Directed flow of Λ from heavy-ion collisions and hyperon puzzle of neutron stars

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14th Int. Conf. on Hypernuclear and Strange Particle Physics (Hyp2022), Jun.27-Jul.1, 2022, Prague, Czech Republic/Online.

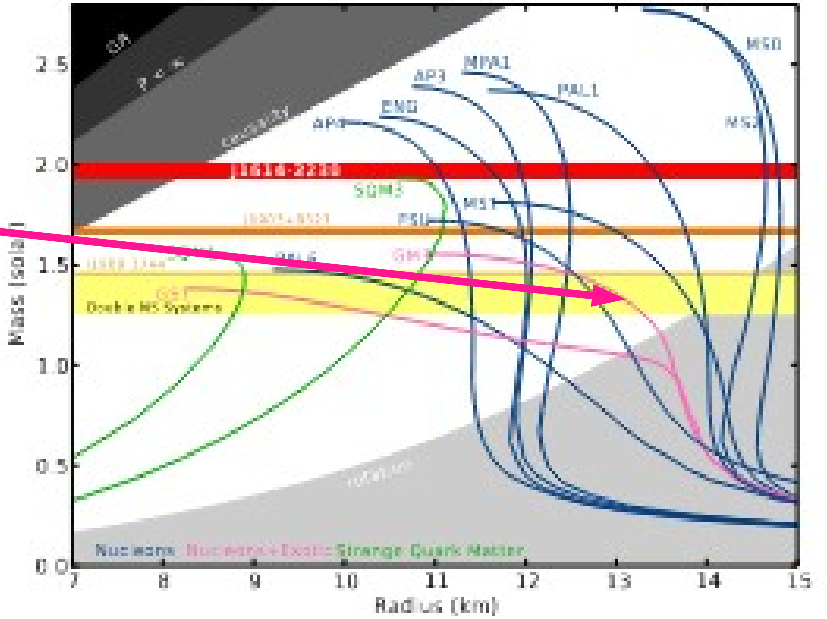

HYP 2022 PRAGUE
14th International Conference on Hypernuclear and Strange Particle Physics
June 27 – July 1, 2022
Prague, Czech Republic

- Introduction – Hyperon puzzle
- U_Λ from chiral EFT
- Directed flow of Λ
- Summary

Y.Nara, A. Jinno, K. Murase, AO, in prep.

Hyperon Puzzle of Neutron Stars

- Observation of massive neutron stars rules out hyperonic EOS ?
  - Attractive $U_\Lambda(\rho)$ causes hyperon mixing in NS at $(2\text{-}4)\rho_0$, softens the EOS, and reduces $M_{max} = (1.3\text{-}1.6)\ M_\odot$
- Proposed solutions
  - Three-body ΛNN repulsion → repulsive $U_\Lambda(\rho)$ at high density
  - Transition to quark matter before Λ appears
  - General relativity → Modified gravity



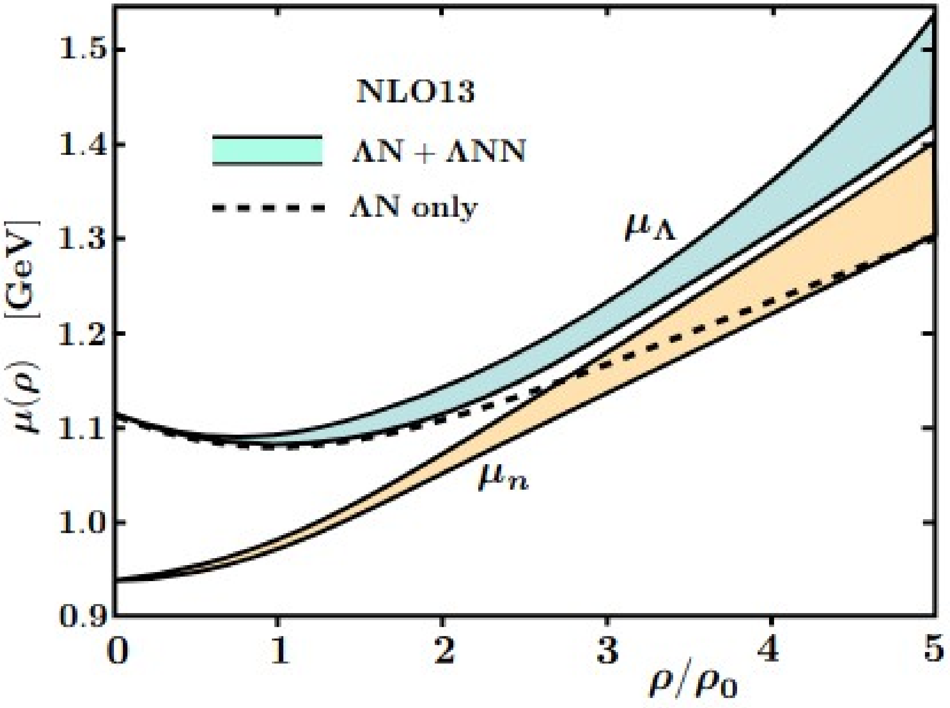
Hyperons

Demorest+(1010.5788)

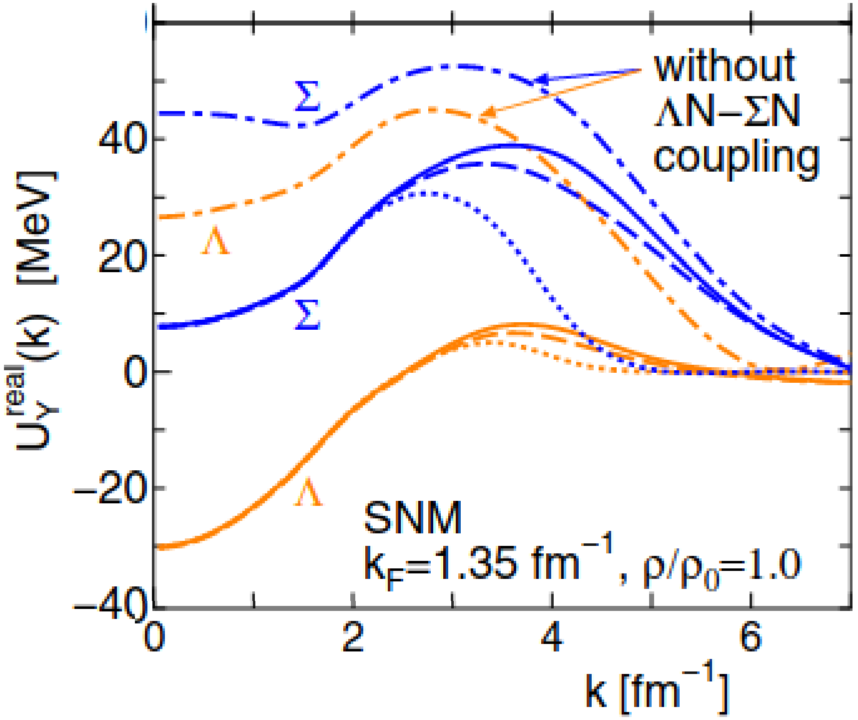
Challenging Subject in Hypernuclear Physics

Repulsive $U_\Lambda(\rho)$ at high density in chiral EFT

- **Chiral effective field theory (chiral EFT) may cause repulsive Λ potential at high densities**
  Gerstung, Kaiser, Weise (2001.10563), Kohno (1802.05388)
- **Yet unknown parameters are tuned to support 2 $M_\odot$ neutron stars.**
  → Repulsion at high densities needs to be verified
  e.g. in heavy-ion collisions.



