Hyperon potentials in dense matter from chiral EFT evaluated via heavy-ion collisions

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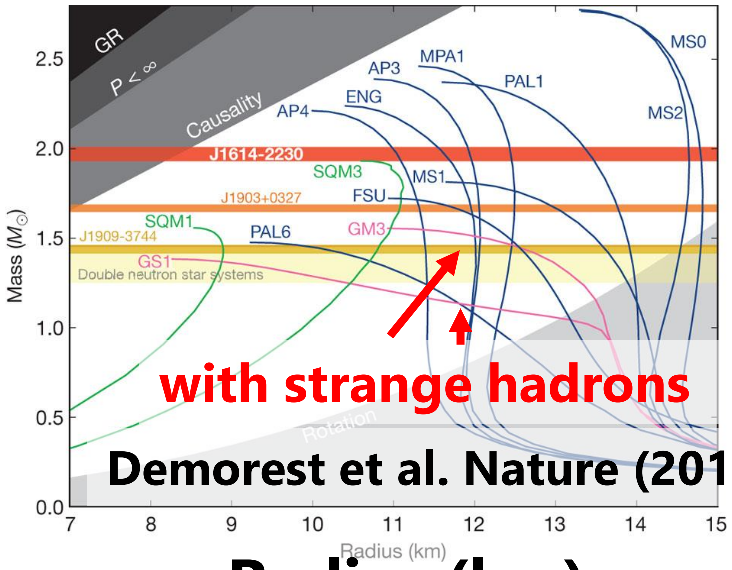
- **Hyperon puzzle of neutron stars and Λ potential**
- **Λ and Σ potentials by chiral YN+YNN forces at NLO**
- **Λ and Σ directed flows**

HIN2025, YITP, April 2-4, 2025

Hyperon puzzle of neutron stars

- (1990-) Hyperons appear within $2-4\rho_0$ in neutron star matter, often resulting in softening of equation of state. e.g. S. Nishizaki, T. Takatsuka, and Y. Yamamoto, Prog. Theor. Phys. 108 (2002) 703.
- The softening problem becomes more serious since the observation of the massive ($2M_{\odot}$) neutron stars first reported in 2010.

Neutron star mass (Solar mass $M_{\odot}$)



Demorest et al. Nature (2010)

Radius (km)

Example of solutions:

1. Suppressing the appearance of hyperons: Repulsive YNN and/or YY forces
2. Avoiding phase transition: Quarkyonic matter, quark-hadron continuity
   e.g. Baym, Hatsuda, Kojo, Powell, Song, & Takatsuka (2018)

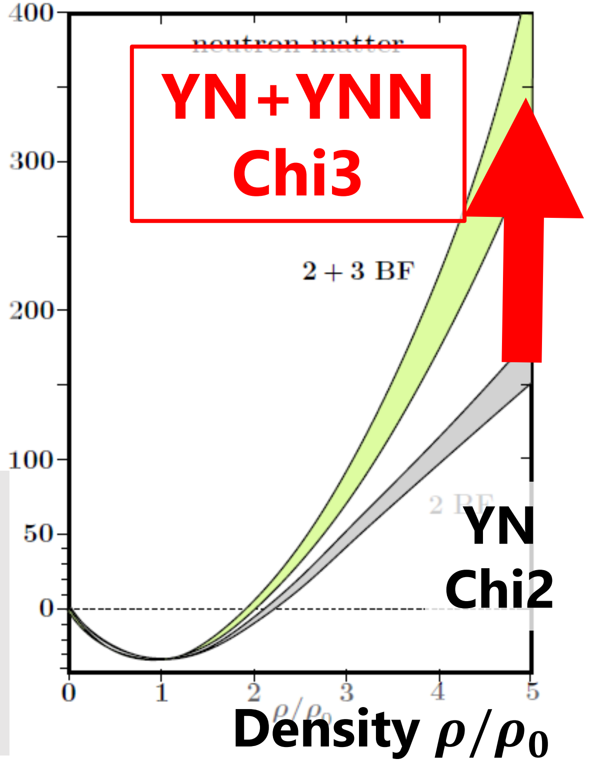
YNN three-body force from chiral EFT

- **Phenomenological YNN three-body force in dense matter** Nishizaki, Yamamoto, & Takatsuka (2002); Lonardoni et al. (2015); Togashi, Hiyama, Yamamoto, & Takano (2016); Friedman & Gal (2023) etc.
- **Chiral effective field theory** **(NLO YN + NLO promoted YNN via decuplet saturation)** **Kohno(2018),** **<u>D. Gerstung, N. Kaiser, and W. Weise (2020)</u>**

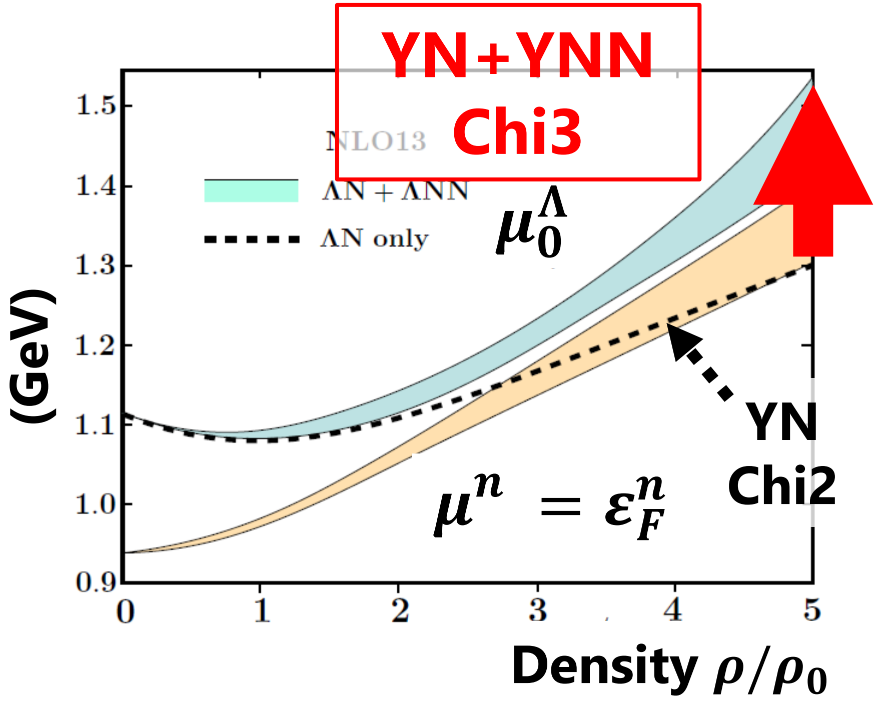
Λ single-particle potential in nuclear matter U_Λ (MeV)

Nuclear matter

Λ



$$\mu_0^\Lambda(\rho) = m_\Lambda + U_\Lambda(\rho)$$



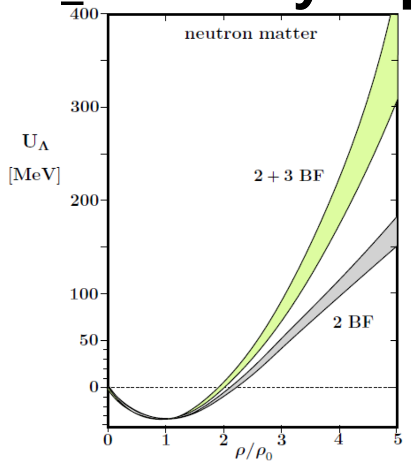
Λ does not appear even at high densities!

Avoiding hyperon puzzle!?

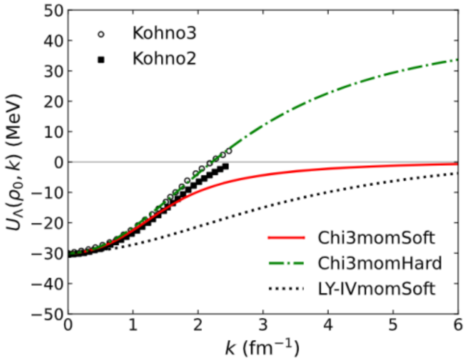
Our previous studies

We have verified that the Λ single-particle potential strongly repulsive at high densities is consistent with two experimental data.

