The Study of Two (Anti-)proton Interaction via Correlation Measurement

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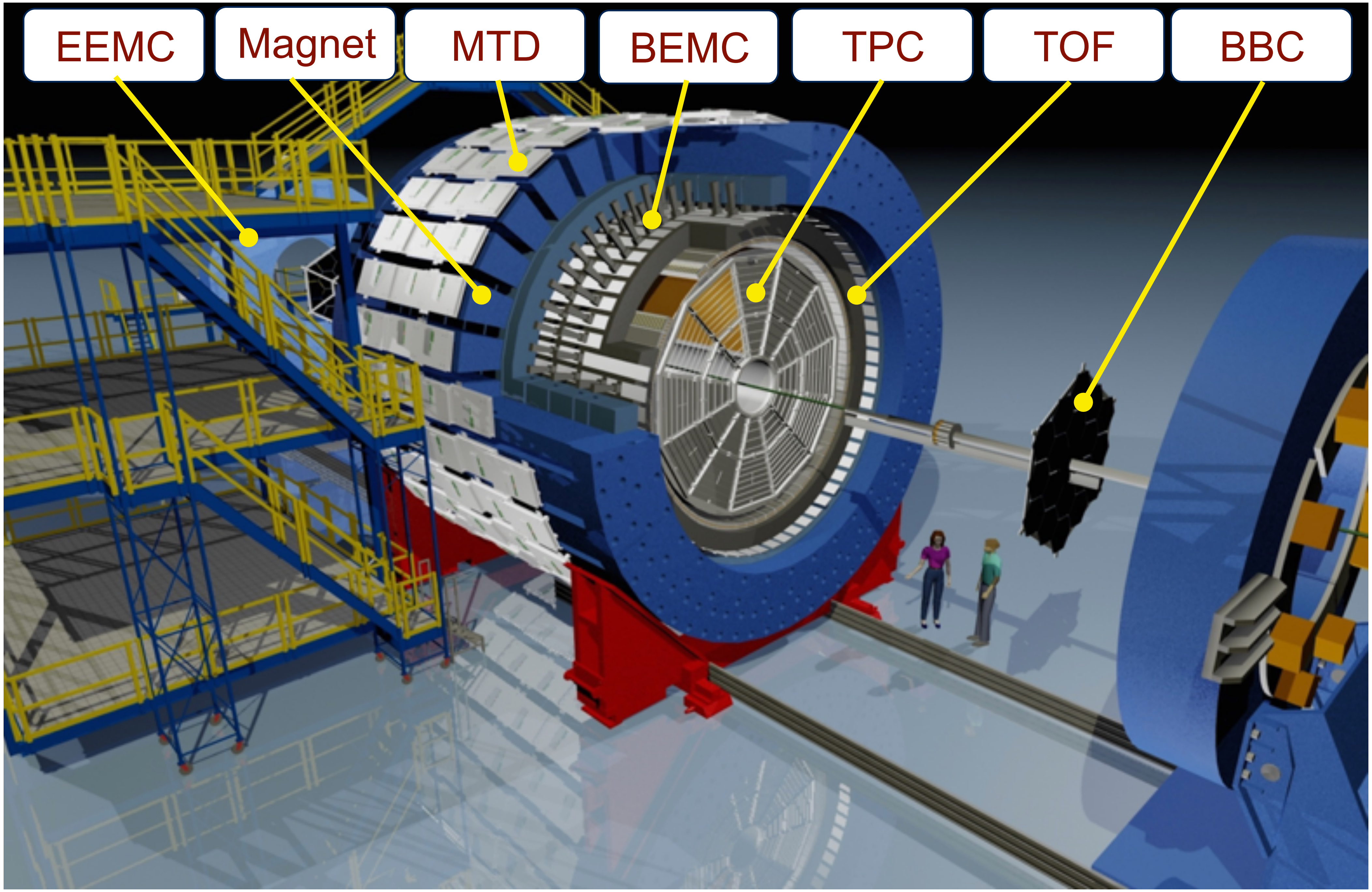
Outline

- Motivation
- Analysis procedure
- Results
- Summary

Motivation

- So far the large body of knowledge on nuclear force was derived from studies made on nucleons or nuclei, not much is known about the nuclear force between anti-nucleons.
- The knowledge of interaction among two anti-protons, the simplest system of anti-nucleons(nuclei), is a fundamental ingredient for understanding the structure of more sophisticated anti-nuclei and their properties.
- With abundantly produced anti-nucleons, RHIC (and LHC too) has the excellent capability of conducting such kind of studies.

