Unveiling the Dynamics of Little-Bang Nucleosynthesis with Femtoscopy

FUDAN UNIVERSITY

孙开佳
（复旦大学）

Outline

I Little-Bang Nucleosynthesis

II "Snowball in Hell" puzzle

III Resolving the puzzle with pion-catalyzed reactions

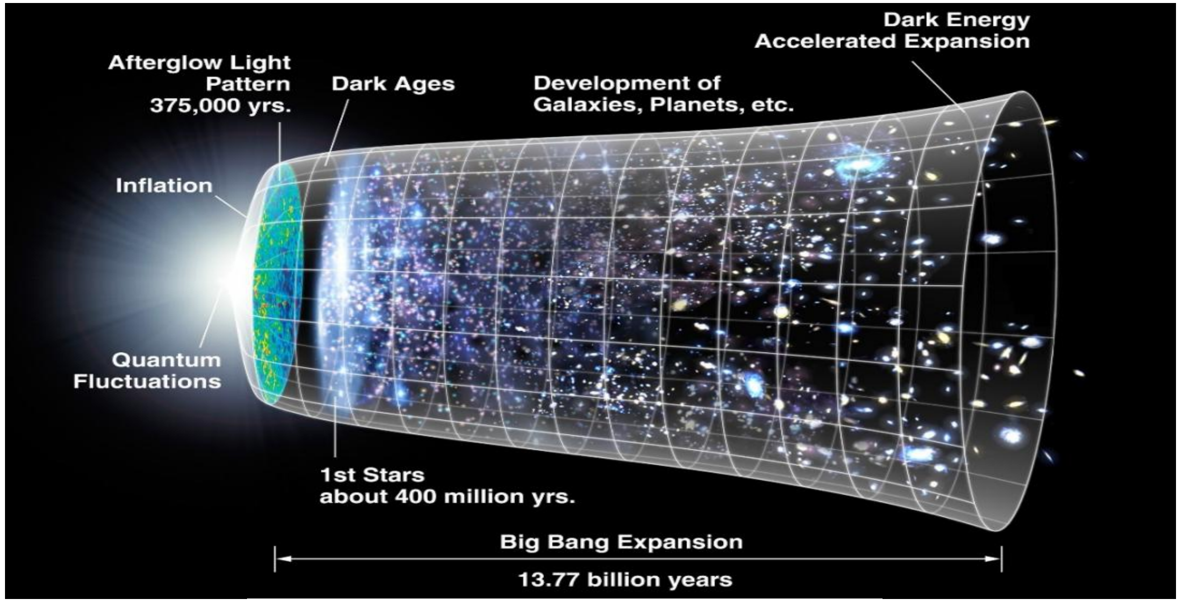
IV Evidence from Femtoscopy

V Outlook

Big-Bang Nucleosynthesis (BBN) (1)

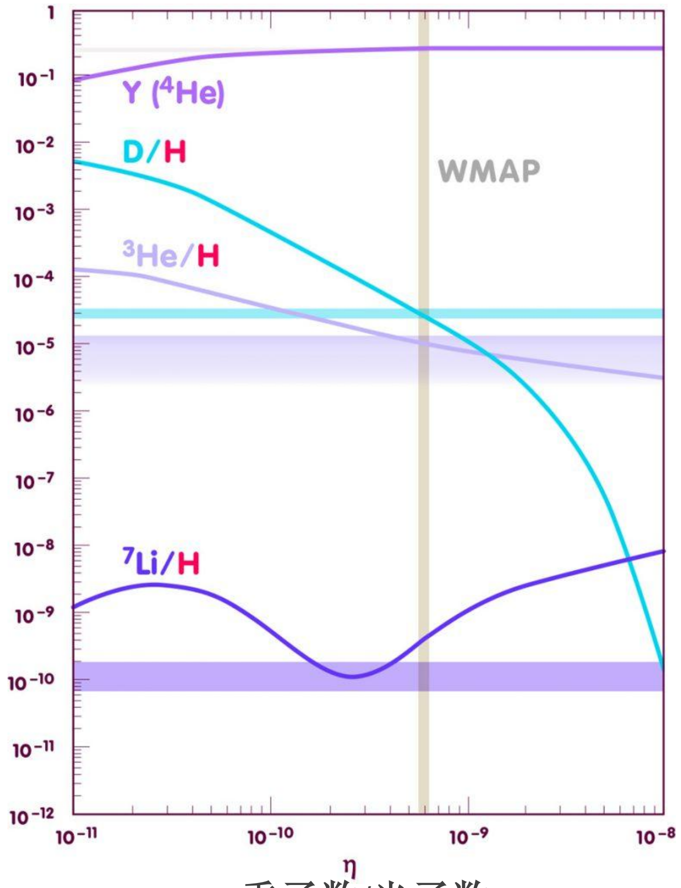
K. A. Olive et al., Phys. Rept. 333, 389–407 (2000)

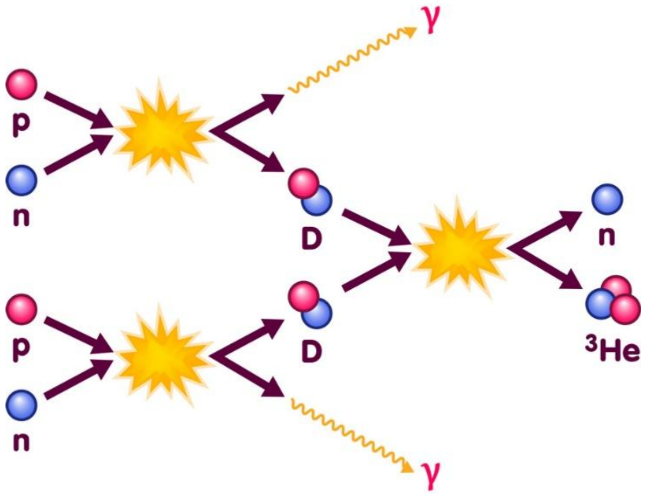
《最初三分钟》S. Weinberg



$t \sim 100\ s, kT < 1\ \text{MeV}$ (10^{10}开尔文, 100亿度)

$$p + n \longrightarrow D + \gamma$$
$$D + p \longrightarrow {}^3He + \gamma$$
$$D + D \longrightarrow {}^3He + n$$
$$D + D \longrightarrow {}^3H + p$$
$${}^3He + n \longrightarrow {}^3H + p$$
$$D + D \longrightarrow {}^4He + \gamma$$
$${}^3He + D \longrightarrow {}^4He + p$$
$${}^3H + D \longrightarrow {}^4He + n.$$



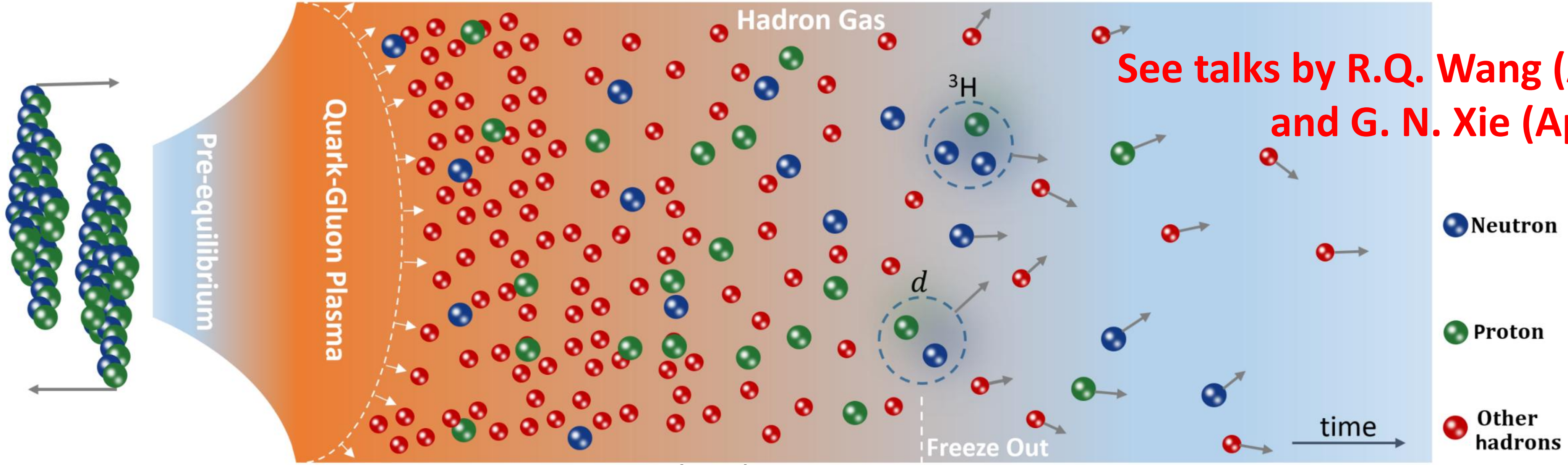


Big Bang nucleosynthesis produced the primordial light elements in the universe.

Little-Bang Nucleosynthesis (LBN) (2)

Relativistic Heavy-Ion Collisions ('Little Bangs') $t \sim 10^{-23} s, T \sim 100$ MeV (10^{12}开尔文, 10000亿度)

See talks by R.Q. Wang (Apr. 27) and G. N. Xie (Apr. 27)



K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nature Commun. 15, 1074 (2024)

nature

Explore content ⌄ About the journal ⌄ Publish with us ⌄

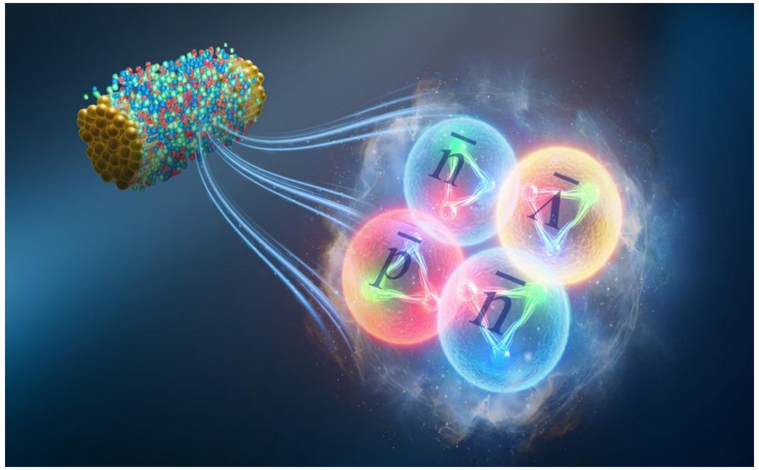
nature > articles > article

Article | Published: 21 August 2024

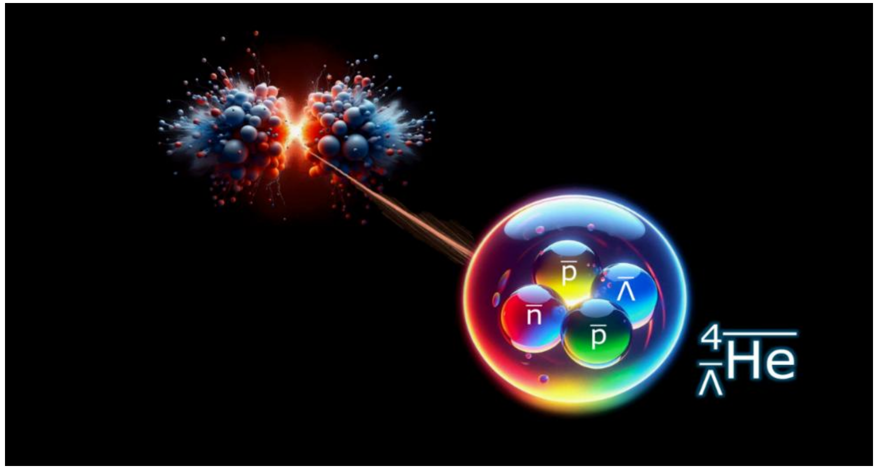
Observation of the antimatter hypernucleus $^4_{\bar{\Lambda}}\bar{\text{H}}$

STAR Collaboration

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



ALICE, PRL 134, 162301 (2025)



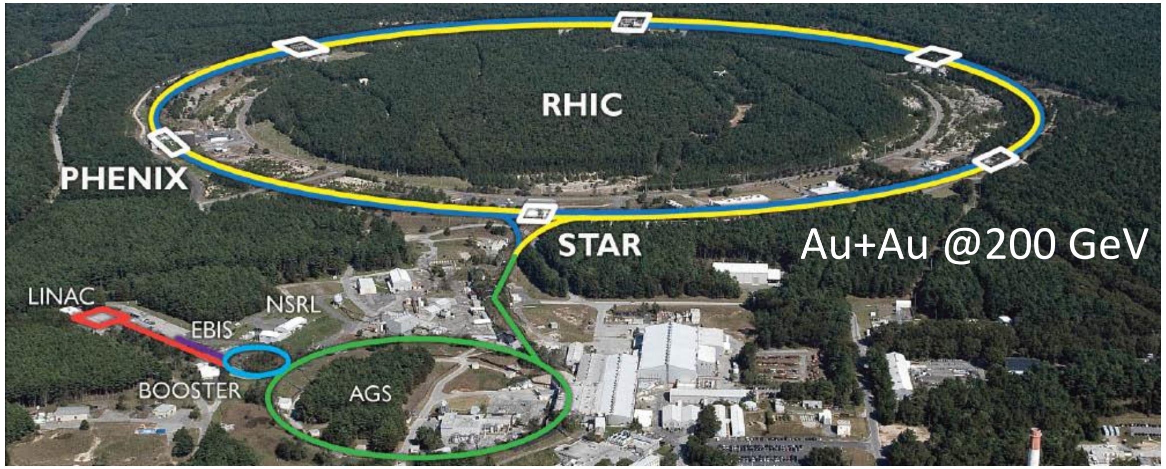
Different from BBN, LBN produce nearly equal amounts of matter and antimatter light nuclei.

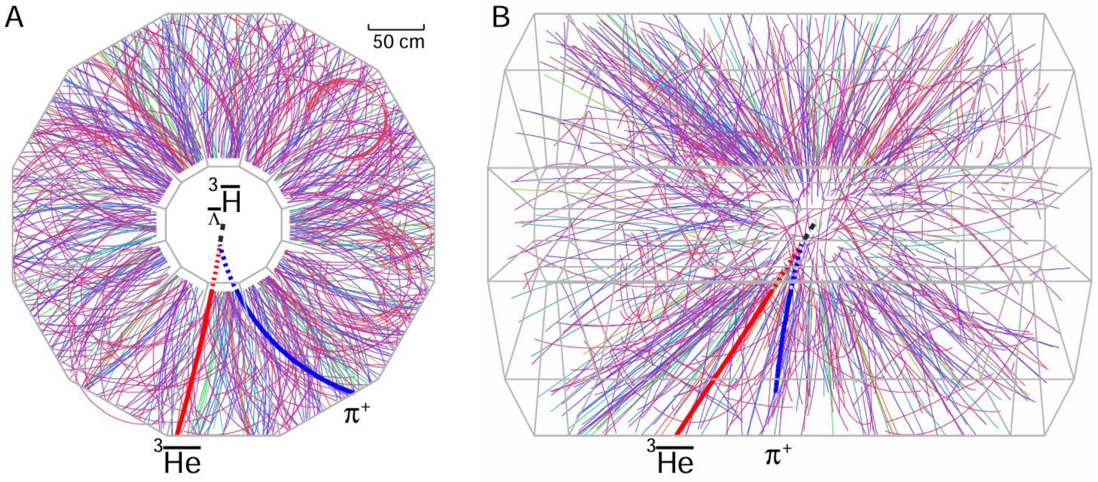
Synthesis of antimatter hypernuclei

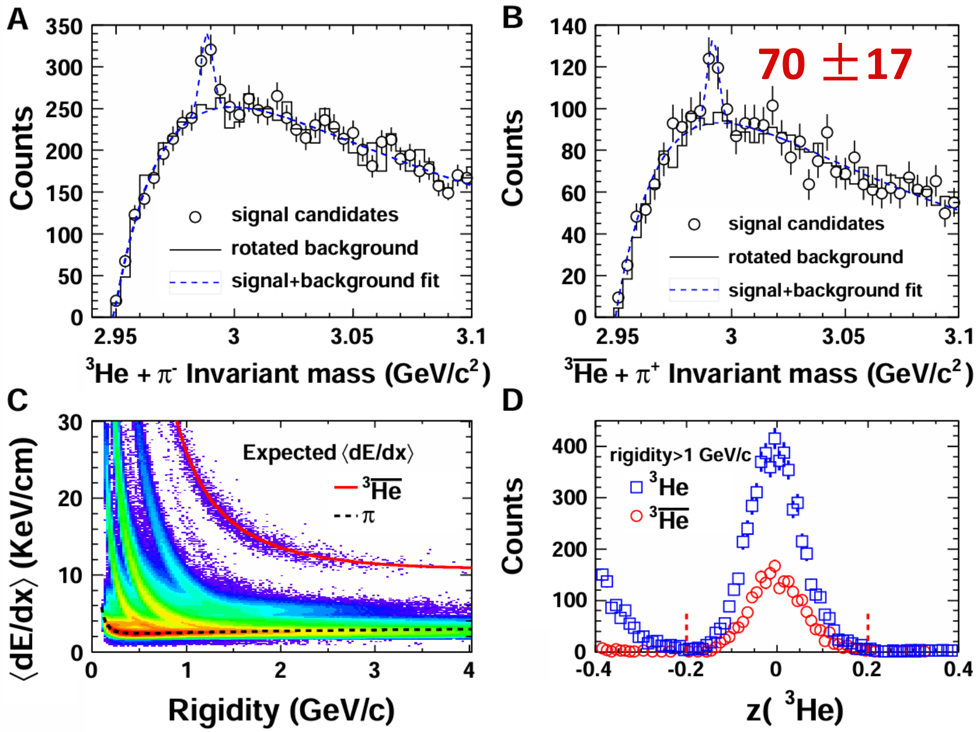
Observation of an Antimatter Hypernucleus

The STAR Collaboration*† STAR, Science 328, 58 (2010)

Nuclear collisions recreate conditions in the universe microseconds after the Big Bang. Only a very small fraction of the emitted fragments are light nuclei, but these states are of fundamental interest. We report the observation of antihypertritons—comprising an antiproton, an antineutron, and an antilambda hyperon—produced by colliding gold nuclei at high energy. Our analysis yields 70 ± 17 antihypertritons ($^{3}_{\bar{\Lambda}}\overline{H}$) and 157 ± 30 hypertritons ($^{3}_{\Lambda}H$). The measured yields of $^{3}_{\Lambda}H$ ($^{3}_{\bar{\Lambda}}\overline{H}$) and ^{3}He ($^{3}\overline{He}$) are similar, suggesting an equilibrium in coordinate and momentum space populations of up, down, and strange quarks and antiquarks, unlike the pattern observed at lower collision energies. The production and properties of antinuclei, and of nuclei containing strange quarks, have implications spanning nuclear and particle physics, astrophysics, and cosmology.







