Warsaw University of Technology

Two-particle correlation at the BES program at STAR

Introduction

- HIC and HBT method
- Correlation femtoscopy
- RHIC / STAR / BES;

Results

- Identical pions
- Other systems
- SI studies

Summary

Hanna Zbroszczyk for the STAR Collaboration

e-mail: *hanna.zbroszczyk@pw.edu.pl*

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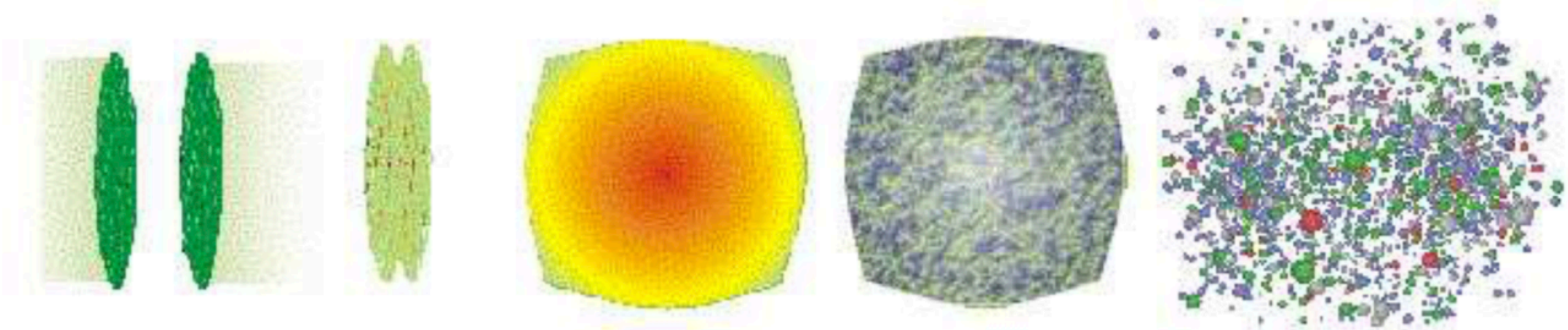
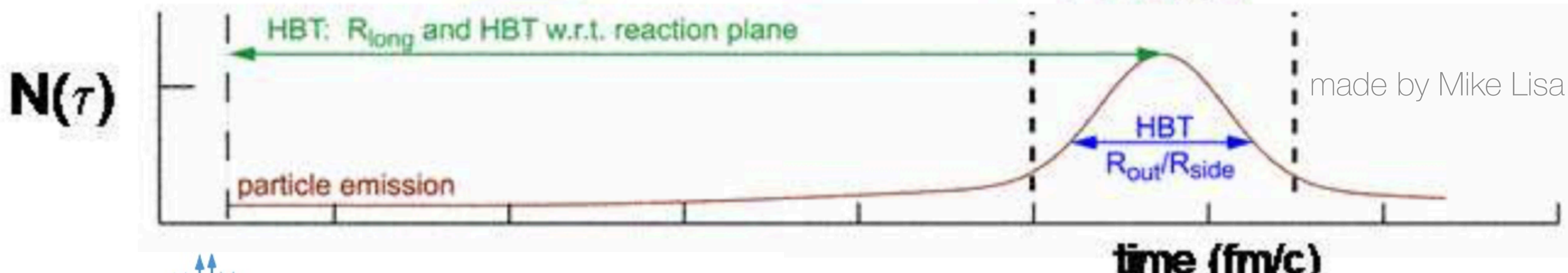
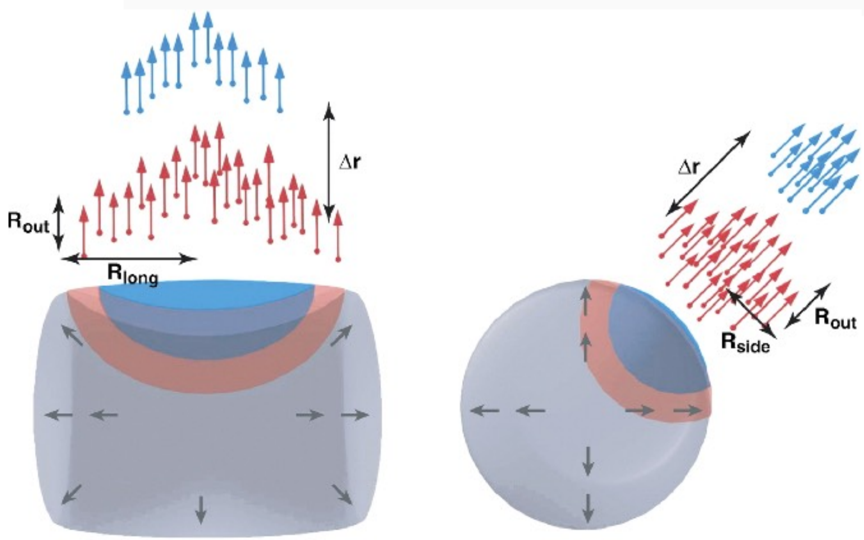
Zymanyi School Winter Workshop, December 6-10 2021, Budapest, Hungary

Introduction

Heavy-Ion collision and **HBT** method







Lisa MA, et al. 2005.
Annu. Rev. Nucl. Part. Sci. 55:357–402

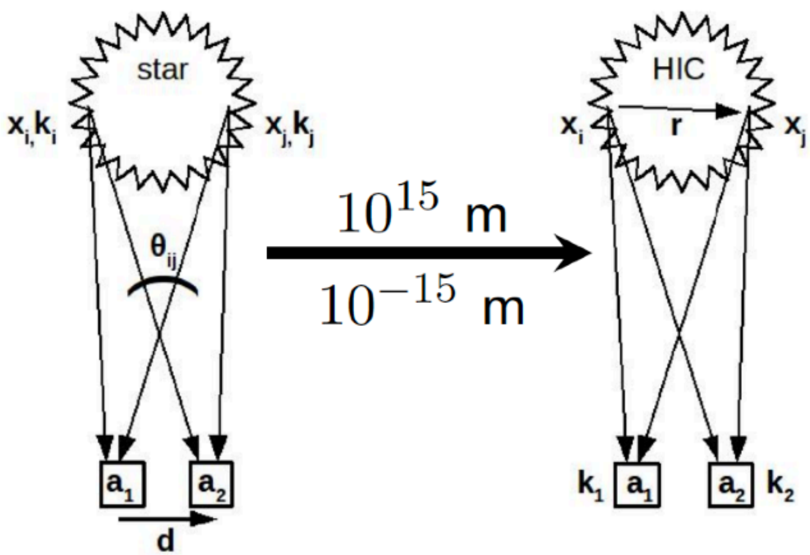
Homogeneity region

long - beam axis
out - pair transverse **p**
side - perpendicular to out and long

Correlation **femtoscopy**

Size: ~10^{-15} m (**fm**)
Time: ~10^{-23} s

Impossible to measure directly!

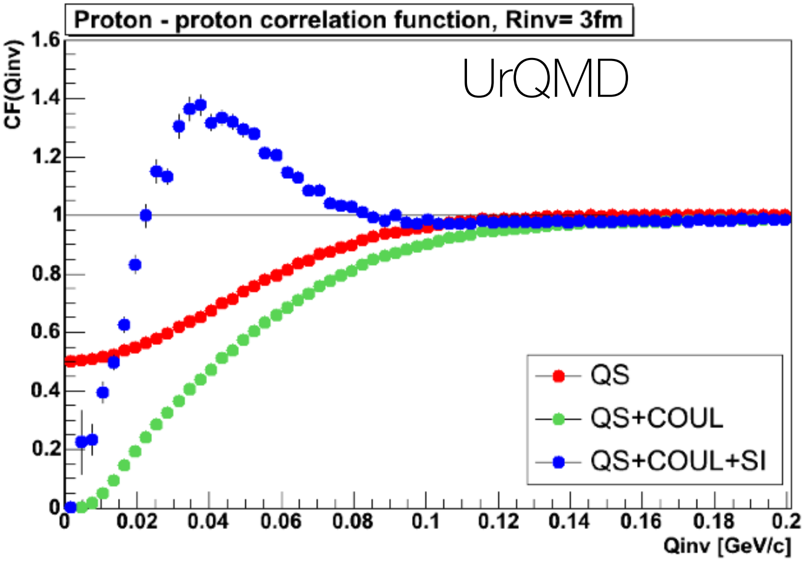


Femtoscopy (**HIC**) inspired by **H**anbury **B**rown and **T**wiss interferometry method (**Astronomy**)

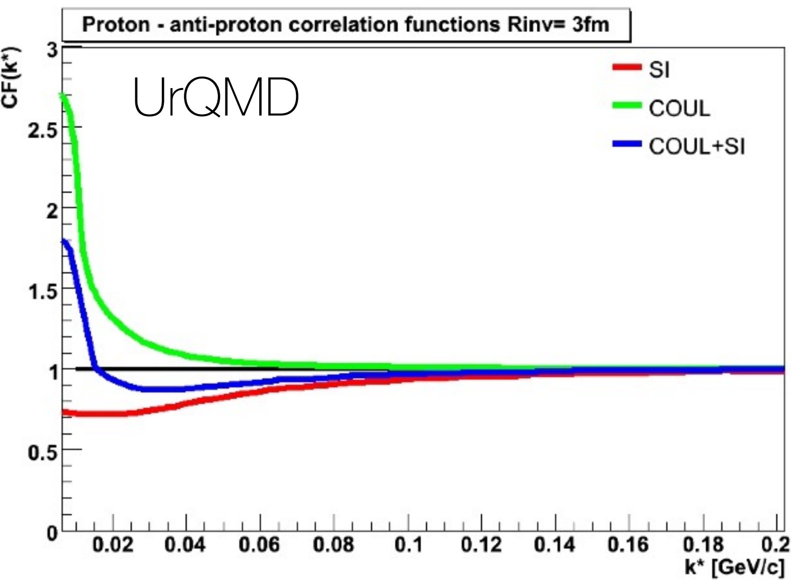
but!

- different scales,
- different measured quantities
- different determined quantities

Hanbury Brown, R.; Twiss, Nature 178, 1046–1048 (1956)



Identical pairs:
- Quantum Statistics- **QS**
- Final State Interactions- **FSI:** Coulomb, Strong



Non-identical pairs:
- Final State Interactions- **FSI:** Coulomb, Strong

Two-particle correlations

x_1, x_2 - space-time sizes (and dynamics) (**can not** be measured directly) →
Close velocity correlations (HBT + FSI)

p_1, p_2 - momenta and momentum difference (**can** be measured directly)

