are comparable in magnitude

Emission delay in data

- ALICE kaon data in hydro-based parametrization: kaons emitted on average later than pions.
- It comes from rescattering via K* resonance (**not included** in blast-wave or Therminator 2 or hydro)
- Goes in **opposite** direction to all other asymmetries

ALICE, Phys.Rev. C96 (2017) no.6, 064613



method	T (GeV)	α_π	α_K	τ_π (fm/c)	τ_K (fm/c)
fit with BW Eq. (8)	0.120	-	-	9.6 ± 0.2	10.6 ± 0.1
fit with BW Eq. (8)	0.144	-	-	8.8 ± 0.2	9.5 ± 0.1
fit with Eq. (9)	0.144	5.0	2.2	9.3 ± 0.2	11.0 ± 0.1
fit with Eq. (9)	0.144	4.3 ± 2.3	1.6 ± 0.7	9.5 ± 0.2	11.6 ± 0.1

Table 4: Emission times for pions and kaons extracted using the Blast-wave formula Eq. (8) and the analytical formula Eq. (9).

V.M. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov; **Nucl.Phys. A929 (2014) 1-8**

Accessing emission delays

ELSEVIER

18 April 1996

Physics Letters B 373 (1996) 30–34

PHYSICS LETTERS B

How to measure which sort of particles was emitted earlier and which later

R. Lednický [1], V.L. Lyuboshitz [2], B. Erazmus, D. Nouais

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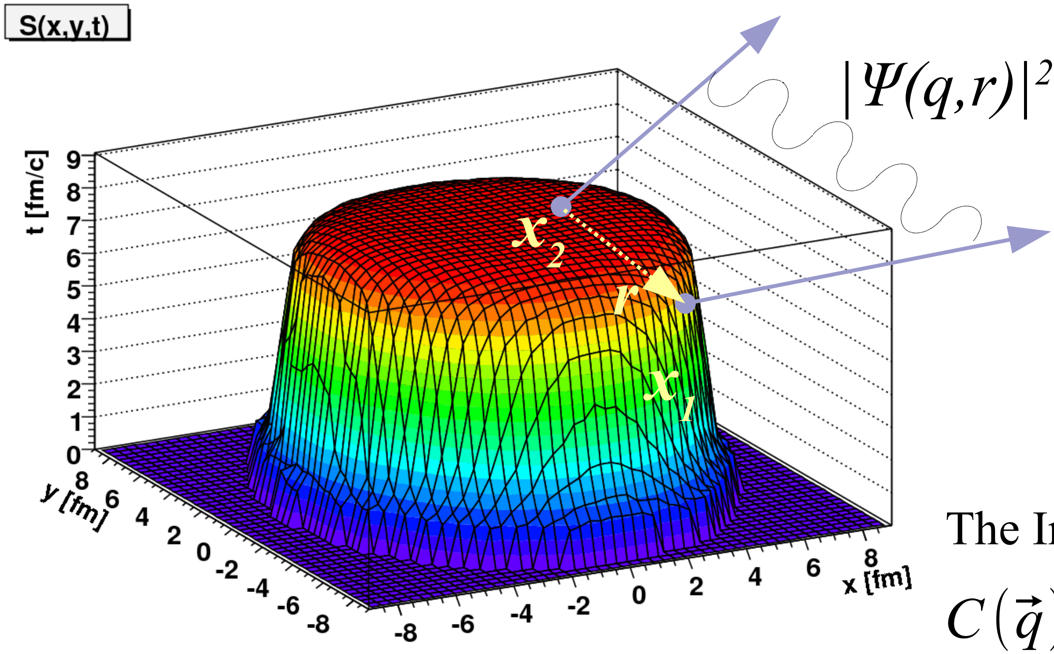
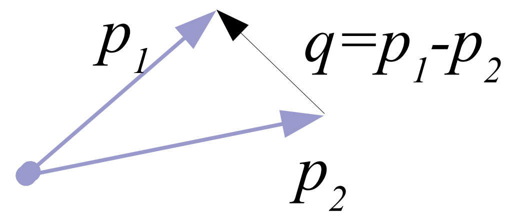
Abstract

A method allowing to directly measure delays in the emission of particles of different types at time scales as short as 10^{-23}–10^{-22} s is suggested.

Measuring space-time extent: femtoscopy



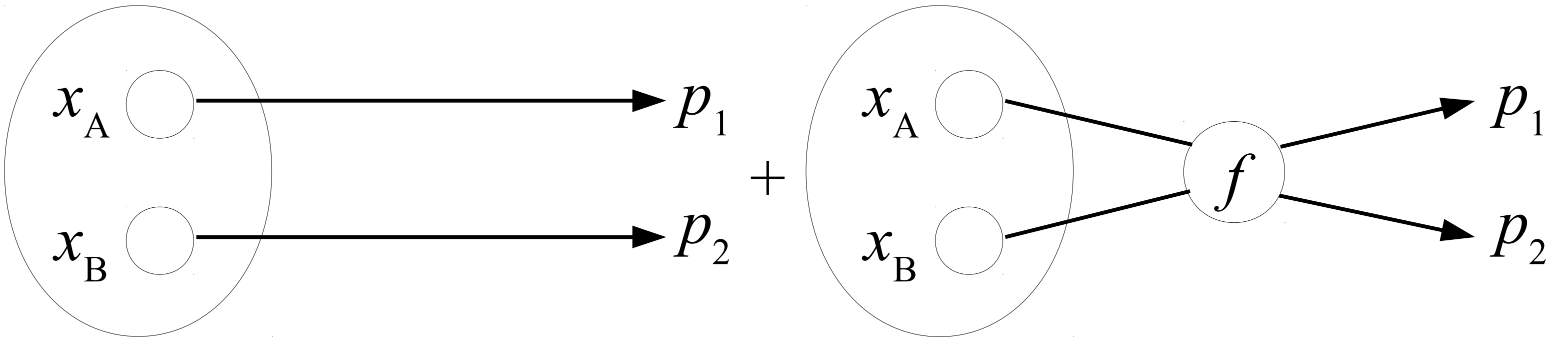


The Integral Equation for Correlation

$$C(\vec{q})=\int S(\boldsymbol{r})|\Psi(\vec{q},\boldsymbol{r})|^2 d^4 r=\langle|\Psi(\vec{q},\boldsymbol{r})|^2\rangle_{pairs}$$

