Anti-matter production and interaction in relativistic heavy-ion collision

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and STAR@RHIC Collaboration

Main collaborators: J.H. Chen, A.H. Tang, Z.B. Xu, L. Xue, Z.Q. Zhang

@ CCNU, 6/6/2016

Outline

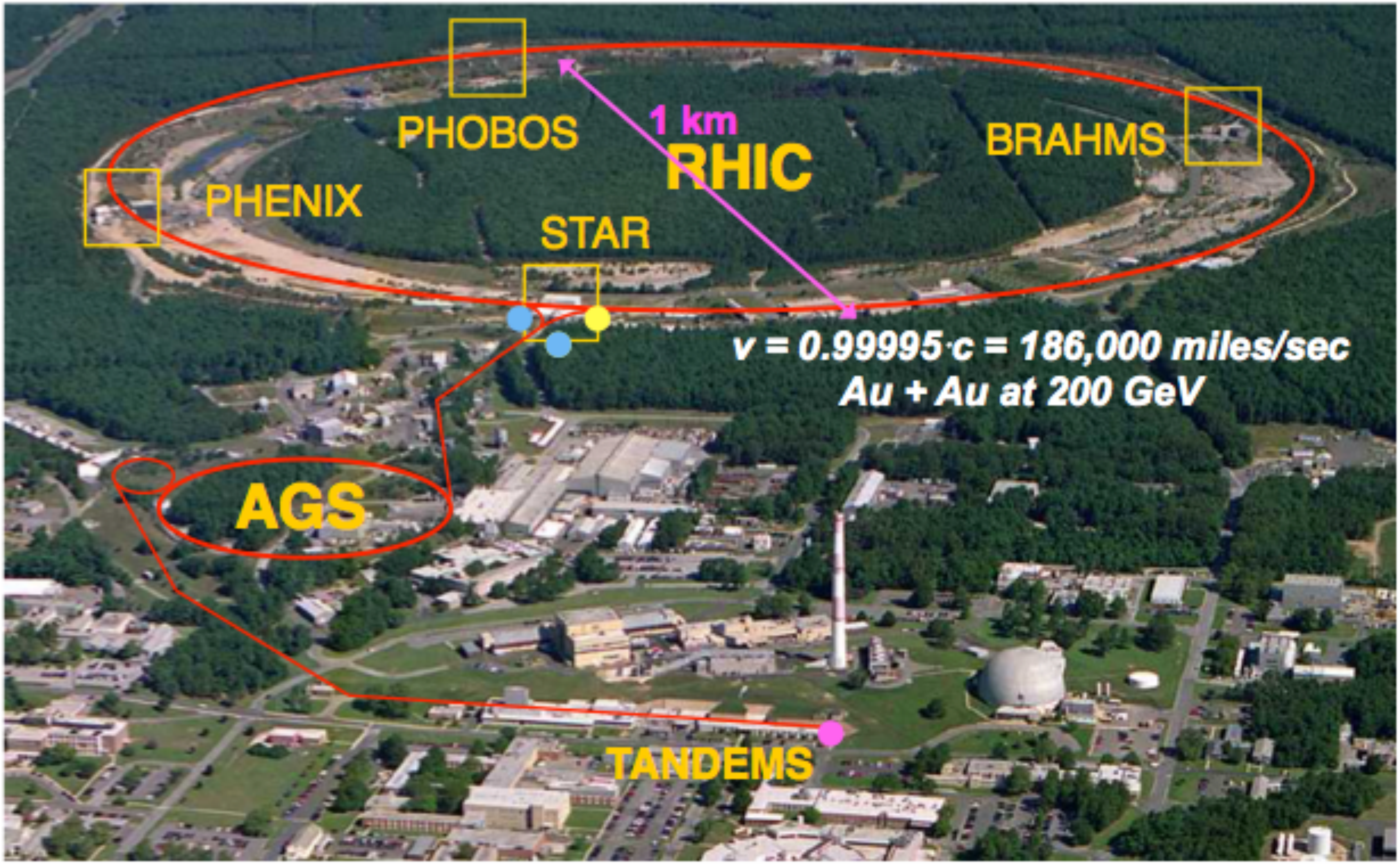
- Motivation and introduction
- Observation of Antimatter nuclei: antihypertriton & antiHelium-4
- Measurement on interaction between antiprotons
- Summary & outlook

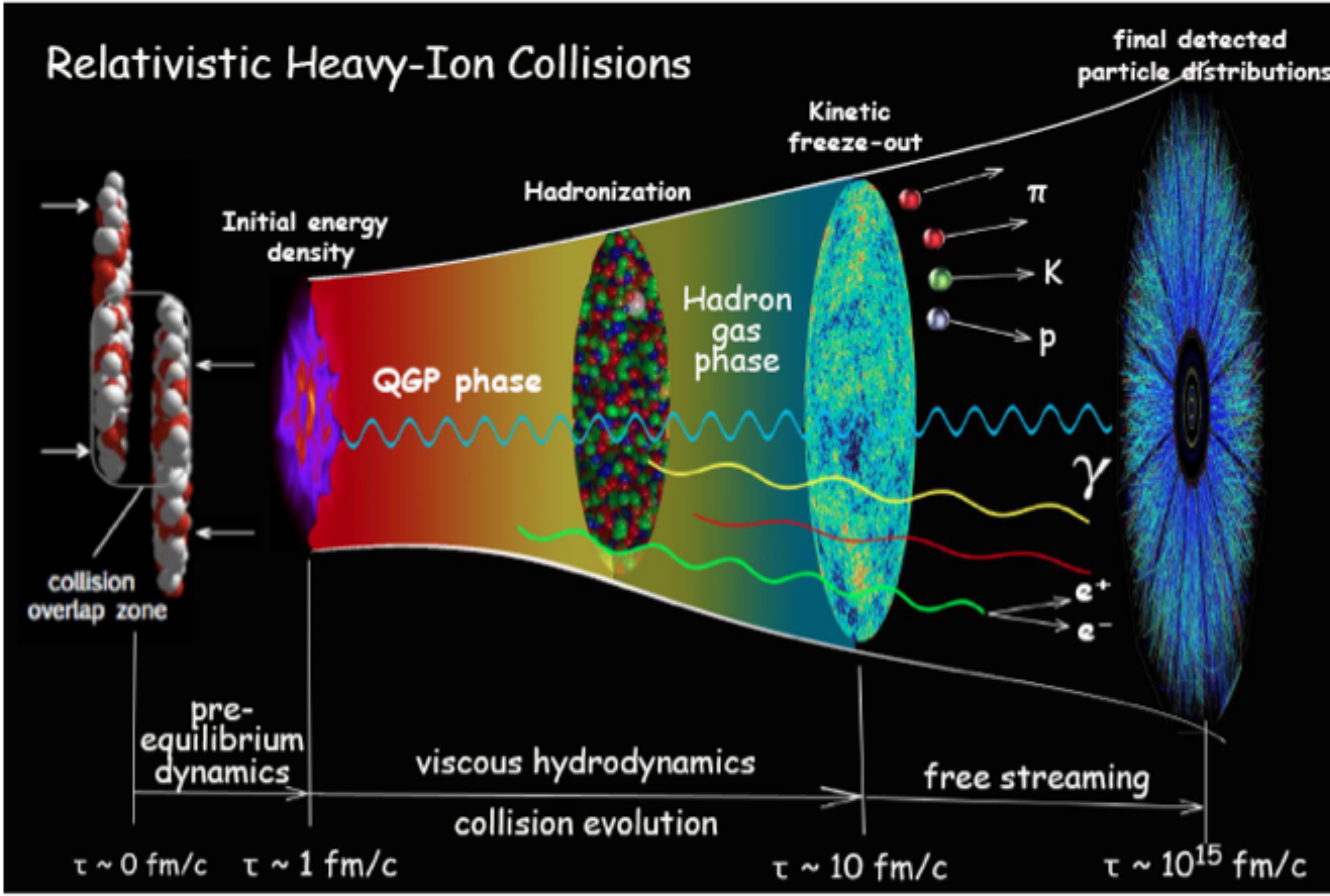
Motivation

- Observation on antimatter nuclei and the studies of their properties are important issues on CPT symmetry.
- Relativistic heavy ion collider provides an unique venue to create an extreme hot and dense matter which can mimic the early Universe. Therefore, more antimatter nuclei could be expected from there.
- Traditionally, antimatter nuclei observed so far are only composed of light antiquarks (ubar, dbar). Is it possible for inclusion of anti-strange quark?
- The record of heaviest antimatter nucleus which was observed in lab is for mass number 3 before 2011. Since a stable structure of Helium4, so it is of very interesting to look for anti-helium 4 in Lab.
- From the interaction viewpoint, the large body of knowledge on nuclear force was derived from studies made on nucleons or nuclei. However, there is no quantitative information 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.

RHIC & its experiments

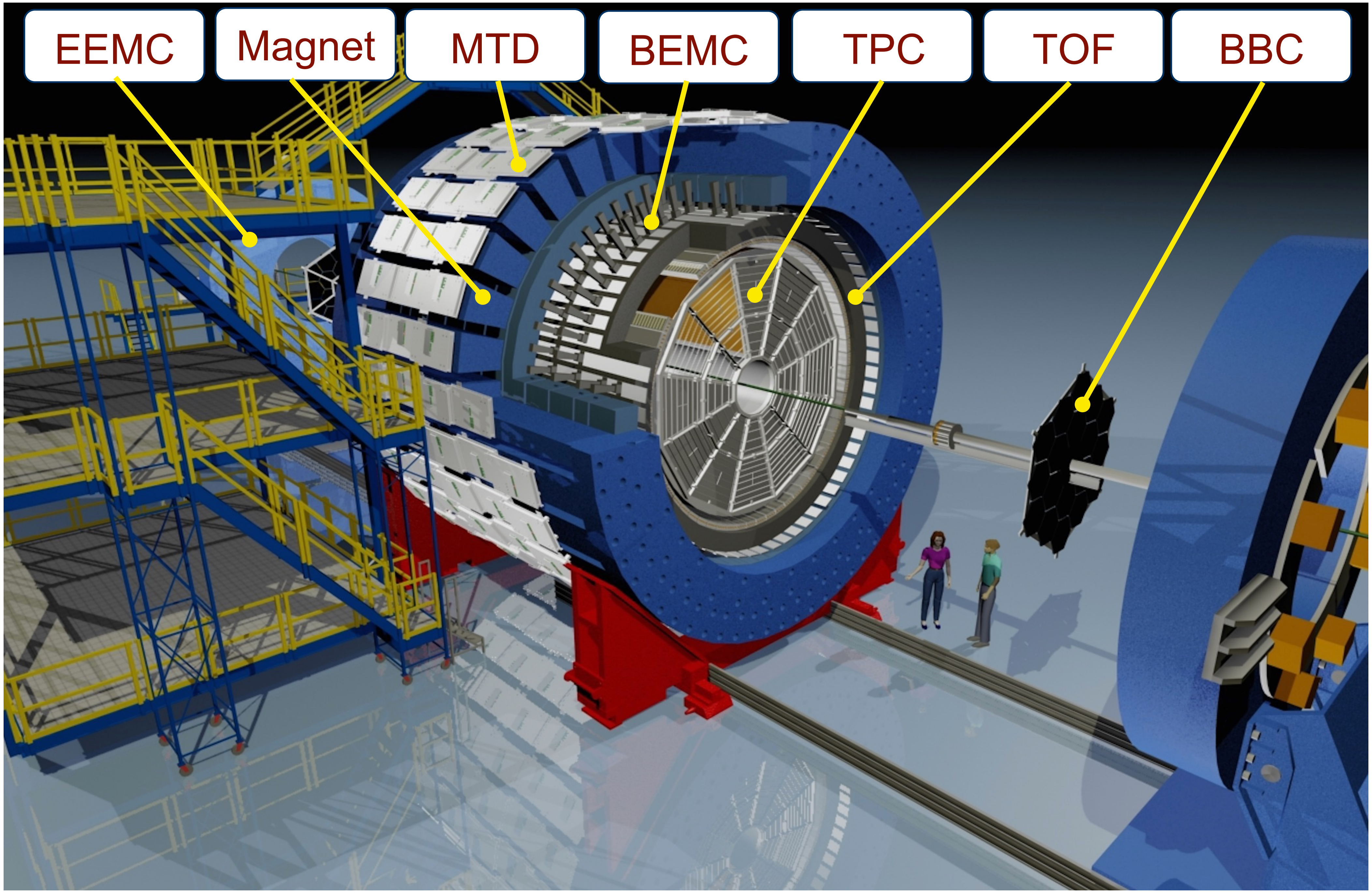
Animations by
Mike Lisa





Relativistic Heavy-Ion Collisions
final detected
particle distributions
Kinetic
freeze-out
Hadronization
Initial energy
density
π
K
p
Hadron
gas
phase
QGP phase
γ
e⁺
e⁻
collision
overlap zone
pre-
equilibrium
dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

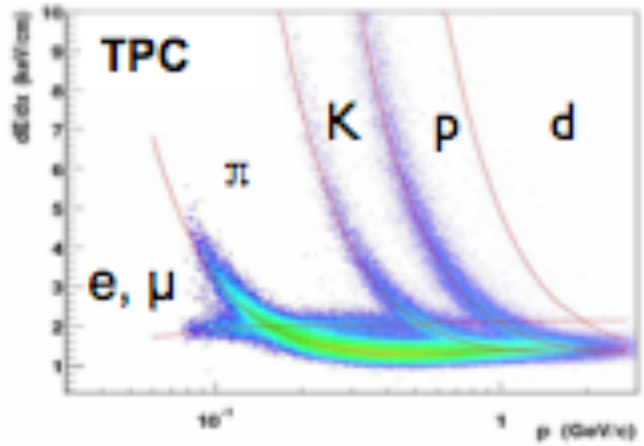
STAR Detectors

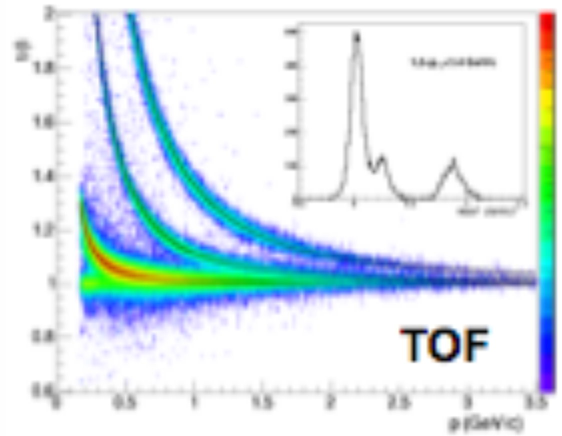


Full 2π coverage; Pseudorapidity coverage ~ ±1 unit

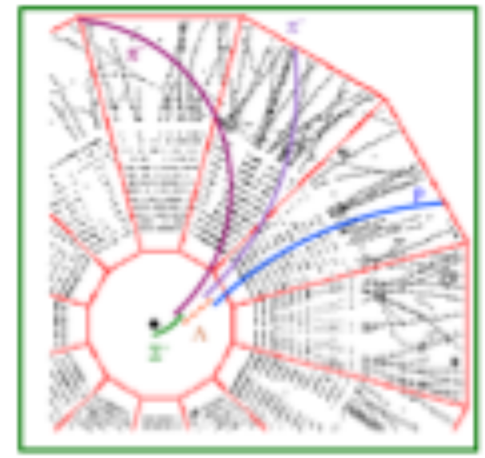
TOF & Muon Telescope Detector (MTD)： Chinese contribution

Particle Identification at STAR

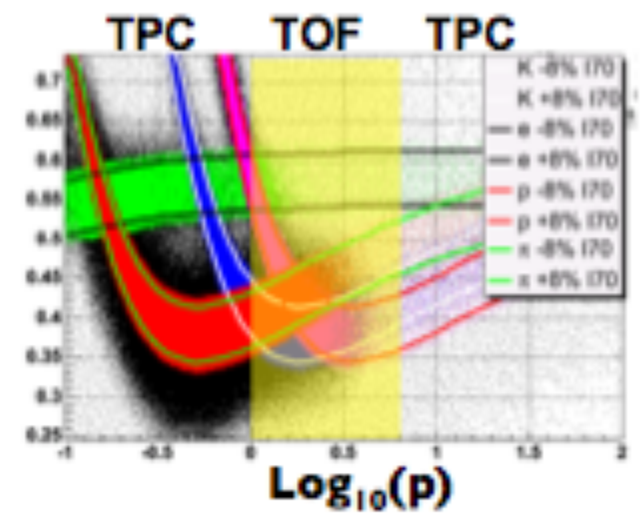


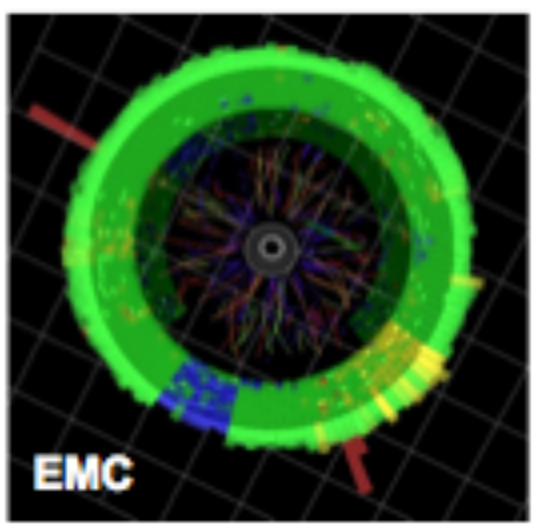


Charged hadrons

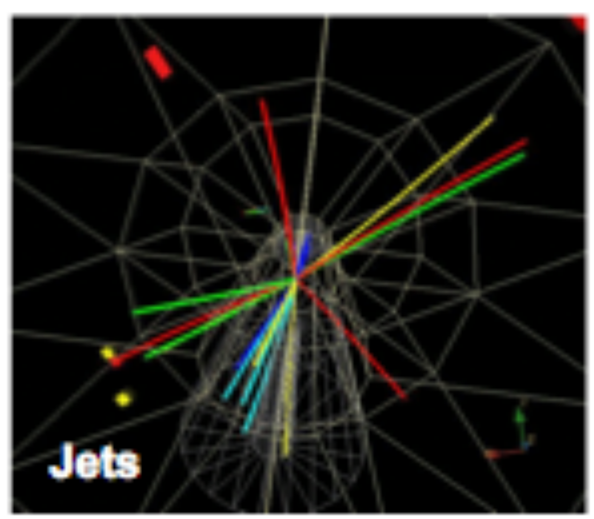


Hyperons & Hyper-nuclei

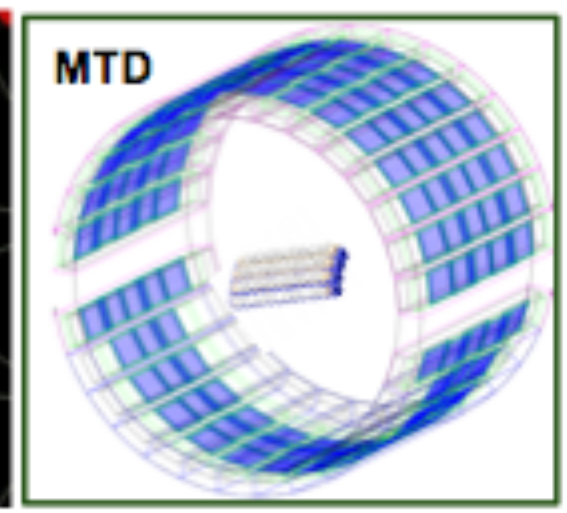




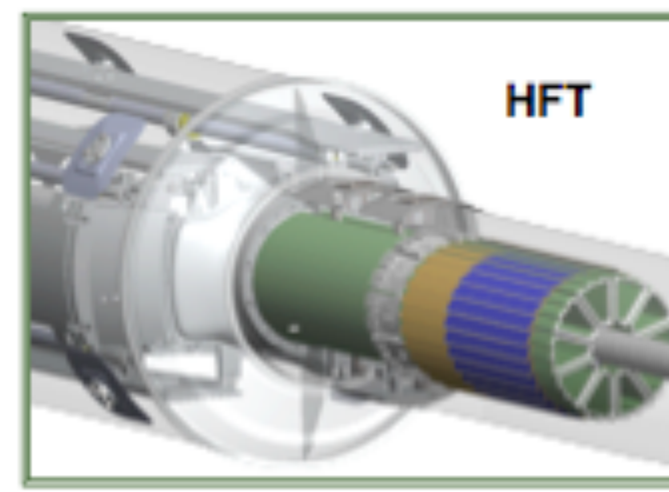
Neutral particles



Jets & Correlations



High p_T muons

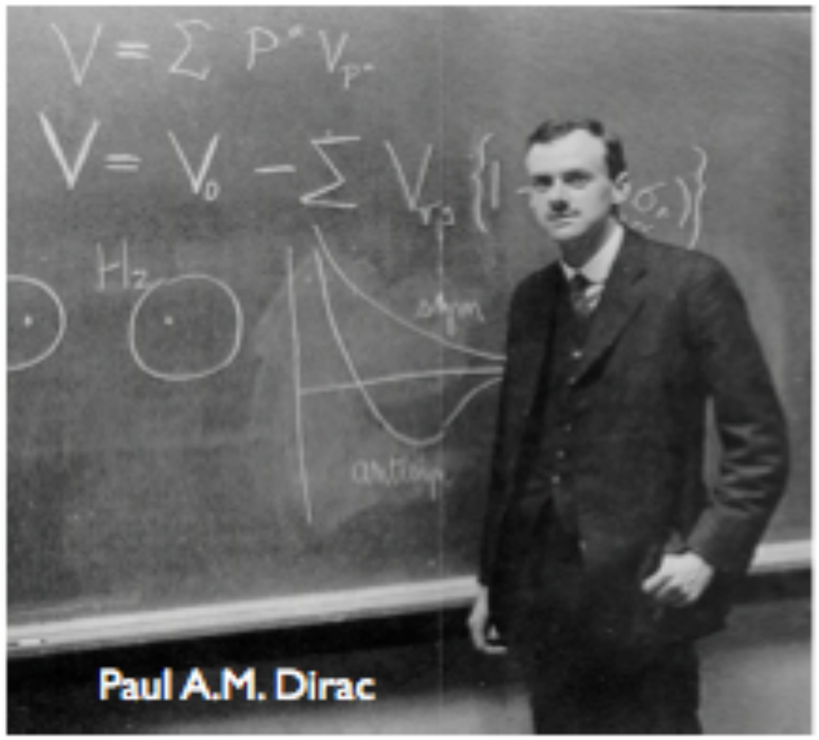


Heavy-flavor hadrons

Multiple-fold correlations among the identified particles!
Nearly perfect coverage at mid-rapidity

RHIC is not only a machine to search for QGP

But also for an **Antimatter** machine



1898: The idea of antimatter can be traced back to the end of 1890s, when Schuster discussed the possibility of the existence of antimatter atoms as well as antimatter solar system by hypothesis in his letter to Nature magazine

1928: Dirac equation unifies Quantum Mechanics and Special Relativity:

$$\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi = 0$$

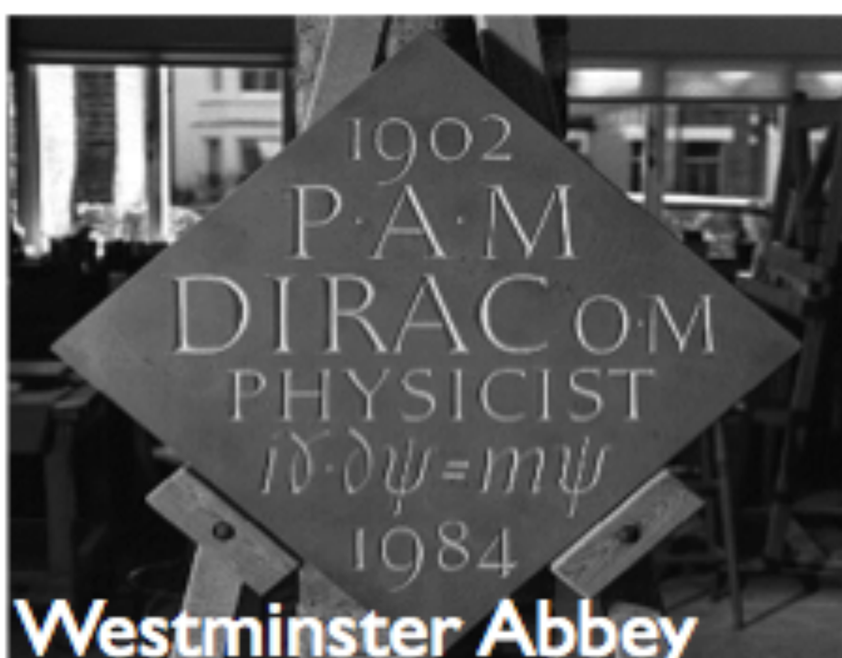
$$\psi = u(p)e^{-i(p\cdot x)}$$

Dirac Algebra:

$$\gamma^{\mu}\gamma^{\nu} + \gamma^{\nu}\gamma^{\mu} = 2g^{\mu\nu} \Rightarrow E = \pm\sqrt{p^2 + m^2}$$

1) Negative energy solutions can be seen as particles traveling backwards in time, equivalent to *anti-particles* traveling forward in time (Feynman & Stückelberg)

2) The # of particles is NOT conserved but #particles - #antiparticles is conserved)



PAUL A. M. DIRAC

Theory of electrons and positrons

Nobel Lecture, December 12, 1933

LETTERS TO THE EDITOR

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Potential Matter.—A Holiday Dream.

