Warsaw University of Technology

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

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STAR

XIV Polish Workshop on Relativistic Heavy-Ion Collisions, Kraków, 6-7 April 2019

Outline

I) Introduction

- RHIC, STAR
- Femtoscopy

II) Geometry aspects

- Centrality dependence
- Energy dependence
- System dependence

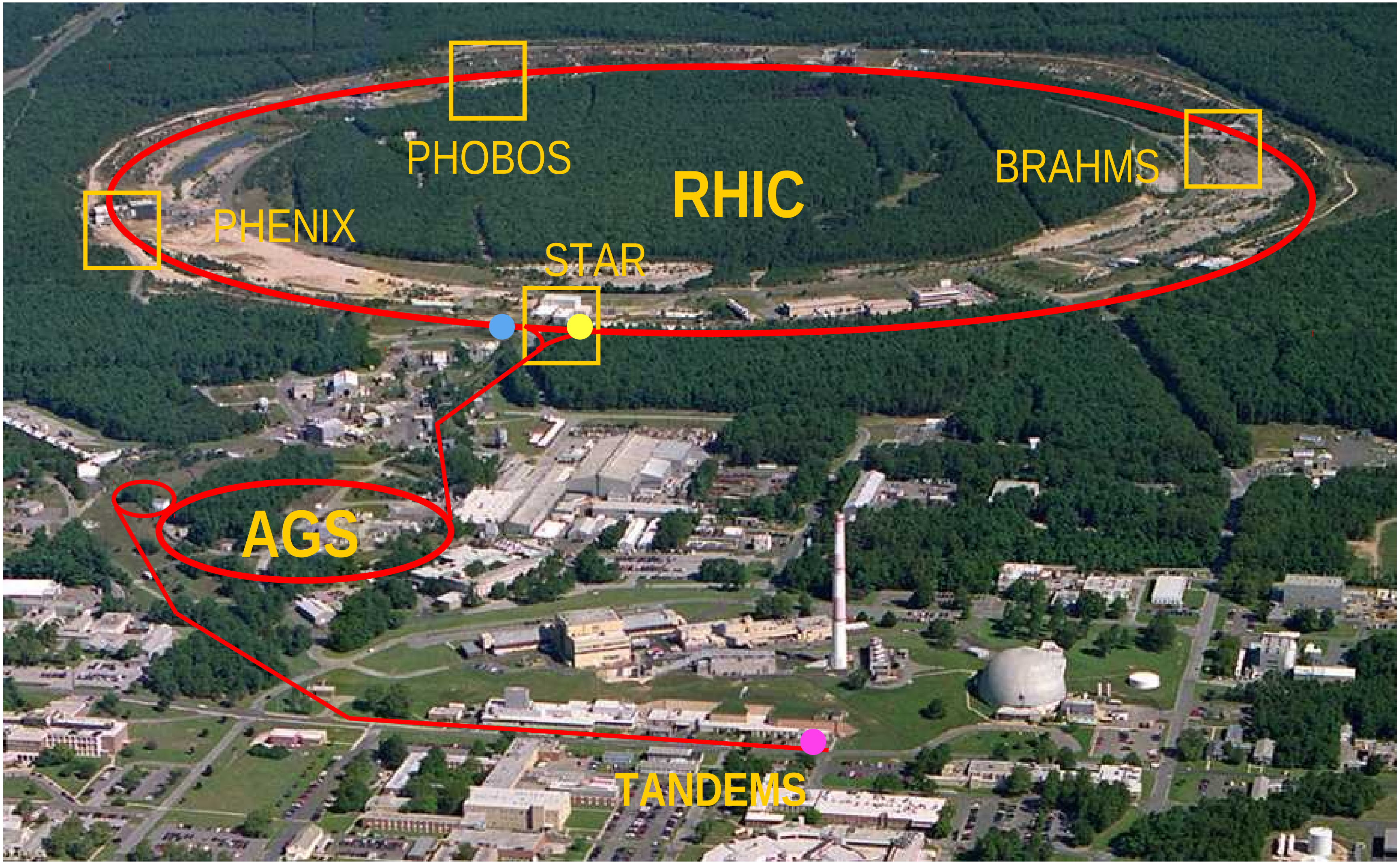
III) Dynamics aspects

- Centrality dependence
- Energy dependence
- System dependence

IV) Conclusions and summary

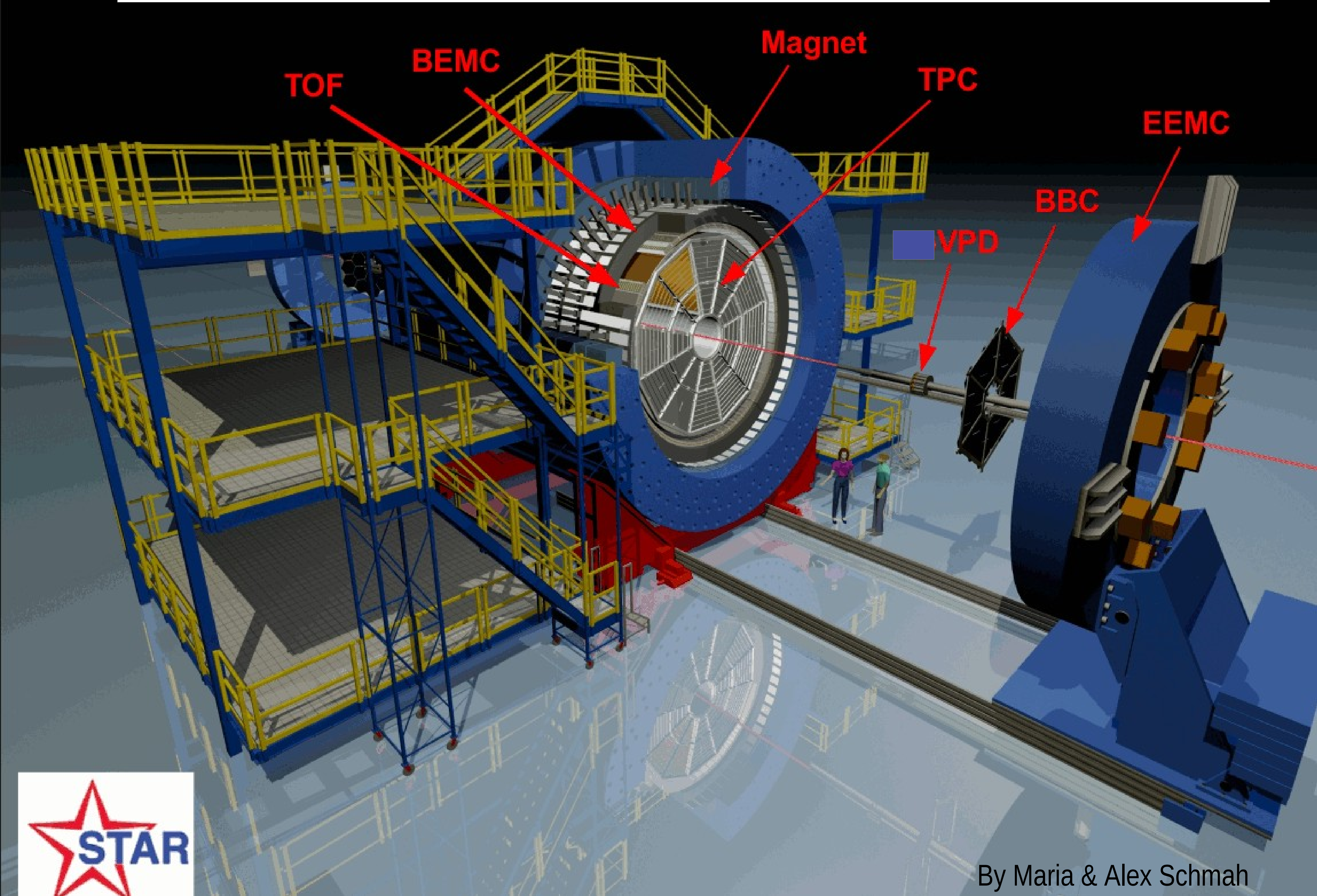
Introduction

Relativistic Heavy Ion Collider (RHIC)
Brookhaven National Laboratory (BNL)