- Use two-particle correlation, coming from the interaction Ψ (quantum statistics (HBT), coulomb and/or strong)
- Measure $C(q)$
- Try to invert the Koonin-Pratt eq. to gain information about S from known Ψ and measured C

Correlation – charged particles



$q = 2k^* = p_1 - p_2$

$r = x_A - x_B$

- Two charged particles interact via Coulomb and strong after their last scattering
  - This gives the final form of the wave-function, for pion-kaon pairs the Coulomb interaction dominates

$$\Psi_{-k^*}(\boldsymbol{r}^*) = e^{i\delta_c}\sqrt{A_c(\eta)}\left[e^{-i\boldsymbol{k}^*\boldsymbol{r}^*}F(-i\eta,1,i\xi)+f_c(k^*)\tilde{G}(\rho,\eta)/r^*\right]$$

$$\xi = \boldsymbol{k}^*\boldsymbol{r}^* + k^* r^* \equiv \rho(1+\cos(\theta^*)),\ \ \rho = k^* r^*,\ \ \eta = (k^* a)^{-1},\ \ a = (\mu z_1 z_2 e^2)^{-1}$$

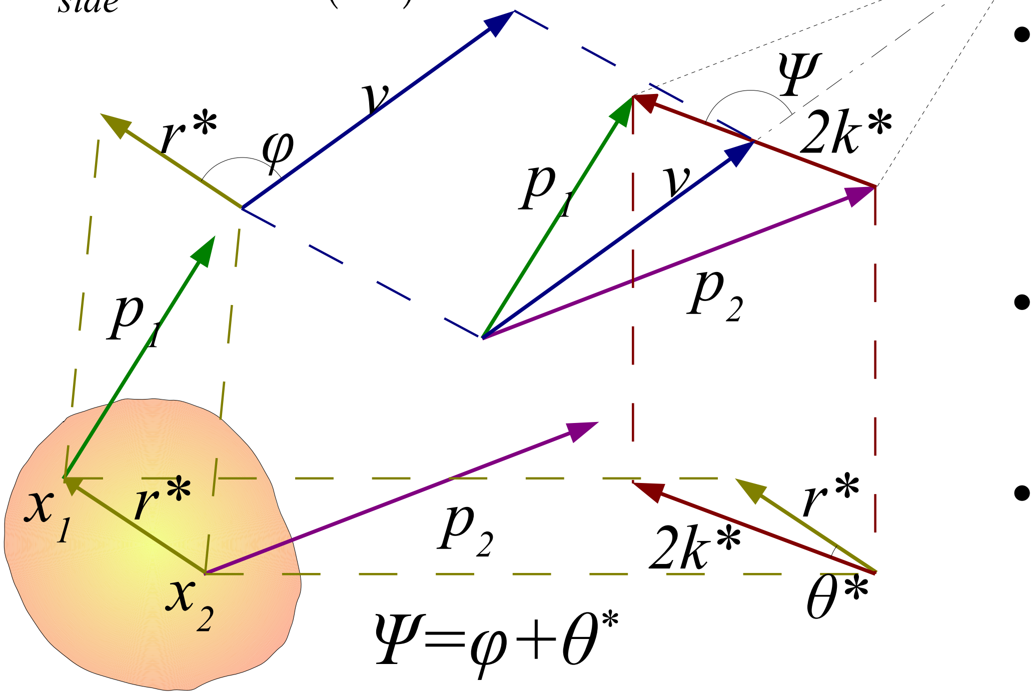
$$F(k^*, r^*, \theta^*) = 1 + r^*(1+\cos\theta^*)/a + (r^*(1+\cos\theta^*)/a)^2 + i k^* r^{*2}(1+\cos\theta^*)^2/a + \ldots$$

