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

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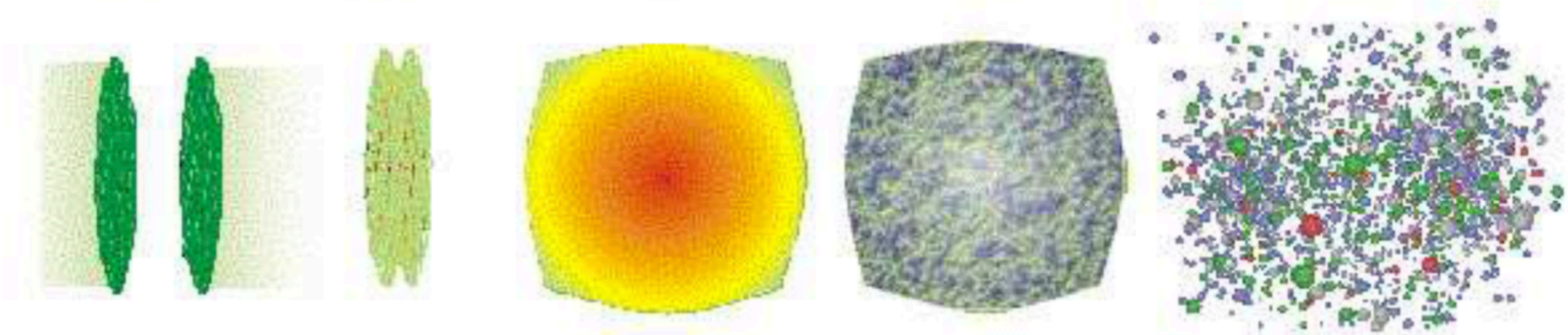
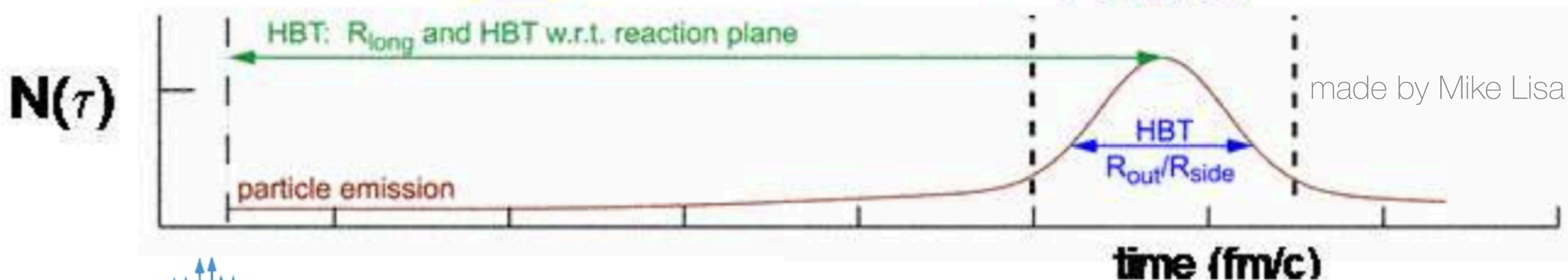
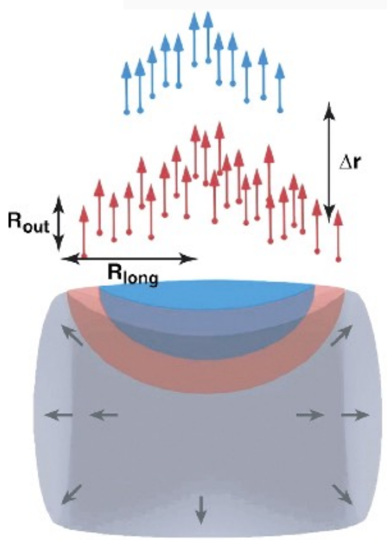
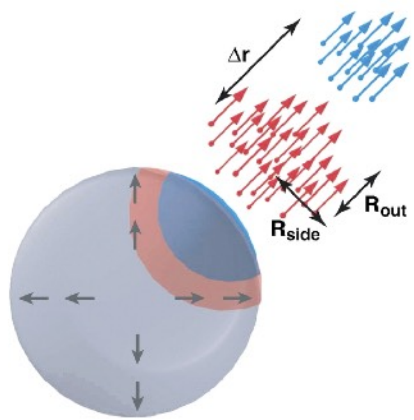
# Introduction

# Heavy-Ion collision and **HBT** method






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

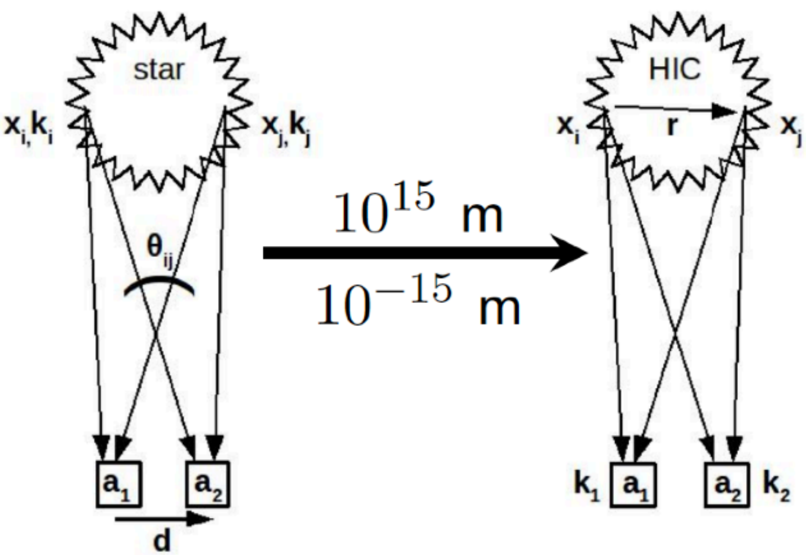
Lisa MA, et al. 2005.
Annu. Rev. Nucl. Part. Sci. 55:357–402

**Homogeneity region**

# Correlation **femtoscopy**


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

**Impossible to measure directly!**



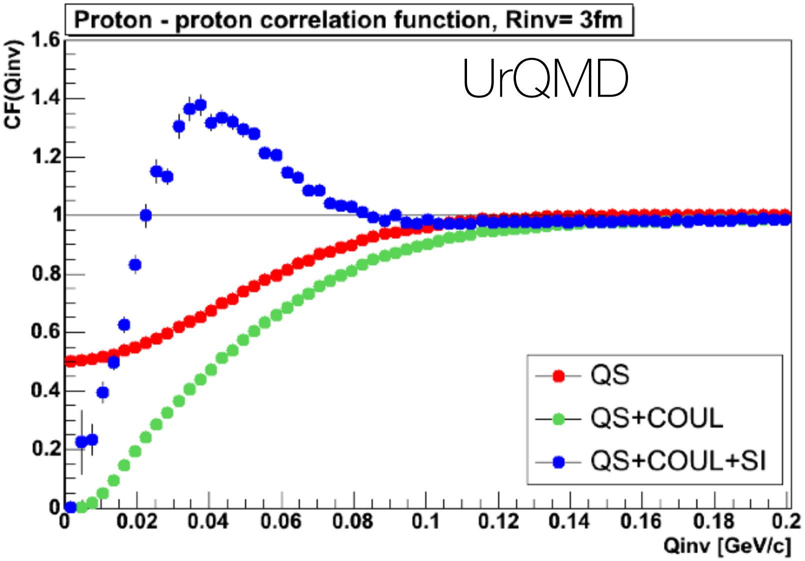

Femtoscopy (**HIC**) inspired by **H**anbury **B**rown and **T**wiss interferometry method (**Astronomy**)

**but!**

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

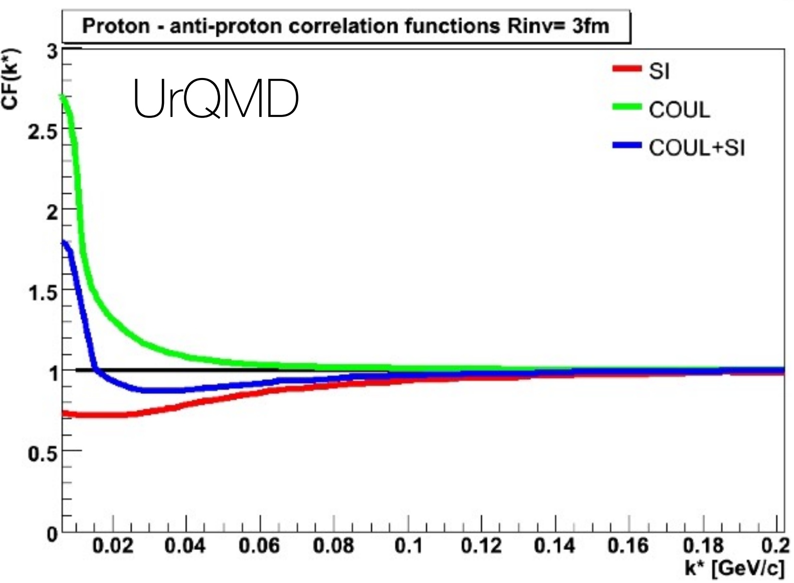
Hanbury Brown, R.; Twiss,
Nature 178, 1046–1048 (1956)

# Two-particle correlations




**Identical** pairs:

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




**Non-identical** pairs:

- Final State Interactions- **FSI:** Coulomb, Strong

$x_1, x_2$ - 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:

