Collectivity in net-baryon dense systems from hadronic transport

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Workshop on High Baryon Density Physics in High-Energy Nuclear Collisions
19-20 Mar. 2026, Berkeley, CA, USA

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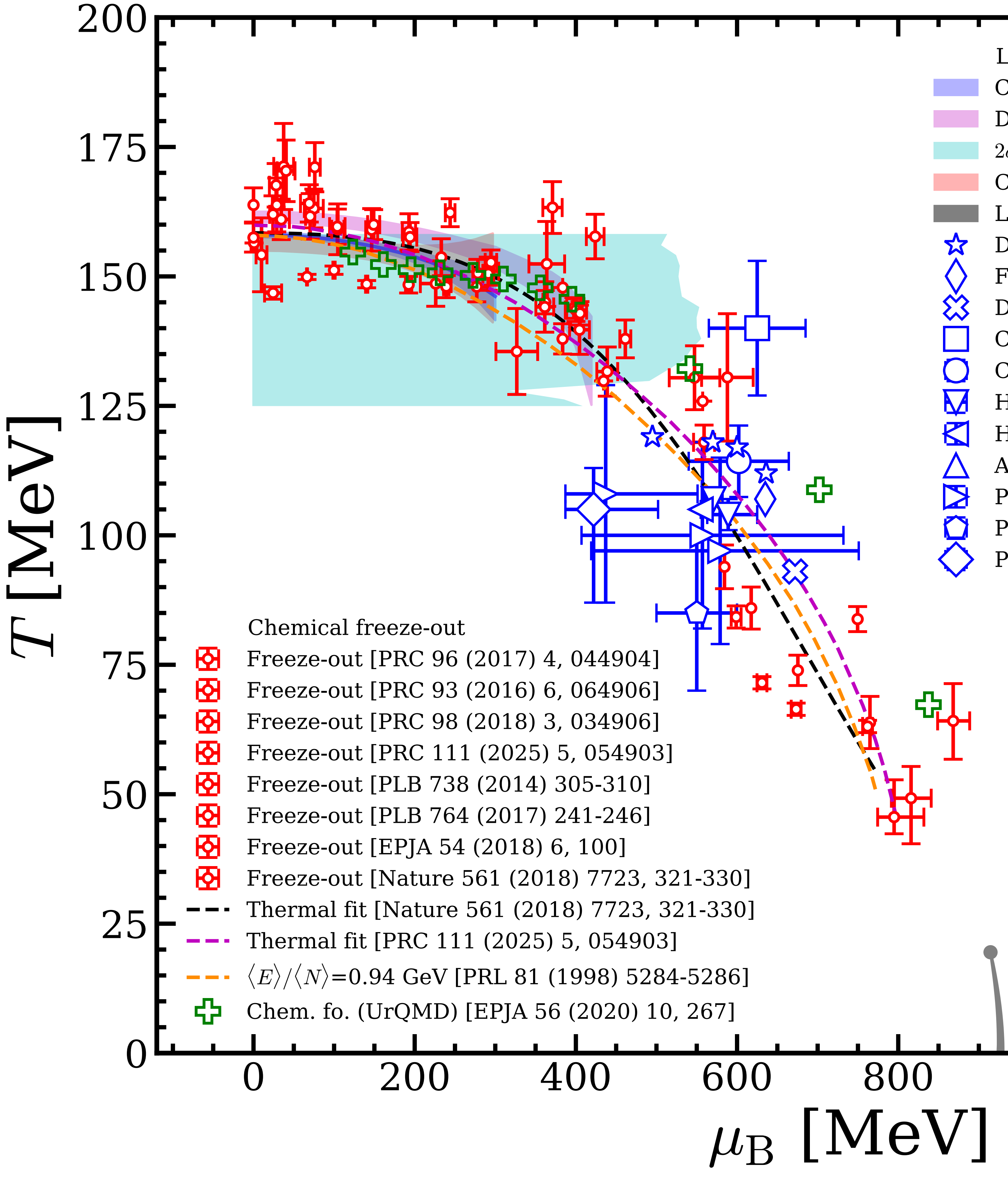
Motivation

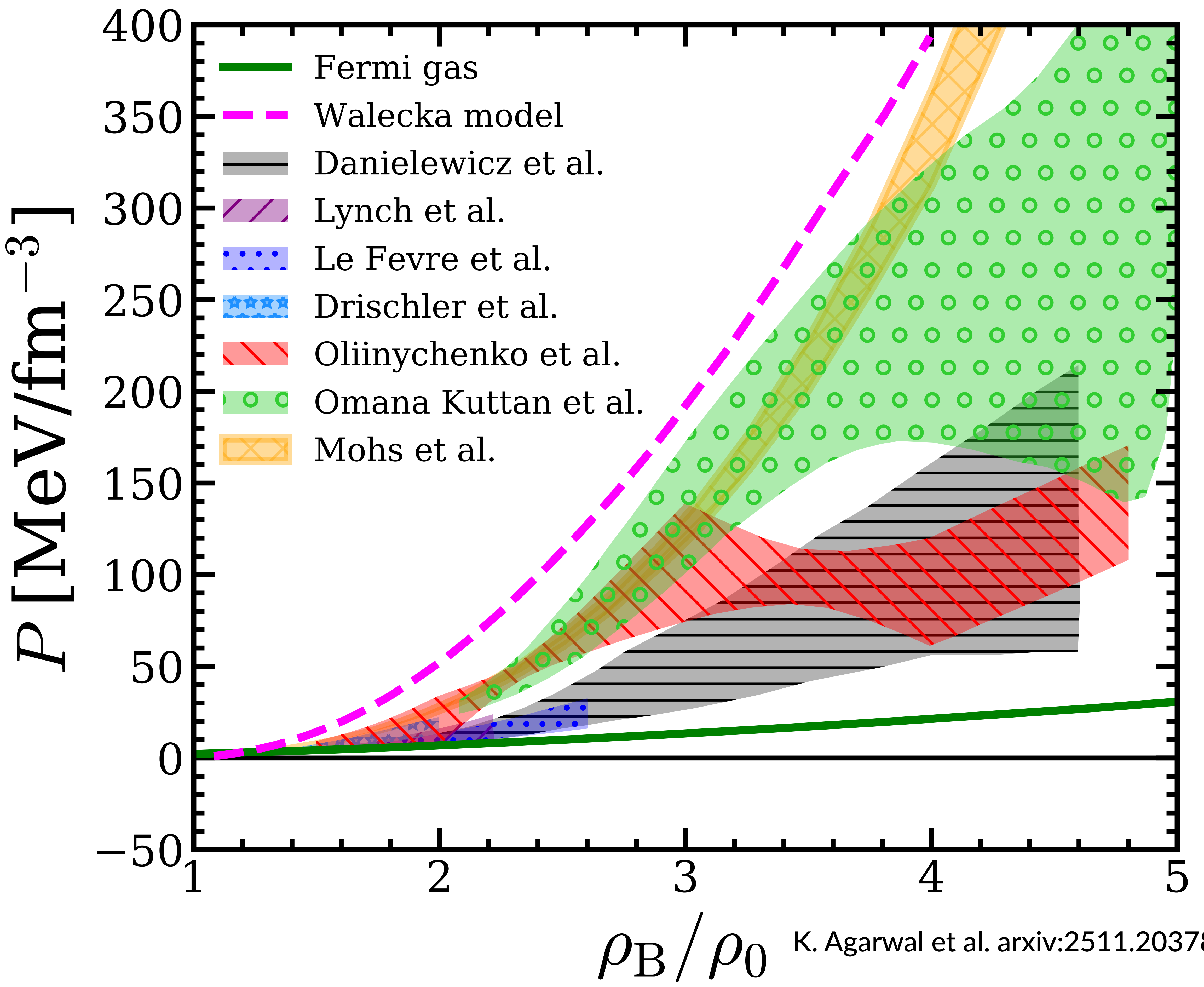
- Study QCD phase diagram
- Chiral crossover at μ = 0 MeV
- Liquid-Gas PT around T = 20 MeV
- No QCD in a box experiment, only dynamical heavy-ion collisions
- Extraction of equilibrium properties non-trivial
- Rely on dynamical (microscopic) models
- (Recent) CEP predictions prefer common region around μ = 600 MeV, T = 100 MeV



K. Agarwal et al. arxiv:2511.20378 [nucl-th]

Motivation

- Equation-of-State well constrained at densities directly accessible in HIC
- EoS less constrained in high ρ_B region due to various reasons. Improvement needs:
  - Better handle on systematics
  - Observables sensitive to $\rho_B > 3\ \rho_0$
  - Bayesian $v_2(y,p_T)$ instead of $\int dy\, dp_T\, v_2(y,p_T)\, dN/dy\, dp_T$
  - Differential measurements of $v_n(y,p_T)$ at STAR-FXT and FAIR, complemented by astro and low energy nuclear reactions



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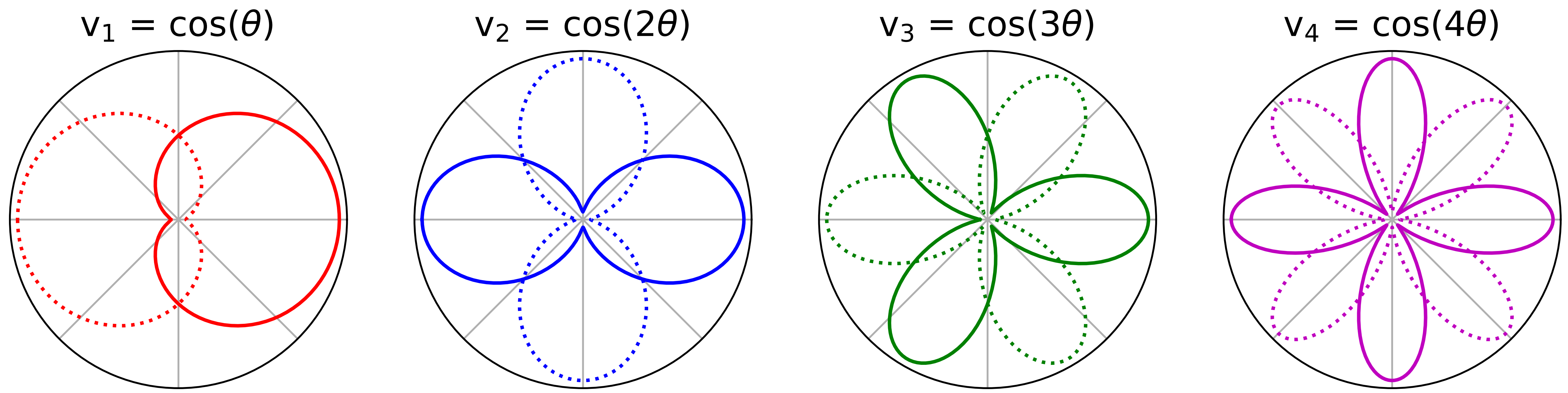
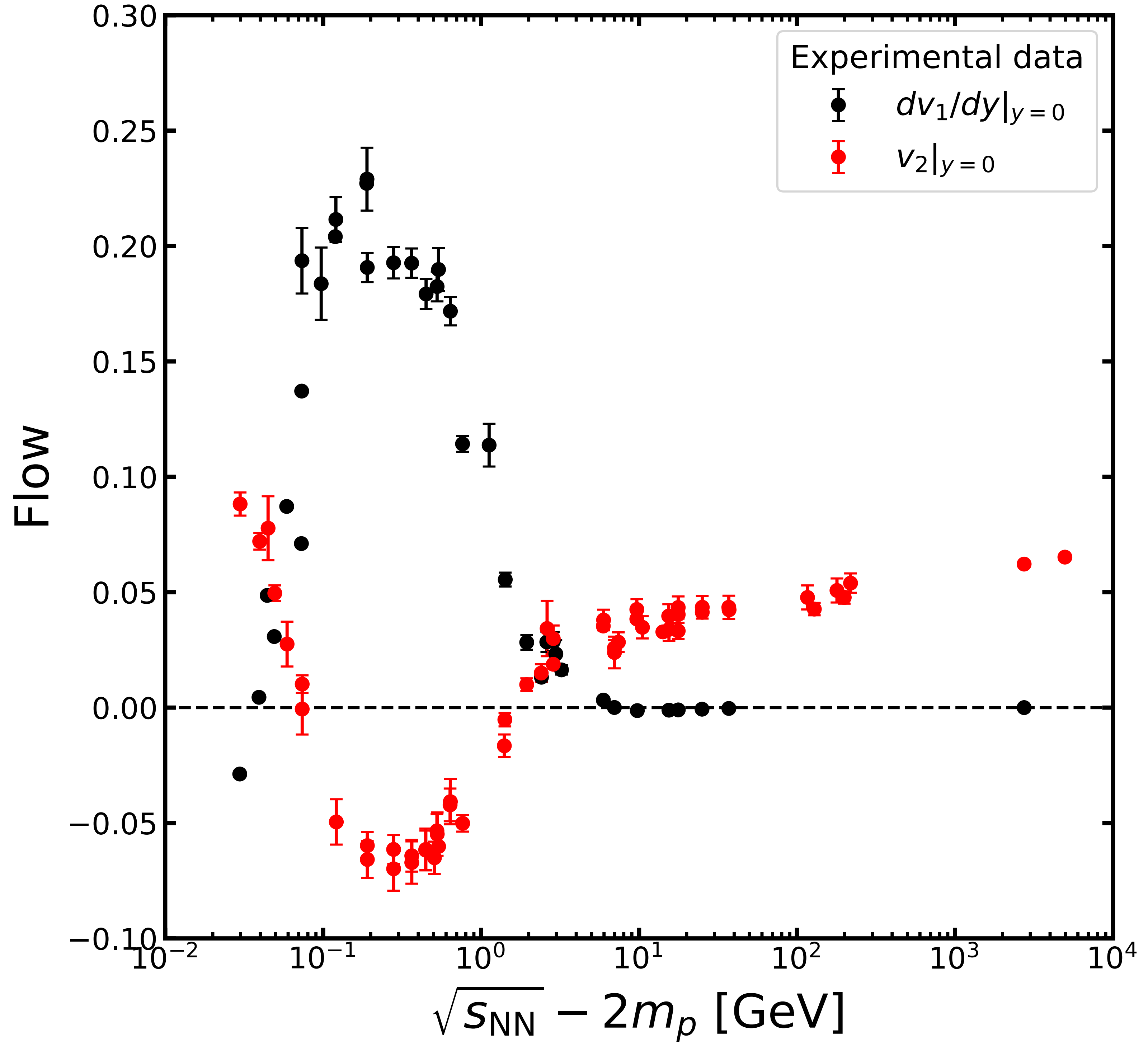
Harmonic flow in a nutshell