Gerstung+('20)



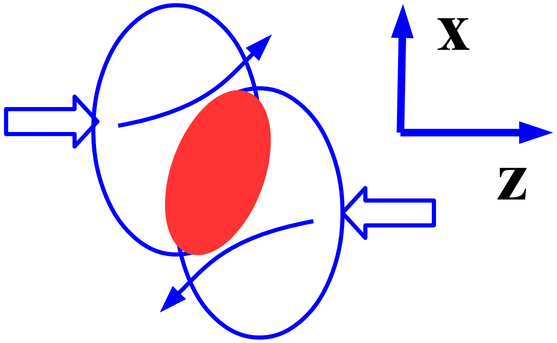
Kohno ('18)

Directed flow of protons

- **Directed flow has been utilized to study EOS**

$$v_1 = \langle \cos\phi \rangle \ (\text{directed flow})\,,\ \langle p_x \rangle \ (\text{side flow})$$

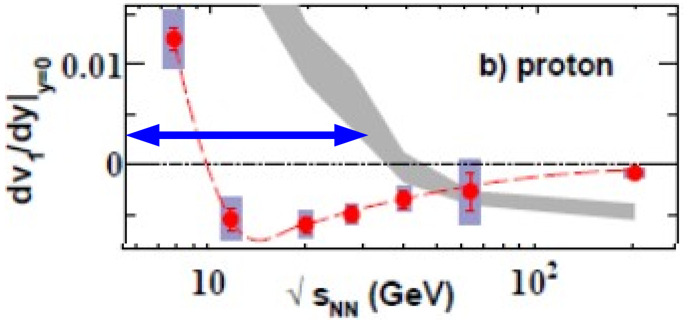
E.g. Sahu, Cassing, Mosel, AO (nucl-th/9907002), Snellings+(nucl-ex/9908001)



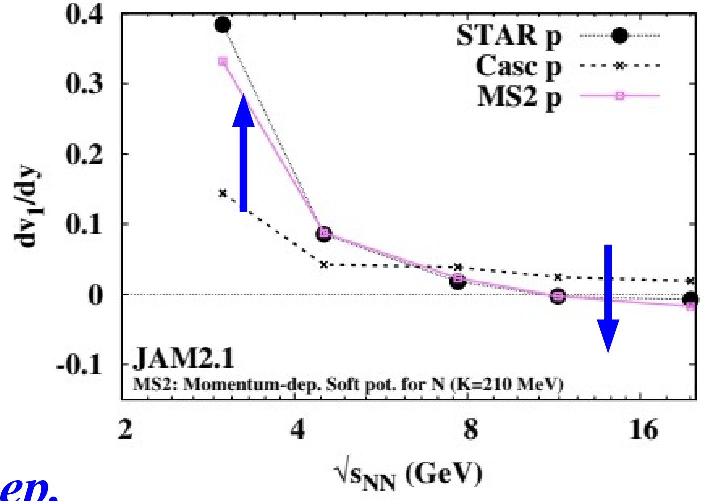
- **Non-monotonic colliding energy dep. of proton v1 slope has been a puzzle**

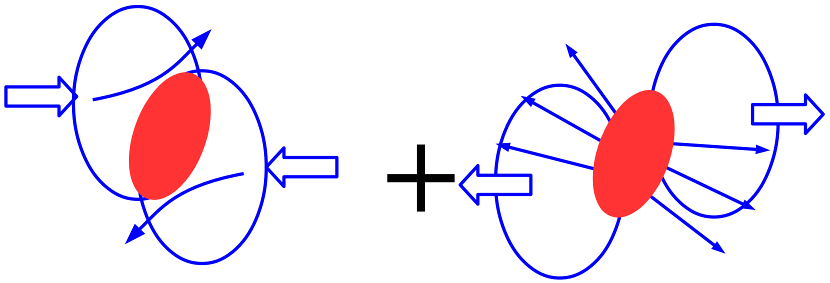
STAR (1401.3043), *Nara+(JAM, '16,'17), Ivanov+ (3FD, 1601.03902), Konchakovski+ (PHSD, 1404.2765)*

  - **An explanation is found.** *Nara+(2109.07594)* **Compression & expansion stages cause different slope → non-monotonicity.**



STAR, PRL112('14)162301 (1401.3043)





Nara, Jinno, Murase, AO, in prep.

Since the directed flow of protons
can be described by a single EOS,
U_Λ may be constrained by Λ flow.

We study Λ flow using U_Λ from chiral EFT.
This is complementary
to precision hypernuclear spectroscopy.

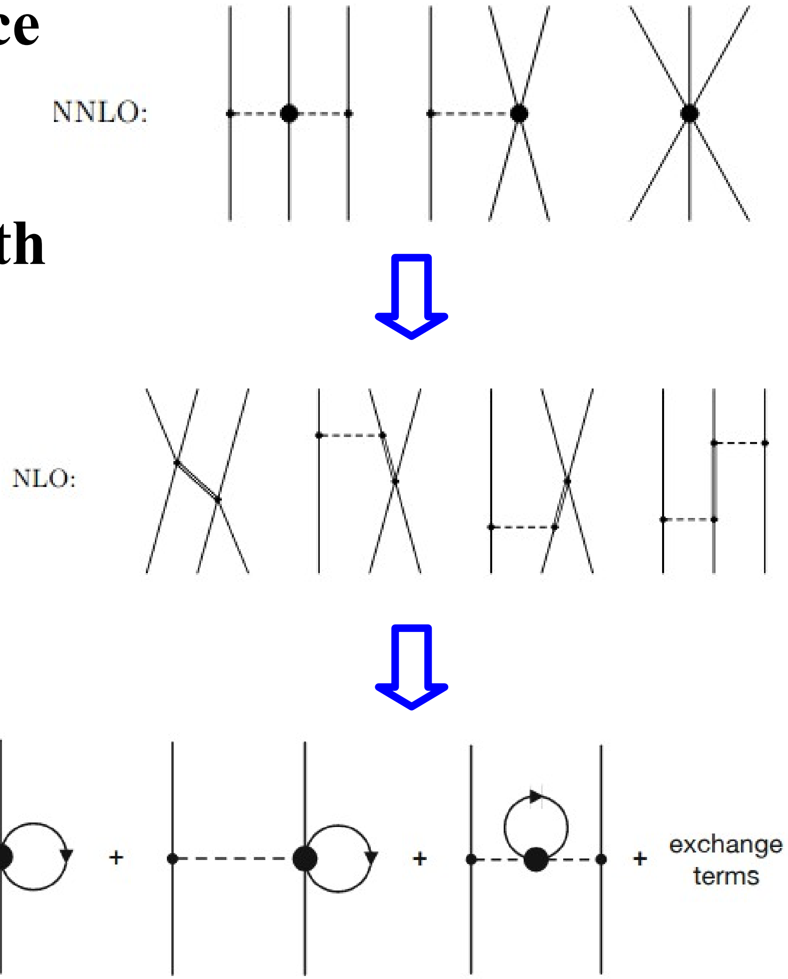
U_Λ from chiral EFT

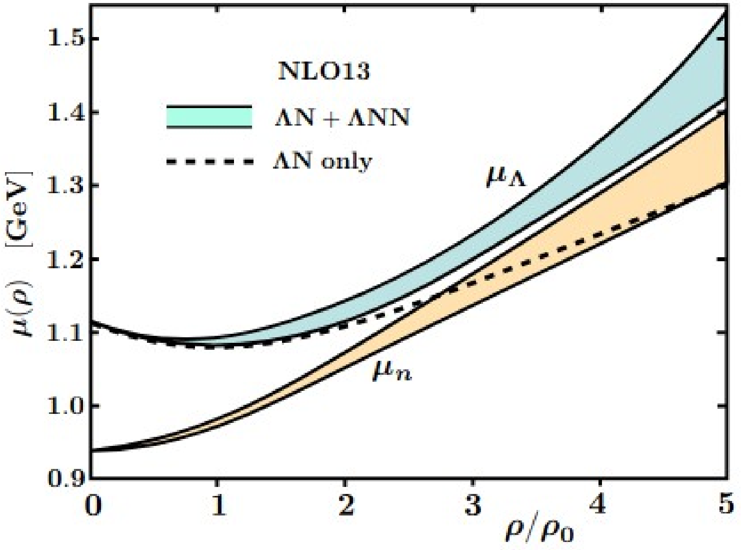
Chiral EFT (decuplet saturation model)

