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

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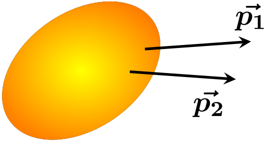
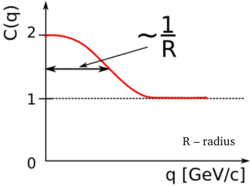
Workshop on Particle Correlation and Femtoscopy
East Lansing, Michigan, July 18-22, 2022

Femtoscopy



$$\vec{q} = \Delta\vec{p}$$
$$\vec{r} = \Delta\vec{x}$$



calculate size (R) of the source

$$C(\vec{p_1}, \vec{p_2}) = \frac{P_{12}(\vec{p_1}, \vec{p_2})}{P_1(\vec{p_1})P_1'(\vec{p_2})}$$

experiment

theory (models)

$$C(\vec{q}) = \frac{A(\vec{q})}{B(\vec{q})}$$

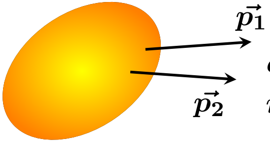
$$C(\vec{q}) = \int d^3r S(\vec{r})|\Psi(\vec{q}, \vec{r})|^2$$

$A(\vec{q})$ - correlated
$B(\vec{q})$ - uncorrelated

$S(\vec{r})$ - source function
(distribution of relative positions of particles)

$\Psi(\vec{q}, \vec{r})$ - pair wave function
(describes interactions between particles)

Femtoscopy



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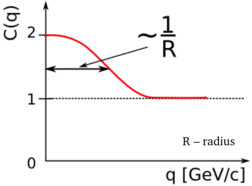

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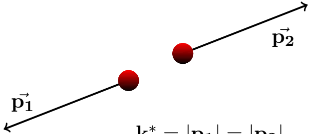
theory (models)

$$C(\vec{q}) = \int d^3r S(\vec{r}) |\Psi(\vec{q}, \vec{r})|^2$$

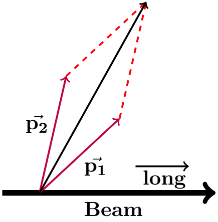
$$S(\vec{r}) = exp\left(-\frac{(r_{out} - \mu_{out})^2}{R_{out}^2} - \frac{r_{side}^2}{R_{side}^2} - \frac{r_{long}^2}{R_{long}^2}\right)$$

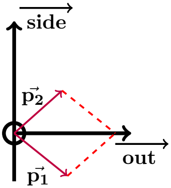
μ_{out} — asymmetry in the *outward* direction

Pair Rest Frame (PRF)



$\mathbf{k}^* = |\mathbf{p_1}| = |\mathbf{p_2}|$





Longitudinally Co-Moving System (LCMS)

G. Bertsch, et al. Phys. Rev. C37, 1896, (1988)

S. Pratt. Phys. Rev. D33, 1314 (1986)

Long: determined by the beam axis

Out: determined by the direction of the pair momentum in the transverse plane

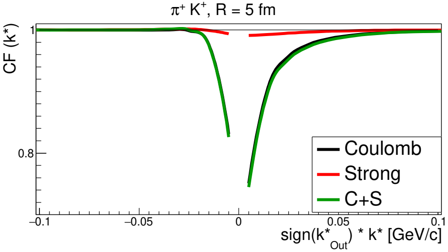
Side: perpedicular to the long and out axes

Final State Interactions (FSI)

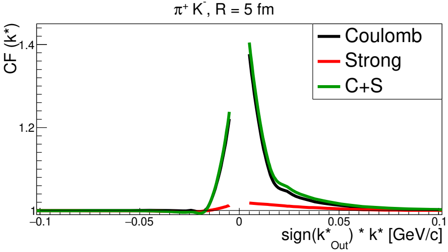
The shape of non-identical particle CF depends on FSI:

- Strong interaction
- ***Coulomb force***
- ~~Quantum Statistic effect~~

Correlation between like-sign pairs



Correlation between unlike-sign pairs

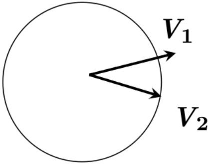


*Theoretical functions using Lednicky weights
**Source assumed as a 3-dimensional Gauss distribution

