

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

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Outline

I) Introduction

- RHIC, STAR
- Femtoscopy

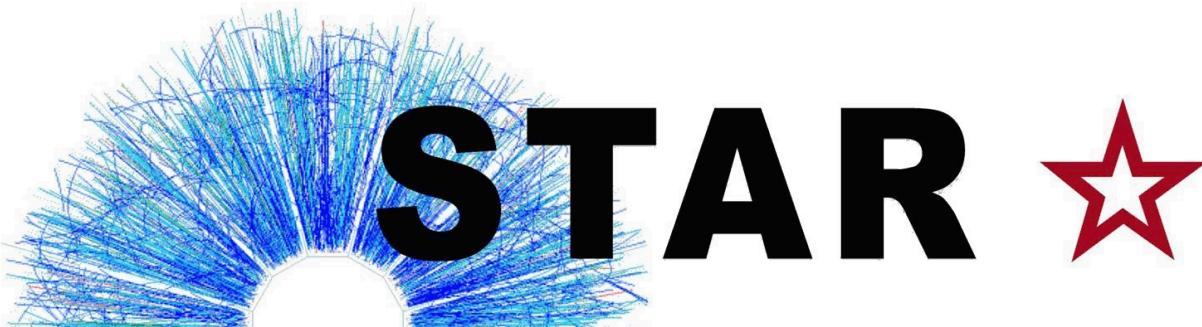
III) Dynamics aspects

- Centrality dependence
- Energy dependence
- System dependence

II) Geometry aspects

- Centrality dependence
- Energy dependence
- System dependence

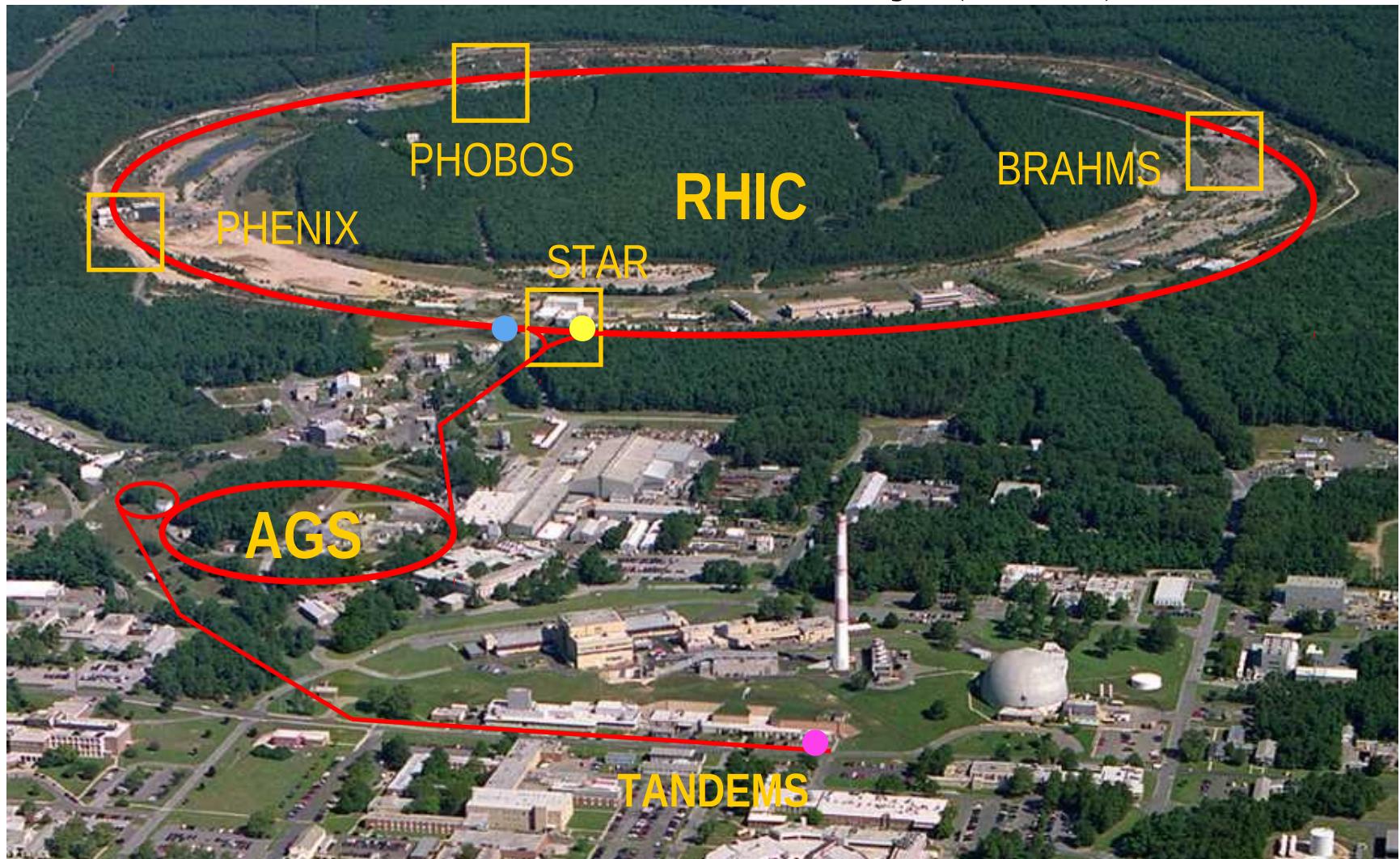
IV) Conclusions and summary





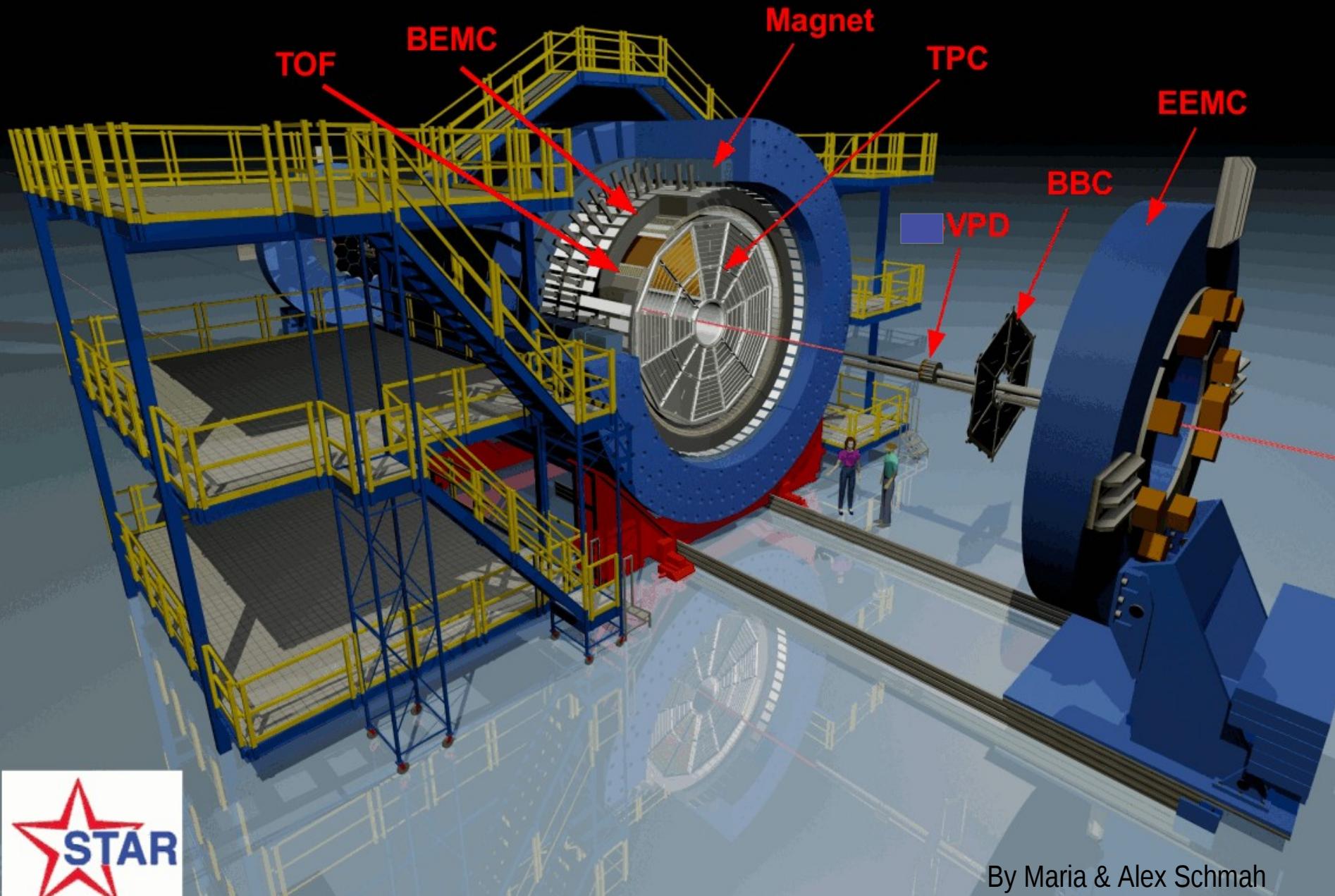
Introduction

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

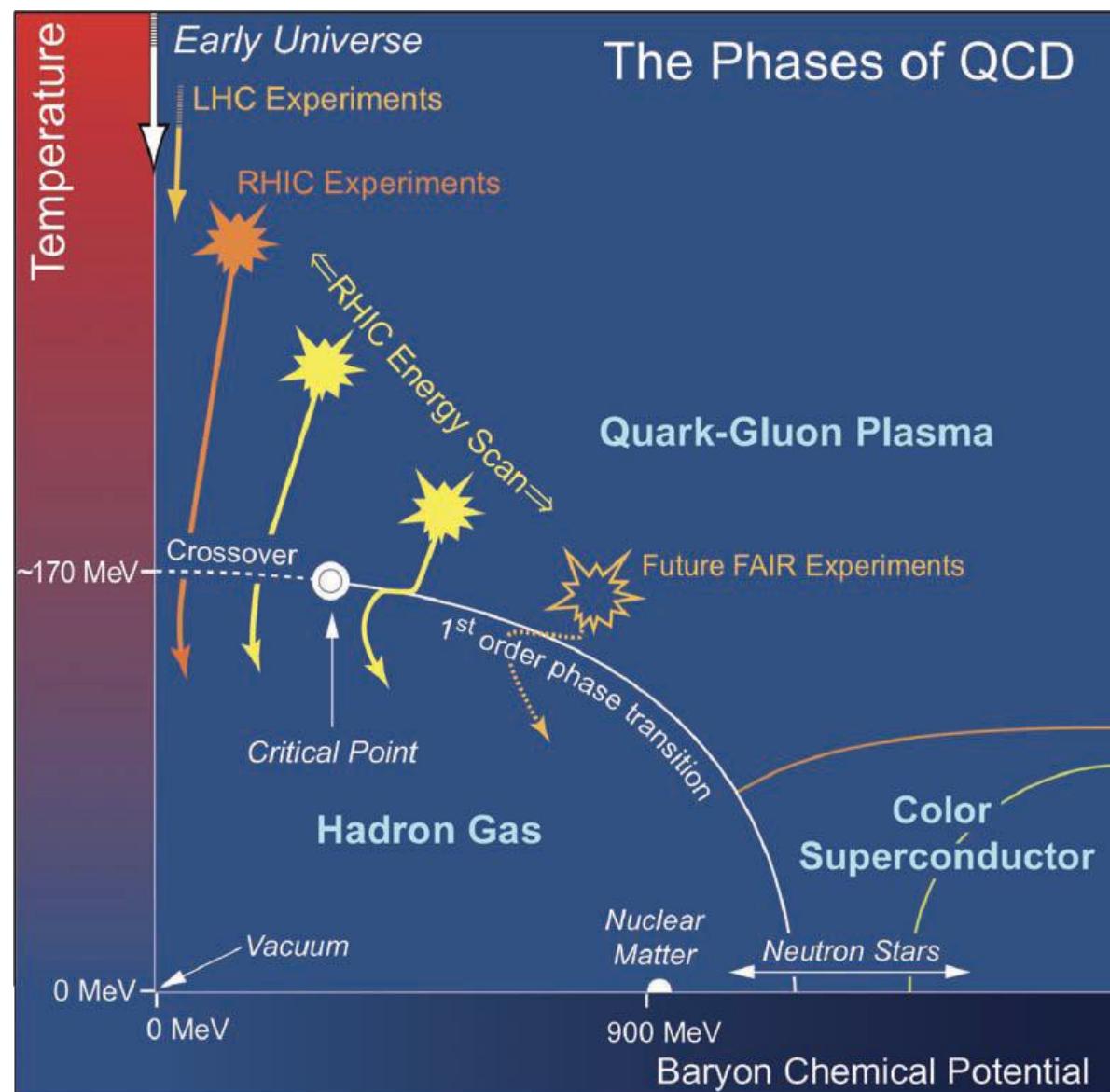


- 2 concentric rings of 1740 superconducting magnets
- 3.8 km circumference

The Solenoidal Tracker At RHIC



Introduction



