Image from BNL newsroom @Aug. 2, 2017

Bulk observables constraining the QCD equation of state and phase structure

Takafumi Niida

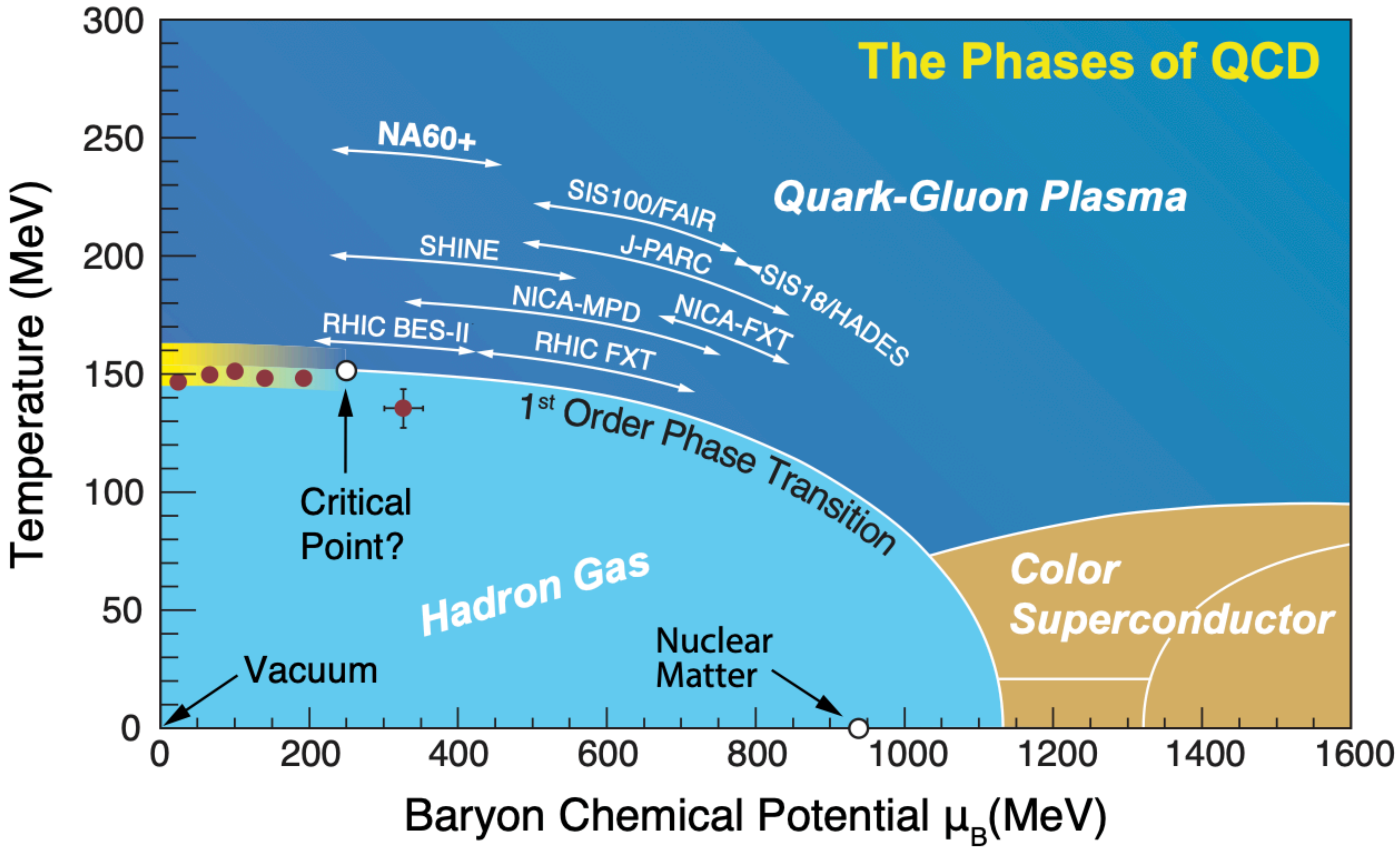
筑波大学
University of Tsukuba

QCD Critical Point and Hydrodynamic Evolution

June 1-4, 2026 @Yukawa Institute for Theoretical Physics

QCD phase diagram

“Conjectured” QCD phase diagram



A. Bzdak et al., Phys. Rep. 853 (2020) 1-87

Lattice QCD suggests:

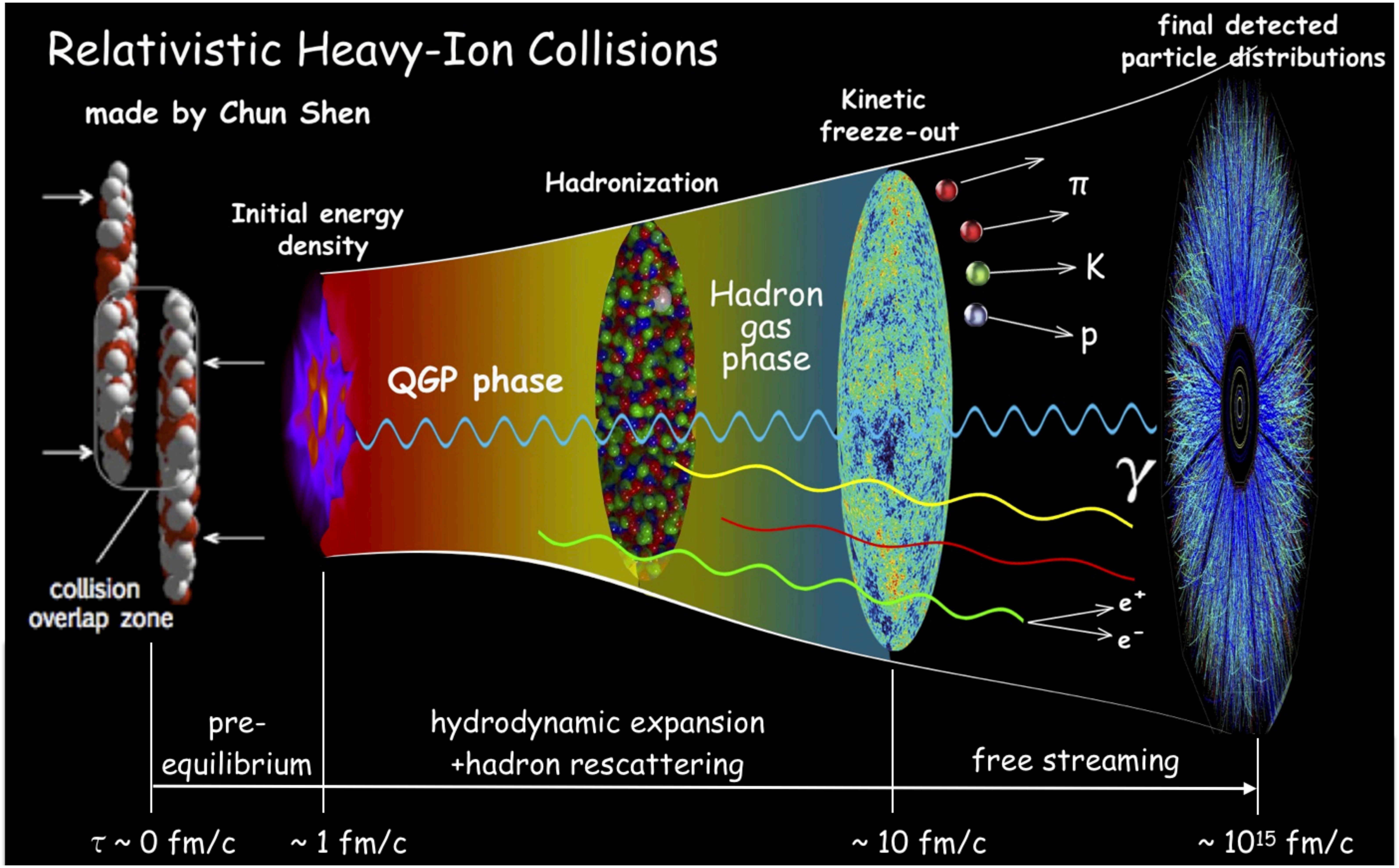
- Smooth crossover at small μ_B
- Pseudo-critical temperature T_{PC} = 156.5 MeV

Y. Aoki et al., Nature 443, 675 (2006)
A. Bazavov et al., PLB795 (2019) 15

Heavy-Ion Collisions Experiment aims to:

- Understand properties of Quark-Gluon Plasma
- Explore the QCD phase structure
  - Where is QCD critical point?
  - Any signal of the first-order phase transition?
  - Onset of QGP formation?

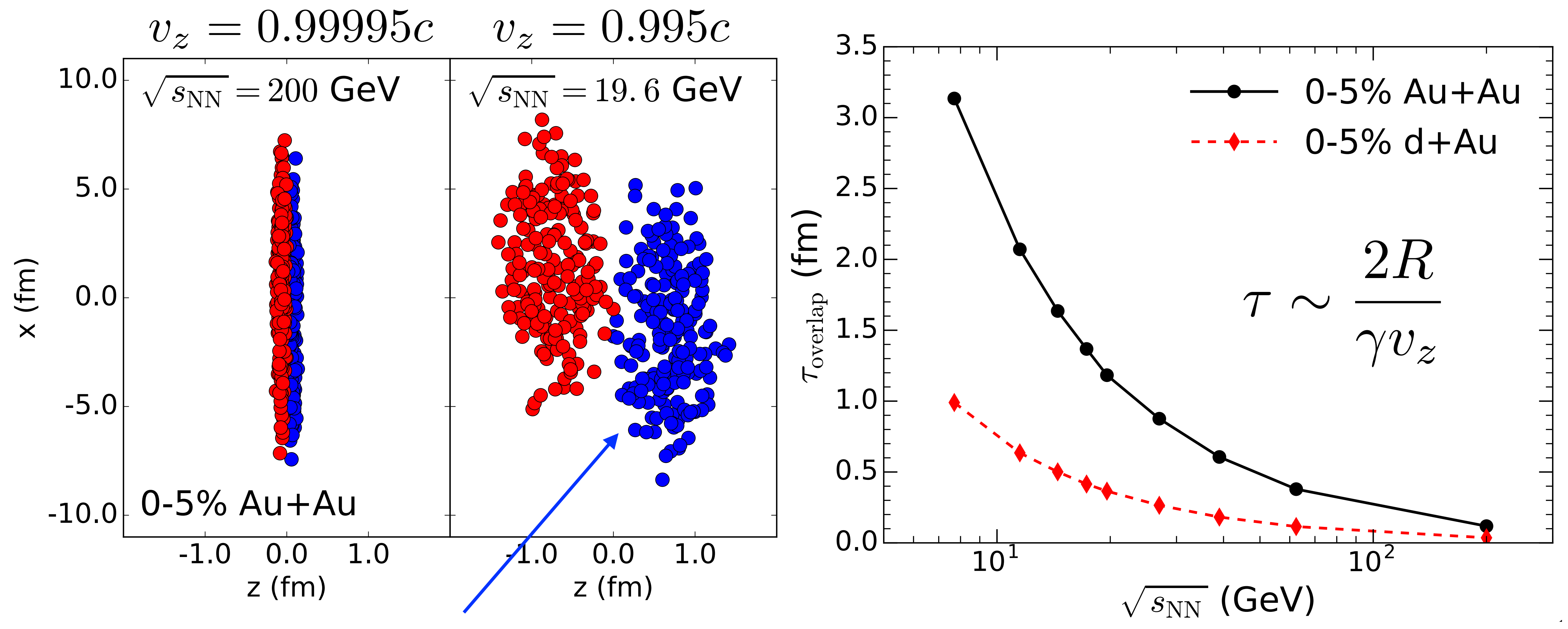
Time evolution of heavy-ion collisions



Understanding the initial state and collision dynamics is essential for probing the QCD phase structure and medium properties

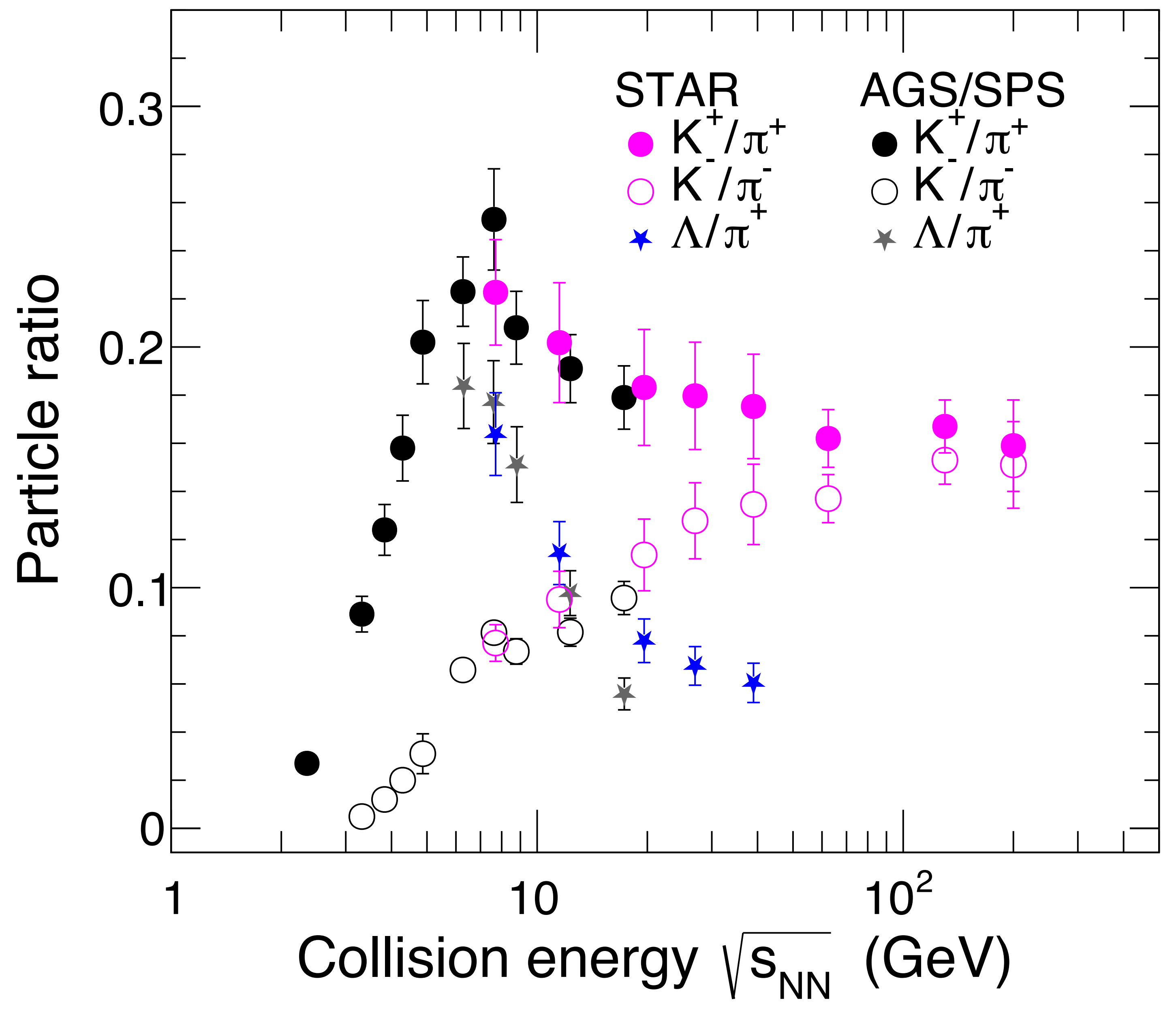
Lowering $\sqrt{s_{NN}}$: Probing the high-baryon-density region

C. Shen and B. Schenke, PRC97.024907(2018)



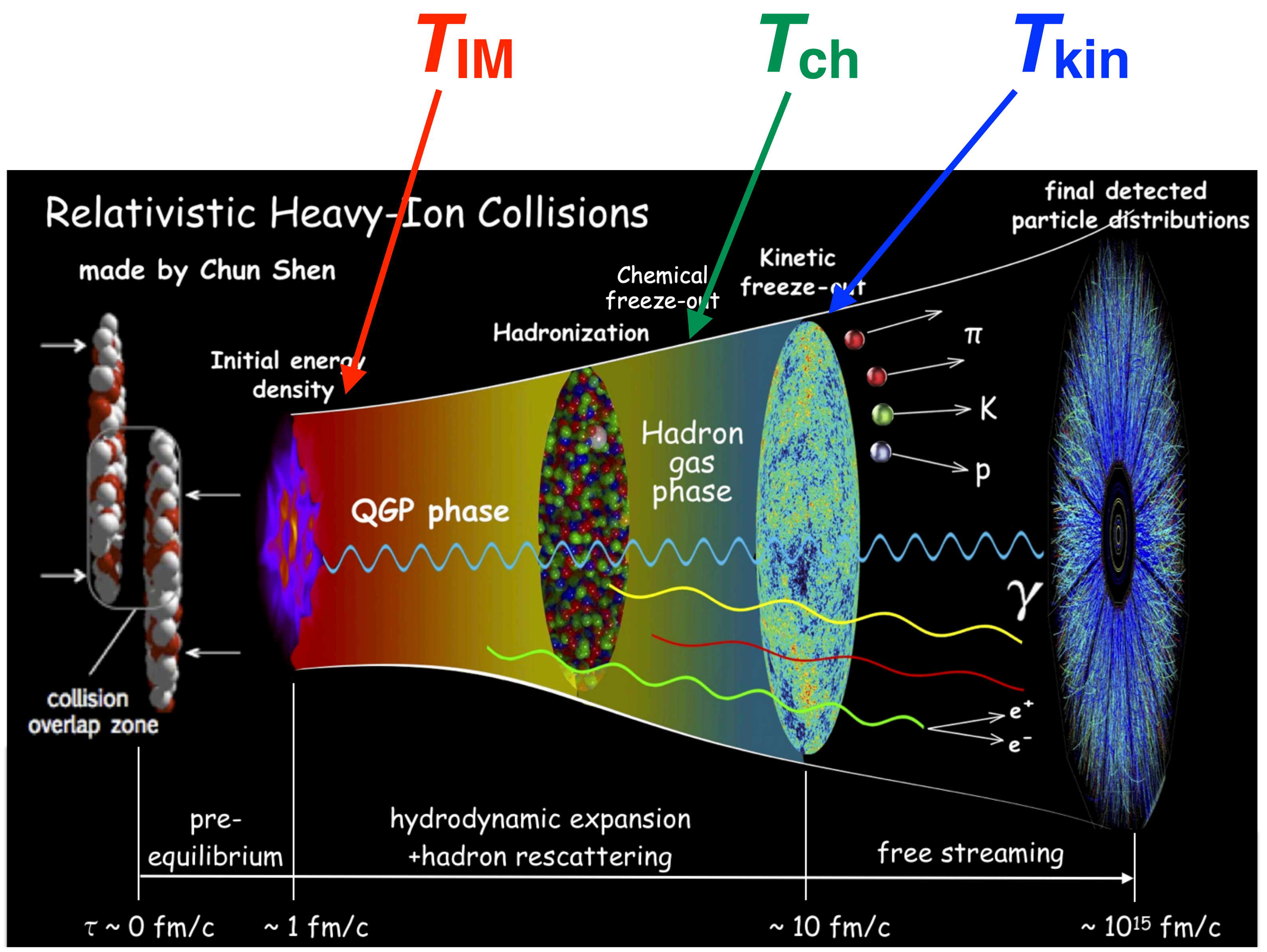
Less Lorentz-contracted at low energy

STAR, PRC96, 044904 (2017)
STAR, PLB831(2022)137152

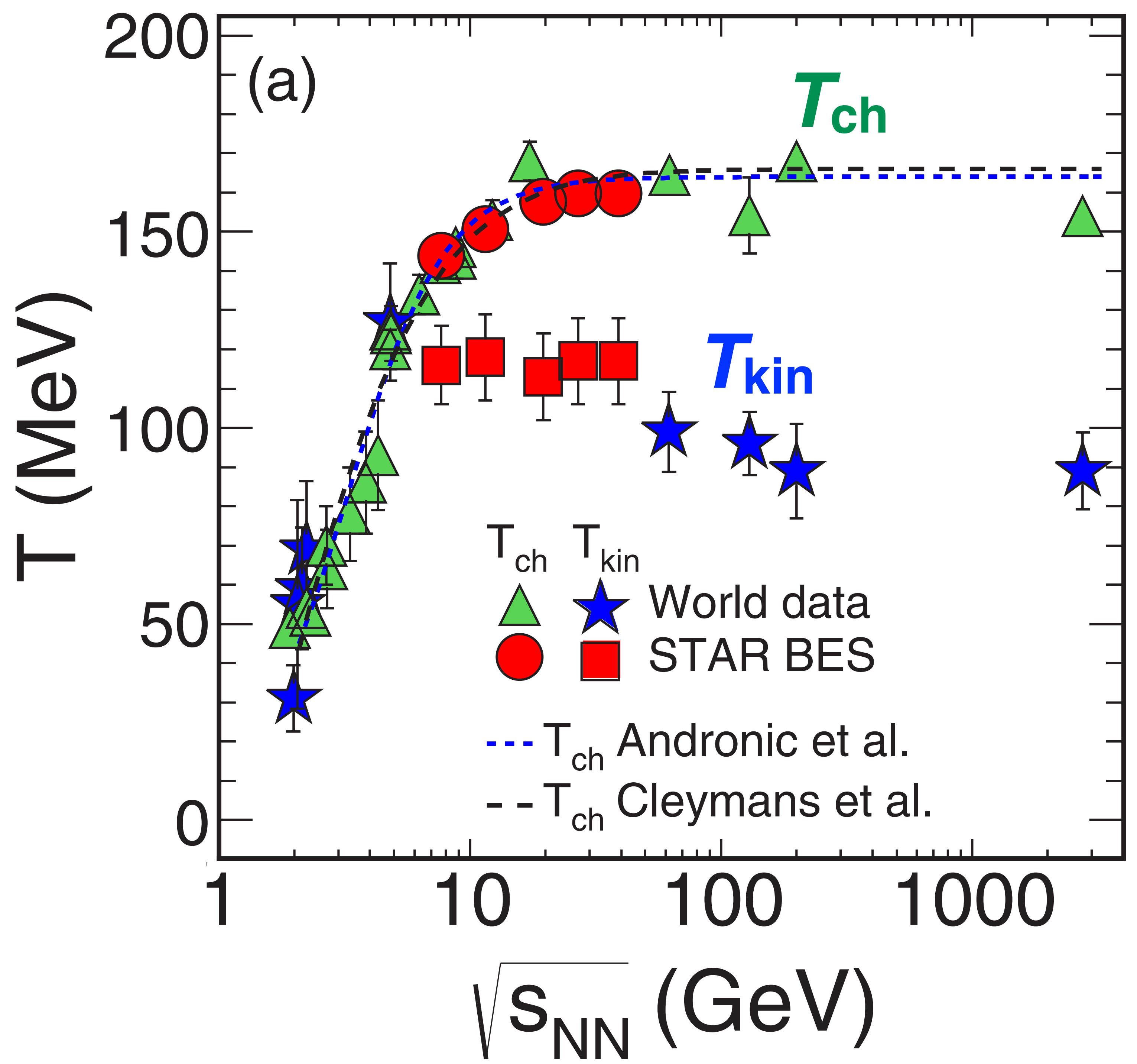


- At lower energy, the passing time increases, leading to more baryons in the reaction region
- Indeed, baryon density seems to become maximum around $\sqrt{s_{NN}}$ = 5-7 GeV
  - Interplay of associate production of K^+ and Λ (N+N->N+Λ+K^+) and particle-antiparticle pair production

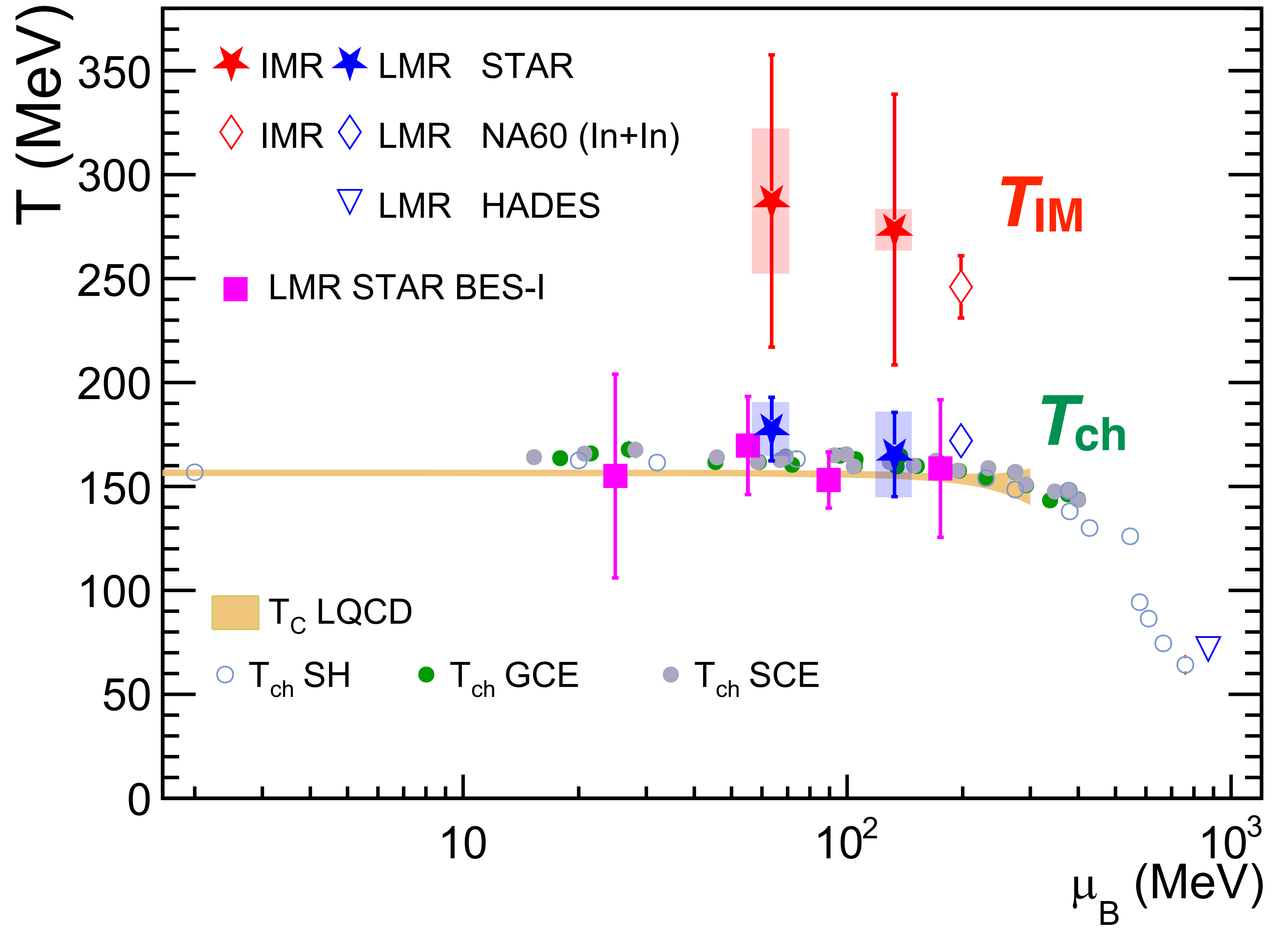
Temperatures at different stages



STAR, PRC96, 044904 (2017)



STAR, Nature Commun. 16, 9098 (2025)

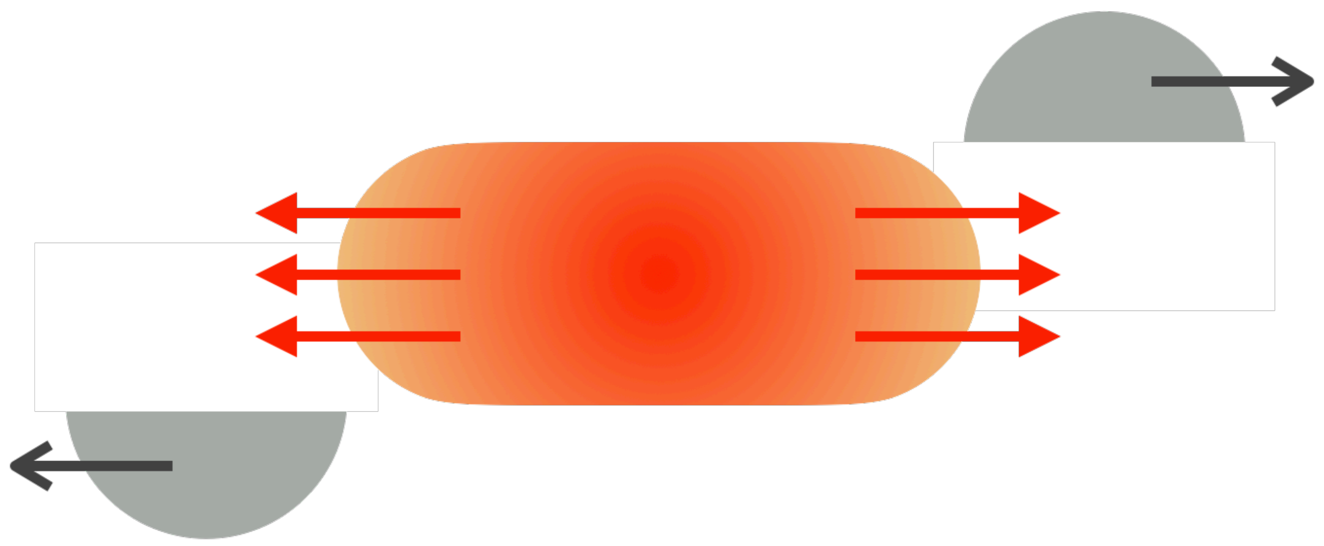
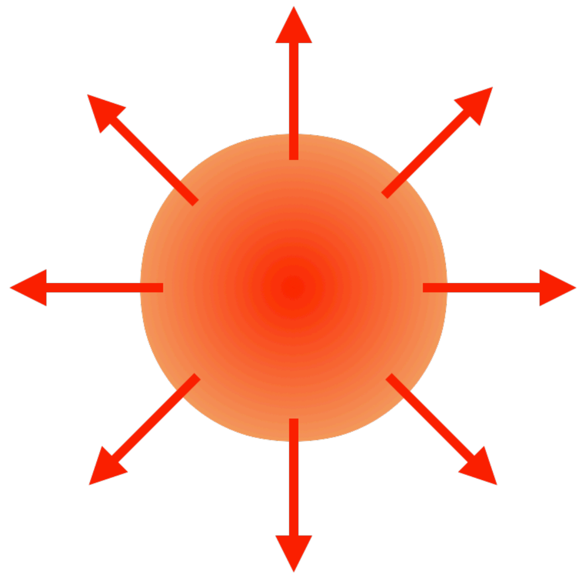
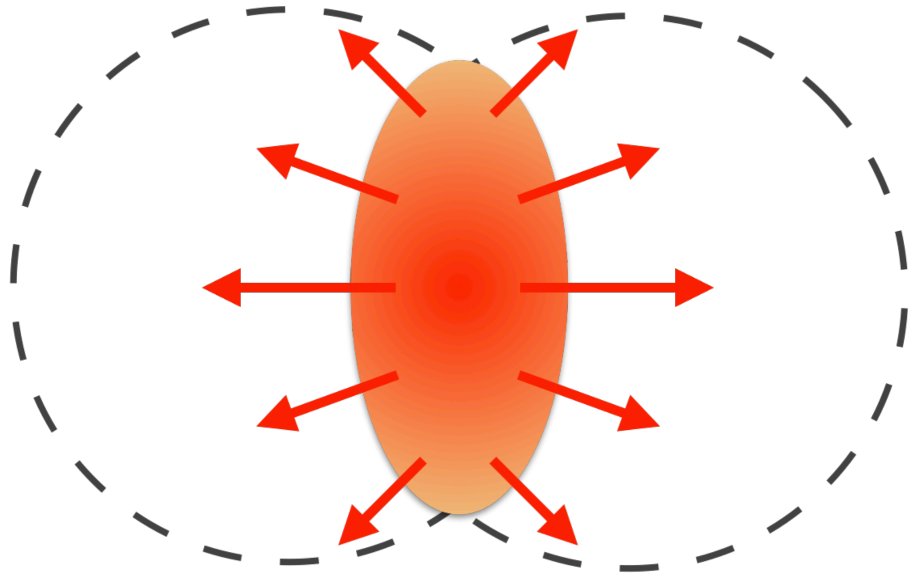


- Chemical freeze-out T_{ch}: Close to T_{PC} and stays constant at $\sqrt{s_{NN}}$ >= 7.7 GeV
- Kinetic freeze-out T_{kin}: Sudden change around $\sqrt{s_{NN}}$ ~ 6-8 GeV, where T_{kin} coincides with T_{ch}

- Temperature via lepton pairs in the intermediate mass T_{IM}
  - Free from blue-shift, dominated by thermal radiation from QGP
  - T_{IM}~280 MeV, much higher than T_{PC} ~156 MeV from LQCD

Collective flow

- Longitudinal collective flow
- Transverse collective flow
  - Radial flow
  - Anisotropic flow