- **Decuplet saturation model**

  S. Petschauer, Haidenbauer, Kaiser, Meißner, Weise (1607.04307)
  D. Gerstung, Kaiser, Weise (GKW)(2001.10563)

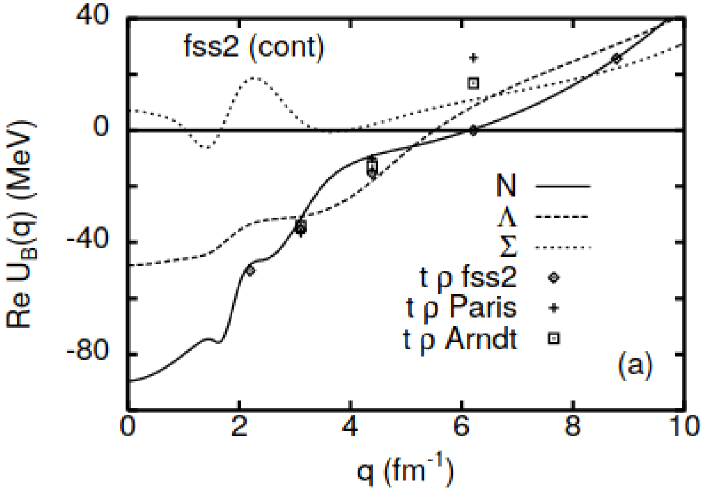
  - **NNLO Diagrams generating 3-body force are assumed to be saturated by decuplet baryon diagrams.**
  - **$U_\Lambda(\rho_0) \sim$ - 30 MeV + Decuplet decay width**
    → one remaining parameter gives uncertainty
  - **Bruckner-Hartree-Fock calc. → $U_\Lambda(\rho)$**



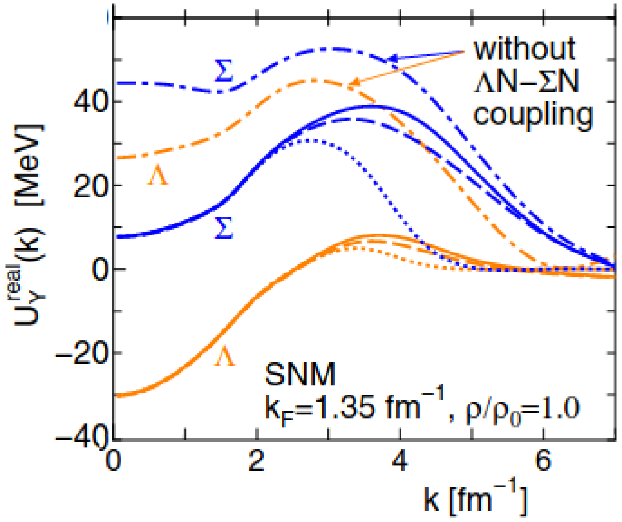


Momentum dependence

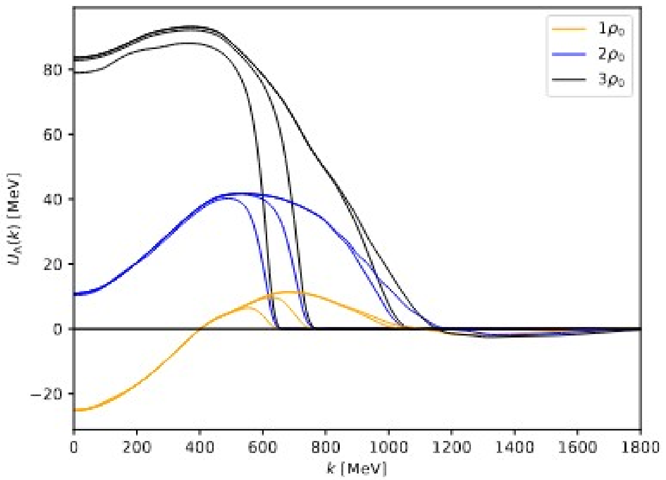
- **3BF from chiral EFT comes from higher-order diagrams**
  → Larger number of propagators and derivatives
  → Momentum dependence is needed (also from BHF calc.)
- **U_Λ(k, ρ) from chiral EFT seems to have stronger mom. dep. than quark model YN potential.**



Fujiwara, Suzuki, Nakamoto, PPNP 58 ('07) 439 (nucl-th/0607013).



Kohno, PRC97 ('18) 035206 (1802.05388).



D. Gerstung, TUM thesis ('20).

U_Λ from Chiral EFT

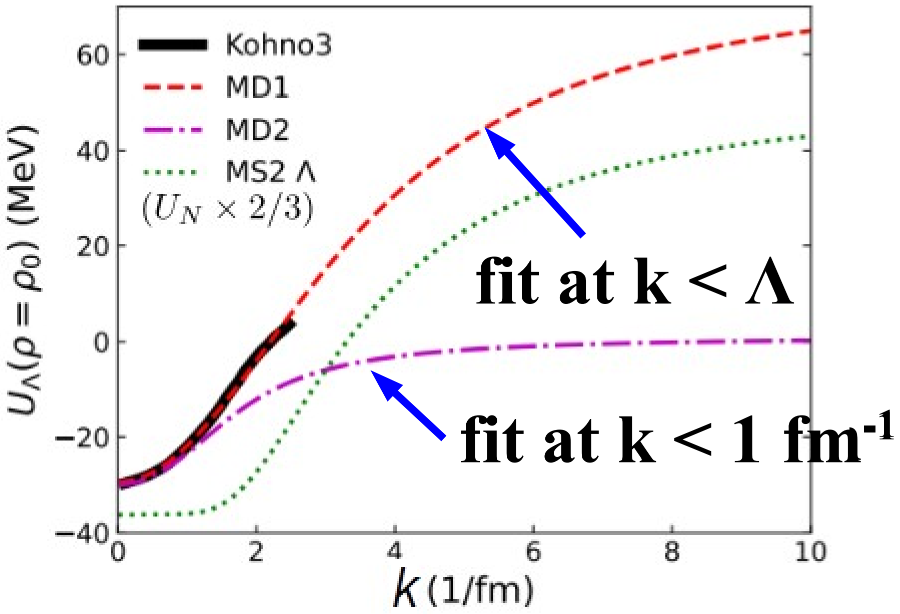
- **Chiral EFT with 3BF and hyperons**
  Gerstung+(2001.10563)(GKW, decuplet saturation model), Kohno (1802.05388)
  - **ρ-dep. potential using Fermi mom. expansion** *Tews+(1611.07133)*
    + momentum dep. fitted to *Kohno('18)*

$$U_\Lambda(\rho,k) = a\frac{\rho}{\rho_0} + b\left(\frac{\rho}{\rho_0}\right)^{4/3} + c\left(\frac{\rho}{\rho_0}\right)^{5/3} + \sum_n \frac{C_n}{\rho_0}\int\frac{d\boldsymbol{k}'}{(2\pi)^3}\frac{f(\boldsymbol{r},\boldsymbol{k}')}{1+(\boldsymbol{k}-\boldsymbol{k}')^2/\mu_n^2}$$

