

基于HIAF集群的高精度测量和新物理前沿研讨会  
中科院近代物理研究所惠州研究部, 2023.7.05-07, 惠州, 中国

# 利用GeV能区重离子碰撞研究高密核物质

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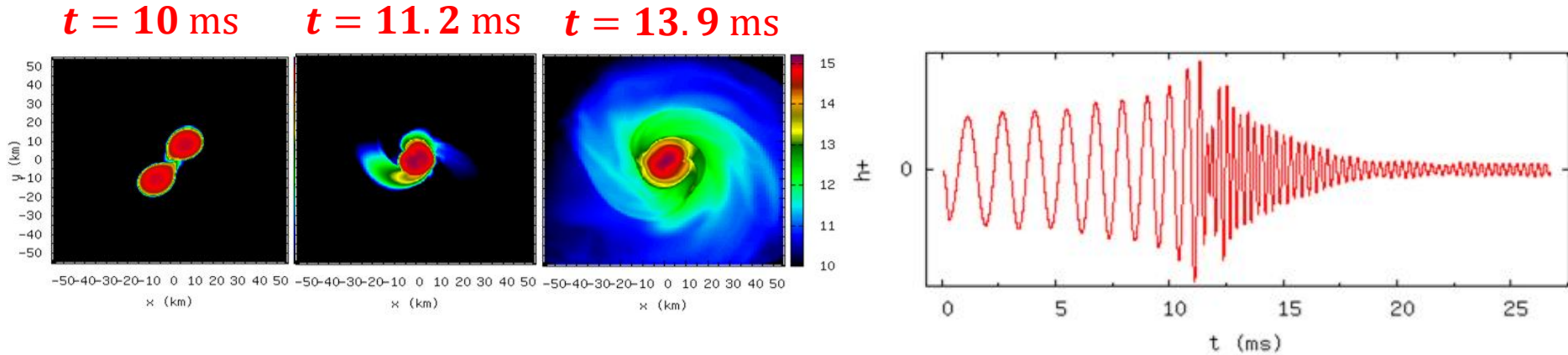
## 二、CEE (HIRFL-CSR) 和 CEE+(HIAF) 的新机遇

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## GW170817 及其与核物质状态方程的关联



### TOV 方程

$$\frac{d\mathcal{M}(r)}{dr} = 4\pi r^2 \varepsilon(r), \quad -\frac{d\mathcal{P}(r)}{dr} = \frac{G\varepsilon\mathcal{M}}{r^2} \left(1 - \frac{2G\mathcal{M}}{r}\right)^{-1} \left(1 + \frac{\mathcal{P}}{\varepsilon}\right) \left(1 + \frac{4\pi r^3 \mathcal{P}}{\mathcal{M}}\right)$$

# 核物质状态方程

The nucleon specific energy of nuclear matter formed in HIC or in neutron star can be written as

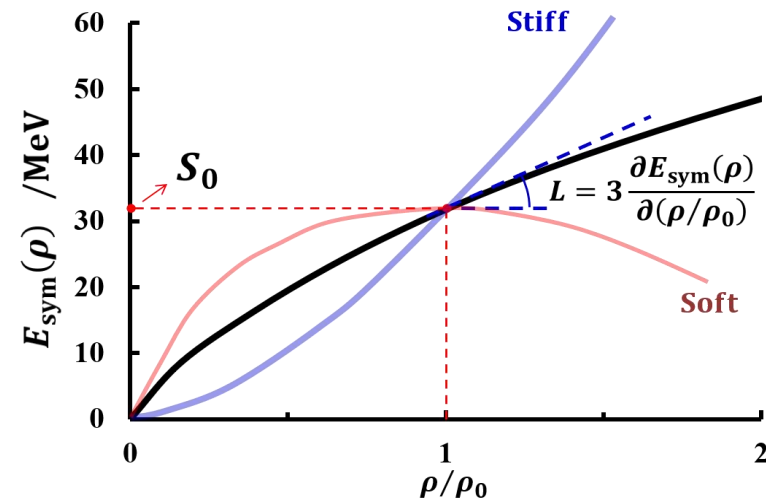
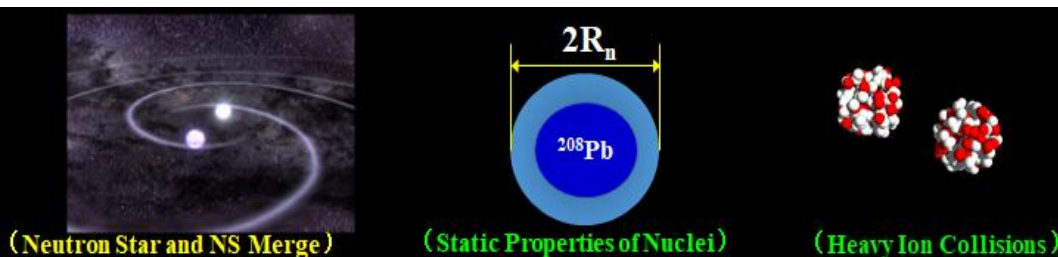
$$E(\rho, \delta) = E_0(\rho) + \delta^2 E_{\text{sym}}(\rho), \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2} \left( \frac{\rho - \rho_0}{3\rho_0} \right)^2 + \frac{J_0}{6} \left( \frac{\rho - \rho_0}{3\rho_0} \right)^3 + \dots$$

$$E_{\text{sym}}(\rho) = E_{\text{sym}}(\rho_0) + L \left( \frac{\rho - \rho_0}{3\rho_0} \right) + \frac{K_{\text{sym}}}{2} \left( \frac{\rho - \rho_0}{3\rho_0} \right)^2 + \frac{J_{\text{sym}}}{6} \left( \frac{\rho - \rho_0}{3\rho_0} \right)^3 + \dots$$

For npe matter, the pressure :

$$P(\rho, \delta) = \rho^2 \frac{\partial E(\rho, \delta)}{\partial \rho} + \frac{1}{4} \rho_e \mu_e = \rho^2 \left[ \frac{\partial E_0}{\partial \rho} + \delta^2 \frac{\partial E_{\text{sym}}}{\partial \rho} \right] + \frac{1}{2} \delta(1 - \delta) \rho E_{\text{sym}}(\rho)$$



# 世界几个主要的GeV能区重离子实验

## 1. Plastic Ball at Bevalac

PRC 42, 640 (1990) ...

## 2. EOS at Bevalac

PRL 78, 2535 (1997); RPC 76, 3911 (1996); PRL 75, 2662 (1995) ...

## 3. FOPI at SIS

NPA 876, 1 (2012); NPA 848, 366 (2010); NPA781, 459 (2007) ...

## 4. KAOS at SIS

PRL 96, 072301 (2006); PRL 95, 012301 (2005) ; PRL 86, 1974 (2001)...

## 5. HADES at SIS

PRL 125, 262301 (2020); PRL 123, 022002 (2019) ; PRC 102, 024914 (2020) ...

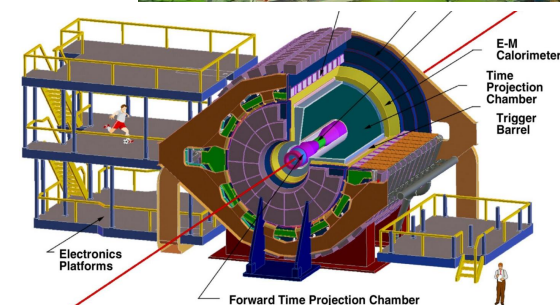
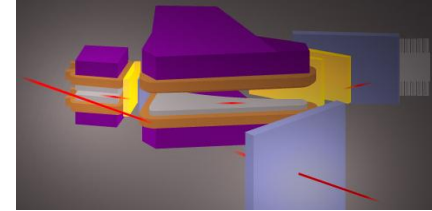
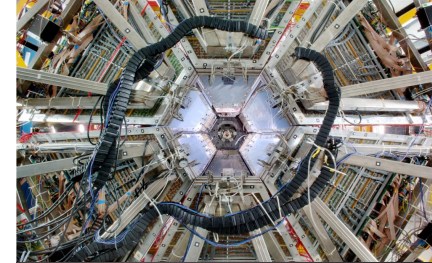
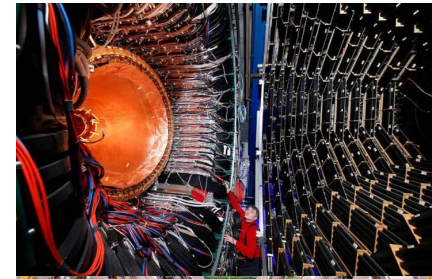
## 6. S $\pi$ RIT at RIBF

PRL 126, 162701 (2021); PLB 822, 136681(2021); PLB813, 136016 (2021)...

## 7. STAR-BES at RHIC

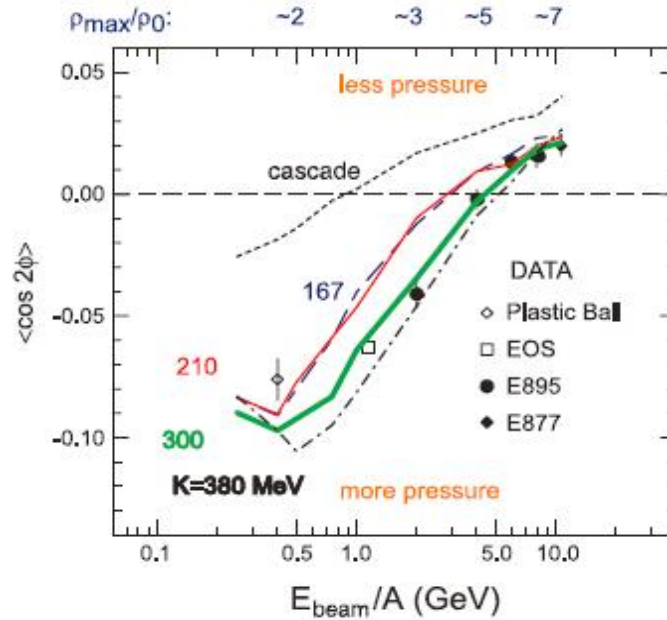
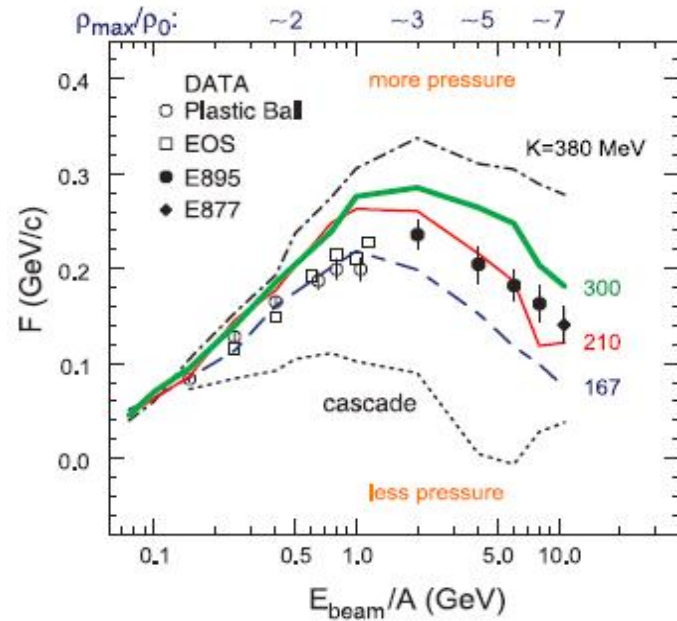
PRL128, 202303 (2022); PLB827, 137503 (2022)...

and a lot more literatures...



# 通过集体流( $v_1, v_2$ )提取核物质状态方程

当两个原子核碰撞，会造成核物质的压缩，形成压力梯度，出现挤压效应，从而产生集体运动，形成所谓的集体流！

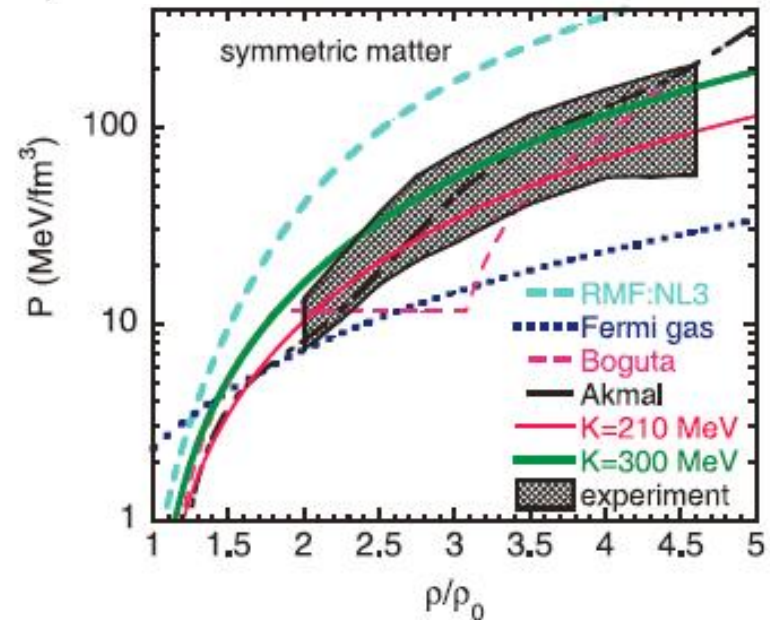


$$\frac{dN}{u_t du_t dy d\phi} = v_0 [1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi)]$$

