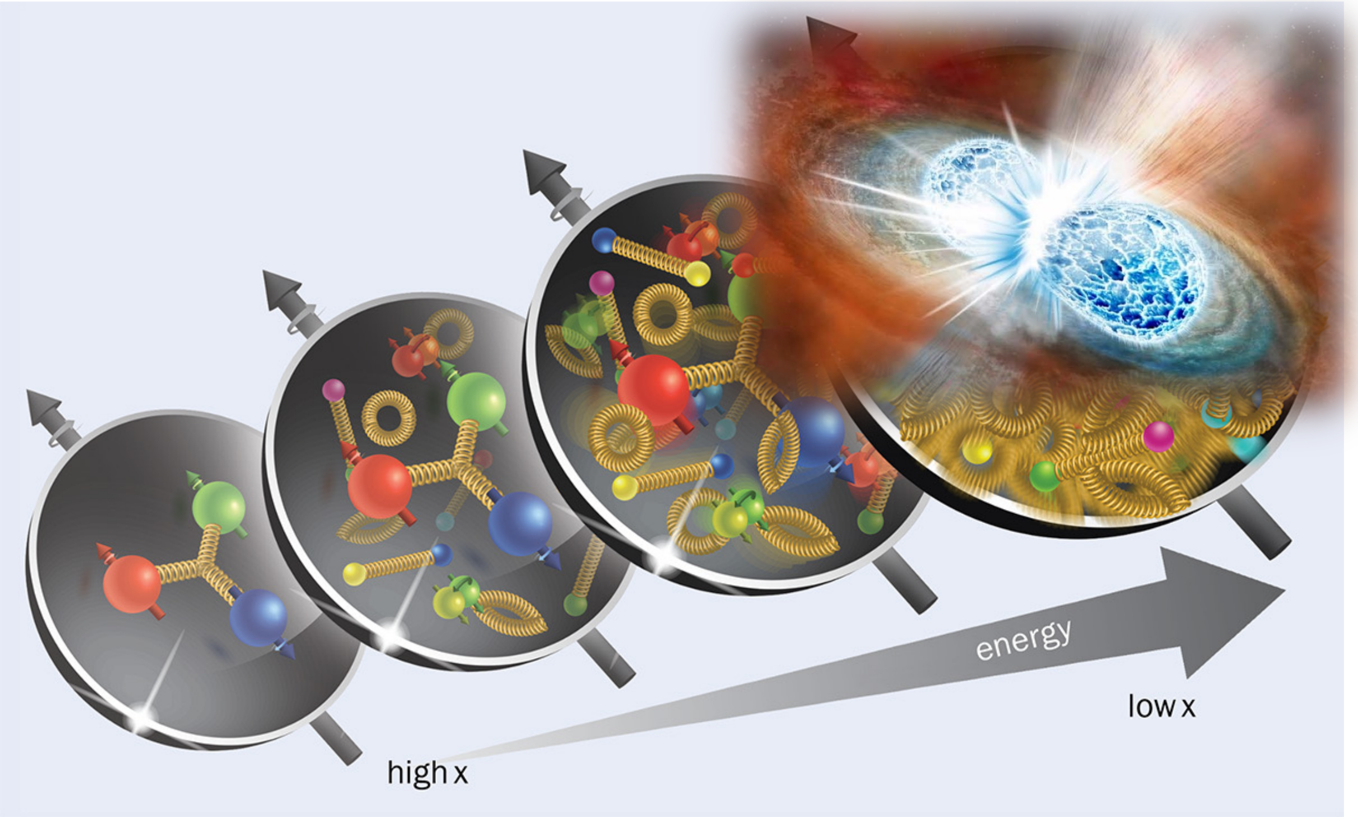
Experiment Overview of nuclear cluster production at RHIC



Zhangbu Xu
(Kent State University)

- B=1: simplest gluon topology in QCD
- B=3,2 nuclear yield ratio as probe of quantum wavefunction overlaps and density fluctuation
- B=4,3 Hypernuclear properties
- Discovery of B=-4 hypernucleus
- Future:
  charmed hypernuclei and Hoyle states

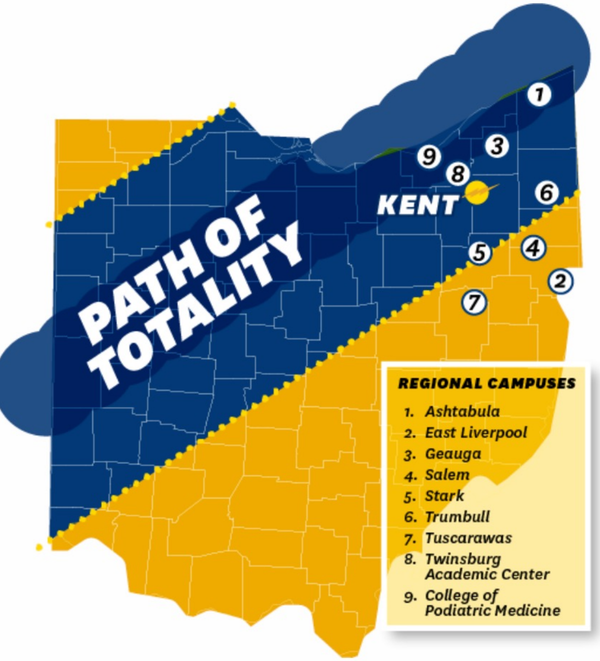
Center for Nuclear Research
KENT STATE UNIVERSITY

In part supported by U.S. DEPARTMENT OF ENERGY Office of Science

EMMI Open Symposium:
Understanding light (anti-)nuclei production at RHIC and LHC

Where is Kent State University?

Path of Totality



Three Minutes of Twilight

On April 8, 2024, Kent, Ohio will be in the path of totality for a solar eclipse where the moon will completely blackout the sun for approximately three minutes at 3:14 p.m. There will not be another total solar eclipse in the U.S. until August 2044; and in Northeast Ohio until September 2099.

Partial Eclipse: 1:59 p.m. to 4:29 p.m.
Total Eclipse: 3:14 p.m. to 3:17 p.m.

Tenskwatawa's prediction

June 16, 1806

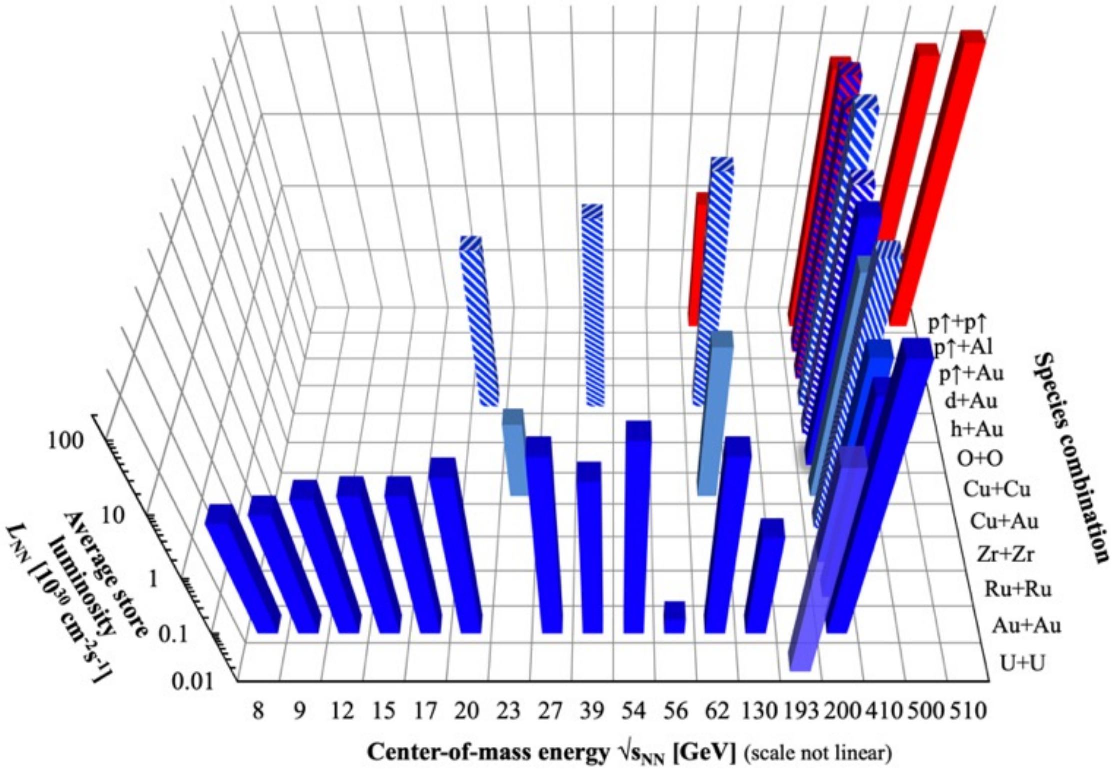
It has been called Tecumseh's Eclipse after the Shawnee chief, Tecumseh. He realized that the only hope for the various tribes in east and central North America was to join. He was assisted by his brother, Tenskwatawa, called The Prophet, who called for a rejection of European influence and a return to traditional values. This tribal unity threatened William Henry Harrison, the Territorial Governor of Indiana and future 9th President of the United States. Harrison tried to discredit the Shawnee leader by challenging Tenskwatawa to prove his powers. He wrote: "If he (Tenskwatawa) is really a prophet, ask him to cause the Sun to stand still or the Moon to alter its course, the rivers to cease to flow or the dead to rise from their graves."

Tenskwatawa declared that the Great Spirit was angry at Harrison and would give a sign. "Fifty days from this day there will be no cloud in the sky. Yet, when the Sun has reached its highest point, at that moment will the Great Spirit take it into her hand and hide it from us. The darkness of night will thereupon cover us and the stars will shine round about us. The birds will roost and the night creatures will awaken and stir." On that day, there was an eclipse, and Harrison's attempt to divide the Shawnee people backfired spectacularly. Then Tecumseh ordered the Great Spirit to release the sun.[1]

Example of versatile colliders and detectors

STAR major upgrades over the last twenty years to improve particle identification and vertex reconstruction and is still evolving with an extension to forward rapidity as of today. pioneered in using new technologies: MRPC, MAPS, GEM and siPM. Estimate 35M(initial) +75M(upgrades)$. PHENIX→sPHENIX

RHIC energies, species combinations and luminosities (Run-1 to 22)

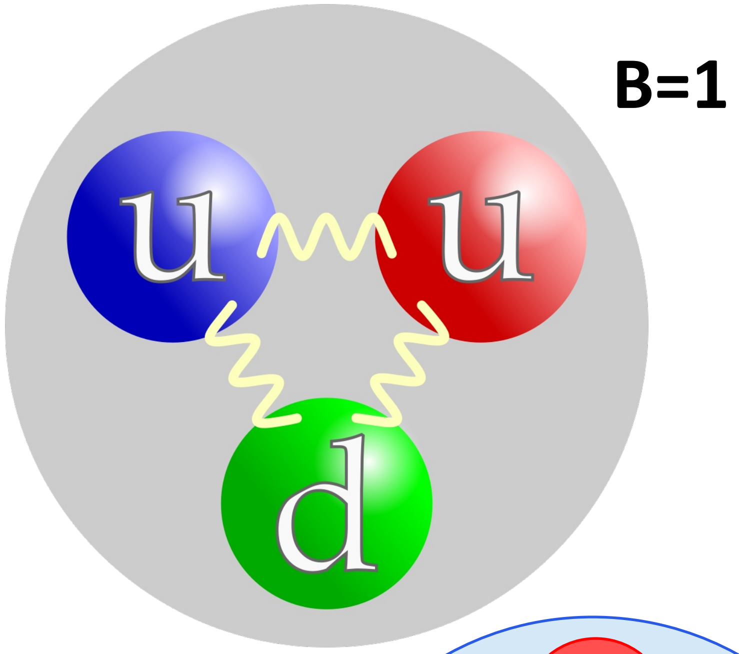


Detector	primary functions	DOE+(in-kind)	year
TPC+Trigger	$\|\eta\| <1$ Tracking		1999-
Barrel EMC	$\|\eta\| <1$ jets/γ/π^0/e		2004-
FTPC	forward tracking	(Germany)	2002-2012
L3	Online Display	(Germany)	2000-2012
SVT/SSD	V0/charm	(France)	2004-2007
PMD	forward photons	(India)	2003-2011
EEMC	$1< \eta <2$ jets/π^0/e	(NSF)	2005-
Roman Pots	diffractive		2009-
TOF	PID	(China)	2009-
FMS/Preshower	$2.5< \eta <4.2$	(Russia)	2008-2017
DAQ1000	x10 DAQ rate		2008-
HLT	Online Tracking	(China/Germany)	2012-
FGT	$1< \eta <2$ $W^{\pm}$		2012-2013
GMT	TPC calibration		2012-
HFT/SSD	open charm	(France/UIC)	2014-2016
MTD	muon ID	(China/India)	2014-
EPD	event plane	(China)	2018-
RHICf	$\eta >5$ π^0	(Japan)	2017
iTPC	$\|\eta\| <1.5$ Tracking	(China)	2019-
eTOF	$-2< \eta <-1$ PID	(Germany/China)	2019-
FCS	$2.5< \eta <4$ calorimeter	(NSF)	2021-
FTS	$2.5< \eta <4$ Tracking	(NCKU/SDU)	2021-

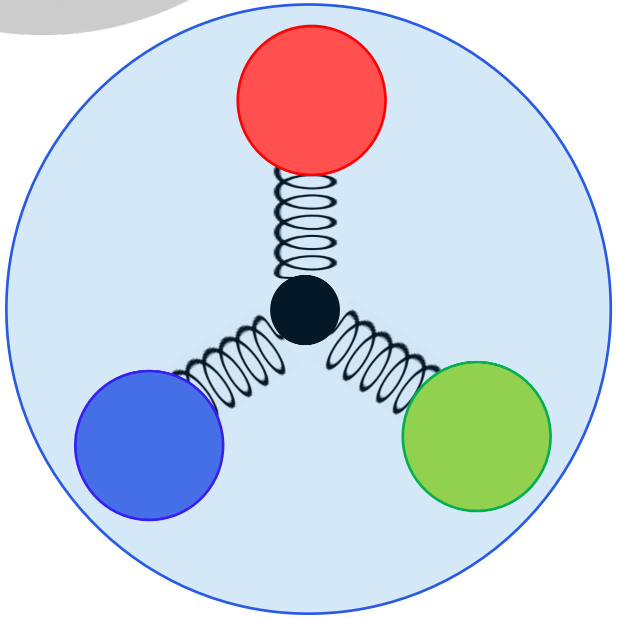
8 new detectors added to STAR since 2014

Baryon Number (B) Carrier

https://en.wikipedia.org/wiki/Quark



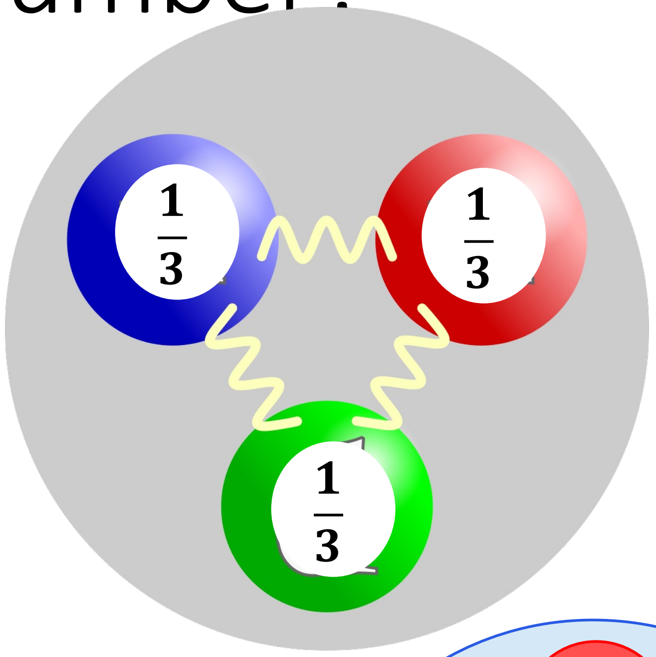
- Textbook picture of a proton
  - Lightest baryon with strictly conserved baryon number
  - Each valence quark carries 1/3 of baryon number
  - Proton lifetime >10^{34} years
  - Quarks are connected by gluons
- Alternative picture of a proton
  - Proposed at the Dawn of QCD in 1970s
  - A Y-shaped gluon junction topology carries baryon number (B=1)
  - The topology number is the strictly conserved number
  - Quarks do not carry baryon number
  - Valence quarks are connected to the end of the junction always

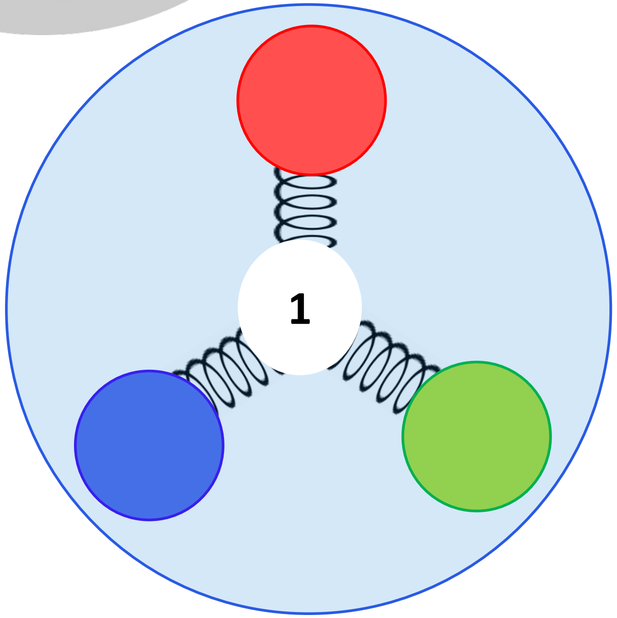


[1]: Artru, X.; String Model with Baryons: Topology, Classical Motion. Nucl. Phys. B 85, 442–460 (**1975**).
[2]: Rossi, G. C. & Veneziano, G. A; Possible Description of Baryon Dynamics in Dual and Gauge Theories. Nucl. Phys. B 123, 507–545 (**1977**)

Measurements of quark baryon number?