U_Λ Density dep.



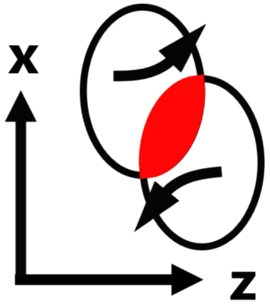
U_Λ Momentum dep.

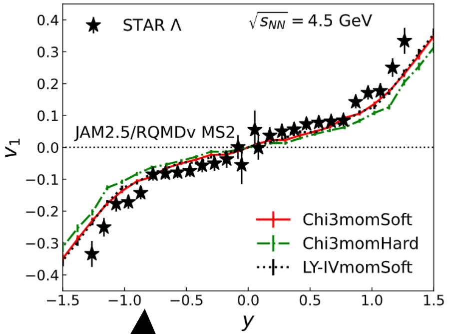


Nuclear matter

Density dep.: D. Gerstung. N. Kaiser, & W. Weise (2020)
Kohno2 (Kohno3): M. Kohno (2018).
Chiral EFT calculation with YN (YN+YNN) interaction.
Chi3: Fitted to the results from chiral EFT.
LY-IV: Lanskoy and Yamamoto (1997).
Skyrme-type Λ potential reproducing Λ binding energies.

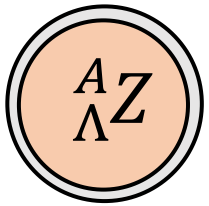
Heavy-ion collision data (Λ+Σ0 directed flow)

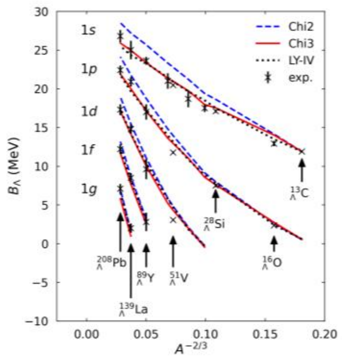




Y. Nara, AJ, K. Murase, & A. Ohnishi, PRC 106, 044902(2022).
(The calculation is done with the new version of JAM2.)

Λ hypernuclear spectroscopy



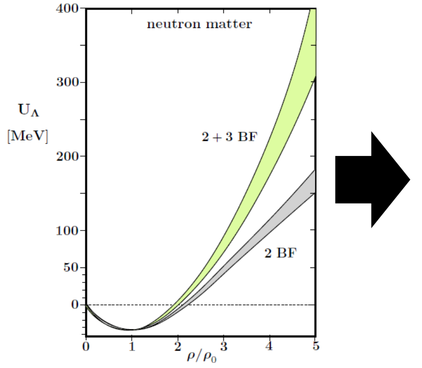


AJ, K. Murase, Y. Nara, & A. Ohnishi, PRC 108, 065803 (2023).

All hyperons feel the same potential as Λ one.

Σ potential should be implemented!

- **Y. Nara, AJ, K. Murase, & A. Ohnishi, PRC 106, 044902(2022).**
  All hyperons and their resonances feel same single-particle potential as Λ.



Λ, Σ, Ξ, Y*

- **The Λ and Σ single-particle potentials have a completely different behavior as reflected in the empirical values:**

  $U\_\Lambda(\rho_0) \approx -30$ MeV (Λ hypernuclear spectroscopy)
  $U\_\Sigma(\rho_0) = 30 \pm 20$ MeV (based on Σ^- atom data and (π^+, K^+) inclusive spectra)

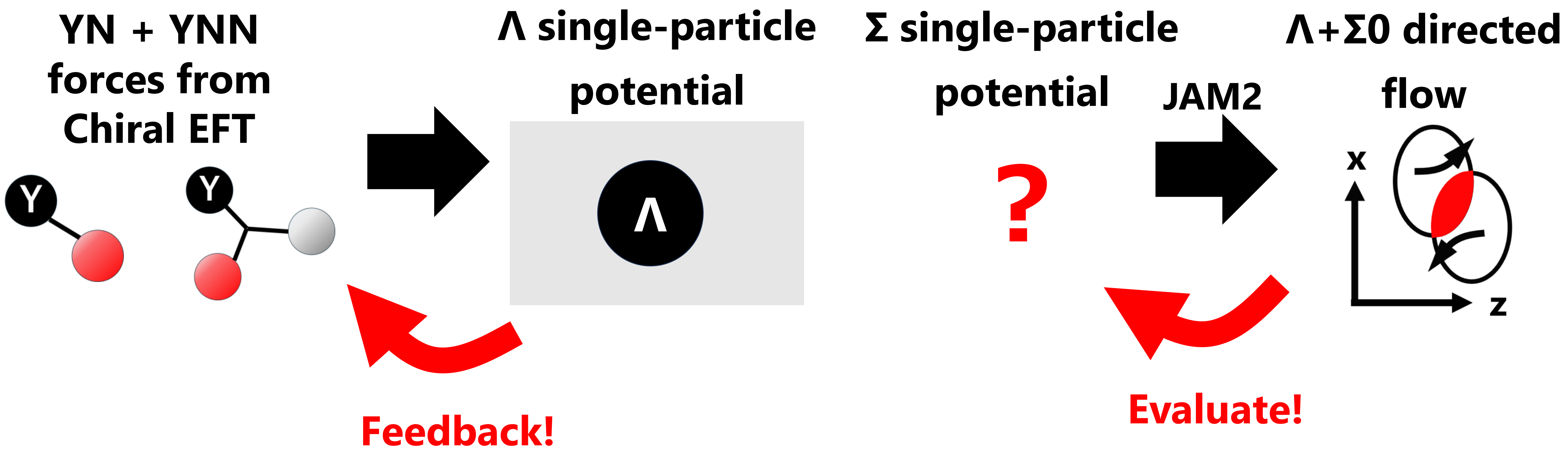
  A. Gal, E. V. Hungerford, & D. J. Millener (2016).

- **The current Λ directed flow is calculated as the Λ+Σ0 directed flow.**
  cf. $\Sigma^0 \rightarrow \gamma + \Lambda$ (~100%)

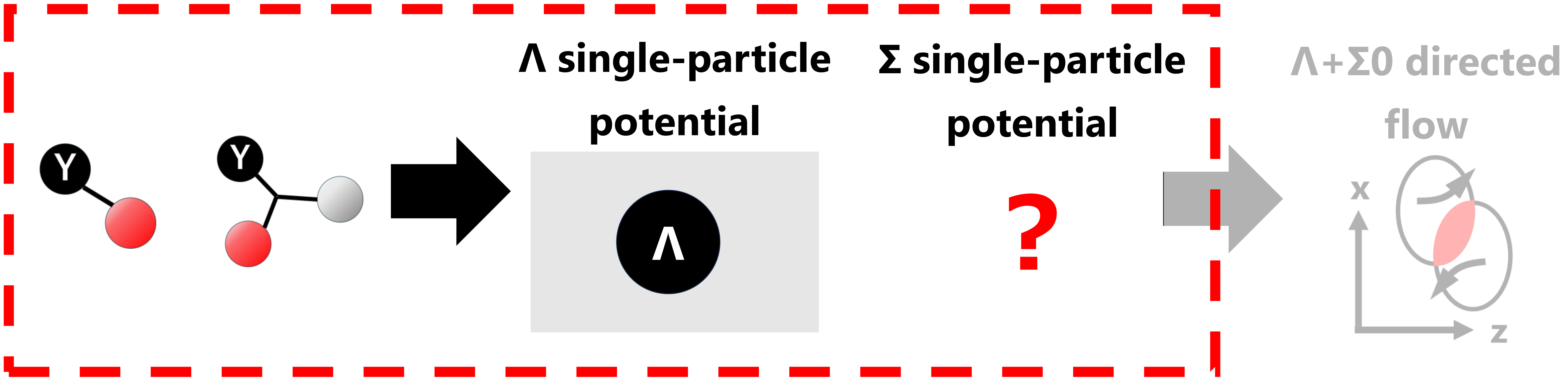
Σ potential may affect the Λ+Σ^0 dynamics in heavy-ion collisions and can be constrained by data!

