Warsaw University of Technology

Geometry and Dynamics in Heavy-Ion Collisions Seen by the Femtoscopy in the STAR Experiment

Sebastian Siejka

for the STAR Collaboration

Warsaw University of Technology

Faculty of Physics

Quark Matter 2018

The 27th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions

Venice, Italy

13-19 May 2018

Outline

1) Tools – femtoscopy, correlation functions and spherical harmonics

2) How does the source geometry depend on centrality and energy of the collision.
   Is it consistent across various systems?

3) What are the source dynamics? Is there a species dependence in the source?

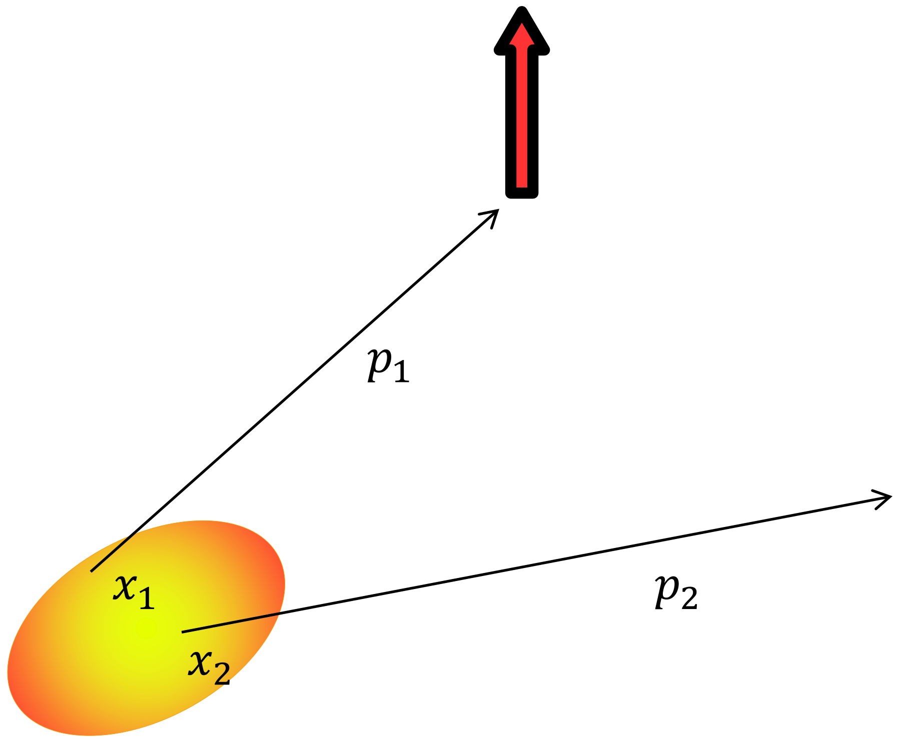
4) Summary and conclusions

Few Words About Femtoscopy

Few Words About Femtoscopy

Correlation function

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



Few Words About Femtoscopy

Single-particle distribution

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

Correlation function

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

S(x,p) - emission function: the distribution of source density probability of finding particle with x and p

Two-particle distribution

$$P_2(p_1,p_2) = E_1E_2\frac{dN}{d^3p_1d^3p_2} = \int d^4\,x_1S(x_1,p_1)d^4x_2S(x_2,p_2)\Phi(x_2,p_2 \mid x_1,p_1)$$

Φ – pair mutual interaction

Correlation function shows echo of emission function as seen through pair mutual interaction.

Types of Correlation Functions

Identical particle combination

- Quantum Statistics (QS)
- Final State Interactions:
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)

Non-identical particle combination

- Final State Interactions:
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)

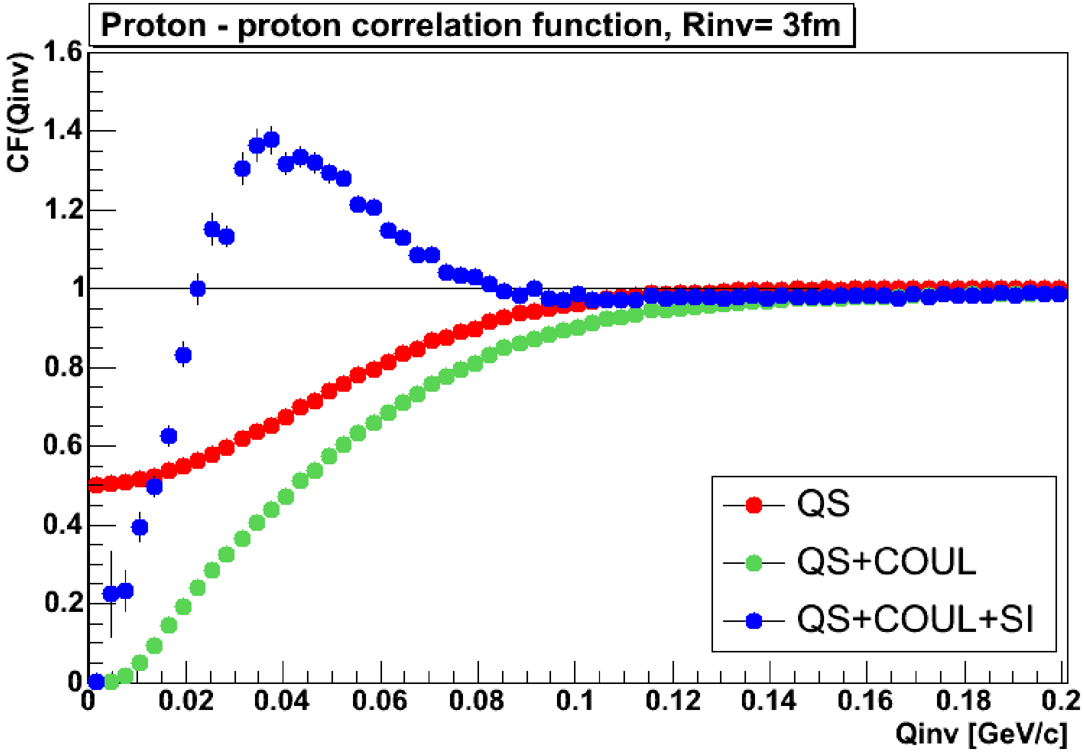
Types of Correlation Functions

Identical particle combination

- Quantum Statistics (QS)
- Final State Interactions:
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)

Non-identical particle combination

- Final State Interactions:
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)



H. Zbroszczyk, Studies of baryon-baryon correlations in relativistic nuclear collisions registered at the STAR experiment. PhD thesis, WUT, 2008.

UrQMD *Au+Au;* $R_{inv} = 3\,fm$

M. Bleicher et al.
J. Phys. G: Nucl. Part. Phys. 25, 1859-1896 (1999)

M. Gyulassy et al.
Phys. Rev. C20, 2267–2292 (1979)

H. D. Boal et al.
Rev. Mod. Phys. 62, 553–602 (1990)

S. E. Koonin et al.
Phys. Lett. B70, 43–47 (1977)

R. Lednický
Sov. J. Nucl. Phys 35, 770–788 (1982)

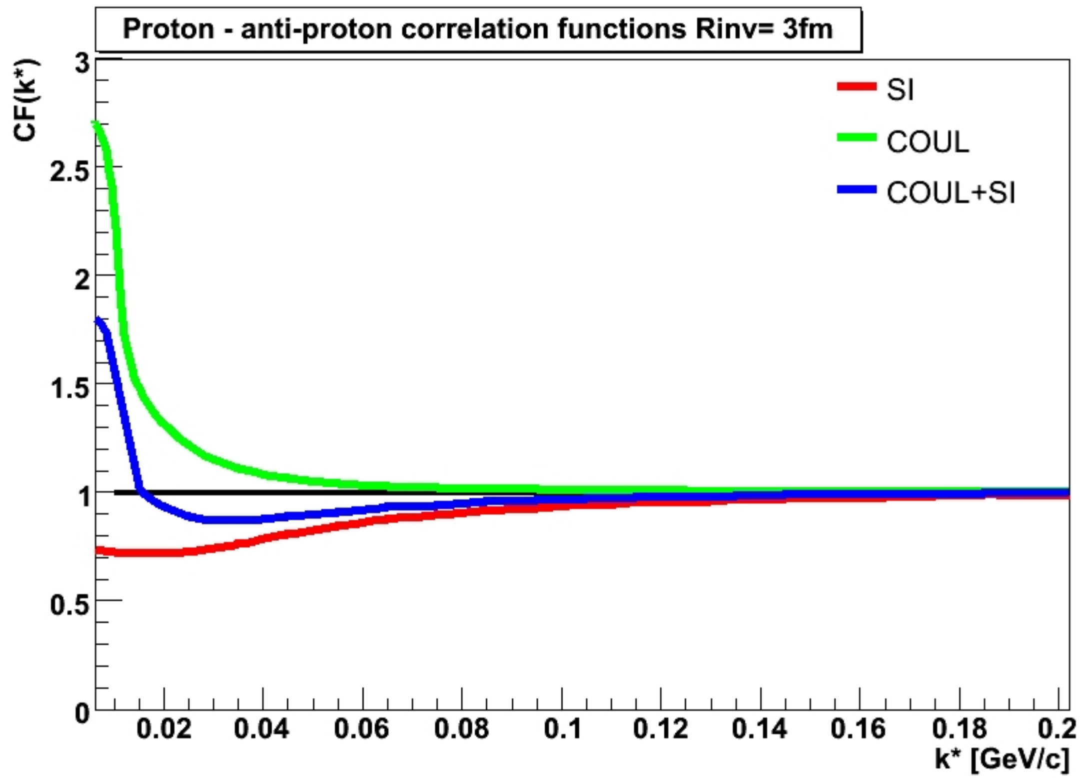
Types of Correlation Functions

Identical particle combination

- Quantum Statistics (QS)
- Final State Interactions:
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)

Non-identical particle combination

- Final State Interactions:
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)



H. Zbroszczyk, Studies of baryon-baryon correlations in relativistic nuclear collisions registered at the STAR experiment. PhD thesis, WUT, 2008.