- Fourier series of azimuthal angular distribution with some reference angle

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n[\varphi - \Psi]\right)$$

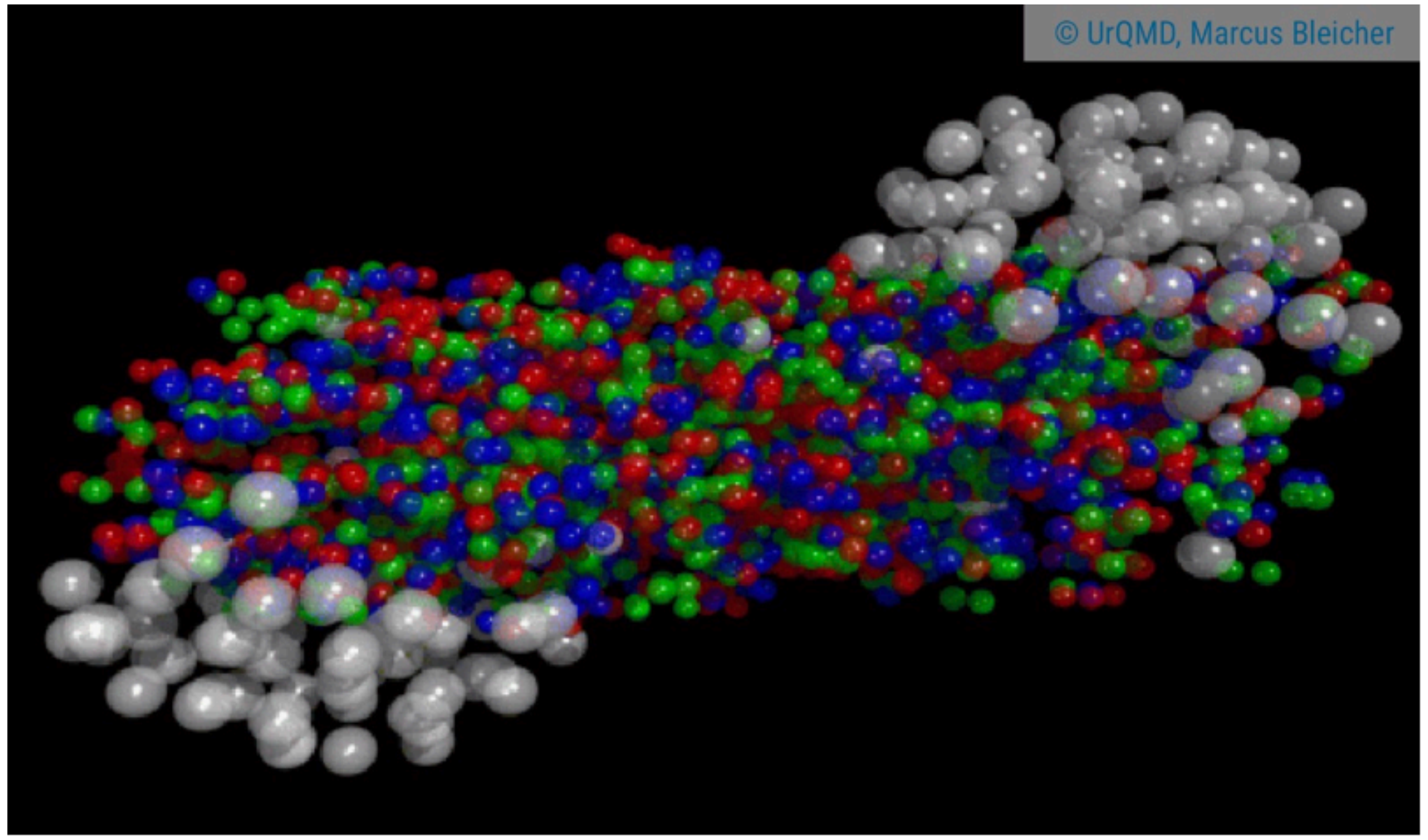
- Low energies: Ψ = (Estimated) reaction plane
- High energies: Ψ = n^{th} order event plane
- Very similar energy dependence of elliptic flow and slope of directed flow
- Density gradient creates pressure encoding EoS, thus anisotropy measures EoS





UrQMD in a nutshell

- Ultra-relativistic Quantum Molecular Dynamics (v4.0)
- QMD: Solve Schrödinger equation for nuclei represented as product state of nucleons with Gaussian wave functions. Centroids of nucleons (only) then propagate on classical trajectories
- Covariant propagation
- 150 Hadron species, including high mass resonances
- String excitation and fragmentation
- Cross sections taken from data or effective models, geometric interpretation
- QMD has potentials in Hamiltonian way (not a mean field)

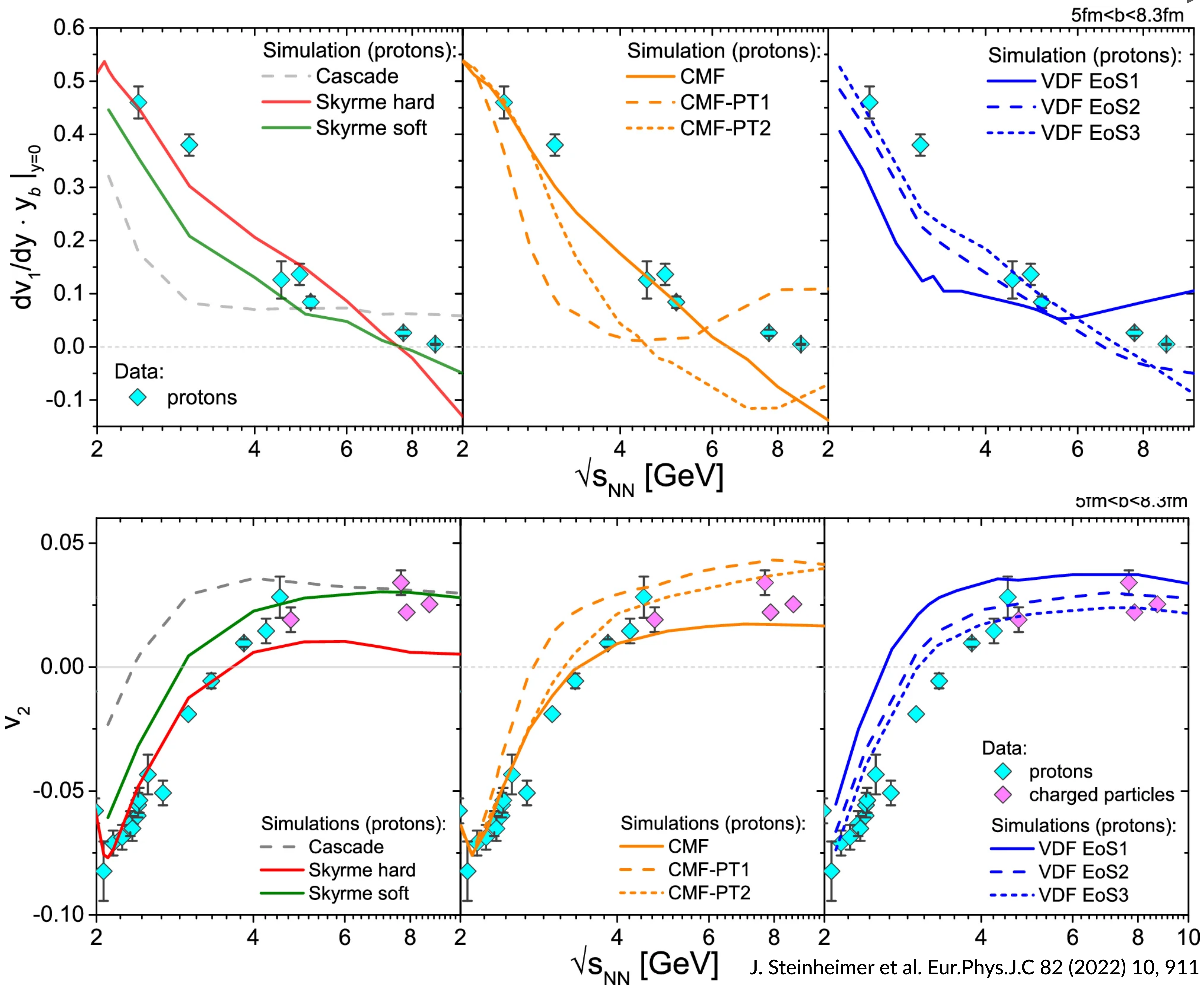


$$\dot{\mathbf{r}}_i = \frac{\partial \langle \hat{H} \rangle}{\partial \mathbf{p}_i} \qquad \dot{\mathbf{p}}_i = -\frac{\partial \langle \hat{H} \rangle}{\partial \mathbf{r}_i}$$

$$V(\rho_B, p) = \frac{1}{\rho_B} \int_0^{\rho_B} \mathrm{d}\rho'_B \, U(\rho'_B, p) \Big|_{p=\text{const.}}$$

Overview of flow in UrQMD

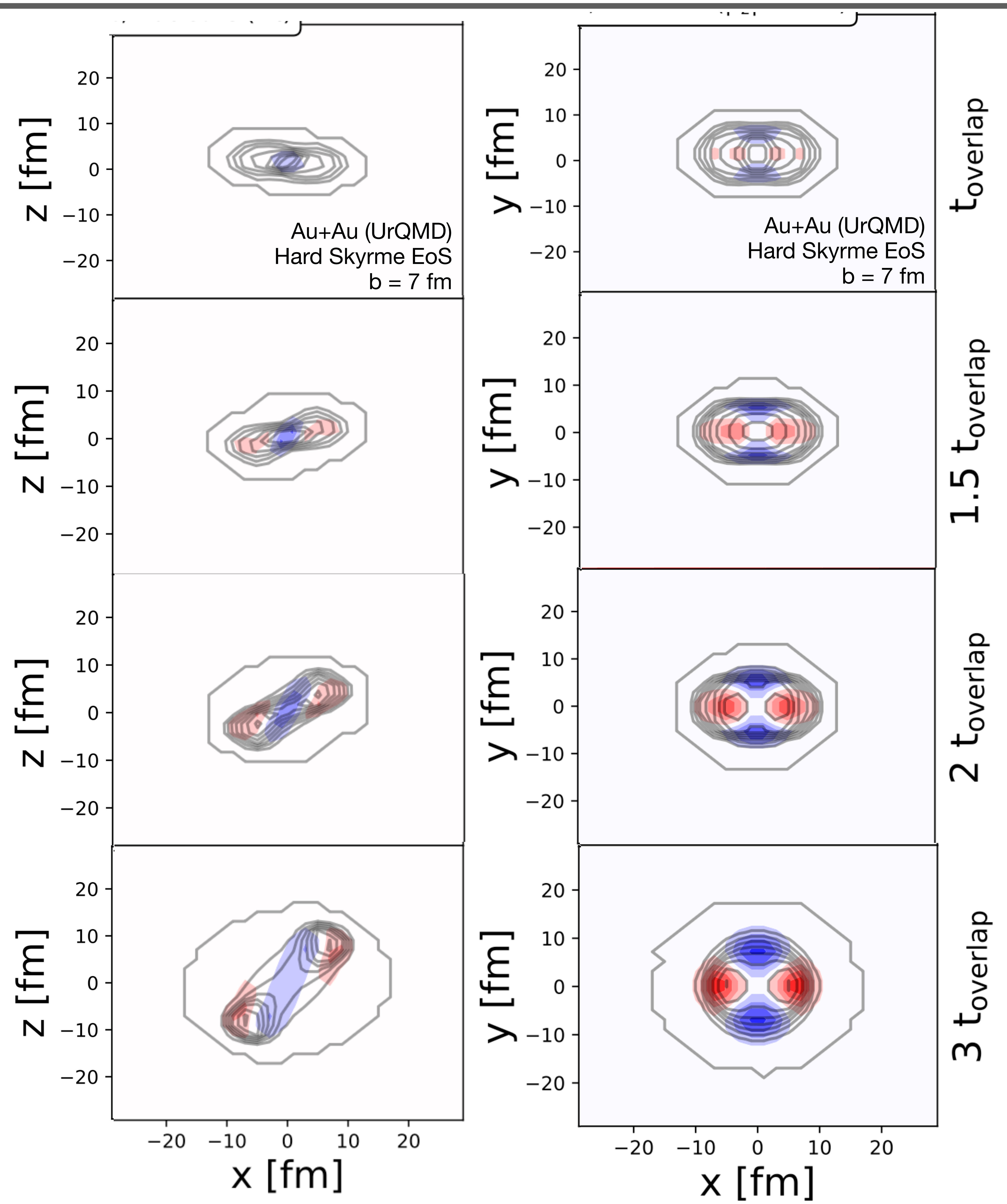
- Directed flow and elliptic flow at HADES is well described when considering cluster production
- Lower energies are better described by hard Skyrme EoS (κ = 380 MeV)
- Higher collision energies favor soft EoS (κ = 210 MeV)
- Phase transition scenarios get v_2 reasonably well, but not dv_1/dy
- Integrated flow coefficient not sufficient to extract EoS parameters, better use differential data



J. Steinheimer et al. Eur.Phys.J.C 82 (2022) 10, 911

Flow evolution: Squeeze-Out or Shadowing?

