2022年第七届手征有效场论研讨会，2022年10月15-17日

Hyperon dynamics and hypernuclear formation in heavy-ion collisions

重离子碰撞中超子产生和超核的形成

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报告内容

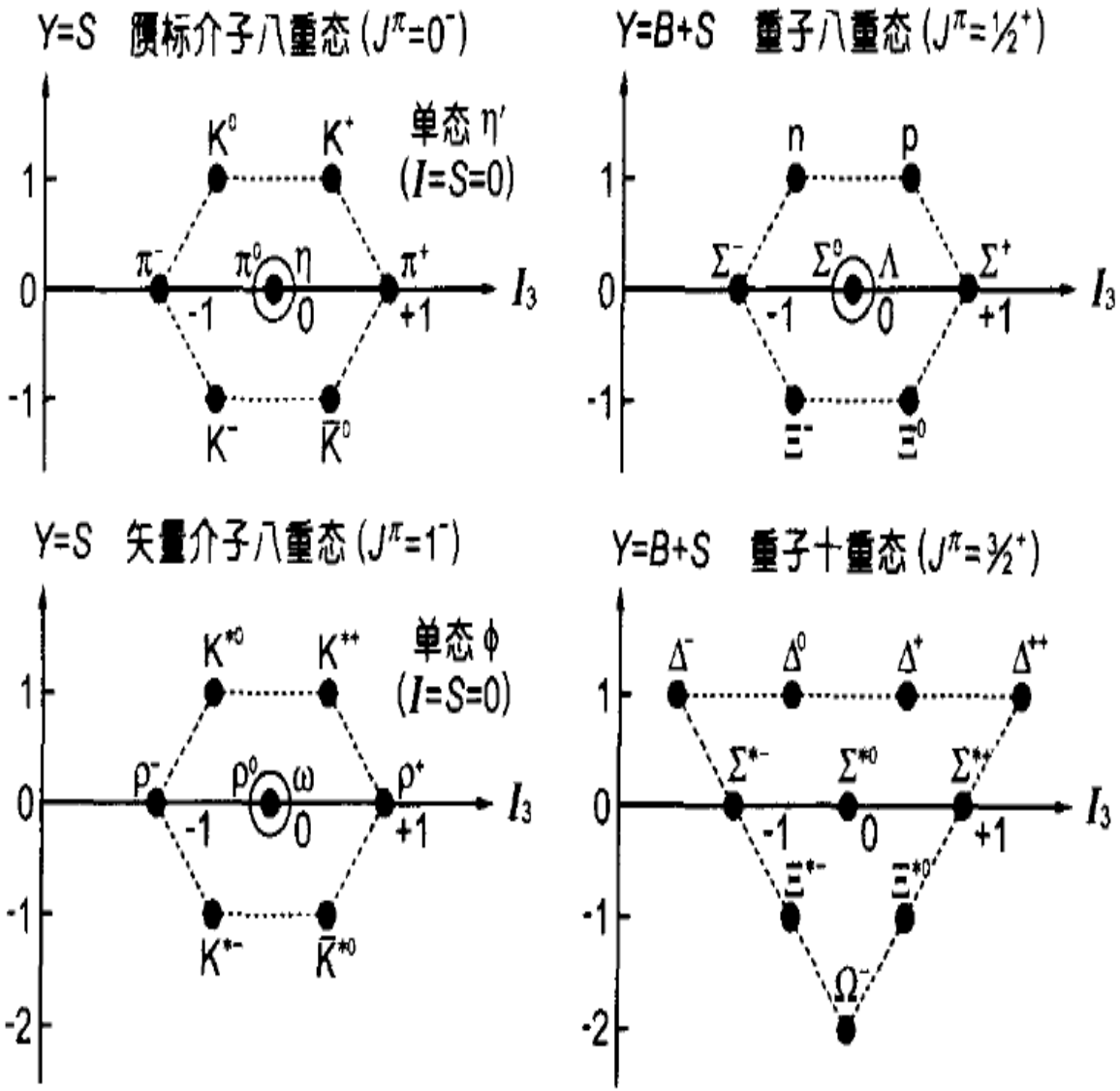
- 奇异性核物理研究现状
- 重离子碰撞中奇异粒子产生
- 原子核碎裂反应和超核形成
- 总结

一、奇异性核物理现状介绍

◆强子的内部结构

Normal baryon

Normal meson

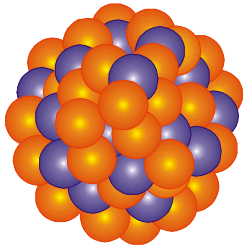


◆核子和核子共振态：八(十)重态重子

◆介子八重态：矢量介子和赝标量介子

◆奇异粒子(含s夸克)主要指介子K(K^0, K^+)和 $\bar{K}$($\bar{K}^0$, K^-), 超子Λ、Σ、Ξ和Ω

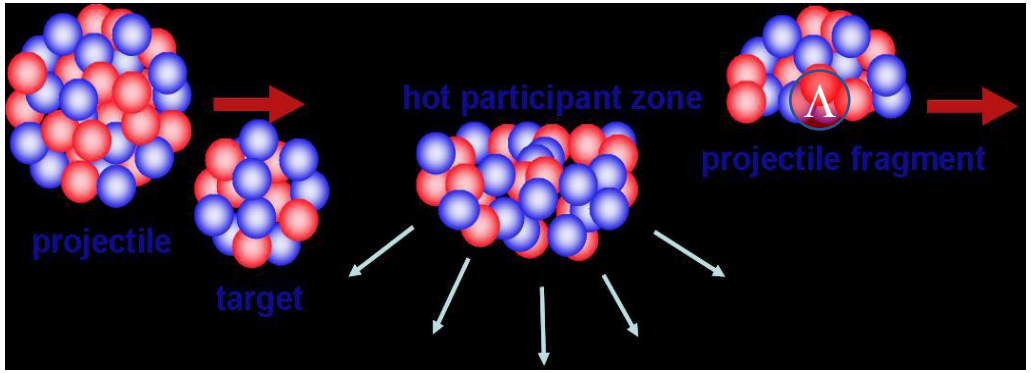
◆含有奇异粒子的原子核-超核

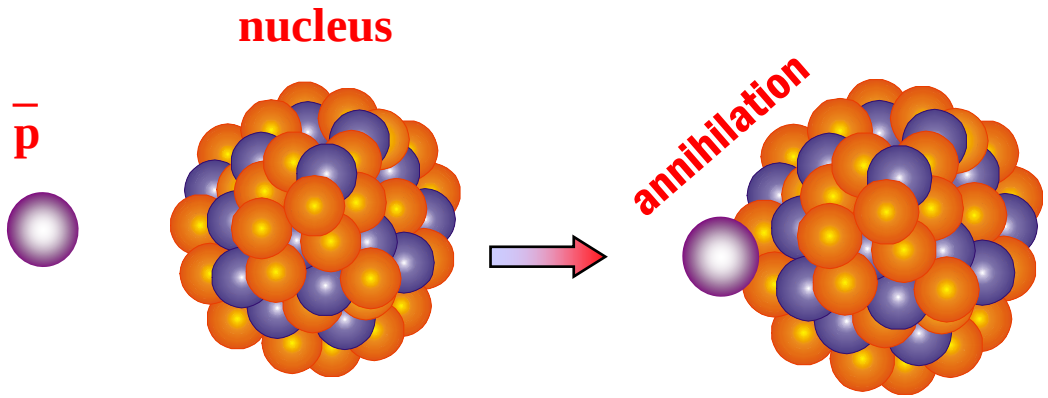


奇异粒子产生：

- **中高能重离子碰撞**
- 强子(质子，反质子，介子)引起的核反应
- 高能电子轰击原子核
- 光核反应

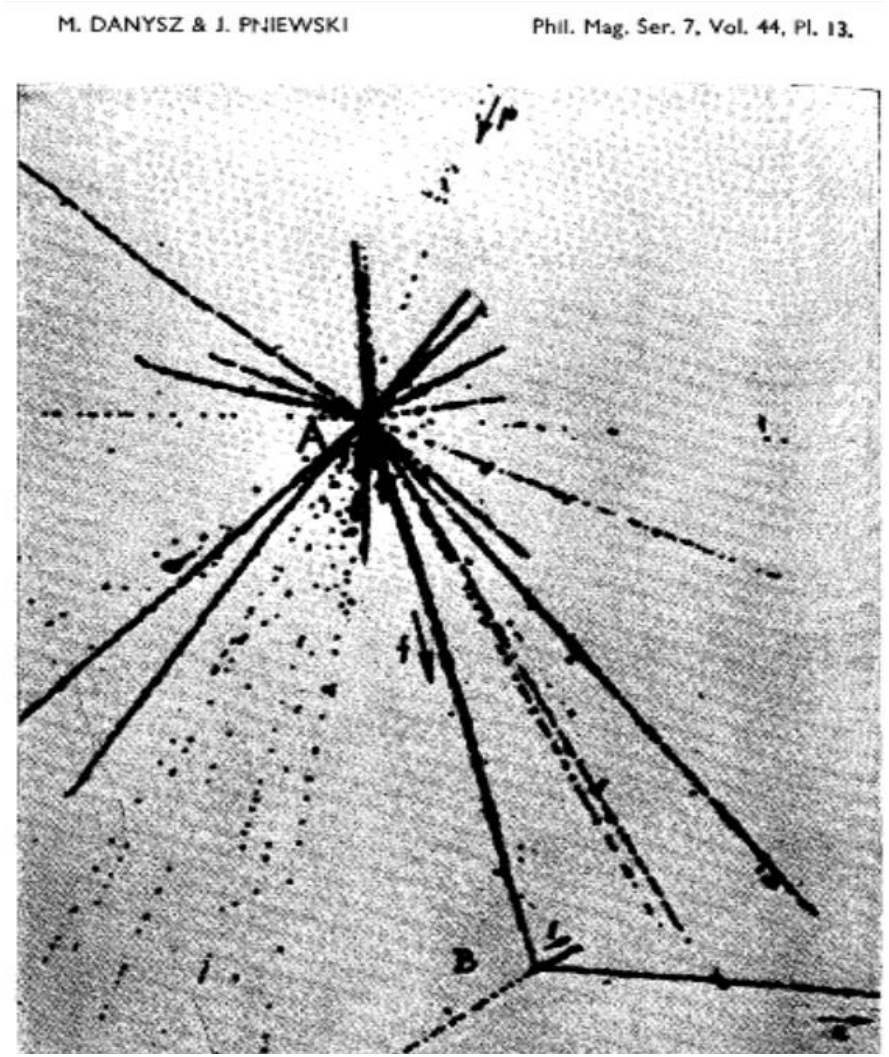
…





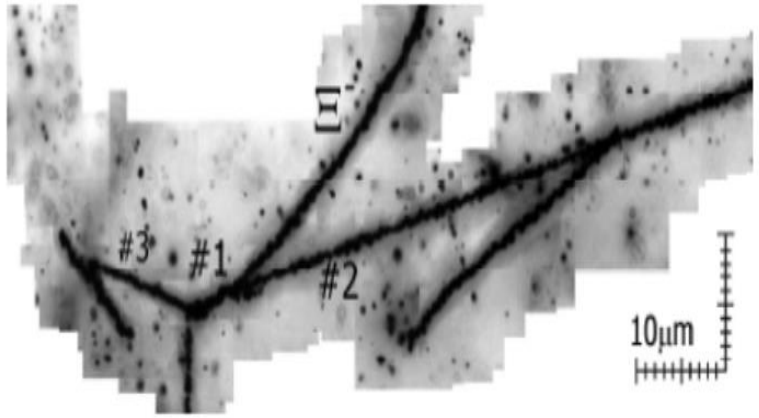
1. 超核实验观测和进展

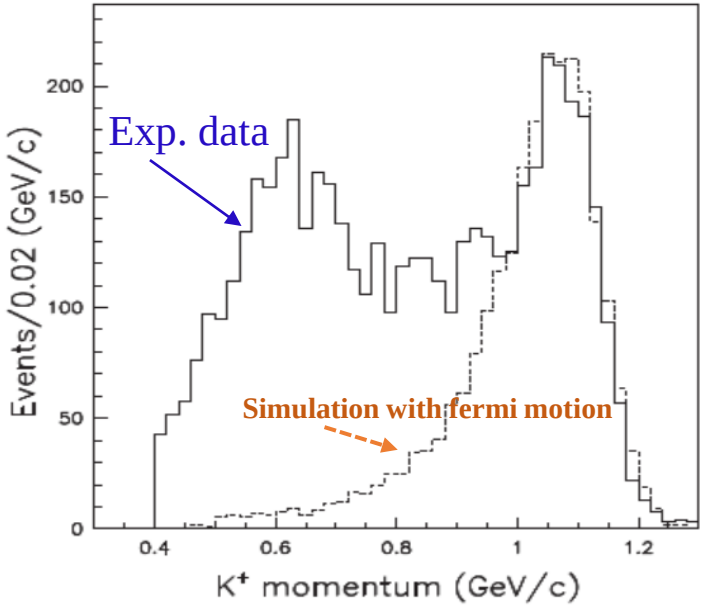
1953年波兰物理学家M. Danysz和J. Pniewski
在宇宙线乳胶实验中首次发现Λ超核



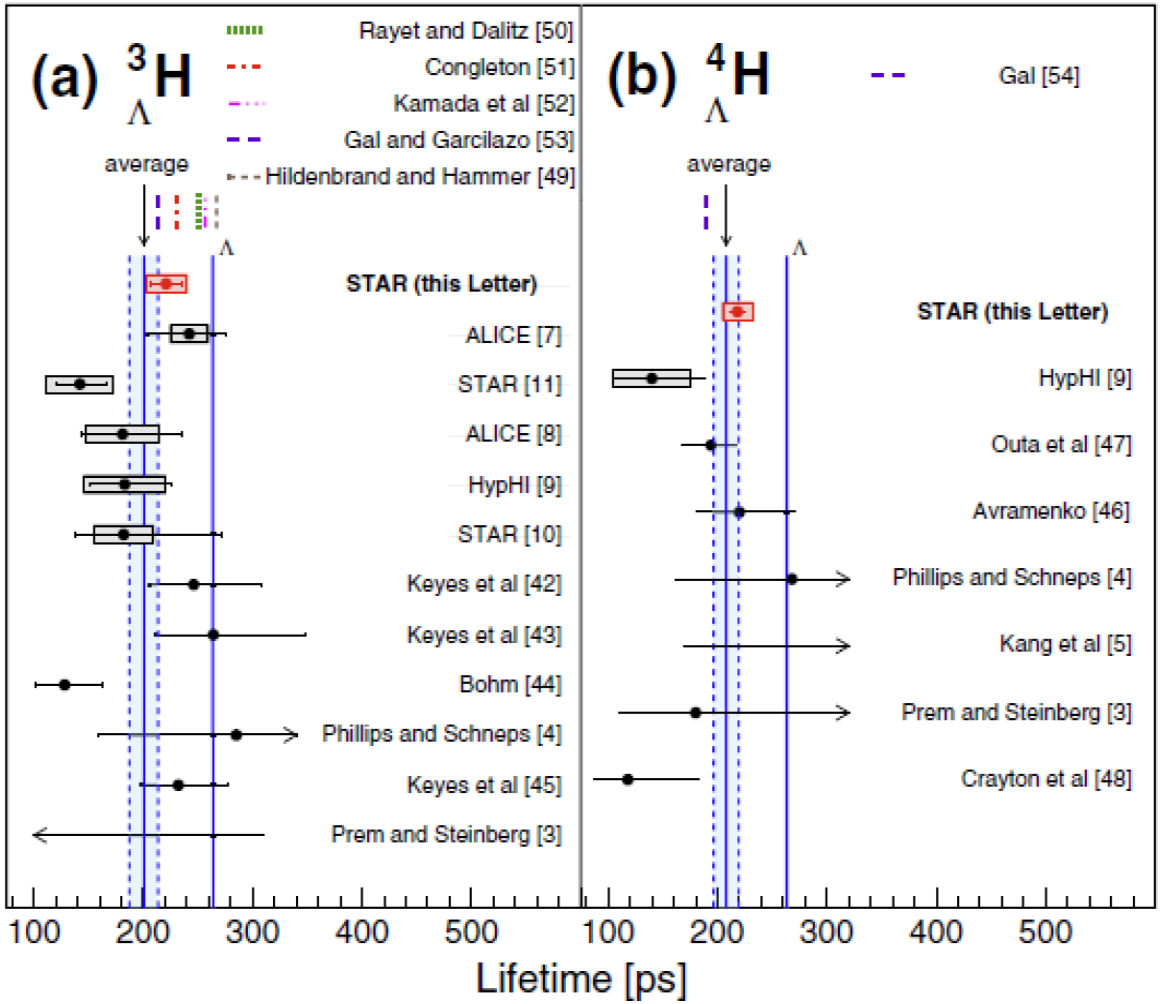
利用（K^-, K^+）产生$_{\Xi}$X超核实验观测

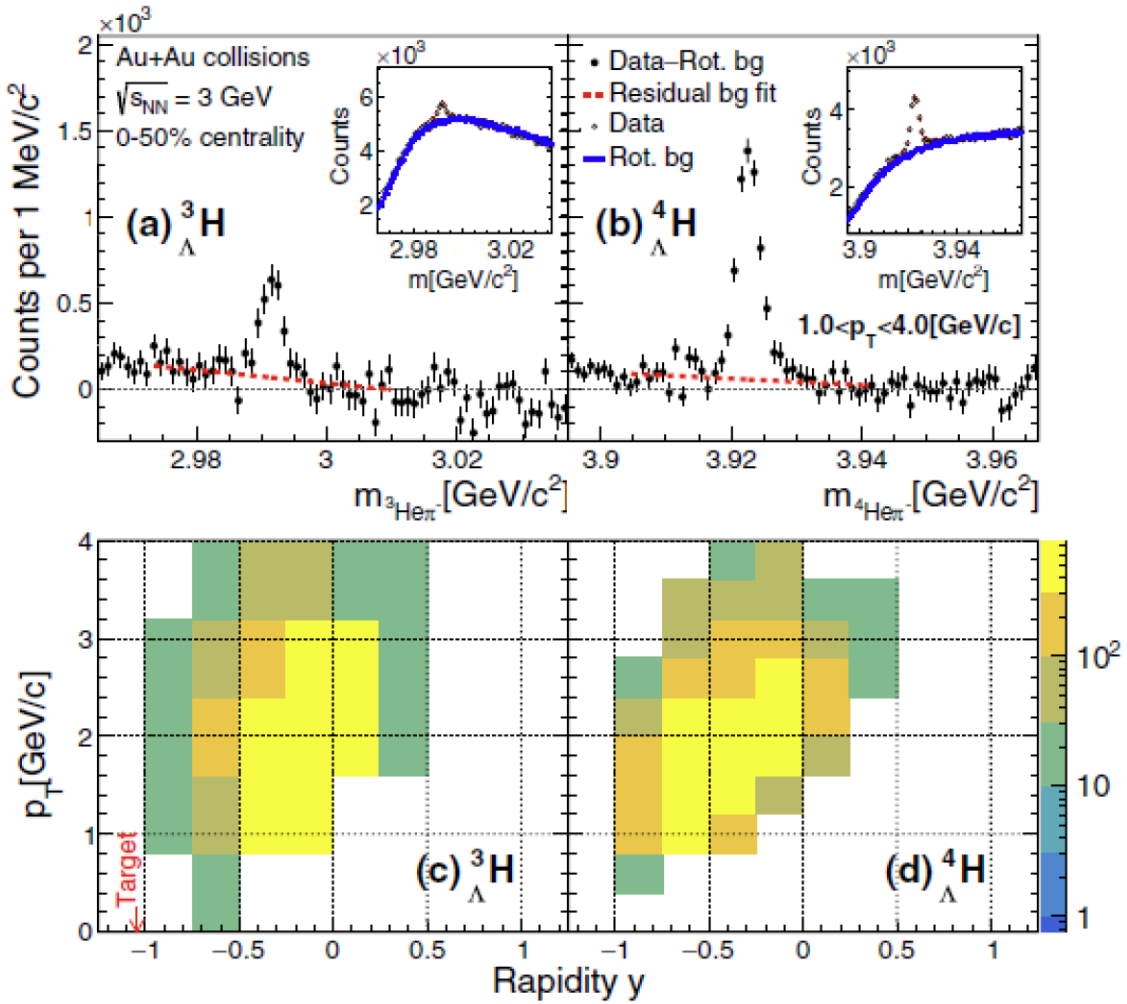
Kazuma Nakazawa et al, J. Phys.: Conf. Ser. 569 (2014) 012082





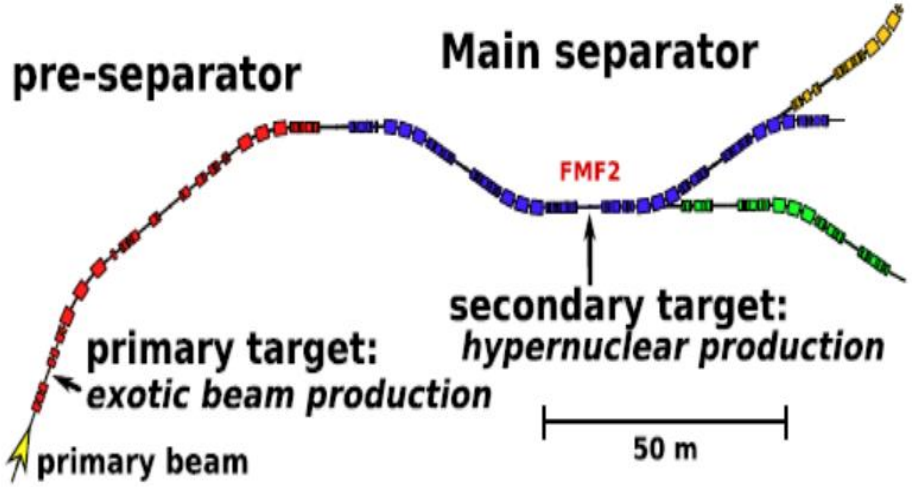
Hypernuclide $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ measured by STAR Collaboration (Phys. Rev. Lett. 128, 202301 (2022))

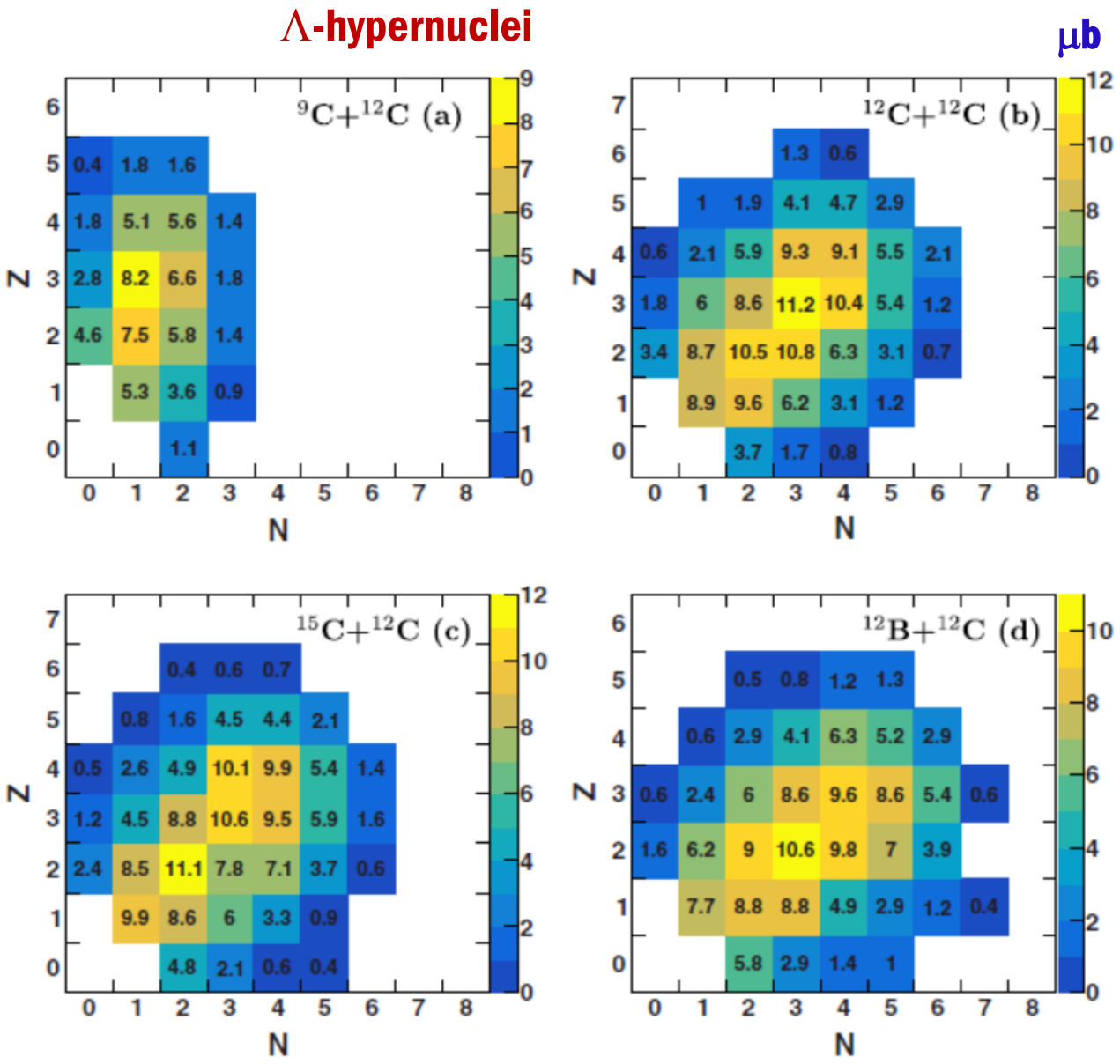




德国GSI产生丰质子/丰质子超核实验条件分析

C. Rappold, J. López-Fidalgo, PRC 94, 044616 (2016)

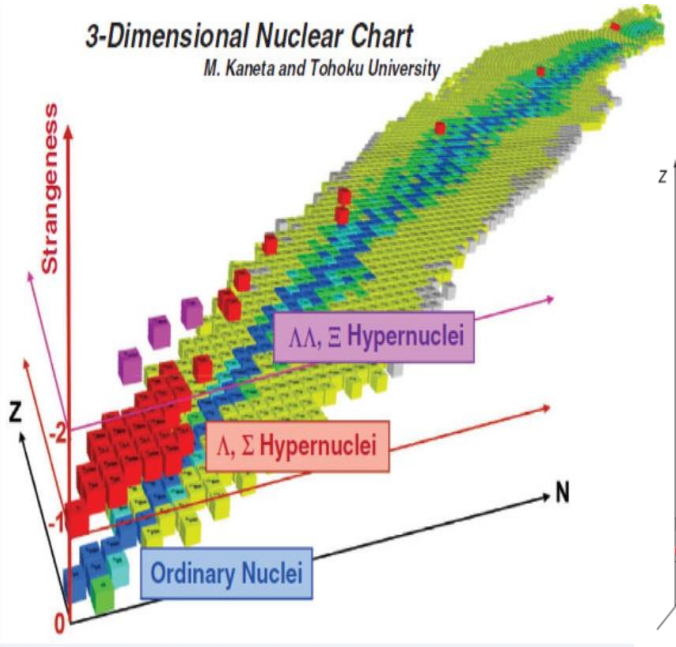


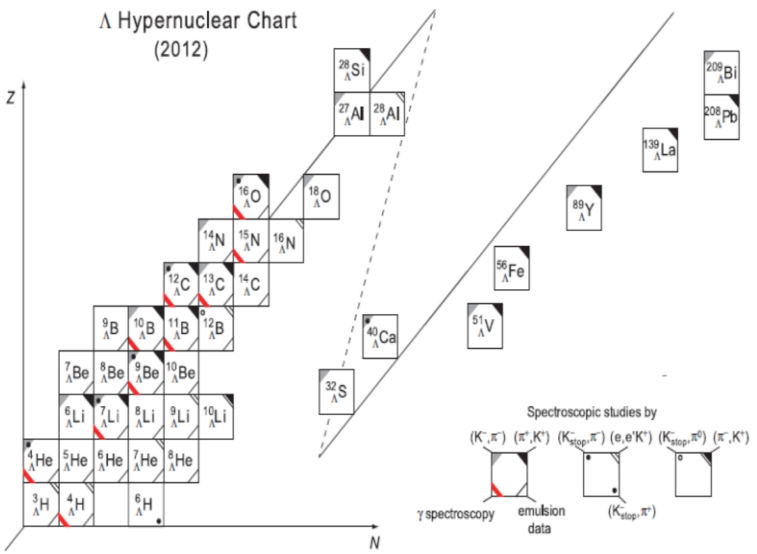


重离子碰撞产生超核的优势

1. 极端丰中子或丰质子超核产生和谱学性质
2. 奇特超核产生(s=-2) $_{\Lambda\Lambda}$X和$_{\Xi}$X
3. 核物质中Λ-Λ和Ξ-N相互作用

