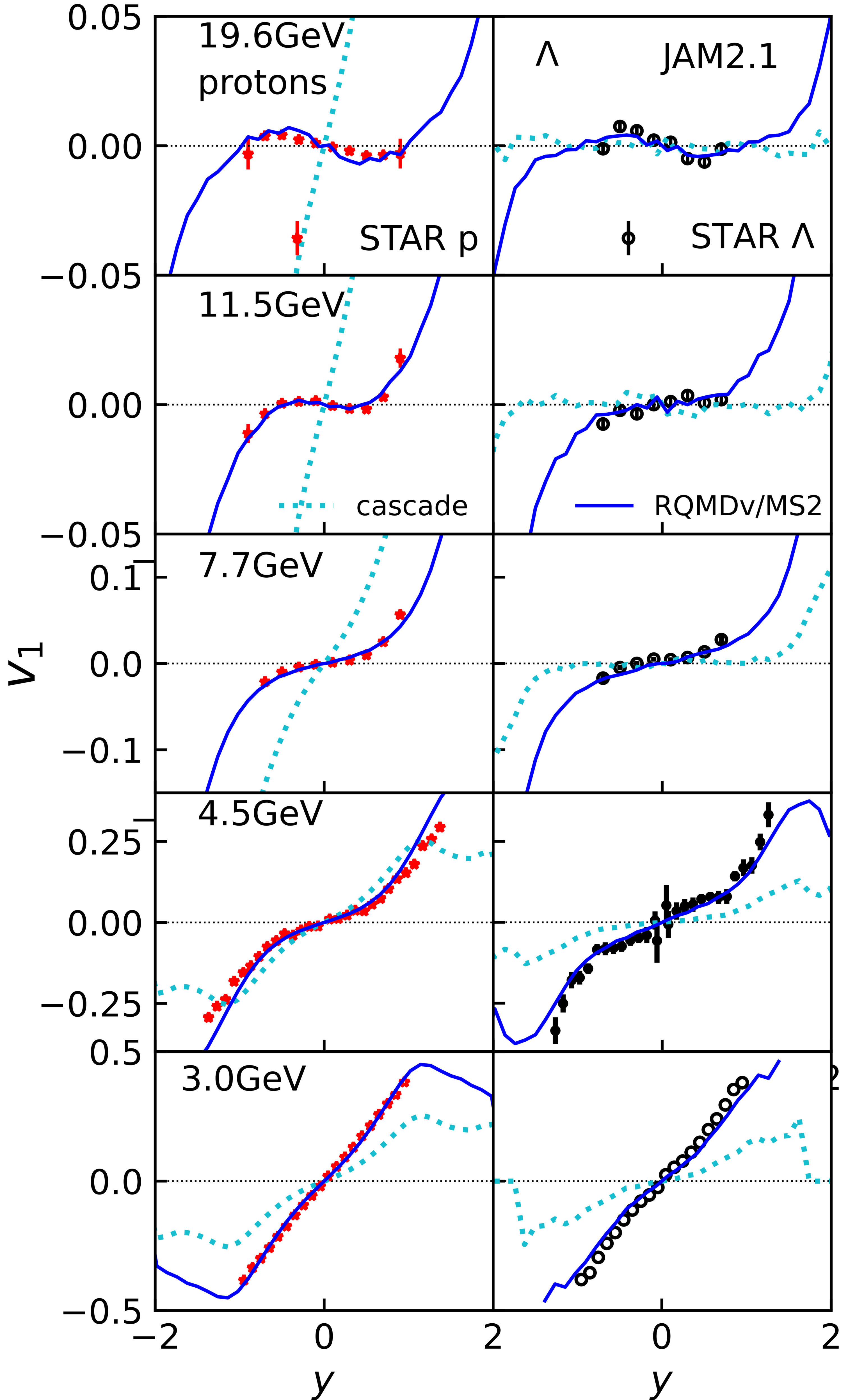
Lambda directed flow from chiral models in JAM

Yasushi Nara (Akita International Univ.)
In collaboration with A.Jinno (Kyoto Uni.v)
and K.Murase (Tokyo Metropolitan Univ.)

- introduction
- σ-ω model, Singlet mode,Parity doublet model
- RQMD
- results

2024/2/19 probing dense baryonic matter with hadrons II:FAIR Phase-0 at GSI

Beam energy dependence of v1 from RQMDv



Y.N. and A. Ohnishi, PRC(2022)

Y.N, A. Jinno, K. Murase, A. Ohnishi, PRC106 (2022)

Skyrme type Loretnz vector potential:

$$p^{*\mu} = p^\mu - U^\mu_{\rm sk}(\rho) - U^\mu_m(p)$$

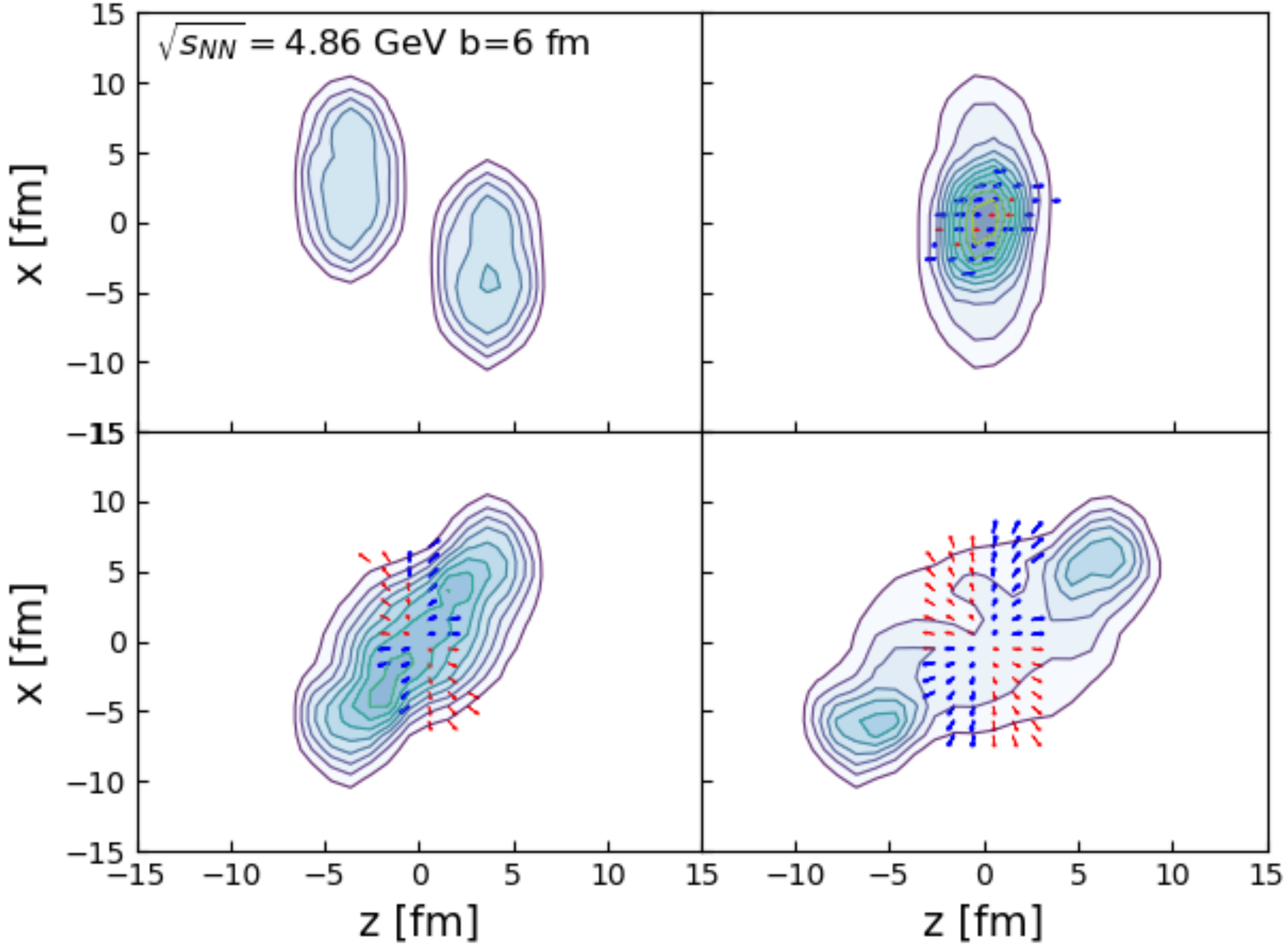
$$U^\mu_{sk} = U_{sk}(n_B)\frac{J^\mu_B}{\sqrt{J^2_B}} \qquad U_{\rm sk}(\rho) = \alpha\left(\frac{\rho}{\rho_0}\right) + \beta\left(\frac{\rho}{\rho_0}\right)^\gamma$$

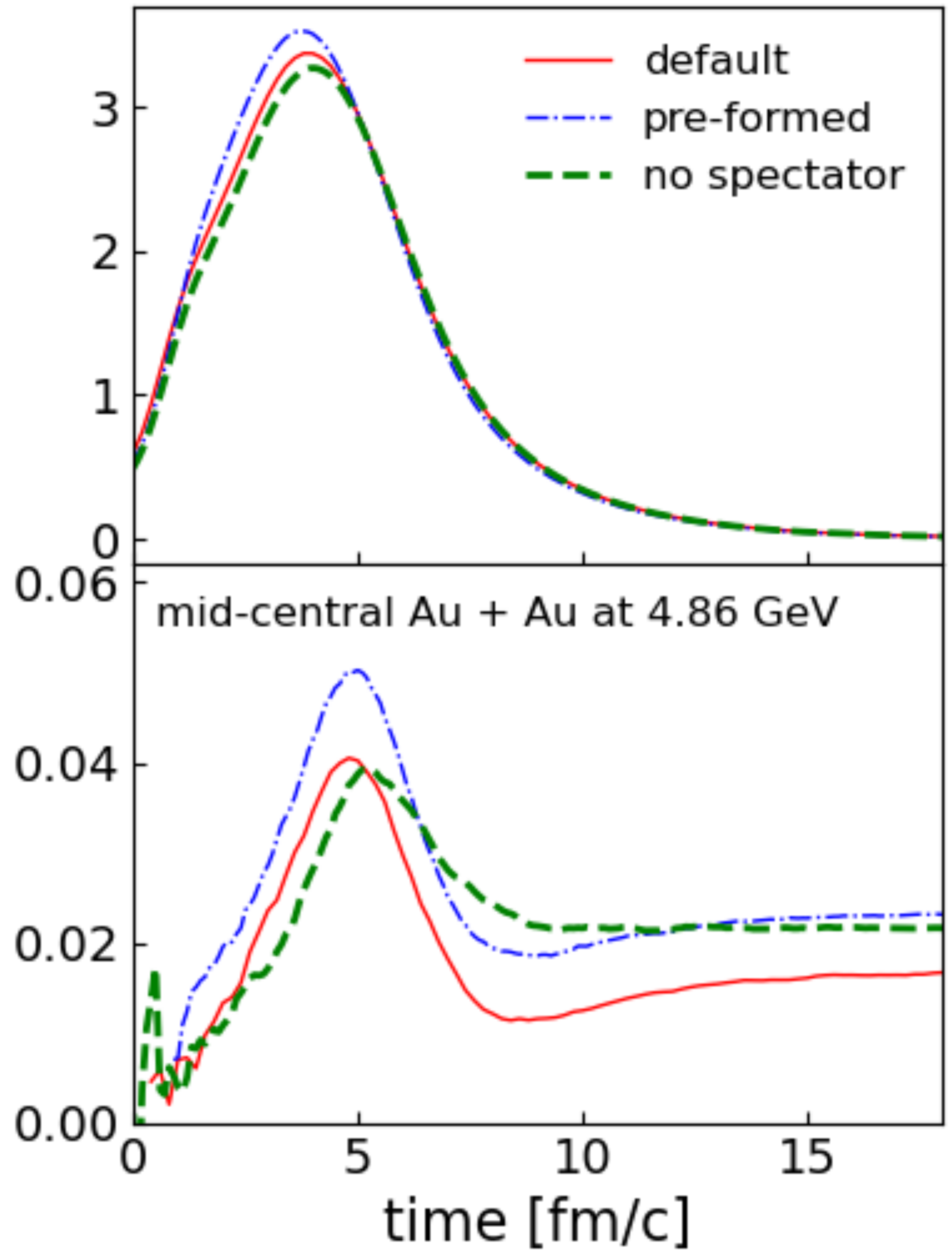
$$U^\mu(p) = \frac{C}{\rho_0}\int d^3p'\frac{p^{*'\mu}}{e'^*}\frac{f(x,p')}{1+[(p-p')-(p-p')\cdot(p'/m')]^2/\mu^2}$$

Lambda v1 is similar to proton v1.