RHIC Top Energy

p+p, p+Al, p+Au, d+Au,
 ^3He +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 QGP signatures

Fixed-Target Program

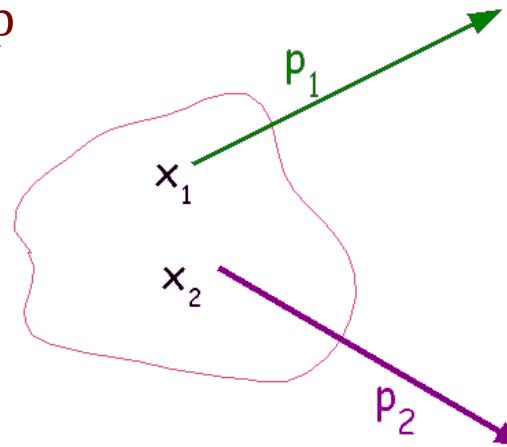
Au+Au = 3.0-7.7 GeV
High baryon density regime
with 420-720 MeV

Few Words About Femtoscopy

Single- and two- particle distributions

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

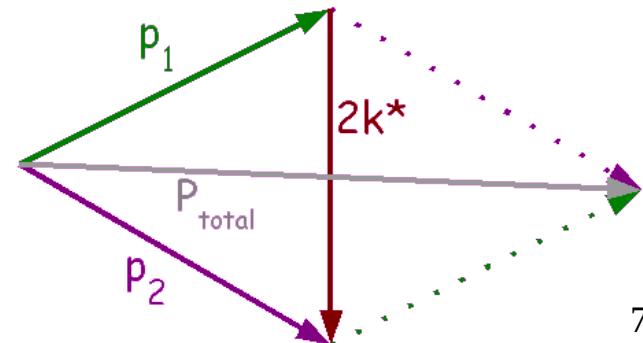
S(x,p) – emission function: the distribution of source density probability of finding particle with x and p



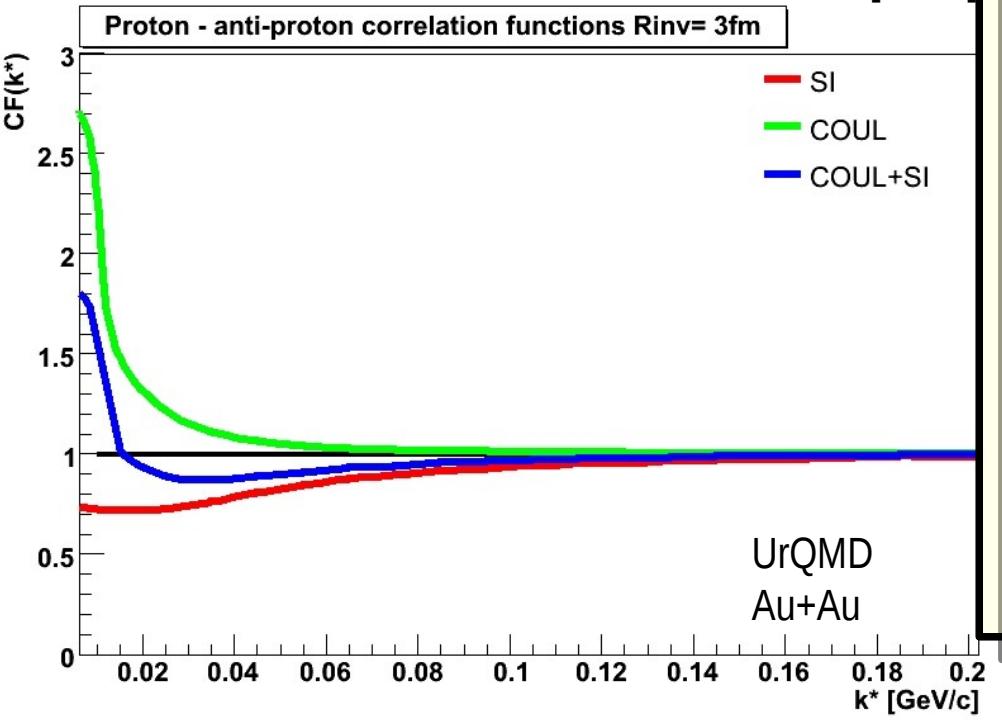
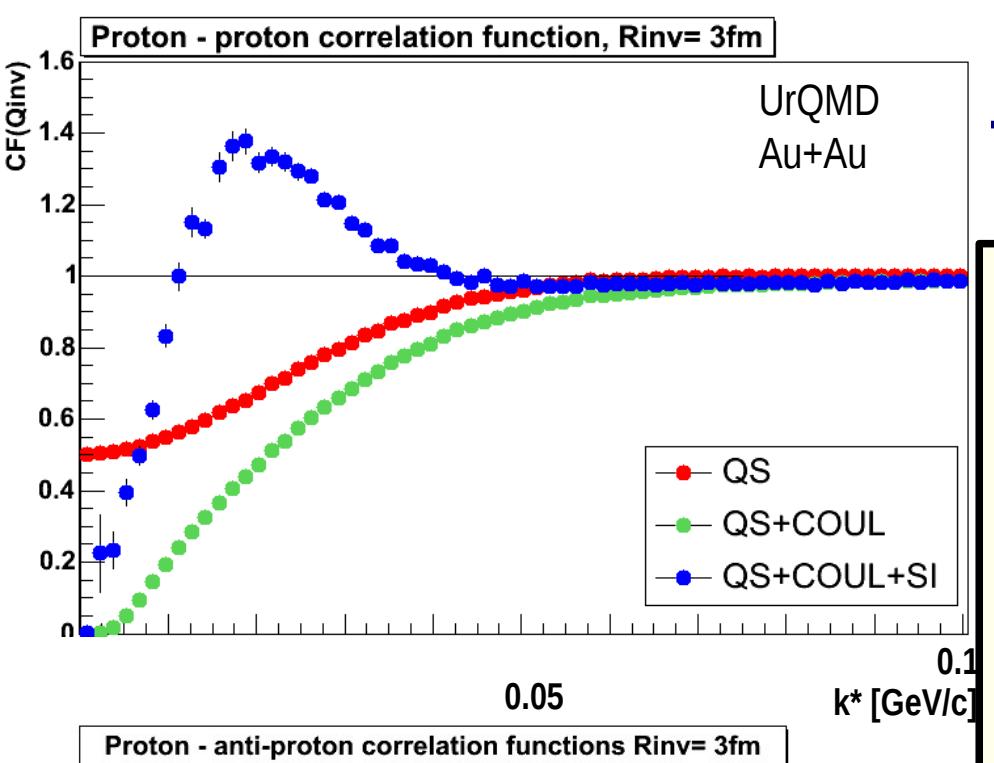
$$P_2(p_1, p_2) = E_1 E_2 \frac{dN}{d^3 p_1 d^3 p_2} = \int d^4 x_1 S(x_1, p_1) d^4 x_2 S(x_2, p_2) \Phi(x_2, p_2 | x_1, p_1)$$

