



中国科学院大学

University of Chinese Academy of Sciences



重离子碰撞中反物质核的发现 与 不稳定轻核的测量

吴俊霖

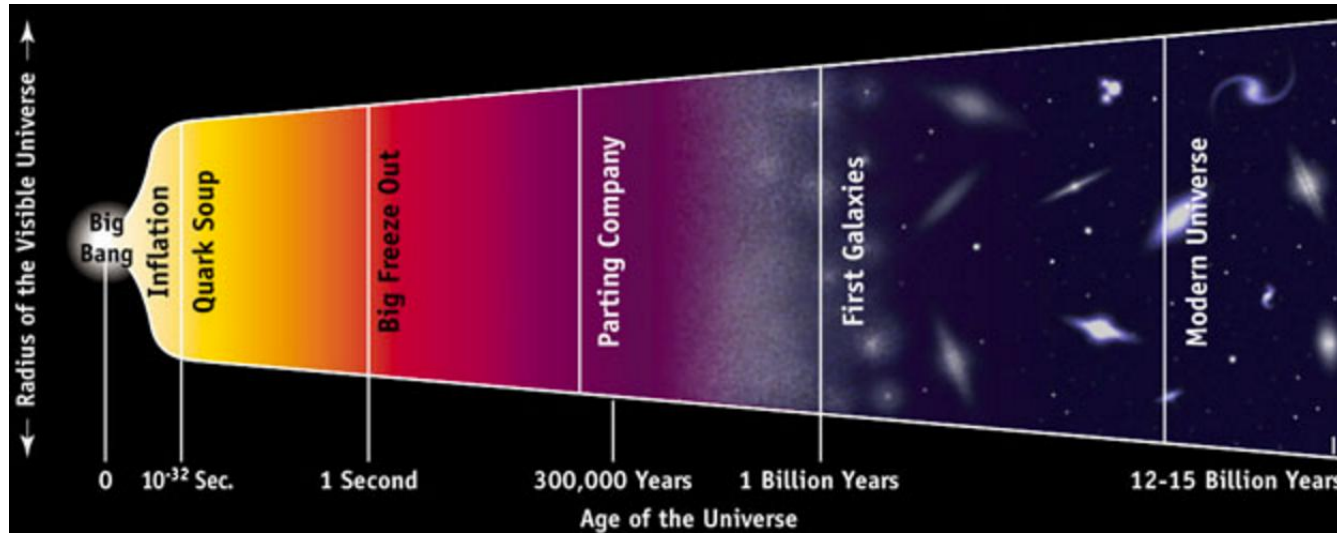
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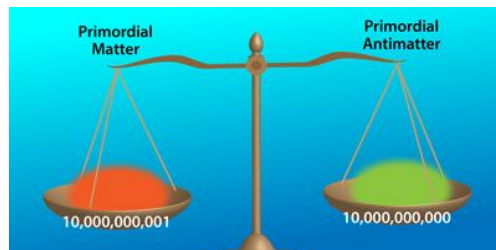
2026.07.09

第一部分：反物质发现和测量历史回顾与现状

研究动机



正反物质性质相同，但我们现在的宇宙宏观物质都是由正物质构成的，也没有观察到大块的反物质天体。
在宇宙大爆炸开始时：
BSU (Baryon-Symmetric Universe)
or
BAU (Baryon-Asymmetric Universe)
?



Sakharov's conditions:

1. Baryon Number Violation
2. C, CP, CPT Violation
3. Departure from Thermal Equilibrium

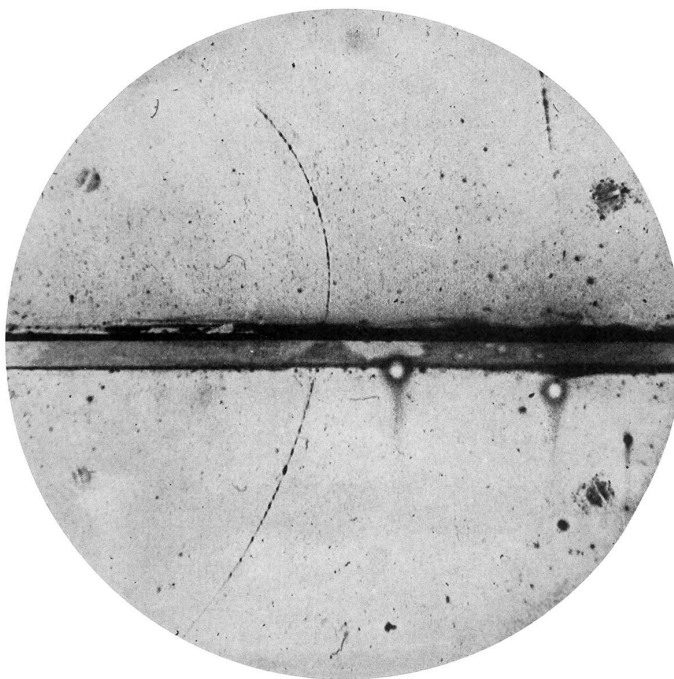


为探究宇宙中正反物质不对称性的问题，实验上一个重要思路是：
探索**新的反物质状态**的存在及其性质，检验标准模型的基本对称性
CPT，寻找物质-反物质不对称性的新机制。

正电子的发现（早期宇宙线实验）



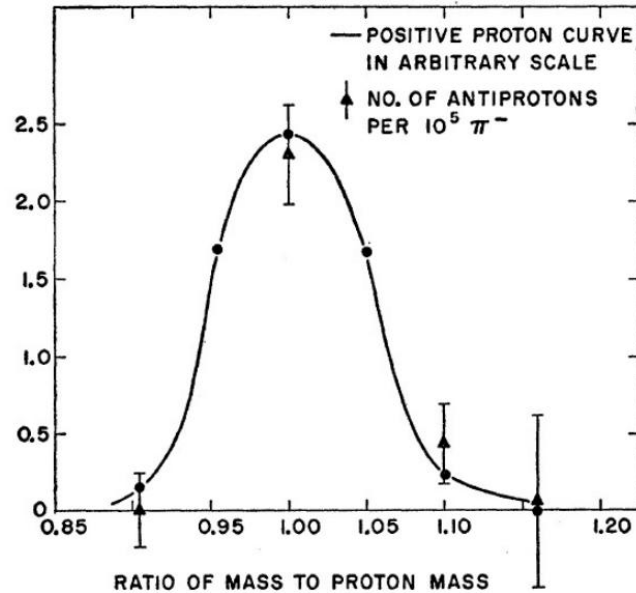
- P.A.M. Dirac, The Quantum Theory of the Electron. Proc. Roy. Soc. Lond. A 117, 610 (1928); 狄拉克方程有负能解 $E = \pm \sqrt{p^2 + m^2}$ 。
- 赵忠尧 硬伽马射线的反常吸收。
- C. D. Anderson 在1932年使用云室在宇宙线中发现了反电子；



Anderson 拍摄的带有反电子径迹的云室照片。

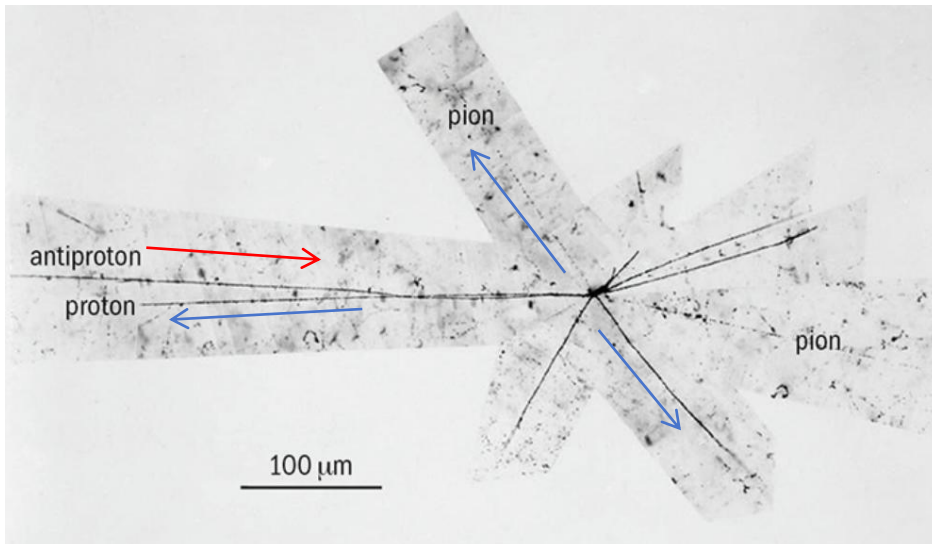
Science 76(1932) 238-239

反质子的发现（早期质子束流实验）



Phys. Rev. 100 (1955) 947–950.

- Reported by Chamberlain, Segre, Wiegand and Ypsilantis in 1955.
- The **Bevatron** at the University of California Radiation Laboratory (now Berkeley Lab) was designed with the search for antiprotons.
- Proton beam energy at 6.5 GeV and Copper target.
- Time-of-flight counters and Cerenkov detectors, was to distinguish antiprotons from π^- .



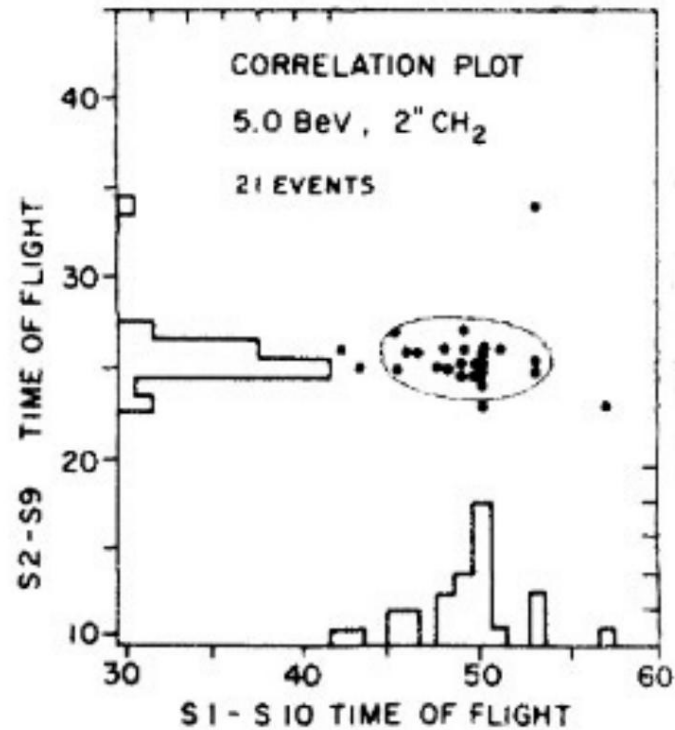
Phys. Rev. 101 (1956) 909–910.

- Selected by a magnetic spectrometer
- Traversed a copper absorber
- Stopped inside the emulsion
- A sample annihilation vertex

反轻核的发现（早期质子束流实验）

Whether antinucleons could form antinuclei?

Are their properties identical to those of their matter partners?



- Alternating Gradient Synchrotron (**AGS**) at Brookhaven National Laboratory
- Dorfan, Eades, Lederman, Lee and Ting in 1965
- 30 GeV protons on a Beryllium target (p-Be)
- 21 antideuteron candidates
- a similar p+Be experiment at the **CERN Proton Synchrotron**, also reported an observation of antideuterons later

Phys. Rev. Lett. 14 (1965) 999–1003

Phys. Rev. Lett. 14 (1965) 1003–1006

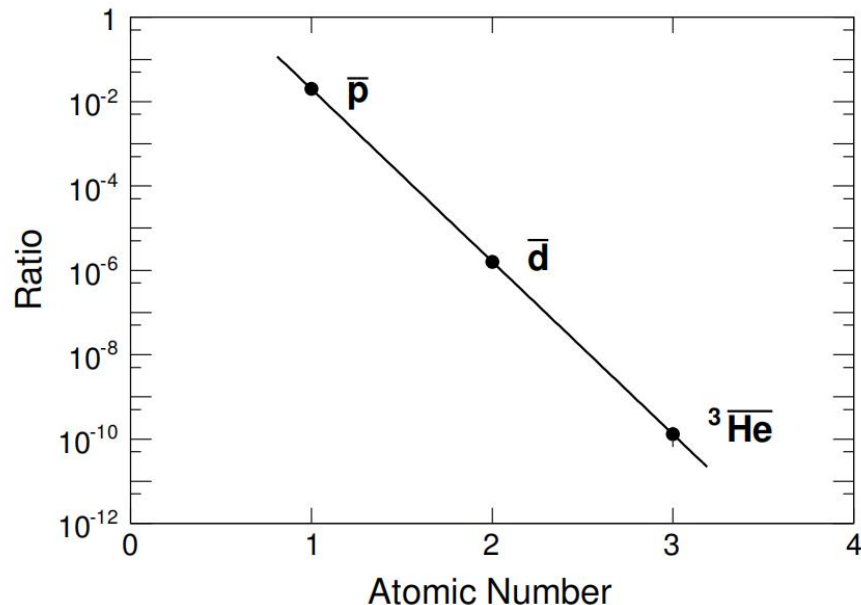
反轻核的发现（早期质子束流实验）

In 1960s, many experiments searched antimatter nuclei.