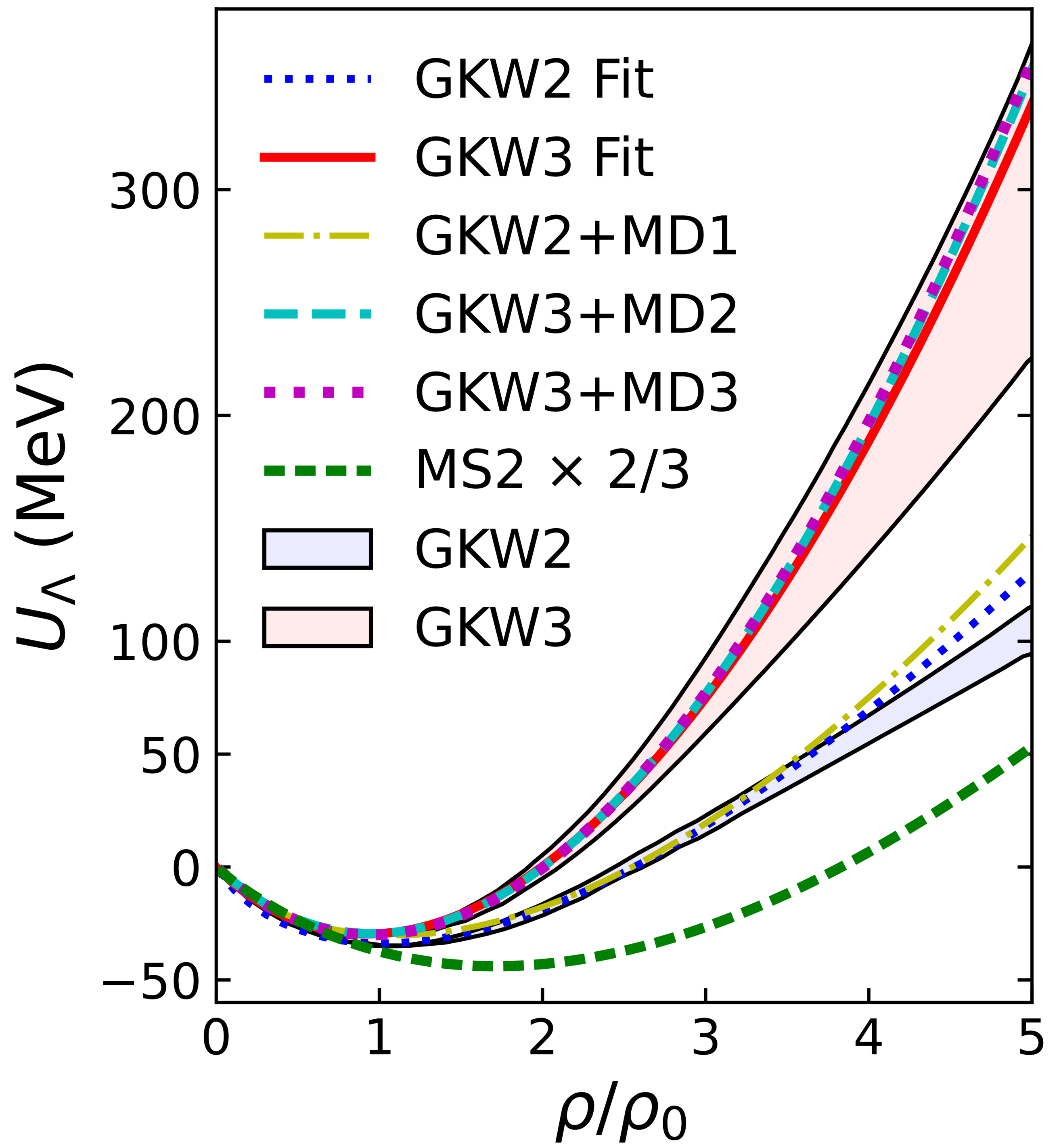
Time evolution of v1

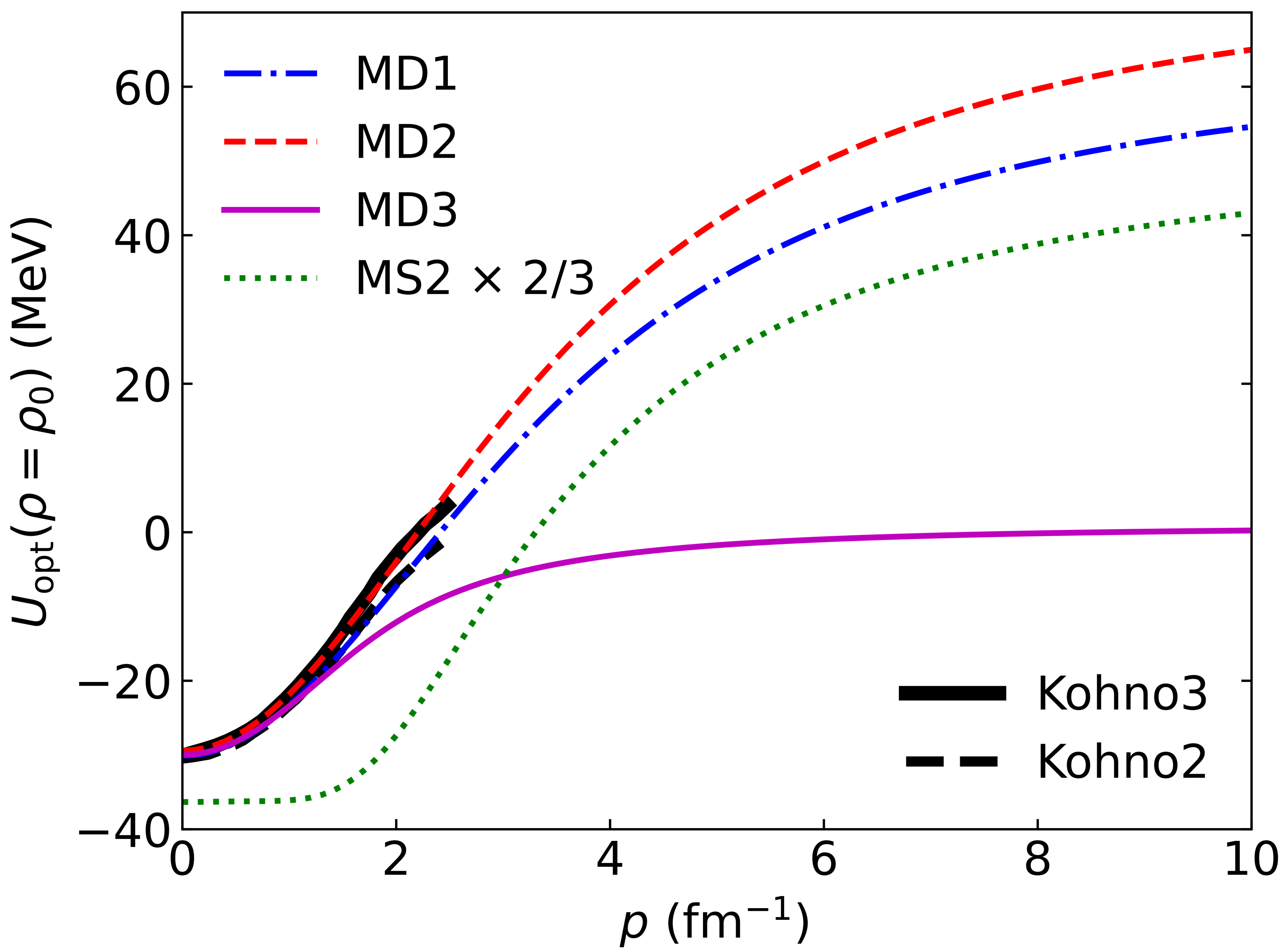
Au＋Au mid-central collision (b=6fm)

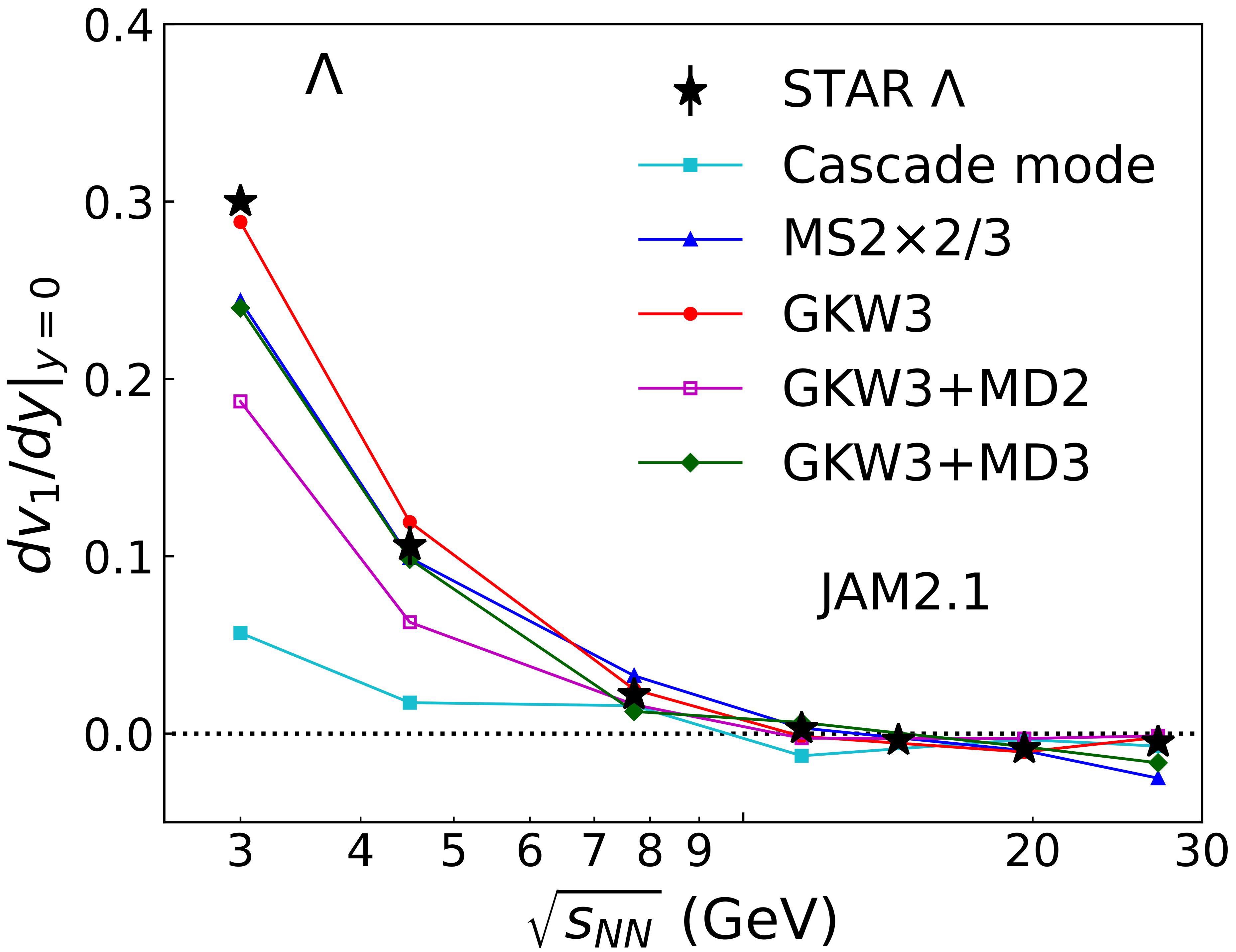




Lambda directed flow







Lambda directed flow (v1) is sensitive to the momentum-dependent interaction.

Y.N, A. Jinno, K. Murase, A.Ohnishi, PRC106 (2022) 044902

motivation

Lambda v1 is sensitive to the momentum dependent interaction, which implies that lambda v1 is sensitive to the scalar interaction in a relativistic approach.

$$e = \sqrt{m^{*2} + (\boldsymbol{p} - \boldsymbol{V})^2} + V^0$$

Previous work suggests that lambda v1 is sensitive to the scalar interaction, while, it may not be sensitive to the vector interaction.

σ-ω model $$m^* = m_N + g_{N\sigma}\sigma$$

Chiral Singlet model $$m^* = g_{N\sigma}\sigma$$

Parity doublet model $$m^*_\pm = \sqrt{a^2\sigma^2 + m_0^2} \pm b\sigma \qquad m_0 = 0 \text{ yields the singlet model.}$$

compare three different models using relativistic quantum dynamics (RQMD)

All models are implemented in JAM2.5: https://gitlab.com/transportmodel/jam2

Models

E.S.Fraga,et.a.PRD108(2023)

σ-ω model

$$m^* = m_N + g_{N\sigma}\sigma$$

$$U(\sigma) = \frac{m_\sigma^2}{2}\sigma^2 + \frac{g_2}{2}\sigma^3 + \frac{g_3}{4}\sigma^4$$

Chiral Singlet model

$$m^* = g_{N\sigma}\sigma$$

$$U(\sigma) = \sum_{i=1}^{4} \frac{a_n}{2^n n!}(\sigma^2 - f_\pi^2)^n - \epsilon(\sigma - f_\pi)$$

Parity doublet model (PDM)

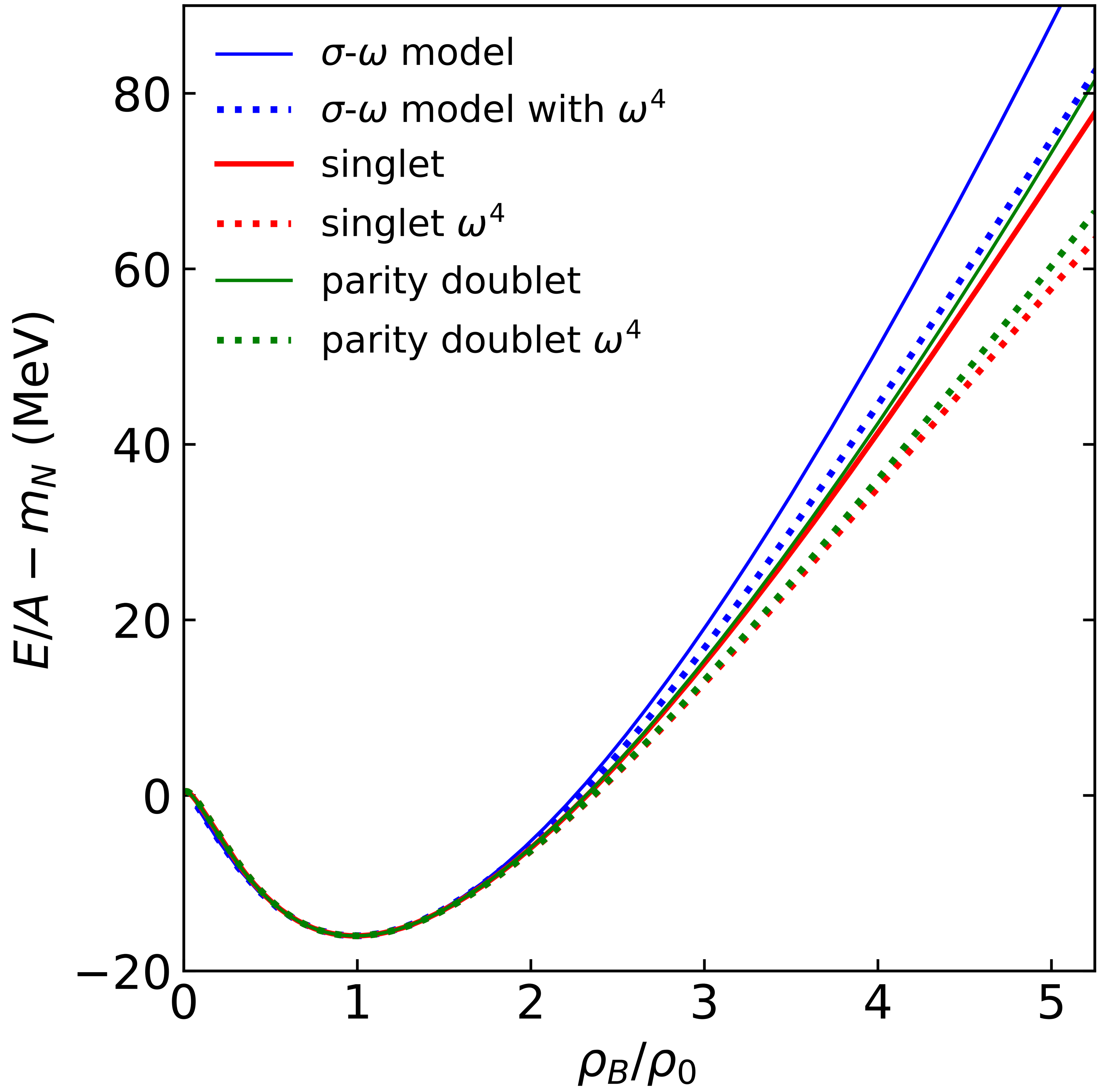
$$m_\pm^* = \sqrt{a^2\sigma^2 + m_0^2} \pm b\sigma$$

$m_0 = 0$ yields the singlet model.

vector interaction: $$V^\mu = \frac{m_\omega^2}{2}\omega^2 + \frac{m_\rho^2}{2}\rho^2 + \frac{m_\phi^2}{2}\phi^2 + \frac{c_4}{4}(\omega^4 + \rho^4 + c_5\omega^2\rho^2)$$

We switch off ρ, ϕ and quartic term

Energy per nucl.



