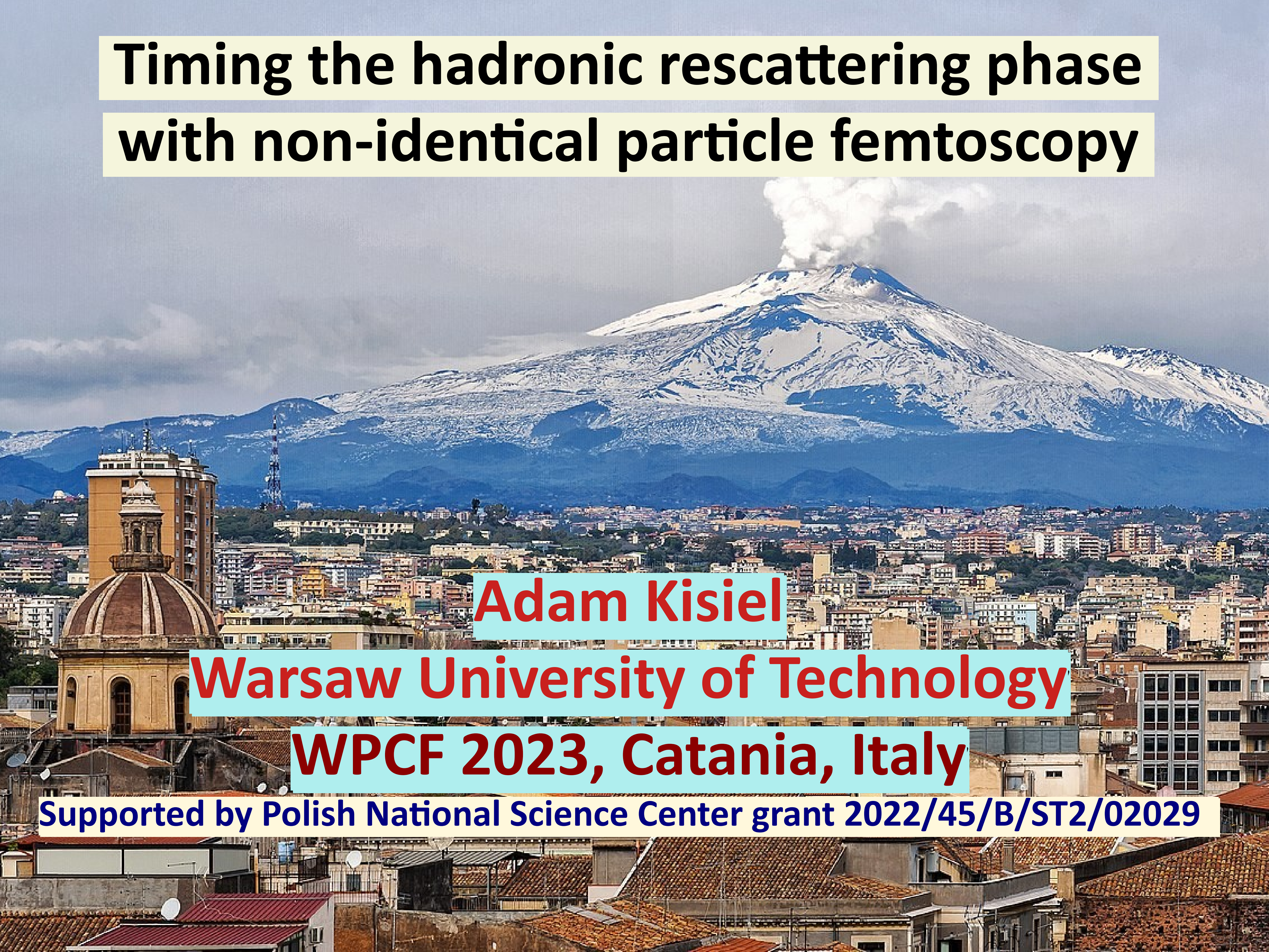
Timing the hadronic rescattering phase with non-identical particle femtoscopy



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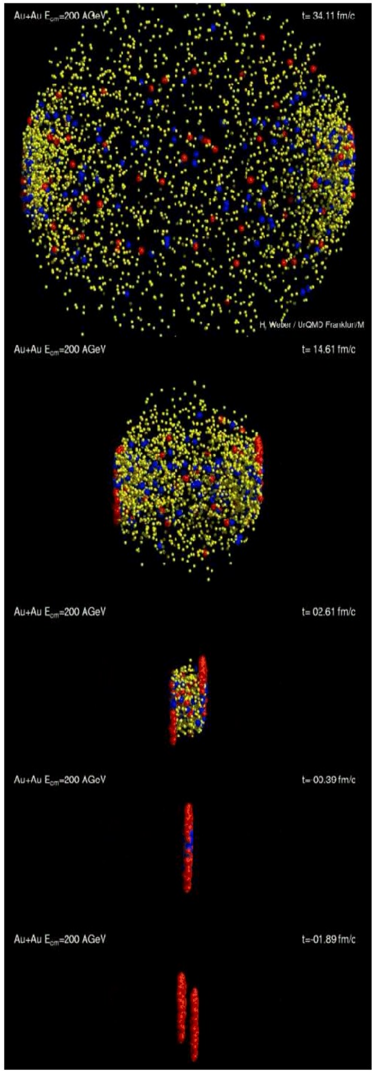
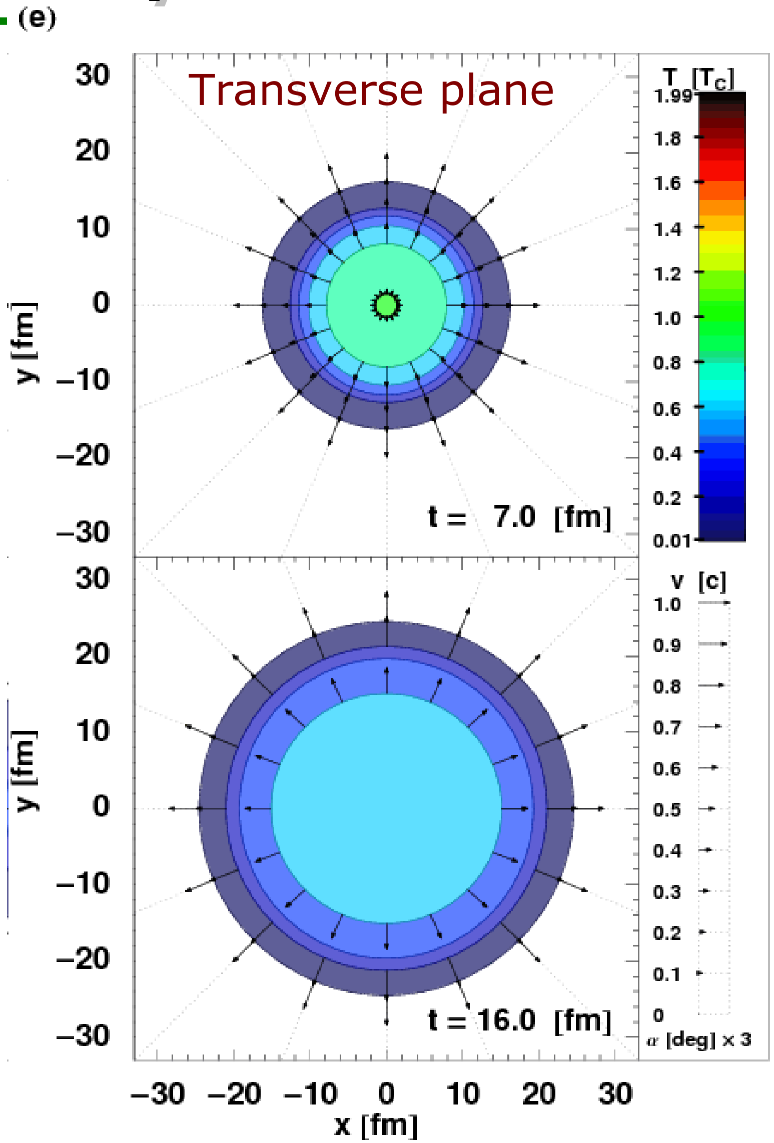
WPCF 2023, Catania, Italy