- Textbook picture of a proton
  - Lightest baryon with strictly conserved baryon number
  - Each valence quark carries 1/3 of baryon number
  - Proton lifetime >10^{34} years
  - Quarks are connected by gluons
- Alternative picture of a proton
  - Proposed at the Dawn of QCD in 1970s
  - A Y-shaped gluon junction topology carries baryon number (B=1)
  - The topology number is the strictly conserved number
  - Quarks do not carry baryon number
  - Valence quarks are connected to the end of the junction always
- **Neither of these postulations has been verified experimentally**





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[2]: Rossi, G. C. & Veneziano, G. A; Possible Description of Baryon Dynamics in Dual and Gauge Theories. Nucl. Phys. B 123, 507–545 (**1977**)

Model implementations of baryons at RHIC

- Many of the models used for heavy-ion collisions at RHIC (HIJING, AMPT, UrQMD) have implemented a nonperturbative baryon stopping mechanism

V. Topor Pop, *et al,* Phys. Rev. C **70**, 064906 (2004)

Zi-Wei Lin, *et al*, Phys. Rev. C **72**, 064901 (2005)

M. Bleicher, *et al,* J.Phys.G **25,** 1859-1896 (1999)

- Baryon Stopping
  - Theorized to be an effective mechanism of stopping baryons in pp and AA

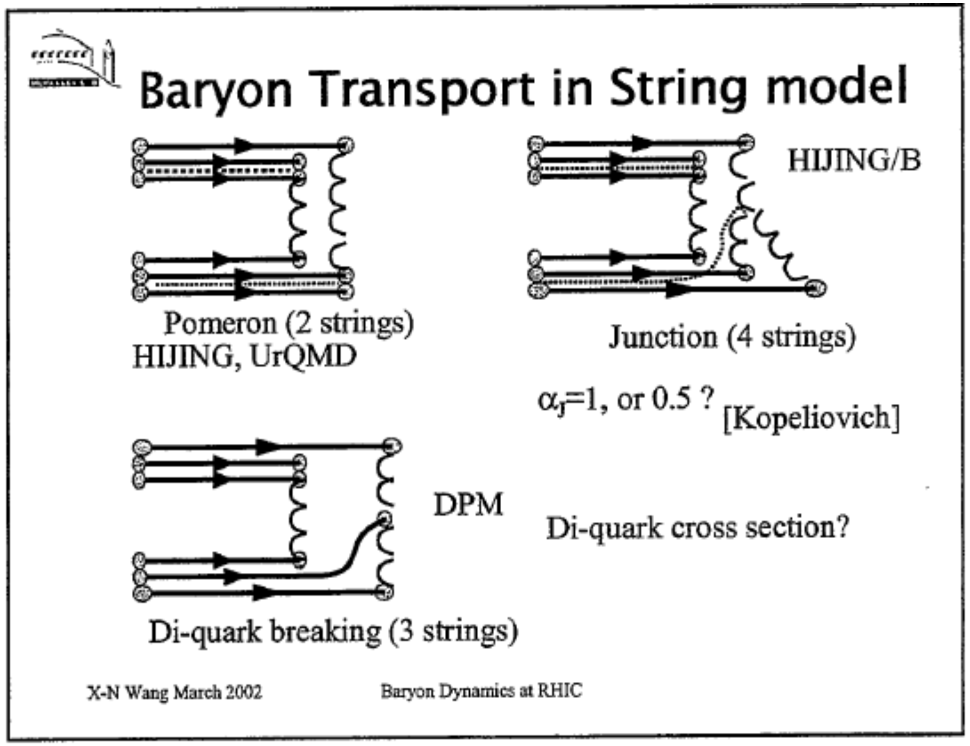
D. Kharzeev, Physics Letters B **378**, 238-246 (1996)

- Specific rapidity dependence is predicted:

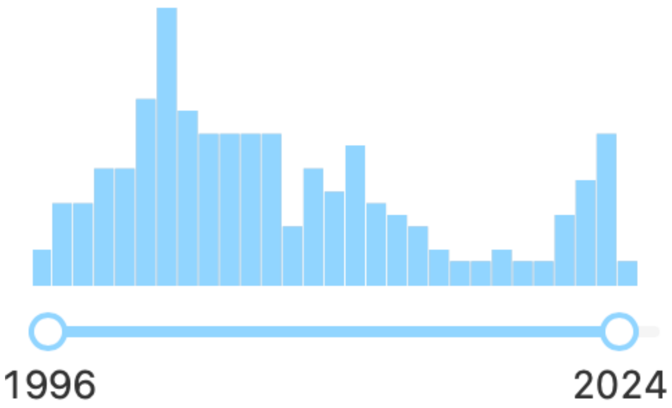
$$p = \sim e^{-\alpha_B y}$$

α_B ~=0.5

2003 RBRC Workshop on "Baryon Dynamics at RHIC"



D. Kharzeev, Physics Letters B **378**, 238-246 (1996)
"Can gluons trace baryon number?"



"Science, however, is never conducted as a popularity contest..." --- Michio Kaku

BUT citations ARE

N·H
ELSEVIER

20 June 1996

Physics Letters B 378 (1996) 238–246

PHYSICS LETTERS B

Can gluons trace baryon number?

D. Kharzeev

Theory Division, CERN, CH-1211 Geneva, Switzerland
and Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld, Germany

Received 15 March 1996
Editor: R. Gatto

Abstract

QCD as a gauge non-Abelian theory imposes severe constraints on the structure of the baryon wave function. We point out that, contrary to a widely accepted belief, the traces of baryon number in a high-energy process can reside in a non-perturbative configuration of gluon fields, rather than in the valence quarks. We argue that this conjecture can be tested experimentally, since it can lead to substantial baryon asymmetry in the central rapidity region of ultra-relativistic nucleus-nucleus collisions.

In QCD, quarks carry colour, flavour, electric charge and isospin. It seems only natural to assume that they also trace baryon number. However, this latter assumption is not dictated by the structure of QCD, and there- … the baryon number $B = 1/3$ to quarks is based merely on the naive quark model classification. But any phys- … state vector which is gauge-invariant – the constraint which is ignored in most of the naive quark model formulations. This constraint turns out to be very severe; in fact, there is only one way to construct a gauge-invariant state vector of a baryon from quarks and gluons [1] (note however that there is a large amount of freedom in choosing the paths connecting x to x_i):

$$B = \epsilon^{ijk}\left[P\exp\left(ig\int_{x_1}^{x}A_\mu dx^\mu\right)q(x_1)\right]_i \times \left[P\exp\left(ig\int_{x_2}^{x}A_\mu dx^\mu\right)q(x_2)\right]_j$$

$$\times\left[P\exp\left(ig\int_{x_3}^{x}A_\mu dx^\mu\right)q(x_3)\right]_k . \quad (1)$$

… $q(x_n)$ make it transform as a quark field at point x instead of at x_n. The ϵ tensor then constructs a local … quark fields (see Fig. 1a). The B in Eq. (1) is a set of gauge invariant operators representing a baryon in QCD. With properly optimised parameters it is used extensively in the first principle computations … lattice Monte Carlo attempting to determine the nucleon mass. The purpose of this work is to study its phenomenological impact on baryon number production in the central region of nucleus-nucleus collisions.

It is evident from the structure of (1) that the trace of baryon number should be associated not with the valence quarks, but with a non-perturbative configuration of gluon fields located at the point x – the "string junction" [1]. This can be nicely illustrated in the string picture: let us pull all of the quarks aw…

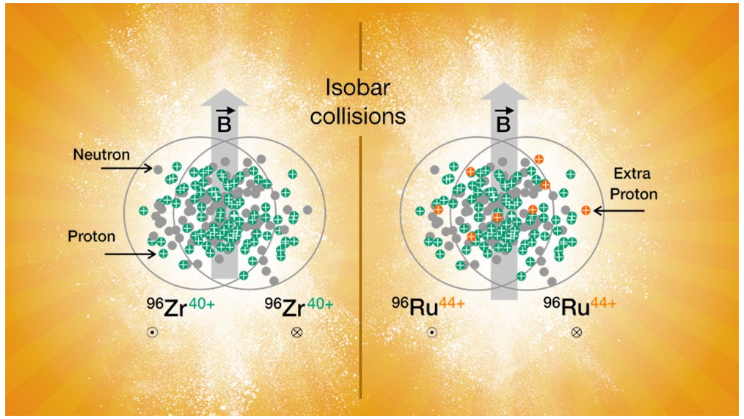
There is only one way to construct a gauge-invariant state vector of a baryon from quarks and gluons

It is evident from th…
that the trace of bar…
be associated not w…
quarks, but with a n…
configuration of glu…
the point x - the "st…

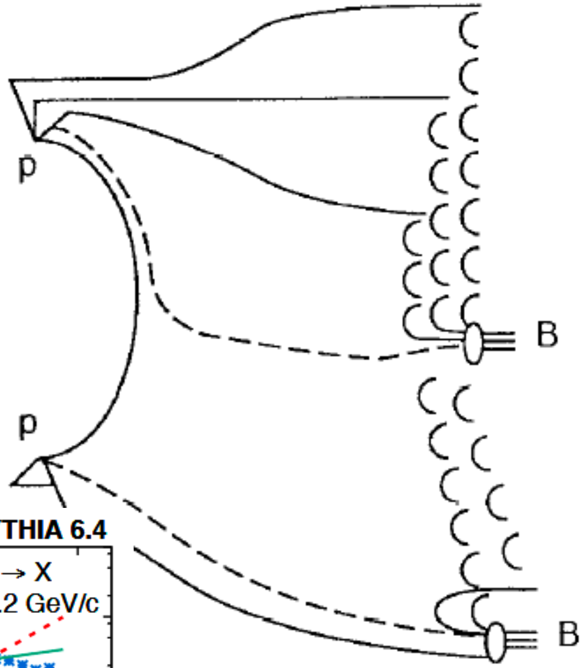
PII S0370-2693(96)00435-2

Three approaches toward tracking the origin of the baryon number

arXiv:2205.05685



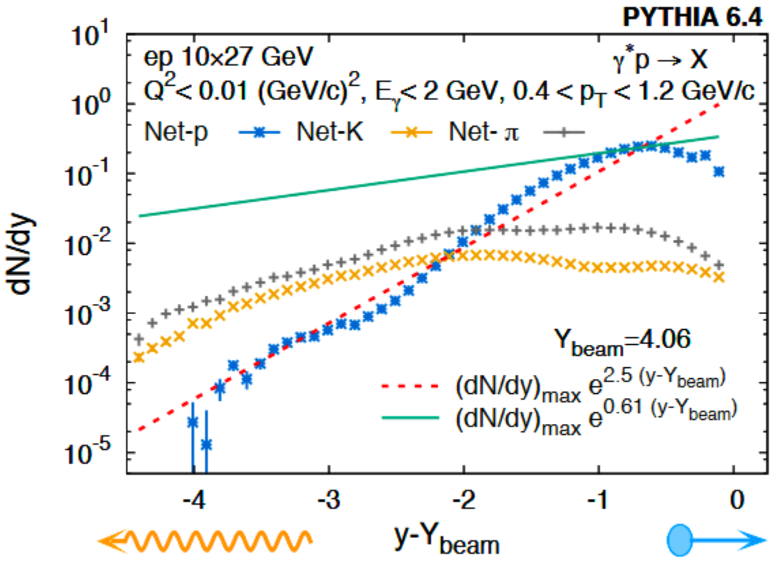
1. STAR Method:
   Charge (Q) stopping vs baryon (B) stopping:
   if valence quarks carry Q and B, Q=B at middle rapidity