J. Chen et al., Phys. Rep. 760, 1 (2018)

Anti-Helium4 @2011

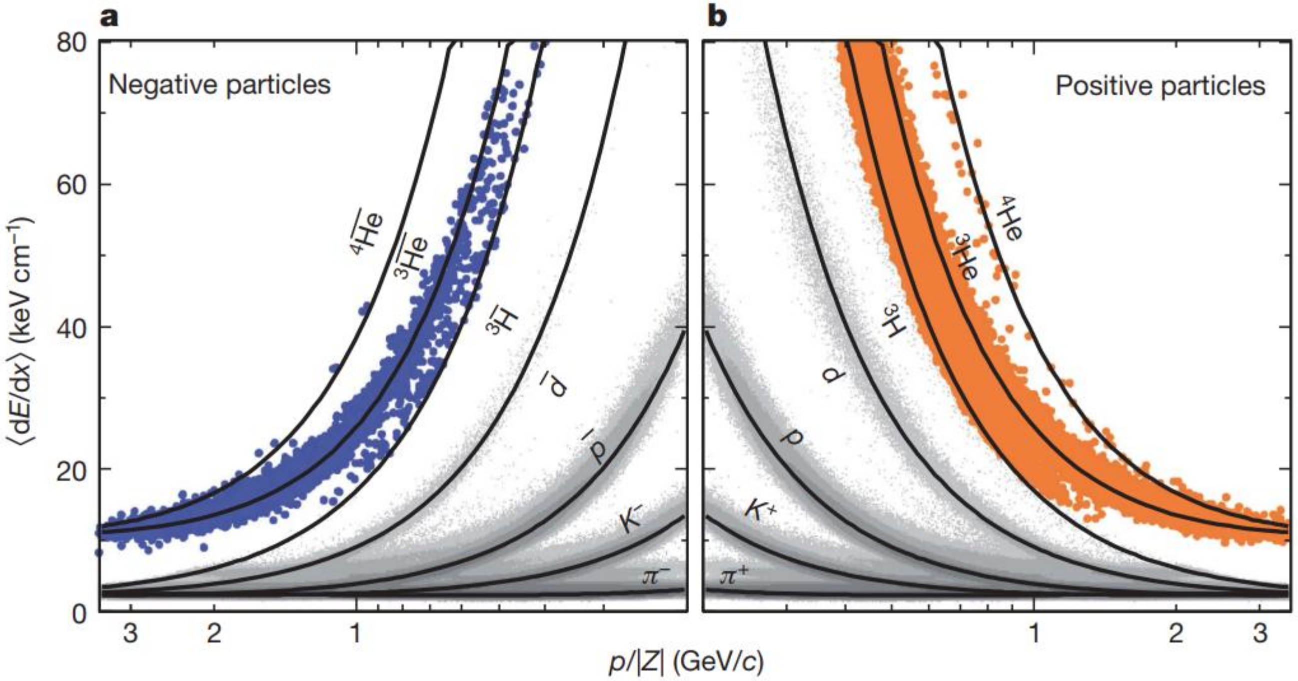
Synthesis of antimatter nuclei

LETTER

doi:10.1038/nature10079

Observation of the antimatter helium-4 nucleus

The STAR Collaboration*



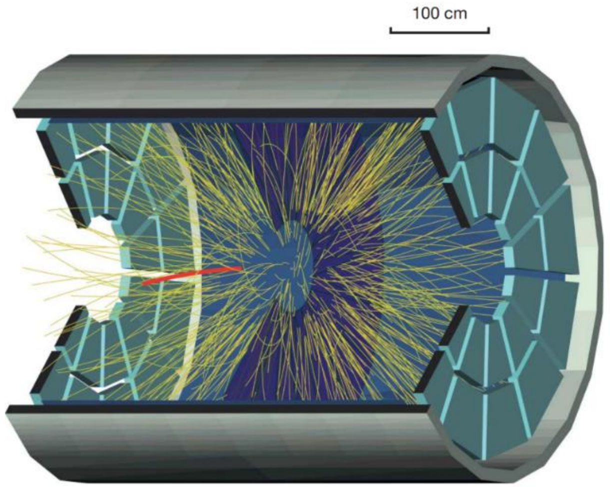
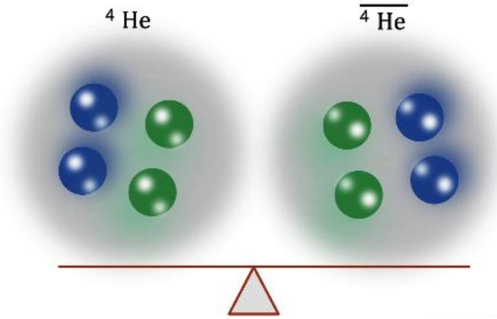
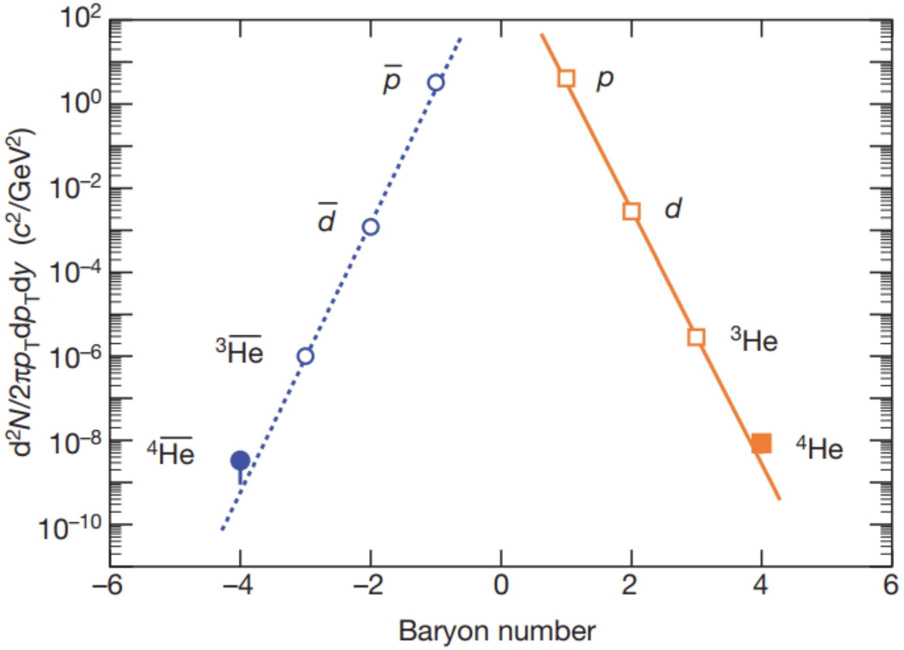


Figure 1 | A three-dimensional rendering of the STAR TPC surrounded by the TOF barrel shown as the outermost cylinder. Tracks from an event which contains a $^4\overline{He}$ are shown, with the $^4\overline{He}$ track highlighted in bold red.

Matter-antimatter asymmetry





Anti-hyperhydrogen-4 @2024

nature STAR, Nature 632, 1026 (2024)

Explore content ⌄ About the journal ⌄ Publish with us ⌄

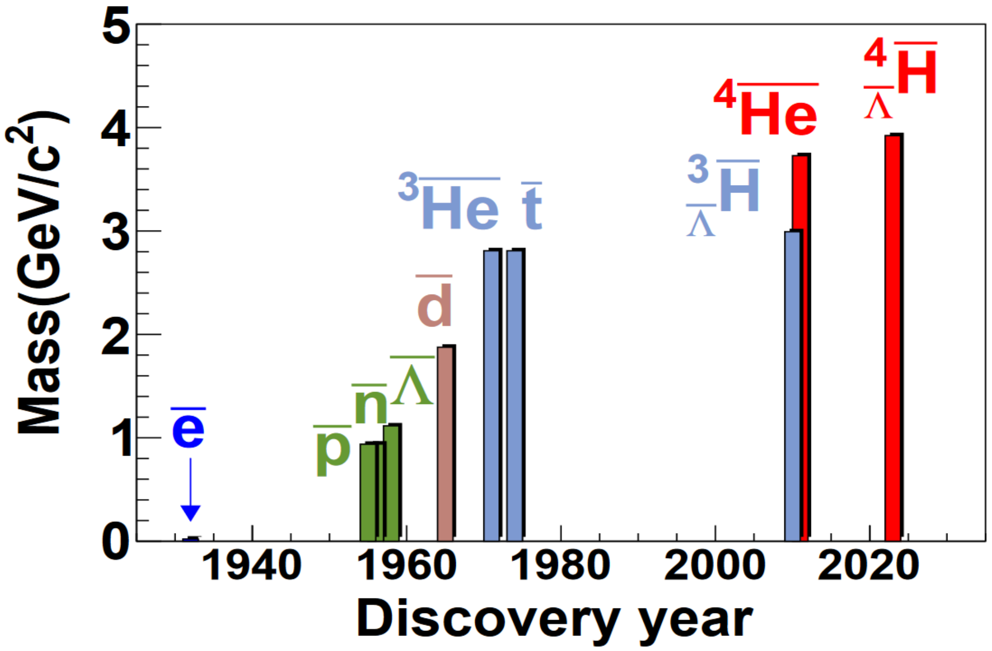
nature > articles > article

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



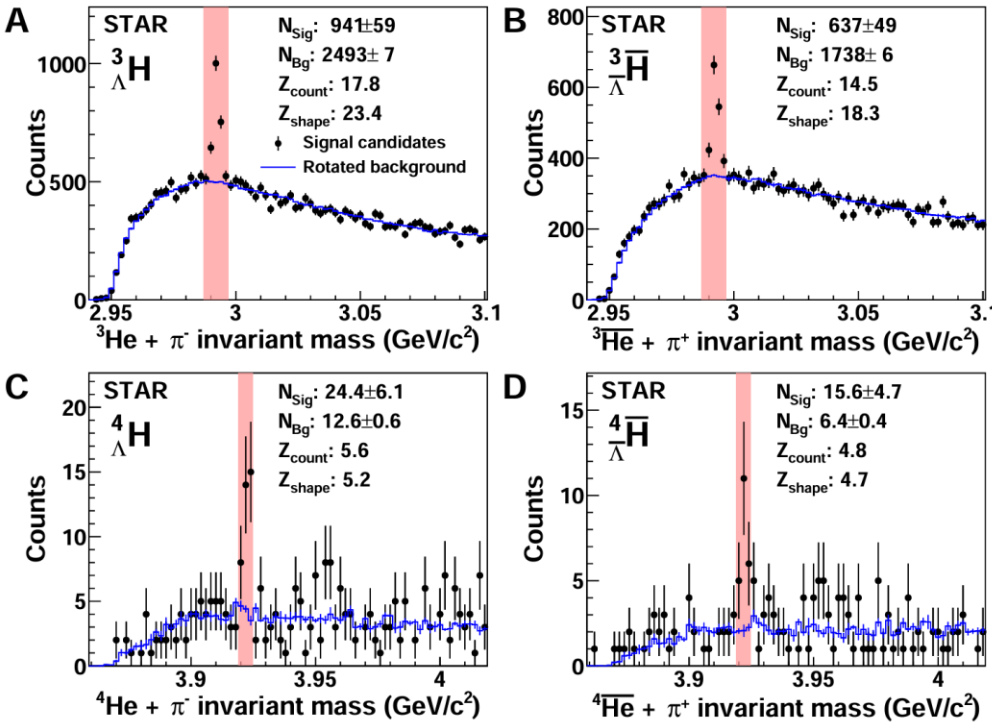
PHYSICAL REVIEW C **93**, 064909 (2016)

Antimatter $^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$ hypernucleus production and the $^{3}_{\Lambda}\mathrm{H}/^{3}\mathrm{He}$ puzzle in relativistic heavy-ion collisions

Kai-Jia Sun[1] and Lie-Wen Chen[1,2,*]
[1]*Department of Physics and Astronomy and Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai 200240, China*
[2]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China*

(Received 26 April 2016; published 29 June 2016)

We show that the measured yield ratio $^{3}_{\Lambda}\mathrm{H}/^{3}\mathrm{He}$ ($^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}/^{3}\overline{\mathrm{He}}$) in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV can be understood within a covariant coalescence model if (anti-)Λ particles freeze out earlier than (anti-)nucleons but their relative freeze-out time is closer at $\sqrt{s_{NN}} = 2.76$ TeV than at $\sqrt{s_{NN}} = 200$ GeV. The earlier (anti-)Λ freeze-out can significantly enhance the yield of (anti)hypernucleus $^{4}_{\Lambda}\mathrm{H}$ ($^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$), leading to that $^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$ has a comparable abundance with $^{4}\overline{\mathrm{He}}$ and thus provides an easily measured antimatter candidate heavier than $^{4}\overline{\mathrm{He}}$. The future measurement on $^{4}_{\Lambda}\mathrm{H}$ ($^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$) would be very useful to understand the (anti-)Λ freeze-out dynamics and the production mechanism of (anti)hypernuclei in relativistic heavy-ion collisions.



15.6 out of 6.4 billion events

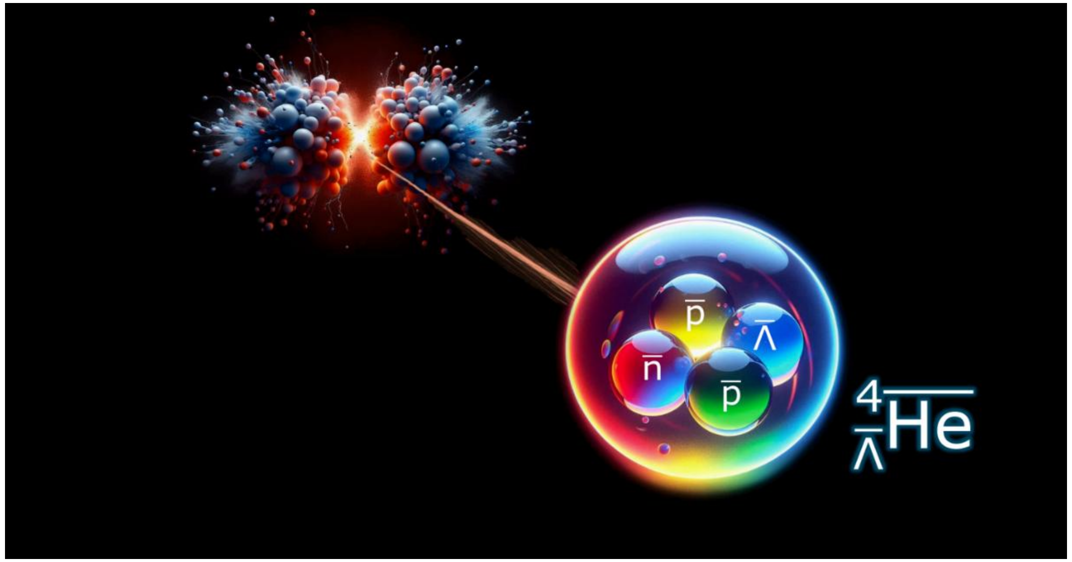
Anti-hyperhelium-4 @2025

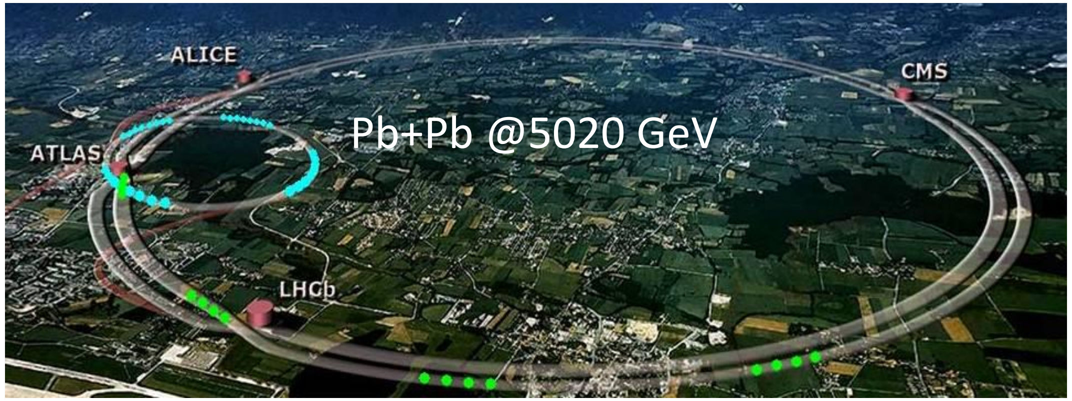
PHYSICAL REVIEW LETTERS **134**, 162301 (2025)

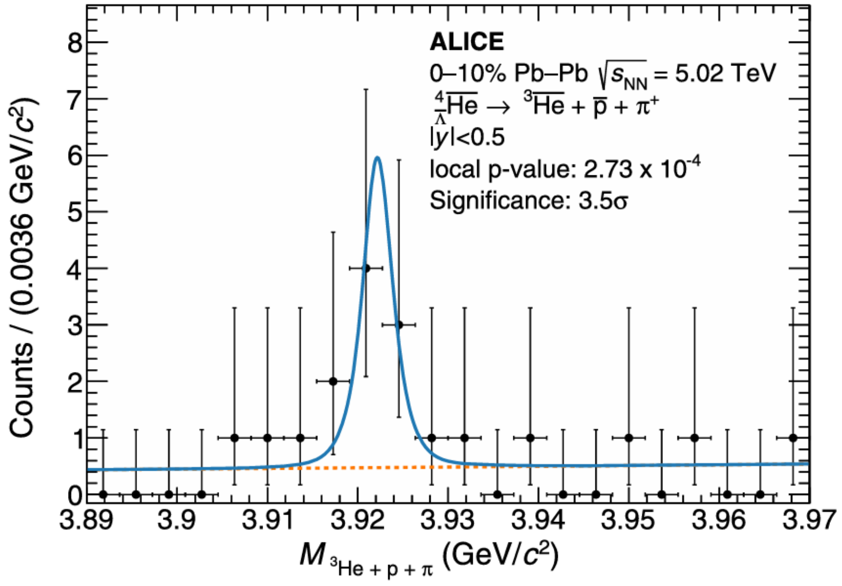
Editors' Suggestion | Featured in Physics

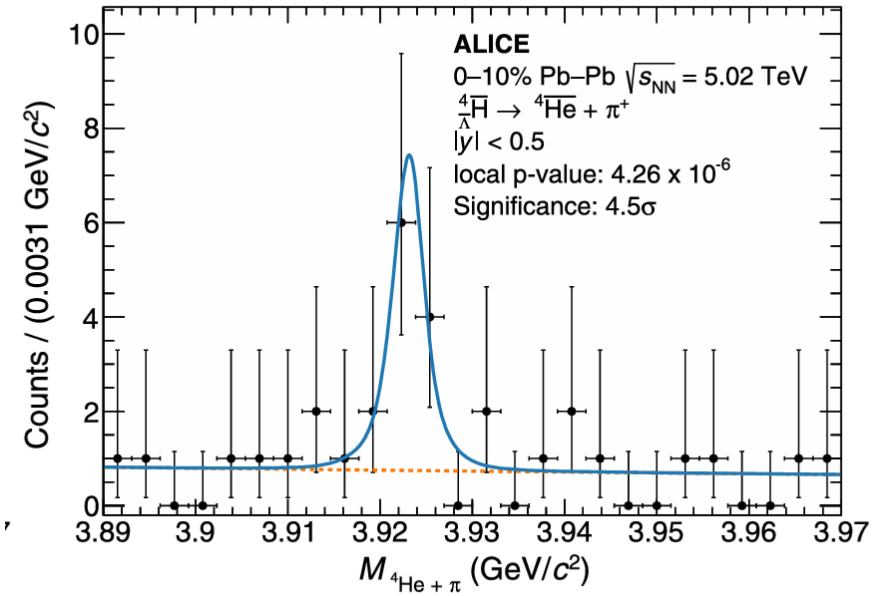
First Measurement of $A = 4$ Hypernuclei and Antihypernuclei at the LHC

S. Acharya *et al.*[*]
(ALICE Collaboration)









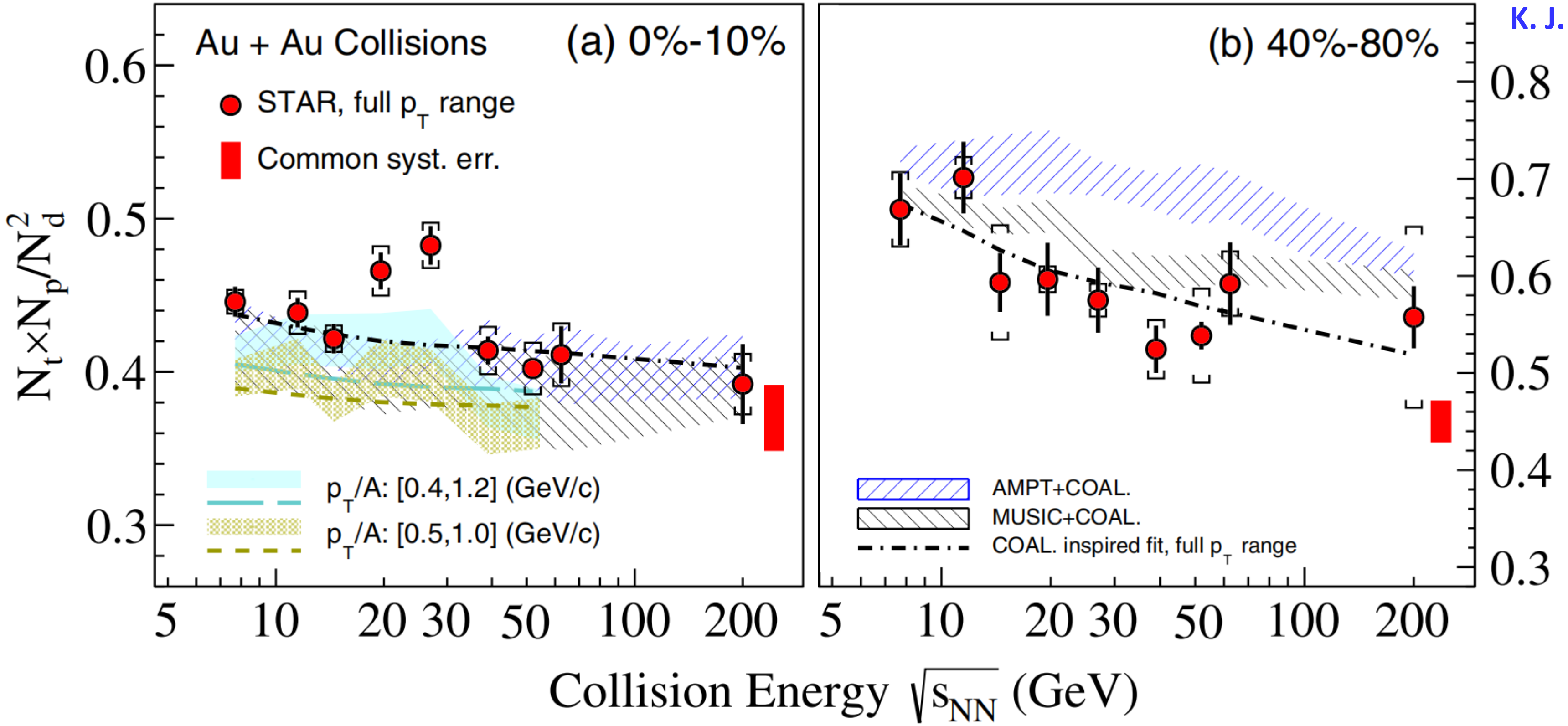
Light Nuclei & QCD Critical Point (7)