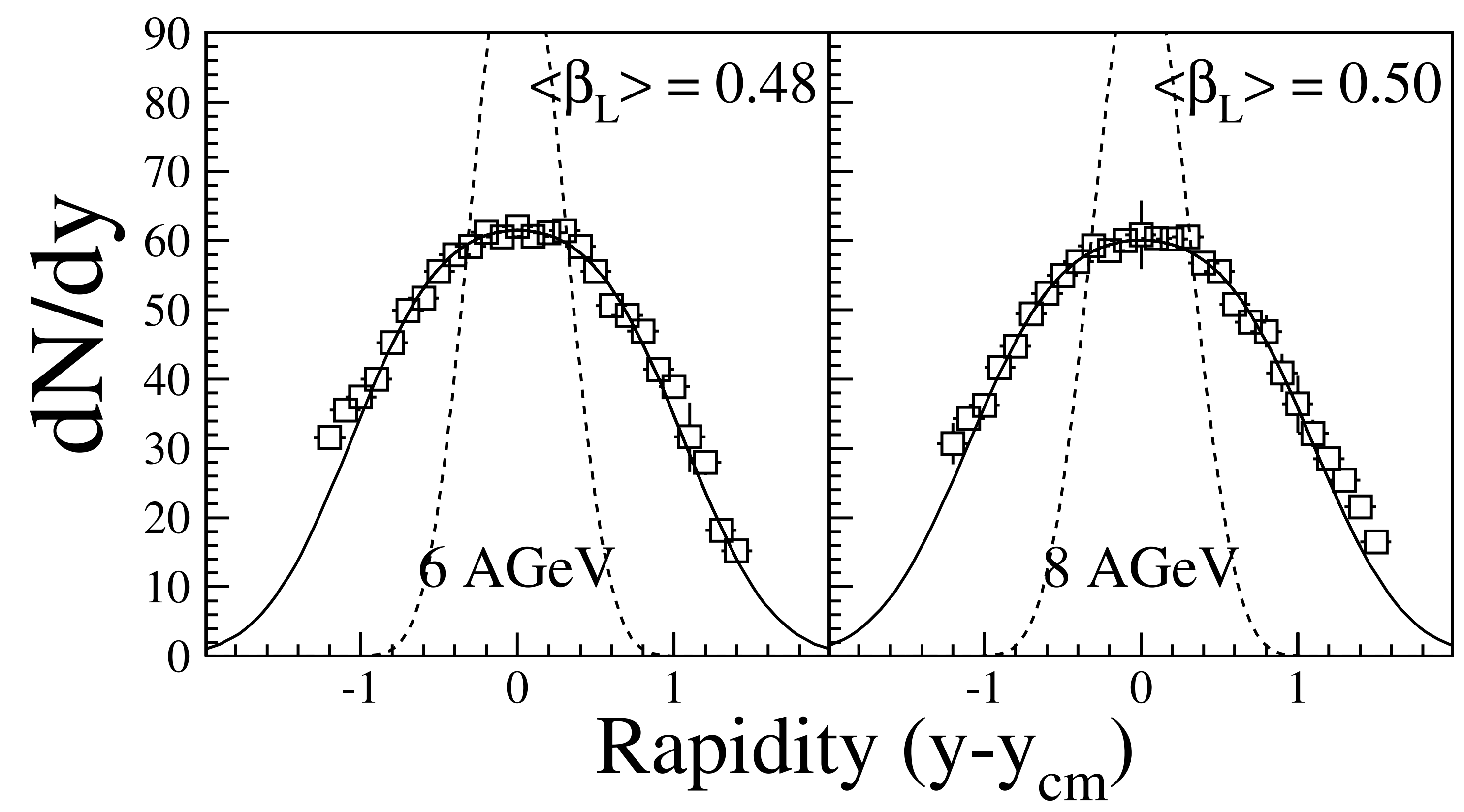




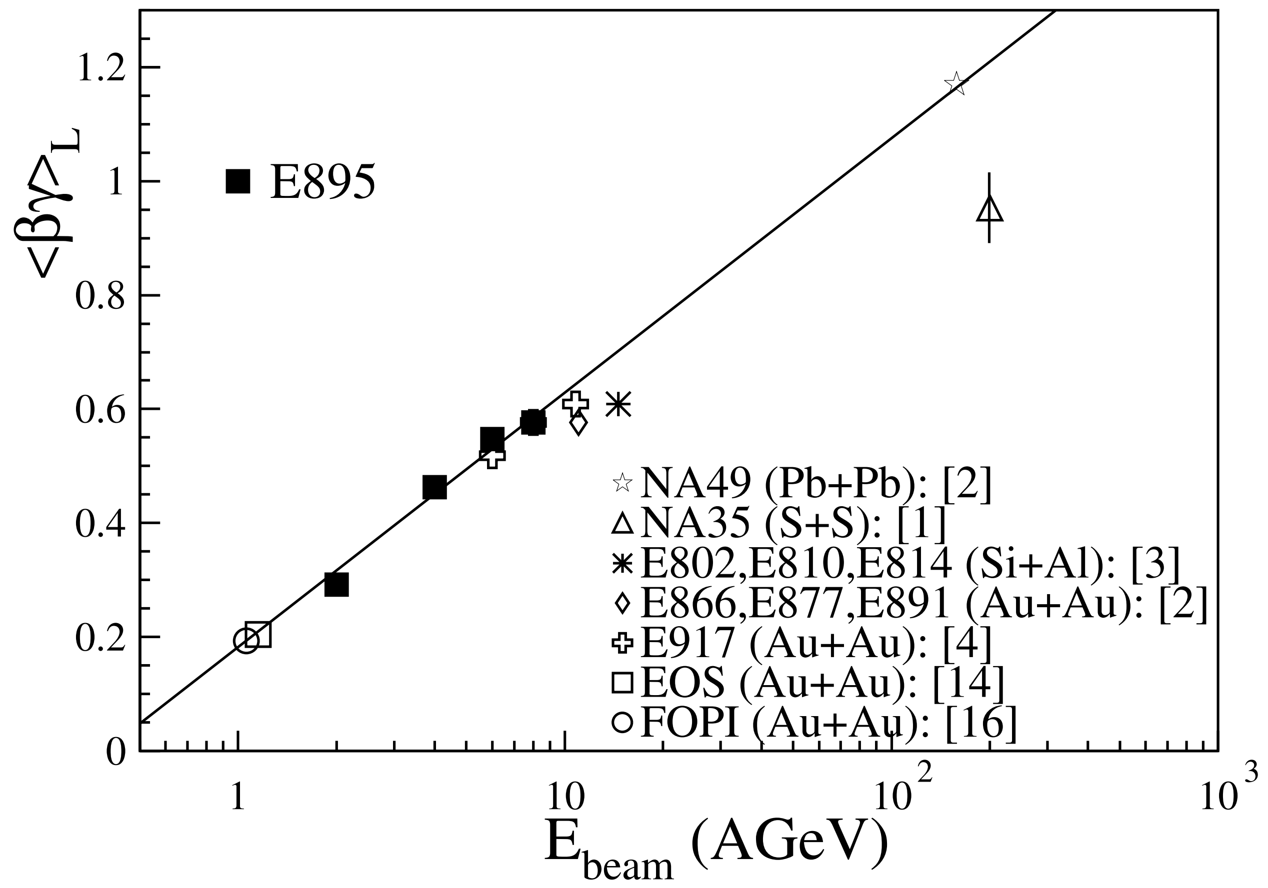
Collective flow

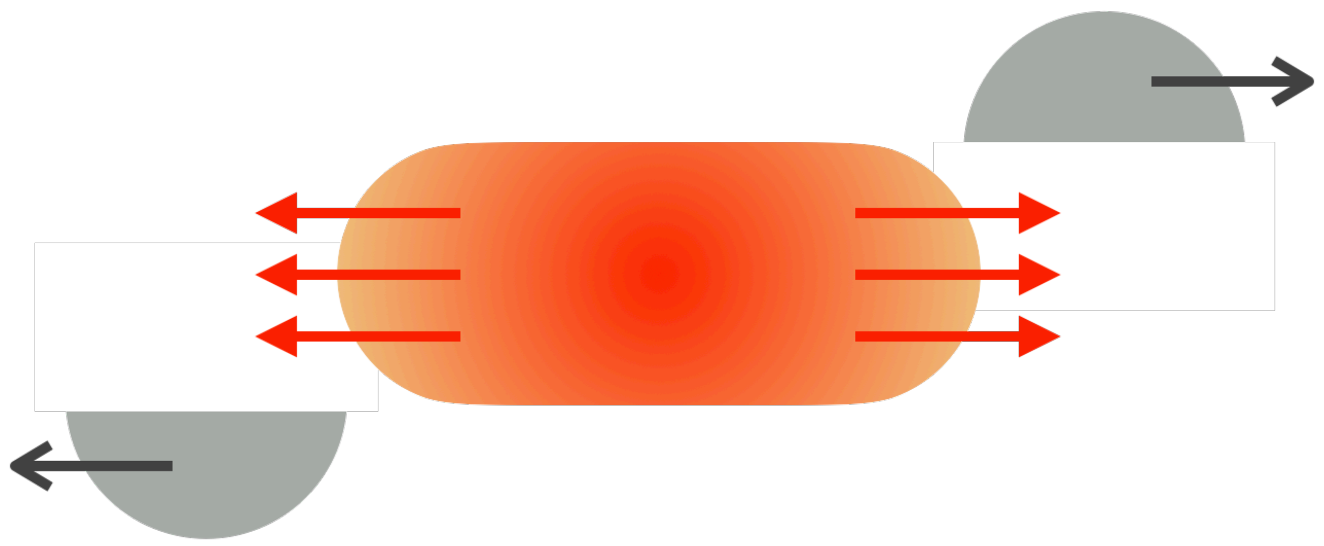
- Longitudinal collective flow
- Transverse collective flow
  - Radial flow
  - Anisotropic flow

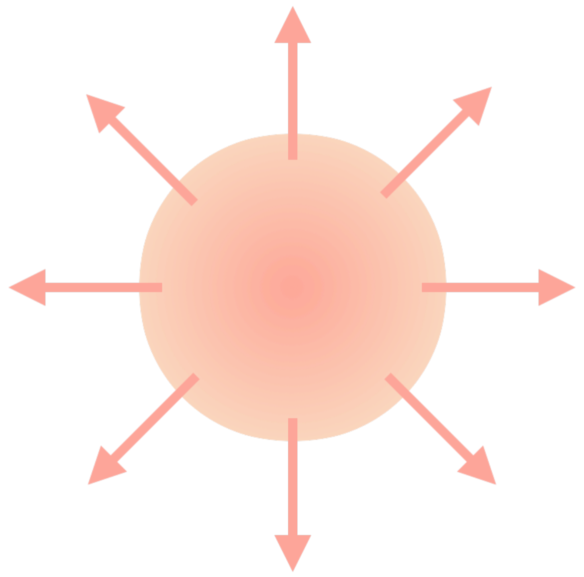
- Related to dN/dη and directed flow
- Longitudinal flow velocity scales with $\log(E_{beam})$

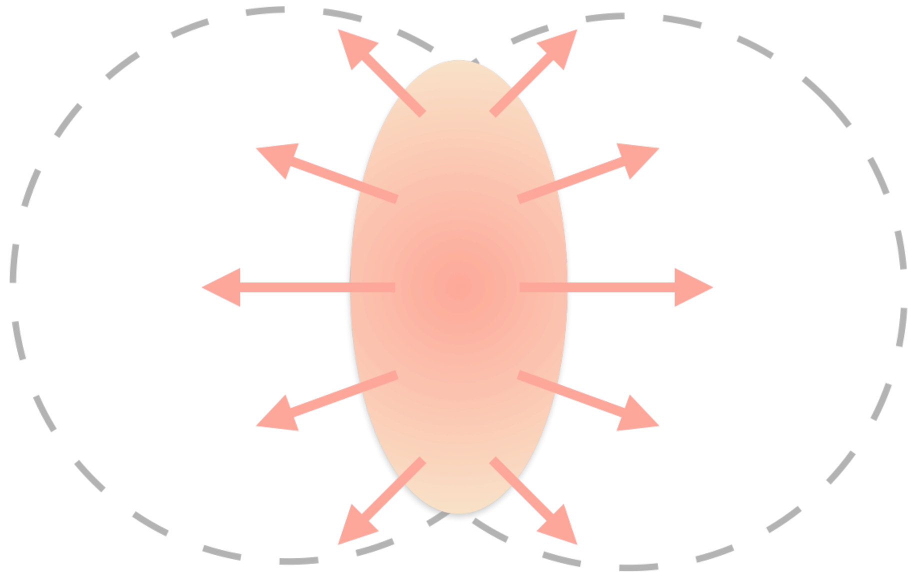
E895, PRL88.102301(2002)









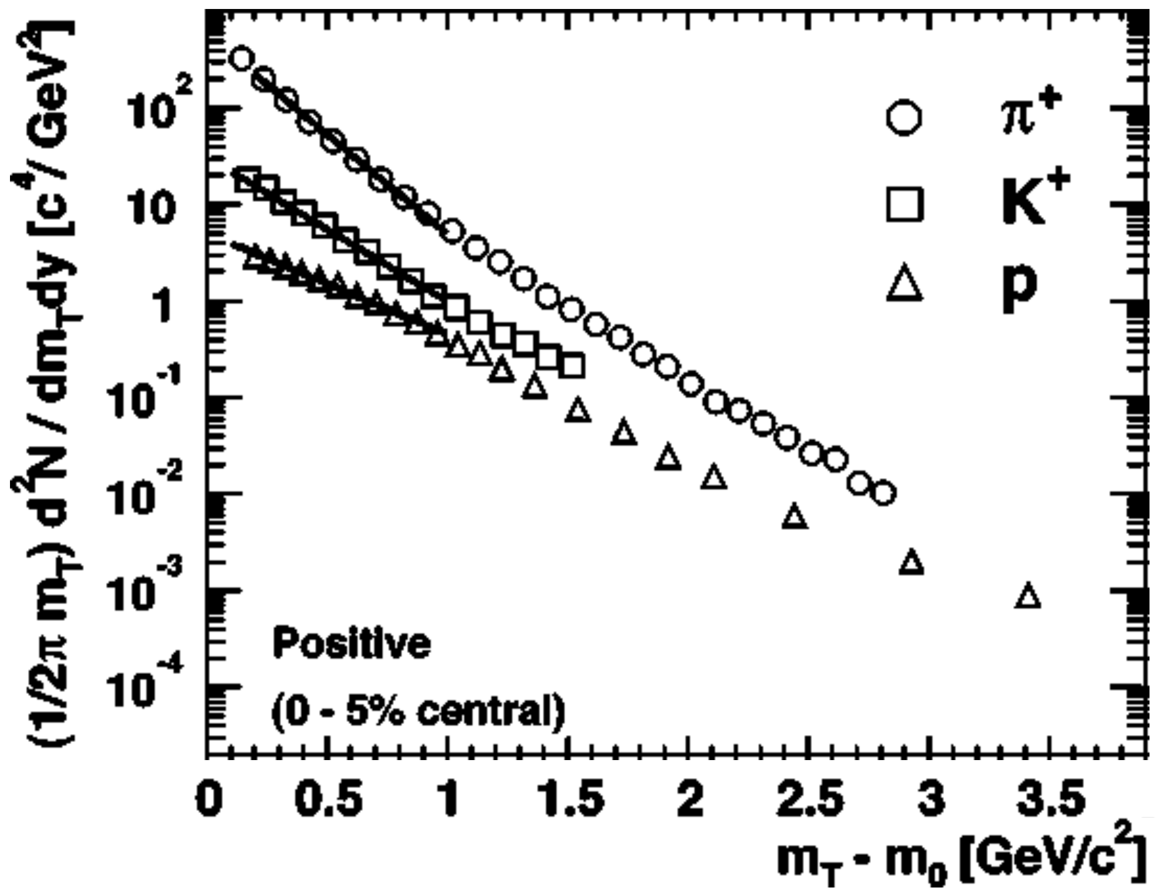


Collective flow

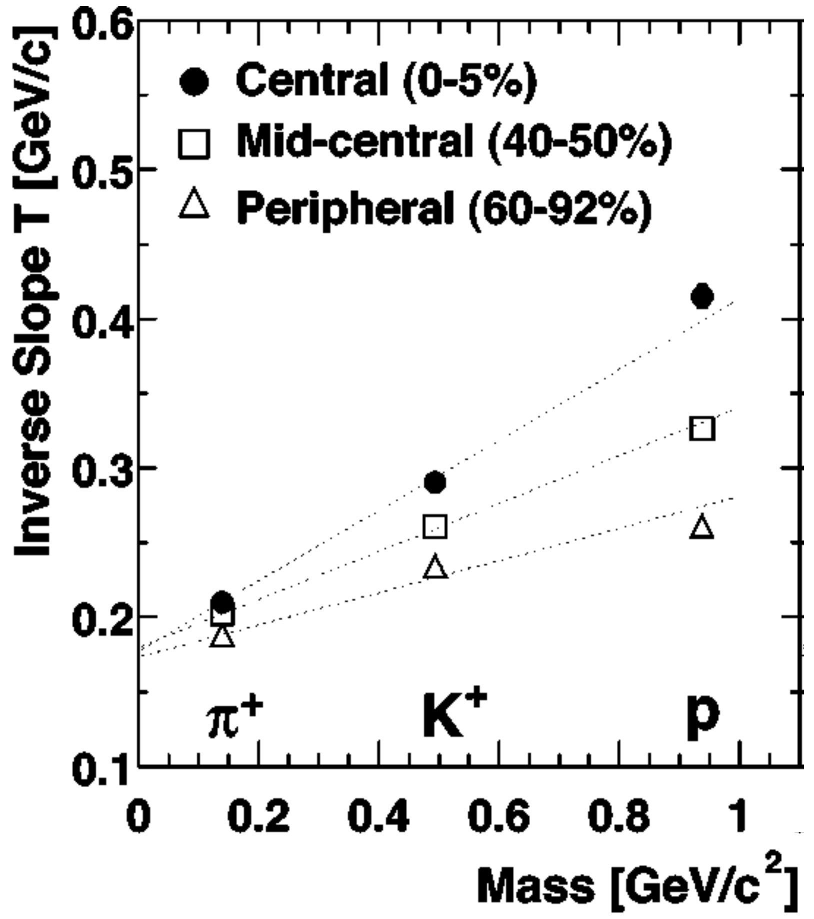
- Longitudinal collective flow
- Transverse collective flow
  - Radial flow
  - Anisotropic flow

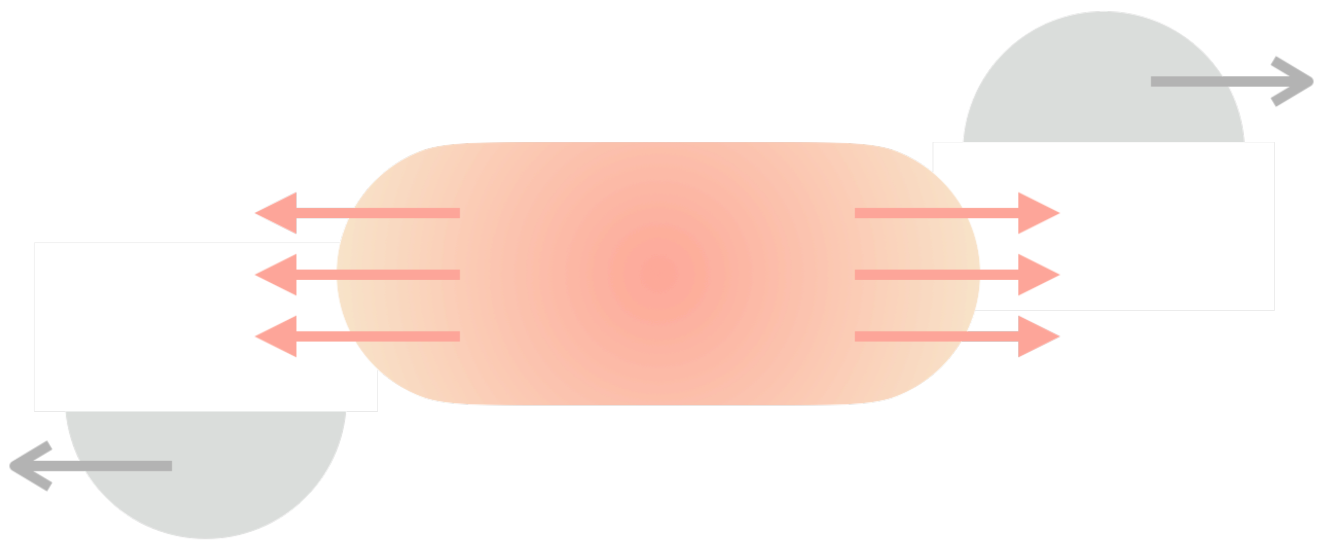
- Radial expansion with a common velocity field
- Studied by spectra, <p_T>, and HBT etc
- "v_0" (p_T fluctuations) has been recently proposed

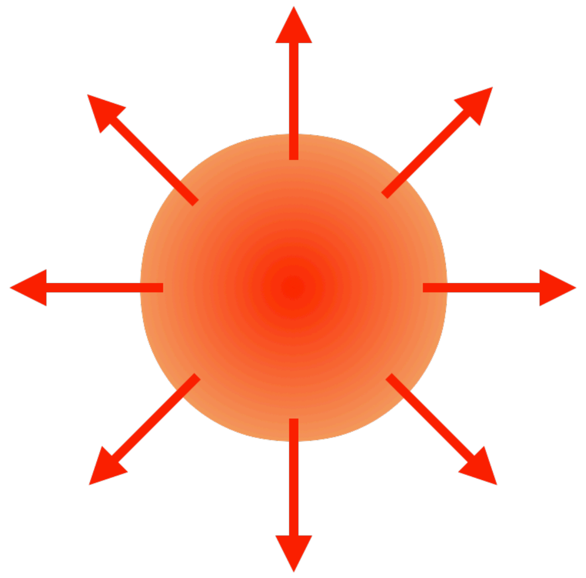
PHENIX, PRC69.034909(2004)

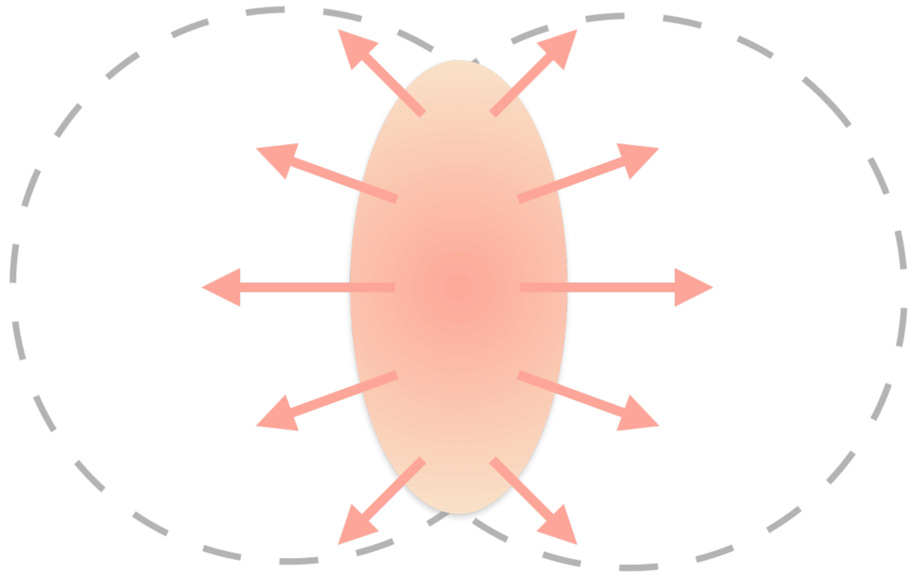


$$T \approx T_0 + \frac{1}{2}m\langle v_r \rangle^2$$







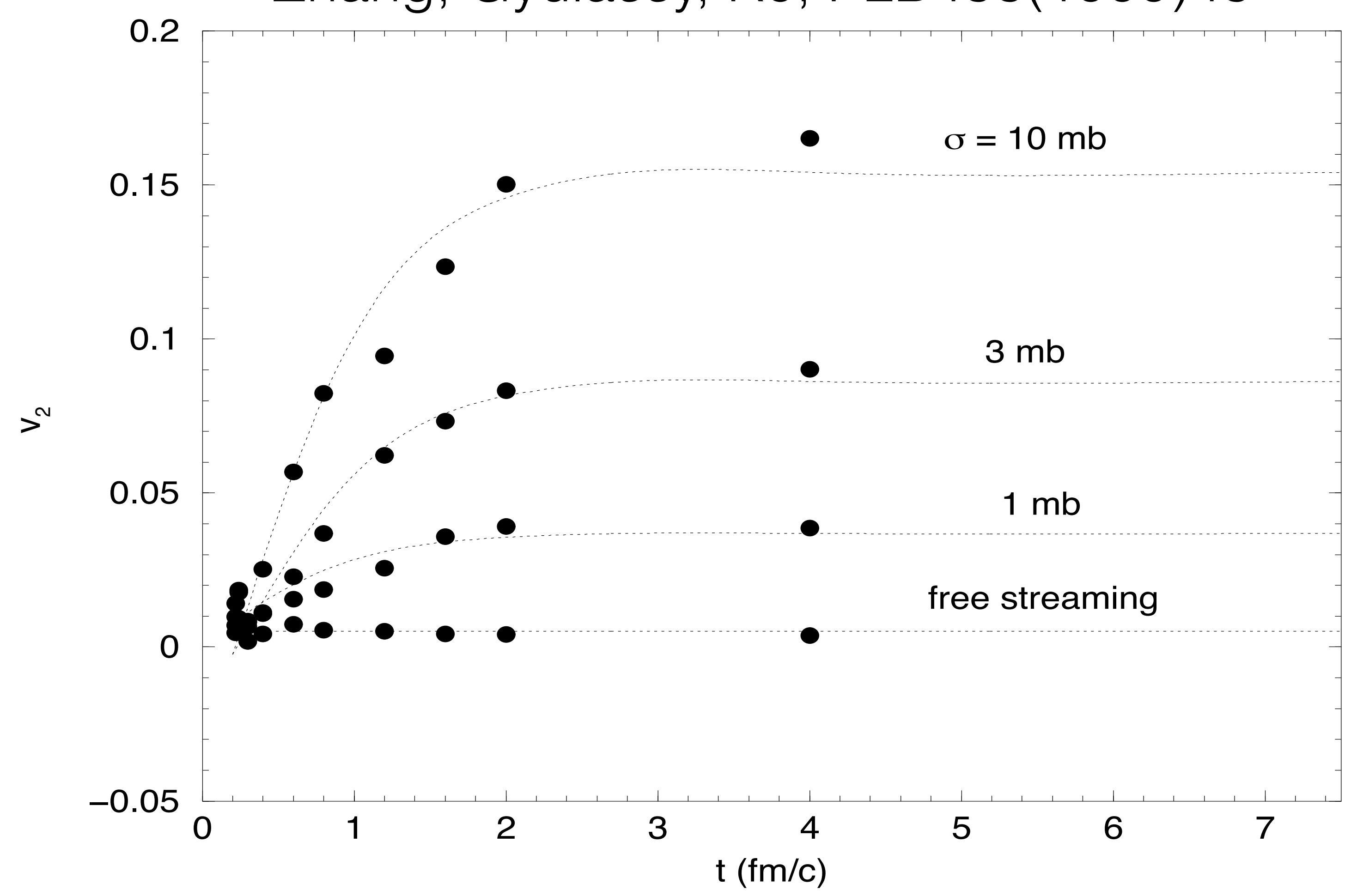


Collective flow

- Longitudinal collective flow
- Transverse collective flow
  - Radial flow
  - Anisotropic flow

- Hydrodynamic response to the initial geometry driven by pressure gradients

Zhang, Gyulassy, Ko, PLB455(1999)45

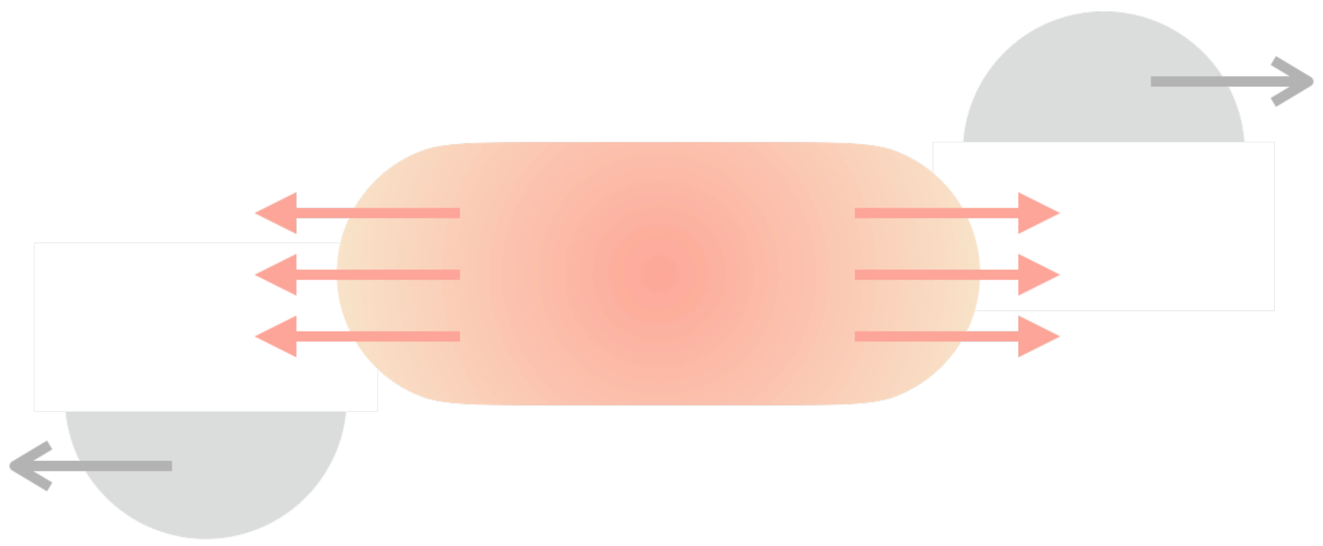


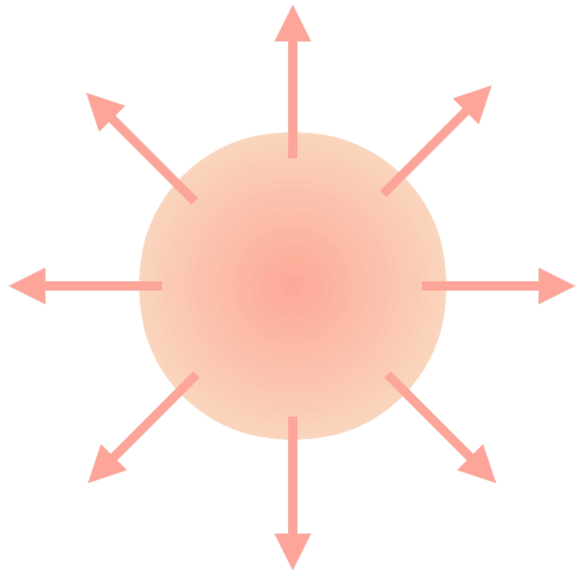
If $\ell/R \ll 1$, hydrodynamics!