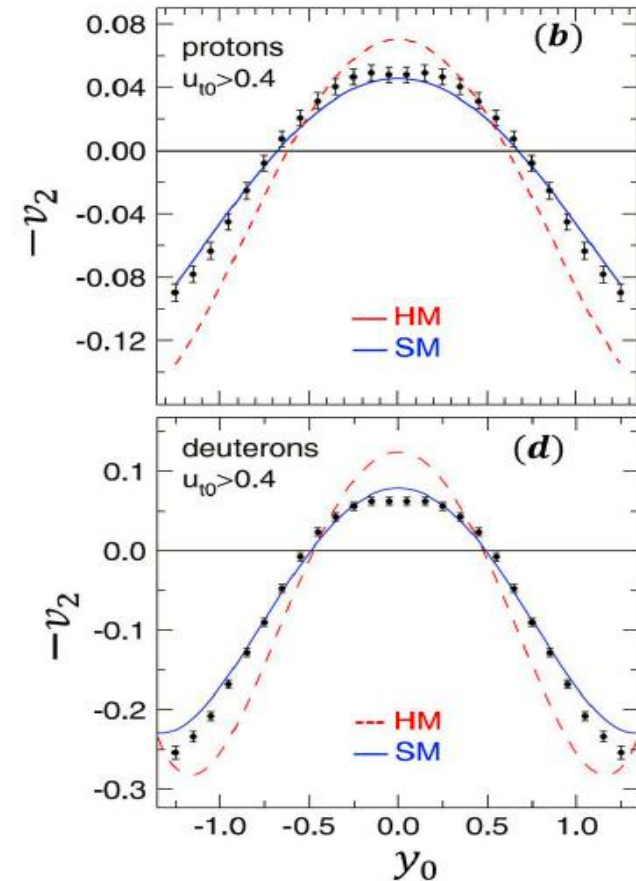
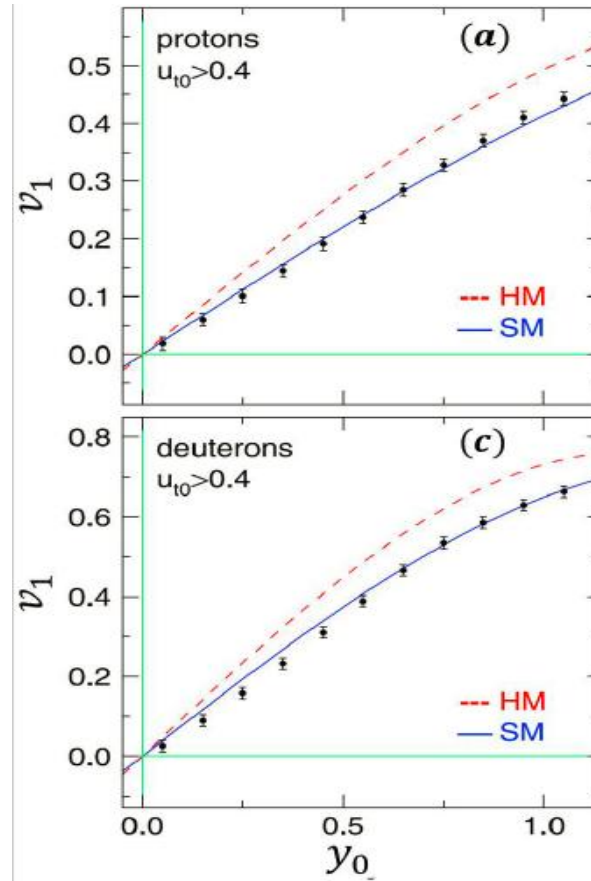
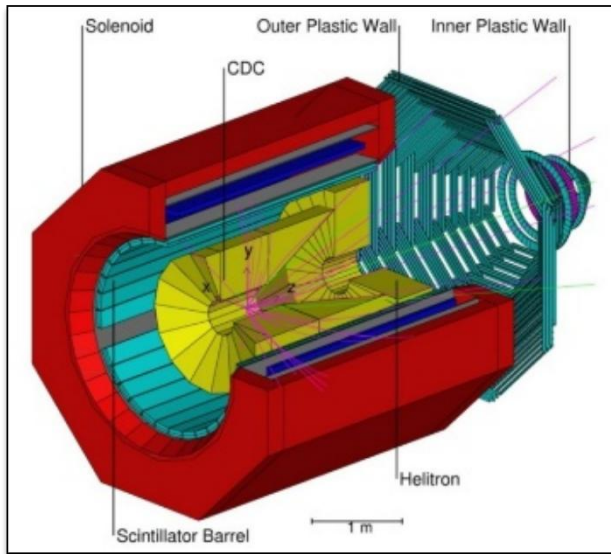
$$v_1 = \left\langle \frac{p_x}{p_t} \right\rangle = \langle \cos(\phi) \rangle,$$

$$v_2 = \left\langle \left( \frac{p_x}{p_t} \right)^2 - \left( \frac{p_y}{p_t} \right)^2 \right\rangle = \langle \cos(2\phi) \rangle$$

P. Danielewicz, R. Lacey, and W. G. Lynch.  
 Determination of the equation of state of dense matter.  
**Science**, 298,1592 (2002)



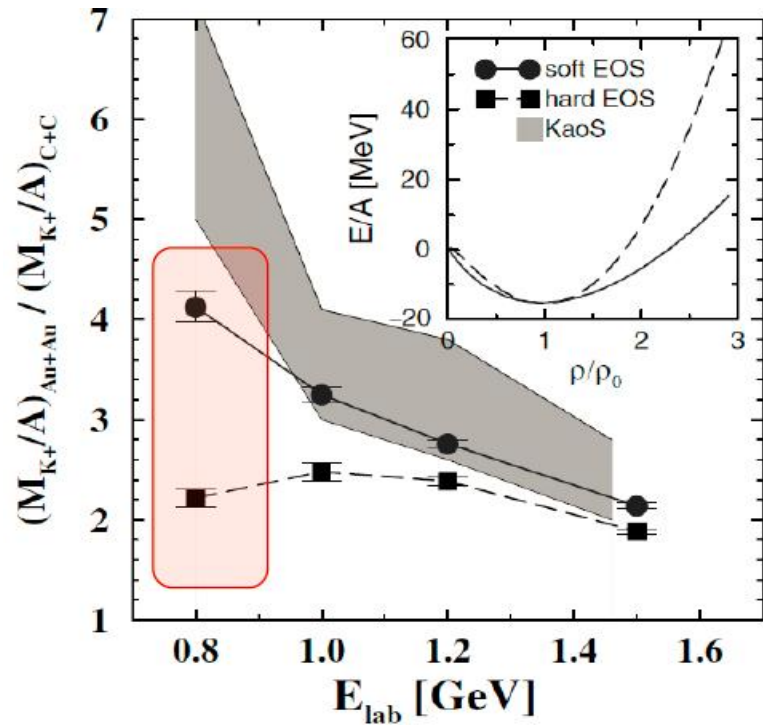
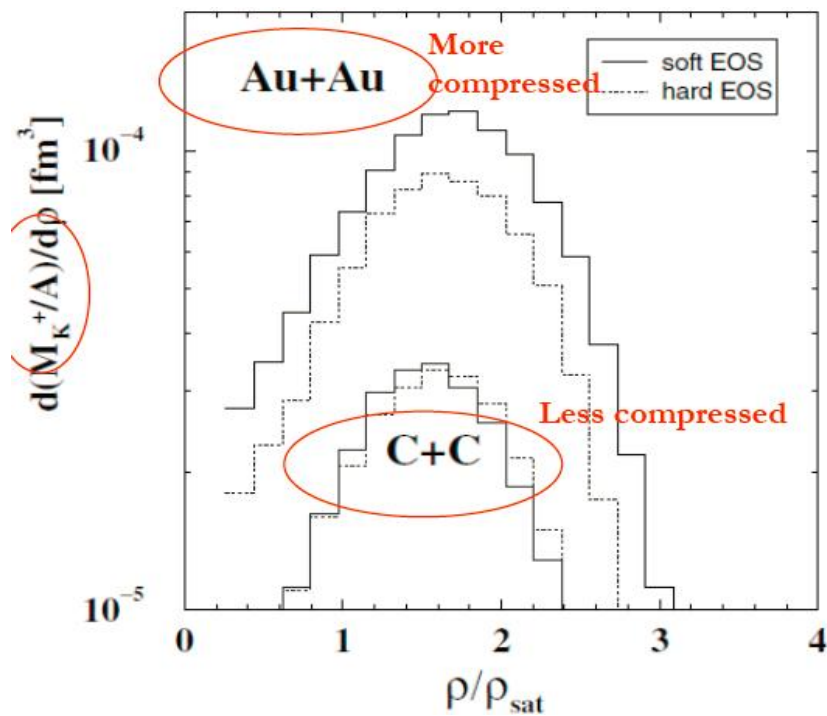
# 集体流( $v_1, v_2$ )提取核物质状态方程



$$v_i = v_i(u_t, y)$$

# K<sup>+</sup>产额提取核物质状态方程

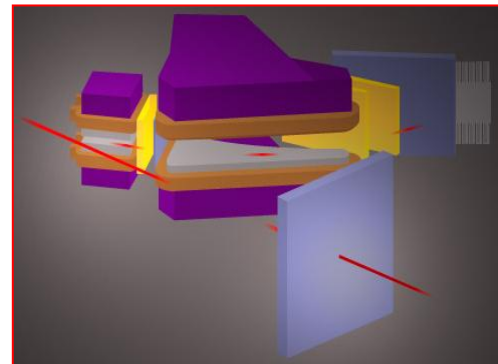
除了集体流之外，介子产额也和其产生时的介质性质密切相关！



J. Aichelin and Che Ming Ko, **PRL** 55,2661 (1985)

C. Fuchs et al., **PRL** 86, 1974 (2001)

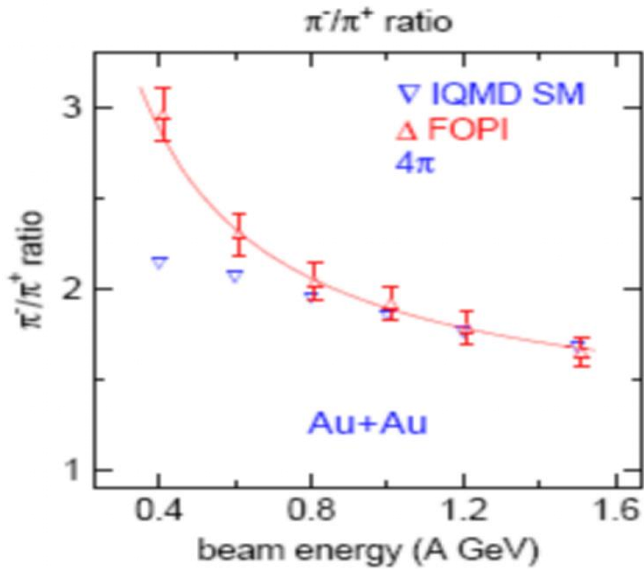
Insensitive in light system C+C; Higher sensitivity found at lower energies



KaoS Collaboration



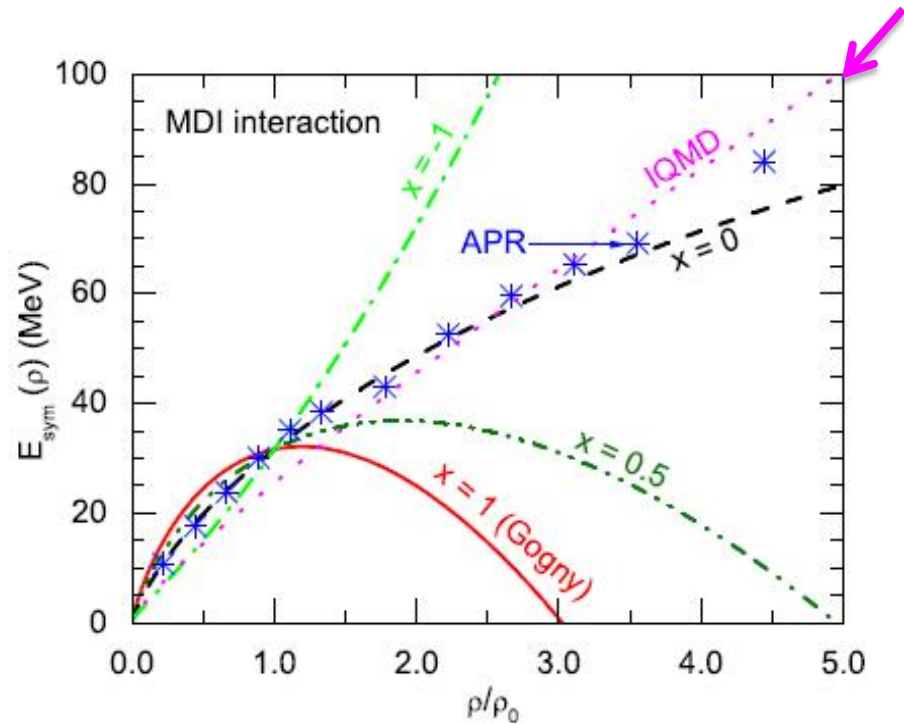
# $E_{\text{sym}}(\rho)$ : $\pi^-/\pi^+$ 产额比与 $E_{\text{sym}}(\rho)$



IQMD: C. Hartnack et al, EPJA 1 (1998) 151

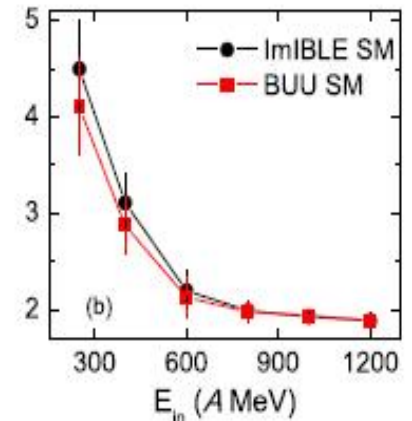
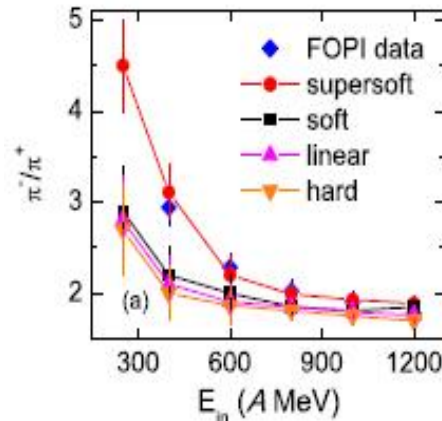
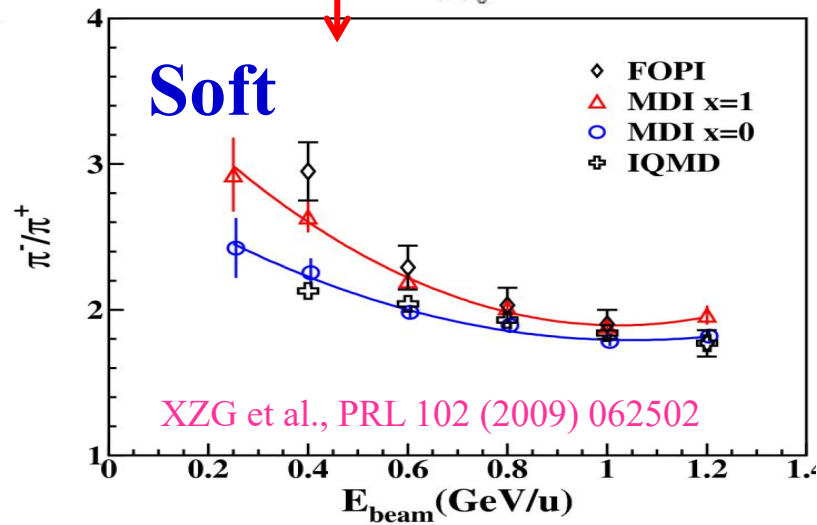
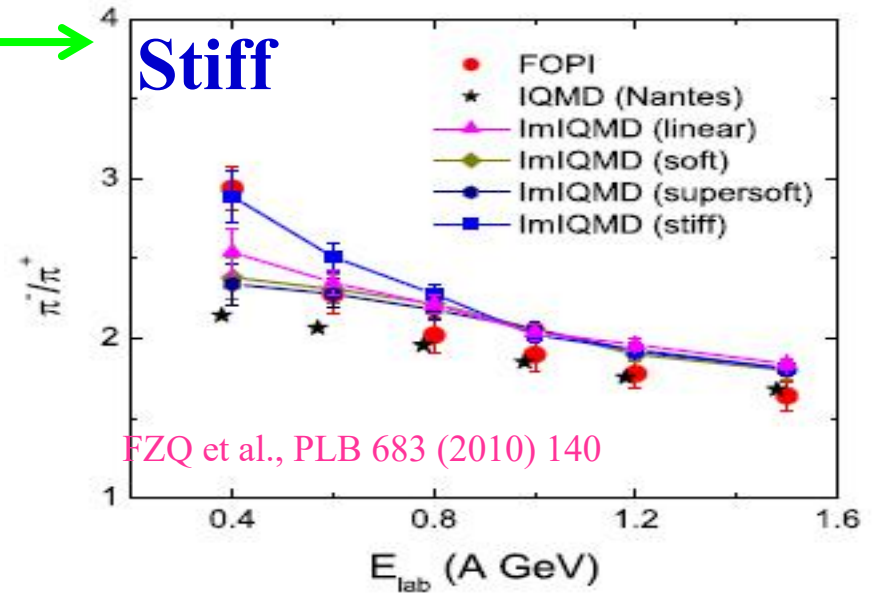
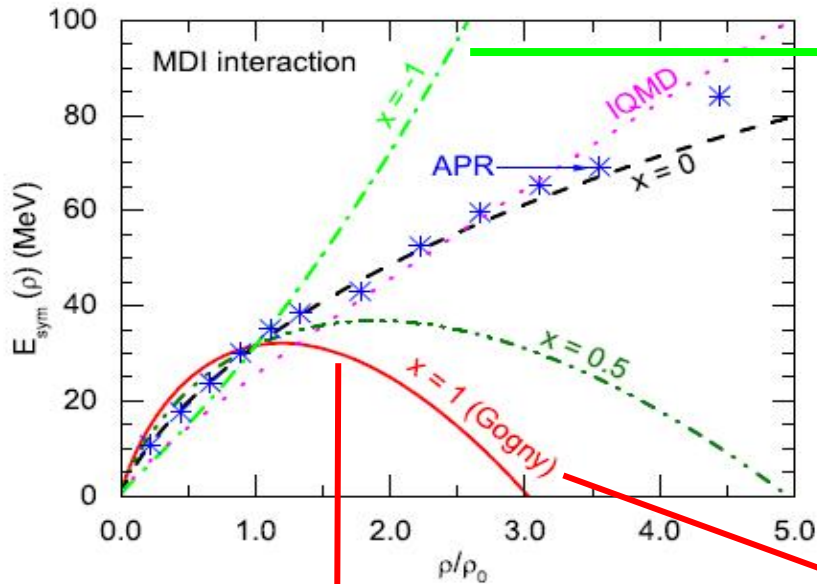
$$V_{\text{sym}}^{ij} = t_6 \frac{1}{\rho_0} T_{3i} T_{3j} \delta(\vec{r}_i - \vec{r}_j), \quad t_6 = 100 \text{ MeV}$$

对应于对称能  $E_{\text{sym}}(\rho) = \frac{25}{2} \frac{\rho}{\rho_0} + (2^{2/3} - 1) \frac{3}{5} E_F^0 \left(\frac{\rho}{\rho_0}\right)^{2/3}$



Need a softer symmetry energy to make the pion production region more neutron-rich!