The correlation function

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



Sources of Correlations



Identical baryon- baryon

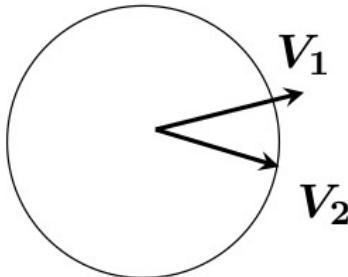
- Quantum Statistics- QS
- Final State Interactions- FSI
 - Coulomb
 - Strong

Non-identical baryon- (anti)baryon

- Final State Interactions- FSI
 - Coulomb
 - Strong

Non-identical Particle Combinations

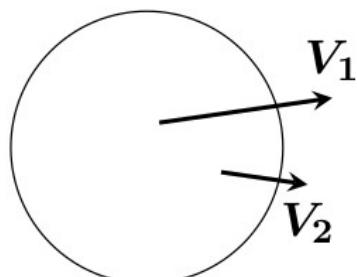
$$t_1 \neq t_2 \\ \Delta r = 0$$



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

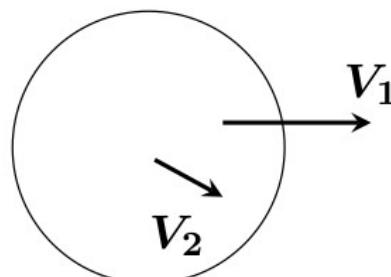
First particle (lighter) faster:

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



Catching up

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



Run away

Catching up
longer interaction,
strong correlation

Running away
shorter interaction,
weak correlation

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

Spherical Harmonics

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

Ω – full solid angle

$Y_l^m(\theta, \phi)$ – spherical harmonic function

$q = |\mathbf{q}|, \theta, \phi$ – 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



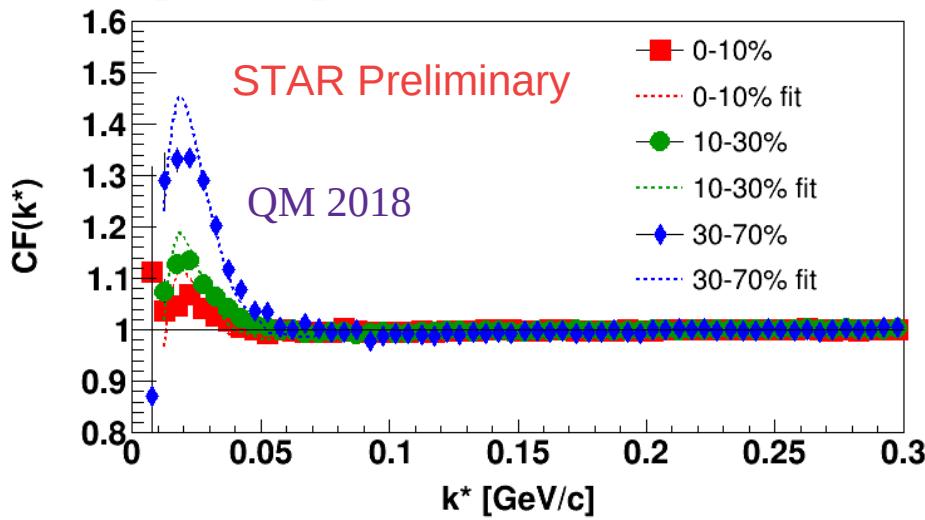
Results



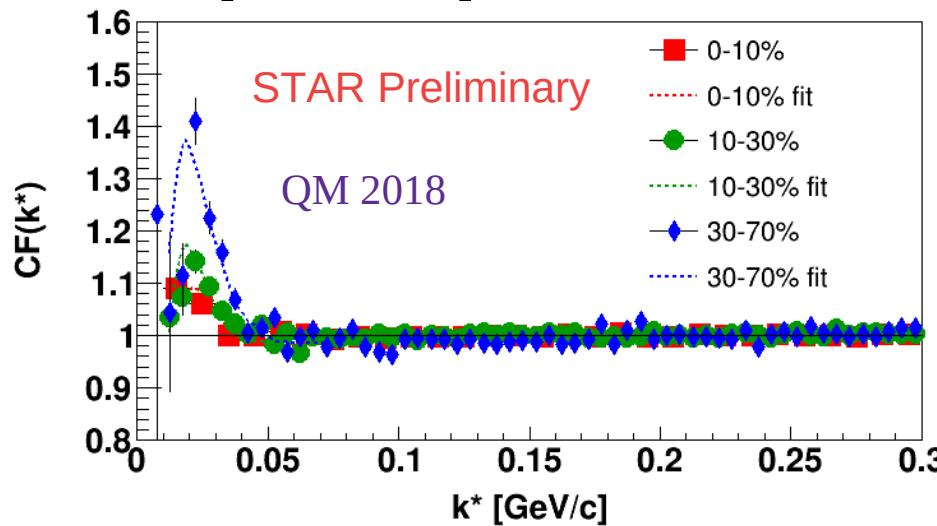
Geometry

Centrality Dependence in Proton Femtoscopy

proton-proton @39 GeV



antiproton-antiproton @39 GeV

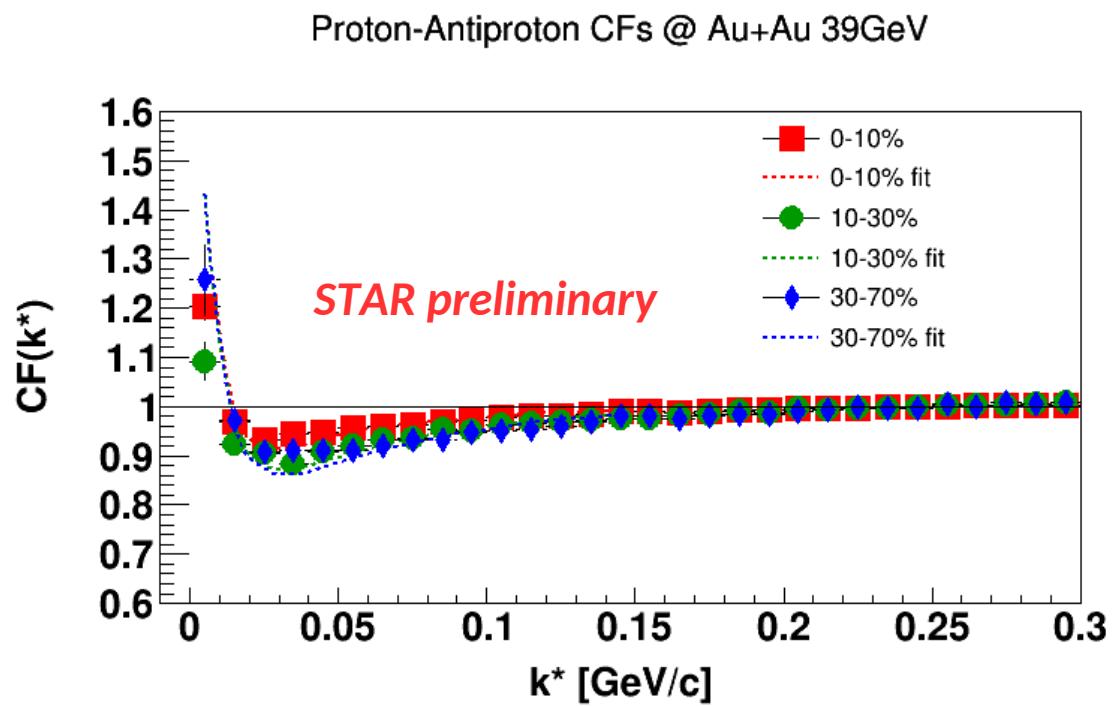
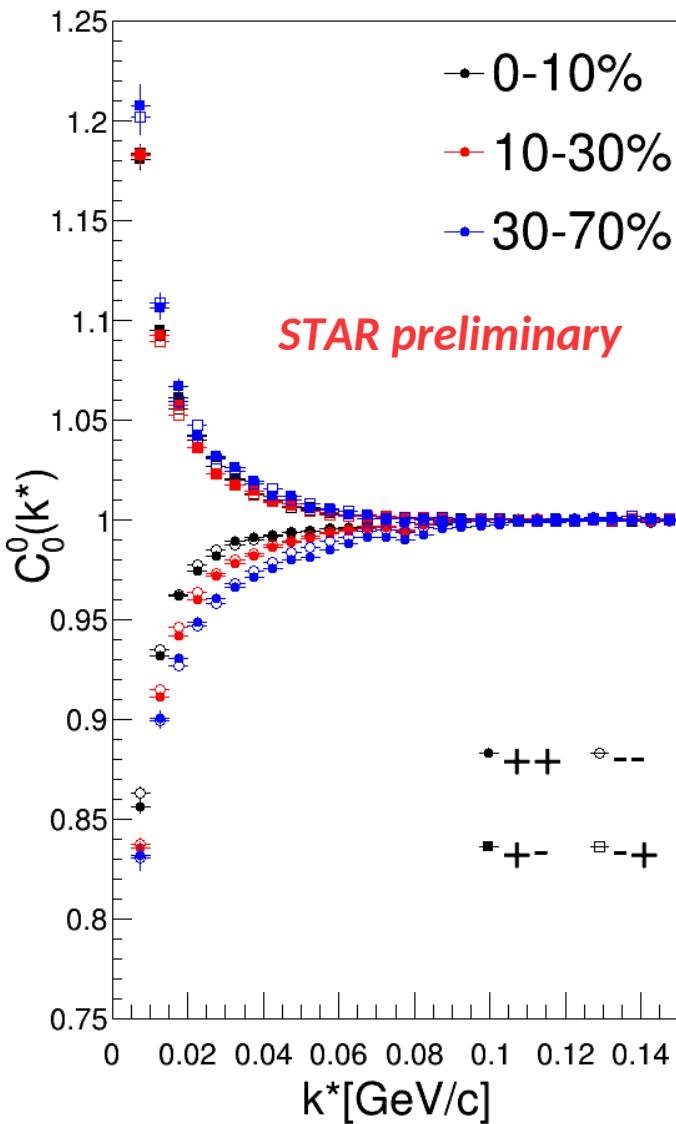


