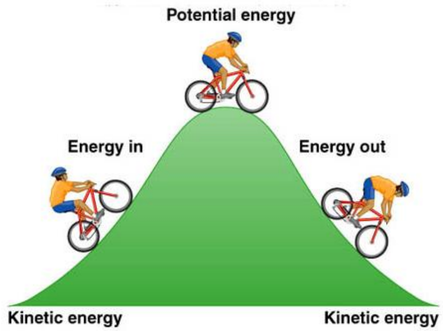
Experimental study of chiral and matter-antimatter symmetries at RHIC

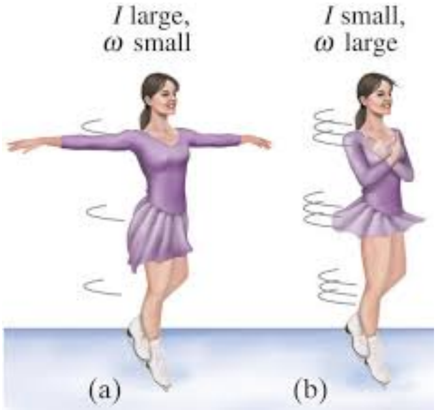
Aihong Tang
BNL Colloquium, Dec 2015

Symmetry is fundamental in describing the world



conservation of energy : shift symmetry of time

conservation of momentum : shift symmetry of position



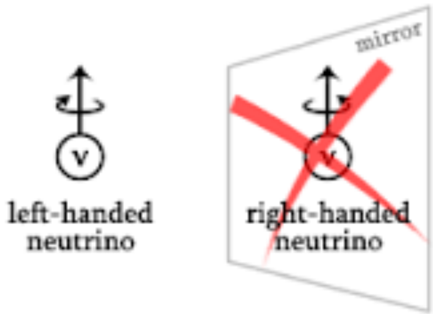
conservation of angular momentum : shift symmetry of angle

Lorentz invariance :
Symmetry of space-time

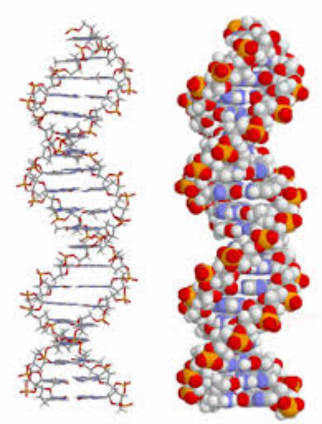
Gauge symmetry :
Conservation of Charge : U(1)
Isospin : SU(2)
Flavor : SU(3)

Supersymmetry …

Symmetry breaking



Neutrinos are left-handed

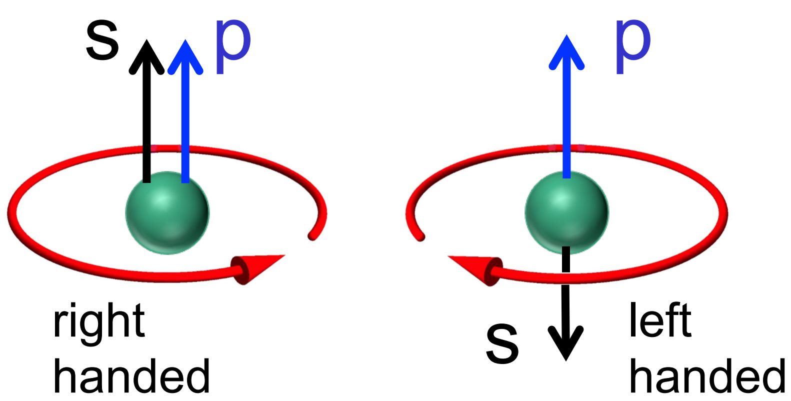


DNAs are right handed

Human-made symmetry breaking

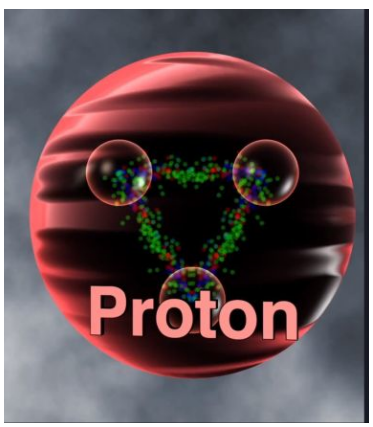
Two Symmetries

Chiral Symmetry



Chiral symmetry describes the invariance of physics laws w.r.t. the right/left handness.

Matter-Antimatter Symmetry

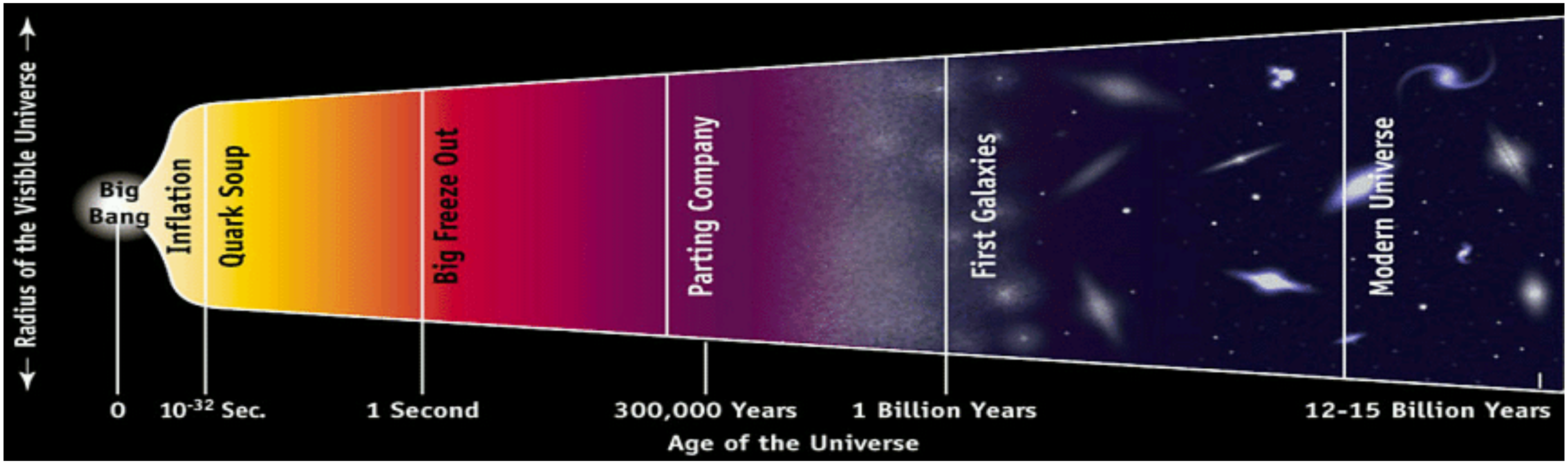


The invariance of physics laws w.r.t. matter/antimatter

Both are believed to be present at the very beginning of the Universe.

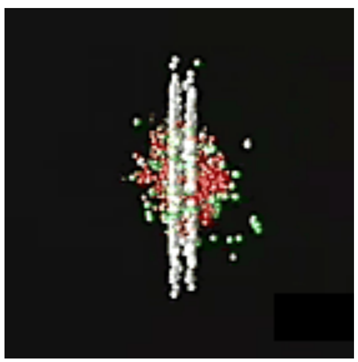
Big Bang and Little Bang

Big Bang

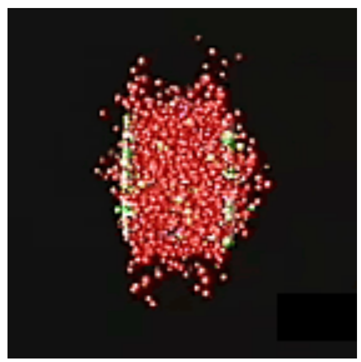


Little Bang: High Energy Heavy Ion Collision

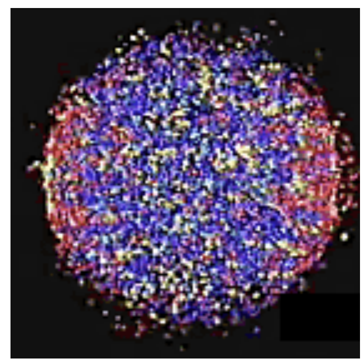
Ions about to collide



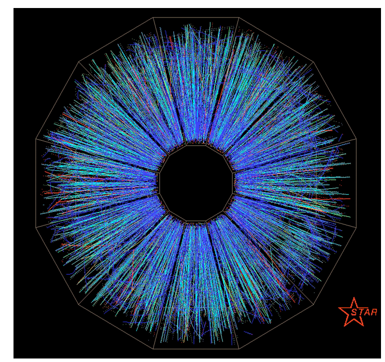
Ion collision



Plasma formation

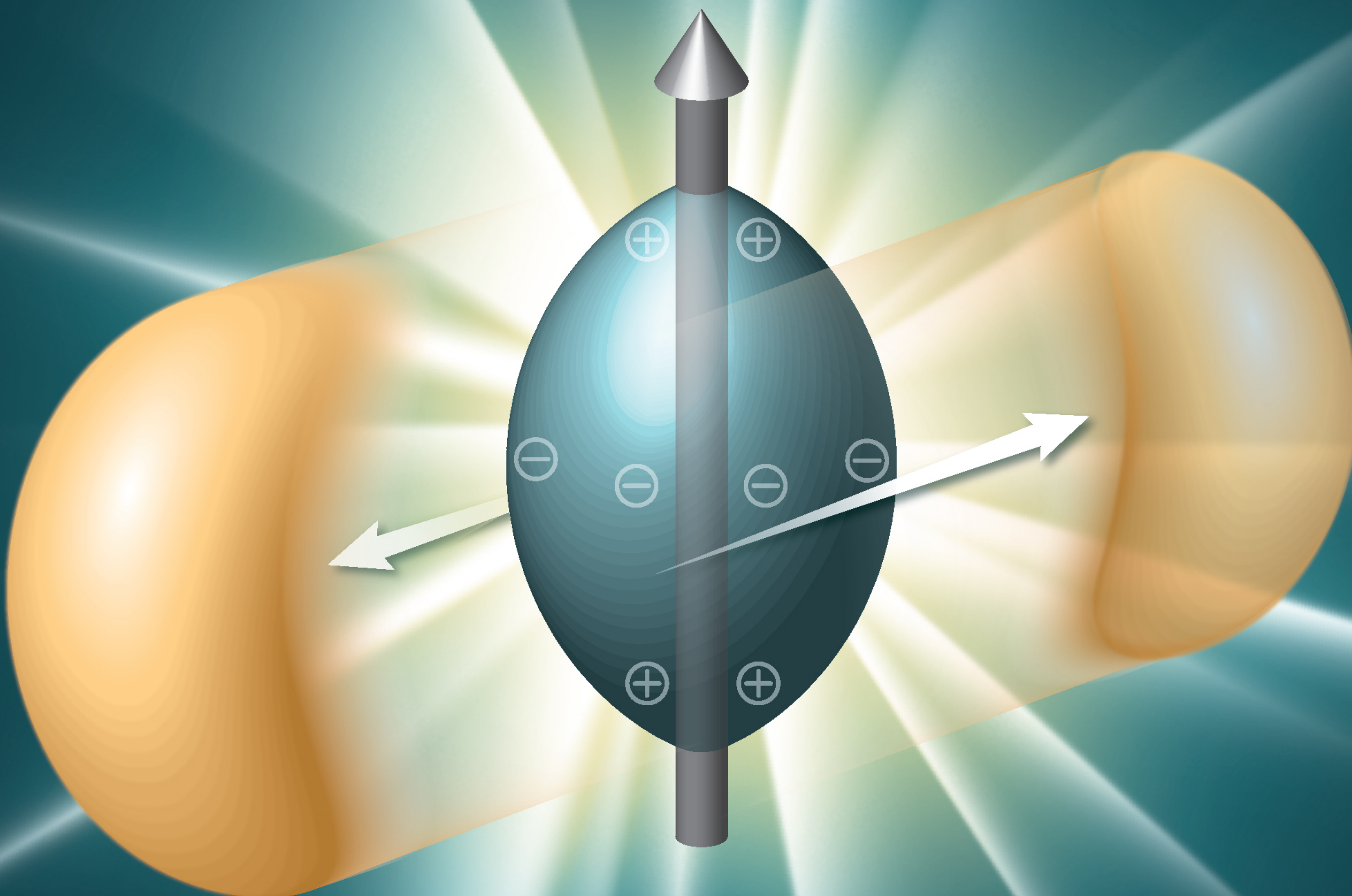


Freeze out



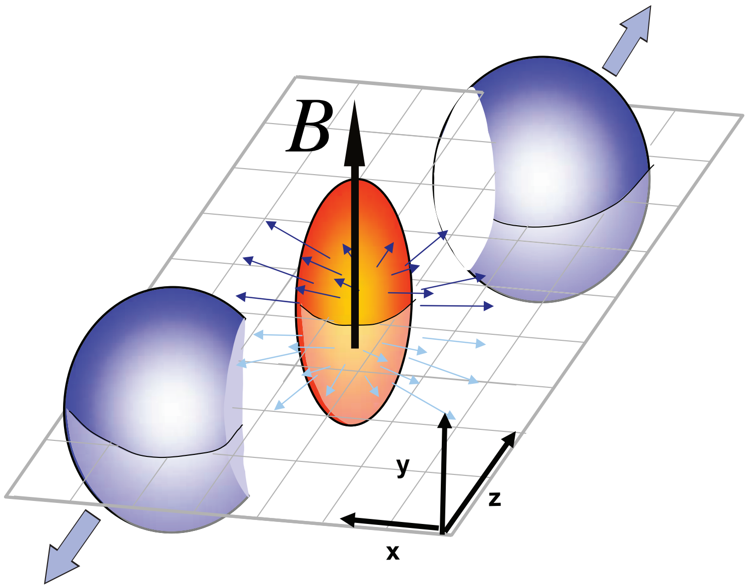
What we "see"