Space-time asymmetry

Time asymmetry

$t_1 \neq t_2$
$\Delta r = 0$

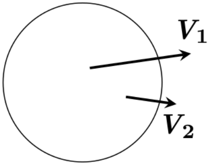


$t_1 > t_2$ - Catching up

$t_1 < t_2$ - Run away

Space asymmetry

$t_1 = t_2$
$\Delta r \neq 0$



Catching up

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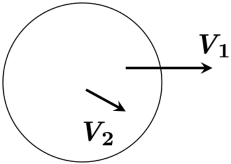


Run away

t — emission time

r — emission point distance from the center

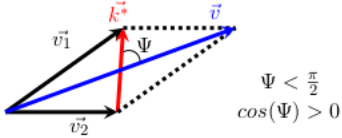
R. Lednicky, et al.,
Phys. Lett. B373,
30-34 (1996)

Catching up
longer interaction, strong correlation
Running away
shorter interaction, weaker correlation

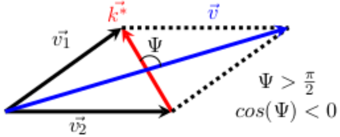
Double ratio method

CFs are calculated in two groups of pairs:

$C_+(k^*)$ — lighter particle is faster
$(cos(\Psi) > 0)$



$C_-(k^*)$ — heavier particle is faster
$(cos(\Psi) < 0)$



C_+ shows a larger deviation from unity than C_- $\rightarrow$ particles are not emitted at the same place and/or time

C_+ and C_- are identical $\rightarrow$ the average space-time emission points of both types of particles

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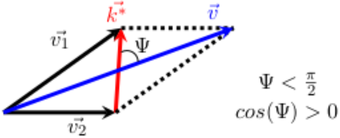

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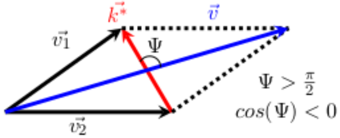
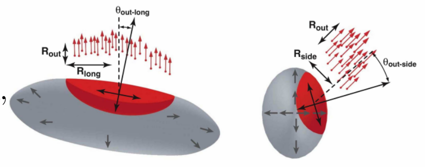


Double ratio:

$$DR(k^*) = \frac{C_+(k^*)}{C_-(k^*)}$$

Emission asymmetries

Collective behavior
– **radial flow** in the transverse plane:
matter is collectively moving ”outward”
from the central axis of the source
to the outside



Ann. Rev. Nucl. Part. Sci 55, 357 (2005)

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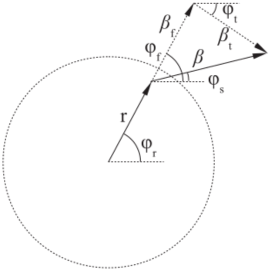

β_f - flow velocity
β_t - thermal velocity (with random direction)

Nonidentical-particle femtoscopy at $\sqrt{s_{NN}}$ = 200 GeV in hydrodynamics with statistical hadronization, A. Kisiel
Phys. Rev. C 81, 064906 (2010)

Space-momentum (x-p) correlation:
direction ϕ_f of transverse velocity is aligned with transverse position vector direction ϕ_r

Emission asymmetries

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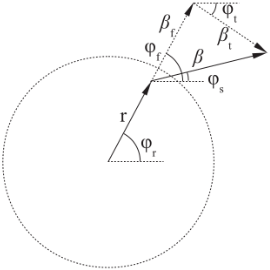

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The thermal component has
a smaller impact on heavier particles

Nonidentical-particle femtoscopy at $\sqrt{s_{NN}}$ = 200 GeV in hydrodynamics with statistical hadronization, A. Kisiel
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The final velocity direction of lighter particles, on average,
is less correlated with emission points than that of heavier particles

$$< x_{out} >= \frac{< r\beta_f >}{< \sqrt{\beta_t^2 + \beta_f^2} >} = \frac{r_0 \beta_0 \beta}{\beta_0^2 + T/m_T}$$

where: $\beta_f = \beta_0 \frac{r}{r_0}$

Emission asymmetries

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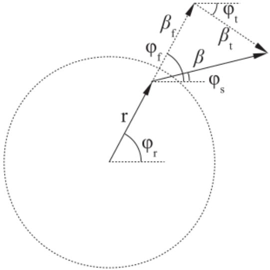

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The final velocity direction of lighter particles, on average,
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Emission asymmetry arises in a system where both thermal and collective velocities exist and are comparable in magnitude

