Probing emission dynamics with with non-identical particle femtoscopy

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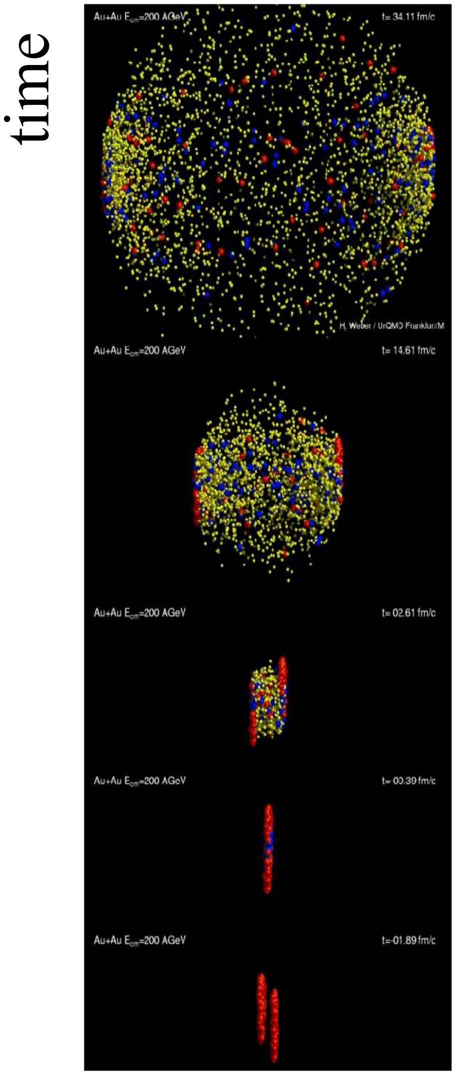
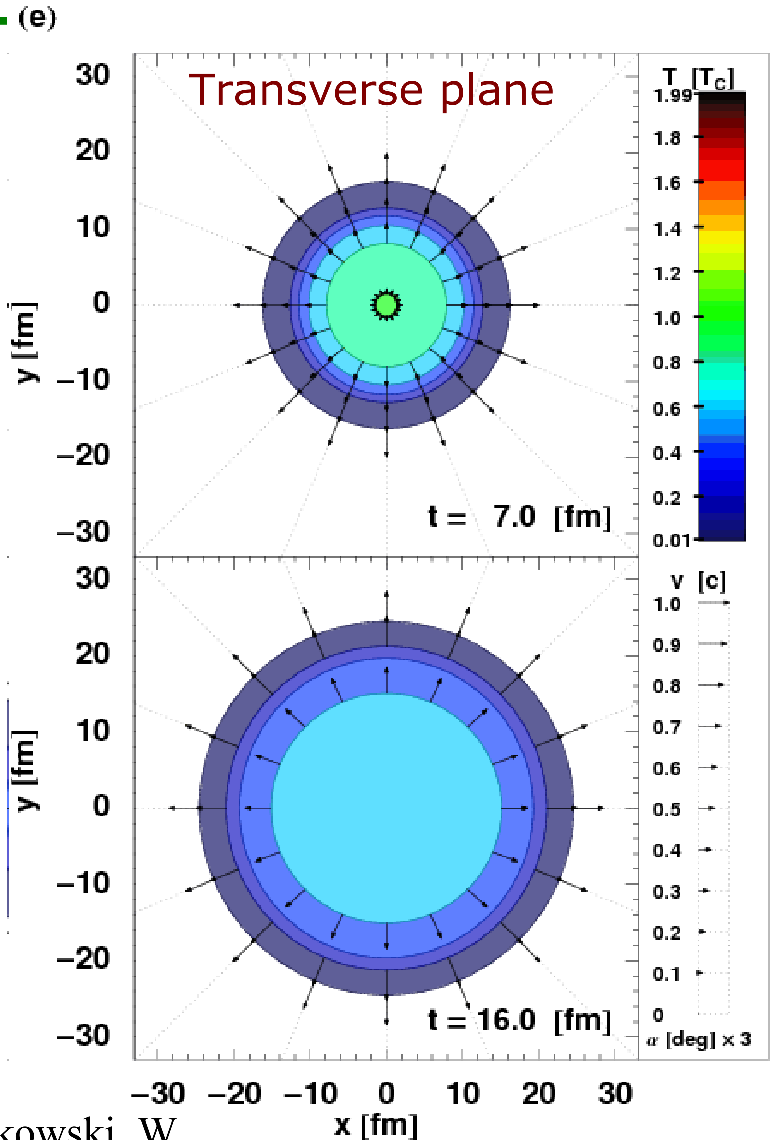
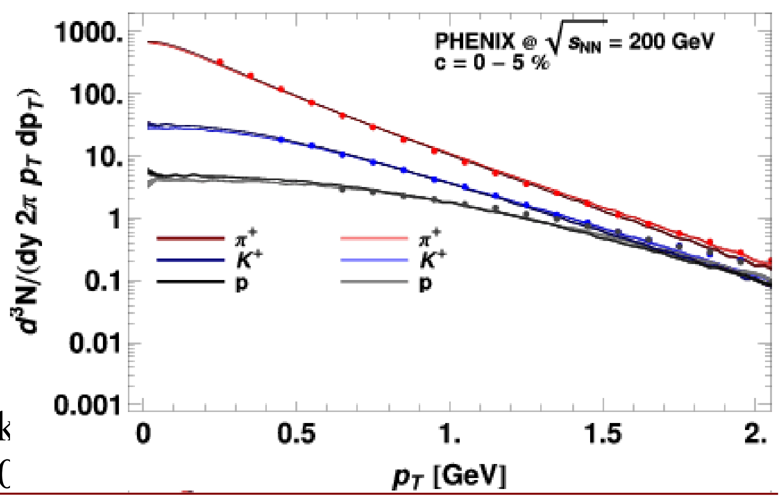
HIC evolution in "thermal" model





Thermintor+Lhyquid3D model: HIC has a QGP phase, modeled in viscous 3+1D hydrodynamics, parameters tuned to data

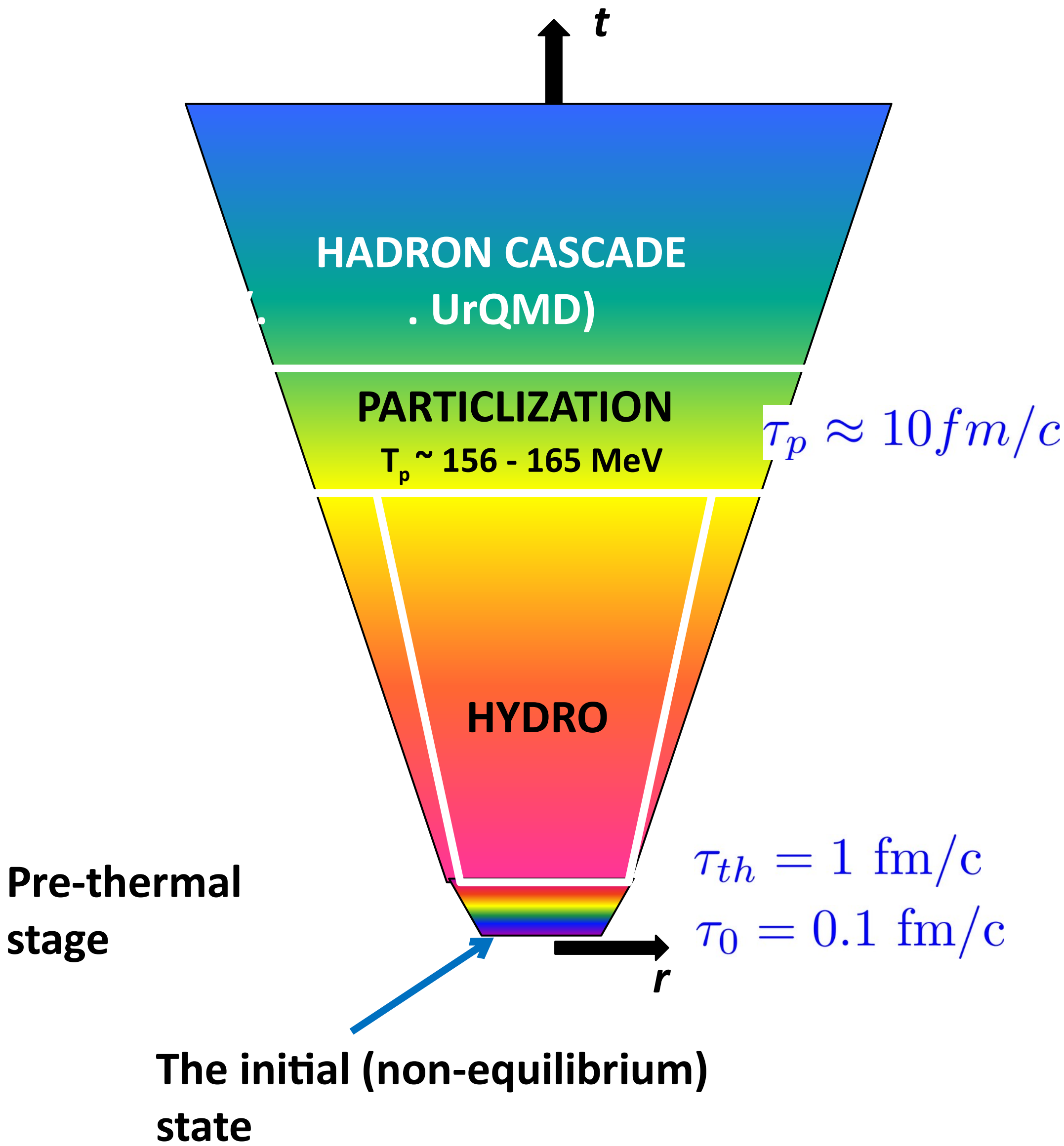
Hadronization and resonance propagation and decay done in Therminator



M. Chojnacki, AK, W. Florkowski, W. Broniowski, Comput.Phys.Commun. 183 (2012) 746-773; arXiv: 1102.0273 [nucl-th]

M. Chojnacki, W. Florkowsk PRC 74 (2006) 03490

Integrated HydroKinetic Model: iHKM



Complete algorithm incorporates the stages:

- **generation of the initial states: (MC Glaub & CGC)**
- **thermalization of initially non-thermal matter;**
- **viscous chemically equilibrated hydrodynamic expansion;**
- **particlization of expanding medium at the hadronization area;**
- **a switch to UrQMD cascade with near equilibrium hadron gas as input;**
- **simulation of observables.**