  - **Range of fit**

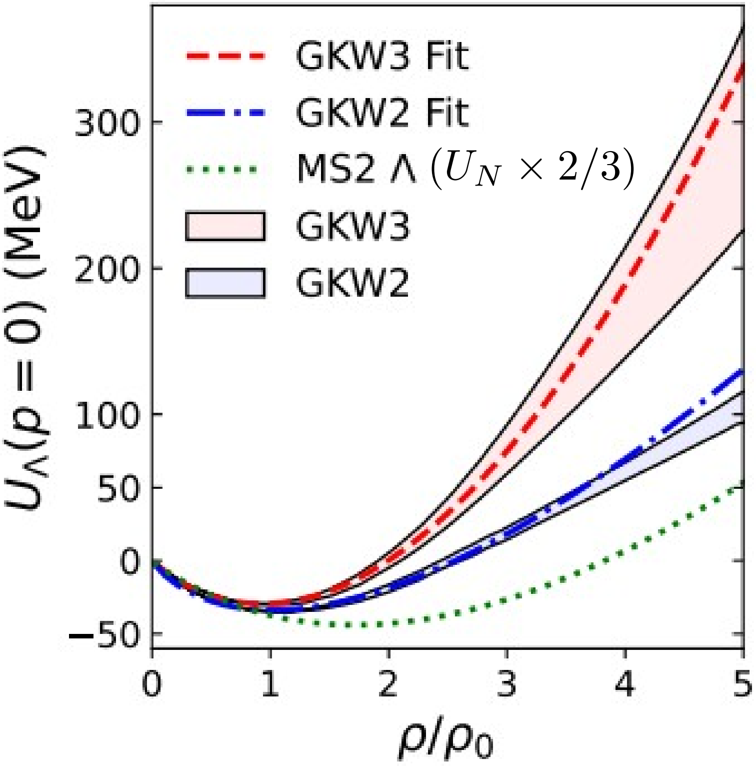
$$\rho \le 3.5\rho_0 \ (\text{unstable above } 3.5\rho_0)$$

$$k \le \Lambda \ (\text{MD1}) \text{ or } k \le 1\ \text{fm}^{-1} \ (\text{MD2})$$



fit at k < Λ

fit at k < 1 fm^{-1}

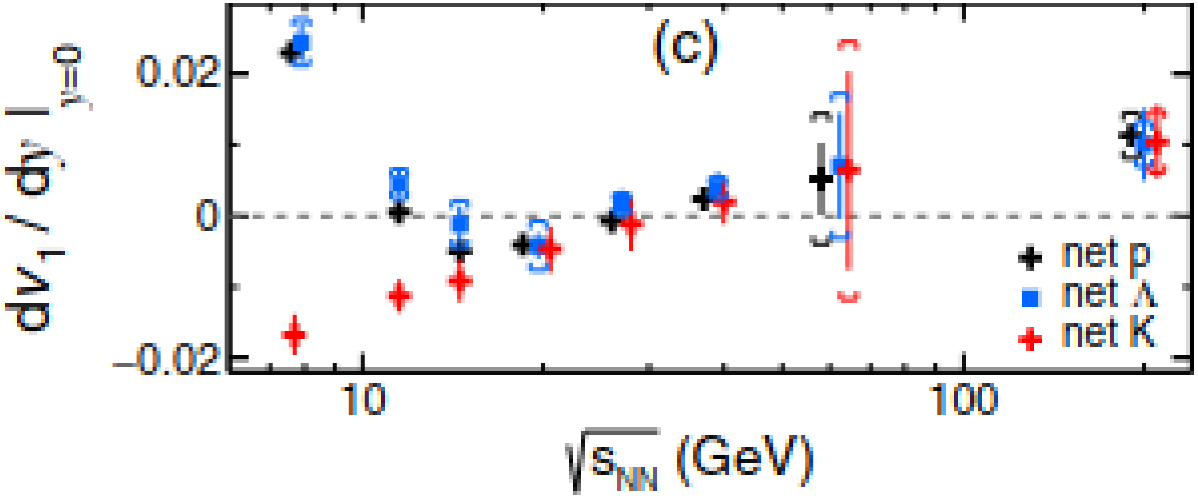


Nara, Jinno, Murase, AO, in prep.

Directed flow of Λ

Directed flow of Λ

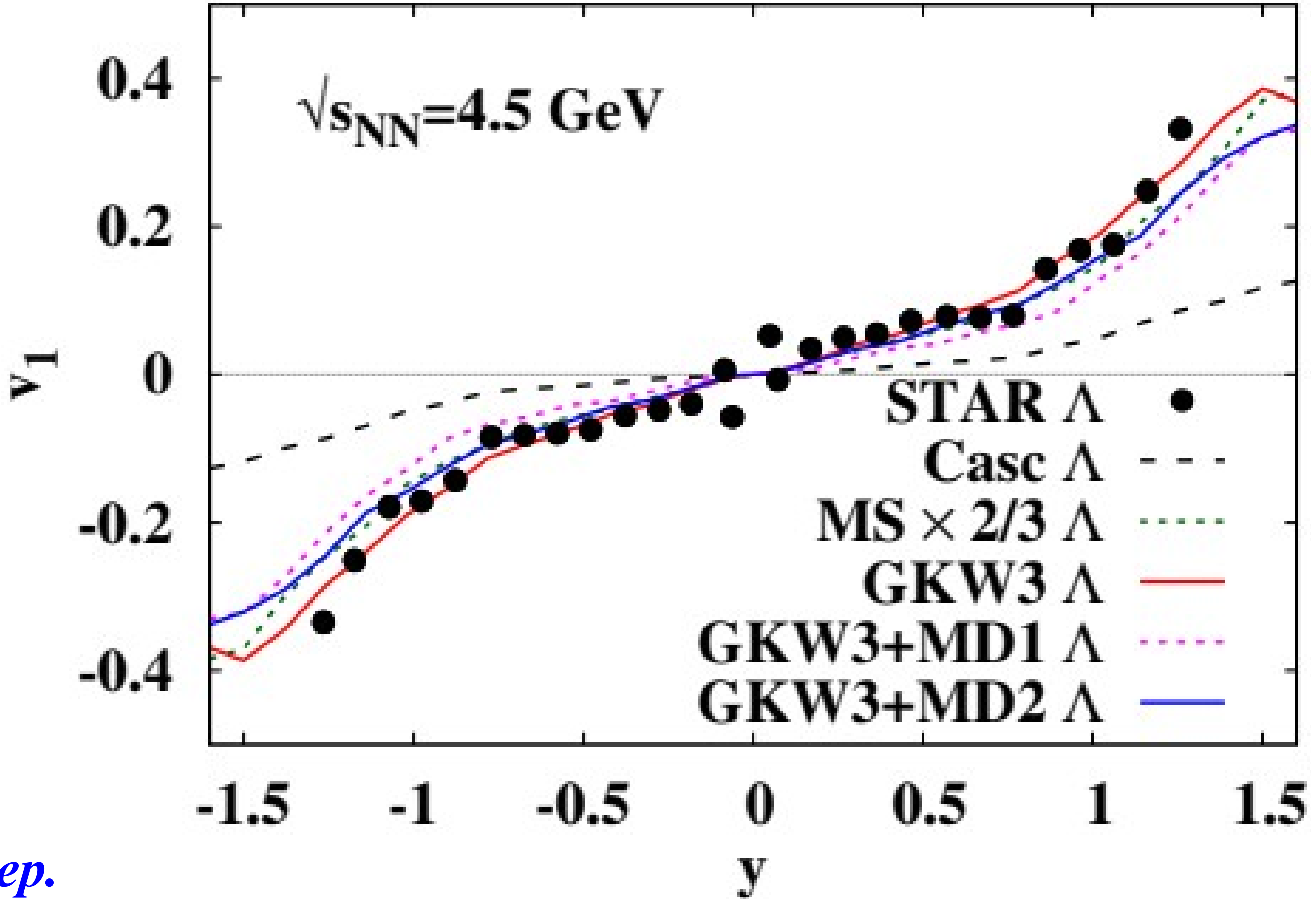
- Directed flow of Λ is expected to be smaller than $v_1(p)$ from the compression+tilted expansion mechanism, but data show $v_1(\Lambda) \sim v_1(p)$ *STAR, PRL120 ('18),062301 (1708.07132)*
  → Stronger repulsion for Λ at high densities ?



- Transport model calculations using an event generator JAM2.1.
  - Collision time scheme is updated *X.-L. Zhao+(2001.10140)*
  - Quark potential in the leading hadron during the formation time is switched on. The gaussian width (simulating interaction range) is tuned to explain proton flow.

