Pion production in heavy-ion collisions near threshold energies

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OUTLINE

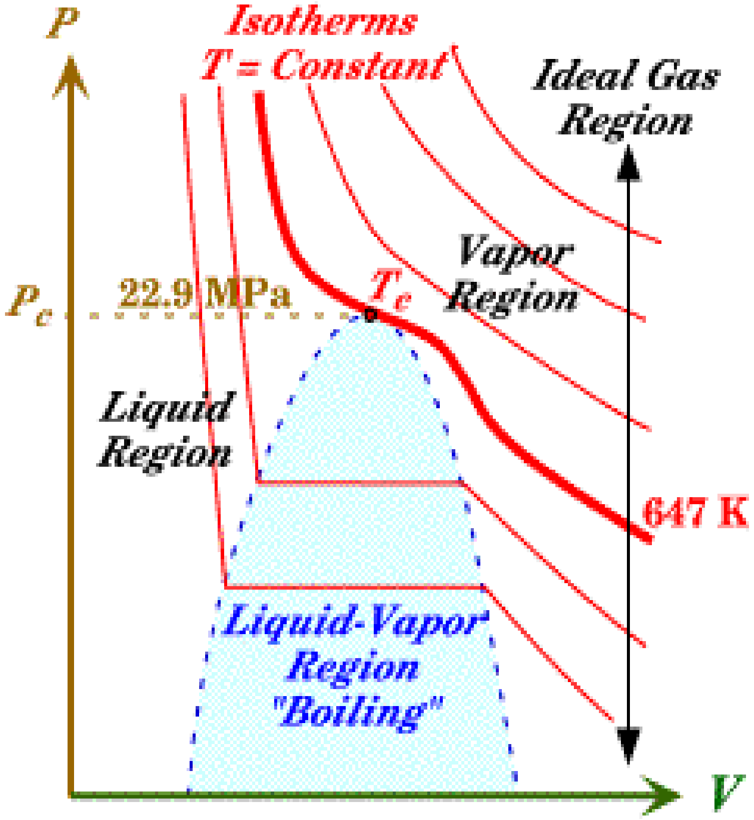
- **Neutron star matter and pion probes in heavy-ion collisions**
- **Transport approach for pion production (LQMD)**
- **π^-/π^+ ratio for constraining the high-density symmetry energy**
- **Summary and perspective**

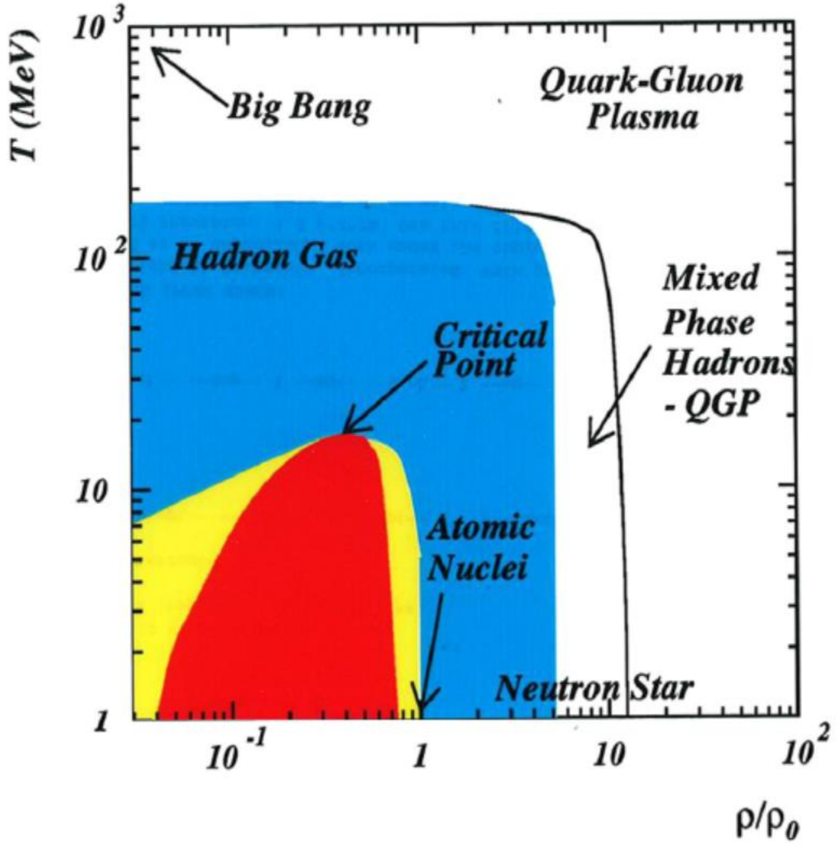
I. Neutron star matter and pion probes in heavy-ion collisions

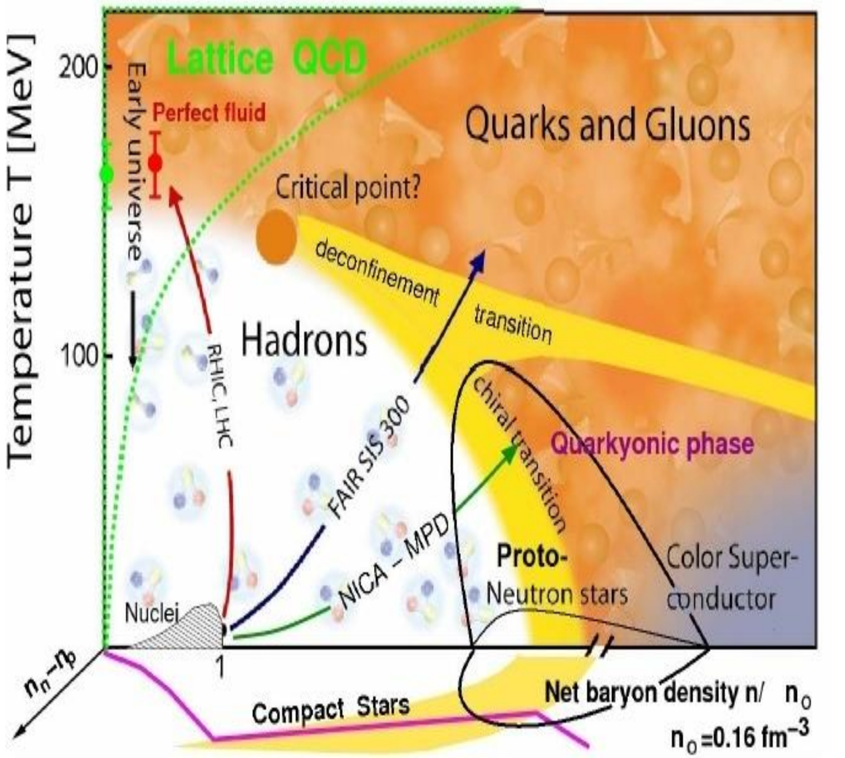
EOS-Equation of State

Van der Waals equation $[p + a(\frac{n}{\mathrm{v}})^2](\mathrm{v} - nb) = nRT$

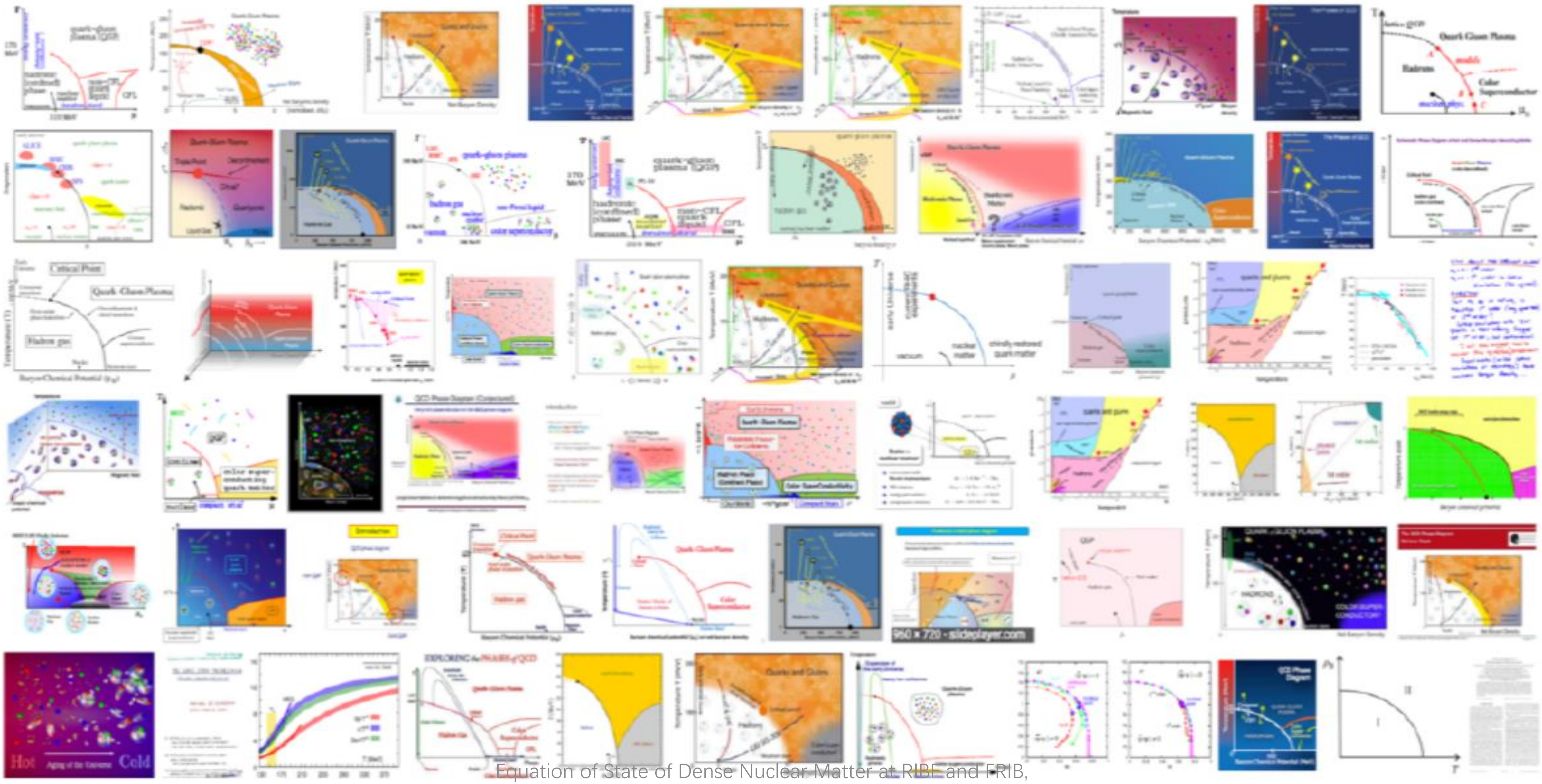
Johannes Diderik van der Waals
1837- 1923
Nobel Laureate in physics 1910
for study of gas and liquid
equation of state







QCD phase structure, WA Zajc / Nuclear Physics A 967 (2017) 265–272



Nuclear symmetry energy

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

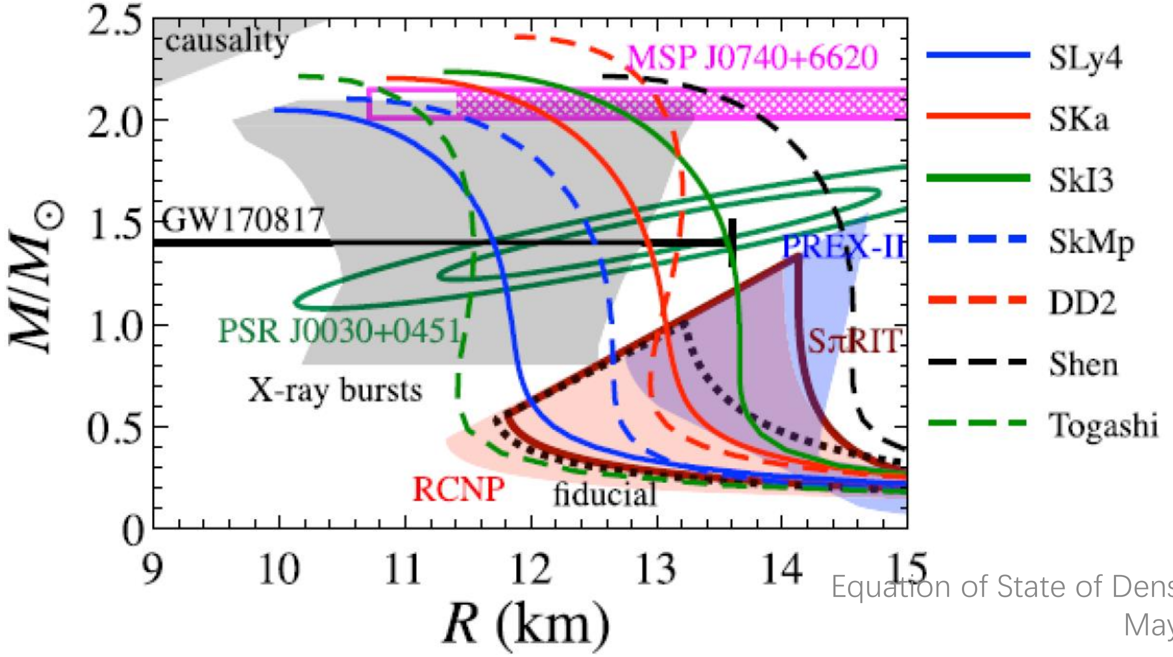
$(\rho \sim \rho_0)$

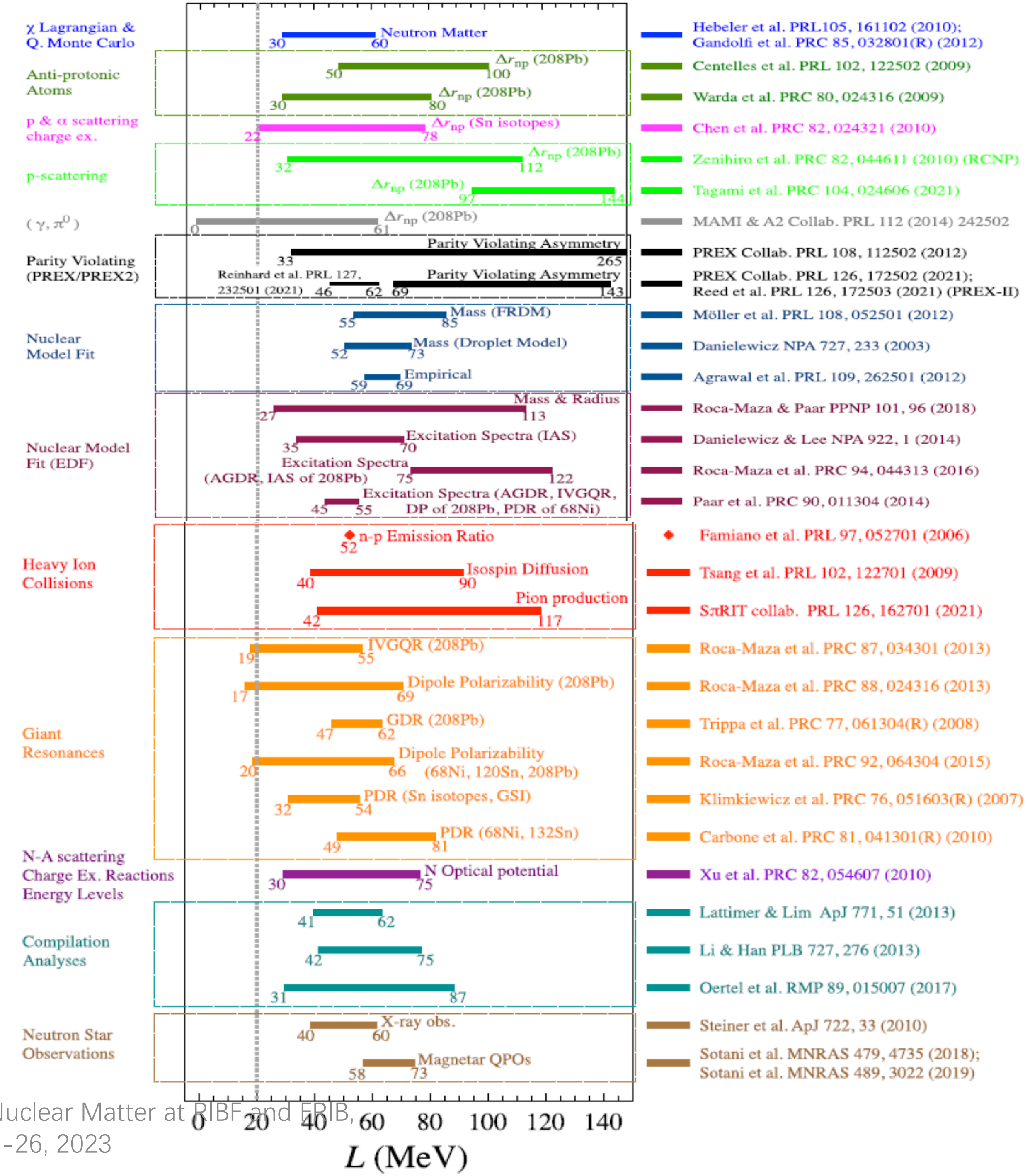
Liquid drop model: $E_{\mathrm{sym}}(\rho_0) \approx 32$ **MeV**

