WARSAW UNIVERSITY OF TECHNOLOGY

Proton-Proton, Proton-Antiproton and Antiproton-Antiproton Correlations

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STAR

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WINTER SCHOOL
ON HEAVY ION PHYSICS

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Outline

1) Motivation and basics of proton femtoscopy

2) Results of the study of two (anti-)proton Interaction via

Correlation Measurement – Au+Au collisions at $\sqrt{(s_{NN})}$ = 200 GeV

3) Results from Beam Energy Scan:

3a) Au+Au collisions at $\sqrt{(s_{NN})}$ = 39 GeV

3b) Au+Au collisions at $\sqrt{(s_{NN})}$ = 11.5 GeV

3c) Au+Au collisions at $\sqrt{(s_{NN})}$ = 7.7 GeV

4) Summary

Motivation

- Comparing radii extracted from various correlations

  → complementary information about the source characteristics

- Studying interactions between anti-nuclei

  → wider understanding of the nuclear matter

- Understanding interactions between antiprotons

  → understanding anti-nuclei

- the knowledge about interactions between two baryons, two antibaryons and between baryons and antibaryons

  → better understanding of nuclear matter

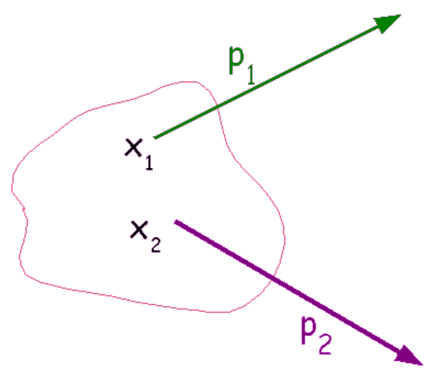
Few words about femtoscopy

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

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

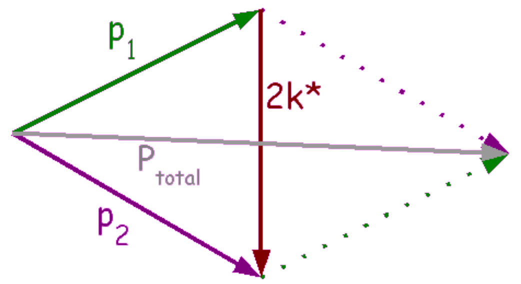


The correlation function

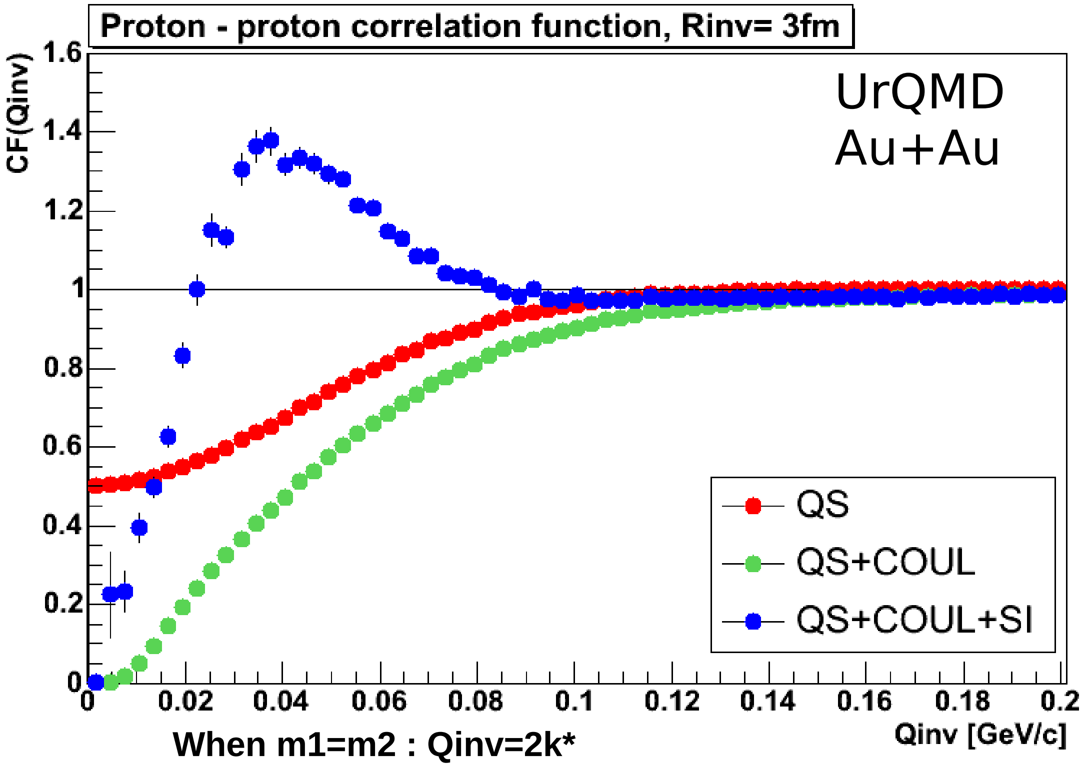
$$C(p_1,p_2)=\frac{P_2(p_1,p_2)}{P_1(p_1)P_1(p_2)}$$