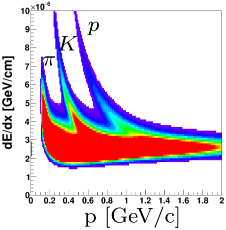
Particle identification

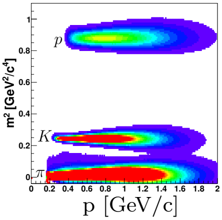
Data selection

Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV, 0-10%

	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]
$\lvert N\sigma \rvert$	< 3.0		
Z [cm]	[-30.0, 30.0]		
$\lvert \eta \rvert$	< 0.5		
m^2 [GeV^2/c^4]	[0.01, 0.03]	[0.21, 0.28]	[0.76, 1.03]
DCA [cm]	< 3.0		

DCA - Distance of Closest Approach





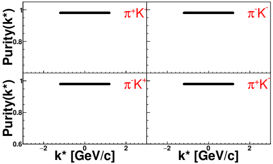
Data selection

	π	K	p
ToF threshold [GeV/c]	0.2	0.41	0.8

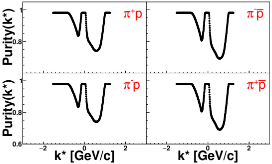
p > ToF threshold $\Rightarrow$ TPC + ToF
p < ToF threshold and information from ToF $\Rightarrow$ TPC + ToF
p < ToF threshold and no information from ToF $\Rightarrow$ TPC

Pair purity:

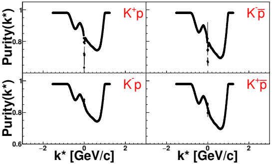
$\pi^{\pm}K^{\pm}$



$\pi^{\pm}p/\bar{p}$

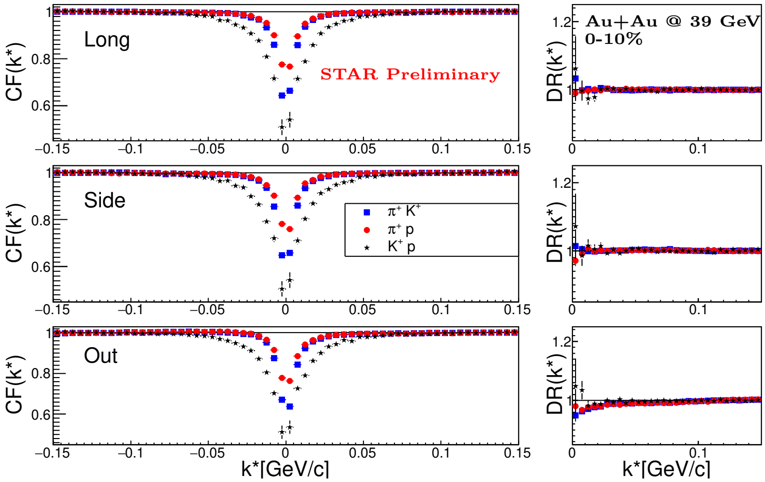


$K^{\pm}p/\bar{p}$



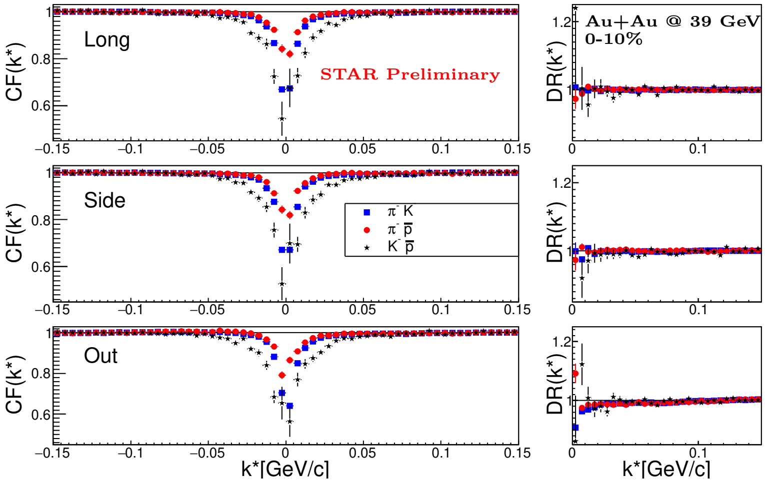
System dependence of nonidentical particle correlations

System comparison ++



- Like sign pairs are dominated by Coulomb interaction
- Kp → strongest correlation
- Visible signal of emission asymmetry