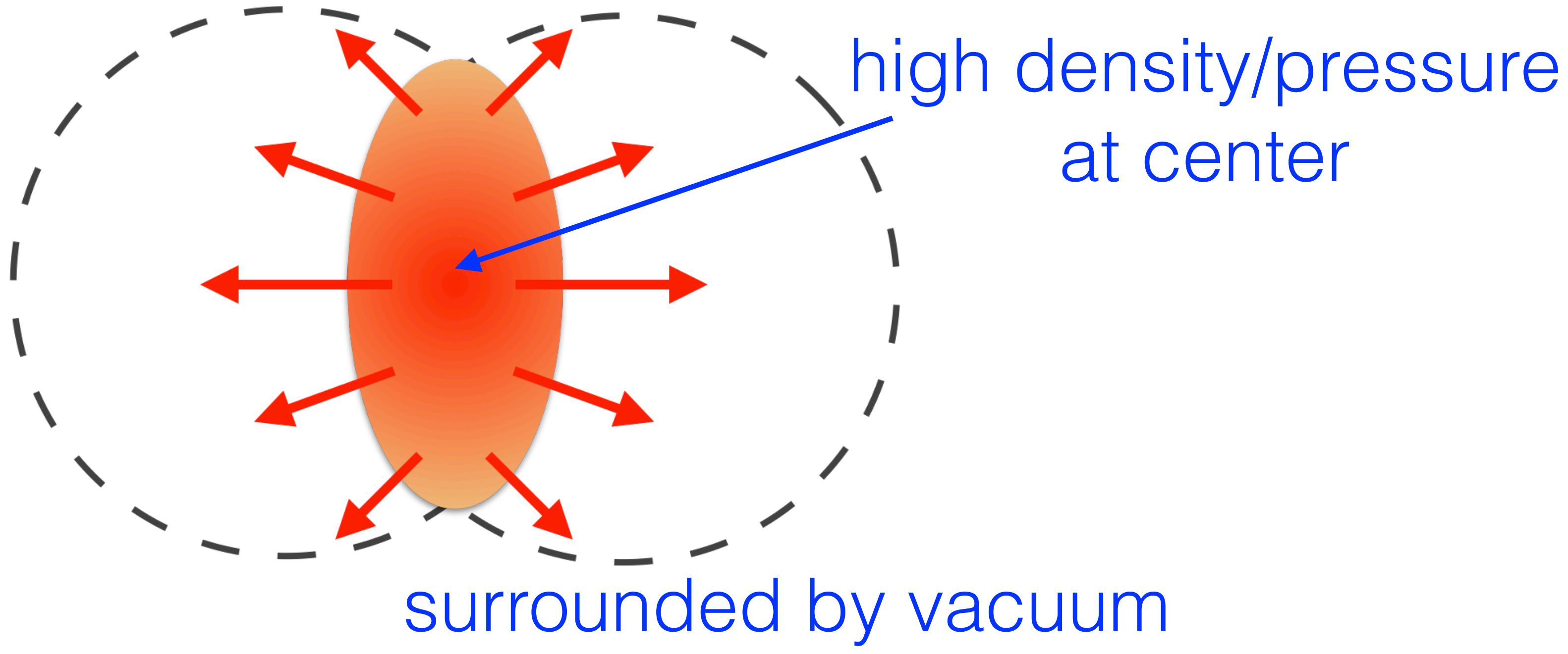
$$\ell = \frac{1}{n\sigma}: \text{ mean free path}$$

$$K_n = \ell/R: \text{ Knudsen number}$$

$$\varepsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \longrightarrow v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

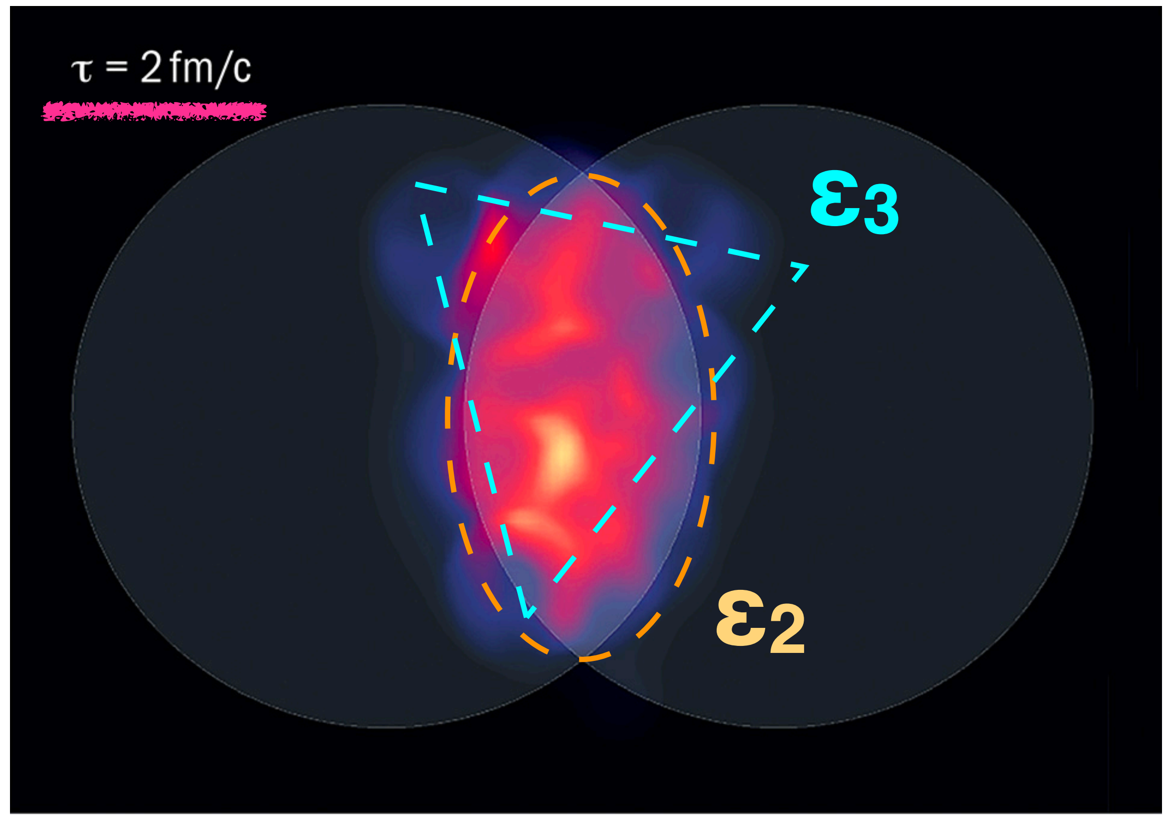


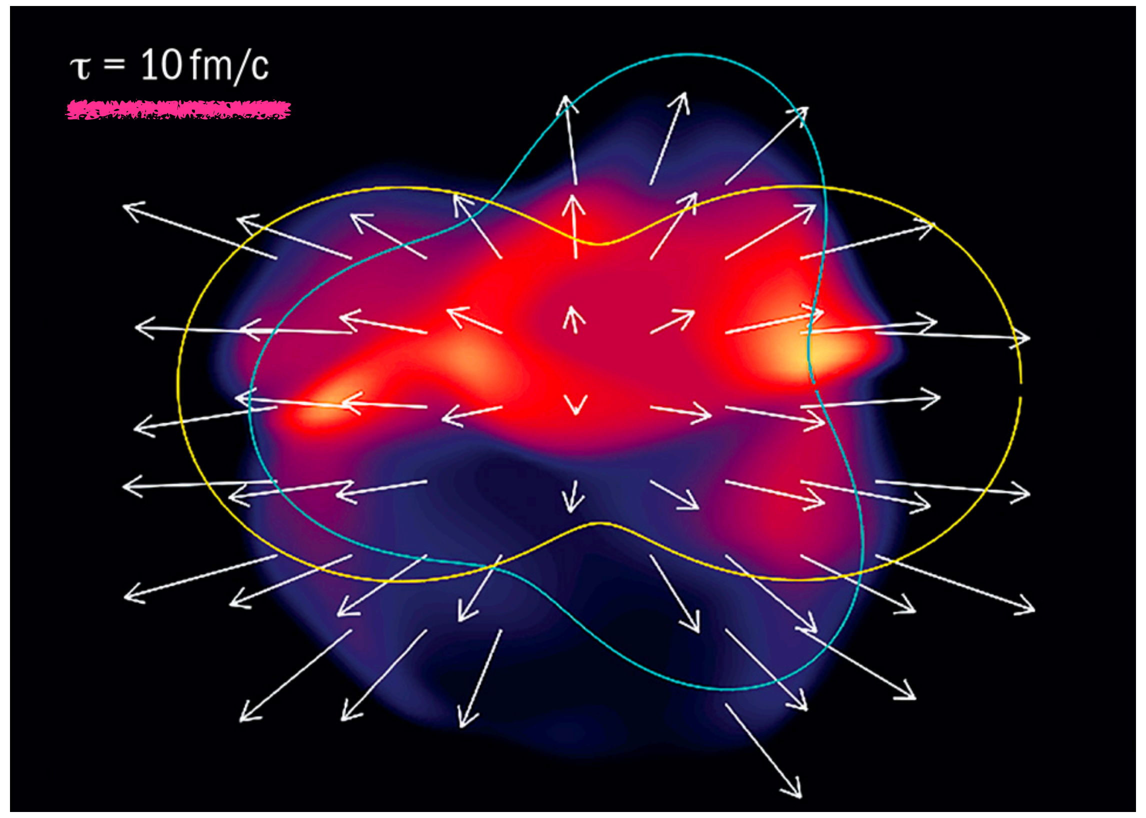




Azimuthal anisotropic flow

Hydrodynamic model (MUSIC), CERN COURIER





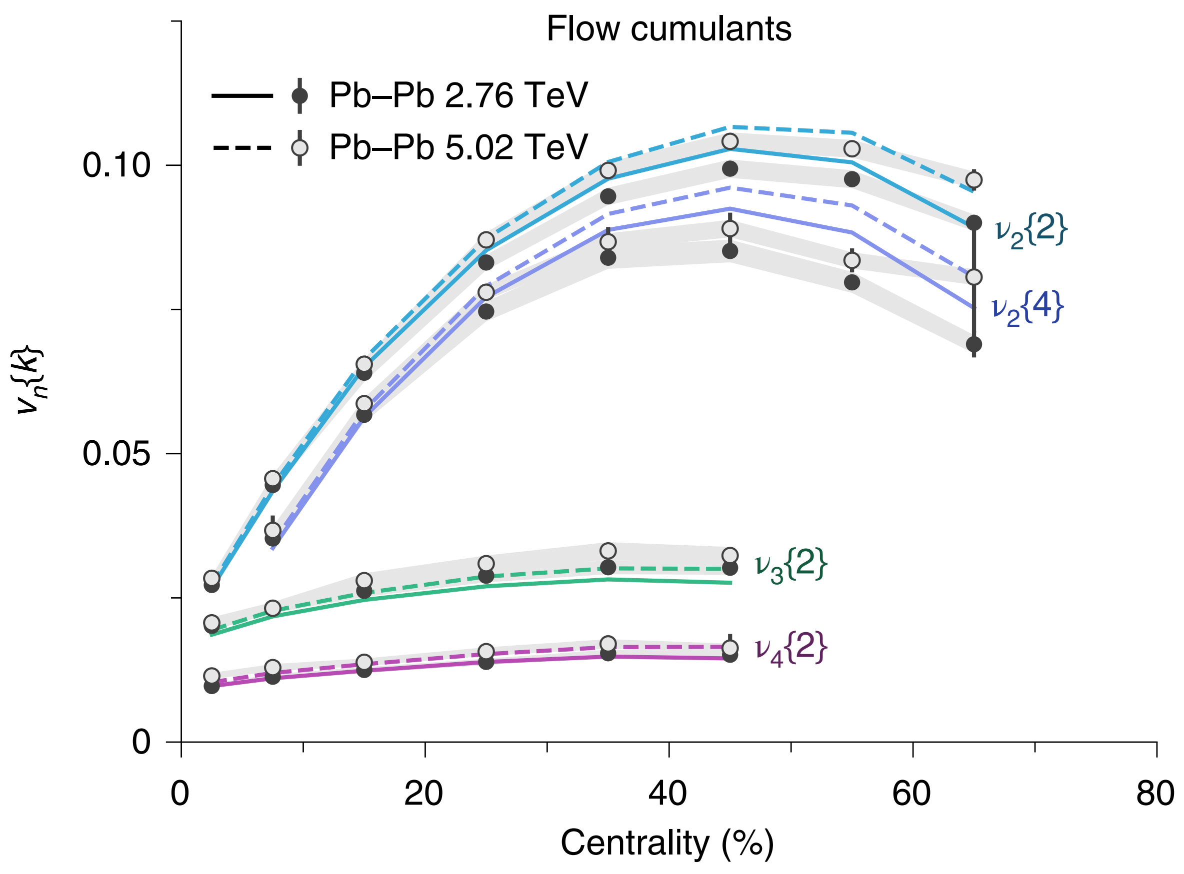
- Extensive study of anisotropic flow for particle collectivity
  - Medium response to the initial geometry with fluctuations

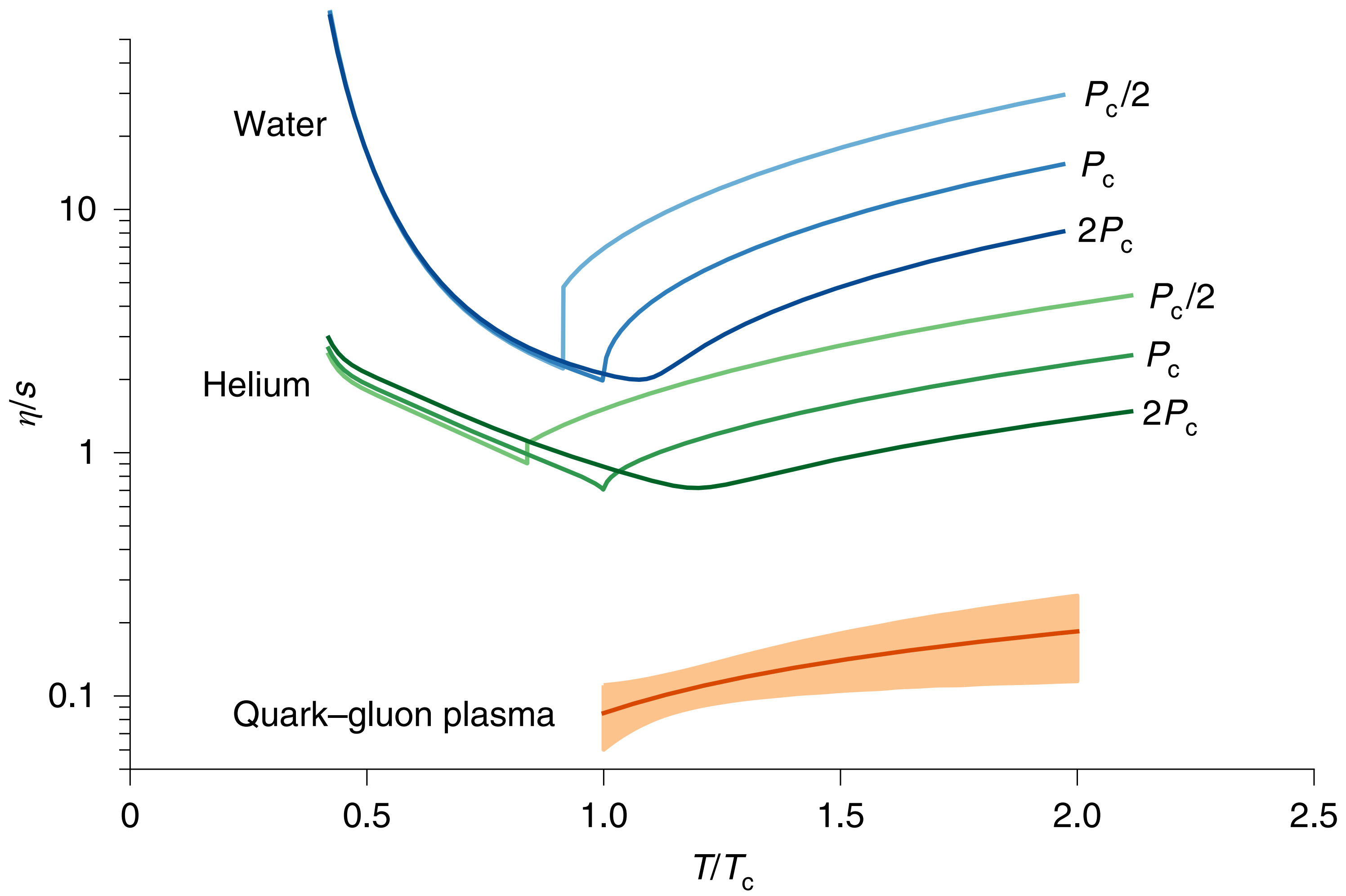
$$\varepsilon_n \propto v_n$$

- Anisotropic flow: Fourier coefficient v_n of azimuthal distributions of final state particles
  - directed (v_1), elliptic (v_2), triangular (v_3) flow

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

ϕ: particle azimuthal angle
relative to the nth-order event plane



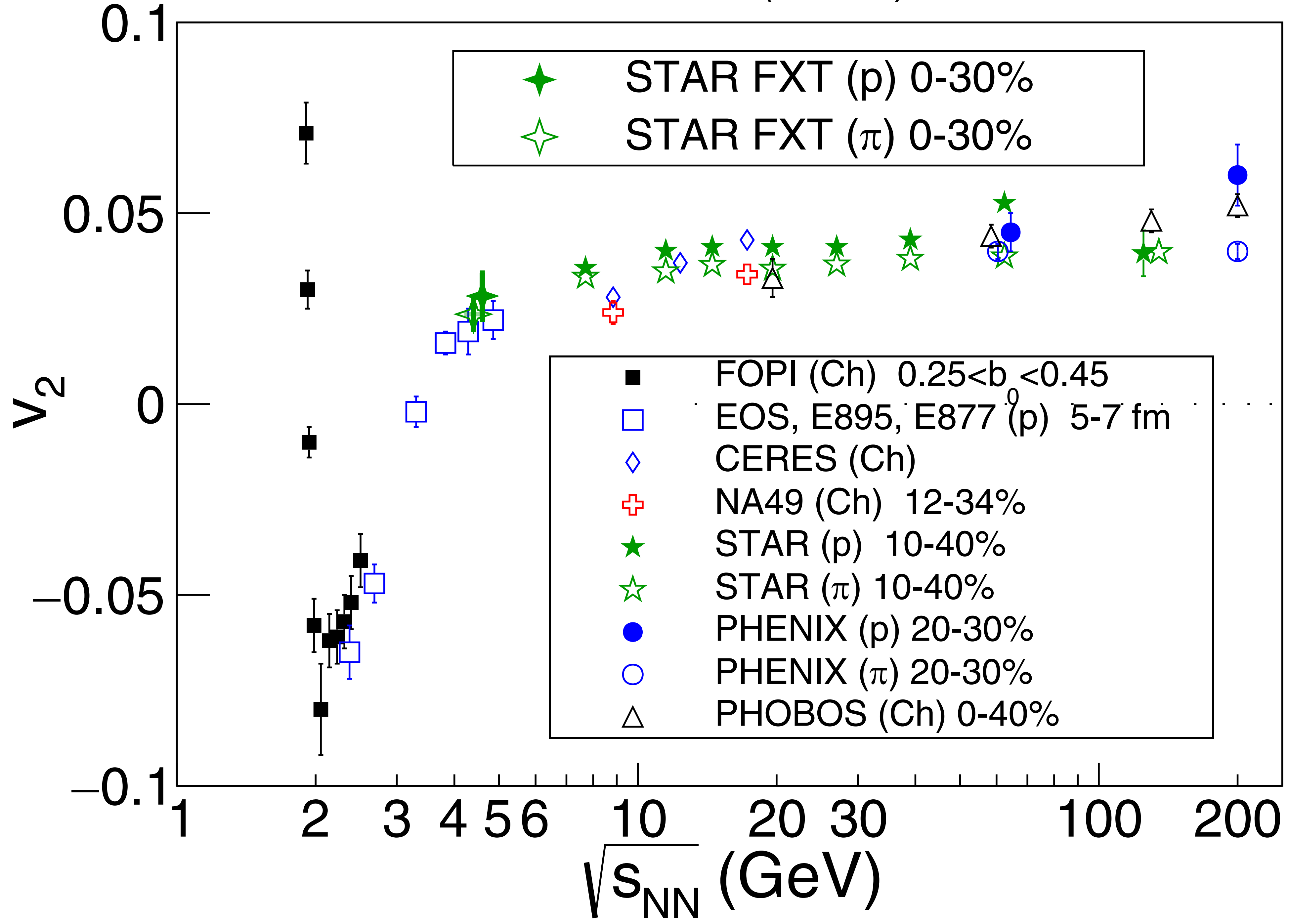


Bernhard et al., Nat. Phys.15, 1113 (2019)

A nearly perfect fluid of quarks and gluons

Energy dependence of elliptic flow

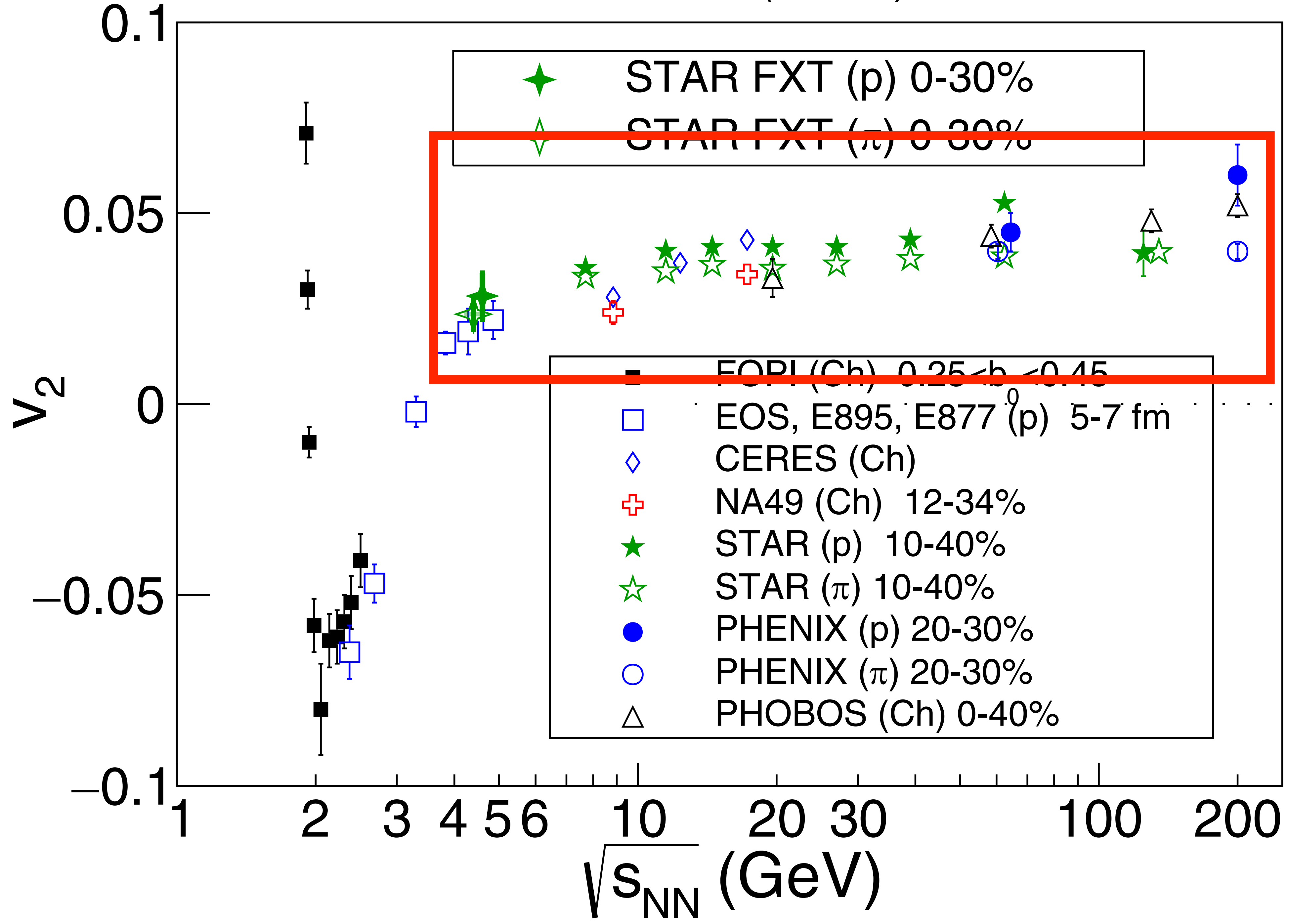
STAR, PRC103, 034908 (2021)



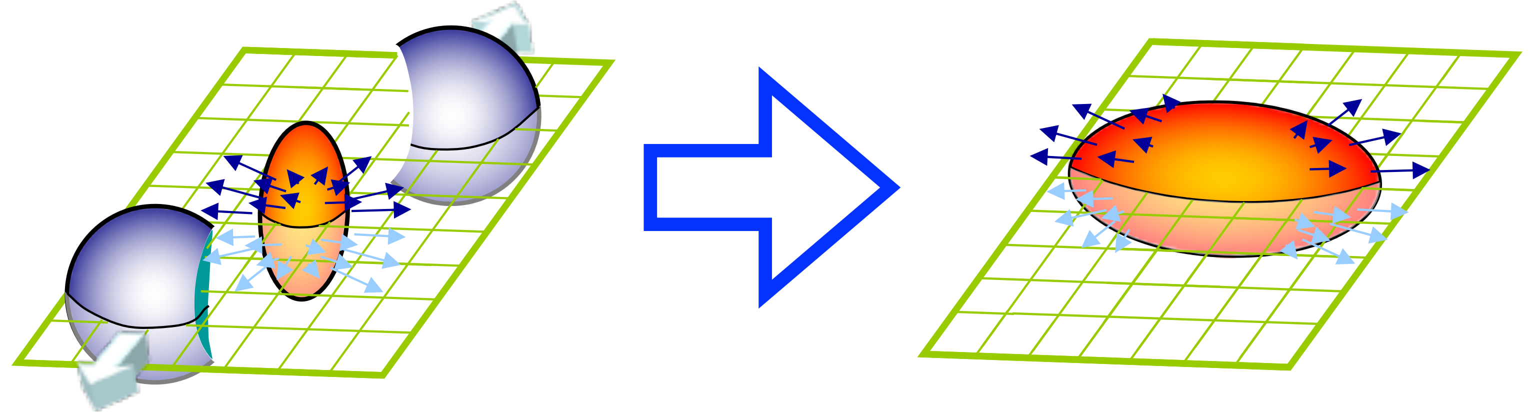
The sign of v_2 changes twice when decreasing the collision energy

Energy dependence of elliptic flow

STAR, PRC103, 034908 (2021)



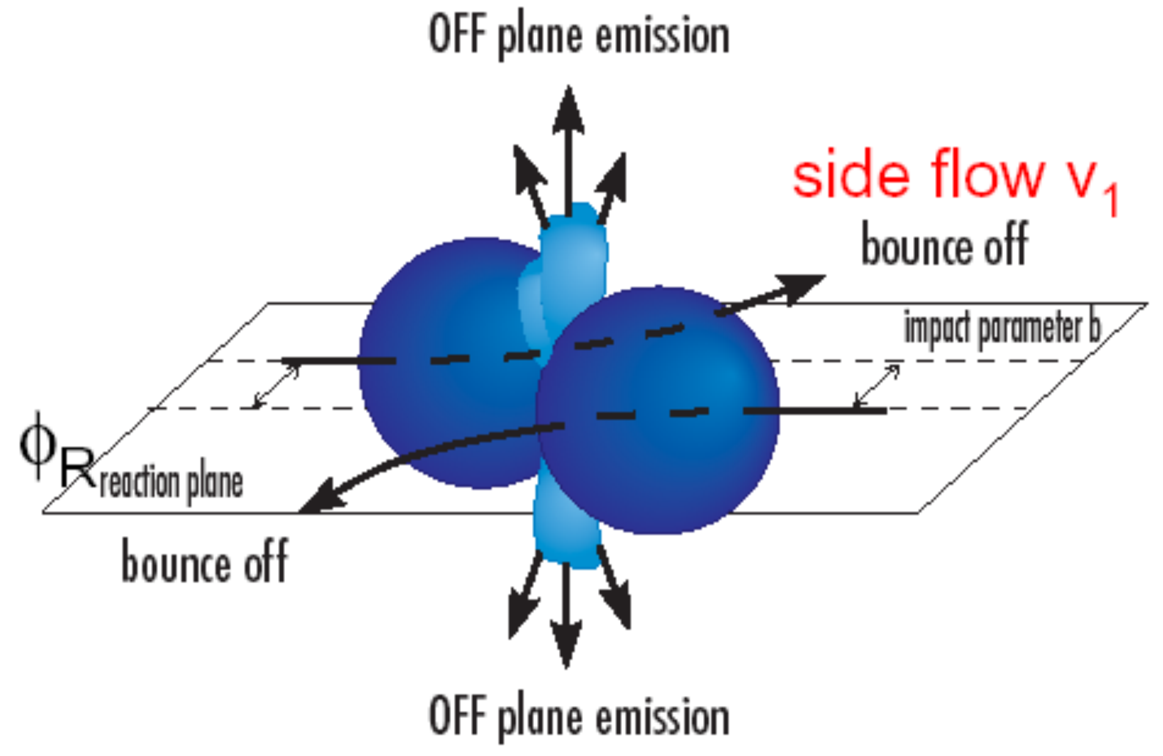
pressure-gradient-driven expansion
(v_2>0 at $\sqrt{s_{NN}}$>4 GeV)



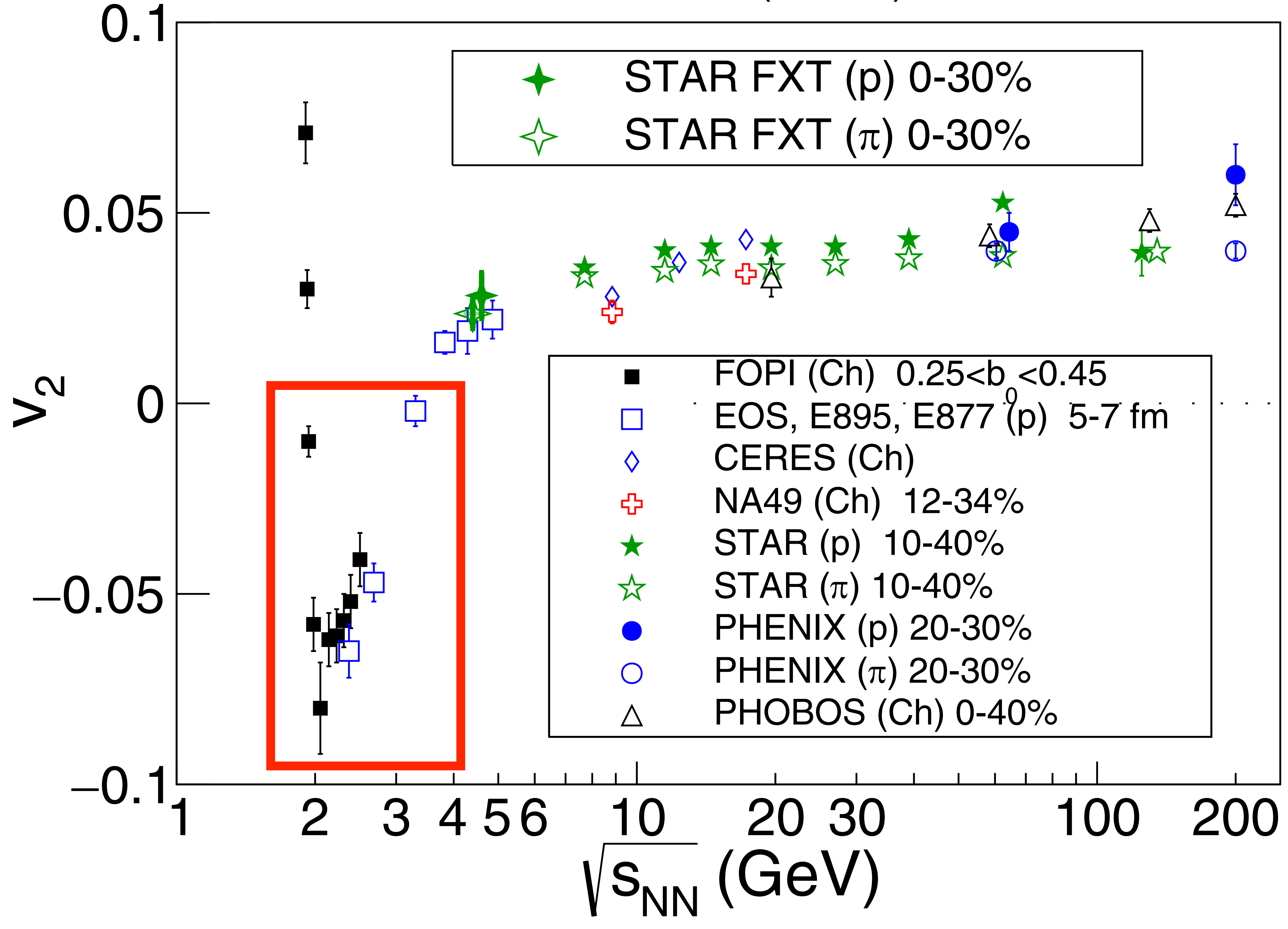
The sign of v_2 changes twice when decreasing the collision energy

Energy dependence of elliptic flow

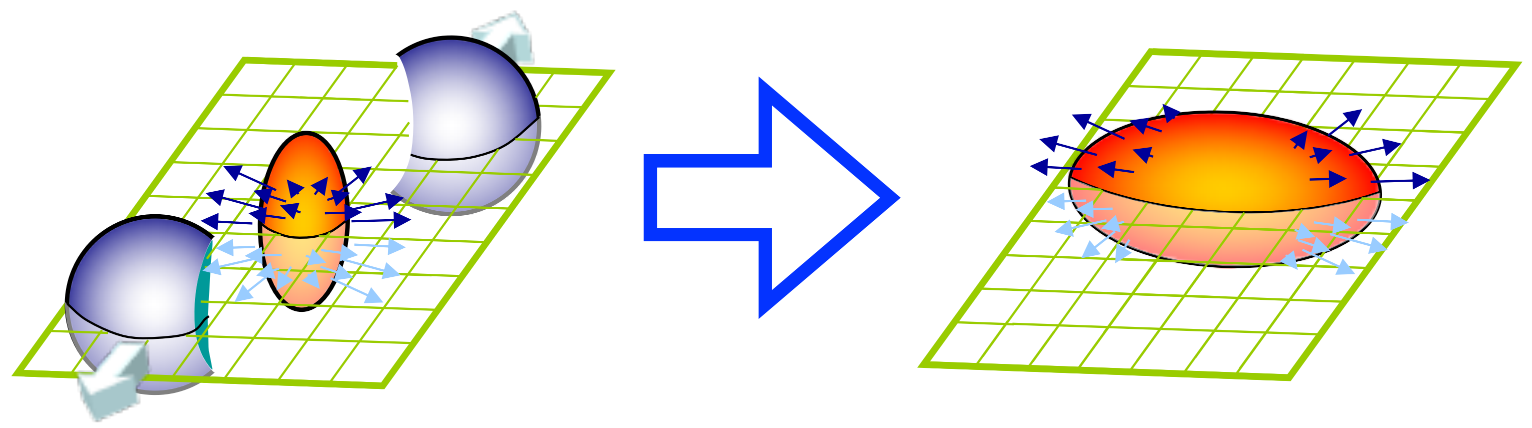
“squeeze-out” emission (v_2<0)



STAR, PRC103, 034908 (2021)



pressure-gradient-driven expansion (v_2>0 at $\sqrt{s_{NN}}$ >4 GeV)