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

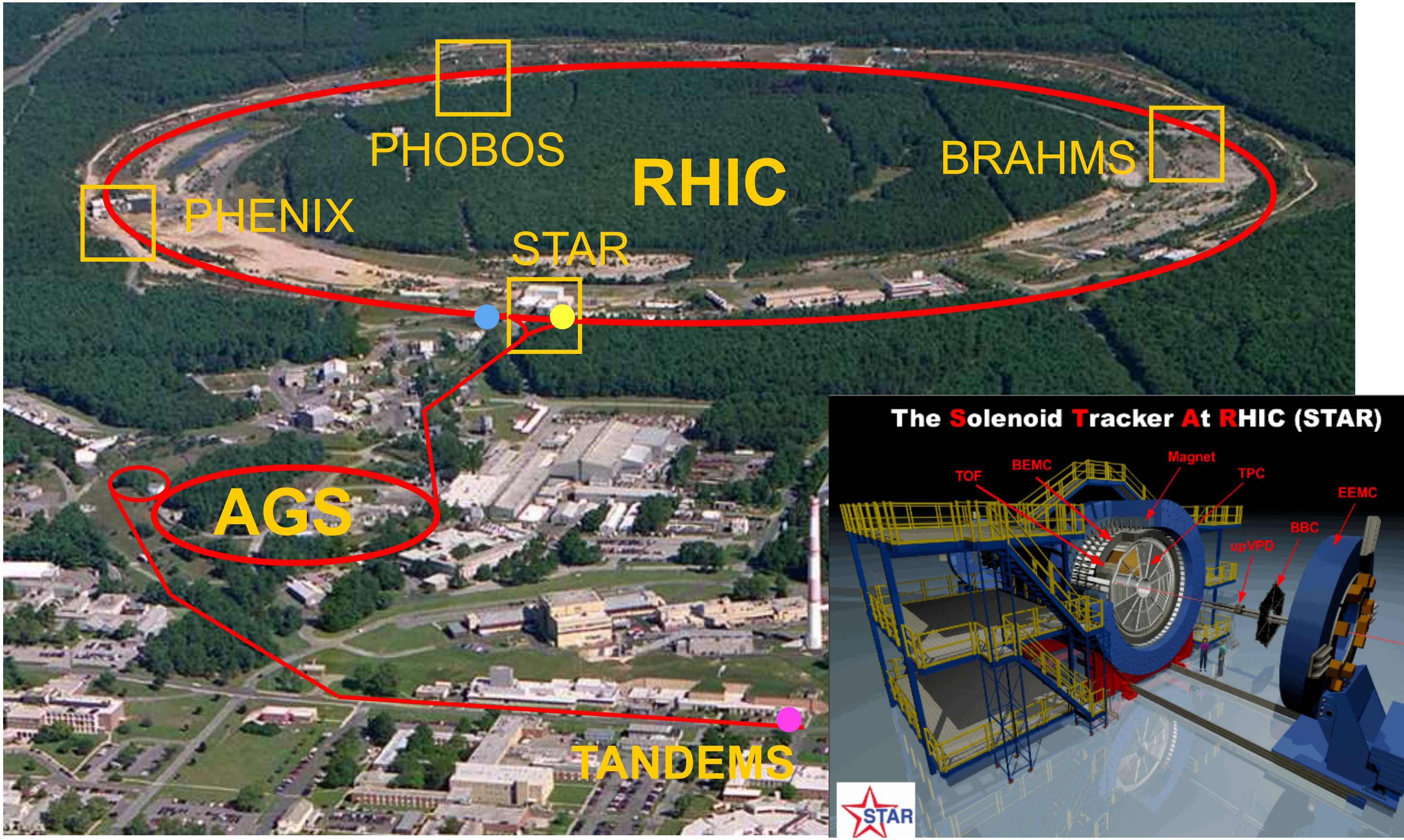
$$P_2(p_1,p_2) = E_1E_2\frac{dN}{d^3p_1d^3p_2}$$

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

The correlation function:

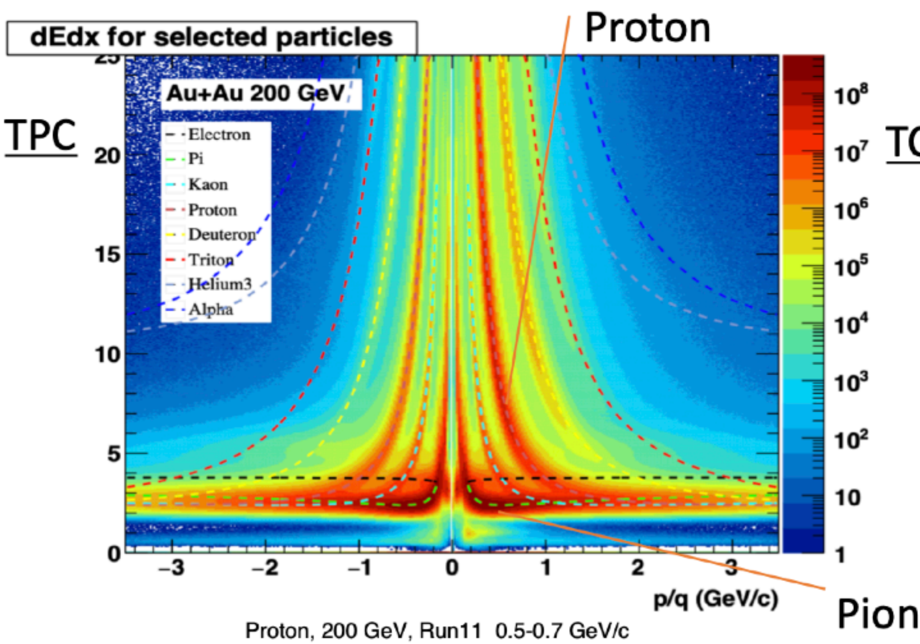
$$C(p_1,p_2) = \frac{P_2(p_1,p_2)}{P_1(p_1)P_1(p_2)}$$

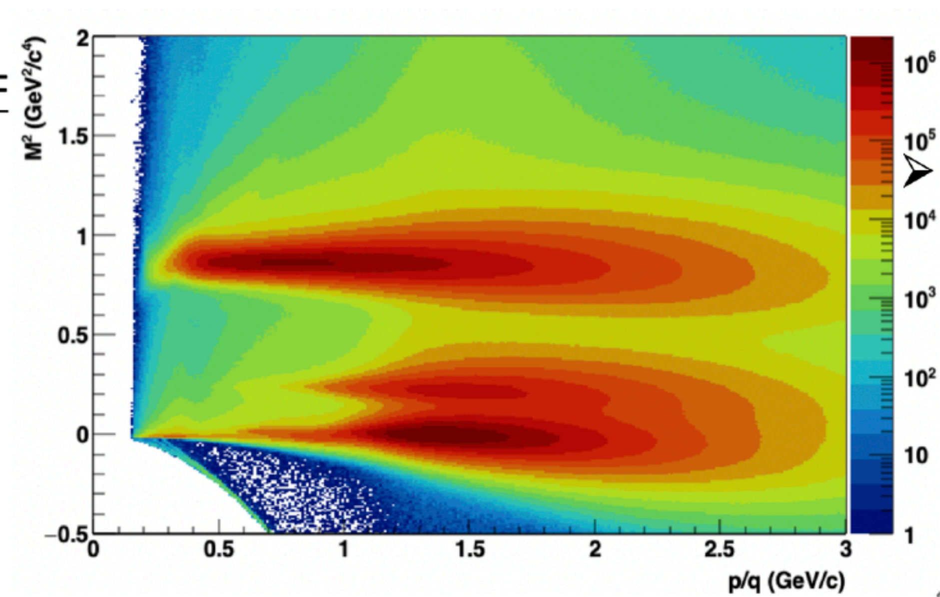
# Relativistic Heavy Ion Collider (**RHIC**)
# Brookhaven National Laboratory (**BNL**), Upton