$m^*/m_N = 0.83 \quad K = 240\,\mathrm{MeV}$

$BE = -16\,\mathrm{MeV}$ at $n_0 = 0.168\,\mathrm{fm}^{-3}$

$m_0 = 0.4, 0.7$ GeV

$U_\Lambda = -30\,\mathrm{MeV},\ U_\Sigma = 20\,\mathrm{MeV}$

$U_\Xi = -20\,\mathrm{MeV}$

$g_{Y\omega}$ is fixed from SU(6)

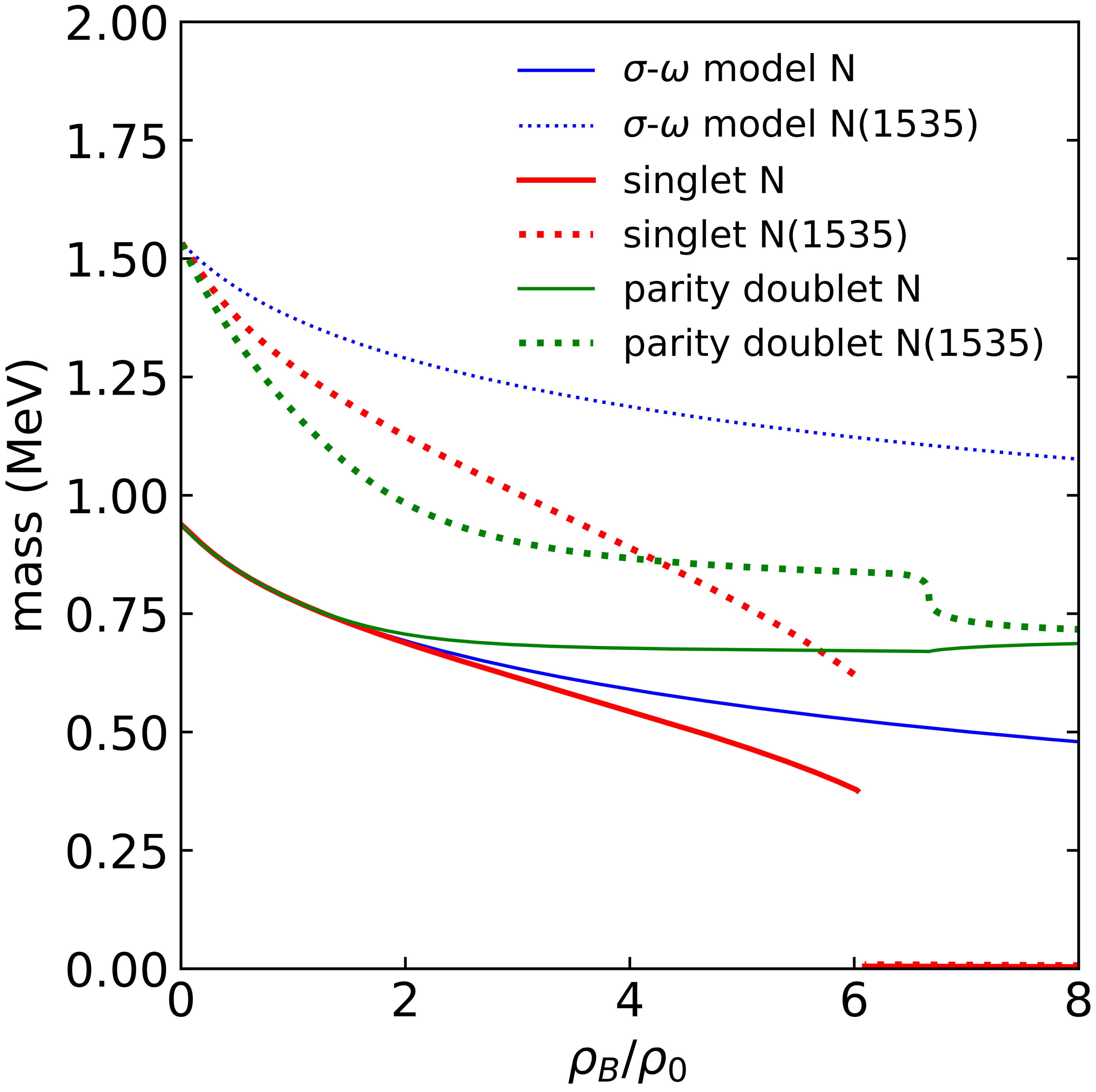
$g_{Y\sigma}$ is fixed from U_Y

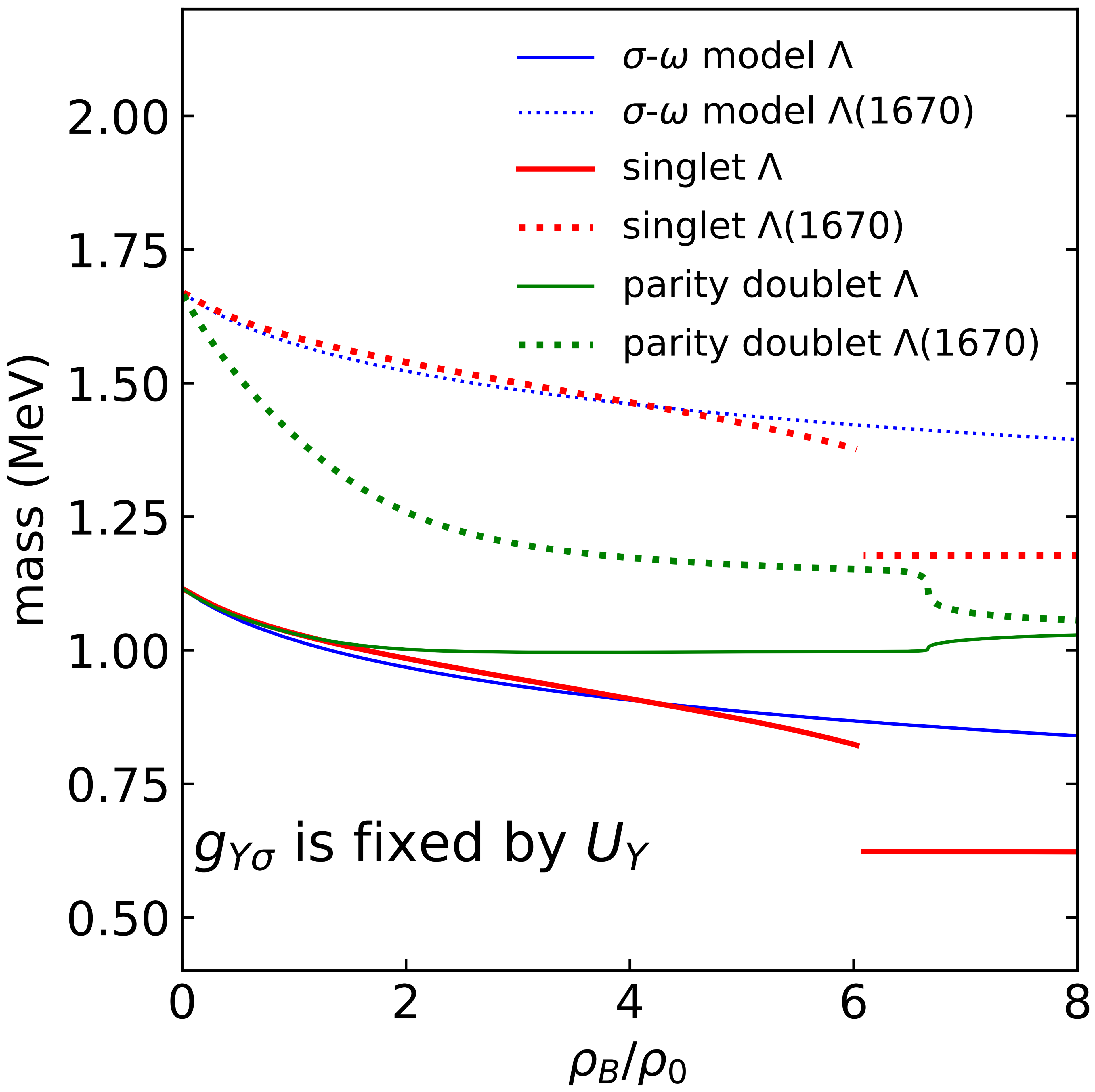
Δ potential : $-150 \le U_\Delta \le -50$ MeV

See E.E. Kolomeitsev et al. NPA961 (2017) 106

hyperon resonance potential depth U_{Y^*} is a free parameter

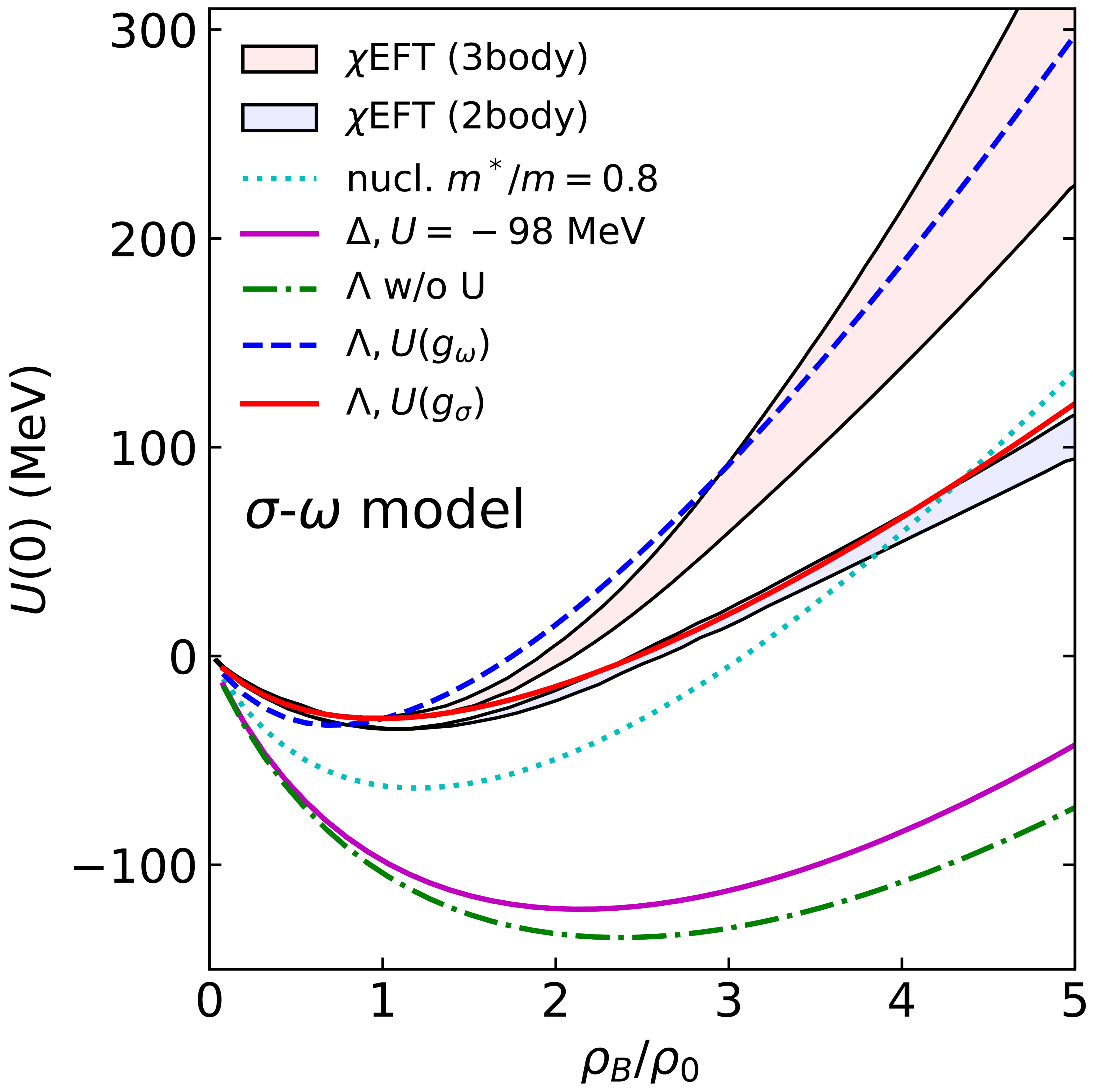
Effective mass





Mass of the Chiral partner decreases faster in the parity doublet model

σ-ω model:Single particle potential



$$U(0) = m_0^* - m + g_{B\omega}\omega_0 = -g_{B\sigma}\sigma_0 + g_{B\omega}\omega_0$$

