第二十届全国中高能核物理大会暨第十四届全国中高能核物理专题研讨会　2025年4月24日至28日　上海

散射截面介质修正对抽取高密区状态方程软硬信息的影响

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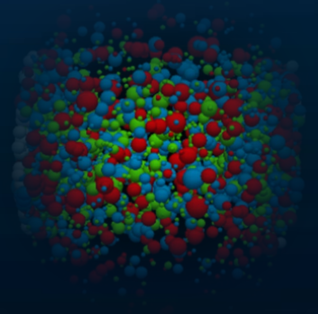
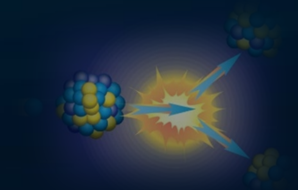
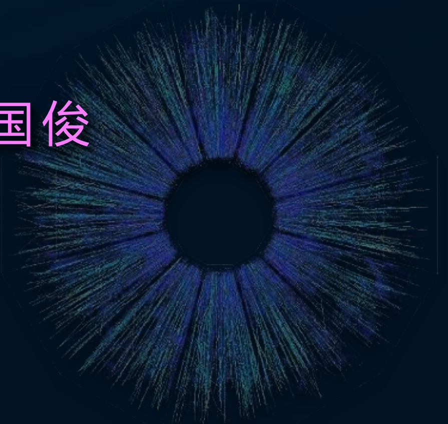

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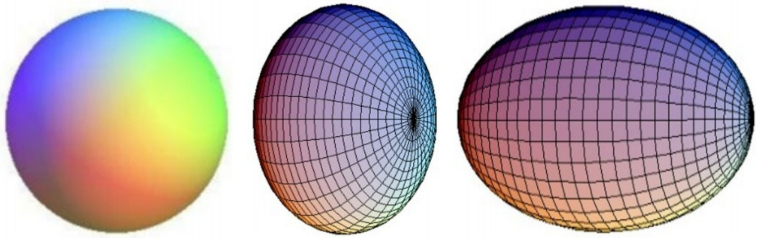
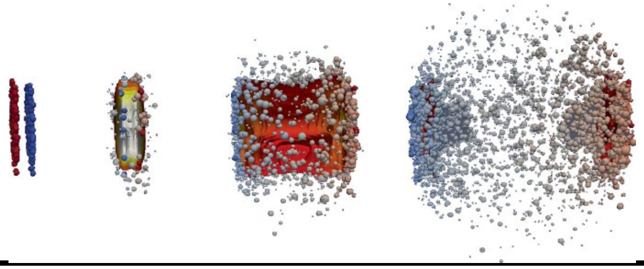
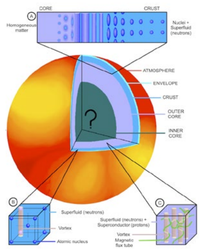
Ⅰ、Background——history







Year	Contents	Key Contributors	Theory & Methods
1930s-40s	Neutron discovery, Fermi Gas Model	Chadwick, Fermi	Nonrelativistic theory
	Liquid drop model, nuclear many-body theory	Bethe, Weizsäcker	
1940s–50s	Brueckner theory, G-matrix	Brueckner	Nonrelativistic Brueckner theory
1950s-1960s	Named “nuclear equation of state”		
1960s–70s	Skyrme interactions, RMF theory…	Skyrme, Walecka…	Relativistic mean field
1980s–90s	Applications to neutron stars, quark matter	Glendenning, Akmal-Pandharipande	
2000s-2010s	Chiral EFT, variational methods	Hebeler, Gandolfi, Carlson	
2010s–20s	Multi-messenger astrophysics constraints	LIGO/Virgo, NICER, Ozel, Lattimer	Bayesian analysis

Ⅰ、Background——history

Google 学术搜索 "nuclear equation of state"

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DL Livesey - Canadian Journal of Physics, 1955 - cdnsciencepub.com
... zero excitation, wo, by the equation log,(w/wo)= S (E)/K where the" n~ Iclear entropy" S (E)/K= J~ E/KT and the" nuclear temperature"(KT) is determined by the nuclear equation of state. ...
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Statistics of Nuclear Levels
L JMB - 1954 - arch.neicon.ru
... The simplest adequate nuclear equation of state is U = (1/11)At² - t + (1/8)A^{2/3}t^{7/3}
MeVwhich leads to D₀ = 0.11A²(U ...
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Experiments involving the Emission of Particles from Compound Nuclei
RS Storey, W Jack, A Ward - Proceedings of the Physical Society, 1960 - iopscience.iop.org
... From their analysis they propose an expression for the nuclear equation of state, and use the parameters U and t. t is essentially our Tm and U is approximately E,* - 8 MeV. The values ...
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Proceedings of the Physical Society. Section A

Statistics of Nuclear Levels

J M B Lang and K J Le Couteur
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Proceedings of the Physical Society. Section A, Volume 67, Number 7
Citation J M B Lang and K J Le Couteur 1954 *Proc. Phys. Soc. A* **67** 586
DOI 10.1088/0370-1298/67/7/303

Statistics of Nuclear Levels †

BY J. M. B. LANG AND K. J. LE COUTEUR
Department of Theoretical Physics, University of Liverpool

Communicated by H. Fröhlich; MS. received 16th February 1954

Abstract. All the available experimental evidence relating to the statistical distribution of dense nuclear levels is collected together and analysed. The simplest adequate nuclear equation of state is

$$U=\tfrac{1}{11}At^2-t+\tfrac{1}{8}A^{2/3}t^{7/3}\ \mathrm{Mev}$$

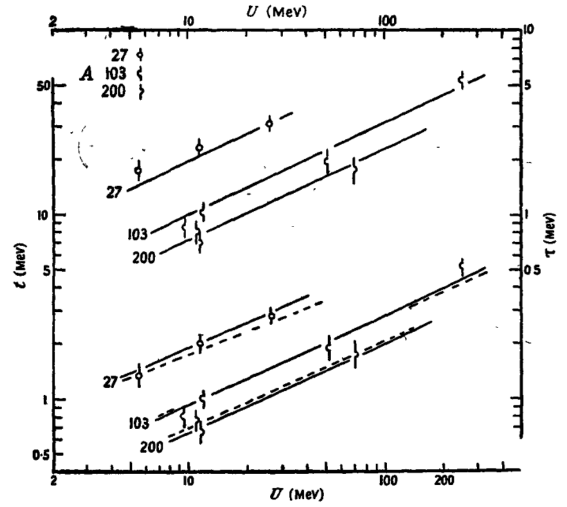
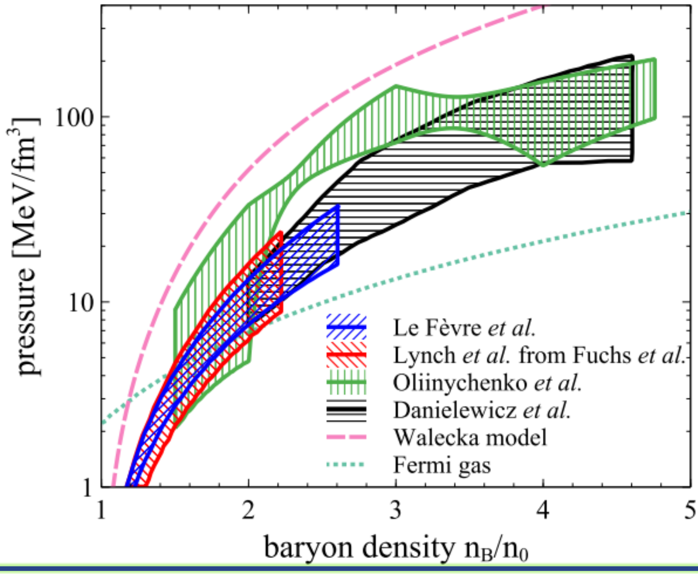
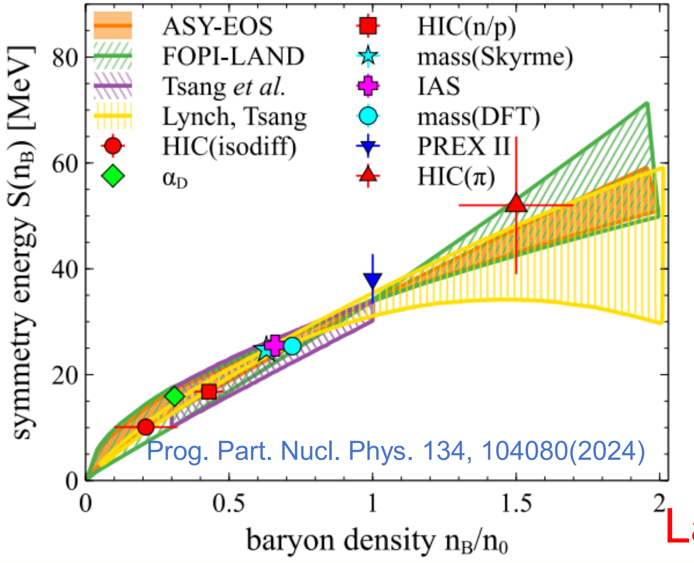
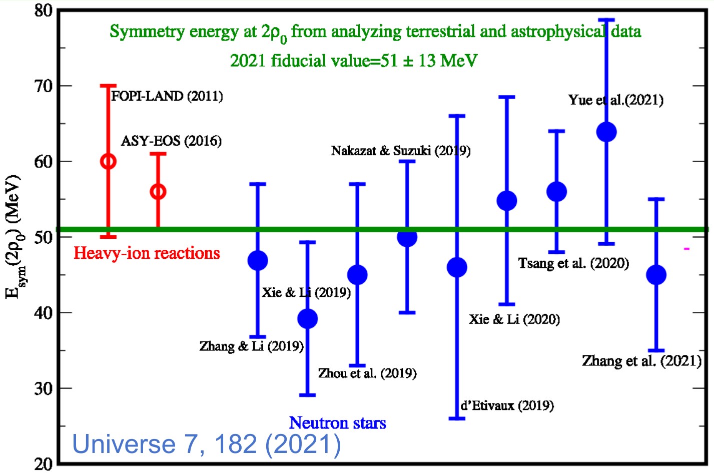


Figure 3. Top: experimental values of energy U and temperature τ for $A=27$, 103, 200 compared with the formula $U=A\tau^2/10{\cdot}5$ Mev.

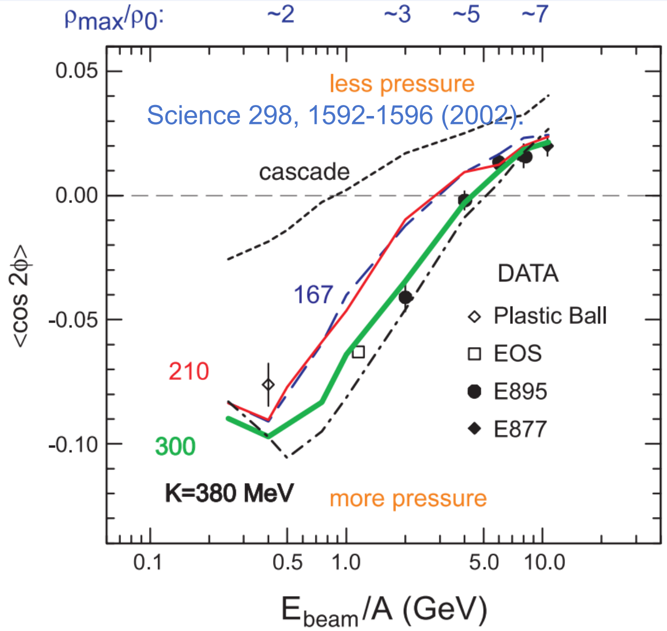
Ⅰ、Background——status

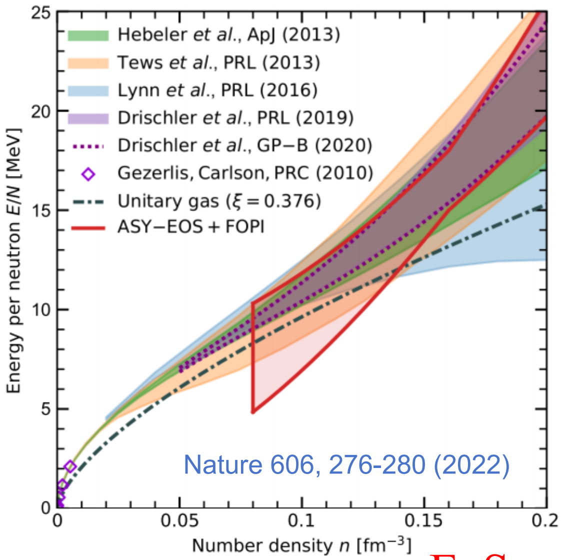


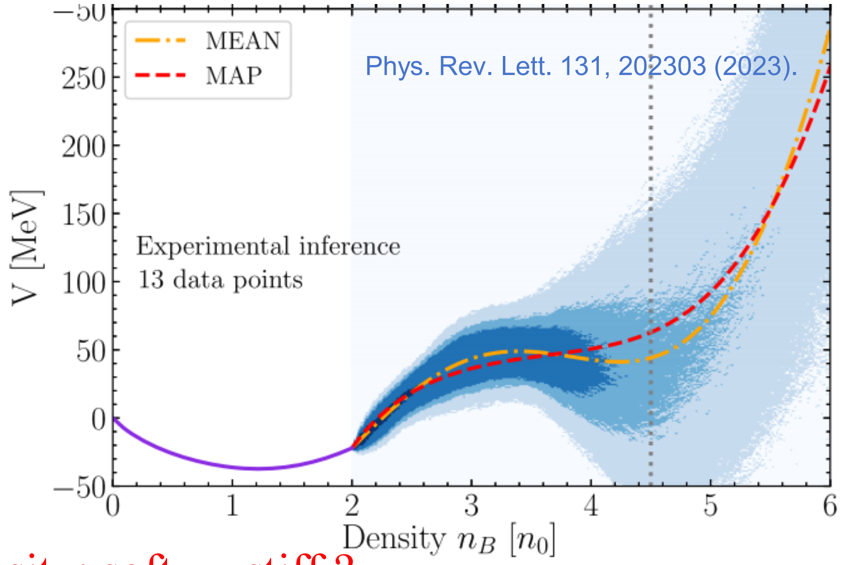




Larger uncertainties at higher densities!!!



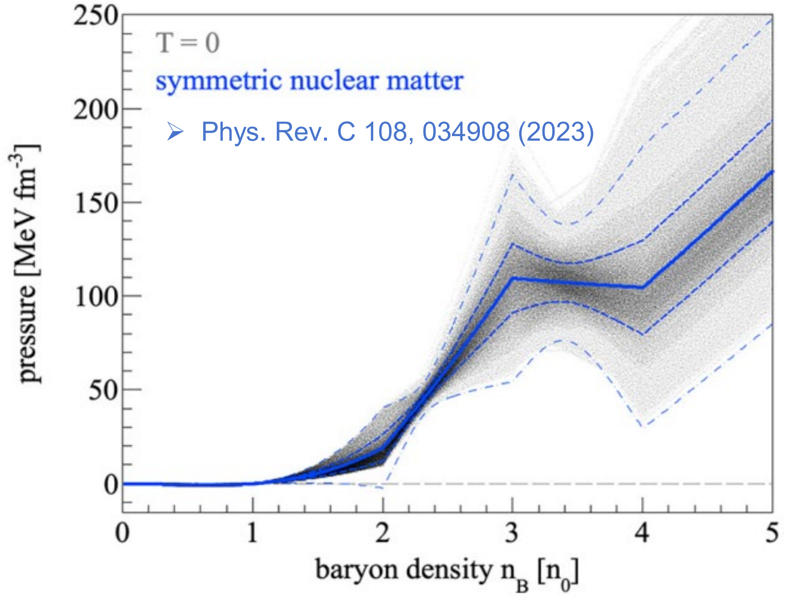




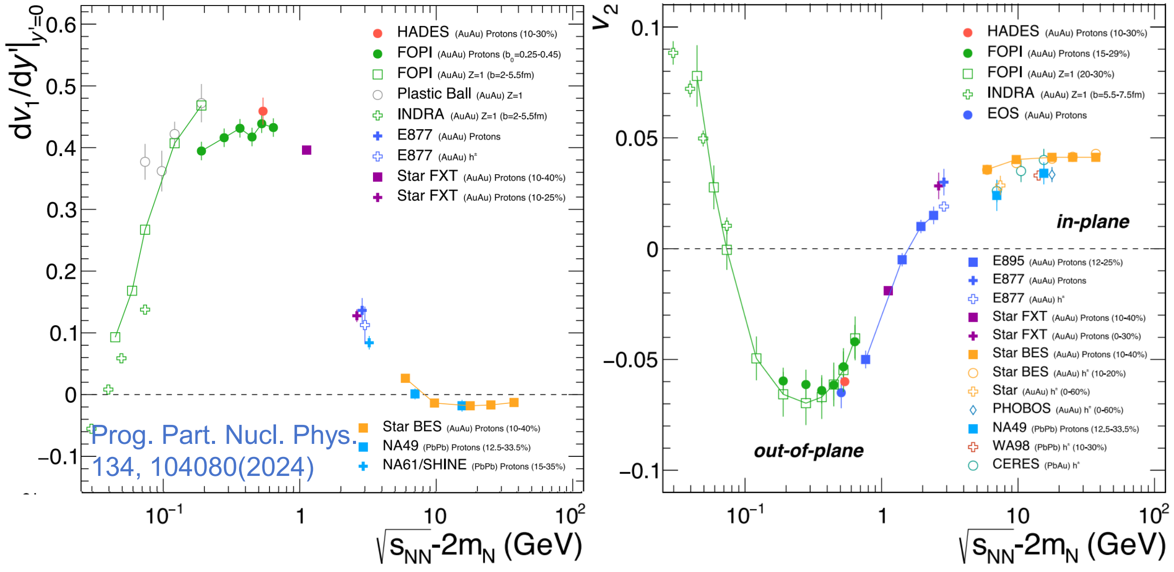
EoS vs. density: soft → stiff ?

