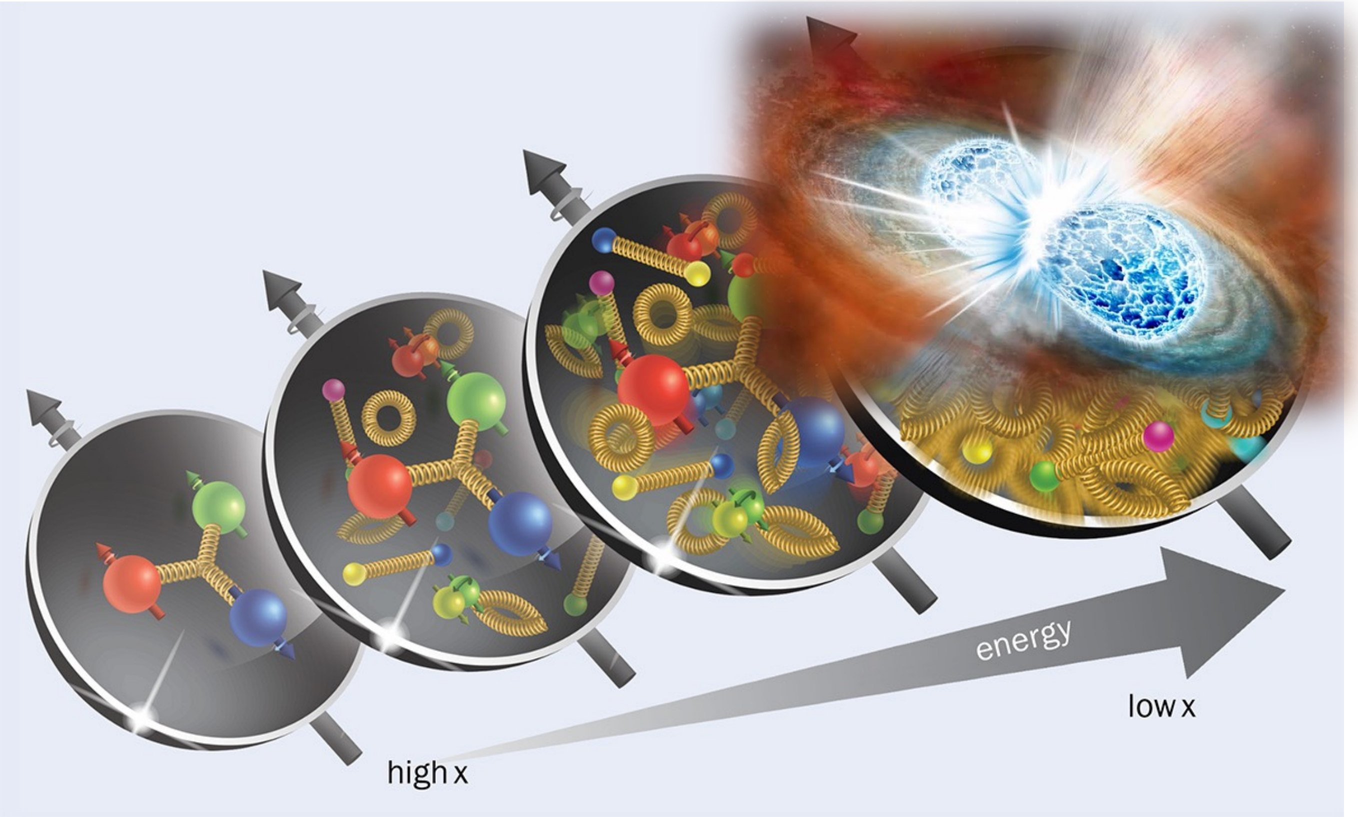
Production of baryon clusters of B=±1 to ±4 in relativistic heavy-ion collisions



Zhangbu Xu
(Kent State University& BNL)

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

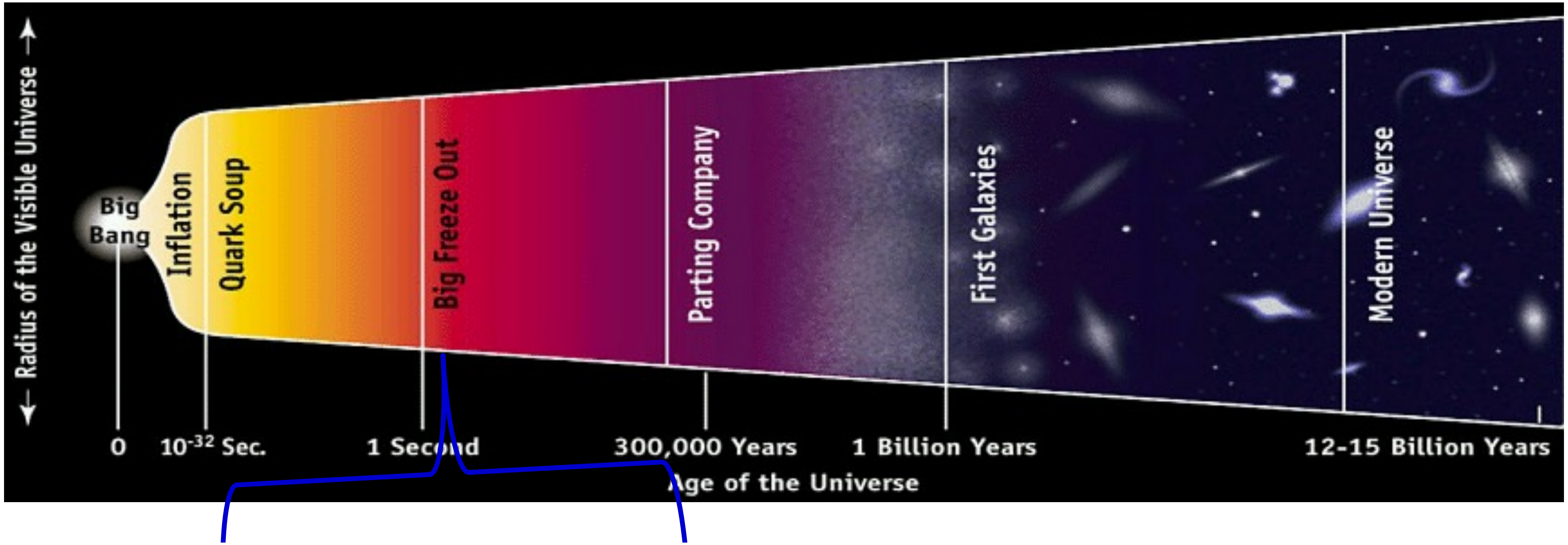
Center for Nuclear Research

KENT STATE UNIVERSITY

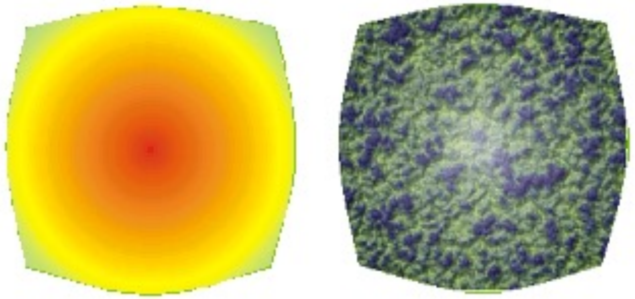
In part supported by
U.S. DEPARTMENT OF ENERGY
Office of Science

Little Big Bangs

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



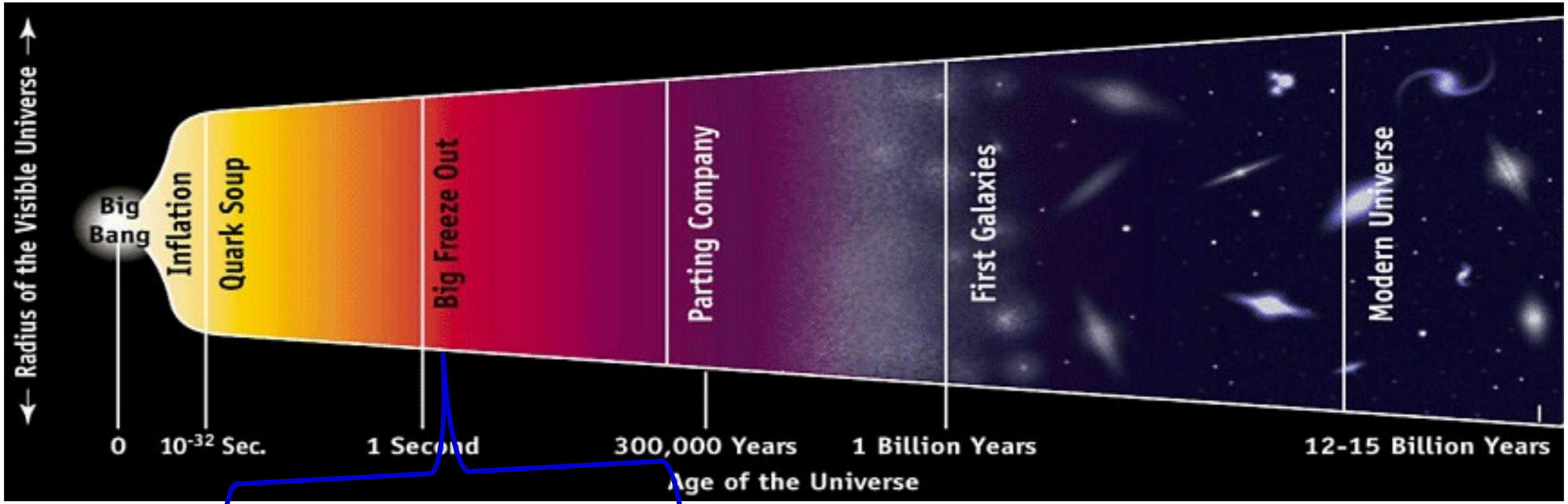
RHIC
LHC



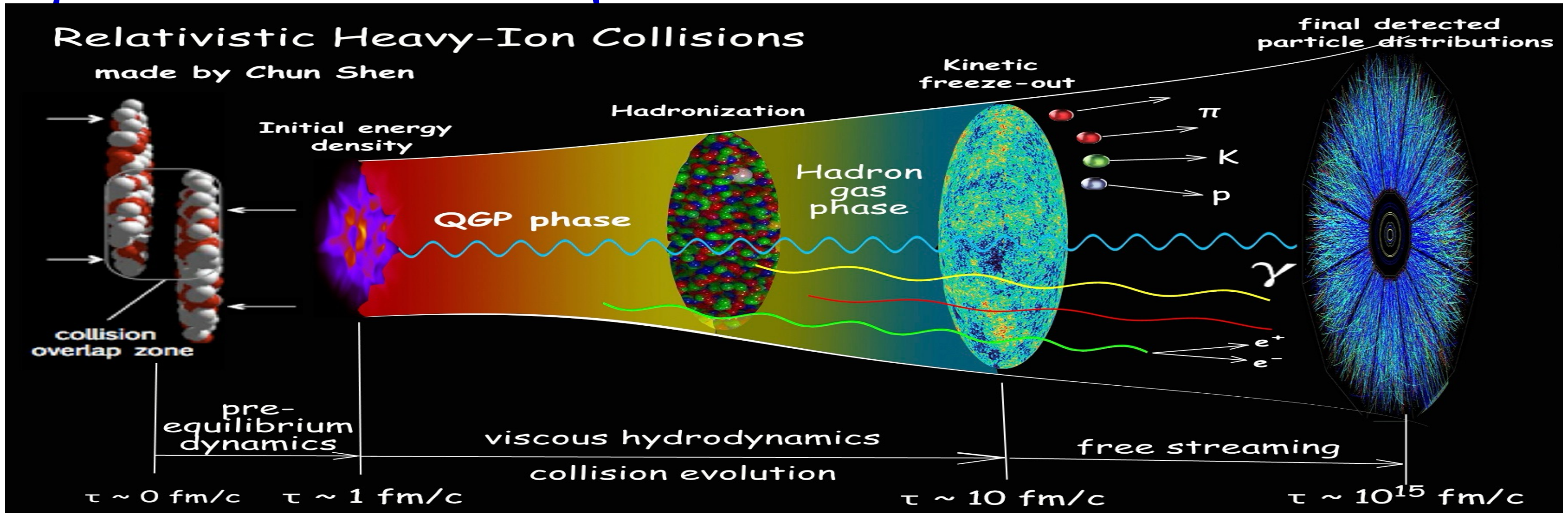
TIME

Little Big Bangs

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



RHIC
LHC

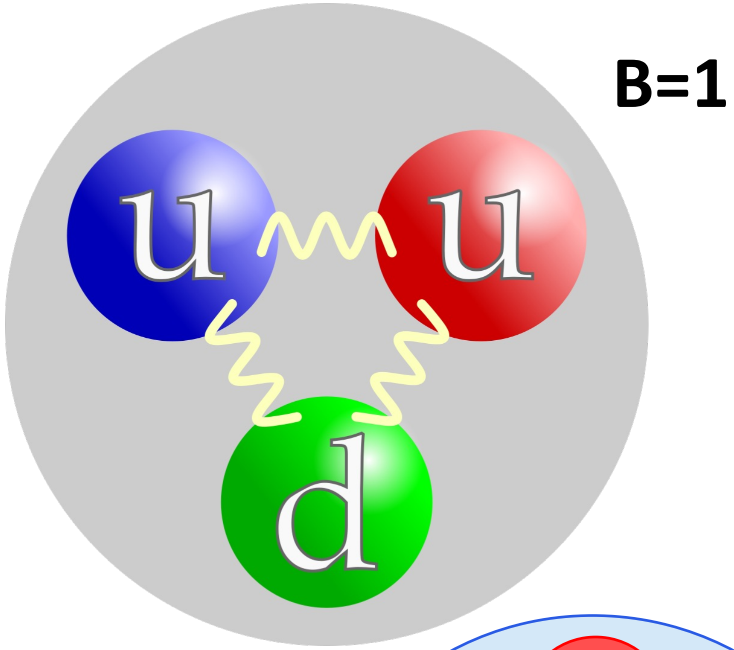


Little; Strong force at work; QGP@10^{-23}s; Fast expansion; Antimatter-matter decouple; repeat trillion times

