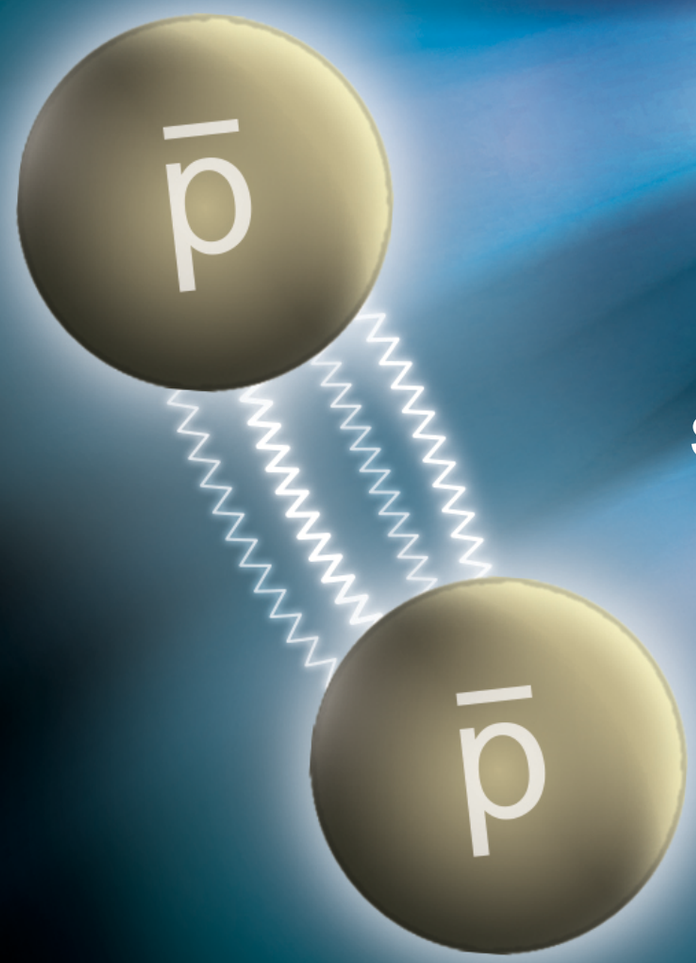
Measurement of interaction between antiprotons

- The STAR Collaboration
  nature 527, 345-348



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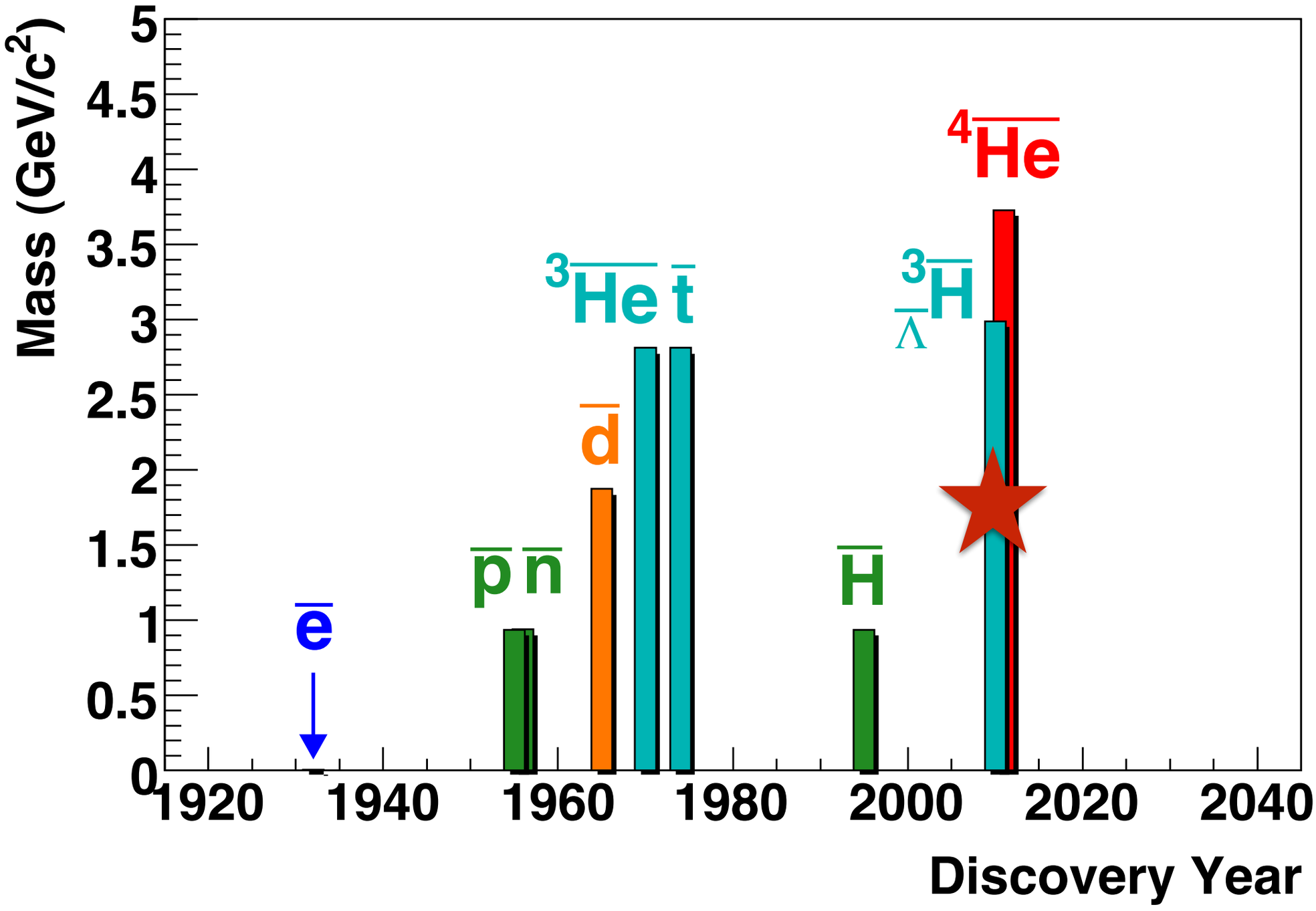
Outline

- Anti-matter history
- Motivation
- Analysis procedure
- Results
- Summary

Antimatter History



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.

Nuclear force : scattering length (f_0) and effective range (d_0)

f_0 is related to the cross section.

At low energy limit, the scattering cross section is given by

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

Here k is the wave number.

d_0 is related to the range of the potential.

In the case of square well potential, d_0 is the range (radius) of the potential.