# $\pi^-/\pi^+$ 产额比探针的模型依赖



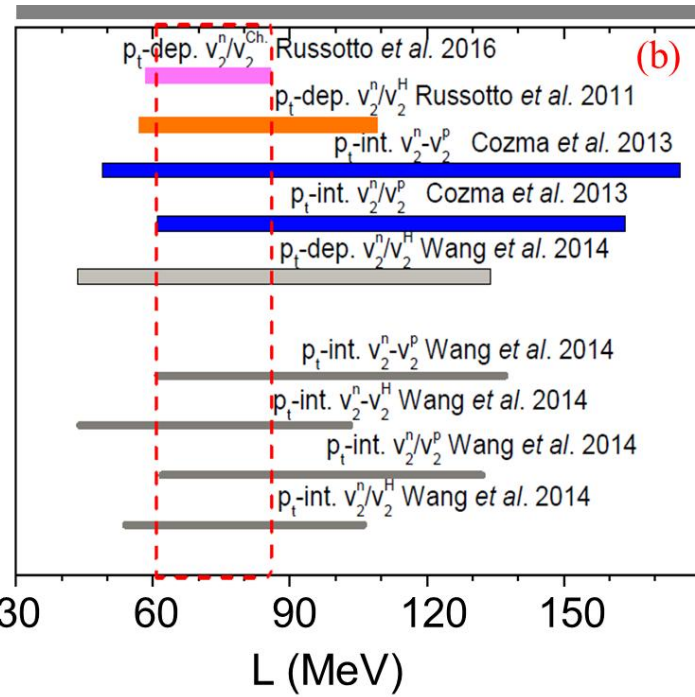
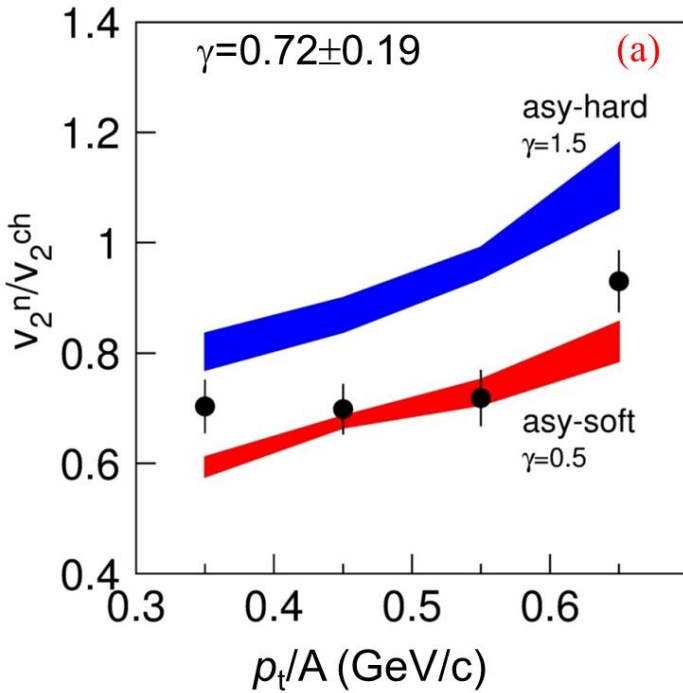
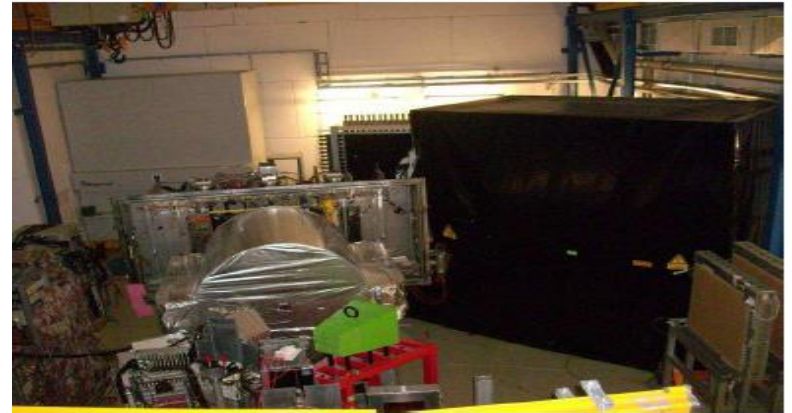
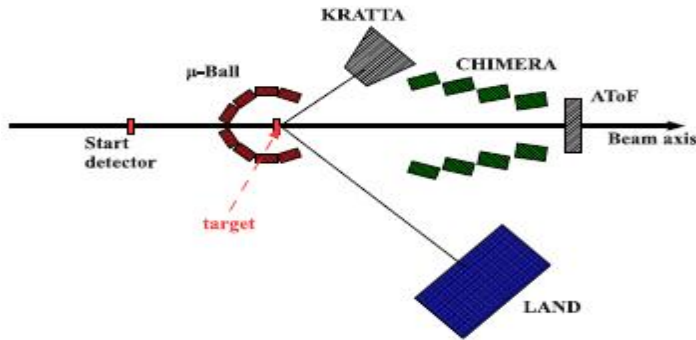
XWJ et al., PLB 718 (2013) 1510

or loss sensitivity on  $\gamma$

J. Hong et al, PRC 90,024605(2010)

# 从 n/p 微分流提取 $E_{\text{sym}}(\rho)$

AnSYS-EOS 合作组



Y. Leifels et al  
**PRL71,963 (1993)**

Russotto et al.,  
**PLB 697,471 (2011);**  
**PRC 94, 034608 (2016)**

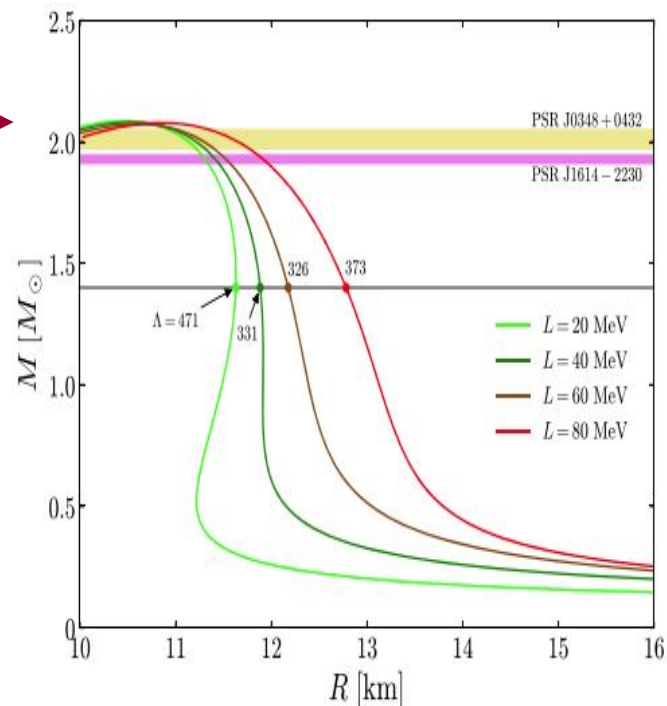
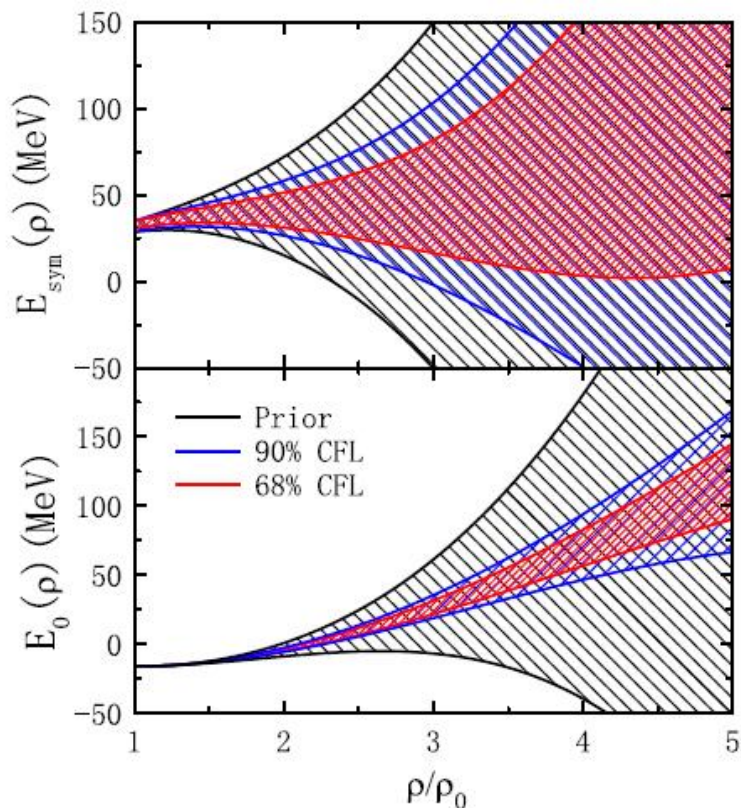
$$E_{\text{sym}}(\rho) = 12 (\rho/\rho_0)^{2/3} + 22 (\rho/\rho_0)^\gamma$$

王永佳等, **Frontiers of Physics**, 15(4):1, 2020.

# 从 GW170817 / PSRJ0740+6620 和 HIC 提取 $E_{\text{sym}}(\rho)$

$R_{1.4} = 11.9_{-1.4}^{+1.4} \text{ km}$ , PRL, 121, 161101, 2018;  $R_{1.4} = 10.8_{-1.6}^{+2.1} \text{ km}$ , PRL, 121, 091102, 2018

1. QMF18:  $L = 40 \text{ MeV}$   
Z. Y. Zhu et al., APJ 862, 98 (2018)



2. 贝叶斯分析,

$$E_{\text{sym}}(2\rho_0) = 39.1_{-8.2}^{+12.1} \text{ MeV} (1\sigma)$$

W. J. Xie et al., APJ 883, 174 (2019)

N. B. Zhang et al., APJ 879, 99 (2019)

# 从 GW170817 / PSRJ0740+6620 和 HIC 提取 $E_{\text{sym}}(\rho)$

## 3. 联合中子星与核物理的数据

Y. Zhou et al., **PRD99** 121301(R) (2019)



$$L(N_c) = 47.3 \pm 7.8 \text{ MeV}$$

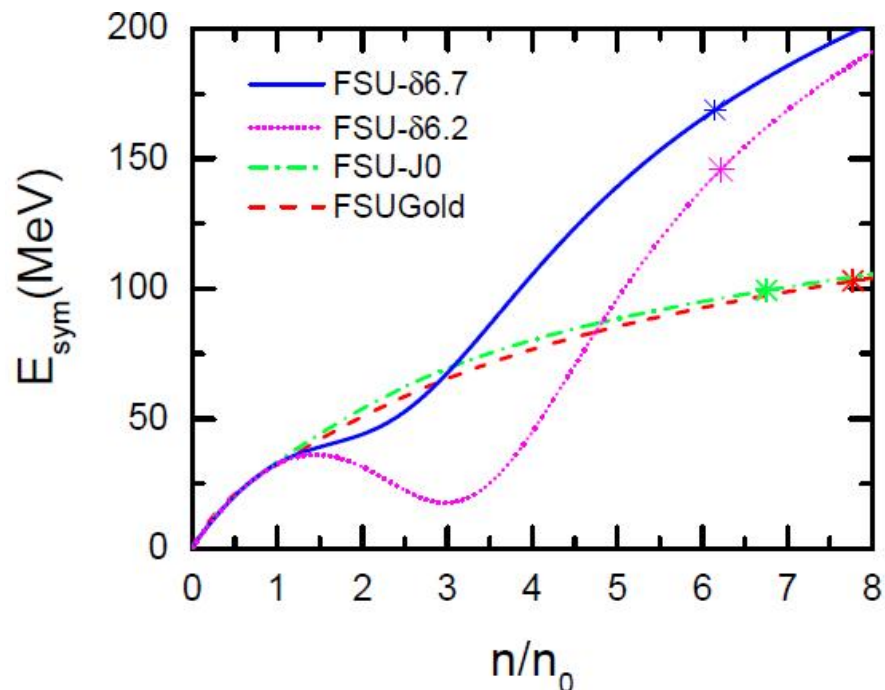
$$E_{\text{sym}}(2\rho_0) = [39.4_{+7.5}^{-6.4}, 54.5_{+3.1}^{-3.2}] \text{ MeV}$$