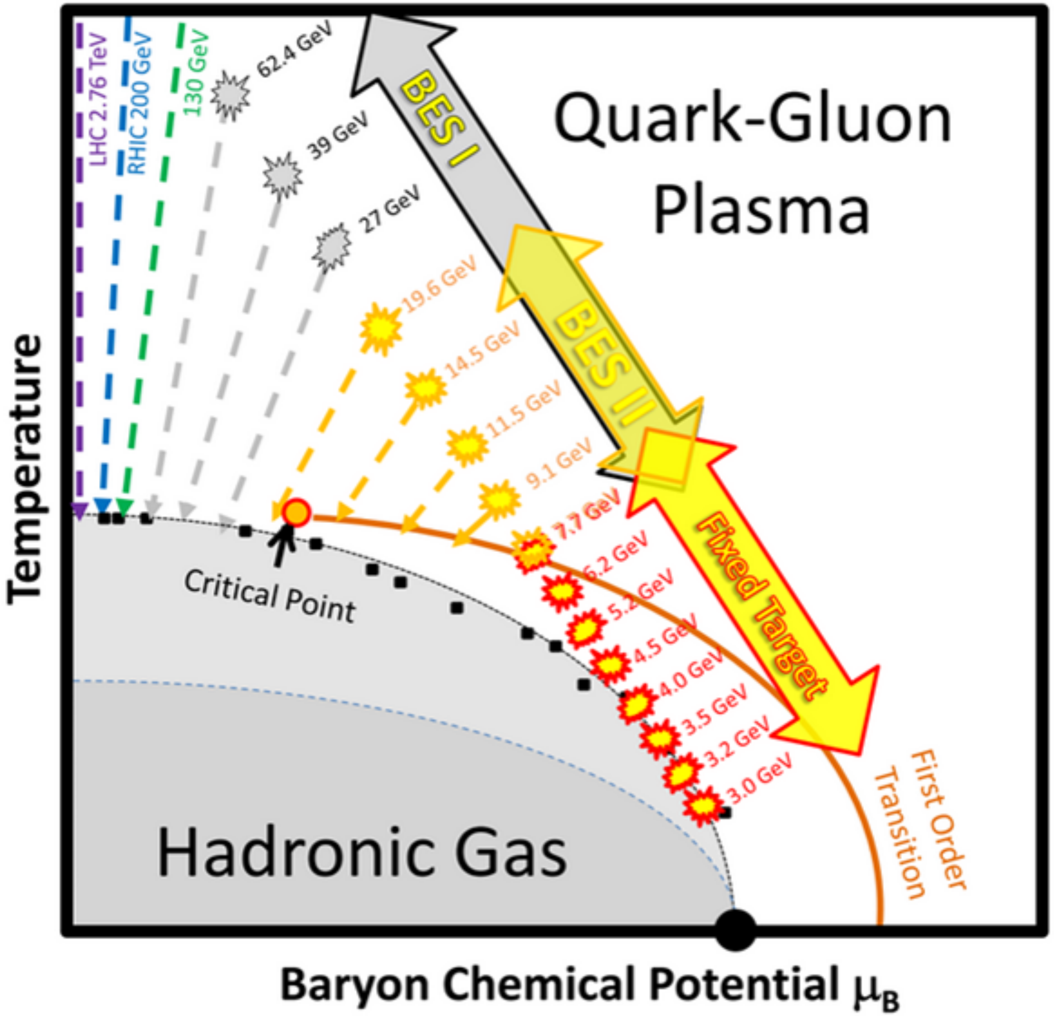
# Particle Identification

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



# 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

**B**eam **E**nergy **S**can

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

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

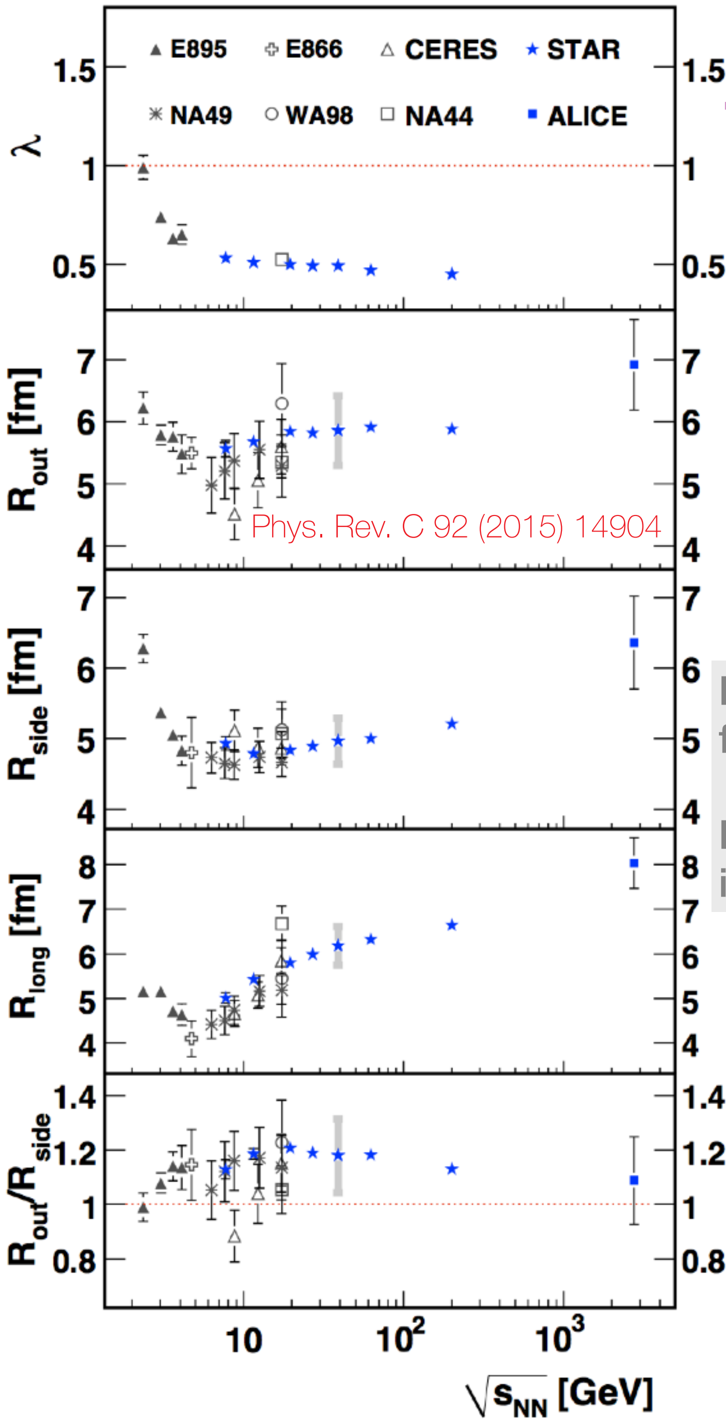
**F**ixed-**T**arget Program

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

High baryon density regime with $\mu_B = 420\text{-}720$ MeV

# Results

# Identical pion femtoscopy

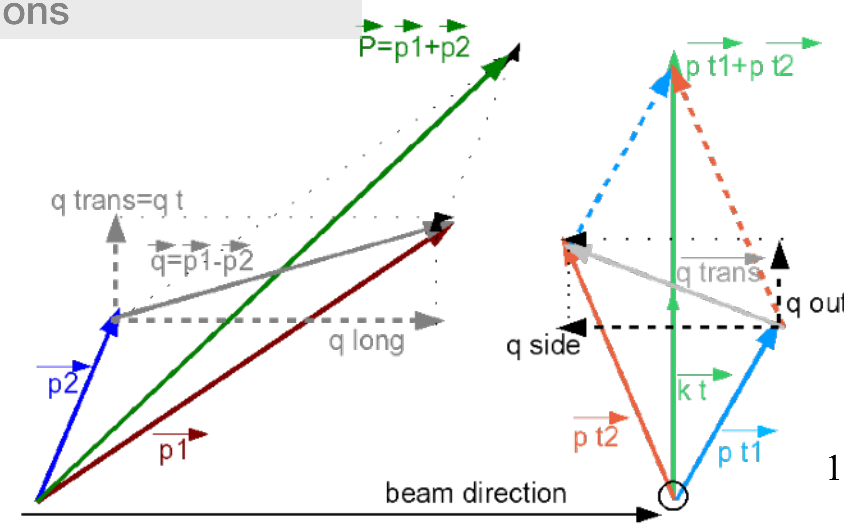



- → $R_{side}$ spatial source evolution in the transverse direction
- → $R_{out}$ related to spatial and time components
- → $R_{out}/R_{side}$ signature of phase transition
- → $R_{out}^2 - R_{side}^2 = \Delta\tau^2 \beta_t^2$; $\Delta\tau$ – emission time
- → $R_{long}$ temperature of kinetic freeze-out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

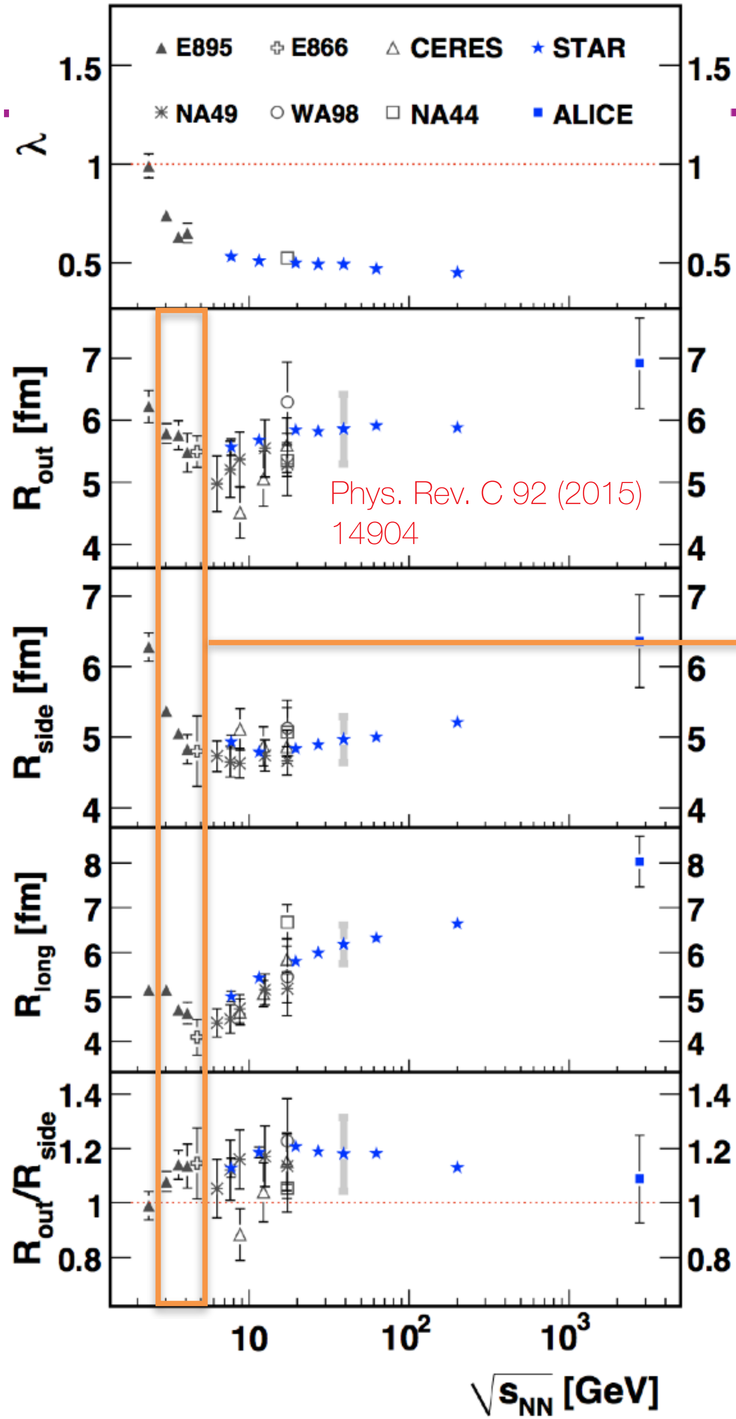
$$C(\vec{q}) = (1-\lambda) + K_{\mathrm{Coul}}(q_{\mathrm{inv}})\lambda$$
$$\times \exp\left(-q_o^2R_o^2 - q_s^2R_s^2 - q_l^2R_l^2 - 2q_oq_sR_{os}^2 - 2q_oq_lR_{ol}^2\right)$$