θ^* is an angle between separation r^* and relative momentum k^*

Accessing asymmetry

$$k^*_{out} \equiv k^* \cos(\Psi)$$
$$k^*_{side} \equiv k^* \sin(\Psi)$$

Transverse plane

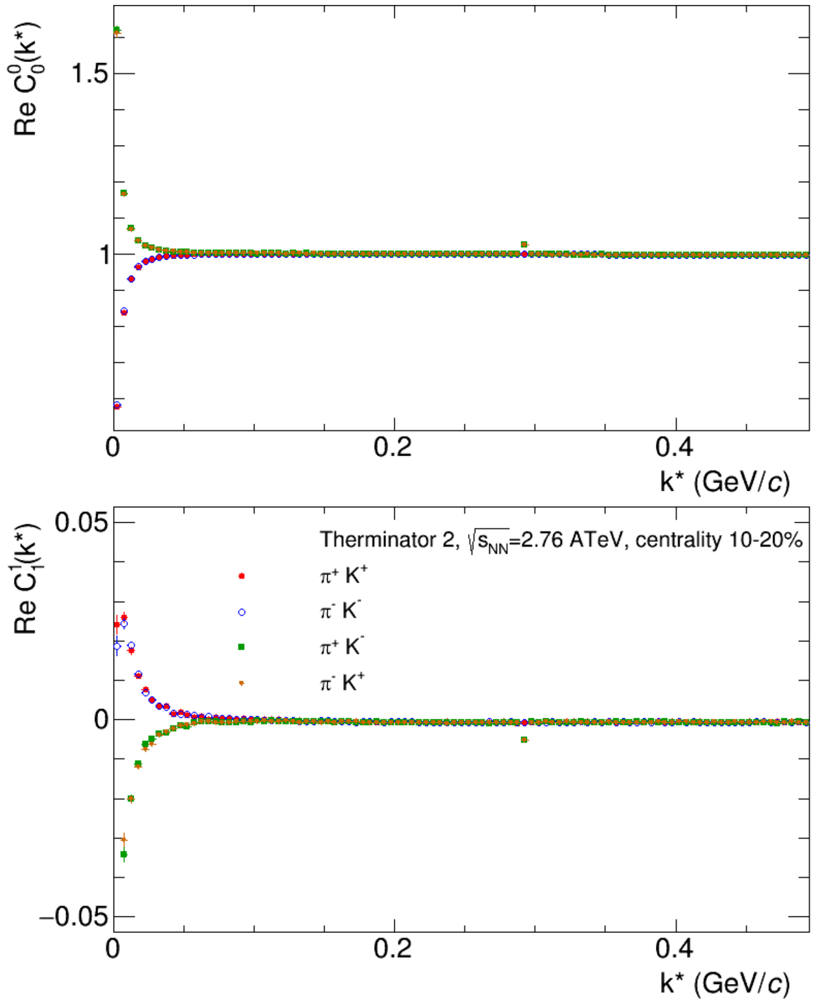


$$\cos(\Psi) = \cos(\varphi)\cos(\theta^*) + \sin(\varphi)\sin(\theta^*)$$
$$sign\langle\cos(\Psi)\rangle = sign\langle\cos(\varphi)\rangle\, sign\langle\cos(\theta^*)\rangle$$

- We want to measure $\langle r^*_{out}\rangle \equiv \langle r^* \cos(\varphi)\rangle$
- But we only measure relative k^* and total momentum v, so we only know Ψ
- We also know that the CF depends on θ^*
- The three angles are connected by a simple sum rule: average cosine signs must also follow
- By looking at the CF vs $\cos(\Psi)$ we are able to access asymmetries

$$if\ |C(\langle\cos(\Psi)\rangle > 0) - 1| > |C(\langle\cos(\Psi)\rangle < 0) - 1|\ then\ \langle\cos(\varphi)\rangle < 0$$

Pion-kaon in Spherical Harmonics

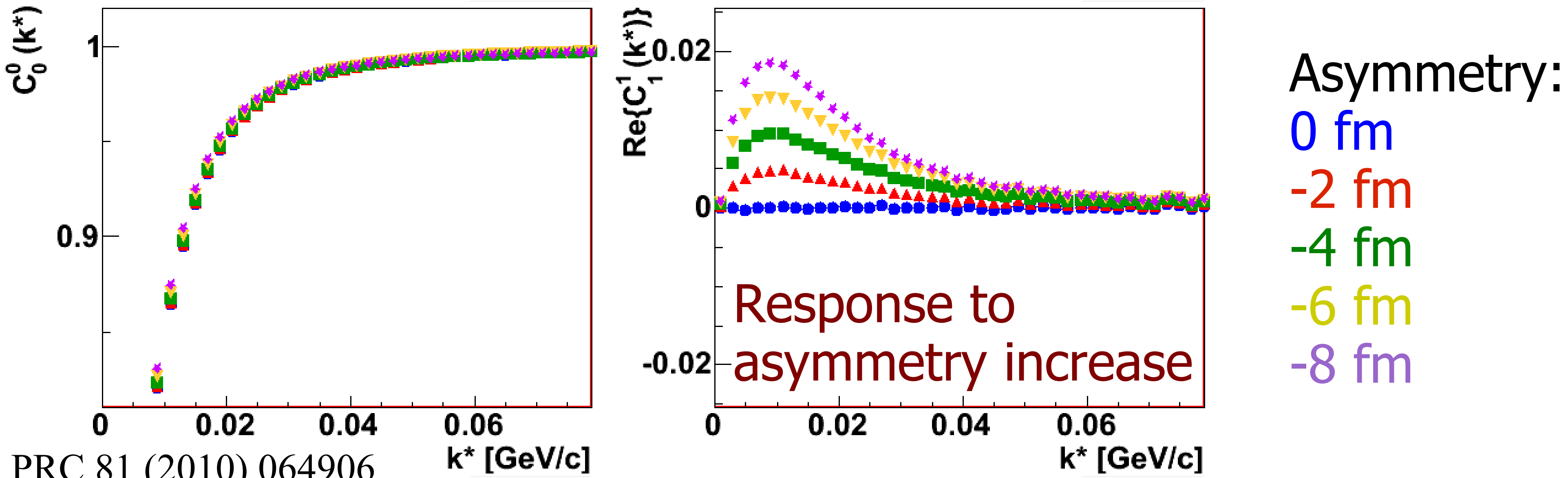


$$C_l^m(q) = \int C(\vec{q})\, Y_l^m(\cos(\theta), \phi)\, d\phi\, d\cos(\theta)$$

- The pion-kaon correlation dominated by Coulomb (effect is quite narrow and opposite for same-sign and opposite-sign pairs)
- Only the l=0,m=0 and l=1,m=1 real components sufficient for analysis
- l=0,m=0 component sensitive to overall system size
- l=1,m=1 component maximizes sensitivity to emission asymmetry
- Higher l – finer details of correlation – not analyze here

Sensitivity to emission asymmetries

$$\Re\{C_1^1\} \sim \int C(\phi, \cos(\theta)) \cos(\phi)\, d\phi\, d\cos(\theta)$$



AK, PRC 81 (2010) 064906

- Increasing emission asymmetry mainly affects Re$\{C_1^1\}$
- No asymmetry gives flat Re$\{C_1^1\}$
- Fitting the two components allows to extract asymmetry

Space and time asymmetry

- The non-identical particle femtoscopy sensitive to the emission asymmetry between particle types, possible because they are not identical
- Measurement sensitive to the difference of the spatial and time asymmetries, not possible to distinguish between them

$$\mu_{out} = \langle r^*_{out} \rangle = \langle \gamma r_{out} - \beta \gamma \Delta t \rangle$$