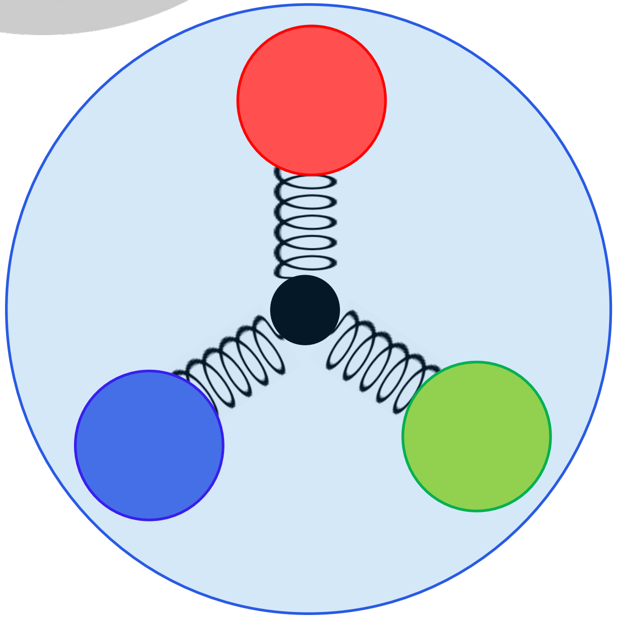
TIME

Baryon Number (B) Carrier

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



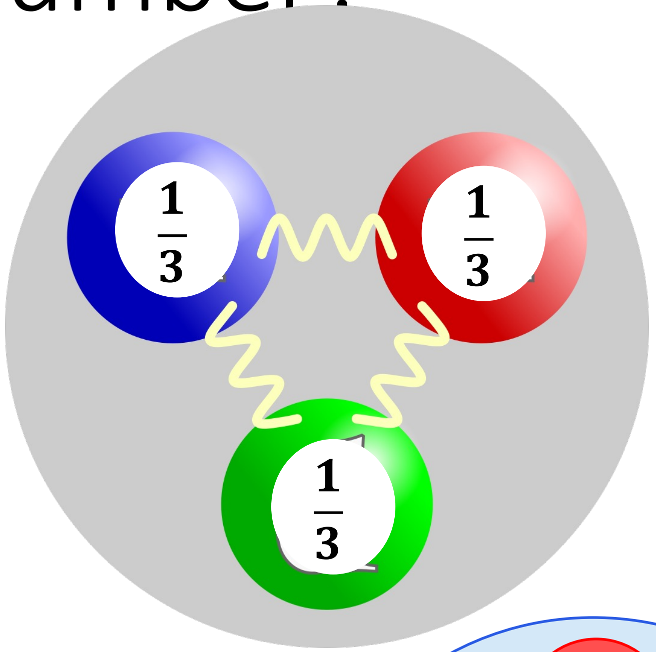
- Textbook picture of a proton
  - Lightest baryon with strictly conserved baryon number
  - Each valence quark carries 1/3 of baryon number
  - Proton lifetime >10^{34} years
  - Quarks are connected by gluons
- Alternative picture of a proton
  - Proposed at the Dawn of QCD in 1970s
  - A Y-shaped 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

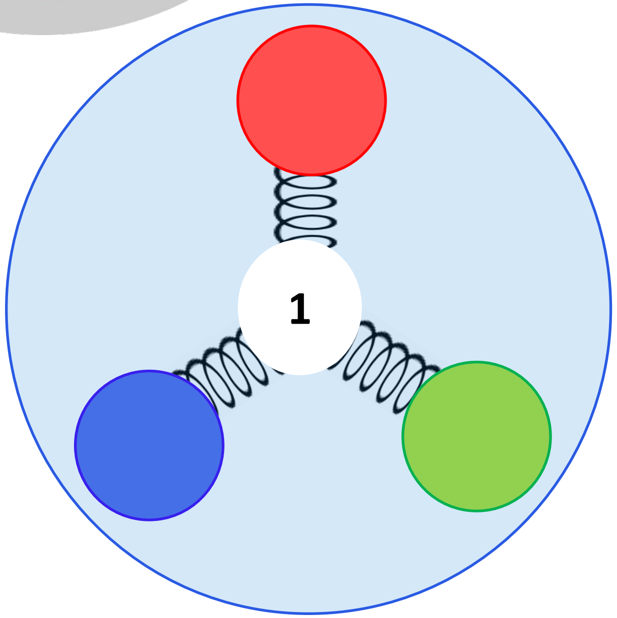


[1]: Artru, X.; String Model with Baryons: Topology, Classical Motion. Nucl. Phys. B 85, 442–460 (**1975**).
[2]: Rossi, G. C. & Veneziano, G. A; Possible Description of Baryon Dynamics in Dual and Gauge Theories. Nucl. Phys. B 123, 507–545 (**1977**)

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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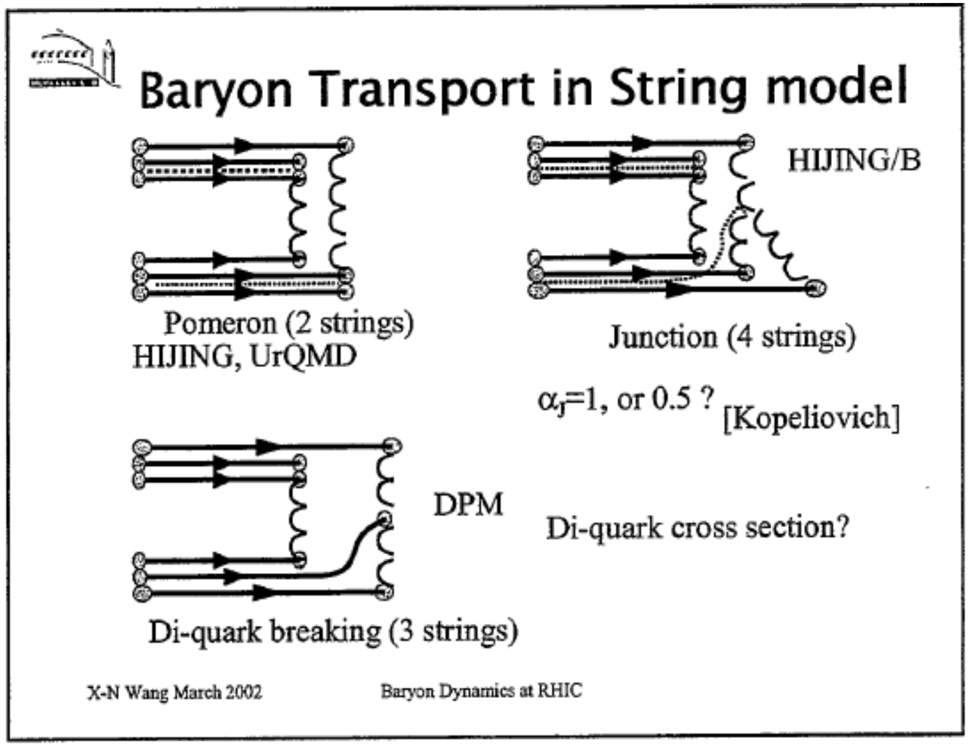
Model implementations of baryons at RHIC

2003 RBRC Workshop on "Baryon Dynamics 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:

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

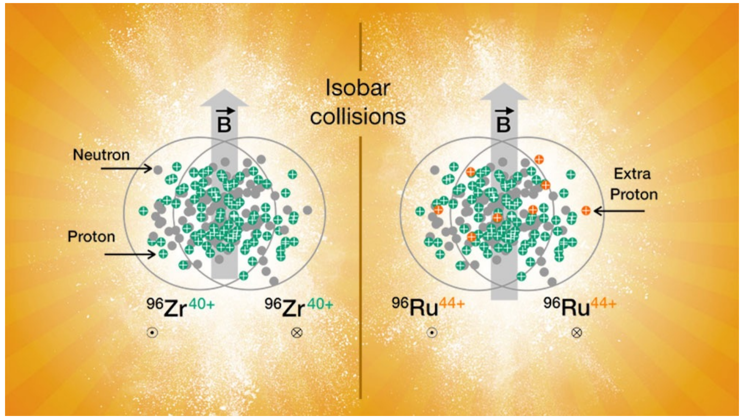
$$\alpha_B \sim= 0.5$$

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

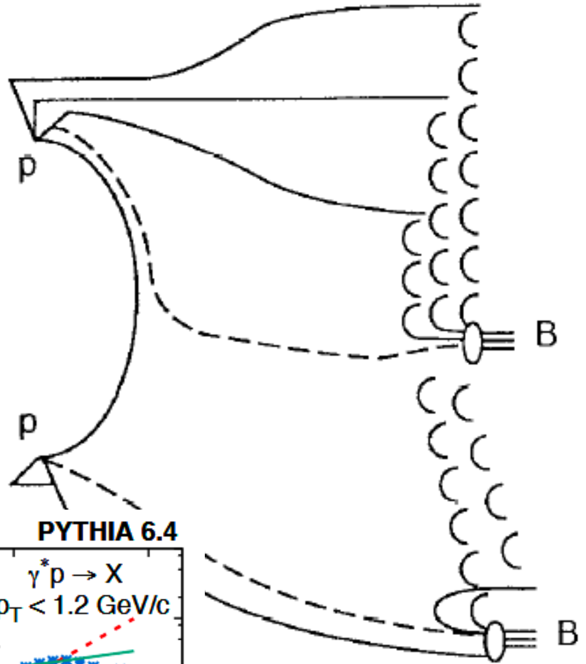
It is evident from the structure of (1) that the trace of baryon number should be associated not with the valence quarks, but with a non-perturbative configuration of gluon fields located at the point x - the "string junction" .