For a short range potential, f_0 and d_0 are related to the s-wave scattering phase shift δ_0 and the collision momentum k by

$$k \cot(\delta_0) \approx \frac{1}{f_0} + \frac{1}{2} d_0 k^2$$

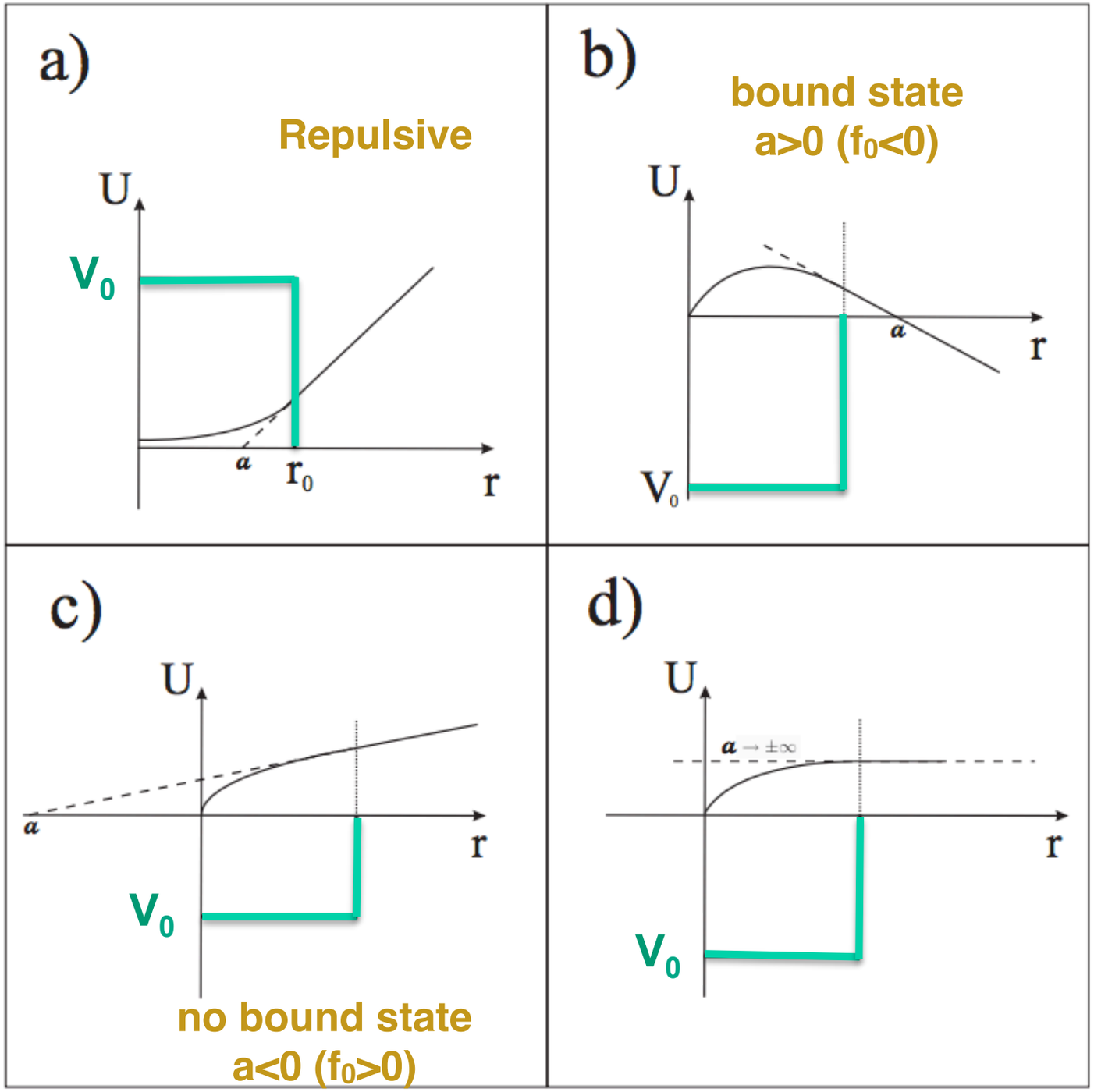
f_0 and d_0 : characterizing the nuclear force

$kr << 1$

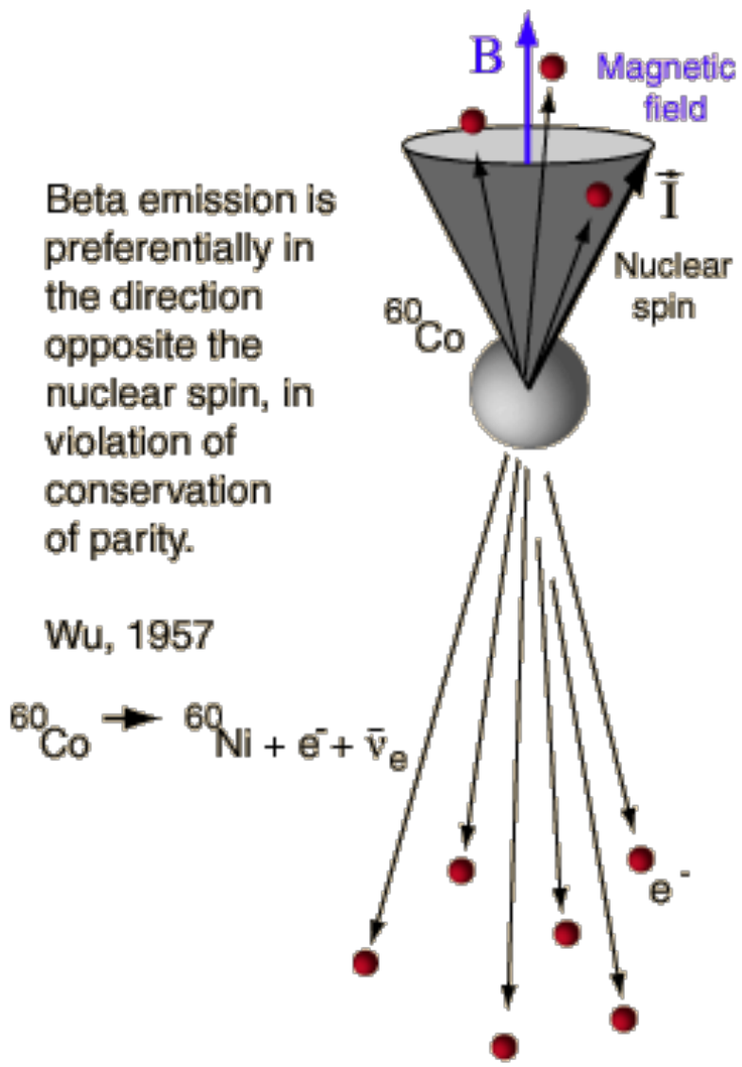
$k \rightarrow 0$

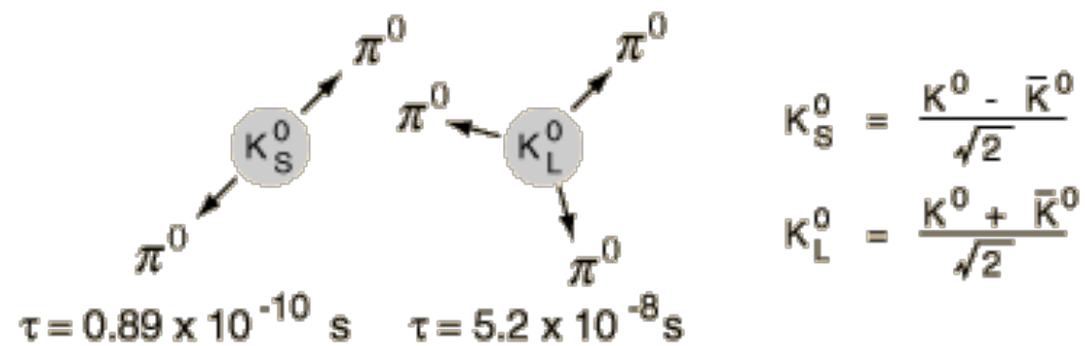
$f_0 \equiv -a$

$d_0 \equiv r_0$



Matter-antimatter symmetry : CPT tests





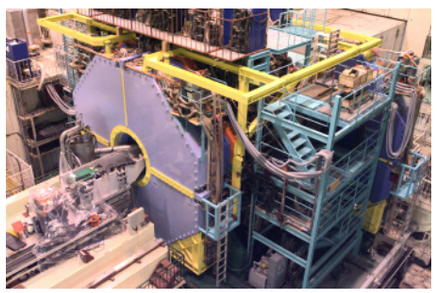
- P- violation : proposed by Lee and Yang. Confirmed by Wu in 1956

- CP- violation : Cronin and Fitch, 1964

CPT is still a hot topic of interest

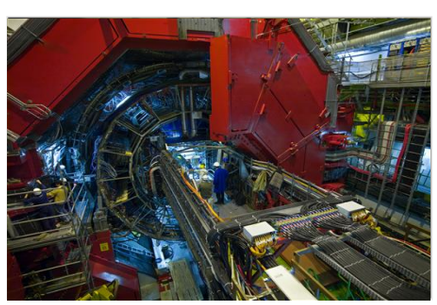
Experiments :

BaBar (SLAC):
CPT violation in B meson system.