Single- and two-particle distributions:

$$P_1(p) = E\frac{dN}{d^3p} = \int d^4x S(x,p)$$

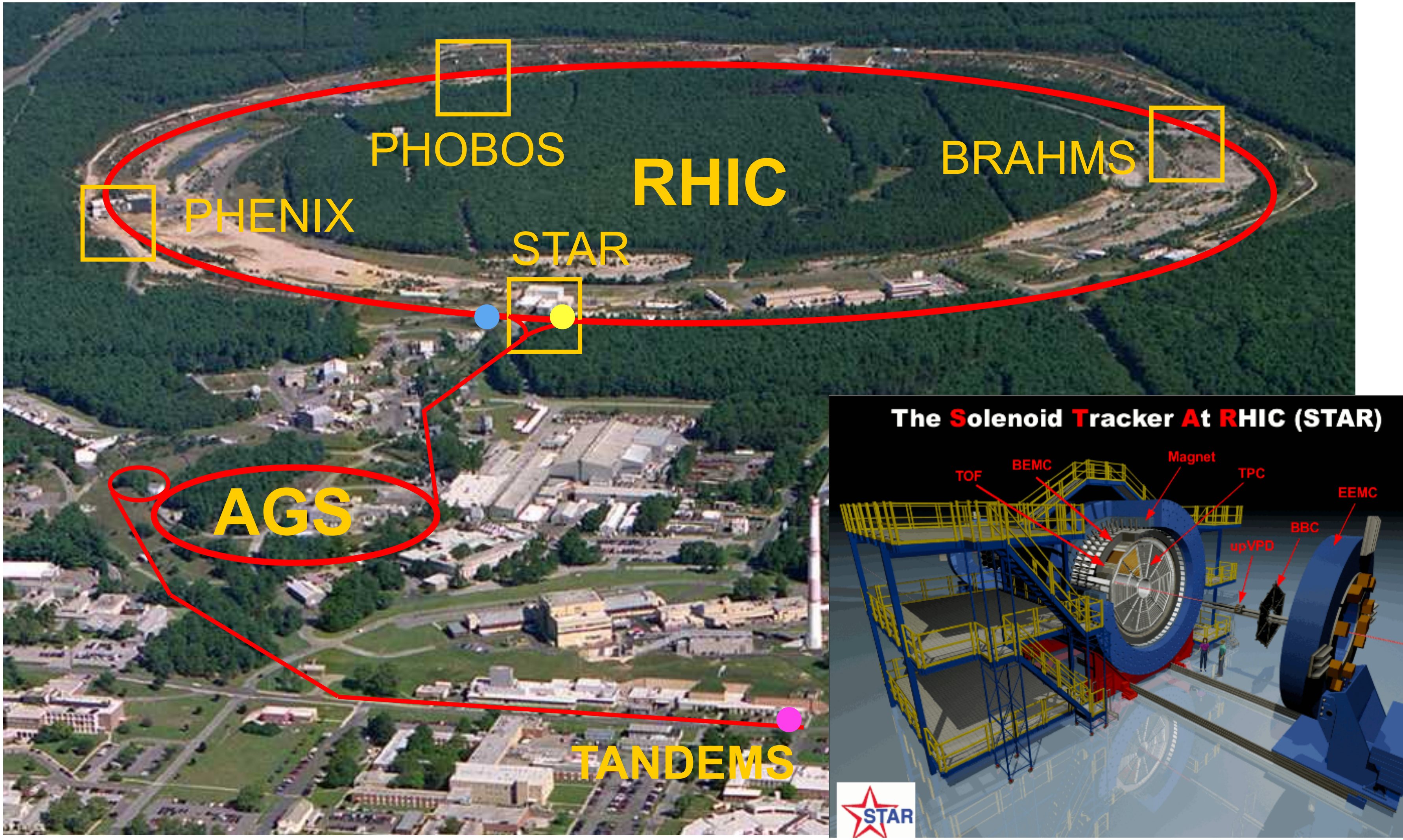
$$P_2(p_1,p_2) = E_1E_2\frac{dN}{d^3p_1d^3p_2}$$

$$P_2(p_1,p_2) = \int d^4x_1 S(x_1,p_1) d^4x_2 S(x_2,p_2)\Phi(x_2,p_2|x_1,p_1)$$

The correlation function:

$$C(p_1,p_2) = \frac{P_2(p_1,p_2)}{P_1(p_1)P_1(p_2)}$$

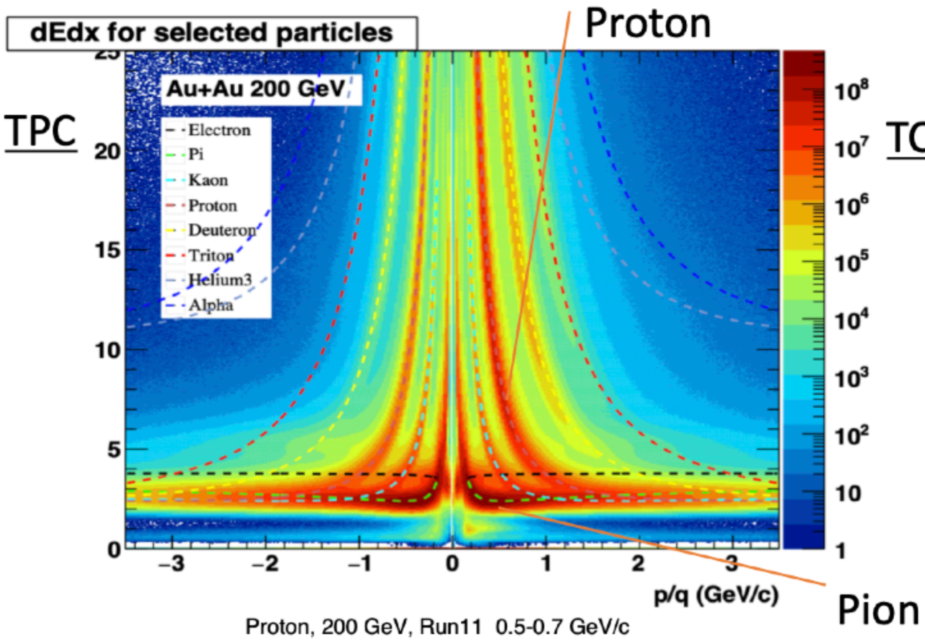
Relativistic Heavy Ion Collider (**RHIC**)
Brookhaven National Laboratory (**BNL**), Upton



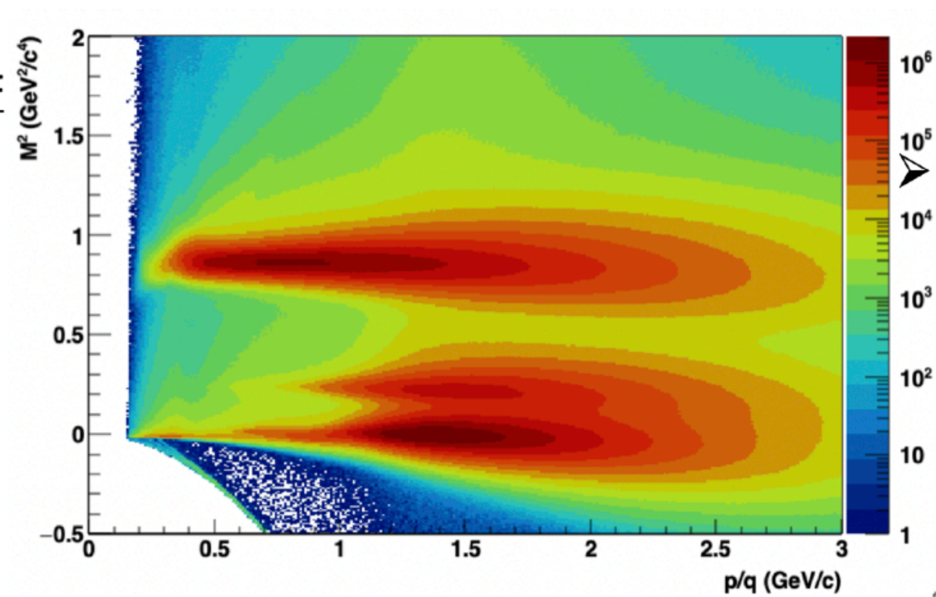
Particle Identification

Particle identification based on dE/dx and time-of-flight

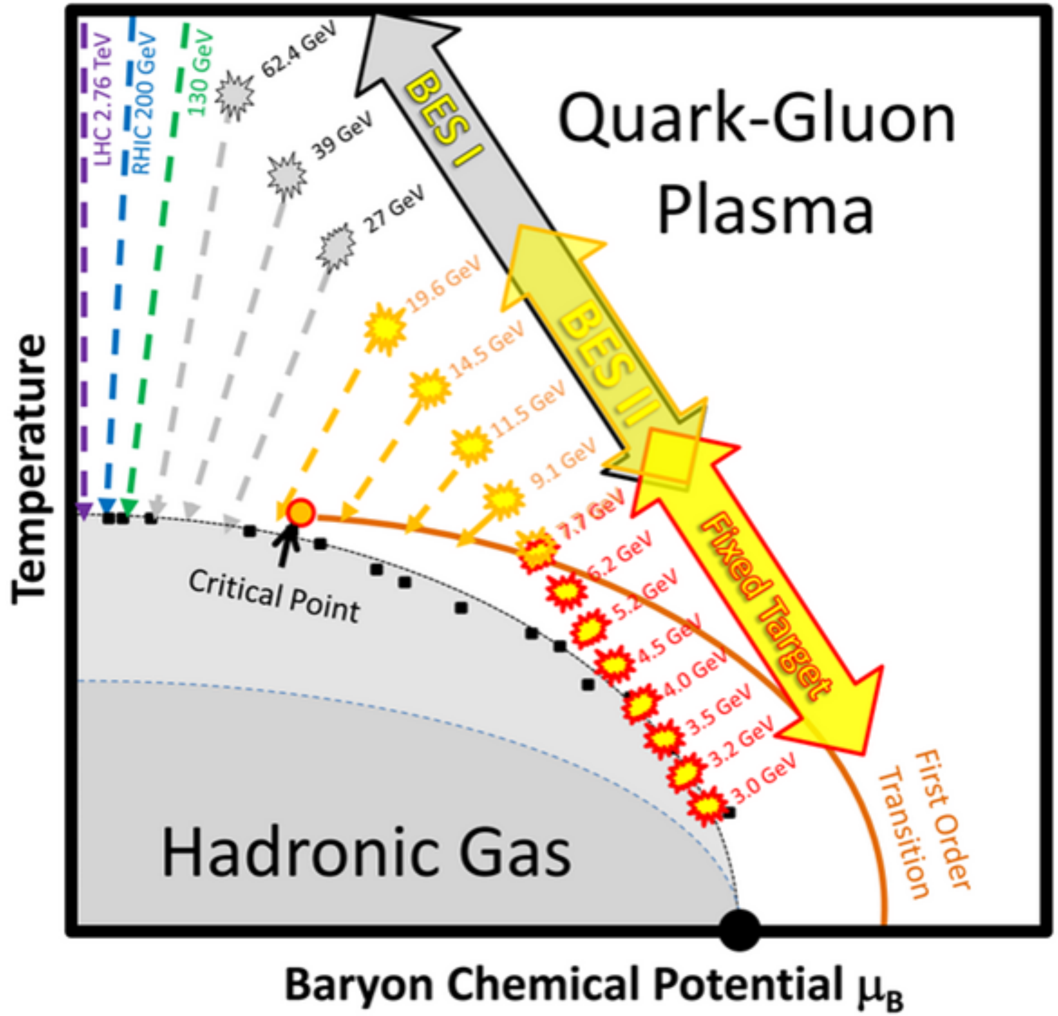
TPC



TOF



Beam Energy Scan Program



RHIC **Top Energy**

p+p, p+Al, p+Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, Ru+Ru, Zr+Zr, Au+Au, U+U

QCD at high energy density/temperature

Properties of QGP, EoS

Beam **E**nergy **S**can

Au+Au at $\sqrt{s_{NN}}$ = 7.7-62 GeV

- QCD phase transition
- Search for critical point
- Turn-off of QGP signatures
- Chiral symmetry restoration