## 4. 考虑 $\delta - \sigma$ 耦合，提出两组新的RMF参数 **FSU- $\delta 6.7$ , FSU- $\delta 6.2$**

F. Li et al., *ApJ* 929, 183 (2022)

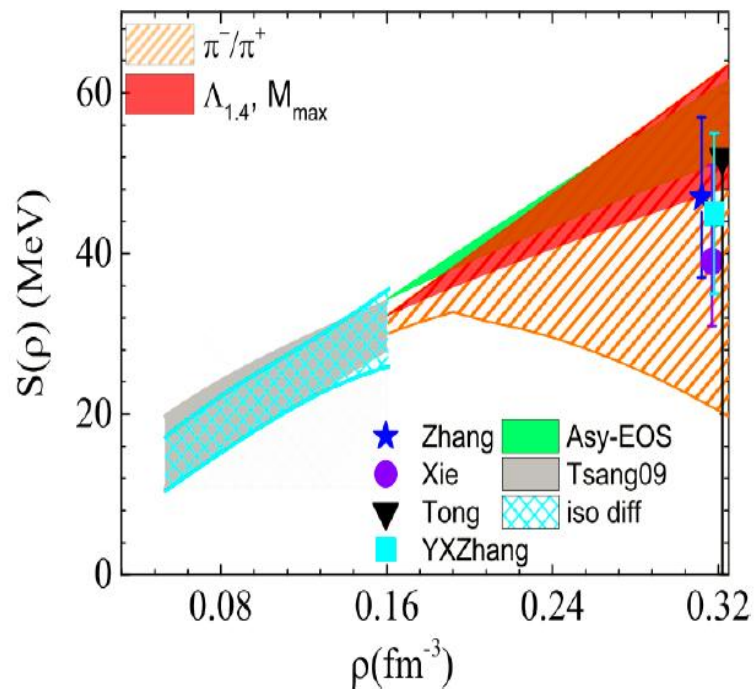
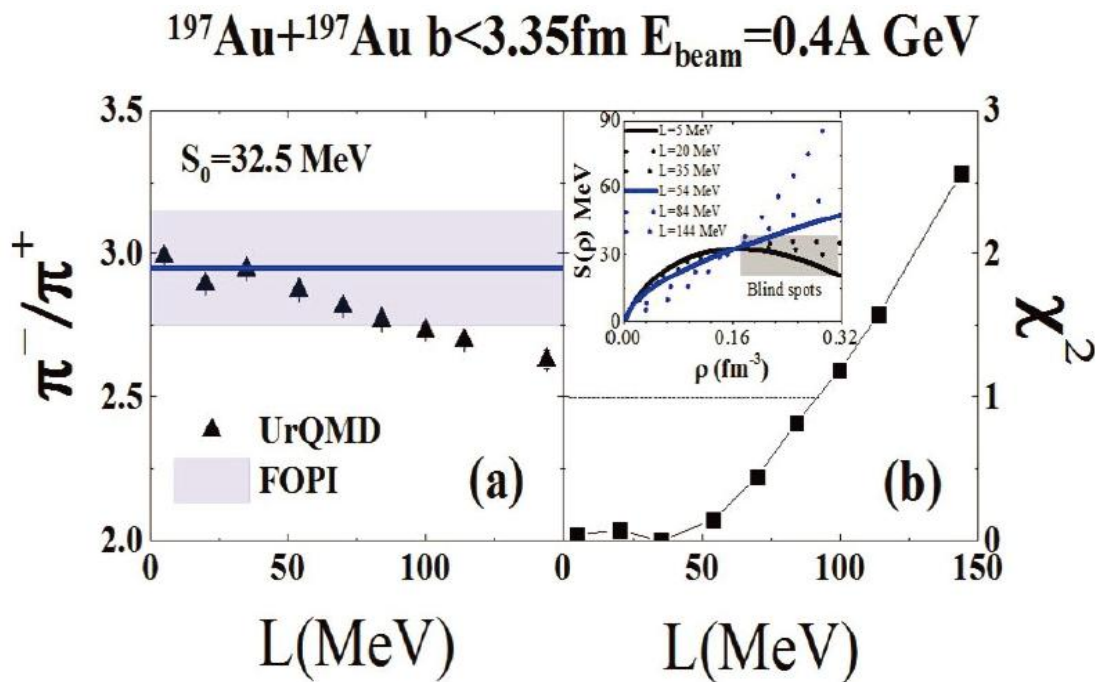
饱和点斜率分别为：

$$L(\rho_0) = 53.5 \text{ MeV}, 48.2 \text{ MeV}$$



# 重离子碰撞和天体观测的结合

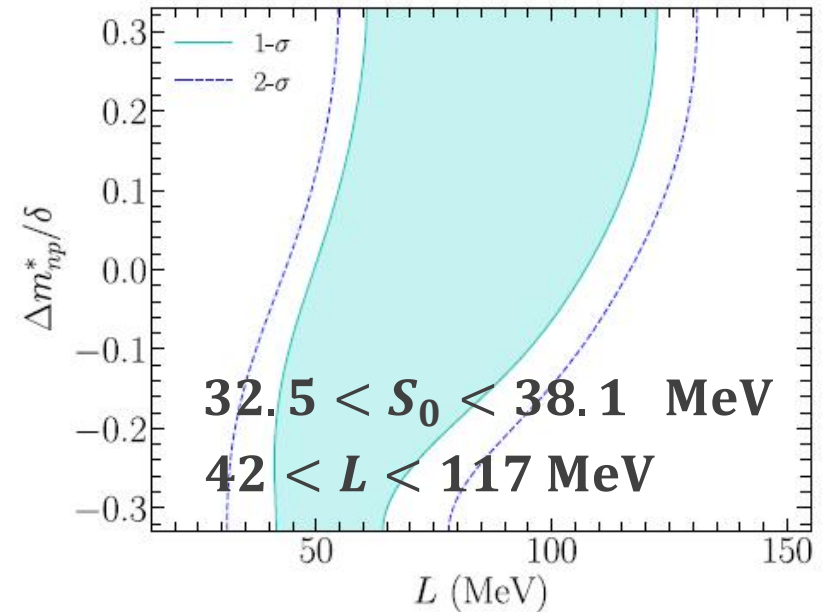
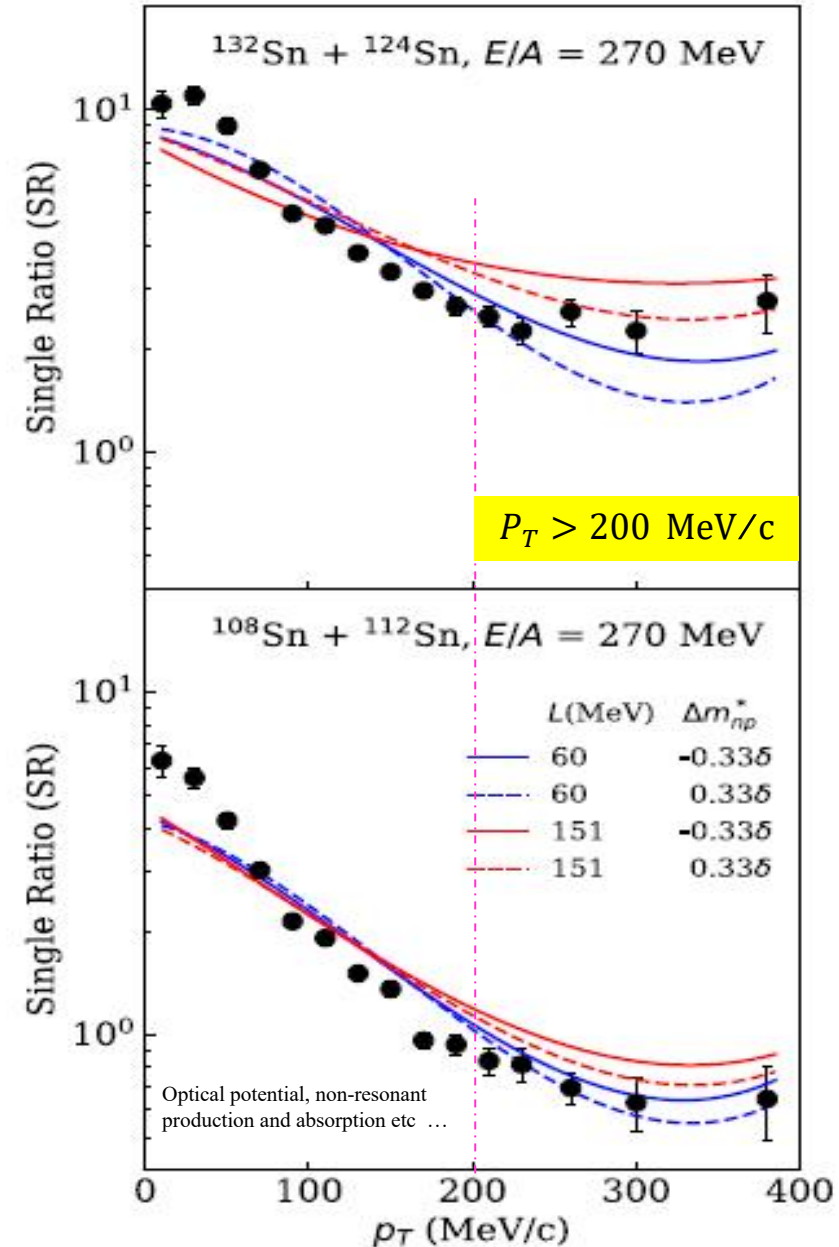
$\pi^-/\pi^+$  的复杂性，引发了大量对重离子反应中 $\pi$ 介子产生和运输的研究，包括阈能效应、介质效应， $\pi$ 介子光学势， $\pi$ - $\Delta$ 循环等：徐骏，张英逊，C-M Ko, Dan Cozma 等等。



联合分析 GW170817/HIC:  $54 < L < 91$  MeV

【Y.Y. Liu et al., PRC 103, 014616 (2021)】

# $S\pi$ RIT 合作组最近进展

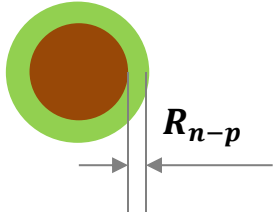


J. Estee et al., **PRL** 126, 162701 (2021)

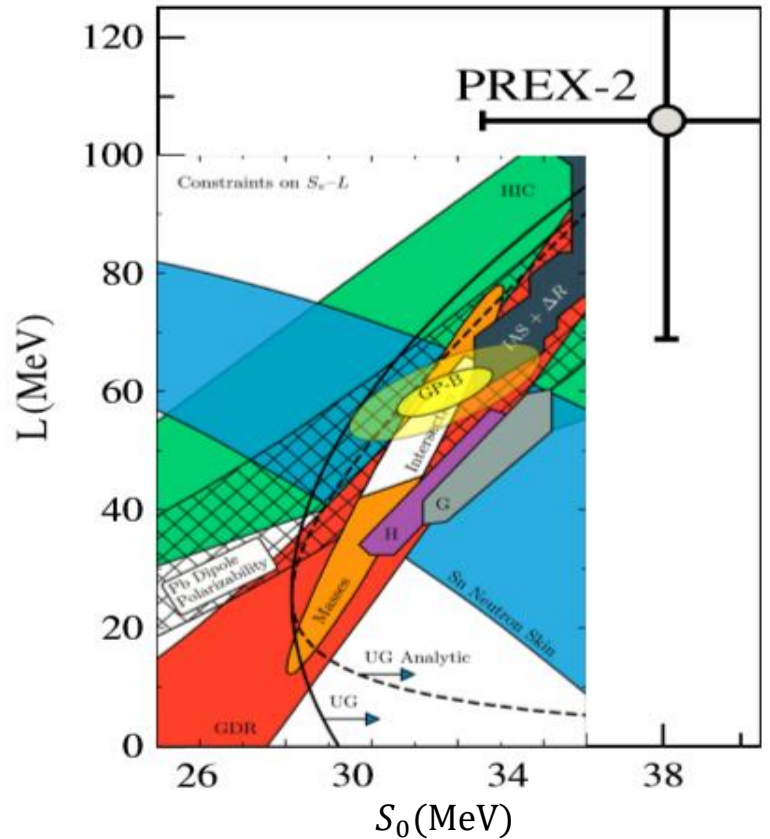
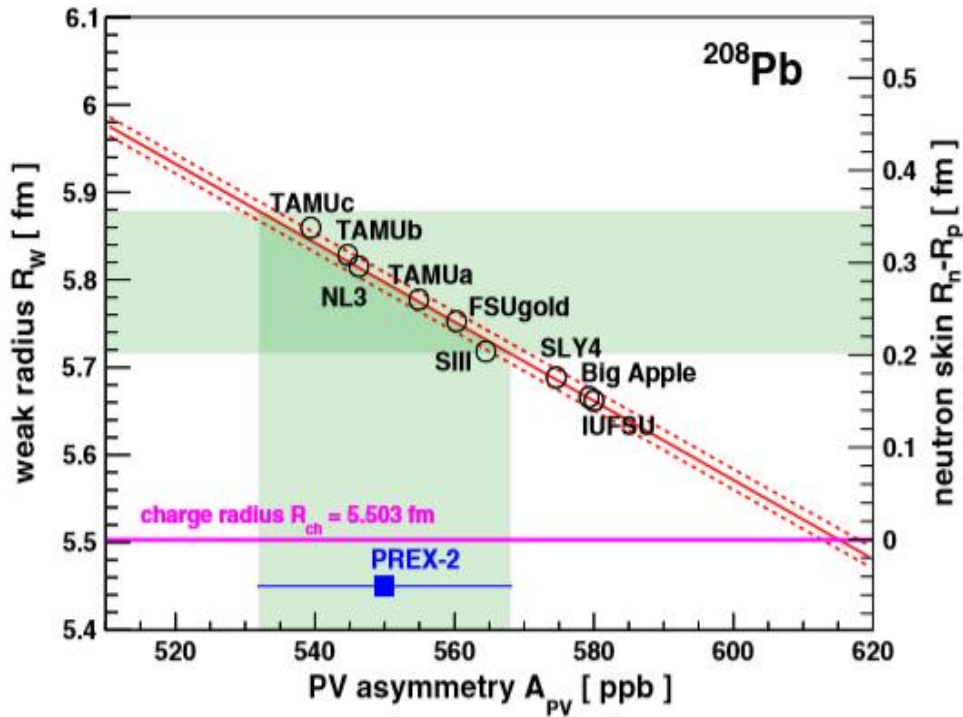


# PREX 实验的最新进展

$^{208}\text{Pb}$



PREX 实验利用宇称破坏的  $e + ^{208}\text{Pb}$  散射，测量  $^{208}\text{Pb}$  中子皮。



$$R_{n-p} = 0.283 \pm 0.071 \text{ fm}$$

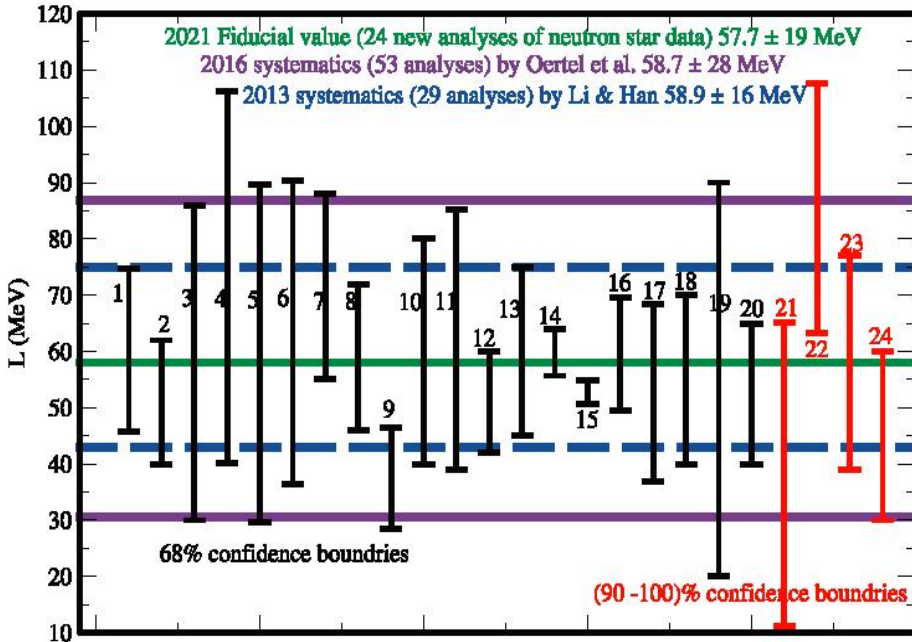
$$L = 106 \pm 37 \text{ MeV}$$

PREX collaboration., PRL 126, 172502 (2021)  
B. T. Reed et al, PRL 126, 172503 (2021)

