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

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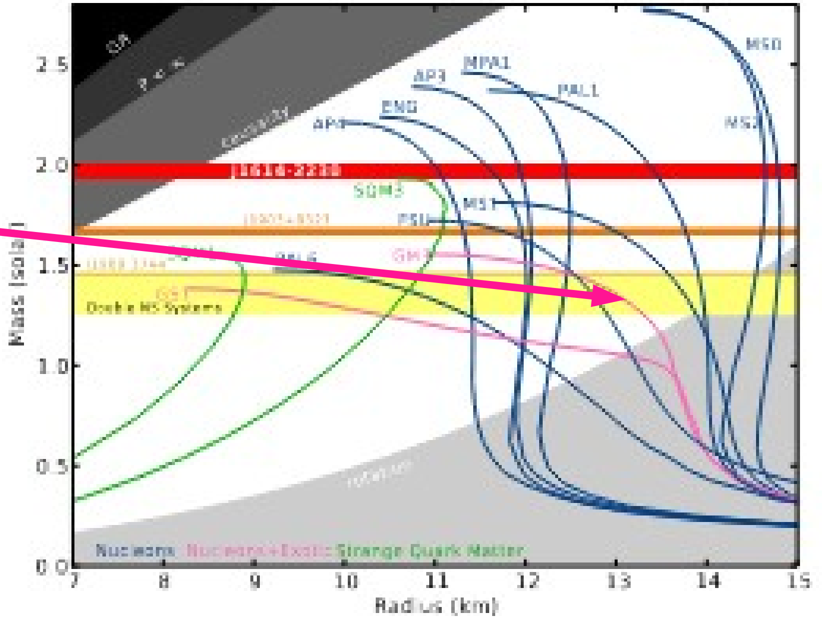
- Introduction – Hyperon puzzle
- Directed flow of protons
- Directed flow of Λ using U_Λ from chiral EFT
- Summary

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

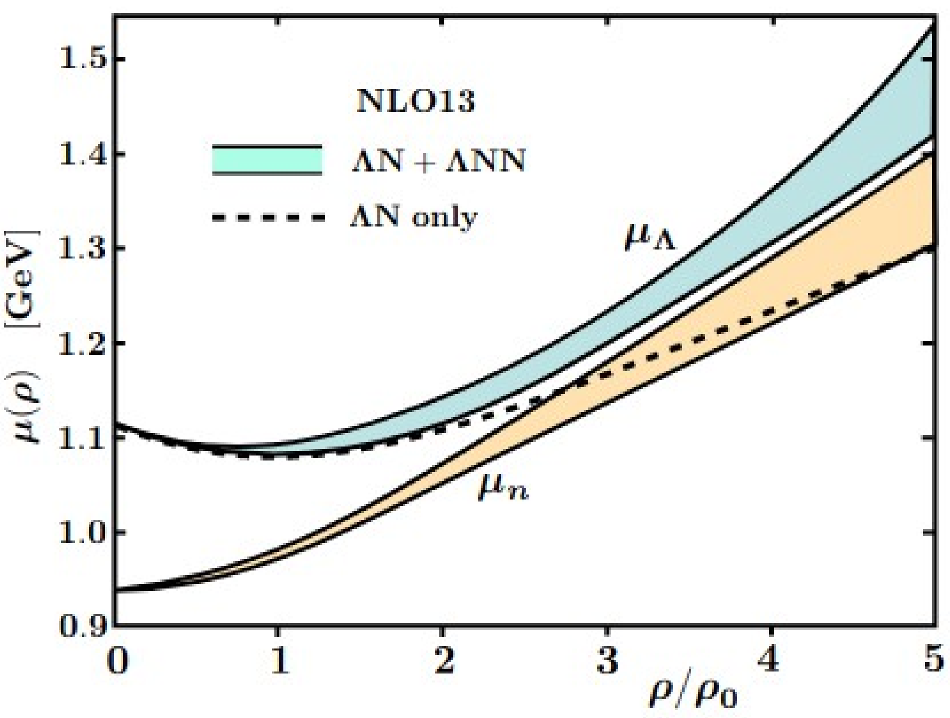


Demorest+(1010.5788)

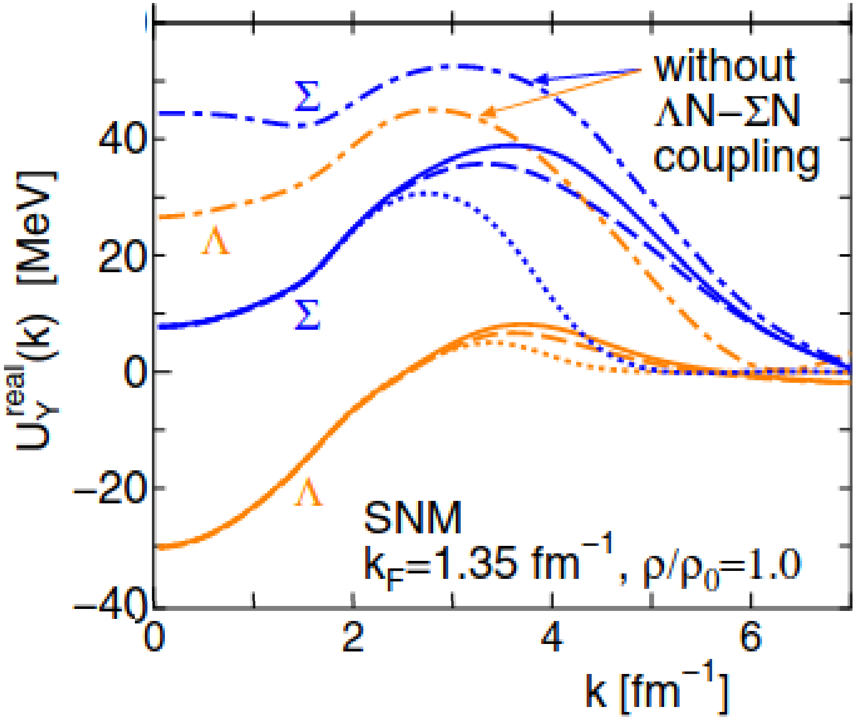
Challenging Subject
in Mean Field Dynamics

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. Collective flows in heavy-ion collisions



Gerstung+('20)



Kohno ('18)

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**

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

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

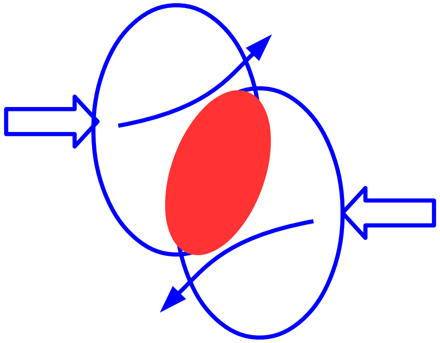
- **Relativistic Quantum Molecular Dynamics**
  - **Transport model applicable to high energies**
    Sorge, Stoecker, Greiner ('89); Maruyama et al. ('96)
  - **Stronger potential effects are necessary → Vector potential**
    Nara et al. ('20), Nara, AO ('21)
  - **Stochastic collisions are also included**

Transport models and then
(High-Energy) Heavy-Ion Collisions are
RELEVANT to Mean Field Dynamics.

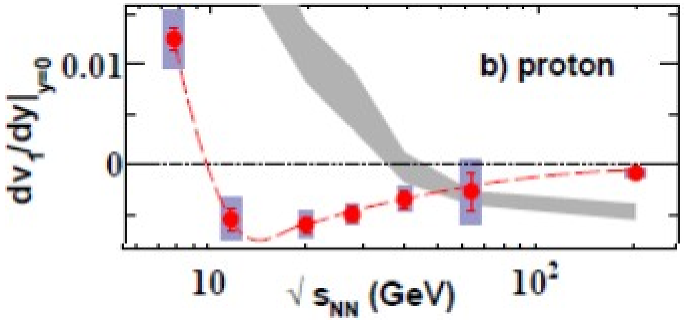
Let us Examine the Effects of U_Λ
at High Densities via Collective Flow(s)
in Heavy-Ion Collisions !