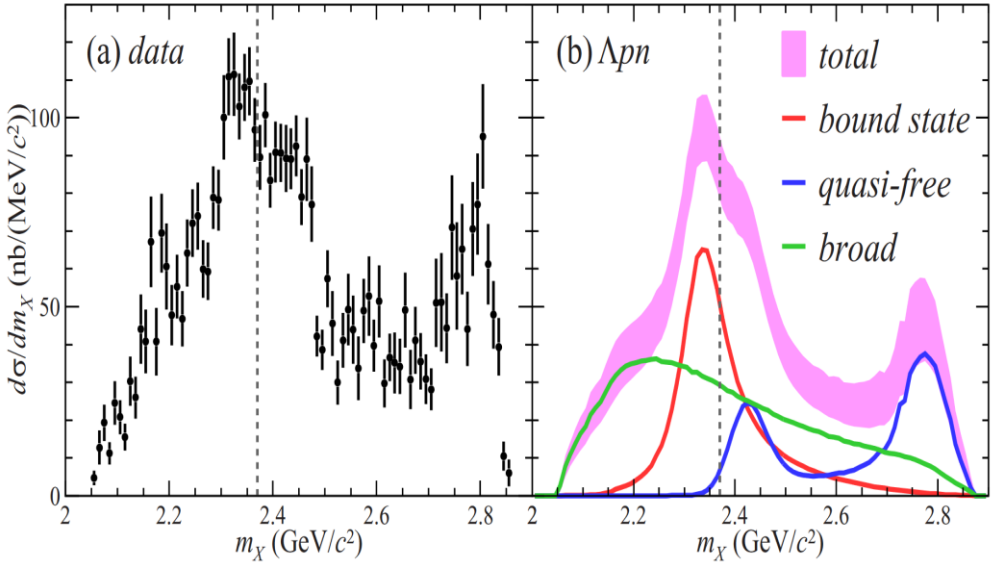
H. Tamura, *Prog. Theor. Exp. Phys.* (2012) 02B012

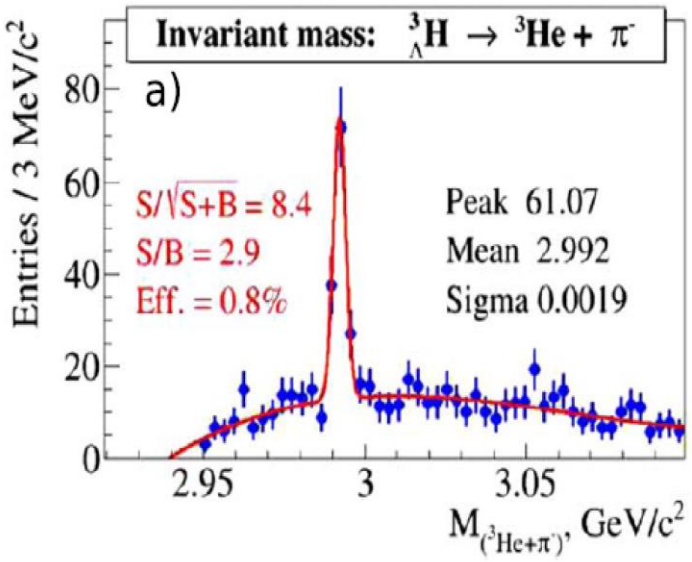


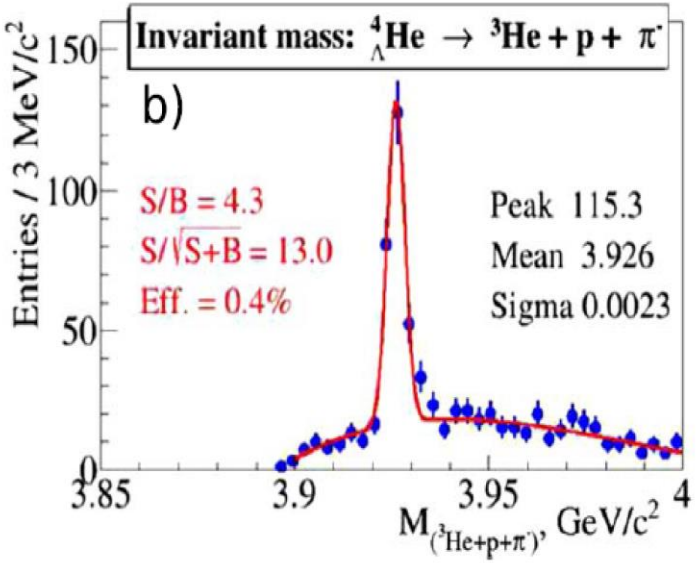


PHYSICAL REVIEW C **102**, 044002 (2020)

Observation of a $\bar{K}NN$ bound state in the ^{3}He(K^-, Λp)n reaction



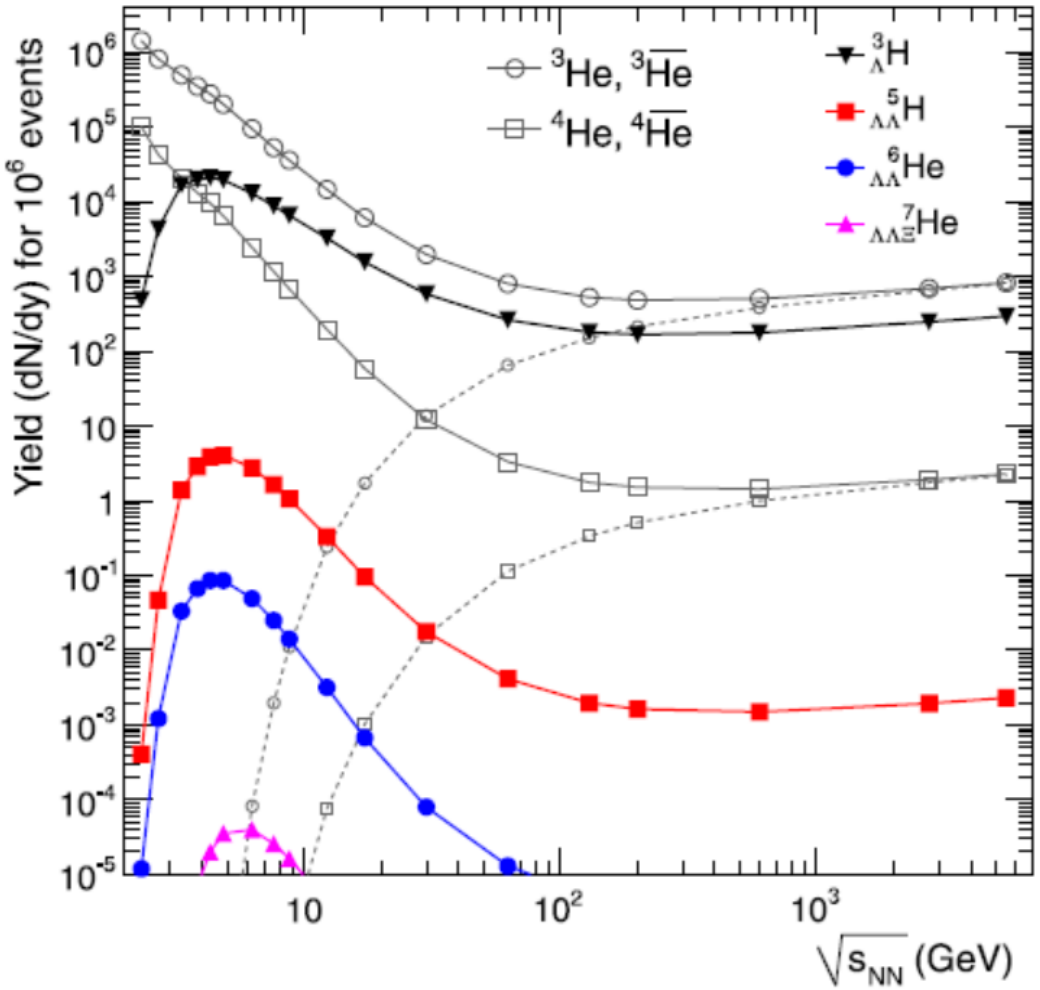




2. 中高能重离子碰撞产生超核理论研究—统计理论

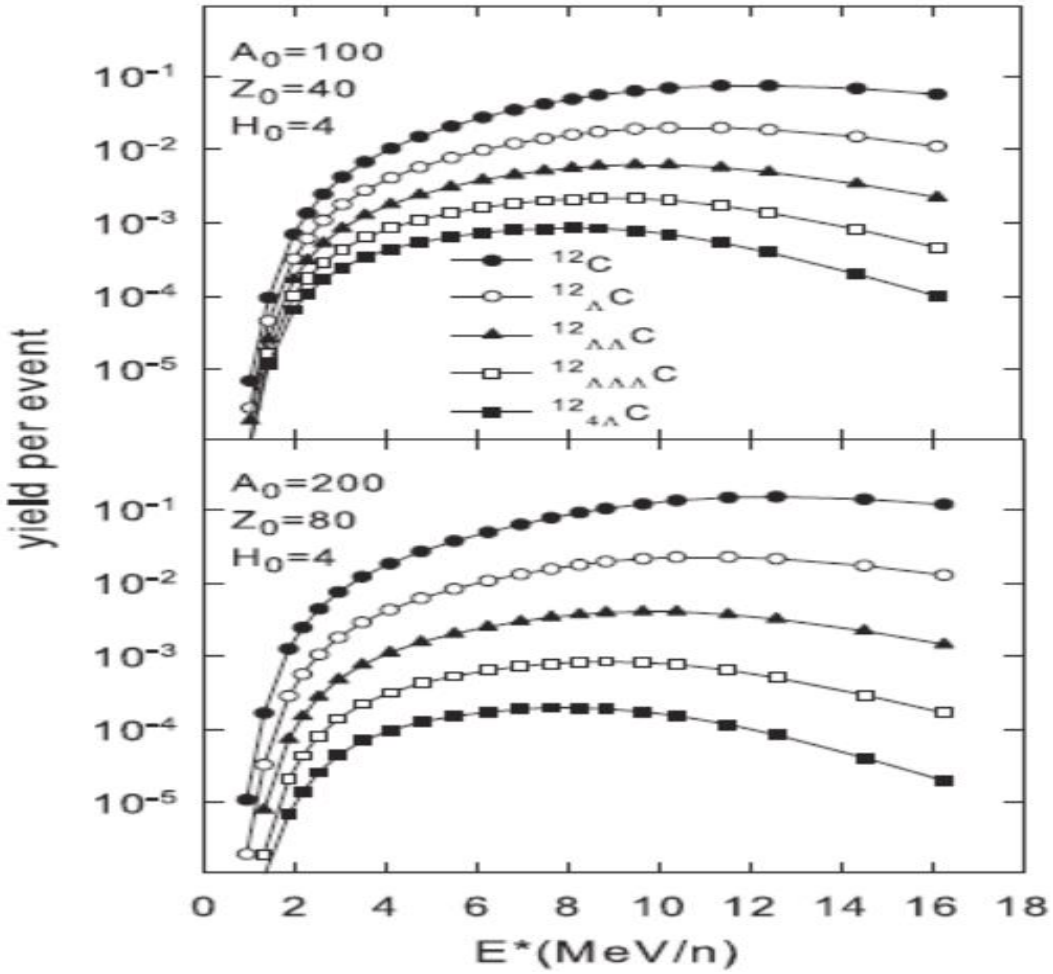
A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker, Physics Letters B 697 (2011) 203–207

Pb+Pb



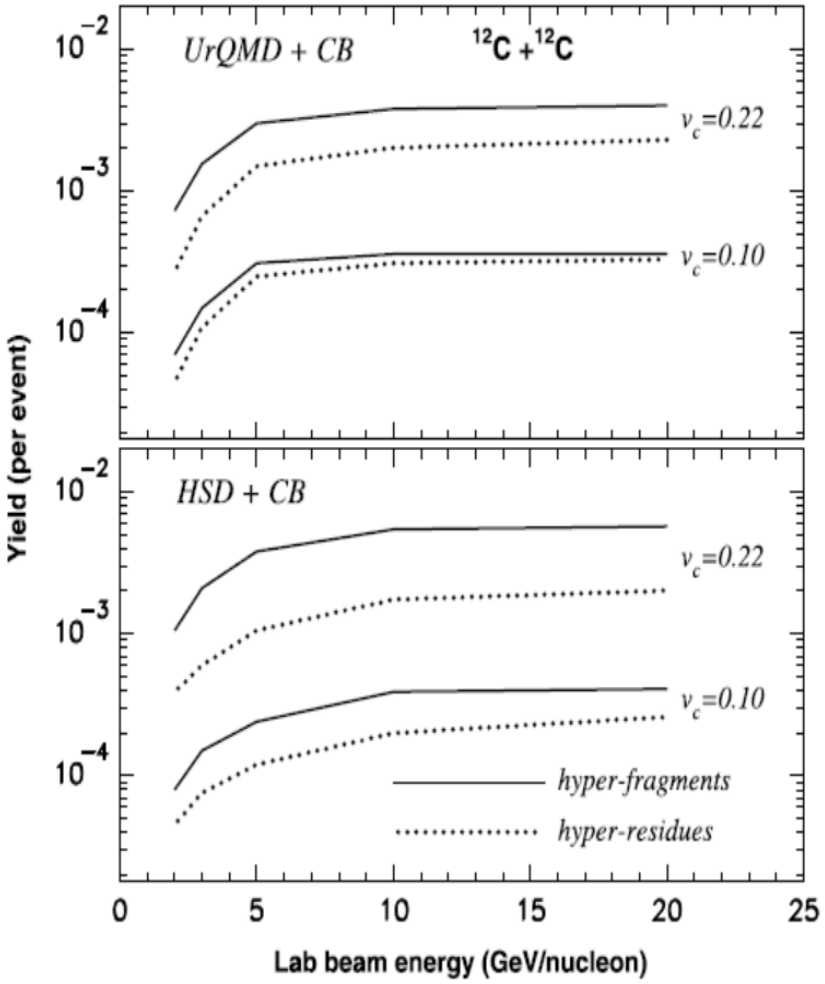
N. Buyukcizmeci, R. Ogul, A. S. Botvina, M. Bleicher, Phys. Scr. 95 075311 (2020)

Statistical multifragmentation model (SMM)



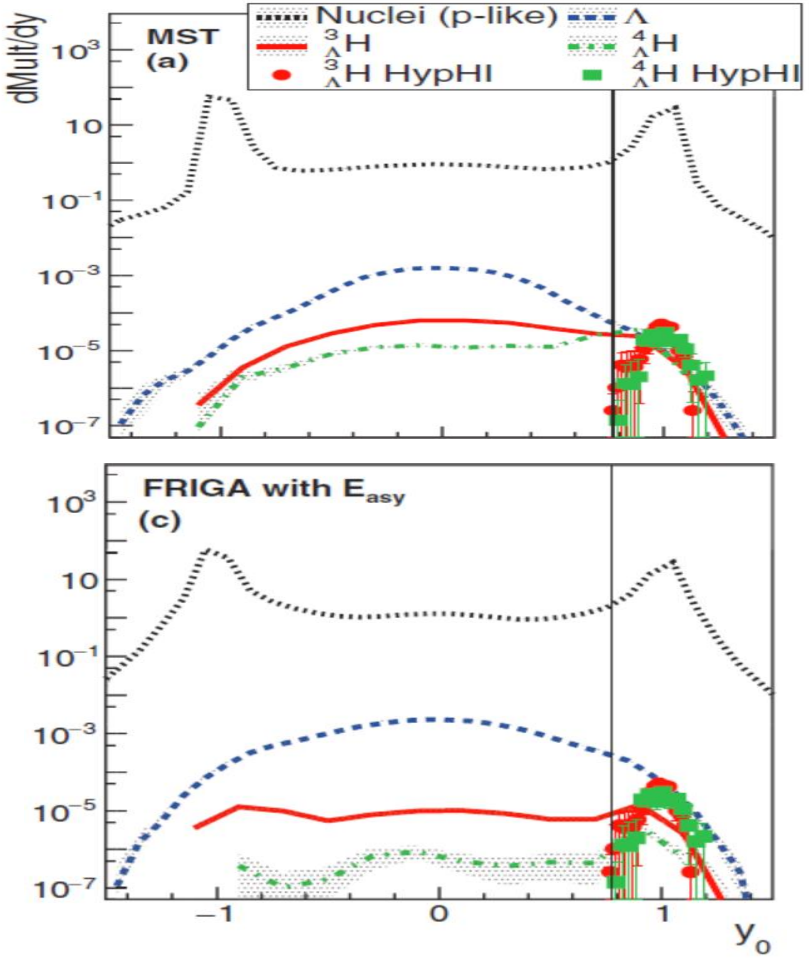
3. 中高能重离子碰撞产生超核理论研究方法
— 输运理论+并合模型

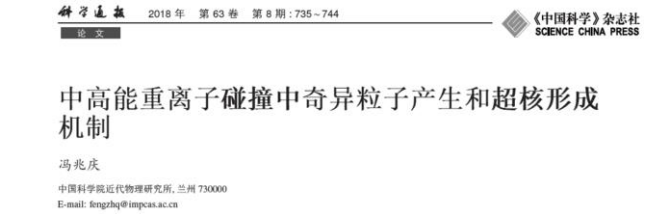
A.S. Botvina, J. Steinheimer, E.Bratkovskaya et al., Physics Letters B 742 (2015)7–14

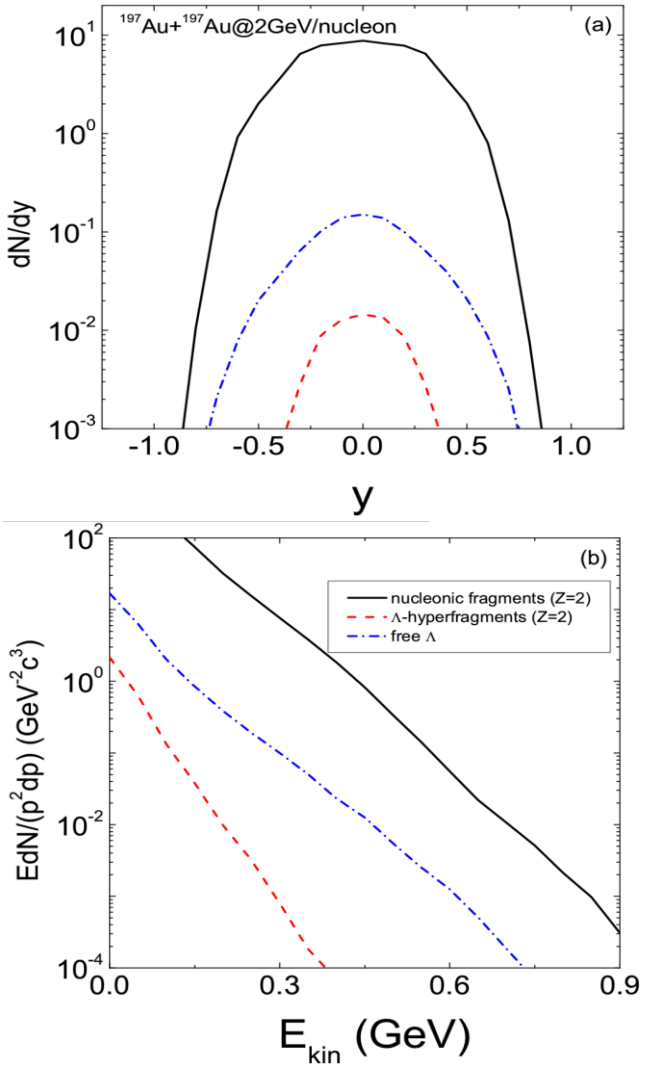


J. Aichelin, E. Bratkovskaya, A. Le Fèvre et al., Physical Review C 101, 044905 (2020)
A. Le Fèvre, J. Aichelin, C. Hartnack and Y. Leifels 100, Physical Review C 034904 (2019)

