Probing of EoS with Clusters and Hypernuclei (arXiv:2507.14255)

PHQMD

5^{th} Workshop on Anti-Matter, Hyper-Matter and Exotica Production

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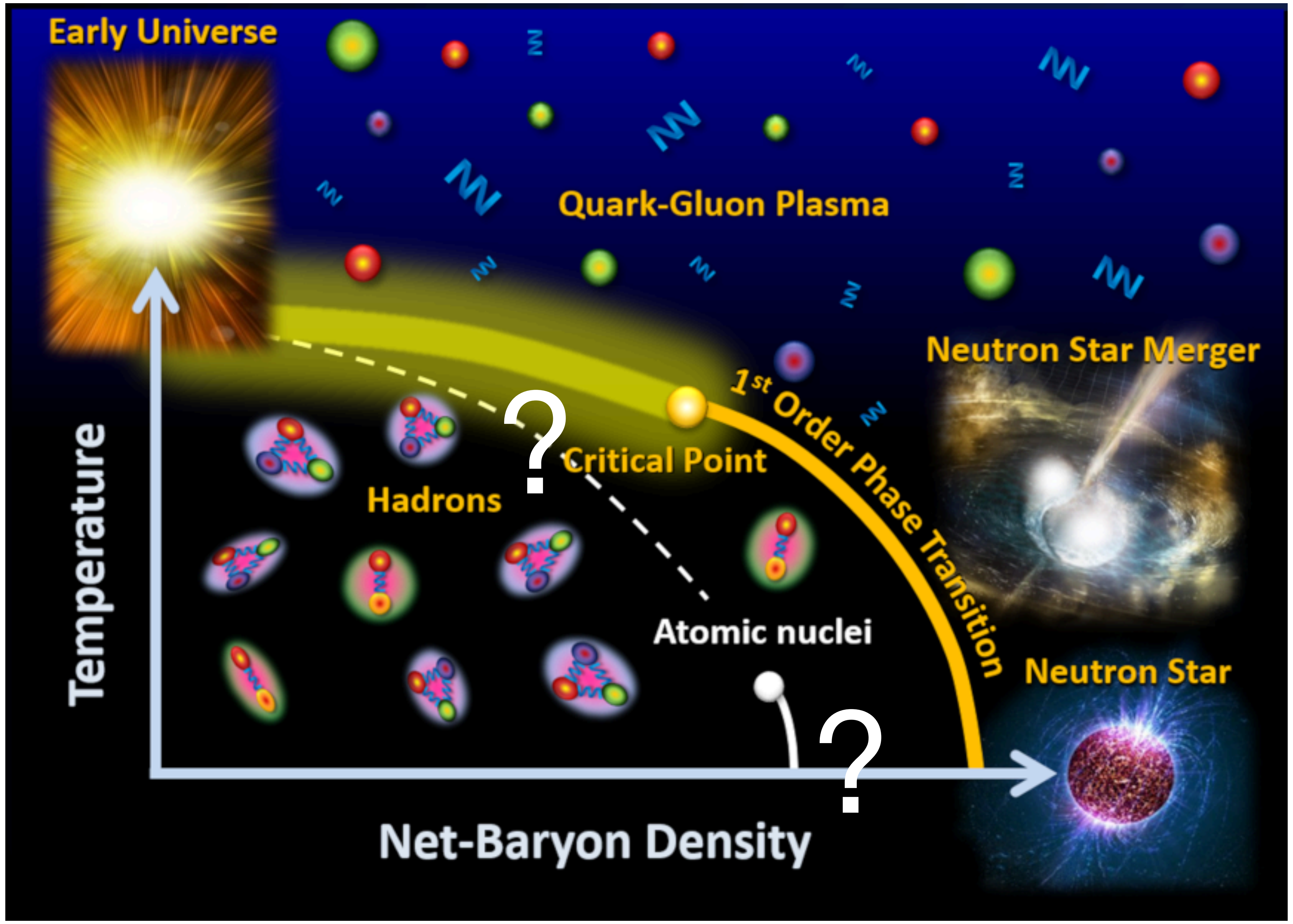
Motivations

- Quest for **Equation of state (EoS)** of strongly interacting matter: a major objective of nuclear physics

- EoS at **high baryon density**: crucial for understanding the behavior of nuclear matter under extreme conditions, such as neutron star cores

- **STAR experiment** recently published new data in Au+Au collisions at $\sqrt{s_{NN}}$ =3 GeV: highest quality dataset to date



- **Parton-Hadron-Quantum-Molecular Dynamics (PHQMD) model** is employed to interpret the new STAR data and investigate the sensitivity of various observables to different equation-of-state scenarios

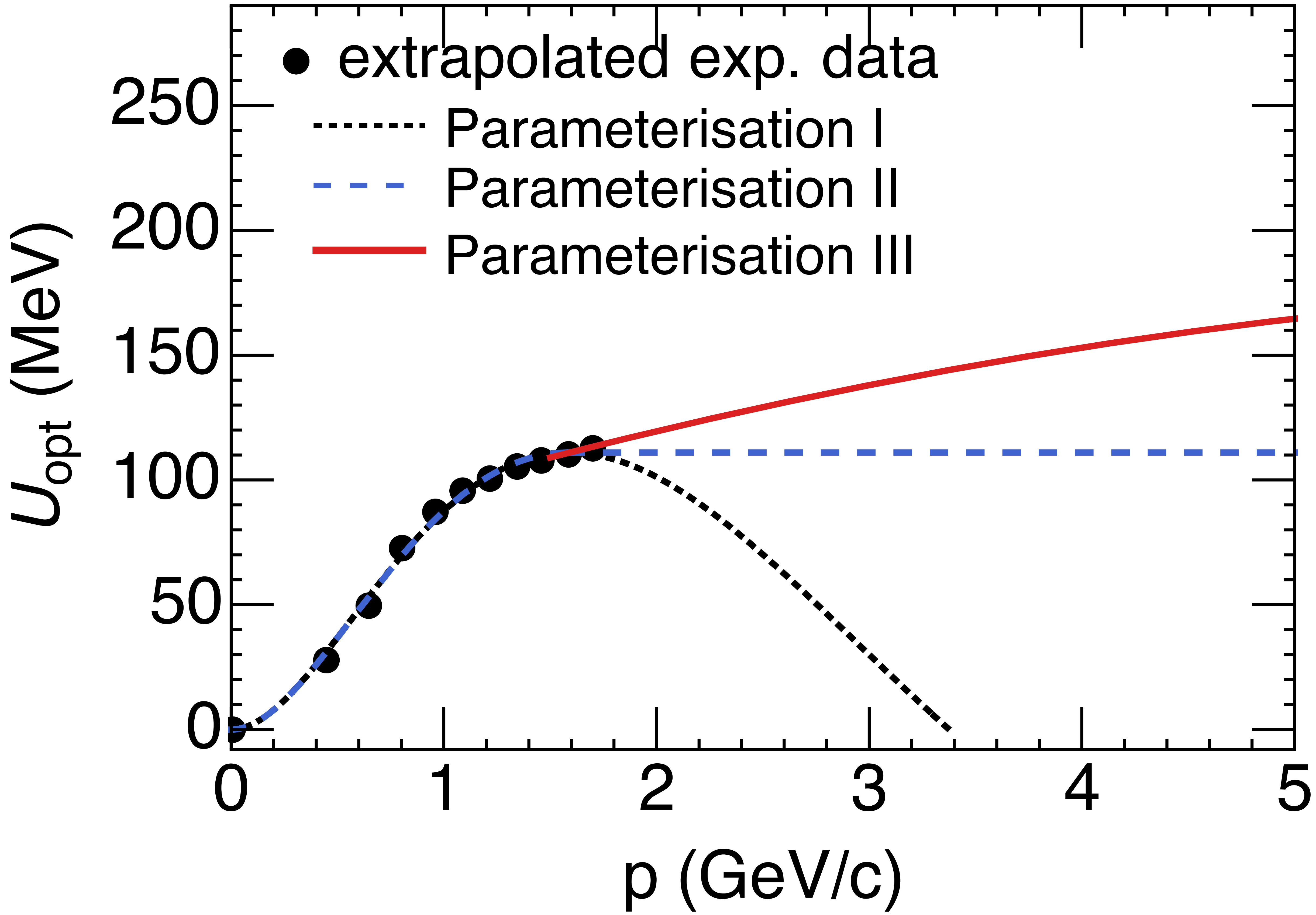
Momentum-Dependent Potential

- For details on the PHQMD model, see S. Gläßel talk on 11/11 (Tue)!
- Consider two **static** EoS models, labeled "soft (**S**)" and "hard (**H**)", which differ in compressibility modulus K, and a **momentum-dependent** soft EoS model (**SM**)
- Momentum-dependent potential

$$V(\mathbf{r_1}, \mathbf{r_2}, \mathbf{p_{01}}, \mathbf{p_{02}}) = (a\Delta p + b\Delta p^2) \times exp[-c\sqrt{\Delta p}]\delta(\mathbf{r_1} - \mathbf{r_2})$$

- Parameters a, b, and c: fitted to the "optical" potential extracted from elastic scattering data in pA

$$U_{SEQ}(p) = \frac{\int^{p_F} V(\mathbf{p} - \mathbf{p_1}) dp_1^3}{\frac{4}{3}\pi p_F^3}$$



Modeling the EoS within PHQMD

- In infinite matter a potential corresponds to an EoS for cold nuclear matter:

$$V_{Skryme,stat} = \alpha \frac{\rho}{\rho_0} + \beta (\frac{\rho}{\rho_0})^\gamma$$

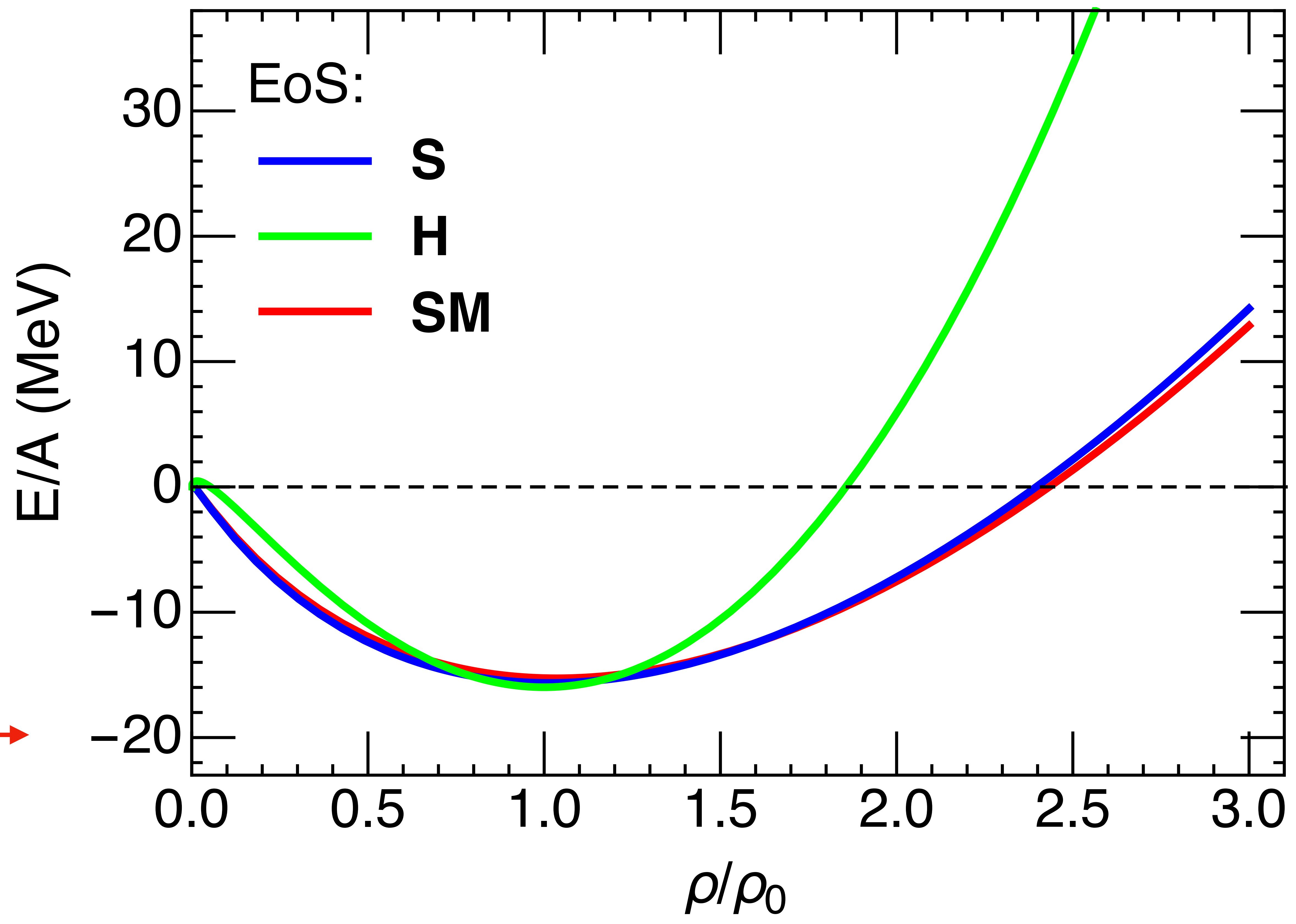
$$V_{mom} = (a\Delta p + b\Delta p^2) exp[-c\sqrt{\Delta p}] \frac{\rho}{\rho_0}$$

$$\frac{E}{A}(\rho) = \frac{3}{5}E_F + V_{Skryme,stat}(\rho) + V_{mom}(\rho)$$

- Parameters α, β, and γ, and compressibility modulus K is varied to construct three EoS