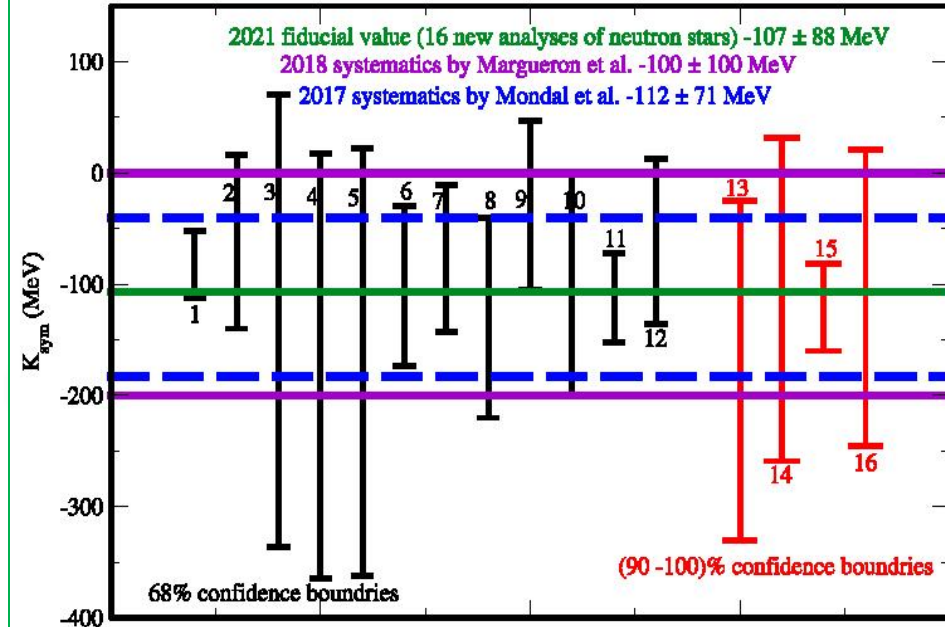


# $E_{\text{sym}}(\rho)$ 的置信结果

## Recent results on $L$



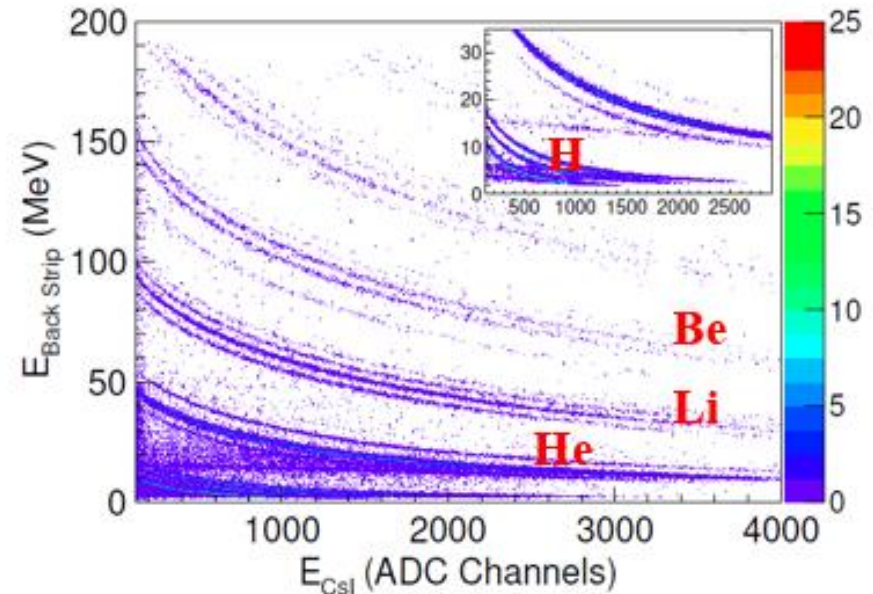
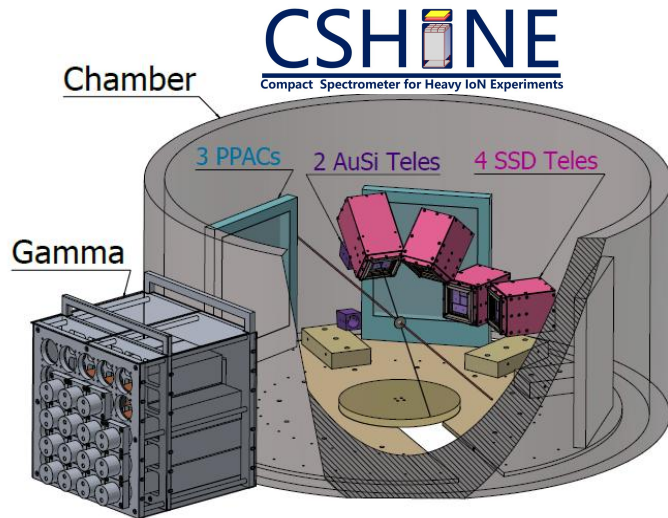
## Recent results on $K_{\text{sym}}$



Bao-An Li et al., *Universe* 7, 182 (2021)

24 new analysis from the NS observables  
In comparison to 2013 and 2016 survey.  
*In tention with* the most recent PREX II results.

# CSHINE: Compact Spectrometer for Heavy Ion Experiment



**NST 32, 4 (2021)**

**NST 33, 40 (2022)**

**NST 33, 162 (2022)**

**NIMA 1011, 165592(2021)**

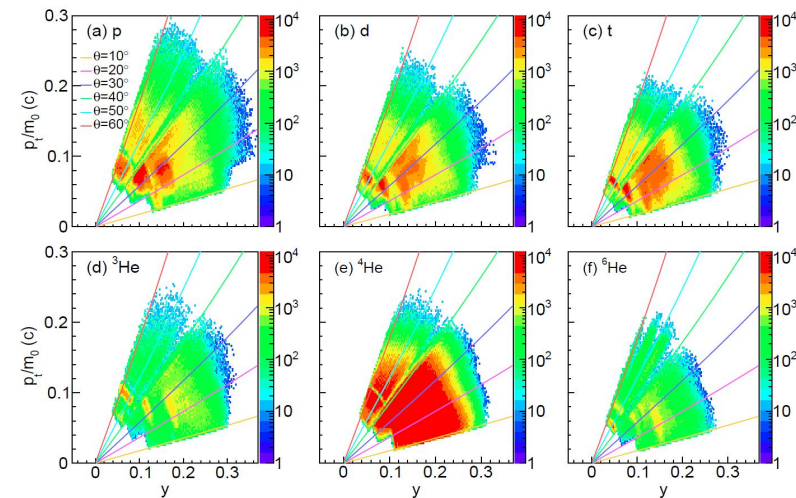
**NIMA 1029, 166461(2022)**

**NIMA 1053, 168330(2023)**

**PRC 95, 041602(R) (2017)**

**PLB 825, 125856 (2022)**

**PRC107, L041601 (2023)**



Future plan: n/p, t/ $^3\text{He}$ , Direct  $\gamma$  in HIC...

# CSHINE 实验在饱和密度附近的 $E_{\text{sym}}(\rho)$ 约束结果

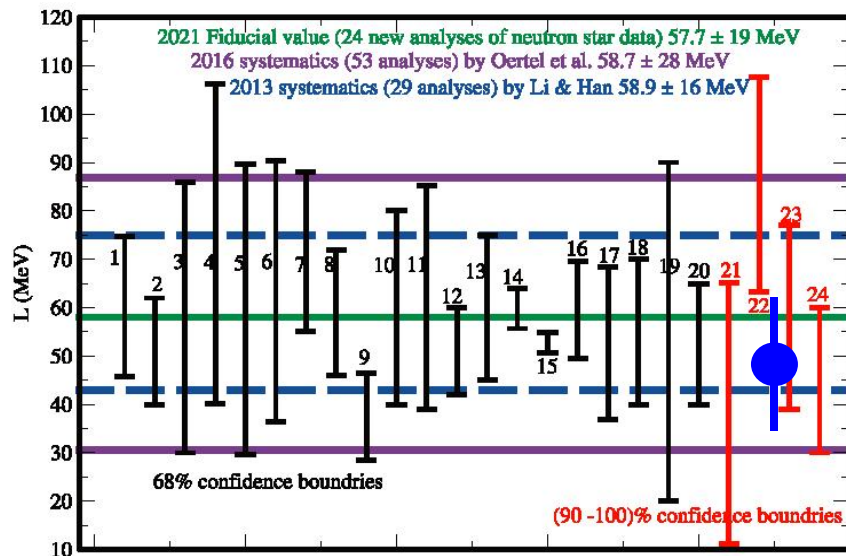
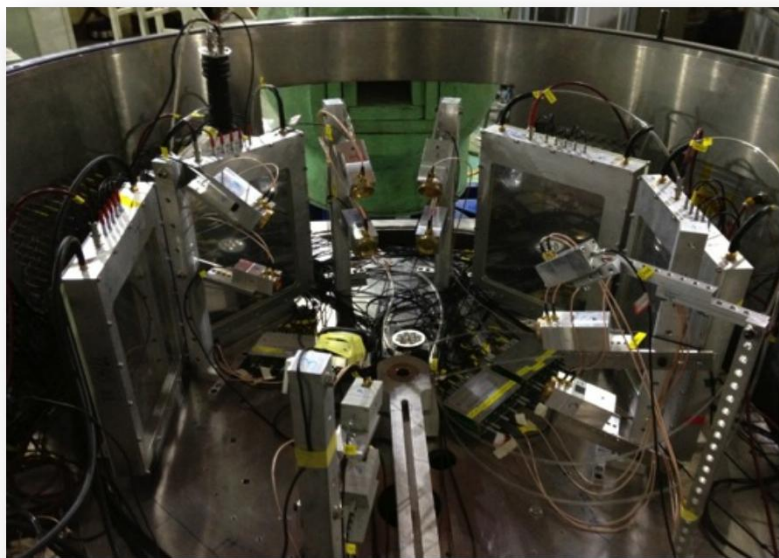
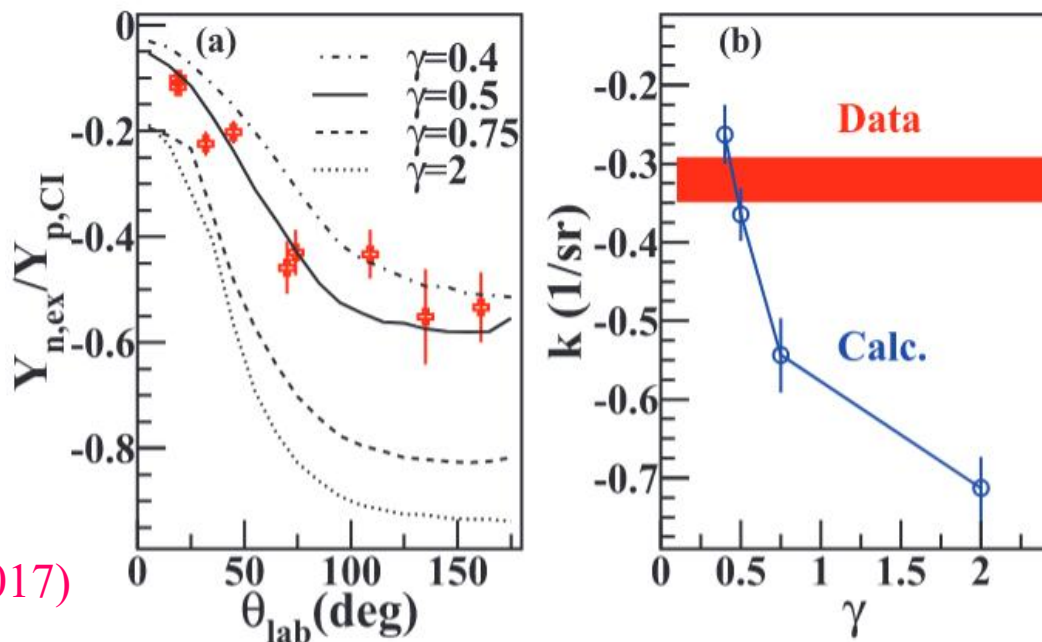
30 MeV/u  $^{40}\text{Ar} + ^{197}\text{Au}$

$E_{\text{sym}}(\rho)$  约束结果:

$L = 47 \pm 14 \text{ MeV (95\%CL)}$

( $S_0 = 28.3 \text{ MeV}$ )

Y. Zhang, ... ZGX, PRC 95,041602(R) (2017)



## 二、CEE (HIRFL-CSR) 和 CEE+(HIAF) 的新机遇

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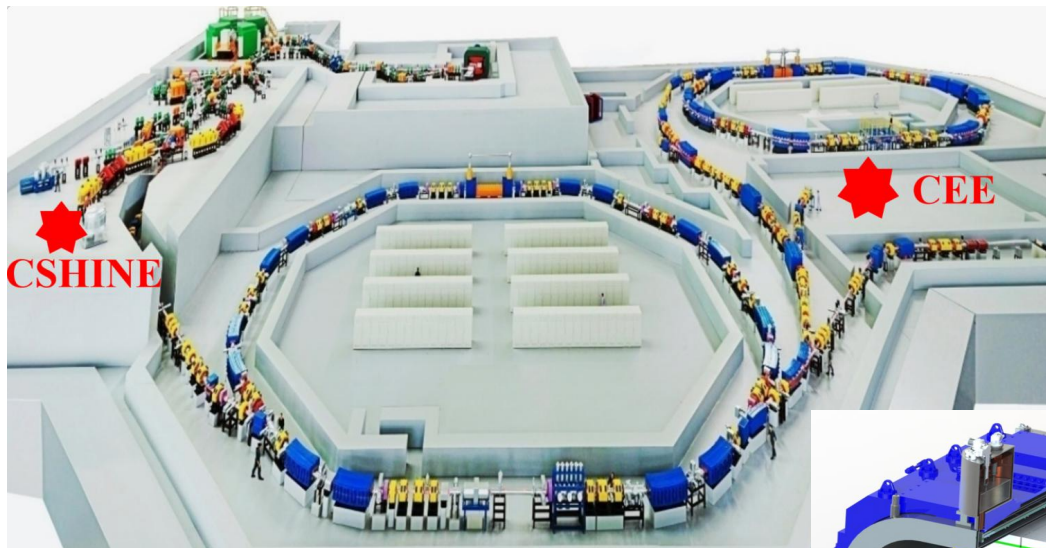
在饱和密度附近或者中等密度区，从 $\rho_0$ 到几倍 $\rho_0$ ，对应束流能量从数百MeV/u至数个GeV/u，已经有不少研究结果；