$^{6}Li+^{12}C$@2A GeV



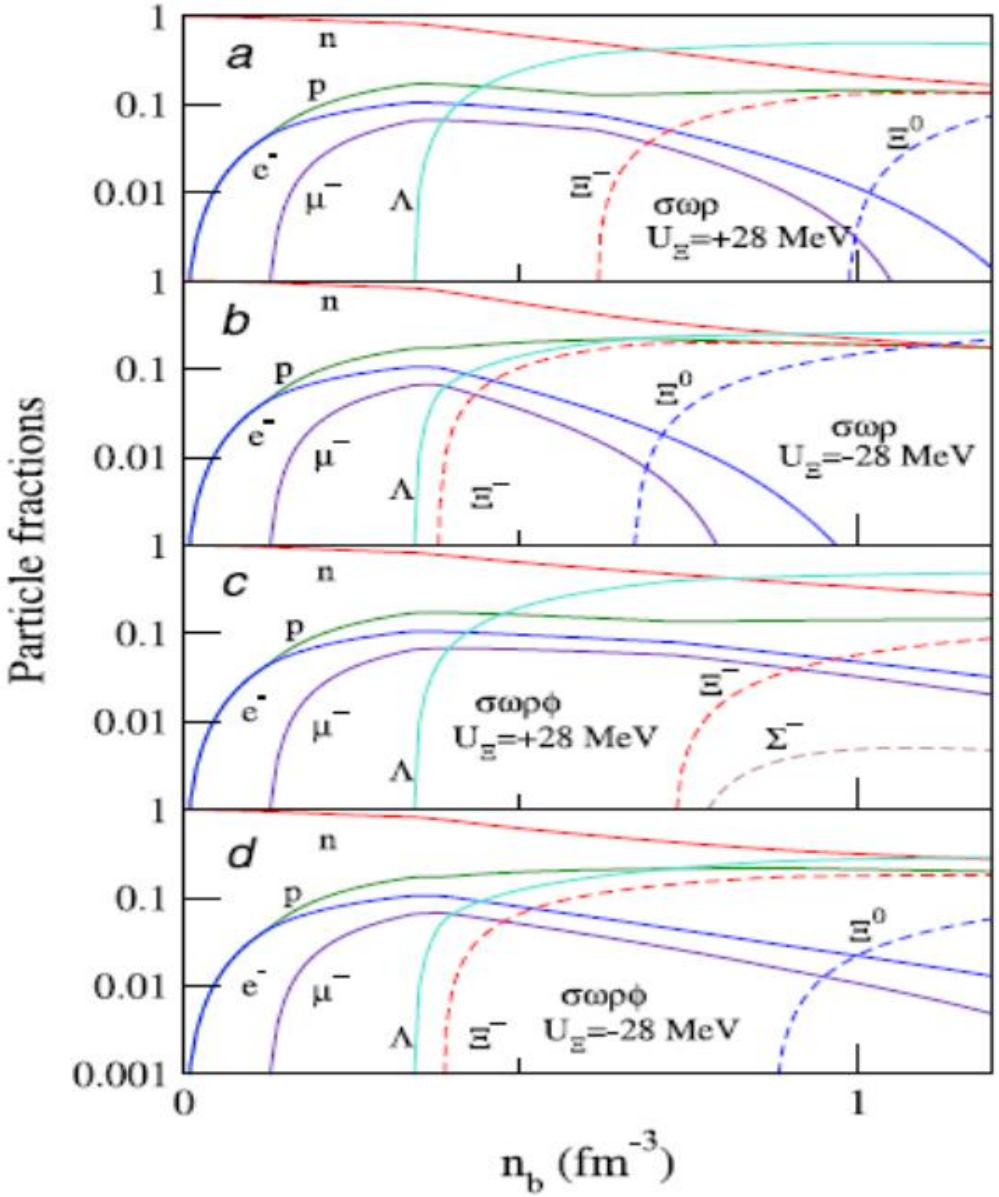


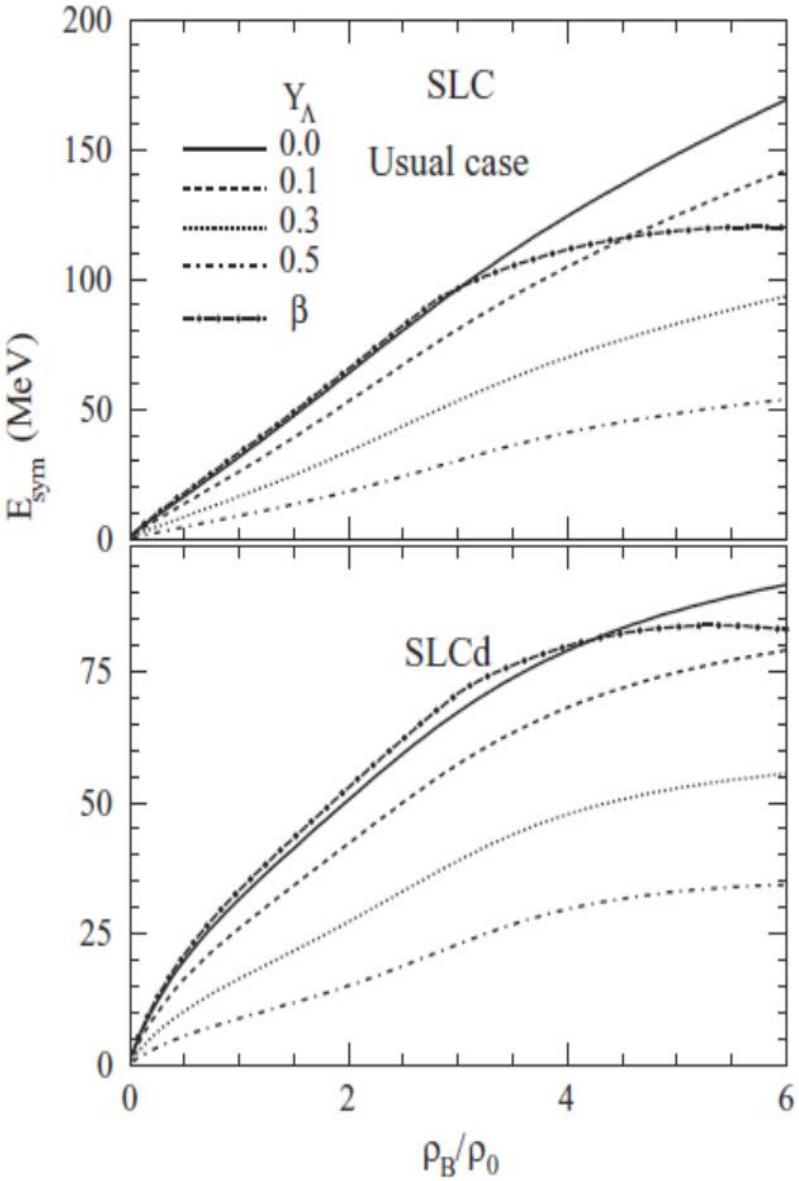


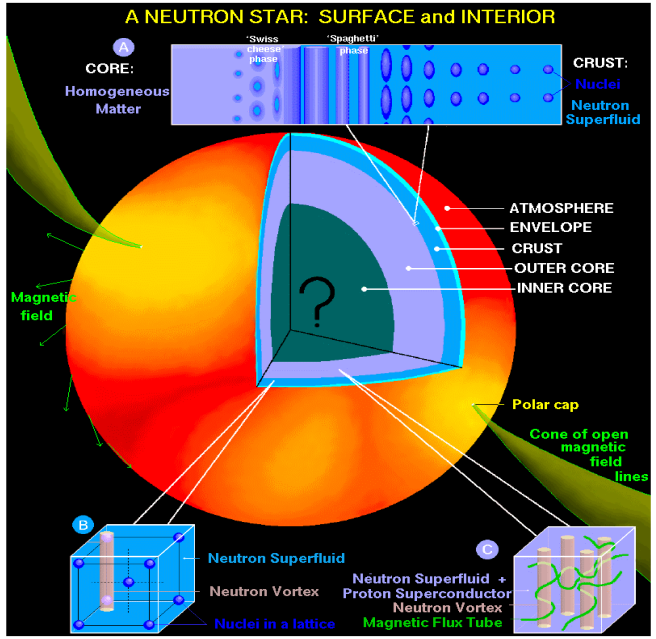
4. 致密物质中超子成分的影响

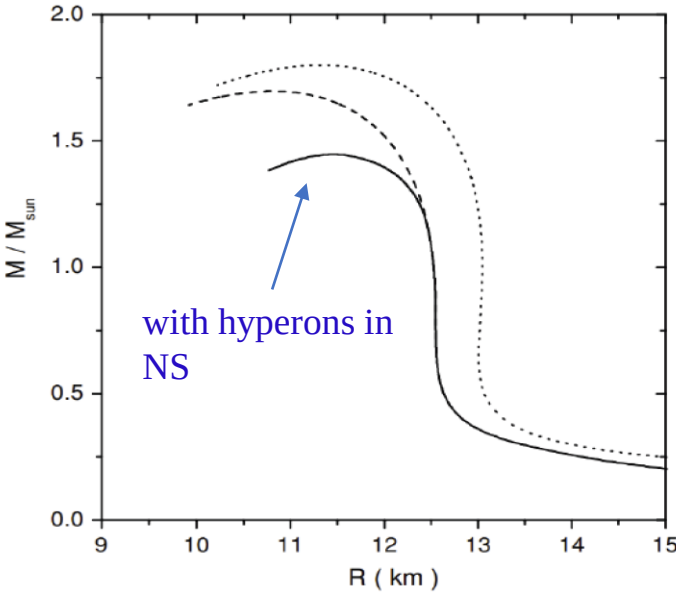
S. Weissenborn, D. Chatterjee, J. Schaffner-Bielich, Nucl. Phys. A 881, 62 (2012)
W. Z. Jiang, R. Y. Yang, and D. R. Zhang, Phys. Rev. C 87, 064314 (2013)

J. M. Lattimer and M. Prakash, Science 304, 536 (2004)









核物质对称能

$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{\rm sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2, \quad (\rho \sim \rho_0)$$

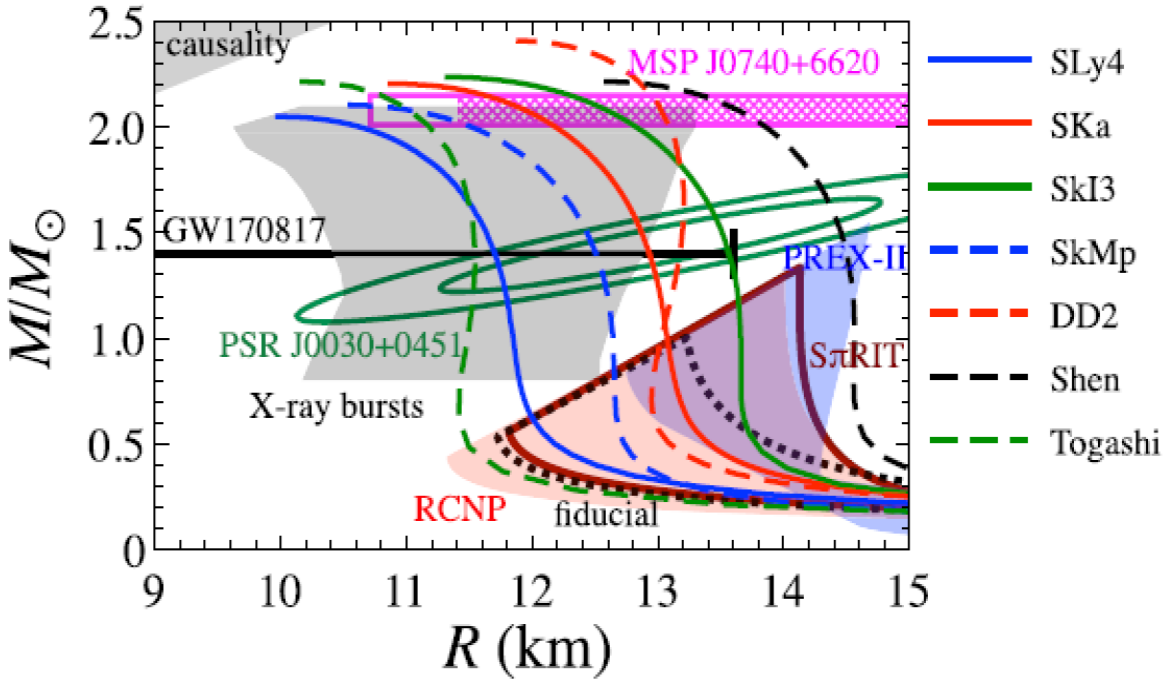
液滴模型

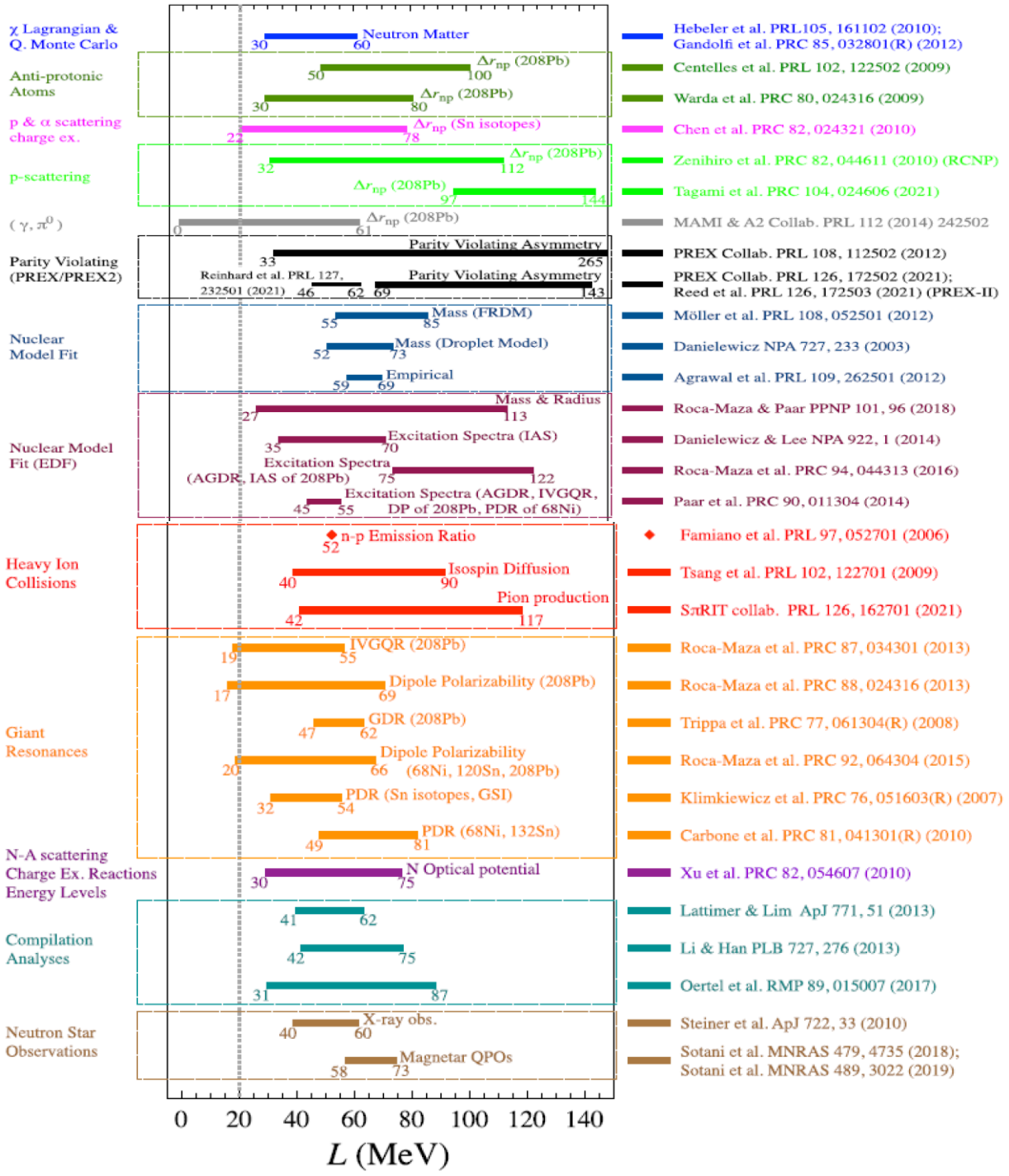
$E_{\rm sym}(\rho_0) \approx 32$ MeV

斜率和曲率参数

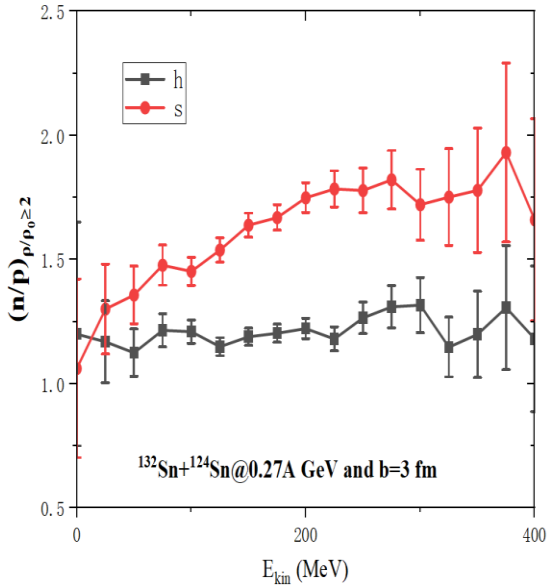
$$L \equiv 3\rho_0 \left.\frac{\partial E_{\rm sym}(\rho)}{\partial \rho}\right|_{\rho=\rho_0} \qquad K_{\rm sym} \equiv 9\rho_0^2 \left.\frac{\partial^2 E_{\rm sym}(\rho)}{\partial \rho^2}\right|_{\rho=\rho_0}$$

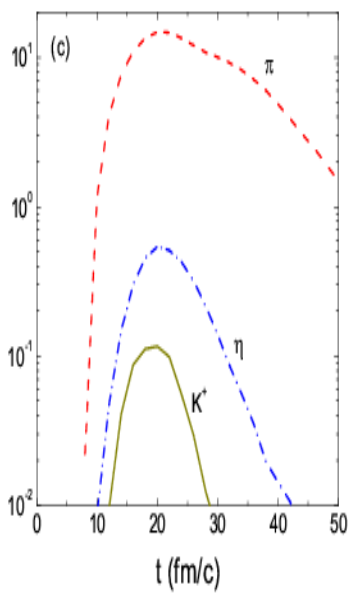
Hajime Sotani, Nobuya Nishimura, and Tomoya Naito, Prog. Theor. Exp. Phys. 041D01 (2022)

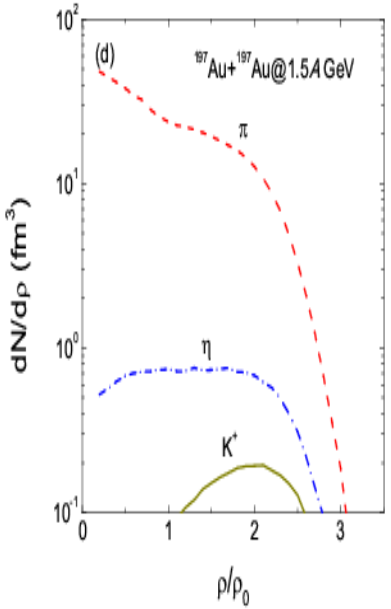


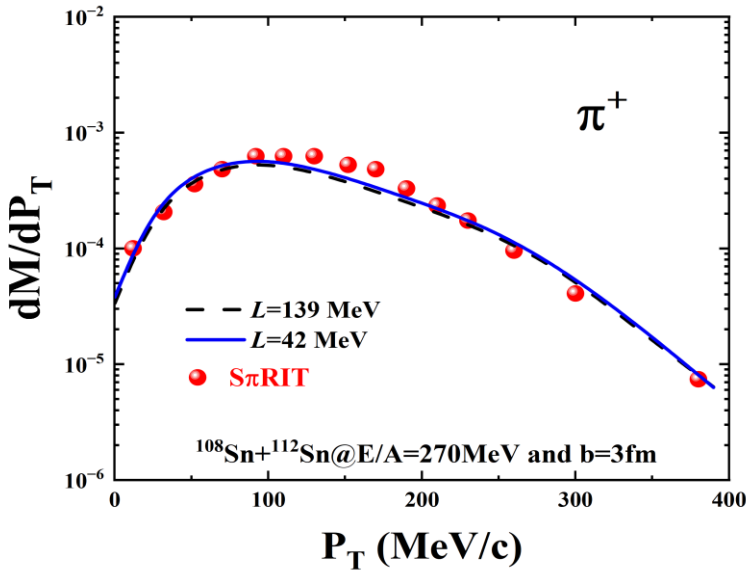


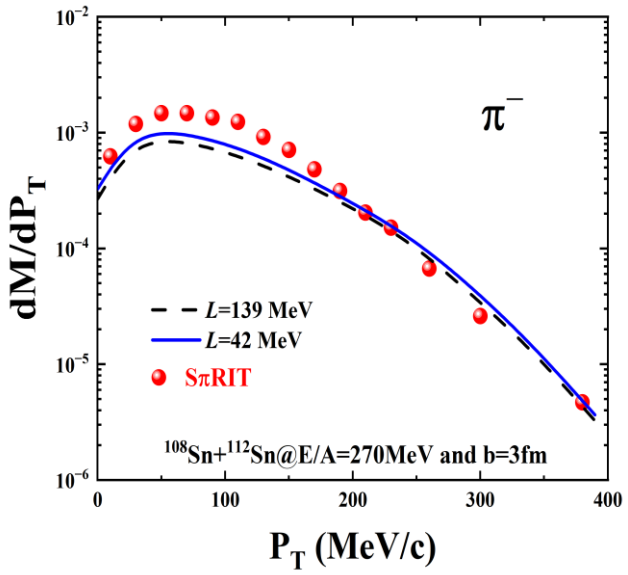
重离子碰撞中同位旋耗散和介子产生





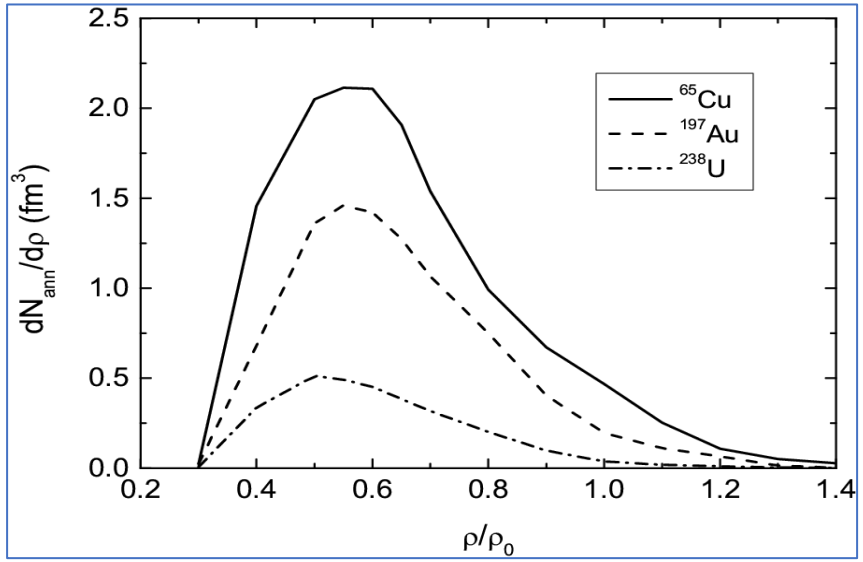


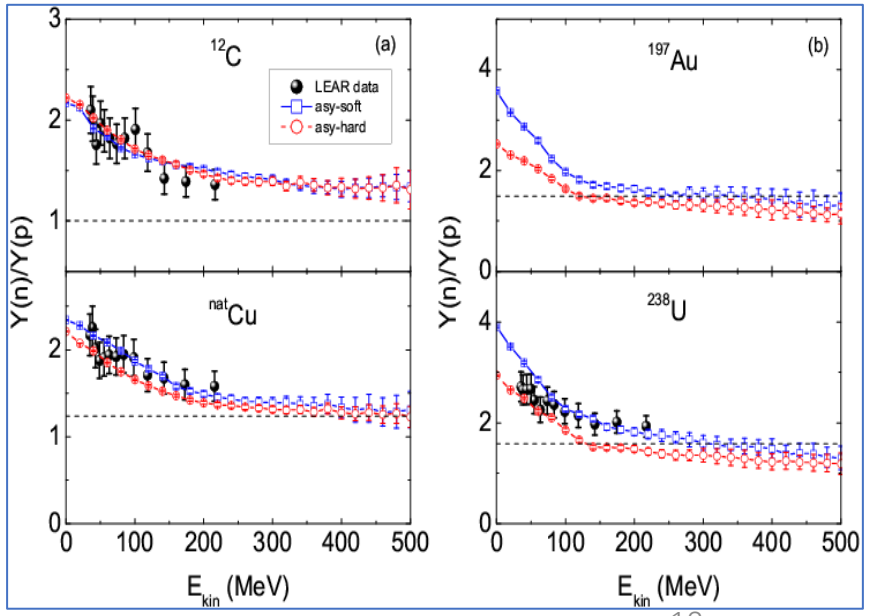




反质子轰击原子核中子和质子产额比值

γ_s=0.5, L=53 MeV





重离子碰撞与中子星物质

Nature 606 (2022) 276

Article

Constraining neutron-star matter with microscopic and macroscopic collisions

https://doi.org/10.1038/s41586-022-04750-w

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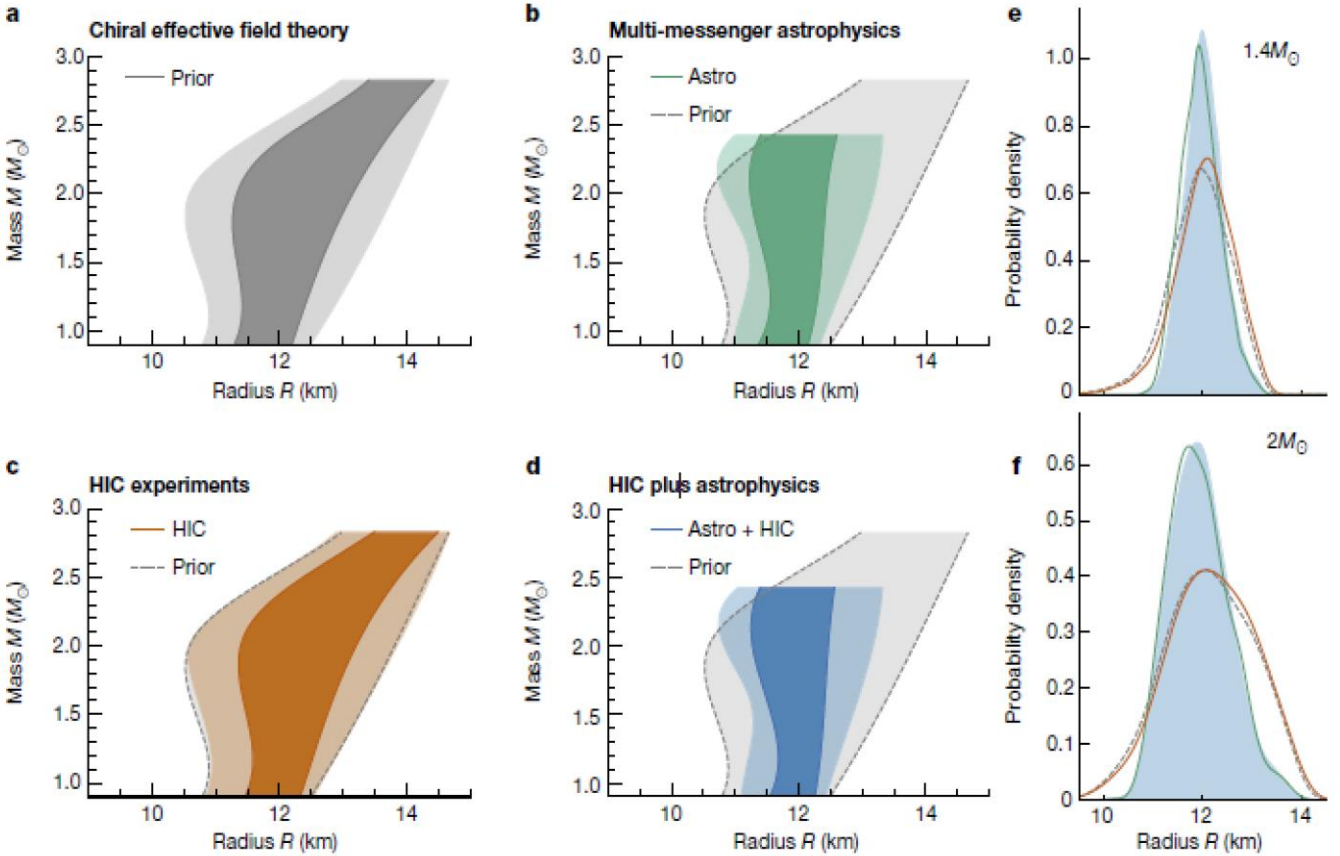
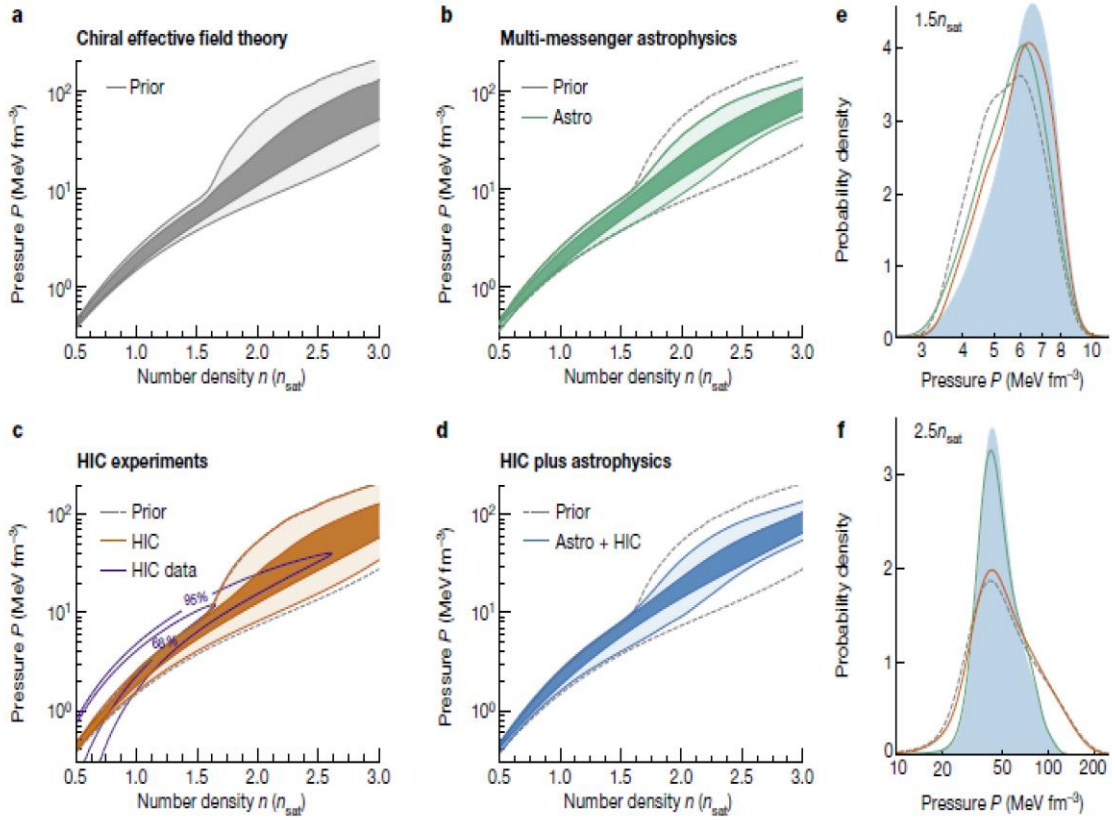
Interpreting high-energy, astrophysical phenomena, such as supernova explosions or neutron-star collisions, requires a robust understanding of matter at supranuclear densities. However, our knowledge about dense matter explored in the cores of neutron stars remains limited. Fortunately, dense matter is not probed only in