- 70 GeV synchrotron at the Institute of High Energy Physics, Protvino (**Serpukhov**), USSR(1967)
- CERN Intersecting Storage Rings the first proton-proton collisions at the ISR (53 GeV, 1971)
- the US National Accelerator Laboratory (NAL) in Illinois (later renamed Fermilab) (200-300GeV, 1972)

anti-He-3 was discovered in 1970 in Serpukhov ~ 5 candidates in p+Al

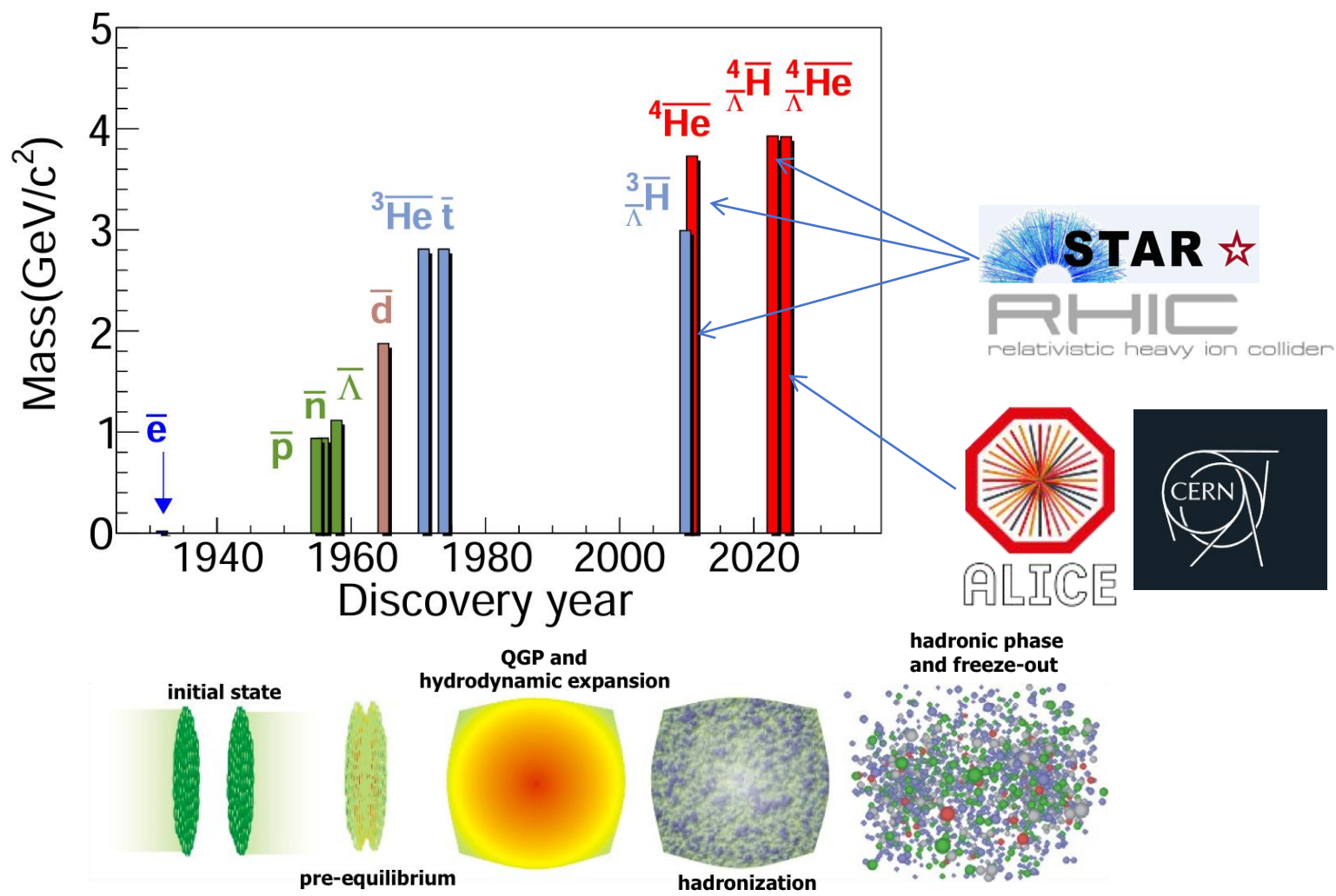
anti-Triton was discovered in 1974 in Serpukhov ~ 4 candidates in p+Al



A=-3 antimatter nuclei yield much low in proton beam experiment.:

- Threshold kinetic energy: A=-1 is 5.6GeV; A=-2 is 15GeV; A=-3 is 28GeV
- Coalescence Penalty Factor $\rho_A(Ap) \propto \rho_{A=1}^A(p)$
- Small system.

反轻核的发现（现代高能重离子碰撞实验）



The heavy ion collision experiment is a large system, which has increased the yield of anti-matter nuclei.

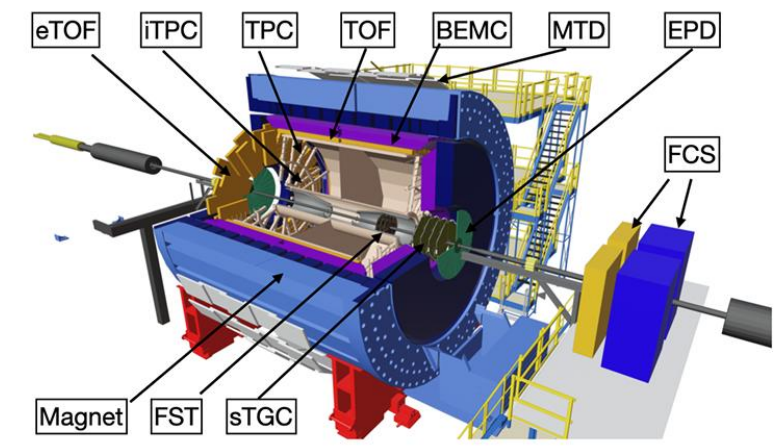


Figure 2. A schematic of the STAR detector.

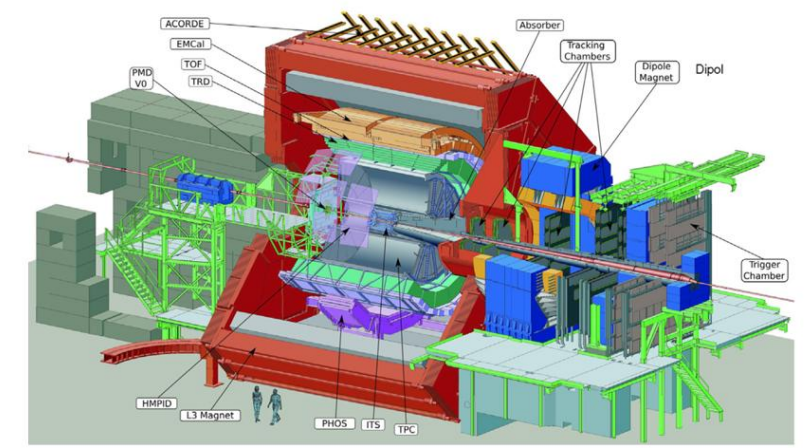
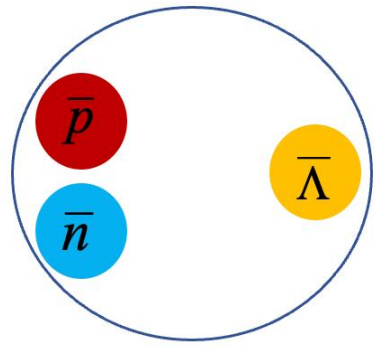
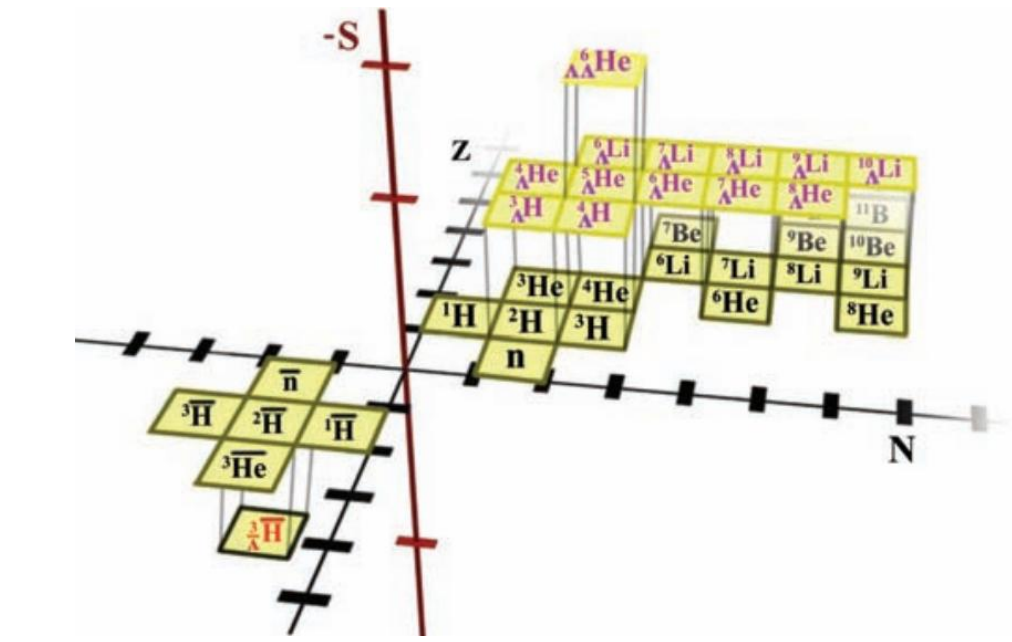


Figure 3. A schematic of the ALICE detector.

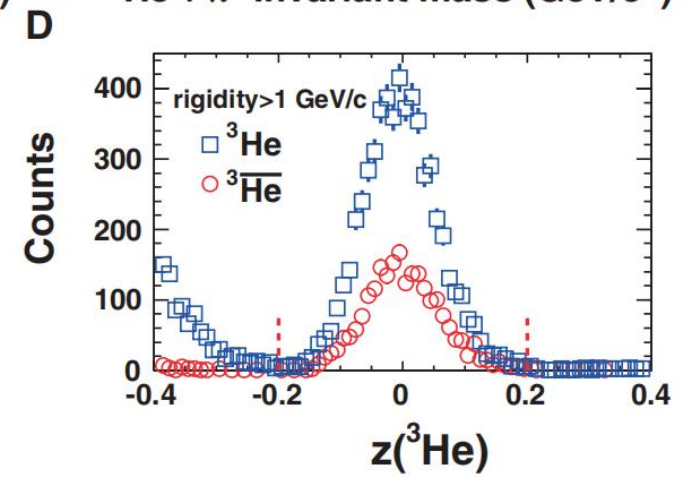
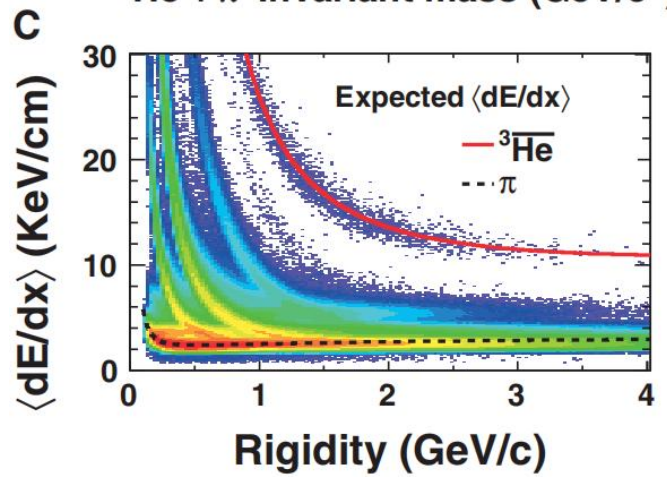
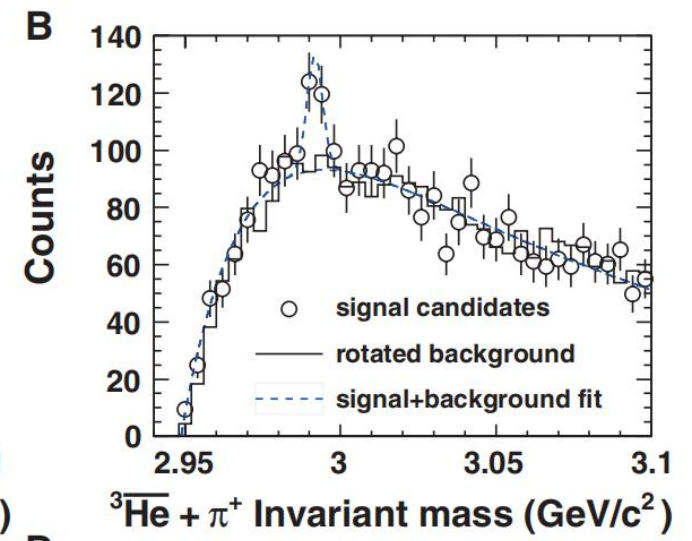
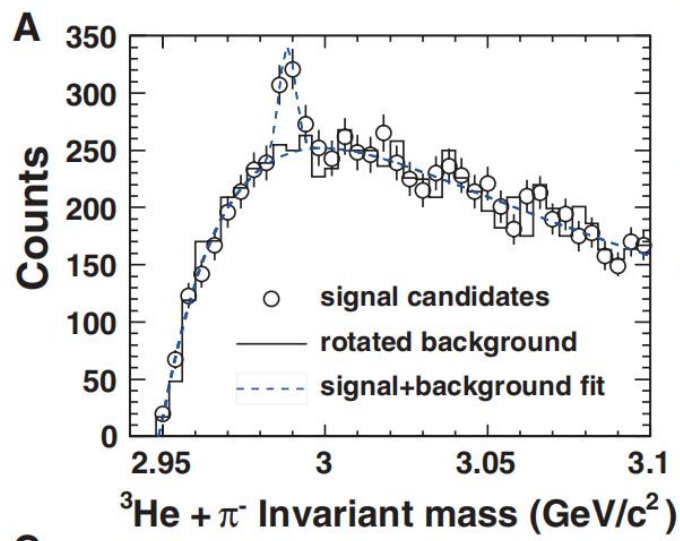
反轻核的发现 (现代高能重离子碰撞实验)



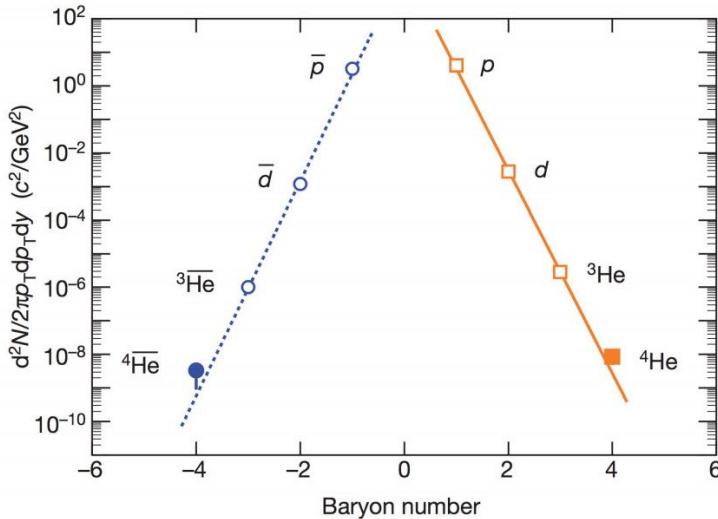
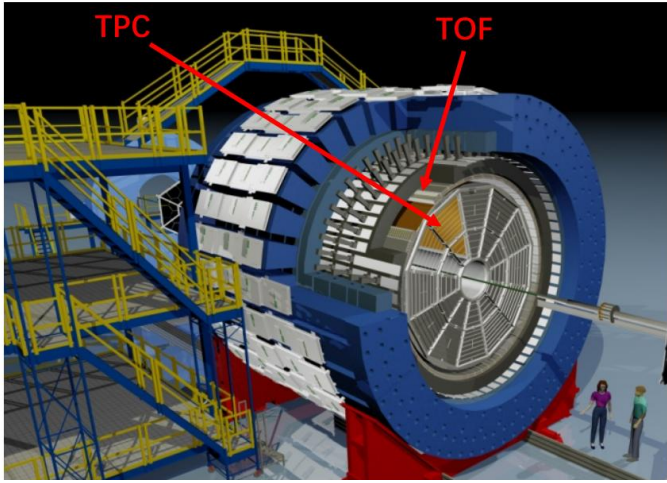
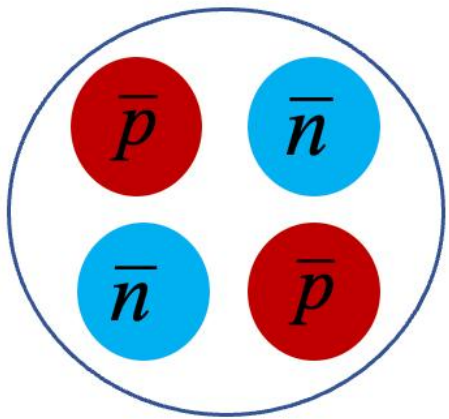
200M Au+Au@200GeV