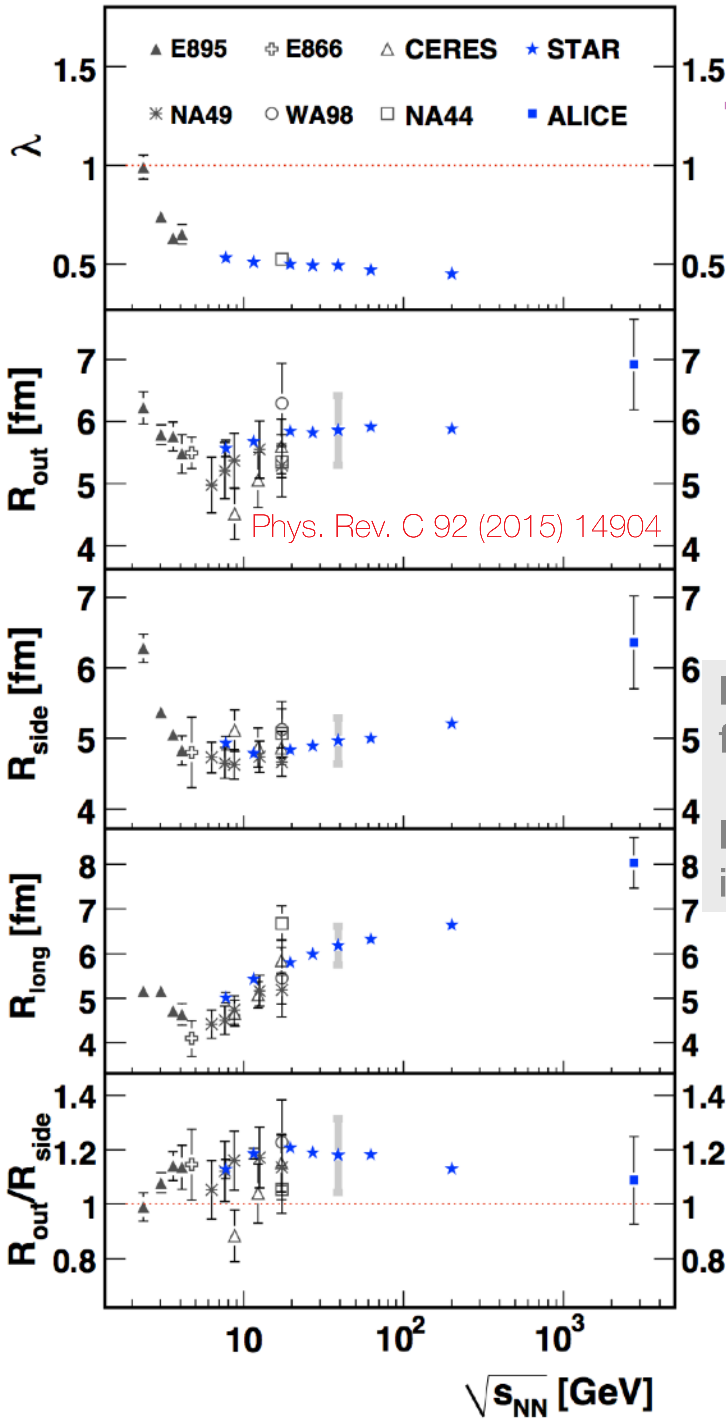
Fixed-**T**arget Program

Au+Au at $\sqrt{s_{NN}}$ = 3.0-7.7 GeV

High baryon density regime with μ_B = 420-720 MeV

Results

Identical pion femtoscopy

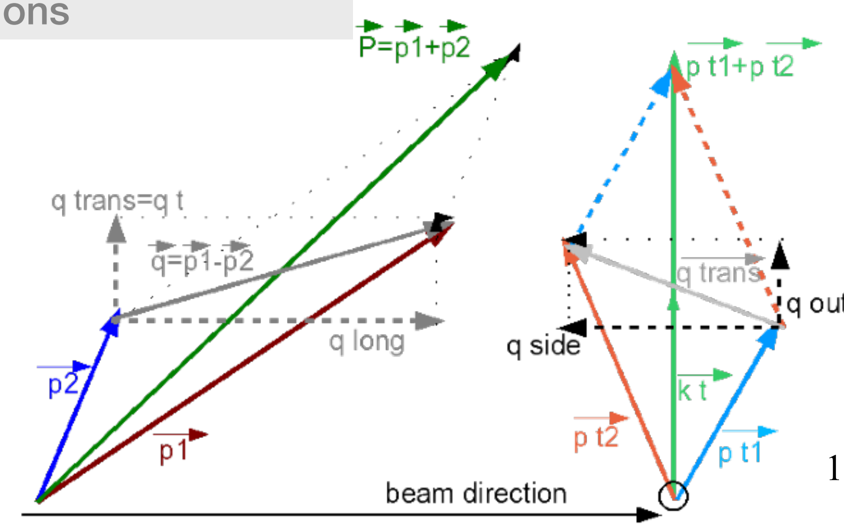


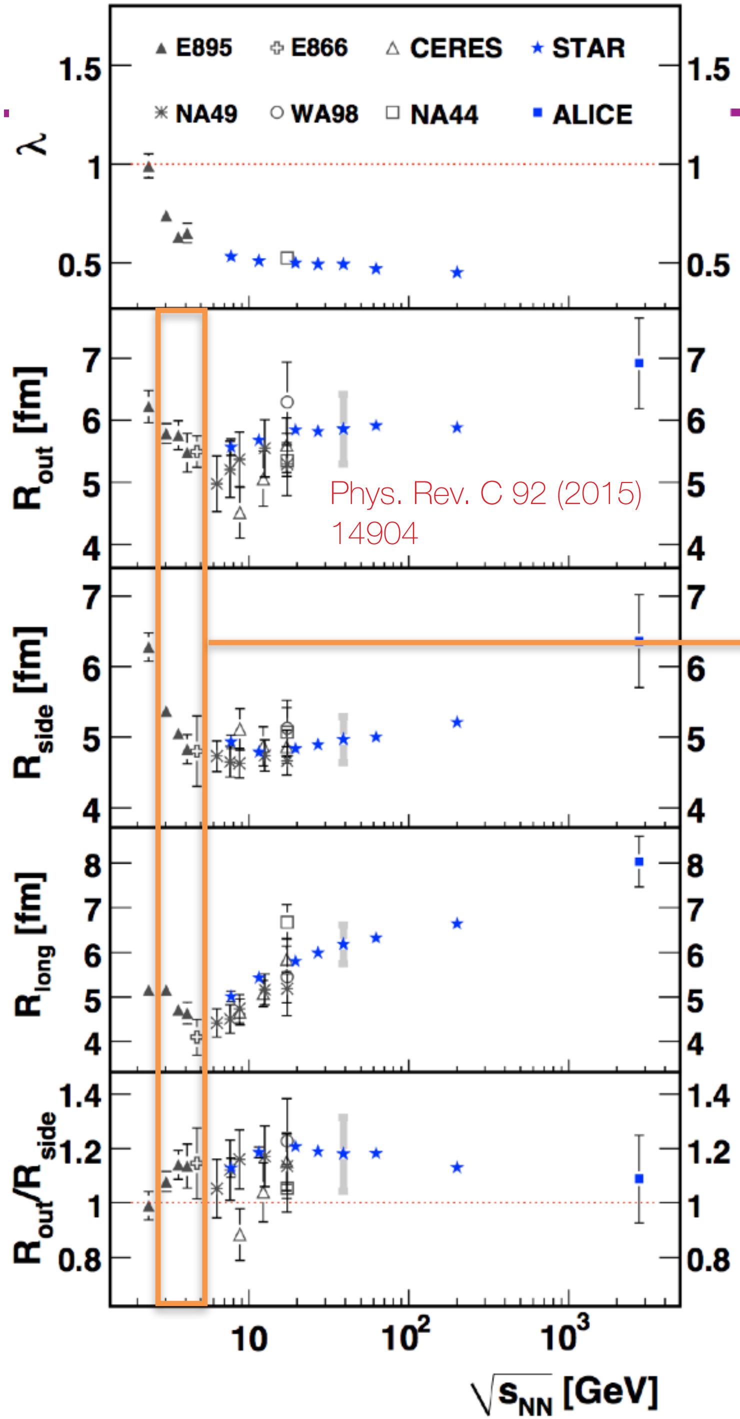
- → R_{side} spatial source evolution in the transverse direction
- → R_{out} related to spatial and time components
- → R_{out}/R_{side} signature of phase transition
- → $R_{out}^2 - R_{side}^2 = \Delta\tau^2 \beta_t^2$; $\Delta\tau$ – emission time
- → R_{long} temperature of kinetic freeze-out and source lifetime

$$C(\vec{q}) = (1-\lambda) + K_{\mathrm{Coul}}(q_{\mathrm{inv}})\lambda$$
$$\times \exp\left(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2 - 2q_o q_s R_{os}^2 - 2q_o q_l R_{ol}^2\right)$$

HBT source sizes determined for a wide range of collision energy;

Non-monotonic behavior seen in three directions





Identical pion femtoscopy

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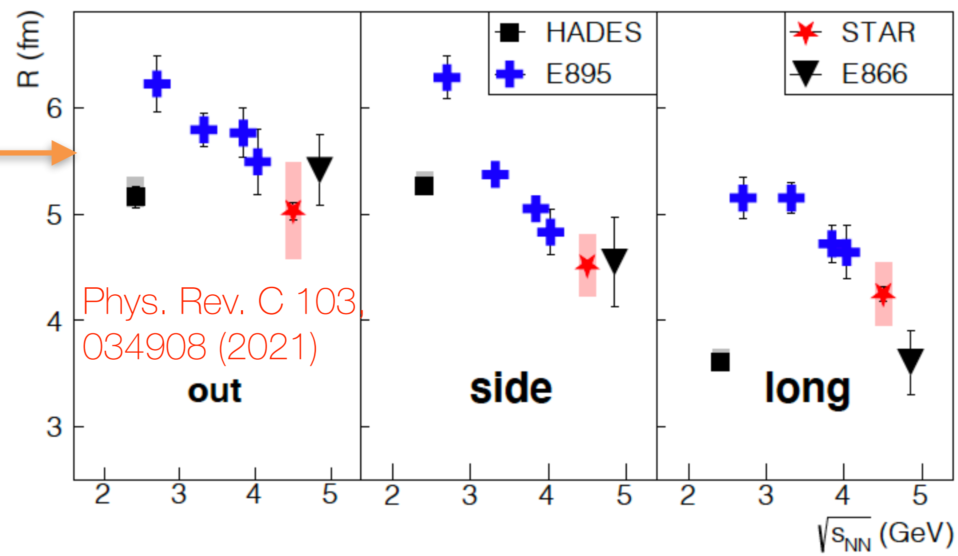
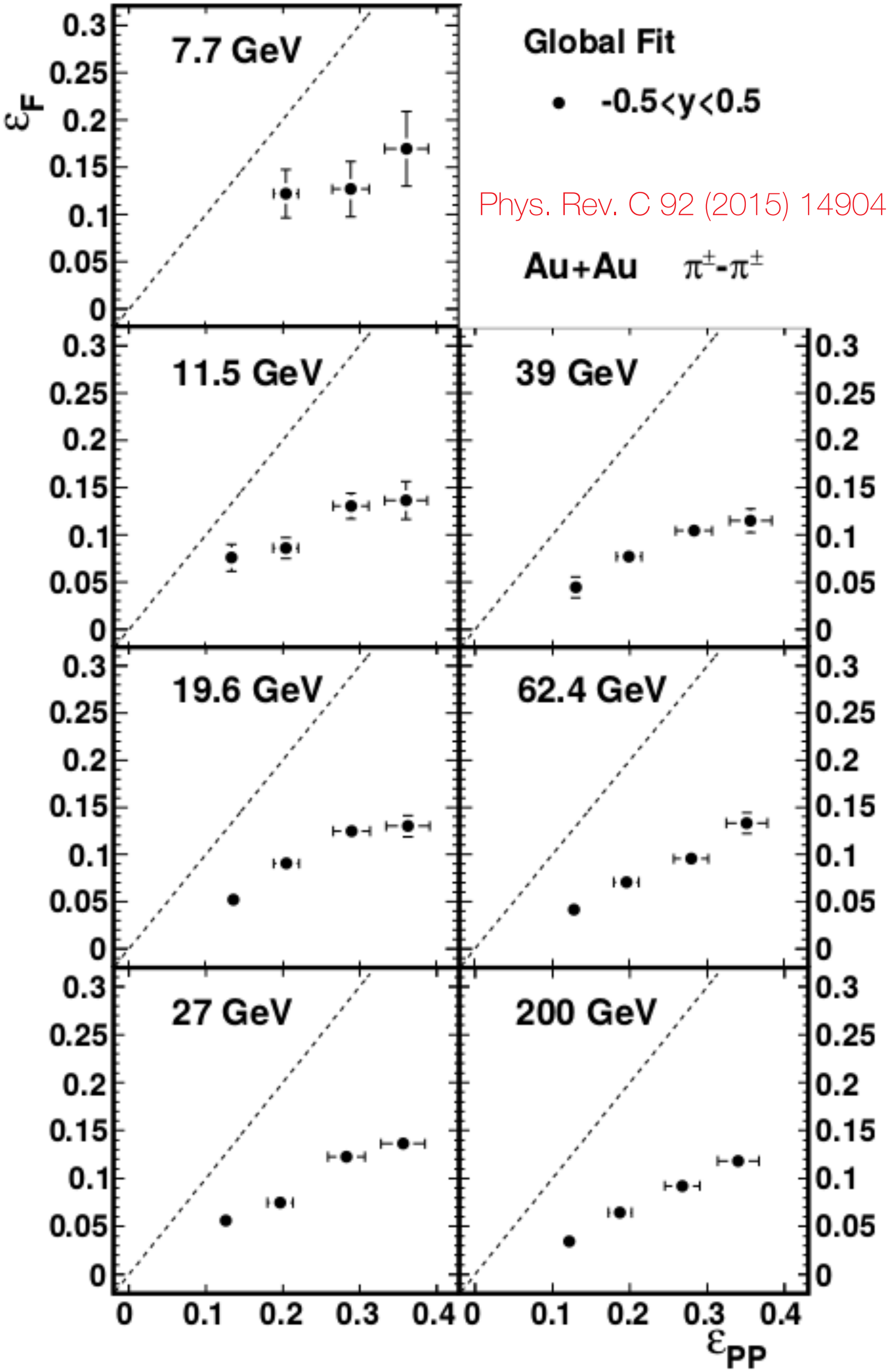