EoS	α [GeV]	β [GeV]	γ	K [MeV]
S	-0.3835	0.3295	1.15	200
H	-0.1253	0.071	2.0	380
SM	-0.478	0.4137	1.1	200

a[GeV^{-1}]	b [GeV^{-3}]	c [GeV^{-1}]
236.326	-20.730	0.901

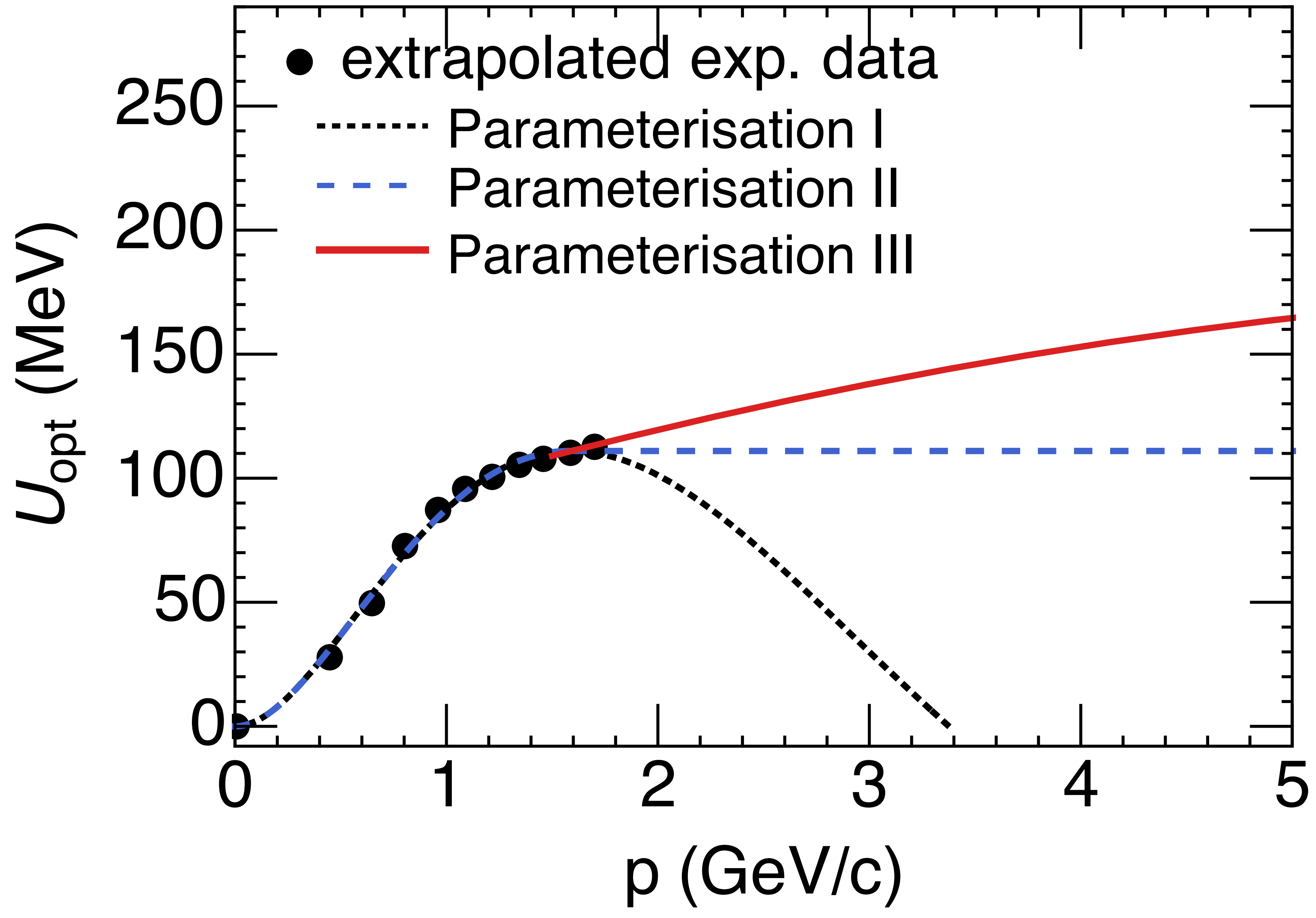


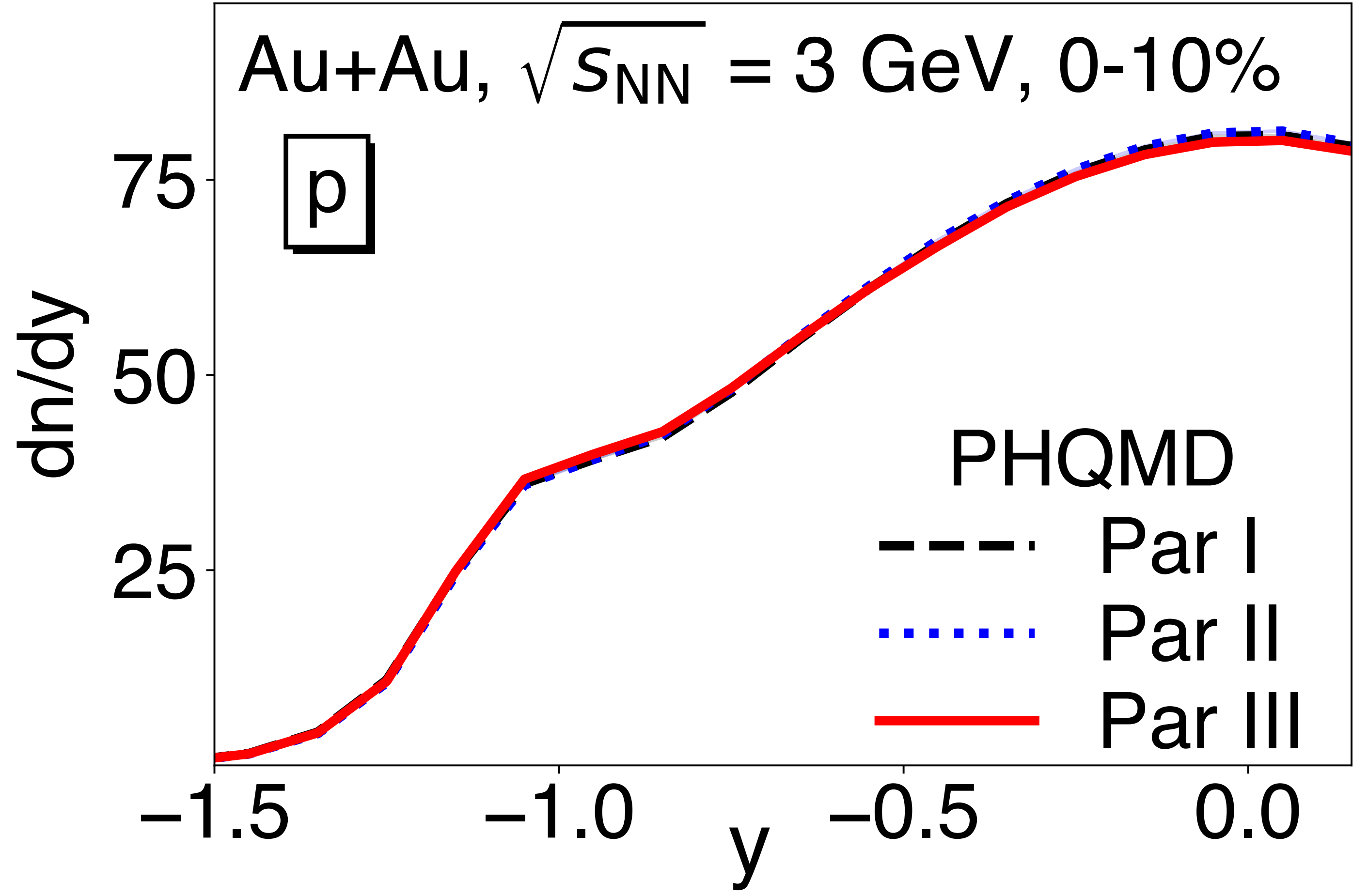
Influence of $U_{opt}(p)$ on Observables

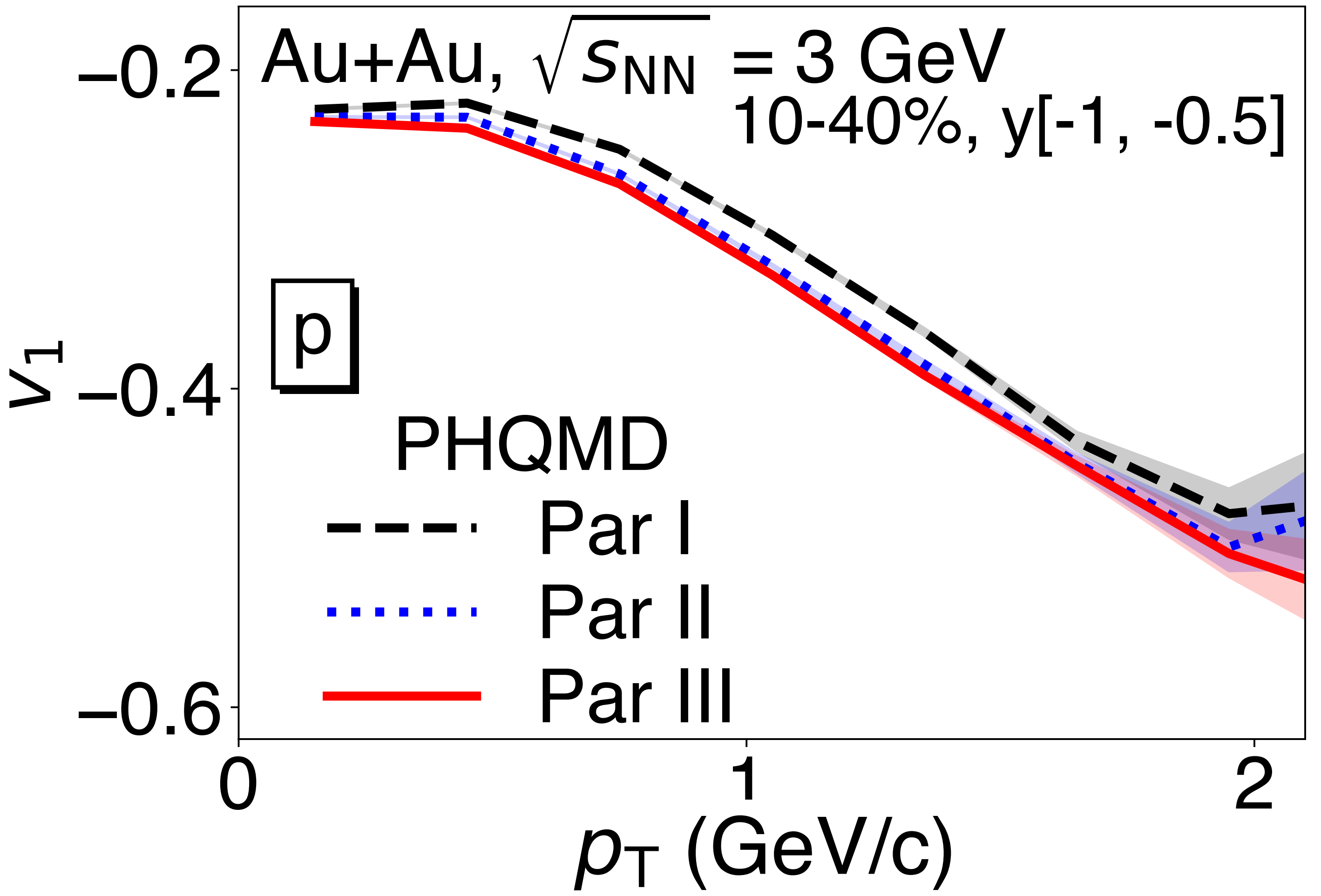
- No experimental data allow for a reliable extrapolation of $U_{opt}(p)$ to large p

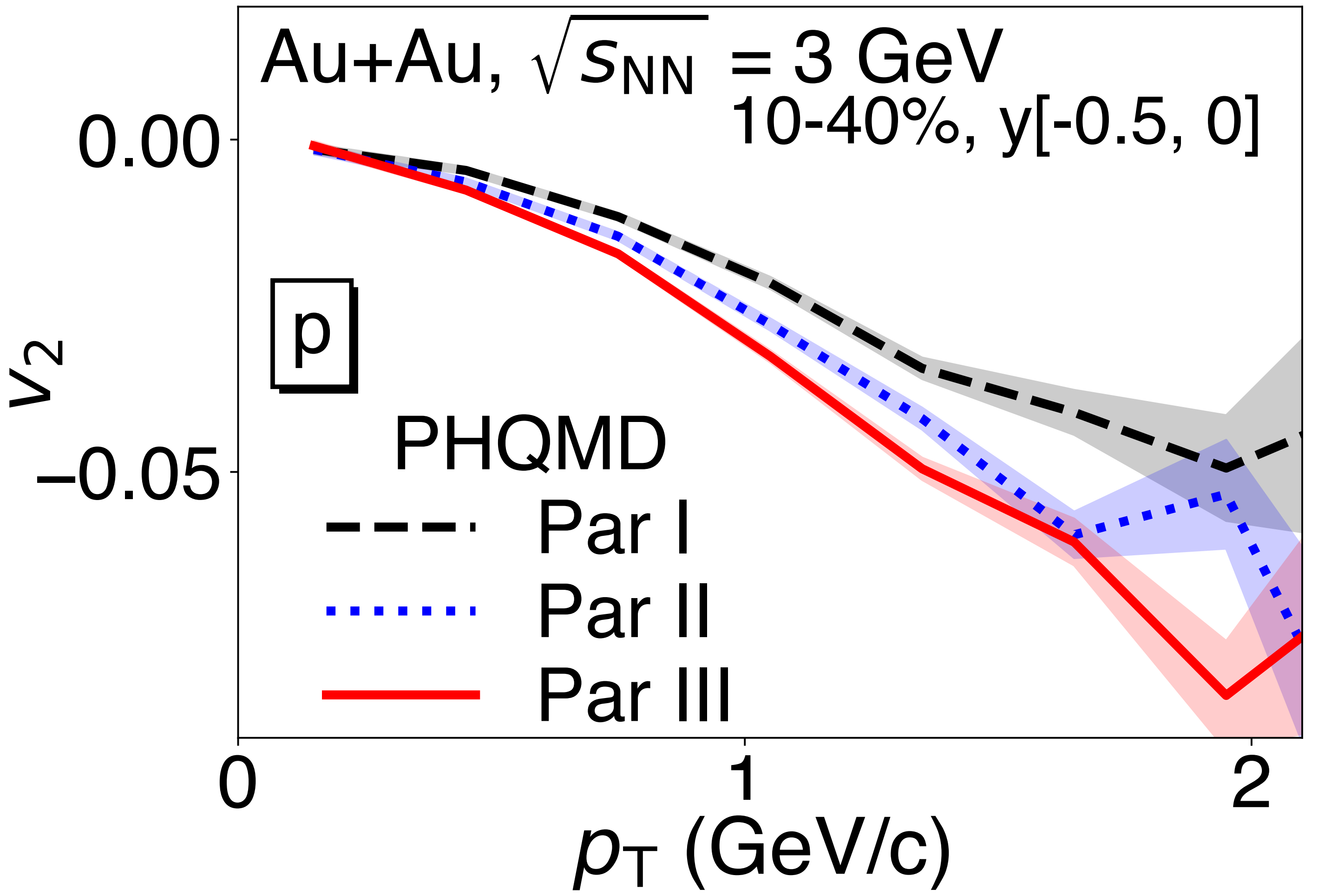
- At 3 GeV, dN/dy and v_1 distributions is practically identical for the three parametrizations; v_2 shows mild differences at higher p_T