Directed flow of protons

Directed flow (v_1)



- **Directed flow (v_1 or $<p_x>$) has been utilized to constrain EOS**
  E.g. Sahu, Cassing, Mosel, AO (nucl-th/9907002), Snellings+(nucl-ex/9908001)
- **Proton v_1 slope problem** *STAR (1401.3043)*
  - **Non-monotonic beam E. dep. of v_1 slope**
  - **Sign change of v_1 slope at $\sqrt{s_{NN}} \sim 10$ GeV**
  - **None of fluid and hybrid models explain the colliding energy dependence using a single EOS**
    Nara+(JAM, 1601.07692, 1611.08023, 1708.05617), Ivanov+(3FD, 1412.1669, 1601.03902), Konchakovski+ (PHSD, 1404.2765)

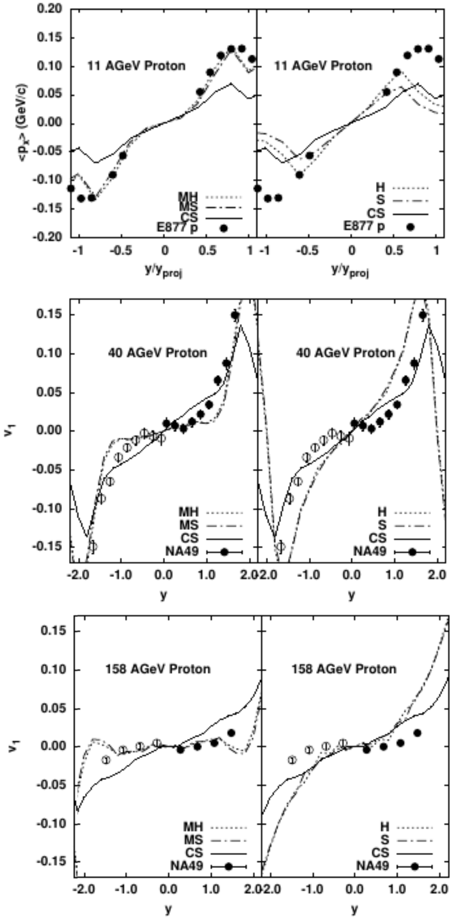


STAR, PRL112('14)162301 (1401.3043)

$$v_1 = \langle \cos\phi \rangle$$

Past tries

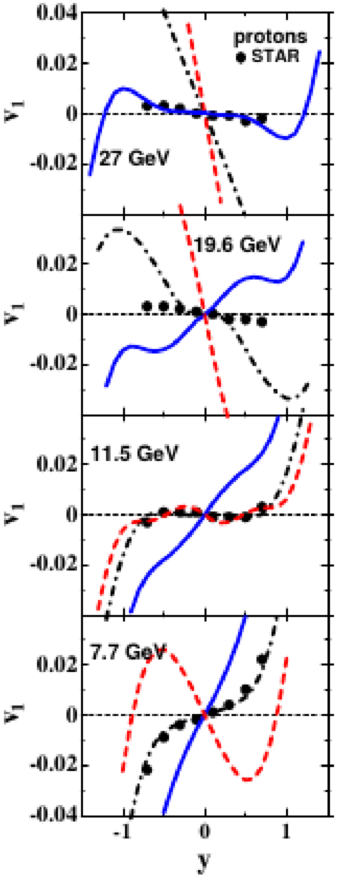
JAM-RQMD



p-dep. p-indep.

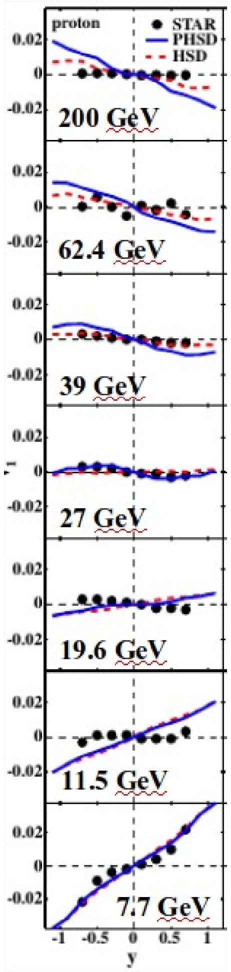
M.Isse, AO, N.Otuka, P.K.Sahu, Y.Nara, PRC72('05)064908 (There was a mistake...)

3FD



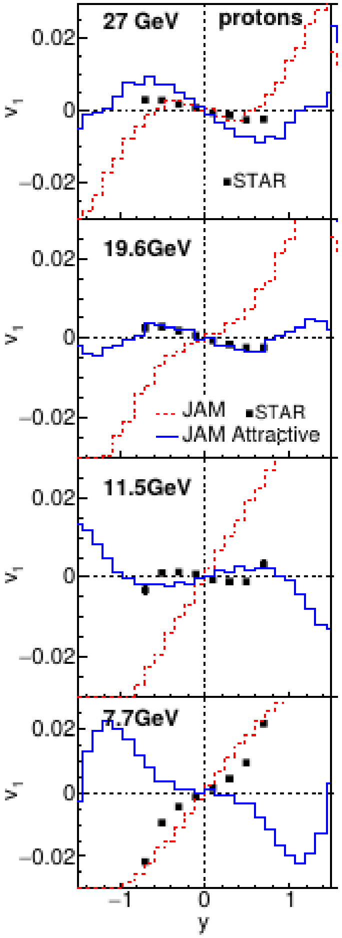
Y.B.Ivanov, A.A.Soldatov, PRC91('15) 024915

HSD/PHSD



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

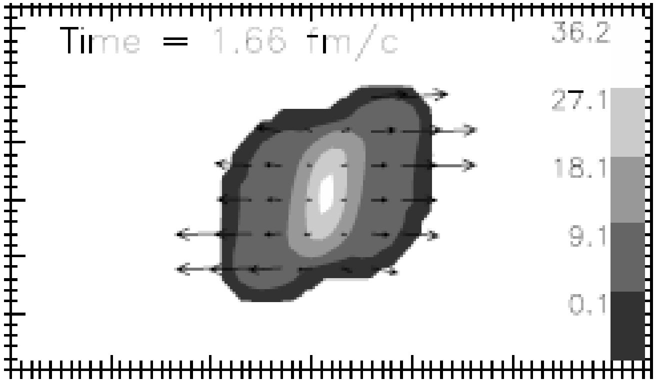
JAM+Att.



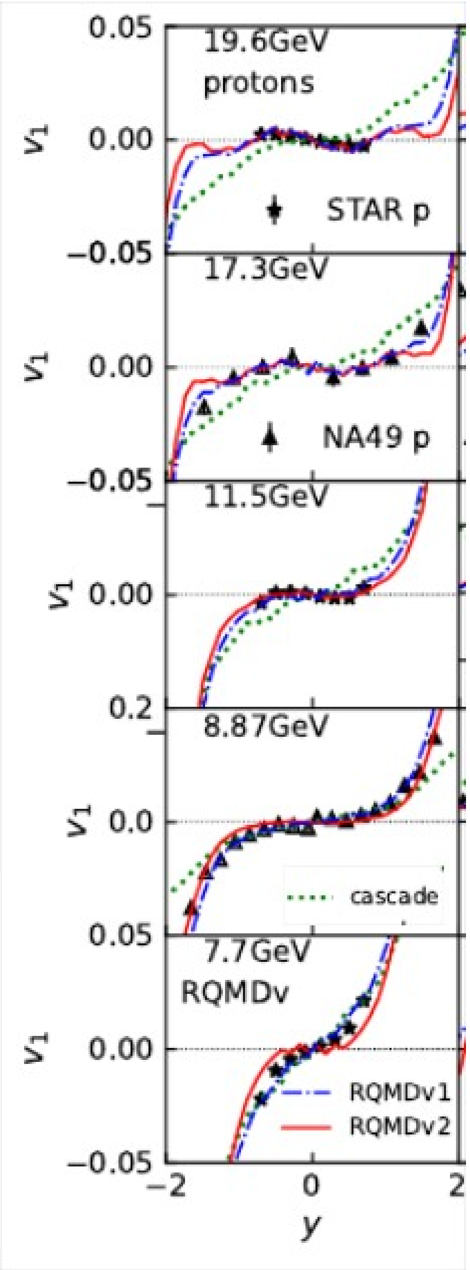
Y.Nara, H.Niemi, AO, H.Stoecker, PRC94 ('16)034906

