

重离子碰撞中 反物质/超核物质的实验研究

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复旦大学

2021年7月

- 简介：对称性和对称破缺
- 寻找对称破缺新实验及新结果
- ✓ 反物质研究进展
- 反超氦核实验新结果和中子星状态方程的联系
- 主要参考文献： STAR Col. *Science* **328** (2010) 58; *Nature* **473** (2011) 355; *Nature* **527** (2015) 345; *PRL* **114** (2015) 022301; *PRC* **97** (2018) 054909; *PLB* **790** (2019) 490; *Nature Phys.* **16** (2020) 409

- 杨振宁教授：“二十世纪物理学的主旋律是：
量子化、对称和相位因子”

《Selected Papers of Chen Ning Yang II With Commentaries》

- 李政道教授：“二十一世纪物理学的挑战是：
夸克禁闭、对称和对称破缺”

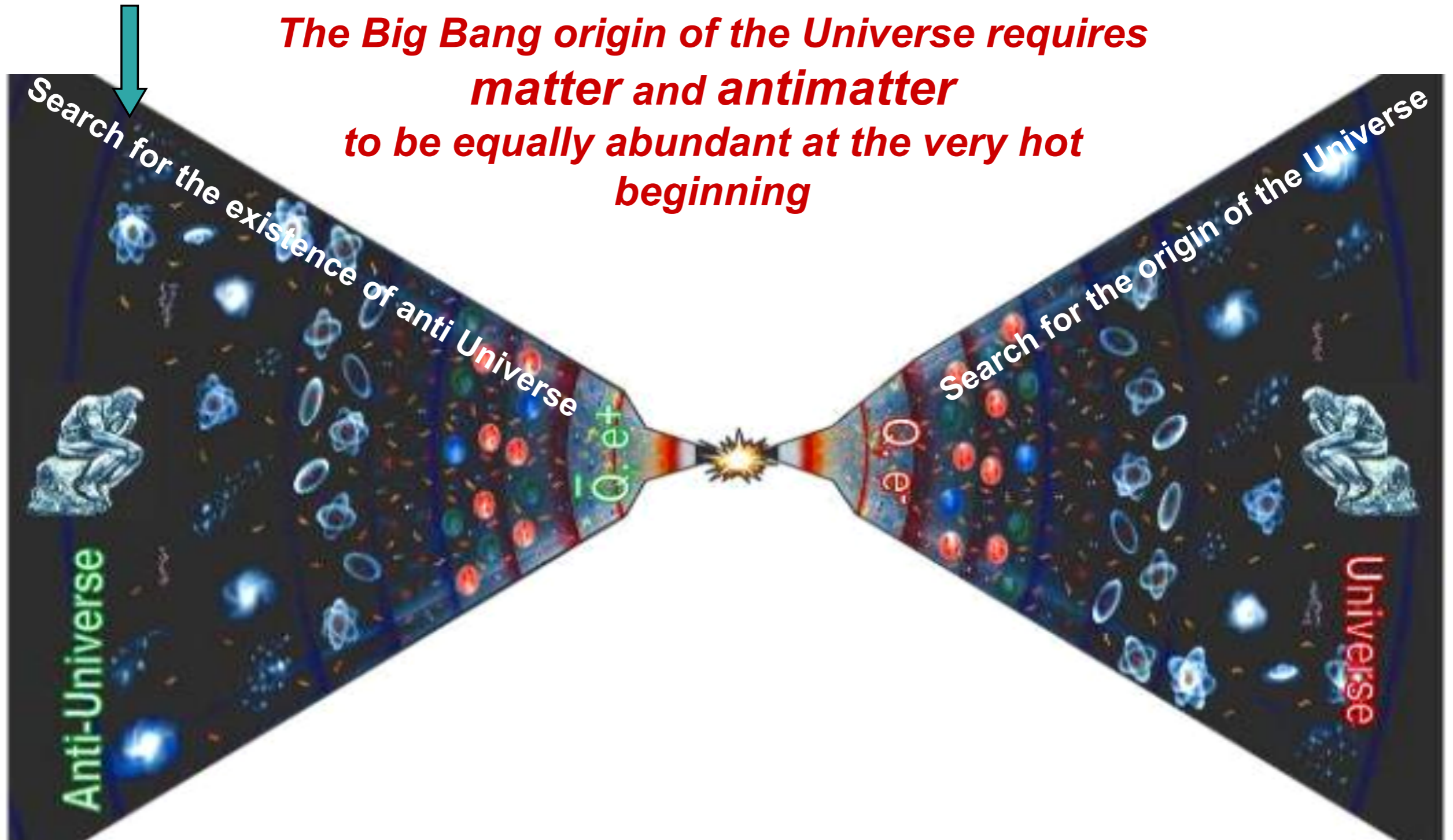
《Missing Symmetries, Unseen Quarks and the Physical Vacuum》

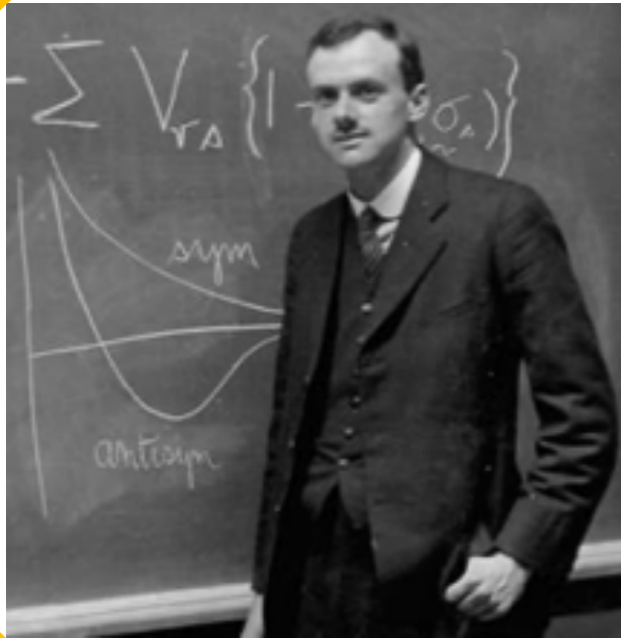
- 周光召教授：“对称性和对称破缺是世界统一性和多样性的根源”

《周光召对理论物理和原子能事业的贡献》

对称性和对称破缺

*The Big Bang origin of the Universe requires
matter and antimatter
to be equally abundant at the very hot
beginning*





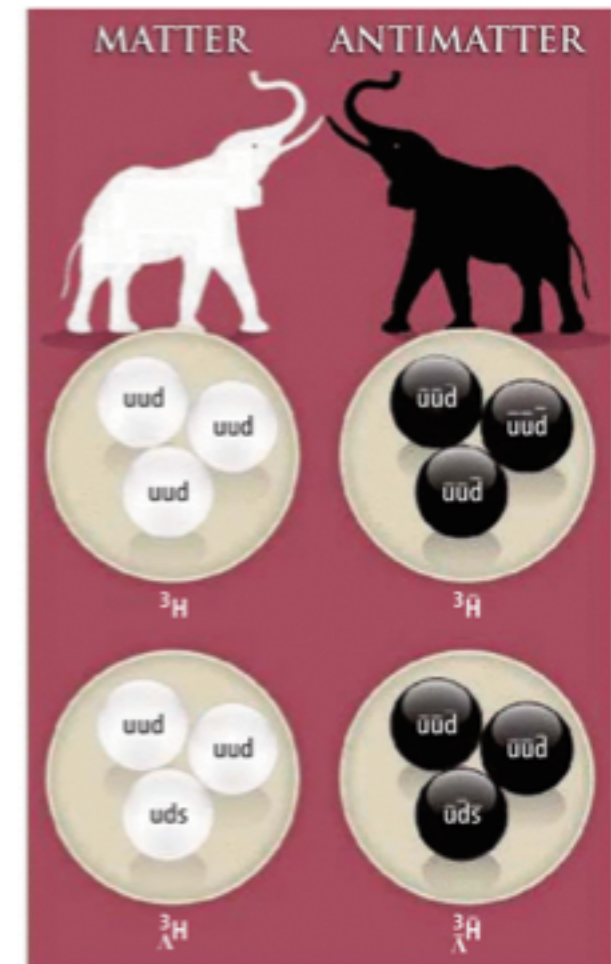
“如果我们在研究自然界的基本物理规律时接受粒子与反粒子完全对称的观点，我们就必须认定地球上乃至整个太阳系主要包含电子和质子的事实纯属偶然。

很有可能在一些其他的星球上情况正好相反，即这些星球主要是由正电子和反质子构成的。实际的情况是，半数的星球由物质组成，而另外半数的星球由反物质组成。这两类星系的光谱完全相同，目前的天文观测手段无法区分它们。”

——保罗狄拉克，1933诺贝尔物理奖颁奖典礼

“Fishing Antihypernuclei out of a Quark-Gluon Soup”,
Thomas D. Cohen,
Science 328 (2010) 55

Quantum field theory predictions:



- 1928年，狄拉克在解释狄拉克方程负能解时引出正电子的概念，预言了正负电子对的湮灭
- 1932年，安德森在宇宙射线中发现了正电子
- 1959年，赛格雷和张伯伦在回旋加速器上发现了反质子
- ...



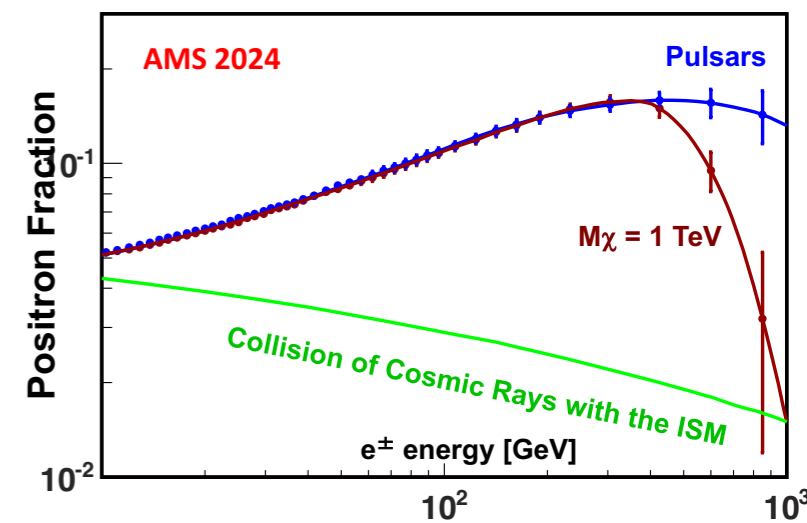
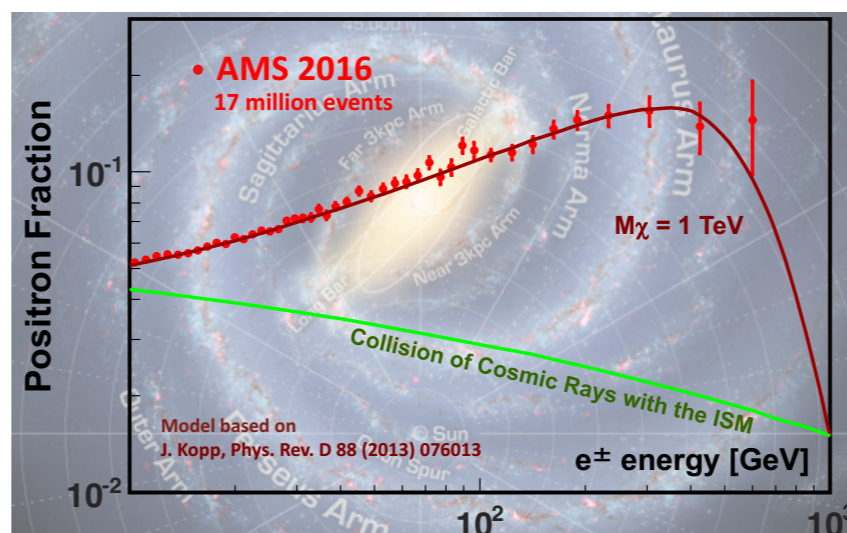
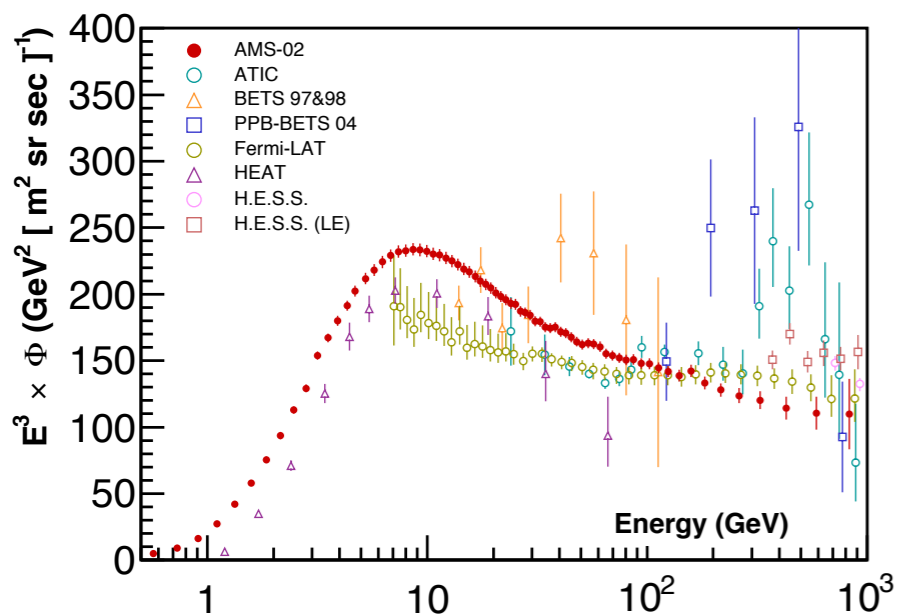
The “Bullet Cluster” is an extremely important object for astrop. research including studies of dark matter. This cluster was formed after the violent collision of two large clusters of galaxies moving at great speeds. The Bullet Cluster is located about 3.8 billion light years from Earth.

人类探索反物质的征程

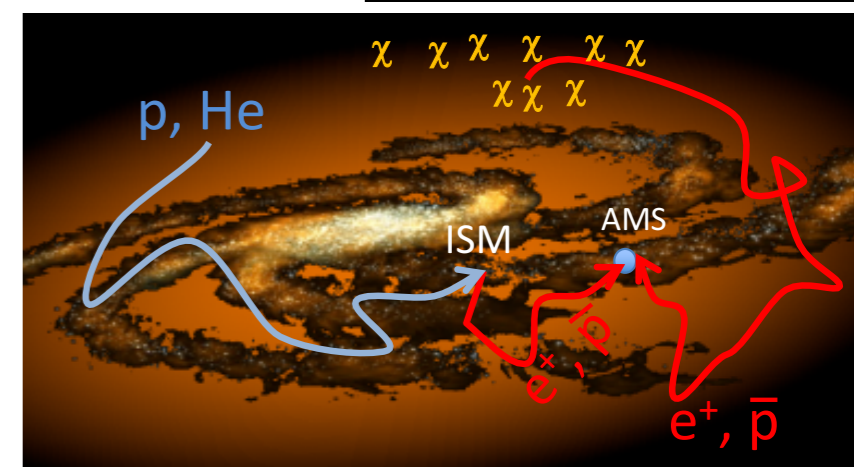
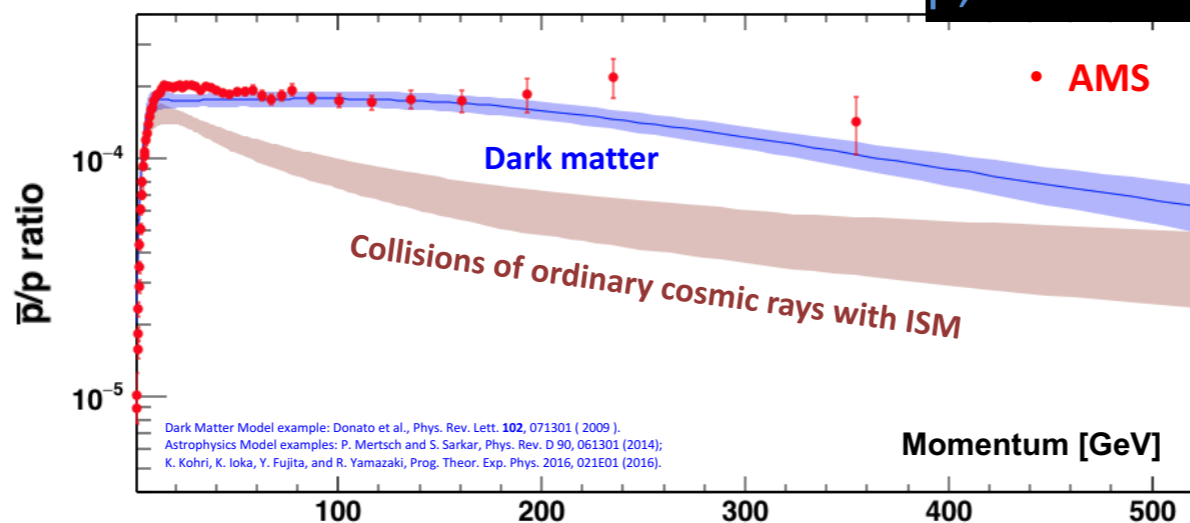
- Search for **anti-helium** in cosmic rays, AMS Col., *Phys. Lett. B* 461 (1991) 387...
- Search for Cosmic-Ray **Antideutrons**, BESS Col. *PRL* 95 (2005) 081101
- An anomalous **positron abundance** in cosmic rays with energies 1.5-100 GeV, PAMELA Col., *Nature* 458 (2009) 607
- Measurement of Separate Cosmic-Ray **Electron and Positron** Spectra with the Fermi Large Area Telescope, Fermi LAT Col. *PRL* 108 (2012) 011103
- Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of **electrons and positrons**, DAMPE Col. *Nature* 552 (2017) 63



AMS-02: 2011/5开始取数, 已采集超过900亿条宇宙射线! 最高精度, 最广能量范围 *PRL* 110, 113, 117, 120, 122, 126...



增强来源:
暗物质?
超新星残留?
脉冲星?



人类探索反物质的征程 (续1)

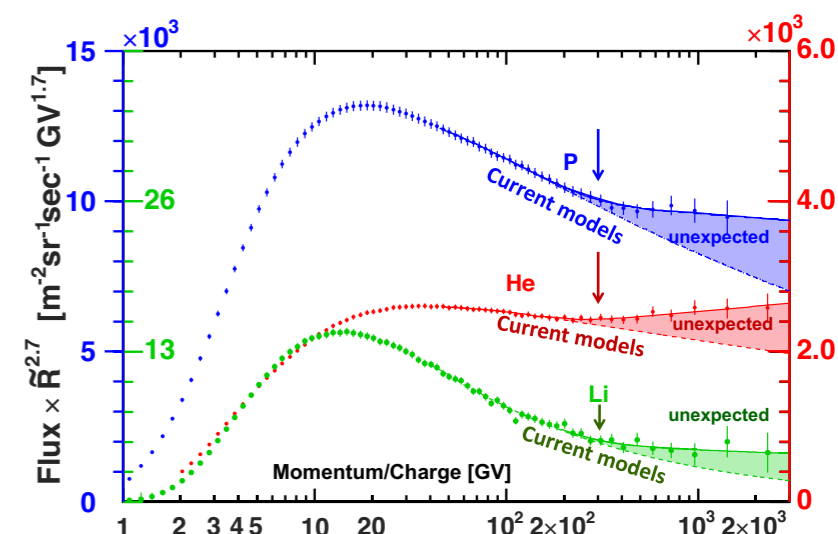
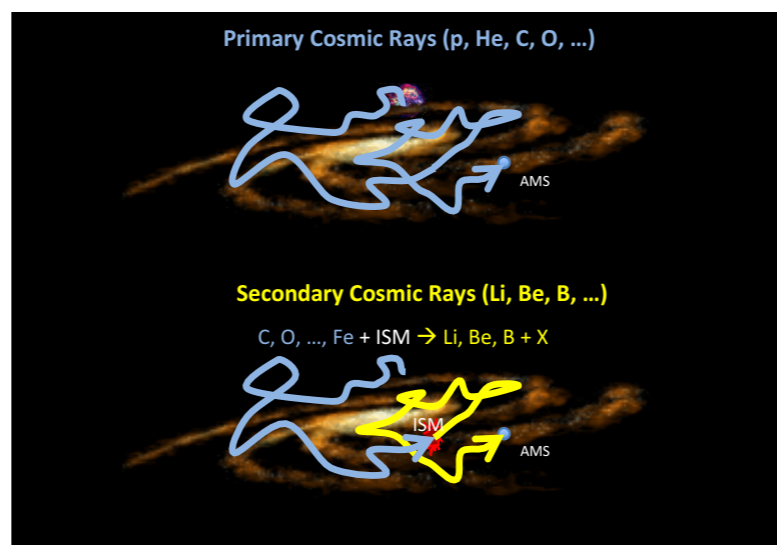
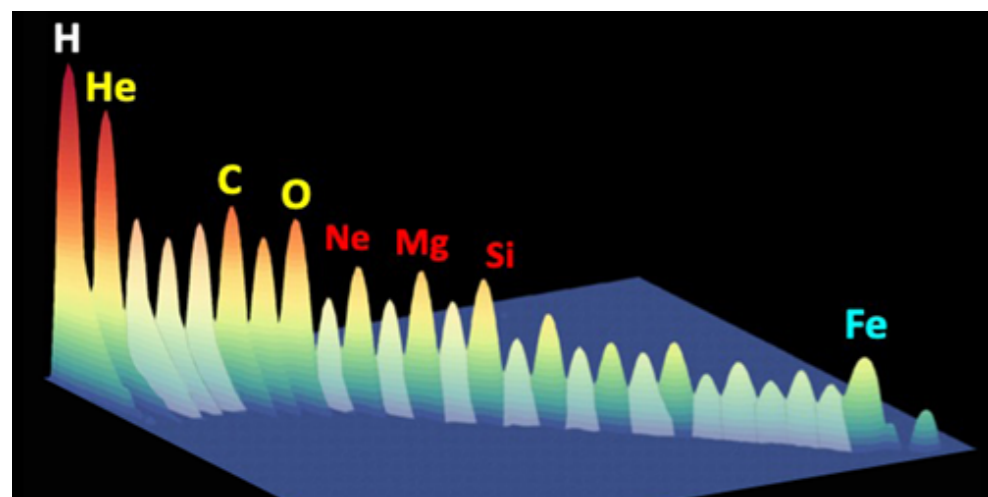
我们最关心的反物质原子核信号？（2016/12/8 丁肇中在CERN汇报5年亮点工作）

To date we have observed a few $Z = -2$ events with mass around ${}^3\text{He}$.

At a signal to background ratio of one in one billion, detailed understanding of the instrument is required.

It will take a few more years of detector verification and to collect more data to ascertain the origin of these events.