Purpose of this research

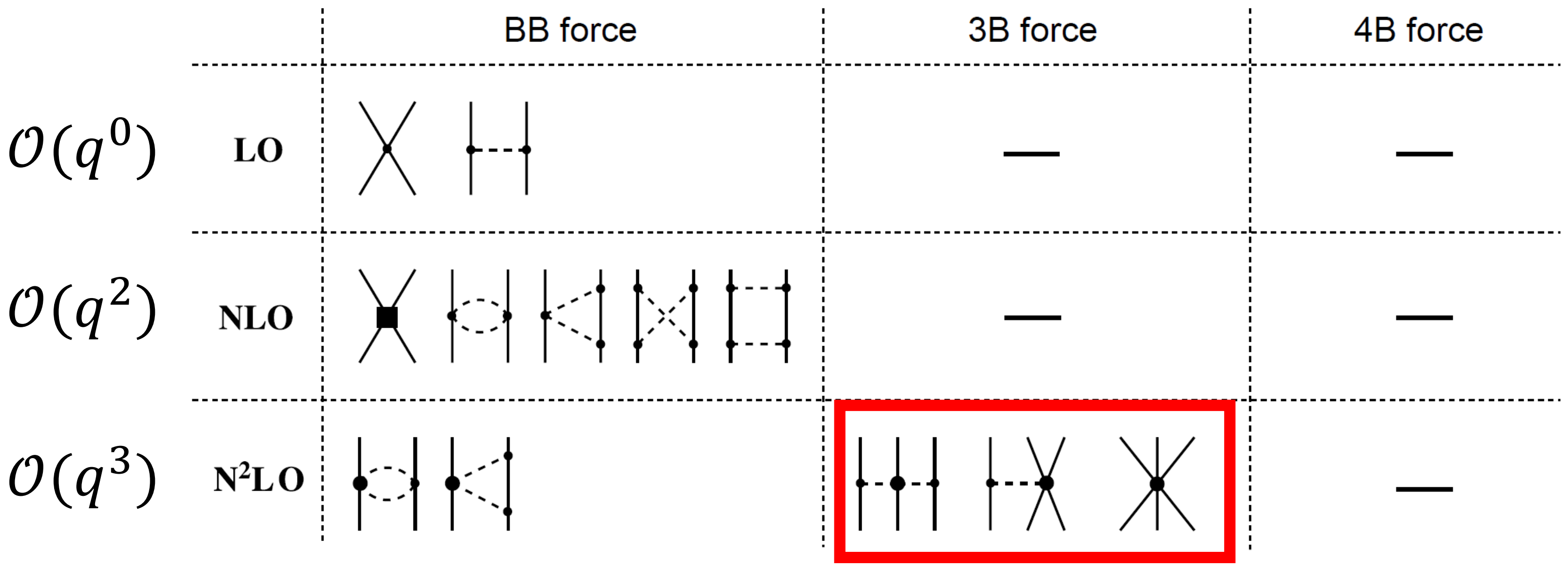
1. **Calculating the Σ potential in nuclear matter based on chiral EFT.**
2. **Implementing the Σ potential to JAM2 and examining its dependence on the Λ+Σ0 directed flow.**



Λ and Σ potentials with chiral YN+YNN forces at NLO



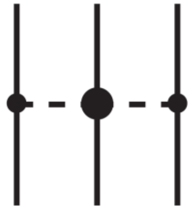
YNN force within chiral EFT (1/2)



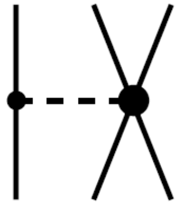
Adopted from
E. Epelbaum’s slide

Too many **low-energy constants (LECs) to be** **determined from the experimental information** **are involved in the SU(3) flavor case.**

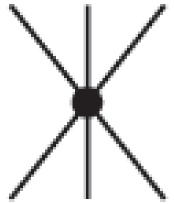
S. Petschauer, N. Kaiser, J. Haidenbauer, U. G. Meißner, & W. Weise (2016)



2 LECs in ΛNN-ΛNN



2 LECs in ΛNN-ΛNN



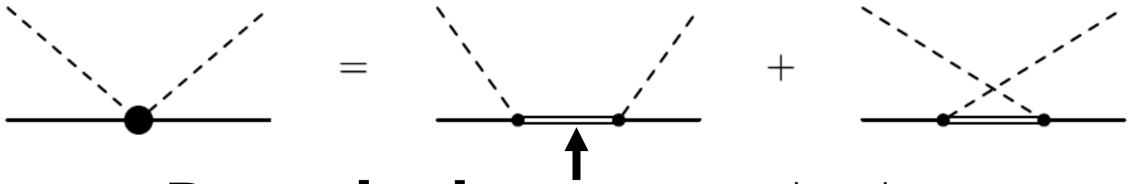
3 LECs in ΛNN-ΛNN
5 LECs in ΣNN-ΣNN
1 LECs in ΛNN-ΣNN

How to decrease the number of LECs while keeping important structures?

- **Decuplet saturation: inserting decuplet baryons**

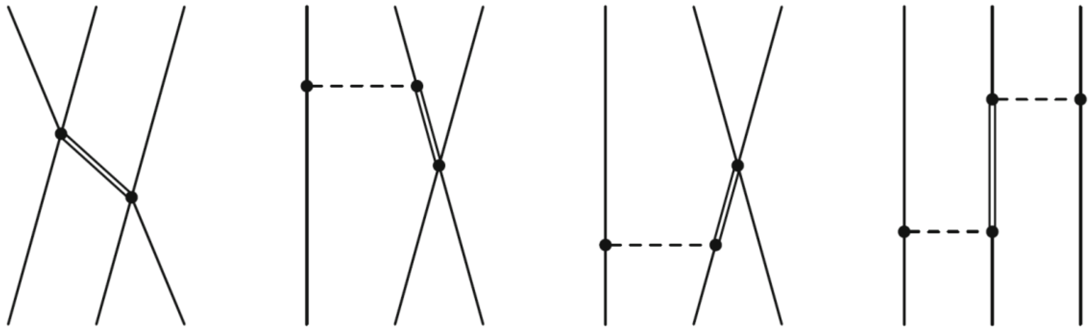
S. Petschauer, J. Haidenbauer, N. Kaiser, U.-G. Meißner, & W. Weise (2017)

E.g. Meson-octet → Meson-octet vertex

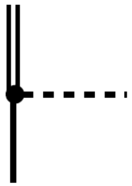


Decuplet baryon $\Delta, \Sigma^*, \Lambda^*$

Decuplet saturated three-body force (Only 3 LECs!)

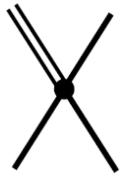


Fujita-Miyazawa type



$\propto C$

Determined from $\Delta \to \pi N$ transition



$\propto H_1, H_2$

H_1 (f^{-2})	H_2 (f^{-2})
−2.650	0.100
−2.200	0.000
−1.800	−0.100
−1.350	−0.200
−0.900	−0.300