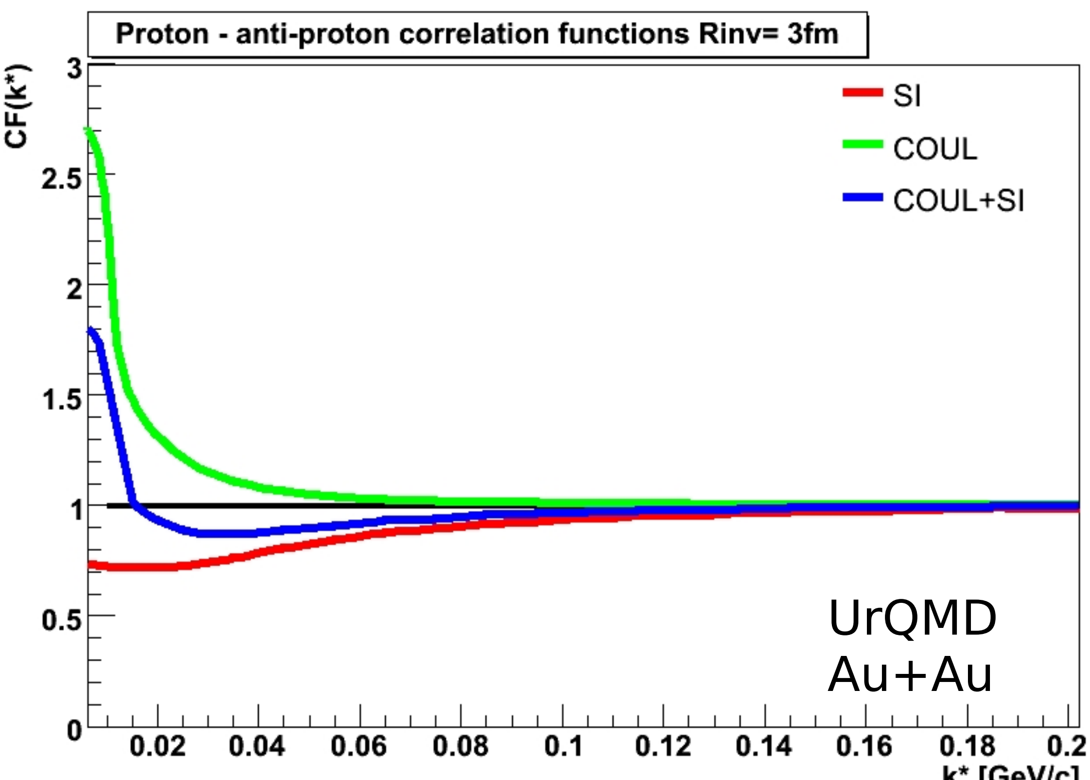
LCMS system: $Q_{inv}=|p_1-p_2|$

PRF system: $k^*=|p_1|=|p_2|$



Proton-(anti)proton correlations





Identical baryon- baryon

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

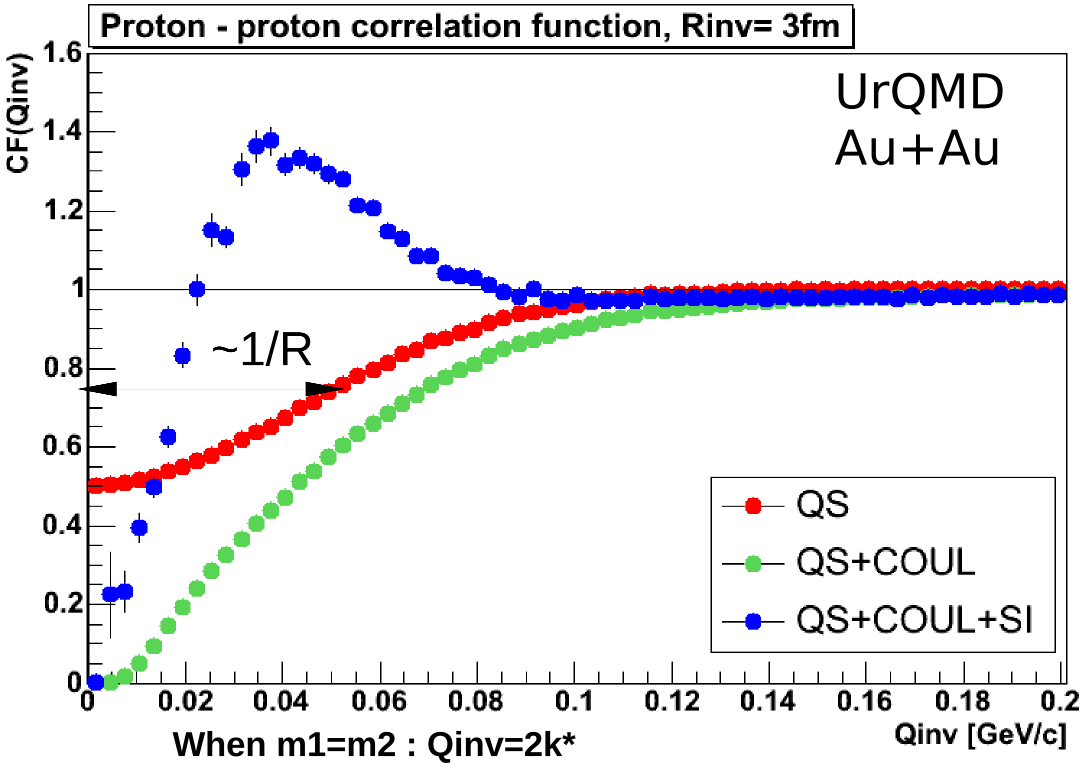
Nonidentical baryon-antibaryon

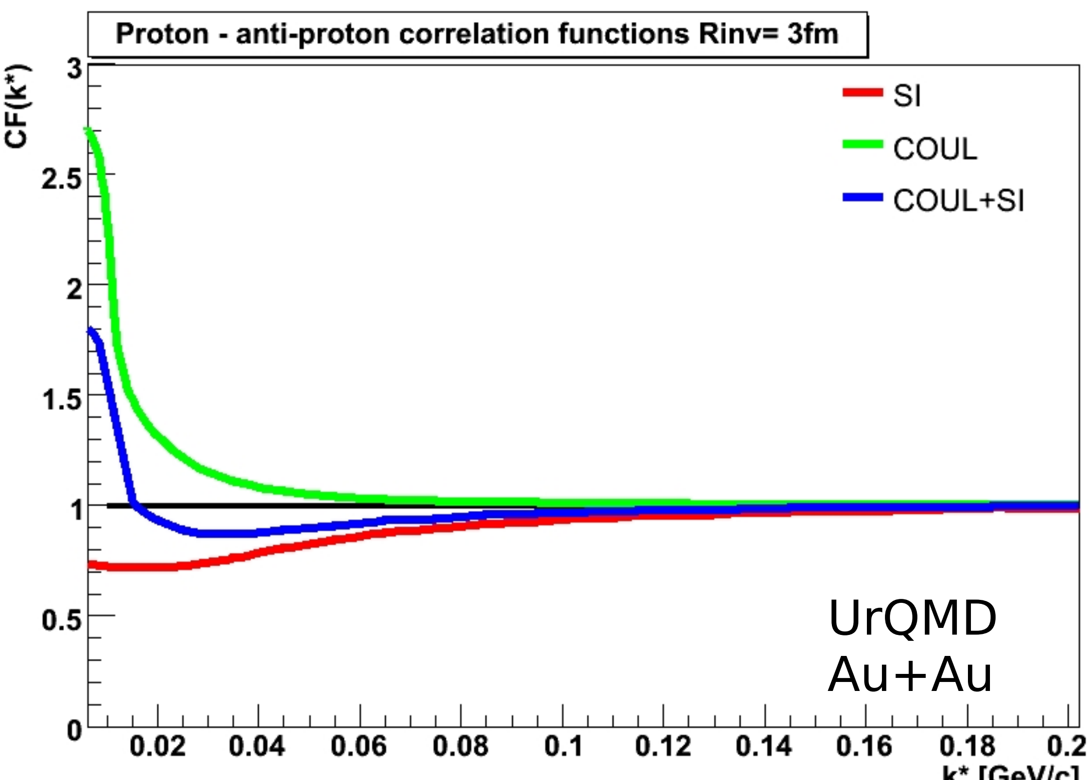
- Final State Interactions- FSI
  - Coulomb
  - Strong

$$Q_{inv}=|p_1-p_2|$$

$$k^*=|p_1|=|p_2|$$

Proton-(anti)proton correlations





<u>Why to do this?</u>

Extracting info on the 'Length of homogeneity' – aka radii using the correlation functions.

The width of the Quantum Statistics part in correlation functions is inversely proportional to the Radius of the “source” size.

$$Q_{inv} = |p_1 - p_2|$$

$$k^* = |p_1| = |p_2|$$

The study of two (anti-)proton interaction via Correlation Measurement

(Nature 527, 345 (2015))

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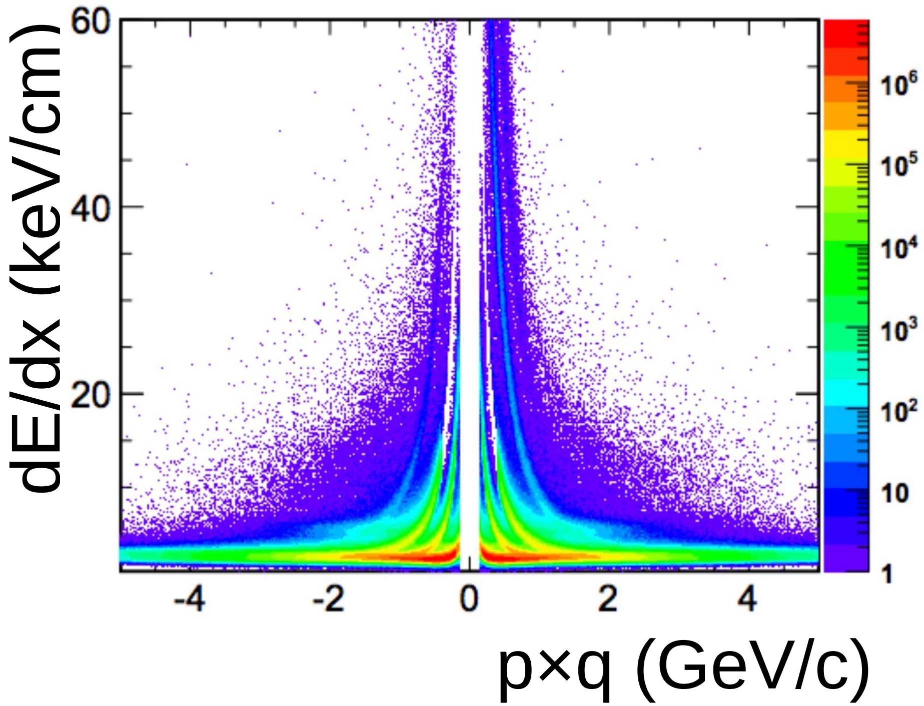
Particle identification

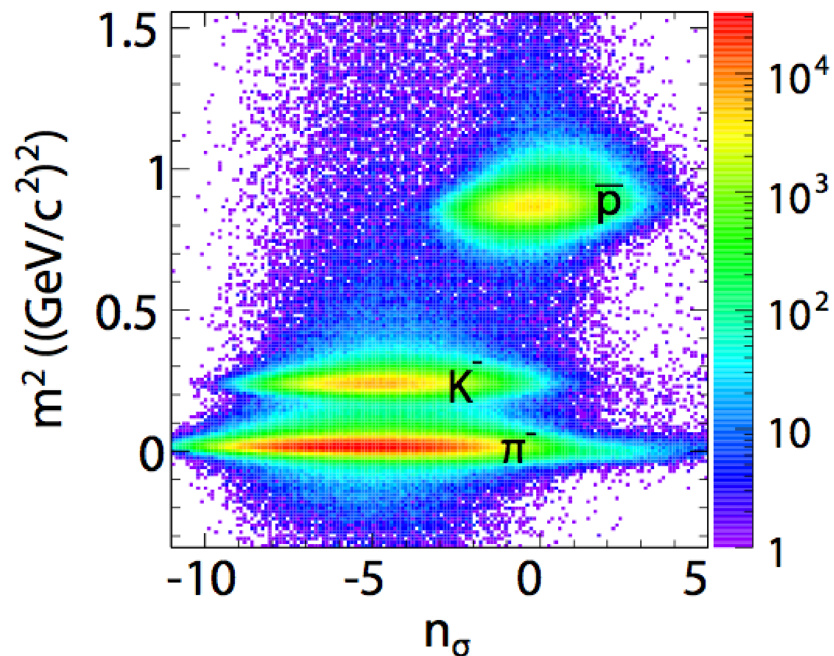
Total: ~500 M events

~250 M events – <u>centrality 30-80%</u>

Cut	Range/value
Momentum (p)	0.4 < p < 2.5 [GeV/c]
Mass window	0.8 < m^2 < 1.0 [GeV^2/c^4]
N σ	-1.5 < N < 1.5

TPC (Time Projection Chamber)





m^2 vs $n\sigma_p$: Negative Charge

We use TPC and TOF (Time of Flight) for the particle identification. The purity for anti-proton is over 99%.

f_0 and d_0

f_0 and d_0 are two important parameters in characterizing the strong interaction between two particles.

The scattering length f_0 in quantum mechanics describes low-energy scattering. The elastic cross section, σ_e, at low energies determined solely by the scattering length:

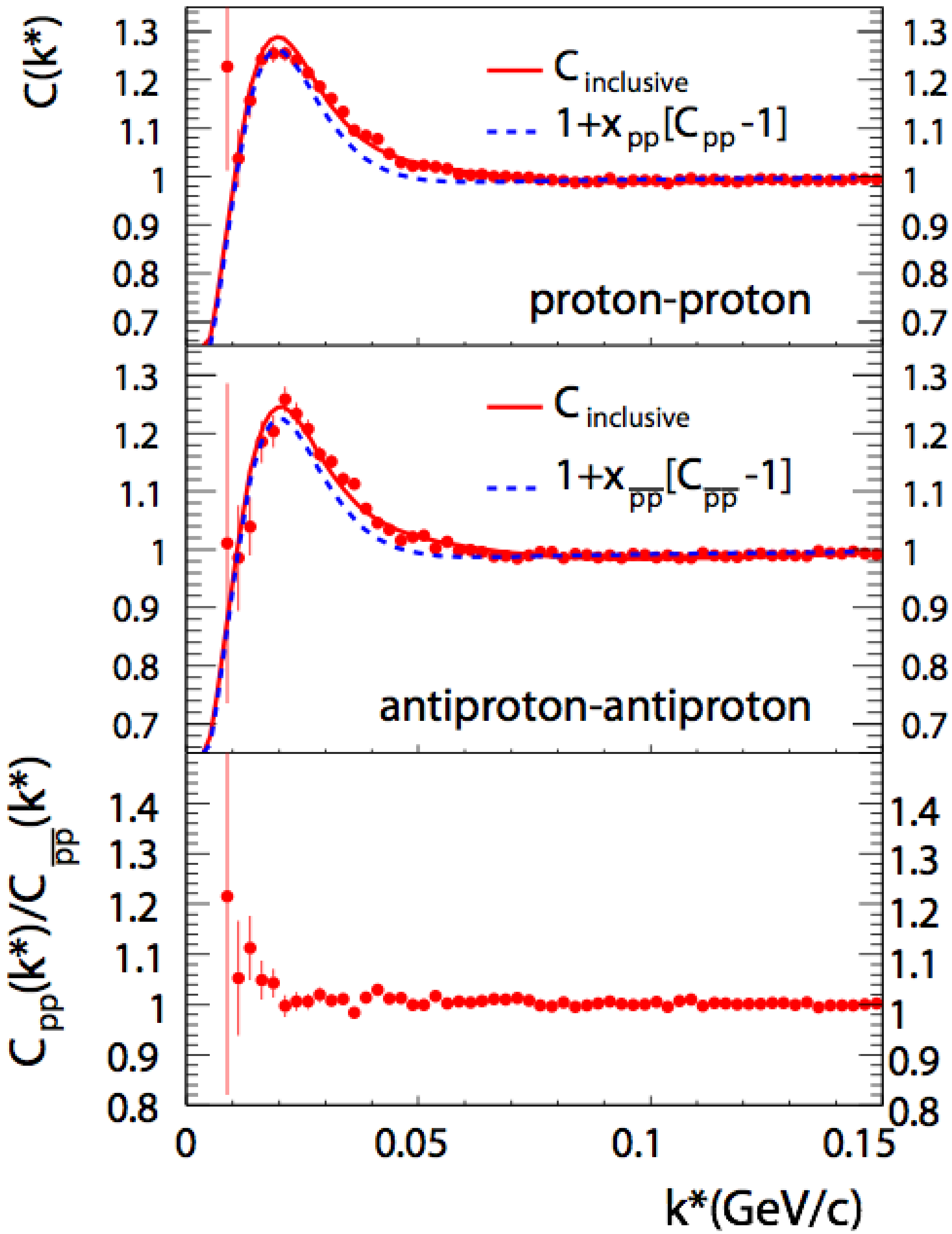
$$\lim_{k \to 0} \sigma_e = 4\pi f_0^2$$

Here k is the wave number.

d_0 is the effective range of strong interaction between two particles. It corresponds to the range of the potential in an extremely simplified scenario - the square well potential.