“The Alpha Magnetic Spectrometer (AMS) on the international space station: Part II – Results from the first seven years” Phys. Rept. 894, 1 (2021)

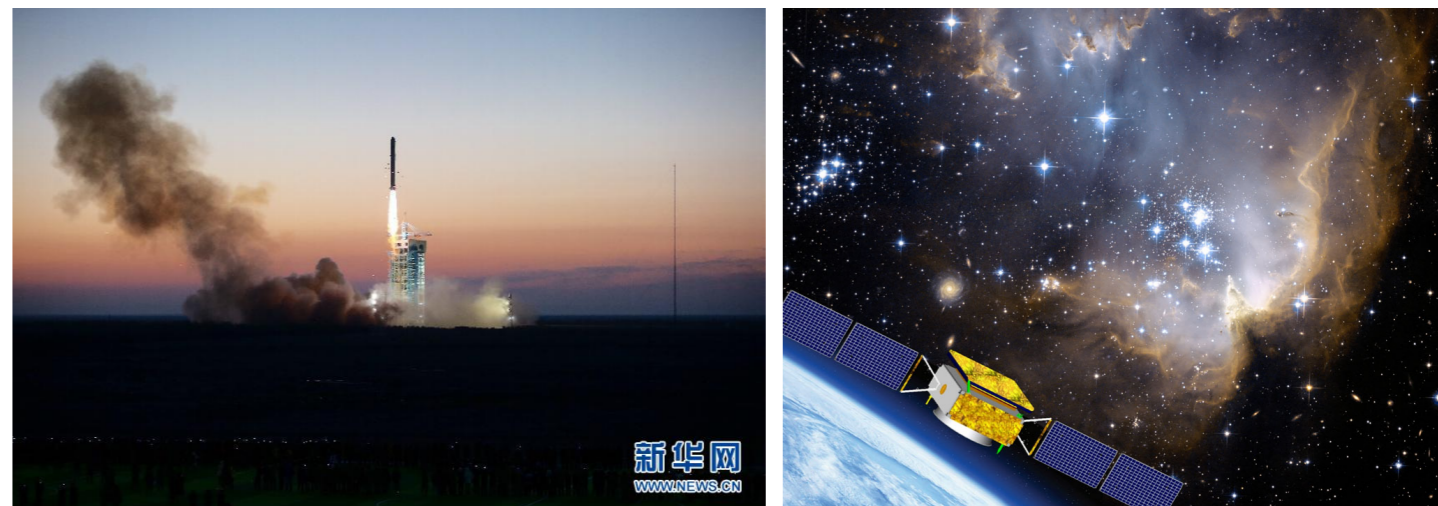


人类探索反物质的征程 (续2)

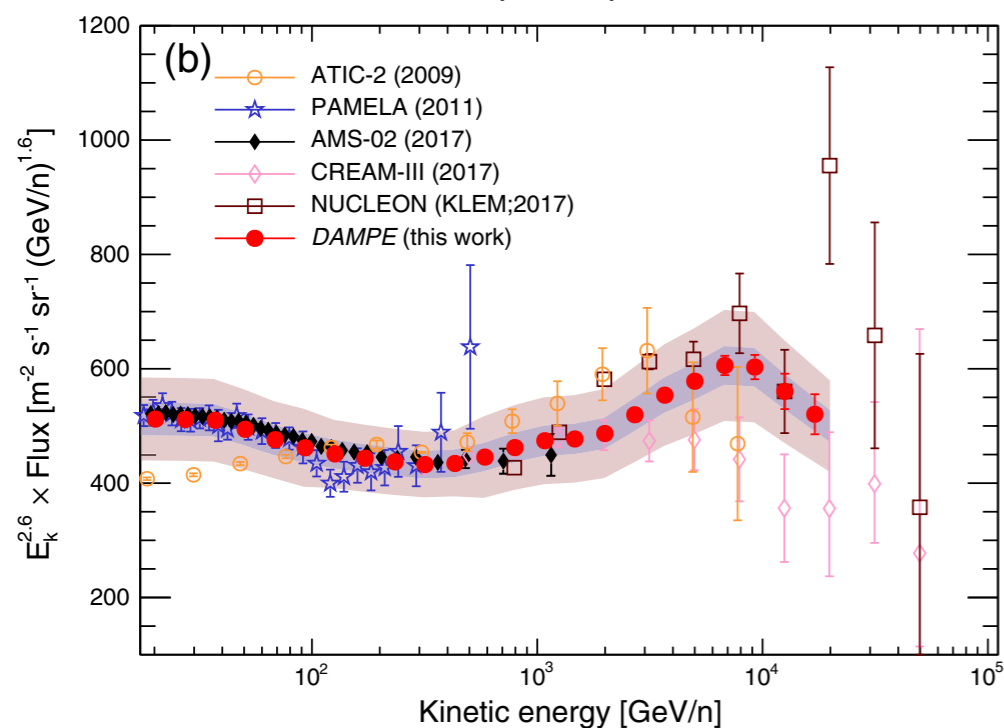
<https://baike.baidu.com/item/暗物质粒子探测卫星/2961031>

DARk Matter Particle Explorer:

- 以更高的能量分辨率和更大的能量测量范围来测量宇宙射线中正负电子之比，以找出可能的暗物质信号
- 主要包括塑料闪烁体探测器、硅微条、量能器等，于2015年12月17日在酒泉卫星发射中心用长征二号丁运载火箭发射升空



PRL 126 (2021) 201102

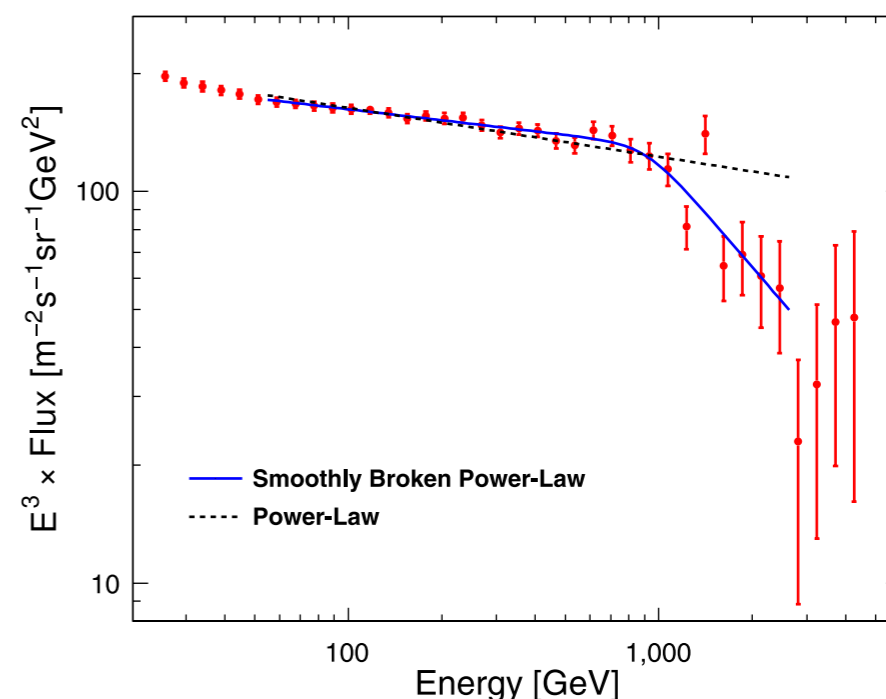


结合质子数据，氦核能谱和质子能谱体现出非常类似的行为，预示着它们存在共同的起源。

“首次直接探测到电子宇宙射线能谱在1 TeV附近的拐折”
2018年度“中国科学十大进展”

悟空号所获得的电子能谱明确表明在**0.9 TeV**附近存在一个拐折，该拐折反映了宇宙中高能电子辐射源的典型加速能力，其精确的下降行为对于判定部分电子宇宙射线是否来自于暗物质起着关键性作用。此外，悟空号所获得的能谱在**1.4 TeV**附近呈现出流量异常迹象，尚需进一步的数据来确认是否存在一个精细结构。

Nature 552 (2017) 63



CP破缺信号：奇异夸克

理论上： $\hat{C}\hat{P}$ 本征态

$$|K_{1,2}^0\rangle = \frac{1}{\sqrt{2}} (|K^0\rangle \pm |\bar{K}^0\rangle)$$

$$|K^0\rangle = |\bar{s}d\rangle$$

$$|\bar{K}^0\rangle = |s\bar{d}\rangle$$

$$\hat{C}\hat{P}|K_{1,2}^0\rangle = \pm|K_{1,2}^0\rangle$$

$$K_1^0 \rightarrow 2\pi \quad \tau = 0.9 \cdot 10^{-10} \text{ s}$$

$$K_2^0 \rightarrow 3\pi \quad \tau = 5.2 \cdot 10^{-8} \text{ s}$$

思考题：相干产生的一对 K^0 /反 K^0 ，是 K_1/K_2 混合态，测量前，我们不清楚哪个是 K_1/K_2 ，测量后，先衰变的是 K_1 ，那么余下的就是 K_2 ？

实验上：30 GeV质子束流轰击铍靶 $\rightarrow K_1/K_2$ 对产生；并设计共轴 K_2 次级束

In 22700 K_2^0 decays, 45 ± 9 were observed

$\hat{C}\hat{P}$ 破缺

$$K_S^0 = K_1^0 - \epsilon K_2^0 \quad K_L^0 = K_2^0 + \epsilon K_1^0 \quad \epsilon \approx 2 \cdot 10^{-3}$$

Franklin,

Historical Studies in the Physical Sciences, 13 (1983) 207

“The discovery and acceptance of CP violation”

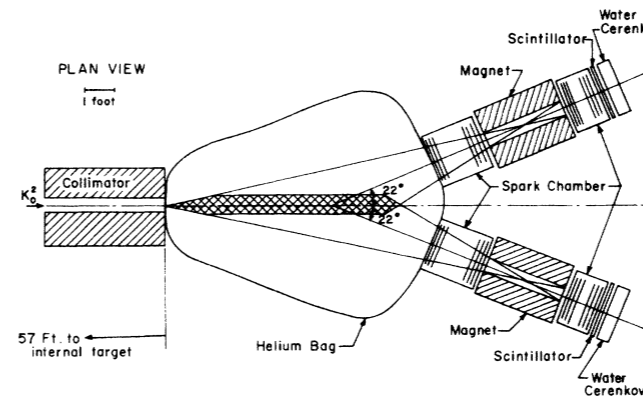


FIG. 1. Plan view of the detector arrangement.

Christenson, Cronin, Fitch, Turlay,
PRL 13 (1964) 138
“Evidence for the 2pi decay of the
 K_2^0 meson”

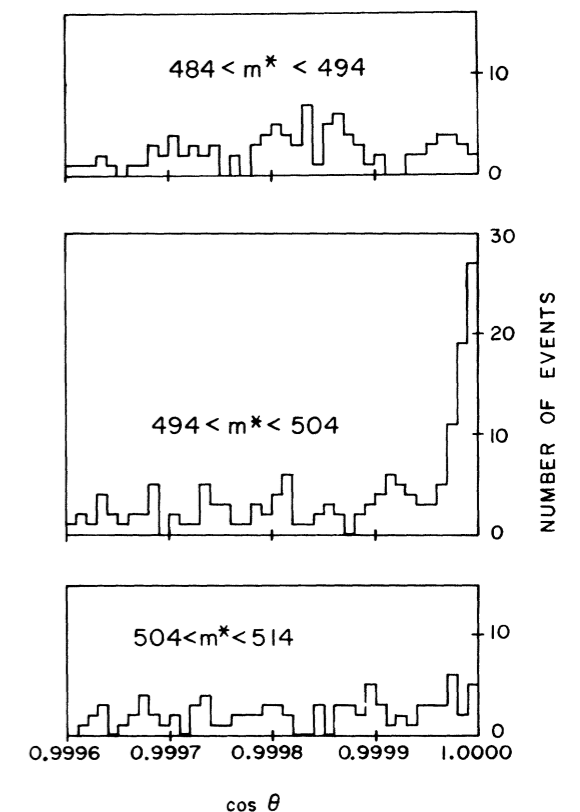


FIG. 3. Angular distribution in three mass ranges for events with $\cos\theta > 0.9995$.

CP破缺信号：底夸克

理论上:

1. **SU(3)破缺, Cabibbo angle,**
描述奇异强子弱相互作用

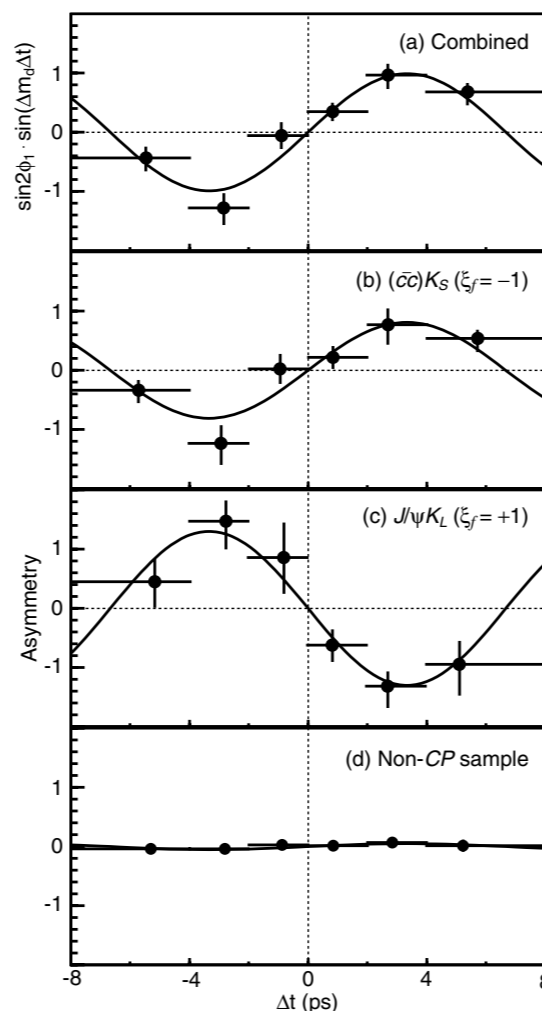
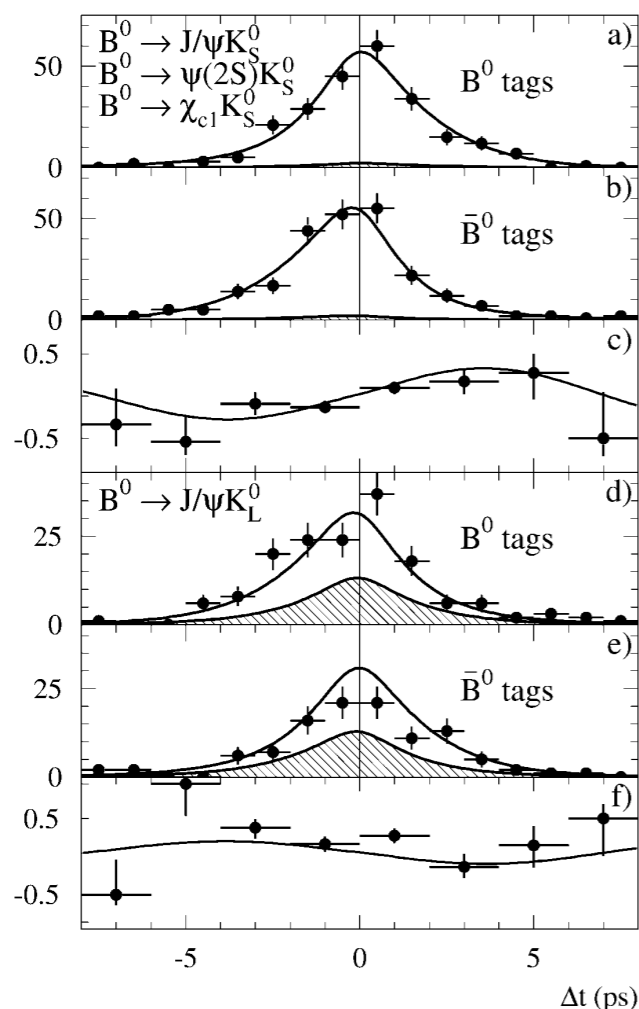
2. 引入新的标量场/规范场, 夸克模型扩展到**6夸克**, 解释**CP破缺**

1. Cabibbo PRL 10 (1963) 531 "Unitary symmetry and leptonic decays"
2. Kobayashi, Maskawa, Prog. Theor. Phys. 49 (1973) 652
"CP-violation in the renormalizable theory of weak interaction"

$$\mathcal{L}_{\text{had}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{mass}} + \mathcal{L}_{\text{strong}} + \mathcal{L}',$$

$$\mathcal{L}' = \bar{q}\psi C \frac{1-\gamma_5}{2} q + \text{h.c.},$$

实验上: **B**介子弱衰变的时间分布测量, **CKM**矩阵



$$A(t) \equiv \frac{\Gamma(\bar{B}^0 \rightarrow f_{CP}) - \Gamma(B^0 \rightarrow f_{CP})}{\Gamma(\bar{B}^0 \rightarrow f_{CP}) + \Gamma(B^0 \rightarrow f_{CP})} = -\xi_f \sin 2\phi_1 \sin \Delta m_d t,$$

BABAR Col. PRL 87 (2001) 091801

$$\sin 2\beta = 0.59 \pm 0.14(\text{stat}) \pm 0.05(\text{syst})$$

Belle Col. PRL 87 (2001) 091802

$$\sin 2\phi_1 = 0.99 \pm 0.14(\text{stat}) \pm 0.06(\text{syst})$$

LHCb Col. PRL 122 (2019) 211803 “Observation of CP violation in charm decays”

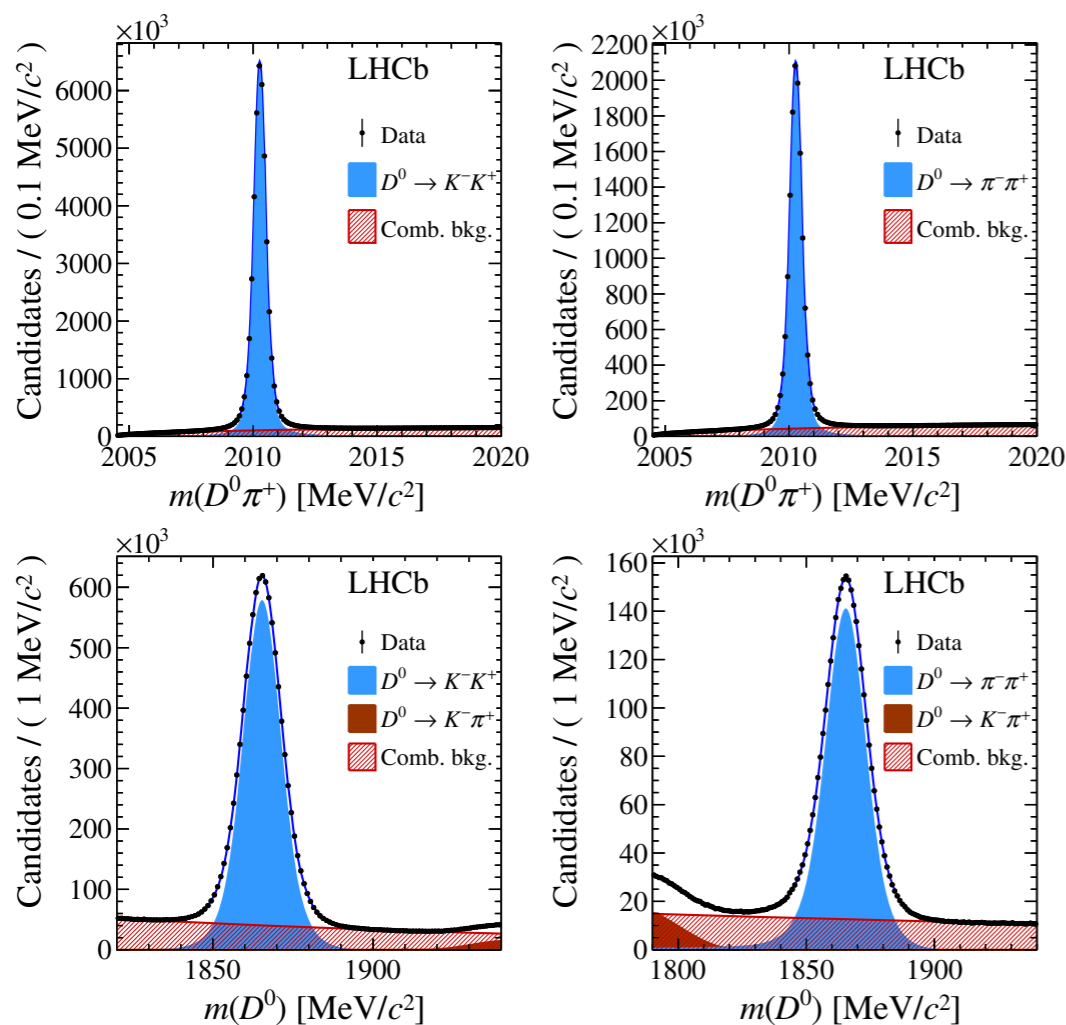


FIG. 1. Mass distributions of selected (top) π^\pm -tagged and (bottom) μ^\pm -tagged candidates for (left) $K^- K^+$ and (right) $\pi^- \pi^+$ final states of the D^0 -meson decays, with fit projections overlaid.

最新实验测量精度：13 TeV 质子对撞，5.9 fb⁻¹

(5.9 fb⁻¹ = 5.9*10¹⁵*10²⁴cm⁻²)

$$A_{CP}(f; t) \equiv \frac{\Gamma(D^0(t) \rightarrow f) - \Gamma(\bar{D}^0(t) \rightarrow f)}{\Gamma(D^0(t) \rightarrow f) + \Gamma(\bar{D}^0(t) \rightarrow f)},$$

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2(\text{stat}) \pm 0.9(\text{syst})] \times 10^{-4},$$

$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8(\text{stat}) \pm 5(\text{syst})] \times 10^{-4}.$$

合并2014，2016和2019年实验数据，得到

LHCb Col. JHEP 07 (2014) 041; PRL 116 (2016) 191601

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4},$$

“The size of CP violation in the SM appears to be **too small** to account for the observed matter-antimatter asymmetry, suggesting the existence of sources of CP violation beyond the SM.”

Kostelecky, the standard model extension (SME)

$$\left| \left[\left(\frac{q_p}{m_p} \right) - \left(\frac{q_{\bar{p}}}{m_{\bar{p}}} \right) \right] / \left(\frac{q}{m} \right)_{\text{av}} \right|$$

PHYSICAL REVIEW D, VOLUME 58, 072002

Measurement of the properties of the $\bar{\Omega}^+$ and Ω^- hyperons

Masses, lifetimes and production rates of Ξ^- and $\bar{\Xi}^+$ at LEP 1

DELPHI Collaboration

Measurement of the mass difference between top and anti-top quarks in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector

ATLAS Collaboration*



PRL 105, 151601 (2010)

PHYSICAL REVIEW LETTERS

week ending
8 OCTOBER 2010

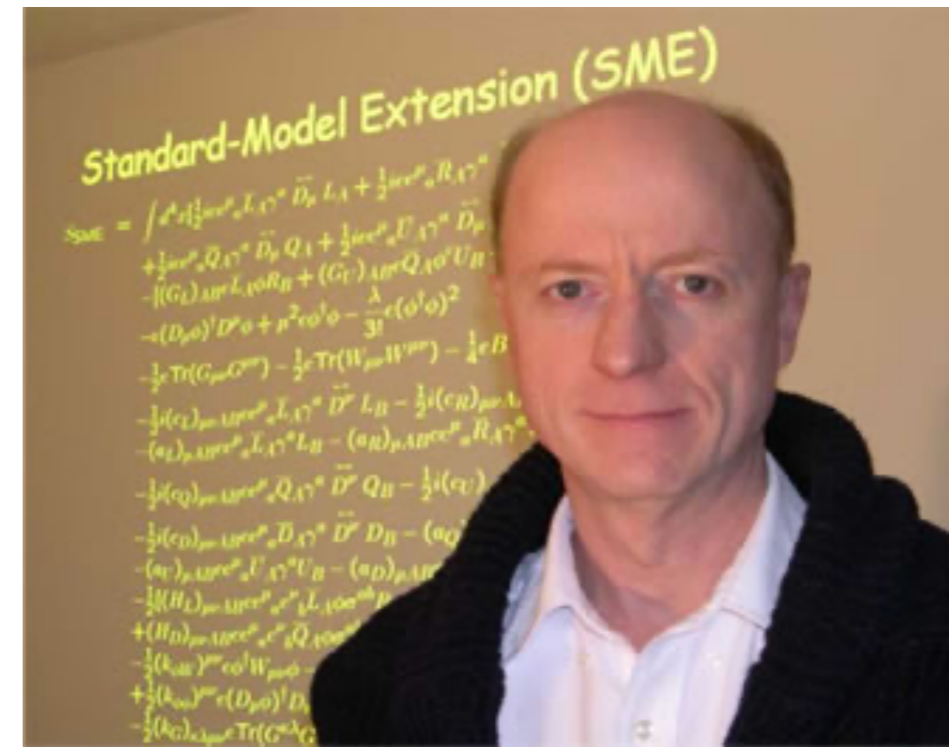
Search for Lorentz Invariance and CPT Violation with the MINOS Far Detector

PRL 106, 152001 (2011)

PHYSICAL REVIEW LETTERS

week ending
15 APRIL 2011

Measurement of the Mass Difference between t and \bar{t} Quarks

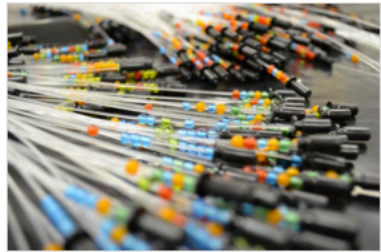


1. 主题会议文集：
Kostelecky, editor,
CPT and Lorentz Symmetry,
World Scientific, Singapore,
1999, 2002, 2005, 2008, 2011...

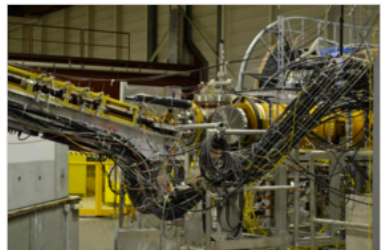
2. 专题综述：
Kostelecky and Russell,
Data tables for Lorentz and CPT violation,
Rev. Mod. Phys. 83 (2011) 11

从强子到原子核

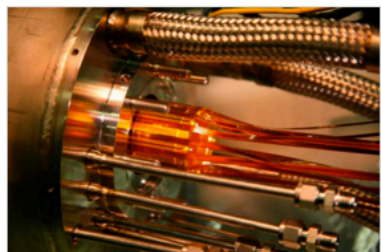
- 往高精度、复杂系统发展



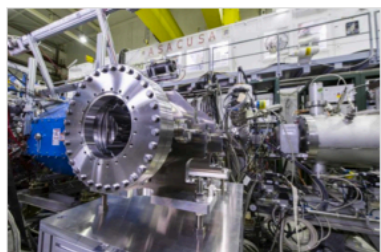
AEGIS (CERN):
antimatter gravity.



ATRAP (CERN):
antimatter magnetic
moment etc.