我们的研究动机：

是否还有其他机遇？

# 兰州低温高密核物质测量谱仪(CEE)

## HIRFL-CSR 加速器群

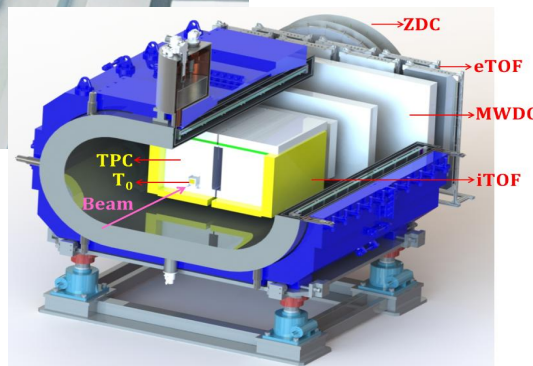


## Cool Storage Ring



### HIRFL-CSR:

P	2.8 GeV
C	1100 MeV/u
U	0.5 GeV/u



如果配备一个先进谱仪

→ 寻找QCD相边界/高重子密度区EOS/相变临界点

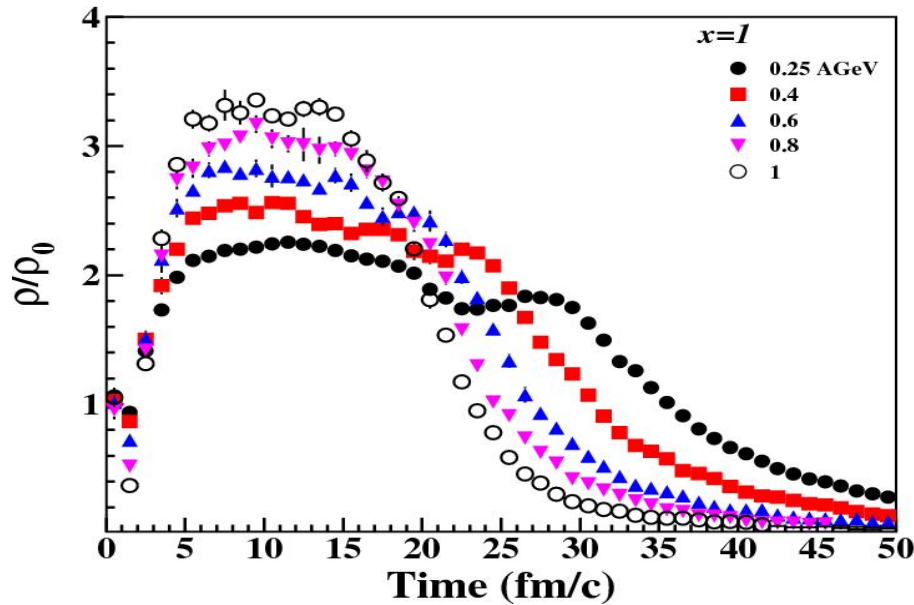
→  $2\rho_0$  密度附近的EOS

→ 超核产生与作用势

# HIRFL-CSR energy region is ideal for $E_{\text{sym}}(\rho)$ studies

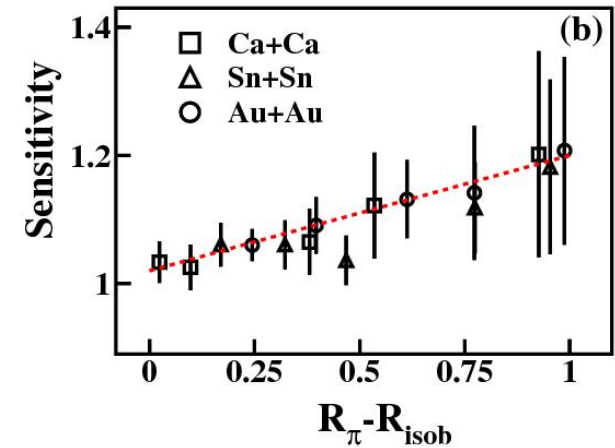
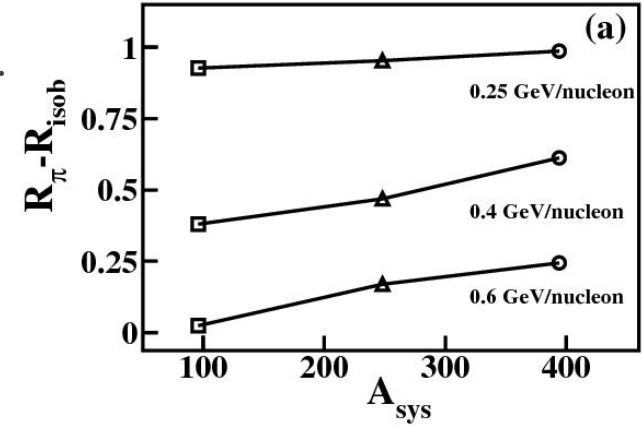
↓ Nuclear matter at  $2\rho_0$  can be produced.

→ The sensitivity of the observable on  $E_{\text{sym}}$  is enhanced.  
(Finite size effect, nuclear transparency)

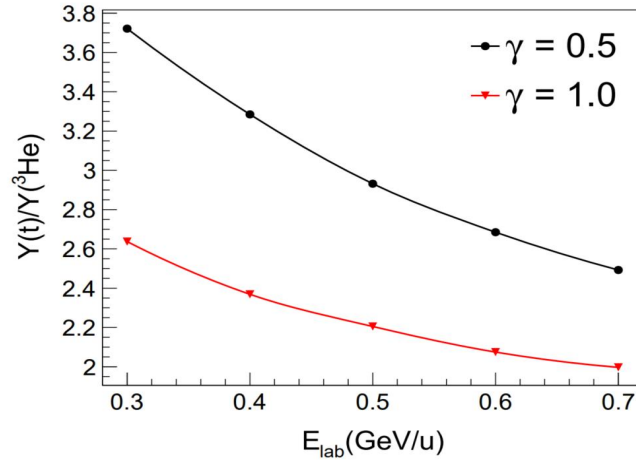
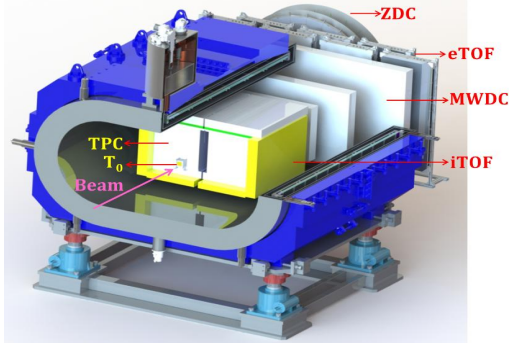


M. Zhang, ZGX et al., PRC 80 (2009) 034616

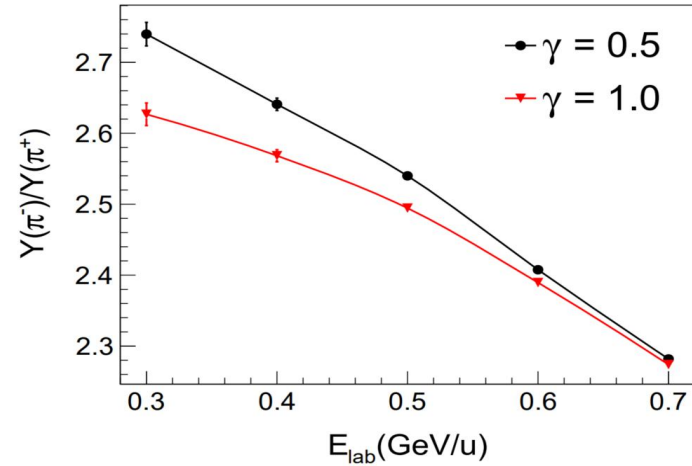
F. Fu ZGX et al, PLB 666 (2008) 359



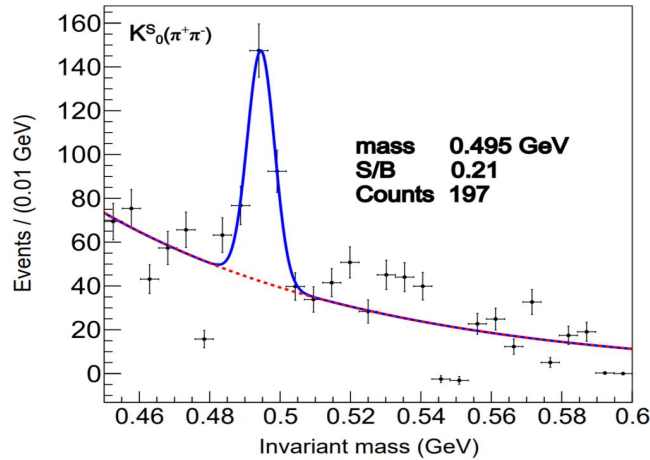
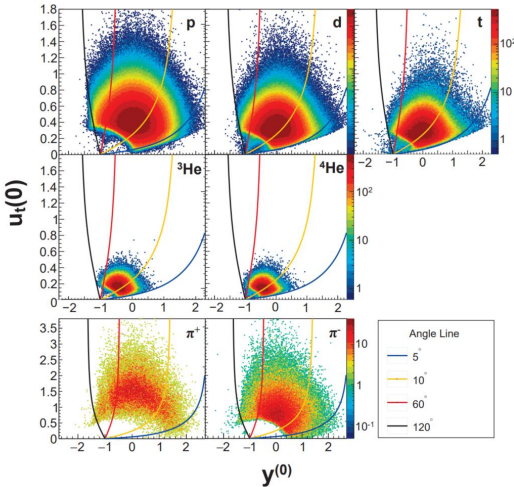
# CEE provides new opportunities for $E_{\text{sym}}(\rho)$ studies



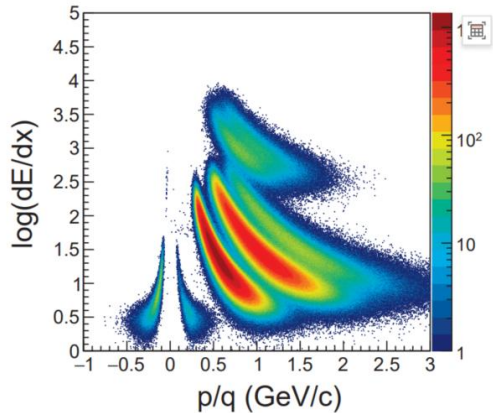
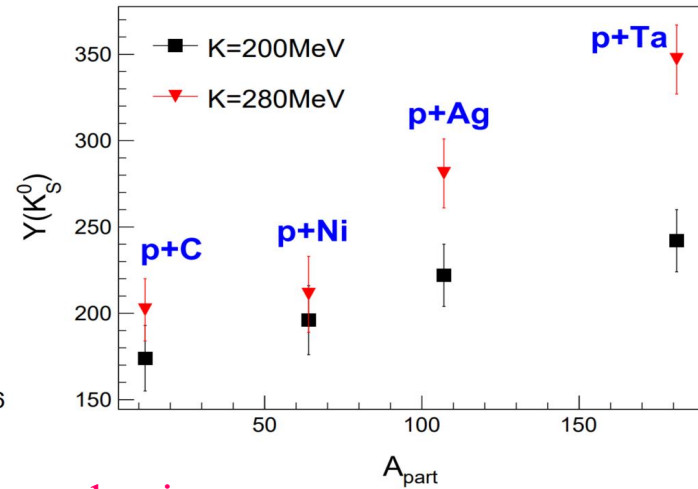
$t/{}^3\text{He}$  Ratio



$\pi^-/\pi^+$  Ratio



$K_S^0$  production

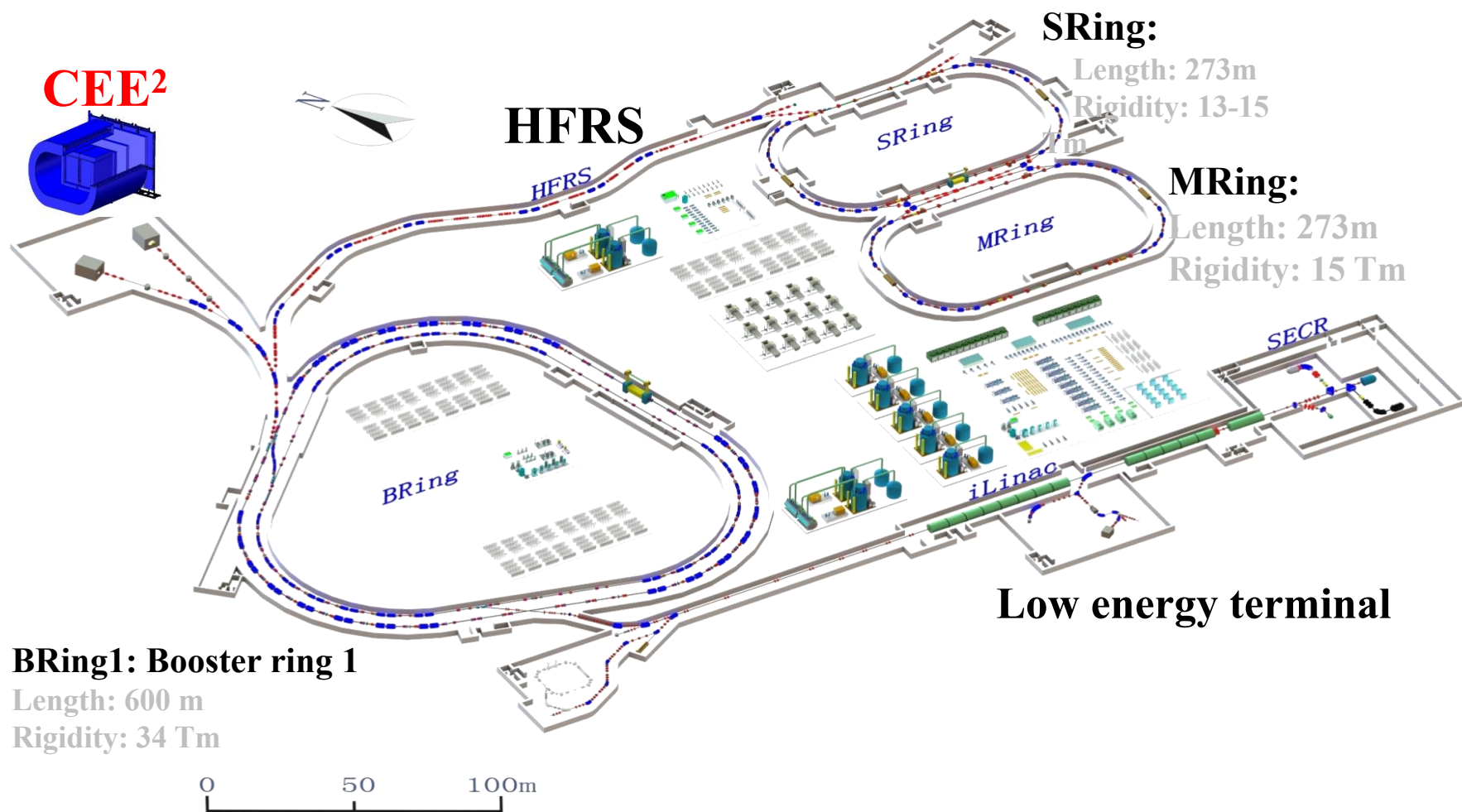


有关CEE的设计和研制进展, 请听张亚鹏的报告

# 将来计划和机遇: HIAF

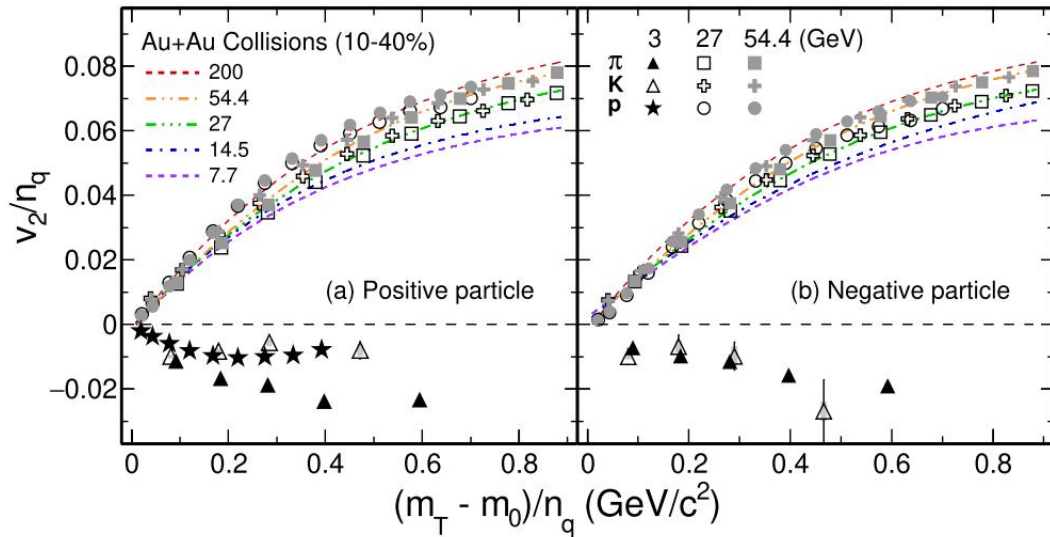
重离子束流能量(A/Z=2)  $\sim 4.5$  GeV/u  $\langle \rangle$  束流强度 HIAF/HIRFL:  $10^3 - 10^4$