Yu.Sinyukov., Akkelin, Hama: PRL 89 (2002) 052301;
… + Karpenko: PRC 78 (2008) 034906;
Karpenko, Yu.Sinyukov : PRC 81 (2010) 054903;
… PLB 688 (2010) 50;
Akkelin. Yu.Sinyukov : PRC 81 (2010) 064901;
Karpenko, Yu.Sinyukov., Werner: PRC 87 (2013) 024914;
Yu.Sinyukov, Naboka, Karpenko : PRC 91 (2015) 014906;
Yu.Sinyukov, Naboka, Karpenko: PRC 93 (2016) 024902.
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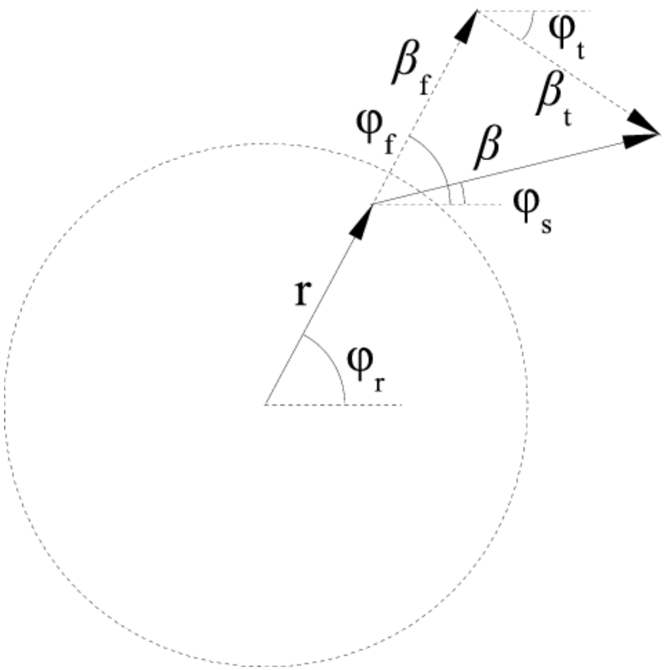
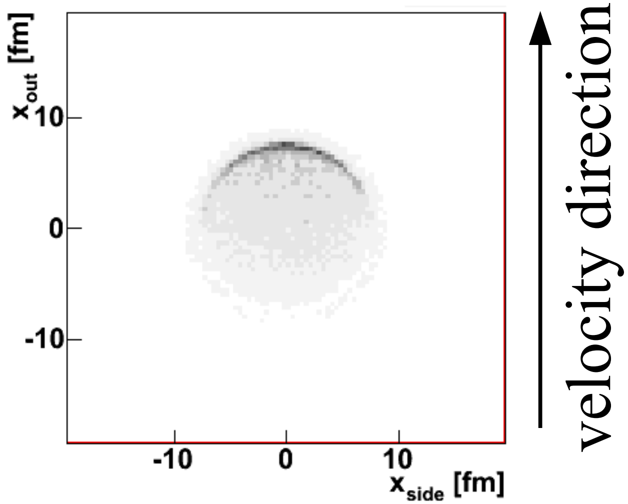
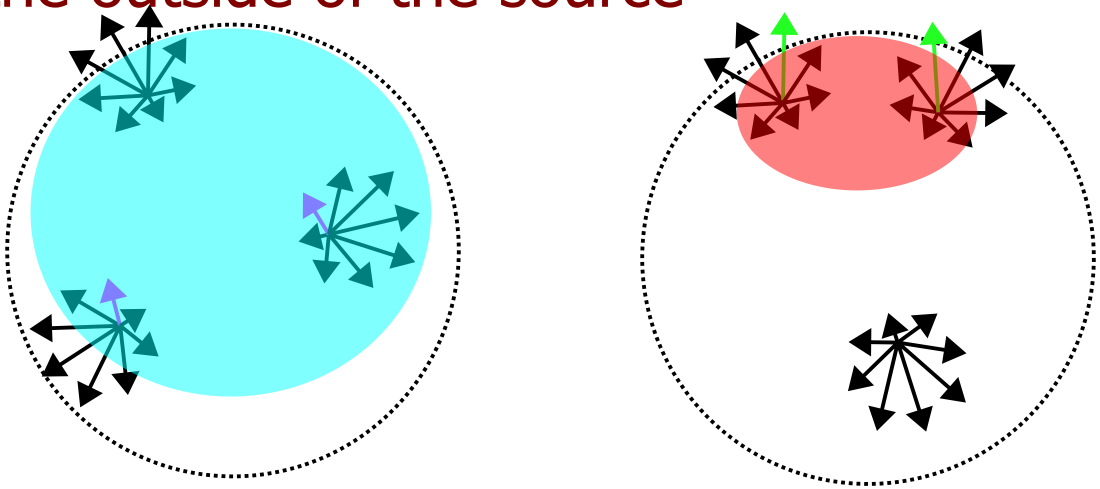
Thermal emission from collective medium



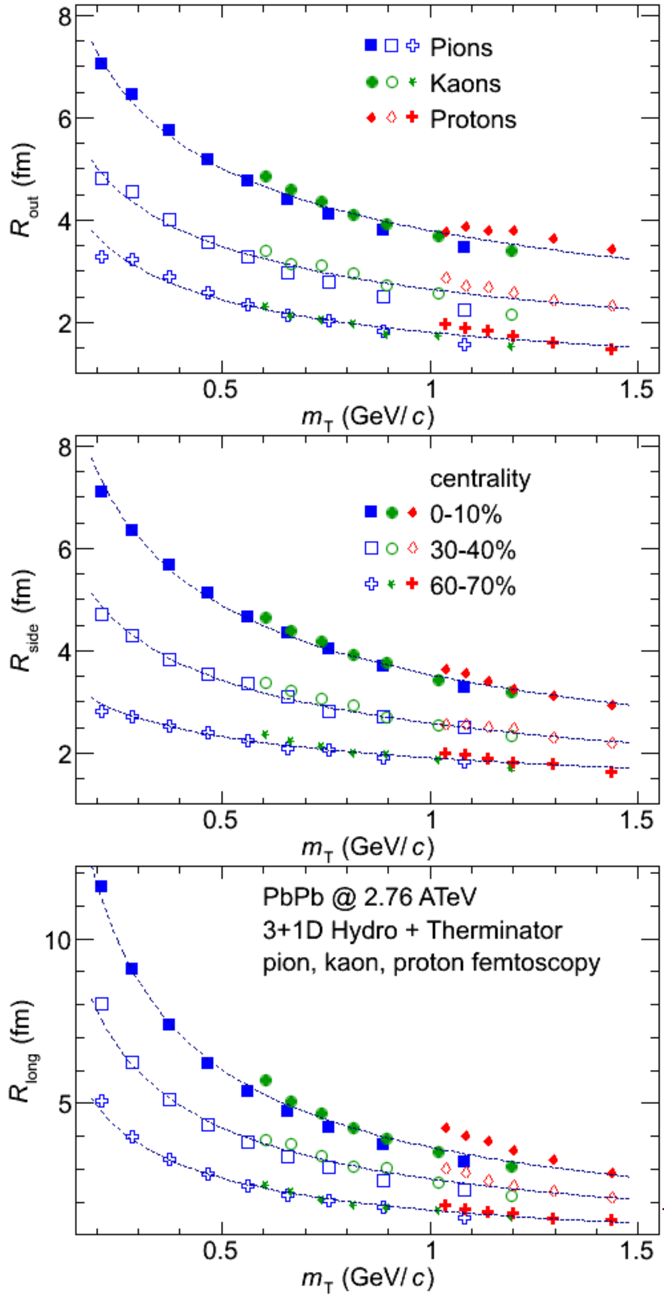
- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source





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

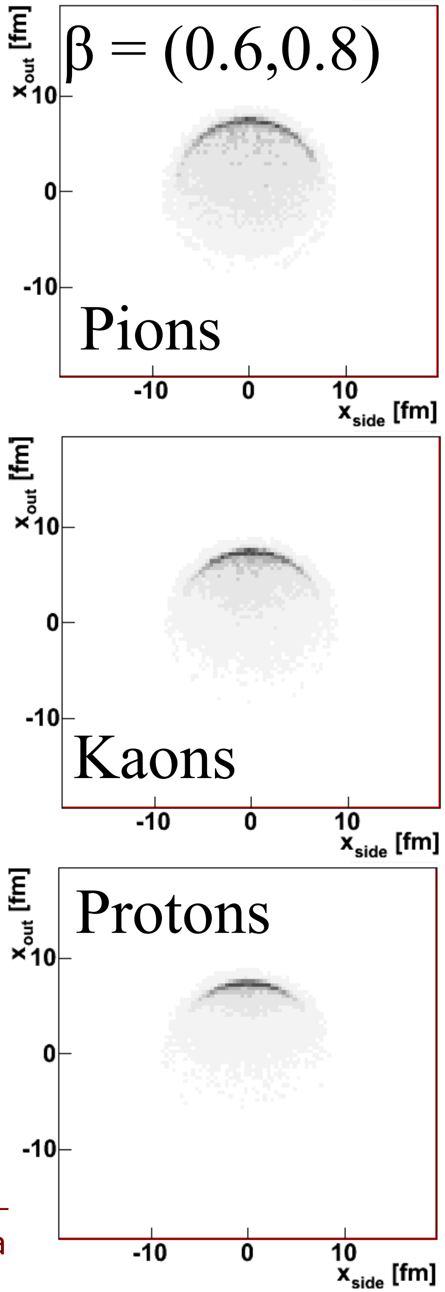
Consequences of flow



- "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

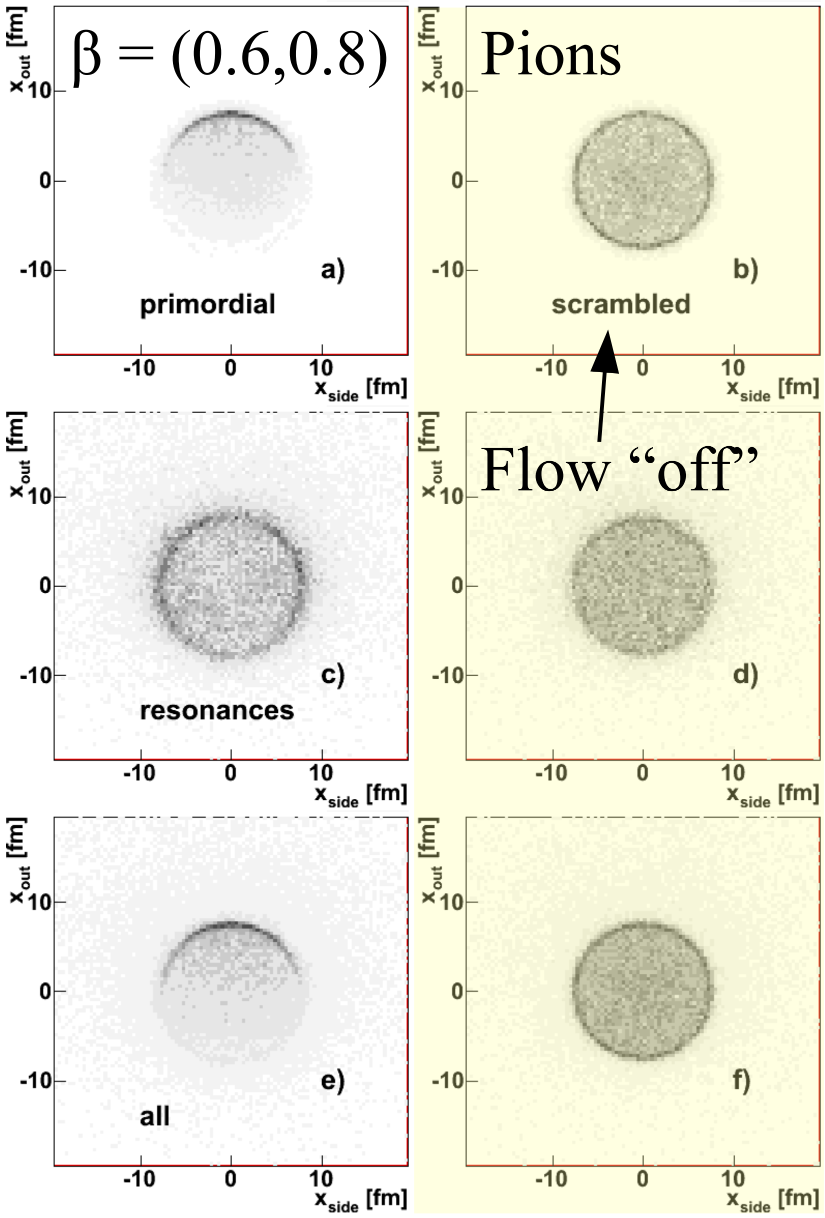
Asymmetry: $\langle r^{\pi K}_{out} \rangle \approx \langle x^{\pi}_{out} \rangle - \langle x^{K}_{out} \rangle$