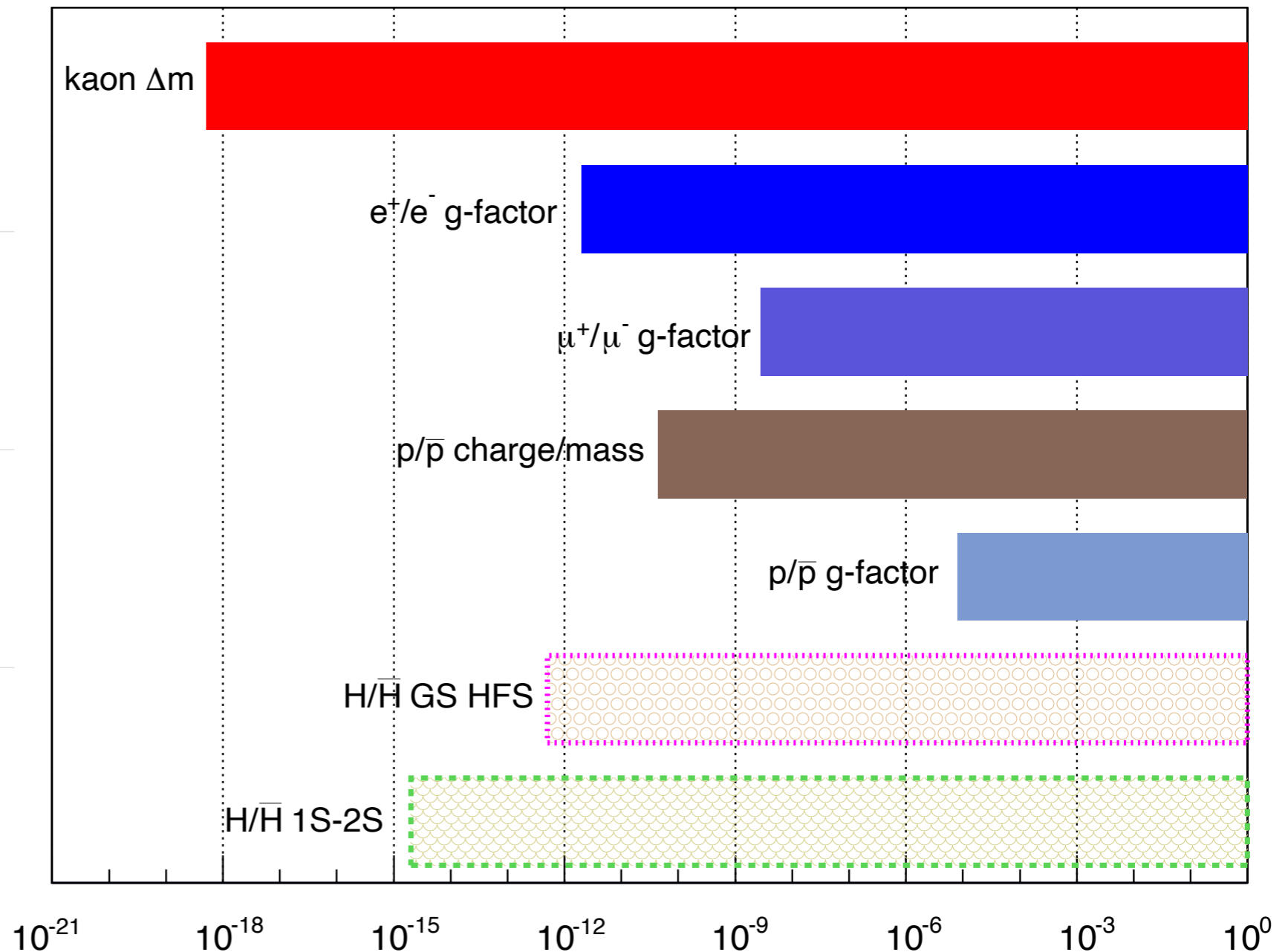


ALPHA (CERN):
antimatter gravity,
charge, etc.



ASACUSA (CERN):
antimatter mass to
charge ratio, hyperfine
structure.

Chen, Keane, Ma, Tang and Xu, Phys. Rept. 760 (2018) 1



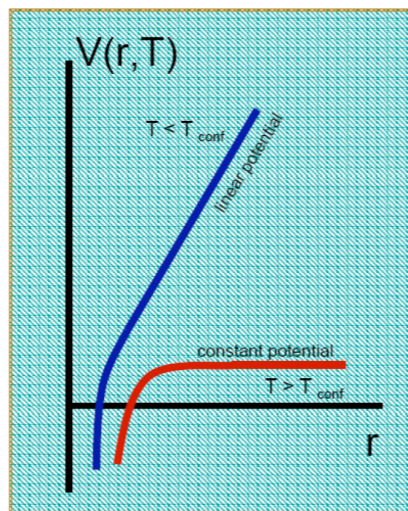
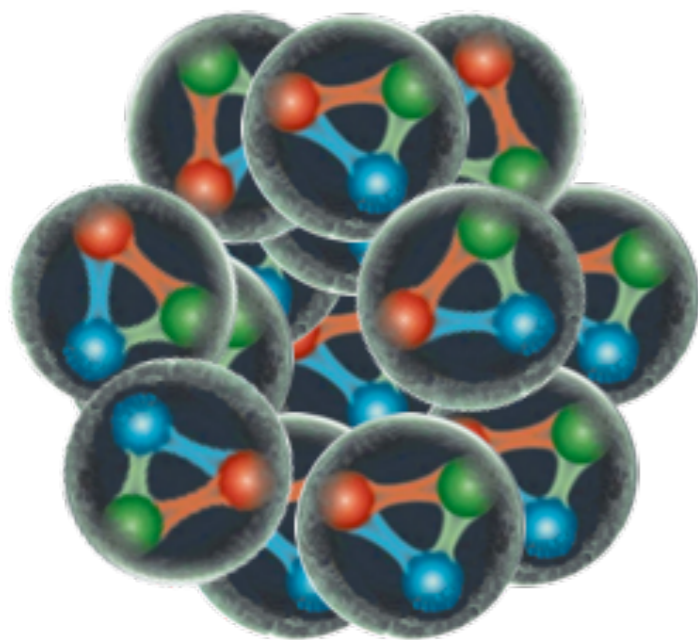
- 最新实验测量: Observation of the mass difference between neutral charm-meson eigenstates, LHCb Col.

$$x_{CP} = (3.97 \pm 0.46 \pm 0.29) \times 10^{-3},$$

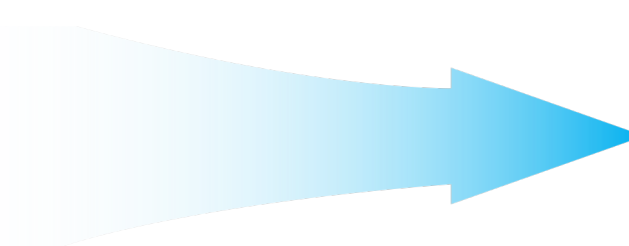
$$y_{CP} = (4.59 \pm 1.20 \pm 0.85) \times 10^{-3},$$

arXiv:2106.03744

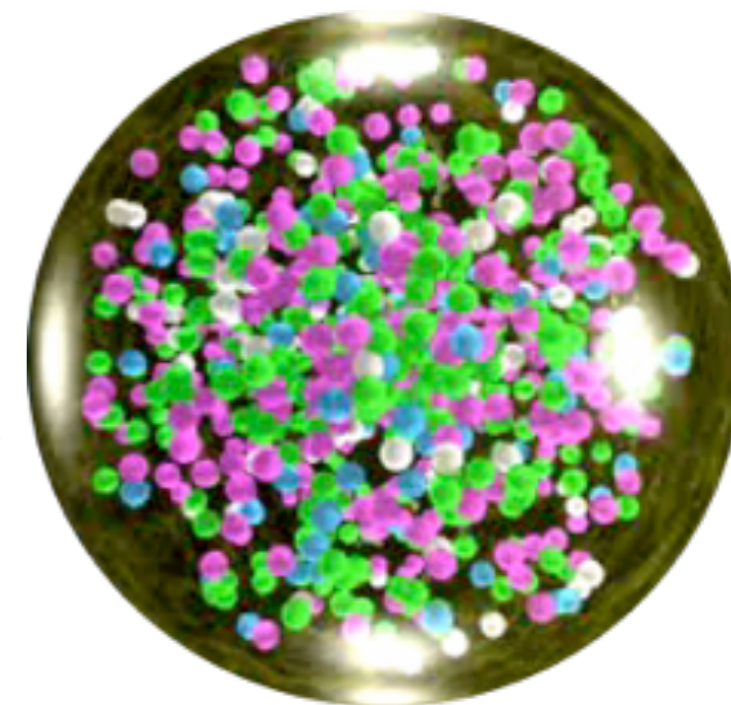
色禁闭



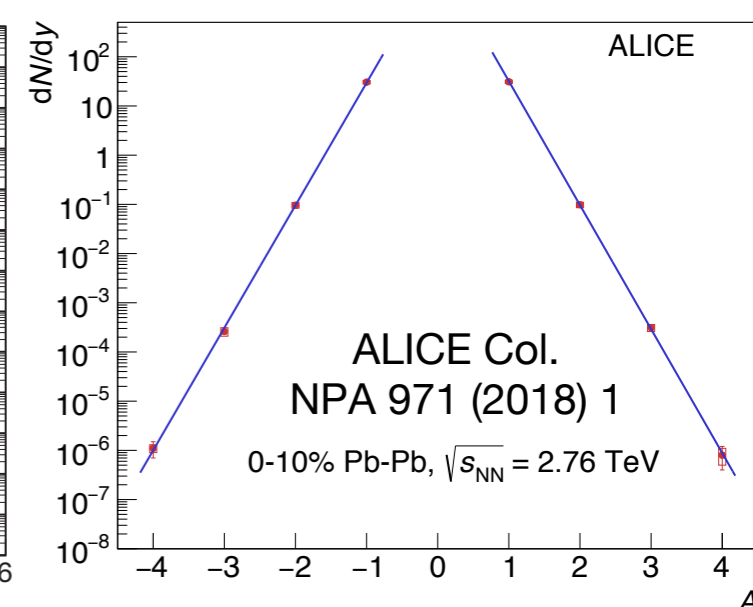
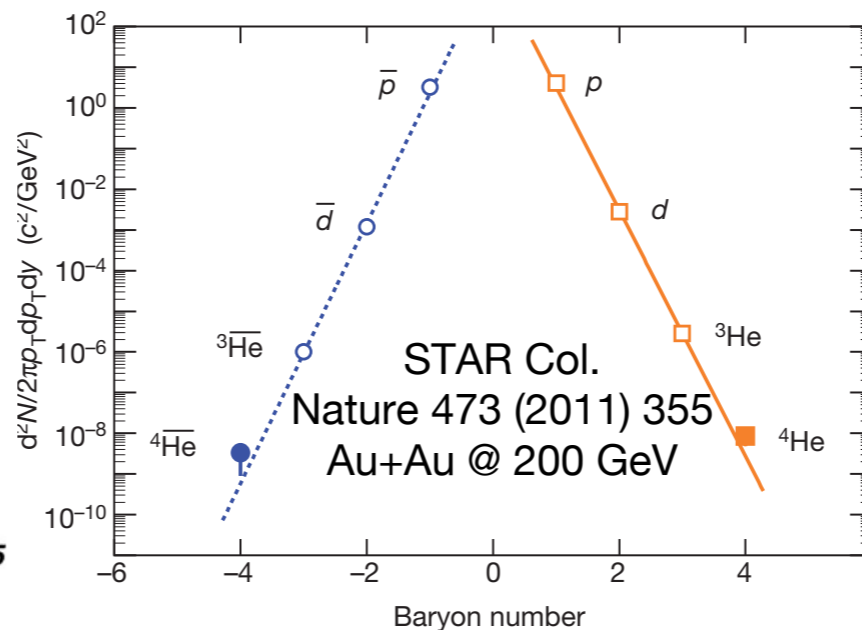
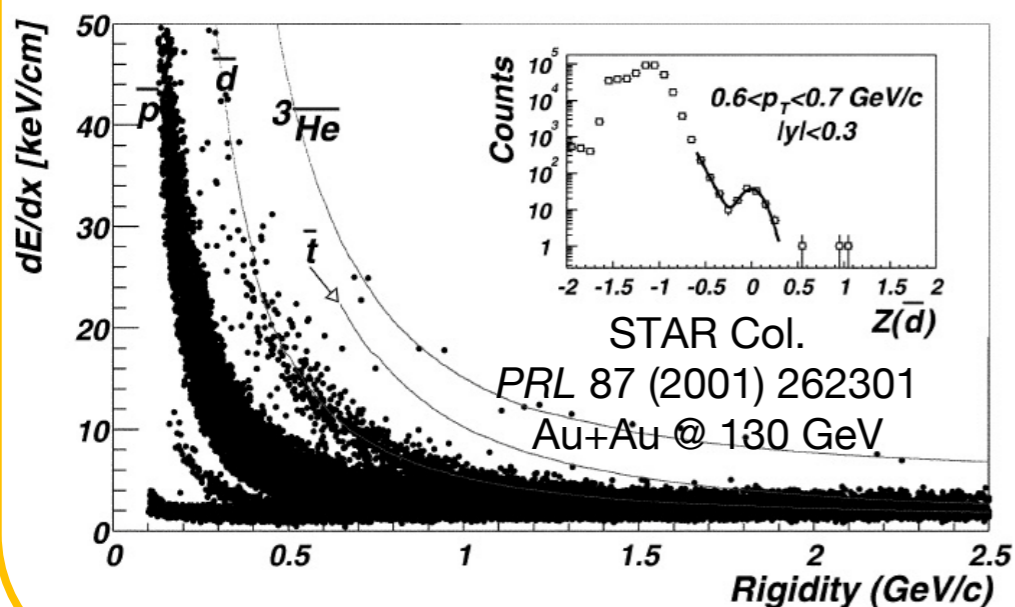
高能重离子对撞



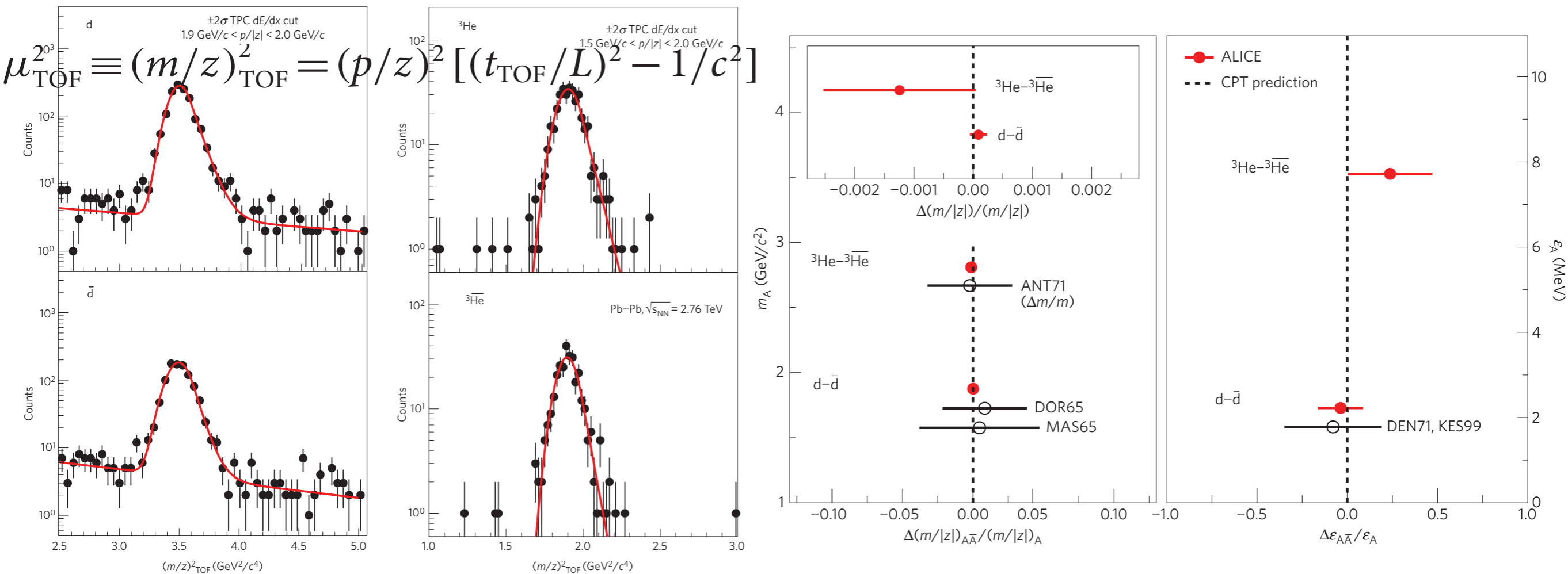
解禁闭



- 实验室研究 $A \geq 2$ 反物质原子核: 2001, 14个反氦3; 2011, 18个反氦4



原子核层面的CPT检验



质量差、相互作用测量

ALICE Col. Nature Phys. 11 (2015) 811

$$\frac{\Delta\mu_{d\bar{d}}}{\mu_d} = (0.9 \pm 0.5(\text{stat.}) \pm 1.4(\text{syst.})) \times 10^{-4}$$

$$\frac{\Delta\epsilon_{d\bar{d}}}{\epsilon_d} = -0.04 \pm 0.05 (\text{stat.}) \pm 0.12 (\text{syst.})$$

$$\frac{\Delta\mu_{{}^3\text{He}}^{{}^3\bar{\text{He}}}}{\mu_{{}^3\text{He}}} = (-1.2 \pm 0.9(\text{stat.}) \pm 1.0(\text{syst.})) \times 10^{-3}$$

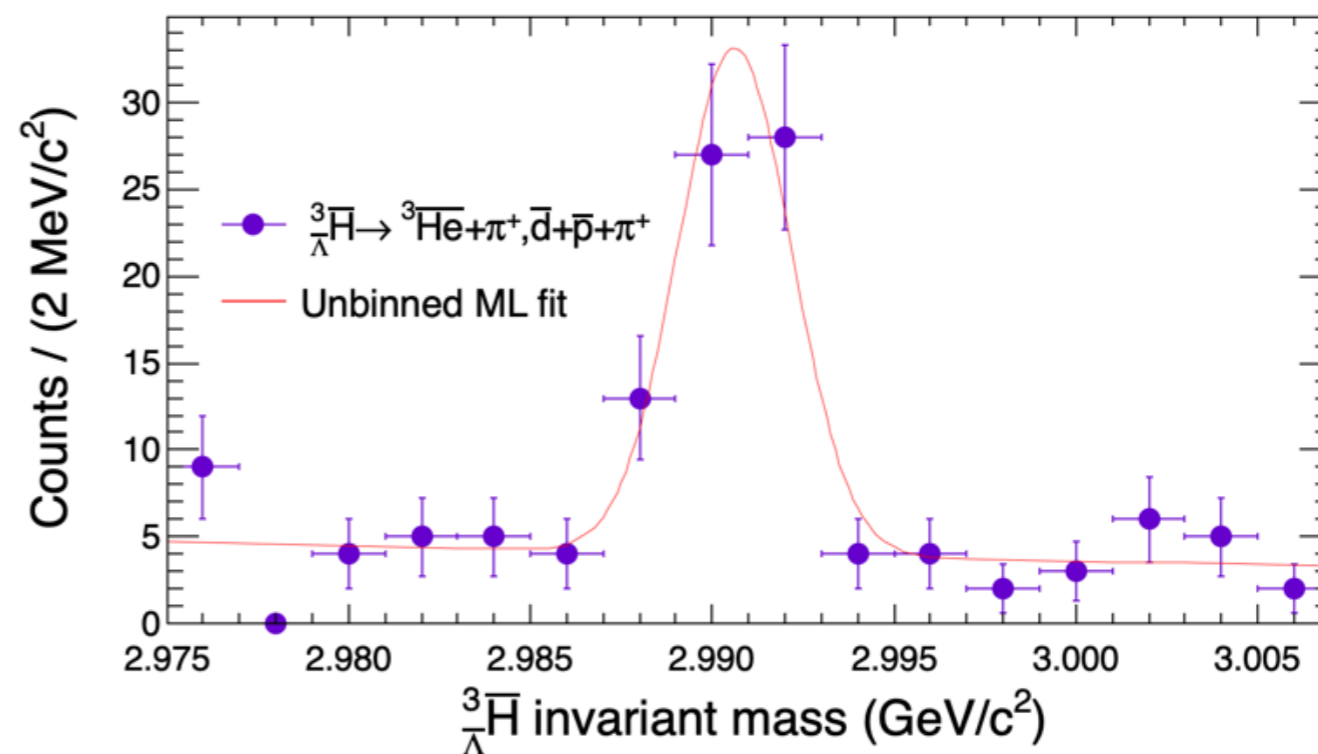
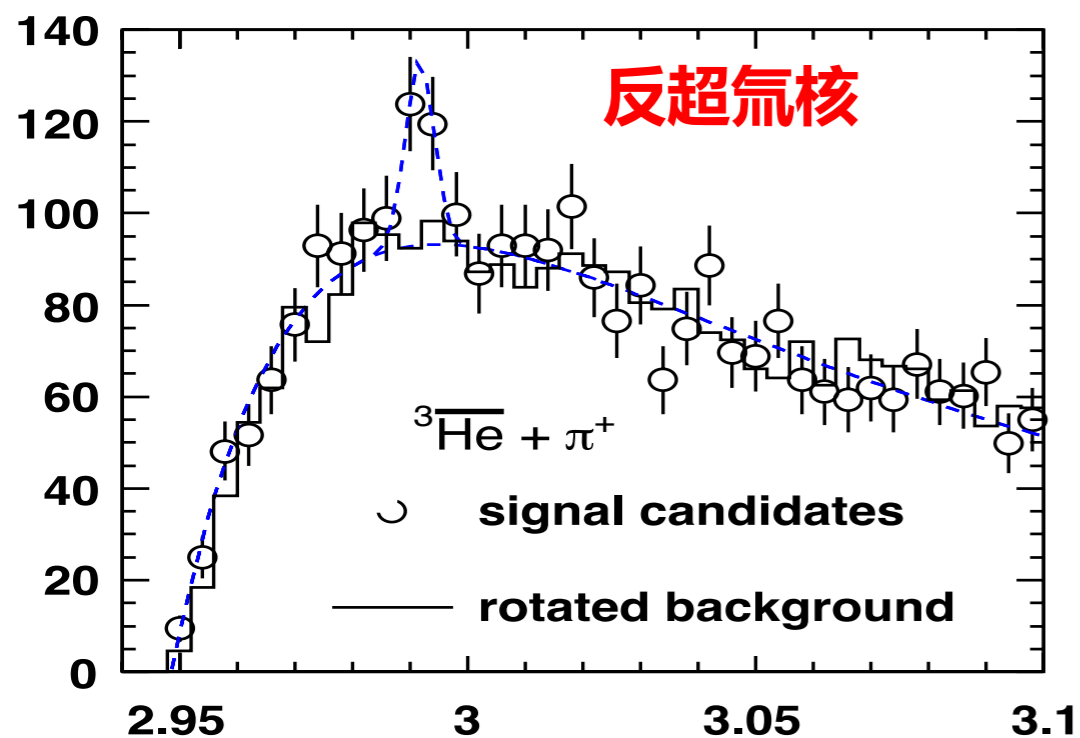
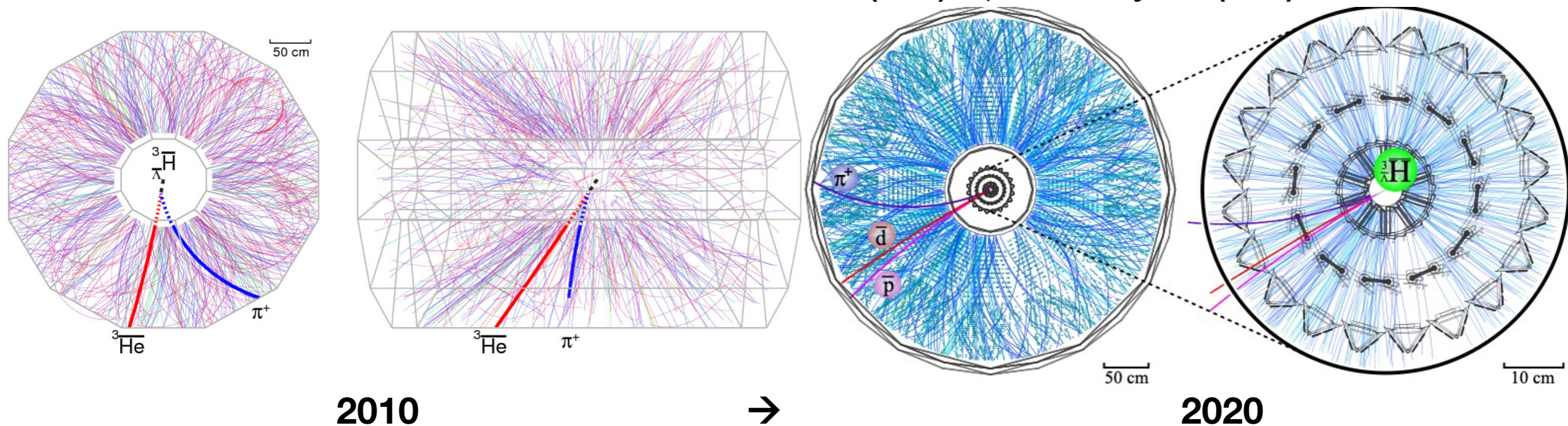
$$\frac{\Delta\epsilon_{{}^3\text{He}}^{{}^3\bar{\text{He}}}}{\epsilon_{{}^3\text{He}}} = 0.24 \pm 0.16 (\text{stat.}) \pm 0.18 (\text{syst.})$$