New data from $\sqrt{s_{NN}}$ = 4.5 GeV follow trend observed for low collision energies

Identical pion femtoscopy



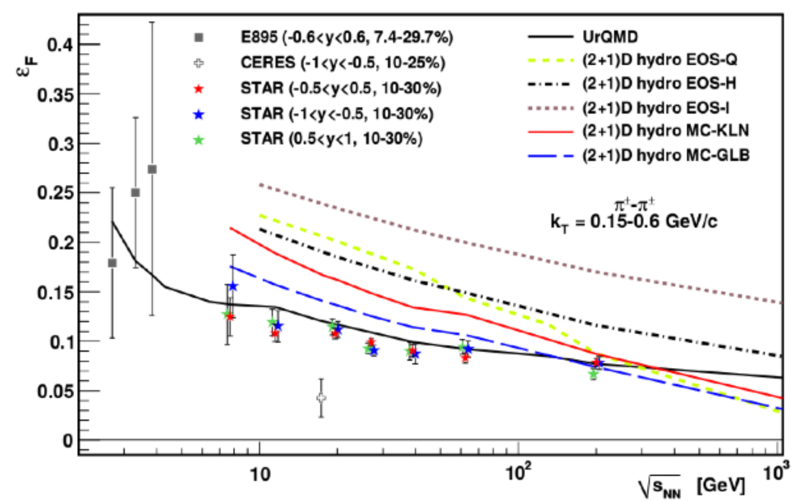
Phys. Rev. C 92 (2015) 14904

$$\varepsilon_{PP} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_x^2 + \sigma_y^2}. \qquad \varepsilon_F = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} \approx 2\frac{R_{s,2}^2}{R_{s,0}^2}$$

$$\sigma_x^2 = \{x^2\} - \{x\}^2 \text{ and } \sigma_y^2 = \{y^2\} - \{y\}^2$$

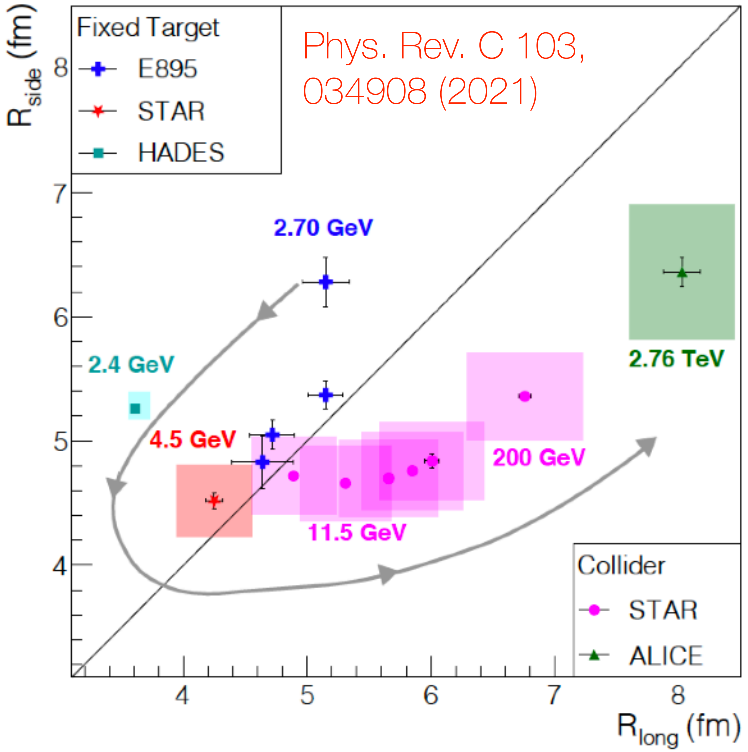
$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2\sum_{n=2,4,6\ldots} R_{\mu,n}^2 \cos(n\Phi) \qquad (\mu = o, s, l, ol)$$

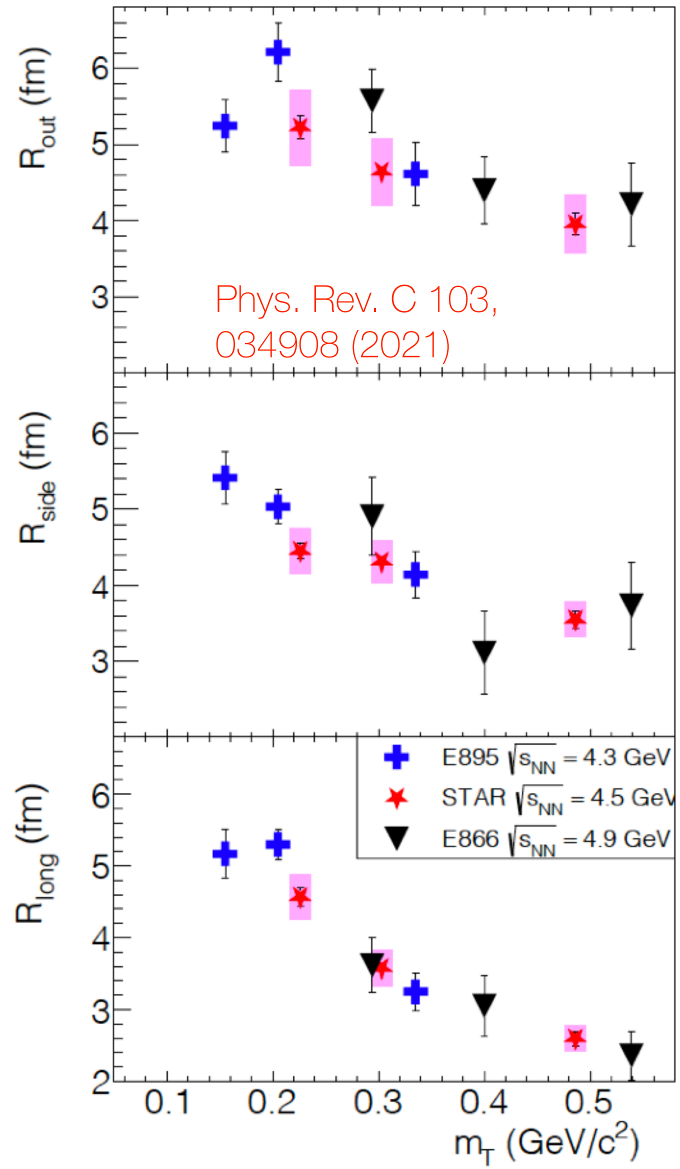
$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2\sum_{n=2,4,6\ldots} R_{\mu,n}^2 \sin(n\Phi) \qquad (\mu = os)$$



System evolves faster in the reaction plane

How to measure a phase transition?





Clear evolution in the freeze-out shape indicated

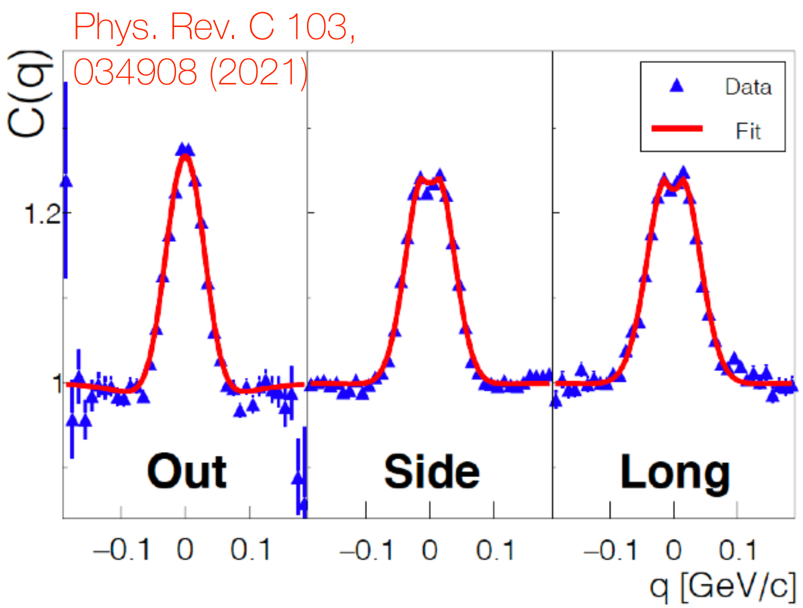
Lower energies: system more oblate ($R_{side} > R_{long}$)

Higher energies: system more prolate ($R_{side} < R_{long}$)

$\sqrt{s_{NN}}$ = 4.5 GeV: round system ($R_{side} \simeq R_{long}$)

Transition region between dynamics dominated by stopping and boost-invariant dynamics.

How to measure a phase transition?