- 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

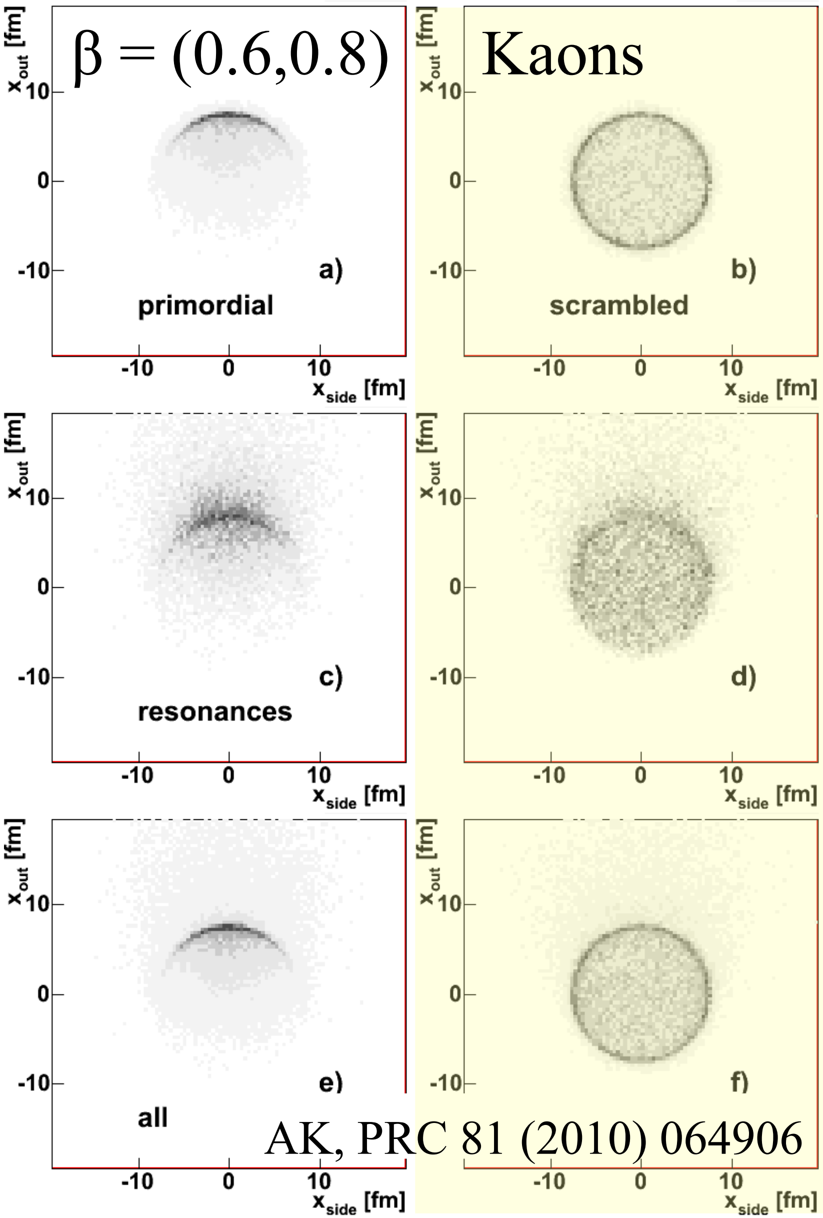


- With flow "off" (space-momentum correlation "off") → no emission shift
- Pions → decay momentum of most resonances larger than pion mass. Decay acts similarly to thermal smearing with large temperature.
- Emission points of pions from resonances strongly randomized – average very close to system center.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



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.

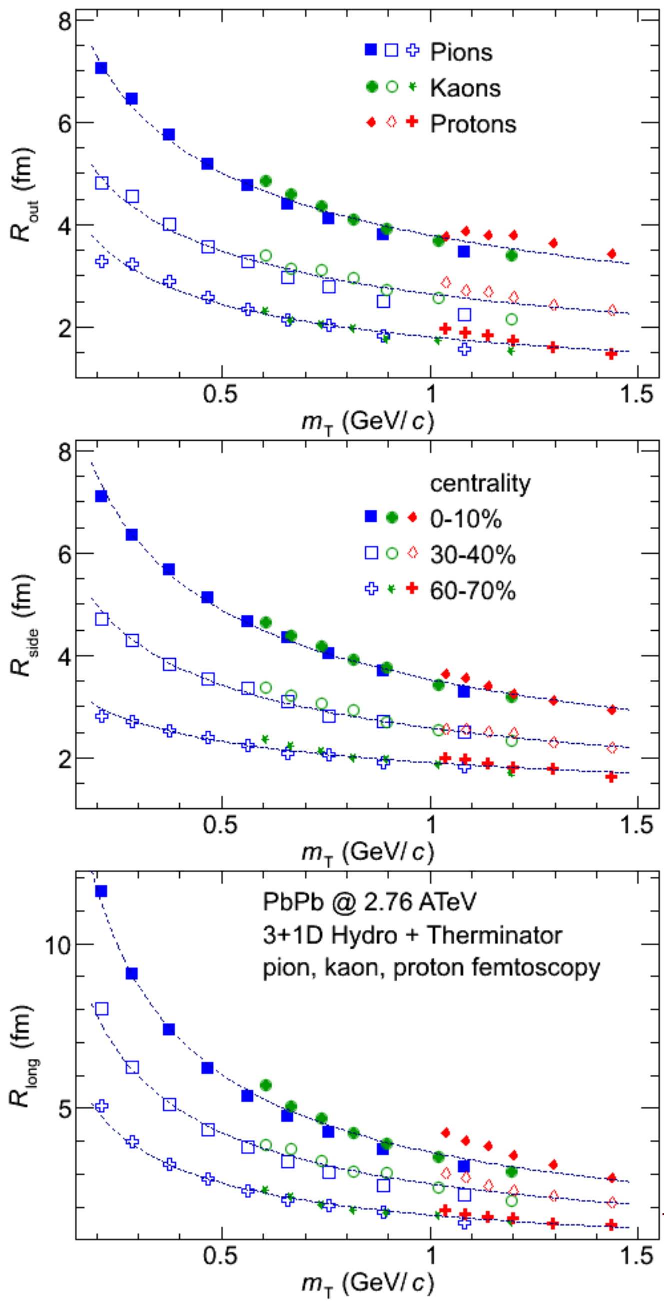
Kaons $\langle x^{K}_{out} \rangle$	primodial	all
	4.47 fm	5.54 fm

- Overall: 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

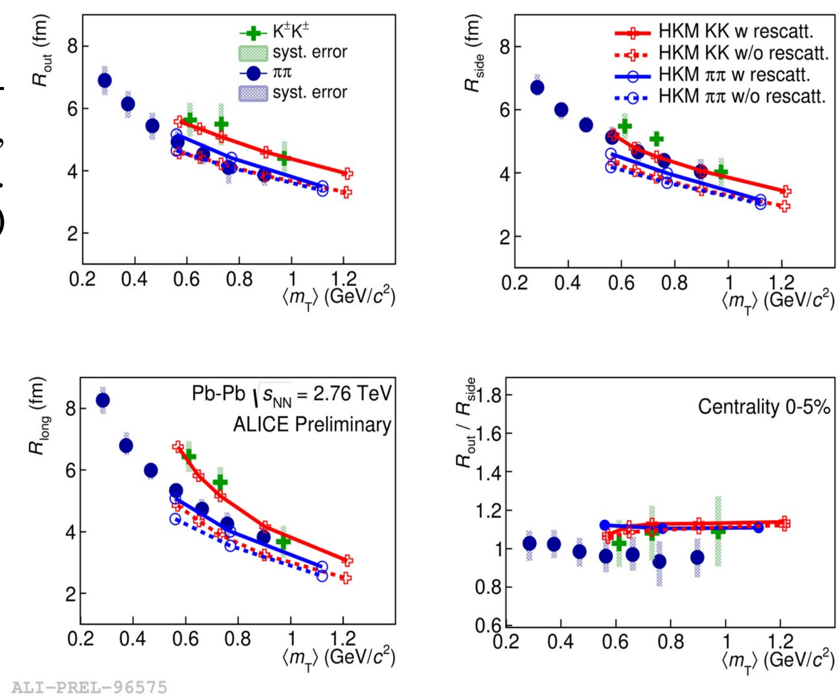
m_T scaling and rescattering



"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)