$$\rho \gtrsim 3 - 4\rho_0$$

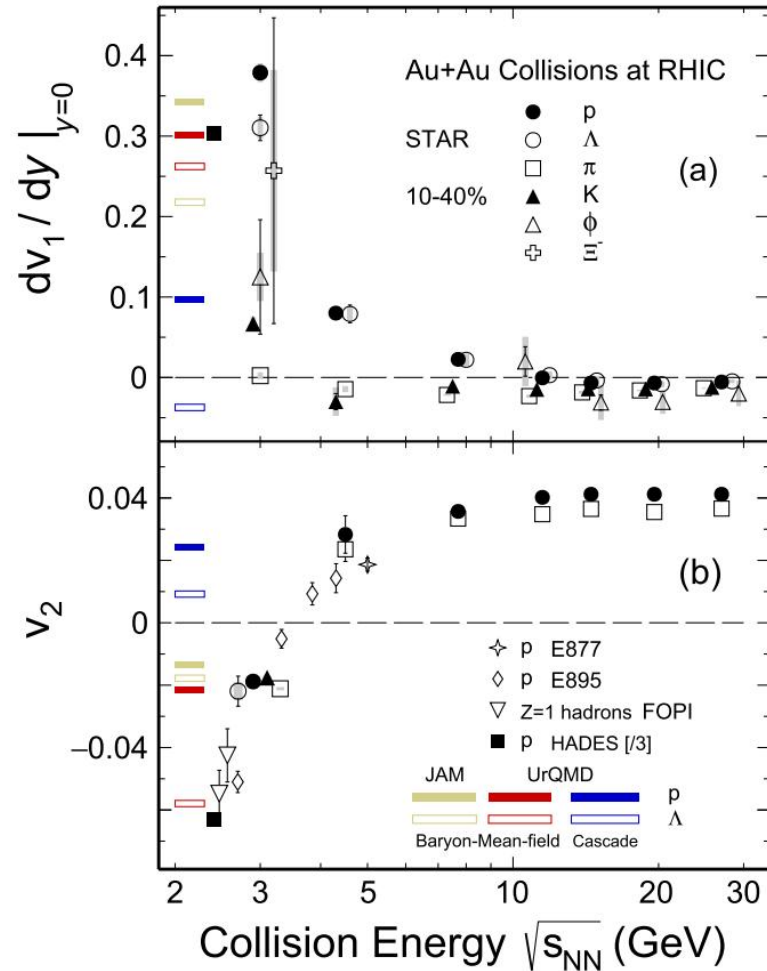




# Recent results of STAR experiment $\sqrt{s_{NN}} = 3 \text{ GeV}$



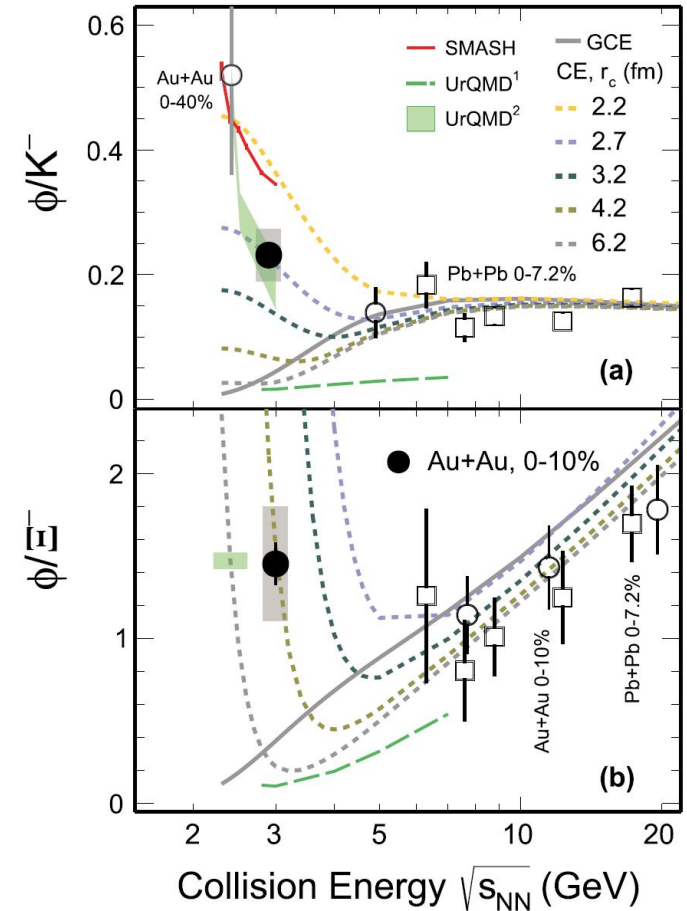
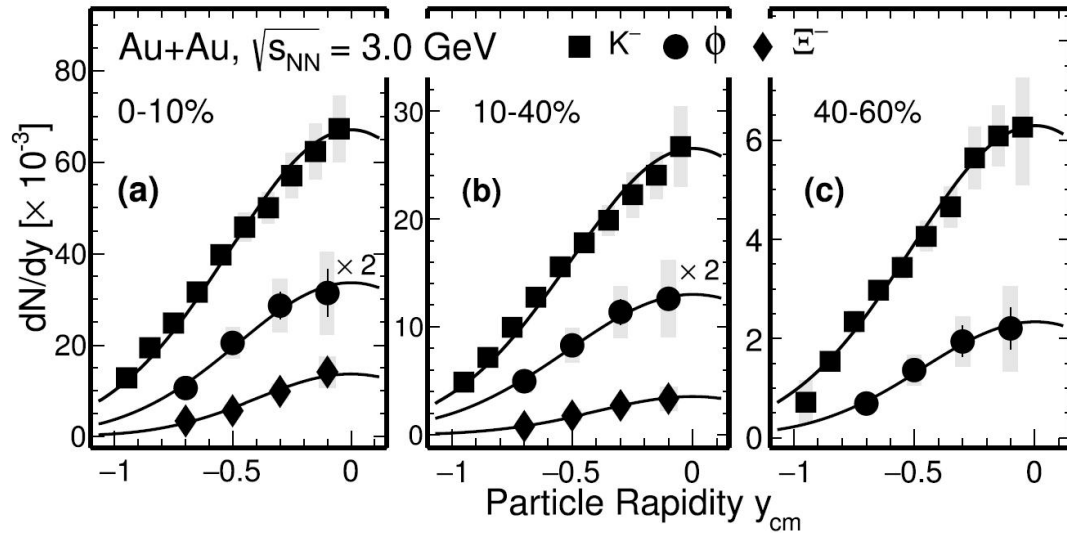
STAR Collaboration, PLB827, 137503 (2022)



At higher energy midcentral collisions the NCQ scaling holds, while at 3 GeV the  $v_2$  at midrapidity is negative and the NCQ scaling is absent, indicating the dense medium formed at  $\sqrt{s_{NN}} = 3 \text{ GeV}$  is likely hadronic matter.

# Recent results of STAR experiment $\sqrt{s_{NN}} = 3$ GeV

STAR Collaboration, **PLB827**, 137003 (2022)



The production yields of  $K^-$ ,  $\phi$  and  $\Xi^-$  production demonstrates the necessity of the Canonical Ensemble for strangeness at low energy heavy-ion collisions. Hadronic transport model calculations (UrQMD and SMASH) including resonance contributions reproduce the data, suggesting a change of the medium properties at 3 GeV compared to those from higher energy collisions.

# 对称核物质EOS的新探针

当入射能量更高，例如在HIAF上，形成的核物质密度更高，有必要寻找更好的观测量。

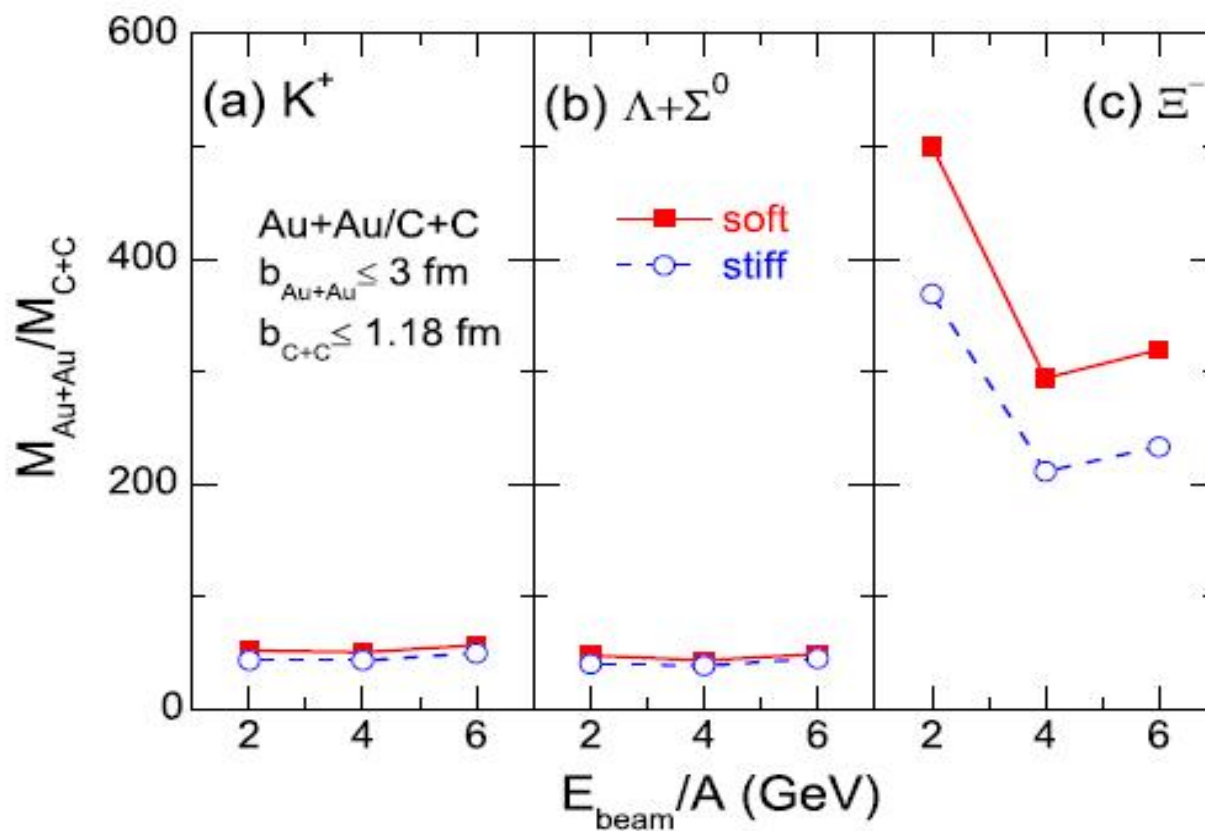
模拟发现， $\Xi^-$  通过次级反应、在更高的密度区域中才能产生，因此对高密区的核物质状态方程敏感。

为了研究中心密度  $\rho > 3\rho_0$  的状态方程，考虑2 GeV/u 以上的重离子碰撞，并考虑如下反应道；



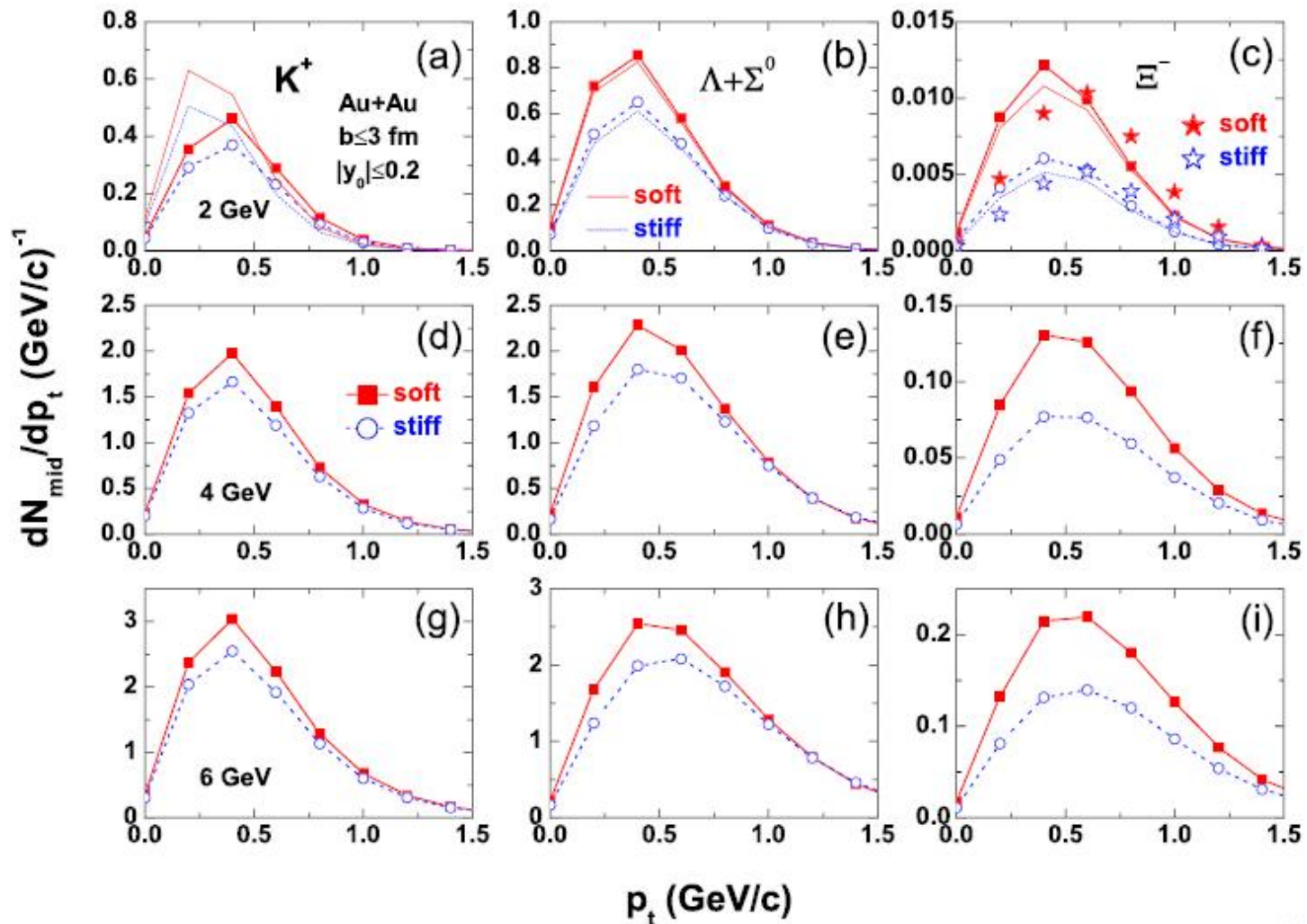
比较了两种不可压缩系数EOS的结果： $K_0 = 200 \text{ MeV}$  和  $K_0 = 300 \text{ MeV}$