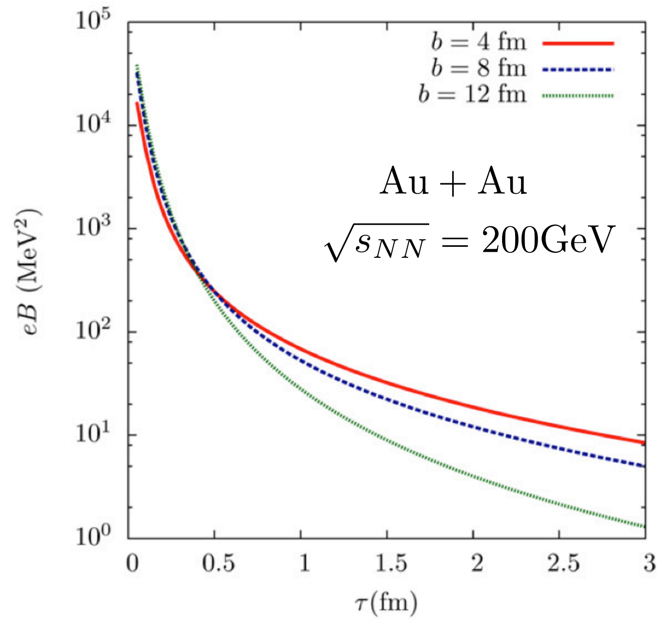
I : Chiral Magnetic Wave : hints of chiral symmetry restoration in Quark Gluon Plasma



STAR ☆ **PRL 114,** 252302 (2015)

The ultra-strong magnetic field in heavy ion collisions

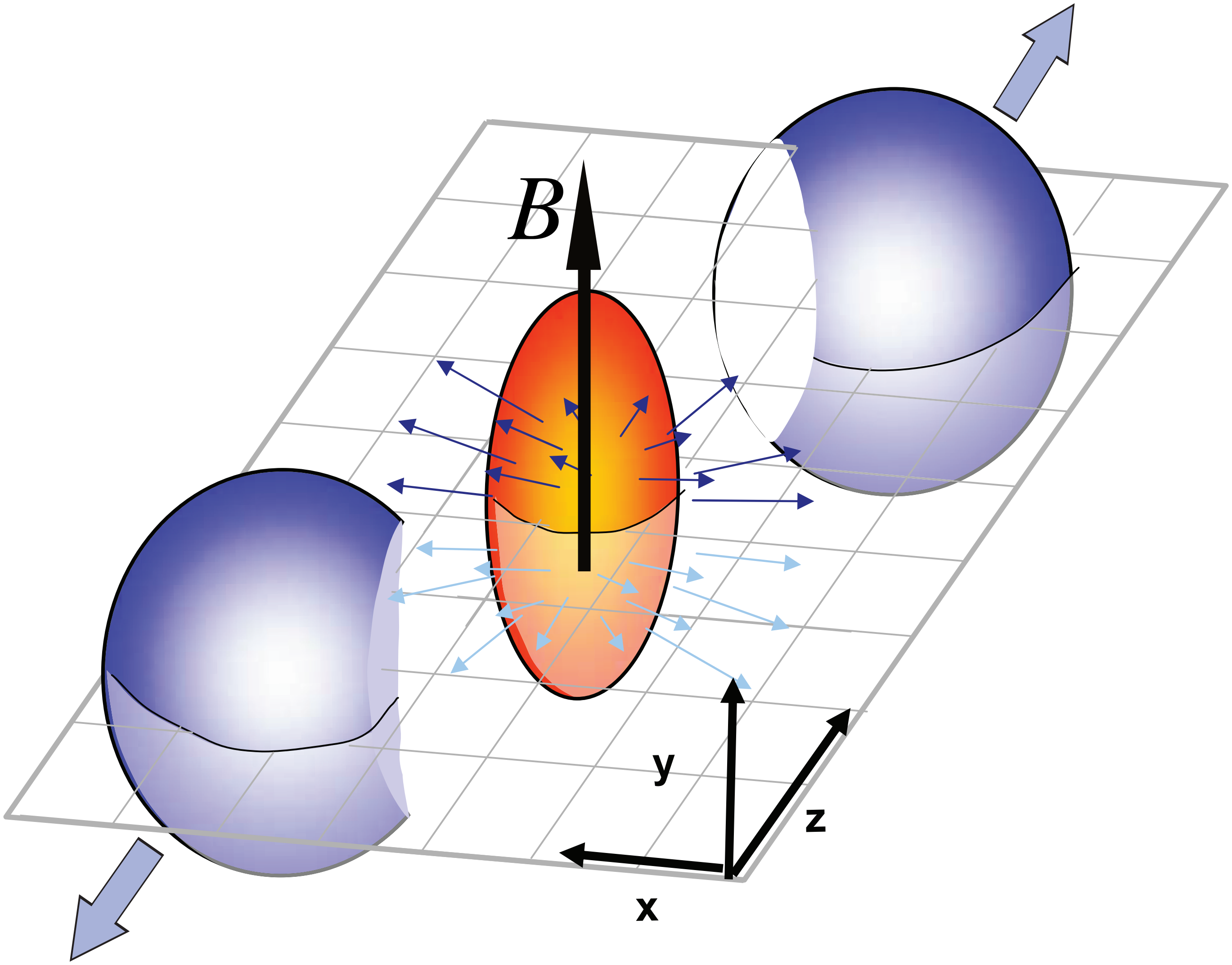




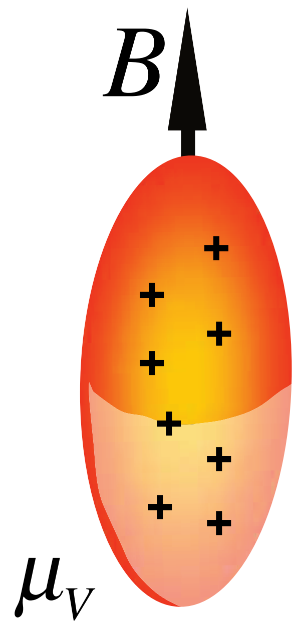
Nuclear Physics A 803, 227 (2008).

Peak value of B generated can reach as high as 10^{15} T !
(FYI, the B at magnetar : ~ 10^9 T).

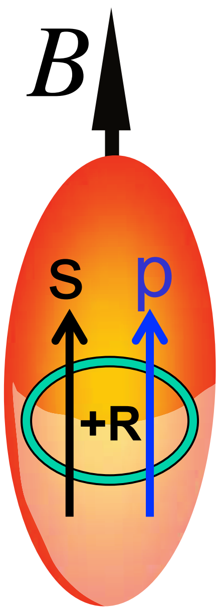
The setup



Chiral Magnetic Wave



Chiral Magnetic Wave

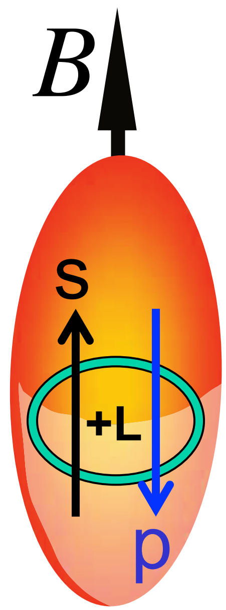


Right-handed quarks moving upwards

$$\langle \vec{s} \rangle \propto (Qe)\vec{B}$$

$$\langle \vec{p} \rangle \propto \mu_A \langle \vec{s} \rangle$$

Chiral Magnetic Wave

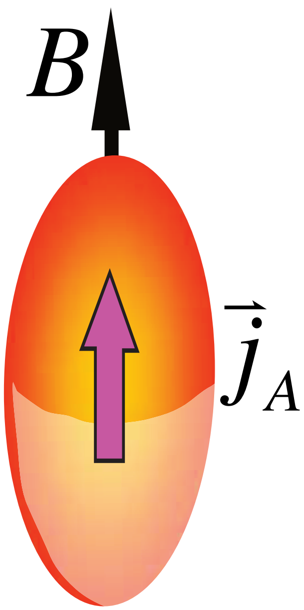


Left-handed quarks
moving downwards

$$\langle \vec{s} \rangle \propto (Qe)\vec{B}$$

$$\langle \vec{p} \rangle \propto \mu_A \langle \vec{s} \rangle$$

Chiral Magnetic Wave



Chiral charge current

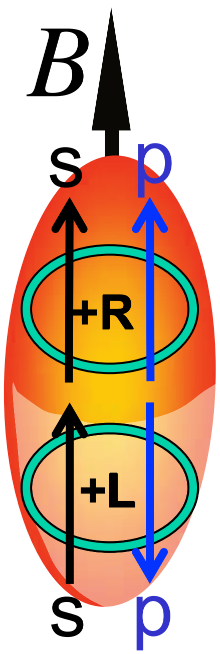
$$j_A = \frac{N_c e}{2\pi^2}\mu_V B$$

Chiral Separation Effect (CSE)

Chiral Magnetic Wave

$(R)_A$ and $(L)_A$:
Excess of chiral charge

Chiral Magnetic Wave

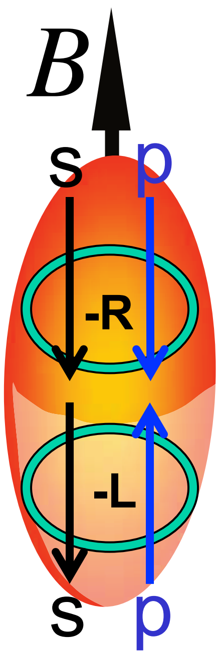


Positively charged quarks moving towards poles

$$\langle \vec{s} \rangle \propto (Qe)\vec{B}$$

$$\langle \vec{p} \rangle \propto \mu_A \langle \vec{s} \rangle$$

Chiral Magnetic Wave

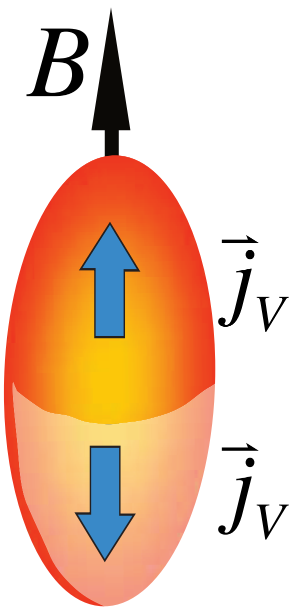


Negatively charged quarks moving towards the equator

$$\langle \vec{s} \rangle \propto (Qe)\vec{B}$$

$$\langle \vec{p} \rangle \propto \mu_A \langle \vec{s} \rangle$$

Chiral Magnetic Wave

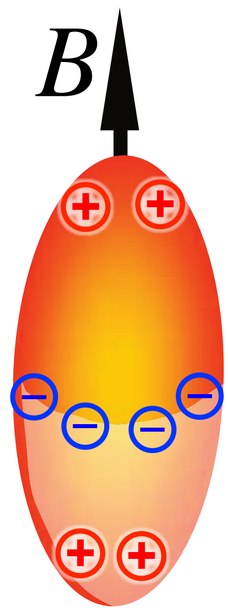


Charge current

$$j_V = \frac{N_c e}{2\pi^2} \mu_A B$$

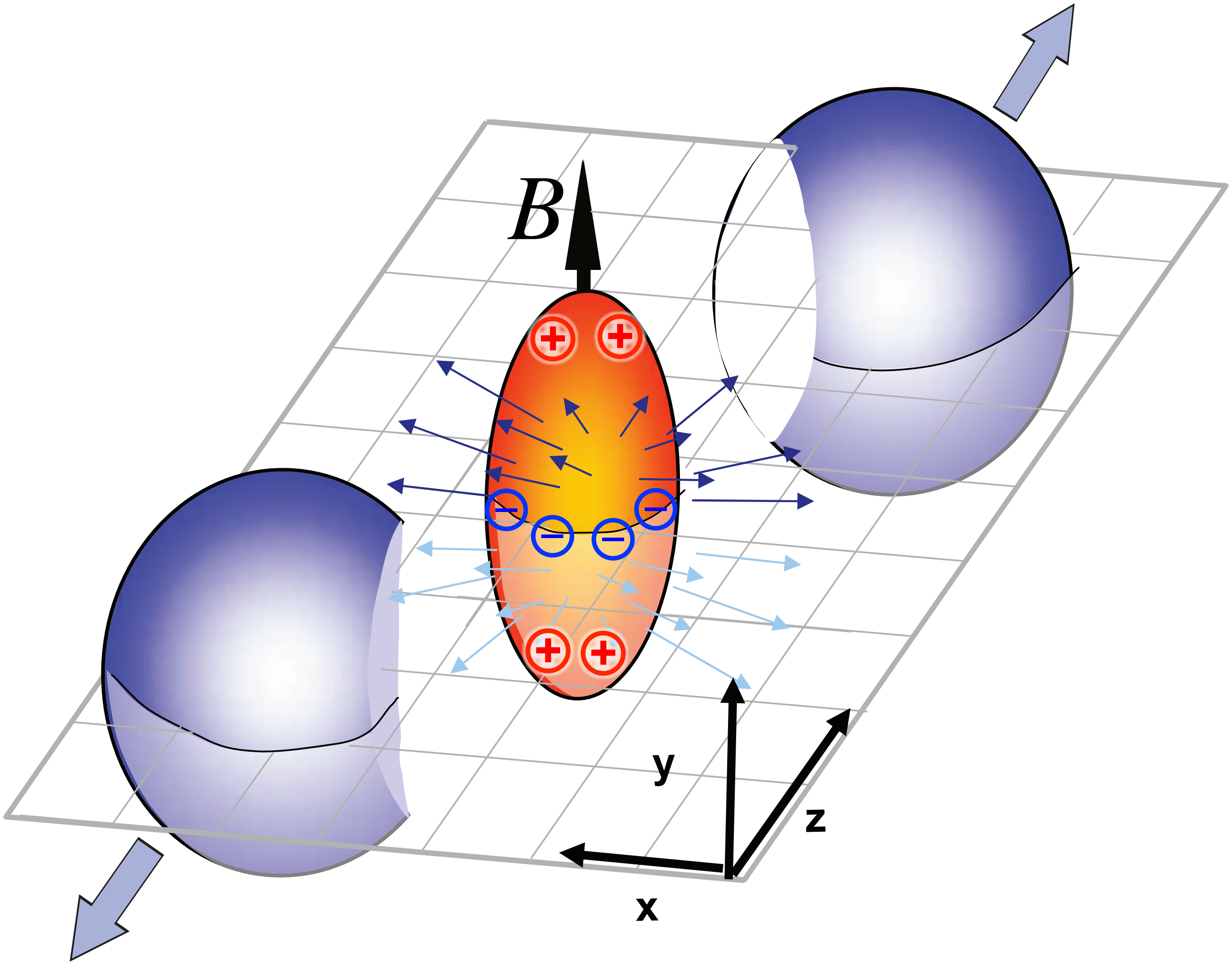
Chiral Magnetic Effect (CME)