2. Kharzeev-STAR Method:
   If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory

$$p = \sim e^{-\alpha_B y}$$

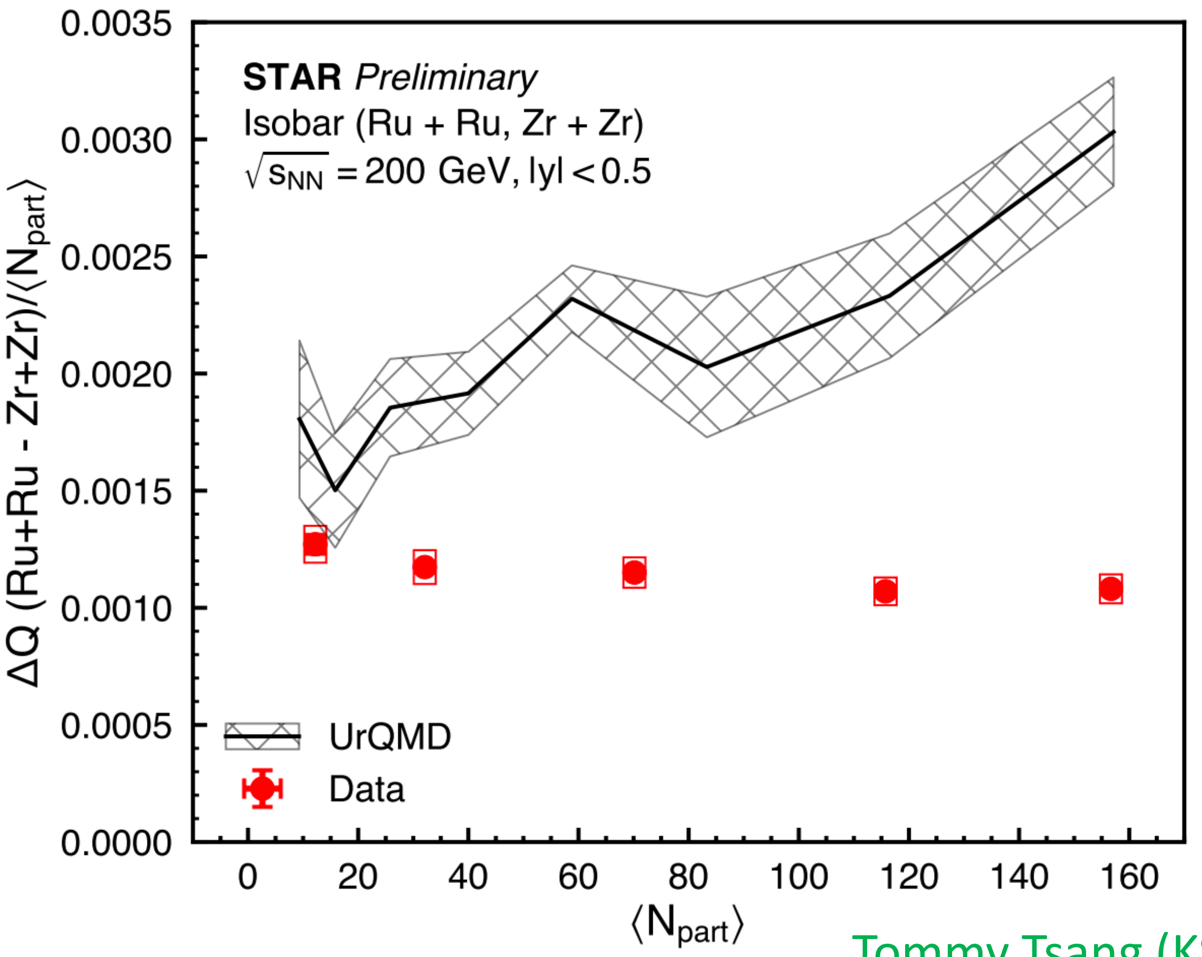
α_B ~=0.5



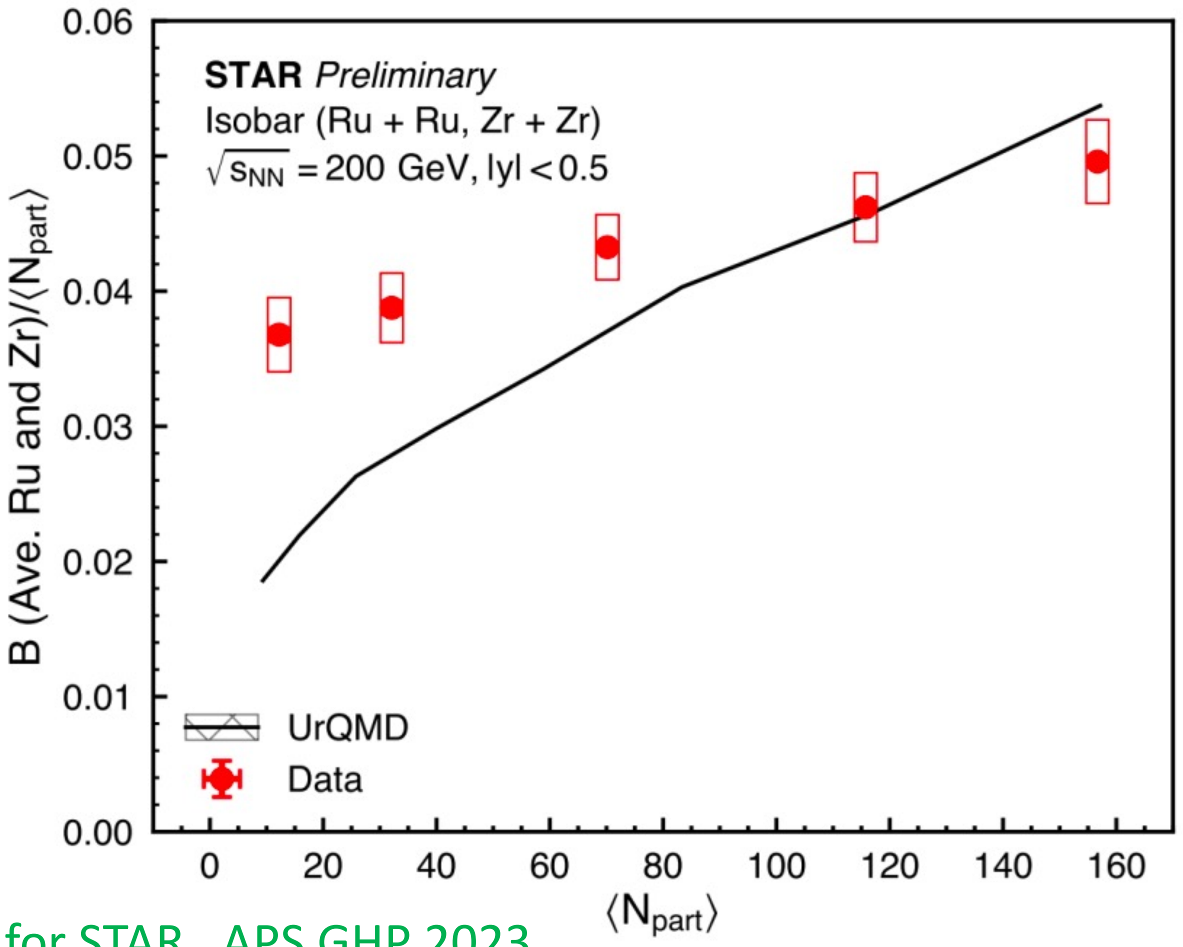
3. Artru Method:
   In γ+Au collision, rapidity asymmetry can reveal the origin

Separate charge and baryon transports

Charge number transport



Baryon number transport



Tommy Tsang (KSU) for STAR, APS GHP 2023

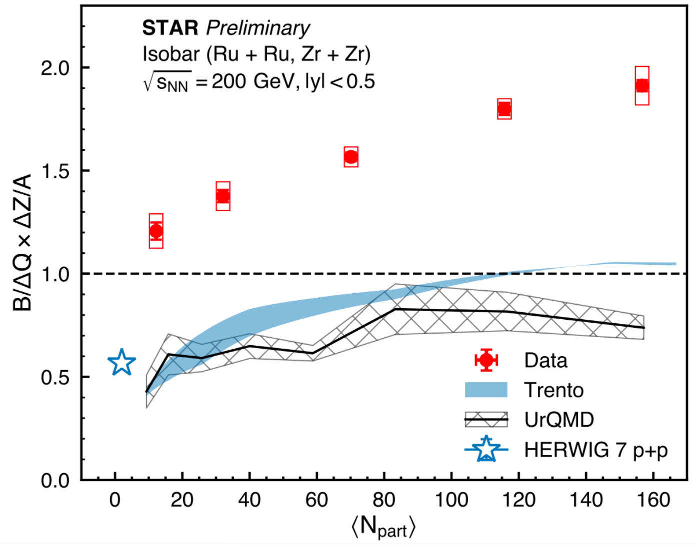
UrQMD matches data on charge stopping better in peripheral; better on baryon stopping in central
overpredicts charge stopping in central; underpredicts baryon stopping in peripheral

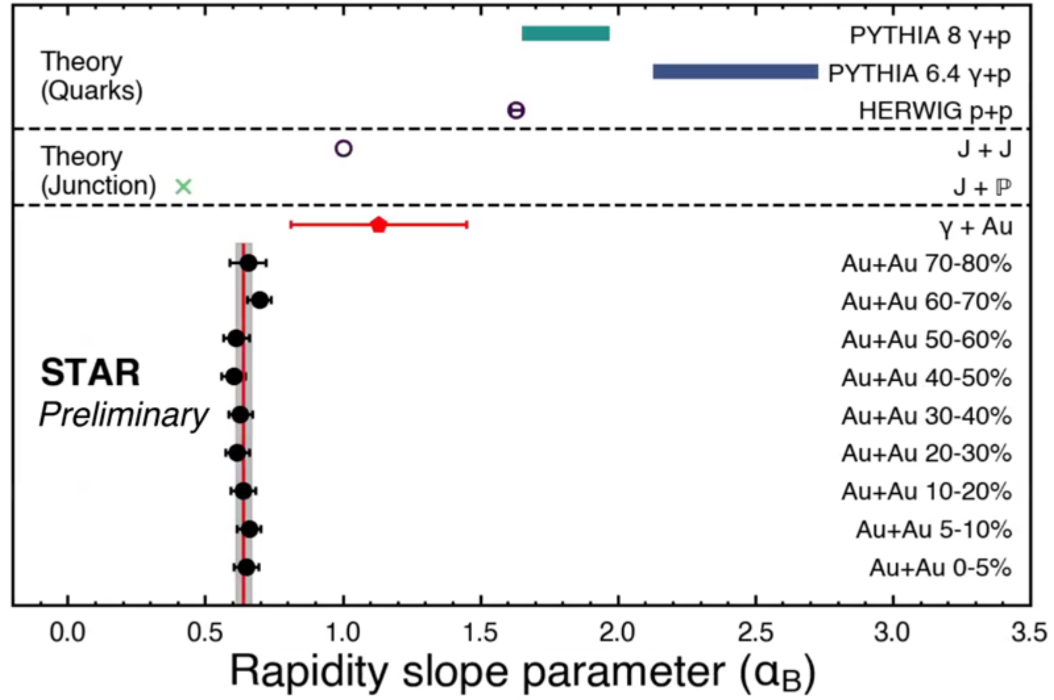
Three approaches toward tracking the origin of the baryon number

1. **STAR Method:**
   Charge (Q) stopping vs baryon (B) stopping:
   if valence quarks carry Q and B, Q=B at middle rapidity
   B/Q=2
2. **Kharzeev-STAR Method:**
   If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory
   α_B=0.61
3. **Artru Method:**
   In γ+Au collision, rapidity asymmetry can reveal the origin
   $\alpha_B(A+A)=0.61< \alpha_B(\gamma+A)=1.1< \alpha_B(PYTHIA)$

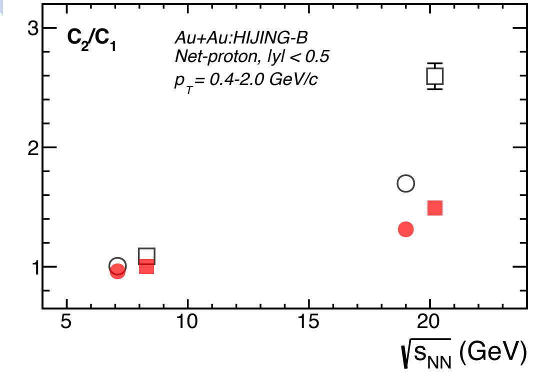
$$p = \sim e^{-\alpha_B y}$$

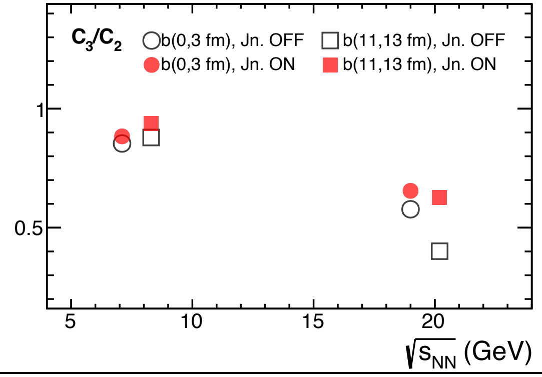
α_B ~=0.5

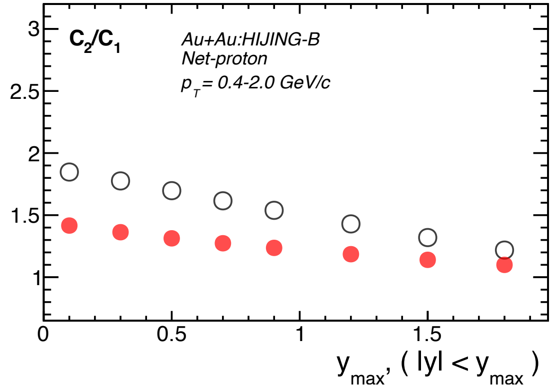


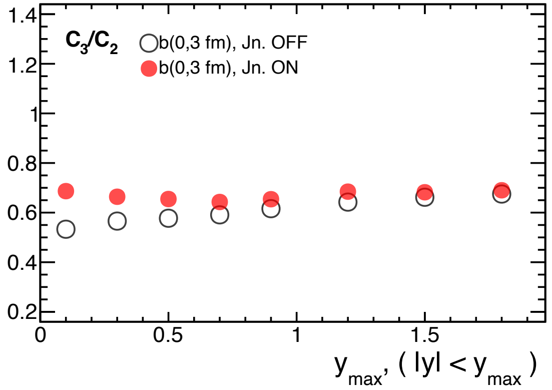


Cumulants of net-proton distributions w/w.o baryon junction

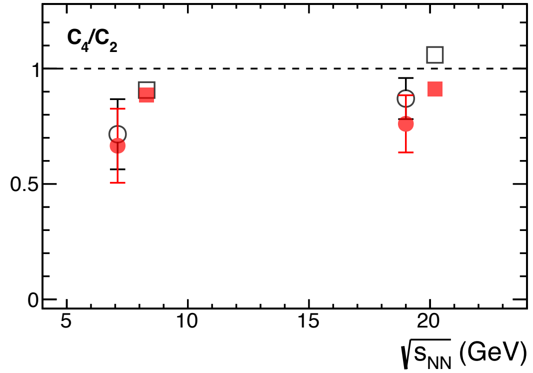






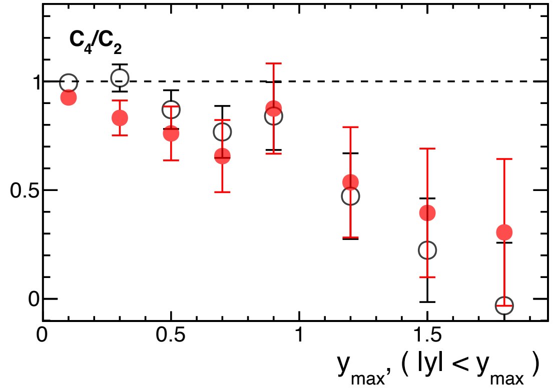


19.6 GeV



Baryon Junction:

- Effect at higher collision energy.
- 2nd order normalized fluctuations are suppressed.
- Distribution gets more skewed.



HIJING simulation w/o junction

Baryon Junction:

Normalized 2nd order fluctuations more suppressed towards mid-rapidity

Bedanga Mohanty @ [CFNS Baryon Dynamics]

B=1,2,3 nuclear yield ratios

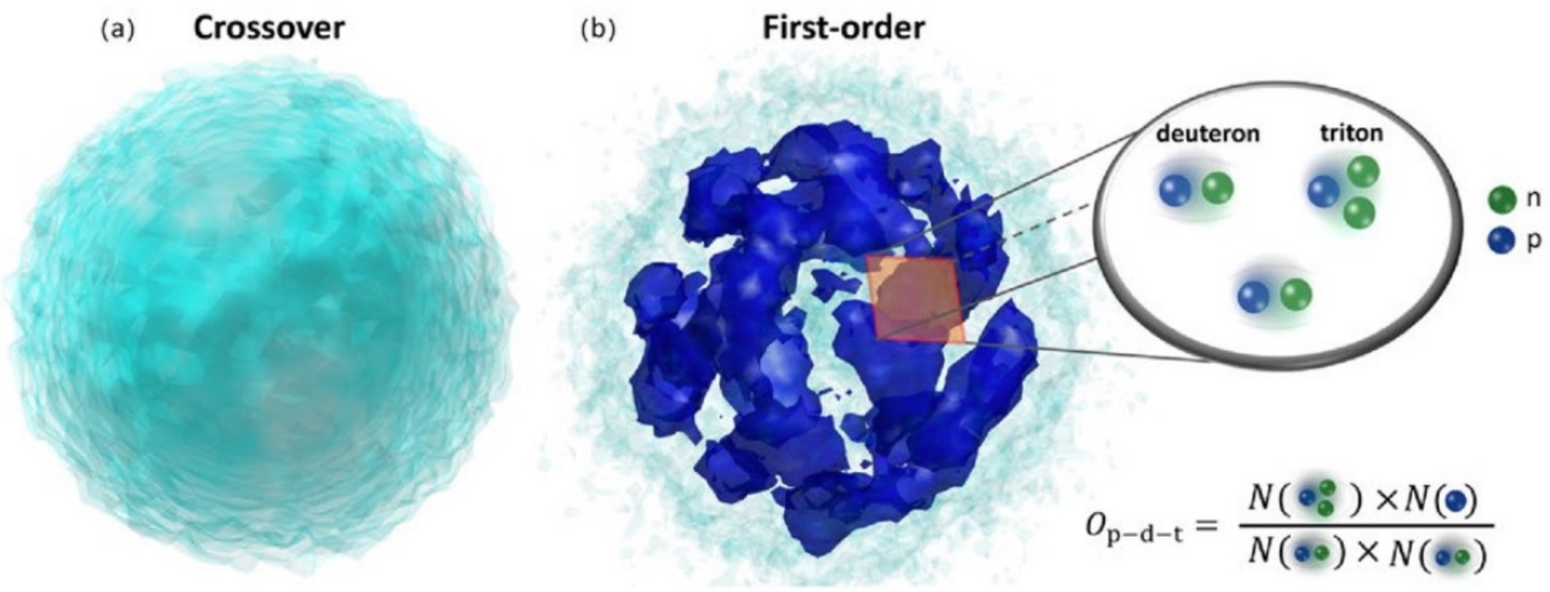


Fig. 1 (Color online) Density distribution of strongly interacting matter in a heavy ion collision after its expansion for the cases of crossover transition (panel **a**) and first-order chiral phase transition (panel **b**). Also shown for illustration of the latter case are deuterons and tritons produced from the density fluctuating hadronic matter and their yield ratio $\mathcal{O}_{\text{p-d-t}} = N_t N_p / N_d^2$, which depends on the magnitude of neutron density distribution as discussed in the text

- Light nuclei production as a probe of the QCD phase diagram

K.J. Sun, et al., PLB 781 (2018) 499

- Probing QCD critical fluctuations from light nuclei production in relativistic heavy-ion collisions