内径系统 (ITS) + 飞行时间探测器联合测量: 氦核的测量精度提高了一个数量级, 实现了氦3的测量; 实验数据支持CPT不变

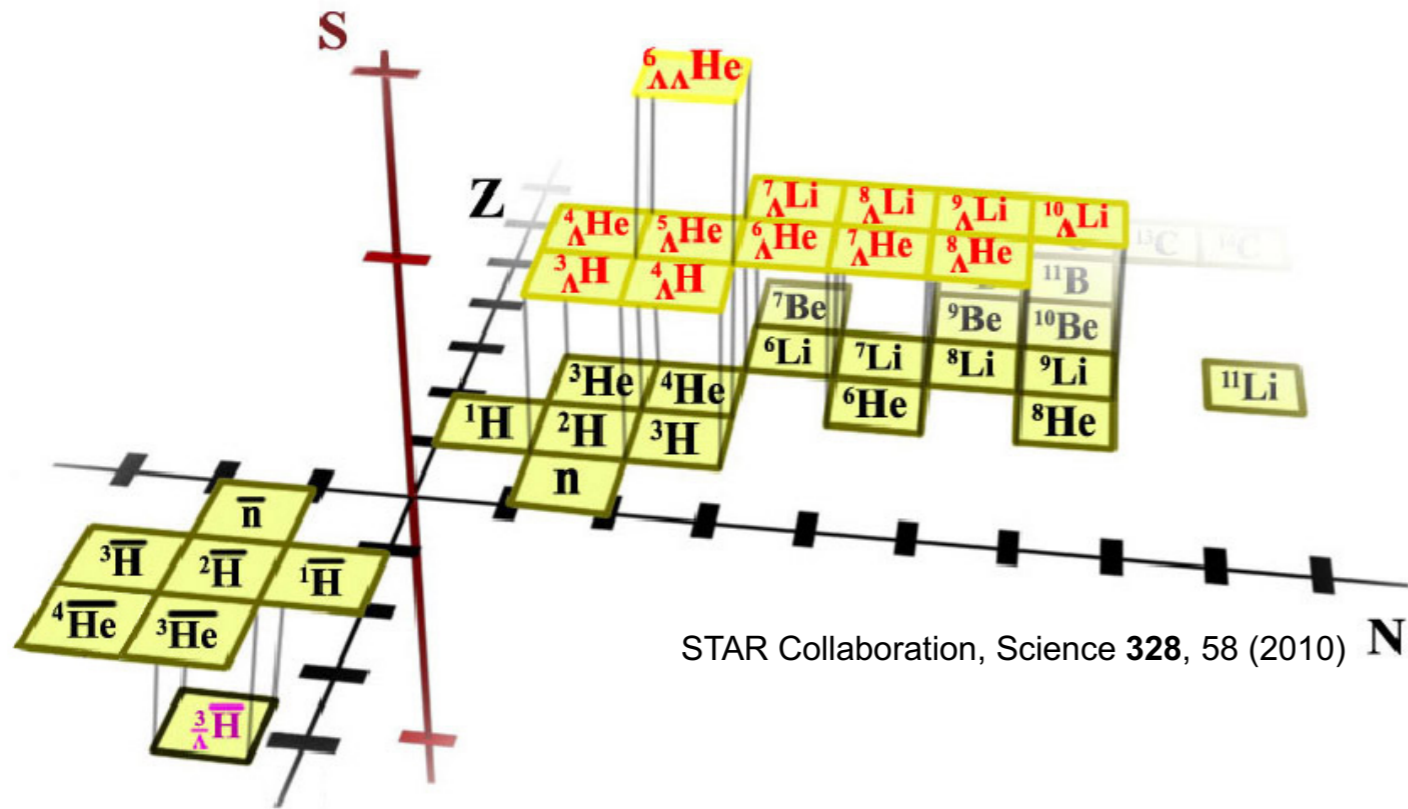
不稳定原子核测量

- 稳定原子核 → 不稳定原子核：反超氦核的发现和测量

STAR Col. Science 328 (2010) 58; Nature Phys. 16 (2020) 409



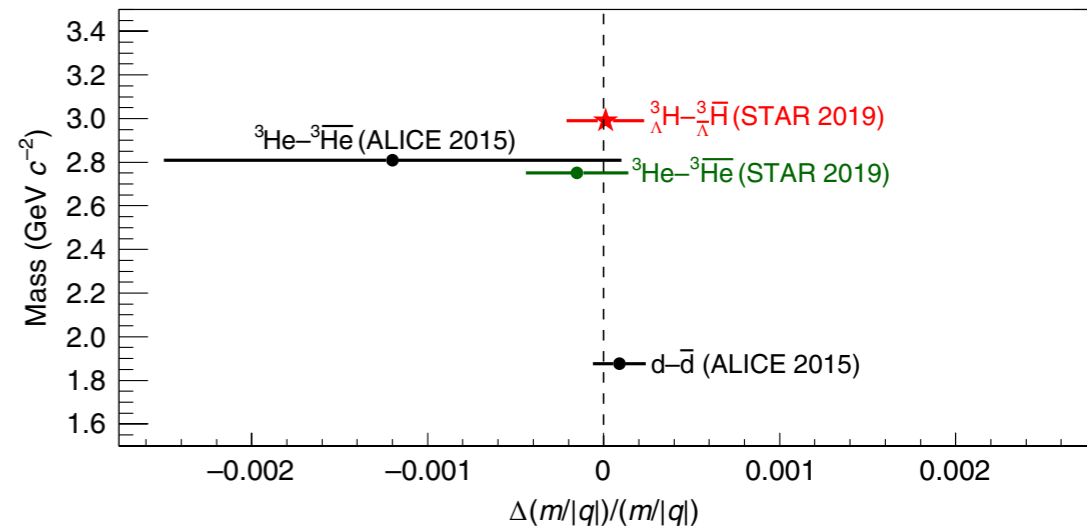
三维核素图：原子核+奇异夸克（新的维度）



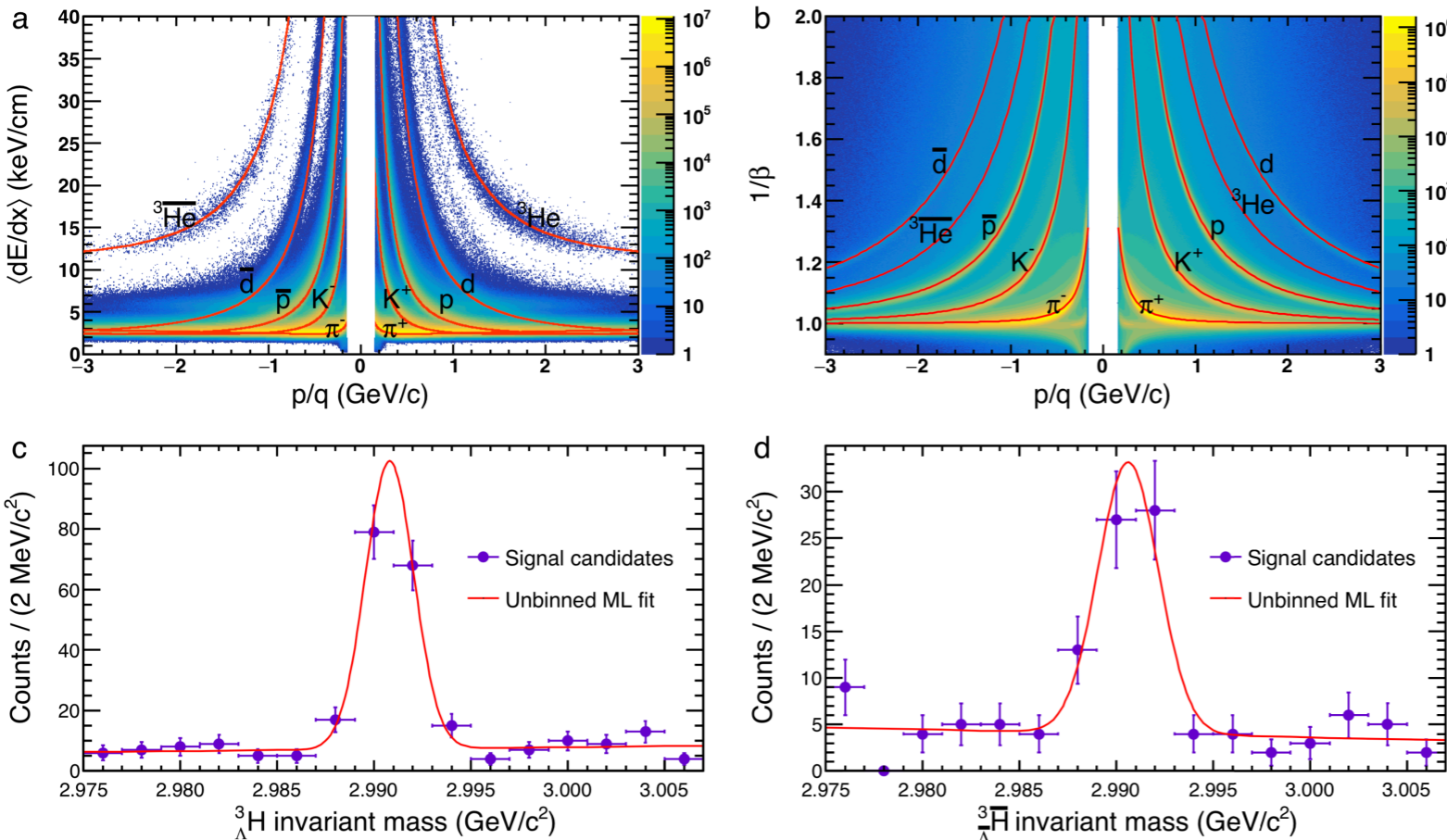
- 反物质超核的发现打开了三维核素图的大门
(2010年度“中国科学十大进展”)

- 反超氦质量精确测量：在奇异原子核层面检验CPT

STAR Collaboration, Nature Phys. **16** (2020) 409

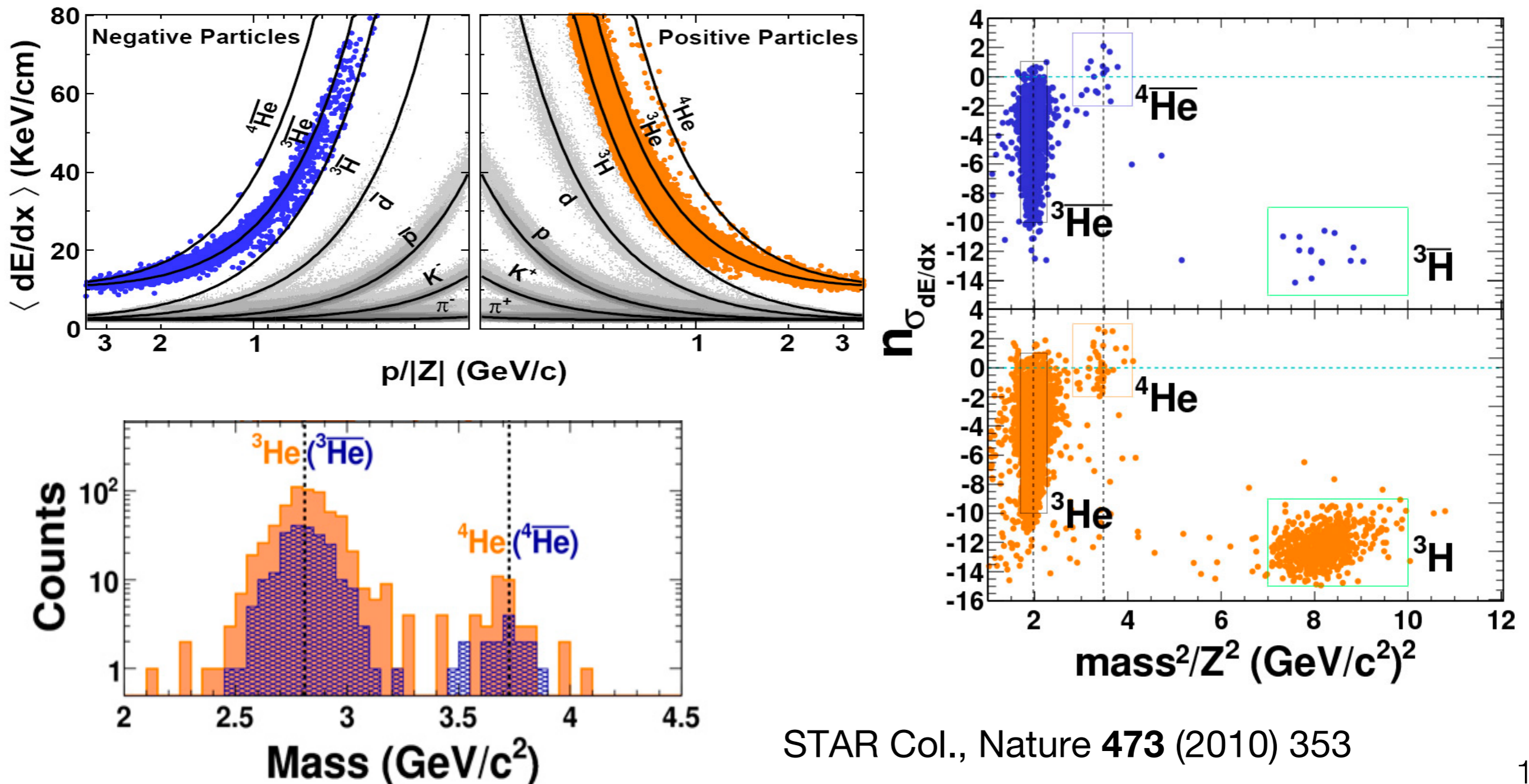


$$\frac{\Delta m}{m} = \frac{m_{\Lambda^3\text{H}} - m_{\Lambda^3\bar{\text{H}}}}{m} = (0.1 \pm 2.0(\text{stat.}) \pm 1.0(\text{syst.})) \times 10^{-4}$$



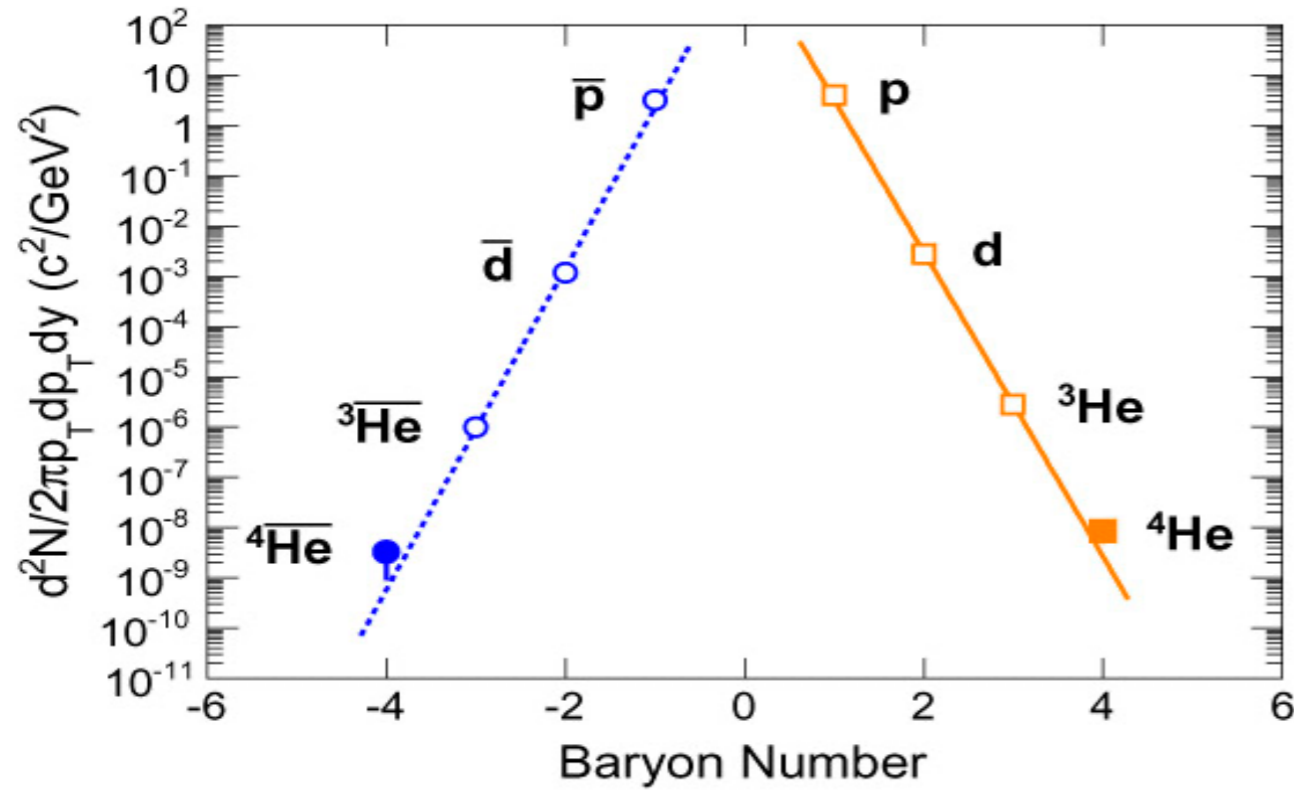
迄今最重反物质原子核的发现

- 1911年，卢瑟福散射实验，原子核
- 2011年，相对论重离子对撞机上观测到反氦4
- 时间投影室单位能损甄别+高阶触发算法快速挑选+飞行时间探测器区分反氦3/反氦4



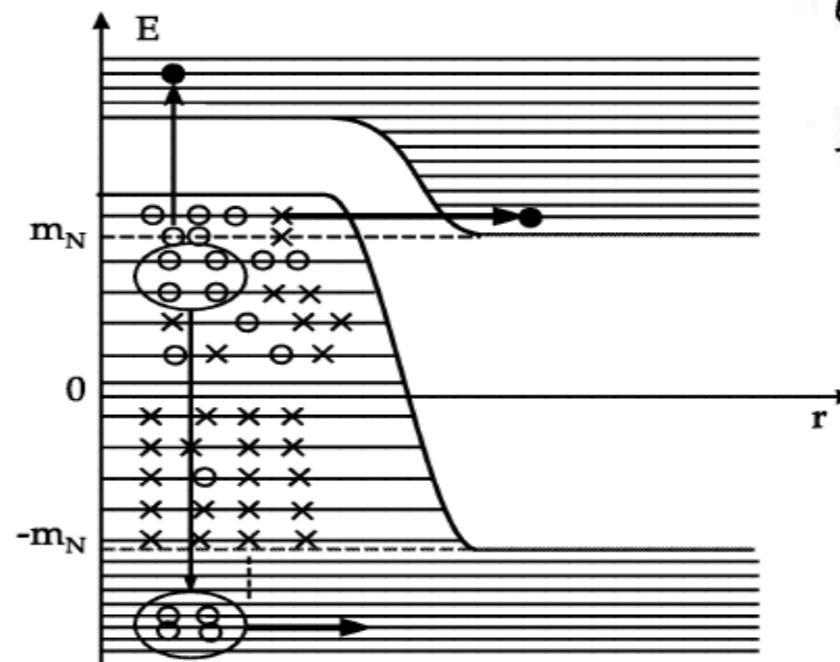
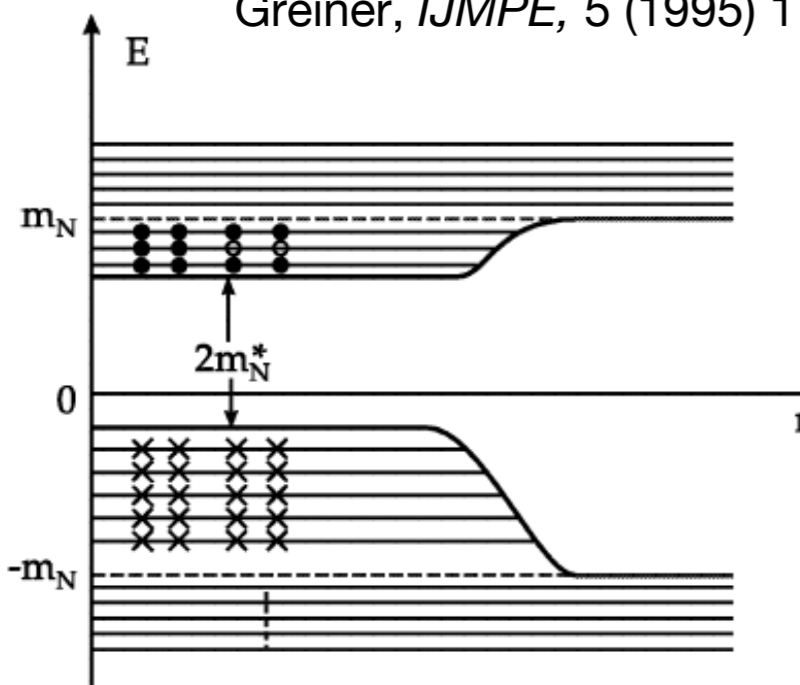
STAR Col., Nature **473** (2010) 353

反物质原子核产生机制



- 反氦4产额符合质量数指数下降，符合统计模型预期
“penalty factor”~1/1600@200GeV
- 下一个稳定反物质原子核A=6;
(penalty factor)² ~ (1600)²
- 新的机制?

Greiner, *IJMPE*, 5 (1995) 1



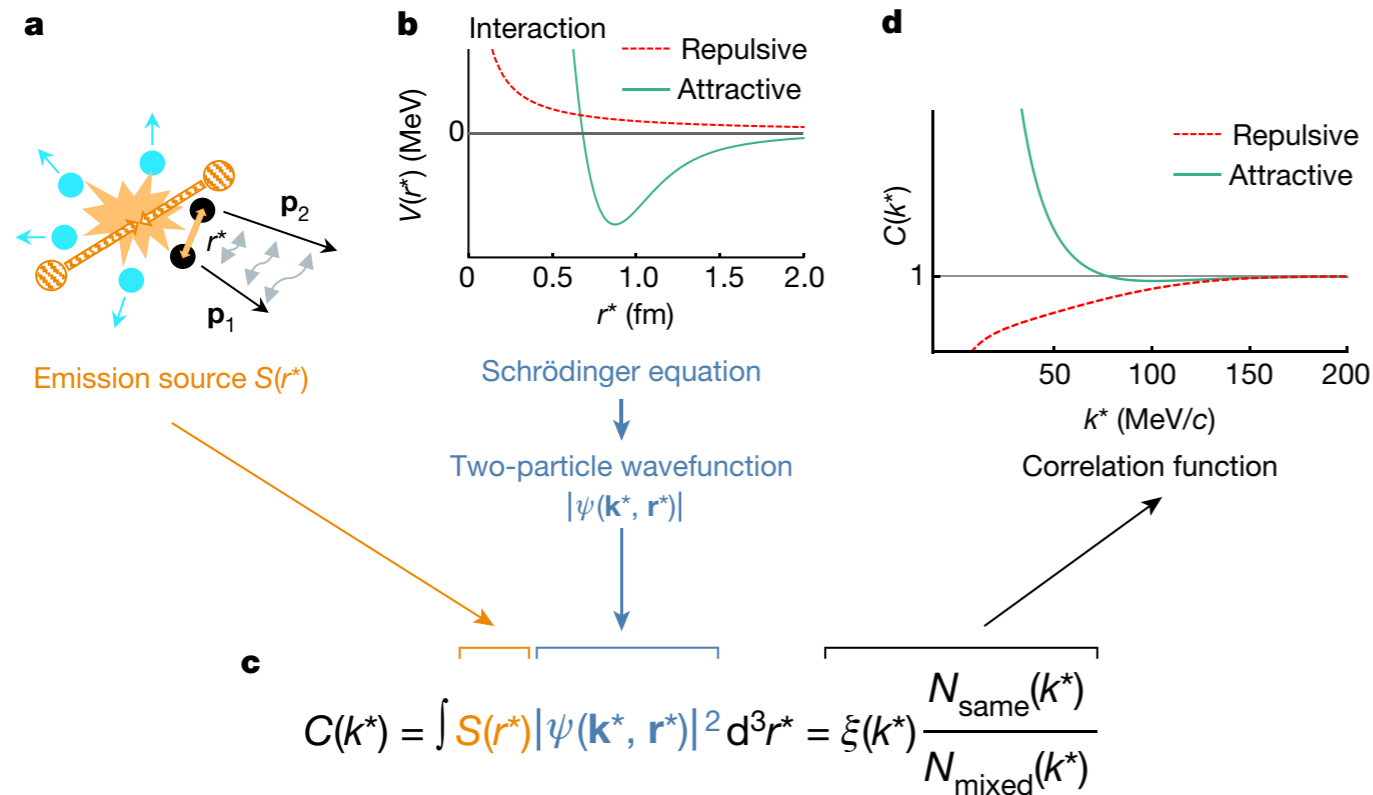
$$U_{\text{Shellmodel}} = g_{\sigma N} \sigma(x) + g_{\omega N} V_{00}(x),$$

$$E = \sqrt{p^2 + (m + g_{\sigma N} \sigma(x))^2} \pm g_{\omega N} V_{00}(x),$$

Idea from Walter Greiner: correlations are present in vacuum, allowing antinucleus like anti- α to be directly excited from the vacuum. Rate for such antinuclei could be much larger than low value predicted by statistical coalescence.