Chiral Magnetic Wave



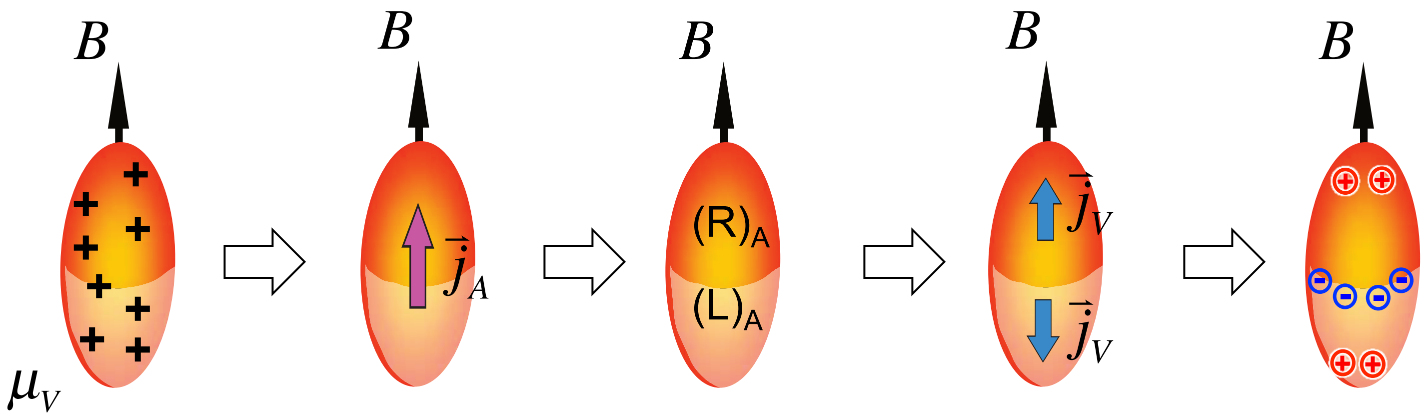
Tendency of negatively (positively) charged particles move to the equator (poles)

Chiral Magnetic Wave



Tendency of negatively (positively) charged particles move to the equator (poles)

Chiral Magnetic Wave



$$j_A = \frac{N_c e}{2\pi^2}\mu_V B$$

$$j_V = \frac{N_c e}{2\pi^2}\mu_A B$$

Chiral Separation Effect (CSE)

Chiral Magnetic Effect (CME)

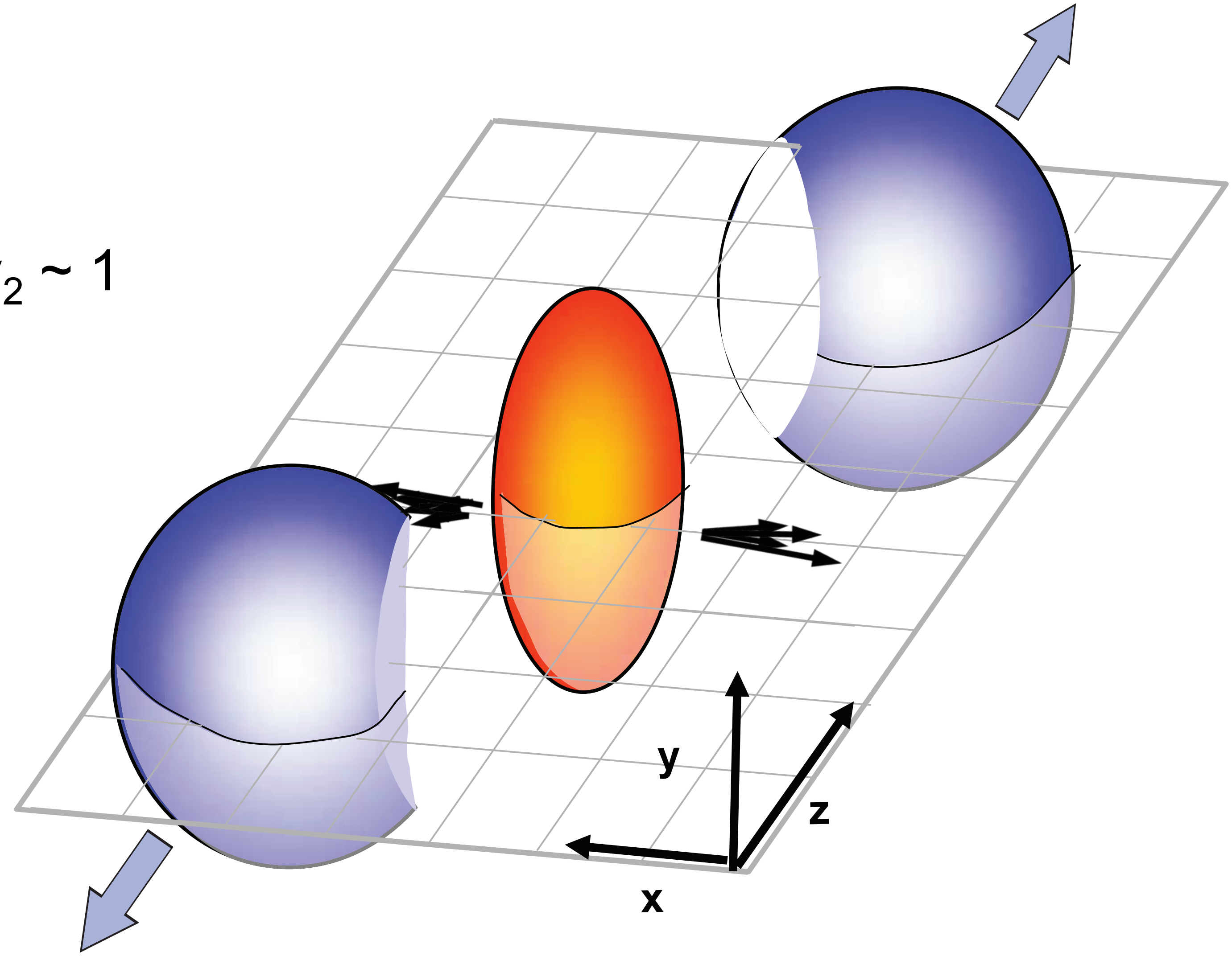
CSE and CME feed on each other, forming a seamless excitation – the Chiral Magnetic Wave (CMW)
(In analogue to EM wave.)

Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, Phys. Rev. Lett. 107, 052303 (2011)

CMW needs CSE and CME at work ➔ **The existence of CMW implies the existence of CSE and CME.**
CMW won't propagate when chiral symmetry is broken ➔ **The existence of CMW is an indication of chiral symmetry restoration.**

v_2

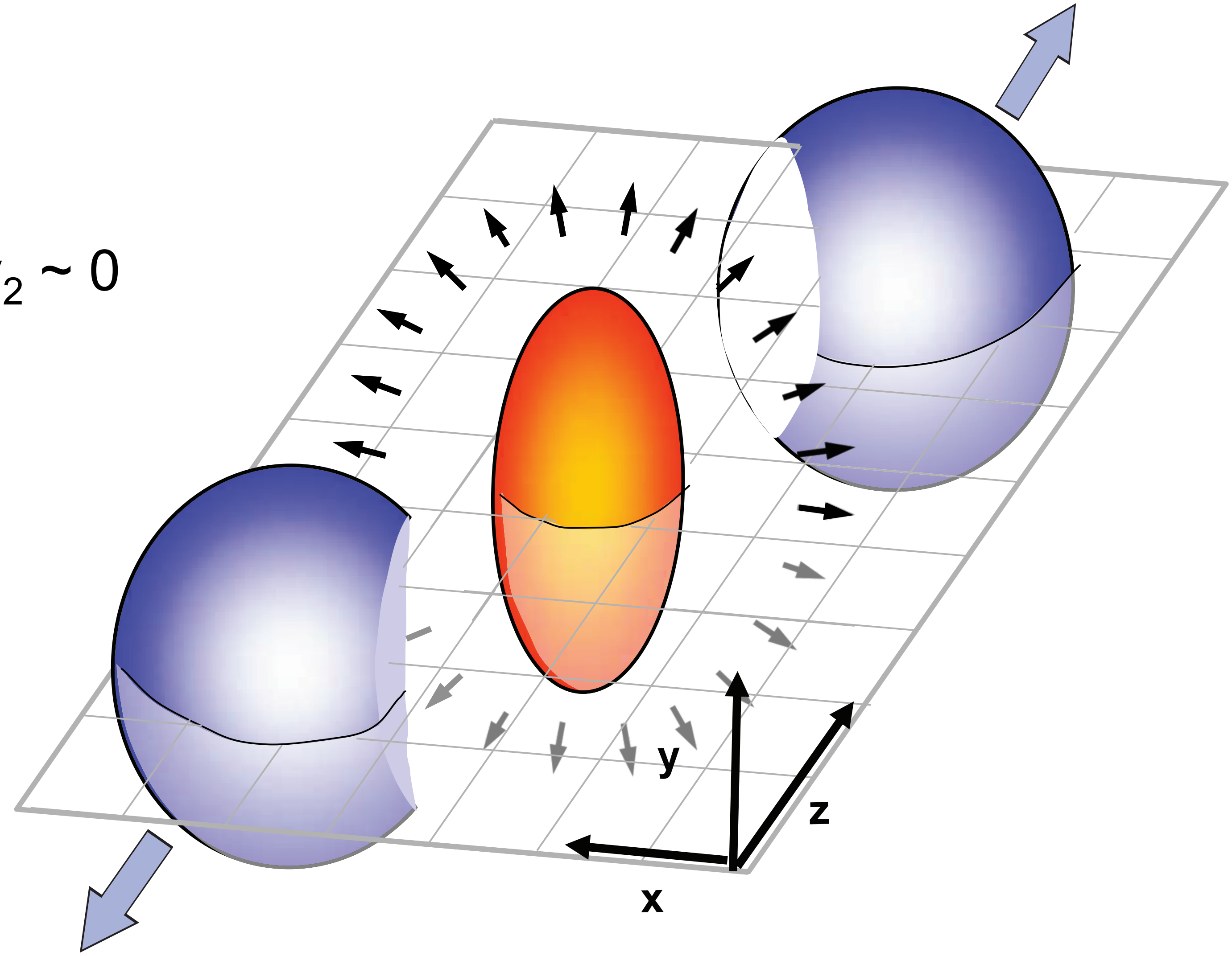
$v_2 \sim 1$



v_2 describes how well particles converge towards “equator”

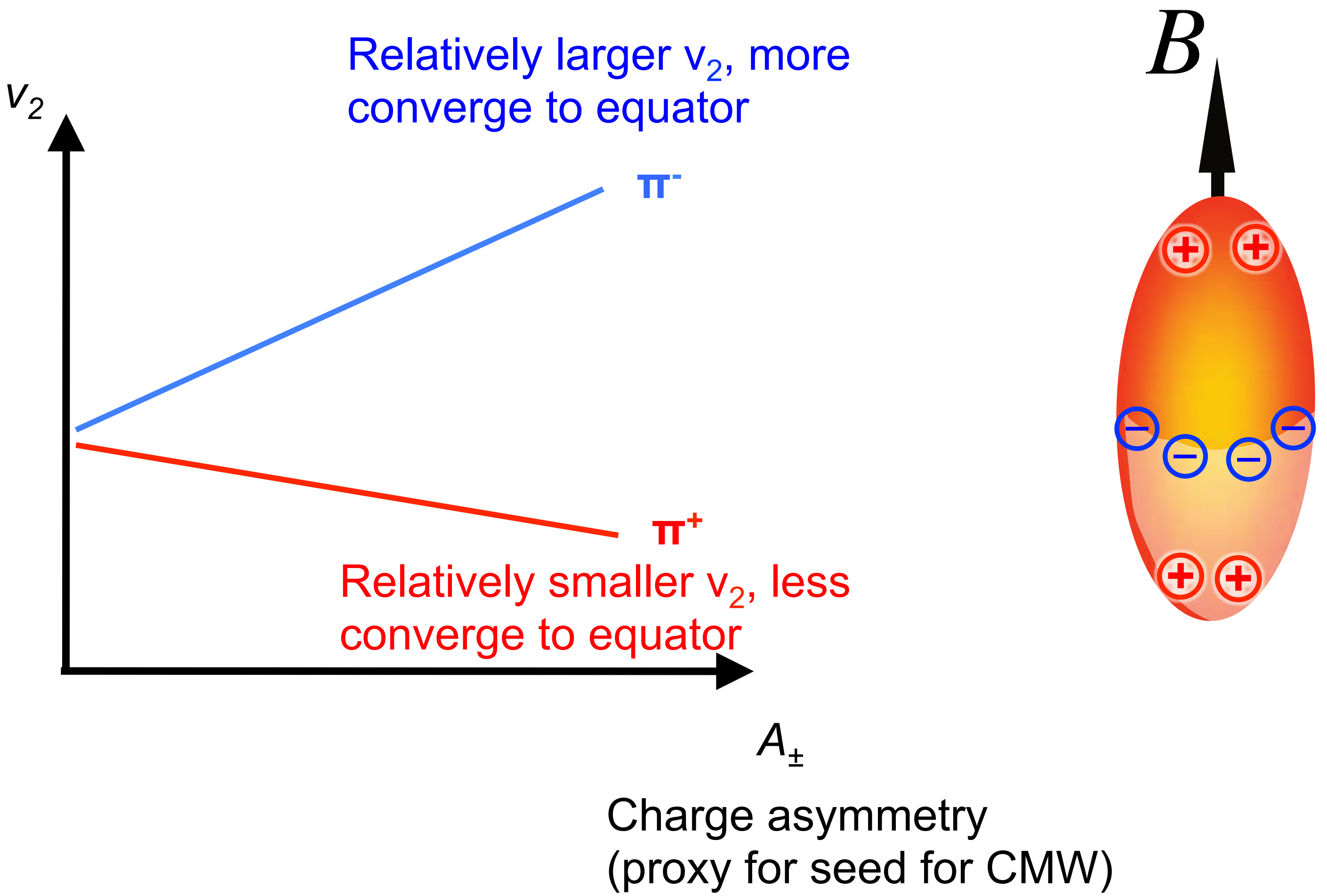
v_2

$v_2 \sim 0$



v_2 describes how well particles converge towards "equator"