An Explanation is found

- **Beam energy dependence of dv_1/dy can be explained with JAM2 in the RQMDv mode.**
  Nara+('16,'17,'18); Y. Nara, AO, arXIv:2109.07594
- **Origin of Positive & Negative Flow Components**
  - **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**

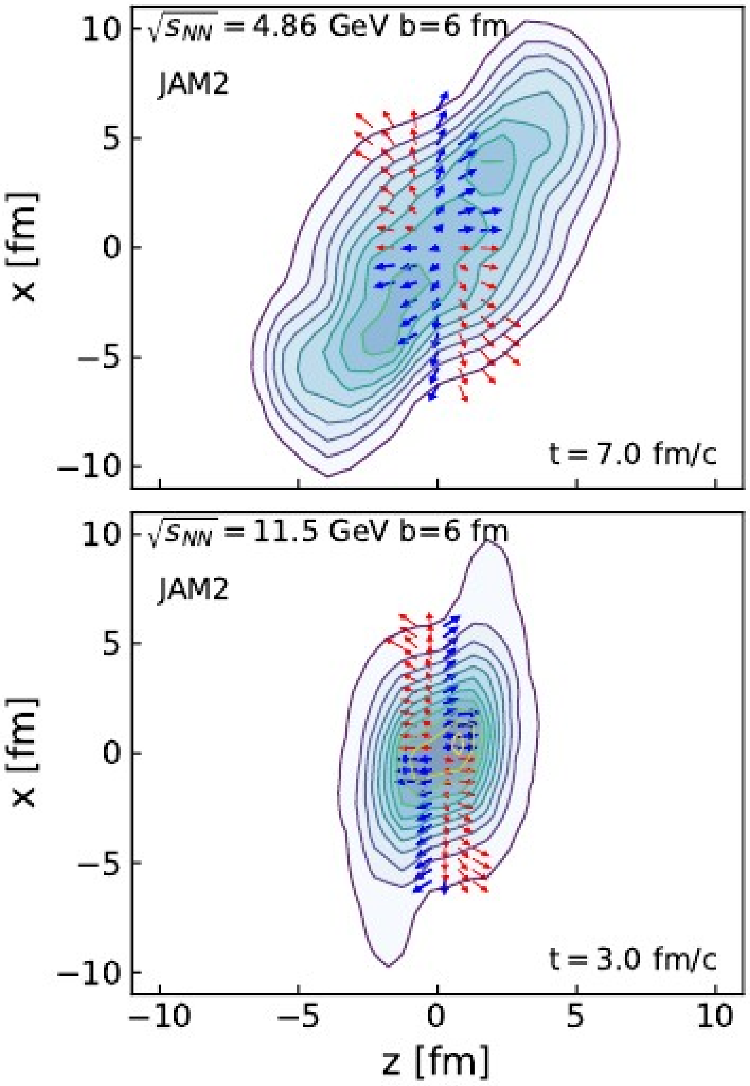


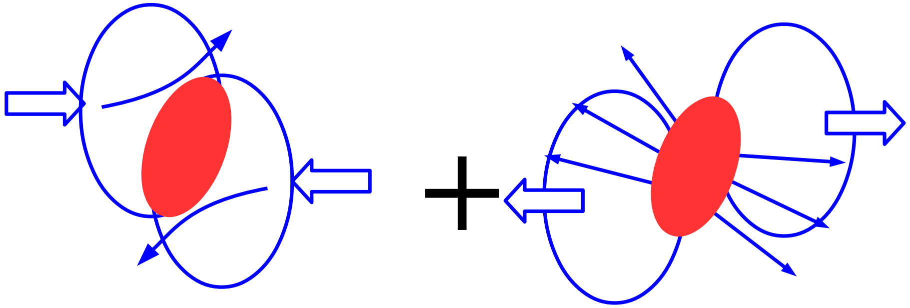
18 GeV, 3-fluid *Toneev et al. ('03)*

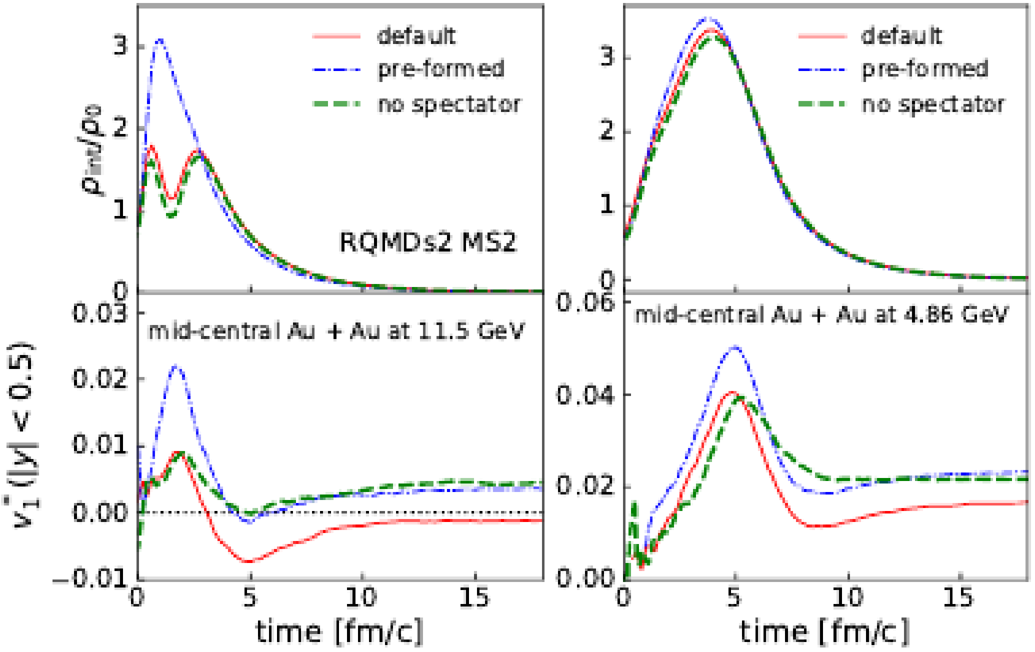


Nara, AO (PRC'('22), 2109.07594)