- Collisions at higher energies (e.g. 5 GeV) will be more sensitive to this extrapolation









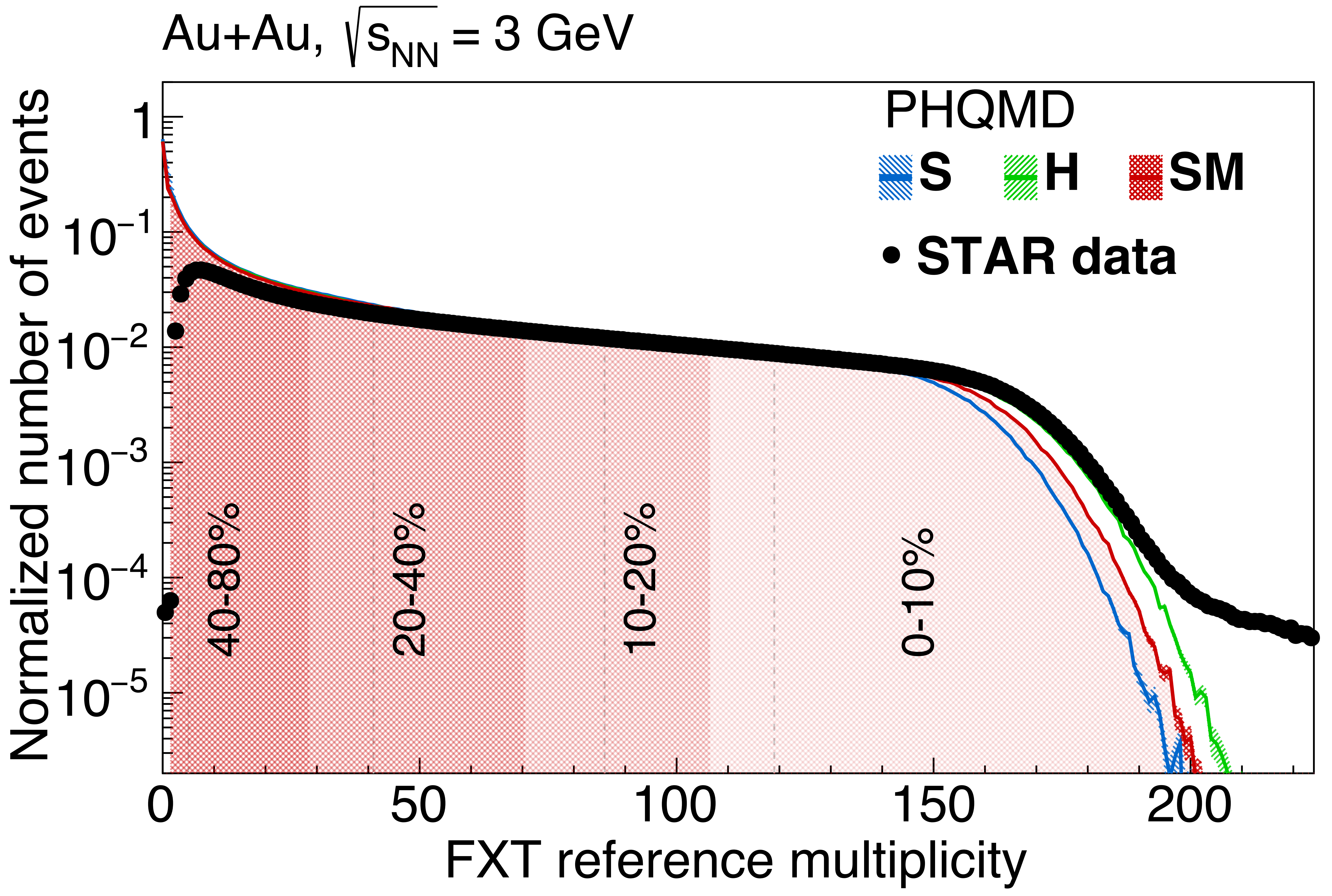
Centrality Definition

- <u>Experimental data</u>: the centrality class is defined by a **Glauber Model fit to the measured charged particle multiplicity** (FXT reference multiplicity, FXTMult) within the acceptance of the STAR Time Projection Chamber (TPC) ($-2.0 < \eta < 0$)

- <u>PHQMD</u>: construct FXTMult using π, K, p:
  - $-2.0 < \eta < 0$
  - $p_T > 0.2$ GeV for π, K, >0.35 for p

- Centrality C_M defined by:

$$C_M = \frac{1}{\sigma^{AA}} \int_M^\infty dM' \frac{d\sigma}{dM'}$$

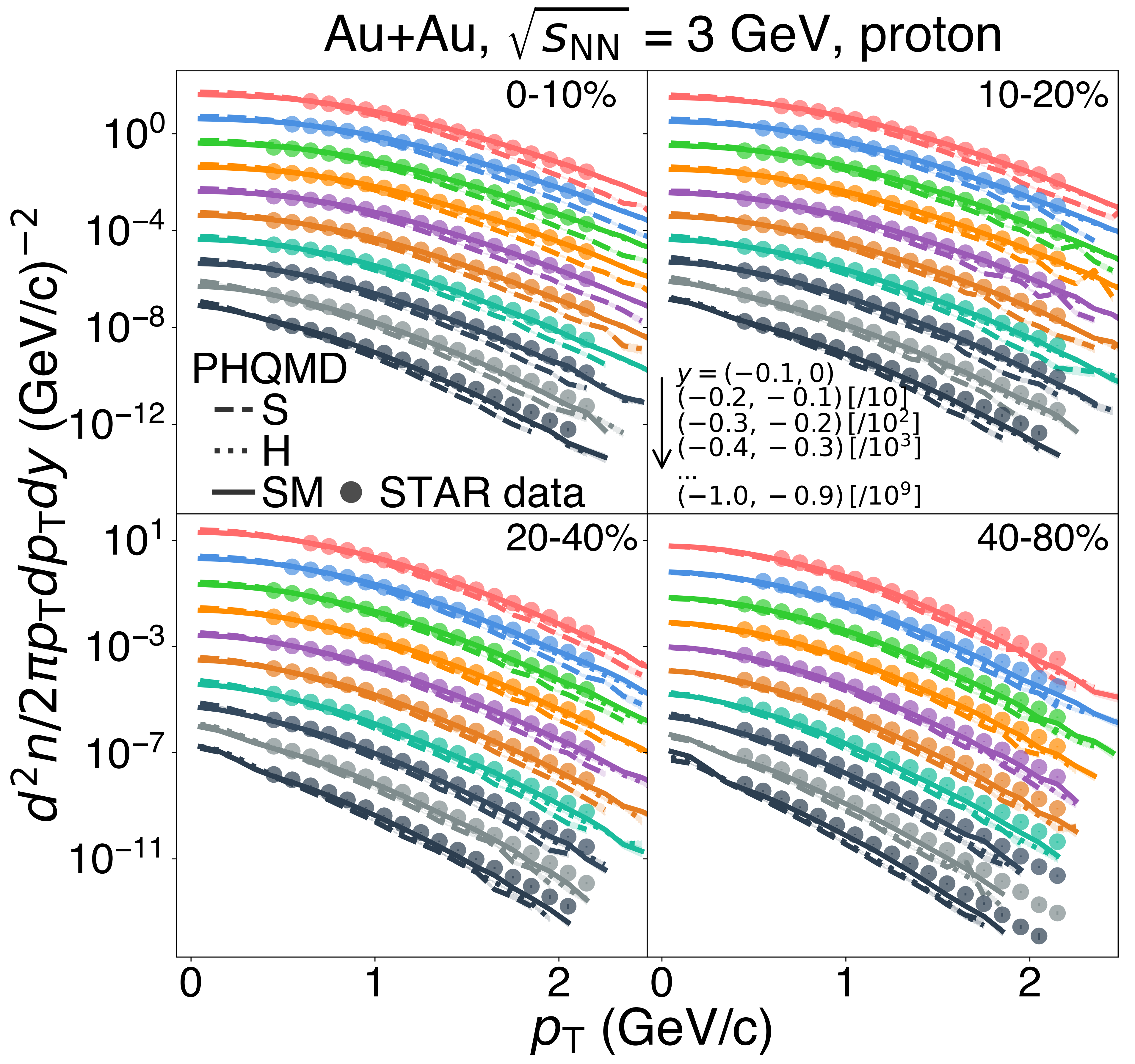


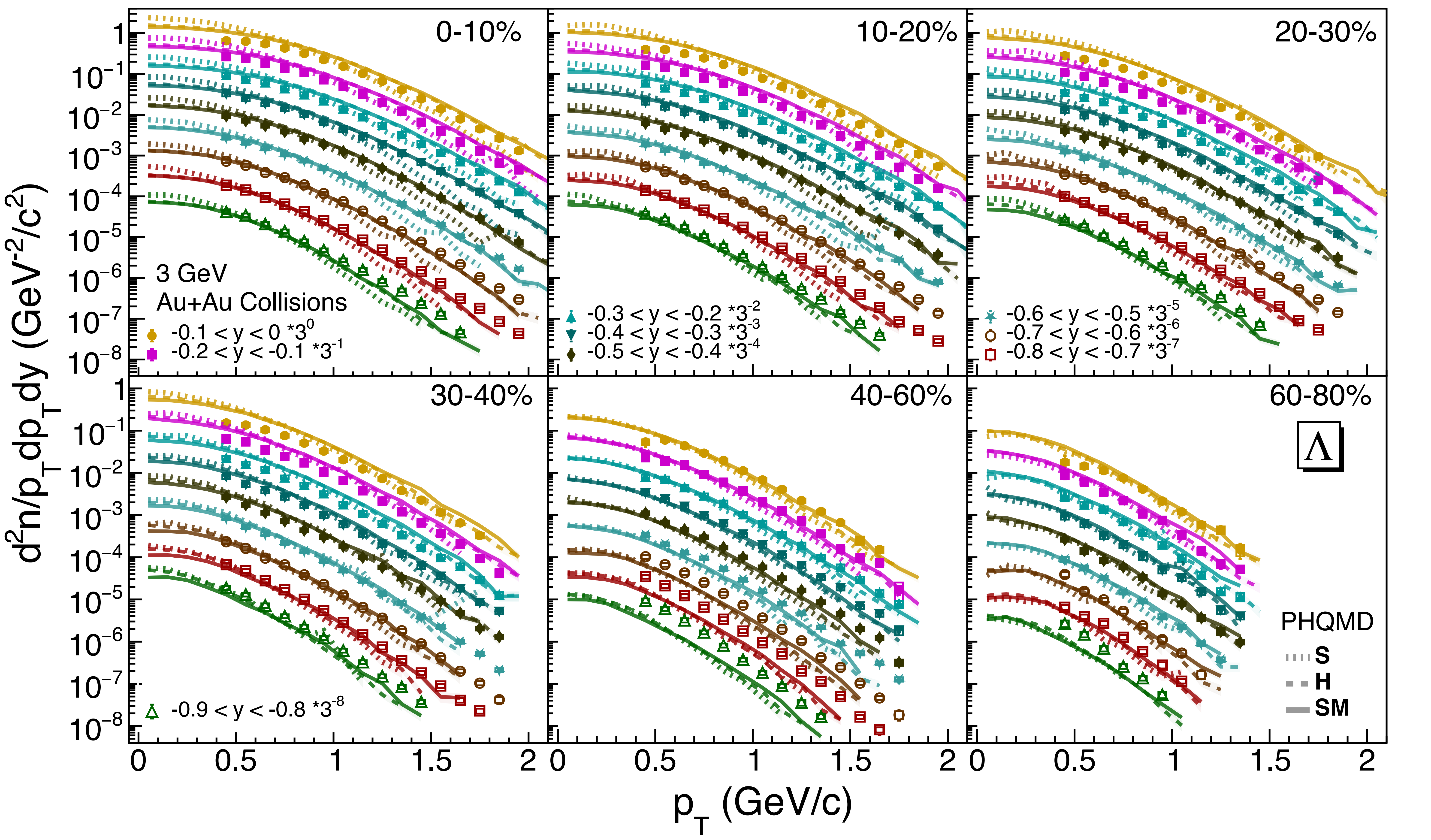
Protons and Λ

STAR data

- proton p_T spectra: Phys. Rev. C 110 (2024) 54911
- Λ p_T spectra: JHEP 2024 (2024) 139
- proton, Λ v_1, v_2: Phys. Lett. B 827 (2022) 137003