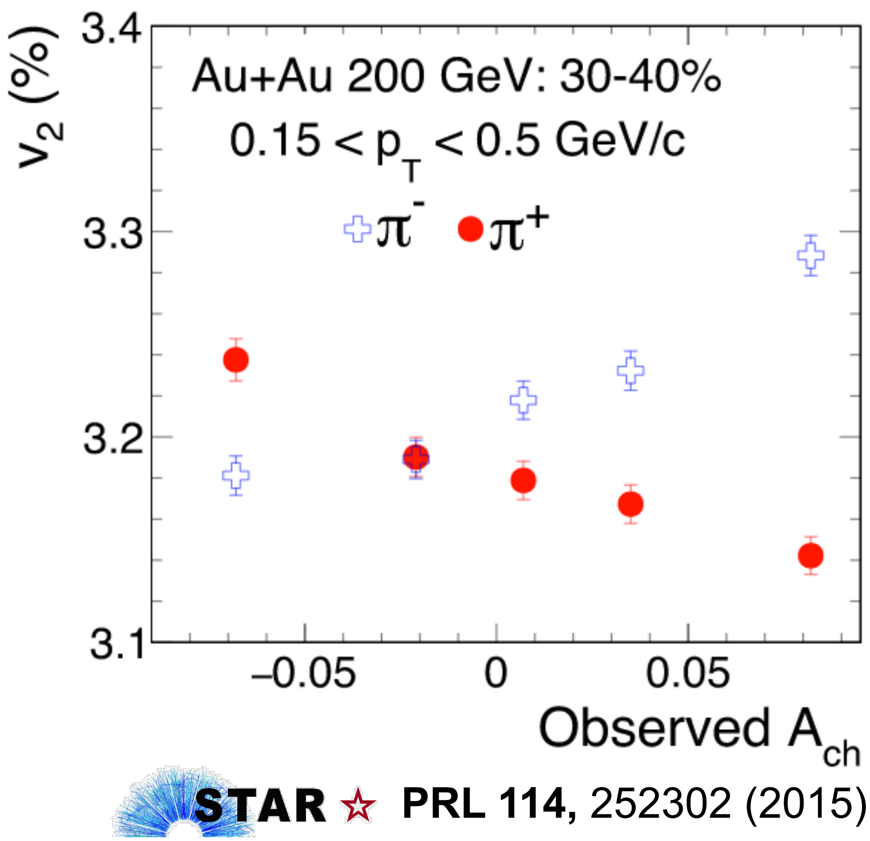
The CMW observable



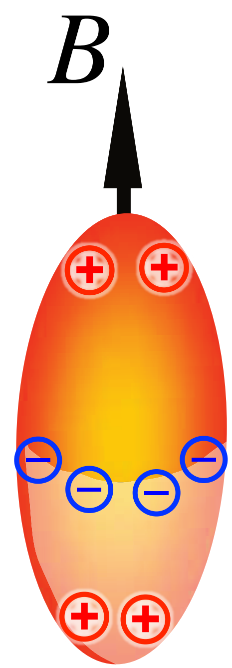
Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, Phys. Rev. Lett. 107, 052303 (2011)

Key signature : Splitting of v_2 between pions with opposite charge

The CMW observable

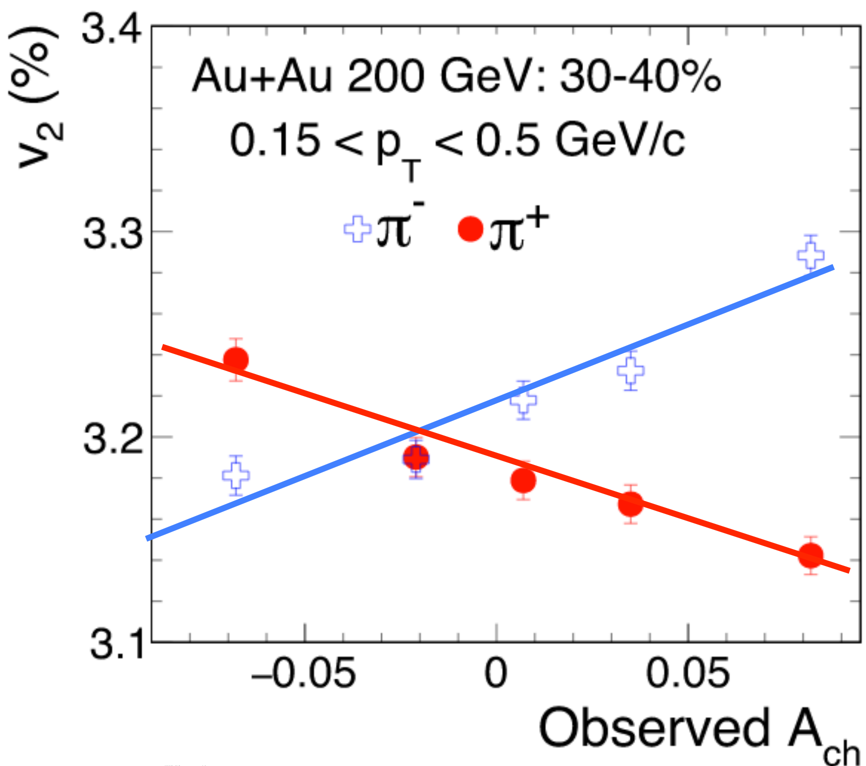


PRL 114, 252302 (2015)

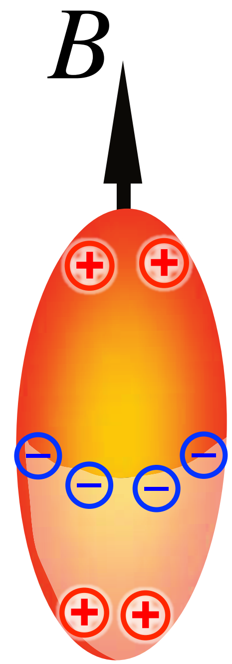


Key signature : Splitting of v_2 between pions with opposite charge

The CMW observable



STAR ☆ **PRL 114,** 252302 (2015)



Key signature : Splitting of v_2 between pions with opposite charge

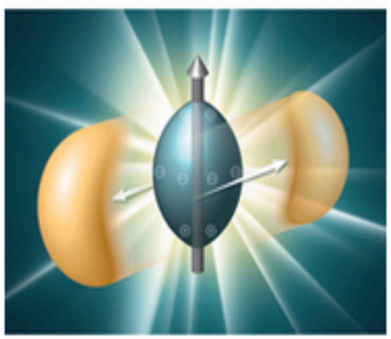
Summary for part I

Editors' Suggestion

Observation of Charge Asymmetry Dependence of Pion Elliptic Flow and the Possible Chiral Magnetic Wave in Heavy-Ion Collisions

L. Adamczyk *et al.* (STAR Collaboration) STAR

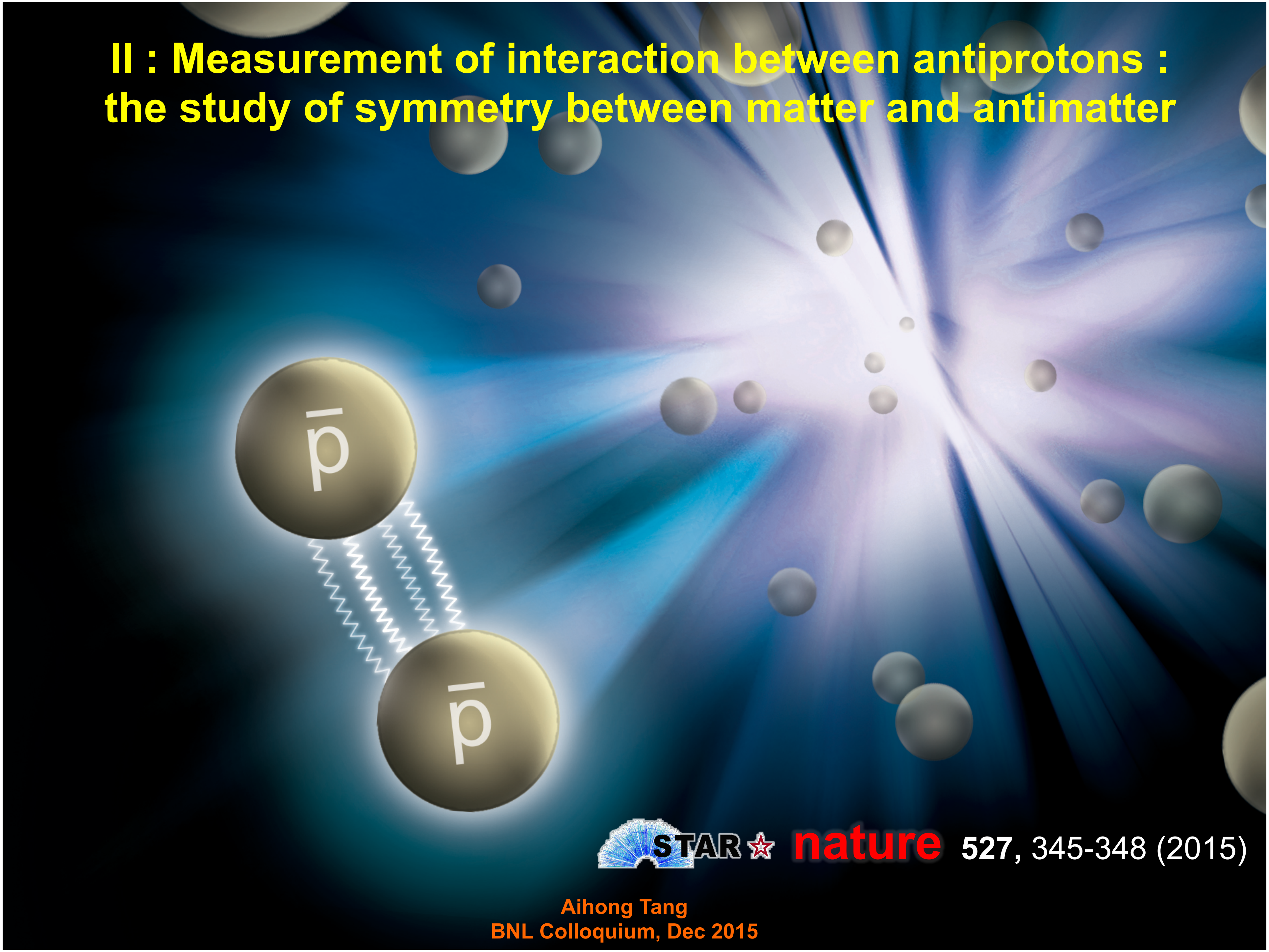
Phys. Rev. Lett. **114**, 252302 (2015) – Published 26 June 2015



A possible signature of chiral symmetry restoration, in the form of a chiral magnetic wave in the quark-gluon plasma, has been observed in heavy-ion collisions at RHIC.

Show Abstract +

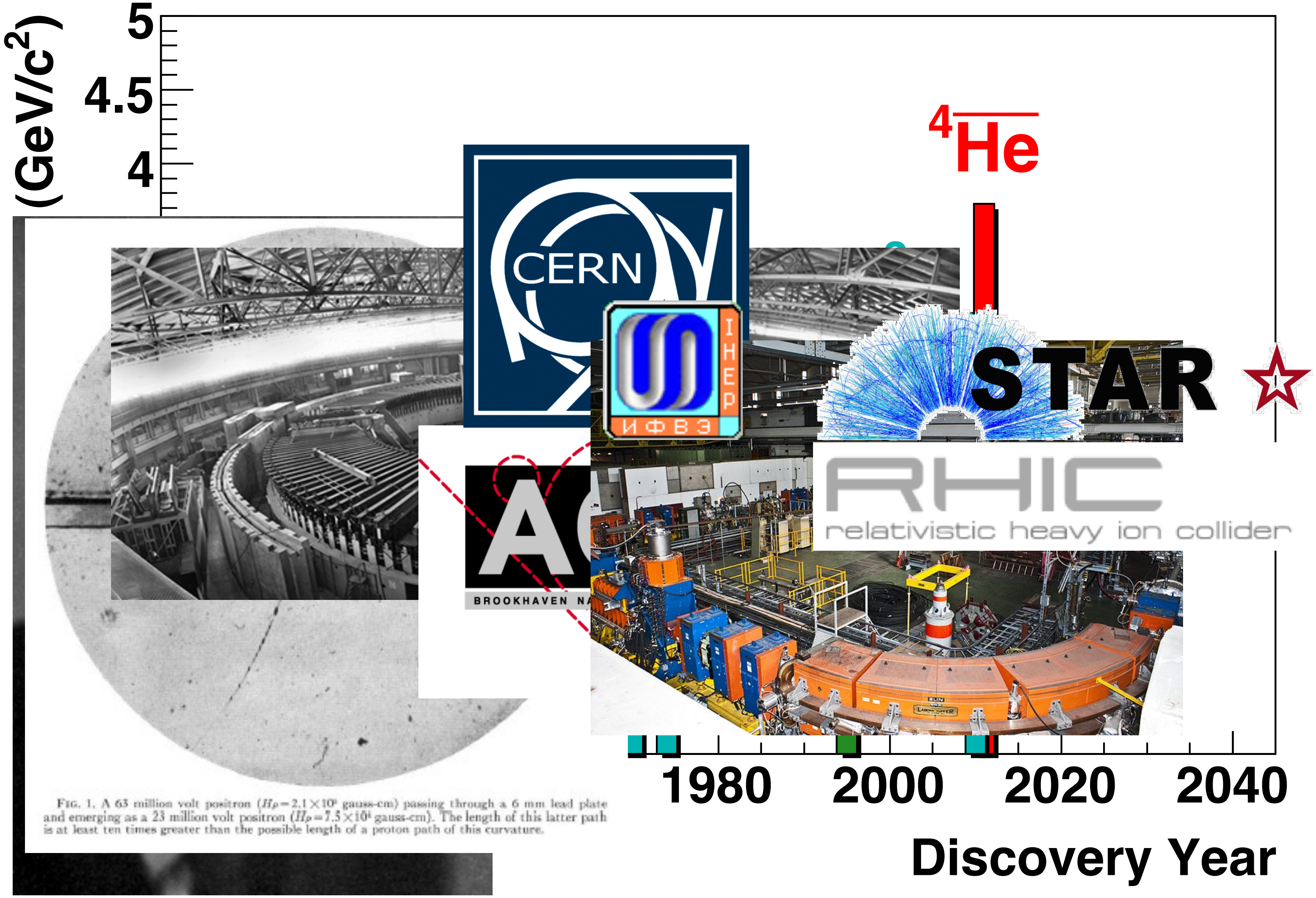
II : Measurement of interaction between antiprotons : the study of symmetry between matter and antimatter