First observation of the Antimatter Hypernucleus

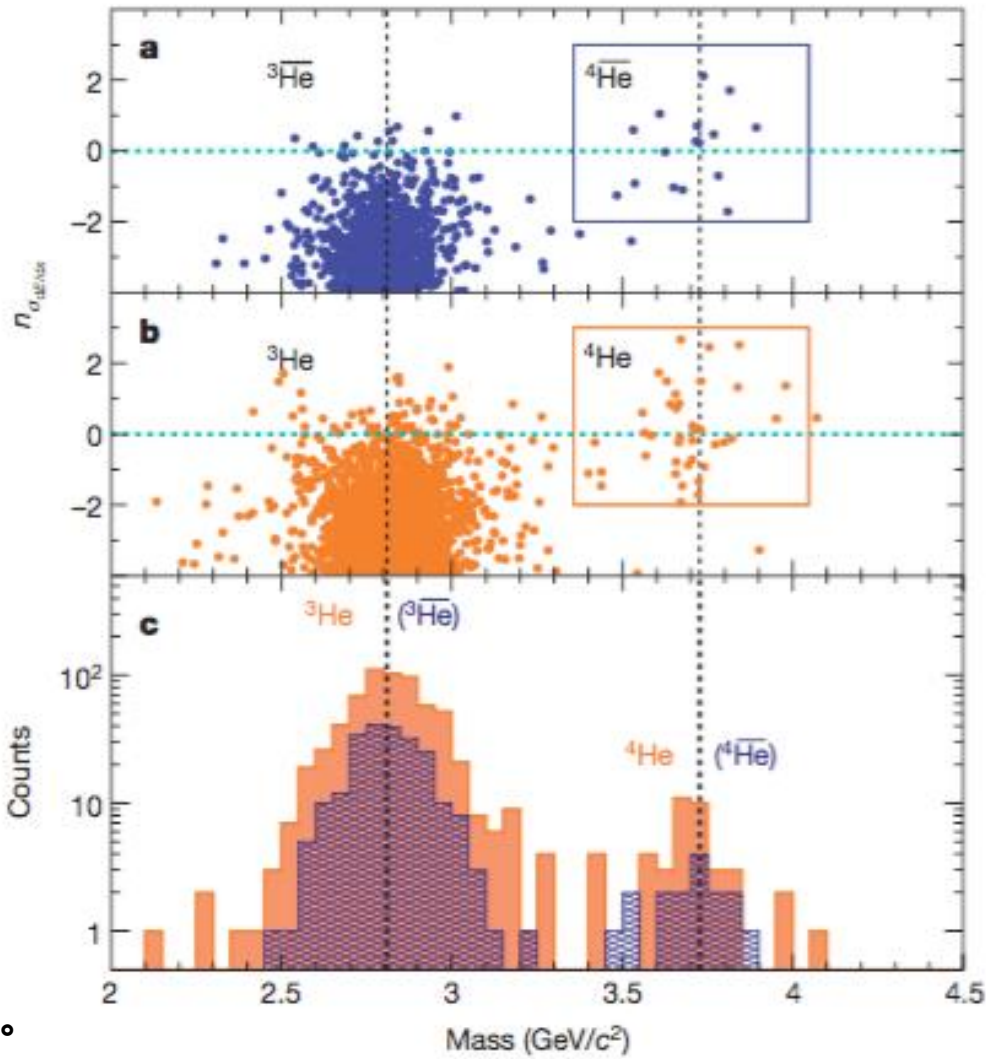
Science, 2010,328:58-62



反轻核的发现 (现代高能重离子碰撞实验)

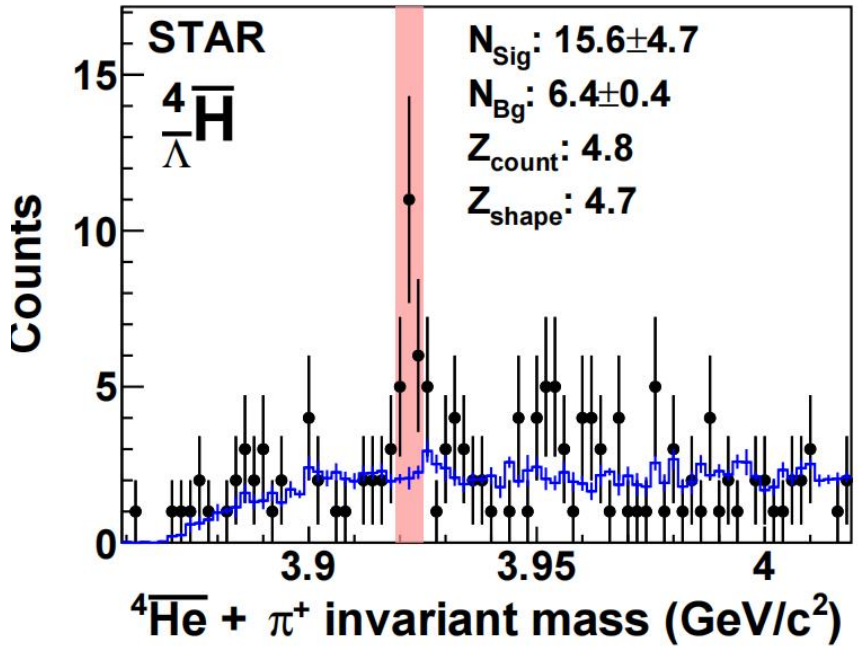
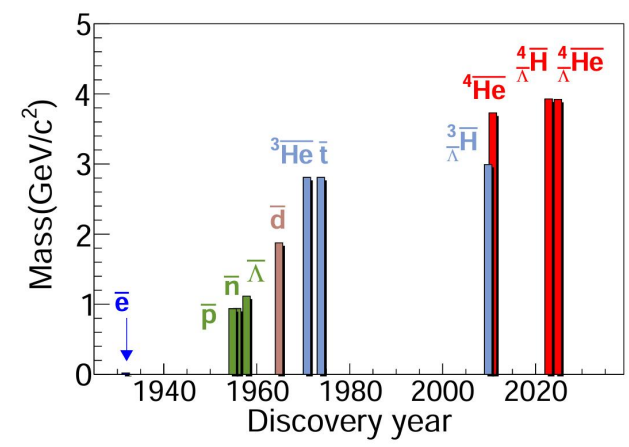
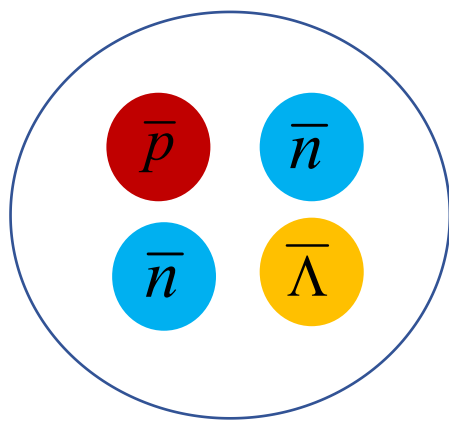
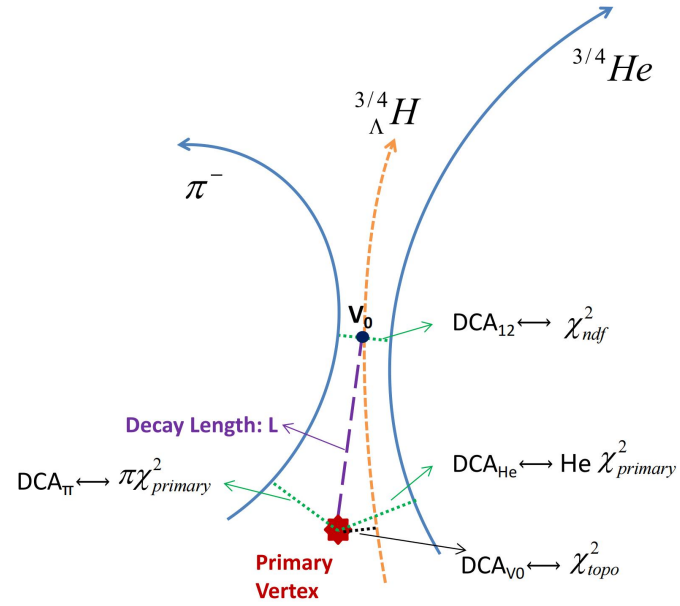


Nature, 2011, 473:353



Time of Flight (TOF)(2010年安装) 根据 M^2/Z^2 做粒子鉴别。
TOF 安装后立刻帮助我们发现了anti-He-4

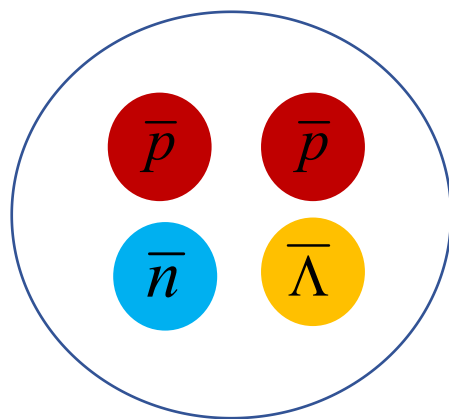
反轻核的发现（现代高能重离子碰撞实验）



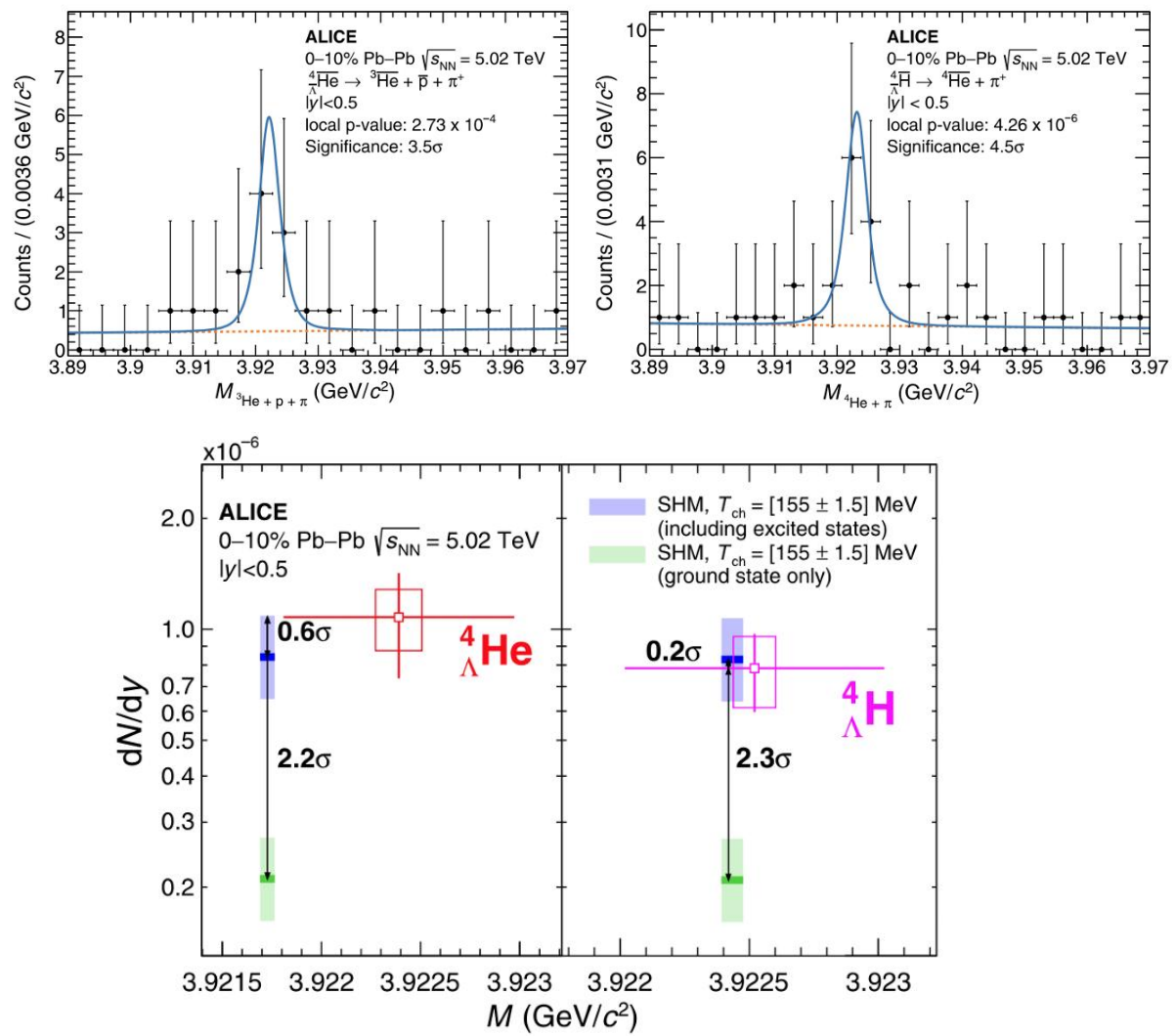
- Kalman Filter Arithmetic
- Isobar Data
ZrZr+RuRu(Isobar)@200GeV ~4.6B
- Combine with AuAu and UU system
- Excited state

反轻核的发现（现代高能重离子碰撞实验）

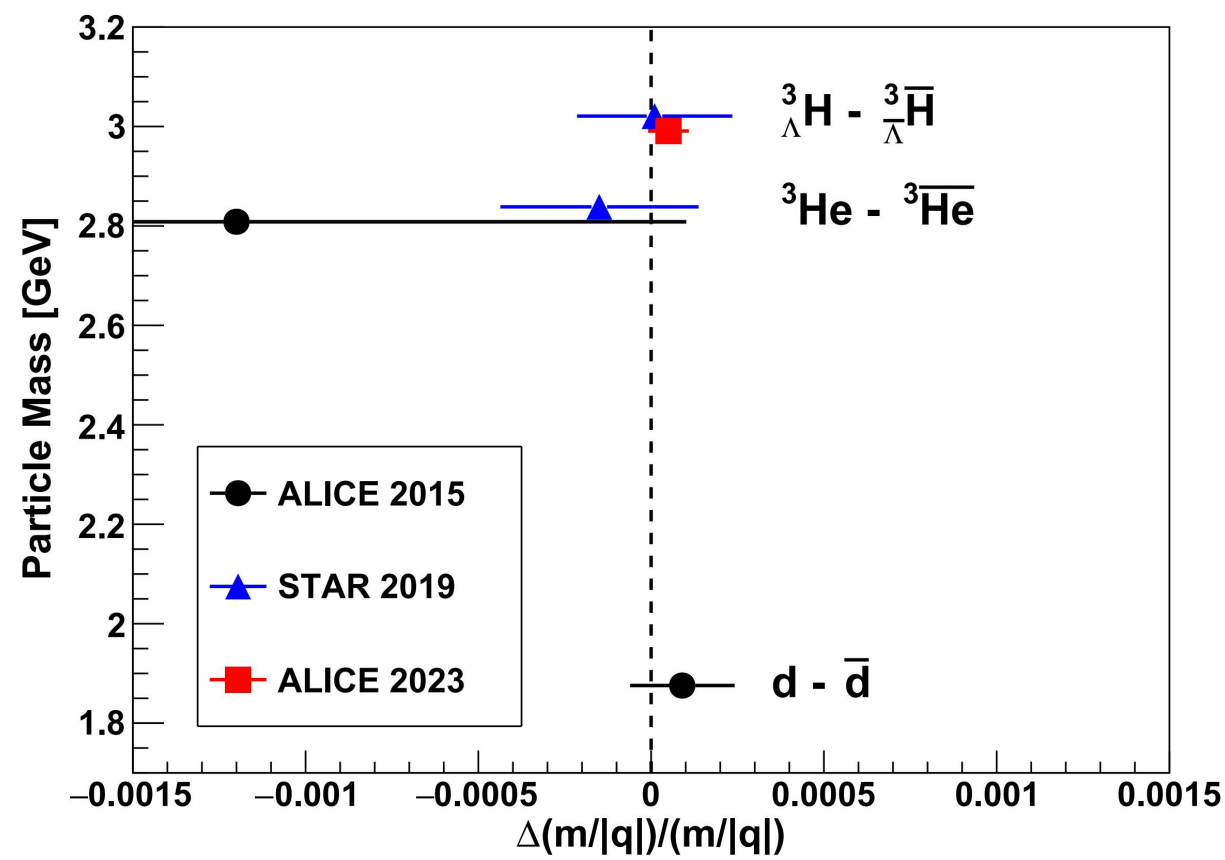
Phys. Rev. Lett. 2025, 134, 162301.