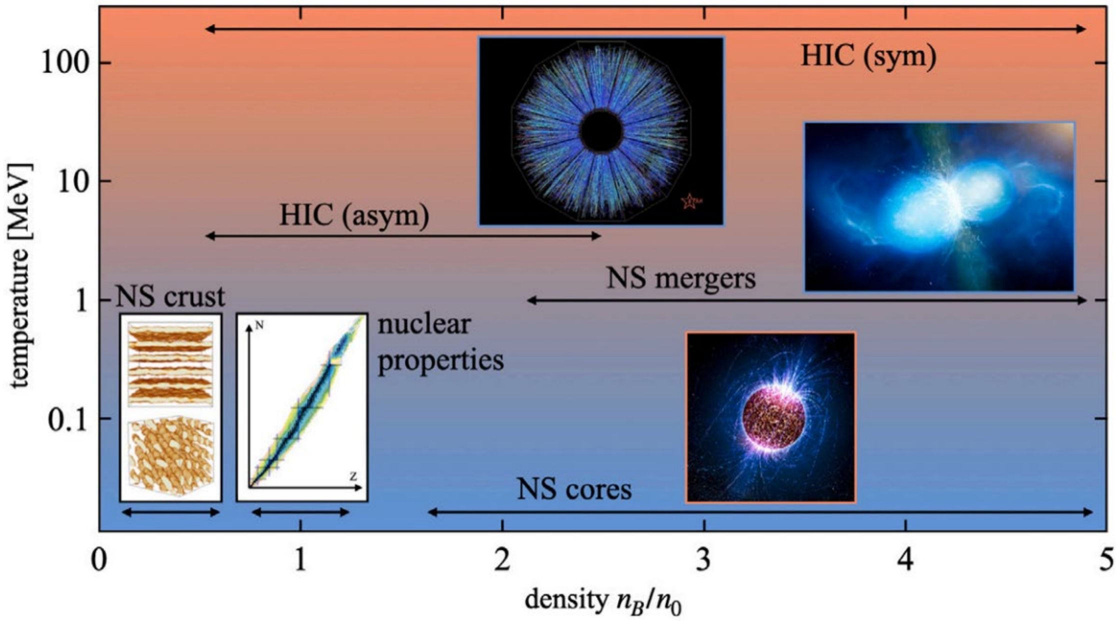
Ⅰ、Background——trends

① 更高密度

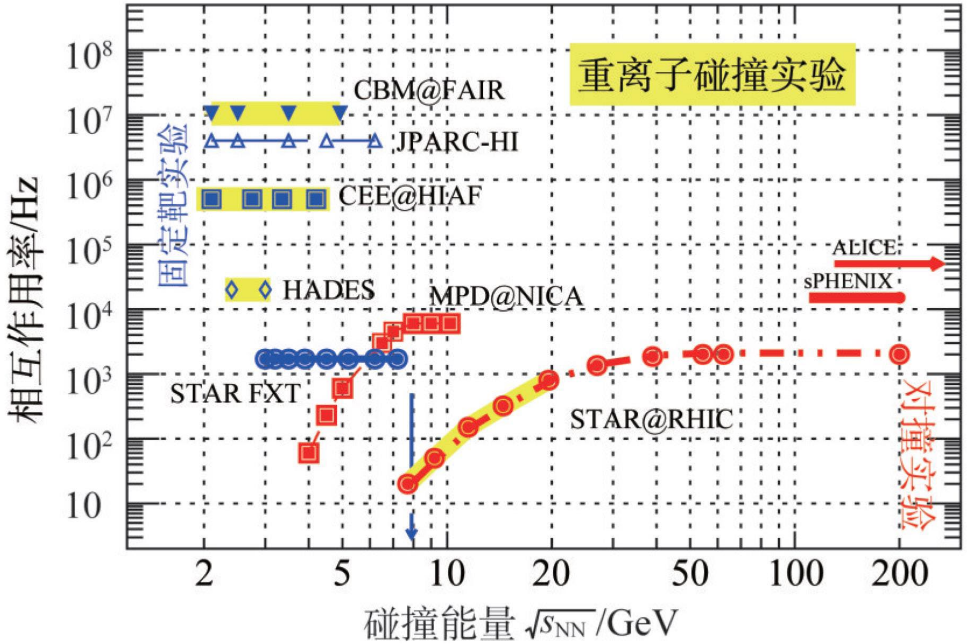


② 密切关联实验条件



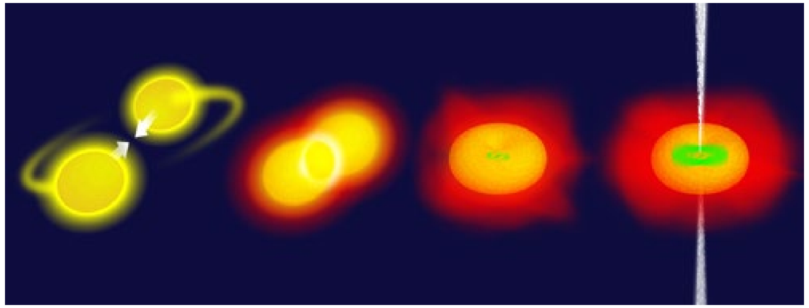


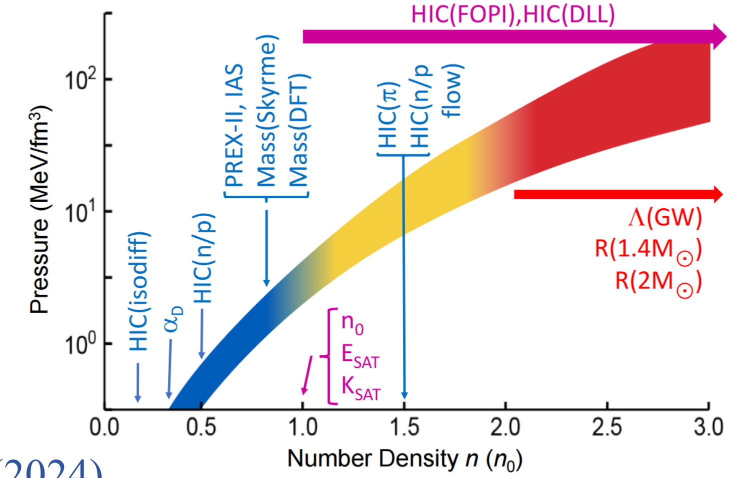
0.2	1.973
0.4	2.066
0.6	2.155
0.8	2.24
1	2.323
1.23	2.414
2	2.697
2.921	3
3	3.024
4	3.32
5	3.592
6	3.844
7	4.081
8	4.304



Ⅰ、Background——trends

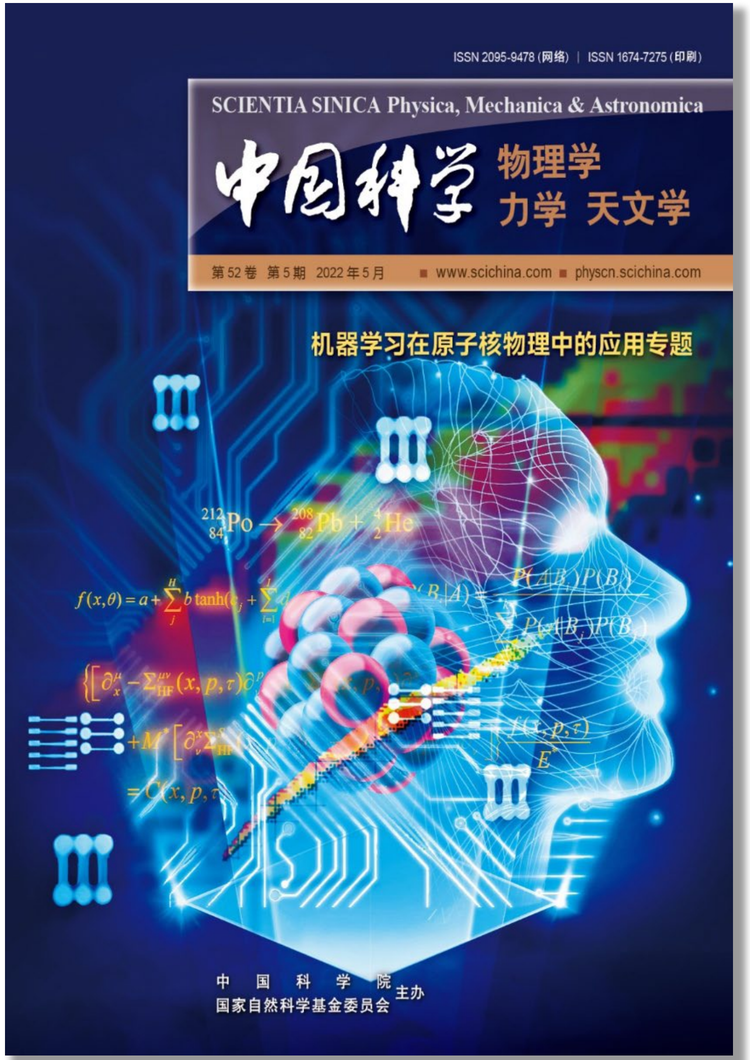
③ HICs+Multimessenger astronomy



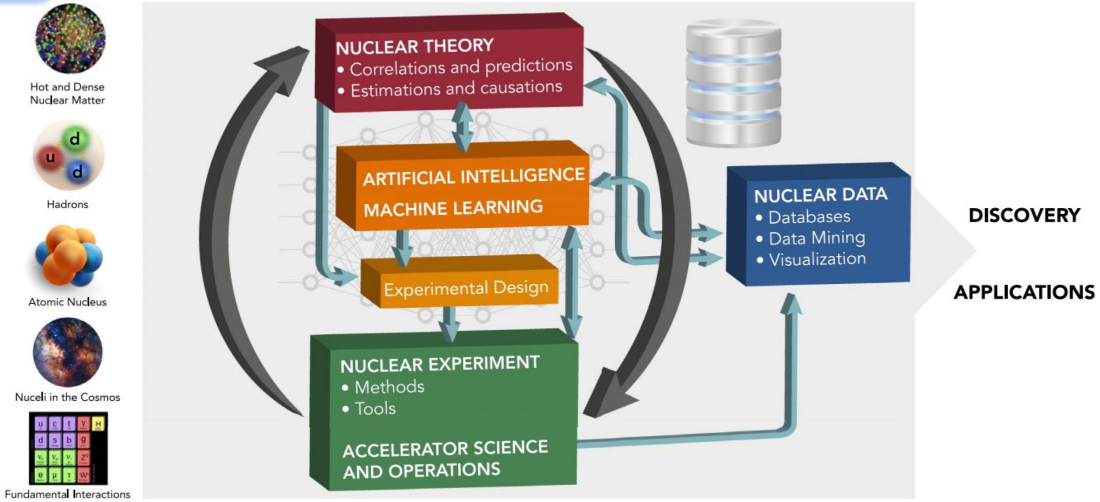


→ M. McLaughlin, Physics 10, 114(2017)

→C. Y. Tsang, et al. Nature Astron. 8, 328-336 (2024).



④ AI4science

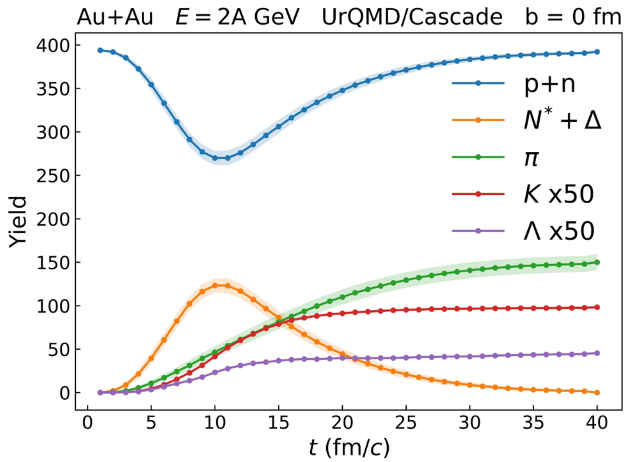


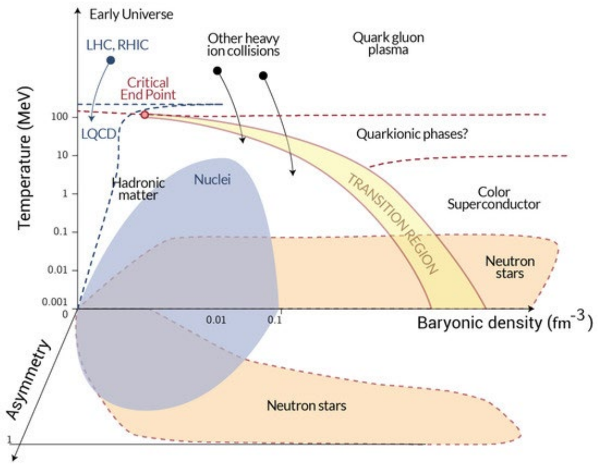
→ A. Boehnlein, M. Diefenthaler, N. Sato, et al. Rev. Mod. Phys. 94, 031003 (2022).

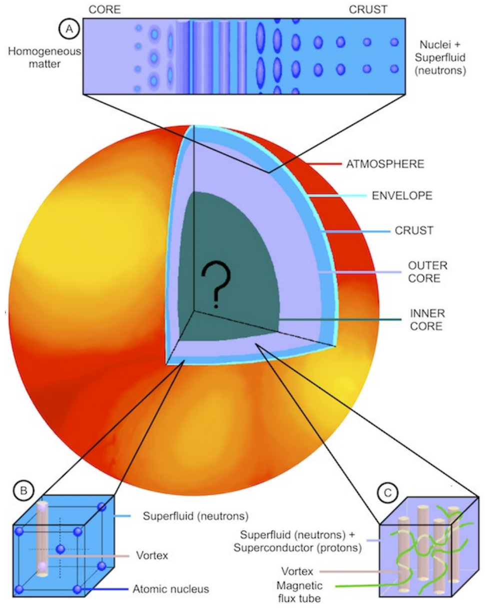
→ W. B. He, Q. F. Li, Y. G. Ma, Z. M. Niu, J. C. Pei and Y. X. Zhang, Sci. China Phys. Mech. Astron. 66, 282001 (2023).