Comparison with data

- **$v_1(\Lambda)$ at (3-27) GeV** *STAR (PRL, (1708.07132); PLB (2108.00908))*.
- **Cascade (w/o potential effects) does not explain the data.**
- **Chiral EFT U_Λ (GKW3) explains the data well.**
- **Strong mom.-dep. (MD1) suppresses v_1 at large |y|.**



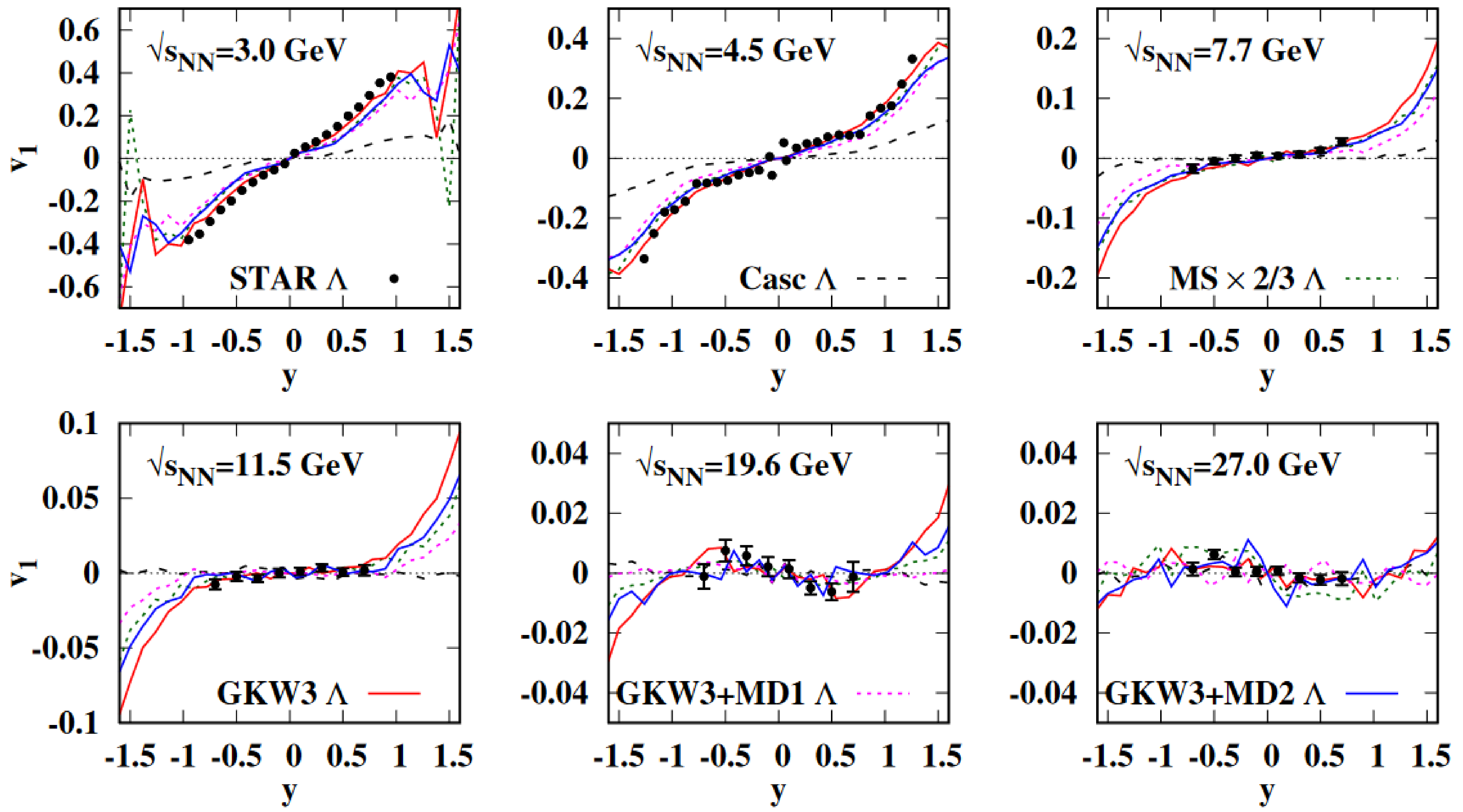
MS2: mom.-dep. soft (K=210 MeV) pot. for N

GKW3: chiral EFT w/ 2+3-body force, no mom. dep.

GKW3+MD1/MD2: GKW3+ mom. dep. from Kohno('18)

Nara, Jinno, Murase, AO, in prep.