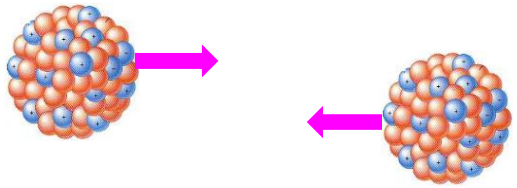




二、量子分子动力学模型 (LQMD)

Nuclear dynamics from 5 MeV/nucleon – 10 GeV/nucleon for HICs, antiproton (proton, π, K, etc)

- **Lanzhou quantum molecular dynamics** (Skyrme interaction, Walecka model with σ, ω, ρ, δ)
- **Isospin physics at intermediate energies** (constraining nuclear symmetry energy at sub- and supra-saturation densities in HICs and probing isospin splitting of nucleon effective mass from HICs)
- **In-medium properties of hadrons in dense nuclear matter from heavy-ion collisions** (extracting optical potentials, i.e., Δ(1232), N*(1440), N*(1535)), hyperons (Λ,Σ,Ξ,Ω) and mesons (π,K,η,ρ,ω,ϕ…), hypernucleus dynamics)
- **Hadron (antiproton, proton, $\pi^{\pm}$, $K^{\pm}$) induced reactions** (hypernucleus production, e.g., Λ(Σ)X, ΛΛX, ΞX, $\bar{\Lambda}$X(S=1), in-medium modifications of hadrons, cold QGP)



1. 基于Skyrme相互作用的量子分子动力学模型 (LQMD-Skyrme)

PHYSICAL REVIEW C 84, 024610 (2011)

Momentum dependence of the symmetry potential and its influence on nuclear reactions

Zhao-Qing Feng*
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China
(Received 11 July 2011; published 19 August 2011)

$$H_B = \sum_i \sqrt{\mathbf{p_i^2} + \mathbf{m_i^2}} + U_{\rm int} + U_{\rm mom}$$

$$U_{loc} = \int V_{loc}(\rho(\mathbf{r}))\, d\mathbf{r}$$

$$V_{loc}(\rho) = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{1+\gamma}\frac{\rho^{1+\gamma}}{\rho_0^{\gamma}} + E_{sym}^{loc}(\rho)\rho\delta^2 + \frac{g_{sur}}{2\rho_0}(\nabla\rho)^2 + \frac{g_{sur}^{iso}}{2\rho_0}\left[\nabla(\rho_n - \rho_p)\right]^2,$$

$$U_{mom} = \frac{1}{2\rho_0}\sum_{i,j,j\neq i}\sum_{\tau,\tau'} C_{\tau,\tau'}\delta_{\tau,\tau_i}\delta_{\tau',\tau_j}\iiint d\mathbf{p}\, d\mathbf{p}'\, d\mathbf{r}\, f_i(\mathbf{r},\mathbf{p},t)$$
$$\times\left[\ln\left(\epsilon(\mathbf{p}-\mathbf{p}')^2+1\right)\right]^2 f_j(\mathbf{r},\mathbf{p}',t).$$

$$E_{sym}(\rho) = \frac{1}{3}\frac{\hbar^2}{2m}\left(\frac{3}{2}\pi^2\rho\right)^{2/3} + E_{sym}^{loc}(\rho) + E_{sym}^{mom}(\rho).$$

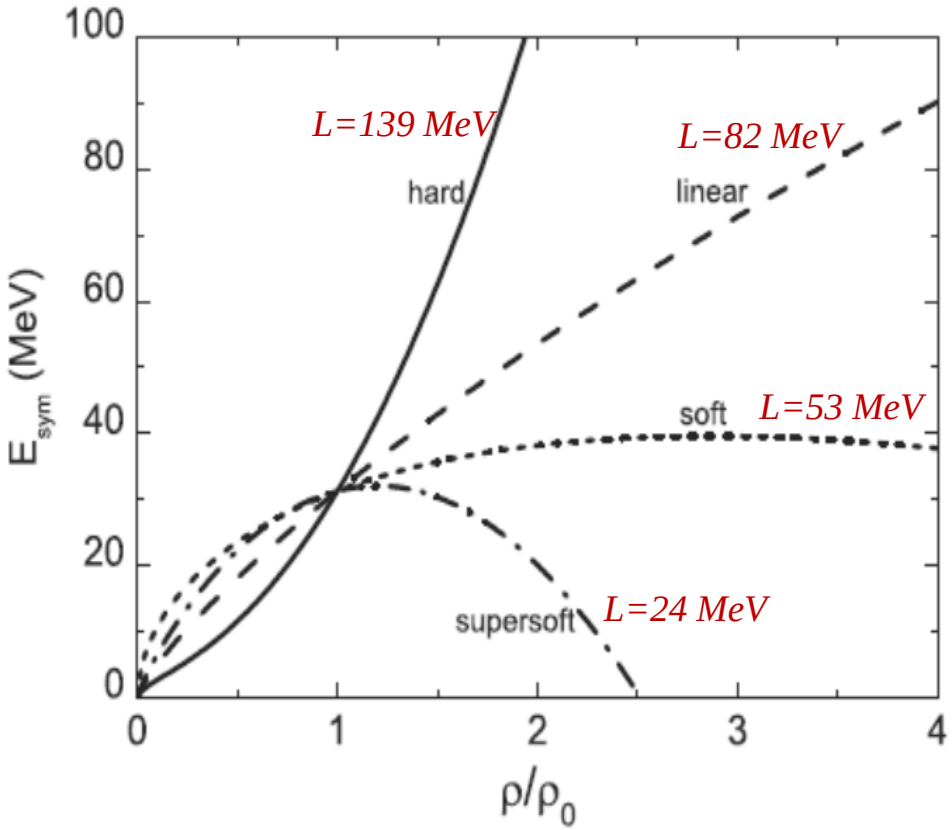
$$E_{sym}^{loc}(\rho) = \frac{1}{2}C_{sym}(\rho/\rho_0)^{\gamma_s}$$

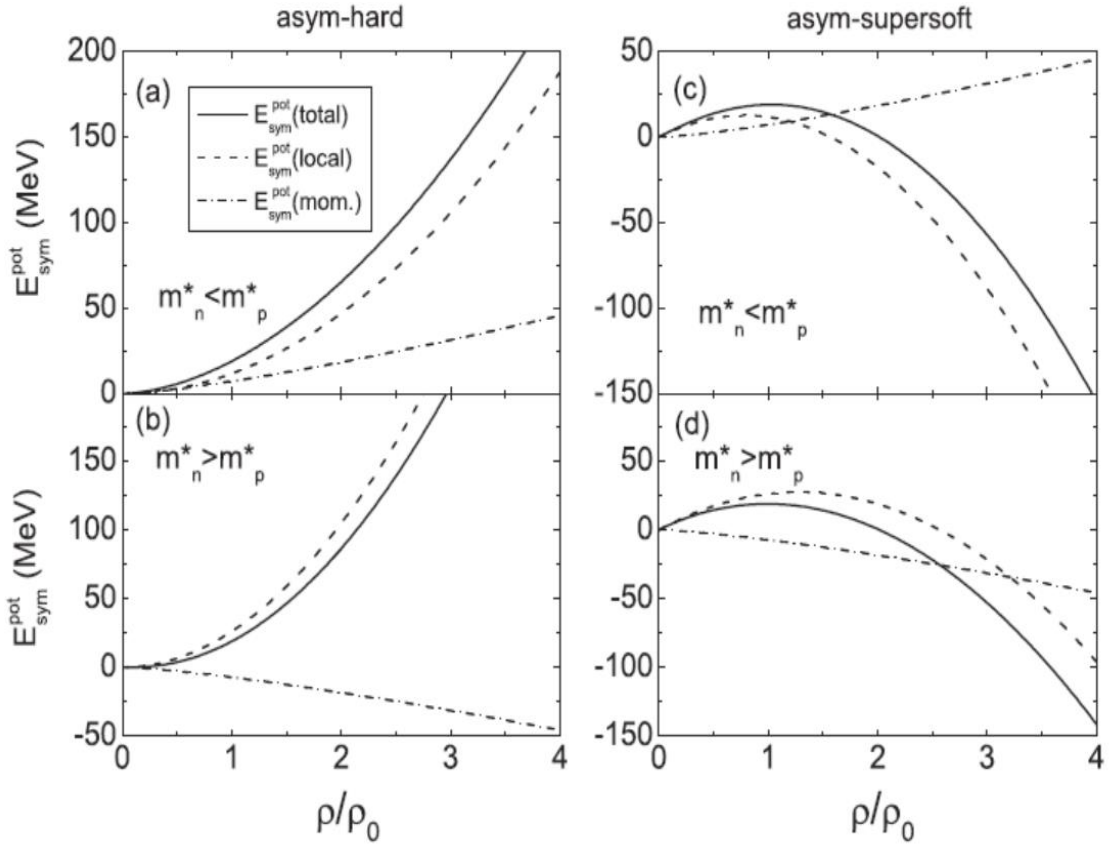
$$E_{sym}^{loc}(\rho) = a_{sym}(\rho/\rho_0) + b_{sym}(\rho/\rho_0)^2.$$

C_{sym}= 38 MeV
a_{sym}= 37.7 MeV
b_{sym}= -18.7 MeV

Table 1: The parameters and properties of isospin symmetric EoS used in the LQMD model at the density of 0.16 fm^{-3}.

Parameters	α (MeV)	β (MeV)	γ	C_{mom} (MeV)	ϵ (c^2/MeV^2)	m^*_∞/m	K_∞ (MeV)
PAR1	-215.7	142.4	1.322	1.76	5×10^{-4}	0.75	230
PAR2	-226.5	173.7	1.309	0.	0.	1.	230





2. 相对论量子分子动力学(LQMD-RMF)

$$L = \bar{\psi}[i\gamma_\mu\partial^\mu - (M_N - g_\sigma\varphi - g_\delta\vec{\tau}\cdot\vec{\delta}) - g_\omega\gamma_\mu\omega^\mu - g_\rho\gamma_\mu\vec{\tau}\cdot\vec{b}^\mu]\psi$$
$$+\frac{1}{2}(\partial_\mu\varphi\partial^\mu\varphi - m_\sigma^2\varphi^2) - U(\varphi) + \frac{1}{2}(\partial_\mu\vec{\delta}\partial^\mu\vec{\delta} - m_\sigma^2\vec{\delta}^2)$$
$$+\frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{b}_\mu\vec{b}^\mu - \frac{1}{4}\vec{G}_{\mu\nu}\vec{G}^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu,$$
$$G_{\mu\nu} = \partial_\mu\vec{b}_\nu - \partial_\nu\vec{b}_\mu,$$
$$U(\varphi) = \frac{g_2}{3}\varphi^3 + \frac{g_3}{4}\varphi^4$$

能量密度：

$$\varepsilon = \sum_{i=n,p} 2\int\frac{d^3k}{(2\pi)^3}\sqrt{k^2 + M_i^{*2}} + \frac{1}{2}m_\sigma^2\varphi^2 + U(\varphi) + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\rho^2 b_0^2 + \frac{1}{2}m_\delta^2\delta_3^2$$

核子的相空间演化：

$$\dot{\mathbf{x}} = \frac{\mathbf{p}_i^*}{p_0^*} + \sum_{i\neq j}^{N}\{\frac{g_v^2}{2m_v^2}z_j^{*\mu}u_{i,\mu}B_iB_j\frac{\partial\rho_{ij}}{\partial\mathbf{p_i}} + \frac{g_v^2}{2m_v^2}z_i^{*\mu}u_{j,\mu}B_iB_j\frac{\partial\rho_{ji}}{\partial\mathbf{p_i}} + \frac{g_v^2}{2m_v^2}z_j^{*\mu}\rho_{ji}B_iB_j\frac{\partial u_{i,\mu}}{\partial\mathbf{p_i}}$$
$$+z_j^{*\mu}\frac{B_iB_j\bar{g}_v^2}{2m_v^2}[\frac{\rho_{ij}}{1-p_{T,ij}^2/\Lambda_v^2}\frac{\partial u_{i,\mu}}{\partial\mathbf{p_i}} + \frac{u_{i,\mu}}{1-p_{T,ij}^2/\Lambda_v^2}\frac{\partial\rho_{ij}}{\partial\mathbf{p_i}} + u_{i,\mu}\rho_{ij}\frac{\partial[1/(1-p_{T,ij}^2/\Lambda_v^2)]}{\partial\mathbf{p_i}}]$$
$$+z_i^{*\mu}\frac{B_iB_j\bar{g}_v^2}{2m_v^2}[\frac{u_{j,\mu}}{1-p_{T,ji}^2/\Lambda_v^2}\frac{\partial\rho_{ji}}{\partial\mathbf{p_i}} + u_{j,\mu}\rho_{ji}\frac{\partial[1/(1-p_{T,ji}^2/\Lambda_v^2)]}{\partial\mathbf{p_i}}]$$
$$-\frac{m_j^*}{p_j^{*0}}\frac{\partial S_j}{\partial\mathbf{p_i}} - \frac{m_i^*}{p_i^{*0}}\frac{\partial S_i}{\partial\mathbf{p_i}}\},$$

$$\dot{\mathbf{p}} = -\sum_{i\neq j}^{N}\{\frac{g_v^2}{2m_v^2}z_j^{*\mu}u_{i,\mu}B_iB_j\frac{\partial\rho_{ij}}{\partial\mathbf{r_i}} + \frac{g_v^2}{2m_v^2}z_i^{*\mu}u_{j,\mu}B_iB_j\frac{\partial\rho_{ji}}{\partial\mathbf{r_i}}$$
$$+z_j^{*\mu}\frac{B_iB_j\bar{g}_v^2}{2m_v^2}\frac{u_{i,\mu}}{1-p_{T,ij}^2/\Lambda_v^2}\frac{\partial\rho_{ij}}{\partial\mathbf{r_i}}$$
$$+z_i^{*\mu}\frac{B_iB_j\bar{g}_v^2}{2m_v^2}\frac{u_{j,\mu}}{1-p_{T,ji}^2/\Lambda_v^2}\frac{\partial\rho_{ji}}{\partial\mathbf{r_i}}$$
$$-\frac{m_j^*}{p_j^{*0}}\frac{\partial S_j}{\partial\mathbf{r_i}} - \frac{m_i^*}{p_i^{*0}}\frac{\partial S_i}{\partial\mathbf{r_i}}\},$$

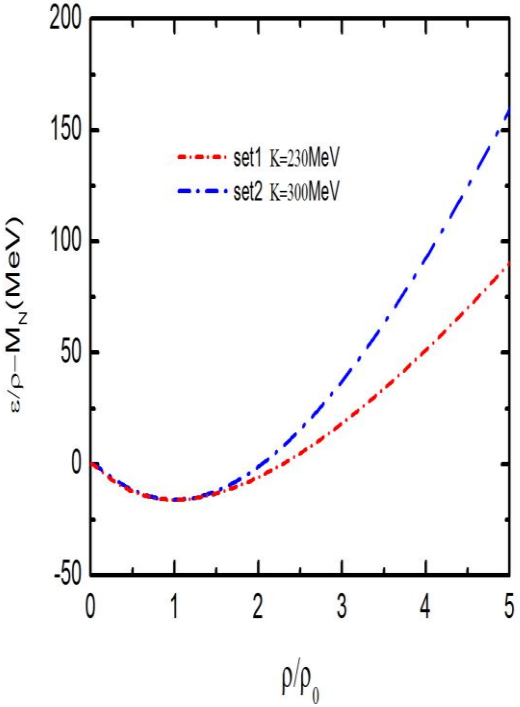
TABLE I: Parameters for the relativistic mean-field theory with non-linear scalar interaction for a binding energy of $E_B = \epsilon/\rho - M_N = -16$ MeV and for normal nuclear matter density of $\rho_0 = 0.16 fm^{-3}$. The σ meson mass m_σ, the ω meson mass m_ω, the ρ meson mass m_ρ and the δ meson mass m_δ are set to be 550, 783, 763 and 500 MeV, respectively.

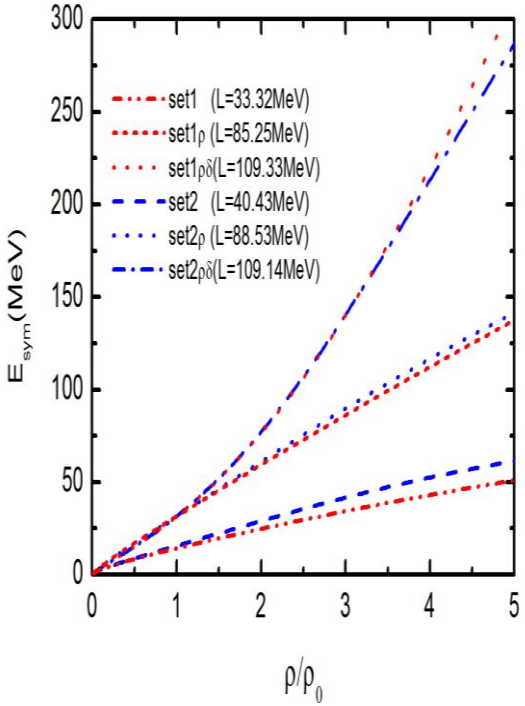
Model	g_σ	g_ω	$g_2(fm^{-1})$	g_3	g_ρ	g_δ	M^*/M_N	E_B(MeV)	K(MeV)	E_{sym}(MeV)	L(MeV)
set1	8.145	7.570	31.900	21.800	-	-	0.813	-16.0	230	14.3	33.3
set1ρ	8.145	7.570	31.900	21.800	4.049	-	0.813	-16.0	230	31.6	85.3
set1$\rho\delta$	8.145	7.570	31.900	21.800	8.673	5.347	0.813	-16.0	230	31.6	109.3
set2	8.830	9.500	11.310	13.750	-	-	0.738	-16.0	300	15.6	40.4
set2ρ	8.830	9.500	11.310	13.750	3.897	-	0.738	-16.0	300	31.6	88.5
set2$\rho\delta$	8.830	9.500	11.310	13.750	7.219	4.280	0.738	-16.0	300	31.6	109.4

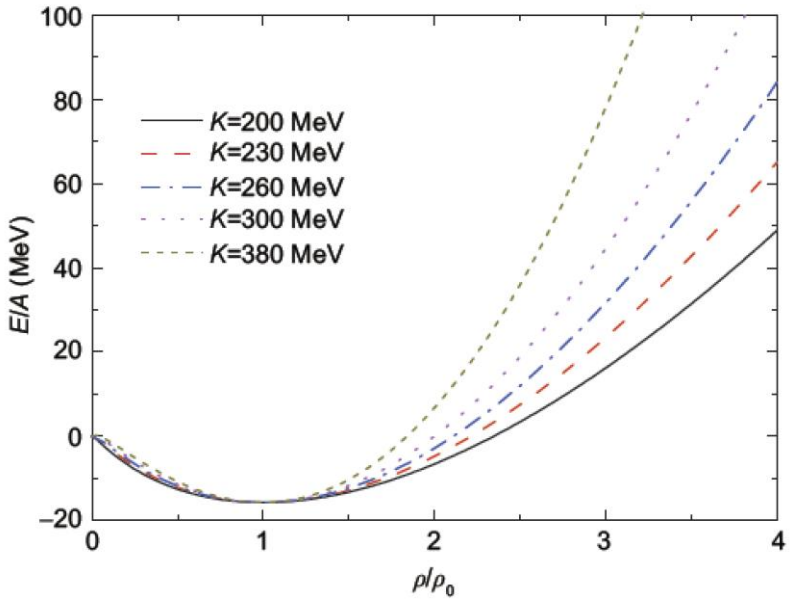
核物质对称能

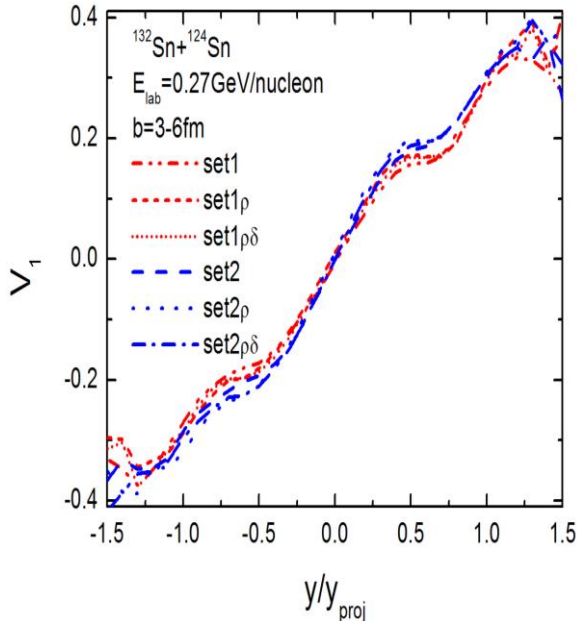
$$E_{sym} = \frac{1}{6}\frac{k_F^2}{E_F^*} + \frac{1}{2}\left[f_\rho - f_\delta\left(\frac{M^*}{E_F^*}\right)\right]\rho$$

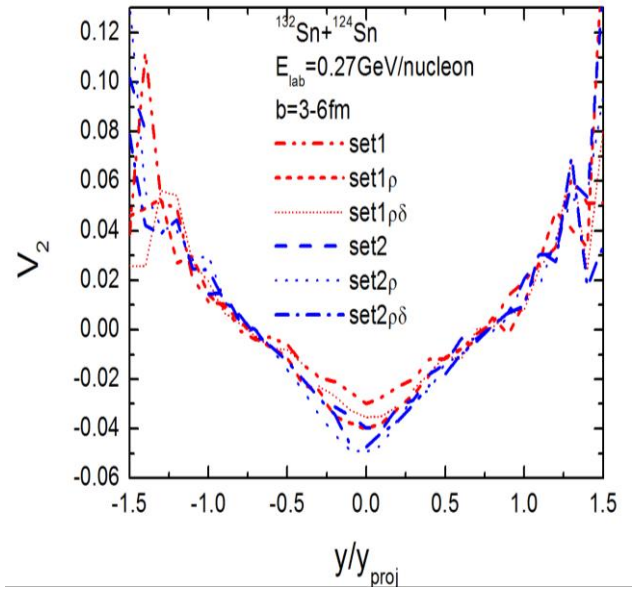
$$f_{\rho,\delta} = g_{\rho,\delta}/m_{\rho,\delta}$$



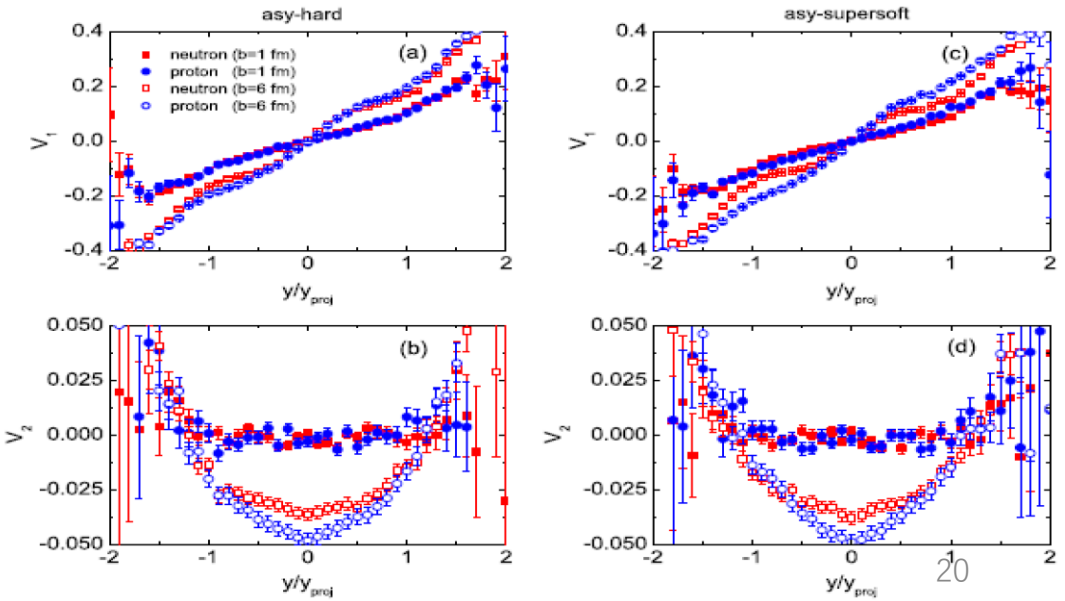








Z.-Q. Feng / Nuclear Physics A 878 (2012) 3–13 9



3. 粒子产生反应道

π and resonances (Δ(1232), N*(1440), N*(1535), …) production:

$$NN \leftrightarrow N\Delta, \quad NN \leftrightarrow NN^*, \quad NN \leftrightarrow \Delta\Delta, \quad \Delta \leftrightarrow N\pi,$$

$$N^* \leftrightarrow N\pi, \quad NN \leftrightarrow NN\pi(s-state), \quad N^*(1535) \leftrightarrow N\eta$$