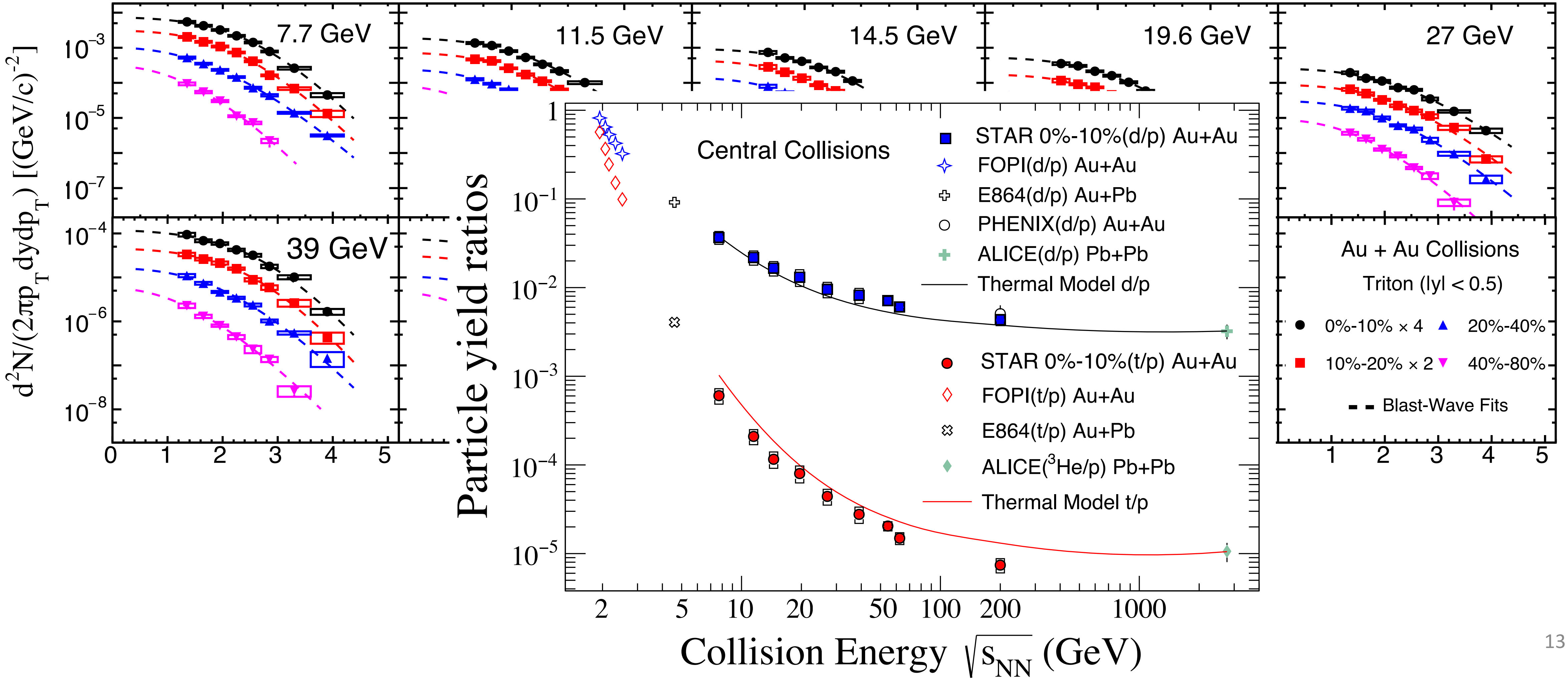
K.J. Sun, et al., PLB 774 (2017) 103

C.M. Ko, NST 34 (2023) 80

$$\mathcal{O}_{\text{p-d-t}} = \frac{N_{^3\text{H}} N_\text{p}}{N_\text{d}^2} = g\frac{1+(1+2\alpha)\Delta n}{(1+\alpha\Delta n)^2},$$

Spectra and two-particle ratios

STAR, Phys.Rev.Lett. 130 (2023) 202301

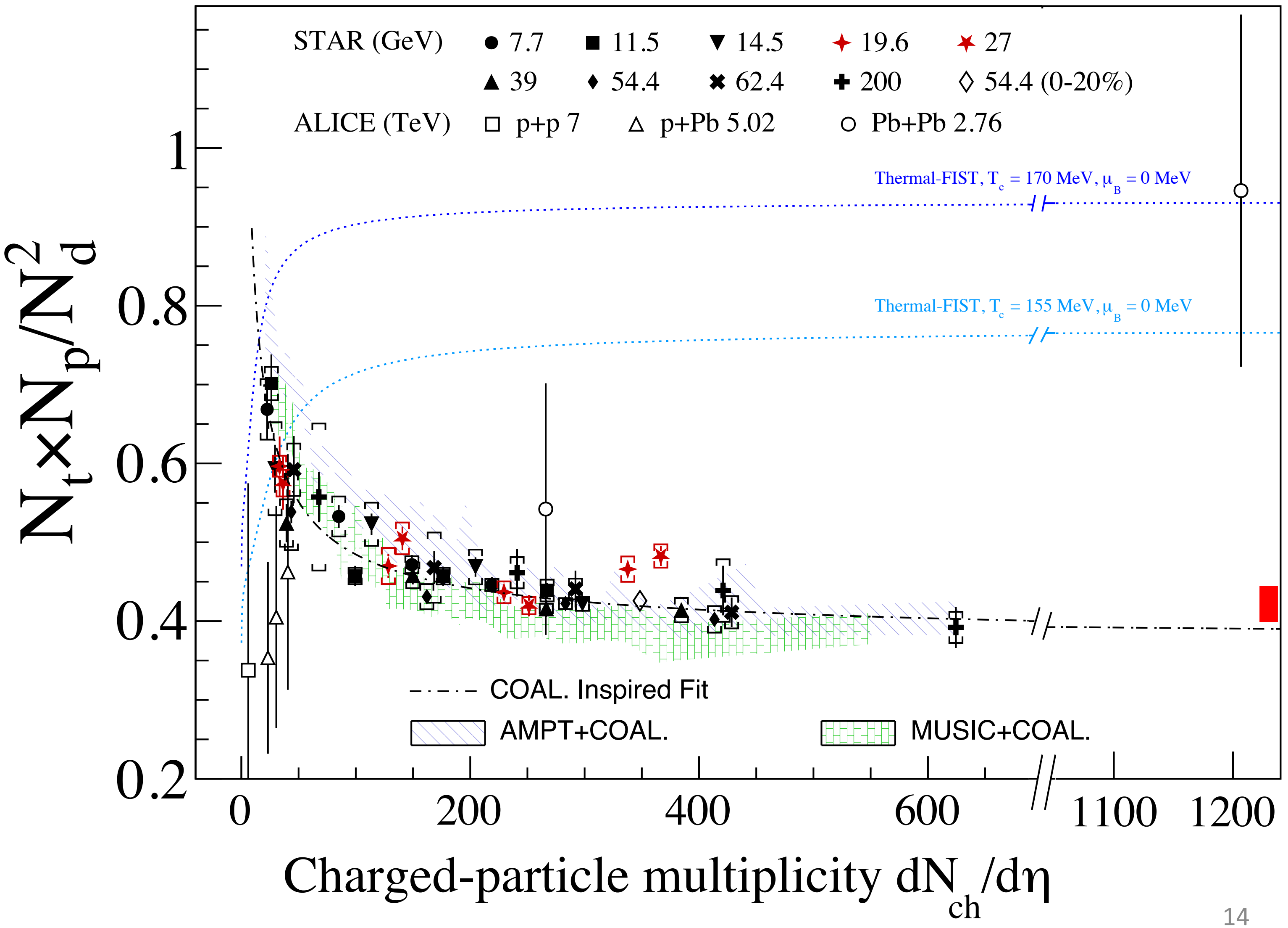


Quantum Wavefunction overlap efficiency

$$\frac{N_t \times N_p}{N_d^2} = p_0 \times \left(\frac{R^2 + \frac{2}{3} r_d^2}{R^2 + \frac{1}{2} r_t^2} \right)^3$$

Coalescence wavefunction overlap between nucleus and nucleons

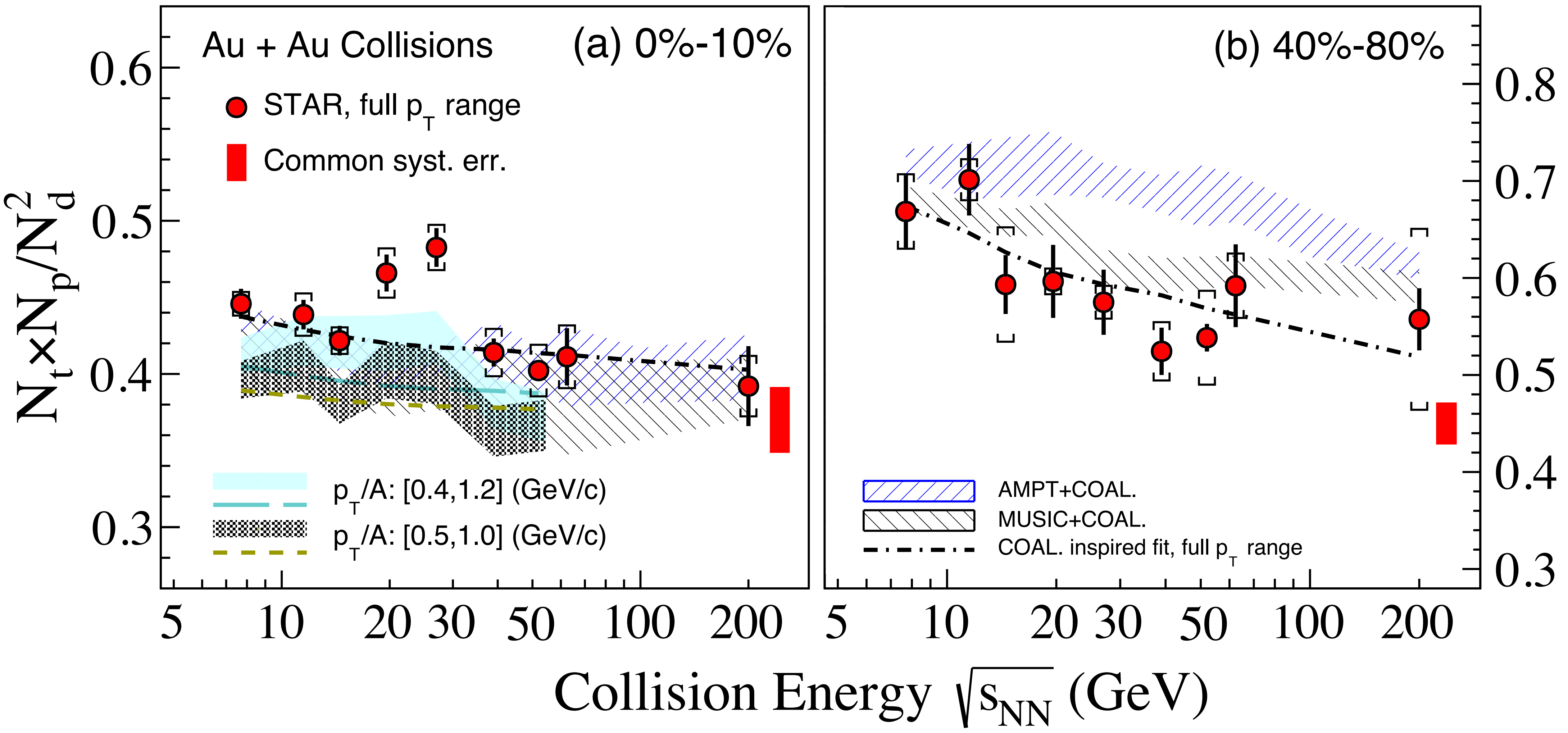
STAR, Phys.Rev.Lett. 130 (2023) 202301



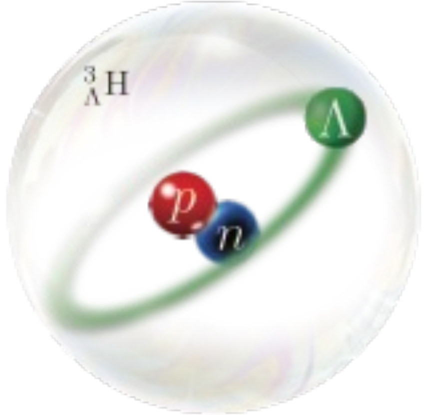
Possible sign of Density Fluctuation

4σ effect, BES-II data x10 statistics

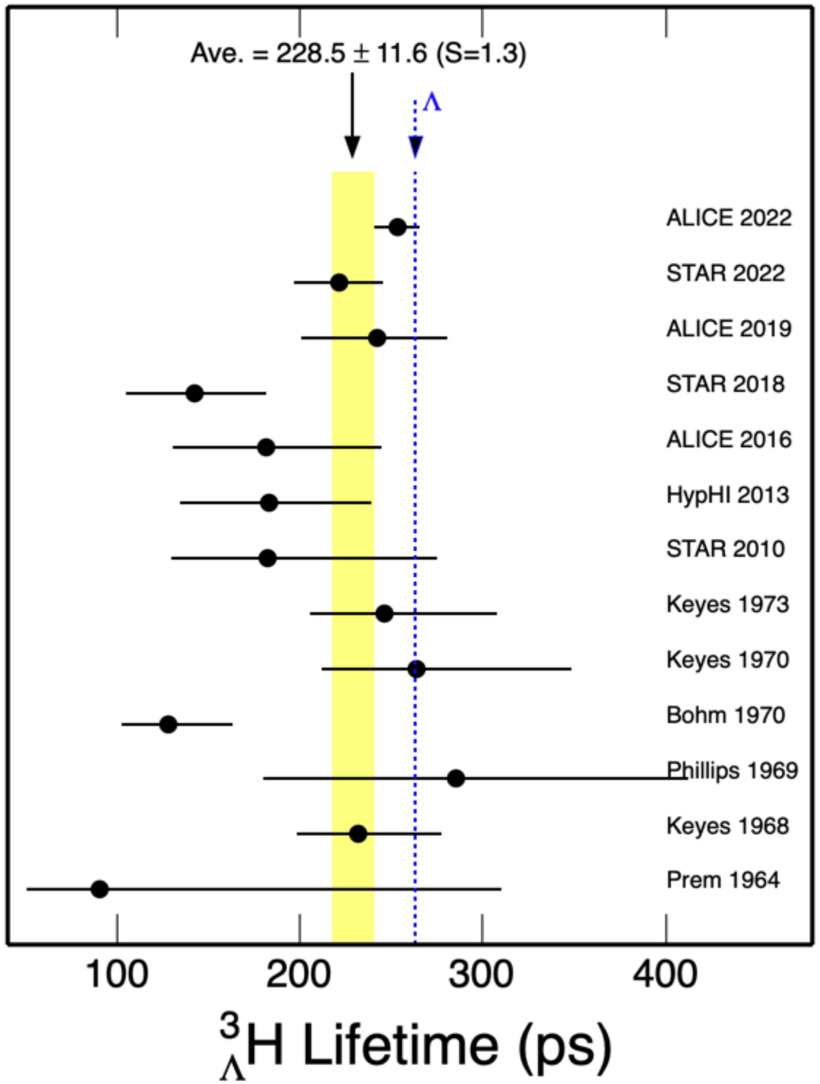
STAR, Phys.Rev.Lett. 130 (2023) 202301

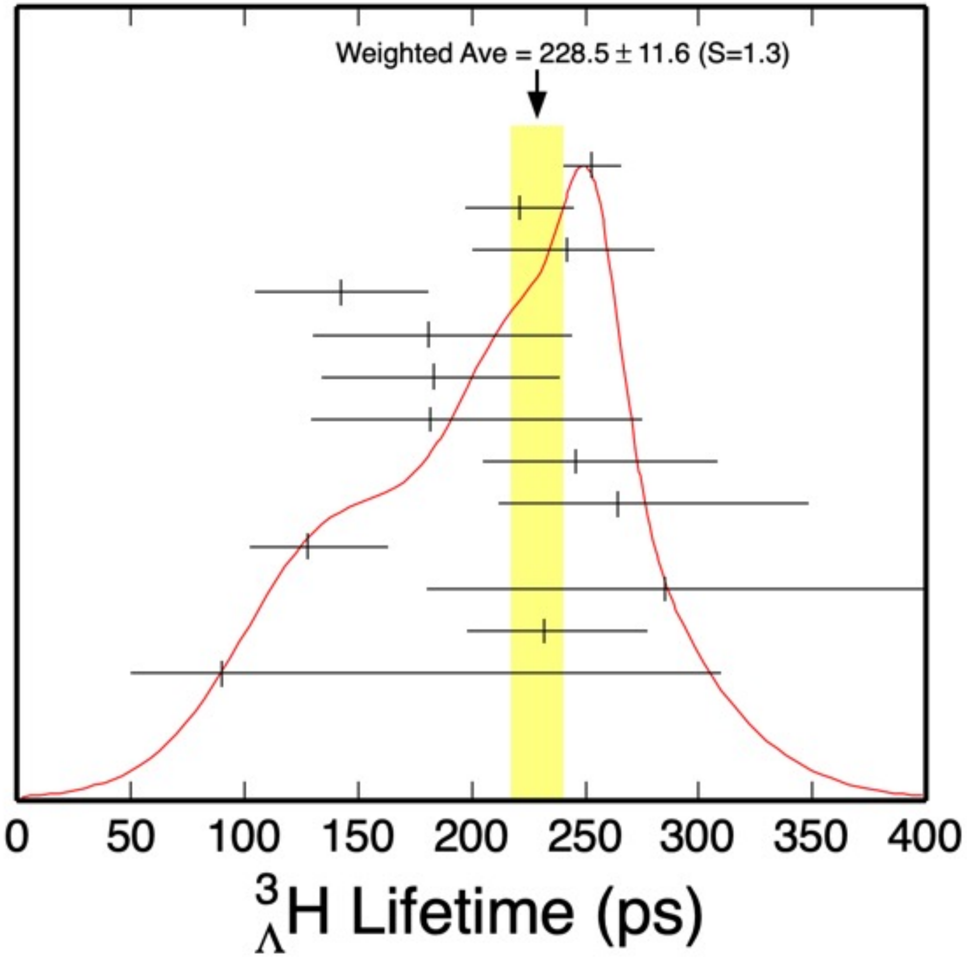


|B|=3 hypertriton lifetime



arXiv:2311.09877





	χ^2
ALICE 2022	3.8
STAR 2022	0.1
ALICE 2019	0.1
STAR 2018	4.9
ALICE 2016	0.6
HypHI 2013	0.7
STAR 2010	0.3
Keyes 1973	0.1
Keyes 1970	0.4
Bohm 1970	8.2
Phillips 1969	
Keyes 1968	0.0
Prem 1964	
	19.3