Supported by Polish National Science Center grant 2022/45/B/ST2/02029

Heavy-ion collision evolution

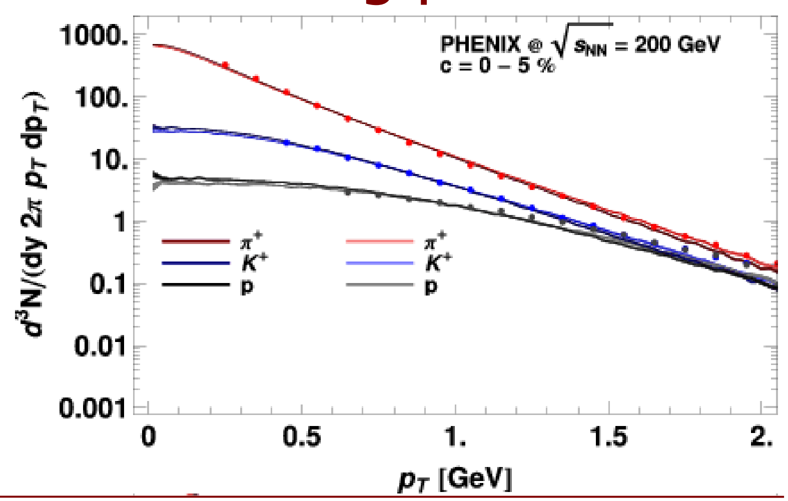
time



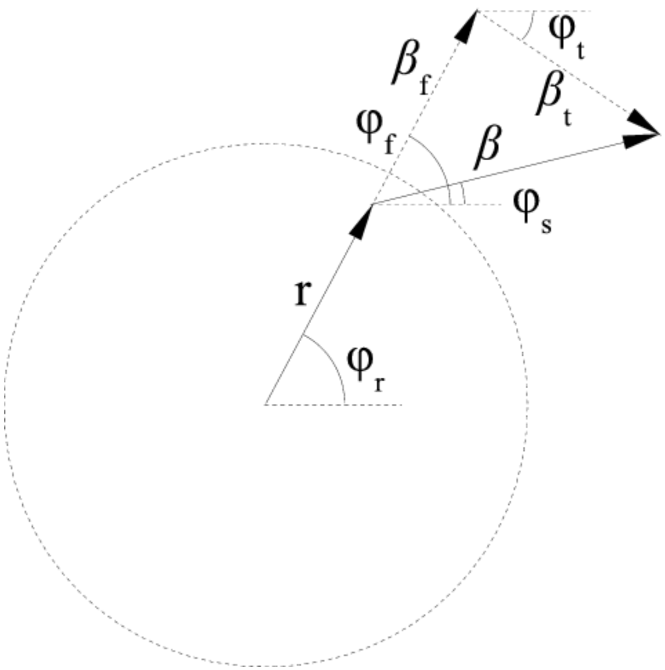


M. Chojnacki, W. Florkowski,
PRC 74 (2006) 034905

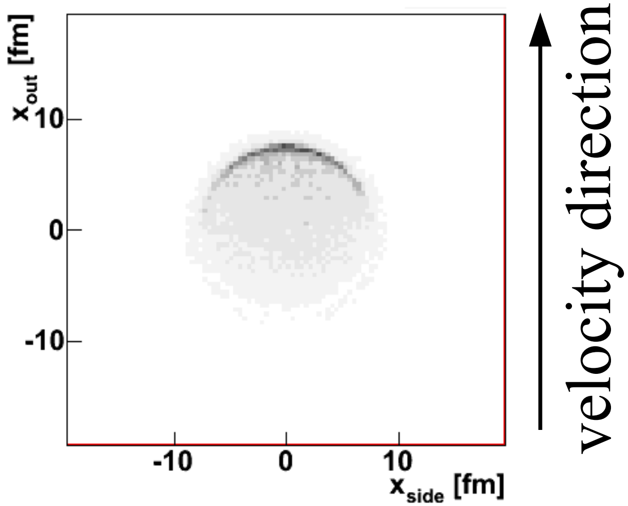
- HIC is expected to go through a QGP phase, where matter is strongly interacting – resulting in the development of collective motion
- "Hydro" expansion is followed by hadronic rescattering phase

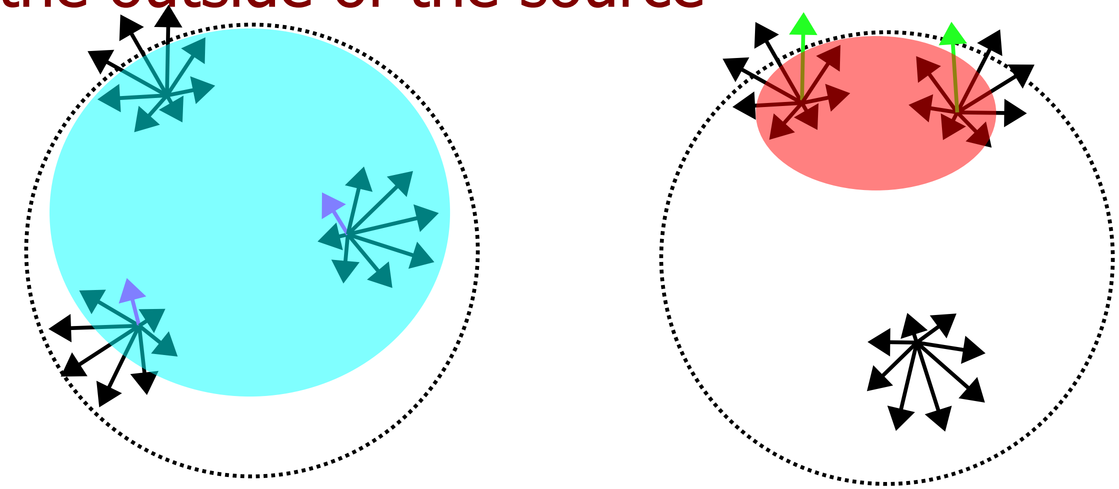


Thermal emission from collective medium



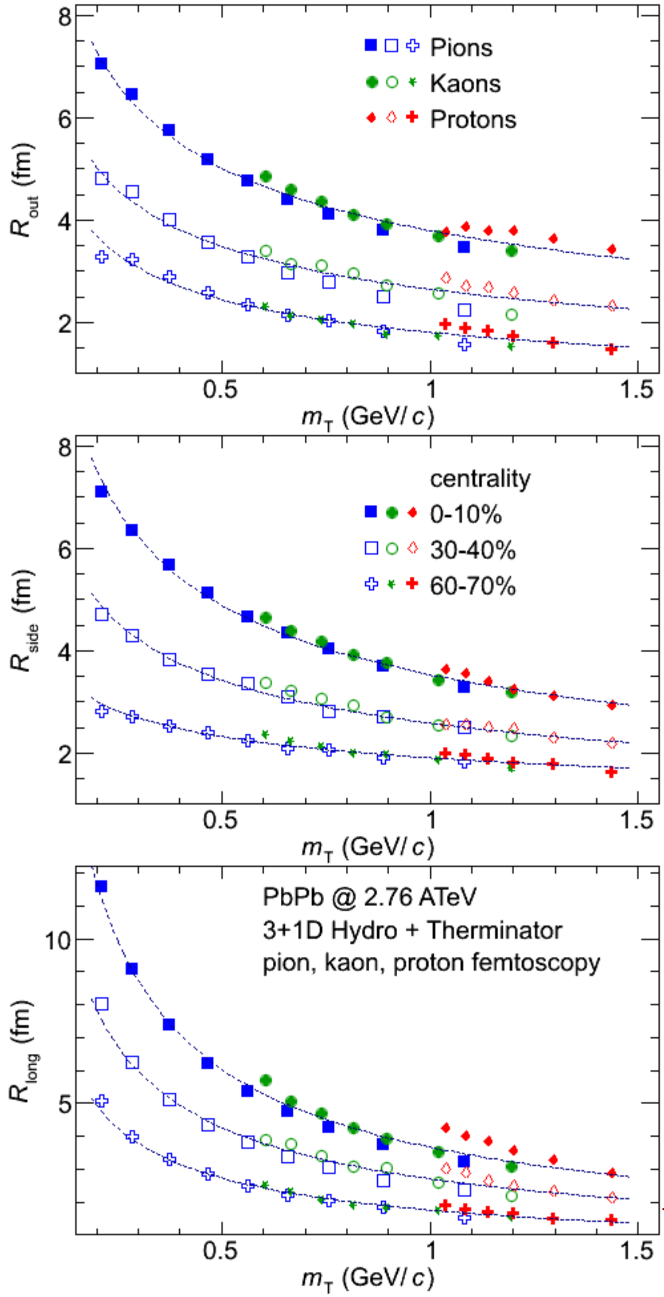
- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source