UrQMD *Au+Au;* $R_{inv} = 3\,fm$

M. Bleicher et al.
J. Phys. G: Nucl. Part. Phys. 25, 1859-1896 (1999)

M. Gyulassy et al.
Phys. Rev. C20, 2267–2292 (1979)

H. D. Boal et al.
Rev. Mod. Phys. 62, 553–602 (1990)

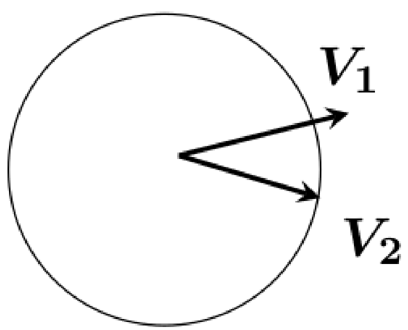
S. E. Koonin et al.
Phys. Lett. B70, 43–47 (1977)

R. Lednický
Sov. J. Nucl. Phys 35, 770–788 (1982)

Source Dynamics – Spacetime Emission Asymmetry

Time asymmetry

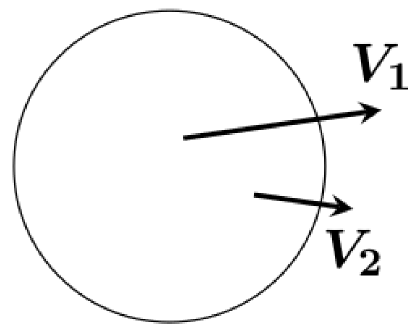
$t_1 \neq t_2$
$\Delta r = 0$



$t_1 > t_2$ - Catching up
$t_2 > t_1$ - Run away

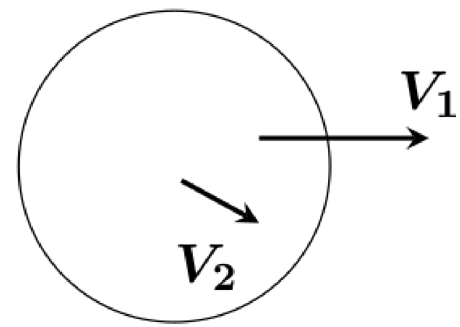
Space asymmetry

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



Catching up

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



Run away

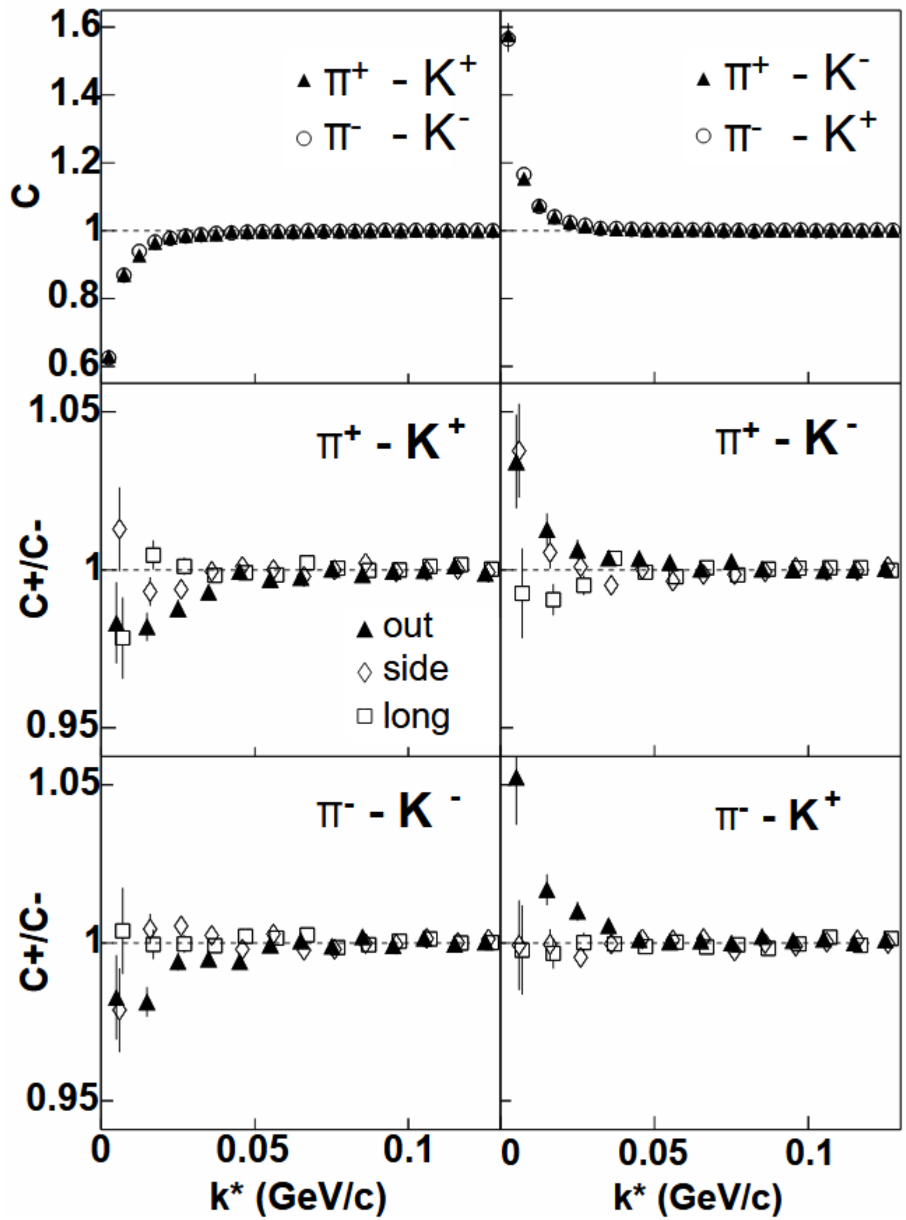
Catching up
longer interaction,
strong correlation

Running away
shorter interaction,
weak correlation

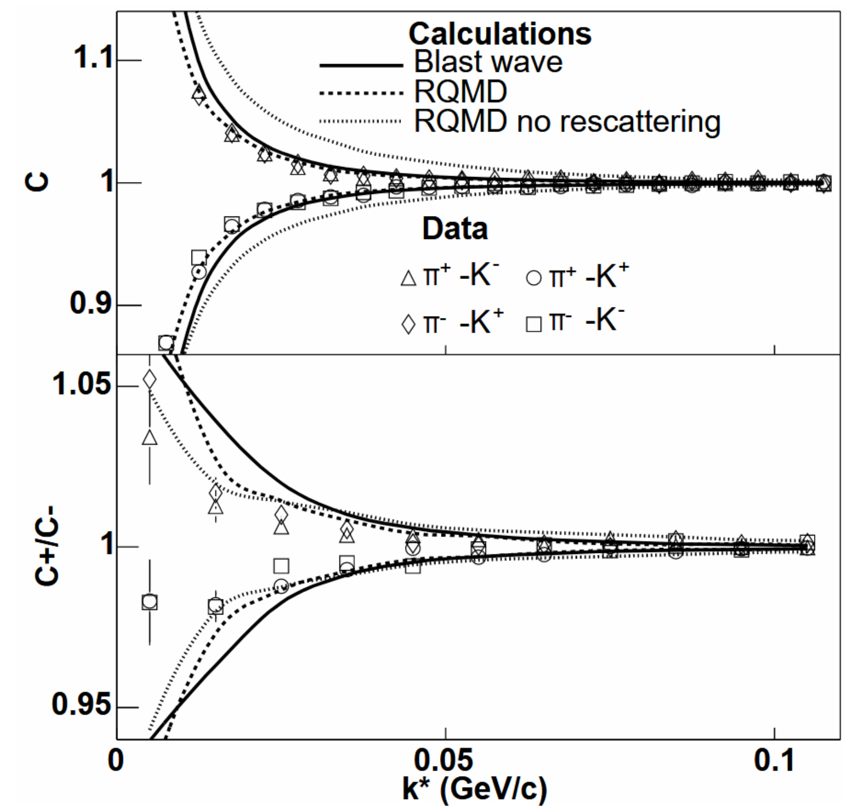
t – emission time
r – emission point distance from the center

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

Source Dynamics – Pion-Kaon Results @ 130 GeV



J. Adams, et al.
Phys. Rev. Lett. 91, 262302 (2003)



	σ (fm)	$\langle \Delta r^*_{out} \rangle$ (fm)	χ^2 / dof
Data	$12.5 \pm 0.4^{+2.2}_{-3}$	$-5.6 \pm 0.6^{+1.9}_{-1.3}$	134.5/110
RQMD	11.8 ± 0.4	-8.0 ± 0.6	205/54
RQMD no rescattering	5.8 ± 0.1	-2.0 ± 0.3	940/54
BWP	9.9 ± 0.1	-6.9 ± 0.3	1020/118

Pions are emitted later and/or closer to the center than kaons.

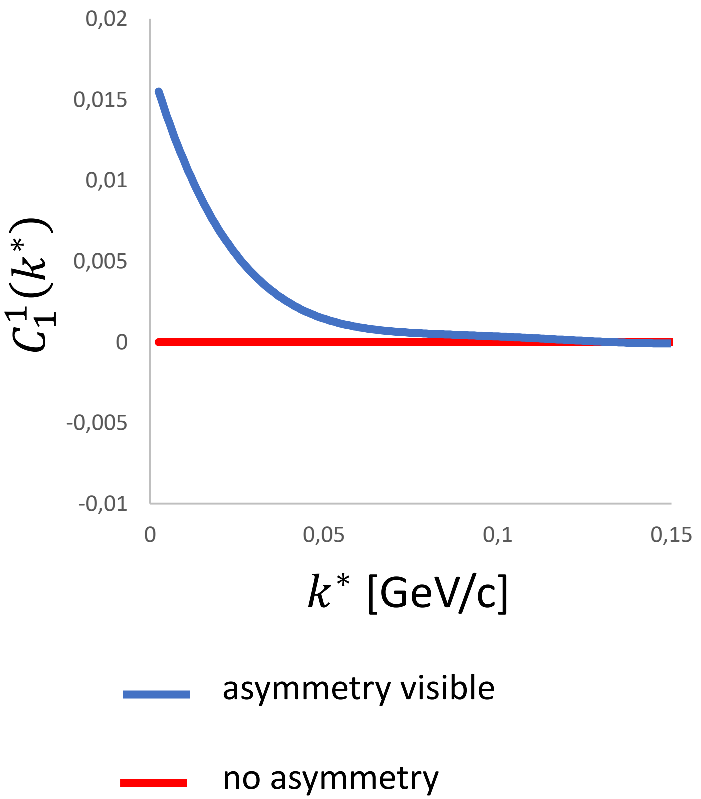
Spherical Harmonics

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

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

C_0^0 -> sensitive to the size of the emitting source (shapes same as correlation function)