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

**Non-monotonic behavior seen in three directions**



# Identical pion femtoscopy

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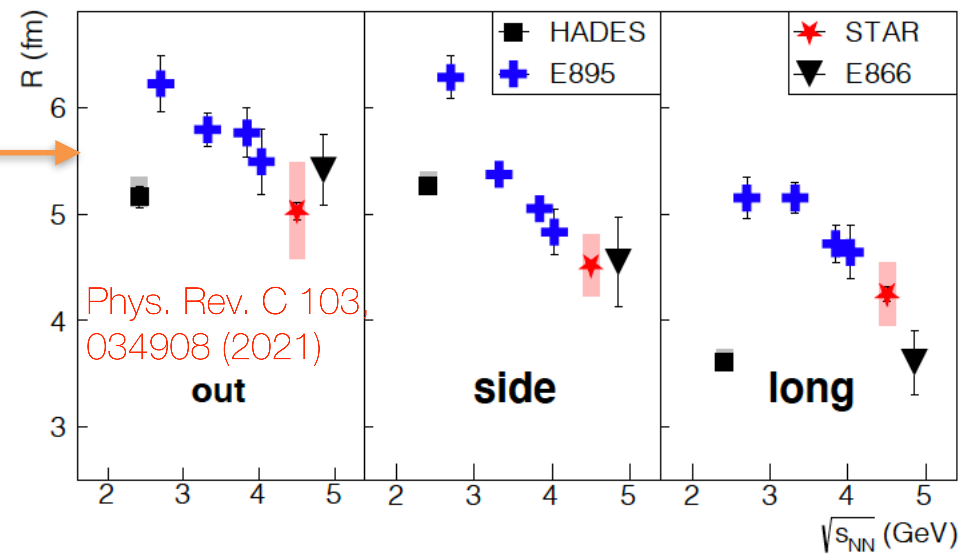
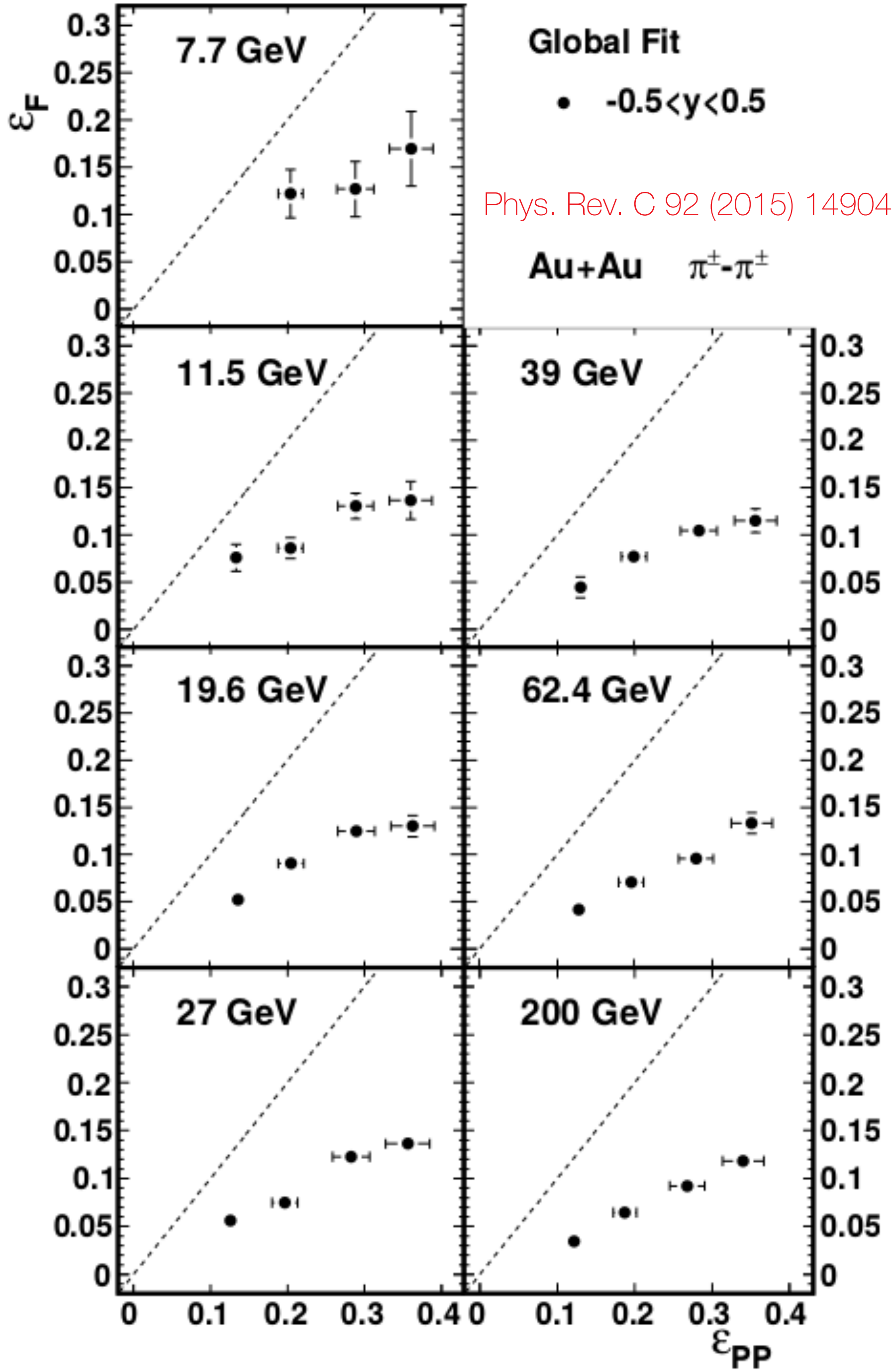



**New data from $\sqrt{s_{NN}}$ = 4.5 GeV follow trend observed for low collision energies**

# Identical pion femtoscopy

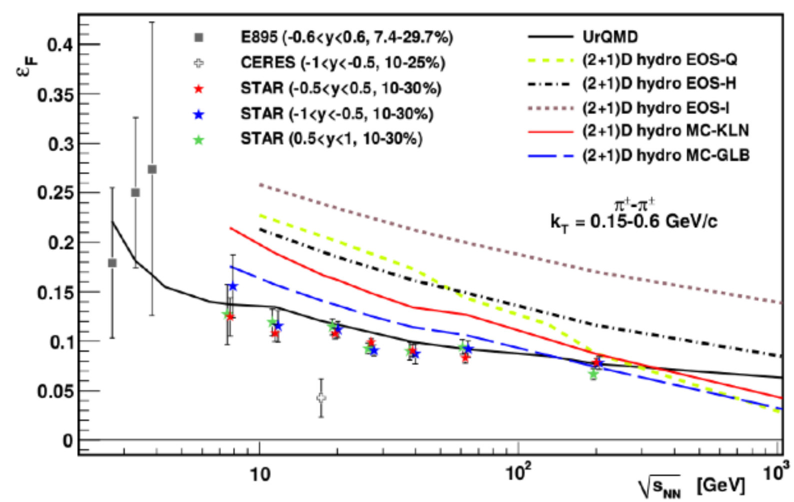



$$\varepsilon_{PP} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_x^2 + \sigma_y^2}. \qquad \varepsilon_F = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} \approx 2\frac{R_{s,2}^2}{R_{s,0}^2}$$

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

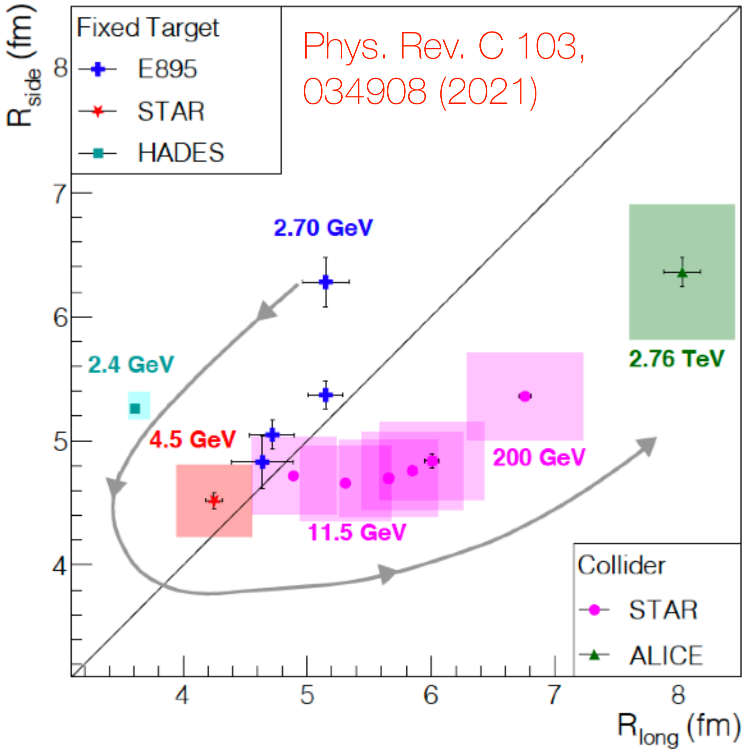
$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2\sum_{n=2,4,6\ldots} R_{\mu,n}^2 \cos(n\Phi) \qquad (\mu = o, s, l, ol)$$

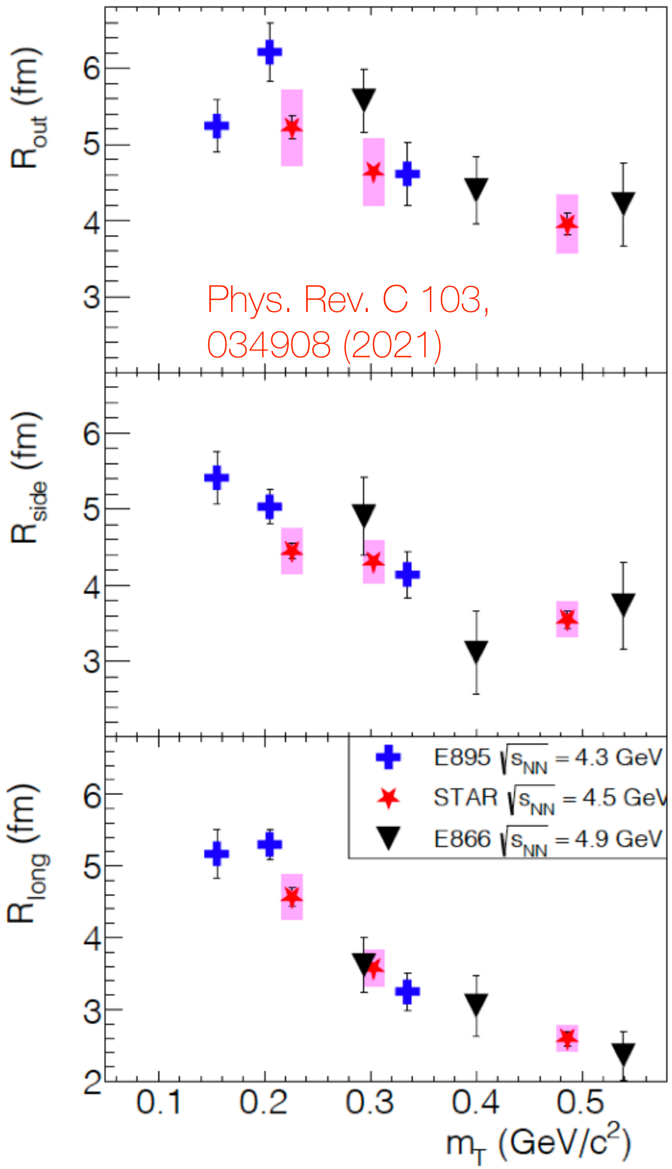
$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2\sum_{n=2,4,6\ldots} R_{\mu,n}^2 \sin(n\Phi) \qquad (\mu = os)$$




System evolves faster in the reaction plane

# How to measure a phase transition?




Clear evolution in the freeze-out shape indicated

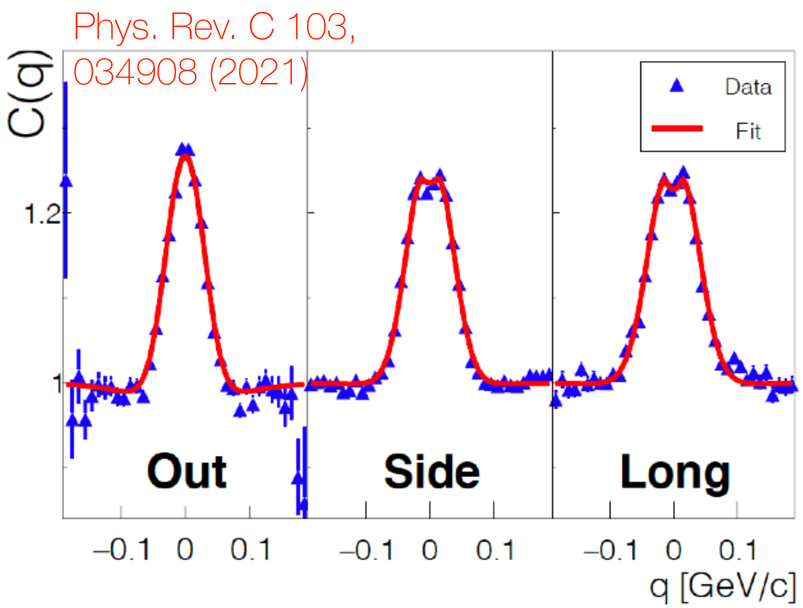
Lower energies: system more oblate ($R_{side} > R_{long}$)

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?

