

**LIPEI DU**

UC BERKELEY / LBNL

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**THEORY PERSPECTIVES ON COLLECTIVE FLOWS AT BES ENERGIES**

**PRE-SQM 2026**

MARCH 20, 2026

Collectivity ~ fluctuations+geometry+transport+chemistry

- ▶ Three complementary observables in this talk:
  - ▶  $v_0(p_T)$ : fluctuations across momentum scales; soft-hard coupling/mode structure
  - ▶  $v_1(y)$ : longitudinal density + stopping; transverse asymmetry + expansion
  - ▶  $v_2(p_T)$ : anisotropic response; test of collectivity paradigm (NCQ, hydro vs transport)

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# **RADIAL FLOW FLUCTUATION** $v_0(p_T)$

# DEFINITION OF $v_0(p_T)$

$$v_0(p_T) = \frac{\langle \delta n(p_T) \delta [p_T]_{\text{ref}} \rangle}{\langle n(p_T) \rangle \sigma_{[p_T]_{\text{ref}}}}$$

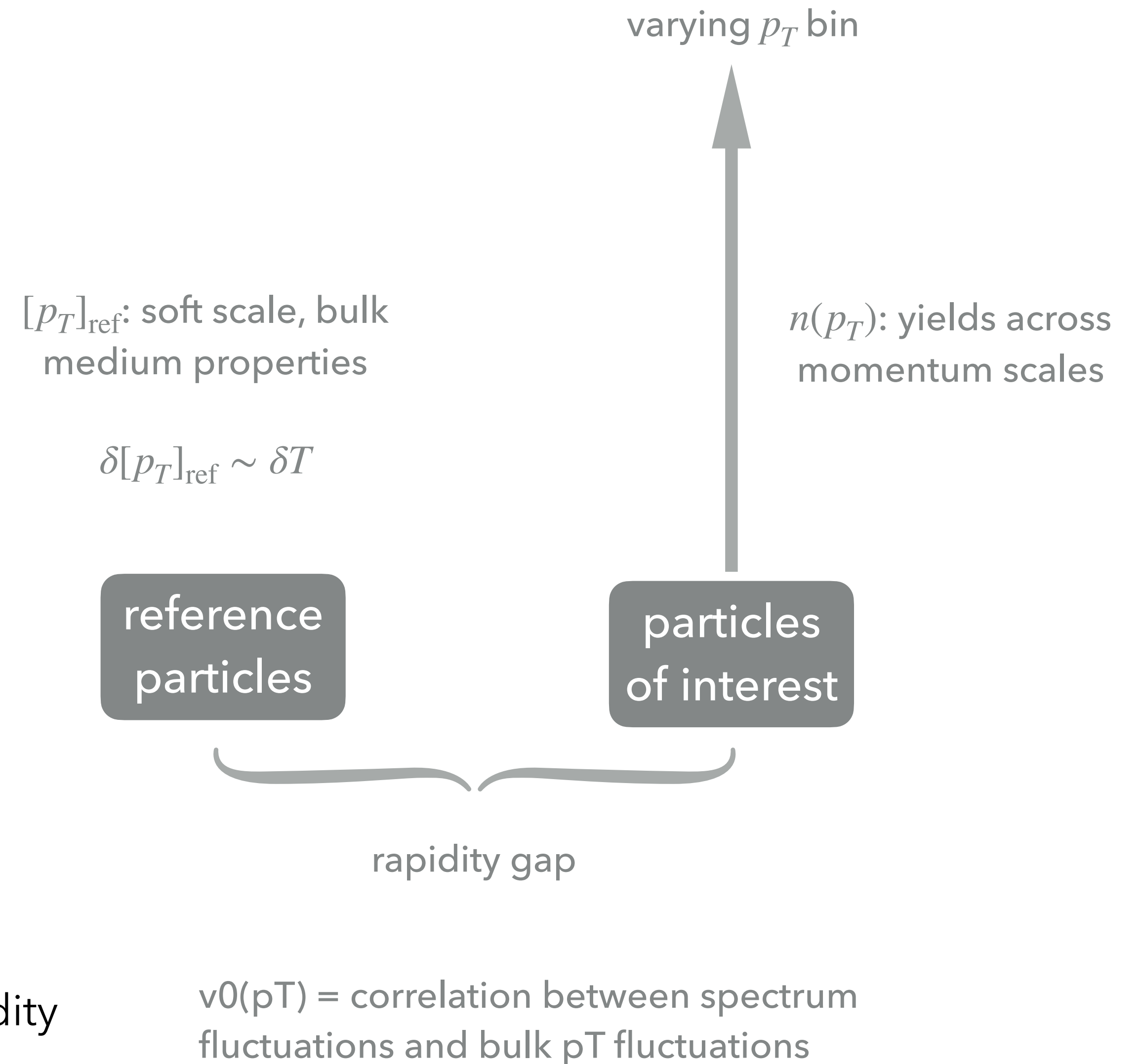
$[\dots]$ : event-wise average;  $\langle \dots \rangle$ : ensemble average

- ▶  $n(p_T)$ : event-wise normalized spectrum

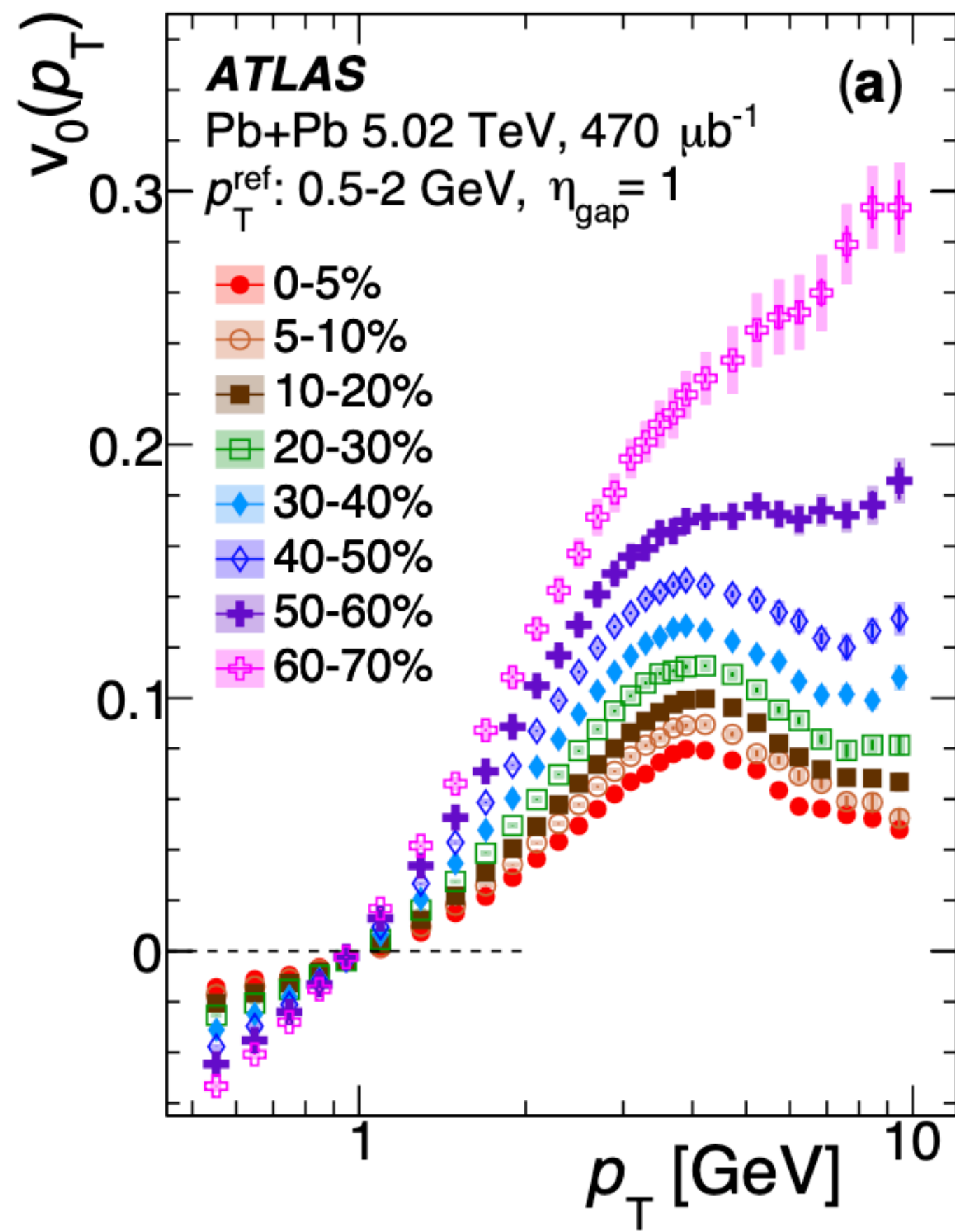
$$n(p_T) = dN/dp_T / \left( \int p_T dN/dp_T \right)$$

- ▶  $\delta n(p_T) = n(p_T) - \langle n(p_T) \rangle$ : fluctuation
- ▶  $[p_T]_{\text{ref}}$ : event-wise mean transverse momentum
- ▶  $\delta [p_T]_{\text{ref}} = [p_T]_{\text{ref}} - \langle [p_T]_{\text{ref}} \rangle$ : fluctuation

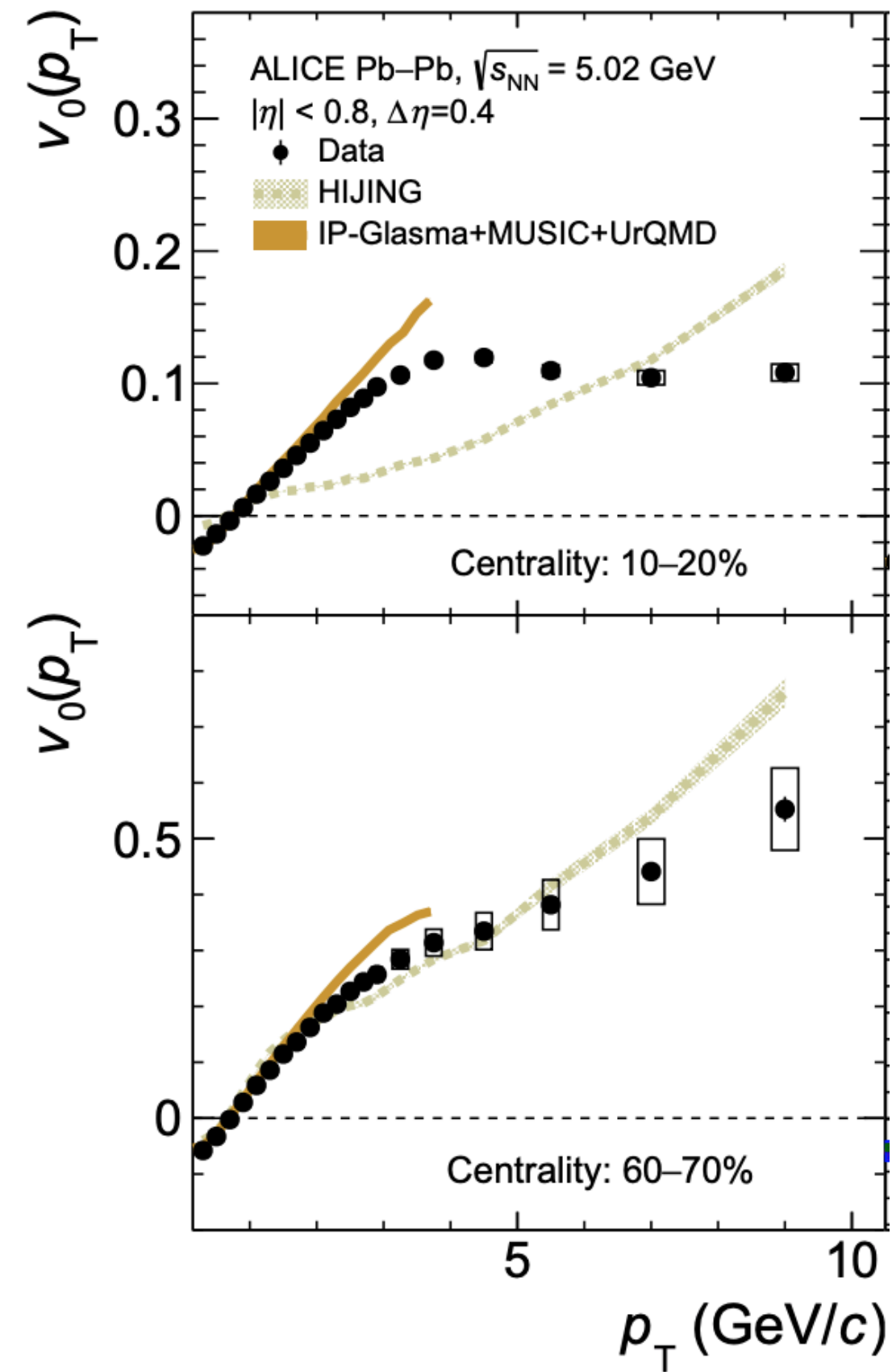
- ▶  $n(p_T)$  &  $[p_T]_{\text{ref}}$  are measured in separated pseudorapidity intervals