C_1^1 -> sensitive to the spacetime emission asymmetry



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

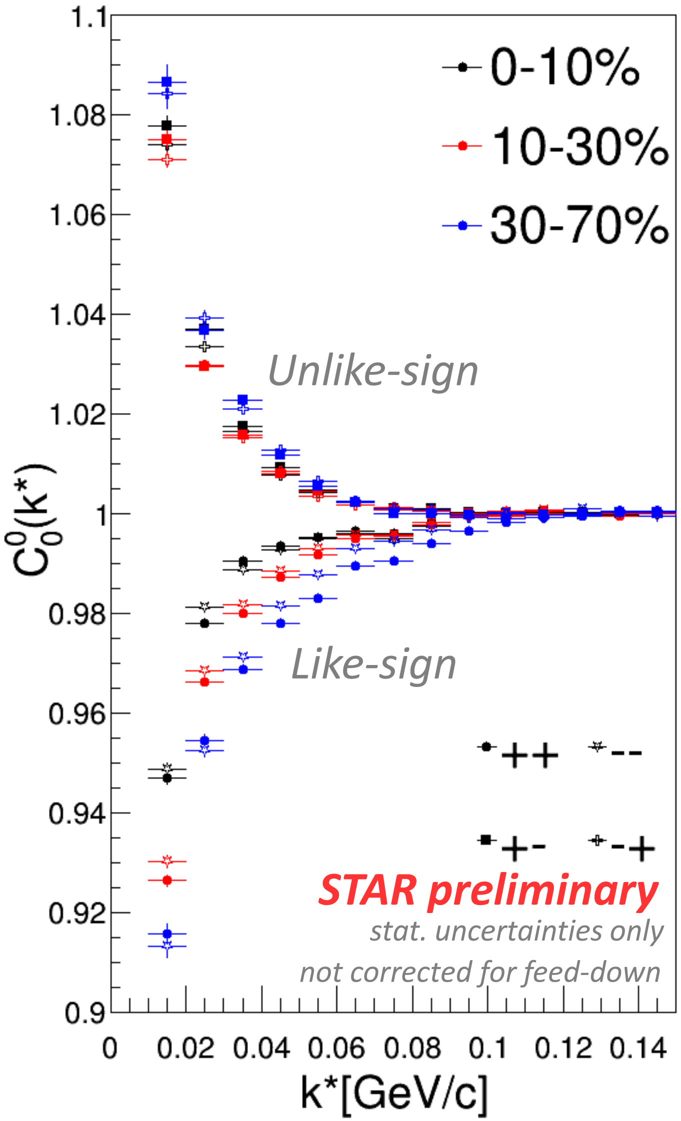
A. Kisiel Phys. Rev. C81:064906 2010

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

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

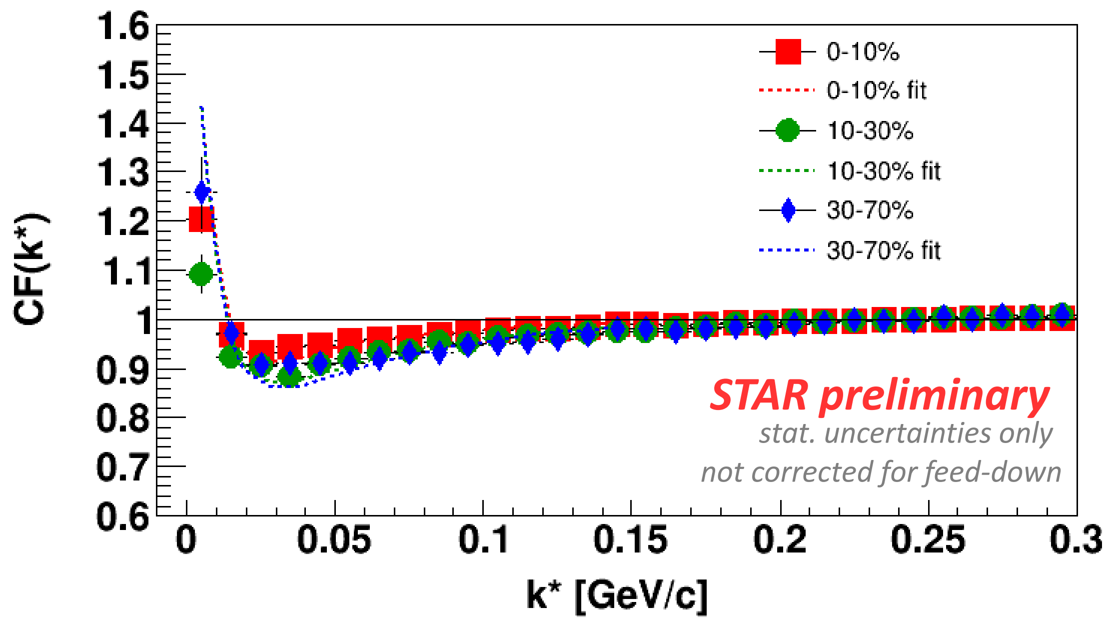
Centrality Dependence (Non-Identical Particle Combinations)

$\pi - K$ @ Au+Au 39 GeV



C_0^0 -> sensitive to size of source

$p - \bar{p}$ @ Au+Au 39 GeV



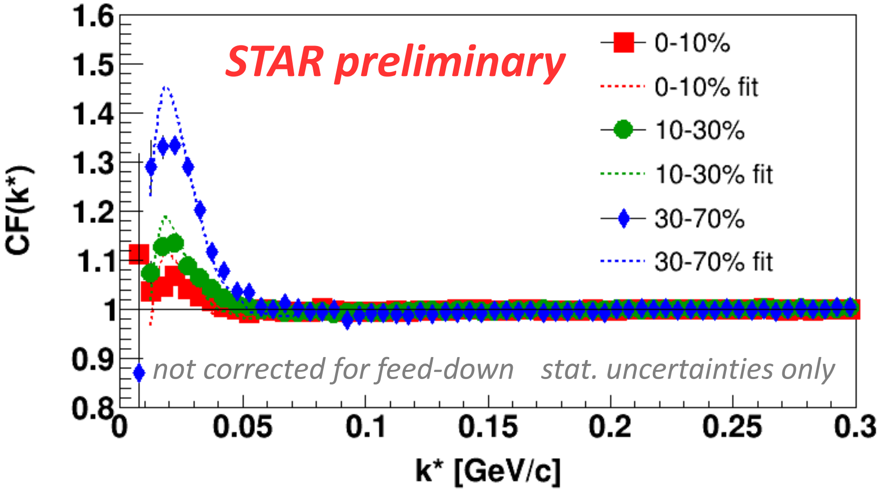
Clear centrality dependence

$\boldsymbol{R}(\mathbf{0\text{–}10\%}) > \boldsymbol{R}(\mathbf{10\text{–}30\%}) > \boldsymbol{R}(\mathbf{30\text{–}70\%})$

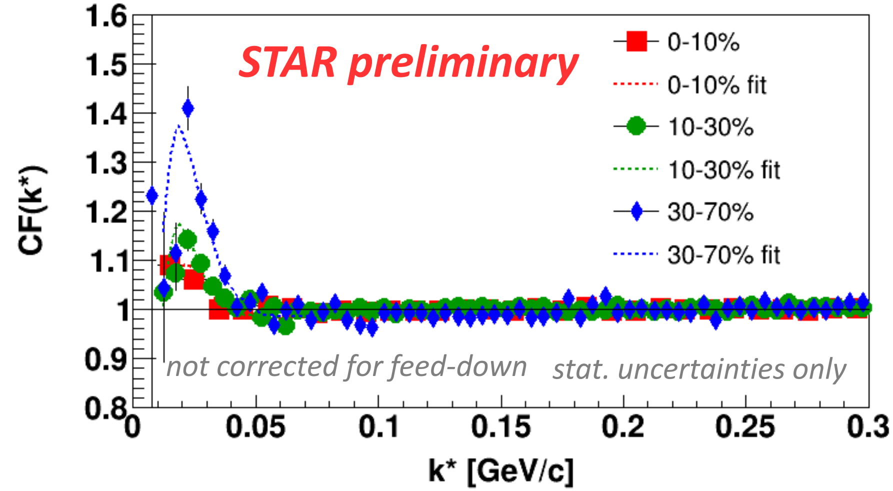
centrality	R_{inv} $p - \bar{p}$ [fm]
0-10%	$\mathbf{3.39} \pm 0.12 \pm 0.14$
10-30%	$\mathbf{2.69} \pm 0.10 \pm 0.12$
30-70%	$\mathbf{2.56} \pm 0.09 \pm 0.12$

Centrality Dependence (Identical Particle Combinations)

$p-p$ @ Au+Au 39 GeV



$\bar{p}-\bar{p}$ @ Au+Au 39 GeV

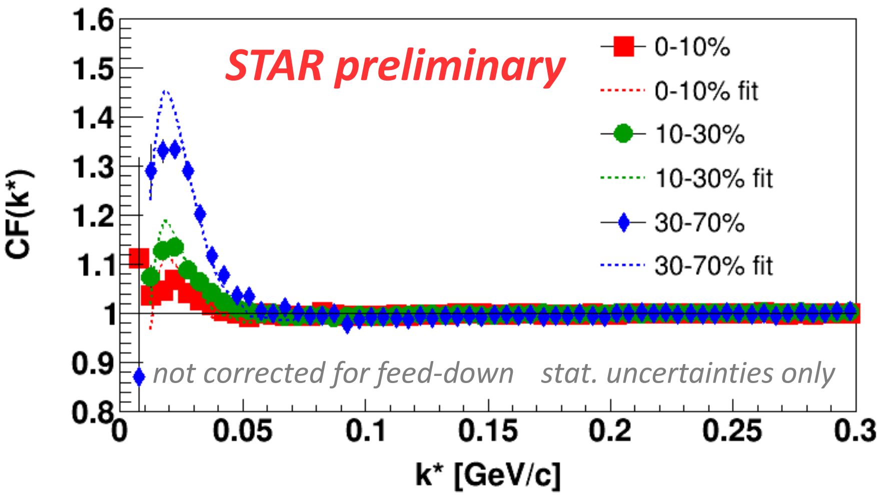


centrality	R_{inv} $p-p$ [fm]	R_{inv} $\bar{p}-\bar{p}$ [fm]
0-10%	$\mathbf{4.00} \pm 0.15 \pm 0.02$	$\mathbf{3.83} \pm 0.20 \pm 0.03$
10-30%	$\mathbf{3.61} \pm 0.13 \pm 0.17$	$\mathbf{3.68} \pm 0.15 \pm 0.11$
30-70%	$\mathbf{2.72} \pm 0.07 \pm 0.07$	$\mathbf{2.95} \pm 0.11 \pm 0.08$

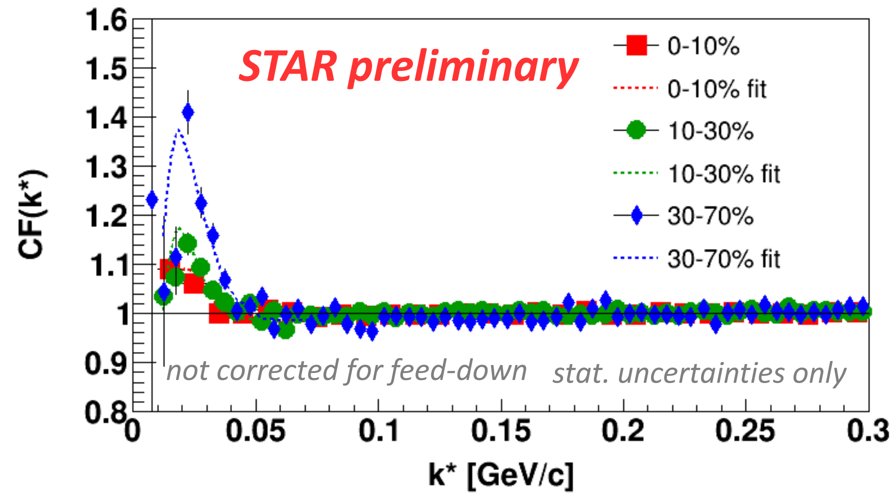
No significant difference between $p-p$ and $\bar{p}-\bar{p}$ correlation functions.