$U(g_\omega)$: $g_{B\omega}$ is fixed by $U = -30$ MeV

$g_{B\sigma} = g_{N\sigma}$

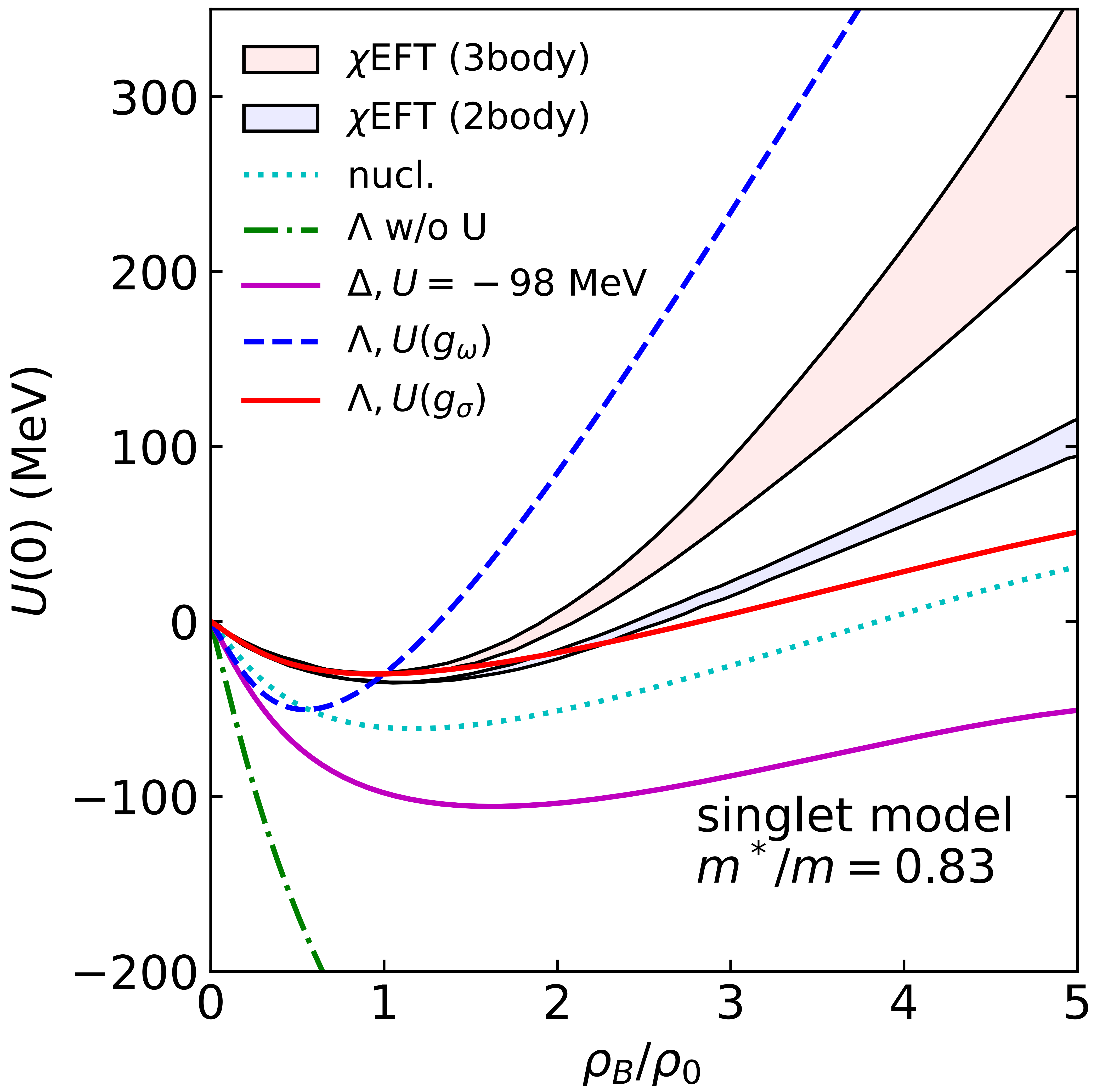
$U(g_\sigma)$: $g_{B\sigma}$ is fixed by $U = -30$ MeV

$g_{B\omega}$ is fixed by SU(6) symmetry

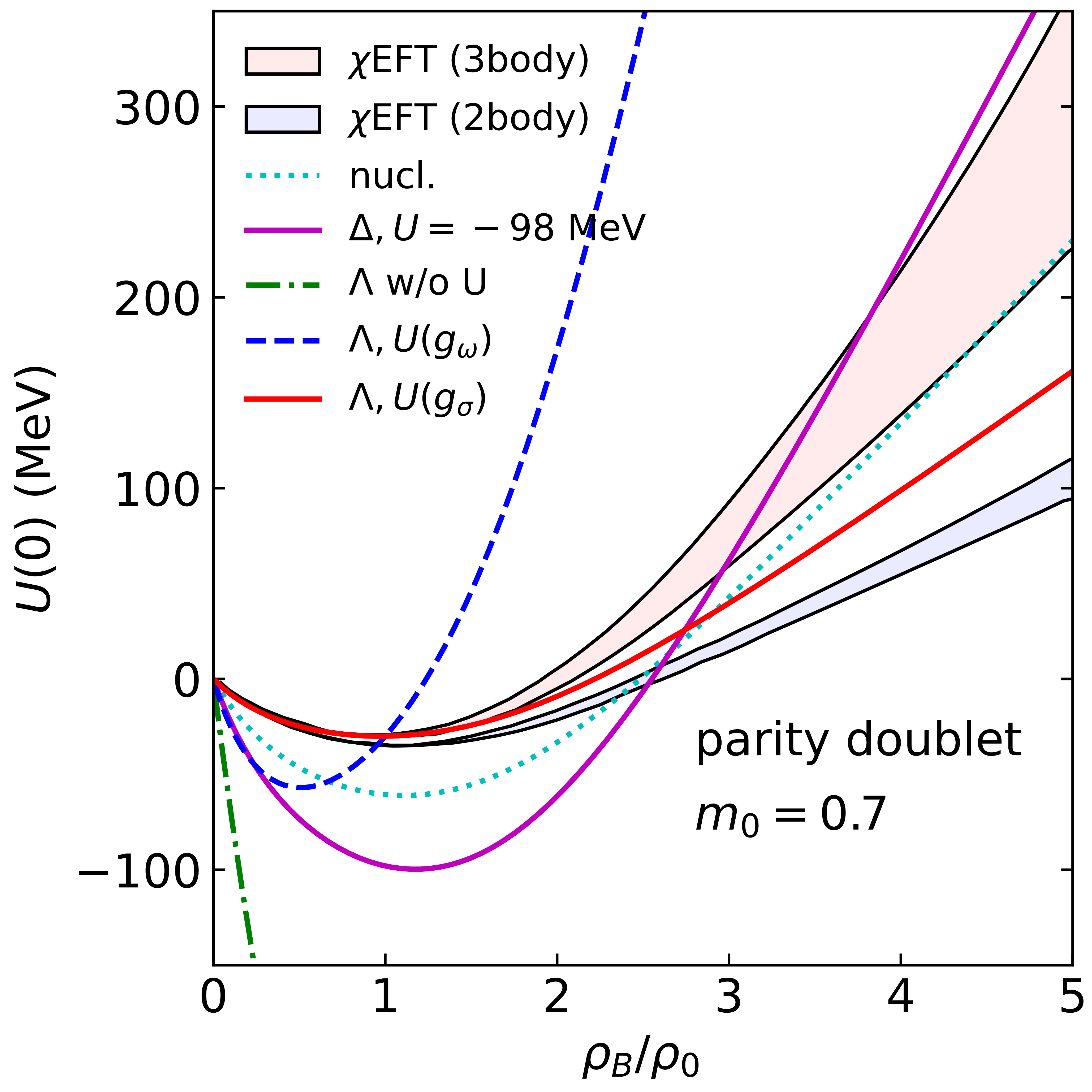
Chiral EFT from D. Gerstung, N. Kaiser, and W. Weise, Eur. Phys. J. A 56, 175 (2020).

Single particle potential

Singlet model

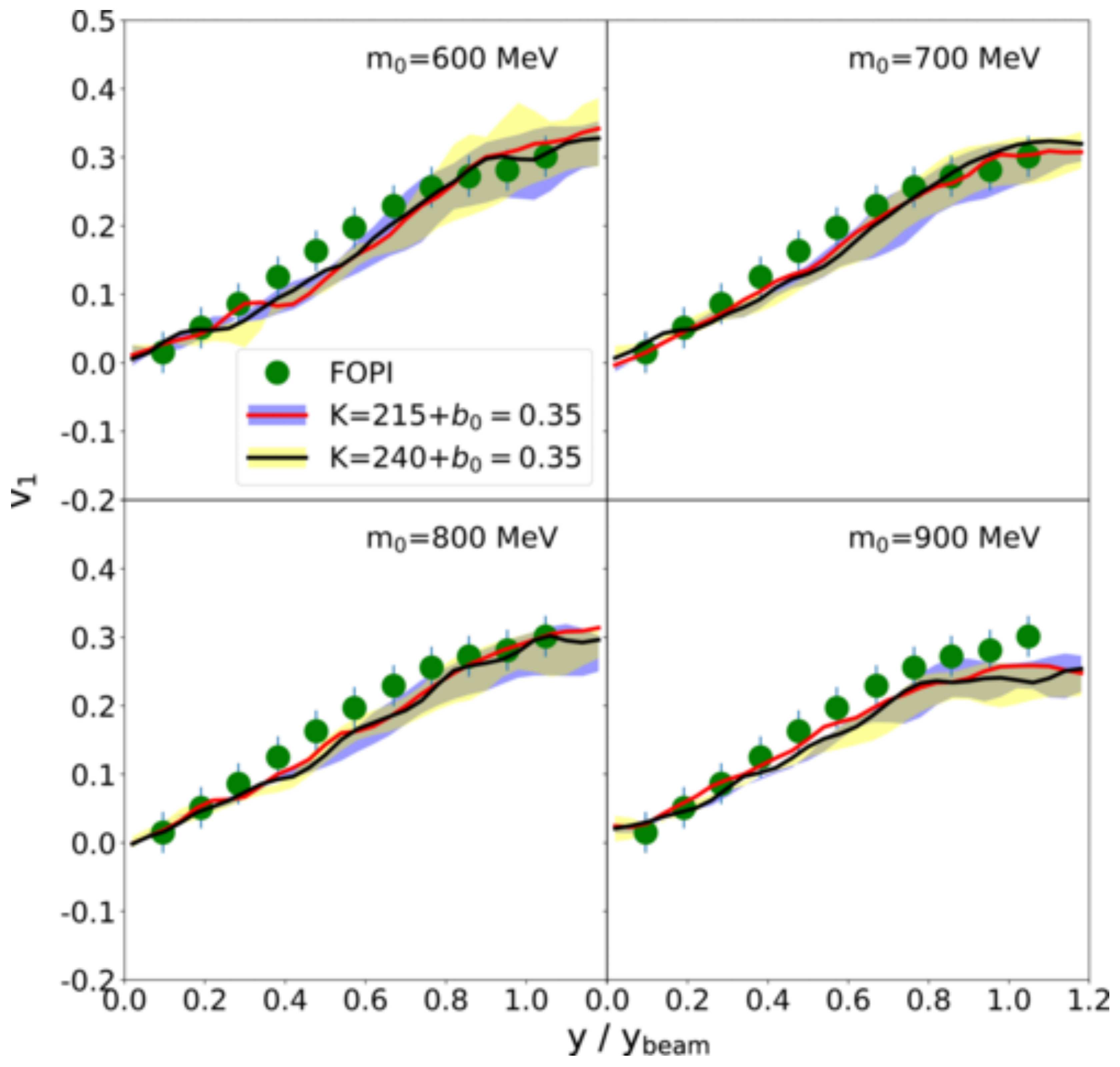


Parity doublet model (PDM)



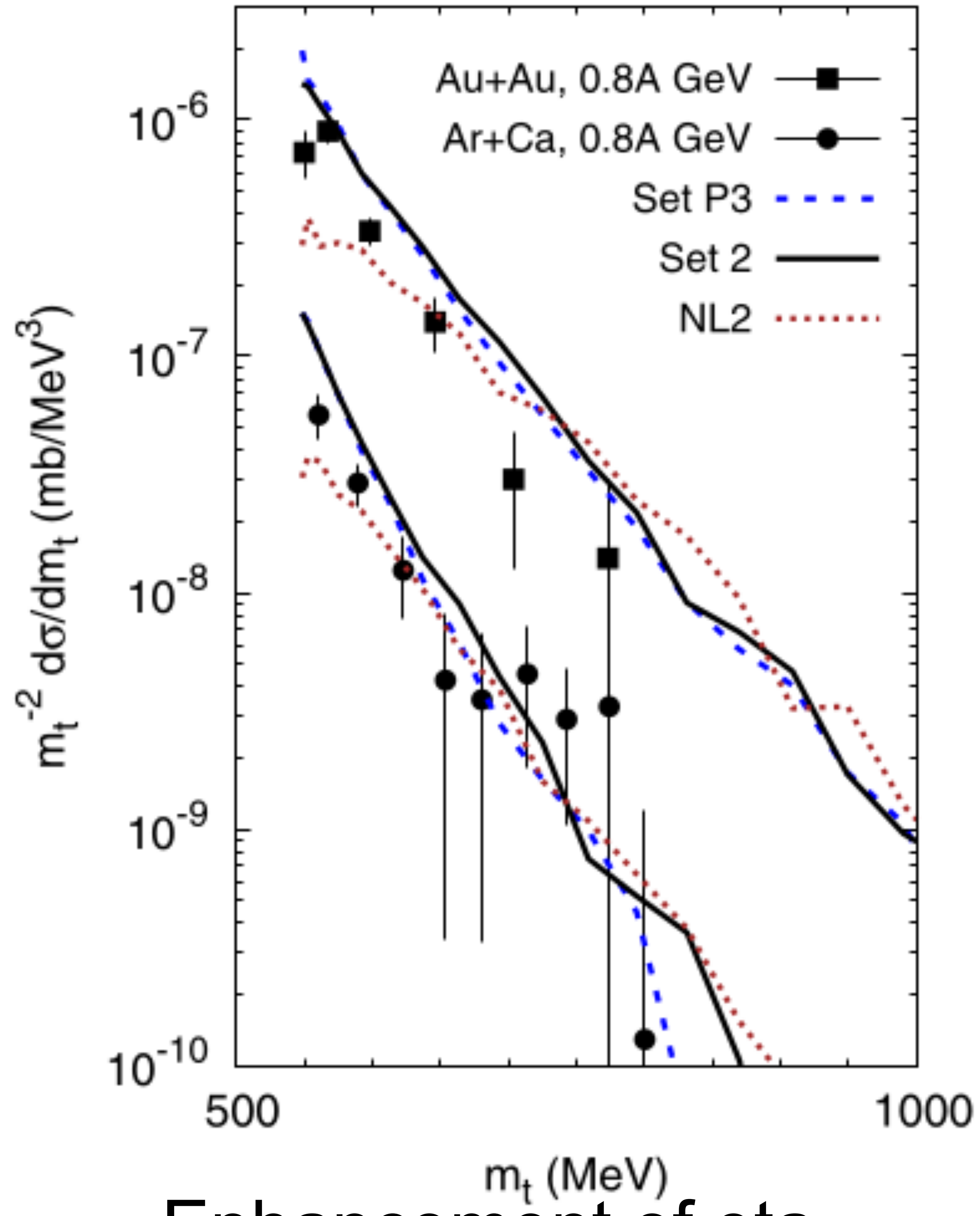
RBUU with parity doublet model at low collision energies