WHEN the year's work is over and all sense of responsibility has left us, who has not occasionally set his fancy free to dream about the unknown, perhaps the unknowable? And what should more frequently cross our dreams than what is so persistently before us in our serious moments of consciousness—the universal law of gravitation. We can leave our spectroscopes and magnets at home, but we cannot fly from the mysterious force which causes the rain-drops to fall from the clouds, and our children to tumble down the staircase. What is gravity? We teach our students to accept the fact and not to trouble about its cause—most excellent advice—but this is vacation time, and we are not restricted to lecture-room science.

Lasage's particles are not satisfactory; they are too materialistic for the holiday mind; but I have always been fascinated by a passage occurring somewhere in Maxwell's writings, where Lord Kelvin is quoted as having pointed out that two sources or two sinks of incompressible liquid will attract each other with the orthodox distance law.

Let us dream, then, of a world in which atoms are sources through which an invisible fluid is pouring into three-dimensioned space. What becomes of this fluid? Does it go on for ever increasing the volume of that all-pervading medium which already fills a vast, but not necessarily infinite, space? When we speak of the constancy of matter, we mean only the constancy of inertia, and how are we to prove that what we call matter is not an endless stream, constantly renewing itself and

Do dreams ever come true?

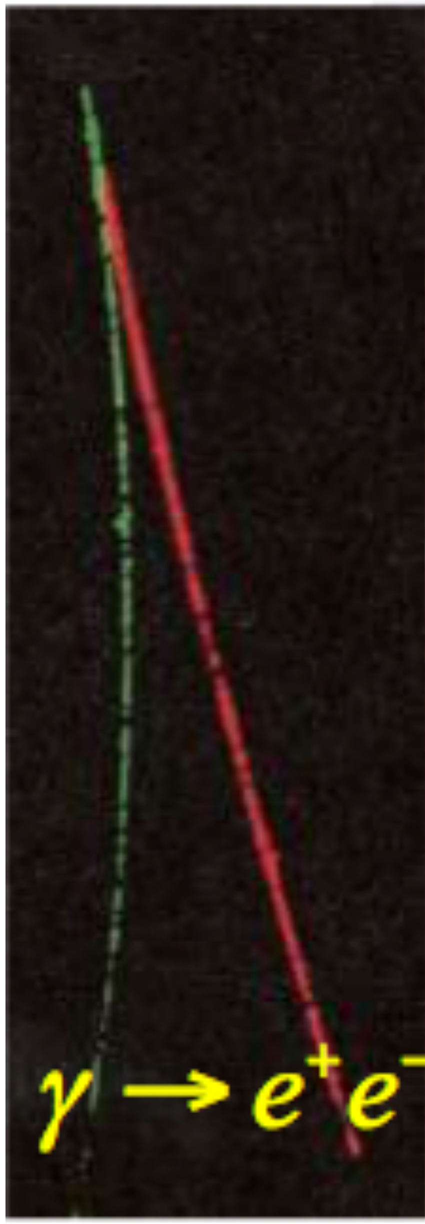
tional velocity of our solar and of many stellar systems, which cannot be self-generated. Unless we threw our laws of dynamics overboard, or imagine the rotation to have been impressed by creation, we must conclude that some outside body or system of bodies is endowed with an equal and opposite angular momentum. What has become of that outside body, and how could it have parted company with our solar system, if attractive forces only were acting? Another unexplained fact is found in the large velocities of some of the fixed stars, which, according to Prof. Newcomb's calculations, cannot be explained by gravitational attractions only.

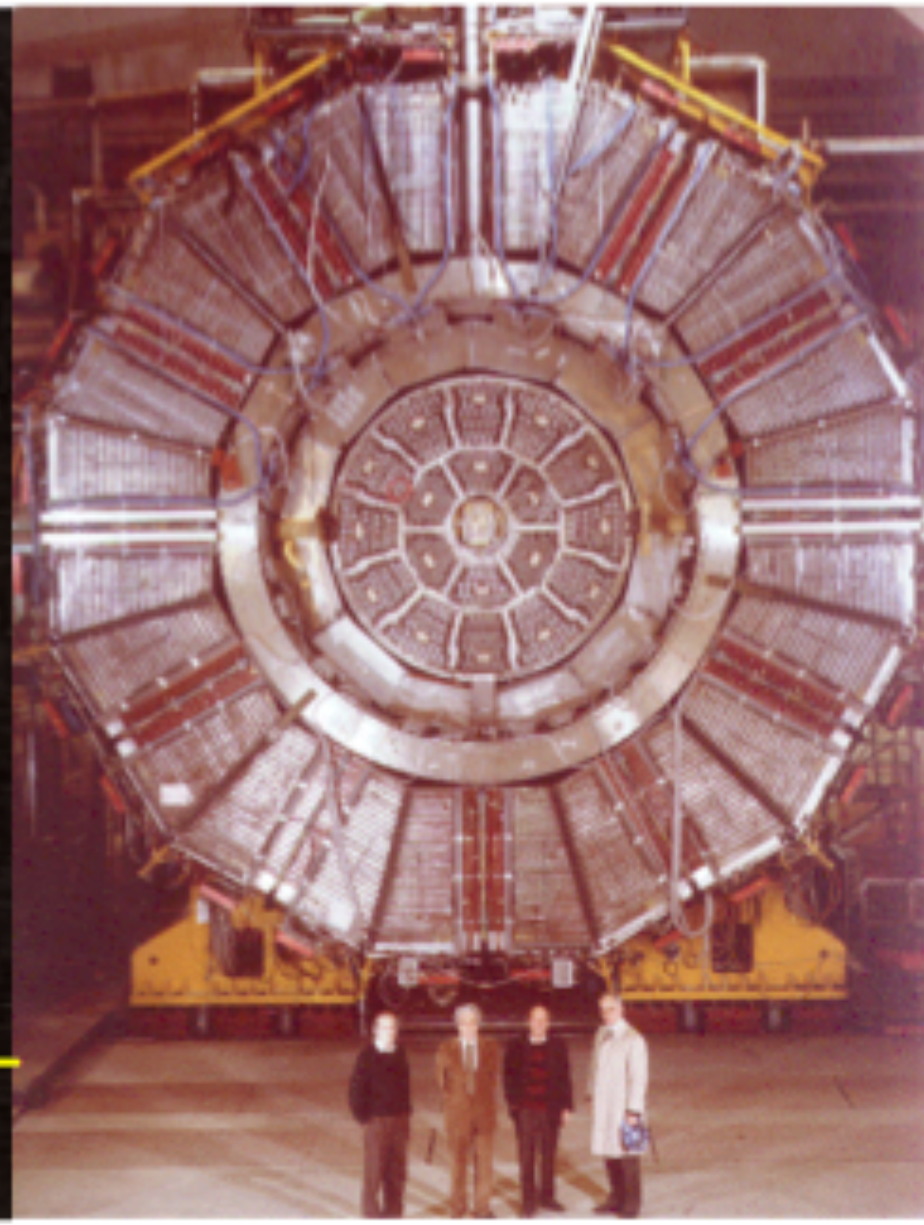
The atom and the anti-atom may enter into chemical combination, because at small distances molecular forces would overpower gravitational repulsions. Large tracts of space might thus be filled unknown to us with a substance in which gravity is practically non-existent, until by some accidental cause, such as a meteorite flying through it, unstable equilibrium is established, the matter collecting on one side, the anti-matter on the other until two worlds are formed separating from each other, never to unite again.

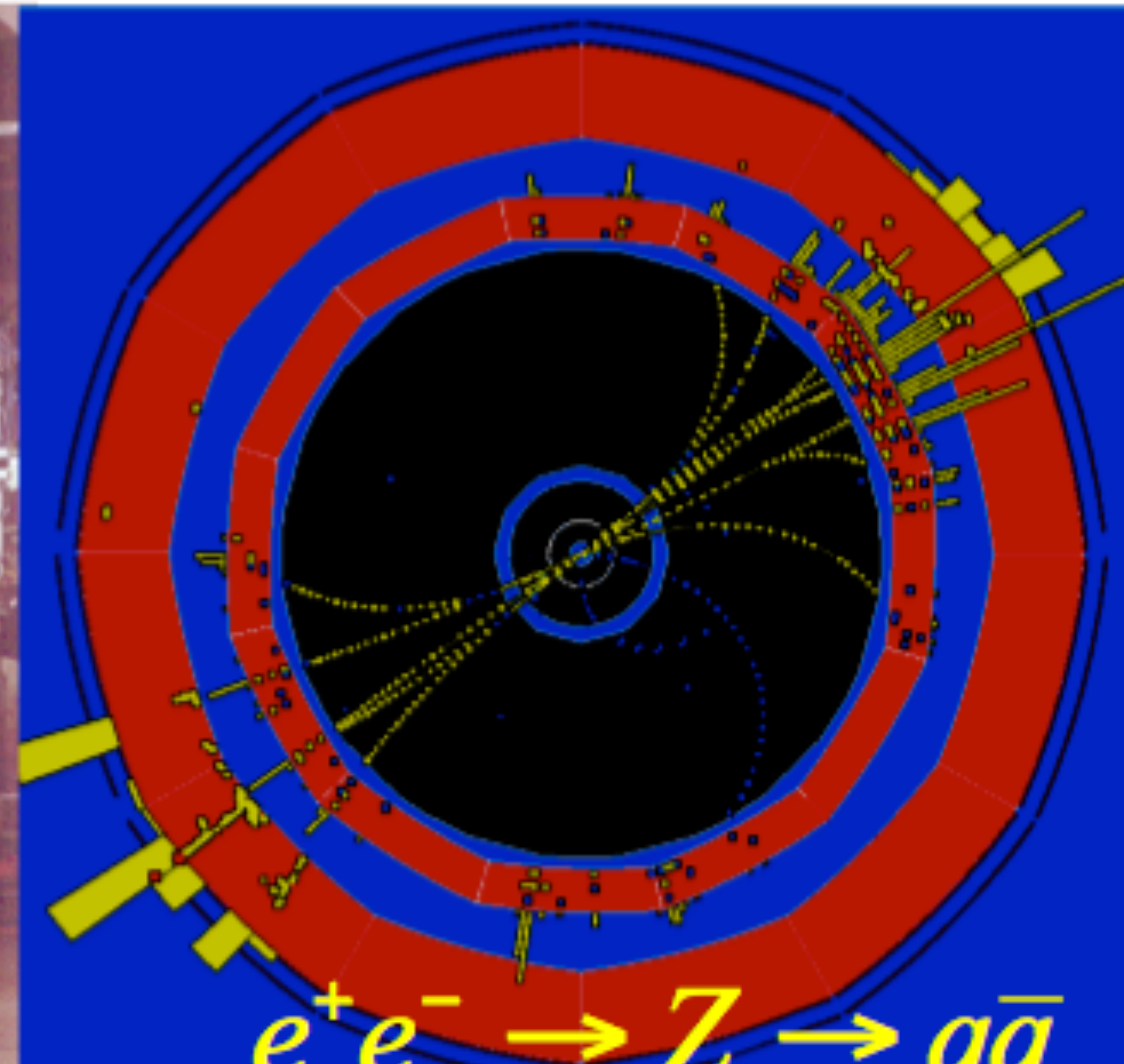
Matter and anti-matter may further coexist in bodies of small mass. Such compound mixtures flying hither and thither through space, coming during their journey into the sphere of influence of our sun, would exhibit a curious phenomenon. The matter circulating in a comet's orbit, the anti-matter repelled and thrown back into space, forming an appendage which is always directed away from the sun. Has any one yet given a satisfying explanation of comets' tails; is the cause of coronal streamers known, and can any one look at a picture of the great prominence of the 1885 eclipse, and still believe that gravitational attraction or electric repulsion is sufficient to account for its extravagant shape? But this is not a scientific discussion. I do not wish to argue in favour of the existence of anti-atoms, but only to give my thoughts a free course in the contemplation of its possibility.

ARTHUR SCHUSTER.

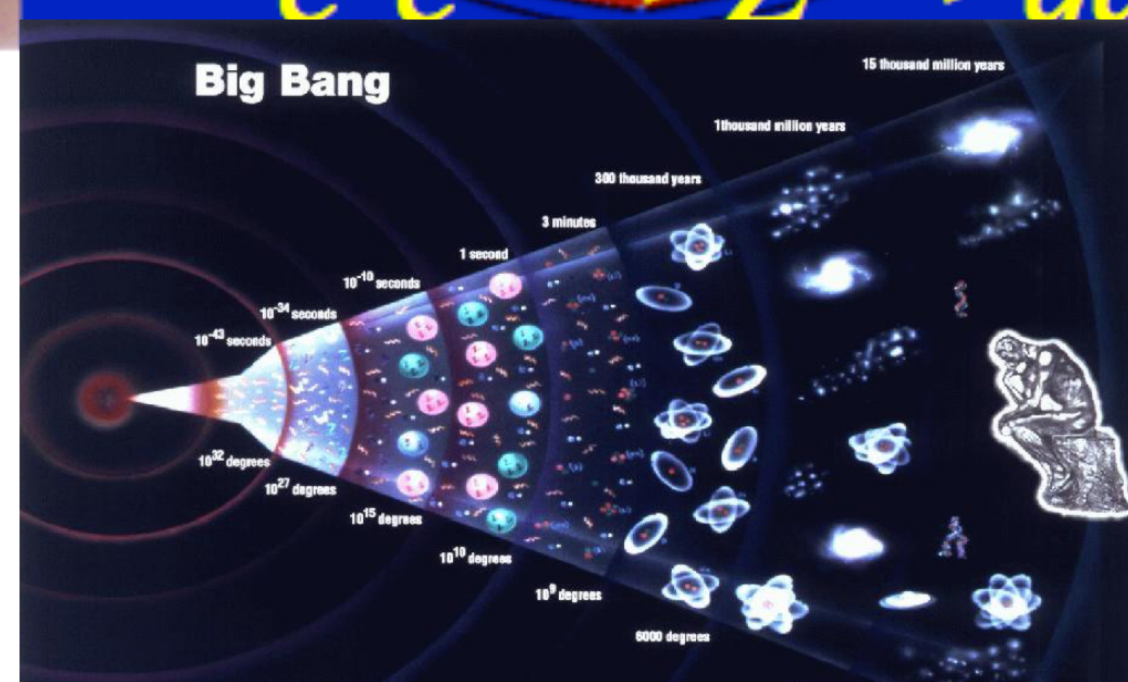
$E=mc^2$: creating Matter and Antimatter



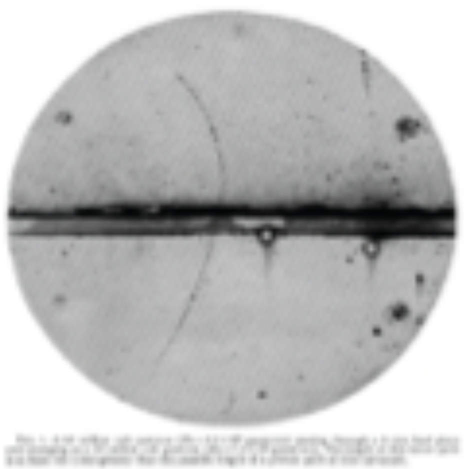




- When creating matter from energy,
- *always* create equal amount of antimatter

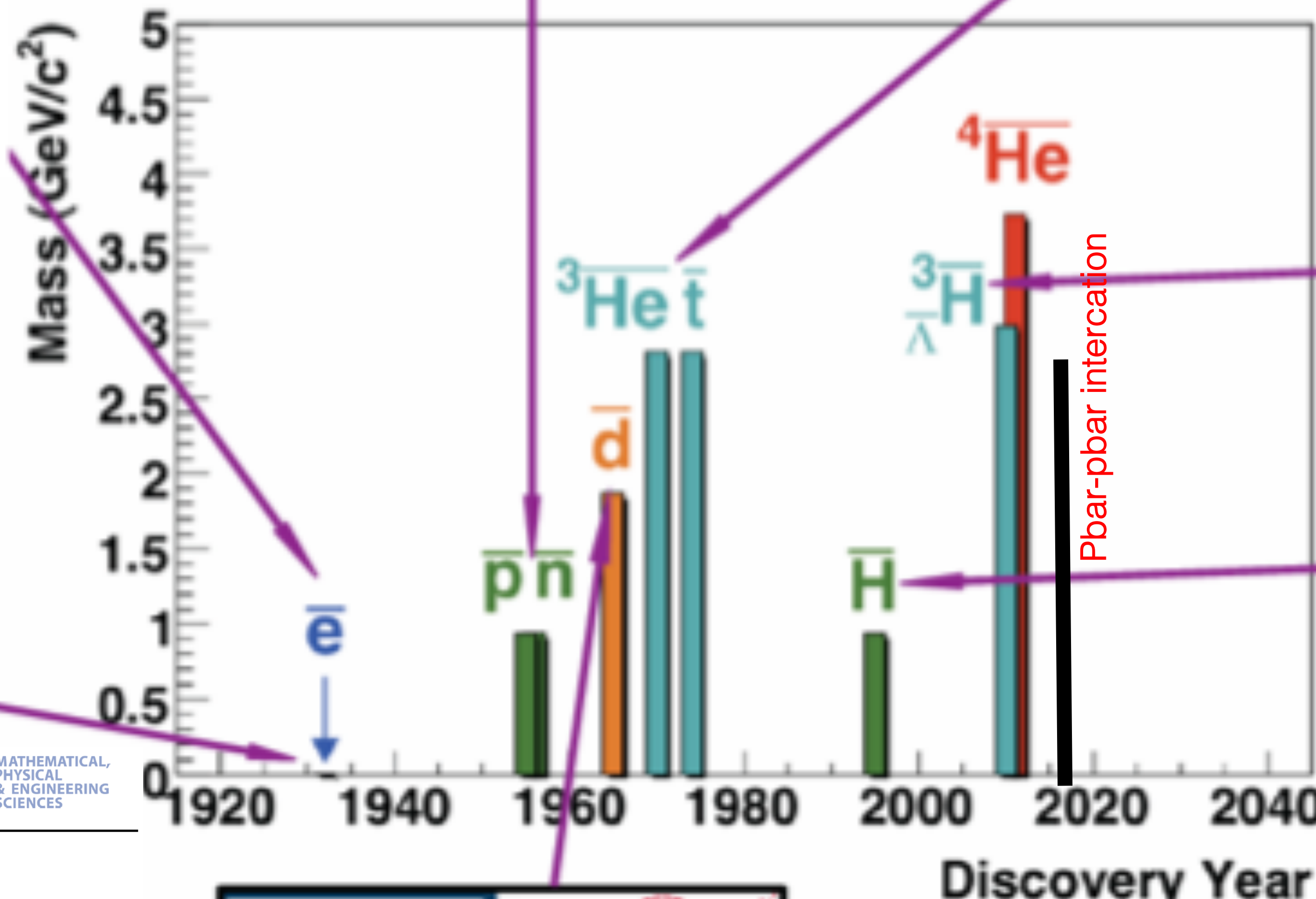


History of antimatter particles



Bevatron facility

IHEP, Russia



CERN

PROCEEDINGS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Quantum Theory of the Electron

P. A. M. Dirac

Proc. R. Soc. Lond. A 1928 **117**, doi: 10.1098/rspa.1928.0023, published 1 February 1928

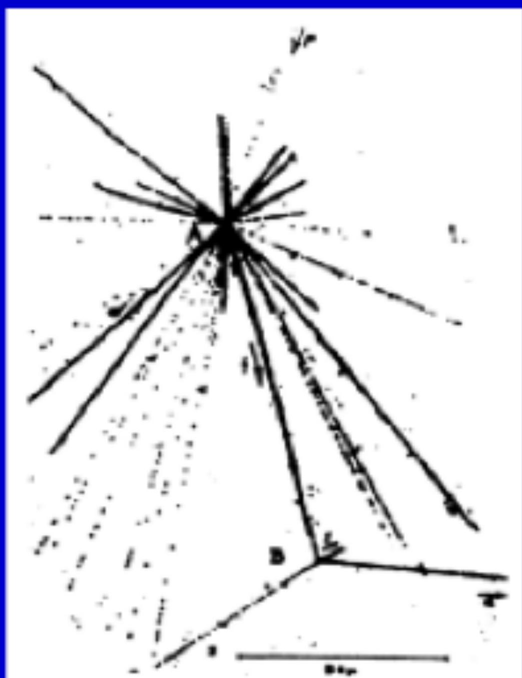
CERN AGS 2000

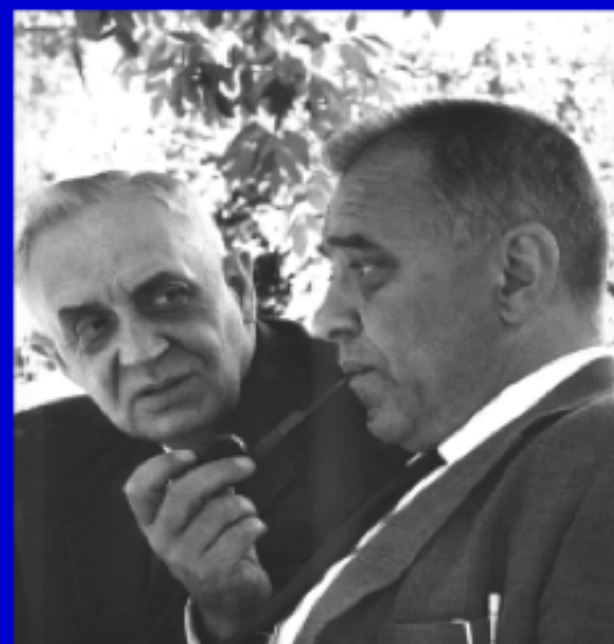
Anderson, C. D. Phys. Rev. 43, 491-494 (1933).
Chamberlain, O. etal. Phys. Rev. 100, 947 (1955).
Dorfan, D.E. etal. Phys. Rev. Lett. 14, 1003 (1965).
Antipov, Y. M. et al.. Yad. Fiz. 12, 311 (1970).
Abelev, B. I. et al., STAR Collaboration. Science 328, 58 (2010).
Abelev, B. I. et al., STAR Collaboration. Nature 473, 353 (2011).
G. B. Andreesn. et al., The ALPHA Collaboration. Nature Physics 7, 558 (2

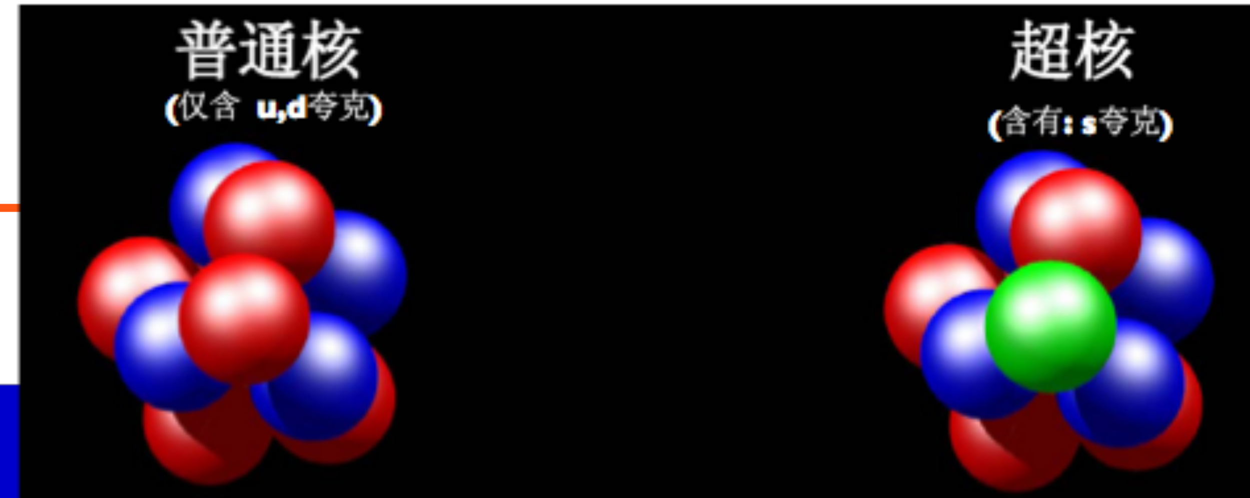
A minireview:
Y. G. Ma, J. Chen, L. Xue, Front. Phys., 2012, 7(6): 637–646

Hypernucleus

Nucleus which contains at least one hyperon in addition to nucleons.