centrality	$R_{inv} p - p$ [fm]	$R_{inv} \bar{p} - \bar{p}$ [fm]	$R_{inv} p - \bar{p}$ [fm]
0-10%	$4.00 \pm 0.15 \pm 0.02$	$3.83 \pm 0.20 \pm 0.03$	$3.39 \pm 0.12 \pm 0.14$
10-30%	$3.61 \pm 0.13 \pm 0.17$	$3.68 \pm 0.15 \pm 0.11$	$2.69 \pm 0.10 \pm 0.12$
30-70%	$2.72 \pm 0.07 \pm 0.07$	$2.95 \pm 0.11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

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



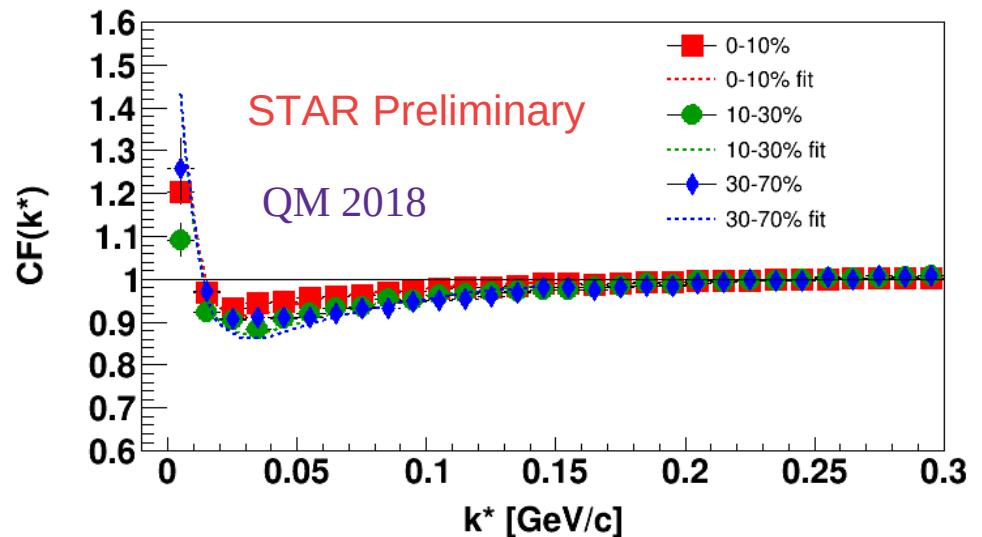
Clear centrality dependence

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

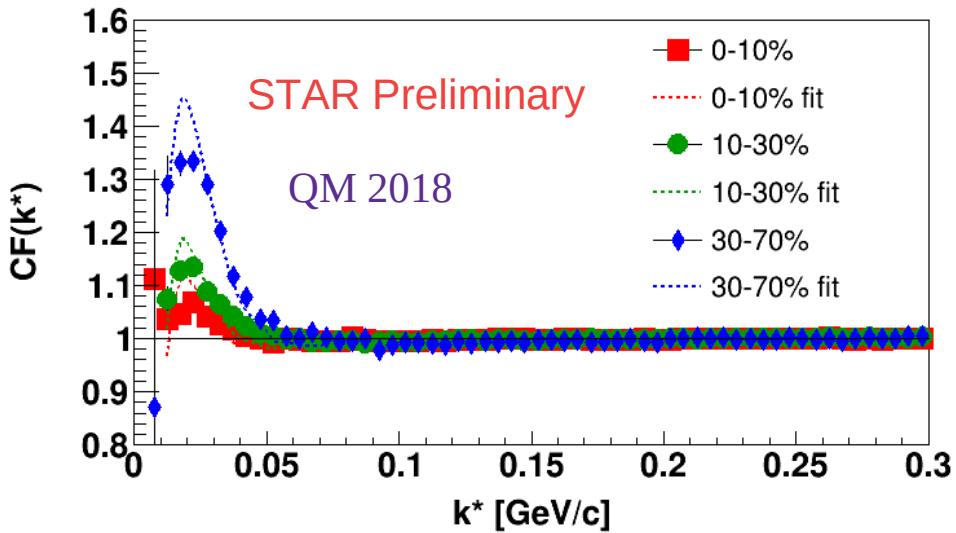
No significant difference between proton-proton and antiproton-antiproton correlation functions