DaeJeon Boltzmann-Uehling-Uhlenbeck (DJBUU)
M. Kim, et.al, RPC101,064614(2020).



v1 is not sensitive to chiral invariant mass for Au+Au at Elab=400A MeV

GiBUU, PRC 105, 034914 (2022)



Enhancement of eta

Relativistic quantum molecular dynamics

RQMD simulates multi-hadron interactions by the scalar and/or vector potentials:

$$m^* = m - S(x,p), \quad p^*_\mu = p_\mu - U_\mu(x,p)$$

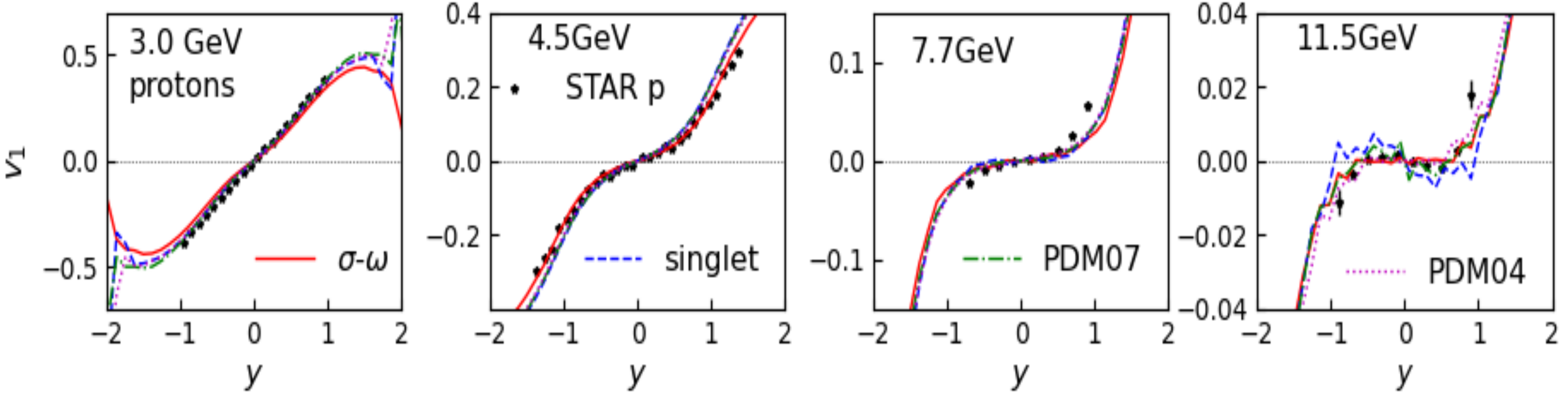
$$H_i = (p_i - V_i)^2 + (m_i - S_i)^2 = p_i^{*2} + m_i^{*2} = 0, \quad (i = 1, \cdots, N)$$

$$\frac{dq_i^\mu}{d\tau} = \sum_j \frac{1}{2\hat{a}\cdot p_j^*}\frac{\partial H_j}{\partial p_{i\nu}} \qquad \frac{dp_i^\mu}{d\tau} = -\sum_j \frac{1}{2\hat{a}\cdot p_j^*}\frac{\partial H_j}{\partial q_{i\nu}}$$

- RQMD.RMF: σ-ω model, PRC (2019), (2020)
- RQMDv: Lorentz vector Skyrme potential PRC(2022)
- Covariant cascade method PRC108(2023)

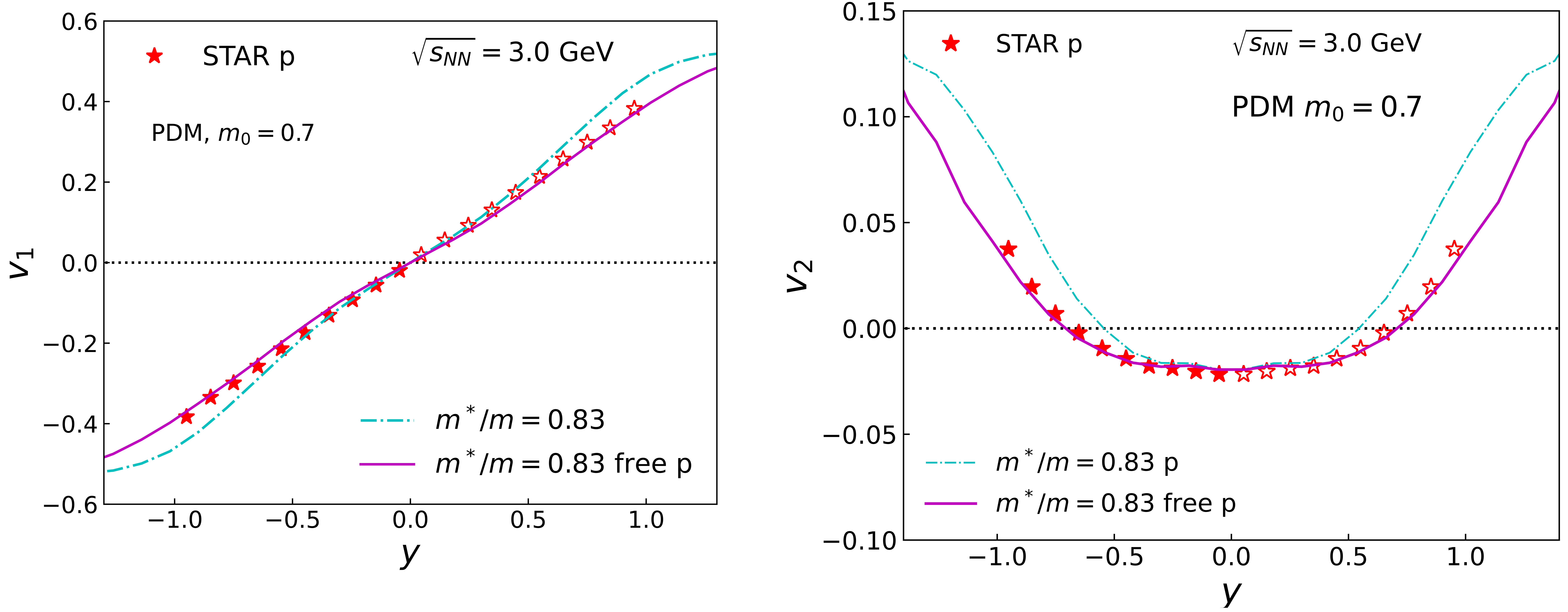
JAM2:https://gitlab.com/transportmodel/jam2

Proton v1



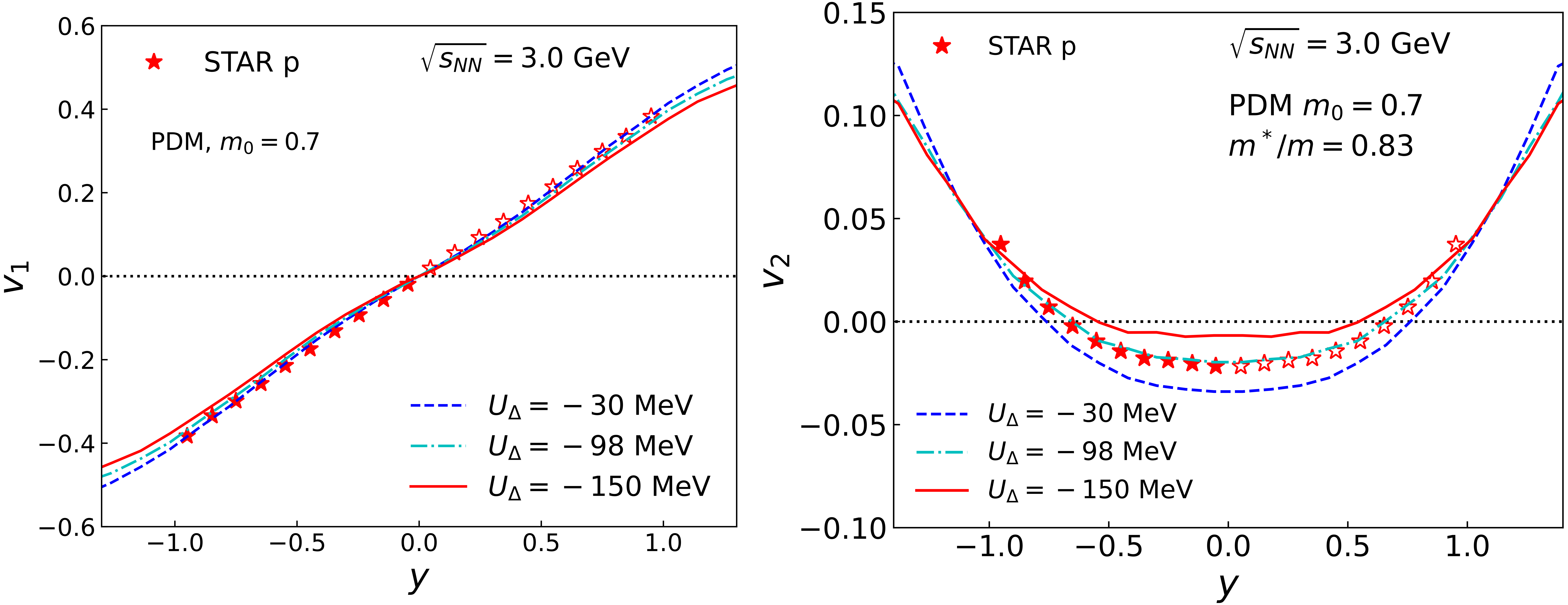
σ-ω, singlet, and parity doublet model can reproduce proton directed flow.

Effect of nuclear cluster



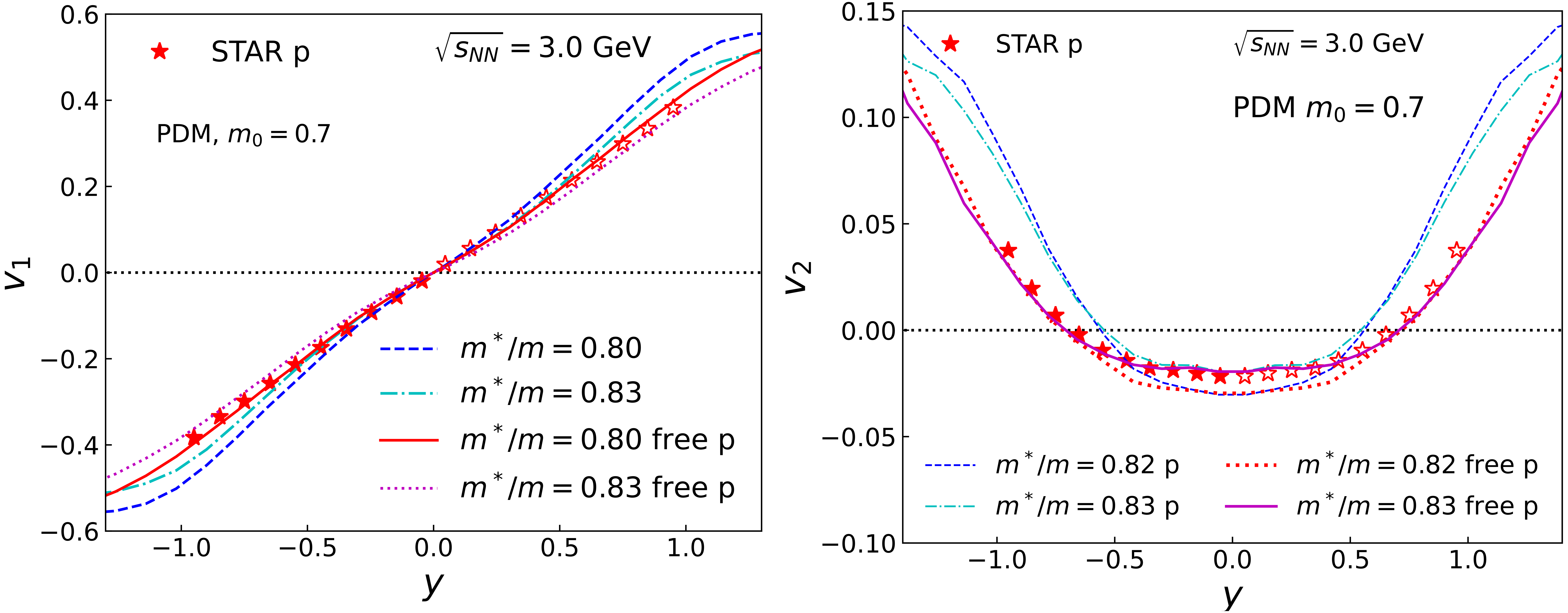
RQMD produces nuclear cluster by potential interaction.