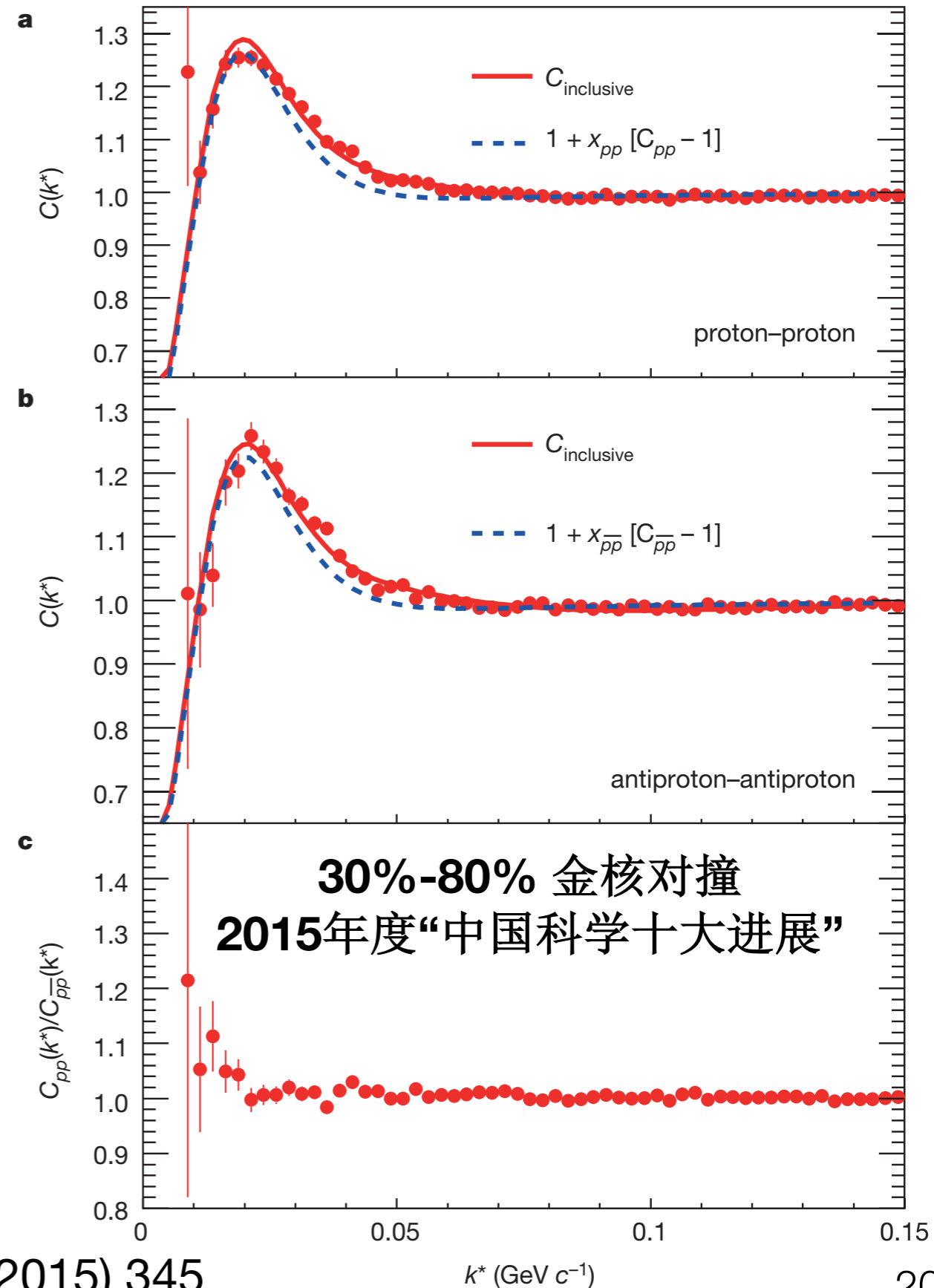
No evidence so far.

- 传统实验方法HBT应用在前沿物理研究，“反质子对”动量关联函数测量，实现反物质间作用力的测量



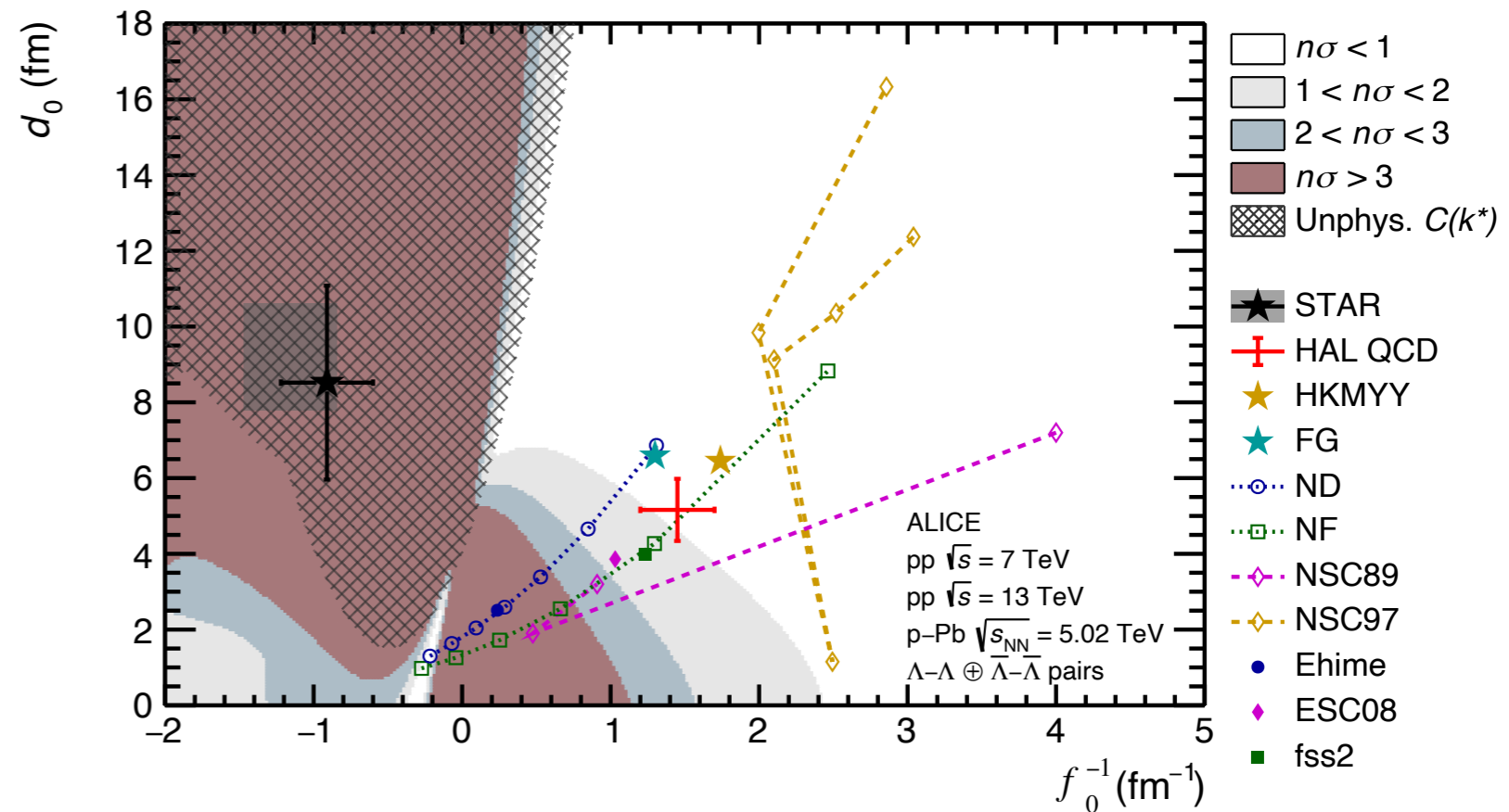
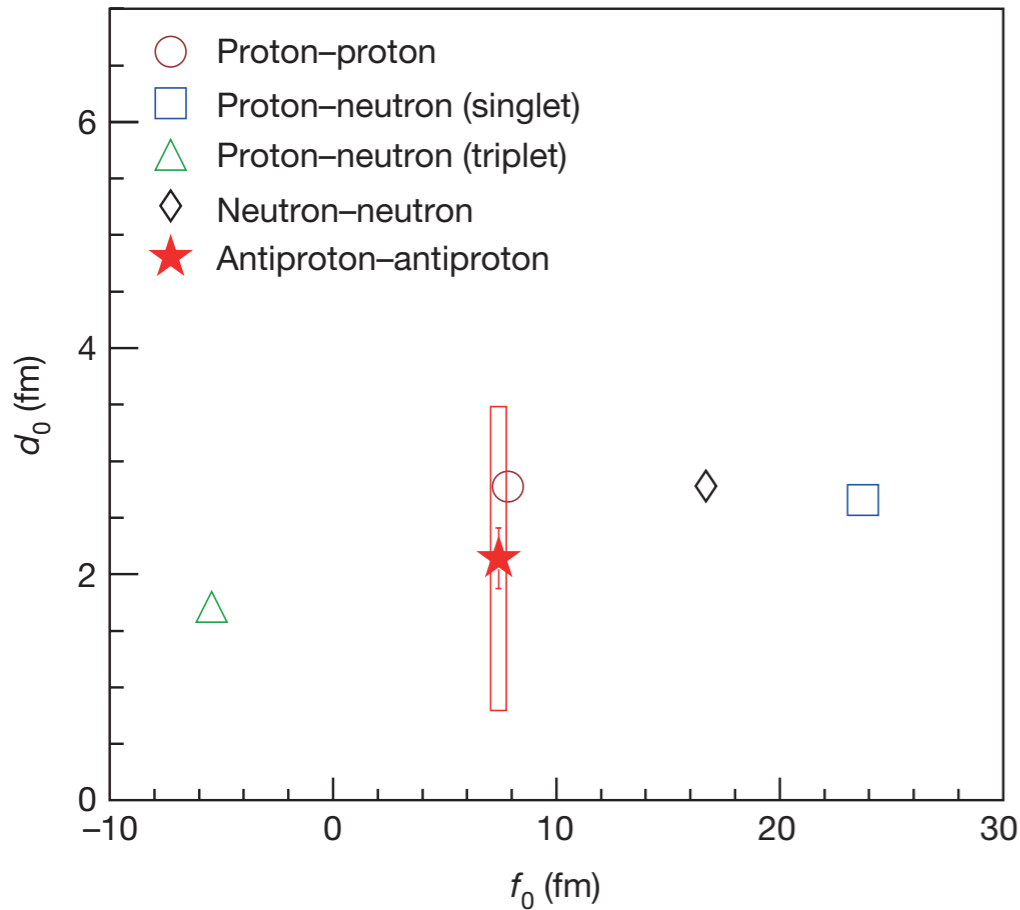
$$C_{\text{inclusive}}(k^*) = 1 + x_{pp} [C_{pp}(k^*; R_{pp}) - 1] + x_{p\Lambda} [\tilde{C}_{p\Lambda}(k^*; R_{p\Lambda}) - 1] + x_{\Lambda\Lambda} [\tilde{C}_{\Lambda\Lambda}(k^*) - 1]$$

k^* : 关联对静止系中动量; $k^* \rightarrow \infty, C(k^*) = 1$



30%-80% 金核对撞
2015年度“中国科学十大进展”

STAR Col., Nature **527** (2015) 345; PRL **114** (2015) 022301; ALICE Col. PLB 797,134822 (2019)



- 和其他方向的联系：散射长度和有效力程是描述超冷原子捕捉中弹性散射的关键参数
- **STAR**采用**LL**模型：Sov. J. Nucl. Phys. **35** (1982) 770

$$C(Q) = N \left[1 + \lambda \left(-\frac{1}{2} \exp(-r_0^2 Q^2) + \frac{1}{4} \frac{|f(k)|^2}{r_0^2} \left(1 - \frac{1}{2\sqrt{\pi} r_0} \frac{d_0}{r_0} \right) + \frac{\text{Re}f(k)}{\sqrt{\pi} r_0} F_1(Qr_0) - \frac{\text{Im}f(k)}{2r_0} F_2(Qr_0) \right) + a_{\text{res}} \exp(-r_{\text{res}}^2 Q^2) \right], \quad (4)$$

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

$$|a_{\Lambda\Lambda}| < |a_{p\Lambda}| < |a_{NN}|$$

注* LL模型取 $f_0 = a_0$
传统散射研究取 $f_0 = -a_0$

反物质研究具有广阔的前景

从(反)夸克, (反)重子, (反)原子核, 到(反)原子实验研究, 记录了人类探索物质形态及研究其基本属性的进程

欧洲核子中心(CERN)开始用反物质原子检验CPT原理的普适性、引力作用下物质反物质的等效性原理等

<https://home.cern/news/news/experiments/new-antimatter-gravity-experiments-begin-cern>

- CERN加速器两年的维护升级完成, 新的实验于2021/6月陆续开始
- 传统反质子减速器(Antiproton Decelerator)+新的减速环ELENA (Extra Low ENergy Antiproton), 将反质子的能量从5.3 MeV减到0.1 MeV, 捕捉率提高近100倍 (AEgIS, ALPHA, ASACUSA, BASE, GBAR等实验组)

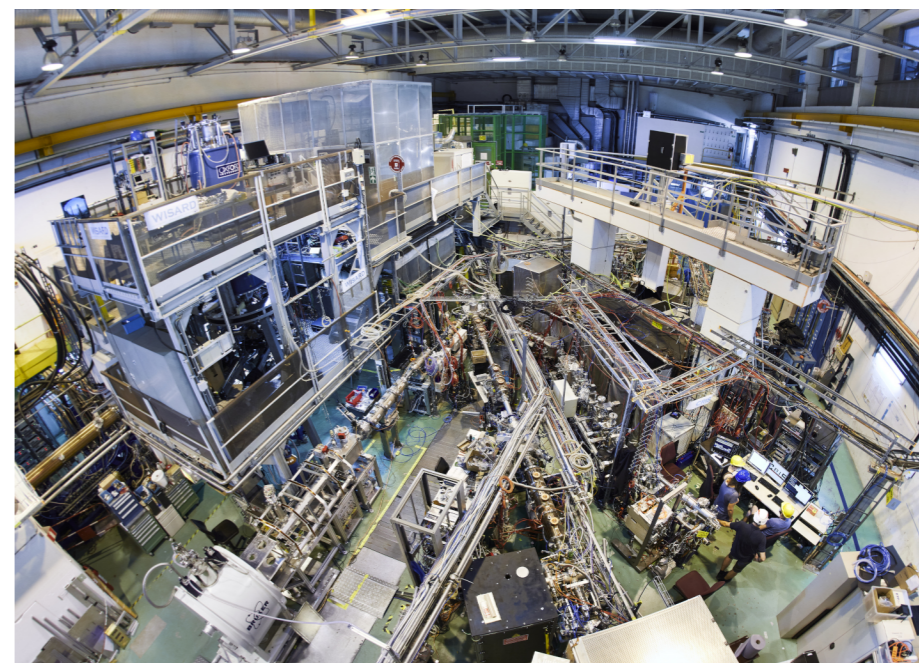
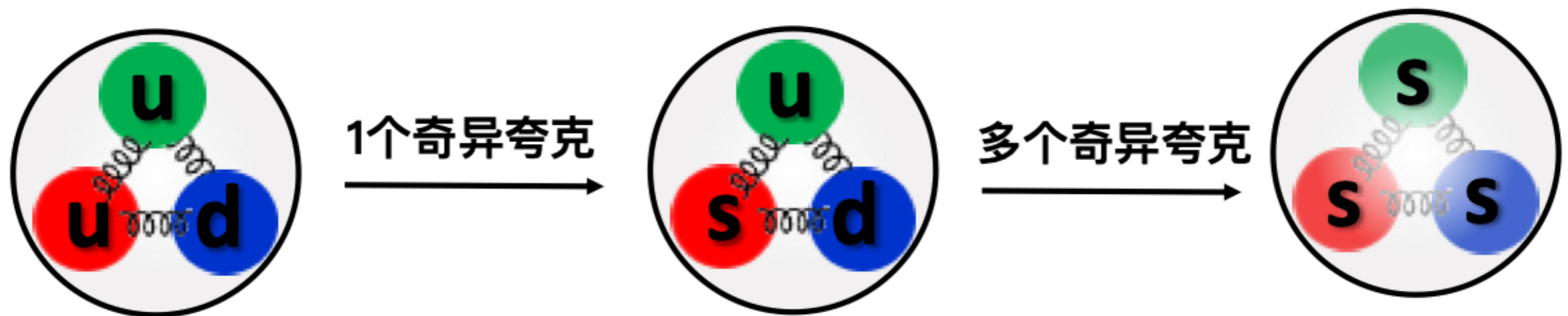


Table 1 Summary of the measured counts.

Sample X	\bar{H}_{cycle}	\bar{p} number N_X	Counts in the S interval n^S	Cosmic ray counts in the S interval n_{μ}^S	Counts in the C interval n^C	Excess counts (S interval), normalized to $N_{\bar{p}e^+}$ $(n^S - n^C \frac{\Delta T^S}{\Delta T^C}) \frac{N_{\bar{p}e^+}}{N_X}$	\bar{H} number
\bar{p}	3498	$(1.58 \pm 0.01) \times 10^9$	42.0 ± 6.5	17.0 ± 0.3	528 ± 23	13.7 ± 4.5	
$\bar{p}e^+$	1211	$(6.08 \pm 0.07) \times 10^8$	16.0 ± 4.0	5.8 ± 0.1	278 ± 17	1.7 ± 1.6	
$\bar{p}e^+$	2206	$(1.08 \pm 0.01) \times 10^9$	79.0 ± 8.9	10.7 ± 0.2	475 ± 22	59.2 ± 8.9	45.6 ± 10.0

AEgIS Col.,
Communications Phys. 4, 19 (2021)

反物质-反奇异夸克物质-多奇异夸克物质



中子星EoS及大质量星信号

- 中子星状态方程：如果含有超子（没有足够的相空间，不衰变），状态方程将变软。直接影响包括最大质量 $\sim 1.4M_{\odot}$

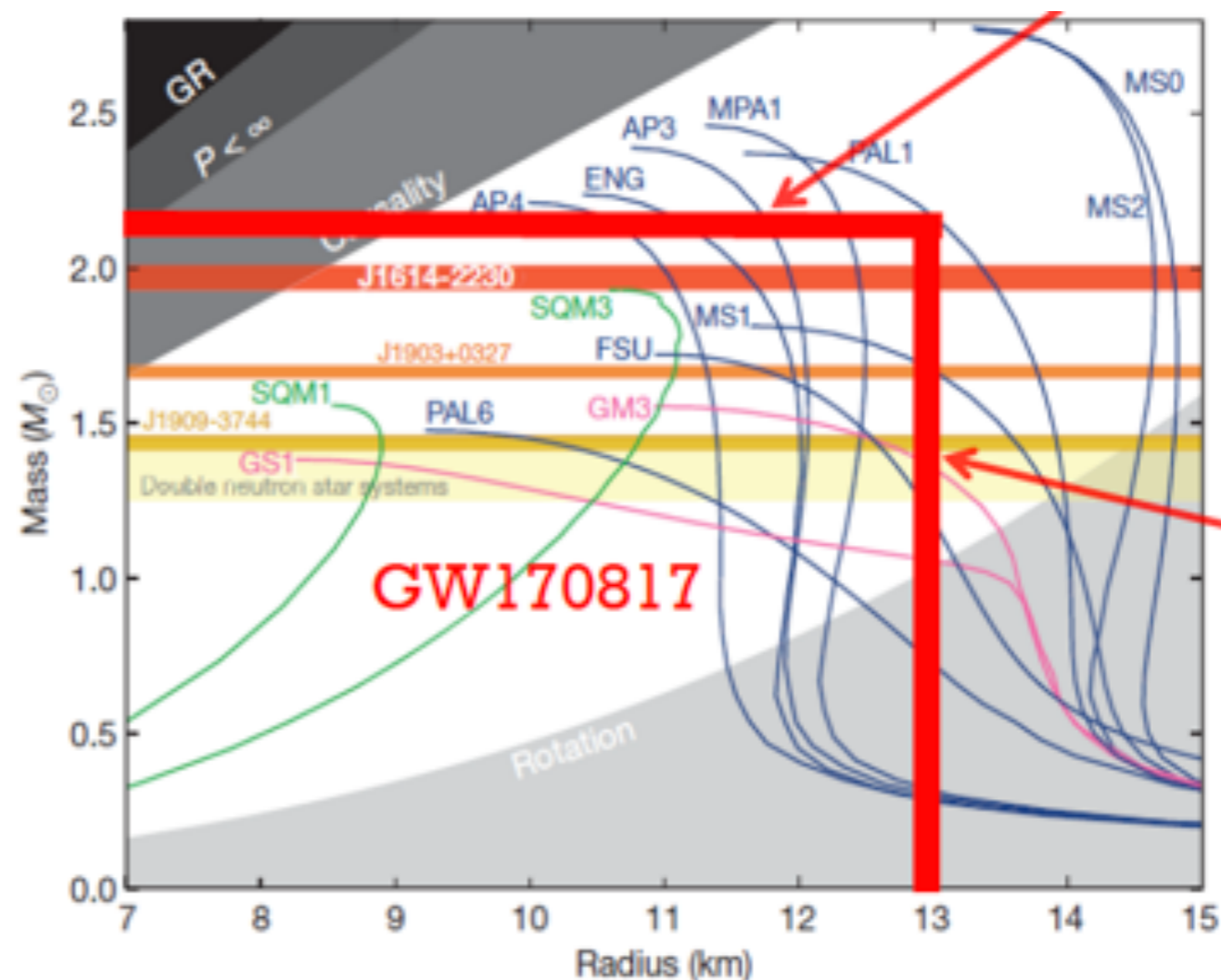
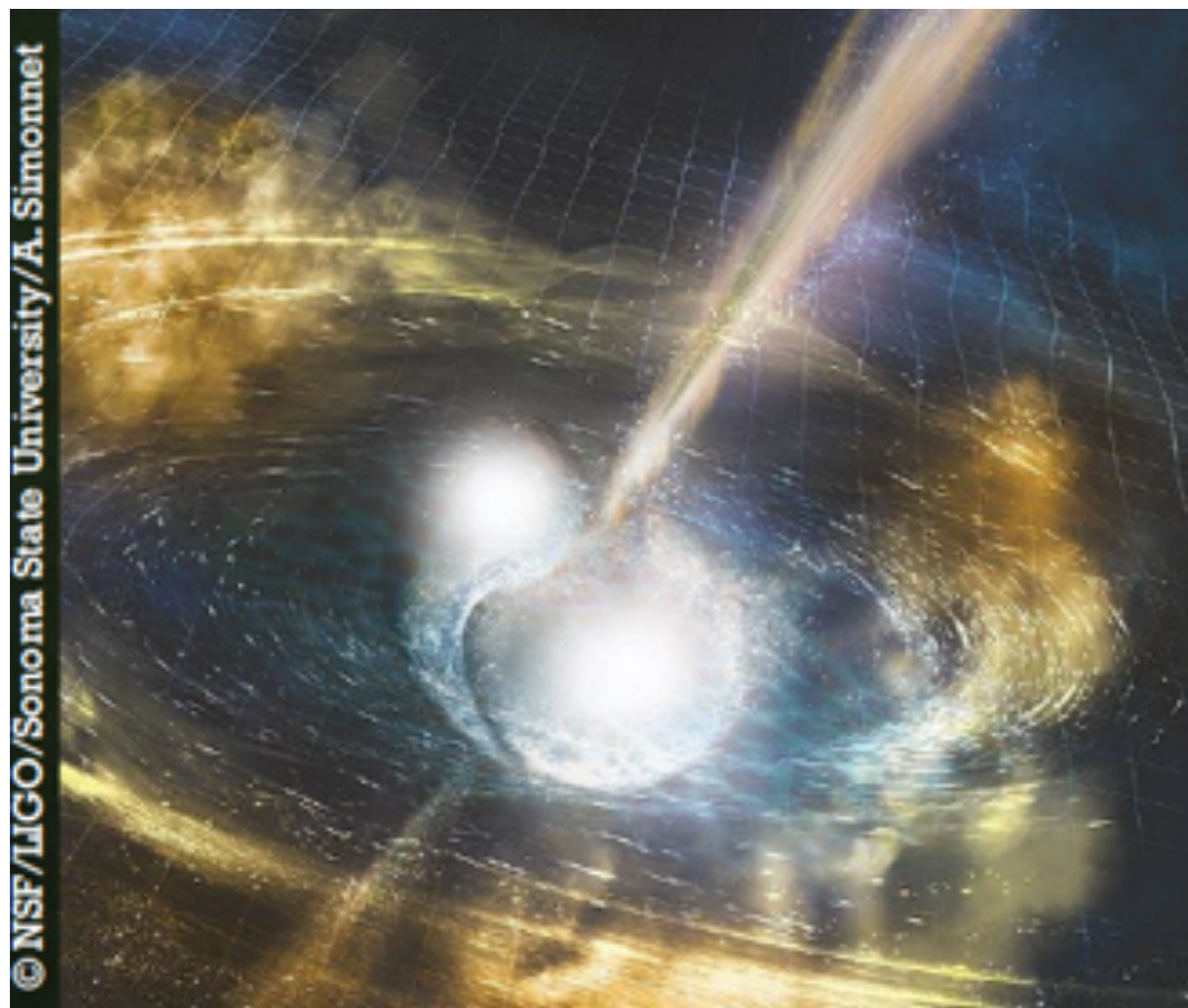
- 双中子星并合引力波信号，也提供了测量中子星质量和半径的途径

The LIGO and Virgo Col., PRL 119, 161101 (2017); 121, 161101 (2018)

$$1.97 M_{\odot} \quad R_1 = 11.9^{+1.4}_{-1.4} \text{ km} \quad R_2 = 11.9^{+1.4}_{-1.4} \text{ km}$$

新的大质量星信号

Antoniadis et al. Nat. Astronomy, 4, 72 (2020)...



如何加深理解“超子迷惑”

- 超子-核子三体相互作用势，是研究中子星状态方程的关键组分
- 中子星里出现超子可能要在重子密度非常高的地方？
- ...