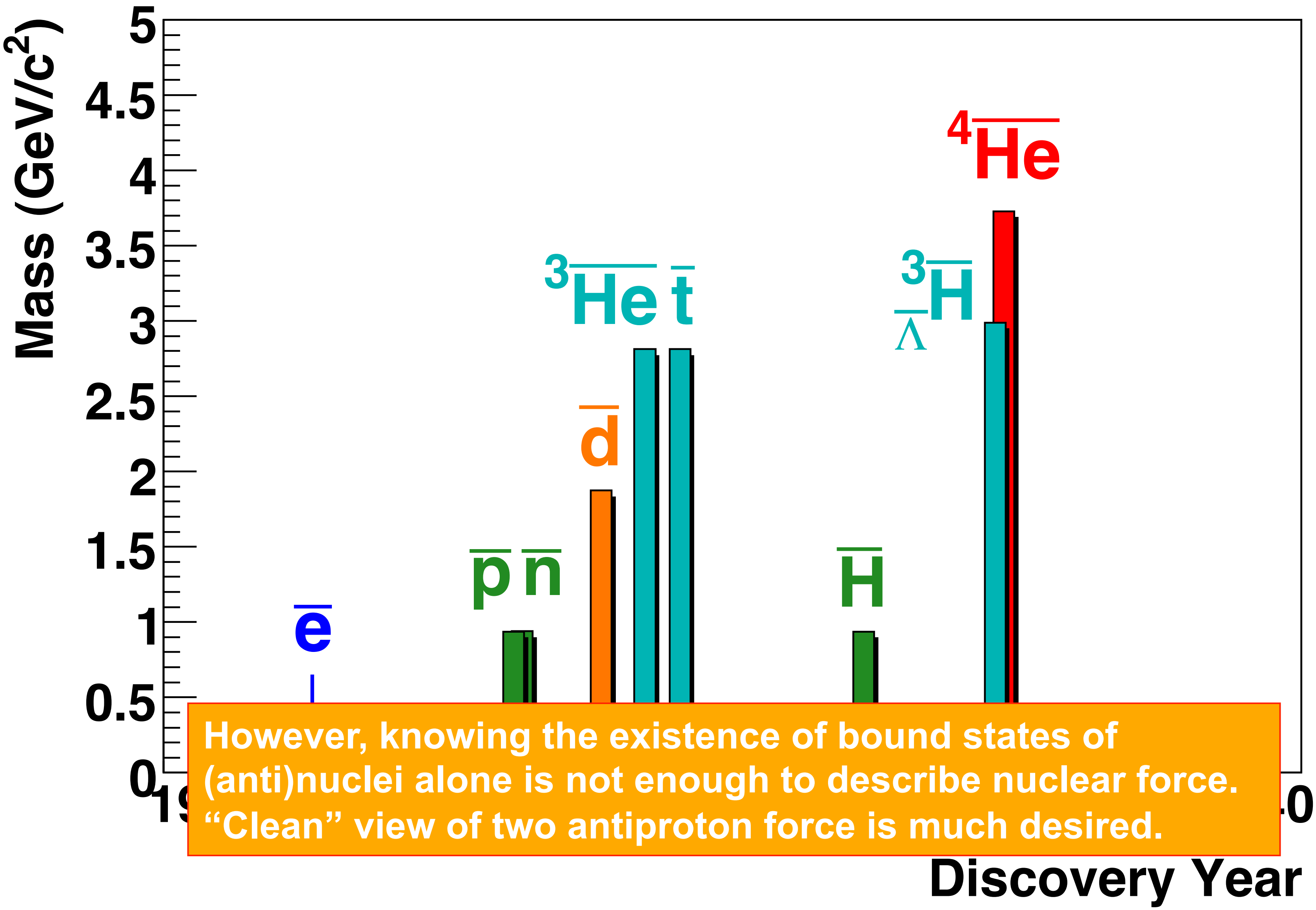
STAR ☆ **nature** **527**, 345-348 (2015)

Aihong Tang
BNL Colloquium, Dec 2015

Antimatter History



Antimatter History



However, knowing the existence of bound states of (anti)nuclei alone is not enough to describe nuclear force. "Clean" view of two antiproton force is much desired.

Nuclear force between antimatter

• So far the large body of knowledge on nuclear force was derived from studies made on nucleons or nuclei, little is known directly about the nuclear force between antinucleons.

• The knowledge of interaction among two anti-protons, one of the simplest system of antinucleons(nuclei), is a fundamental ingredient for understanding the structure of more-complex antinuclei and their properties.

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

$$\sigma = 4\pi f_0^2$$

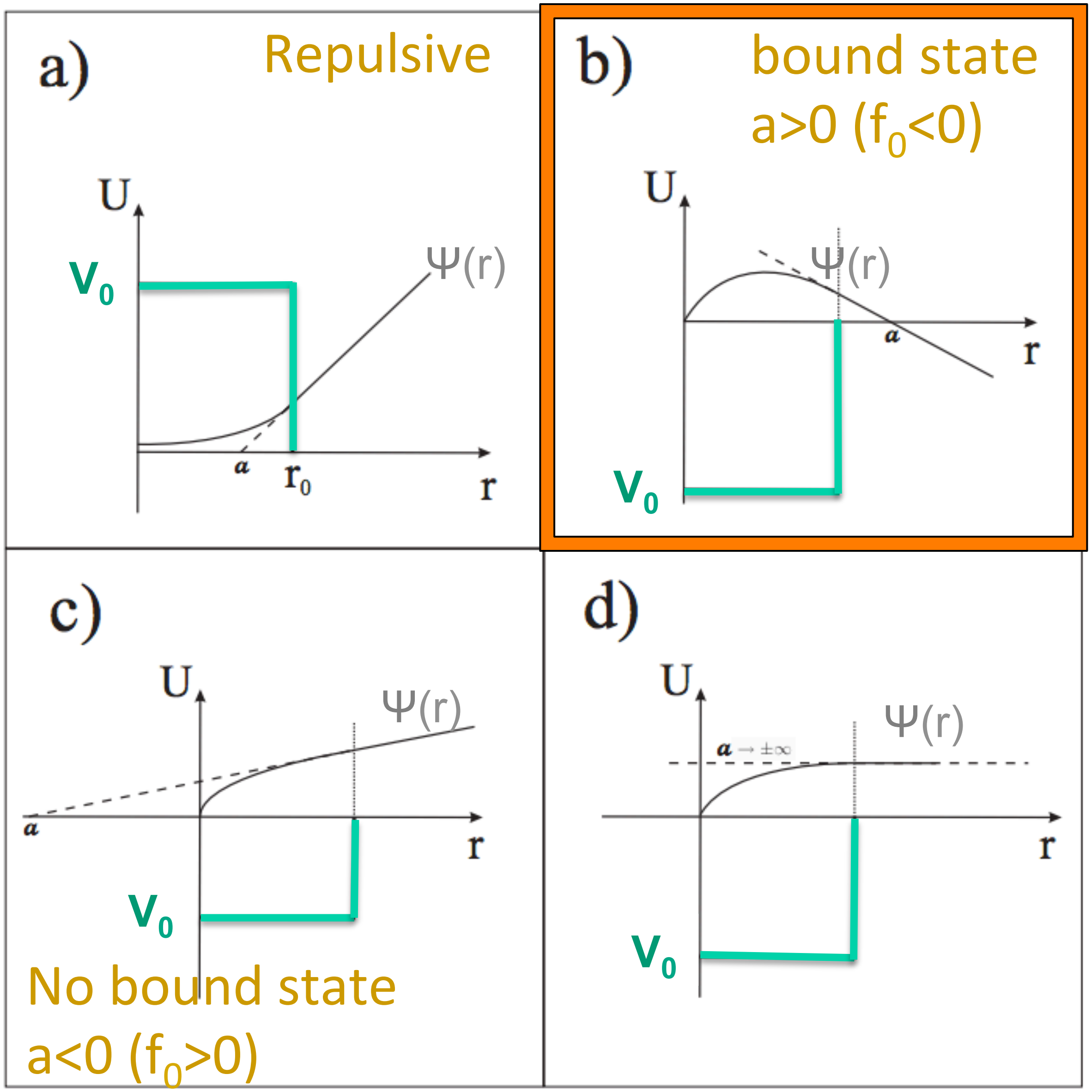
d_0 is related to the range of the potential.

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



$kr << 1$

$k \to 0$

$f_0 \equiv -a$

$d_0 \equiv r_0$

f_0 and d_0 : How to measure them in scattering experiments

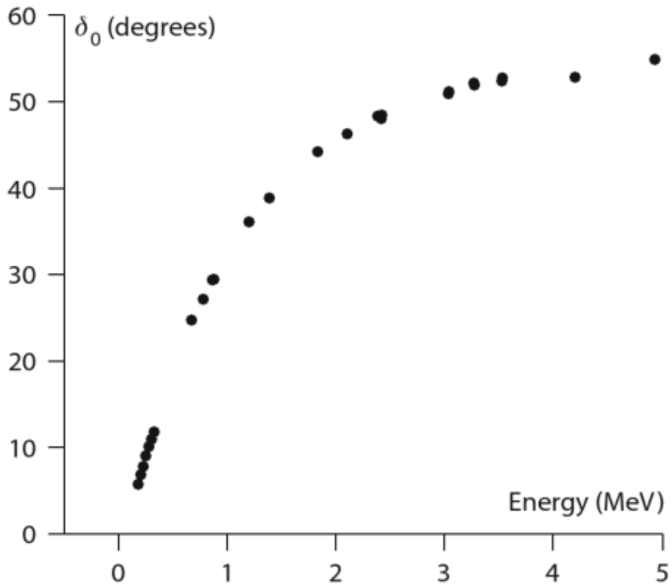


Figure 2.11 Phase shift variation as a function of the incident proton energy for proton-proton collision. The experimental points are from reference [JB50].

$$\frac{d\sigma}{d\Omega} = \left[\left(\frac{d\sigma}{d\Omega}\right)_c + \left(\frac{d\sigma}{d\Omega}\right)_n + \left(\frac{d\sigma}{d\Omega}\right)_{cn}\right]$$

Coulomb Nuclear Crossterm

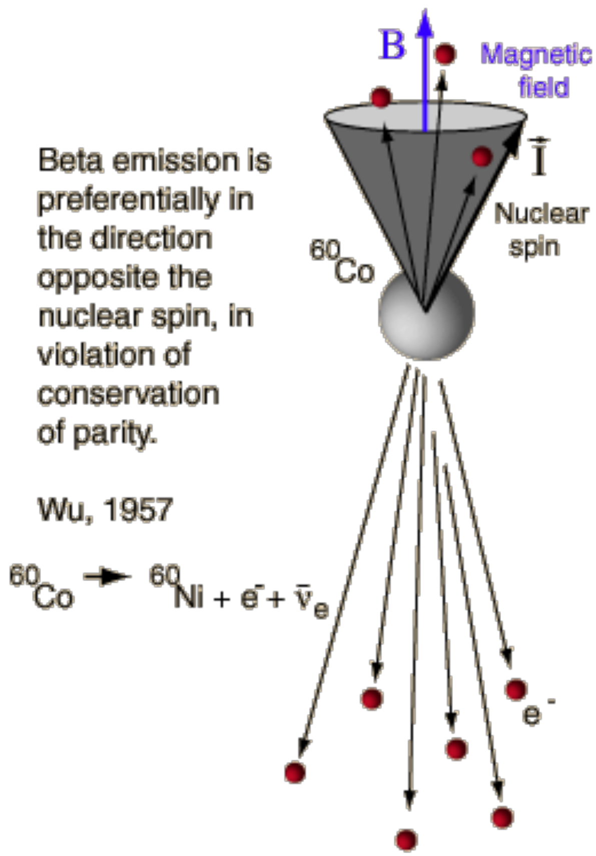
$$\left(\frac{d\sigma}{d\Omega}\right)_n = \frac{\sin^2\delta_0}{k^2}$$

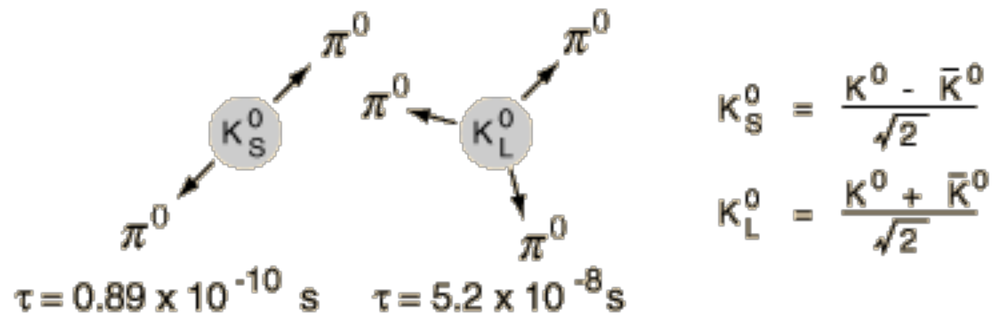
$$k\cot(\delta_0) \approx \frac{1}{f_0} + \frac{1}{2}d_0 k^2$$

"*Nuclear physics in a nutshell*",
Carlos A. Bertulani. Princeton U Press (2007).