Condition 1: Λ hypernuclei $U_\Lambda(\rho_0) \approx -30$ MeV

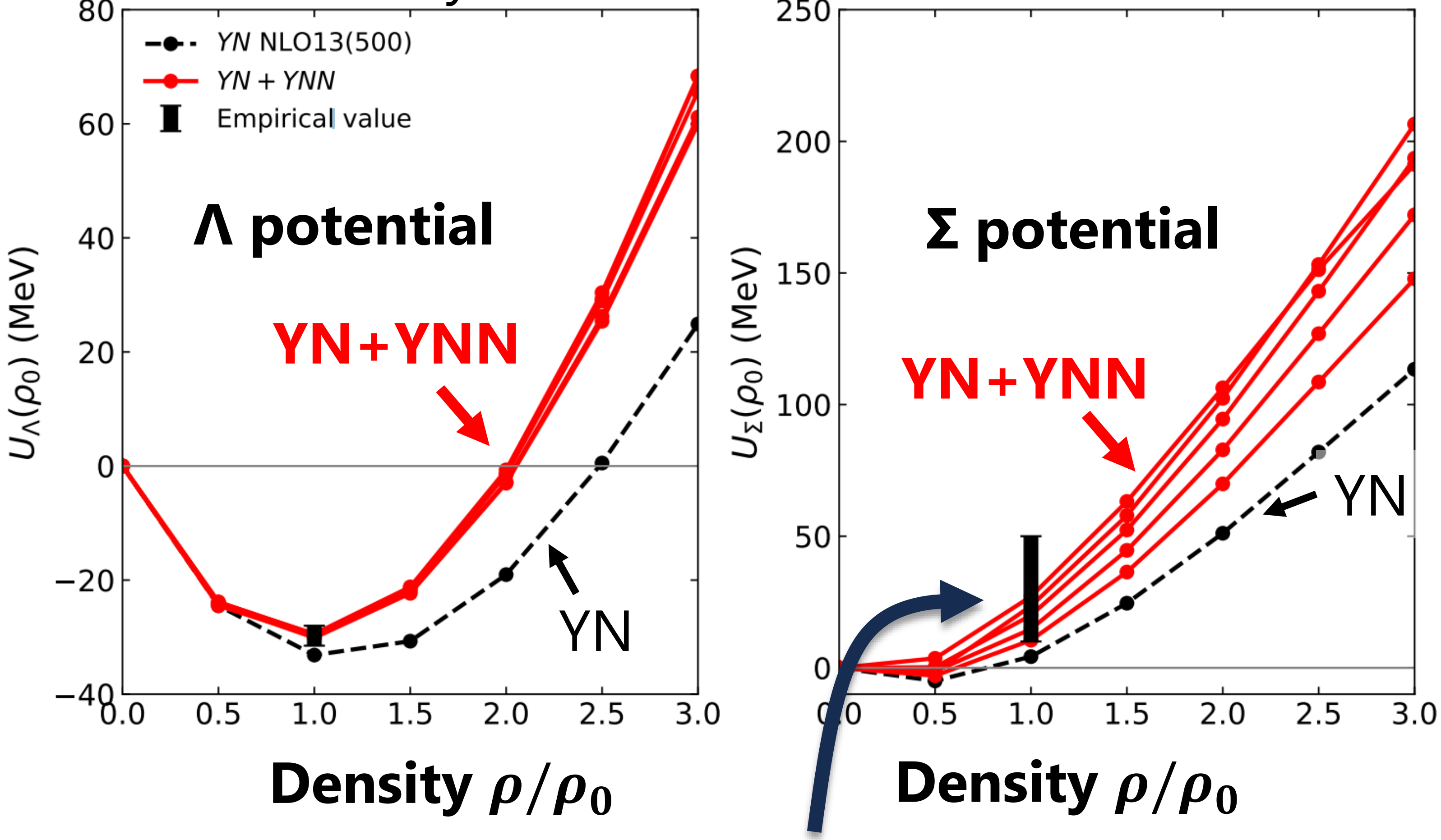
Condition 2: NO Λ in neutron stars $U_\Lambda(3\rho_0) > 80$ MeV in pure neutron matter

D. Gerstung, N. Kaiser, & W. Weise (2020).

NLO13(500) YN + YNN

<u>AJ</u>, K. Murase, and Y. Nara, arXiv:2501.09881 (2025) (Proceeding for EXA/LEAP2024)

Symmetric nuclear matter

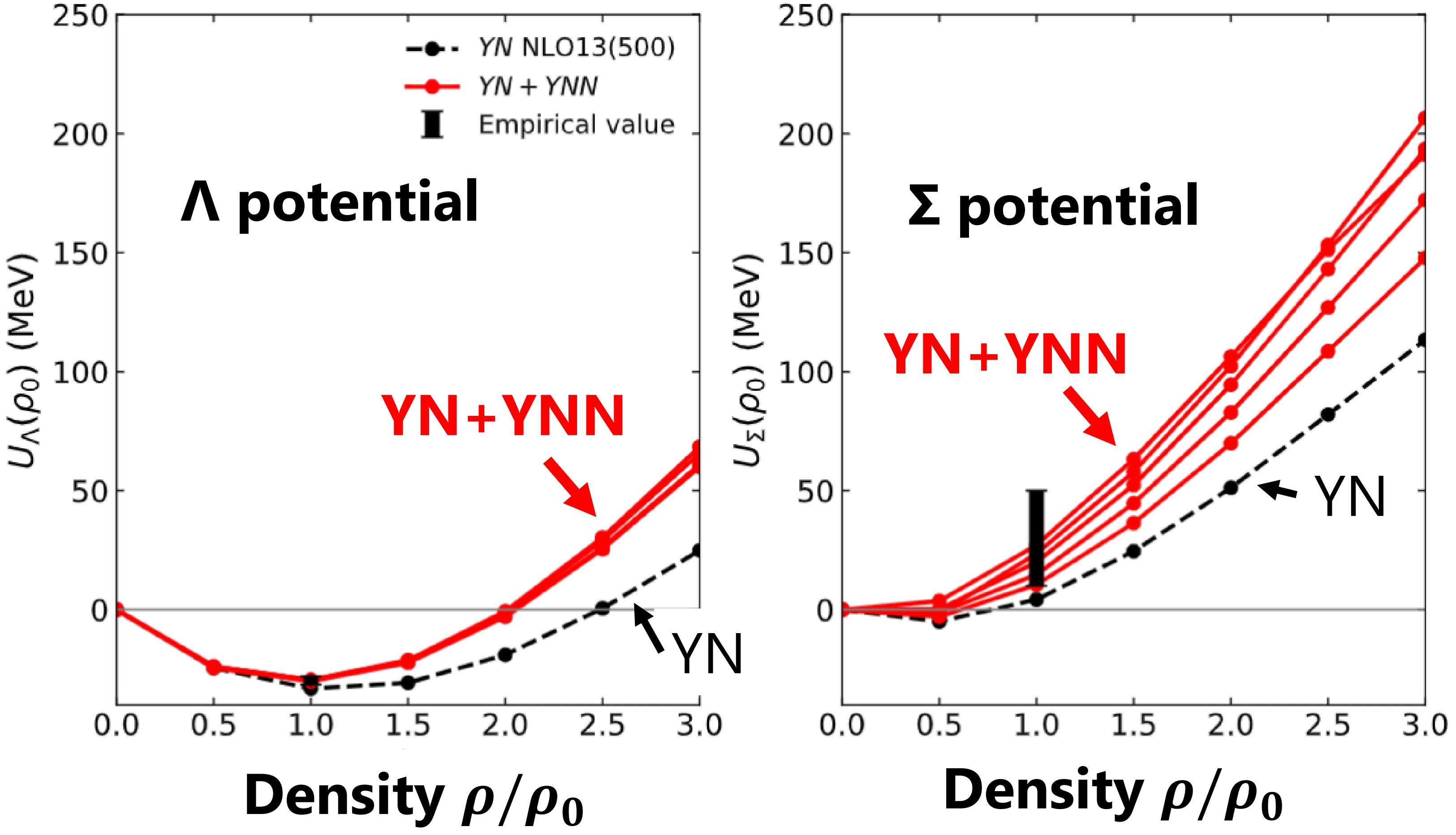


For the Λ potential, YNN force produces <u>40 MeV</u> of repulsion at $3\rho_0$.

Low-energy constants (H_1, H_2) can be chosen in such a way that
- **<u>Λ's do not appear in neutron stars</u> and**
- **the empirical value of <u>U_Σ is reproduced</u>.**

Empirical value of the Σ potential: $U_\Sigma(\rho_0) = 30 \pm 20$ MeV
A. Gal, E. V. Hungerford, & D. J. Millener (2016).

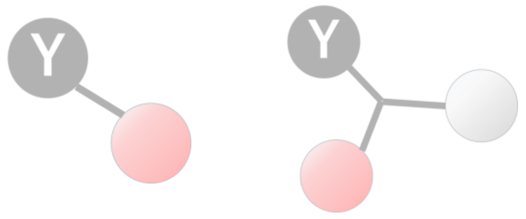
Symmetric nuclear matter



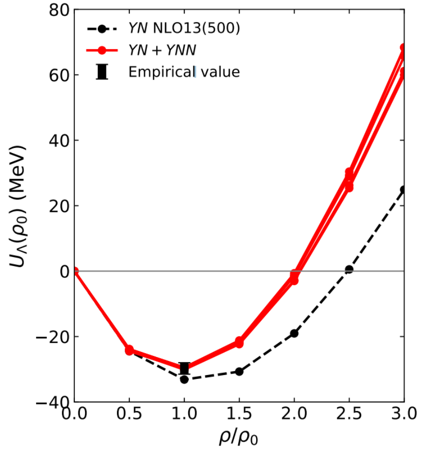
The Λ and Σ potentials behave completely differently!

