Dynamics of particle emission probed by femtoscopic correlations in the STAR experiment

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Abstract

One of methods to study the properties of hot and dense nuclear matter created in high-energy nuclear collisions is femtoscopic measurements. This method provides information about space-time characteristics of the particle emission region, which has a size and lifetime of the order of 10^{-15} m and 10^{-23} s, respectively. From non-identical particle correlations, one can obtain information about asymmetry in the emission process between those two particles' species [1]. Such an emission asymmetry gives us knowledge of which type of particles, on average, are emitted earlier and from which region of the source. Using different combinations of pion, kaon, and proton pairs, one can obtain comprehensive knowledge on geometric and dynamic (emission time) properties of the particle emitting source. Such investigation could provide information about differences among the emissions of light mesons (pions), strange mesons (kaons), and baryons (protons).

Particle identification

- Time Projection Chamber (TPC) – measures particle momentum and ionization energy loss (dE/dx)
- Time Of Flight (TOF) – measures time of flight from the collision point to the detector

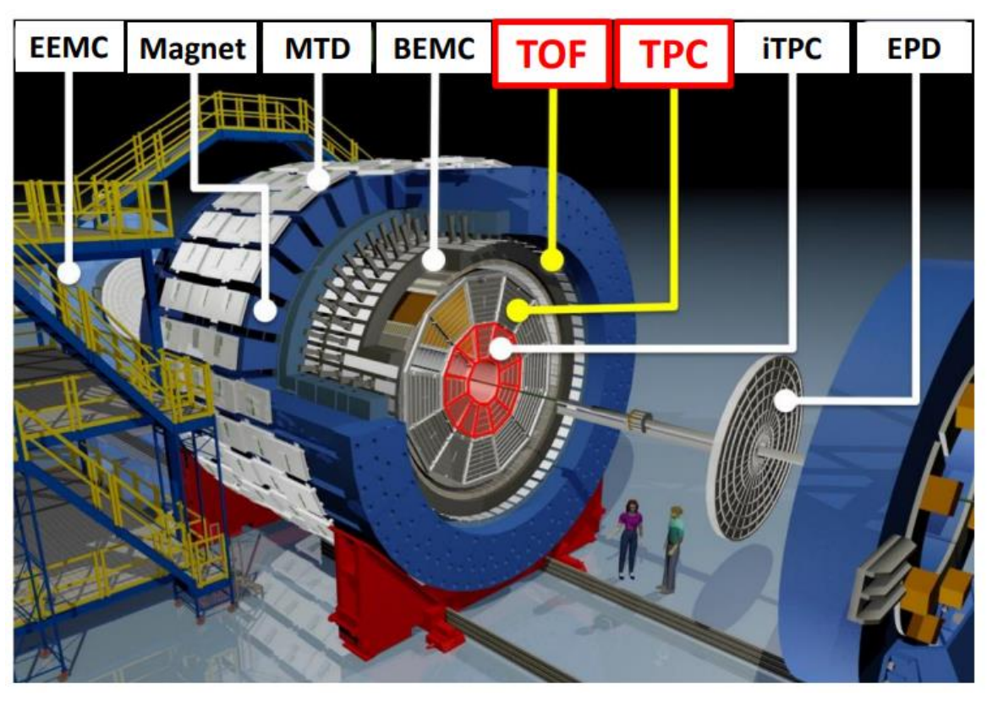
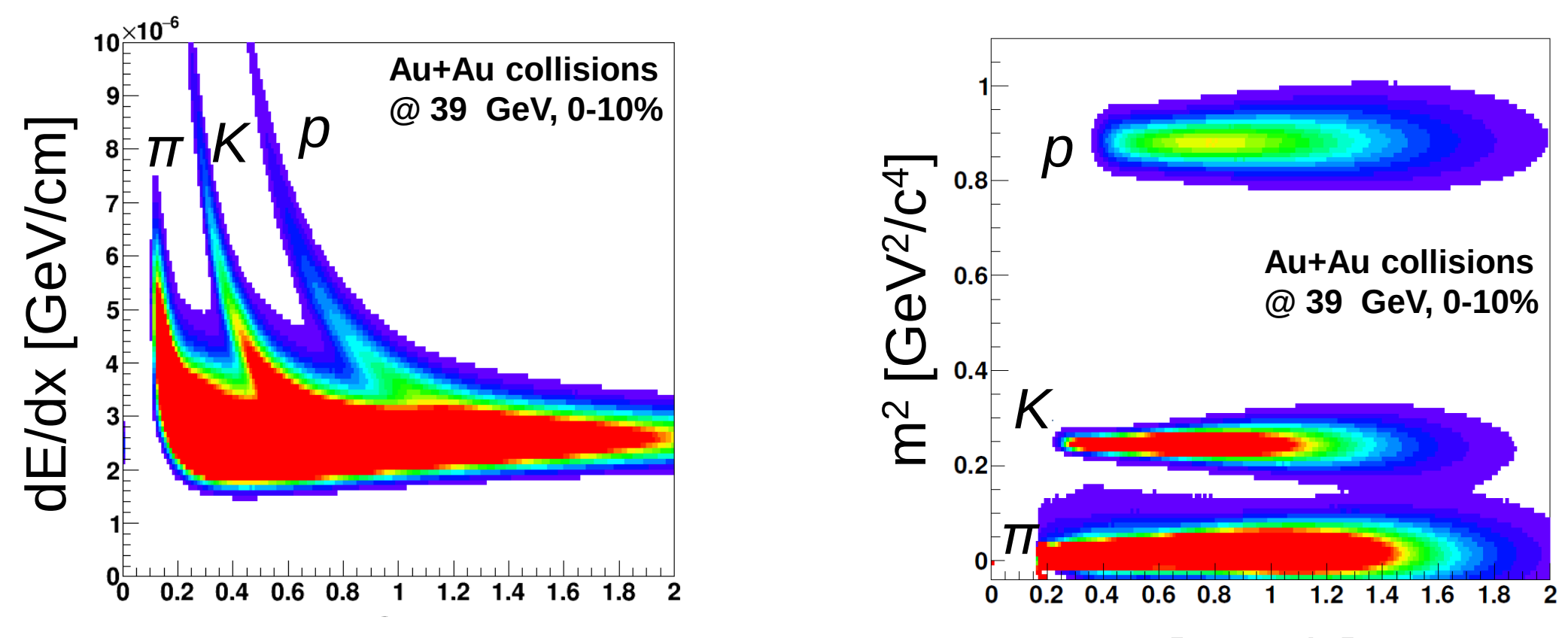