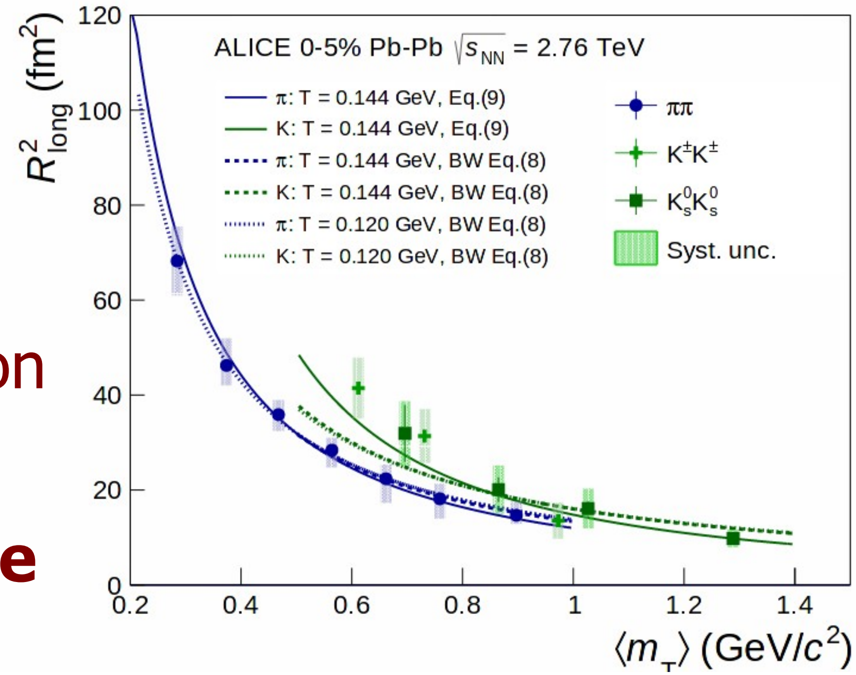


AK, M.Gałażyn, P.Bożek; Phys.Rev.C90 (2014) 6, 064914

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

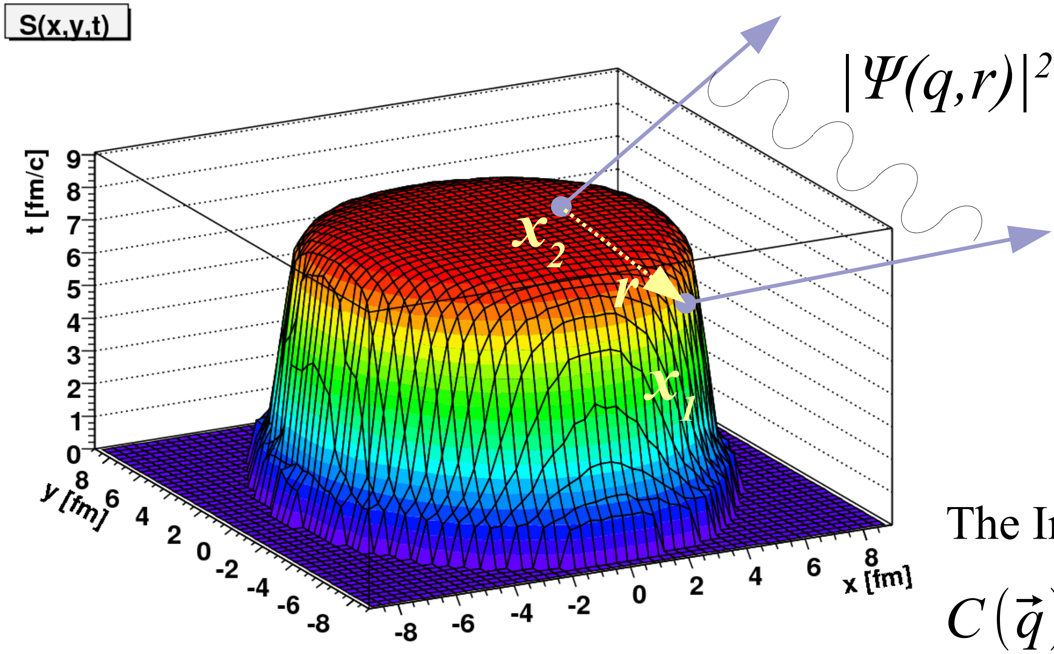


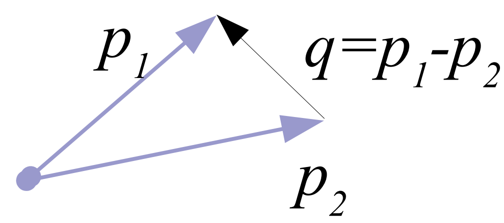
method	T (GeV)	α_π	α_K	τ_π (fm/c)	τ_K (fm/c)
fit with BW Eq. (8)	0.120	-	-	9.6 ± 0.2	10.6 ± 0.1
fit with BW Eq. (8)	0.144	-	-	8.8 ± 0.2	9.5 ± 0.1
fit with Eq. (9)	0.144	5.0	2.2	9.3 ± 0.2	11.0 ± 0.1
fit with Eq. (9)	0.144	4.3 ± 2.3	1.6 ± 0.7	9.5 ± 0.2	11.6 ± 0.1

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**

Femtoscopy: size and asymmetry



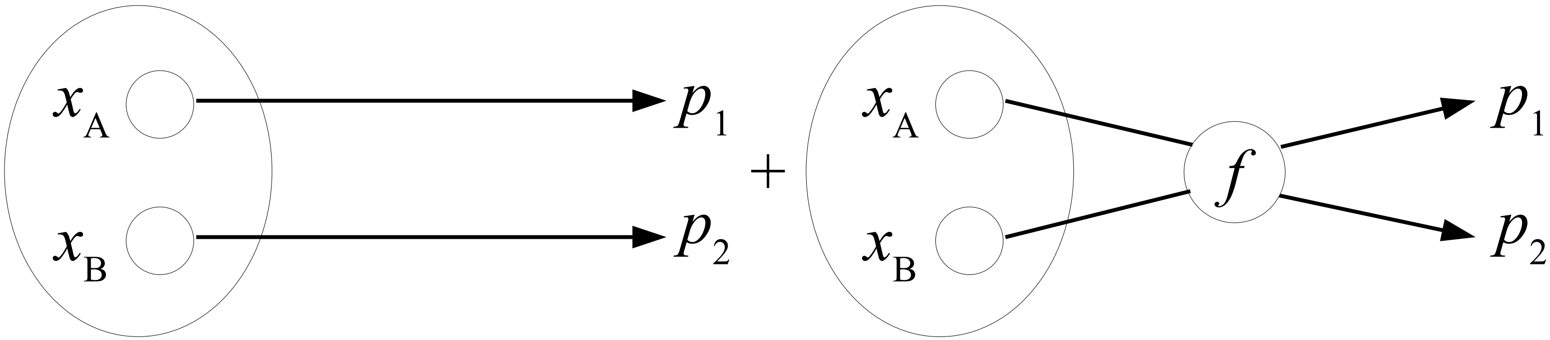


The Integral Equation for Correlation

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

- 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 last scattering** (measurement after rescattering phase)
  - This gives the final form of the wave-function, for pion-kaon pairs the Coulomb interaction dominates

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

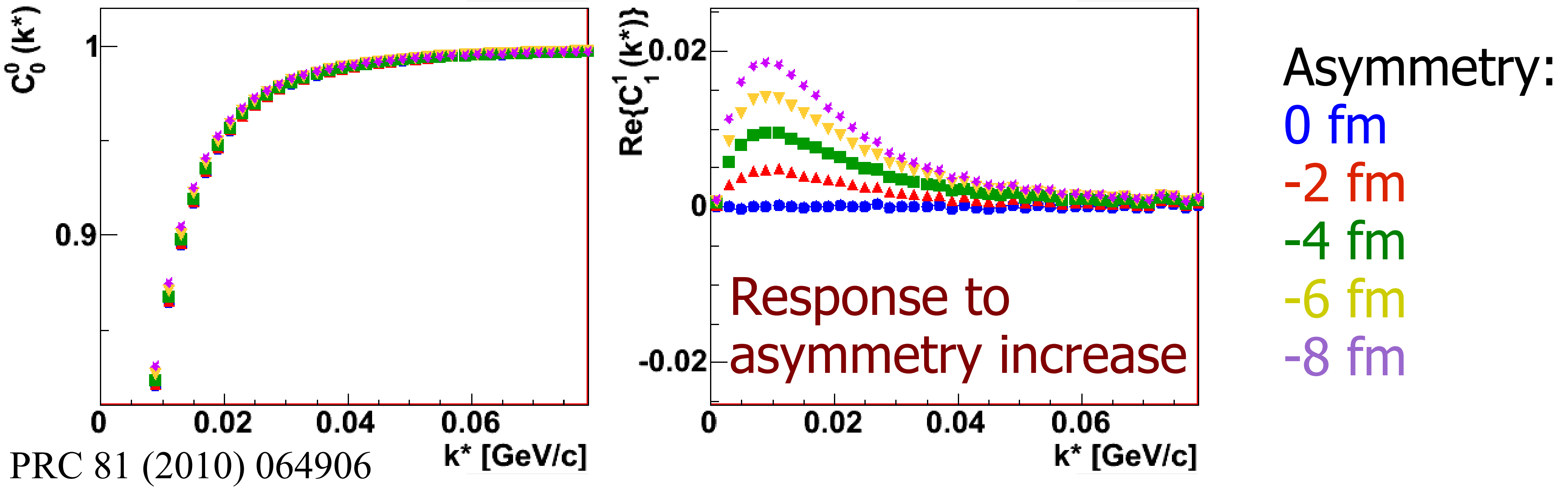
$$\xi = \boldsymbol{k}^*\boldsymbol{r}^* + k^*r^* \equiv \rho(1+\cos(\theta^*)),\ \ \rho = k^*r^*,\ \ \eta = (k^*a)^{-1},\ \ a = (\mu z_1 z_2 e^2)^{-1}$$

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

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

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

- Spherical harmonics maximally sensitive to asymmetry
- 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

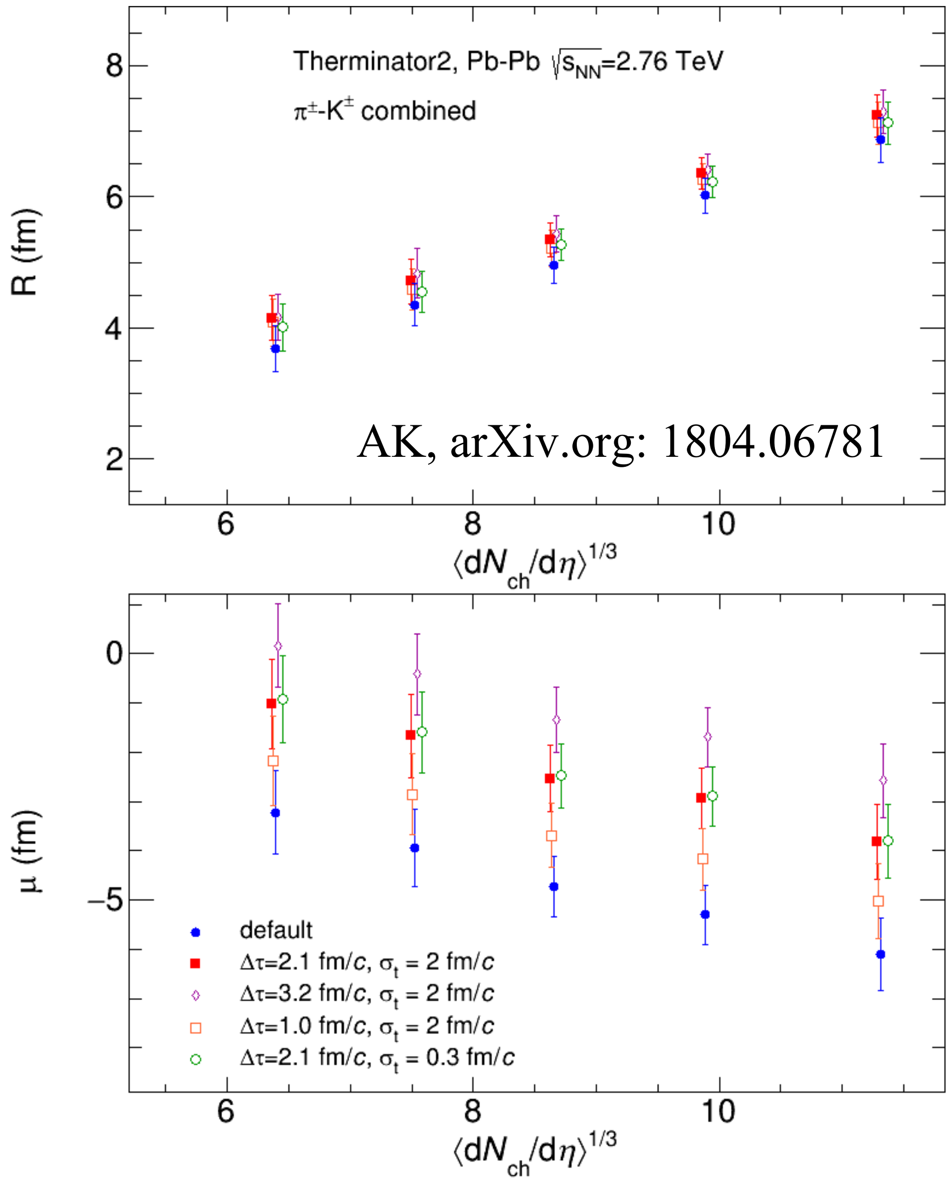
- The non-identical particle femtoscopy sensitive to the emission asymmetry between particle types, possible because they are not identical
- Measurement is done in Pair Rest Frame (PRF), but we are interested in source parameters in LCMS
- Transformation to PRF combines the spatial and time asymmetries in LCMS, not possible to distinguish between them in measurement