Ⅰ、Background——questions

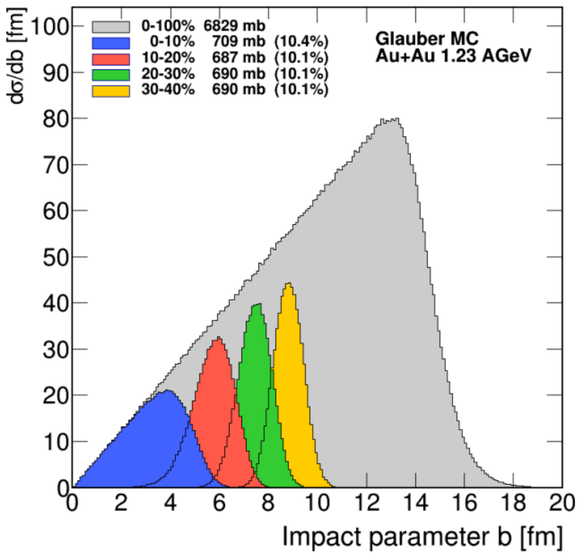
a）丰富的粒子种类和复杂的核环境

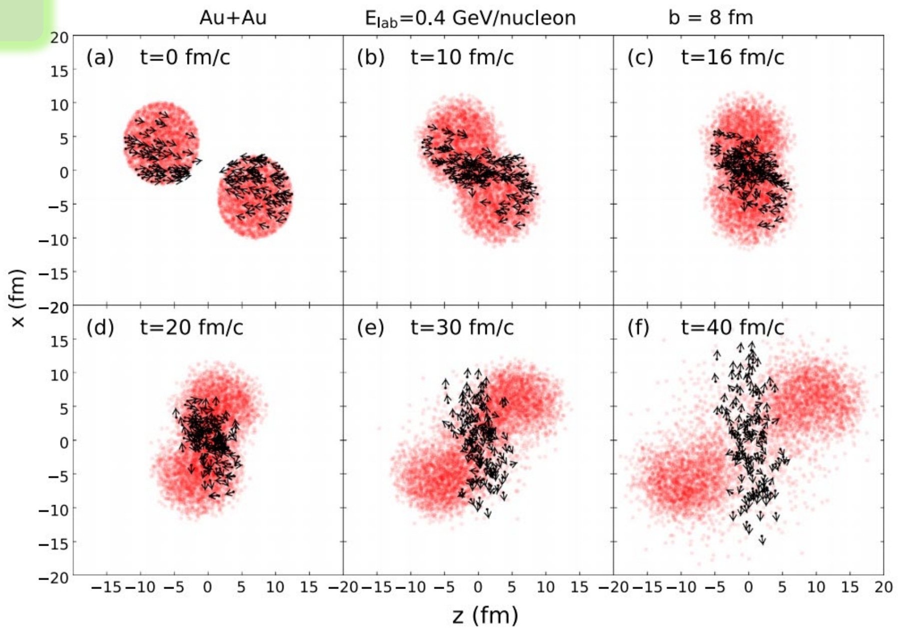


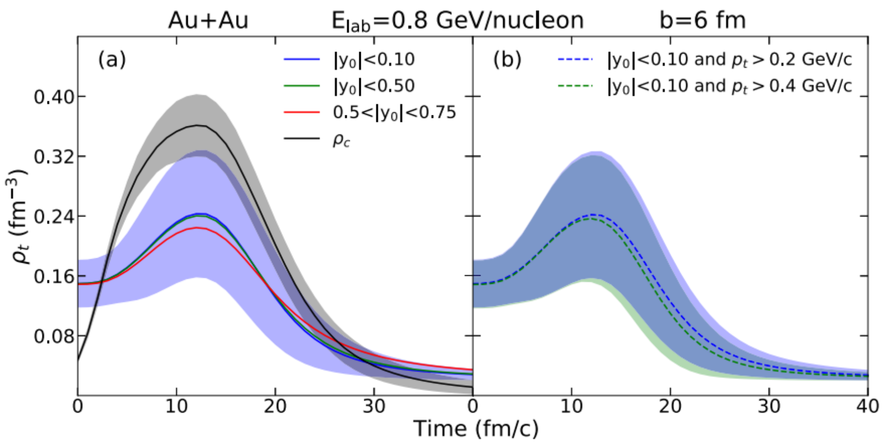




b）理论模拟与实验条件的差异

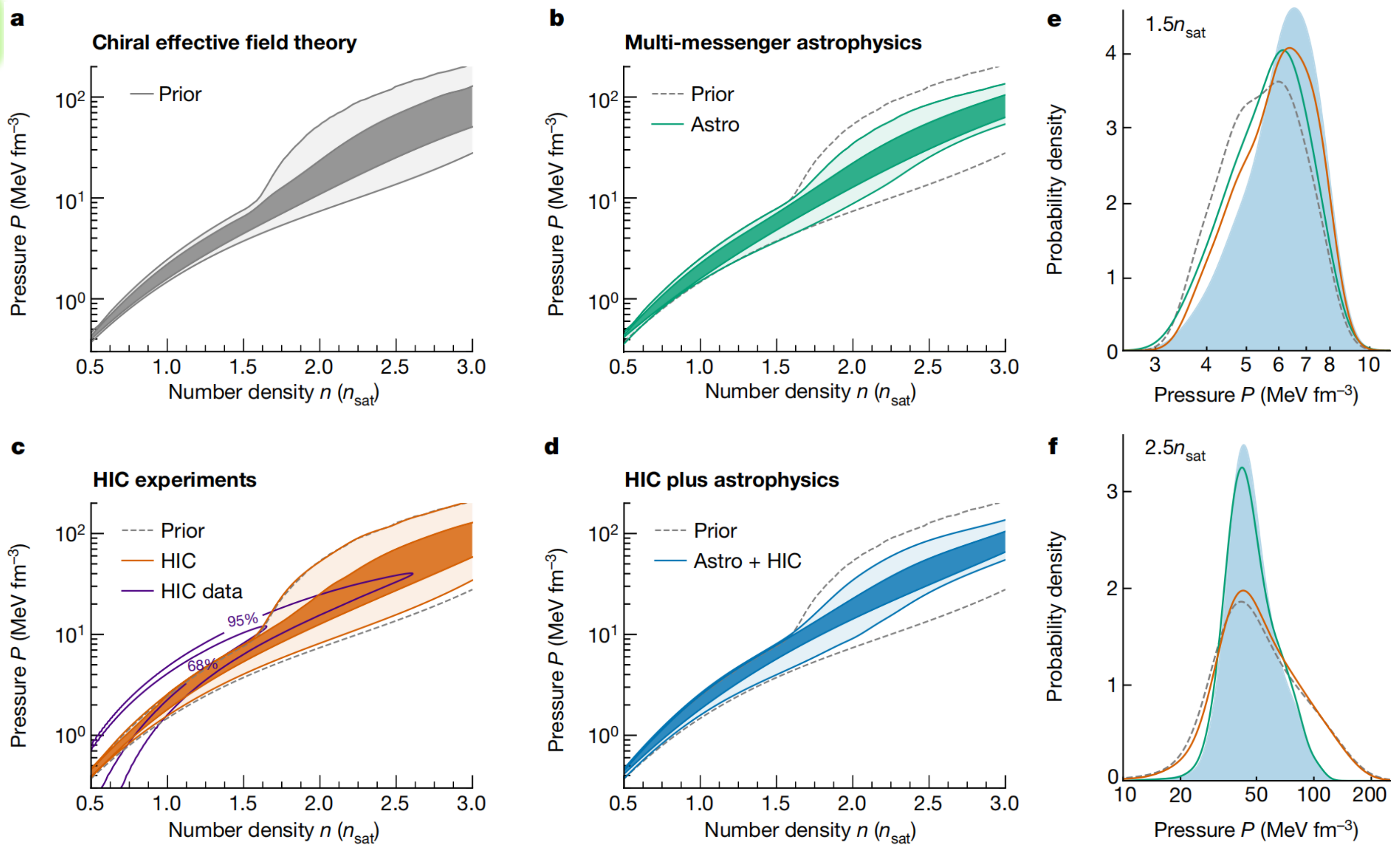






Ⅰ、Background——questions

c）不确定度分析



Joint analyses can shed light on the properties of neutron-rich supranuclear matter over the density range probed in neutron stars.

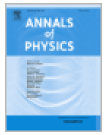
→ S. Huth, P. T. H. Pang, I. Tews, T. Dietrich, et al. Nature 606, 276-280 (2022).

Ⅱ、 Self-consistent RBUU transport theory

RBUU transport theory：

Annals of Physics

Volume 83, Issue 2, April 1974, Pages 491-529



A theory of highly condensed matter ☆

J.D Walecka

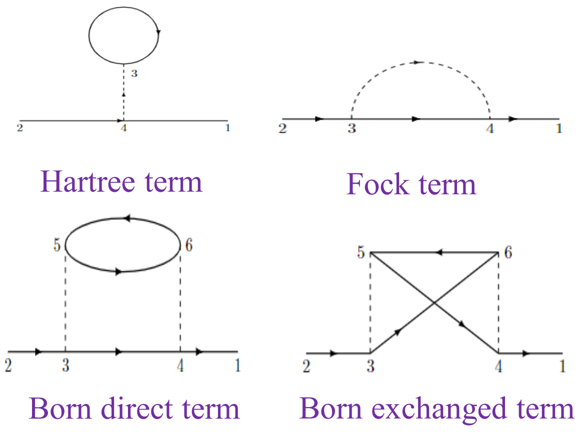
Physics Reports

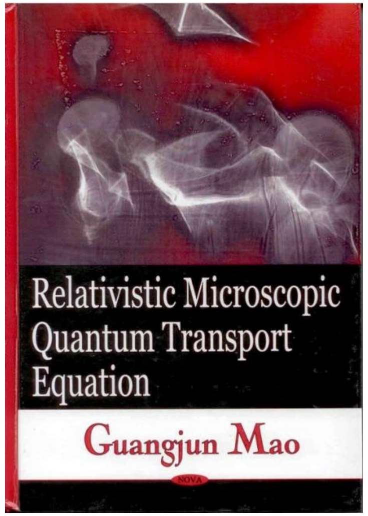
Volume 118, Issues 1–2, February 1985, Pages 1-131

Equilibrium and nonequilibrium formalisms made unified

Kuang-chao Chou, Zhao-bin Su *, Bai-lin Hao, Lu Yu

Feynman diagram





Publisher: Nova Science Pub Inc; UK ed. edition (April 8, 2005)

ISBN-10: 159454395X

ISBN-13: 978-1594543951

BUU equation

$$\left(\partial_t + \frac{\mathbf{p}}{m} \cdot \nabla_{\mathbf{R}} - \nabla_{\mathbf{R}} U(R,t) \cdot \nabla_{\mathbf{p}}\right) f(\mathbf{p},\mathbf{R},t) \equiv I(f)$$

sc-RBUU equation

$$\left\{\left[\partial_X^{\mu} - \sum\nolimits_{HF}^{\mu\nu}(X,p,t)\partial_{\nu}^{\bar{p}} - \partial_{\bar{p}}^{\nu}\,\mathrm{Re}\sum\nolimits_F^{\mu}(X,p,t)\partial_{\nu}^{X}\right]\frac{\bar{p}_{\mu}}{M_{\mathrm{Re}}^{*}} \right.$$
$$\left. + \partial_{\nu}^{X}\left[\sum\nolimits_H(X) + \mathrm{Re}\sum\nolimits_F(X,p,t)\right]\partial_p^{\nu} - \partial_p^{\nu}\,\mathrm{Re}\sum\nolimits_F(X,p,t)\partial_{\nu}^{X}\right\} \times \frac{M}{E(\bar{p})} f\left(X,\vec{\bar{p}}\right)$$
$$= \frac{1}{2}\int \frac{d\vec{p}_2}{(2\pi)^3}\frac{d\vec{p}_3}{(2\pi)^3}\frac{d\vec{p}_4}{(2\pi)^3}(2\pi)^4\,\delta\left(\vec{\bar{p}} + \vec{p}_2 - \vec{p}_3 - \vec{p}_4\right)\delta\left(E(\bar{p}) + E(p_2) - E(p_3) - E(p_4)\right)$$
$$\times W_{el,in}(\bar{p},p_2,p_3,p_4)\left(F_{el,in}^{2} - F_{el,in}^{1}\right)$$

Ⅱ、 Self-consistent RBUU transport theory

The collision term can be expressed as:

$$C(x,p)=\frac{1}{2}\int\frac{d^3p_2}{(2\pi)^3}\int\frac{d^3p_3}{(2\pi)^3}\int\frac{d^3p_4}{(2\pi)^3}(2\pi)^4\delta^{(4)}\left(p+p_2-p_3-p_4\right)W\left(p,p_2,p_3,p_4\right)\left(F_2-F_1\right),$$

$$W\left(p,p_2,p_3,p_4\right)=G_1\left(p,p_2,p_3,p_4\right)+G_2\left(p,p_2,p_3,p_4\right)+p_3\leftrightarrow p_4,$$

$$\begin{aligned}F_1&=f(\mathbf{x},\mathbf{p},\tau)f(\mathbf{x},\mathbf{p}_2,\tau)[1-f_\Delta(\mathbf{x},\mathbf{p}_3,\tau)][1-f\left(\mathbf{x},\mathbf{p}_4,\tau\right)],\\F_2&=[1-f(\mathbf{x},\mathbf{p},\tau)][1-f\left(\mathbf{x},\mathbf{p}_2,\tau\right)]f_\Delta\left(\mathbf{x},\mathbf{p}_3,\tau\right)f\left(\mathbf{x},\mathbf{p}_4,\tau\right),\end{aligned}$$

The relationship between the scattering cross section and the collision term is:

$$\int\frac{d^3p_3}{(2\pi)^3}\int\frac{d^3p_4}{(2\pi)^3}(2\pi)^4\delta^{(4)}\left(p+p_2-p_3-p_4\right)W\left(p,p_2,p_3,p_4\right)=\int v\sigma(s,t)d\Omega.$$

Therefore the collision term can be expressed as:

$$C(x,p)=\frac{1}{2}\int\frac{d^3p_2}{(2\pi)^3}v\sigma(s,t)\left(F_2-F_1\right)d\Omega.$$

→ G. Mao, Z. X. Li, Y. Z. Zhuo, Y. L. Han and Z. Q. Yu, Phys. Rev. C 49, 3137-3146 (1994).

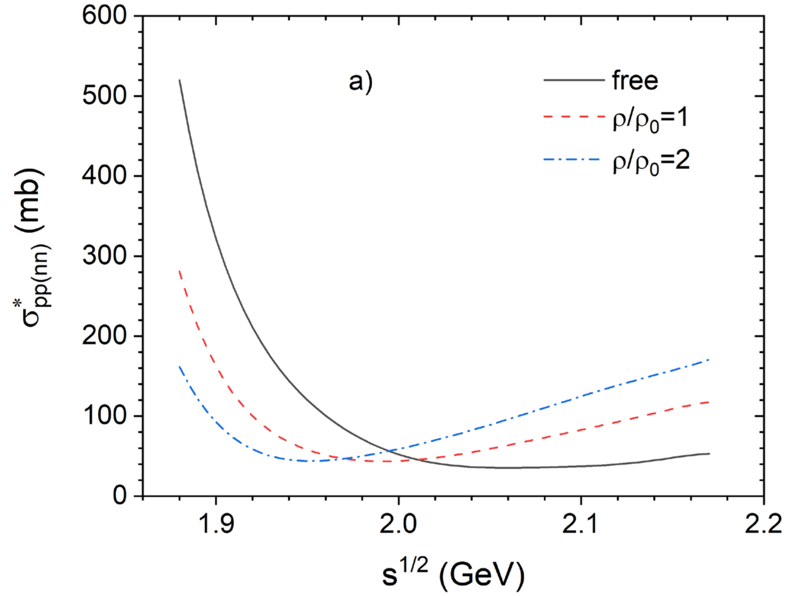
Ⅲ、NN → NN elastic cross section

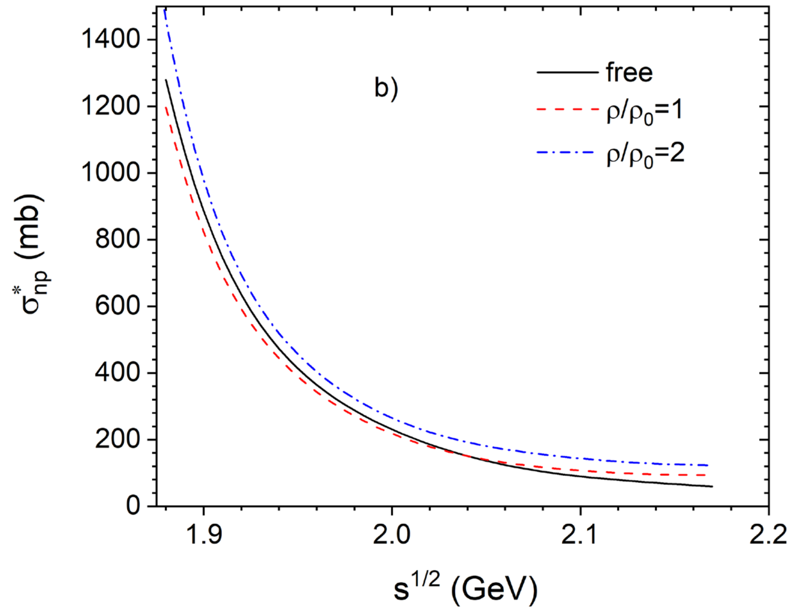
L_I is the interaction Lagrangian density of nucleons coupled to σ, ω, ρ, and π mesons and reads as

$$L_I = g_\sigma \bar{\Psi}\Psi\sigma - g_\omega \bar{\Psi}\gamma_\mu \Psi \omega^\mu + g_\pi \bar{\Psi}\gamma_\mu \gamma_5 \boldsymbol{\tau}\cdot\Psi\partial^\mu \boldsymbol{\pi}$$

$$-\frac{1}{2} g_\rho \bar{\Psi}\gamma_\mu \boldsymbol{\tau}\cdot\Psi\boldsymbol{\rho}^\mu,$$

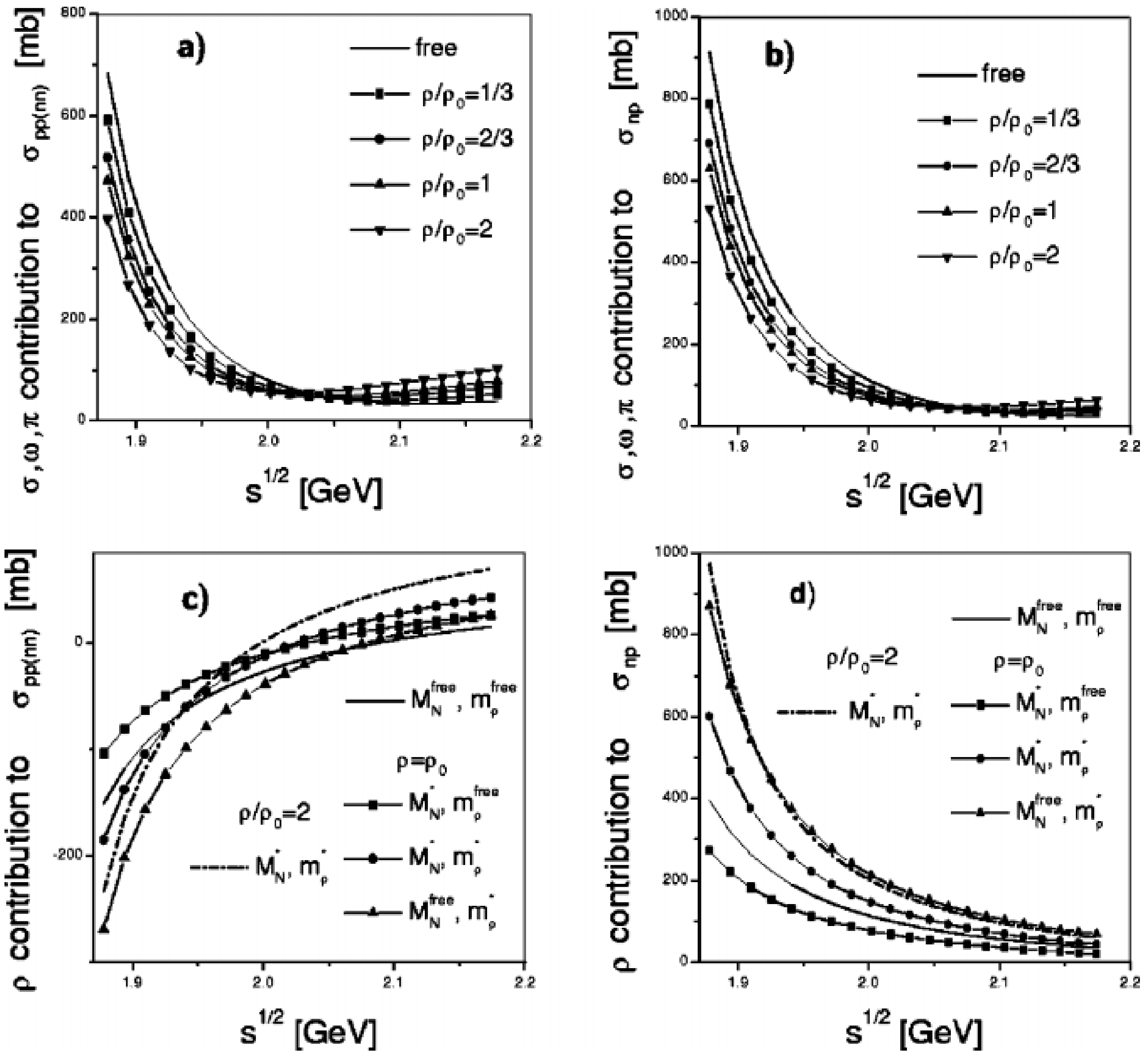
- The medium correction of NN elastic cross sections is isospin dependent.
- σ^*_{np} depends on the baryon density weakly, while $\sigma^*_{pp(nn)}$ depends on the baryon density significently. Which is due to the different effects of the medium correction of nucleon mass and ρ meson mass on σ^*_{np} and $\sigma^*_{pp(nn)}$, respectively.