Belle (KEK):
CPT violation in decays of B meson.

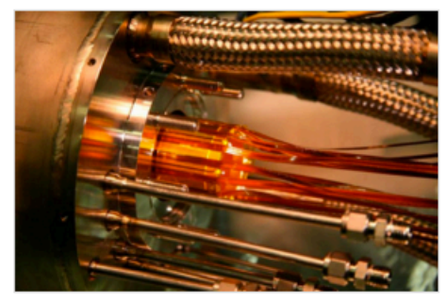
CPLEAR (CERN):
CPT violation in neutral kaon system.



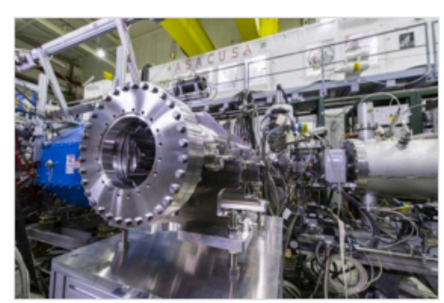
ALICE (CERN):
Antinuclei mass.
Nature physics 11 811 (2015)

AEGIS (CERN):
antimatter gravity.

ATRAP (CERN):
antimatter magnetic moment etc.



ALPHA (CERN):
antimatter gravity, charge, etc.



ASACUSA (CERN):
antimatter mass to charge ratio, hyperfine structure.

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Experiments :

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At RHIC we have the capability to test the CPT from a different aspect.

CPLEAR (CERN):
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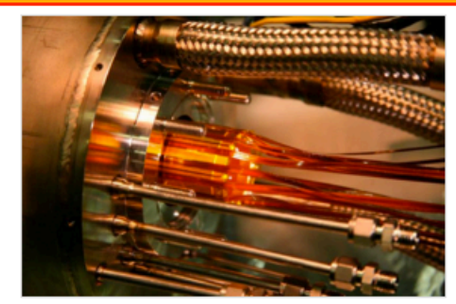

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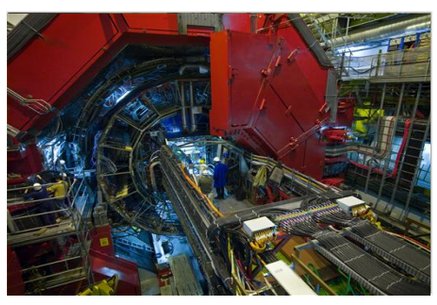

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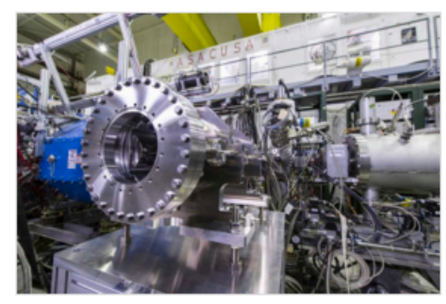