Confidence Level = 0.036

Potential discrepancy?

arXiv:2311.09877

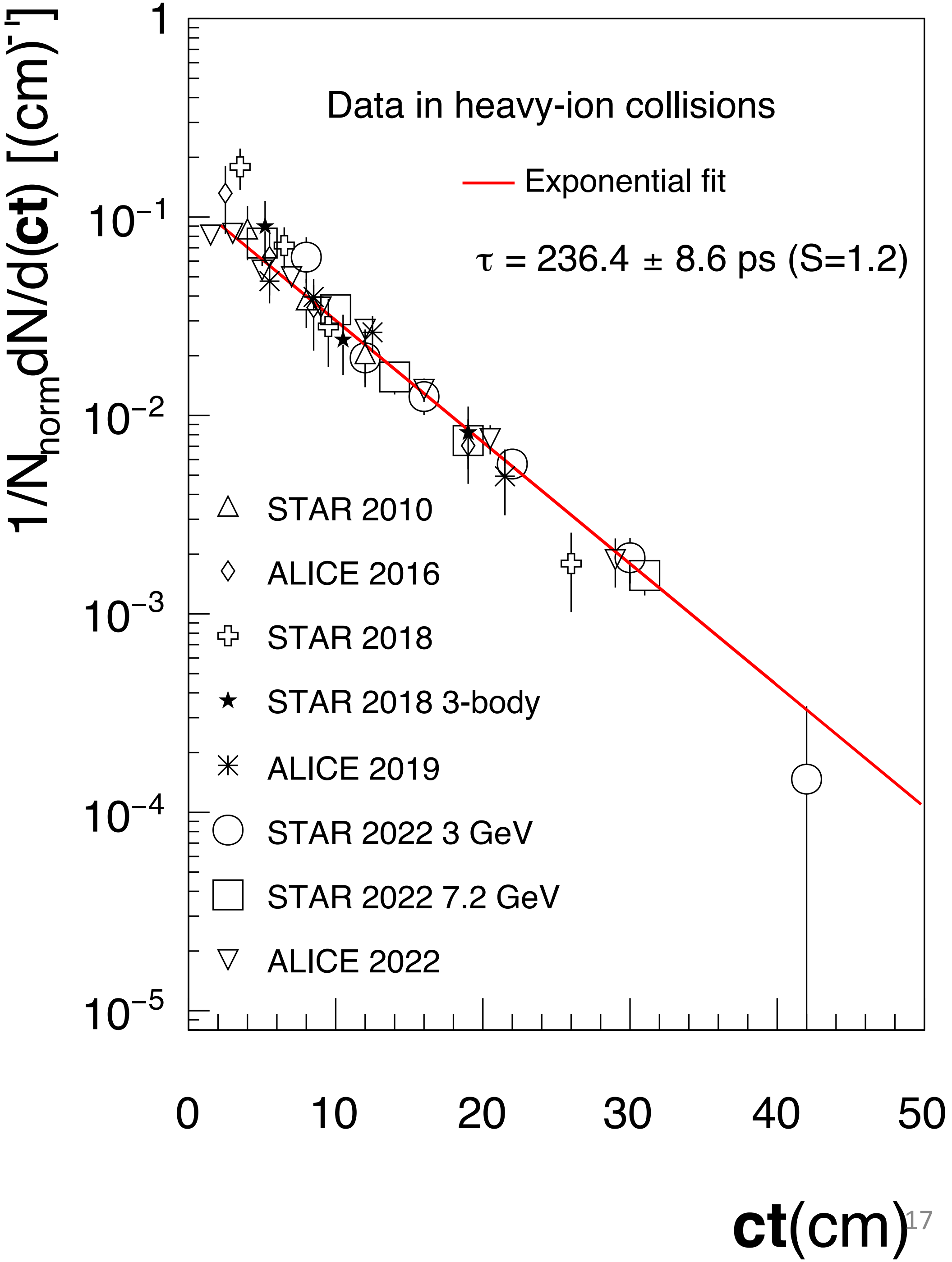
Simultaneous fit to all heavy-ion data

Scale yields to one common exponential function

Result consistent with other (average) methods

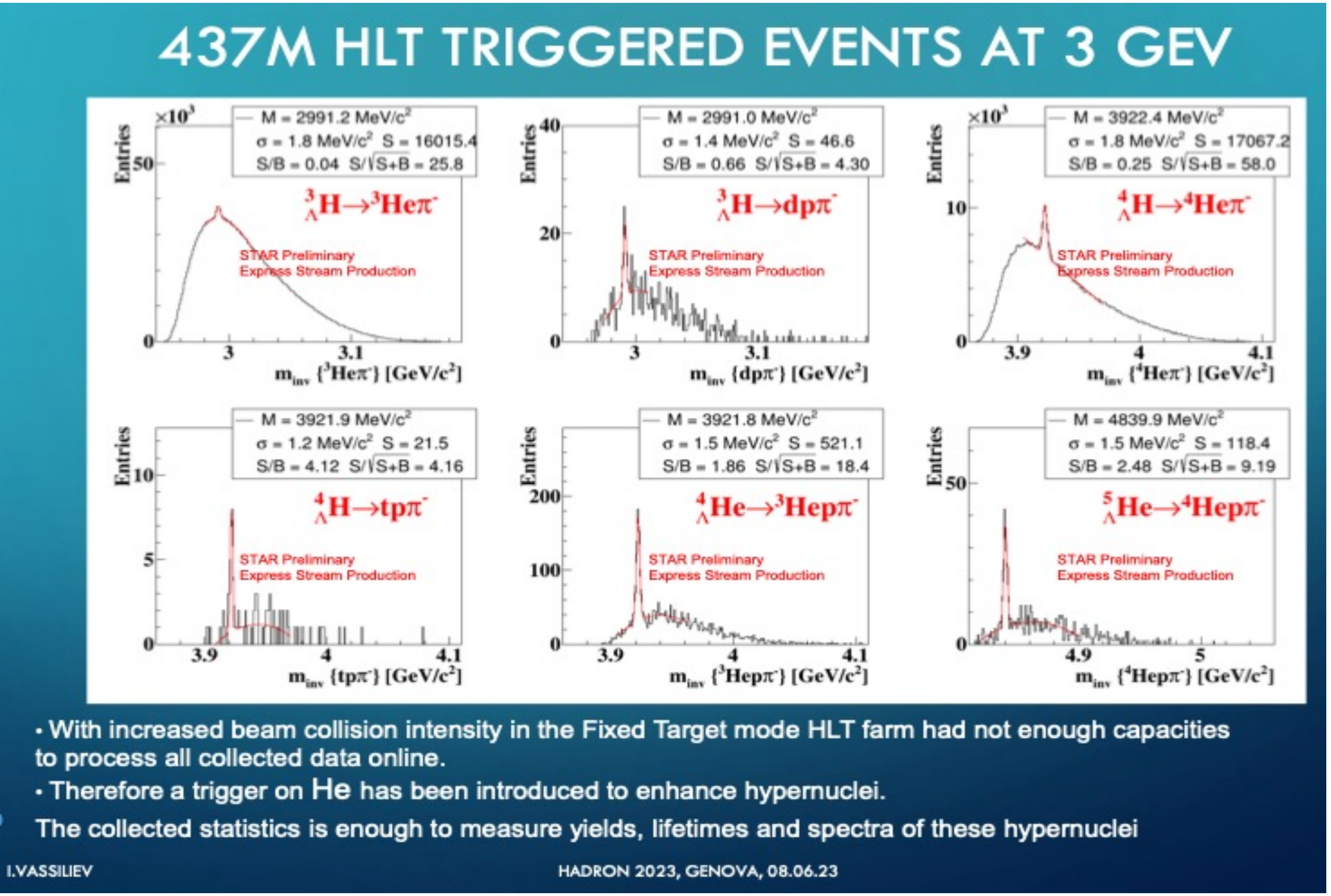
About 3σ smaller than Lambda lifetime

STAR 2018 first cτ point appears high
ALICE 2022 first cτ point appears low

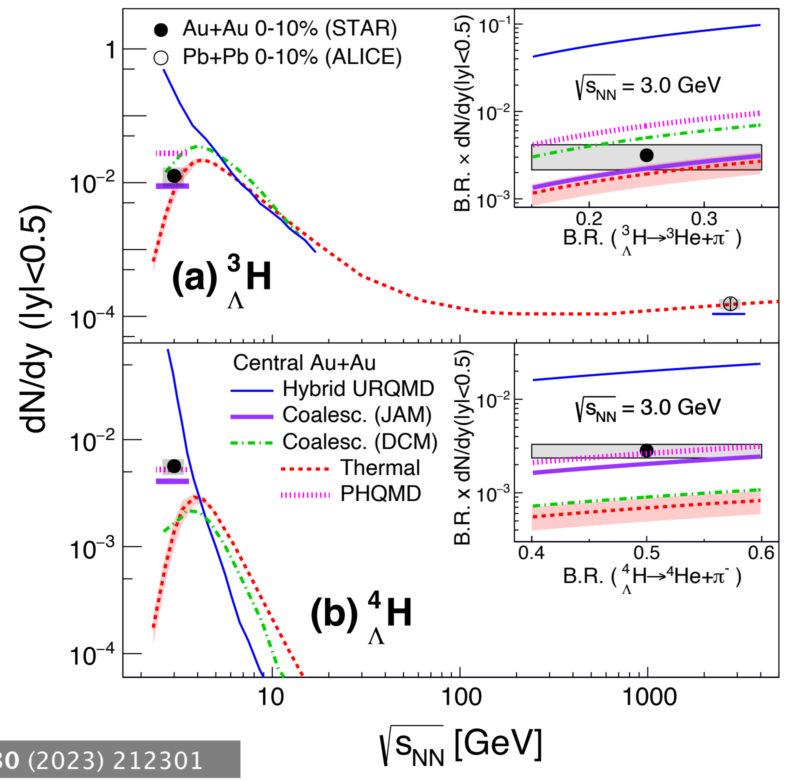


A zoo of hypernucleus measurements

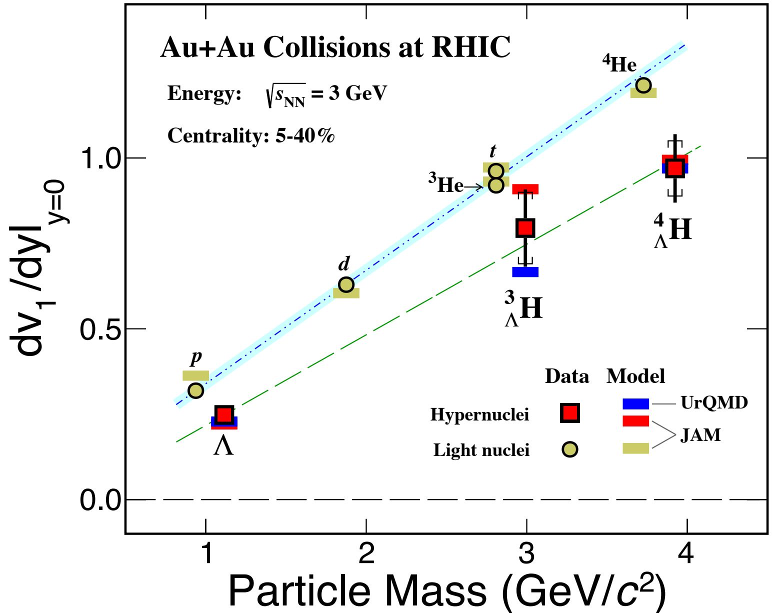
"Fluctuation and correlation measurements", Hanna Zbroszczyk



Phys. Rev. Lett. **128** (2022) 202301



Phys. Rev. Lett. **130** (2023) 212301



Search for heavy antimatter and baryon objects

Rapid Communication

Strangelet search

B. I. Abelev *et al.* (STAR Collab
Phys. Rev. C **76**, 011901(R) – Pu

nature

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nature › letters › article

Published: 24 April 2011

Observation of the antimatter helium-4 nucleus

The STAR Collaboration

Nature **473**, 353–356 (2011) | Cite this article

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nature › nature physics › letters › article

Letter | Published: 09 March 2020

Measurement of the mass difference and the binding energy of the hypertriton and antihypertriton

The STAR Collaboration

Nature Physics **16**, 409–412 (2020) | Cite this article

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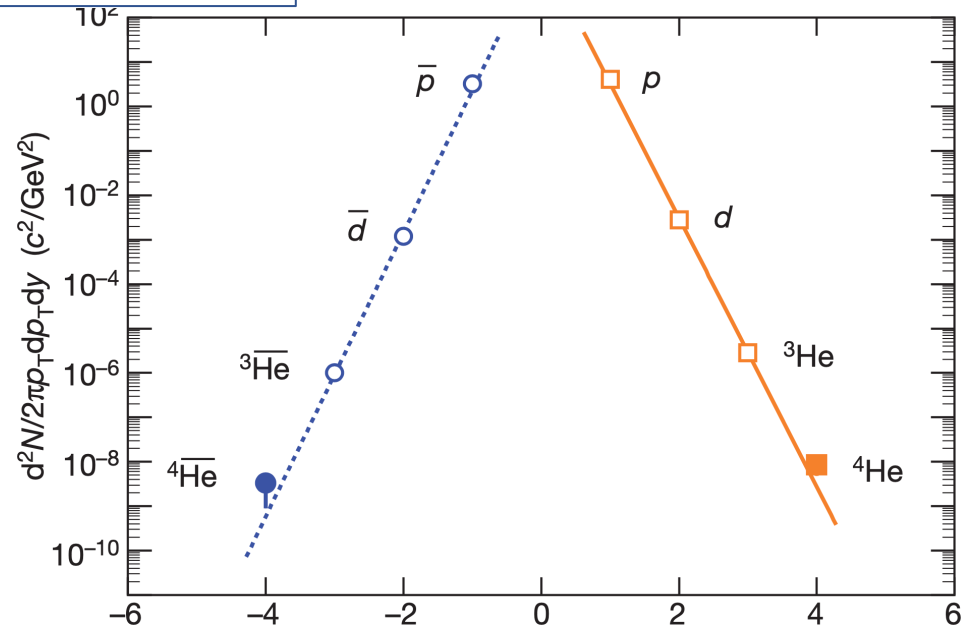
RESEARCH ARTICLE

Observation of an Antimatter Hypernucleus

THE STAR COLLABORATION, B. I. ABELEV, M. M. AGGARWAL, Z. AHAMMED, A. V. ALAKHVERDYANTS, I. ALEKSEEV, B. D. ANDERSON, D. ARK
Y. ZOULKARNEEVA +382 authors Authors Info & Affiliations

SCIENCE • 4 Mar 2010 • Vol 328, Issue 5974 • pp. 58-62 • DOI: 10.1126/science.1183980

