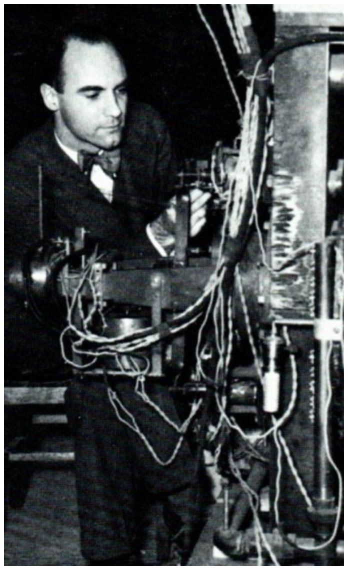
The Antimatter and Hypernuclei at RHIC

Zhangbu Xu
(for the STAR Collaboration)

- Heavy and Exotic Antimatter
- What RHIC can discover?
  - ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$ signal (for discovery)
  - Anti-alpha and how we discovered it
- What can we do with the discovery?
  - Production Rates for antimatter
  - Even Heavier antimatter?
- Outlook

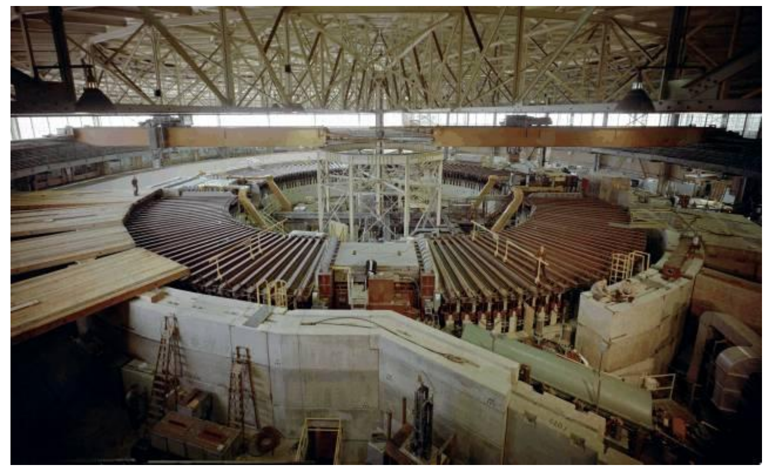
History of Antimatter

In 1928, Paul Dirac theorized possibility of antimatter as one of his equations for quantum mechanics had two “solutions” (regular matter and antimatter)

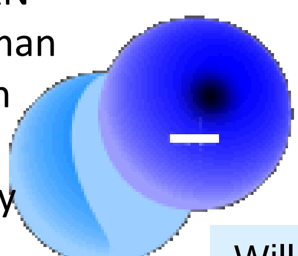


In 1932, Carl Anderson discovered positrons while studying cosmic rays

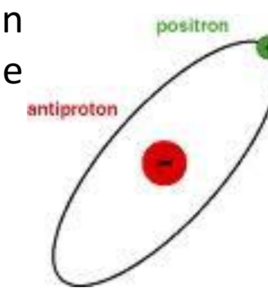
Two teams working at the Bevatron in Lawrence Berkeley National Lab discovered antiprotons and antineutrons in 1955 and 1956



In 1965, Antoni Zichichi of CERN and Leon Lederman of Brookhaven National Lab simultaneously discovered antideuteron

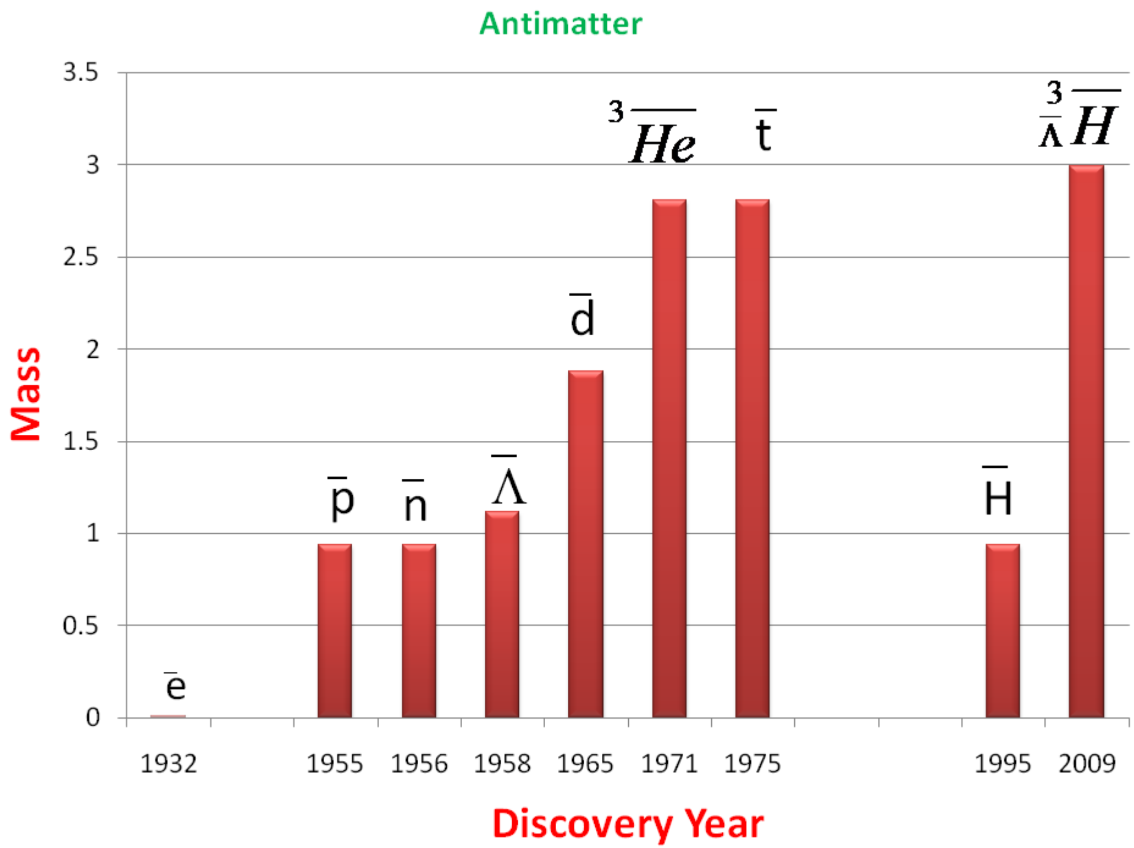


In 1995, CERN created antihydrogen atoms at the LEAR by slowing the antiprotons and attaching positrons



Will Pascucci, Choate Rosemary Hall; Wallingford, CT
2010 Summer High-School Student

What is Antimatter?



"Those who say that antihydrogen is antimatter should realize that we are not made of hydrogen and we drink water, not liquid hydrogen"
-- Dirac
Quoted from A. Zichichi (2008)
Antiparticles and antimatter: the basic difference

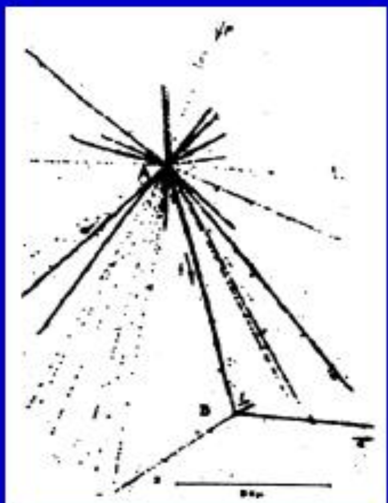
1. Annihilate with normal matter
   π^+, π^- are each other's antiparticle
2. Nuclear force
3. Relatively long lifetime

Science AAAS

Observation of an Antimatter Hypernucleus
The STAR Collaboration, *et al.*
Science **328**, 58 (2010);
DOI: 10.1126/science.1183980

What are Hypernuclei （超核）？

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

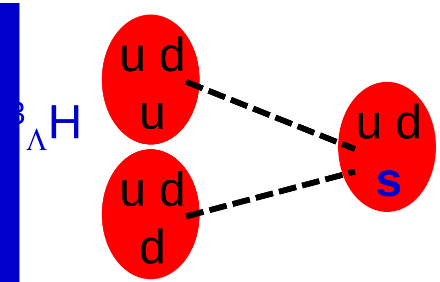


The first hypernucleus was discovered by Danysz and Pniewski in 1952. It was formed in a cosmic ray interaction in a balloon-flown emulsion plate.

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

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

Hypernuclei of lowest A



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

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

- 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)

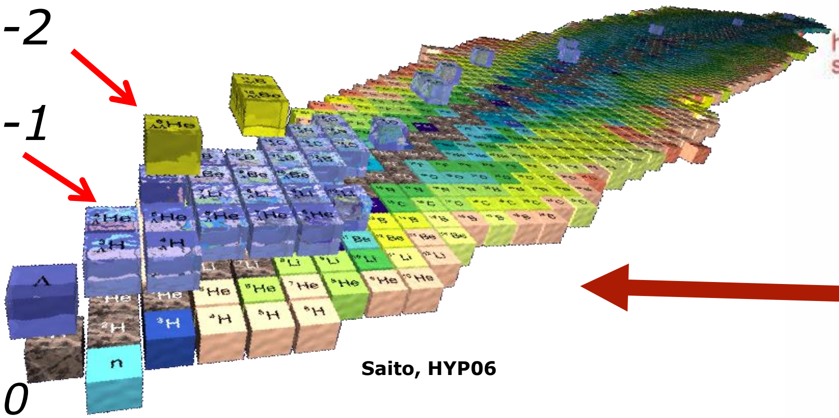
from Hypernuclei to Neutron Stars

hypernuclei ⟵ Λ-B Interaction ⟶ Neutron Stars

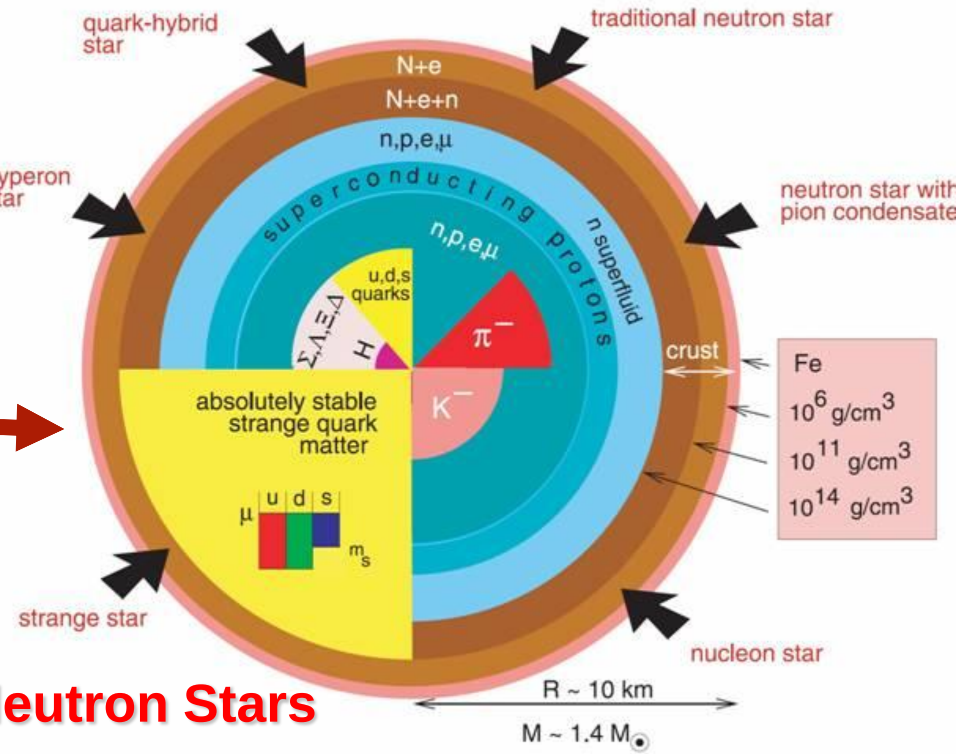
S=-2

S=-1

S=-0



Saito, HYP06



Several possible configurations of Neutron Stars

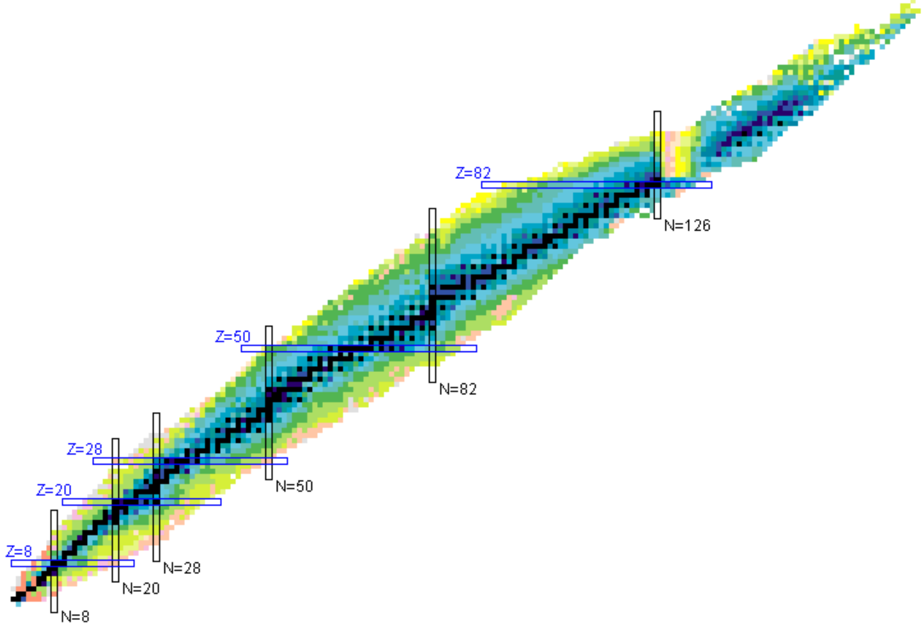
- **Kaon condensate, hyperons, strange quark matter**

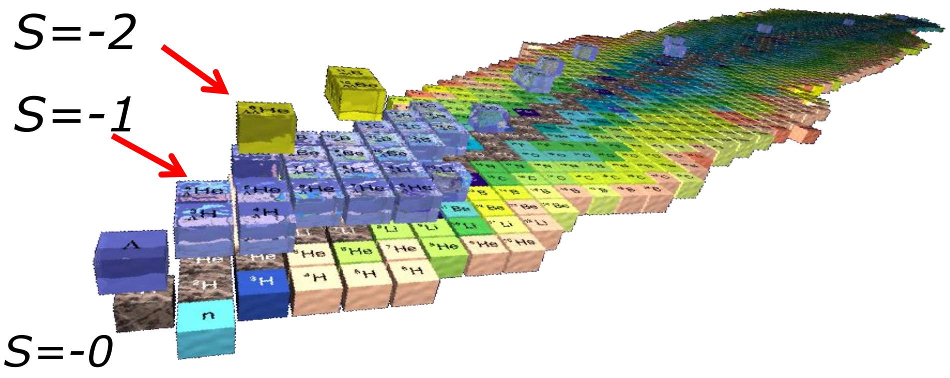
J.M. Lattimer and M. Prakash, "The Physics of Neutron Stars", Science 304, 536 (2004)
J. Schaffner and I. Mishustin, *Phys. Rev. C* 53 (1996): Hyperon-rich matter in neutron stars

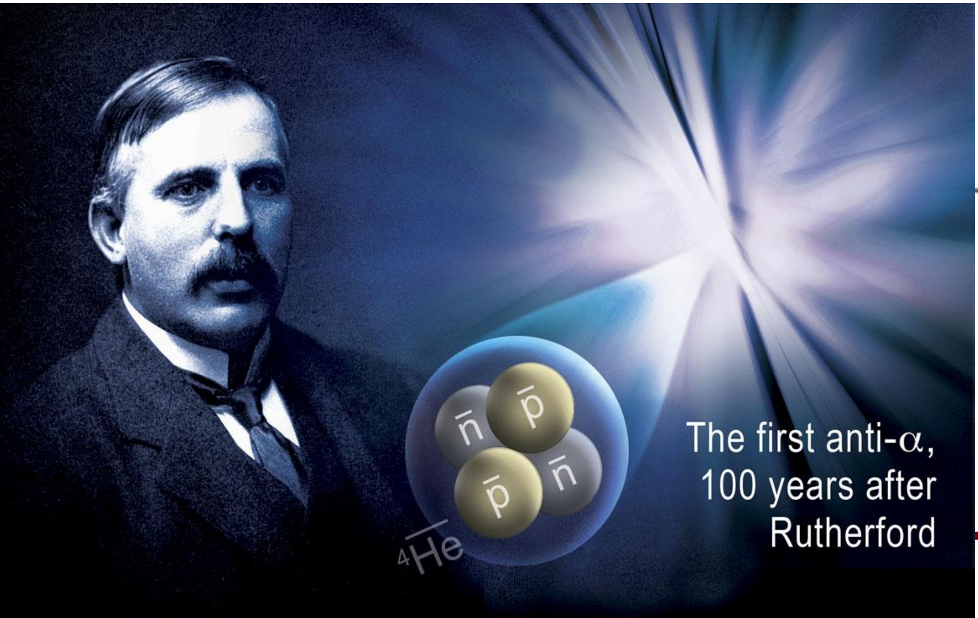
Single **and *double* hypernuclei in the laboratory:**

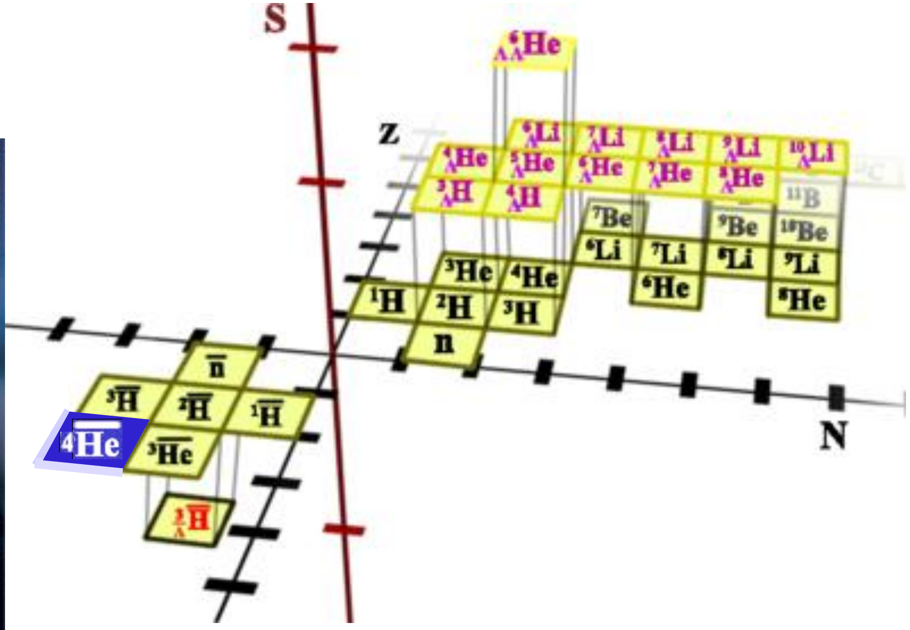
- **study the strange sector of the baryon-baryon interaction**
- **provide info on EOS of neutron stars**