- Pb+Pb collisions at $\sqrt{s_{NN}}=5.02\text{TeV}$
- Excited state



检验CPT对称性



ALICE 和 STAR实验报告了在氦核-反氦核、 ${}^3_{\Lambda}\text{H}$ - ${}^3_{\Lambda}\bar{\text{H}}$ 之间，没有显著的质量（束缚能）差异。

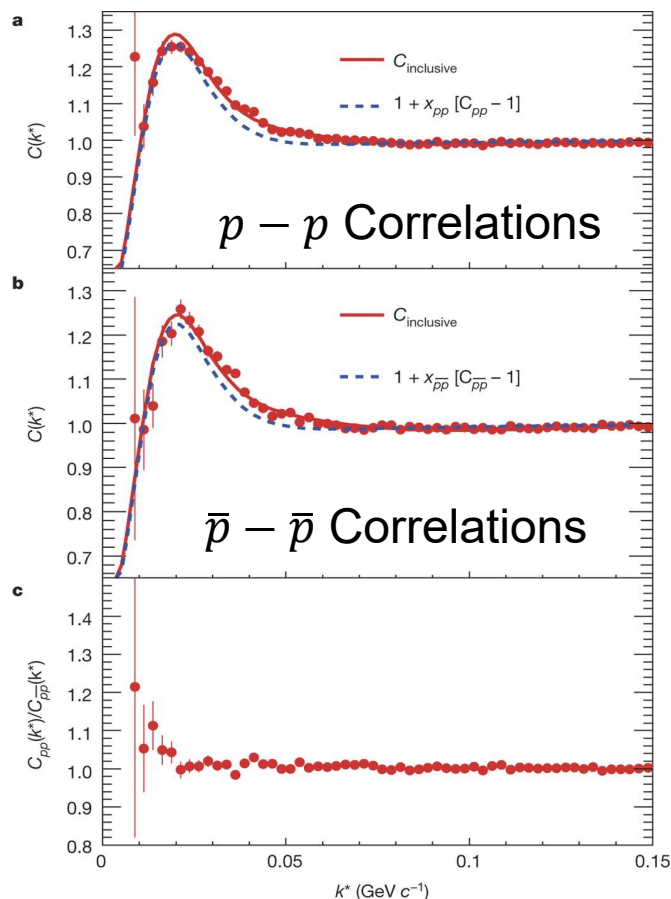
超核的寿命也可以用于检验CPT对称性。2023年，ALICE也发表了 ${}^3_{\Lambda}\text{H}$ 与 ${}^3_{\Lambda}\bar{\text{H}}$ 寿命差精确的测量结果。

$$\frac{\tau_{{}^3_{\Lambda}\text{H}} - \tau_{{}^3_{\Lambda}\bar{\text{H}}}}{\tau_{{}^3_{\Lambda}\text{H}}} = [3 \pm 7(\text{stat}) \pm 4(\text{syst})] \times 10^{-2}$$

在2015年，STAR也发表过反质子-反质子之间的关联函数，其与质子-质子的关联函数没有差别。

- *Nature Phys.* 11 (2015) 10, 811-814
- *Nature Phys.* VOL 16, April 2020, 409–412
- *PHYSICAL REVIEW LETTERS* 131, 102302 (2023)
- *Nature* volume 527, pages345–348 (2015)

检验CPT对称性



- *Nature Phys.* 11 (2015) 10, 811-814
- *Nature Phys.* VOL 16, April 2020, 409–412
- *PHYSICAL REVIEW LETTERS* 131, 102302 (2023)
- *Nature* volume 527, pages345–348 (2015)

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在2015年，STAR也发表过反质子-反质子之间的关联函数，其与质子-质子的关联函数没有差别。

探测器进步对反物质发现的作用

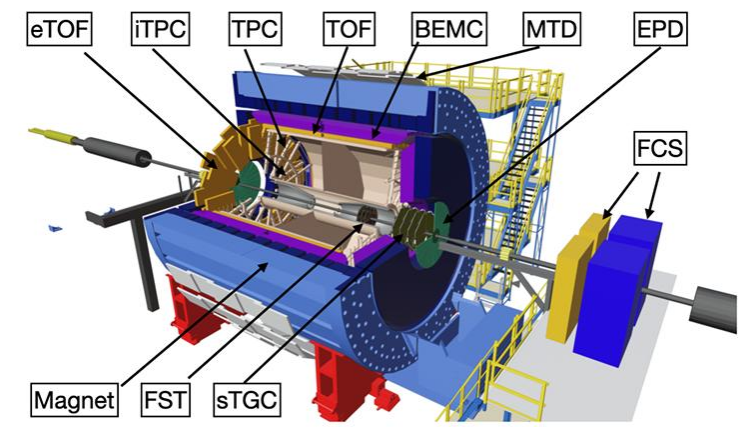
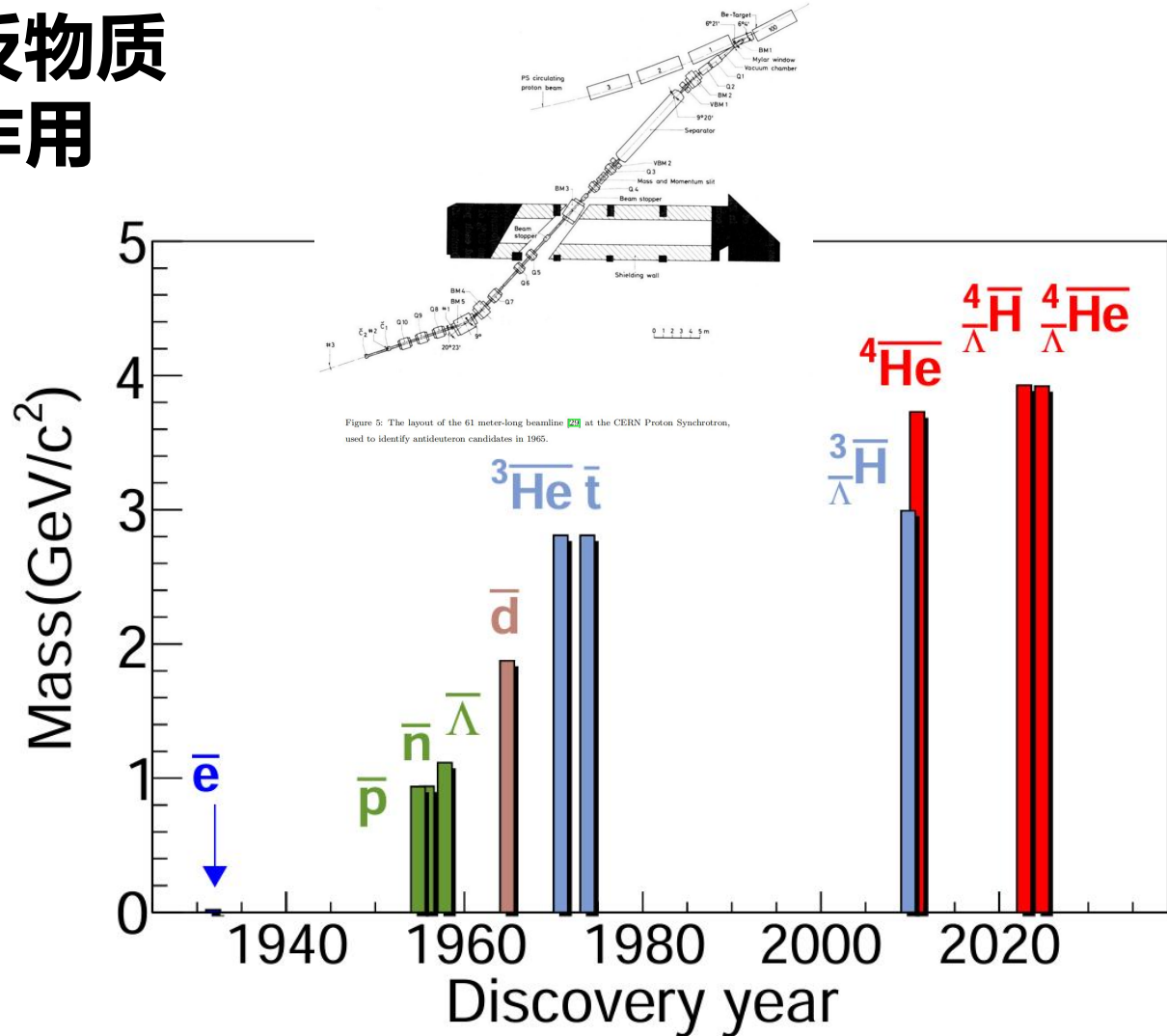
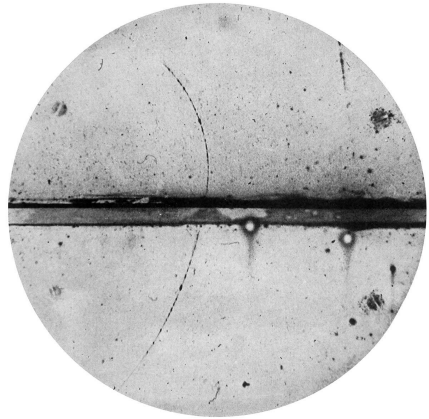


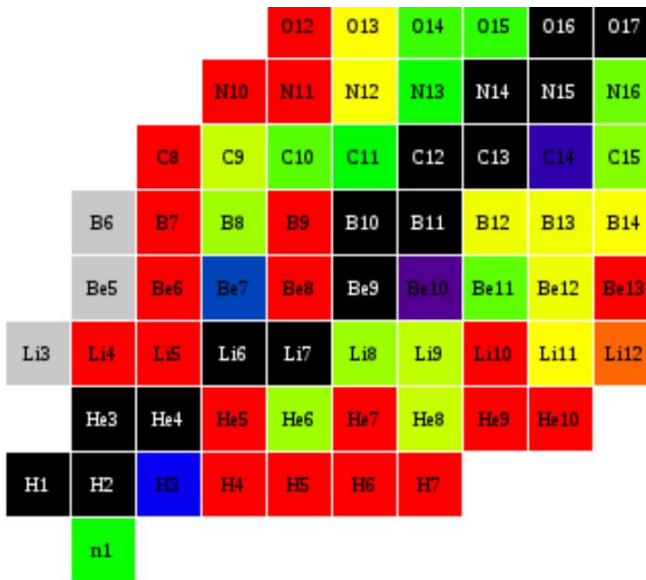
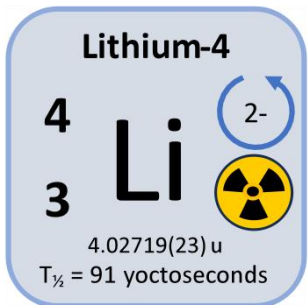
Figure 2. A schematic of the STAR detector.

宇宙线
气泡室、乳胶室

质子束流实验
有限的接受度的探
测器系统

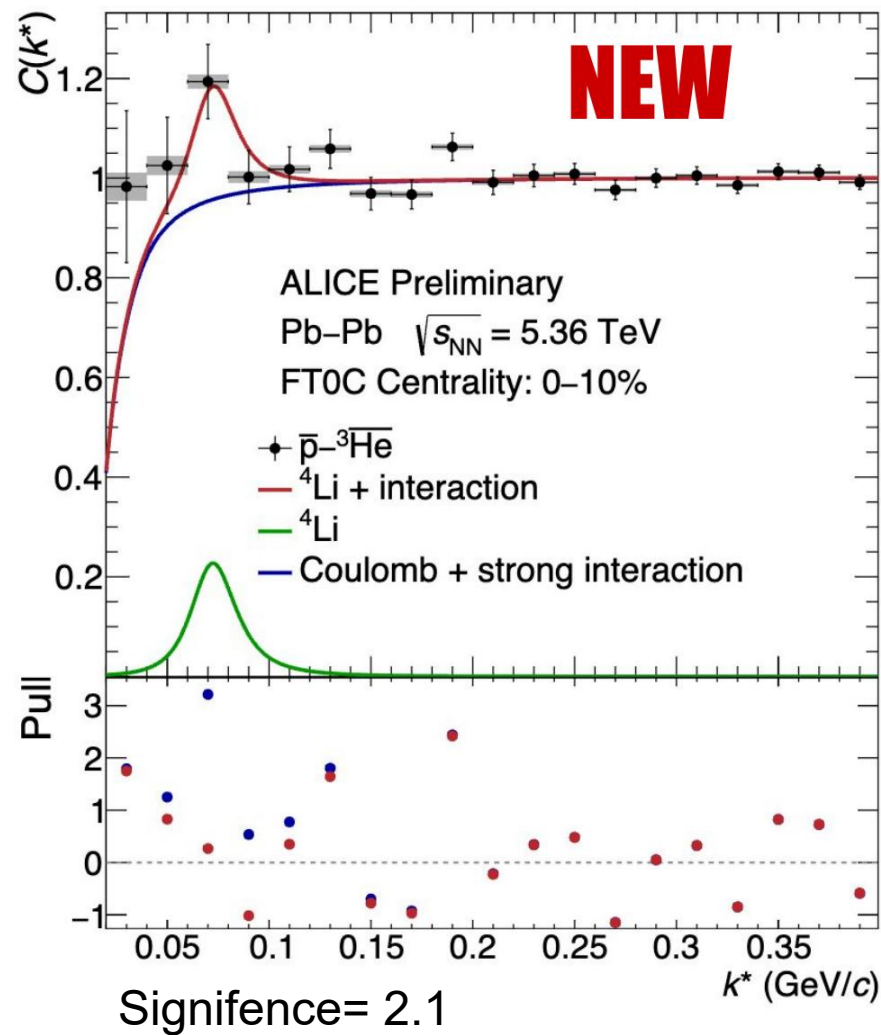
重离子碰撞实验
大型探测器谱仪

反物质核的最新进展



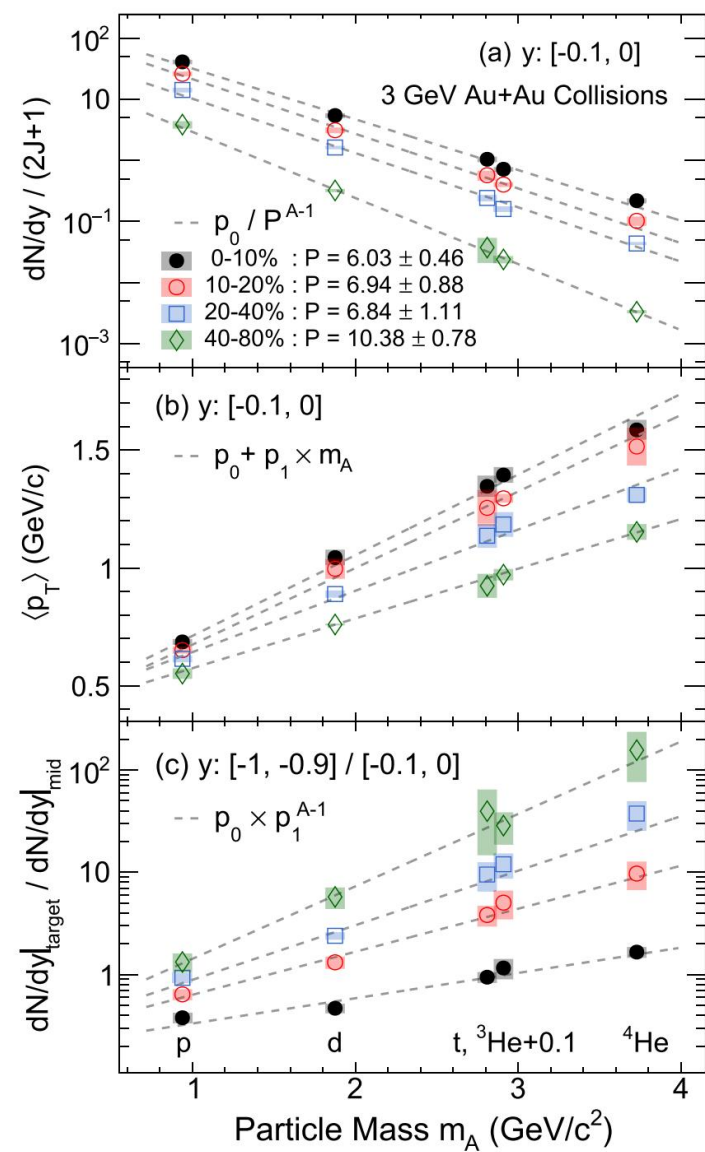
- Is the method for extracting resonant nuclear signal correct?
- Why is the yield of anti-Li-4 much lower than that of anti-He-4?