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

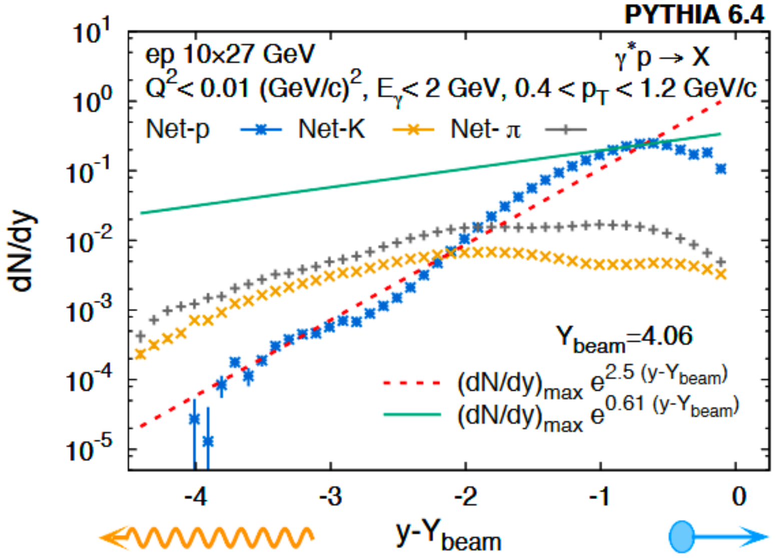


2. Kharzeev-STAR Method:
   If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory

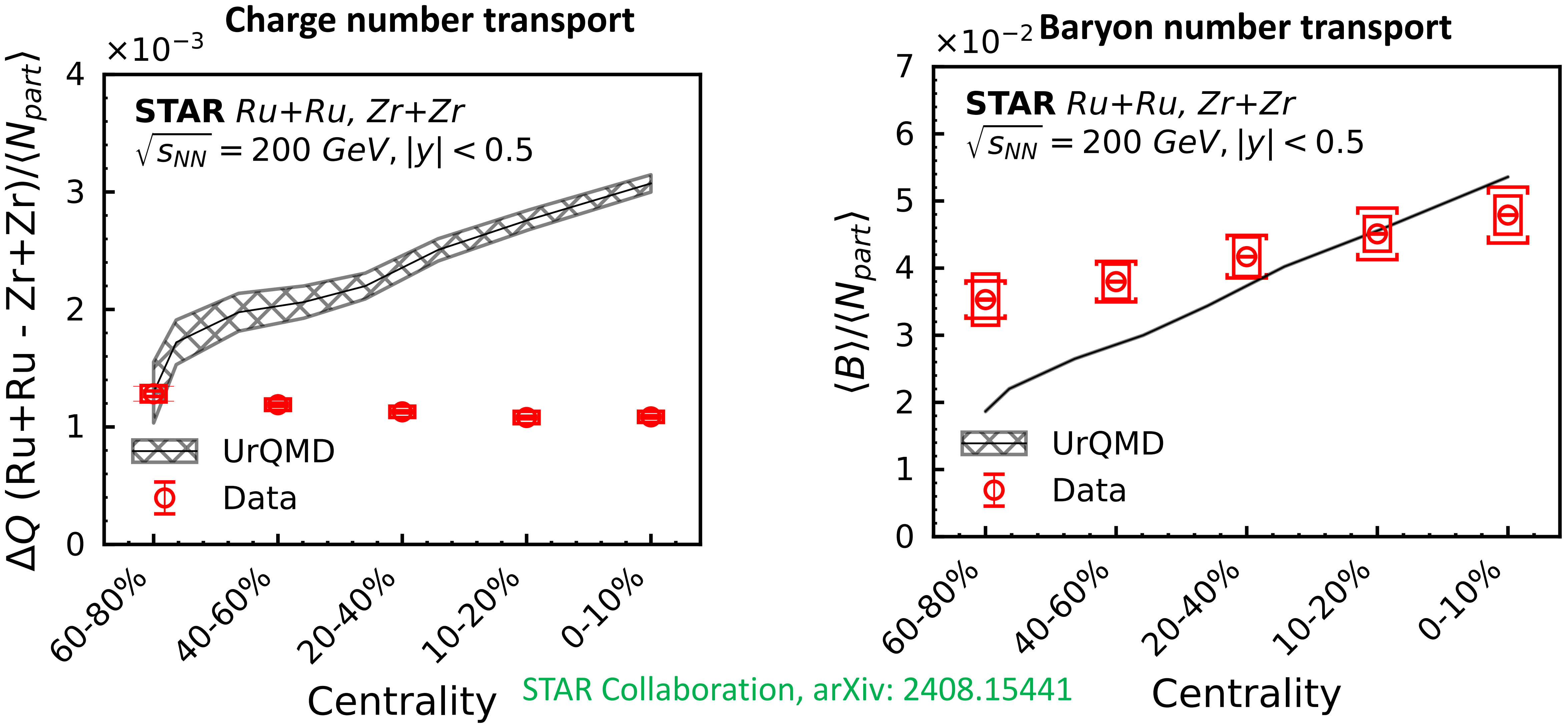
$$p = \sim e^{-\alpha_B y}$$

α_B ~=0.5

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



Separate charge and baryon transports

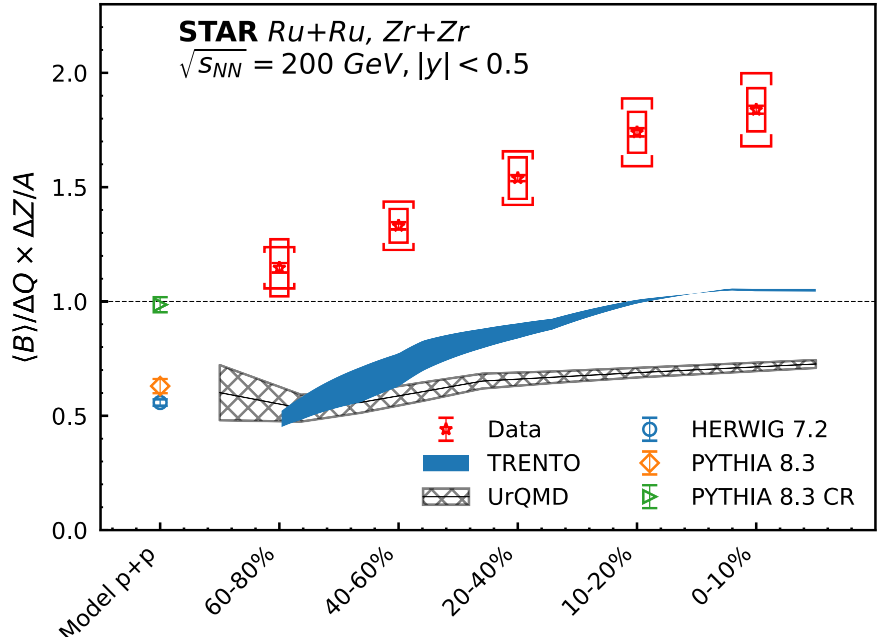


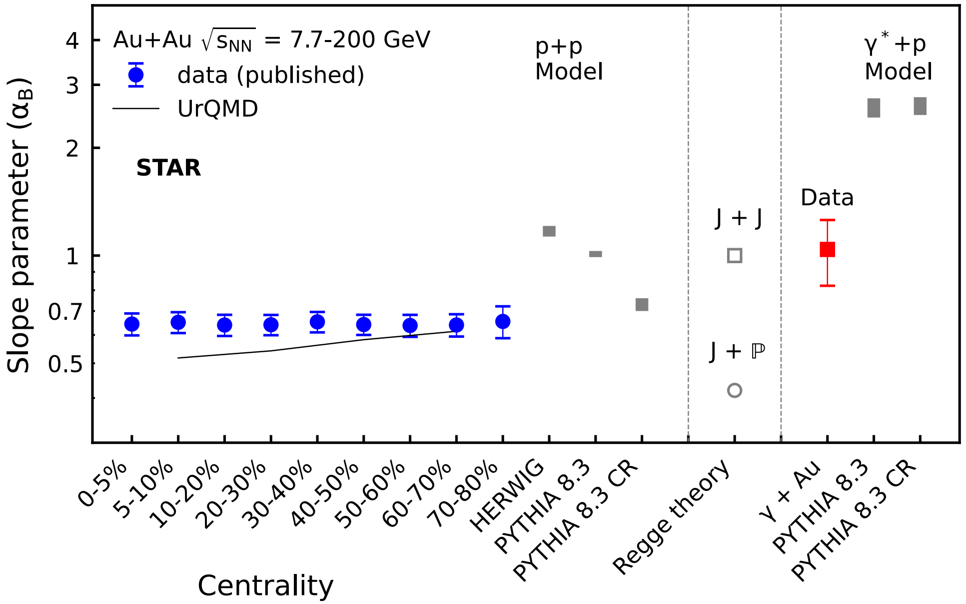
STAR Collaboration, arXiv: 2408.15441

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
   $p = \sim e^{-\alpha_B y}$
   α_B ~=0.5
3. Artru Method:
   In γ+Au collision, rapidity asymmetry can reveal the origin
   α_B(A+A)=0.61< α_B(γ+A)=1.1< α_B(PYTHIA)





B=1,2,3 nuclear yield ratios

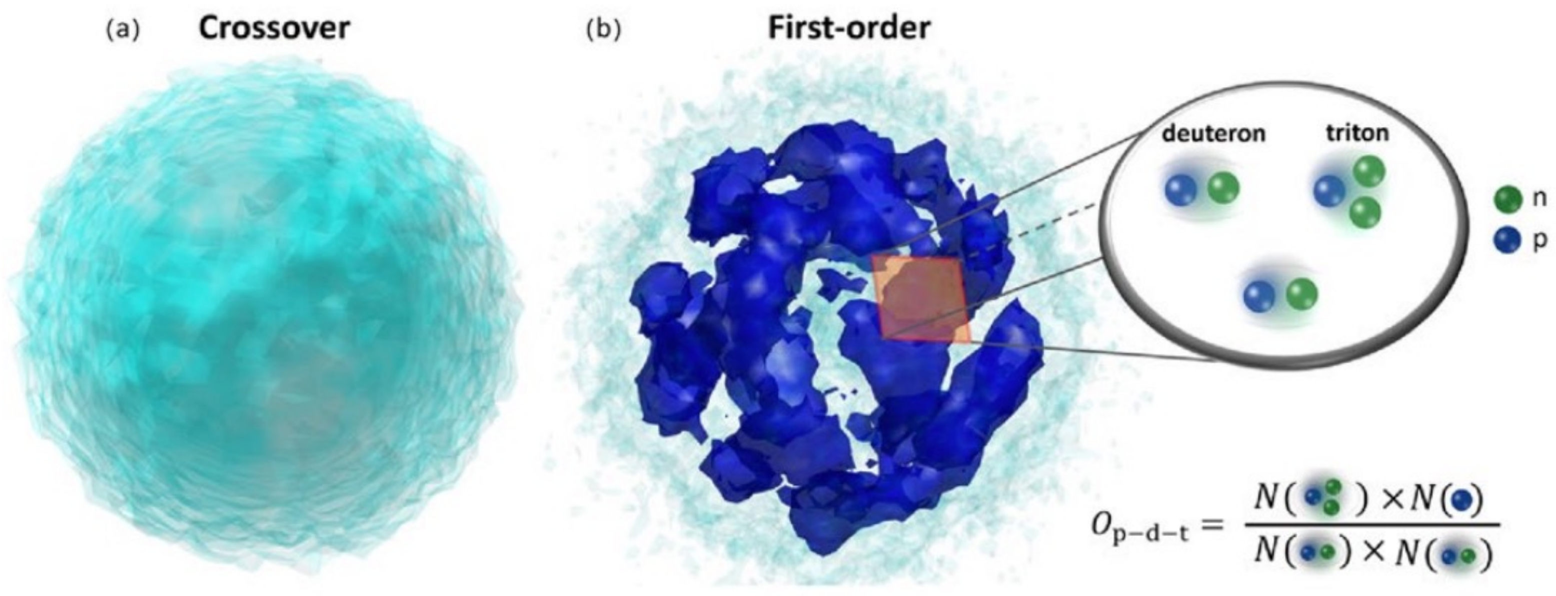


Fig. 1 (Color online) Density distribution of strongly interacting matter in a heavy ion collision after its expansion for the cases of crossover transition (panel **a**) and first-order chiral phase transition (panel **b**). Also shown for illustration of the latter case are deuterons and tritons produced 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

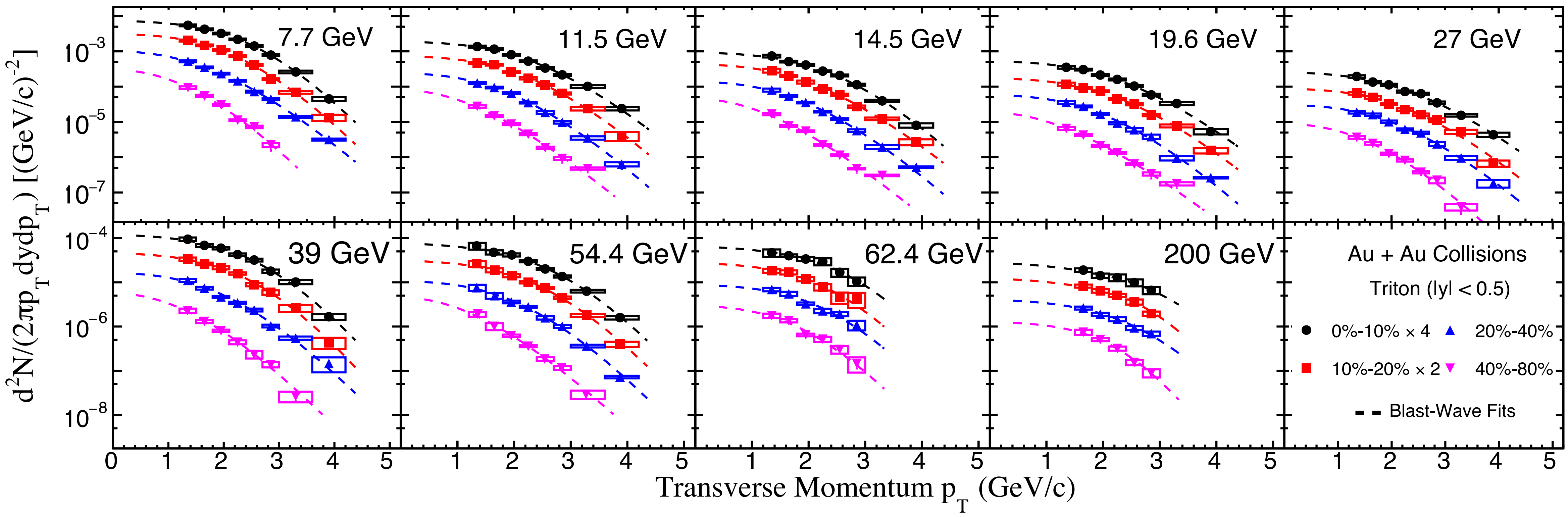
K.J. Sun, et al., PLB 774 (2017) 103

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

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

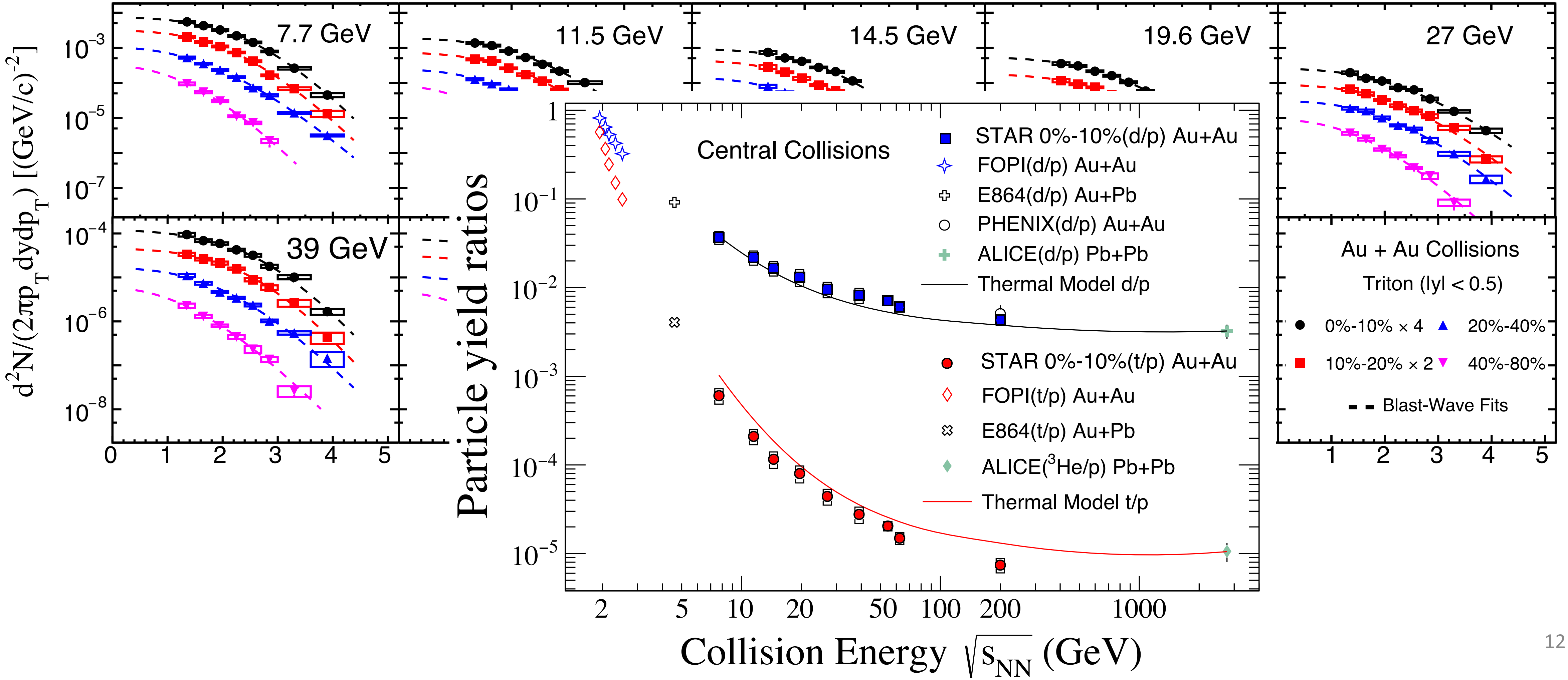
Spectra and two-particle ratios

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



Spectra and two-particle ratios

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

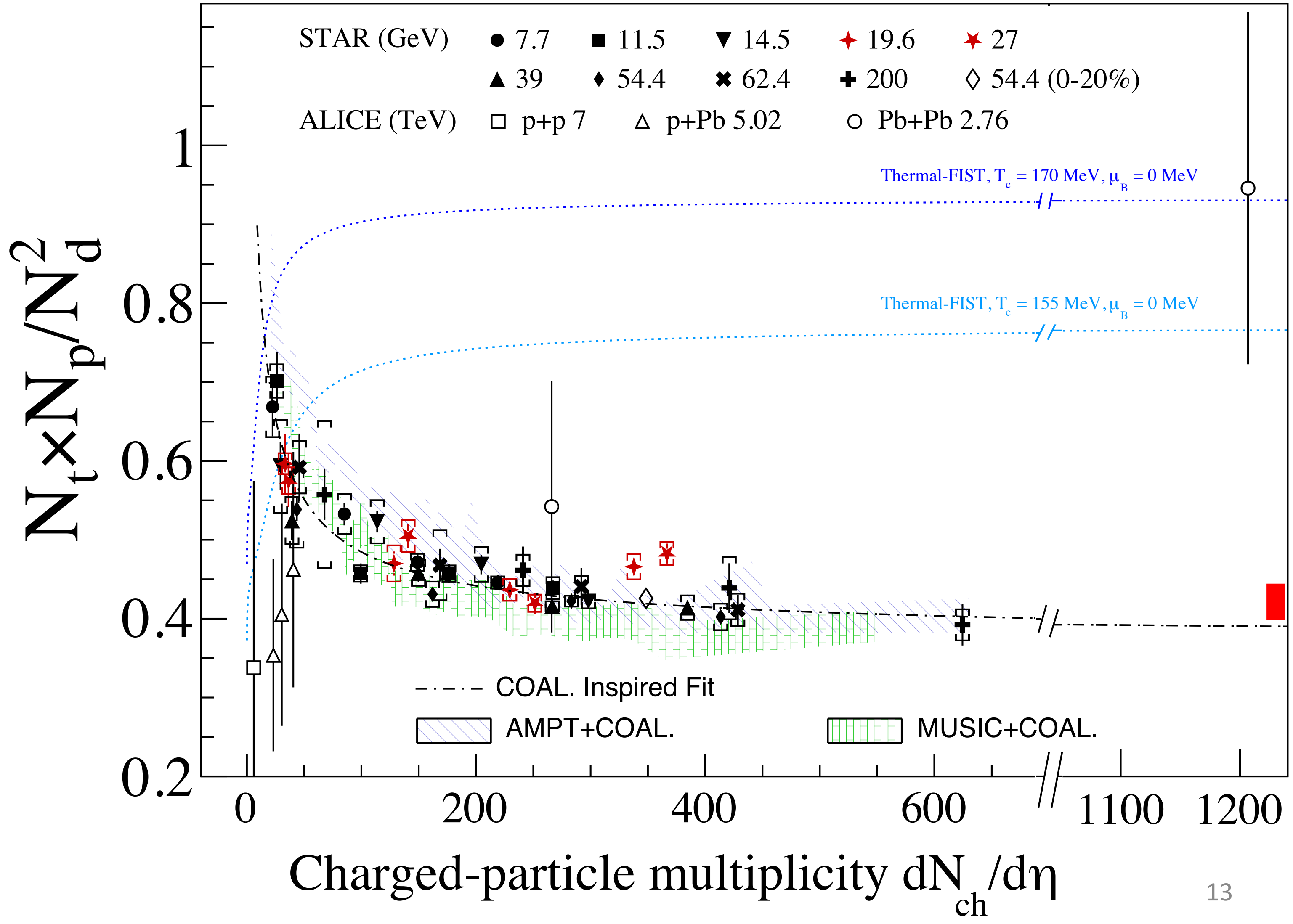


Quantum Wavefunction overlap efficiency

STAR, Phys.Rev.Lett. 130 (2023) 202301
RHIC+LHC data, C. Pinto, X.F. Luo, XZB,EMMI RRTF 04/24