3-D Chart of Nuclides

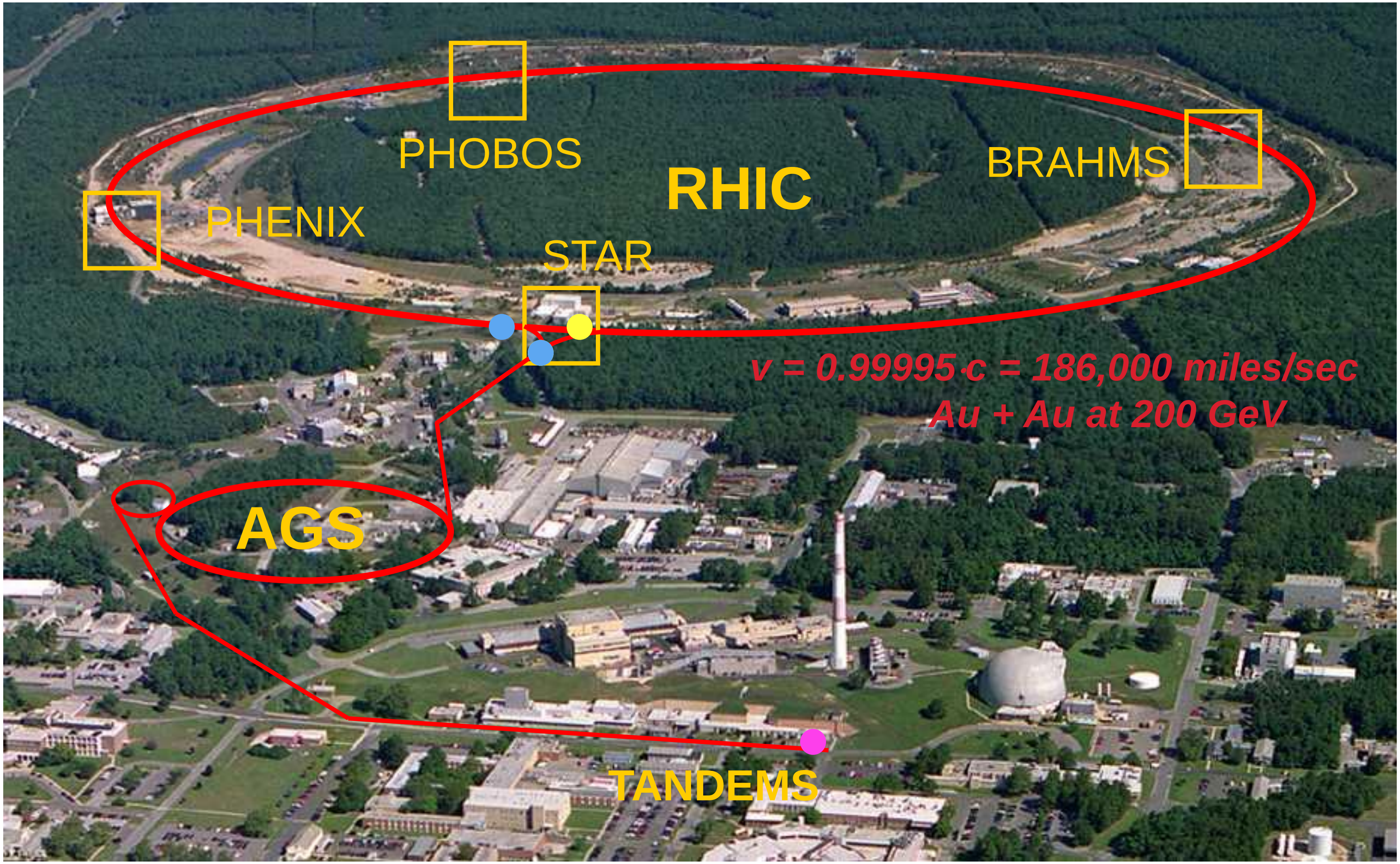








Relativistic Heavy Ion Collider (RHIC)

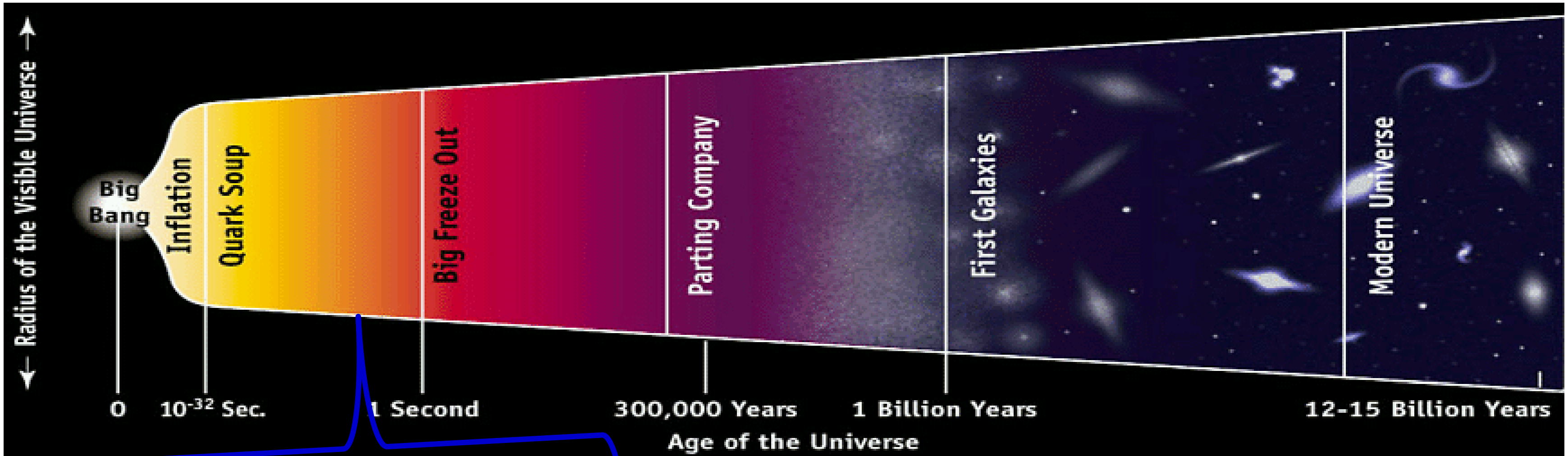


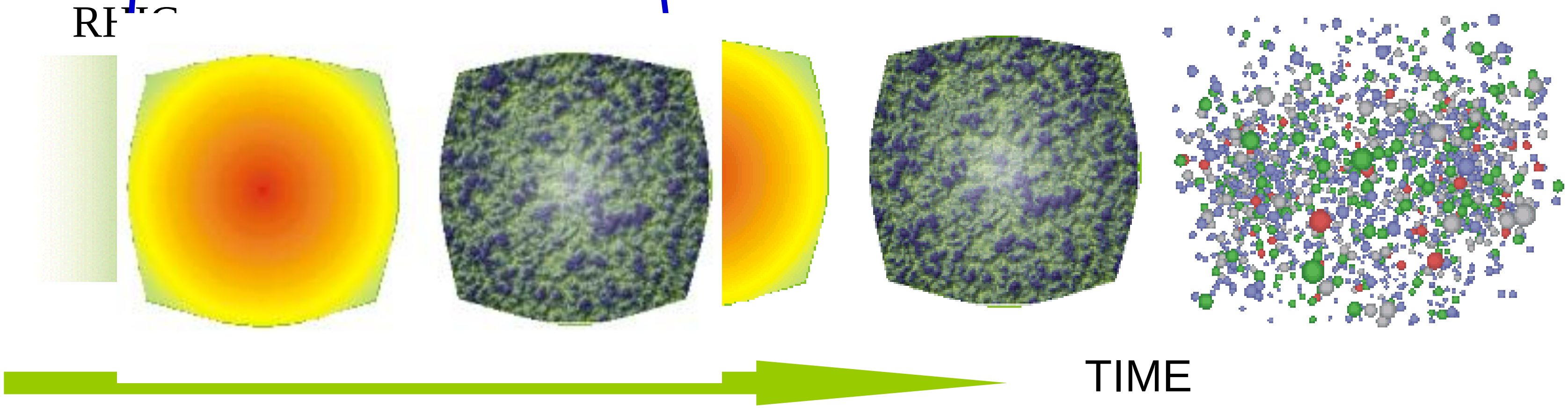
Animation M. Lisa


STAR

Little Big Bang

BIG; All 4 forces at work; Gravitation dominates; QGP@10^{-6}s; Slow expansion; Antimatter-matter annihilate;





Little; Strong force at work; QGP@10^{-23}s; Fast expansion; Antimatter-matter decouple; repeat trillion times

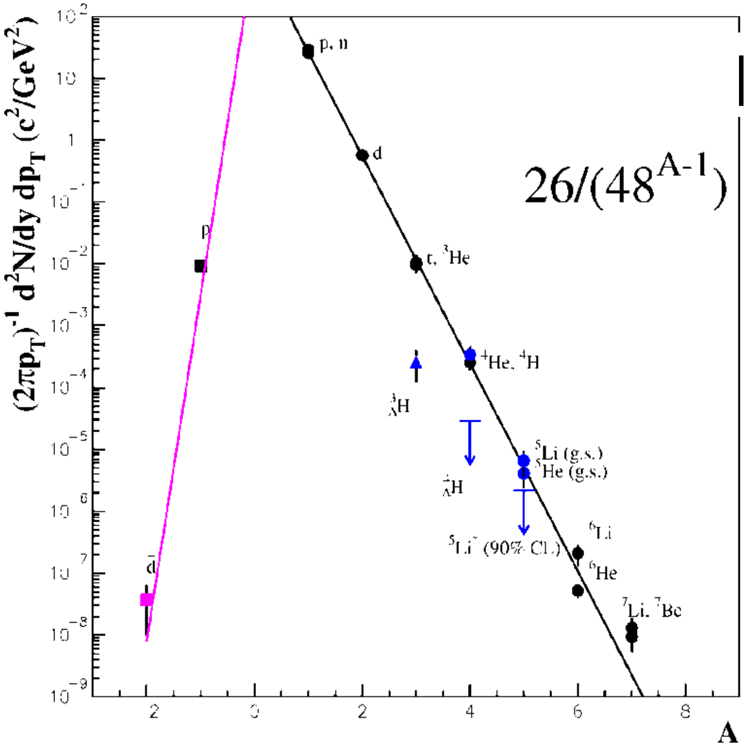
Can we observe hypernuclei at RHIC?

- Low energy and cosmic ray experiments (wikipedia):

  hypernucleus production via
  - Λ or K capture by nuclei
  - the direct strangeness exchange reaction

  hypernuclei observed
  - energetic but delayed decay,
  - measure momentum of the K and π mesons

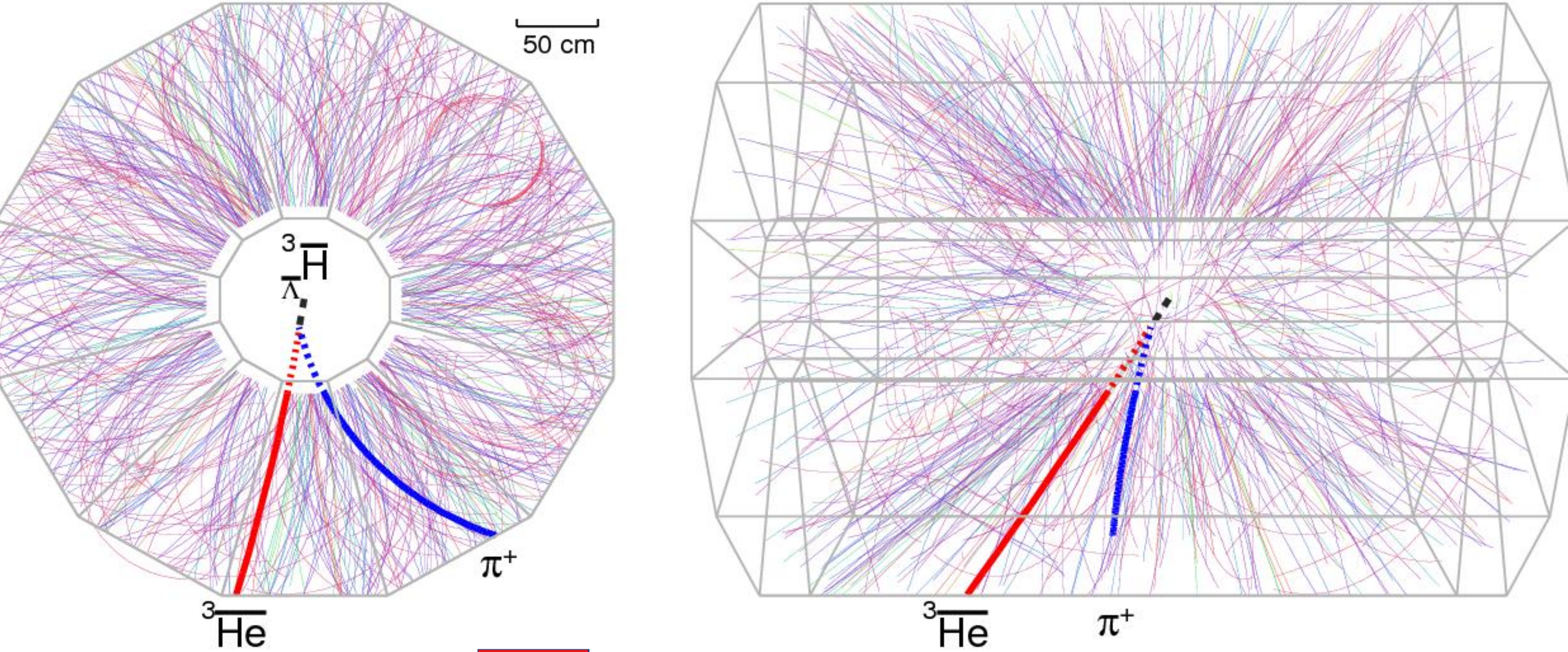
- In high energy heavy-ion collisions:
  - nucleus production by coalescence, characterized by penalty factor.   聚并
  - AGS data[1] indicated that hypernucleus production will be further suppressed.
  - What's the case at RHIC?



[1] AGS-E864, Phys. Rev. C70,024902 (2004)

A candidate event at STAR

Run4 (2004)
200 GeV Au+Au collision



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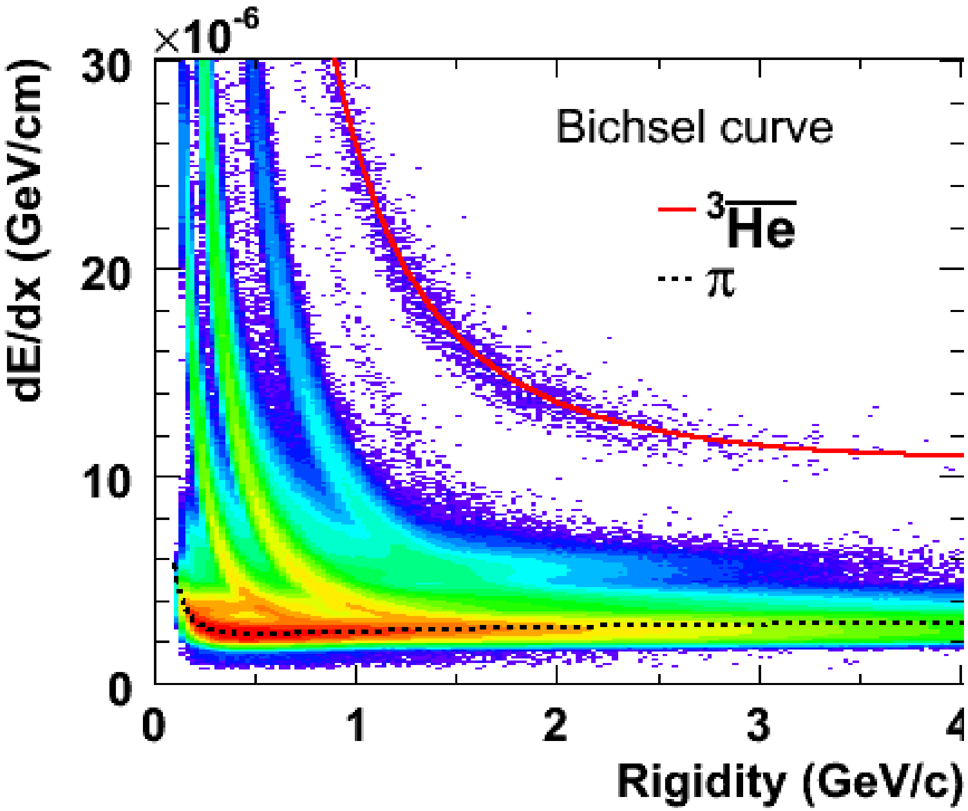
^{3}He & anti-^{3}He selection



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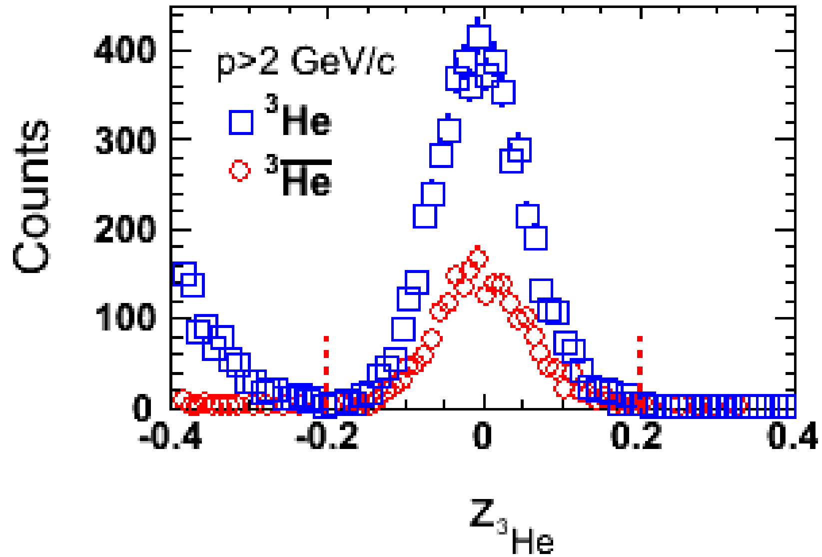


$$Z = \ln\left(\frac{\langle dE/dx \rangle}{\langle dE/dx \rangle^{Bichsel}}\right)$$