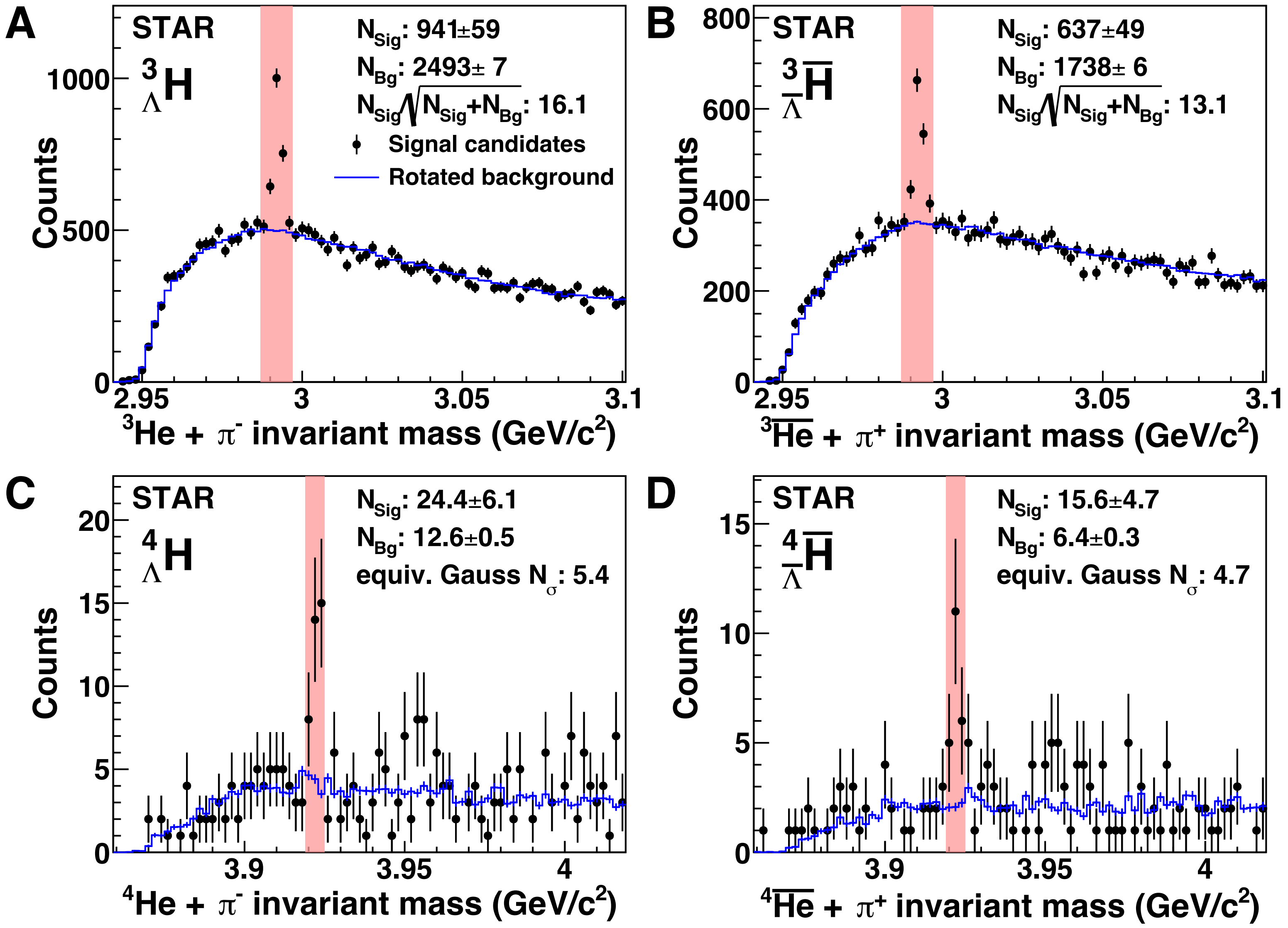


Observation of antimatter H4Lambda

STAR, arXiv: 2310.12674

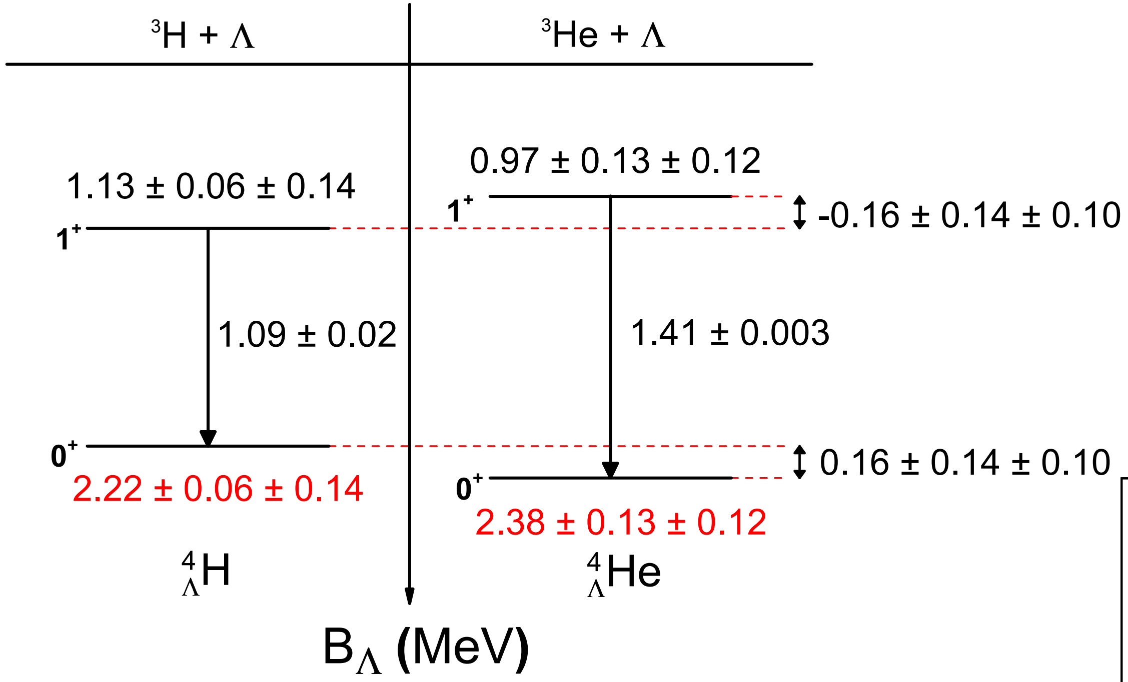
J.L. Wu (STAR), SQM2022

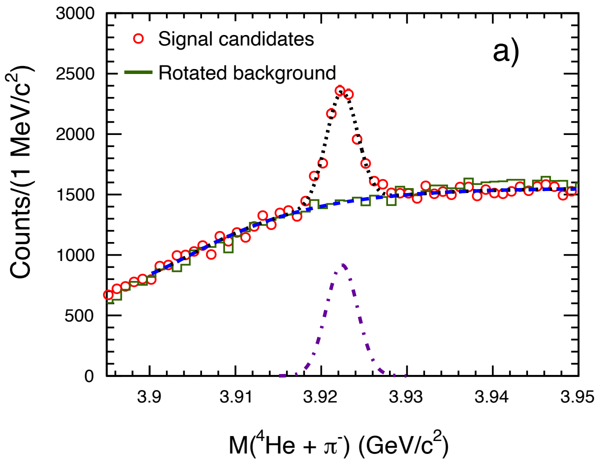
Au+Au: 2010+2011
U+U: 2012
Zr+Zr/Ru+Ru: 2018

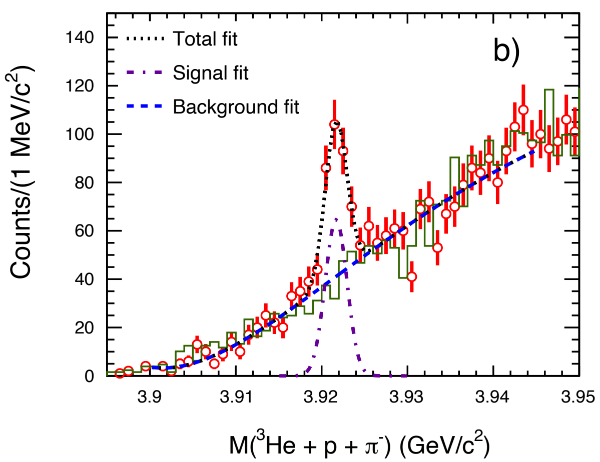


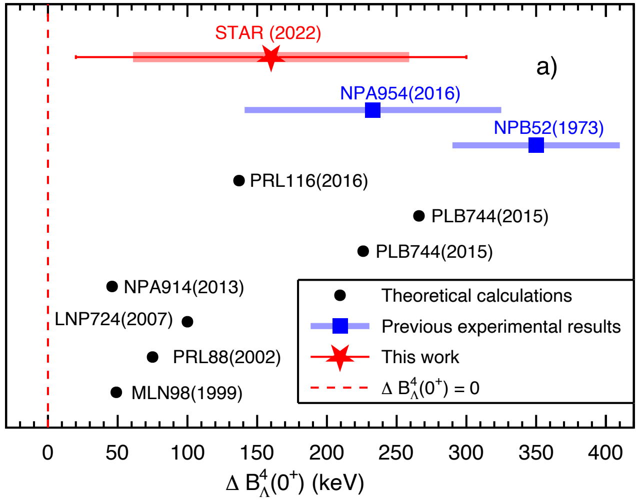
Charge Symmetry Breaking in B=4 hypernuclei

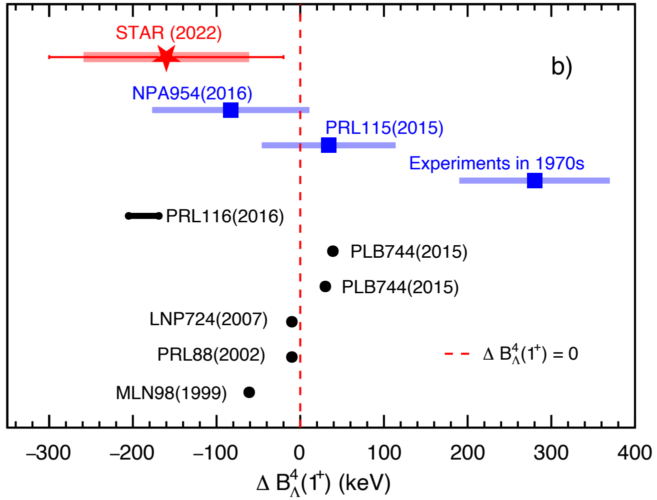
STAR, Phys. Lett. B **834** (2022) 137449











A puzzling CSB (70s):
both 0+ and 1+ large and positive ΔB

New measurements:
small and symmetric ΔB

STAR Discovery potential at EIC

Heavy-flavor states

http://belle.kek.jp/belle/talks/moriondQCD10/pakhlov.ppt

Many (>10) states poorly consistent with quark model

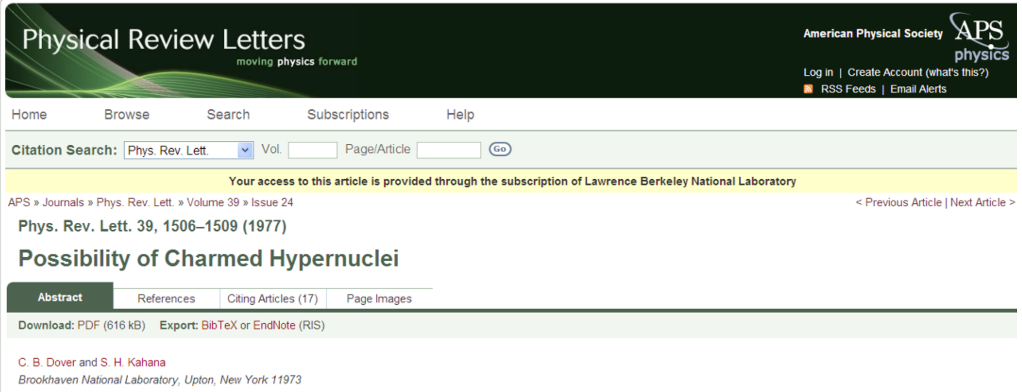
State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \to \eta Y_s(2175)$
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi, D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$
$X(3915)$	3914 ± 4	23 ± 9	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)	$B \to KY(3940)$
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)	$e^+e^- \to J/\psi X(4160)$
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^-(ISR)
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	e^+e^-(ISR)
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^-(ISR)
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4050)$
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4250)$
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^-\Upsilon(1,2,3S)$	$e^+e^- \to Y_b$

observed last 6 years by B-factories

How about baryon states?

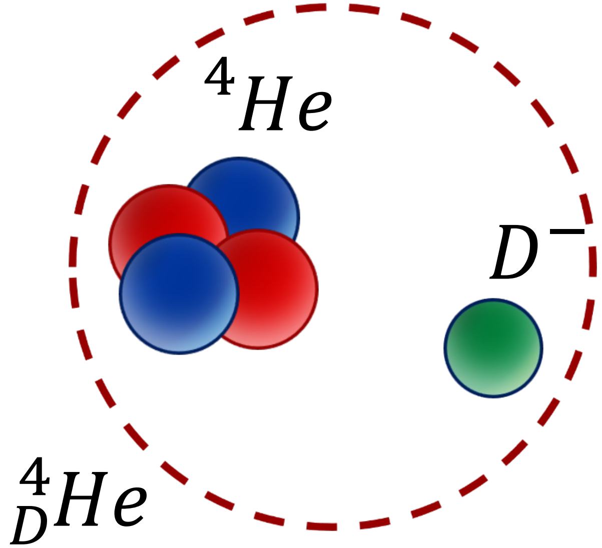
Heavy-flavor hypernuclei

- Predicted to exist (70's)
- Cannot be produced in pp, ep collisions
- Cannot be detected in fixed target experiment
- Only solution: **EIC**
- EIC enough energy for charm and bottom hypernuclei
- Vertex detector at Fragmentation region
  Displace vertex: 3cm



xzb
LBL Heavy-Ion Tea Seminar
05/2010

Search for Stable Charmed Mesic Nucleus $_{D^-}{}^4He$ in Heavy-Ion and EIC



Stable and existence due to Coulomb force

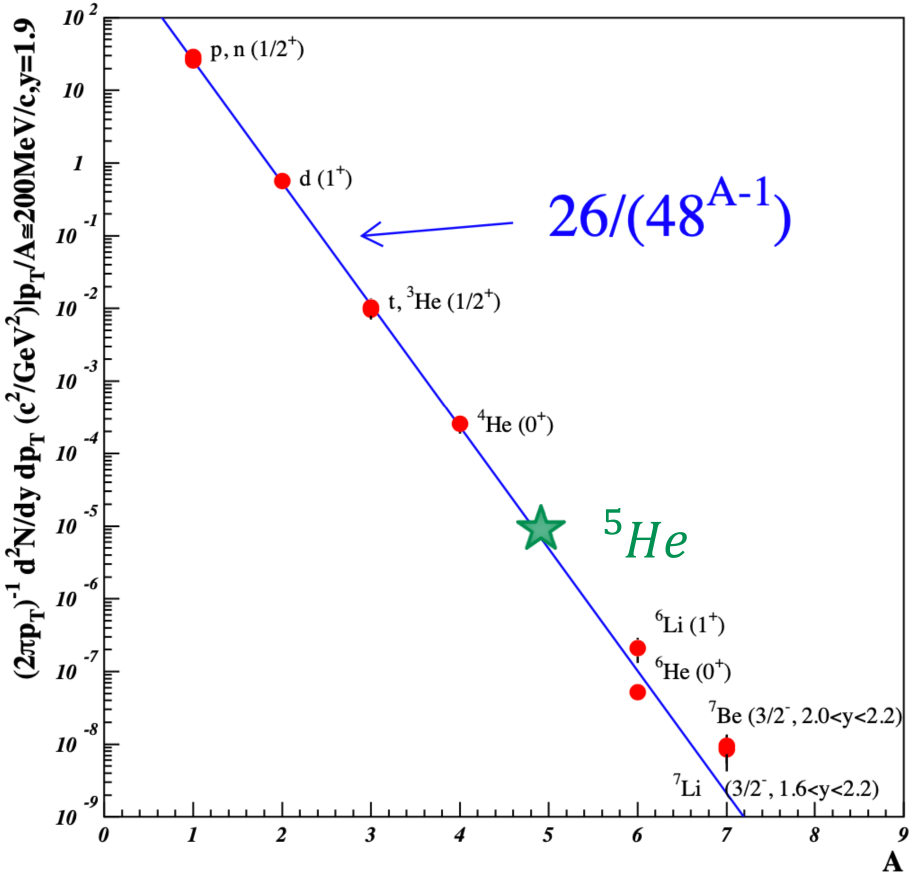
PYTHIA: D^-/n~=5×10^{-4} p+p collisions at AGS and RHIC forward kinematics