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

Coalescence wavefunction overlap between nucleus and nucleons



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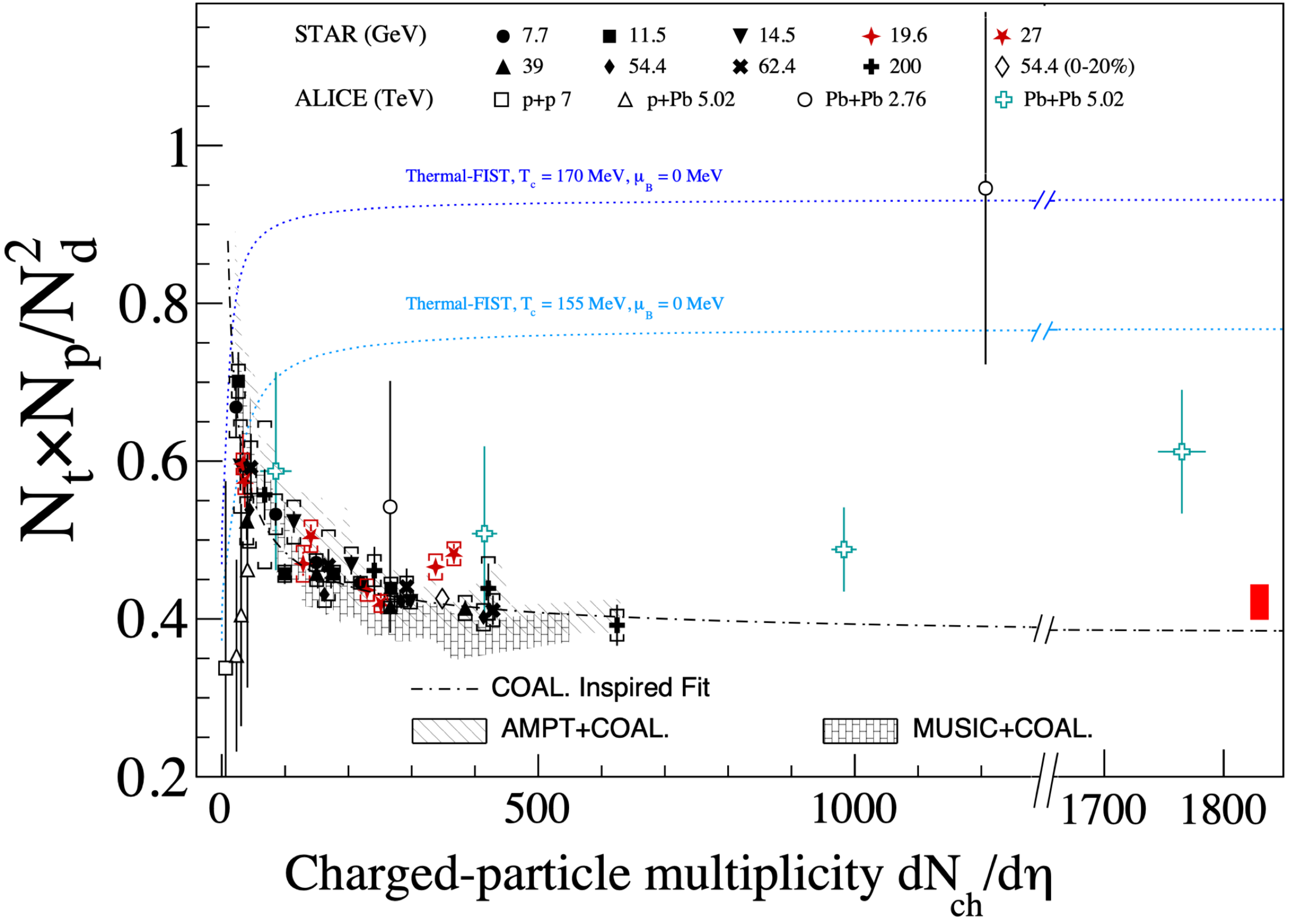
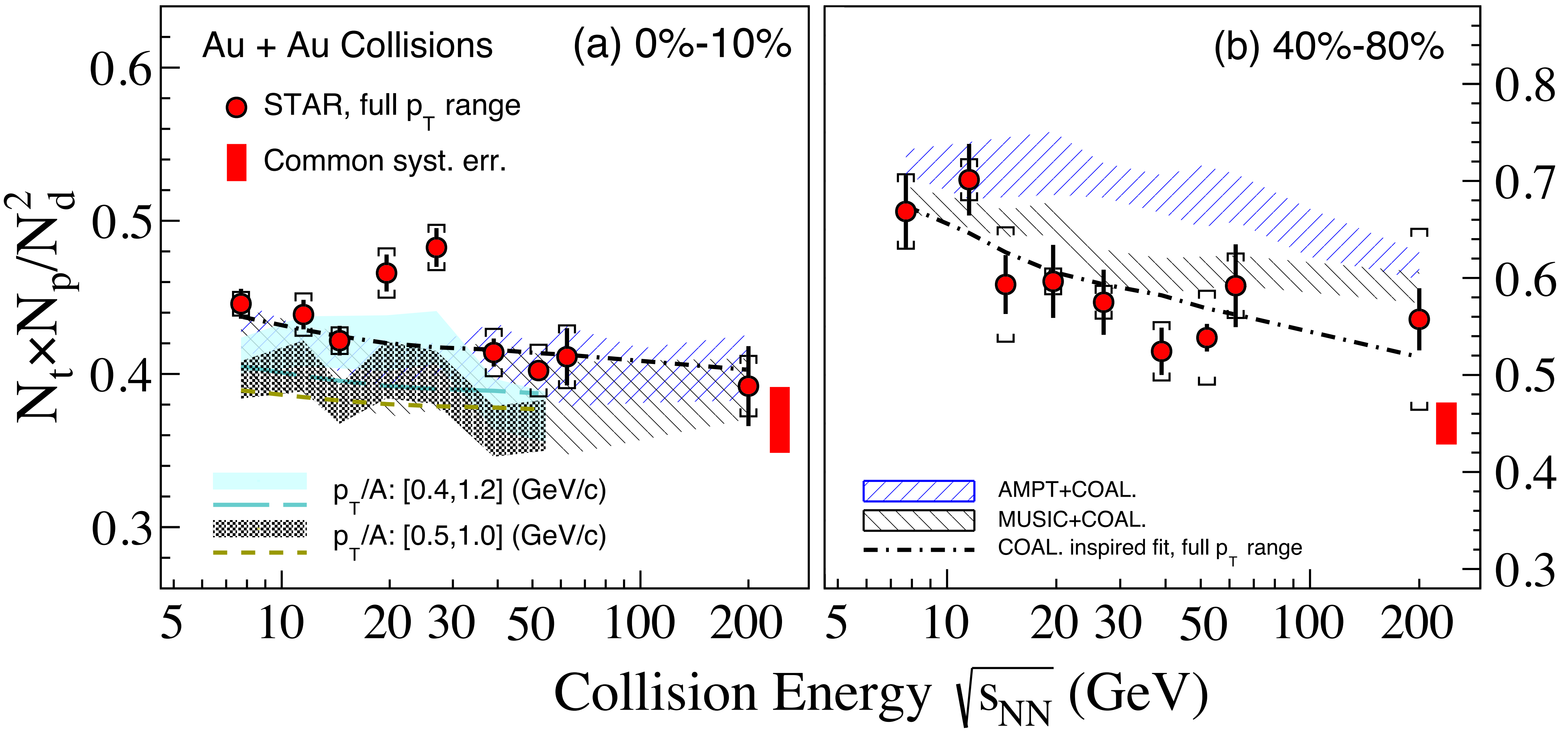


ExtreMe Matter Institute EMMI
EMMI Rapid Reaction Task Force
Understanding light (anti-)nuclei production at RHIC and LHC
April 8 - 12, 2024
SB1 Lecture Hall, GSI, Darmstadt , Germany

Possible sign of Density Fluctuation

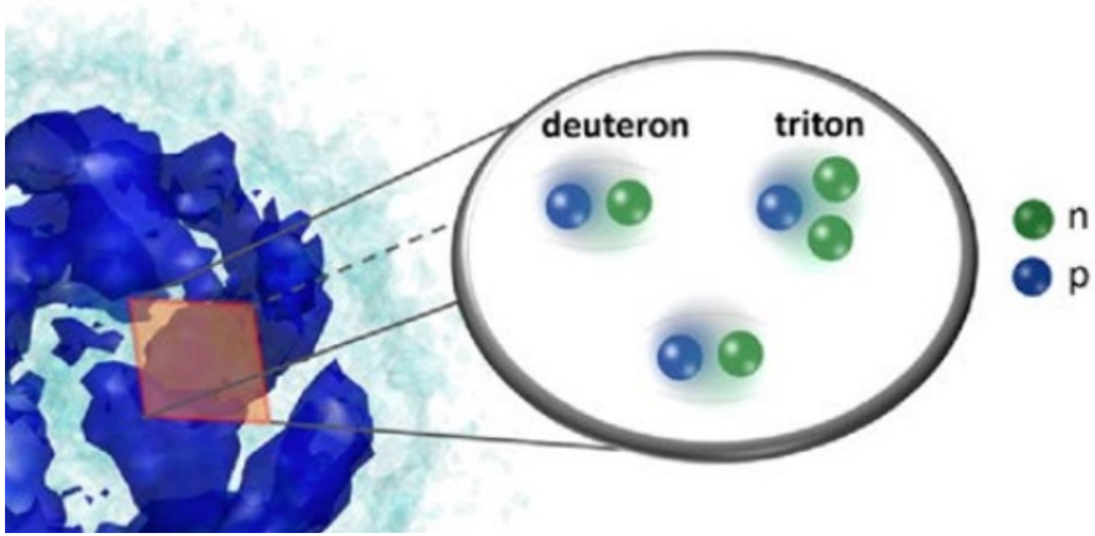
4σ effect, BES-II data x10 statistics

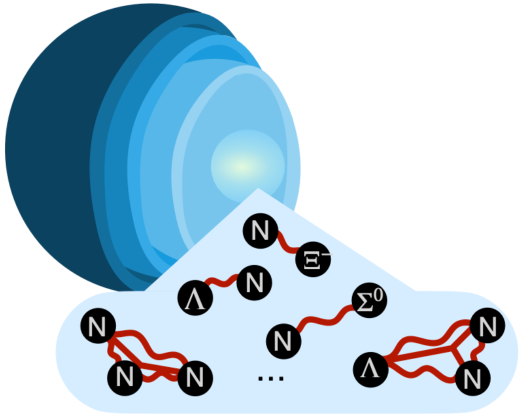
STAR, Phys.Rev.Lett. 130 (2023) 202301

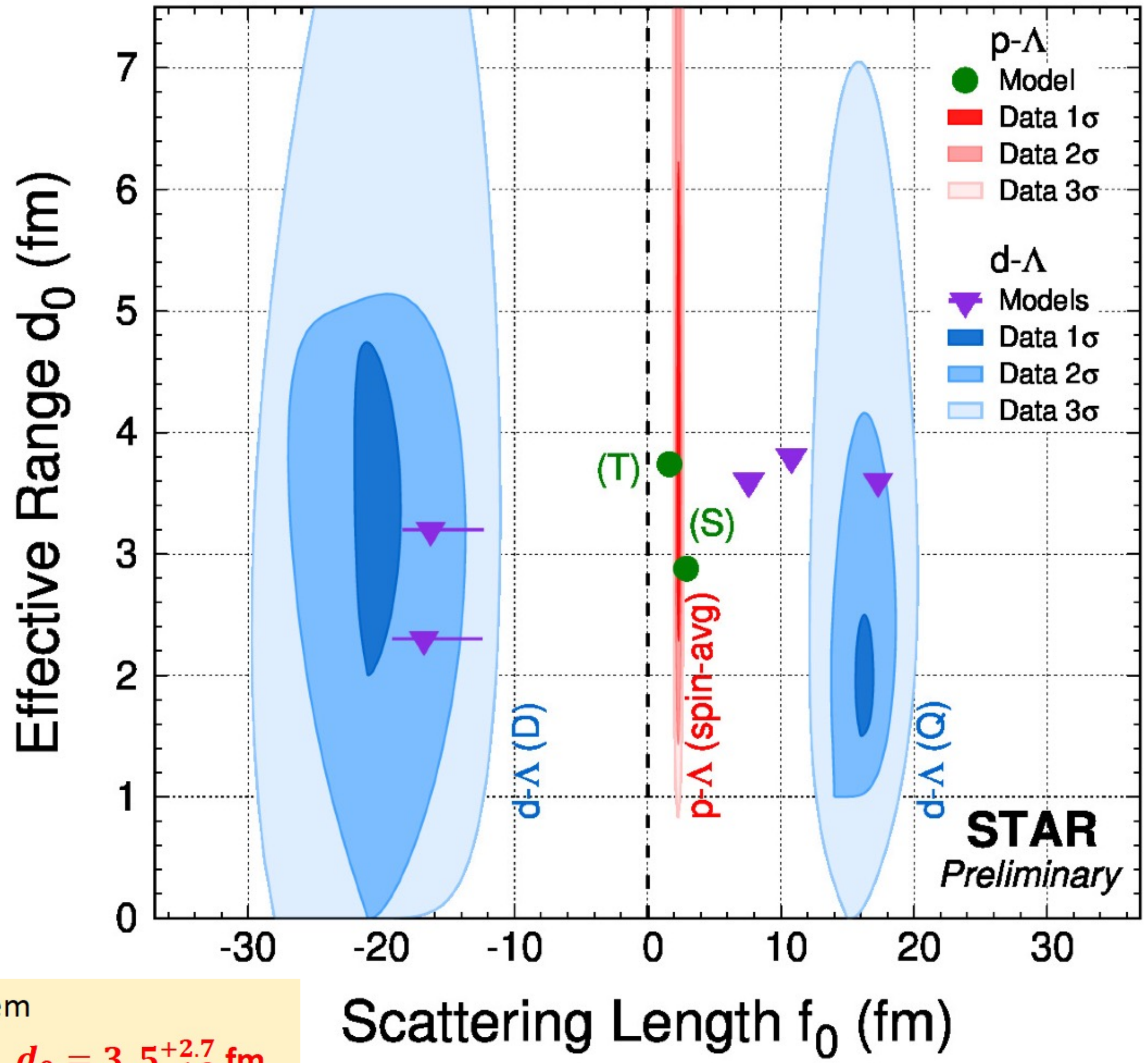


Few-body correlations at RHIC and LHC

Collision system size: 1-10fm
Scattering length: ~fm
d-p, n-p-p, p-p-p, p-p-Λ, d-Λ