Select pure ^{3}He sample: -0.2<Z<0.2 & dca <1.0cm & p >2 GeV

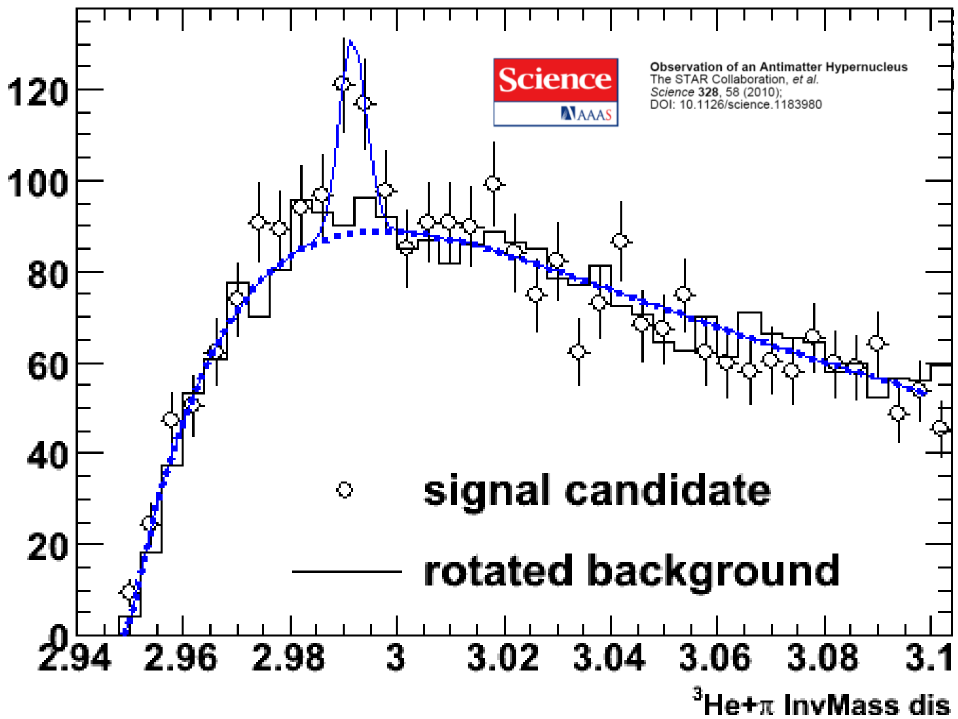
^{3}He: 2931(MB07) + 2008(central04) + 871(MB04) = 5810

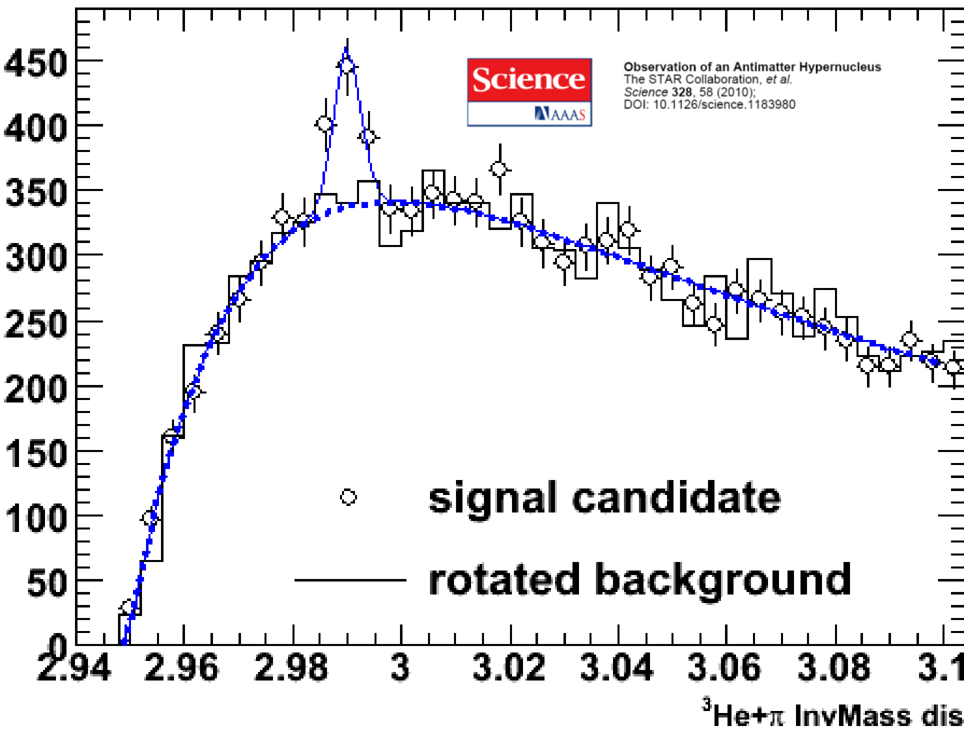
Anti-^{3}He: 1105(MB07) + 735(central04) + 328(MB04) = 2168

$^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$ and Combined signals

$^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$

Combine hypertriton and antihypertriton signal:
225±35



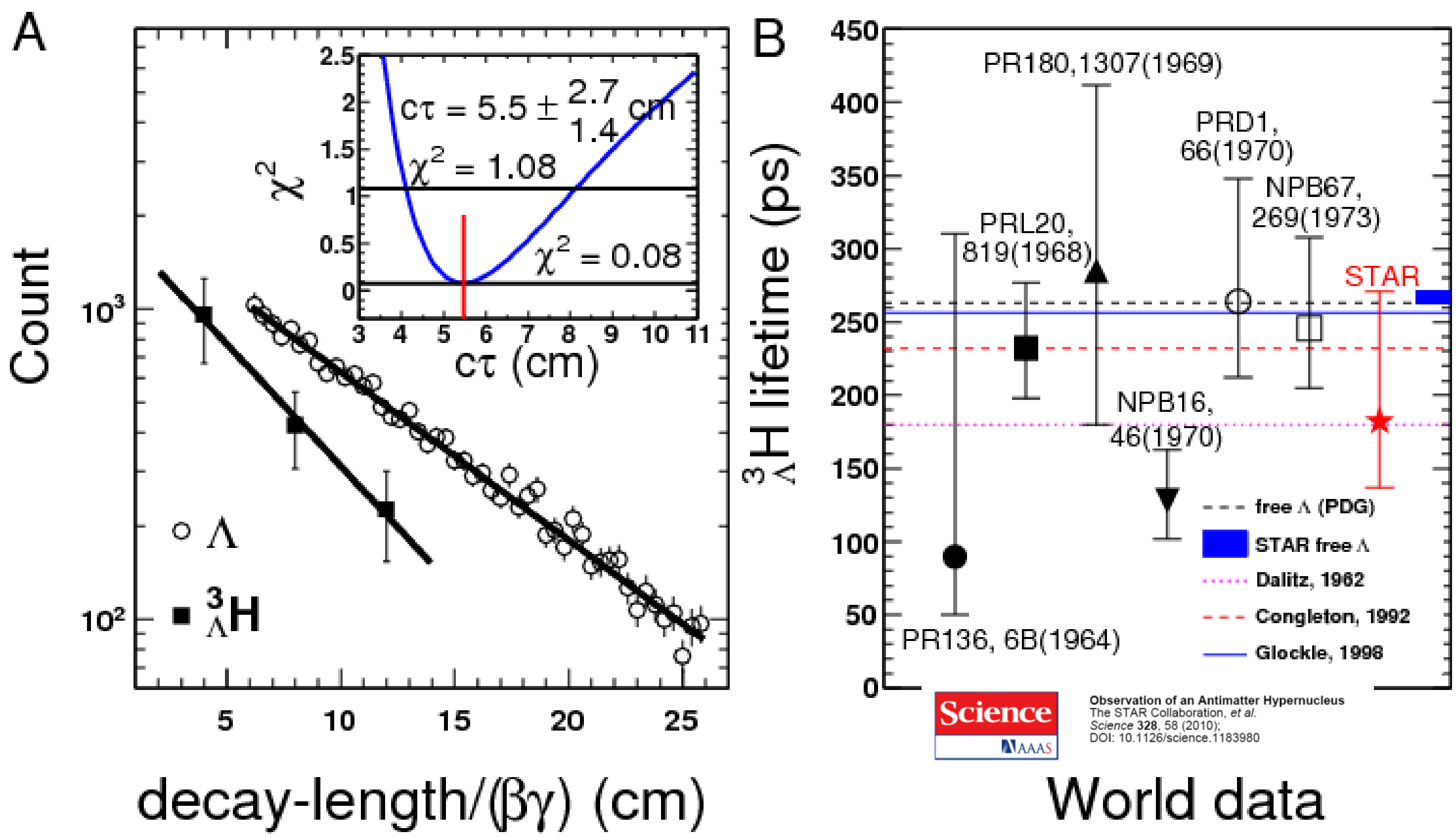


- Signal observed from the data (bin-by-bin counting): **70±17**;

Mass: 2.991±0.001 GeV; Width (fixed): 0.0025 GeV;

This provides a >6σ signal for discovery

Lifetime of a hypertriton



- Lifetime related to binding energy
- Theory input: the Λ is lightly bound in the hypertriton

[1] R. H. Dalitz, *Nuclear Interactions of the Hyperons* (Oxford Uni. Press, London, 1965).

[2] R.H. Dalitz and G. Rajasekharan, Phys. Letts. 1, 58 (1962).

[3] H. Kamada, W. Glockle at al., Phys. Rev. C 57, 1595(1998).

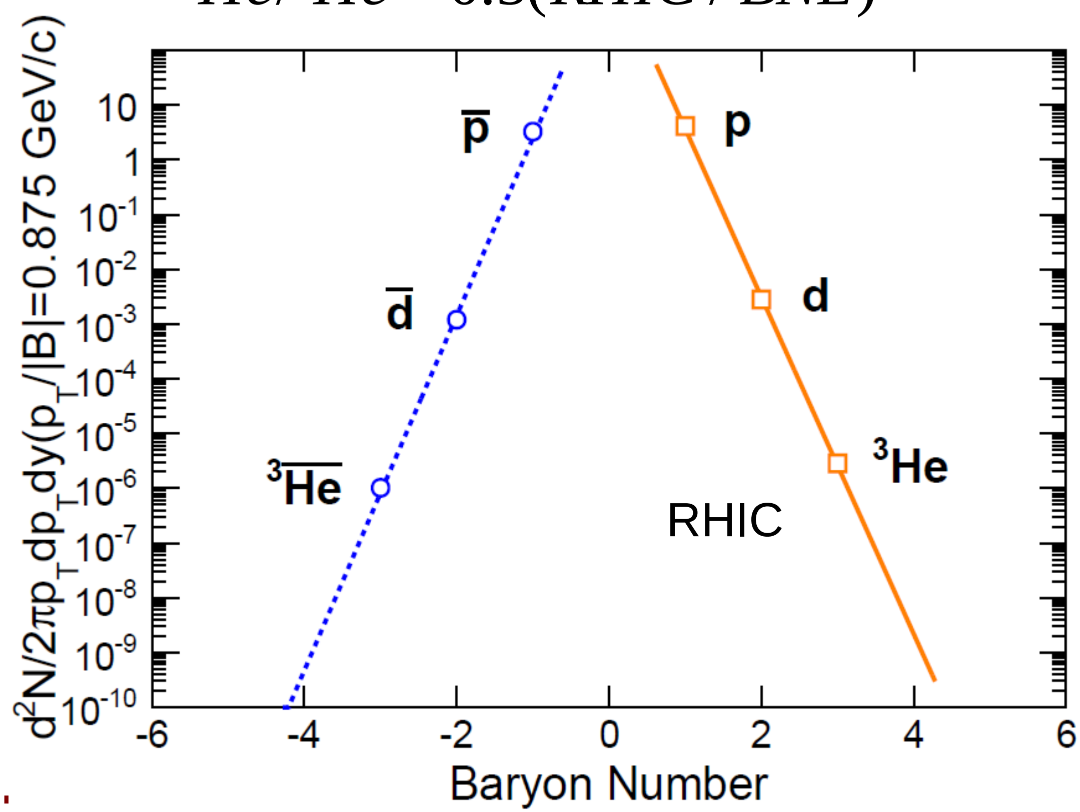
Matter and antimatter are not created equal

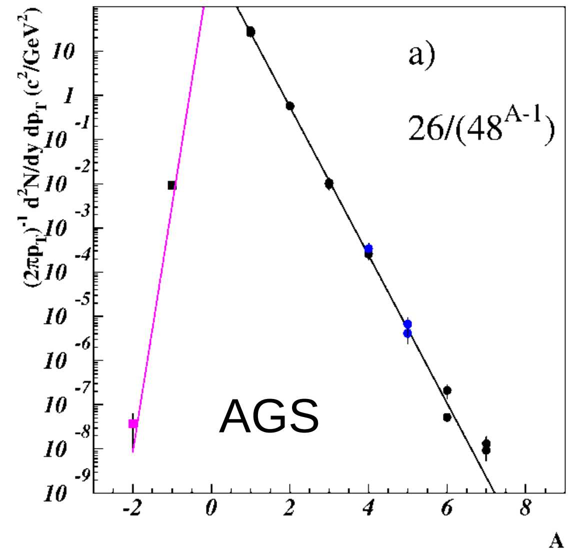
But we are getting there !

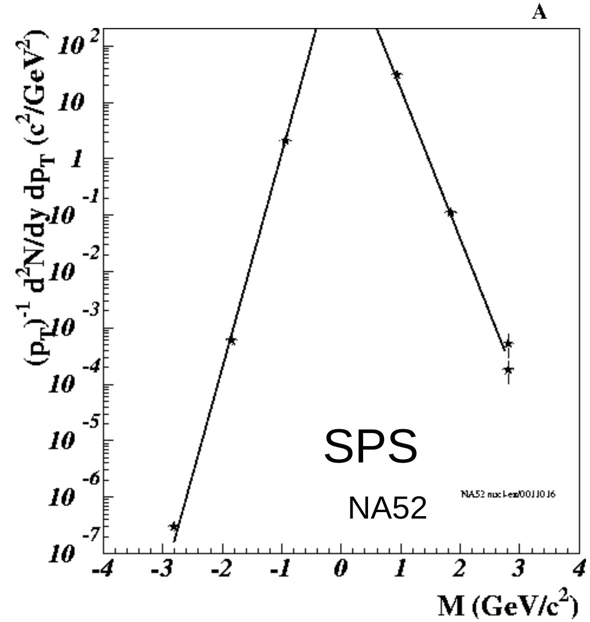
$$^{3}\overline{He}/^{3}He \approx 10^{-11} \quad \text{(AGS,Cosmic)}$$

$$^{3}\overline{He}/^{3}He \approx 10^{-3}(SPS/CERN)$$

$$^{3}\overline{He}/^{3}He \approx 0.5(RHIC/BNL)$$

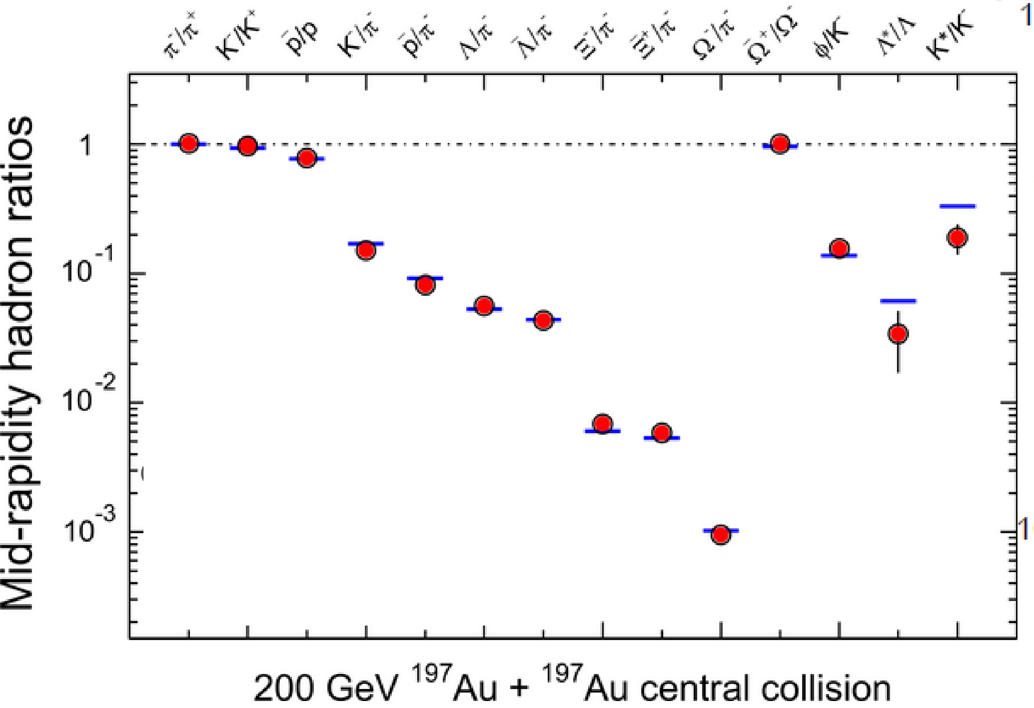




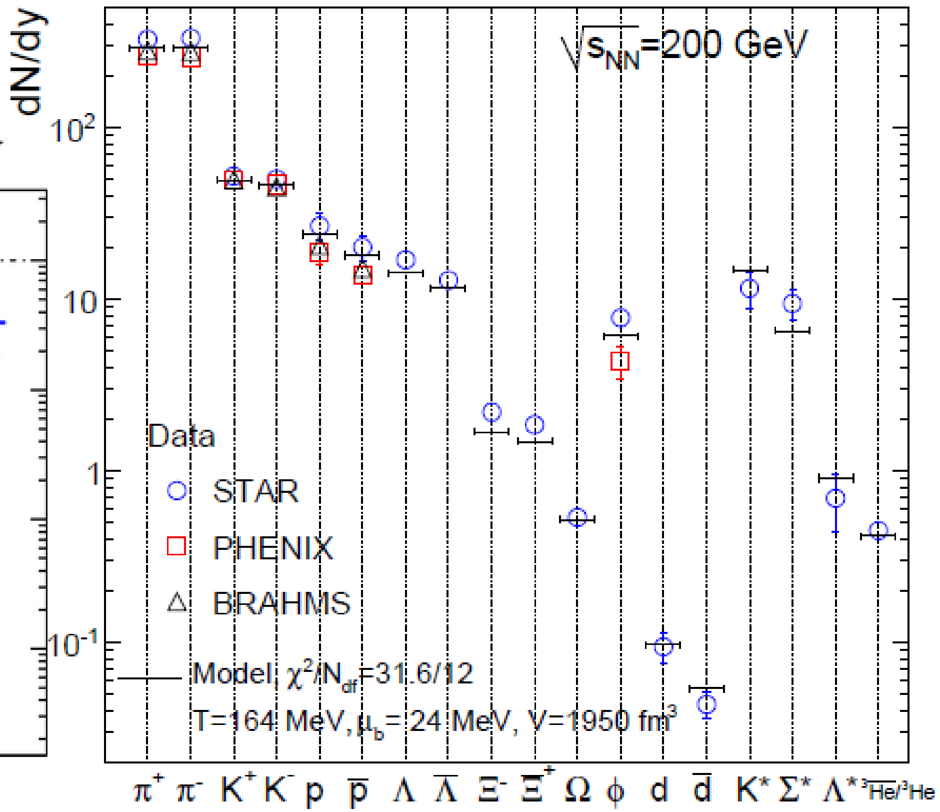


Flavors (u,d, s) are not created equal except in possible QGP

J. Rafelski and B. Muller, Phys.Rev.Lett.48:1066,1982



STAR whitepaper, NPA757(2005)



A. Andronic, P.Braun-Munzinger, J.Stachel, Phys. Lett. B 673 (2009) 142

A. Andronic, P.Braun-Munzinger, K.Redlich, J.Stachel, Phys. Lett. B 652 (2007) 259; B 678 (2009) 350; arXiv:1002.4441

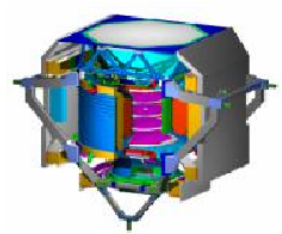
Antinuclei in nature (new physics)

To appreciate just how rare nature produces antimatter (strange antimatter)

Tour of the AMS Experiment - Windows Internet Explorer

http://cyclo.mit.edu/~bmonreal/frames.phys.html

RHIC: an antimatter machine



Welcome to the web page of the AMS-02 experiment. Click on the links below to learn more!