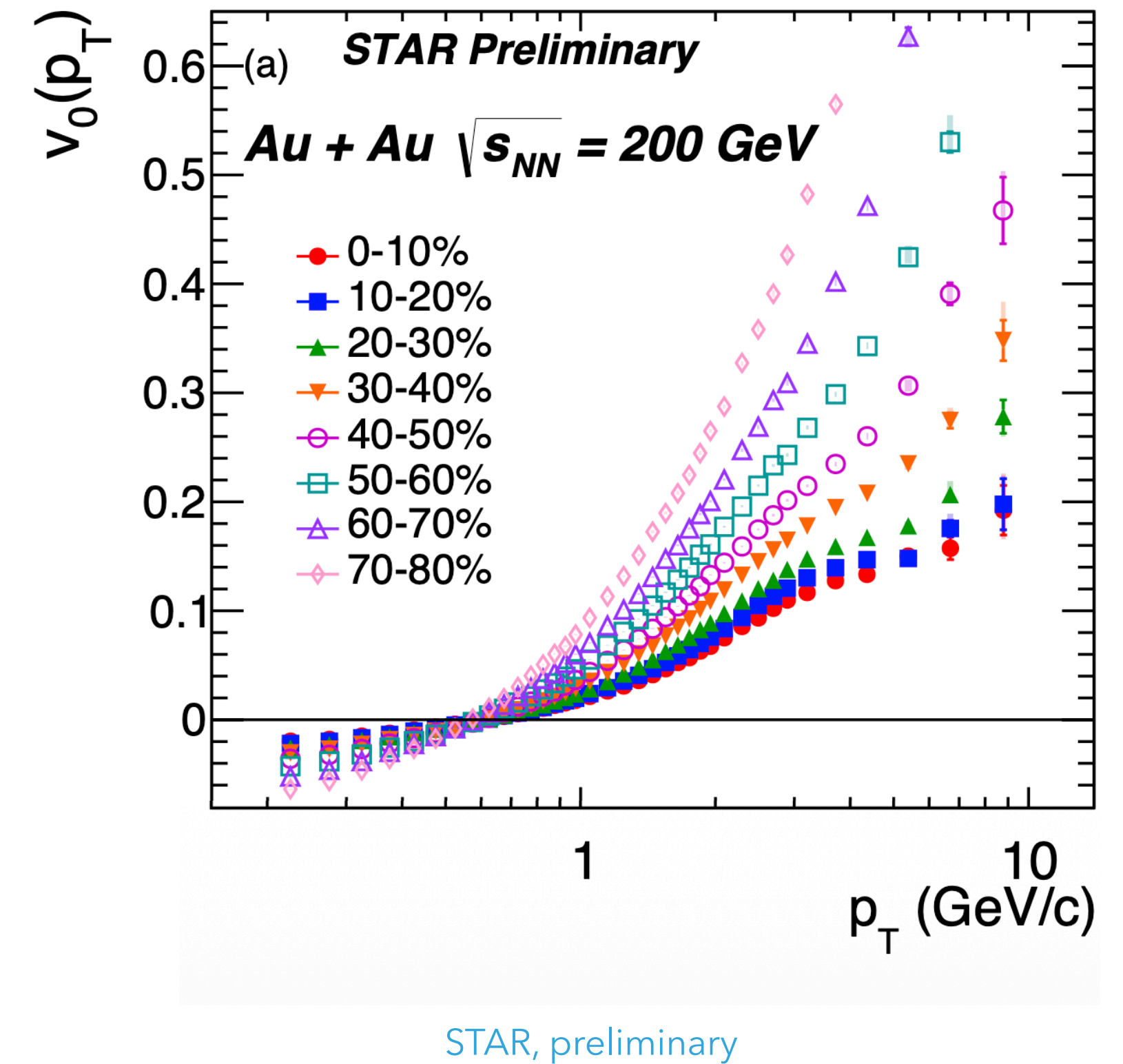
# MEASUREMENTS



ATLAS, 2503.24125

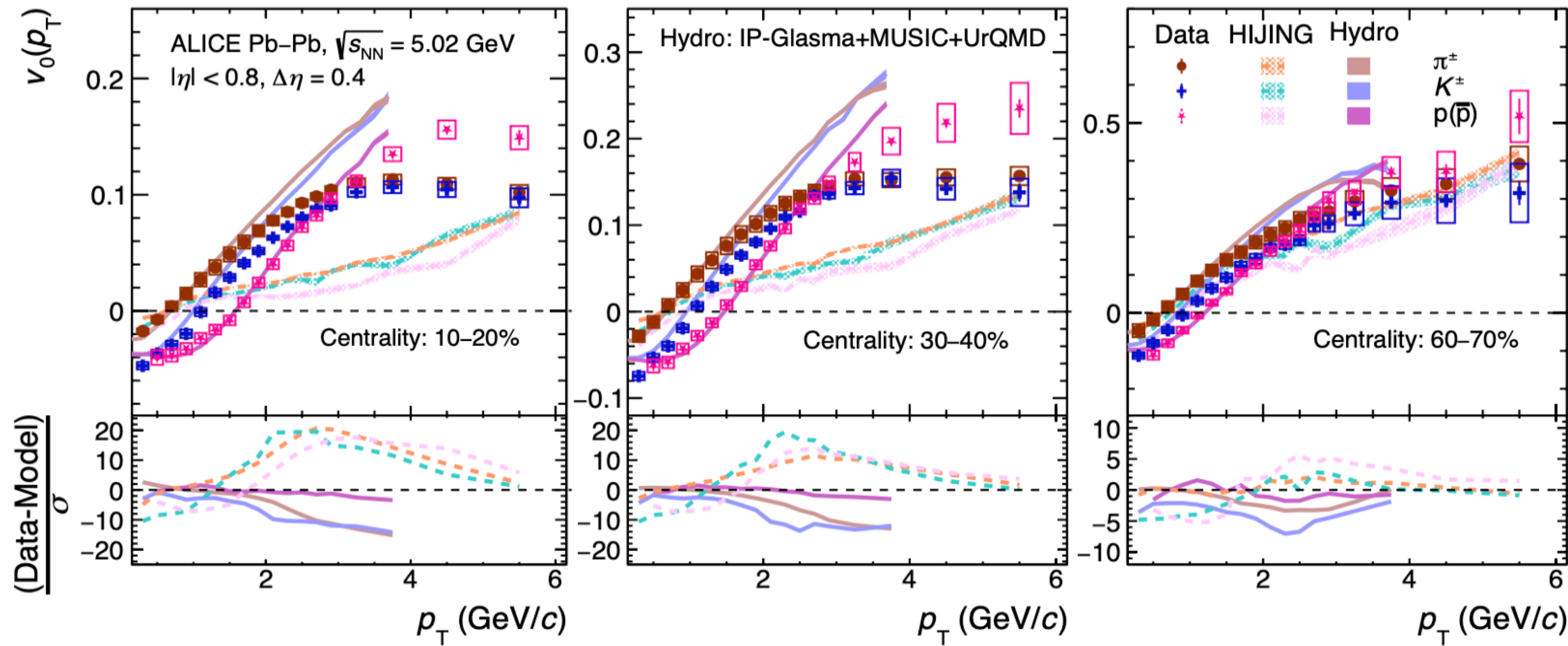


ALICE, 2504.04796



- ▶ A rise-plateau-downturn structure in central collisions at the LHC

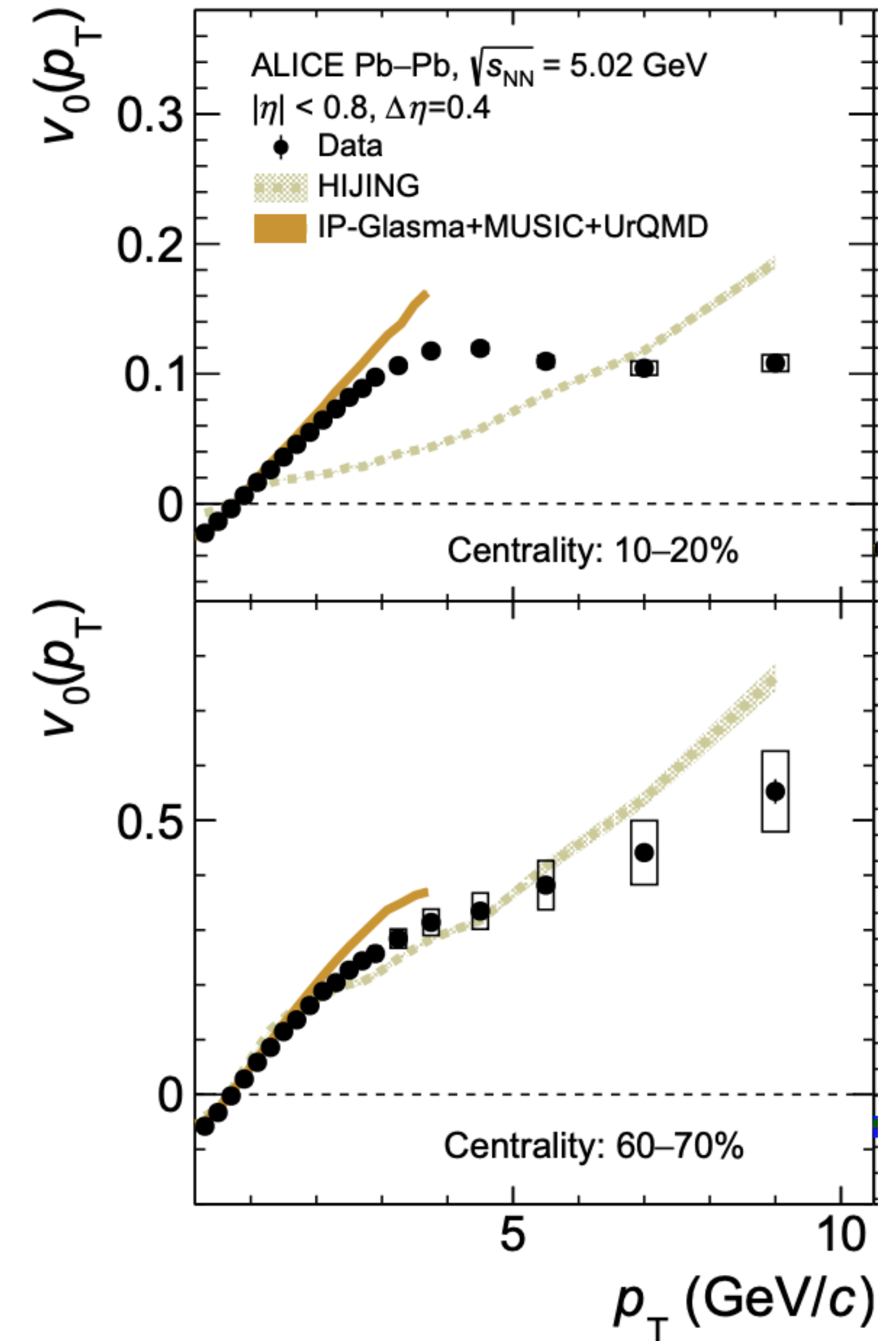
# MODEL-DATA COMPARISON



ALICE, 2504.04796

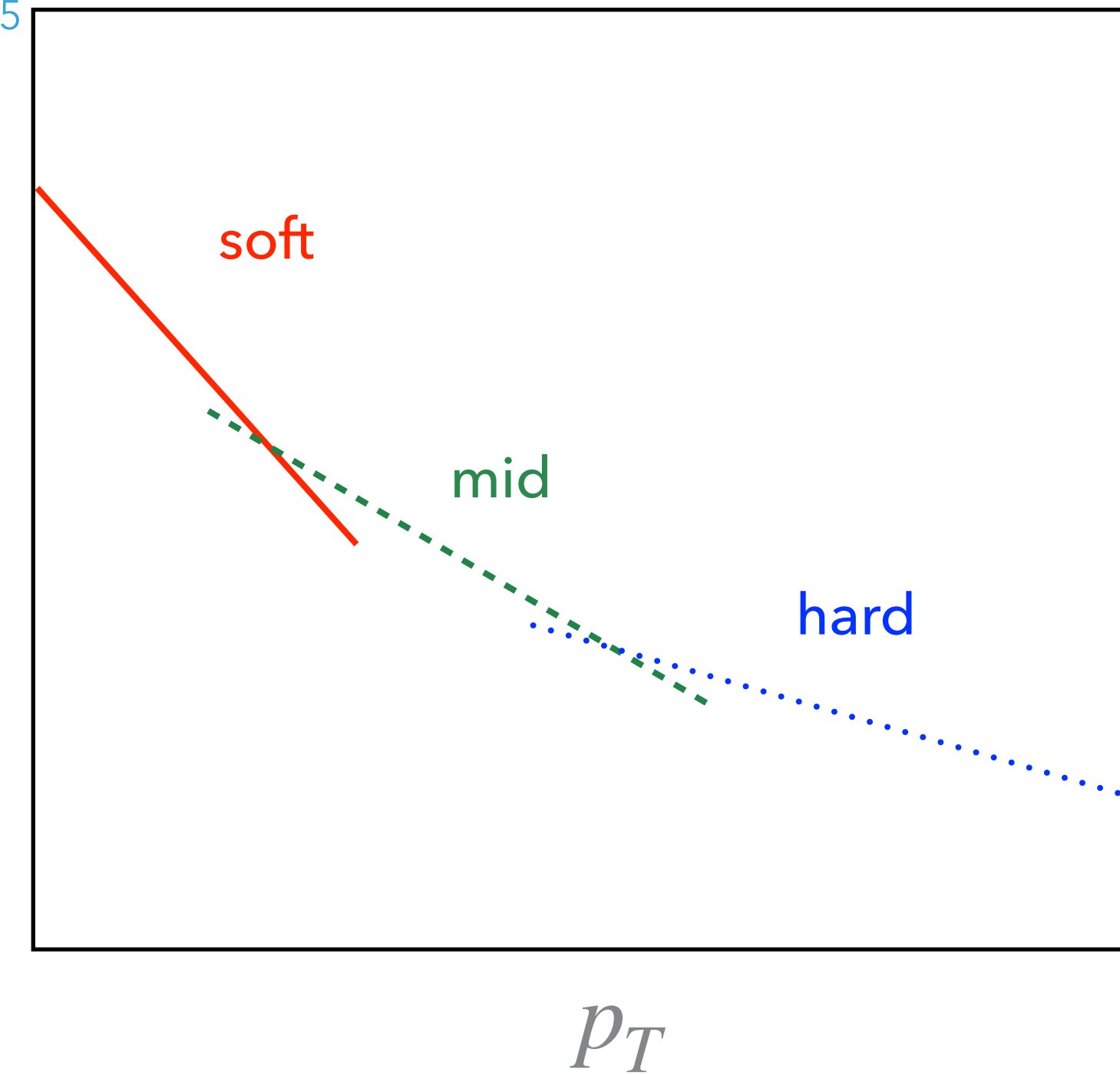
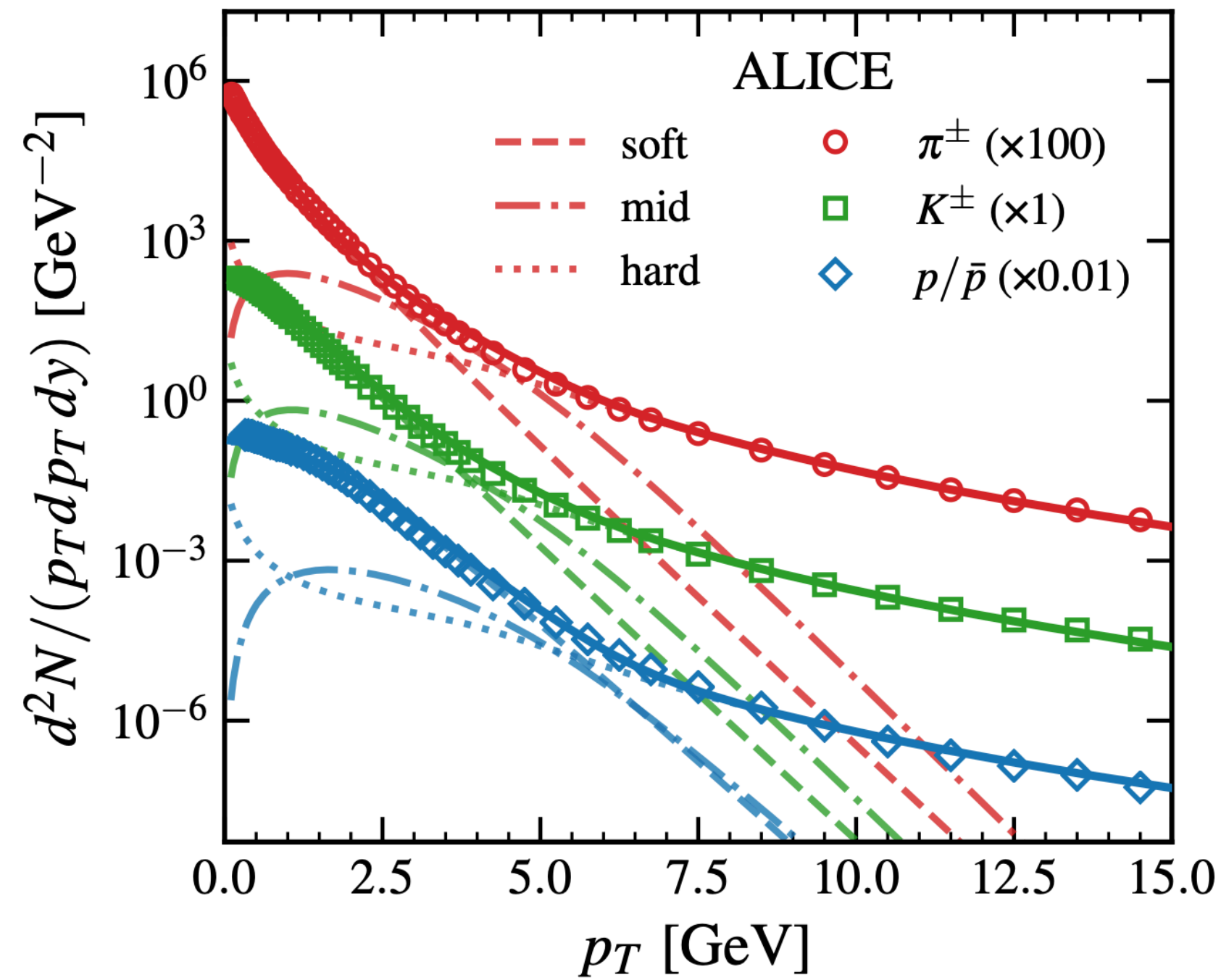
$$v_0(p_T) = \frac{\langle \delta n(p_T) \delta [p_T]_{\text{ref}} \rangle}{\langle n(p_T) \rangle \sigma_{[p_T]_{\text{ref}}}}$$

- ▶ Soft (hydrodynamic) description breaks down at  $p_T \gtrsim 2$  GeV
- ▶ Indicates additional (non-soft) dynamical contributions



# THREE-COMPONENT TOY MODEL

L. Du & P. M. Jacobs, 2512.10265

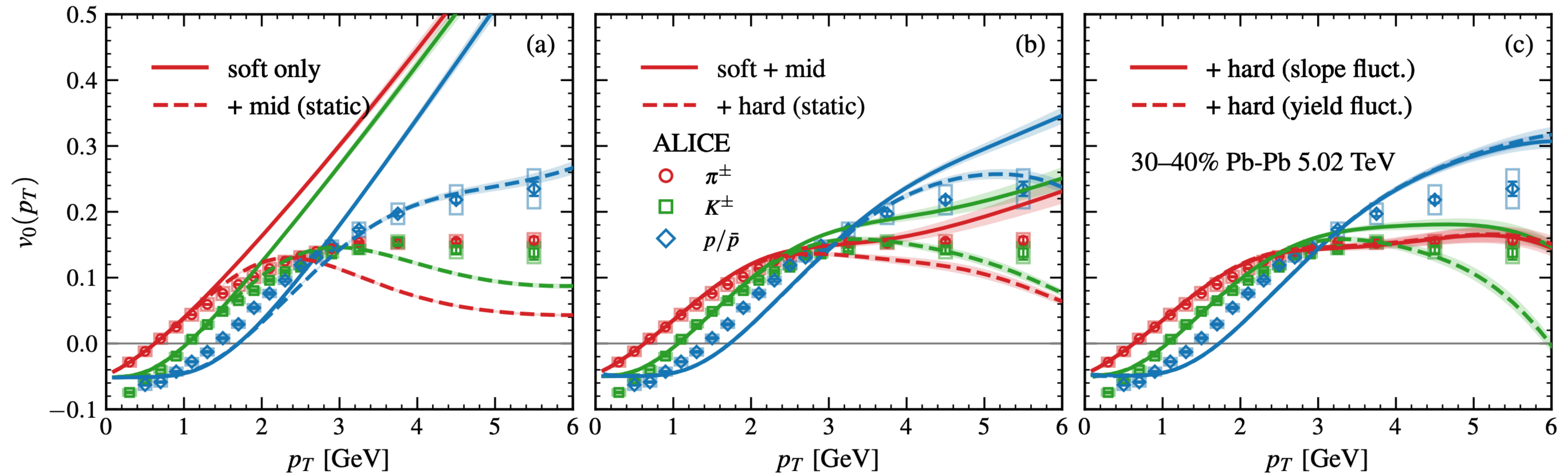


$$n(p_T) = n_{\text{soft}}(p_T) + n_{\text{mid}}(p_T) + n_{\text{hard}}(p_T)$$

- ▶  $n(p_T)$ : normalized  $p_T$  spectrum  $dN/dp_T / (\int p_T dN/dp_T)$
- ▶ Each component responds differently to bulk fluctuations

- ▶ soft: bulk collective flow (blast-wave)
- ▶ mid: hadronization (coalescence)
- ▶ hard: jet/non-thermal (power-law)