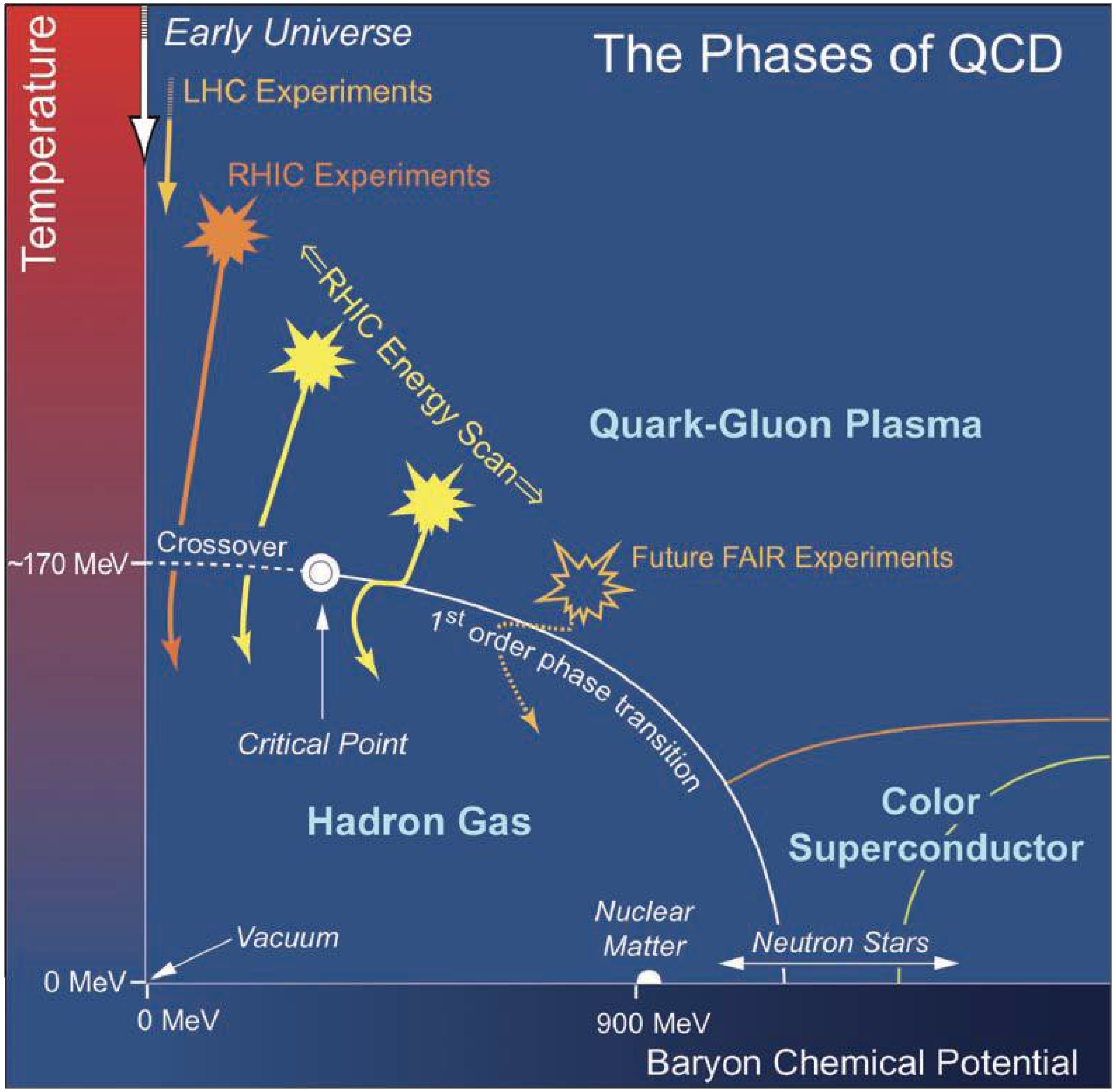
- 2 concentric rings of 1740 superconducting magnets
- 3.8 km circumference

The Solenoidal Tracker At RHIC



By Maria & Alex Schmah

Introduction



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 Energy Scan
Au+Au 7.7-62 GeV
QCD phase transition
Search for critical point
Turn-off of the QGP signatures

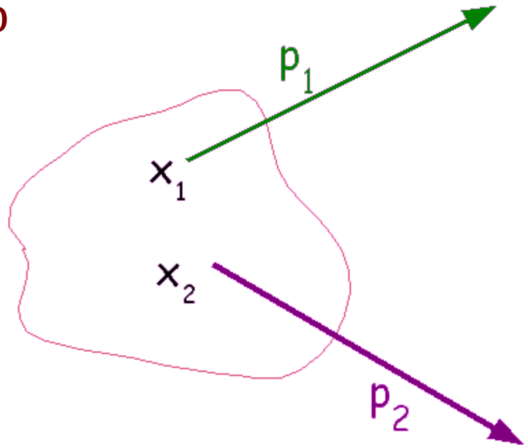
Fixed-Target Program
Au+Au =3.0-7.7 GeV
High baryon density regime with 420-720 MeV

Few Words About Femtoscopy

Single- and two- particle distributions

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

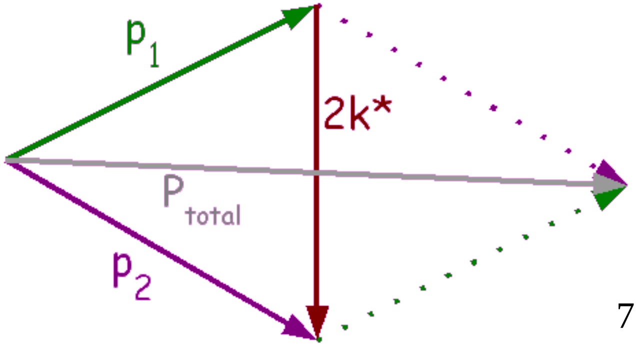
S(x,p) – emission function: the distribution of source density probability of finding particle with x and p



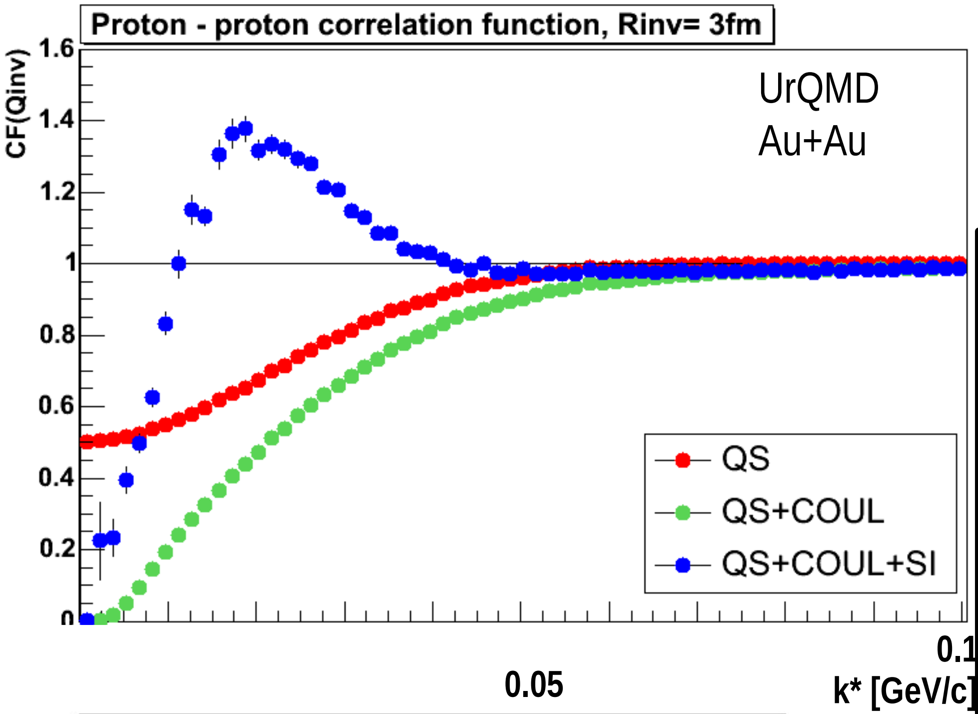
$$P_2(p_1,p_2)=E_1E_2\frac{dN}{d^3p_1d^3p_2}=\int d^4x_1S(x_1,p_1)\,d^4x_2S(x_2,p_2)\,\Phi(x_2,p_2|x_1,p_1)$$