System Dependence in Proton Femtoscopy @39 GeV

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

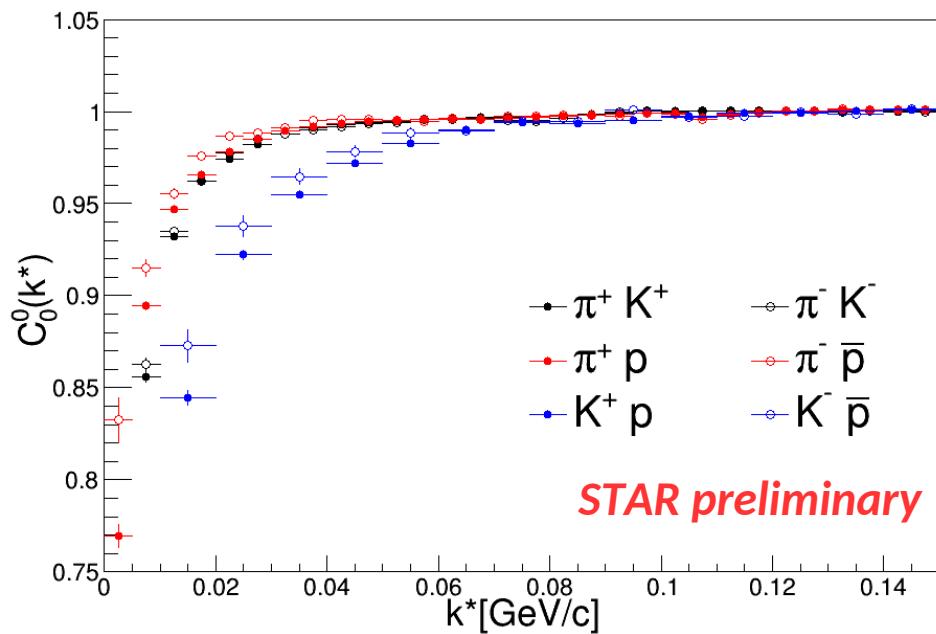


proton-proton @39 GeV



proton-antiproton @39 GeV

System Dependence in Nonidentical Particles @39 GeV

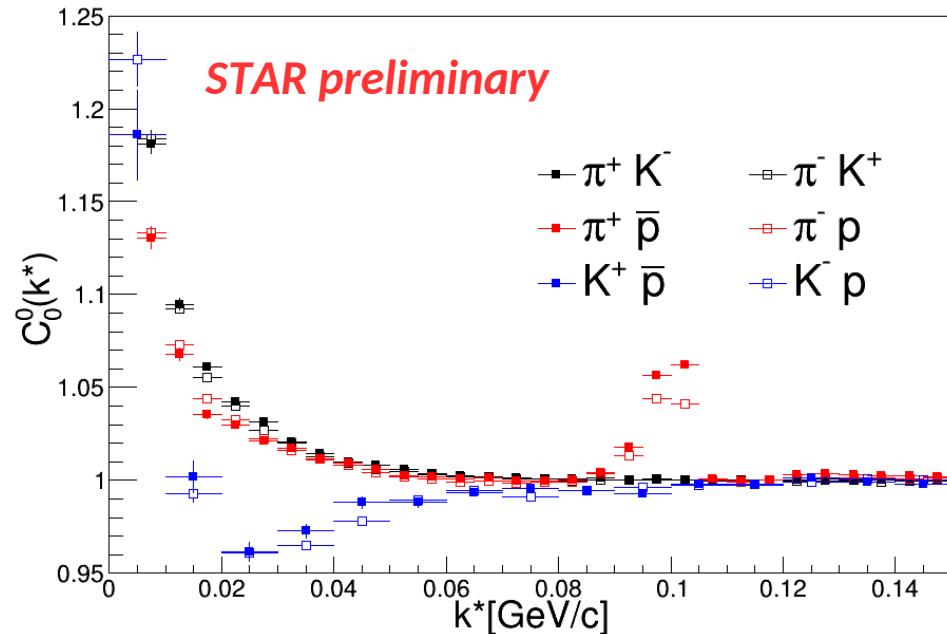


Clear system dependence

Same sign: correlations dominated by Coulomb interaction

Coulomb strength depends on Bohr radius of the pair

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

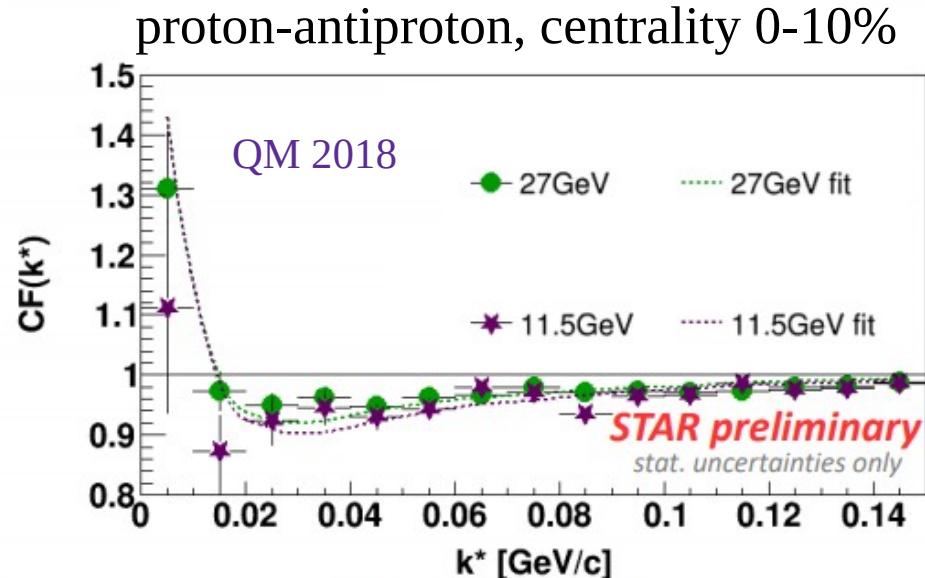
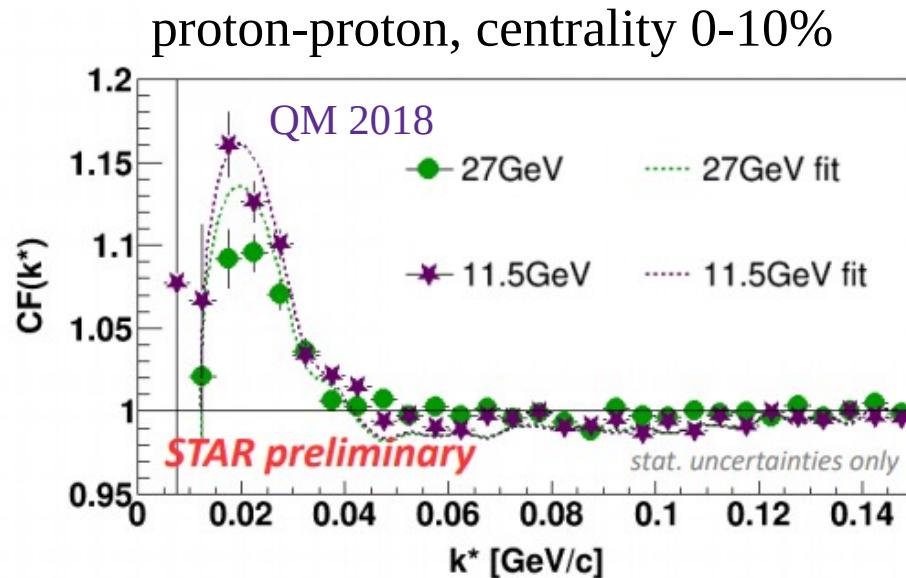


different shape due to strong interaction

Opposite sign: interaction more complicated

Strong interaction not negligible in $K - p$.

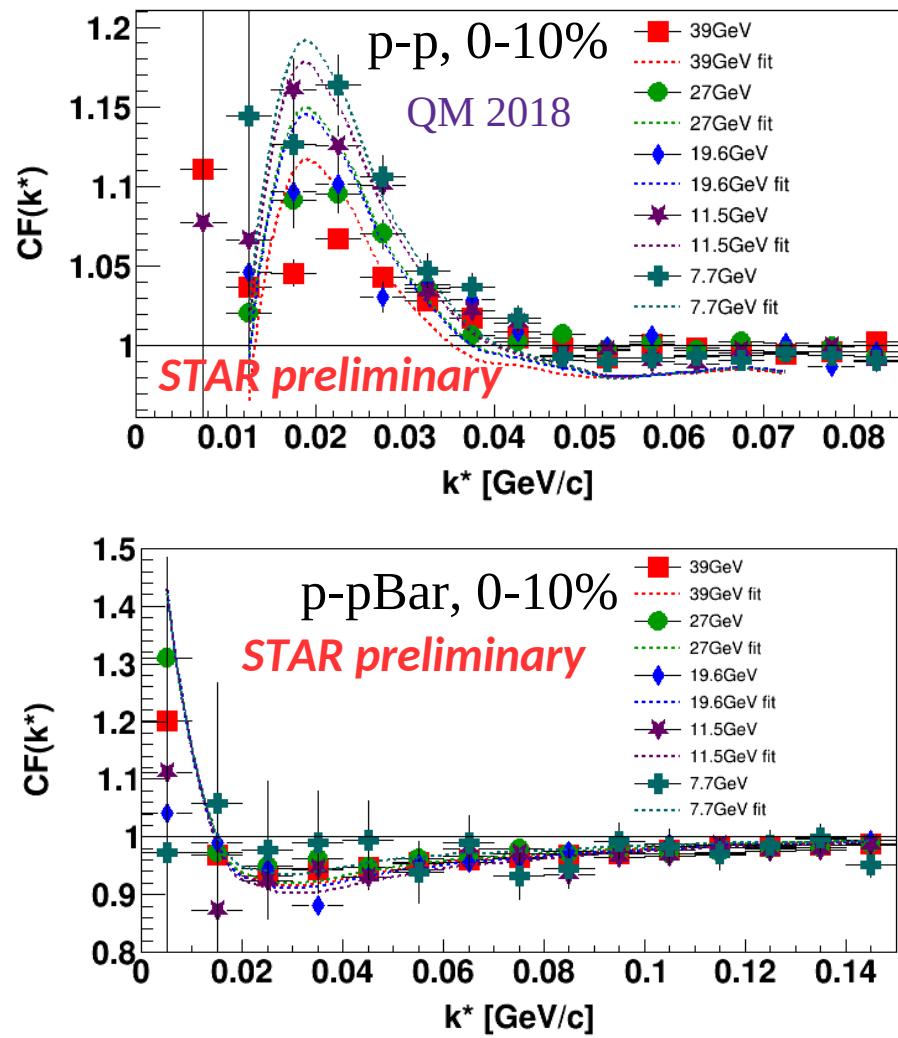
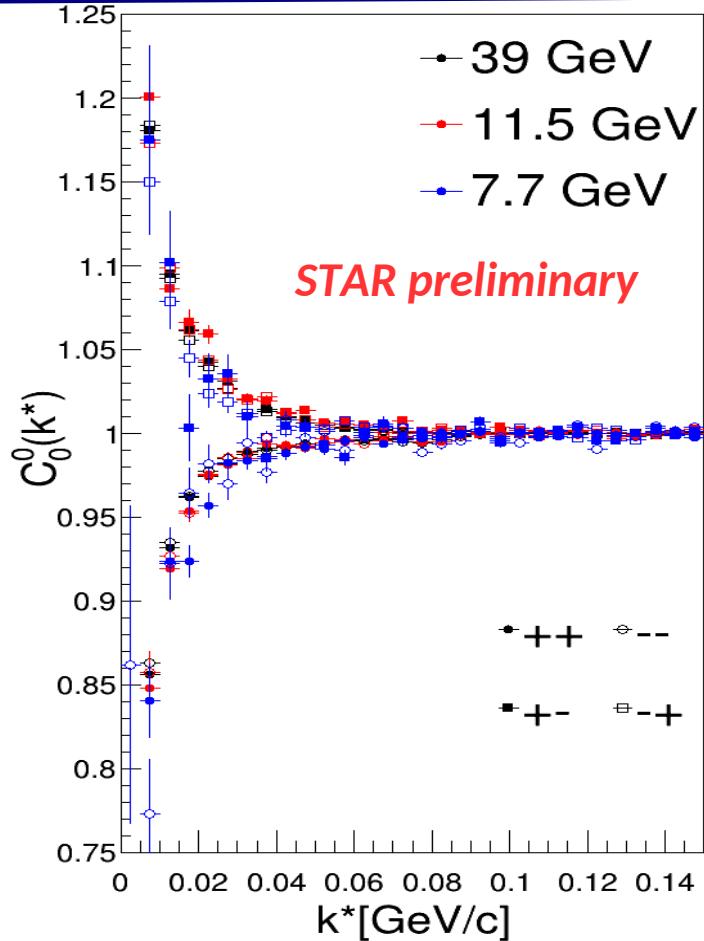
Energy Dependence in Proton Femtoscopy