# 对称核物质EOS的新探针



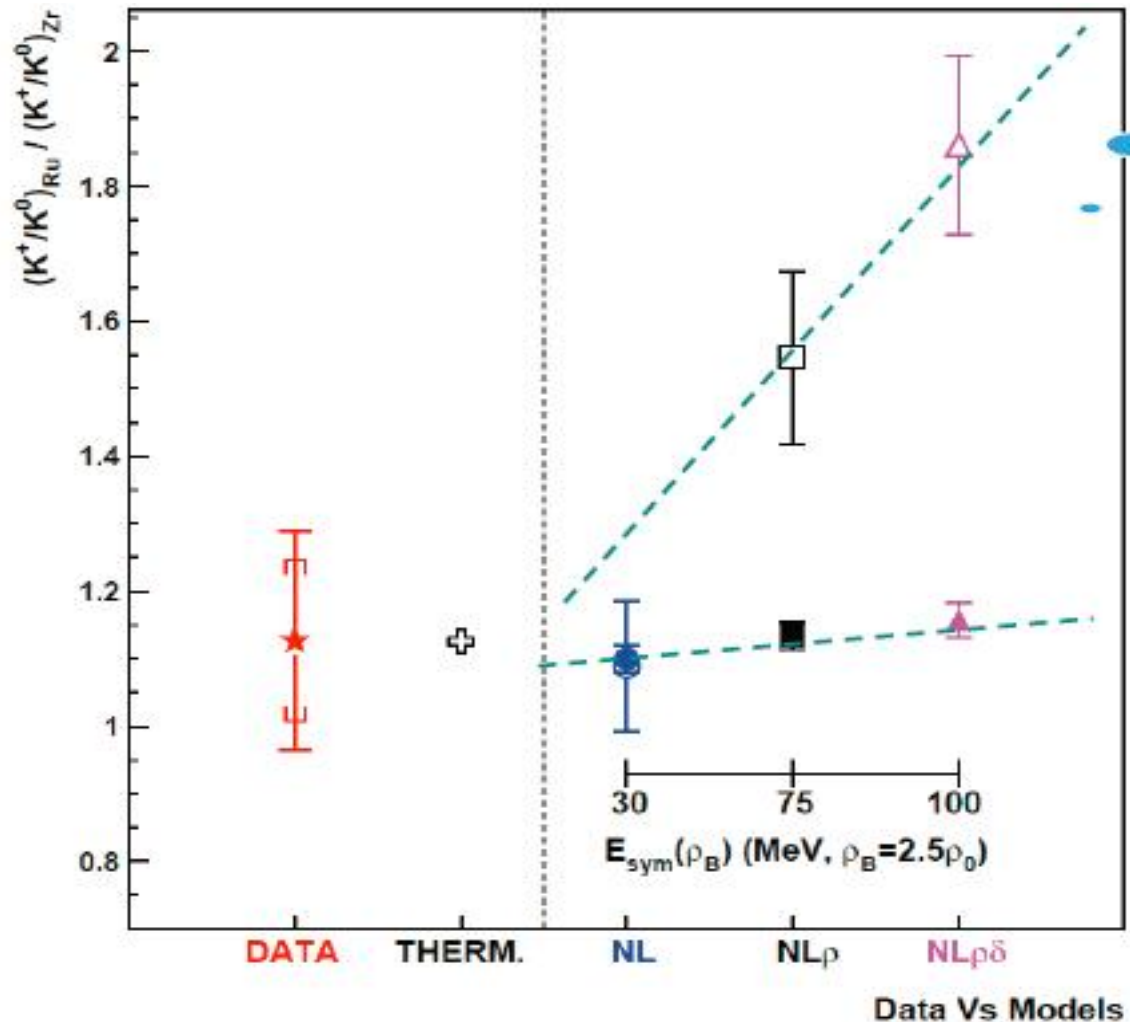
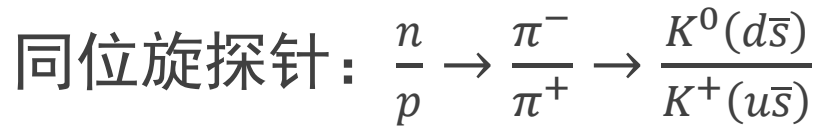
从右图比较可以看出，随着入射能量升高，single strangeness 的敏感度减小了【与G. Ferini et al., PRL97, 202301 (2006) 的结论一致】，但是 double strangeness  $\Xi^-$  的产额，对EOS的依赖非常敏感。

# 对称核物质EOS的新探针



对EOS的依赖敏感度最大的范围，在 $p_t$ 分布的峰值处。  
平均场和Strange hadrons的耦合，对 $\Lambda + \Sigma^0$ 和 $\Xi^-$ 结果影响不大。  
质量改变不是 $\Xi^-$ 产额对EOS的敏感依赖的原因。

# 更高密度区 $E_{\text{sym}}(\rho)$ 的探针



→ Collision dynamic effect reduces the sensitivity

→ Experimental precision not high enough to pin down  $E_{\text{sym}}(\rho)$

→  $NN \rightarrow N\Delta^-$  cancels out part of the  $N/Z$  asymmetry;

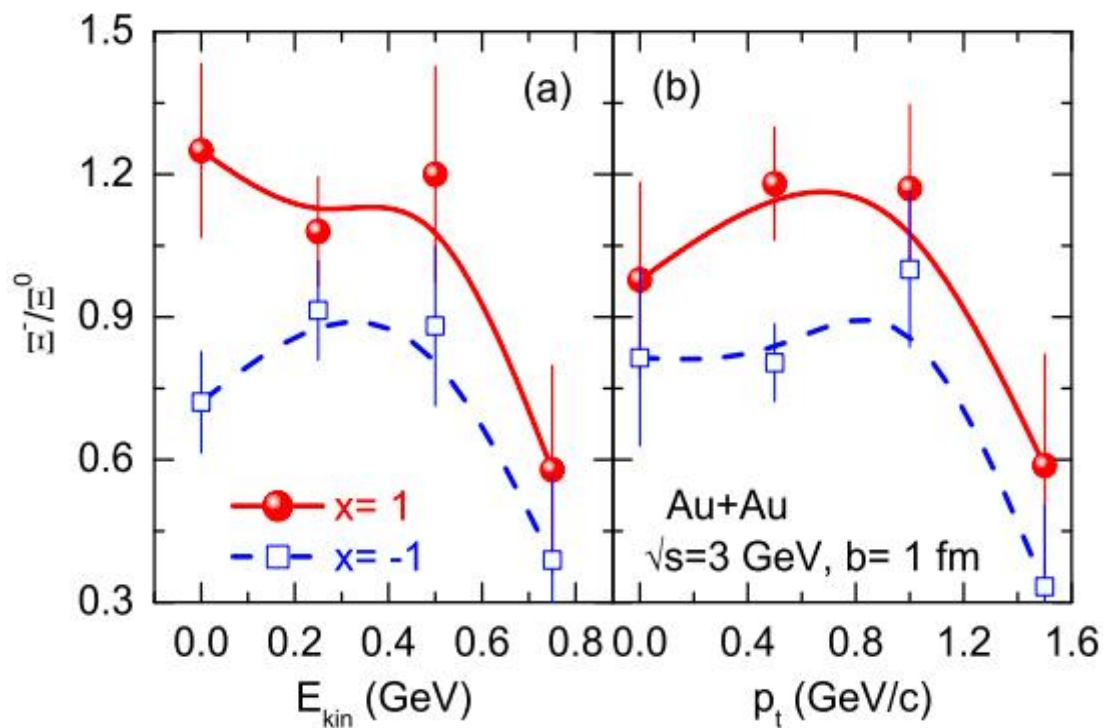
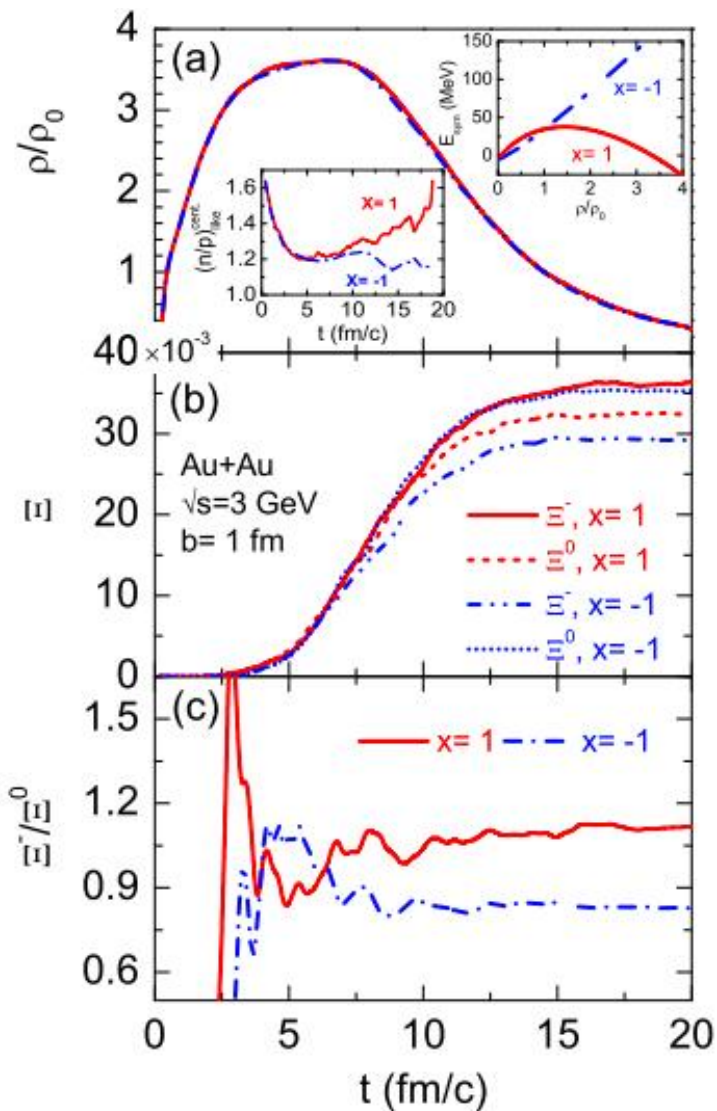
FOPI collaboration, PRC 75, 011901 (2007)

更重的系统，更大的N/Z跨度  
优化的束流能量

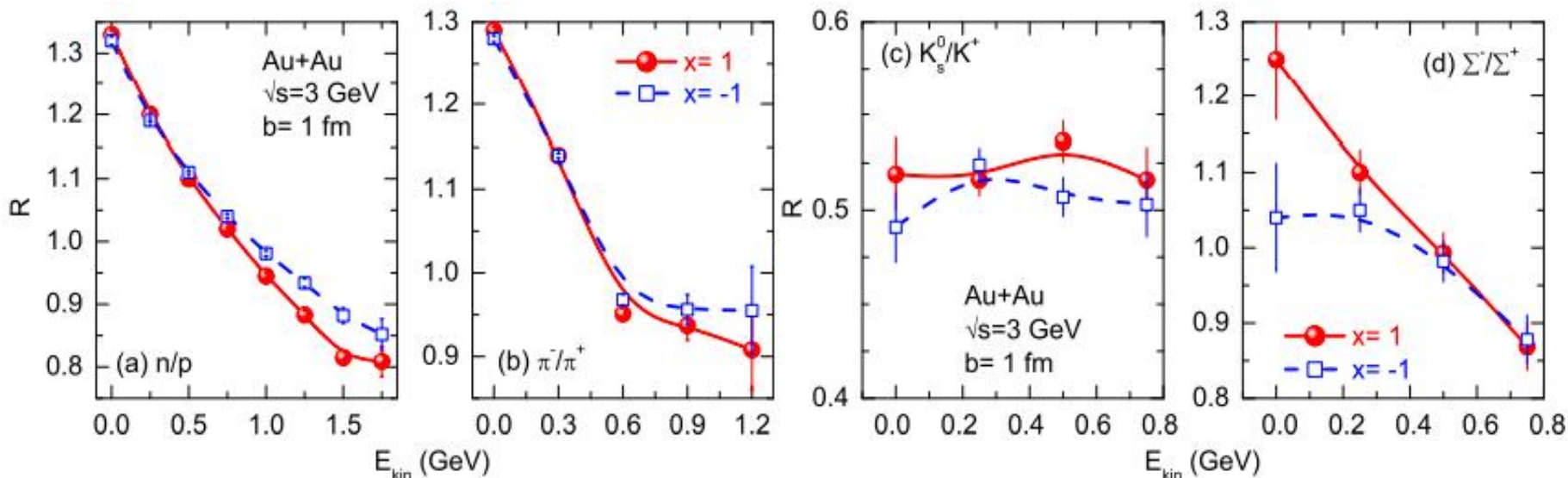
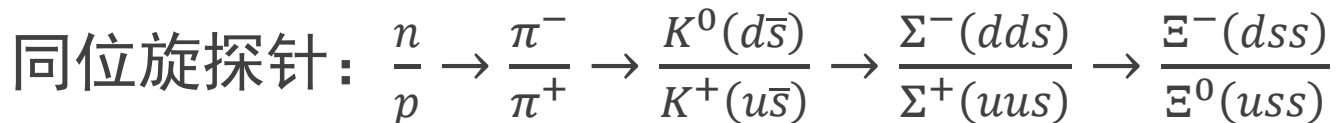
# 更高密度区 $E_{\text{sym}}(\rho)$ 的探针

同位旋探针： $\frac{n}{p} \rightarrow \frac{\pi^-}{\pi^+} \rightarrow \frac{K^0(d\bar{s})}{K^+(u\bar{s})} \rightarrow \frac{\Sigma^-(dds)}{\Sigma^+(uus)} \rightarrow \frac{\Xi^-(dss)}{\Xi^0(uss)}$

束流能量增加

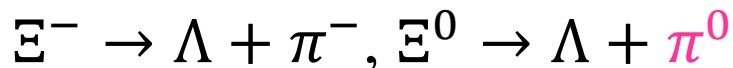
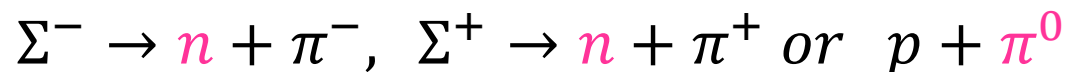


# 更高密度区的对称能 $E_{\text{sym}}(\rho)$ 的约束



via  $\pi + N \rightarrow \Sigma$  secondly process, isospin effect carried by pions are passed to strangeness.

**实验难点：需要对末态中性粒子的重建和鉴别**





# 三、小结

重离子碰撞产生短暂的、微量的、压缩状态的“核物质”，因此是研究核物质状态方程(nEOS)的一个自然的手段！nEOS的研究，也是世界几个大型核物理实验室投放力量的方向。

基于国内大科学装置HIRFL，也可以产生一些成果（例如CSHINE上的相关工作）。

CEE 将在 GeV/u能区，为nEOS的研究，提供一些新的机遇。可测的物理量有轻碎片、 $\pi^-/\pi^+$  和  $K^0$ 介子等。

HIAF的建成，将在更高密度区( $\rho \gtrsim 3\rho_0$ )，为nEOS研究提供很好的研究机遇。在这一能区，多奇异子重子是很好的探针。

- 可以用重系统中的  $\Xi^-$  产额探测对称核物质不可压缩系数；
- 可以用  $\Xi^-/\Xi^0$ ， $\Sigma^-/\Sigma^+$  等奇异探针约束对称能。