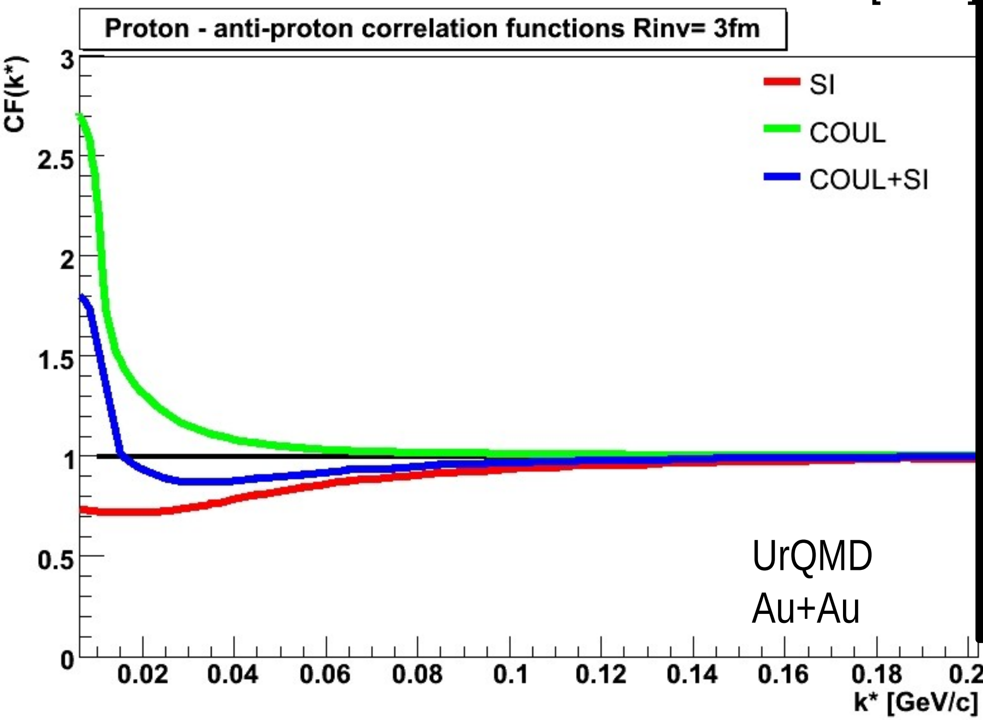
The correlation function

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



Sources of Correlations





Identical baryon- baryon

- Quantum Statistics- **QS**

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

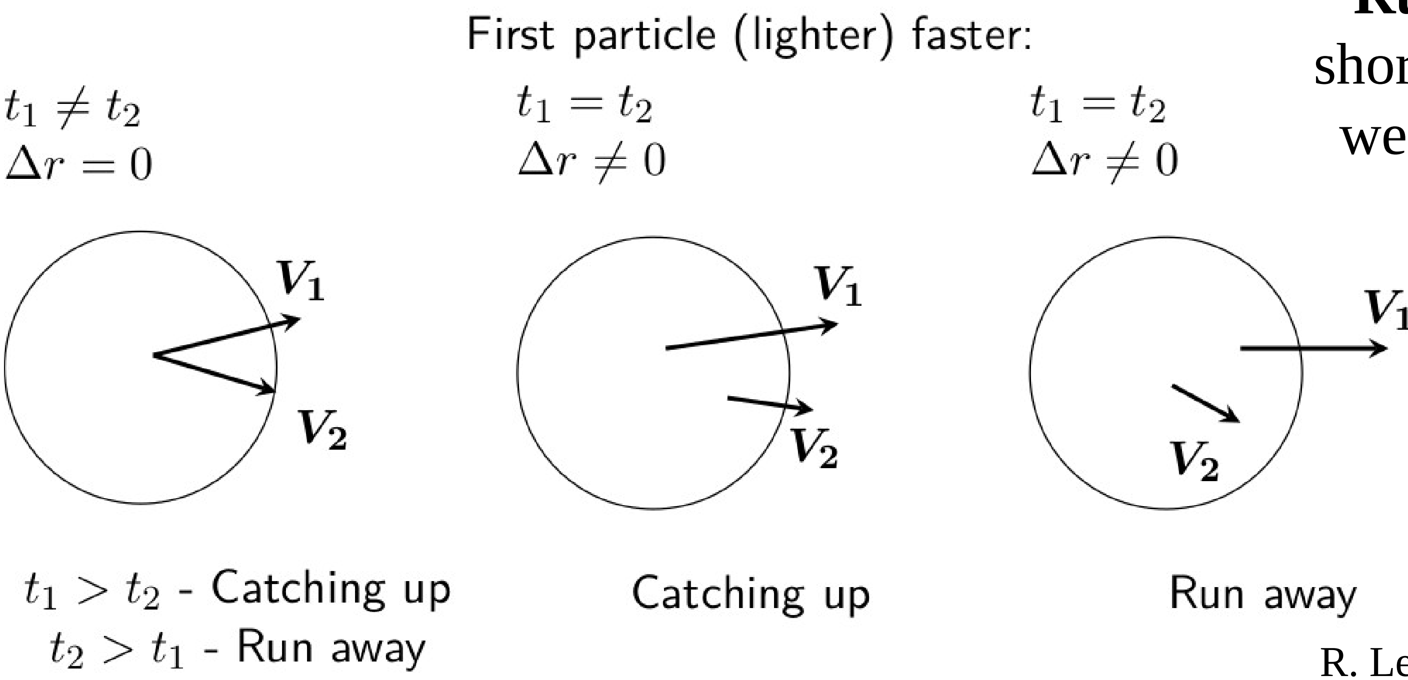
Non-identical baryon-(anti)baryon

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

Non-identical Particle Combinations

Catching up
longer interaction,
strong correlation

Running away
shorter interaction,
weak correlation



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

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
C_1^1 -> sensitive to the emission asymmetry

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

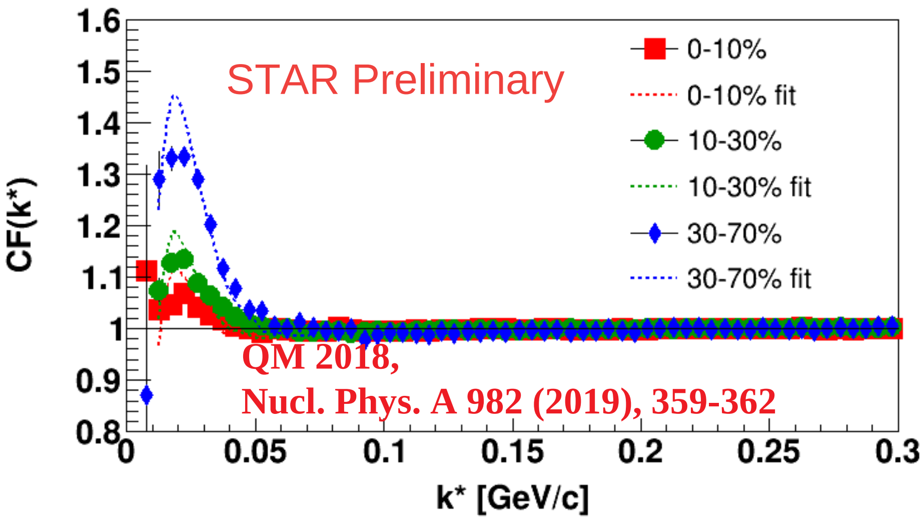
P. Danielewicz and S.Pratt.
Phys. Rev. C75:034907 2007