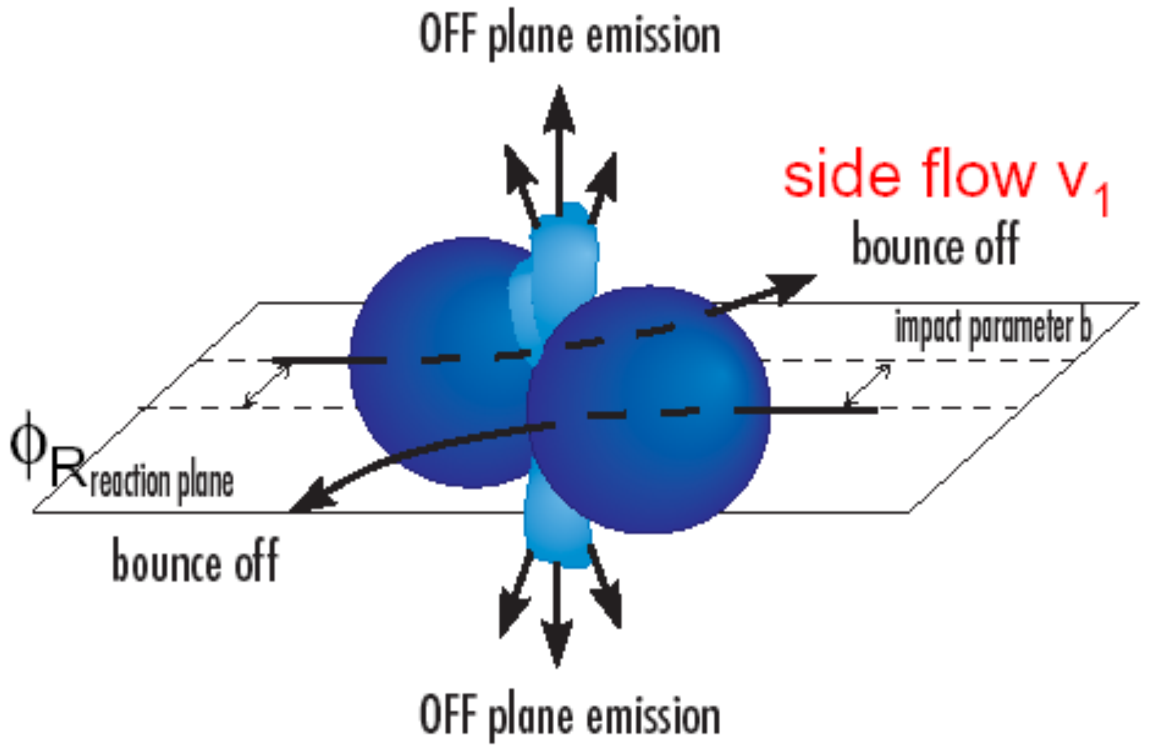


The sign of v_2 changes twice when decreasing the collision energy

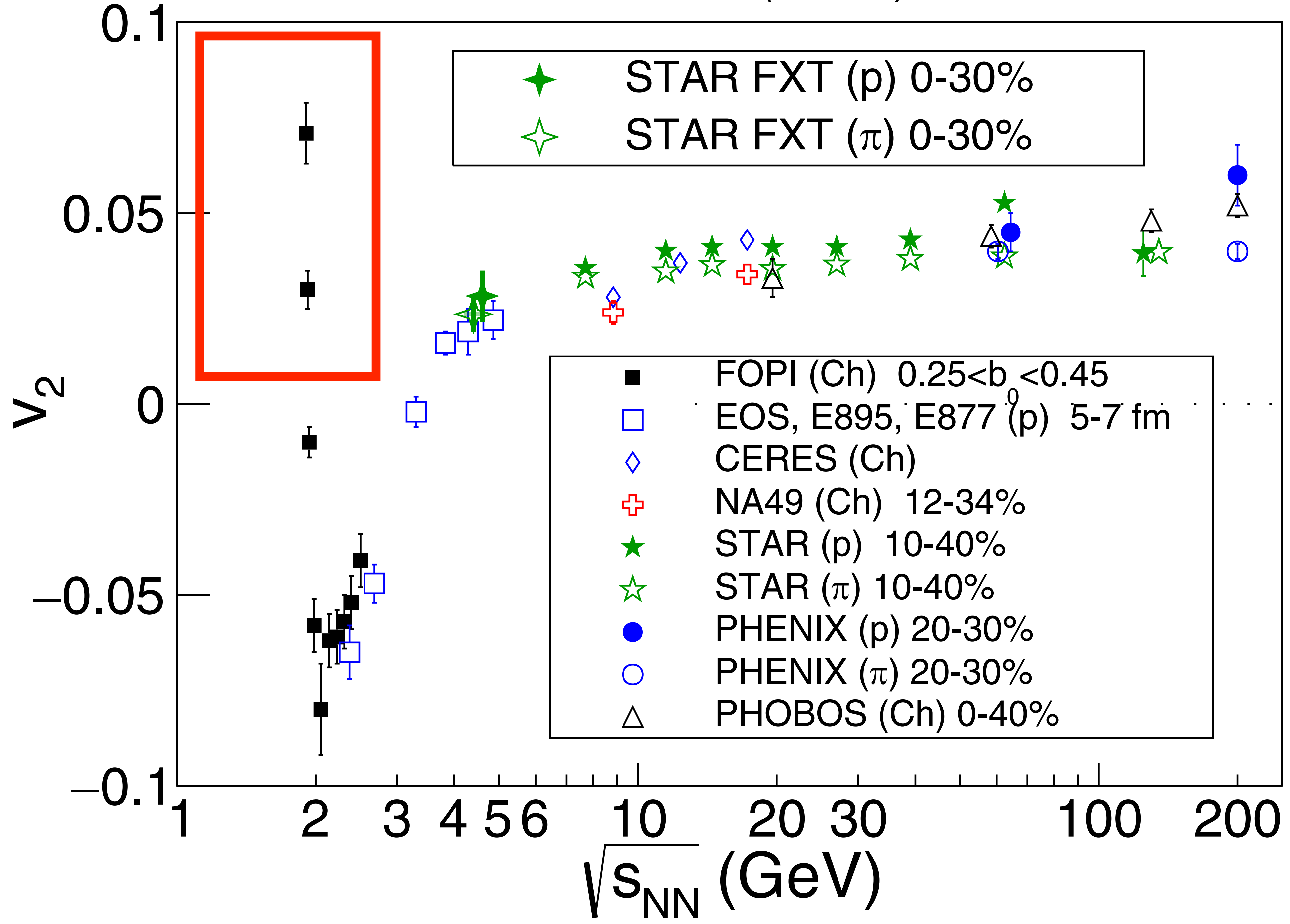
Energy dependence of elliptic flow

Rotating system of projectile-target
(v_2>0 at $\sqrt{s_{NN}}$ <1.4 GeV)

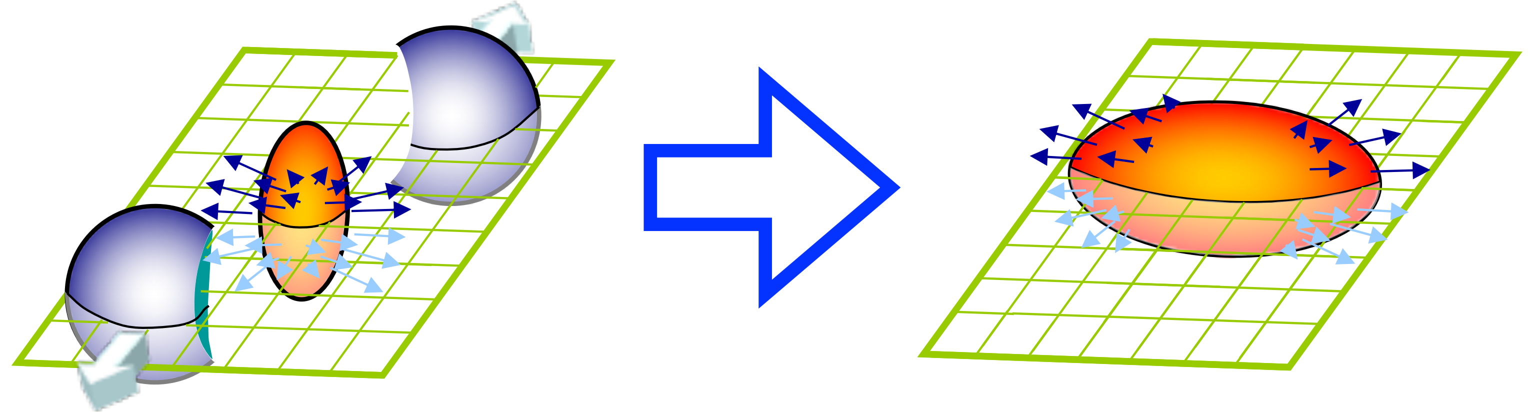
"squeeze-out" emission (v_2<0)



STAR, PRC103, 034908 (2021)



pressure-gradient-driven expansion
(v_2>0 at $\sqrt{s_{NN}}$ >4 GeV)



The sign of v_2 changes twice when decreasing the collision energy

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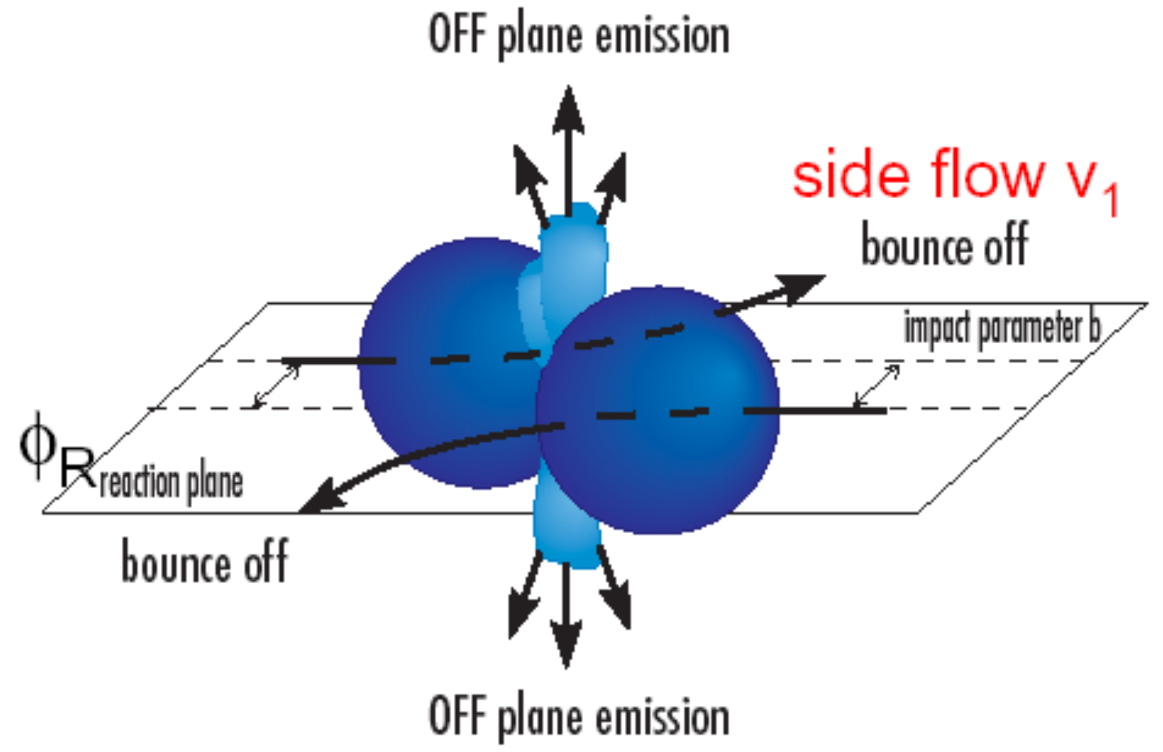
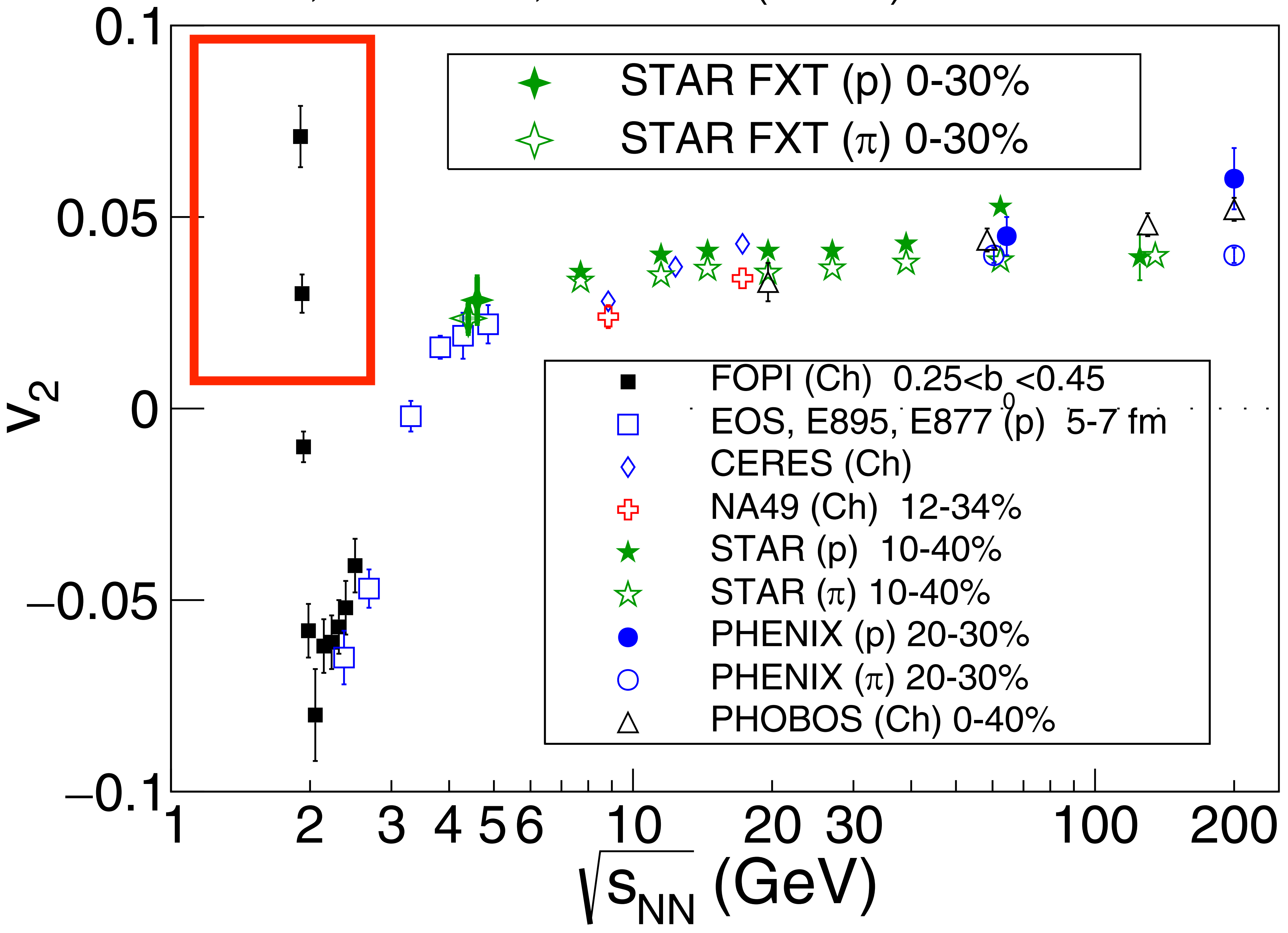


STAR, PRC103, 034908 (2021)



pressure-gradient-driven expansion
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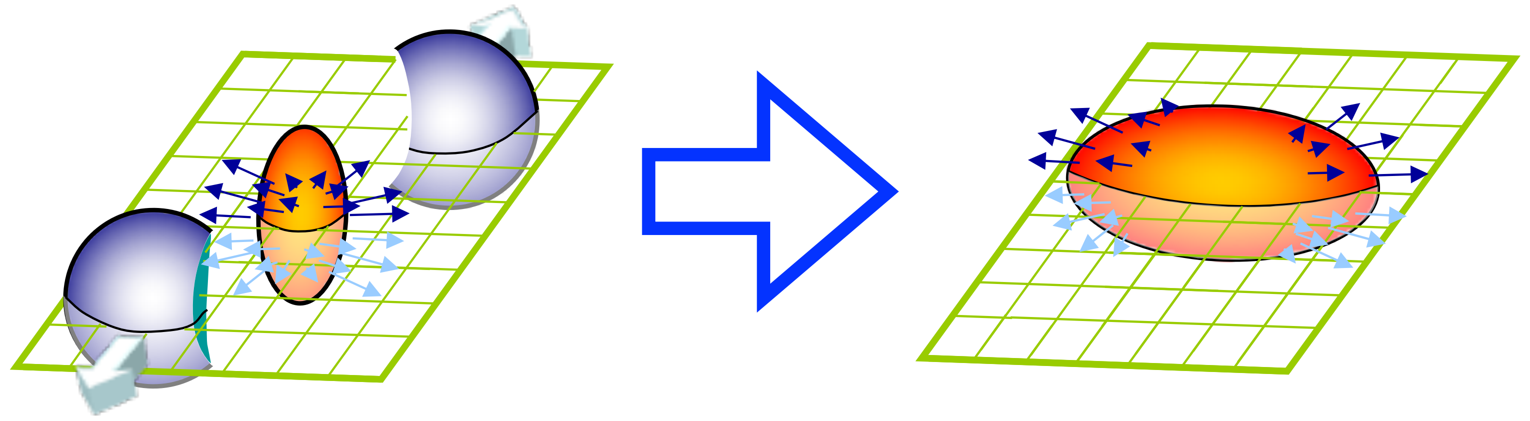
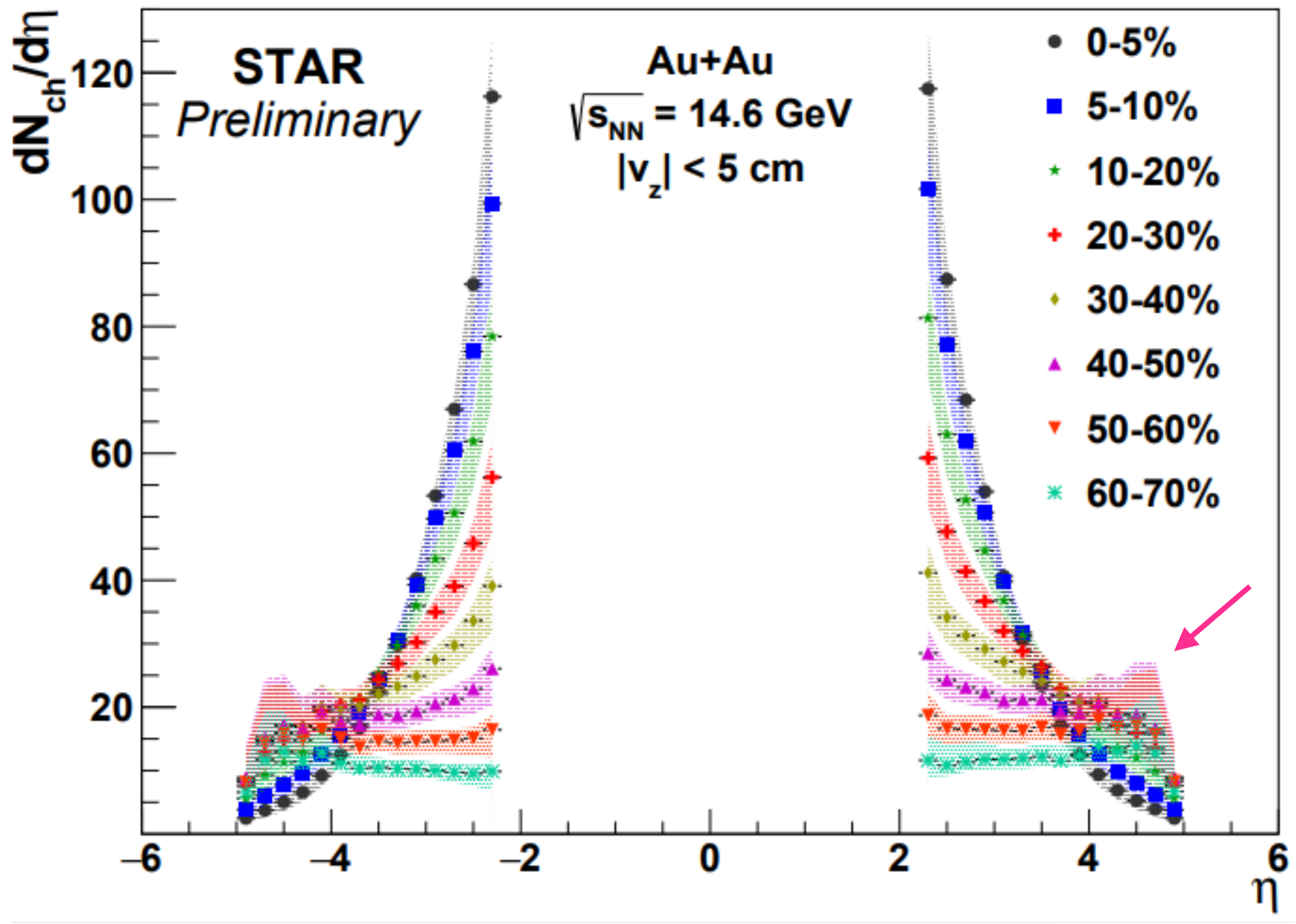


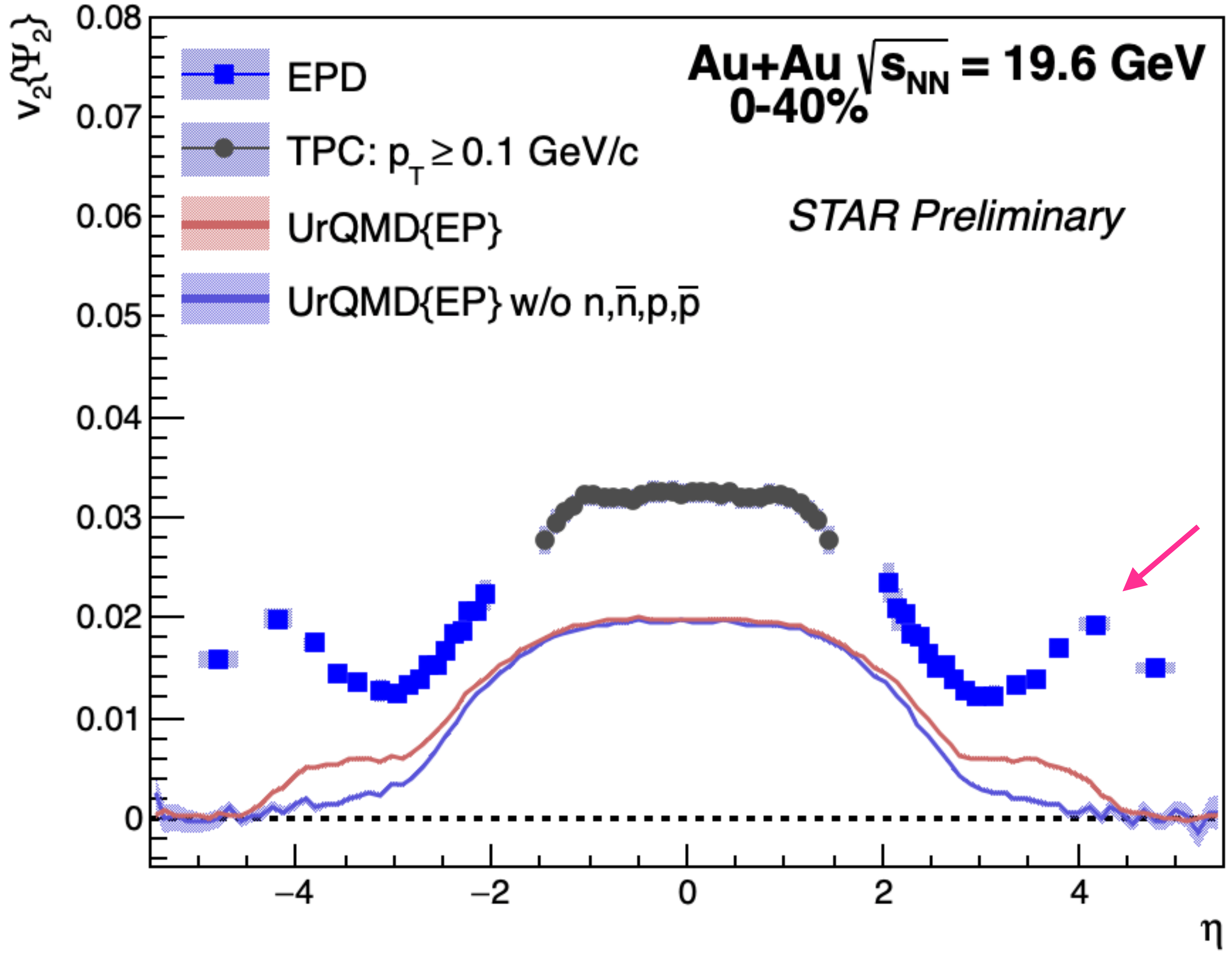
The sign of v_2 changes twice when decreasing the collision energy
Understanding of spectator effects is also important

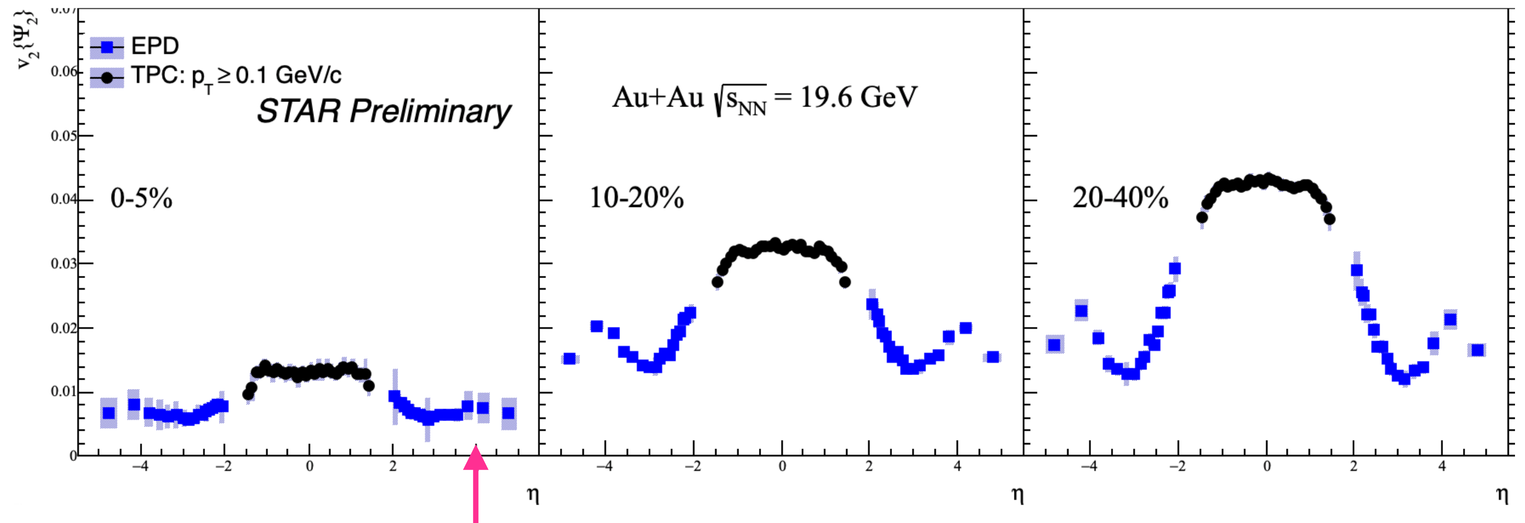
Spectators in dN/dη and $v_2(\eta)$

B. Korodi (STAR), WPCF2024



M. Isshiki (STAR), Hot Quarks 2025





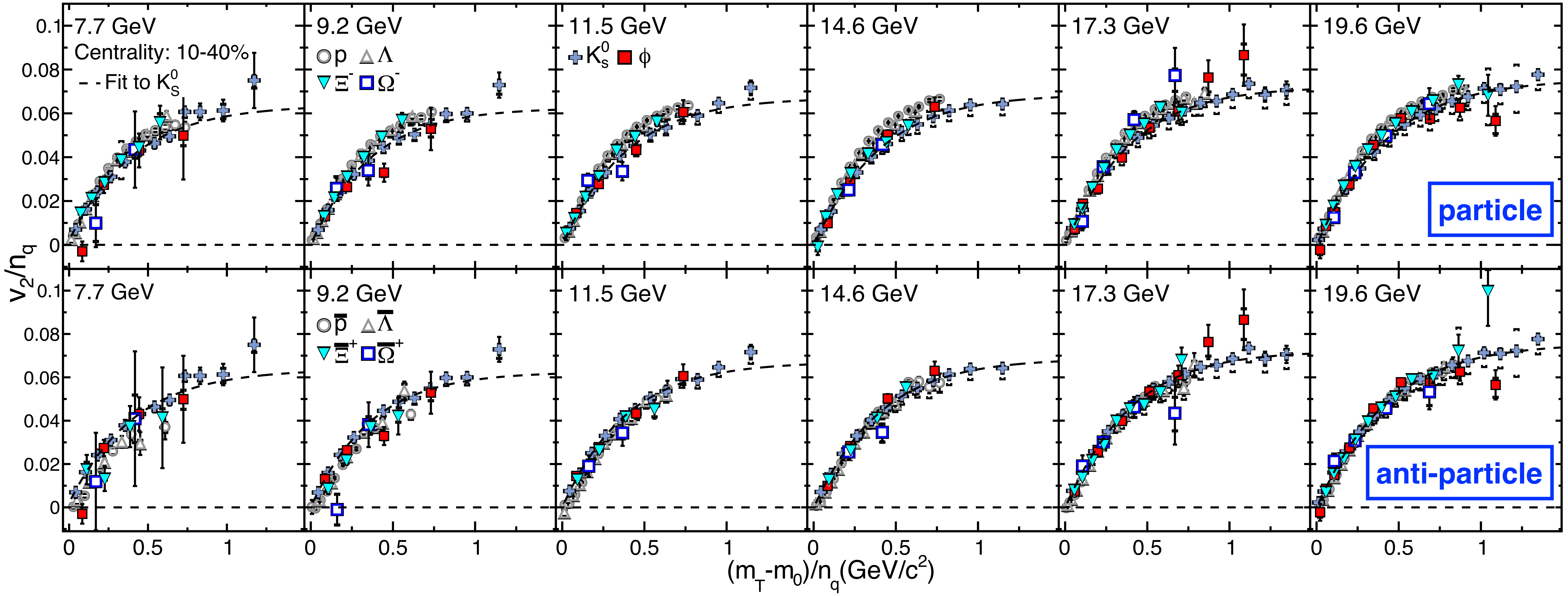
Bump is gone in most central collisions

- At lower energies, spectator effects are indeed visible
- Observables sensitive to η/s(T, μ_B). Important to understand the spectator effect before extracting the medium properties, e.g. in Bayesian analysis

Danicol et al., PRL116.212301(2016)
See Chun Shen's talk

NCQ scaling vs. beam energy

STAR, arXiv:2605.27815

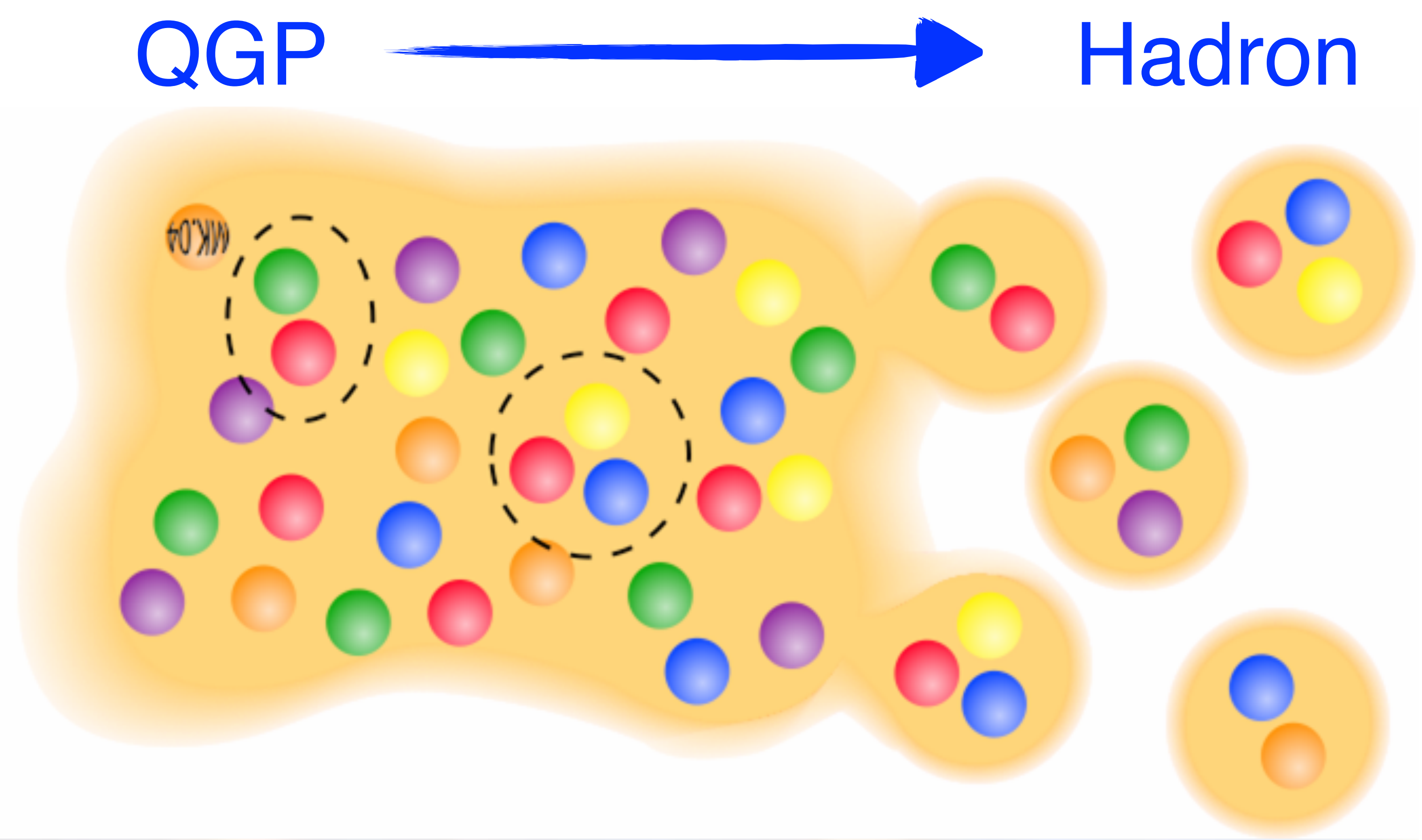


$$\frac{dN_M}{d\phi} \propto (1 + 2v_{2,q}\cos 2\phi)^2 \approx (1 + 4v_{2,q}\cos 2\phi),$$

$$\frac{dN_B}{d\phi} \propto (1 + 2v_{2,q}\cos 2\phi)^3 \approx (1 + 6v_{2,q}\cos 2\phi),$$

$$v_{2,M}(p_T) \sim 2v_{2,q}(p_T/2),\ v_{2,B}(p_T) \sim 3v_{2,q}(p_T/3).$$

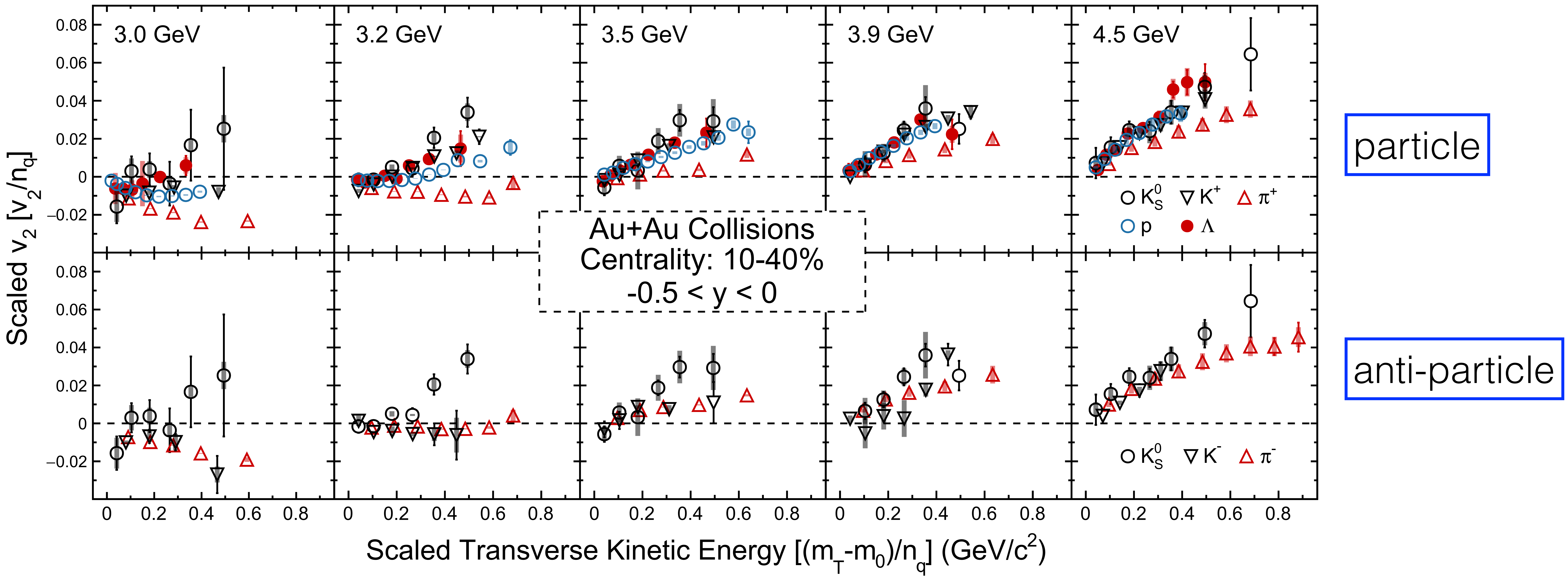
Molnar and Voloshin, PRL91,092301 (2003)
Fries et al., PRL90, 202303 (2003)
Greco et al., PRL90, 202302 (2003)



- NCQ scaling holds down to $\sqrt{s_{NN}}$ >= 7.7 GeV for light hadrons (π, K, p, ϕ, Λ) and multi-strangeness (Ξ, Ω)

Where does the NCQ scaling break?