PHYSICAL REVIEW LETTERS **130,** 202301 (2023)

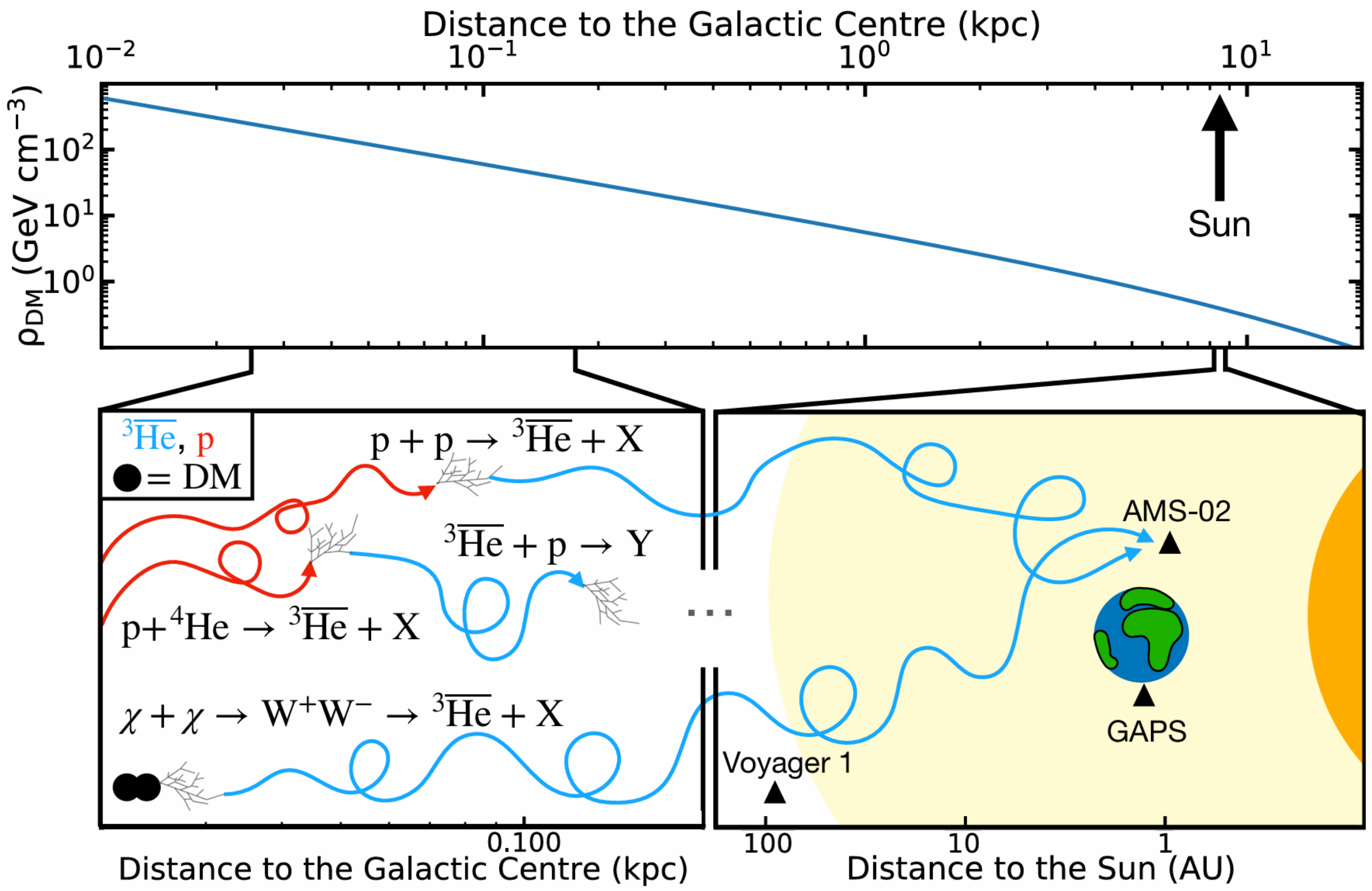
Beam Energy Dependence of Triton Production and Yield Ratio ($N_t \times N_p/N_d^2$) in Au + Au Collisions at RHIC

$$\frac{N_t N_p}{N_d^2} \approx \frac{1}{2\sqrt{3}}\left[1 + \Delta\rho_n + \frac{\lambda}{\sigma} G\left(\frac{\xi}{\sigma}\right)\right]$$

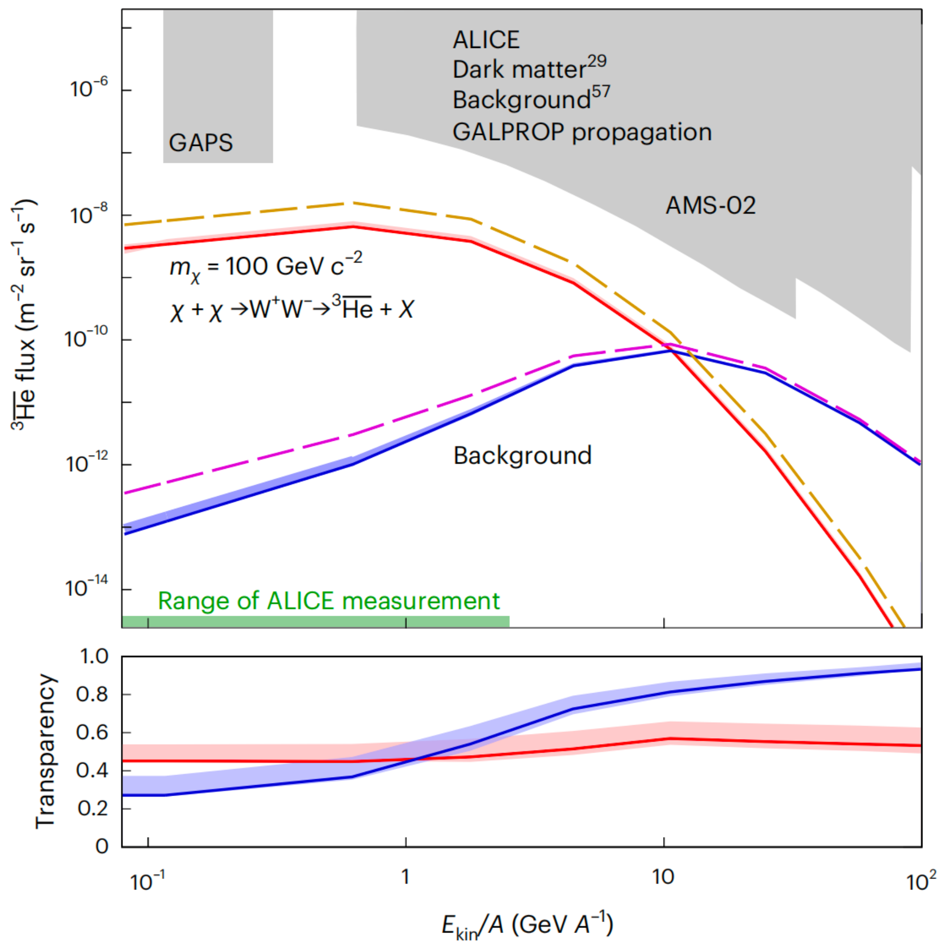
K. J. Sun, L. W. Chen et al., Phys. Lett. B 774, 103 (2017)
K. J. Sun , L. W. Chen et al., Phys. Lett. B 781, 499 (2018)
K. J. Sun et al., Phys. Lett. B 816, 136258 (2020)



Search of Antimatter and Dark Matter in Space (8)



ALICE, Nature Phys. 19, 61-71 (2023)



Due to their extremely low astrophysical background, light antinuclei in space provide an important indirect probe for dark matter detection

Outline

I Little-Bang Nucleosynthesis

II "Snowball in Hell" puzzle

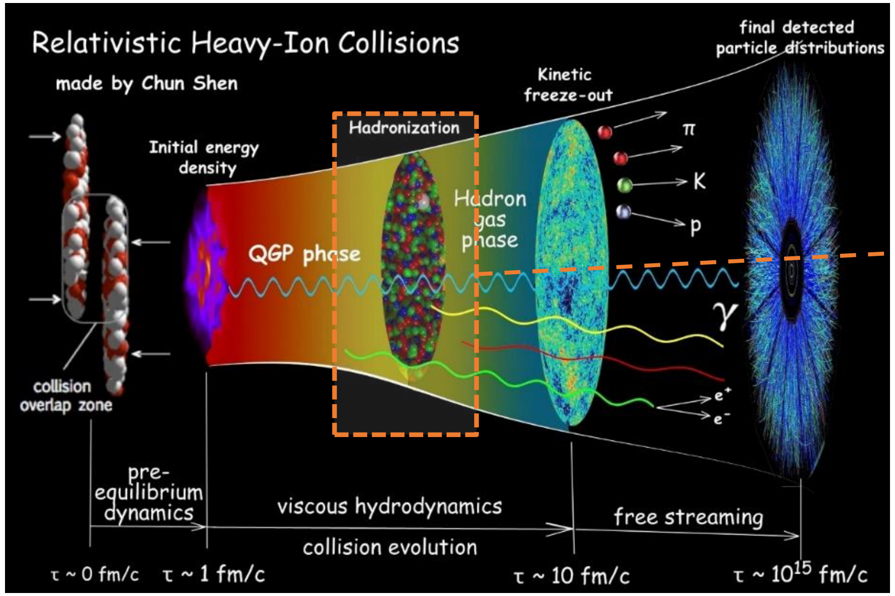
III Resolving the puzzle with pion-catalyzed reactions

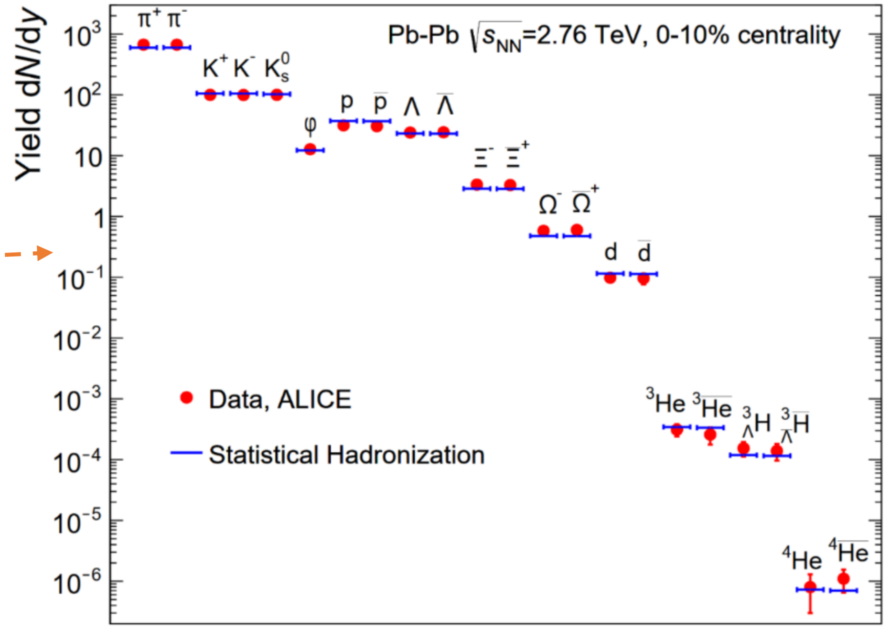
IV Evidence from Femtoscopy

V Outlook

Production Mechanism: Statistical Hadronization (9)

Andronic, Braun-Munzinger, Redlich, Stachel, Nature 561, 321 (2018)





$$N_h \approx \frac{\gamma_h g_h V_C}{2\pi^2} m_h^2 T_C K_2(\frac{m_h}{T_C})$$

$$\approx \gamma_h g_h V_C (\frac{m_h T_C}{2\pi})^{3/2} e^{-m_h/T_C}$$

T_C: Chemical freeze-out temperature, which is close to the chiral transition temperature (LQCD)

γ_h : Fugacity

Light (hyper)nuclei and ordinary hadrons share the same high chemical freezeout temperature $T_c = 156.6 \pm 1.7$ MeV , which almost coincides with the pseudo transition temperature from the QGP phase to the hadron phase.

The comparison between theoretical calculations and experimental data indicates that the yields of light nuclei can be described by chemical freeze-out at T=156 MeV

"Snowball in Hell" Puzzle

ALICE investigates 'snowballs in hell'

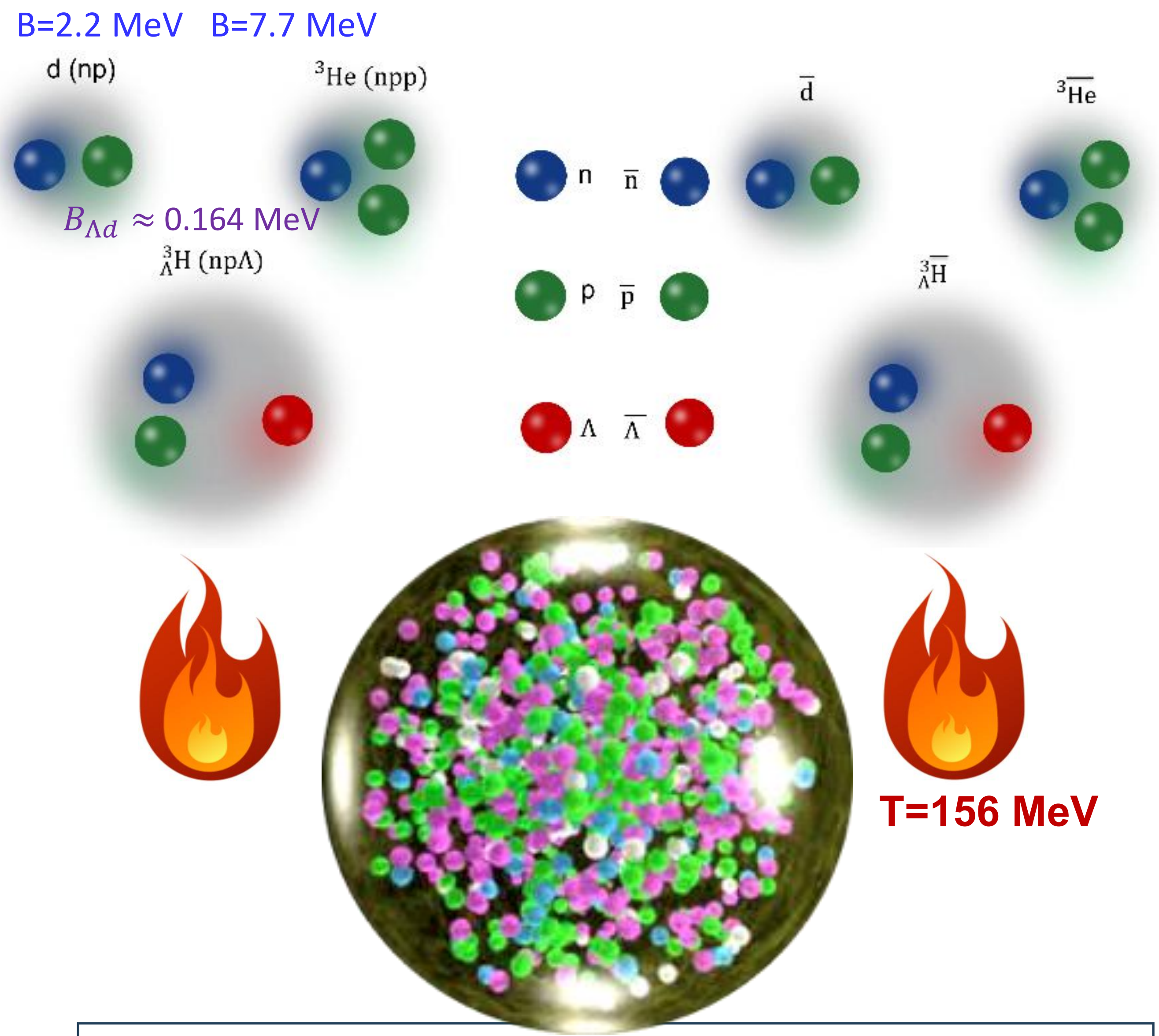
26 August 2015 Peter Braun-Munzinger, Benjamin Dönigus,

How is it that loosely bound objects are observed in high-energy nuclear collisions?

An interesting question is whether the yields of composite objects can be understood in the same grand-canonical scheme as discussed above, or whether such loosely bound objects follow a different systematics. The deuteron binding energy, for example, is only 2.23 MeV, and the energy needed to separate the Λ hyperon from a hypertriton nucleus – a bound state of a proton, neutron and Λ – is only about 130 keV, which is much smaller than the chemical freeze-out temperature, T_{chem} = 156 MeV.

Furthermore, the radii of such loosely bound objects are generally very large, even exceeding significantly the range of the nuclear force that binds them. The rms radius of the deuteron is 2.2 fm, for example. Even more dramatically, because of the molecular structure of the hypertriton ((p+n) + Λ), its rms radius, which in this case is the rms separation between the d nucleus and the Λ hyperon, is about 10 fm – that is, larger than the radius of the whole fireball.

To understand this, thermodynamics comes to the rescue. If there are no more inelastic collisions after chemical freeze-out, then the transition from the QGP to hadronic matter is followed by an isentropic expansion (i.e. with no change in entropy). Early studies of nucleus–nucleus collisions at the Berkeley Bevalac already showed that, for systems with isentropic expansion, the entropy/net-baryon is proportional to log(d/p), implying that the yield of deuterons and antideuterons is determined by the entropy in the hot phase of the fireball. The same mechanism is at play at LHC energies: in this way, the "snowballs" can survive "hell", as the experimental data from the ALICE collaboration show.

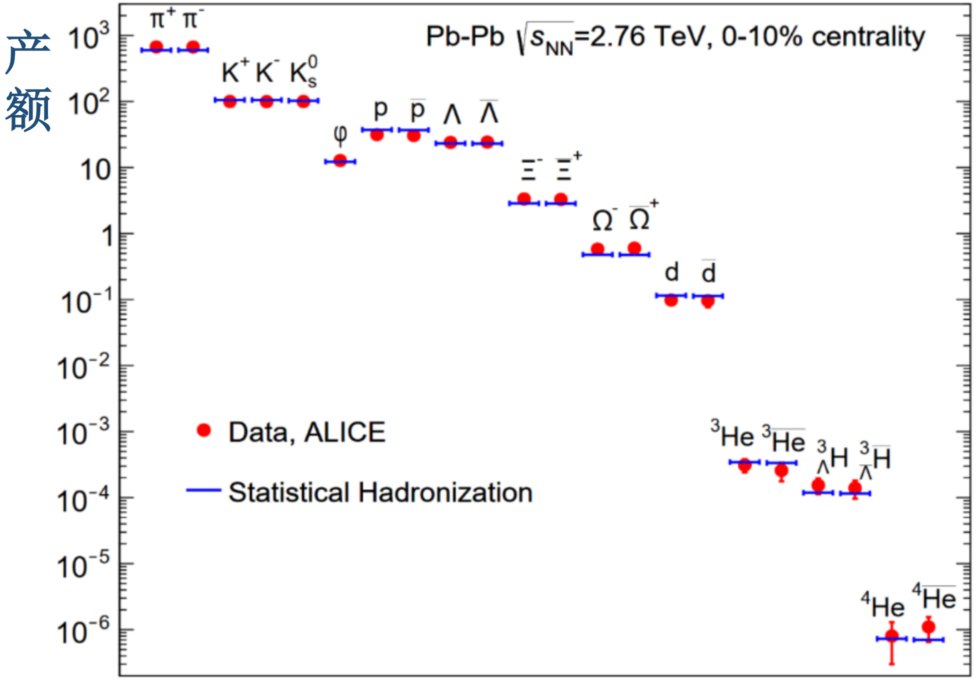


The binding energy of light nuclei is much smaller than T=156 MeV

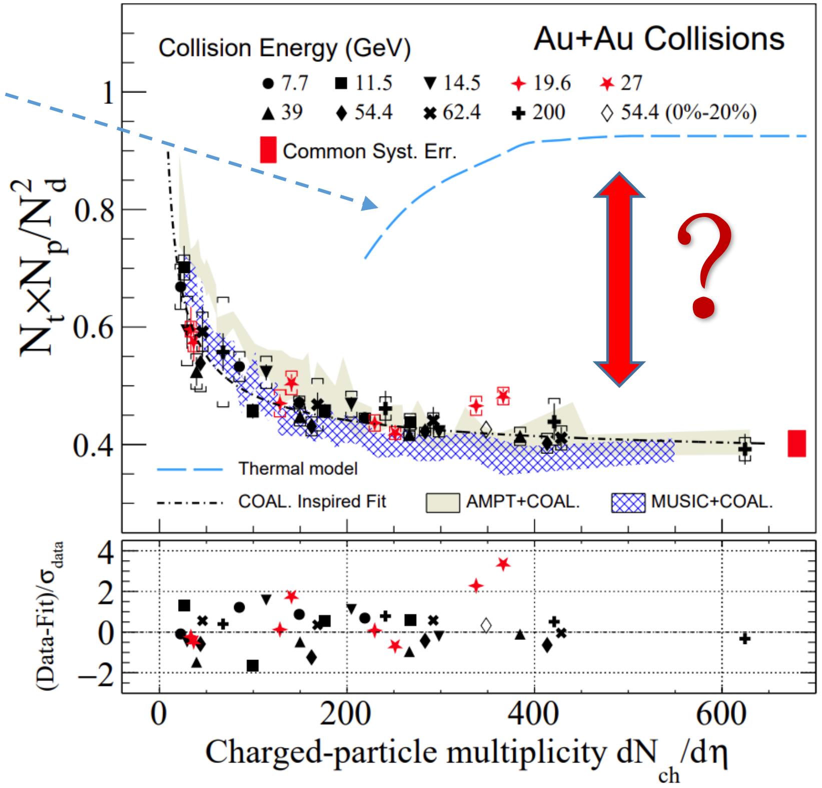
‘Triton Yield’ Puzzle

2018 → 2023

统计强子化模型
[A. Andronic *et al.*, *Nature* 561, 321 (2018)]



RHIC-STAR大型国际实验合作组
Phys. Rev. Lett. 130, 202301 (2023)



Theory and experiment are in tension, as the statistical hadronization model predicts a triton yield that is approximately twice the experimental value.