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

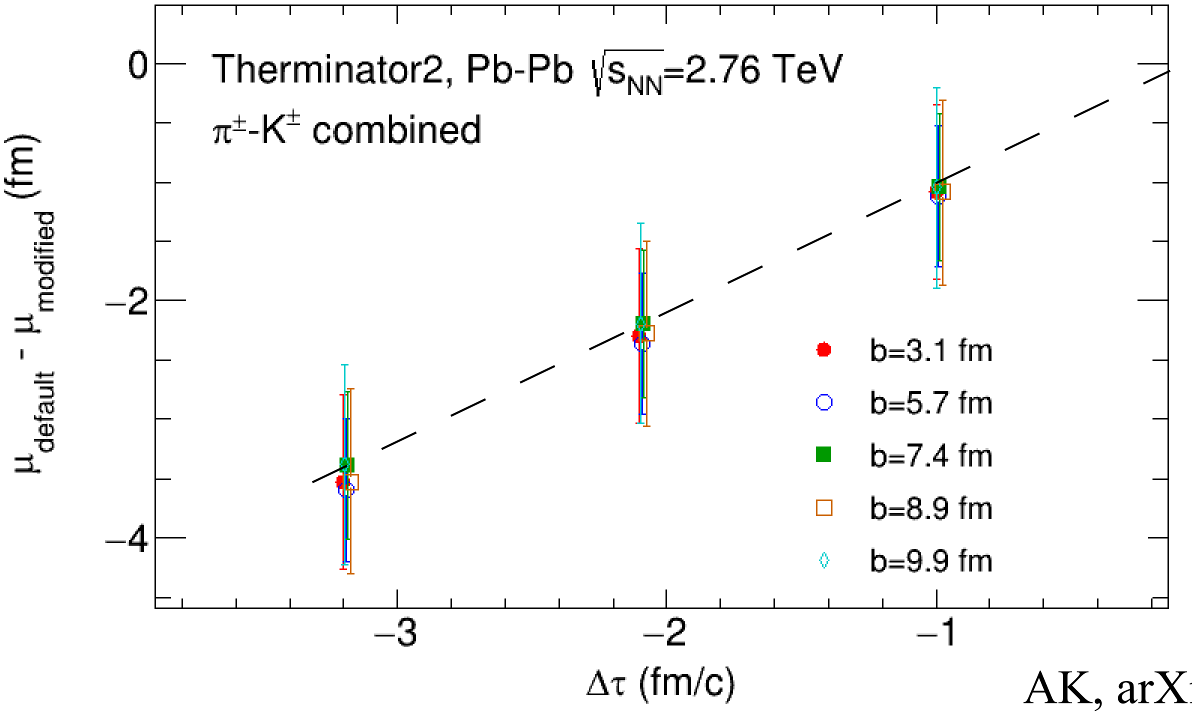
- "Spatial" asymmetry r_{out} arises in flowing medium, difficult to produce otherwise
- "Time" asymmetry Δt may have various origins, some not connected to flow

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



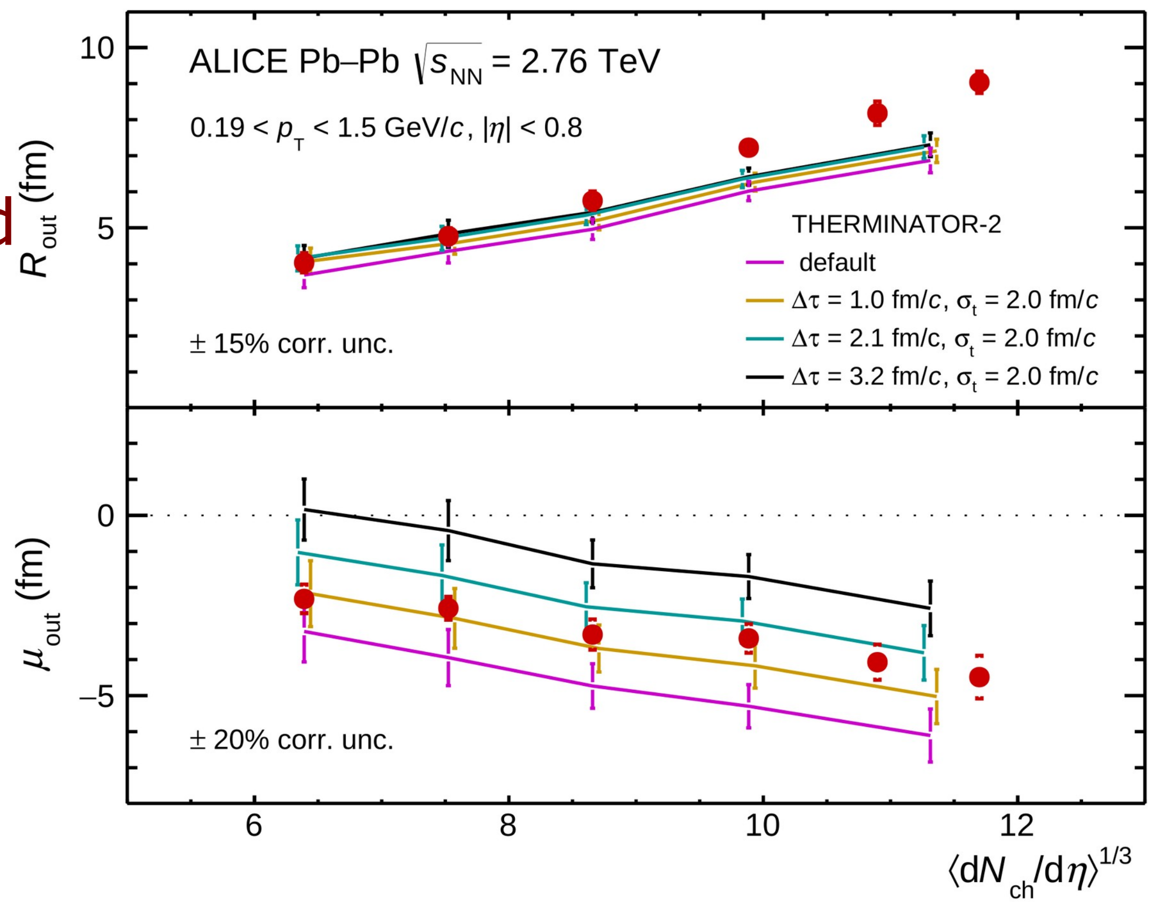
AK, arXiv.org: 1804.06781

- 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

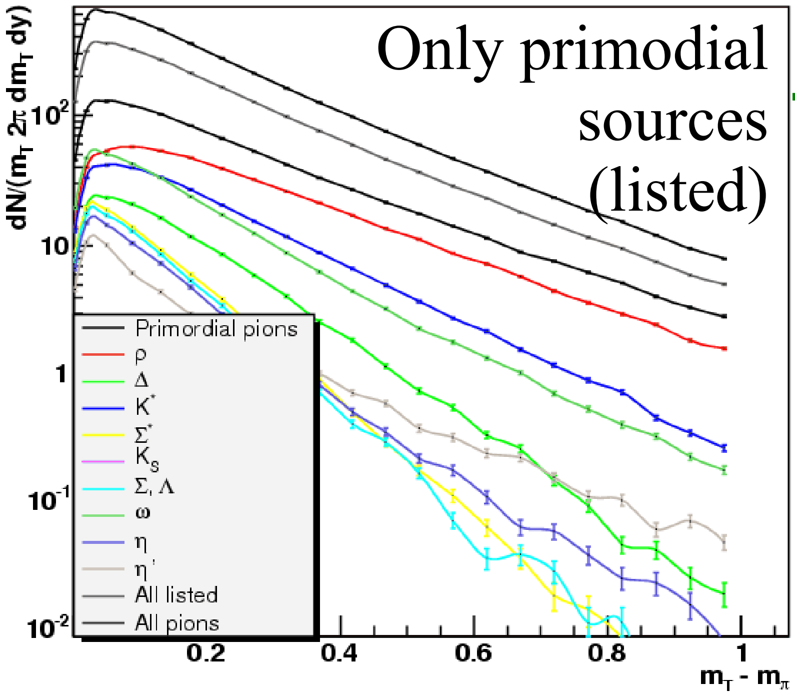
- ALICE published first pion-kaon results from LHC
- System size well reproduced (similarly to identical pion and kaon femtoscopy)
- Emission asymmetry in "default" baseline case larger than in data
- Asymmetry with 2.1 fm/c kaon delay consistent with data: **probe of duration of hadronic rescattering**