The first hypernucleus was discovered by Danysz and Pniewski in 1952. It was formed in a cosmic ray interaction in a balloon-flown emulsion plate.

M. Danysz and J. Pniewski, Phil. Mag. 44 (1953) 348

No one has ever observed **any** antihypernucleus before 2010

Hypernuclei of lowest A

$$ {}^{3}_{\Lambda}H(n+p+\Lambda) $$

$$ {}^{3}_{\overline{\Lambda}}\overline{H}(\overline{n}+\overline{p}+\overline{\Lambda}) $$

- Y-N interaction: a good window to understand the baryon potential
- Binding energy and lifetime are very sensitive to Y-N interactions
- Hypertriton: **ΔB=130±50 KeV; r~10fm**
- Production rate via coalescence at RHIC depends on overlapping wave functions of **n+p+**Λ in final state
- Important first step for searching for other exotic hypernuclei (double-Λ)

Data-set and track selection

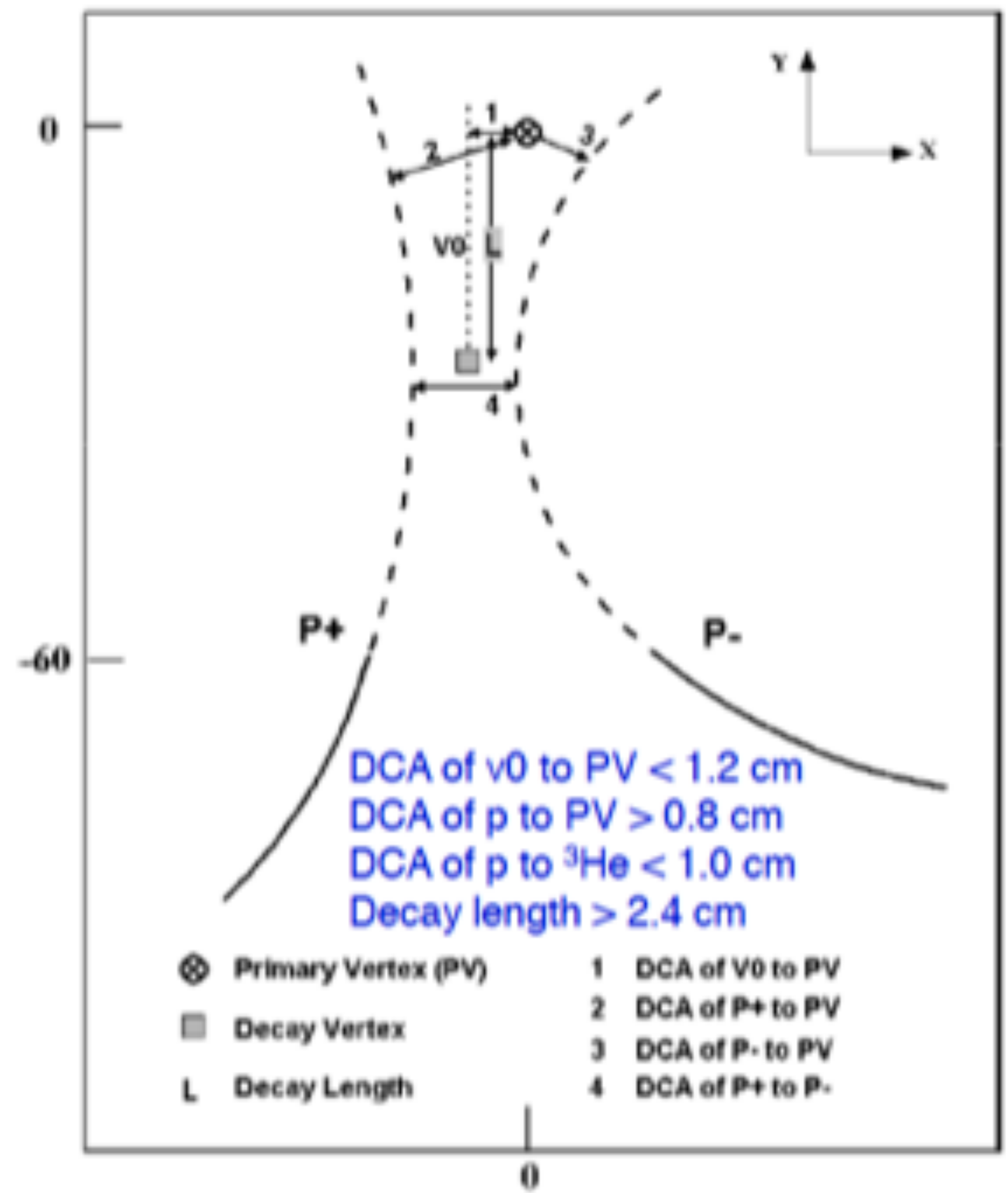
$^{3}_{\Lambda}H$ mesonic decay, m=2.991 GeV, B.R. 0.25;

$$^{3}_{\bar{\Lambda}}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+}$$

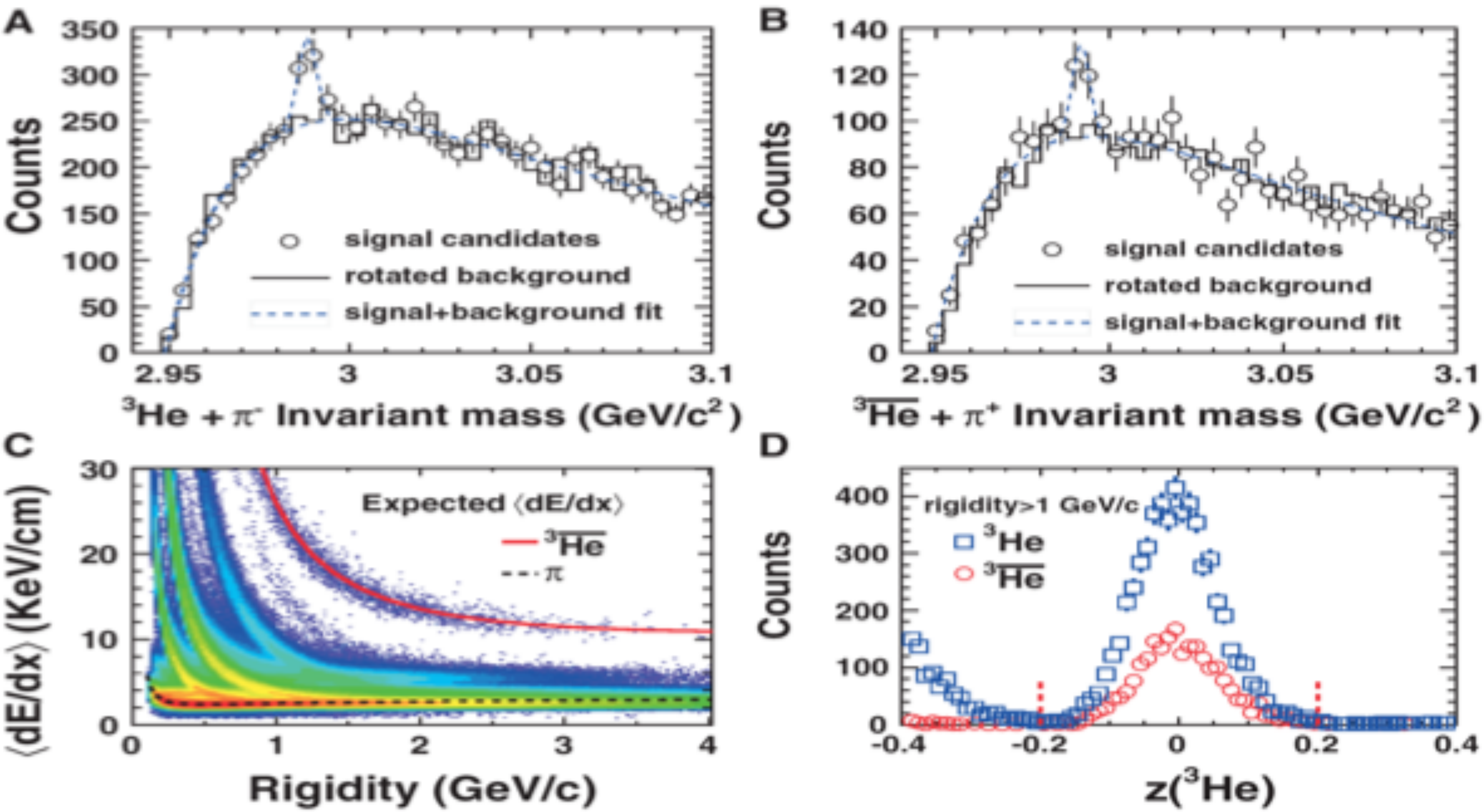
$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$$

- Data-set used, Au+Au 200 GeV
  - ✓~67M Run7 MB,
  - ✓~23M Run4 central,
  - ✓~22M Run4 MB,
  - ✓|VZ| < 30cm
- Track quality cuts, global track
  - ✓nFitsPts > 25, nFitsPts/Max > 0.52
  - ✓nHitsdEdx > 15
  - ✓P_t > 0.20, |eta| < 1.0
  - ✓Pion n-sigma (-2.0, 2.0)

Secondary vertex finding technique



Observation of anti-hypernucleus from RHIC-STAR



STAR, Science 328 (2010) 58

$^{3}_{\Lambda}\overline{\mathrm{H}}$® $^{3}\overline{\mathrm{He}}+\pi^{+}$ 70±17 antihypertritons

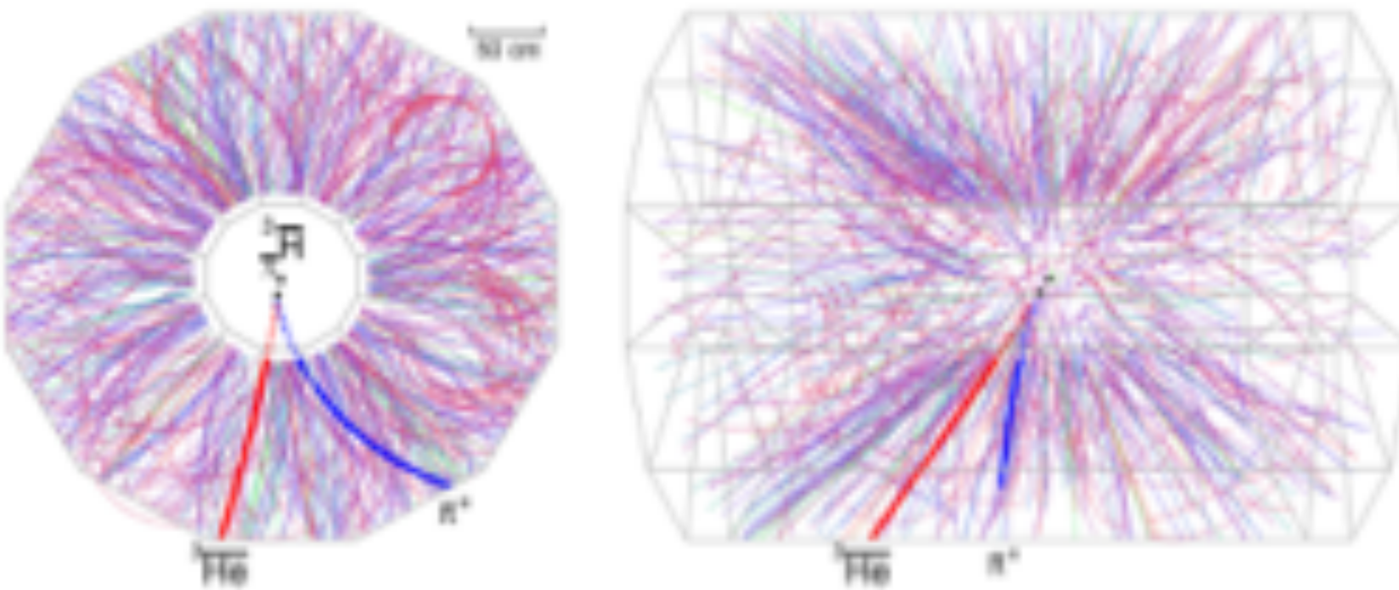
$^{3}_{\Lambda}\mathrm{H}$® $^{3}\mathrm{He}+\pi^{-}$ 157 ±30 hypertritons

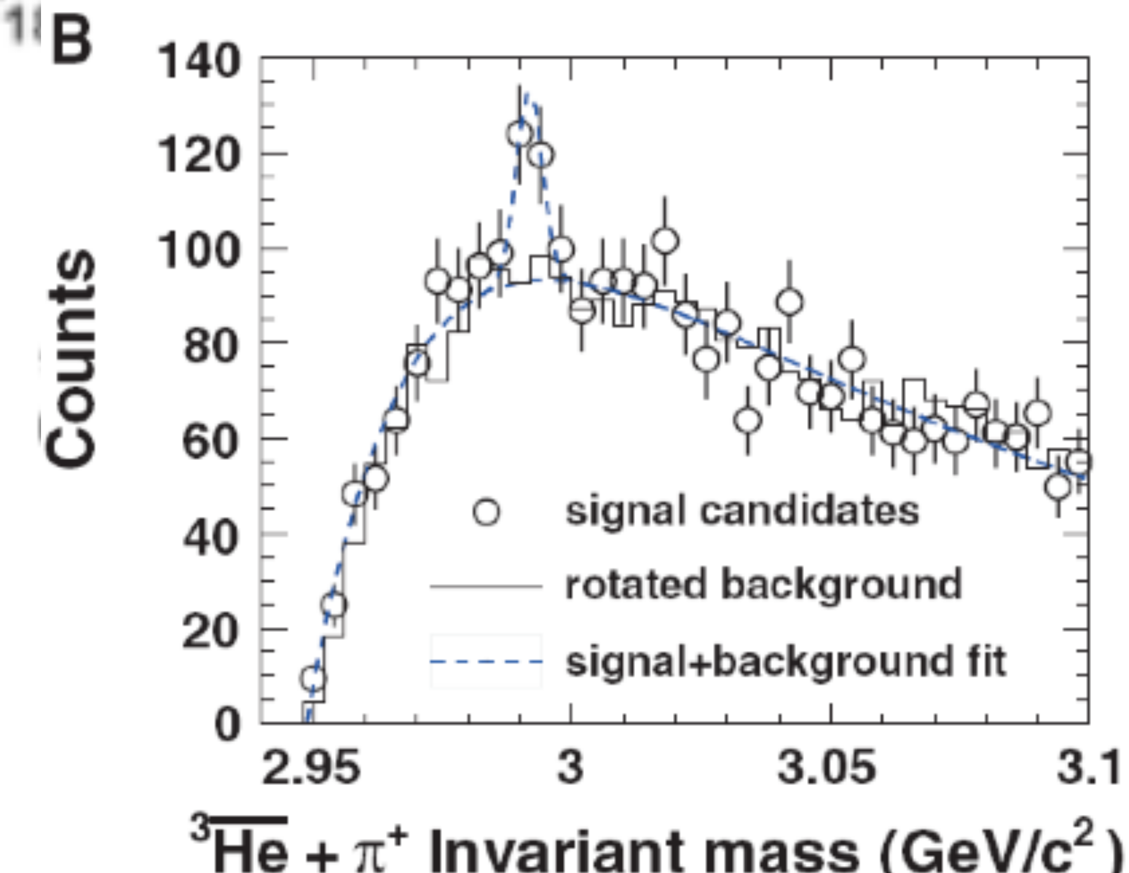
About 89 million minimum-bias events
22 million most central collisions events

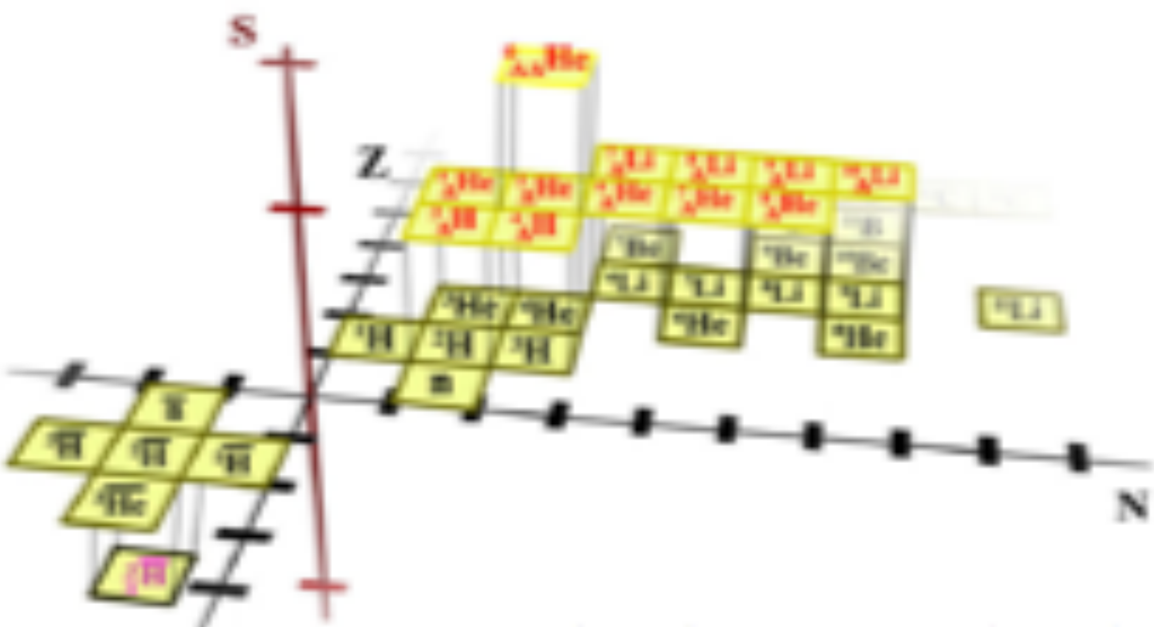
The anti-hypertriton observation

Jinhui Chen (SINAP), APS G. E. Valley Prize, 2012

Observation of an Antimatter Hypernucleus
The STAR Collaboration, *et al.*
Science **328**, 58 (2010);
DOI: 10.1126/science.11







- Anti-hypertriton, the first anti-nucleus containing an anti-strange quark, extends the 3-D chart of nuclides into the new octant of strange anti-matter
- Strangeness popular factor represents the strength of local baryon-strangeness correlation, experimental probe for QCD phase transition. S. Zhang et al., *Phys. Letts. B 684 (2010) 224*