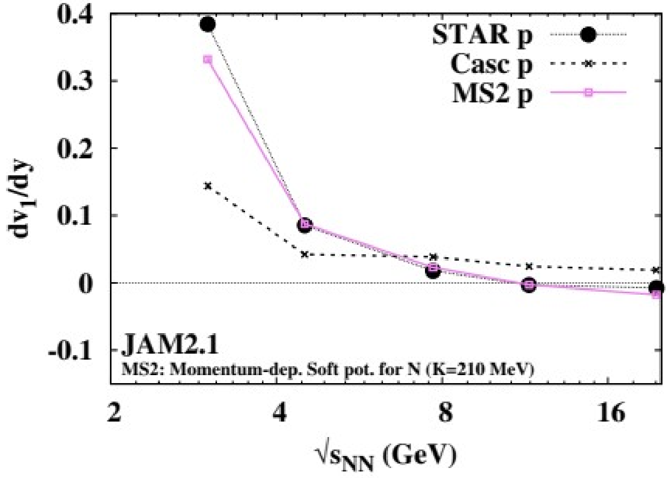
Comparison with data

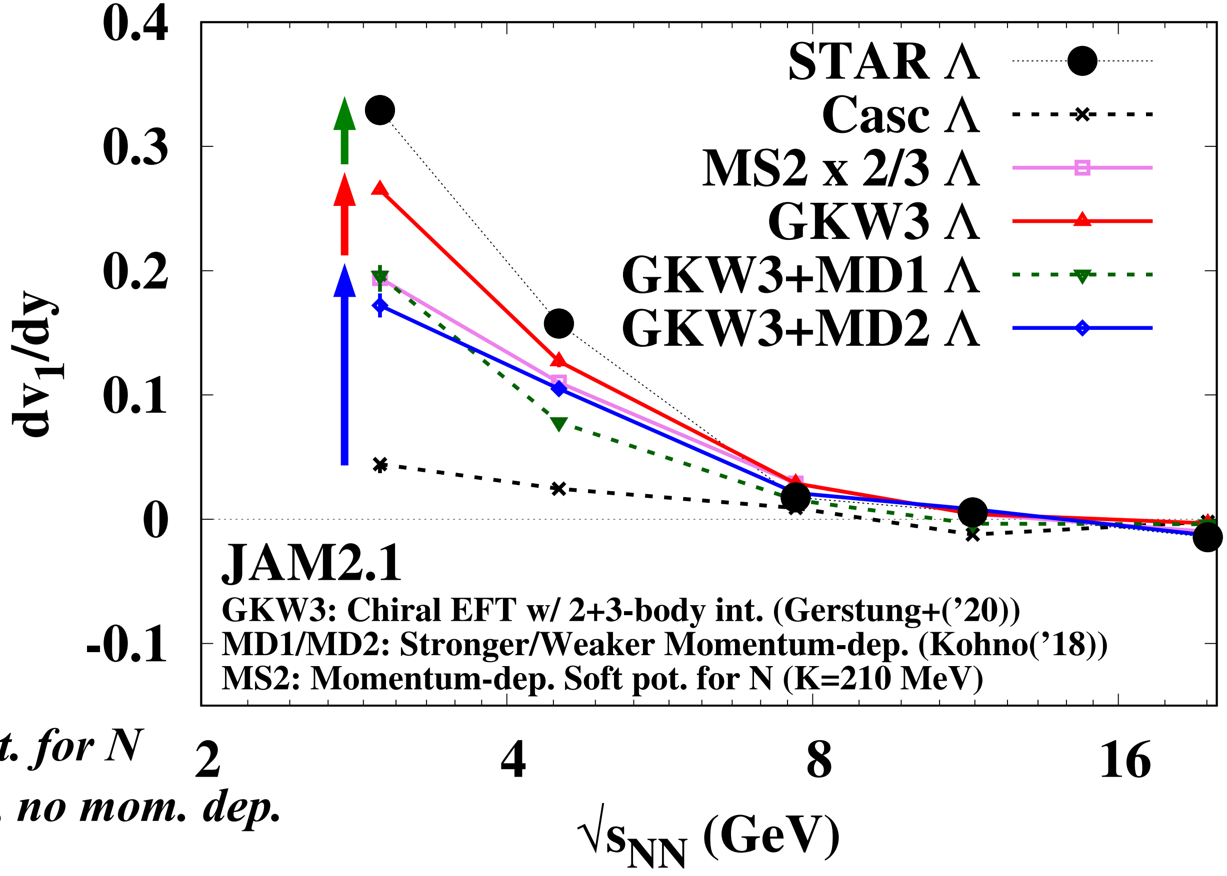


Nara, Jinno, Murase, AO, in prep.

v_1 slope

- U_Λ from chiral EFT describes the v_1 slope of Λ ($dv_1(\Lambda)/dy$) well.
  - Repulsive potential at high densities may realize a large v_1 value at low colliding energy.
  - dv_1/dy at 3 GeV is slightly underestimated (also for protons).
    → Why ?





MS2: mom.-dep. soft (K=210 MeV) pot. for N
GKW3: chiral EFT w/ 2+3-body force, no mom. dep.
GKW3+MD1/MD2:
chiral EFT w/ 2+3-body force, with mom. dep.

Nara, Jinno, Murase, AO, in prep.

Summary

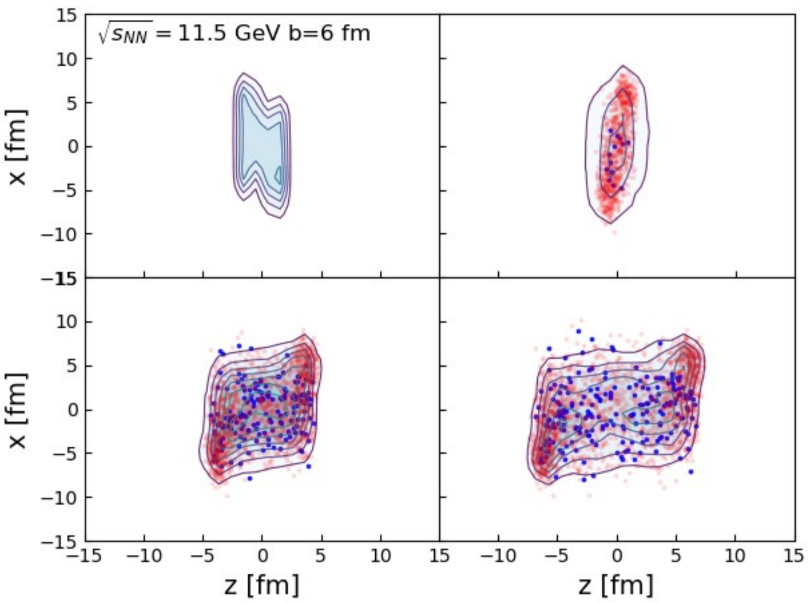
- **The directed flow (v_1) of Λ from HIC is studied by using the Λ potential from chiral EFT with 2+3-body interactions, which can support 2 solar mass neutron stars.**
  - **Λ flow is found to be sensitive to U_Λ !**
  - **U_Λ from chiral EFT with no or weak momentum dependence is consistent with the directed flow data from heavy-ion collisions.**
    [Similar results for $\langle p_x \rangle$ at $\sqrt{s_{NN}}$=3.0 GeV, D.C. Zhang+ (2107.00277)]
  - **Momentum dependence of U_Λ needs to be evaluated carefully.**
  - **The forward and backward v_1 values seem to be more sensitive to the Λ potential at high densities and/or high momentum.**
  - **v_1 of p and Λ are sensitive to the details of the transport scheme, such as the potential during the formation time and the collision time choice.**
- **How can we pin down U_Λ at high densities further ?**
  - **More data at 3-10 GeV with wider rapidity coverage.**
  - **Elliptic flow (v_2) and other observables**
  - **Λ-nucleus scattering (Emulsion or Femtoscopy) → mom. dep.**
  - **Hypernuclear spectroscopy**

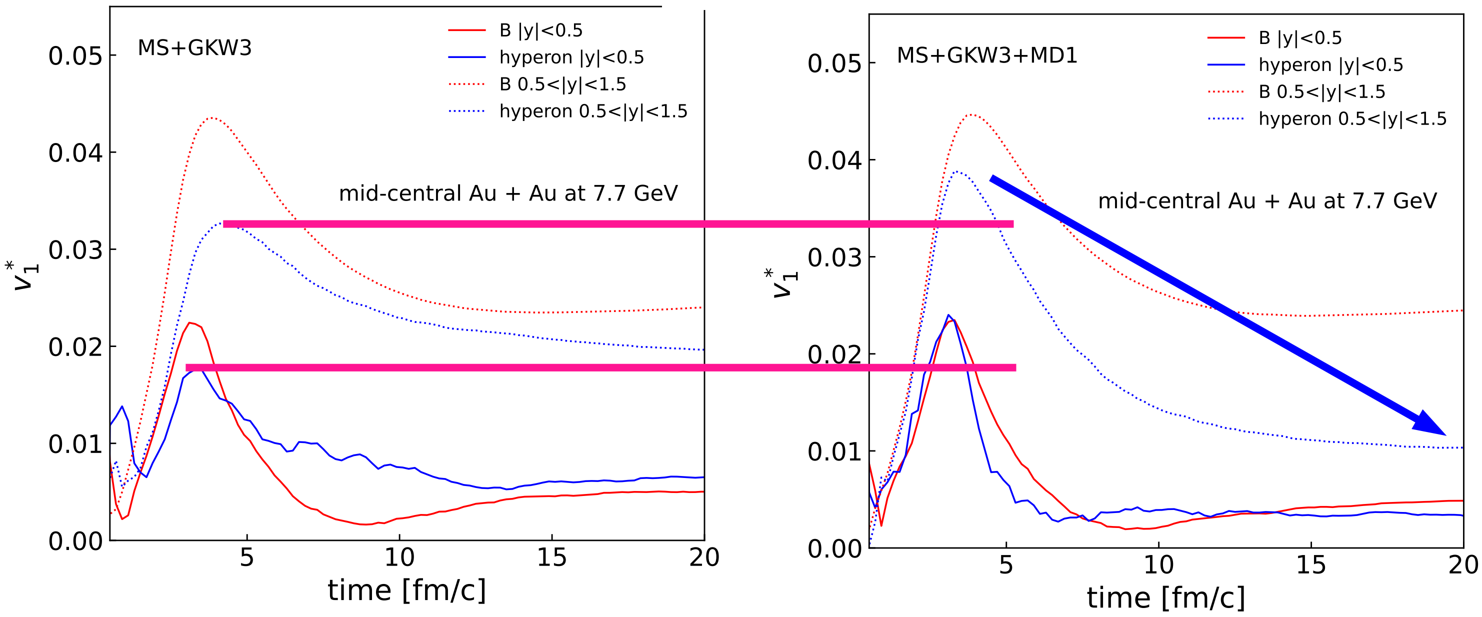
Nara, Jinno, Murase, AO, in prep.

Thank you for your attention !

Effects of mom.-dep. potential

- Momentum dep. of U_Λ enhances both compression / expansion effects on v_1 slope.
  - More repulsion for finite p particles in the compression stage.
  - Stronger reduction of v1 from repulsion partly from spectators (?).