System comparison ——



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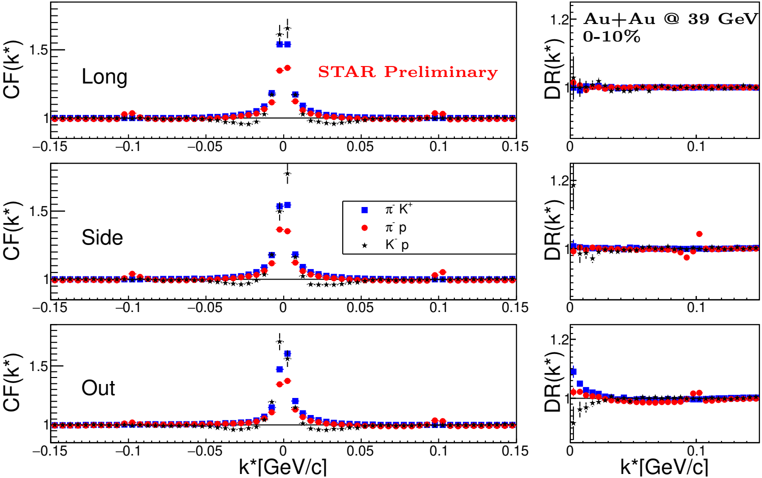
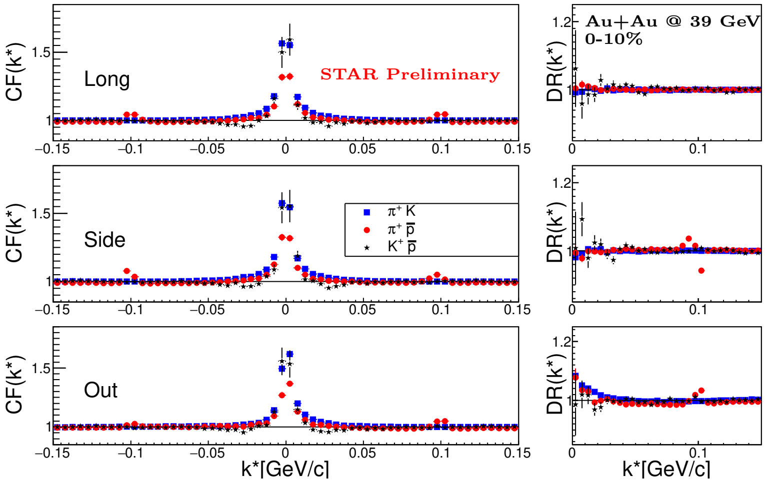
System comparison −+



- Strong interaction not negligible in $K^-p/K^+\bar{p}$
- Λ peak visible in $\pi^-p/\pi^+\bar{p}$
- Visible signal of emission asymmetry

System comparison $+-$



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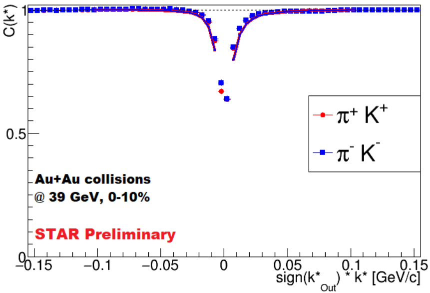
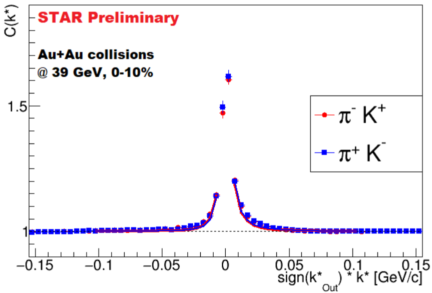
πK fits





$\pi^+ K^+$
$$R = 9.2 \pm 0.8 \pm 0.7 \text{ fm}$$
$$\mu = -4.8 \pm 0.6 \pm 1.0 \text{ fm}$$

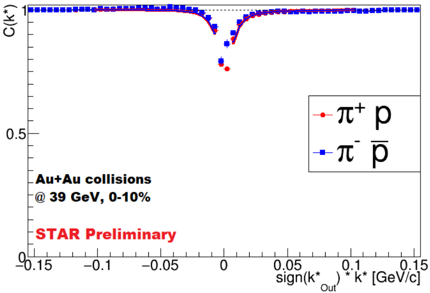
$\pi^- K^-$
$$R = 9.0 \pm 0.7 \pm 0.8 \text{ fm}$$
$$\mu = -4.8 \pm 0.7 \pm 0.6 \text{ fm}$$