Correlations and the ratio – Au+Au @ 200 GeV

publication: Nature 527, 345 (2015)



Correlations and the ratio – Au+Au @ 200 GeV

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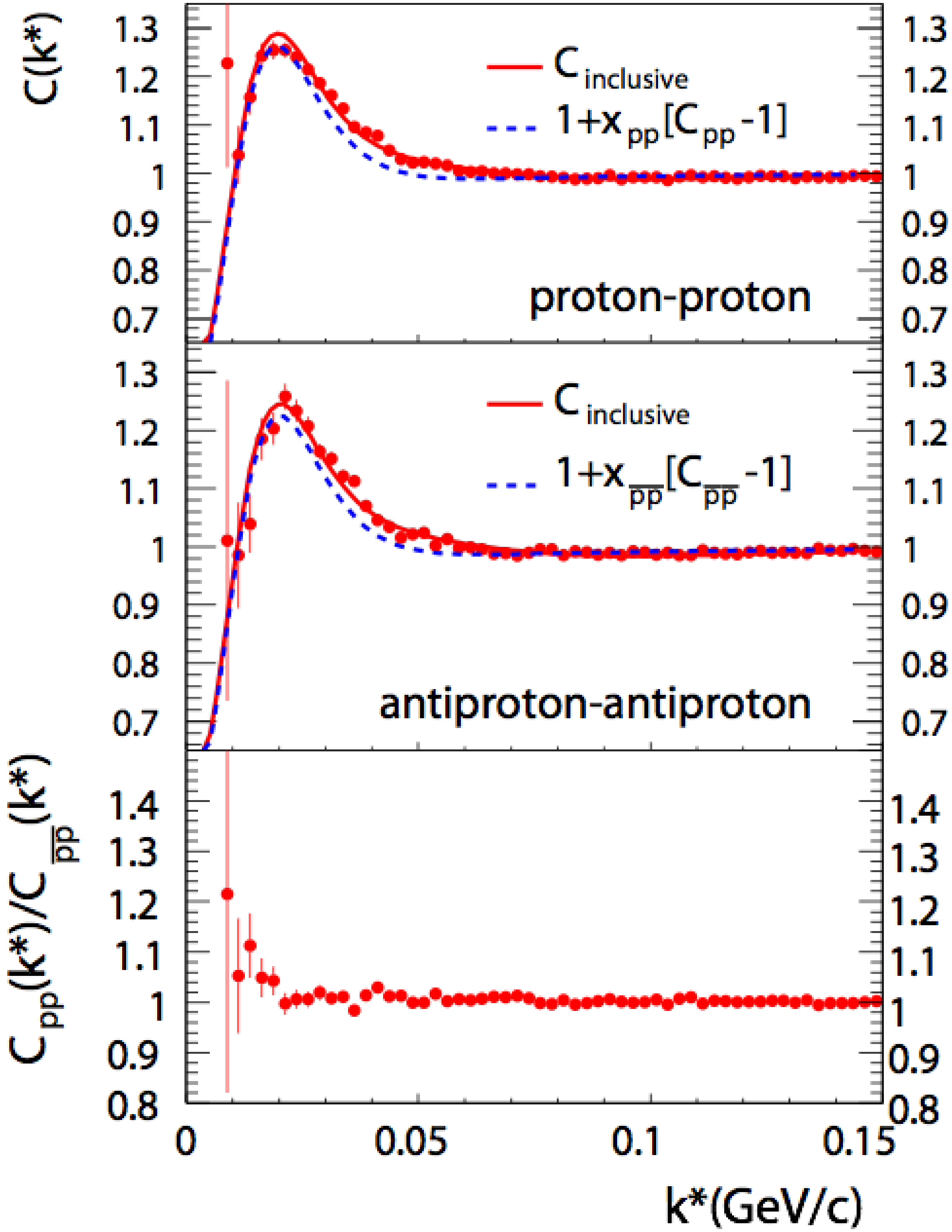
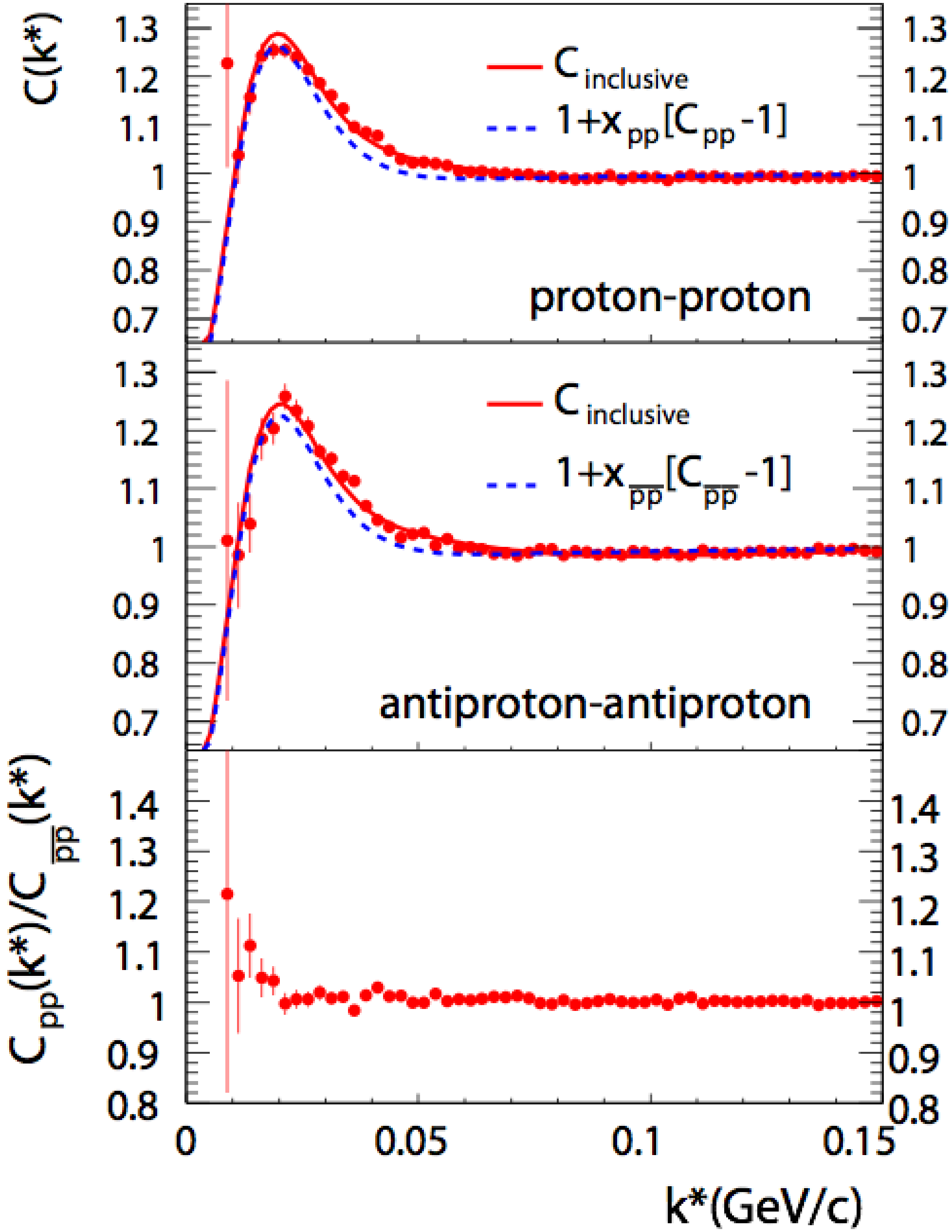


Fit results:
For proton-proton CF,
R=2.75±0.01fm,

For pbar-pbar CF,
R=2.80±0.02fm,

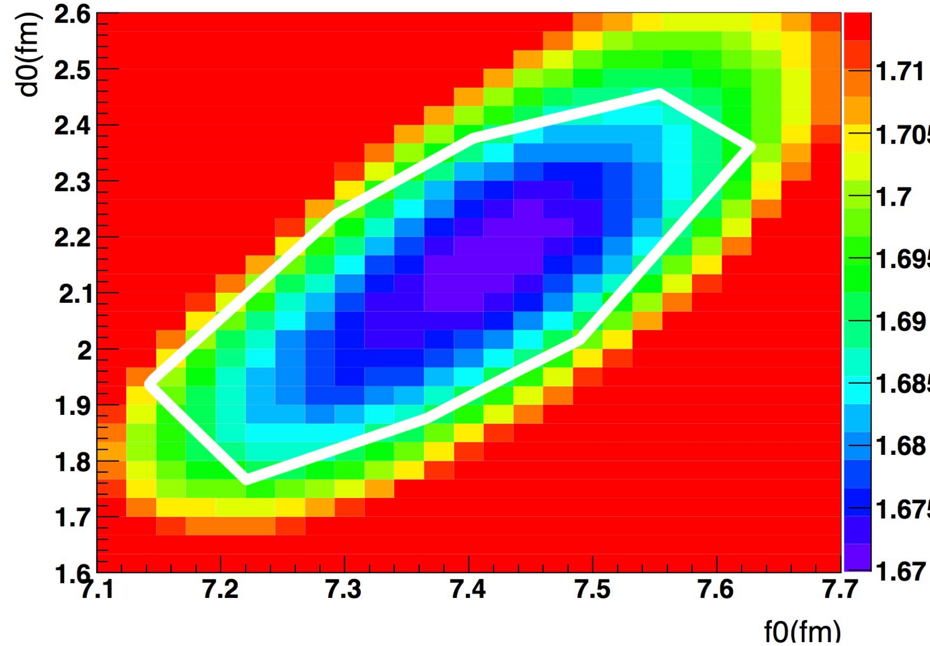
Correlations and the ratio – Au+Au @ 200 GeV

publication: Nature 527, 345 (2015)



Fit results:
For proton-proton CF,
R=2.75±0.01fm, χ^2/NDF=1.66;

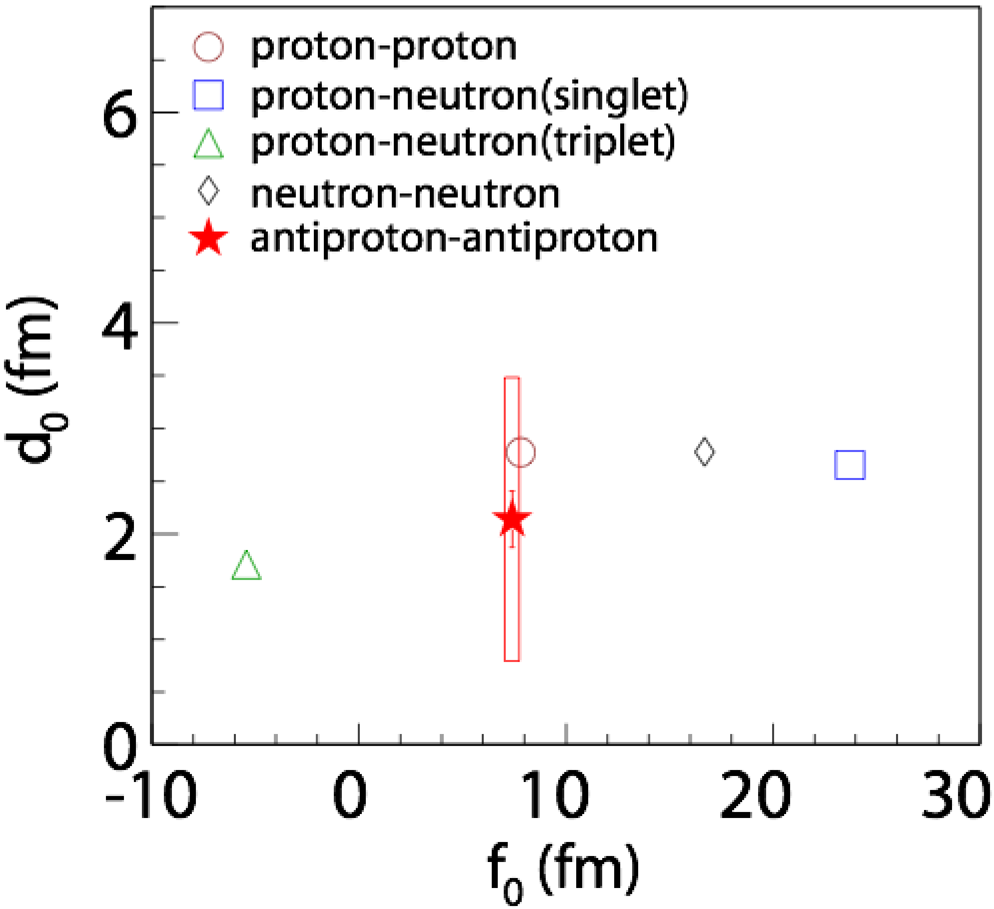
For pbar-pbar CF,
R=2.80±0.02fm, f_0=7.41±0.19fm,
d_0=2.14±0.27fm, χ^2/NDF=1.61;



χ^2/NDF contour,
1 sigma boundary in white

f_0 and d_0 for antiproton-antiproton

publication: Nature 527, 345 (2015)



- Within errors, the f0 and d0 for the antiproton-antiproton interaction are consistent with the ones for the proton-proton interaction.
- The result provides a quantitative verification of matter-antimatter symmetry in the context of the forces responsible for the binding of (anti)nuclei.
- Our measurements provide input for descriptions of the interaction among antiprotons, one of the simplest systems of anti-nucleons(nuclei).