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

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

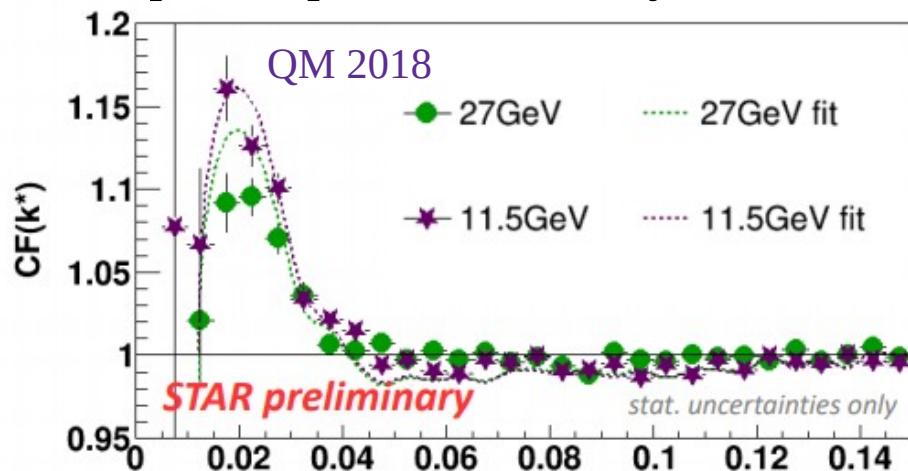
Energy Dependence



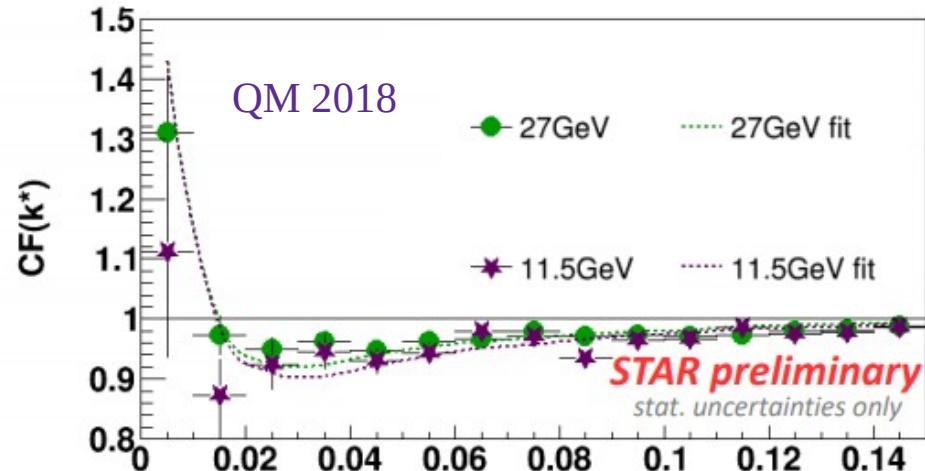
Energy dependence more significant for proton-proton than for proton-antiproton and pion-kaon systems.

Energy Dependence

proton-proton, centrality 0-10%

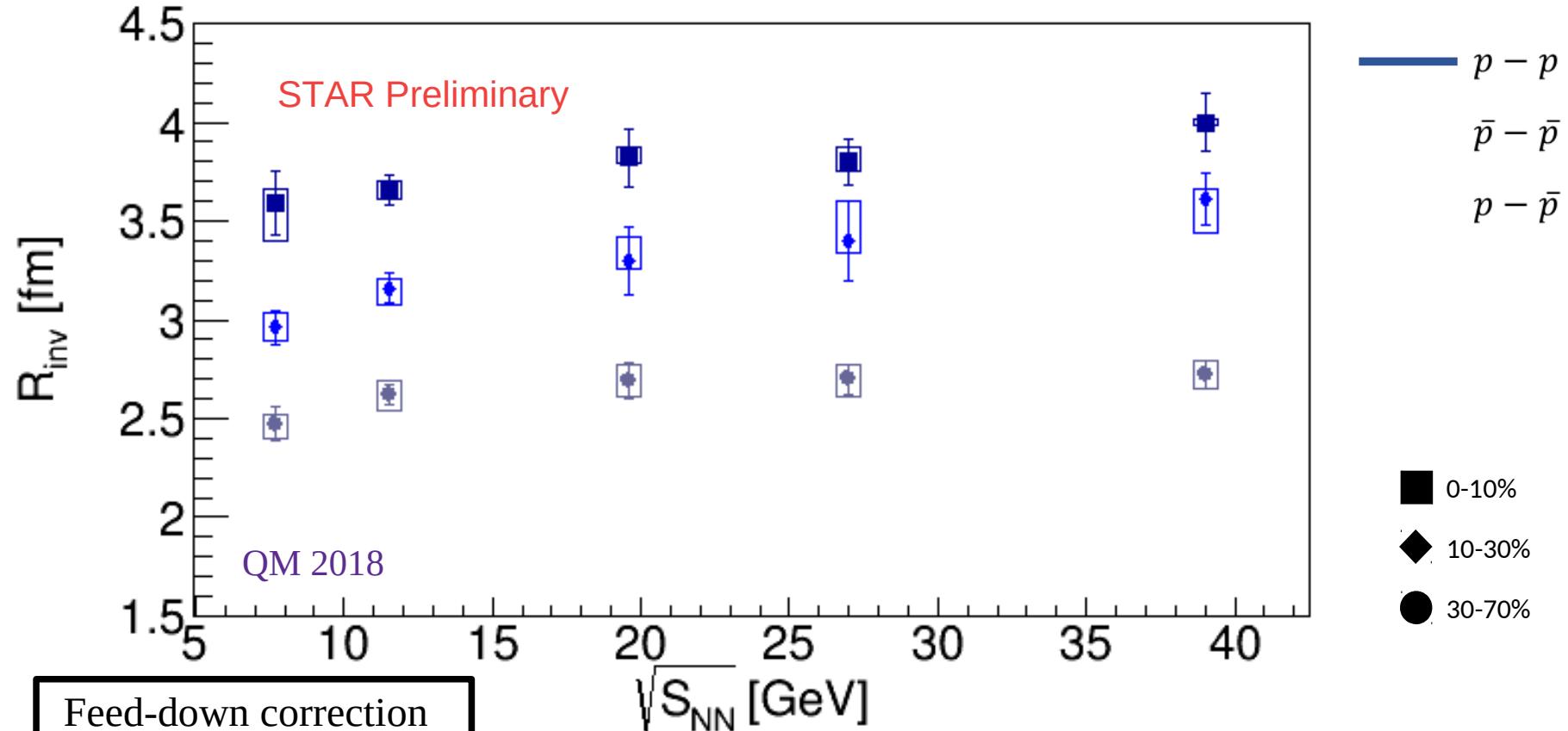


proton-antiproton, centrality 0-10%



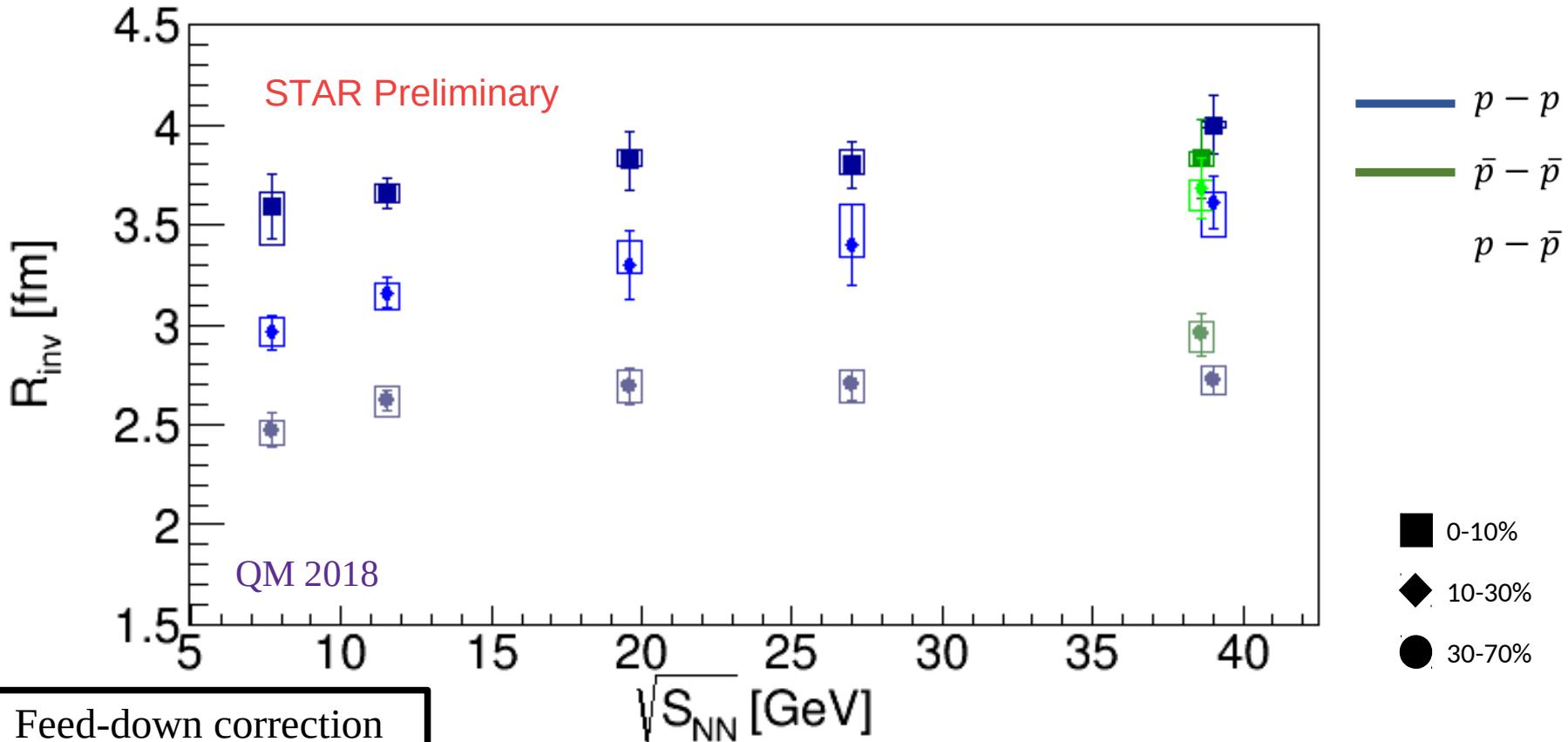
Energy dependence more significant for proton-proton than for proton-antiproton system.