Effect of delta potential



Parity doublet model for m0=0.7GeV (PDM07)

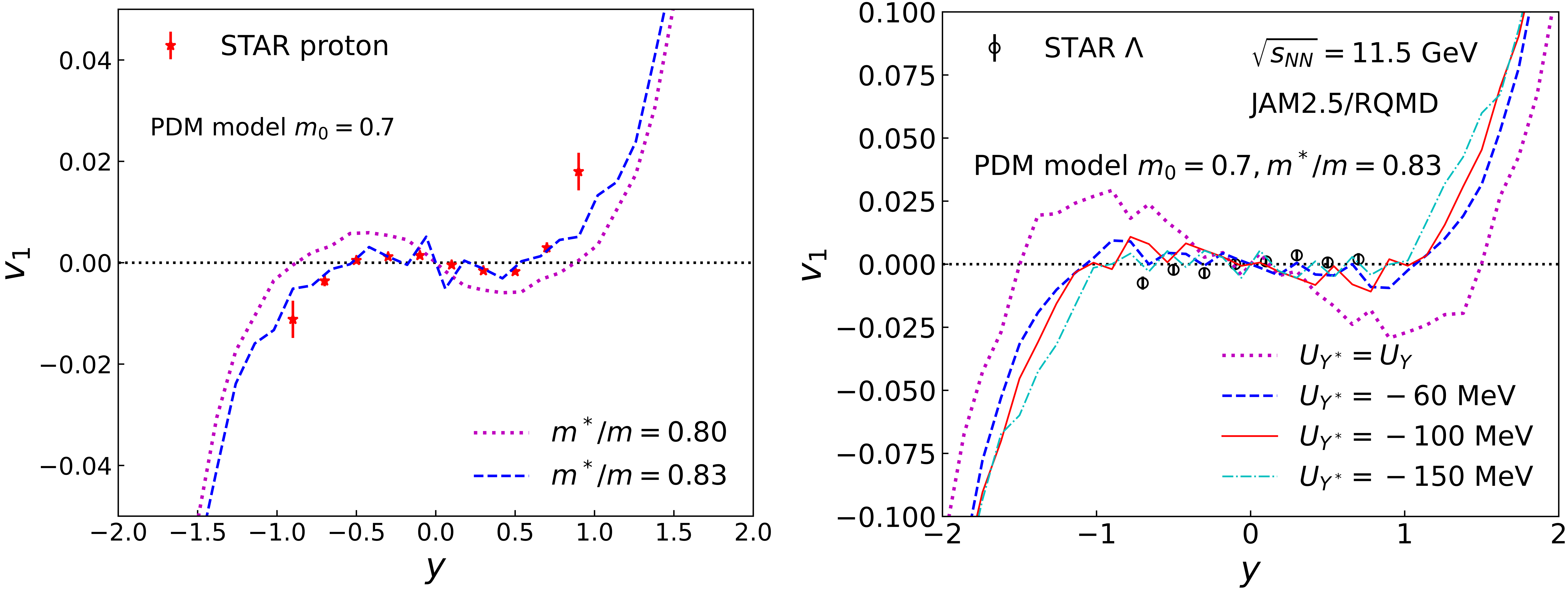
Proton v1 from PDM at 3.0 GeV



Lambda v1 and v2 from PDM at 3.0 GeV

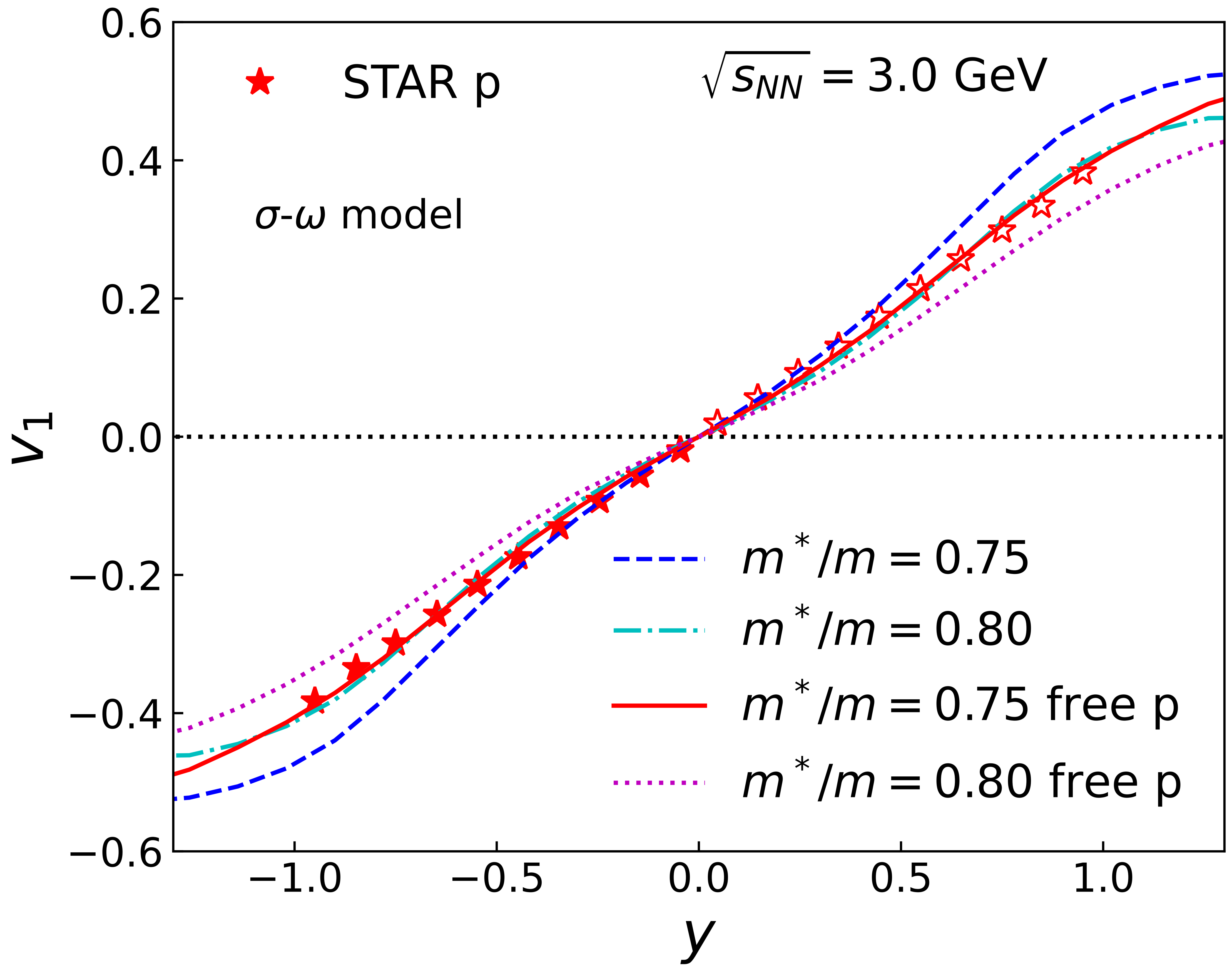
Proton and Λ v1 from PDM at 4.5 GeV

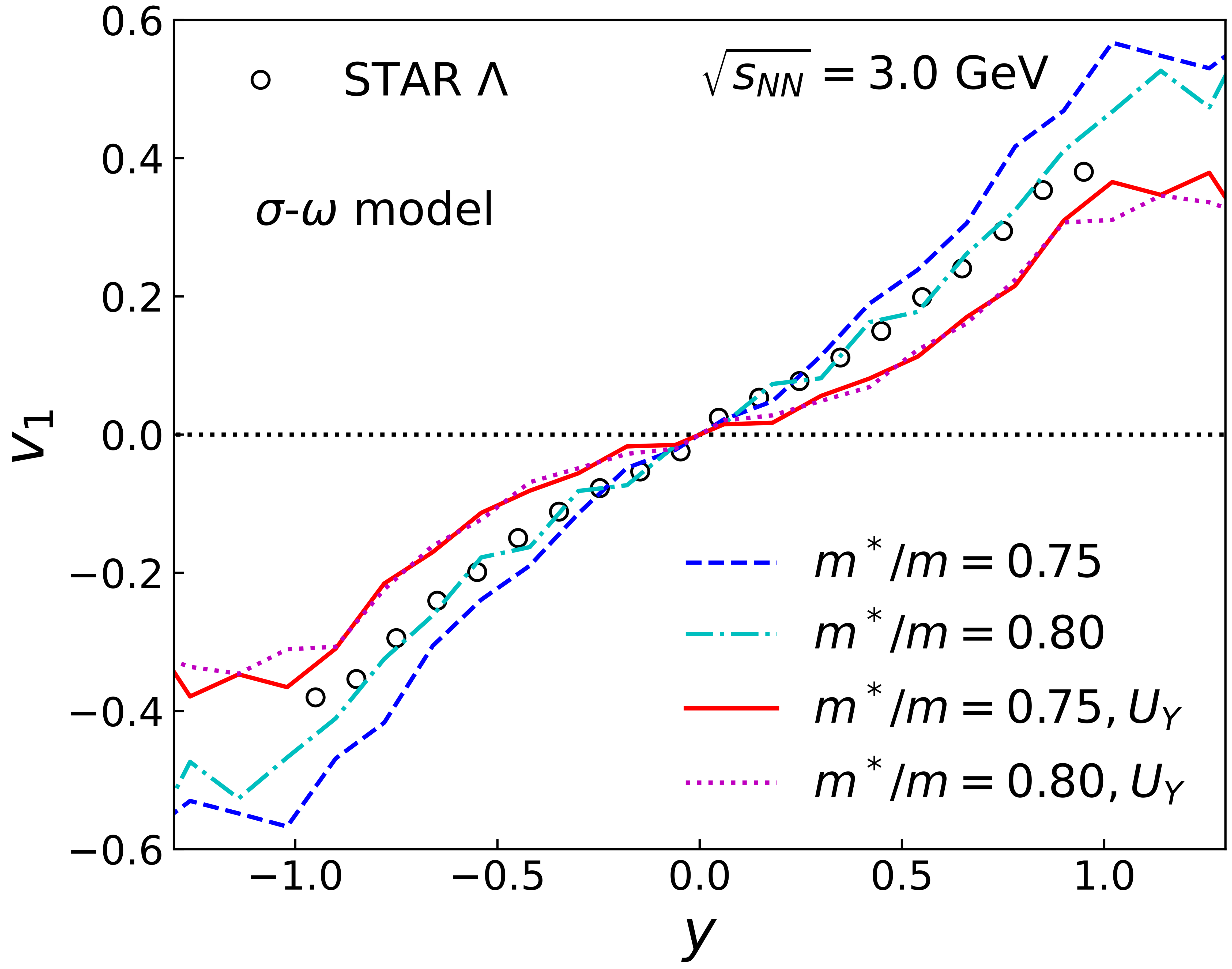
Proton and Λ v1 from PDM at 11.5 GeV



σ-ω model

v1 from σ-ω model at 3.0GeV





σ-ω model cannot fit the proton and lambda v1 with the same parameters at 3 GeV.
σ-ω model significantly underestimates Λ v1 when experimetnal hyperon potential is used.