Two-proton correlations at Beam Energy Scan energies

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Data selection

Example monitors for Au+Au collisions @ 39 GeV

Total: ~101 M events

~63 M events – centrality 30-80%

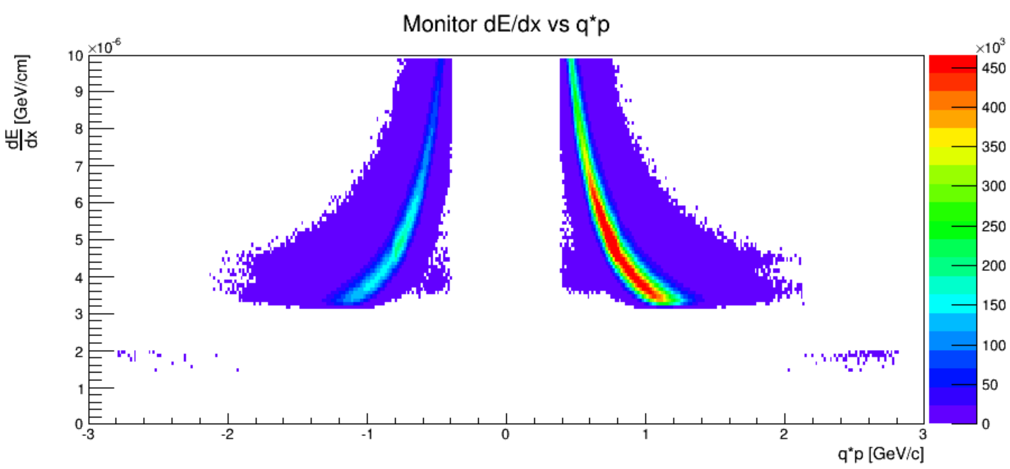
~26 M events – centrality 10-30%

~13 M events – centrality 0-10%

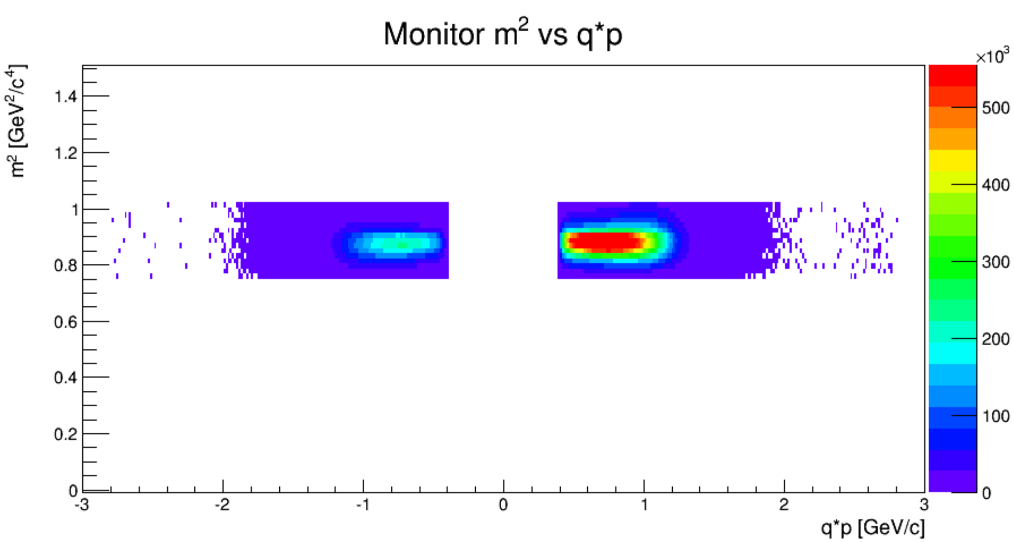
Centrality selection based on MC Glauber calculation

Cut	Range/value
Momentum (p)	**0.4 < p < 3.0 [GeV/c]**
Mass window	**$0.76 < m^2 < 1.03$ [GeV^2/c^4]**
N σ	**-3.0 < N < 3.0**