- Spin-avg for f_0 & d_0 p-Λ system

  $f_0 = 2.32^{+0.12}_{-0.11}$ fm $\quad d_0 = 3.5^{+2.7}_{-1.3}$ fm

- Successfully separate two spin states in d-Λ

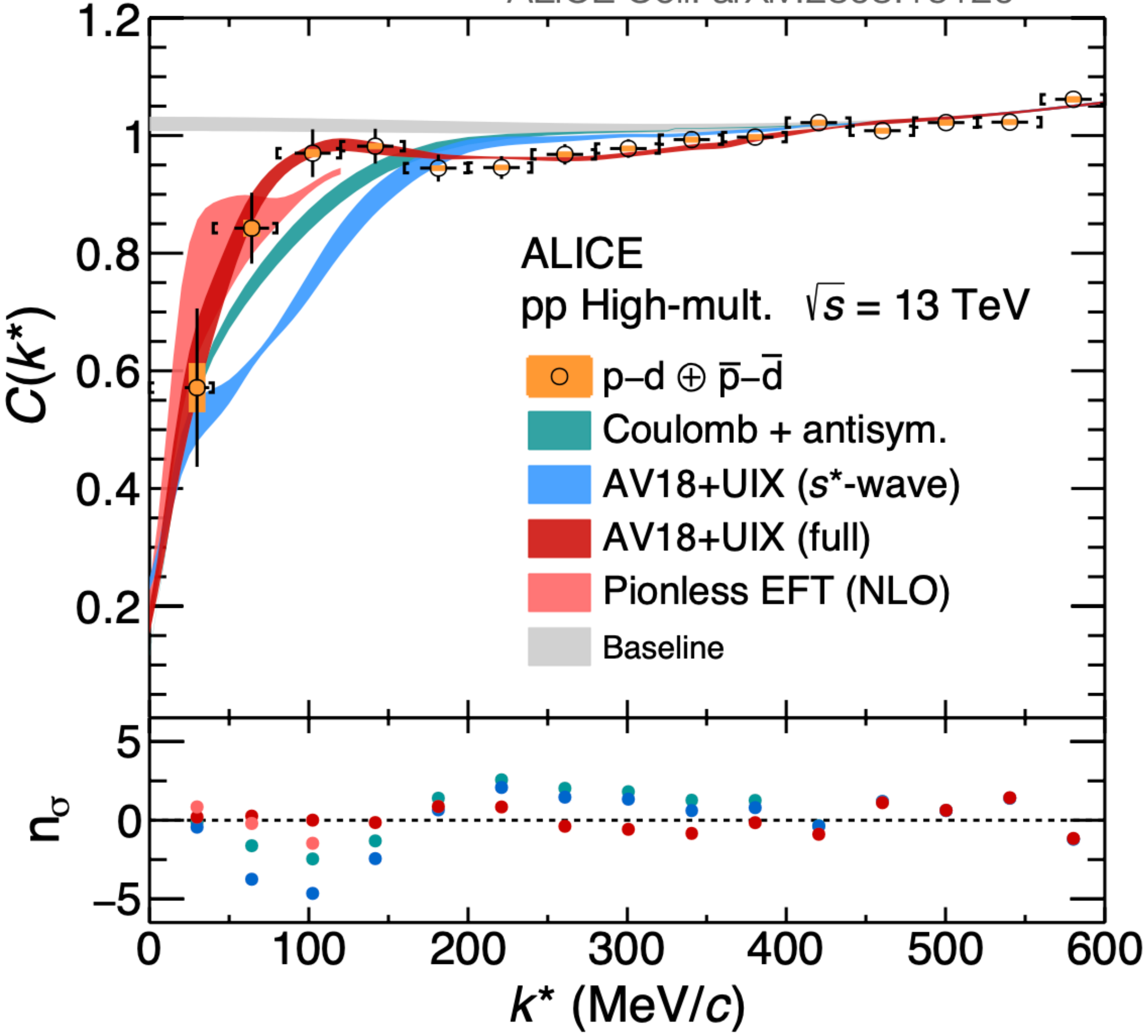
  $f_0(\mathrm{D}) = -20^{+3}_{-3}$ fm $\quad d_0(\mathrm{D}) = 3^{+2}_{-1}$ fm

  $f_0(\mathrm{Q}) = 16^{+2}_{-1}$ fm $\quad d_0(\mathrm{Q}) = 2^{+1}_{-1}$ fm

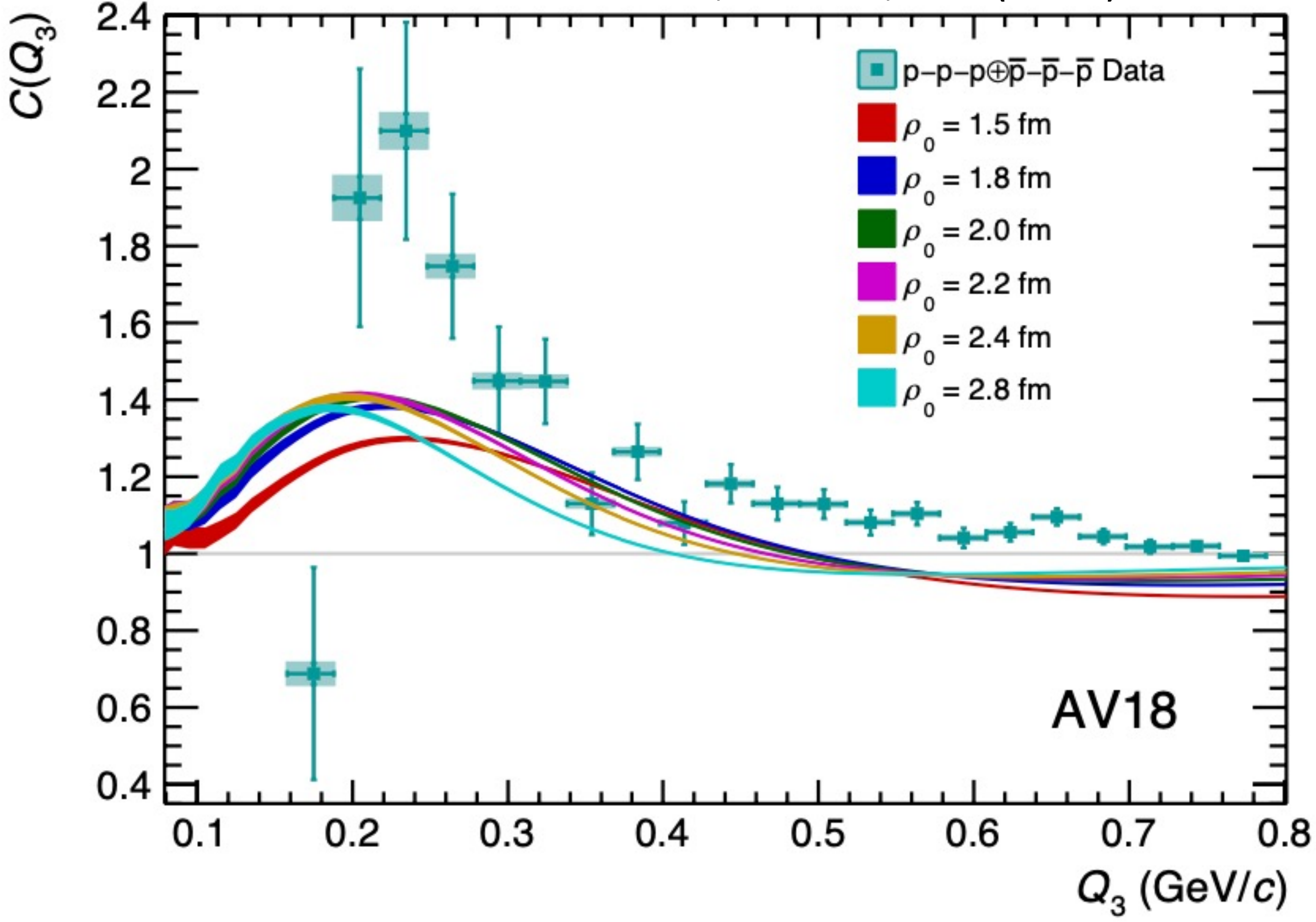
D. Lonardoni et al, PRL 114, 092301 (2015)
J. Schaffner-Bielich et al, NPA 835 (2010)

Three-nucleon correlations at LHC

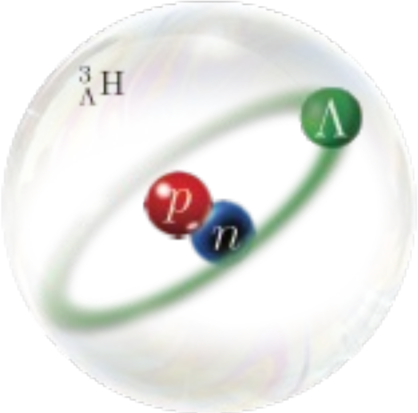
ALICE Coll. arXiv:2308.16120



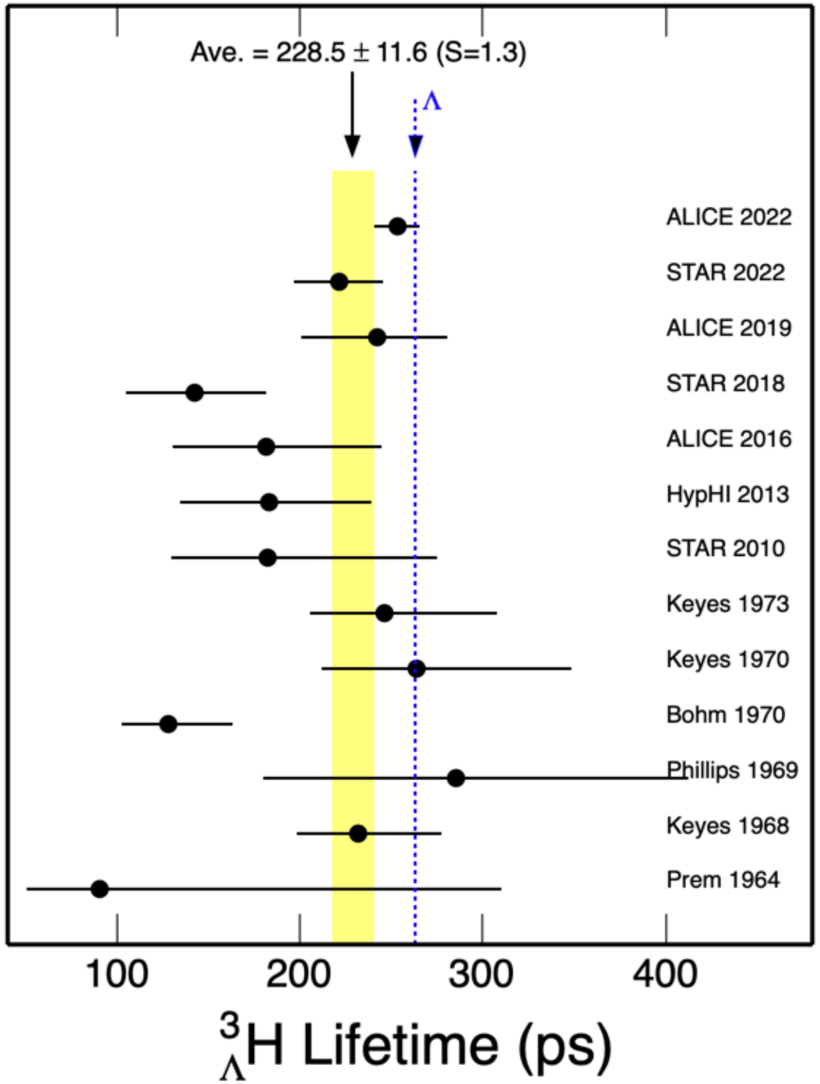
ALICE Collaboration, EPJA 59, 145 (2023)