Singlet model

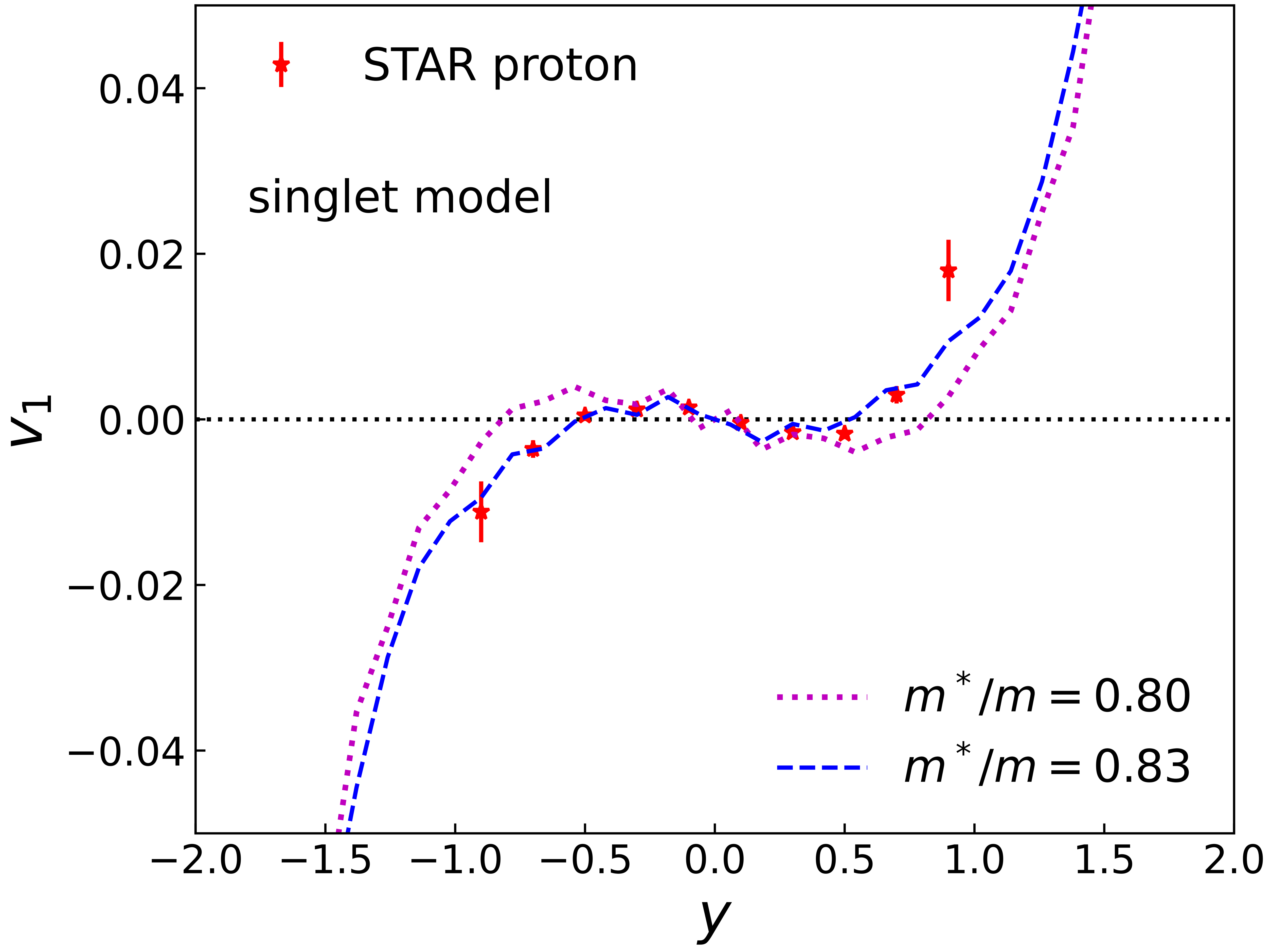
v1 from singlet model at 3.0GeV

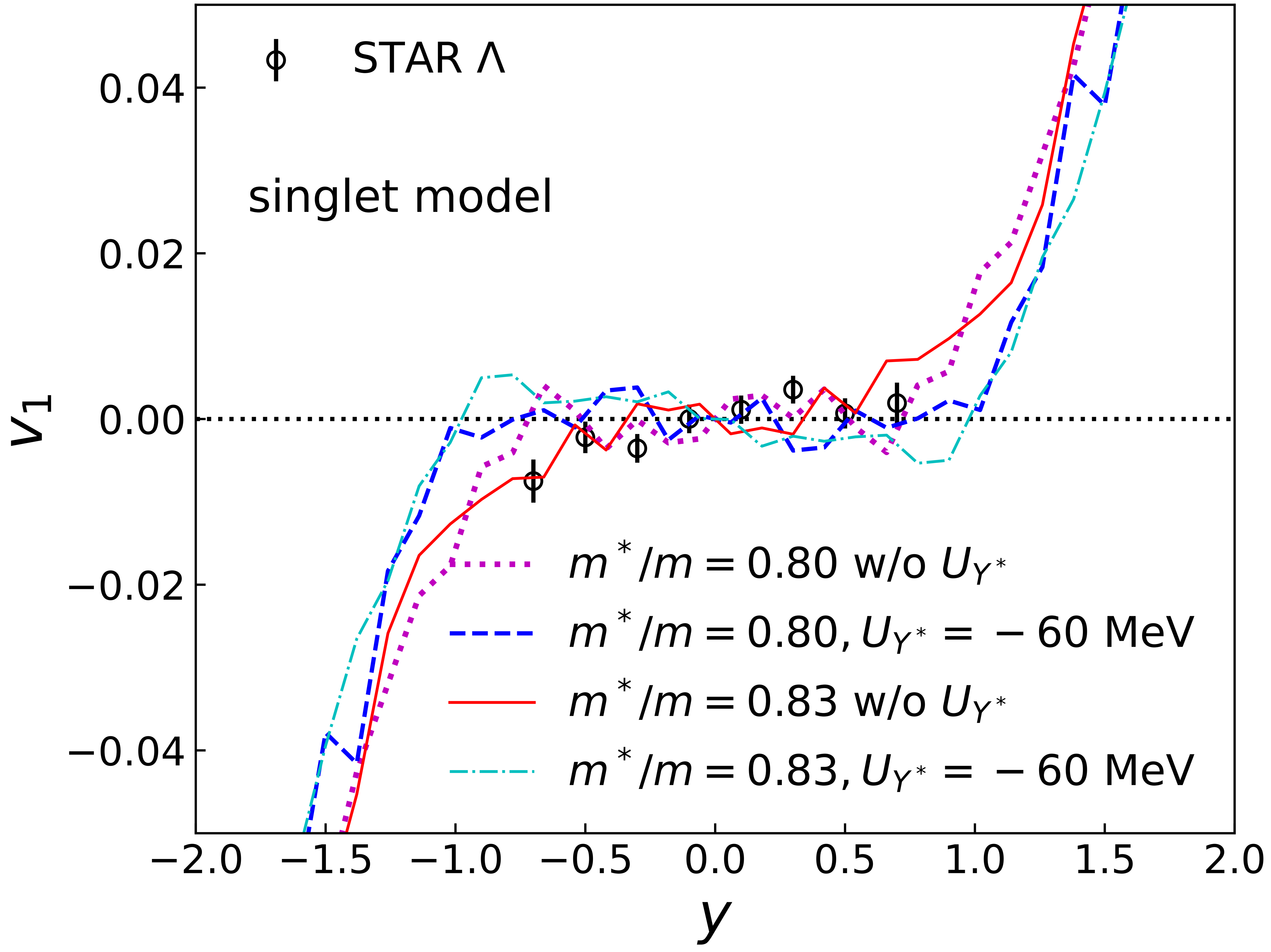
Very deep hyperon resonance (Y*) potential is required to fit the lambda v1 in singlet model.

v2 from singlet model at 3.0GeV

v1 from singlet model at 4.5GeV

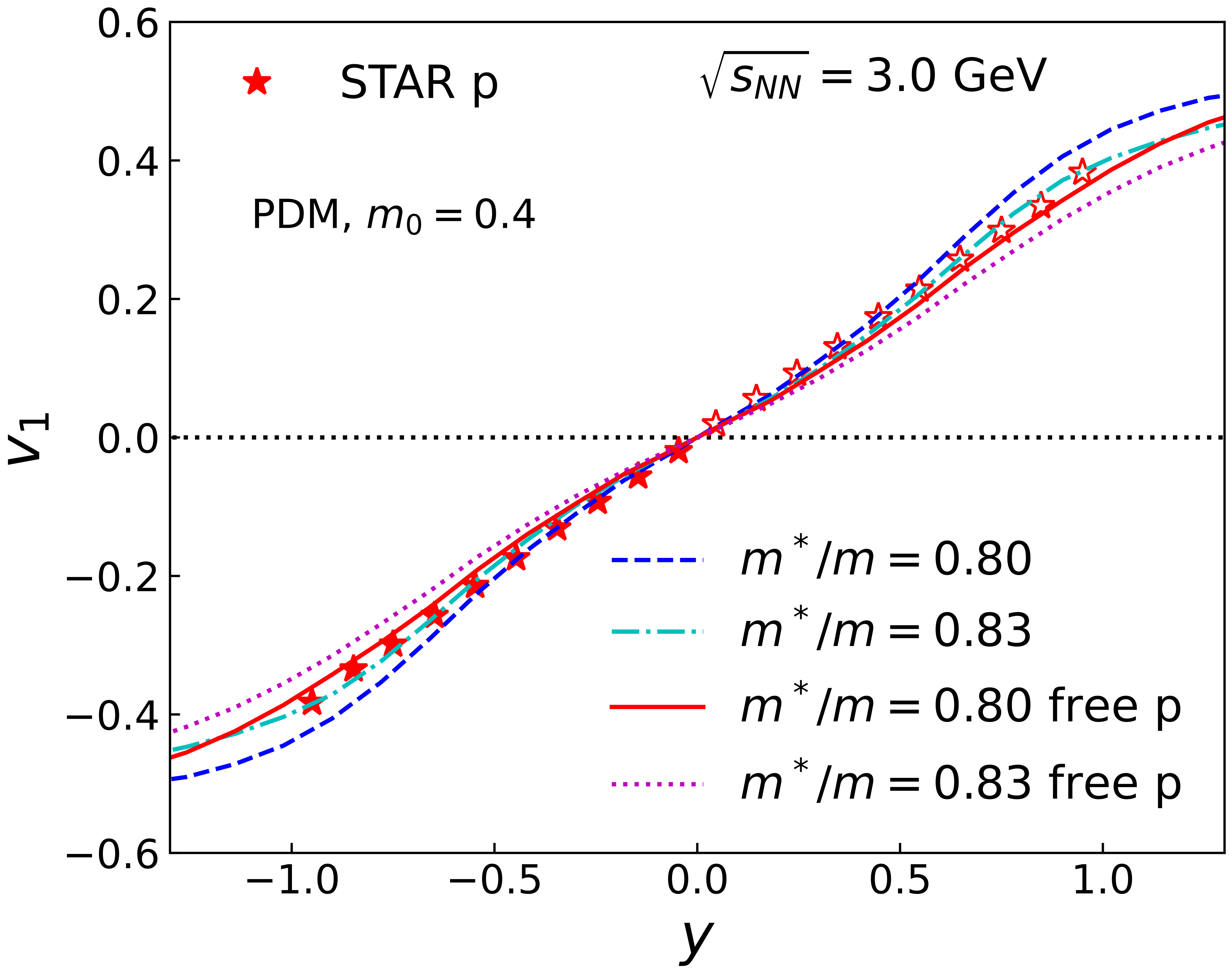
v1 from singlet model at 11.5GeV

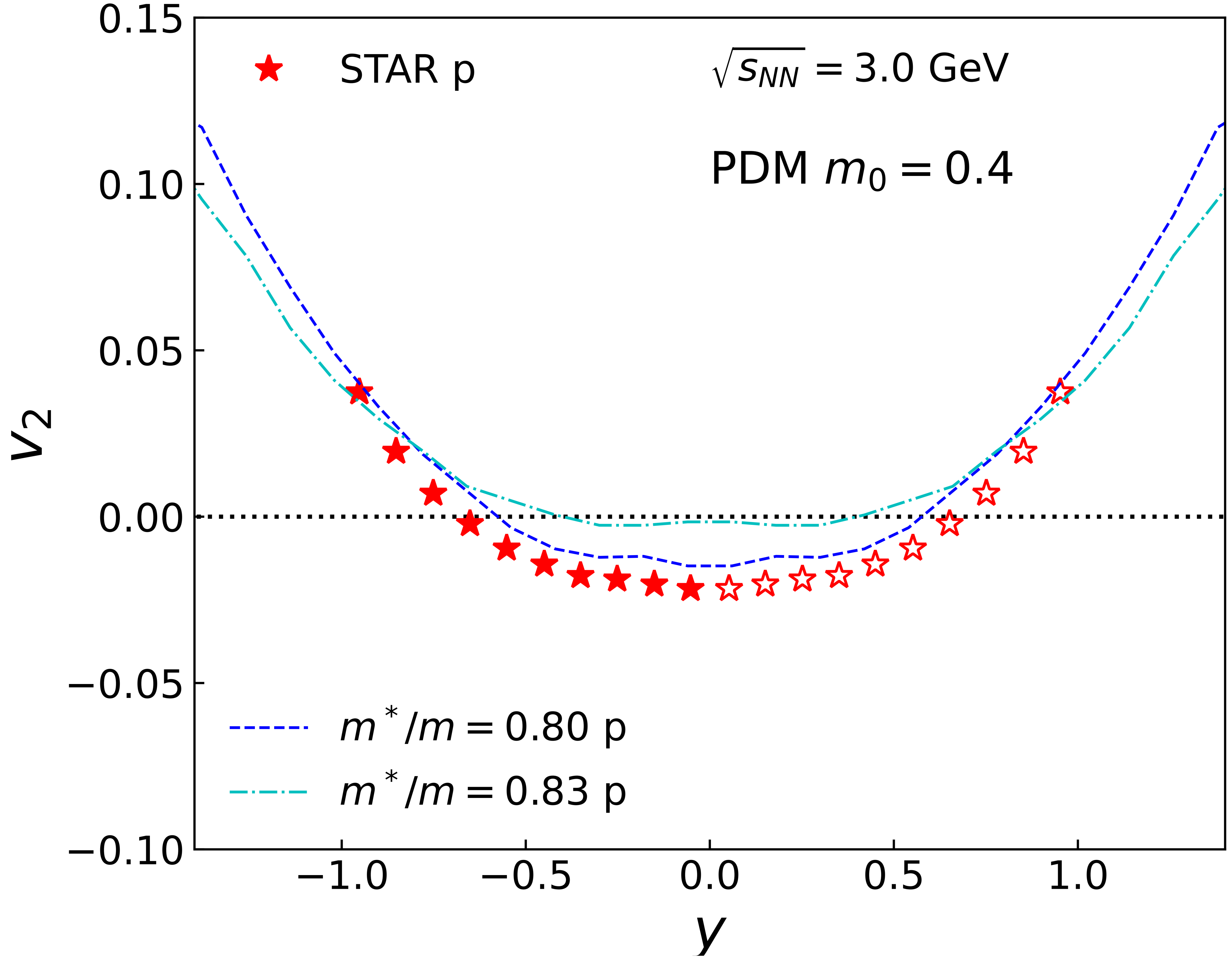




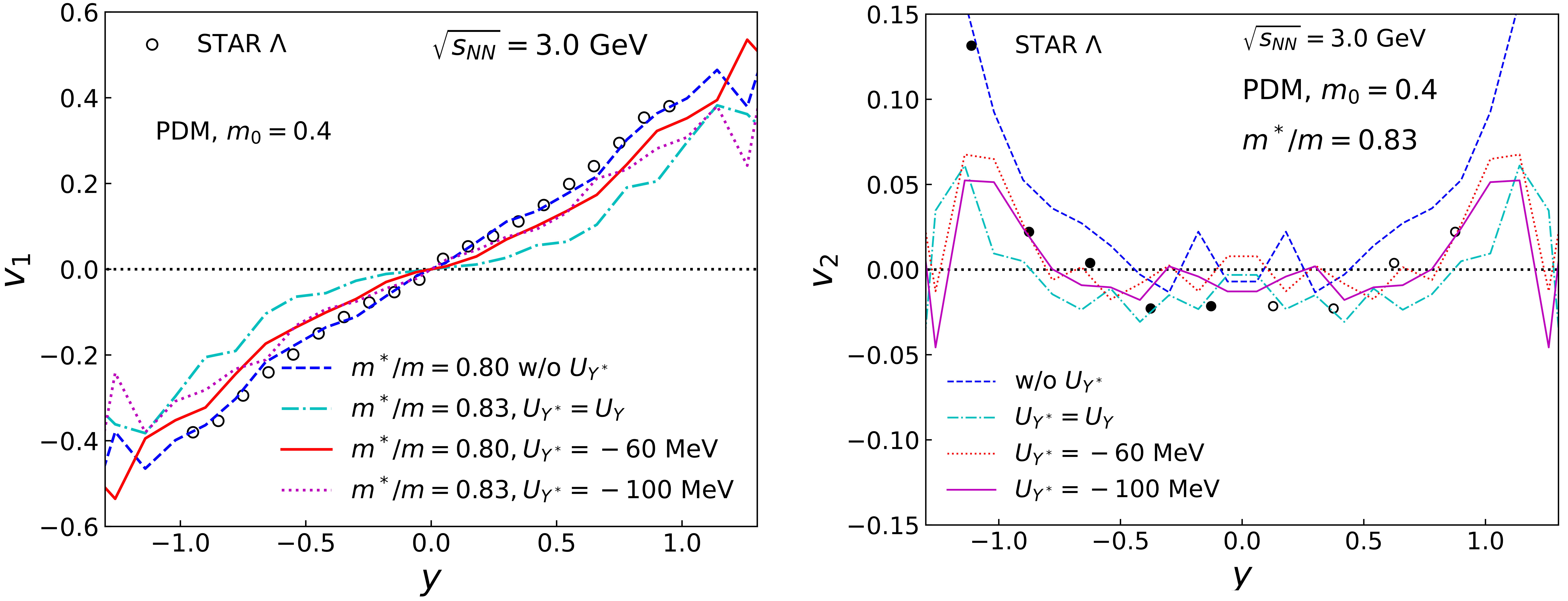
Parity doublet model for m0=0.4GeV (PDM04)