$_{D^-}{}^4He$ yield 10^{-8} per collision

STAR@RHIC:
Estimate 1×10^5/year in forward acceptance
But without vertex detector

CBM@FAIR high baryon, good vertex
LHCb@LHC forward with good vertex

EIC ion forward direction:
clean environment with good vertex
Nuclear cluster



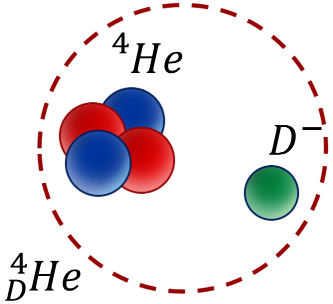
Phys. Rev. C **61**, 064908

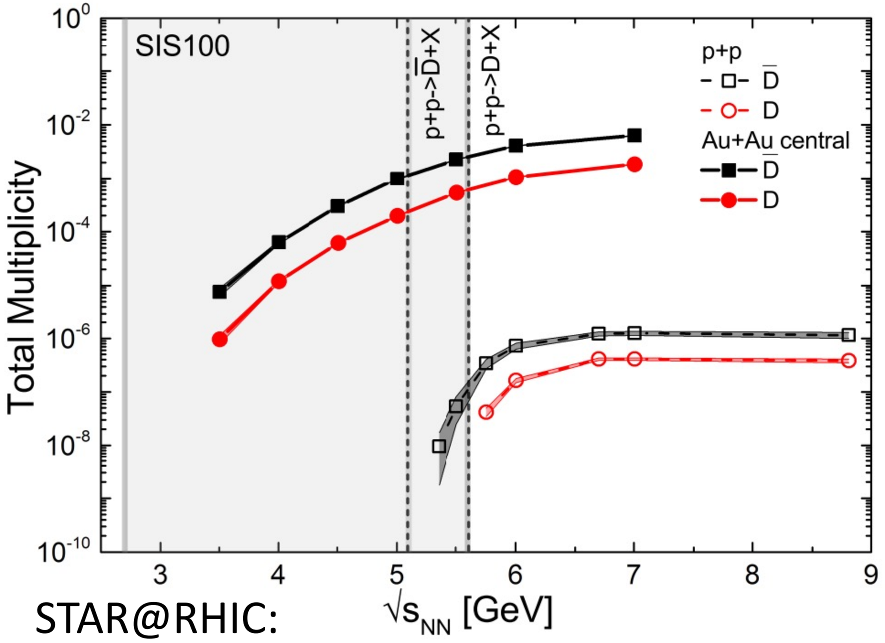
Zhangbu Xu (BNL)
Cheng-Wei Lin, Yi Yang (NCKU)
DNP (2022), EMMI (2023)

Search for Stable Charmed Mesic Nucleus ${}_{D^-}{}^{4}He$ at CBM

J. Steinheimer, A. Botvina, M. Bleicher, PRC 95 (2017) 014911

Zhangbu Xu (BNL)
Cheng-Wei Lin, Yi Yang (NCKU)
DNP (2022), EMMI (2023)





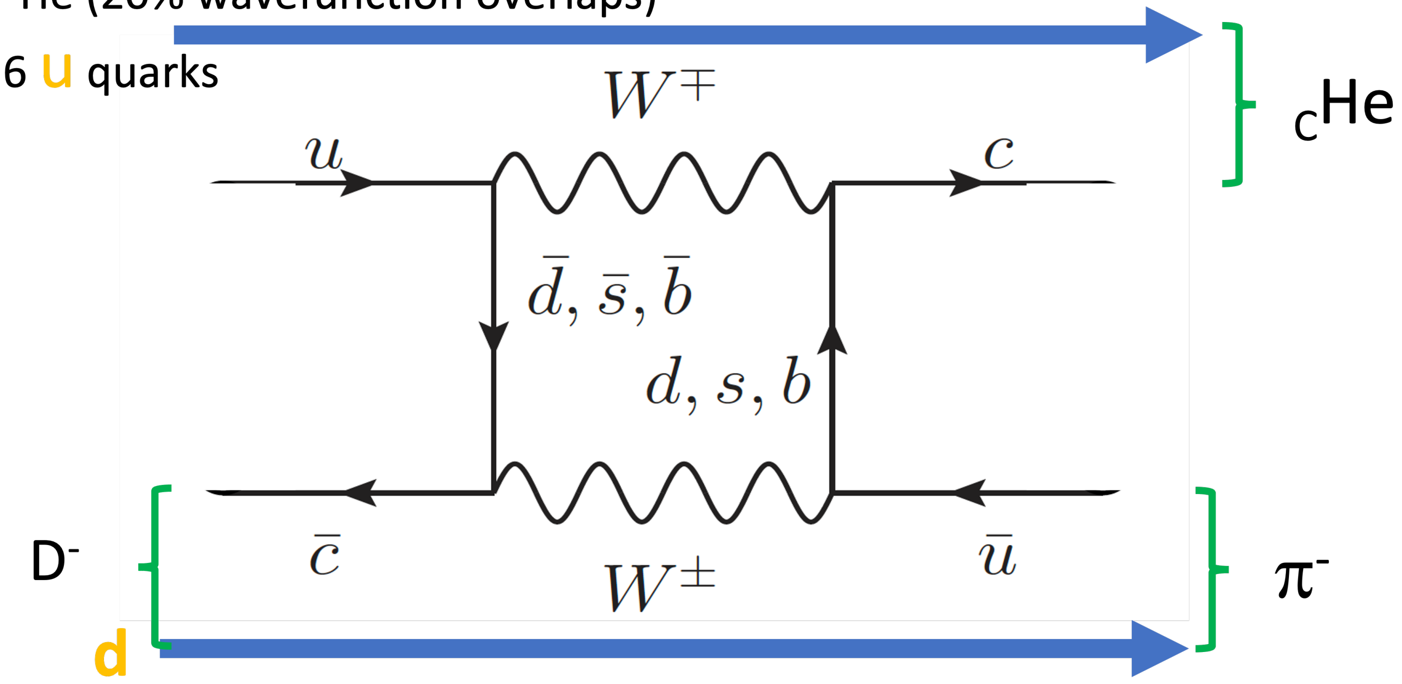
STAR@RHIC:
Estimate 1x10^5/year in forward acceptance
But without vertex detector

CBM@FAIR high baryon, good vertex
LHCb@LHC forward with good vertex

EIC ion forward direction:
clean environment with good vertex

Charm Quark Oscillation with large mass difference

^{4}He (20% wavefunction overlaps)
6 u quarks



12

Projected Discovery of antimatter Helium-4 nucleus from STAR

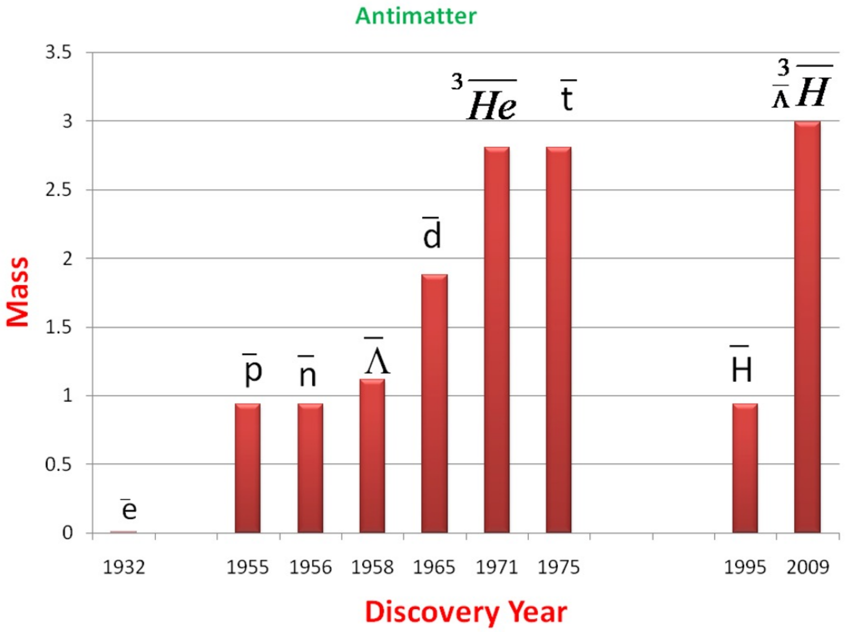
How many possible antimatter nuclei can we discover?

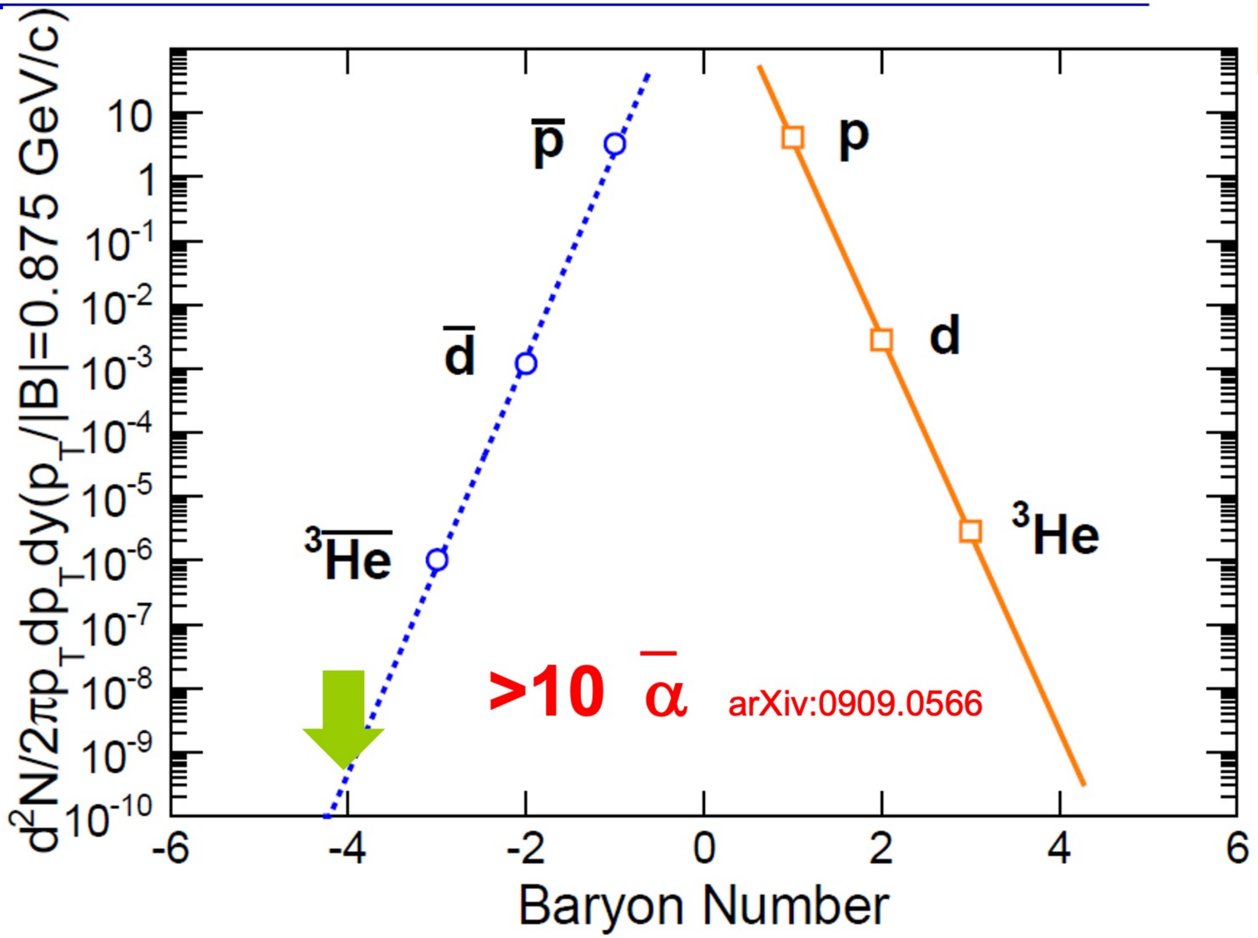
Anti-hypertriton, anti-alpha;

Anti-hyperH4?

Can we get to antimatter ^{6}He?

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





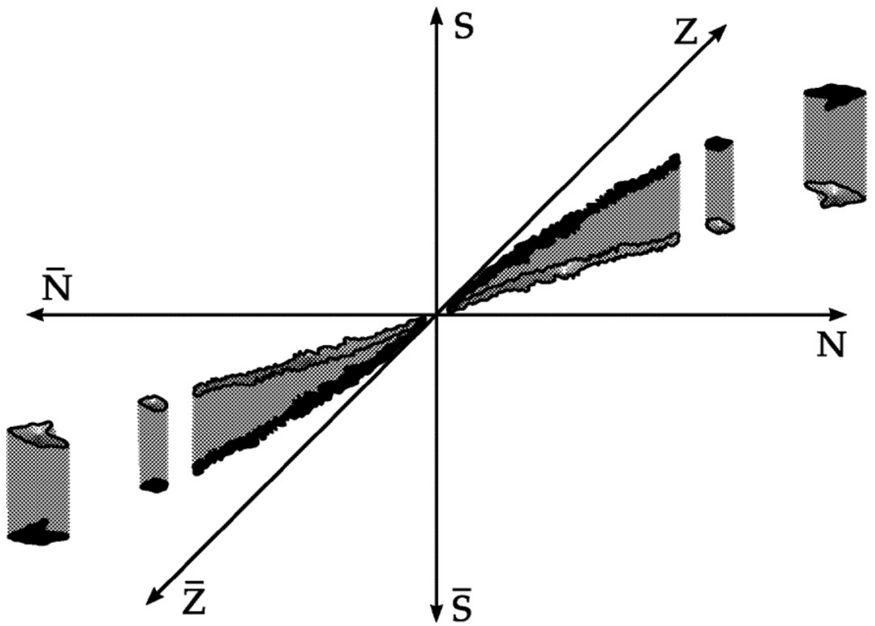
xzb: AAAS annual meeting 01/2011

Heaviest Antimatter Found; Made in U.S. Atom Smasher

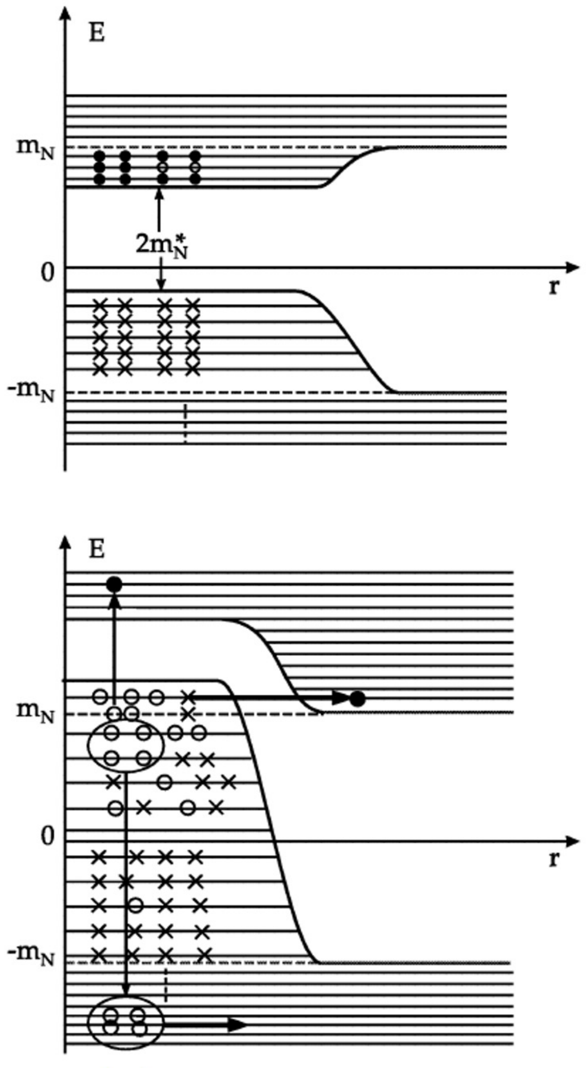
hypernuclei and antimatter from correlations in the Vacuum

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

Walter Greiner



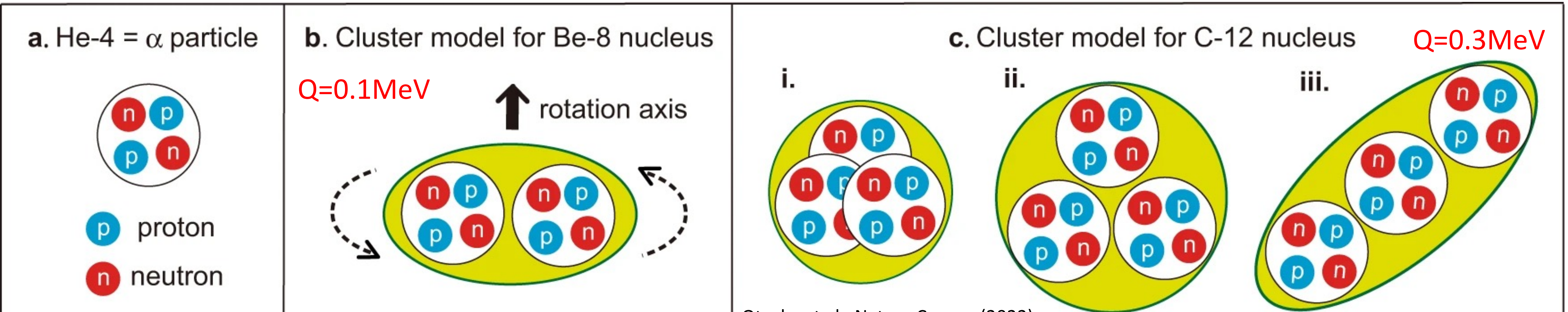
Real 3-D periodic table



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

xzb
LBL Heavy-Ion Tea Seminar
05/2010

Hoyle Mechanism of creating heavier elements



Otsuka et al., Nature Comm. (2022)

ON NUCLEAR REACTIONS OCCURRING IN VERY HOT STARS. I. THE SYNTHESIS OF ELEMENTS FROM CARBON TO NICKEL

F. HOYLE*
MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

Received December 22, 1953

It is convenient to replace reaction (24) by

$$\alpha + \alpha \rightleftarrows Be^8, \qquad Be^8 + \alpha \rightarrow C^{12} + \gamma. \qquad (27)$$

This is a permissible step, since the lifetime of the unstable Be^8 is appreciably longer than the time required for a "nuclear" collision of two α-particles; that is, longer than the α-particle radius divided by the relative velocity. The merit of reaction (27) is that the number density n_4^8 of Be^8 nuclei is given in terms of the number density n_2^4 of α-particles by the equation of statistical equilibrium (Hoyle 1946),

$$\log n_4^8 = 2 \log n_2^4 - 34.53 - \tfrac{3}{2} \log T - \frac{0.464}{T}, \qquad (28)$$

where the disintegration energy of Be^8 is taken as 0.092 mev, and T is in units of 10^9 ° K.