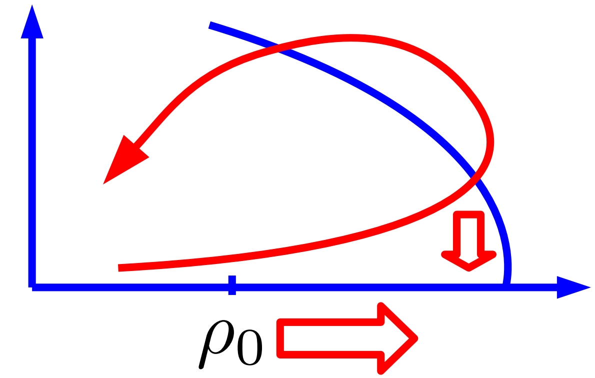


Nara, Jinno, Murase, AO, in prep.

Approaches to repulsive U_Λ at high densities

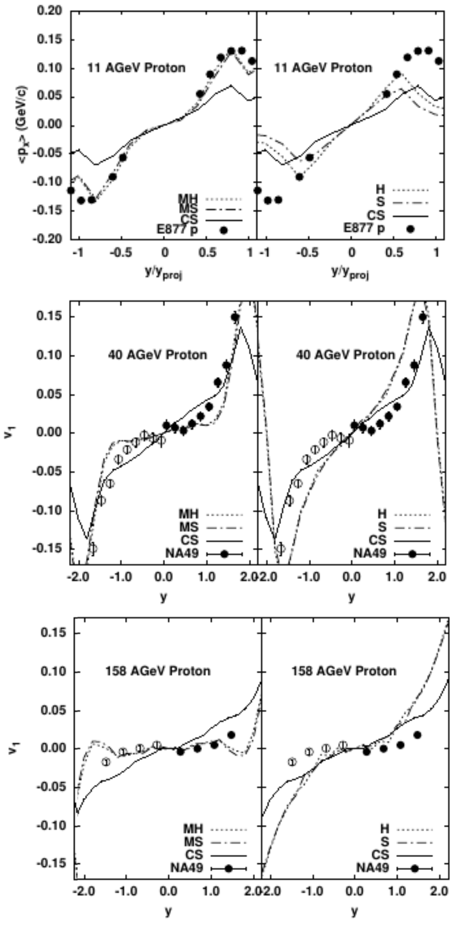
- **Top-down approach: Lattice QCD calculation at high densities**
  - **The sign problem needs to be solved.**
- **Bottom-up approach: Precision experiments of hypernuclei**
  - **Comparison of data and calculated results with (reliable) ΛN potential together with (uncertain) ΛNN potential**
  - **Extrapolation to high densities ($\rho \sim \rho_0$ to $\rho=(2\text{-}5)\rho_0$) is necessary.**
- **Phenomenological approach: Hyperons in heavy-ion collisions**
  - **High-density matter is created during HIC.**
  - **Λ flow using theoretical U_Λ can be compared with data.**
  - **Non-equilibrium effects need to be taken care of.**

We study Λ flow in HIC using U_Λ from chiral EFT (Phenomenology based on first-principles results)



Past tries

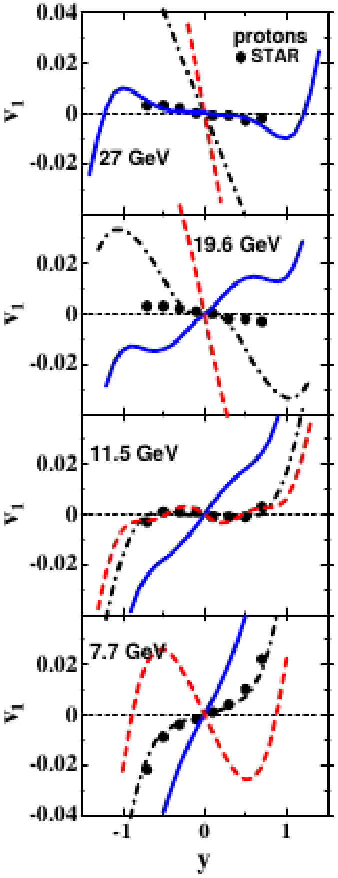
JAM-RQMD



p-dep. p-indep.

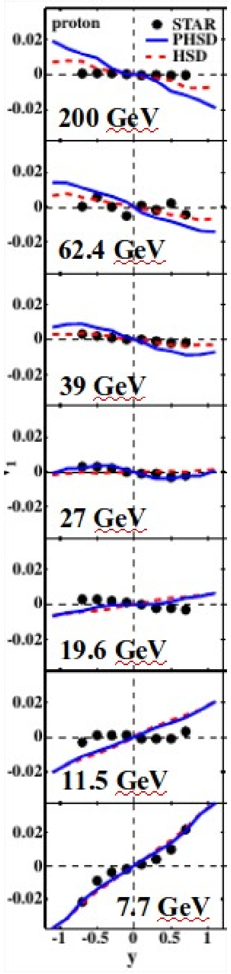
M.Isse, AO, N.Otuka, P.K.Sahu, Y.Nara, PRC72('05)064908 (There was a mistake...)

3FD



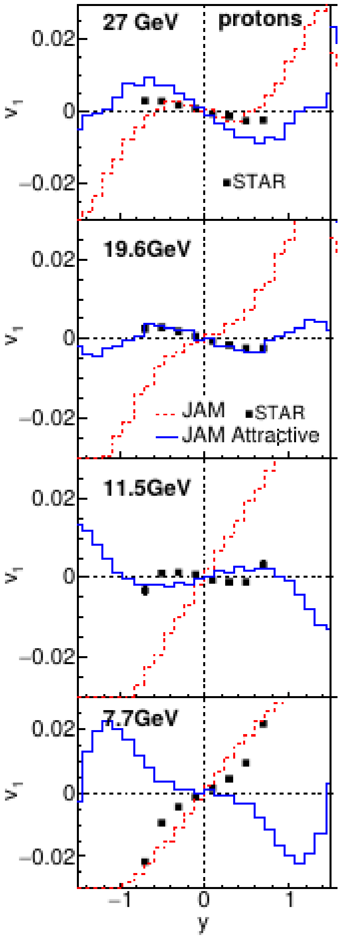
Y.B.Ivanov, A.A.Soldatov, PRC91('15) 024915

HSD/PHSD



V.P.Konchakovski, W.Cassing, Y.B.Ivanov, V. D. Toneev, PRC90('14)014903

JAM+Att.



Y.Nara, H.Niemi, AO, H.Stoecker, PRC94 ('16)034906

Directed flow of protons

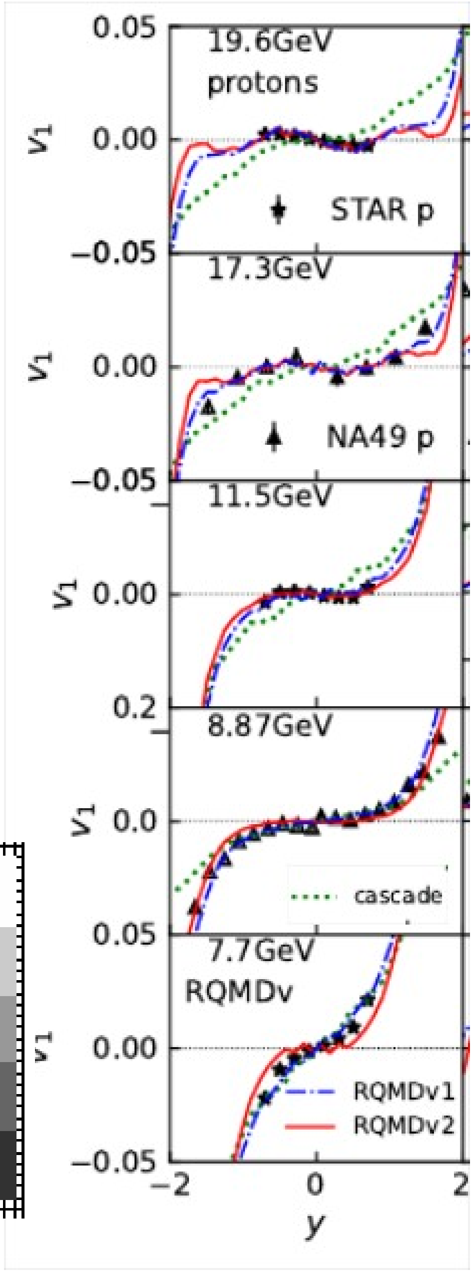
- **Origin of Positive & Negative Flow Components**