→ Q. F. Li, Z. X. Li, G. J. Mao, Phys. Rev. C 62, 014606(2000).

Ⅲ、 NN → NN elastic cross section



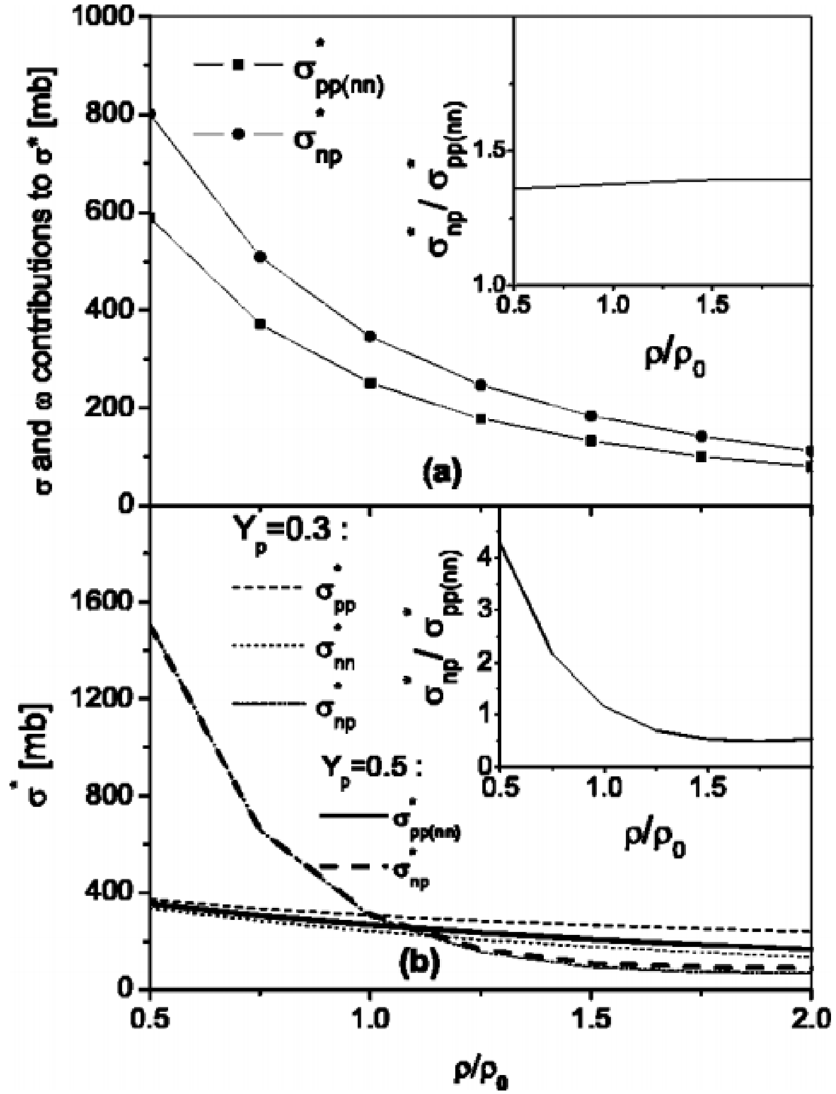
The ρ meson field plays a dominant role in the isospin dependence of the NN elastic cross sections.

→ Q. F. Li, Z. X. Li, G. J. Mao, Phys. Rev. C 62, 014606(2000).

Ⅲ、NN → NN elastic cross section

The scalar-isovector δ meson is further introduced into the effective Lagrangian to calculate the in-medium NN elastic cross section

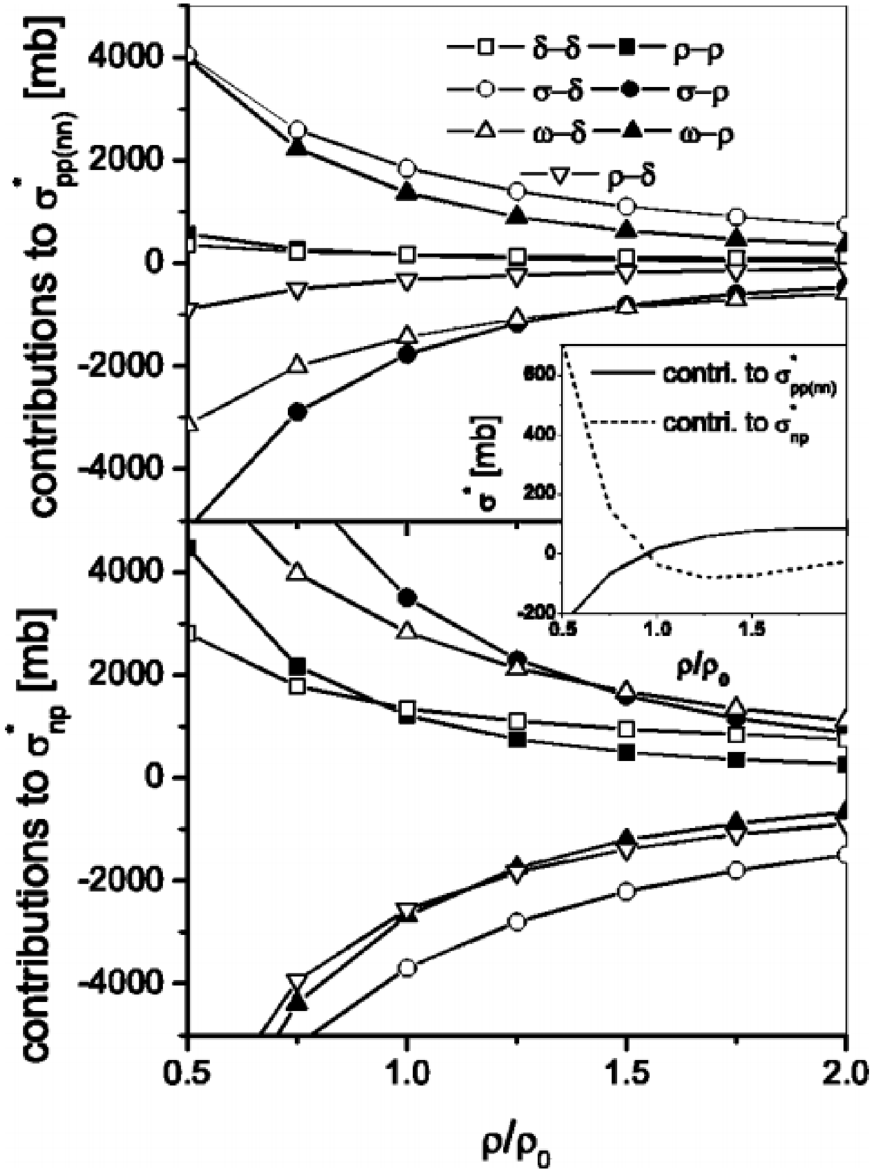
$$L=\overline{\Psi}[i\gamma_\mu\partial^\mu - M_N]\Psi + \tfrac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \tfrac{1}{4}F_{\mu\nu}\cdot F^{\mu\nu} + \tfrac{1}{2}\partial_\mu\boldsymbol{\delta}\partial^\mu\boldsymbol{\delta}$$
$$-\tfrac{1}{4}L_{\mu\nu}\cdot L^{\mu\nu} - \tfrac{1}{2}m_\sigma^2\sigma^2 + \tfrac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \tfrac{1}{2}m_\delta^2\boldsymbol{\delta}^2 + \tfrac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu$$
$$+g_\sigma\overline{\Psi}\Psi\sigma - g_\omega\overline{\Psi}\gamma_\mu\Psi\omega^\mu + g_\delta\overline{\Psi}\boldsymbol{\tau}\cdot\Psi\boldsymbol{\delta}$$
$$-\tfrac{1}{2}g_\rho\overline{\Psi}\gamma_\mu\boldsymbol{\tau}\cdot\Psi\boldsymbol{\rho}^\mu,$$

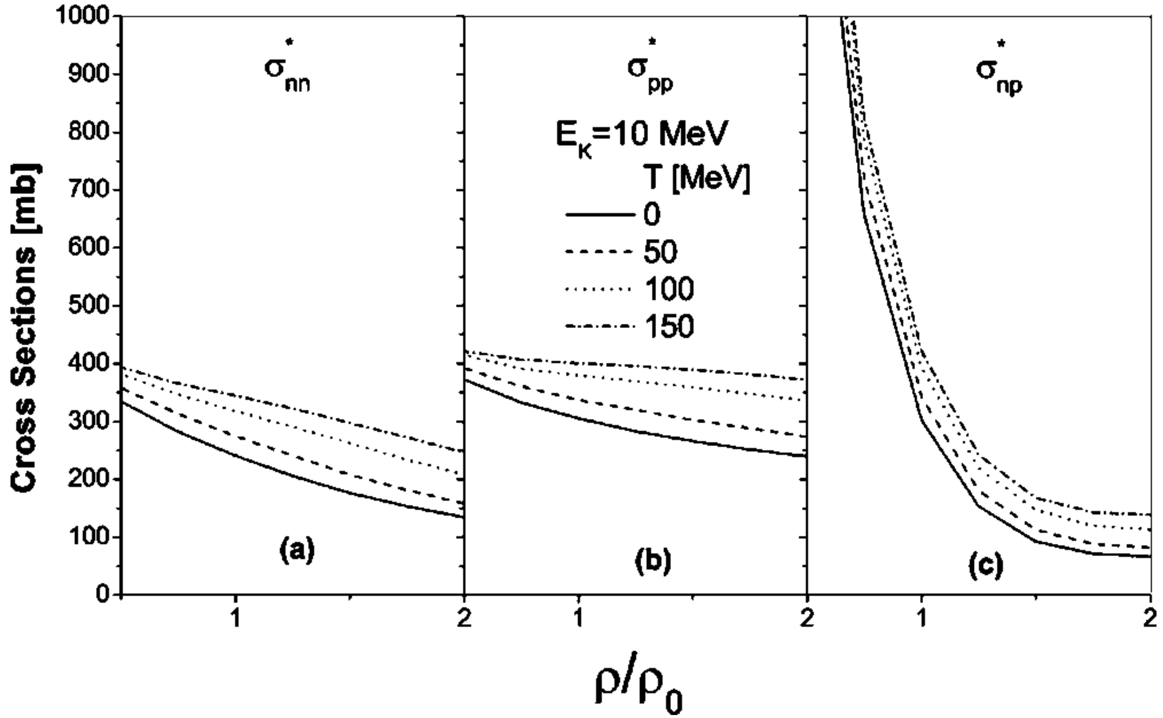


The density dependence of σ^*_{np} and $\sigma^*_{pp(nn)}$ is very different, at low densities, the σ^*_{np} is about three to four times larger than $\sigma^*_{pp(nn)}$, it means that at dense nuclear matter the isospin effect on in-medium NN cross section almost washes out.

→ Q. F. Li, Z. X. Li, E. G. Zhao, Phys. Rev. C 69, 017601 (2004).

Ⅲ、 NN → NN elastic cross section





- The isospin effect on the density dependence of the in-medium NN elastic cross section is dominantly contributed by the isovector δ and ρ mesons.
- The temperature effect of nuclear medium on σ^*_{np} and $\sigma^*_{pp(nn)}$ is weaker compared with the density effect.

→ Q. F. Li, Z. X. Li, E. G. Zhao, Phys. Rev. C 69, 017601 (2004).

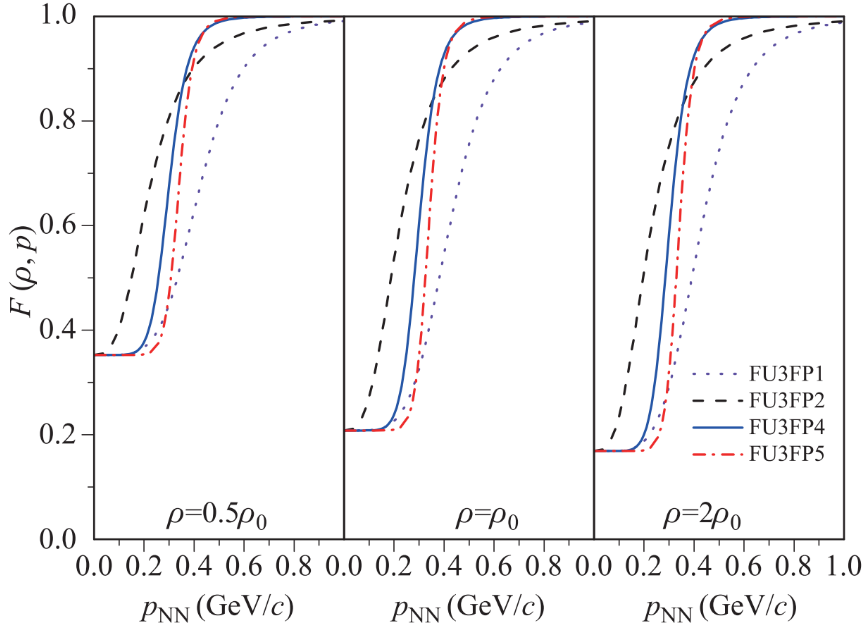
Ⅲ、NN → NN elastic cross section

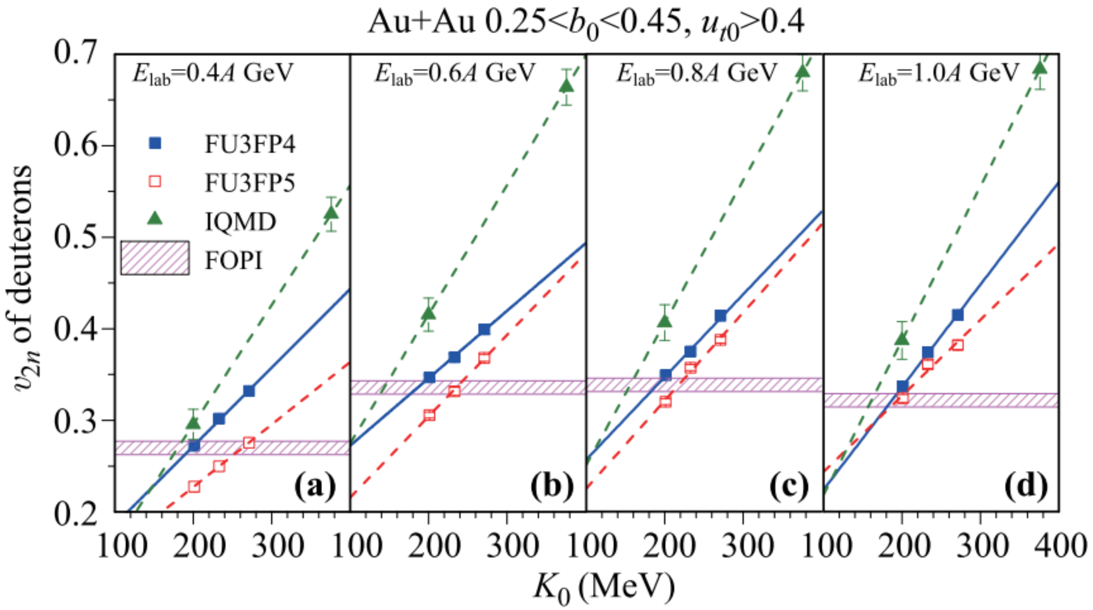
➢ Used in the UrQMD model

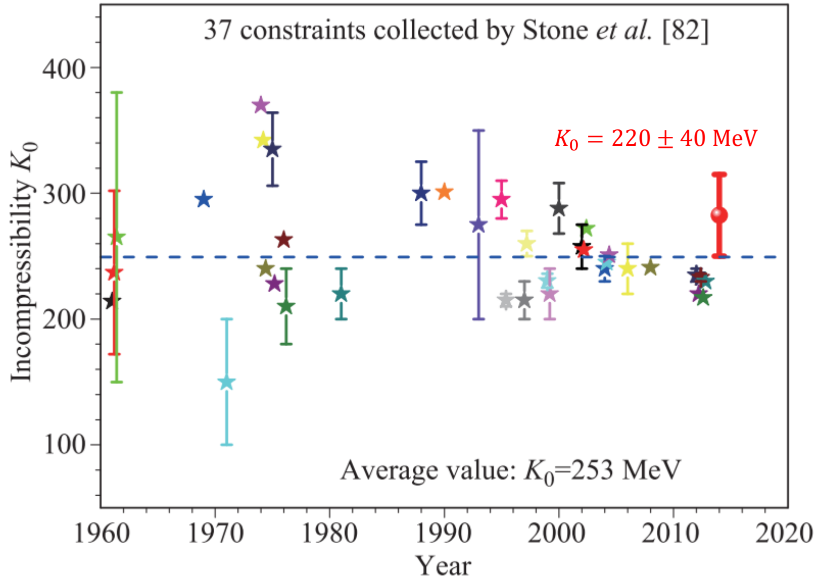
$$\sigma^*_{\mathrm{tot}} = \sigma_{\mathrm{in}} + \sigma^*_{\mathrm{el}} = \sigma_{\mathrm{in}} + F(\rho, p)\sigma_{\mathrm{el}},$$