Centrality Dependence (Identical Particle Combinations)

$p-p$ @ Au+Au 39 GeV



$\bar{p}-\bar{p}$ @ Au+Au 39 GeV



centrality	R_{inv} $p-p$ [fm]	R_{inv} $\bar{p}-\bar{p}$ [fm]	R_{inv} $p-\bar{p}$ [fm]
0-10%	$\mathbf{4.00} \pm 0.15 \pm 0.02$	$\mathbf{3.83} \pm 0.20 \pm 0.03$	$\mathbf{3.39} \pm 0.12 \pm 0.14$
10-30%	$\mathbf{3.61} \pm 0.13 \pm 0.17$	$\mathbf{3.68} \pm 0.15 \pm 0.11$	$\mathbf{2.69} \pm 0.10 \pm 0.12$
30-70%	$\mathbf{2.72} \pm 0.07 \pm 0.07$	$\mathbf{2.95} \pm 0.11 \pm 0.08$	$\mathbf{2.56} \pm 0.09 \pm 0.12$

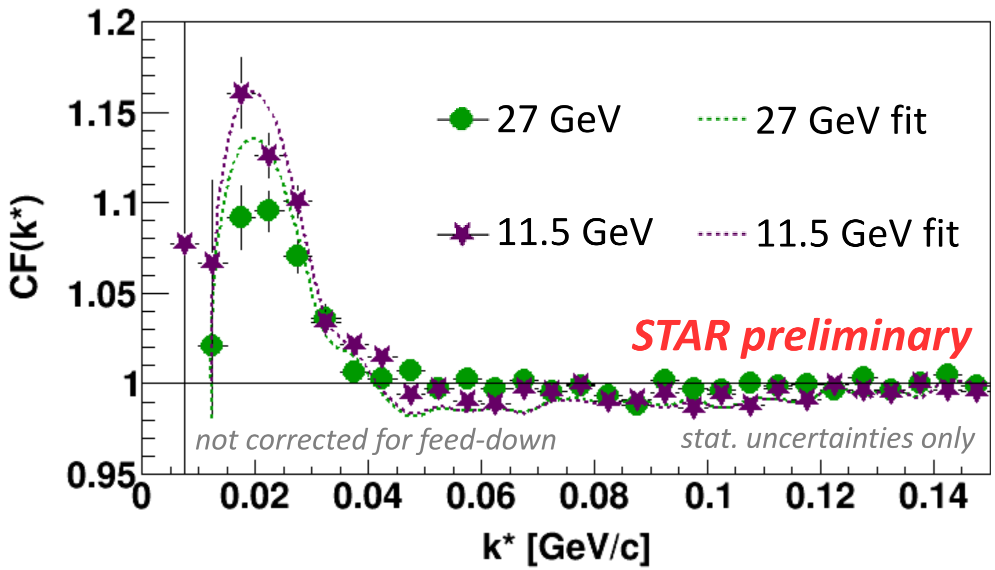
No significant difference between $p-p$ and $\bar{p}-\bar{p}$ correlation functions.

Feed-down correction for residual correlations is in progress.

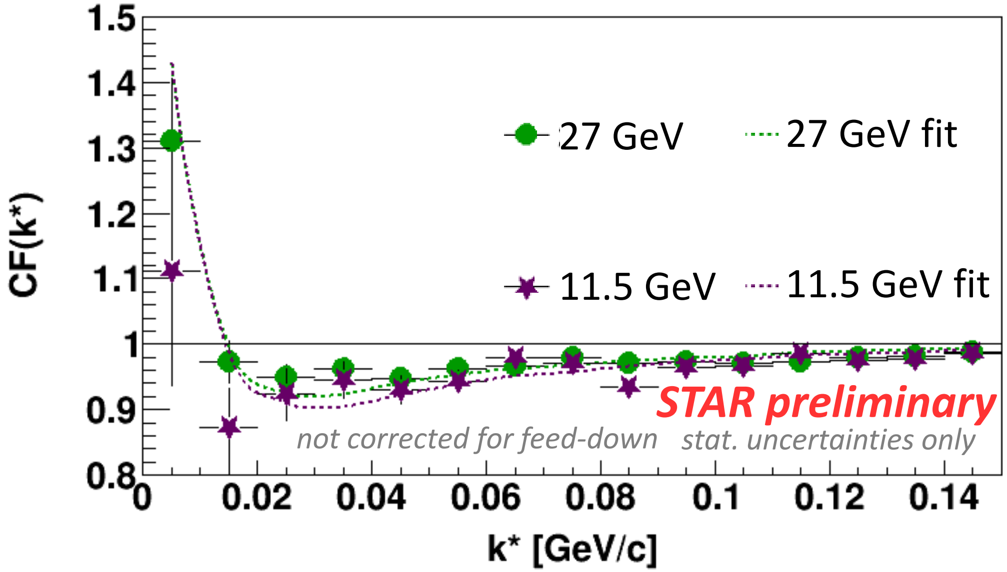
Radii from $p-p$ and $\bar{p}-\bar{p}$ systems differ from radii from $p-\bar{p}$ system –> residual correlations contaminate correlation functions.

Energy Dependence

$p - p$: Au+Au 0-10%



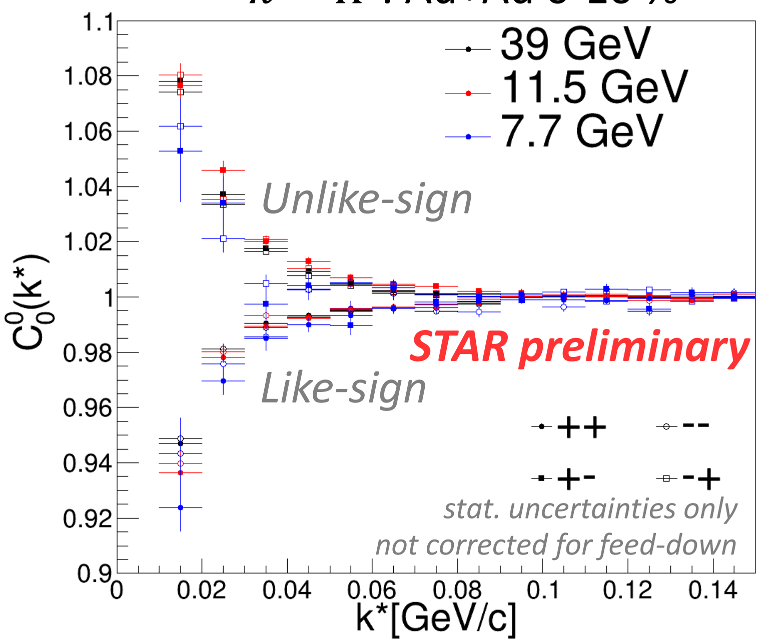
$p - \bar{p}$: Au+Au 0-10%



Energy dependence more pronounced for $p - p$ system than for $p - \bar{p}$ system.

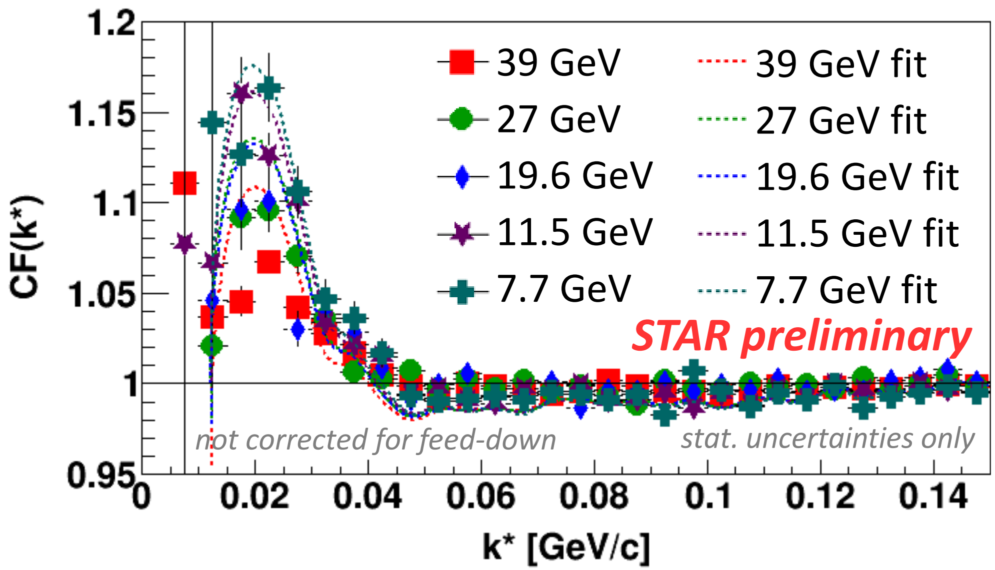
energy	R_{inv} $p - p$ [fm]	R_{inv} $p - \bar{p}$ [fm]
7.7 GeV	$\mathbf{3.59} \pm 0.16 \pm 0.19$	
11.5 GeV	$\mathbf{3.66} \pm 0.08 \pm 0.05$	$\mathbf{3.30} \pm 0.42 \pm 0.28$
19.6 GeV	$\mathbf{3.82} \pm 0.15 \pm 0.06$	$\mathbf{3.32} \pm 0.25 \pm 0.13$
27 GeV	$\mathbf{3.80} \pm 0.12 \pm 0.08$	$\mathbf{3.49}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

$\pi - K$: Au+Au 0-10 %

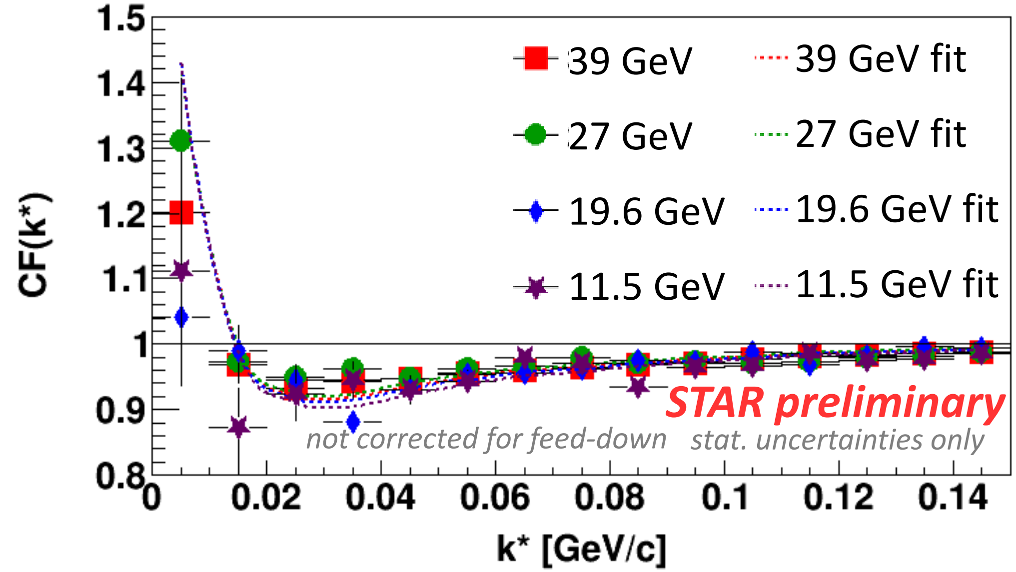


Energy Dependence

$p - p$: Au+Au 0-10%



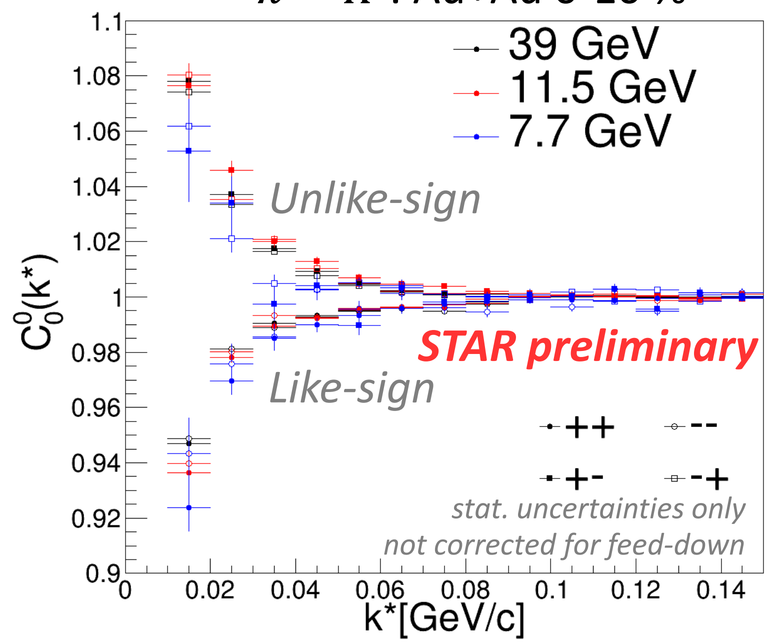
$p - \bar{p}$: Au+Au 0-10%



Energy dependence more pronounced for $p - p$ system than for $p - \bar{p}$ system.