In scattering experiments, f_0 and d_0 can be extracted by studying the phase shift vs. energy. (While at RHIC we extract them differently - by studying the CF).

Matter-antimatter symmetry : CPT tests

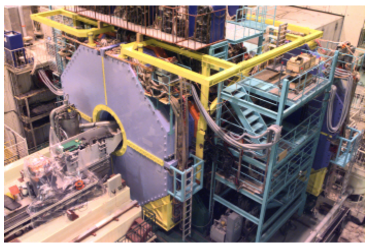




- P- violation : proposed by Lee and Yang. Confirmed by Wu in 1956
- CP- violation : Cronin and Fitch, 1964

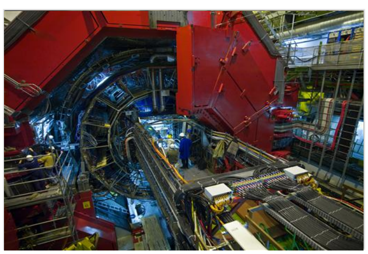
CPT is still a hot topic of interest

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



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

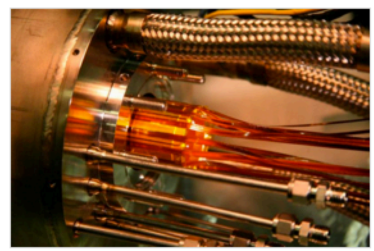
CPLEAR (CERN):
CPT violation in neutral kaon system.



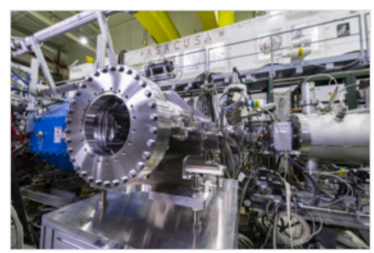
ALICE (CERN):
Antinuclei mass.
Nature physics 11 811 (2015)

AEGIS (CERN):
antimatter gravity.

ATRAP (CERN):
antimatter magnetic moment etc.



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



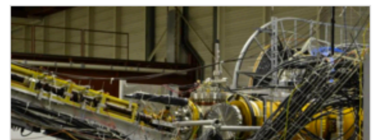
ASACUSA (CERN):
antimatter mass to charge ratio, hyperfine structure.

CPT is still a hot topic of interest

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

AEGIS (CERN):
antimatter gravity.

Belle (KEK):
CPT violation in

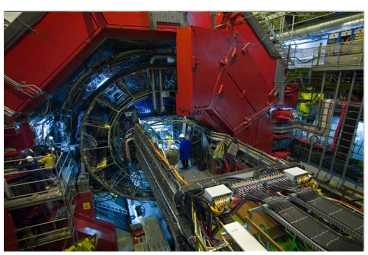


ATRAP (CERN):
antimatter magnetic

Although various prior CPT tests have been many orders of magnitude more precise than this work, there is value in independently verifying each distinct prediction of CPT symmetry.

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

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



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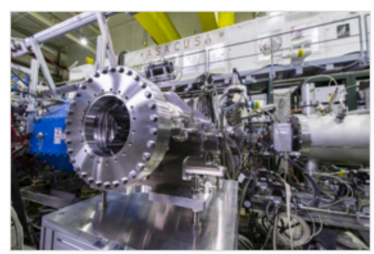
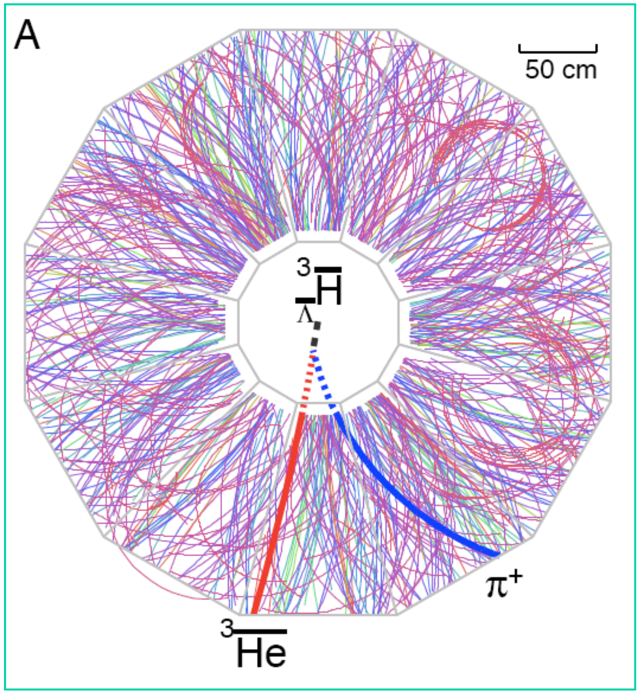
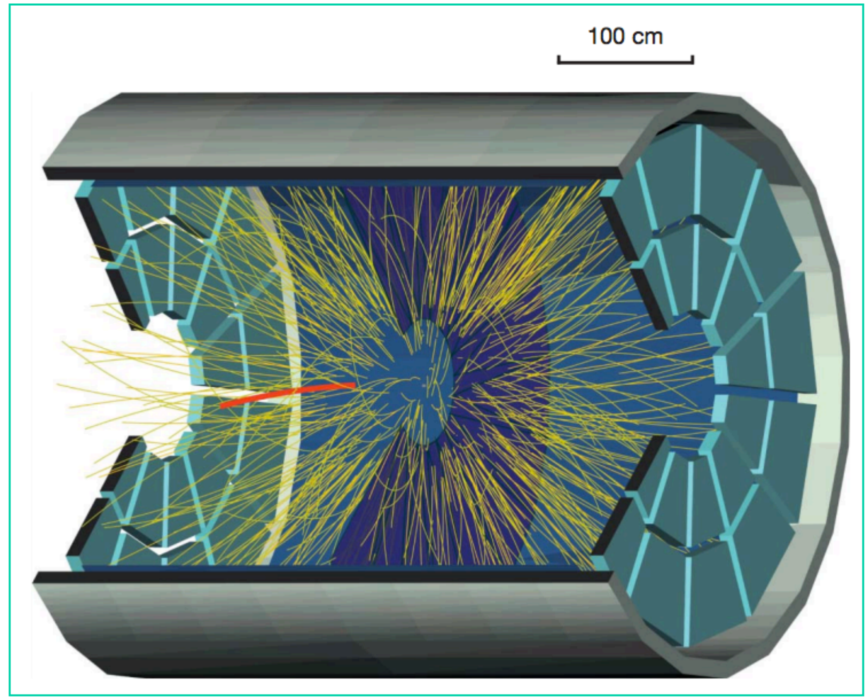
Antinuclei mass.
Nature physics 11 811 (2015)



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

RHIC : an ideal environment for antimatter production





Science

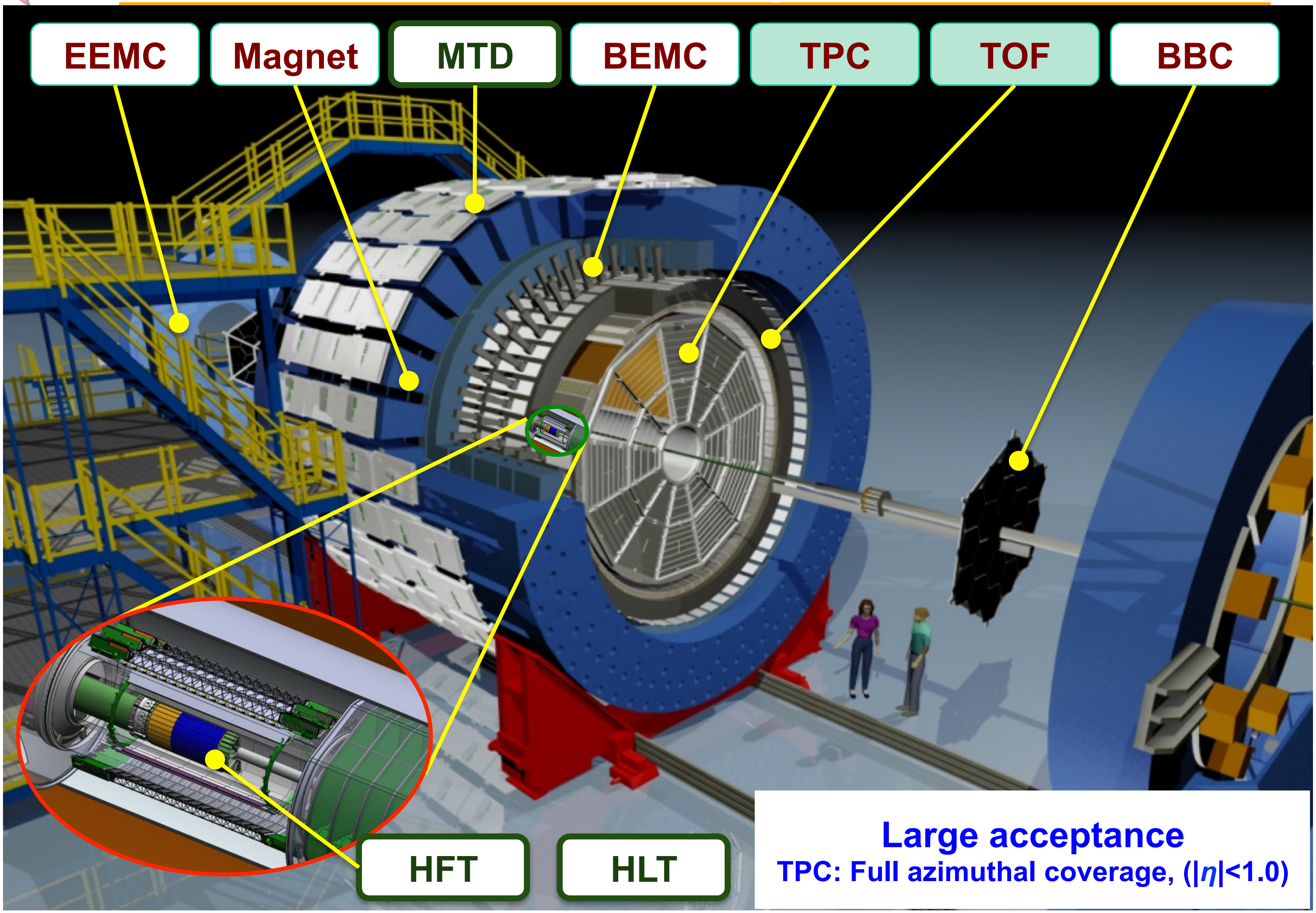
nature

STAR ☆ ***Science* 328,** 58 (2010)

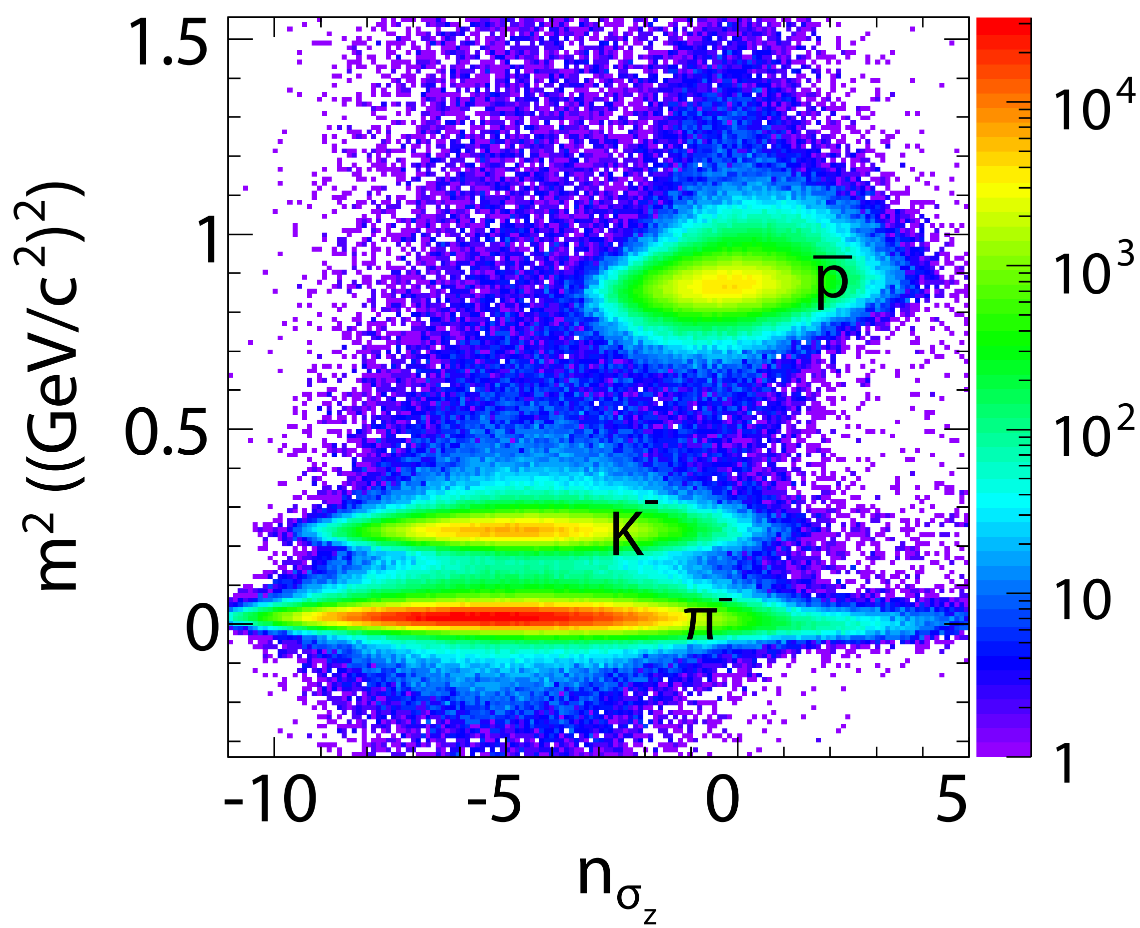
STAR ☆ ***Nature* 473,** 353 (2011)

- With abundantly produced antinucleons, RHIC (and LHC too) has the excellent capability of conducting this study.