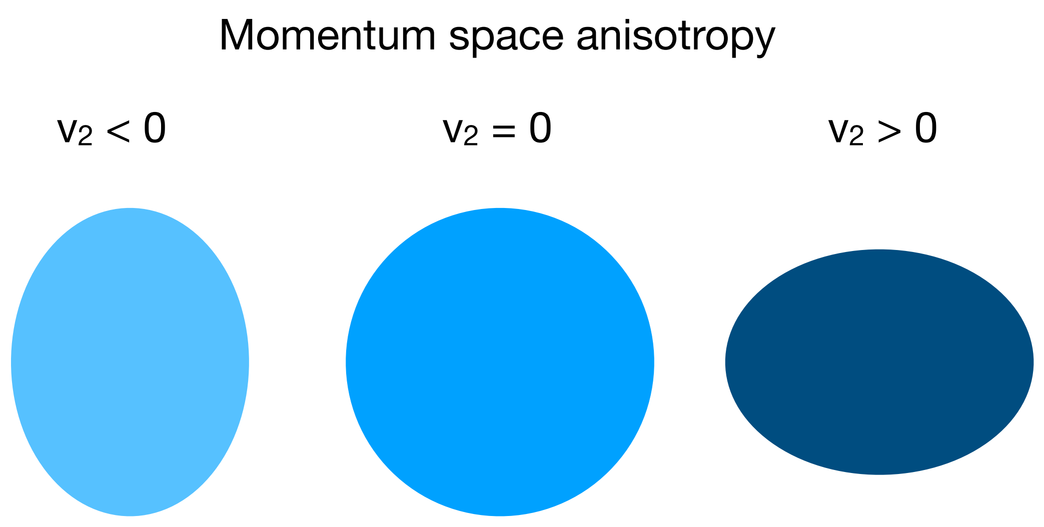
- Shadowing: $\langle p_x \rangle > \langle p_y \rangle$ then p_x absorption
- Squeeze-out: $\langle p_y \rangle > \langle p_x \rangle$
- Important to understand how EoS creates v_2 and how to interpret data-theory comparison
- Reality (UrQMD) more intricate than expected
- Initial squeeze-out of not-yet stopped nucleons
- Followed by strong in-plane pressure being absorbed by the spectator
- Matter bridge forms forming the final v_2
- Potential de-/accelerates baryons in/out of midrapidity until decoupling



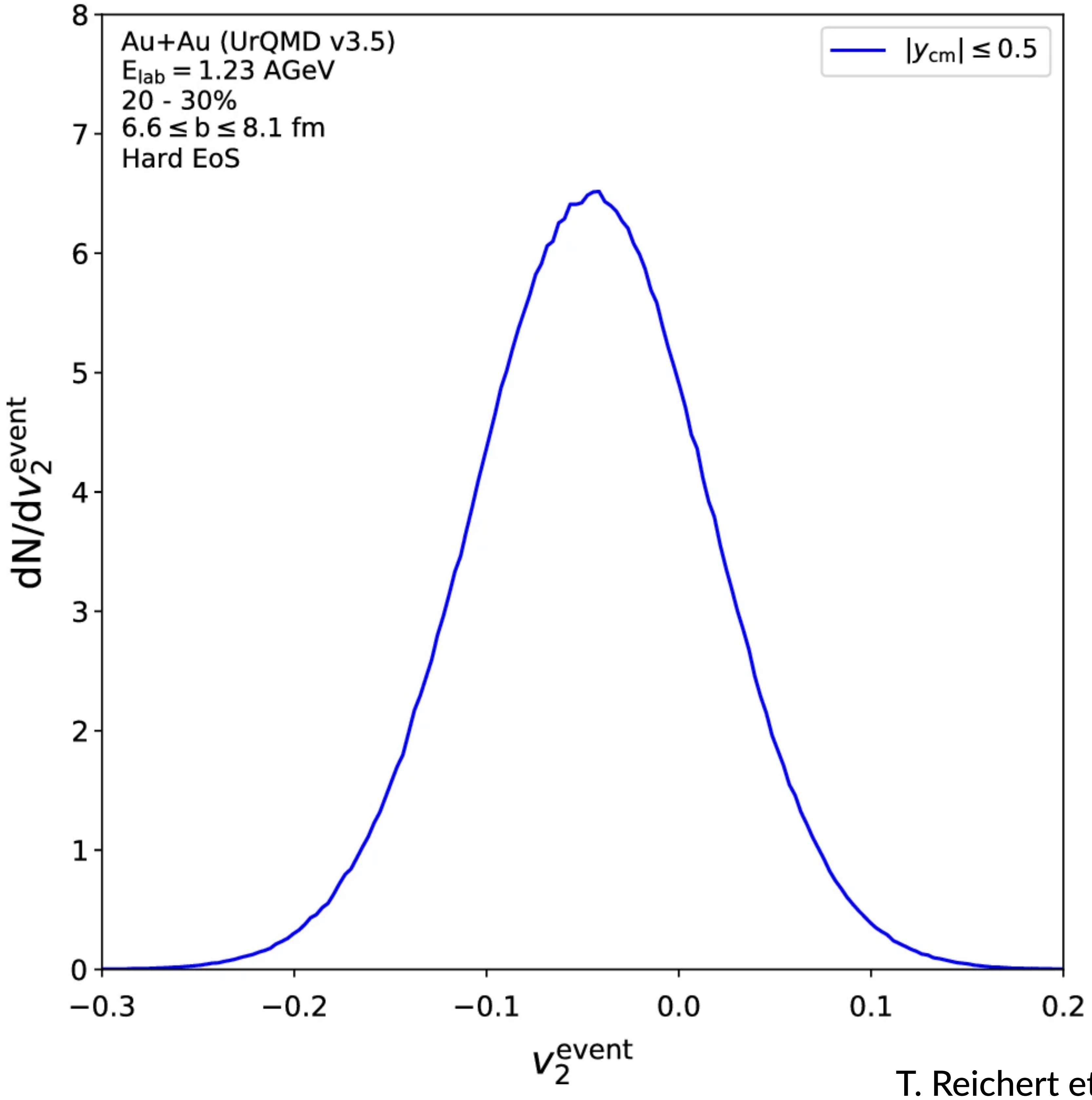
T. Reichert et al. Phys.Rev.C 111 (2025) 5, 054916

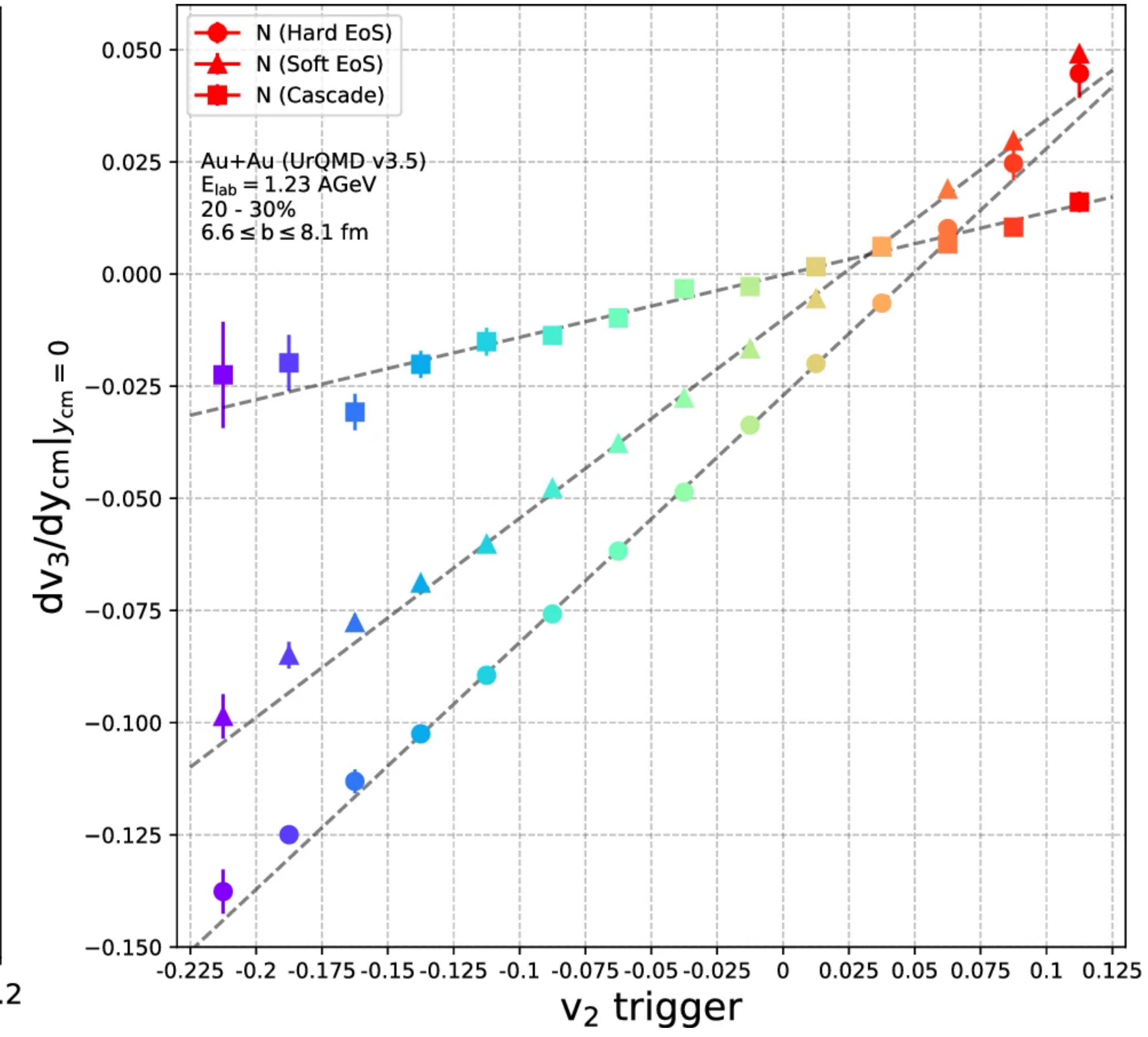
Flow fluctuations and correlations

- Elliptic flow strongly fluctuates on an event-by-event basis
- Define event classes based on final momentum space ellipticity
- Correlations with flow harmonics show up as direct dependence on the $v_2^{trigger}$
- Pronounced sensitivity of the correlations to employed EoS
- Under investigation at HADES



$$\frac{dv_3}{dy} \propto \frac{dv_1}{dy} \cdot v_2 \Rightarrow v_3 \propto v_2 \cdot v_1$$