Giorgio Alberto Lucia
on behalf of the ALICE Collaboration in SQM2026

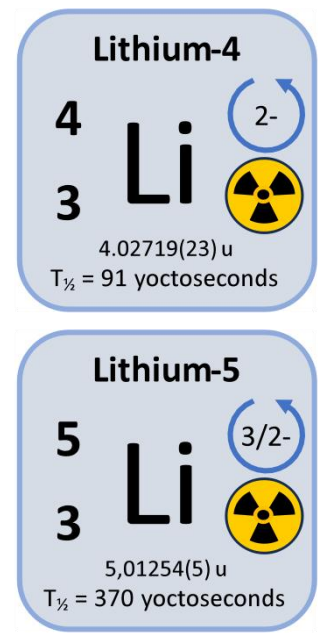
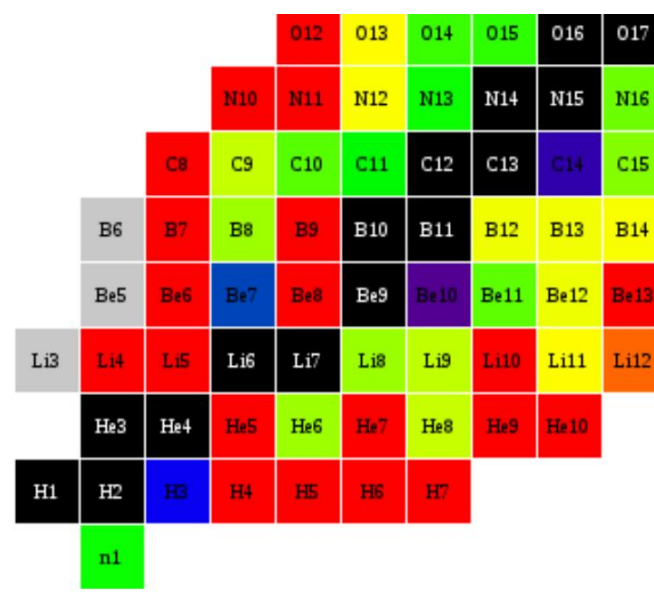


第二部分：高能重离子碰撞实验不稳定共振轻核的测量进展

Motivation



1. Present systematic studies of light nuclei production at $\sqrt{s_{NN}} = 3$ GeV, extending published results on stable light nuclei (*STAR Collaboration, Physical Review C 110, 054911 (2024)*).



Motivation

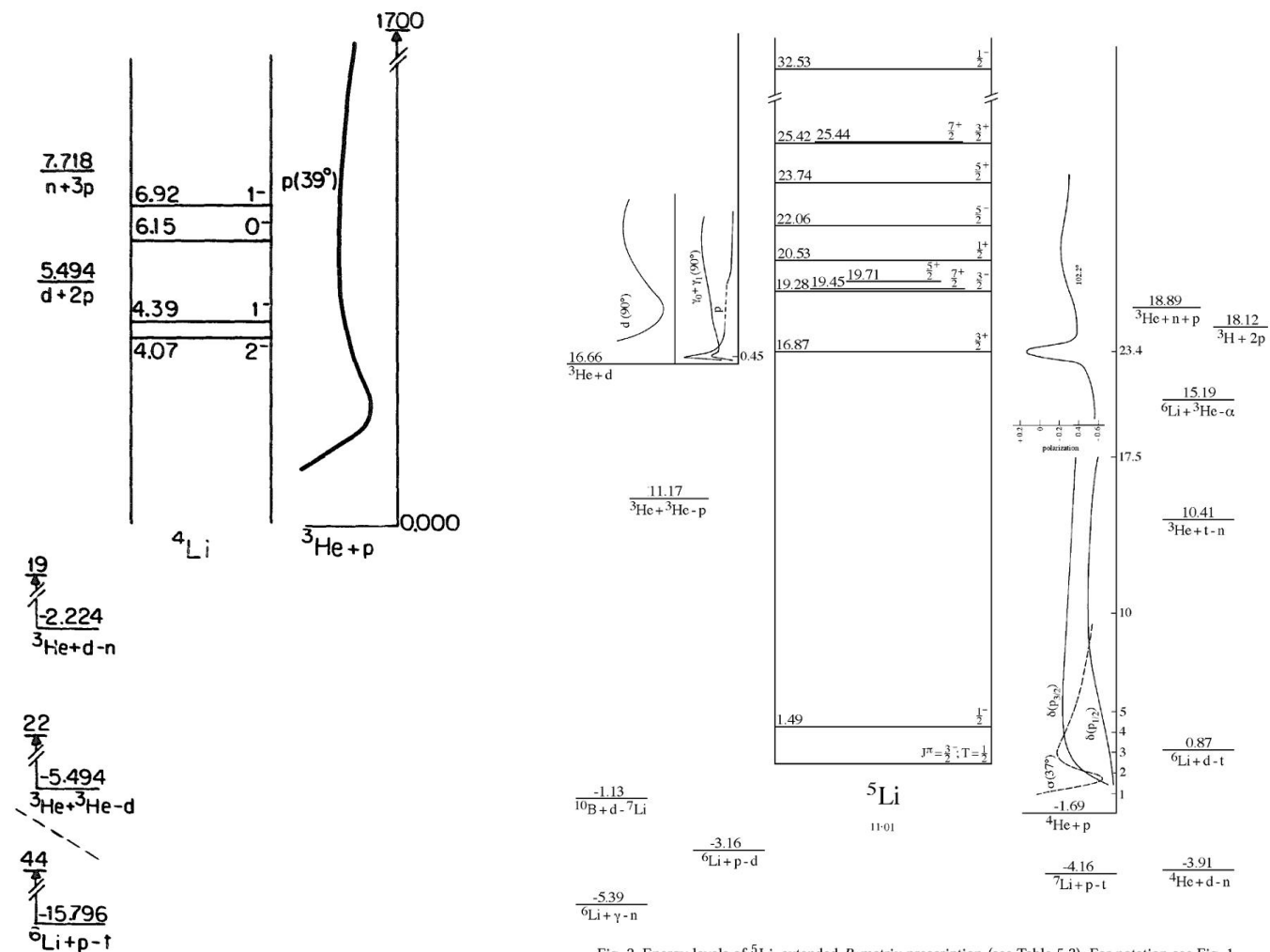


Fig. 2. Energy levels of ${}^5\text{Li}$, extended R -matrix prescription (see Table 5.3). For notation see Fig. 1.

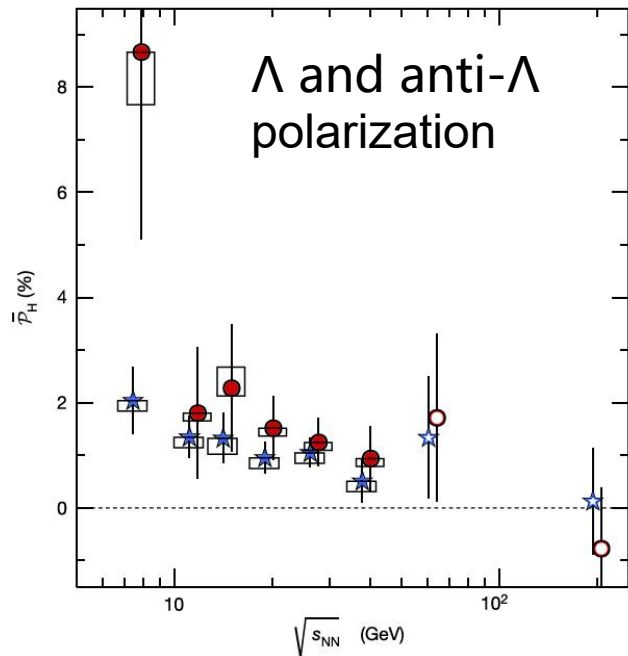
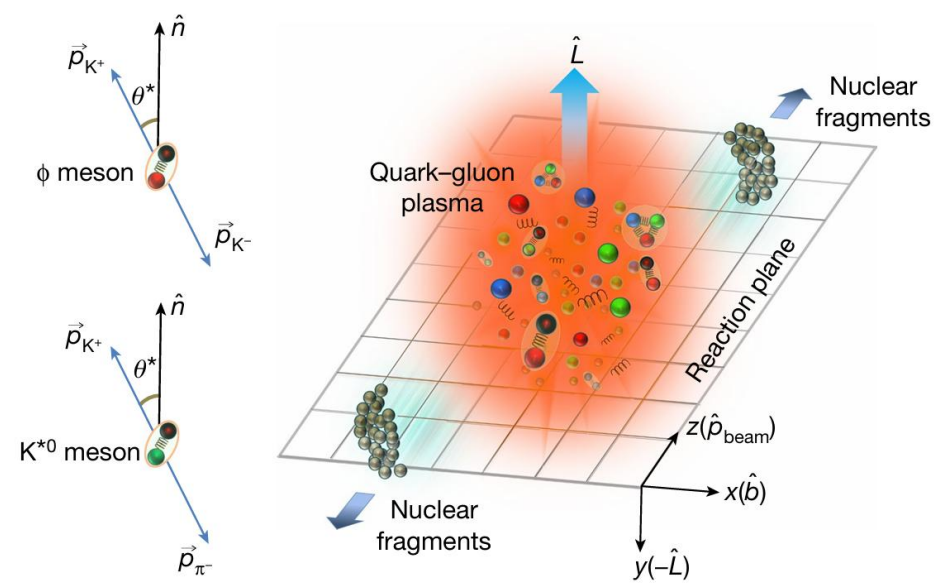
2. Thermal production v.s. coalescence v.s. other possible mechanisms.

To further understand the production mechanisms of light nuclei via resonance state point view.

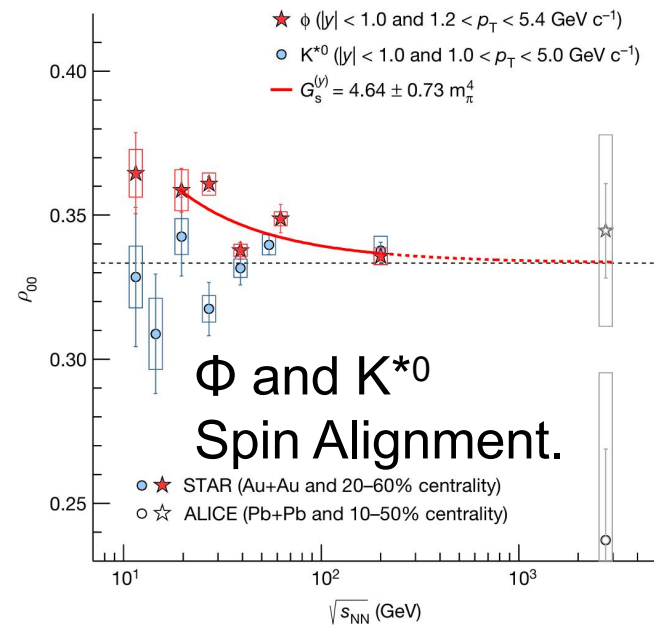
- The mass of the resonance state is higher than the sum of its components.
- Resonance states are mostly produced by elastic scattering.

Motivation

3. Unstable light nuclei will decay, which allows us to measure their polarization or Spin Alignment.
This analysis will be the basis of polarization measurement.



Nature volume 548, pages62–65 (2017)



Nature volume 614, pages244–248 (2023)

- magnetic field
- Spin-orbit angular momentum coupling
- QCD chirality symmetry
-



Spin Physics

Motivation

4. Unstable light nuclei will decay, which allows us to measure their polarization or Spin Alignment.
This analysis will be the basis of polarization measurement.

Global Spin Alignment of (Anti-) ^4Li in Non-Central Heavy-Ion Collisions

Yun-Peng Zheng,^{1,2} Dai-Neng Liu,^{1,2} Lie-Wen Chen,^{3,*} Jin-Hui Chen,^{1,2,†} Che Ming Ko,^{4,‡} Yu-Gang Ma,^{1,2,§} Kai-Jia Sun,^{1,2,¶} Jun Xu,^{5,**} and Bo Zhou^{1,2,††}

¹Key Laboratory of Nuclear Physics and Ion-beam Application (MOE),
Institute of Modern Physics, Fudan University, Shanghai 200433, China

²Shanghai Research Center for Theoretical Nuclear Physics,
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³State Key Laboratory of Dark Matter Physics, Key Laboratory for Particle Astrophysics and Cosmology (MOE),
and Shanghai Key Laboratory for Particle Physics and Cosmology,

School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China

⁴Cyclotron Institute and Department of Physics and Astronomy,
Texas A&M University, College Station, Texas 77843, USA

⁵School of Physics Science and Engineering, Tongji University, Shanghai 200092, China

(Dated: September 22, 2025)

Non-central heavy-ion collisions produce hot and dense nuclear matter with significant fluid vorticity, which can induce global polarizations or alignments of particles with non-zero spins along the direction of the total orbital angular momentum. This phenomenon has been observed for hyperons and vector mesons in experiments. In the present study, we demonstrate that polarized nucleons lead to global spin alignment of the unstable nucleus ^4Li , which can be measured through its strong decays via $^4\text{Li} \rightarrow ^3\text{He} + p$. Assuming that ^4Li is formed through the coalescence of polarized nucleons at kinetic freeze-out, we obtain the angular distribution of the daughter particle ^3He in the rest frame of the polarized ^4Li . Taking kinetically freeze-out nucleons from an isotropic and thermalized fireball of constant vorticity and including quantum corrections up to $\hbar^2$ in the coalescence calculation through the Moyal star product, we find that the angular distribution of ^3He has a $\cos(2\theta^*)$ dependence with θ^* being its angle with respect to the quantization axis of ^4Li . We also find that the ^3He angular distribution depends on both the vorticity and the polarization of kinetically freeze-out nucleons. Future measurements on the spin alignment of ^4Li in heavy-ion collisions thus offer a promising method to probe the spin dynamics, vortical structure, and spin-dependent equation-of-state of the nuclear matter produced in these collisions.