STAR, PRL135, 072301 (2025)



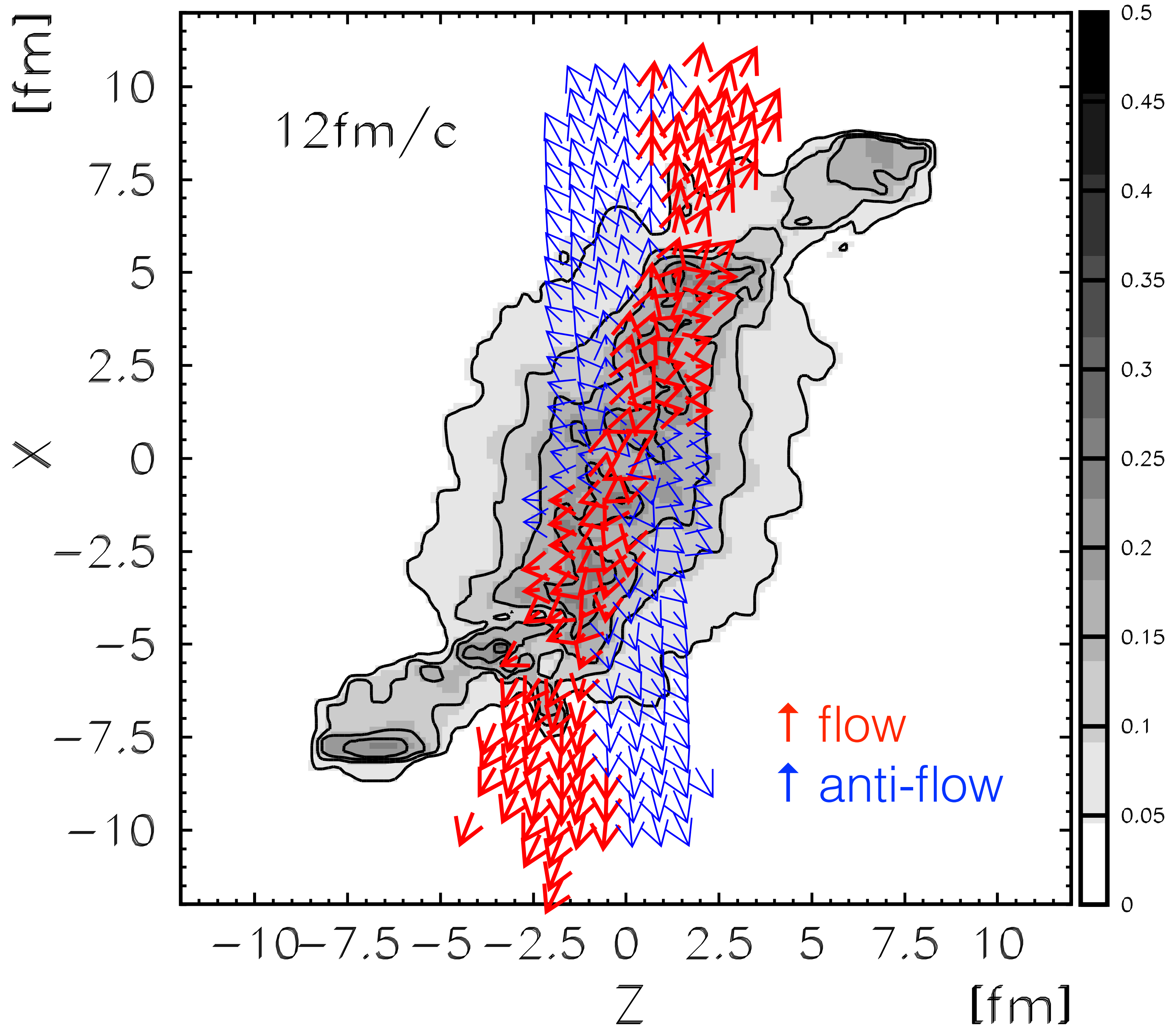
- NCQ scaling starts to break below $\sqrt{s_{NN}}$ = 4.5 GeV
- Turning-off of partonic collectivity between $\sqrt{s_{NN}}$ = 4.5-7.7 GeV ?
  - Spectator shadowing effect needs to be understood

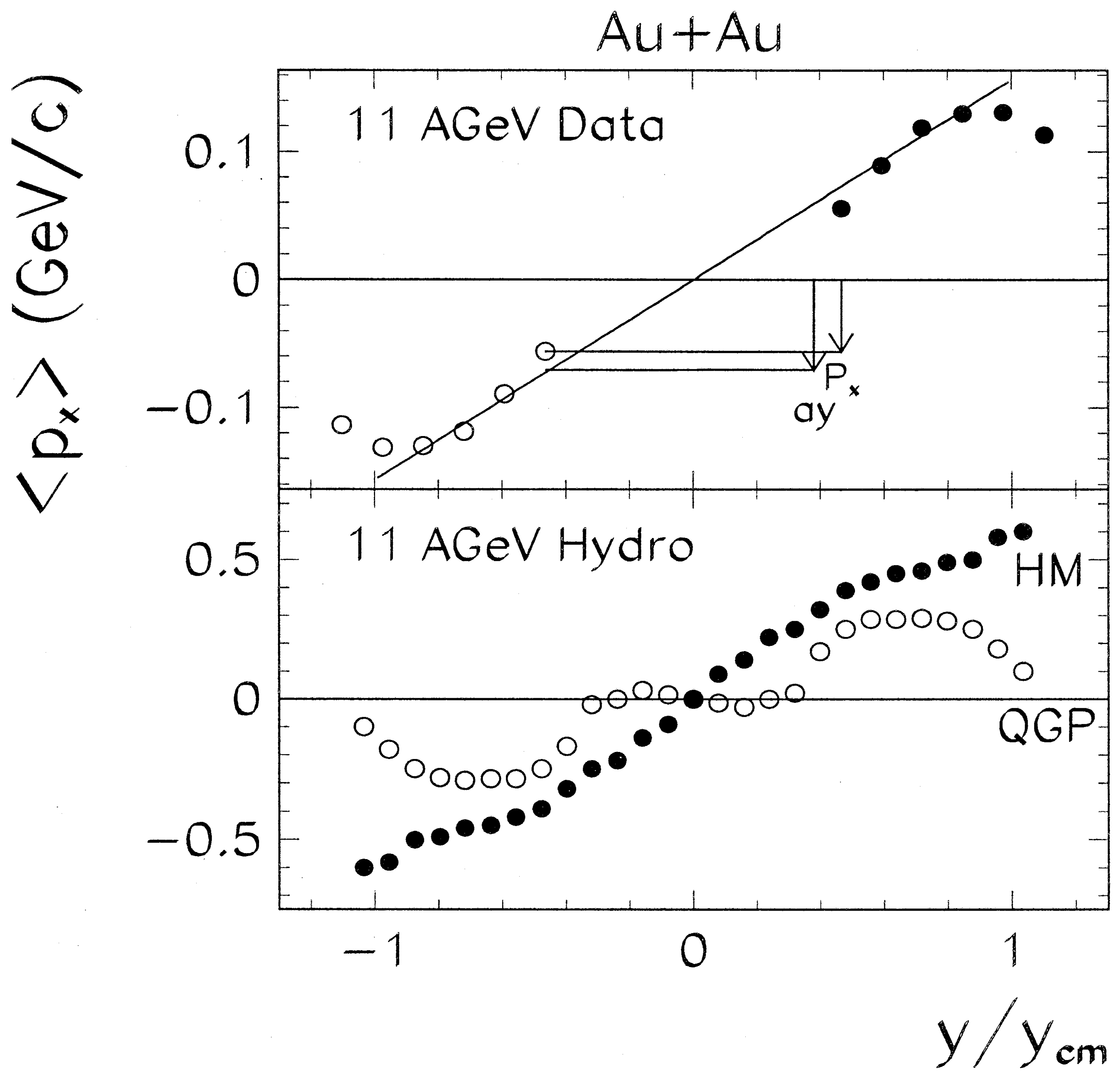
T. Reuchert and I. Karpenko, arXiv:2603.02927

Directed flow

- Directed flow: collective sideward motion of particles $v_1 = \langle \cos(\phi - \Psi_{RP}) \rangle$
  - Proposed as a sensitive probe to EOS and 1st-order phase transition

Csernai and Rohrich, PLB458(1999)454
Brackmann et al., PRC61.024909(2000)

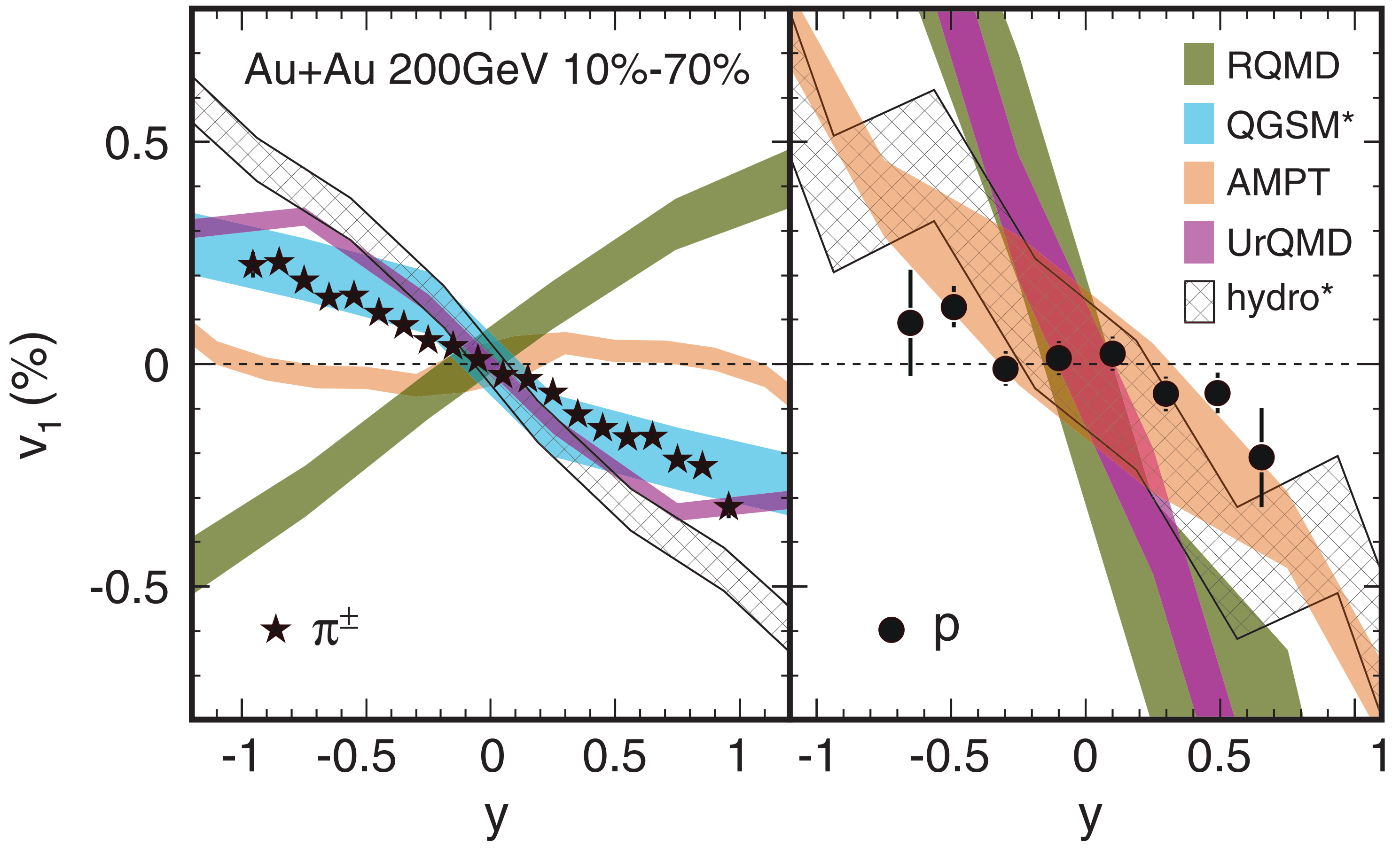




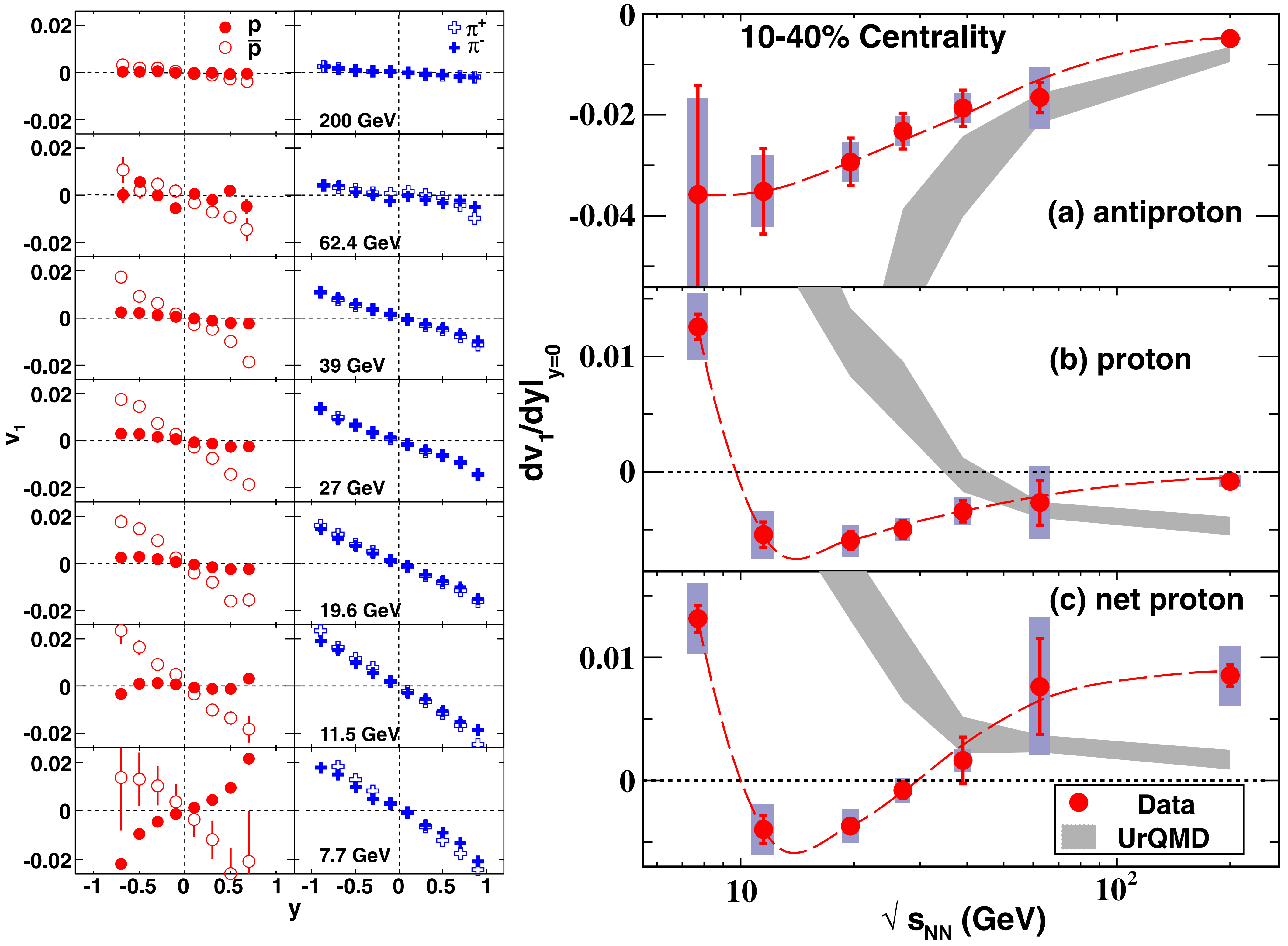
"Wiggle" structure or minimum dv_1/dy due to anti-flow (or third flow)
driven by pressure gradient (+ spectator shadowing), if the softening of EOS happens

Extensive studies of v_1

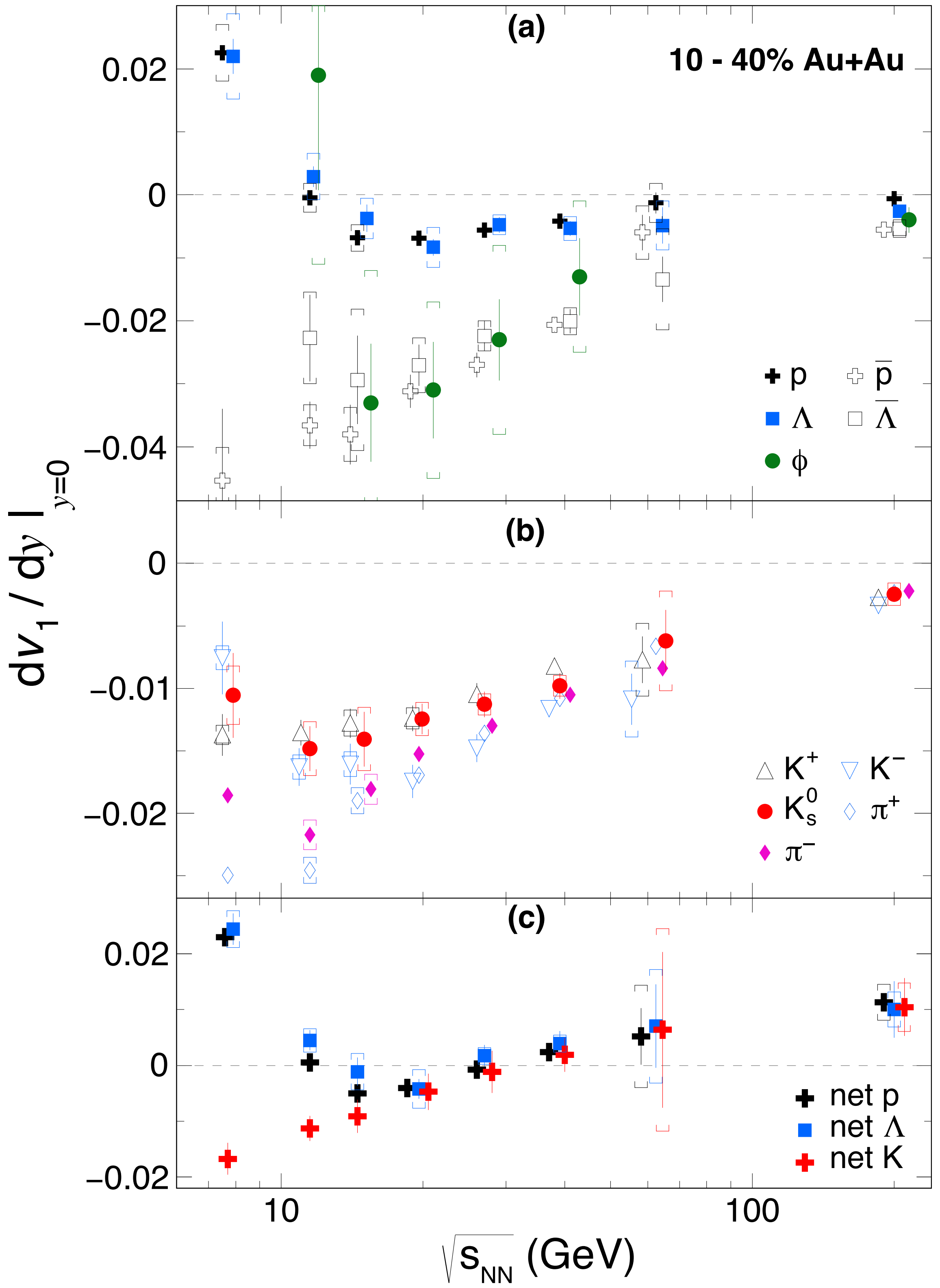
STAR, PRL108.202301 (2012)



STAR, PRL112.162301 (2014)



STAR, PRL120.062301 (2018)



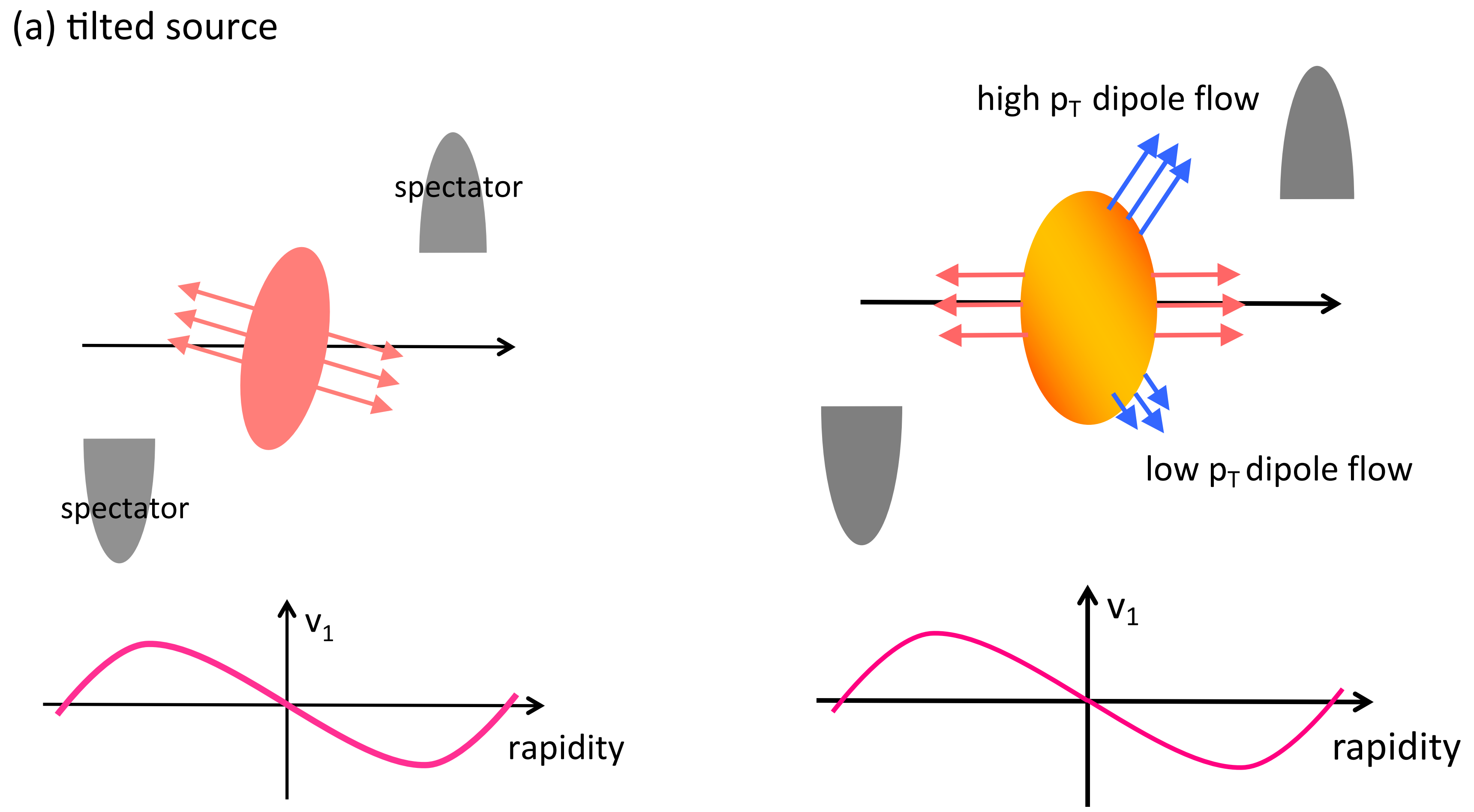
- Indeed, the minimum of dv_1/dy was observed around $\sqrt{s_{NN}}$ = 10-20 GeV for some of particles
- However, most of models satisfactorily explain the data ($\sqrt{s_{NN}}$ and particle-species dependence simultaneously)

Origin of Directed flow

STAR, PRC98, 014915(2018), TN(STAR), QM2018

- Origin of characteristic rapidity dependence of v_1 "~"
  - Initial source tilt with longitudinal expansion
  - Density asymmetry at non-zero rapidity (dipole flow)
  - Baryon stopping

Bozek and Wyskiel, PRC81.054902(2010)
Heinz and Kolb, J.Phys.G30:S1229(2004)
Snellings et al., PRL84.2803(2000)



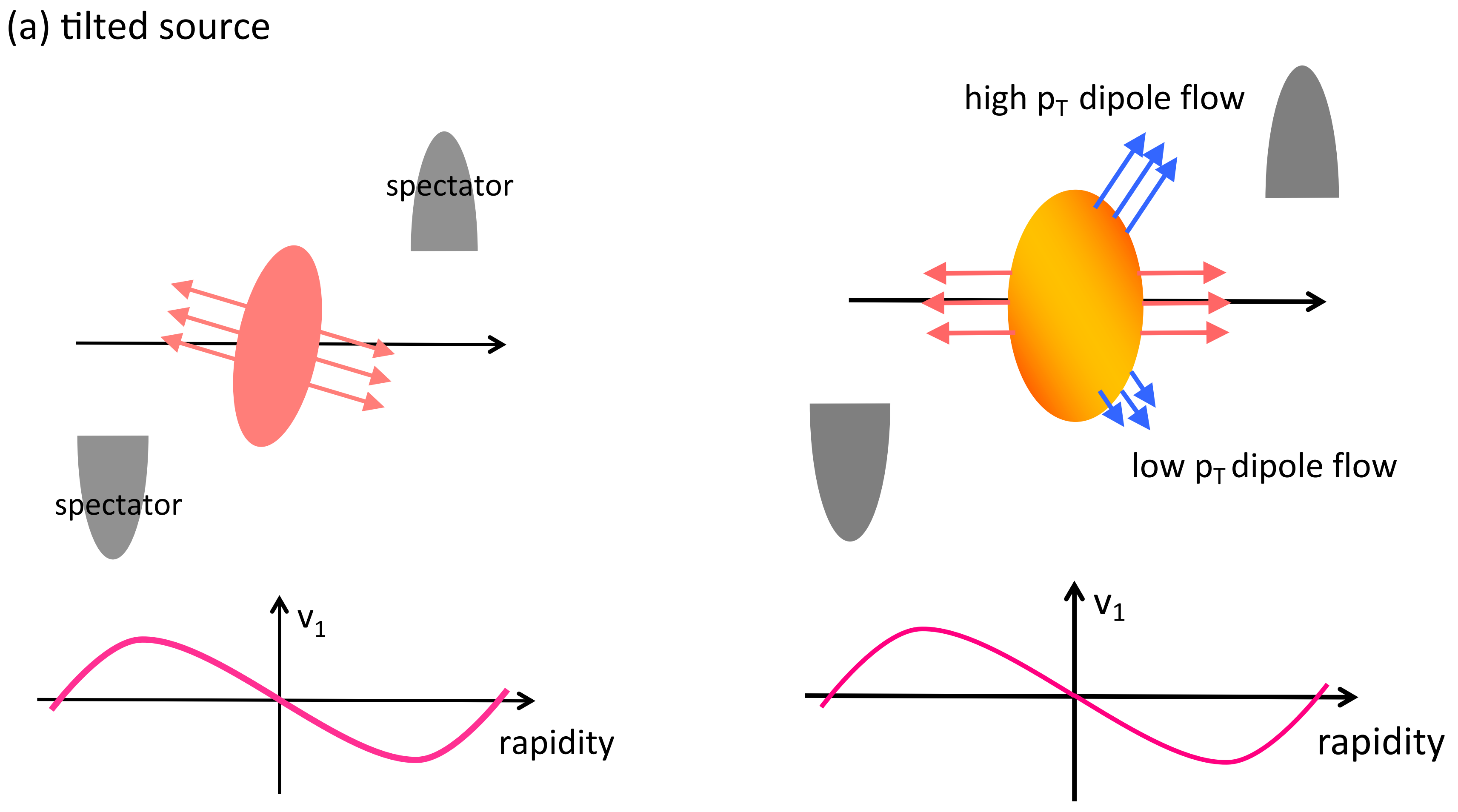
- Contribution from the tilt to v_1^{odd}: ~2/3 at RHIC, ~1/3 at the LHC

STAR, PRC98, 014915 (2018)

- Connection to global vorticity with the initial tilt

Origin of Directed flow

STAR, PRC98, 014915(2018), TN(STAR), QM2018



- Origin of characteristic rapidity dependence of v_1 "~"
  - Initial source tilt with longitudinal expansion
  - Density asymmetry at non-zero rapidity (dipole flow)
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Bozek and Wyskiel, PRC81.054902(2010)
Heinz and Kolb, J.Phys.G30:S1229(2004)
Snellings et al., PRL84.2803(2000)

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STAR, PRC98, 014915 (2018)