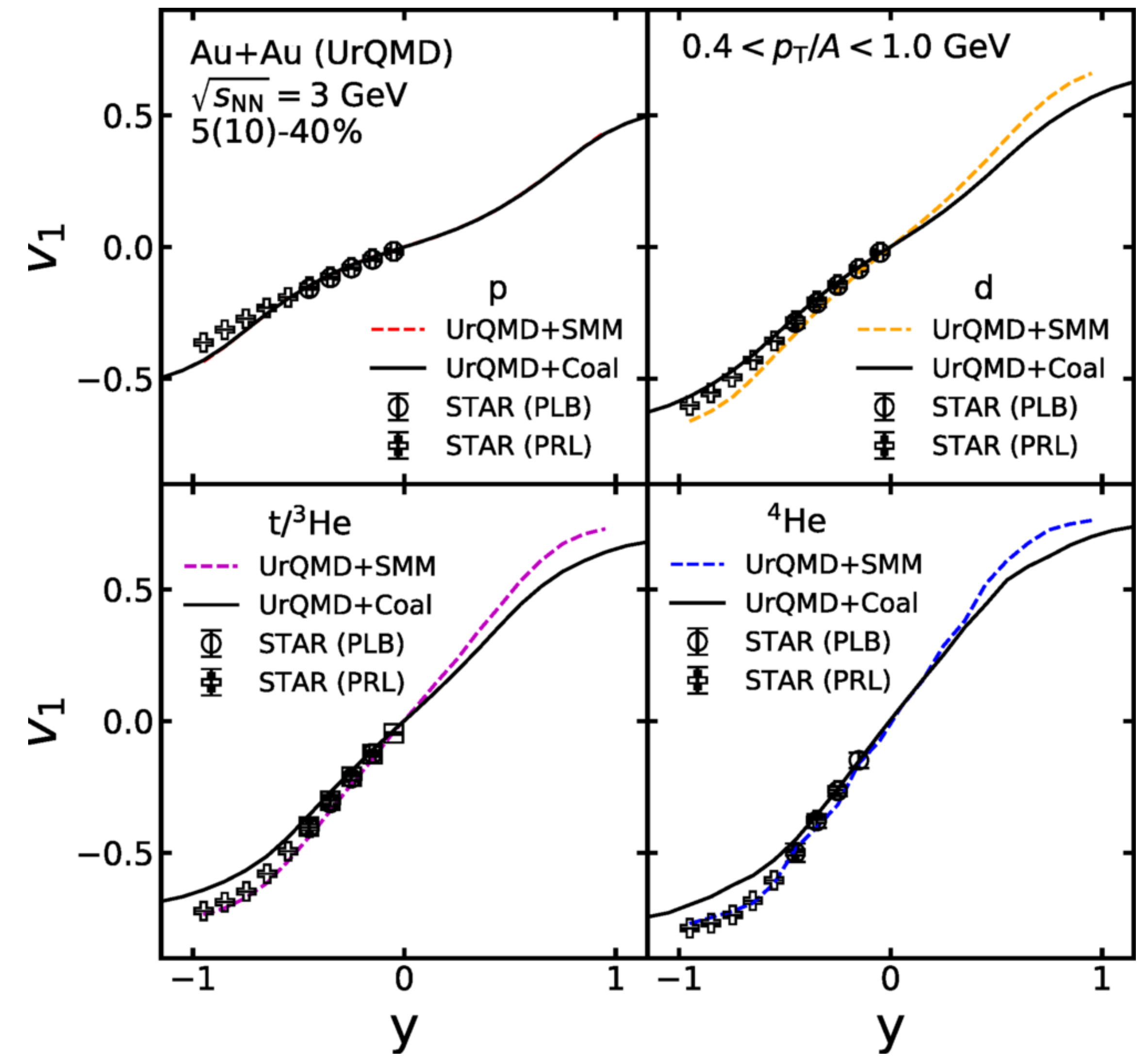


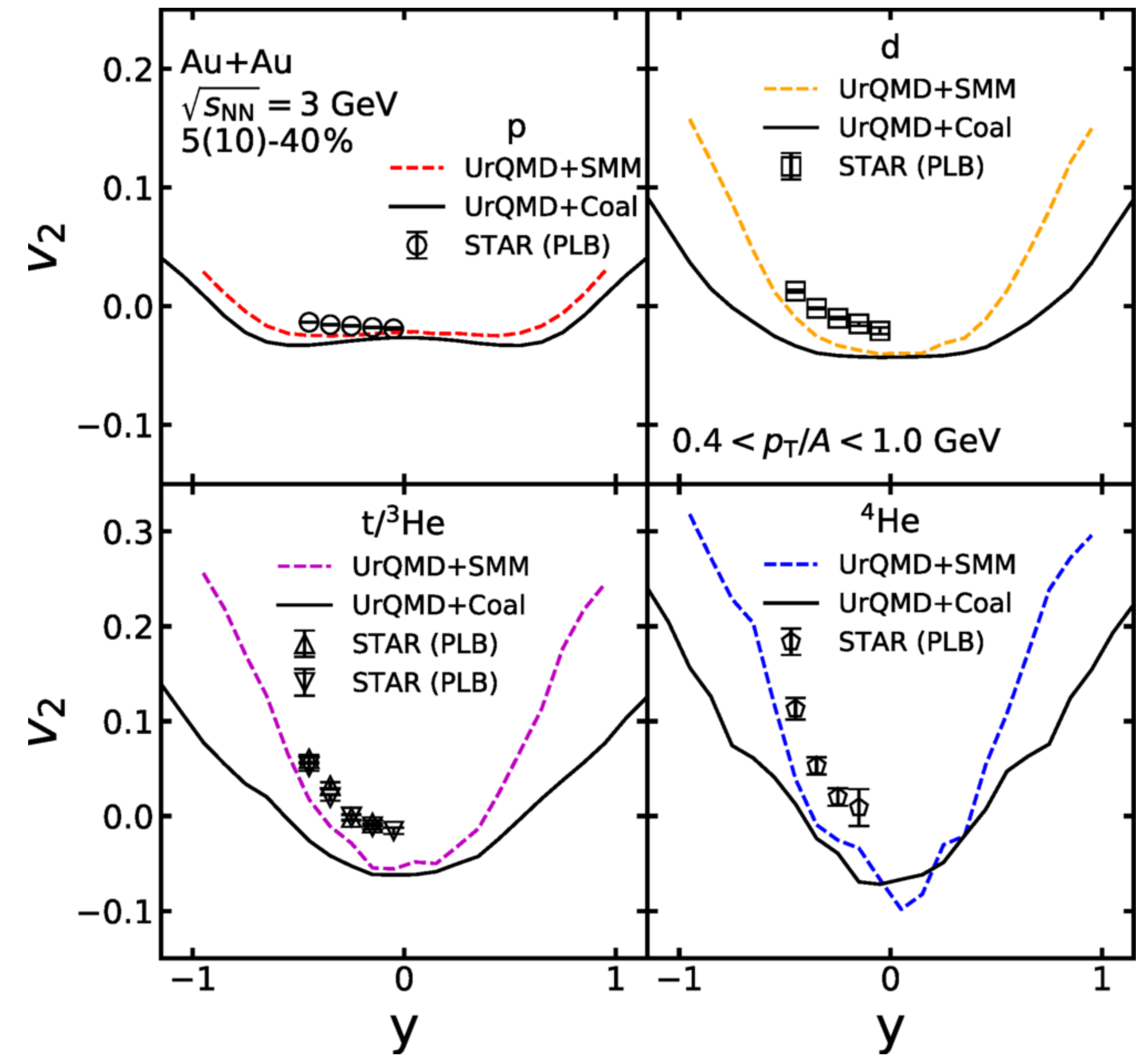


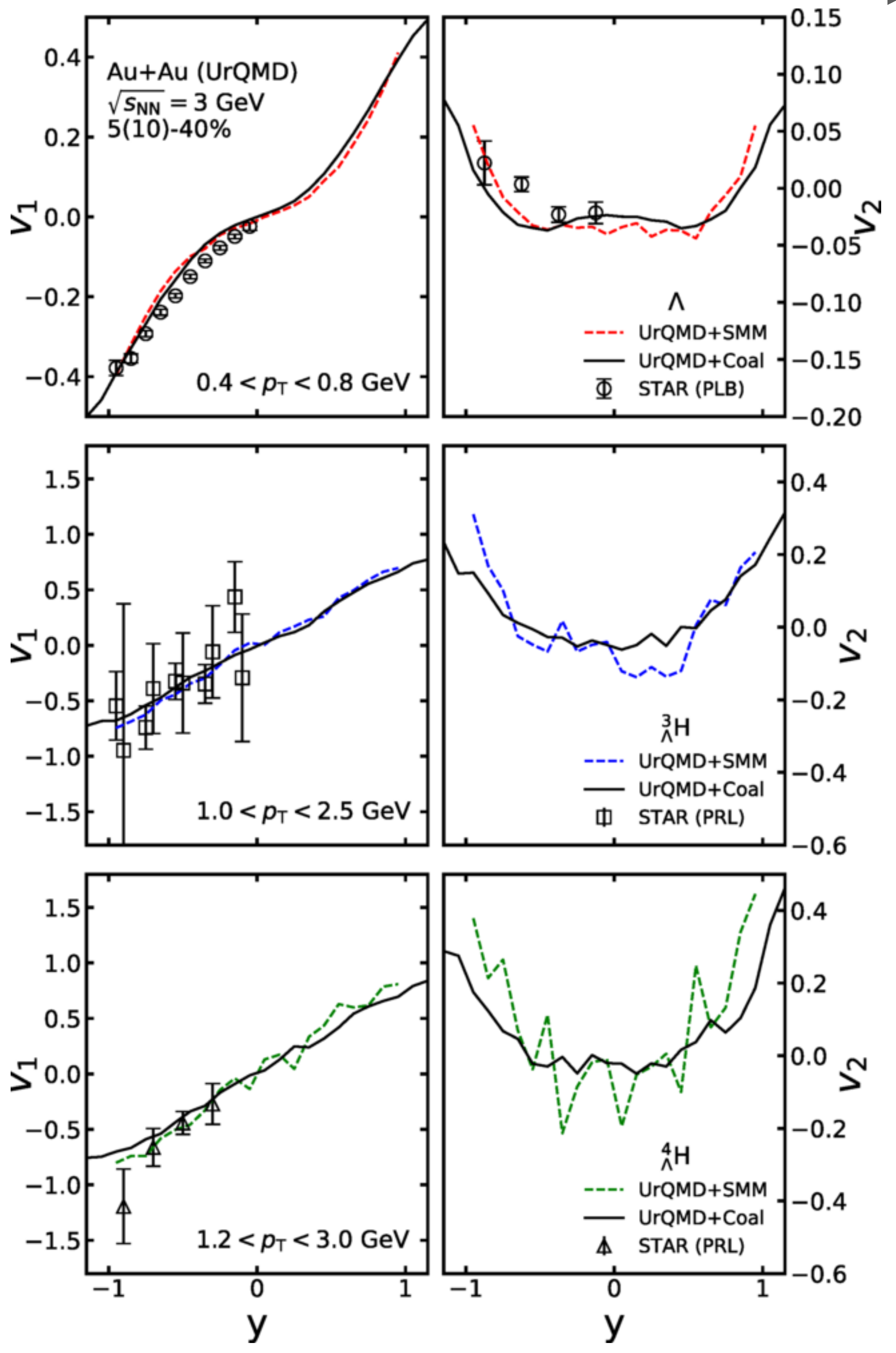
T. Reichert et al. Eur.Phys.J.C 82 (2022) 6, 510

Flow of light nuclei and hypernuclei

- Production either with coalescence or statistical multi-fragmentation model
- Directed flow of p, d, t, ^{3}He, ^{4}He well described
- Elliptic flow of p, d, t, ^{3}He, ^{4}He favors SMM approach
- Λ v_1 and v_2 well described (using more precisely measured NΛ cross section by CLAS)
- Hypernuclei v_1 fairly well described by both approaches and predicted hypernuclei v_2 for STAR-FXT







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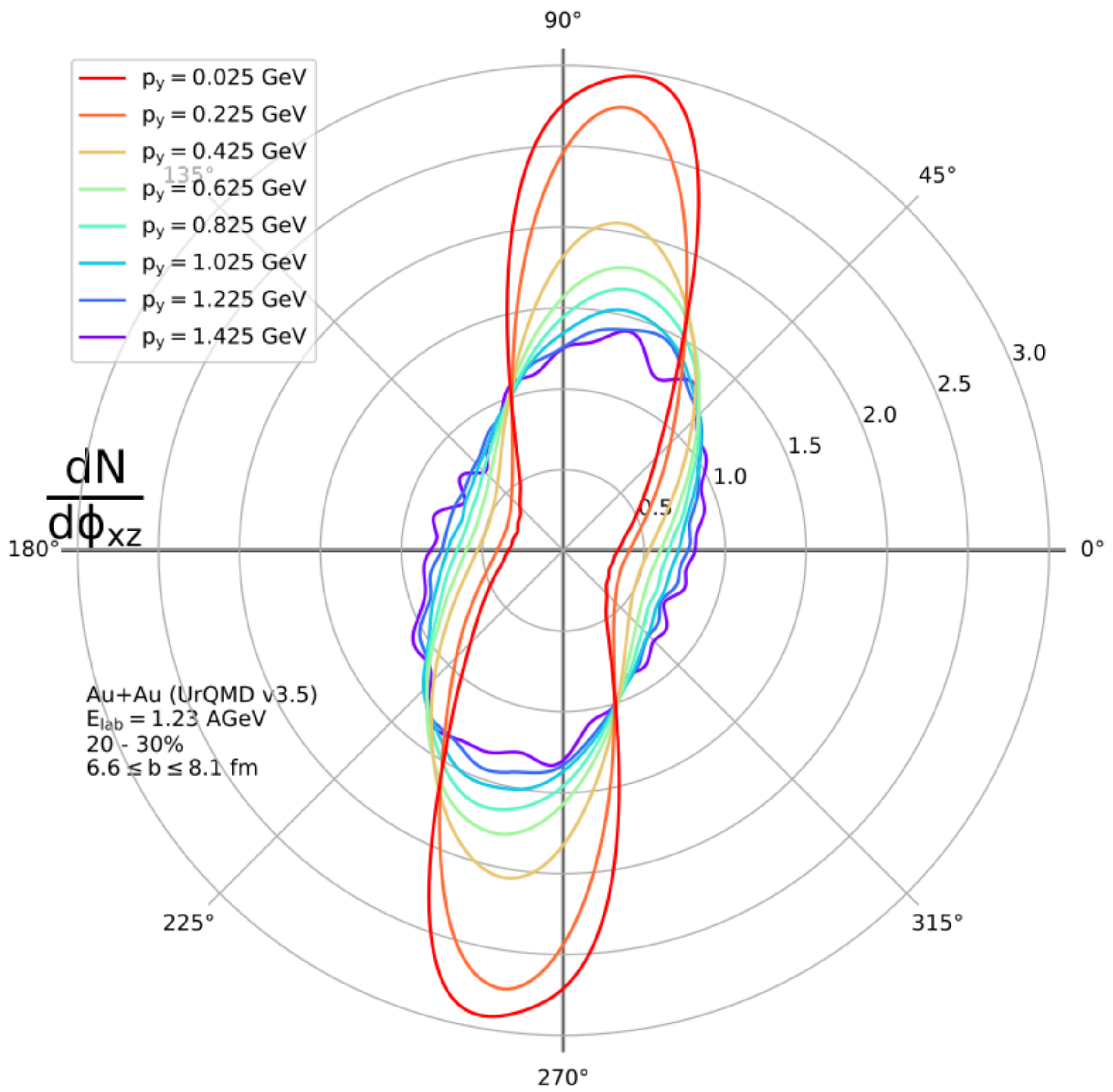
Extending harmonic flow to 3D

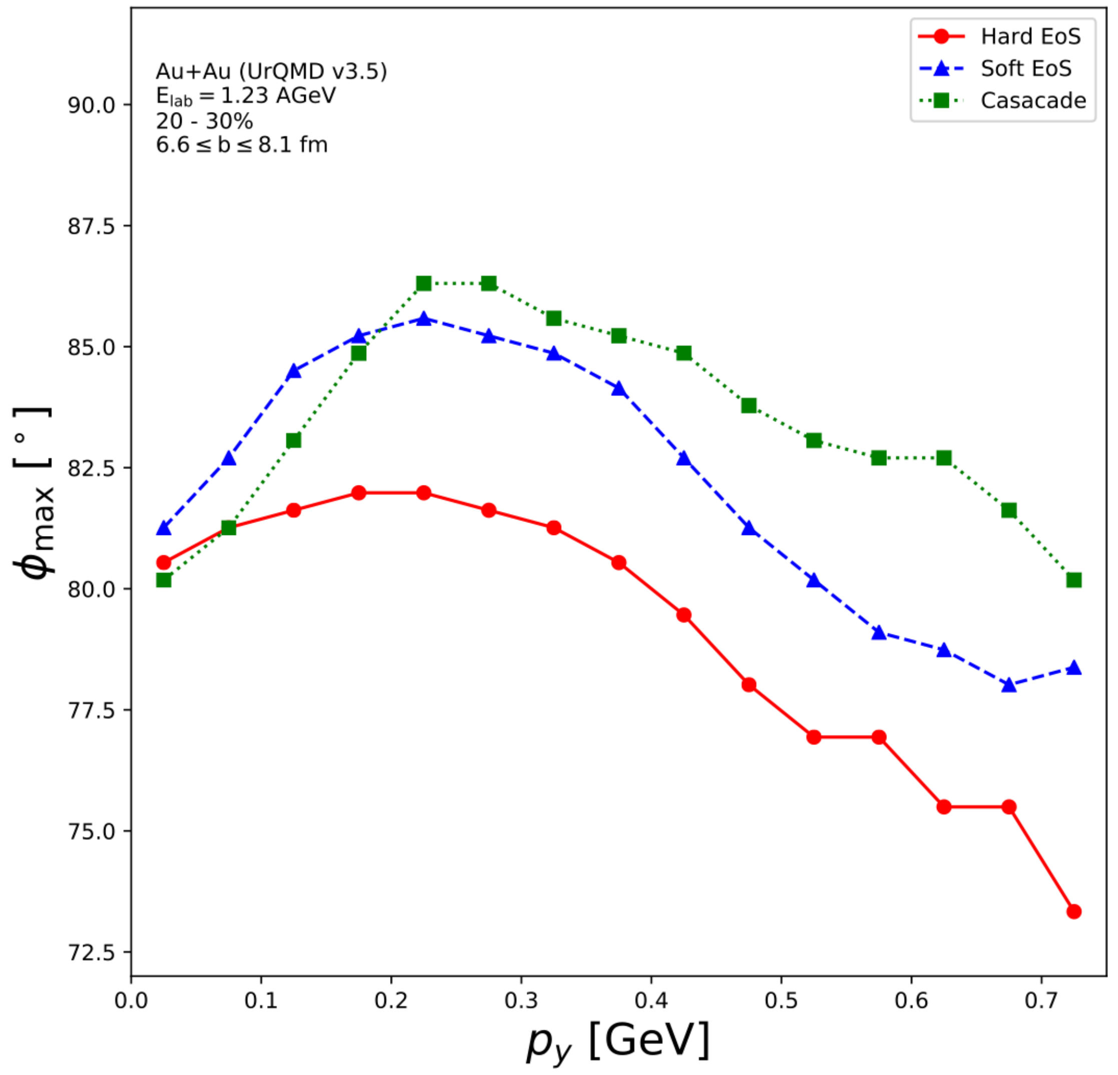
- Harmonic flow is traditionally measured in transverse plane
- Apply technique to x-z and y-z planes