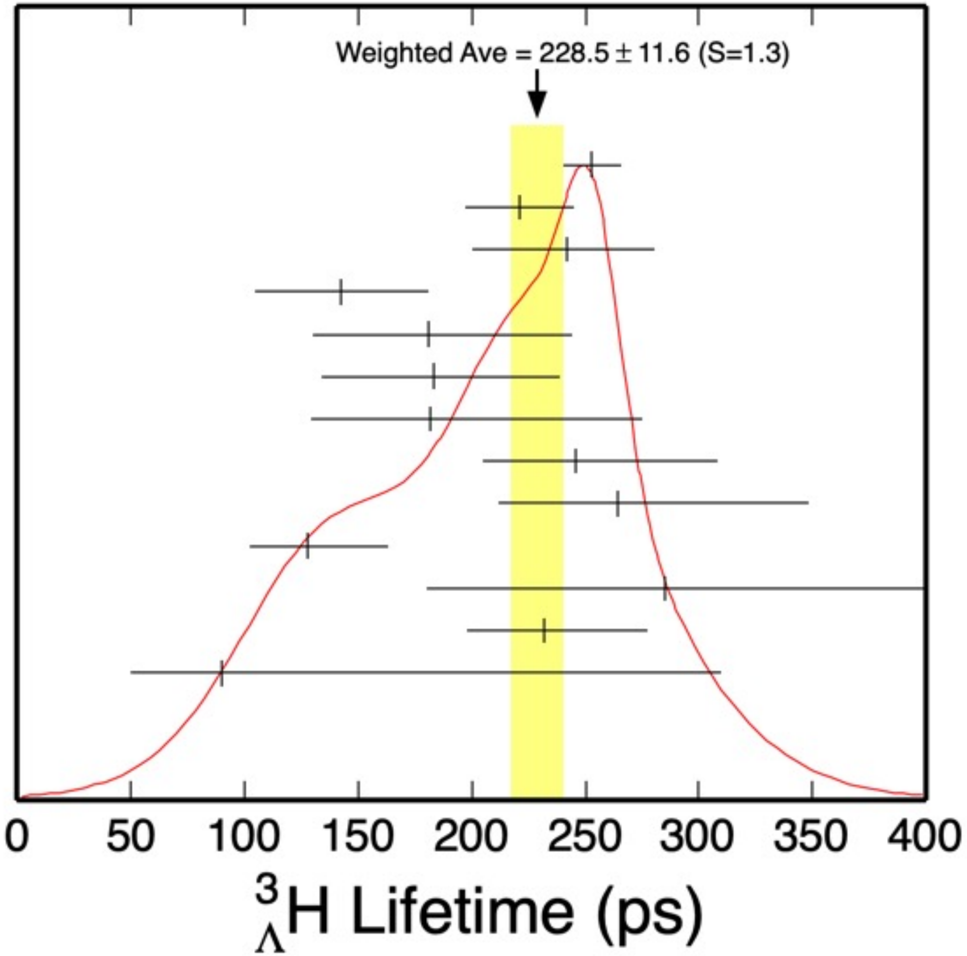


|B|=3 hypertriton lifetime



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

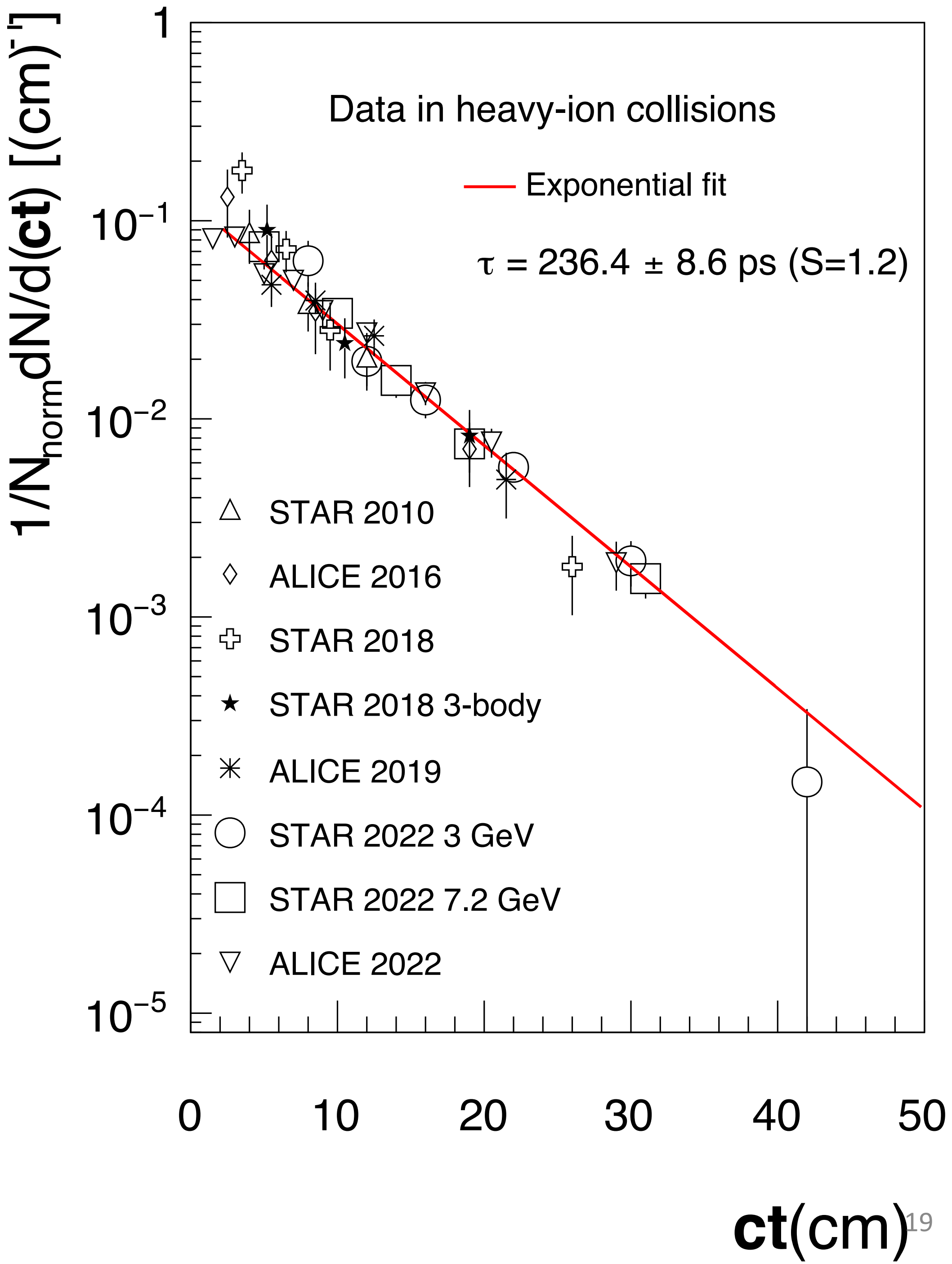
Simultaneous fit to all heavy-ion data

Scale yields to one common exponential function

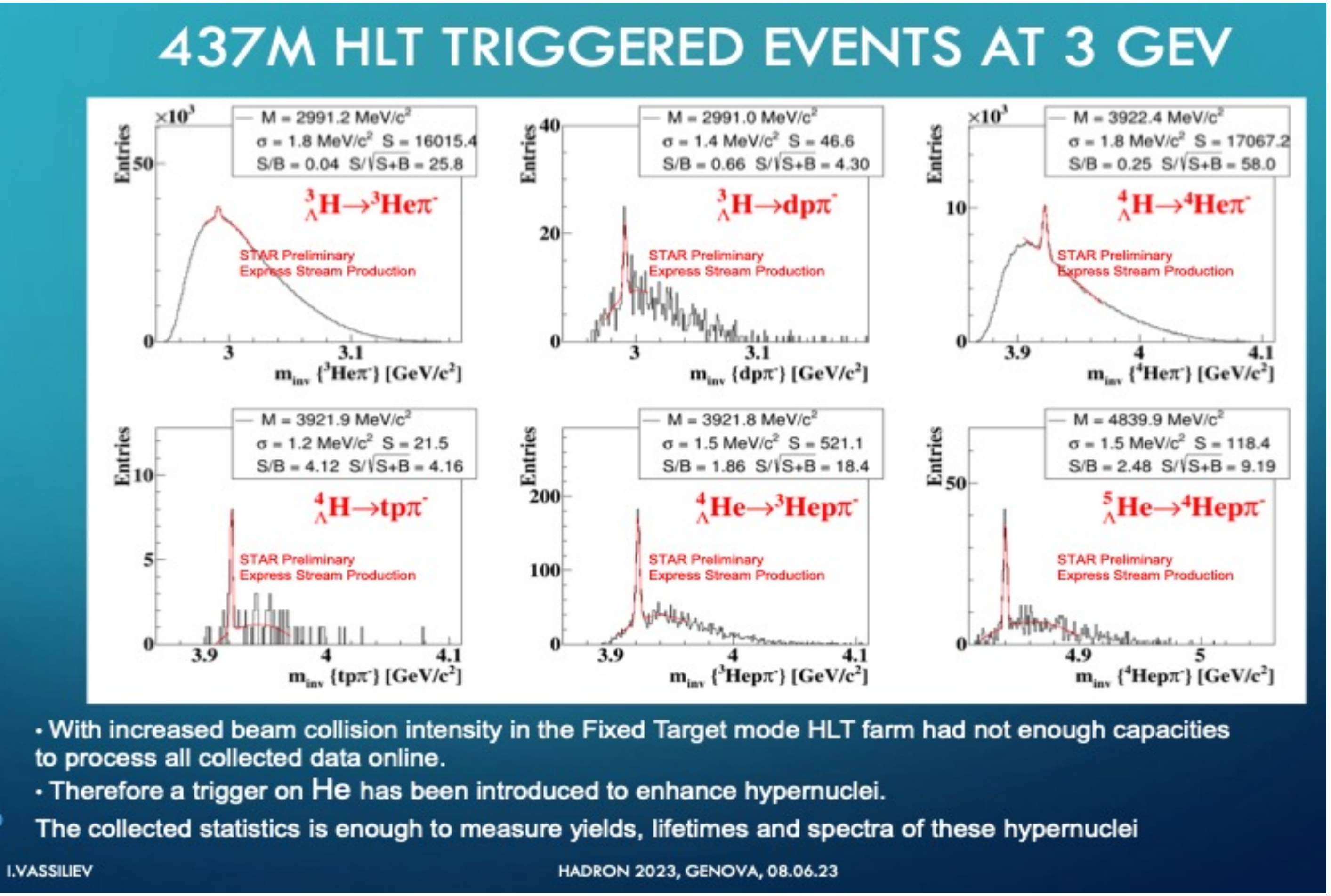
Result consistent with other (average) methods

About 3σ smaller than Lambda lifetime

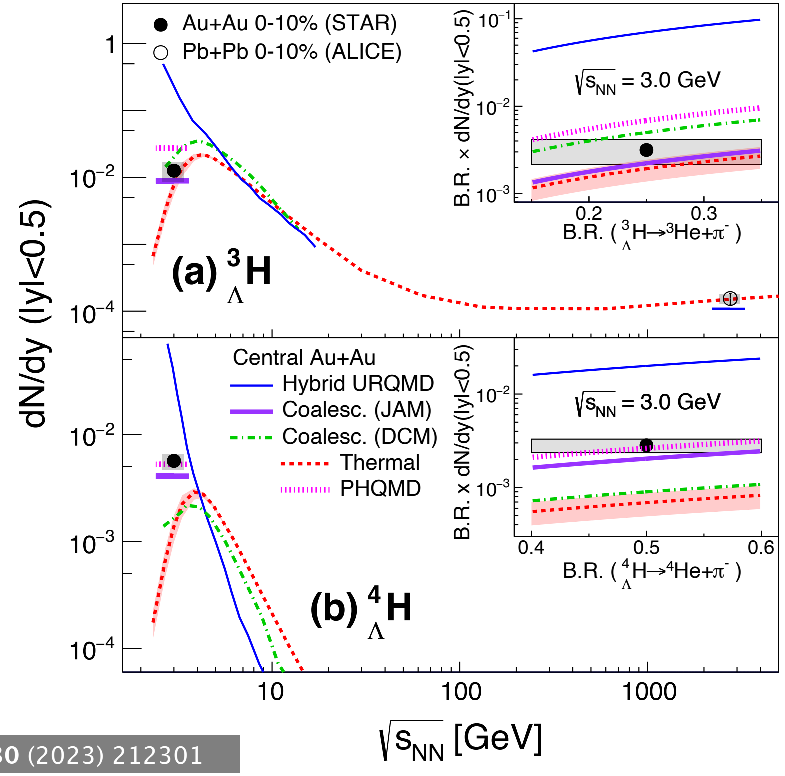
STAR 2018 first cτ point appears high
ALICE 2022 first cτ point appears low