Positive and Negative Contributions



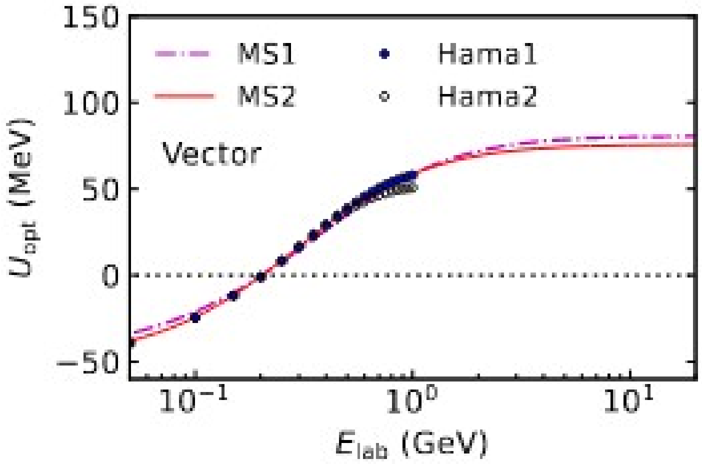


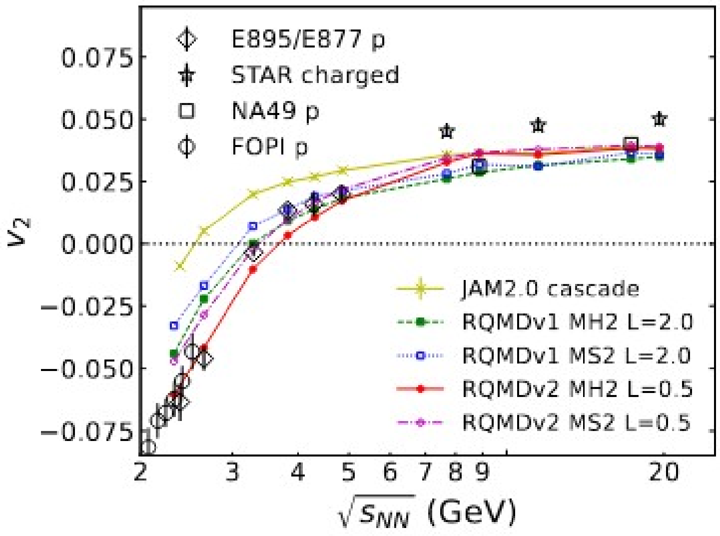


Nara, AO (PRC'('22), 2109.07594)

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 ?





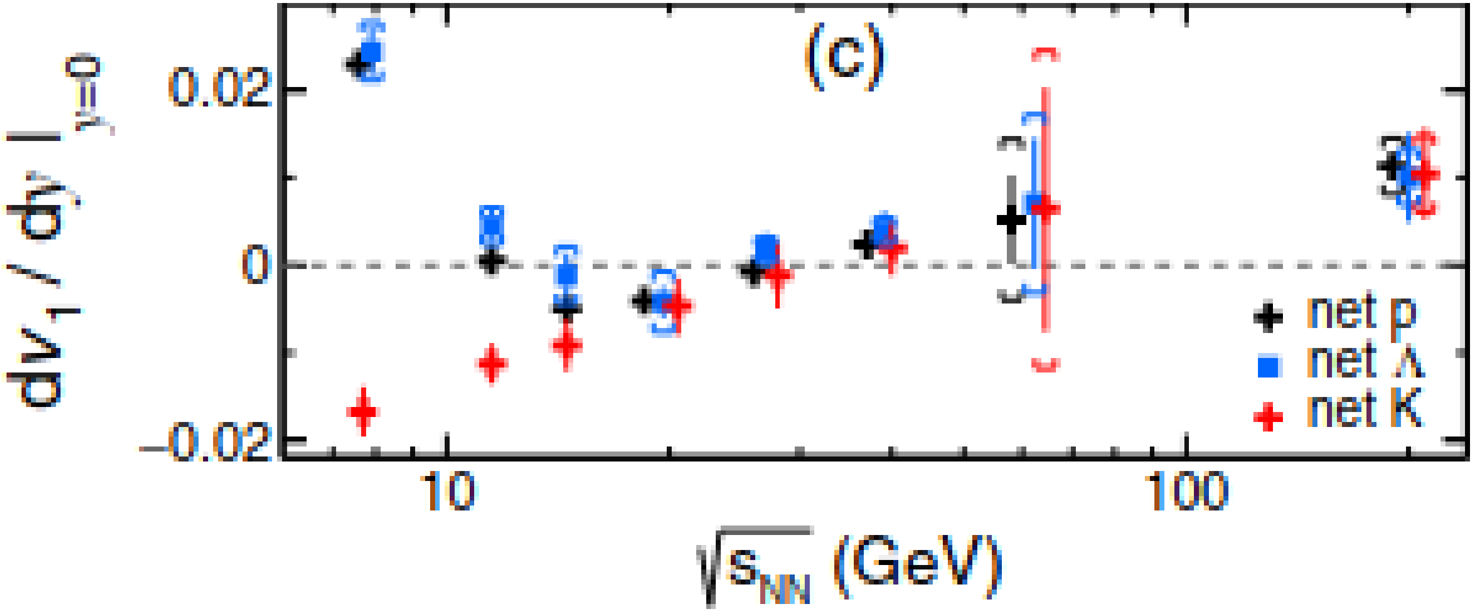
Nara, AO (PRC'('22), 2109.07594)

Directed flow of Λ using U_Λ from chiral EFT

Why Directed flow (v_1) of p and Λ

- **Directed flow of Λ**
  - **In the compression+tilted expansion mechanism, directed flow of Λ is expected to be smaller than p (Λs are produced during the compression stage).**
  - **Data show $v_1(\Lambda) \sim v_1(p)$** *STAR, PRL120 ('18),062301 (1708.07132)*

    → Stronger repulsion for Λ at high densities ?



Let us examine Λ directed flow using $U_\Lambda(\rho)$ from chiral EFT !