Slope parameter and curvature parameter

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

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





Neutron star matter and heavy-ion collisions

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Article

Constraining neutron-star matter with microscopic and macroscopic collisions

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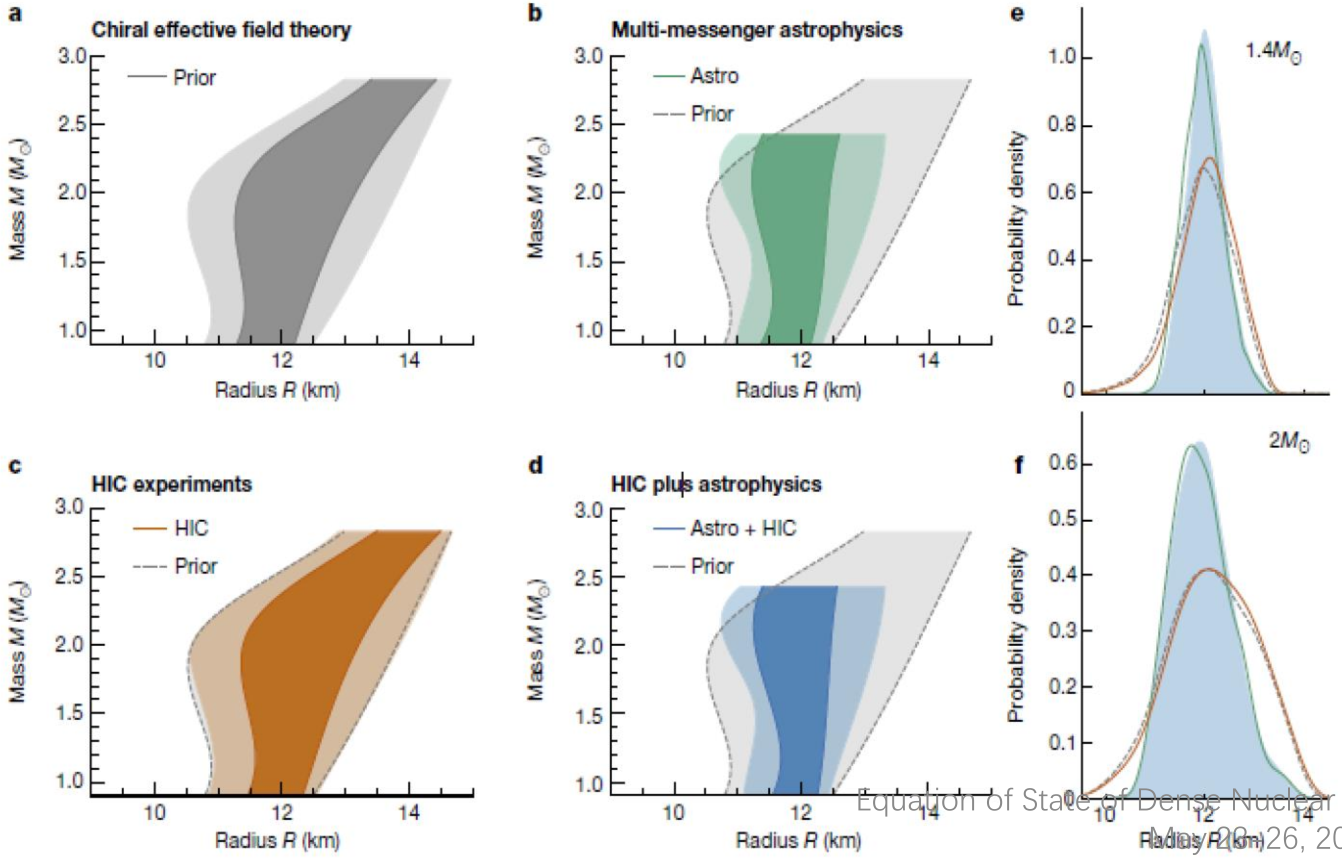
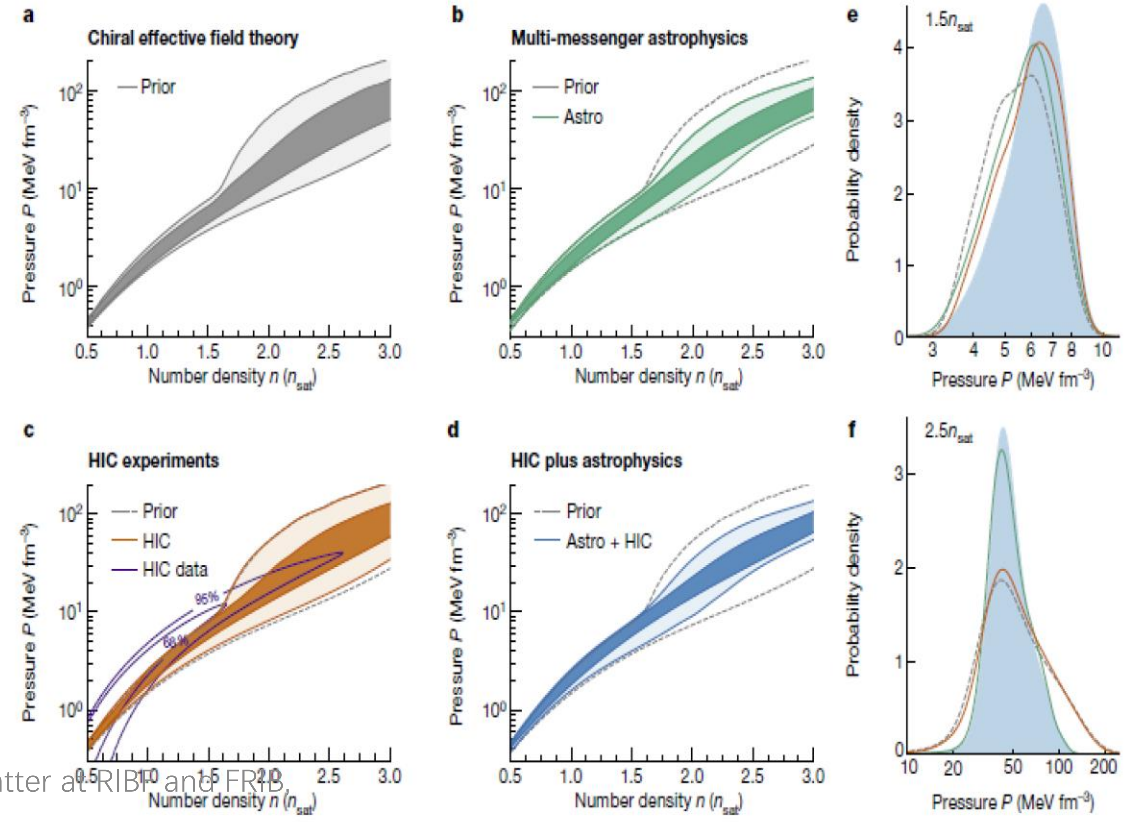
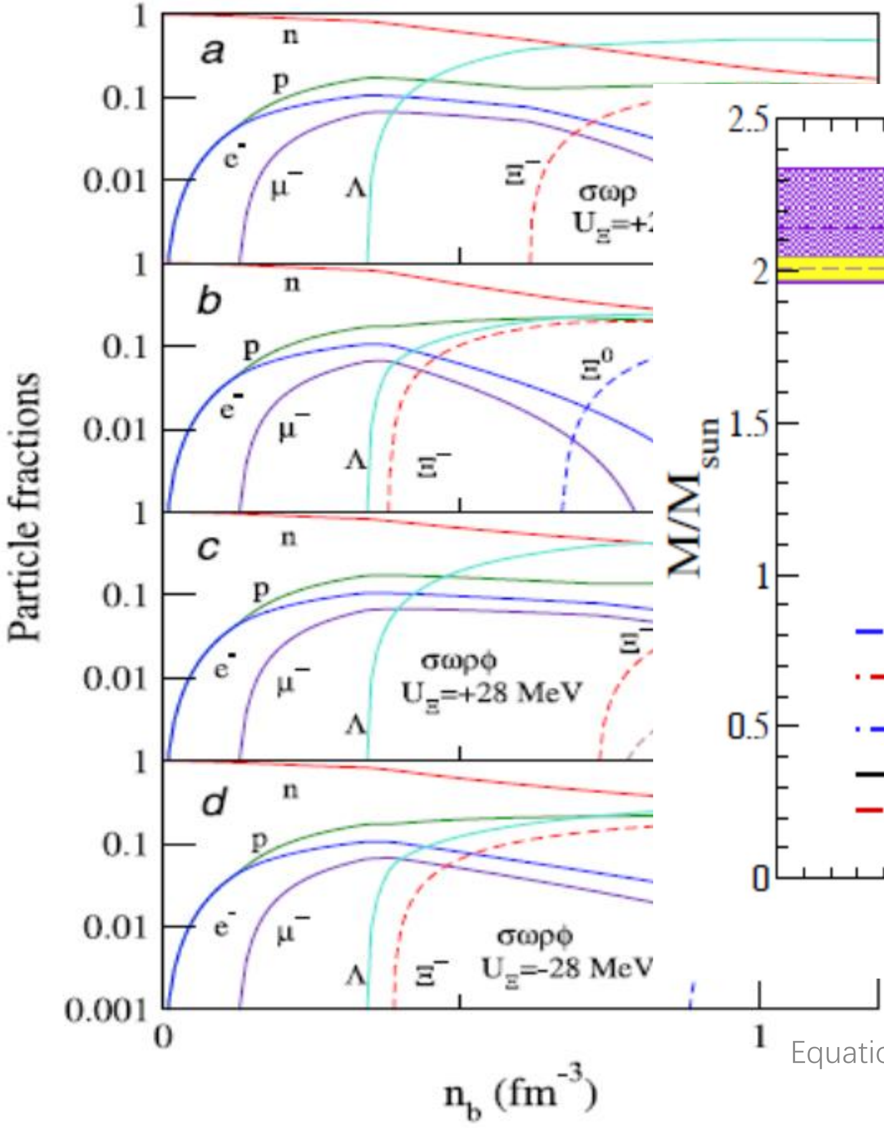
Interpreting high-energy, astrophysical phenomena, such as supernova explosions or neutron-star collisions, requires a robust understanding of matter at supranuclear densities. However, our knowledge about dense matter explored in the cores of neutron stars remains limited. Fortunately, dense matter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

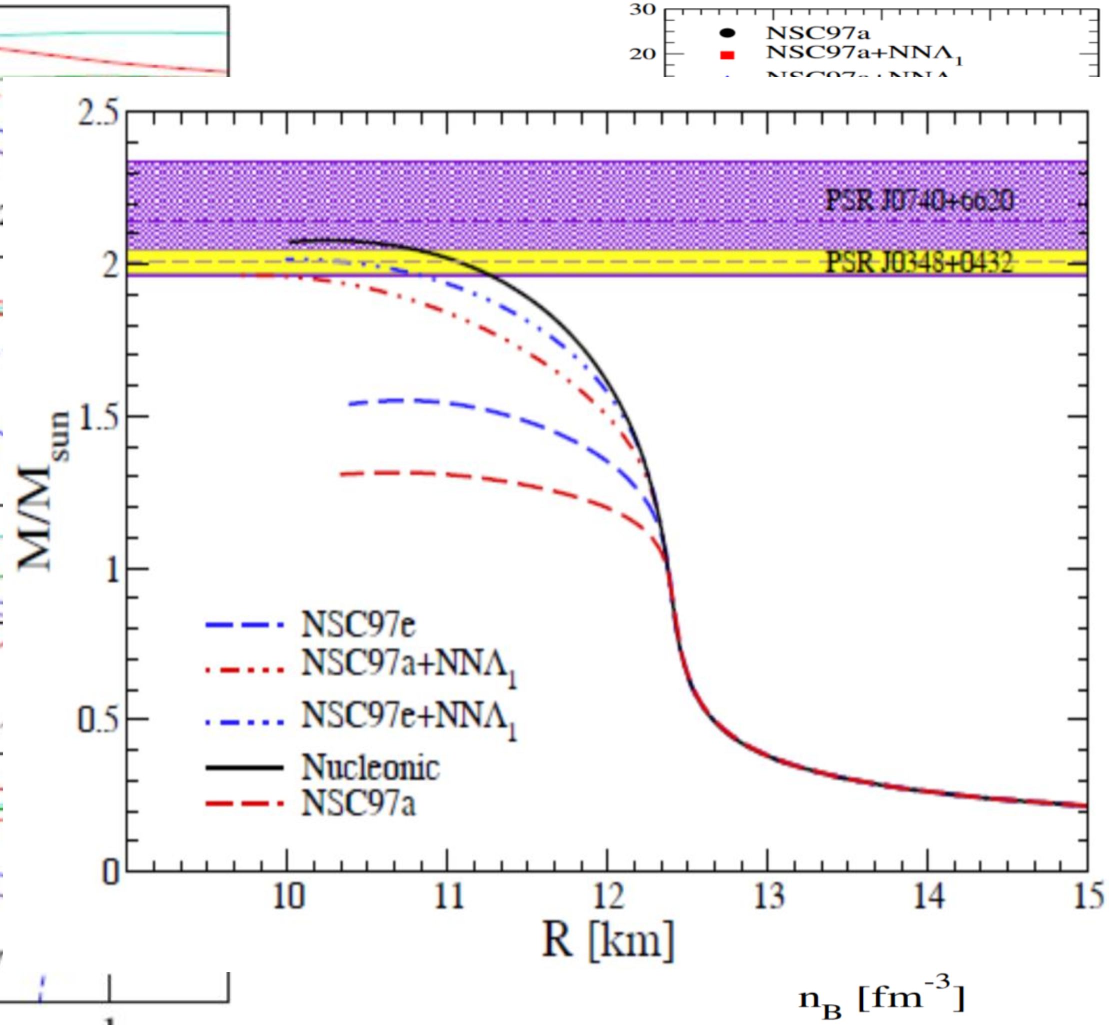


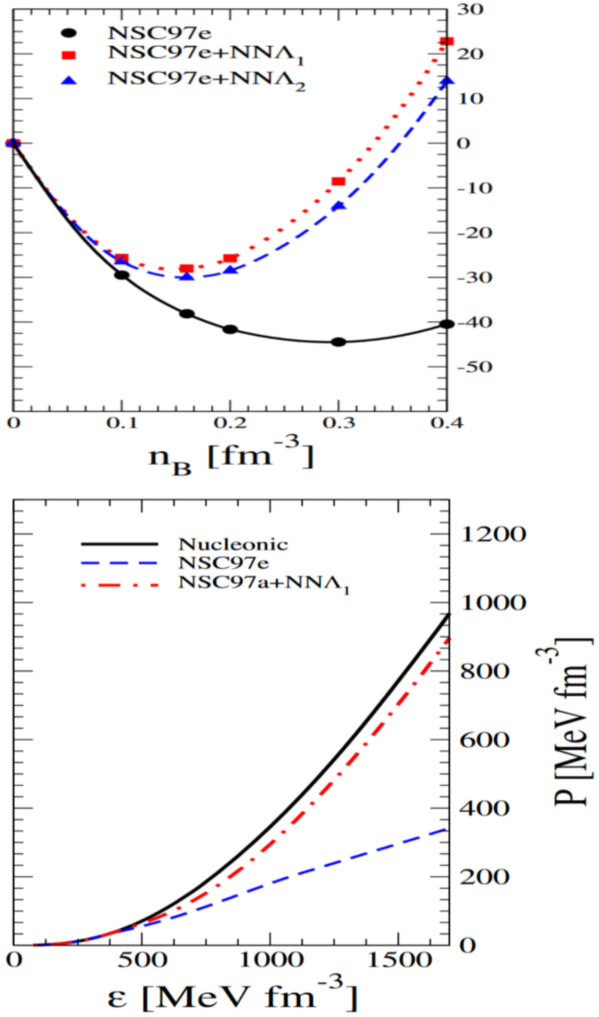


Hyperons in neutron stars

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)
D. Logoteta, I. Vidaña, I. Bombaci, Eur. Phys. J. A 55, 207 (2019)







Transport models for heavy-ion collisions

Progress in Particle and Nuclear Physics 125 (2022) 103962

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Review

Transport model comparison studies of intermediate-energy heavy-ion collisions

Hermann Wolter [1,*], Maria Colonna [2], Dan Cozma [3], Pawel Danielewicz [4,5], Che Ming Ko [6], Rohit Kumar [4], Akira Ono [7], ManYee Betty Tsang [4,5], Jun Xu [8,9], Ying-Xun Zhang [10,11], Elena Bratkovskaya [12,13], Zhao-Qing Feng [14], Theodoros Gaitanos [15], Arnaud Le Fèvre [12], Natsumi Ikeno [16], Youngman Kim [17], Swagata Mallik [18], Paolo Napolitani [19], Dmytro Oliinychenko [20], Tatsuhiko Ogawa [21], Massimo Papa [2], Jun Su [22], Rui Wang [9,23], Yong-Jia Wang [24], Janus Weil [25], Feng-Shou Zhang [26,27], Guo-Qiang Zhang [9], Zhen Zhang [22], Joerg Aichelin [28], Wolfgang Cassing [25], Lie-Wen Chen [29], Hui-Gan Cheng [14], Hannah Elfner [12,13,20], K. Gallmeister [25], Christoph Hartnack [28], Shintaro Hashimoto [21], Sangyong Jeon [30], Kyungil Kim [17], Myungkuk Kim [31], Bao-An Li [32], Chang-Hwan Lee [33], Qing-Feng Li [24,34], Zhu-Xia Li [10], Ulrich Mosel [25], Yasushi Nara [35], Koji Niita [36], Akira Ohnishi [37], Tatsuhiko Sato [21], Taesoo Song [12], Agnieszka Sorensen [38,39], Ning Wang [11,40], Wen-Jie Xie [41], (TMEP collaboration)

Table 1
List of transport models that participated in the TMEP code comparisons discussed in this paper. The columns give the information on the name of the code, the main correspondents of the code, the energy range intended for the code, the treatment of effects of relativity (see Section 2.1), and the comparisons in which the code participated. The different comparisons are listed in the last column in the table by a numbers n, which refer to the subsections 3.n, where they are described in detail: n = 1 for Au+Au collisions around 1 AGeV, n = 2 for Au+Au collision at 100 and 400 AMeV, n = 3 for box-Vlasov, n = 4 for box-cascade with only nucleons, n = 5 for box-cascade with pion and Δ resonance production, and n = 6 for the prediction of pion ratios for Sn+Sn collisions.

BUU Type	Code Correspondents	Energy Range [A GeV]	Relativity	Comparisons
BLOB	P. Napolitani, M. Colonna	0.01–0.5	non-rel	2
BUU-VM	S. Mallik	0.02–1	rel	3,4,5
DJBUU	Y. Kim, S. Jeon, M. Kim, C.-H. Lee, K. Kim	0.05–2	cov	3
GiBUU	J. Weil, T. Gaitanos, K. Gallmeister, U. Mosel	0.05–40	rel/cov	1,2,3,4
IBL	W.J. Xie, F.S. Zhang	0.05–2	rel	2
IBUU	J. Xu, L.W. Chen, B.A. Li	0.05–2	rel	2,3,4,5
LBUU(LHV)	R. Wang, Z. Zhang, L.-W. Chen	0.01–1.5	rel	3
pBUU	P. Danielewicz	0.01–12	rel	1,2,3,4,5,6
PHSD	E. Bratkovskaya, W. Cassing	0.1–200	rel/cov	1,6
RBUU	T. Gaitanos	0.05–2	cov	1,2
RVUU	Z. Zhang, C.M. Ko, T. Song	0.05–2	cov	1,2,3,4,5
SMASH	D. Oliinychenko, H. Elfner, A. Sorensen	0.5–200	cov	3,4,5,6
SMF	M. Colonna, P. Napolitani	0.01–0.5	non-rel	2,3,4
χBUU	Z. Zhang, C.M. Ko	0.01–0.5	non-rel	6
QMD Type	**Code Corespondents**	**Energy Range [AGeV]**	**Relativity**	**Comparisons**
AMD	A. Ono	0.01–0.3	non-rel	2
AMD+JAM	N. Ikeno, A. Ono	0.01–0.3	non-rel+rel	6
BQMD/IQMD	A. Le Fèvre, J. Aichelin, C. Hartnack, R. Kumar	0.05–2	rel	1,2,6
CoMD	M. Papa	0.01–0.3	non-rel	2,4
ImQMD	Y.X. Zhang, N. Wang, Z.X. Li	0.02–0.4	rel	2,3,4
IQMD-BNU	J. Su, F.S. Zhang	0.05–2	rel	2,3,4,5,6
IQMD-SINAP	G.Q. Zhang	0.05–2	rel	2
JAM	A. Ono, N. Ikeno, Y. Nara, A. Ohnishi	1–158	rel	4,5
JQMD 2.0	T. Ogawa, K. Niita, S. Hashimoto, T. Sato	0.01–3	rel	4,5
LQMD(IQMD-IMP)	Z.Q. Feng, H.G. Cheng	0.01–10	rel	2,3,4,5
TuQMD/dcQMD	D. Cozma	0.1–2	rel	1,2,3,4,5,6
UrQMD	Y. J. Wang, Q. F. Li, Y. X. Zhang	0.05–200	rel	1,2,3,4,6

Pion production in heavy-ion collisions near threshold energies

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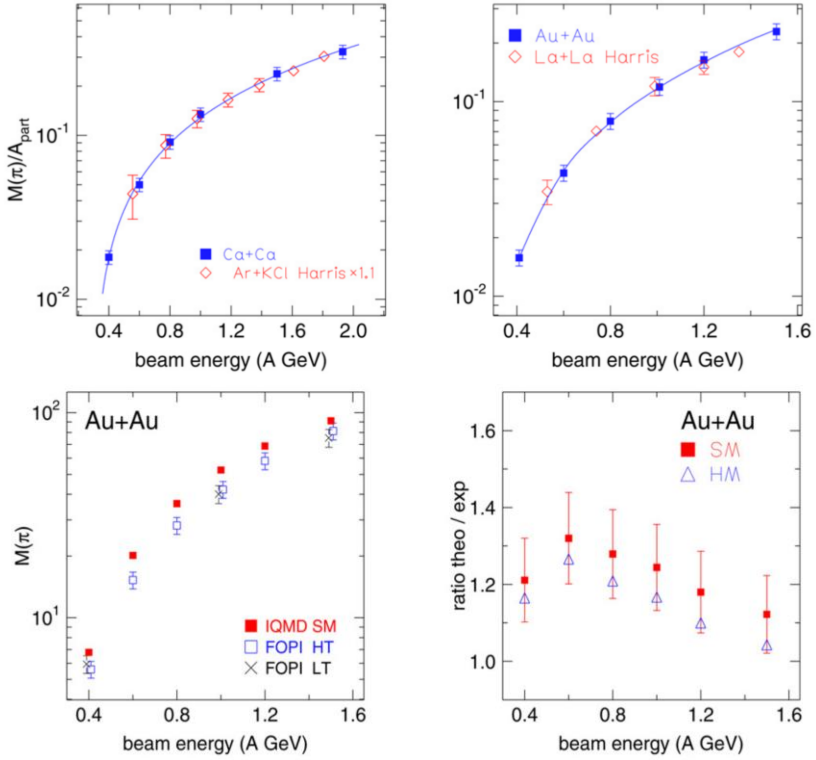
Nuclear Physics A 781 (2007) 459–508
NUCLEAR PHYSICS A

Systematics of pion emission in heavy ion collisions in the 1 *A* GeV regime

FOPI Collaboration
W. Reisdorf [a,*], M. Stockmeier [b], A. Andronic [a], M.L. Benabderrahmane [b], O.N. Hartmann [a], N. Herrmann [b], K.D. Hildenbrand [a], Y.J. Kim [a], M. Kiš [a,c], P. Koczoń [a], T. Kress [a], Y. Leifels [a], X. Lopez [a], M. Merschmeyer [b], A. Schüttauf [a], V. Barret [d], Z. Basrak [c], N. Bastid [d], R. Čaplar [c], P. Crochet [d], P. Dupieux [d], M. Dželalija [c], Z. Fodor [e], Y. Grishkin [e], B. Hong [f], T.I. Kang [f], J. Kecskemeti [g], M. Kirejczyk [h], M. Korolija [c], R. Kotte [i], A. Lebedev [e], T. Matulewicz [h], W. Neubert [i], M. Petrovici [j], F. Rami [k], M.S. Ryu [f], Z. Seres [g], B. Sikora [h], K.S. Sim [f], V. Simion [j], K. Siwek-Wilczyńska [h], V. Smolyankin [e], G. Stoicea [j], Z. Tymiński [h], K. Wiśniewski [h], D. Wohlfarth [i], Z.G. Xiao [a,l], H.S. Xu [l], I. Yushmanov [m], A. Zhilin [e]



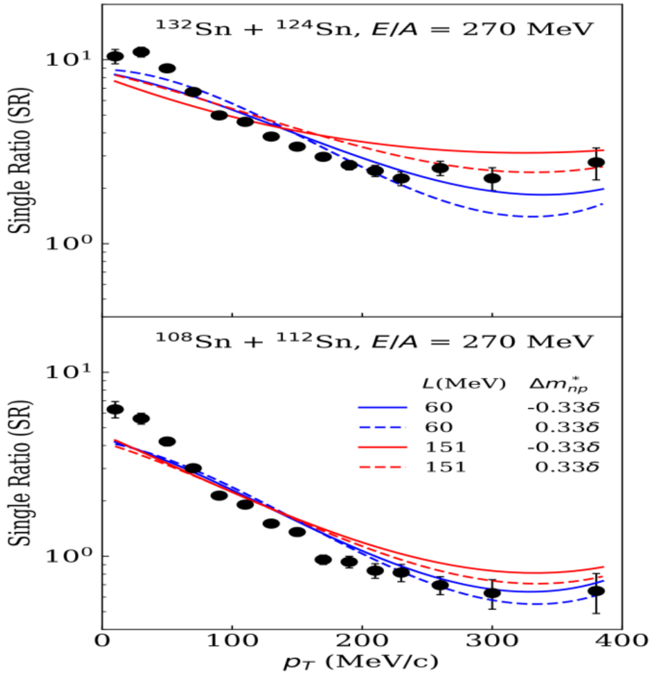
PHYSICAL REVIEW LETTERS 126, 162701 (2021)