# MULTI-COMPONENT ORIGIN OF $v_0(p_T)$

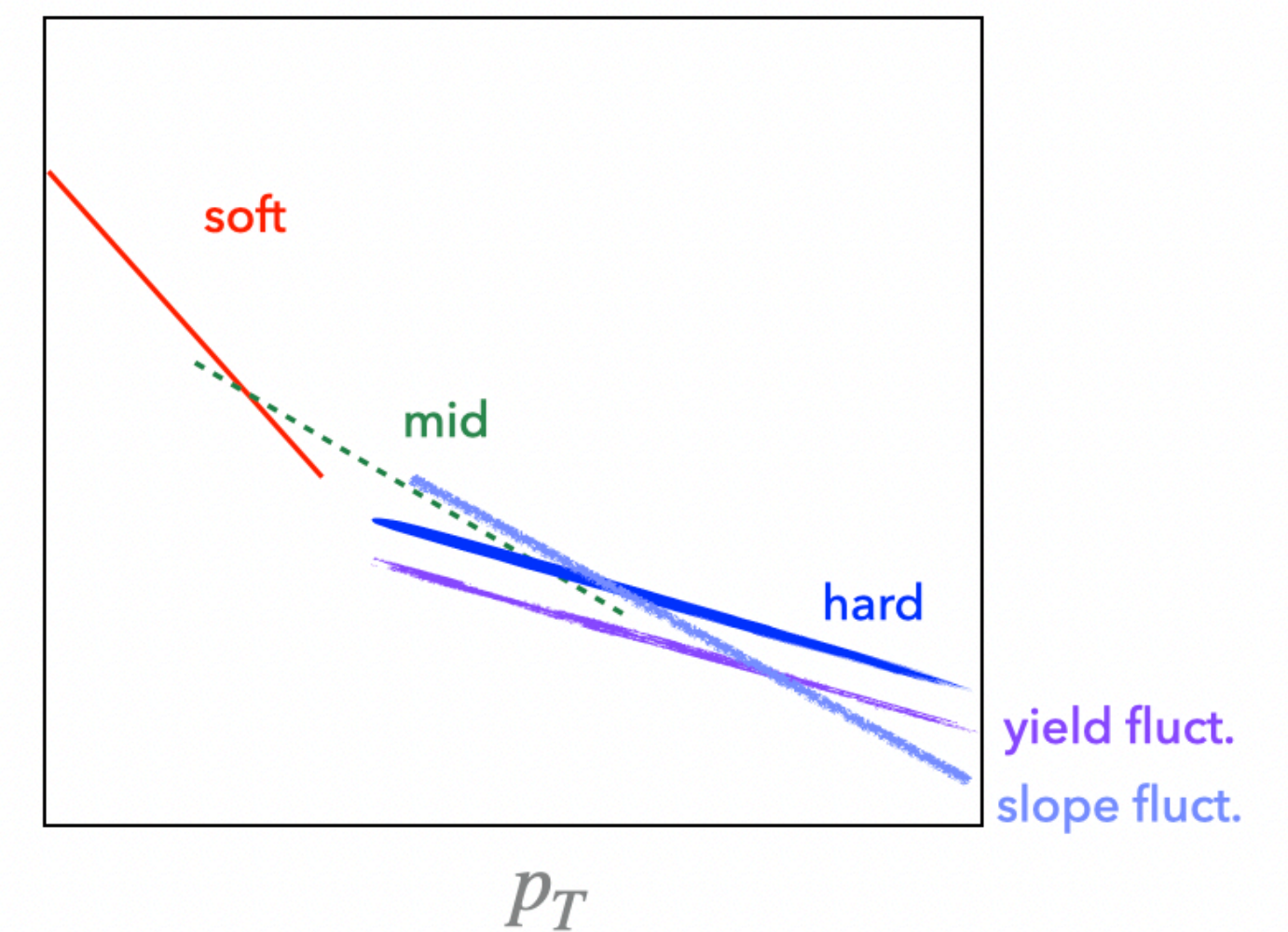


► Successively adding components and their fluctuations reproduces the data

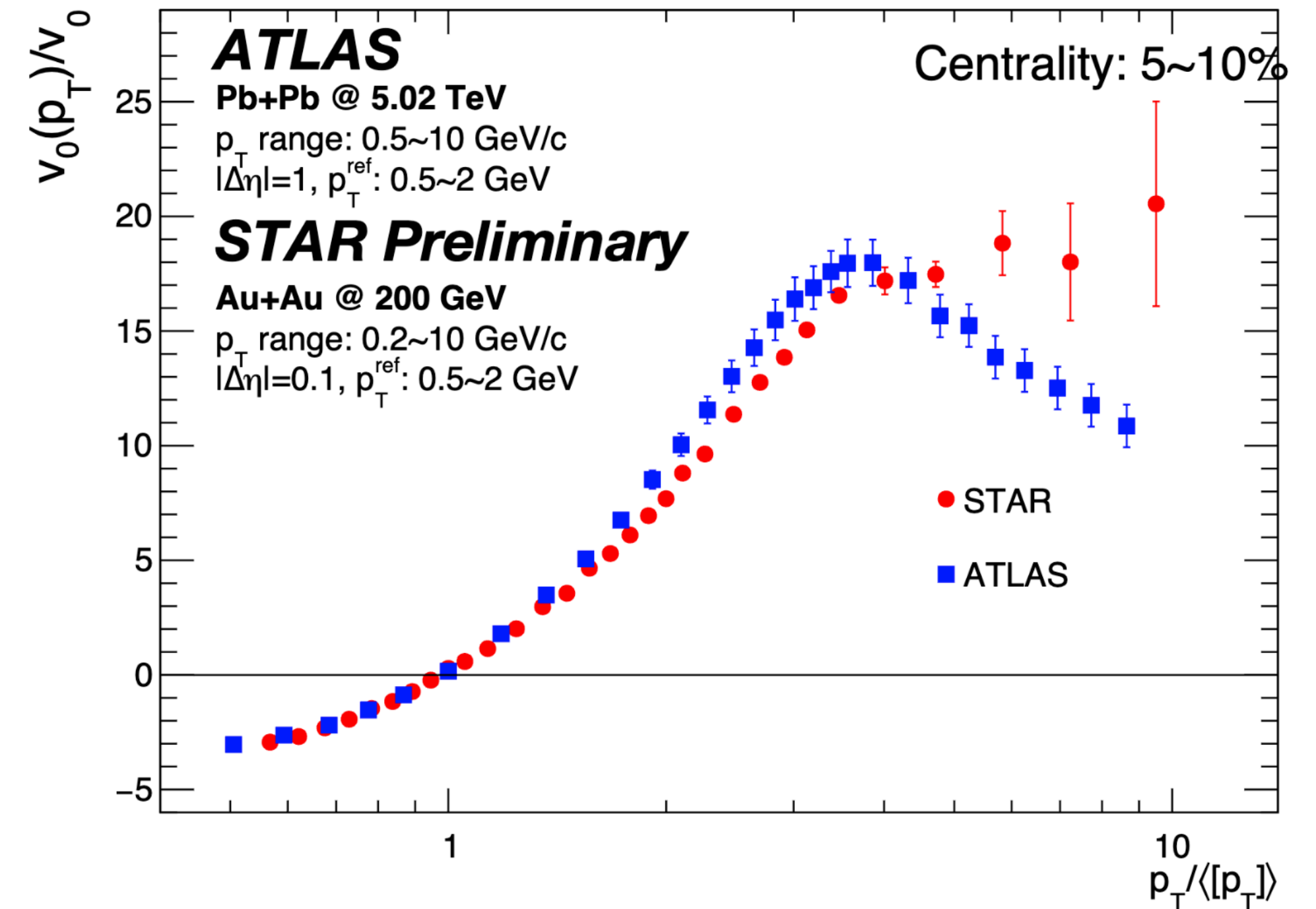
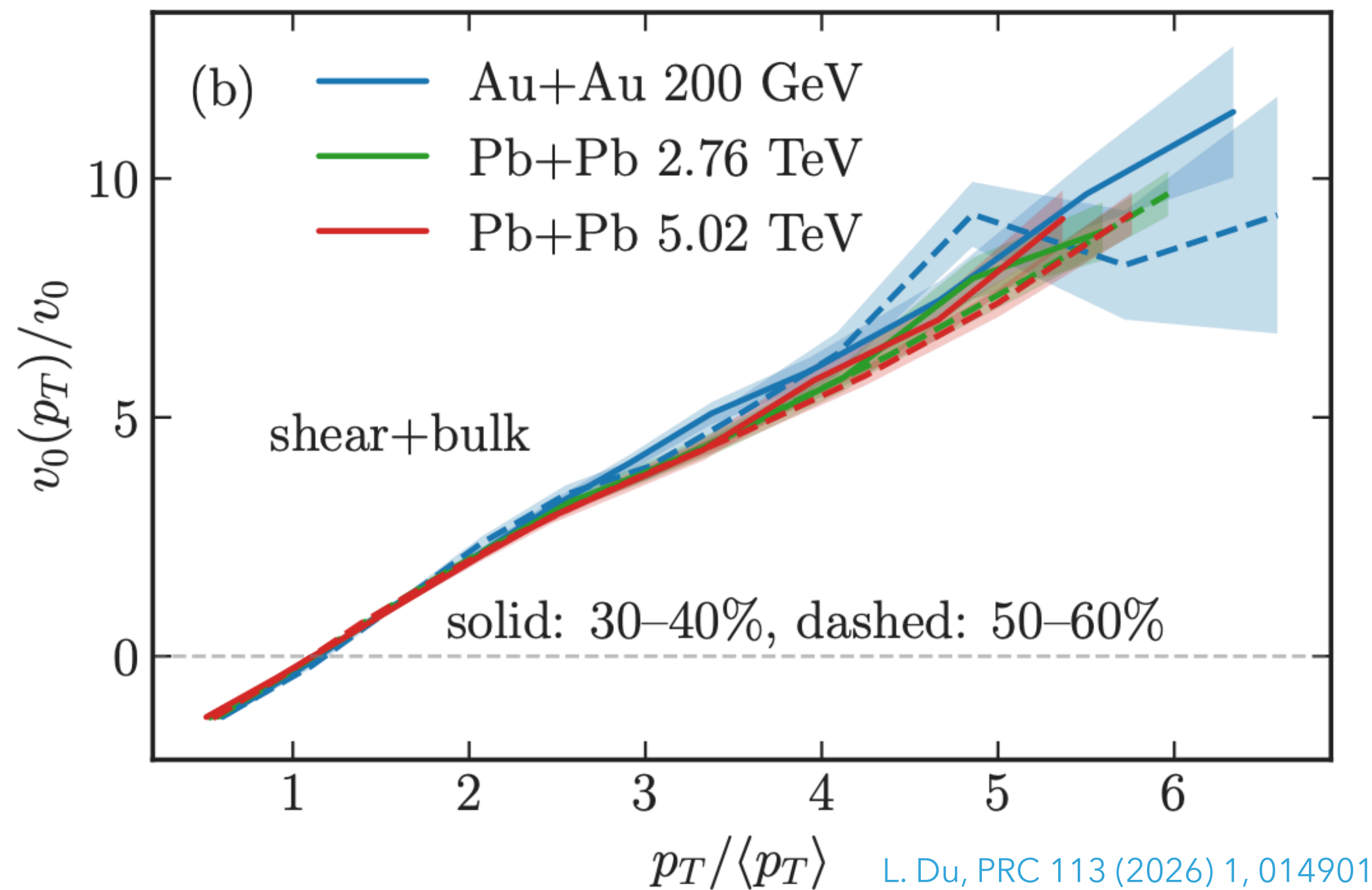
$$v_0(p_T) = \frac{\langle \delta n(p_T) \delta [p_T]_{\text{ref}} \rangle}{\langle n(p_T) \rangle \sigma_{[p_T]_{\text{ref}}}}$$

$$\langle n(p_T) \rangle = \langle n_{\text{soft}}(p_T) \rangle + \langle n_{\text{mid}}(p_T) \rangle + \langle n_{\text{hard}}(p_T) \rangle$$

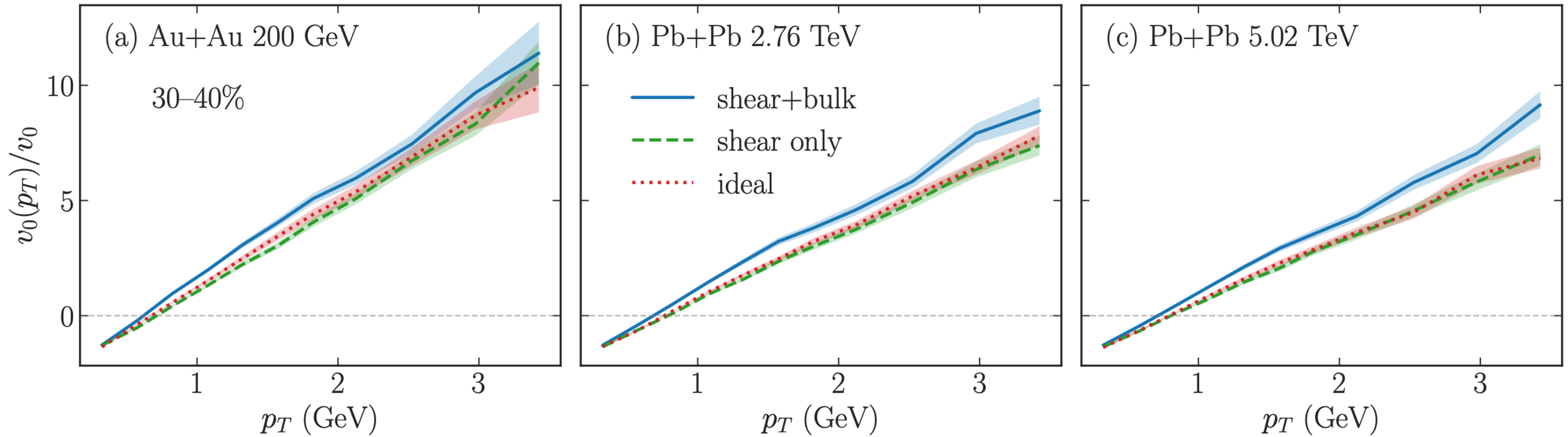