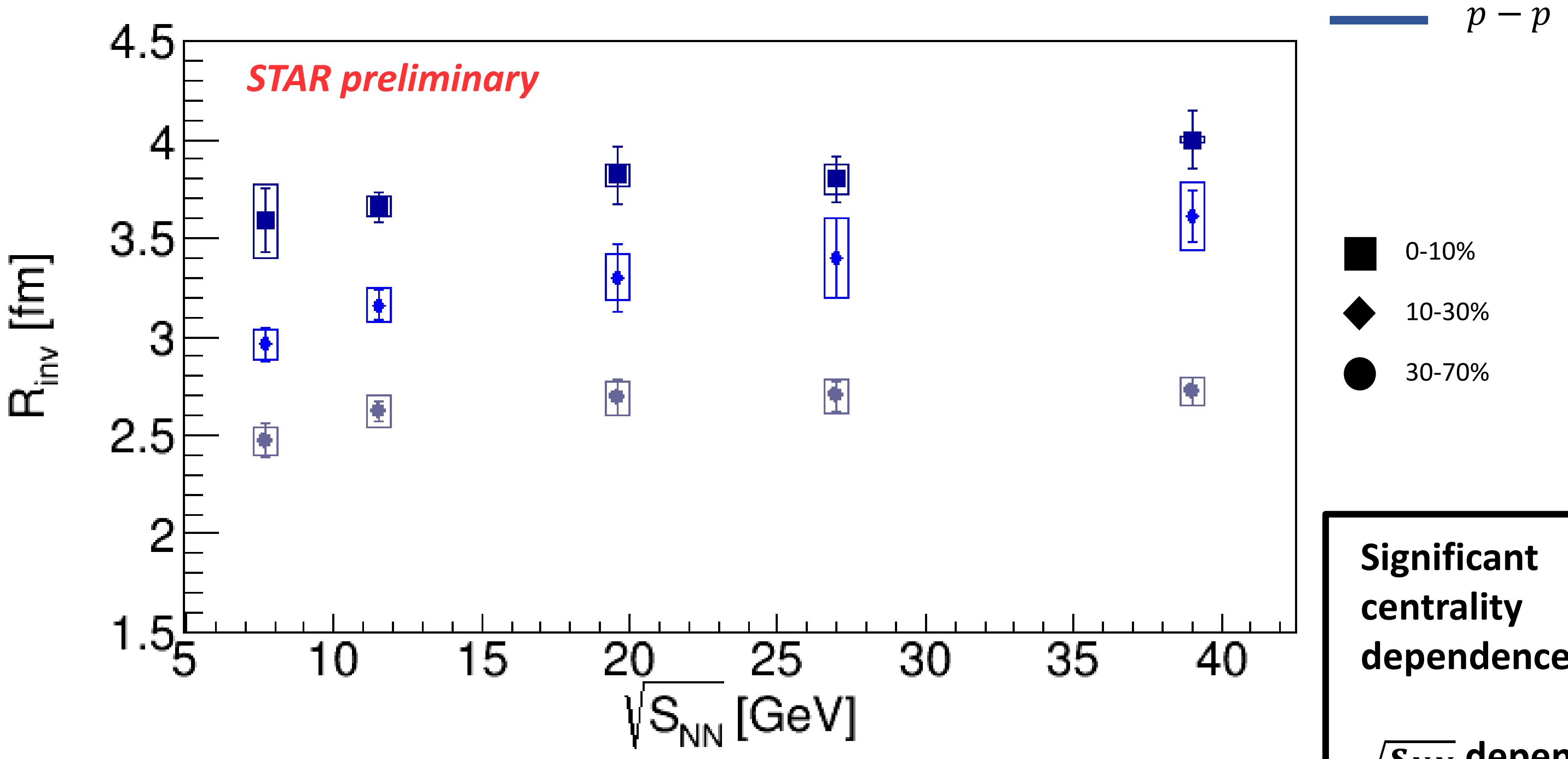
energy	R_{inv} $p - p$ [fm]	R_{inv} $p - \bar{p}$ [fm]
7.7 GeV	$\mathbf{3.59} \pm 0.16 \pm 0.19$	
11.5 GeV	$\mathbf{3.66} \pm 0.08 \pm 0.05$	$\mathbf{3.30} \pm 0.42 \pm 0.28$
19.6 GeV	$\mathbf{3.82} \pm 0.15 \pm 0.06$	$\mathbf{3.32} \pm 0.25 \pm 0.13$
27 GeV	$\mathbf{3.80} \pm 0.12 \pm 0.08$	$\mathbf{3.49}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

$\pi - K$: Au+Au 0-10 %



Energy and Centrality Dependence

R_{inv} dependence



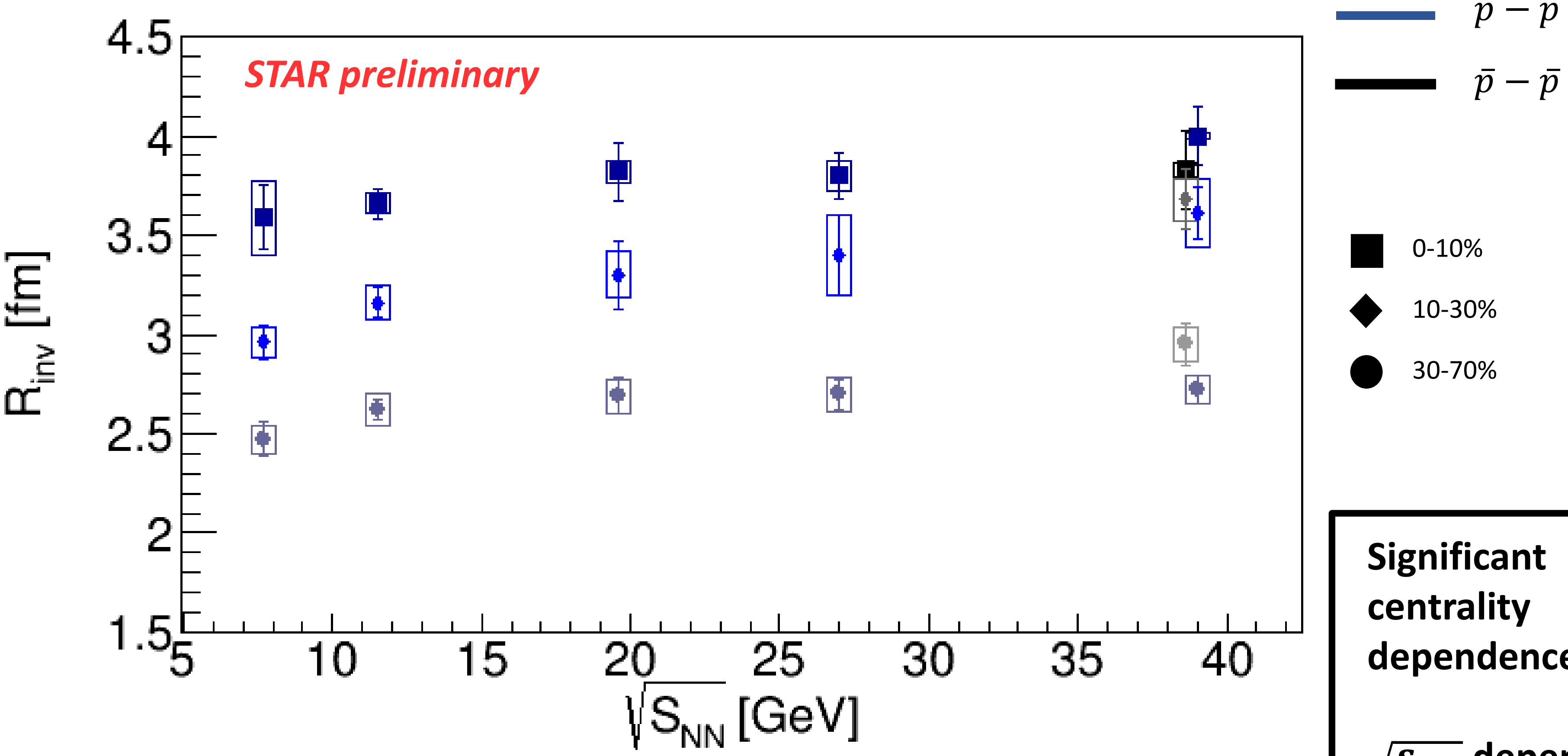
Significant centrality dependence.

$\sqrt{s_{NN}}$ dependence weak for all centralities.

Feed-down correction may decrease significance of centrality dependence.

Energy and Centrality Dependence

R_{inv} dependence



Significant centrality dependence.