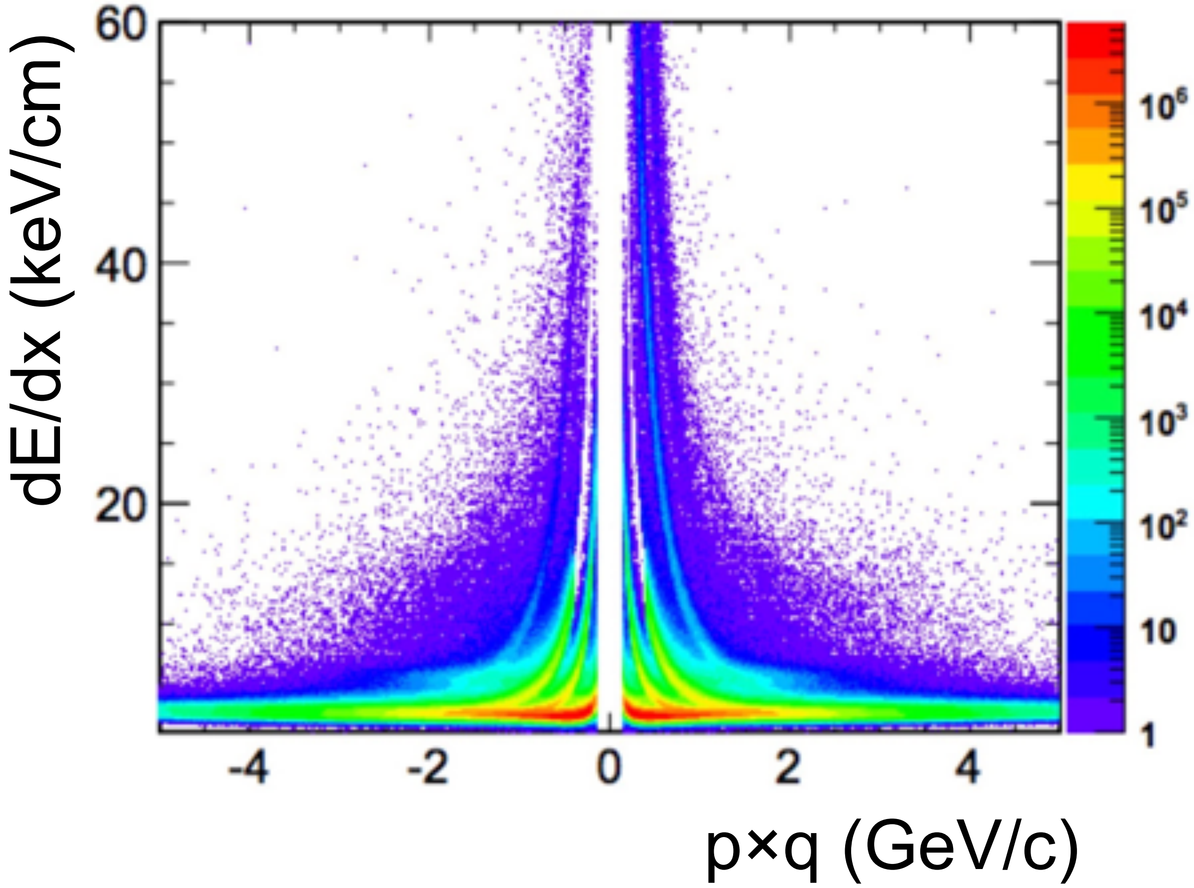
STAR Detectors

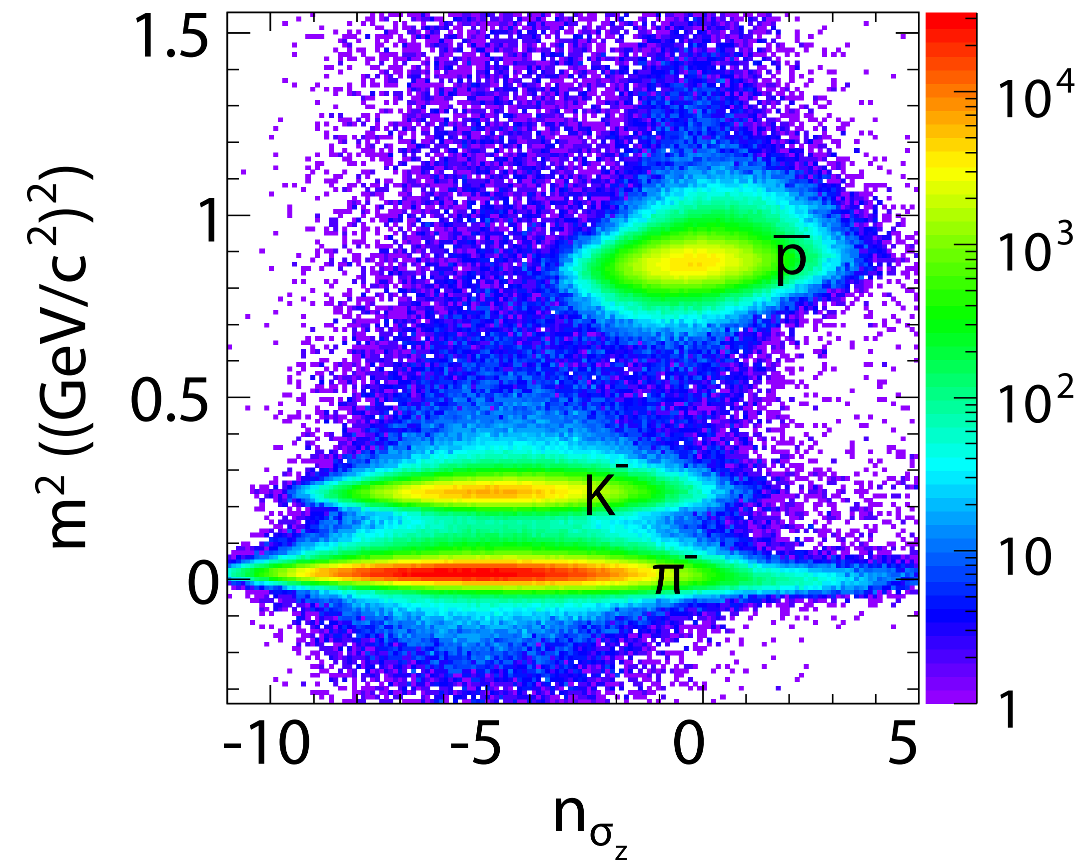


Full 2π coverage; Pseudorapidity coverage ~ ±1 unit

Particle Identification

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%.

Femtoscopy Analysis

Correlation Function(CF):

$$C_{measure}(k^*) = \frac{A(k^*)}{B(k^*)}$$

A(k*) - real pair,
B(k*) - pair from mixed event
k* - half of relative momentum between two particles

Purity correction:

$$C_{corrected}(k^*) = \frac{C_{measured}(k^*)-1}{Pairpurity(k^*)} + 1$$

Formula to fit our data

Inside our (anti)proton sample, there are secondary (anti)protons that are indistinguishable from primordial ones. In the residual protons, the Lambda decay channel gives the most contribution. We fit the data by the following equation

$$C_{meas}(k^*_{pp}) = 1+x_{pp}[C_{pp}(k^*;R_{pp})-1]+x_{p\Lambda}[\widetilde{C}_{p\Lambda}(k^*_{pp};R_{p\Lambda})-1]+x_{\Lambda\Lambda}[\widetilde{C}_{\Lambda\Lambda}(k^*_{pp};R_{\Lambda\Lambda})-1]$$

where

$$\widetilde{C}_{\Lambda\Lambda}(k^*_{pp}) = \sum_{k^*_{\Lambda\Lambda}} C_{\Lambda\Lambda}(k^*_{\Lambda\Lambda})T(k^*_{\Lambda\Lambda},k^*_{pp}) \quad \text{and} \quad \widetilde{C}_{p\Lambda}(k^*_{pp}) = \sum_{k^*_{p\Lambda}} C_{p\Lambda}(k^*_{p\Lambda})T(k^*_{p\Lambda},k^*_{pp})$$