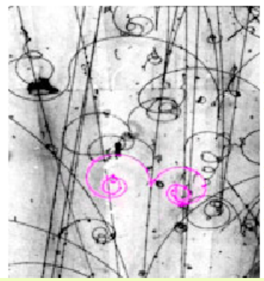
The Alpha Magnetic Spectrometer (AMS)

A particle physics experiment in space

1. What is AMS?
2. Mission overview
3. Science goals

Physics Topics

1. (introduction)
2. antimatter galaxies
3. cold dark matter
4. strangelets



Antimatter Galaxies

Where is all the antimatter in the universe? The Universe appears to have been created 13.7 billion years ago, in an explosion called the "Big Bang". This explosion actually created all of the Universe's particles out of a burst of energy. Now, particle physicists have been studying how particles behave when subjected to this sort of energy, and after decades of work, we understand high-energy particles very well. There is one nagging unanswered question, though: our best particle-physics studies show that matter and antimatter are always created in equal amounts. You can't make a proton without making an antiproton. You can't make an electron without making an antielectron.

Seeing a mere antiproton or antielectron does not mean much– after all, these particles are byproducts of high-energy particle collisions. However, complex nuclei like anti-helium or anti-carbon are almost never created in collisions.

Seeing a mere antiproton or antielectron does not mean much - after all, these particles are byproducts of high-energy particle collisions. However, complex nuclei like anti-helium or anti-carbon are almost never created in collisions. But they would be made abundantly by nuclear fusion in an anti-star!

So, AMS will search for anti-helium nuclei. First we try to very cleanly identify particles with the right charge (+-2); then we examine these particles' tracks and see how they bend in the magnetic field. Ordinary helium will bend to the left, antimatter helium will bend to the right. A single really clean detection would be really exciting!

(back to top) - (back to AMS Tour)

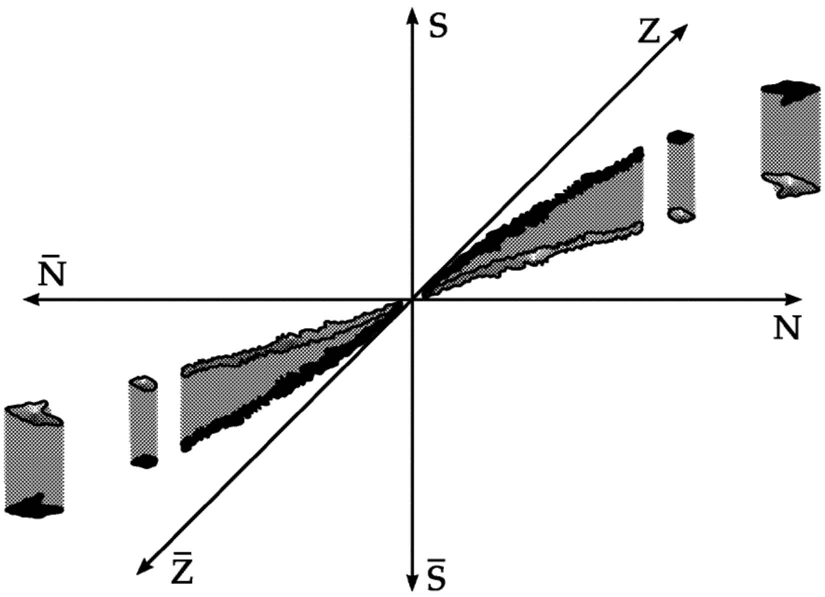
AMS antiHelium/Helium sensitivity: 10^{-9}

Dark Matter, Black Hole→ antinucleus production via coalescence

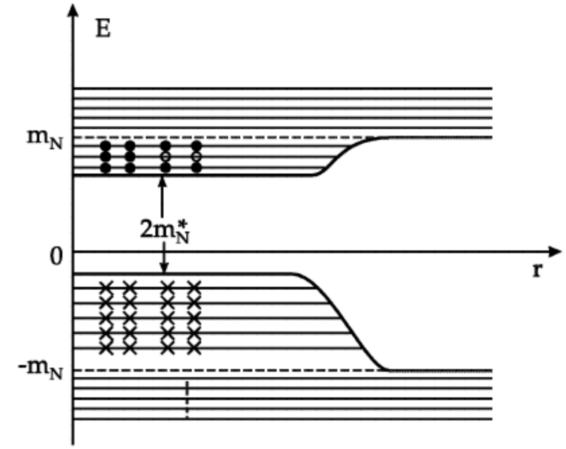
hypernuclei and antimatter from correlations in the Vacuum

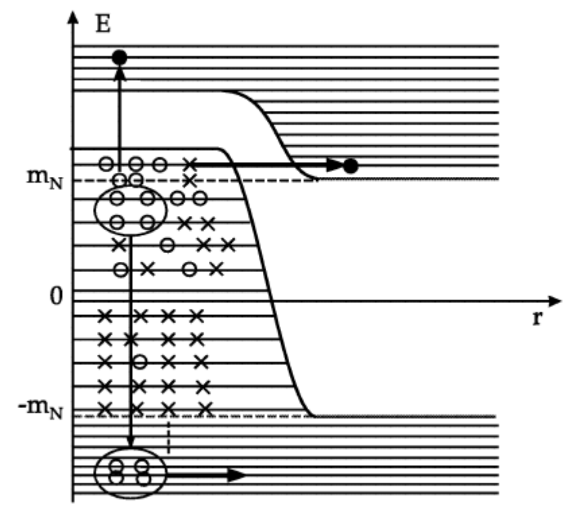
Fundamental Issues in the Physics of Elementary Matter:
Cold Valleys and Fusion of Superheavy Nuclei - Hypernuclei – Antinuclei – Correlations in the Vacuum

Walter Greiner



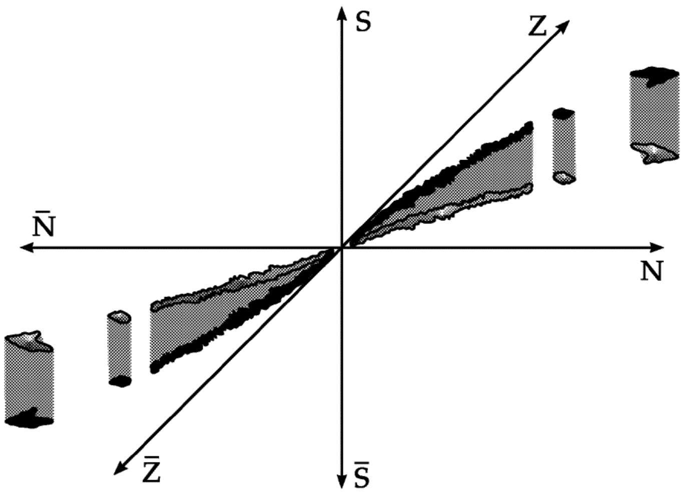
Real 3-D periodic table

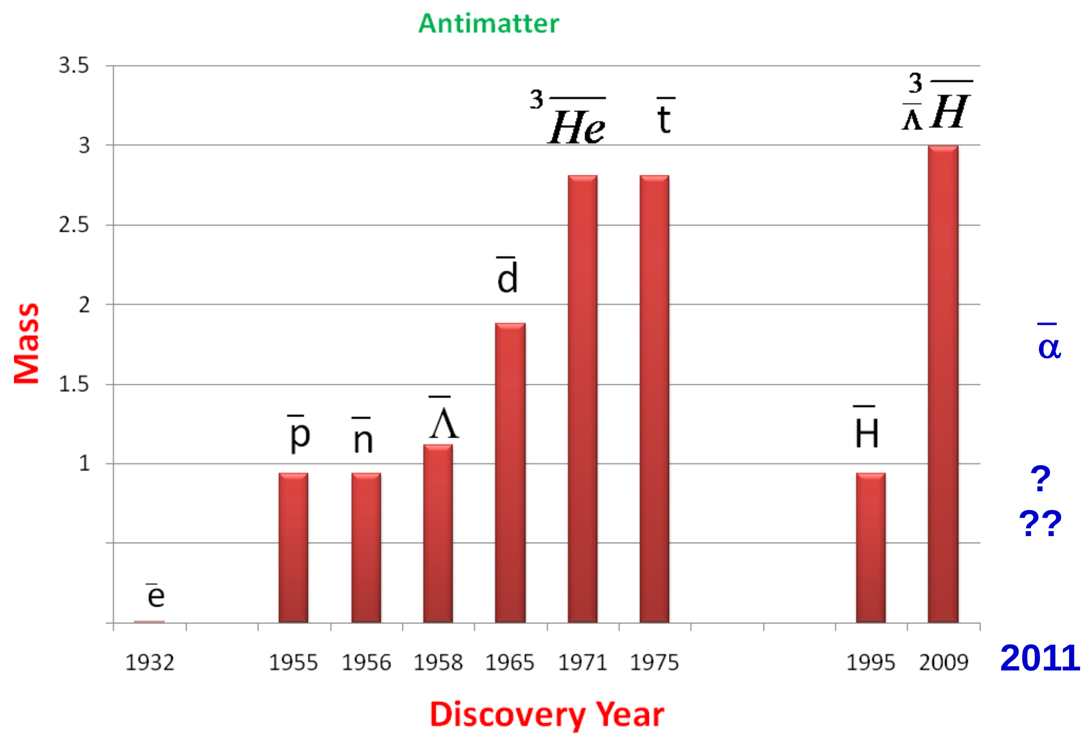


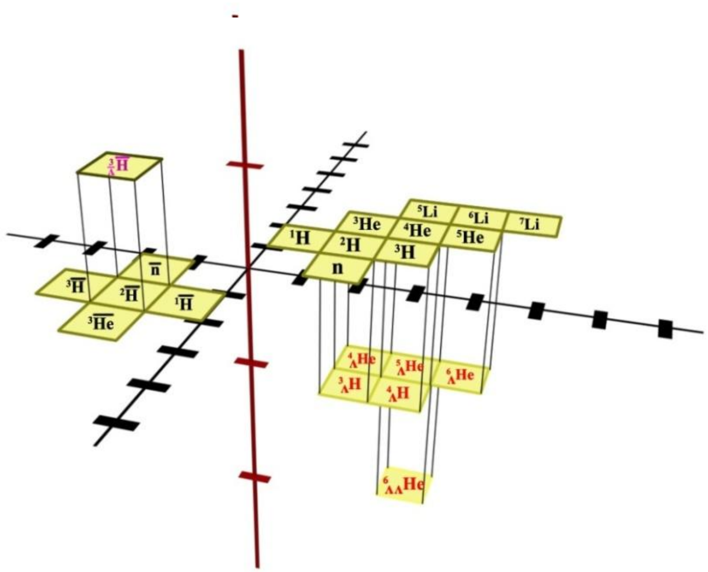


Pull $\bar{\alpha}$ from vacuum (Dirac Sea)

Antimatter Project: 40 years per step







The extension of the periodic system into the sectors of hypermatter (strangeness) and antimatter is of general and astrophysical importance. … The ideas proposed here, the verification of which will need the **commitment for 2-4 decades of research, could be such a vision with considerable** attraction for the best young physicists… I can already see the enthusiasm in the eyes of young scientists, when I unfold these ideas to them — similarly as it was 30 years ago,…

---- Walter Greiner (2001)

Projected Discovery of antimatter Helium-4 nucleus from STAR

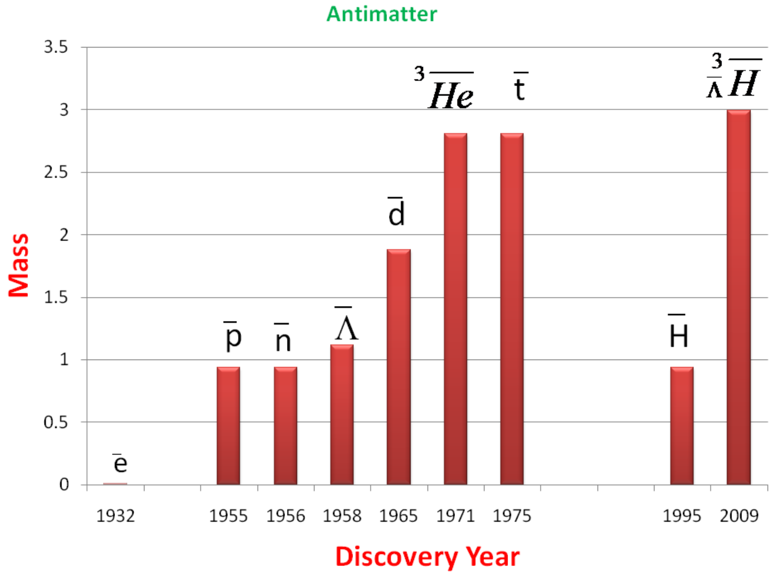
How many possible antimatter nuclei can we discover?

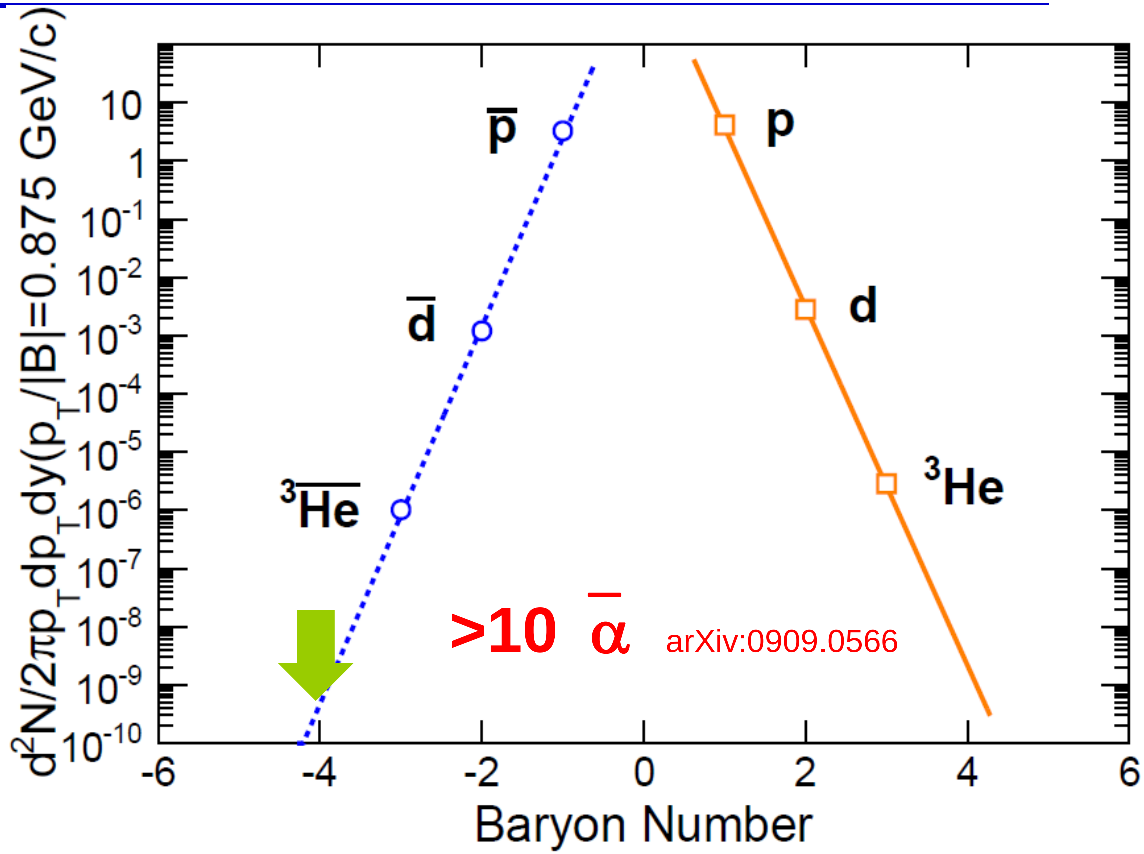
Anti-hypertriton, anti-alpha;

Anti-hyperH4?

Can we get to antimatter ^{6}He?

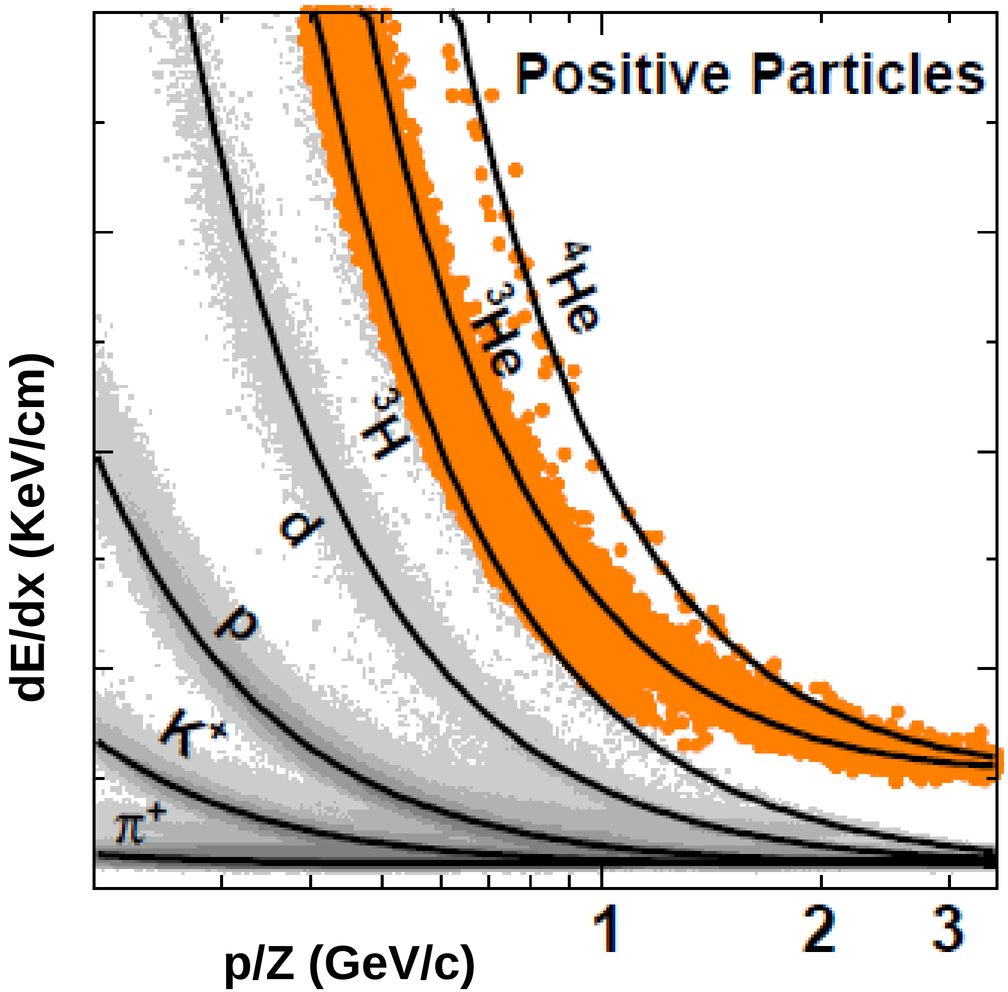
Unless technology and Physics change dramatically, **NO**!