- "Spatial" asymmetry r_{out} arises in flowing medium, difficult to produce otherwise
- "Time" asymmetry Δt may have various origins, some not connected to flow

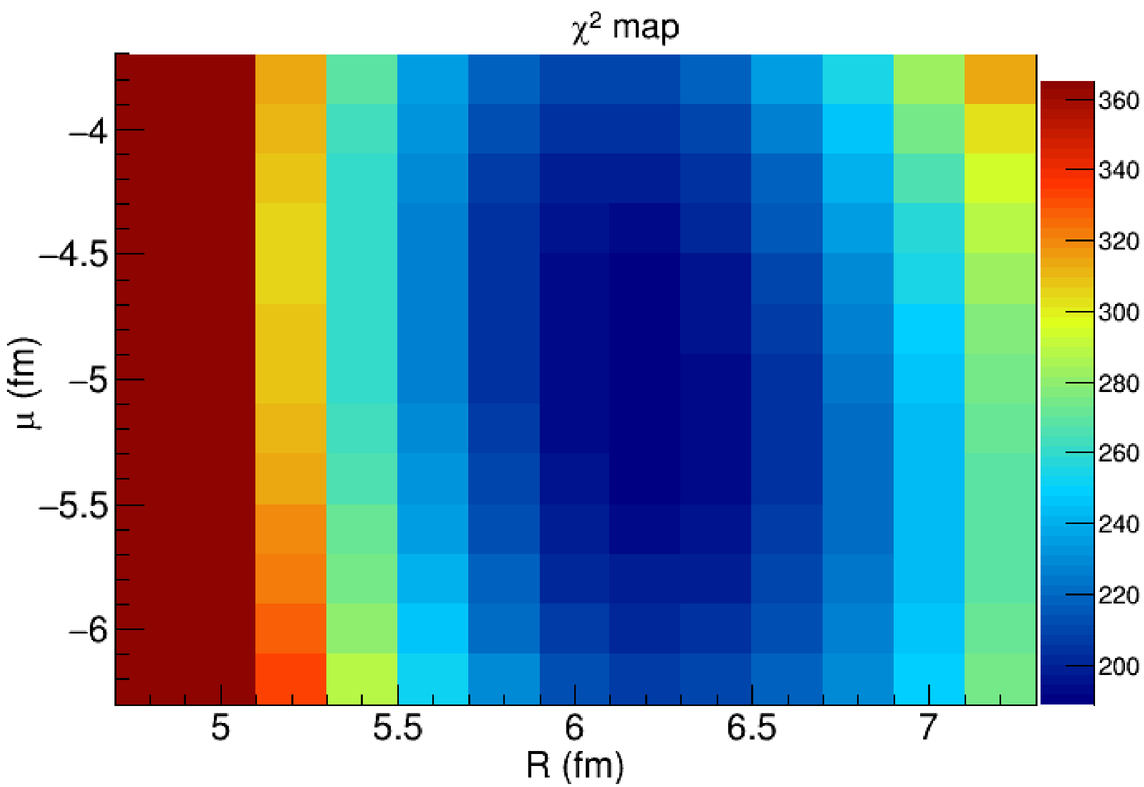
Simulations in Therminator2

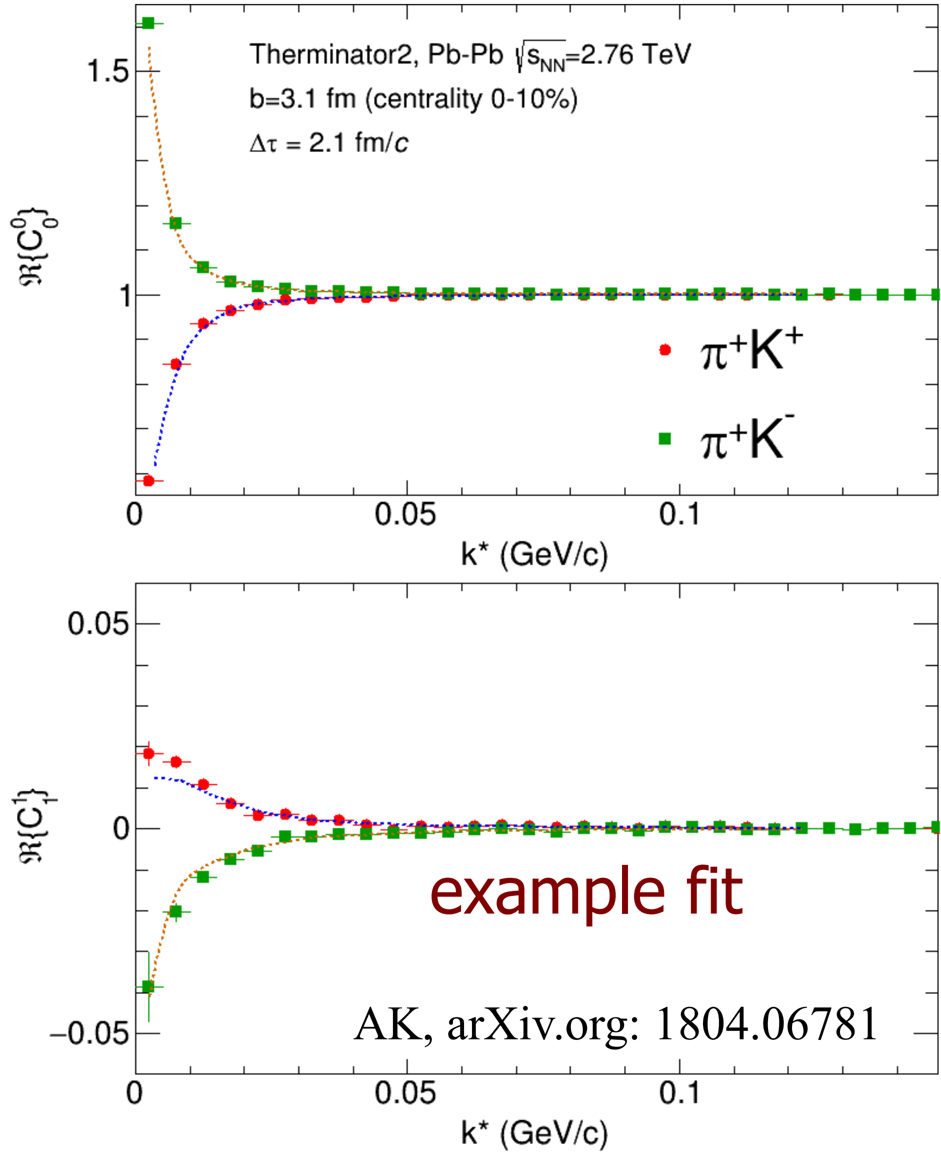
- Used hypersufrace from (3+1)D viscous hydrodynamic code coupled to Therminator2 statistical hadronization
  - Tuned to ALICE Pb-Pb Collisions, 2.76 ATeV
  - Centrality 0-10%, 10-20%, 20-30%, 30-40%, 40-50%
  - The same datasample as used for identical pion/kaon calculation
  - Calculated separately for π^+K^-, π^-K^+, π^+K^+, π^-K^-, then statistically averaged to get one datapoint per centrality
- Optional: Introduce ad-hoc emission time delay for kaons with delay for each particle selected randomly from a Gaussian distribution of a given width and mean
- Calculated correlation function with only Coulomb