Fig. 1 STAR detector [2].

	π	K	p
p_T [GeV/c]	[0.1 – 1.2]	[0.1 – 1.2]	[0.4 – 2.5]
p [GeV/c]	[0.1 – 1.2]	[0.1 – 1.2]	[0.4 – 3.0]
Momentum threshold [GeV/c]	0.2	0.41	0.8
Mass squared window [GeV²/c⁴]	[0.01 – 0.03]	[0.21 – 0.28]	[0.76 – 1.03]
|Nσ|	≤ 3.0		
Pseudorapidity |η|	≤ 0.5		
DCA [cm]	≤ 3.0		

*DCA - Distance of the closest approach

**Momentum threshold – above these values information from TOF detector is needed



Mass of the particle m can be calculated by combining velocity β (from TOF) and momentum p (TPC):

$$m^2 = p^2\left(\frac{1}{\beta^2} - 1\right)$$

Fig. 2 Particle energy loss and mass squared as a function of particle momentum.

Correlation functions

Correlation functions are calculated for two groups of pair:

- $C_+(k^*)$ – first (lighter) particle is faster
- $C_-(k^*)$ – second (heavier) particle is faster

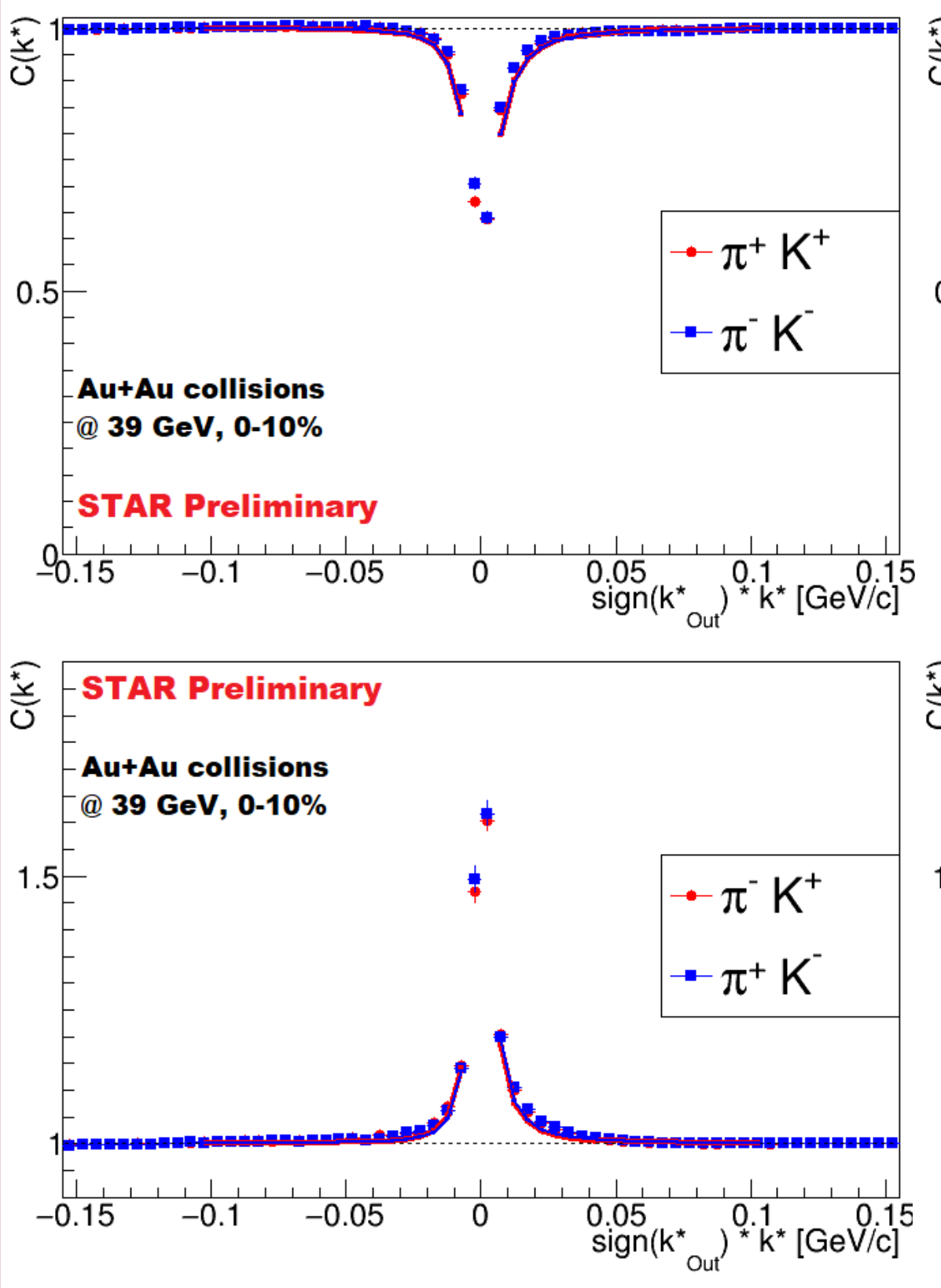


Fig. 4 Like-sign (top) & unlike-sign (bottom) pion-kaon correlation functions at central Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV.