Proton and Λ Transverse Momentum Distributions at 3 GeV

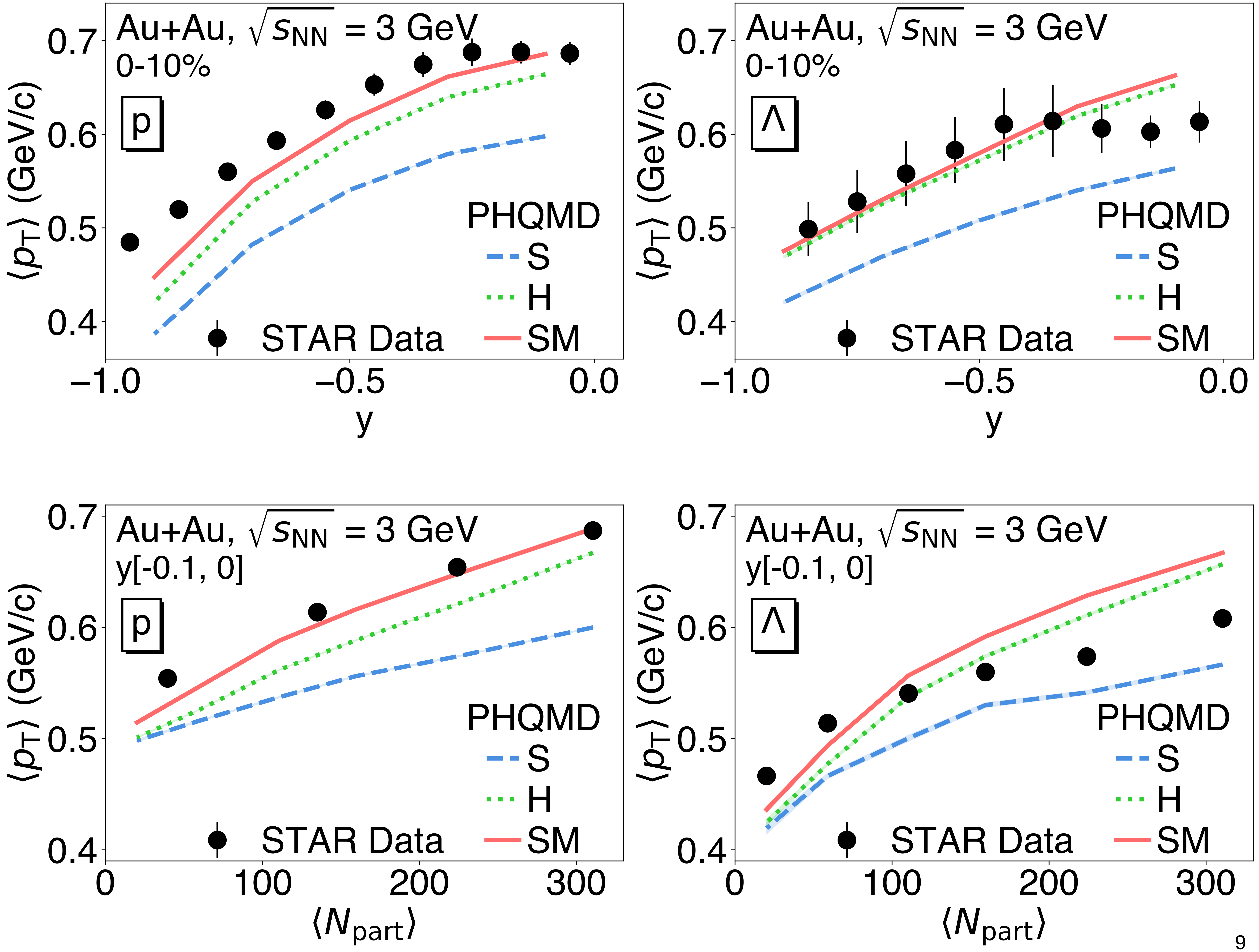




Mean Transverse Momentum $\langle p_T \rangle$

$$\langle p_T \rangle = \frac{\int p_T \frac{dN}{dp_T} dp_T}{\int \frac{dN}{dp_T} dp_T}$$

- **S** EOS underestimate both p and Λ data
- **H** and **SM** EOS come much closer to the data
    - Deviations at y=0 may warrant further study
- $\langle p_T \rangle$ of $p > \langle p_T \rangle$ of Λ
    - Fraction of protons may be spectator protons at such low energies



Kinetic Freeze-Out Parameters

- Blast-wave fits to separate influence from the temperature and the collective expansion on the transverse momentum spectra

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T sinh\rho(r)}{T_{kin}}\right) K_1\left(\frac{m_T cosh\rho(r)}{T_{kin}}\right)$$

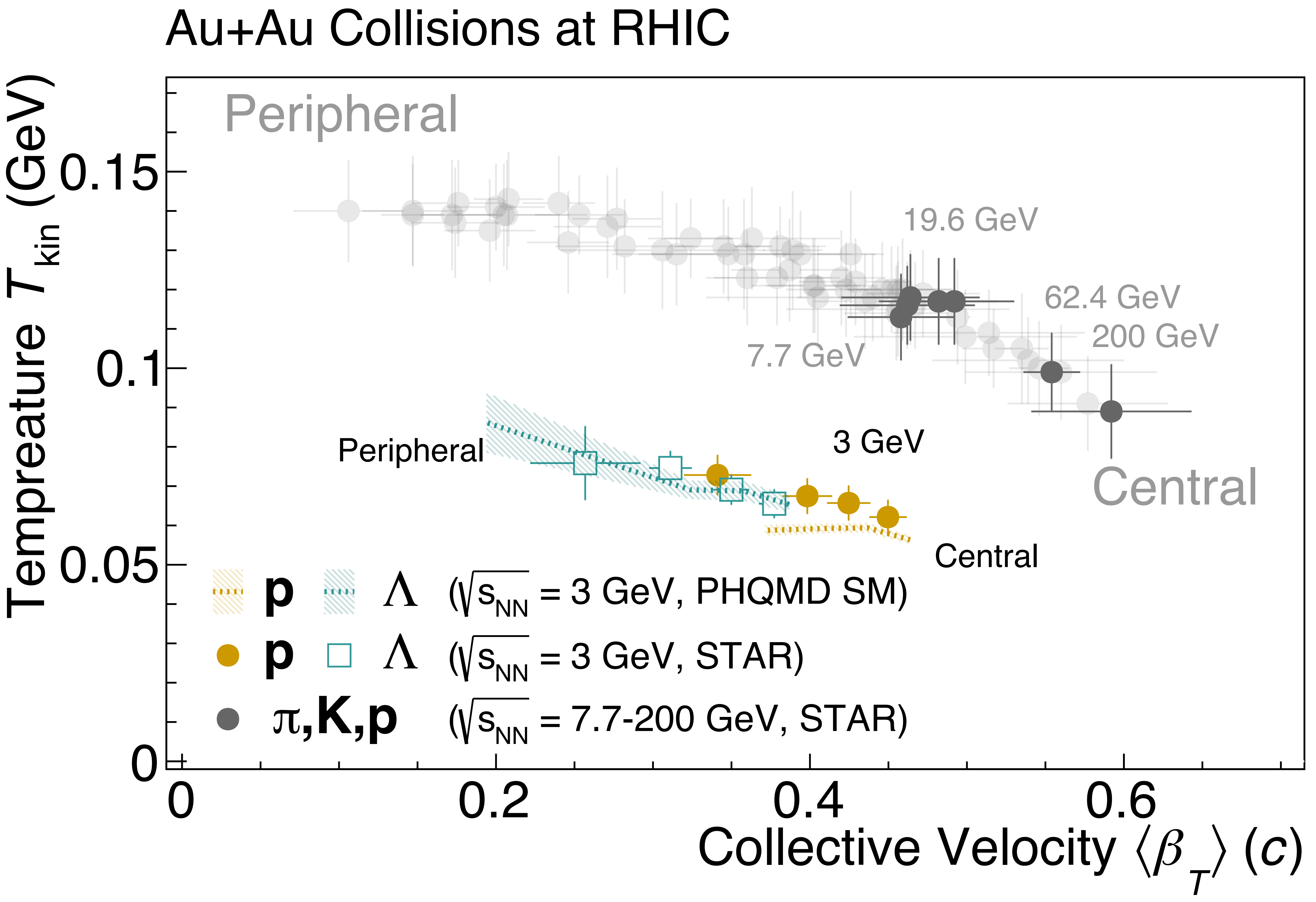
$$\rho(r) = tanh^{-1}(\beta_T)$$

- Kinetic freeze-out temperature: T_{kin}
- Average transverse velocity: $\langle\beta_T\rangle$

- Similar T_{kin}, but larger $\langle\beta_T\rangle$ for protons
- At fireball center, nucleon density is higher, collective velocity is smaller

Production probability of Λs higher close to the center of the fireball

- PHQMD describes the trends observed in the data well



Azimuthal Anisotropy

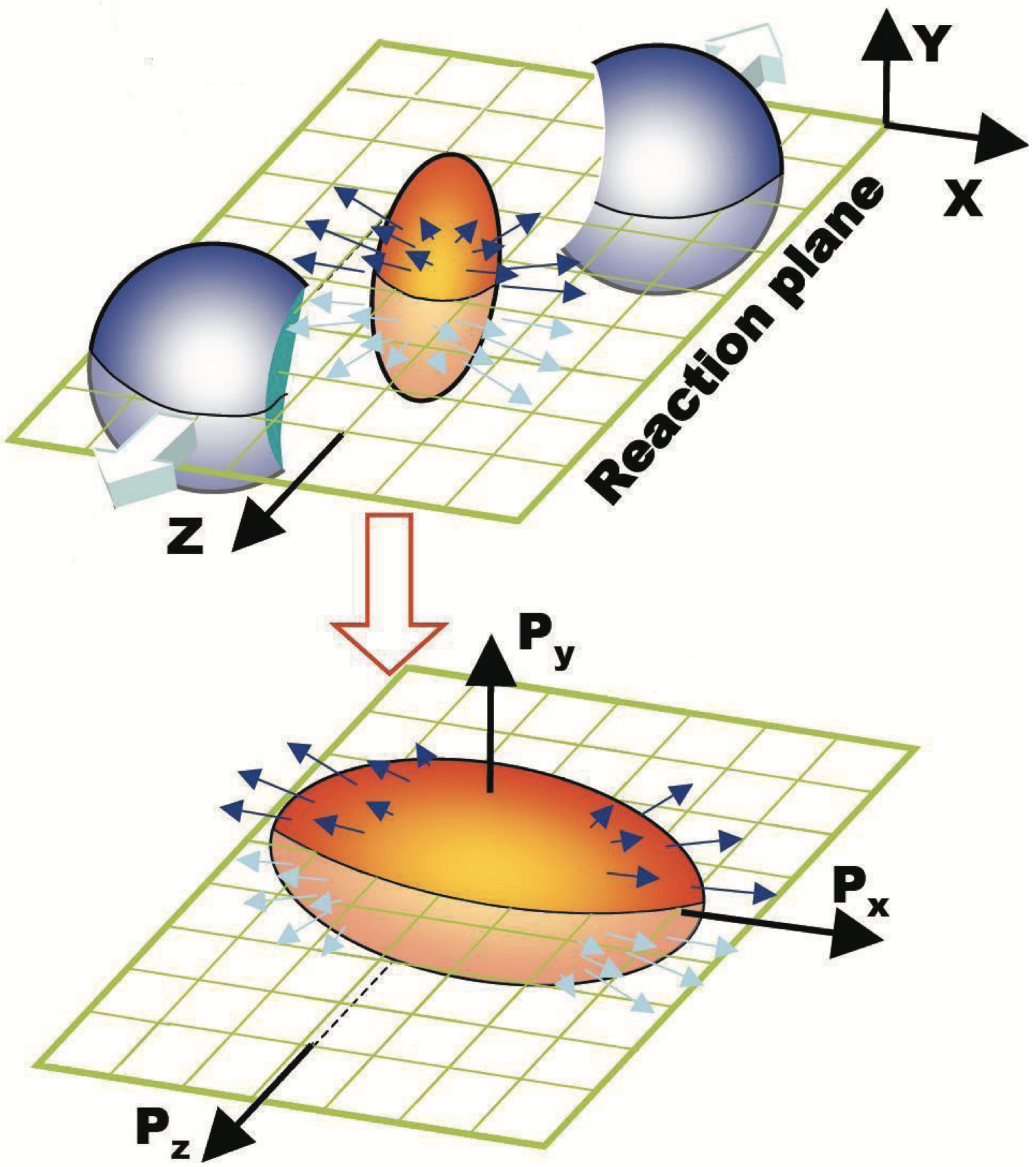
A. M. Poskanzer and S. A. Voloshin, PRC 58 (1998) 1671

- In non-central collisions, initial spatial anisotropy → pressure gradients → momentum space anisotropy

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_1^{\infty} 2v_n cos[n(\phi - \Psi_{rp})]\right)$$

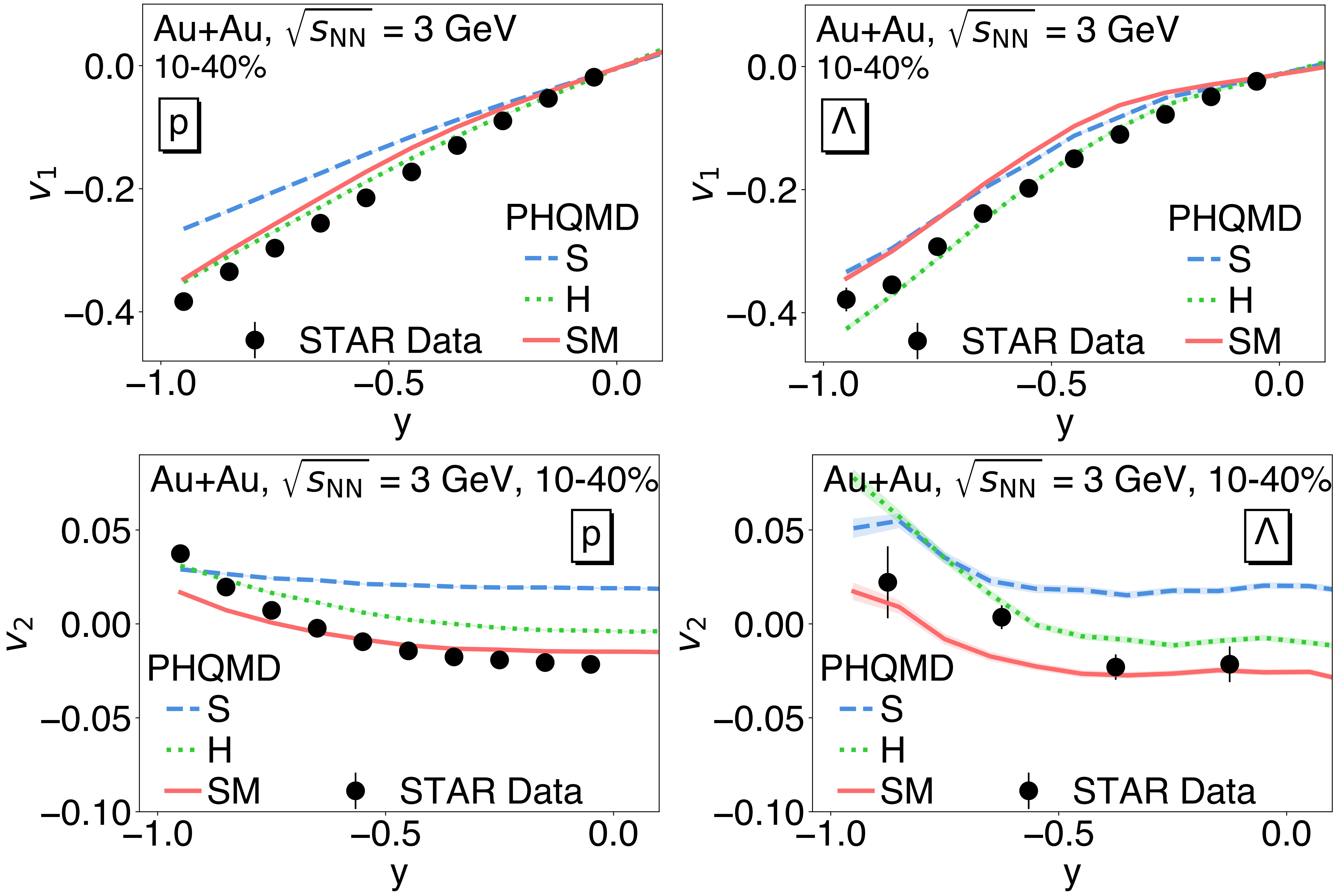
  - Directed flow: $v_1 = \langle cos(\phi - \Psi_{rp})\rangle$
  - Elliptic flow: $v_2 = \langle cos[2(\phi - \Psi_{rp})]\rangle$