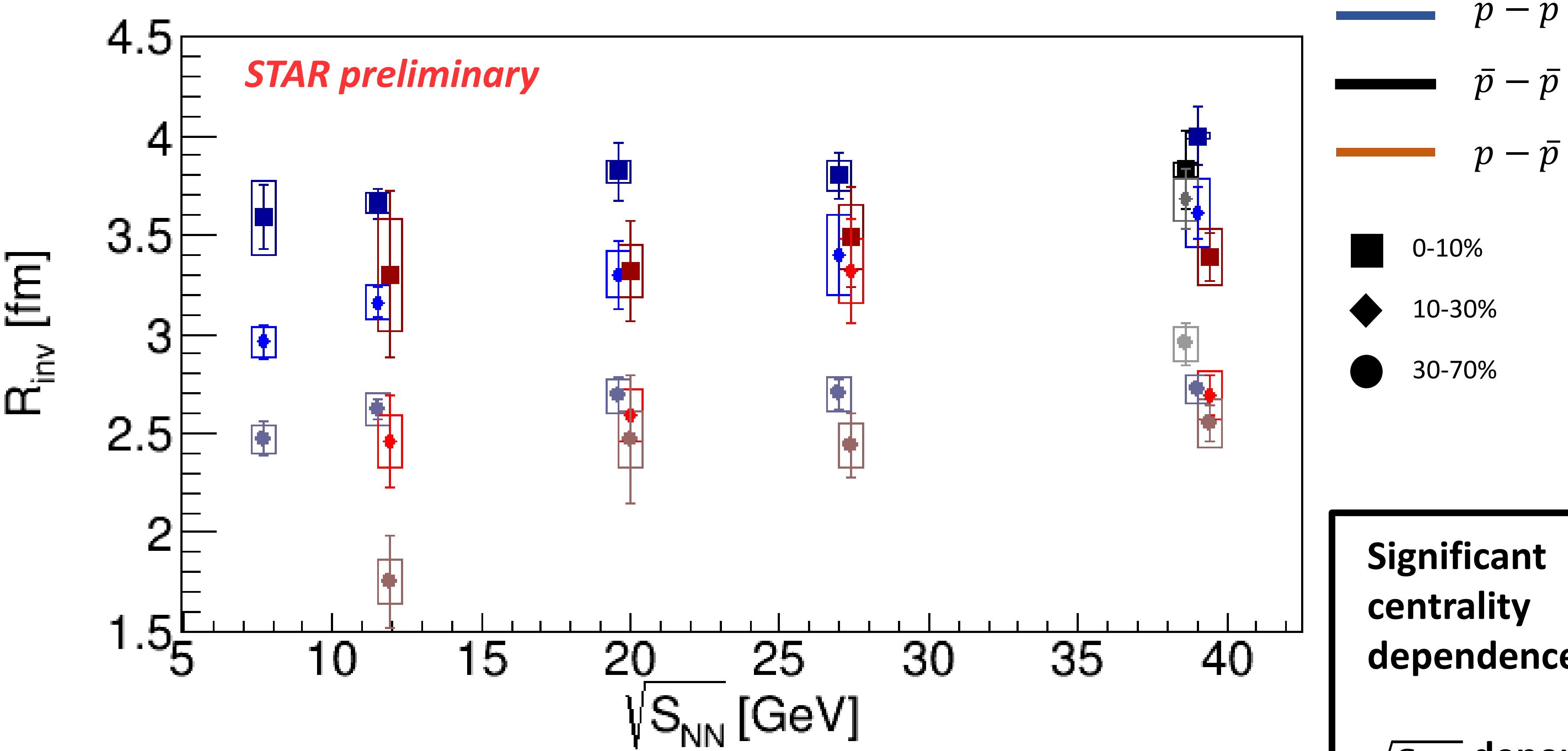
$\sqrt{s_{NN}}$ dependence weak for all centralities.

No significant difference between $p-p$ and $\bar{p}-\bar{p}$ correlation functions at $\sqrt{s_{NN}}$ = 39 GeV

Feed-down correction may decrease significance of centrality dependence.

Energy and Centrality Dependence

R_{inv} dependence



Significant centrality dependence.

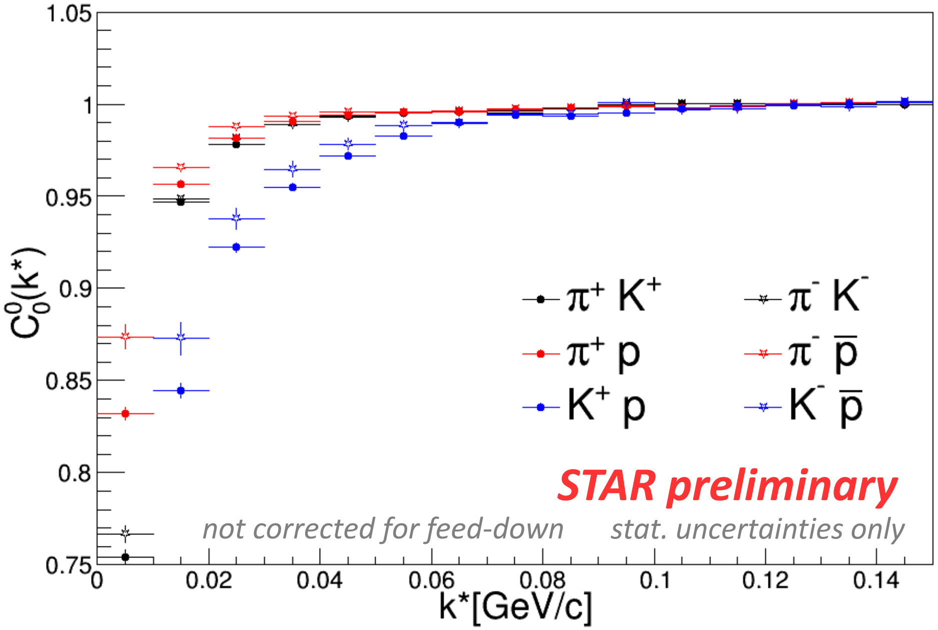
$\sqrt{s_{NN}}$ dependence weak for all centralities.

No significant difference between $p-p$ and $\bar{p}-\bar{p}$ correlation functions at $\sqrt{s_{NN}}$ = 39 GeV

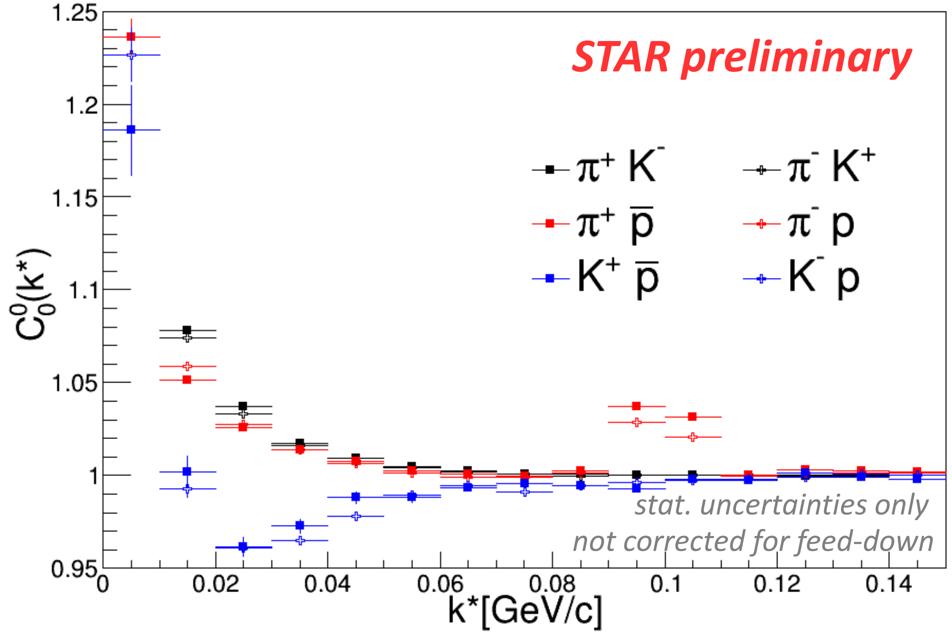
Feed-down correction may decrease significance of centrality dependence.

System Dependence

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



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



Clear system dependence

Like-sign: correlations dominated by Coulomb interaction

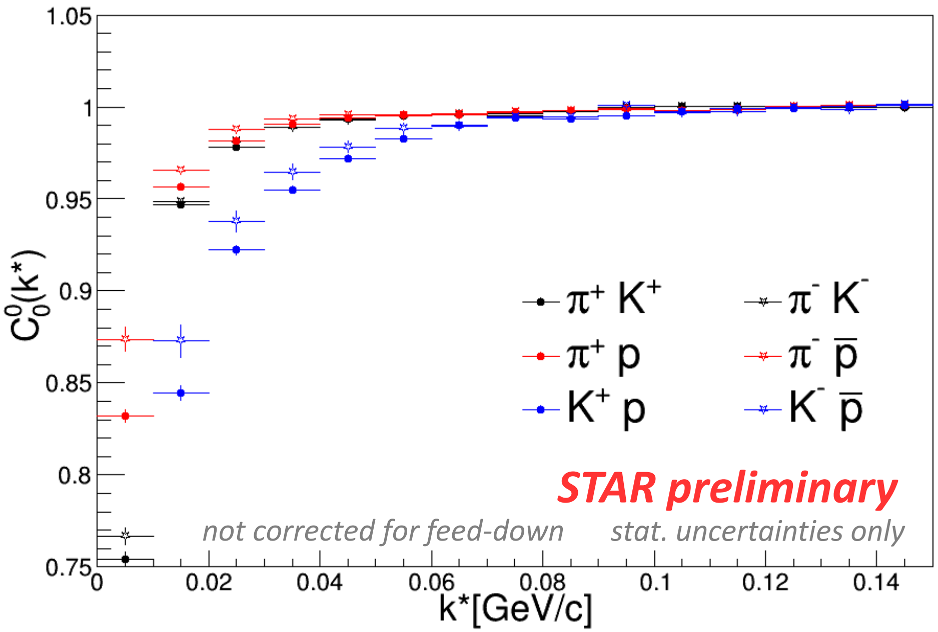
Coulomb strength depends on Bohr radius of the pair