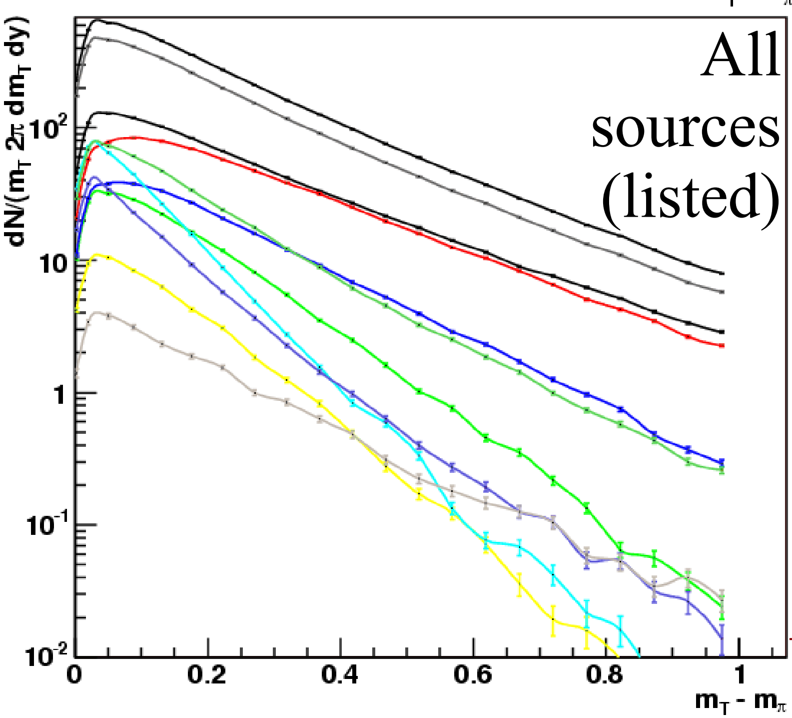
ALICE; Phys.Lett.B 813 (2021) 136030; arXiv: 2007.08315 [nucl-ex]