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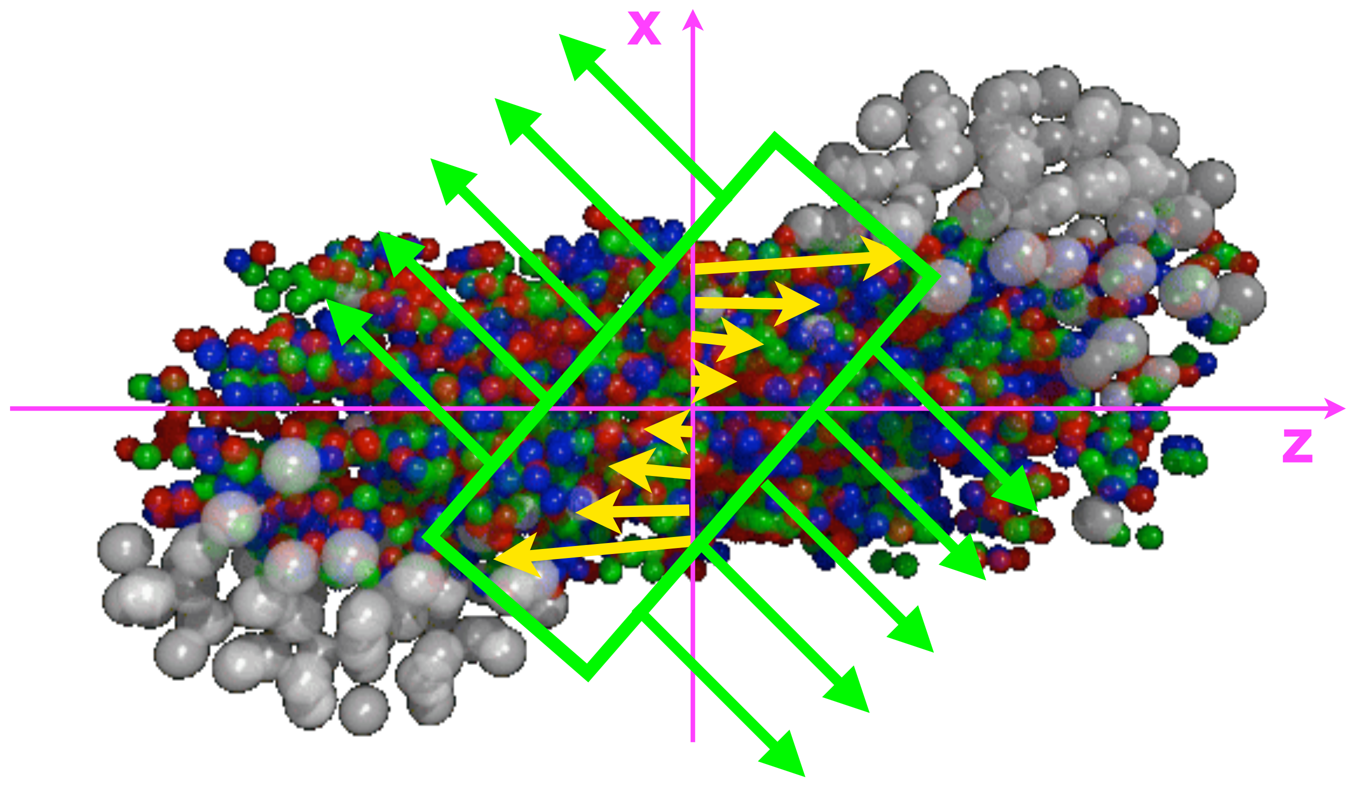

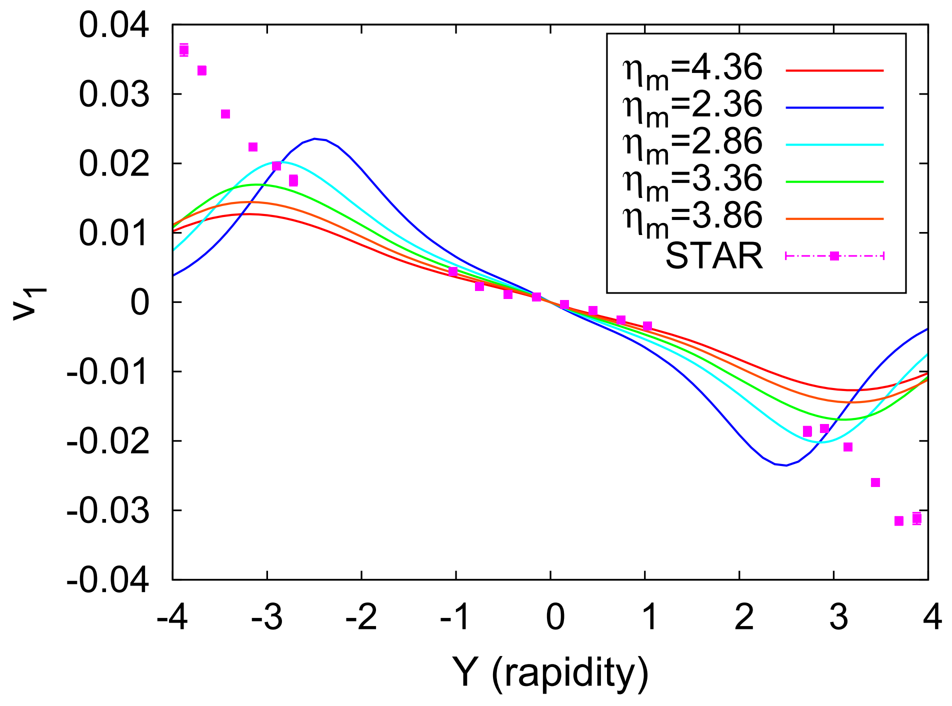

Fig. 6 Directed flow of pions for different values of η_m parameter with $\eta/s = 0.1$ compared with STAR data [22]

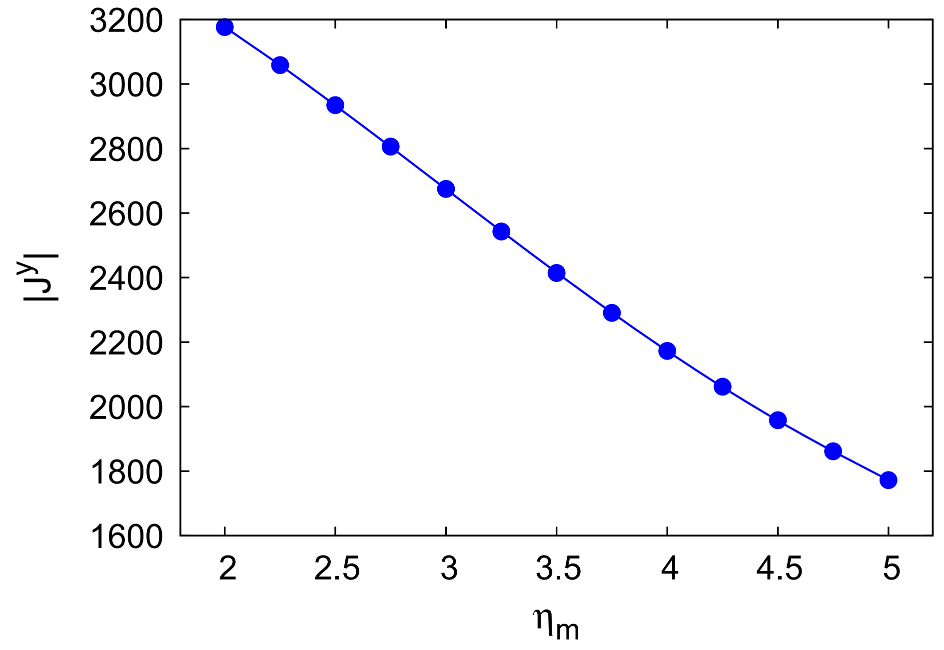

Fig. 9 Angular momentum (in $\hbar$ units) of the plasma with Bjorken initial conditions as a function of the parameter η_m

Better description of v_1 with the tilt, which leads to vorticity

F. Becattini et al., Eur. Phys. J. C (2015)75:406

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STAR, PRC98, 014915(2018), TN(STAR), QM2018

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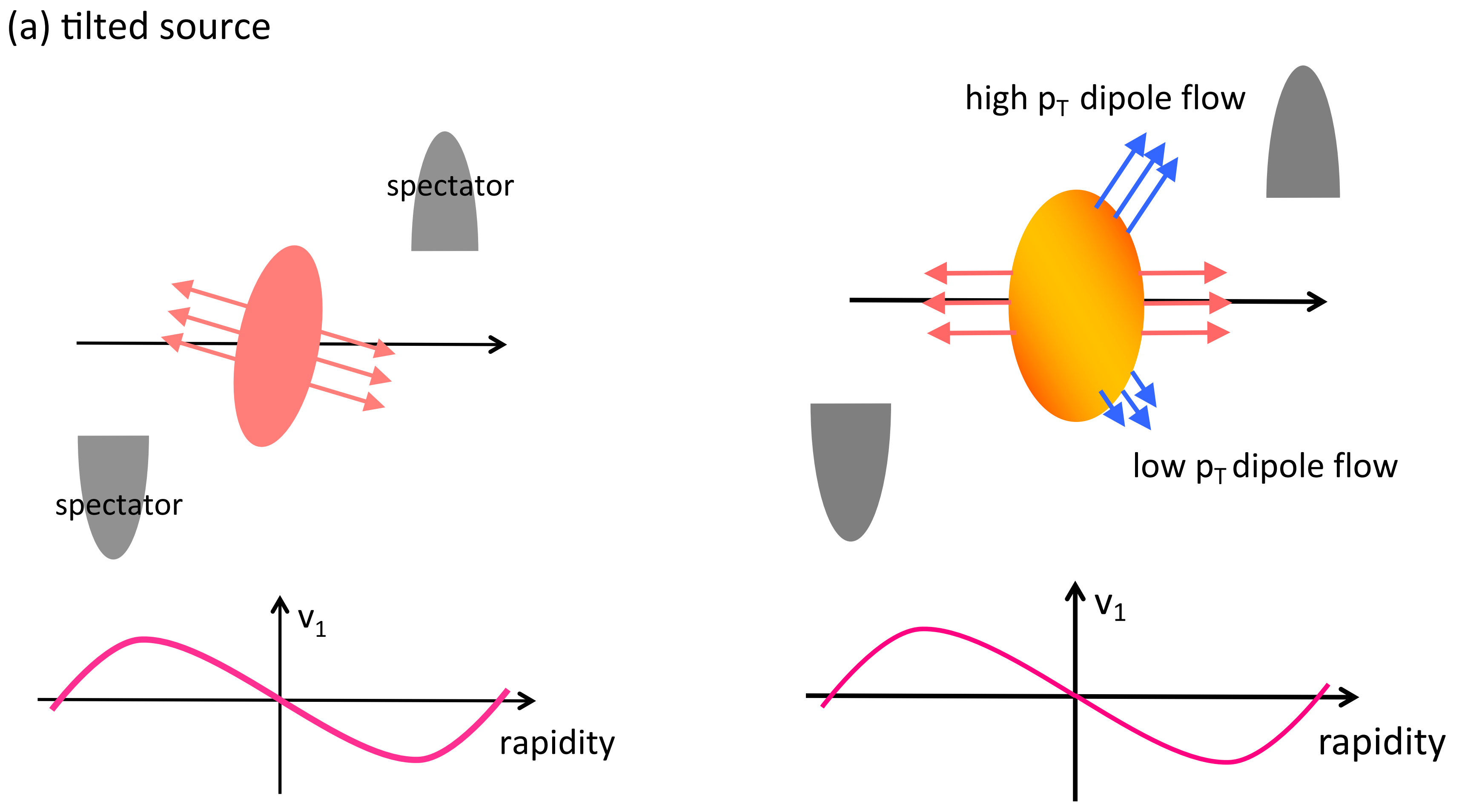

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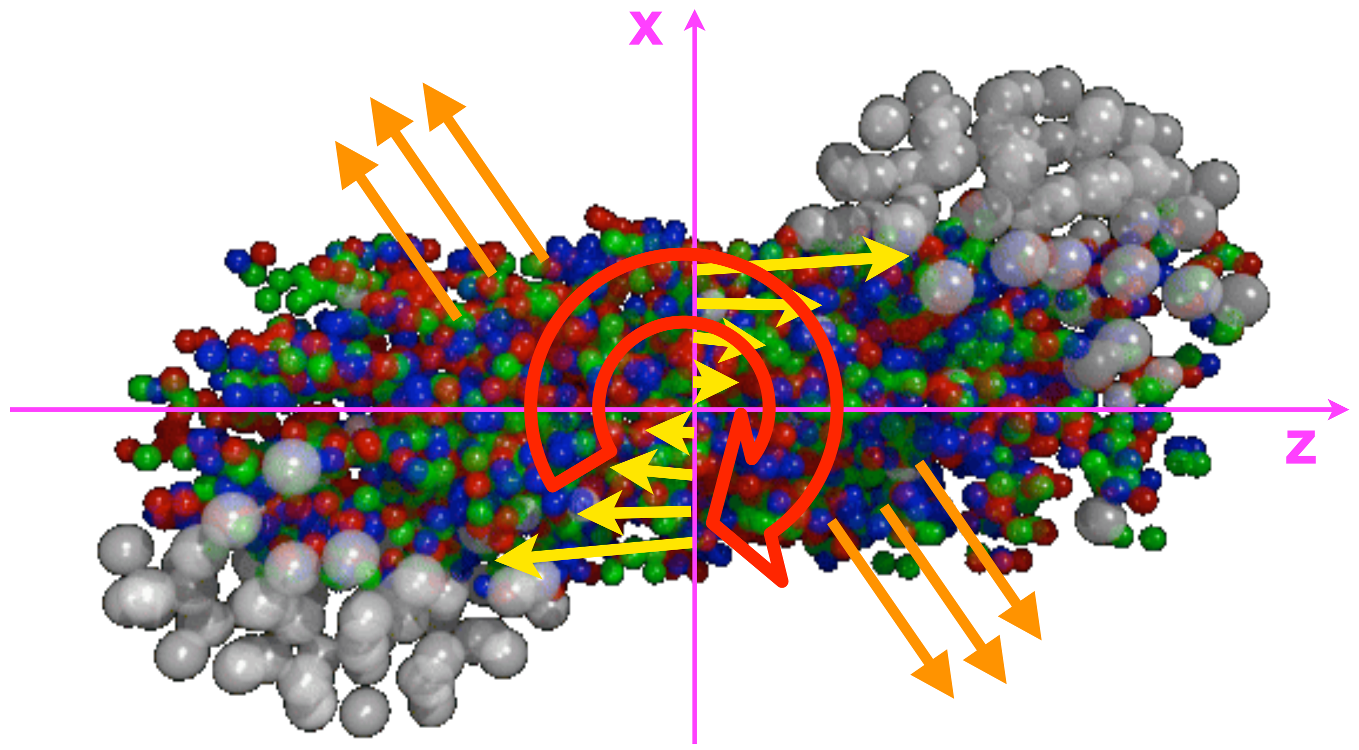

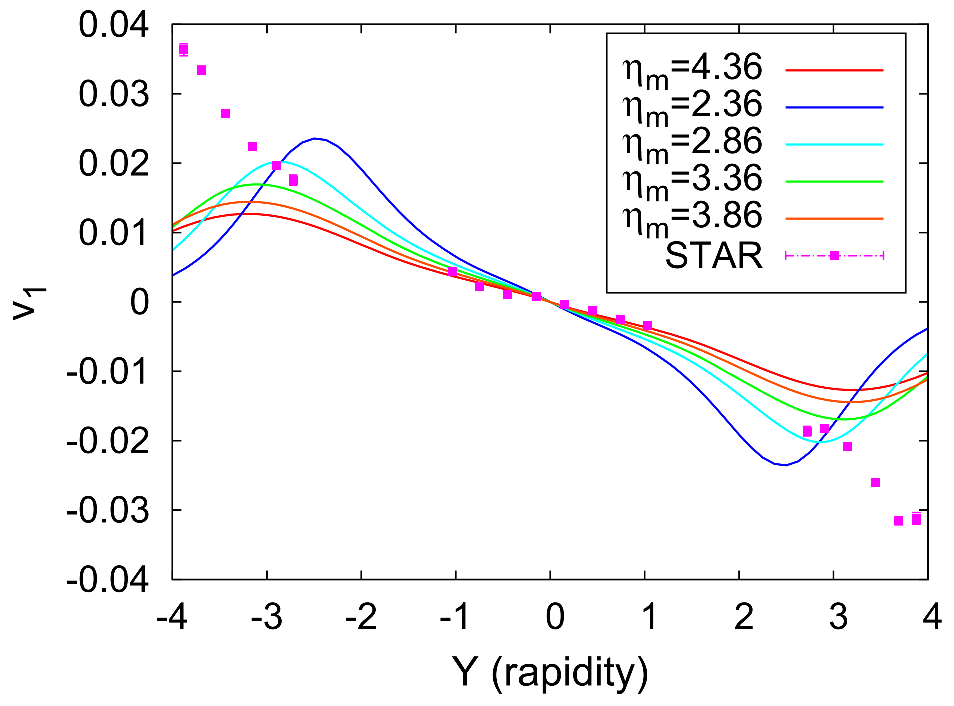

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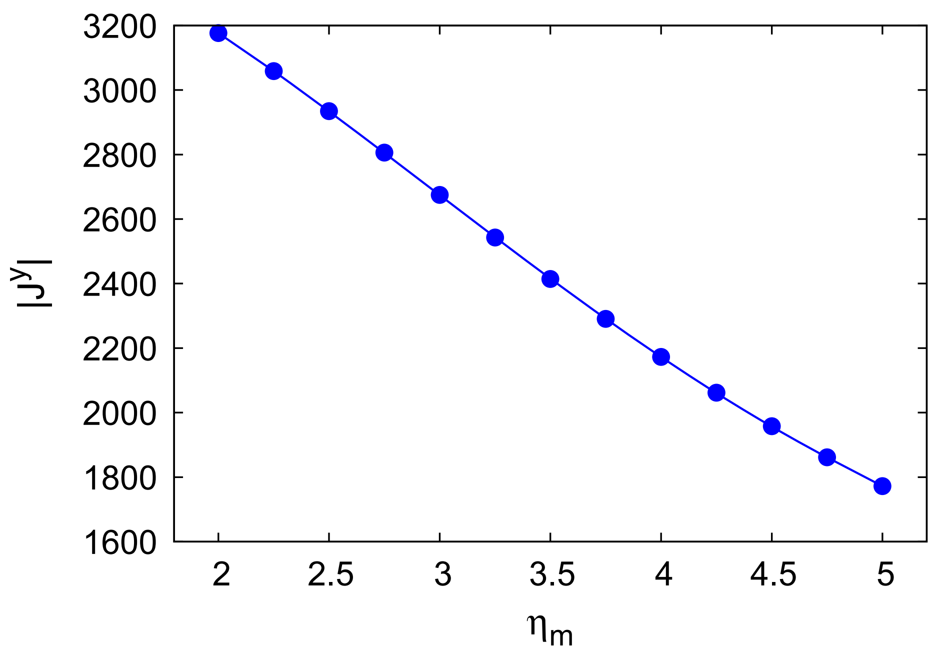

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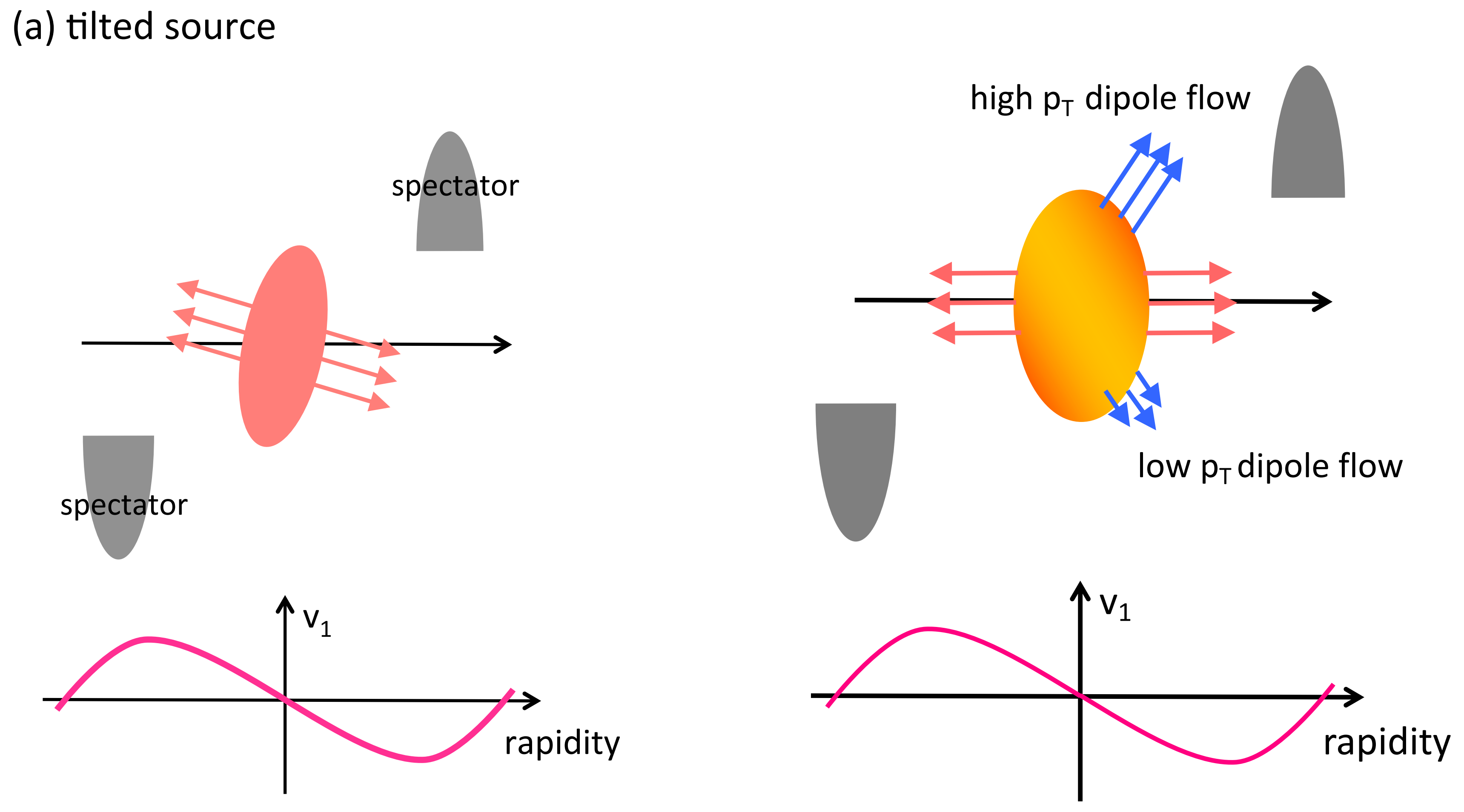

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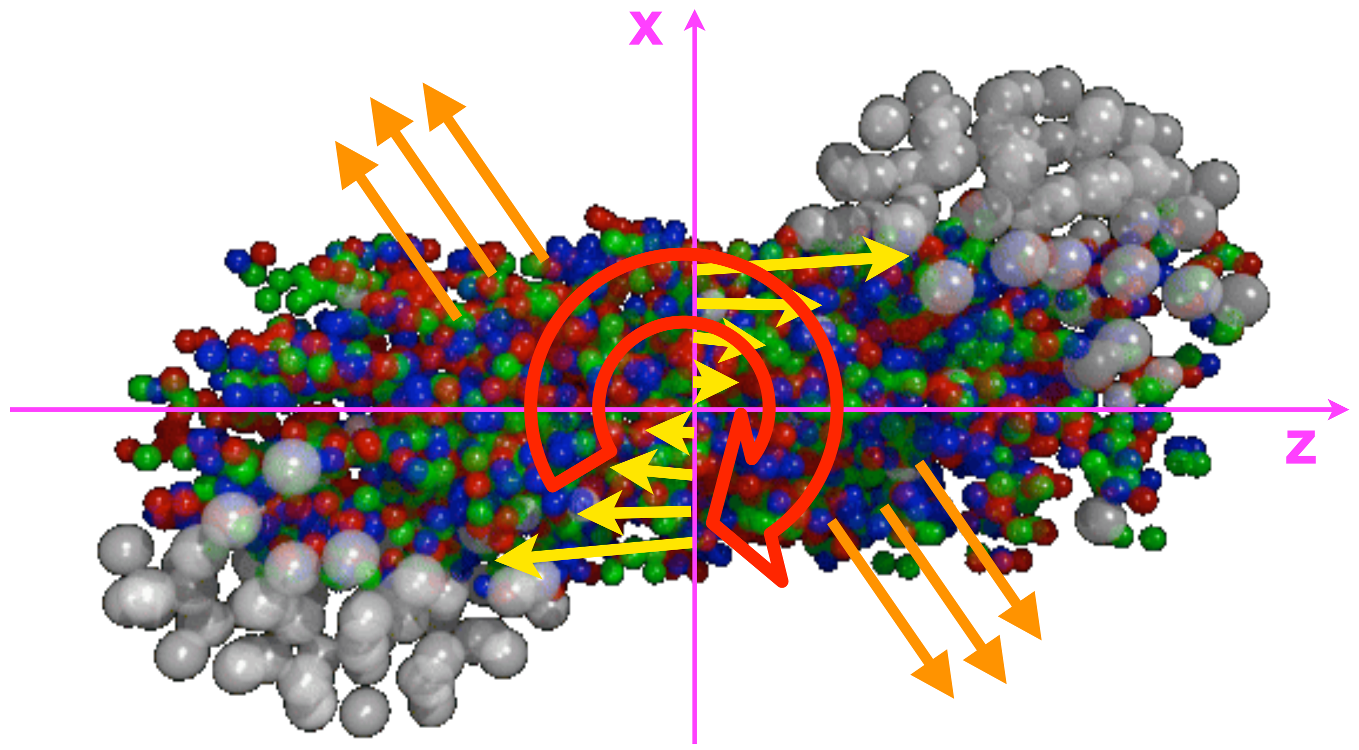

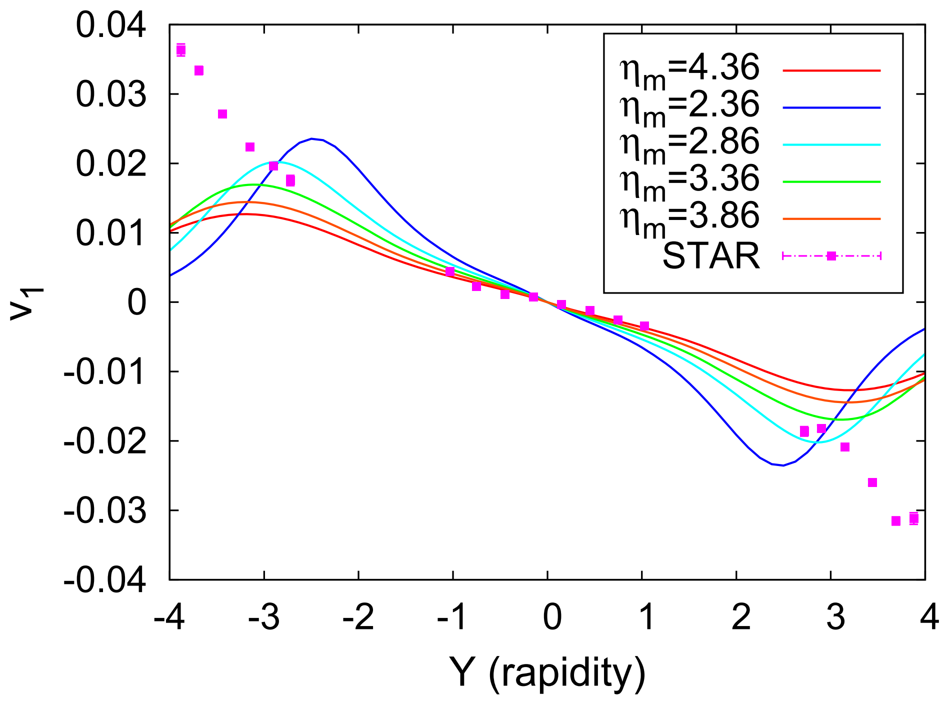

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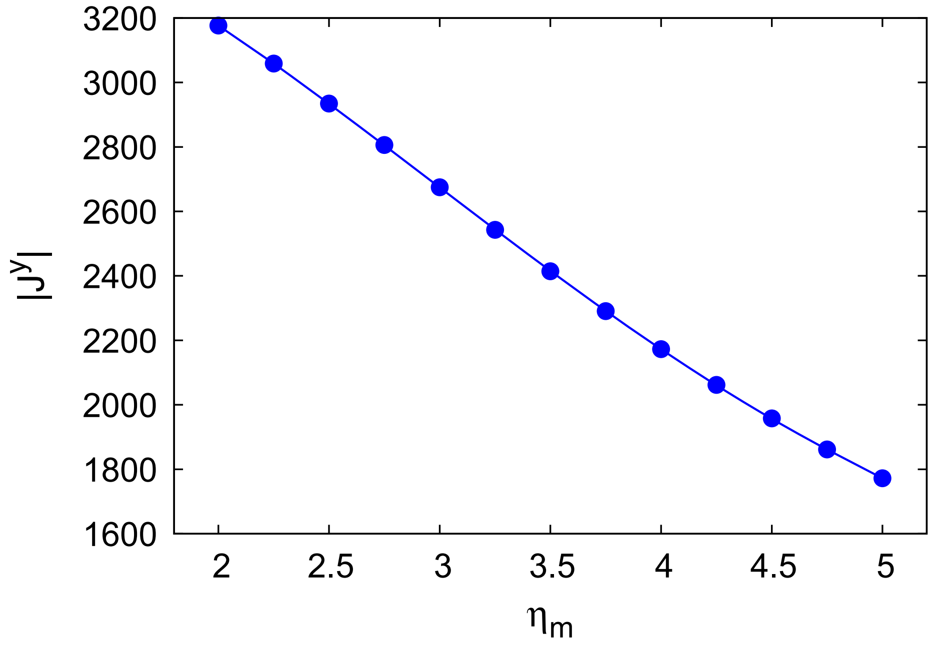


Fig. 9 Angular momentum (in $\hbar$ units) of the plasma with Bjorken initial conditions as a function of the parameter η_m

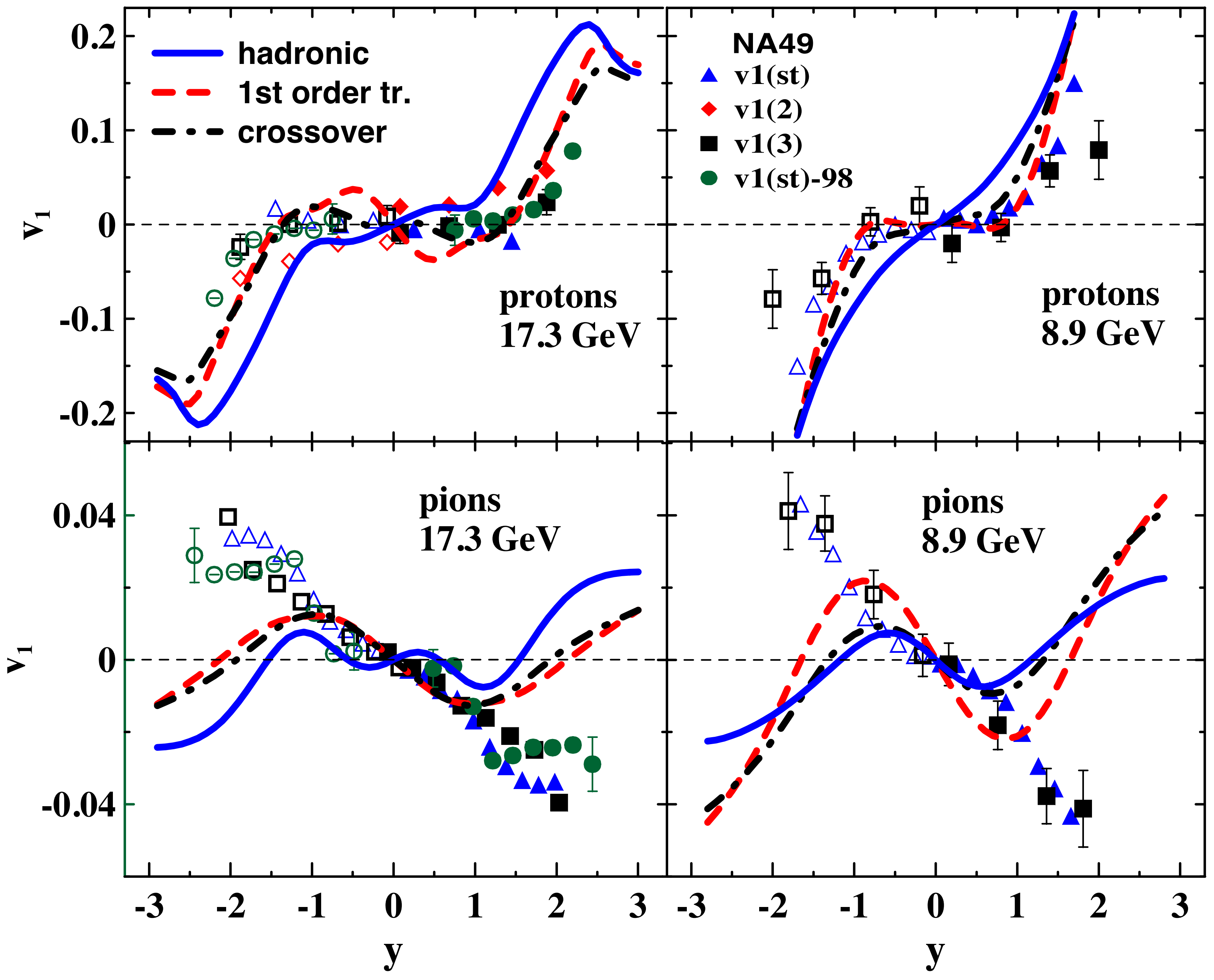
Importance of 3D initial conditions at lower energies
(No longer longitudinal boost-invariant)

Better description of v_1 with the tilt, which leads to vorticity

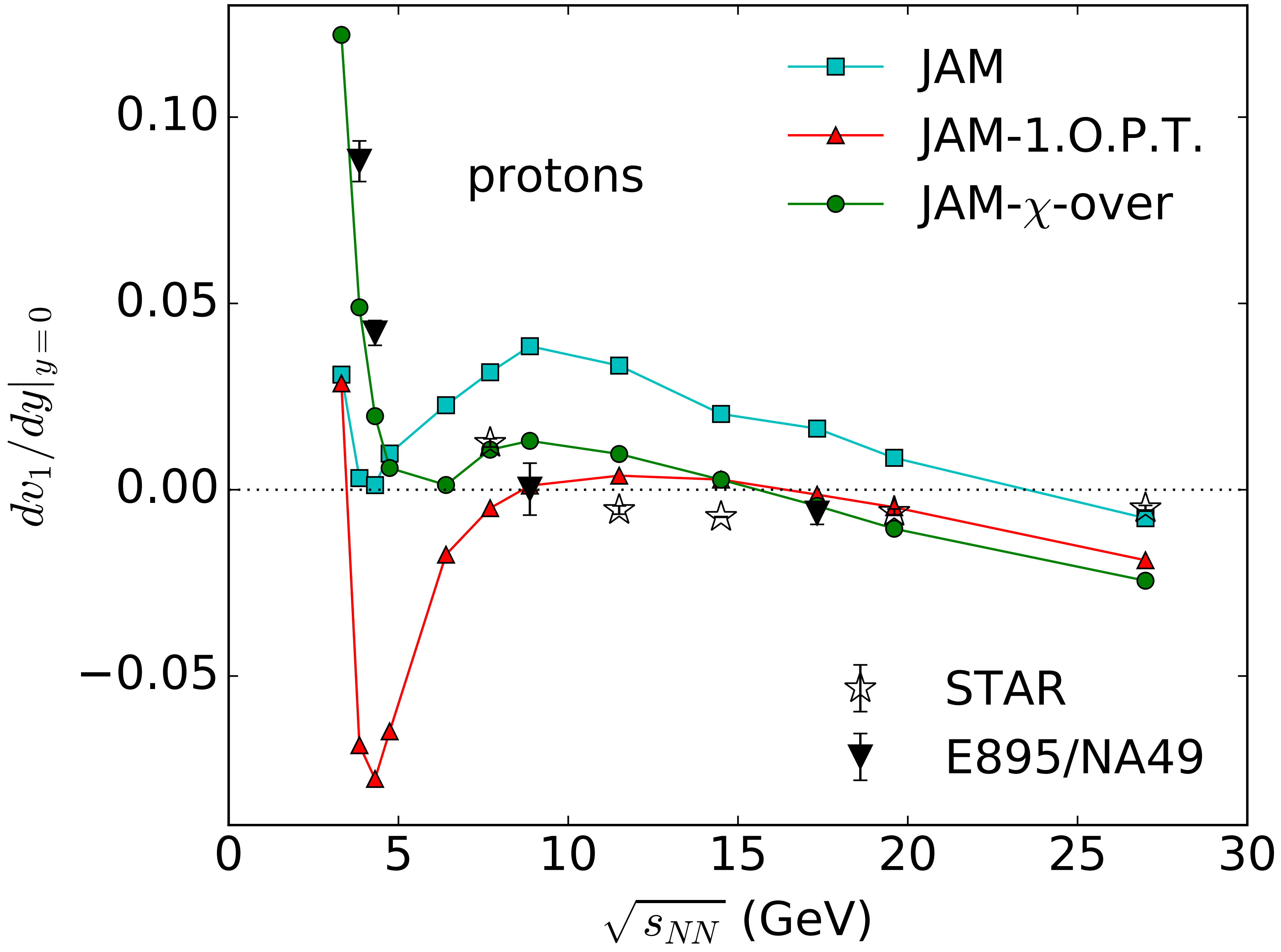
F. Becattini et al., Eur. Phys. J. C (2015)75:406

Model calculations with different EOS

Y. Ivanov and A. A. Soldatov, Phys.Rev.C91, 024915 (2015)



Y. Nara et al., PLB769(2017)543



- Many model studies show that v_1 is sensitive to EOS
- At low energies, baryonic mean-field plays a role

see more plots in Y. Nara's talk

Y. Nara and A. Ohnishi, Phys.Rev.C105, 014911 (2022)

Why femtoscopy (historically)?