Sensitive probes of the EoS of nuclear matter at high baryon density



Directed Flow and Elliptic Flow

- Directed flow v_1:
  - Similar to $\langle p_T \rangle$, **S** EOS do not provide good description, **H** EOS describe data well
  - **SM** EOS underestimate Λ
    - Choice of Λ potential?
- Elliptic flow v_2:
  - **SM** EOS describe data well, **S** predicts wrong sign at mid-rapidity



Most of the 3 GeV Au+Au data best described by SM EOS

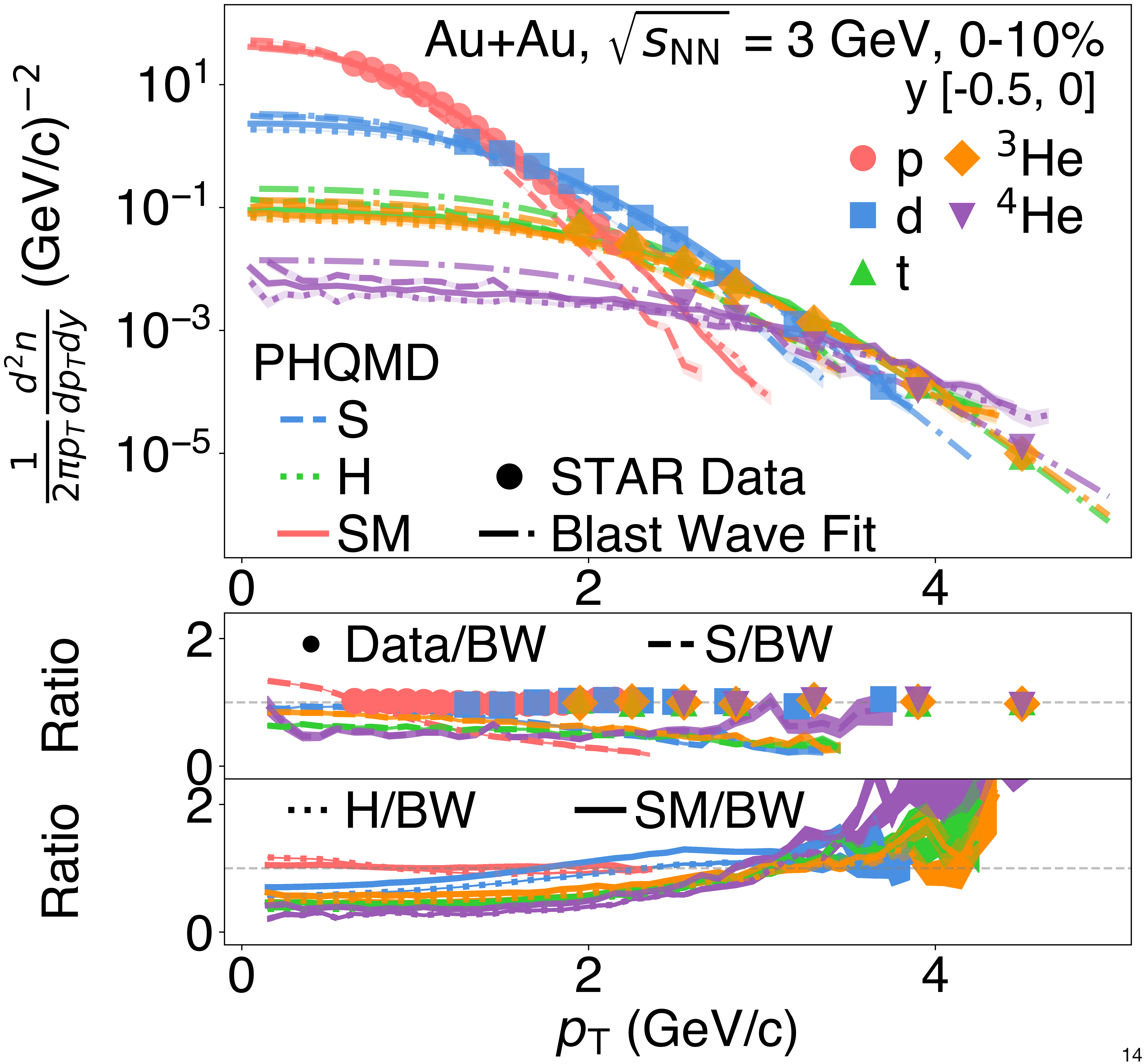
Nuclei and Hypernuclei

STAR data

- $d, t, {}^3\text{He}, {}^4\text{He}$ p_T spectra: Phys. Rev. C 110 (2024) 54911
- ${}^3_\Lambda\text{H}, {}^4_\Lambda\text{H}$ p_T spectra: Phys. Rev. Lett. 128 (2022) 202301
- $d, t, {}^3\text{He}, {}^4\text{He}$ v_1, v_2: Phys. Lett. B 827 (2022) 136941
- ${}^3_\Lambda\text{H}, {}^4_\Lambda\text{H}$ v_1 : Phys. Rev. Lett. 130 (2023) 212301

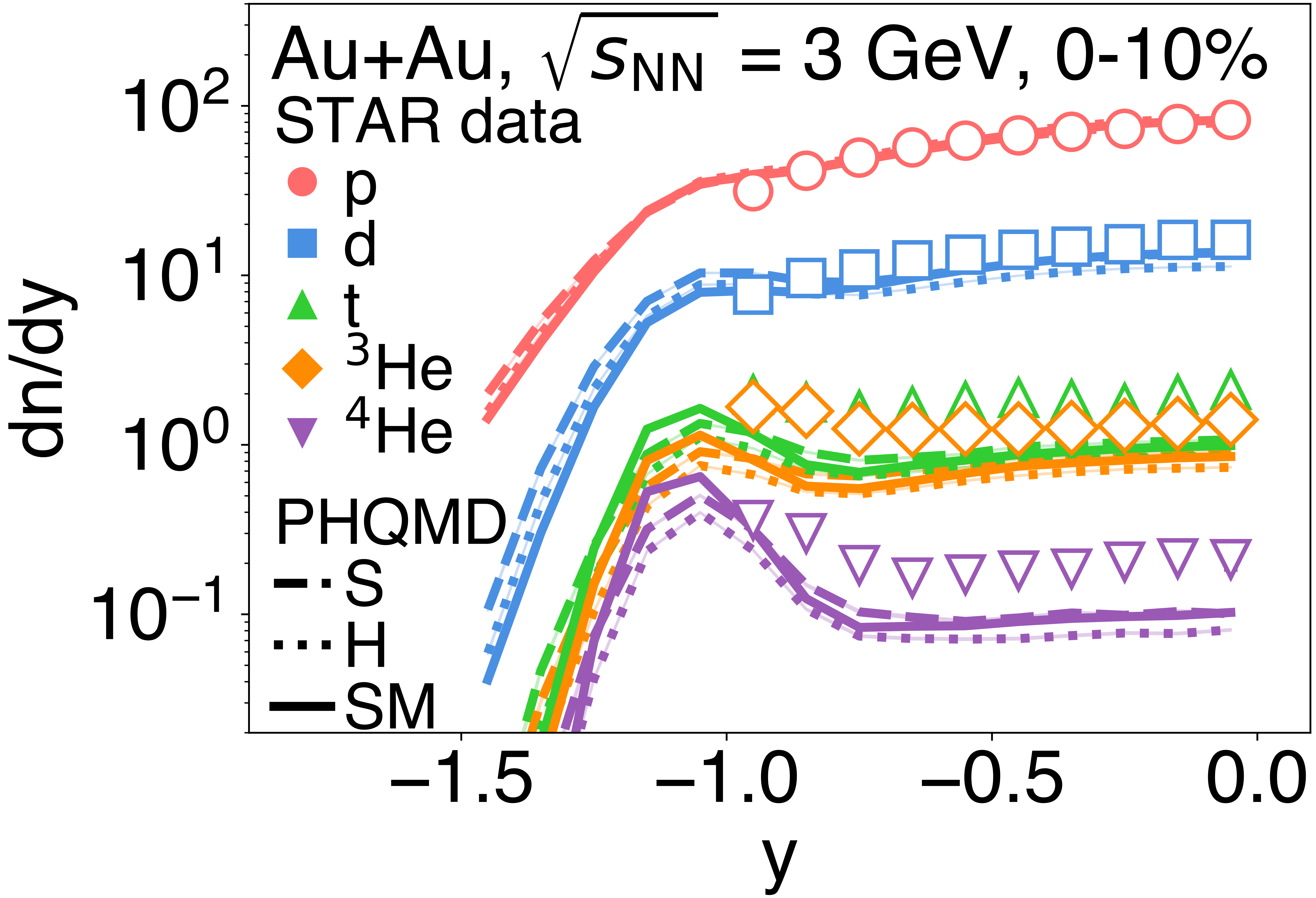
Nuclei p_T spectra

- **S** EOS is systematically lower than data for all clusters
- For d, **H** and **SM** EOS are mostly consistent with data, however there is a **tension in the slope**
- For t, ^{3}He, and ^{4}He, the deviations are larger, with PHQMD underestimating the data



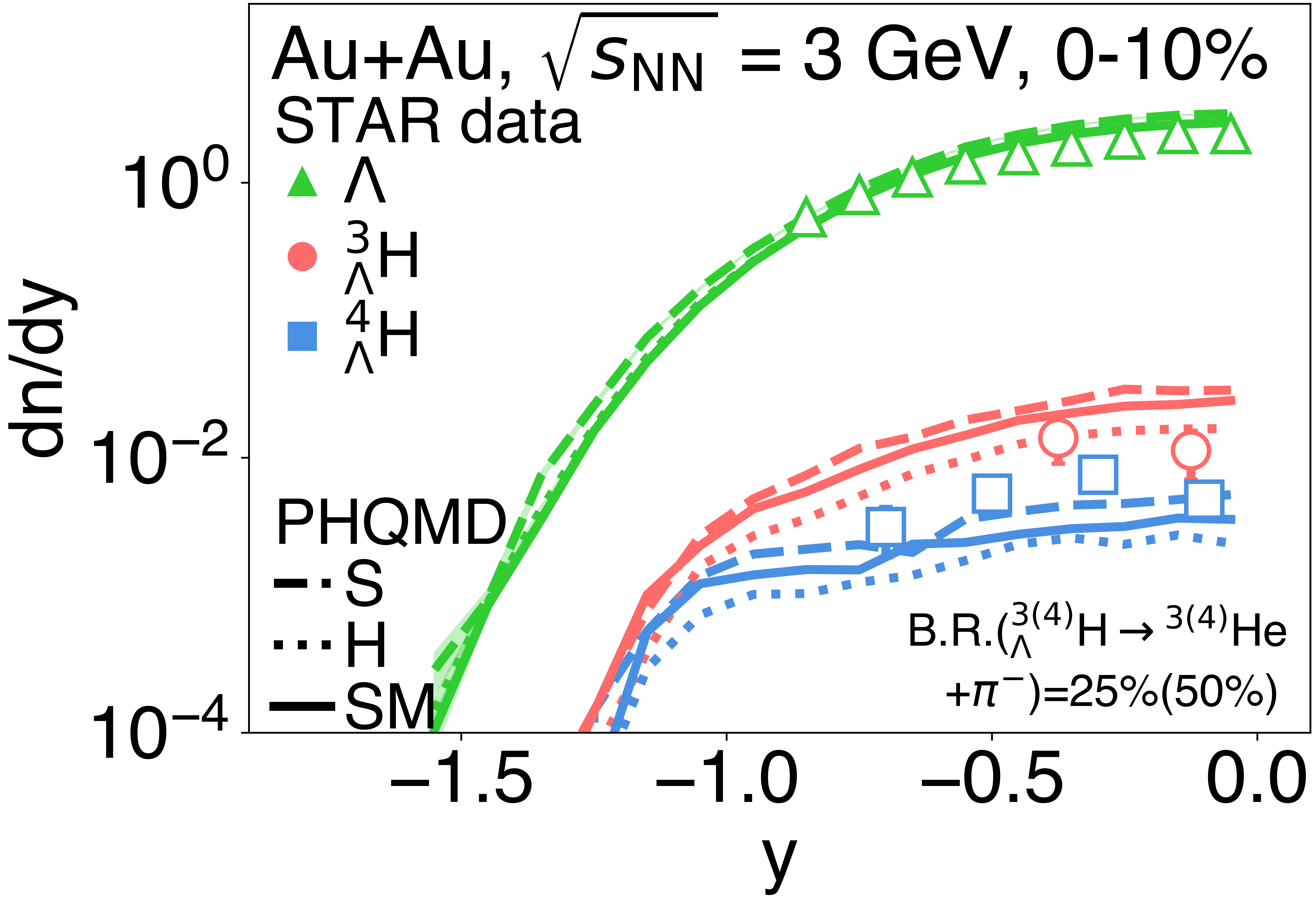
Nuclei dN/dy

- p yields well reproduced
- H EoS predicts a lower d yield compared to S and SM EoS
  - d yields reproduced within 20% with S and SM
- **Larger deviations for heavier clusters**