Outline

I Little-Bang Nucleosynthesis

II "Snowball in Hell" puzzle

III Resolving the puzzle with pion-catalyzed reactions

IV Evidence from Femtoscopy

V Outlook

Pion-catalyzed Reaction?

nature communications

Article

https://doi.org/10.1038/s41467-024-45474-x

Unveiling the dynamics of little-bang nucleosynthesis

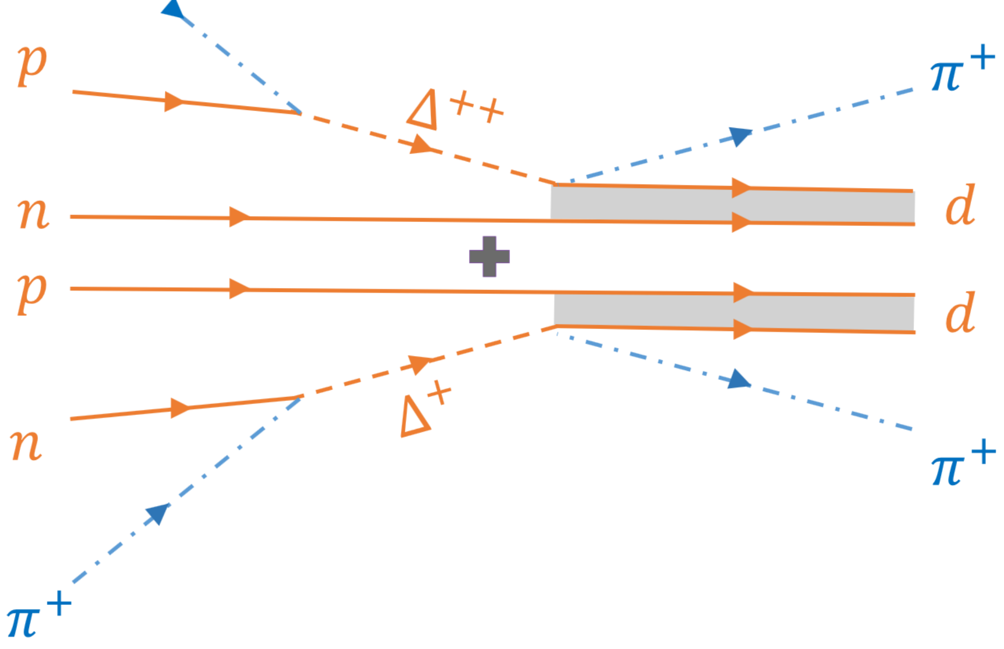
Received: 7 June 2023

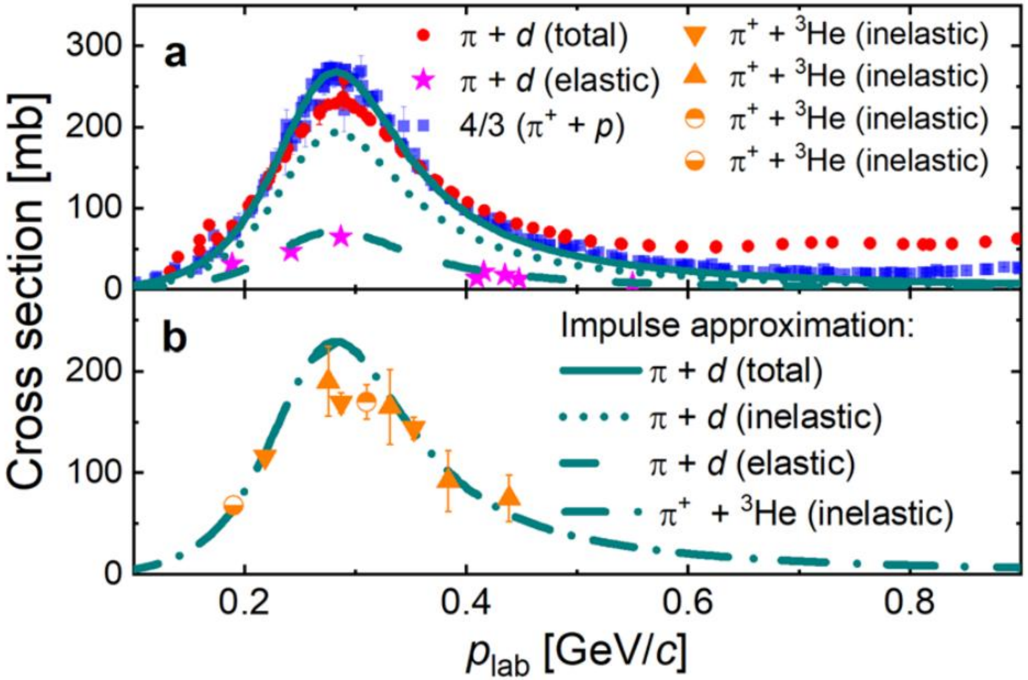
Accepted: 23 January 2024

Kai-Jia Sun[1,2] ✉, Rui Wang[1,3], Che Ming Ko[4], Yu-Gang Ma[1,2] ✉ & Chun Shen[5,6]

Pion-Catalyzed reaction

$$\pi + N + N \leftrightarrow \pi + d$$





Peak comes from intermediate Delta resonance

$$\sigma_{\pi^+ p \to \Delta^{++}} = \frac{2\pi}{q^2}\Gamma(m_\Delta)\mathcal{A}(m_\Delta)$$

$$\Gamma = \frac{0.47 q^3}{m_\pi^2 + 0.6 q^2},$$

$$\mathcal{A}(\sqrt{s_{\rm cm}}) = \frac{1}{0.948}\frac{4 m_0^2 \Gamma}{(s_{\rm cm} - m_0^2)^2 + m_0^2 \Gamma^2}$$

Relativistic Kinetic Equations

K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nat. Commun. 15, 1074 (2024)

R. Wang, Y. G. Ma, L. W. Chen, C. M. Ko, K. J. Sun, and Z. Zhang, PRC 108, L031601 (2023)

Relativistic kinetic equation for $\pi NN \leftrightarrow \pi d$

$$\frac{\partial f_d}{\partial t} + \frac{\mathbf{P}}{E_d} \cdot \frac{\partial f_d}{\partial \mathbf{R}} = -\mathcal{K}^{>} f_d + \mathcal{K}^{<}(1+f_d)$$

with collision integral:

$$\text{R.H.S.} = \frac{1}{2g_d E_d} \int \prod_{i=1'}^{3'} \frac{d^3\mathbf{p}_i}{(2\pi)^3 2E_i} \frac{d^3\mathbf{p}_\pi}{(2\pi)^3 2E_\pi} \frac{E_d d^3\mathbf{r}}{m_d}$$
$$\times 2m_d W_d(\tilde{\mathbf{r}}, \tilde{\mathbf{p}}) \left(\overline{|\mathcal{M}_{\pi^+ n \to \pi^+ n}|^2} + n \leftrightarrow p\right)$$
$$\times \Big[-\Big(\prod_{i=1'}^{3'} (1 \pm f_i) \Big) g_\pi f_\pi g_d f_d + \frac{3}{4} \Big(\prod_{i=1'}^{3'} g_i f_i \Big)$$
$$\times (1+f_\pi)(1+f_d) \Big] \times (2\pi)^4 \delta^4(p_{\text{in}} - p_{\text{out}})$$

Nonlocal collision integral to take into account the effects of finite nuclei sizes. W_d denotes deuteron Wigner function.

Impulse approximation (IA):

Length/energy scale:

$\lambda_{thermal} \sim 0.5\, fm \ll r_{np} \sim 4\, fm$

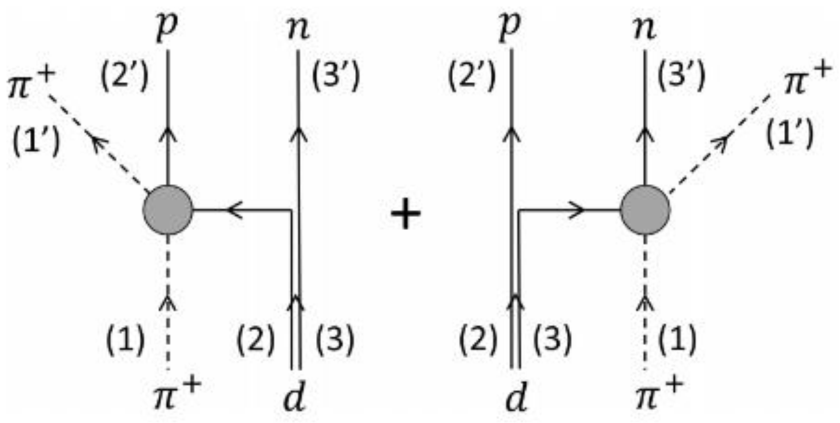
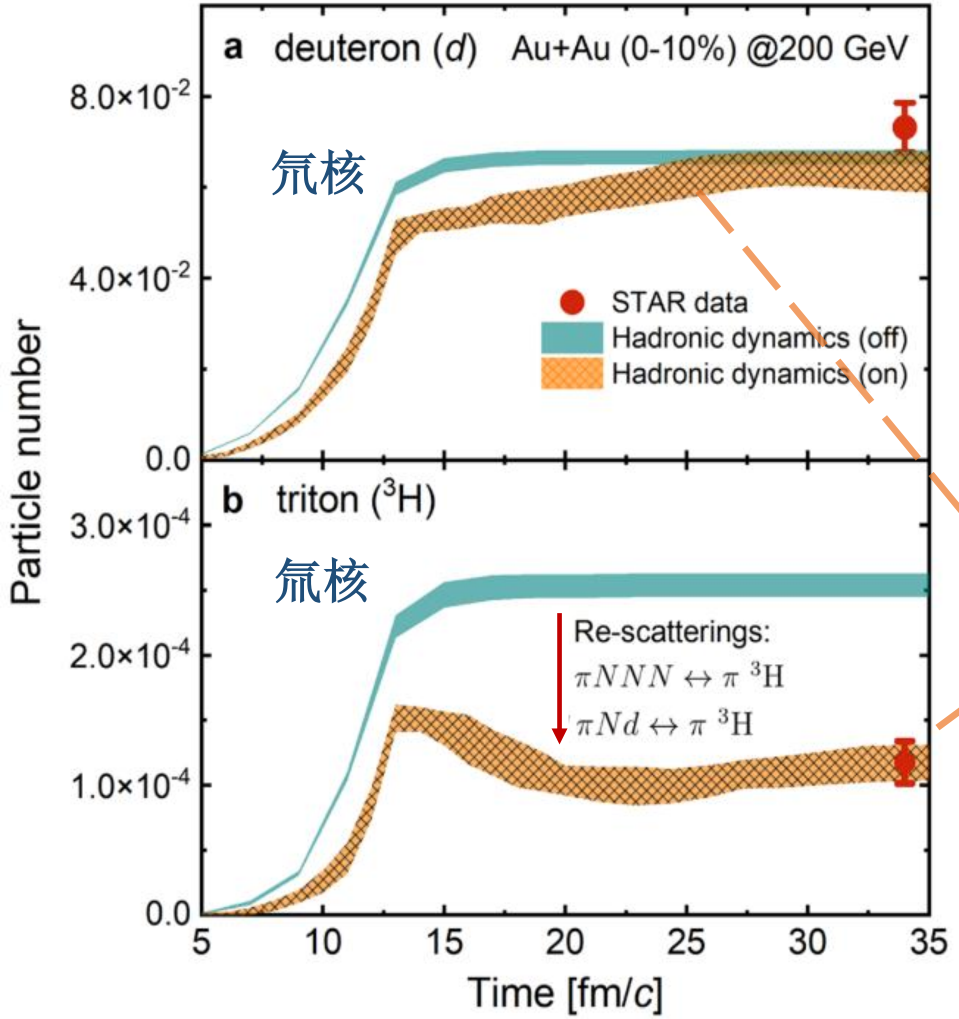


FIG. 1. Diagrams for the reaction $\pi^+ d \leftrightarrow \pi^+ np$ in the impulse approximation. The filled bubble indicates the intermediate states such as a Δ resonance.

Develop numerical methods to solve relativistic quantum many-body transport equations.

Pion-catalyzed Effects at RHIC Energies

K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nat. Commun. 15, 1074 (2024)



Statistical Hadronization + **Pion-catalyzed reaction**

$\pi NN \leftrightarrow \pi d$

$\pi NNN \leftrightarrow \pi\ ^3\mathrm{H}$

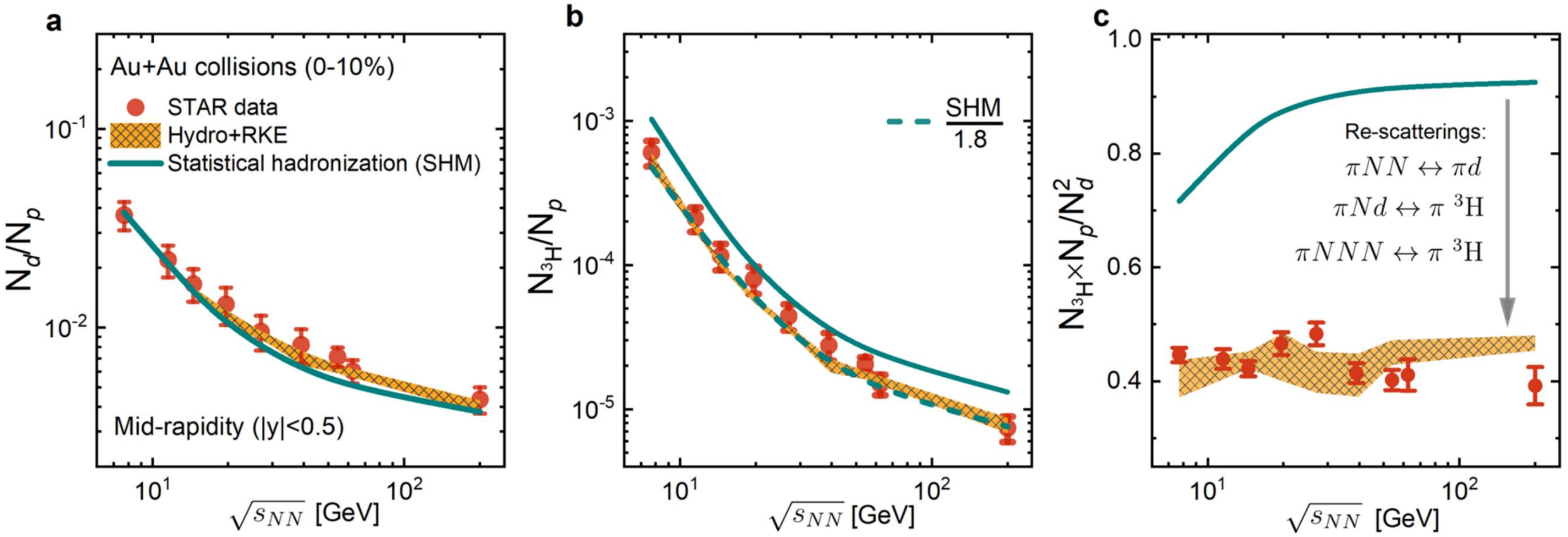
$\pi Nd \leftrightarrow \pi\ ^3\mathrm{H}$

New prediction

[Theoretical finding] Pion-catalyzed reactions reduce the triton yield by half

Pion-catalyzed Effects at RHIC Energies

K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nat. Commun. 15, 1074 (2024)
Data from STAR, PRL 130, 202301 (2023)



[Theoretical finding] Pion-catalyzed reactions reduce the triton yield by half

Outline

I Little-Bang Nucleosynthesis

II "Snowball in Hell" puzzle

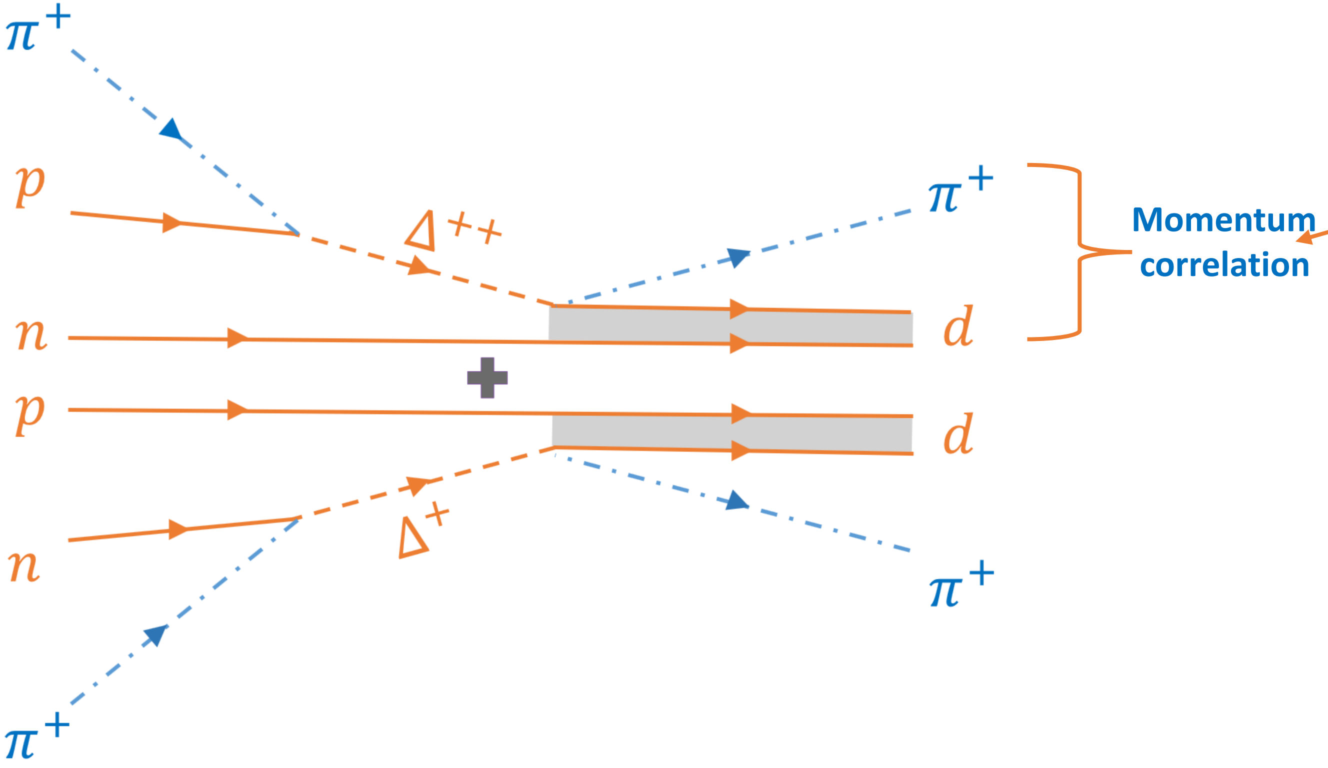
III Resolving the puzzle with pion-catalyzed reactions

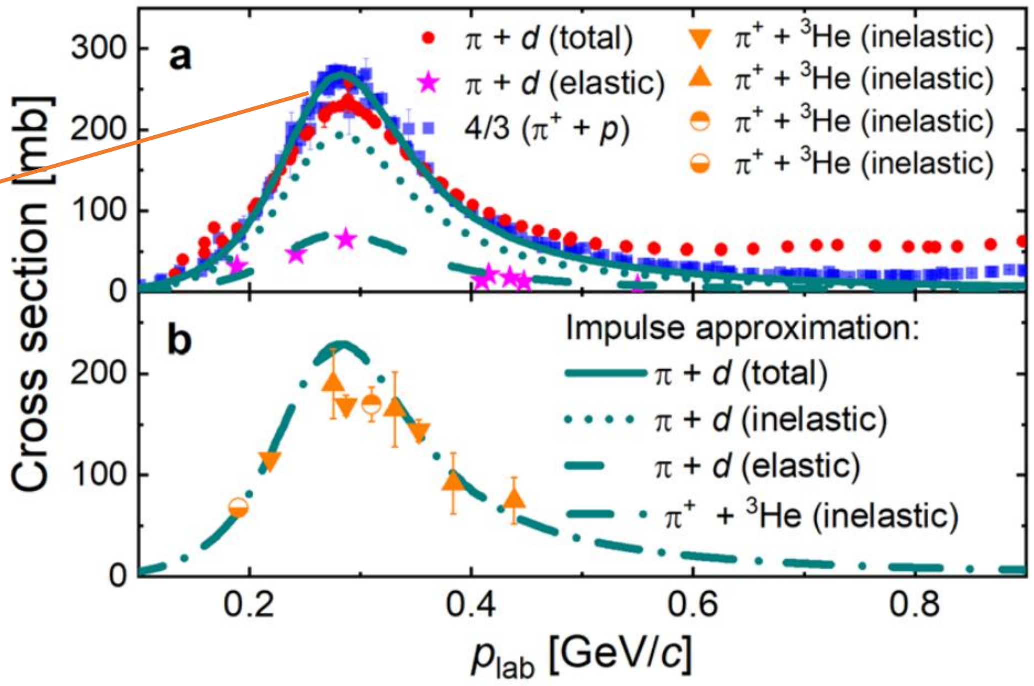
IV Evidence from Femtoscopy

V Outlook

More Evidence?