STAR detector complex



Particle Identification



$$z = \ln \frac{\langle dE/dx \rangle}{\langle dE/dx \rangle_{expected}}$$

PID by Time Projection Chamber (TPC) and Time of Flight detector (TOF). Purity for anti-protons is over 99%.

Correlation analysis

Correlation Function (CF):

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

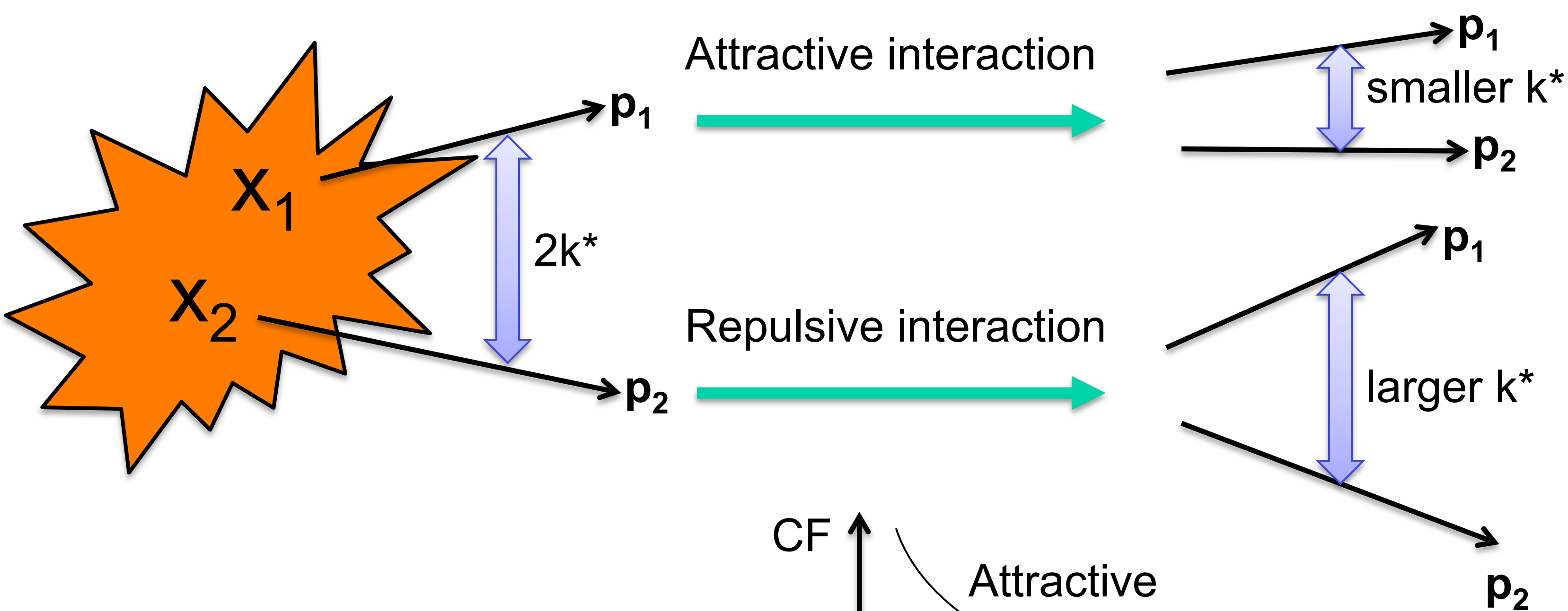
In practice,

$$C(k^*)_{measured} = \frac{\text{real pairs from same events}}{\text{pairs from mixed events}}$$

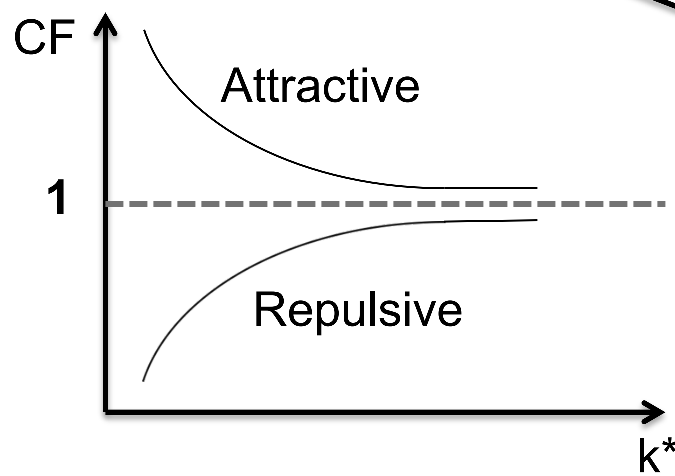
Purity correction :

$$C(k^*) = \frac{C(k^*)_{measured} - 1}{\text{PairPurity}(k^*)} + 1$$

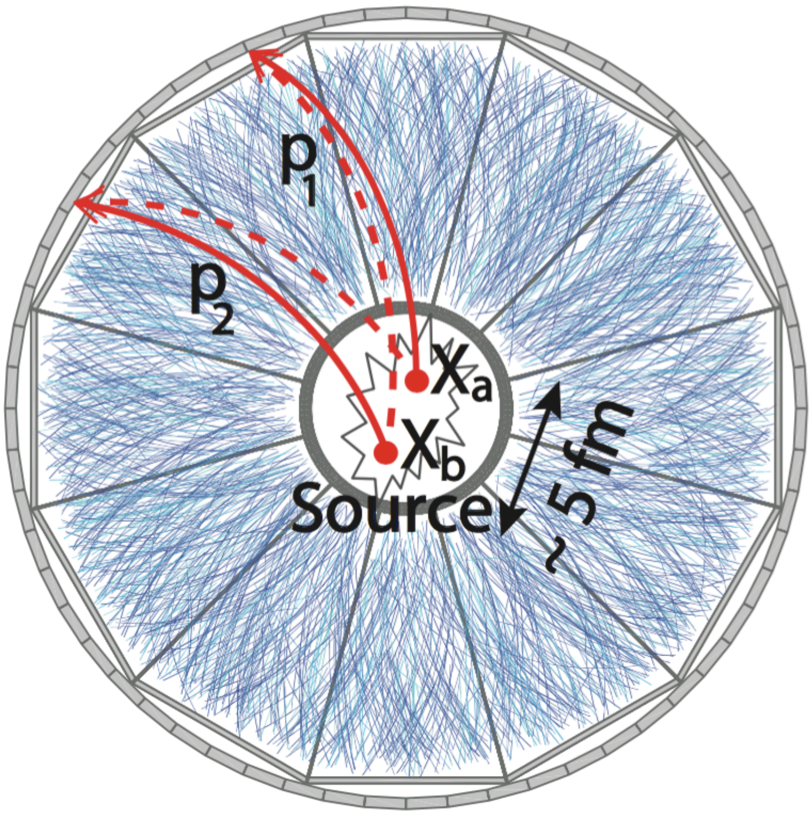
Correlation analysis



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.



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

Connecting f_0 & d_0 to CF

CF ←

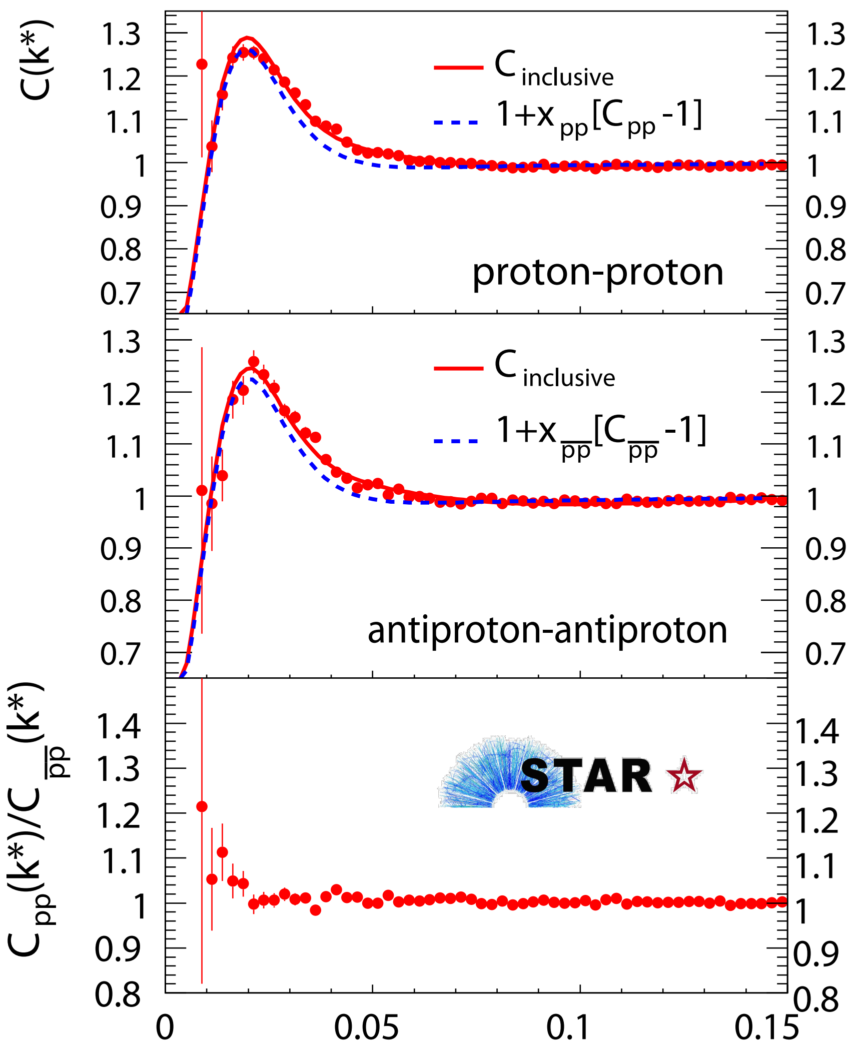
wave function

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

Scattering amplitude

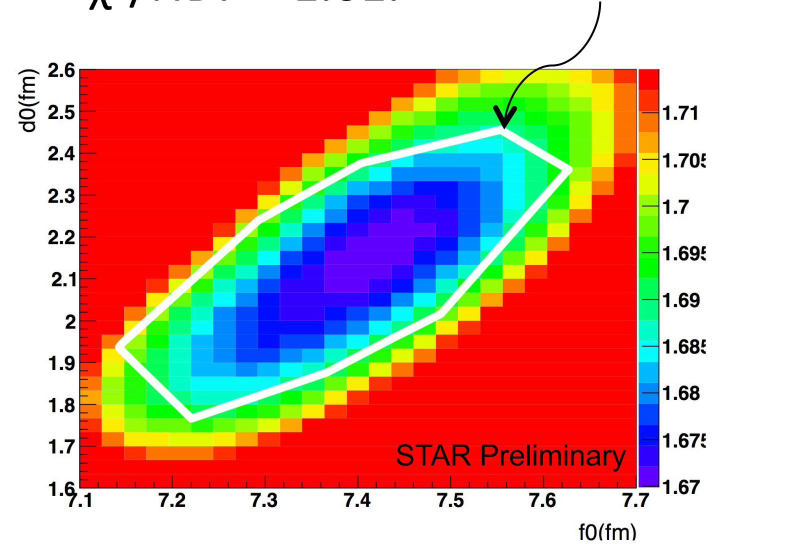
$$f_c(k^*) = \left[\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_c}h(\eta) - ik^* A_c(\eta)\right]^{-1}$$

Correlation functions

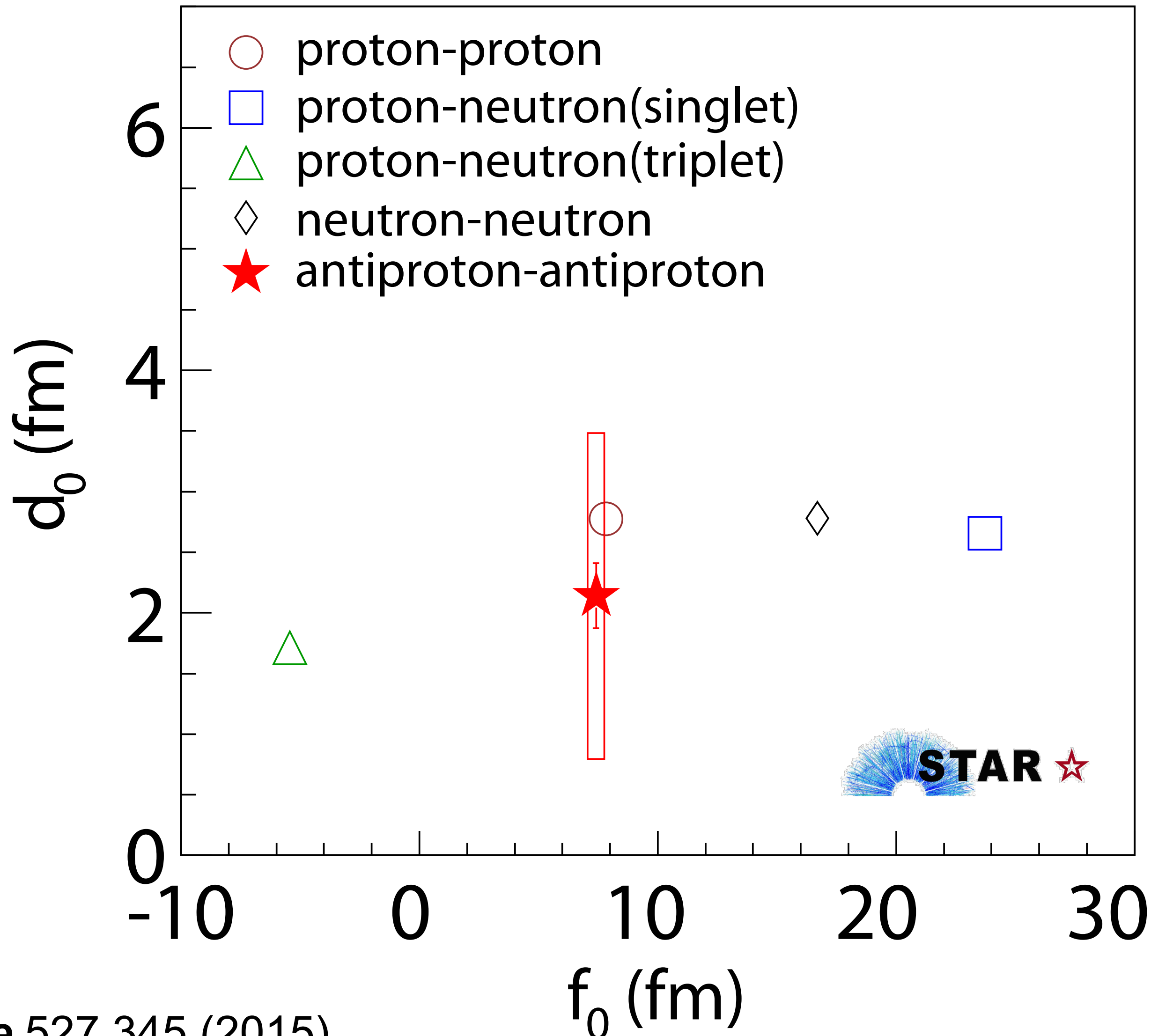


Nature 527 345 (2015)

- For proton-proton CF
  R = 2.75 ±0.01 fm;
  χ^2/NDF = 1.66.
- For antiproton-antiproton CF
  R = 2.80 ±0.02 fm;
  f_0 = 7.41 ± 0.19 fm;
  d_0 = 2.14 ± 0.27 fm;
  χ^2/NDF = 1.61.



f_0 and d_0



Nature 527 345 (2015)

Summary for part II

• 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.