Results

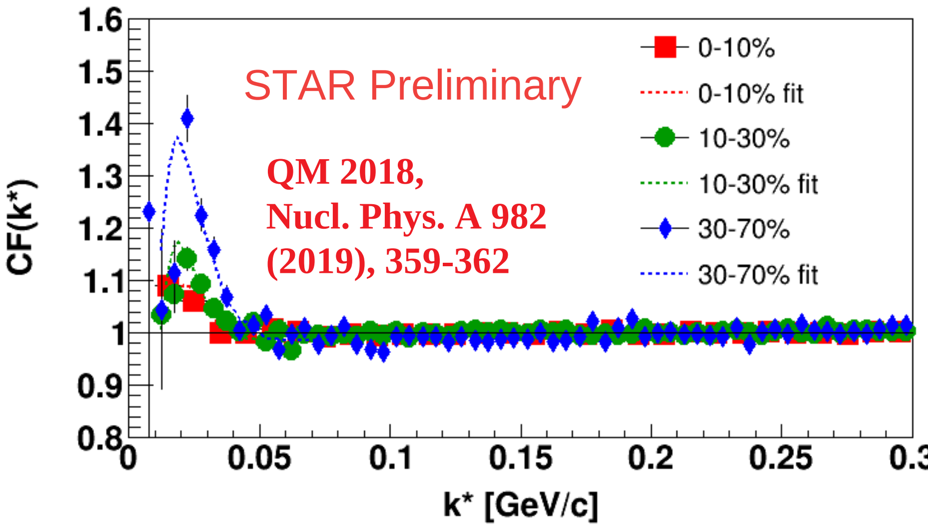
Geometry

Centrality Dependence in Proton Femtoscopy

proton-proton @39 GeV



antiproton-antiproton @39 GeV

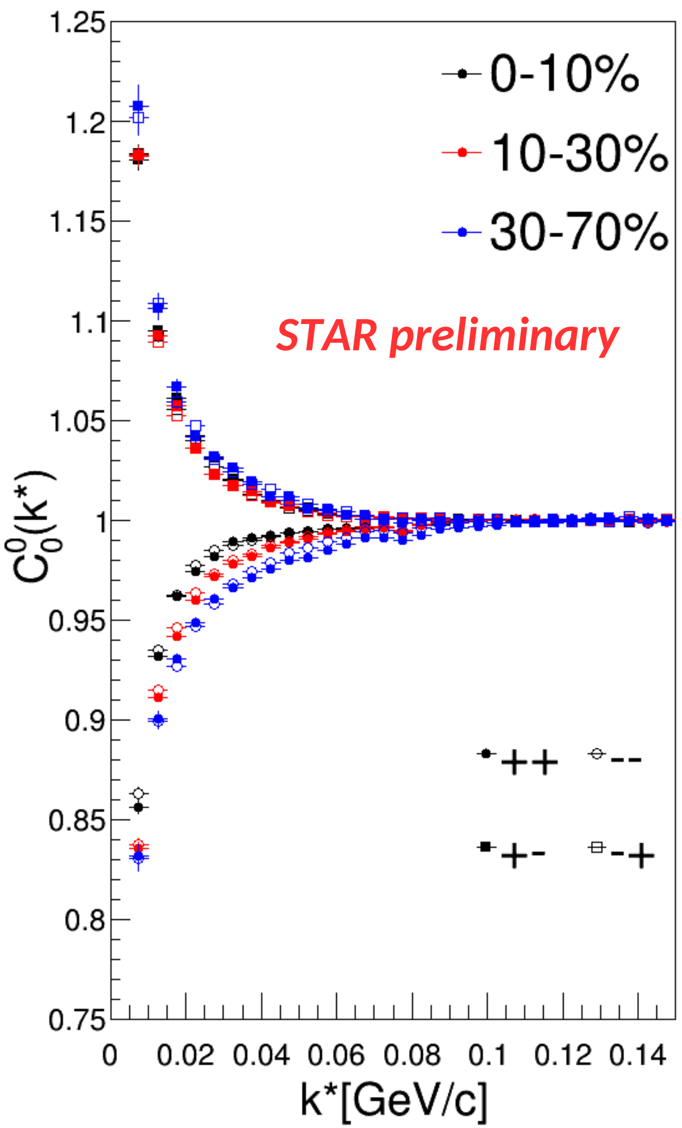


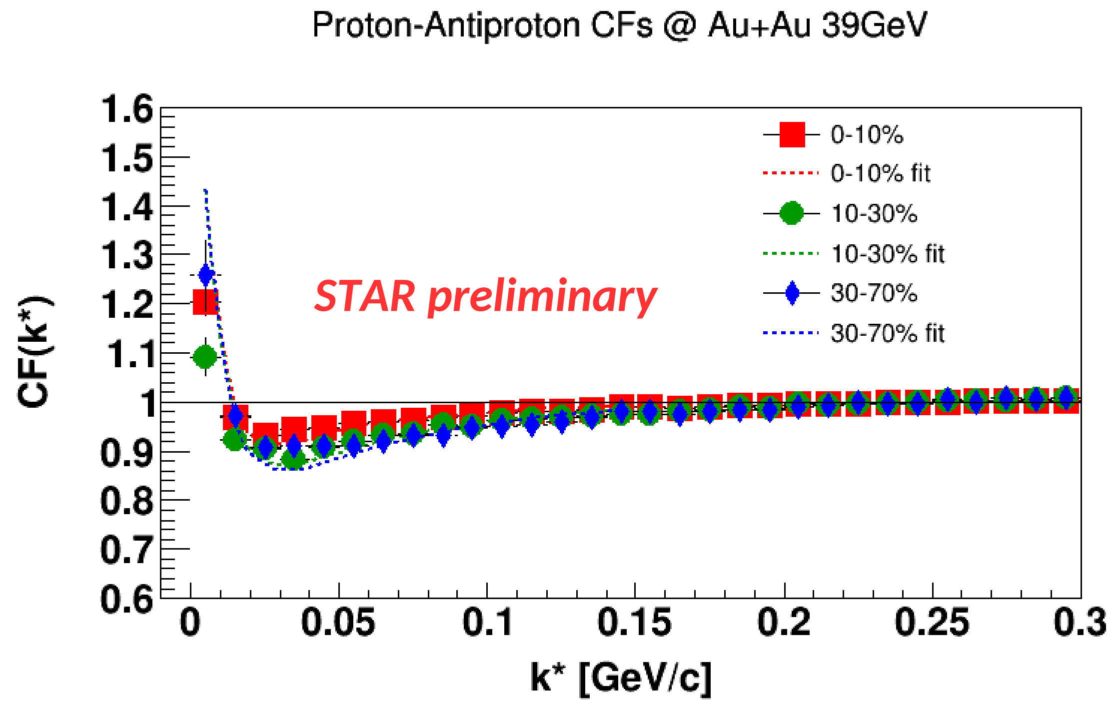
centrality	R_{inv} $p-p$ [fm]	R_{inv} $\overline{p}-\overline{p}$ [fm]	R_{inv} $p-\overline{p}$ [fm]
0-10%	$\mathbf{4.00} \pm 0.15 \pm 0.02$	$\mathbf{3.83} \pm 0.20 \pm 0.03$	$\mathbf{3.39} \pm 0.12 \pm 0.14$
10-30%	$\mathbf{3.61} \pm 0.13 \pm 0.17$	$\mathbf{3.68} \pm 0.15 \pm 0.11$	$\mathbf{2.69} \pm 0.10 \pm 0.12$
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 proton-proton and antiproton-antiproton correlation functions

R_{inv} – 1D radius in LCMS system

Centrality Dependence in Nonidentical Particles @39 GeV





Clear centrality dependence

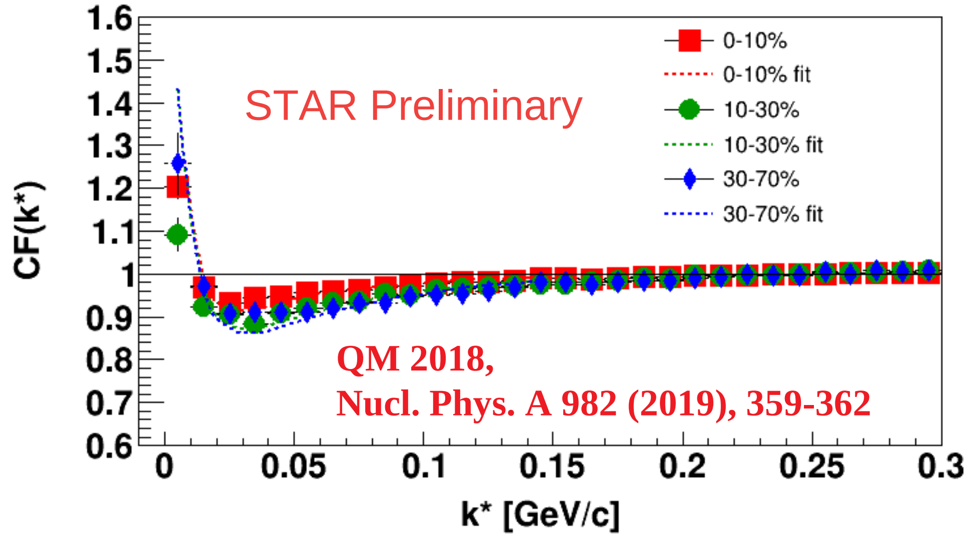
$$R(0-10\%) > R(10-30\%) > R(30-70\%)$$

QM 2018,
Nucl. Phys. A 982 (2019), 359-362

No significant difference between proton-proton and antiproton-antiproton correlation functions

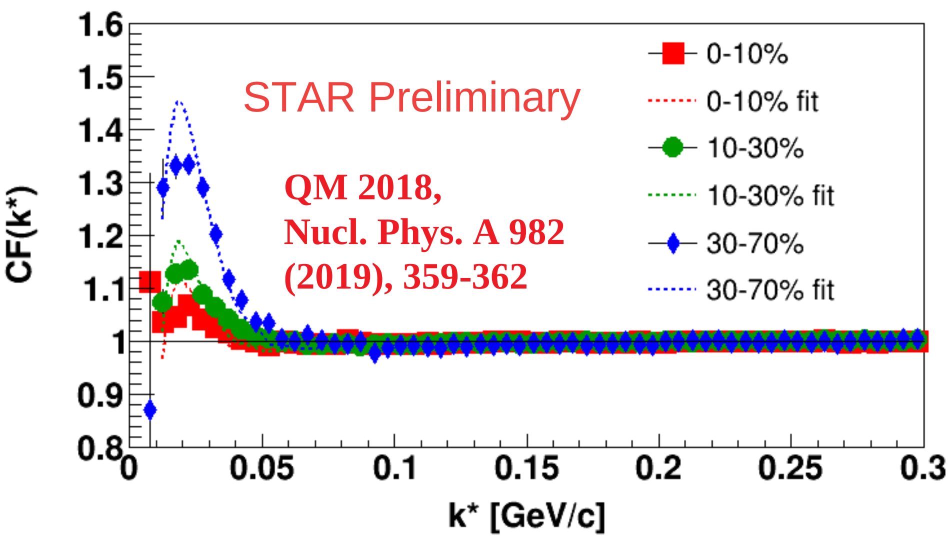
System Dependence in Proton Femtoscopy @39 GeV

Radii from proton-proton and antiproton-antiproton systems differ from those from proton-antiprootn system → Residual Correlations.
Residual feed-down correction needs to be applied.