Probing the Symmetry Energy with the Spectral Pion Ratio

J. Estee,[1,2,*] W. G. Lynch,[1,2,†] C. Y. Tsang,[1,2] J. Barney,[1,2] G. Jhang,[1] M. B. Tsang,[1,2,‡] R. Wang,[1] M. Kaneko,[3,4] J. W. Lee,[5] T. Isobe,[3,§] M. Kurata-Nishimura,[3] T. Murakami,[3,4,||] D. S. Ahn,[3] L. Atar,[6,7] T. Aumann,[6,7] H. Baba,[3] K. Boretzky,[7] J. Brzychczyk,[8] G. Cerizza,[1] N. Chiga,[3] N. Fukuda,[3] I. Gasparic,[9,3,6] B. Hong,[5] A. Horvat,[6,7] K. Ieki,[10] N. Inabe,[3] Y. J. Kim,[11] T. Kobayashi,[12] Y. Kondo,[13] P. Lasko,[14] H. S. Lee,[11] Y. Leifels,[7] J. Łukasik,[14] J. Manfredi,[1,2] A. B. McIntosh,[15] P. Morfouace,[1] T. Nakamura,[13] N. Nakatsuka,[3,4] S. Nishimura,[3] H. Otsu,[3] P. Pawłowski,[14] K. Pelczar,[8] D. Rossi,[6] H. Sakurai,[3] C. Santamaria,[1] H. Sato,[3] H. Scheit,[6] R. Shane,[1] Y. Shimizu,[3] H. Simon,[7] A. Snoch,[16] A. Sochocka,[8] T. Sumikama,[3] H. Suzuki,[3] D. Suzuki,[3] H. Takeda,[3] S. Tangwancharoen,[1] H. Toernqvist,[6,7] Y. Togano,[10] Z. G. Xiao,[17] S. J. Yennello,[15,18] and Y. J. Zhang[17]

(SπRIT Collaboration)

M. D. Cozma[1,19,¶]



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评 述 高温高密核物质形态研究专题

CSR能区的高重子密度核物质研究进展

王世陶[1], 胡强[1], 孙亚洲[1], 马朋[1], 何军[1,2], 冯兆庆[1,3], 张松[4], 孙志宇[1*], 王建松[1,5*]

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Progress of study on the properties of nuclear matter with high baryon density at CSR energy region

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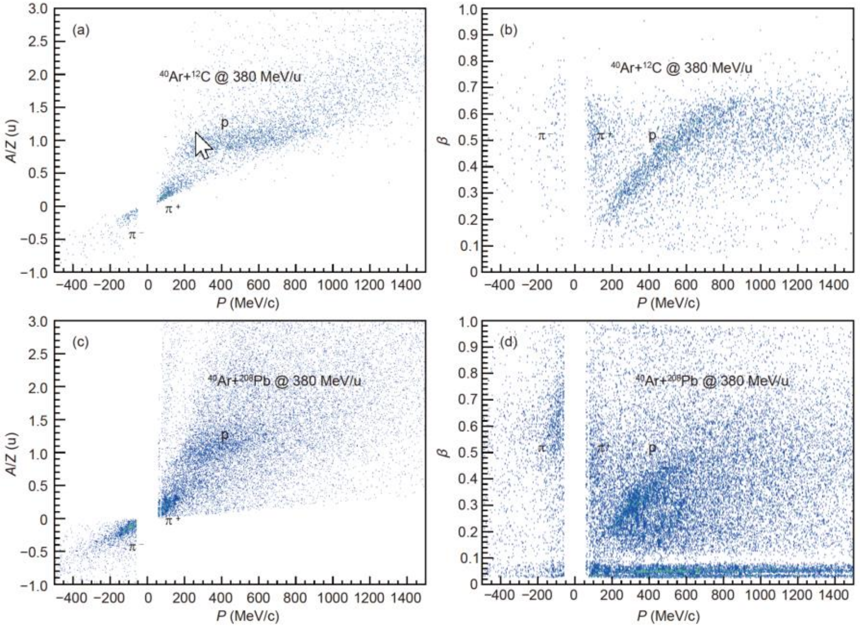
This review is focused on the low energy part of the QCD phase diagram, the properties of the nuclear matter with high baryon density which could be experimentally studied at the large scale facility for nuclear physics in China, such as the split of nucleon effect mass, symmetric energy of high baryon density nuclear matter, the properties of hadrons in the nuclear medium. The properties of nuclear matter with high baryon density and the resonance states of hadron have been studied theoretically and some physical observables related to the properties of nuclear matter with high baryon density are pointed out under the heavy ion collisions with the energy at the region of 0.5–1.2 GeV/u. The existing experimental setup at HIRFL-CSR has been improved and a test experiment has been performed. The results show the ability to explore the properties of the nuclear matter with high baryon density. Our studies are helpful to design and built a professional spectrometer for the low energy part of the QCD phase diagram in the near future.

QCD phase diagram, resonant state of nucleon, nuclear matter with high baryon density

PACS: 25.70.Lm, 25.75.Dw, 21.65.+f

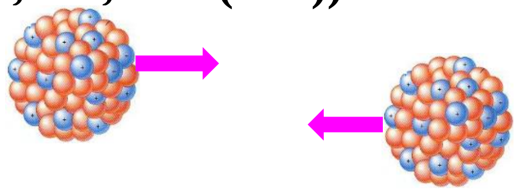
doi: 10.1360/SSPMA-2019-0046



II. Transport approach for pion production (LQMD)

Heavy-ion collisions (5 MeV – 5 GeV/nucleon) and hadron induced reaction (p, $\bar{p}$, π, K, e, 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) and mesons (π,K,η,ρ,ω,ϕ…), hypernucleus dynamics)
- **Nuclear cluster and hypernuclear cluster production** (production cross section, transverse momentum spectra, rapidity distribution, collective flows, e.g., Λ(Σ)X, ΛΛX, ΞX, $\bar{\Lambda}$X(S=1))



1. Skyrme energy-density functional (LQMD-Skyrme)

PHYSICAL REVIEW C **84**, 024610 (2011)

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

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(Received 11 July 2011; published 19 August 2011)

$$H_B = \sum_i \sqrt{\mathbf{p}_i^2 + \mathbf{m}_i^2} + U_{\rm int} + U_{\rm mom}$$

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

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

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

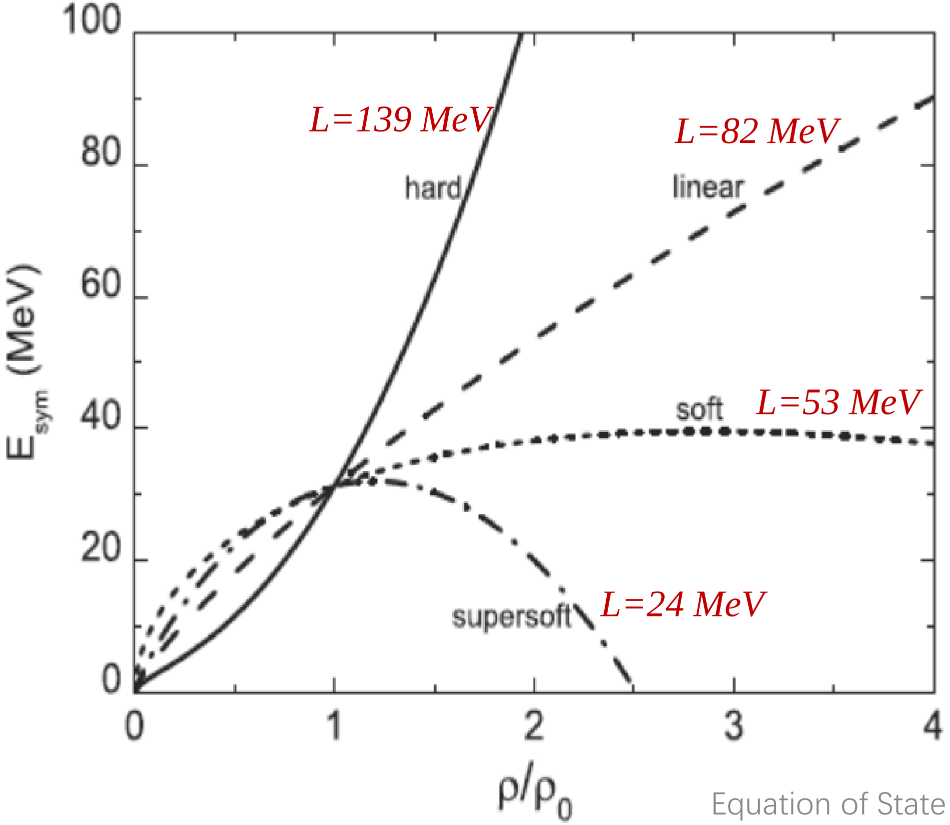
$$\boxed{E_{\rm sym}(\rho) = \frac{1}{3}\frac{\hbar^2}{2m}\left(\frac{3}{2}\pi^2\rho\right)^{2/3} + E_{\rm sym}^{loc}(\rho) + E_{\rm sym}^{mom}(\rho).}$$

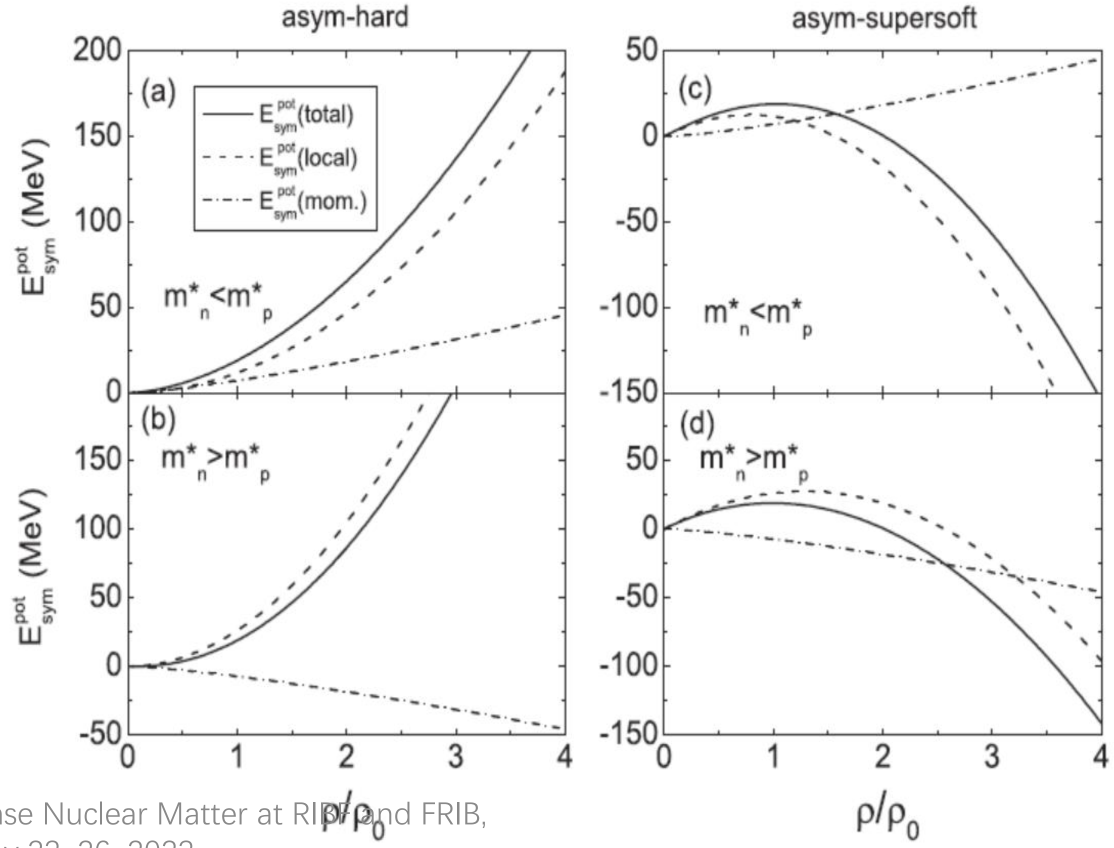
$$E_{\rm sym}^{loc}(\rho) = \frac{1}{2}C_{sym}(\rho/\rho_0)^{\gamma_s} \qquad E_{\rm sym}^{loc}(\rho) = a_{sym}(\rho/\rho_0) + b_{sym}(\rho/\rho_0)^2.$$

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. Covariant energy-density functional (LQMD-RMF)

Si-Na Wei, Zhao-Qing Feng, arXiv:2302.09984

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

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

Energy density functional

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

Temporal evolution in phase space

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

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

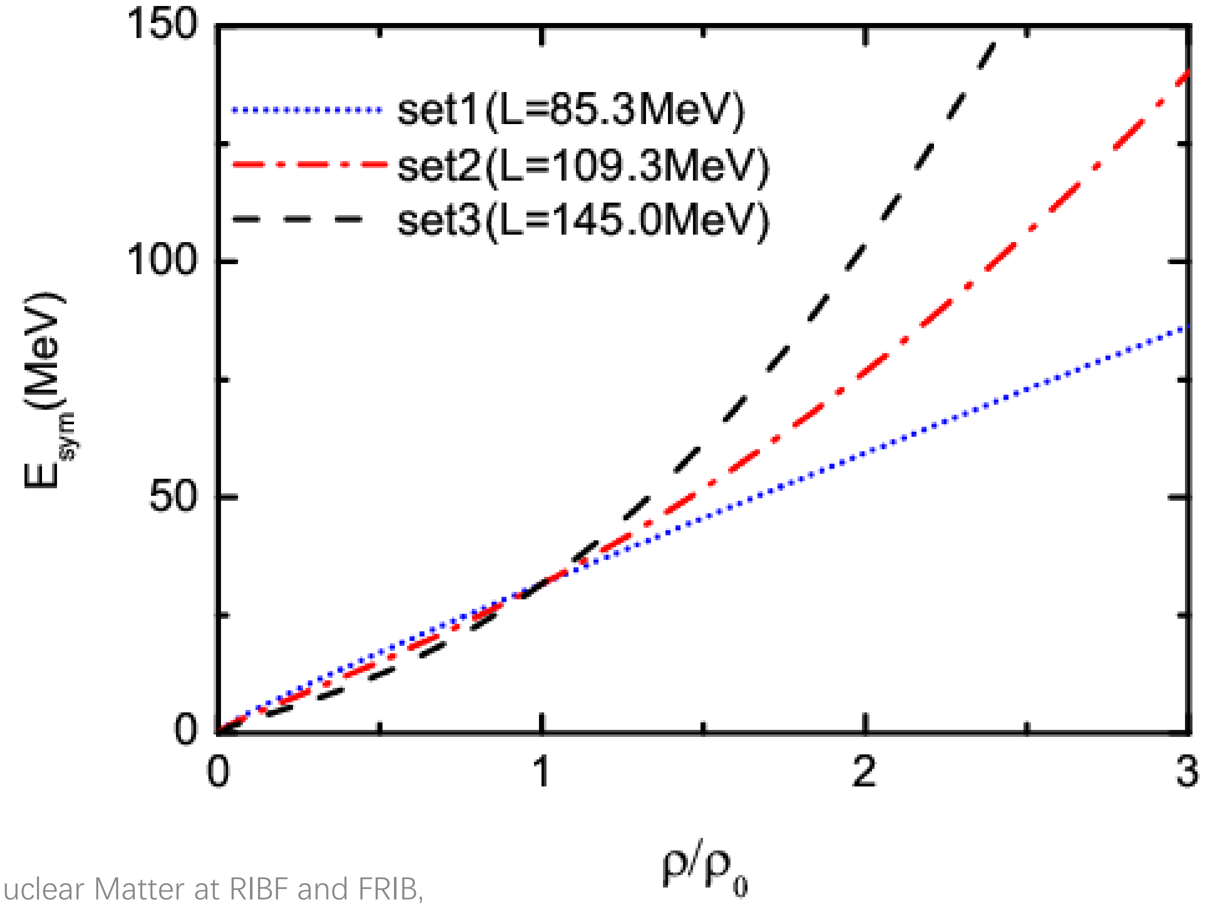
TABLE I: Parameter sets for RMF. The saturation density ρ_0 is set to be 0.16 fm^{-3}. The binding energy of saturation density is $E/A - M_N = -16$ MeV. The isoscalar-vector ω and isovector-vector ρ masses are fixed to their physical values, $m_\omega = 783$ MeV and $m_\rho = 763$ MeV. The remaining meson mass m_σ is set to be 550 MeV.

model	g_σ	g_ω	g_2 (fm^{-1})	g_3	g_ρ	g_δ	K (MeV)	$E_{sym}(\rho_0)$ (MeV)	L (ρ_0)(MeV)
set1	8.145	7.570	31.820	28.100	4.049	-	230	31.6	85.3
set2	8.145	7.570	31.820	28.100	8.673	5.347	230	31.6	109.3
set3	8.145	7.570	31.820	28.100	11.768	7.752	230	31.6	145.0

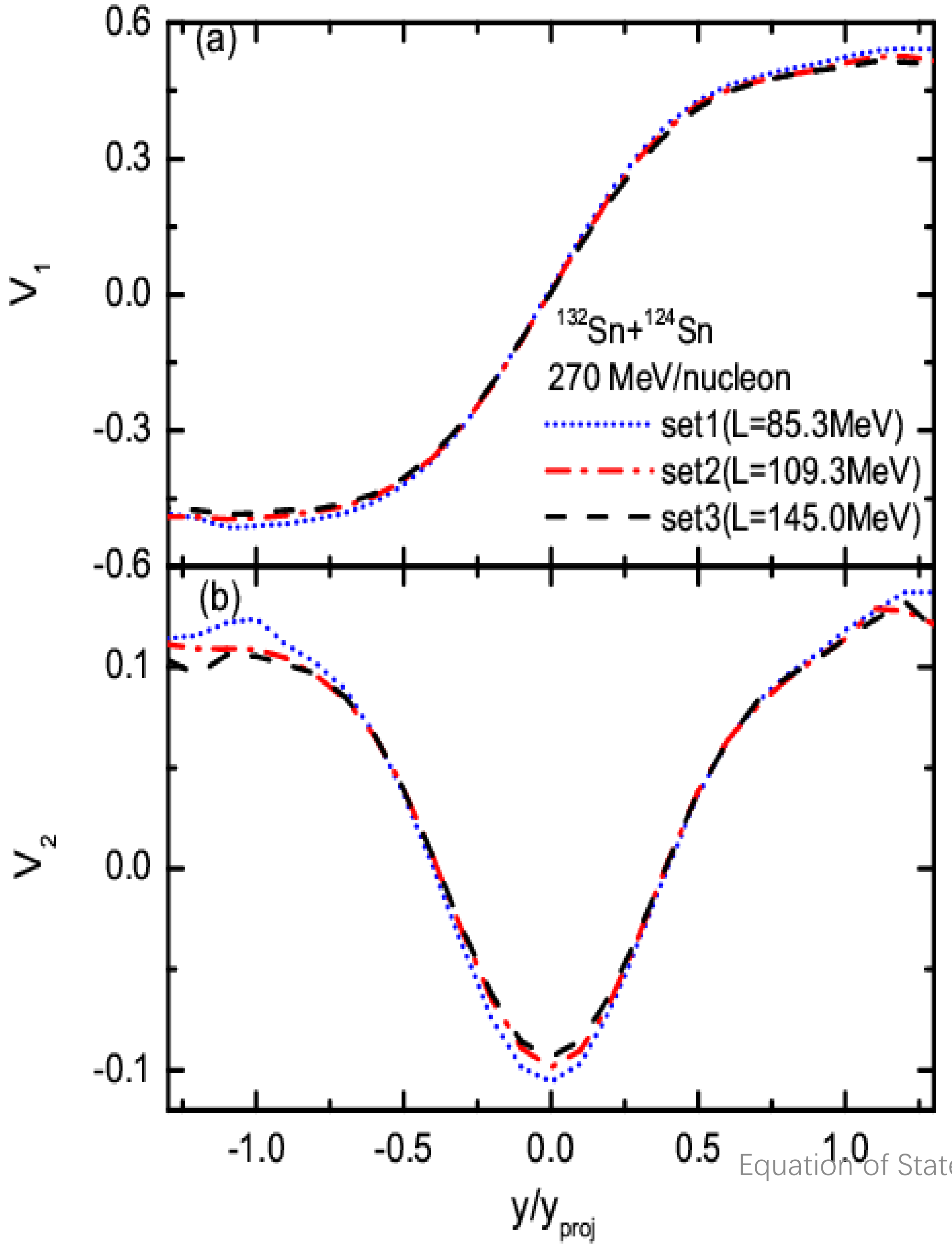
Symmetry energy in LQMD-RMF

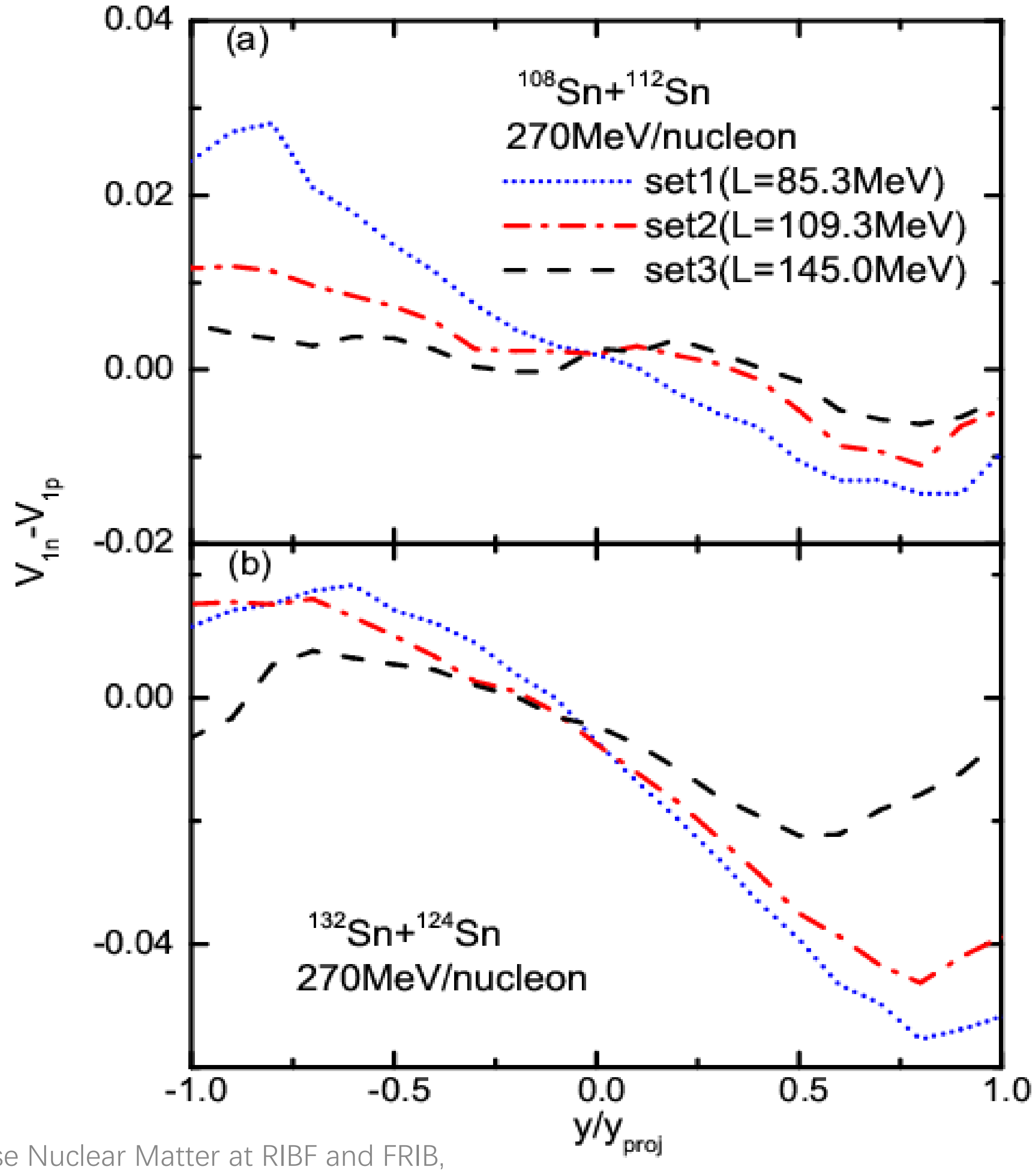
$$E_{sym} = \frac{1}{6}\frac{k_F^2}{E_F^*} + \frac{1}{2}\left[f_\rho - f_\delta\left(\frac{M^*}{E_F^*}\right)\right]\rho$$