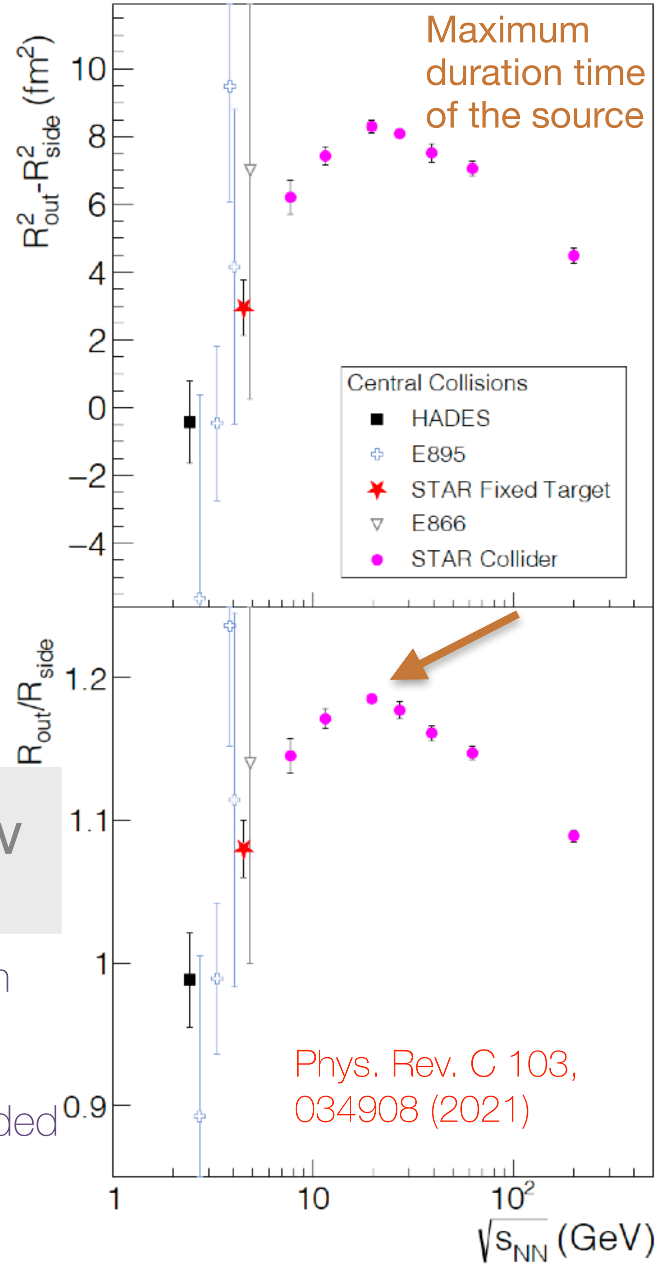


$$R_{out}^2 - R_{side}^2 = \beta_t^2 \Delta\tau^2$$

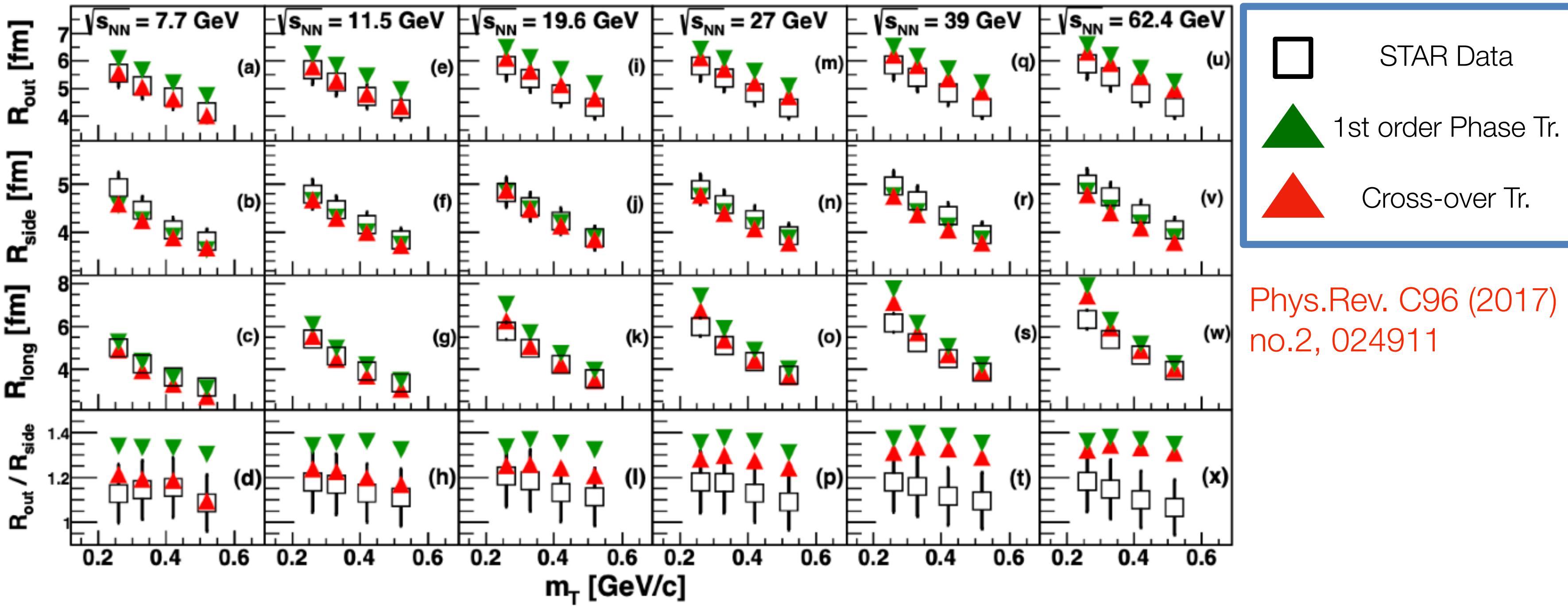
Visible peak in $\frac{R_{out}}{R_{side}}(\sqrt{s_{NN}})$ near the $\sqrt{s_{NN}} \simeq 20$ GeV

QCD calculations predict a peak near to the QGP transition threshold - signature of first-order phase transition?

Theoretical attention from hydro and transport models needed



How to measure a phase transition?



Phys.Rev. C96 (2017) no.2, 024911

Pre-thermal phase → Hydrodynamical phase → Hydronic cascades

UrQMD | vHLEE | UrQMD

vHLLE (3+1)-D viscous hydrodynamics
Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher
Phys.Rev. C 91, 064901 (2015), arXiv:1502.01978,1509.3751

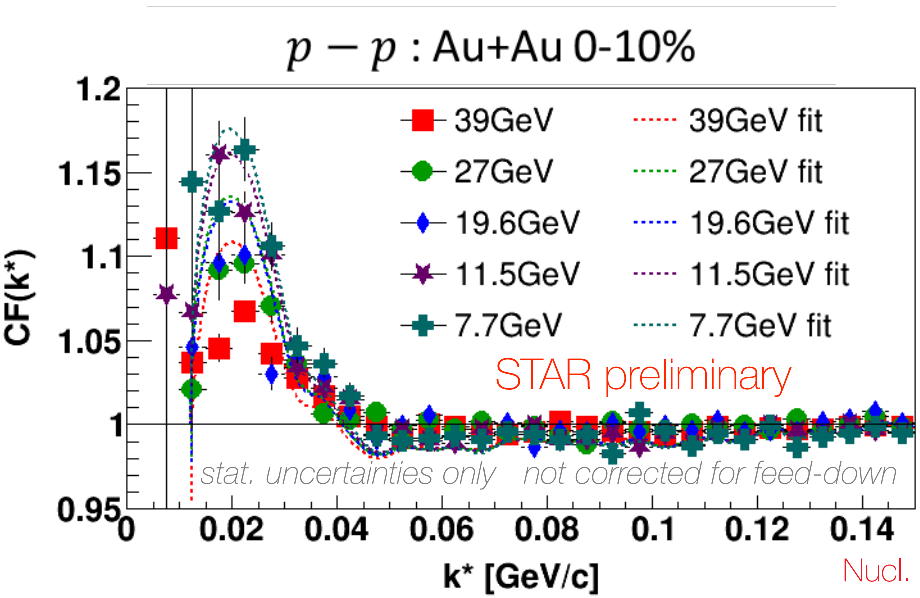
vHLEE+UrQMD model verifies sensitivity of HBT measurements to the first-order phase transition

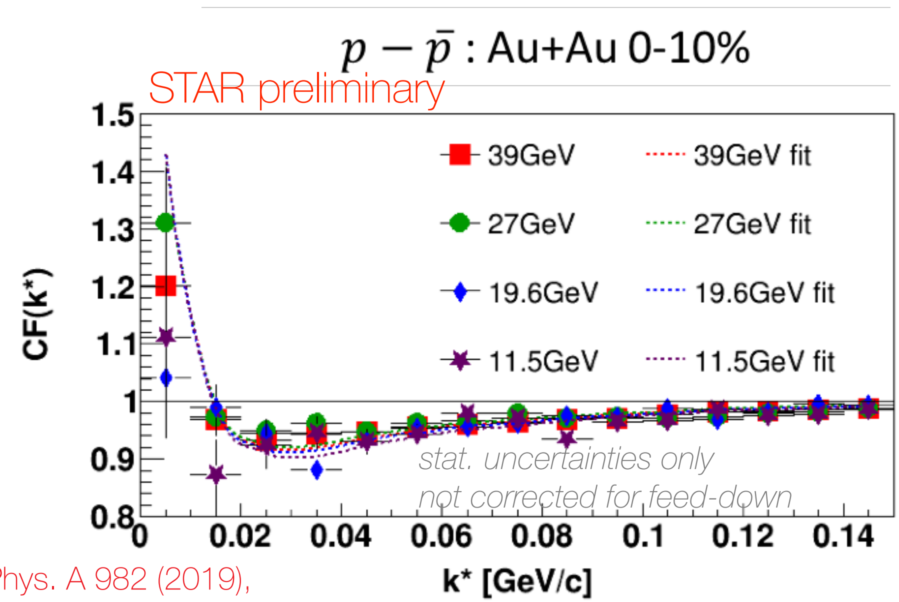
HadronGas + Bag Model → 1st order PT

P.F. Kolb, et al, PR C 62, 054909 (2000)

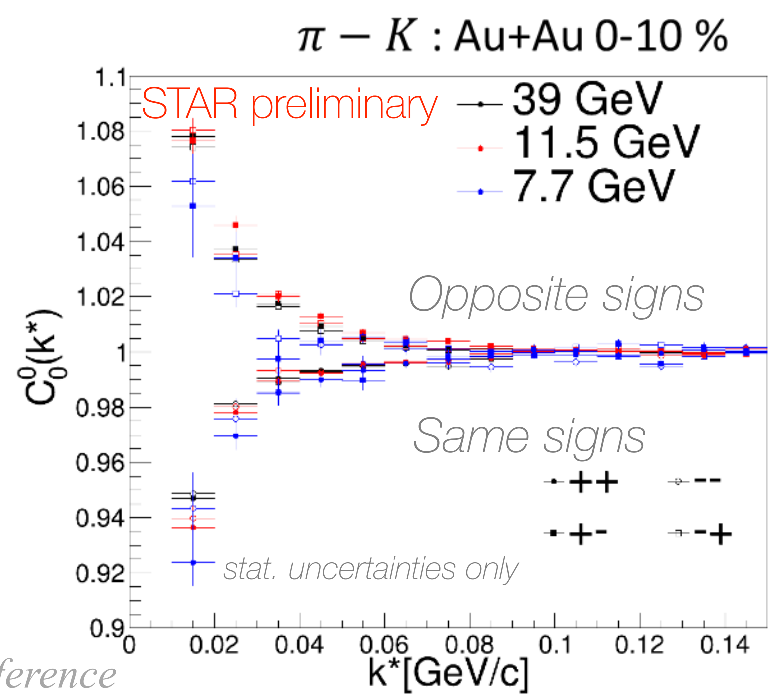
Chiral EoS → crossover PT (XPT)
J. Steinheimer, et al, J. Phys. G 38, 035001 (2011)

Other systems: energy dependence





Nucl. Phys. A 982 (2019), 359-362



energy	R_{inv} $p - p$ [fm]	R_{inv} $p - \bar{p}$ [fm]
7.7 GeV	$\mathbf{3.59} \pm 0.16 \pm 0.19$	
11.5 GeV	$\mathbf{3.66} \pm 0.08 \pm 0.05$	$\mathbf{3.30} \pm 0.42 \pm 0.28$
19.6 GeV	$\mathbf{3.82} \pm 0.15 \pm 0.06$	$\mathbf{3.32} \pm 0.25 \pm 0.13$
27 GeV	$\mathbf{3.80} \pm 0.12 \pm 0.08$	$\mathbf{3.49} \pm 0.25 \pm 0.16$
39 GeV	$\mathbf{4.00} \pm 0.15 \pm 0.02$	$\mathbf{3.39} \pm 0.12 \pm 0.14$

Clear energy dependence seen

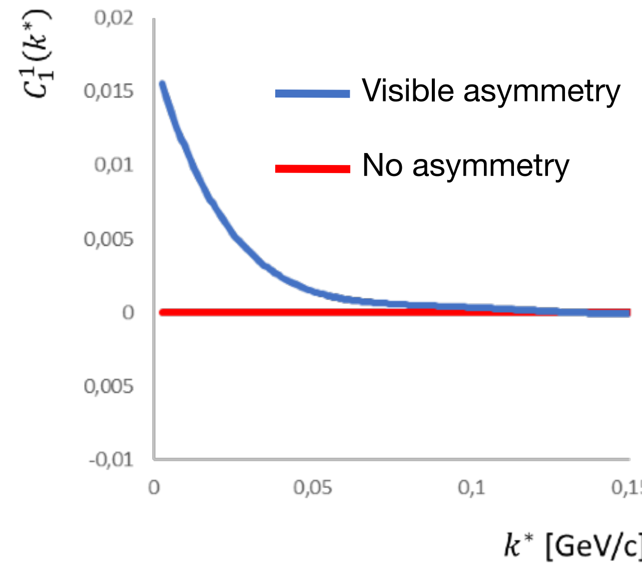
k - momentum of the first particle in the Pair Rest Frame reference*