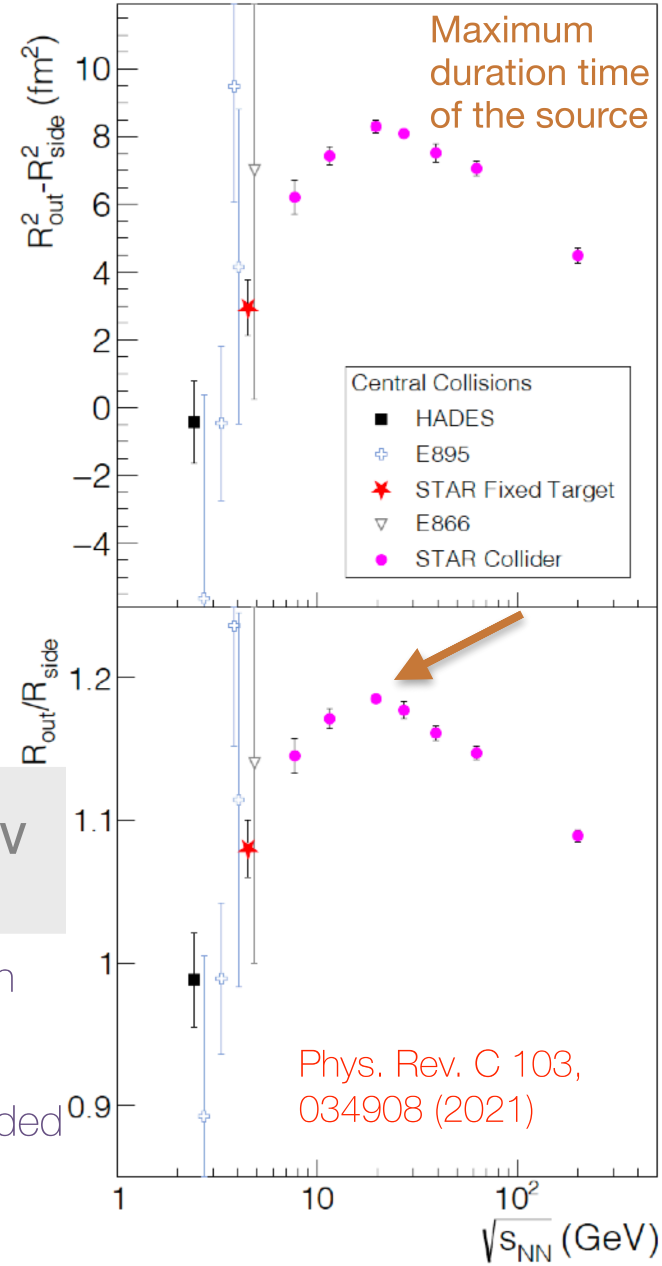



$$R_{out}^2 - R_{side}^2 = \beta_t^2 \Delta\tau^2$$

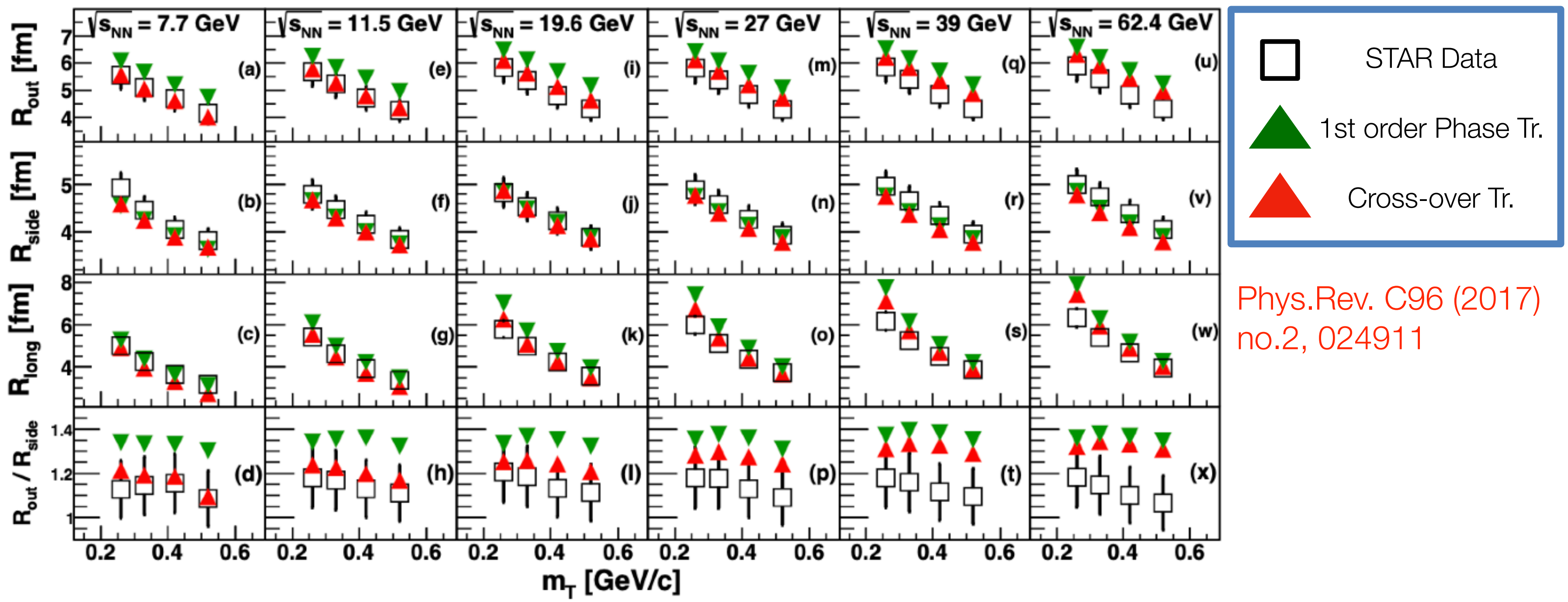
**Visible peak in $\frac{R_{out}}{R_{side}}(\sqrt{s_{NN}})$ near the $\sqrt{s_{NN}} \simeq 20$ GeV**

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

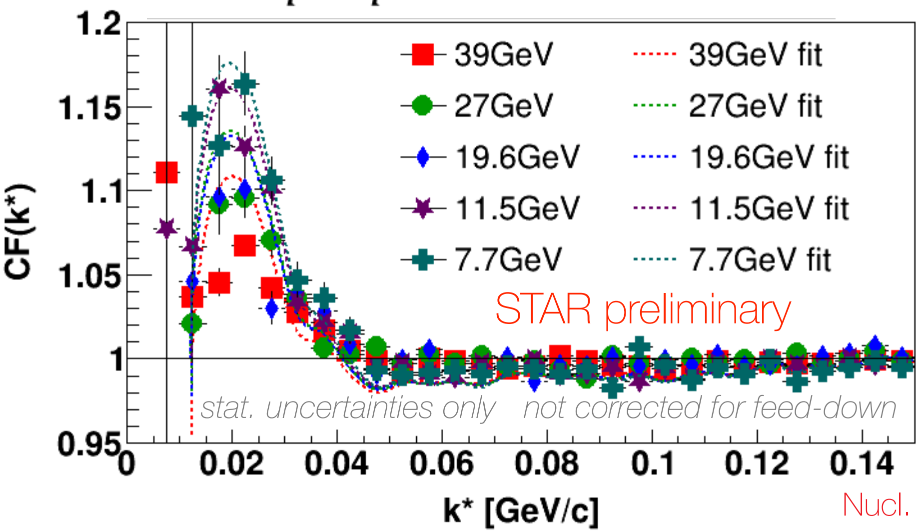
**vHLEE+UrQMD model verify sensitivity of HBT measurements to the first-order phase transition**

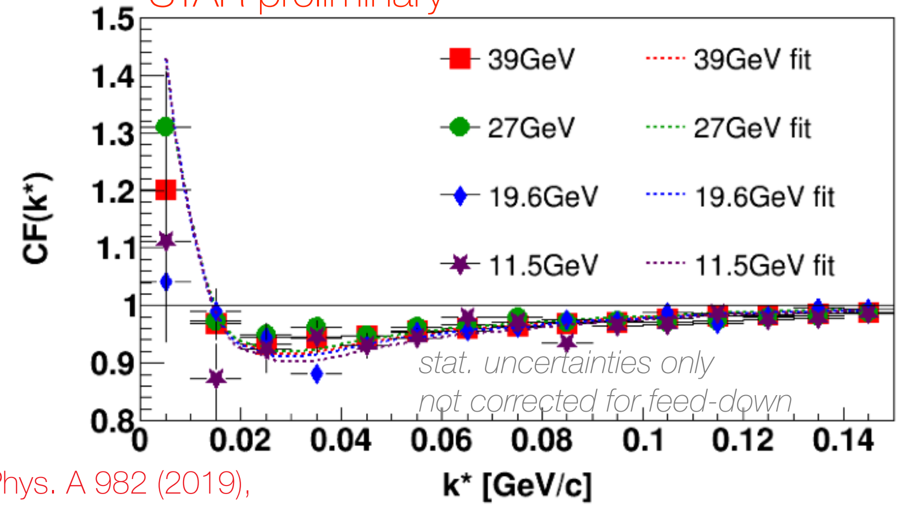
HadronGas + Bag Model → $1^{st}$ order PT