Hypernuclei dN/dy

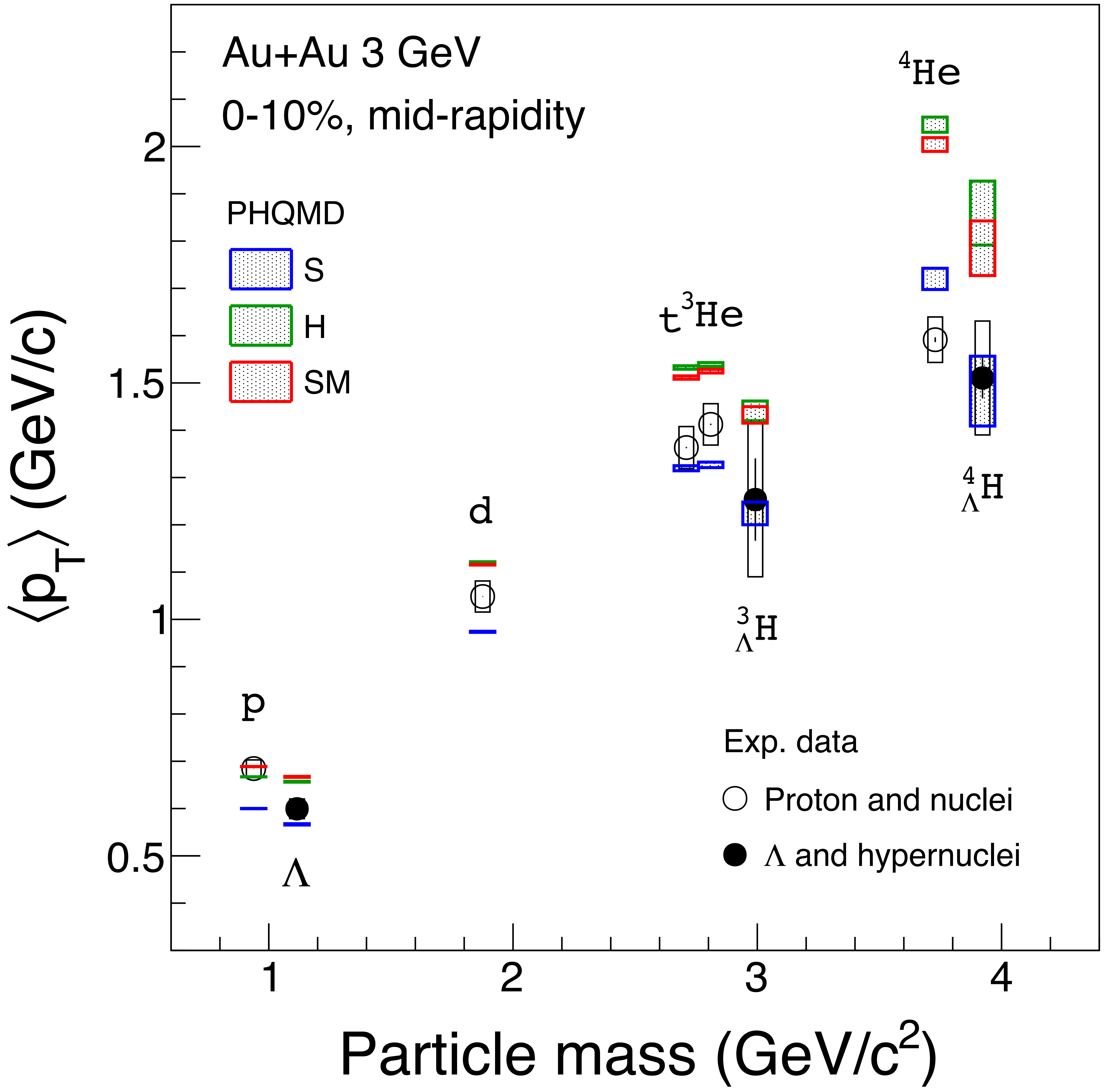
- Λ yields yield has a mild sensitivity to the EoS
- ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H: S EoS predicts the largest yield, followed by SM and H EoS
  - Approx. factor of 2 difference b/w S and H EoS



Higher sensitivity of the hypernuclei yields to EoS compared to other particles

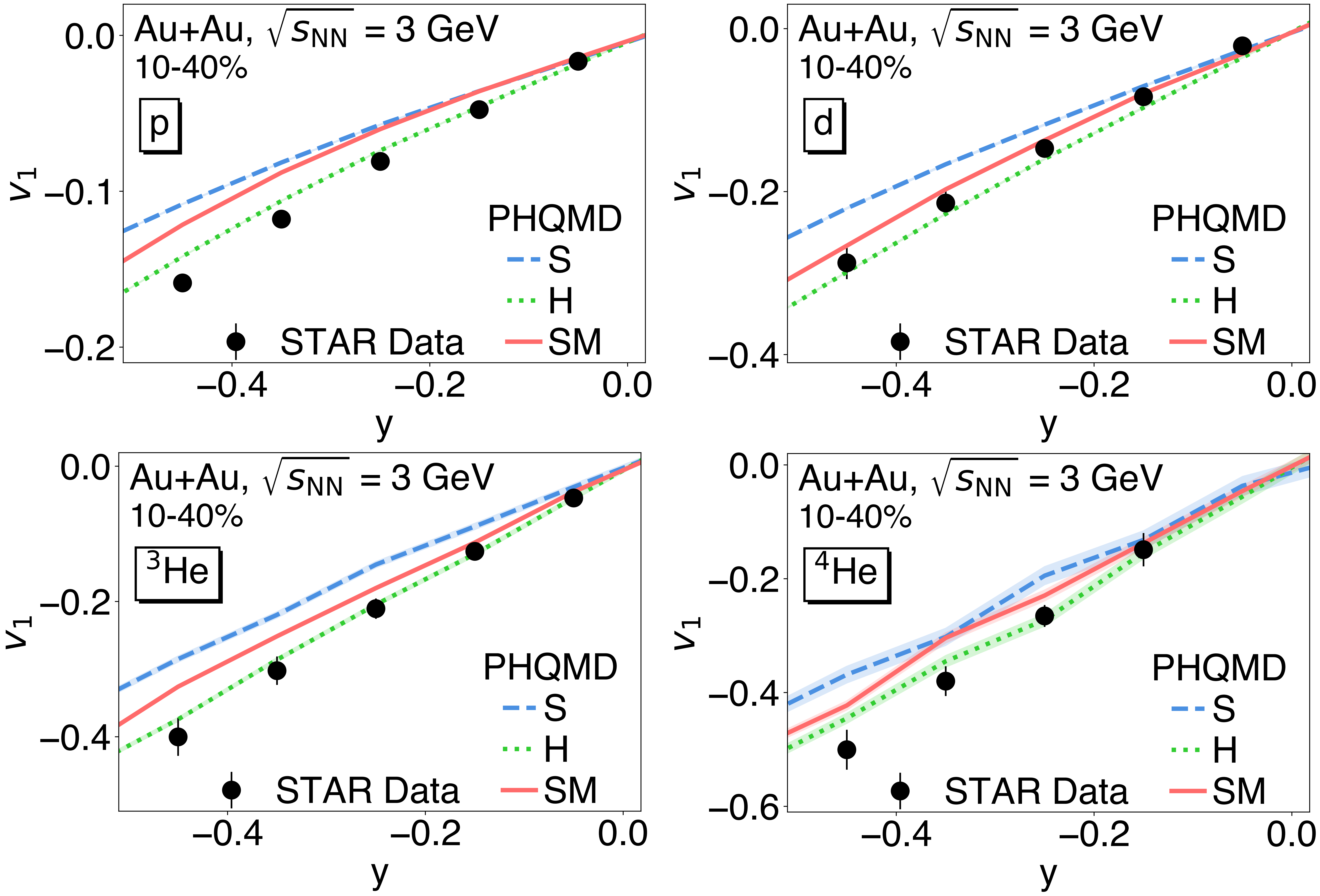
Nuclei and Hypernuclei $\langle p_T \rangle$

- Although **H** and **SM** EOS describe the $\langle p_T \rangle$ of protons, they **overestimate the $\langle p_T \rangle$ of all the nuclei**
  - Underprediction of the yield of low p_T clusters and disagreement of the extrapolation of the experimental data to $p_T \to 0$ w.r.t. PHQMD
- **H** and **SM** EOS also tend to overestimate the $\langle p_T \rangle$ of hypernuclei



Rapidity Dependence of Nuclei Directed Flow

- **S** EOS underestimates proton and all clusters
- **H** EOS provides a better description compared to **SM**

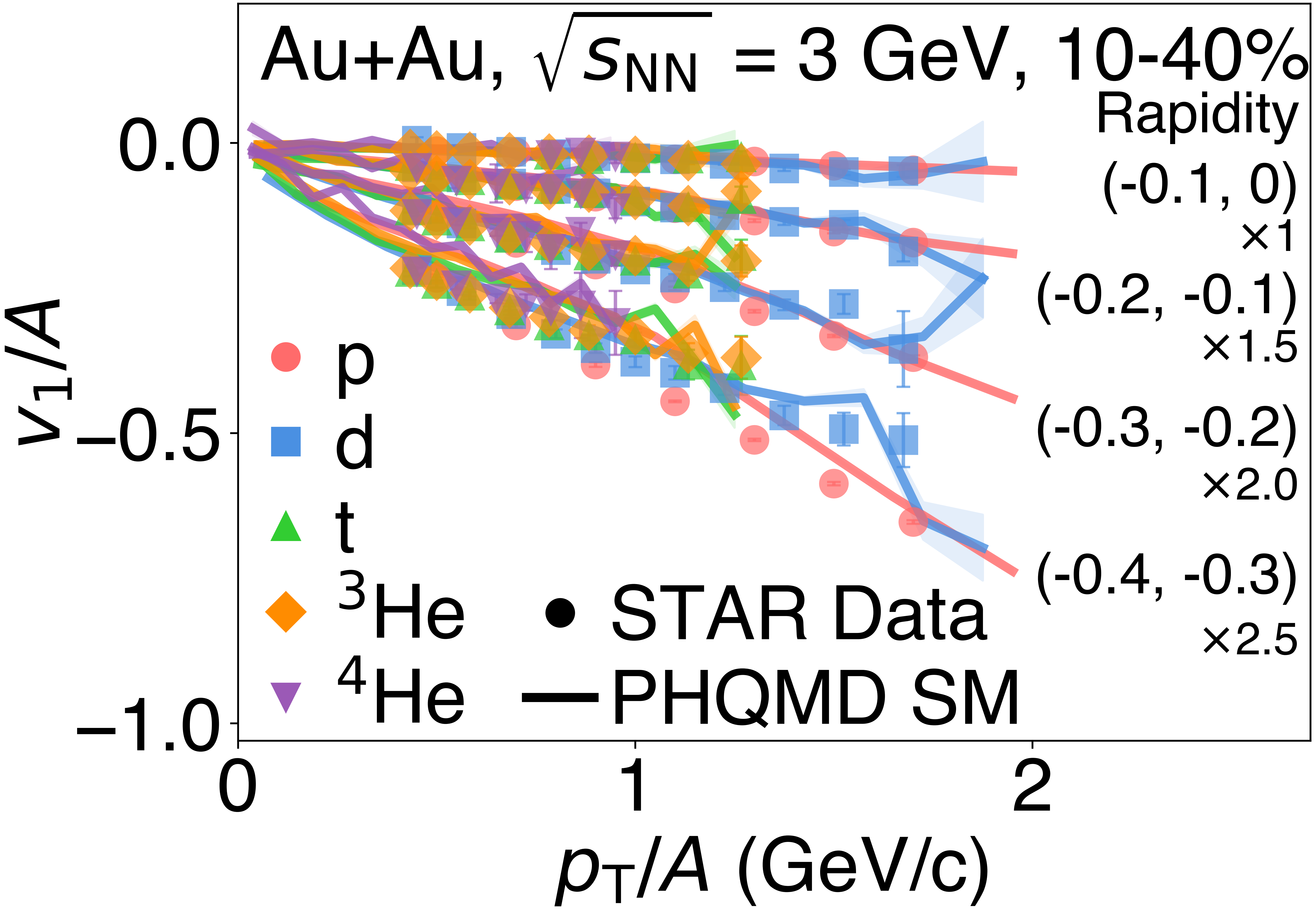


p_T Dependence of Nuclei Directed Flow (v_1)

- v_1 vs p_T scales with mass number for $y = (-0.3, 0)$, reproduced by PHQMD

- Deviations from mass number scaling for $y = (-0.4, -0.3)$

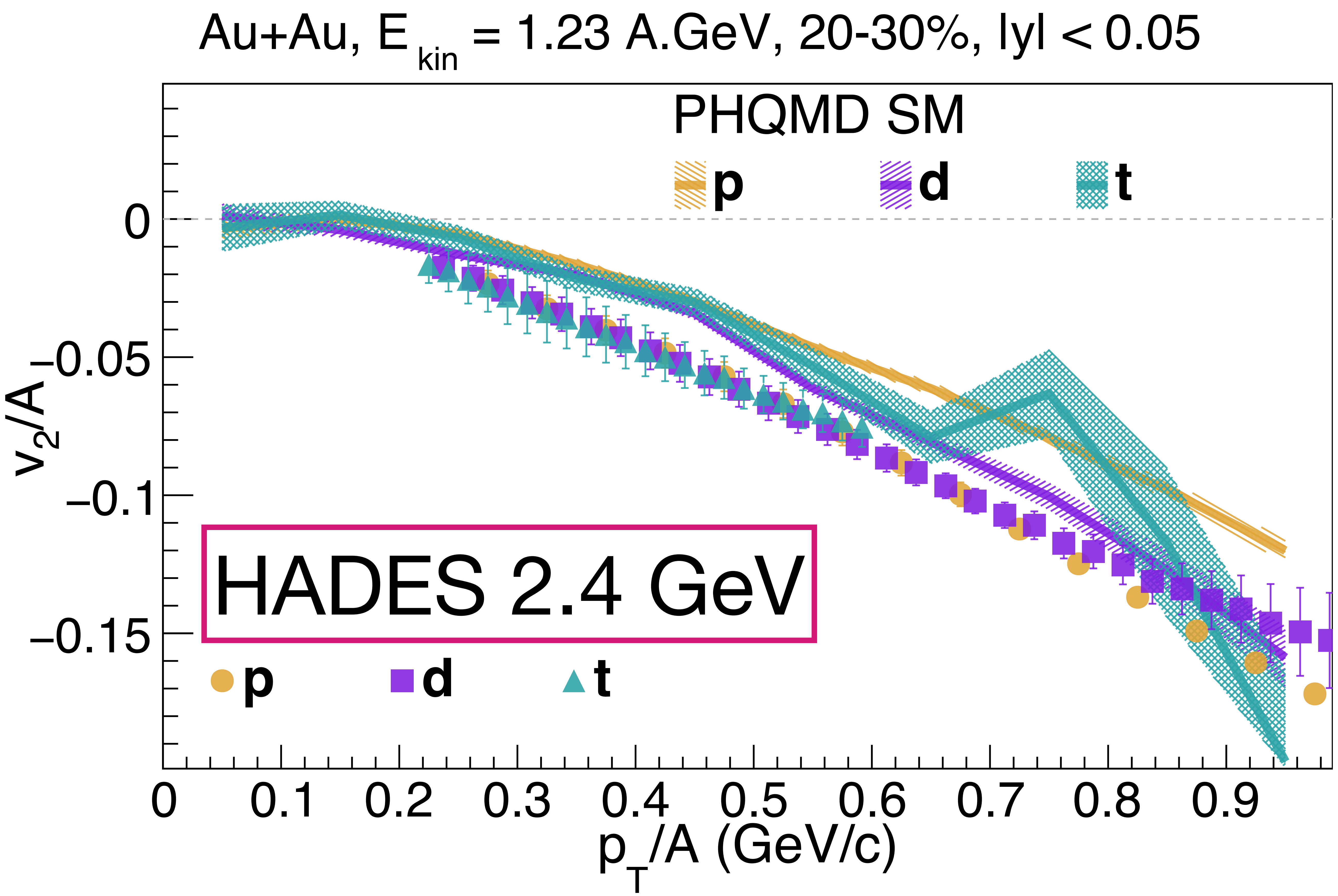
- Measurements at backward rapidity are important