$K - p$ – lowest Bohr radius, strongest correlation

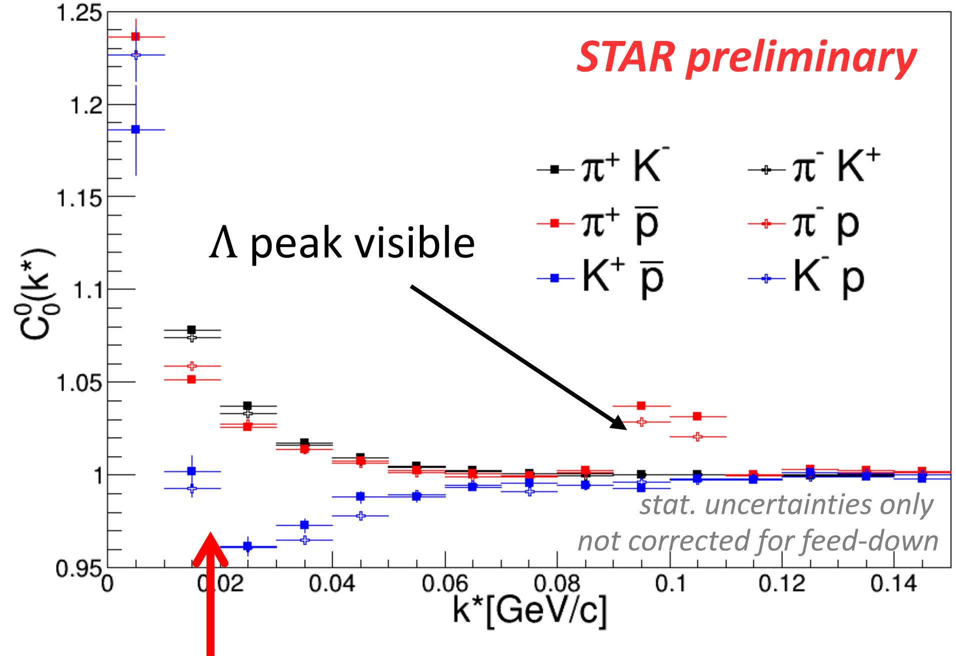
C_0^0 -> sensitive to size of source

System Dependence

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



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



$C_0^0(K-p)$ different shape due to strong interaction

Clear system dependence

Like-sign: correlations dominated by Coulomb interaction

Coulomb strength depends on Bohr radius of the pair

$K-p$ – lowest Bohr radius, strongest correlation

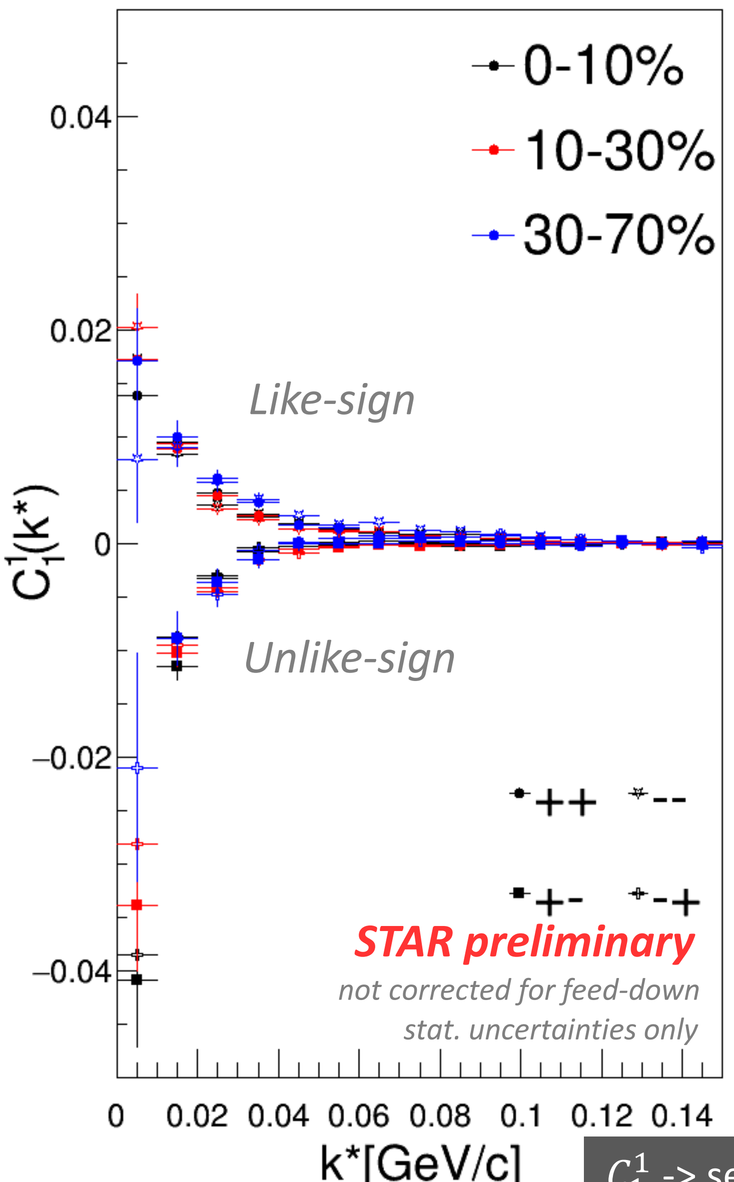
Unlike-sign: interaction more complicated

Strong interaction not negligible in $K-p$.

C_0^0 -> sensitive to size of source

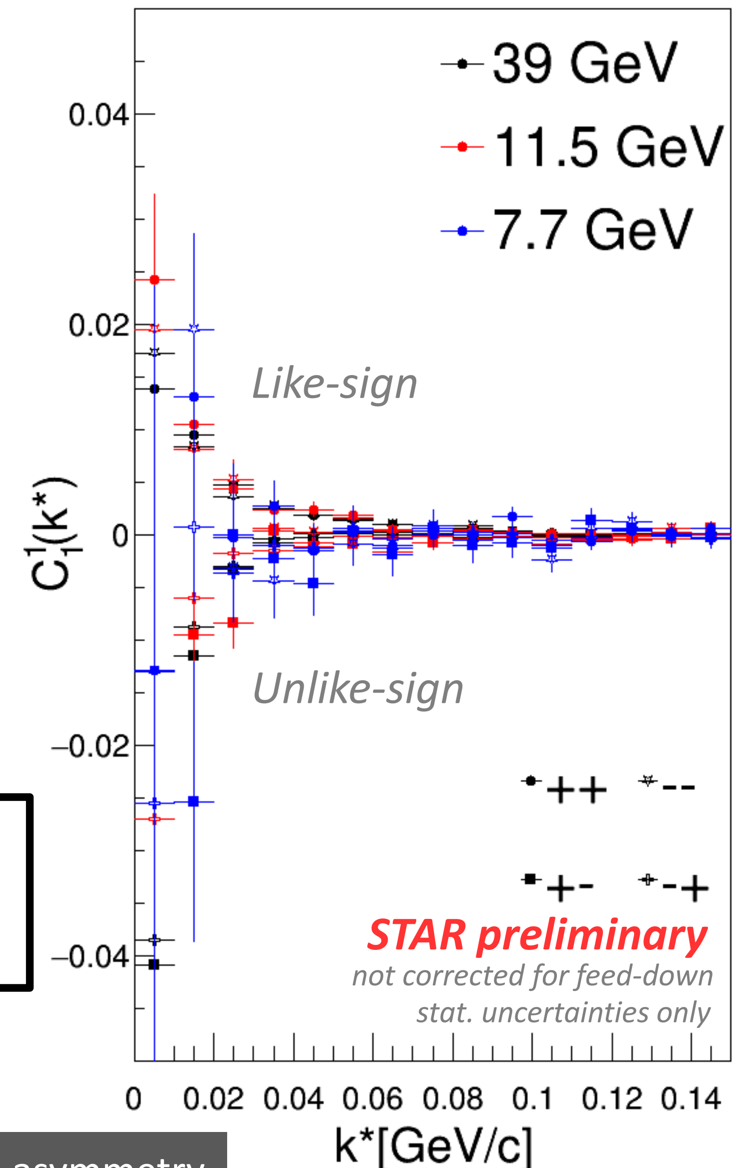
Source Dynamics – Centrality and Energy Dependence

$\pi - K$ @ Au+Au 39 GeV



Clear signal of emission asymmetry

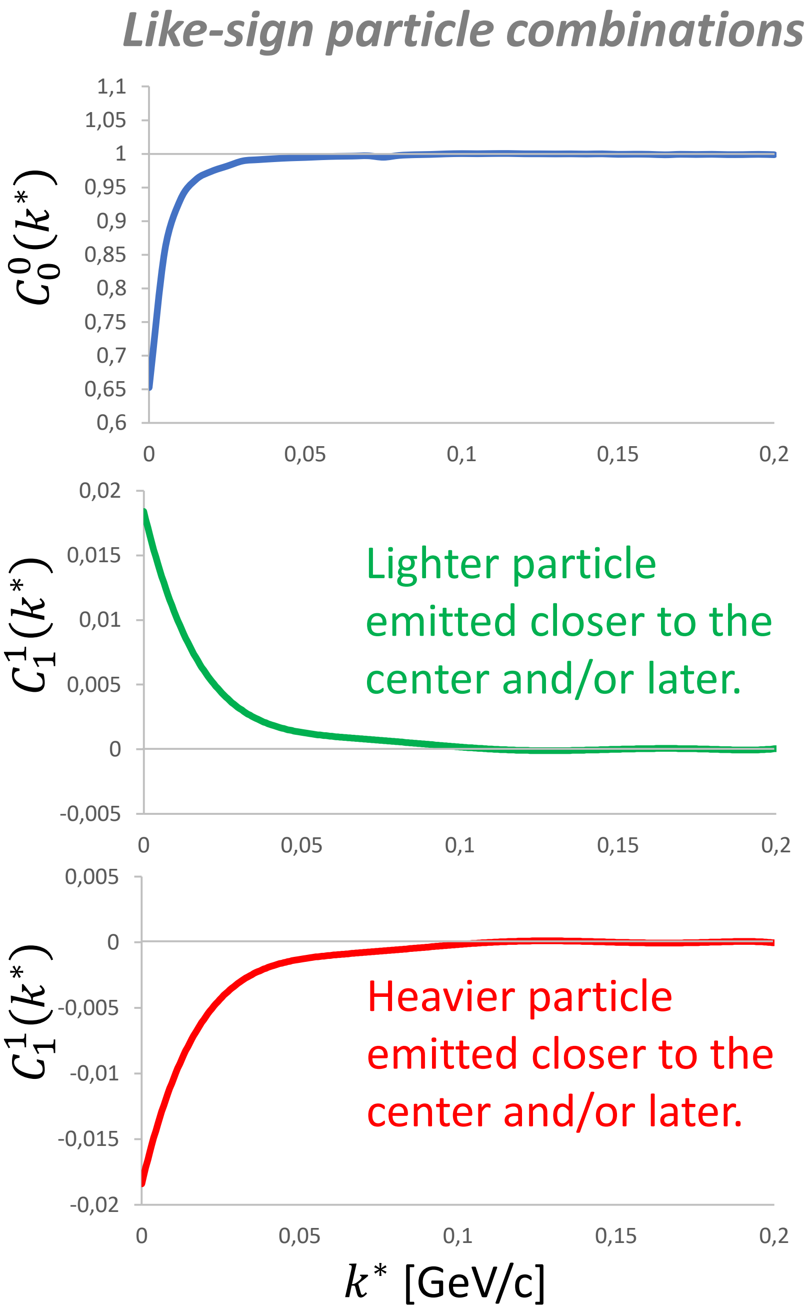
$\pi - K$: Au+Au 0-10%

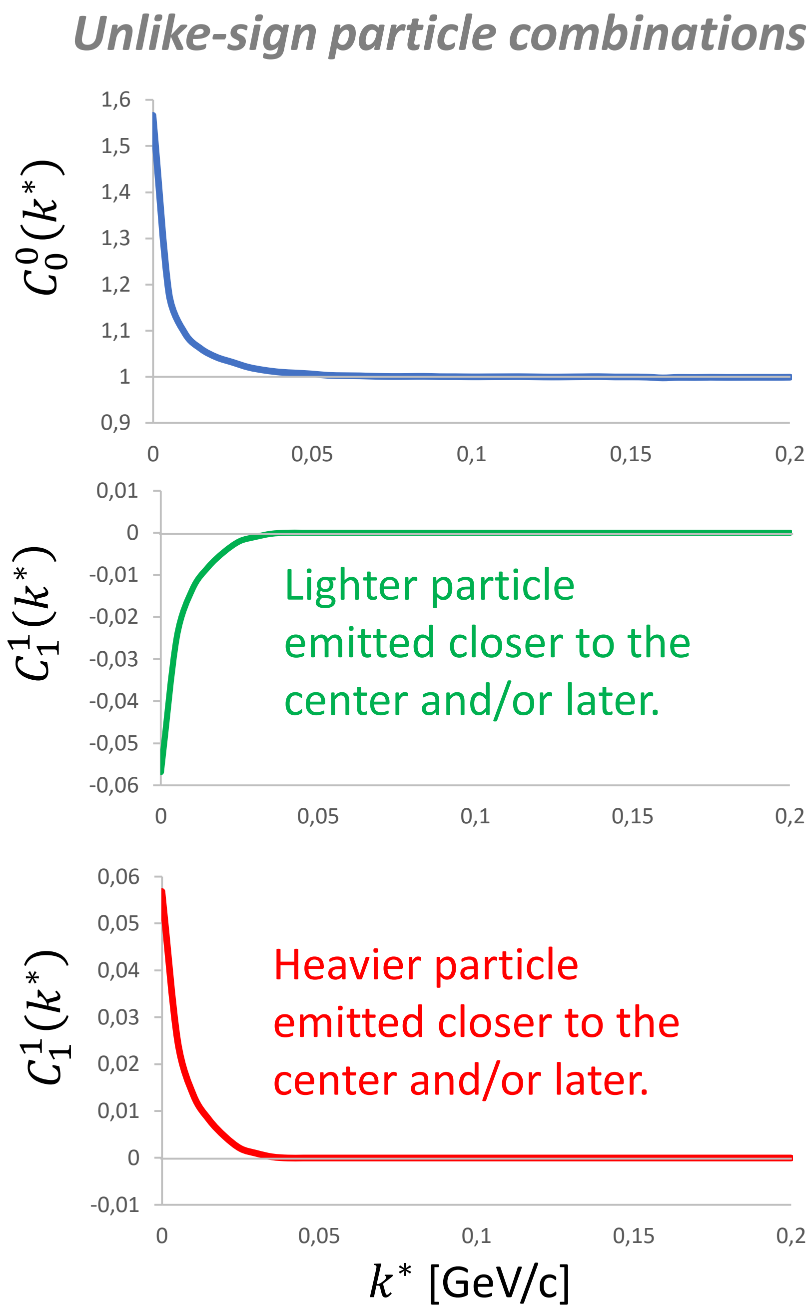


Asymmetry does not disappear for low energies.