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

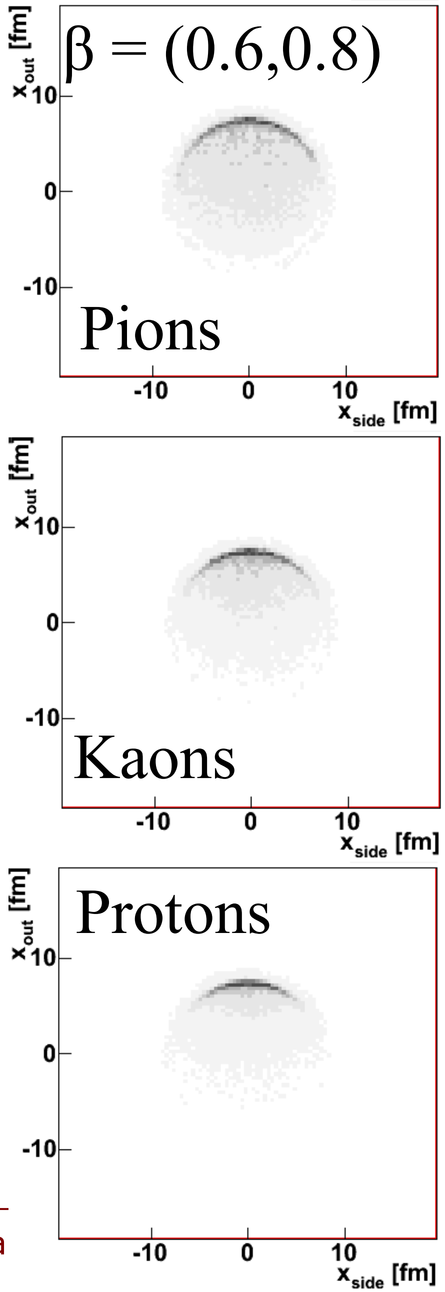
Consequences of flow



- "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:

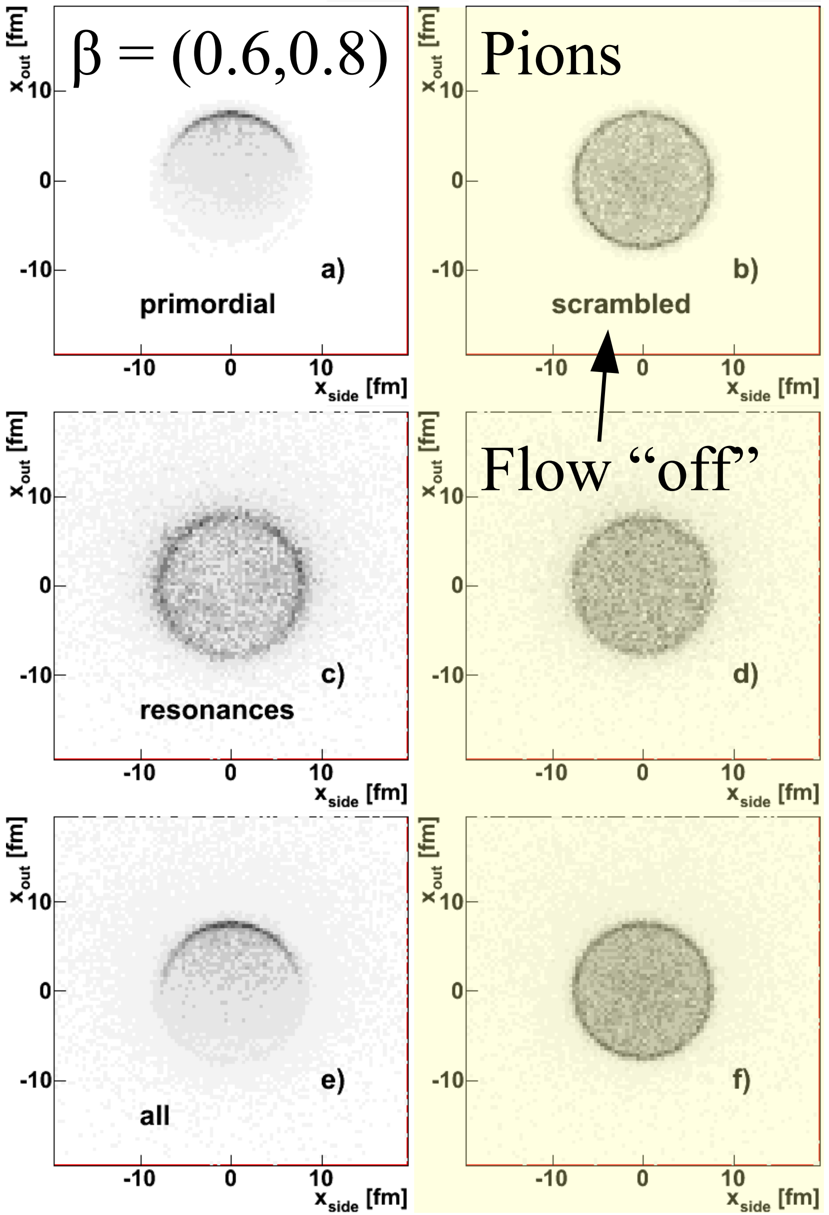
Pions $\langle x_{out}^{\pi} \rangle$	Kaons $\langle x_{out}^{K} \rangle$	Protons $\langle x_{out}^{p} \rangle$
2.83 fm	4.47 fm	5.61 fm

Asymmetry: $\langle r_{out}^{\pi K} \rangle \approx \langle x_{out}^{\pi} \rangle - \langle x_{out}^{K} \rangle$

- 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

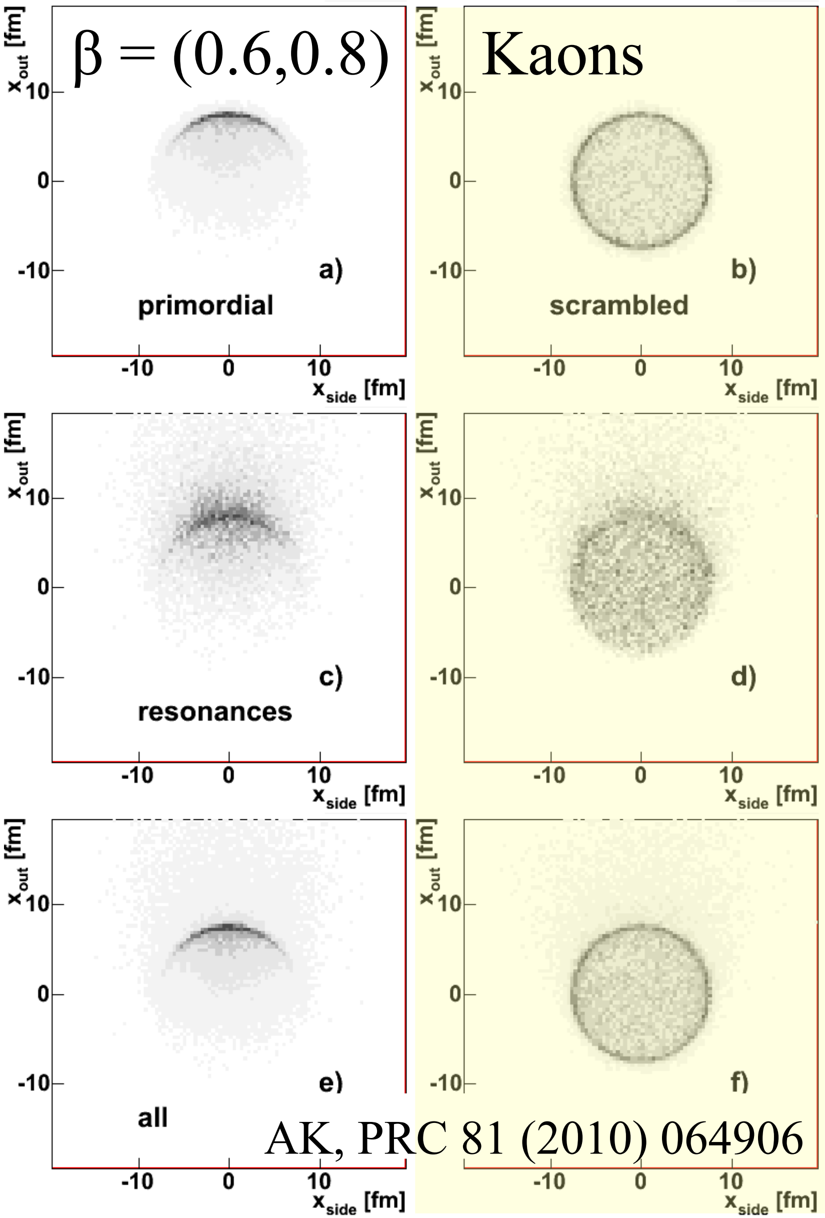


- With flow "off" (space-momentum correlation "off") → no emission shift
- Pions → decay momentum of most resonances larger than pion mass. Decay acts similarly to thermal smearing with large temperature.
- Emission points of pions from resonances strongly randomized – average very close to system center.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