"This paper announces an important discovery! … offers important original contribution to the forces in antimatter!" – *Nature* Referee A

"… significance of the results can be considered high since this is really the first and only result available on the interaction between the antiprotons ever." – *Nature* Referee B

"… are of fundamental interest for the whole nuclear physics community and possible even beyond for atomic physics applications or condensed matter physicists. … I think that this paper is most likely one of the five most significant papers published in the discipline this year" – *Nature* Referee C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Discussion and Future Directions

Discussion and future directions : CMW

Our finding is consistent with the existence of CMW, and so far no conventional models, as currently implemented, can explain the data. However, this is one aspect of a group of anomalous chiral effects, which to claim a discovery, more work needs to be done collectively between experimentalists and theorists.

Experiment : differential study of CMW, isobars, U+U, chiral vortical effect, chiral electric separation effect, Beam Energy Scan II, LHC measurements, etc.

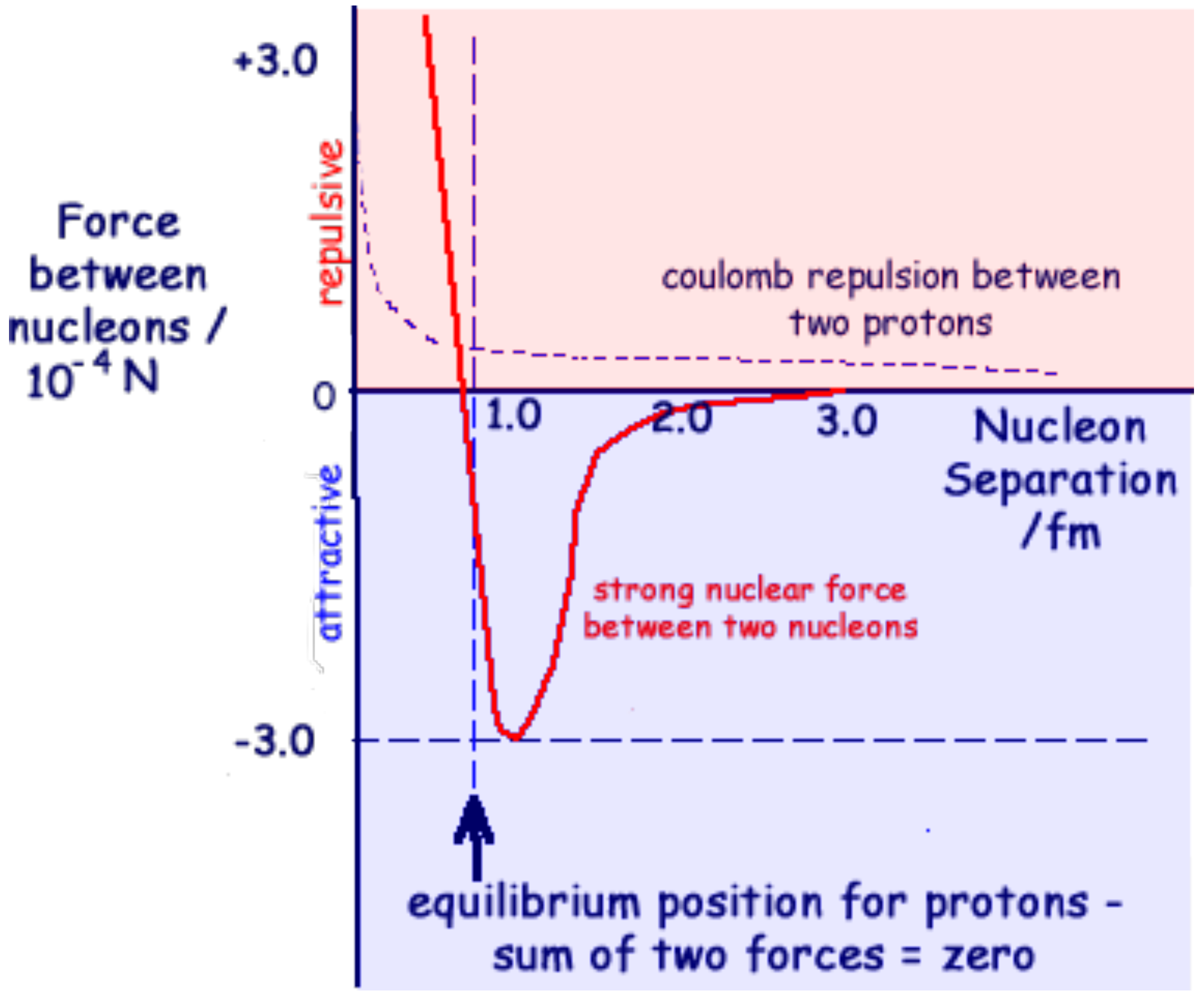
Theory : realistic modeling of charge initial conditions, lifetime of B, reconcile controversial predictions/calculations, development of chiral magnetohydrodyamics etc.

Discussion and future directions : matter-antimatter symmetry

- Improvement on the control of systematics.
- Refine fitting procedure.
- Analyze further accumulated data.

Backup Slides

Nuclear force range



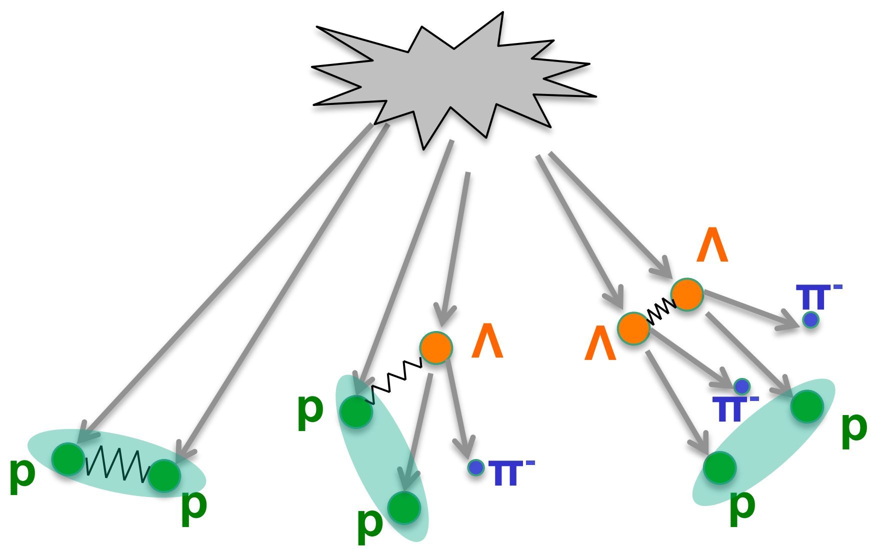
CPT is still a hot topic of interest

Theory :

• SM extensions are developed to use constrain parameters of effective field theories explicitly violating CPT (Kostelecky & Russel, Rev. Mod. Phys. 83 2011)
• CPT violation through Quantum Gravity Decoherence.
• Cosmological CPT violation.
• At the GUT scale where forces are supposed to be originated, CPT symmetry is no longer guaranteed (string theory).

(for review, see for example, e-print : hep-ph/0504143)

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

Taking dominant contributions due to residual correlation, the measured correlation function can be expressed as :

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

where

$$\tilde{C}_{p\Lambda}(k^*_{pp}) = \int C_{p\Lambda}(k^*_{p\Lambda})T(k^*_{p\Lambda},k^*_{pp})dk^*_{p\Lambda}$$

and

$$\tilde{C}_{\Lambda\Lambda}(k^*_{pp}) = \int C_{\Lambda\Lambda}(k^*_{\Lambda\Lambda})T(k^*_{\Lambda\Lambda},k^*_{pp})dk^*_{\Lambda\Lambda}$$

- $C_{pp}(k^*)$ and $C_{p\Lambda}(k^*_{p\Lambda})$ are calculated by the Lednicky and Lyuboshitz model.
- $C_{\Lambda\Lambda}(k^*_{\Lambda\Lambda})$ is from STAR publication (PRL 114 22301 (2015)).
- Regard $R_{p\Lambda}$ and $R_{\Lambda\Lambda}$ are equal to R_{pp}.
- T is the corresponding tranform matirces, generated by THERMINATOR2, to transform $k^*_{p\Lambda}$ to k^*_{pp}, as well as $k^*_{\Lambda\Lambda}$ to k^*_{pp}.

Connecting f_0 & d_0 to CF

The theoretical correlation function can be obtained with

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

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

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

$$f_c(k^*) = \left[\frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - \frac{2}{a_c} h(\eta) - ik^* A_c(\eta) \right]^{-1}$$ is the s-wave scattering amplitude

renormalized by Coulomb interaction.

$\eta = (k^* a_c)^{-1}$, $a_c = 57.5$ fm

$\rho = k^* r^*$, $\xi = k^* r^* + \rho$

$A_c(\eta) = 2\pi\eta \left[\exp(2\pi\eta) - 1 \right]^{-1}$

F is the confluent hypergeometric function

$\tilde{G}(\rho, \eta) = \sqrt{A_c(\eta)} \left[G_0(\rho, \eta) + iF_0(\rho, \eta) \right]$ is a combination of the regular (F_0) and singular (G_0) s-wave Coulomb functions. Proton pairs are from THERMINATOR2 when deriving theoretical C(K*)

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)/$\sqrt{12}$

Other systematics that are not considered in this analysis :

- Non-Coulomb electromagnetic contribution due to magnetic interactions
- Vacuum polarization
- Finite proton size

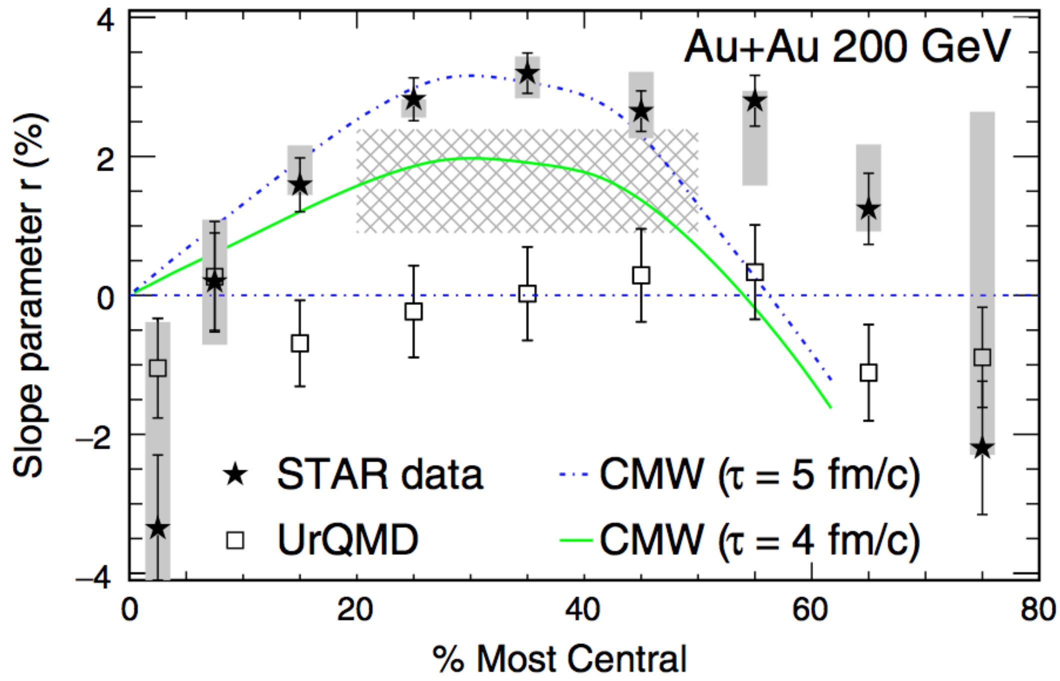
These effects change the f_0 and d_0 at the level of a few percent in total.

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)

CMW : Compare to predictions



v_2 splitting as a function of charge asymmetry between π+ and π- is consistent with CMW prediction.

Imply that both Chiral Magnetic Effect and Chiral Separation Effect are at work.

Imply chiral restoration.