Lonardonni et al., PRC 87, 014303 (2013); PRL 114, 092301 (2015)

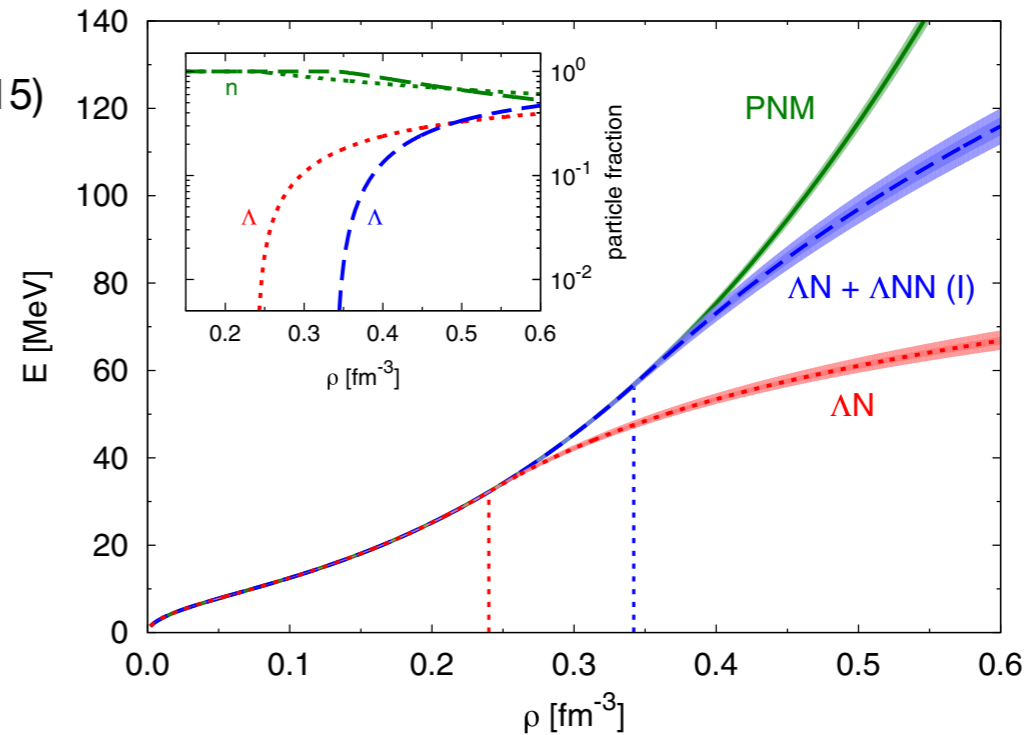
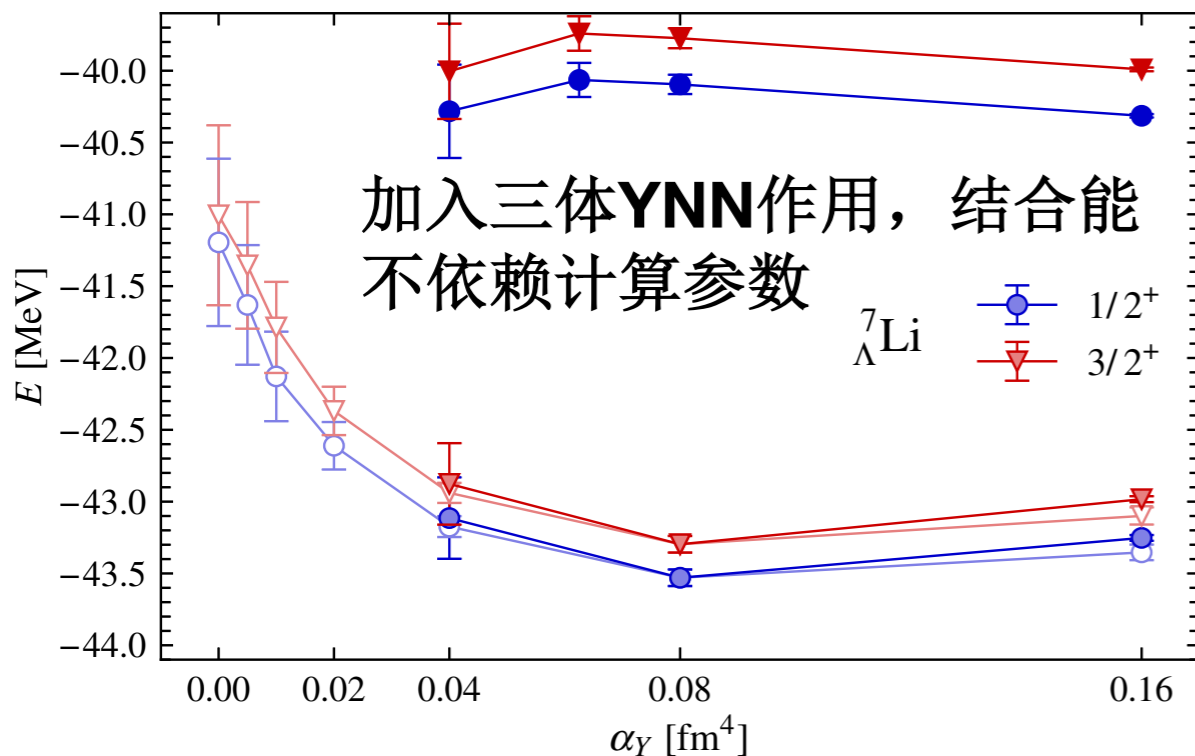
AFDMC计算

$$H = \sum_i \frac{p_i^2}{2m_n} + \sum_\lambda \frac{p_\lambda^2}{2m_\Lambda} + \sum_{i<j} v_{ij} + \sum_{i<j<k} v_{ijk} + \sum_{\lambda,i} v_{\lambda i} + \sum_{\lambda,i<j} v_{\lambda ij},$$

Wirth et al., PRL 117, 182501 (2016); PRC 97, 064315 (2018)

ab initio计算, Λ - Σ conversion

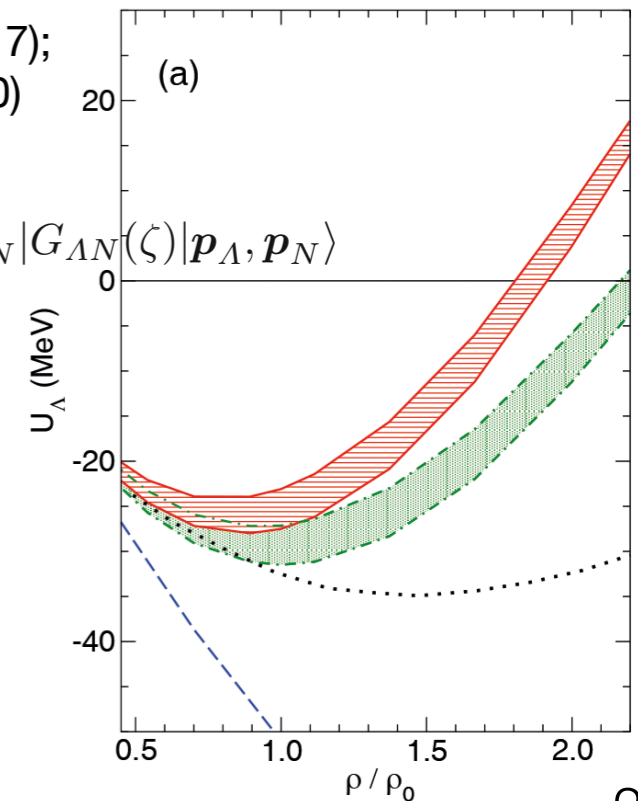
$$H = H(0) = T_{\text{int}} + V_{\text{NN}} + V_{3\text{N}} + V_{\text{YN}} + \Delta M$$



Haidenbauer et al., EPJA 53, 121 (2017); EPJA 56, 91 (2020)

Chiral EFT计算

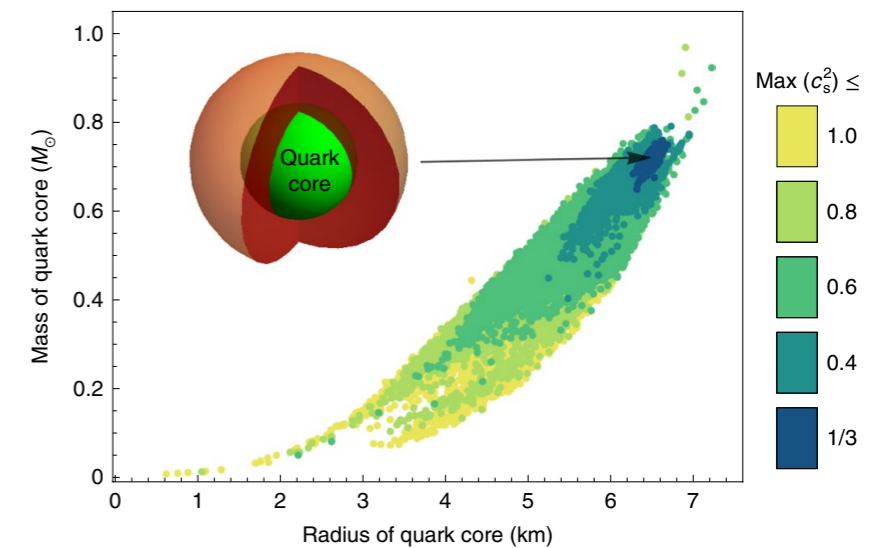
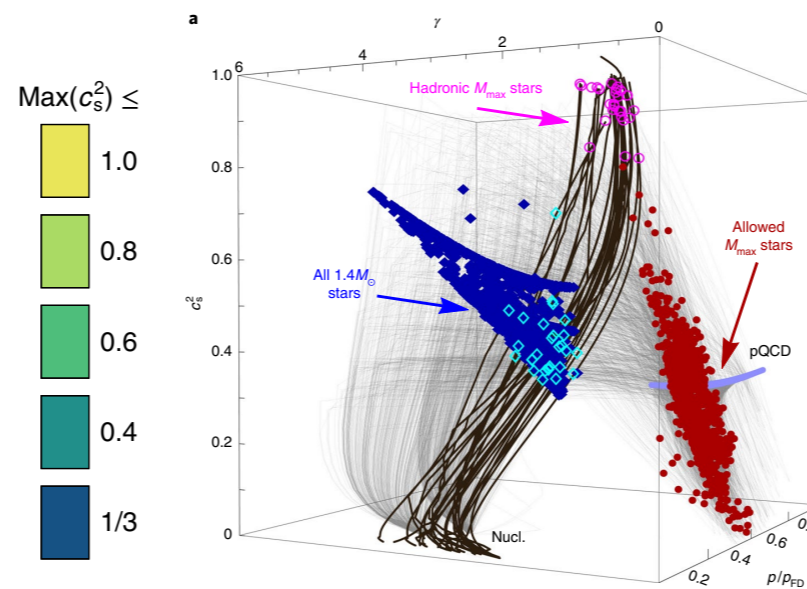
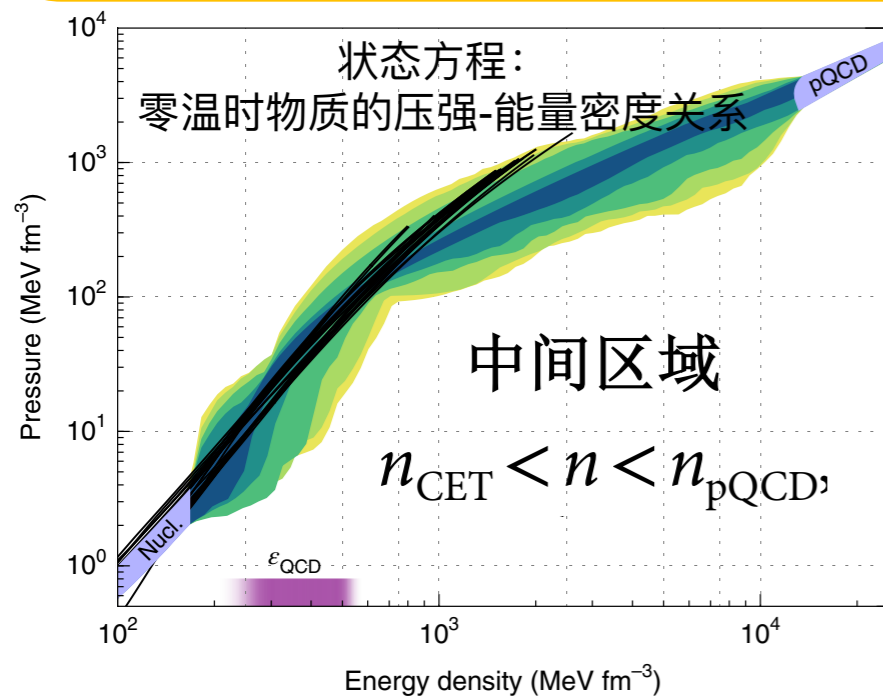
$$U_\Lambda(p_\Lambda, \rho) = \int_{|\mathbf{p}_N| < k_F} \frac{d^3 p_N}{(2\pi)^3} \text{Tr} \langle \mathbf{p}_\Lambda, \mathbf{p}_N | G_{\Lambda N}(\zeta) | \mathbf{p}_\Lambda, \mathbf{p}_N \rangle$$



大质量星含夸克物质或被证实

“Evidence for quark-matter cores in massive neutron star” Annala, Gorda, Kurkela, Nattila, Vuorinen, Nature Phys. 16, 907 (2020); PRL 120, 172703 (2018)

570k中间区域独立EoS分析；作者的选择：“given an interpolated EoS, the smallest density from which gamma is continuously less than 1.75 to asymptotic densities is identified with the onset of quark matter”



研究人员解释说，我们周围所有普通物质都由原子组成，原子核由质子、中子及围绕在其周围的电子组成。但在中子星内部，原子会坍塌成密度极高的核物质，其中中子和质子紧紧“依偎”在一起，因此整个中子星可视为一个巨大的核。科学家一直不清楚，质量最大中子星内核中的物质是否会坍塌成更奇特的夸克物质。

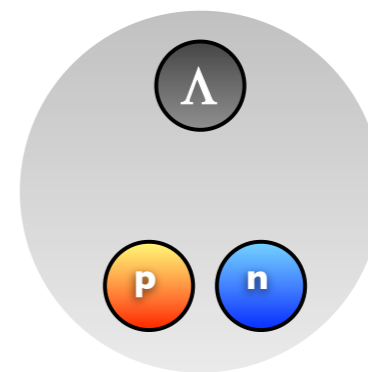
第一原则性计算表明，最大稳定质量中子星核内的物质，与夸克物质的相似度远高于与普通核物质的相似度，同时该夸克物质核的直径可能超过整个中子星直径的一半。

促成这一新发现的关键在于天体物理学研究近期取得的两个重要成果：中子星并和产生的引力波的测定，以及对质量接近两倍太阳质量的大型中子星的探测。

科技日报：http://digitalpaper.stdaily.com/http_www.kjrb.com/kjrb/html/2020-06/04/content_446111.htm?div=-1

重离子碰撞实验的切入点：超核少体系统。早期实验数据的统计误差大，结论不明显

	$B_{\Lambda} \pm \Delta B_{\Lambda}$ (MeV)	δB_{Λ} (MeV)
	Bohm et al. ^{a)}	This work
${}^3_{\Lambda}\text{H}$	0.01 ± 0.07	0.15 ± 0.08
		0.14 ± 0.11

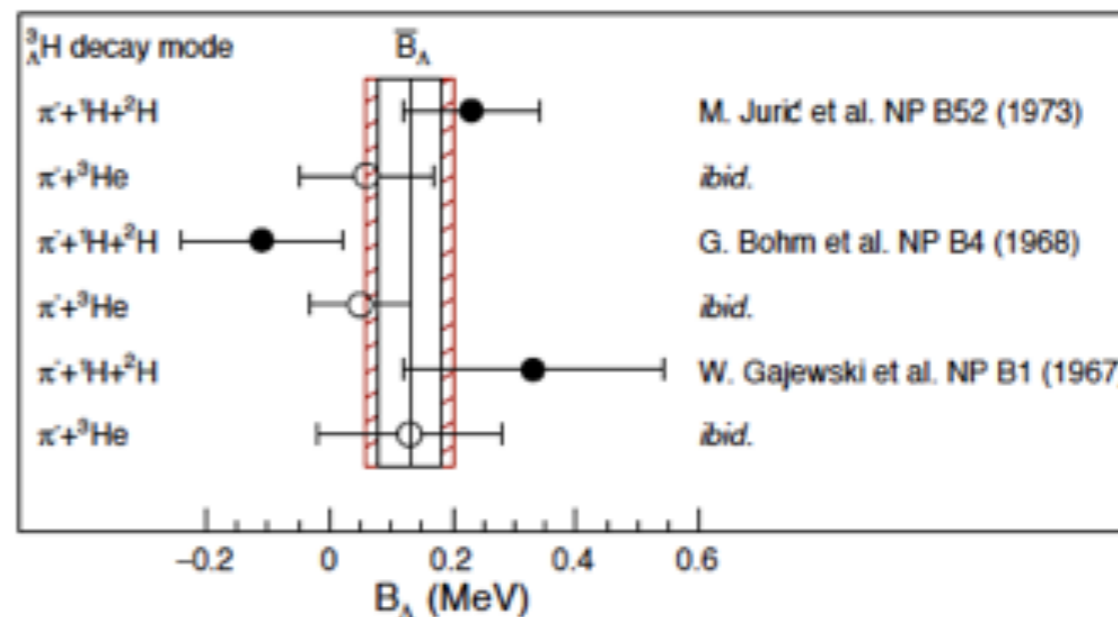
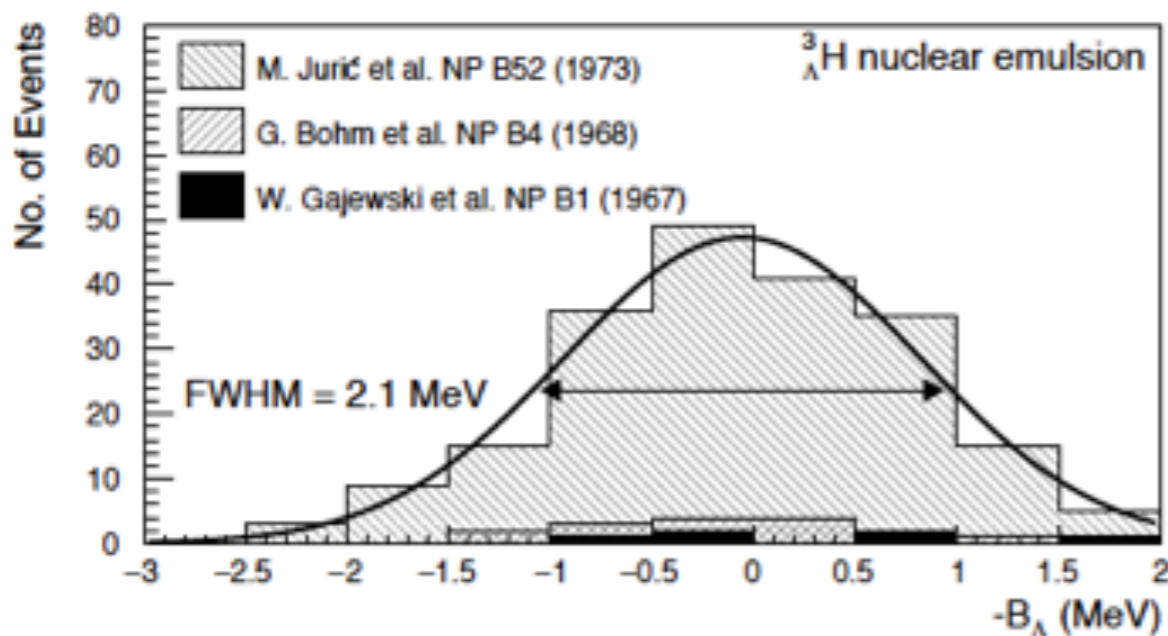


$$B_{\Lambda} = 0.13 \pm 0.05 \text{ MeV}$$

G. Bohm et al., Nucl. Phys. B4, 511 (1968)

This work : M. Juric, G. Bohm et al., Nucl. Phys. B52,1 (1973)

Achenbach, PoS (Hadron 2017) 207



“I feel that we are far from seeing the end of this road. A good deal of theoretical work on this 3-body system would still be well justified.” Dalitz Nucl. Phys. A 754, 14 (2005)

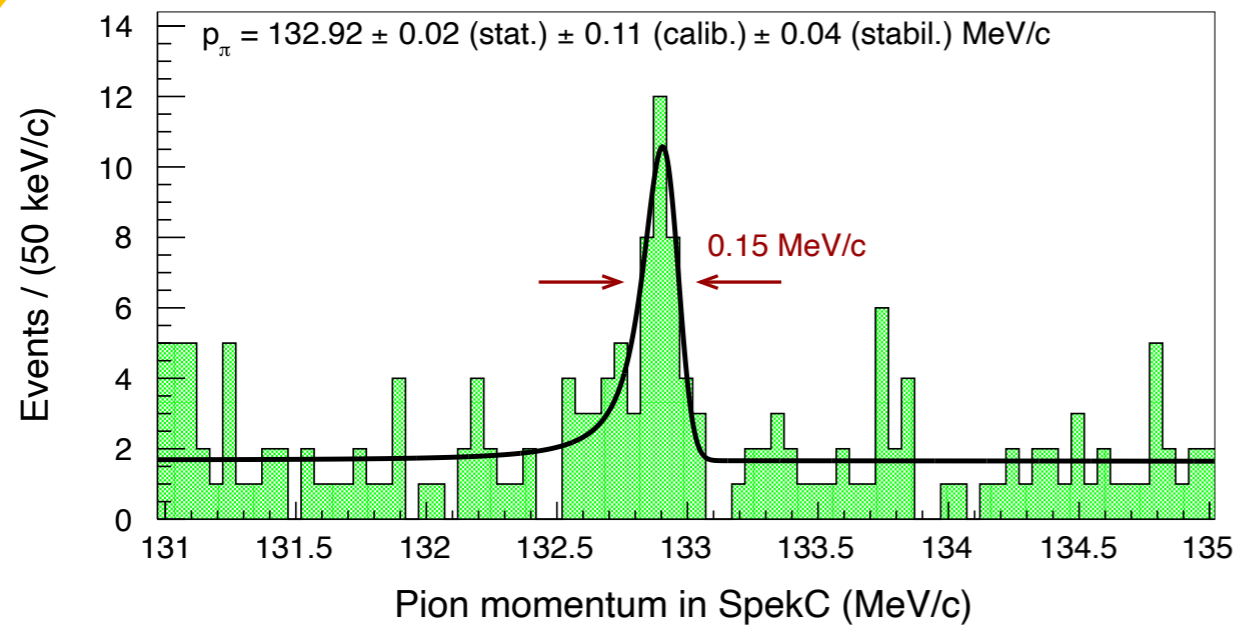
超核少体系统显著的问题

(MeV)	$B_{\Lambda}(^3_{\Lambda}\text{H})$	$B_{\Lambda}(^4_{\Lambda}\text{H}_{\text{g.s.}})$	$E_x(^4_{\Lambda}\text{H}_{\text{exc.}})$	$B_{\Lambda}(^5_{\Lambda}\text{He})$
Exp.	0.13(5)	2.16(8)	1.09(2)	3.12(2)
Dalitz	0.10	2.24	0.36	≥ 5.16
NSC97f(S)	0.18	2.16	1.53	2.10
AFDMC(I)	–	1.97(11)	–	5.1(1)
AFDMC(II)	–1.2(2)	1.07(8)	–	3.22(14)
LO χ EFT(600)	0.11(1)	2.31(3)	0.95(15)	5.82(2)
LO χ EFT(700)	–	2.13(3)	1.39(15)	4.43(2)

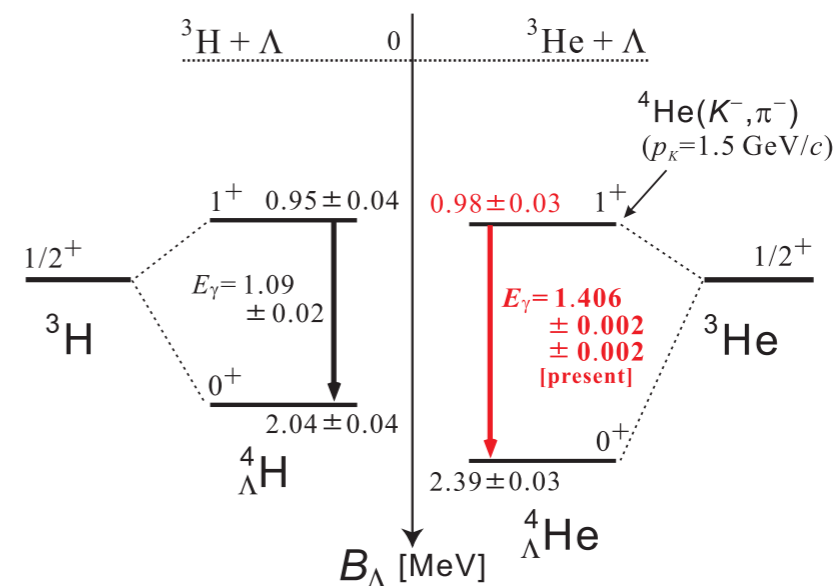
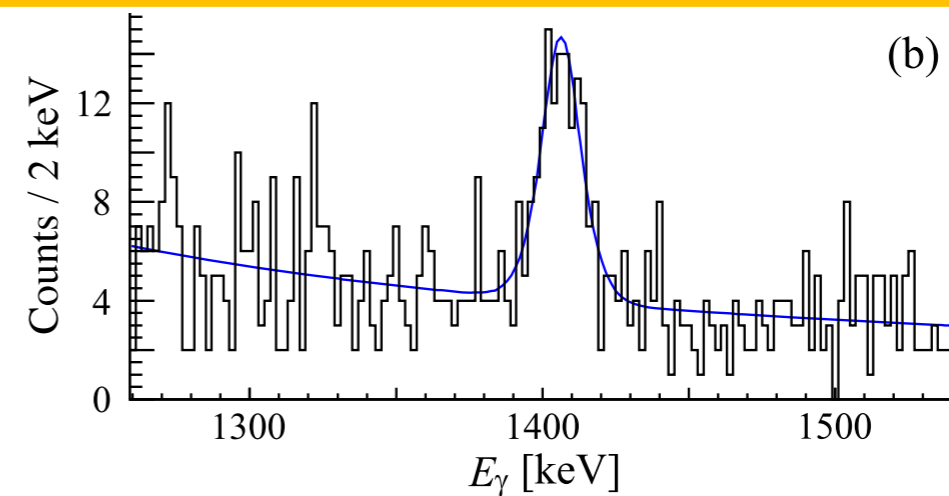
“Resolving the Lambda Hypernuclear Overbinding Problem in Pionless Effective Field Theory”