M. Chojnacki, AK, W. Florkowski, W. Broniowski, Comput.Phys.Commun. 183 (2012) 746-773; arXiv: 1102.0273 [nucl-th]

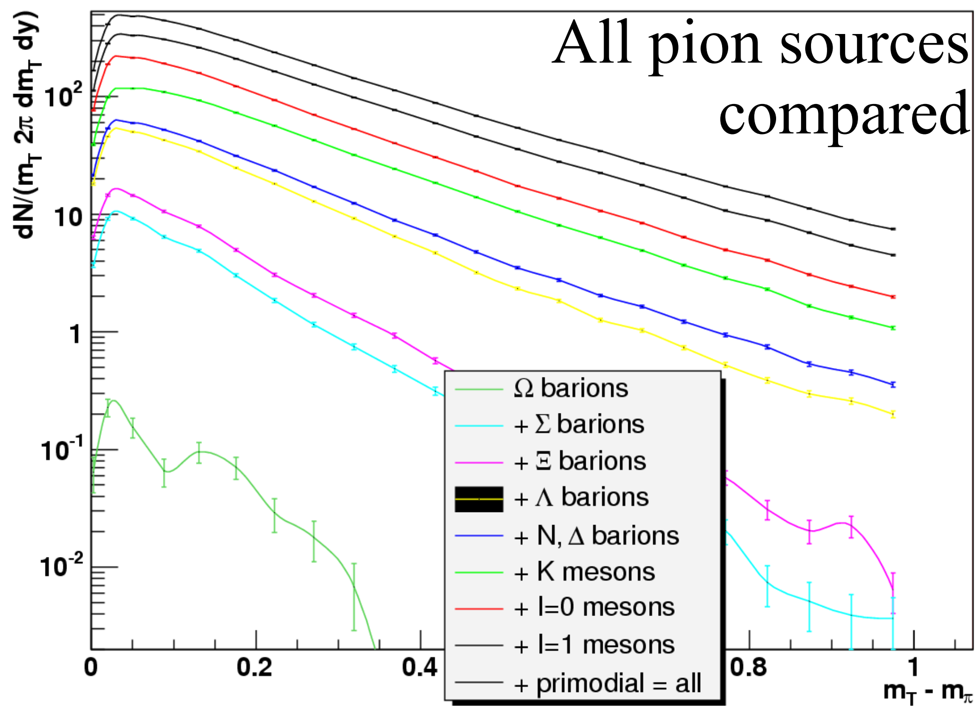
Resonance contribution to pions vs p_T



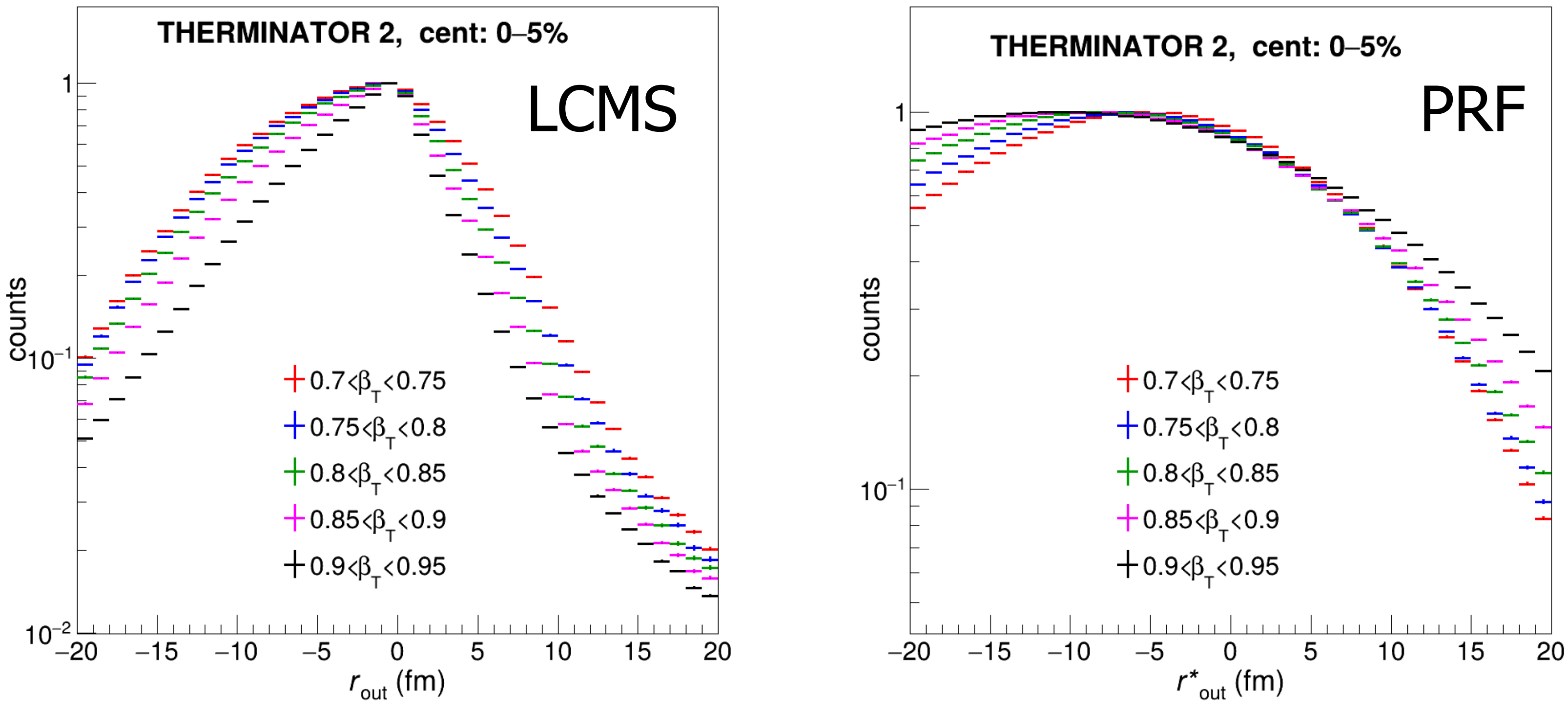


Pions from resonance decays exhibit differences in p_T slope to primordial

At various pair momenta resonance contribution potentially different

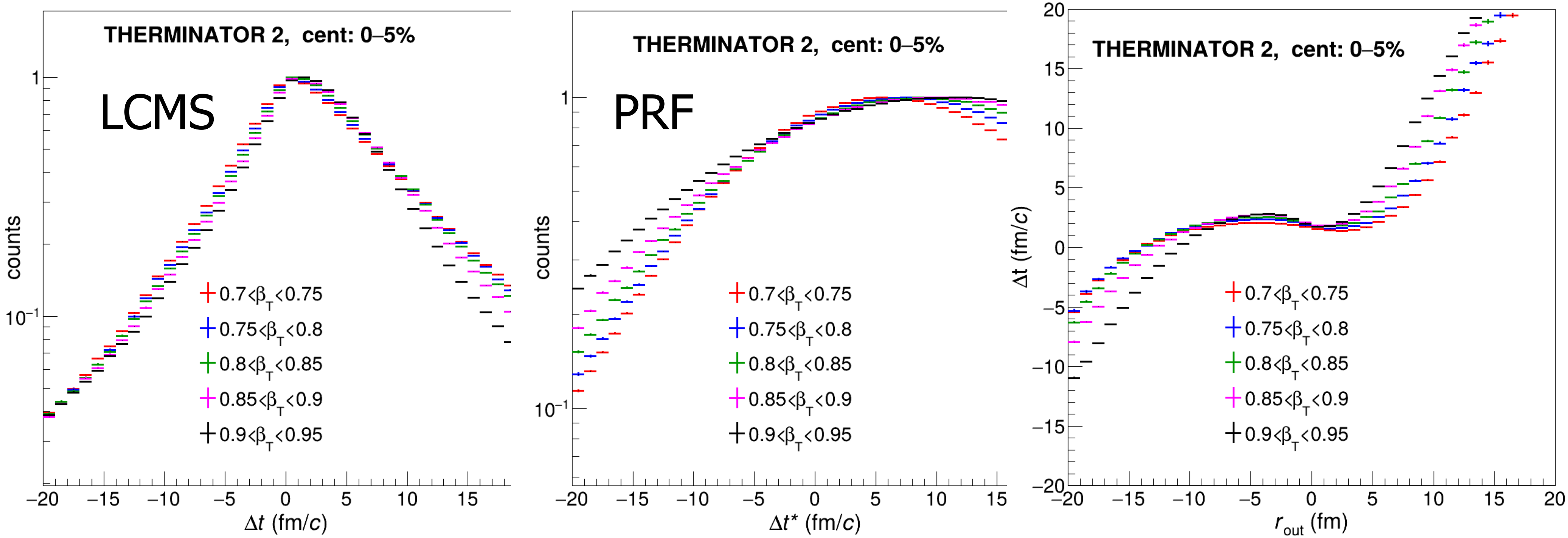


Spatial distributions vs pair velocity β_T



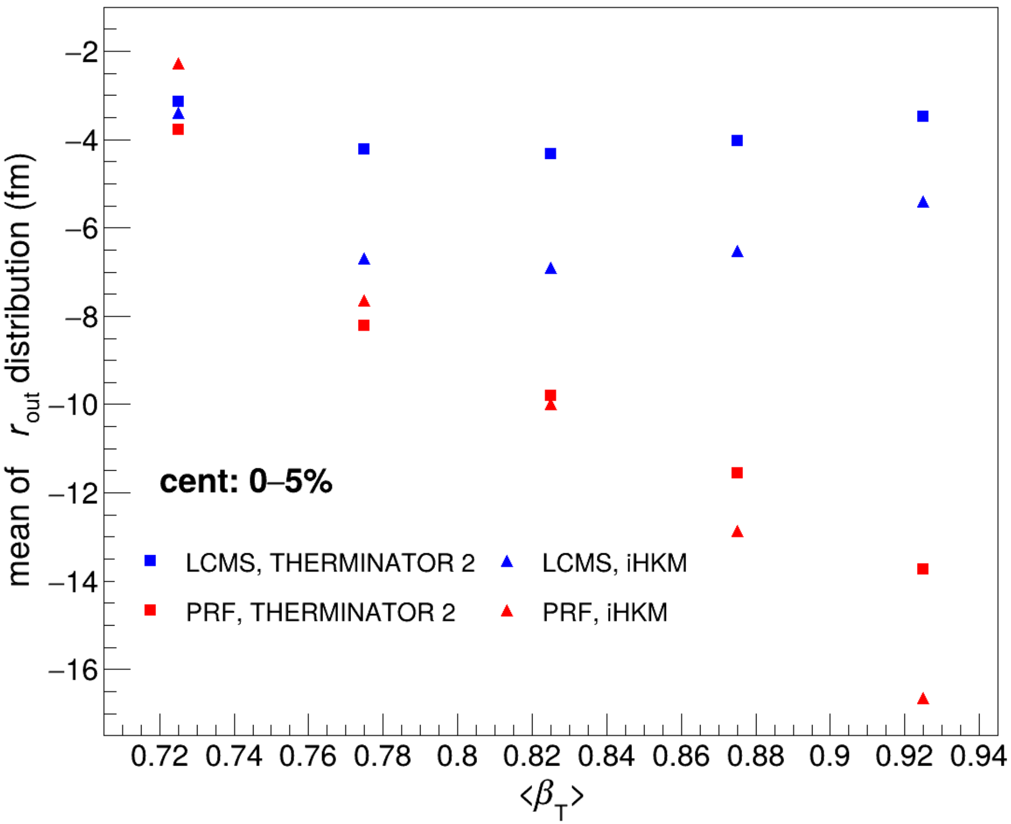
- Spatial distributions visibly evolve with pair velocity
- They are significantly non-symmetric – non-trivial to decide how to estimate their parameters (mean and width) – and to which values the experimental measurement is sensitive

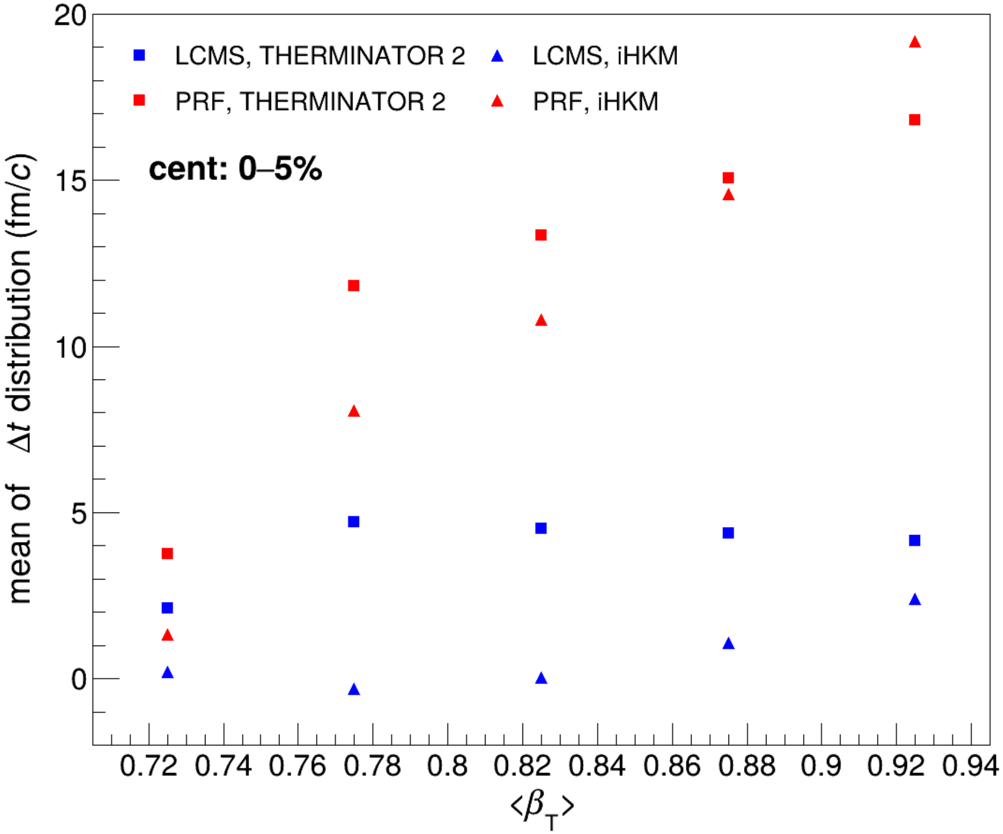
Time distributions vs β_T



- Similar strong asymmetry seen in emission time difference
- What is the “time asymmetry” then?
- In addition space and time difference clearly correlated

Estimating model input

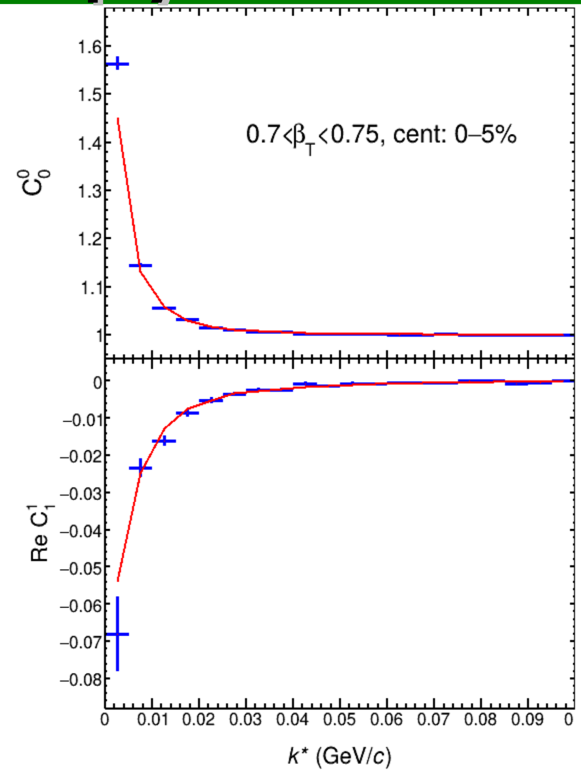


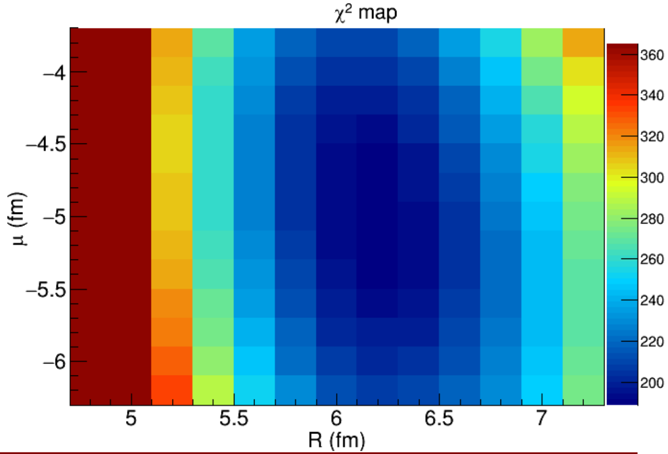


- In LCMS the space distribution exhibits non-monotonic behaviour vs. pair velocity
- Time difference also shows evolution
- Two models with similar trends, quantitative differences

CorrFit: numerical femtoscopy fits

- When CF depends on full FSI, no analytical form of correlation function exists
- CorrFit combines:
  - Flexible assumption of source function (LCMS/PRF, 1D/3D/asymmetry, any functional form – also non-Gaussian)
  - Modular wave-function calculator, working for any pair type and choice of FSI
  - Flexible form of correlation function (LCMS/PRF, 1D/3D/SH/DR, multiple)
  - Pair kinematics taken directly from data
- Calculates numerically CF at each grid point, compares to "data" – fit with χ^2 minimization