C_1^1 -> sensitive to spacetime emission asymmetry

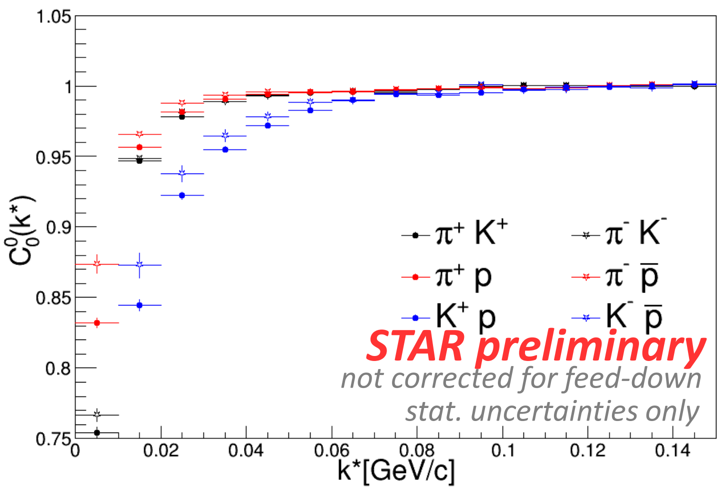
Source Dynamics – System Dependence

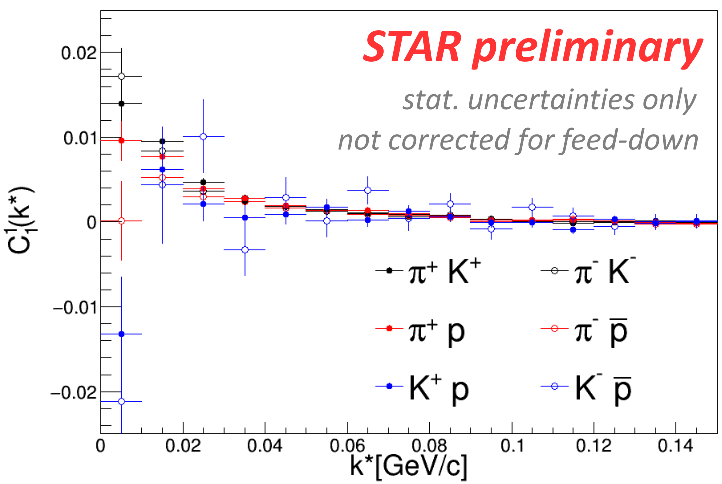




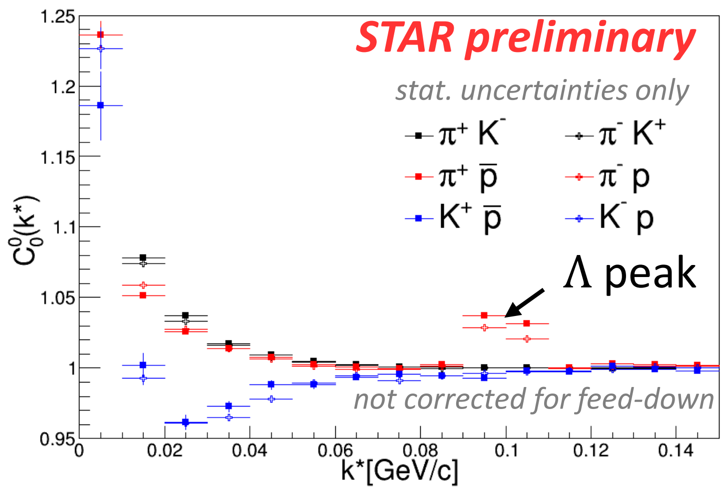
Source Dynamics – System Dependence

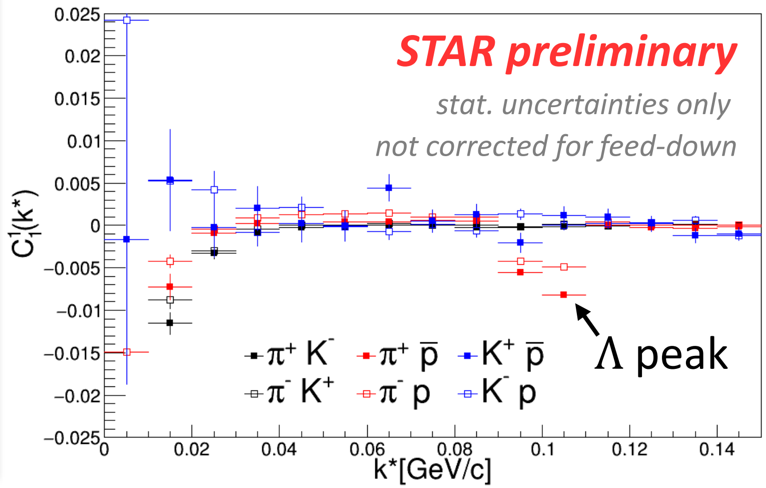
Like-sign 0-10% @ Au+Au 39 GeV





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



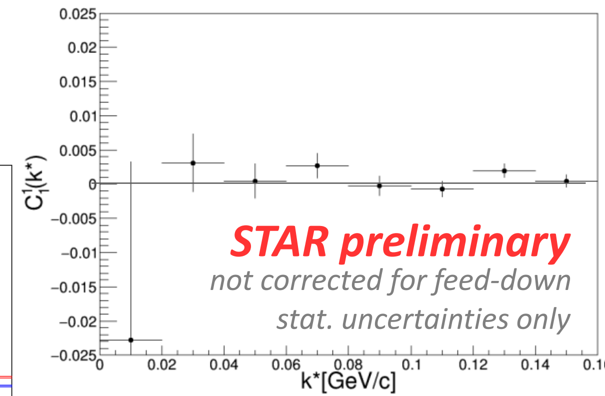


C_0^0 -> sensitive to size of source

C_1^1 -> sensitive to spacetime emission asymmetry

BES II will improve results.

$p - \bar{p}$ 0-10% @ Au+Au 39 GeV



Expected ordering of particles:

Lighter particle is emitted closer to the centre and/or later.

No visible asymmetry between protons and antiprotons – similar masses.

Heavier particles have stronger push by flow towards the edge of source than lighter particles. Heavier particles freeze-out earlier.

A. Kisiel
Phys. Rev. C81:064906 2010

Summary

Geometry:
- Visible centrality, system and energy dependence of source size at BES energies
- **No visible difference between proton-proton and antiproton-antiproton correlation functions at $\sqrt{s_{NN}} = 39$ GeV**
- **Correlation functions contaminated by residual correlations – residual correction required**
- **Strong interaction not negligible in kaon-proton**

Summary

Geometry:

- Visible centrality, system and energy dependence of source size at BES energies
- **No visible difference between proton-proton and antiproton-antiproton correlation functions at $\sqrt{s_{NN}} = 39$ GeV**
- **Correlation functions contaminated by residual correlations – residual correction required**
- **Strong interaction not negligible in kaon-proton**

Dynamics:

- Clear signal of emission asymmetry for particles with different masses at BES energies
- Asymmetry does not disappear for low energies

Summary

Geometry:

- Visible centrality, system and energy dependence of source size at BES energies
- **No visible difference between proton-proton and antiproton-antiproton correlation functions at $\sqrt{s_{NN}} = 39$ GeV**
- **Correlation functions contaminated by residual correlations – residual correction required**
- **Strong interaction not negligible in kaon-proton**

Dynamics:

- Clear signal of emission asymmetry for particles with different masses at BES energies
- Asymmetry does not disappear for low energies
- **Lighter particles are emitted closer to the center of the source and/or later than heavier particles – flow gives heavier particles stronger push to the edge**

Summary

Geometry:

- Visible centrality, system and energy dependence of source size at BES energies
- **No visible difference between proton-proton and antiproton-antiproton correlation functions at $\sqrt{s_{NN}} = 39$ GeV**
- **Correlation functions contaminated by residual correlations – residual correction required**
- **Strong interaction not negligible in kaon-proton**

Dynamics:

- Clear signal of emission asymmetry for particles with different masses at BES energies
- Asymmetry does not disappear for low energies
- **Lighter particles are emitted closer to the center of the source and/or later than heavier particles – flow gives heavier particles stronger push to the edge**

Thank you for your attention

BACKUP

Coulomb Interaction and Bohr Radius of the Pair

Pair mutual interaction:

$$\boldsymbol{\Phi}^{(+)}_{-k^*}(r^*) = \sqrt{A_C(\eta)}\left[e^{-ik^*r^*}F(-i\eta,1,i\xi) + f_C(k^*)\frac{\bar{G}(\rho,\eta)}{r^*}\right]$$

A_C – Gamow factor

$\xi = k^*r^*(1+\cos\theta^*)$

$\eta = \frac{1}{k^*a_C}$ where a_C is the Bohr radius of the pair

$\rho = k^*r^*$

F – confluent hypergeometric function

$\bar{G}$ - combination of regular and singular s-wave Coulomb function

f_C - Coulomb-modified strong interaction scattering amplitudę

θ^* - angle between pair relative momentum k^* and relative position r^*

A. Kisiel
Braz. J. Phys.37:917-924 (2007)

Pair	$\pi^+\pi^\pm$	$\pi^+K^\pm$	$\pi^\pm p$	$K^+K^\pm$	$K^\pm p$	$pp^\pm$
a_C, fm	$\pm$387.5	$\pm$248.6	$\pm$222.5	$\pm$109.6	$\pm$83.6	$\pm$57.6
Q_C, MeV/c	6.4	10.0	11.1	22.6	29.7	43.0

a_C - pair Bohr radius including the sign of the interaction

$Q_C \equiv 2k^*_C = \frac{4\pi}{|a|}$ - characteristic width of Coulomb interaction

R. Lednicky
DIRAC Note 2004-06,
CERN (27.11.2004)