Elliptic Flow (v_2) of Nuclei

V. Kireyeu et al., arXiv:2411.04969

- HADES 2.4 GeV data show mass number scaling for elliptic flow v_2 up to $p_T/A = 1$ GeV



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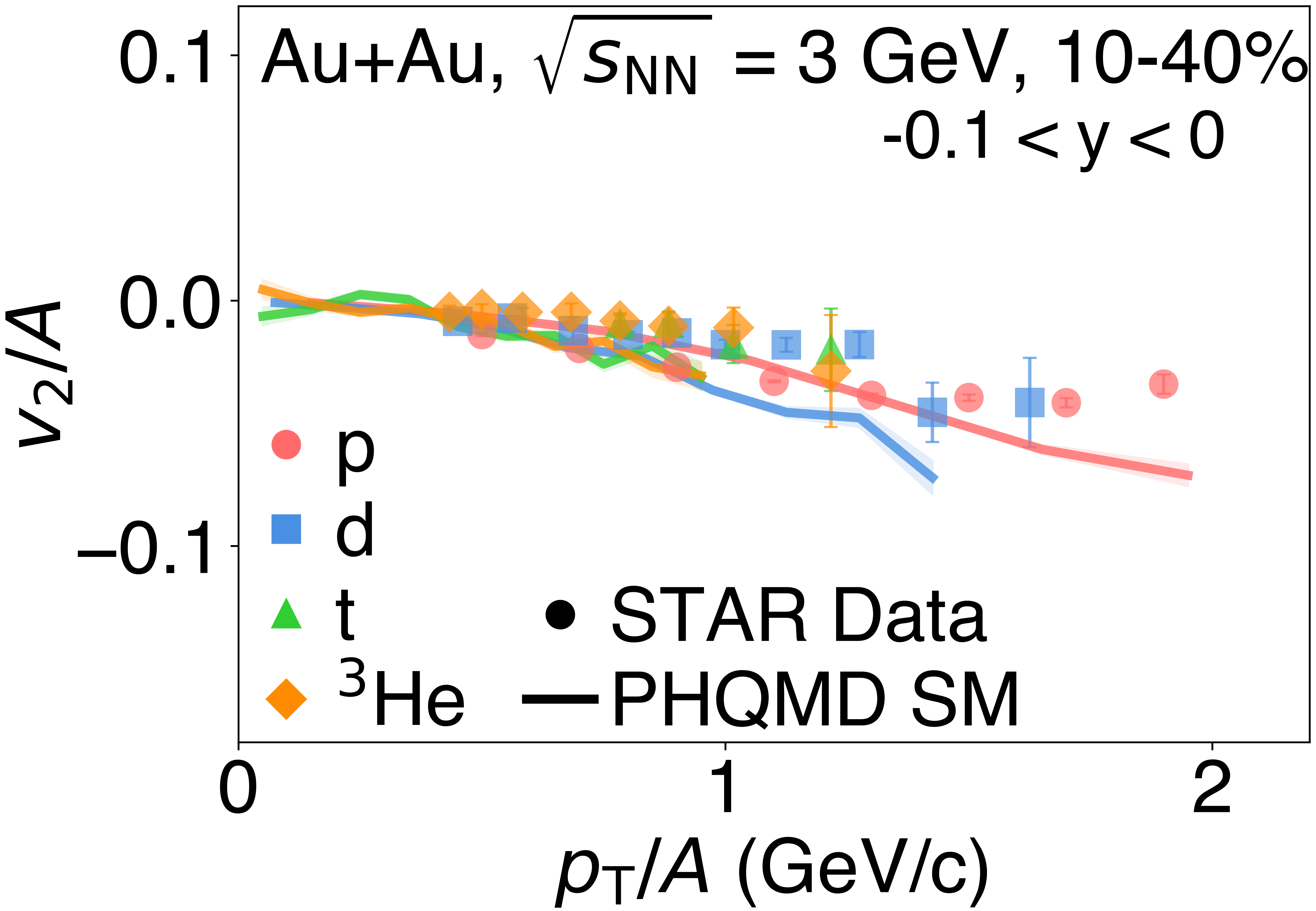
- Elliptic flow for the data at 3 GeV **do not show mass number scaling**



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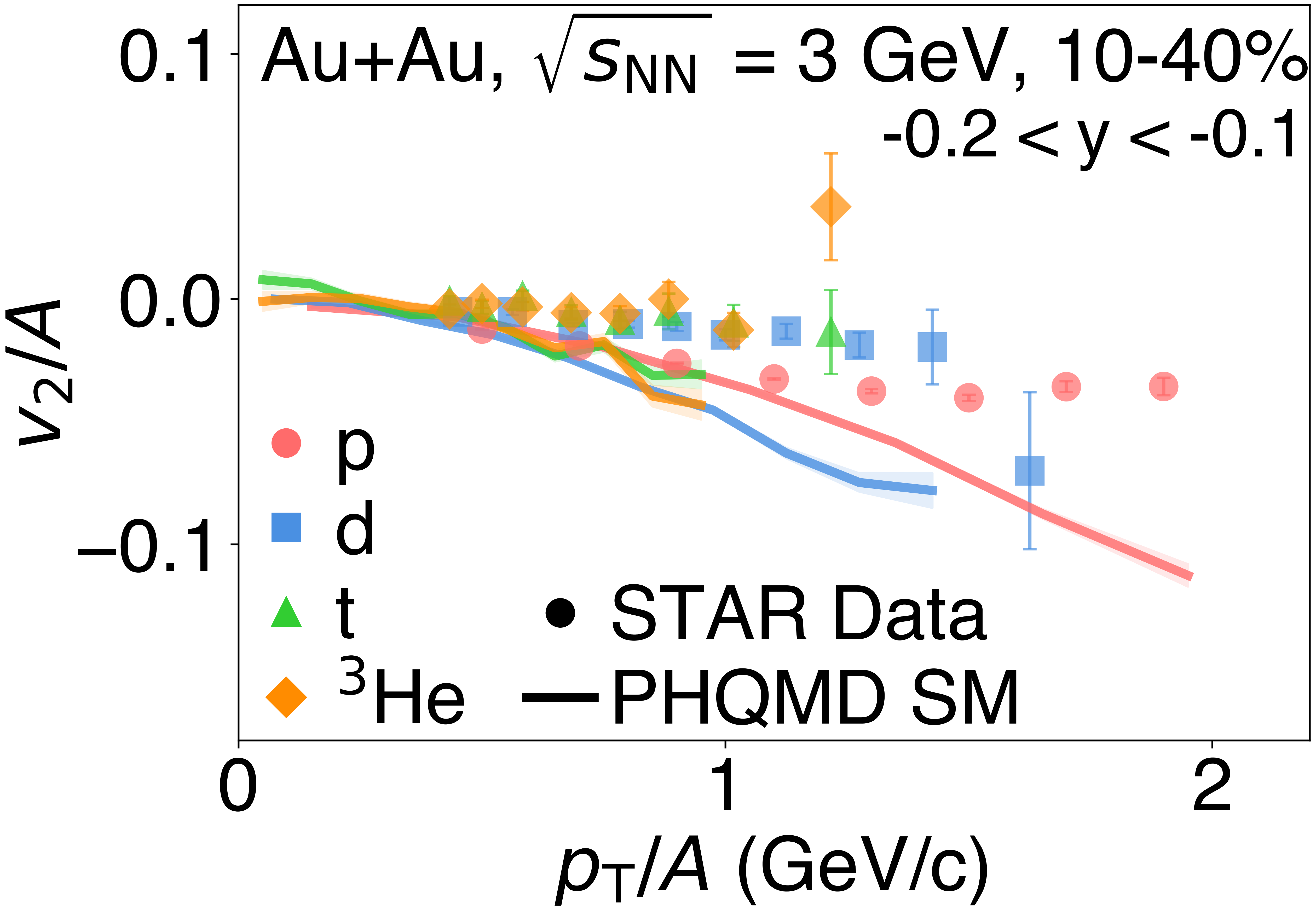

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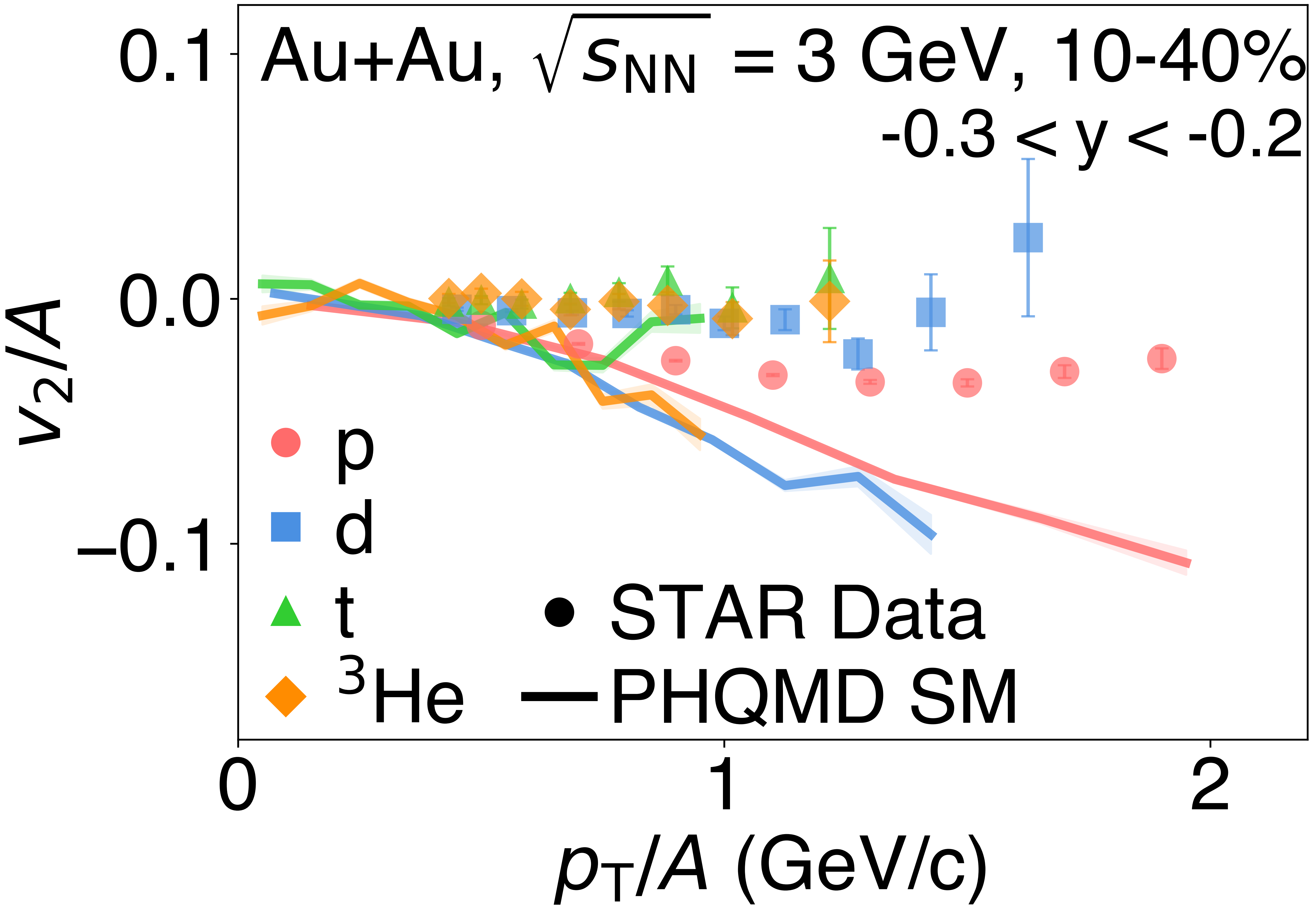
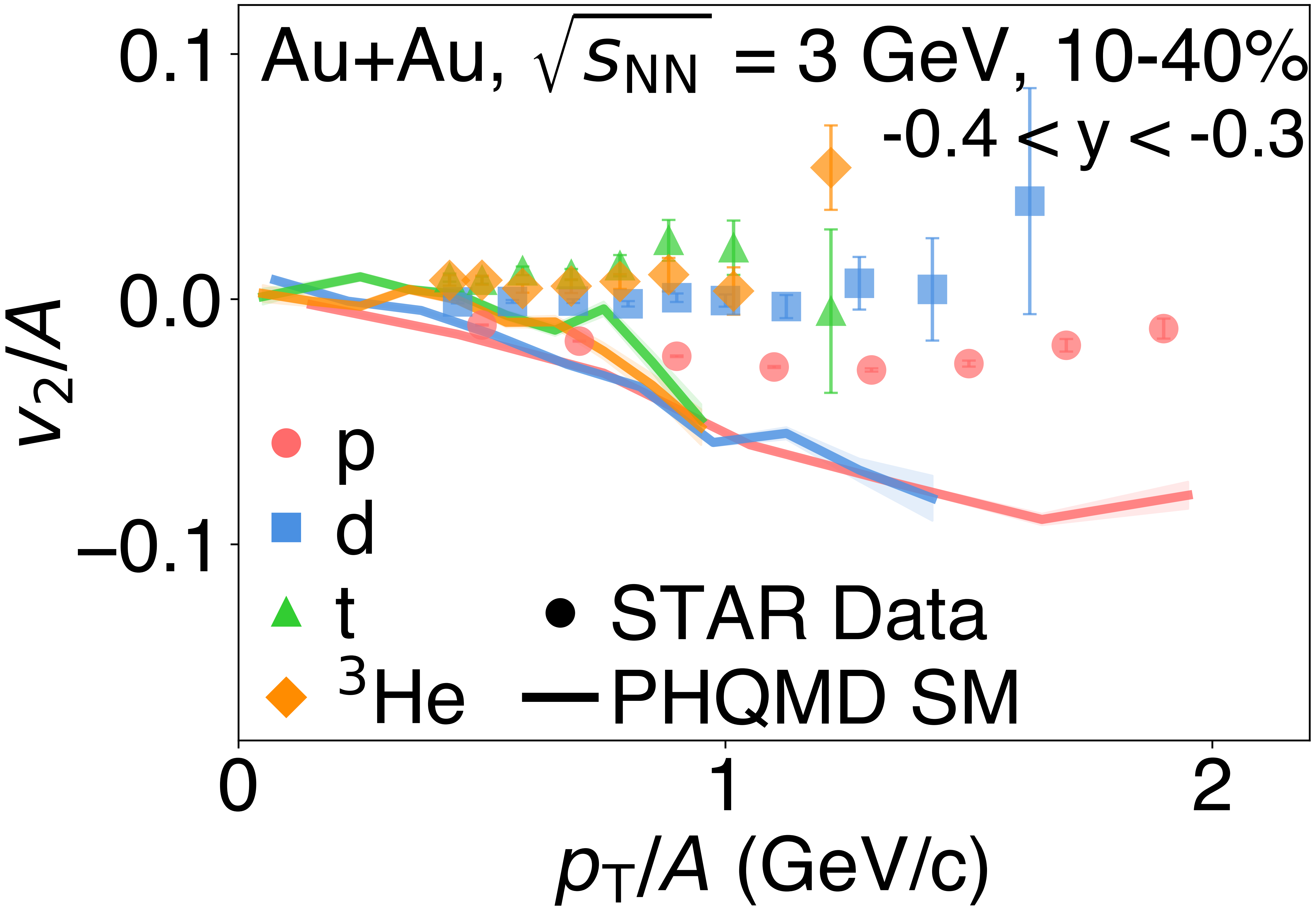