TPC



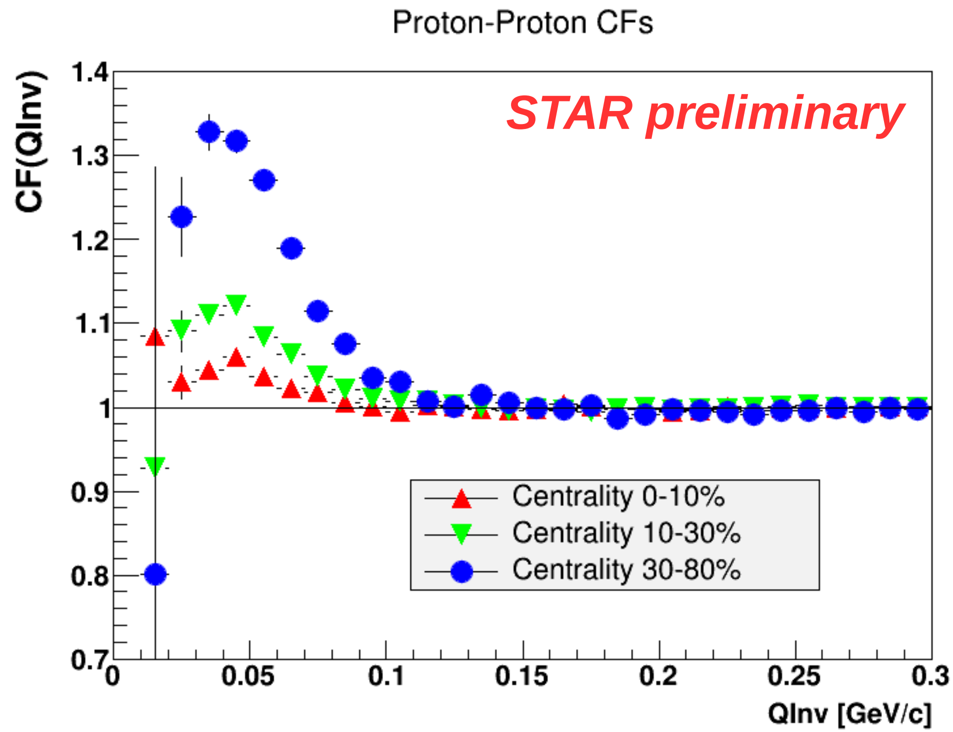
ToF

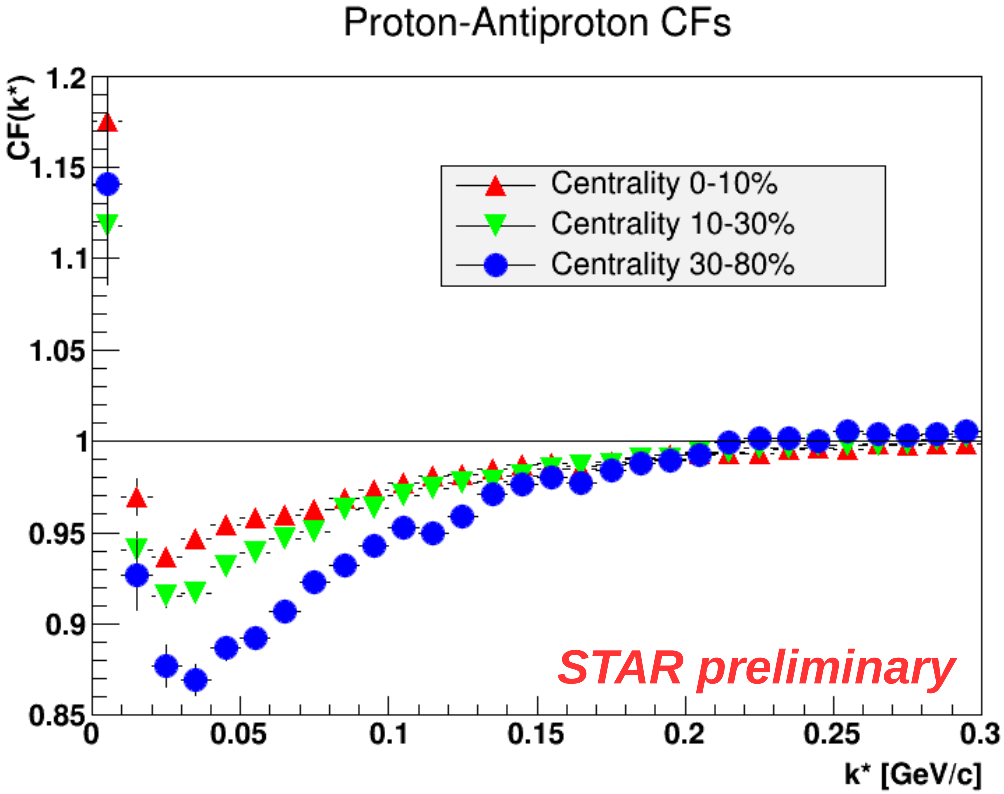


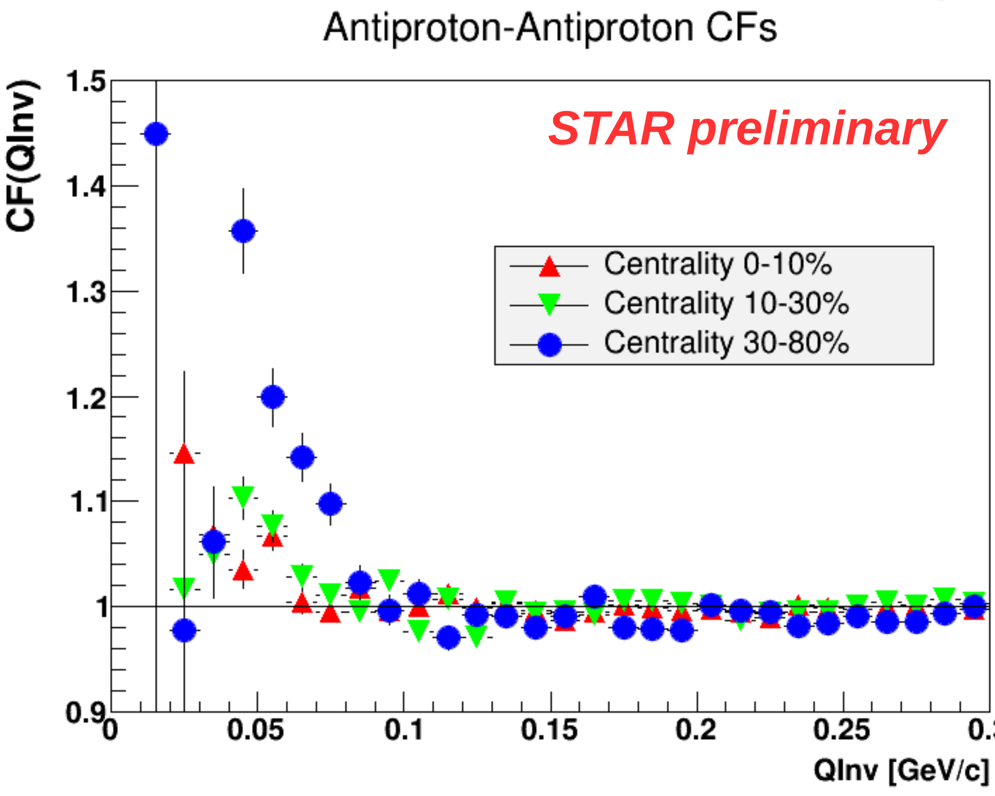
Analysis Au+Au collisions @ 39 GeV

Measured correlation functions are shown

Clear centrality dependence



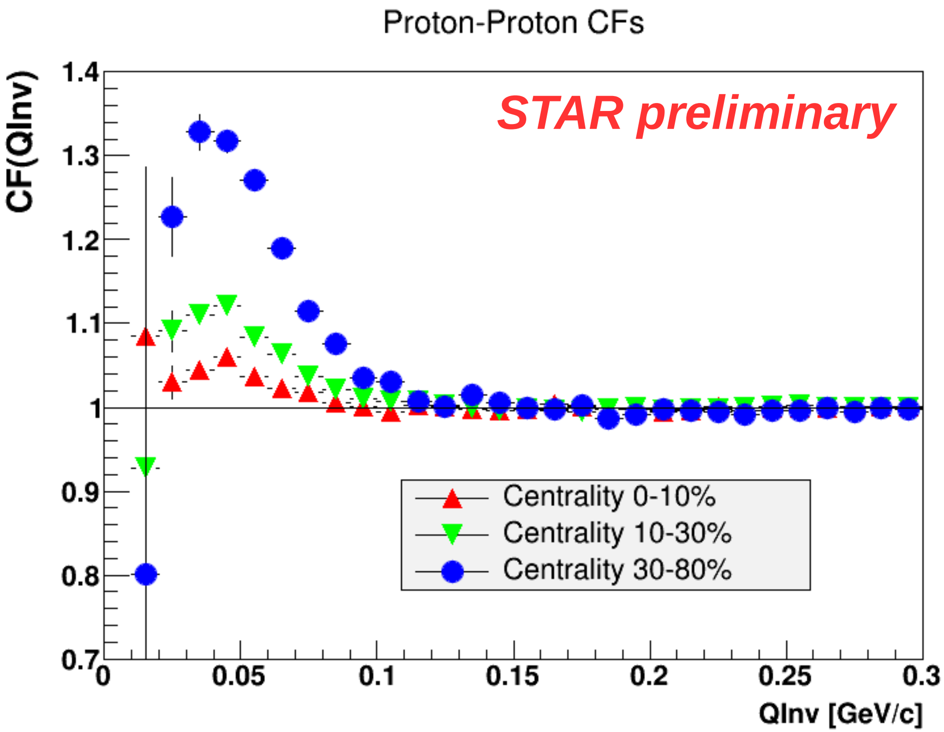


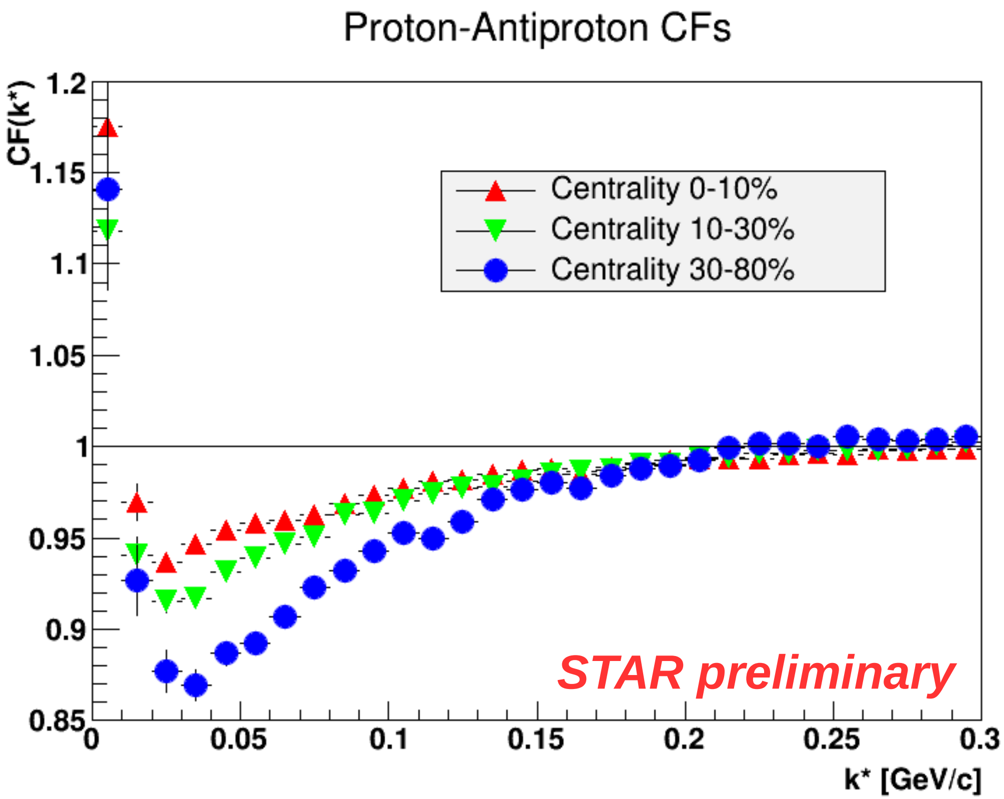


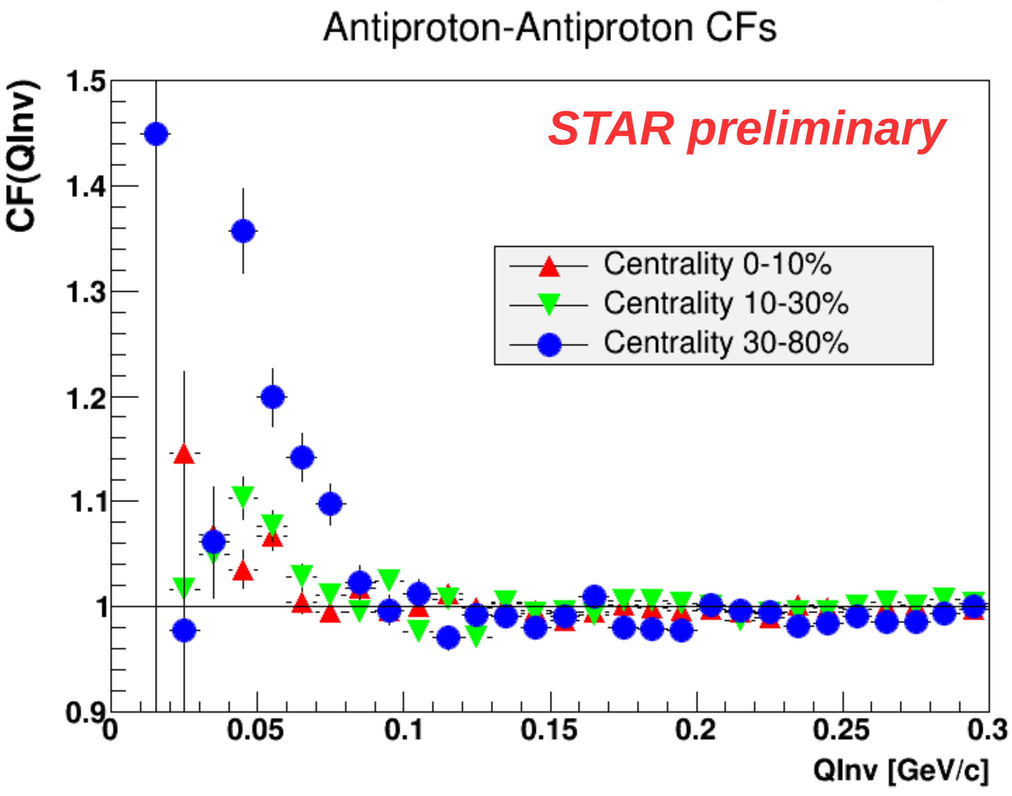
Analysis Au+Au collisions @ 39 GeV

Clear centrality dependence

$$R_{p-p}(0-10\%) > R_{p-p}(10-30\%) > R_{p-p}(30-80\%)$$







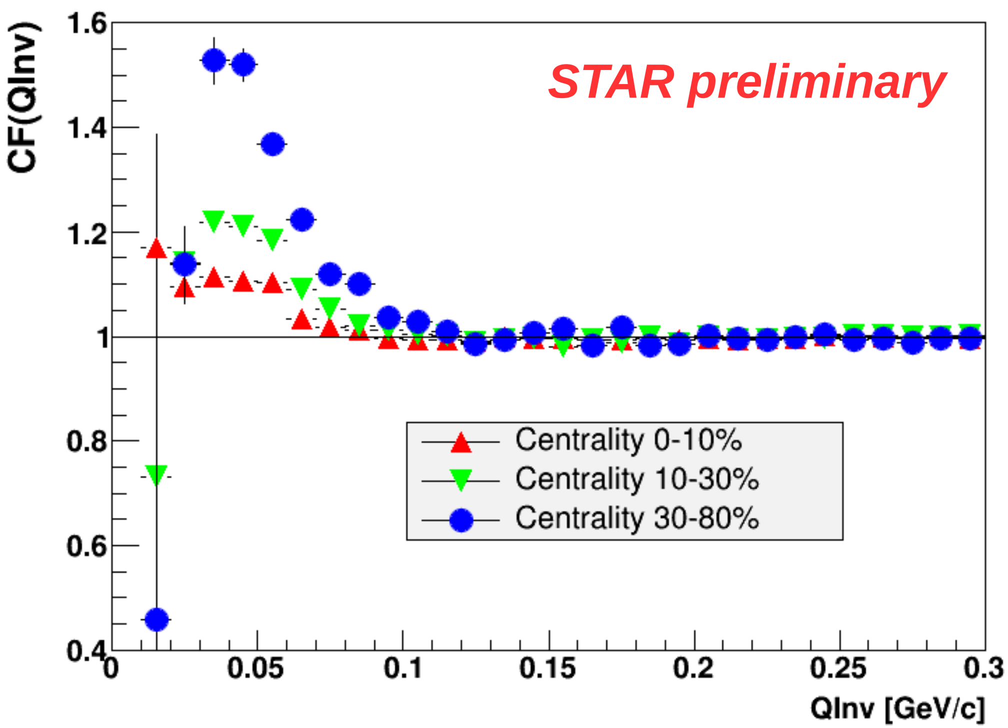
Analysis Au+Au collisions @ 7.7 GeV and 11.5 GeV