- $C_{pp}(k^*)$ and $C_{p\Lambda}(k^*_{p\Lambda})$ are calculated by the Lednicky and Lyuboshitz model.
- $C_{\Lambda\Lambda}(k^*_{\Lambda\Lambda})$ is from STAR published paper (Phys. Rev. Lett. 114 (2015) 22301).
- We regard $R_{p\Lambda}$ and $R_{\Lambda\Lambda}$ are equal to R_{pp}.
- T is the corresponding transform matrices generated by THERMINATOR2 model to transform the $k^*_{p\Lambda}$ to k^*_{pp} or $k^*_{\Lambda\Lambda}$ to k^*_{pp}.

f_0 and d_0

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

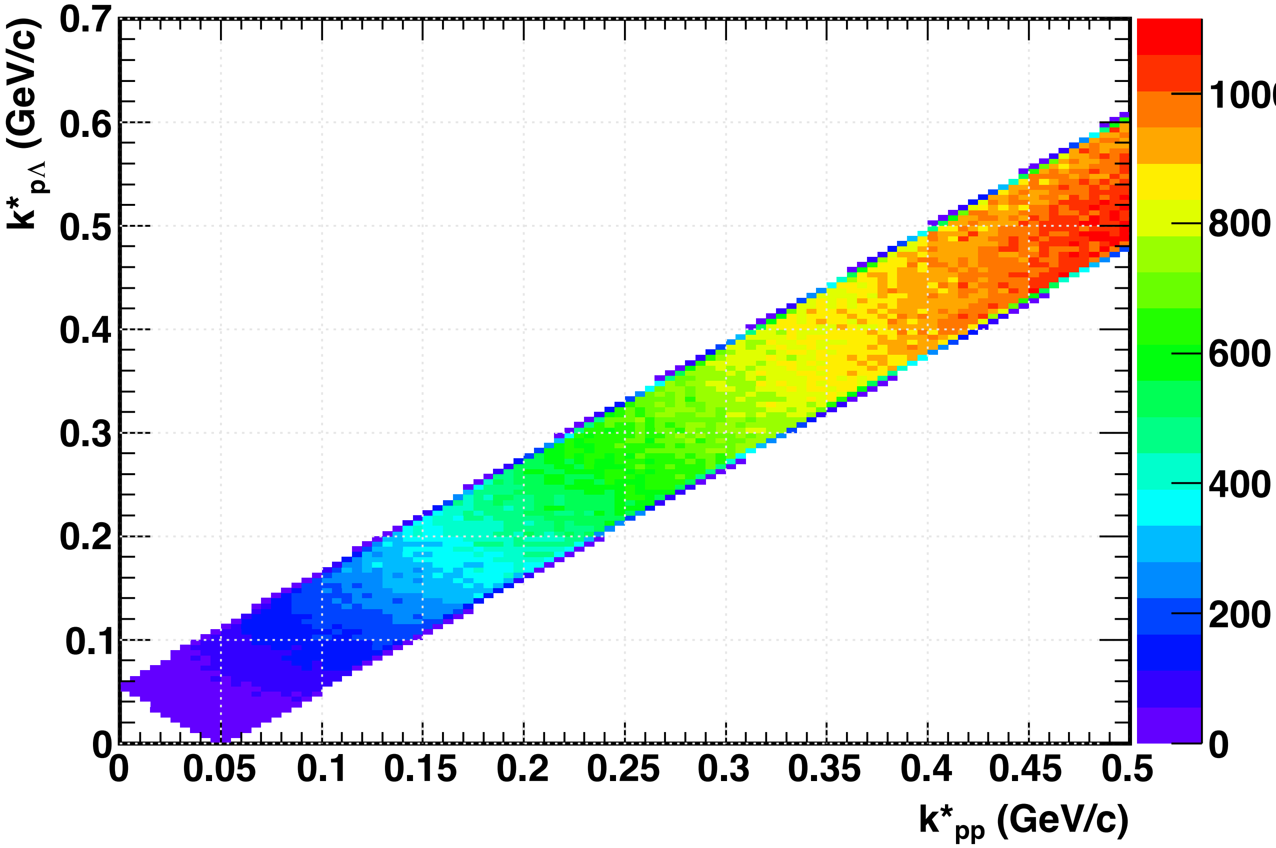
$$\lim_{k \to 0} \sigma_e = 4\pi f_0^2$$