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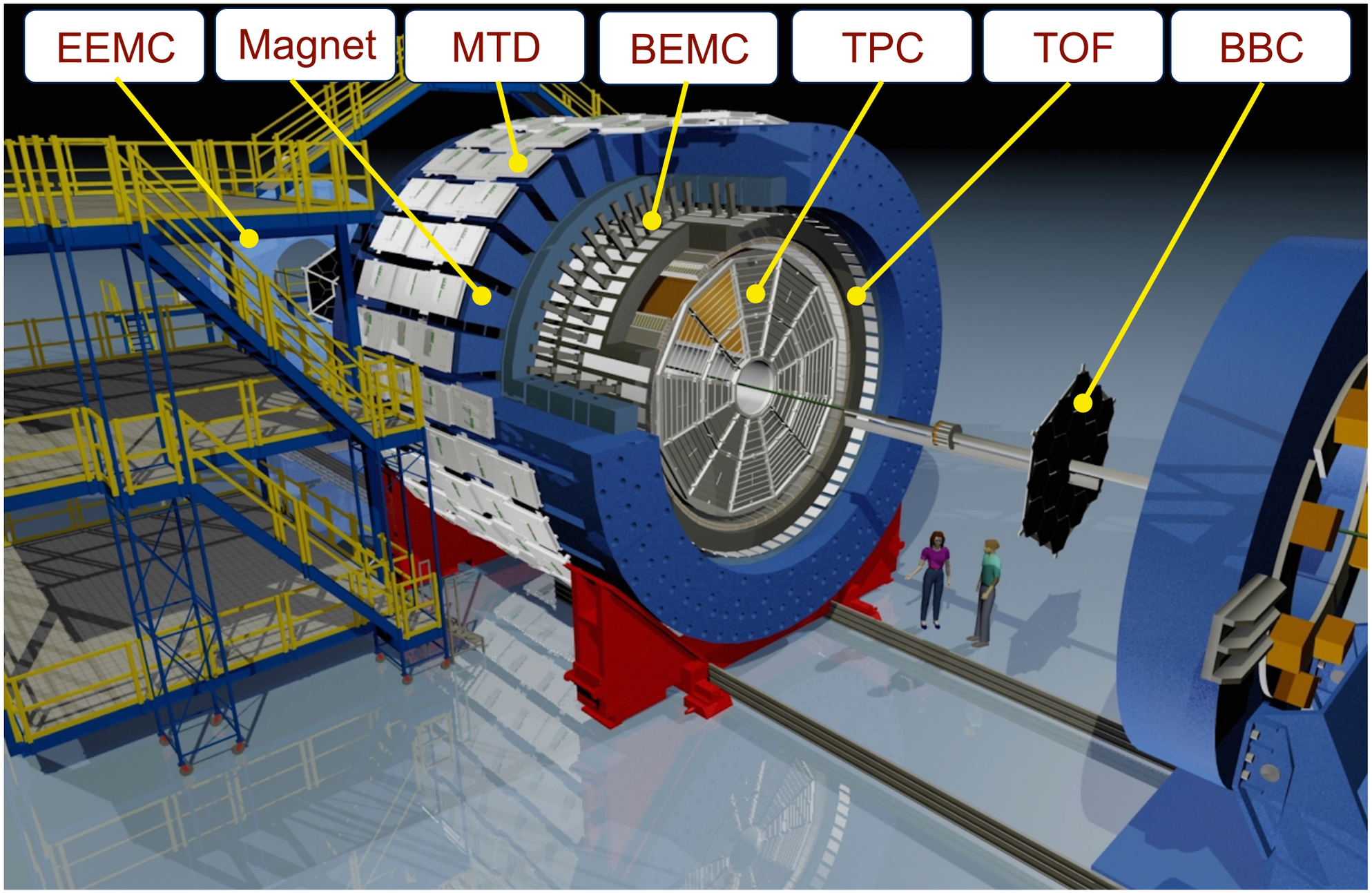
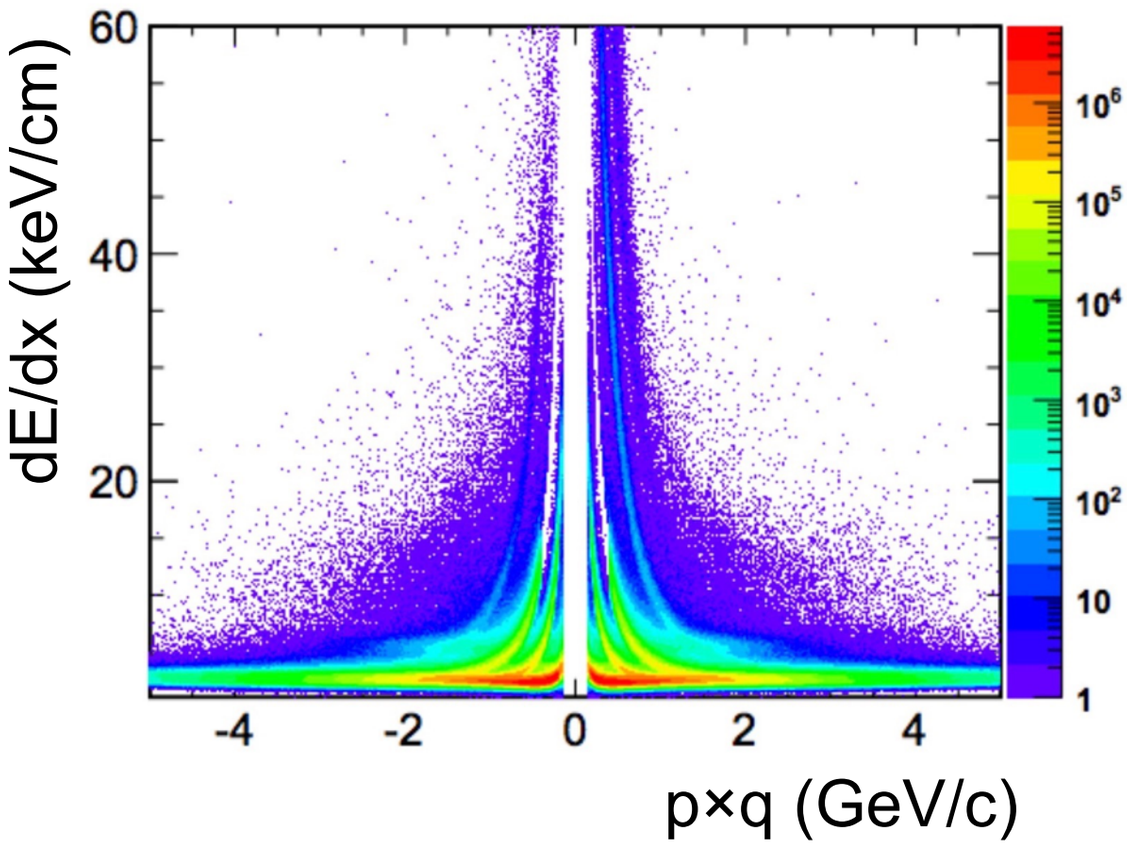
STAR Detectors

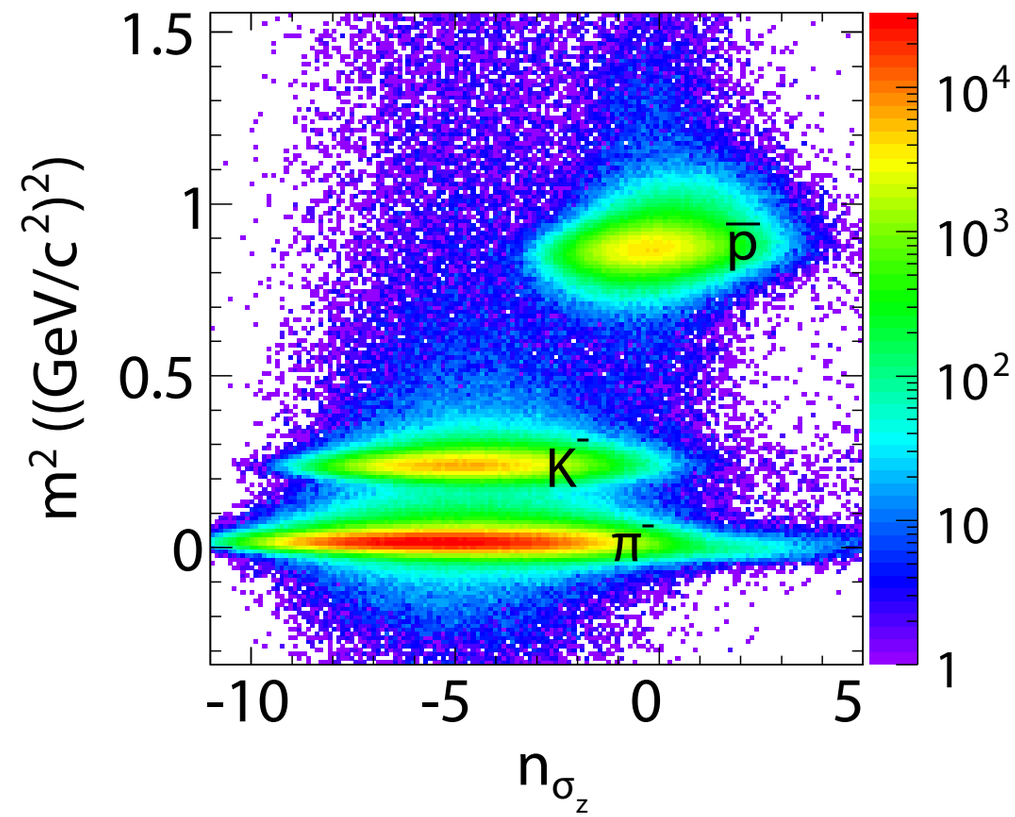


Full 2π coverage; Pseudorapidity coverage ~ ±1 unit

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%.