$$\langle \delta n(p_T) \delta [p_T]_{\text{ref}} \rangle = \langle \delta n_{\text{soft}} \delta [p_T]_{\text{ref}} \rangle + \langle \delta n_{\text{mid}} \delta [p_T]_{\text{ref}} \rangle + \langle \delta n_{\text{hard}} \delta [p_T]_{\text{ref}} \rangle$$



# SCALING BEHAVIOR OF $v_0(p_T)$ ACROSS SYSTEMS



- ▶  $v_0(p_T)/v_0$  approximately scales with  $p_T/\langle p_T \rangle$  at low  $p_T$
- ▶ Suggests a universal response of the system to bulk fluctuations
- ▶ Important question: whether this scaling persists at BES energies, where the system is more baryon-rich and more transport-dominated.

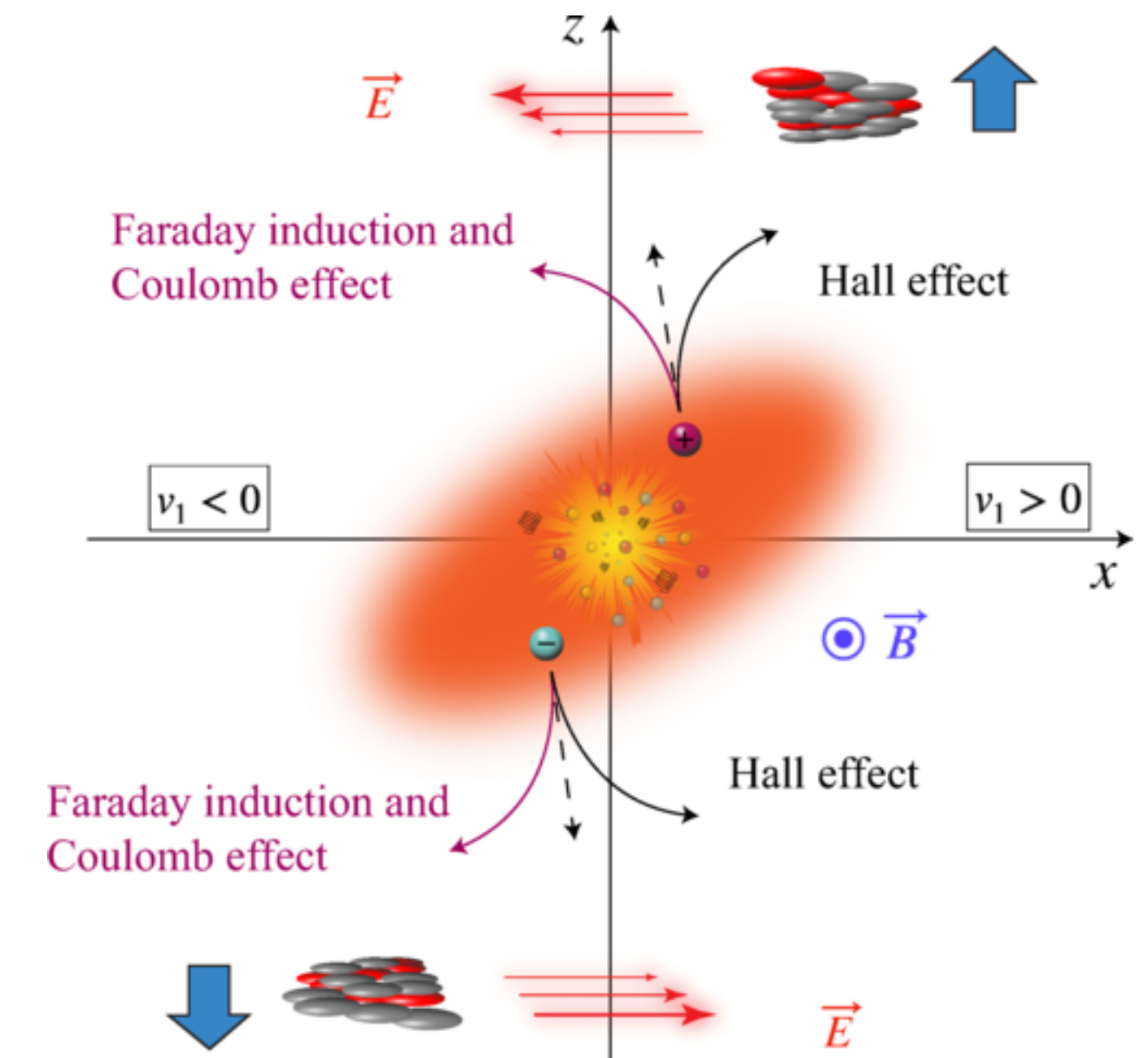
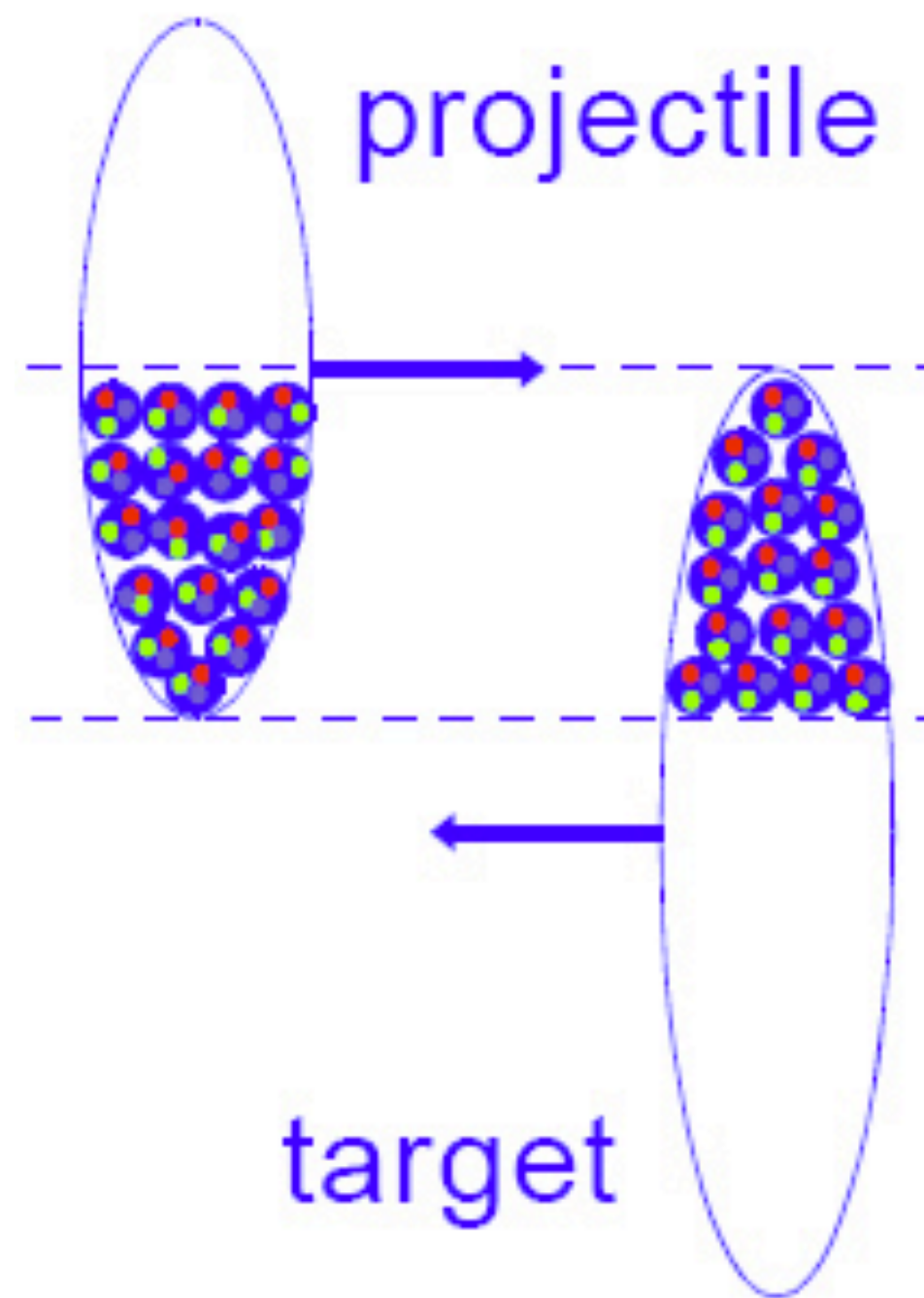