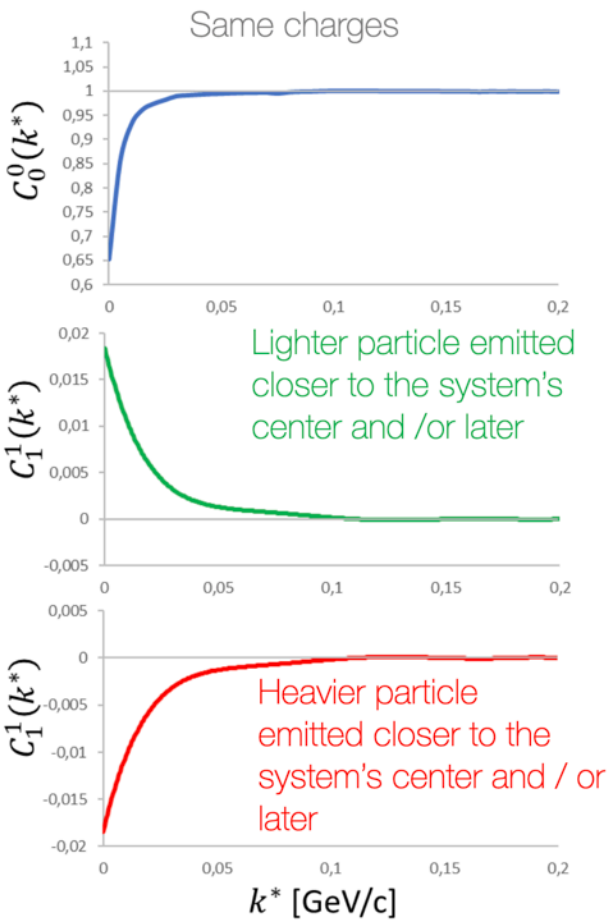
Non-identical particle correlations - introduction

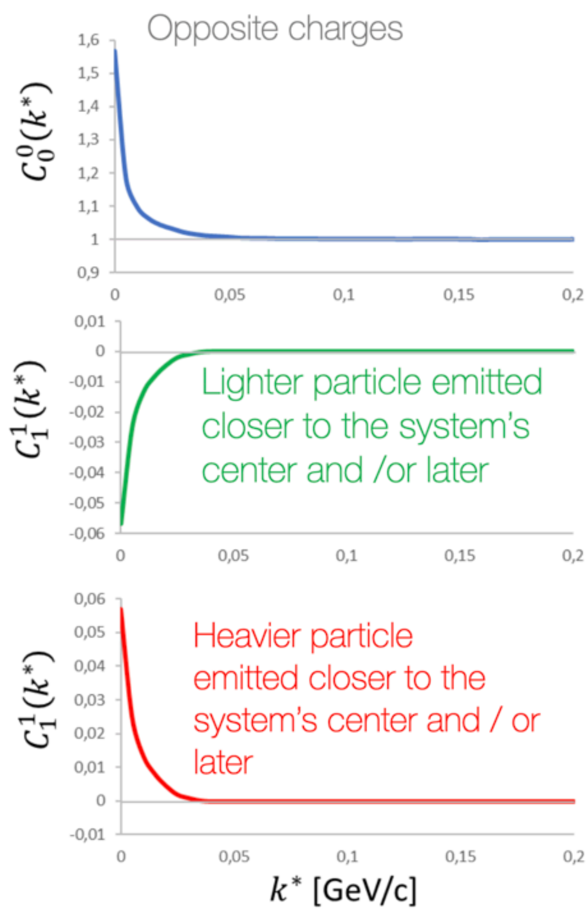
$C(\boldsymbol{q}) = \sum_{l,m} C_l^m(q) Y_l^m(\theta,\phi)$ $\qquad C_l^m(q) = \int_\Omega C(q,\theta,\phi) Y_l^m(\theta,\phi) d\Omega$

Ω – full solid angle
$Y_l^m(\theta,\phi)$ – spherical harmonic function
$q = |\boldsymbol{q}|, \theta, \phi$ – spherical coordinates

C_0^1 → source **size**
C_1^1 → space-time **asymmetry**







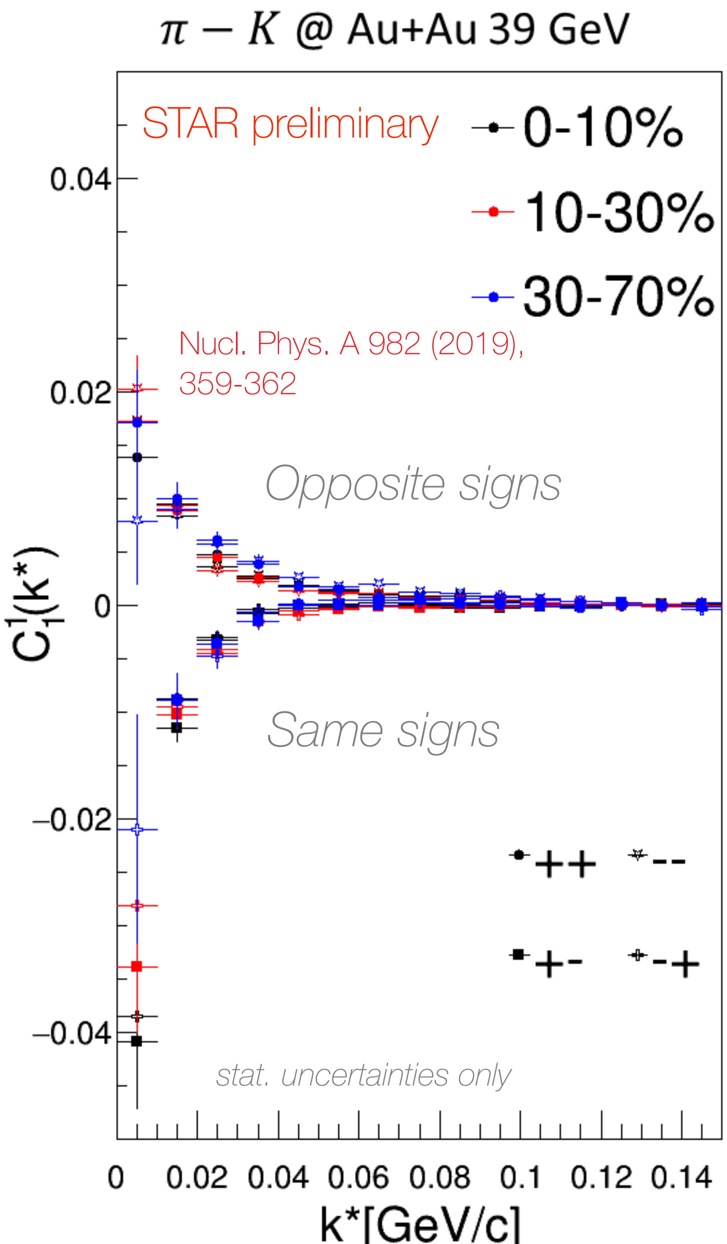
P. Danielewicz and S.Pratt.
Phys. Lett. B618: 60 2005

P. Danielewicz and S.Pratt.
Phys. Rev. C75:034907 2007

A. Kisiel
Phys. Rev. C81:064906 2010

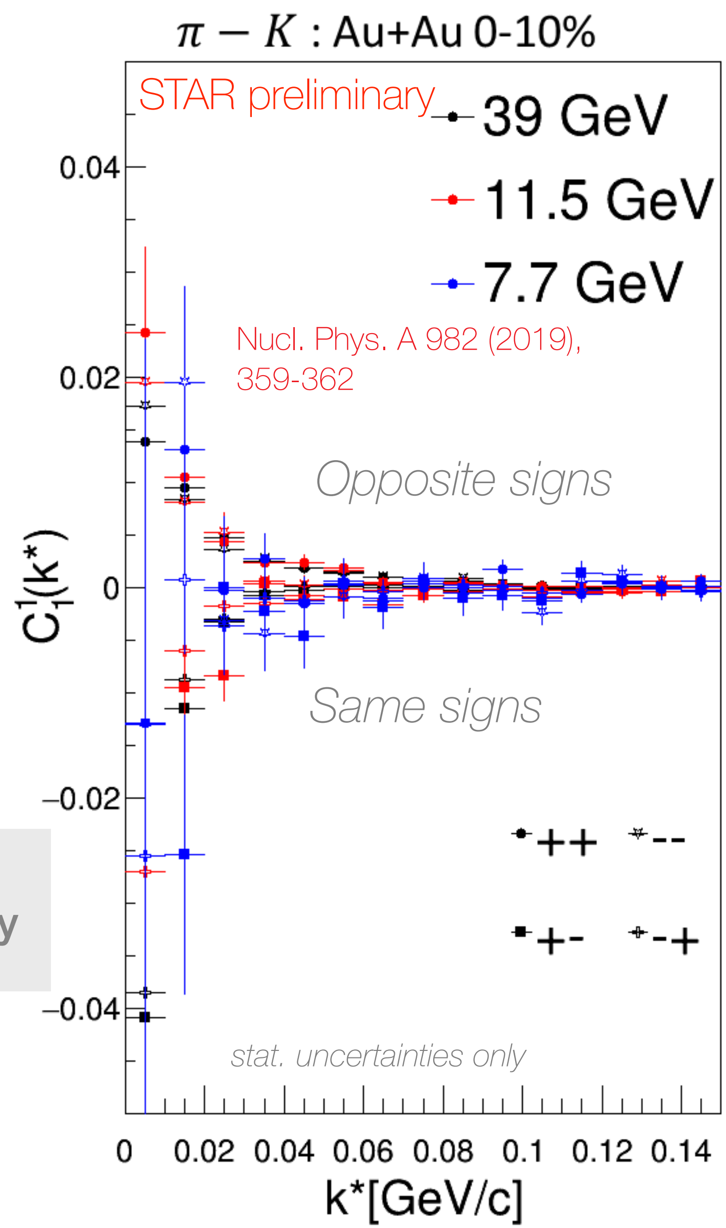
A. Kisiel and D. A. Brown
Phys. Rev. C80:064911 2009

Source dynamics: **centrality** and **energy** dependencies



Asymmetry does not disappear in lower energies

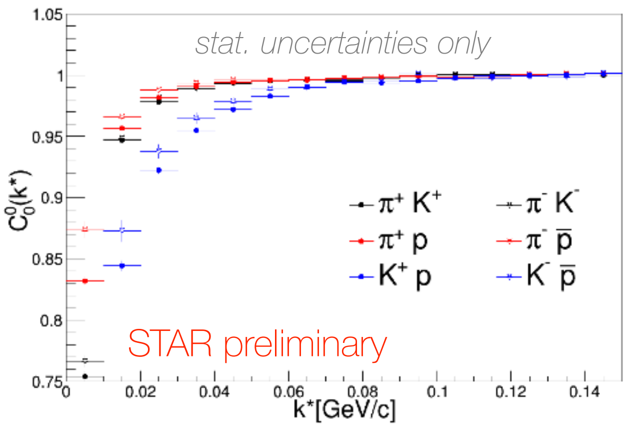
Clear signal of emission asymmetry

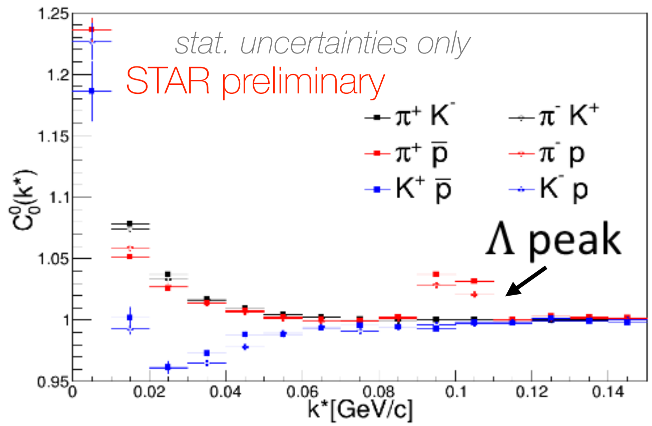


Source dynamics: **system** dependence

Like-sign 0-10% @ Au+Au 39 GeV

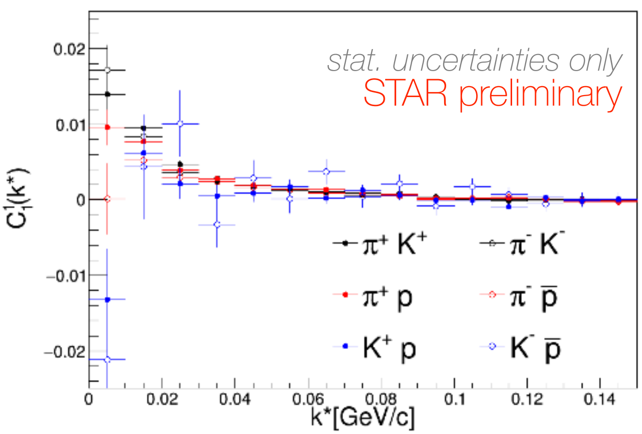
Unlike-sign 0-10% @ Au+Au 39 GeV

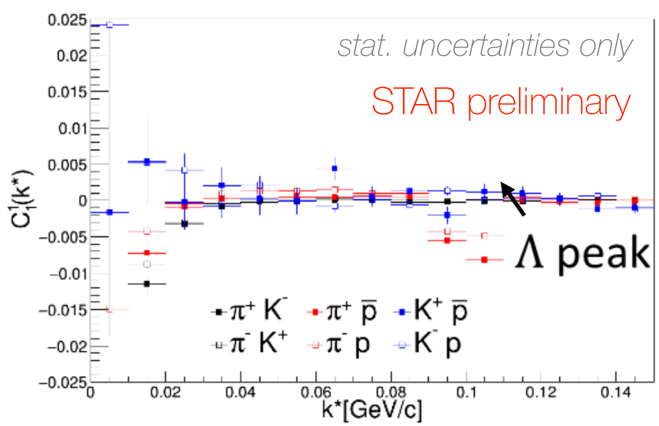




Determined by **Coulomb** Interactions

Determined by full **FSI**: **Coulomb** and **Strong** interactions (kaon-proton)