2009 prediction

How to identify Helium-4

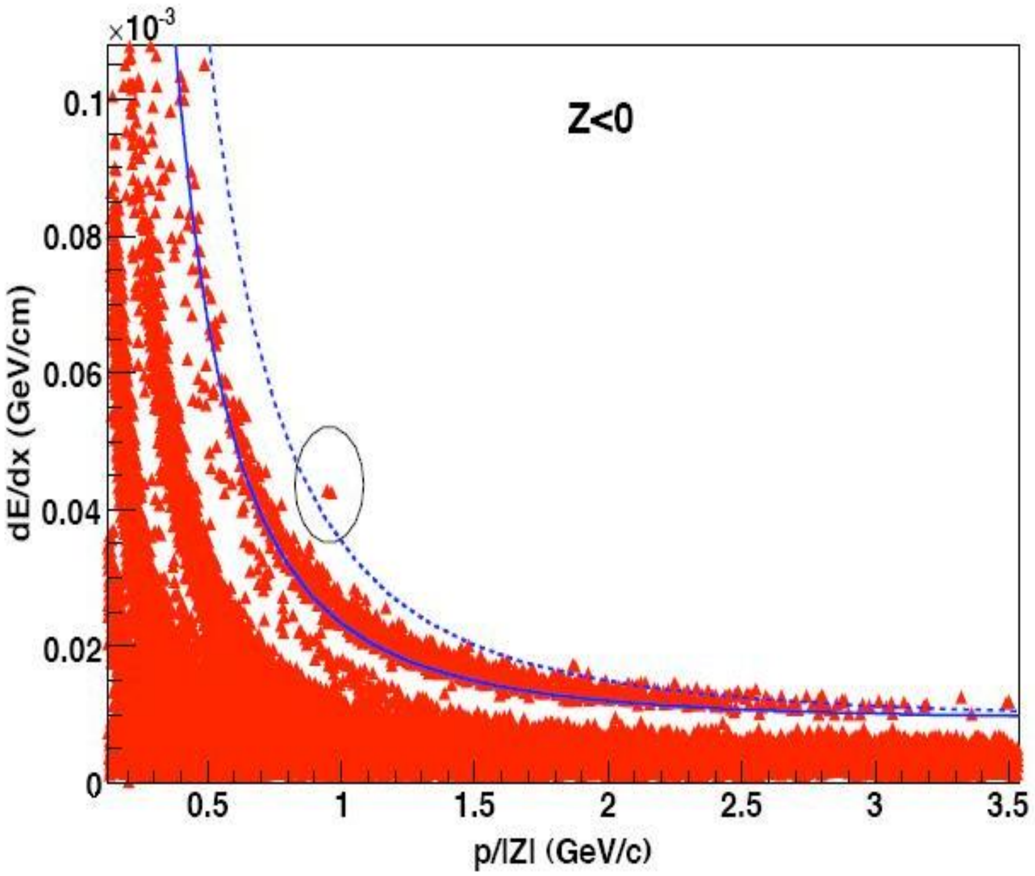


dE/dx in Time Projection Chamber

Separation at low pT
Merged with Helium-3 at p>3.5GeV/c
Most of the statistics at that range

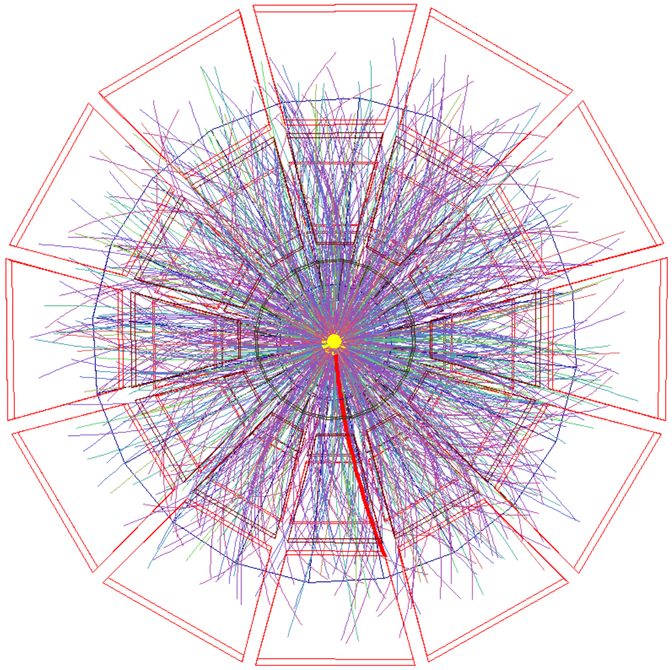
Need a different detector

Candidates identified by TPC (2007)



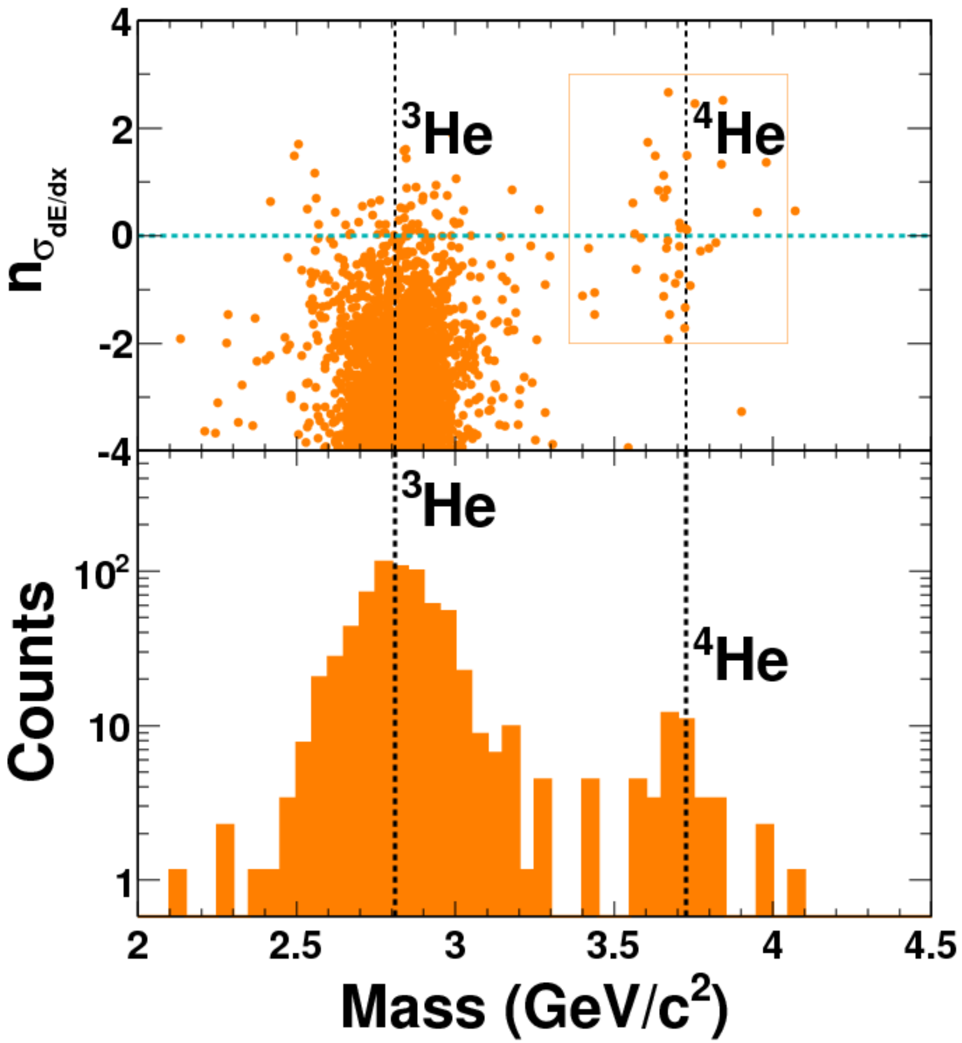
Two candidates;
Clean separation;

To confirm the discovery:
need more statistics and
confirmation using new detector



Jianhang Zhou (Rice) PHD thesis 2009
[Light (Anti-)Nuclei Production in the STAR Experiment at RHIC]

The Power of Time-of-Flight Detector



$$m^2 = p^2(1/\beta^2 - 1)$$

Two detectors confirm each other
With different methods:
dE/dx vs mass

Clean separation of Helium isotopies

Data Acquisition 10→100→1000Hz

TOF 100% installed in 2009:
A US-China joint Project for STAR

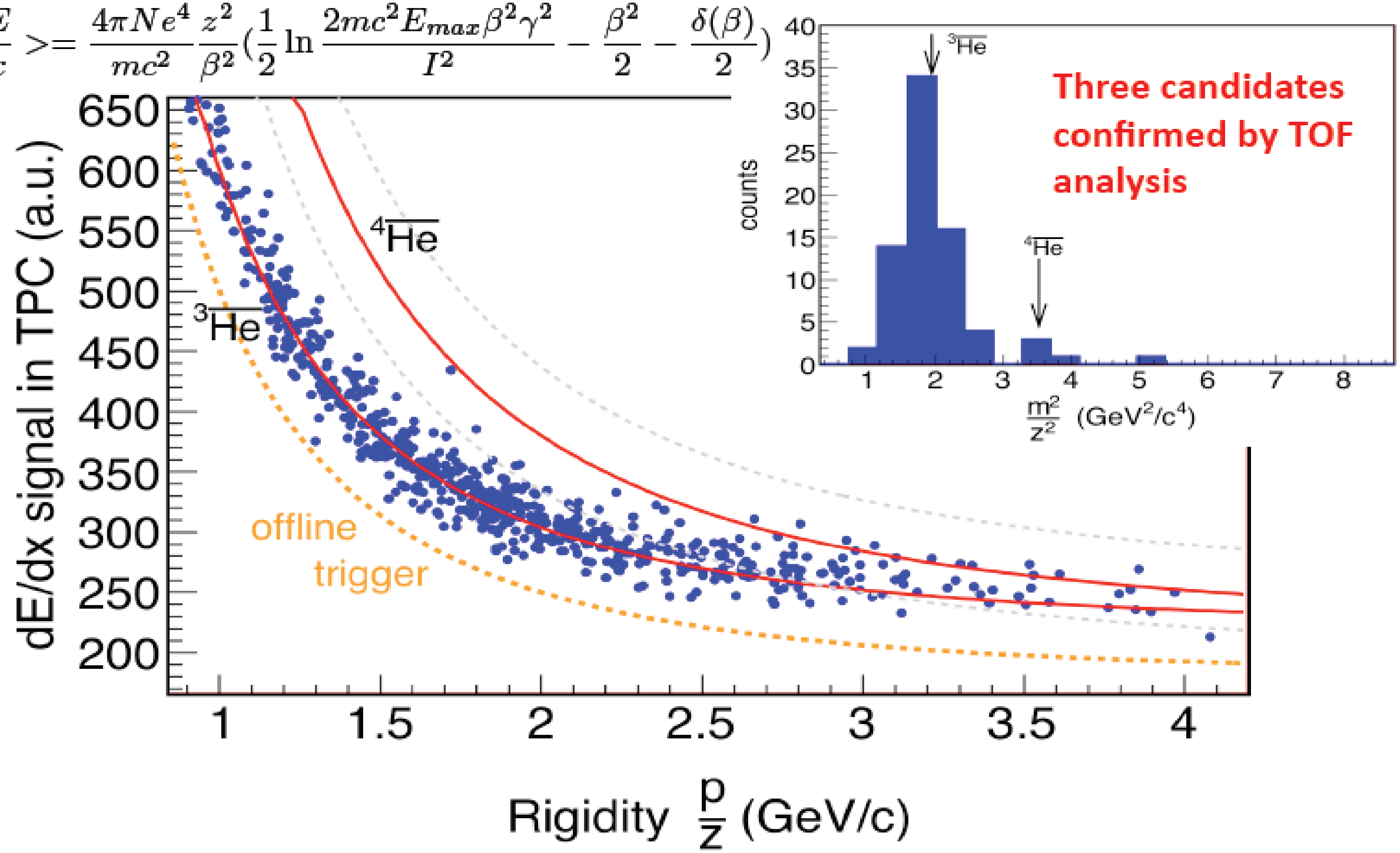
High-Level Trigger for express output

More details on Sunday in talk by Hao Qui (H7.00007)

Anti-Alpha candidates in Pb-Pb

Time of flight (sensitive to m/z-ratio): $m = \frac{z \cdot R}{\sqrt{\gamma^2 - 1}}$

$$< \frac{dE}{dx} >= \frac{4\pi N e^4}{mc^2}\frac{z^2}{\beta^2}\left(\frac{1}{2}\ln\frac{2mc^2 E_{max}\beta^2\gamma^2}{I^2} - \frac{\beta^2}{2} - \frac{\delta(\beta)}{2}\right)$$



STAR

[1103.3312] Observation of the antimatter helium

http://arxiv.org/abs/1103.3312

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[1103.3312] Observation of the antimatter helium

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arXiv.org > nucl-ex > arXiv:1103.33

Nuclear Experiment

Observation of the anti

STAR Collaboration

(Submitted on 16 Mar 2011 (v1), last revised 2

High-energy nuclear collisions create a
antimatter are formed with comparable
quickly from matter, and avoid annihila
antimatter. The antimatter helium-4 nu
antineutrons (baryon number B=-4). It
and is present in cosmic radiation at th
accelerators, where the rate of antinuc
present the observation of the antimat
STAR experiment at RHIC in 10^9 re
yield is consistent with expectations fro

Comments: 19 pages, 4 figures. Submitted t

Subjects: **Nuclear Experiment (nucl-ex)**

Cite as: arXiv:1103.3312v2 [nucl-ex]

Submission history

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Observation of the antimatter helium-4 nucleus

The STAR Collaboration

Affiliations | Contributions

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

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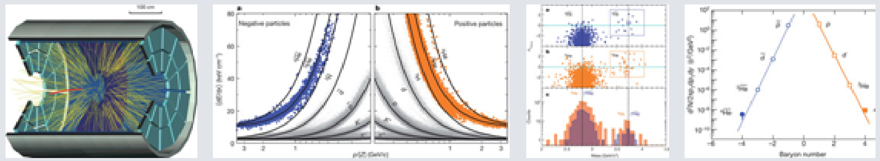
High-energy nuclear collisions create an energy density similar to that of the Universe microseconds after the Big Bang[1]; in both cases, matter and antimatter are formed with comparable abundance. However, the relatively short-lived expansion in nuclear collisions allows antimatter to decouple quickly from matter, and avoid annihilation. Thus, a high-energy accelerator of heavy nuclei provides an efficient means of producing and studying antimatter. The antimatter helium-4 nucleus ($^4\overline{\mathrm{He}}$), also known as the anti-α ($\overline{\alpha}$), consists of two antiprotons and two antineutrons (baryon number $B = -4$). It has not been observed previously, although the α-particle was identified a century ago by Rutherford and is present in cosmic radiation at the ten per cent level[2]. Antimatter nuclei with $B < -1$ have been observed only as rare products of interactions at particle accelerators, where the rate of antinucleus production in high-energy collisions decreases by a factor of about 1,000 with each additional antinucleon[3,4,5]. Here we report the observation of $^4\overline{\mathrm{He}}$, the heaviest observed antinucleus to date. In total, 18 $^4\overline{\mathrm{He}}$ counts were detected at the STAR experiment at the Relativistic Heavy Ion Collider (RHIC; ref. 6) in 10^9 recorded gold-on-gold (Au+Au) collisions at centre-of-mass energies of 200 GeV and 62 GeV per nucleon–nucleon pair. The yield is consistent with expectations from thermodynamic[7] and coalescent nucleosynthesis[8] models, providing an indication of the production rate of even heavier antimatter nuclei and a benchmark for possible future observations of $^4\overline{\mathrm{He}}$ in cosmic radiation.

Figures at a glance



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Existence is no surprise

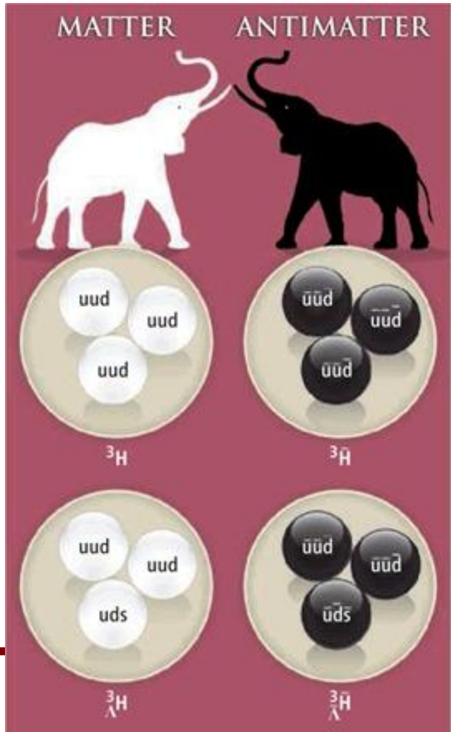
It's still unclear whether finding the antihypertriton will have practical implications for physics, said Frank Close, a physicist at the University of Oxford and author of the book *Antimatter*. "One way of saying it is it's **stamp collecting**. Some stamps are more exciting than others," he said. "The fact that this particle has been found **confirms our general belief** that antimatter should exist just as much as matter exists," Close added. --- February 2011, National Geographic

"It is an enormous technical achievement that they can extract these rarely produced objects," says Tom Cohen, a nuclear physicist at the University of Maryland, College Park. "But everybody believed—I should almost say knew—
that anti-alpha particles could exist." Cohen compares the feat with climbing the world's tallest mountain: "It's really impressive that you can do it, but the fact that there's **a summit to Mount Everest is not a big surprise**."

"It's really, really very impressive that they're able to do that, to see these rare events and convincingly isolate them," he says. "What they've found is that **there is no shock**; it's where it's predicted to be."