L. Du, PRC 113 (2026) 1, 014901

- ▶ Sensitivity to bulk viscosity and to shear viscosity is less clean at lower beam energies.

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**DIRECTED FLOW**  $v_1(y)$

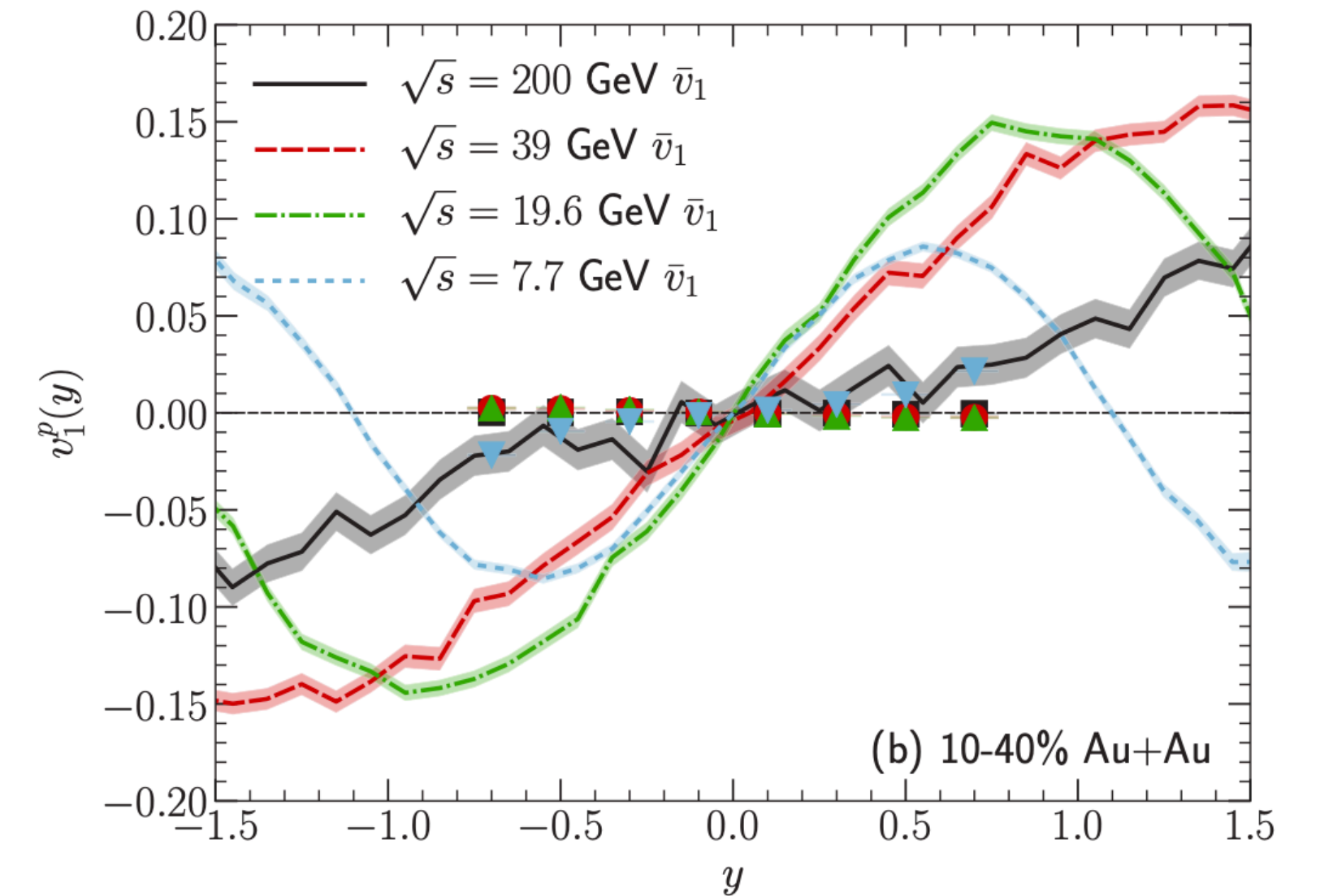
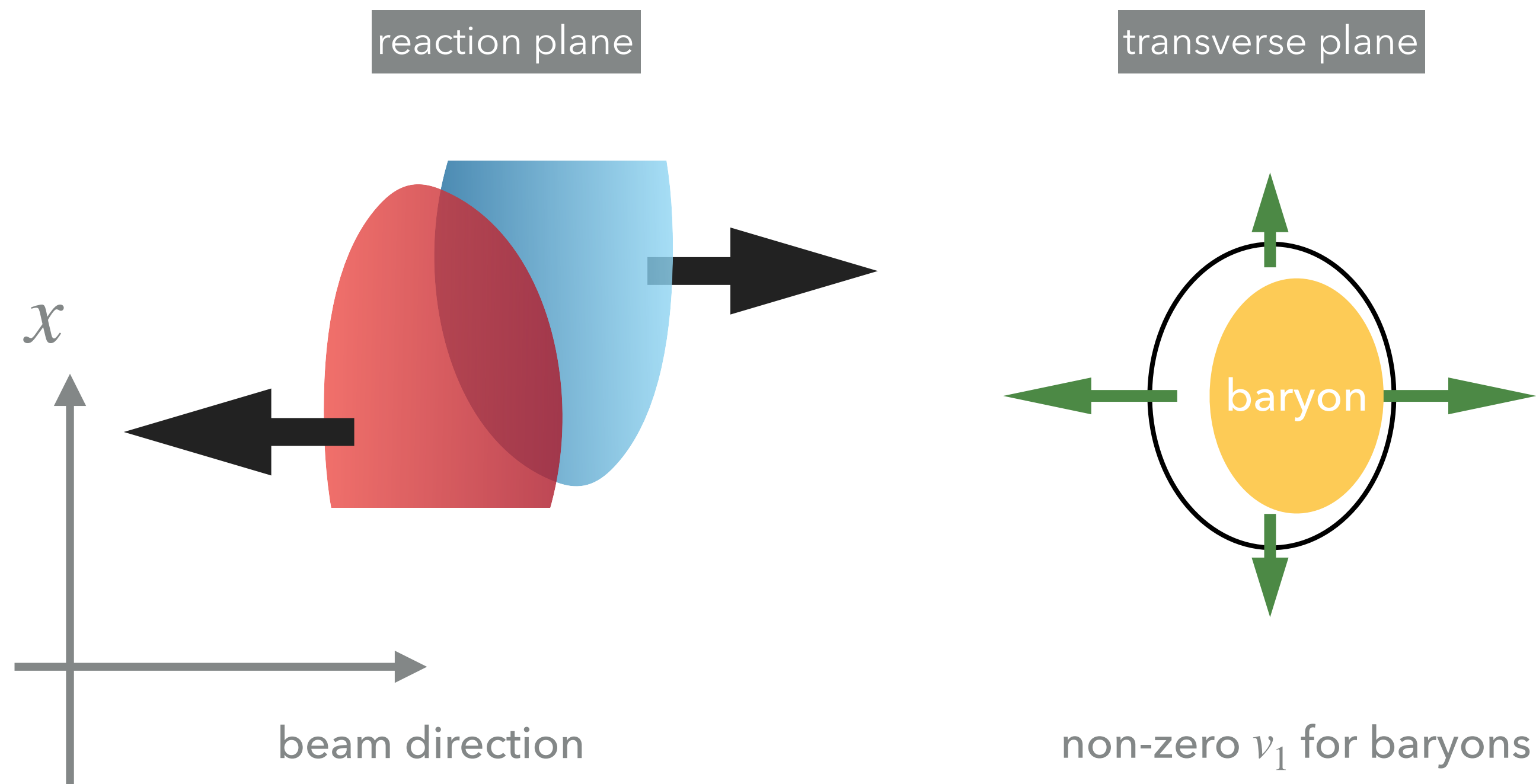


▶ At BES,  $v_1(y)$  is controlled by THREE intertwined ingredients:

- ▶ Longitudinal charge distribution (yields vs rapidity)
- ▶ Transverse asymmetry of that distribution (geometry in  $x - \eta$ )
- ▶ Expansion/charge-dependent dynamics (EM fields + finite chemical potentials)