If the transition from QGP to hadron gas (HG) is the first-order, the HG volume (or emission duration) is expected to increase to conserve entropy

Pratt, PRD33, 1314 (1986)
Bertsch, NPA498 (1989) 173

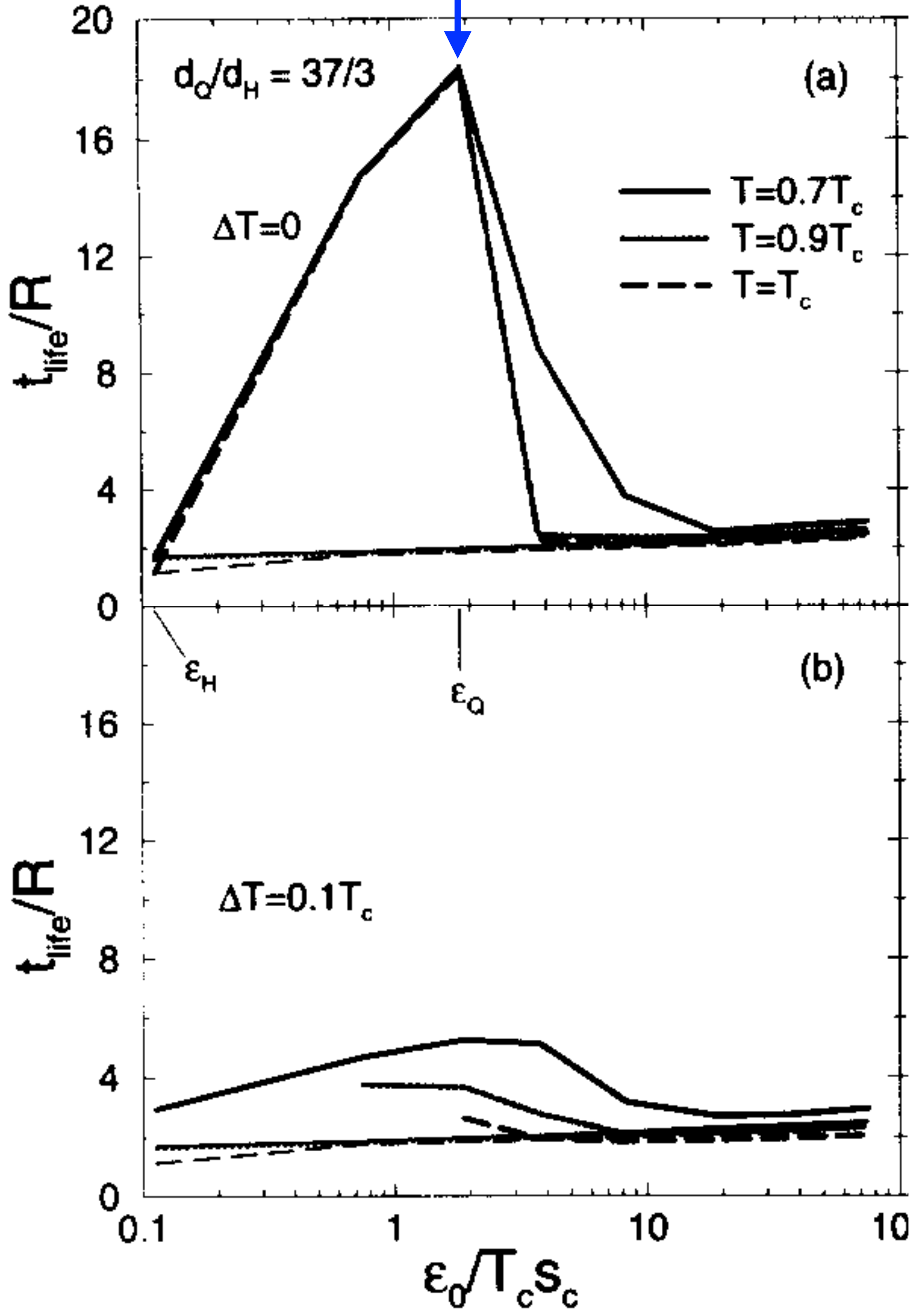
$$S_{\rm total} = s_{\rm QGP} V_{\rm QGP} = s_{\rm H} V_{\rm H}$$

$$\frac{\tau_{\rm H}}{\tau_{\rm c}} = \frac{s_{\rm QGP}}{s_{\rm H}} = \frac{d_{\rm QGP}}{d_{\pi}}$$

s: entropy density
d: degree of freedom
$\tau_{c(H)}$: time when the transition happens (ends)

Yagi, Hatsuda, and Miake, Cambridge UP. (2005)

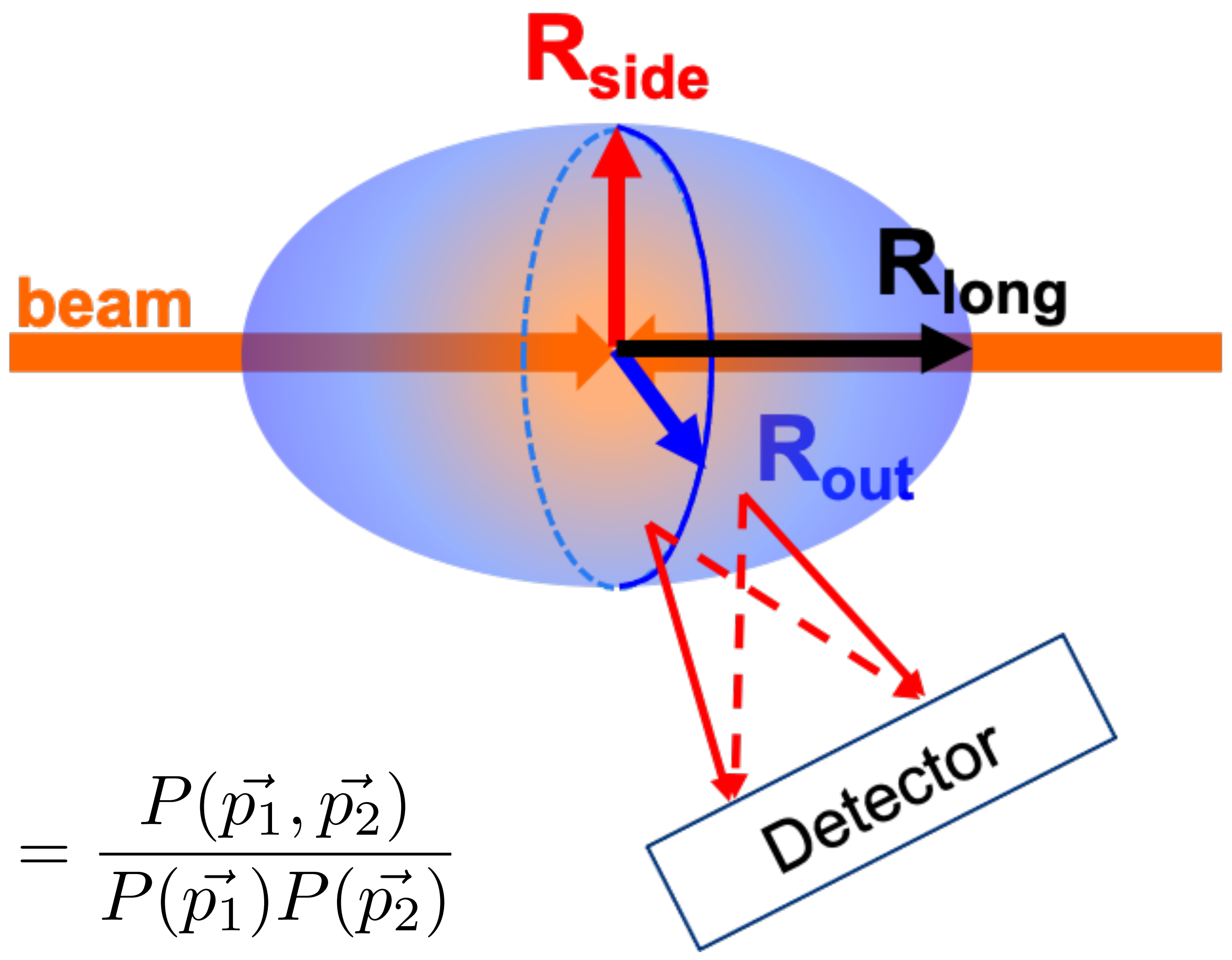
System lifetime peaks at CP



Rischke and Gyulassy, NPA608 (1996) 479

R_{out}/R_{side}

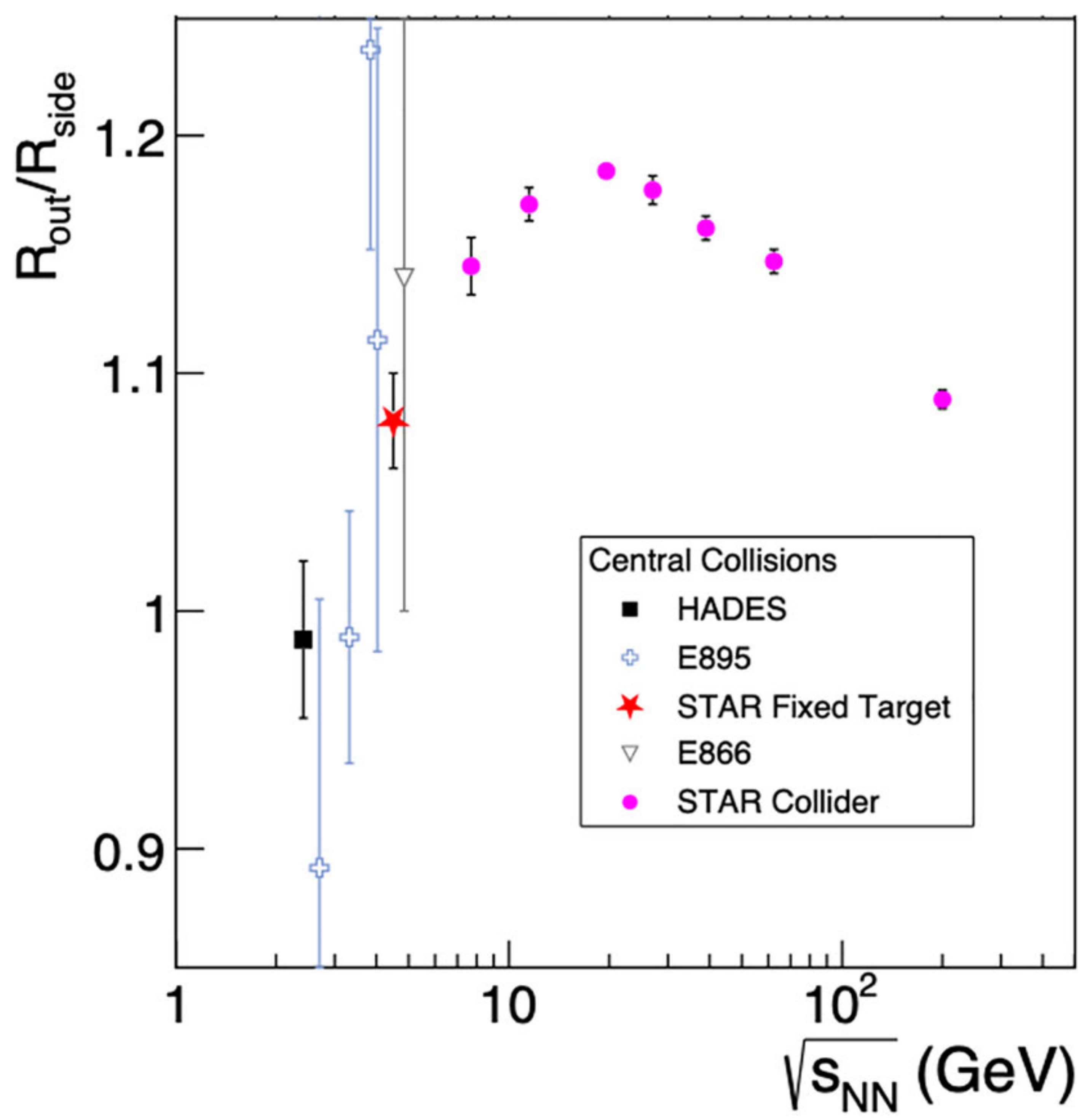
Pratt, PRD33, 1314 (1986), Bertsch, Gong and Tohyama, PRC37,1896 (1988)
Bertsch, NPA498, (1989)173



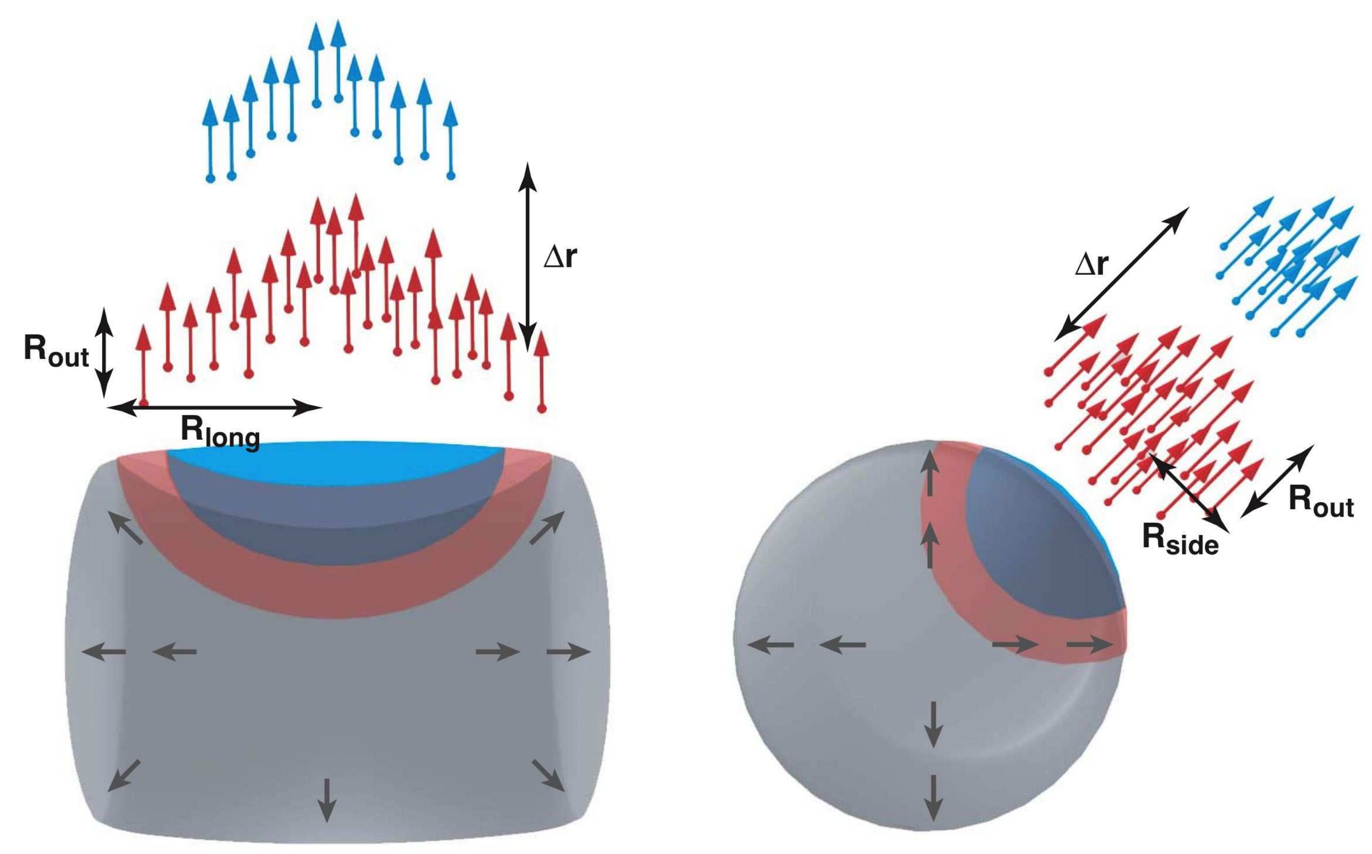
$$C(k^*) = \frac{P(\vec{p_1}, \vec{p_2})}{P(\vec{p_1})P(\vec{p_2})} = \int S(\vec{r})\,|\Psi(k^*, \vec{r})|^2\, d\vec{r}$$

"HBT" radii (Gaussian source): R_{out}, R_{side}, R_{long}

STAR, PRC103, 034908 (2021)



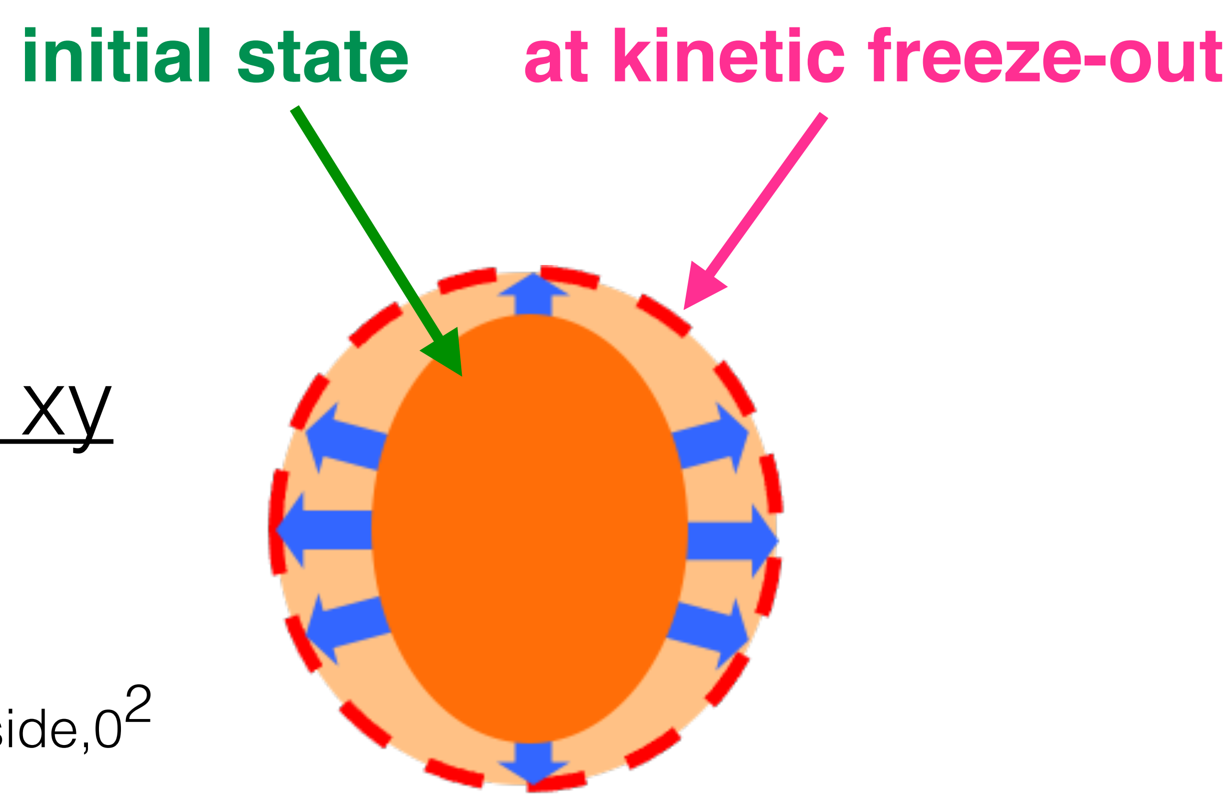
M. Lisa et al., Ann.Rev.Nucl.Part.Sci.55:357 (2005)



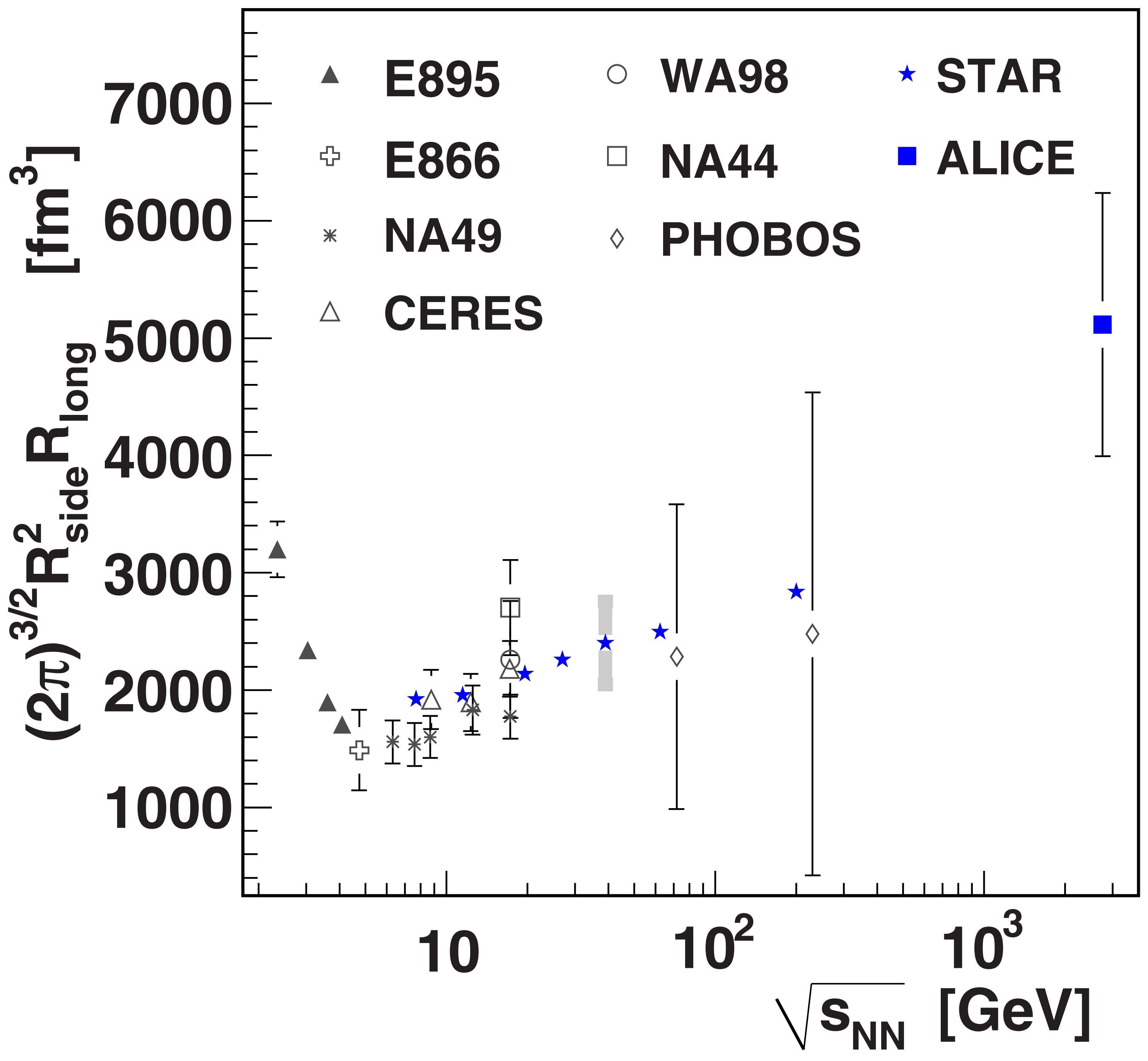
"*Length of homogeneity*"
Akkelin and Sinyukov, PLB356(1995)525

- Pion R_{out}/R_{side} shows a peak around $\sqrt{s_{NN}}$ = 20 GeV
  - Indication of the softening of EOS?
- Note: We don't measure the whole size in an expanding source (x-p correlation)