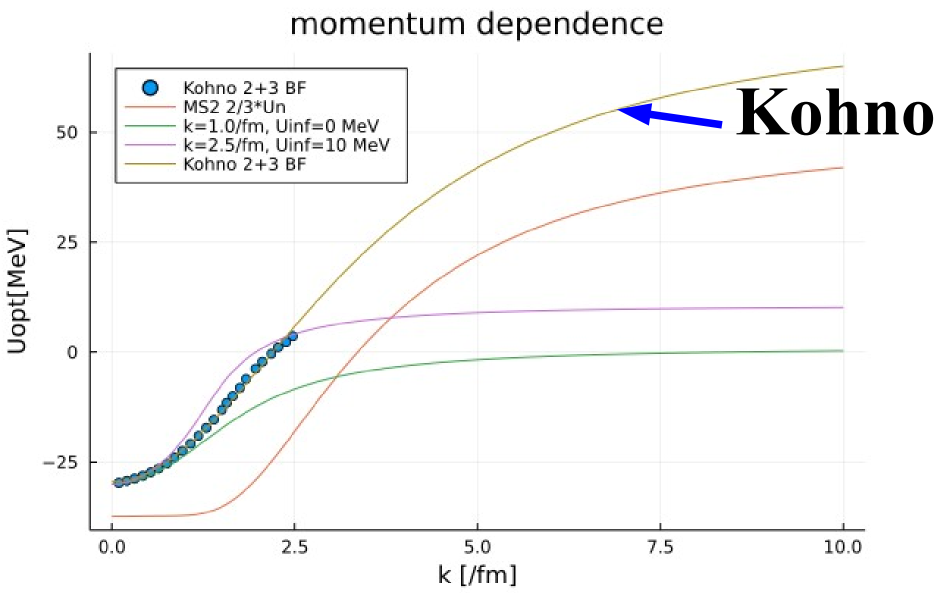
U_Λ from Chiral EFT

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

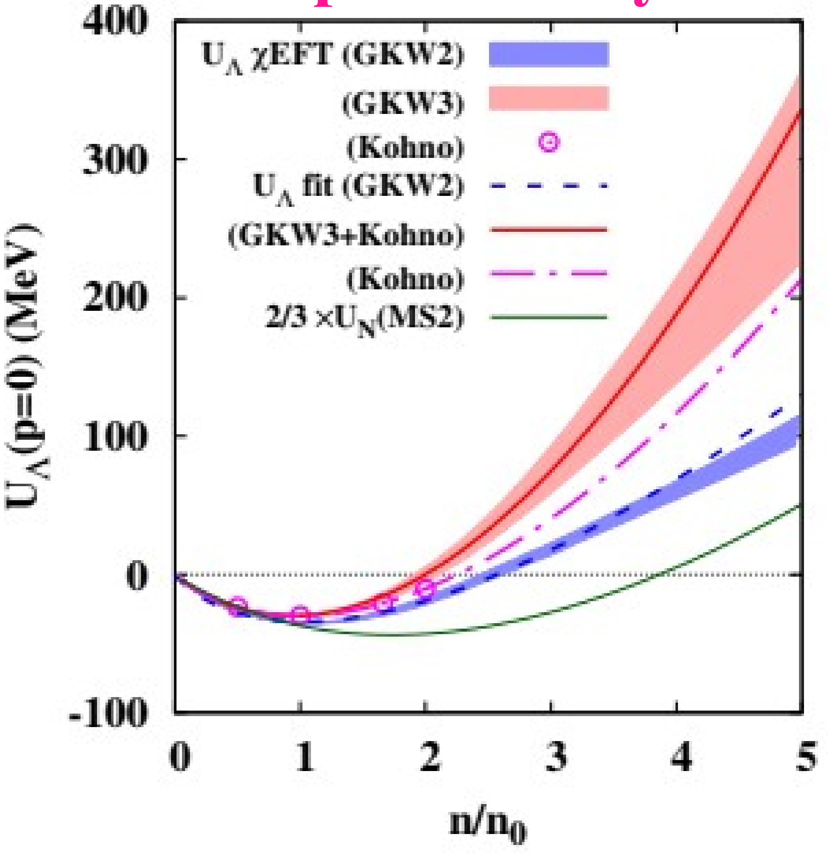
$$U_{\rm sk}(\rho) = a(\rho/\rho_0) + b(\rho/\rho_0)^{4/3} + c(\rho/\rho_0)^{5/3}$$

  - **Momentum dep. fit to** *Kohno('18)*

$$U^0_{\rm m}(\boldsymbol{p}) = \frac{C}{\rho_0}\int \frac{d\boldsymbol{p}'}{(2\pi)^3}\frac{f(\boldsymbol{r},\boldsymbol{p}')}{1+(\boldsymbol{p}-\boldsymbol{p}')^2/\mu^2}$$

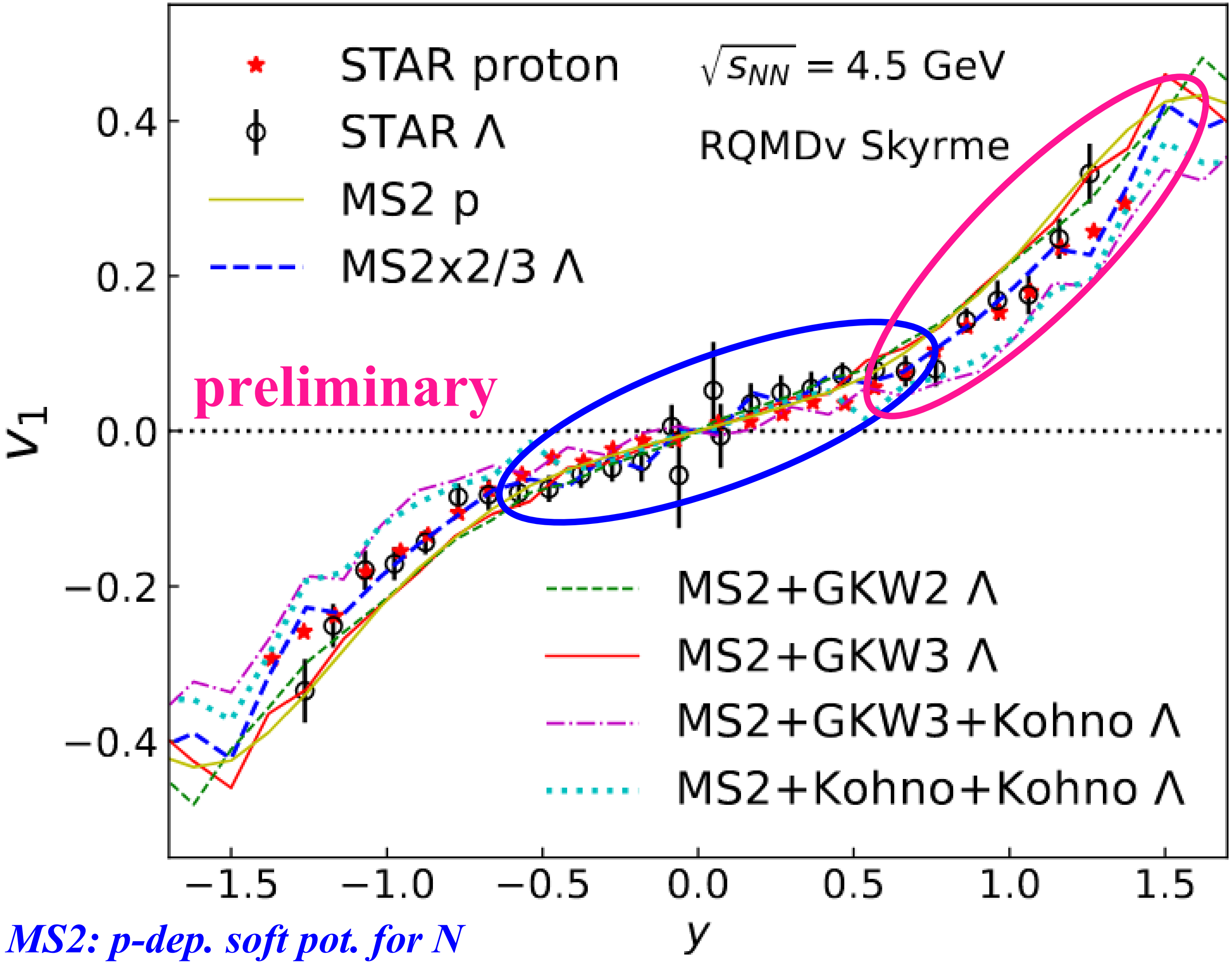


preliminary



Nara, Jinno, Murase, AO, in prep.

$\sqrt{s_{NN}}$=4.5 GeV



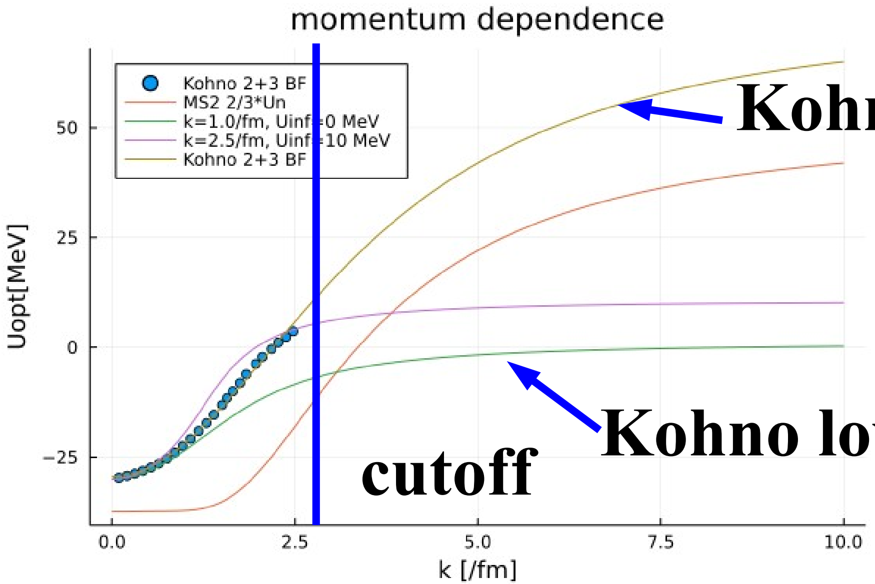
- **Slope (y=0) is OK with**
  - **chiral EFT U_Λ (p-indep.)**
  - **$U_\Lambda = 2/3\ U_N$**
- **v_1 at large |y| needs stiffer U_Λ**
  - **chiral EFT (p-indep.)**
- **p-dep. U_Λ seems to underestimate v_1**

MS2: p-dep. soft pot. for N
GKW2: chiral EFT with 2-body int.
GKW3: chiral EFT with 2+3 body int.
GKW3+Kohno: GKW3 with p-dep. from Kohno
Kohno+Kohno: ρ- and p-dep. from Kohno

Nara, Jinno, Murase, AO, in prep.