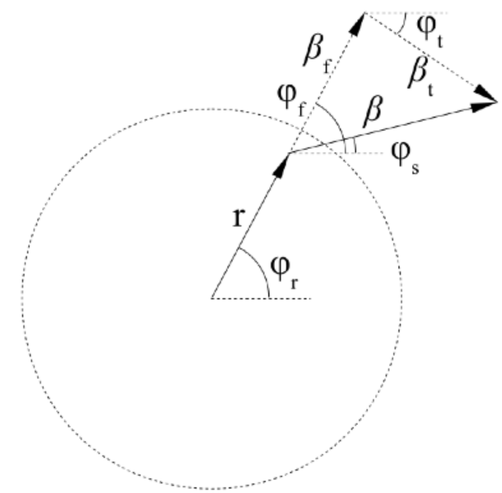


Nucl. Phys. A 982 (2019), 359-362

Heavier particles directed towards edge of the source.

Heavier particles freeze-out earlier

Phys. Rev. C81:064906 2010

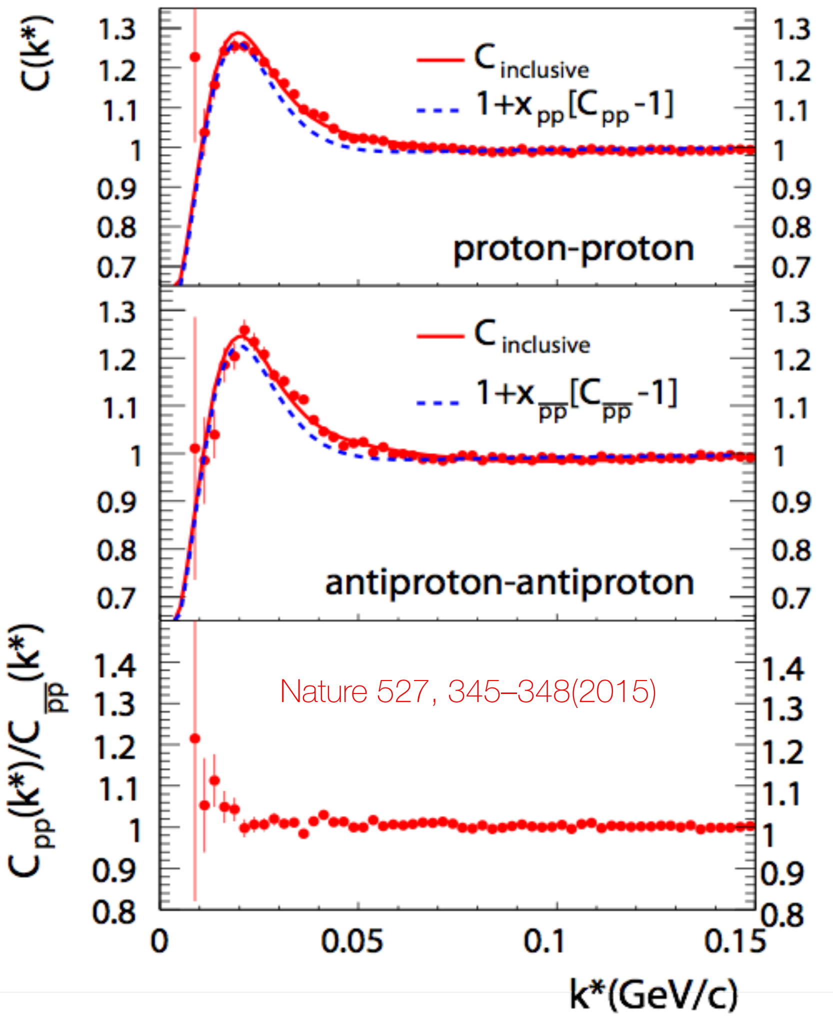


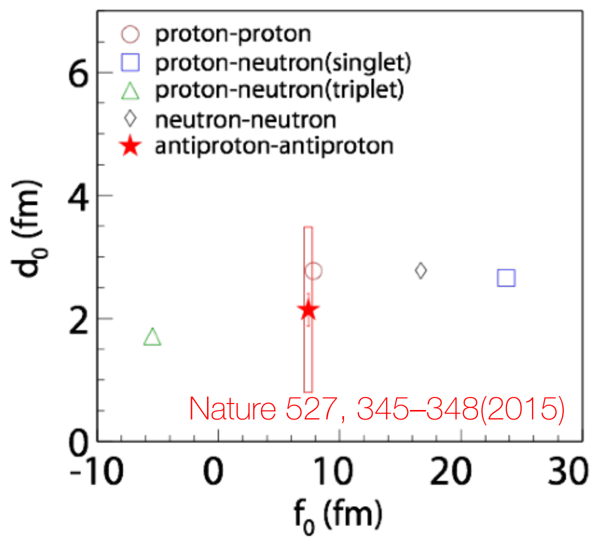
$$\langle x_{out} \rangle = \frac{\langle r\beta_f \rangle}{\left\langle \sqrt{\beta_t^2 + \beta_f^2} \right\rangle} = \frac{r_0 \beta_0 \beta}{\beta_0^2 + T/m_t},$$

β_f - the same for both particles

$\beta_t \sim 1/m_T$ - smaller for heavier particles

Strong interactions between anti-nucleons





f_0 and d_0 - parameters of strong interaction

Scattering length f_0

Effective range d_0

Elastic cross section σ_e

$$\lim_{k\to 0} \sigma_e = 4\pi f_0^2$$

p-p CF,
R=2.75±0.01fm; χ2/NDF = 1.66;
antiproton-antiproton CF,
R=2.80±0.02fm , f_0=7.41±0.19fm,
d_0=2.14±0.27fm; χ2/NDF=1.61

- f_0 and d_0 for the antiproton-antiproton interaction consistent with parameters for the proton-proton interaction.
- Descriptions of the interaction among antimatter (based on the simplest systems of anti-nucleons) determined.
- A quantitative verification of matter-antimatter symmetry in context of the forces responsible for the binding of (anti)nuclei.

Strange Baryon Correlations (including p-Ω)

Binding energy **Ebin** [MeV]

Scattering length **a0** [fm]

Effective range **reff** [fm]

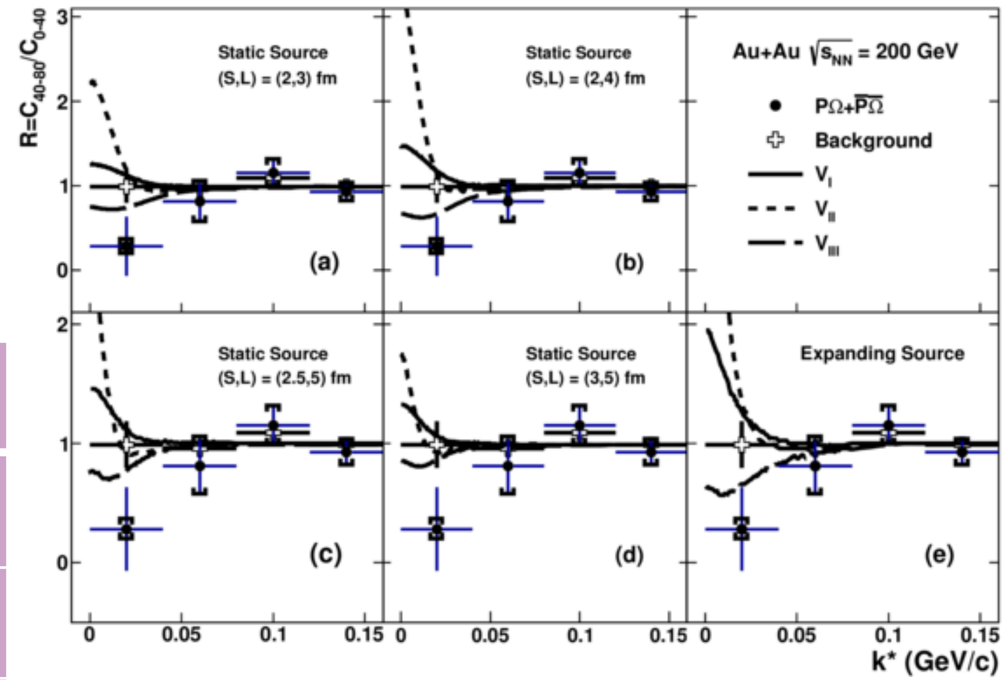
for 3 scenarios:

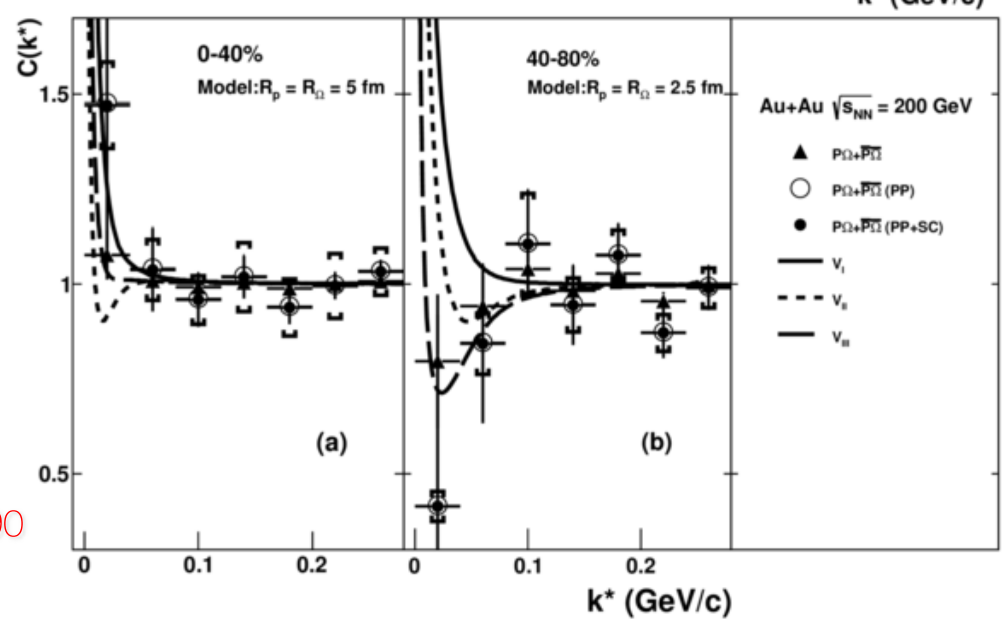
K. Morita et al. Phys. Rev. C 94, 031901 (2016)

	V1	V2	V3
Ebin [MeV]	-	6.3	26.9
a0 [MeV]	-1.12	5.79	1.29
reff [MeV]	-1.16	0.96	0.65

A comparison of the measured correlation functions from Au+Au collisions with theoretical predictions