Elliptic Flow (v_2) of Nuclei

- HADES 2.4 GeV GeV data show mass number scaling for elliptic flow v_2 up to $p_T/A = 1$ GeV
- Elliptic flow for the data at 3 GeV **do not show mass number scaling**
- Deviations are more obvious away from mid-rapidity



Suggests that at 3 GeV clusters are not a random selection of nucleons but a selective process

Summary

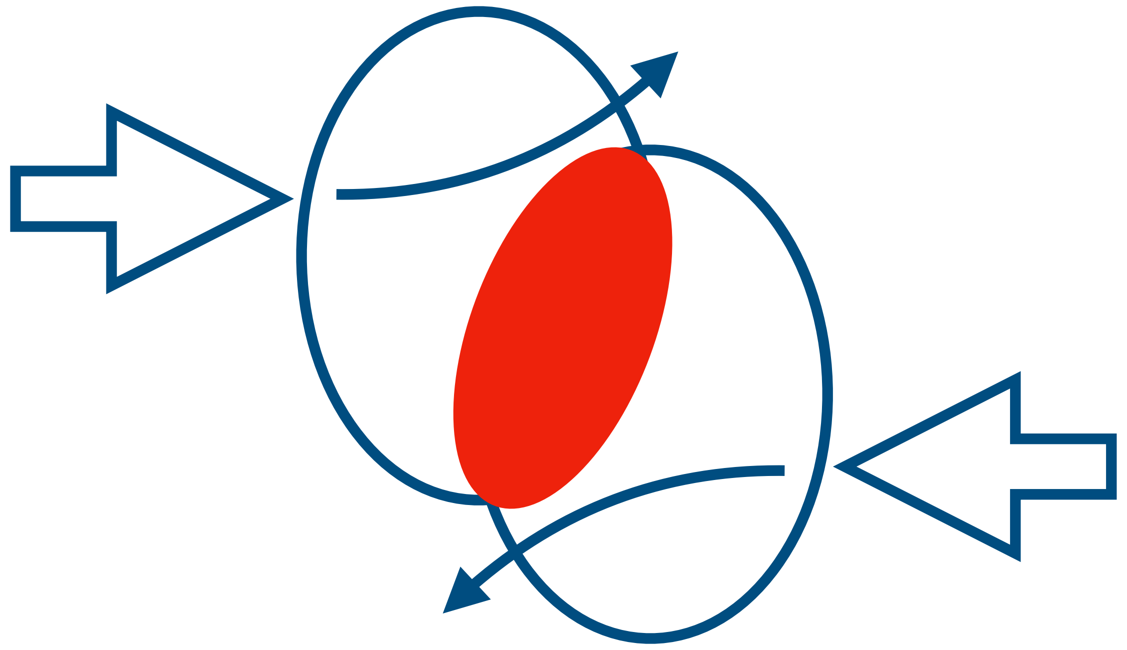
- Compared the results of PHQMD calculations using **3 different EoS, soft (S), hard (H), and soft with momentum dependence (SM)** with STAR **3 GeV Au+Au** data

Probes of EOS	
Probes of EOS	• **Different EoS gives quite different results for $\langle p_T \rangle$, v_1 and v_2 of baryons and clusters** • **Hypernuclei yields show high sensitivity to EoS**
Proton and Λ	• **Proton and Λ data mostly described by SM EoS** • Λ has similar T_{kin} with proton while having smaller β, suggests higher production probability of Λs close to center of fireball
Clusters and hypernuclei	• Stronger discrepancy b/w PHQMD results and data for heavier clusters • v_2 **for data do not show A scaling, suggests that clusters are not a random selection of nucleons but a selective process**

Thank you for listening!!

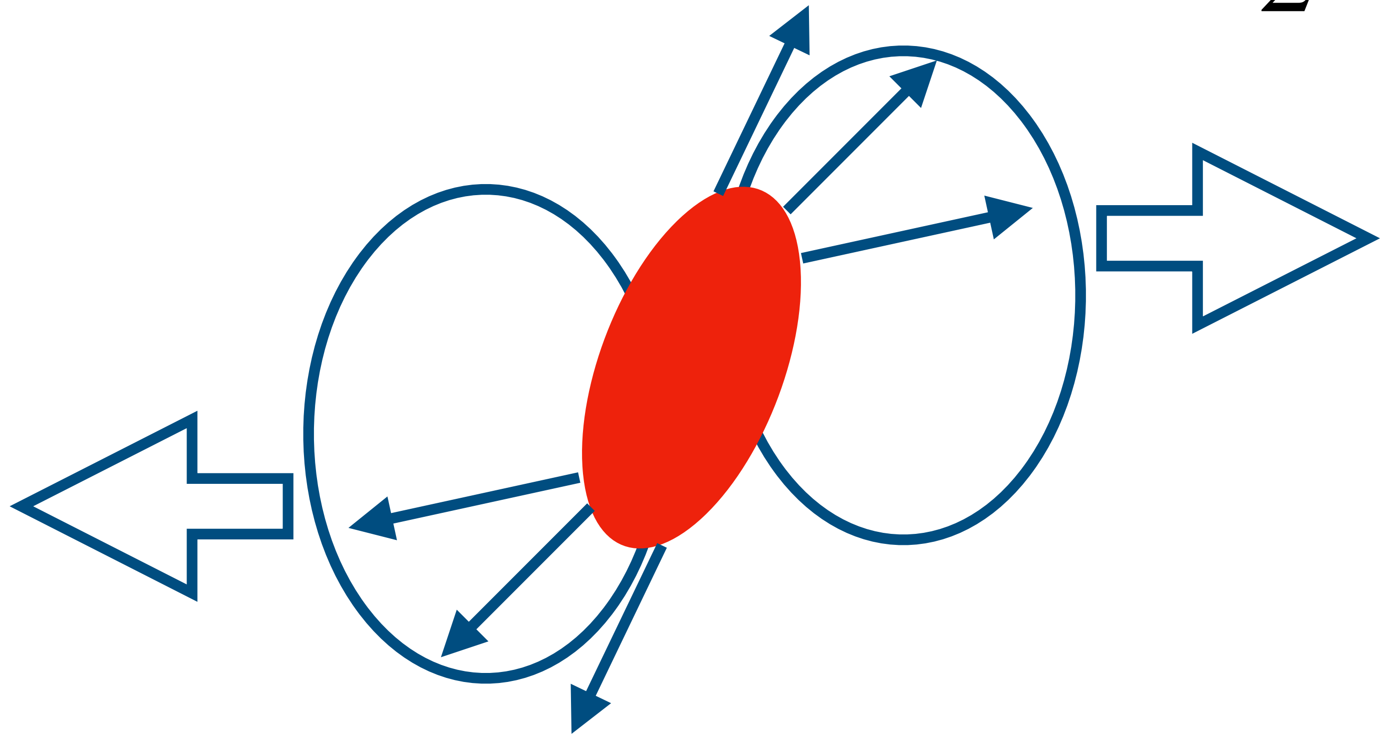
Energy Dependence of Directed and Elliptic Flow

- Larger proton and Λ v_1 at 3 GeV

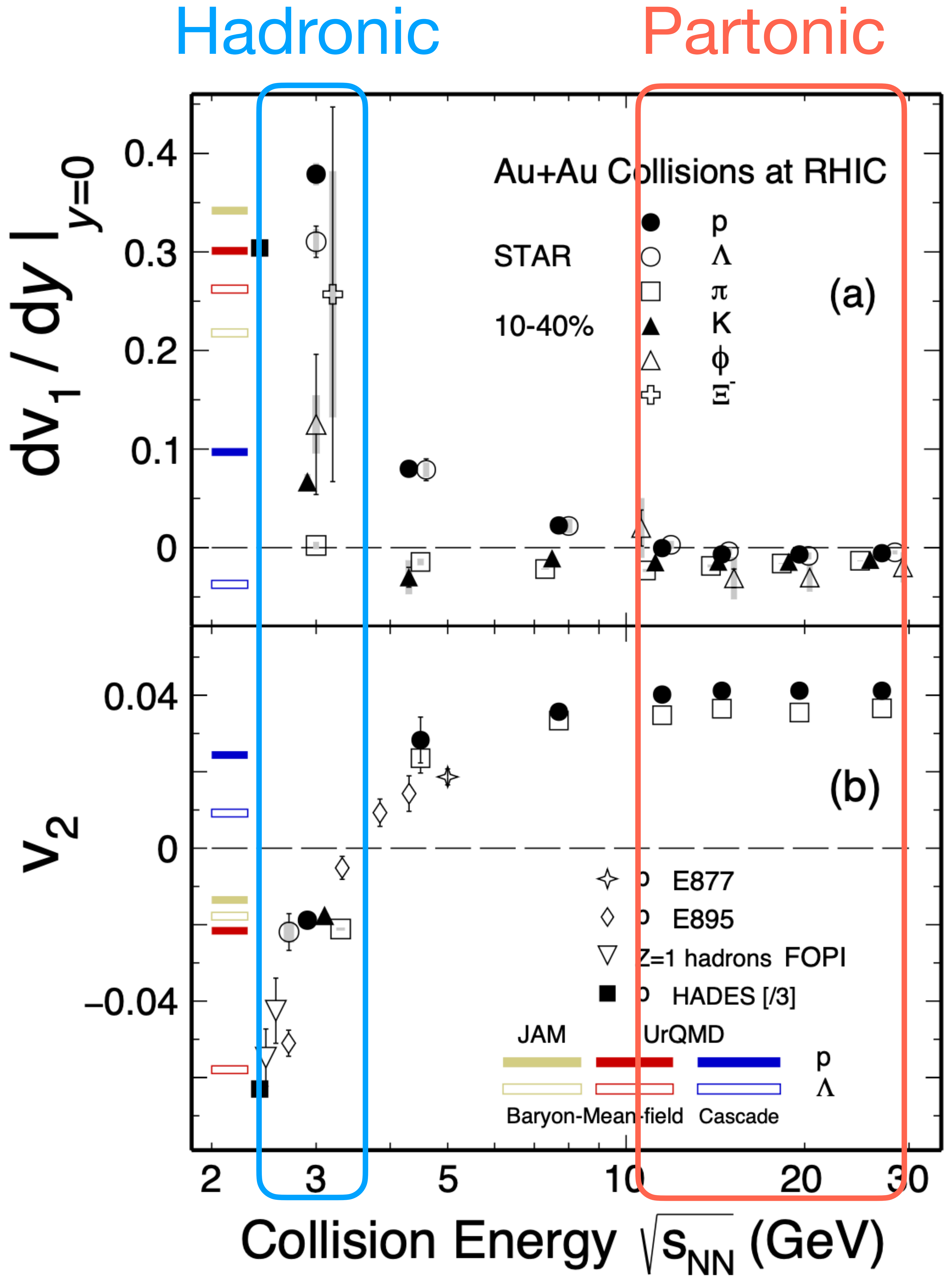


- "*Side splash*" due to repulsive baryon-baryon interactions

- Negative proton and Λ v_2 at 3 GeV



- *Nuclear shadowing*: spectators inhibit in-plane flow



Parton-Hadron-Quantum-Molecular Dynamics

= n-body microscopic transport approach for the description of heavy-ion collisions with dynamical cluster formation

PHSD + QMD + MST

Relativistic considerations

but: mean-field potentials
=> correlations are smeared out

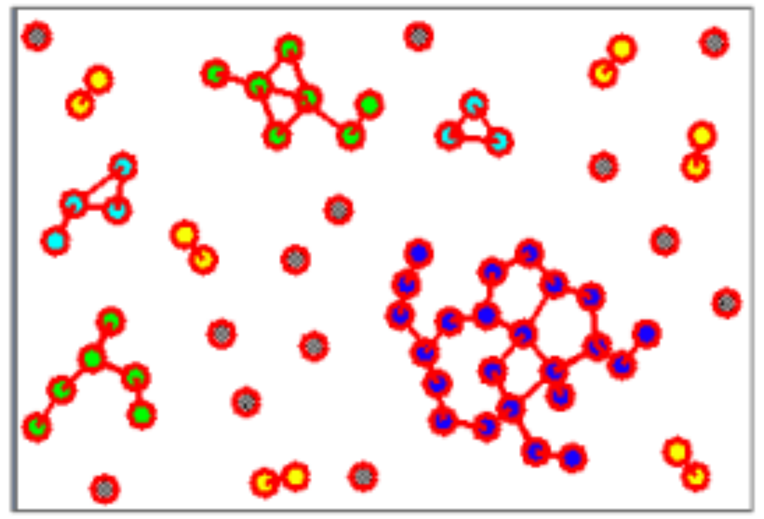
Correlations between baryons

n-body transport approach

=> formation of clusters due to potential interactions

Cluster recognition

search for accumulations of particles in coordinate space



See S. Gläßel talk on 11/11 (Tue)!

J. Aichelin et al., PRC 101 (2020) 044905 PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168(2009)