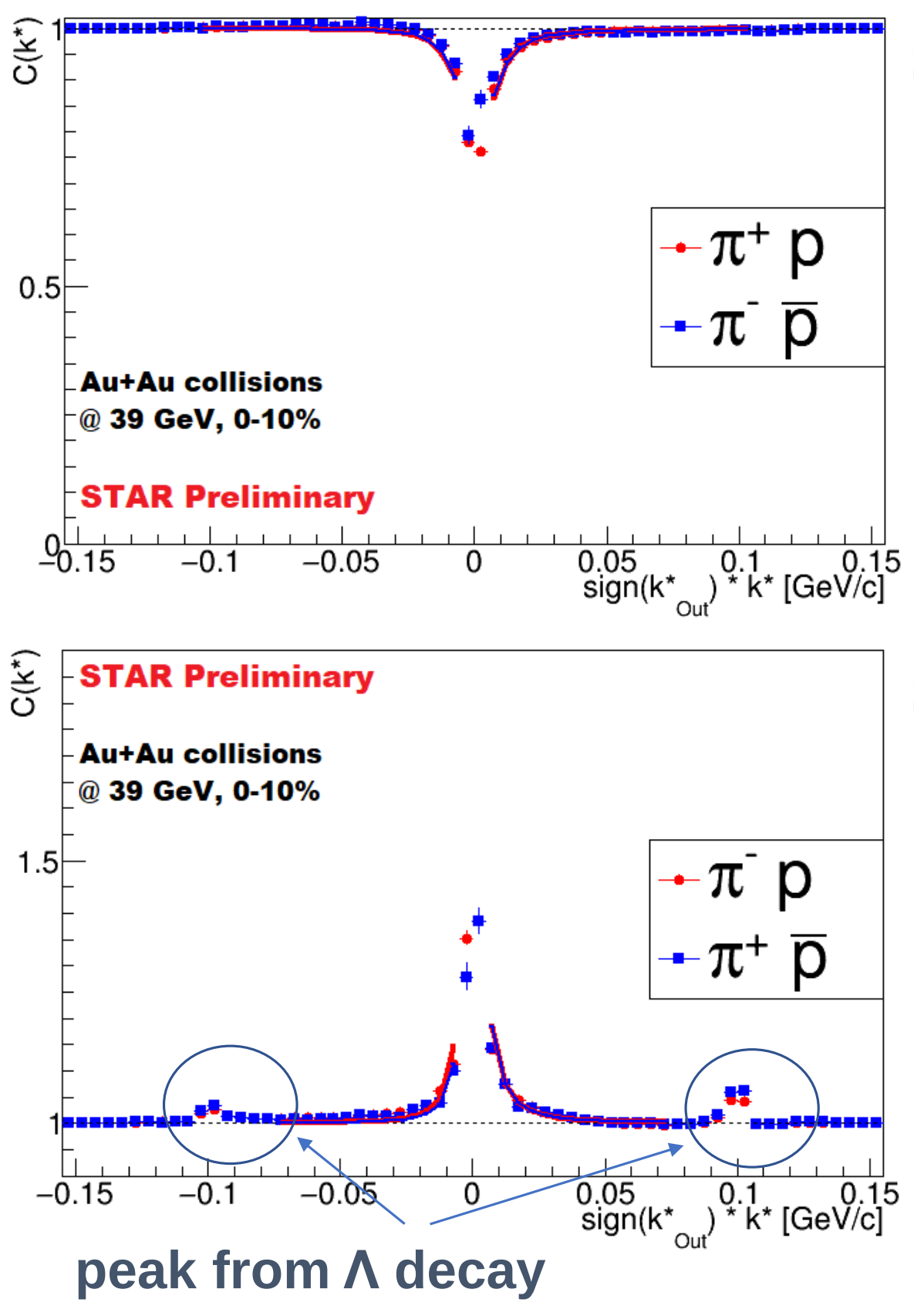


Fig. 5 Like-sign (top) & unlike-sign (bottom) pion-proton correlation functions at central Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV.