K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nat. Commun. 15, 1074 (2024)





Pion-Catalyzed reaction

$\pi + N + N \leftrightarrow \pi + d$

Delta-assisted reaction

$\pi + N \leftrightarrow \Delta,$

$\Delta + N \leftrightarrow \pi + d$

Pion-catalyzed reactions lead to pion–deuteron correlations (resonance peak)

Peak comes from intermediate Delta resonance

$$\sigma_{\pi^+p\to\Delta^{++}} = \frac{2\pi}{q^2}\Gamma(m_\Delta)\mathcal{A}(m_\Delta)$$

$$\Gamma = \frac{0.47q^3}{m_\pi^2 + 0.6q^2},$$

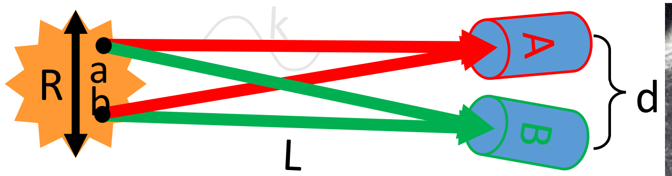
$$\mathcal{A}(\sqrt{s_{\rm cm}}) = \frac{1}{0.948}\frac{4m_0^2\Gamma}{(s_{\rm cm} - m_0^2)^2 + m_0^2\Gamma^2}$$

Correlation Femtoscopy

Hanbury Brown-Twiss (HBT) intensity interferometry

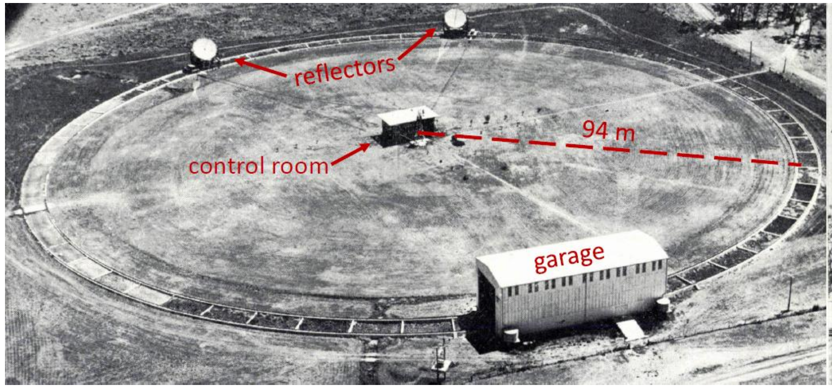
HBT 强度干涉

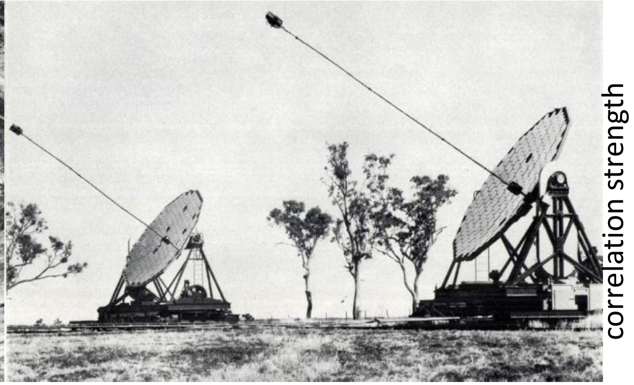
Nature 178, 1046 (1956)

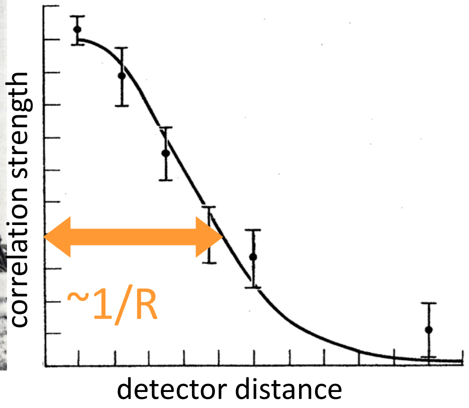


$$C_{AB}(\Delta) = \frac{\langle I_A I_B \rangle}{\langle I_A \rangle \langle I_B \rangle} = 1 + \frac{1}{2}\cos\frac{kRd}{L}$$

$R_{\text{Star}} \sim 10^{8} - 10^{11} m$





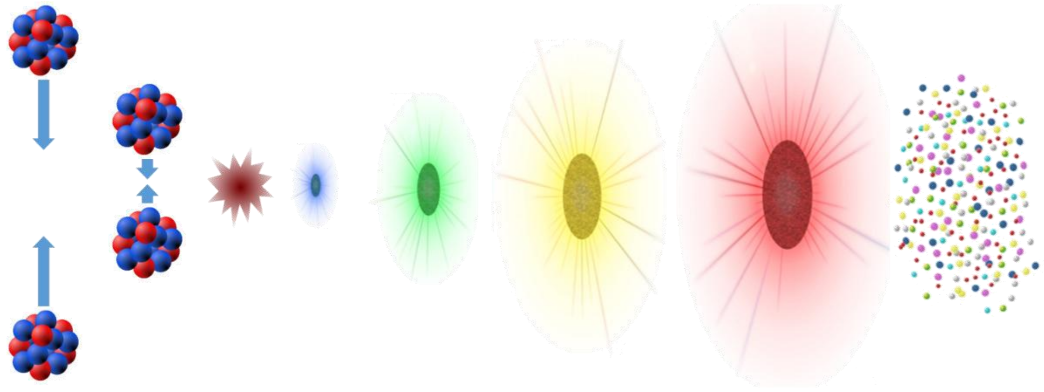


Correlation Femtoscopy

关联费米显微镜

See talk by L. S. Geng (Apr. 25)

$R_{\text{HIC}} \sim 10^{-15}\ m$



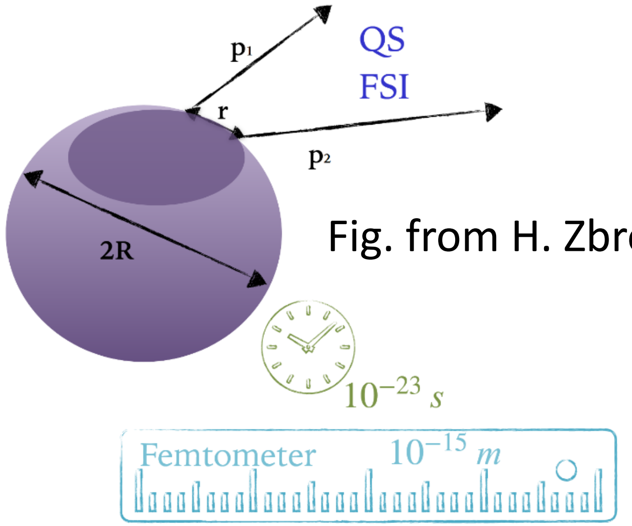
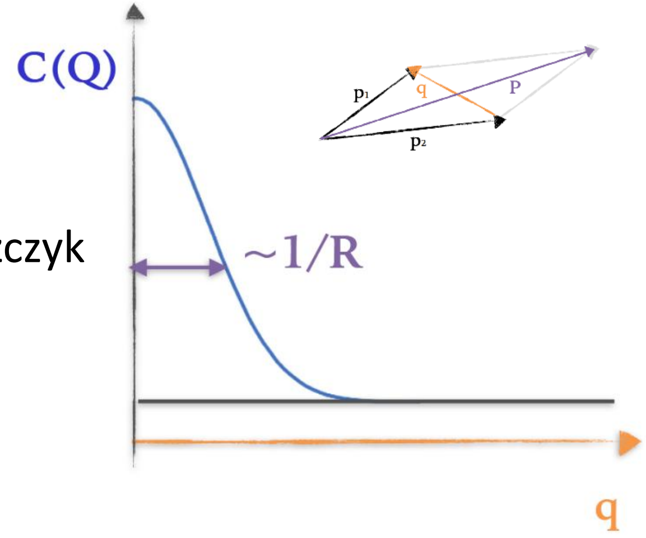


Fig. from H. Zbroszczyk



U. Heinz and B. Jacak, Ann. Rev. Nucl. Part. Sci. 49, 529 (1999)

Lednicky-Lyuboshitz model

Slide from Hanna Zbroszczyk

$$C(k^*) = \int S(r^*)\,|\Psi(r^*,k^*)|^2 d^3r$$

$$S(r^*) = (2\sqrt{\pi}r_0)^{-3} e^{-\frac{r^{*2}}{4r_0^2}}$$

$$\Psi^S(r^*,k^*) = e^{-ik^*r^*} + f^S(k^*)\frac{e^{ik^*r^*}}{r^*}$$

$$f^S(k^*) = \left(\frac{1}{f_0^S} + \frac{1}{2}d_0^S k^{*2} - ik^*\right)^{-1}$$

Strong

$$|\Psi^C(r^*,k^*)| = \sqrt{A_C}\,e^{-ik^*r^*}F(-i\eta,1,i\zeta)$$

$$A_C(\eta) = \frac{2\pi}{k^* a_c}\left(exp\left(\pm\frac{2\pi}{k^* a_c}\right) - 1\right)^{-1}$$

Coulomb

S-wave scattering

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

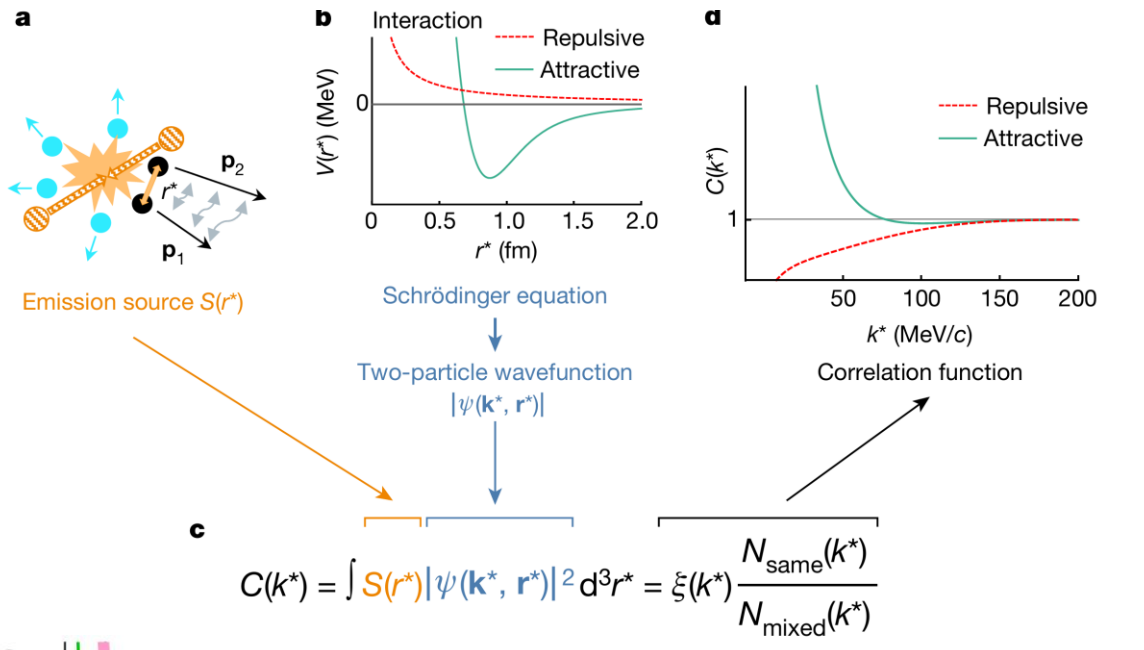
For identical systems one has to include QS (Fermi-Dirac / Bose-Einstein) as well.

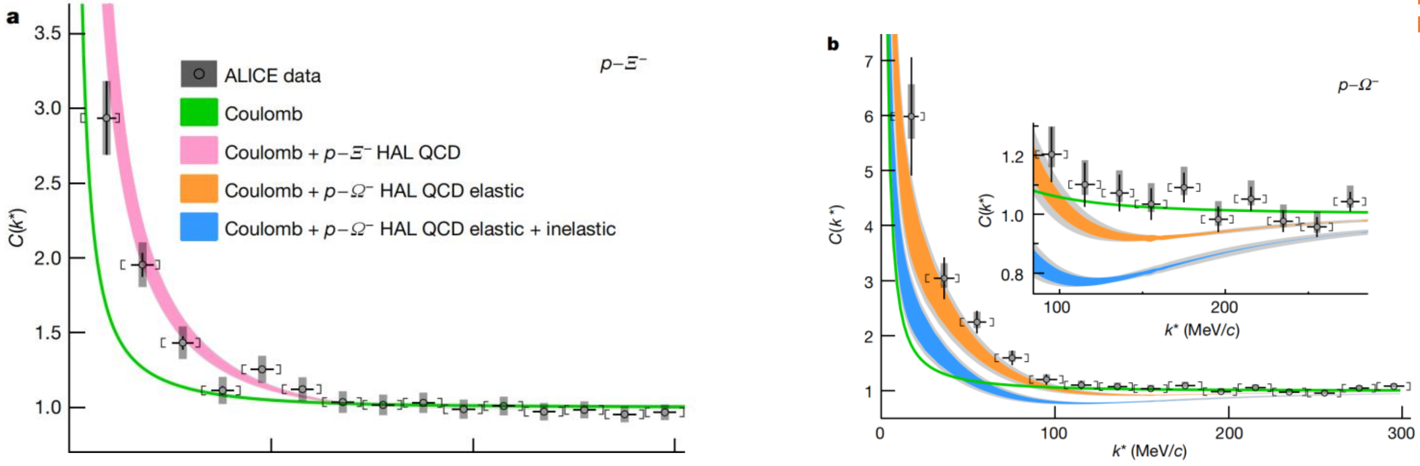
Recent progress

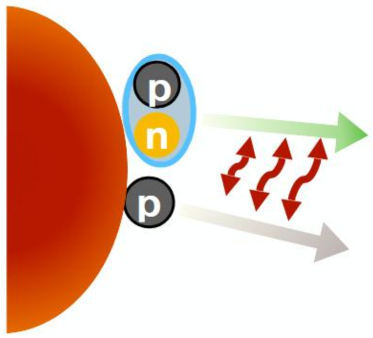
Article

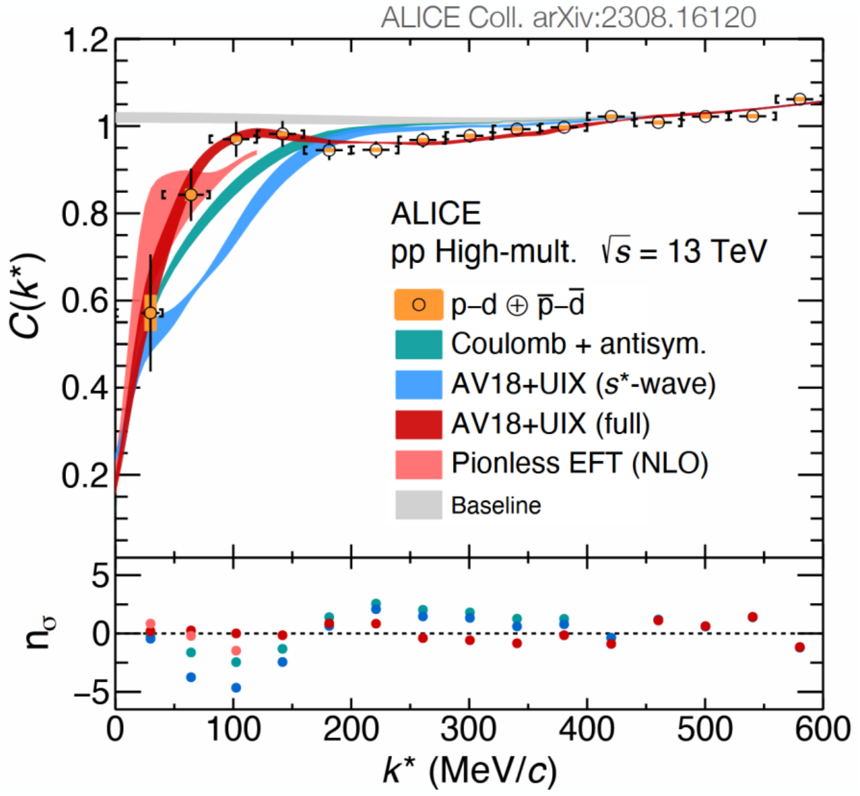
Unveiling the strong interaction among hadrons at the LHC

Nature 232, 588 (2025)







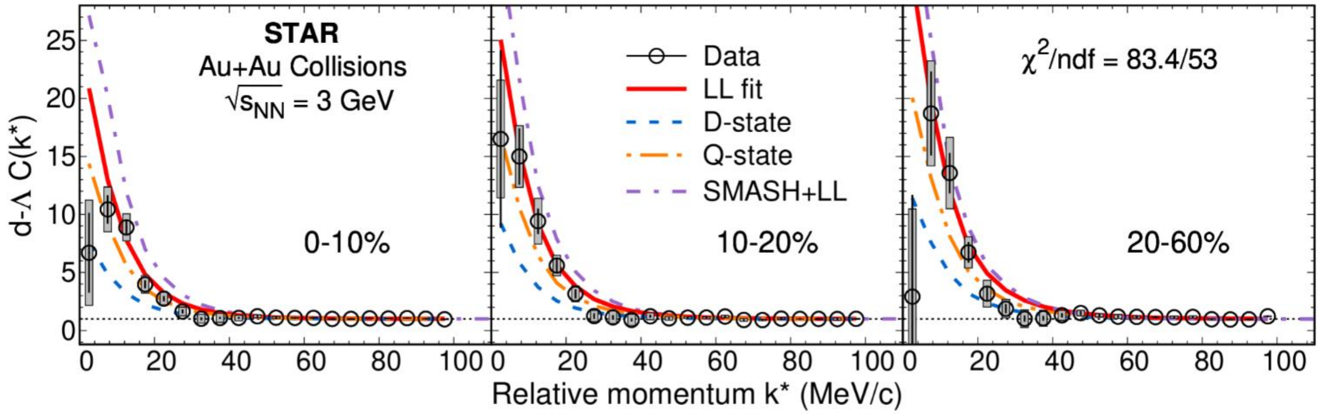


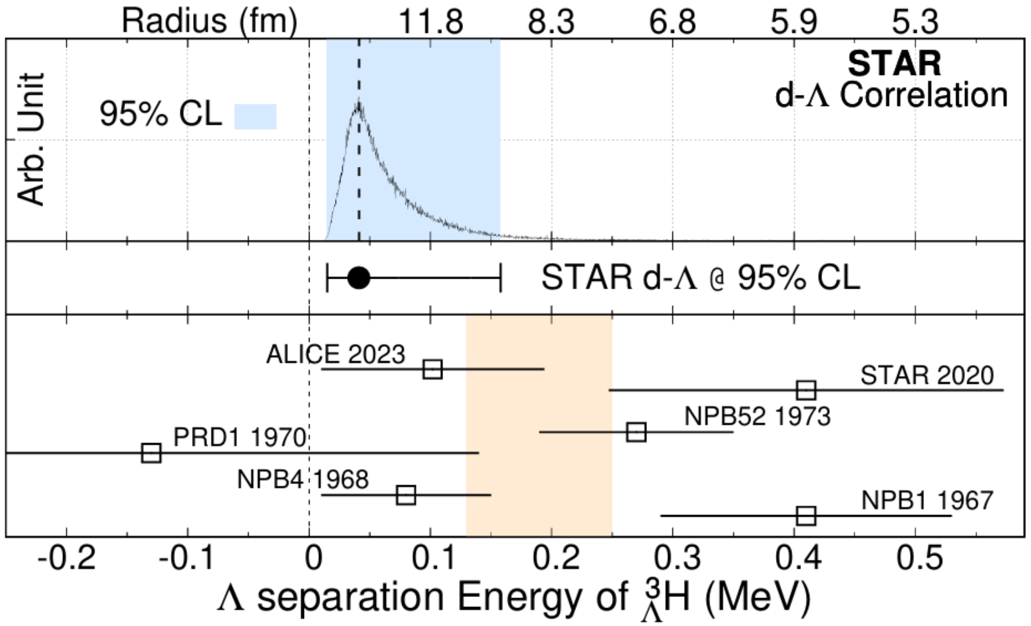
Recent progress

First observation of deuteron-Λ correlations at RHIC

(STAR Collaboration)