- How is the polarization of the nucleon measured?
- ^4Li Spin Alignment $\Rightarrow$ nucleon polarization

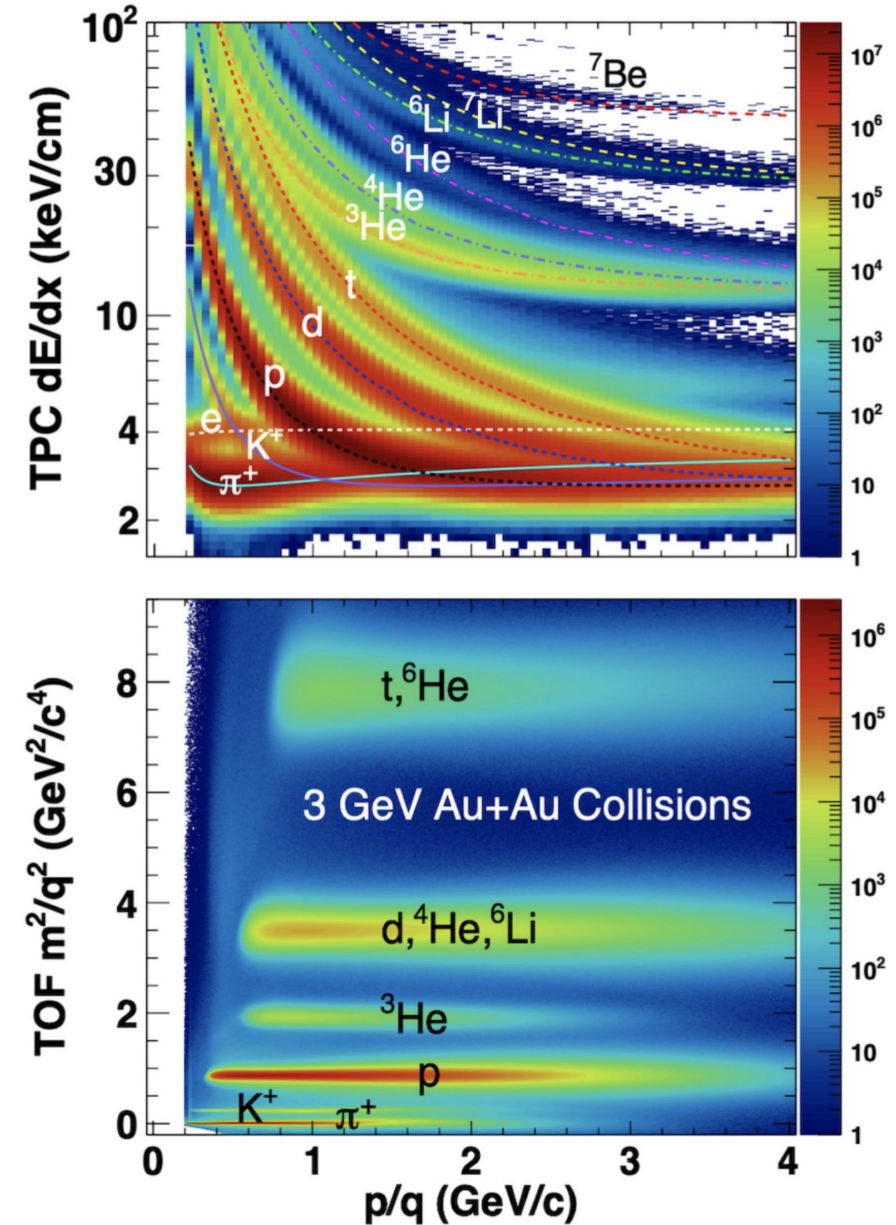
$$\frac{dN}{\sin \theta^* d\theta^*} = \frac{1}{2} \left[1 - \frac{2}{3} \mathcal{P}_N^2 (3 \cos^2 \theta^* - 1) \right].$$

But A very simple question:
How to obtain the number of ^4Li signals?
Before this research, it was still unclear.

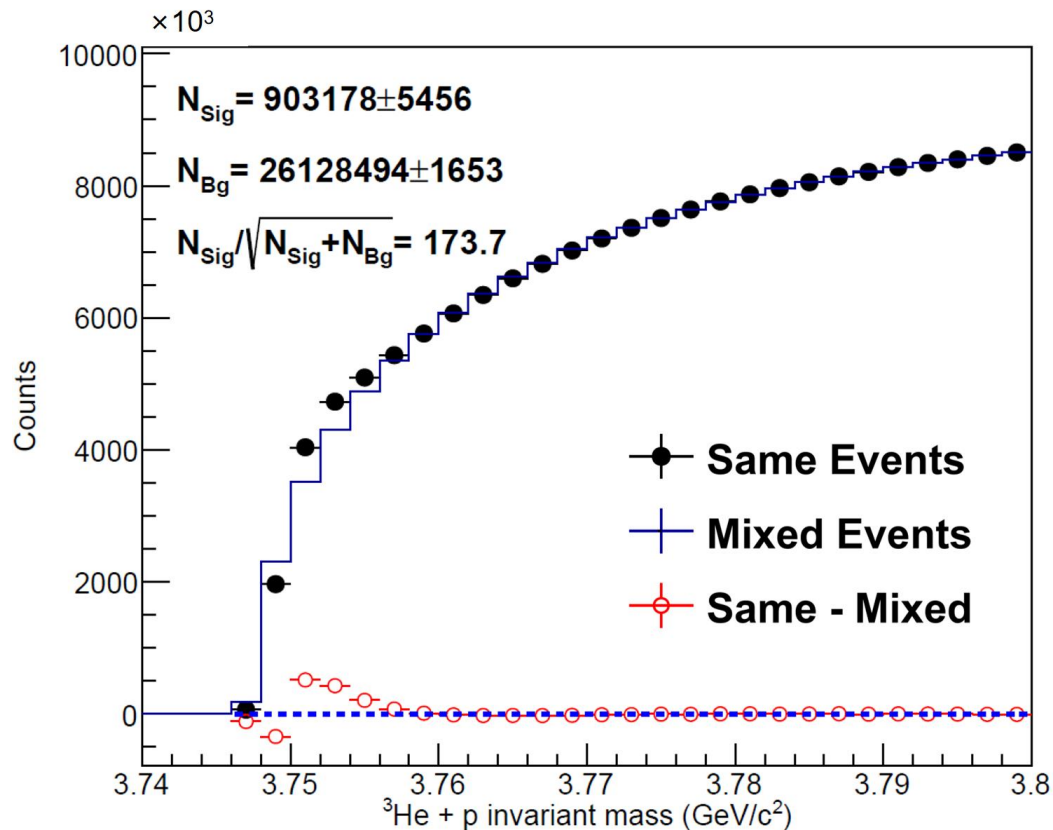
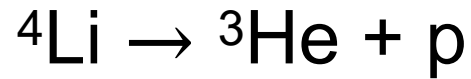
Particle Identification



- ${}^4\text{Li}$ and ${}^5\text{Li}$ Reconstruction channels:
 - ${}^4\text{Li} \rightarrow {}^3\text{He} + \text{p}$ (B.R. = 100%)
 - ${}^5\text{Li} \rightarrow {}^4\text{He} + \text{p}$ (B.R. = 100%)
- Good particle identification capability based on TPC (dE/dx) and TOF (m^2/q^2) for charged particles: p, ${}^3\text{He}$ and ${}^4\text{He}$.



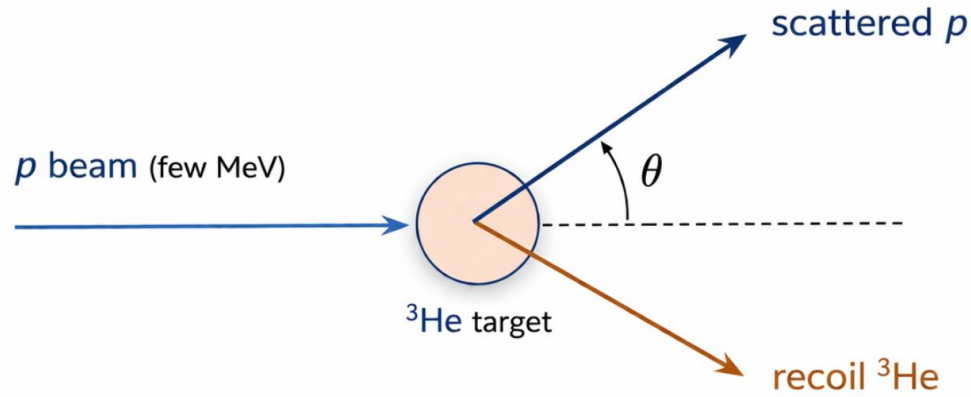
Background Handling



- The signal region is close to the threshold.
- Mixed-event (or rotation) background can lead to negative signal counts.
- The p-³He correlation is mixed with ⁴Li signal region.
- **The correlated background needs to be accounted.**

What is ^4Li ? How was ^4Li first identified?

T. A. Tombrello, Physical Review Volume 138, Number 1B



Elastic scattering: $p + ^3\text{He} \rightarrow p + ^3\text{He}$

1. Measure the scattering cross-section, spin-related coefficients or polarization angle distribution. (Few MeV beam energy)

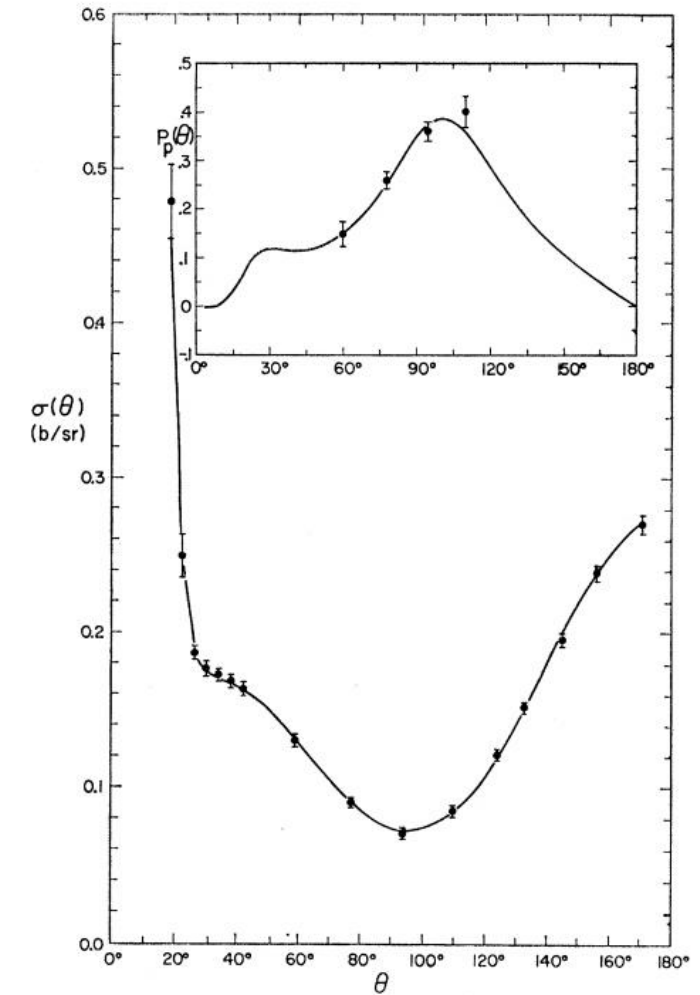
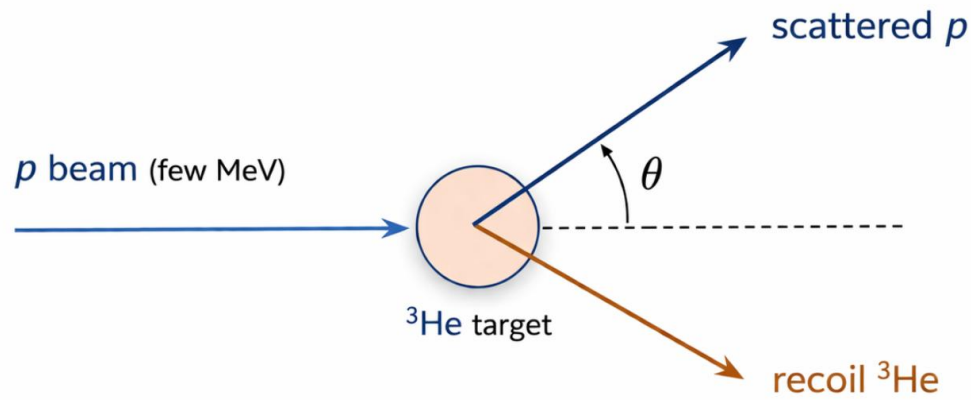


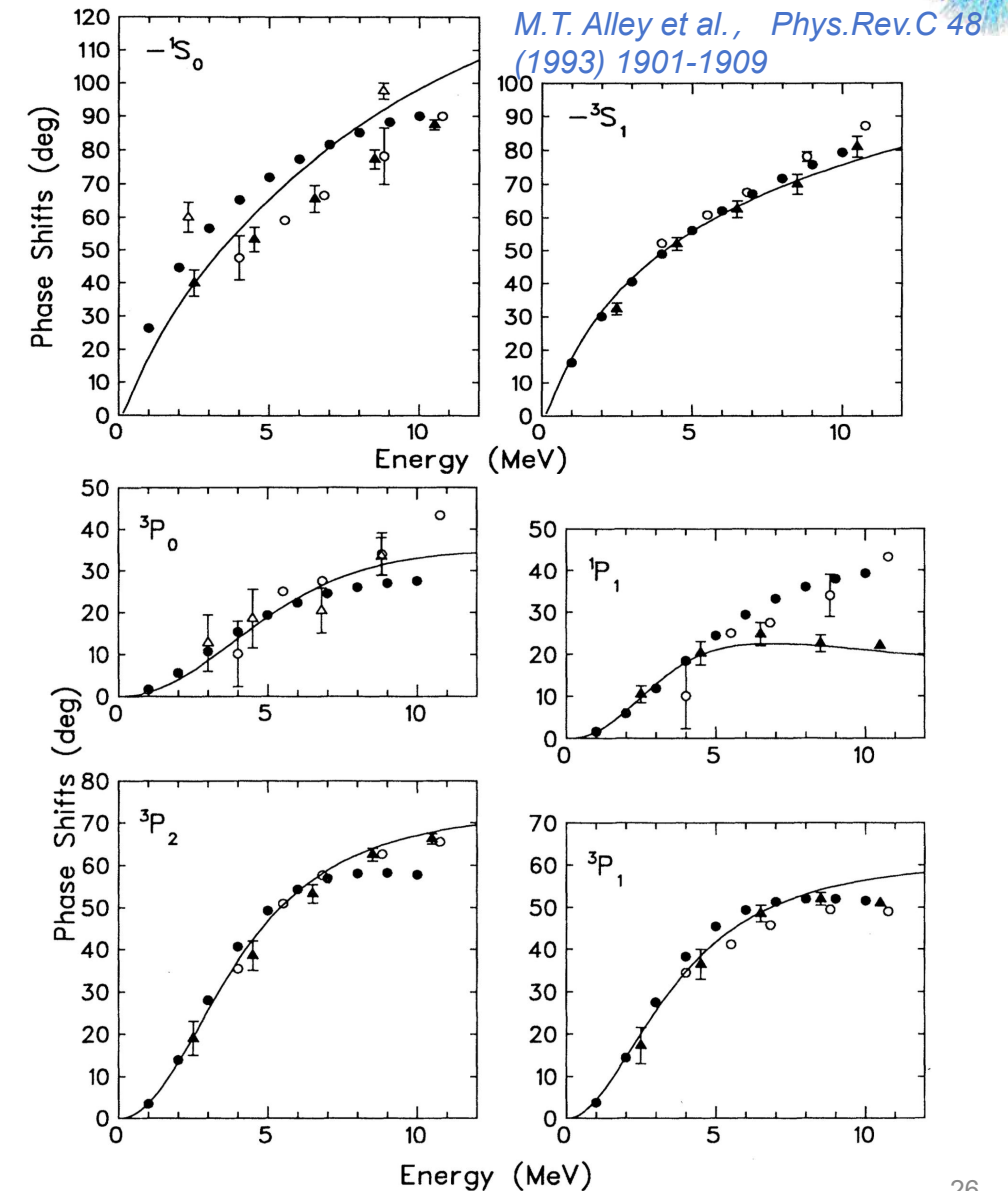
FIG. 5. The scattering and polarization data of Ref. 7 together with the fit corresponding to solution I at a proton energy of 4.00 MeV.