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



Collective flows of protons and flow difference with LQMD-RMF





3. Pion-nucleon potential

Z. Q. Feng et al., Phys. Rev. C 92 (2015) 044604

$$\omega_{\tau_z}(\rho,\vec{p}) = \omega_{isoscalar}(\rho,\vec{p}) + C_{iso}^{\pi}\tau_z\delta\left(\frac{\rho}{\rho_0}\right)^{\gamma_\pi}$$

$$C_\pi = \rho_0\hbar^3/(4f_\pi^2) = 36\ \mathrm{MeV},$$

τ_z=1, 0, -1 for π^-, π^0 and π^+

Evaluation of $\omega_{isoscalar}$

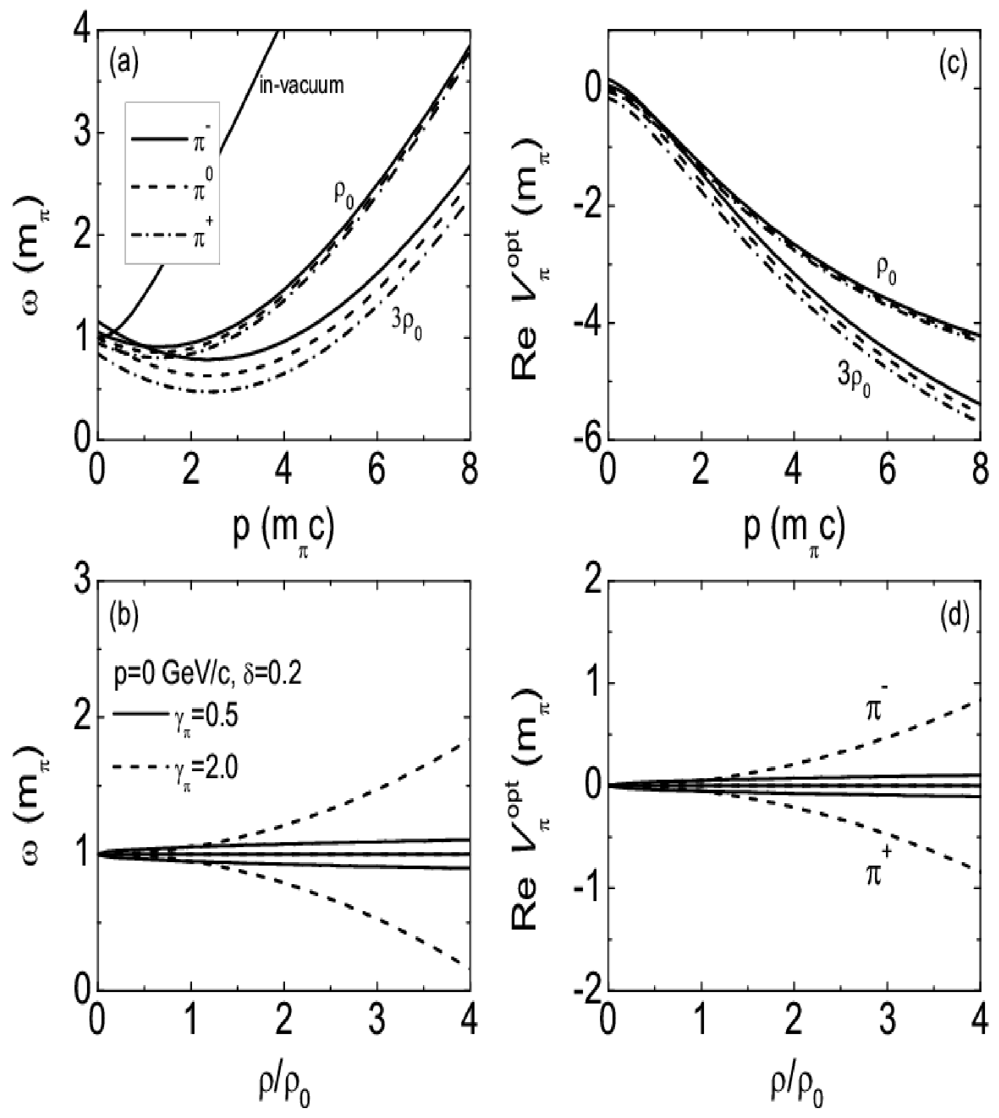
1) phenomenological ansatz from pionic atom

C. Gale and J. Kapusta, Phys. Rev. C 35, 2107 (1987);
C. Fuchs et al., Phys. Rev. C 55, 411 (1997);
Z. Q. Feng and G. M. Jin, Phys. Rev. C 82, 044615 (2010))

2) Δ-hole model

L. Xiong, C. M. Ko, V. Koch, Phys. Rev. C 47, 788 (1993);
C. Fuchs et al., Phys. Rev. C 55, 411 (1997)

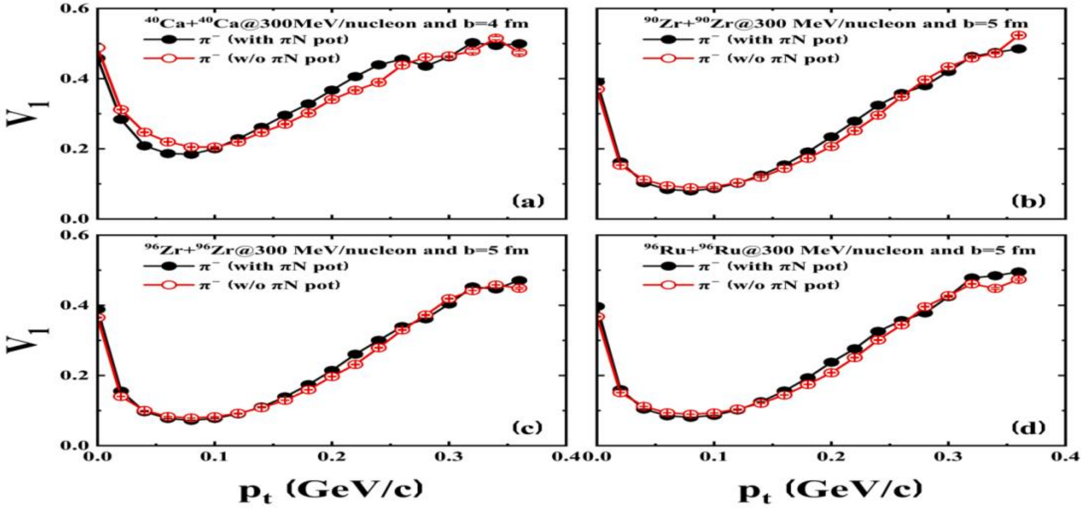
$$\omega_{\text{isoscalar}}(\mathbf{p}_i,\rho_i) = S_\pi(\mathbf{p}_i,\rho_i)\omega_{\pi\text{-like}}(\mathbf{p}_i,\rho_i) + S_\Delta(\mathbf{p}_i,\rho_i)\omega_{\Delta\text{-like}}(\mathbf{p}_i,\rho_i)$$

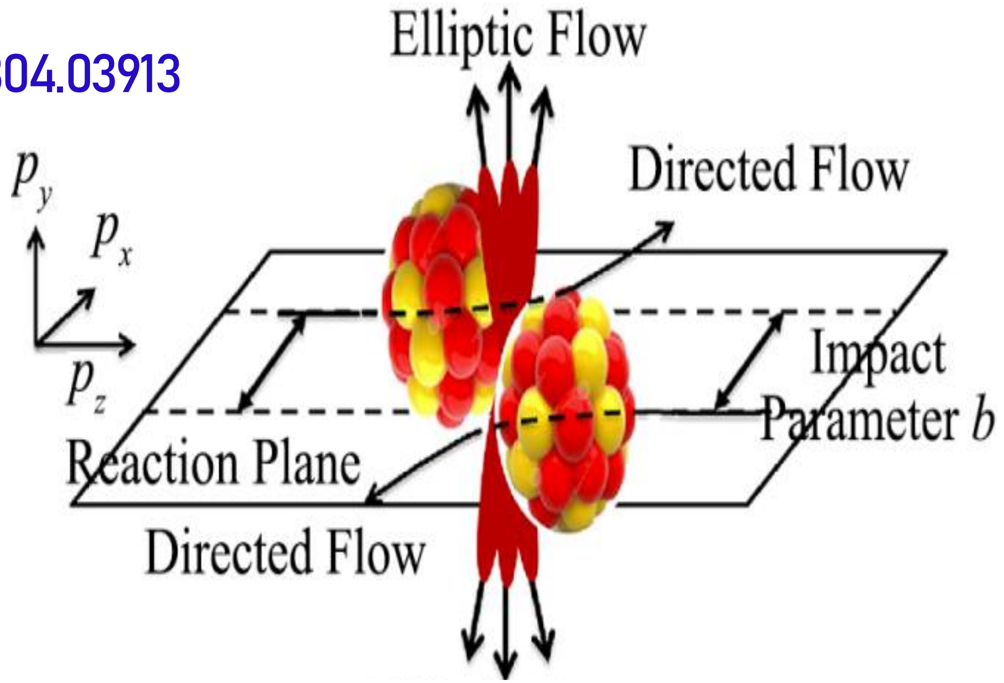


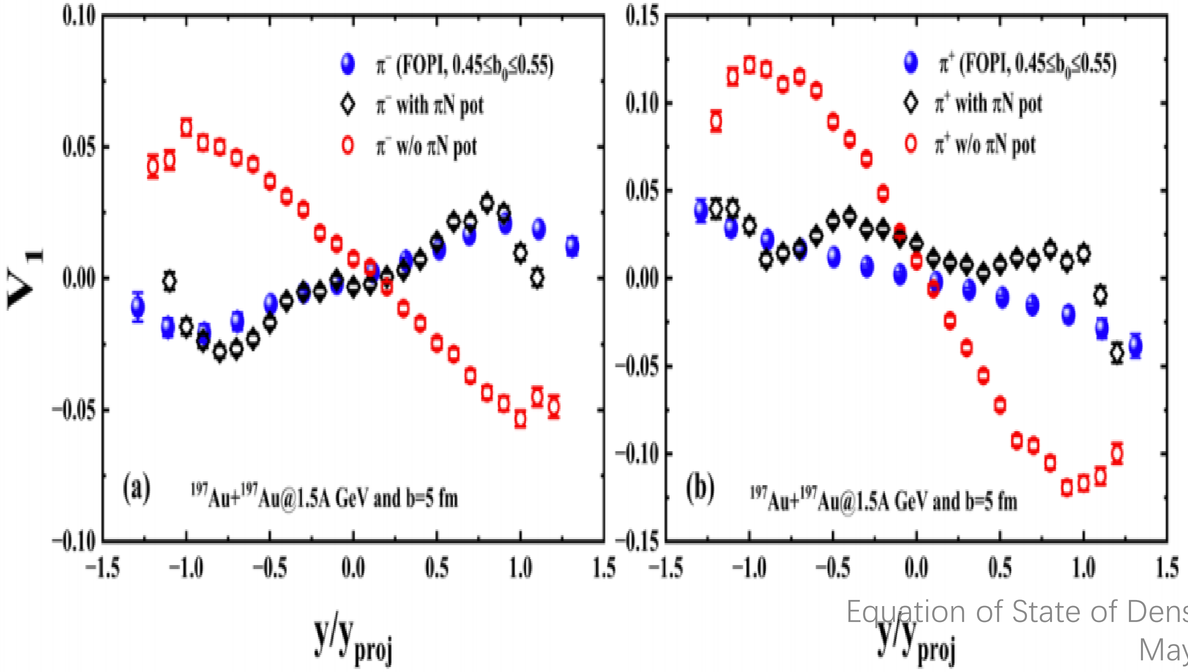
Collective flows of clusters and pions in heavy-ion collisions at GeV energies

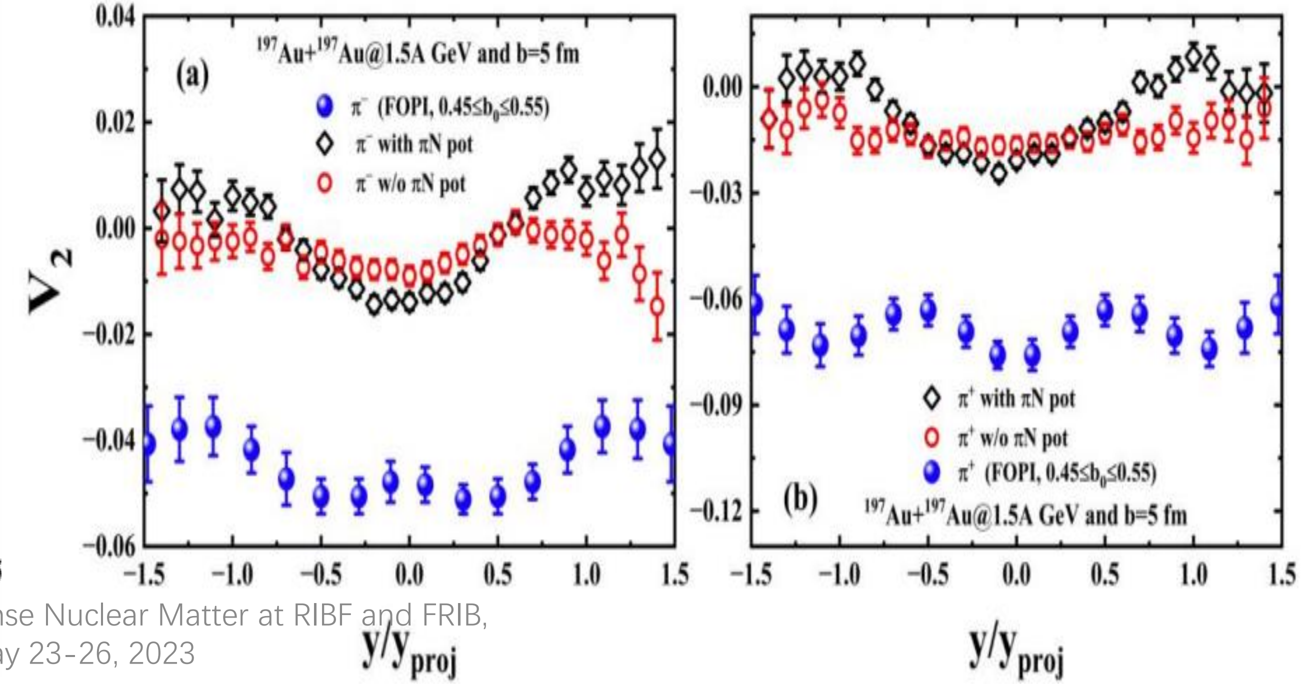
arXiv:2304.03913

Heng-Jin Liu, Hui-Gan Cheng, and Zhao-Qing Feng*
School of Physics and Optoelectronics, South China University of Technology, Guangzhou 510640, China
(Dated: March 25, 2023)









4. Energy conservation for pion production

Shedding light on the pion production in heavy-ion collisions for constraining the high-density symmetry energy

Heng-Jin Liu, Hui-Gan Cheng, and Zhao-Qing Feng*
School of Physics and Optoelectronics, South China University of Technology, Guangzhou 510640, China
(Dated: March 19, 2023)

arXiv:2302.02131, PLB (submitted)

$$\sqrt{m_\Delta^2+\mathbf{p}_\Delta^2}+U_\Delta(\rho_\Delta,\mathbf{p}_\Delta) = \sqrt{m_N^2+(\mathbf{p}_\Delta-\mathbf{p}_\pi)^2} + U_N(\rho_N,\mathbf{p}_N)+\omega_\pi(\rho_\pi,\mathbf{p}_\pi)+V_{\pi N}^{\mathrm{Coul}},$$

$$U_{\Delta^-}=U_n,\ U_{\Delta^{++}}=U_p,$$

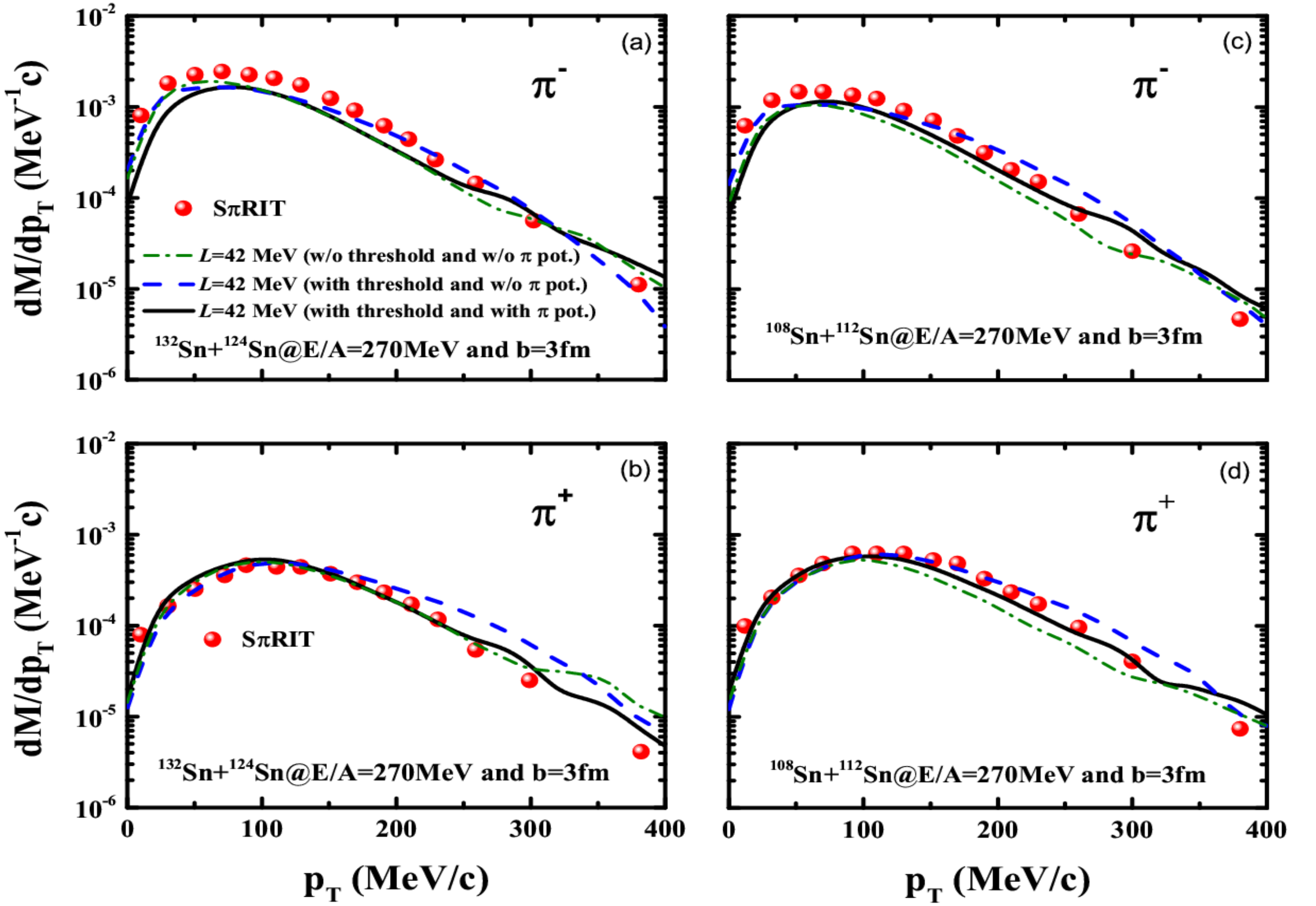
$$U_{\Delta^+}=\frac{1}{3}U_n+\frac{2}{3}U_p,$$

$$U_{\Delta^0}=\frac{1}{3}U_p+\frac{2}{3}U_n.$$

The Coulomb potential only exist for the charged pairs of

$$\Delta^0 \leftrightarrow \pi^- + p \text{ and } \Delta^{++} \leftrightarrow \pi^+ + p.$$

U_n and U_p are the single-particle potentials of neutron and proton, which are density, isospin and momentum dependent in nuclear medium.