Collisions between resonances, NN*↔NΔ, NN*↔NN*

Strangeness channels:

$$BB \to BYK, BB \to BBK\overline{K}, B\pi(\eta) \to YK, YK \to B\pi,$$

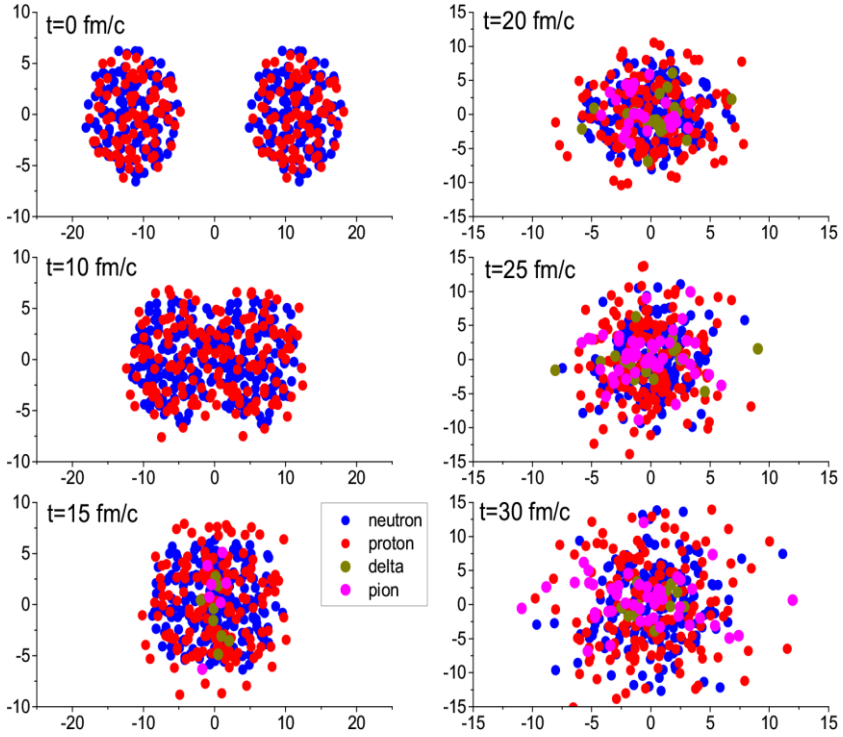
$$B\pi \to NK\overline{K}, Y\pi \to B\overline{K}, \quad B\overline{K} \to Y\pi, \quad YN \to \overline{K}NN,$$

$$BB \to B\Xi KK, \overline{K}B \leftrightarrow K\Xi, YY \leftrightarrow N\Xi, \overline{K}Y \leftrightarrow \pi\Xi.$$

Reaction channels with antiproton:

$$\bar{p}N \to \overline{N}N, \quad \overline{N}N \to \overline{N}N, \overline{N}N \to \overline{B}B, \overline{N}N \to \overline{Y}Y$$

$$\overline{N}N \to \text{annihilation}(\pi, \eta, \rho, \omega, K, \overline{K}, K^*, \overline{K}^*, \phi)$$



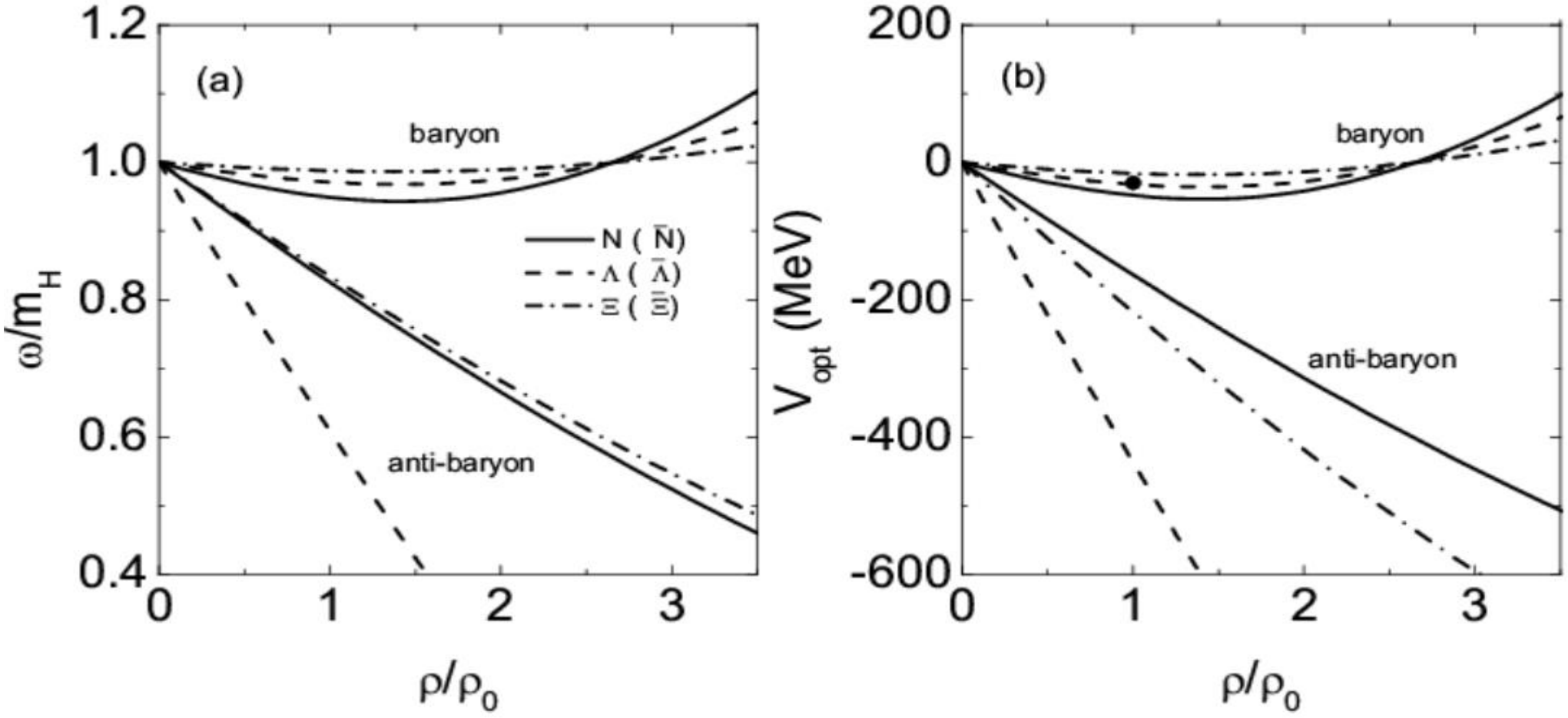
Statistical model with SU(3) symmetry for annihilation
(E.S. Golubeva et al., Nucl. Phys. A 537, 393 (1992))

The **PYTHIA** and **FRITIOF** code are used for baryon(meson)-baryon and antibaryon-baryon collisions at high invariant energies

4. 超子(反超子)平均场

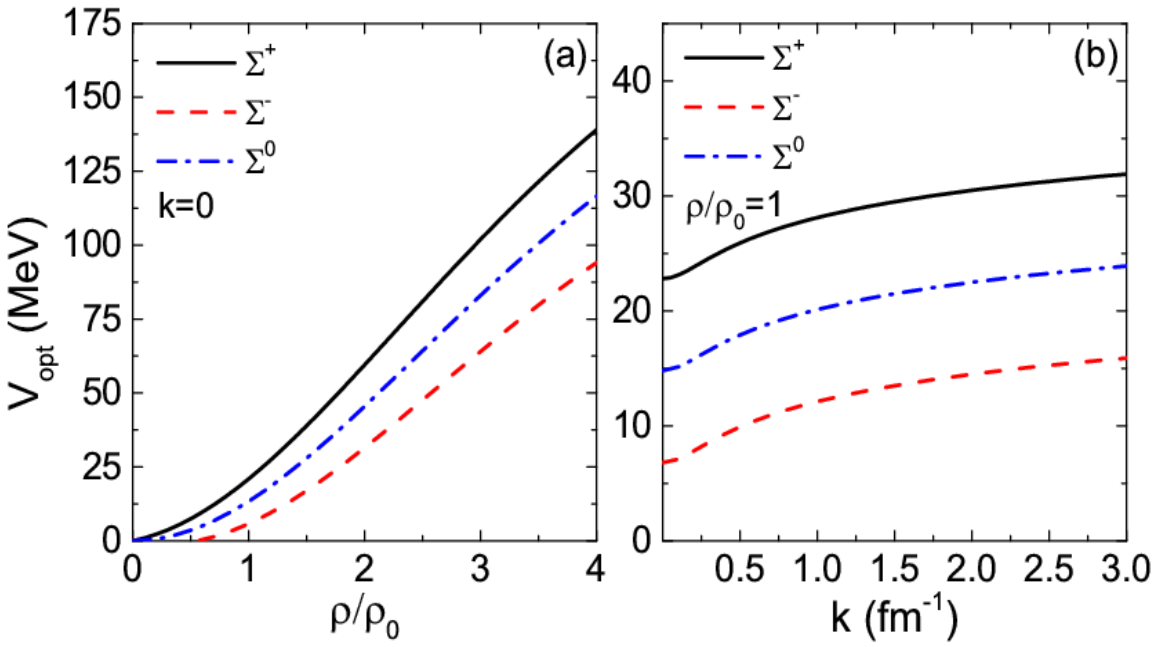
A factor ξ is introduced in evaluating self-energies of the antinucleon, e.g., $\xi=0.25$ *for* $V_{\bar{N}N}$ **= -160** *MeV at* $\rho = \rho_0$

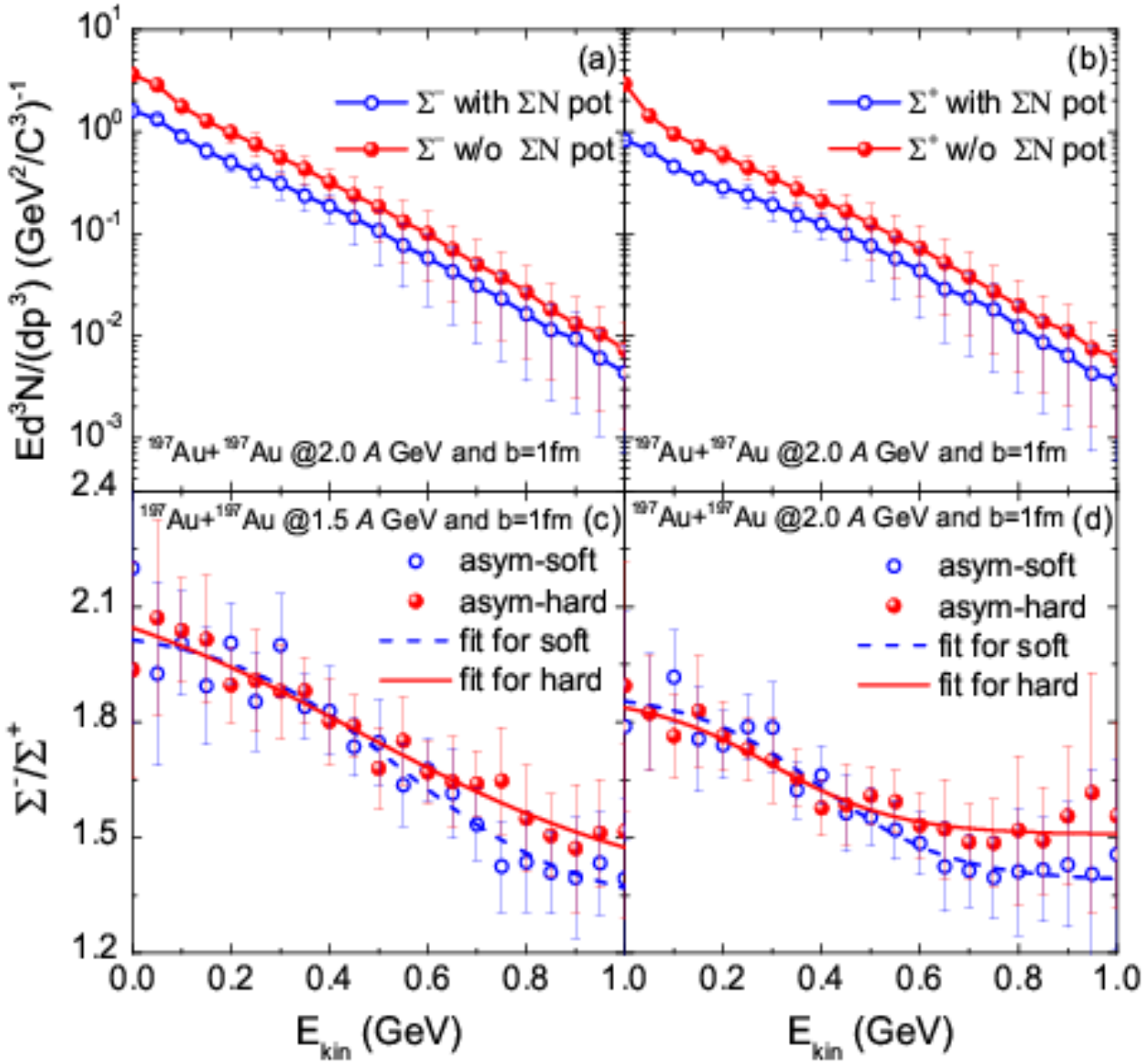
$$H_M = \sum_{i=1}^{N_M} \left(V_i^{\mathrm{Coul}} + \omega(\mathbf{p}_i, \rho_i)\right) \quad \omega(\mathbf{p}_i, \rho_i) = \sqrt{\left(m_H + \Sigma_S^H\right)^2 + \mathbf{p}_i^2} + \Sigma_V^H \quad V_{opt}(\mathbf{p}, \rho) = \omega(\mathbf{p}, \rho) - \sqrt{\mathbf{p}^2 + m^2}$$



Ding-Chang Zhang, Hui-Gan Cheng and Zhao-Qing Feng. *Chinese Physics Letters* 38 (2021) 092501.
(arXiv: 2107.00277, editor's suggestion)

$$V_{\rm opt}^{\Sigma}(p_i,\rho_i) = V_0(\rho_i/\rho_0)^{\gamma_s} + V_1(\rho_n-\rho_p)t_\Sigma\rho_i^{\gamma_s-1}/\rho_0^{\gamma_s} + C_{\rm mom}\rho_i\ln(\epsilon p_i^2+1)$$

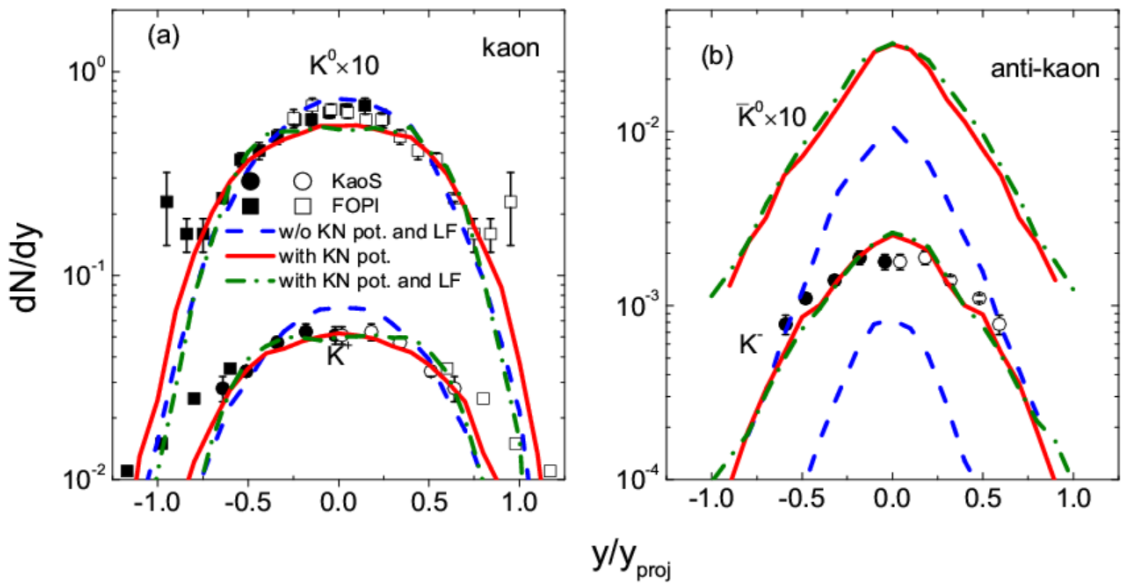




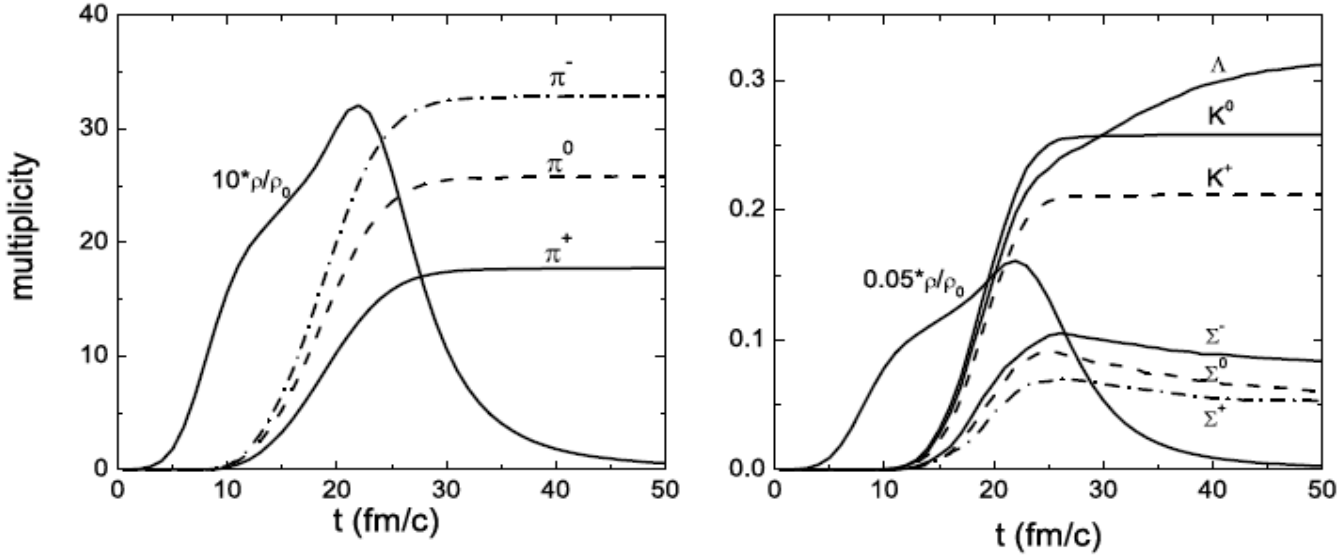
5. 重离子碰撞中K介子和超子产生

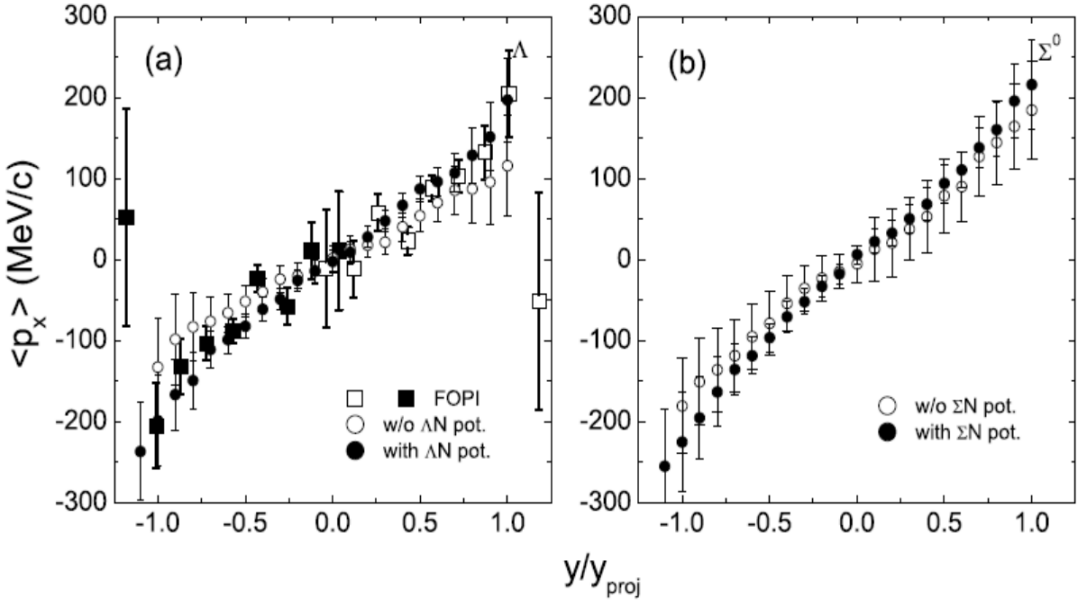
Phys. Rev. C 82 (2010) 057901; Phys. Rev. C 87, 064605 (2013); Nuclear Physics A 919 (2013) 32-45

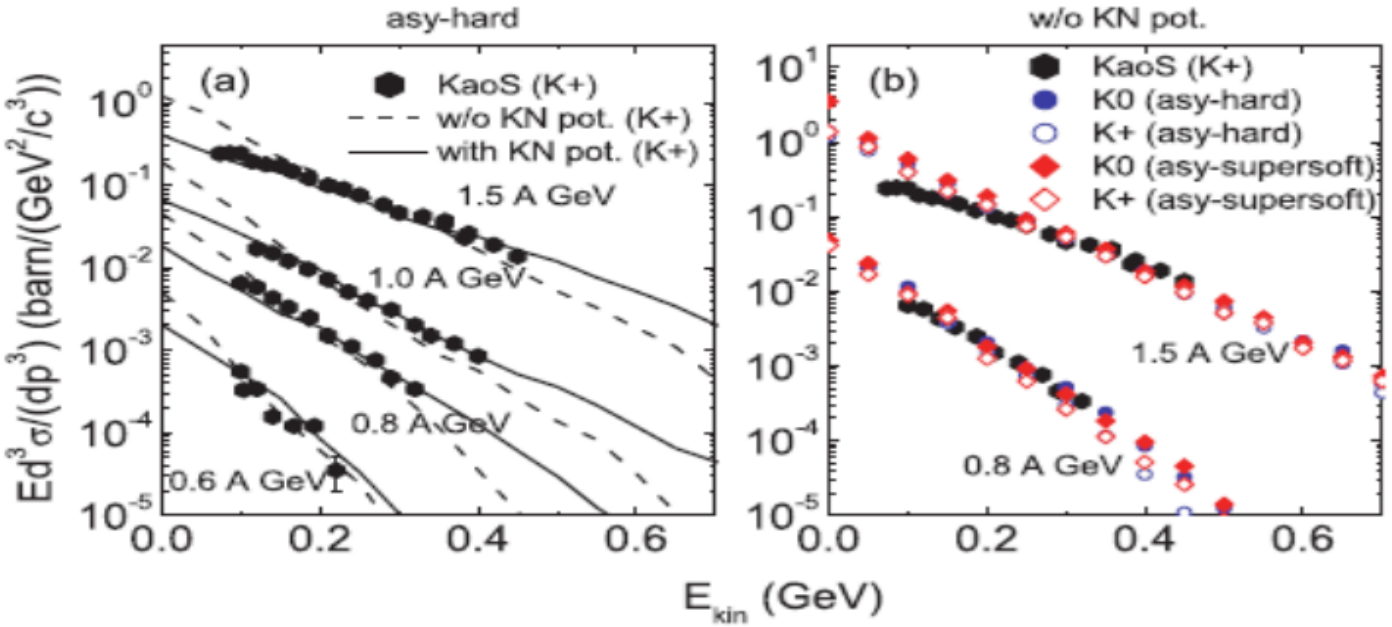
^{58}Ni+^{58}Ni@1.93*A GeV*



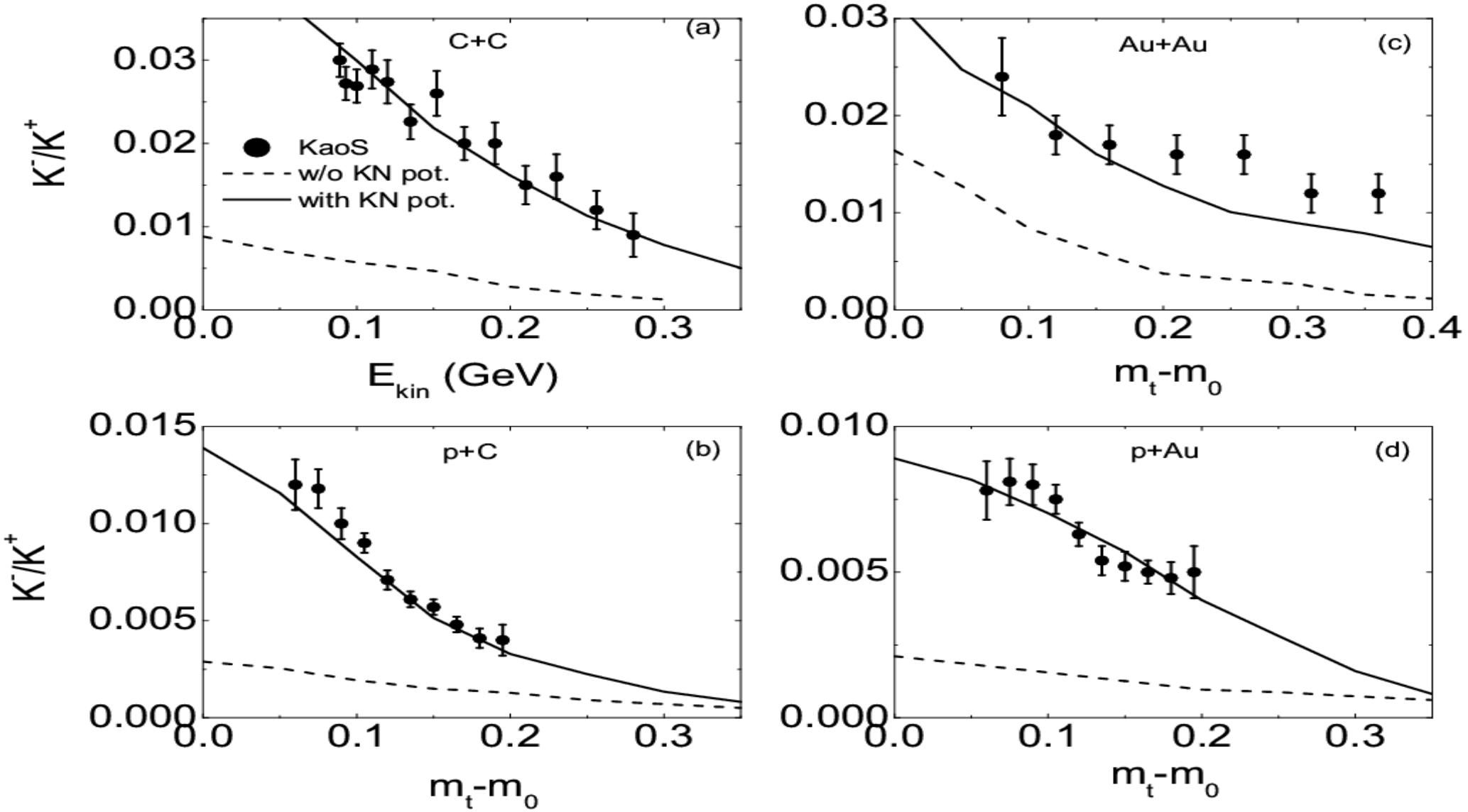
^{197}Au+^{197}Au@1.5*A*GeV





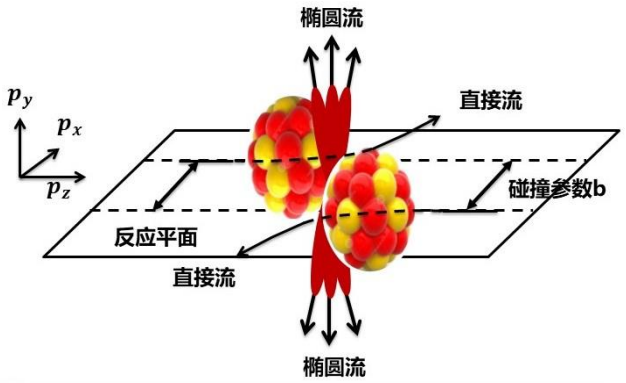


The K^-/K^+ ratio in collisions of $^{12}C + ^{12}C$ at 1.8*A* GeV and protons on ^{12}C and ^{197}Au with 2.5 GeV