Correlation Analysis

Correlation Function(CF):

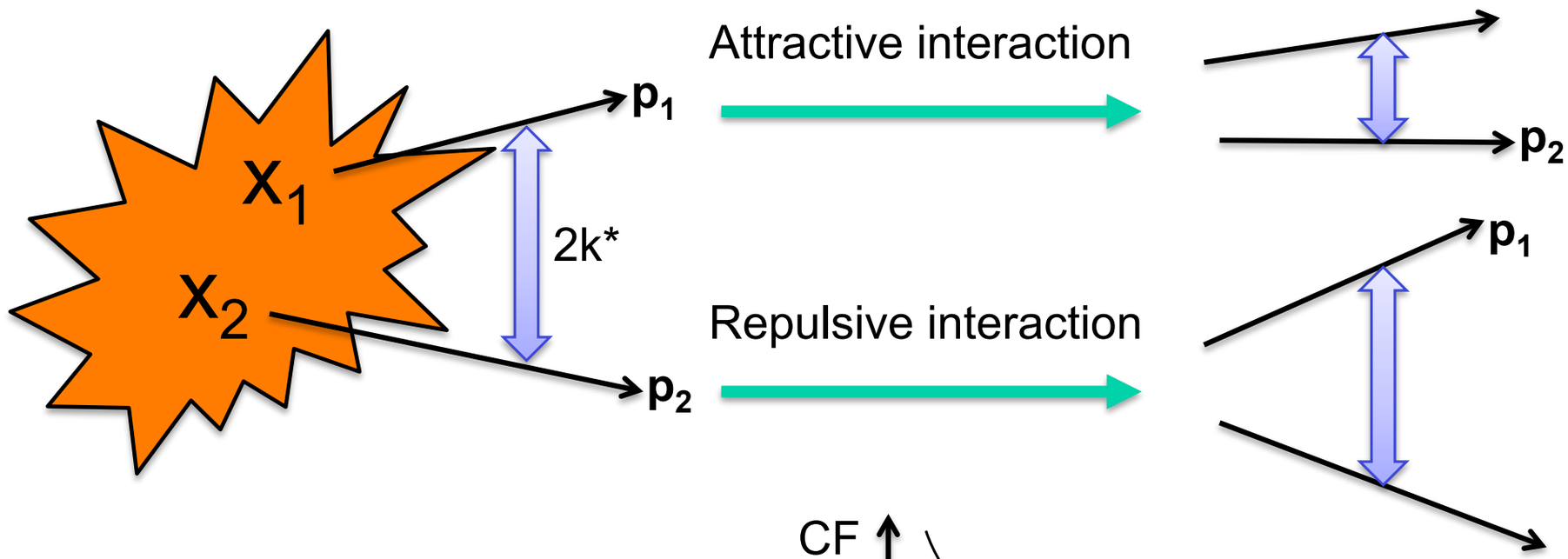
$$C_{measure}(k^*) = \frac{A(k^*)}{B(k^*)}$$

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

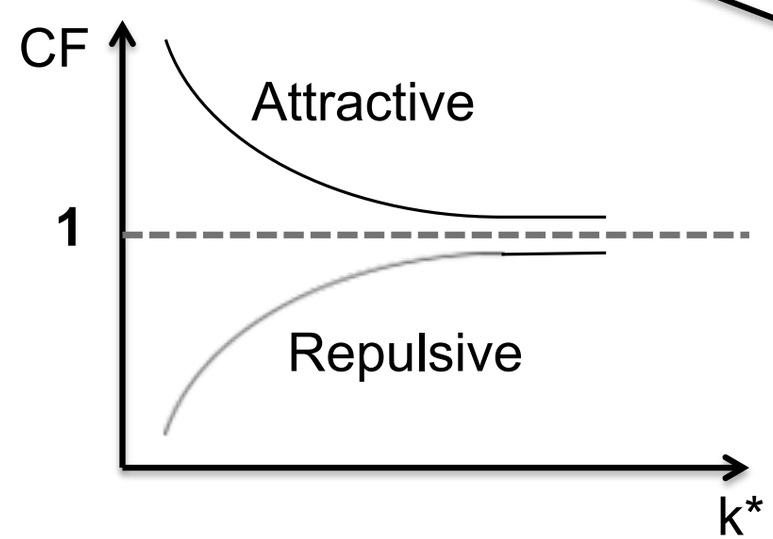
Purity correction:

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

Correlation Analysis

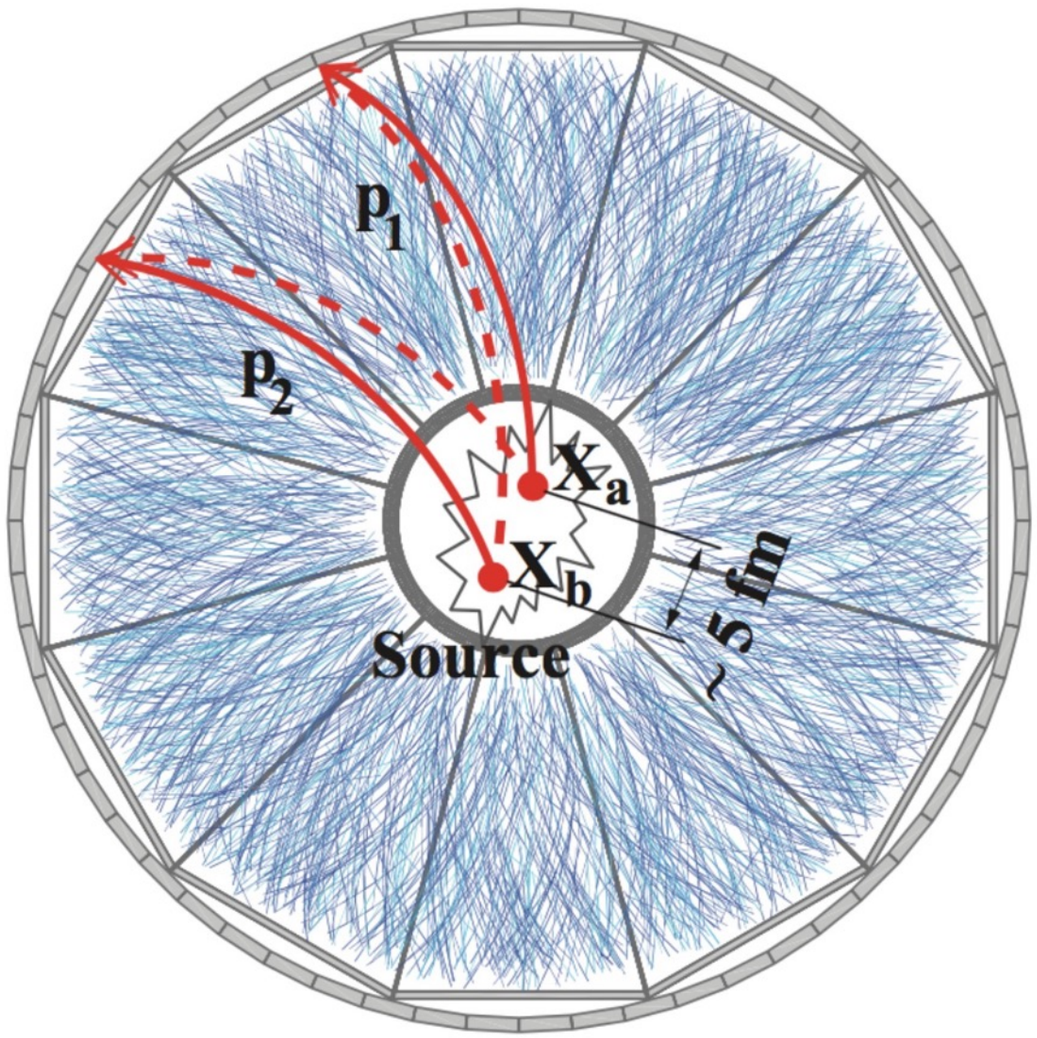


For example, if there is only Coulomb interaction between two particles



Two-particle correlation function is sensitive to the separation distribution of the source and interaction in the final state.