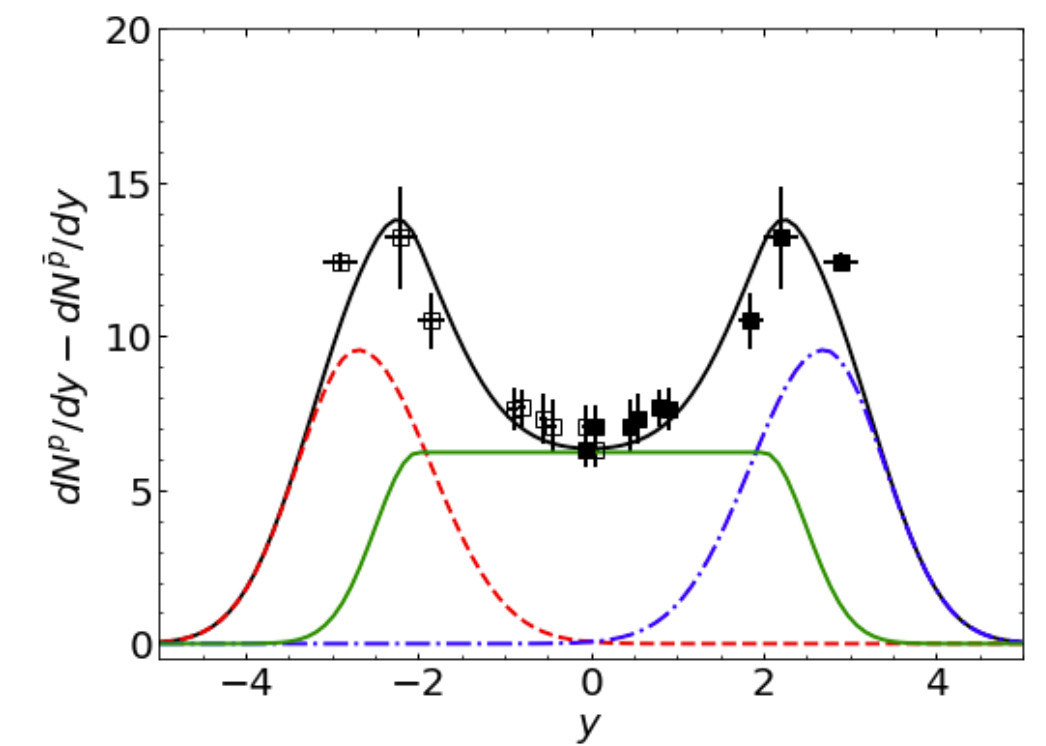
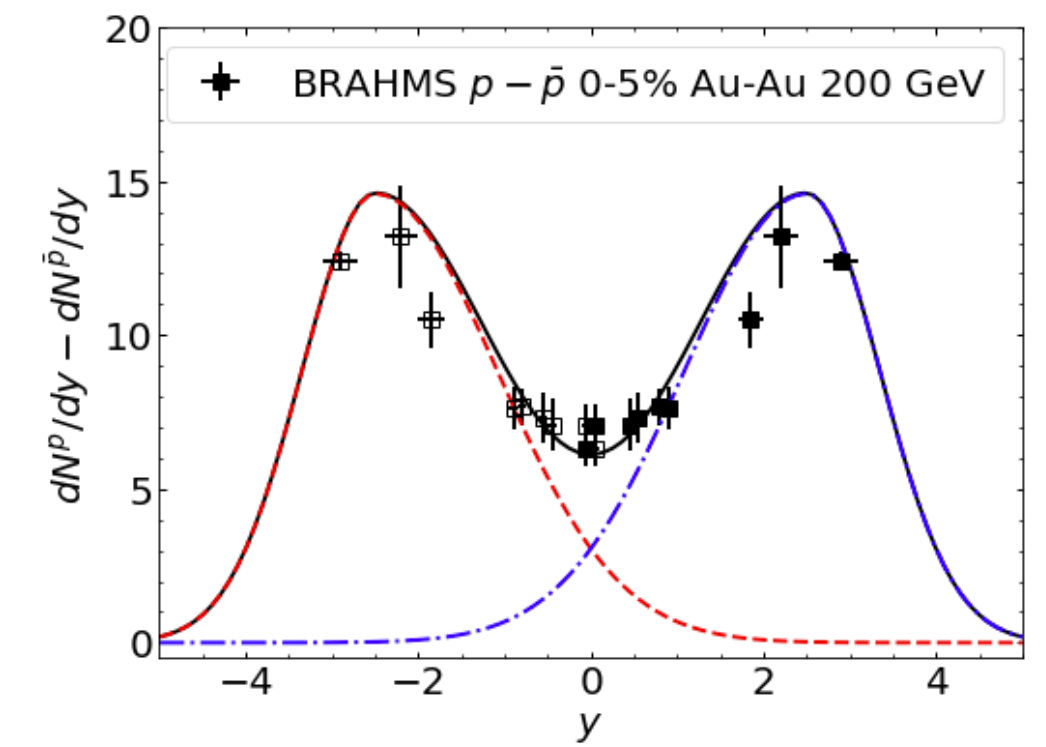
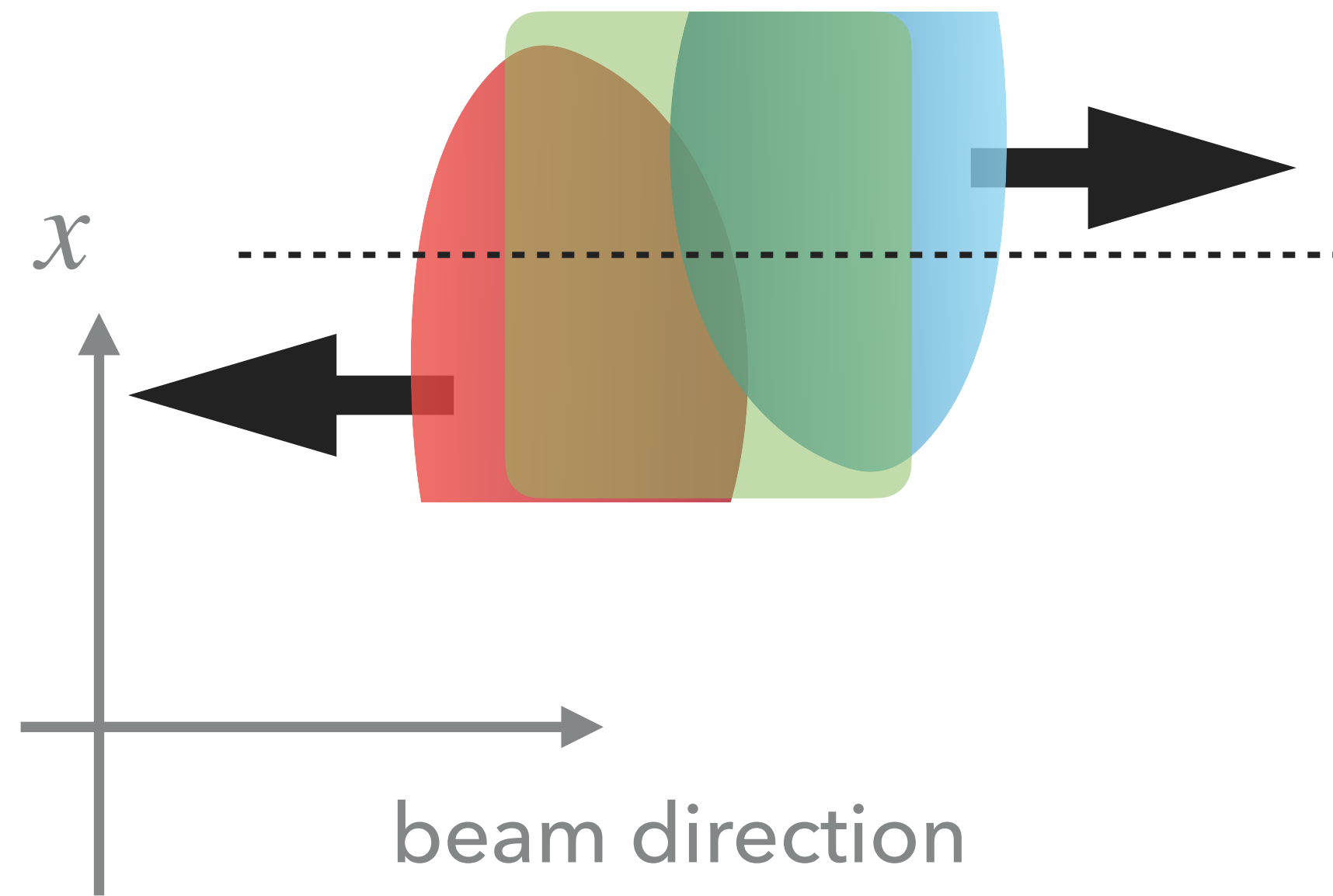
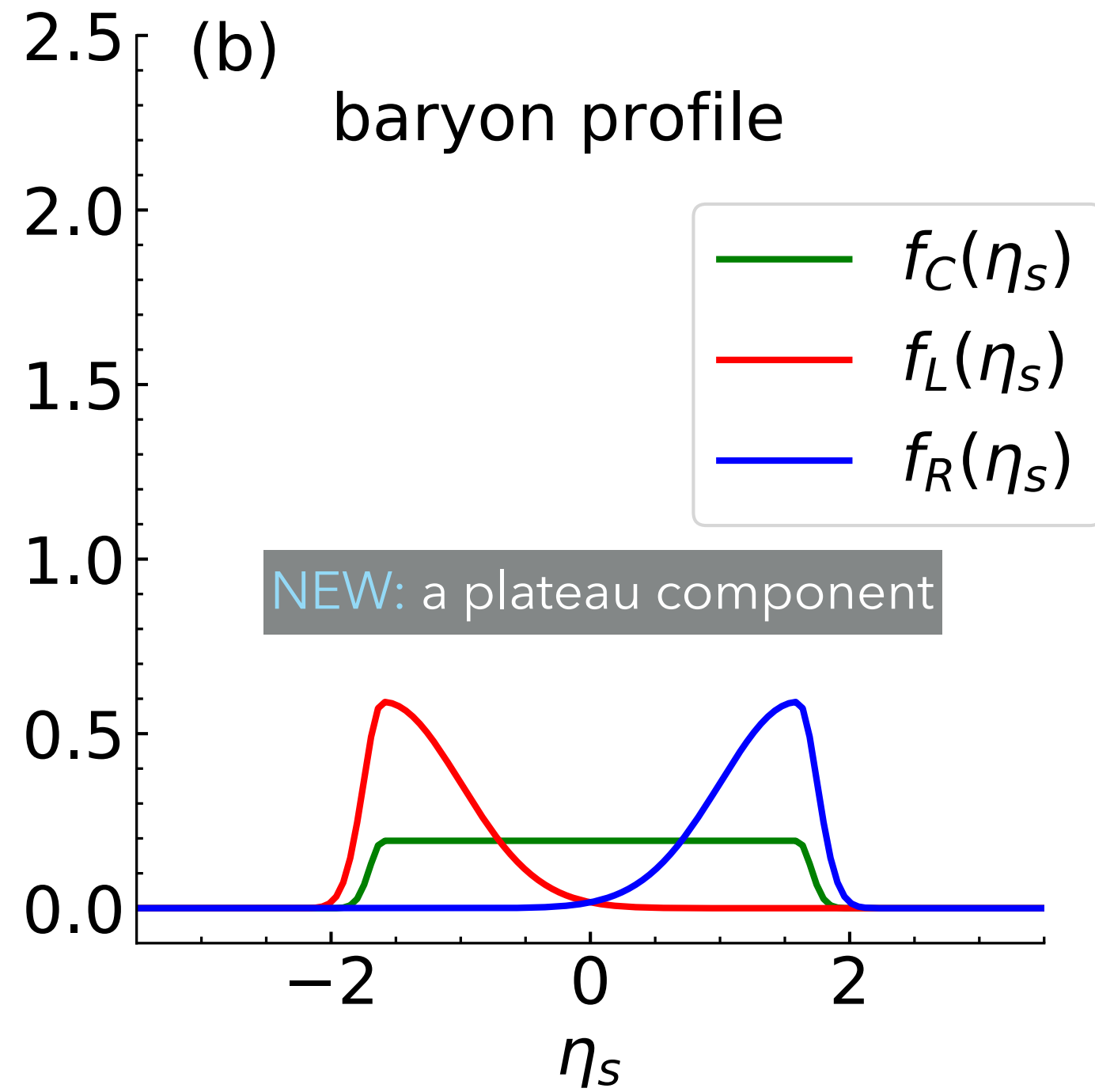
$\Delta v_1(y)$  receives contributions from both EM fields and finite chemical potentials

$v_1(y) \sim (\text{longitudinal density}) \times (\text{transverse asymmetry}) \times (\text{expansion response})$



Shen and Alzhrani, PRC102, 014909 (2020)

- ▶  $v_1(y)$  is generated by mapping spatial baryon asymmetry into momentum space via transverse expansion
- ▶ Standard stopping models produce too strong spatial asymmetry  $\rightarrow$  overpredict  $v_1(y)$