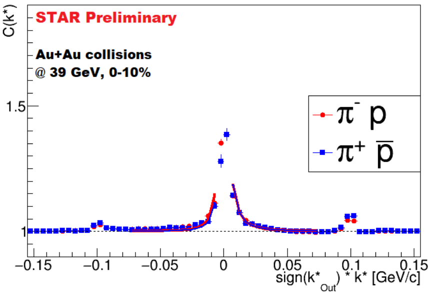
$\pi^- K^+$
$$R = 12.2 \pm 0.7 \pm 0.7 \text{ fm}$$
$$\mu = -4.5 \pm 0.6 \pm 0.9 \text{ fm}$$

$\pi^+ K^-$
$$R = 11.8 \pm 0.8 \pm 0.7 \text{ fm}$$
$$\mu = -6.1 \pm 0.7 \pm 1.1 \text{ fm}$$

- Difference between source sizes for like and unlike sign pairs
- Influence of resonance decays?

$\pi p(\bar{p})$ fits





$\pi^+ p$

$R = 11.9 \pm 1.7 \pm 1.2$ fm

$\mu = -3.0 \pm 0.7 \pm 0.6$ fm

$\pi^- p$

$R = 11.9 \pm 1.4 \pm 0.8$ fm

$\mu = -4.0 \pm 2.9 \pm 0.8$ fm

$\pi^- \bar{p}$

$R = 11.9 \pm 0.7 \pm 0.8$ fm

$\mu = -6.0 \pm 2.9 \pm 1.7$ fm

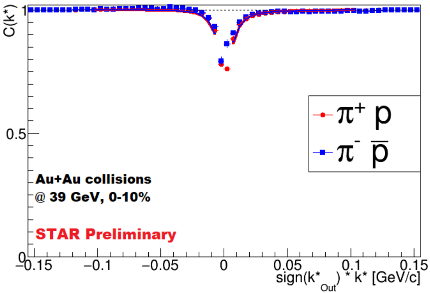
$\pi^+ \bar{p}$

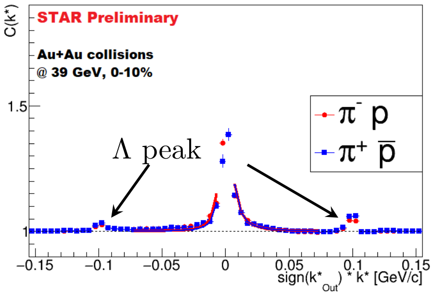
$R = 12.5 \pm 1.0 \pm 0.9$ fm

$\mu = -6.5 \pm 1.5 \pm 1.0$ fm

- Source sizes comparable for like and unlike sign pairs
- Difference between asymmetry sizes for p and $\bar{p}$ pairs

$\pi p(\bar{p})$ fits





$\pi^+ p$

$$R = 11.9 \pm 1.7 \pm 1.2 \text{ fm}$$
$$\mu = -3.0 \pm 0.7 \pm 0.6 \text{ fm}$$

$\pi^- p$

$$R = 11.9 \pm 1.4 \pm 0.8 \text{ fm}$$
$$\mu = -4.0 \pm 2.9 \pm 0.8 \text{ fm}$$

$\pi^- \bar{p}$

$$R = 11.9 \pm 0.7 \pm 0.8 \text{ fm}$$
$$\mu = -6.0 \pm 2.9 \pm 1.7 \text{ fm}$$

$\pi^+ \bar{p}$

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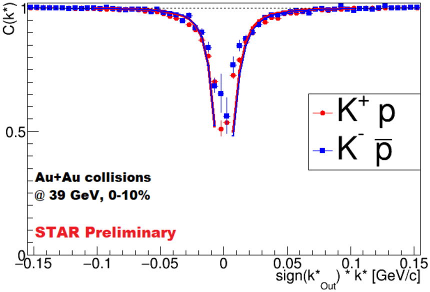
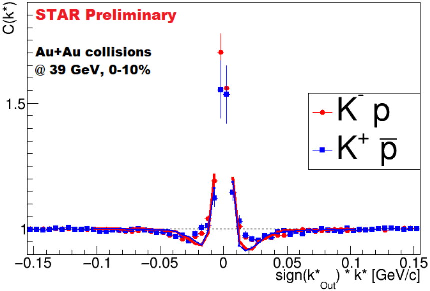
$Kp(\bar{p})$ fits