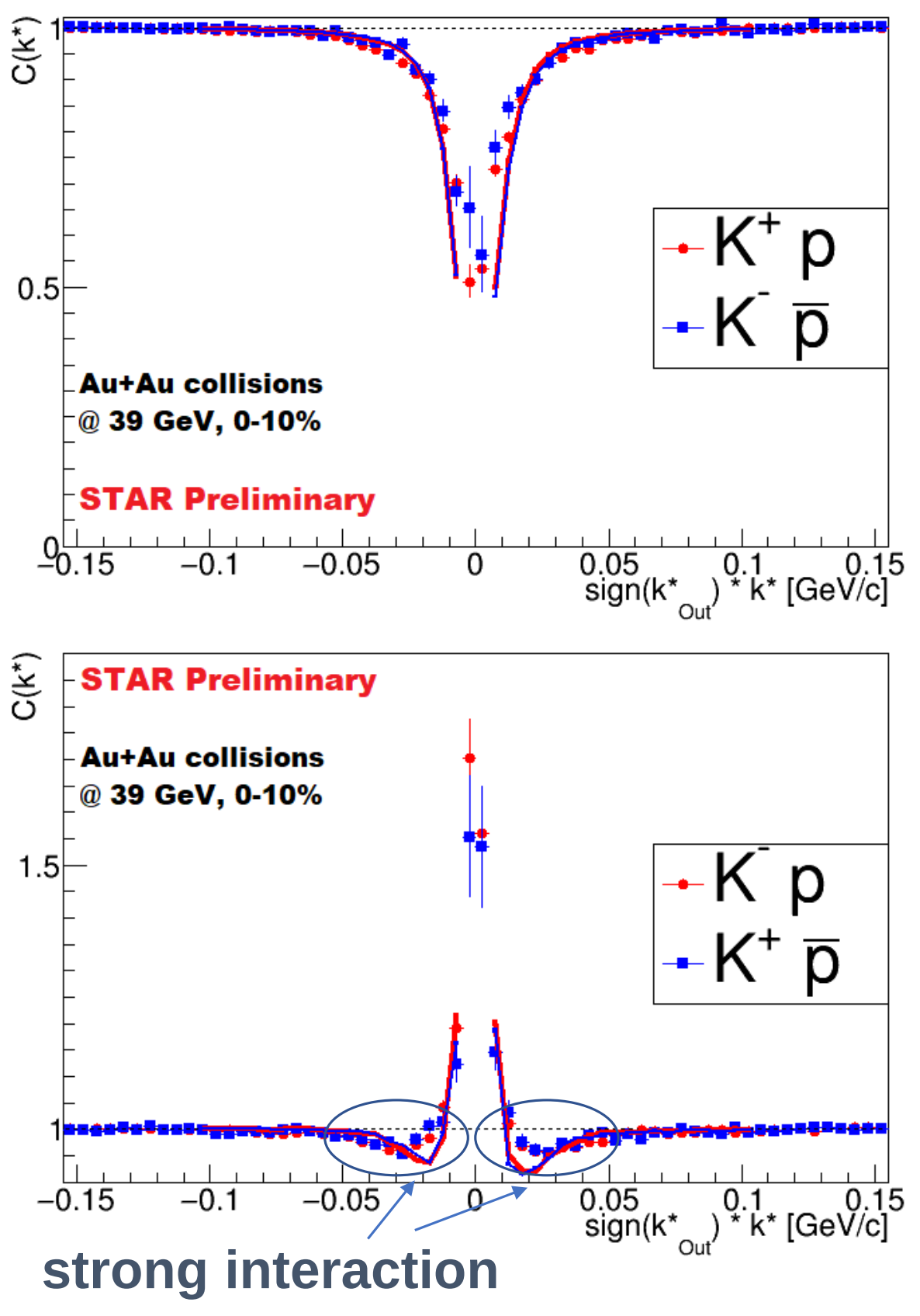


Fig. 6 Like-sign (top) & unlike-sign (bottom) kaon-proton correlation functions at central Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV.