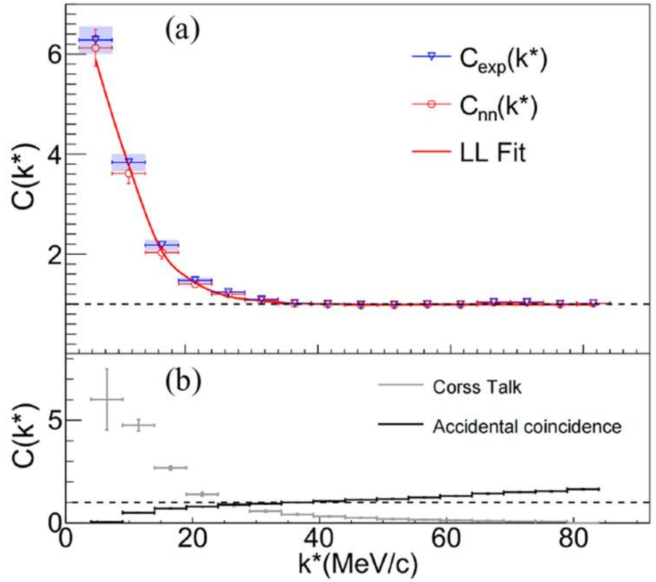
(Dated: November 20, 2025)

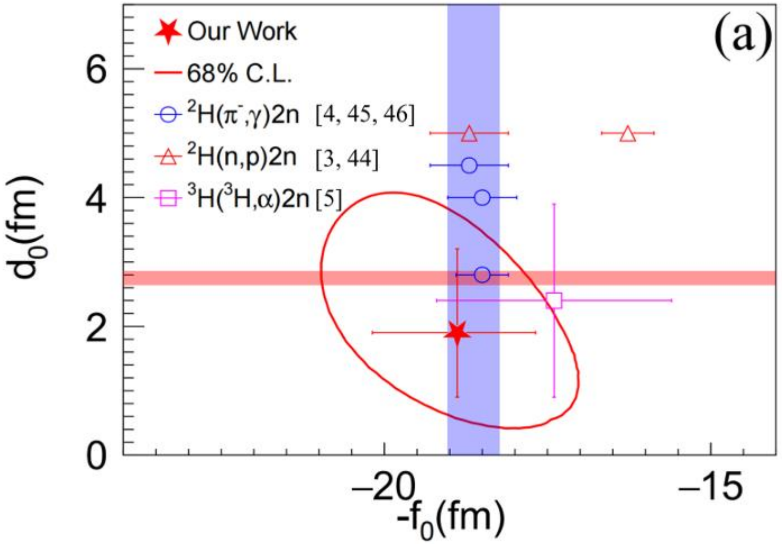




PHYSICAL REVIEW LETTERS **134,** 222301 (2025)

Extracting Neutron-Neutron Interaction Strength and Spatiotemporal Dynamics of Neutron Emission from the Two-Particle Correlation Function



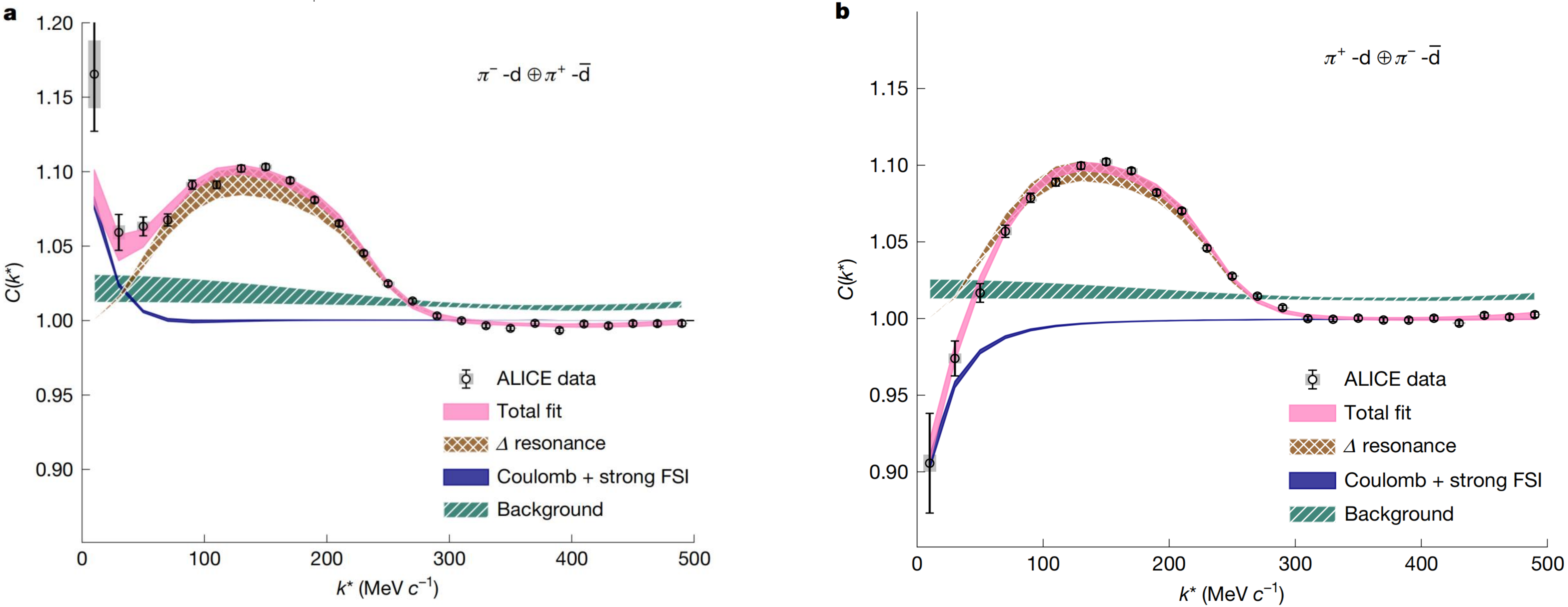


New ALICE Measurements

ALICE, Nature 648 (2025) 8093, 306-311

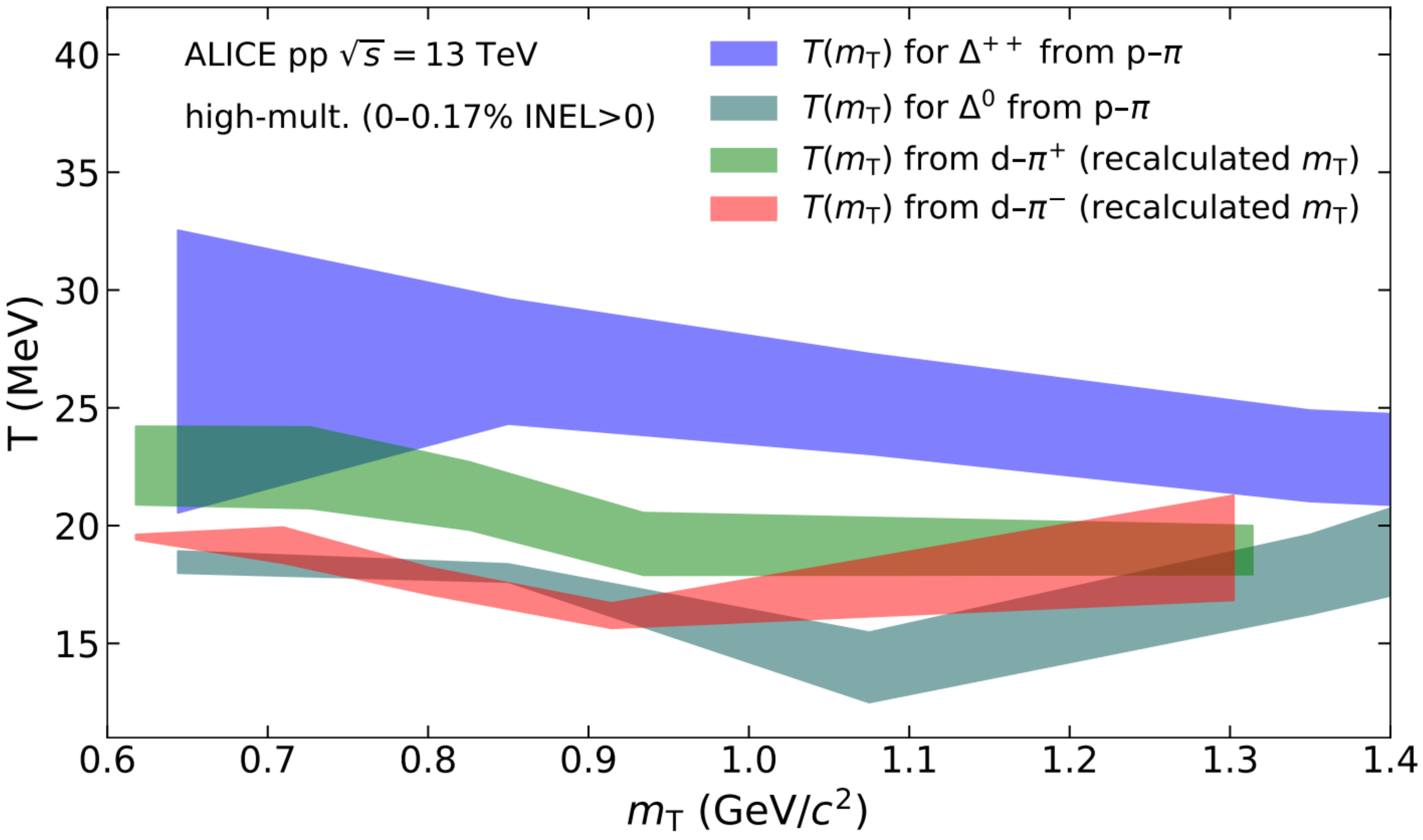
Article

Observation of deuteron and antideuteron formation from resonance-decay nucleons



[Experimental Discovery] A clear resonance peak induced by pion-catalyzed reactions has been observed.

New ALICE Measurements



$$C_\Delta(k^*) = \mathcal{N}_\Delta \times PS(p_{T,\Delta}, T) \times \mathrm{Sill}(M_\Delta, \Gamma_\Delta)$$

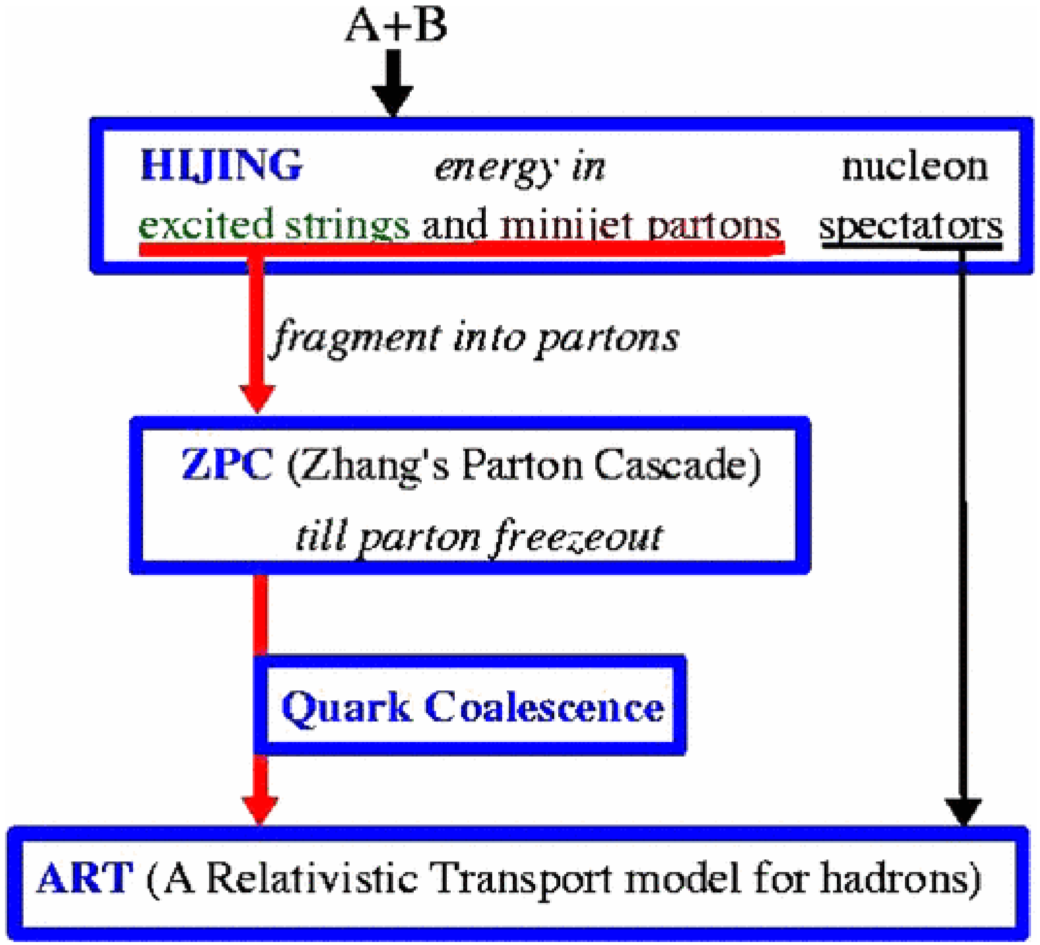
$$PS(p_{T,\Delta}, T) \propto \frac{M}{\sqrt{M^2 + p_{T,\Delta}^2}} \exp\left[-\frac{\sqrt{M^2 + p_{T,\Delta}^2}}{T}\right]$$

The very low temperatures need to be understood

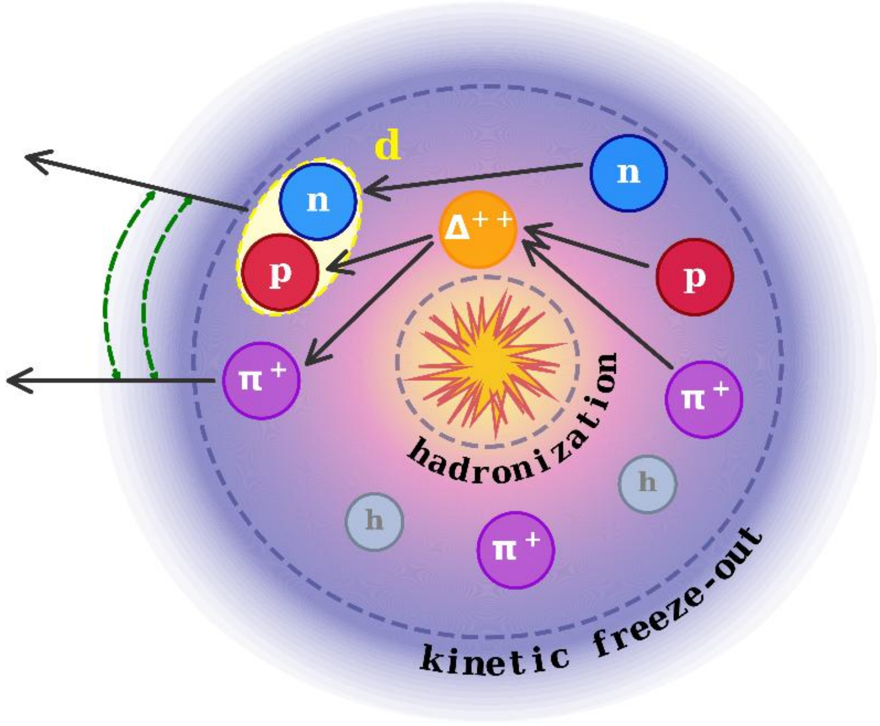
Pion-nucleus femtoscopy

L-Y Zhang, et.al, arXiv:2511.10298 (2025)

AMPT Model



Z. W. Lin et al., Phys. Rev. C 72, 064901 (2005)

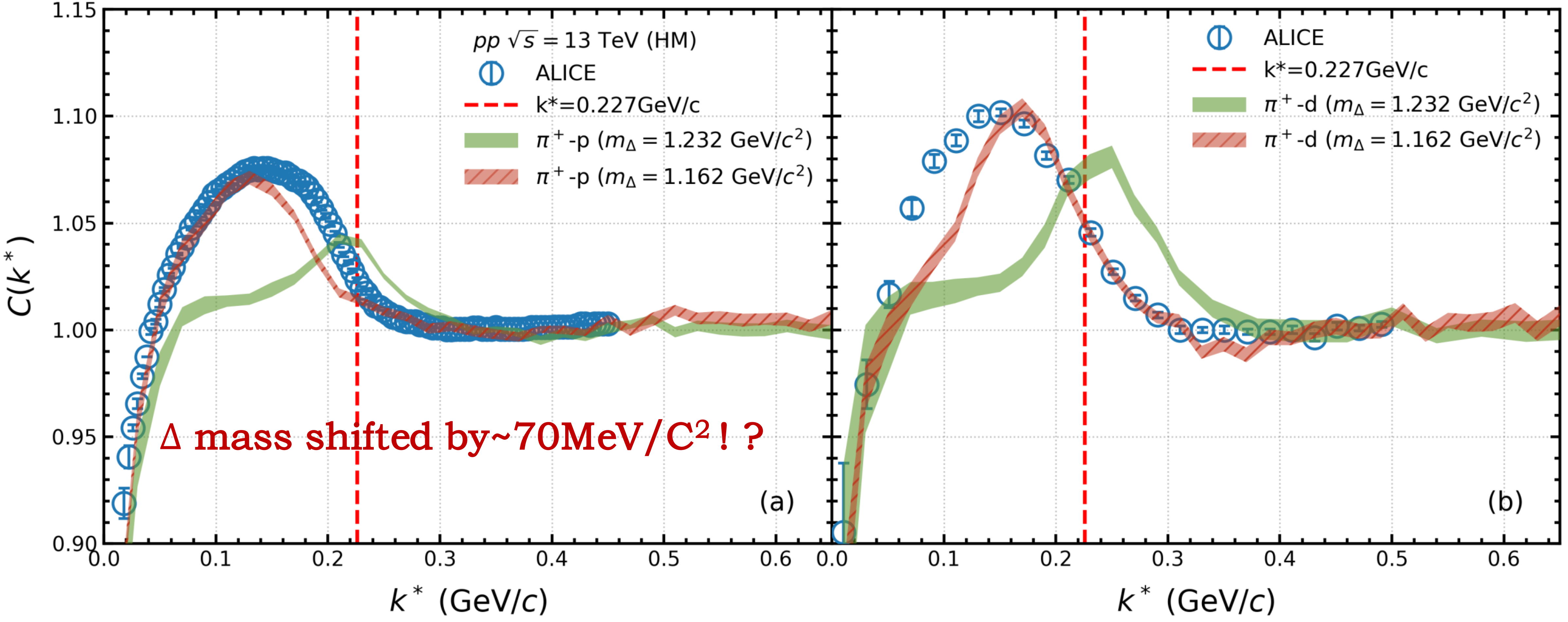


Pion-catalyzed reaction
$(\pi^+ np \leftrightarrow \pi^+ d)$

K-J Sun, et.al, Nature Commun, 15, 1074 (2024)