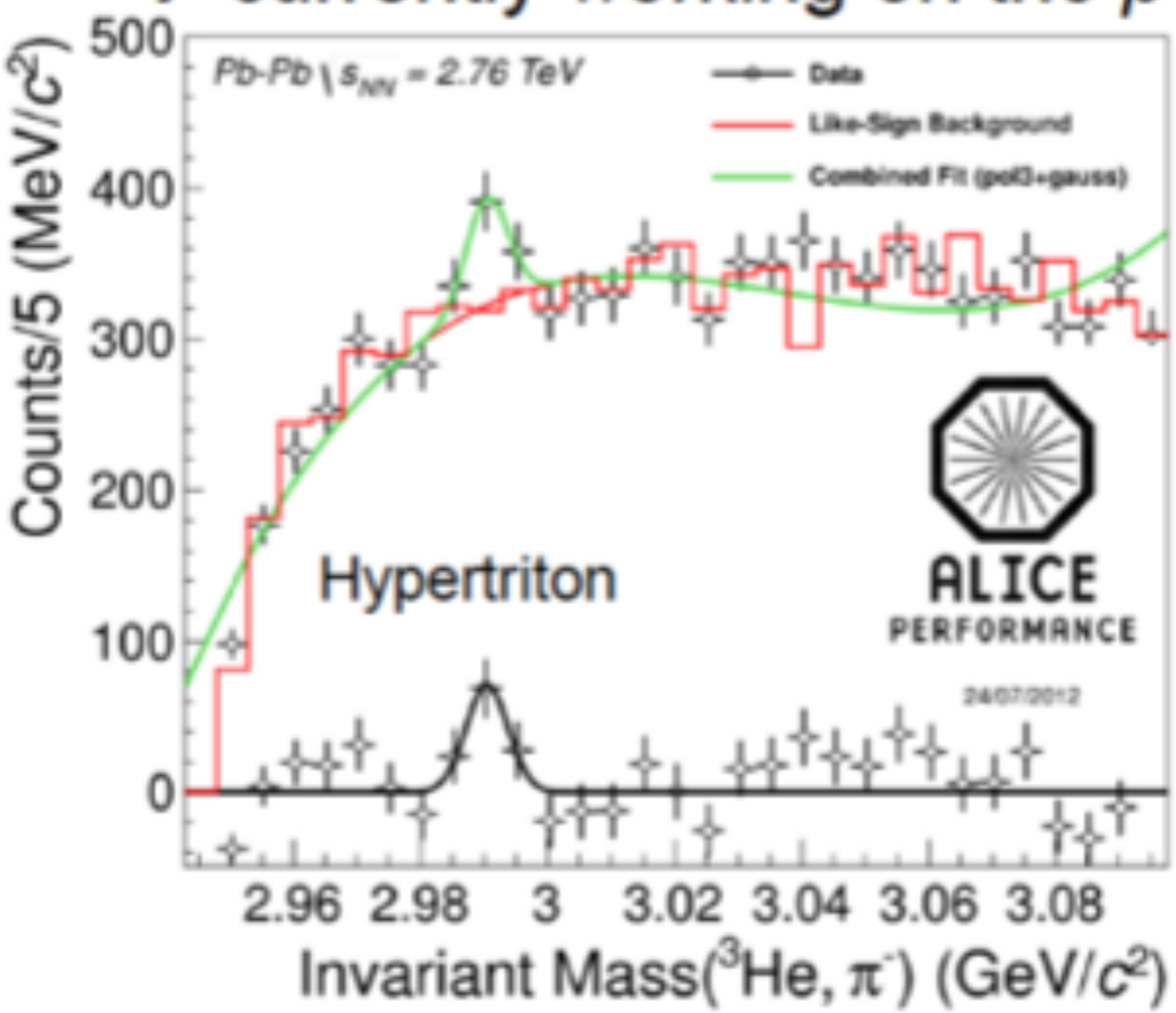
STAR Col. *Science 328 (2010) 58-62*

ALICE's observation for (anti-)hypertriton

Hypertriton

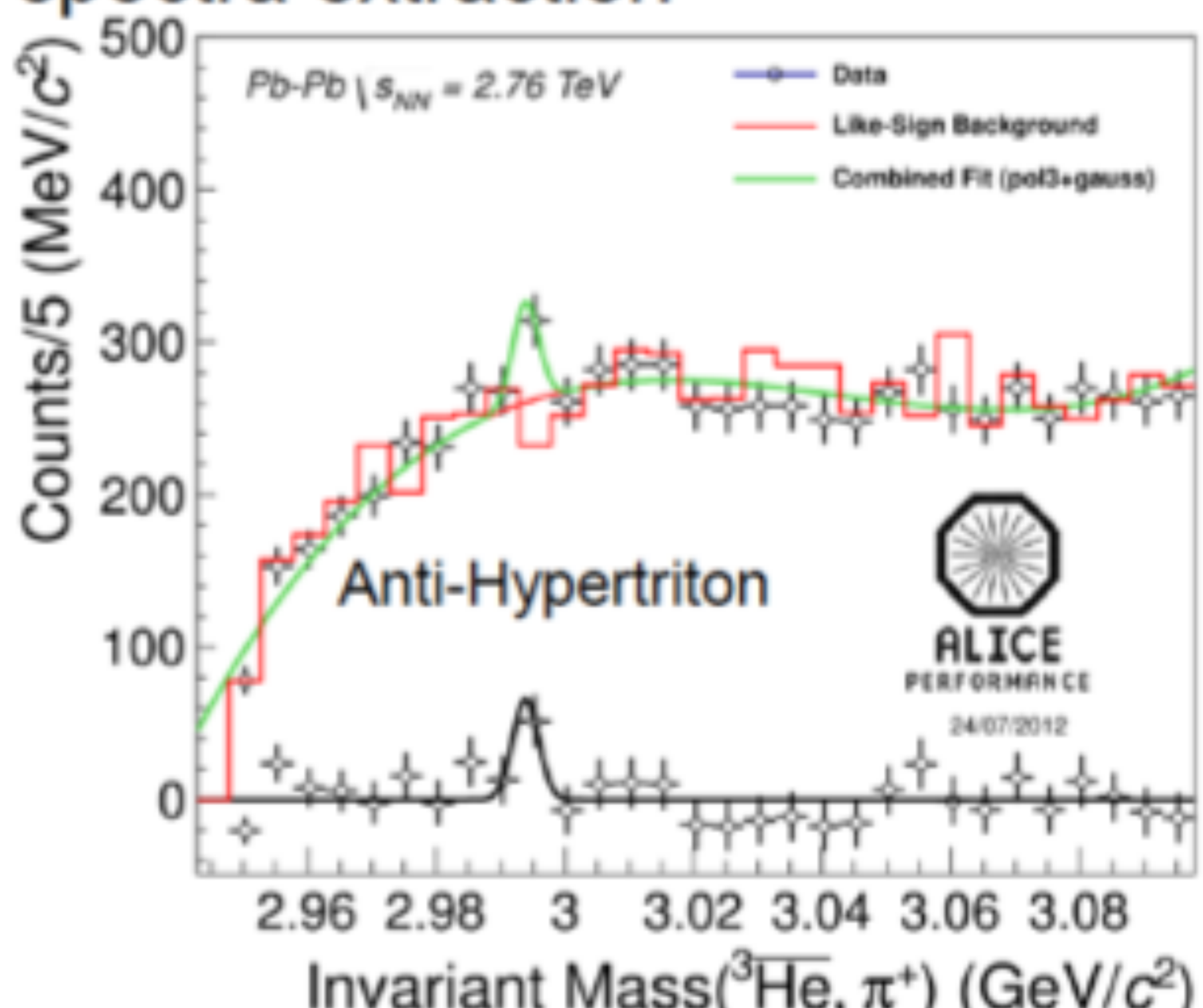
Signal of the hypertriton from the 2011 run

→ currently working on the p_T spectra extraction



$\mu = (2.990 \pm 0.001)$ GeV/c^2

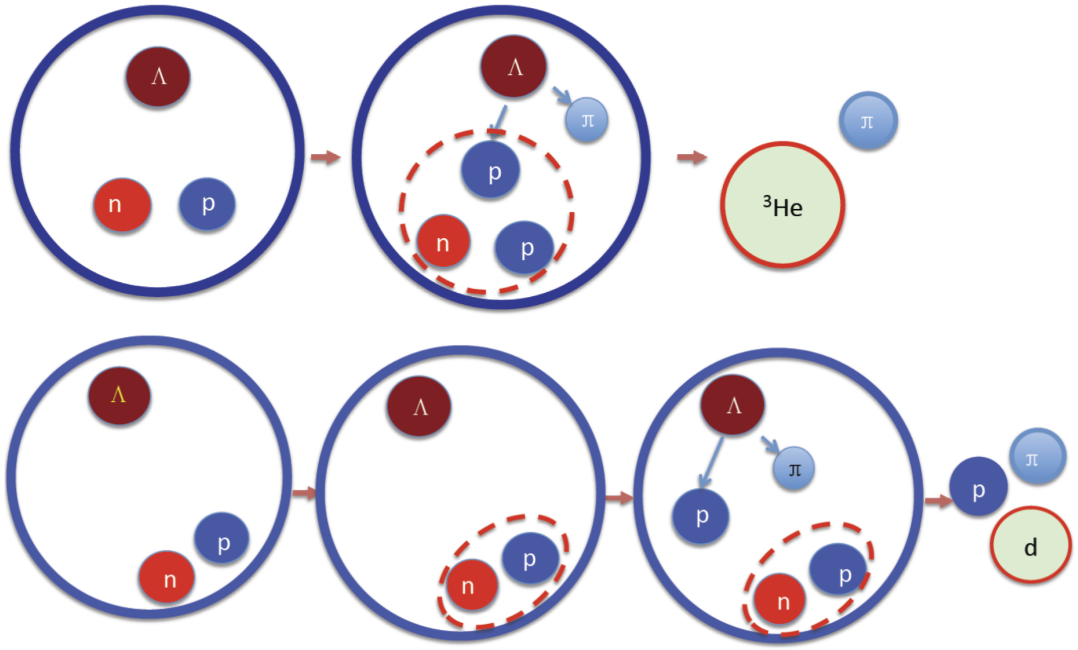
$\sigma = (3.35 \pm 0.7) \times 10^{-3}$ GeV/c^2



$\mu = (2.993 \pm 0.001)$ GeV/c^2

$\sigma = (2.00 \pm 1.2) \times 10^{-3}$ GeV/c^2

lifetime measurement is critical to understand the structure of hypertriton



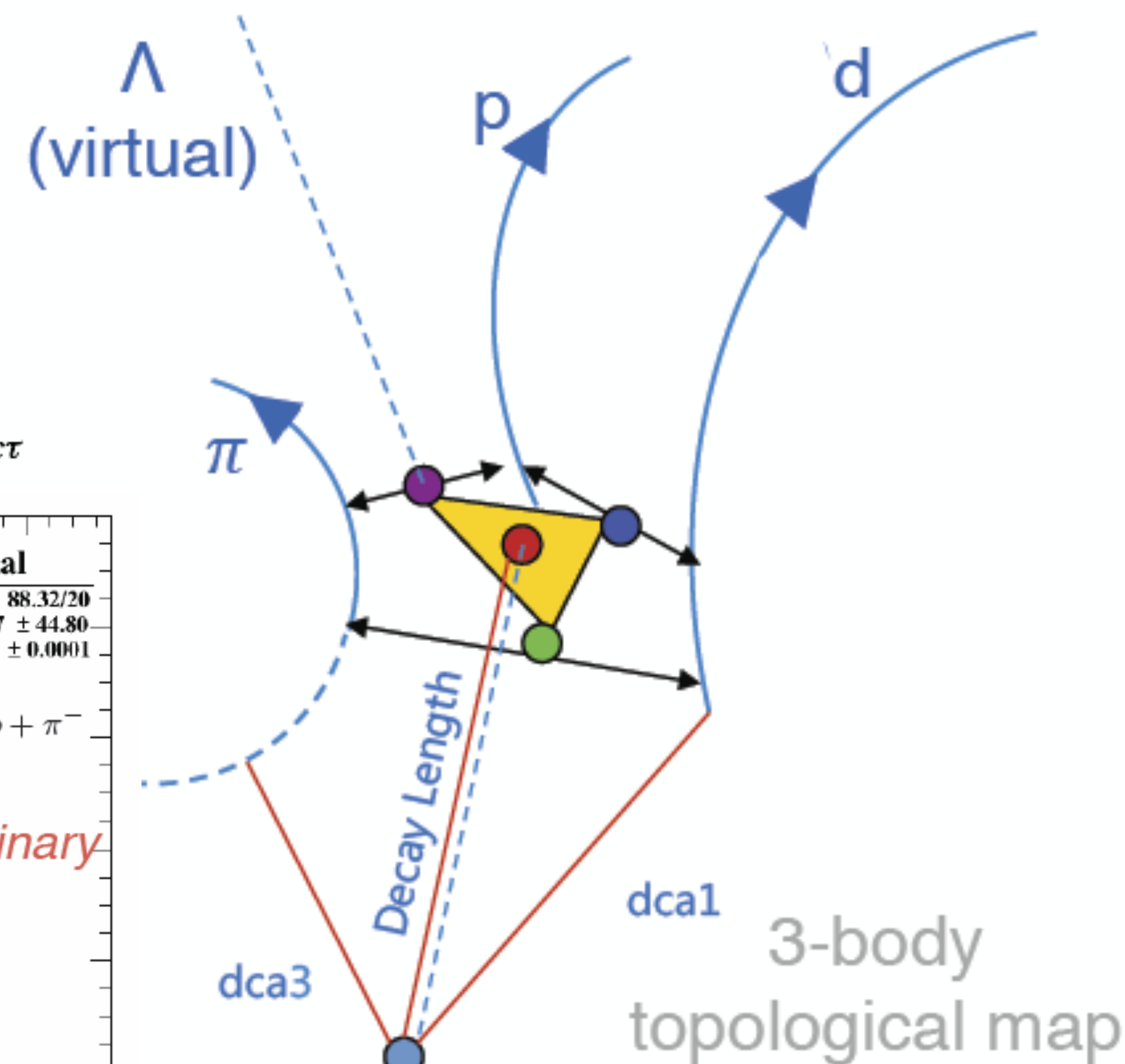
Channel	Theoretical B.R.
$^3He+\pi^-$	24.88%
$d+p+\pi^-$	40.15%

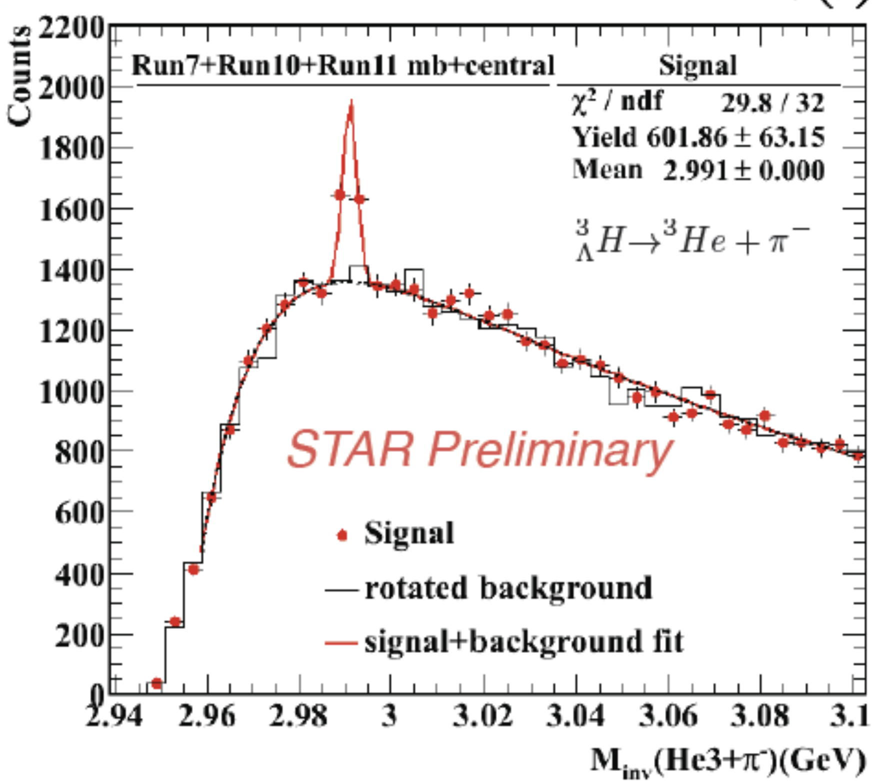
*Physical Review C.57.1595(1998)

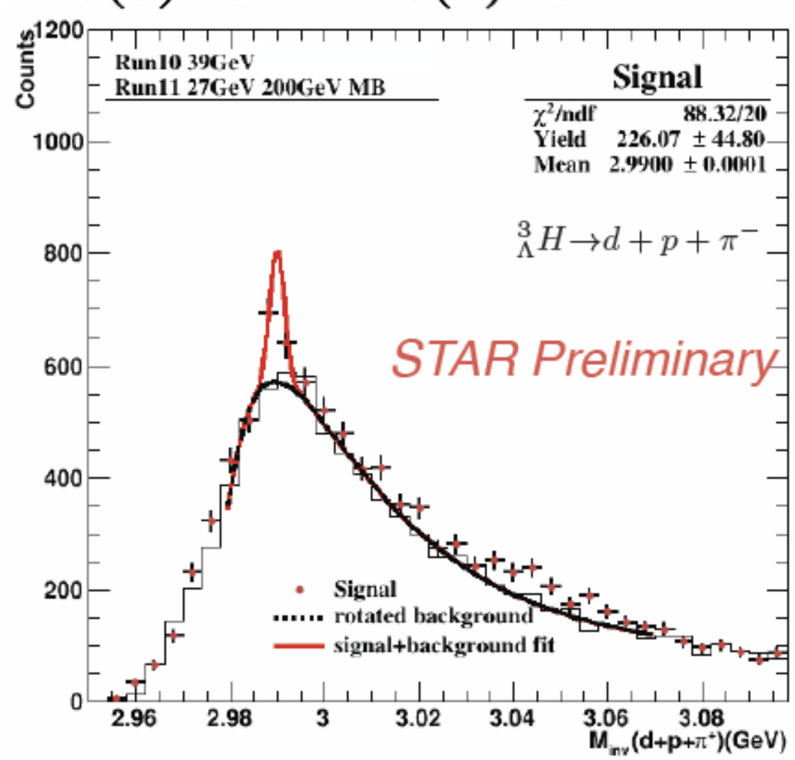
$$^3_\Lambda H \rightarrow {}^3He + \pi^-$$

$$^3_\Lambda H \rightarrow d + p + \pi^-$$

$$N(t) = N(0) \times e^{-t/\tau} = N(0) \times e^{-L/\beta\gamma c\tau}$$

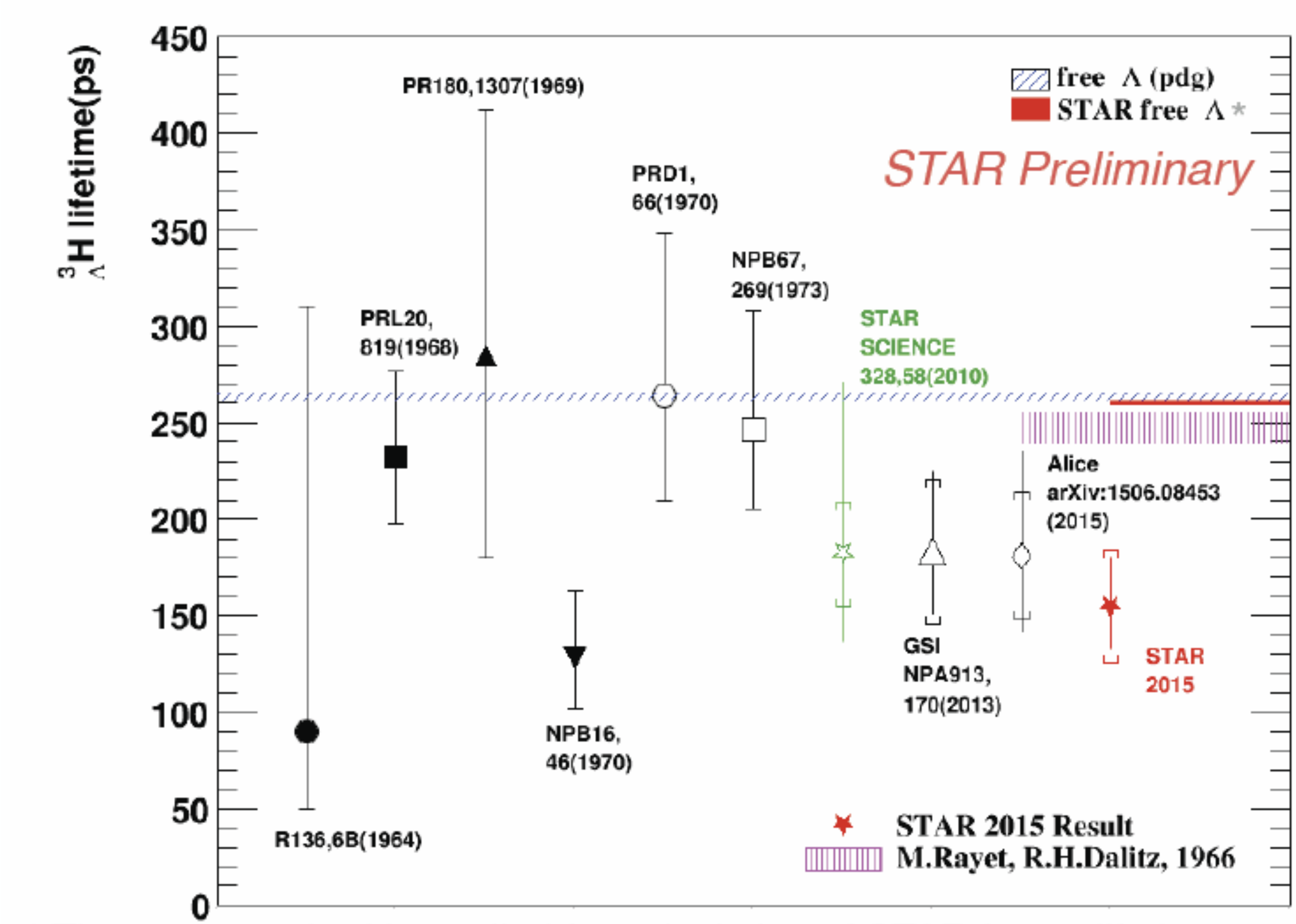






Y. Xu & Y. Zhu (SINAP)

World data for hypertriton lifetime: a puzzle?

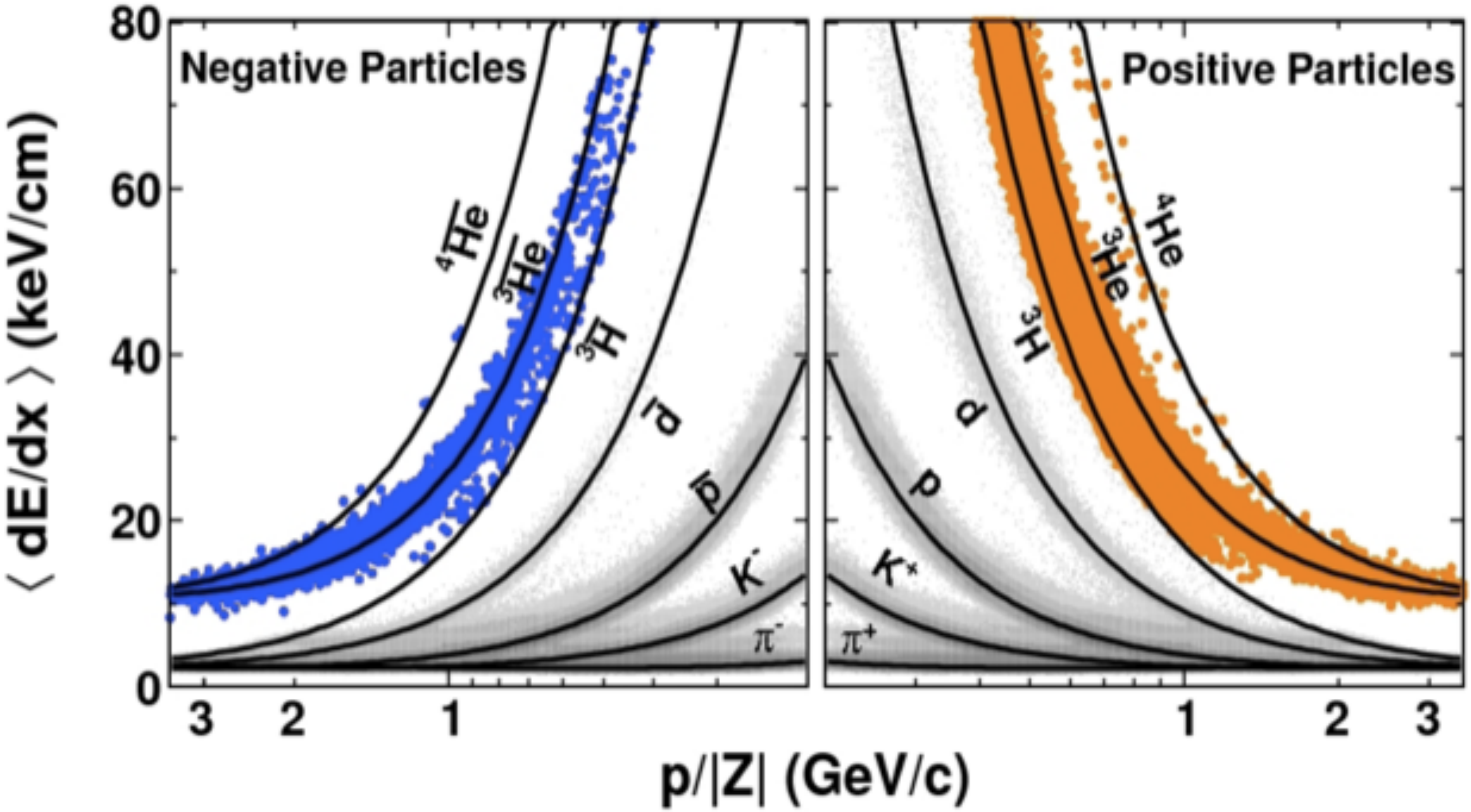


* The same method is applied for calculation of STAR free Λ lifetime.