$$F(\rho, p) = \begin{cases} f_0 & p_{NN} > 1\ \mathrm{GeV}/c, \\ \frac{F_\rho - f_0}{1+(p_{NN}/p_0)^\kappa} + f_0 & p_{NN} \leqslant 1\ \mathrm{GeV}/c, \end{cases}$$

$$F_\rho = \lambda + (1-\lambda)\exp\left[-\frac{\rho}{\zeta\rho_0}\right]$$



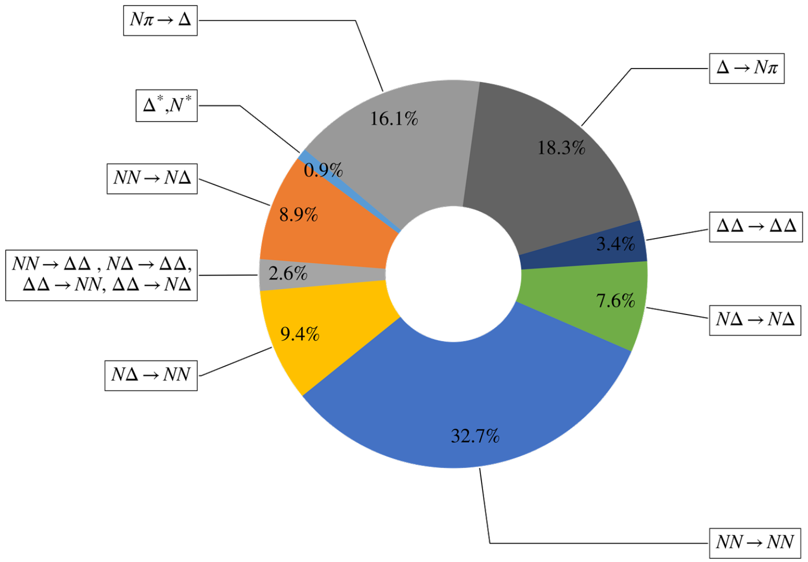


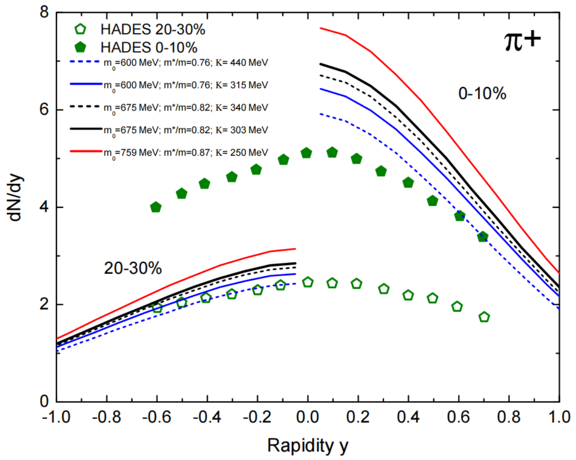


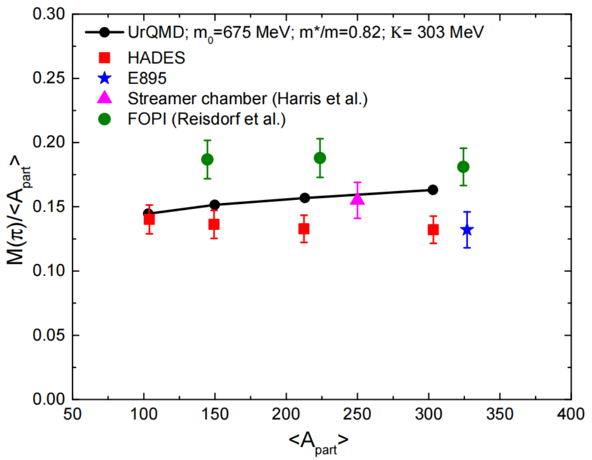
Q. Li, et. al., J. Phys. G 32, 407 (2006). Q. Li, *et al.*, Phys. Rev. C **83**, 044617 (2011), Y. Wang, *et al.*, Front. Phys. **15**, 44302 (2020).

IV、Δ related cross sections

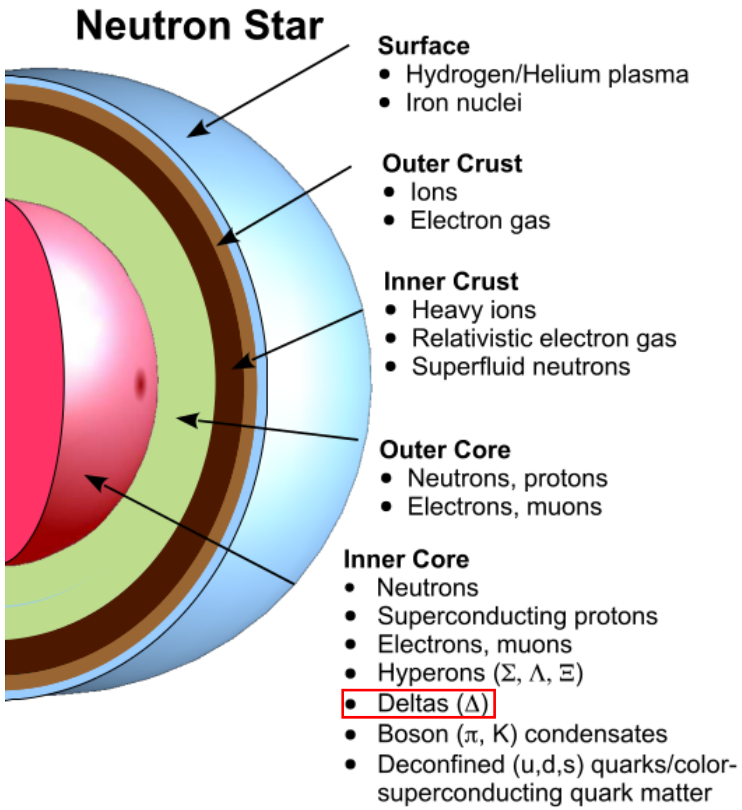
$\sqrt{s_{NN}}$=2.6 GeV, Au+Au (b=0 fm)







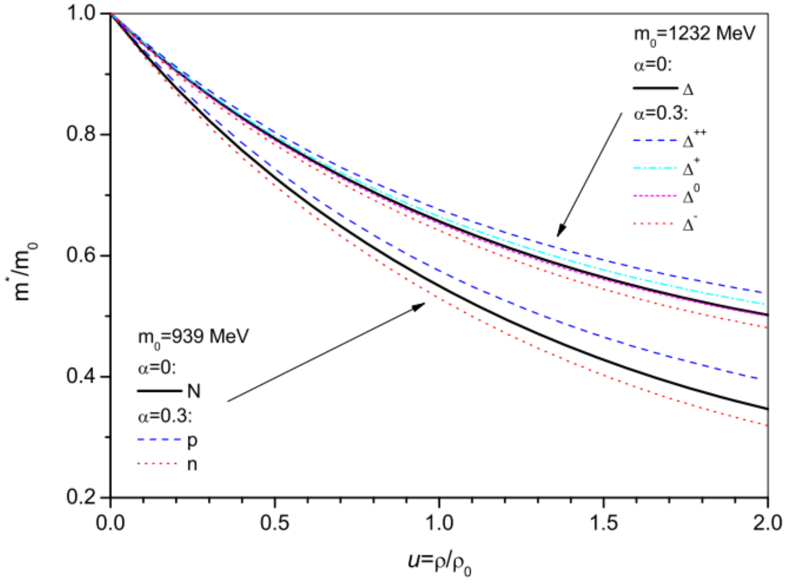
neutron star

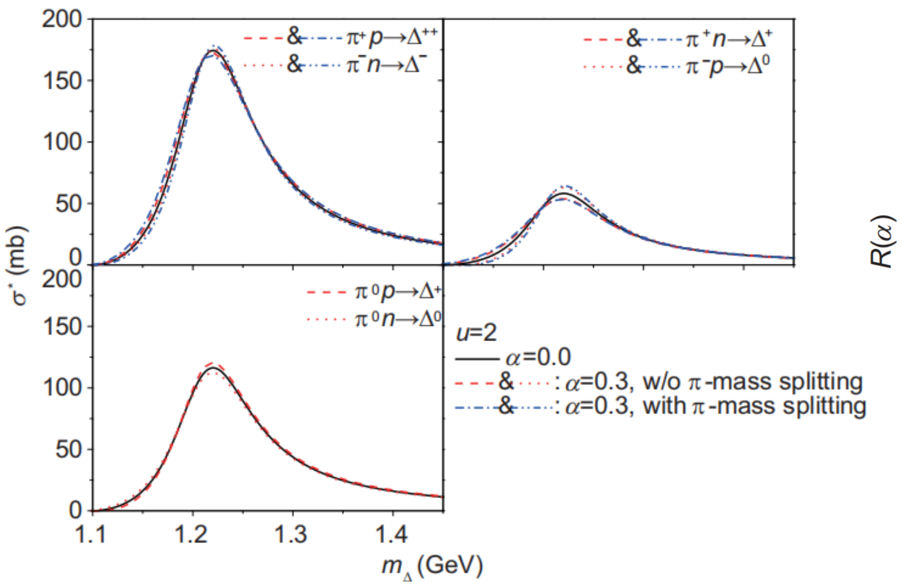


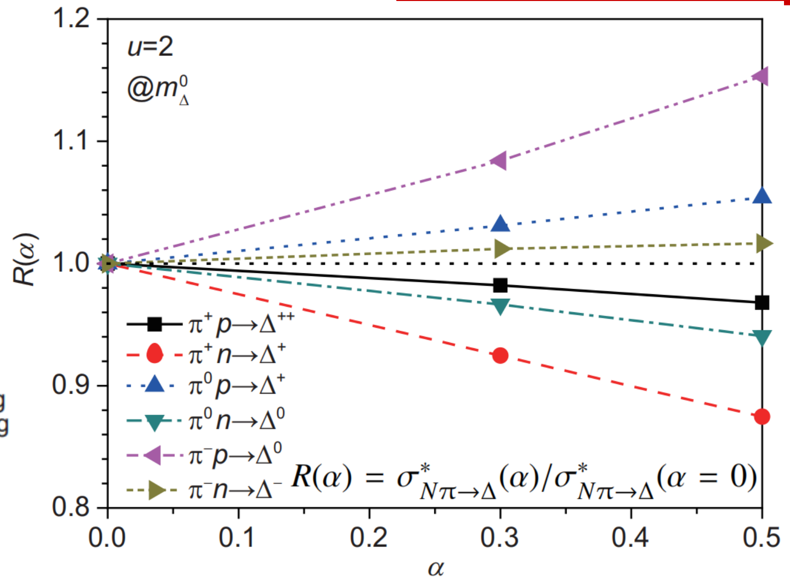
R. B. Jacobsen, V. Dexheimer and R. Luciano Sonego Farias, Astron. Nachr. 344, e230038 (2023).

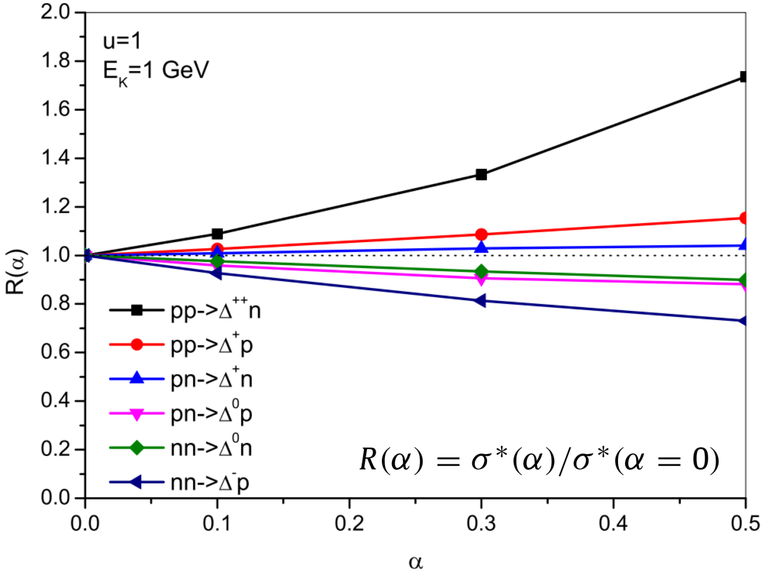
J. Steinheimer, M. Omana Kuttan, T. Reichert, Y. Nara and M. Bleicher, [arXiv:2501.12849 [hep-ph]].

IV、hard- and soft- Δ production cross sections









- Similar to the NN elastic ones, the reductions of NΔ inelastic cross sections is also isospin dependent and the effect is largest and of opposite sign for the Δ^{++} and Δ^{-} states.
- The mass-splitting effect on $\sigma^*_{\pi N\to\Delta}$ which is mainly from the mass splittings of nucleon and Δ baryons,
- the largest mass-splitting influence is reflected in the production of Δ^0 and Δ^+ isobars.

→ Q. F. Li and Z. X. Li, Phys. Lett. B 773, 557-562 (2017); Sci. China Phys. Mech. Astron. 62, 972011 (2019).

IV、NN → NΔ cross section

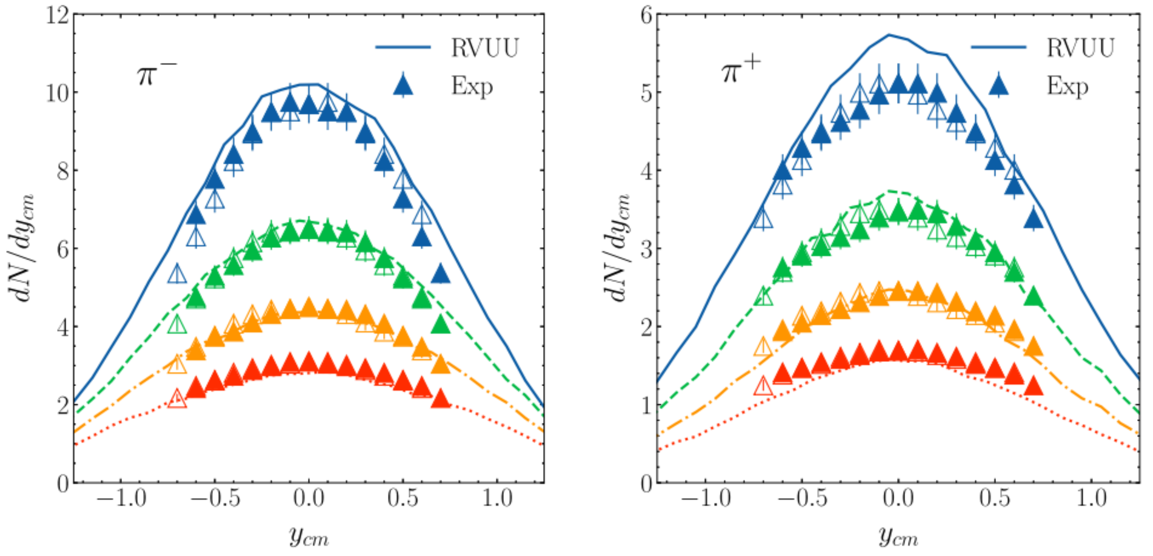
Also, recent theoretical studies (see e.g., Refs. [52,53]) indicate that the exchange of the δ meson in the NN → NΔ scattering can also cause a splitting of the suppression factors for the Δ production cross sections in different channels.

$$\sigma^*_{NN\to N\Delta}(\rho) = \sigma_{NN\to N\Delta}\, e^{-\alpha^{\pm}(\rho/\rho_0)^{3/2}}, \quad (10)$$

where α^+ corresponds to the constant factor to be used for Δ^+ and Δ^{++} production and α^- is to be used for the Δ^0 and Δ^- channels. For the in-medium Δ absorption cross sections $\sigma^*_{N\Delta\to NN}$,

$\sigma_{NN\to N\Delta}$ ($\alpha^+ = \alpha^- = 0$) and $\sigma^*_{NN\to N\Delta}$ with $\alpha^+ = \alpha^- = 0.6$ and with $\alpha^+ = 0.39$ and $\alpha^- = 0.7$ (see Eq. (10)). Experimental results are from Ref. [35].