What is ^4Li ? How was ^4Li first identified?

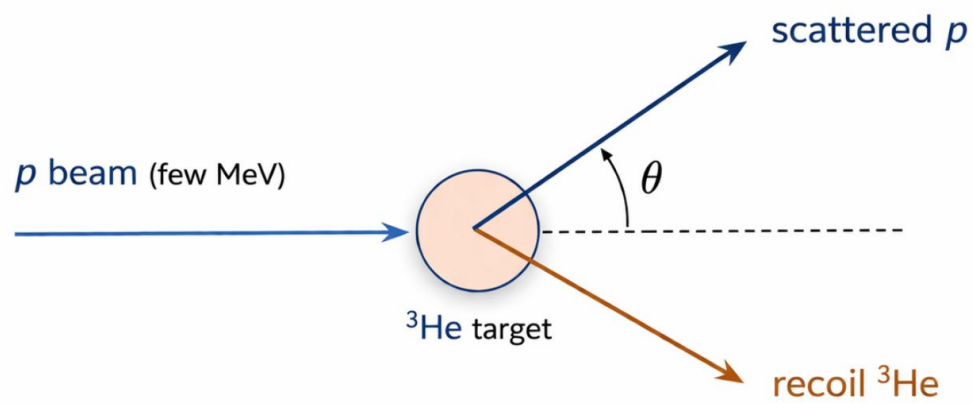


Elastic scattering: $p + {}^3\text{He} \rightarrow p + {}^3\text{He}$

1. Measure the scattering cross-section, spin-related coefficients or polarization angle distribution. (Few MeV beam energy)
2. Phase-Shift analysis for each partial wave.

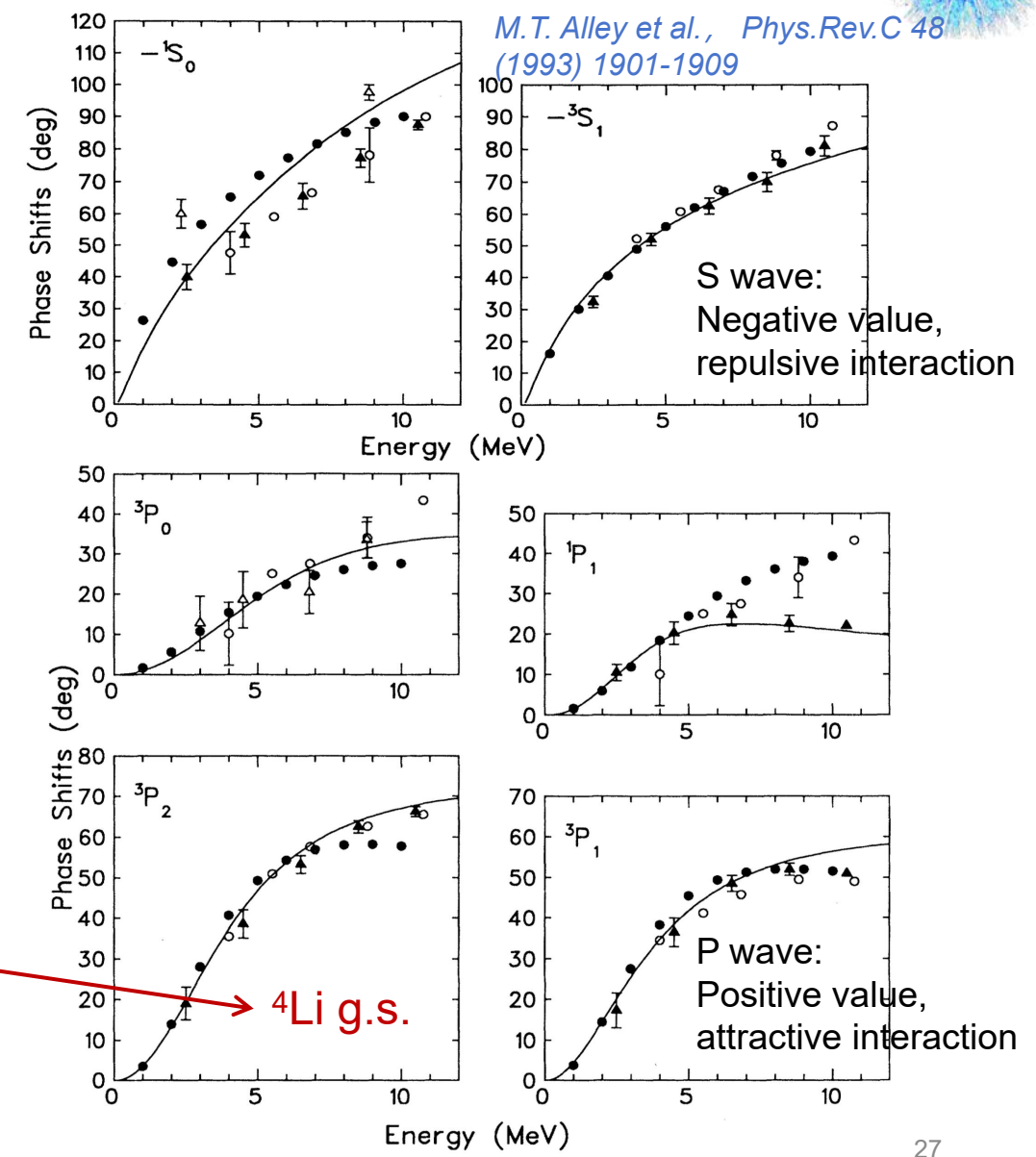


What is ${}^4\text{Li}$? How was ${}^4\text{Li}$ first identified?



Elastic scattering: $p + {}^3\text{He} \rightarrow p + {}^3\text{He}$

1. Measure the scattering cross-section, spin-related coefficients or polarization angle distribution. (Few MeV beam energy)
2. Phase-Shift analysis for each partial wave.
3. The phase shift of a specific partial wave shows a rapid change with energy, suggesting the existence of a resonance state here.



Signal Extraction Technique

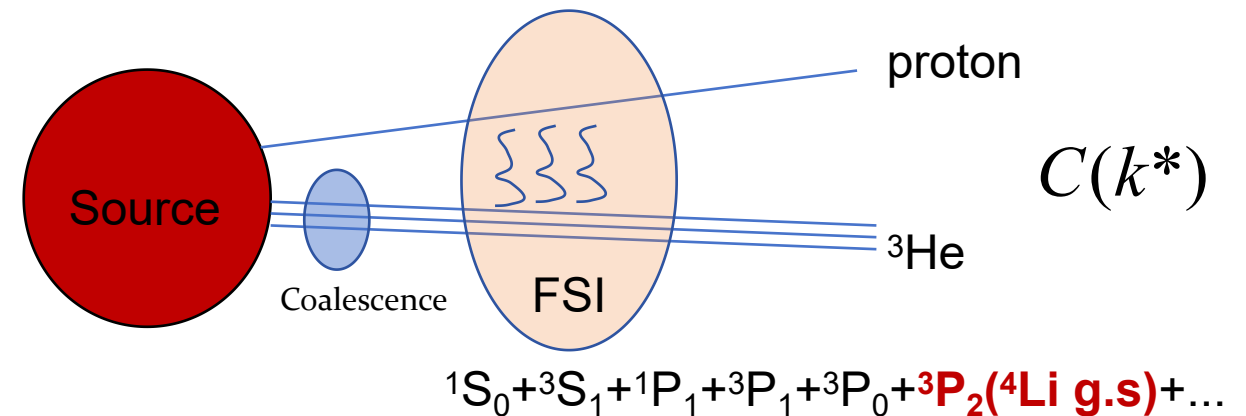


1. The final-state interaction (FSI) of nuclear in HIC, corresponds to the low-energy nuclear scattering!
2. 3P_2 wave of p - ^3He is ^4Li . Other partial-waves (3P_1 , 3P_0 , 1P_1 , 1S_0 , 3S_1 ...) also contribute in the signal area.
3. Correlation function $C(k^*)$ can be used to describe this FSI.

Definition of the correlation function $C(k^*)$

$$C(k^*) = \frac{P(\vec{p}_1, \vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)} = \underbrace{\frac{N_{\text{foreground}}(k^*)}{N_{\text{background}}(k^*)}}_{\text{experimental}}$$

- P: The probability of observing particles with given momenta.
- k^* : Daughter particle momentum in rest frame of particle pair.



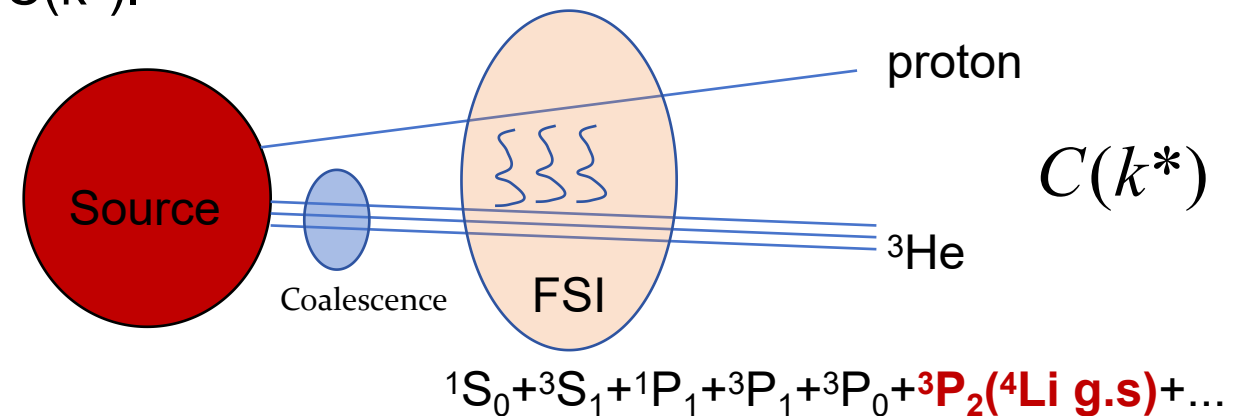
Signal Extraction Technique



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3. Correlation function $C(k^*)$ can be used to describe this FSI.
4. Lednicky-Lyuboshitz(LL) model is used to fit $C(k^*)$.

LL model :

- Wave function: $\psi(\vec{k}^*, \vec{r}) = \psi_{\text{ingoing}} + f \cdot \psi_{\text{outgoing}}$
- Source function: $S(\vec{r})$
- Scattering amplitude: f
- Koonin-Pratt equation: $C(\vec{k}^*) = \int d^3r S(\vec{r}) |\psi(\vec{k}^*, \vec{r})|^2$



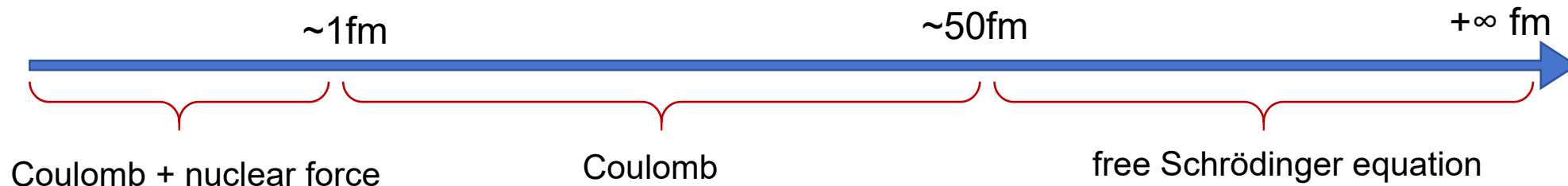


Signal Extraction Technique

Three assumptions of LL model:

1. Asymptotic wave function: Confluent Hypergeometric function+ f^* Coulomb wave function
(The solution of the Schrödinger equation under the Coulomb potential)

$$\psi(\vec{r}^*, \vec{k}^*) = \sqrt{A_c(\eta)} \left[\underbrace{e^{i\vec{k}^* \cdot \vec{r}^*} F(-i\eta, 1, ik^* r^* - i\vec{k}^* \cdot \vec{r}^*)}_{\text{ingoing}} + f_{NC} \underbrace{\frac{G_l(\rho, \eta)}{r^*}}_{\text{outgoing}} \right]$$



2. Gaussian Source.

$$S(\vec{r}) = \frac{1}{(4\pi R_g^2)^{\frac{3}{2}}} e^{-\frac{\vec{r}^2}{4R_g^2}}$$

R_g : The radius of the Gaussian source

Signal Extraction Technique

Three assumptions of LL model:

3. Partial-wave scattering amplitude (f):

Yu.V. Orlov, Nuclear Physics A 1004(2020) 122060

$$\tilde{f}_l^{NC}(k) = \frac{1}{C_l^2 k (\cot \delta_l - i)} \xrightarrow[\text{Taylor expansion}]{l=0, \text{ even-order}} \tilde{f}_0^{NC} = \left[\frac{1}{f_0} + \frac{1}{2} d_0 k^2 - 2k\eta H(\eta) - ikC_0^2(\eta) \right]^{-1}$$