Let's implement them to JAM2!

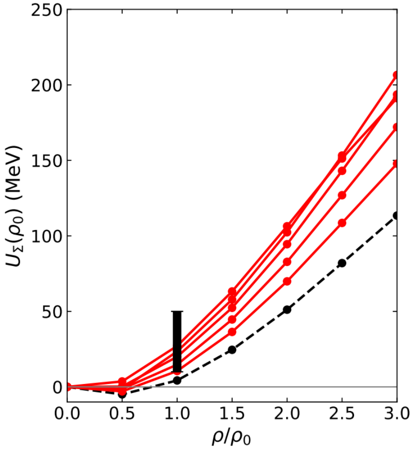
Λ and Σ directed flows



Λ single-particle potential

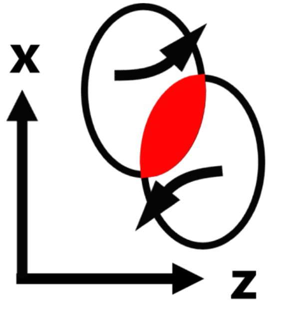


Σ single-particle potential



JAM2

Λ+Σ0 directed flow



Directed flow v_1 ($\sqrt{s_{NN}} \approx 3 - 5$ GeV)

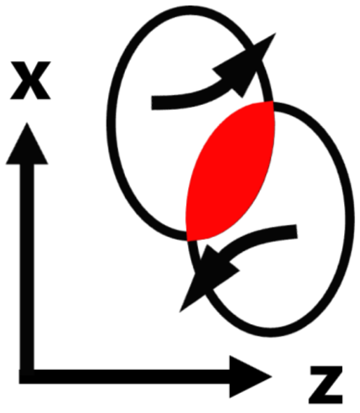
- **The anisotropic collective flow $v_n = \langle \cos n\phi \rangle$ has been extensively investigated to extract the properties of dense matter equation of states.**

  Recent review: A. Sorensen et al., Prog. Part. Nucl. Phys. 134 (2024) 104080.

- **Directed flow: $v_1 = \langle \cos\phi \rangle = \langle p_x / p_T \rangle$ as a function of the rapidity $y = \tanh^{-1}\left(\frac{p_z}{E}\right)$**

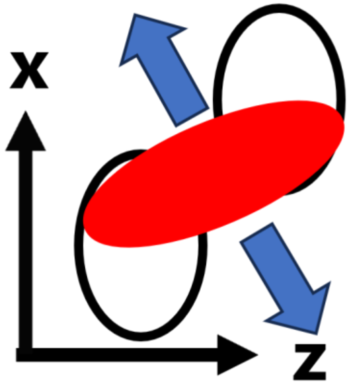
  $(p_T^2 = p_x^2 + p_y^2)$

Early (compression) stage



$v_1 > 0$ **for** $y > 0$

Later (expansion) stage



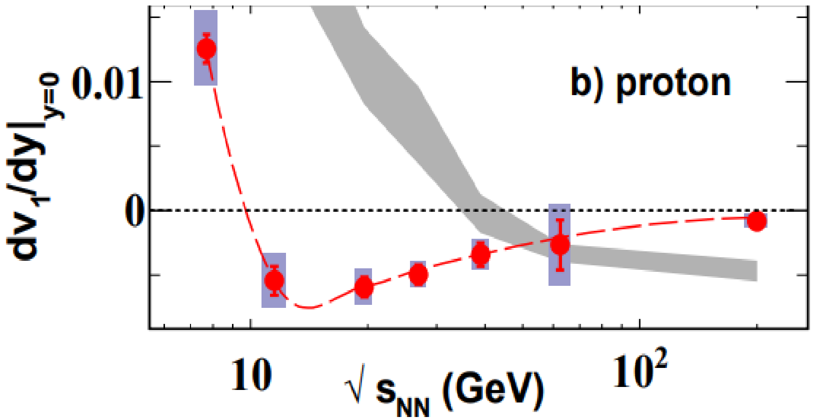
$v_1 < 0$ **for** $y > 0$

v_1 has a non-trivial dependence on EOS.

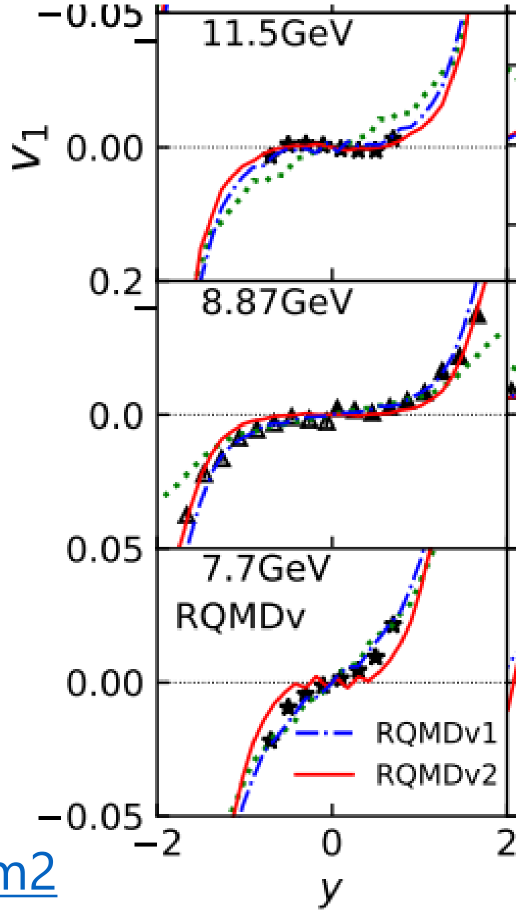
Proton directed flow v_1

- **Proton directed flow slope dv_1/dy exhibits sign change at $\sqrt{s_{NN}} = 11.5$ GeV.**

STAR Collaboration, Phys. Rev. Lett. 112 (2014) 162301.



Signal of the 1st order phase transition?



- **In 2022, it is shown $\sqrt{s_{NN}}$ dependence of proton $v1$ can be explained without phase transition by the relativistic quantum molecular dynamics model with the Lorentz-vector potential (RQMDv) implemented in JAM2.**

Y. Nara and A. Ohnishi, PRC (2022) https://gitlab.com/transportmodel/jam2

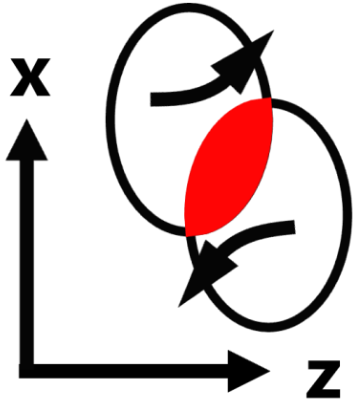
➡ **Let's discuss hyperon v_1!**

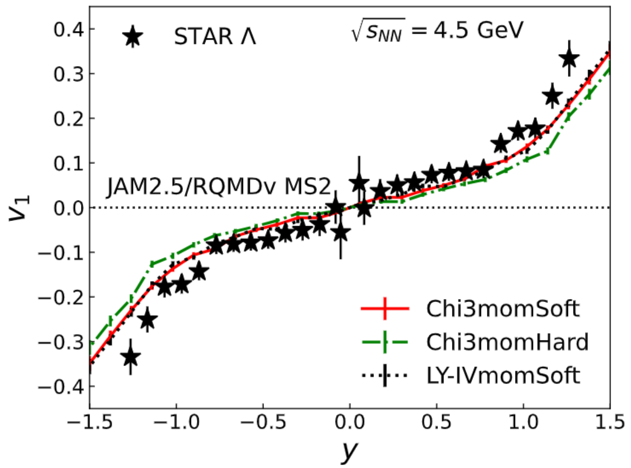
(Note) Possibility of 1st PT is not excluded.