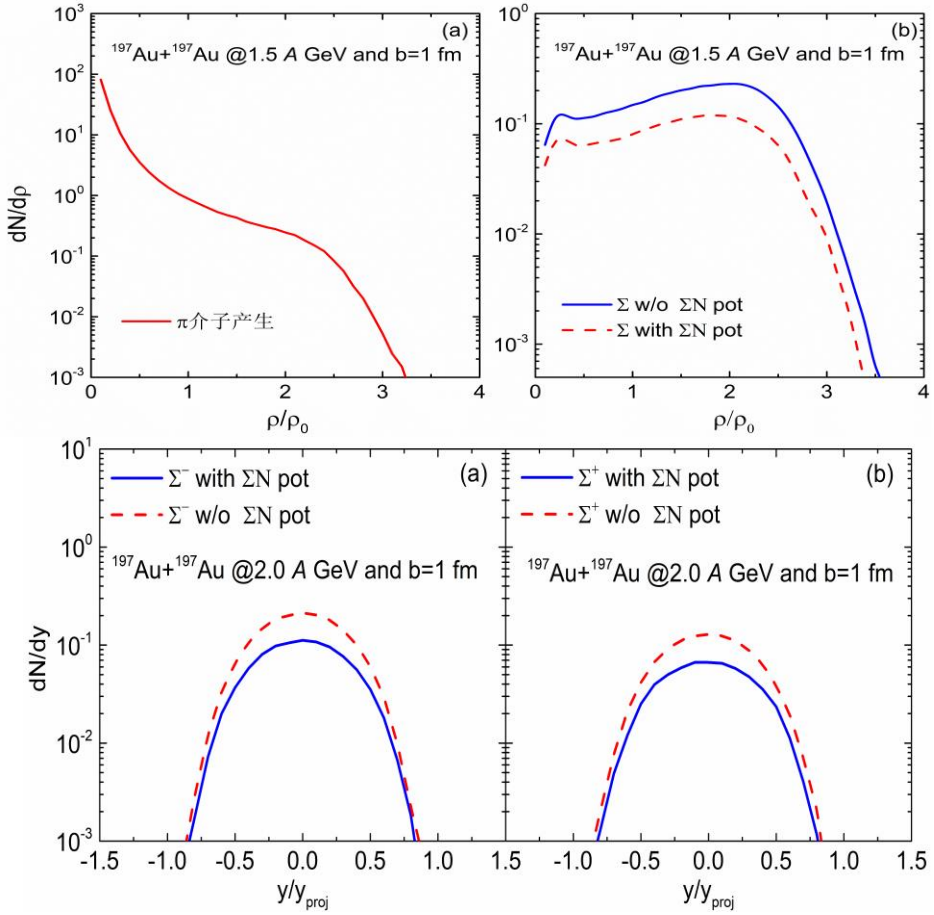
$V_{K+}(\rho_0)$= 28 MeV, $V_{K-}(\rho_0)$= -100 MeV

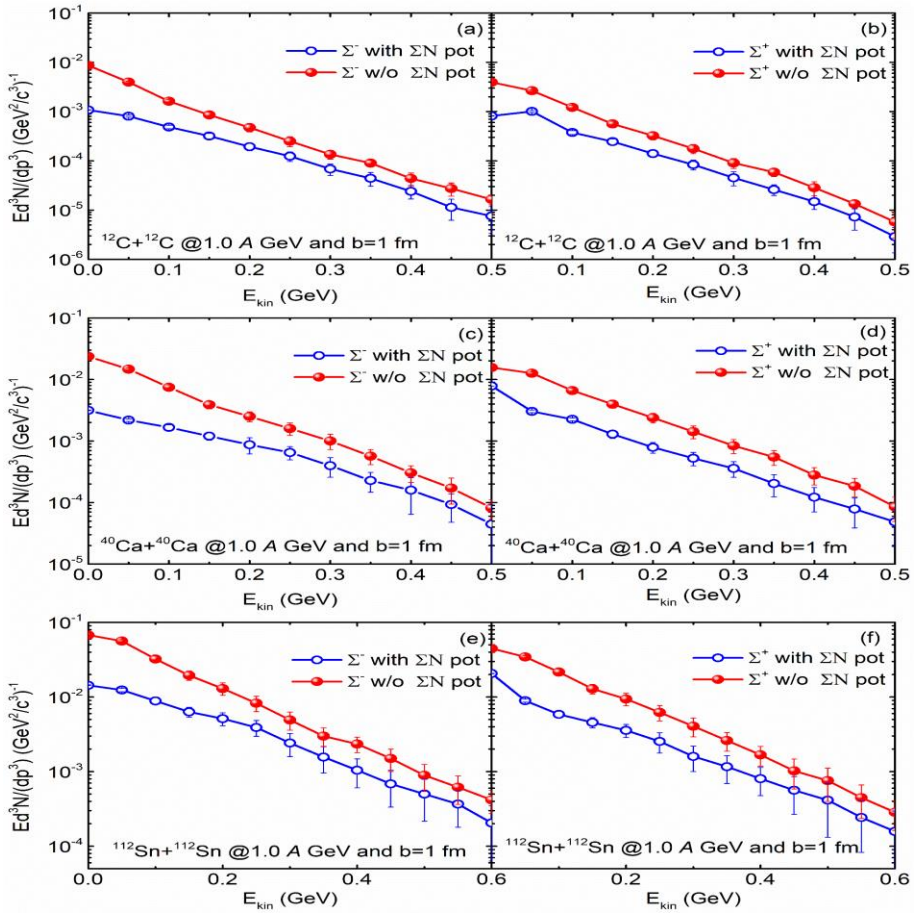
重离子碰撞中Σ超子分布 (Ding-Chang Zhang, Hui-Gan Cheng and Zhao-Qing Feng, Chinese Physics Letters 38 (2021) 092501)

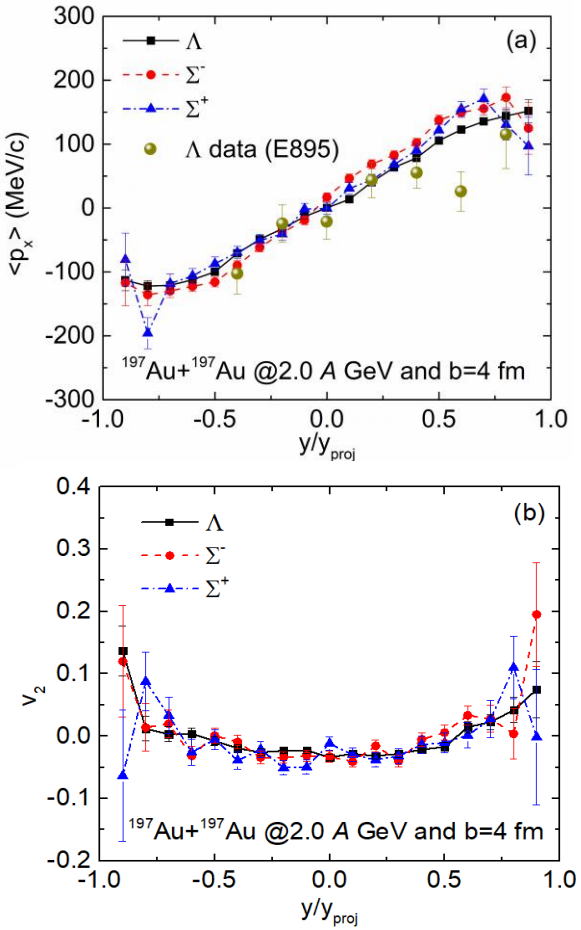


出射粒子的角分布可按傅里叶展开表示为：$\frac{dN}{d\phi}(y,p_t) = N_0[1 + 2v_1(y,p_t)\cos\phi + 2v_2(y,p_t)\cos 2\phi]$

其中ϕ为出射粒子的方位角（$\tan\phi = p_y/p_x$）







E895 data, Physical Review Letters, 2001, 86(12): 2533-2536

三、原子核碎裂反应和超核形成

Physics Reports 510 (2012) 119–200

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Strangeness production close to the threshold in proton–nucleus and heavy-ion collisions

Christoph Hartnack[a], Helmut Oeschler[b,*], Yvonne Leifels[c], Elena L. Bratkovskaya[d,e], Jörg Aichelin[a]

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Progress in Particle and Nuclear Physics 56 (2006) 1–103

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Review

Kaon production in heavy ion reactions at intermediate energies

Christian Fuchs*

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Physics Reports 512 (2012) 1–124

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Transport-theoretical description of nuclear reactions

O. Buss, T. Gaitanos, K. Gallmeister, H. van Hees, M. Kaskulov, O. Lalakulich, A.B. Larionov[1], T. Leitner, J. Weil, U. Mosel*

Institut für Theoretische Physik, Universität Giessen, Germany

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Progress in Particle and Nuclear Physics 53 (2004) 225–237

Progress in Particle and Nuclear Physics

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Review

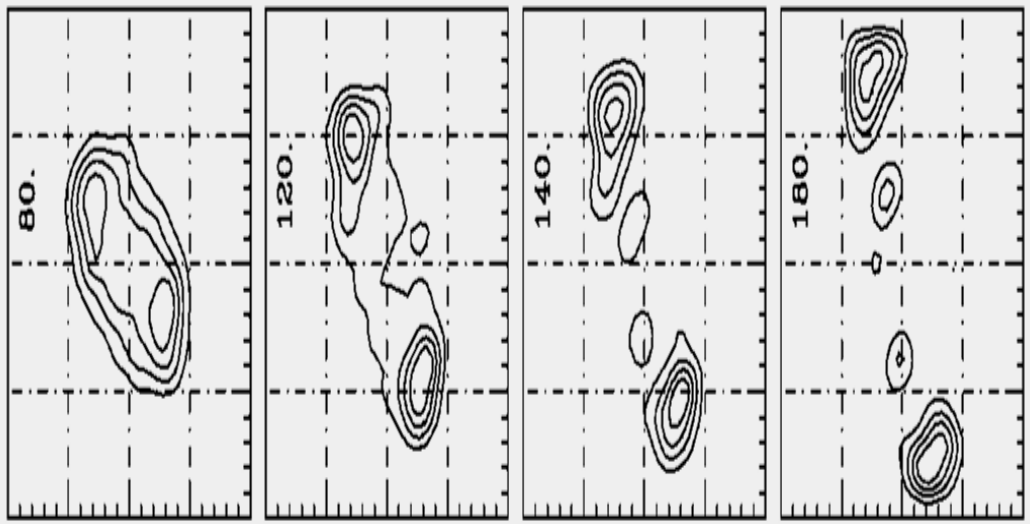
Strangeness dynamics in relativistic nucleus–nucleus collisions

E.L. Bratkovskaya[a], M. Bleicher[a], W. Cassing[b,*], M. van Leeuwen[c,d], M. Reiter[a], S. Soff[a], H. Stöcker[a], H. Weber[a]

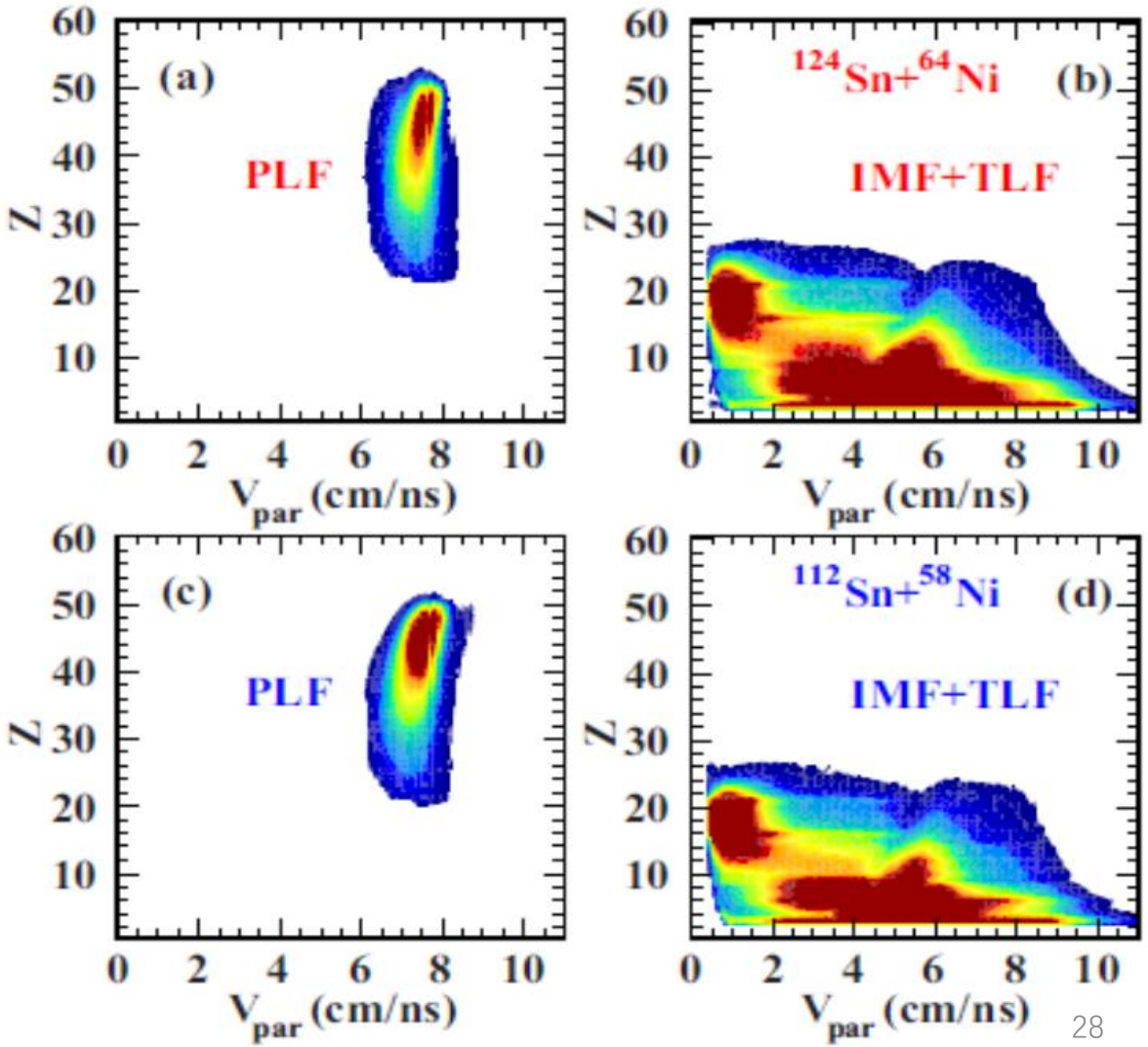
1. 费米能区(10A–100A MeV)重离子碰撞中的同位旋效应

Experiments:
INDRA (GANIL), CHIMERA (LNS), NSCL (MSU)
SSC (HIRFL) …

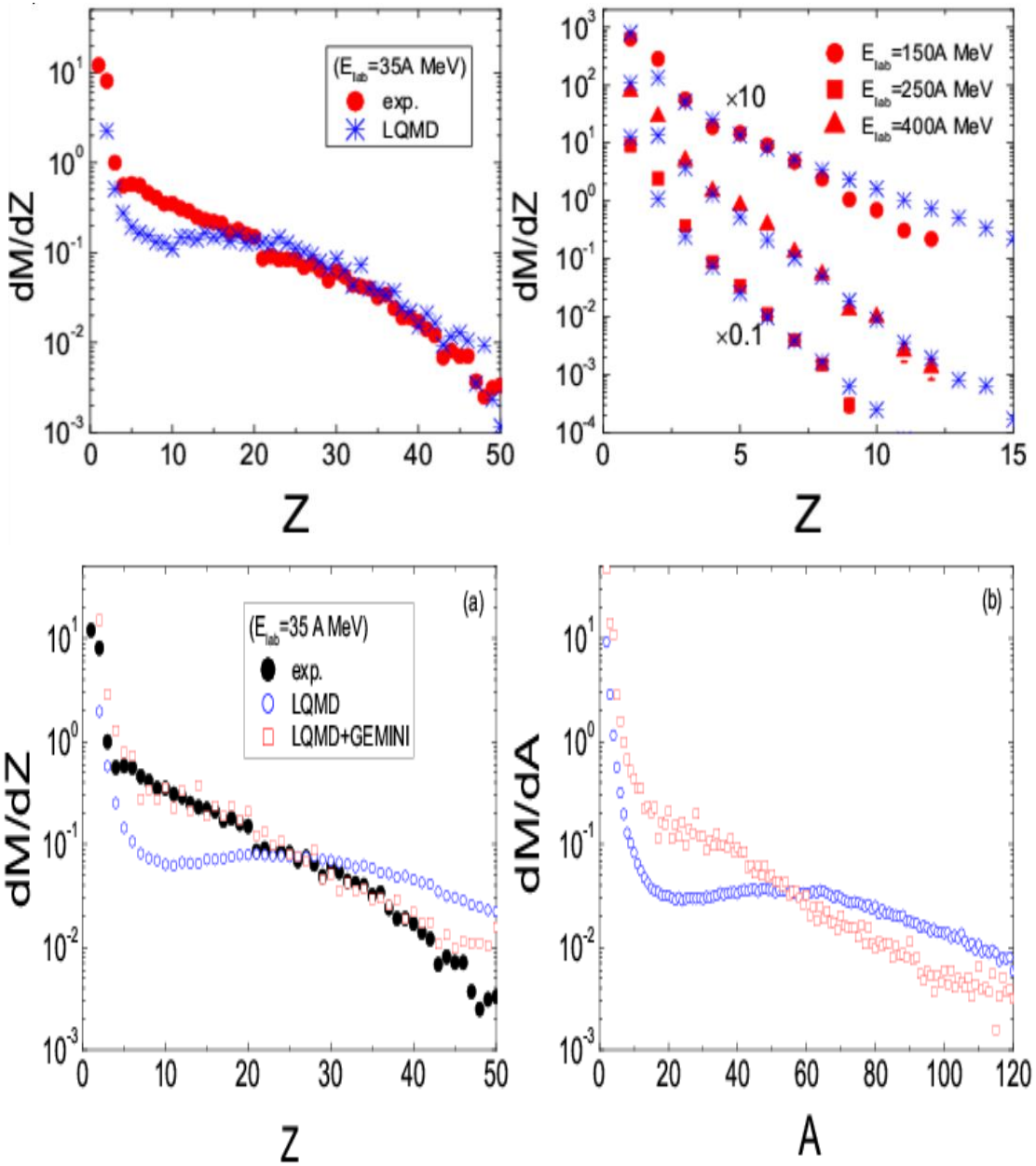
密度演化等高图

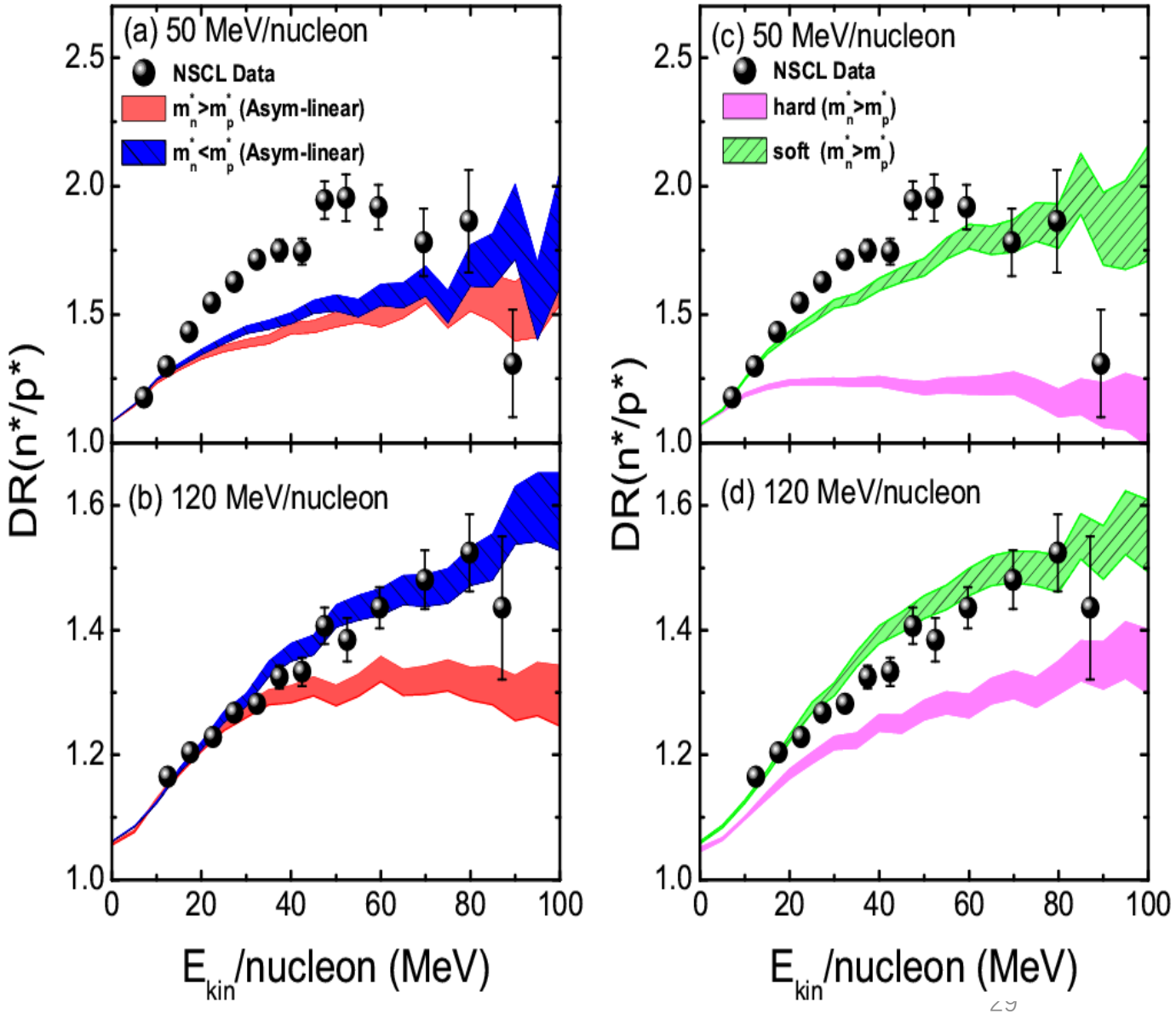


P. Russotto *et al.*, PRC 91, 014610 (2015)

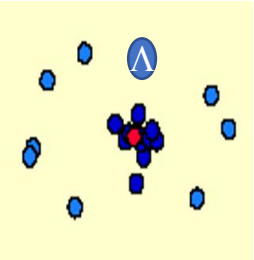


$^{197}Au+^{197}Au$ 碰撞中碎裂分布 (Phys. Rev. C 82, 044615 (2010); 94, 014609 (2016), Chin. Phys. C 41 (2017) 104104)