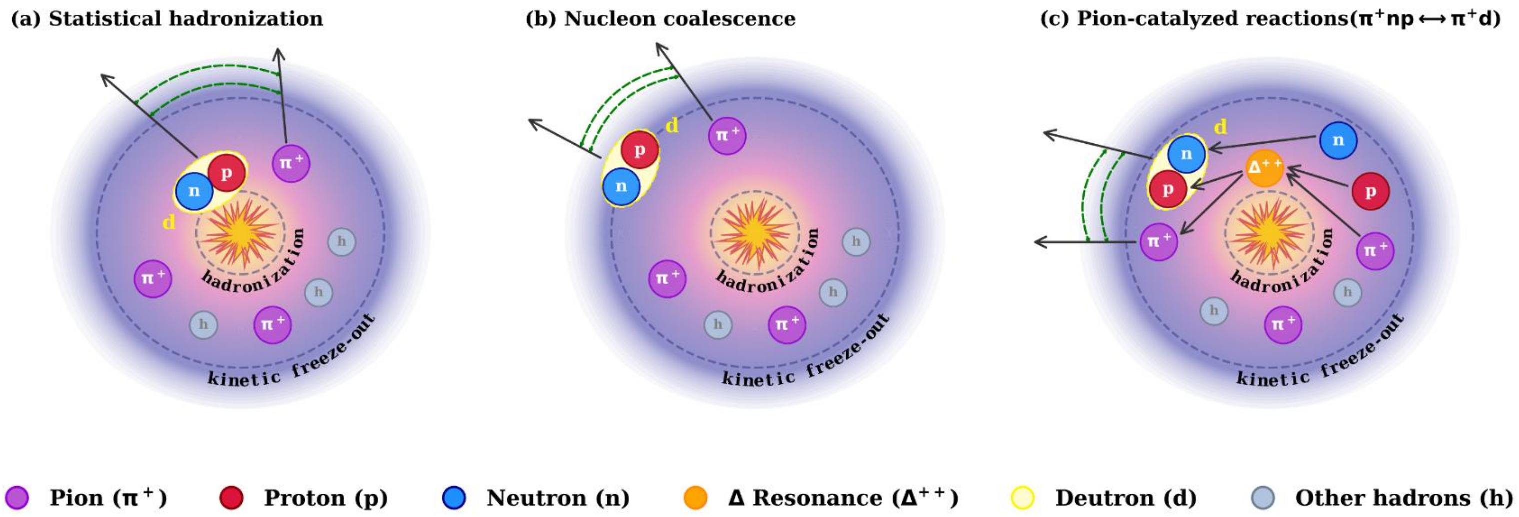
Pion-nucleus femtoscopy

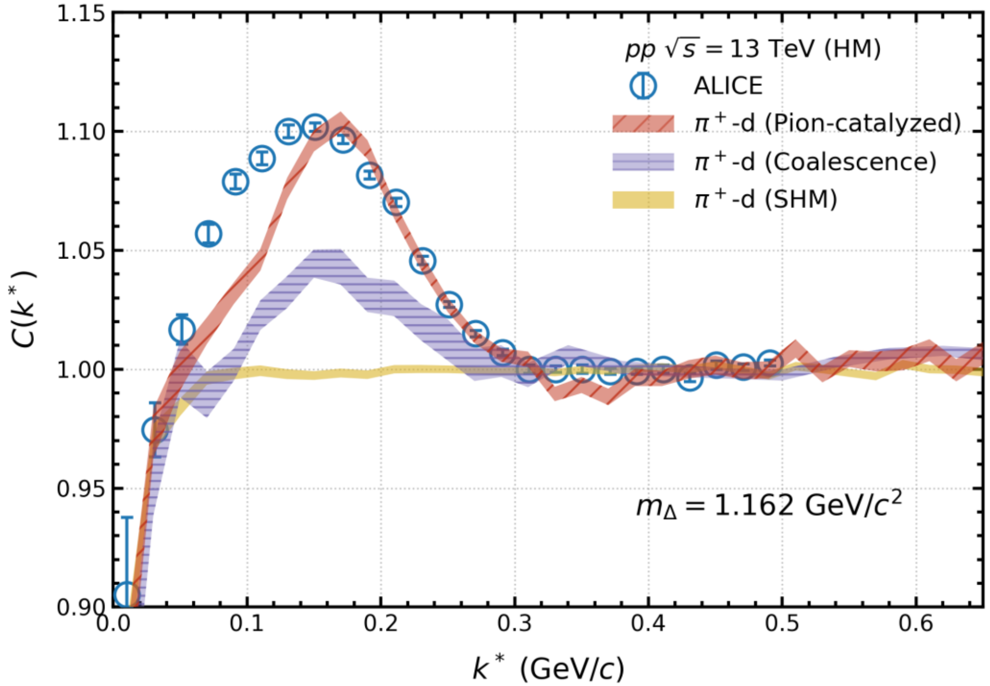
L-Y Zhang, et.al, arXiv:2511.10298 (2025)



Pion-nucleus femtoscopy

L-Y Zhang, et.al, arXiv:2511.10298 (2025)





Model-to-data comparison shows that light (anti-)nuclei production is dominated by pion-catalyzed reaction ($\boldsymbol{\pi NN \leftrightarrow \pi d}$) at the LHC

Outline

I Little-Bang Nucleosynthesis

II "Snowball in Hell" puzzle

III Resolving the puzzle with pion-catalyzed reactions

IV Evidence from Femtoscopy

V Outlook

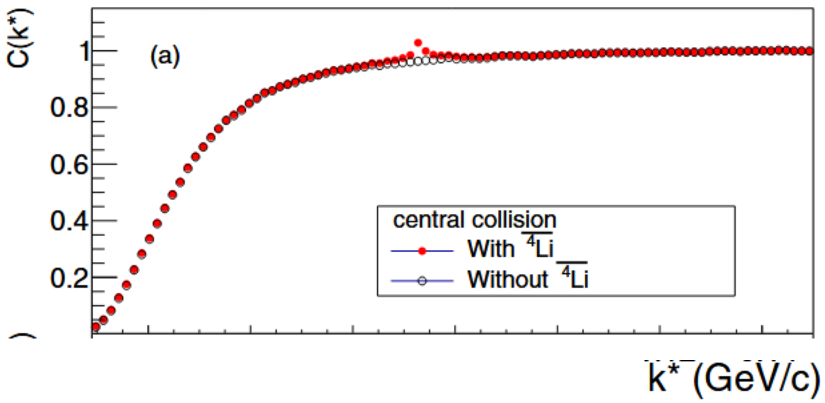
Next antimatter？

PHYSICAL REVIEW C **102**, 064901 (2020)

$\text{Anti}-{}^{4}Li \rightarrow \bar{p} + \overline{{}^{3}He}$

Searching for $\overline{{}^{4}\text{Li}}$ via the momentum-correlation function of $\bar{p}$-$\overline{{}^{3}\text{He}}$

Bao-Shan Xi (郗宝山),[1,2,3] Zheng-Qiao Zhang (张正桥),[1,*] Song Zhang (张松),[4] and Yu-Gang Ma (马余刚)[4,1,†]

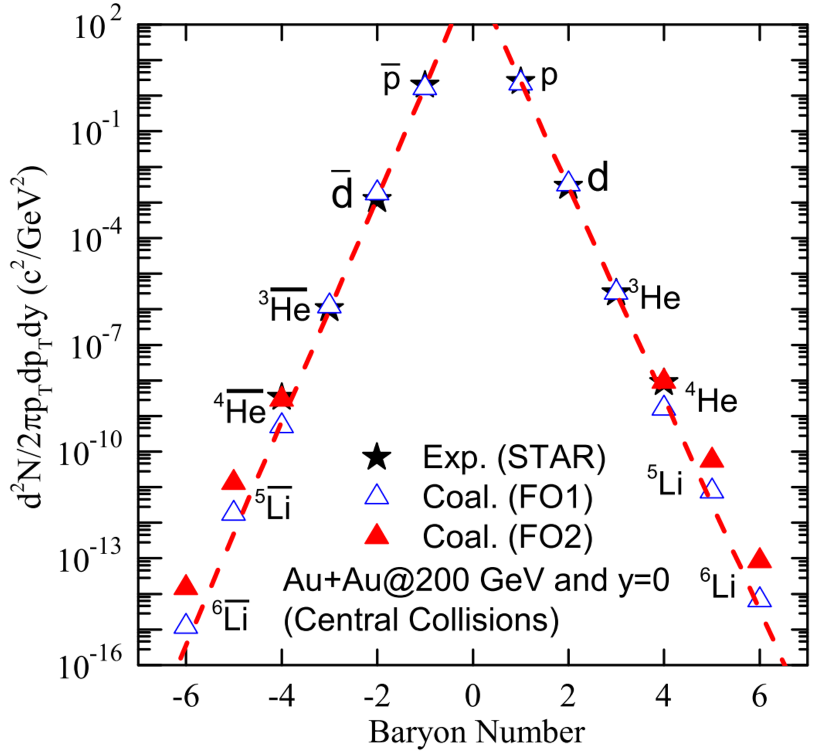


Production of antimatter ^{5,6}Li nuclei in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Kai-Jia Sun[a], Lie-Wen Chen[a,b,*]

A B S T R A C T

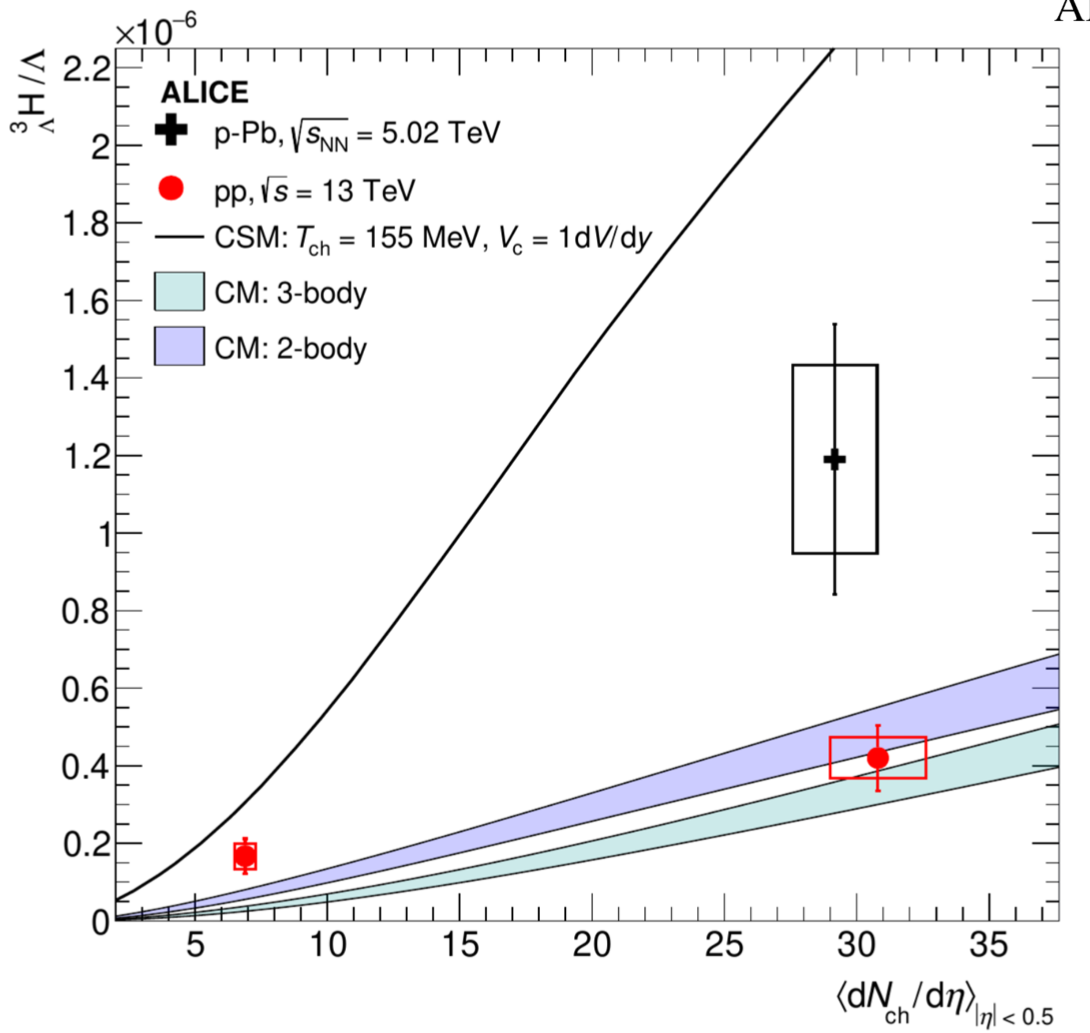
Combining the covariant coalescence model and a blast-wave-like analytical parametrization for (anti-)nucleon phase–space freezeout configuration, we explore light (anti-)nucleus production in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Using the nucleon freezeout configuration (denoted by FO1) determined from the measured spectra of protons (p), deutrons (d) and ^{3}He, we find the predicted yield of ^{4}He is significantly smaller than the experimental data. We show this disagreement can be removed by using a nucleon freezeout configuration (denoted by FO2) in which the nucleons are assumed to freeze out earlier than those in FO1 to effectively consider the effect of large binding energy value of ^{4}He. Assuming the binding energy effect also exists for the production of ^{5}Li, $^5\overline{\text{Li}}$, ^{6}Li and $^6\overline{\text{Li}}$ due to their similar binding energy values as ^{4}He, we find the yields of these heavier (anti-)nuclei can be enhanced by a factor of about one order, implying that although the stable (anti-)^{6}Li nucleus is unlikely to be observed, the unstable (anti-)^{5}Li nucleus could be produced in observable abundance in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV where it may be identified through the p–^{4}He ($\bar{p}$–$^4\overline{\text{He}}$) invariant mass spectrum. The future experimental measurement on (anti-)^{5}Li would be very useful to understand the production mechanism of heavier antimatter.

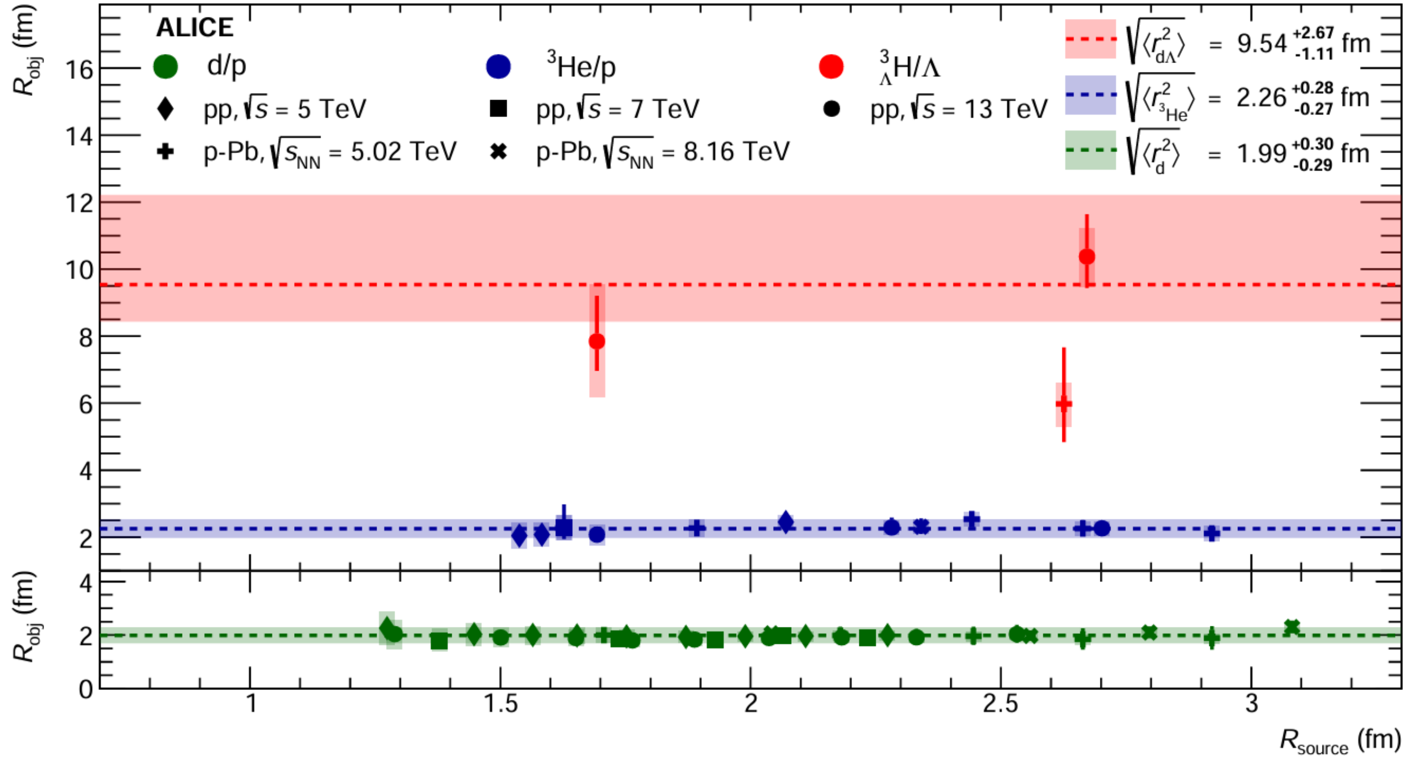


Wave-Function Femtometry: Hypertriton - The Ultimate Halo Nucleus

$$\frac{{}^{3}_{\Lambda}\mathrm{H}}{\Lambda} = \frac{7.1\times10^{-6}\times0.85}{\left[1+\left(\sqrt{\frac{2}{9}}\cdot\frac{\sqrt{\langle r^2_{\mathrm{d}\Lambda}\rangle}}{R}\right)^2\right]^{3/2}\left[1+\left(\frac{3.2}{2R}\right)^2\right]^{3/2}},$$

ALICE Collaboration*





Spin Polarization of Hypernuclei

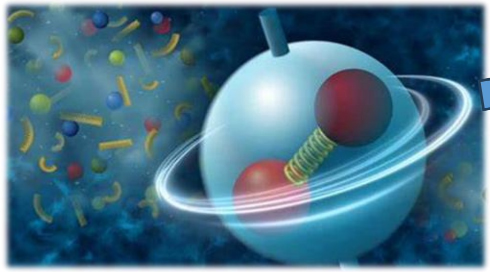
PRL 94, 102301 (2005)
PLB 629, 20 (2005)
（**Liang&Wang**）

Nature 548, 62 (2017)
(STAR)

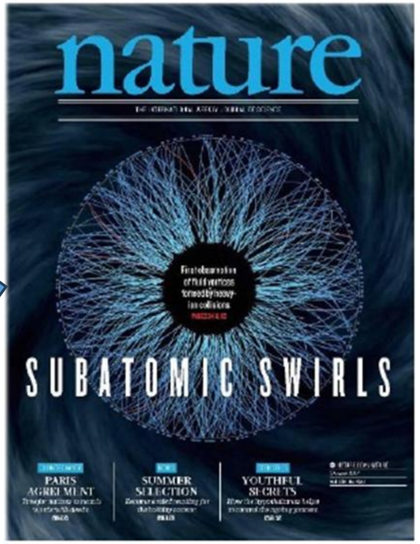
Nature 614, 244 (2023)
(STAR)

PRL 134, 022301 (2025)
Y. G. Ma's Group

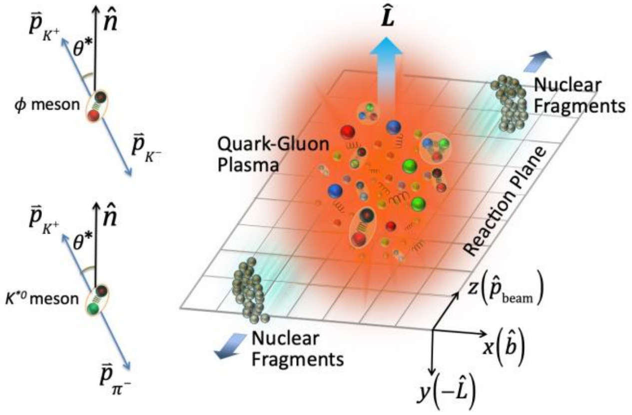
Spin polarization of hyperons in non-central heavy-ion collisions



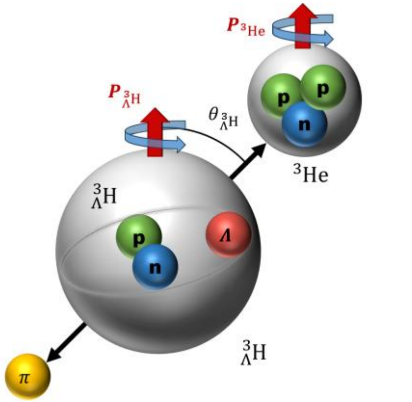
Observation of spin polarization of Lambda hyperon



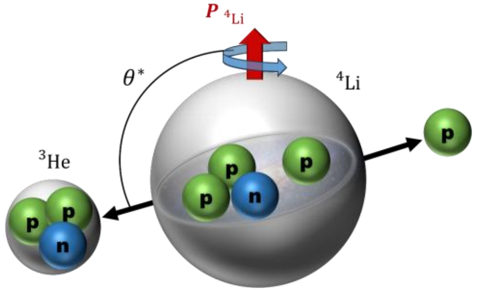
Unexpectedly large spin alignment of phi meson



Spin polarization of Hypertriton and Li-4



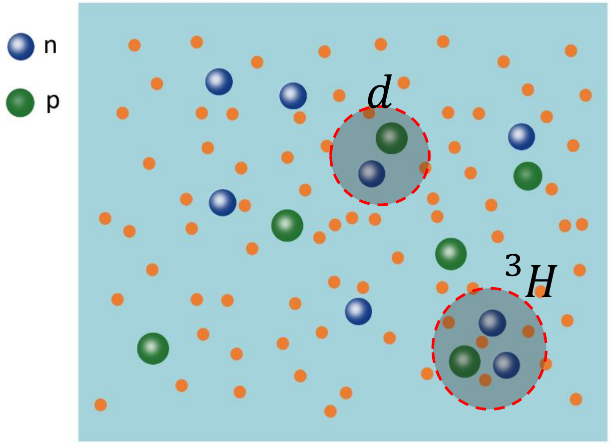
arXiv:2509. 15286 (2025)

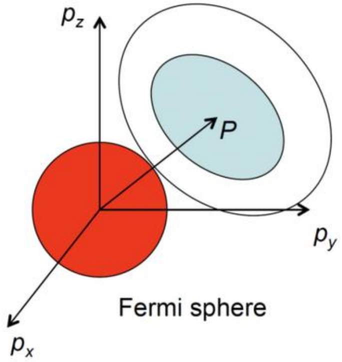


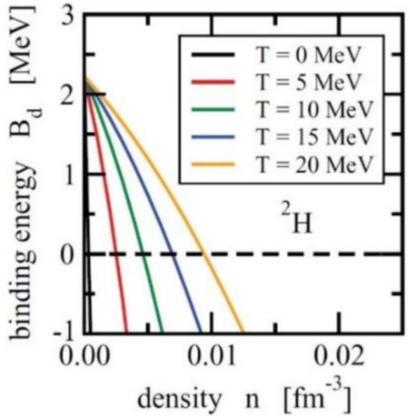
Mott Effect at High Baryon Density

Mott effect due to Pauli blocking

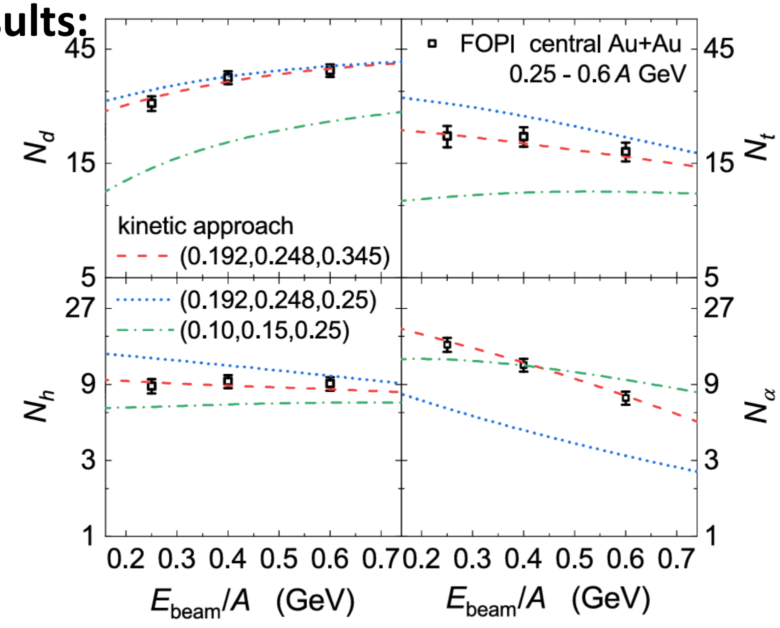
R. Wang, Z. Zhang, Y. G. Ma, L. W. Chen, C. M. Ko, and K. J. Sun, arXiv: 2507.16613, production in PRL.