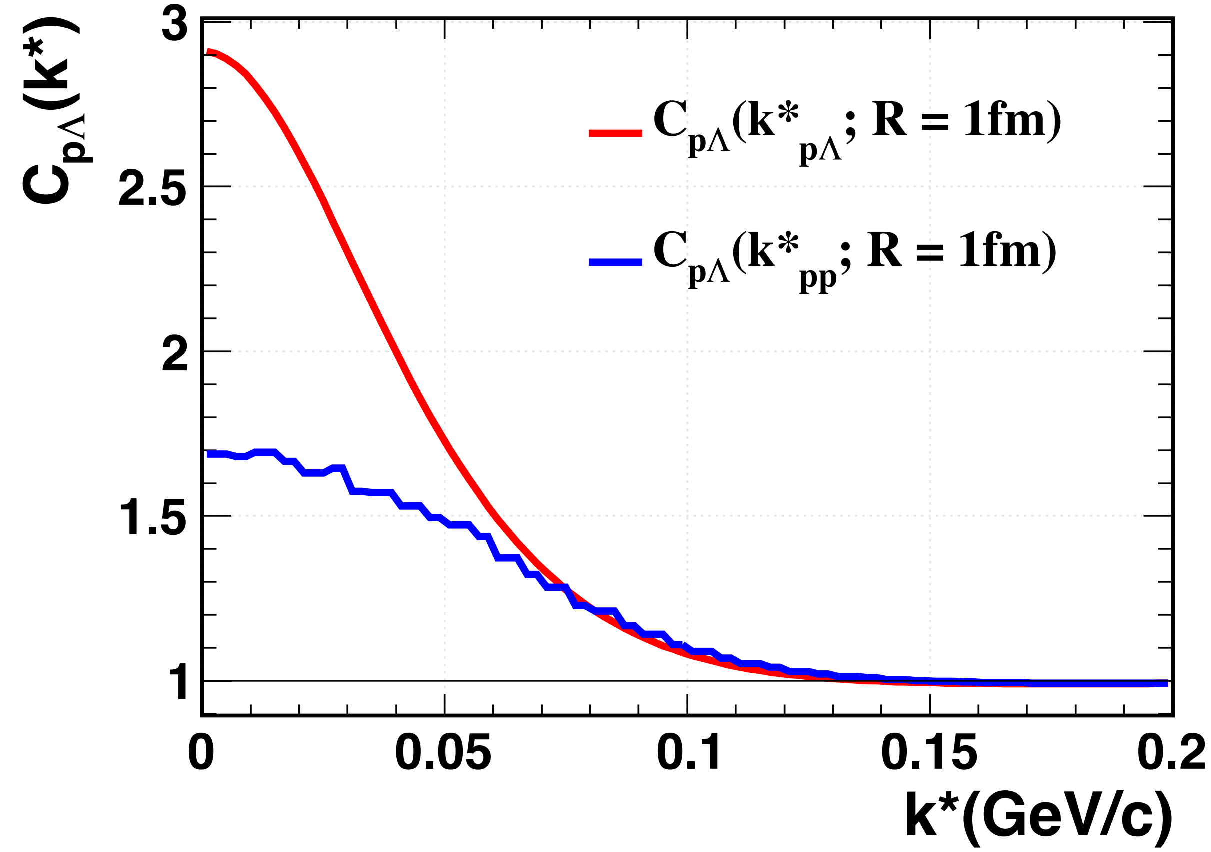
Here k is the wave number.

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.

- f_0 and d_0 are two important parameters in characterizing the strong interaction between two particles.
- The part $C_{pp}(k^*; R_{pp})$ in the equation we used to fit the data is calculated based on f_0 and d_0.