5. hadron-hadron scattering channels

PHYSICAL REVIEW C **82**, 057901 (2010)

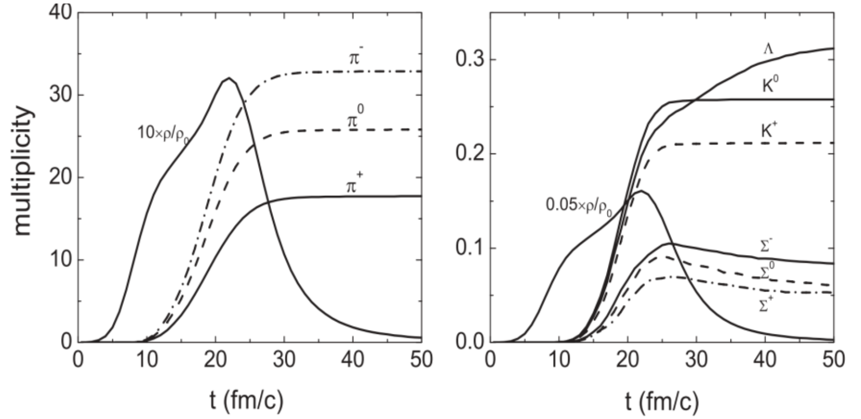
Dynamics of strangeness production in heavy-ion collisions near threshold energies

Zhao-Qing Feng* and Gen-Ming Jin
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China

(Received 20 September 2010; published 29 November 2010)

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

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



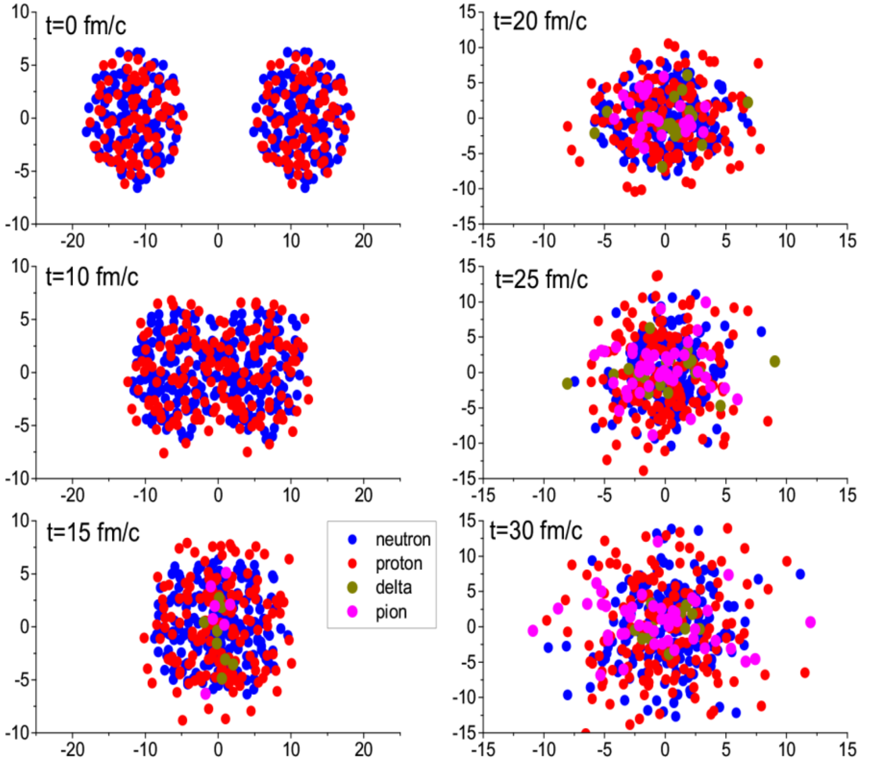
Collisions between resonances, NN*↔NΔ, NN*↔NN*

Strangeness channels:

$$BB \rightarrow BYK, BB \rightarrow BBK\overline{K}, B\pi(\eta) \rightarrow YK, YK \rightarrow B\pi,$$
$$B\pi \rightarrow NK\overline{K}, Y\pi \rightarrow B\overline{K}, \quad B\overline{K} \rightarrow Y\pi, \quad YN \rightarrow \overline{K}NN,$$
$$BB \rightarrow B\Xi KK, \overline{K}B \leftrightarrow K\Xi, YY \leftrightarrow N\Xi, \overline{K}Y \leftrightarrow \pi\Xi.$$

Reaction channels with antiproton:

$$\overline{p}N \rightarrow \overline{N}N, \quad \overline{N}N \rightarrow \overline{N}N, \overline{N}N \rightarrow \overline{B}B, \overline{N}N \rightarrow \overline{Y}Y$$
$$\overline{N}N \rightarrow \mathtt{annihilation}(\pi, \eta, \rho, \omega, K, \overline{K}, K^*, \overline{K}^*, \phi)$$



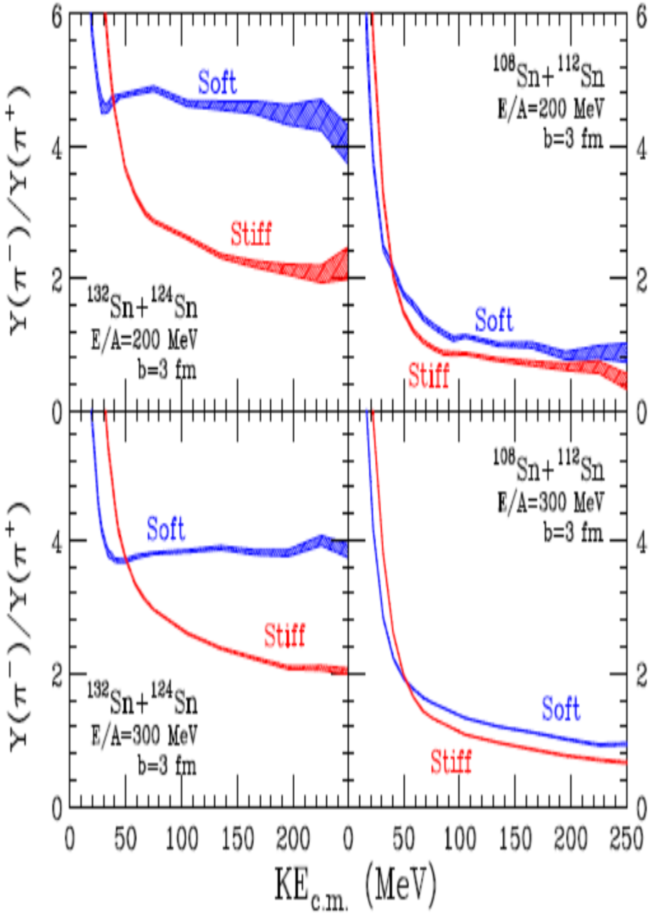
Statistical model with SU(3) symmetry for annihilation
(E.S. Golubeva et al., Nucl. Phys. A 537, 393 (1992))

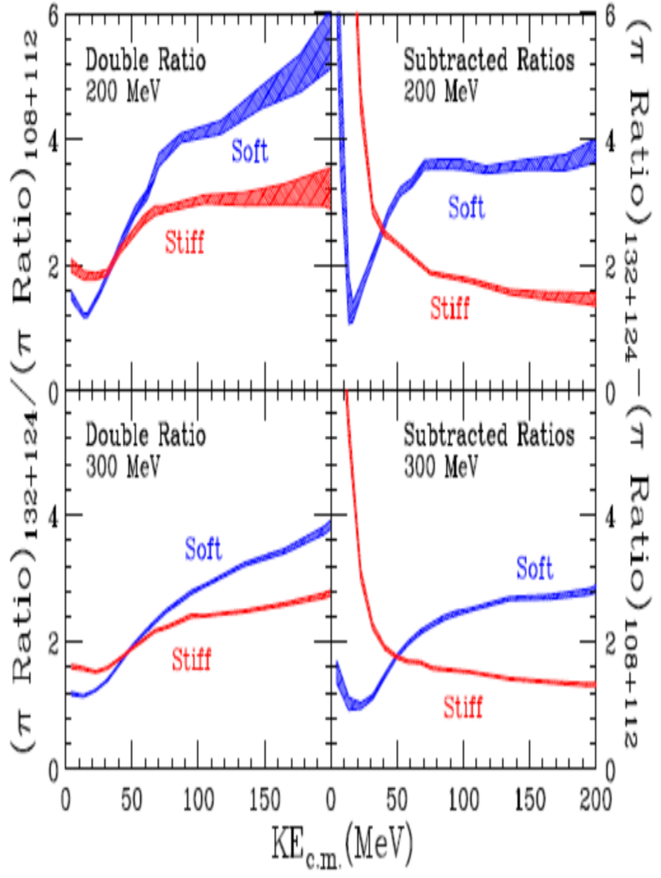
III. π^-/π^+ ratio for constraining the high-density symmetry energy

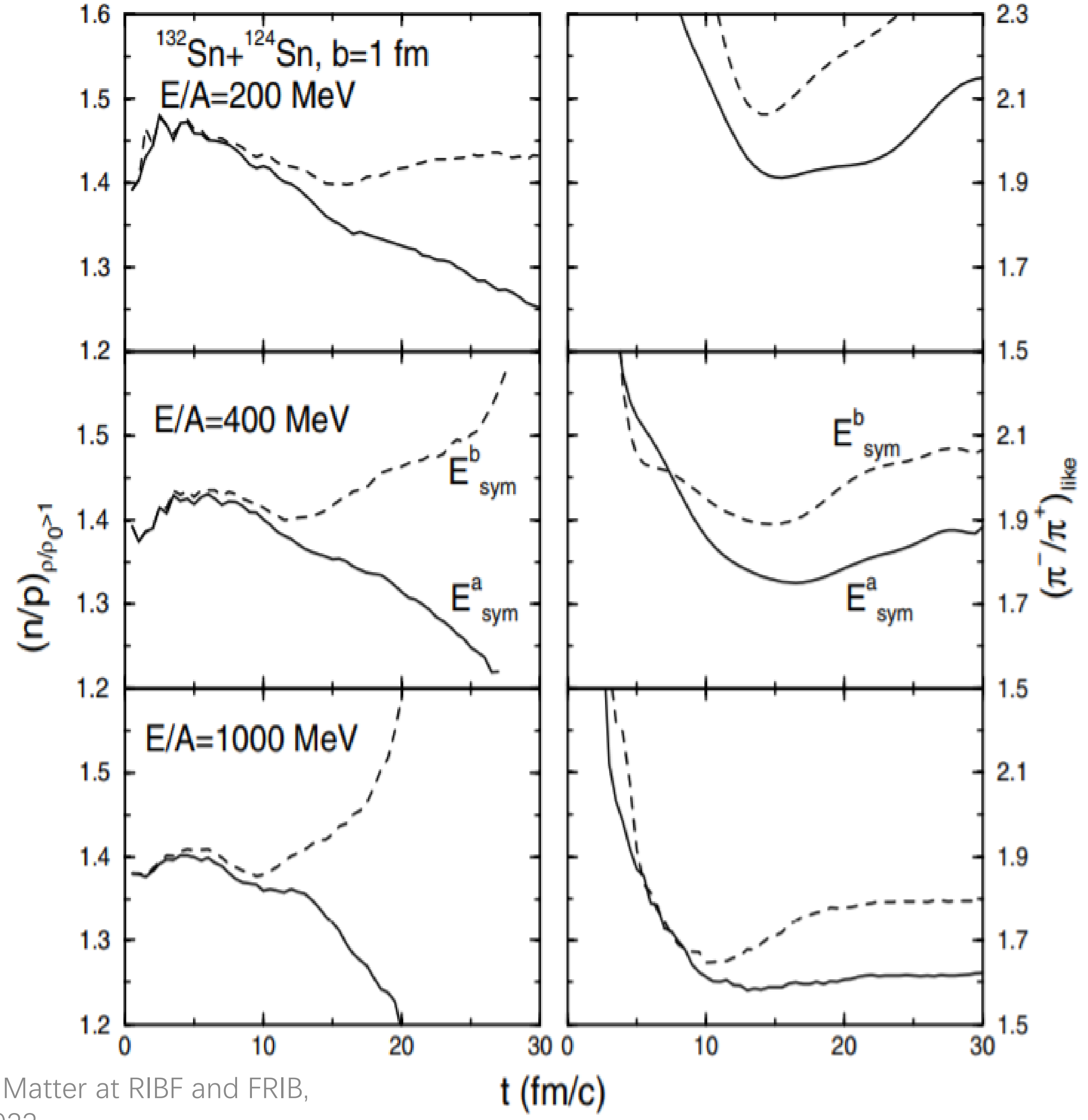
Kinetic energy spectra of π^-/π^+ ratio

Bao-An Li, Phys. Rev. Lett. 88, 192701 (2002)

M. B. Tsang et al., Phys. Rev. C 95, 044614 (2017)

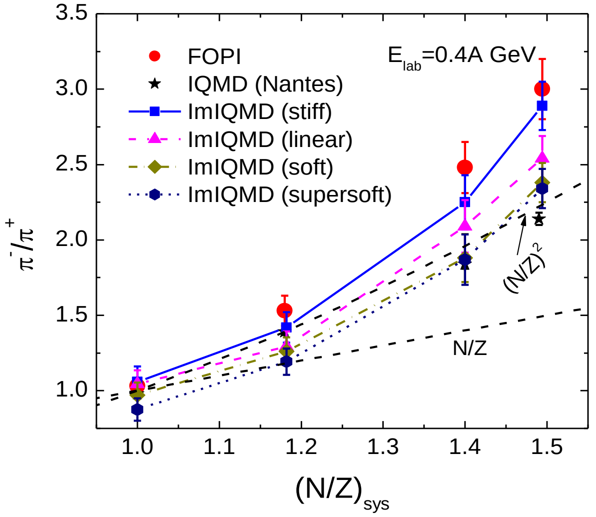


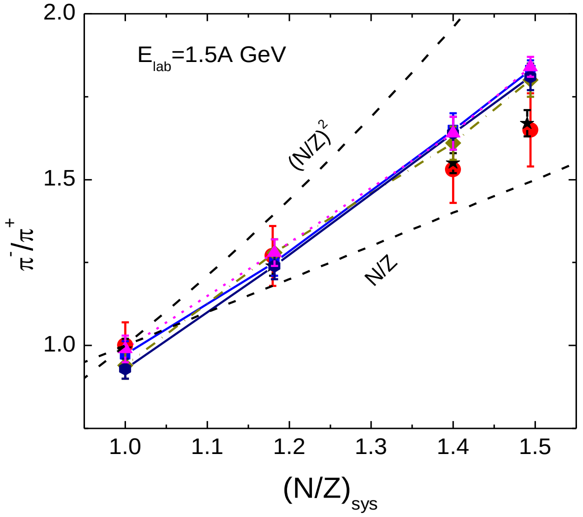




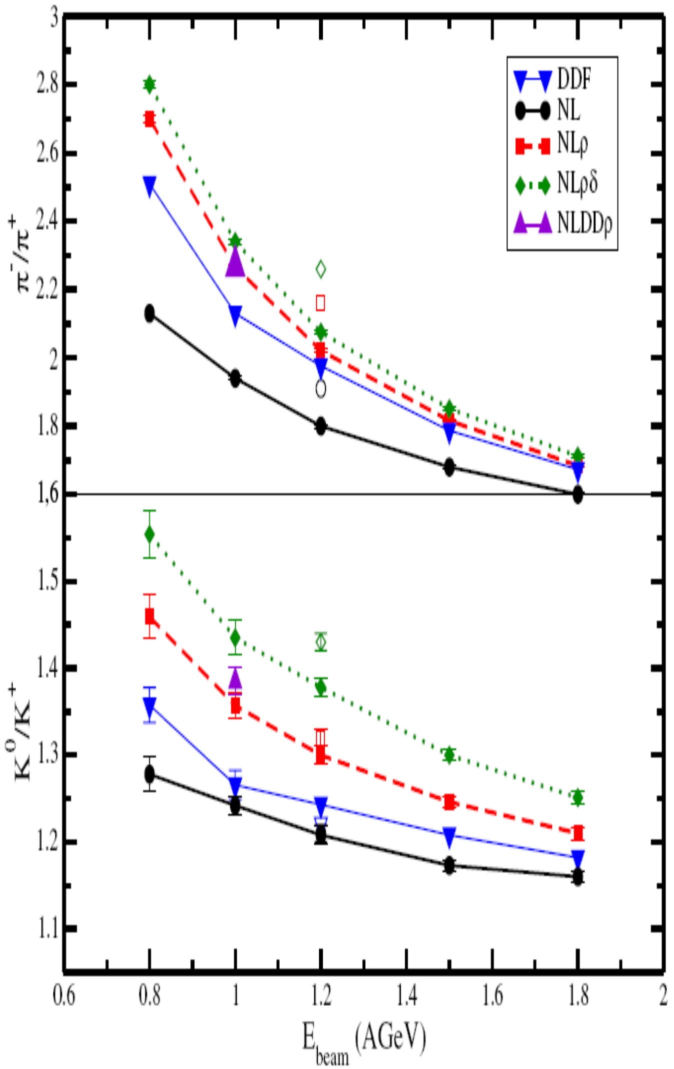
Pion production near threshold energies in heavy-ion collisions