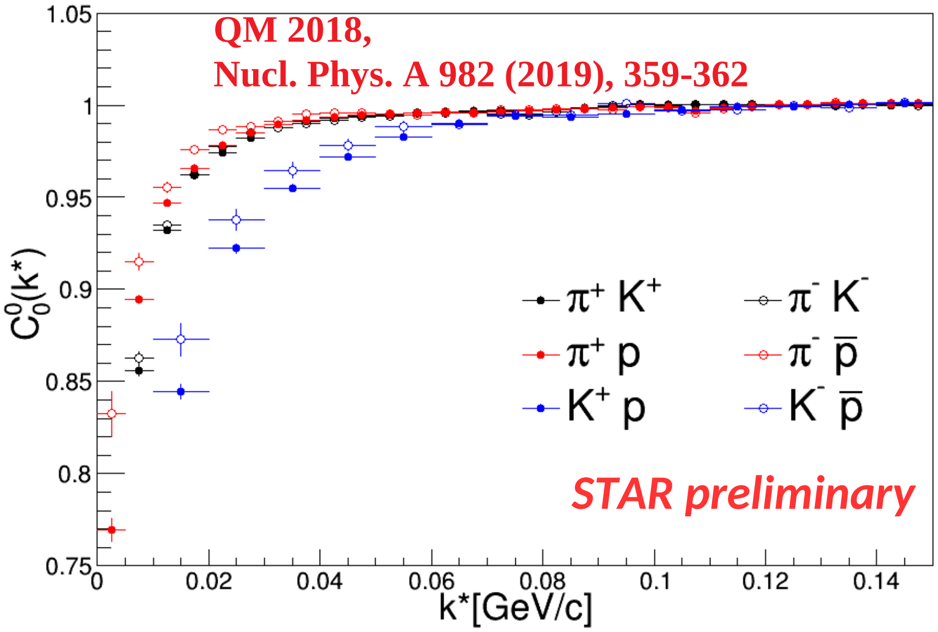


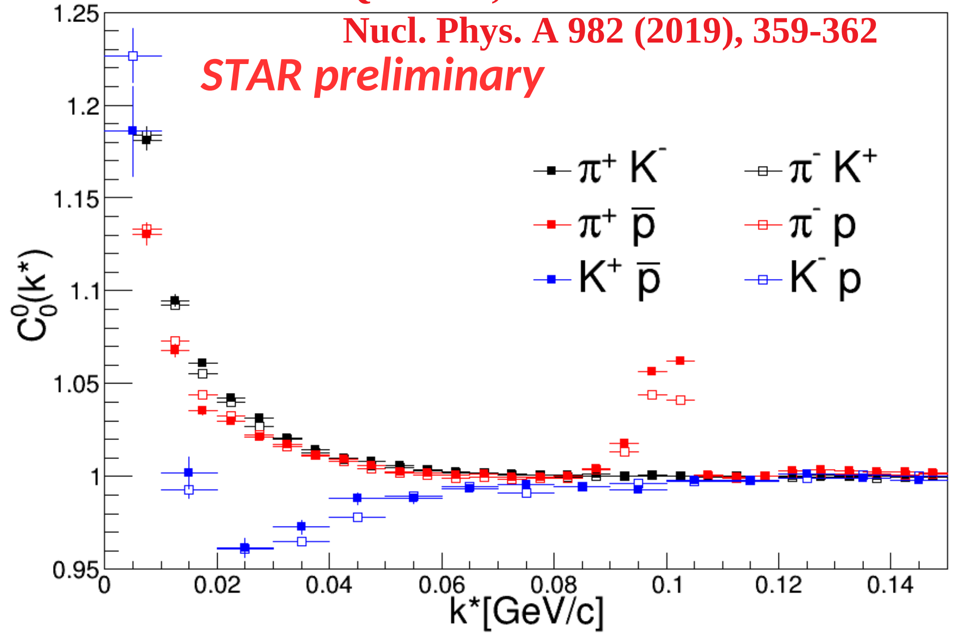
proton-antiproton @39 GeV

proton-proton @39 GeV



System Dependence in Nonidentical Particles @39 GeV





Clear system dependence

Same sign: correlations dominated by Coulomb interaction

Coulomb strength depends on Bohr radius of the pair

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

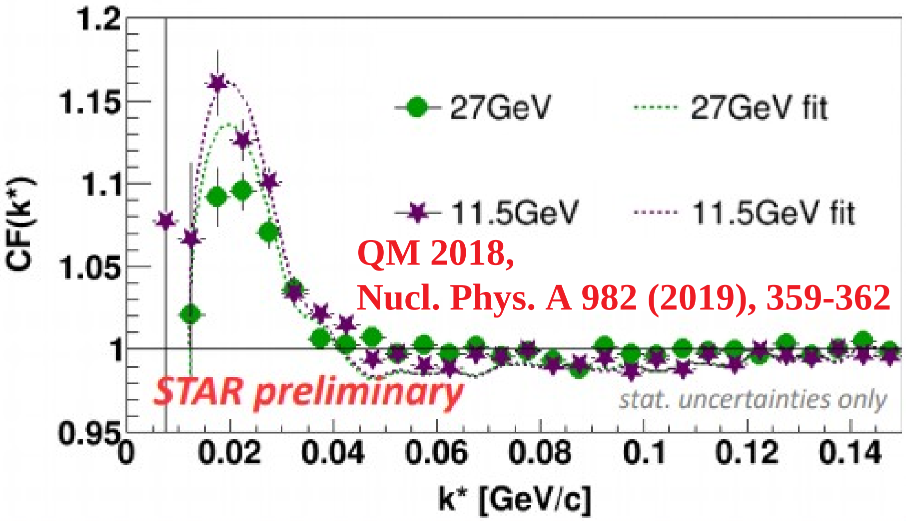
Different shape due to strong interaction

Opposite sign: interaction more complicated

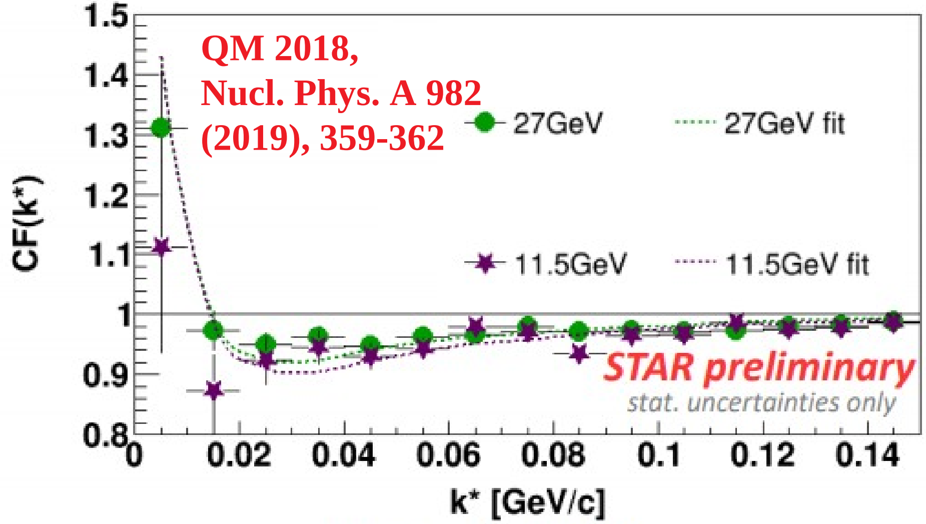
Strong interaction not negligible in $K - p$.

Energy Dependence in Proton Femtoscopy

proton-proton, centrality 0-10%



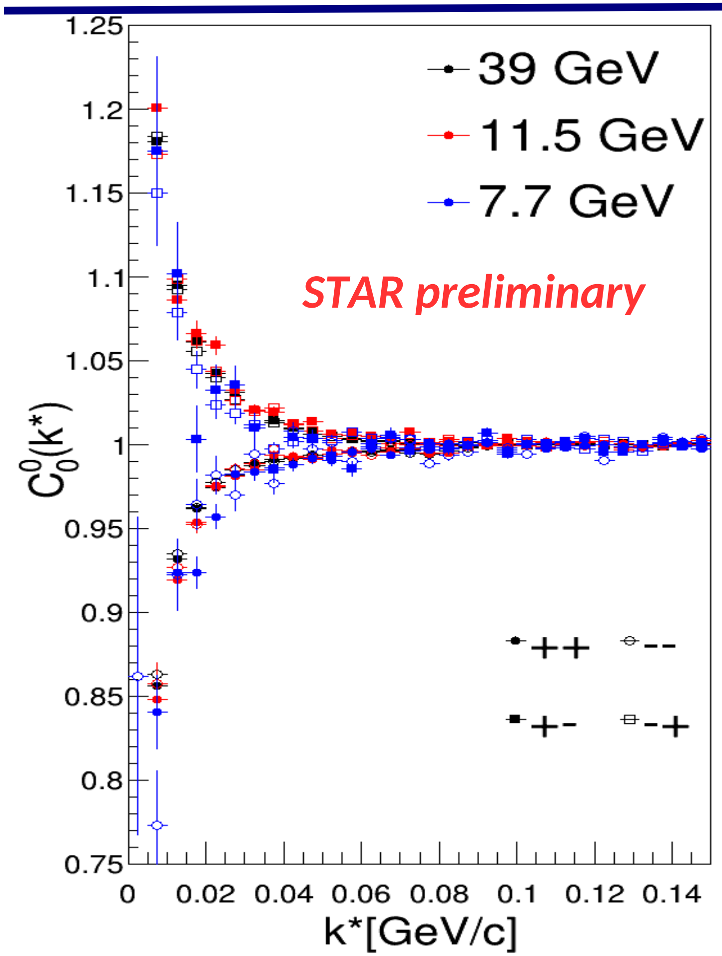
proton-antiproton, centrality 0-10%

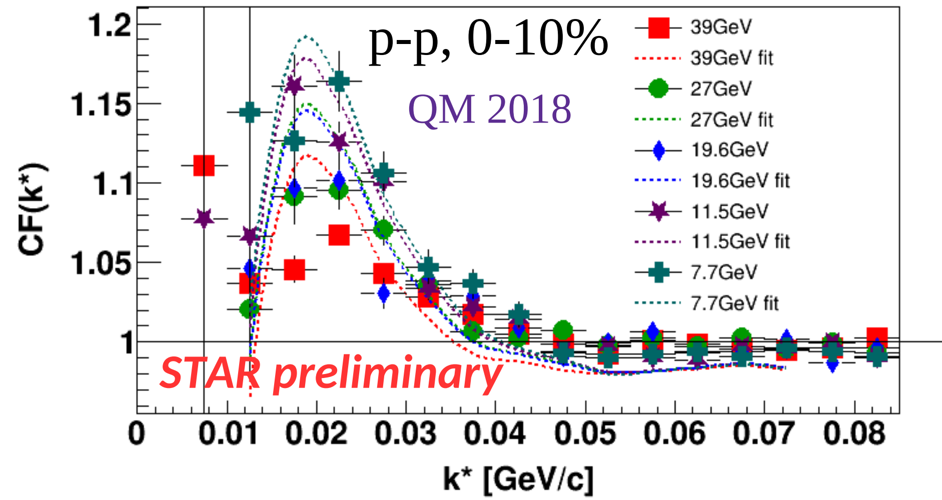


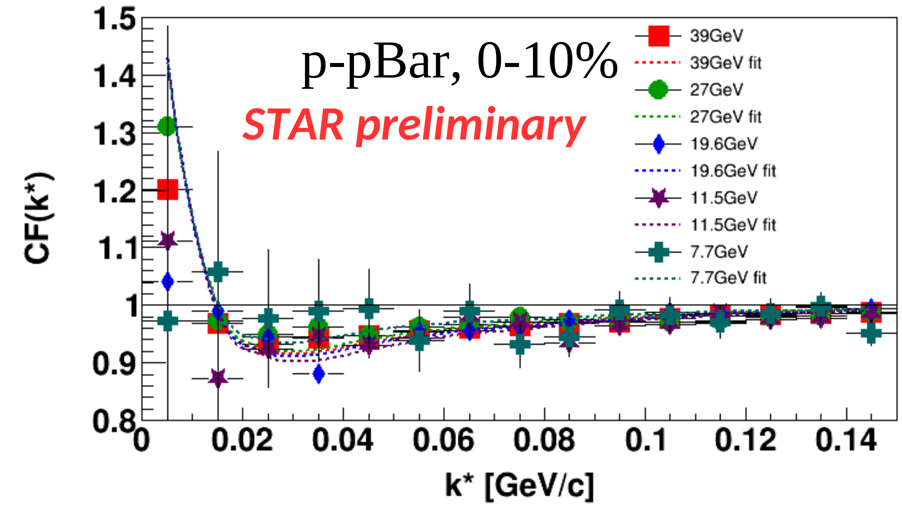
energy	R_{inv} $p-p$ [fm]	R_{inv} $p-\bar{p}$ [fm]
7.7 GeV	$\mathbf{3.59} \pm 0.16 \pm 0.19$	
11.5 GeV	$\mathbf{3.66} \pm 0.08 \pm 0.05$	$\mathbf{3.30} \pm 0.42 \pm 0.28$
19.6 GeV	$\mathbf{3.82} \pm 0.15 \pm 0.06$	$\mathbf{3.32} \pm 0.25 \pm 0.13$
27 GeV	$\mathbf{3.80} \pm 0.12 \pm 0.08$	$\mathbf{3.49}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

Energy dependence more significant for proton-proton than for proton-antiproton system.