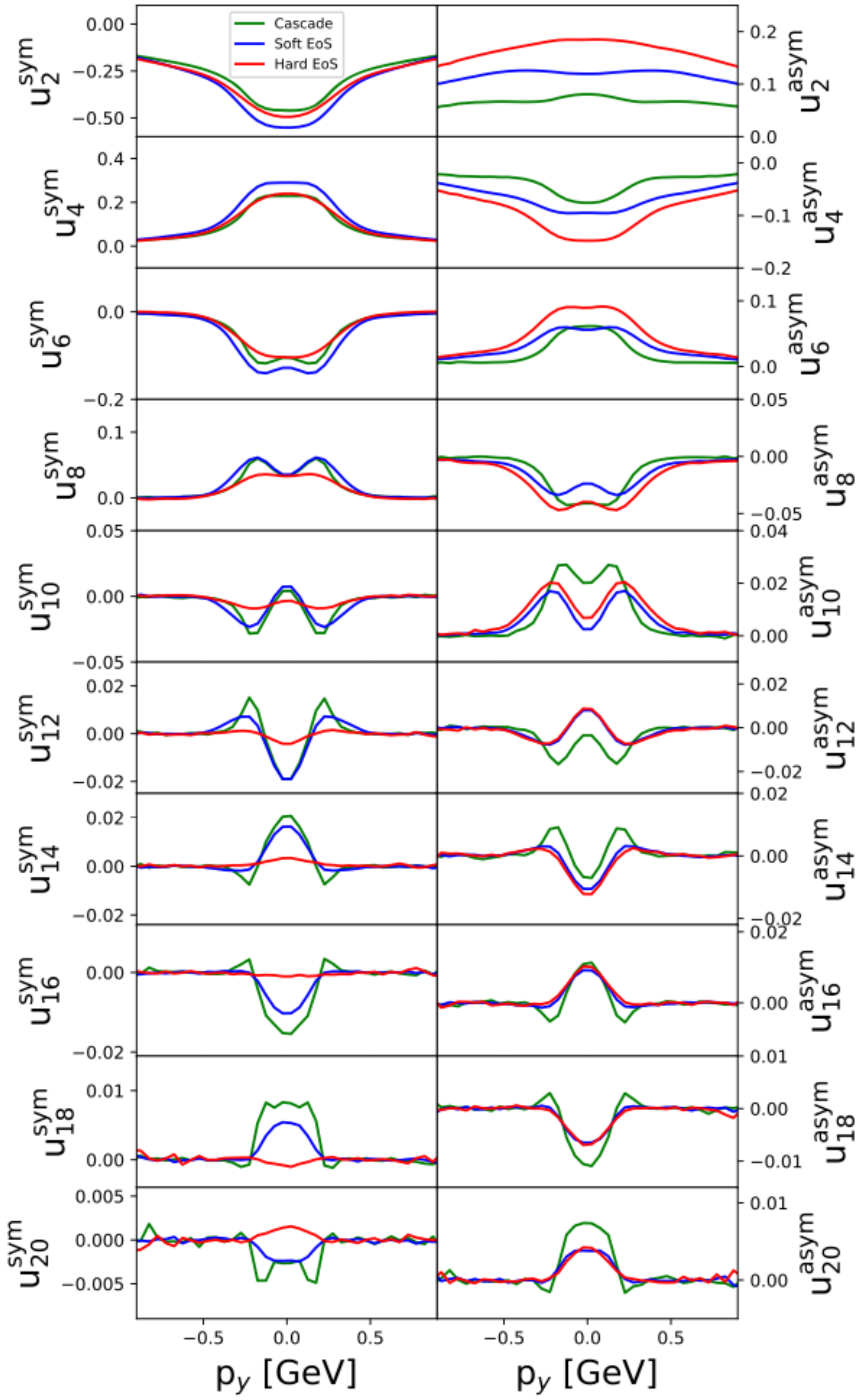
$$\frac{dN}{d\phi_{xz}} = 1 + 2\sum_{n=1}^{\infty} u_n^{\mathrm{sym}} \cos(n(\phi_{xz} - \Psi_{TP})) + u_n^{\mathrm{asym}} \sin(n(\phi_{xz} - \Psi_{TP}))$$

$$\frac{dN}{d\phi_{yz}} = 1 + 2\sum_{n=1}^{\infty} w_n^{\mathrm{sym}} \cos(n(\phi_{yz} - \Psi_{PP})) + w_n^{\mathrm{asym}} \sin(n(\phi_{yz} - \Psi_{PP}))$$

- Difficult to measure, but results complement traditional measurements
- Max. deflection angle depends on EoS



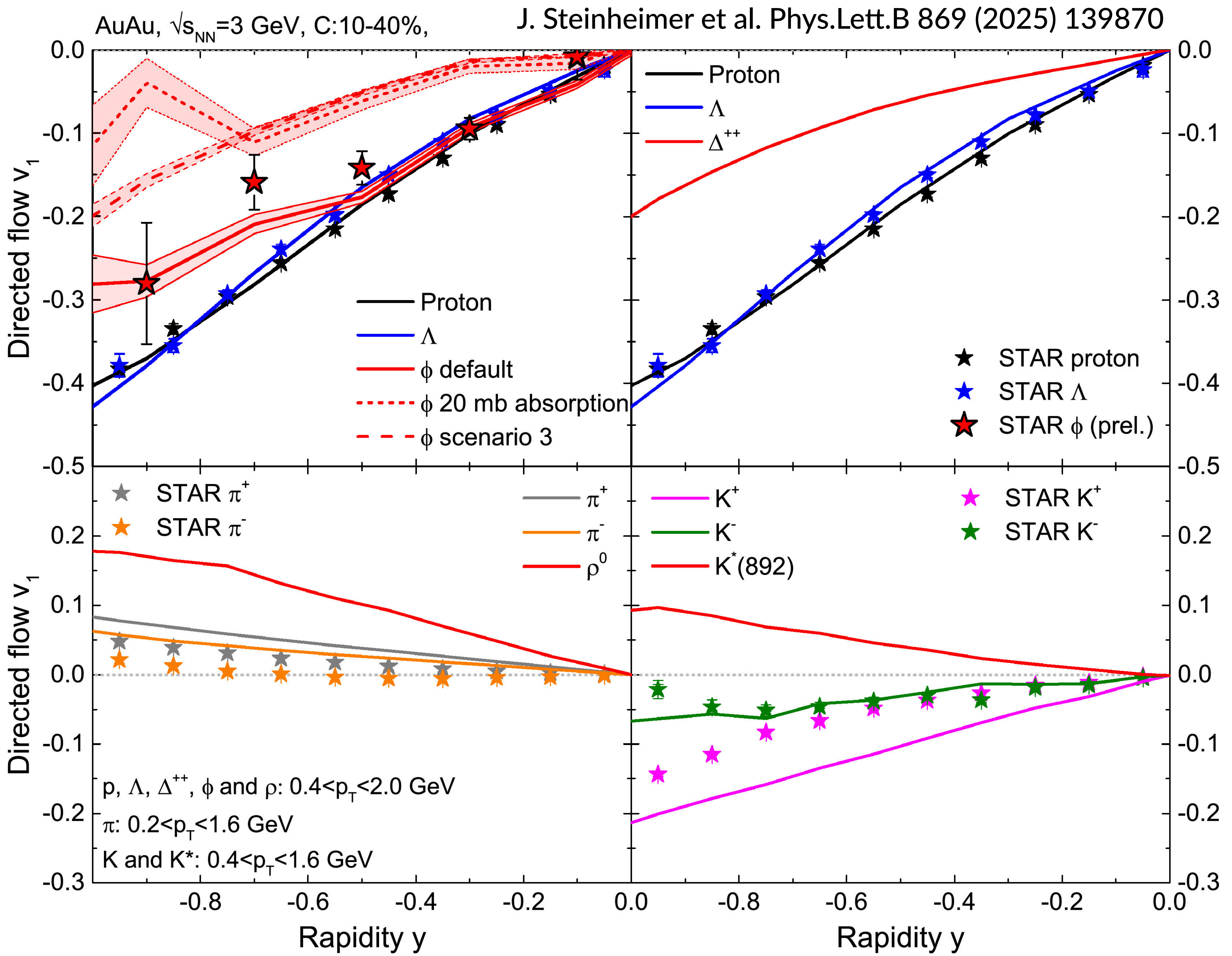




T. Reichert et al. Nucl.Phys.A 1041 (2024) 122790

Flow of resonances: φ vs Δ^{++}, K*, ρ^0

- Preliminary measurements of φ v_1 by STAR indicate large positive slope
- How is the φ produced?
- N*(m > m_p+m_φ) have finite BR for N* —> N + φ decay
- φ thus follows proton flow
- Δ^{++}, K*, ρ^0 decay in the medium, daughter particles need to escape without scattering to render the resonance measureable
- φ is thus prime observable to determine φ+N cross section



Flow of resonances: N*(1650)

- Check a resonance whose decay channels have different absorption probabilities on nuclear matter
- N*(1650) perfect candidate
- πN (50%), KΛ (4%), Γ_0=160 MeV
- All reconstructed N*(1650) and those in the πN channel follow the π flow due to absorption P_{esc}
- Reconstructable N*(1650) in KΛ are between the proton flow and pion flow due to less absorption of the Kaon and Lambda
- Tool to constrain in-medium cross sections

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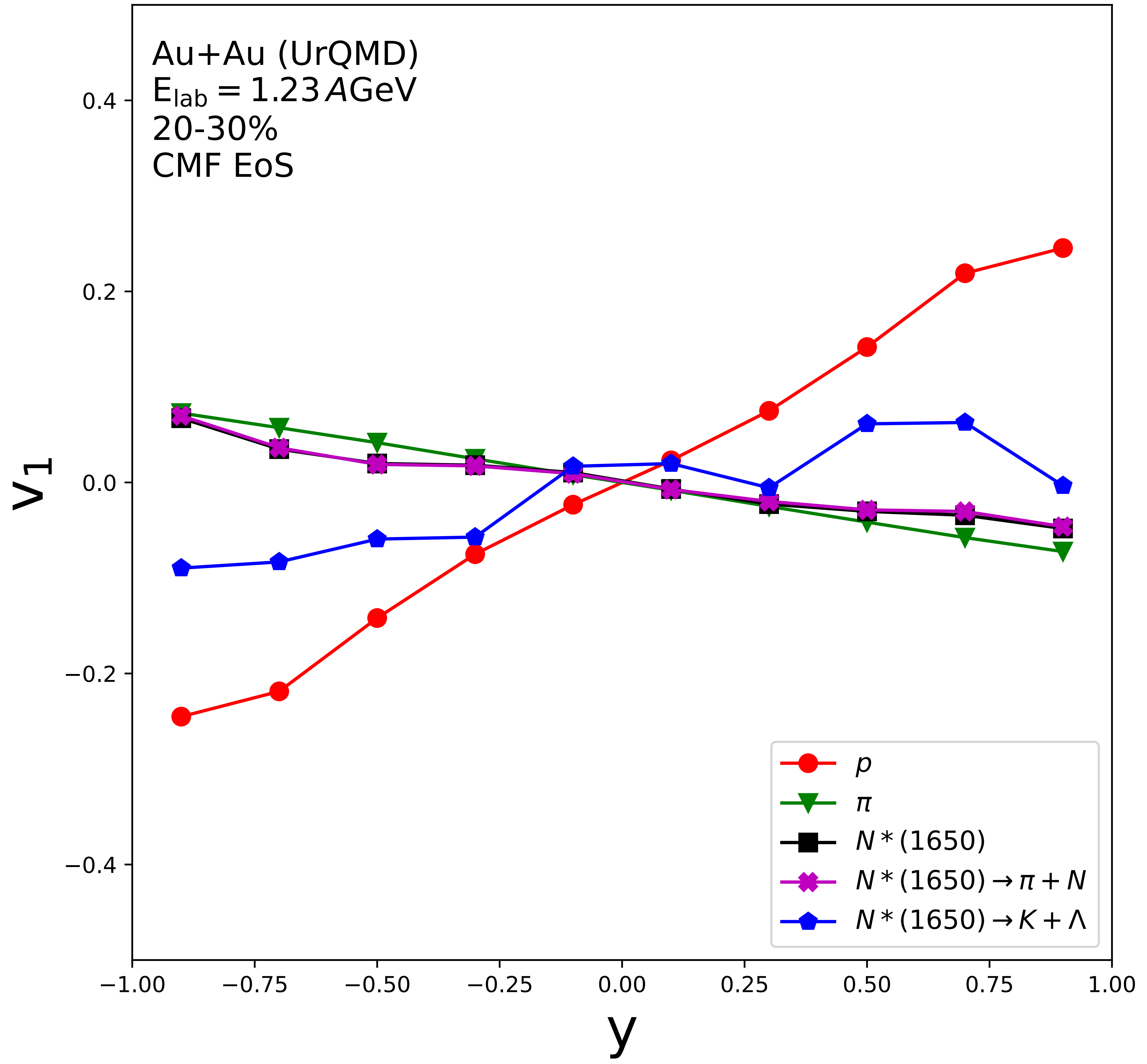