Proton Femtoscopy in BES



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

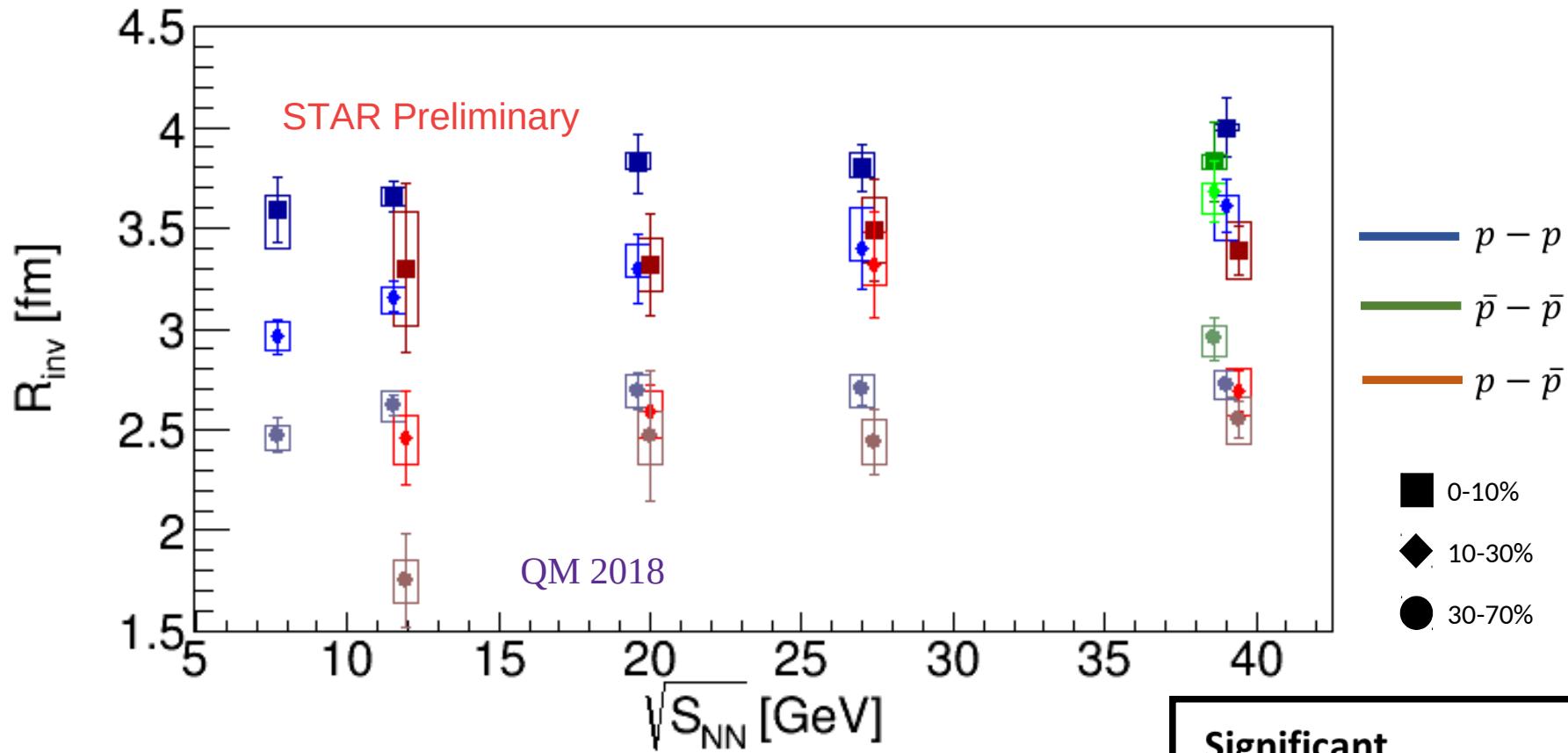
Proton Femtoscopy in BES



Feed-down correction
may decrease
significance of
centrality dependence.

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

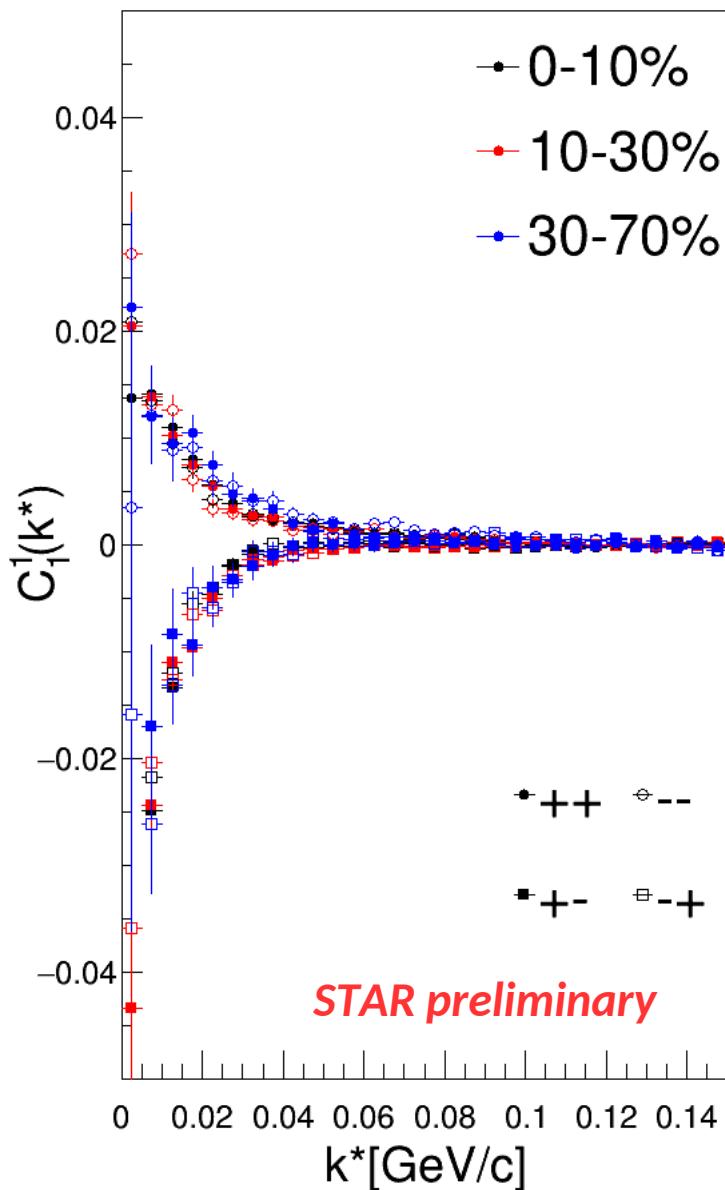
Significant centrality dependence.