Fitting non-identical correlation

- Calculate numerically the correlation function for points on the (R,μ) grid, where source is defined in LCMS as:

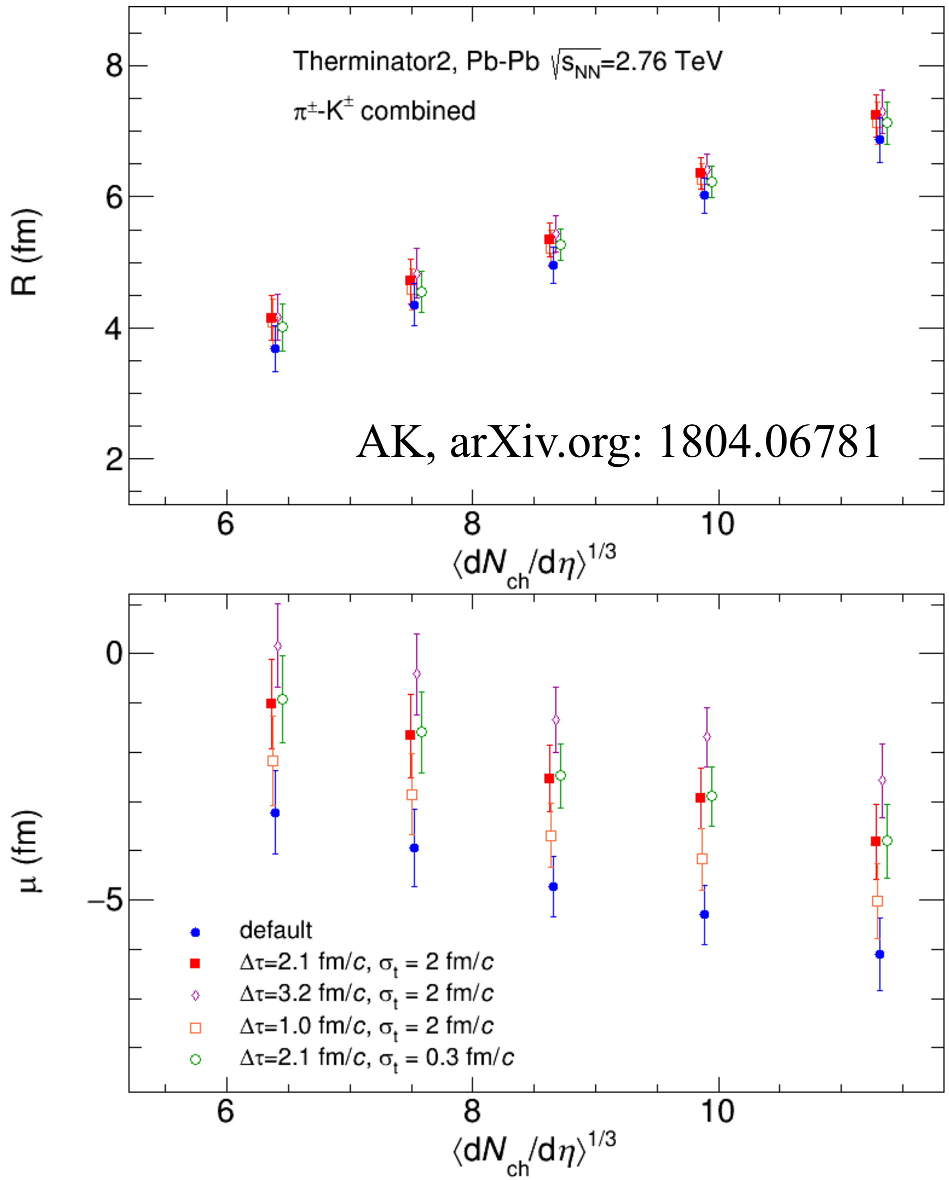
$$S(\vec{r}) \sim \exp\left(-\frac{(r_{out}-\mu_{out})^2}{R^2} - \frac{r_{side}^2}{R^2} - \frac{r_{long}^2}{\alpha^2 R^2}\right)$$