Scattering length is positive and favor pΩ bound state hypothesis





Phys.Lett.B 790 (2019) 490

Particle Identification for hyperons

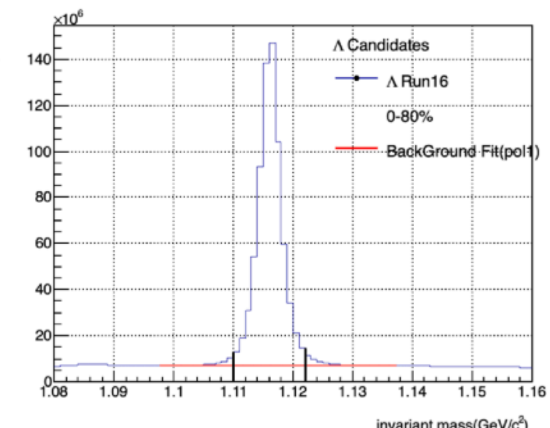
Reconstruction of Λ and Ξ

	Decay channel	Mass (from PDG 2018)
Λ (uds) $\bar{\Lambda}$	$\Lambda -> \pi^- + p$ $\bar{\Lambda} -> \pi^+ + \bar{p}$ (63.9%)	1.115683 (GeV/c^2)
$\Xi\ (dss)$ $\bar{\Xi}$	$\Xi -> \Lambda + \pi^+$ $\bar{\Xi} -> \bar{\Lambda} + \pi^-$ (99.87%)	1.32171 (GeV/c^2)

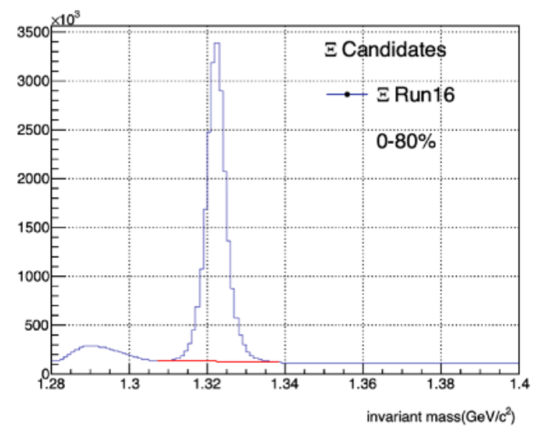
- KFParticle package was used.
  KFParticle is based on Kalman filter.
- Very good Purity for Λ(~88%) and Ξ(~90%).

Invariant mass

Λ



Ξ



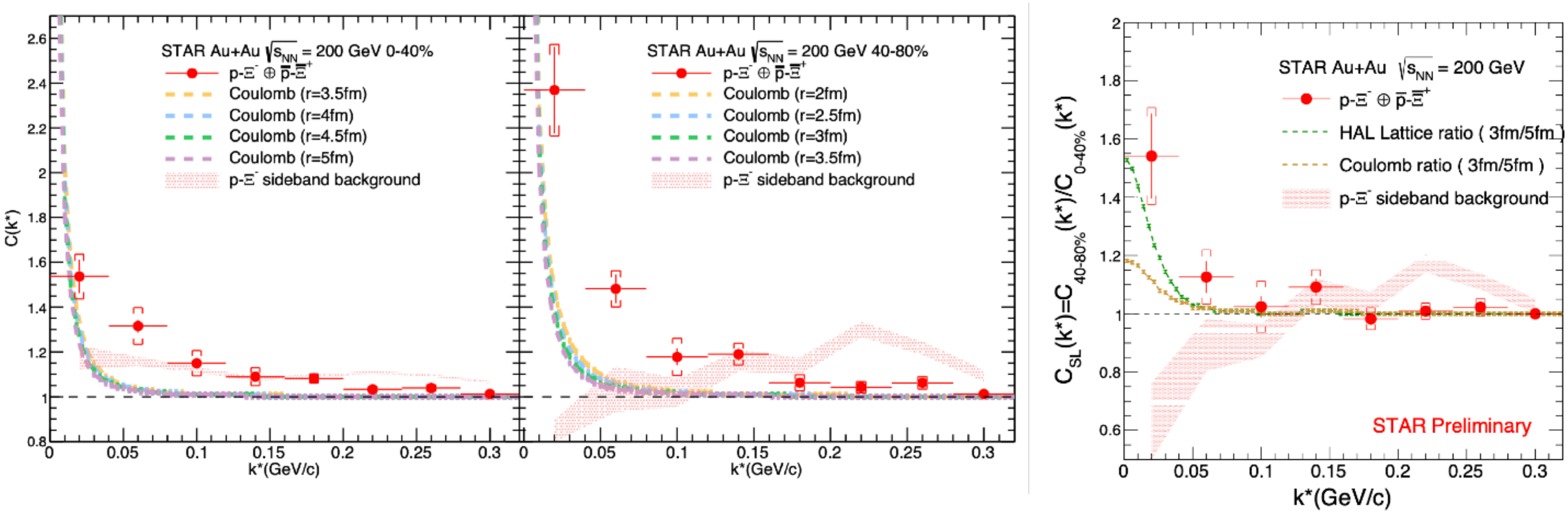
Daughter particle selection for Λ and Ξ

For pion
- $|\ n_{\sigma,\pi}\ | < 3$
- $-0.15 < \mathrm{Mass}^2 < 0.15\ (\mathrm{GeV}/c^2)^2$

For proton
- $|\ n_{\sigma,p}\ | < 3$
- $0.5 < \mathrm{Mass}^2 < 1.5\ (\mathrm{GeV}/c^2)^2$

For Λ and Ξ
- $p_T \geq 0.4\ \mathrm{GeV}/c$
- $|y| < 1.0$

Studies of strong interactions



Strong and Coulomb

Final State Interactions.

$C(k^*)$ ratio of small to large systems,

$$C_{SL}(k^*) = \frac{C(k^*)_{40-80\%}}{C(k^*)_{0-40\%}}$$

$C_{SL}(k^*)$ is more sensitive to strong interaction with largely canceled Coulomb interaction[1].

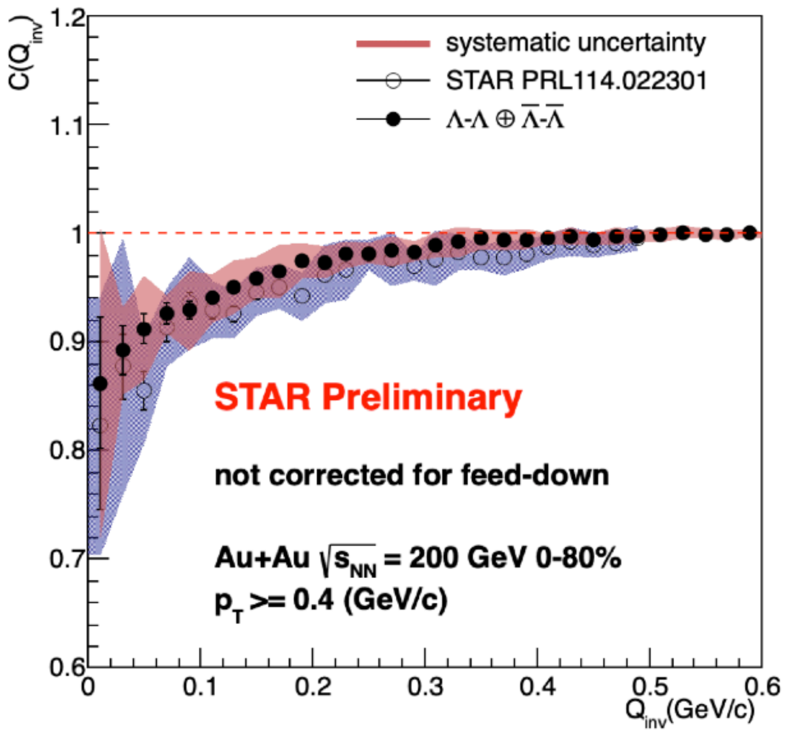
- Below k^* = 0.1 GeV/c, the signal is enhanced beyond the Coulomb interaction and background.
- Similar to lattice QCD calculation [2] which suggests an attractive strong interaction between p and Ξ^-.

[1] K. Morita et al, Phys. Rev. C94(2016) 031901
[2] T.Hatsuda Nuclear Physics A 967 (2017) 856–859

Search for bound states?

Hyperon-Hyperon (Y-Y) and Hyperon-Nucleon (Y-N) interactions: important to study exotic hadronic states (e.g. H-dibaryon) and to understand the EoS of neutron stars.

Do bound state of Y-N and Y-Y (S=-2) exist ?



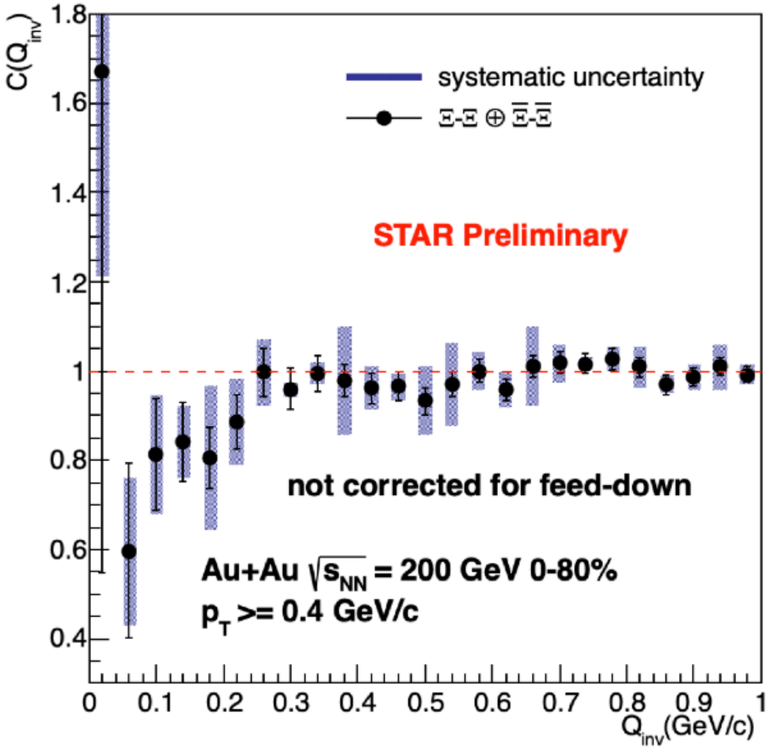
New high statistics data ~4 times larger than before

Not corrected for feed-down.

Anti-correlation seen

Possible to determine possible bound state

Search for bound states?



[1] J. Haidenbauer et al., Eur. Phys. J. A 51: 17 (2015)

[2] T,Doi et al., EPJ Web Conf. 175 (2018) 05009

First measurement of Ξ-Ξ correlation in Au+Au collisions.

Lattice QCD/chiral EFT calculations indicate an attractive interaction, but not strong enough to form a bound state [1,2].

The result shows anti-correlation at $2k^* < 0.25$ GeV/c.

Combination of quantum statistics, strong interaction, and Coulomb interaction.

Feed-down and Coulomb effects need to be evaluated for further discussion.

More events will be taken in 2023 and 2025

Summary

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- Femtoscopic source parameters determined for a wide range of collisions energy;

- Non-monotonic behavior of $R(\sqrt{s_{NN}})$ seen in three directions;
- New data for $\sqrt{s_{NN}}$ = 4.5 GeV follow trend observed for low collision energies;
- Data for $\sqrt{s_{NN}}$ = 7.7 GeV and higher collision energies indicated that the system evolves faster in the reaction plane;
- System created for $\sqrt{s_{NN}}$ = 4.5 GeV is round-shaped ($R_{side} \simeq R_{long}$);
- Visible peaks in around $\sqrt{s_{NN}} \simeq 20$ GeV at R_{out}/R_{side} and $R^2_{out} - R^2_{side}$ consistent with prediction of QGP transition threshold;
- vHLEE + UrQMD verifies sensitivity of HBT measurements to changes in EOS;

- A clear energy dependence of source sizes for particles combinations other than pions;
- A clear signal of emission asymmetry between nonidentical particle combinations;
- Heavier particles directed towards the edge of the source or freeze-out earlier.

Studies of strong interactions possible

Thank you for Your attention

Backup slides