In future, with more data for antihypertriton, it could be tested for the precise lifetime difference between hypertriton and anti-hypertriton

Y. Xu & Y. Zhu (SINAP)

Observation of the antimatter helium-4 nucleus
STAR Coll.: Nature (2011)



Nature (2011) DOI: doi:10.1038/nature10079 || **STAR Experiment**
Received 14 March 2011 | Accepted 04 April 2011 | Published online 24 April 2011

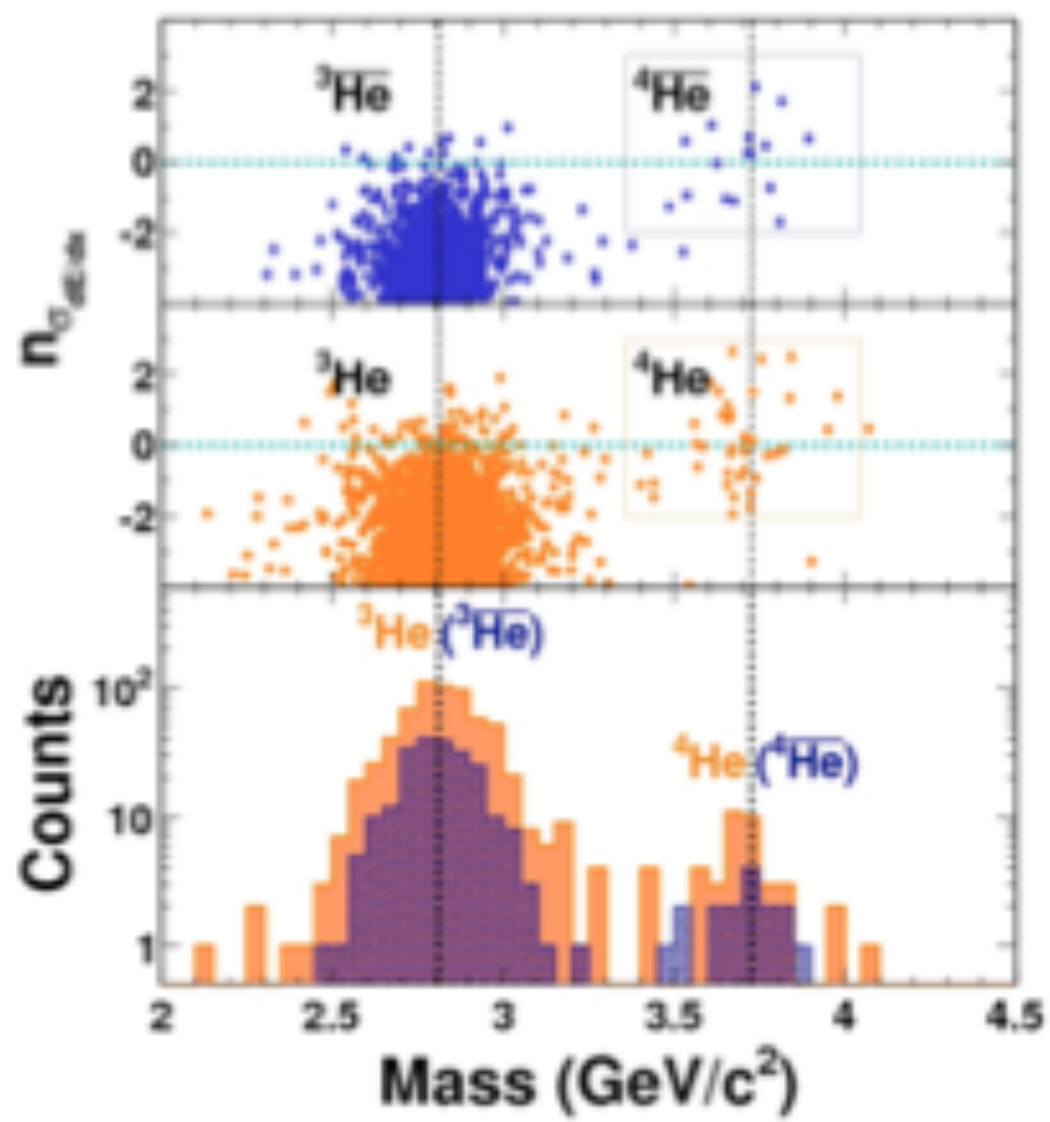
Observation of the anti-helium4

nature

Observation of the antimatter helium-4 nucleus

The STAR Collaboration*

Liang Xue, PhD Thesis of SINAP, 2012



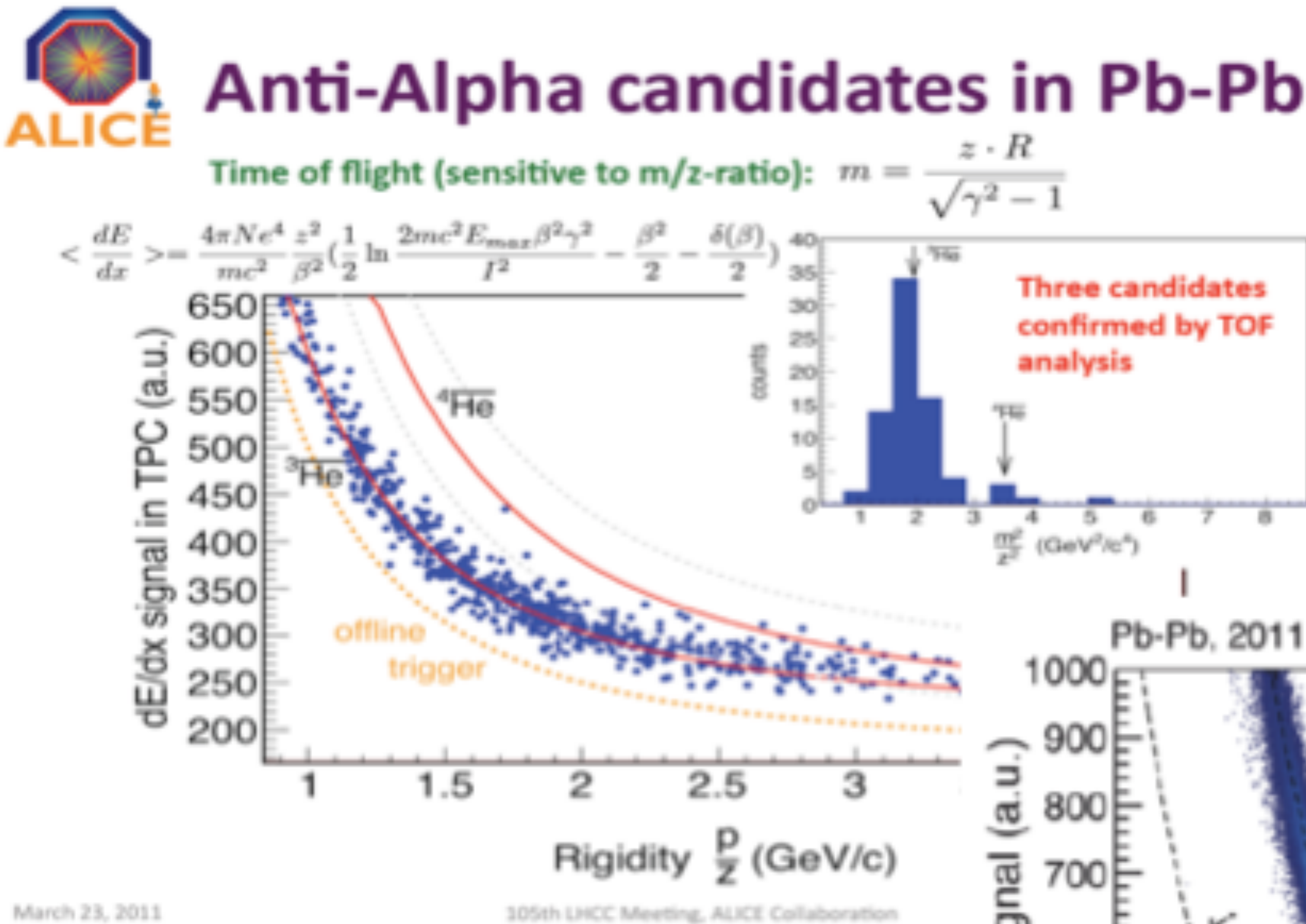
Mass ID with TOF

★ 18 anti-helium4, the heaviest antinucleus ever detected, were identified in STAR data

STAR Col.: *Nature 473 (2011) 353*

30

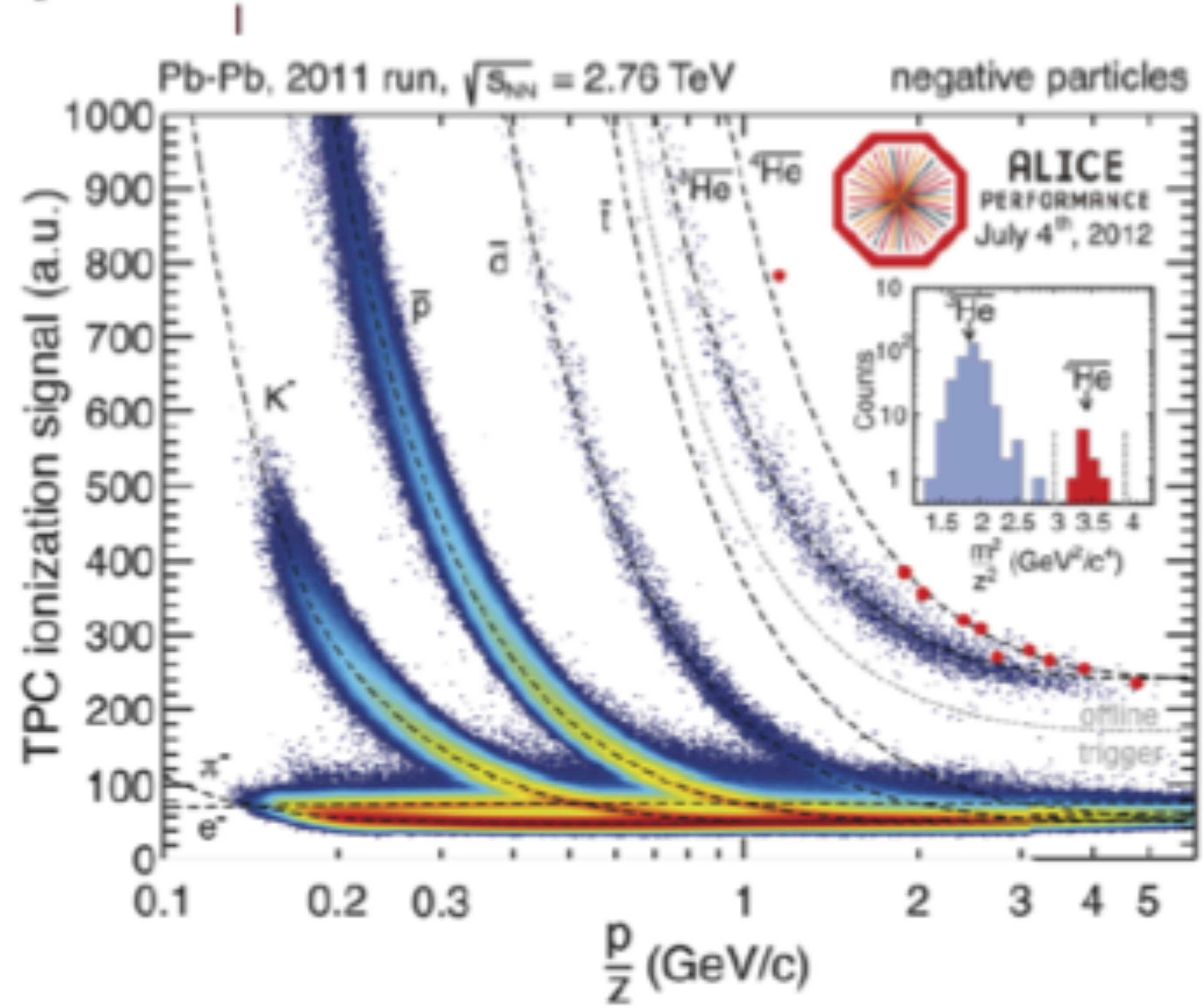
STAR



STAR :
Paper submitted to Nature on March 14th.

Posted on arXiv on March 16th.

Alice :
Candidates presented to public on March 23rd.



Without STAR's High Level Trigger, anti-helium 4 would be eventually observed at RHIC, but LHC would claim the prize for sure.

Special thanks to CAD for providing us high quality beam in run 2010, which makes this discovery possible.

Precision measurement of the mass difference between light nuclei and anti-nuclei by ALICE Collaboration

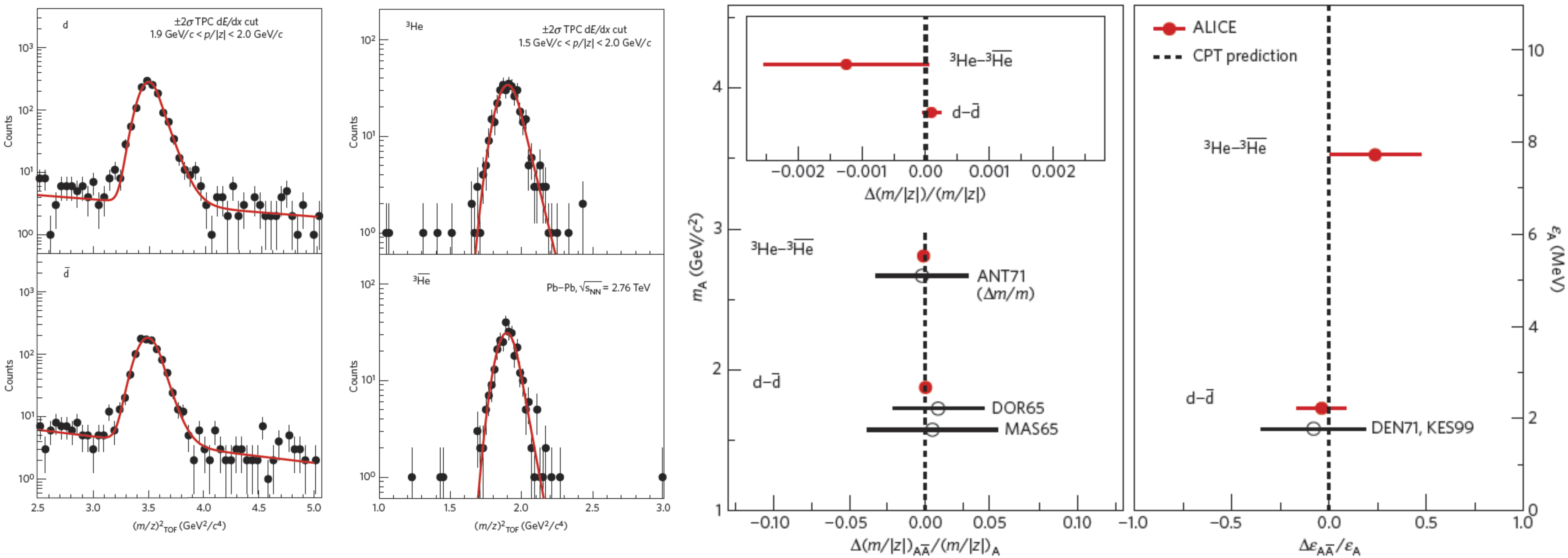
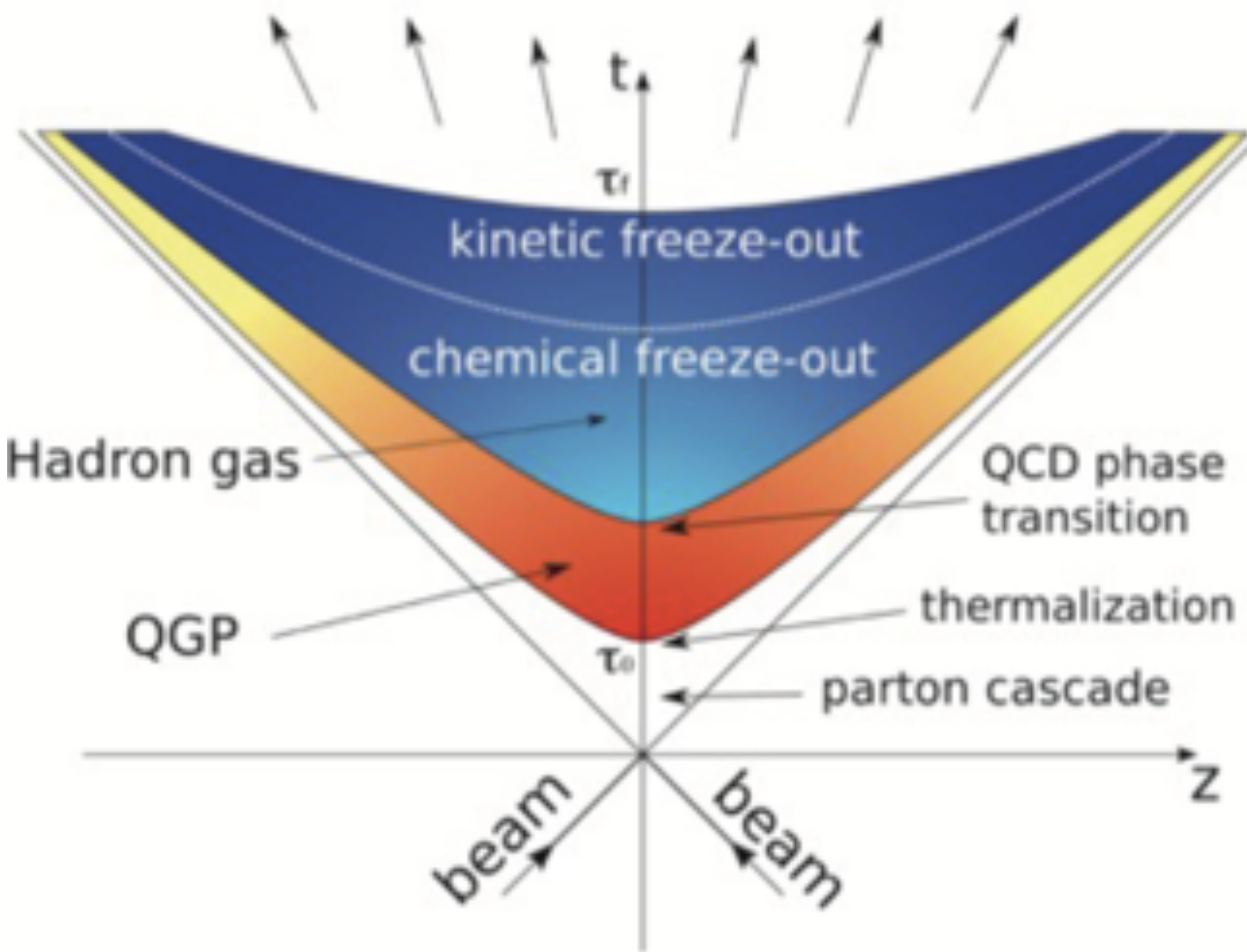


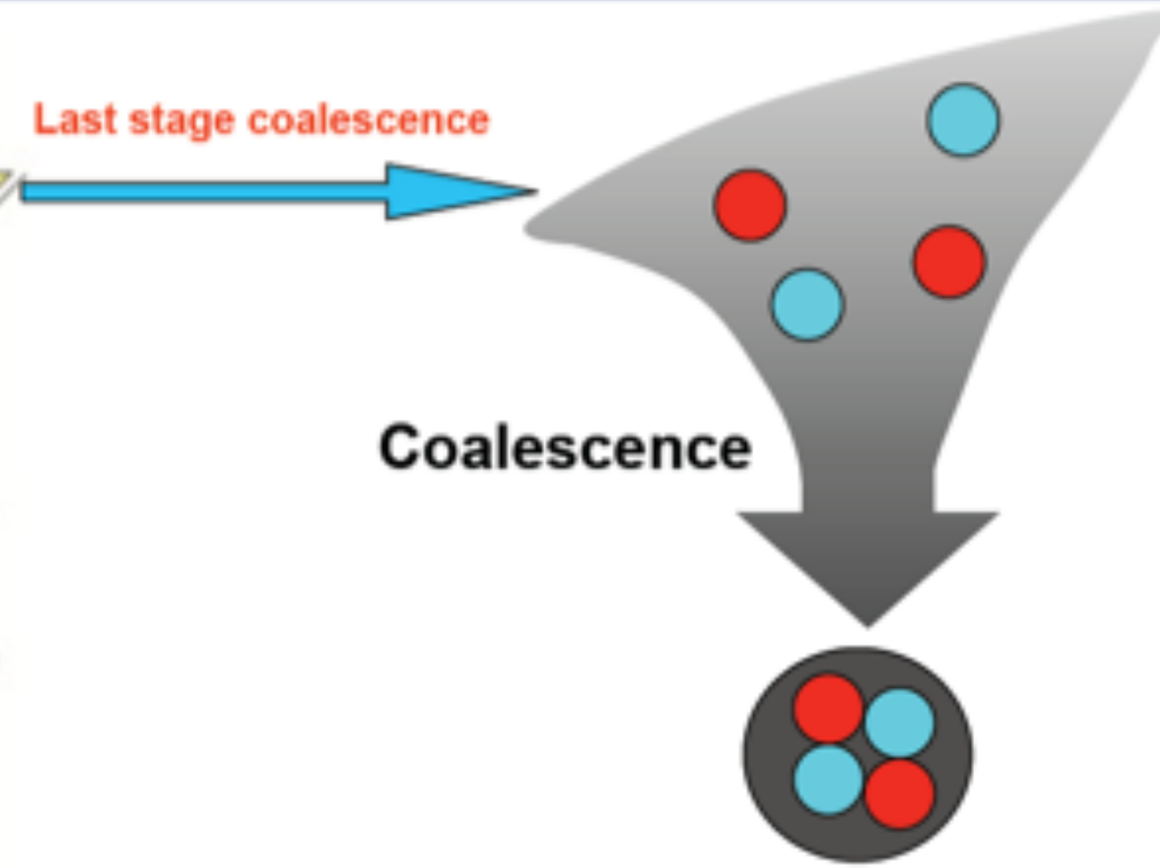
Figure 3 | Measurements of the mass-over-charge ratio and binding energies differences for d–$\bar{\text{d}}$ and ^{3}He–$^3\overline{\text{He}}$. The left panel shows ALICE measurements of the mass-over-charge ratio differences compared with CPT invariance expectation (dotted lines) and existing mass measurements MAS65 (ref. 26), DOR65 (ref. 27) and ANT71 (ref. 28). The inset shows the ALICE results on a finer $\Delta(m/z)/(m/z)$ scale. The right panel shows our determination of the binding energy differences compared with direct measurements from DEN71 (ref. 29) and KES99 (ref. 30). Error bars represent the sum in quadrature of the statistical and systematic uncertainties (standard deviations).