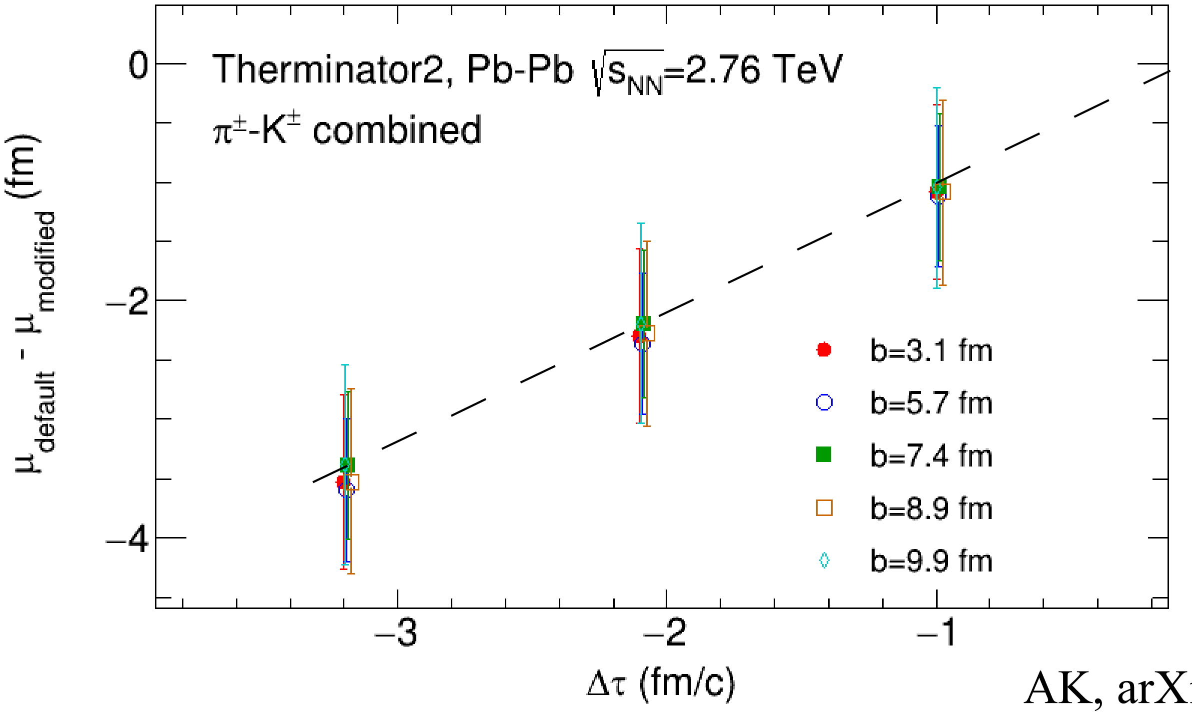


Results

- First model calculation for pion-kaon correlations for Pb-Pb collisions at the LHC
- Introduction of time delay has little influence on size. Width of time delay dist. also small effect
- Emission asymmetry directly sensitive to time delay introduced in the calculation, as expected
- Direct measurement of emission time delays possible also for heavy-ion environment with flow (but model dependent)



Linearity of response

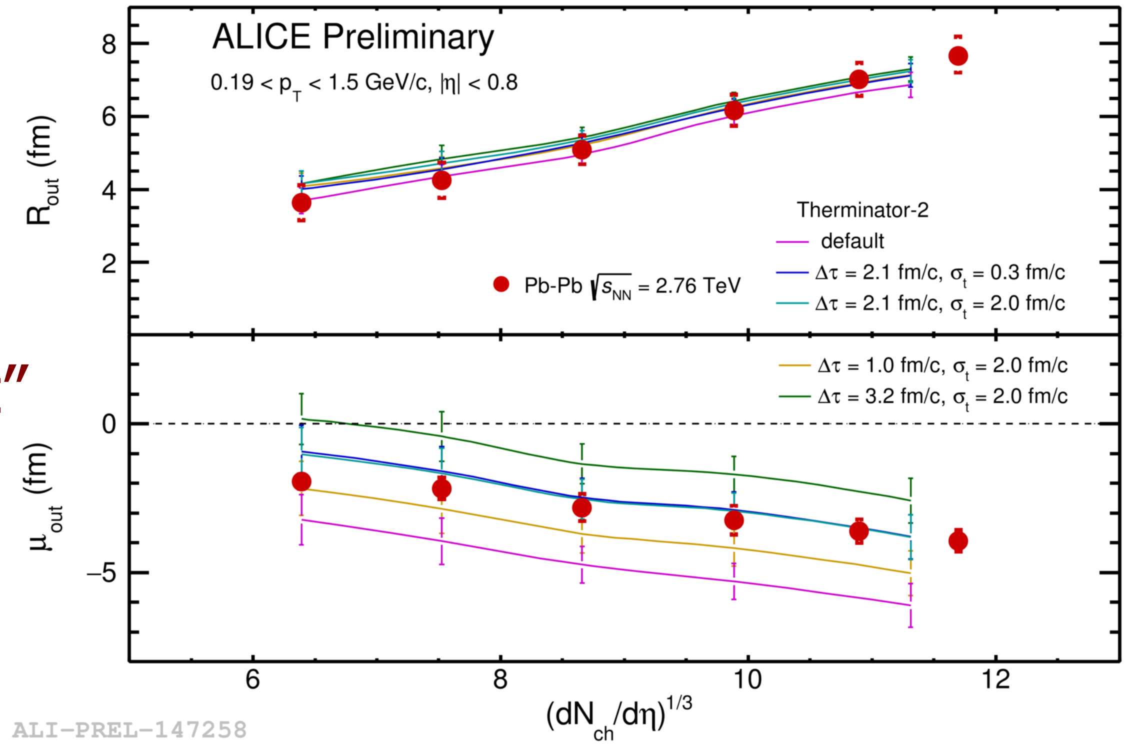


AK, arXiv.org: 1804.06781

- Difference between “default” calculation and one with time delay plotted vs. the introduced time delay
- Clear monotonic, linear, one-to-one correspondence observed, regardless of the system size. Very robust probe.