"Some of my colleagues take it for granted that there obviously has to be an anti-alpha. My view, and I am a theorist, is that it **is just an idea** – of course a good idea - **until it is actually seen**. The fact that you encountered the antihypertriton - no one's obvious choice - on the way, is a sign that probing the attainable structure of antimatter is a real scientific adventure. "

Science Perspectives Vol 328



Predictability is a shock

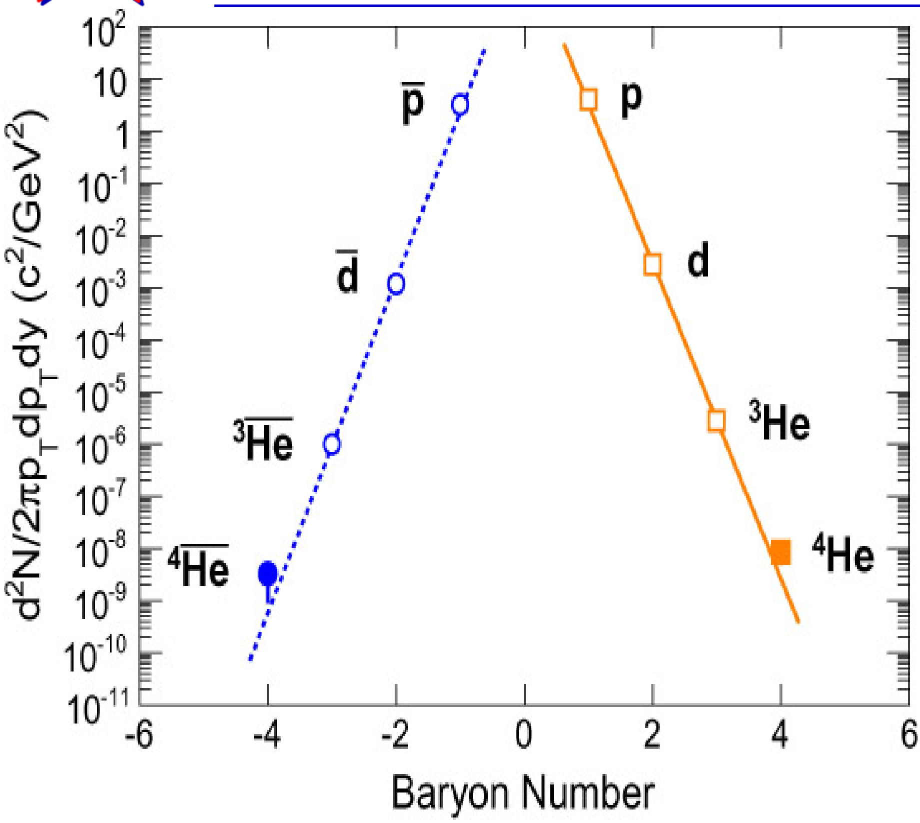
If I told you that:

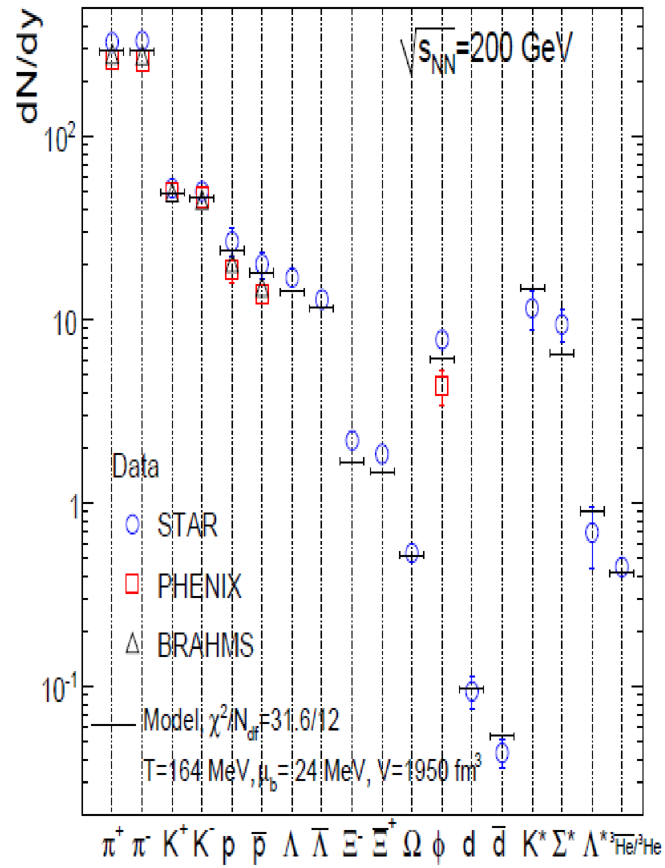
1. create a state of matter at 4×10^{12} degree out of a few thousands of particles
2. Matter and antimatter do not annihilate at energy density 100 times the normal nuclear density
3. Anti-nuclei and nuclei with weak binding energy carry information from the QGP phase transition (Temperature = 160MeV)
4. All particles maintain statistical equilibrium (no sign of annihilation but coalescence)
5. Models that assume thermal equilibrium correctly account for yields spanning 11 orders of magnitude.
   $\pm$0.00000000001

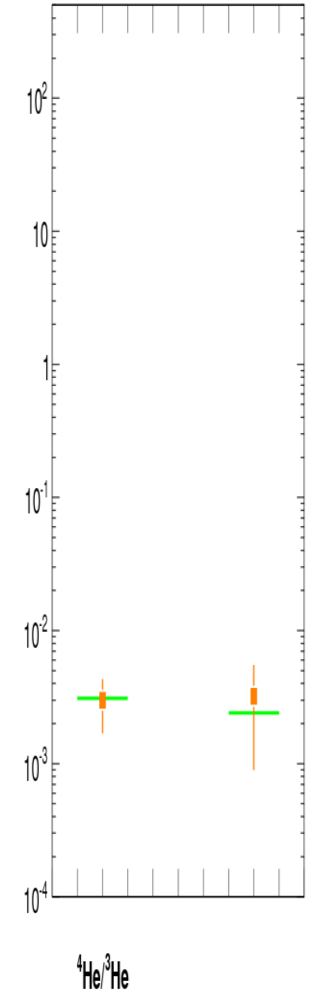
How many of you would say that “I expect that!”?

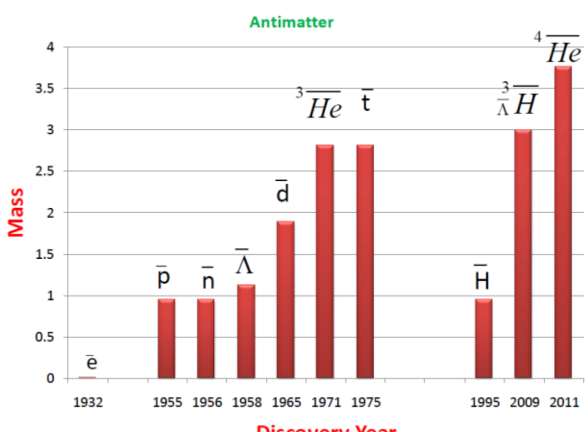
That is what we did when we found all these
Heavy antimatter nuclei!

Predictable Production Rate



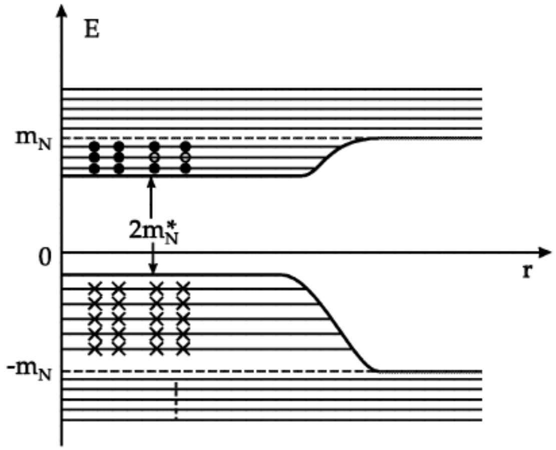


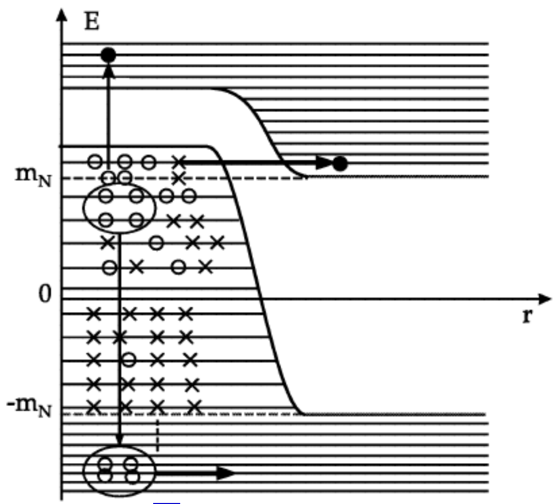


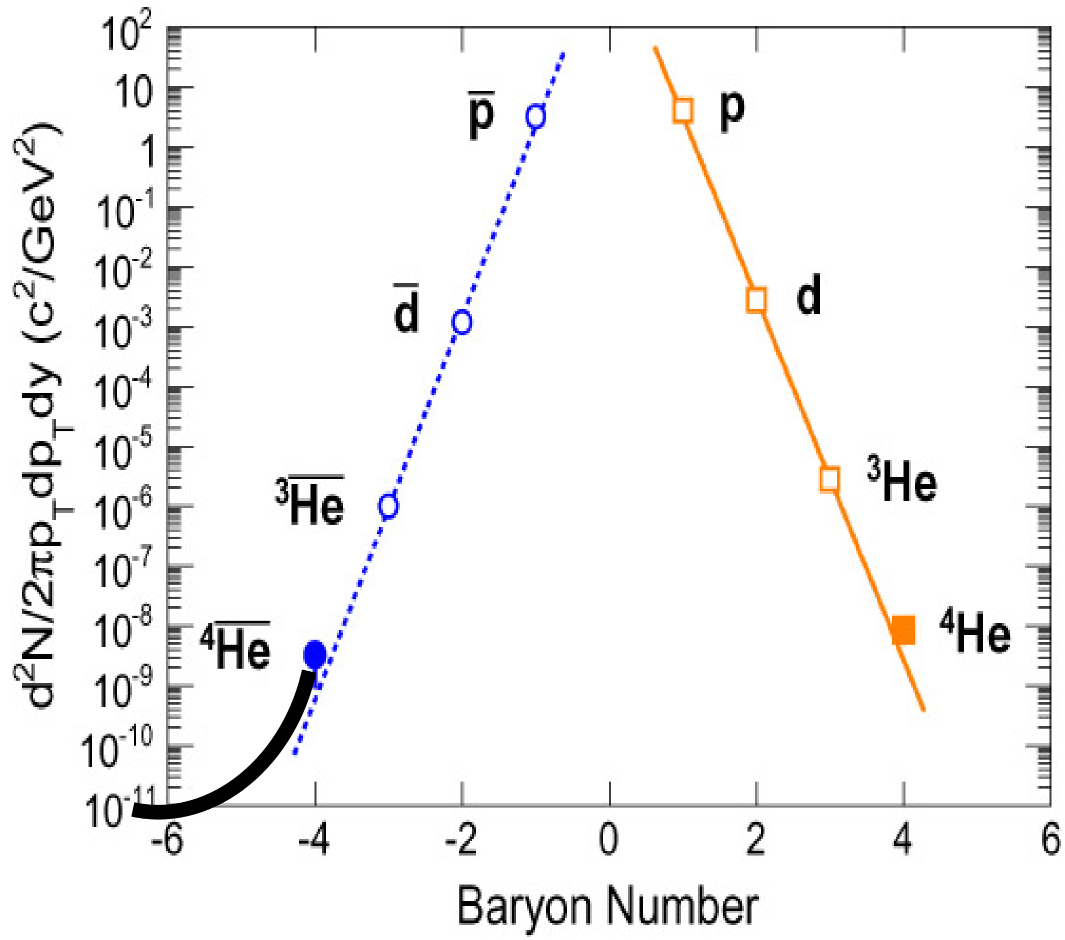


Why is it so predictable?
T=164MeV?

Even Heavier Antimatter







- Pull $\bar{\alpha}$ from vacuum (Dirac Sea)

Search for antimatter Unstable Nuclei

NEXT:

Discover antimatter Unstable Nuclei:

$^{4}Li \rightarrow {}^{3}He+p$

$^{4}He^{*} \rightarrow d+d,\ t+p$

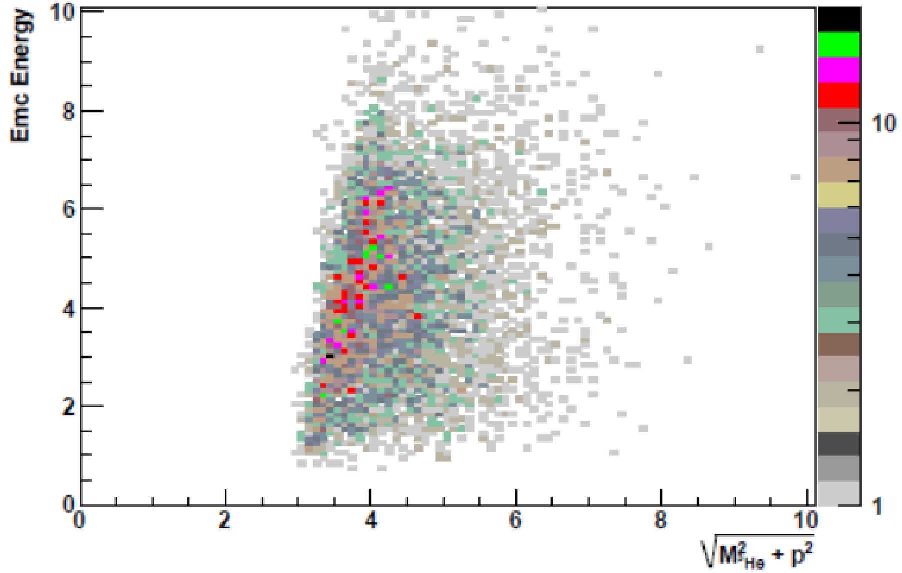
$^{5}Li \rightarrow {}^{4}He+p$

$^{4}_{\Lambda}H \rightarrow {}^{4}He+\pi$

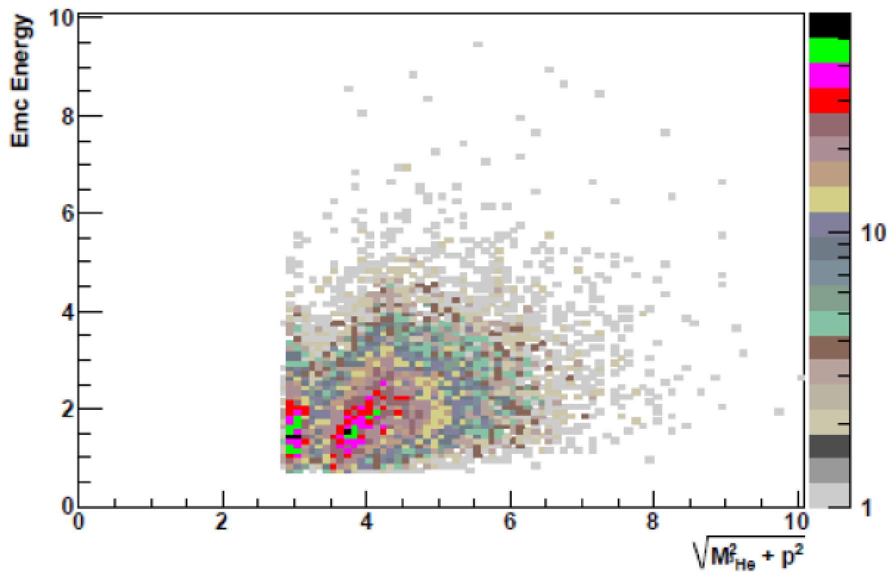
- Clear energy excess:
  EMC energy vs TPC Energy
  He3bar (top panel) He3 (bottom panel)
  Run10, He3bar efficiency with Et>2.5GeV is 62%

Proposed Trigger:

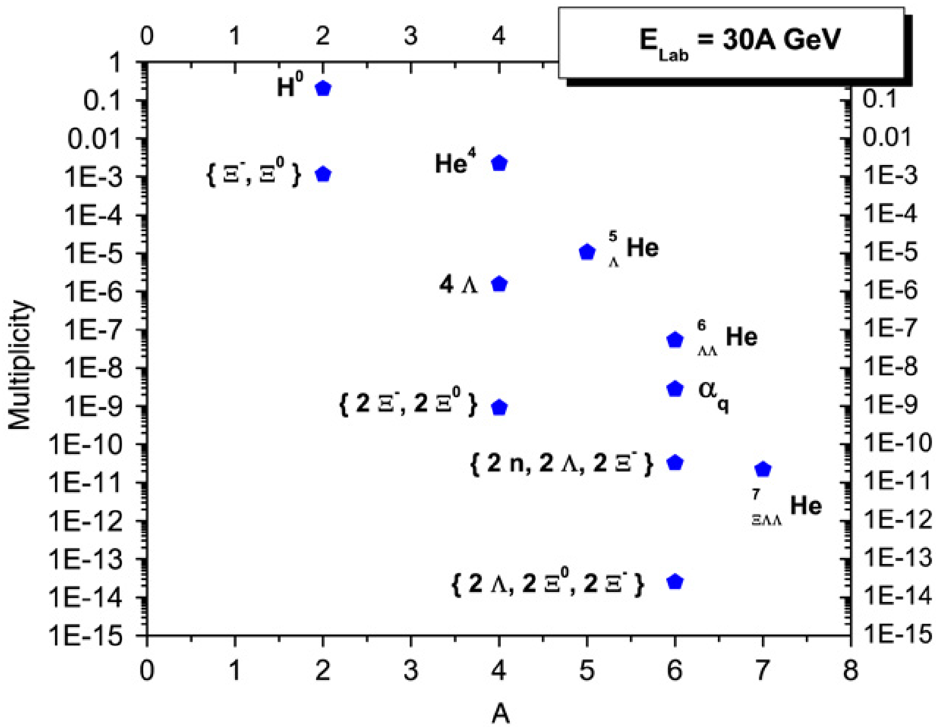
- L0 EMC HT>1.8 or 2.5GeV
- L0 decision on TPC sector readout
- Read events at high rate with 1--2 TPC sectors (He3bar and pbar close in sector)
- Full RHIC II luminosity
- Two order of magnitude enhancement