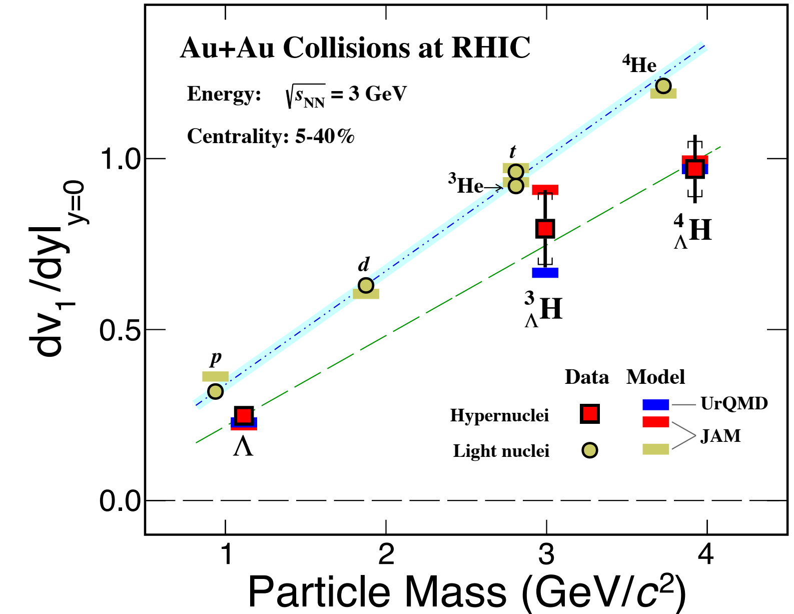
A zoo of hypernucleus measurements



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

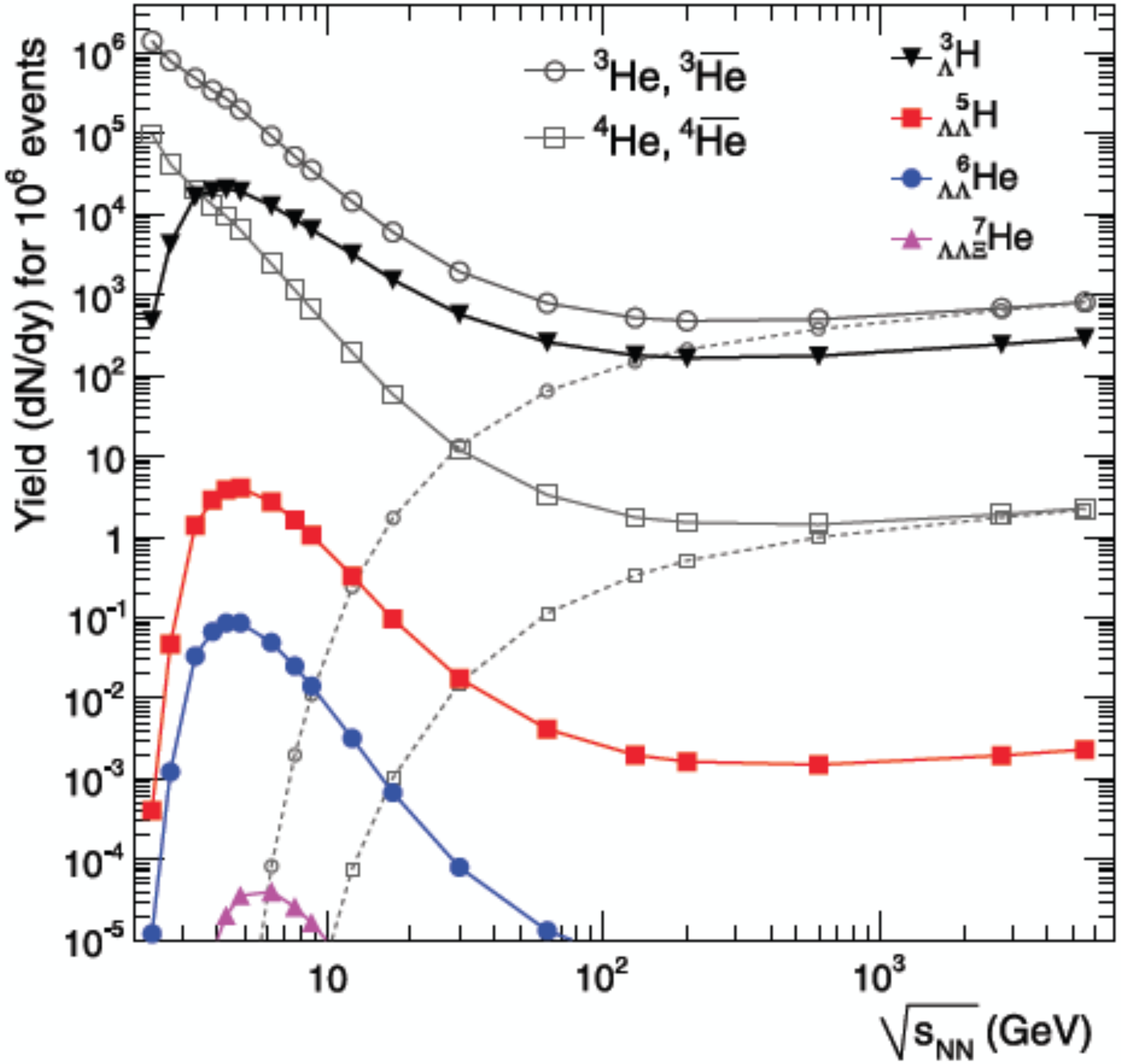


Phys. Rev. Lett. **130** (2023) 212301

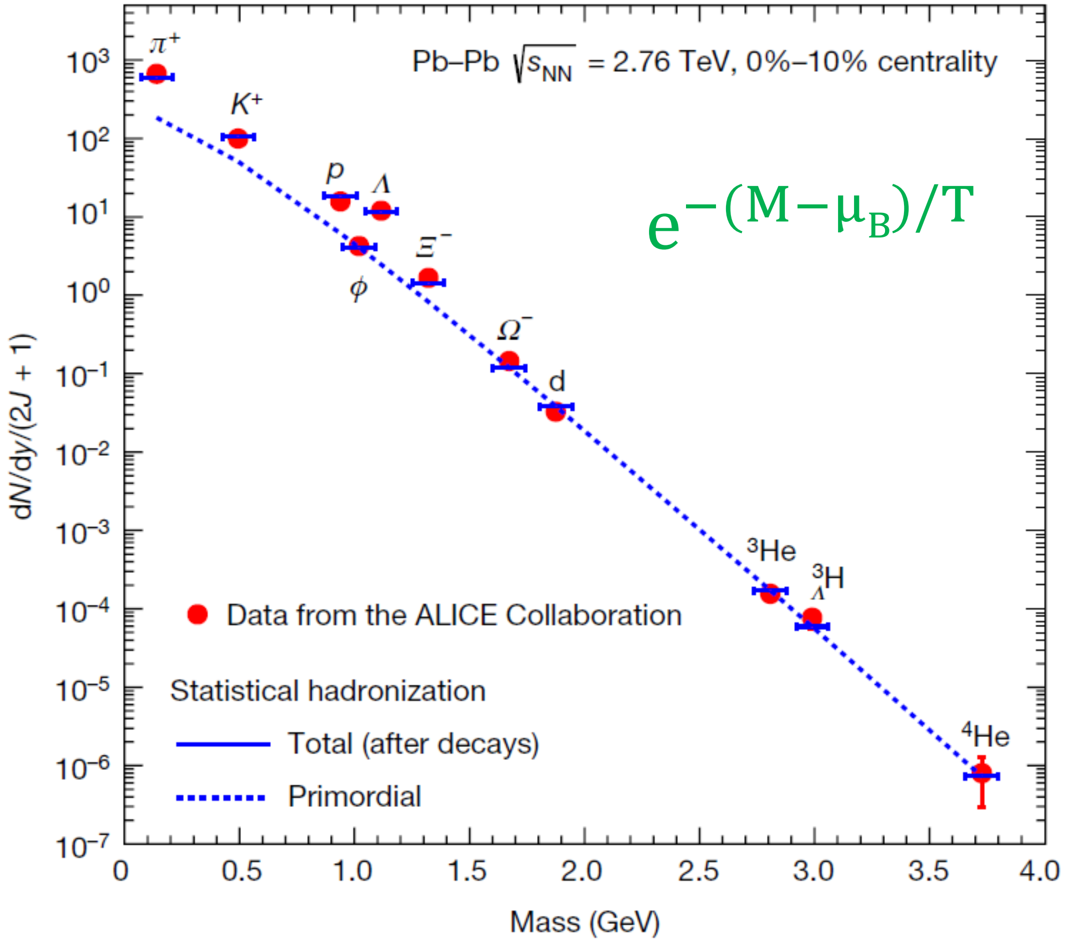


Statistical Hadronization: powerful projections

FAIR RHIC Beam Energy Scans LHC



Andronic et al., Nature 561, 321–330 (2018)



$$e^{-(M-\mu_B)/T}$$

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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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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Article | Published: 21 August 2024

Observation of the antimatter hypernucleus $^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$

STAR Collaboration

Nature **632**, 1026–1031 (2024) | Cite this article

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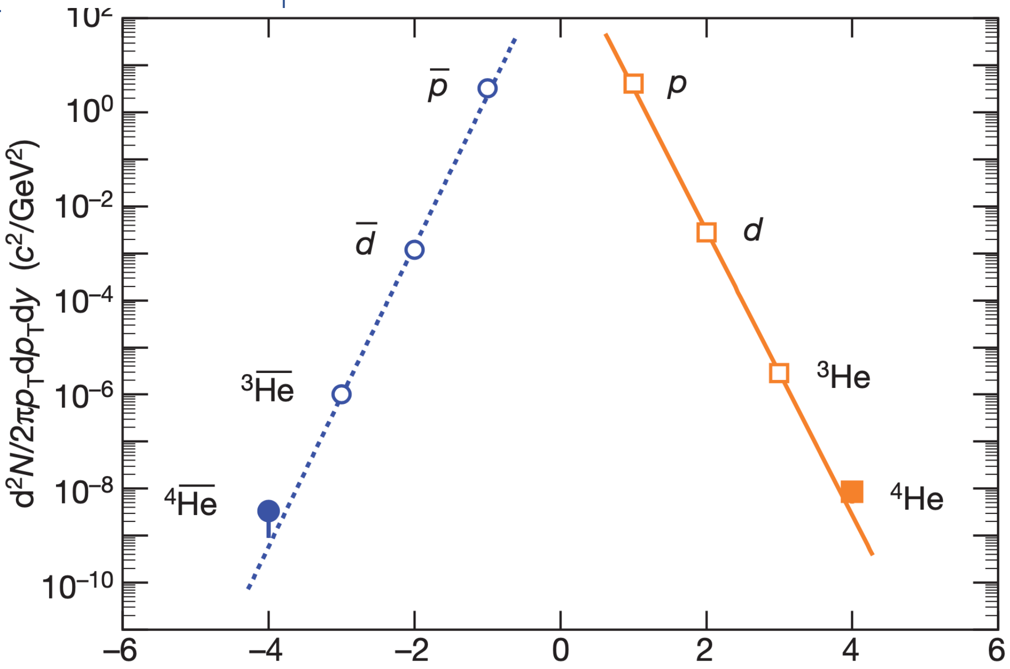
HOME › SCIENCE › VOL. 328, NO. 5974 › OBSERVATION OF AN ANTIMATTER HYPERNUCLEUS

RESEARCH ARTICLE

Observation of an Antimatter Hypernucleus

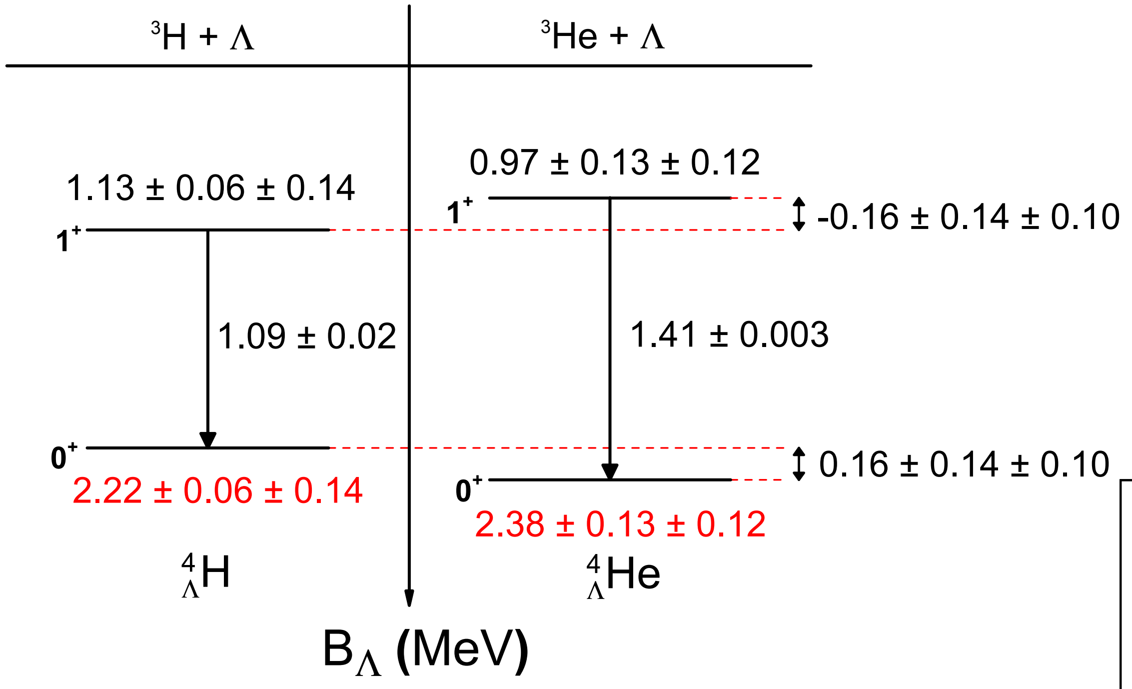
THE STAR COLLABORATION, B. I. ABELEV, M. M. AGGARWAL, Z. AHAMMED, A. V. ALAKHVERDYANTS, I. ALEKSEEV, B. D. ANDERSON, D. ARK
Y. ZOULKARNEEVA +382 authors Authors Info & Affiliations

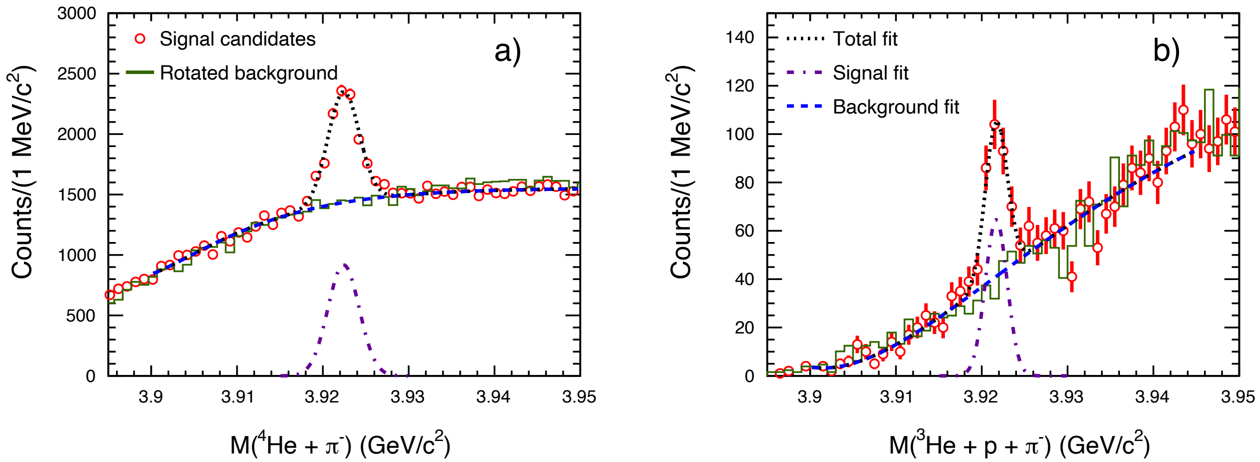
SCIENCE • 4 Mar 2010 • Vol 328, Issue 5974 • pp. 58-62 • DOI: 10.1126/science.1183980

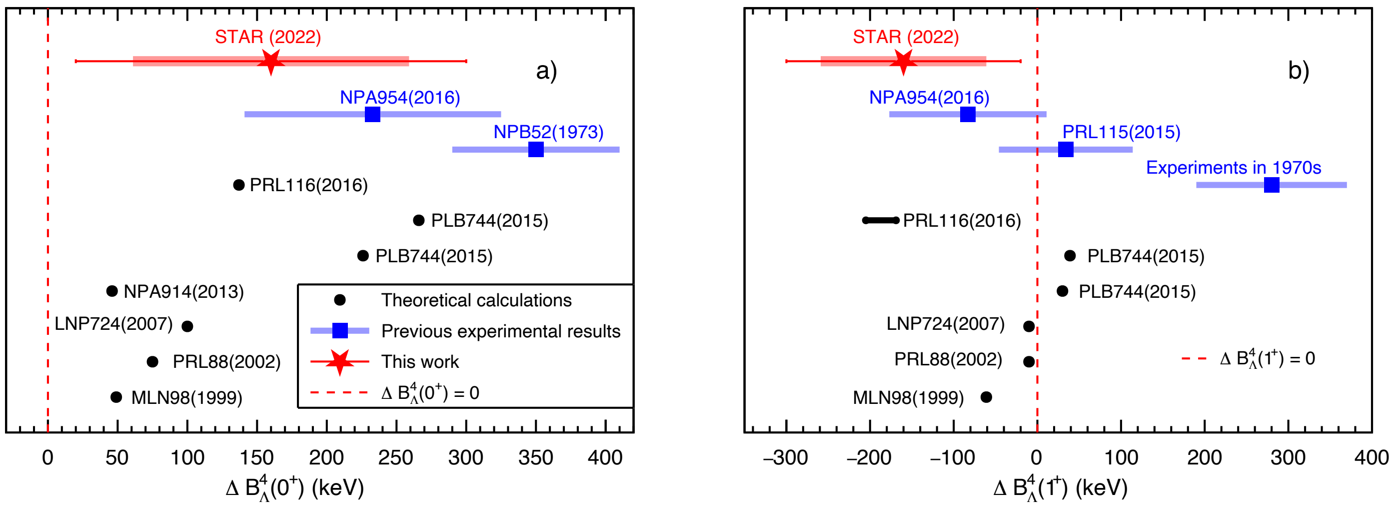


Charge Symmetry Breaking in B=4 hypernuclei

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

xzb
LBL Heavy-Ion Tea Seminar
05/2010

Discovery potential at EIC

Heavy-flavor states

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

Many (>10) states poorly consistent with quark model

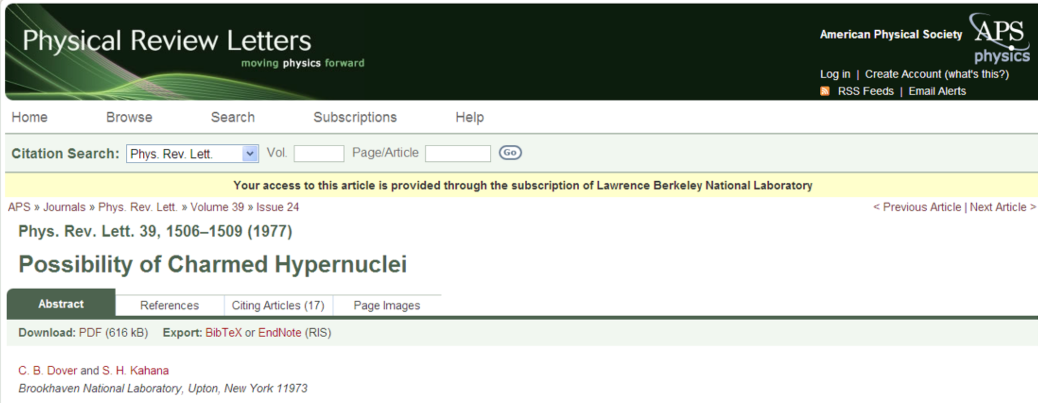
State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \to \eta Y_s(2175)$
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi, D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$
$X(3915)$	3914 ± 4	23 ± 9	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$
$Z(3930)$	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