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

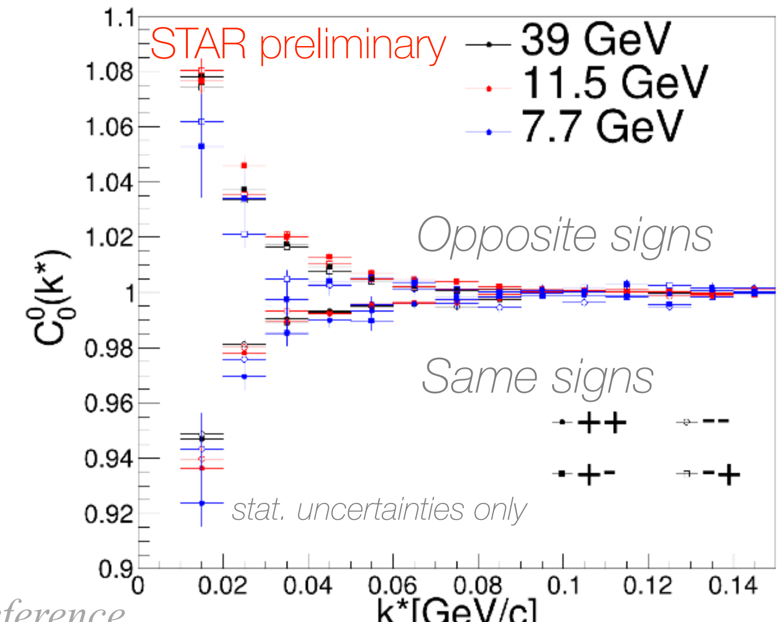



Nucl. Phys. A 982 (2019), 359-362

| 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**



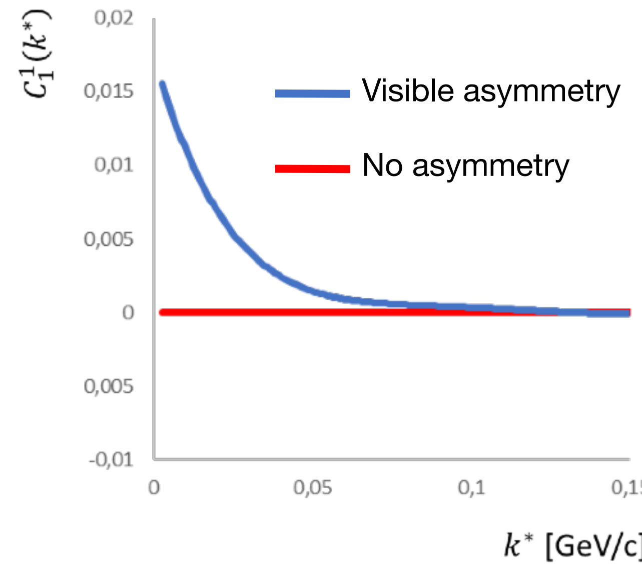

*k* - momentum of the first particle in the Pair Rest Frame reference*

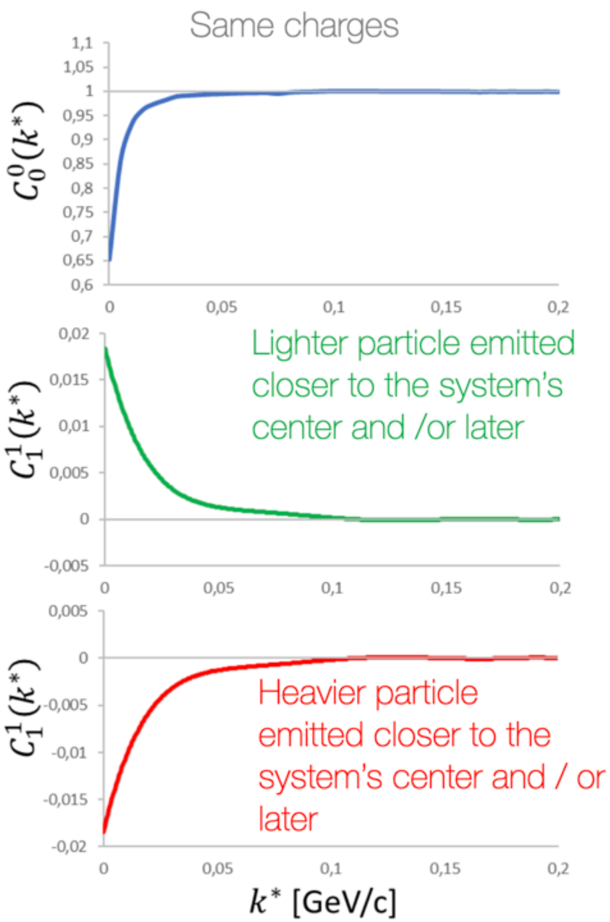
# Non-identical particle correlations - introduction

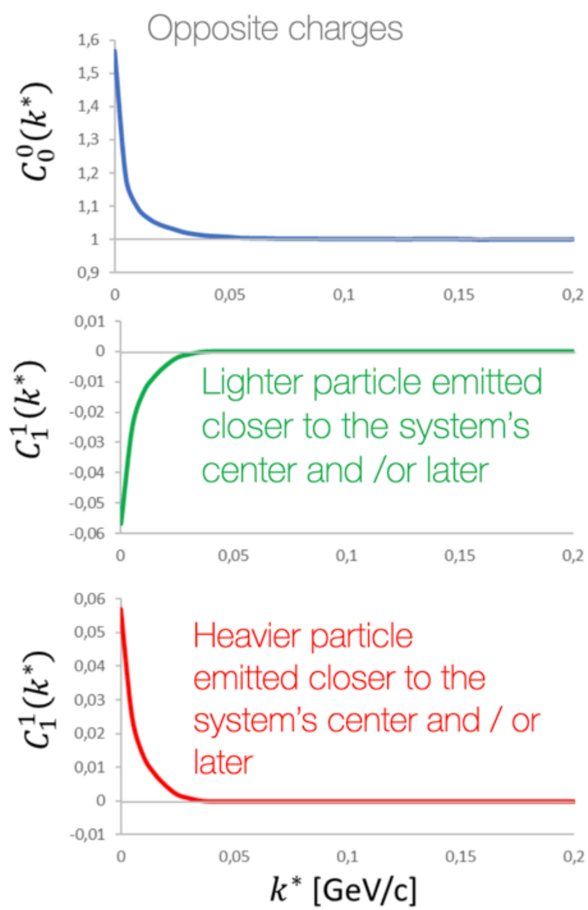
$C(\mathbf{q}) = \sum_{l,m} C_l^m(q) Y_l^m(\theta,\phi)$ $\qquad$ $C_l^m(q) = \int_\Omega C(q,\theta,\phi) Y_l^m(\theta,\phi) d\Omega$

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

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





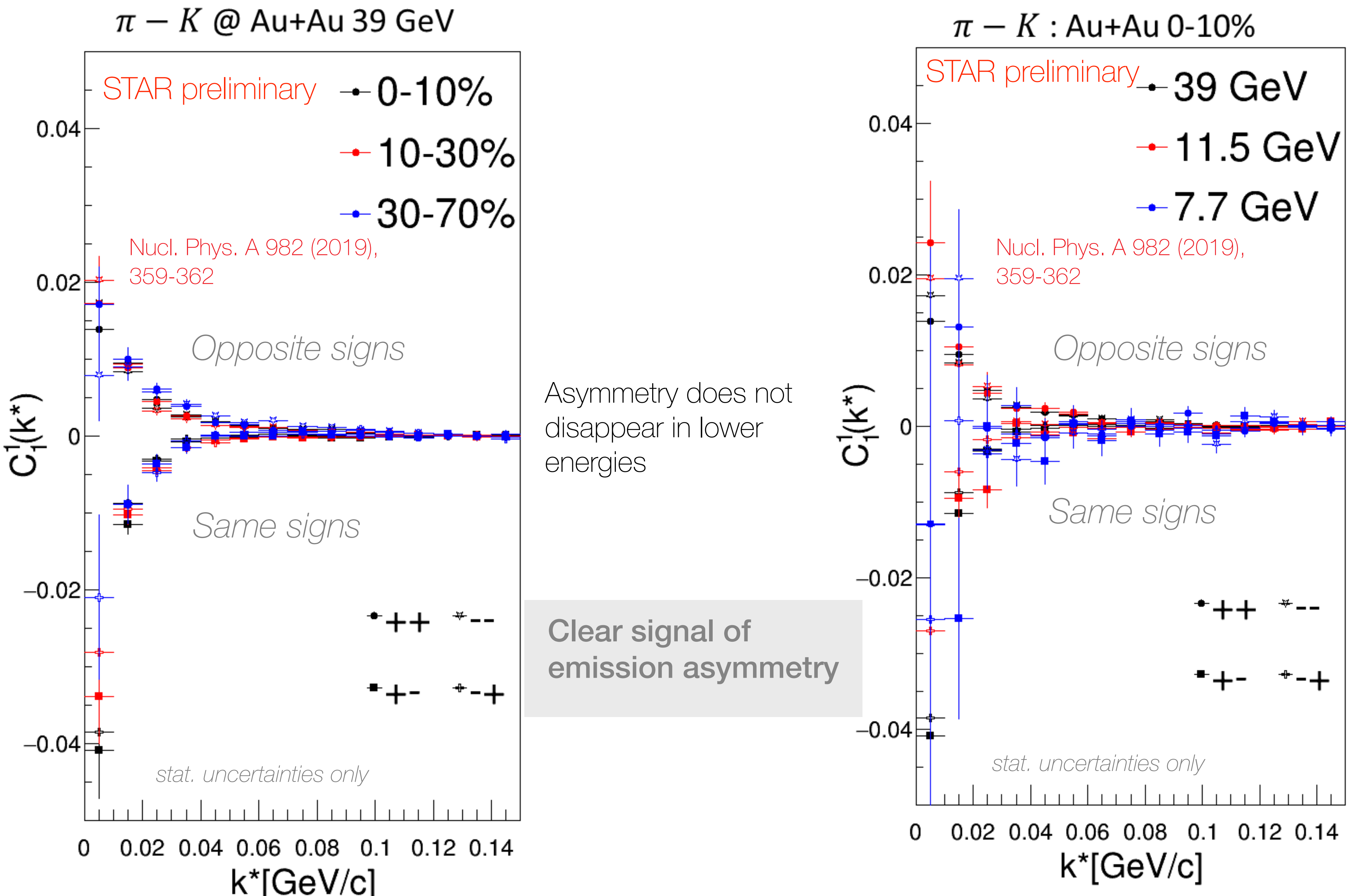
P. Danielewicz and S.Pratt. Phys. Lett. B618: 60 2005