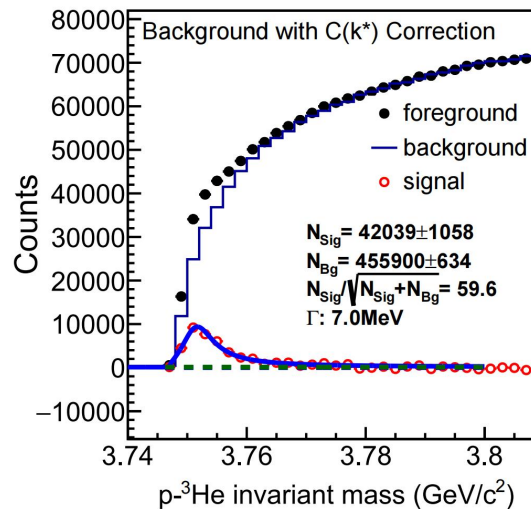
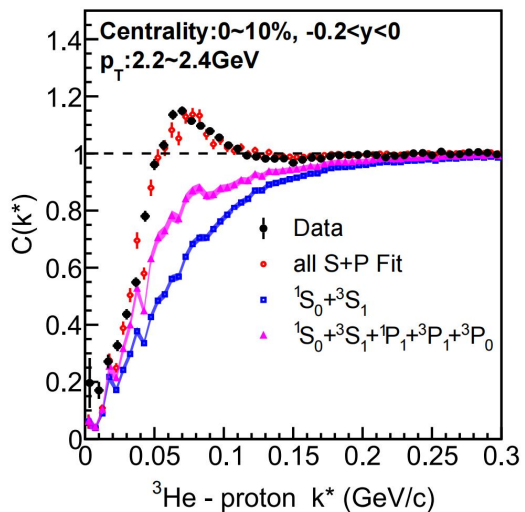
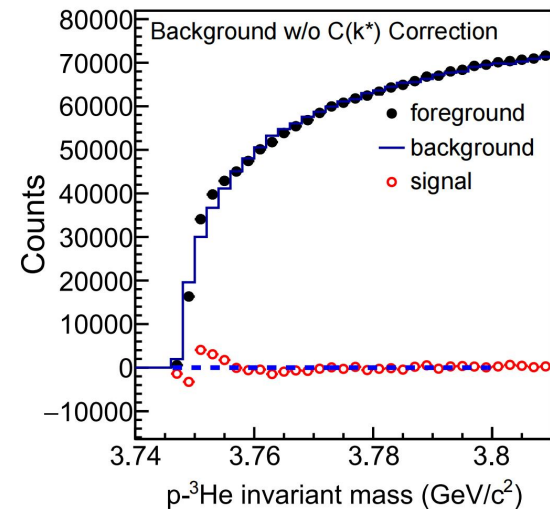
For any partial wave phase-shift data Only for S wave

$$\text{p-}^3\text{He: } C = n * \left(\frac{1}{4} C(^1S_0) + \frac{3}{4} C(^3S_1) \right) + (1-n) * \left(\frac{3}{12} C(^1P_1) + \frac{1}{12} C(^3P_0) + \frac{3}{12} C(^3P_1) + \frac{5}{12} C(^3P_2) \right)$$

$$\text{p-}^4\text{He: } C = n * C(S) + (1-n) * \left(\frac{1}{3} C(P_{1/2}) + \frac{2}{3} C(P_{3/2}) \right)$$

- n is fraction of the S wave, Gauss Source size R_g , both are determined by fitting the experimental data.
- Spin degeneracy factor $\frac{(2S+1)}{(2s_1+1)(2s_2+1)} \cdot \frac{(2J+1)}{(2L+1)(2S+1)}$

Signal Extraction Technique

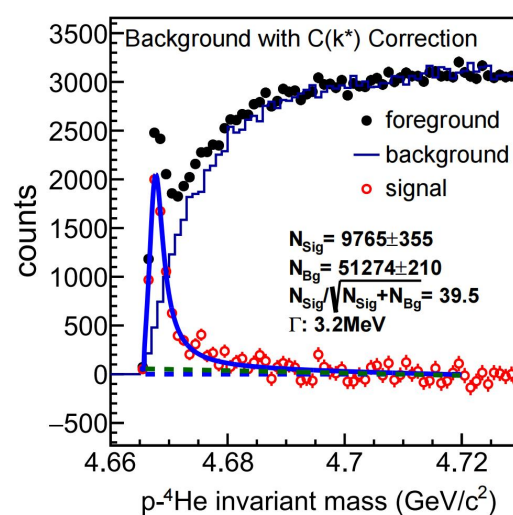
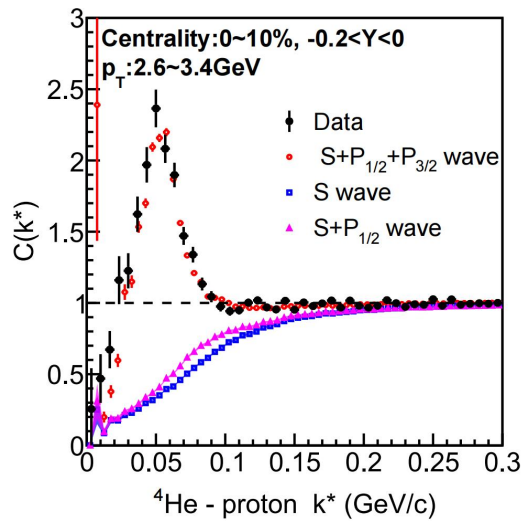
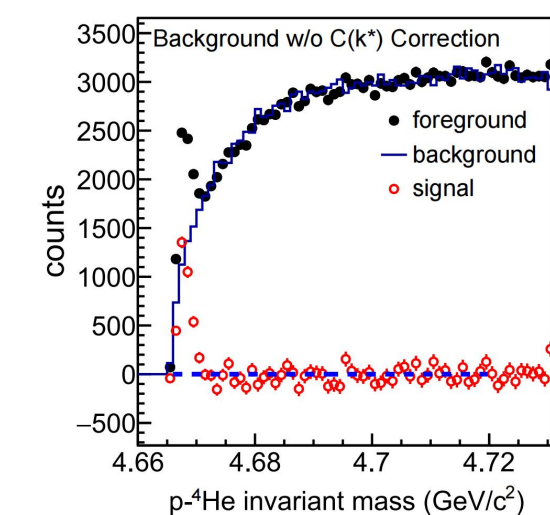


$$d^{\text{sill}}(E) = \frac{2E}{\pi} \frac{\sqrt{E^2 - E_{th}^2} \tilde{\Gamma}}{(E^2 - M^2)^2 + (E^2 - E_{th}^2) \tilde{\Gamma}^2} \theta(E - E_{th})$$

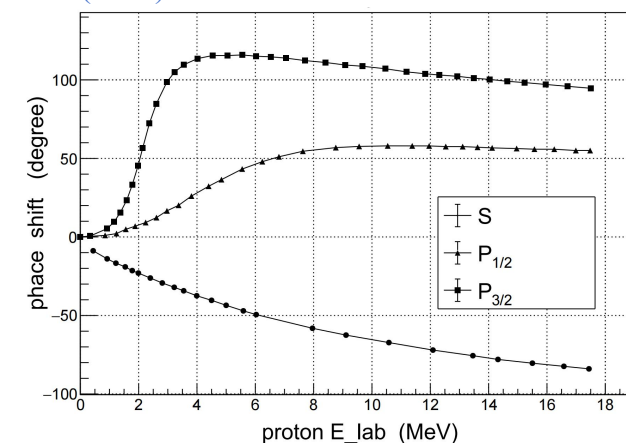
$$\tilde{\Gamma} = \frac{\Gamma M}{\sqrt{M^2 - E_{th}^2}}$$

- The blue line shows the fit using the Sill function

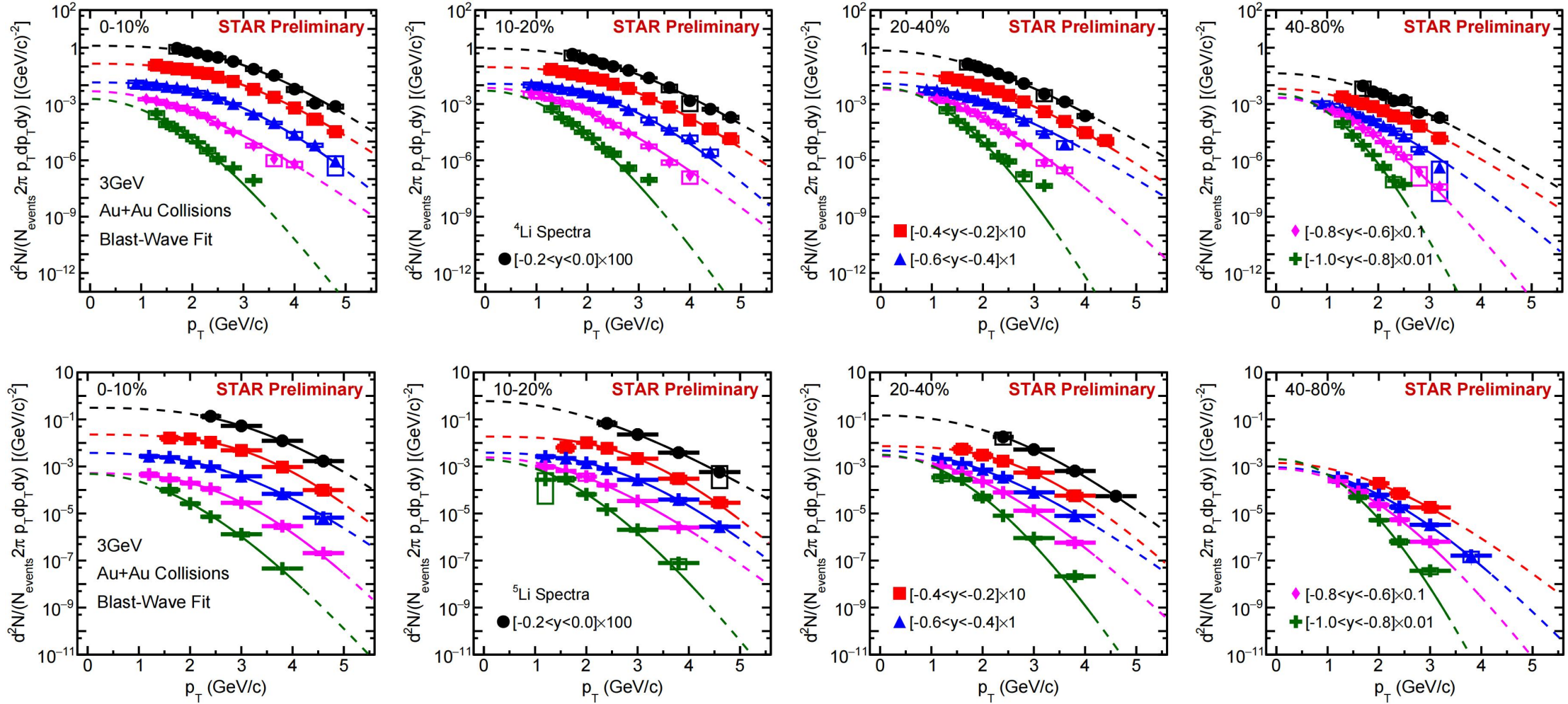
Francesco Giacosa et al., Eur. Phys. J. A (2020) 56:193



P. Schwandt et al., Nuclear Physics A163 (1971) 432-448



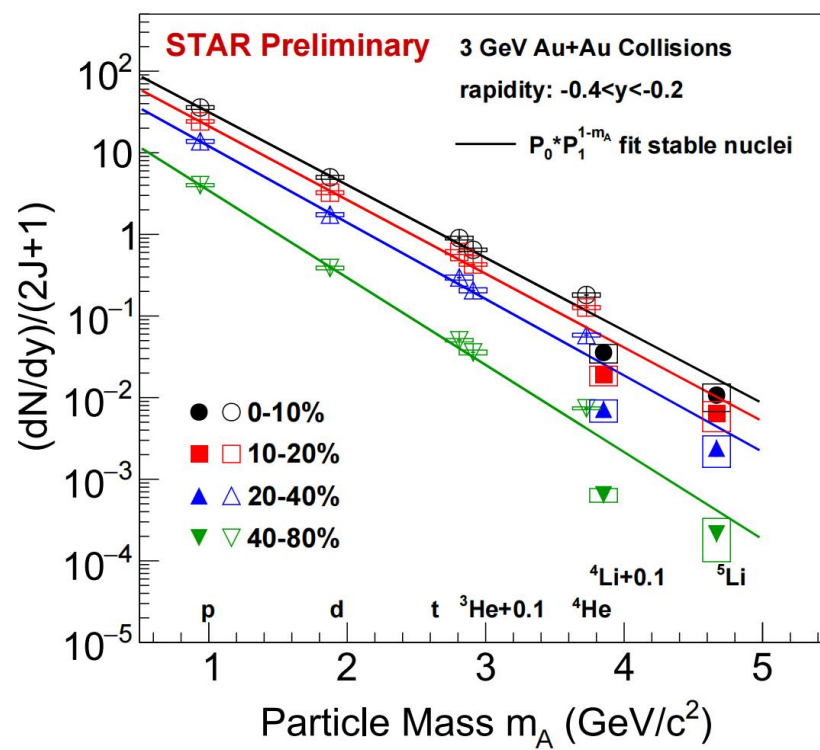
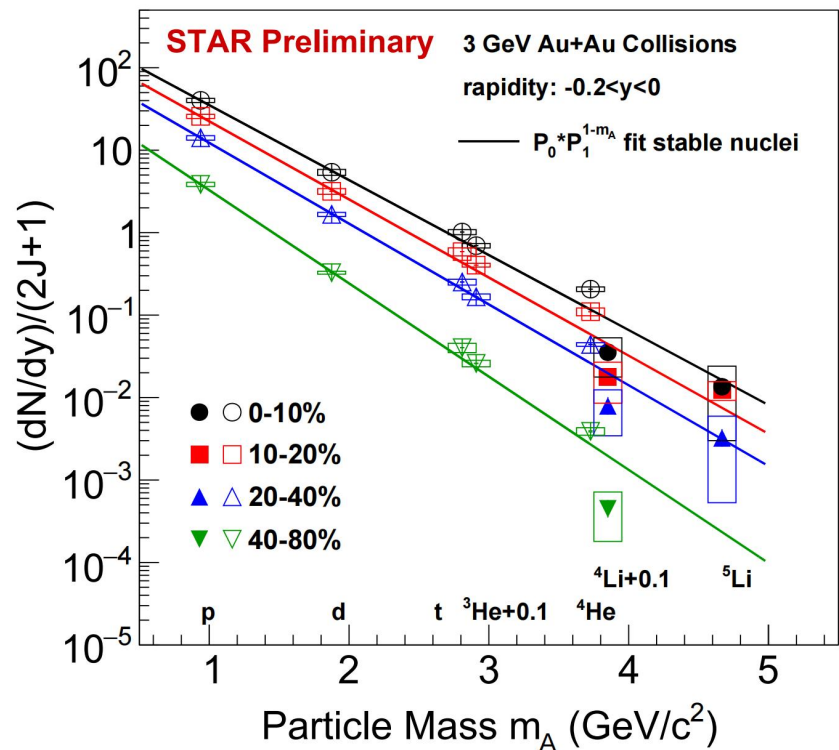
p_T Spectra



$$\frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh \rho}{T}\right) K_1\left(\frac{m_T \cosh \rho}{T}\right)$$

- Efficiencies are obtained using Monte Carlo simulations embedded to data.

dN/dy Yield and mean p_T



- The baseline was obtained by fitting the stable light nucleus yields with an exponential function.
- The yield of ^4Li is significantly lower than the baseline in midrapidity.

stable light nuclei data: STAR Collaboration, PHYSICAL REVIEW C 110, 054911 (2024)

- Production mechanism of unstable light nuclei: **it is influenced not only by the mass number A , but also by the partial-wave scattering cross sections of its constituents.**

$$\sigma_l(E) = \frac{4\pi(2l+1)}{k^2} \sin^2(\delta_l(E))$$

$$p\text{-}^3\text{He} \quad \sigma(^3\text{P}_2) < p\text{-}^4\text{He} \quad \sigma(\text{P}_{3/2})$$



1. A review of antimatter nuclei research in experiment field.
1. First measurement of unstable light nuclei (${}^4\text{Li}$ and ${}^5\text{Li}$) yield in Au+Au at $\sqrt{s_{NN}} = 3$ GeV with STAR.
2. A new method to extract near-threshold resonance signals. Partial wave method+phase-shift data + Lednicky–Lyuboshitz model.
3. ${}^4\text{Li}$ yield (over $2J+1$) is significantly lower than that of ${}^4\text{He}$, which implies that the production mechanisms may be different.



Thanks very much for your
attention!