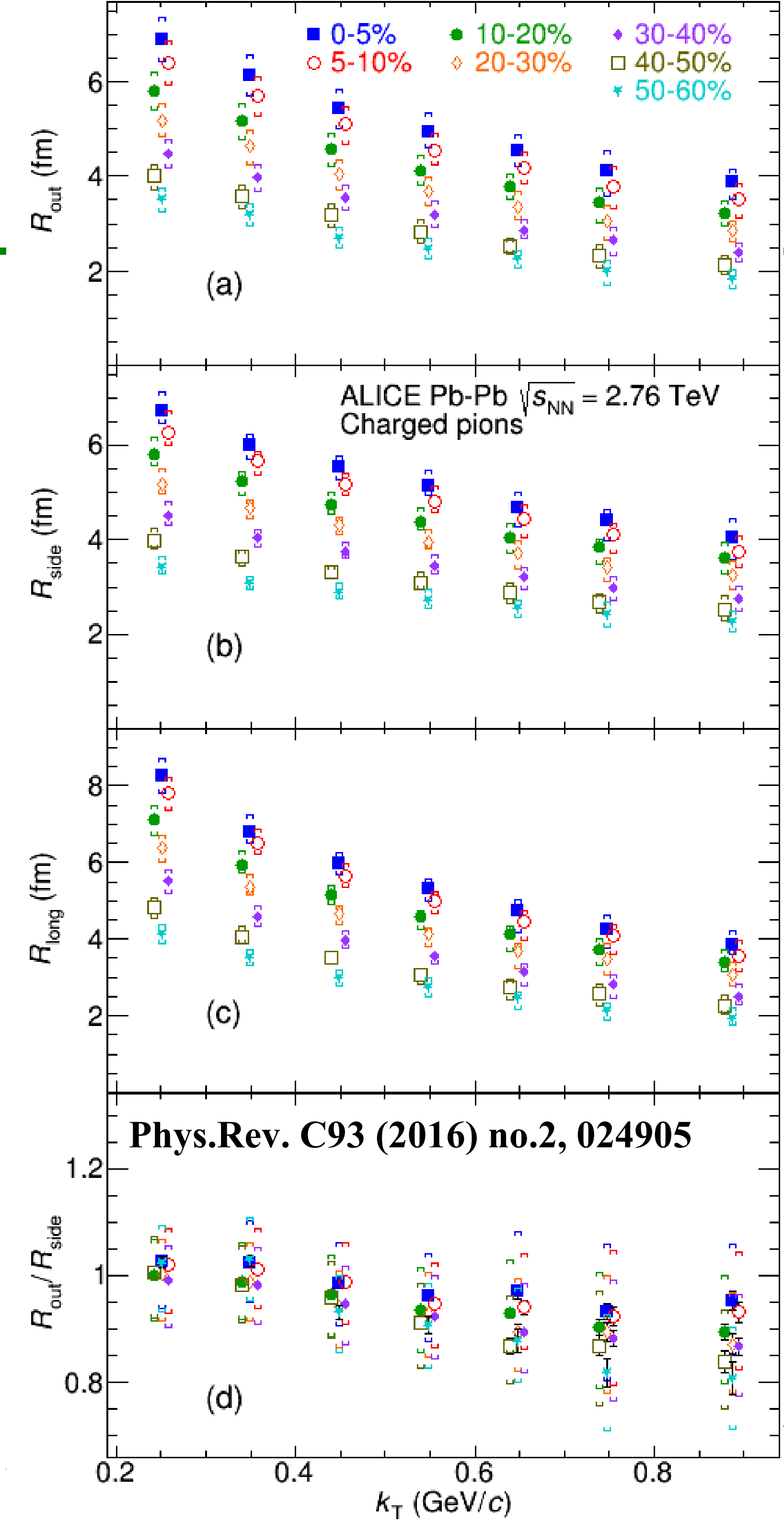
- Kaons → decay momentum of most resonances smaller than Kaon mass. Kaons retain the shift of the heavy (shifted more!) resonances.
- Emission points of kaons from resonances strongly pushed by flow – average far from system center.

Kaons $\langle x_{out}^{K} \rangle$	primodial	all
	4.47 fm	5.54 fm

- Overall: resonance propagation and decay **enhances** flow-induced difference between pion and kaon average emission points.

Difference in emission time

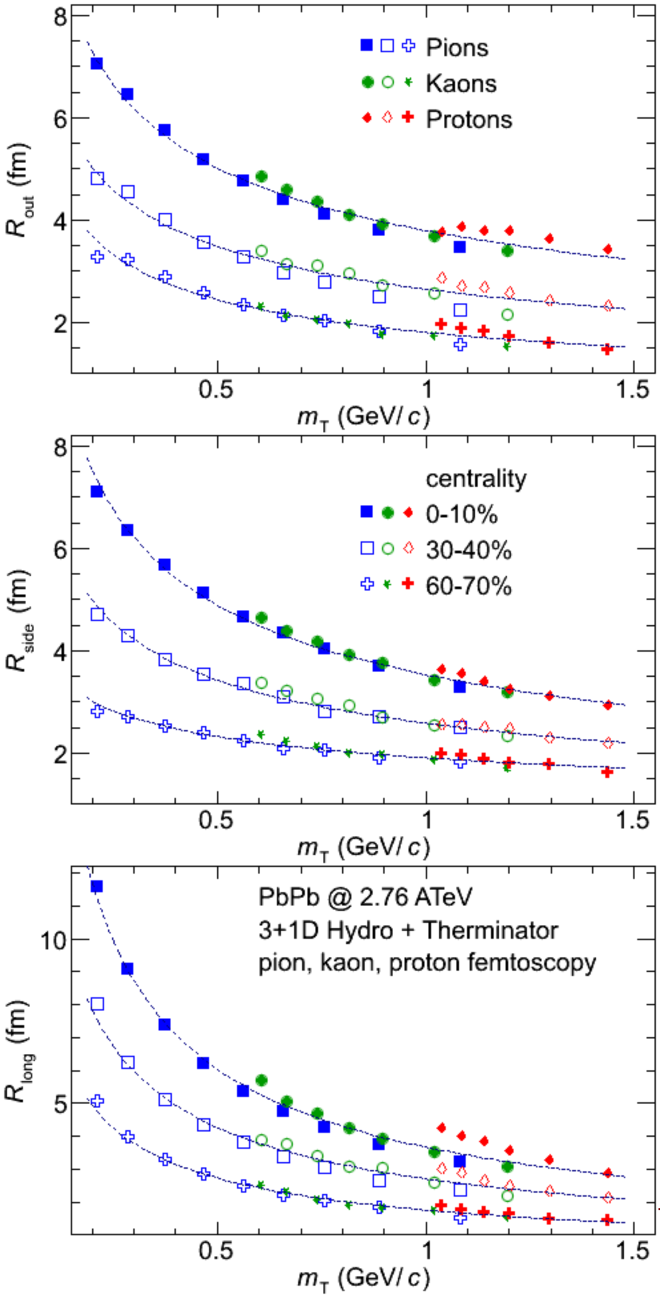
- Hydrodynamics predicts emission of higher p_T particles earlier (on average) than low p_T.
- At the same velocity pions are then emitted later than kaons.
- This effect goes in the same direction as emission asymmetry from flow
- In addition pions are more abundantly produced from resonances, which 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



ALICE Data on radii vs. centrality and k_T

- Femtoscopic radii vs. k_T for 7 centrality classes in central rapidity region
- Radii universally grow with event multiplicity and fall with pair momentum
- Both dependencies in agreement with calculations from collective models (hydrodynamics), both quantitatively and qualitatively
- When compared to results from RHIC – all expected trends visible (larger size, steeper k_T dependence, R_{out}/R_{side}~1)

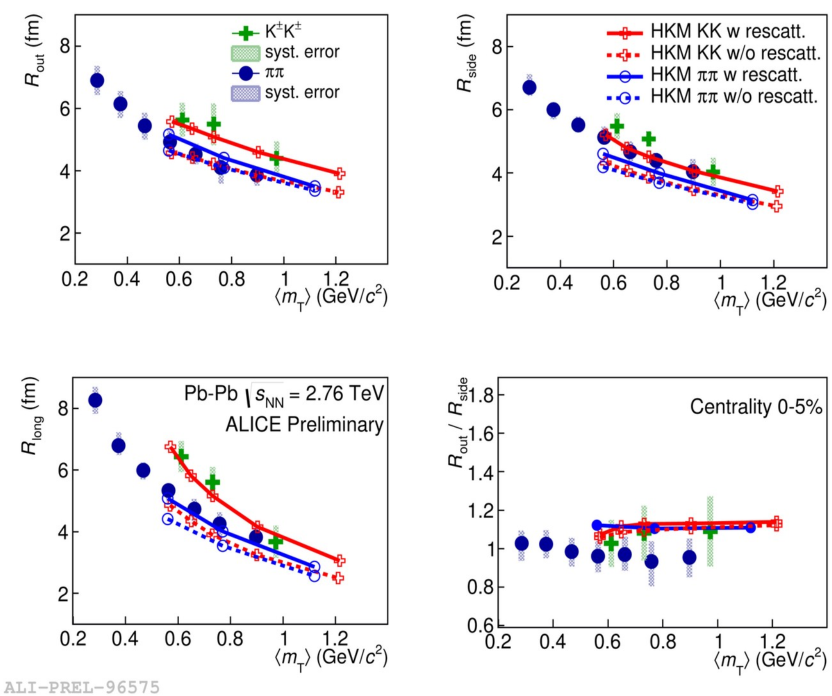
m_T scaling and rescattering



"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
- "Hydro" + **rescattering** → breaking of scaling

M. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov; Nucl.Phys. A 929 (2014)

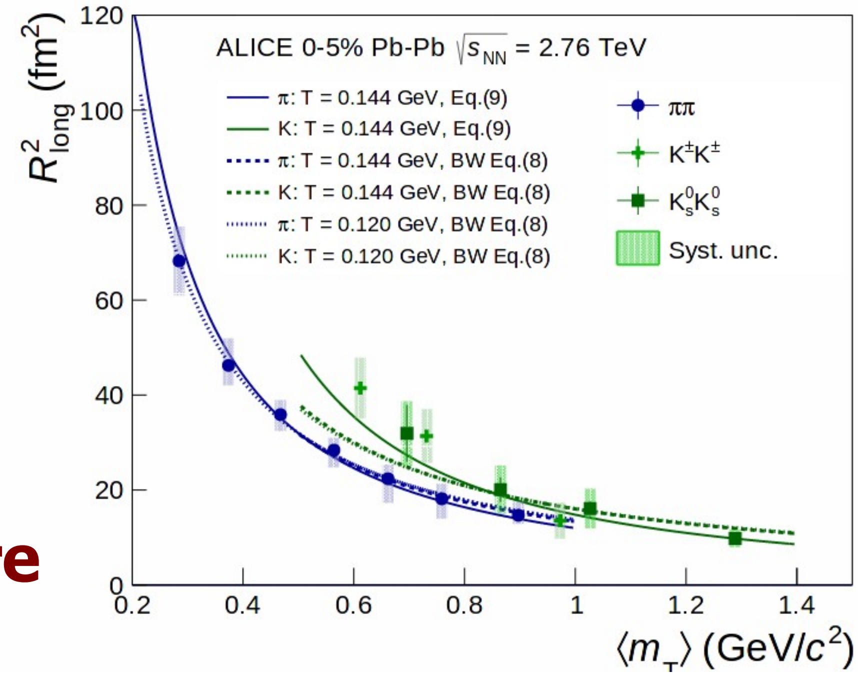


AK, M.Gałażyn, P.Bożek; Phys.Rev.C90 (2014) 6, 064914

Emission delay in data

- ALICE kaon femto: kaons emitted on average later than pions.
- Delay from **rescattering** via K* resonance (**not included** in Therminator 2), in **opposite** direction to all other asymmetries
- Time delay: **rescattering signature on top of "flow" baseline**

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

N·H
ELSEVIER

18 April 1996

PHYSICS LETTERS B

Physics Letters B 373 (1996) 30–34

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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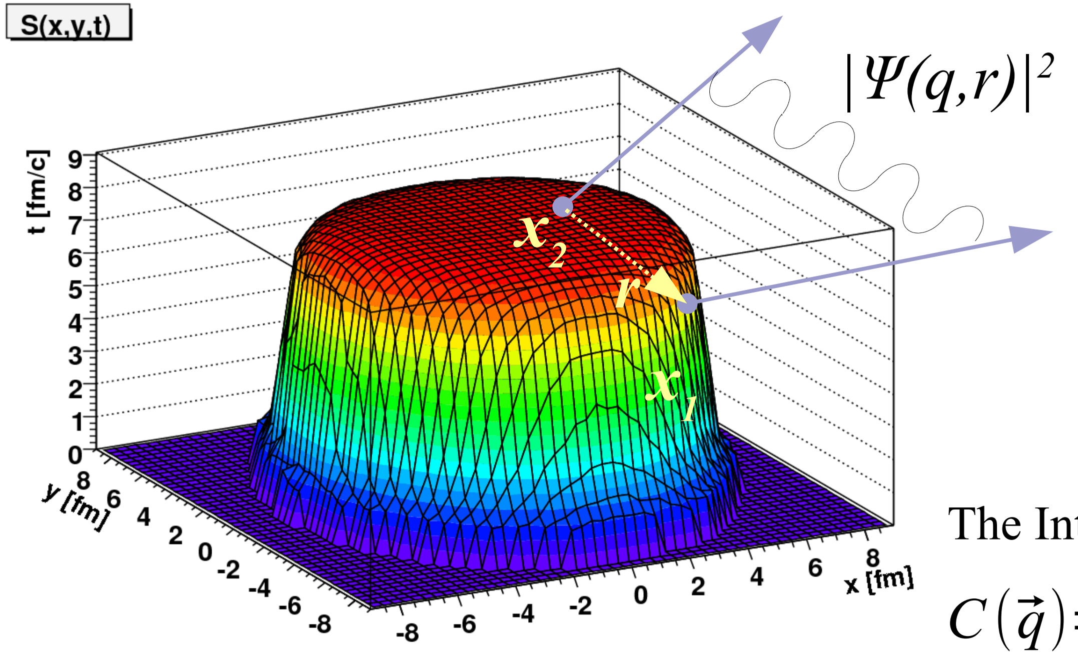
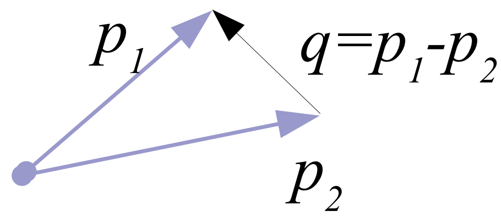
Received 24 November 1994; revised manuscript received 16 January 1996
Editor: R.H. Siemssen

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.

Femtoscopy: size and asymmetry



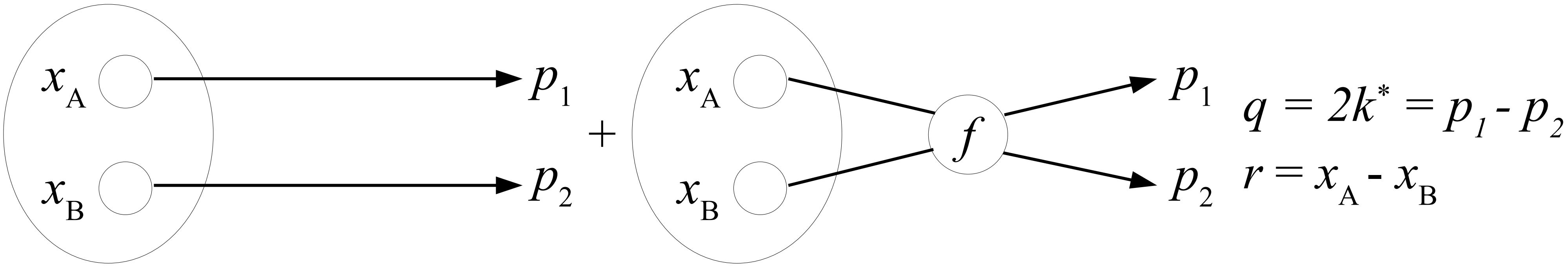


The Integral Equation for Correlation

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

- 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



- Two charged particles interact via Coulomb and strong **after last scattering** (measurement after rescattering phase)
  - This gives the final form of the wave-function, for pion-kaon pairs the Coulomb interaction dominates