Measured correlation functions are shown

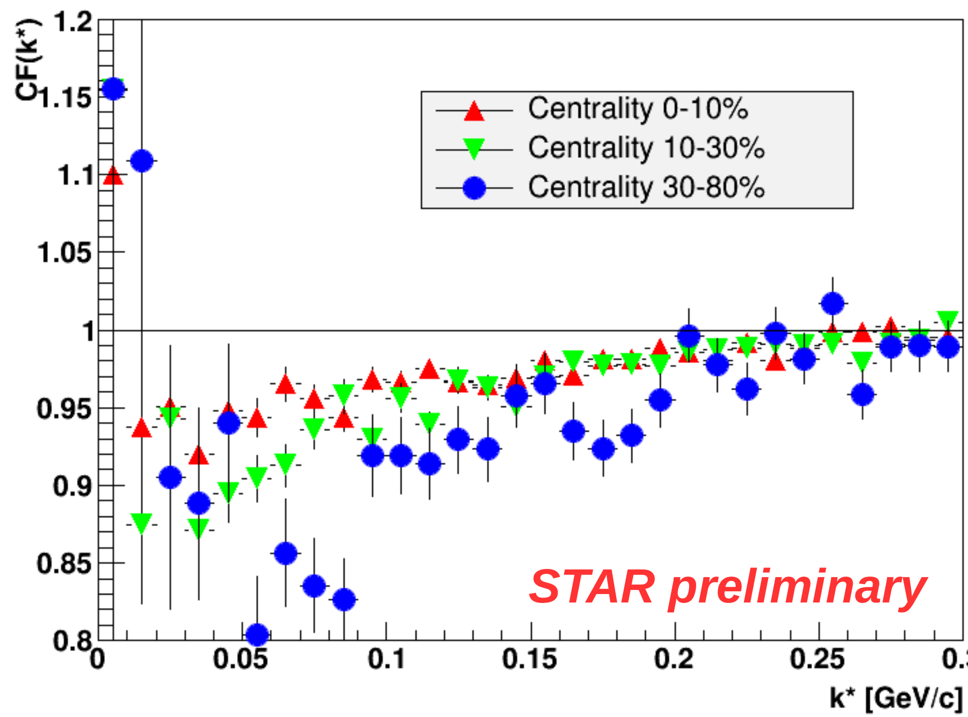
Clear centrality dependence

$$R_{p-p}(0-10\,\%) > R_{p-p}(10-30\,\%) > R_{p-p}(30-80\,\%)$$

Proton-Proton CFs - 11.5 GeV



Proton-Antiproton CFs - 11.5 GeV



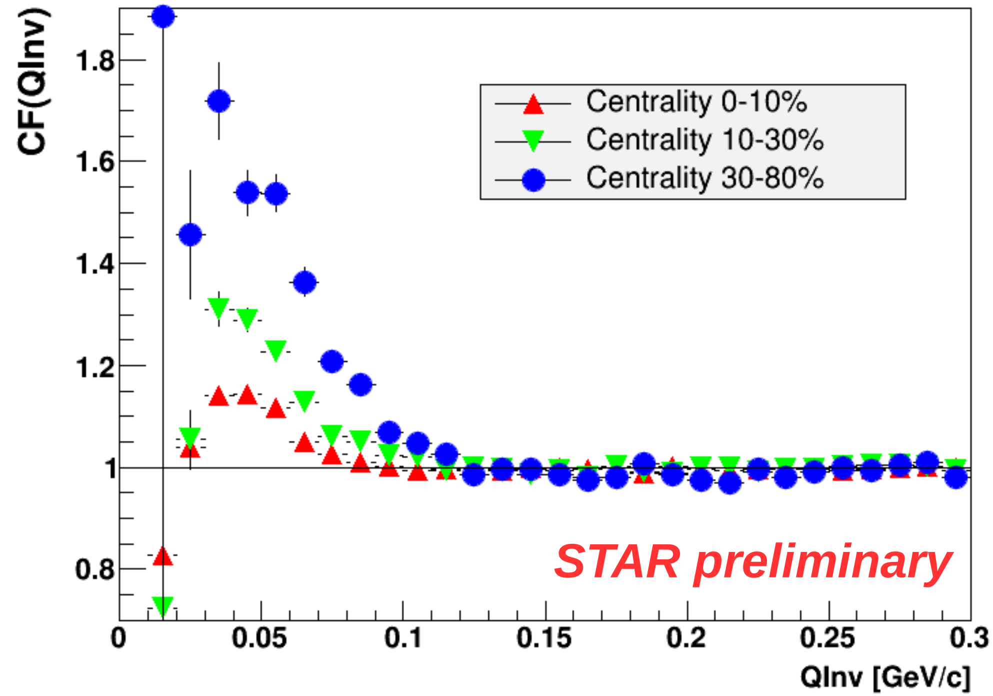
Analysis Au+Au collisions @ 7.7 GeV and 11.5 GeV