Extensions in JAM2 after Nara et al. (2022)

Several updates have been made after the Λ v1 paper:

Y. Nara, AJ, K. Murase, & A. Ohnishi, PRC 106, 044902(2022).





Updates

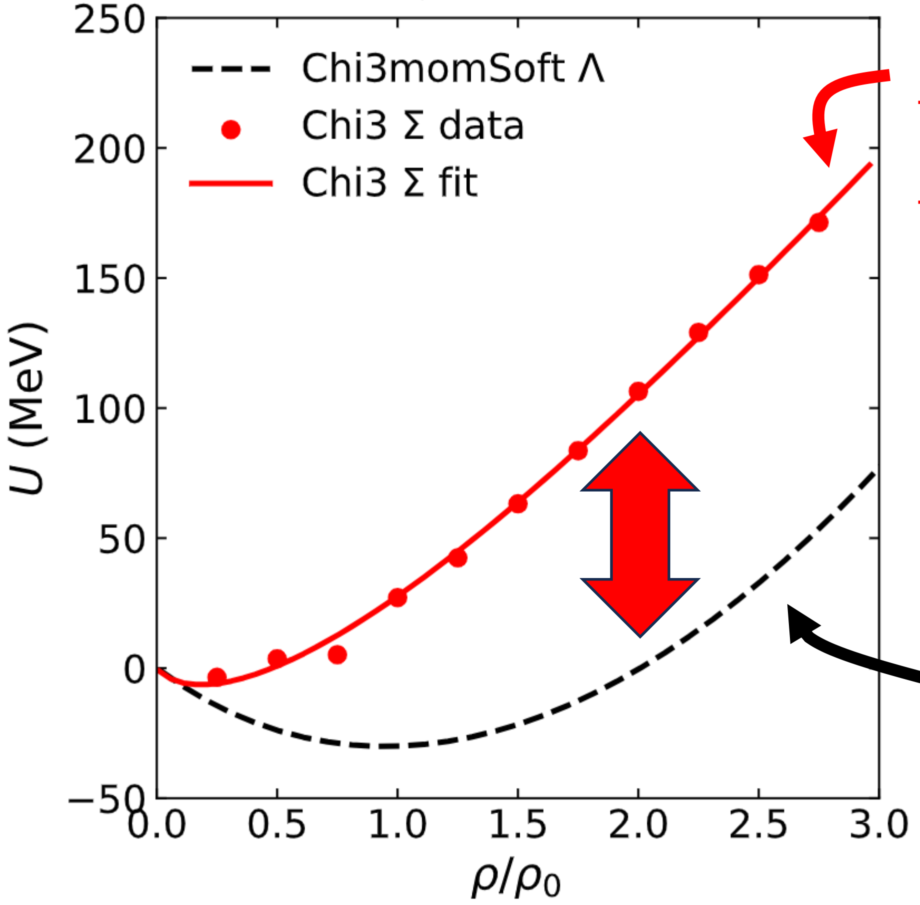
- **Covariant collision term**
  Y. Nara, AJ, T. Maruyama, K. Murase, and A. Ohnishi, Phys. Rev. C 108, 024910 (2023).
- **New covariant RQMD model (RQMDv2) QM2025 Poster**
  Y. Nara, AJ, K. Murase, in preparation.
- **YN cross section by chiral N2LO**
  Some ΣN cross sections are decreased.

Σ0 v1 is influenced to some extent, while Λ+Σ0 v1 is similar.

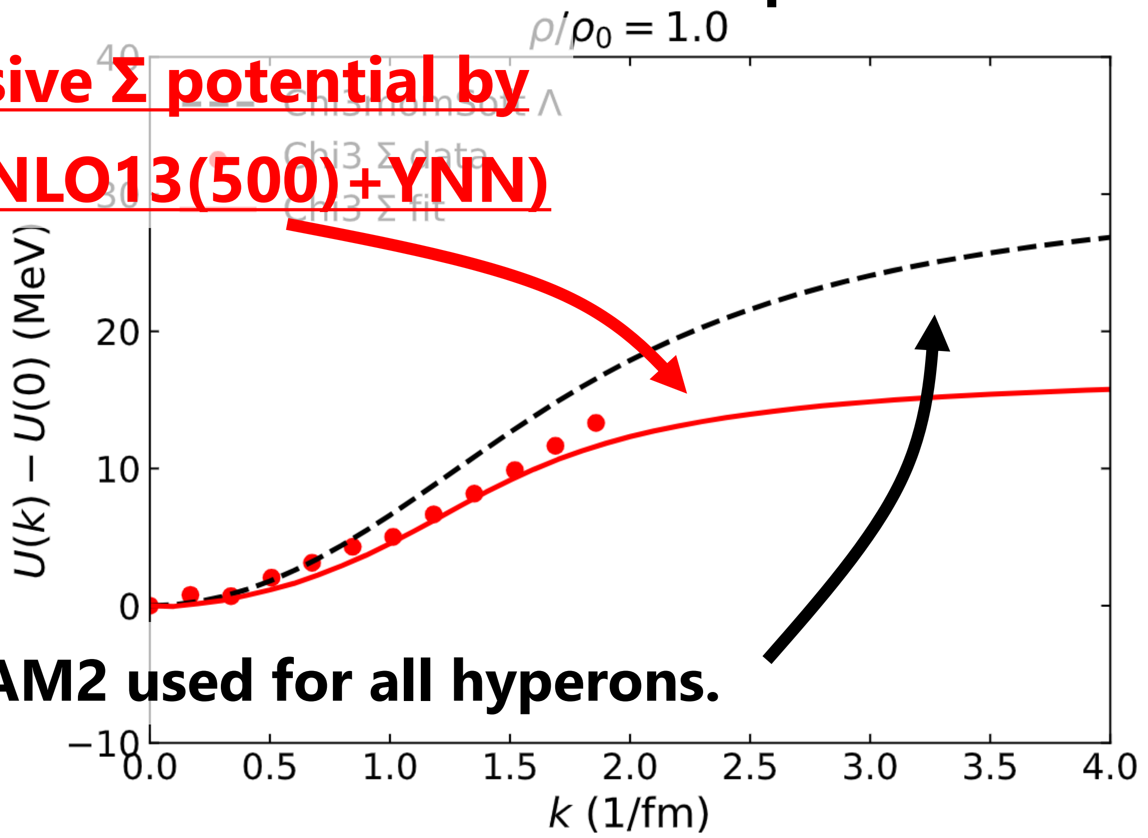
Σ single-particle potentials

For fitting procedure, see Y. Nara, AJ, K. Murase, & A. Ohnishi, PRC 106, 044902(2022).