Final State Interaction



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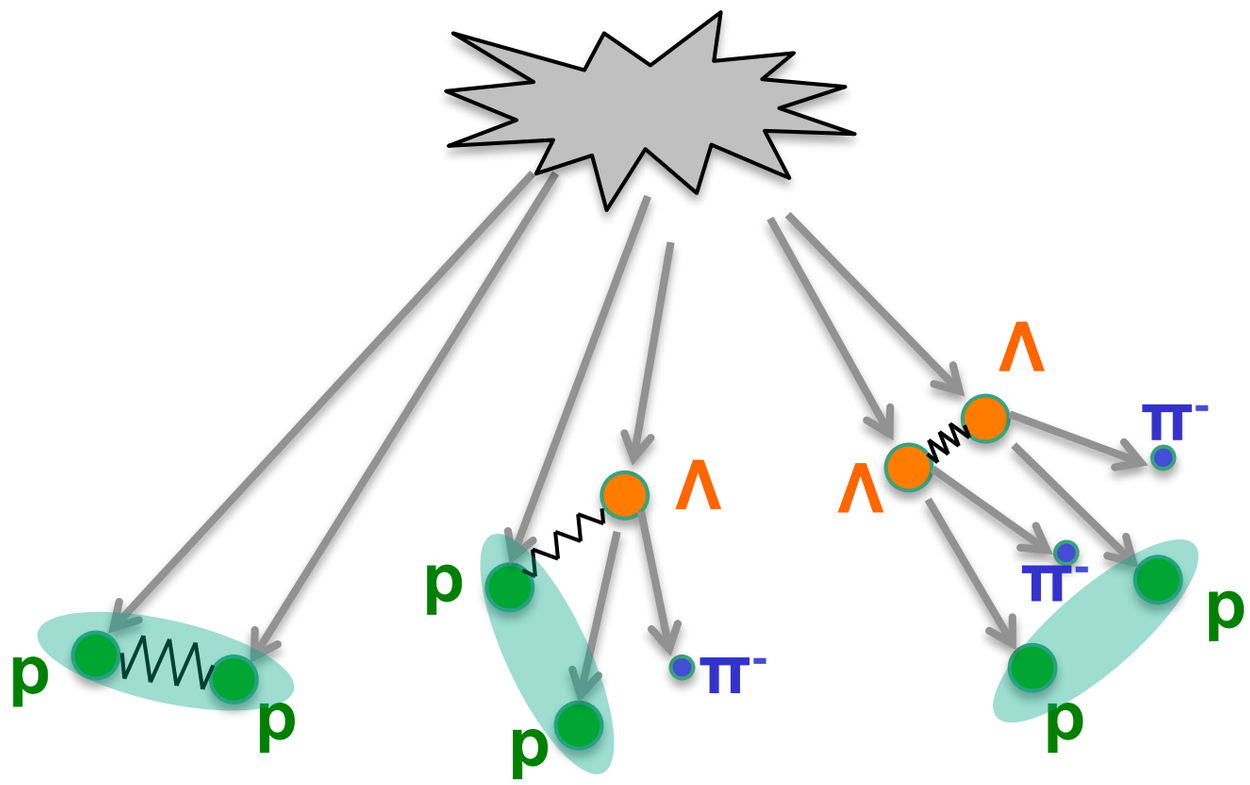
- Quantum Statistics Effects
- Final State Interactions
  - Formation of resonances
  - Coulomb
  - Nuclear interaction

Residual Correlation



The observed (anti)protons can come from weak decays of already correlated primary particles, hence introducing residual correlations which contaminate the CF.

Residual Correlation

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

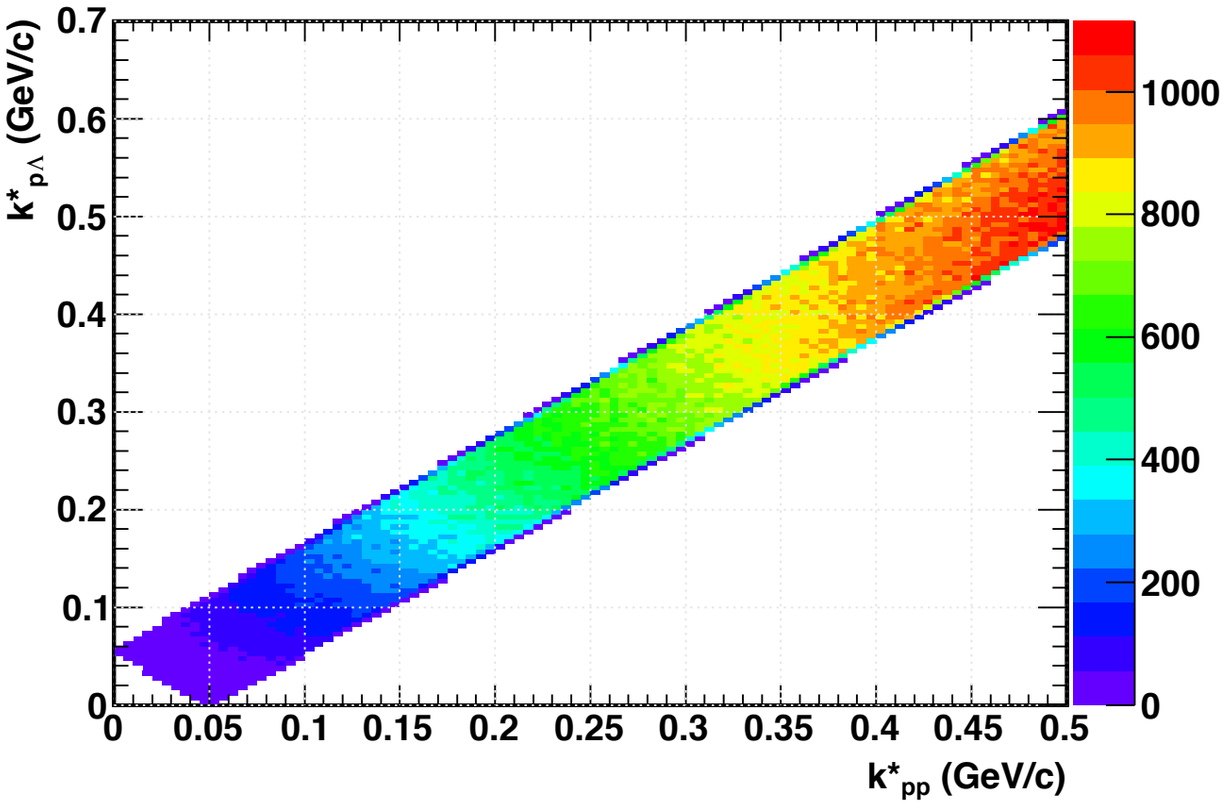
$$C_{meas}(k^*_{pp}) = 1 + x_{pp}[C_{pp}(k^*; R_{pp}) - 1] + x_{p\Lambda}[\widetilde{C}_{p\Lambda}(k^*_{pp}; R_{p\Lambda}) - 1] + x_{\Lambda\Lambda}[\widetilde{C}_{\Lambda\Lambda}(k^*_{pp}; R_{\Lambda\Lambda}) - 1]$$