Contessi, Barnea and Gal, PRL 121, 102502 (2018)

λ (fm $^{-1}$)	Alexander[B]	NSC97f	χ LO	χ NLO
4	2.59(3)	2.32(3)	2.99(3)	2.40(3)
$\rightarrow \infty$	3.01(10)	2.74(11)	3.96(08)	3.01(06)



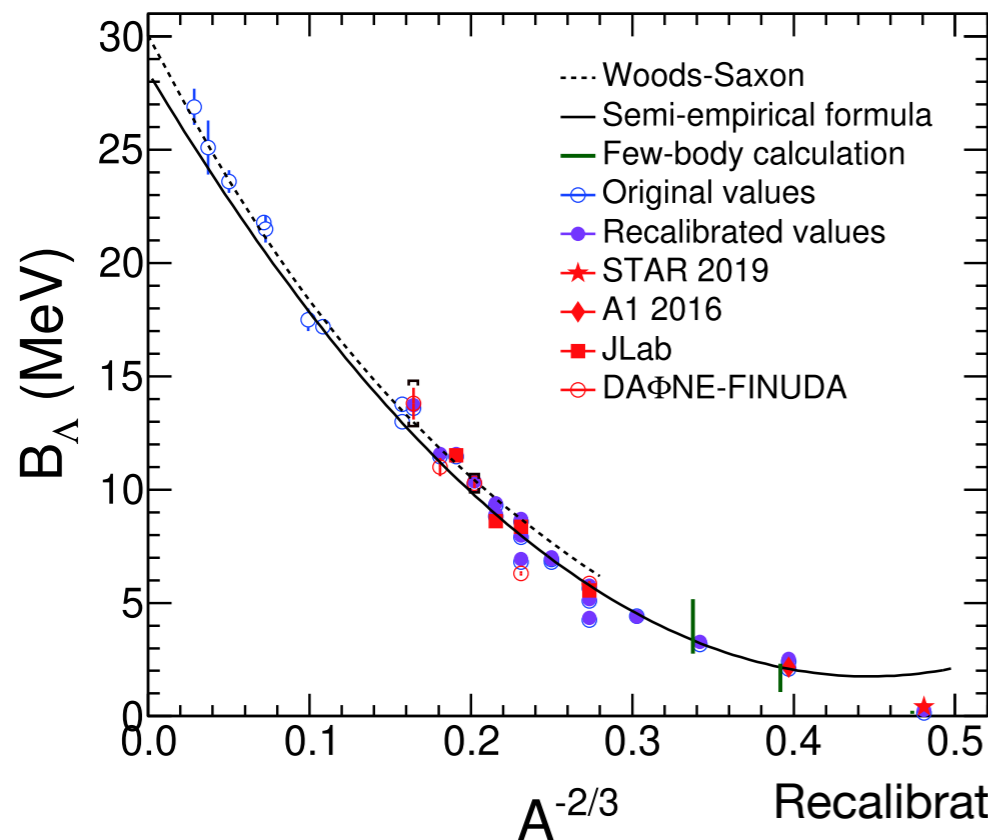
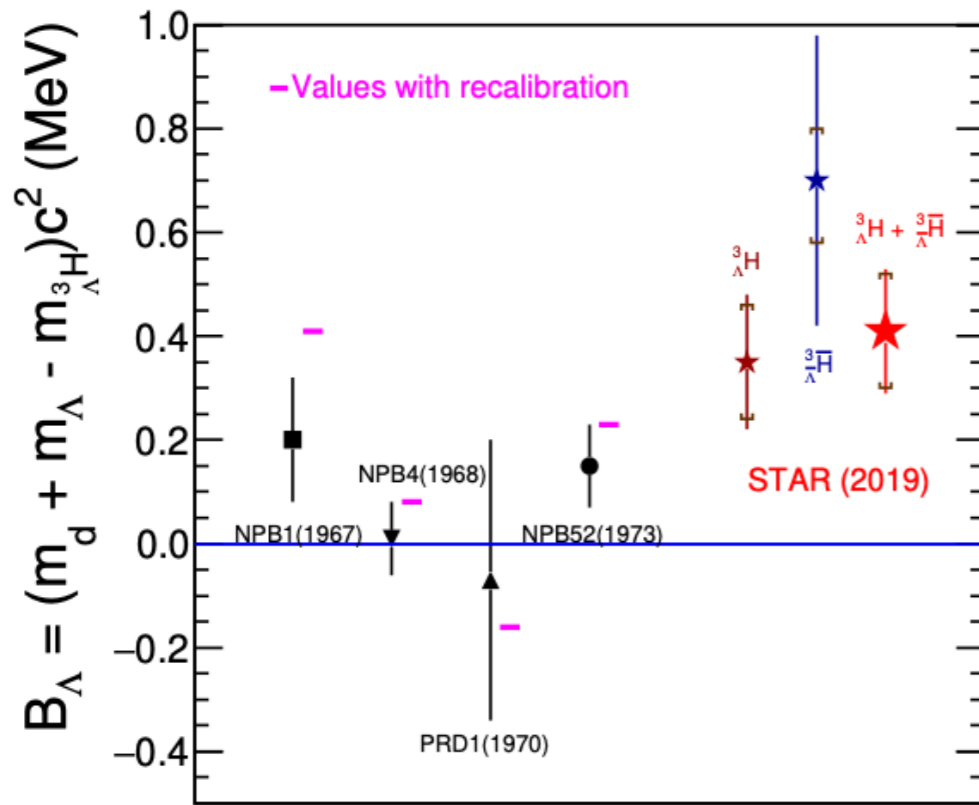
MAMI A1 Col. PRL 114, 232501 (2015);
J-PARK E13 Col., PRL 115, 222501 (2015)



STAR Col., Nature Phys. **16** (2020) 409

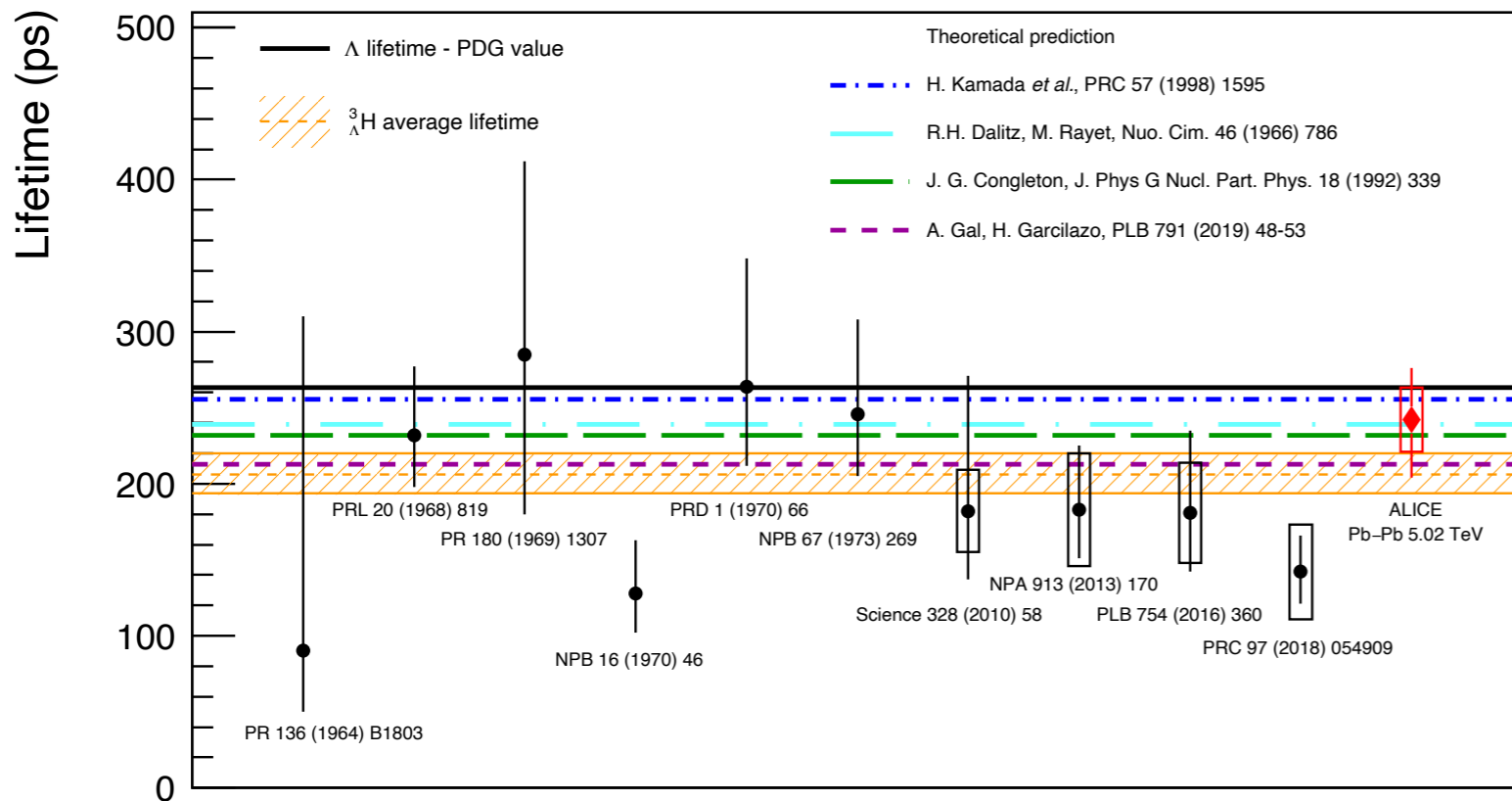
$$B_{\Lambda} = 0.41 \pm 0.12(\text{stat.}) \pm 0.11(\text{syst.}) \text{ MeV}$$

- 结合能是pionless有效场理论计算自由输入参数
Hildenbrand, Hammer, Phys. Rev. C 100, 034002 (2019)
- 结合能直接影响了YN相互作用（手征有效场理论）
Haidenbauer, Meibner, Nogaa, Phys. Lett. B 801, 135189; Eur. Phys. J.A 56, 3 (2020)

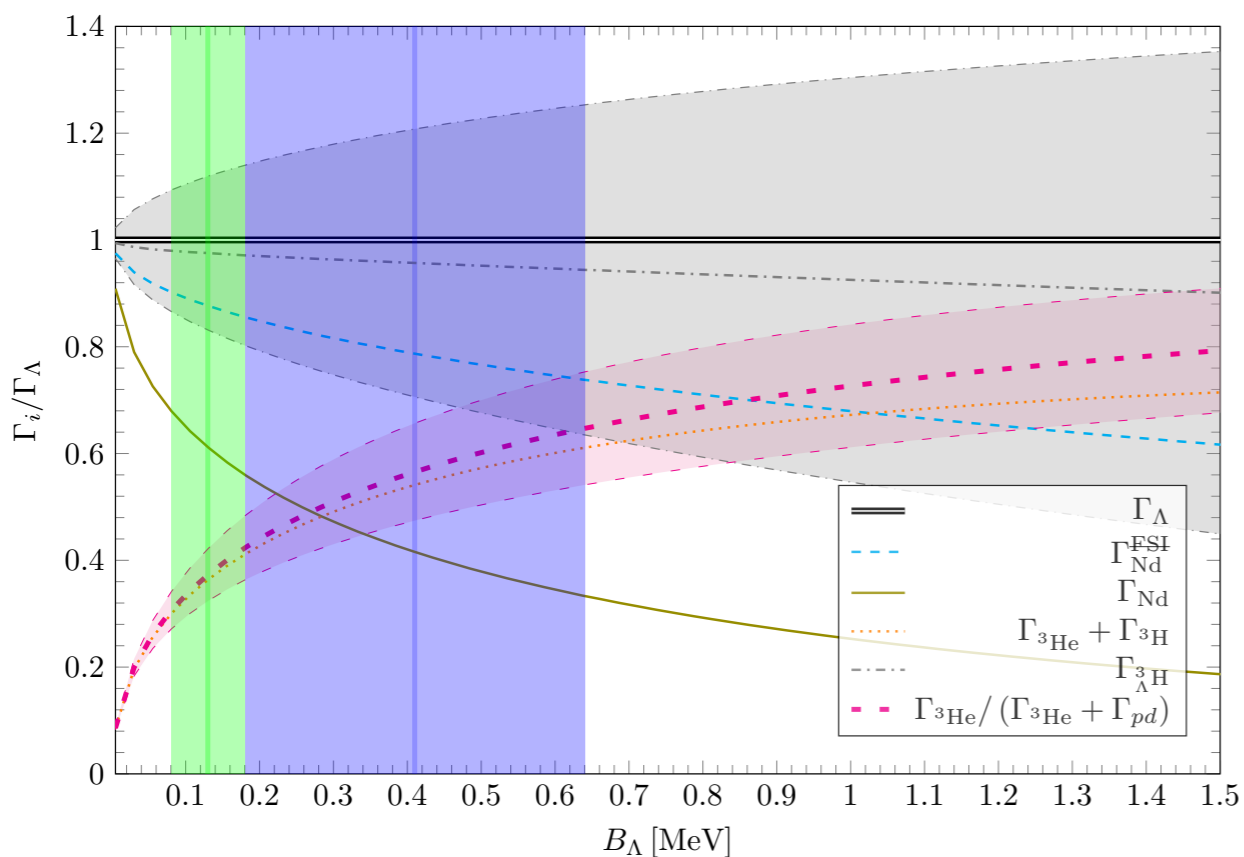


YN interaction	${}^3_{\Lambda}\text{H}$
NLO13(650) w/ Σ	0.087
NLO13(650) w/o Σ	0.095
NLO19(650) w/ Σ	0.095
NLO19(650) w/o Σ	0.100
Jülich'04 w/ Σ	0.046
Jülich'04 w/o Σ	0.162
NSC97f w/ Σ	0.099
NSC97f w/o Σ	0.062

结合能和衰变寿命



- 早期实验数据给出不一致测量结果
- 现代加速器测量指出超氦核寿命比 Λ 超子的小
ALICE Col. Phys. Lett. B 797, 134905 (2019)

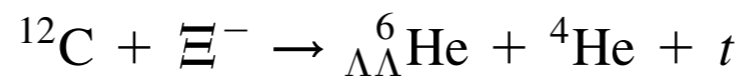
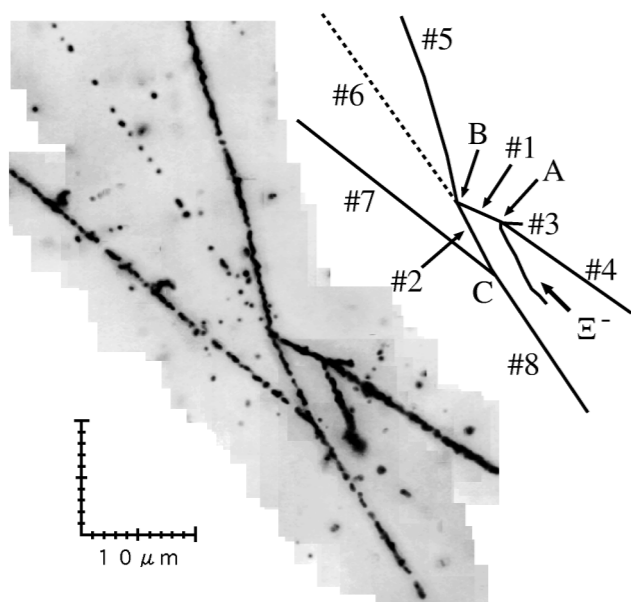


Perez-Obiol, Gazda, Friedman and Gal, arXiv:2006.16718
Hildenbrand and Hammer, arXiv:2007.10122
→ 从130到410 KeV, 对寿命的影响很小

Observable	$B_\Lambda = 0.13 \text{ MeV}$		$B_\Lambda = 0.41 \text{ MeV}$	
α_-	0.642	0.732	0.642	0.732
$(\Gamma_{pd} + \Gamma_{nd}) / \Gamma_\Lambda$	0.612	0.612	0.415	0.416
$(\Gamma_{³He} + \Gamma_{³H}) / \Gamma_\Lambda$	0.382	0.363	0.569	0.541
$\Gamma_{³H} / \Gamma_\Lambda$	0.992	0.975	0.984	0.956
$\Gamma_{³He} / (\Gamma_{³He} + \Gamma_{pd})$	0.384	0.373	0.578	0.566
$\tau_{³H} [\text{ps}]$	264.7	269.8	267.6	275.0

看更多奇异夸克自由度

- 2015年工作的出发点：格点QCD理论的发展，是否能够回答“H粒子”问题？
- Nagara event仍然是目前对 Λ - Λ 作用最好的测量 PRL 106, 162001 (2011); 106, 162002 (2011)...



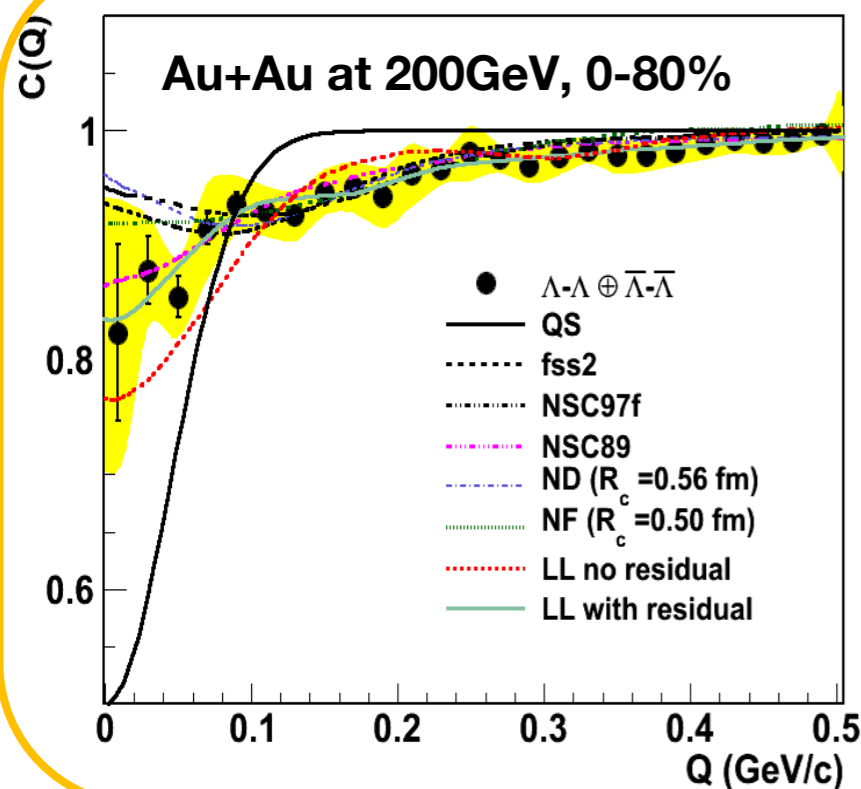
Takahashi et al., PRL 87, 212502 (2001)

$$\Delta B_{\Lambda\Lambda}(\Lambda\Lambda^A Z) = B_{\Lambda\Lambda}(\Lambda\Lambda^A Z) - 2B_{\Lambda}(\Lambda^{A-1} Z). \quad (1)$$

$$M_H > 2M_{\Lambda} - B_{\Lambda\Lambda}, \quad (2)$$

$$\left. \begin{array}{l} (1) \\ (2) \end{array} \right\} \begin{array}{l} 1.01 \pm 0.20^{+0.18}_{-0.11} \text{ MeV} \\ 2223.7 \text{ MeV}/c^2 \end{array}$$

E373 (KEK-PS), PRC 88, 014003 (2013) $\rightarrow 0.67 \pm 0.17 \text{ MeV}$

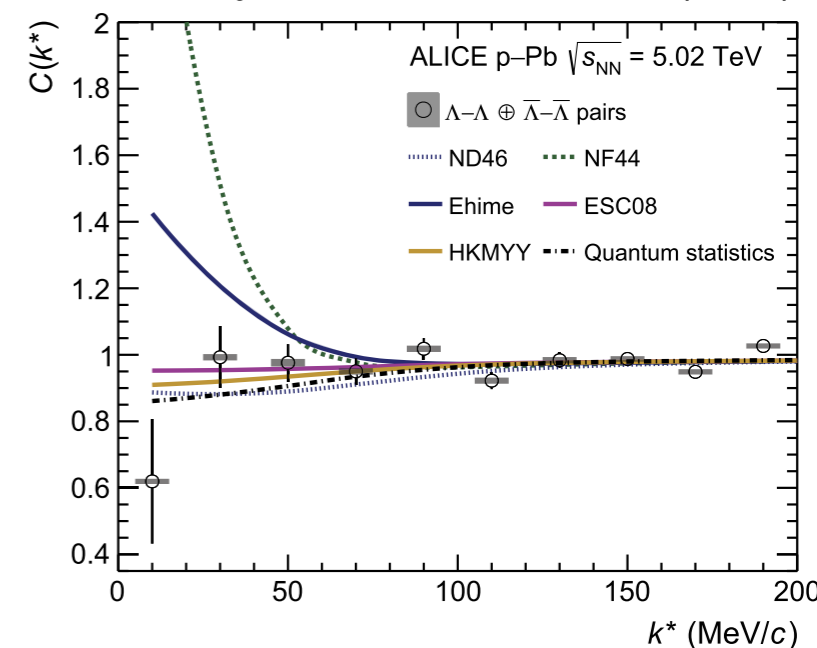
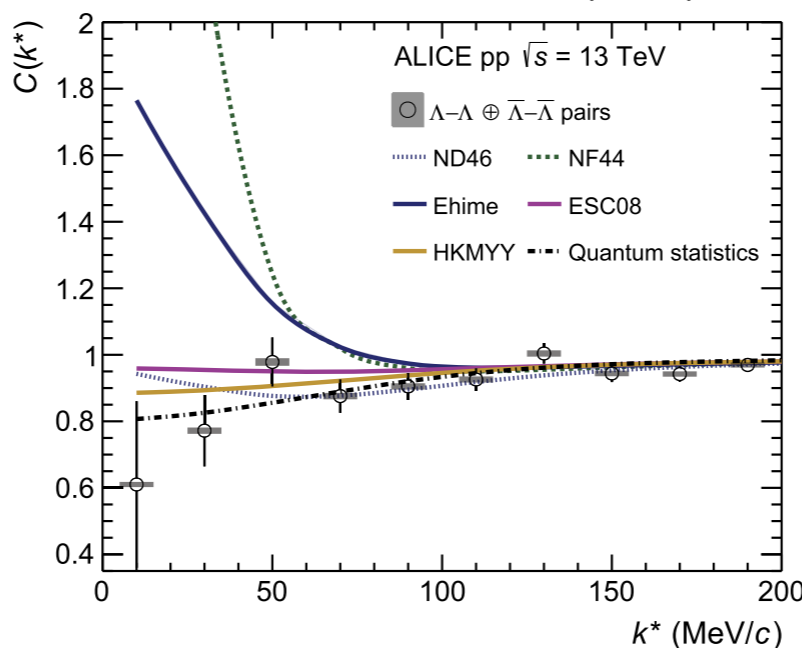