Constituent quark number scaling

- Assume quark coalescence picture for hadron formation at low - moderate p_T

- Then azimuthal distribution of hadrons is given by product of partons' azimuthal distribution

$$F_M(\phi) = f^2(\phi)$$

$$F_B(\phi) = f^3(\phi)$$

- Inserting Fourier series & rearranging terms yields

$$V_2^M = \frac{1}{N}\left[2v_2 + 2v_2v_4 + 2v_4v_6 + \dots\right]$$

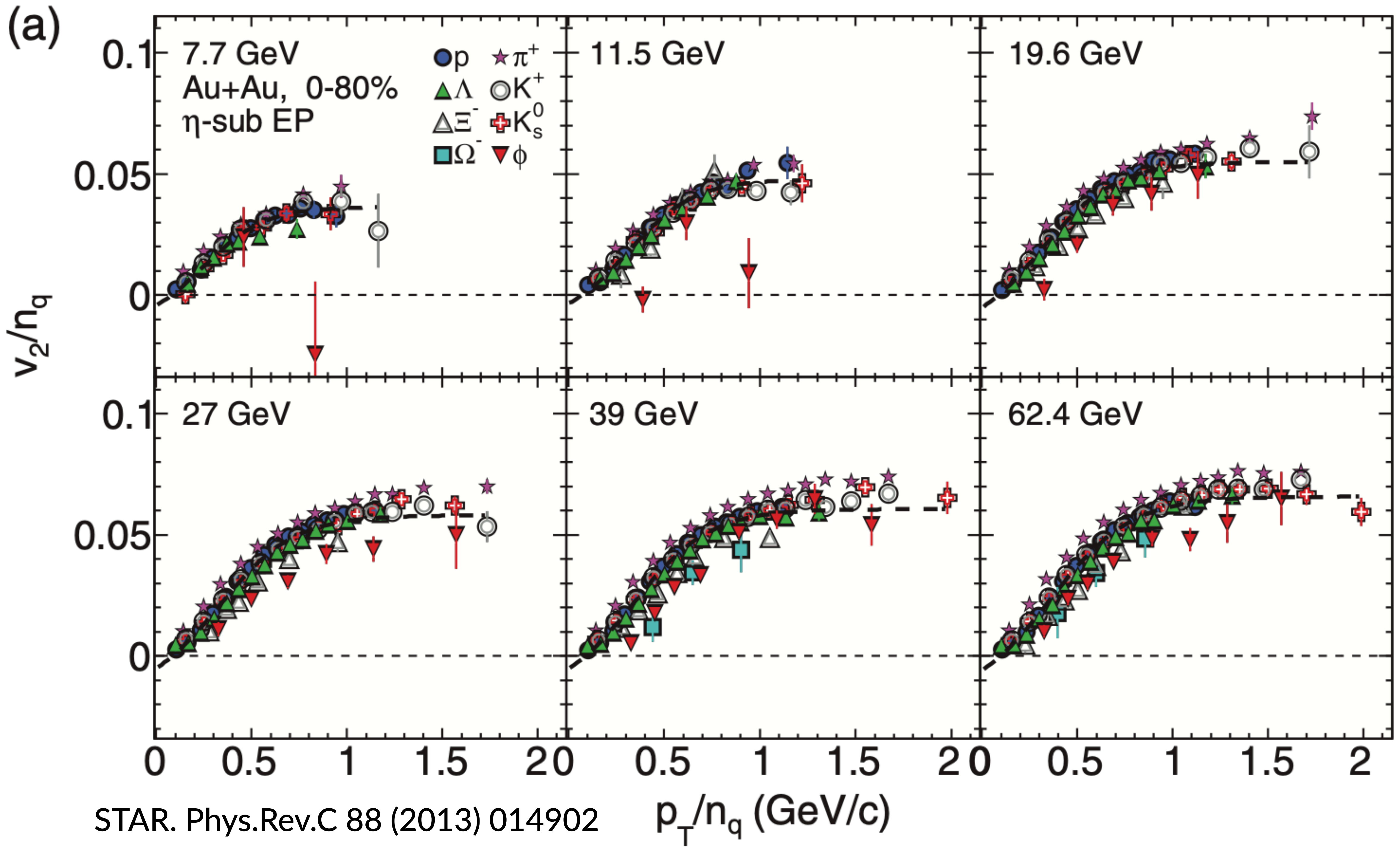
$$V_2^B = \frac{1}{N}\left[3v_2 + 6v_2v_4 + 6v_4v_6 + 3v_2^3 + \dots\right]$$

P. Kolb et al. Phys.Rev.C 69 (2004) 051901
D. Molnar et al. Phys.Rev.Lett. 91 (2003) 092301
C. Nonaka et al. Phys.Lett.B 583 (2004) 73-78

- In leading order this yields the commonly applied scaling relations

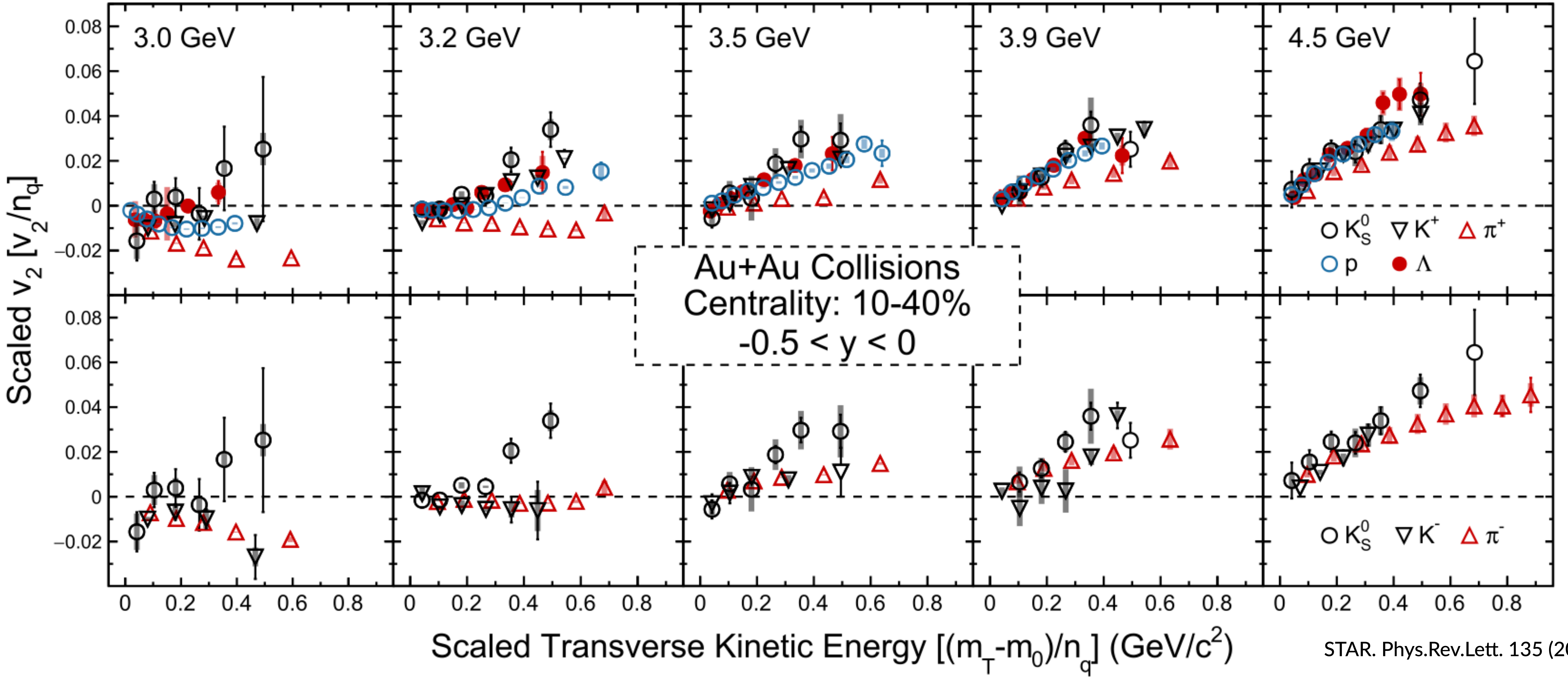
$$V_2^M(p_T) = 2v_2(p_T/2)$$

$$V_2^B(p_T) = 3v_2(p_T/3)$$



STAR. Phys.Rev.C 88 (2013) 014902

Breaking of constituent quark number scaling



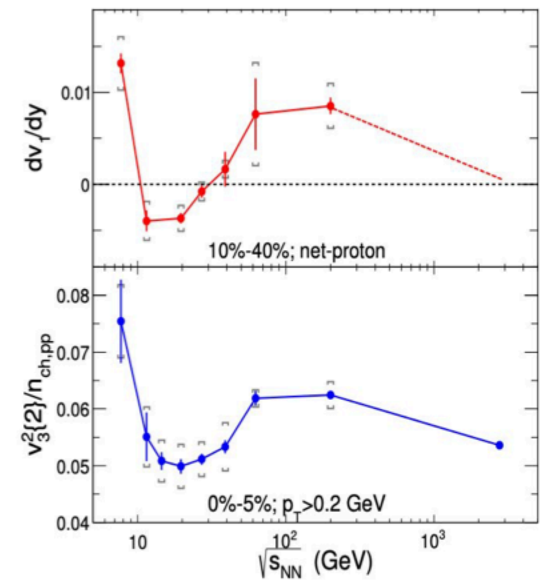
STAR. Phys.Rev.Lett. 135 (2025) 7, 072301

- „Onset of Constituent Quark Number Scaling in Heavy-Ion Collisions at RHIC“
- But this regime is dominated by shadowing. How does a quark coalescing source look shadowed?

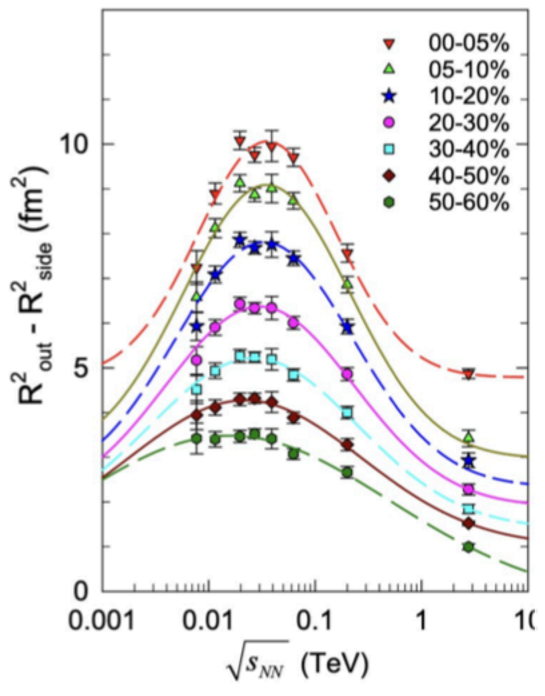
Breaking of constituent quark number scaling

Holes and bumps at ~20 GeV

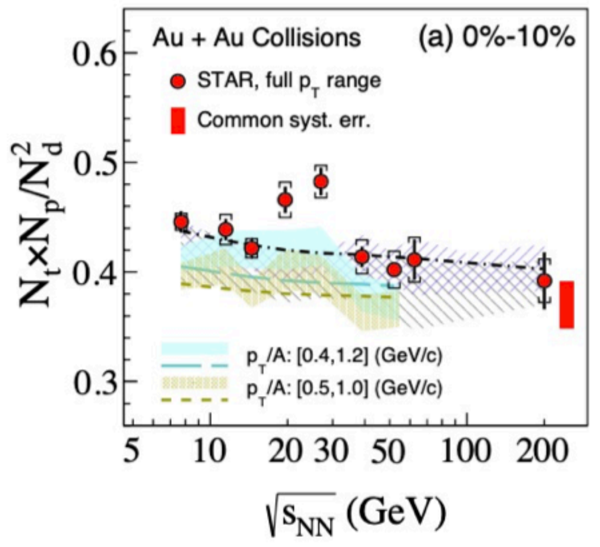
- Flow $\frac{dv_1}{dy}, \frac{v_3^2}{n_{ch}}$ show minimum



- HBT shows maximum



- Clusters $\frac{tp}{d^2p}$ show peak



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Slide taken from V. Koch and V. Skokov's summary talk of INT-25-3a

- NCQ scaling breaks in the same region, where all peaks, bumps and dips seem to gather

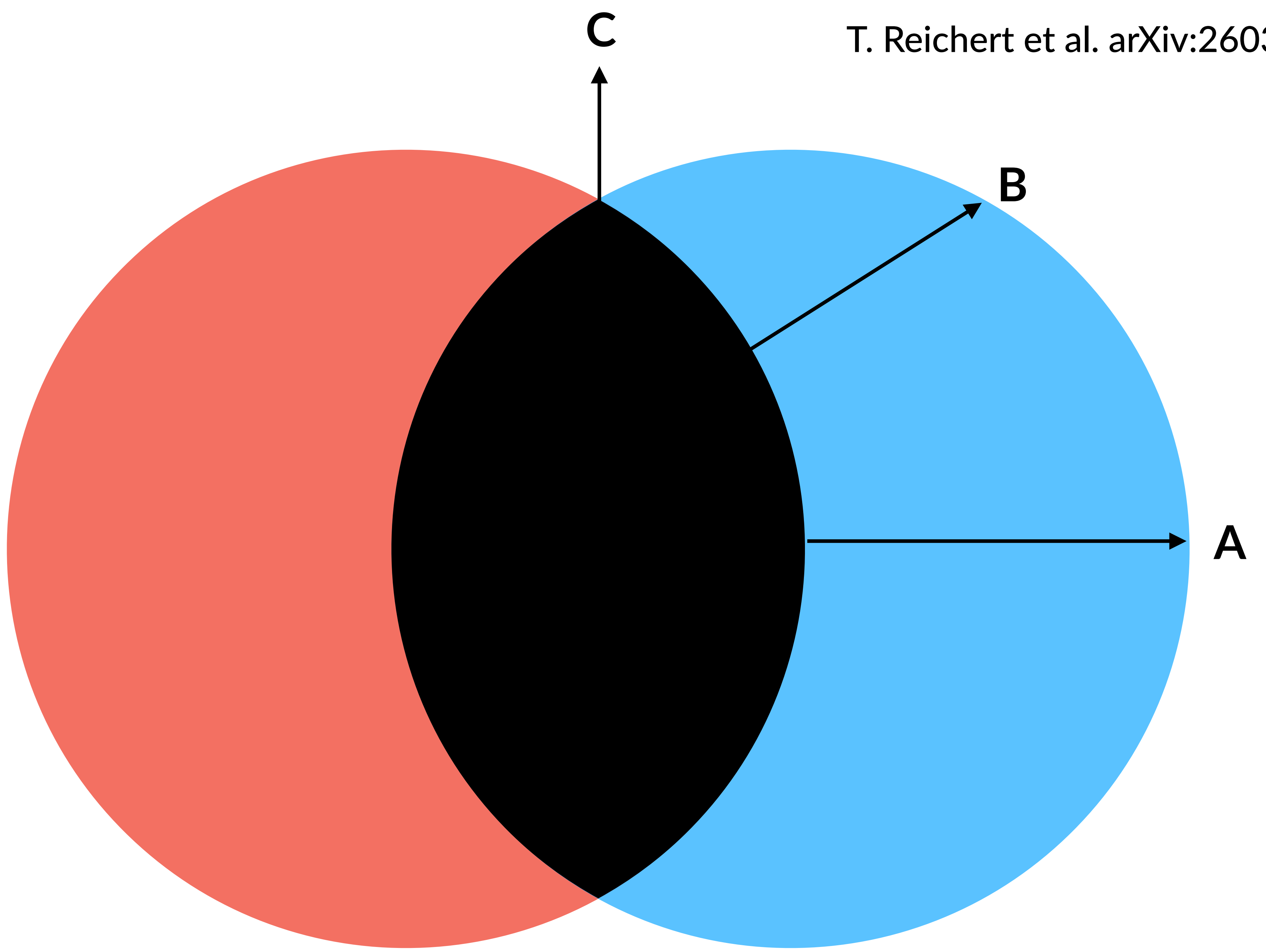
Shadowing: Transverse escape probability