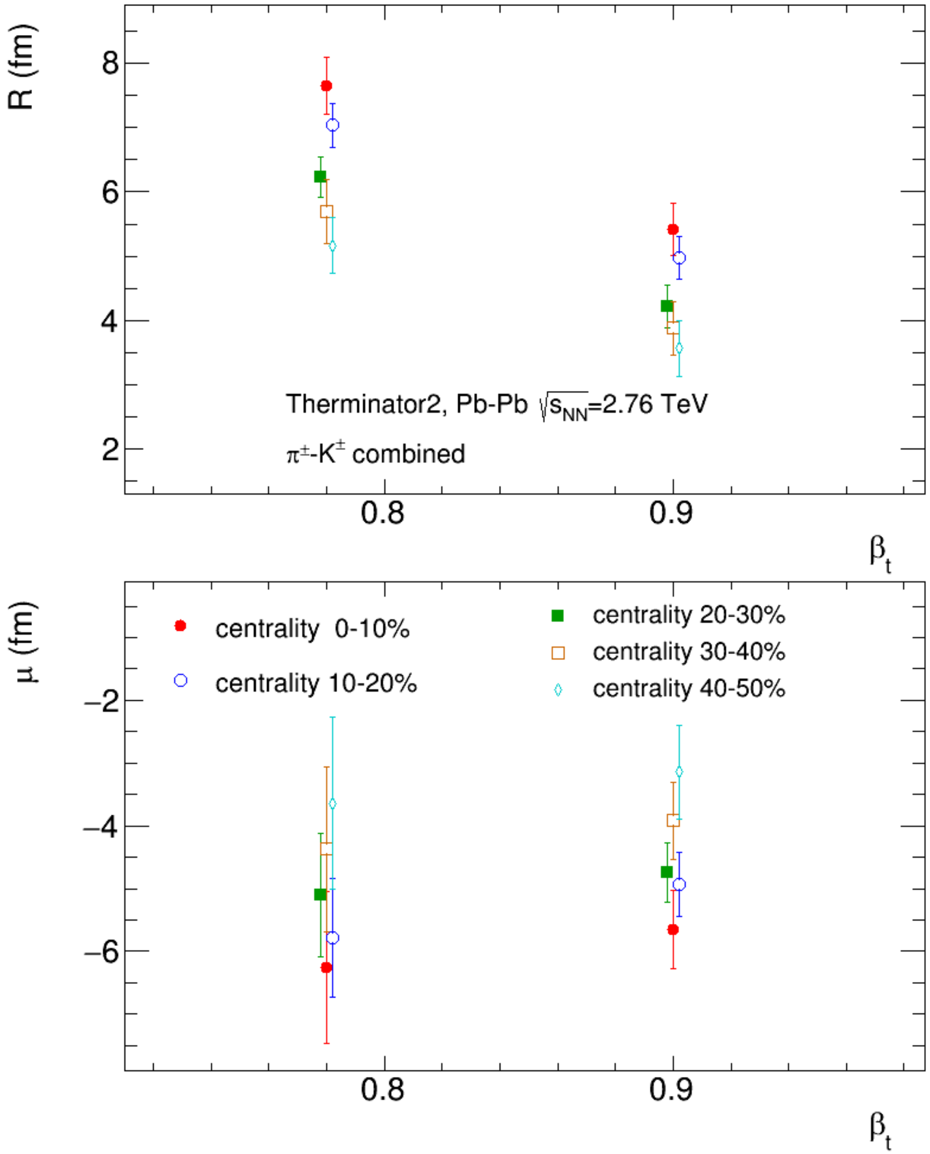
Comparison to data

- ALICE has shown first pion-kaon results from LHC at QM2018
- System size well reproduced (similarly to identical pion and kaon femtoscopy)
- Emission asymmetry in “default” case larger than in data
- Asymmetry with 2.1 fm/c kaon delay consistent with data: internal consistency with identical kaon femtoscopy