大系统



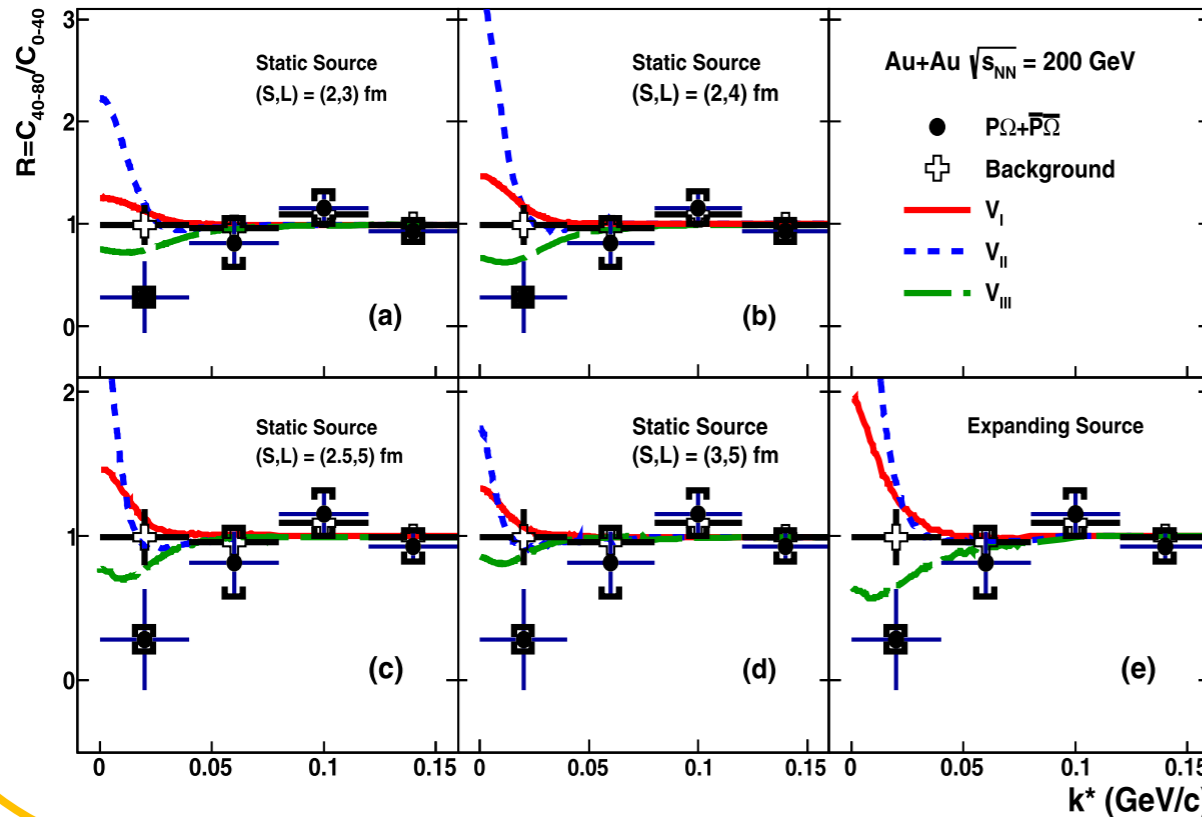
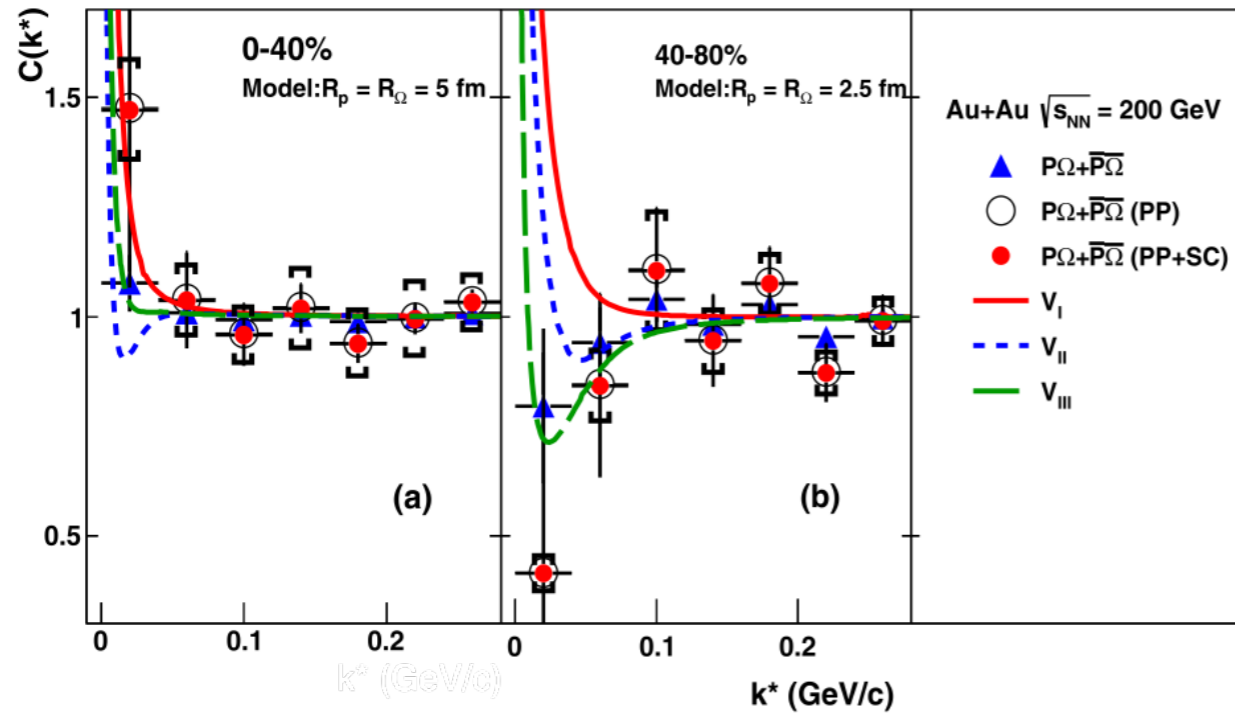
小系统 (源尺寸差异)

STAR Col. PRL 114, 022301 (2015); ALICE Col. Phys. Lett. B 797,134822 (2019)

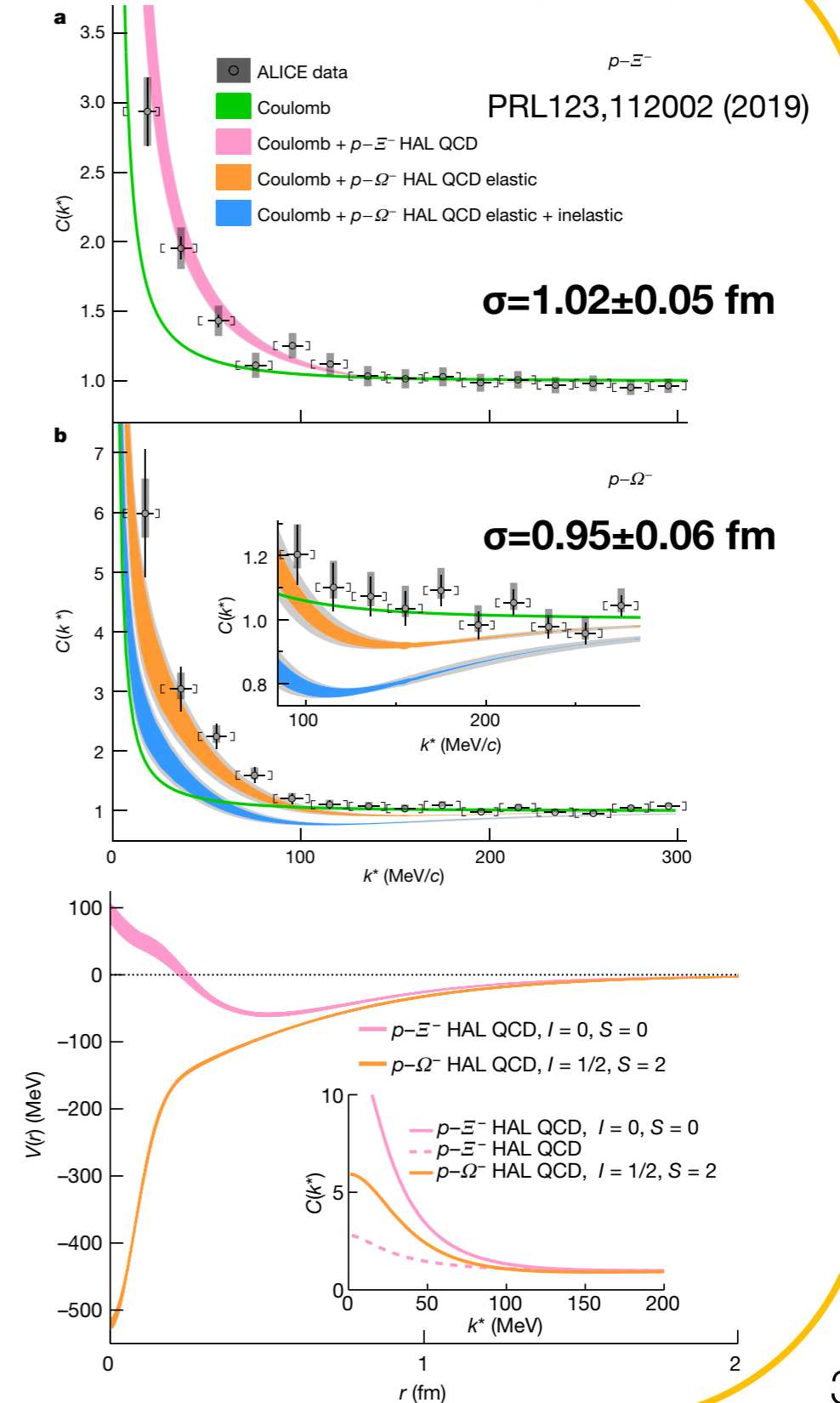


STAR Col. Phys. Lett. B 790, 490 (2019);

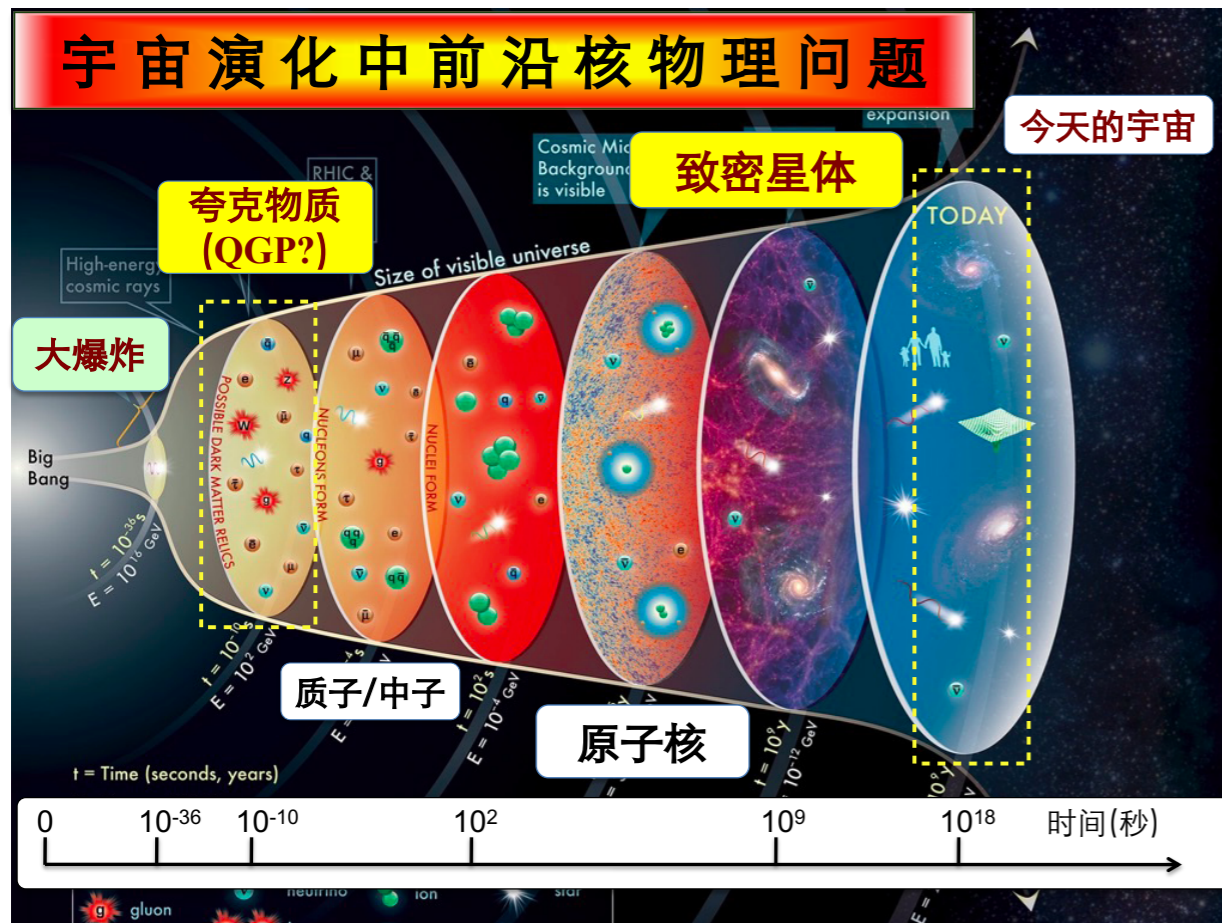
ALICE Col. Nature 588, 232 (2020)



大系统
VS
小系统



- 重离子碰撞：研究宇宙早期物质的理想实验场所，一系列关键核物理问题



Early days of RHIC discoveries and the topics that continue

- Jet quenching
- Flow

And hot topics nowadays:

- Global/local pol.
- CME/CMW
- QCD phase diagram
- ...

Strong evidences pointing to a “dense, opaque, low-viscous, pre-hadronic liquid state of matter not anticipated before RHIC”

RHIC white paper: NPA 757 (2005)

- 相关的若干问题:

✓ **A=4**原子核的**CPT**检验

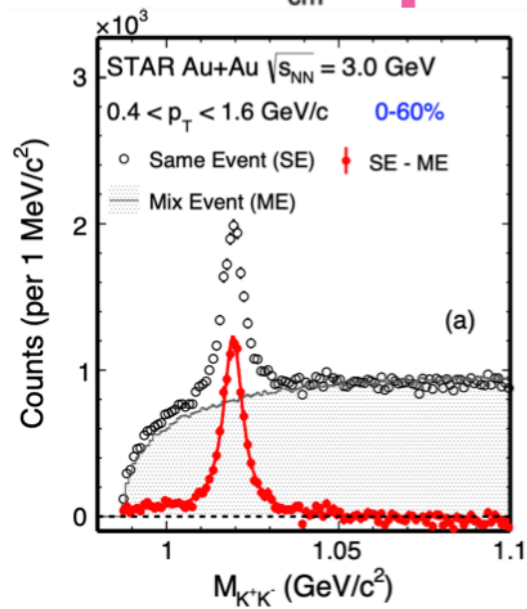
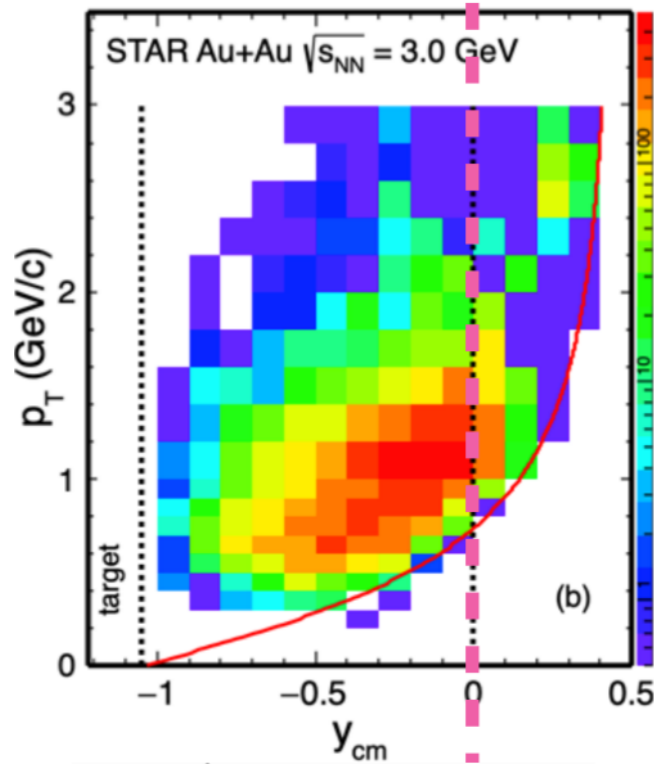
✓ 最轻的**Ξ**超核是什么?

Hiyama et al., “Possible lightest Xi Hypernuclei with Modern Xi-N Interactions” (PRL 2020)

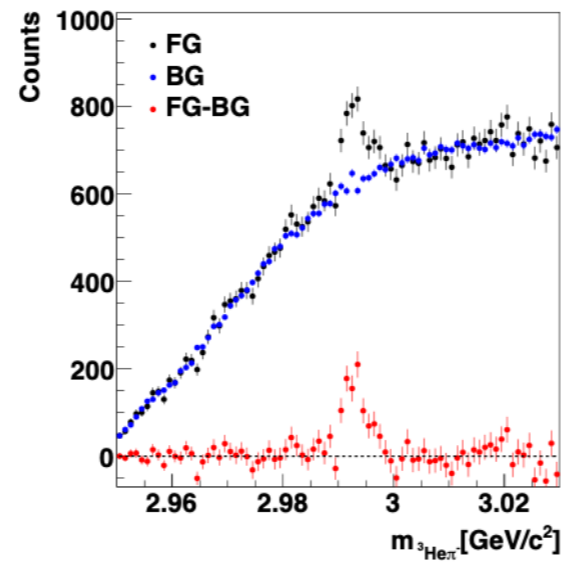
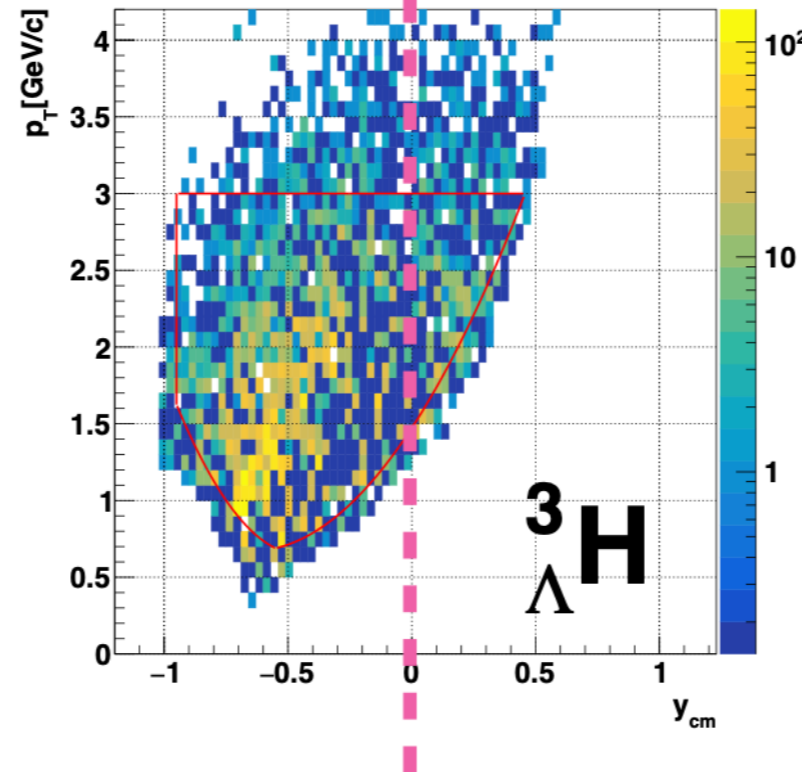
✓ 中子星内核有超子吗?

Watson et al., “Identification of strontium in the merger of two neutron stars” (Nature 2019)

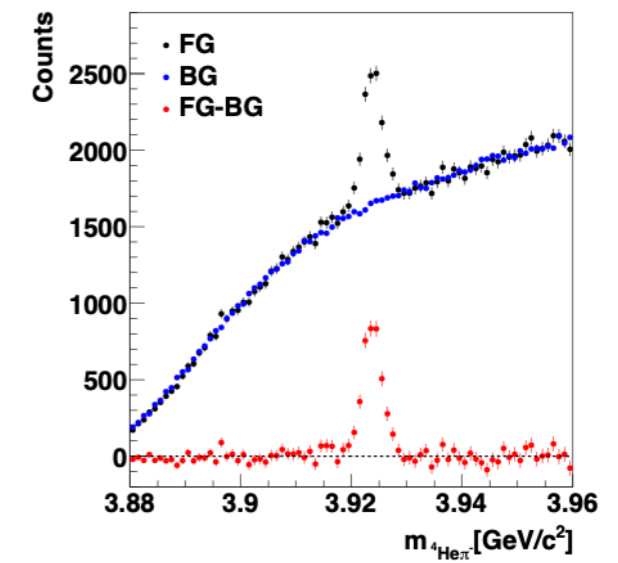
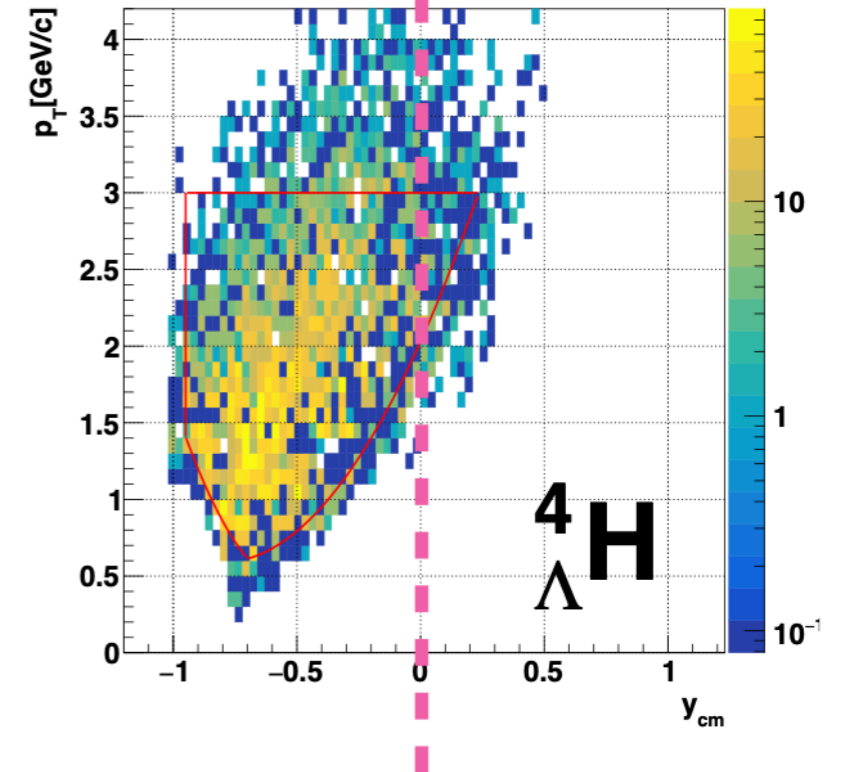
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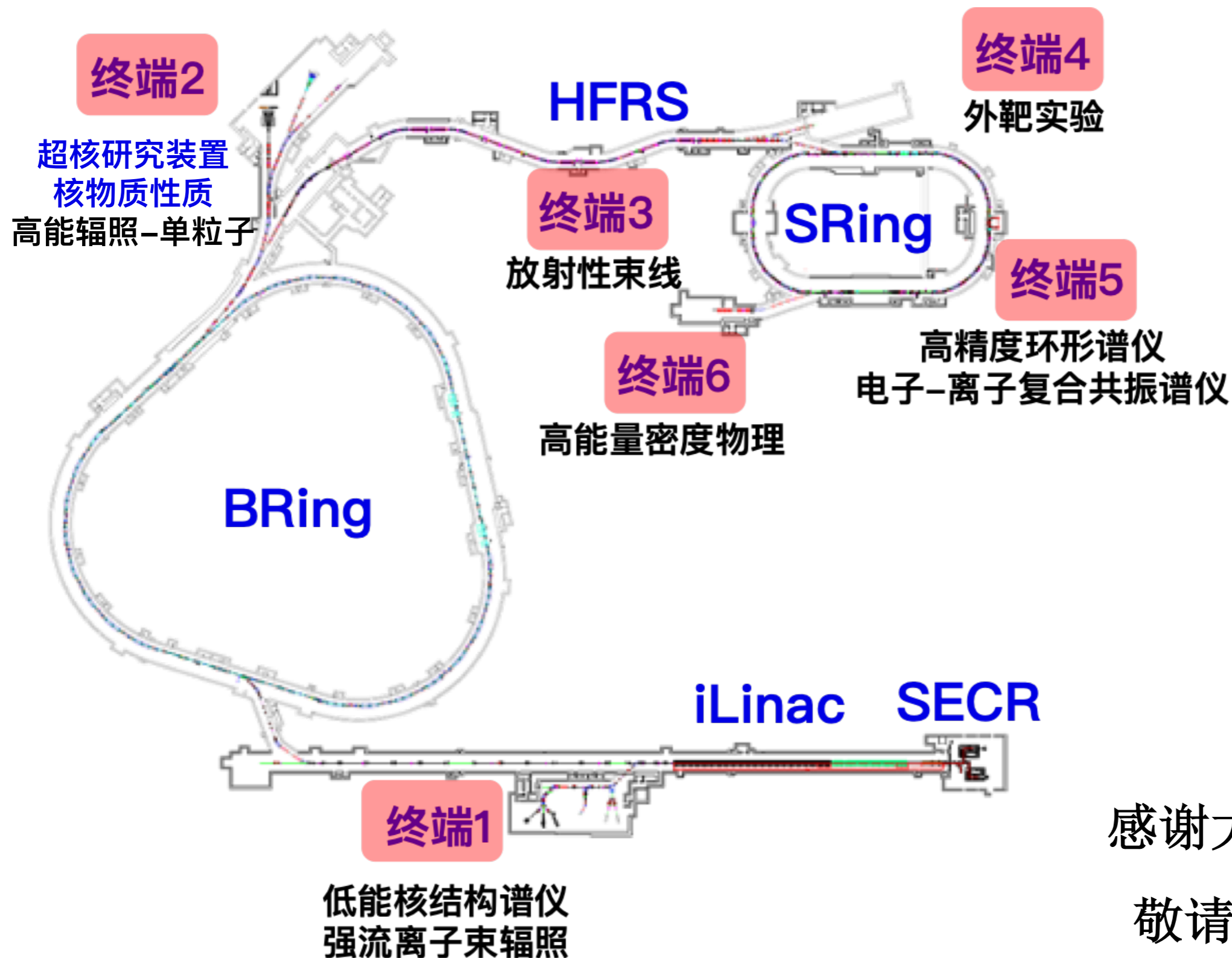
${}^3_{\Lambda}H$



${}^4_{\Lambda}H$



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