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

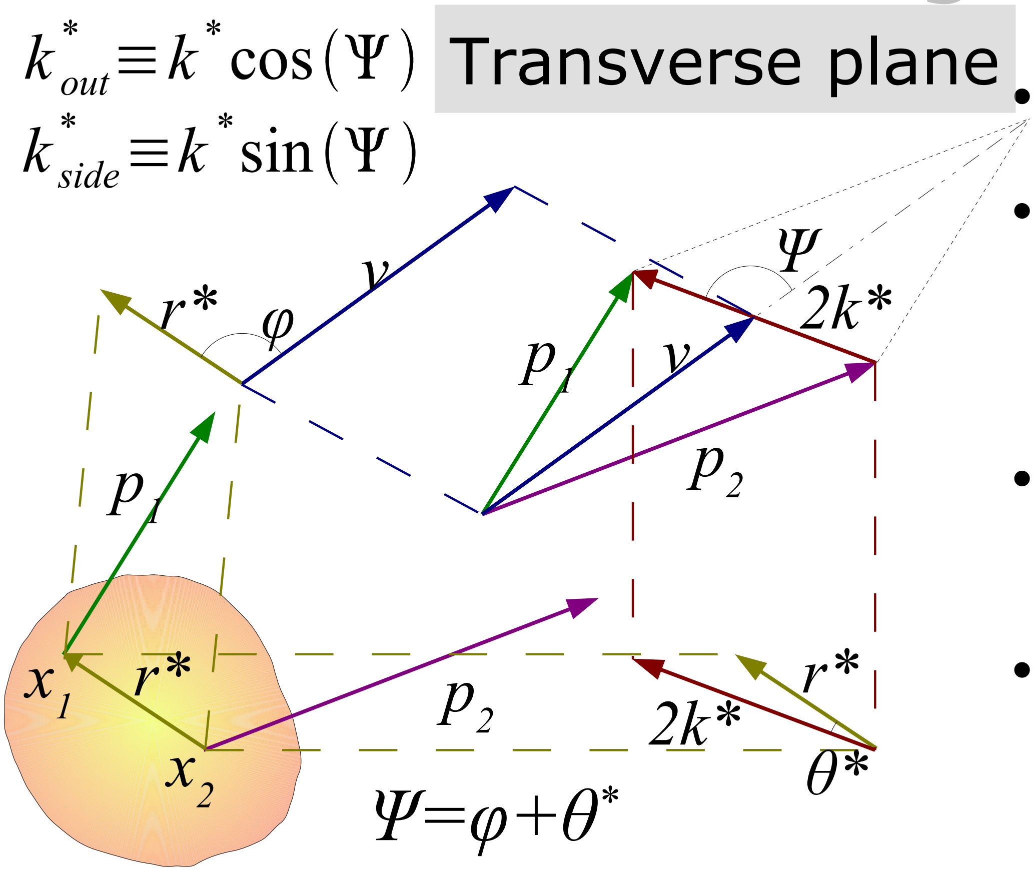
$$\xi = \boldsymbol{k}^*\boldsymbol{r}^* + k^*r^* \equiv \rho(1+\cos(\theta^*)),\ \ \rho = k^*r^*,\ \ \eta = (k^*a)^{-1},\ \ a = (\mu z_1 z_2 e^2)^{-1}$$

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

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

Accessing asymmetry

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

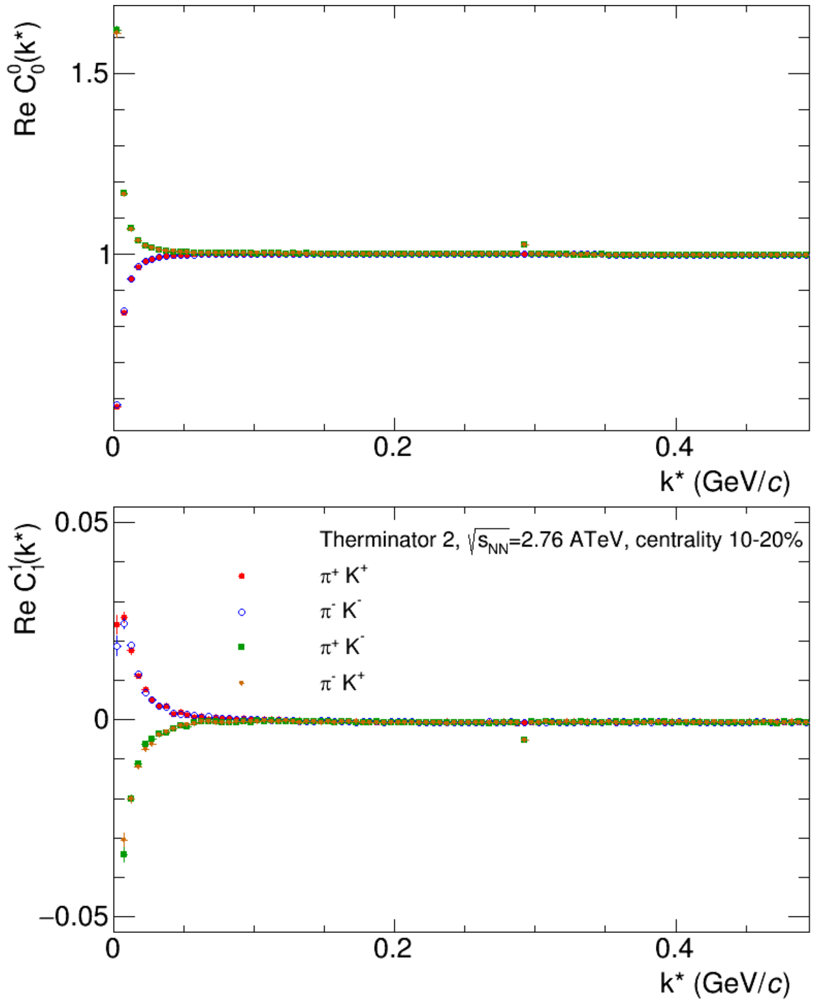


$$\cos(\Psi) = \cos(\varphi)\cos(\theta^*) + \sin(\varphi)\sin(\theta^*)$$
$$sign\langle\cos(\Psi)\rangle = sign\langle\cos(\varphi)\rangle\, sign\langle\cos(\theta^*)\rangle$$

- 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

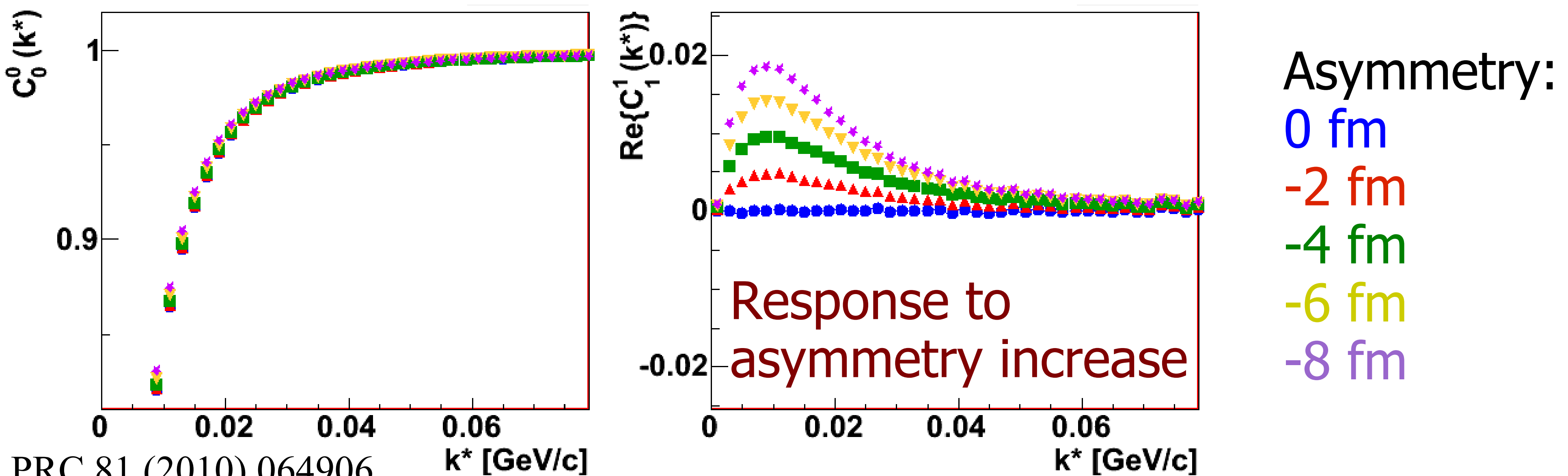


$$C_l^m(q) = \int C(\vec{q}) Y_l^m(\cos(\theta), \phi) \, d\phi \, d\cos(\theta)$$

- 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 ("flow") and time asymmetry