The values are compatible, within uncertainties, with zero and represent a CPT invariance test in systems bound by nuclear forces.

nature physics LETTERS
PUBLISHED ONLINE: 17 AUGUST 2015 | DOI: 10.1038/NPHYS3432

Production mechanism





$$E_A \frac{d^3N_A}{d^3p_A} \propto B_A(E_p \frac{d^3N_p}{d^3p_p})^A$$

The formation of light anti(nuclei), anti (hypernuclei) by coalescence occurred at the last stage of heavy ion collisions, when the system is already reached its kinetic freeze-out temperature.

Sato, H. & Yazaki, K. Phys. Lett. B 98, 153-157 (1981)
Butler, S. T. & Perarson, C. A. Phys. Rev. Lett. 7, 69-71 (1961)
B. I. Abelev et al. (Star Collaboration) arXiv 0909.0566v1

coalescence vs thermal

TABLE I: Particle ratios from Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV/c. The ^3He ($^3\overline{He}$) yield have been corrected for $^3_\Lambda H$ ($^3_{\bar\Lambda}\bar{H}$) feed-down contribution.

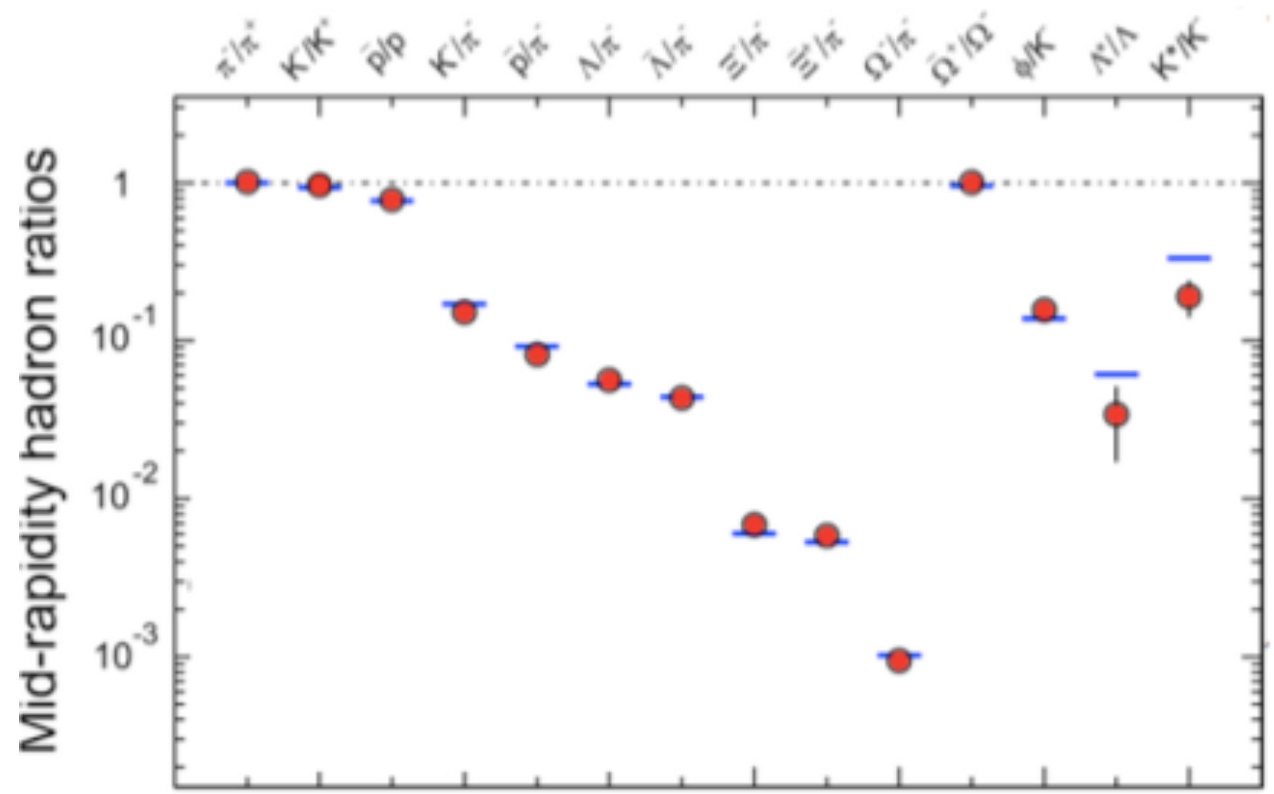
Particle type	Ratio
$^3_{\bar\Lambda}\bar{H}/^3_\Lambda H$	$0.49 \pm 0.18 \pm 0.07$
$^3\overline{He}/^3He$	$0.45 \pm 0.02 \pm 0.04$
$^3_{\bar\Lambda}\bar{H}/^3\overline{He}$	$0.89 \pm 0.28 \pm 0.13$
$^3_\Lambda H/^3He$	$0.82 \pm 0.16 \pm 0.12$

In a coalescence picture:

$$^3_\Lambda\overline{H}/^3_\Lambda H \propto (\bar{p}/p)(\bar{n}/n)(\bar{\Lambda}/\Lambda)$$

$$^3\overline{He}/^3He \propto (\bar{p}/p)^2(\bar{n}/n)$$

0.45 ~ $(0.77)^3$



200 GeV ^{197}Au + ^{197}Au central collision
STAR whitepaper, NPA757(2005)

$$N_i = V g_i \int \frac{d^3p}{(2\pi)^3} \exp\left(-\frac{E_i}{T} + \frac{\mu_i}{T}\right)$$

Relativistic Heavy Ion collisions :

High antibaryon density

High temperature

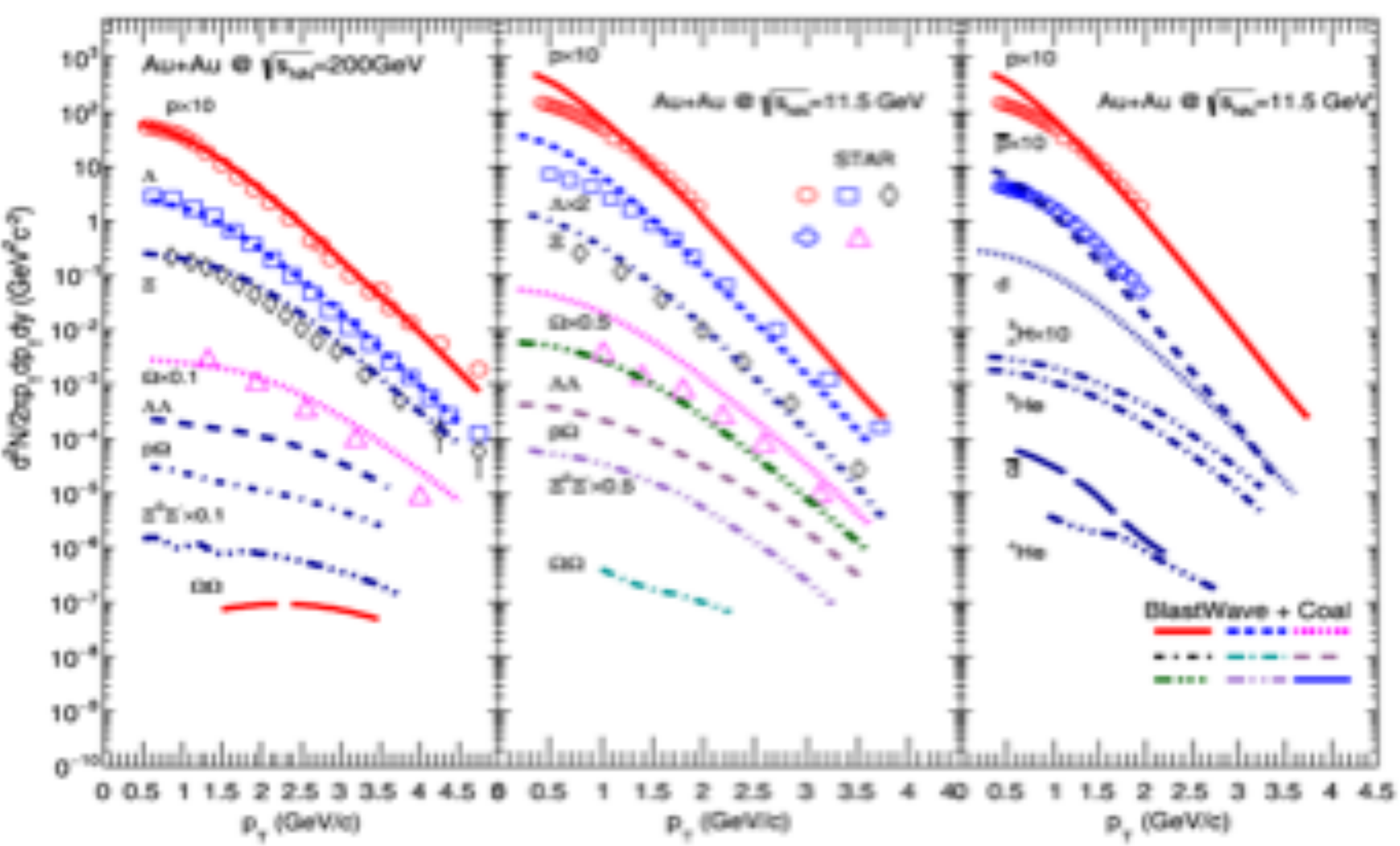
Favorable environment for both production mechanisms.

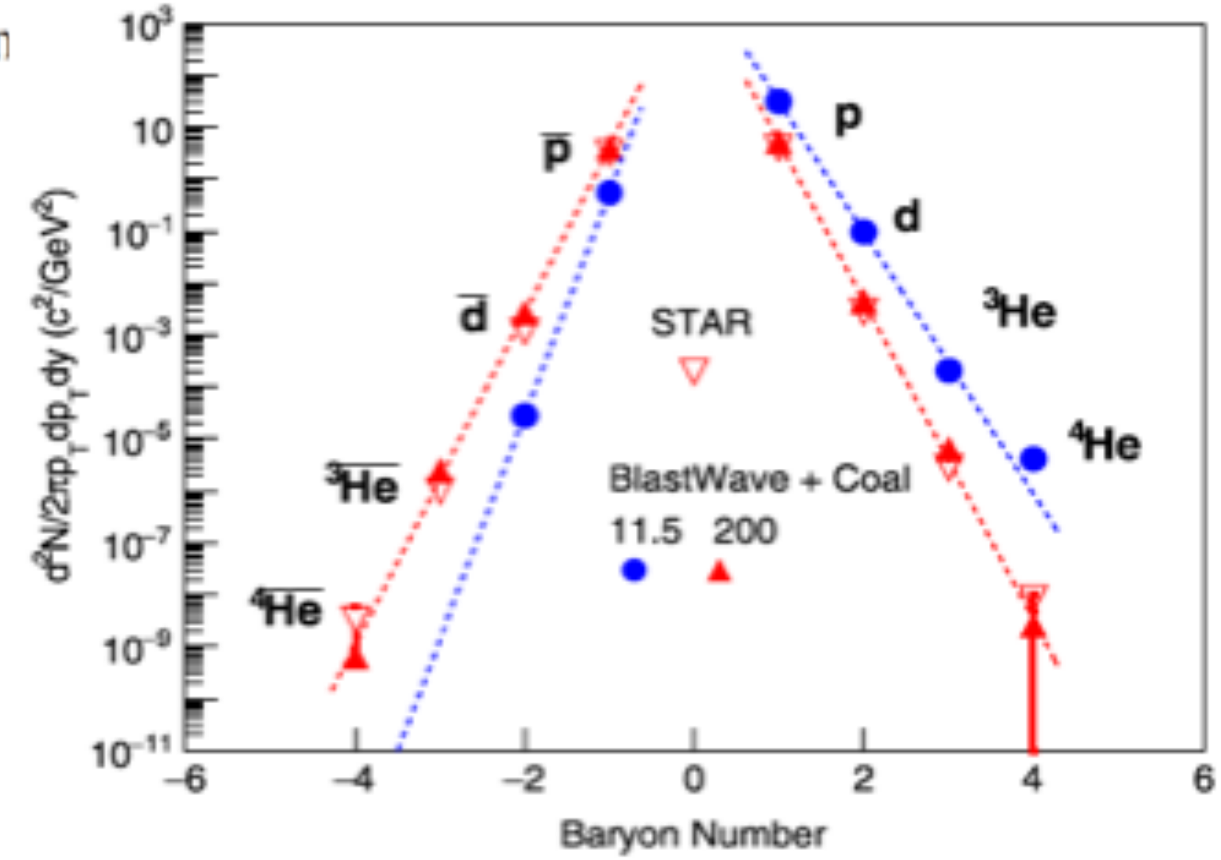
Antimatter asymmetry at low energy

Production of multistrange hadrons, light nuclei and hypertriton in central Au+Au collisions at $\sqrt{s_{NN}} = 11.5$ and 200 GeV

N. Shah*, Y.G. Ma, J.H. Chen, S. Zhang   Physics Letters B 754 (2016) 6–10

Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China



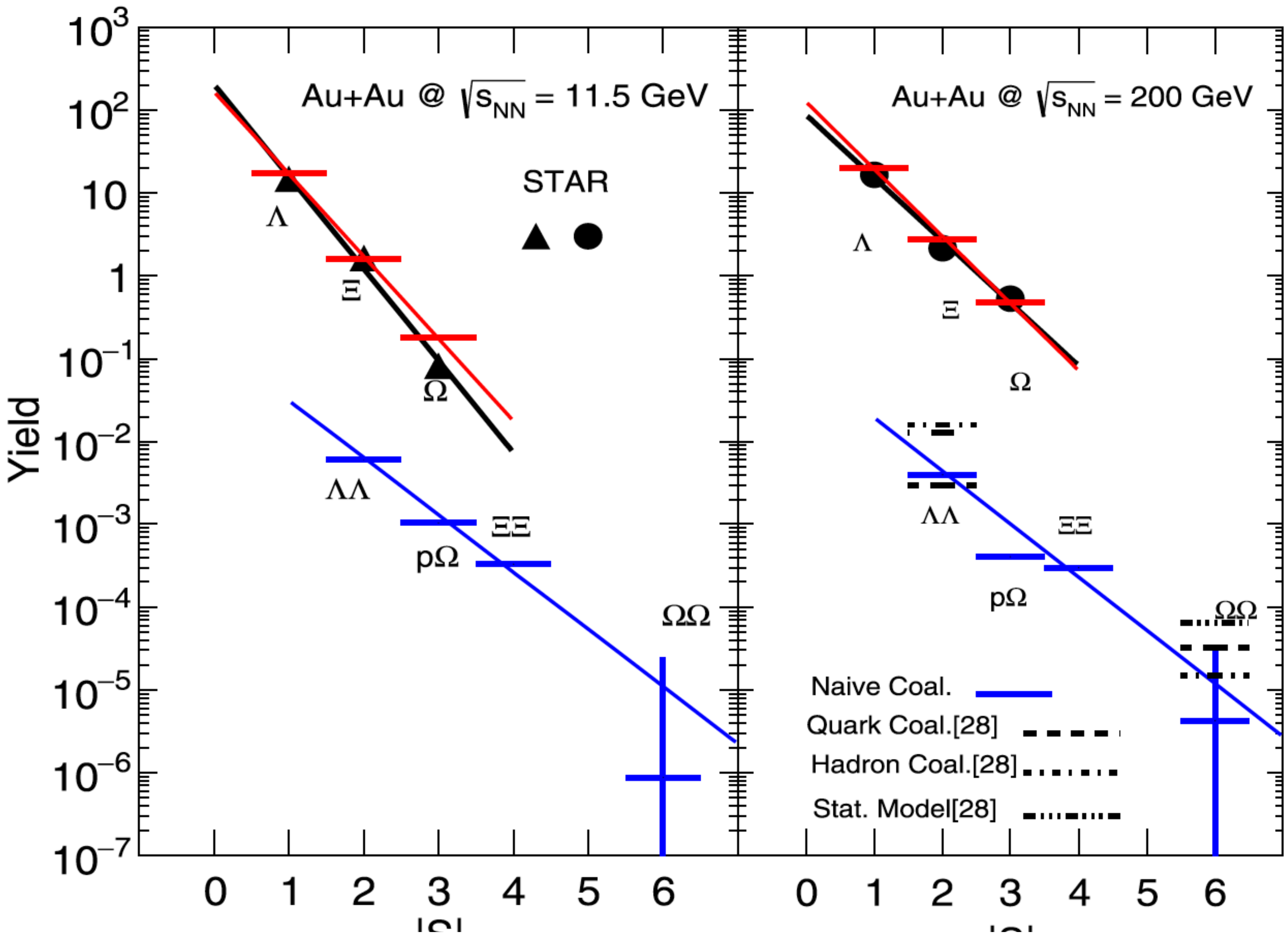


Obtained fit values for reduction factor are 1.2×10^3 (1.5×10^3) and 0.33×10^3 (1.95×10^4) for adding one more nucleon (antinucleon) to the system for $\sqrt{sNN}$=200 and11.5GeV respectively.

The difference in reduction factor between matter and antimatter shows a significant energy (temperature) dependence.

In hydrodynamic blast-wave model +coalescence model:
L. Xue, YGM et al., PRC 85,064912 (2013);
N. Saha, YGM et al., PLB 754, 6 (2016)

Exotic particle yield vs strangeness



The *pT* integrated yield of multistrange hadrons falls exponentially as strangeness quantum number increases.

Experimental data for LL & pOmega, see Jinhui Chen's talk this afternoon.

Table 1
p_T integrated yields of light nuclei, hypertriton and dibaryons in Au+Au collisions.

$\sqrt{s_{NN}}$ (GeV)	$dN_{^3\text{He}}/dy$	$dN_{^3_\Lambda\text{H}}/dy$	$dN_{^4\text{He}}/dy$	$dN_{\Lambda\Lambda}/dy$	$dN_{p\Omega}/dy$	$dN_{\Xi^0\Xi^-}/dy$	$dN_{\Omega\Omega}/dy$
11.5	1.06×10^{-2}	2.04×10^{-3}	3.63×10^{-5}	2.46×10^{-2}	2.12×10^{-3}	6.68×10^{-4}	1.63×10^{-6}
200	1.65×10^{-4}	1.05×10^{-4}	3.30×10^{-7}	7.24×10^{-3}	4.24×10^{-4}	2.75×10^{-4}	3.25×10^{-6}

Questions?

Even though we can explain the production rates of matter and matter using naïve coalescence model or thermal model,

Why the antinucleons can be bound to form an antinucleus?

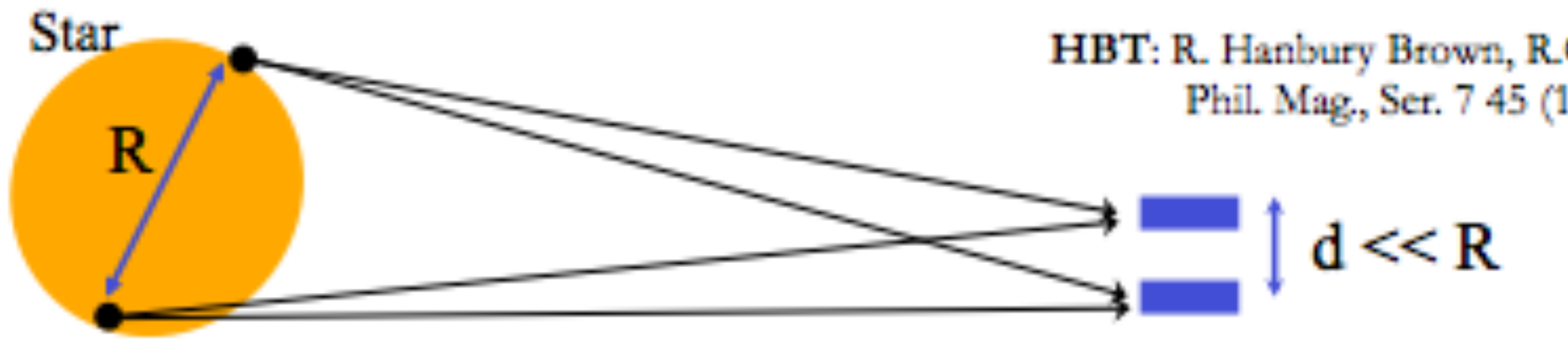
What is the interaction force between antinucleon-antinucleon?

Is there any difference from nucleon-nucleon interaction?

An intensity interferometry method provides a way to explore pp (pbar-pbar) interaction

Intensity interferometry: from large scales ...

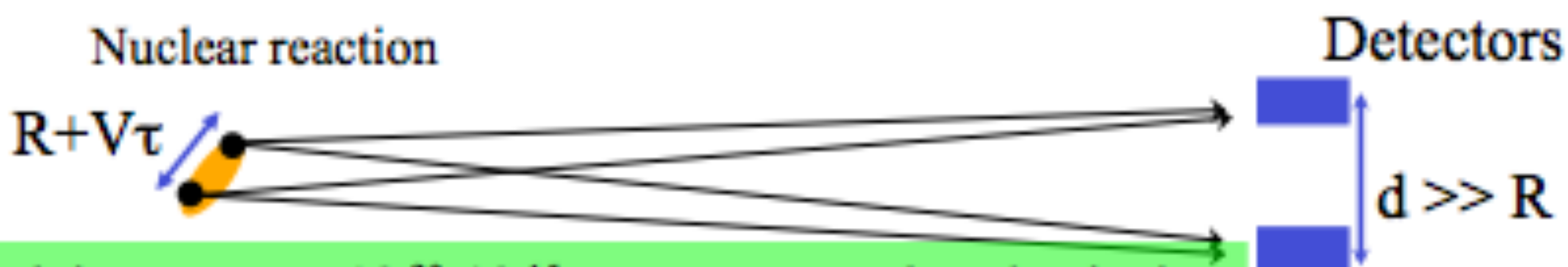
HBT: R. Hanbury Brown, R.Q. Twiss, Phil. Mag., Ser. 7 45 (1954) 663



Static systems: exploring the geometry (size, R)

... to subatomic physic scales
(π–π, K-K, γ–γ, p-p, n-n, IMF-IMF, ...)