v1 from PDM04 at 3.0GeV

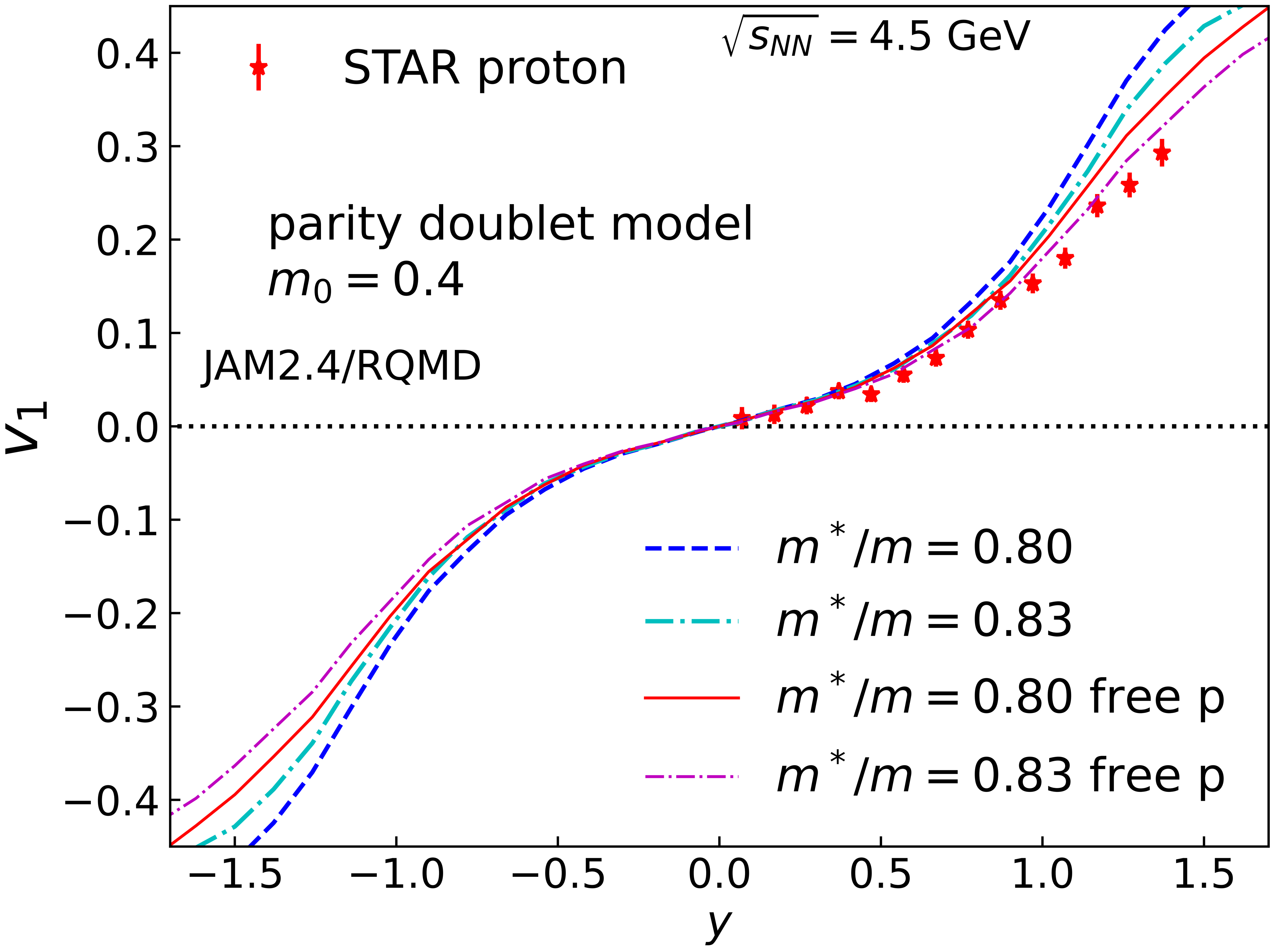


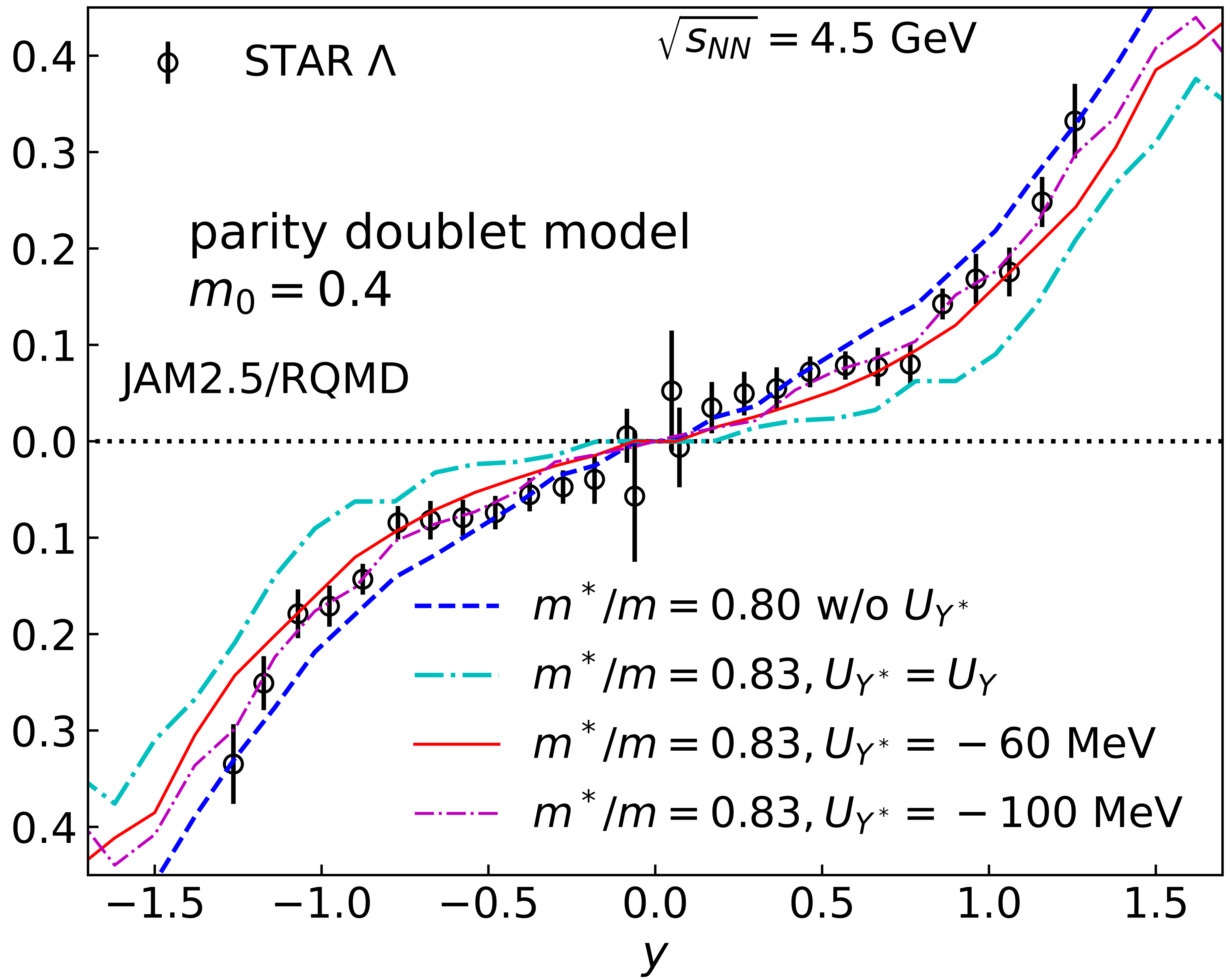


v1 from PDM04 at 3.0GeV

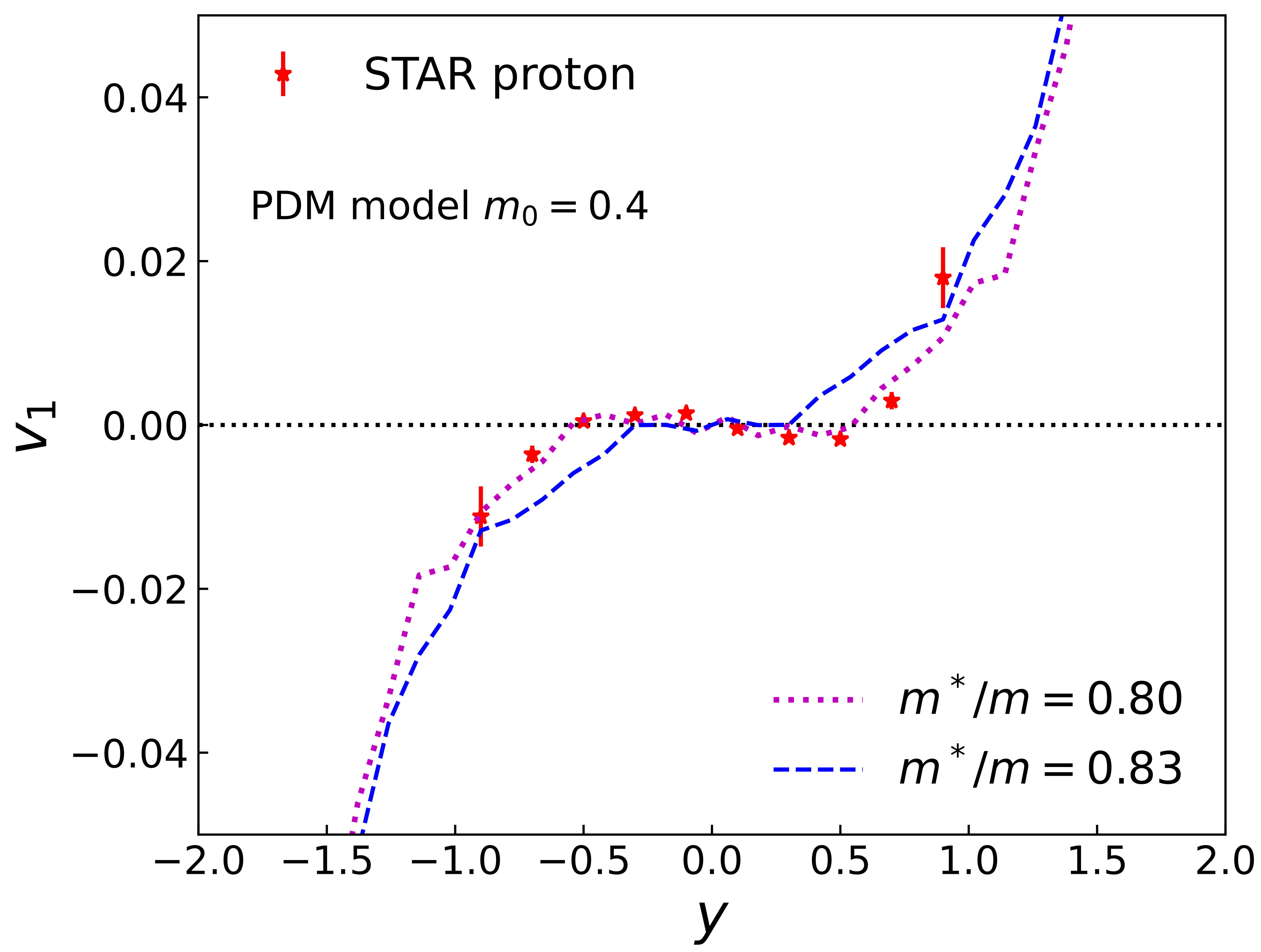


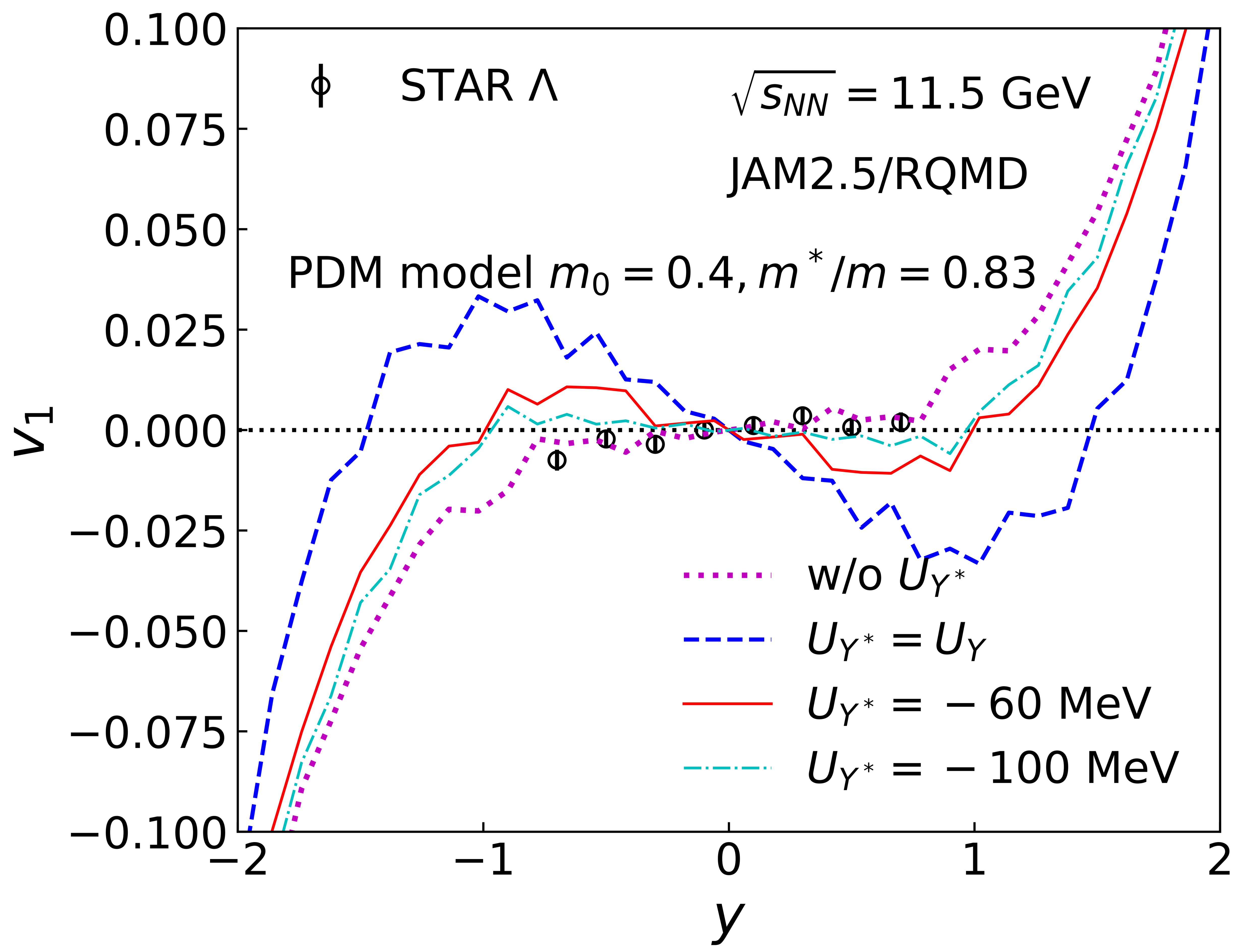
v1 from PDM04 at 4.5GeV





PDM04 11.5GeV





summary

- We have compared directed flow of protons and lambdas with the STAR data at 3.0, 4.5, 7.7, and 11.5 GeV from σ-ω model and chiral models based on the RQMD transport model.
- Parity doublet model (PDM) can reproduce directed flow of protons and lambda with a single parameter set for a wide range of beam energies when relatively deeper hyperon resonance Y* potentials are assumed.

	σ-ω model	singlet model	PDM07	PDM04
proton v1	○	○	○	○
Λ v1	x	△	○	△