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



Dynamics

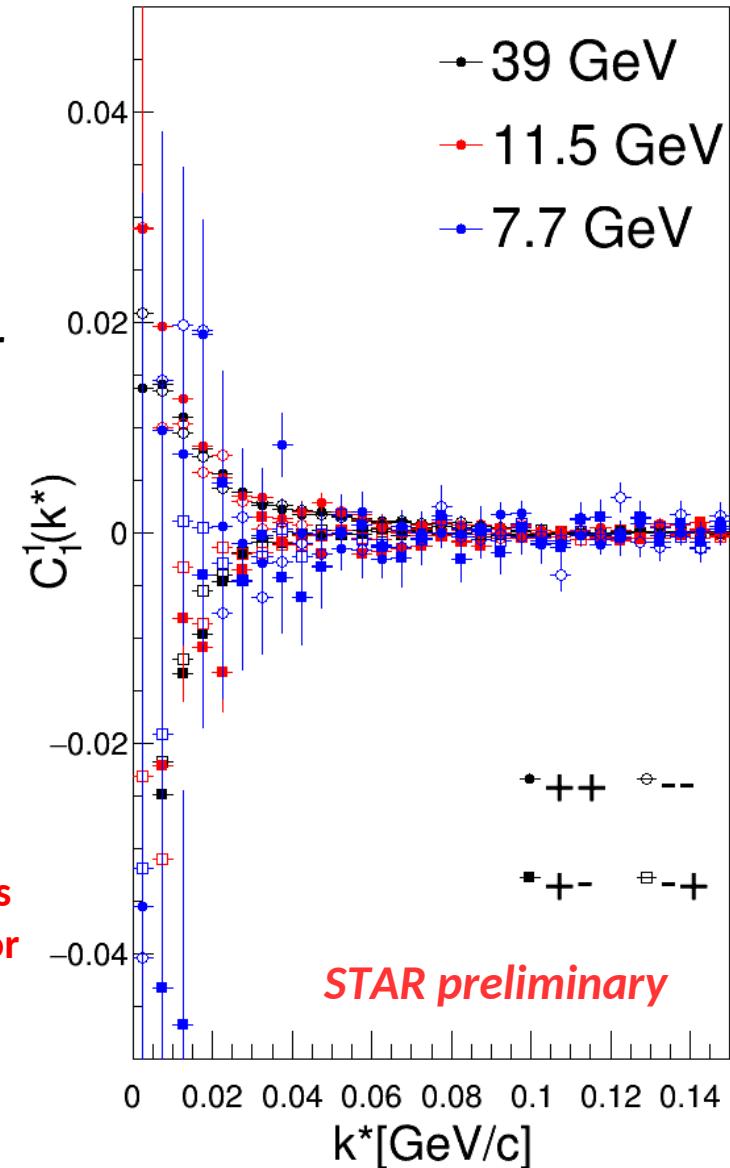
Centrality and Energy Dependencies



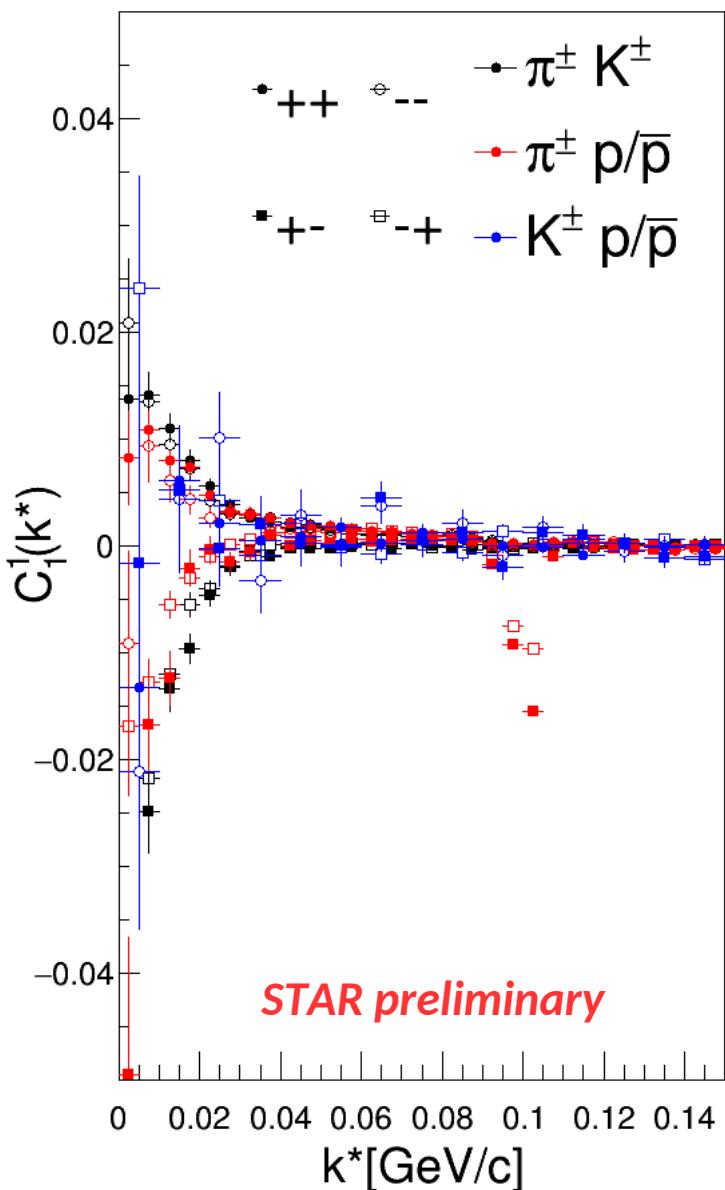
Clear signal of emission asymmetry

Pions emitted closer to center and/or later than Kaons

Asymmetry does not disappear for low energies.



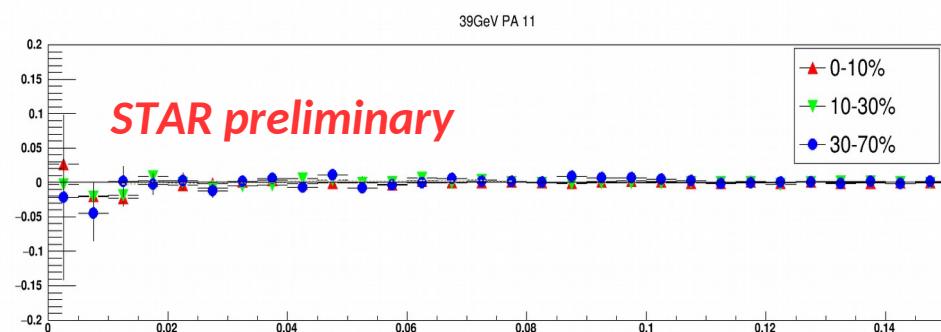
System Dependence @39 GeV



Expected ordering of particles:

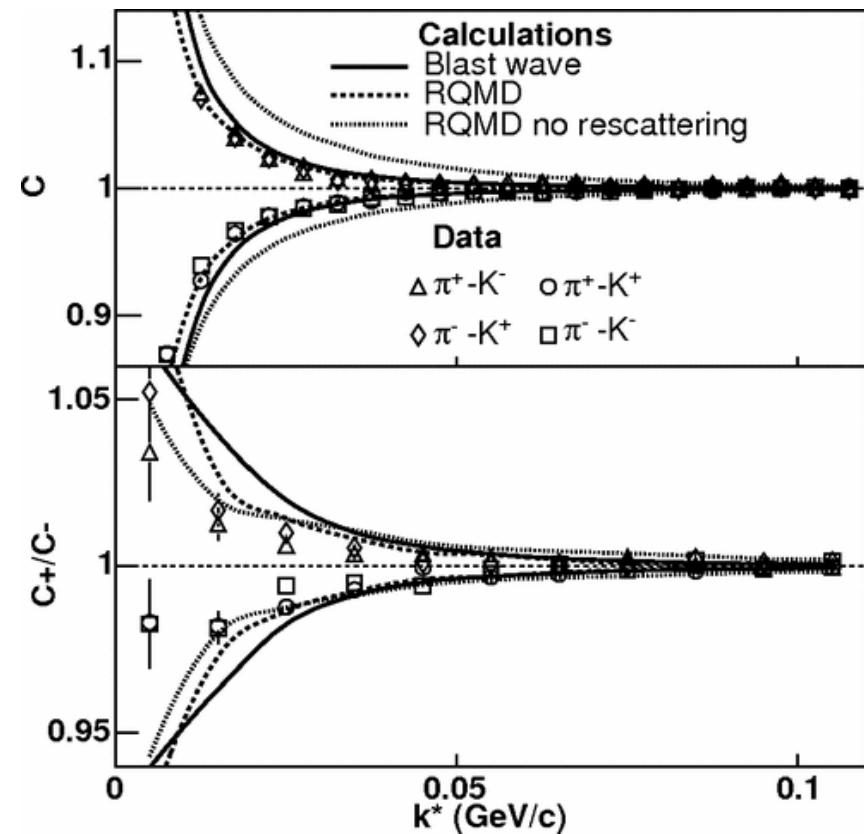
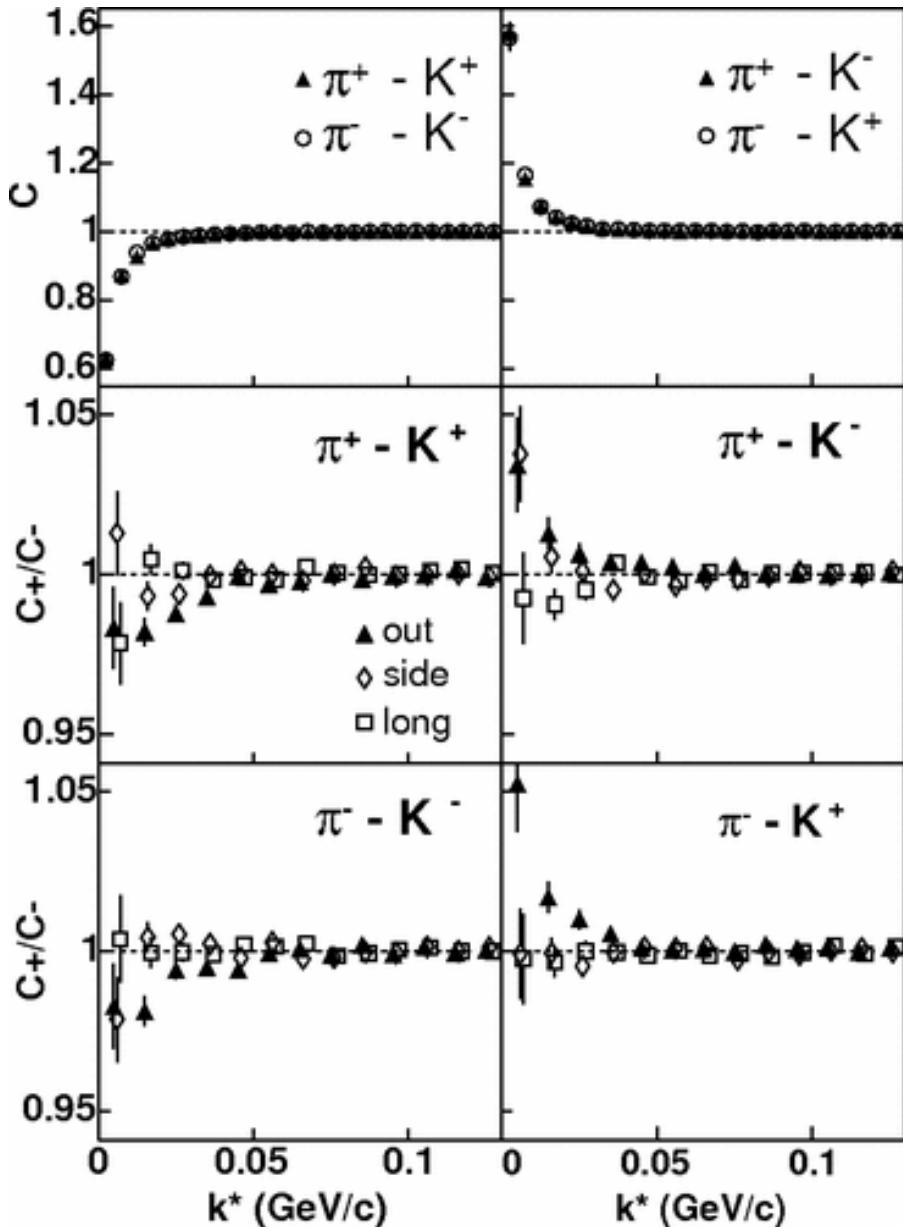
Lighter particle is emitted closer to the center and/or later.

No visible asymmetry between Protons and Antiprotons
- similar masses.



**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	$1020/118$

26

Kaons are emitted earlier and/or further than Pions.



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 at GeV

Correlation functions contaminated by residual correlations – residual correction required

Strong interaction not negligible in Kaon-Proton

Summary about 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 pushes heavier particles harder to the edge

Thank you!

Backup

Correlation Function

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

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

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

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

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

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

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