PHYSICAL REVIEW VOLUME 92, NUMBER 3 NOVEMBER 1, 1953

The 7.68-Mev State in C^{12}

D. N. F. DUNBAR,* R. E. PIXLEY, W. A. WENZEL, AND W. WHALING
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

(Received July 21, 1953)

Magnetic analysis of the alpha-particle spectrum from $N^{14}(d,\alpha)C^{12}$ covering the excitation energy range from 4.4 to 9.2 Mev in C^{12} shows a level at 7.68±0.03 Mev. At E_d=620 kev, θ_{lab}=90°, transitions to this state are only 6 percent of those to the level at 4.43 Mev.

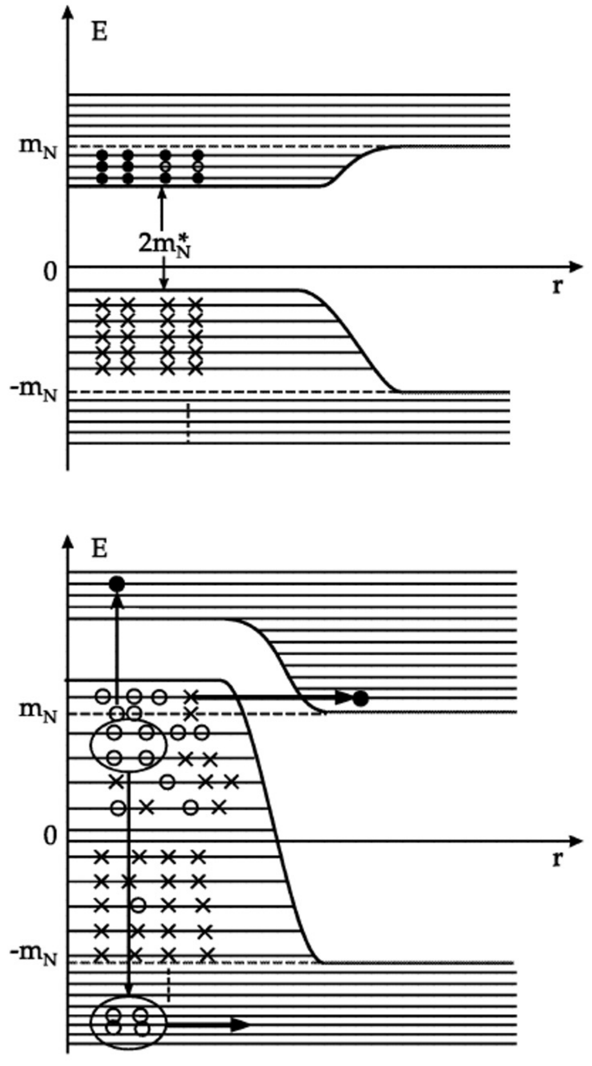
SALPETER[1] and Öpic[2] have pointed out the importance of the $Be^8(\alpha,\gamma)C^{12}$ reaction in hot stars which have largely exhausted their central hydrogen. Hoyle[3] explains the original formation of elements heavier than helium by this process and concludes from the observed cosmic abundance ratios of O^{16}:C^{12}:He^4 that this reaction should have a resonance at 0.31 Mev or at 7.68 Mev in C^{12}.

An early measurement of the range of the alpha particles from $N^{14}(d,\alpha)C^{12}$ indicated a level in C^{12} at 7.62 Mev.[4] However, a recent magnetic analysis of this reaction failed to detect a transition to any level

How do Hoyle States appear at RHIC?

In coalescence picture

- Prepare the alpha (anti-alpha) at the early stage (hot and dense)
- Those alpha clusters scatter around, and form heavier ^{8}Be (0.1MeV) and $^{12}C^*$ (0.3MeV) because those excited levels are really close to the free alpha energy level $\delta R \delta p$ (very small δp and very large δR)



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

In thermodynamics picture

- Prepare the alpha (anti-alpha) at the early stage (hot and dense)
- The alpha clusters re-thermalized at later stage with a large fugacity (similar to charm thermalization) and therefore form Prepare the alpha (anti-alpha) at the early stage (hot and dense) at much later time and lower density and low temperature

Another way of picturing this

No penalty of wavefunction overlap due to late-stage alpha coalescence

$$\frac{N_t \times N_p}{N_d^2} = p_0 \times \left(\frac{R^2 + \frac{2}{3} r_d^2}{R^2 + \frac{1}{2} r_t^2} \right)^3$$

Coalescence wavefunction overlap between nucleus and nucleons

A=8 formation to 4+4 formation (A~=5)

Benefit of alpha cluster formation at early stage (two-stage formation)

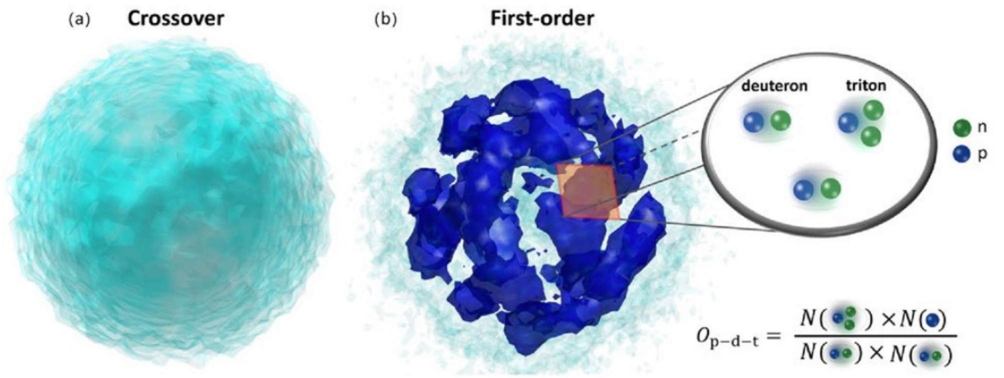
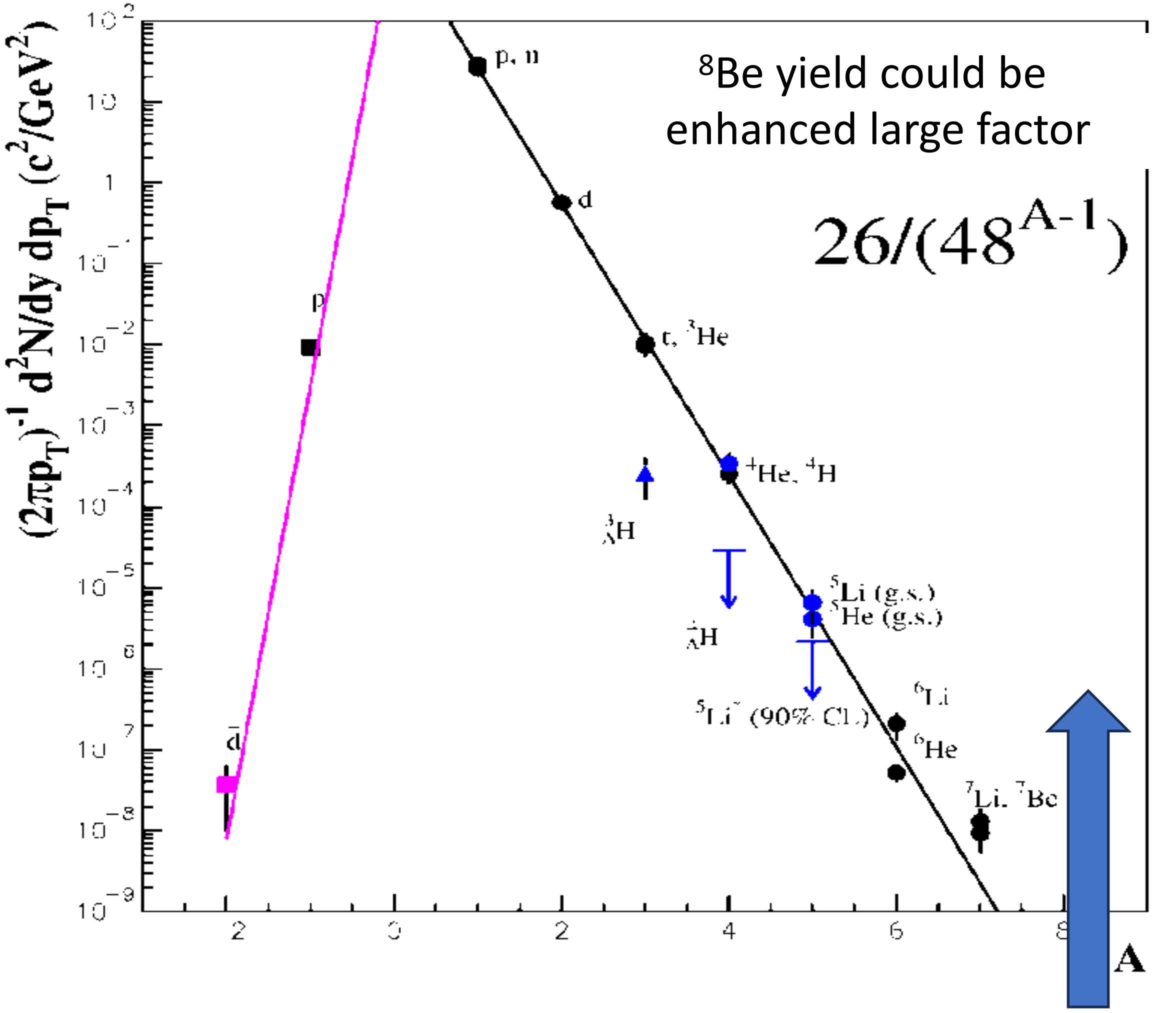
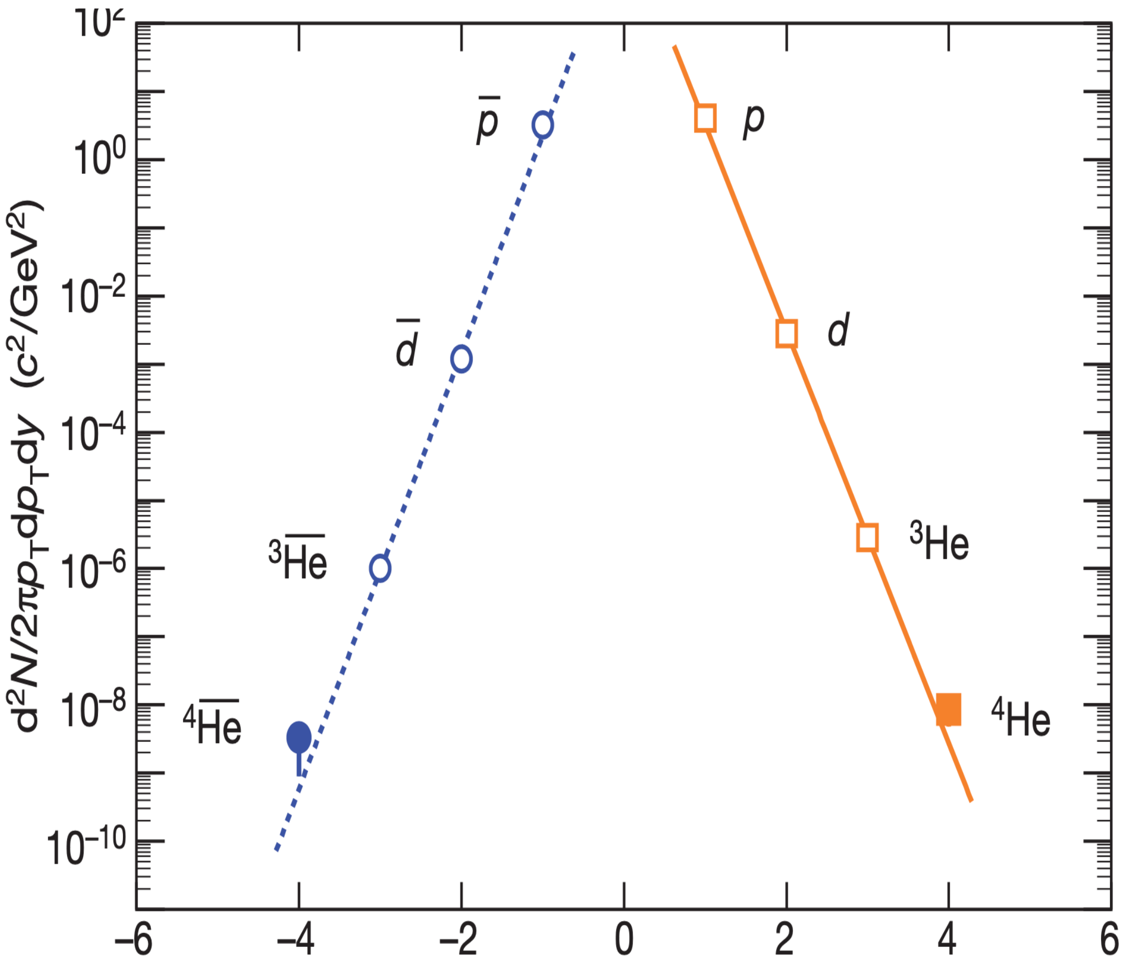


Fig. 1 (Color online) Density distribution of strongly interacting matter in a heavy ion collision after its expansion for the cases of crossover transition (panel **a**) and first-order chiral phase transition (panel **b**). Also shown for illustration of the latter case are deuterons and tritons produced from the density fluctuating hadronic matter and their yield ratio $\mathcal{O}_{\text{p-d-t}} = N_t N_p / N_d^2$, which depends on the magnitude of neutron density distribution as discussed in the text

^{8}Be and ^{12}C enhanced yields





Could be between |A|=5 and |A|=8 extrapolation
Even better at CBM due to slow expansion and redistribution of alpha clusters

Conclusions

- Discovery of the heaviest antimatter nuclear cluster (hyperhydrogen 4)
- Continue to improve our measurements on hypernuclear lifetime and binding energy (CSB)
- Use nuclear yields to study production mechanism, quantum wavefunction overlap: thermal vs coalescence model
- Use nuclear yield ratios as a sensitive probe of nucleon density fluctuation

- Baryon number is a strictly conserved quantum number,
  keeps the Universe as is
- We did not know what its carrier is;
  It had not been experimentally verified one way or the other until now;
- Explore other signatures
- Charmed hypernuclei (EIC, LHC, CBM)
- Hoyle States (STAR FXT, CBM) and antimatter ^{8}Be (LHC?)