2. 超核碎片构造和动力学分析



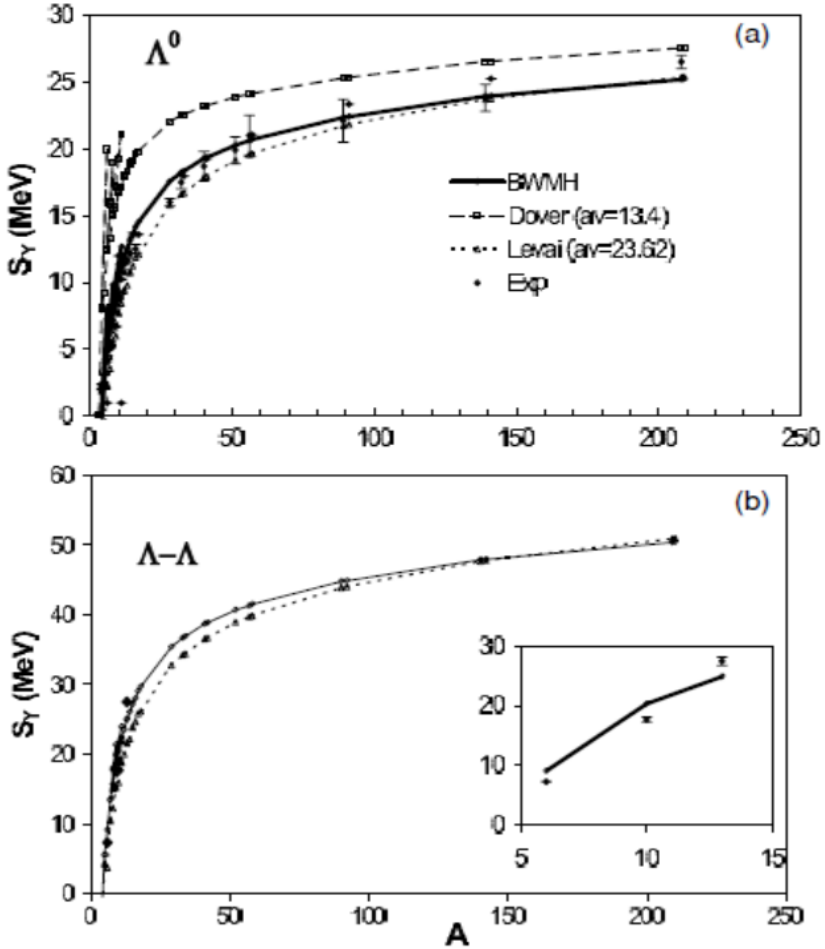
1) Classical coalescence approach in phase space for nuclides of Z>2 combined with the GEMINI decay code (minimum spanning tree (MST) procedure)

$|r_i - r_j| \leq 3$ fm, $|r_i - r_Y| \leq 4.5$ fm , $|p_i - p_j| \leq 0.3$ GeV/c

C. Samanta et al, J. Phys. G: Nucl. Part. Phys. 32 (2006) 363

Binding energy:

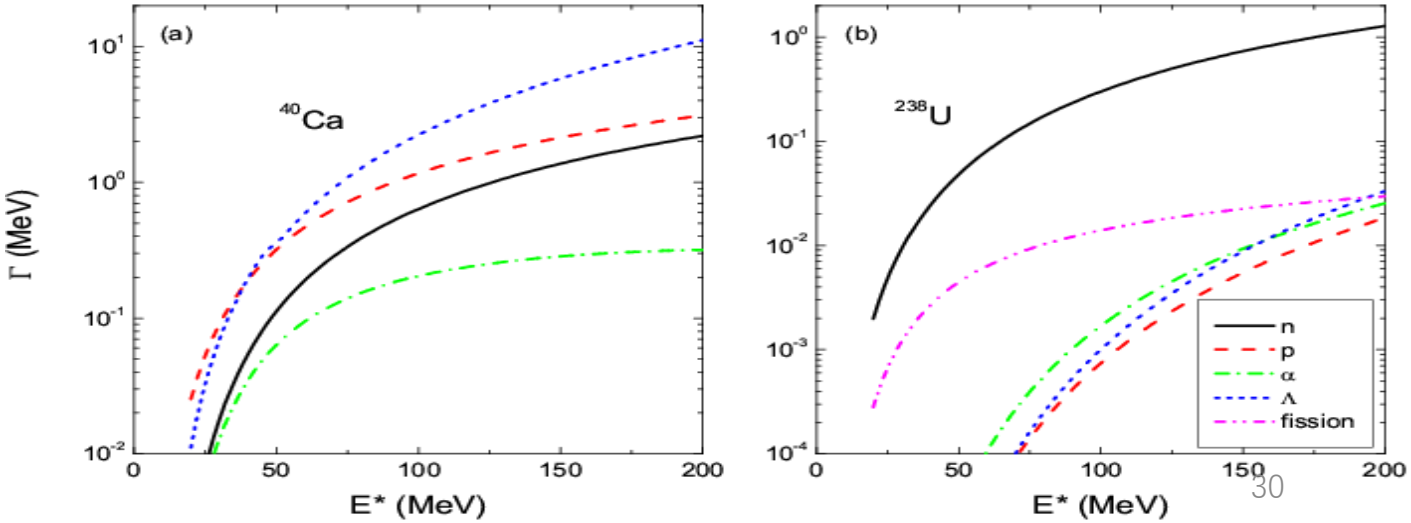
$$E_B(Z_i, N_i) = \sum_j \sqrt{p_j^2 + m_j^2} - m_j + \frac{1}{2} \sum_{j,k,k\neq j} \int f_j(\mathbf{r}, \mathbf{p}, t) f_k(\mathbf{r}', \mathbf{p}', t) \times v(\mathbf{r}, \mathbf{r}', \mathbf{p}, \mathbf{p}') d\mathbf{r}\, d\mathbf{r}'\, d\mathbf{p}\, d\mathbf{p}' + \frac{1}{6} \sum_{j,k,l} \sum_{k\neq j, k\neq l, j\neq l} \int f_j(\mathbf{r}, \mathbf{p}, t) f_k(\mathbf{r}', \mathbf{p}', t) \times f_l(\mathbf{r}'', \mathbf{p}'', t) v(\mathbf{r}, \mathbf{r}', \mathbf{r}'', \mathbf{p}, \mathbf{p}', \mathbf{p}'') \times d\mathbf{r}\, d\mathbf{r}' d\mathbf{r}'' d\mathbf{p}\, d\mathbf{p}' d\mathbf{p}'',$$



Excitation energy $E^*(Z_i, N_i, nY)$

$= E_B(Z_i, N_i, nY) - E_{LD}(Z_i, N_i, nY)$

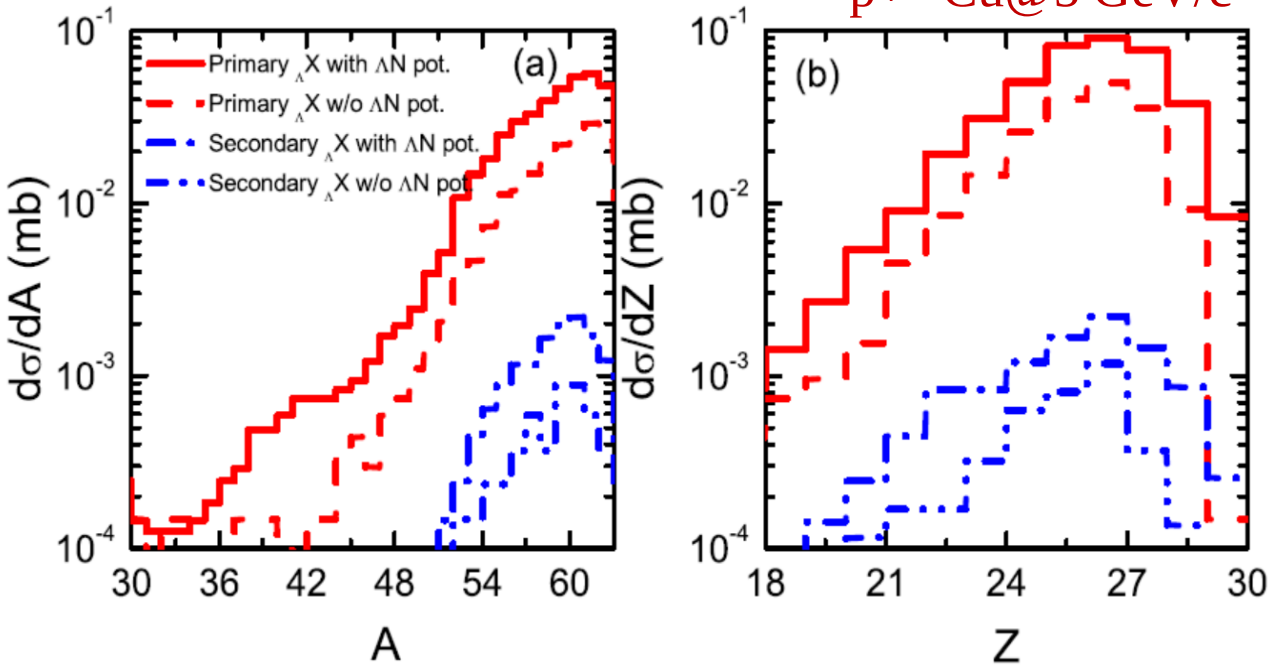
The decay of excited hypernucleus is described by the GEMINI code!

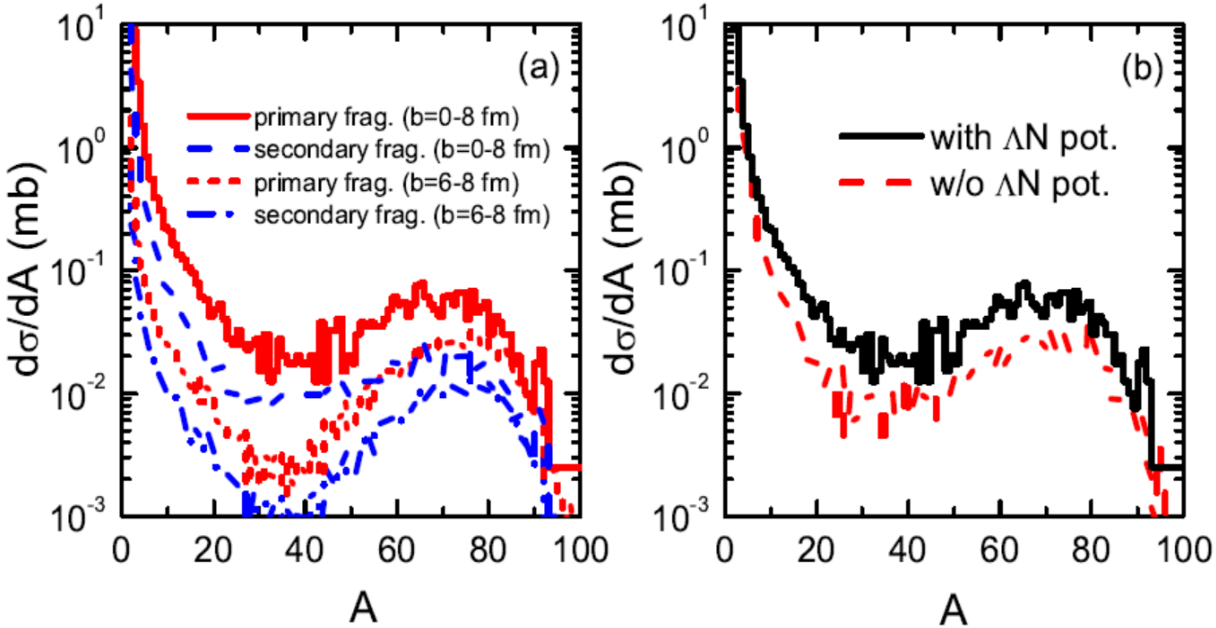


Influence of the statistical decay and hyperon-nucleon potential on the hyperfragment production induced by proton, K- and antiproton (Physical Review C 101, 064601 (2020); 101, 014605 (2020); 101, 064601 (2020))

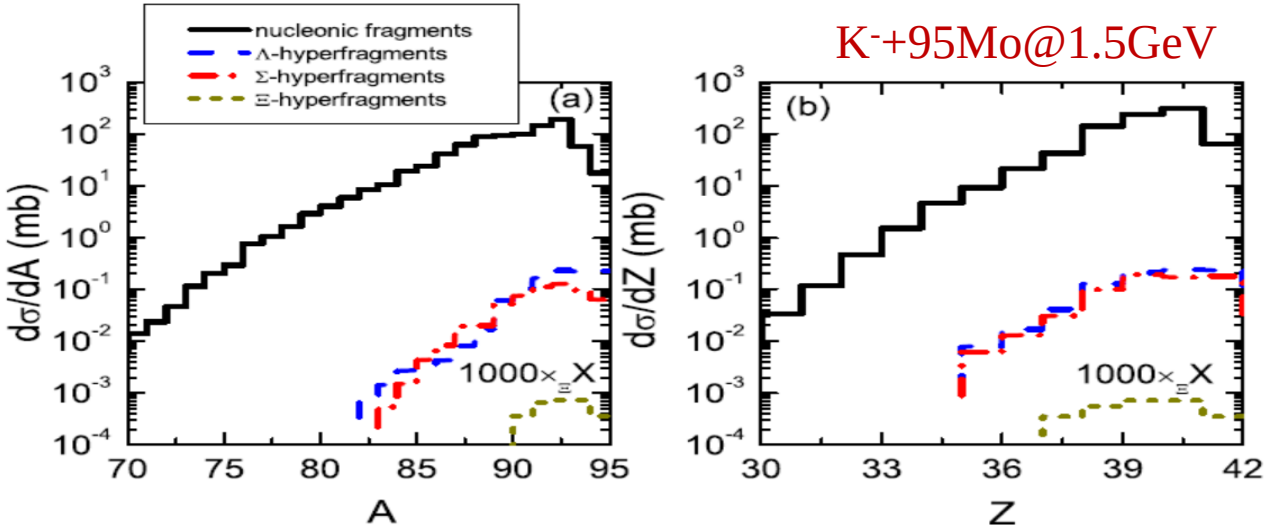
$^{124}Sn+^{124}Sn$@2A GeV/nucleon

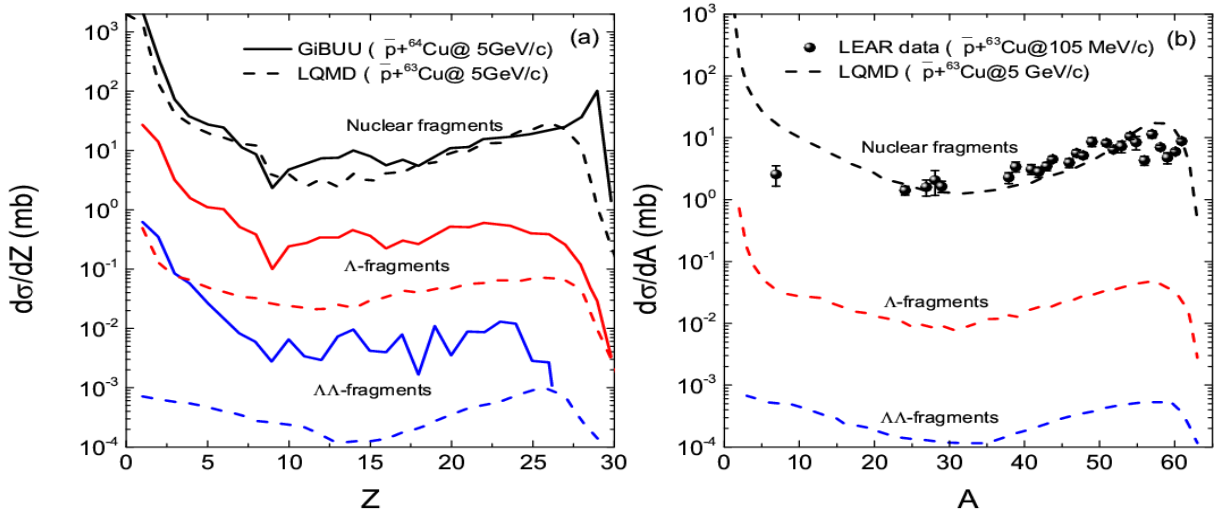
$p+^{63}Cu$@5 GeV/c





K^-+95Mo@1.5GeV





2) Wigner density approach for Z≤2

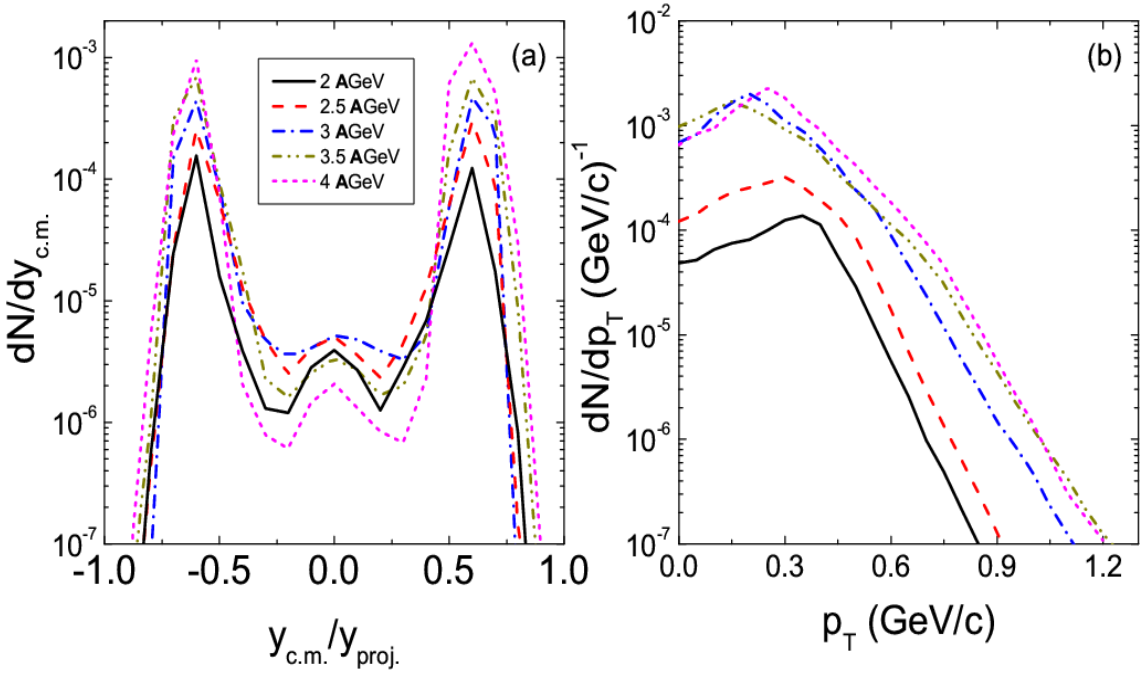
R. Mattiello et al., Phys. Rev. C 55, 1443 (1997)

$$\frac{dN_M}{d^3P} = G_M \binom{A}{M}\binom{M}{Z}\frac{1}{A^M}\int \prod_{i=1}^{Z} f_p(\mathbf{r}_i,\mathbf{p}_i) \prod_{i=Z+1}^{M} f_n(\mathbf{r}_i,\mathbf{p}_i)$$

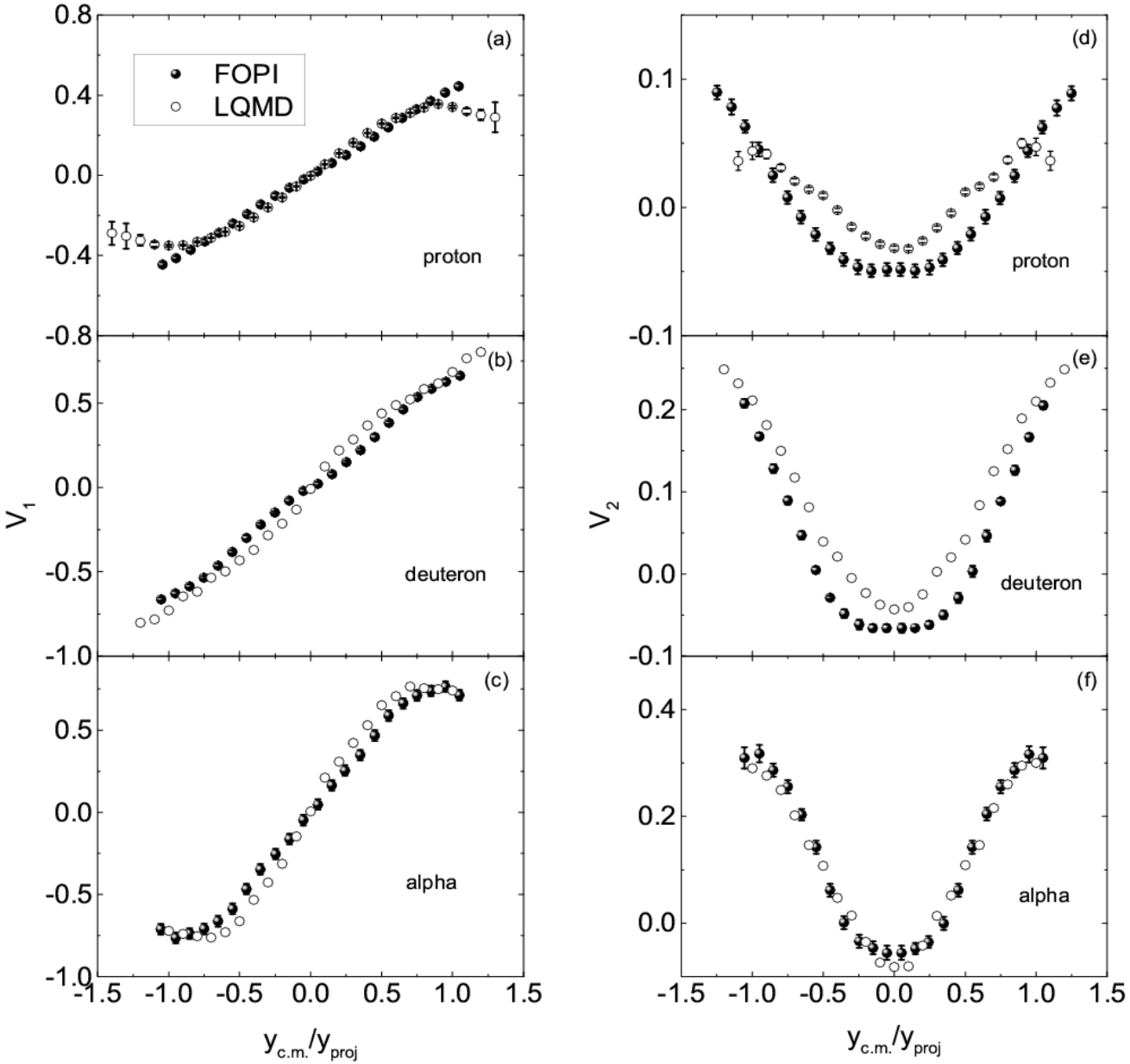
$$\times \rho^W(\mathbf{r}_{k_1},\mathbf{p}_{k_1},...,\mathbf{r}_{k_{M-1}},\mathbf{p}_{k_{M-1}})$$

$$\delta(\mathbf{P}-(\mathbf{p}_1+...+\mathbf{p}_M))d\mathbf{r}_1 d\mathbf{p}_1 ... d\mathbf{r}_M d\mathbf{p}_M$$

$^3_\Lambda$H via ^{197}Au+^{197}Au

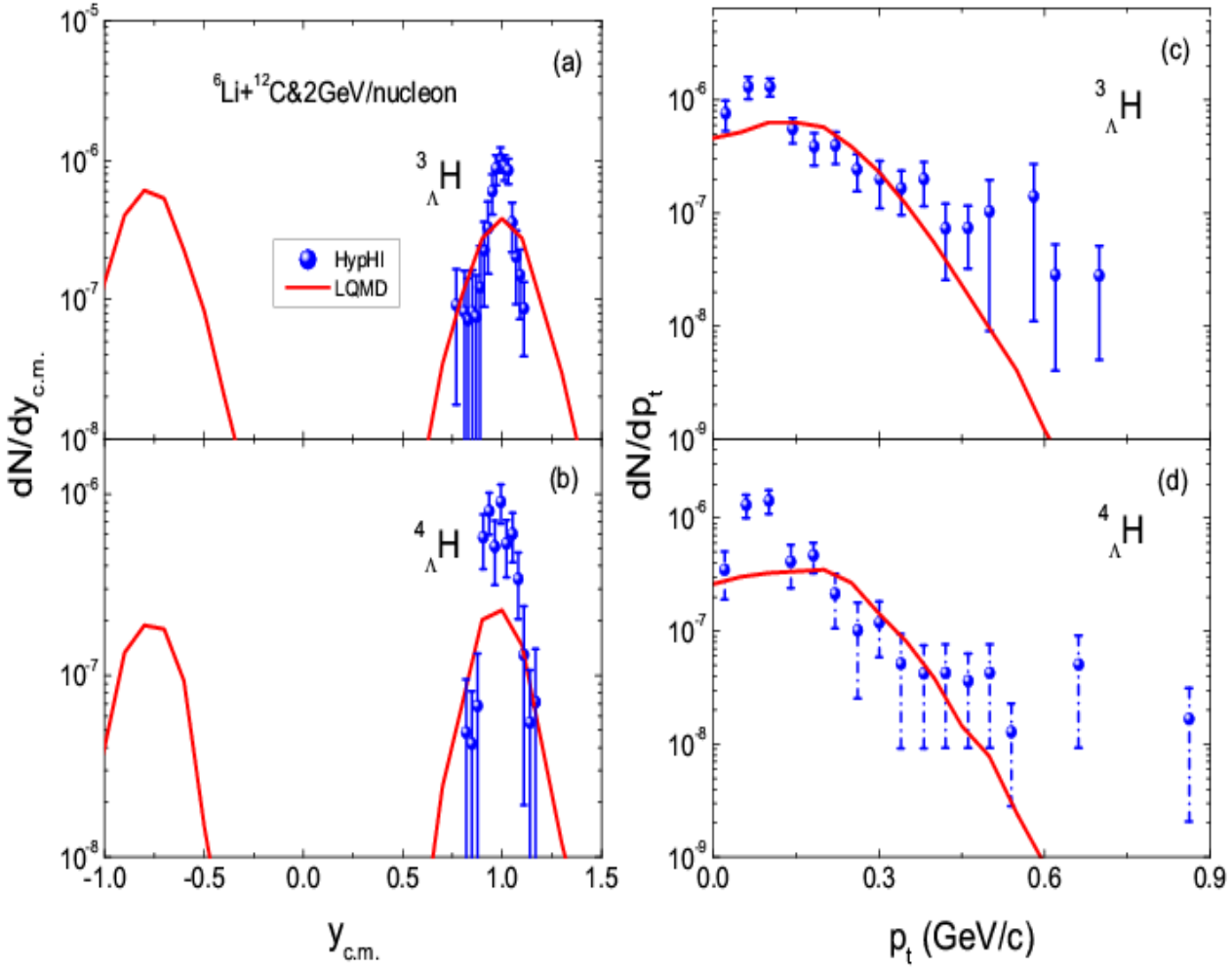


Cal: Eur. Phys. J. A, 57 (2021) 18; FOPI data, Nucl. Phys. A 876, 1 (2012)