*solid lines represent theoretical fits of the correlation function,
**statistical uncertainties only

References

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Femtoscopy

Theoretical correlation function can be described by the Koonin-Pratt formula [3, 4]:

$$C(\vec{k^*}) = \int d\vec{r}\,|\psi(\vec{k^*},\vec{r})|^2 S(\vec{r})$$

where $\vec{k^*}$ is particle momentum in pair rest frame, $\vec{r}$ is relative distance between two particles, $\psi(\vec{k^*},\vec{r})$ is a pair wave function that expresses interactions between particles, and $S(\vec{r})$ is the source function – distribution of relative positions of particles.

The source of non-identical particles is assumed as a 3-dimensional Gauss distribution with sizes R in *out*, *side* and *long* directions, and the mean μ value corresponding to the emission asymmetry:

$$S(\vec{r}) \propto \exp\left(-\frac{(r_{out}-\mu)^2}{2R_{out}^2} - \frac{r_{side}^2}{2R_{side}^2} - \frac{r_{long}^2}{2R_{long}^2}\right)$$

Bertsch-Pratt parametrization

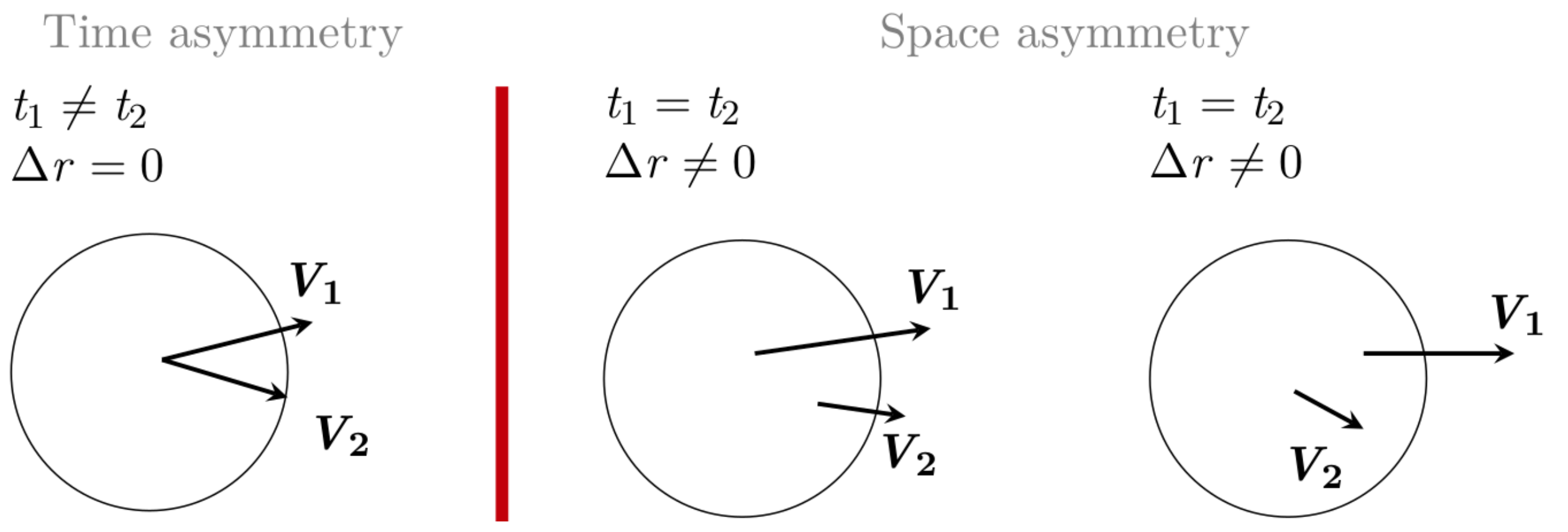
Long: determined by the beam axis
Out: determined by the direction of the pair momentum in transverse plane
Side: perpendicular to long and out

Emission asymmetry

Asymmetries in the emission process may arise from long-lived resonances, bulk collective effects, or differences in the freeze-out scenario for different particle species [5].