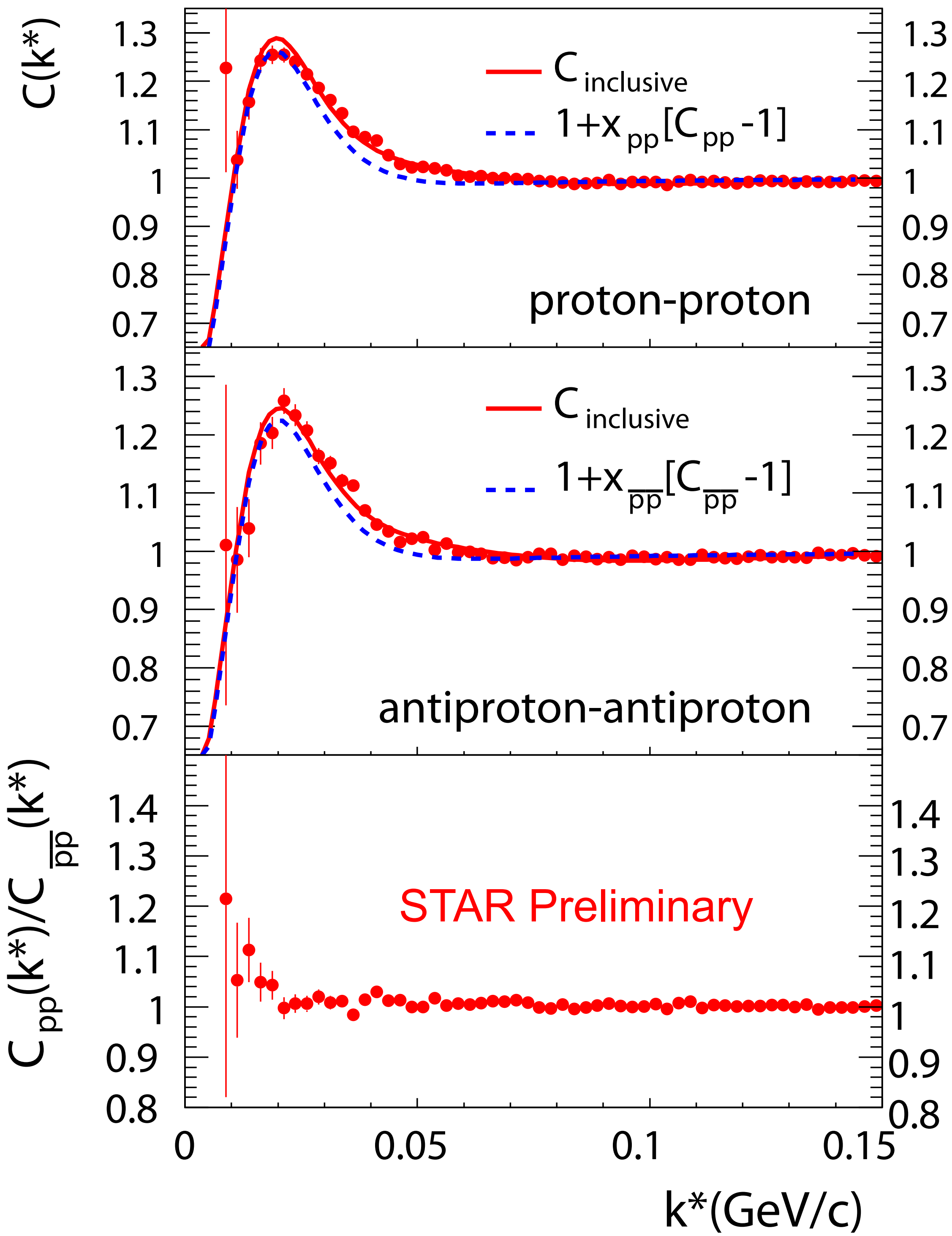
Transformation matrix





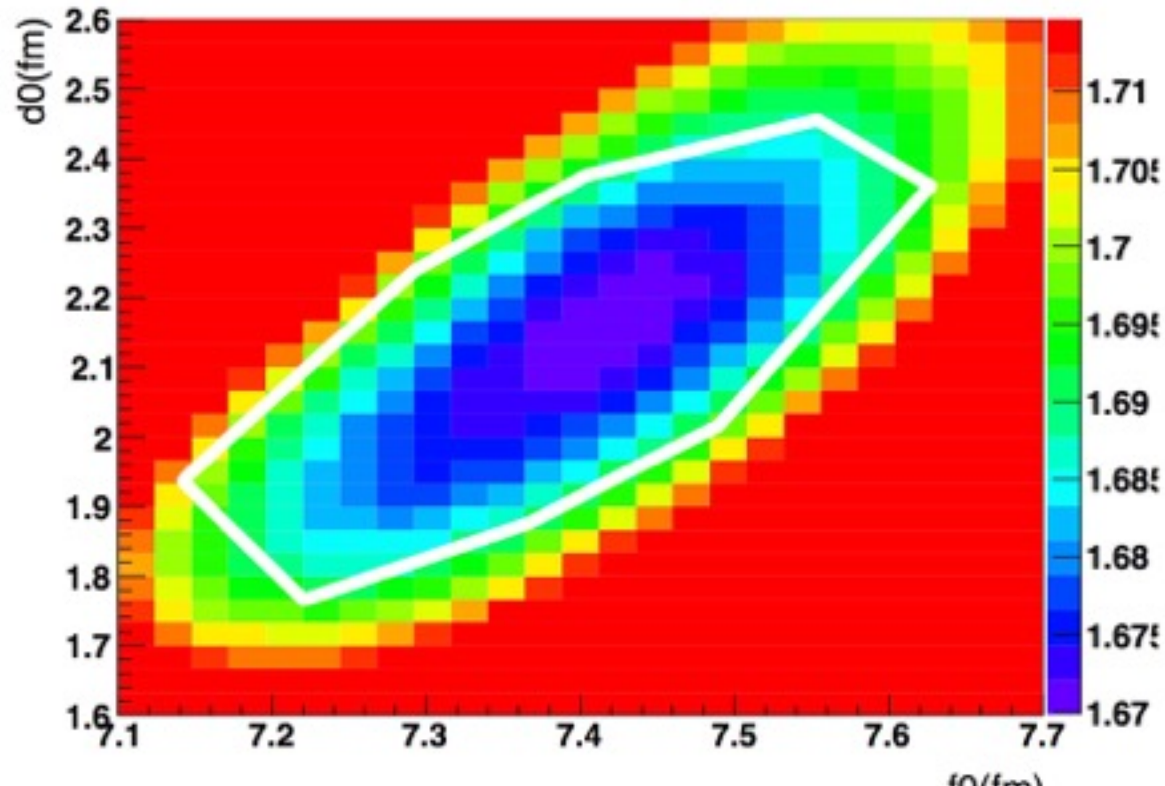
- The transformation matrix is derived from THERMINATOR2 to transform $k^*_{p\Lambda}$ to k^*_{pp}.
- Particle cuts for the transformation matrix: |eta|<0.7,0.4<rigidity<2.5, 0.4GeV/c<pt<2.5GeV/c.