Energy Dependence in Various Systems



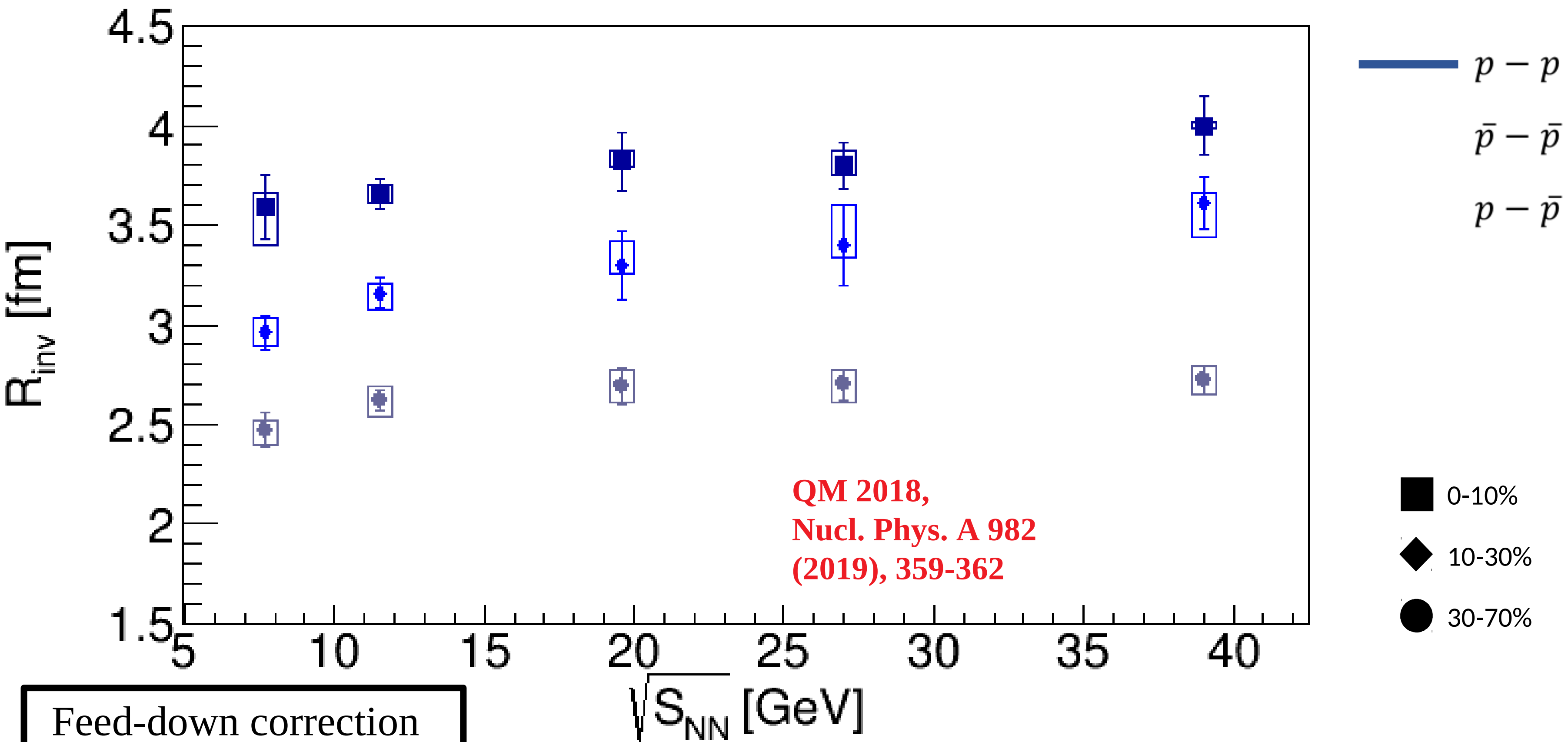




Energy dependence more significant for proton-proton than for proton-antiproton and pion-kaon systems.

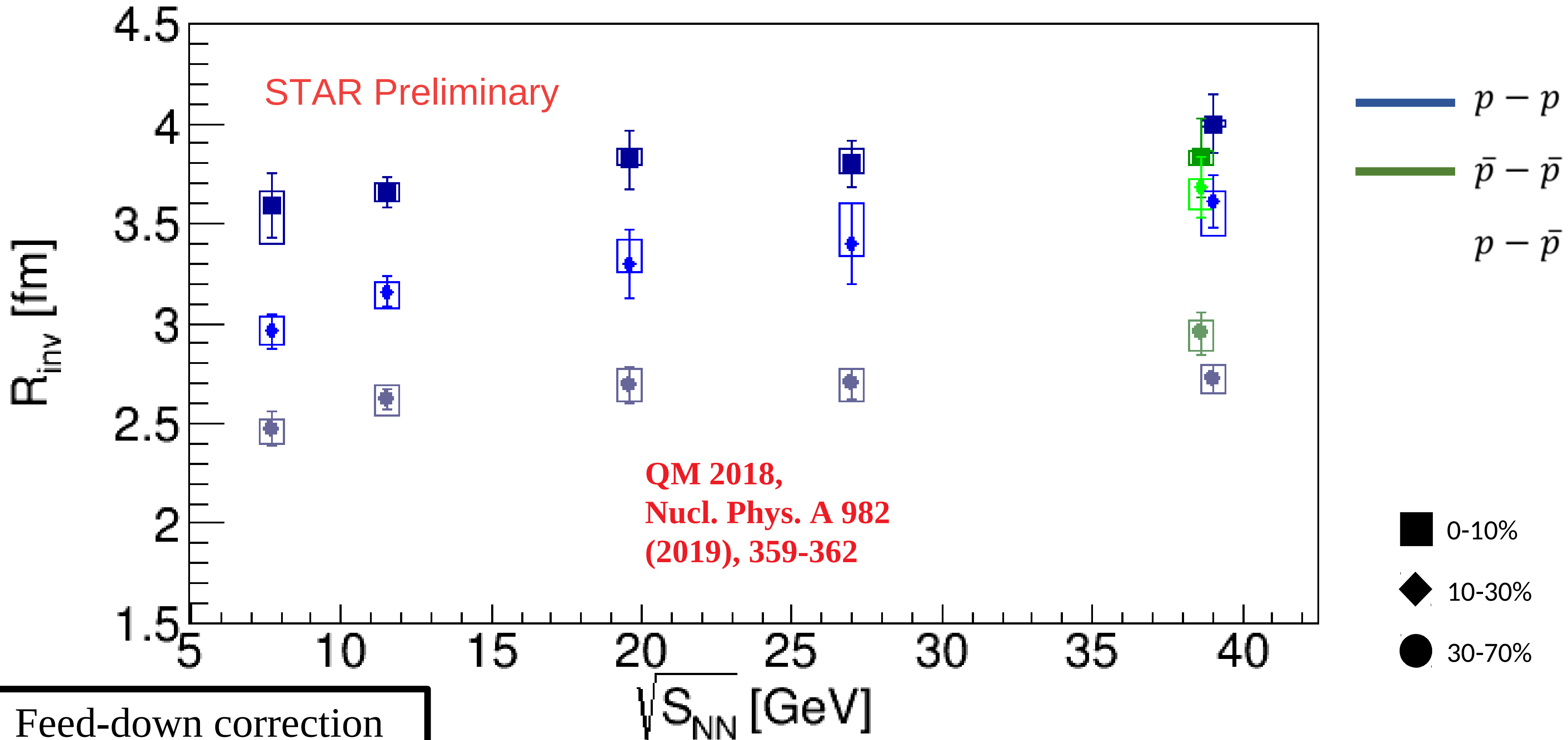
QM 2018,
Nucl. Phys. A 982 (2019), 359-362

Proton Femtoscopy in BES



Feed-down correction may decrease significance of the centrality dependence.

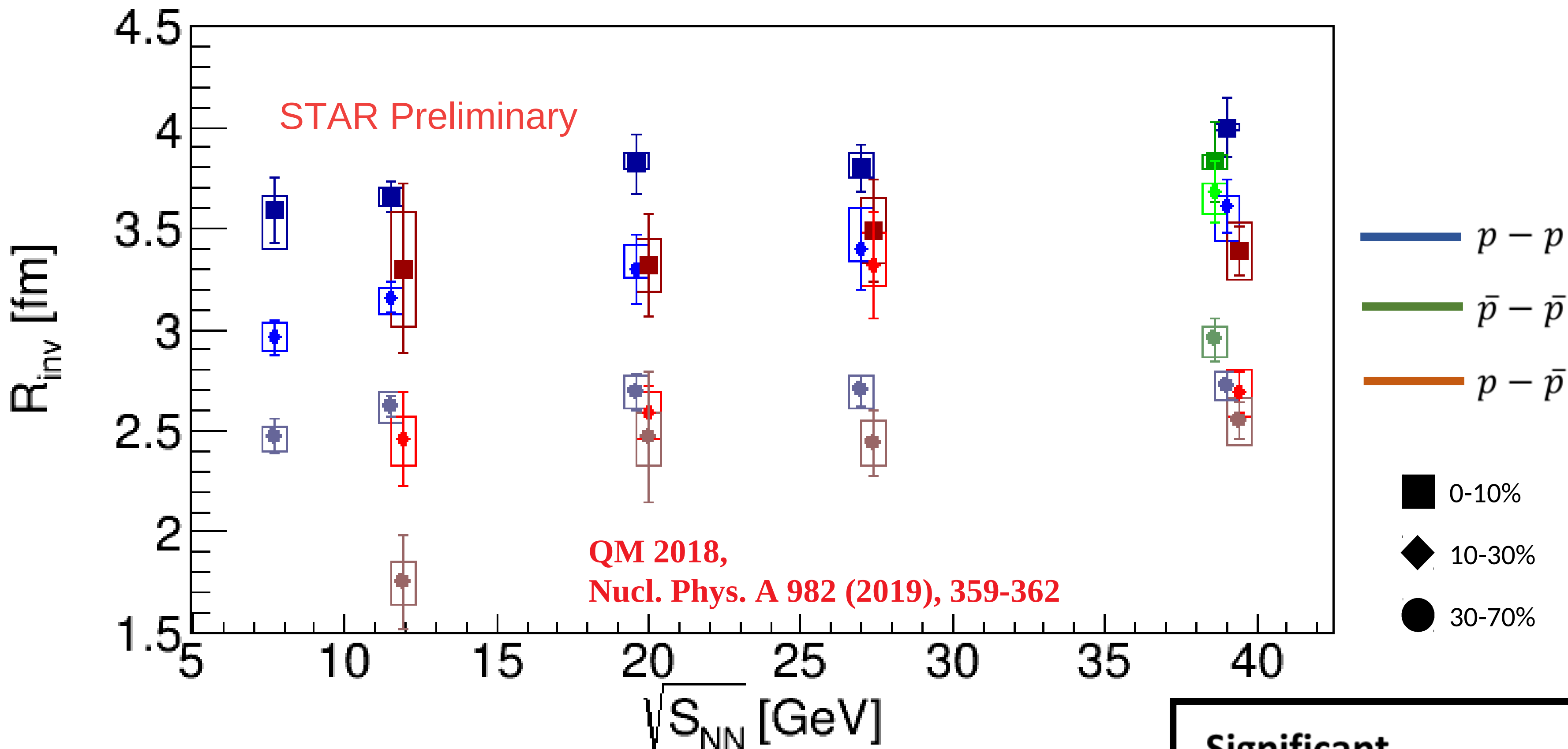
Proton Femtoscopy in BES



Feed-down correction may decrease significance of centrality dependence.