T. Reichert et al. arXiv:2603.02927

- Hadrons have different escape probabilities in transverse plane
- Strong absorption through the spectator
- Free expansion out of plane
- Escape probability given by optical depth / opaqueness have defined angular dependence

$$P_{\mathrm{esc}}(\phi) = S(t_0)\,\exp\left(-\int_{t_0}^{\infty} \mathrm{d}t'\, R(t', r', \phi')\right)$$

$$R(t, r, \phi) = \sigma_{h+N}(\sqrt{s})\,|\,v_{\mathrm{rel}}\,|\,\rho(t, r, \phi)$$



- Write escape probability as Fourier series

$$P_{\mathrm{esc}}(\phi) \propto 1 + 2\sum_{n=1}^{\infty} p_n \cos\left(n[\phi - \Psi]\right)$$

Quark coalescence in the shadowing regime

- Assume source emitting hadrons formed by quark coalescence that is surrounded by a spectator remnant

- The measureable hadron spectrum is then not

$$F_M(\phi) = f^2(\phi)$$

$$F_B(\phi) = f^3(\phi)$$

- But it becomes

$$\mathscr{F}_M(\phi) = f^2(\phi) P_{\rm esc}(\phi)$$

$$\mathscr{F}_B(\phi) = f^3(\phi) P_{\rm esc}(\phi)$$

T. Reichert et al. arXiv:2603.02927

- Where the quark distribution can be written as Fourier series

$$f(\phi) \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n[\phi - \Psi])$$

- But so can the escape probability

$$P_{\rm esc}(\phi) \propto 1 + 2 \sum_{n=1}^{\infty} p_n \cos(n[\phi - \Psi])$$

- Which is species dependent via the cross section and the penetration time through the spectator

Quark coalescence in the shadowing regime

- Multiplying and rearranging terms recovers the known result if no shadowing is present (p_n = 0)
- In addition there is a plethora of new cross terms affecting the measureable elliptic flow signal
- In leading order, the measured elliptic flow $\mathscr{V}_2$ doesn't scale, but the unshadowed $V_2 = \mathscr{V}_2 - p_2$ one does
- Explains higher order flow without symmetry:

$$\mathscr{V}_3^M(p_T) \propto 2p_1^M v_2 + 2p_2^M v_1$$

- Task to calculate p_n is straight forward for transport modelers

$$\mathcal{V}_2^M = \frac{1}{C_0^M}[2v_2 + v_1^2 + 2v_1v_3 + 2v_2v_4$$
$$+ p_1^M\,(2v_1 + 2v_3 + 4v_1v_2 + 2v_2v_3 + 2v_1v_4 + 2v_3v_4)$$
$$+ p_2^M\,(1 + 2v_4 + 2v_1^2 + 3v_2^2 + 2v_3^2 + 2v_4^2 + 2v_1v_3)$$
$$+ p_3^M\,(2v_1 + 2v_1v_2 + 4v_2v_3 + 2v_1v_4 + 2v_3v_4)$$
$$+ p_4^M\,(2v_2 + v_1^2 + v_3^2 + 2v_1v_3 + 4v_2v_4)]$$

$$\mathscr{V}_2^M(p_T) - p_2^M(p_T) = 2v_2(p_T/2)$$

$$\mathscr{V}_2^B(p_T) - p_2^B(p_T) = 3v_2(p_T/3)$$

T. Reichert et al. arXiv:2603.02927

Toy model: Ballistic Glauber

- Check the idea with a simple toy model
- Take a ballistic Glauber model, i.e. Woods-Saxon like nuclei propagating on straight lines

$$\rho(t,r) = \frac{\gamma\rho_0}{1+\exp\left(\frac{r(t)-R}{\sigma_r}\right)}$$

$$r(t) = \sqrt{\left(x \mp \frac{b}{2}\right)^2 + y^2 + \gamma^2\left(z \pm \frac{R_0}{\gamma} \mp \beta t\right)^2}$$

- Assume perfect quark coalescence with parton v_2

$$v_2^q(p_\mathrm{T}) = v_{2,\max}^2 \tanh\left(p_\mathrm{T}/\Lambda\right)$$

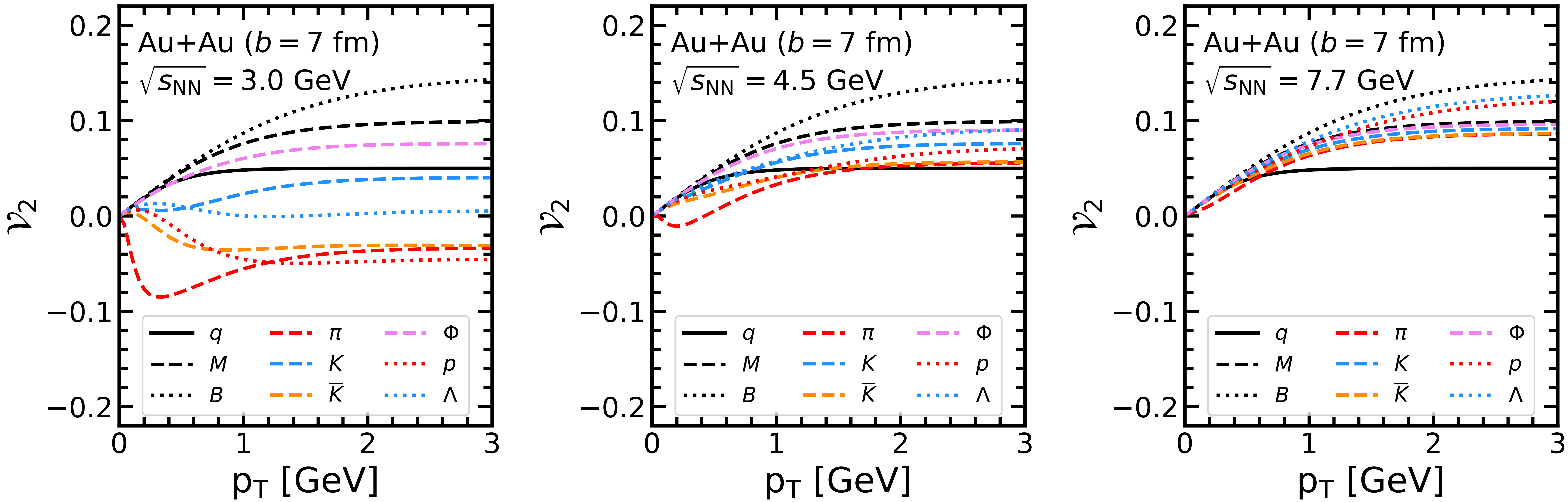
- Assume that all hadrons are emitted at $t = t_\mathrm{overlap}$ with $t_\mathrm{overlap} = R/(\gamma\beta)$ from the origin of the system
- Calculation done at midrapidity y=0 (respectively at the center of the system z=0)
- Calculate absorption integral with time dependent WS density profile and constant cross sections

$$P_\mathrm{esc}(\phi) = \exp\left(-\int_{t_0}^{\infty} \mathrm{d}t'\, R(t',r',\phi')\right)$$

$$R(t,r,\phi) = \sigma_{h+N}(\sqrt{s})\,|\,v_\mathrm{rel}\,|\,\rho(t,r,\phi)$$

V. Vovchenko et al. Phys.Rev.C 90 (2014) 044907
T. Reichert et al. arXiv:2603.02927

Toy model calculations: Measured v_2



- Stronger splitting between different hadron v_2 at lower energy than at high energy
- Stronger deviation for hadrons with larger absorption cross section (pion, anti-Kaon)
- Qualitatively resembles splitting seen at STAR-FXT and HADES

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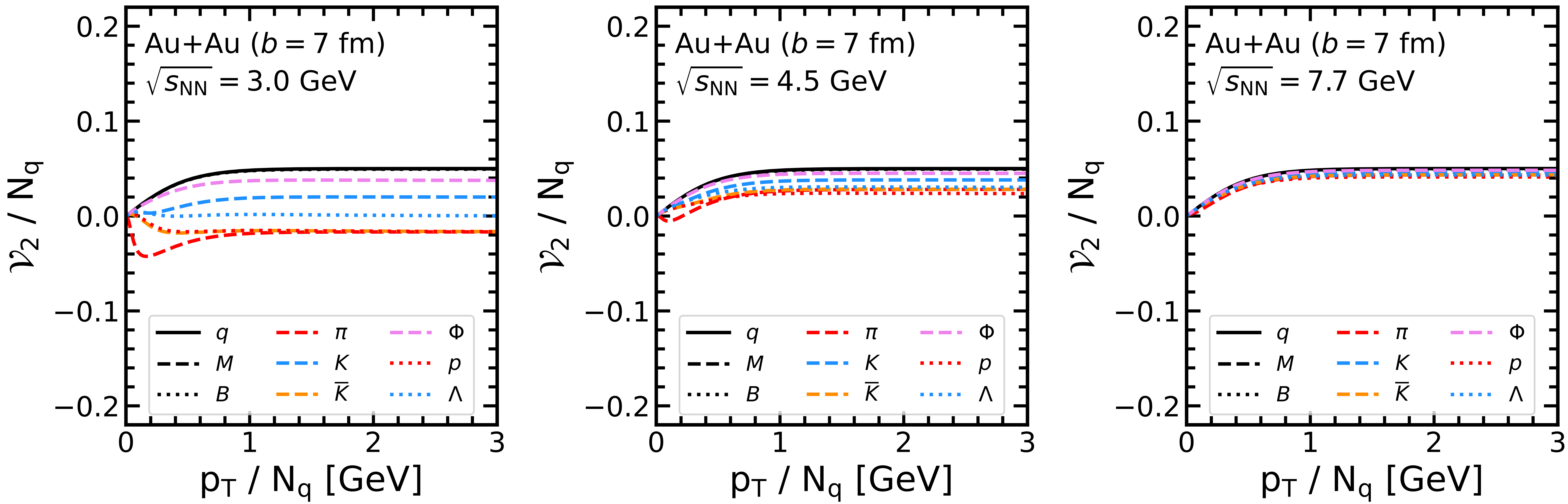
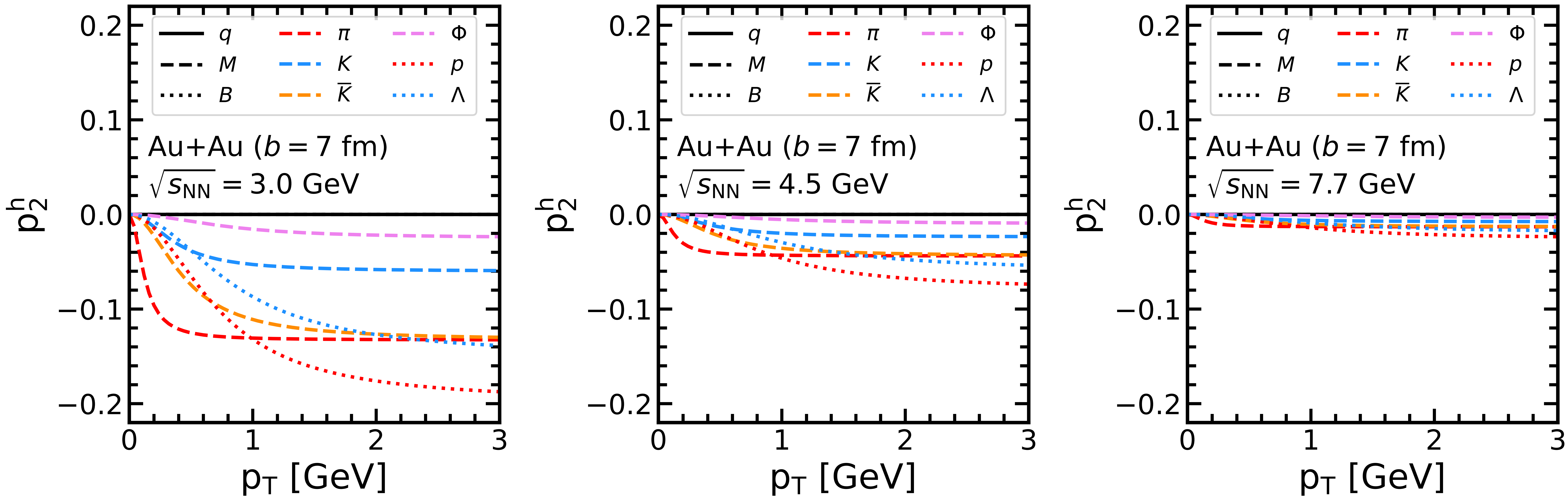
Toy model calculations: NCQ-scaled measured v_2



- Naively trying to scale with NCQ fails at 3 GeV, works at 7.7 GeV
- The hadron emitting source is shadowed and the measured $\mathscr{V}_2$ is distorted
- The ϕ meson best reproduces the ideal curve due to its small absorption cross section