Measured correlation functions are shown

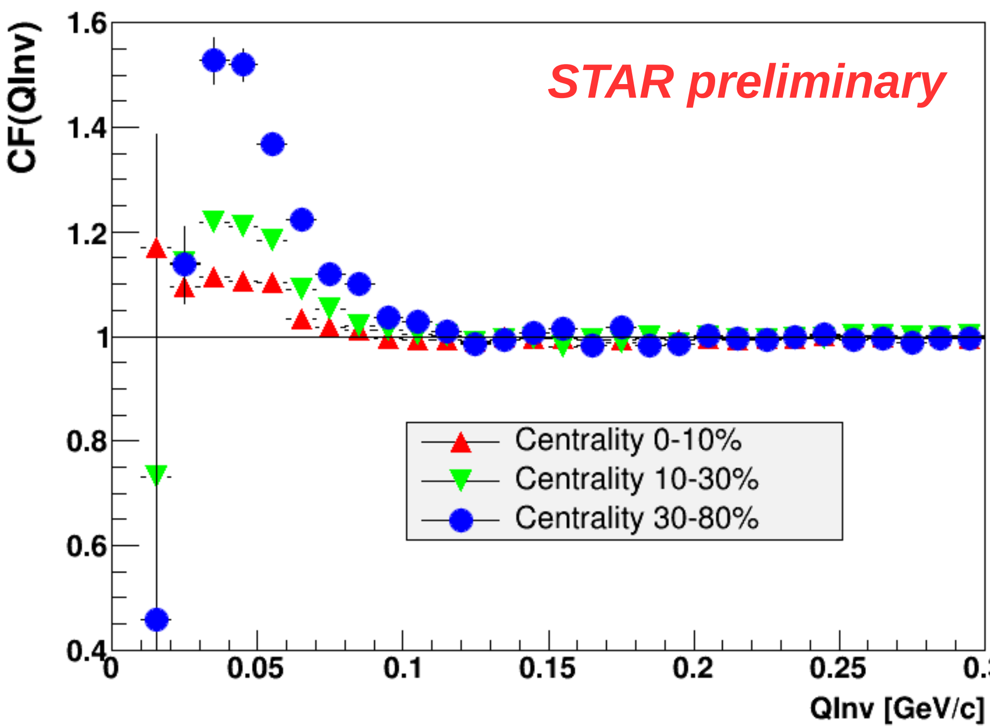
Clear centrality dependence

$$R_{p-p}(0-10\,\%) > R_{p-p}(10-30\,\%) > R_{p-p}(30-80\,\%)$$

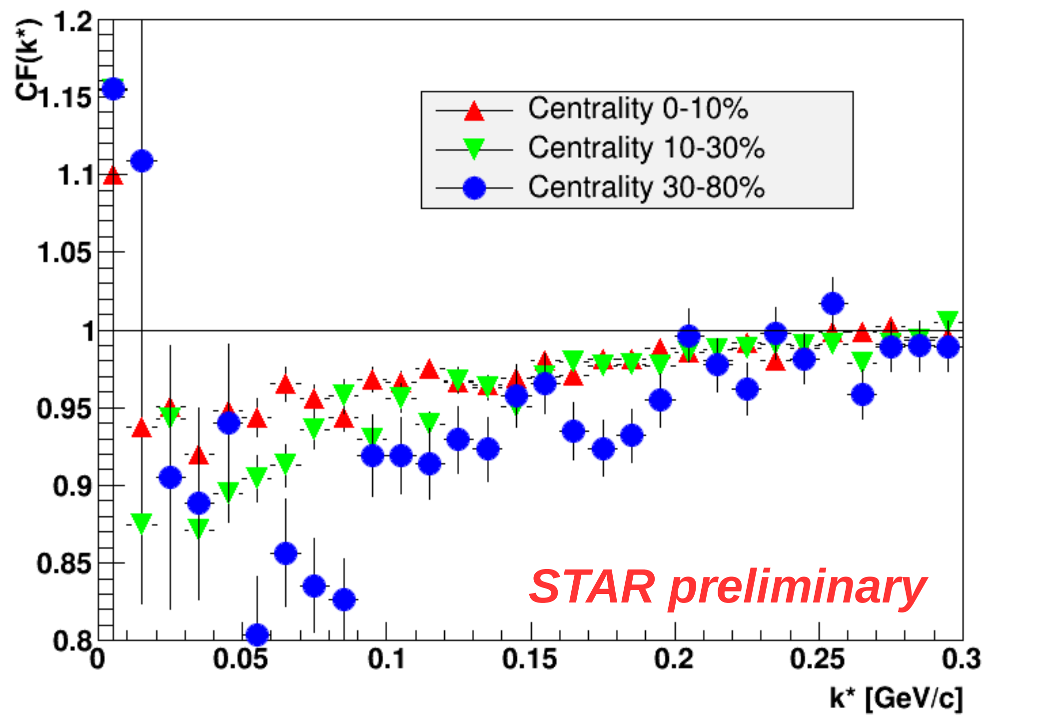
Proton-Proton CFs - 7.7 GeV



Proton-Proton CFs - 11.5 GeV



Proton-Antiproton CFs - 11.5 GeV

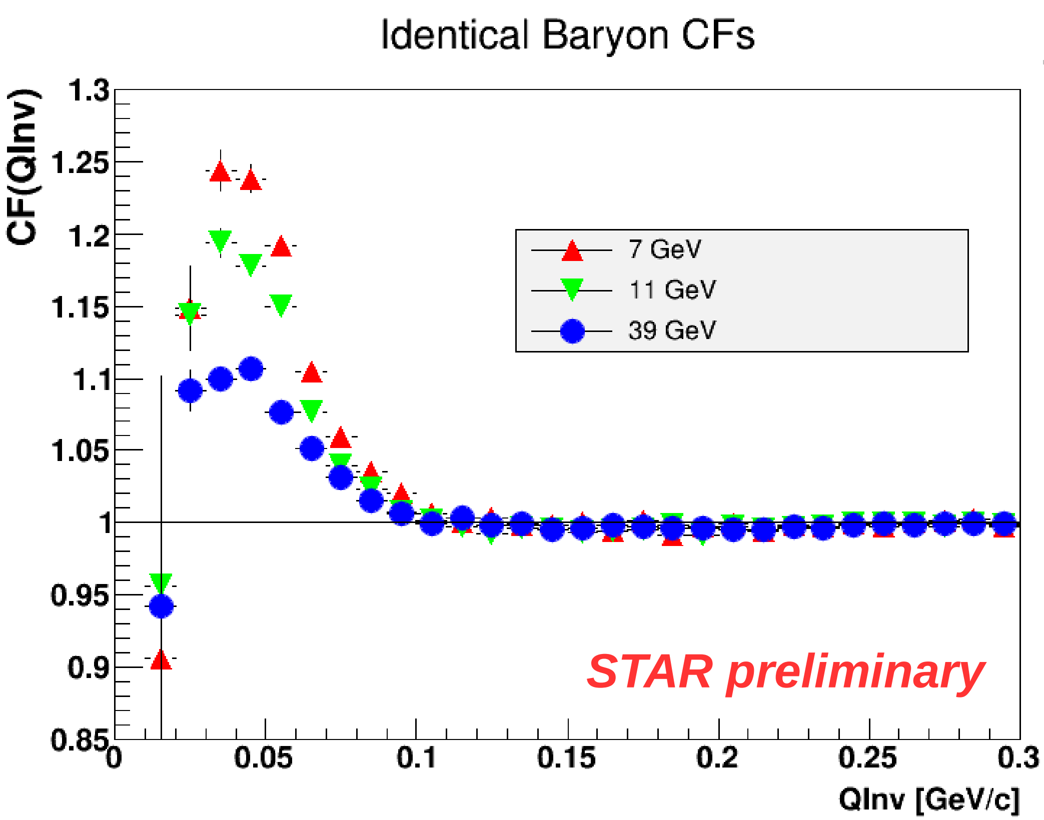


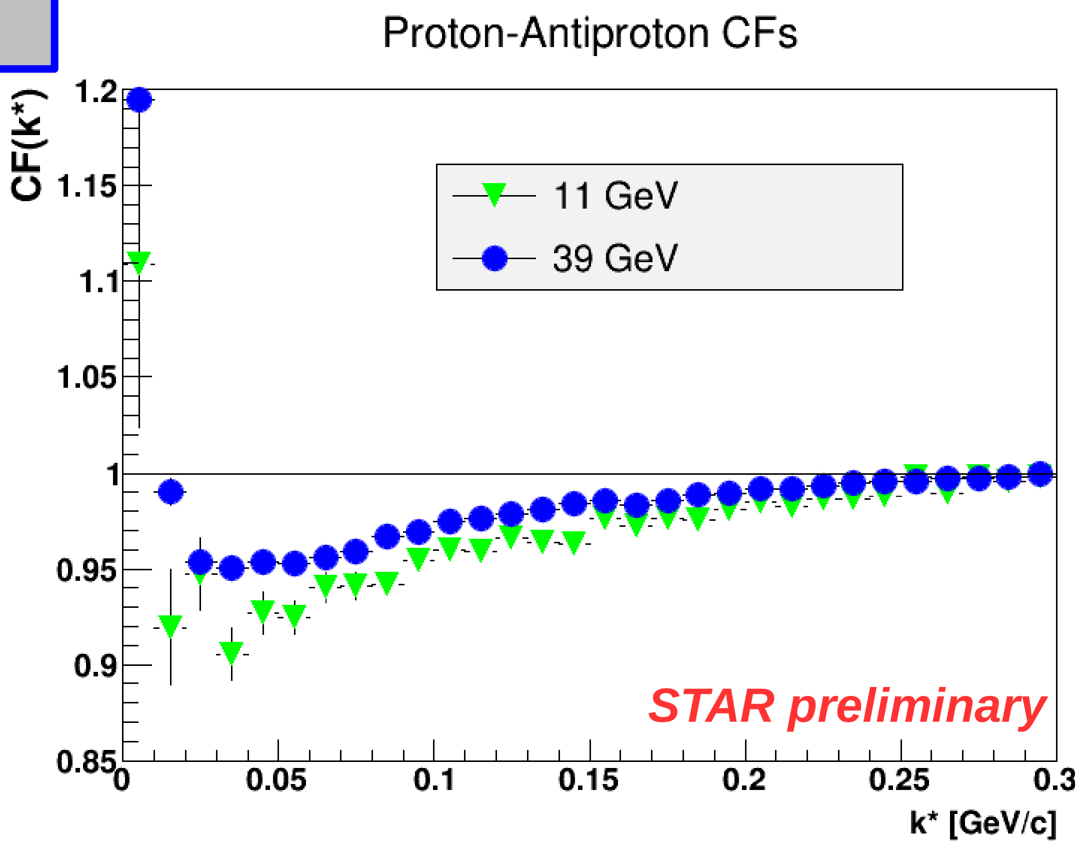
Analysis Au+Au collisions MB comparison

Antiproton-Antiproton pairs have been added to Proton-Proton pairs in order to have Identical Baryon CFs with increased statistics

Measured correlation functions are shown

Clear energy dependence





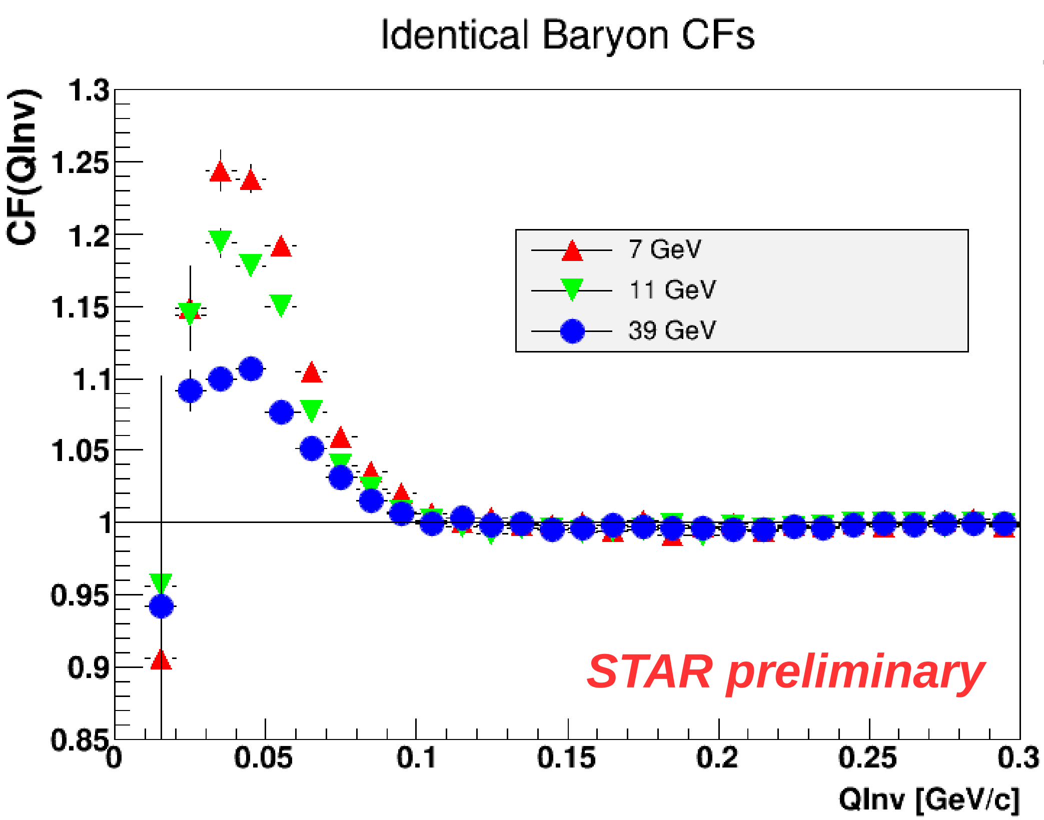
Plots are Minimum Bias
(Centrality 0-80%)

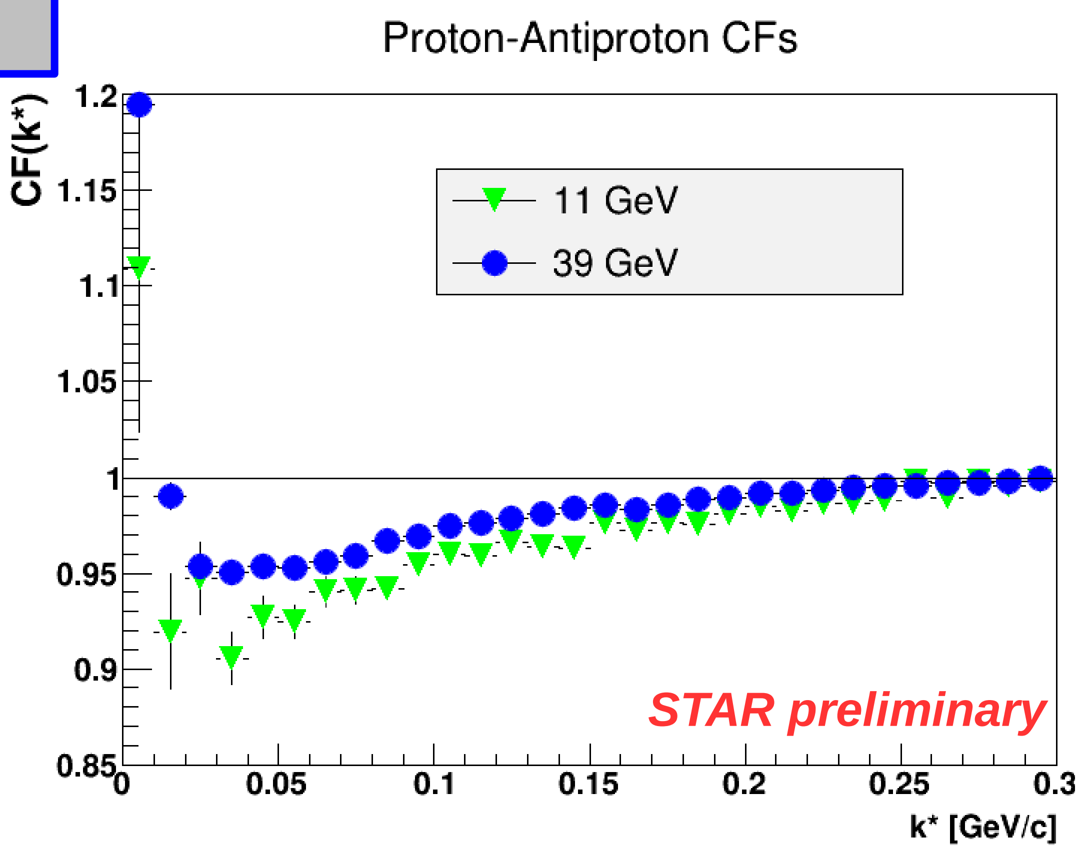
Analysis Au+Au collisions MB comparison

Antiproton-Antiproton pairs have been added to Proton-Proton pairs in order to have Identical Baryon CFs with increased statistics

Clear energy dependence

$$R_{p-p}(39\,GeV) > R_{p-p}(11.5\,GeV) > R_{p-p}(7.7\,GeV)$$





Plots are Minimum Bias (Centrality 0-80%)