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

Proton Femtoscopy in BES



Feed-down correction may decrease significance of centrality dependence.

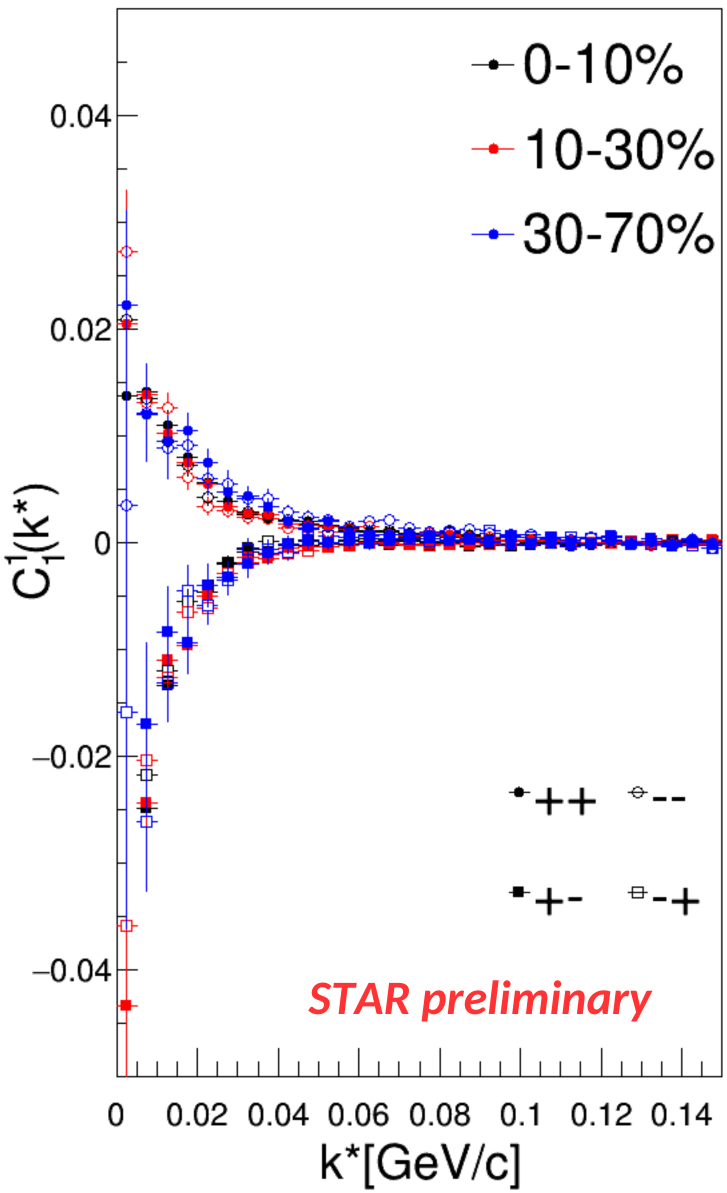
No significant difference between $p-p$ and $\bar{p}-\bar{p}$ correlation functions at $\sqrt{s_{NN}}$ = 39 GeV

Significant centrality dependence.

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

Dynamics

Centrality and Energy Dependencies in π-K systems

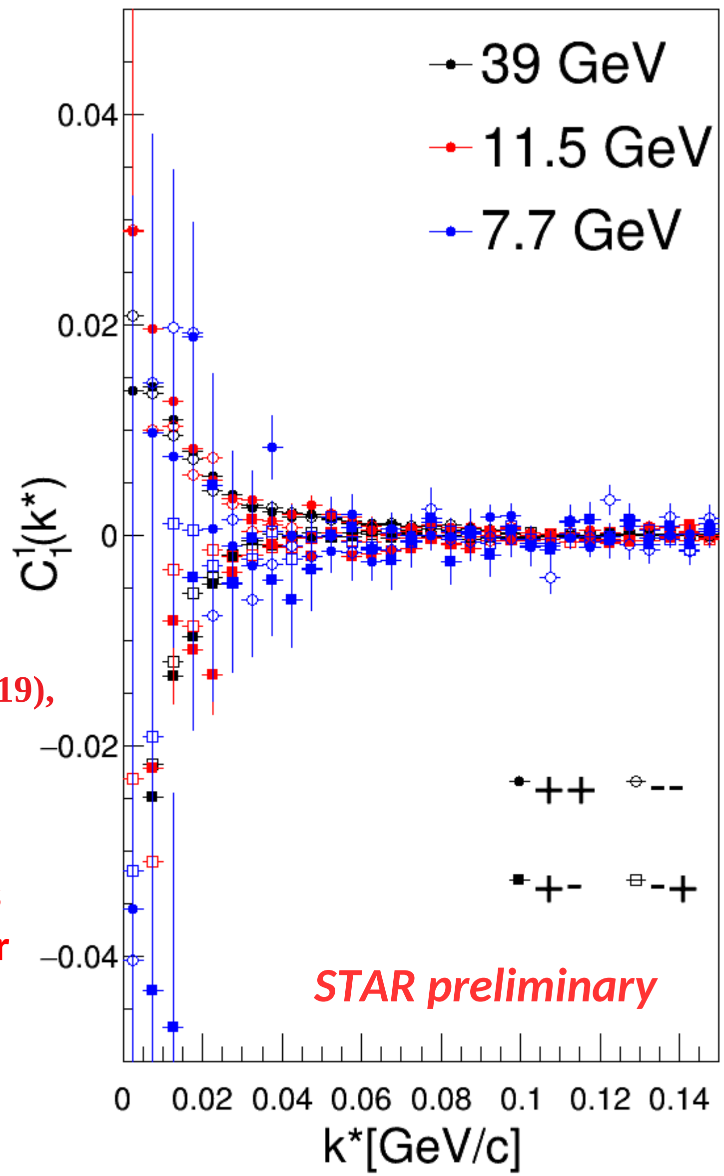


Clear signal of emission asymmetry

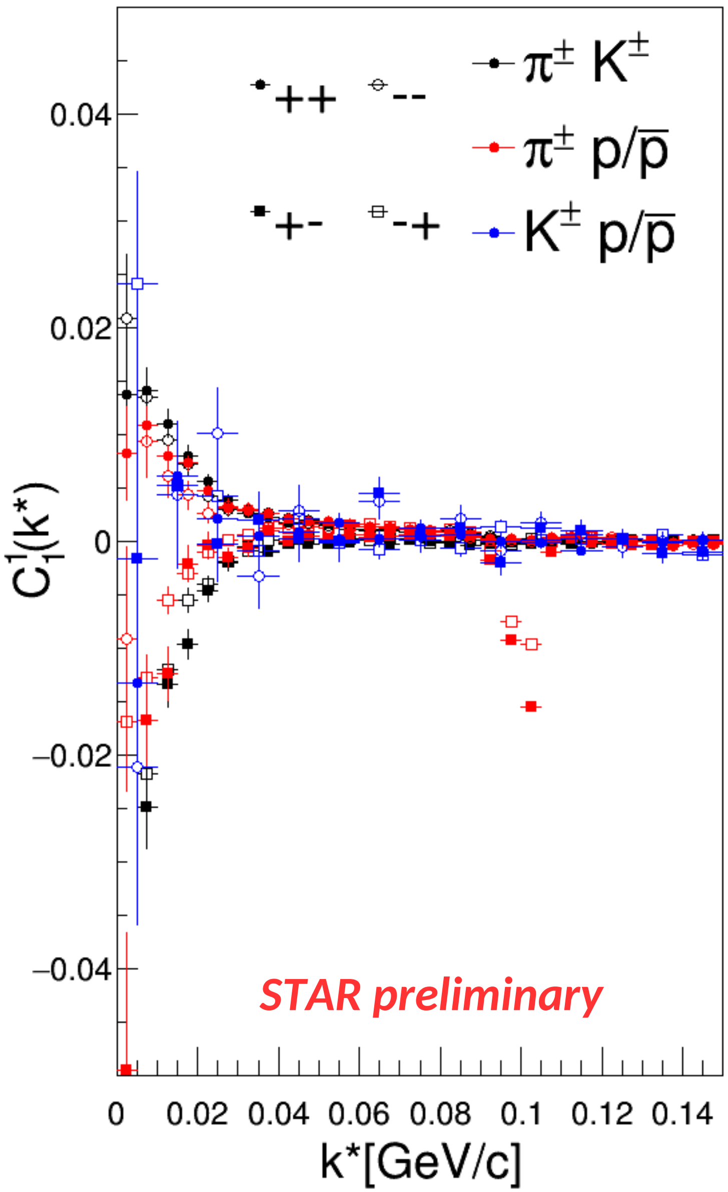
Pions emitted closer to center and/or later than Kaons

QM 2018,
Nucl. Phys. A 982 (2019), 359-362

Asymmetry does not disappear for low energies.