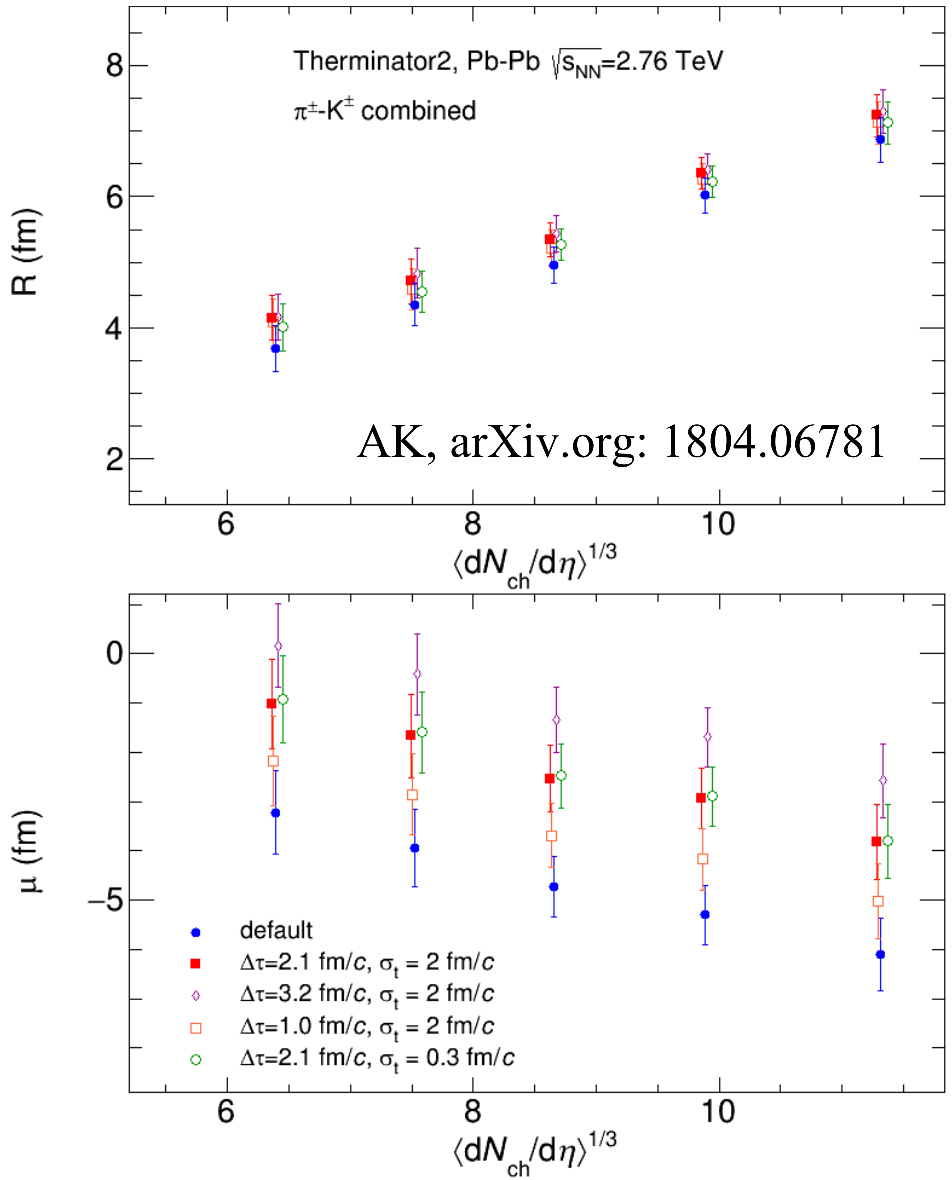
- The non-identical particle femtoscopy sensitive to the emission asymmetry between particle types, possible because they are not identical
- Measurement sensitive to the difference of the spatial and time asymmetries in LCMS, not possible to distinguish between them

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

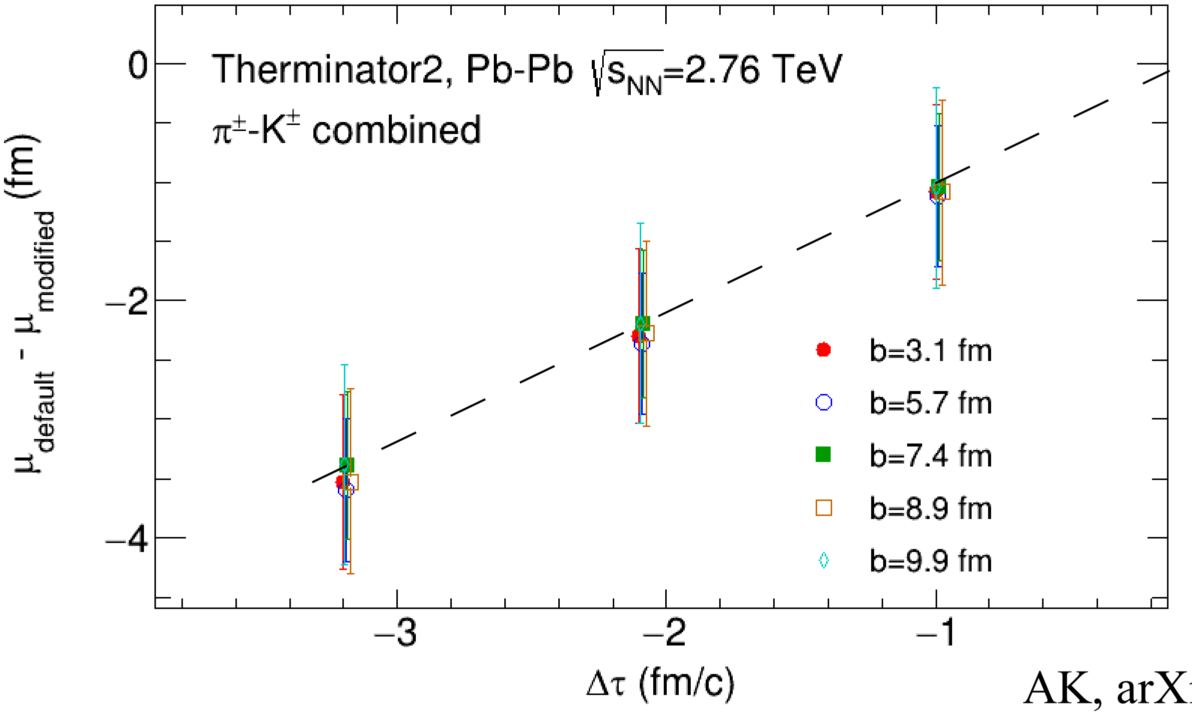
- "Spatial" asymmetry r_{out} arises in flowing medium, difficult to produce otherwise
- "Time" asymmetry Δt may have various origins, some not connected to flow

Asymmetry baseline

- Model calculation of pion-kaon correlations for Pb-Pb at the LHC with flow and resonances but **no rescattering** (baseline)
- Additional time delay has little effect on size.
- Emission asymmetry directly sensitive to additional time delay
- **Rescattering** shows up as "additional time delay" for kaons directly influencing asymmetry



Linearity of response



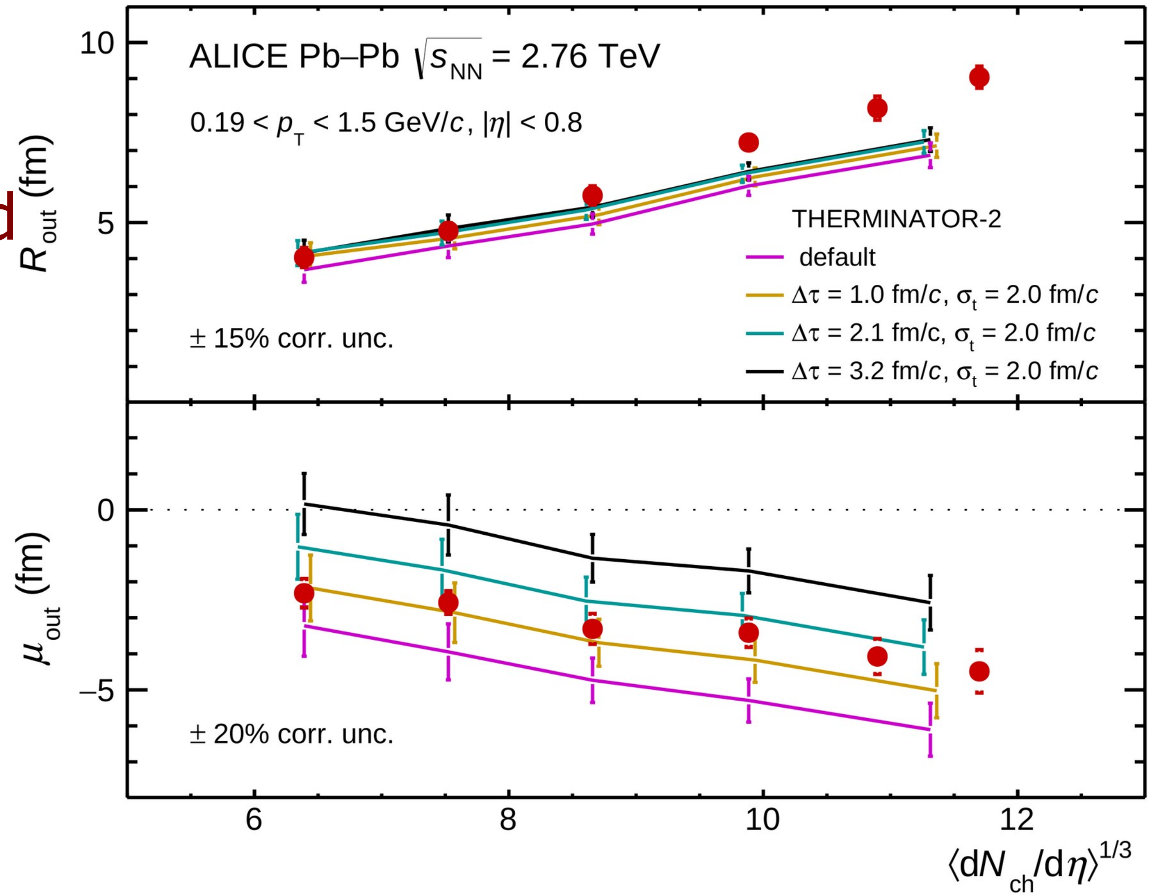
AK, arXiv.org: 1804.06781

- Difference between "default" calculation (baseline) and one with time delay (+rescattering) plotted vs. added time delay
- Clear monotonic, linear, one-to-one correspondence observed, regardless of the system size. Very robust probe.