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



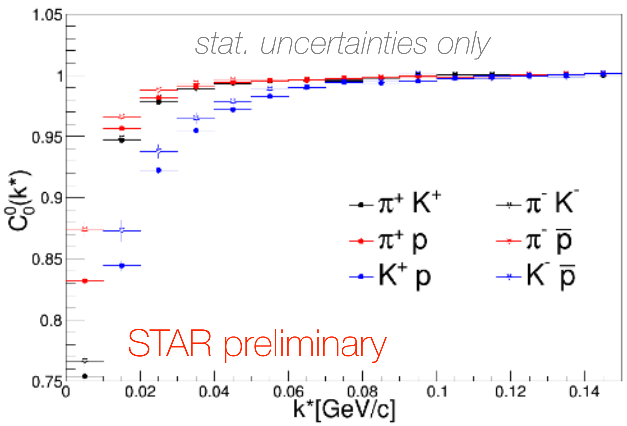

Asymmetry does not disappear in lower energies

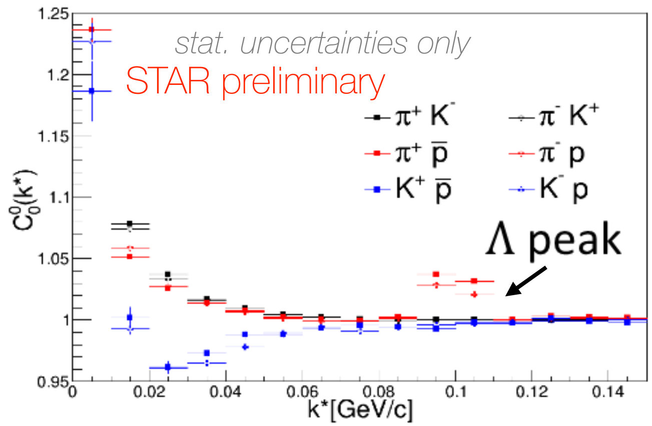
**Clear signal of emission asymmetry**

# Source dynamics: **system** dependence

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

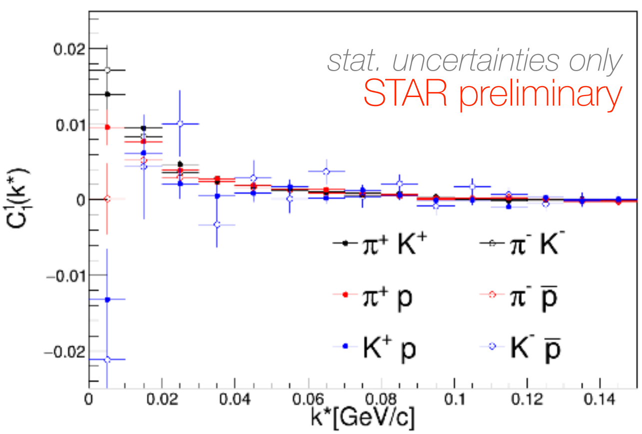
Unlike-sign 0-10% @ Au+Au 39 GeV

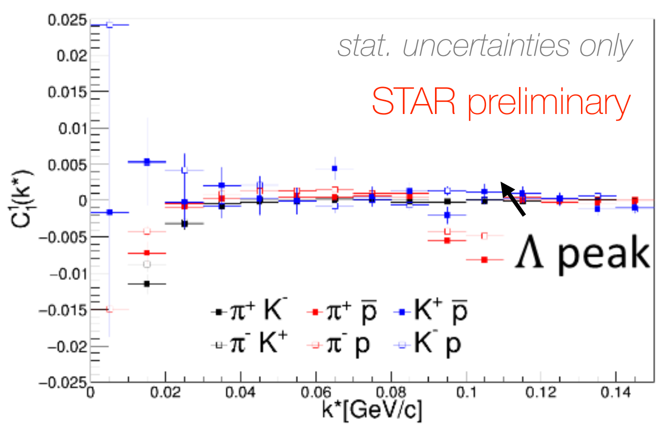



Determined by **Coulomb** Interactions

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



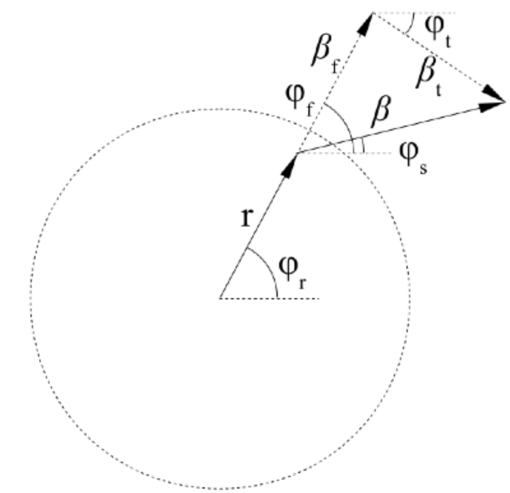




Nucl. Phys. A 982 (2019), 359-362

**Heavier particles directed towards edge of the source.**

**Heavier particles freeze-out earlier**

Phys. Rev. C81:064906 2010

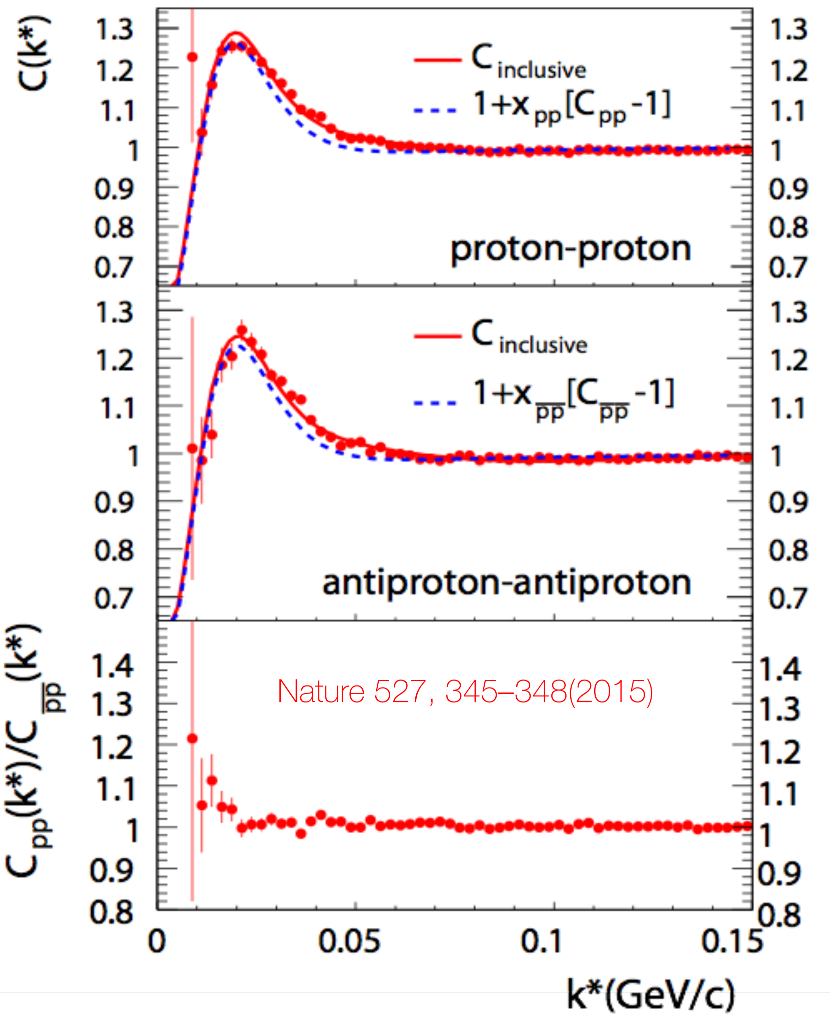


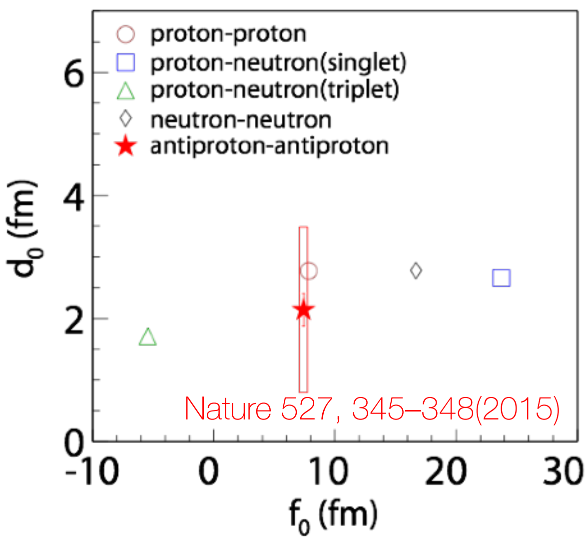

$$\langle x_{out} \rangle = \frac{\langle r\beta_f \rangle}{\left\langle \sqrt{\beta_t^2 + \beta_f^2} \right\rangle} = \frac{r_0 \beta_0 \beta}{\beta_0^2 + T/m_t},$$

$\beta_f$ - 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 $\sigma_e$

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

- $f_0$ 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.

**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

# Strange Baryon Correlations (including p-Ω)

Binding energy **$E_{bin}$** [MeV]

Scattering length **$a_0$** [fm]

Effective range **$r_{eff}$** [fm]

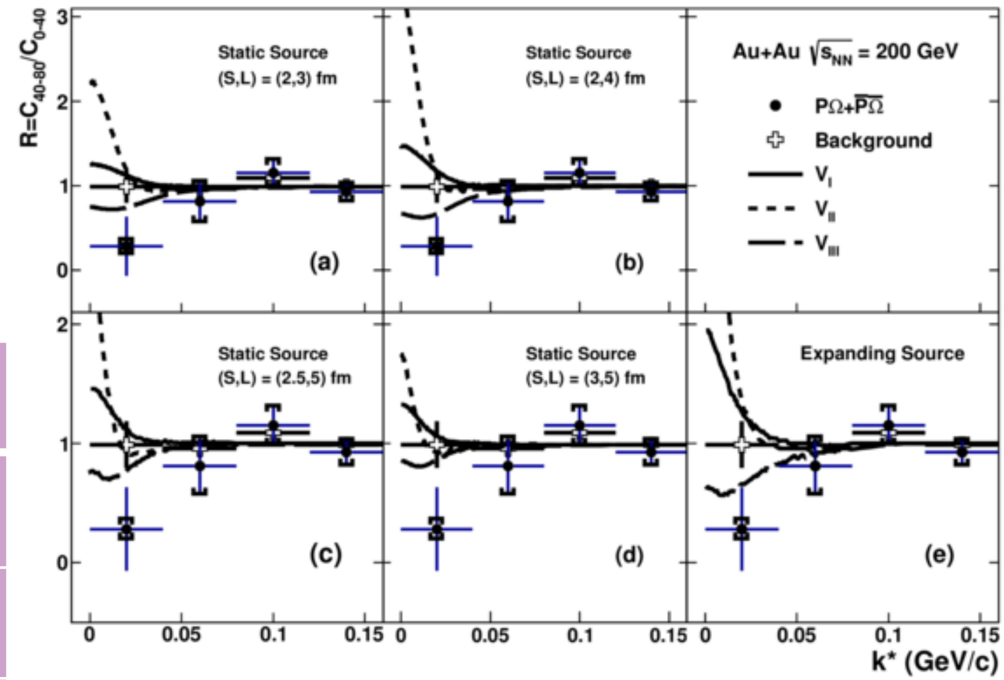
for 3 scenarios:

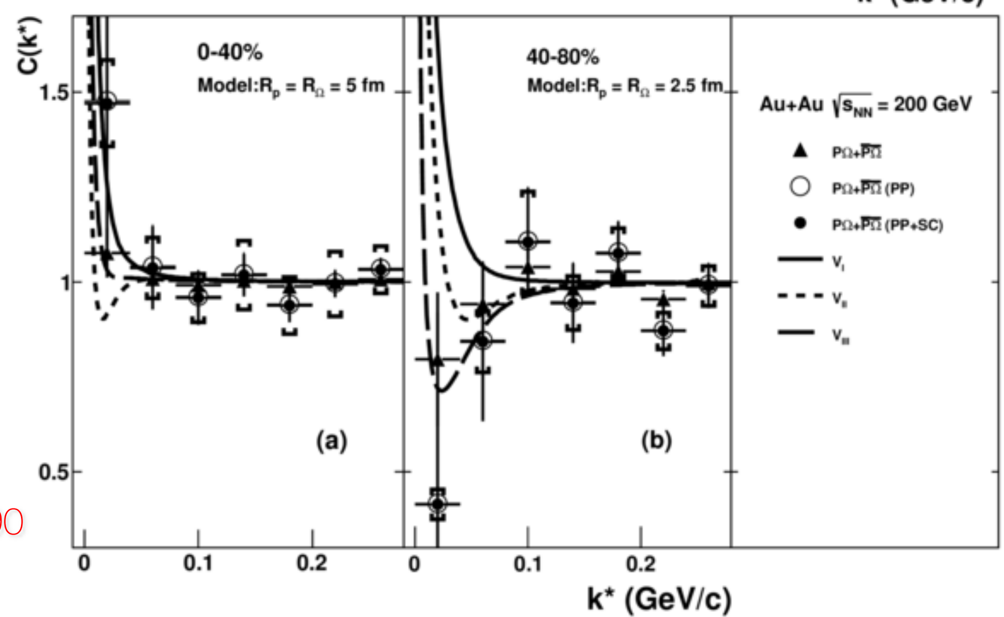
K. Morita et al. Phys. Rev. C 94, 031901 (2016)

| | $V_1$ | $V_2$ | $V_3$ |
|---|---|---|---|
| **$E_{bin}$ [MeV]** | - | 6.3 | 26.9 |
| **$a_0$ [MeV]** | -1.12 | 5.79 | 1.29 |
| **$r_{eff}$ [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

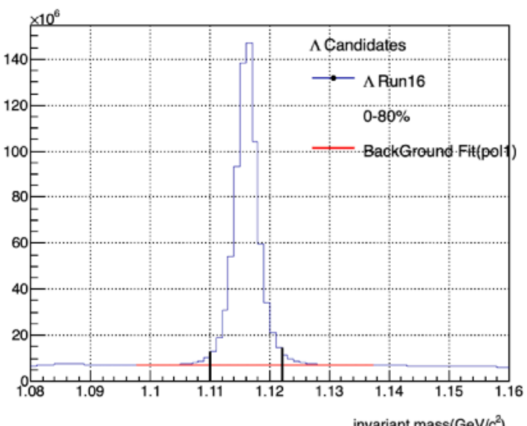
## Reconstruction of Λ and Ξ

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

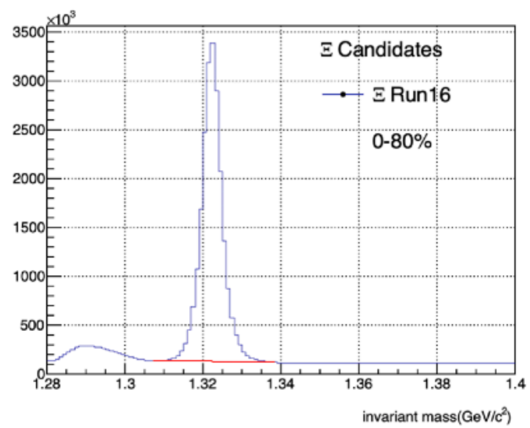
- KFParticle package was used.
  KFParticle is based on Kalman filter.
- Very good Purity for Λ(~88%) and Ξ(~90%).

Invariant mass

Λ




Ξ



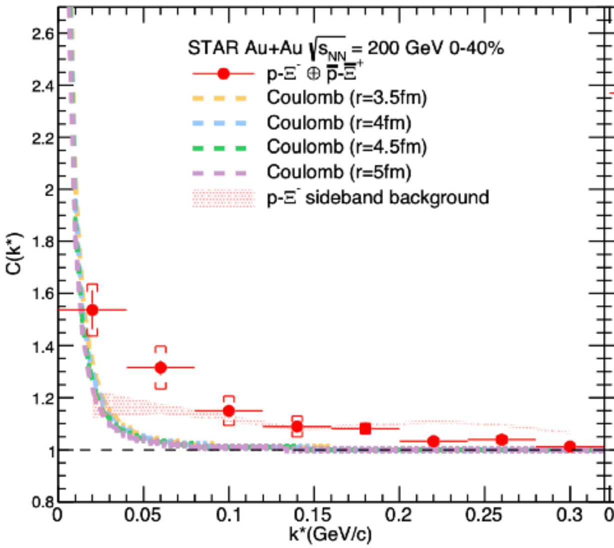

Daughter particle selection for Λ and Ξ

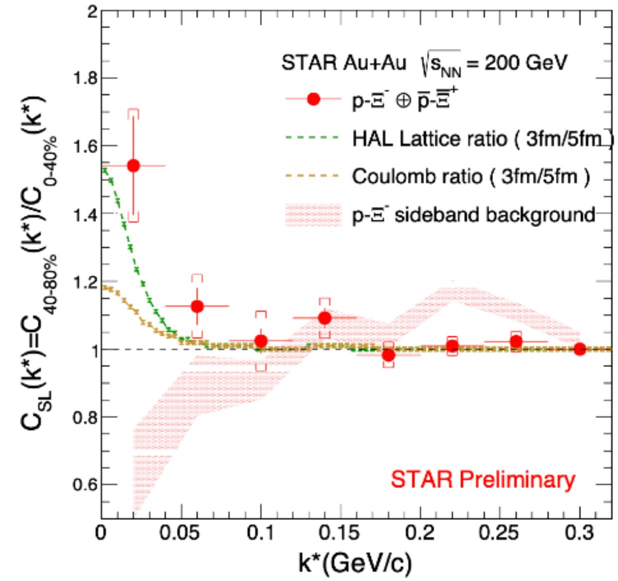
For pion
- $|n_{\sigma,\pi}| < 3$
- $-0.15 < \mathrm{Mass}^2 < 0.15\ (\mathrm{GeV}/c^2)^2$

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].

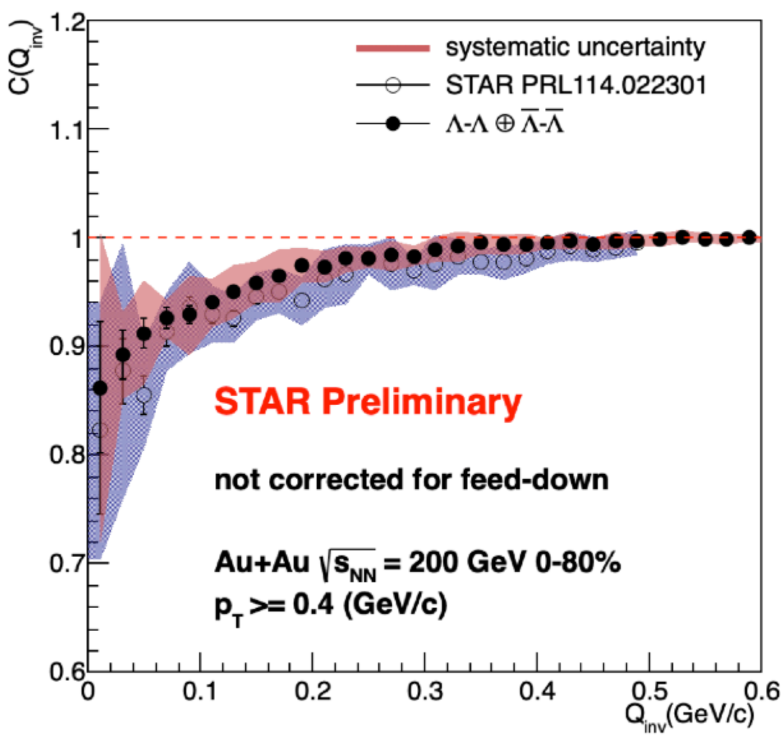
- Below $k^*$ = 0.1 GeV/c, the signal is enhanced beyond the Coulomb interaction and background.
- Similar to lattice QCD calculation [2] which suggests an attractive strong interaction between p and $\Xi^-$.


[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 ?



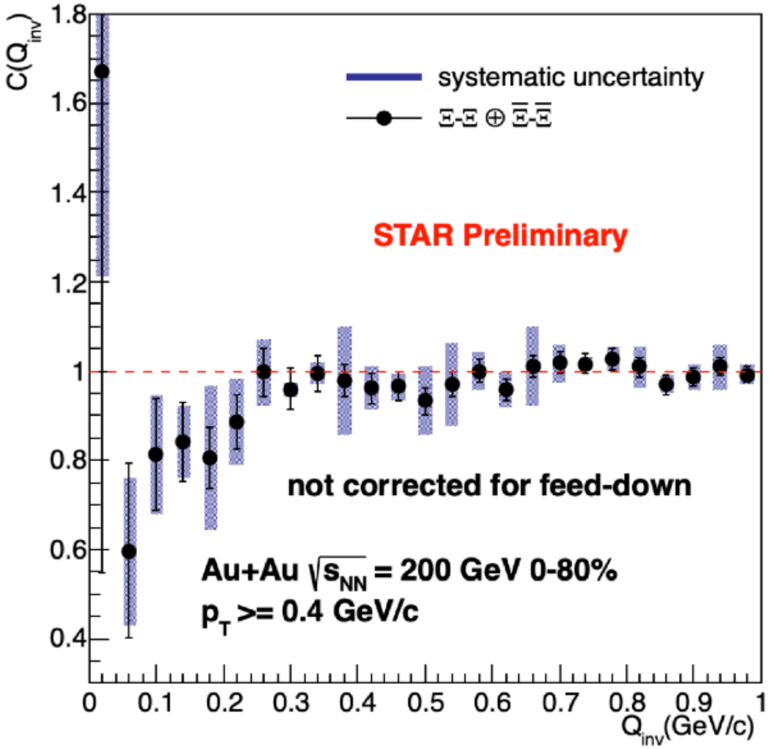

New high statistics data ~4 times larger than before

Not corrected for feed-down.

Anti-correlation seen

Possible to determine possible bound state

# Search for bound states?




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


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

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

# Summary

# Summary

- 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 $R_{out}^2 - R_{side}^2$ consistent with prediction of QGP transition threshold;
- vHLEE + UrQMD verify 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