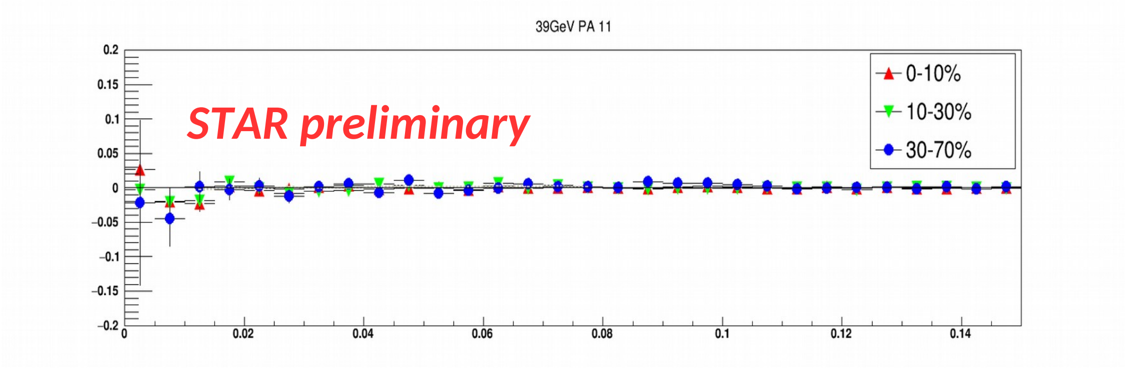


System Dependence @39 GeV



Expected ordering of particles:
Lighter particle is emitted closer to the center and/or later.

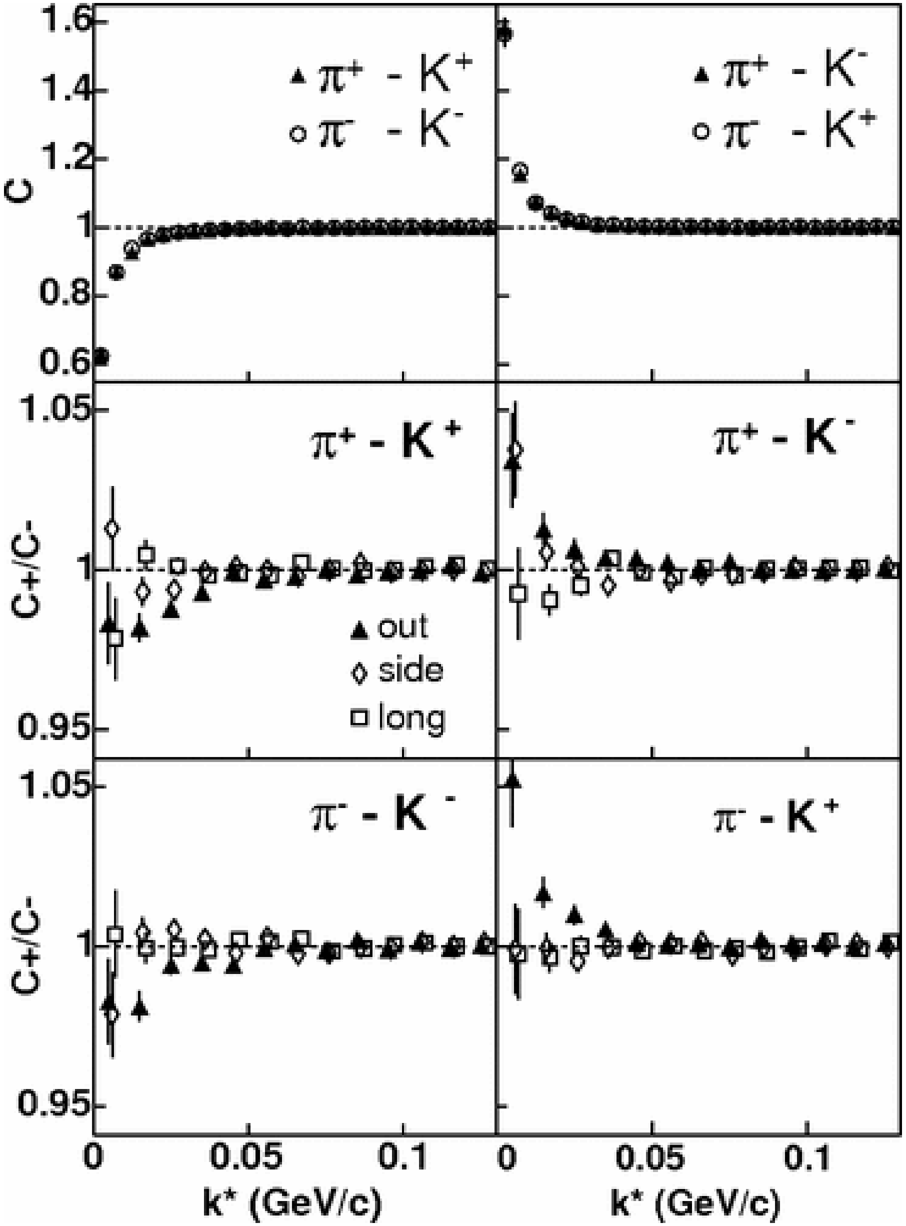
No visible asymmetry between protons and antiprotons – similar masses.

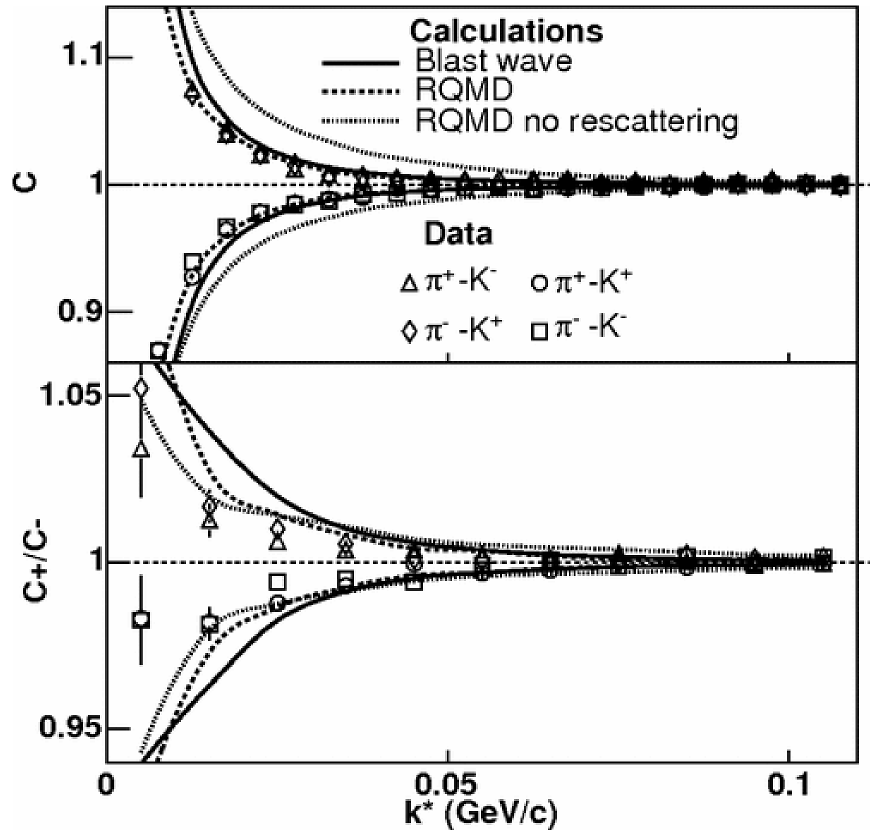


QM 2018,
Nucl. Phys. A 982 (2019), 359-362

Heavier particles pushed by flow outwards stronger than lighter particles.

Pion-Kaon Results @ 130GeV





	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

Kaons are emitted earlier and/or further than Pions.

Phys. Rev. Lett. 91, 262302 (2003)

Conclusions & Summary

Summary about Geometry

Geometry:

- Clear centrality dependence of source size at BES energies
- Clear system dependence of source size at BES energies
- Visible energy dependence of source size at BES energies

No visible difference between Proton-Proton and Antiproton-Antiproton correlation functions

Correlation functions contaminated by residual correlations – residual correction required

Strong interaction seen not negligible in Kaon-Proton

Summary about Dynamics

Clear signal of emission asymmetry for particles with different masses at BES energies

Asymmetry not disappeared for low energies

Lighter particles emitted closer to the center of the source and/or later than heavier particles – flow pushes heavier particles harder to the edge

Thank you!

Backup

Correlation Function

$$CF(k^*) = \frac{\sum_{pair} \delta(k^*_{pair} - k^*) w(k^*, r^*)}{\sum_{pair} \delta(k^*_{pair} - k^*)}$$

$$w(k^*, r^*) = |\psi^{S(+)}_{-k^*}(r^*) + (-1)^S \psi^{S(+)}_{k^*}(r^*)|^2/2$$

$$\psi^{S(+)}_{-k^*}(r^*) = e^{i\delta_c}\sqrt{A_c(\eta)}[e^{-ik^*r^*}F(-i\eta, 1, i\xi) + f_c(k^*)\frac{\widetilde{G}(\rho,\eta)}{r^*}]$$

$$f_c(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_c}h(k^* a_c) - ik^* A_c(k*)]^{-1}$$

is the s-wave scattering amplitude renormalized by Coulomb interaction.

$A_C(k^*) = (2\pi/k^* a_c)\frac{1}{exp(2\pi/k^* a_c) - 1}$, $h(x) = \frac{1}{x^2}\sum_{n=1}^{\infty}\frac{1}{n(n^2 + x^{-2})} - C + ln|x|$,

and $\widetilde{G}(\rho, \eta) = \sqrt{A_c(k^*)}(G_0(\rho, \eta) + iF_0(\rho, \eta))$ is a combination of regular (F_0) and singular (G_0) s-wave Coulomb functions.