Momentum dependence of U_Λ

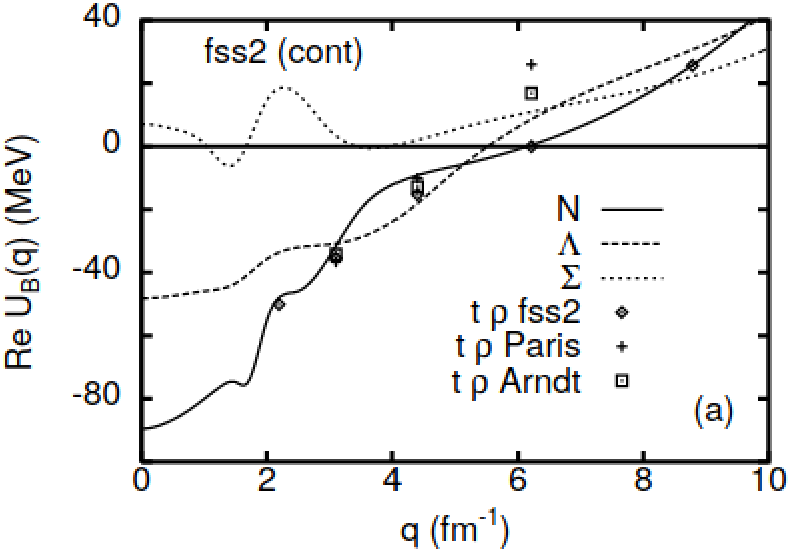
- Can we rely on U_Λ up to 2 GeV/c ?
  - The cutoff is 550 MeV/c ~ 2.75 fm^{-1} in Kohno ('18)
  - Quark model YN interaction gives weaker p-dep.
- Chiral EFT results at $k < 1\ \mathrm{fm}^{-1}$ are fitted and used (Kohno low-k)



Kohno

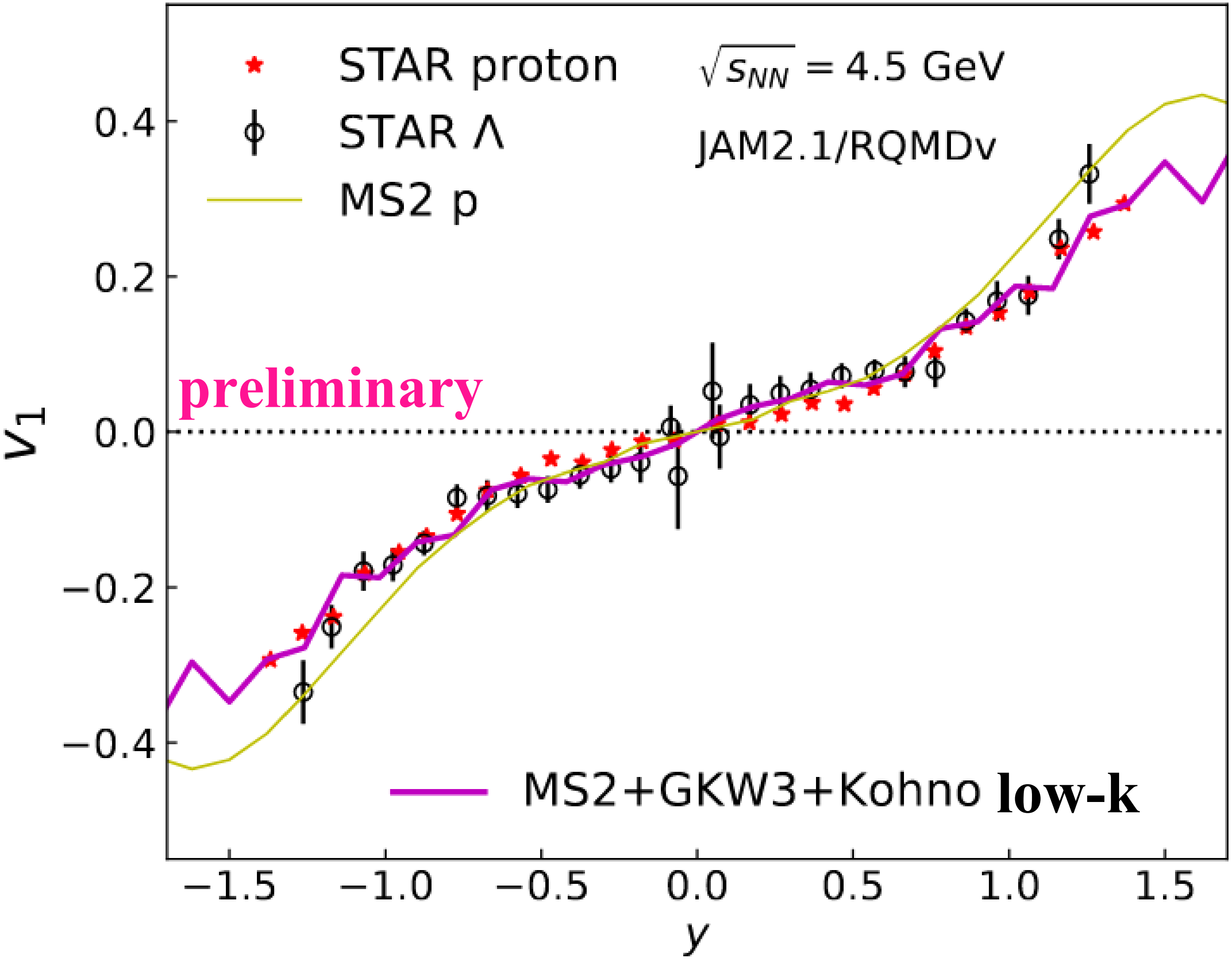
Kohno low-k

cutoff



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

$\sqrt{s_{NN}}$=4.5 GeV (with p-dep. of Kohno low-k)



Chiral EFT at low momentum seems to be consistent with the Λ directed flow.