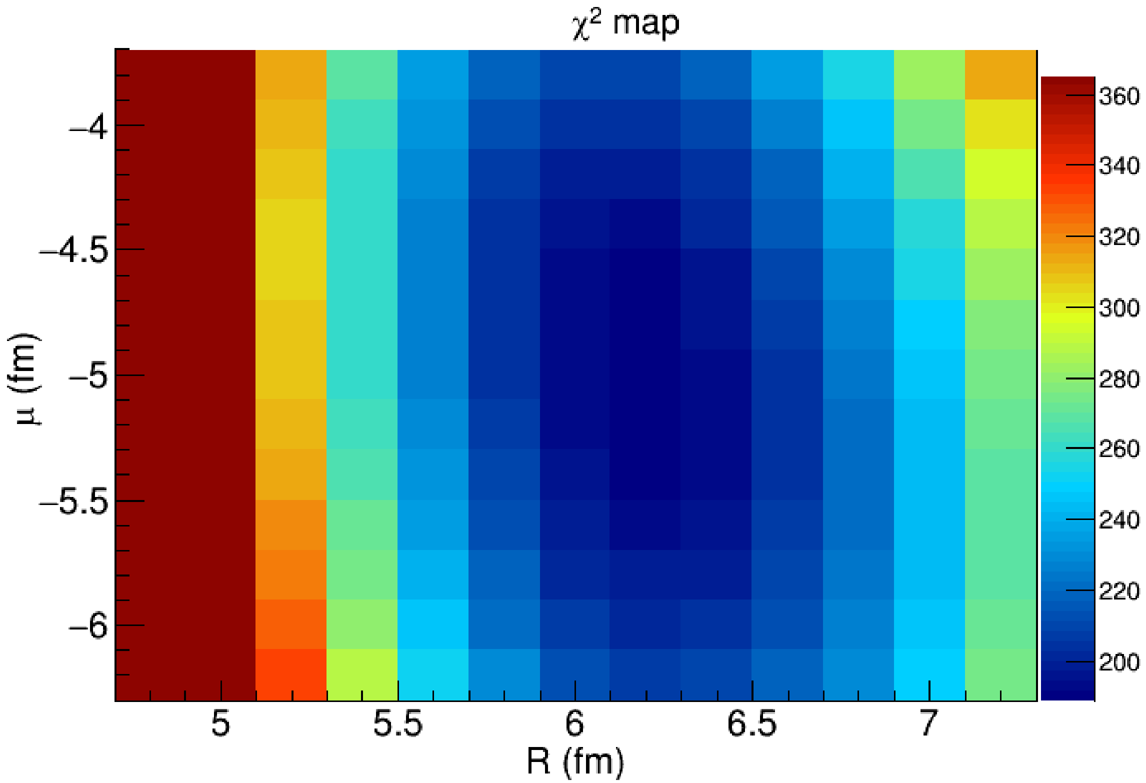


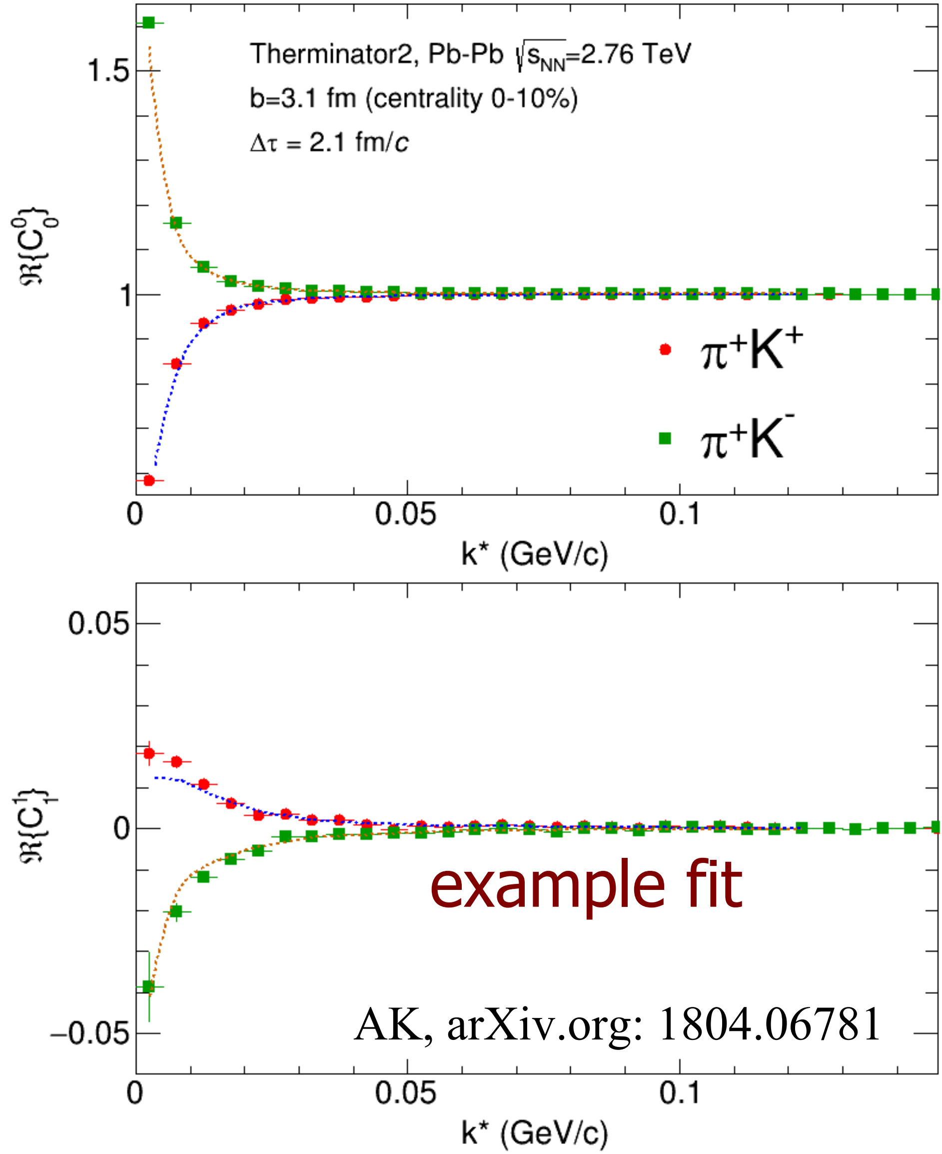


Fitting non-identical correlation

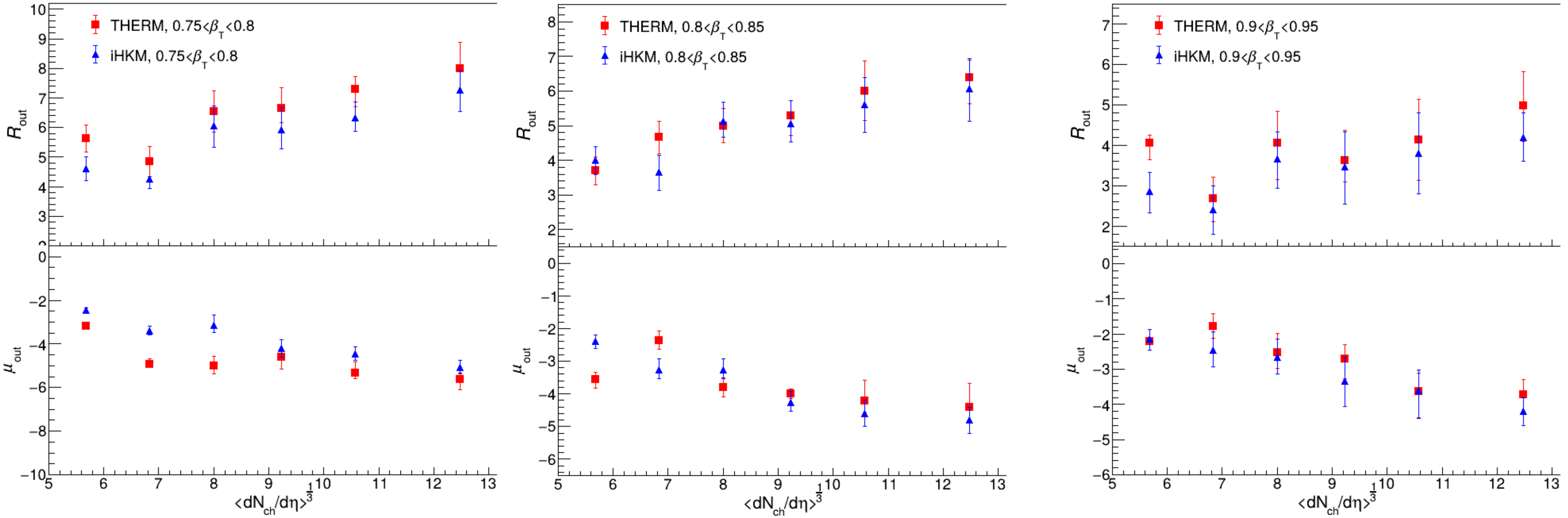
- Calculate numerically the correlation function for points on the (R,μ) grid, where source is defined in LCMS as:

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



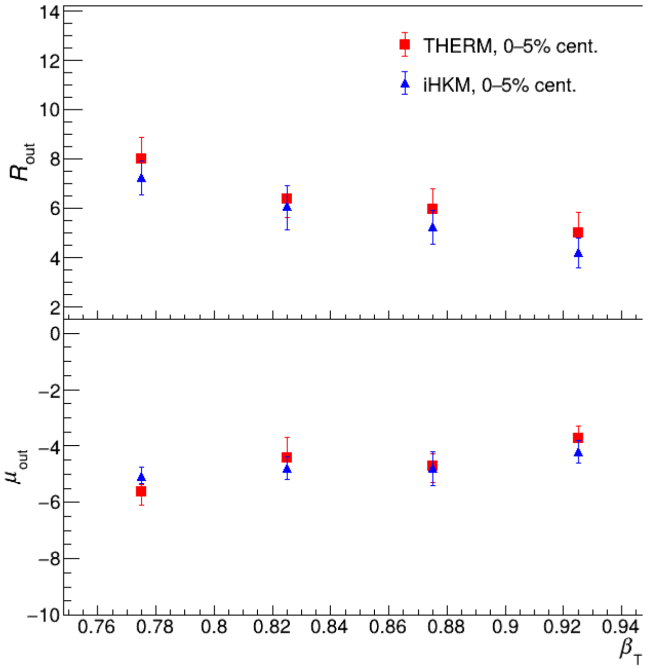


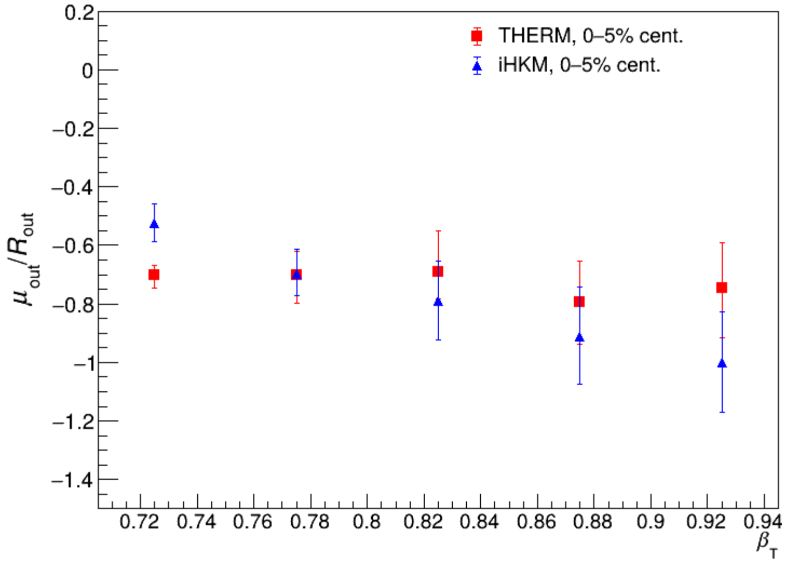
Centrality dependence

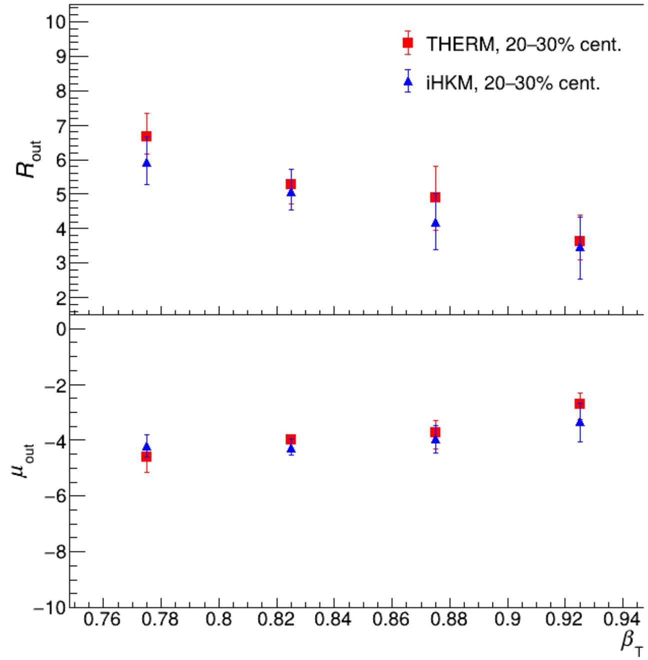


- "Experimental-like" analysis performed differentially in pair velocity and centrality in two models
- Therminator2 gives larger radii and asymmetry at low β_T
- Fitted values very similar in both models

Pair velocity dependence







- Observed emission asymmetry, scaled to the overall system size evolves differently in two models as function of β_T
- “Constant” behaviour in Therminator, increasing asymmetry with velocity in iHKM
- Interpretation still in progress

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”
- Two models, with different treatment of the hadronic rescattering phase tested and compared, predictions for the experiment ready
- Intriguing trends vs. pair velocity and centrality observed, interpretation still under investigation