Correlations and the ratio



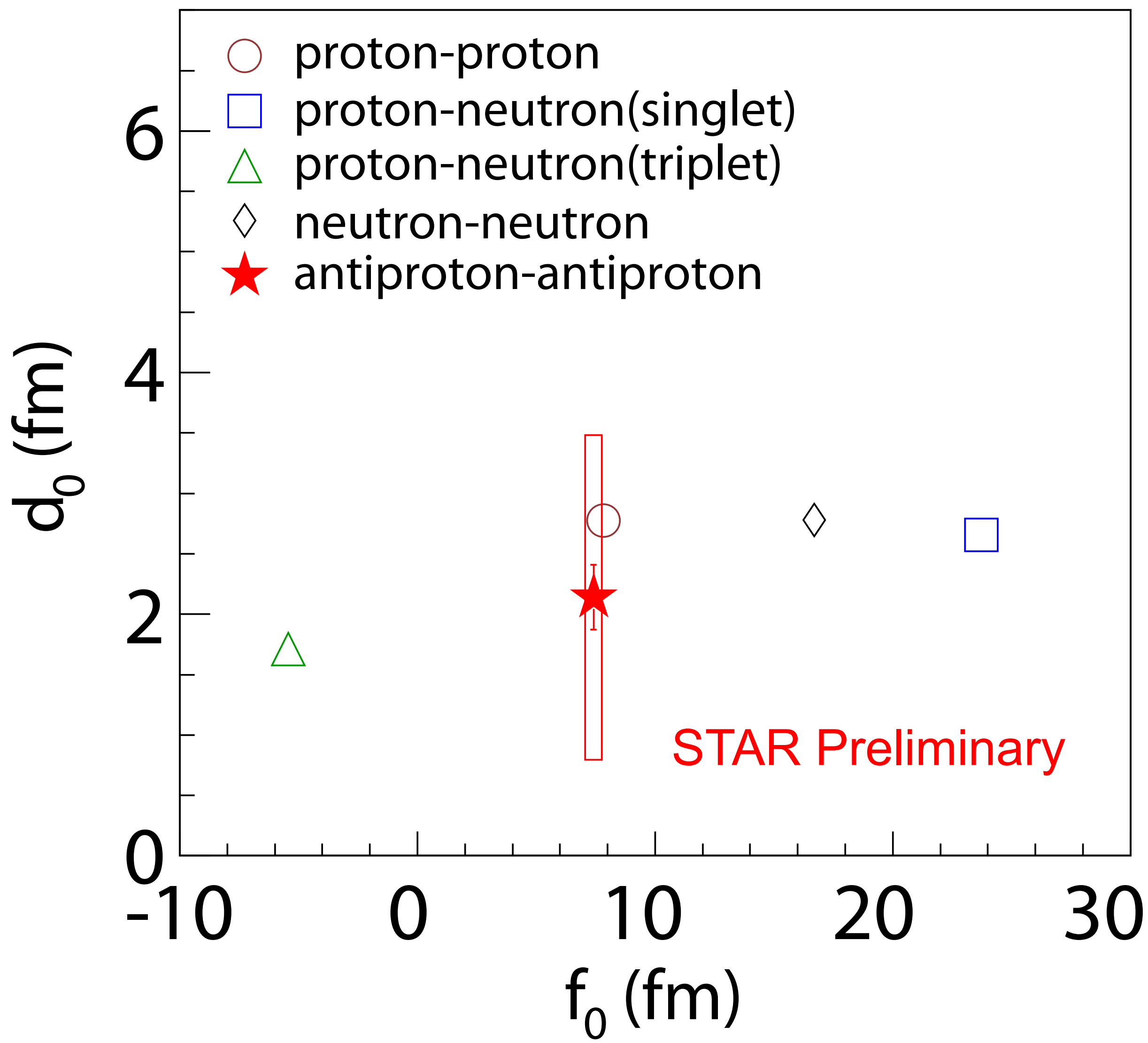
Fit results:
For proton–proton CF,
R=2.75±0.01fm; χ^2/NDF = 1.66;

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



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

Summary

- We report the result of antiproton-antiproton correlation function from 200GeV Au+Au collisions. Parameters f_0, d_0 are extracted from the correlation function and the interaction between the two anti-protons is found to be attractive.
- This direct information on the interaction between two anti-protons, one of the simplest systems of anti-nucleons, provides a fundamental ingredient for understanding the structure of more complex anti-nuclei and their properties.

THANKS!

backup

Antiproton-antiproton Correlation Function

The theoretical correlation function can be obtained with:

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

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

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

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

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.

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f_0 and d_0

The scattering length in quantum mechanics describes low-energy scattering. It is defined as the following low-energy limit.

$$\lim_{k\to 0} k \cot\delta(k) = -\frac{1}{a} \, ,$$

where a is the scattering length, k is the wave number, and $\delta(k)$ is the s-wave phase shift The elastic cross section, σ_e , at low energies is determined solely by the scattering length,

$$\lim_{k\to 0} \sigma_e = 4\pi a^2 \, .$$

In our fitting formula, $f_0 = -a$.

d_0 is effective range and

$$d_0 = 2\int_0^\infty (v_0^2 - u_0^2) dr,$$

where $\frac{v_0}{r}$ is the wave function inside the nuclear-force well at zero incident kinetic energy, and $\frac{u_0}{r}$ is the asymptotic wave function, outside the range of the nuclear force at zero incident kinetic energy.