	M(π^-)	M(π^+)
HADES	$11.1 \pm 0.6 \pm 0.6$	$6.0 \pm 0.3 \pm 0.3$
$\alpha^+ = \alpha^- = 0$	17.2	8.7
$\alpha^+ = \alpha^- = 0.6$	11.8	5.4
$\alpha^+ = 0.39,\ \alpha^- = 0.7$	11.3	6.2

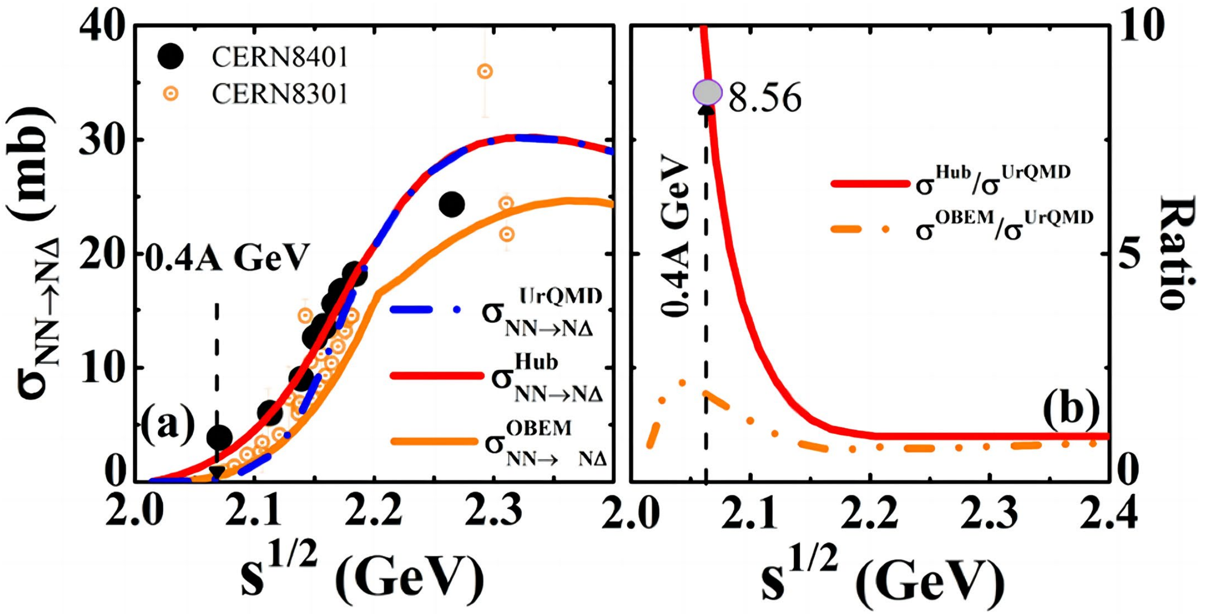


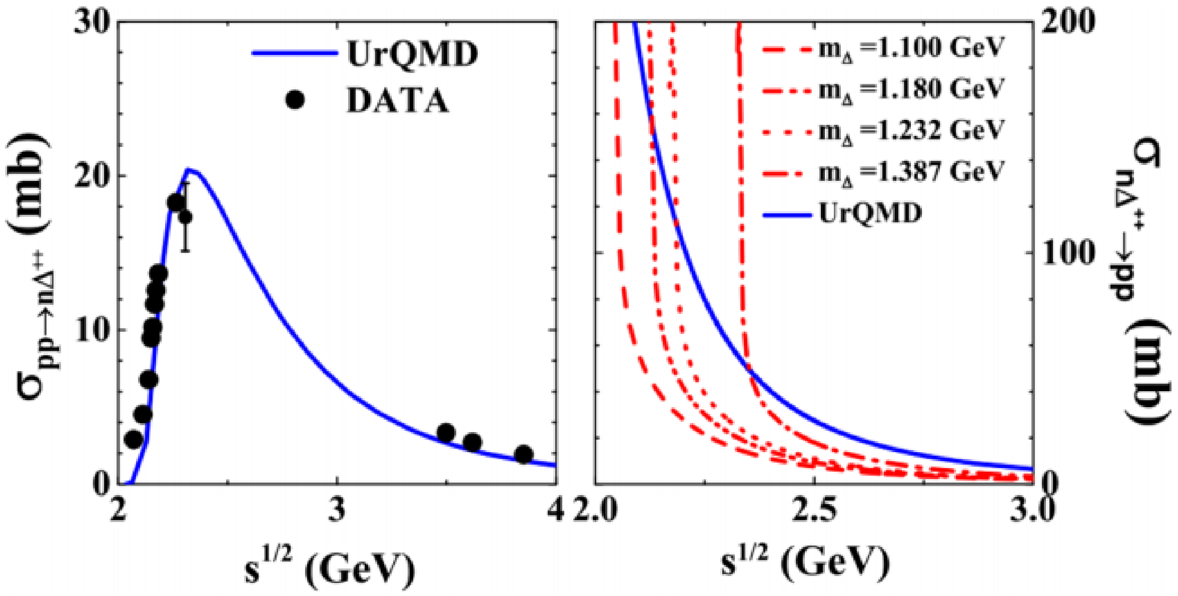
[52] Q. Li, Z. Li, Phys. Lett. B (ISSN 0370-2693) 773 (2017) 557, https://www.sciencedirect.com/science/article/pii/S0370269317307116.

→K. Godbey, Z. Zhang, J. W. Holt and C. M. Ko, Phys. Lett. B 829, 137134 (2022).

IV、NN ↔ NΔ cross section

➢ NN→NΔ cross section in UrQMD





- The $\sigma^{UrQMD}_{NN\to N\Delta}$ underestimated the data by approximately 3 mb at 0.4A GeV.
- Hubbert function form:

$$\sigma_{NN\to N\Delta}(\sqrt{s}) = A_1 + \frac{4A_2 \times e^{-(\sqrt{s}-A_3)/A_4}}{(1+e^{-(\sqrt{s}-A_3)/A_4})^2}, \quad \sqrt{s} < 2.21\,\mathrm{GeV}$$

- Δ mass dependence of the NΔ → NN cross section.

$$\sigma^{OBEM}_{N\Delta\to NN}(\sqrt{s}, m_\Delta) = \frac{1}{1+\delta_{N_1N_2}} \frac{1}{64\pi^2} \int \frac{|\mathbf{p}'_{12}|}{\sqrt{s_{34}}\sqrt{s_{12}}|\mathbf{p}'_{34}(m_\Delta)|} \times \overline{|\mathcal{M}_{N\Delta(m_\Delta)\to NN}|^2} d\Omega,$$

→ Y. Y. Liu, Y. J. Wang, Y. Cui, C. J. Xia, Z. X. Li, Y. J. Chen, Q. F. Li and Y. X. Zhang, Phys. Rev. C 103, 014616 (2021).
→ Y. Y. Liu, J. P. Yang, Y. J. Wang, Q. F. Li, Z. X. Li, C. J. Xia and Y. X. Zhang, Nucl. Sci. Tech. 36, 45 (2025)

IV、NN ↔ NΔ cross section

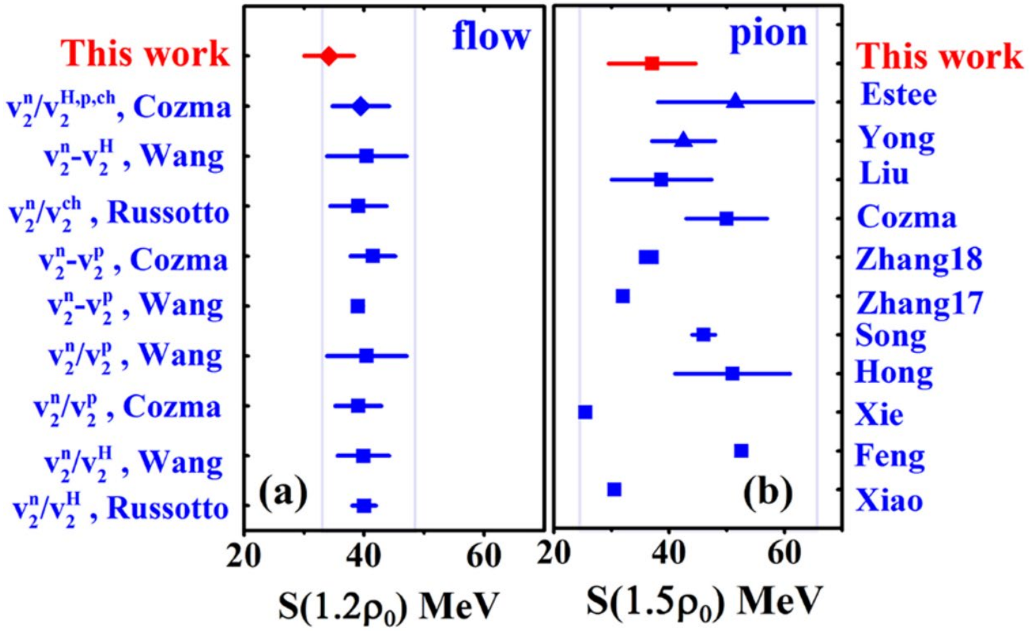
➢ Symmetry energy at characteristic densities

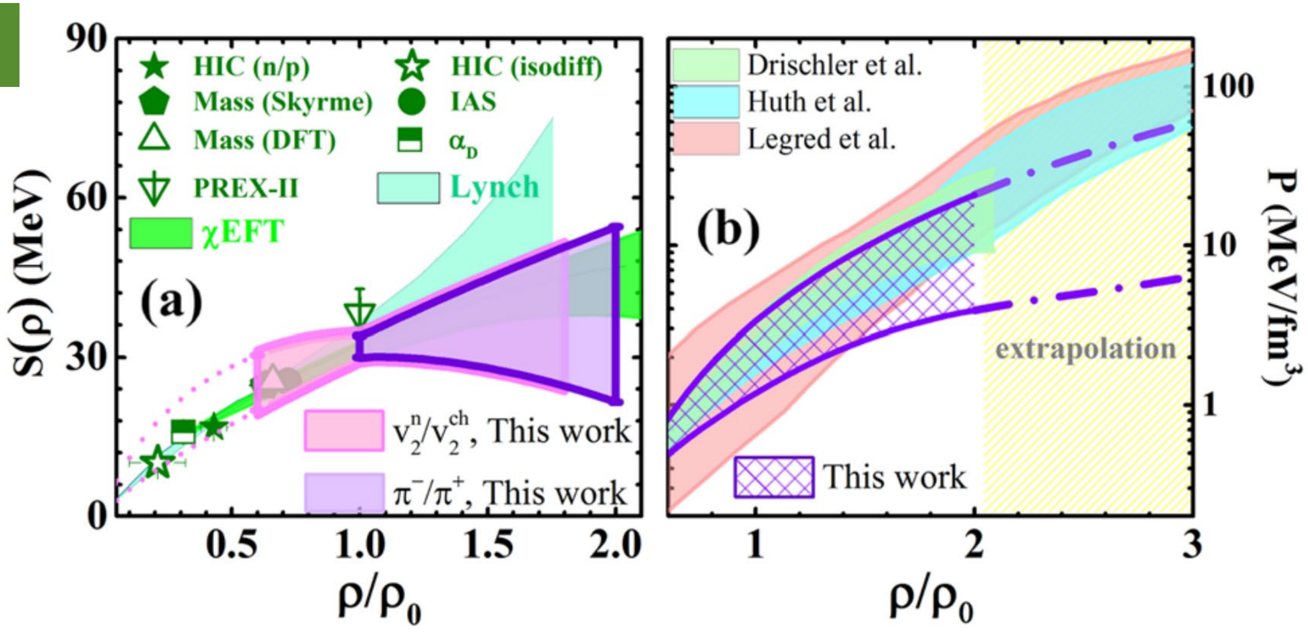
the momentum change in the reaction plane

$$\langle\rho\rangle^{\text{flow}}_{\text{char},|\Delta p_x|}=\frac{\int_{t_0}^{t_1}\Sigma_i|\Delta p_x^i(t)/\Delta t|\rho_c(t)\mathrm{d}t}{\int_{t_0}^{t_1}\Sigma_i|\Delta p_x^i(t)/\Delta t|\mathrm{d}t}$$

the momentum change in the transverse direction

$$\langle\rho\rangle^{\text{flow}}_{\text{char},|\Delta p_t|}=\frac{\int_{t_0}^{t_1}\Sigma_i|\Delta p_t^i(t)/\Delta t|\rho_c(t)\mathrm{d}t}{\int_{t_0}^{t_1}\Sigma_i|\Delta p_t^i(t)/\Delta t|\mathrm{d}t}$$





flow: $1.2 \pm 0.6\ \rho_0$ pion: $1.5 \pm 0.5\ \rho_0$

$S(1.2\rho_0) = 34 \pm 4$ MeV $L = 5{\sim}70$ MeV

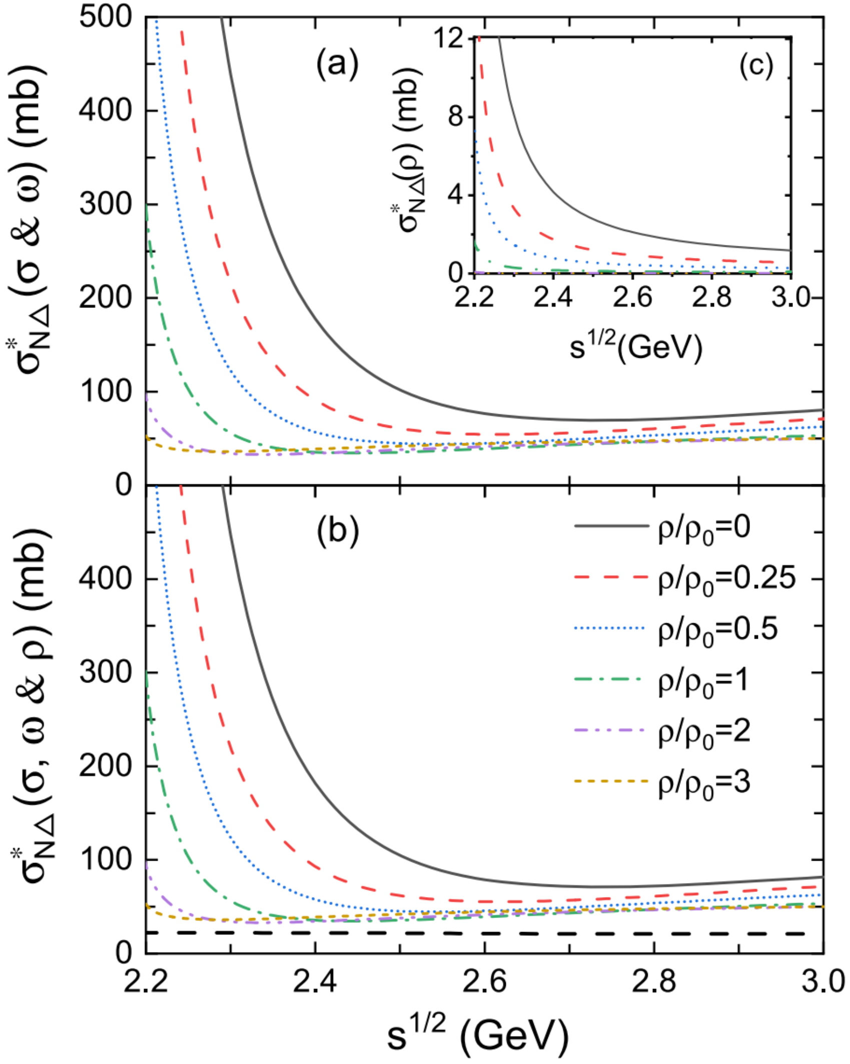
$S(1.5\rho_0) = 36 \pm 8$ MeV $S_0 = 30{\sim}40$ MeV

- Overlaps with the constraints from the theoretical calculation using the chiral efective fIeld theory (χEFT).