K^+p
$R = 7.5 \pm 0.3 \pm 1.7$ fm
$\mu = -1.5 \pm 0.6 \pm 1.0$ fm

$K^-\bar{p}$
$R = 9.0 \pm 1.0 \pm 1.2$ fm
$\mu = -2.5 \pm 0.6 \pm 1.5$ fm

K^-p
$R = 8.3 \pm 0.5 \pm 1.5$ fm
$\mu = -0.5 \pm 0.7 \pm 0.7$ fm

$K^+\bar{p}$
$R = 8.5 \pm 0.5 \pm 1.6$ fm
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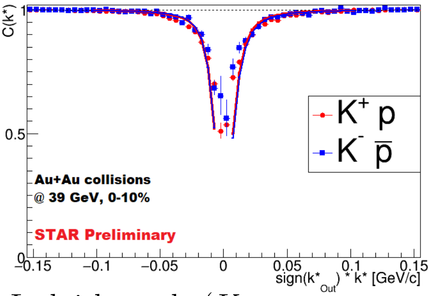
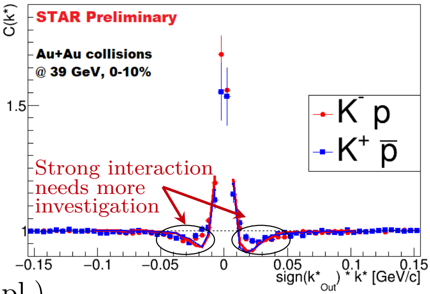
$Kp(\bar{p})$ fits



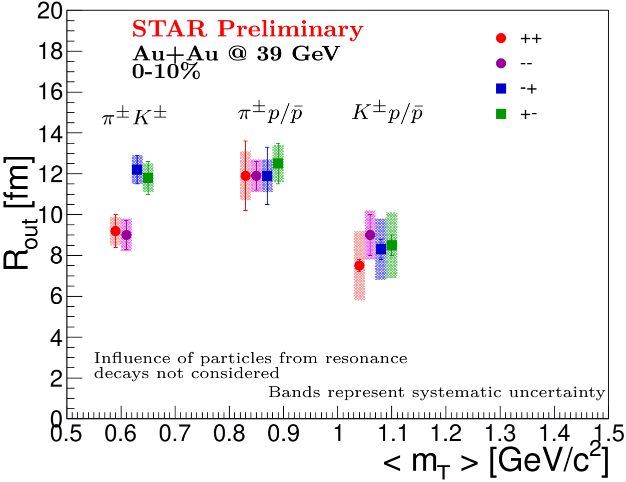


Lednicky code (K^-p s-wave scatt. ampl.)

$\Re a_{K^-p} = -1.05$ fm
$\Im a_{K^-p} = 0.75$ fm

Values from
B. Borasoy, U.-G. Meißner, and R. Nißler,
Phys. Rev. C 74, 055201 (2006)

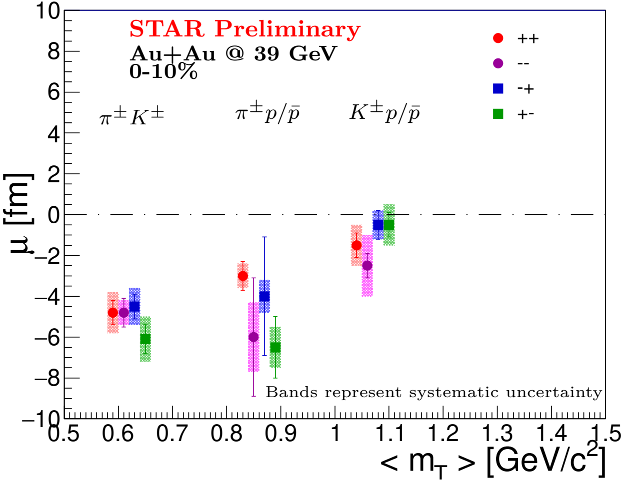
Source size dependence on the system



- Similar source sizes for πK, πp, and significantly smaller for Kp expected ✓

A. Kisiel, Phys. Rev. C 81, 064906 (2010)

Emission asymmetry dependence on the system



- Expected dependence: $\mu_{\pi p} \gtrsim \mu_{\pi K} > \mu_{Kp}$ ✓

A. Kisiel, Phys. Rev. C 81, 064906 (2010)

Summary

- Asymmetry is visible in each kind of analyzed pair
- Lighter particles are emitted closer to the center and/or later (indicated by negative values of μ)
- Model calculations are needed to estimate the influence of particles from resonance decays
- Pairs from lambda resonances have a negligible impact on the correlation effect
- Only kaon-proton $C(k^*)$ has visible and significant strong interaction
  - Kp strong interaction needs more investigation

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Thank you for your attention!