LQMD: Phys. Lett. B 683 (2010) 140

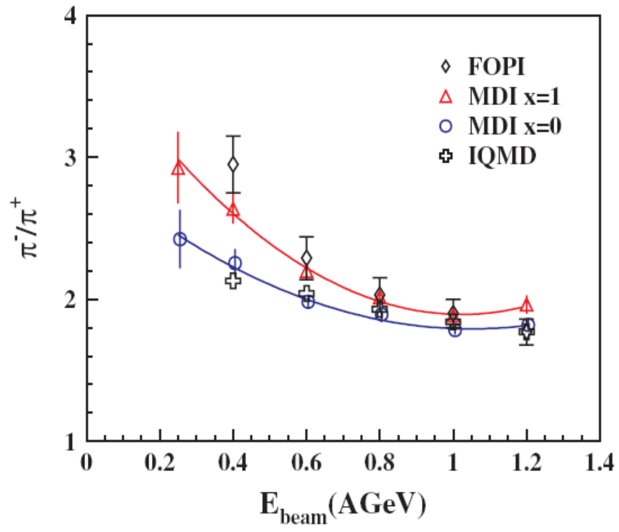


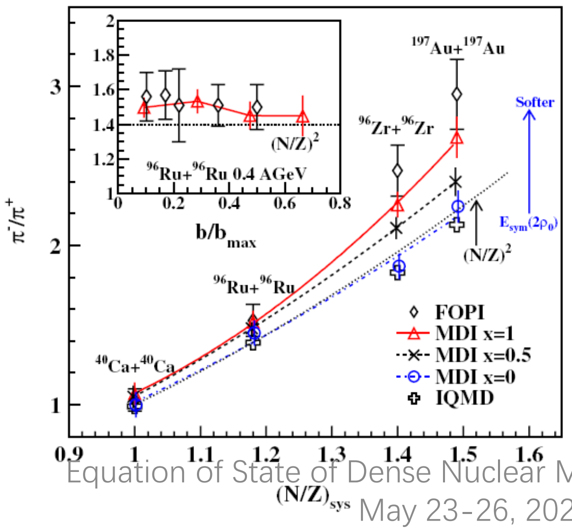


RBUU: PRL97 (2006) 202301



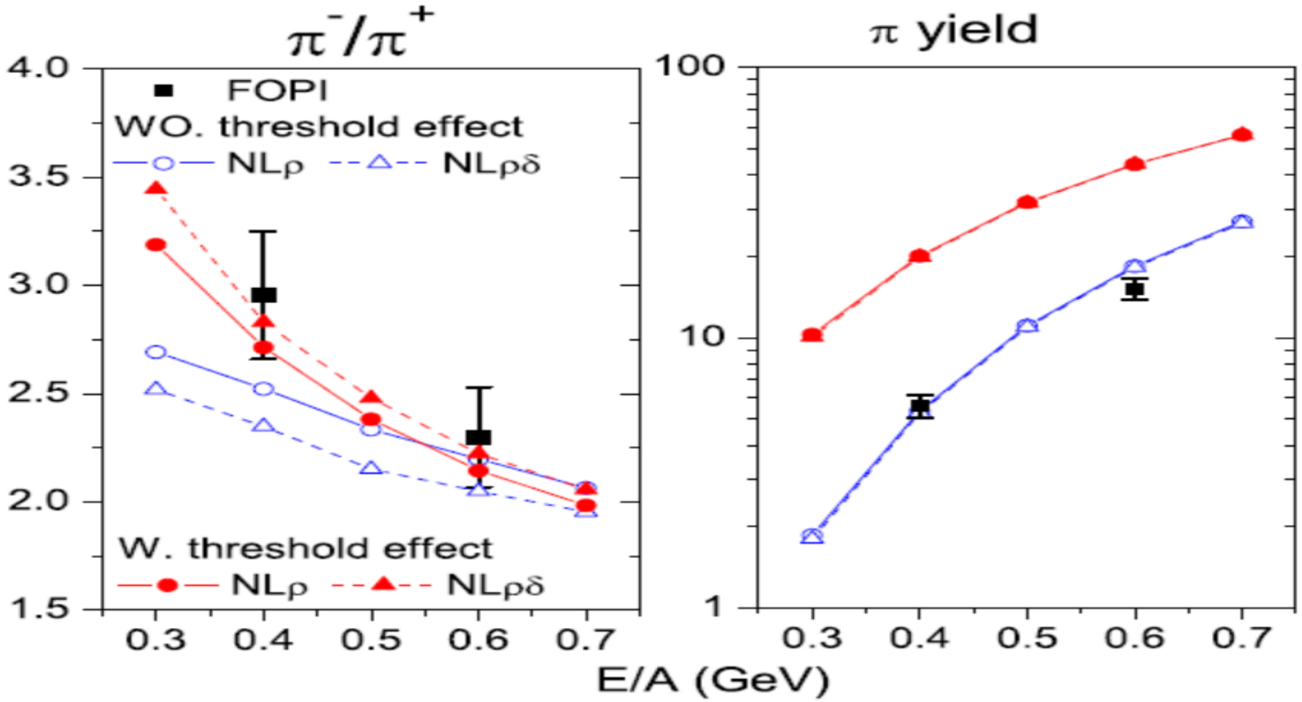
IBUU04: PRL102(2009)062502

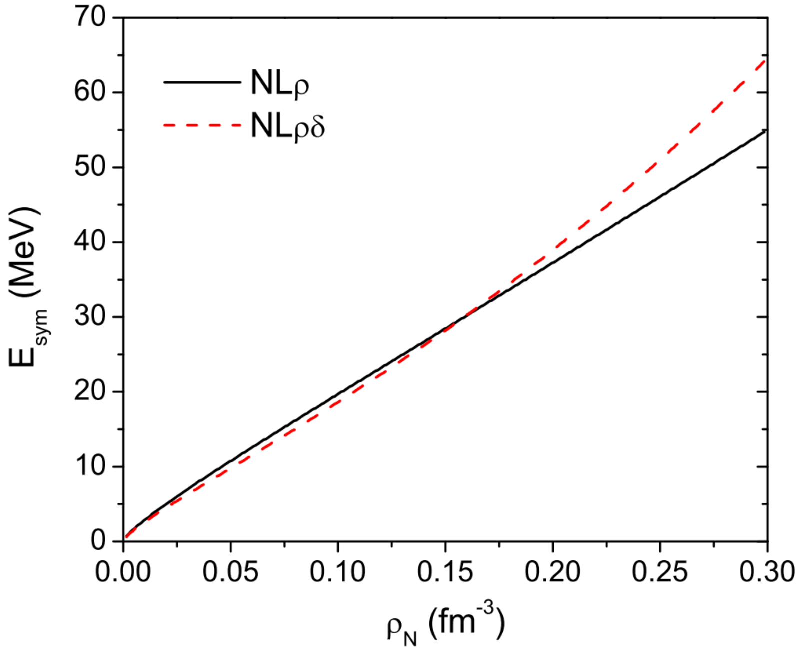


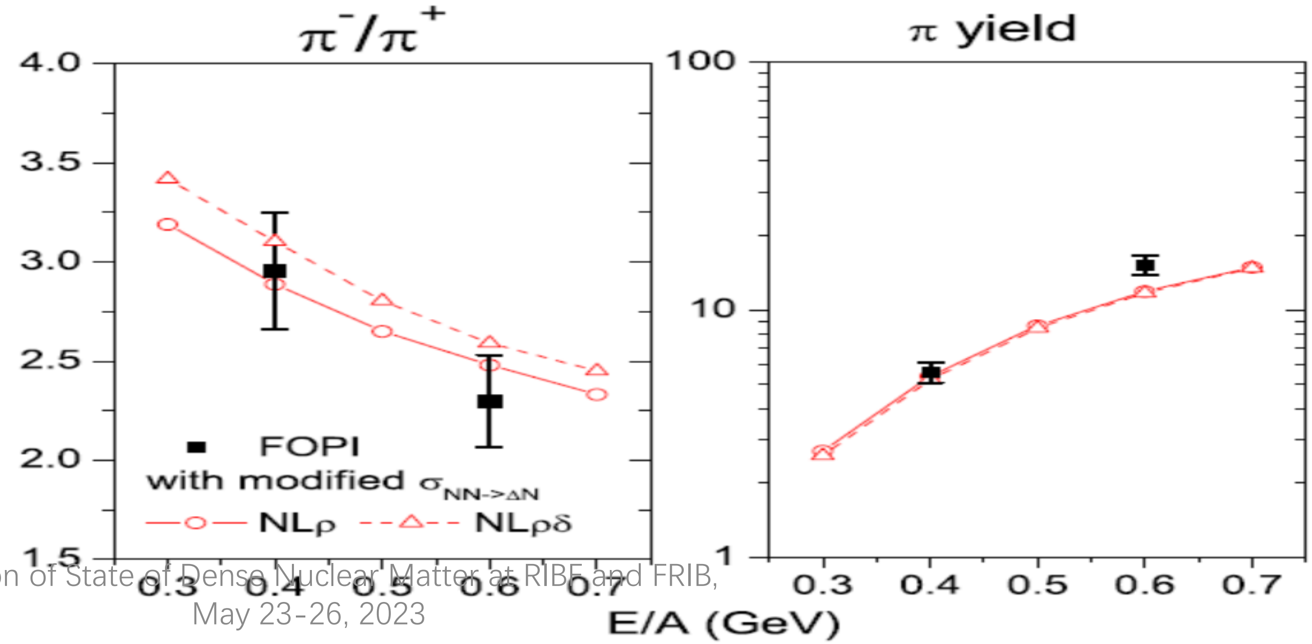


Threshold effects of Δ production by the relativistic Vlasov-Uehling-Uhlenbeck (RVUU)

Taesoo Song, Che Ming Ko,
Phys. Rev. C 91, 014901 (2015)

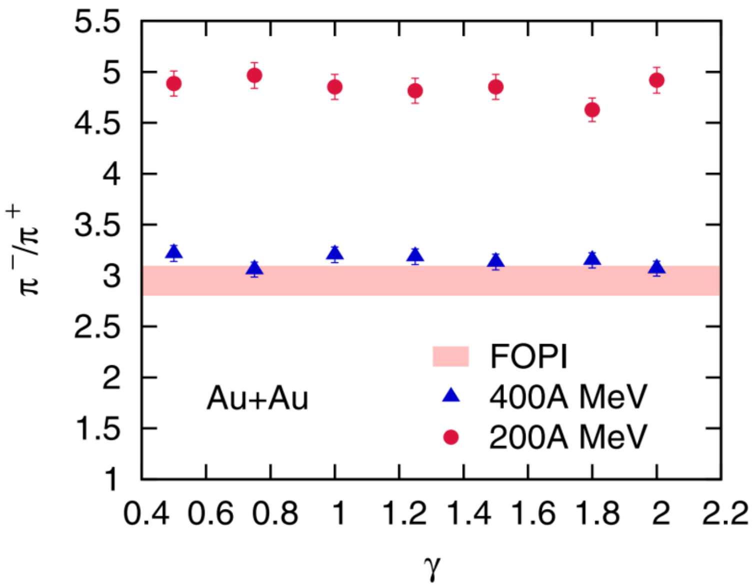


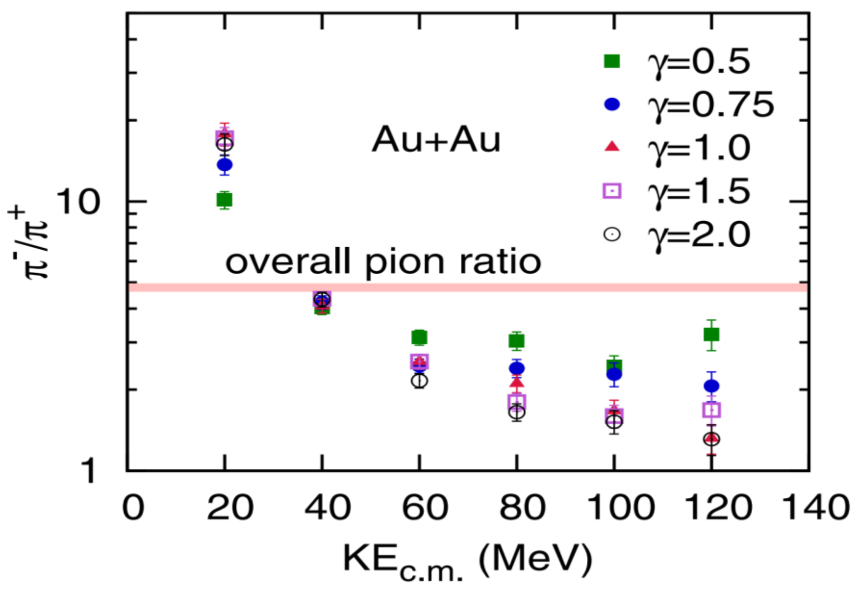


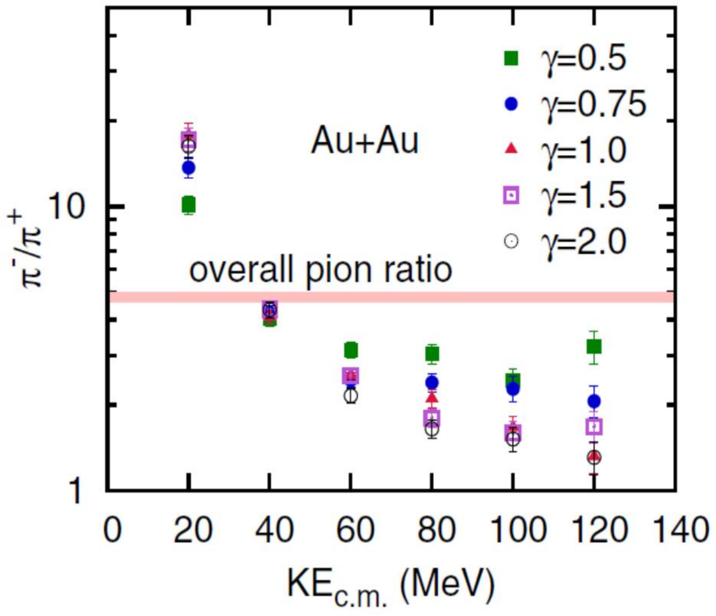


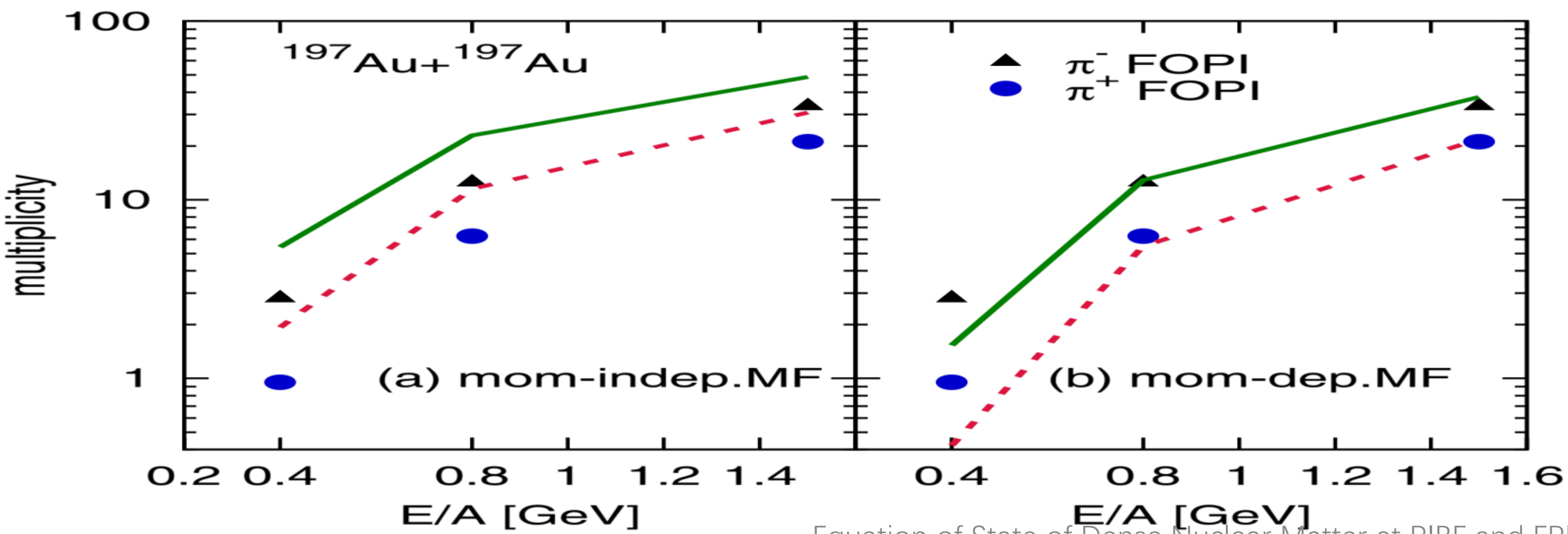
Jun Hong and P. Danielewicz,
Phys. Rev. C 90, 024605 (2014)

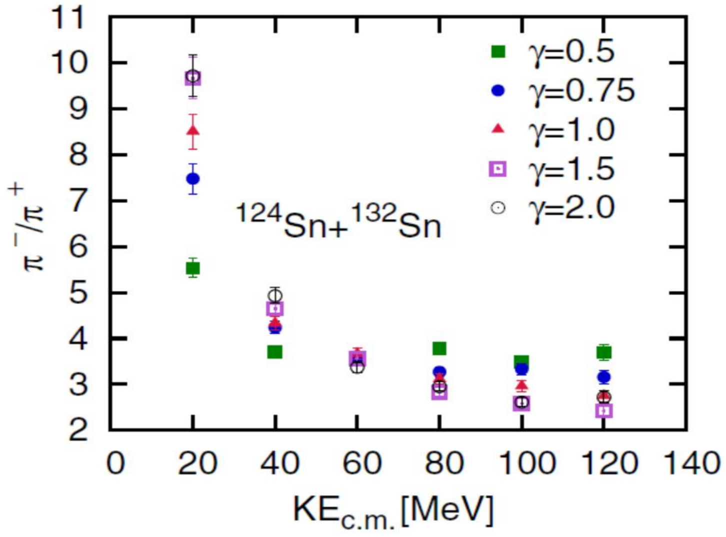
pBUU with γ being the stiffness parameter of SE





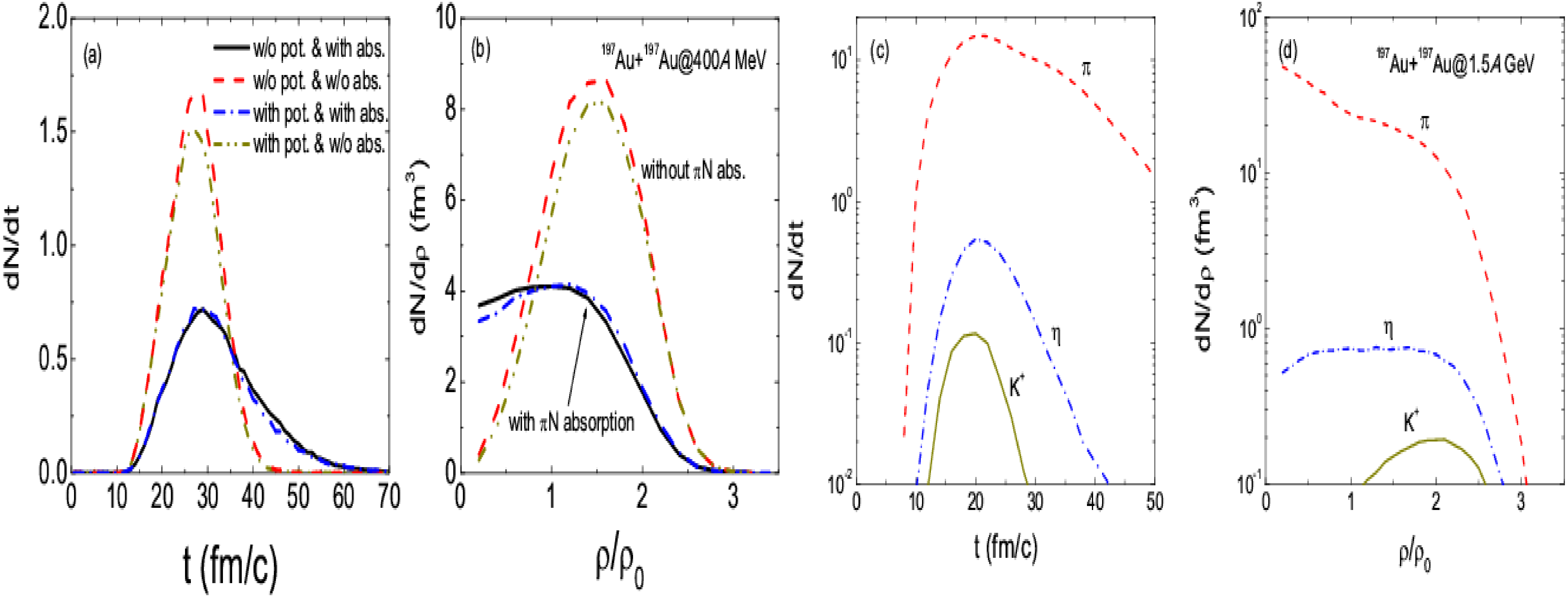




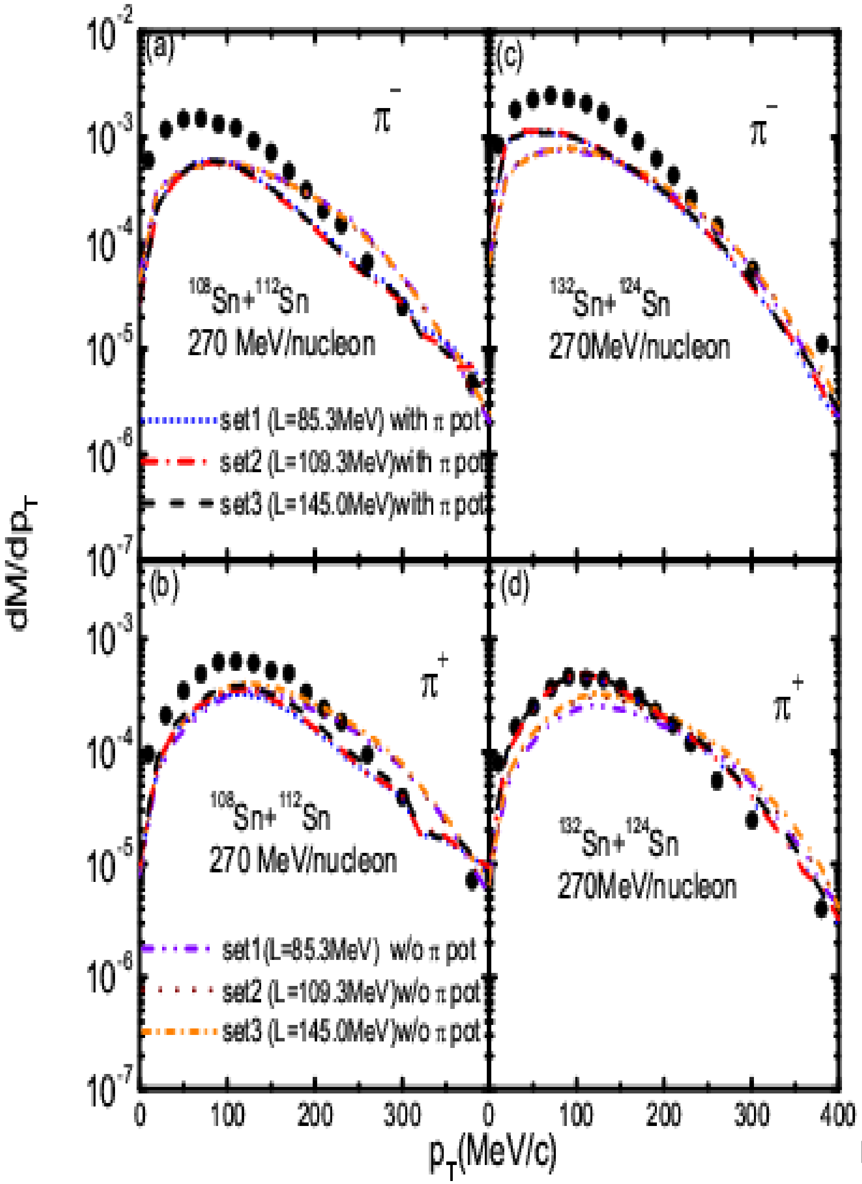


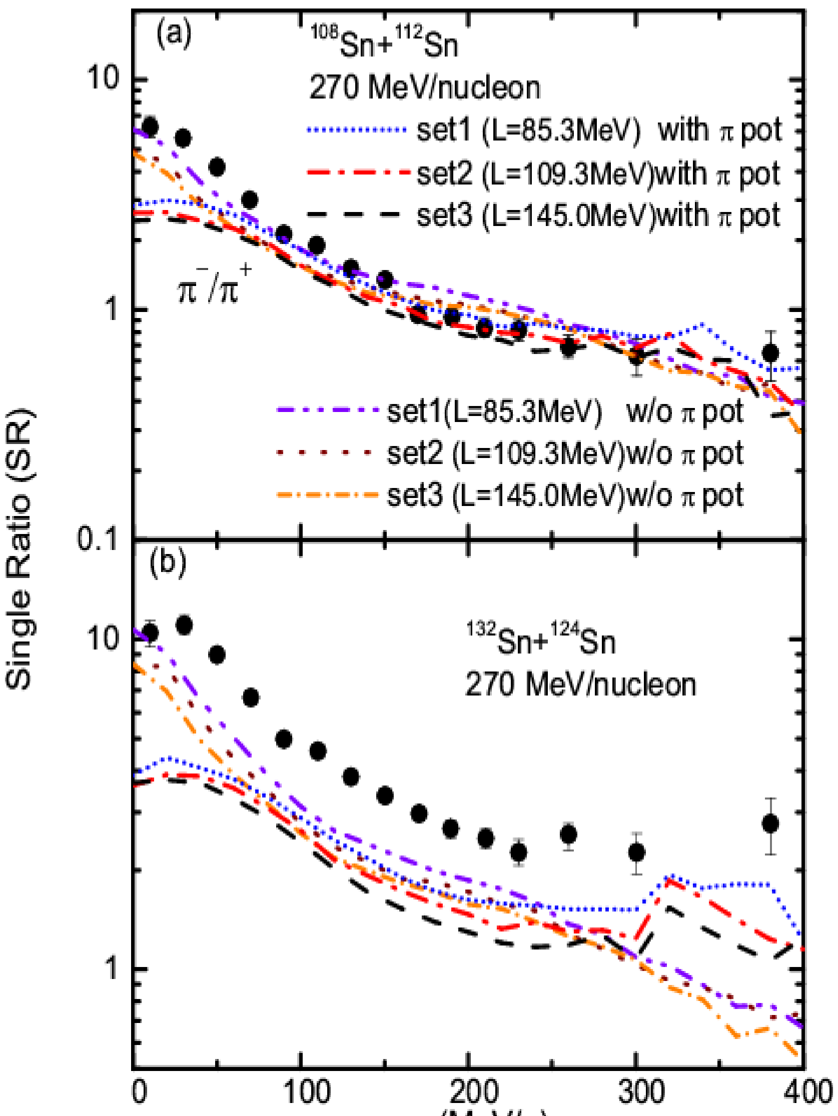
Temporal evolution of production rate and density profiles of particles in collisions of ^{197}Au+^{197}Au