Summary

- (anti)proton femtoscopy sensitive to Quantum Statistic Effects and
  Final State Interactions
- Different strong interaction due to annihilation processes
- **the result of antiproton-antiproton CF**
  from 200 GeV Au+Au collisions (Nature 527, 345 (2015)):
    * extracted f_0 and d_0
    * this result provides a fundamental ingredient for understanding the structure
      of more complex anti-nuclei and their properties
- **Data analysed: 7.7 GeV, 11.5 GeV, 39 GeV**
- proton – proton, antiproton – antiproton and proton – antiproton systems checked
    → The range of correlations different for identical and nonidentical
      particle combinations
- From the proton – proton, antiproton – antiproton and proton – antiproton correlation functions we find source size parameters are dependent on collision energy as well as the collision centrality
    * the higher the collision energy the larger the source parameter

$$R_{p-p}(39\,GeV) > R_{p-p}(11.5\,GeV) > R_{p-p}(7.7\,GeV)$$

    * the more central the collision the larger the source parameter

$$R_{p-p}(0-10\,\%) > R_{p-p}(10-30\,\%) > R_{p-p}(30-80\,\%)$$

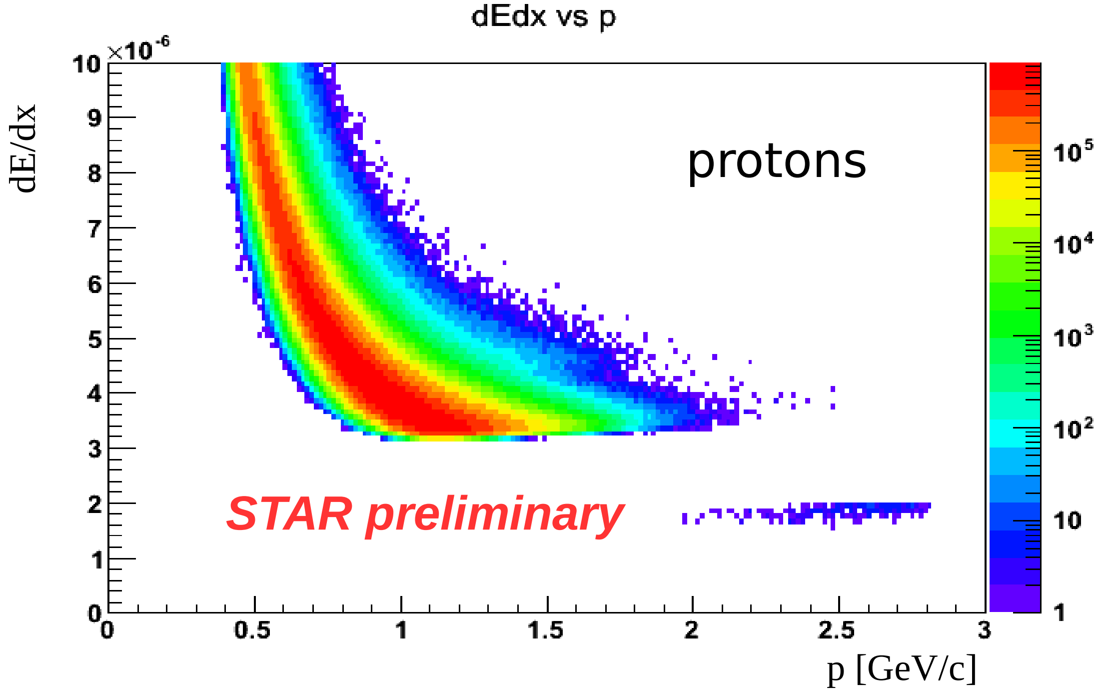
Thank You for Your attention!

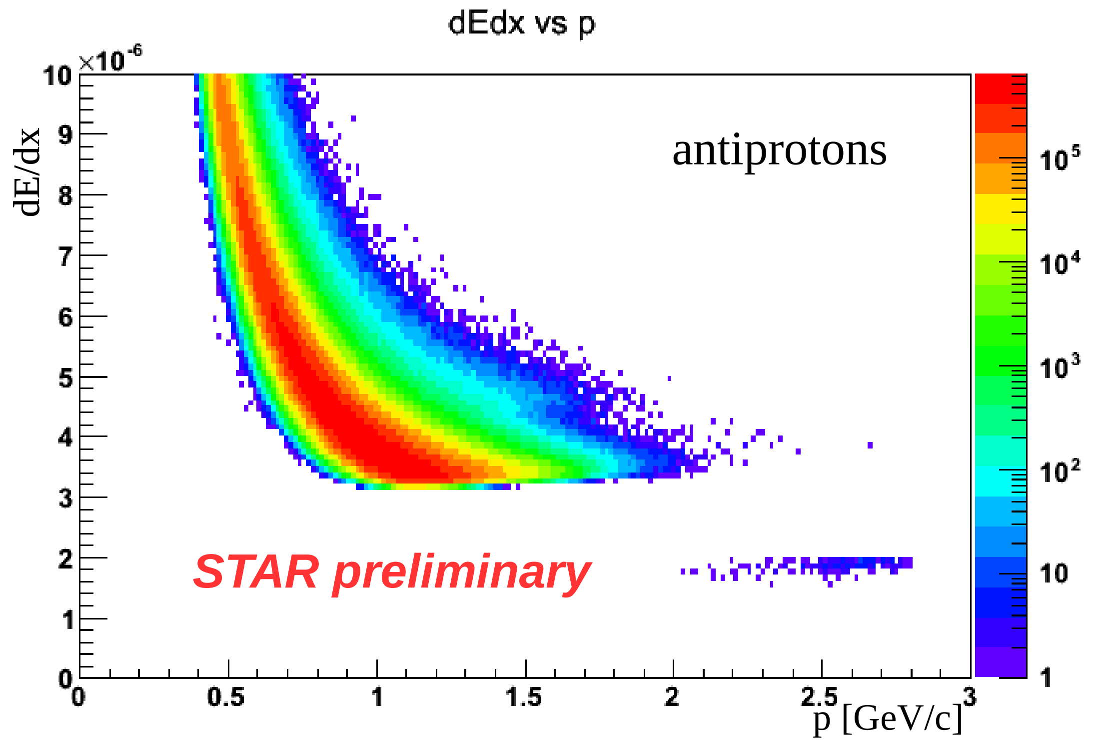
BACKUP

Multiplicity

	Events	Tracks	Pairs
39 GeV (0-10%)	13 M	71 M (protons) 20 M (antiprotons)	394 M (p-p) 32 M (pbar-pbar) 111 M (p-pbar)
39 GeV (10-30%)	26 M	91 M (protons) 28 M (antiprotons)	326 M (p-p) 30 M (pbar-pbar) 100 M (p-pbar)
39 GeV (30-80%)	63 M	58 M (protons) 21 M (antiprotons)	77 M (p-p) 9 M (pbar-pbar) 27 M (p-pbar)
11.5 GeV (0-10%)	1.3 M	13 M (protons) 398 k (antiprotons)	129 M (p-p) 120 k (pbar-pbar) 4.0 M (p-pbar)
11.5 GeV (10-30%)	2.6 M	15 M (protons) 537 k (antiprotons)	93 M (p-p) 108 k (pbar-pbar) 3.2 M (p-pbar)
11.5 GeV (30-80%)	6.4 M	9 M (protons) 183 k (antiprotons)	19 M (p-p) 34 k (pbar-pbar) 0.4 M (p-pbar)
7.7 GeV (0-10%)	0.47 M	6.1 M (protons) 43 k (antiprotons)	79 M (p-p) 3.9 k (pbar-pbar) 566 k (p-pbar)
7.7 GeV (10-30%)	0.93 M	6.9 M (protons) 55 k (antiprotons)	53 M (p-p) 3.2 k (pbar-pbar) 358 k (p-pbar)
7.7 GeV (30-80%)	2.04 M	3.3 M (protons) 4 k (antiprotons)	11 M (p-p) 1.0 k (pbar-pbar) 9 k (p-pbar)

Analysis Au+Au collisions @ 200 GeV





Total: 210 mln events

126 mln events - centrality 30 – 80%

57 mln events – centrality 10-30%

27 mln events – centrality 0 -10%

$p \in [0.4, 3.0]$ GeV/c

$pT \in [0.4, 2.5]$ GeV/c

$|\eta| < 0.5$

Nhits $\in [15, 50]$

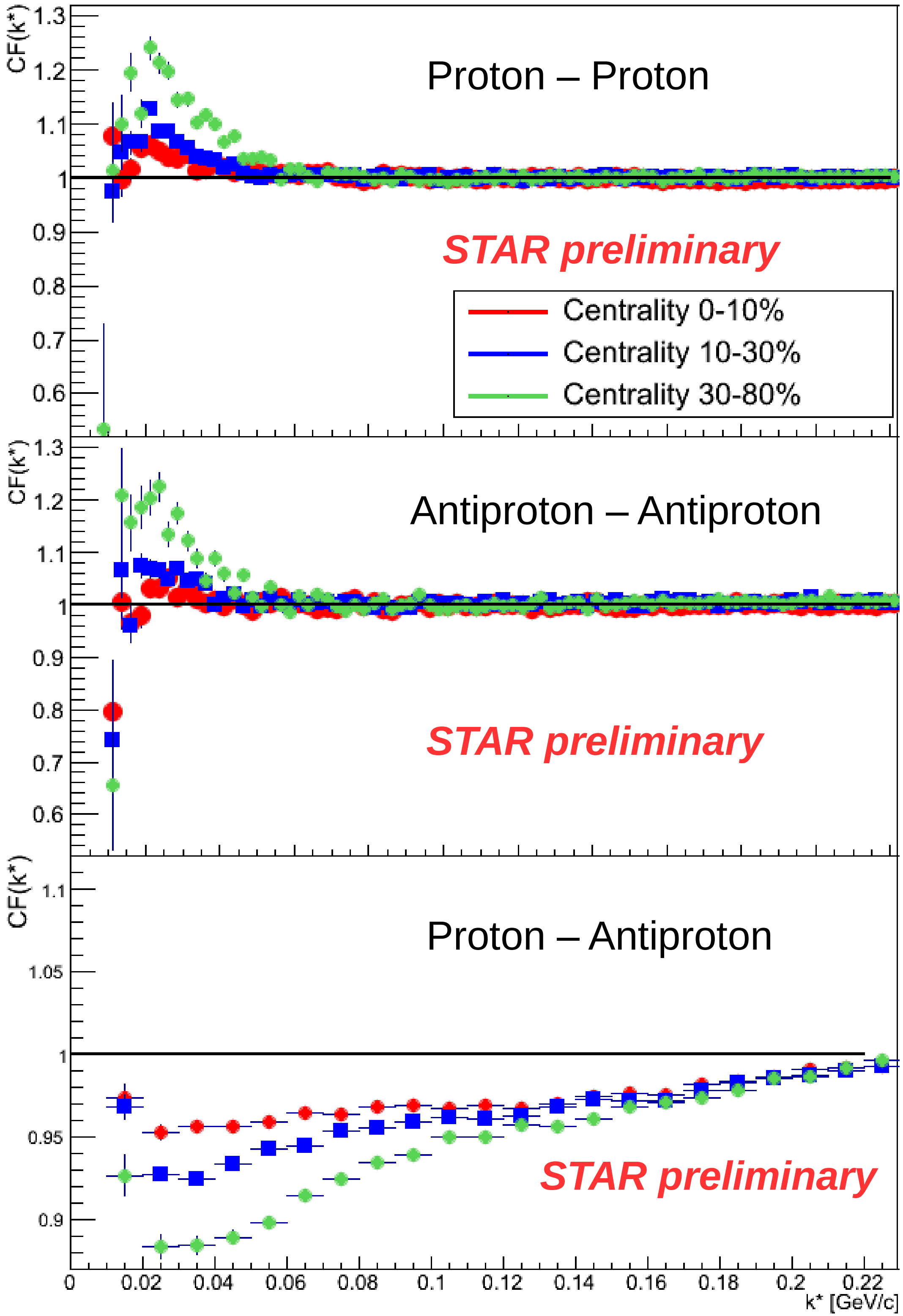
DCA <1cm

$N\sigma$ p < 3.0

$N\sigma$ π, K > 3.0

$m^2 \in [0.76, 1.03]$

For each particle TPC & TOF signal is required.



Analysis Au+Au collisions @ 200 GeV

Measured correlation functions are shown

Clear centrality dependence

Antiproton-antiproton Correlation Function

The theoretical Correlation Function can be obtained with:

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

where:

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

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

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

is the wave scattering amplitude renormalized by Coulomb interaction

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

$$\tilde{G}(\rho,\eta) = \sqrt{A_c(k^*)}\,(G_0(\rho,\eta) + iF_0(\rho,\eta))$$

is a combination of regular (F_0) and singular (G_0) s-wave Coulomb Funtions