The separation comes from:

- space asymmetry (flow)
- emission time difference



t – emission time,
r – particles' emission points distance,
V_1, V_2 - velocity of the particle

Fig. 3 Two types of asymmetry – time ($t_1 \neq t_2$) and spatial ($\Delta r \neq 0$).

- Moving away scenario – faster particle is emitted earlier (or closer to the edge of the source)
- Catching up scenario – faster particle is emitted later (or closer to the center of the source

Results

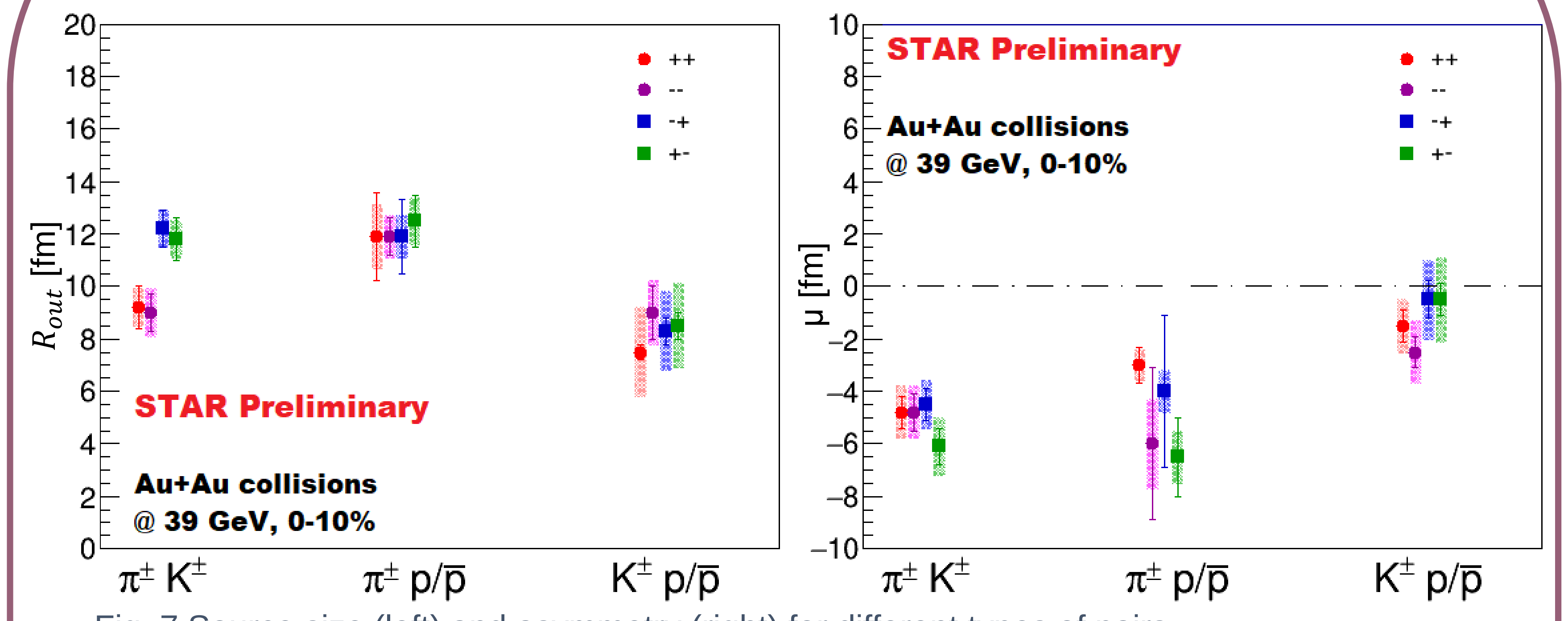


Fig. 7 Source size (left) and asymmetry (right) for different types of pairs.

*Influence of particles from resonance decays not considered,
**color bands represent systematic uncertainties.

Summary

- Asymmetry is visible in each kind of analyzed pair
- Lighter particles are emitted closer to the center and/or later (indicated by negative value of μ)
- Pairs from lambda resonance have a negligible impact on the correlation effect
- Only kaon-proton $C(k^*)$ has visible and significant strong interaction