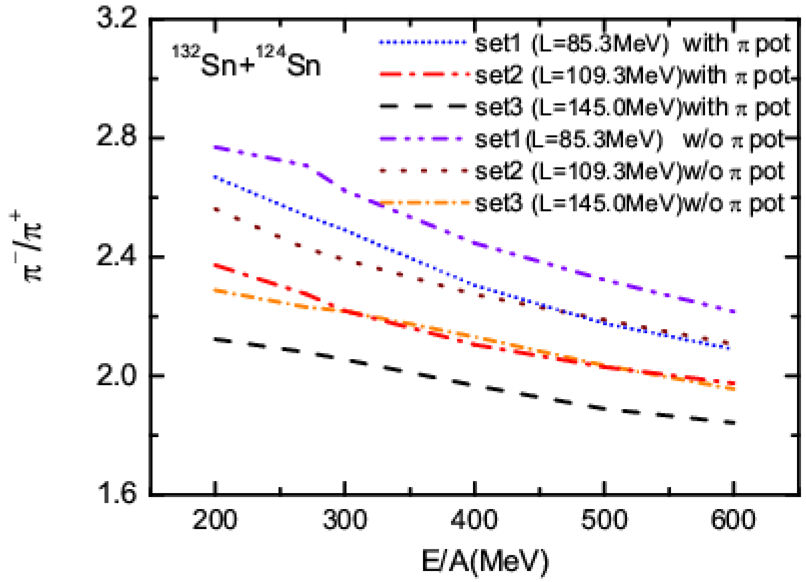
Zhao-Qing Feng, Nuclear Science and Techniques 29 (2018) 40. (Invited review) (arXiv:1802.10294)

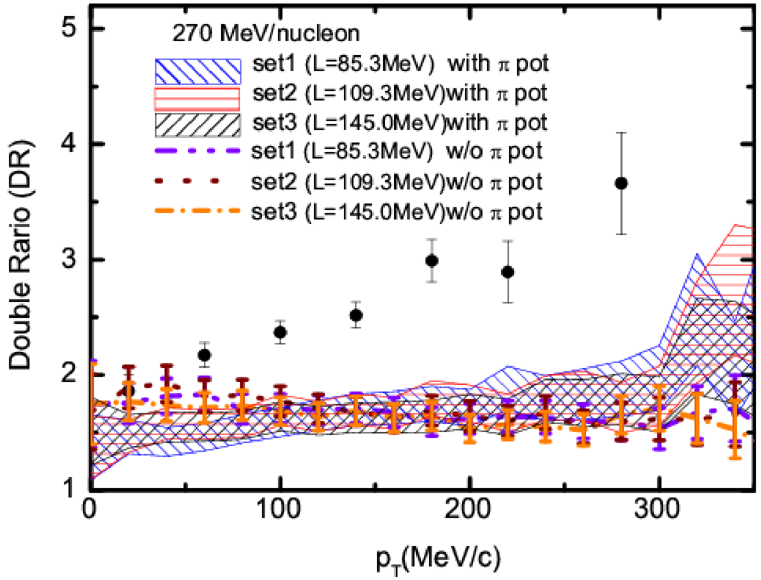


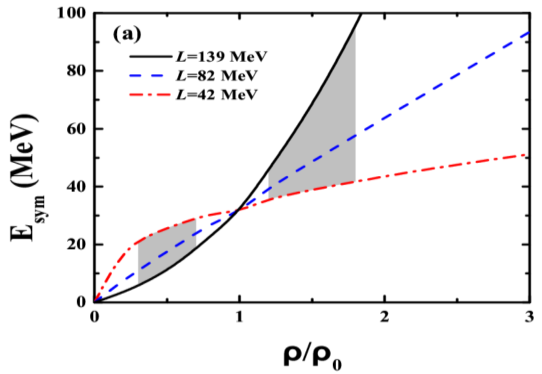
Pion production in isotopic nuclear reactions by LQMD-RMF (Si-Na Wei, Zhao-Qing Feng, arXiv:2302.09984, PRC, no threshold correction!) The data are taken from J. Estee et al. (SπRIT Collaboration), Phys. Rev. Lett. 126, 162701 (2021).







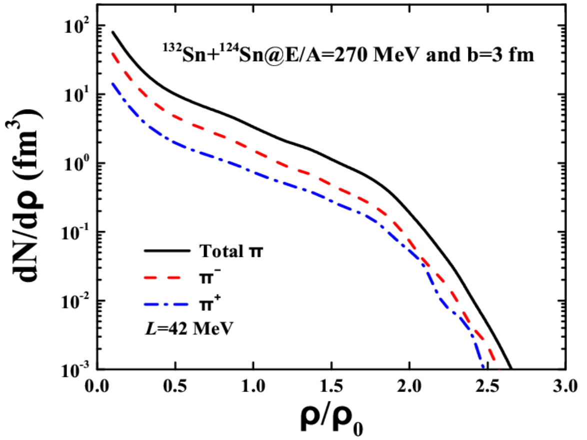


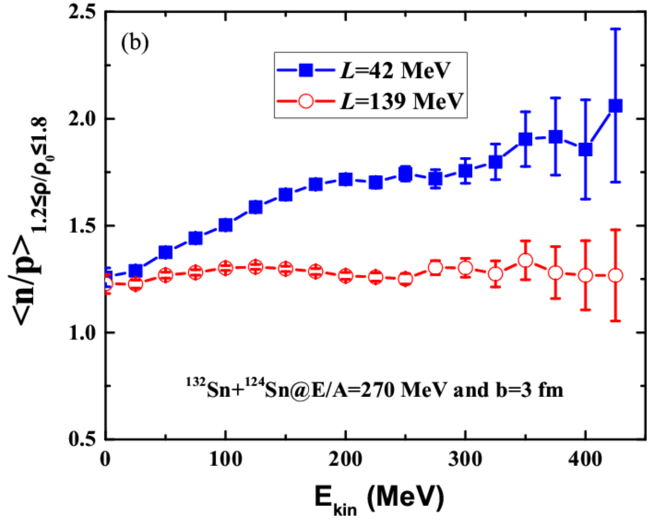


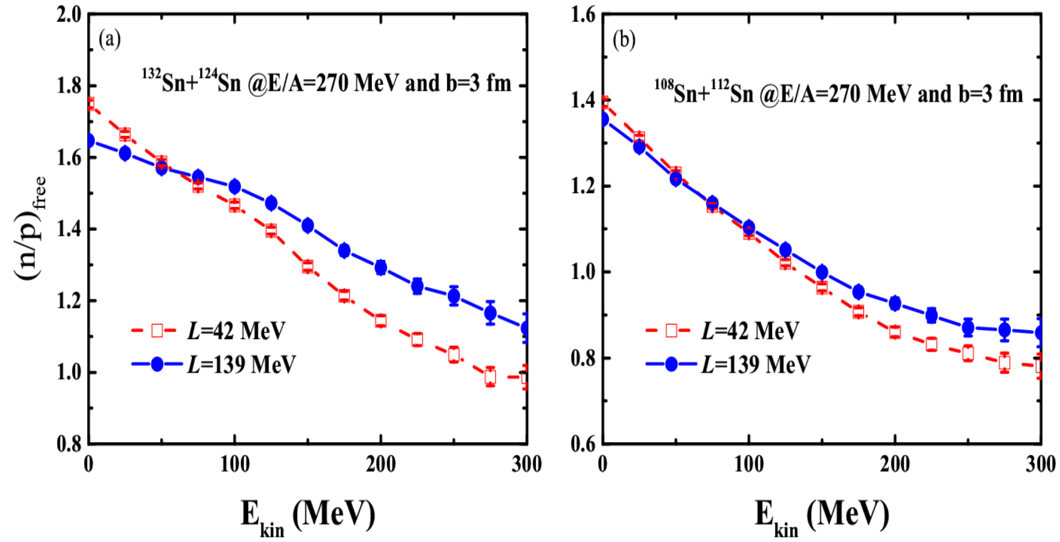
Shedding light on the pion production in heavy-ion collisions for constraining the high-density symmetry energy

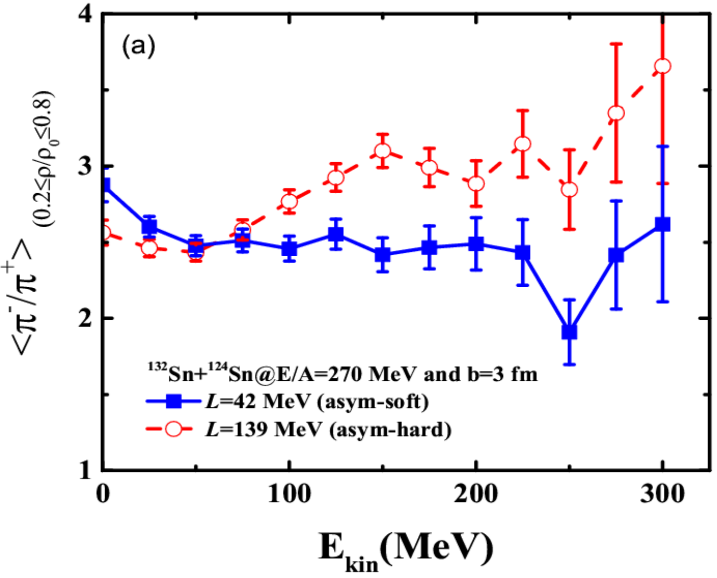
arXiv:2302.02131, PLB (submitted)

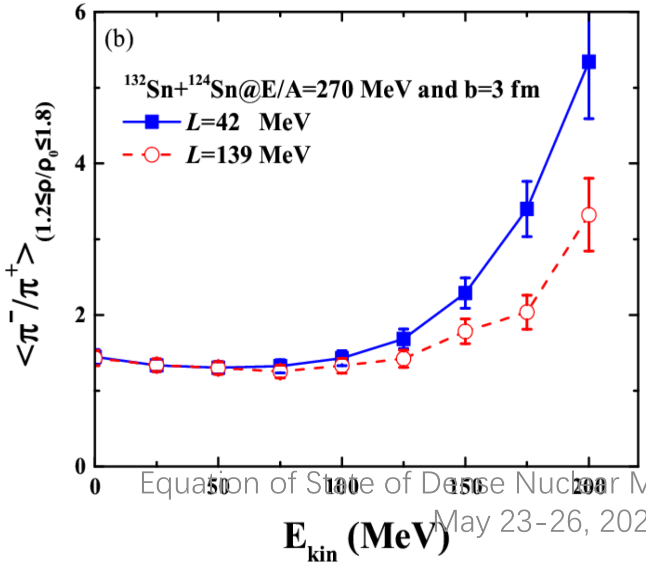
Heng-Jin Liu, Hui-Gan Cheng, and Zhao-Qing Feng*
School of Physics and Optoelectronics, South China University of Technology, Guangzhou 510640, China
(Dated: March 19, 2023)

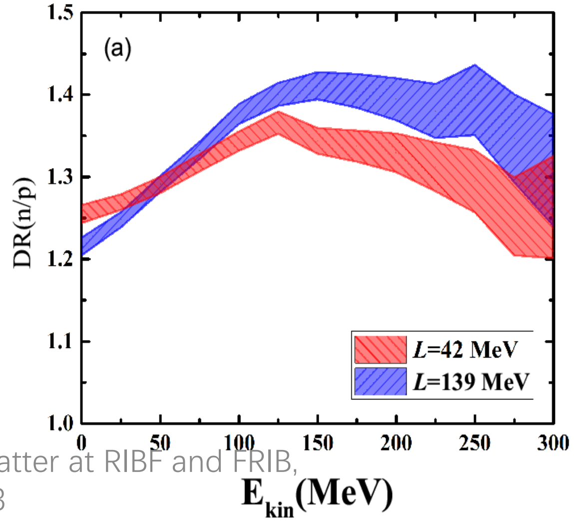


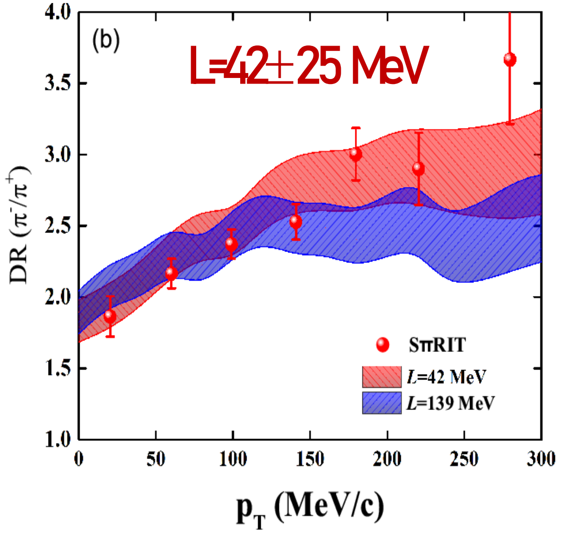








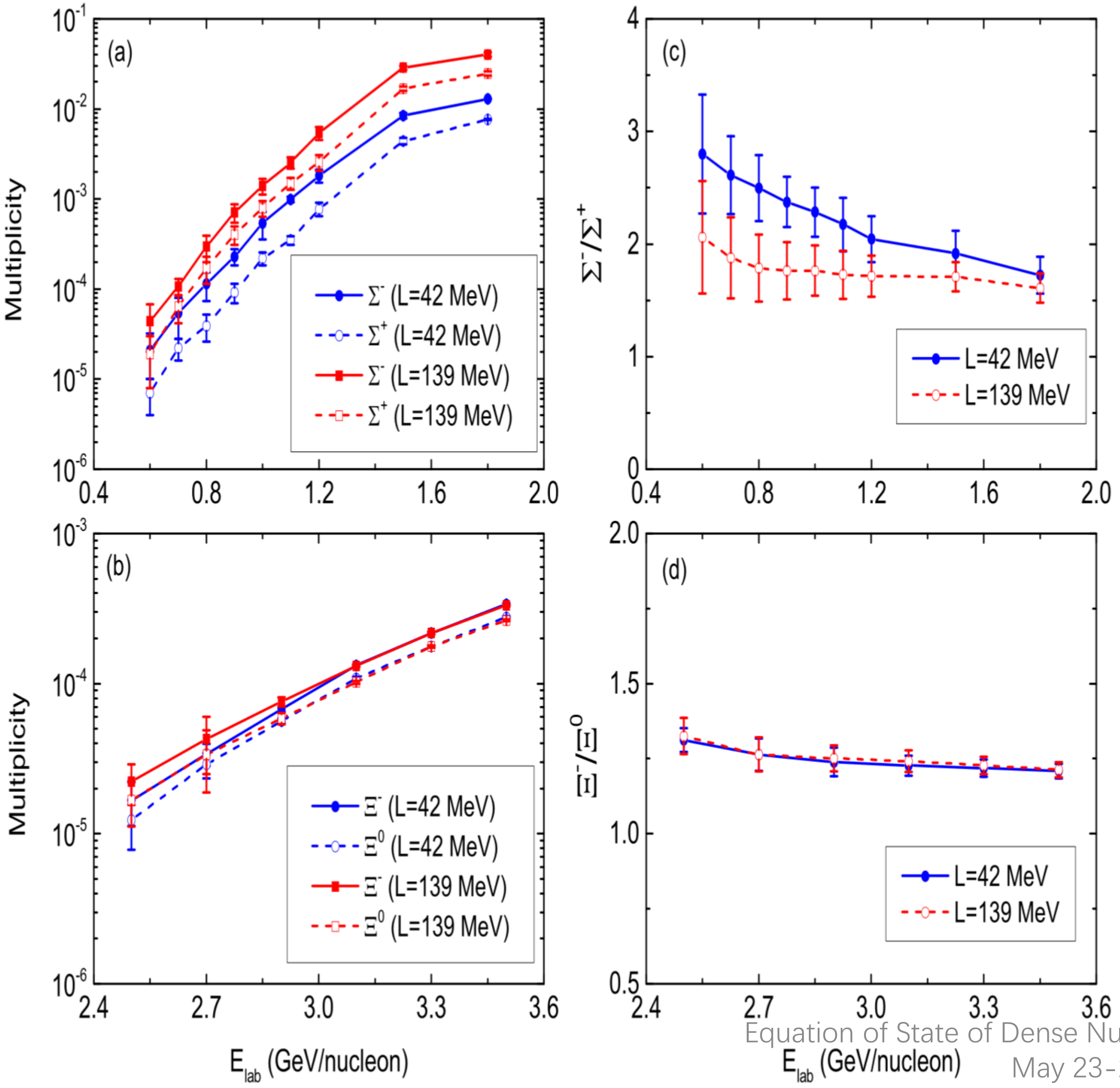


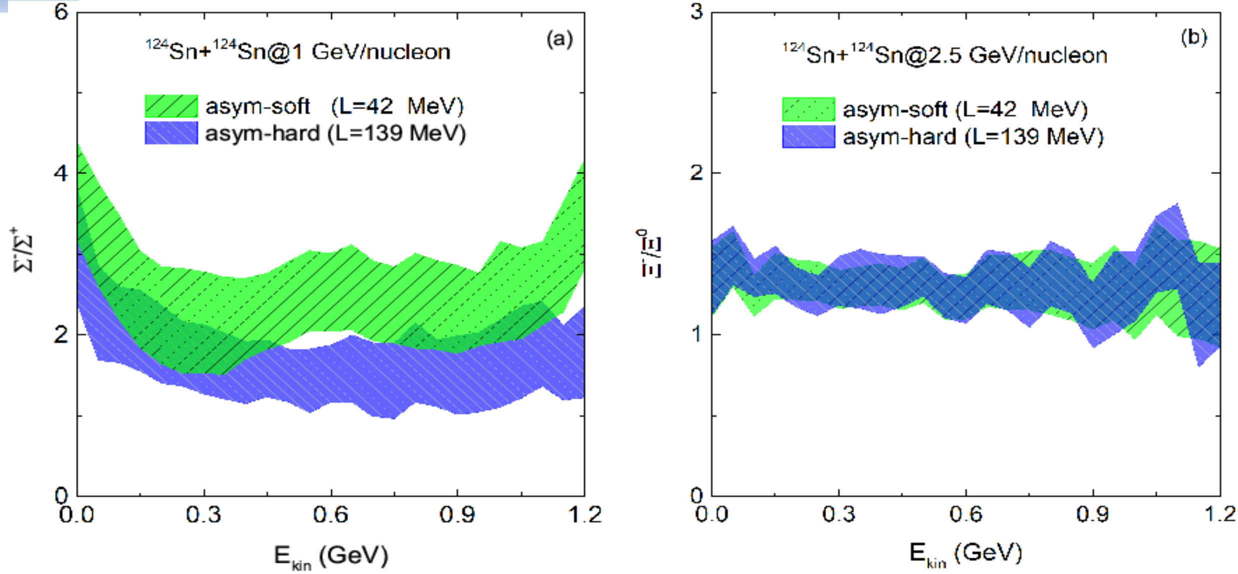


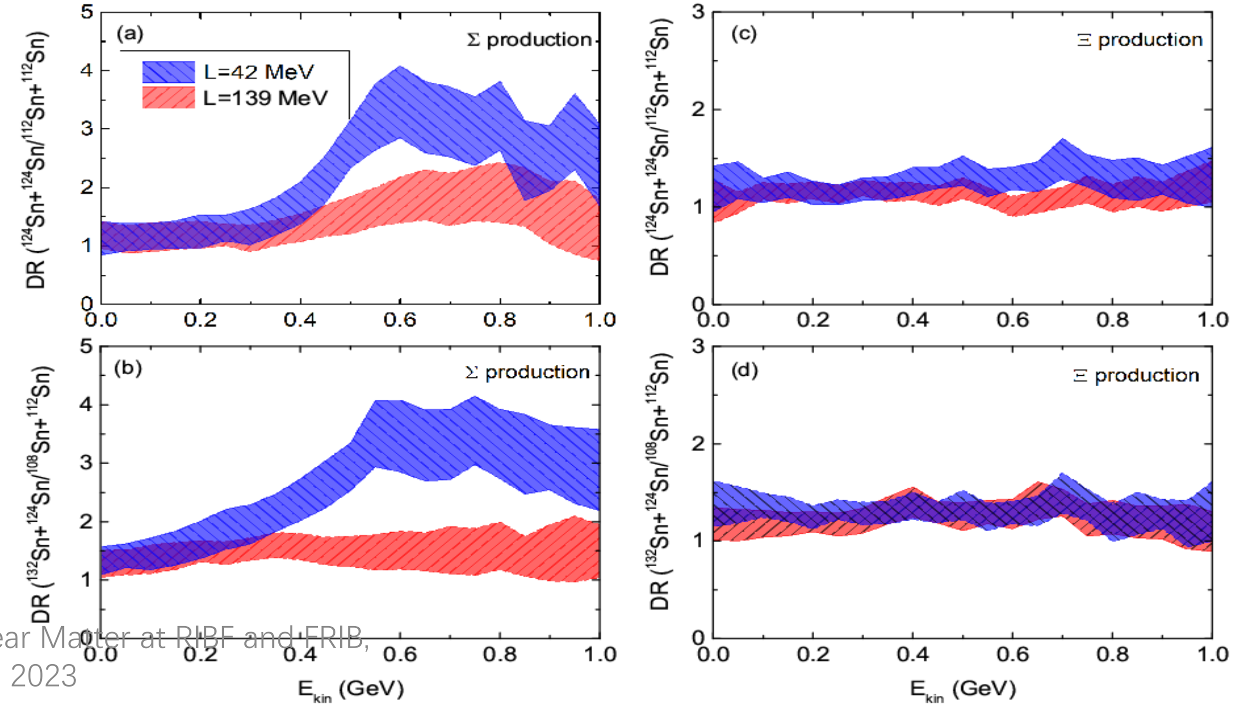
Σ-/Σ+ and Ξ-/Ξ- for constraining the high-density SE