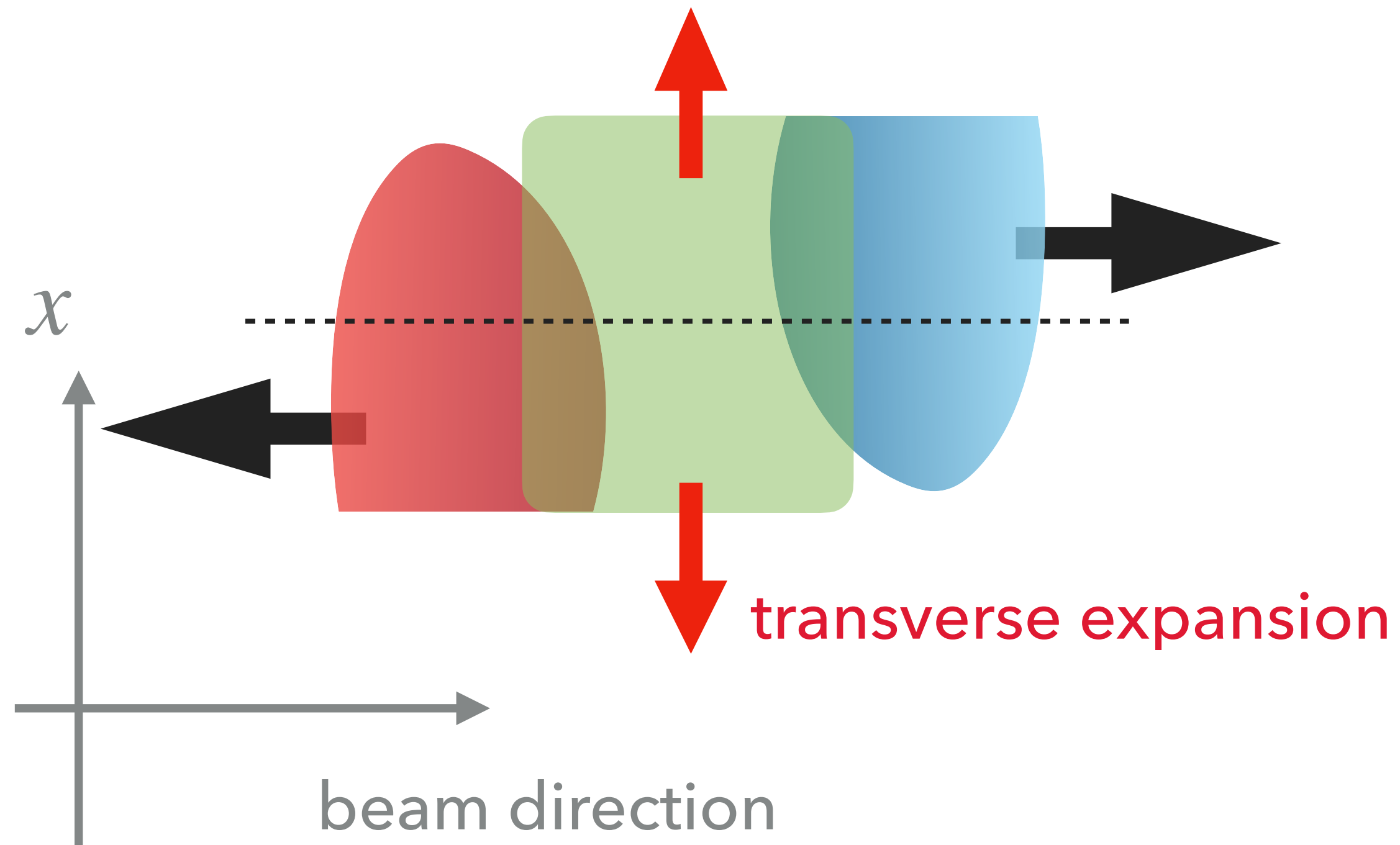


Only for illustration

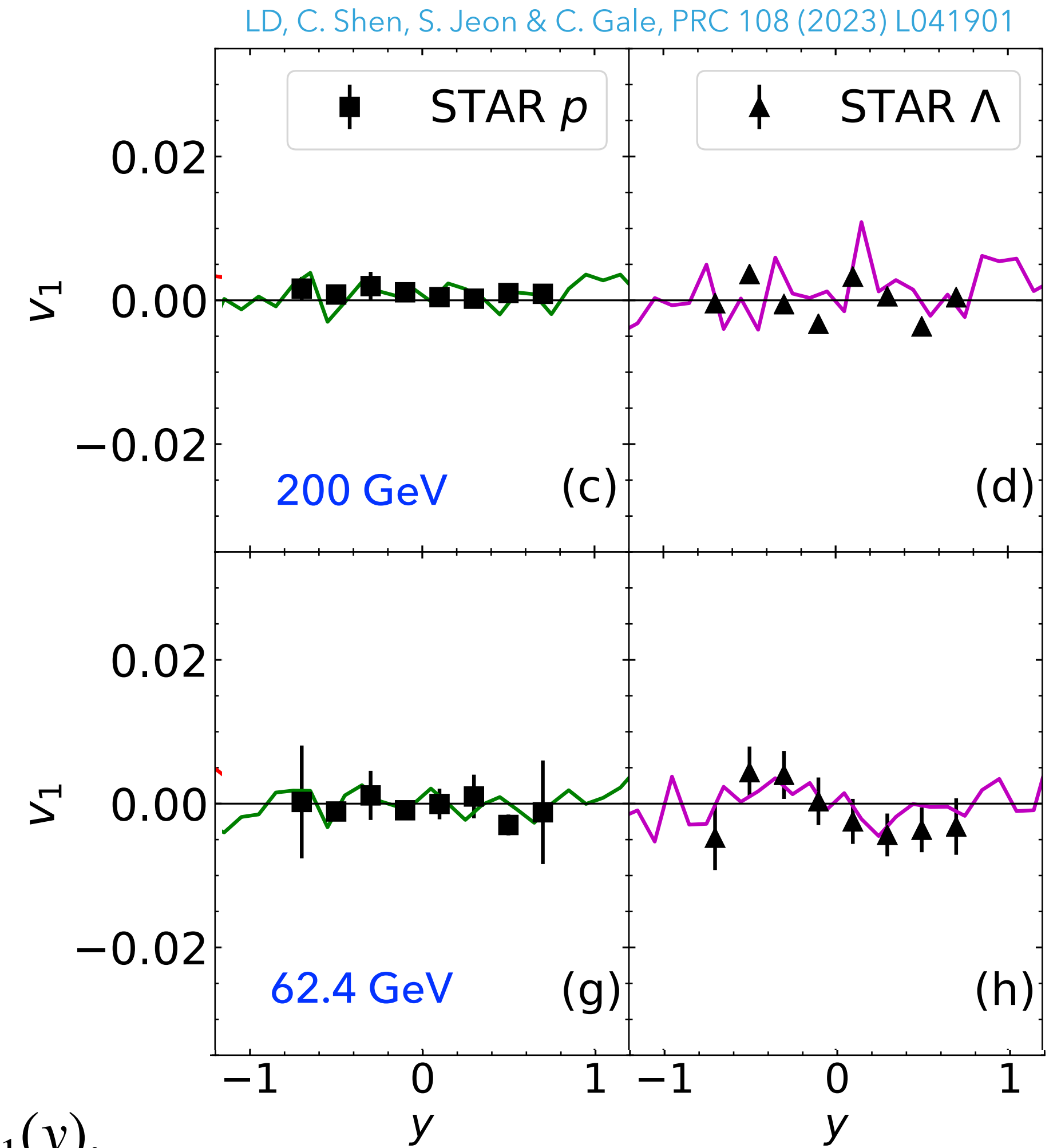
LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

- ▶ Simultaneous description of  $dN/dy + v_1(y)$  requires a plateau component
- ▶  $dN/dy$  alone is not sufficient to constrain baryon stopping

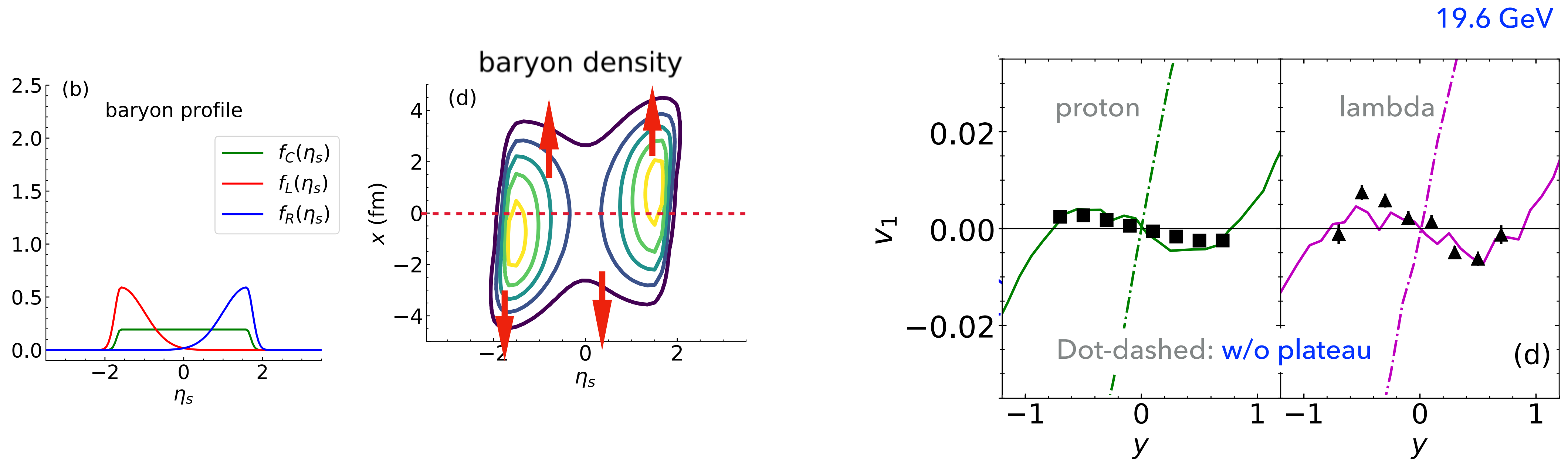
# WHY BARYON $v_1(y)$ IS SMALL AT HIGH ENERGIES



- ▶ More plateau  $\rightarrow$  weaker spatial asymmetry  $\rightarrow$  smaller  $v_1(y)$ .
- ▶ At high energies, the plateau component reduces spatial asymmetry, leading to small  $v_1(y)$



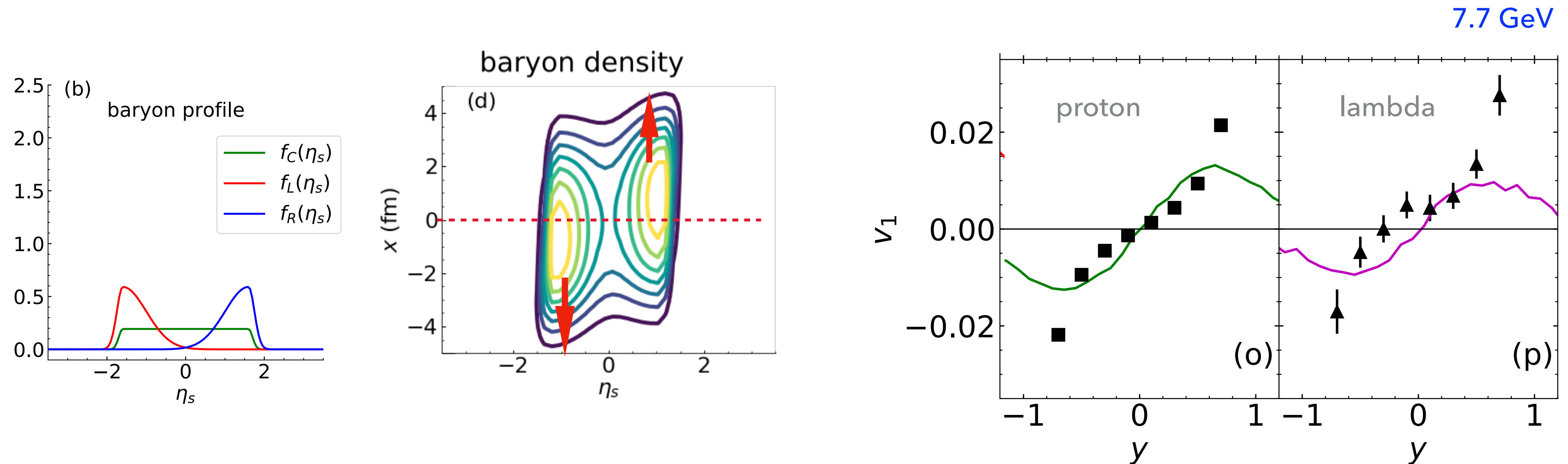
Data: STAR, PRL 112, 162301 (2014); PRL 120, 062301 (2018)



Initial baryon distributions in the reaction plane for 10-40% Au+Au@19.6 GeV

LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

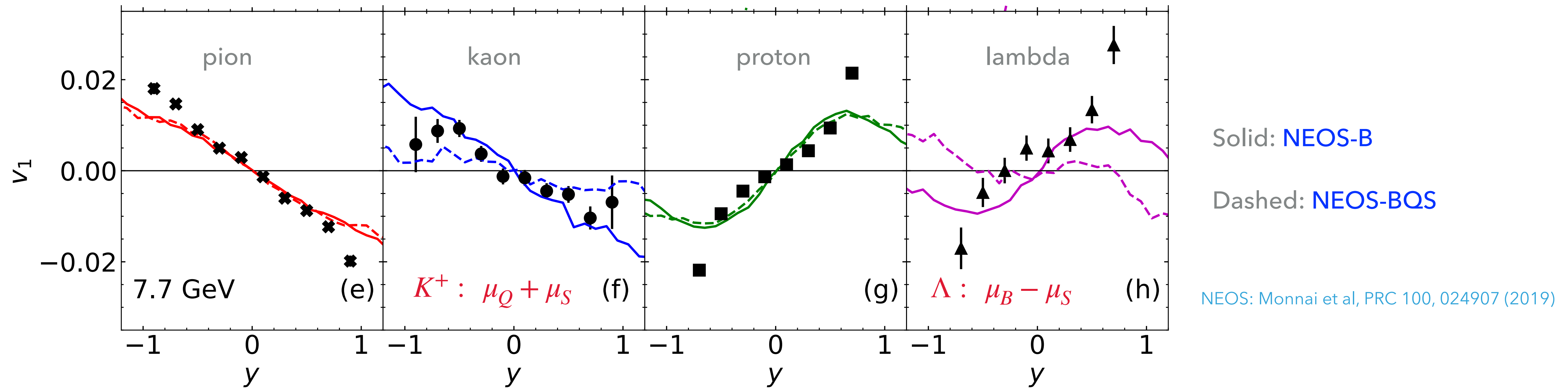
- ▶ Competition between asymmetric density and transverse expansion generates a double sign change
- ▶ This naturally produces a negative slope at midrapidity
- ▶ The observed sign change emerges from geometry + expansion, without requiring a first-order phase transition



Initial baryon distributions in the reaction plane for 10-40% Au+Au@7.7 GeV

LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

- ▶ Stronger baryon stopping → enhanced asymmetry → positive slope
- ▶ Compared to 19.6 GeV, reduced plateau leads to stronger spatial asymmetry
- ▶ The evolution of  $dv_1/dy$  from negative to positive is driven by changes in baryon density profiles



- ▶ Two limits of EoS: NEOS-B,  $\mu_S = \mu_Q = 0$  and NEOS-BQS,  $n_S = 0, n_Q = 0.4n_B$  (2D projection of a 4D EOS)
- ▶ Local strangeness neutrality suppresses the  $v_1(y)$  of  $K^+$  and  $\Lambda$  around midrapidity, and even alters the sign of  $\Lambda$ 's  $v_1(y)$  beyond  $|y| \gtrsim 0.6$
- ▶ The  $v_1(y)$  of identified particles can be used to probe EoS at finite chemical potentials.