Density dependence



Momentum dependence

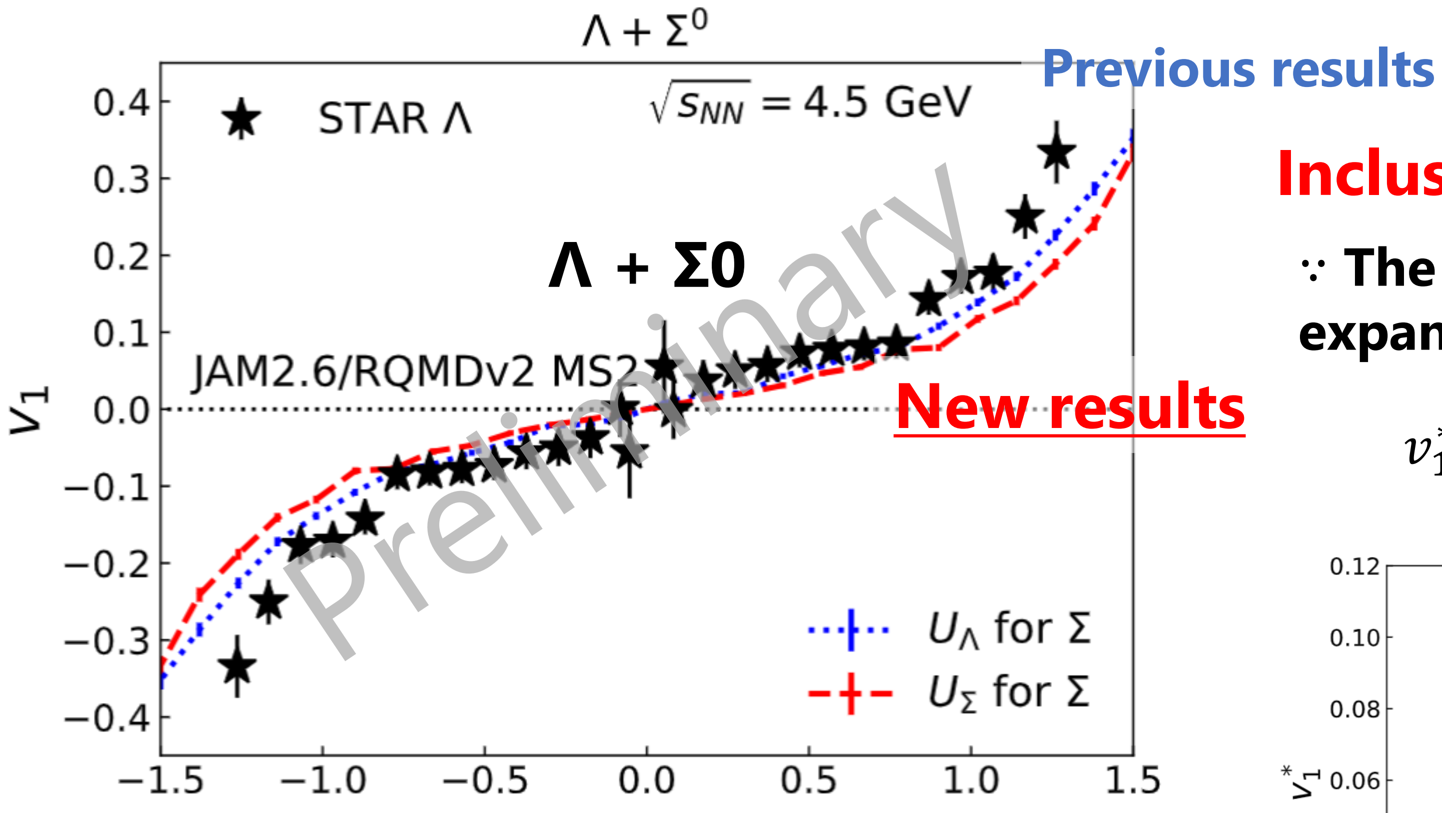


Most repulsive Σ potential by chiral EFT (NLO13(500)+YNN)

Current JAM2 used for all hyperons.

Can this difference be found in hyperon directed flows?

Λ+Σ0 v1 at $\sqrt{s_{NN}}$=4.5 GeV

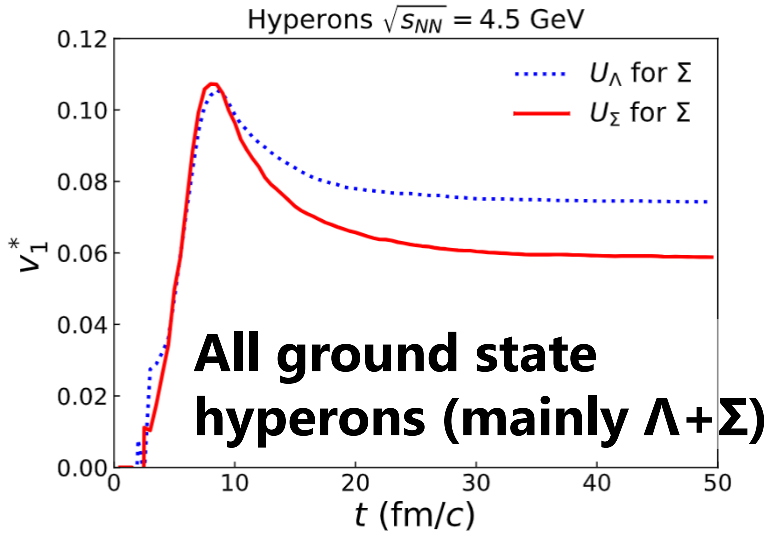


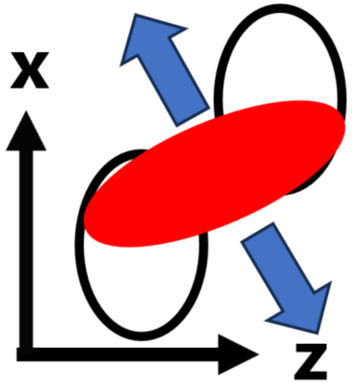
Rapidity $y = \tanh^{-1}\left(\frac{p_z}{E}\right)$

Inclusion of Σ potential decreases v1.

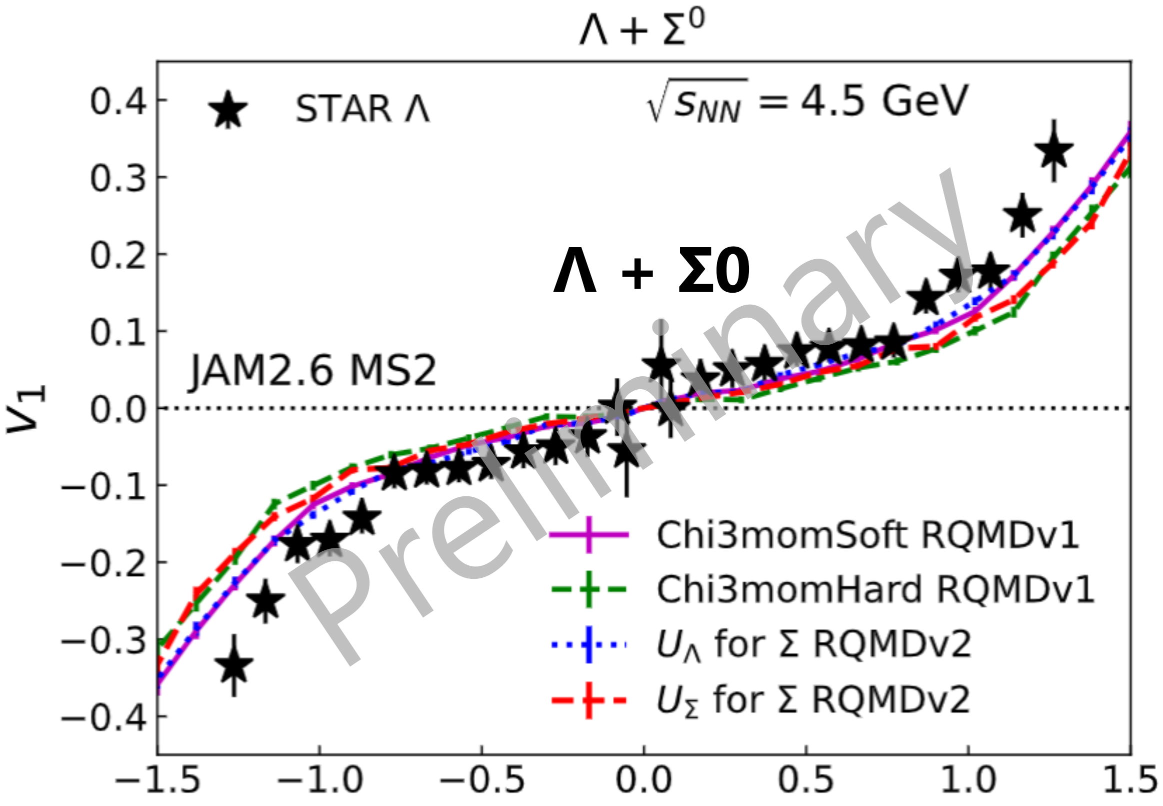
∵ **The Σ repulsion suppresses v1 in the expansion stage by forming the tilted matter.**

$$v_1^* = \int_{-1}^{1} \mathrm{sgn}(y) v_1(y) dy$$





Comparison to the previous results



Rapidity $y = \tanh^{-1}\left(\frac{p_z}{E}\right)$

Current models

Y. Nara, AJ, K. Murase, A. Ohnishi, Phys. Rev. C 106, 044902 (2022).

All hyperons and their resonances feel same potential.