G. Goldhaber et al., PR 120 (1960) 300

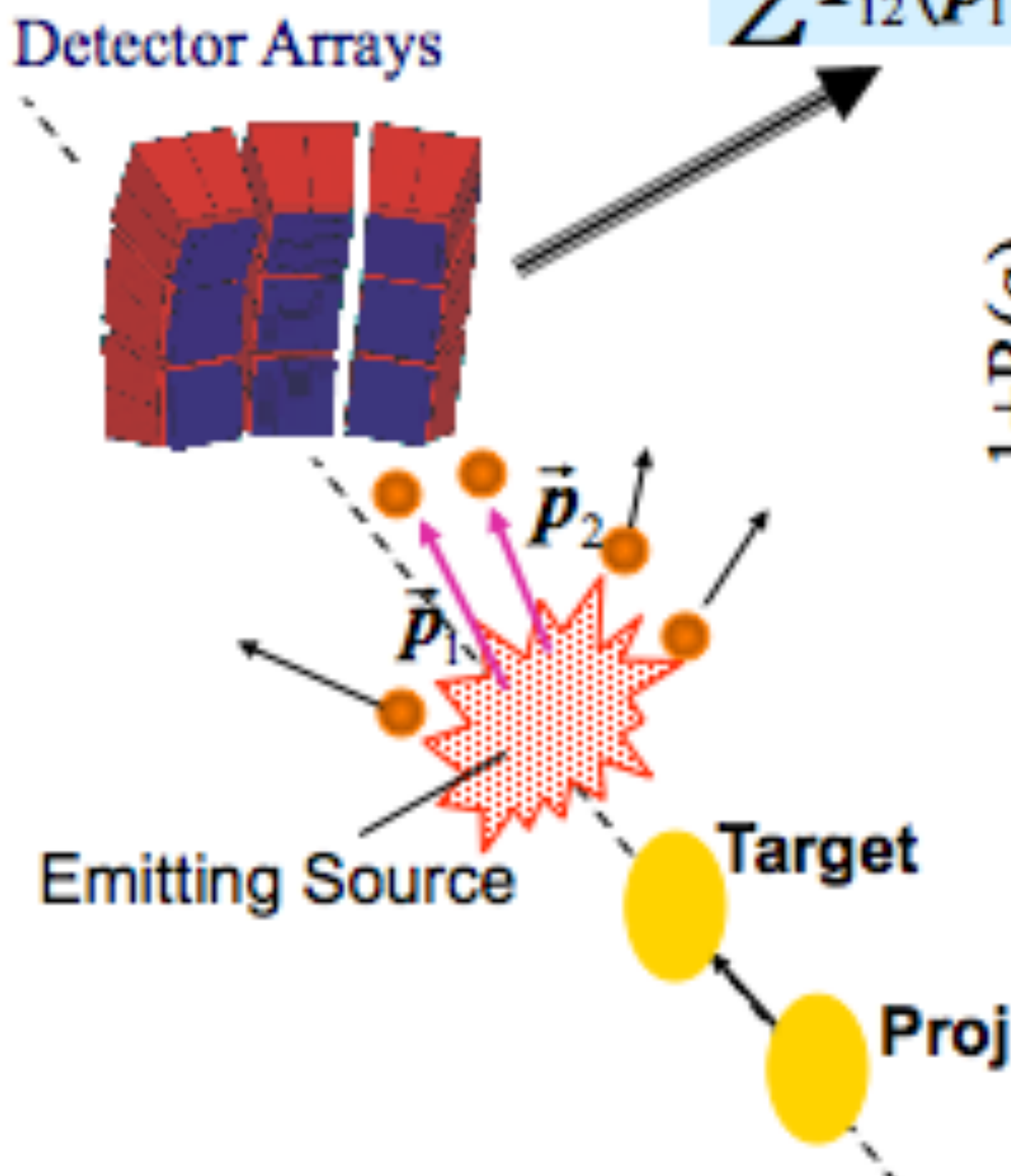


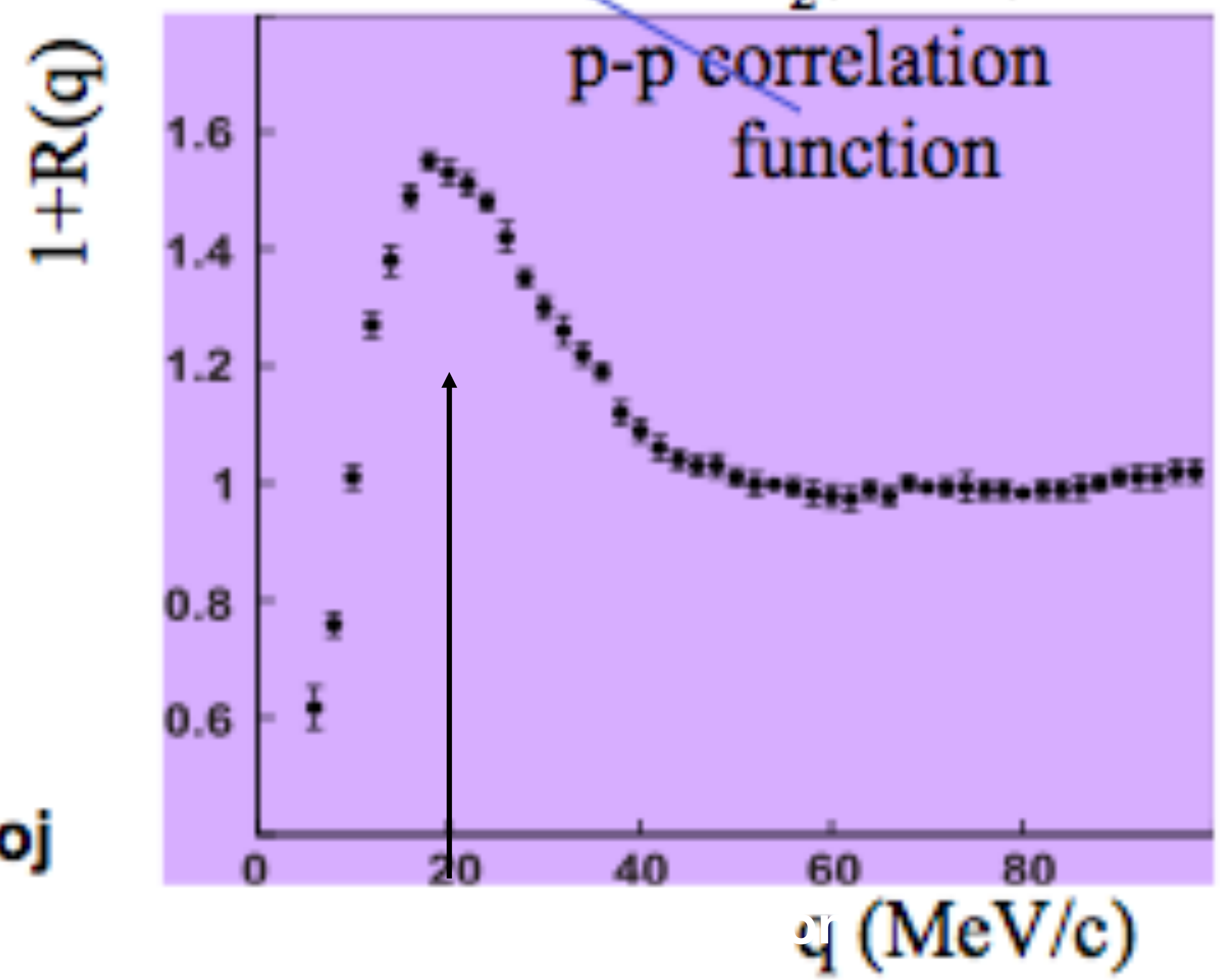
Fast evolving systems: 10^{-23}-10^{-15} sec: geometry changing in time

Two-Proton correlation functions

$$\sum Y_{12}(\vec{p}_1,\vec{p}_2) = [1+R(q)]\cdot \sum Y_1(\vec{p}_1)\cdot Y_2(\vec{p}_2)$$

$$q = \frac{1}{2}\left|\vec{p}_1 - \vec{p}_2\right|$$





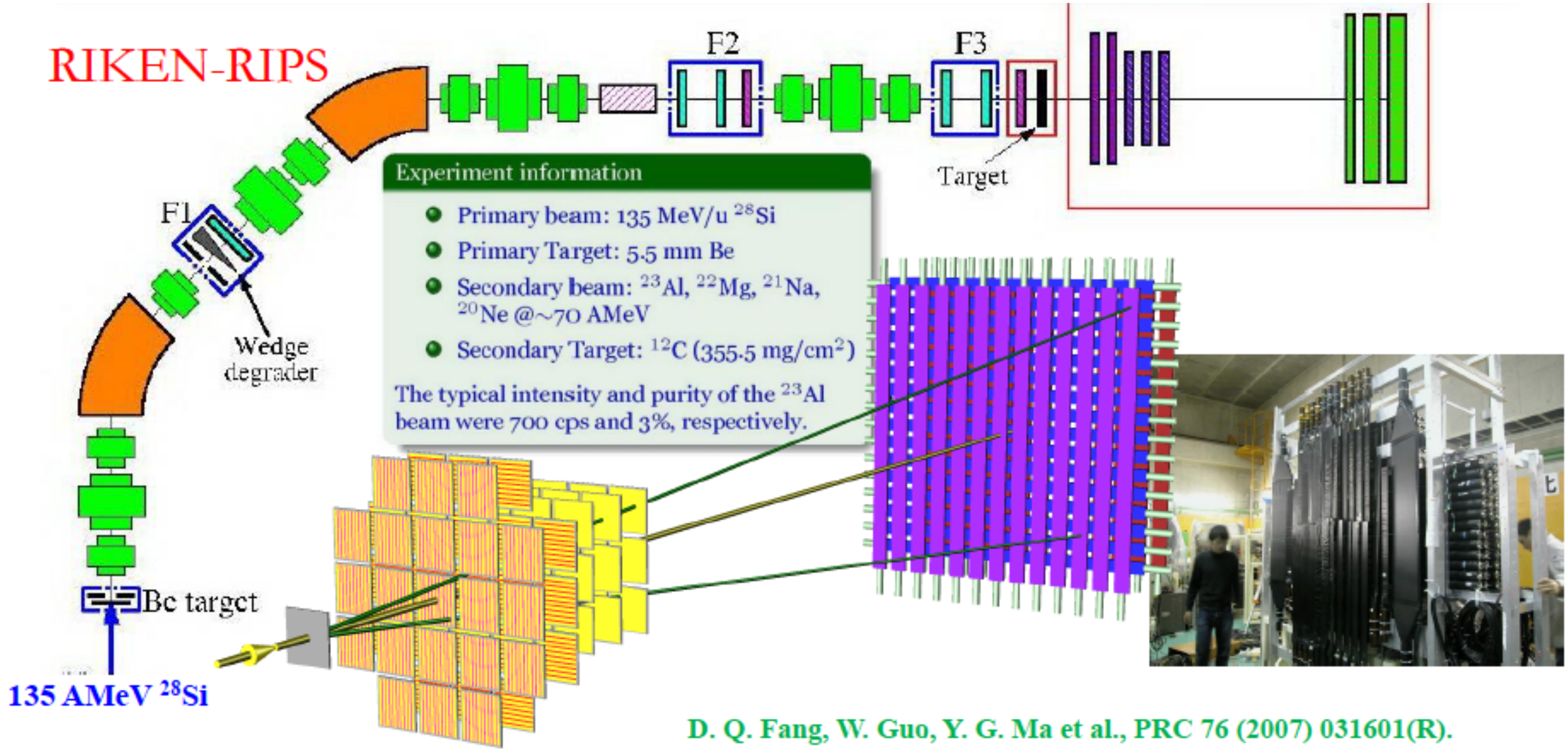
R(q) sensitive to the space-time properties of emitting sources -for pp

Many works have been done at low-E HIC. eg. B. Lynch, Pochldzalla, C. Gelbke, Pratt et al.

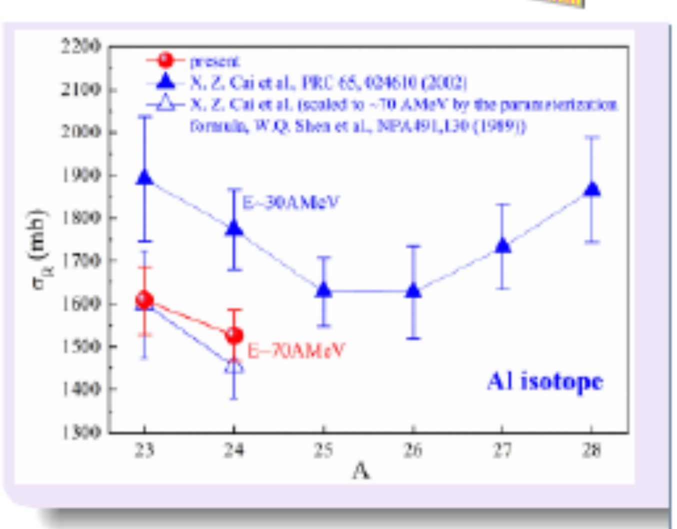
However, there is no any antiproton-antiproton measurement so far.

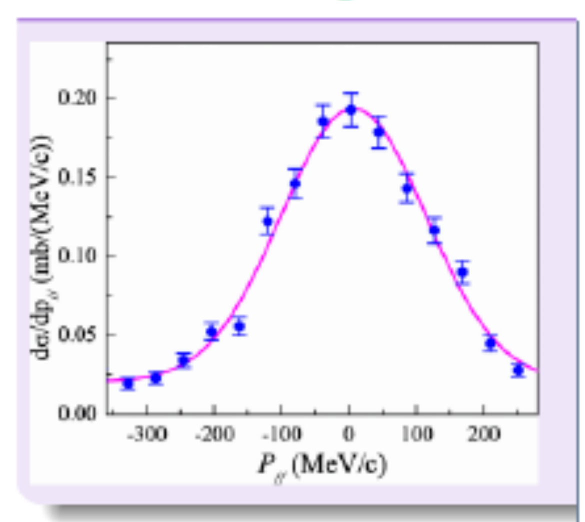
If so , antiproton interaction parameter could be extracted.

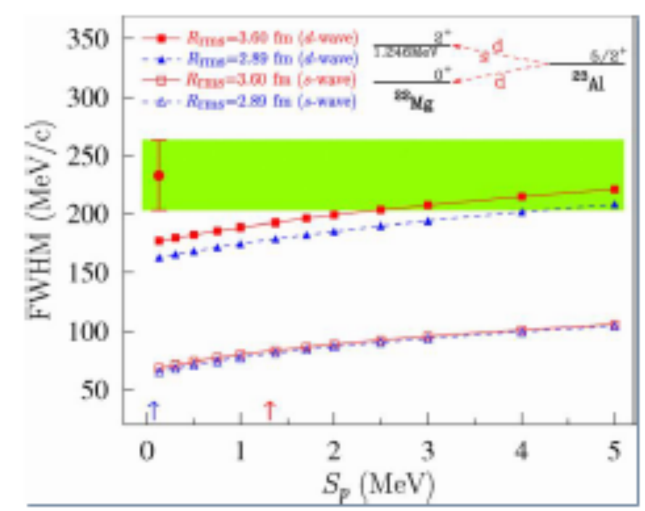
An example: p-p correlation measurement in low energy HIC



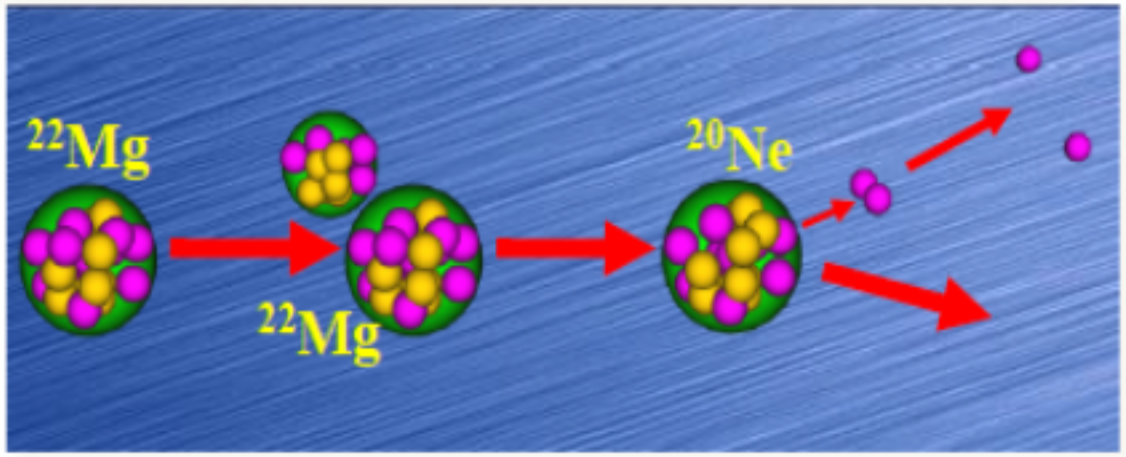
D. Q. Fang, W. Guo, Y. G. Ma et al., PRC 76 (2007) 031601(R).





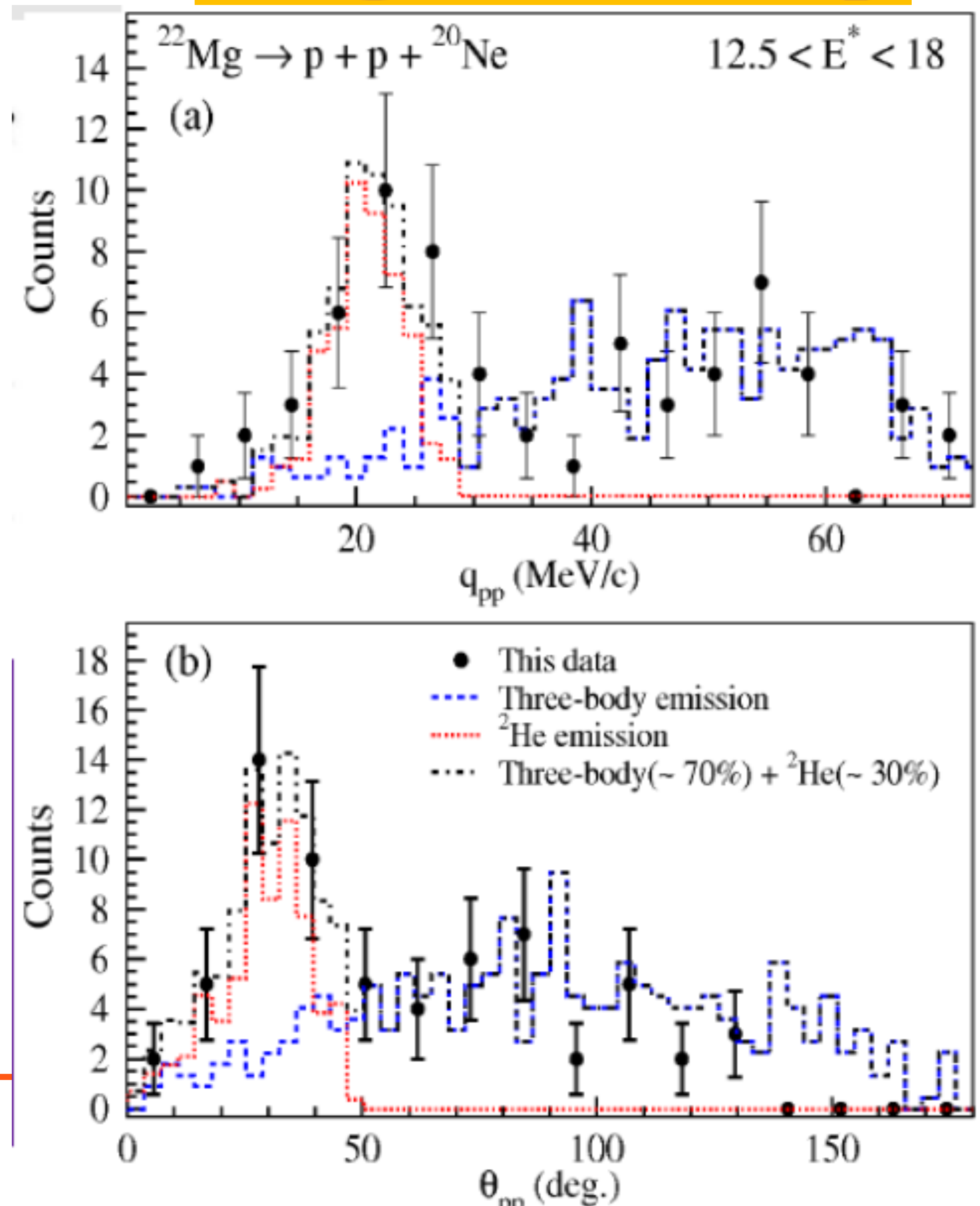


Our p-p correlation measurement for 22Mg



Q_pp~20MeV/c & theta_pp ~ 30deg, indicating a strong 2p emission component for 22Mg

$^{22}Mg \rightarrow {}^{20}Ne + 2p$



Physics Letters B 743 (2015) 306–309

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Different mechanism of two-proton emission from proton-rich nuclei ^{23}Al and ^{22}Mg