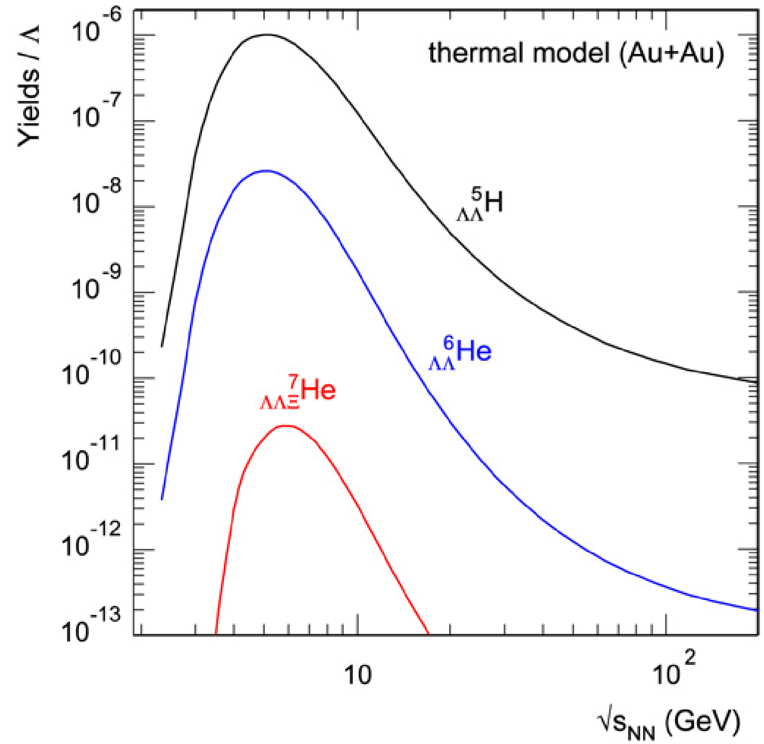


Anti-He3 and He3 energy deposit in calorimeter



Exotic Hypernuclei

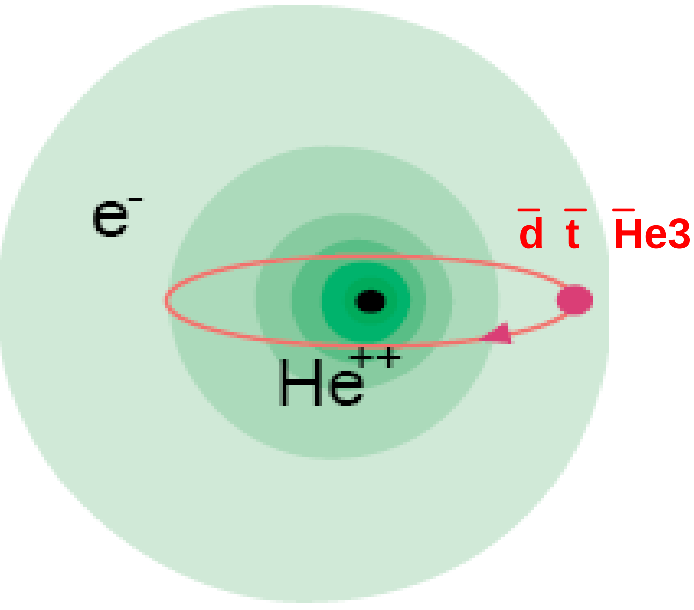




A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A 772 (2006) 167.
P. Braun-Munzinger, J. Stachel, J. Phys. G 21 (1995) L17
A. Andronic: SQM09

Creating first Antinucleus Atomcules

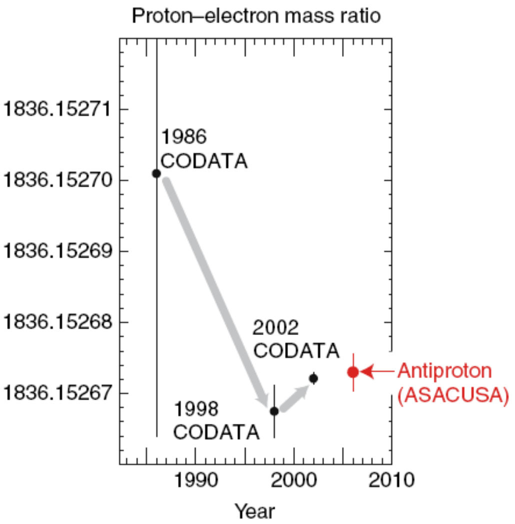
Metastable antiproton-helium atom discovered at KEK:
Iwasaki, **PRL** 67 (1991); **nature** 361 (1993) 238
Mass difference: p-pbar < 2×10^{-9}; Hori, **PRL** 96 (2006);
measurement of baryon mass and magnetic moment
for CPT test at LEAR/CERN
http://asacusa.web.cern.ch/ASACUSA/index-e.html



What happens if we replace antiproton with **antideuteron, antitriton or antiHelium3**

Atomic structure should be the same for antideuteron and antitriton (-1 charge)
Reduced mass M* will be different.

Only RHIC can answer this question with enough antimatter nuclei for such study



Possible Physics Topics:

- Measure antinucleus mass and magnetic moment for CPT test,
- Study the antinucleus annihilation process (sequence)
- antinucleus-nucleus Annihilation (what do they create? Hot or cold matter)
- Maybe even antiAlpha Atomcule

Muonic Hydrogenlike Atoms

RAPID COMMUNICATIONS

PHYSICAL REVIEW D VOLUME 48, NUMBER 9 1 NOVEMBER 1993

Production of muon-meson atoms in ultrarelativistic heavy-ion collisions

Gordon Baym,* Gerald Friedman, R. J. Hughes, and Barbara V. Jacak
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 9 November 1992)

Ultrarelativistic heavy-ion collisions should produce hydrogen-atom-like Coulomb bound states of muons and mesons. Such atoms could provide a convenient way to measure the muon momentum distribution. We estimate the production rate of pion-muon atoms expected from heavy-ion colliders.

PACS number(s): 25.75.+r, 13.85.Rm, 24.60.Ky, 36.10.−k

Soft leptons produced in the early evolution of an ultrarelativistic heavy-ion collision are a potentially important probe of the collision volume. It is difficult to measure the spectrum of directly produced soft leptons because of the large number of charged particles created in the collision and the need to separate the directly produced leptons from those arising from hadronic decays. However, it has been suggested [1] that the detection of muon-meson atoms, consisting of a muon electromagnetically bound to a π or K meson, provides a method to study the soft lepton spectrum. With magnetic analysis, such neutral atoms can be readily separated from the large flux of charged particles [2]. On the other hand, π-π and K-K atoms annihilate long before detection, and muons produced by most weak hadronic decays are not captured by directly produced mesons to form atoms because they are generally made too late in the evolution of the collision. Pion-muon atoms provide a sample of muons of transverse momentum below 1 GeV/c, a momentum range otherwise experimentally inaccessible due to contamination by muons from hadronic decays and difficulties in particle identification. Measurements in this range are capable of probing thermal electromagnetic emission processes in an initial plasma with a temperature ~200 MeV.

$m_{red}=(m_1^{-1}+m_2^{-1})^{-1}$ is the reduced mass for the relative motion of the constituents (of masses m_1 and m_2). A π-μ atom is ≈450 fm in radius, and a K-μ atom ≈250 fm. Consequently, atom formation occurs well after freeze-out through coalescence of particles sufficiently close in phase space, and is sensitive only to the particle distributions at freeze-out.

Other atoms such as K-μ, π-π, and K-π will be produced in heavy-ion collisions in addition to π-μ. As probes of the muon spectrum, K-μ atoms are less effective than π-μ atoms, because K-μ atoms primarily include muons only of small transverse momenta. To form a K-μ atom, the kaon must have a transverse momentum larger than that of the muon by a factor m_K/m_μ, and thus the transverse-momentum fraction of the muons is $\approx\frac{1}{6}$ that of K-μ atom. On the other hand, the constituents of π-μ atoms have comparable masses and thus are formed from mesons of comparable transverse momenta. π-π and K-π atoms are of less interest as they contain no leptons. We calculate here only the production rate for π-μ atoms, although the calculation is readily extended to other types of atoms.

In a hydrogenic atom, the relative velocity v_{rel} of the two constituents is $\alpha c/n$, the Bohr velocity, where n is the principal quantum number (=1 in the ground state)

PHYSICAL REVIEW C VOLUME 59, NUMBER 5 MAY 1999

Hydrogenlike atoms from ultrarelativistic nuclear collisions

Joseph Kapusta* and Agnes Mocsy†
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455
(Received 3 December 1998)

The number of hydrogenlike atoms produced when heavy nuclei collide is estimated for central collisions at the Relativistic Heavy Ion Collider using the sudden approximation of Baym *et al.* As first suggested by Schwartz, a simultaneous measurement of the hydrogen and hadron spectra will allow an inference of the electron or muon spectra at low momentum where a direct experimental measurement is not feasible. [S0556-2813(99)03605-5]

PACS number(s): 25.75.−q

VOLUME 48, NUMBER 16 PHYSICAL REVIEW LETTERS 19 APRIL 1982

Measurement of the Rate of Formation of Pi-Mu Atoms in K_L^0 Decay

S. H. Aronson, R. H. Bernstein, G. J. Bock, R. D. Cousins, Jr.,[a] J. F. Greenhalgh,[b] D. Hedin,[c] M. Schwartz, T. K. Shea, G. B. Thomson,[d] B. Winstein
Brookhaven National Laboratory, Upton, New York 11973, and University of Chicago, Chicago, Illinois 60637, and Stanford University, Stanford, California 94305, and University of Wisconsin, Madison, Wisconsin 53706
(Received 5 February 1982)

Hydrogenlike atoms consisting of a pion and a muon can be formed in $K_L^0\to\pi\mu\nu$ decays. In an intense, high-energy K_L^0 beam, 320 pi-mu atoms were detected and simultaneously the K_L^0 flux was monitored by recording ordinary $K_L^0\to\pi\mu\nu$ decays. The first measurement is reported of the branching ratio $R=\Gamma(K_L^0\to\text{pi-mu atom}+\nu)/\Gamma(K_L^0\to\pi\mu\nu)=(3.88\pm0.41)\times10^{-7}$, using a subset of 155 atoms. This ratio may be sensitive to anomalous interactions between the pion and the muon. In the absence of such interactions, theory predicts $R=(4.43\pm0.12)\times10^{-7}$.

PACS numbers: 13.20.Eb, 13.60.-r, 14.40.Aq, 36.10.-k

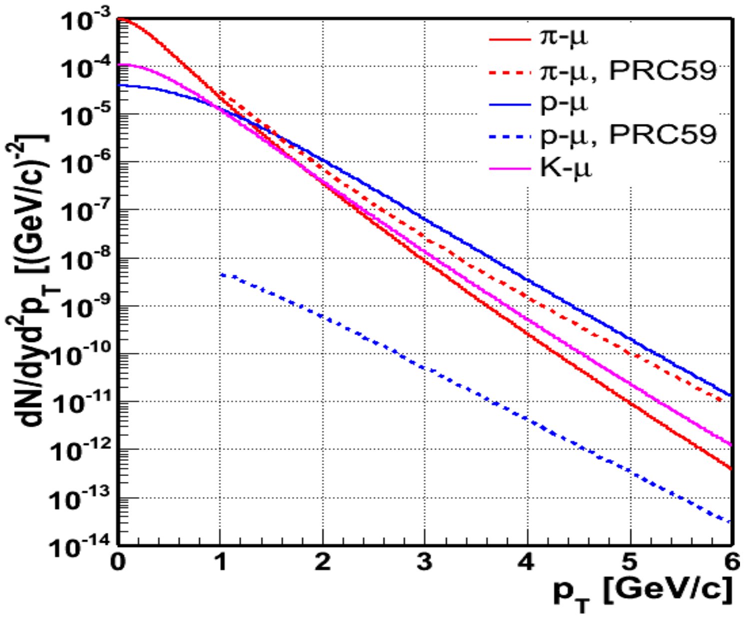
- Exciting possible new discoveries:
  K-μ atoms;
  antimatter mounic hydogen: $\bar{p}$-μ^+

$$\frac{dN_{\rm atom}}{dy\,d^2p_{\perp,\rm atom}}=8\pi^2\zeta(3)\alpha^3m_{\rm red}^2\frac{dN_h}{dy\,d^2p_{\perp,h}}\frac{dN_l}{dy\,d^2p_{\perp,l}}. \quad (1)$$

- Direct measure of single lepton spectrum from thermal radiation

Rate Estimates

- Muon PID using TOF/TPC/MTD
- the antimatter muonic hydrogen:
  >1000 candidates in 500M central events
- MTD trigger for π-μ high-pt atoms with single TPC sector readout



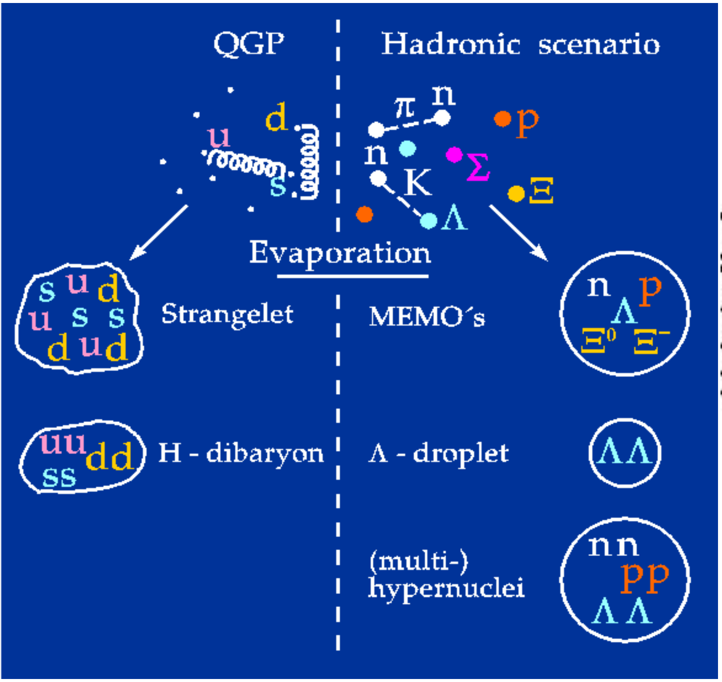
Atom	μ pt (GeV/c)	Hadron pt	Atom pt	dN/dy
π−μ	[0.17,0.3]	[0.22,0.4]	[0.39,0.7]	3e-4
K-μ	[0.17,0.3]	[0.8,1.4]	[0.97,1.7]	3e-5
p-μ	[0.17,0.3]	[1.5,2.7]	[1.7,3.0]	1e-5
π−μ	>1.5	>2	>3.5	1e-8

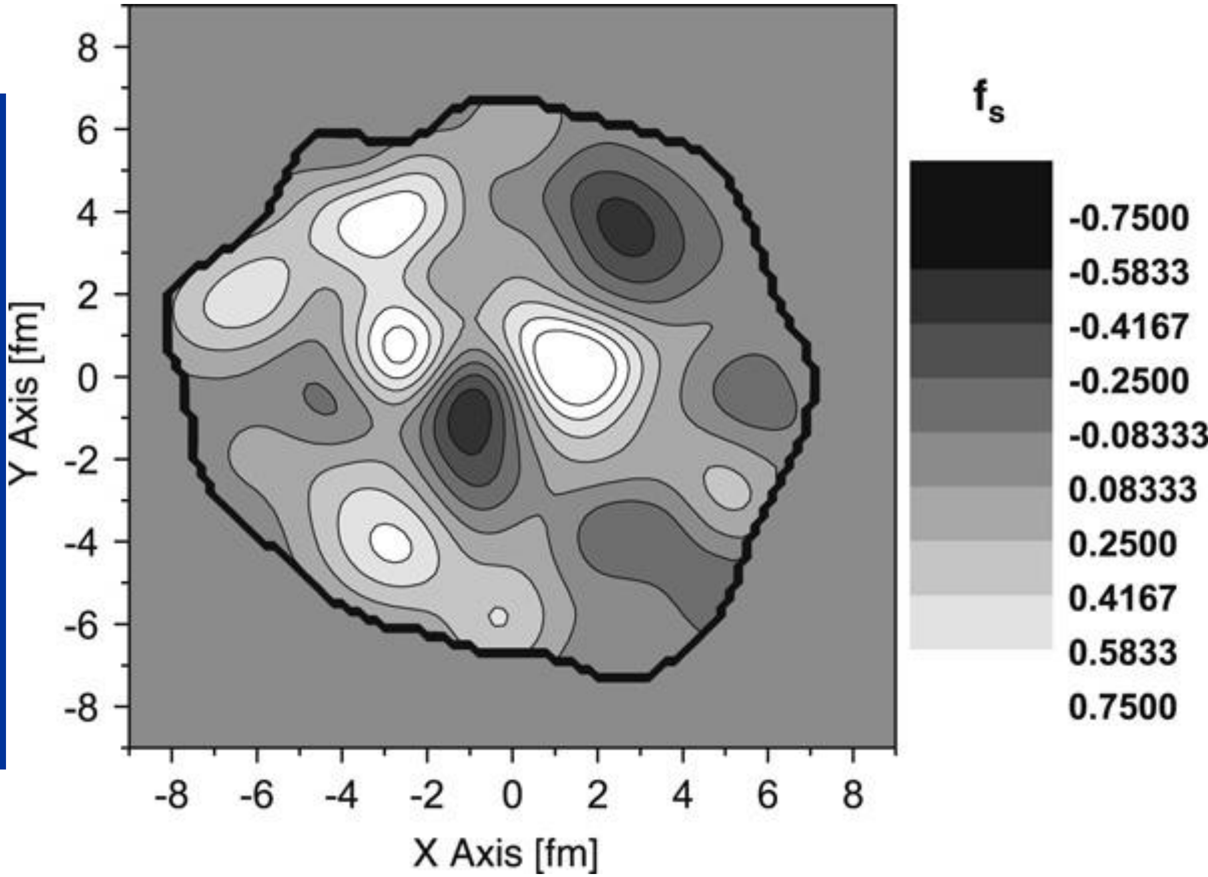
Conclusion and Outlook

- $^{3}_{\Lambda}\overline{\mathrm{H}}$ has been observed for 1st time; significance ~4σ.
- Discovery of antimatter Helium-4

- **$_{\Lambda}^{3}H \rightarrow d+p+\pi$ channel measurement: *d* and $\bar{d}$ via ToF.**
- **Search for other hypernucleus: $^{4}_{\Lambda}H$, double Λ-hypernucleus.**
- **heavier antinuclei, antinucleus atomcules, muonic hydrogen**
- **RHIC: best antimatter machine**

Strangeness Fluctuation





UrQMD E-by-E Distribution of the strangeness to baryon fraction in the transverse plane (z=0 fm).

Jan Steinheimer , Horst Stoecker, Ingo Augustin, Anton Andronic, Takehiko Saito,Peter Senger,
Progress in Particle and Nuclear Physics 62 (2009) 313317
J. Steinheimer: SQM09

Yields as a measure of Density Fluctuation

Volume 98B, number 3 PHYSICS LETTERS 8 January 1981

probability $F_d(\boldsymbol{p})$, which is determined by the deuteron internal wave function ψ_d and the spatial distribution functions D_p and D_n through eq. (9). If the $\boldsymbol{k}$-dependences of $P_p(\boldsymbol{k})$ and $P_n(\boldsymbol{k})$ are weak compared with the $\boldsymbol{p}$-dependence of $F_d(\boldsymbol{p})$, eq. (8) becomes equivalent to eq. (1) for $Z = N = 1$ with

$$\tfrac{4}{3}\pi p_0^3 = \int \mathrm{d}\boldsymbol{p}\, F_d(\boldsymbol{p})\,. \tag{10}$$

Using eq. (9), one can express the coalescence volume in terms of ψ_d, D_p and D_n as

$$\tfrac{4}{3}\pi p_0^3 = 2^3 \cdot \tfrac{3}{4} \cdot (2\pi)^3 \int \mathrm{d}\boldsymbol{r}\, |\psi_d(\boldsymbol{r})|^2 D_2(\boldsymbol{r})\,, \quad D_2(\boldsymbol{r}) \equiv \int \mathrm{d}\boldsymbol{r}'\, D_p(\boldsymbol{r}-\boldsymbol{r}')D_n(\boldsymbol{r}')\,. \tag{11,12}$$

$D_2(\boldsymbol{r})$ gives the distribution of the p–n relative coordinate in the HX and is closely related to the interaction volume introduced by Mekjian [6]. In fact, if the spatial size of the internal wave function ψ_d is much smaller than that of the HX, then eq. (11) gives

$$\tfrac{4}{3}\pi p_0^3 \simeq 2^3 \cdot \tfrac{3}{4} \cdot (2\pi)^3 D_2(0)\,. \tag{13}$$

A=2 ➔ Baryon density $\langle\rho_B\rangle$

$D_2(0)$ thus corresponds to the inverse of the interaction volume. In the actual situation, however, the size of the deuteron is comparable to that of the HX and therefore one has to use eq. (11) to relate the coalescence volume with the spatial size of the HX.