Zhao-Qing Feng, arXiv: 2303.04415, Phys. Lett. B (submitted)

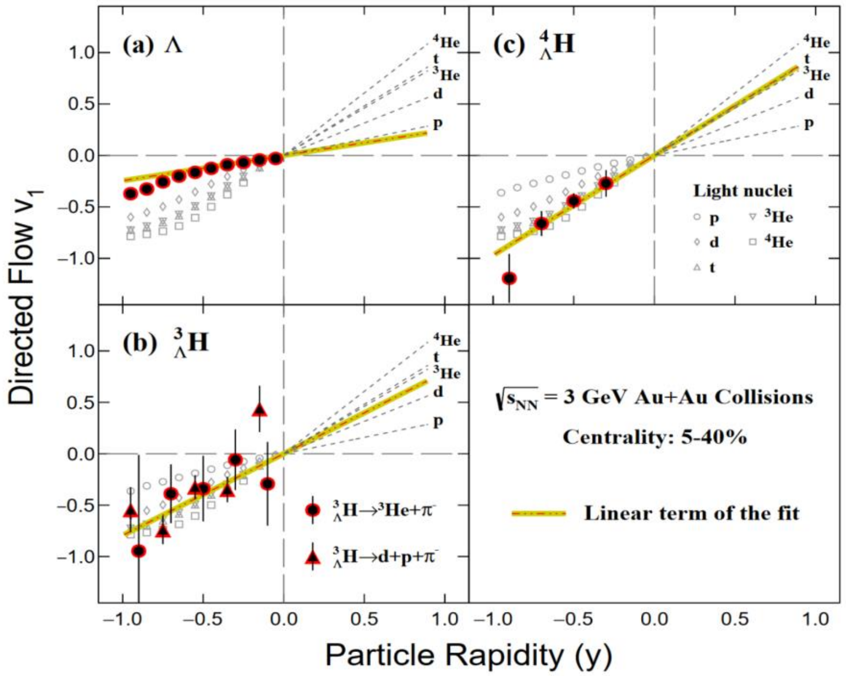
124Sn+124Sn

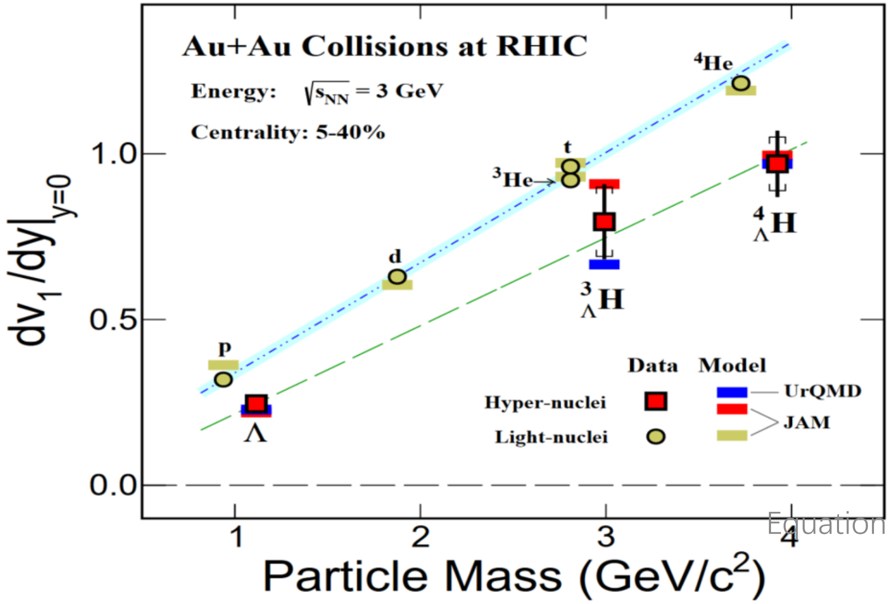




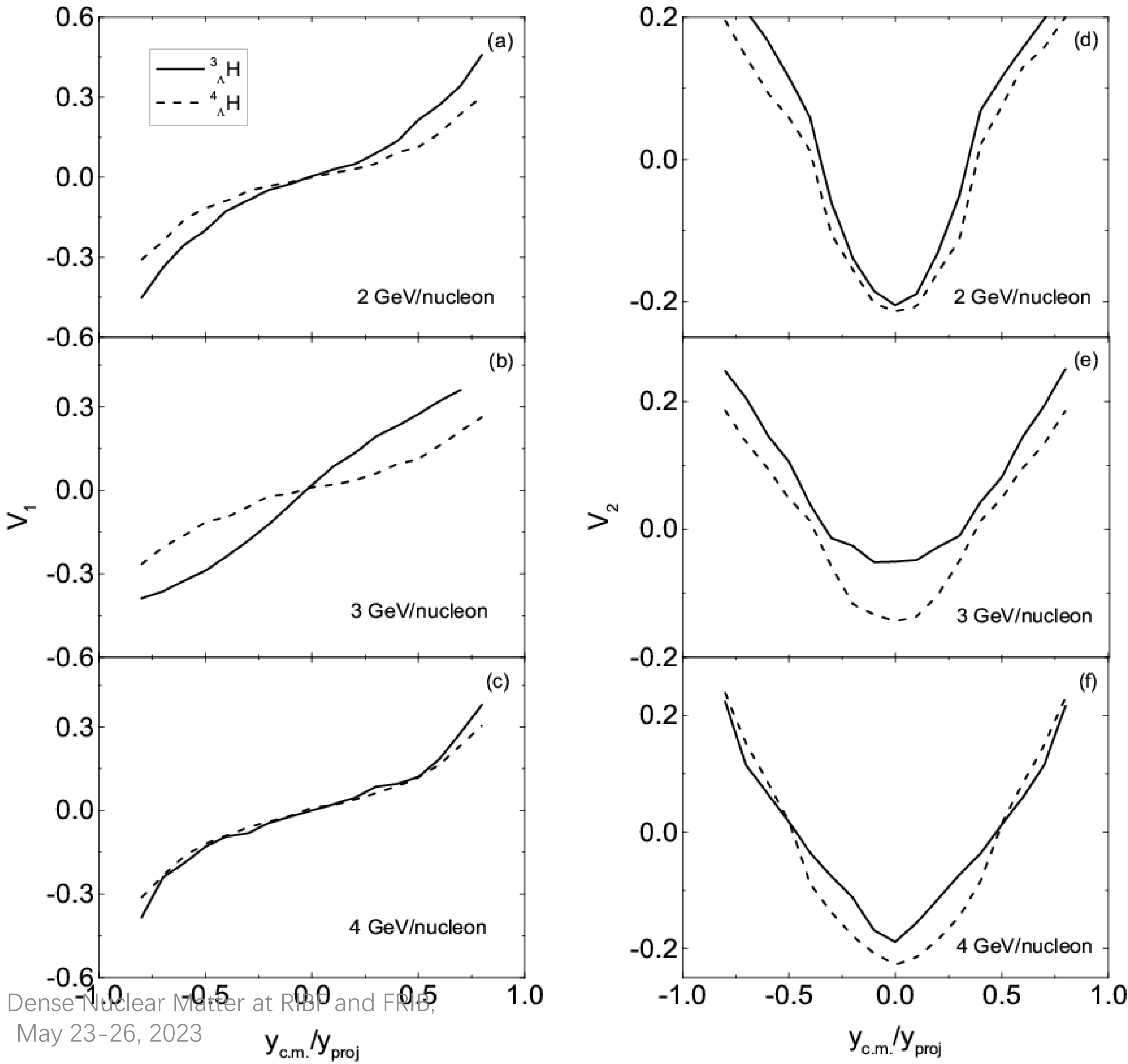


The STAR Collaboration, arXiv:2211.16981 (PRL, accepted)





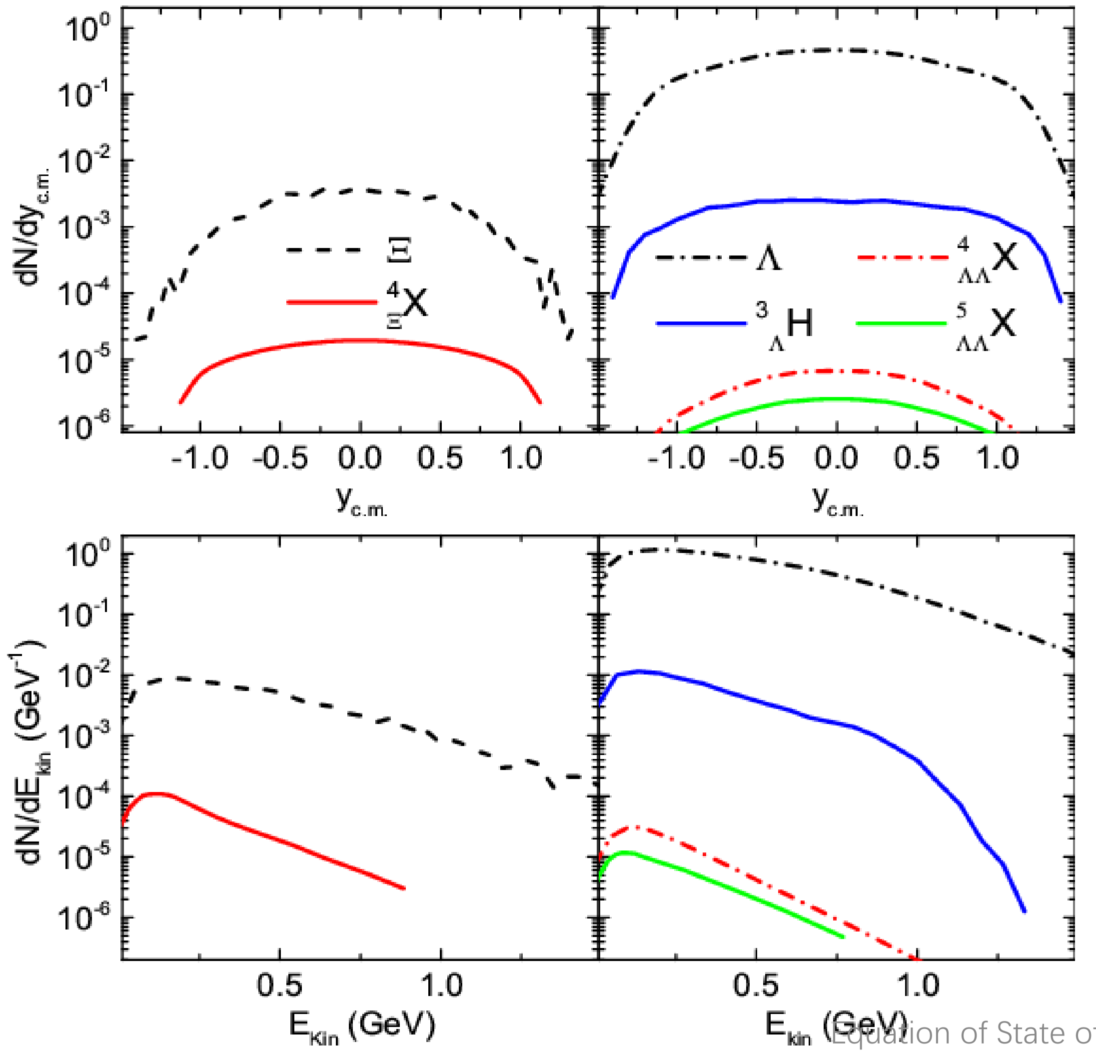
Zhao-Qing Feng, Eur. Phys. J. A, 57 (2021) 18



Multi-strangeness hypernuclide production

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

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



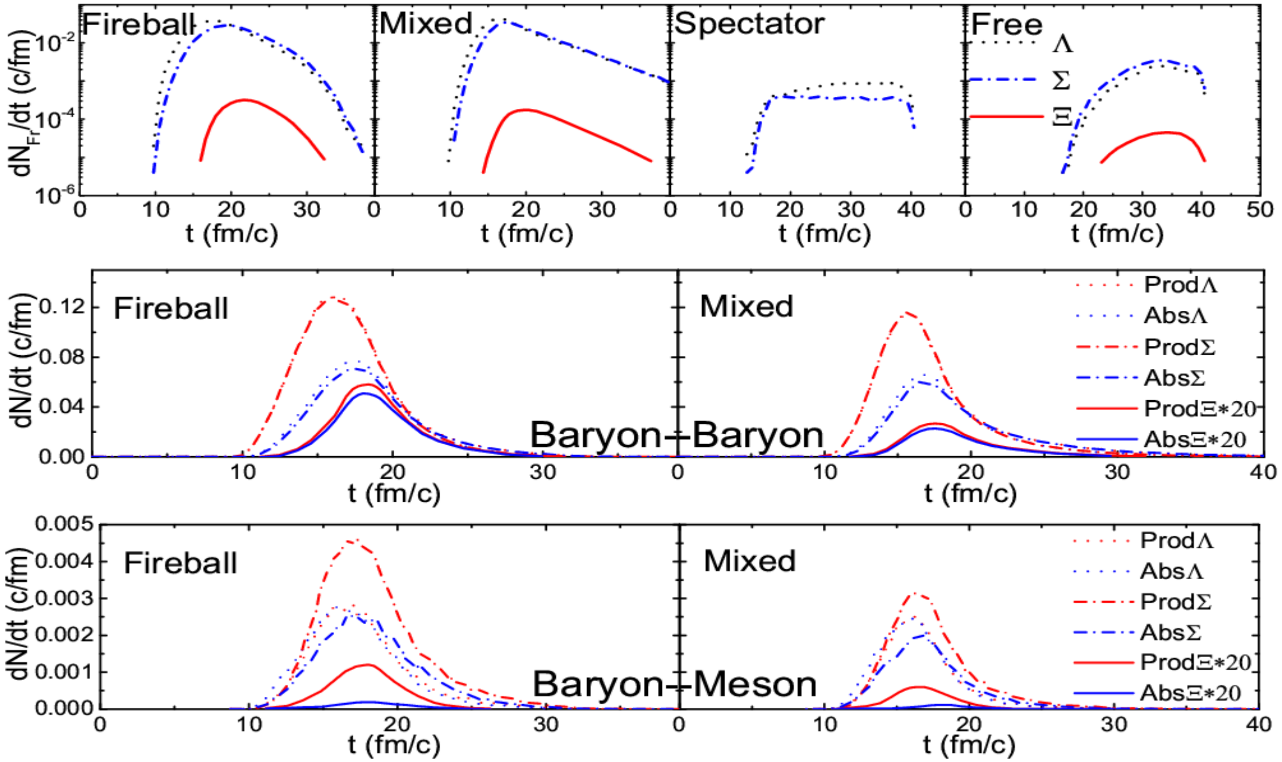
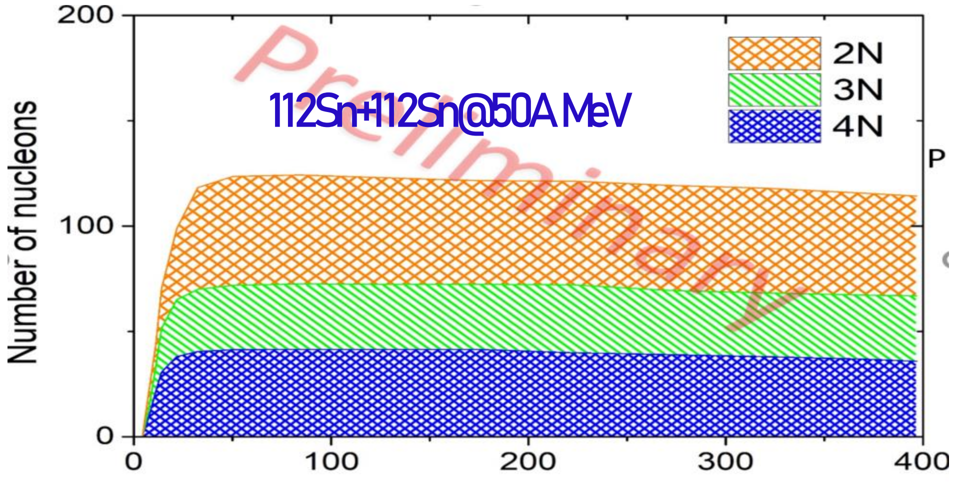


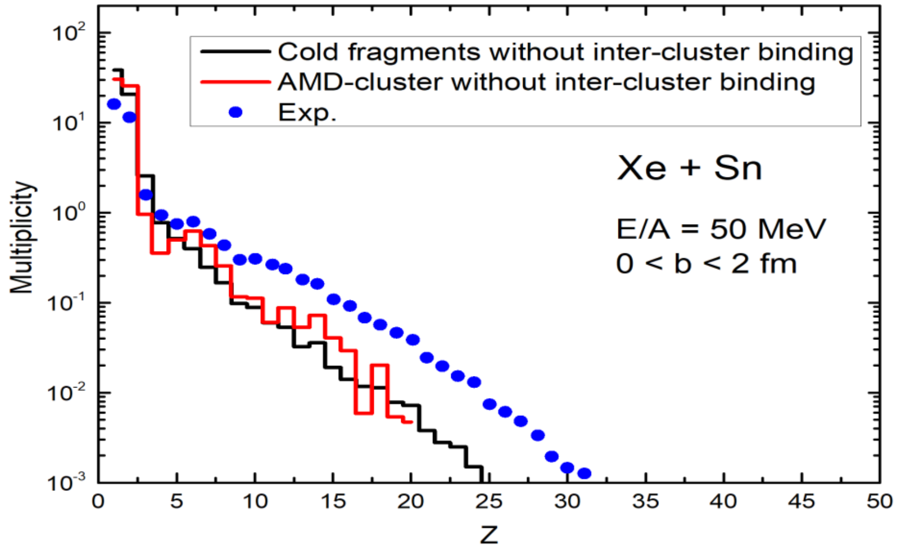
TABLE I. Comparison between cross sections of double lamda hypernuclei calculated with r_0 = 3.5 fm for Λ in ^{197}Au + ^{197}Au and ^{40}Ca + ^{40}Ca collisions at 3A GeV

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}	$\lesssim 10^{-6}$

IV. Summary and perspective

- A soft symmetry energy with the slope parameter of $L(\rho_0)$ = 42±25 MeV by using the standard error analysis within the range of 1σ is obtained by analyzing the experimental data from the SπRIT collaboration in reactions of ^{108}Sn+^{112}Sn and ^{132}Sn+^{124}Sn at 270 MeV/nucleon.
- The Σ^-/Σ^+ ratio depends on the stiffness of symmetry energy, in particular at the beam energy below the threshold value (E_{th}=1.58 GeV), i.e., the kinetic energy spectra of the single ratios, excitation functions and energy spectra of the double ratios in the isotopic reactions of ^{108}Sn + ^{112}Sn, ^{112}Sn + ^{112}Sn, ^{124}Sn + ^{124}Sn and ^{132}Sn + ^{124}Sn. The double strangeness ratio Ξ^-/Ξ^0 weakly depends on the symmetry energy because of the hyperon-hyperon collision mainly contributing the Ξ production below the threshold energy (E_{th} = 3.72 GeV).
- Nuclear clusters and hypernuclear clusters for probing the high-density symmetry energy in the near future, t/^{3}He, $_\Lambda$t/$^3_\Lambda$He etc.





AMD calculation by Akira Ono, J. Phys. Conf. Ser. 420 (2013) 012103

Thank you for your attention