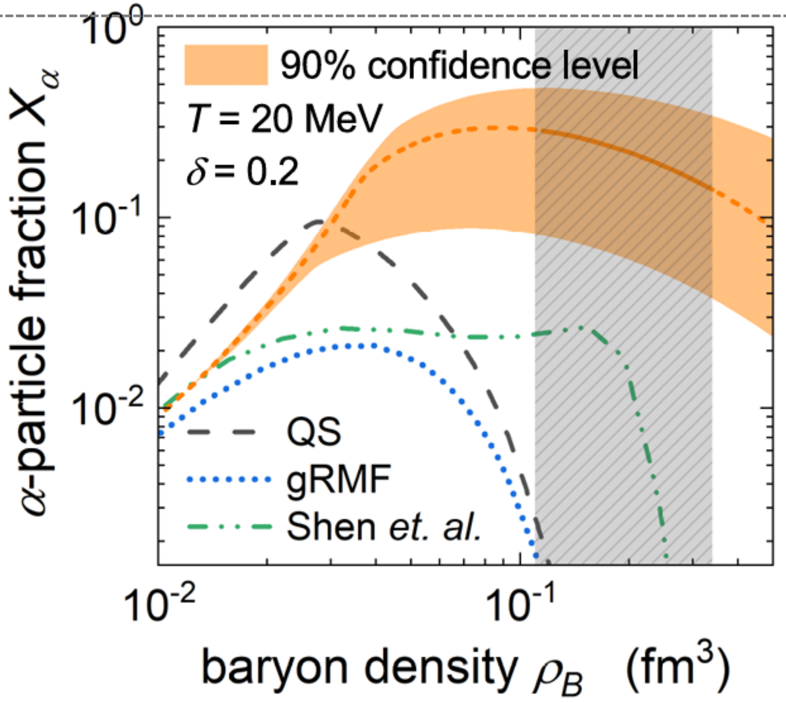






Main results:

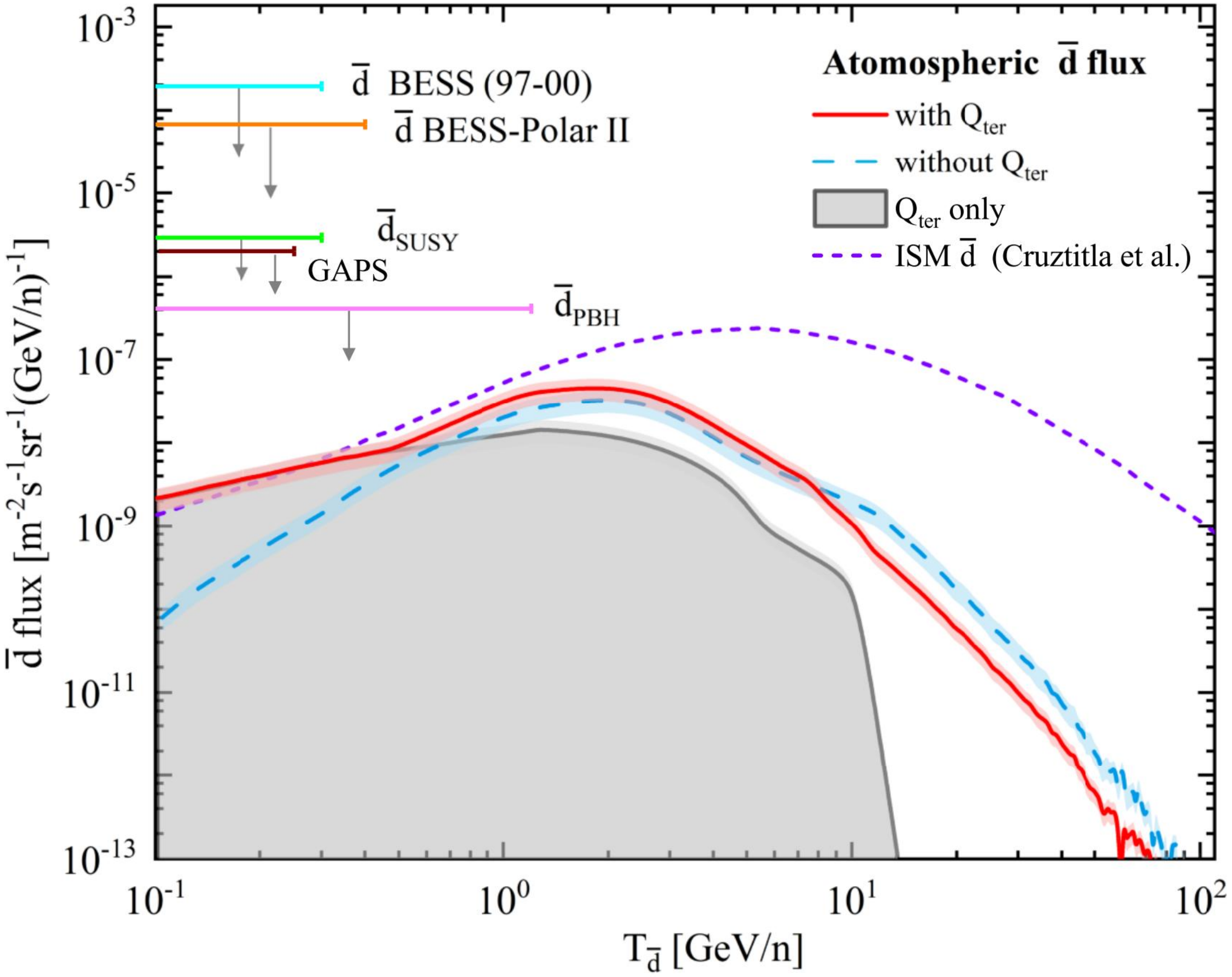




Stronger alpha clustering effect

Anti-deuteron Flux in Atmosphere

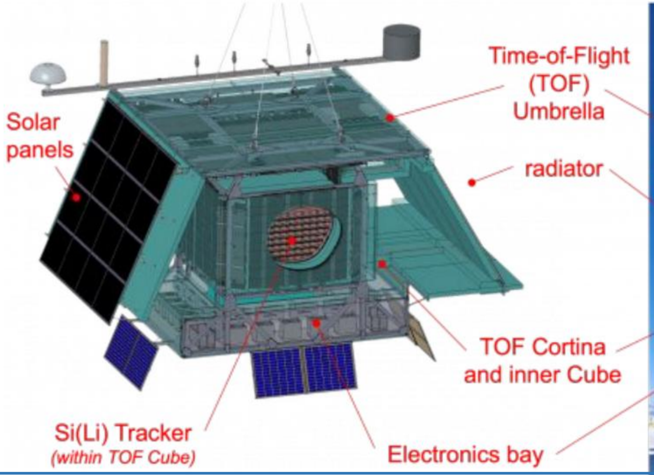
J. Pu, X. Li, K. J. Sun, C. W. Ma, L. W. Chen, JHEP 08 (2025) 002



Antimatter Nucleus Signal ?

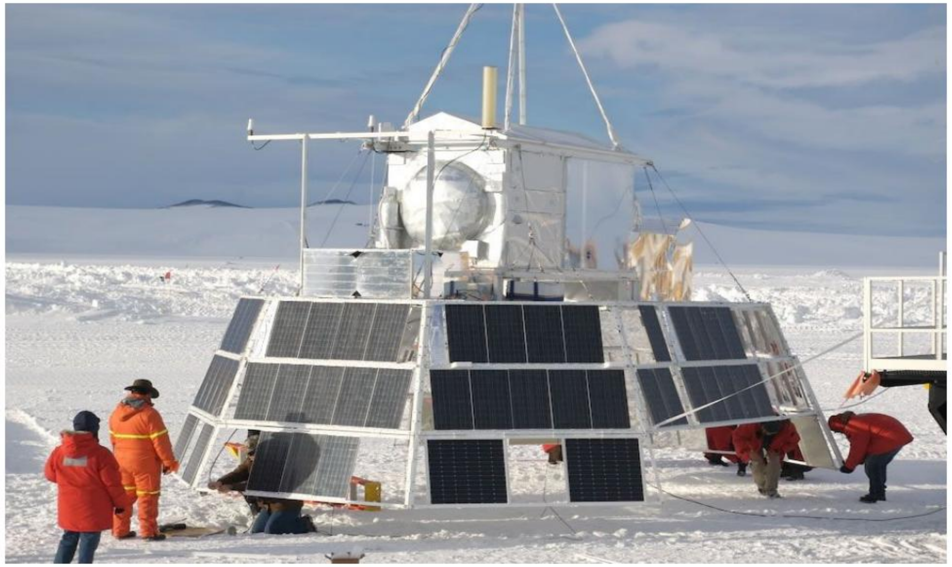
AMS-02

GAPS



Thanks a lot for your listening

Bess Polar-II

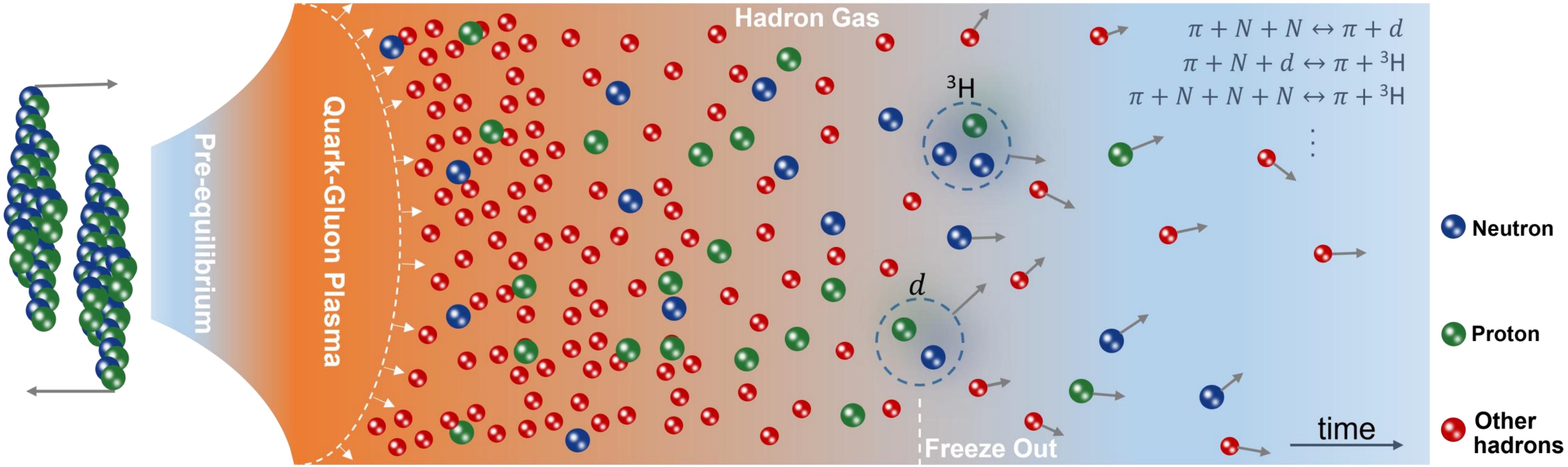


COSI and more

Backup

Microscopic Dynamics of LBN

$t \sim 10^{-23}s, T \sim 100$ MeV (10^{12}开尔文, 10000亿度)



K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nature Commun. 15, 1074 (2024)

Unlike Big Bang nucleosynthesis, in high-energy nuclear collisions ("little bangs"), (anti)matter light nuclei are predominantly produced via meson-induced (resonant) catalyzed reactions. Antimatter light nuclei undergo multiple cycles of breakup and regeneration; however, due to the extremely short timescales, they do not have sufficient time to annihilate and ultimately decouple from the system, propagating to the detector.

Final-State Coalescence & Wavefunction Femtometry (20)

Suppression of light nuclei production in collisions of small systems at the Large Hadron Collider

Kai-Jia Sun [a,b,*], Che Ming Ko [a,b], Benjamin Dönigus [c]

K. J. Sun, C. M. Ko and B. Dönigus, Phys. Lett. B 792, 132 (2019)

$$N_d \propto \frac{1}{\left[1+\left(\frac{2r_d^2}{3R^2}\right)\right]^{\frac{3}{2}}}$$

Production

Structure

$$N_{{}^3_\Lambda \mathrm{H}} \propto \frac{1}{\left[1+\left(\frac{r^2_{{}^3_\Lambda \mathrm{H}}}{2R^2}\right)\right]^{3}}$$

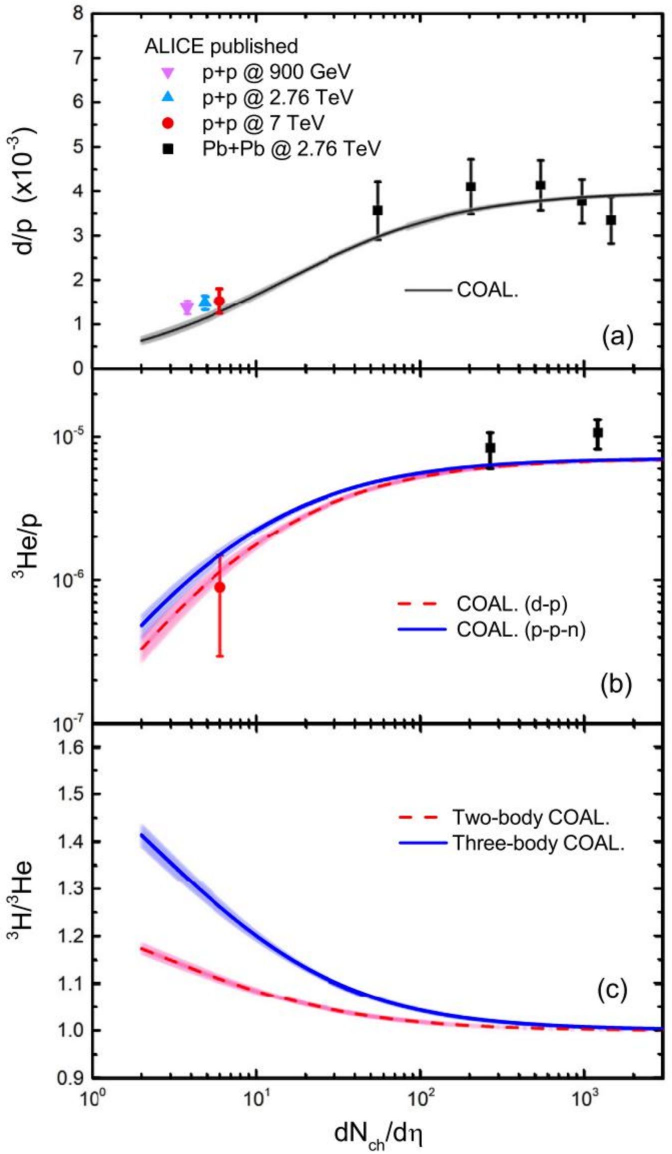
can be inferred from Femtoscopy

$$\frac{N_d}{N_p} \approx \frac{4.0\times 10^{-3}}{[1+\frac{2r_d^2}{3R^2}]^{3/2}} \qquad \frac{N_{{}^3He}}{N_p} \approx \frac{7.1\times 10^{-6}}{[1+\frac{r^2_{{}^3He}}{2R^2}]^{3}}$$

$$\frac{N_{{}^3_\Lambda H}}{N_\Lambda} \approx \frac{7.1\times 10^{-6}}{[1+\frac{r^2_{{}^3_\Lambda H}}{2R^2}]^{3}}$$

:3-body coal.

K. J. Sun, C. M. Ko, and B. Dönigus, Phys. Lett. B792, 132-137(2019)

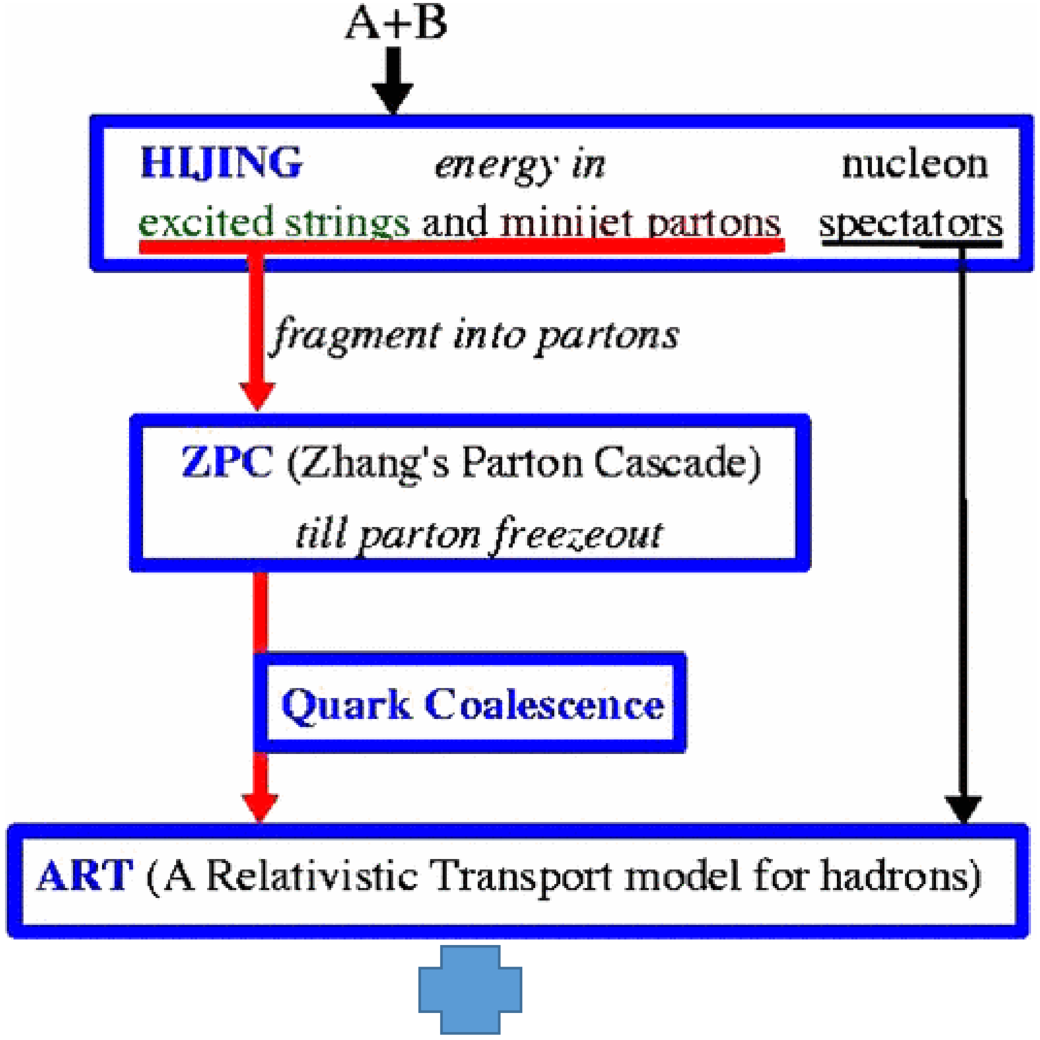


R. Scheibl and U. W. Heinz, PRC59. 1585(1999);
F. Bellini et al., PRC99,054905(2019);
Dai-Neng Liu et al., Phys. Lett. B 855 (2024) 138855

Anti-deuteron Flux in Atmosphere (22)

Z. W. Lin et al., Phys. Rev. C 72, 064901 (2005)

AMPT Model



Phase-space coalescence with Wigner function

J. Pu, X. Li, K. J. Sun, C. W. Ma, L. W. Chen, JHEP 08 (2025) 002