Expressions analogous to eqs. (8–10) can be obtained for the other composite particles such as ^{3}H, ^{3}He and ^{4}He. In the case of triton (^{3}H) one gets

$$P(1, 2; \boldsymbol{k}) = \int \mathrm{d}\boldsymbol{p}_1\, \mathrm{d}\boldsymbol{p}_2\, F_t(\boldsymbol{p}_1, \boldsymbol{p}_2) P_p(\boldsymbol{k}+\boldsymbol{p}_1) P_n(\boldsymbol{k} - \tfrac{1}{2}\boldsymbol{p}_1 + \boldsymbol{p}_2) P_n(\boldsymbol{k} - \tfrac{1}{2}\boldsymbol{p}_1 - \boldsymbol{p}_2)\,, \tag{14}$$

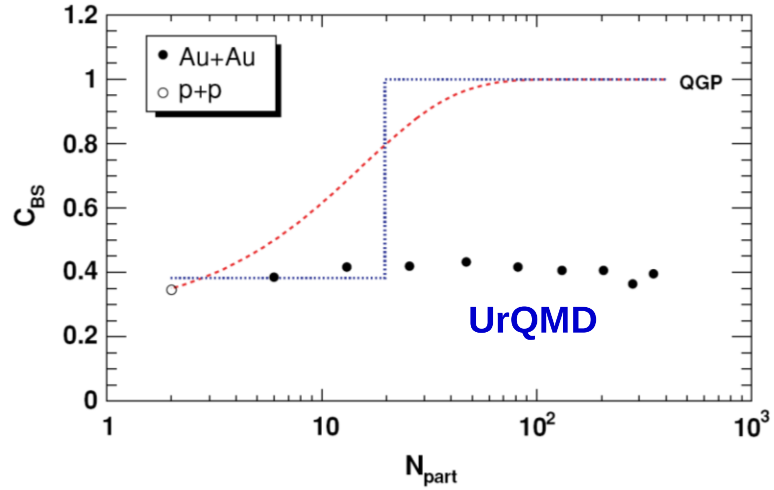
$$F_t(\boldsymbol{p}_1, \boldsymbol{p}_2) = 3^3 \cdot \tfrac{1}{4} \int \frac{\mathrm{d}\boldsymbol{q}_1 \mathrm{d}\boldsymbol{q}_2}{(2\pi)^6}\, \tilde{\psi}_t^*(\boldsymbol{p}_1 + \tfrac{1}{2}\boldsymbol{q}_1, \boldsymbol{p}_2 + \tfrac{1}{2}\boldsymbol{q}_2) \tilde{\psi}_t(\boldsymbol{p}_1 - \tfrac{1}{2}\boldsymbol{q}_1, \boldsymbol{p}_2 - \tfrac{1}{2}\boldsymbol{q}_2)$$

$$\times \tilde{D}_p(\boldsymbol{q}_1) \tilde{D}_n(-\tfrac{1}{2}\boldsymbol{q}_1 + \boldsymbol{q}_2) \tilde{D}_n(-\tfrac{1}{2}\boldsymbol{q}_1 - \boldsymbol{q}_2)\,, \tag{15}$$

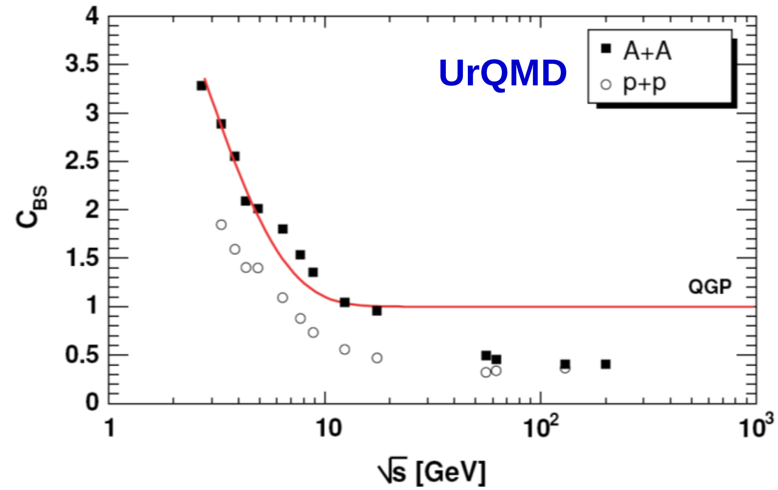
where $\tilde{\psi}_t$ is the Fourier transform of the triton internal wave function ψ_t. The coalescence volume is related to F_t as

$$\tfrac{1}{2}(\tfrac{4}{3}\pi p_0^3)^2 = \int \mathrm{d}\boldsymbol{p}_1\, \mathrm{d}\boldsymbol{p}_2\, F_t(\boldsymbol{p}_1, \boldsymbol{p}_2)\,. \tag{16}$$

A=3 ➔ $\langle\rho_B^2\rangle$; $\langle\rho_\Lambda\rho_B\rangle$



S. Haussler, H. Stoecker, M. Bleicher, PRC73

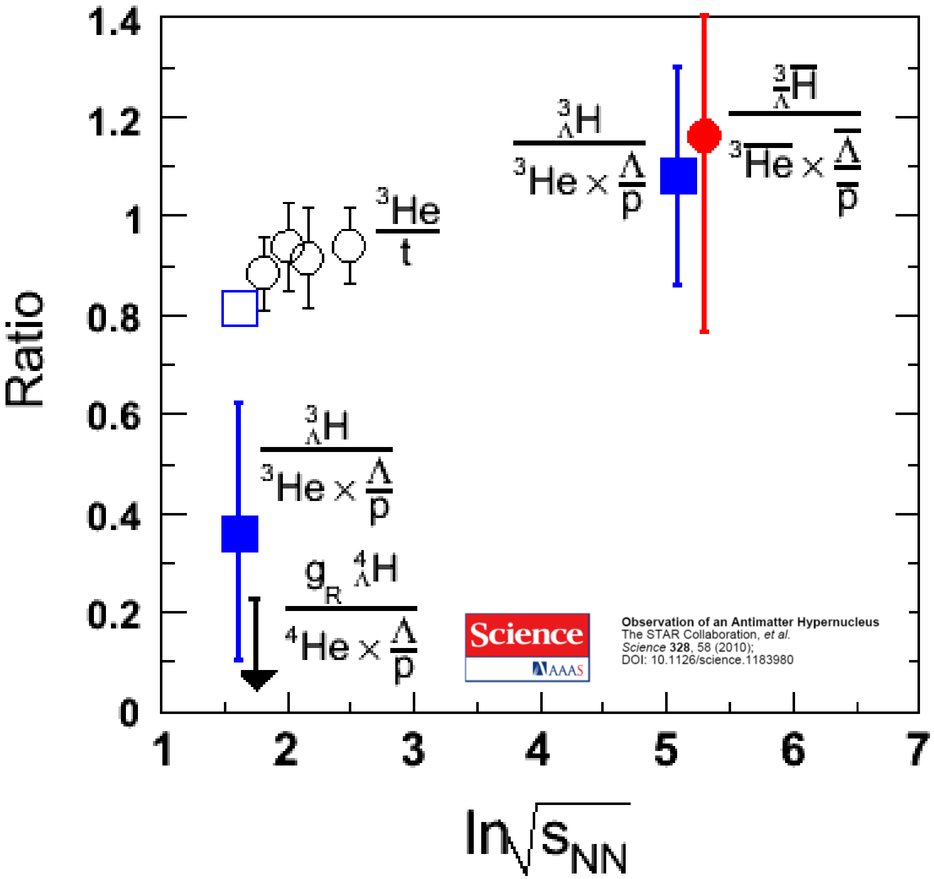


Caution:

measurements related to **local** (strangeness baryon)-baryon correlation

Simulations of (all strangeness)—(all baryon) correlation

$(^3He, t, {}^3_\Lambda H) \rightarrow (u, d, s)$



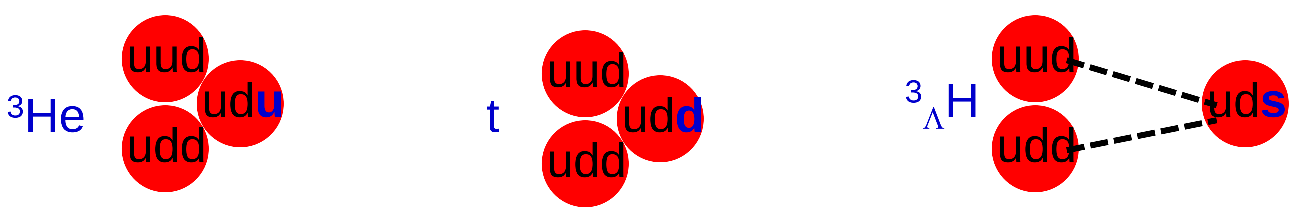
- A=3, a simple and perfect system
  9 valence quarks,
  $(^3He, t, {}^3_\Lambda H) \rightarrow (u, d, s)+4u+4d$

- Ratio measures Lambda-nucleon correlation

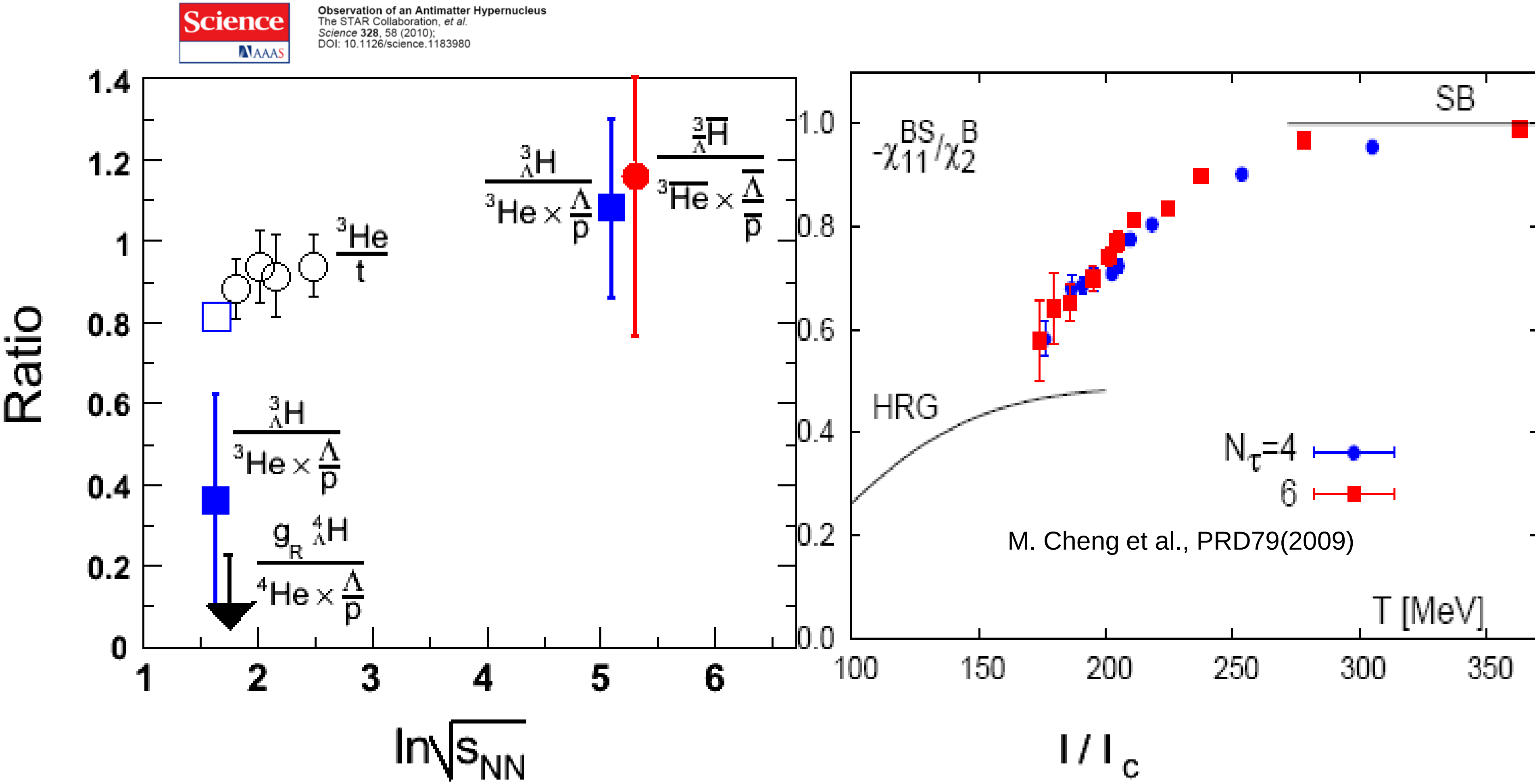
- RHIC: Lambda-nucleon similar phase space
- AGS: systematically lower than RHIC

➔ Strangeness phase-space equilibrium

- $^3He/t$ measures charge-baryon correlation



${}^{3}_{\Lambda}H/{}^{3}He$: Primordial Λ-B correlation

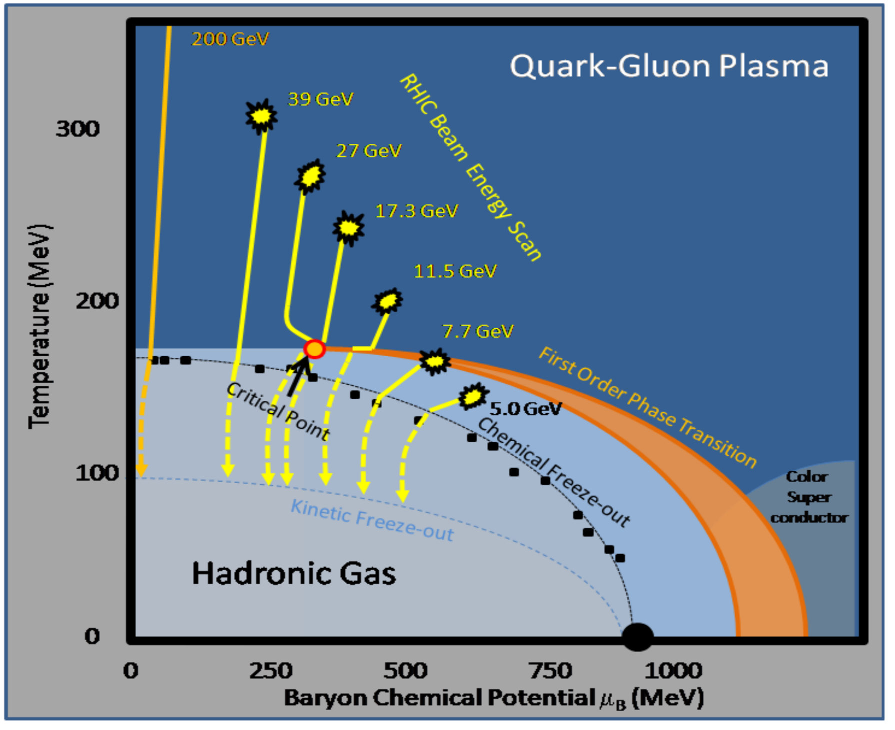


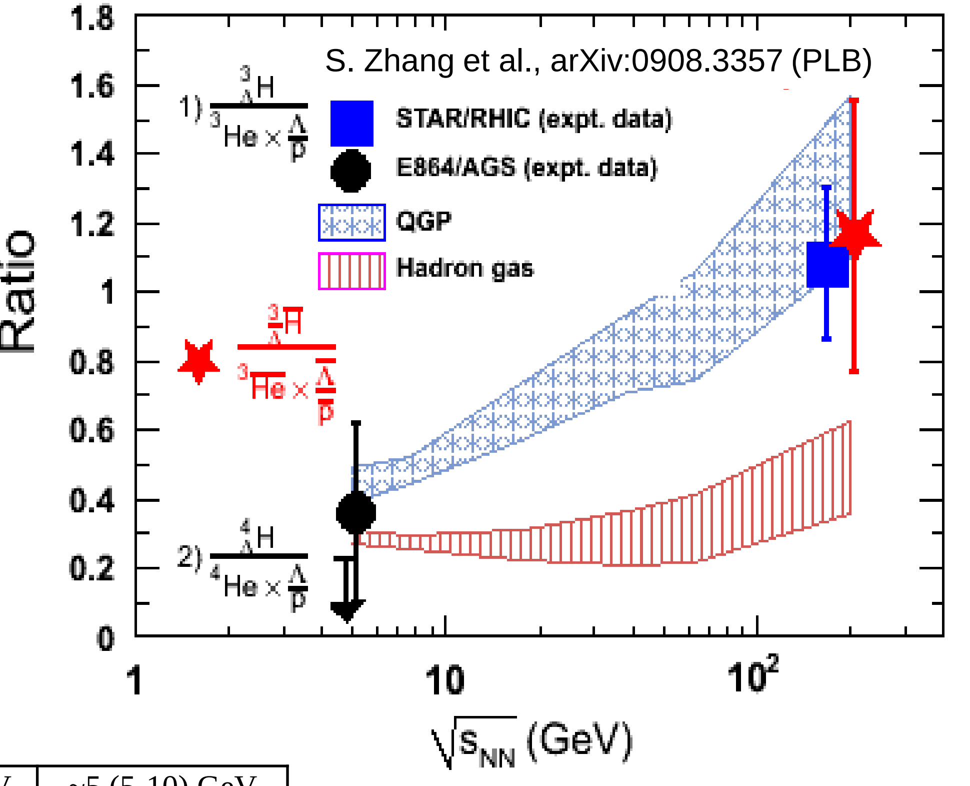
Caution:

measurements related to local (strangeness baryon)-baryon correlation

Lattice Simulations of (all strangeness)—(all baryon) correlation at zero chemical potential

Energy scan to establish the trend





Beam energy	200(30—200) GeV	~17 (10—30)GeV	~5 (5-10) GeV
Minbias events# (5σ)	300M	**~10—100M**	**~1—10M**
Penalty factor	1448	368	48
^{3}He invariant yields	1.6x10^{-6}	2x10^{-4}	0.01
$^3_\Lambda$H/^{3}He assumed	1.0	0.3	0.05

Hypertriton only
STAR: DAQ1000+TOF