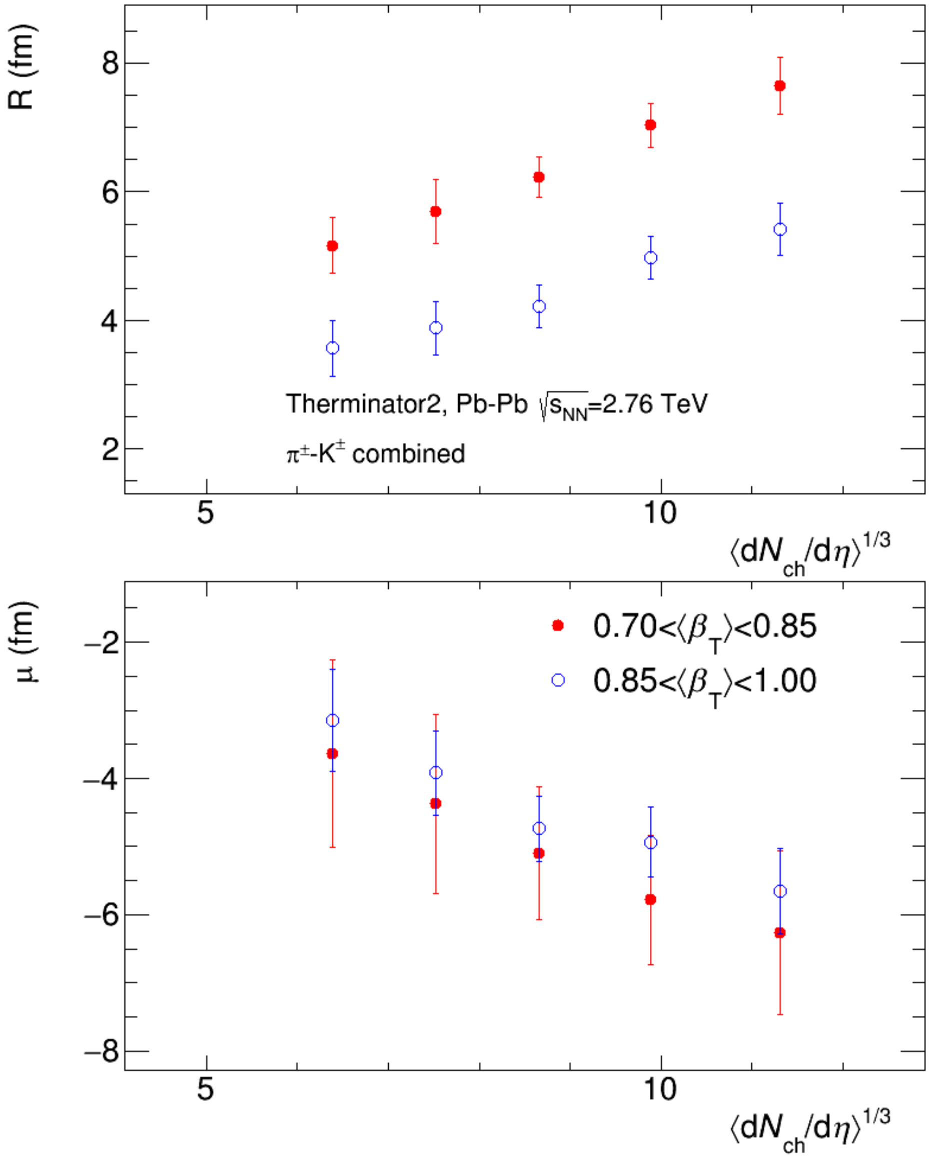
Ashutosh K. Pandey (ALICE); QM2018

Fits vs. pair velocity



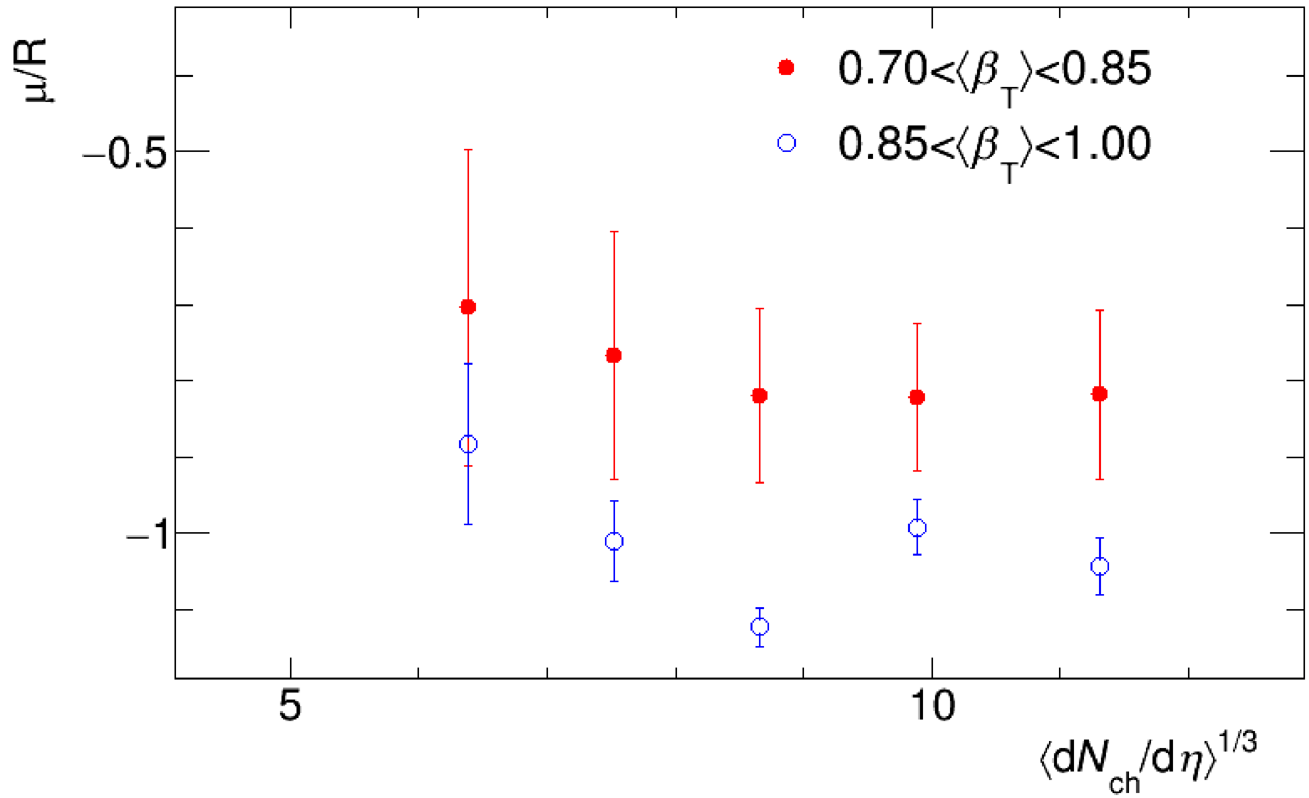
- Calculations also done vs. pair transverse velocity – combining two collectivity signatures in one measurement
- Size of the system decreases with pair velocity – clear signature of collectivity
- Emission asymmetry is also clearly observed for both pair velocity intervals

Centrality dependence



- Correlations show linear size dependence with cube root of multiplicity, similar to all identical-particle correlation analyses (pion, kaon, proton, 1D, 3D, etc.)
- Emission asymmetry also seems to linearly scale with multiplicity, regardless of pair velocity range

Scaled asymmetry



- Emission asymmetry scaled with system size:
  - Relatively constant with multiplicity – may be smaller at peripheral collisions
  - Grows with pair velocity

Summary

- Pion-kaon correlations an unique way to analyze the collectivity and emission time ordering in heavy-ion collisions
- Emission asymmetry directly sensitive to emission time delays between particle species (but some model dependence)
- New, precise, independent measure of time delays, which can probe effects such as emission time delay from rescattering via resonances
- Addition of pair velocity dependence combines two signatures of collectivity in one analysis
- Relative asymmetry increase and total size decrease observed for high velocity, first time both effects seen together.