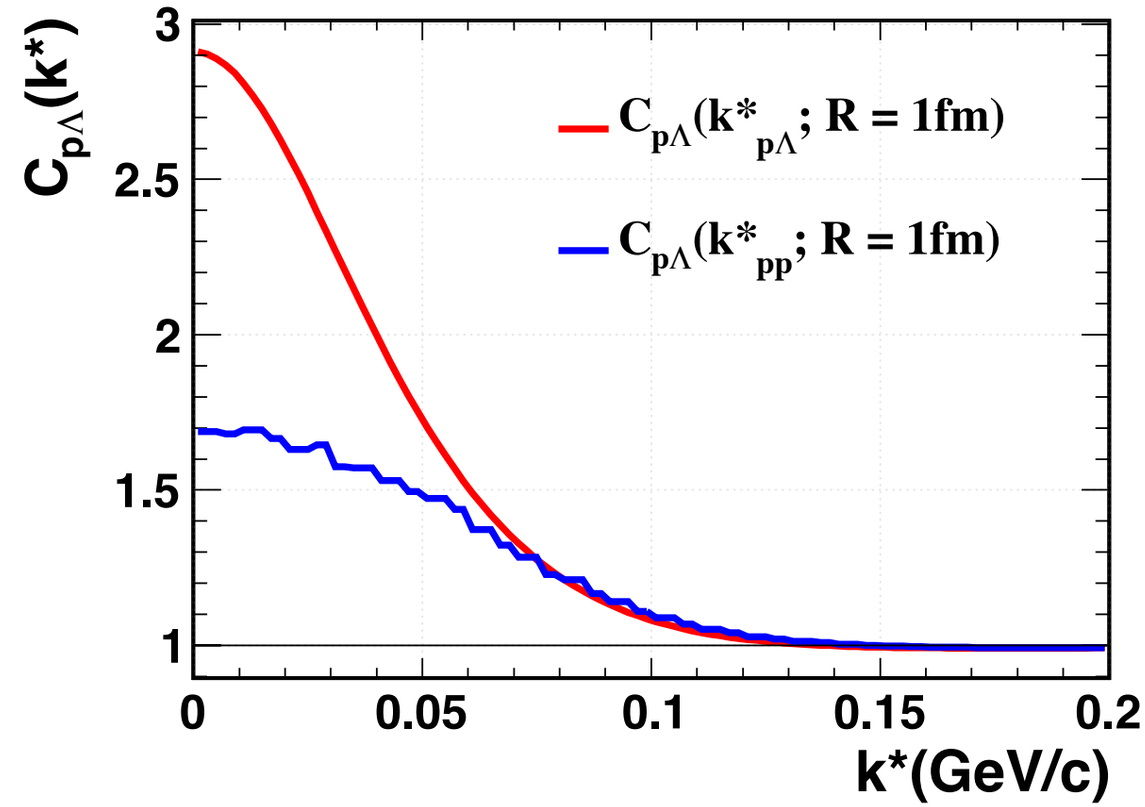
where

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

- $C_{pp}(k^*)$ 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}.

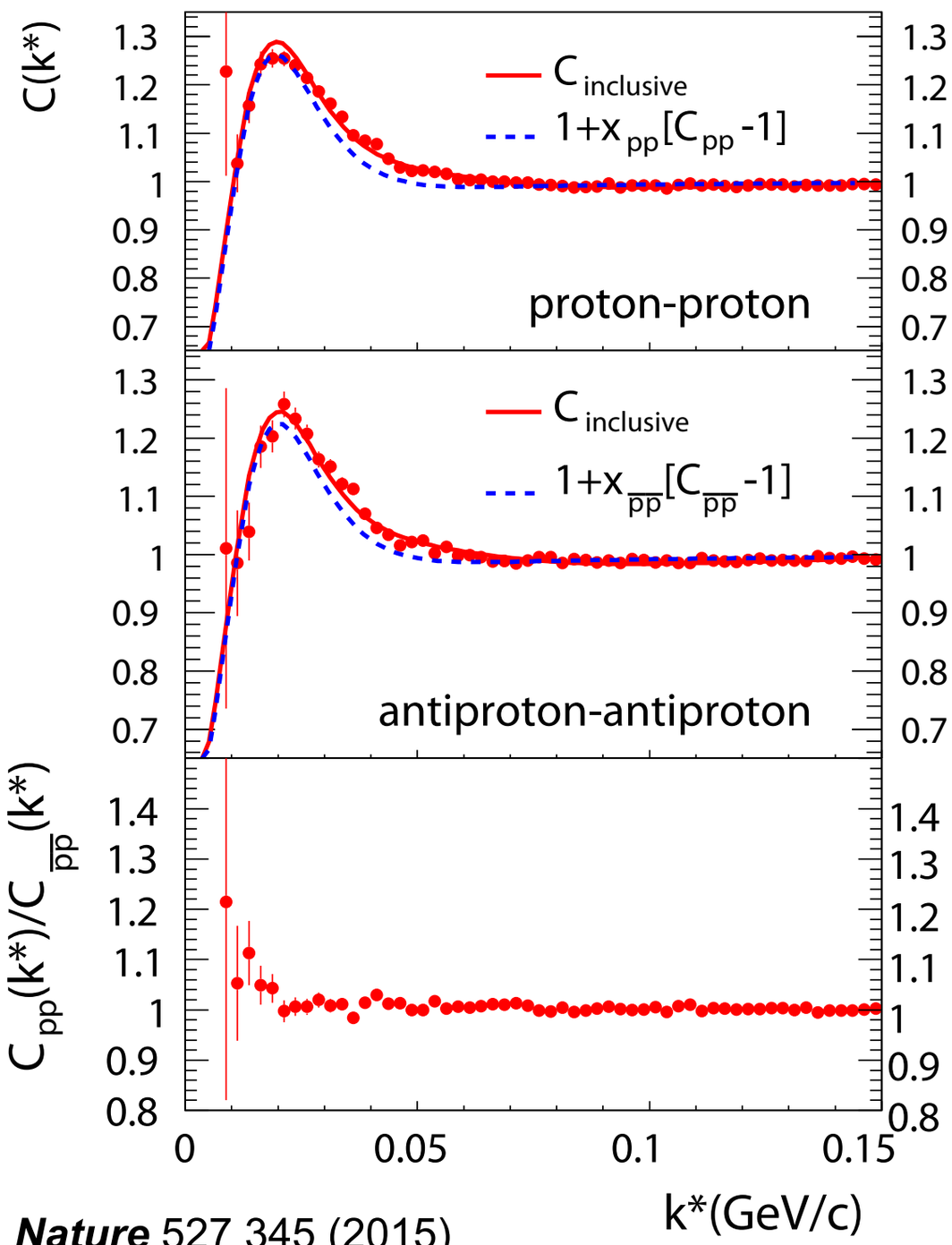
Transformation matrix





The transformation matrix is derived from THERMINATOR2 to transform $k^*_{p\Lambda}$ to k^*_{pp} .