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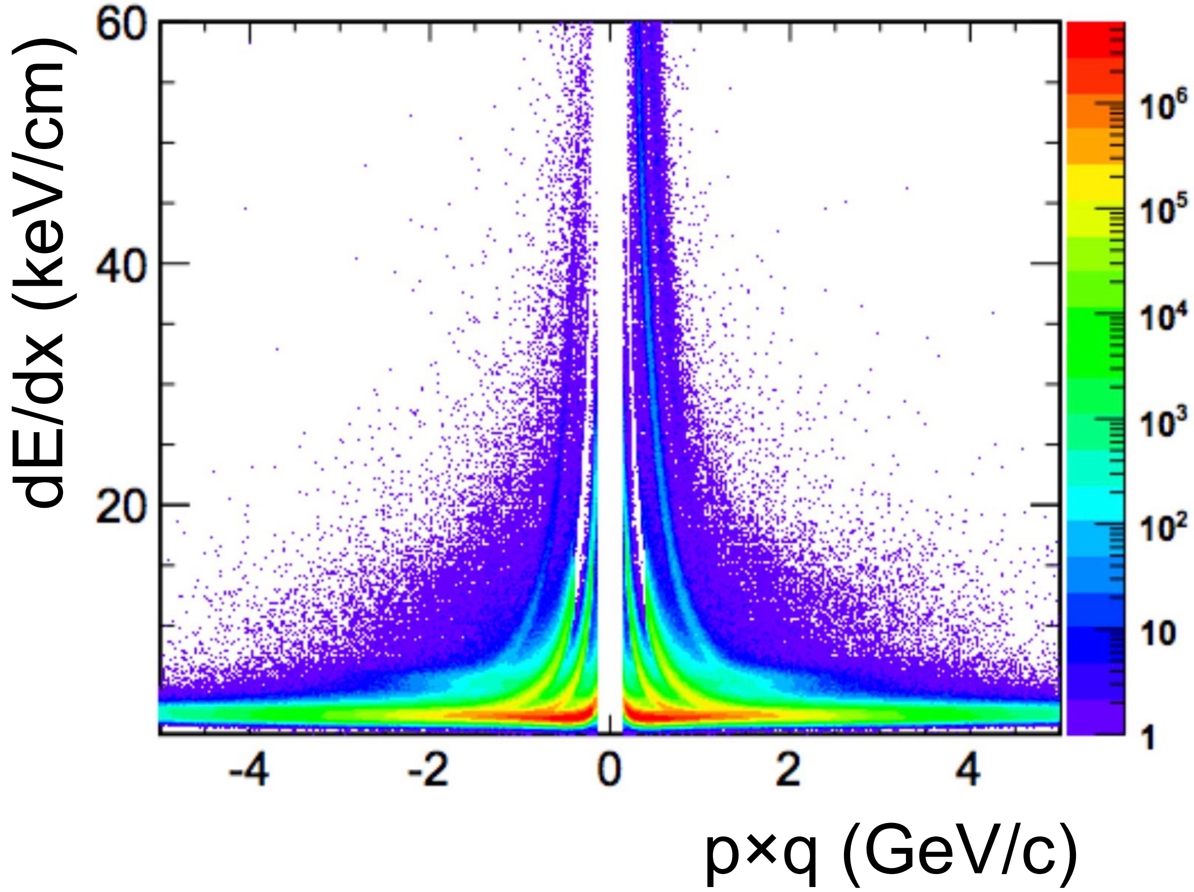
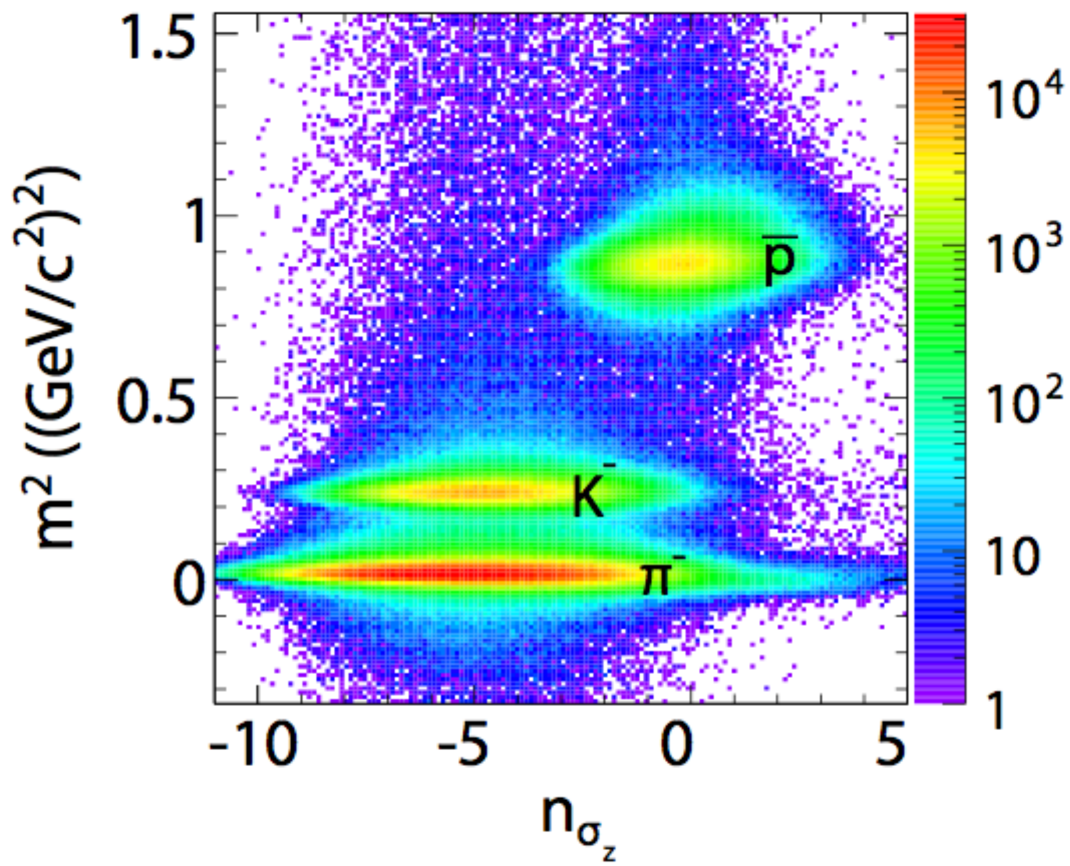
Particle Identification

TPC (Time Projection Chamber)



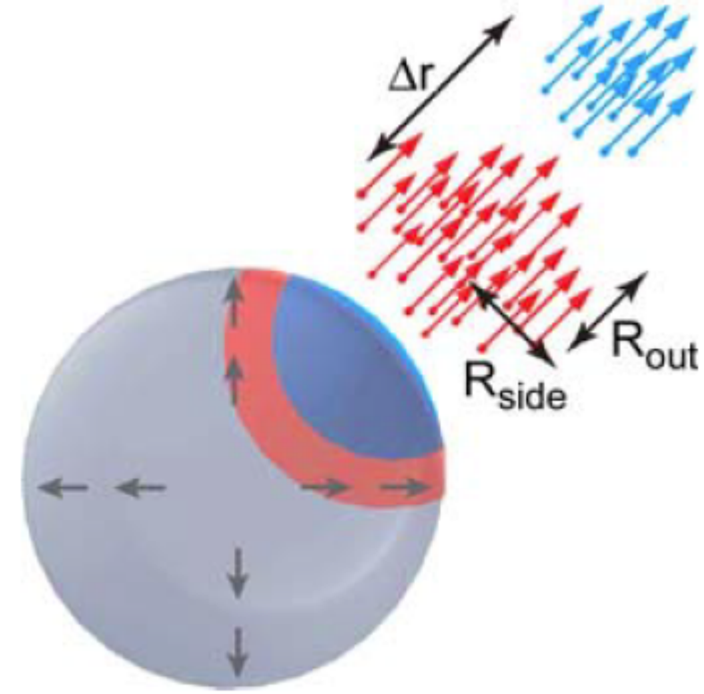
TOF



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 events

k* - half of relative momentum between two particles

Residual correlation

Inside our (anti)proton sample, there are secondary (anti)protons that are indistinguishable from primordial ones. Taking the case for proton as an example, two main weak decay channels give the most contribution :

$\Lambda \rightarrow p + \pi^-$ ~26%

$\Sigma^+ \rightarrow p + \pi^0$ ~5%

As the Lambda decay contribute the most secondary (anti)protons, in our analysis we only consider the contribution from Lambda decay.

Formula to fit our data

In this case, once we got the correlation function, 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

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

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

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}.

Antiproton-antiproton Correlation Function

The theoretical correlation function can be obtained with: **Lednický and Lyuboshitz analytical model**

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

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

and the equal-time ($t^* = 0$) reduced Bethe–Salpeter amplitude is:

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

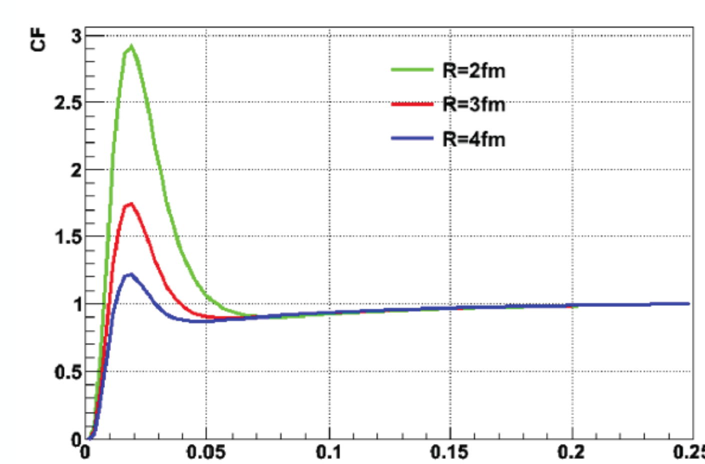
$$f_c(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_c}h(k^* a_c) - ik^* A_c(k*)]^{-1}$$

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.

proton-proton CFs from Ledniky formula



STAR

f_0 & 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,

The scattering length is a measurement of how particles deviate as they travel from source to destination

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

Here k is the wave number.

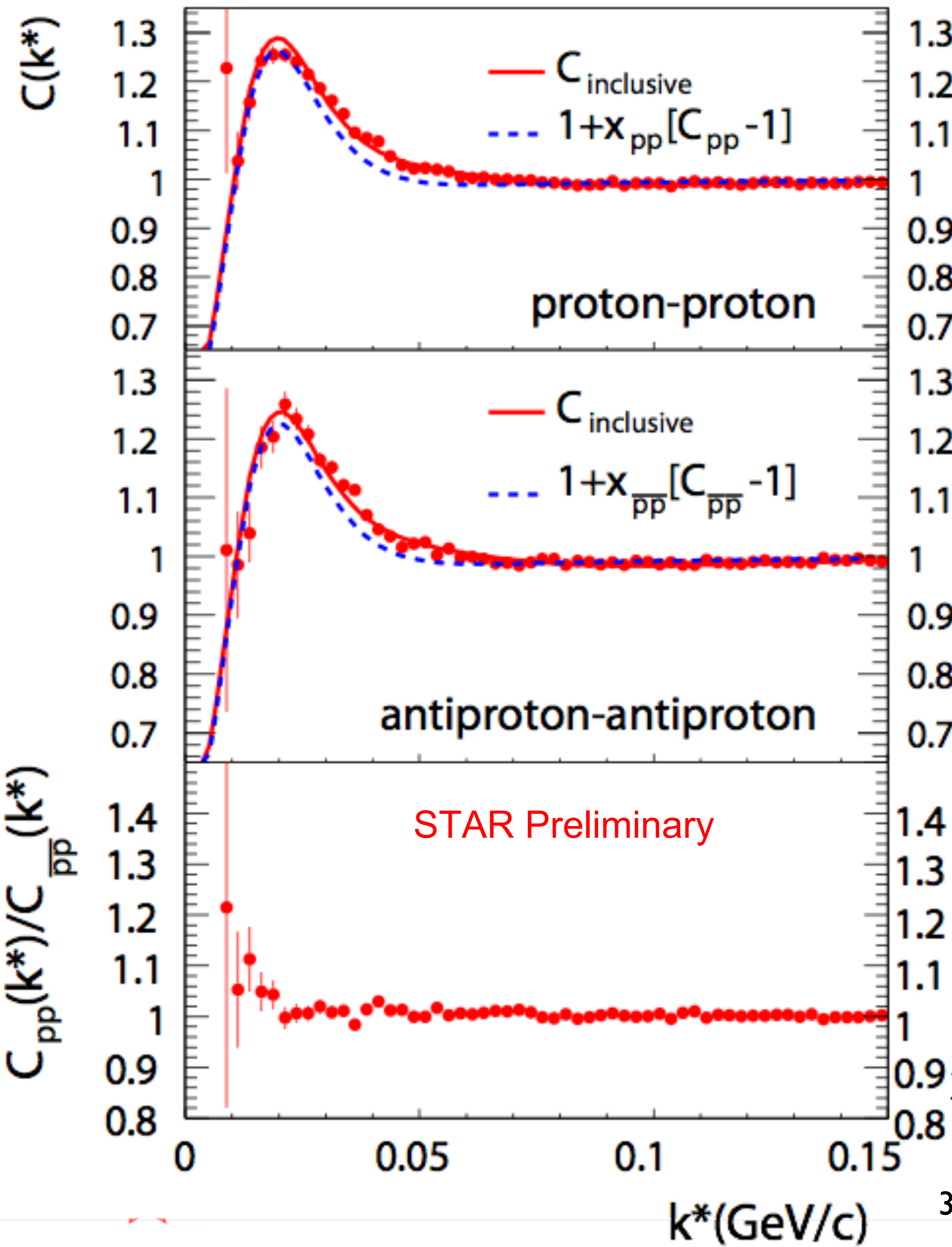
d_0 is the effective range of strong interaction between two particles. It corresponds to the range of the potential in an extremely simplified scenario - the square well potential.

The effective range indicates how close particles need to be for their charges to influence each other, like magnets.

- 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.

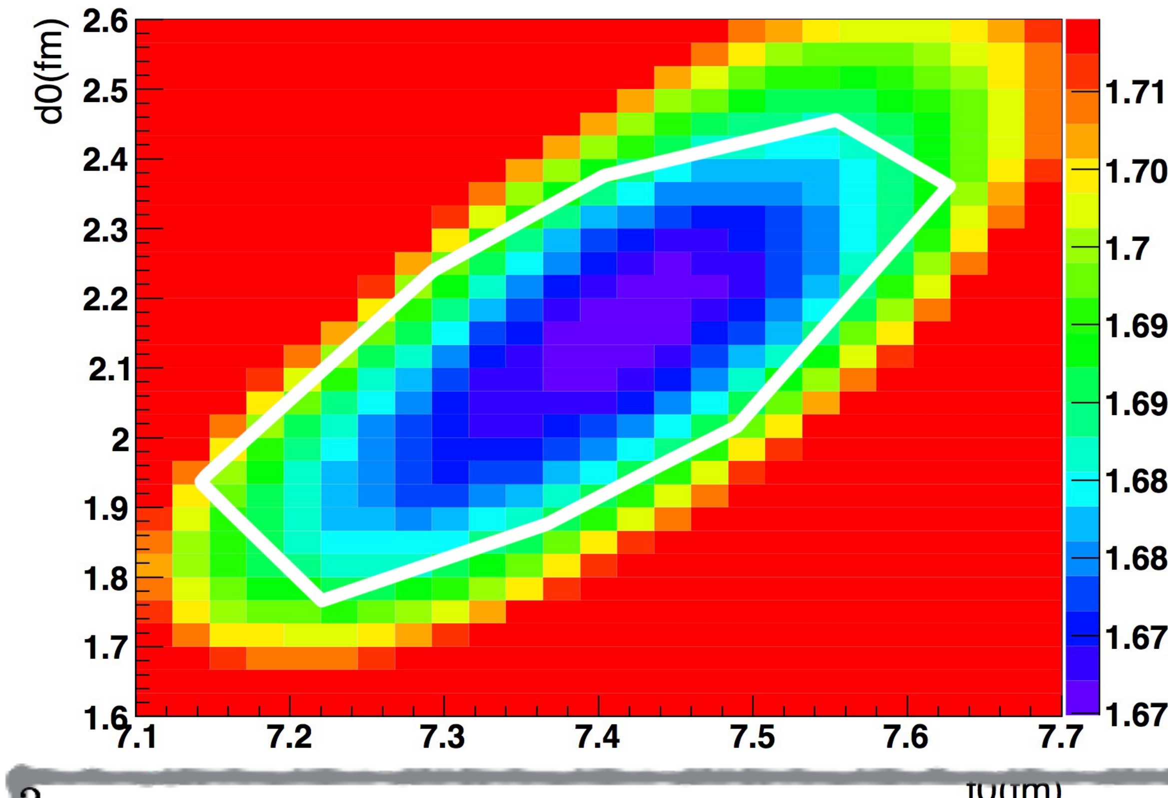
STAR

Correlations and the ratio



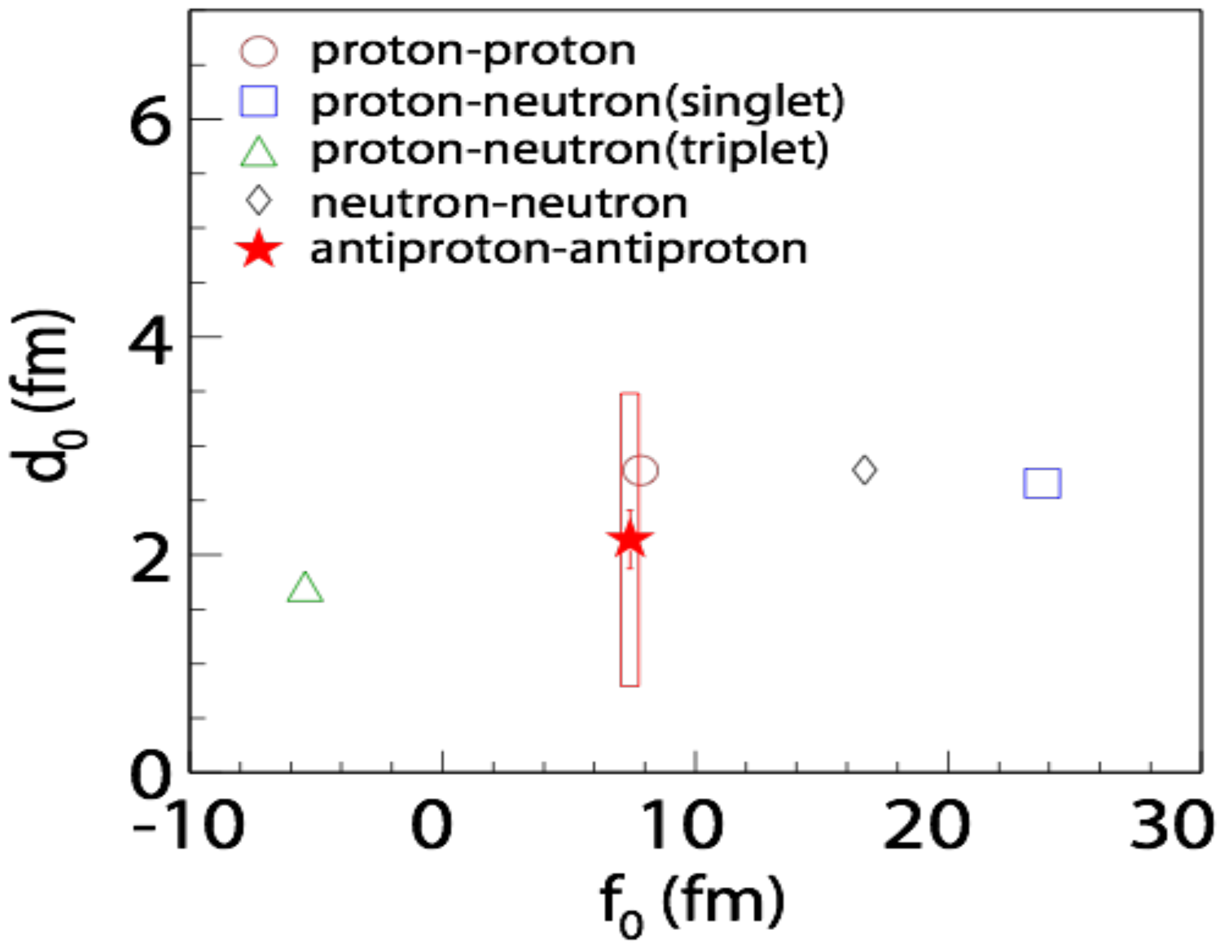
Fit results:
For proton–proton CF,
R=2.75±0.01fm; χ^2/NDF = 1.66;

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



nature 527, 325 (2015)

Within errors, the f0 and d0 for the antiproton-antiproton interaction are consistent with the ones for the proton-proton interaction.

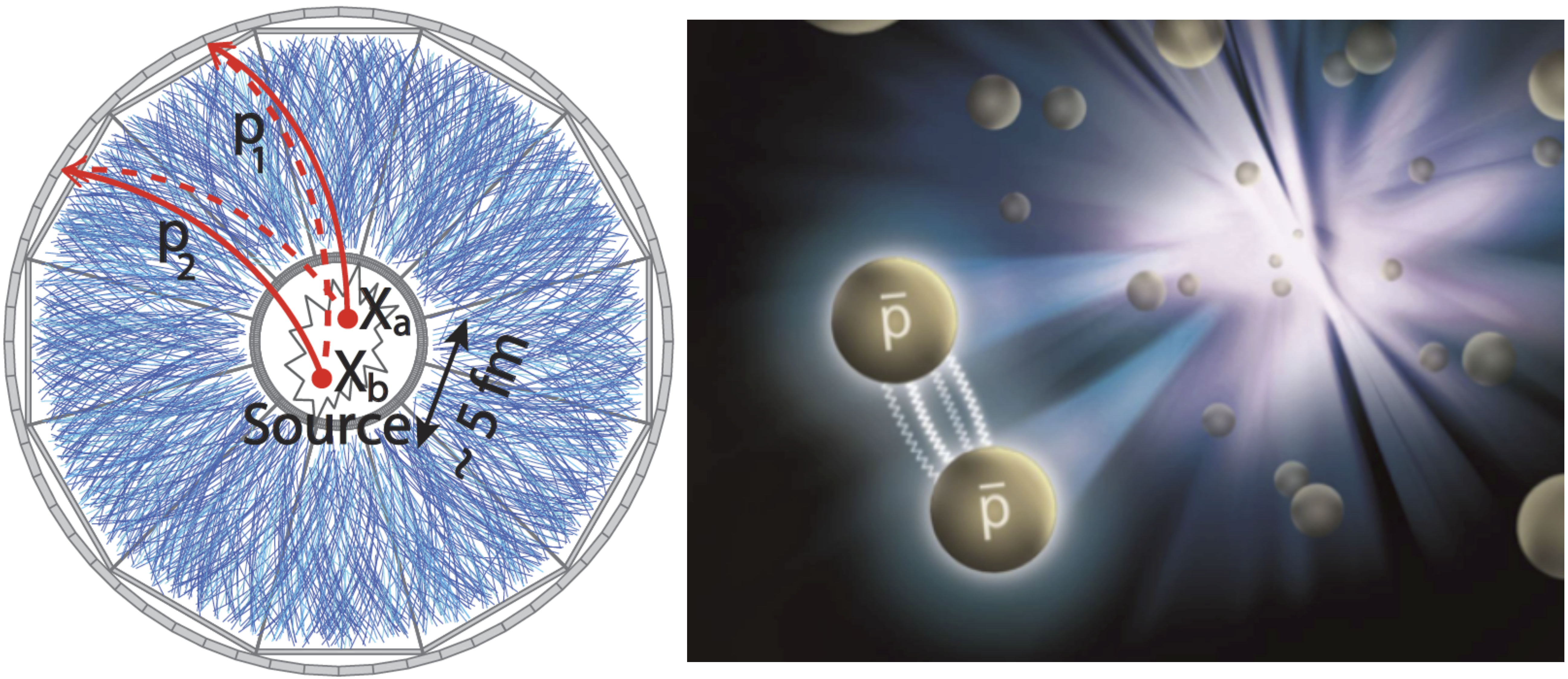
Our measurements provide input for descriptions of the interaction among antiprotons, one of the simplest systems of anti-nucleons(nuclei).

The result provides a quantitative verification of matter-antimatter symmetry in the context of the forces responsible for the binding of (anti)nuclei. CPT symmetry still works!

STAR(Z.Q. Zhang, Y. G. Ma, A. Tang et al.)
Z.Q. Zhang, PhD Thesis (2016)

See, Huan-Qiao Zhang, Research highlight in <<National Science Review>> (2016) issue 2: First measurement of strong interaction between antiprotons

a carton view on pbar-pbar correlation



A schematic of the two-particle correlation process in a heavy-ion collision.

Summary

- RHIC is not only a machine for Quark Gluon Plasma, but also a machine for antimatter production.
- First anti-hypernucleus, anti-hypertriton was observed in 2010 and anti-helium-4 was observed in 2011. The former one was discovered by the invariant mass reconstruction and the later was directly observed by energy loss and ToF.
- We report the result of antiproton-antiproton correlation function from 200GeV Au+Au collisions. The interaction parameters scattering length f_0 & effective rage d_0 are, for the first time, 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.
- Within the current errors, antiproton-antiproton interaction is the same as proton-proton interaction, it indicates the CPT symmetry still works for interaction.

outlook

（1） Possible future improvement of the measurement could be made by reducing the uncertainty from the **Λ–Λ** CF, which dominates our systematic error, by further accumulation of data.

（2） A similar extraction of **f**0 and **d**0 could also be repeated with (anti)proton– (anti)proton CF measured at the Large Hadron Collider, where the yield ratio of antiproton to proton is close to unity.

Thanks for your attention!

祝大家六六大顺！