- ▶ longitudinal baryon distribution
- ▶ transverse dependence of stopping
- ▶ equation of state at finite chemical potentials
- ▶ early-time EM response
- ▶ multi-charge transport dynamics
  
- ▶  $v_1(y)$  is a multi-dimensional probe: geometry + chemistry + fields
- ▶ sign change  $\neq$  unique QCD phase transition signal

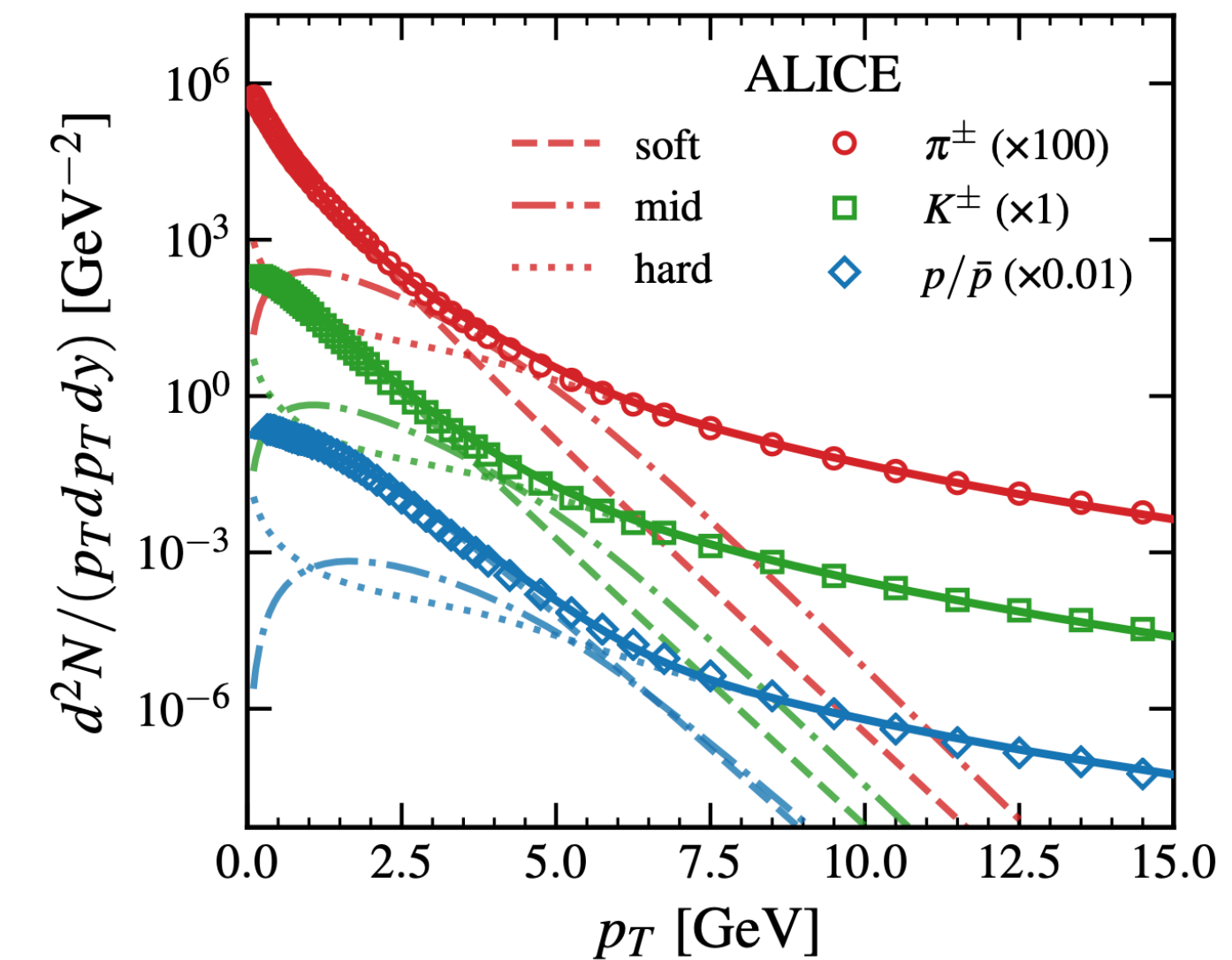
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**ELLIPTIC FLOW**  $v_2(p_T)$

- ▶ NCQ scaling:  $v_2/n_q$  vs  $p_T/n_q$  collapses across hadrons
- ▶ Coalescence argument

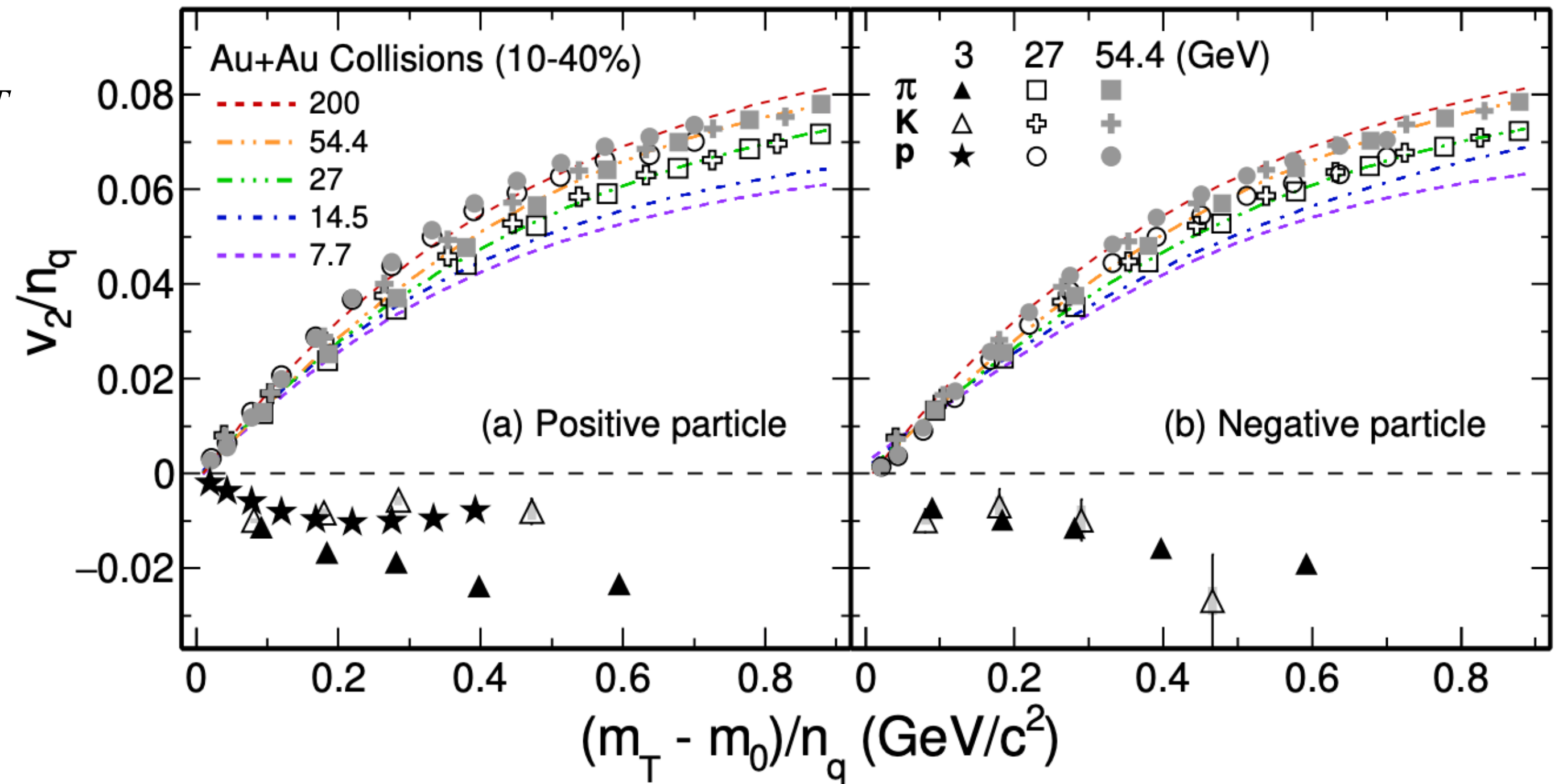
$$v_2^{\text{hadron}} \approx n_q v_2^{\text{quark}} \rightarrow \frac{v_2^{\text{hadron}}}{n_q} \sim f\left(\frac{p_T}{n_q}\right)$$

- ▶ only expected in intermediate  $p_T$
- ▶ This interpretation requires:
  - ▶ partonic collectivity
  - ▶ hadronization via coalescence
  - ▶ minimal hadronic distortion



- ▶  $p_T$  regimes
  - ▶ Low  $p_T$ : hydro (collective flow)
  - ▶ Intermediate  $p_T$ : recombination/coalescence
  - ▶ High  $p_T$ : fragmentation

- ▶ Experiments (RHIC/BES):
  - ▶ approximate scaling at intermediate  $p_T$
  - ▶ deviations: 10-20%
- ▶ Non-universality:
  - ▶ species dependent
  - ▶ energy dependent
- ▶ Common interpretation: → evidence for partonic collectivity and quark coalescence
- ▶ Key question: Is approximate scaling sufficient to establish partonic collectivity?



$m_T - m_0$  : transverse kinetic energy

### (A) LHC (clean QGP environment):

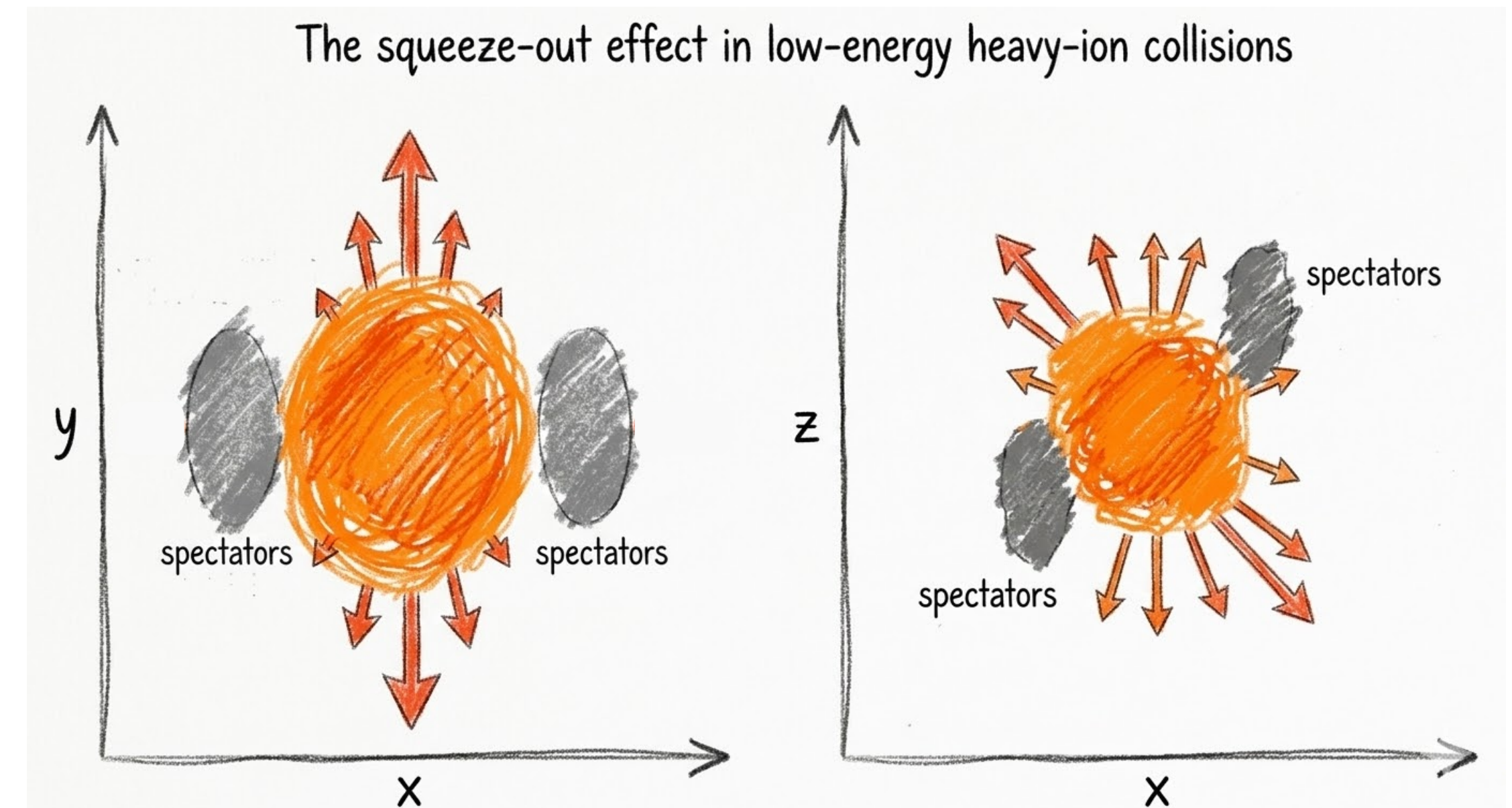
- ▶ QGP is well established
- ▶ whether NCQ scaling is only approximate
- ▶ whether systematic violations are observed
- ▶ Stronger conclusion: NCQ scaling is not a robust signature even in a QGP?

### (B) Multistage evolution:

- ▶ Hydro (QGP) → Hadronization → Afterburner
- ▶ Key question: When is NCQ scaling formed?
  - ▶ before hadronic rescattering?
  - ▶ after hadronic rescattering?
  - ▶ Quantify hadronic-stage modifications

Scaling may emerge or be modified during the hadronic stage

- ▶ Mechanism: Shadowing & squeeze-out
  - ▶ spectator blocking → out-of-plane emission
  - ▶ in-plane particles undergo more rescattering / absorption
- ▶ Implications for NCQ scaling:
  - ▶ Hadronic-stage dynamics strongly modify flow
  - ▶ Mapping from quark → hadron is not preserved
  - ▶ Final-state interactions can distort or generate scaling



final flows at BES = early pressure + spectator blocking + hadronic transport + ...

shadowing also contributes to  $v_1(y)$

- ▶ Key insights: [Tom Reichert, Iurii Karpenko, 2603.02927: Unshadowing NCQ scaling](#)
  - ▶ Even with perfect quark coalescence, NCQ scaling can be violated by hadronic effects (e.g. shadowing)
  - ▶ Breaking of NCQ scaling  $\neq$  disappearance of QGP
- ▶ NCQ scaling is neither a necessary nor a sufficient condition for QGP?
- ▶ Questions:
  - ▶ Is NCQ breaking at low BES due to:
    - ▶ absence of a long-lived partonic stage?
    - ▶ or strong hadronic rescattering?
  - ▶ Which particle species provide the cleanest probes?
  - ▶ Can we disentangle quark collectivity from coalescence kinematics?

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# **SUMMARY**

- ▶ (A)  $v_0$  and  $v_1$ : constrain the system
  - ▶  $v_0$ : reveals interplay of soft / mid / hard components
  - ▶  $v_1$ : controlled by longitudinal density (stopping) & transverse asymmetry + expansion
  - ▶ Energy dependence of  $v_1$  reflects baryon density profiles
- ▶ (B) Collectivity is multistage at BES
  - ▶ Early pressure + spectator blocking + hadronic transport
  - ▶ Strong late-stage modifications
  - ▶ Flow is not purely partonic
- ▶ (C) NCQ scaling: interpretation must be revisited
  - ▶ Approximate scaling with systematic deviations
  - ▶ Sensitive to hadronic-stage effects
  - ▶ NCQ scaling is neither necessary nor sufficient for QGP?