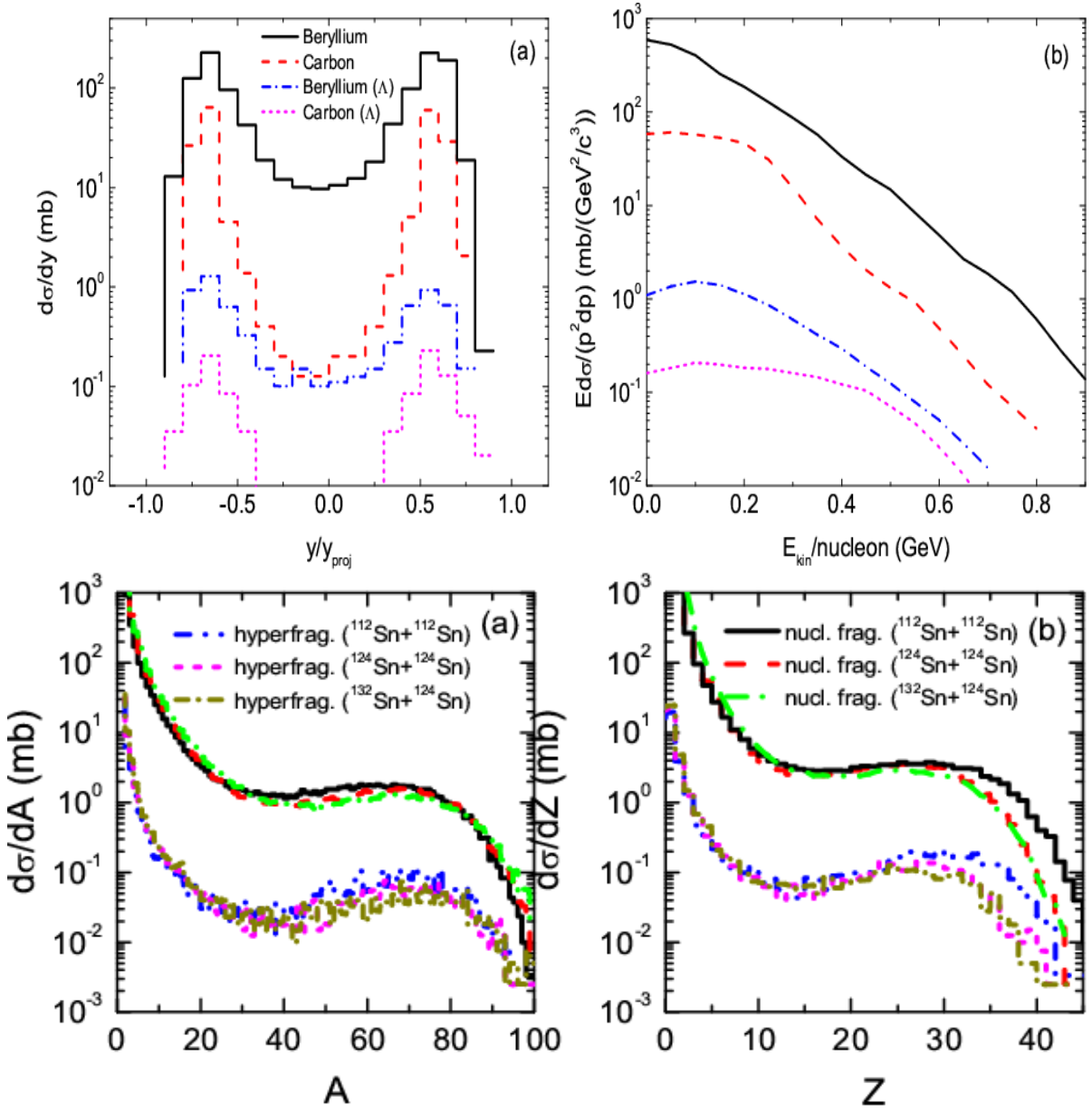


3. 重离子碰撞中超核的形成

Z. Q. Feng, Phys. Rev. C 102, 044604 (2020)
Data: C. Rappold et al., (HypHI collaboration)
Phys. Lett. B 747, 129 (2015).



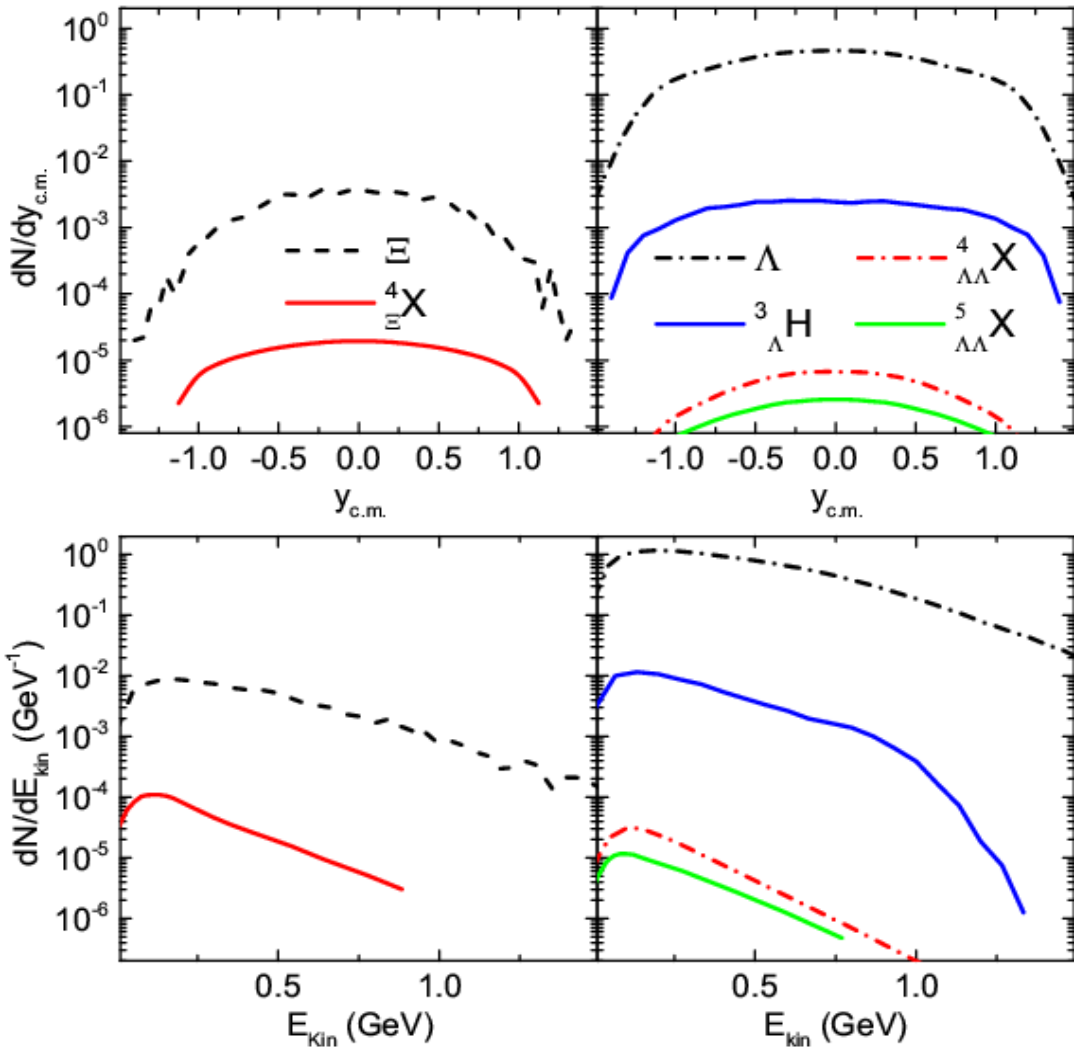
^{124}Sn+^{124}Sn@2A GeV

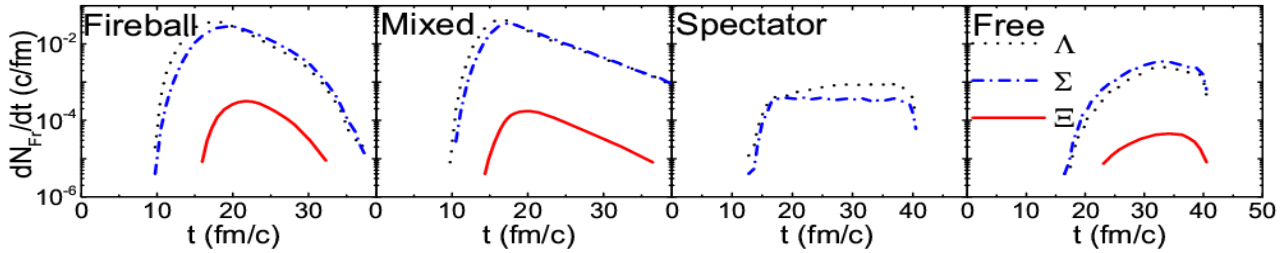


Multi-strangeness hypernuclide production

H.G. Cheng, Z. Q. Feng, Phys. Lett. B 824 (2022) 136849

^{197}Au+^{197}Au@3A GeV





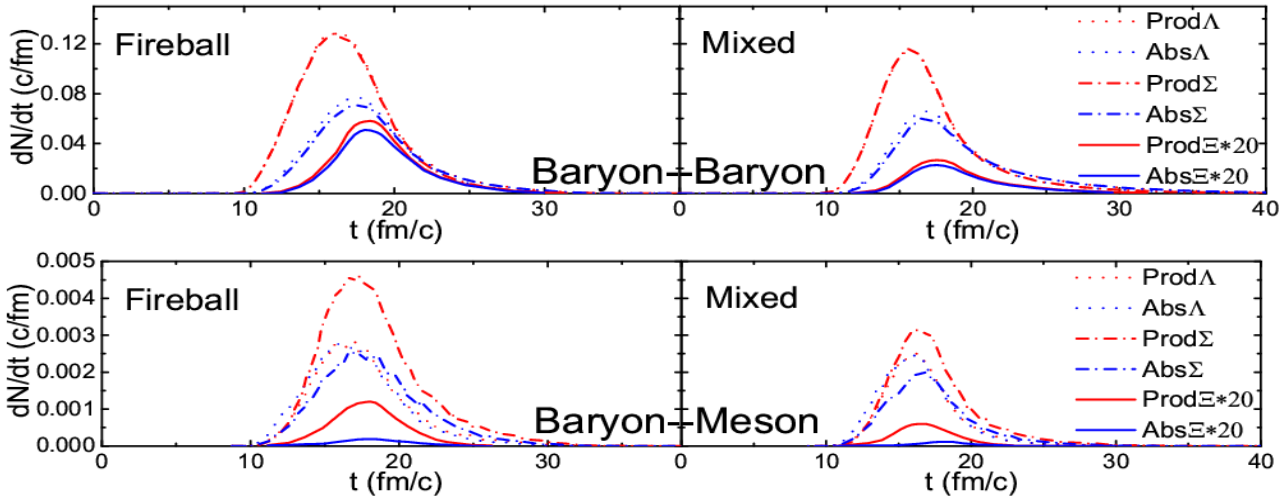
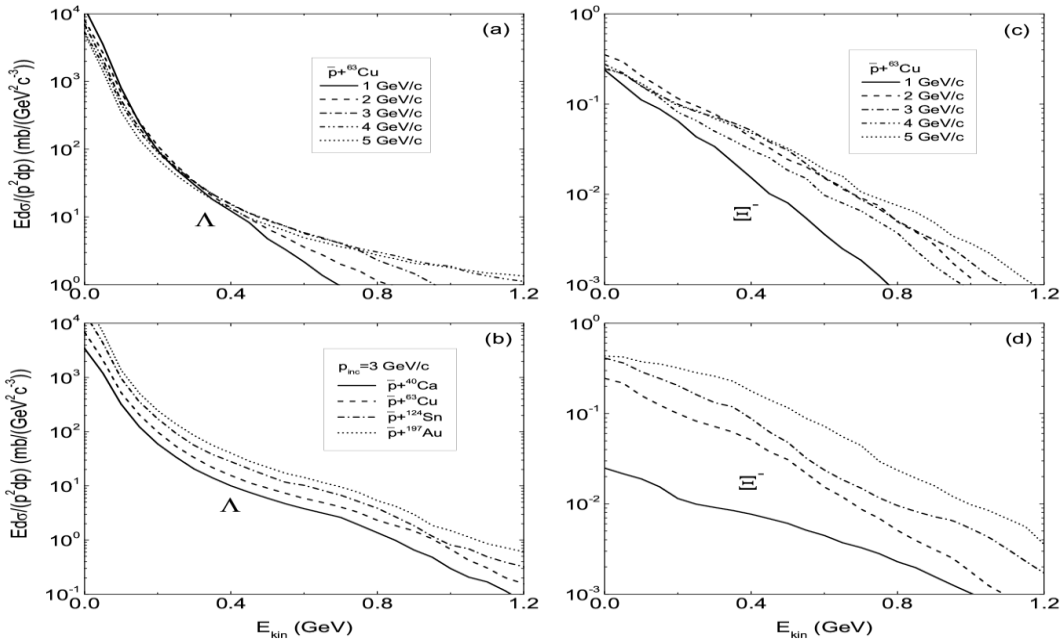


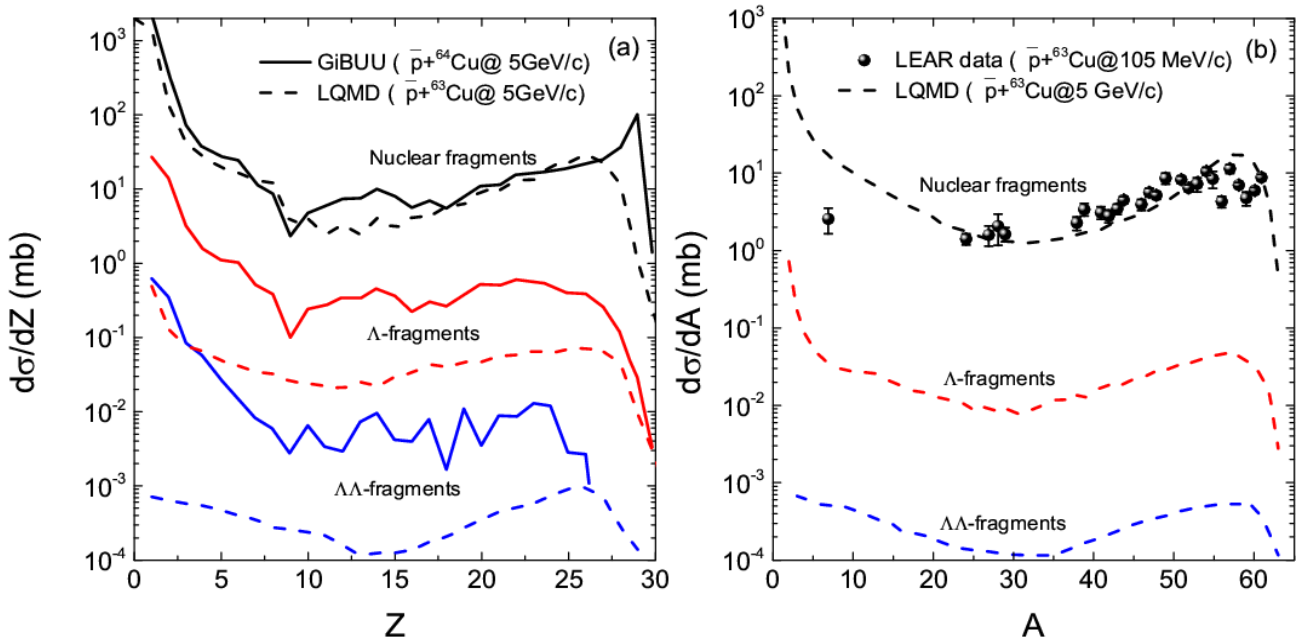
TABLE I. Comparison between cross sections of double lamda hypernuclei calculated with $r_0 = 3.5$ fm for Λ in ^{197}Au + ^{197}Au and ^{40}Ca + ^{40}Ca collisions at 3A GeV

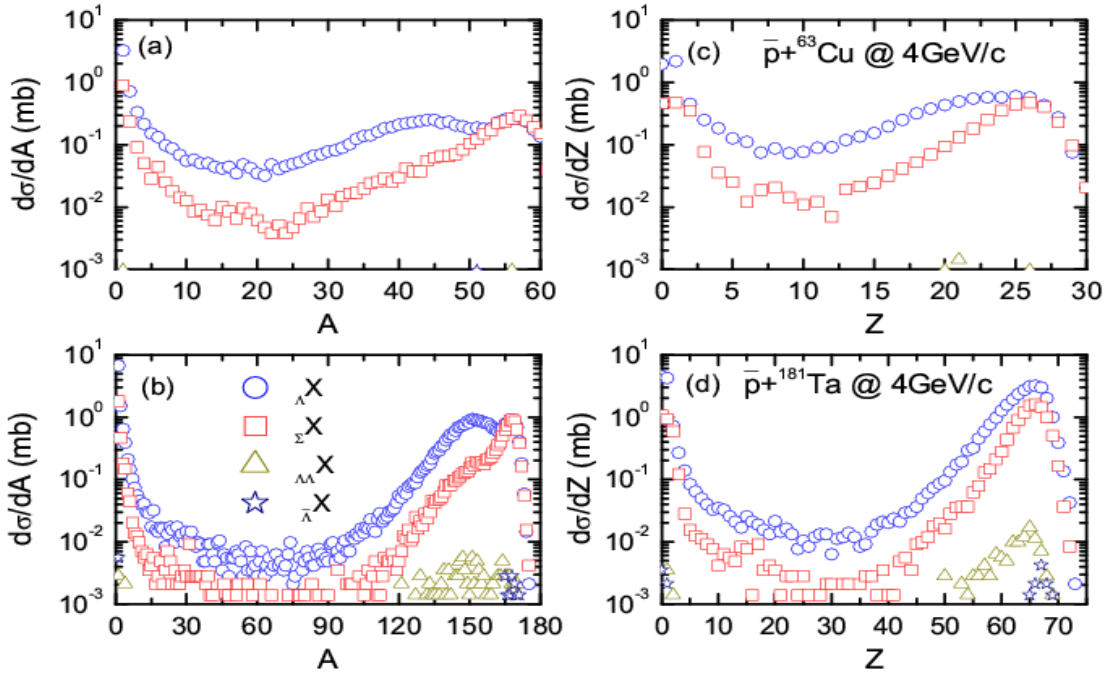
Hypernuclei	Cross sections (mb)	
	^{197}Au + ^{197}Au	^{40}Ca + ^{40}Ca
$^{4}_{\Lambda\Lambda}$H	2.6×10^{-2}	1.0×10^{-4}
$^{4}_{\Lambda\Lambda}$He	1.0×10^{-2}	$\sim 10^{-5}$
$^{5}_{\Lambda\Lambda}$H	5.9×10^{-3}	$\sim 10^{-5}$
$^{5}_{\Lambda\Lambda}$He	5.1×10^{-3}	$\sim 10^{-5}$
$^{5}_{\Lambda\Lambda}$Li	1.4×10^{-3}	$\sim 10^{-6}$
$^{6}_{\Lambda\Lambda}$He	2.2×10^{-3}	$\sim 10^{-6}$
$^{7}_{\Lambda\Lambda}$He	6.8×10^{-4}	$\lesssim 10^{-6}$

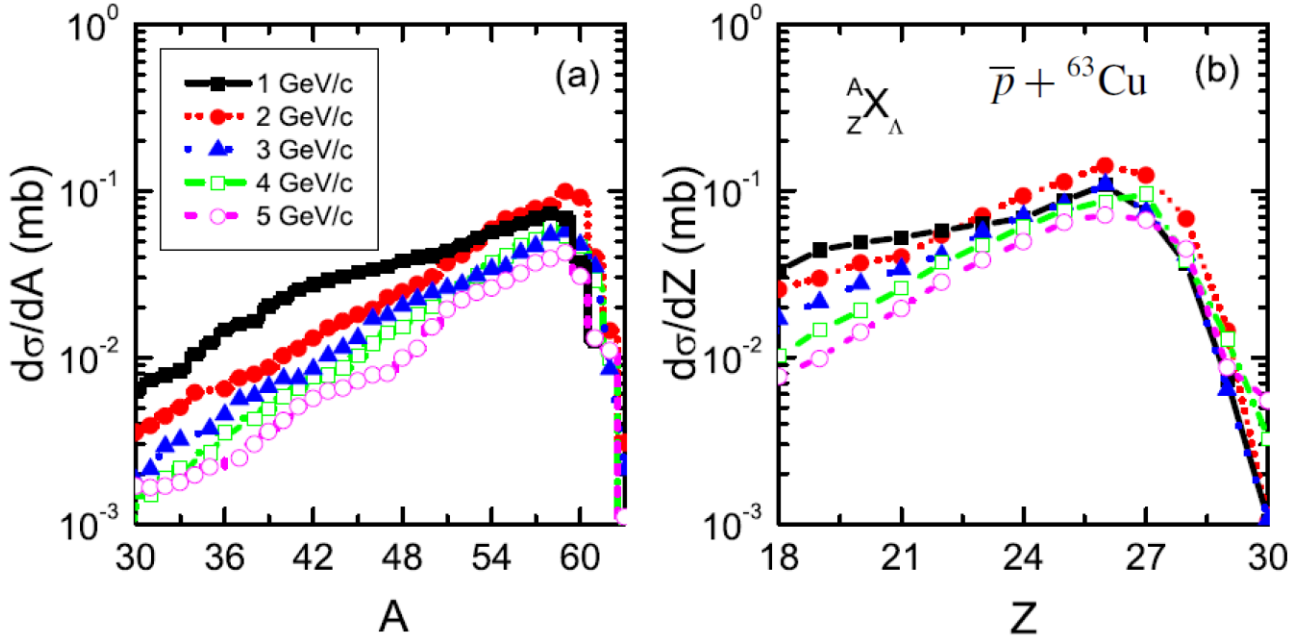
4.反质子引起的核反应中超子的产生和超核形成

Z. Q. Feng, Phys. Rev. C 89, 044617 (2014); Phys. Rev. C 93, 041601(R) (2016); Phys. Rev. C 101, 064601 (2020)



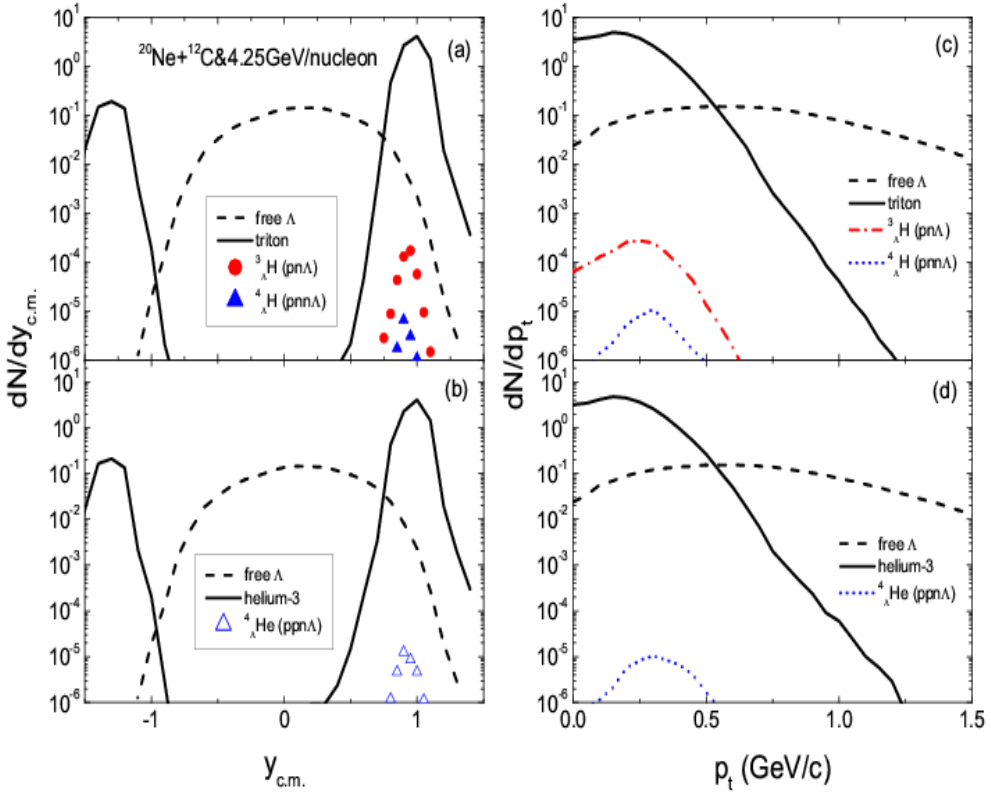






四、总结

- 碰撞区域产生的超子被“旁观者”(旁观核子)俘获后形成超核，轻质量超核可以在类弹、类靶和中心快度区域产生，重质量超核只能在类弹(靶)区域产生
- 重离子碰撞可以产生**极端丰中子/丰质子超核、多奇异性超核**。入射能量4.25GeV/核子^{20}Ne+^{12}C反应可以在HIAF上做超核研究测试实验。
- 问题：核子-核子碰撞中涉及超子的三体和四体碰撞直接产生的超核(轻质量、高动量、奇异性，如nnΛ, nnΛΛ, $_{\Lambda}^{5}$H, $_{\Lambda}^{6}$H)还没有考虑！




谢谢大家！
D3