T. Reichert et al. arXiv:2603.02927

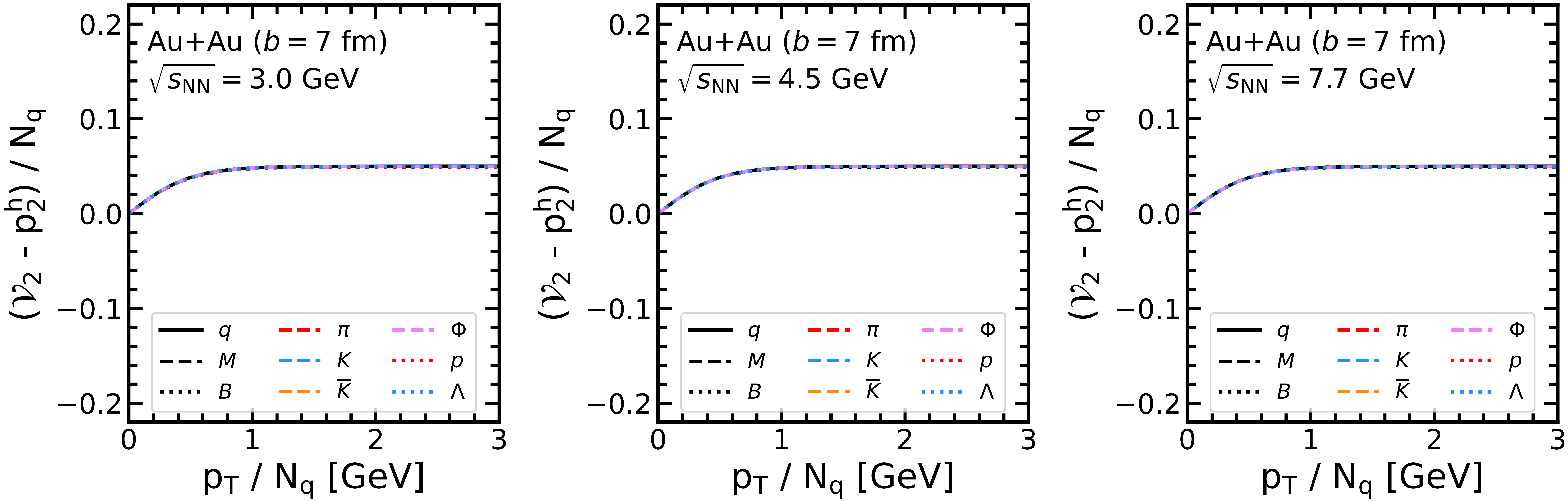
Toy model calculations: Shadowing p_2



- The second order shadowing coefficient decreases strongly with increasing energy (velocity of the spectator)
- The coefficients naturally saturate faster for lighter particles
- Let's apply the correction

T. Reichert et al. arXiv:2603.02927

Toy model calculations: NCQ-scaled unshadowed v_2



- The unshadowed elliptic flow $\mathscr{V}_2 - p_2^h$ scales perfectly with the number of constituent quarks as a function of p_T/N_q
- Can be directly applied to experimental data once p_n are known for each hadron
- Task to calculate p_n is straight forward for transport modelers

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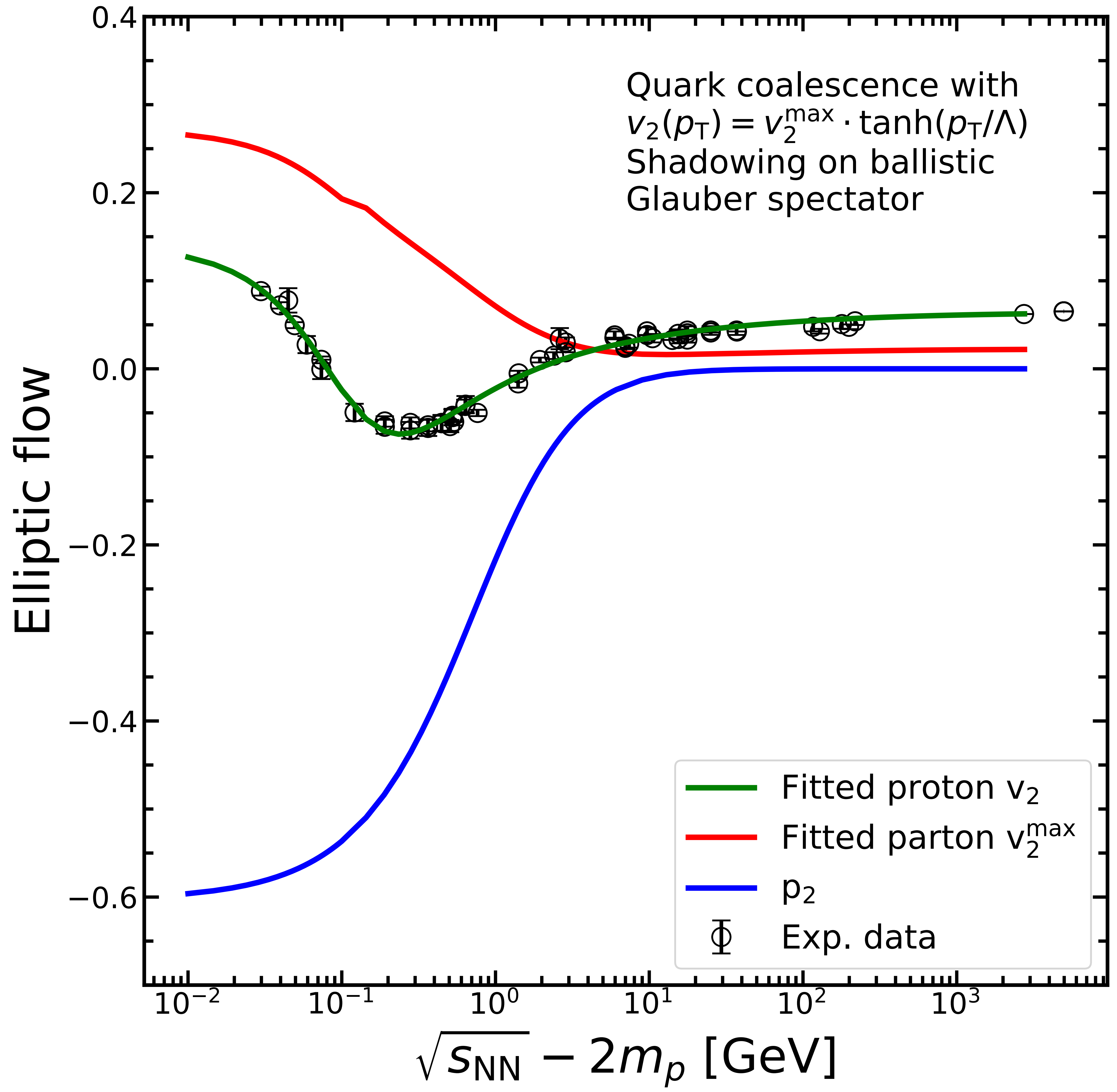
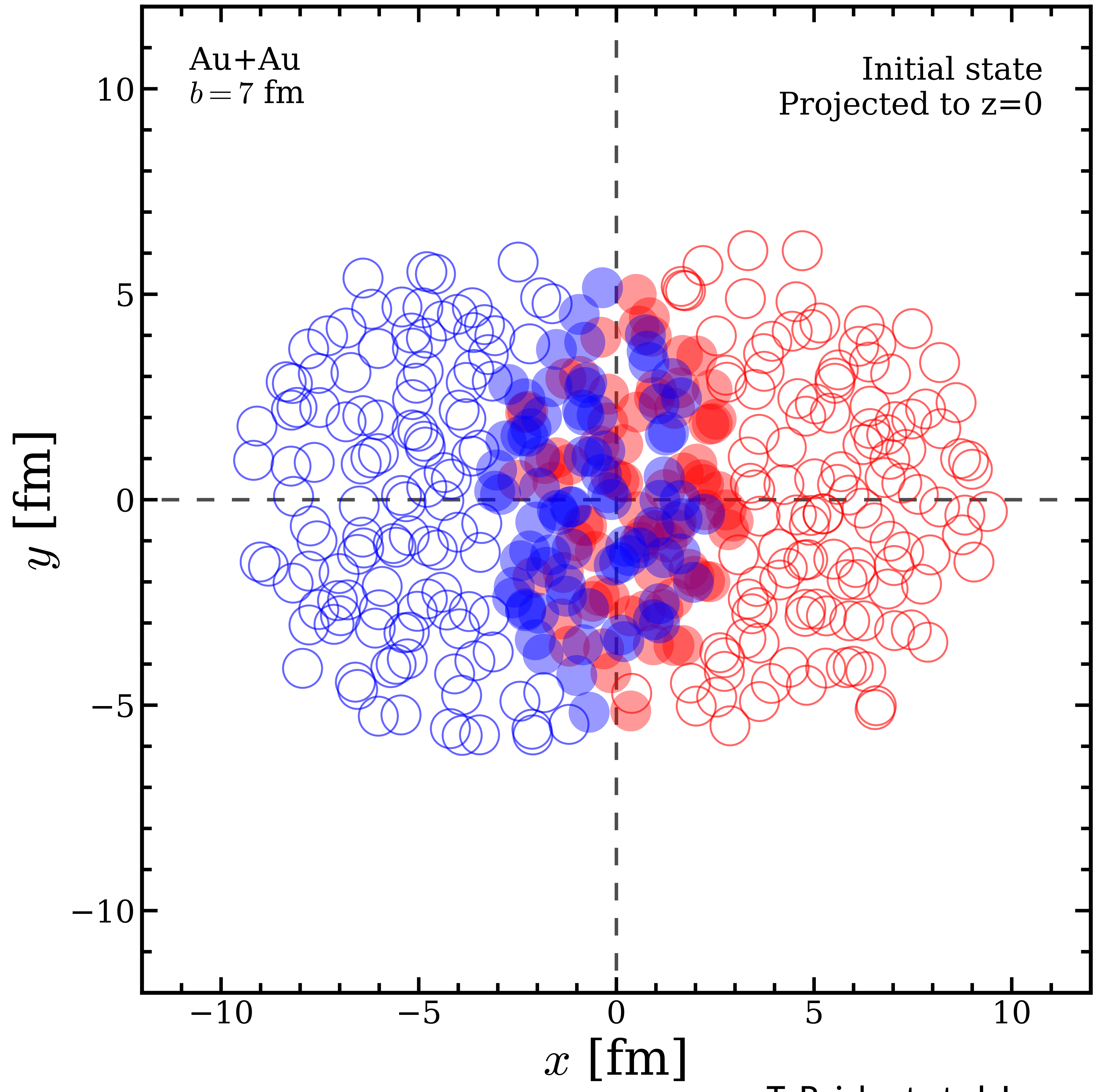
Toy model calculations: Energy dependence

- Fit toy model to world data on integrated proton v_2 at midrapidity
- Perfect quark coalescence with $v_2^q(p_T) = v_{2,\max}^2 \tanh\left(p_T/\Lambda\right)$ shadowed by ballistic Glauber spectator with σ_{pp}=40mb. Integrated v_2 from thermal proton spectrum
- Describes v_2 from TeV collisions to keV collisions…
- Fitted partonic v_2 increases drastically below $\sqrt{s_{NN}}$ < 5 GeV to counter shadowing p_2



UrQMD calculations of unshadowing

- Remove Glauber-like spectators from initial state before starting simulation
- Use frozen Fermi approx. ensuring that nuclei keep shape
- Procedure automatically recovers real scenario at higher $\sqrt{s_{NN}}$ where spectators decouple directly
- Checked that dN/dy at y=0 remains unchanged, although beyond y=0 yields and spectra vary
- Let's calculate v_2 and compare to default UrQMD



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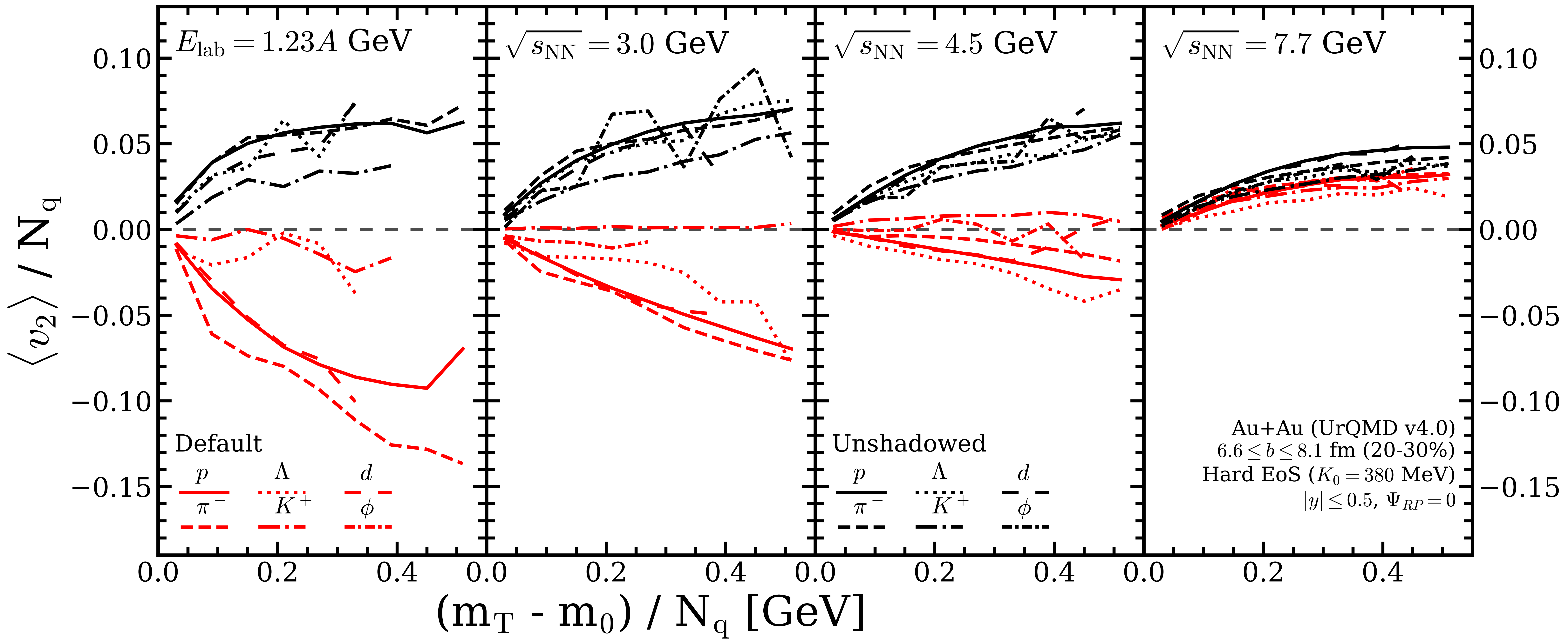
UrQMD calculations of unshadowing



- Partial recovering of „NCQ“ scaling (UrQMD has no quarks)
- At least a fraction of „The onset of NCQ scaling“ is due to shadowing
- Remember threshold effect in Kaon, Lambda, phi production

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Summary

- Collectivity remains a rich information source to study the high μ_B region of QCD
- Flow evolution is more complicated than naively assumed, v_2 is generated by intricate interplay of squeeze-out, shadowing and geometry
- Flow fluctuations and correlations are promising and sensitive new observables
- 3D flow analysis complements existing observables
- Light nuclei and hyper nuclei collectivity allows to access formation and ΛN / ΛNN interaction
- Violation of NCQ scaling has to be corrected for shadowing
- Once p_n are calculated in sophisticated model, NCQ scaling can be revisited, onset of QGP be found

Workshop on High Baryon Density Physics in High-Energy Nuclear Collisions
19-20 Mar. 2026, Berkeley, CA, USA

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