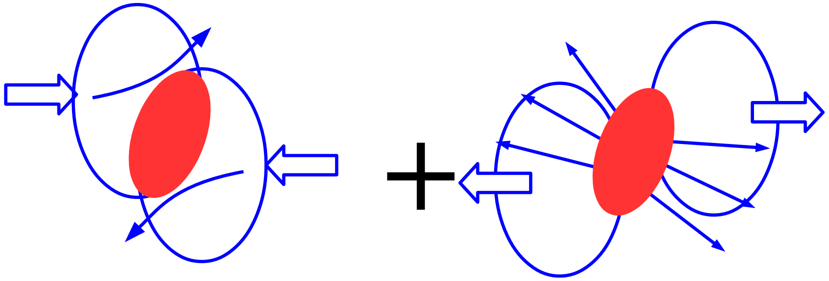
  Nara+('16,'17,'18); Y. Nara, AO, arXIv:2109.07594

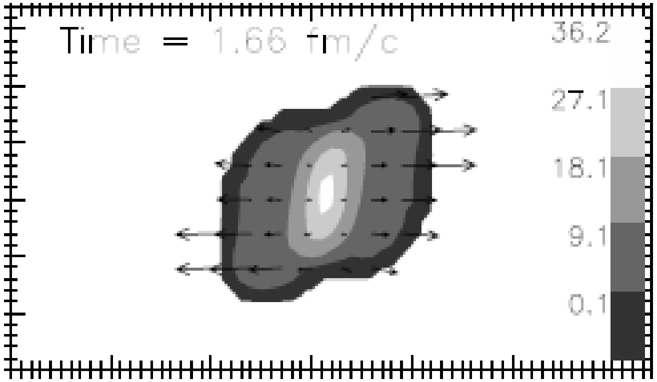
  - **Compression stage → repulsive pot. at high ρ → positive flow ($dv_1/dy > 0$)**
  - **Expansion stage → tilted matter formation → negative flow ($dv_1/dy < 0$)**

    (E.g. 3FD, Tonnev+('03)

- **Balance of two contributions may cause non-monotonic colliding energy dep. of v_1 slope**







18 GeV, 3-fluid *Toneev et al. ('03)*

Nara, AO (PRC'('22), 2109.07594)

Semi-Classical Nuclear Transport Theories

- **Wigner(-Weyl) transform of TDHF = Vlasov equation**
  - **Wigner transform of density matrix=Wigner fn. (phase space dist.)**
  - **Wigner transform of commutator ~ i $\hbar \times$ Poisson bracket**

$$i\hbar\frac{d\rho}{dt} = [h, \rho] \to \frac{\partial f}{\partial t} + \boldsymbol{v}\cdot\boldsymbol{\nabla} f - \boldsymbol{\nabla} U \cdot \boldsymbol{\nabla}_p f = 0$$

$$\left[f = \rho_W, [A, B]_W = i\hbar\{A_W, B_W\}_{PB} + \mathcal{O}(\hbar^2)\right]$$

  - **Test particle solution of the Vlasov equation → Classical EOM**

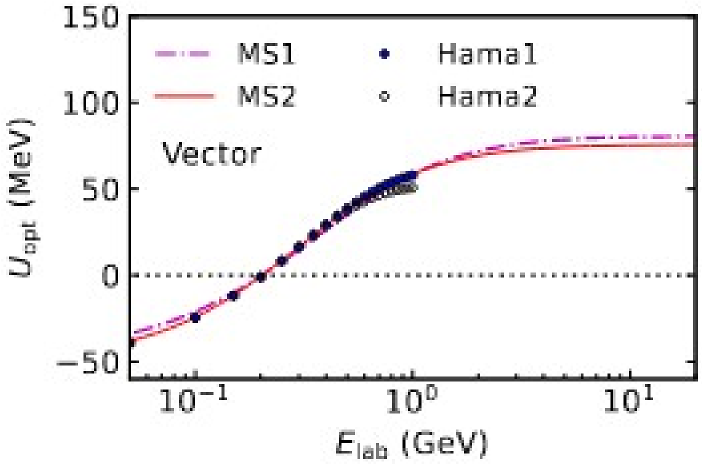
$$f(\boldsymbol{r},\boldsymbol{p}) = \frac{(2\pi)^3}{N}\sum_{i=1,NA}\delta(\boldsymbol{r}-\boldsymbol{r}_i)\delta(\boldsymbol{p}-\boldsymbol{p}_i)$$

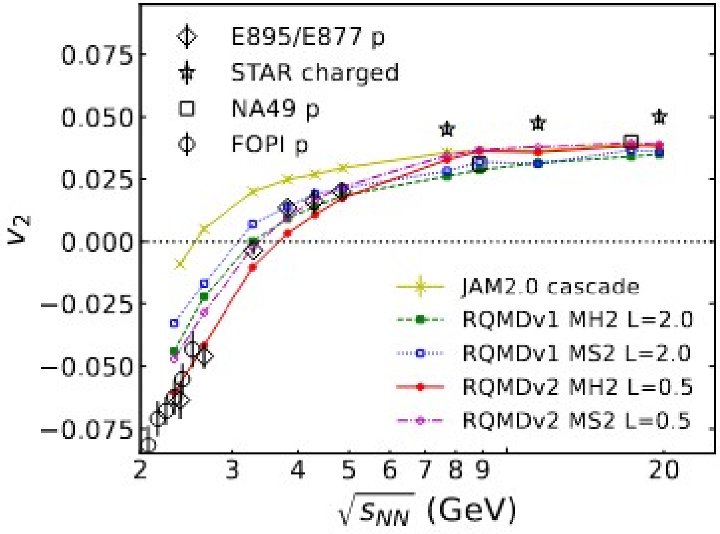
$$\to \frac{d\boldsymbol{r}_i}{dt} = \left.\frac{\partial h}{\partial \boldsymbol{p}}\right|_{\boldsymbol{p}=\boldsymbol{p}_i} = \frac{\boldsymbol{p}}{m} + \left.\frac{\partial U}{\partial \boldsymbol{p}}\right|_{\boldsymbol{p}=\boldsymbol{p}_i}, \quad \frac{d\boldsymbol{p}_i}{dt} = -\left.\frac{\partial U}{\partial \boldsymbol{r}}\right|_{\boldsymbol{r}=\boldsymbol{r}_i}$$

- **Relativistic Quantum Molecular Dynamics**
  - **Transport model applicable to high energies**
    Sorge, Stoecker, Greiner ('89); Maruyama et al. ('96)
  - **Stronger potential effects are necessary → Vector potential**
    Nara et al. ('20), Nara, AO ('21)
  - **Stochastic collisions are also included**

Can we access EOS by using flows ?

- **EOS from Flow is a Notorious problem!**
  - **Momentum-dependent potential can simulate stiff EOS, and then we cannot extract stiffness. (1980s ~)**
  - **Directed flow value depends on the details of the theoretical treatment.**
- **A New (?) Hope (Episode IV)**
  - **After fixing momentum-dependent pot. from pA scattering data and explaining v_1 data, EOS dependence of v_2 (elliptic flow) remains ! (Global analysis of multiple observables will help.)**
- **How about Λ ?**





Nara, AO (PRC'('22), 2109.07594)