New models

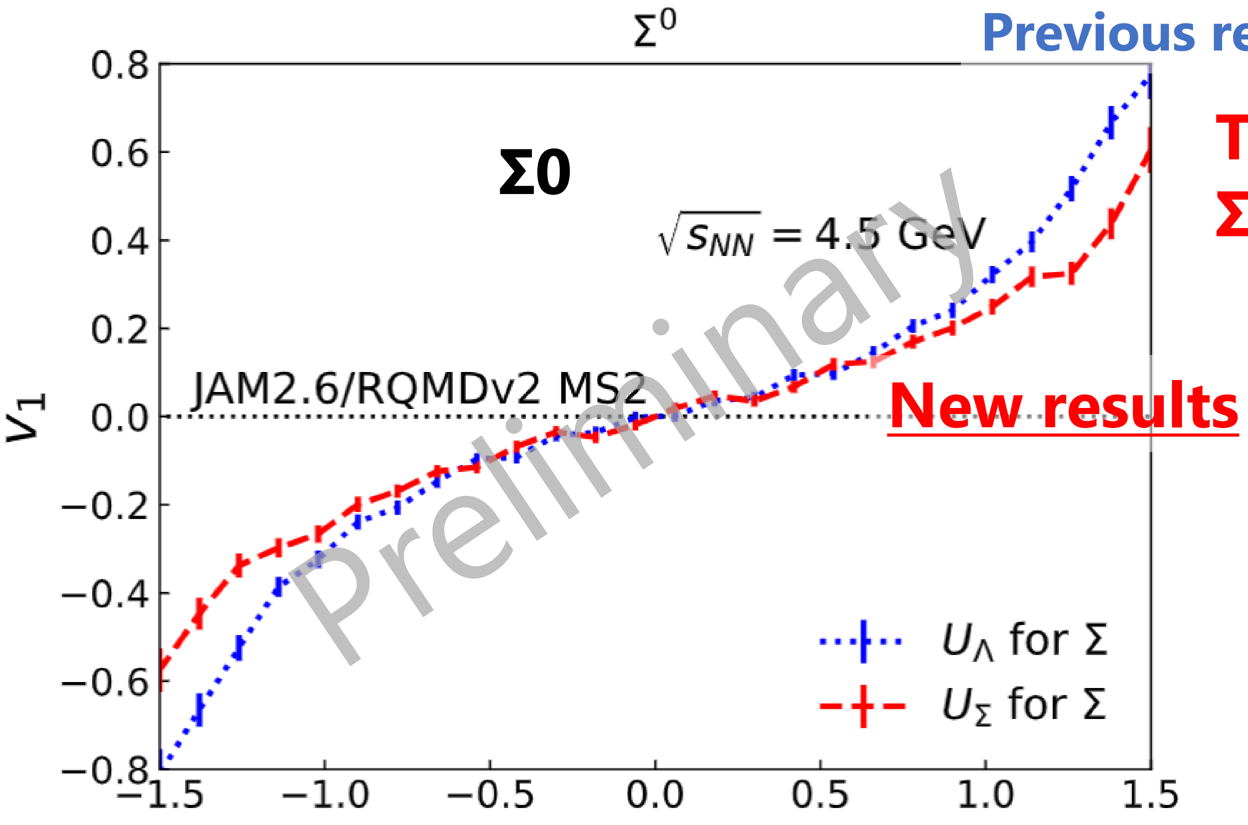
New RQMD, chiral N2LO YN cross sections, Sigma potential

Hard momentum dependence ~ **Lambda + Sigma potentials**

Soft momentum dependence ~ Lambda potential for all hyperons

Sigma potential has influence as the same level as the uncertainty in the momentum dependence.

Σ0 v1 at $\sqrt{s_{NN}}$=4.5 GeV



The v1 difference is more significant for Σ0 than for Λ+Σ0.

Σ potential still has large uncertainty.

Cf. Empirical value of the Σ potential:

$$U_\Sigma(\rho_0) = 30 \pm 20 \text{ MeV}$$

A. Gal, E. V. Hungerford, & D. J. Millener (2016).

Σ potential can be constrained via Σ v1!

Rapidity $y = \tanh^{-1}\left(\frac{p_z}{E}\right)$

Cf. HADES has successfully reconstructed Σ0.

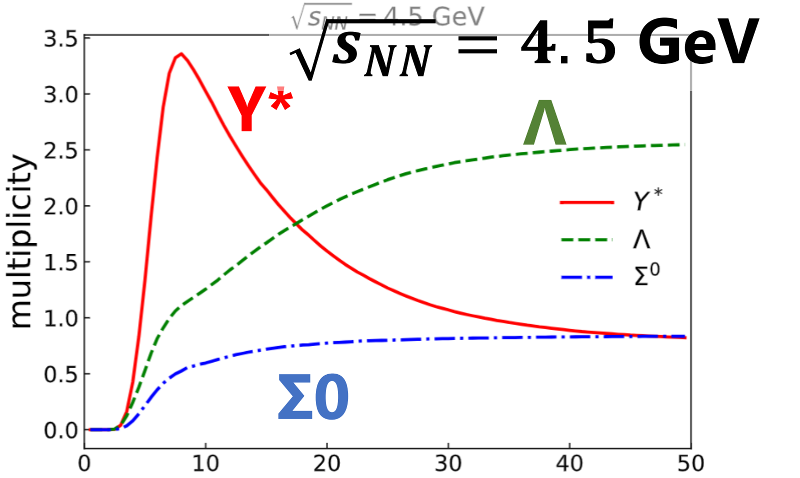
Sigma0 reconstruction in Ag+Ag collisions at 1.58 A GeV with HADES Marten Becker (Giessen) at SQM2024

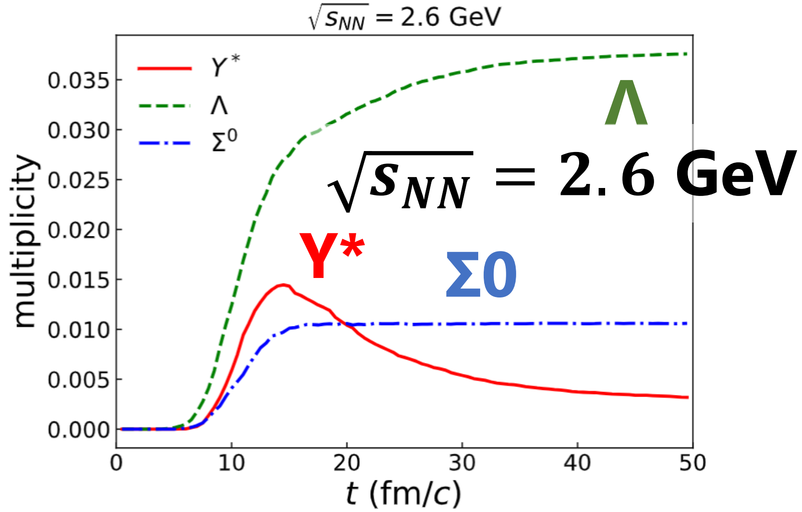
WIP projects for quantitative modeling

- **Calculating hyperon potentials with chiral N2LO YN+YNN**
  YN: J. Haidenbauer, U.-G. Meißner, A. Nogga, & H. Le, Eur. Phys. J. A 59 (2023) 3, 63.
  YNN: working with Johann Haidenbauer.

- **Implementing potentials of hyperon resonances (Y*) by employing the parity doublet model with Y. Nara and K. Murase**

- **To avoid the uncertainty in Y*, lower collision energy (HADES energy) may be preferred.**





Summary

- The Λ single-particle potential is a key to solve the hyperon puzzle of neutron stars.
- NLO13(500) YN and YNN forces based on the decuplet saturation:
  NLO13 YN force results in the strongly repulsive Λ potential that avoids the hyperon puzzle and is consistent with the empirical value of the Σ single-particle potential.
- Several updates have been made to the event generator JAM2.
- The Λ (+Σ0) directed flow is sensitive to the Σ potential and can be used to constrain the hyperon potentials in dense matter.

Future work

- Calculating hyperon potentials with chiral N2LO YN+YNN
- Implementing potentials of hyperon resonances (Y*)