→ Y. Y. Liu, J. P. Yang, Y. J. Wang, Q. F. Li, Z. X. Li, C. J. Xia and Y. X. Zhang, Nucl. Sci. Tech. 36, 45 (2025)

IV、NΔ → NΔ elastic cross section

➢ Density dependence (σ, ω, ρ meson field)



$$L_I = g^{\sigma}_{NN}\bar{\Psi}\Psi\sigma - g^{\omega}_{NN}\bar{\Psi}\gamma_\mu\Psi\omega^\mu - g^{\rho}_{NN}\bar{\Psi}\gamma_\mu\boldsymbol{\tau}\cdot\Psi\boldsymbol{\rho}^\mu$$
$$+ g^{\sigma}_{\Delta\Delta}\bar{\Psi}_\Delta\Psi_\Delta\sigma - g^{\omega}_{\Delta\Delta}\bar{\Psi}_\Delta\gamma_\mu\Psi_\Delta\omega^\mu$$
$$- g^{\rho}_{\Delta\Delta}\bar{\Psi}_\Delta\gamma_\mu\boldsymbol{\tau}\cdot\Psi_\Delta\boldsymbol{\rho}^\mu.$$

Also, in the coupling ‘constants’:

$$g^i_{NN}(\rho) = g_i(\rho_{sat})f_i(\xi), \quad i=\sigma,\omega, \quad f_i(\xi) = a_i\frac{1+b_i(\xi+d_i)^2}{1+c_i(\xi+d_i)^2}, \quad \xi = \frac{\rho}{\rho_{sat}}.$$

$$g^{\rho}_{NN}(\rho) = g_\rho(\rho_{sat})e^{-a_\rho(\xi-1)}. \qquad \frac{g^{\sigma}_{\Delta\Delta}}{g^{\sigma}_{NN}} = 1.0, \quad \frac{g^{\omega}_{\Delta\Delta}}{g^{\omega}_{NN}} = 0.8, \quad \frac{g^{\rho}_{\Delta\Delta}}{g^{\rho}_{NN}} = 0.7;$$

1. A. R. Raduta, Phys. Lett. B 814, 136070 (2021).
2. G. A. Lalazissis, T. Niksic, D. Vretenar, and P. Ring, Phys. Rev. C 71, 024312 (2005).

➢ An overall suppression of $N\Delta \rightarrow N\Delta$ cross section, especially at low energies.

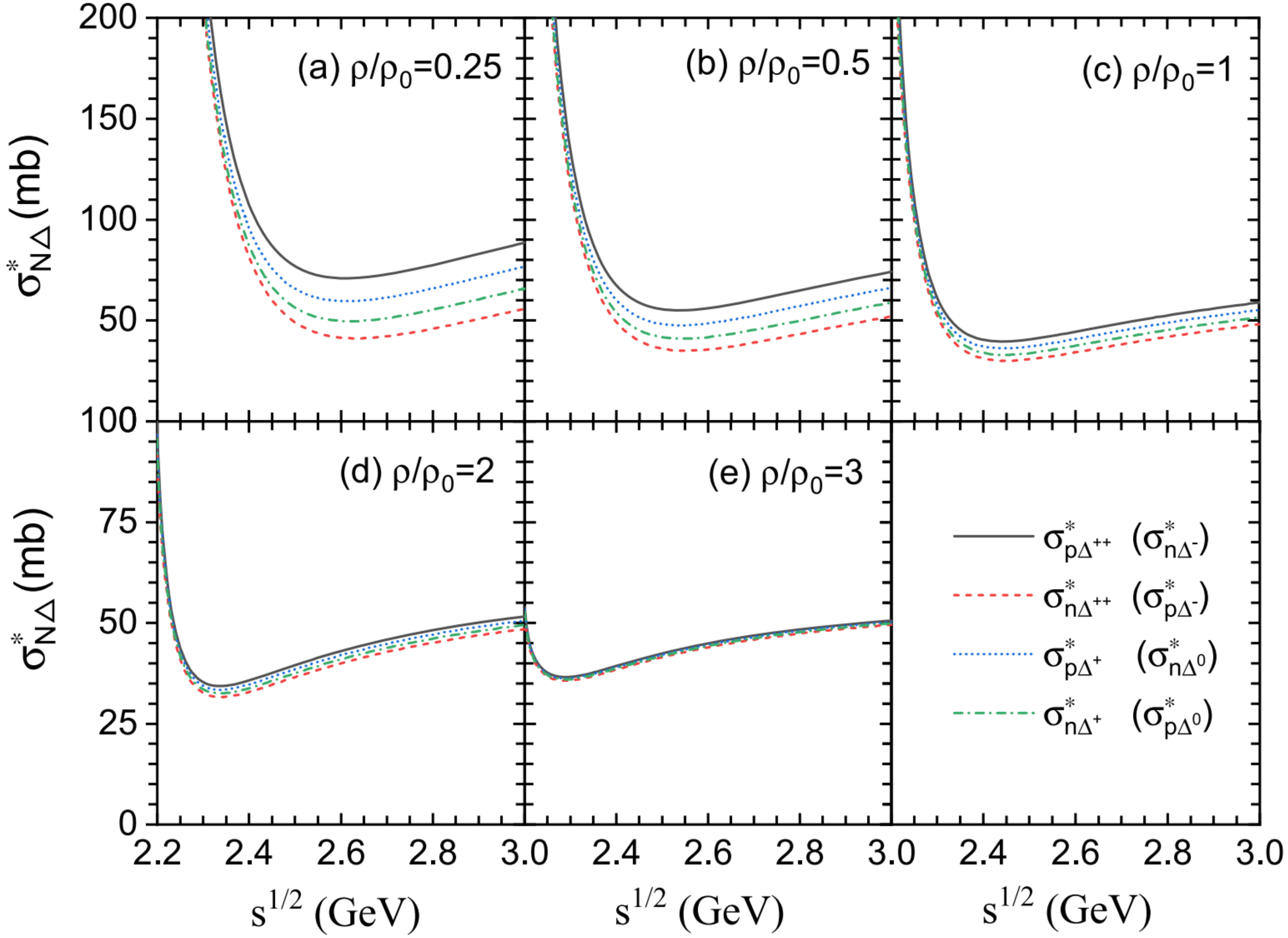
➢ Due to the density-dependent coupling constants adopted in this work, the decrease in cross section with density is faster.

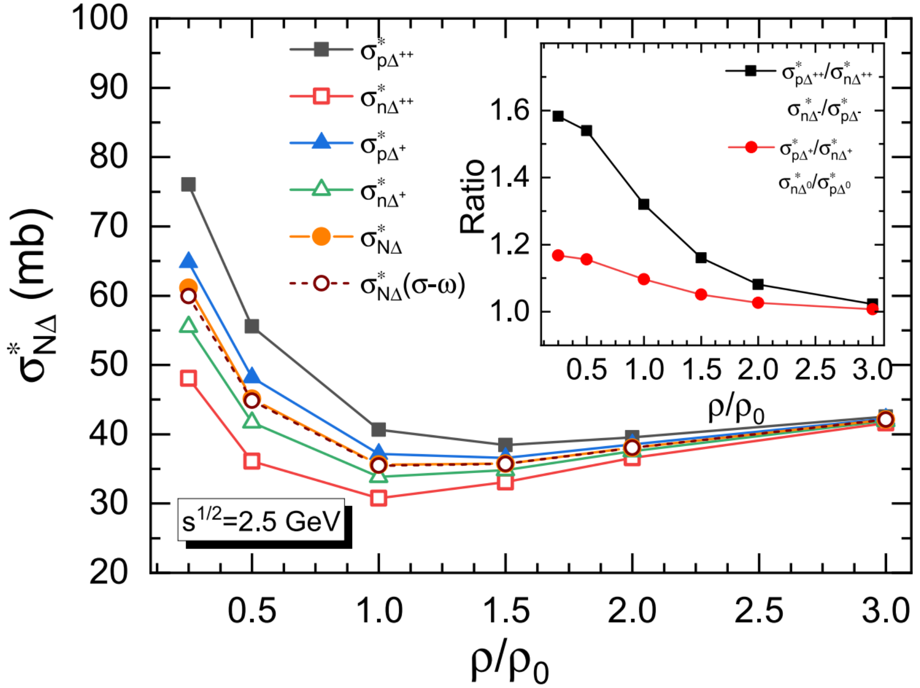
➢ Compared to σ and ω, the contribution of ρ meson exchange is weak especially at high energies.

→ M. Z. Nan, P. C. Li, Y. J. Wang, Q. F. Li, W. Zuo, Eur. Phys. J. A 60, 131 (2024).

IV、NΔ → NΔ elastic cross section

➢ Density dependence (σ, ω, ρ meson field)





➢ The inclusion of ρ meson exchange leads to obvious isospin effect especially at low densities.

➢ With increasing density, the isospin effect is fading away…

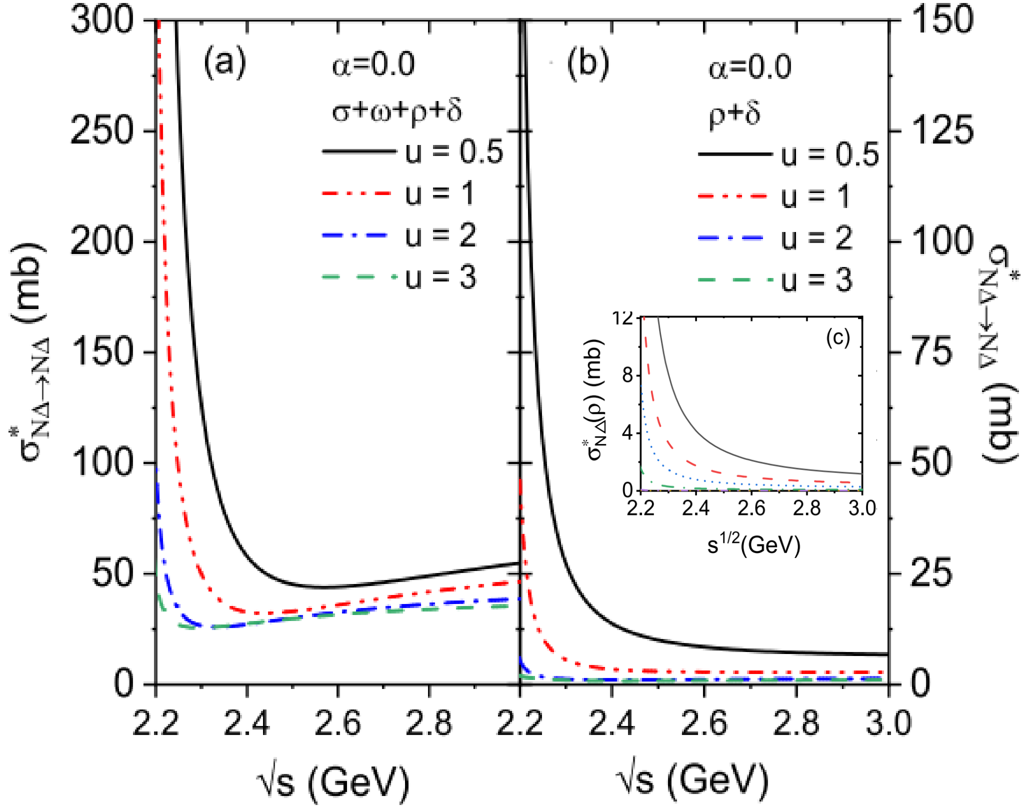
➢ When the density reaches 3ρ0, the isospin effect almost disappears.

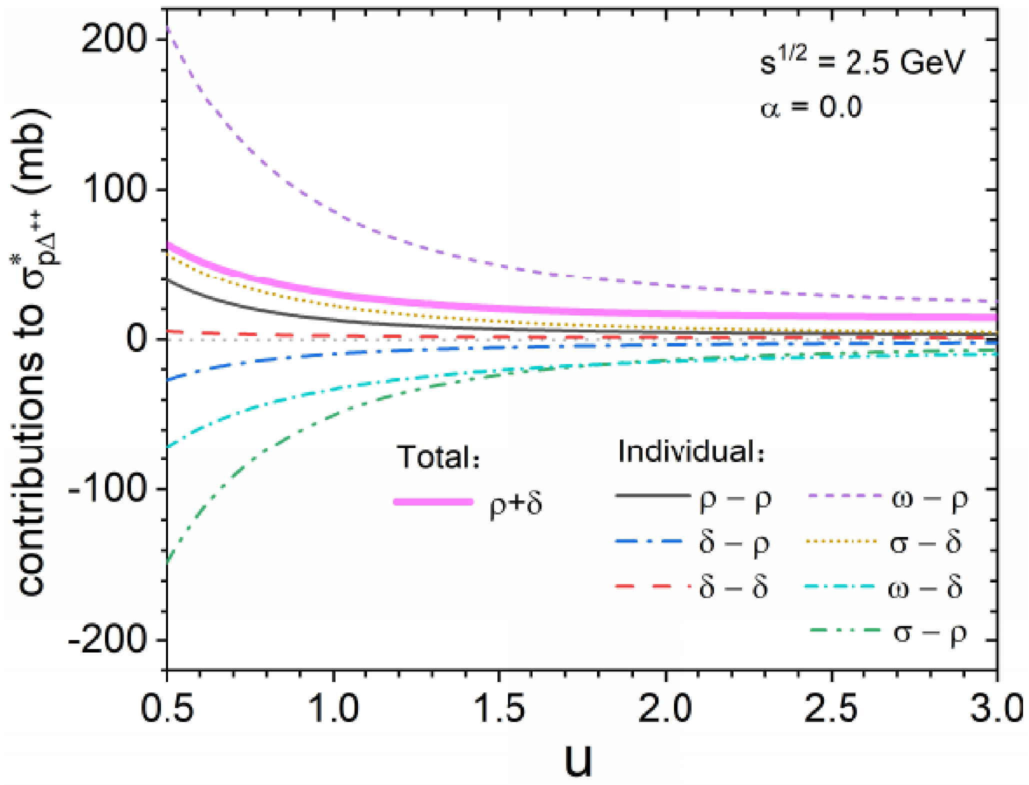
→ M. Z. Nan, P. C. Li, Y. J. Wang, Q. F. Li, W. Zuo, Eur. Phys. J. A 60, 131 (2024).

IV、 NΔ → NΔ elastic cross section

➢ Density dependence ($\sigma, \omega, \rho, \delta$ meson field)

→ M. Z. Nan, P. C. Li, Q. F. Li, W. Zuo, [arXiv:2412.13497 [nucl-th]]