Correlations and the ratio



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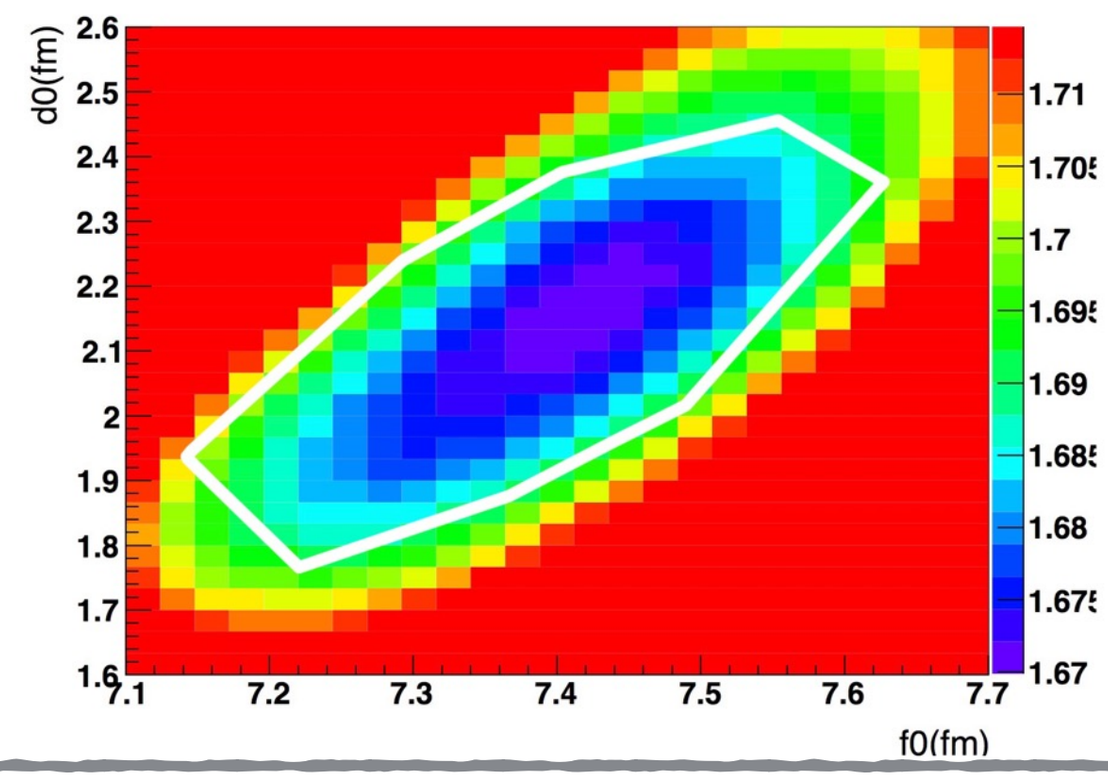
For proton–proton CF,
R=2.75±0.01fm; χ^2/NDF = 1.66;

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

Systematics

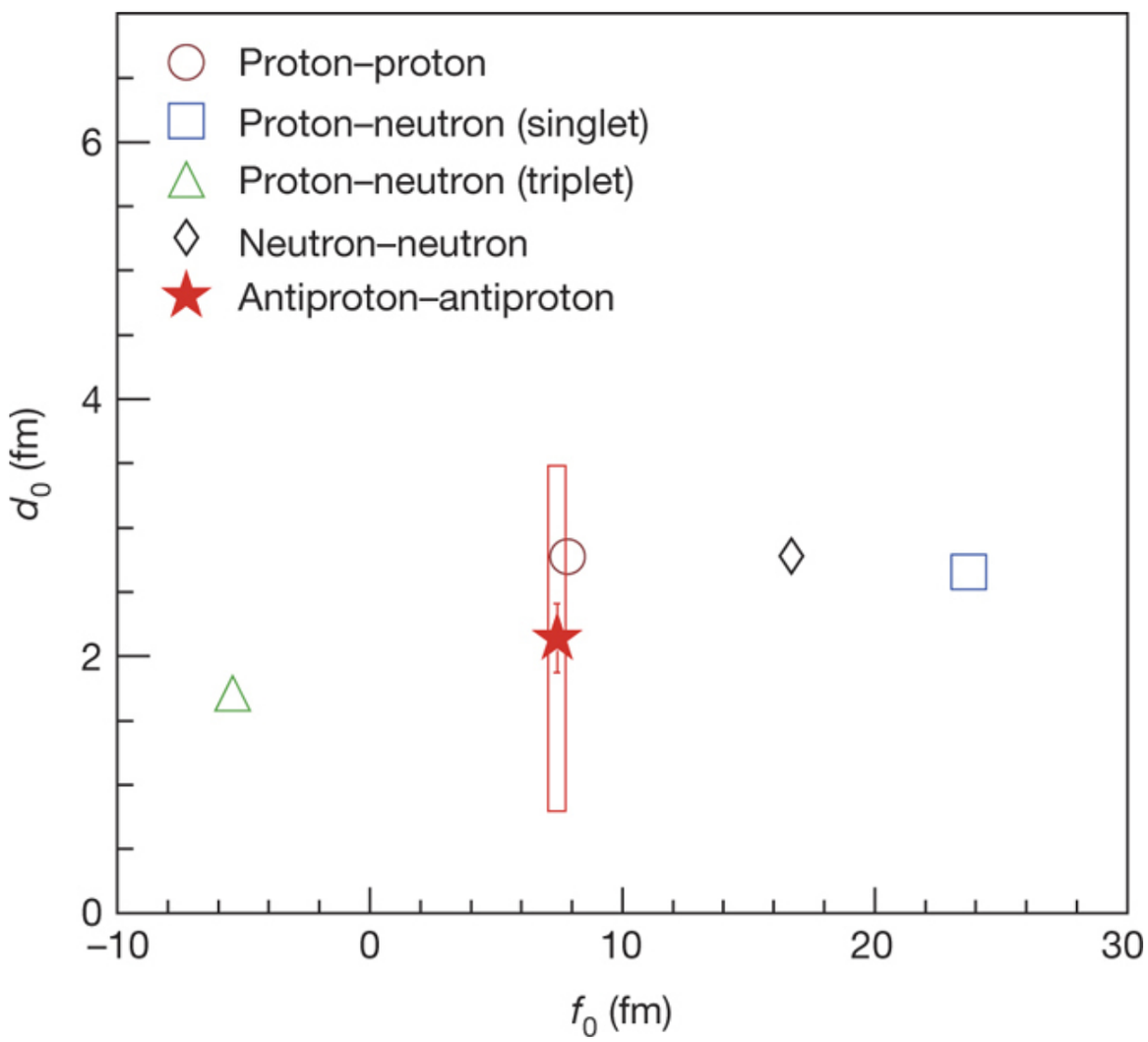
The decomposition of systematics of this analysis:

	Δf_0 ($\pm$ fm)	Δd_0 ($\pm$ fm)	$\Delta R_{\bar{p}\bar{p}}$ ($\pm$ fm)	ΔR_{pp} ($\pm$ fm)
experimental cuts	0.14	0.33	0.01	0.03
uncertainty of p-Λ CF	0.17	0.19	0.03	0.01
uncertainty of Λ-Λ CF	0.36	1.34	0.03	0.03
THERMINATOR2 model	0.07	0.09	< 0.01	< 0.01

Final systematics is given by (max-min)/√12

L. Mathelitsch and B. J. VerWest, Phys. Rev. C 29, 739-745 (1984).
L. Heller Rev. of Mod. Phys. 39, 584-590 (1967).
J. R. Bergervoet, P.C. van Campen W.A. van der Sanden, and J.J. de Swart, Phys. Rev. C 38, 15-50 (1988)

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.

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Summary

- The first direct measurement of interaction between two antiprotons is performed by STAR. The force between two antiprotons is found to be attractive, and is as as strong as that between protons. Corresponding scattering length and effective range are found to agree with that for the force between protons.
- Besides examining CPT from a new aspect, this measurement provides a fundamental ingredient for understanding the structure of more complex anti-nuclei and their properties.

My contribution

- The idea of this paper was first proposed by Prof. Yugang Ma.
- Directed by Yugang Ma and Aihong Tang.
- Finished the entire data analysis in two and half years.
- Participated in all the discussions about this analysis in STAR Collaboration.
- Completely involved in the written and revision of this paper.

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.

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.