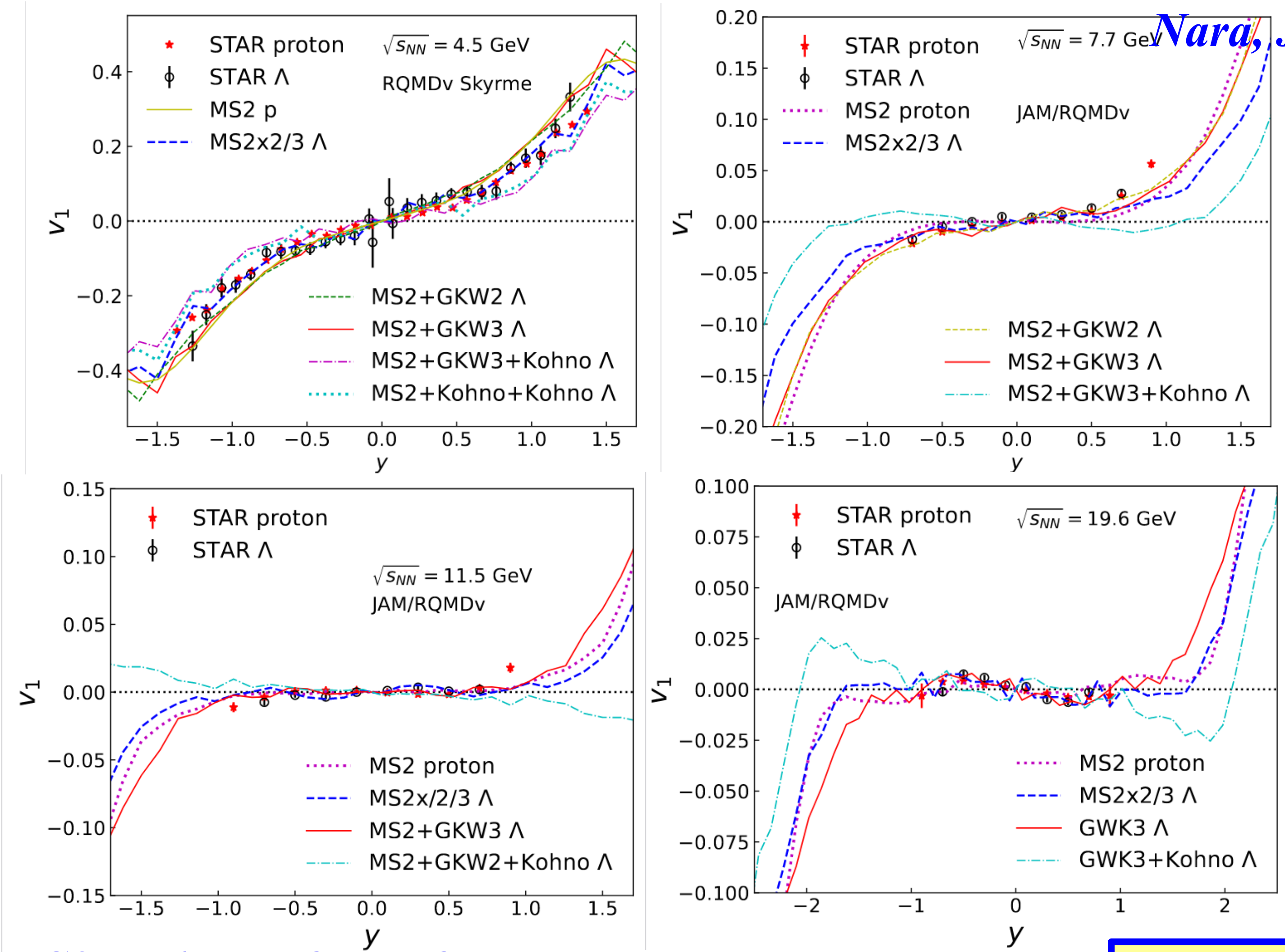
Summary

- The directed flow (v_1) of Λ from HIC is studied by using the Λ potential from chiral EFT with 3-body potential, which can support 2 solar mass neutron stars.
  - U_Λ from chiral EFT is not inconsistent with the directed flow data from heavy-ion collisions.
    [Similar results for <px> at √sNN=3.0 GeV are obtained by D.C. Zhang+ (2107.00277)]
  - Momentum dependence may be weaker than the explicit results.
    (We should not rely on results at k > Λ/2)
  - $v_1(\Lambda)$ is not very sensitive to the density dep. of U_Λ.
    (Λ produced from N in the compression stage succeeds the v_1 of N)
  - The forward and backward v_1 values seem to be sensitive to the Λ potential at high densities and/or high momentum.
- How can we pin down U_Λ at high densities ?
  - Λ-nucleus scattering (Emulsion or Femtoscopy) → mom. dep.
  - Elliptic flow (v_2) and other observables
  - Hypernuclear spectroscopy

Nara, Jinno, Murase, AO, in prep.

Thank you for your attention !

Directed flow of Λ at $\sqrt{s_{NN}}$=(4.5-19.6) GeV

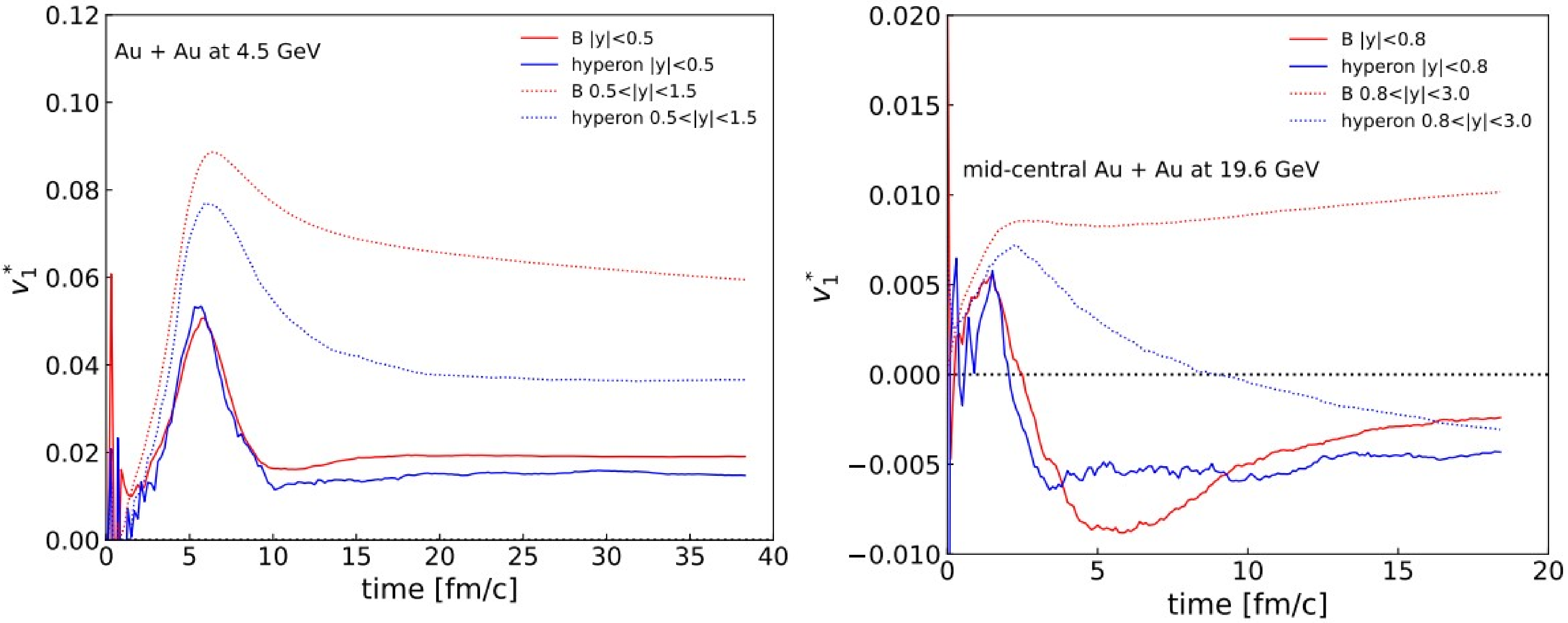


Nara, Jinno, Murase, AO, in prep.

MS2: p-dep. soft pot. for N
GKW2: chiral EFT with 2-body int.
GKW3: chiral EFT with 2+3 body int.
GKW3+Kohno: GKW3 with p-dep. from Kohno
Kohno+Kohno: ρ- and p-dep. from Kohno