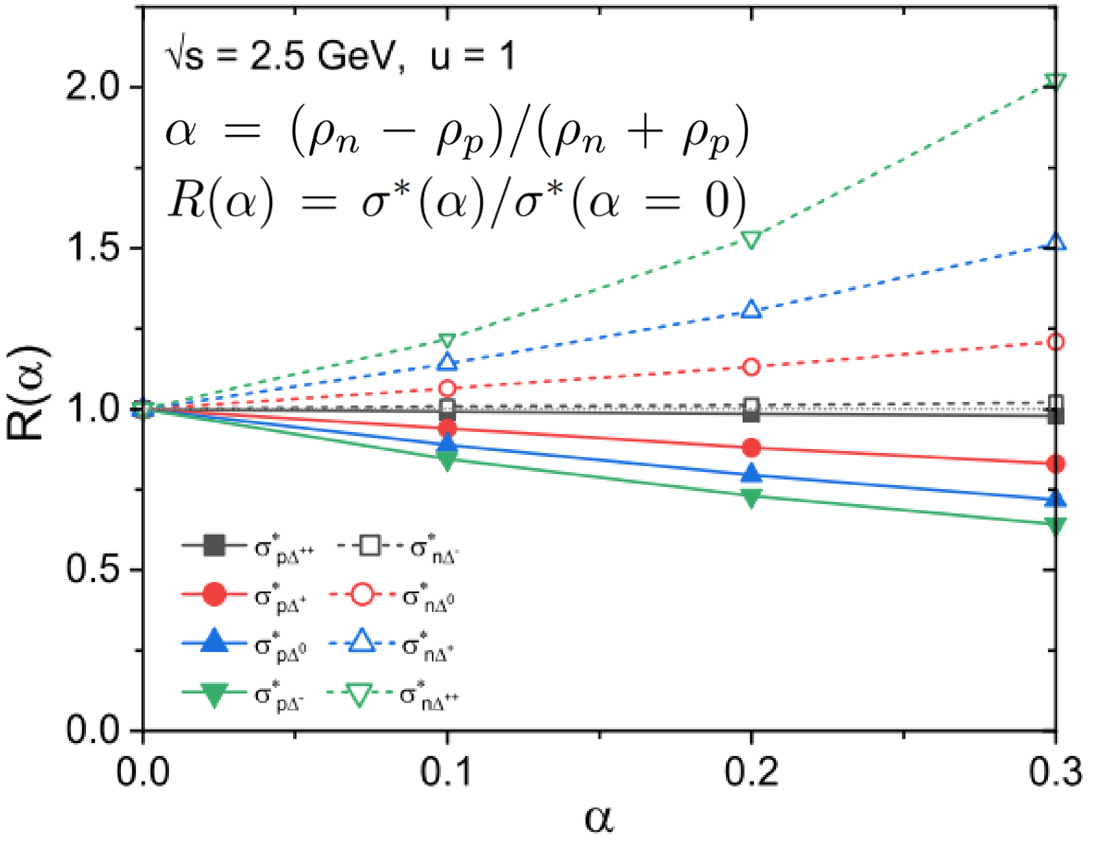


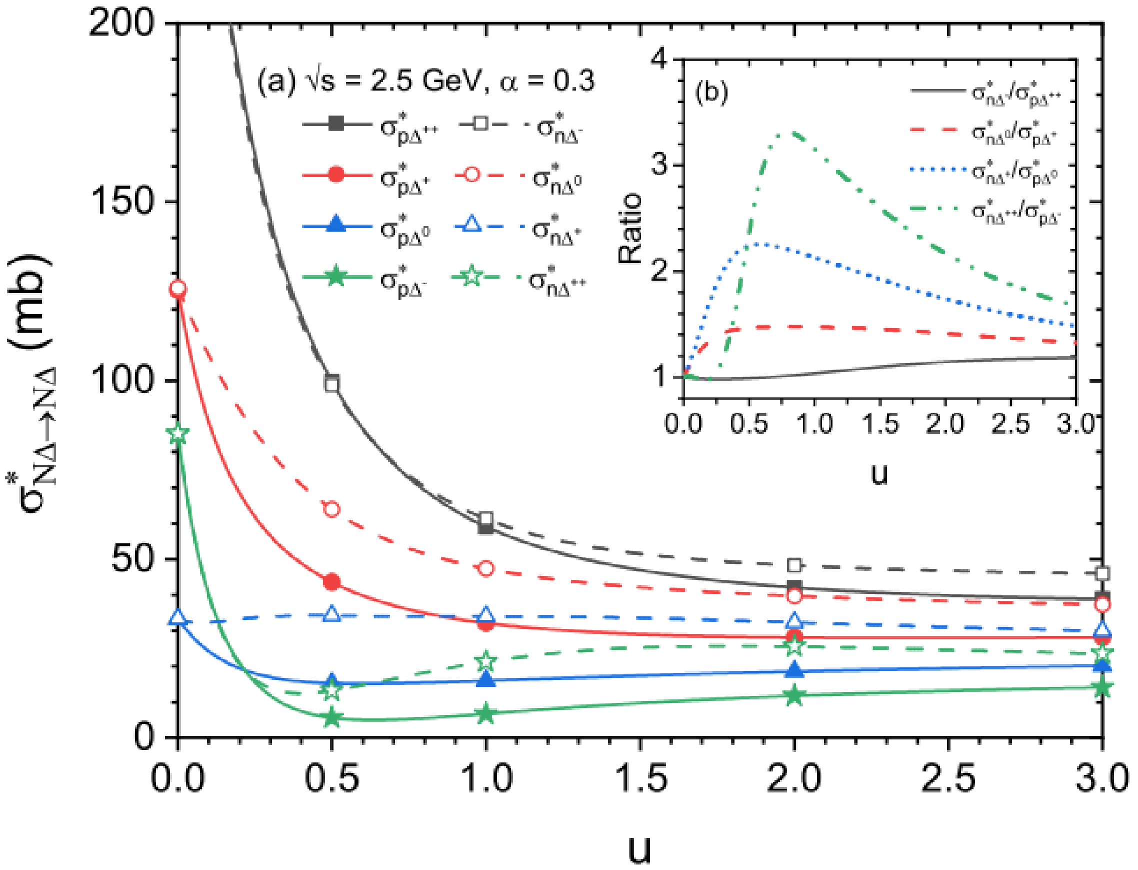
- $\sigma^*_{N\Delta}$ decreases with increasing density, indicating a visible density dependent suppression of nuclear medium.
- The ρ and δ meson related-terms have a larger contribution than that of ρ meson field.
- The contribution of each meson exchange term decreases with increasing reduced density, the baryon-baryon-meson coupling constants and the effective masses of nucleons and Δ particles.
- Obvious cancellation effect, but the net-contribution of ρ and δ related exchange terms to the $\sigma^*_{p\Delta^{++}}$ is larger than 0.

IV、NΔ → NΔ elastic cross section

➢ Density dependence ($\sigma, \omega, \rho, \delta$ meson field)

→ M. Z. Nan, P. C. Li, Q. F. Li, W. Zuo, [arXiv:2412.13497 [nucl-th]]

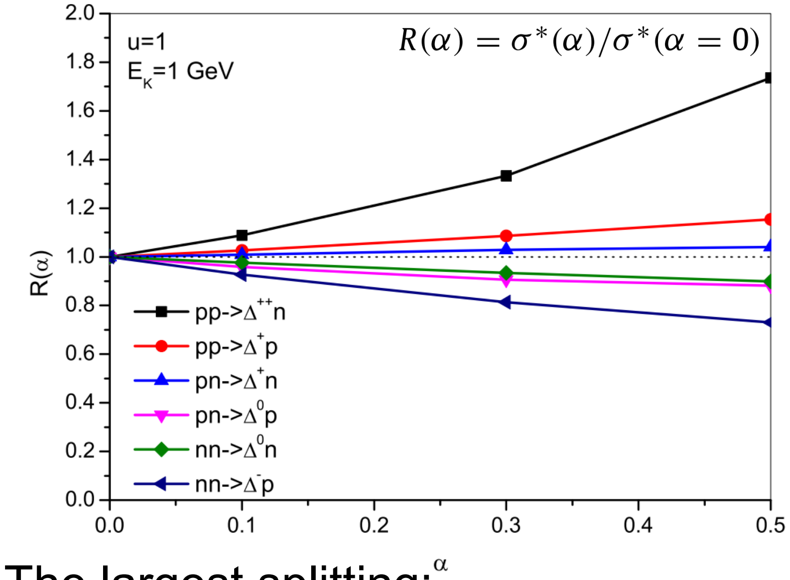


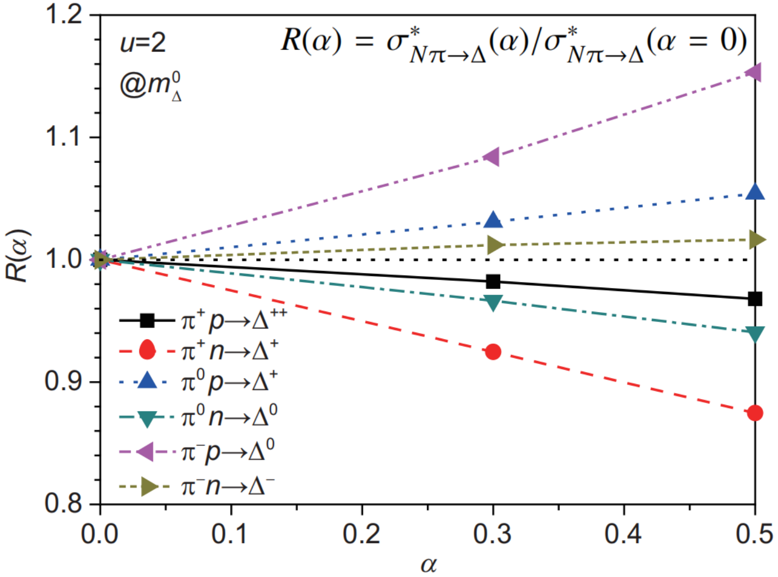


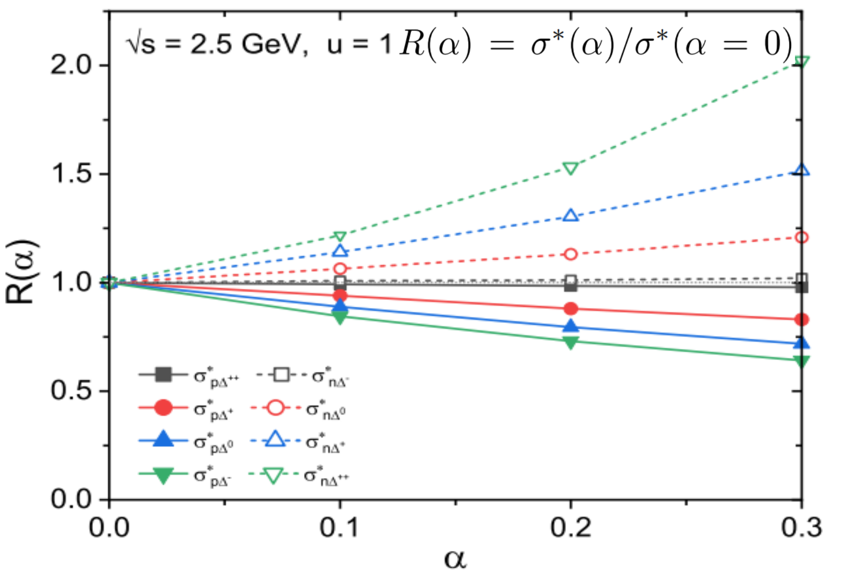
- $R(\alpha)$ for pΔ channels is decreased, while that for nΔ channels is increased as α increases from 0.0 to 0.3, since the contribution of δ meson exchange to the effective masses of protons, neutrons and Δ-isobars have opposite signs.
- The isospin effect, which introduced by isovector ρ and δ meson fields, in NΔ → NΔ channel should not be negligible even at such a high energy and density.

IV、Δ-related cross sections

➢ Isospin dependence ($\sigma, \omega, \rho, \delta$ meson field)







The largest splitting:

$$pp \rightarrow n\Delta^{++} \quad \ldots \quad nn \rightarrow p\Delta^{-}$$

$$\pi^{-}p \rightarrow \Delta^{0} \quad \ldots \quad \pi^{+}n \rightarrow \Delta^{+}$$

$$n\Delta^{++} \rightarrow n\Delta^{++} \quad \ldots \quad p\Delta^{-} \rightarrow p\Delta^{-}$$

The smallest splitting:

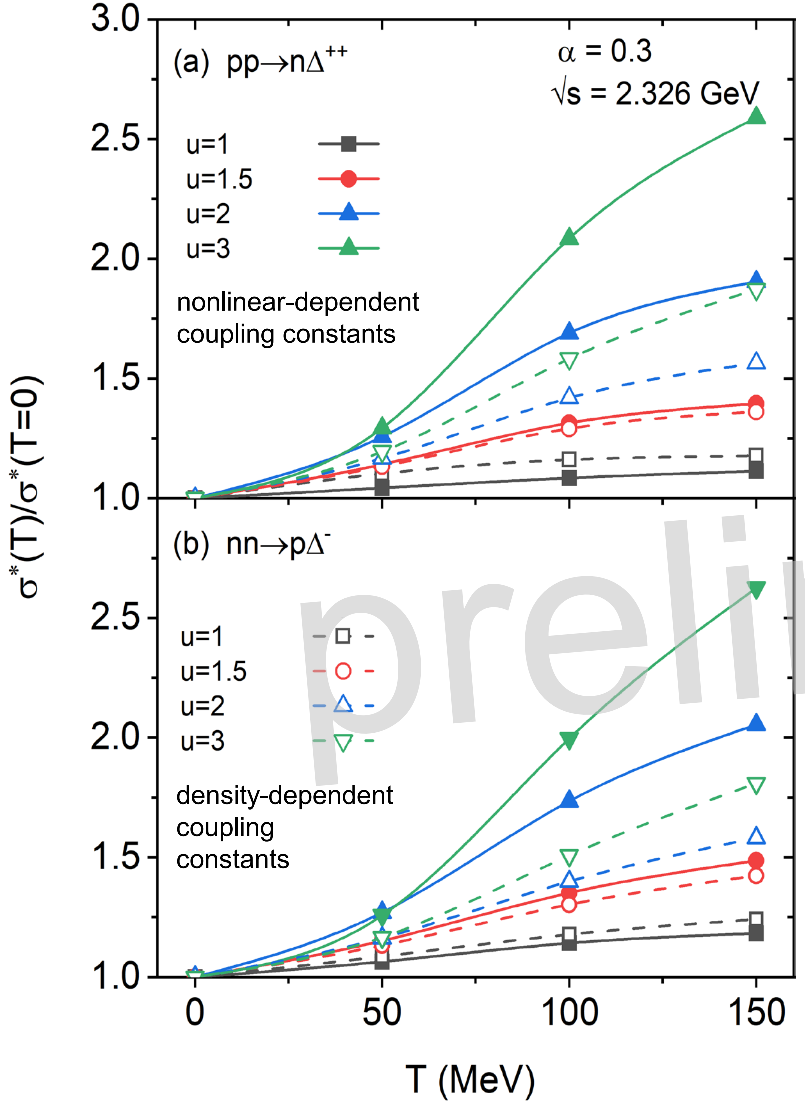
$$pn \rightarrow n\Delta^{+} \quad \ldots \quad nn \rightarrow n\Delta^{0}$$

$$\pi^{-}n \rightarrow \Delta^{-} \quad \ldots \quad \pi^{+}p \rightarrow \Delta^{++}$$

$$p\Delta^{++} \rightarrow p\Delta^{++} \quad \ldots \quad n\Delta^{-} \rightarrow n\Delta^{-}$$

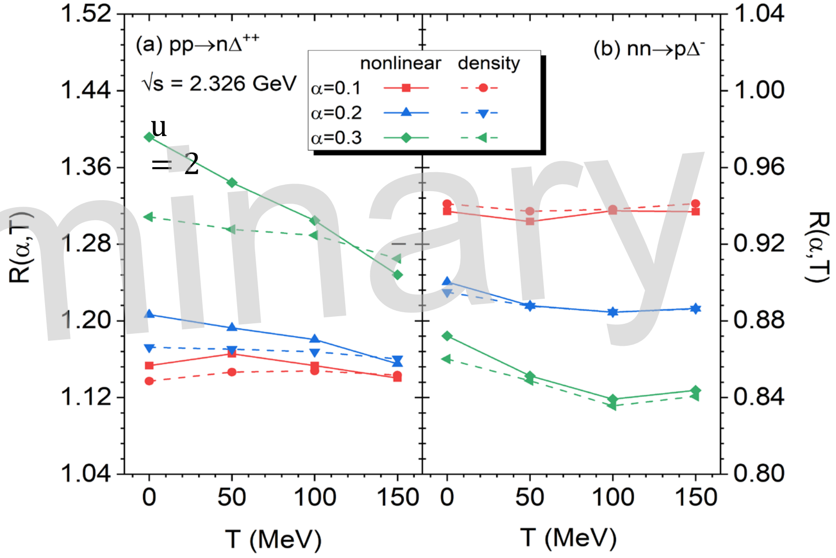
IV、T dependent NN → NΔ cross section

➢ Temperature dependence



$$U_{NL}(\sigma,\omega^{\mu},\vec{\delta},\vec{\rho}^{\mu}) = \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4 - \Lambda_s({g^{\sigma}_{NN}}^2\sigma^2)({g^{\delta}_{NN}}^2\vec{\delta}^2) - \Lambda_v({g^{\omega}_{NN}}^2\omega_{\mu}\omega^{\mu})({g^{\rho}_{NN}}^2\vec{\rho}_{\mu}\cdot\vec{\rho}^{\mu}).$$

$$\begin{aligned} L_I =& g^{\sigma}_{NN}\bar{\Psi}\Psi\sigma + g^{\delta}_{NN}\bar{\Psi}\vec{\tau}\cdot\Psi\vec{\delta} - g^{\omega}_{NN}\bar{\Psi}\gamma_{\mu}\Psi\omega^{\mu} \\ &- g^{\rho}_{NN}\bar{\Psi}\gamma_{\mu}\vec{\tau}\cdot\Psi\vec{\rho}^{\mu} + g^{\sigma}_{\Delta\Delta}\bar{\Psi}_{\Delta}\Psi_{\Delta}\sigma + g^{\delta}_{\Delta\Delta}\bar{\Psi}_{\Delta}\vec{\tau}\cdot\Psi_{\Delta}\vec{\delta} \\ &- g^{\omega}_{\Delta\Delta}\bar{\Psi}_{\Delta}\gamma_{\mu}\Psi_{\Delta}\omega^{\mu} - g^{\rho}_{\Delta\Delta}\bar{\Psi}_{\Delta}\gamma_{\mu}\vec{\tau}\cdot\Psi_{\Delta}\vec{\rho}^{\mu} \\ &+ g^{\pi}_{NN}\bar{\Psi}\gamma_{\mu}\gamma_5\vec{\tau}\cdot\Phi\partial^{\mu}\vec{\pi} - g^{\pi}_{N\Delta}\bar{\Psi}_{\Delta\mu}\partial^{\mu}\vec{\pi}\cdot S^{+}\Psi \\ &- g^{\pi}_{N\Delta}\Psi S\bar{\Psi}_{\Delta\mu}\cdot\partial^{\mu}\vec{\pi}, \end{aligned}$$



- Nonlinear-dependent coupling constants

$$g_{\sigma} = 9.22, g_{\omega} = 11.3$$
$$g_2 = 13.08\ \mathrm{fm}^{-1}, g_3 = -31.60\ \mathrm{fm}^{-1}$$
$$g_{\delta}^2/4\pi = 2.488 \quad g_{\rho}^2/4\pi = 3.39$$
$$\Lambda_{\sigma\delta} = 50, \quad \Lambda_{\omega\rho} = 173.77$$

R. Machleidt, Adv. Nucl. Phys. 19, 189 (1989).
N. Zabari, S. Kubis, and W. Wojcik, Phys. Rev. C 100, 015808 (2019)

- Density-dependent coupling constants

DD-MEδ

X. Roca-Maza, X. Vinas, M. Centelles, P. Ring and P. Schuck, Phys. Rev. C 84, 054309 (2011)

➢ at the density $<1.5\rho_0$, results from two channels close to each other.

➢ As the density increases, the T dependence increases.

➢ As the isospin asymmetry increases, the T dependence increases.

V、Summary and outlook

- The non-equilibrium dynamic theory and model are critical to understanding the dense nuclear matter;
- The self-consistent RBUU transport theory is further developed;
- The energy-, density-, isospin-, and temperature-dependent NN→NN、NN→NΔ、Nπ → Δ、NΔ → NΔ cross sections are analyzed within sc-RBUU framework, and partly introduced into the UrQMD model;
- The influence of the in-medium effects of cross-section on EoS sensitive observables should be carefully considered.

- Analyzing the differences between the HIC and neutron star environments: composition, isospin asymmetry, temperature, gravity, ...;
- Effects of different compositions on the EoS;
- Parameterize the cross-section and introduce it into the microscopic transport model;
- Multi-observables Bayesian inference.

感谢聆听 欢迎合作！

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