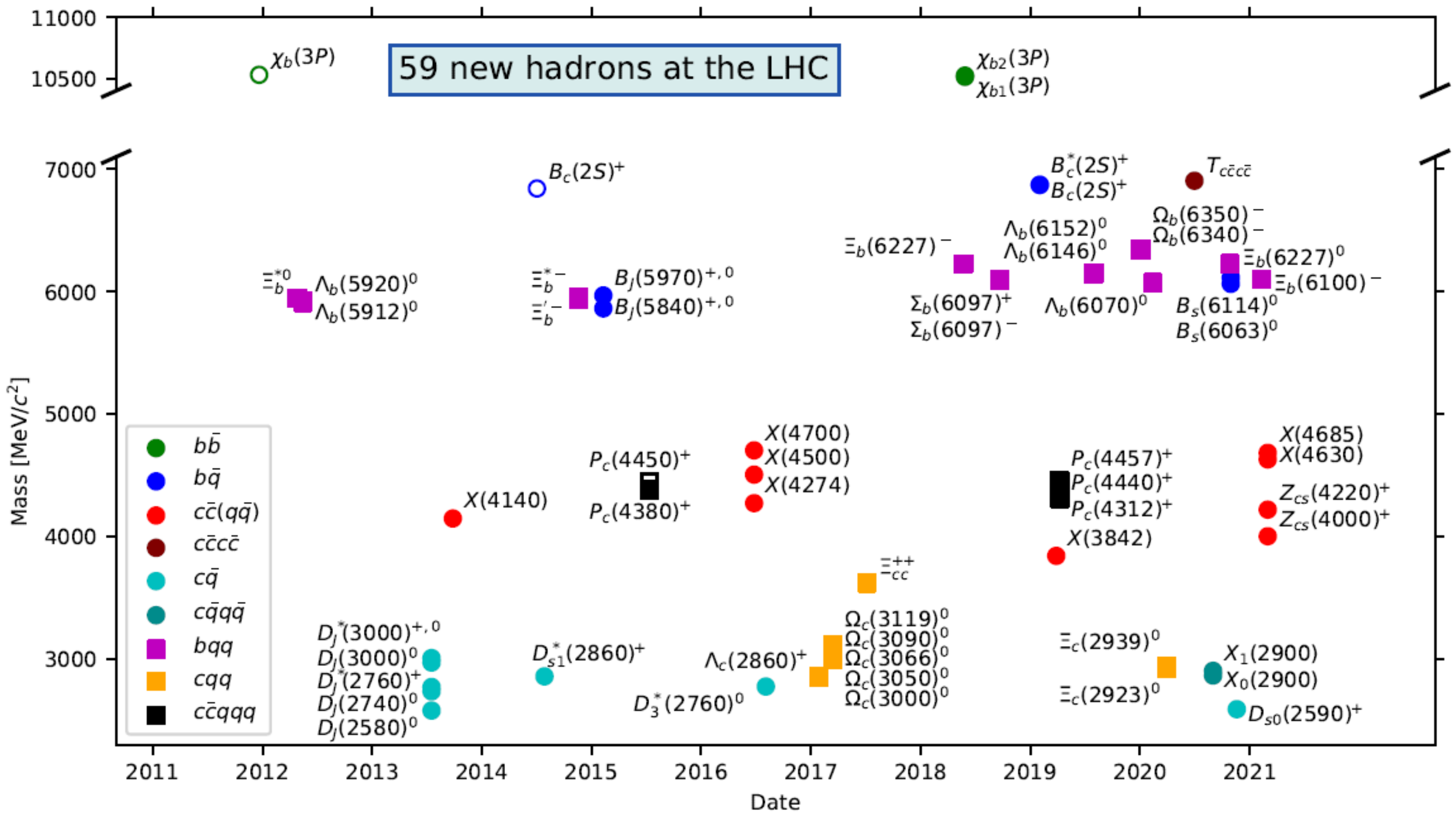


Discovery potential at EIC

xzb
LBL Heavy-Ion Tea Seminar
05/2010

Heavy-flavor states

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



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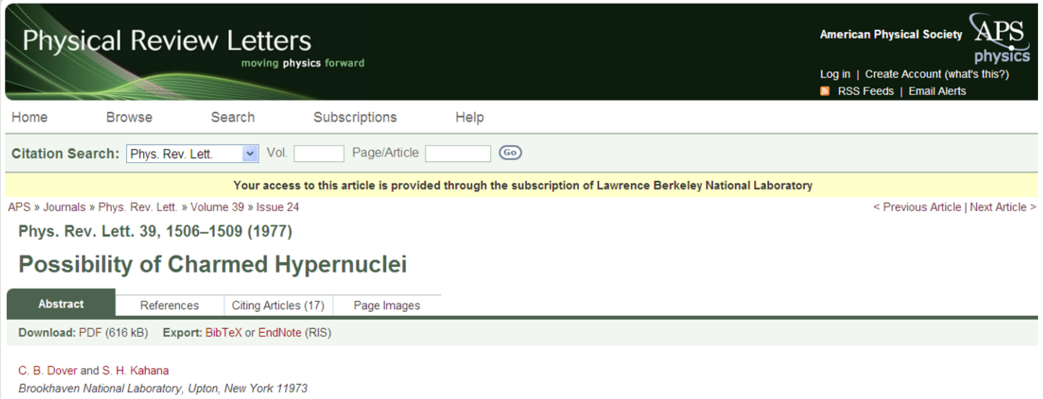
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Possibility of Charmed Hypernuclei
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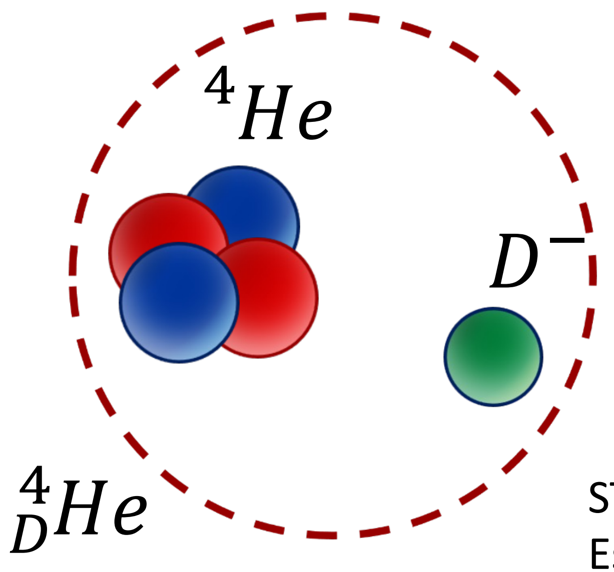
Download: PDF (616 kB) Export: BibTeX or EndNote (RIS)
C. B. Dover and S. H. Kahana
Brookhaven National Laboratory, Upton, New York 11973

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



Stable and existence due to Coulomb force

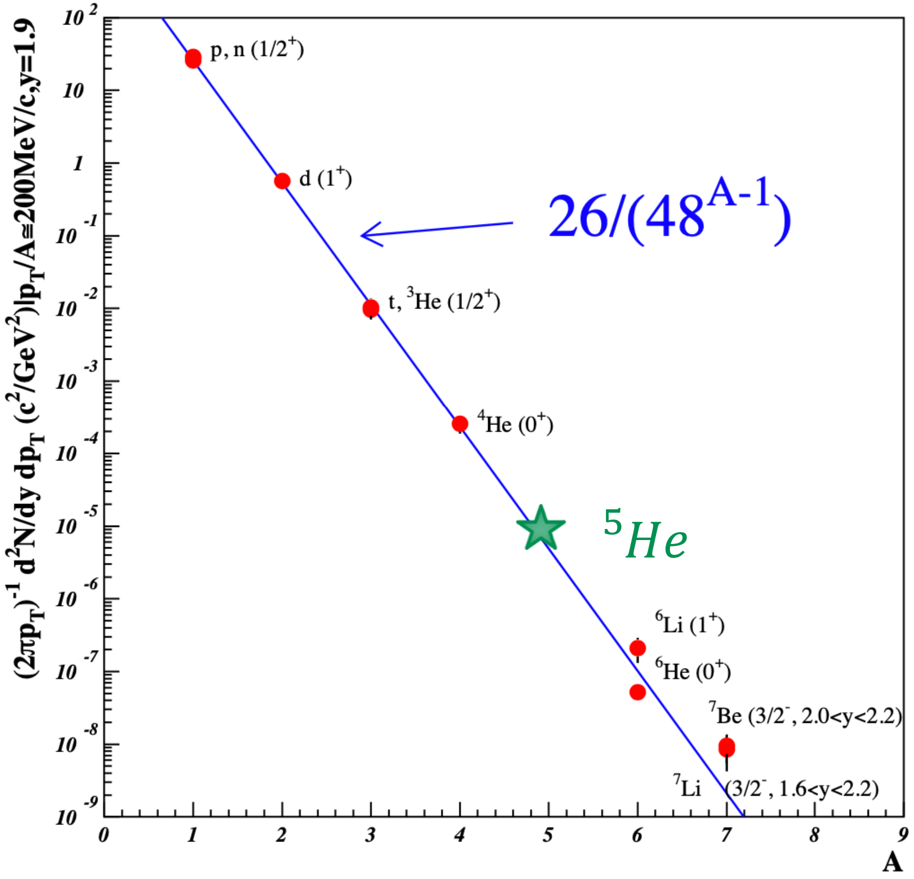
PYTHIA: $D^-/n \sim= 5\times10^{-4}$ p+p collisions
at AGS and RHIC forward kinematics

$_{D^-}{}^4He$ 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



E864@AGS Phys. Rev. C **61**, 064908

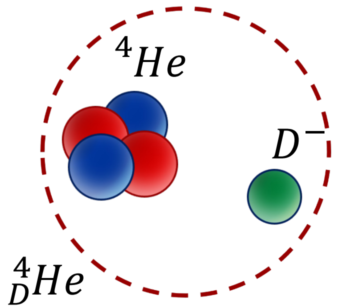
Zhangbu Xu (BNL)
Cheng-Wei Lin, Yi Yang (NCKU)

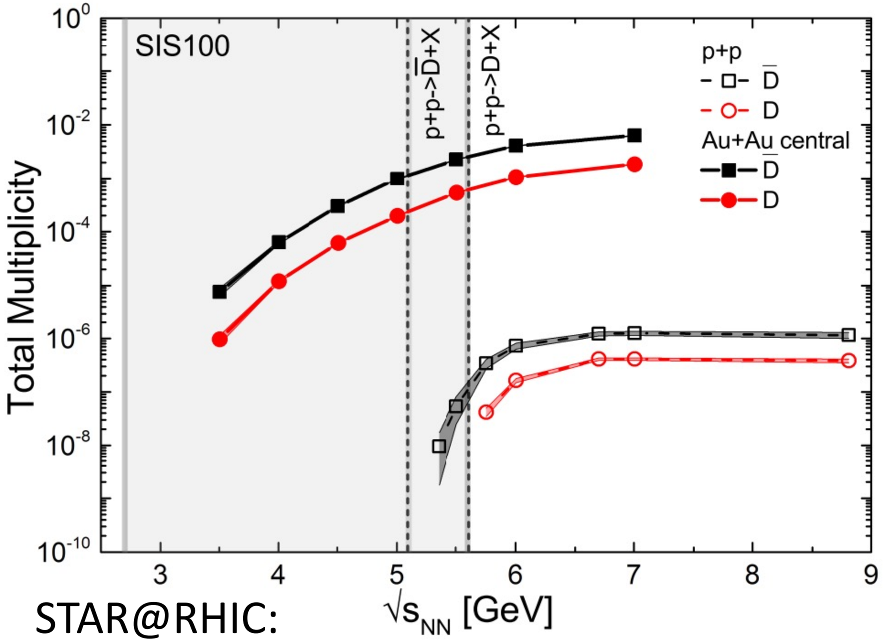
DNP (2022), EMMI (2023)

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

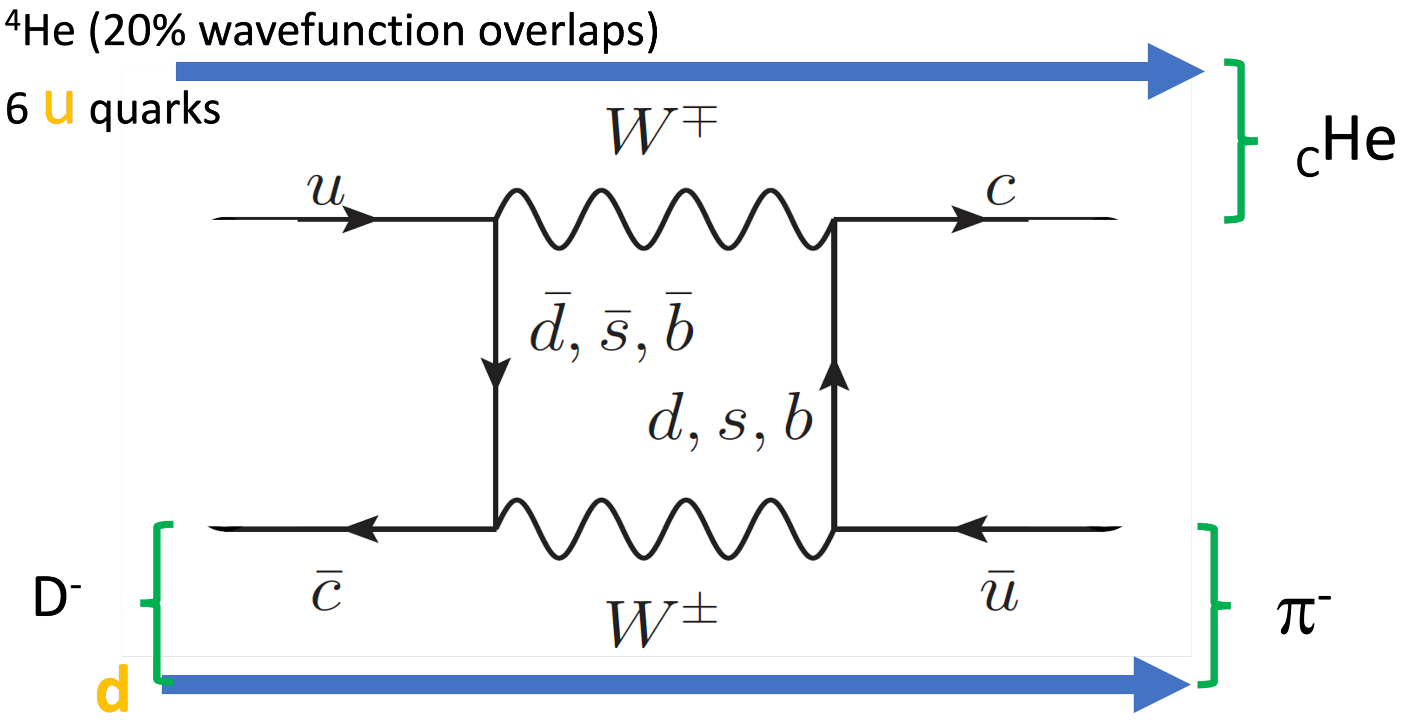
J. Steinheimer, A. Botvina, M. Bleicher, PRC 95 (2017) 014911

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





Charm Quark Oscillation with large mass difference



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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; use baryon transport to study its tracer
- Explore other signatures
- Two and three-nucleon correlations sensitive to scattering length and bound states
- Charmed hypernuclei (EIC, LHC, FAIR)