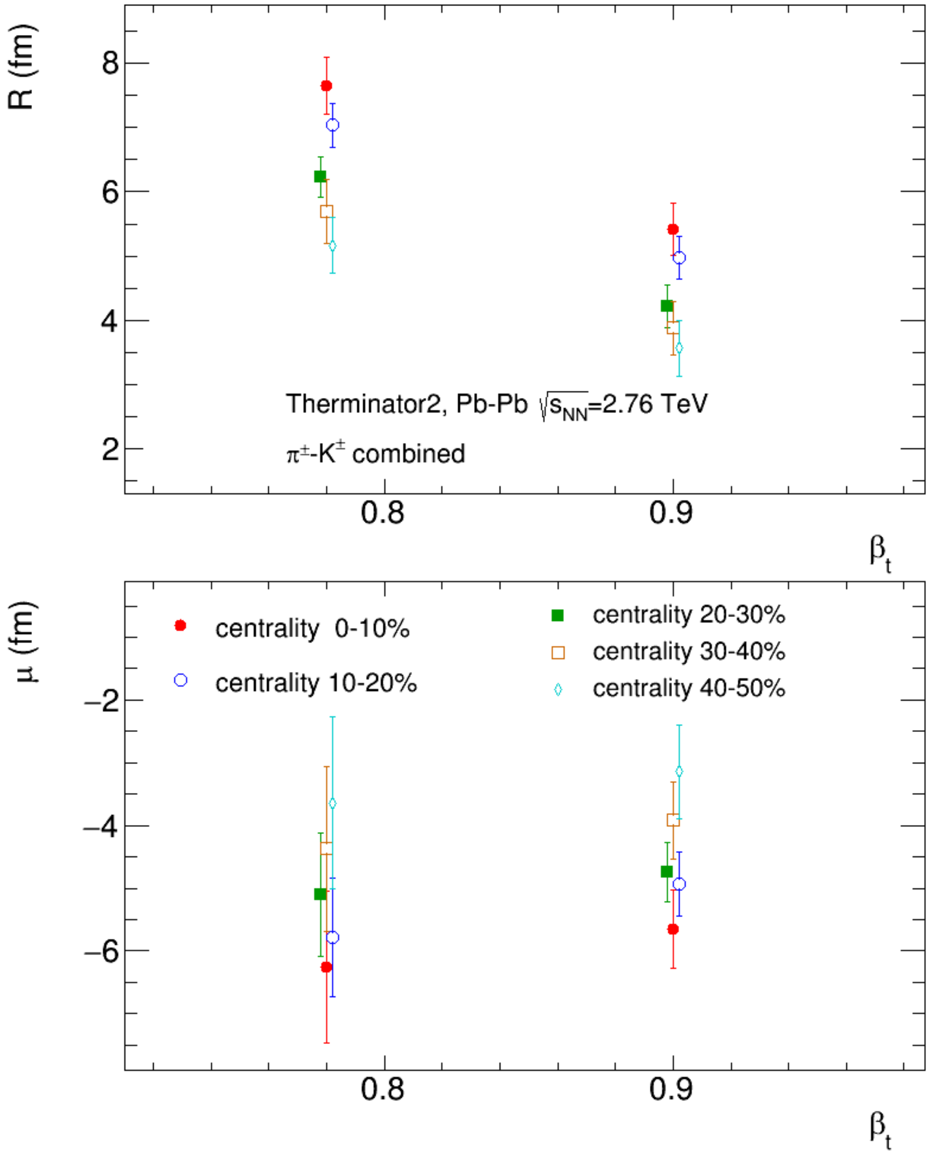
Comparison to data

- ALICE published first pion-kaon results from LHC
- System size well reproduced (similarly to identical pion and kaon femtoscopy)
- Emission asymmetry in "default" baseline case larger than in data
- Asymmetry with 2.1 fm/c kaon delay consistent with data: **probe of duration of hadronic rescattering**

ALICE; Phys.Lett.B 813 (2021) 136030; arXiv: 2007.08315 [nucl-ex]

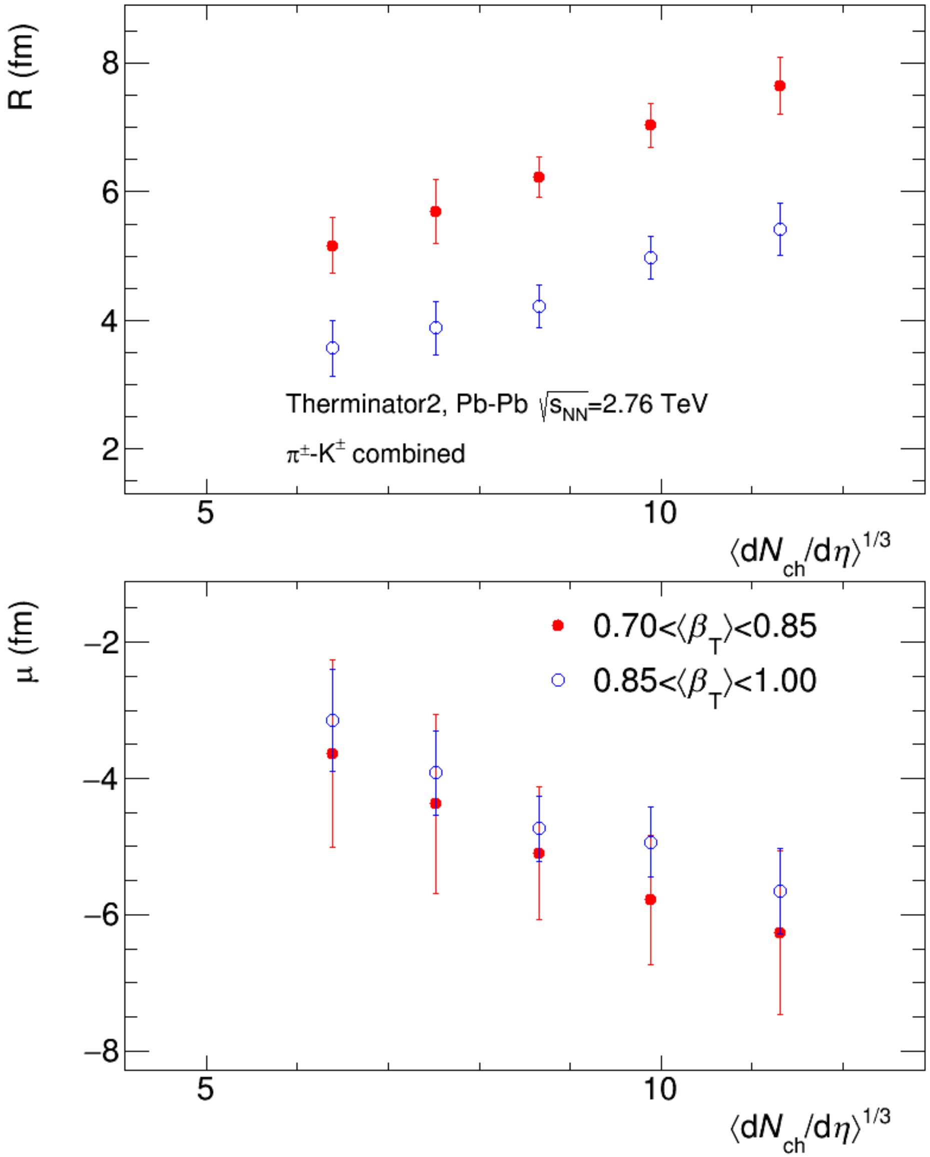


Fits vs. pair velocity



- Calculations 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
- Differential probe of rescattering duration at seveal momentum ranges

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

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 on top of the flow “baseline”
- ALICE experimental data consistent with duration of hadronic rescattering phase on the order of 2 fm/c
- Measurement can be extended to pair velocity and centrality dependence