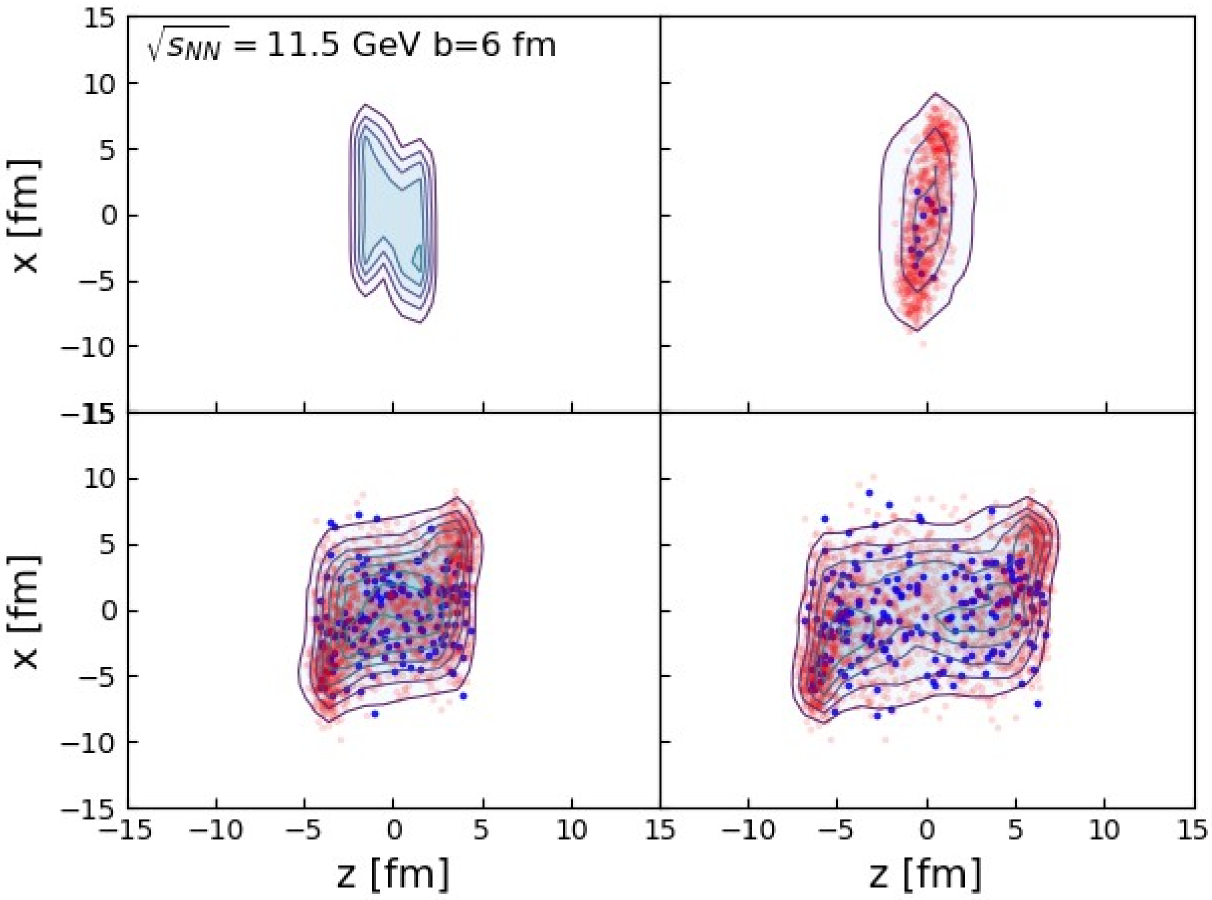
U_Λ having the ρ-dep. in chiral EFT roughly explains the v_1 slopes.

Time dependence of v1



Courtesy of Y. Nara

Lambda position: 11.5GeV 20events

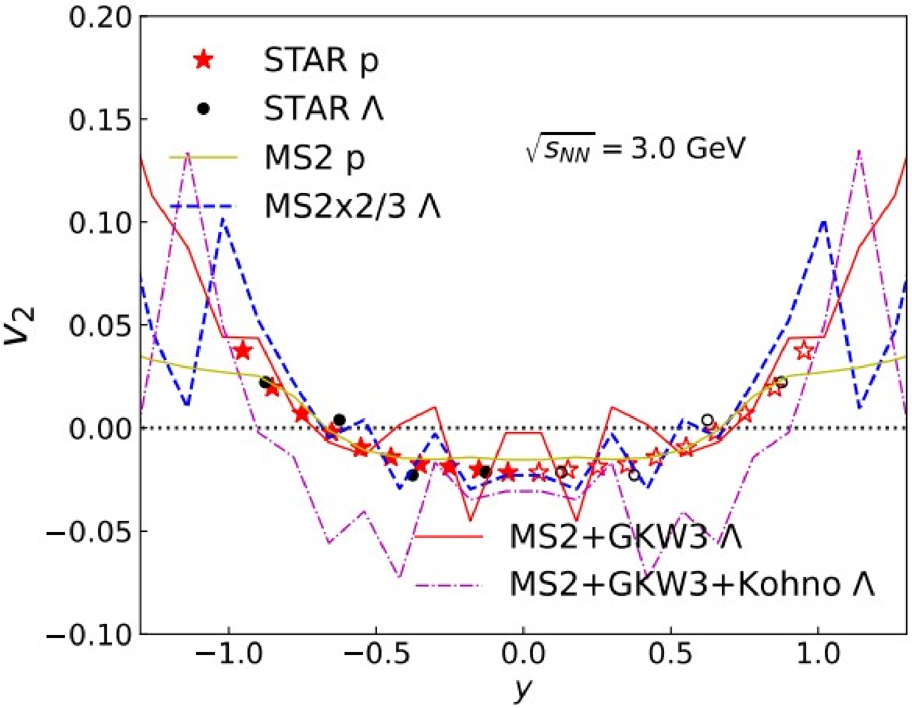


Red: nucleons
Blue: Lambda + Sigma0

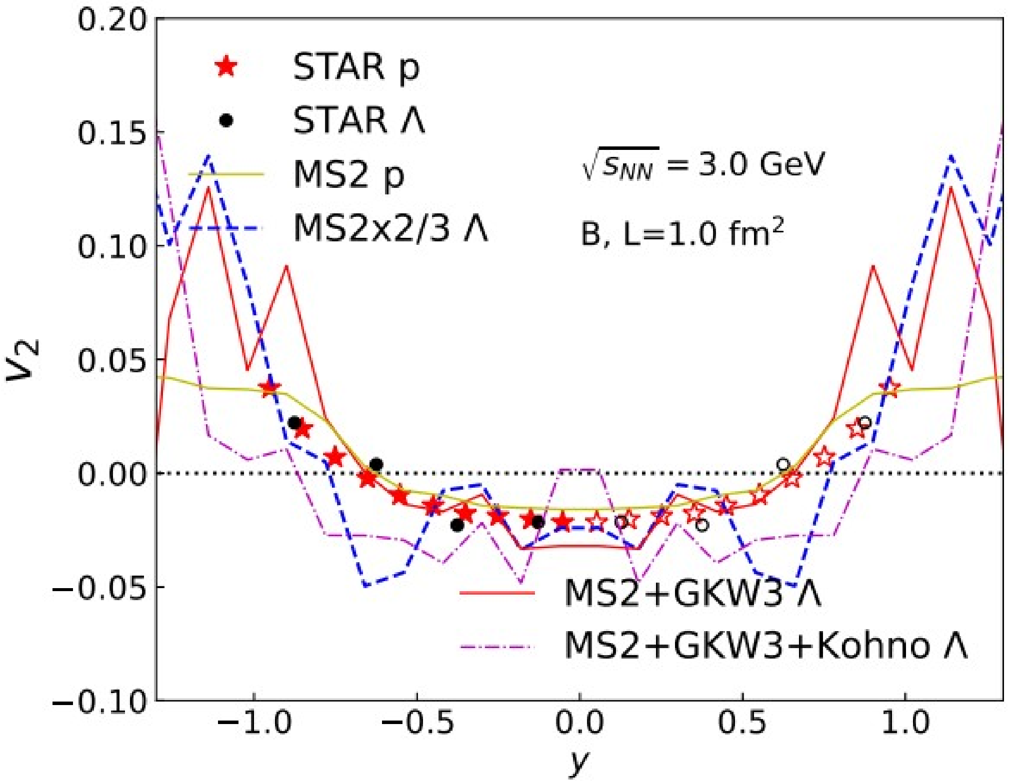
Courtesy of Y. Nara

V2 from Au + Au @ 3.0GeV

Collision order=collision time = (t1+t2)/2, L=0.5 fm^2



CO=CT= min(t1,t2), L=1.0 fm^2



Courtesy of Y. Nara