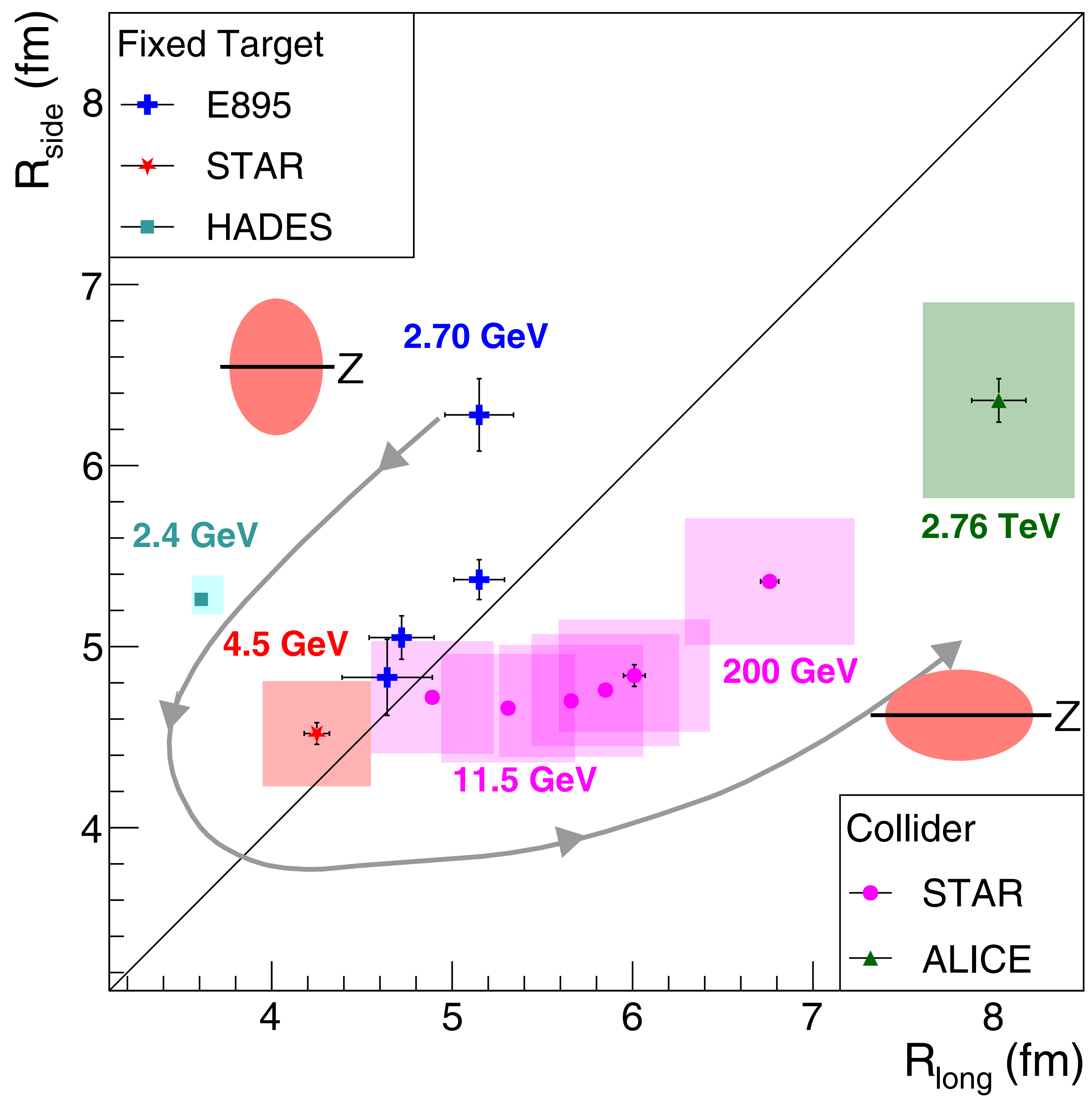
System size and shape



System volume

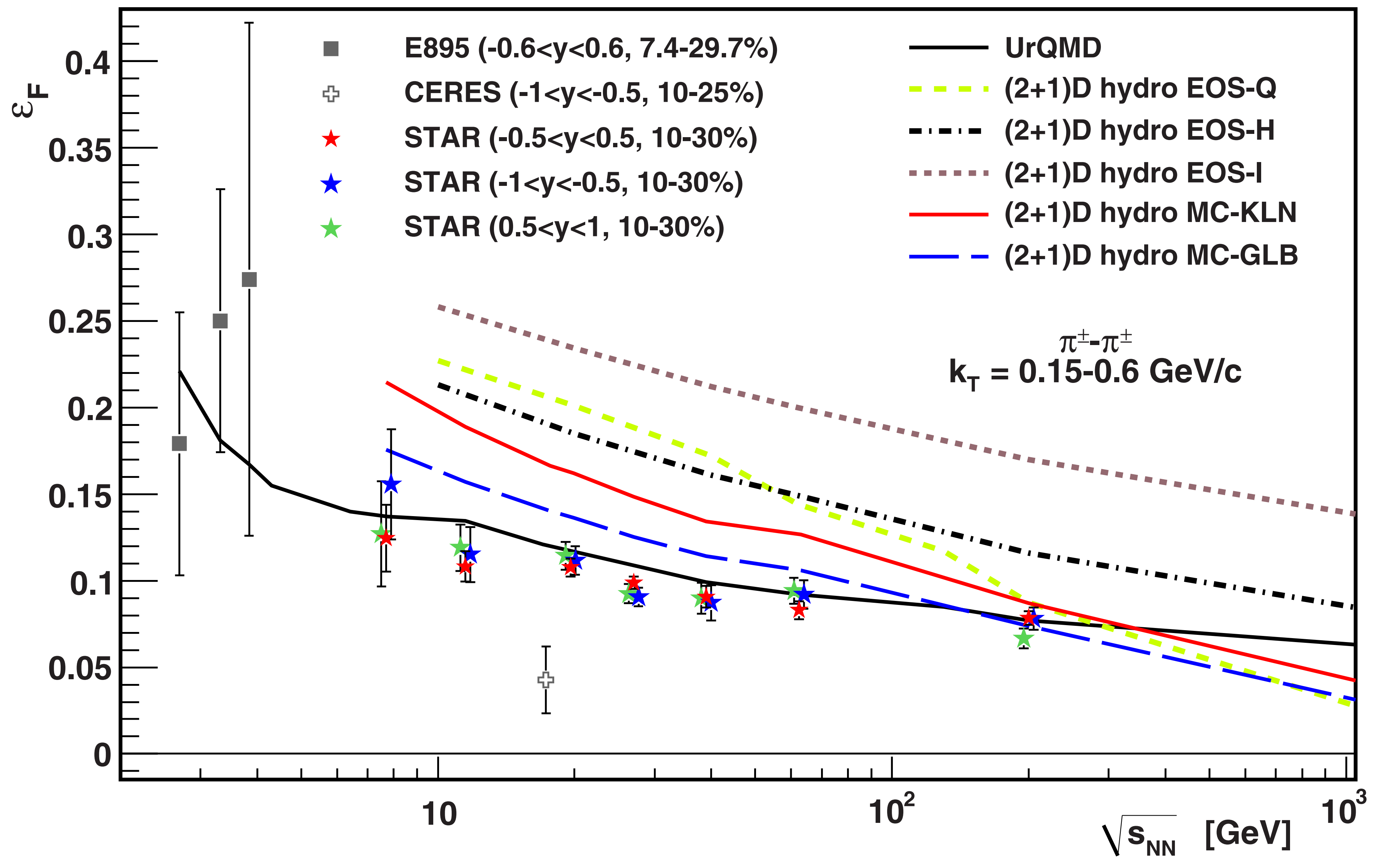


System shape along z



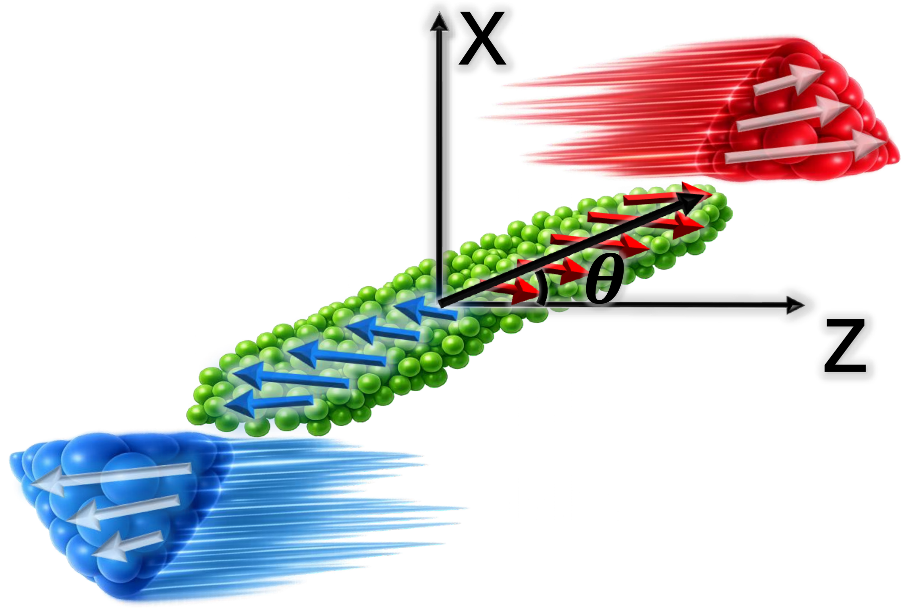
System shape in xy

$\varepsilon_F \sim 2R_{side,2}^2/R_{side,0}^2$

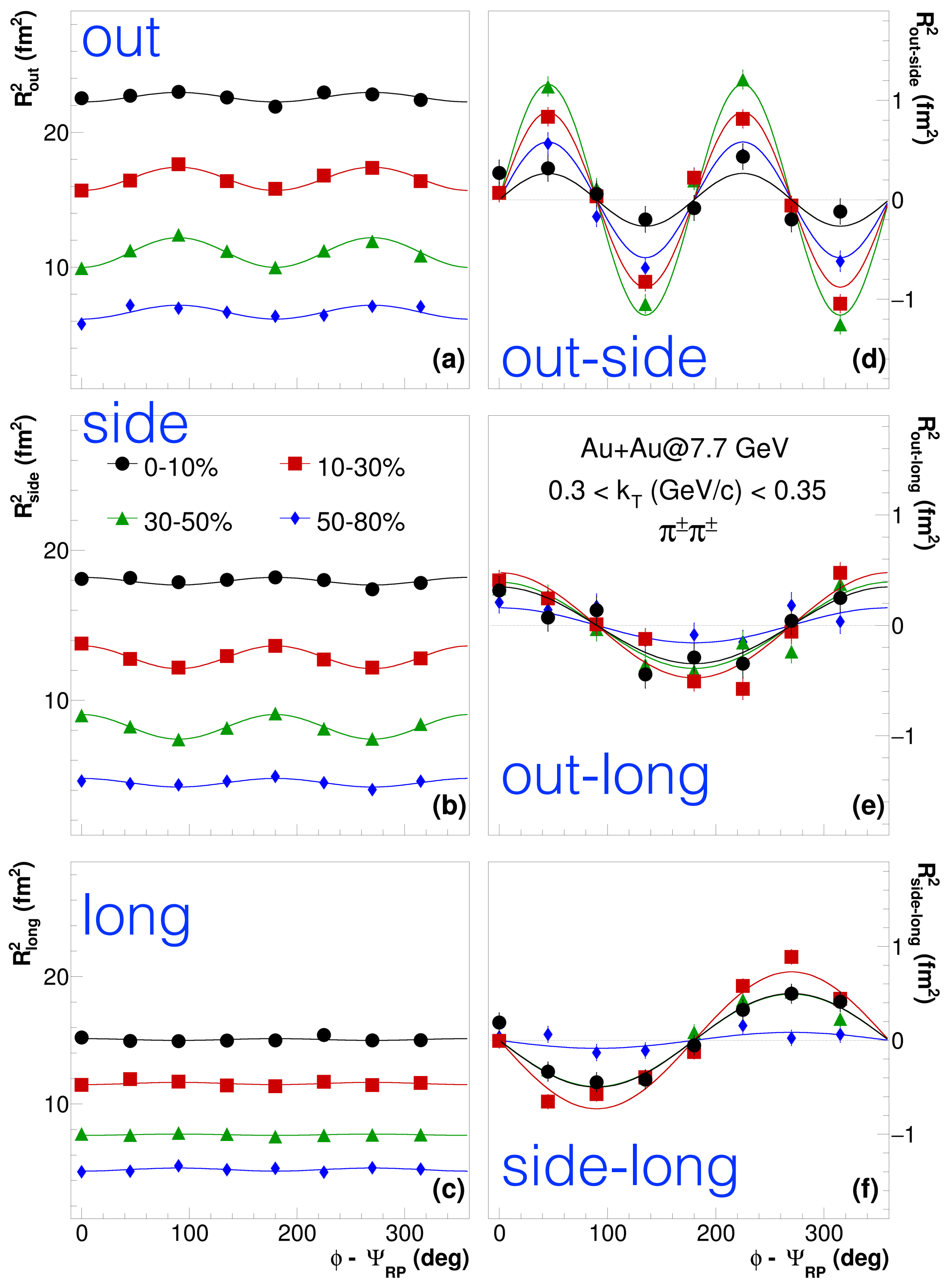


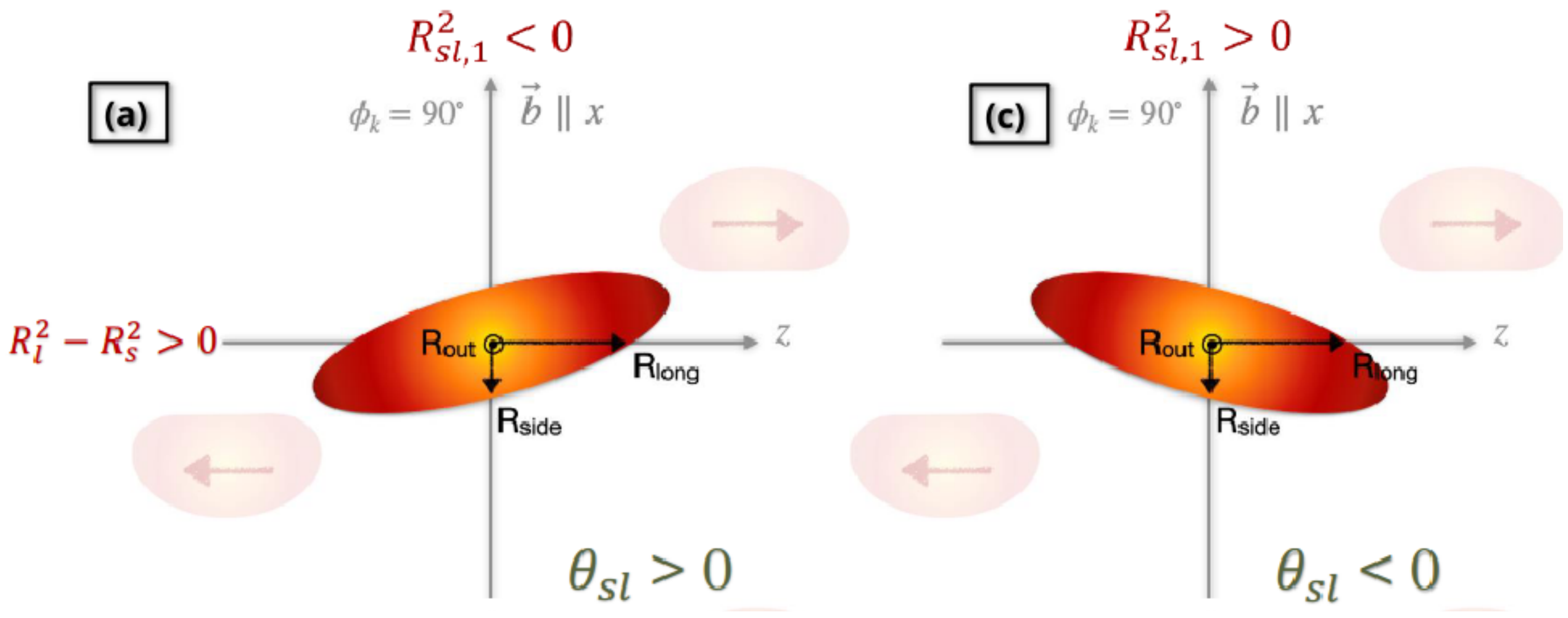
- System volume increases by a factor of ~2 from RHIC to the LHC
- “Oblate” from “prolate” shape in AGS→SPS→RHIC/LHC (nuclear stopping to nuclear transparency)
- Eccentricity is reduced from the initial to final-state at higher $\sqrt{s_{NN}}$: strong in-plane expansion, sensitive to EOS

Final-state tilt angle probed by pion HBT

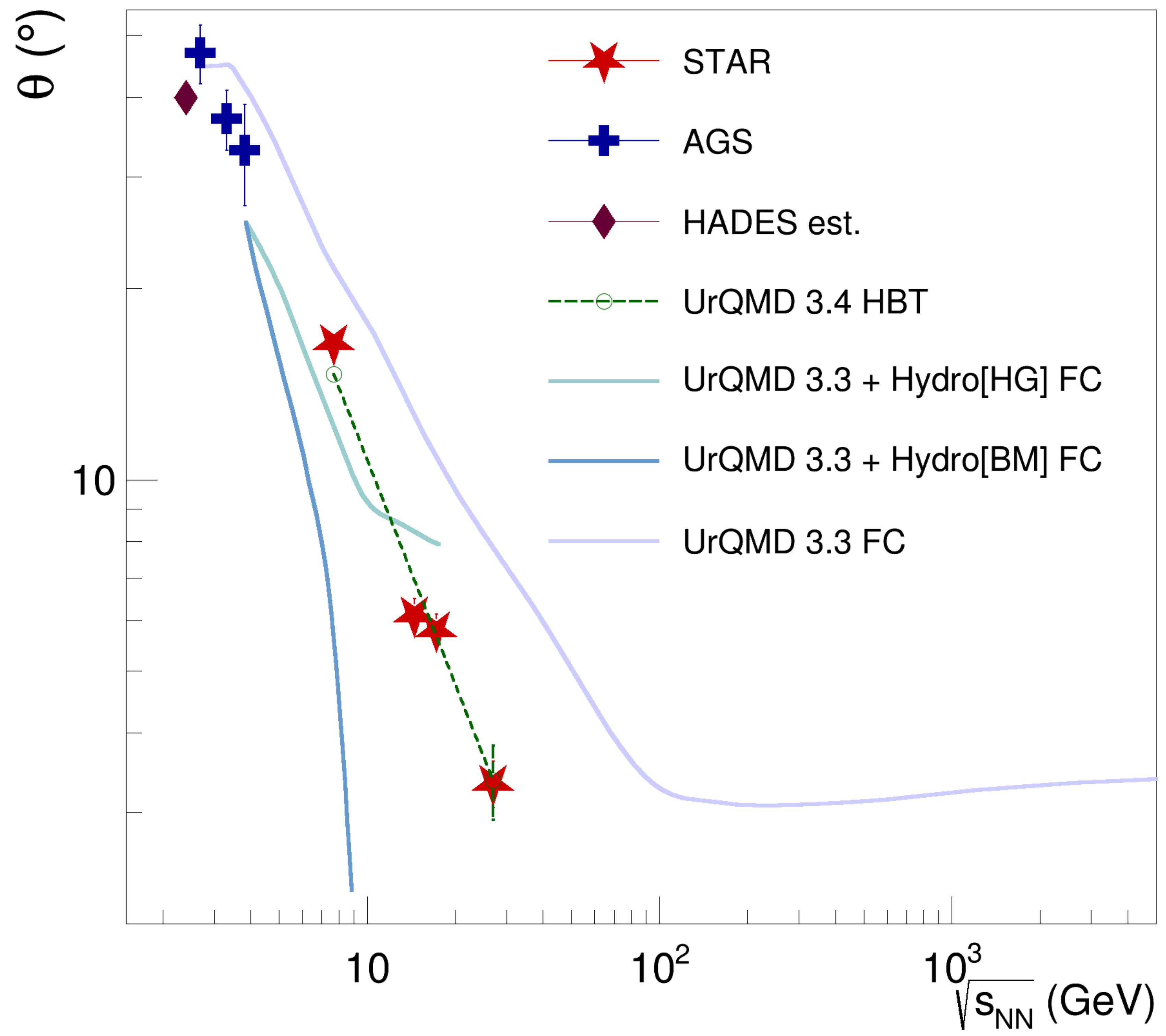


STAR, arXiv:2605.15013





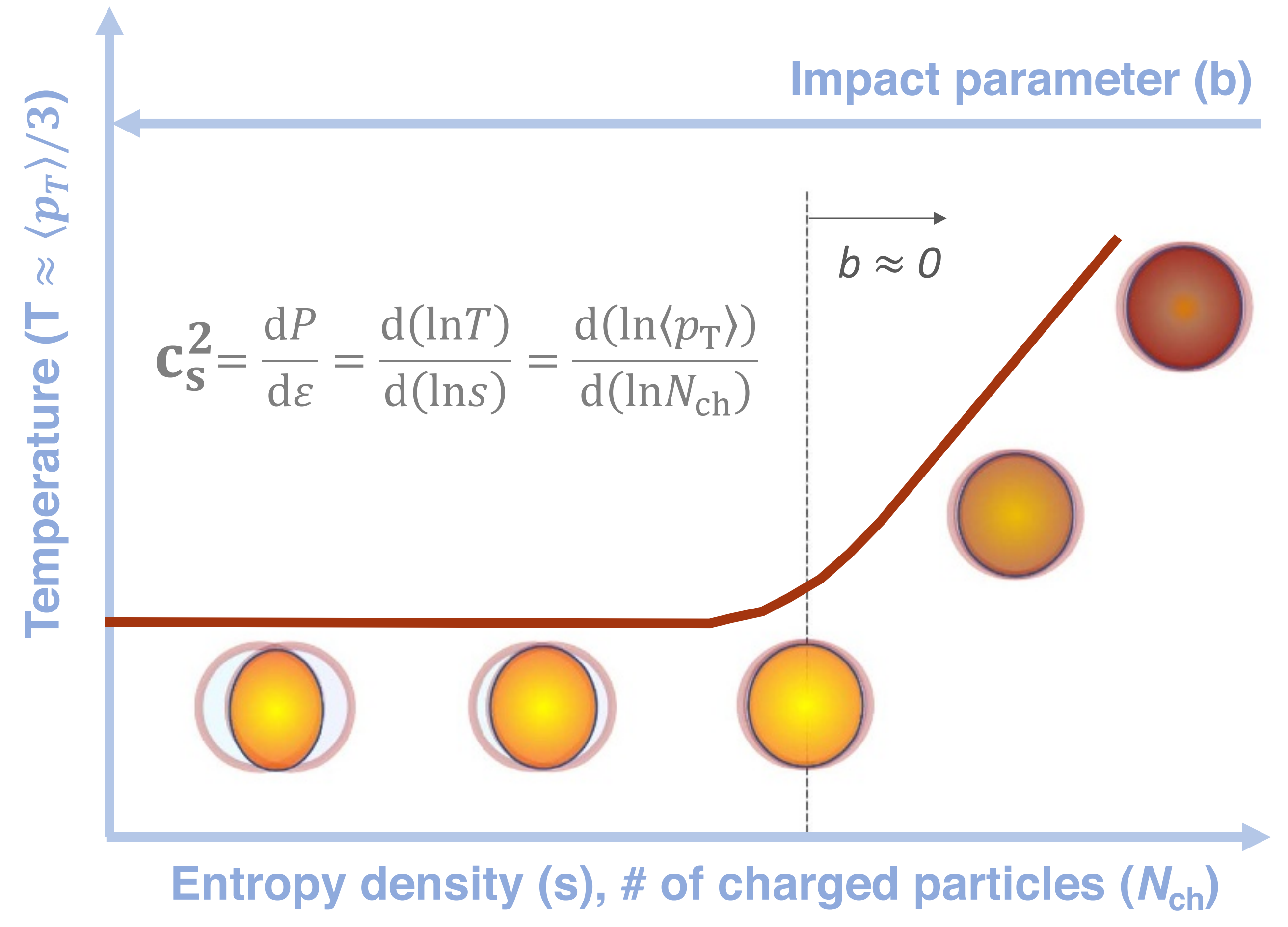
$$\theta_{\text{side-long}} = \frac{1}{2}\arctan\left(\frac{-4\,R^2_{\text{side-long},1}}{R^2_{\text{long},0} - R^2_{\text{side},0} + 2\,R^2_{\text{side},2}}\right)$$



- Tilt angle θ at freeze-out increases at lower $\sqrt{s_{NN}}$ as expected and is found to be sensitive to EOS
- Caveat: Not only geometrical effect but also dynamical effect

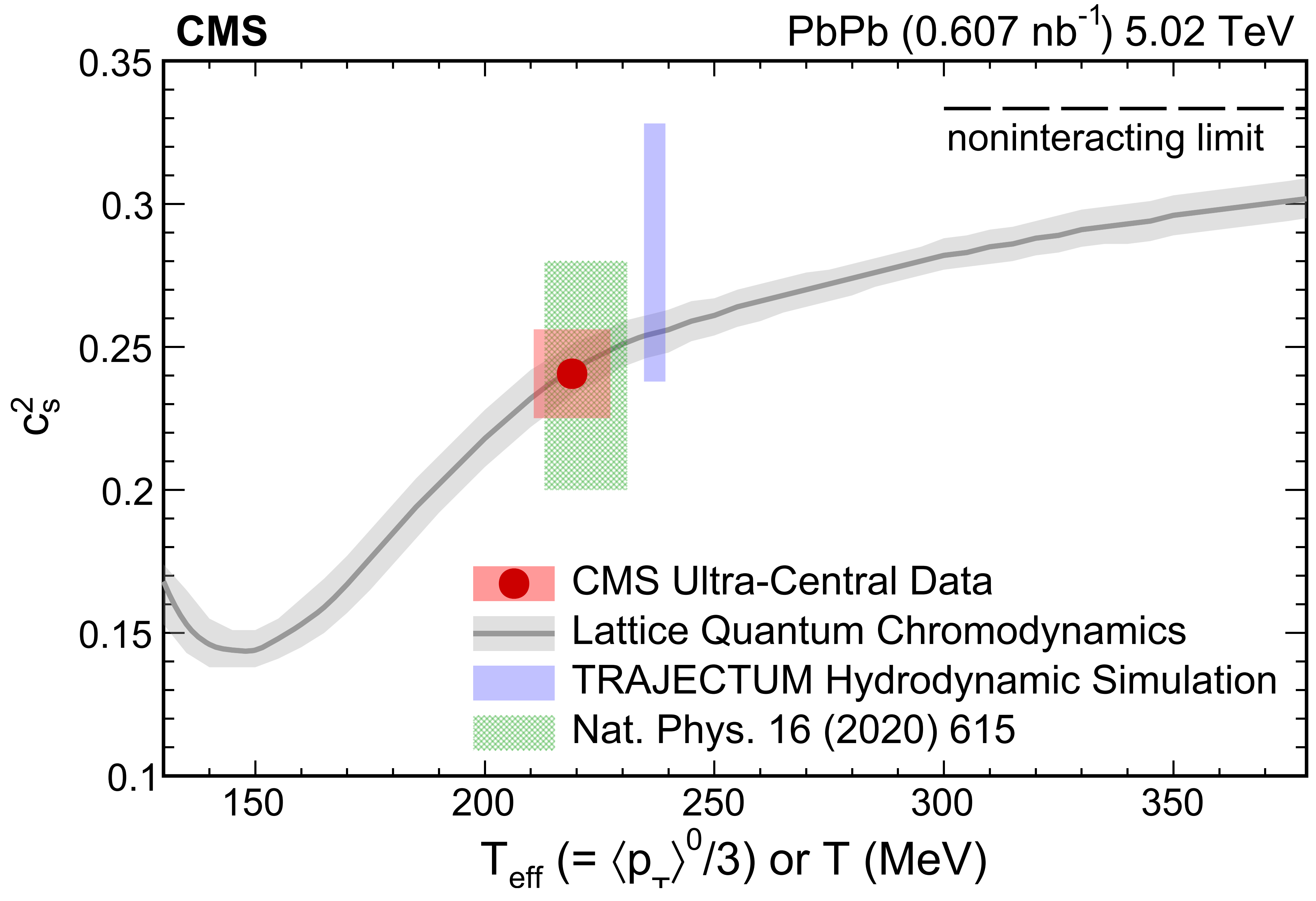
Extracting speed of sound in QGP

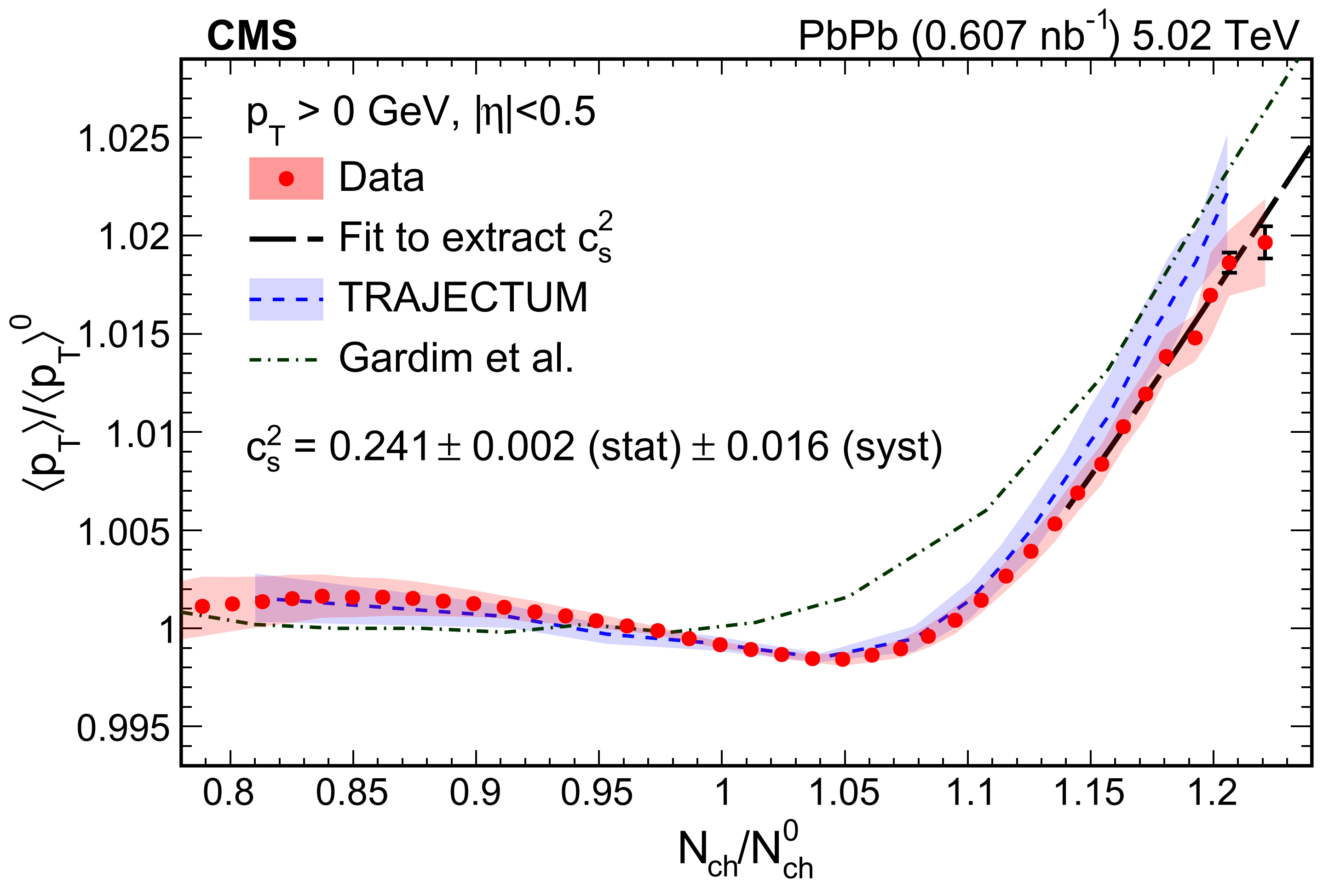
CMS, Rep.Prog.Phys.87(2024) 077801



Gardim et al., Nat.Phys.16, 615(2020)
Gardim et al., PLB809(2020)135749

$$c_s^2 = \frac{dP}{d\varepsilon} = \frac{s dT}{T ds} = \frac{d\langle p_T\rangle/\langle p_T\rangle}{dN_{ch}/N_{ch}}$$

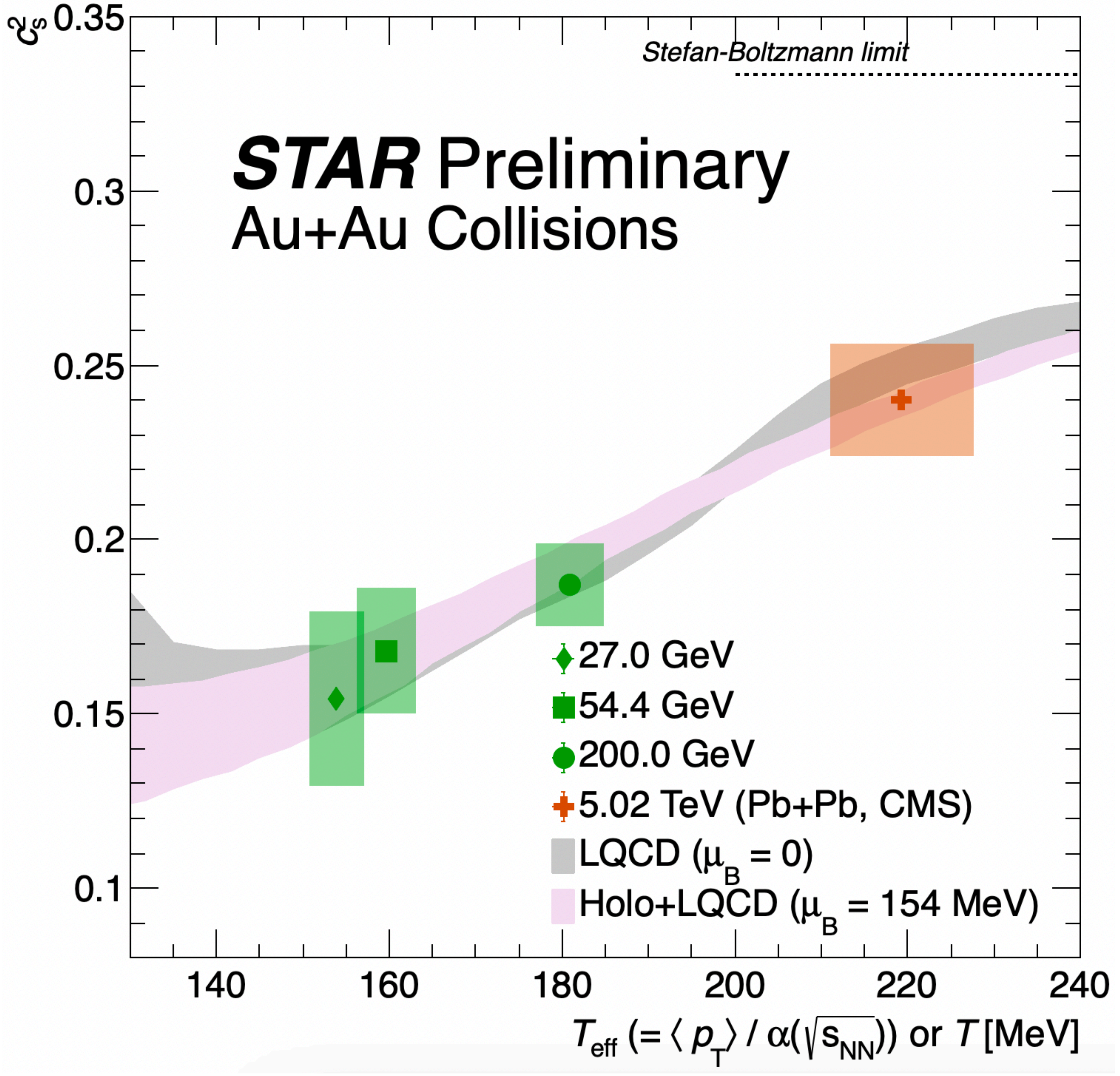




- Fix the volume by selecting ultra-central events, and see entropy variation due to quantum fluctuations
- Rise of <p_T> is observed in ultra-central collisions
- The extracted C_s^2 agrees with LQCD

CMS, Rep.Prog.Phys.87(2024) 077801
ATLAS, PRL133, 252301(2024)
ALICE, JHEP11(2025)076

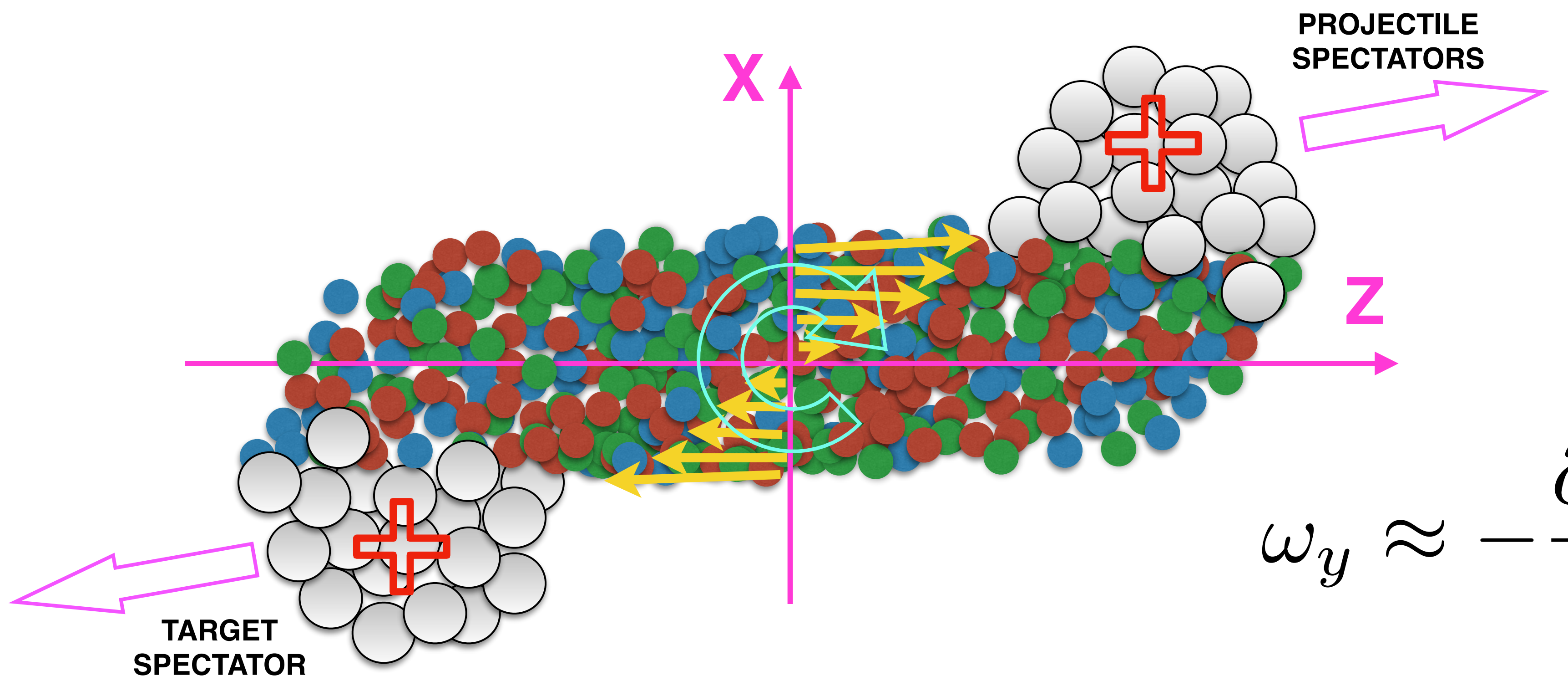
Temperature dependence of C_s^2



- Interesting to see that STAR BES data fall on the same curves as LQCD
- Caveats:
  - Assumptions $\langle p_T \rangle \propto T,\ N_{ch} \propto S,\ T_{eff} = \langle p_T \rangle / 3$ may be questionable
  - Self-correlation due to centrality selection makes a factor of ~2 difference
  - Kinematic cuts, e.g. low p_T cut, also affect the results (a factor of ~4)

G. Nijs and W. Schee, Phys.Lett.B853 (2024) 138636
ALICE, JHEP11(2025)076
L. Gavassino et al., Phys.Rev.C112, 054903 (2025)

Global polarization



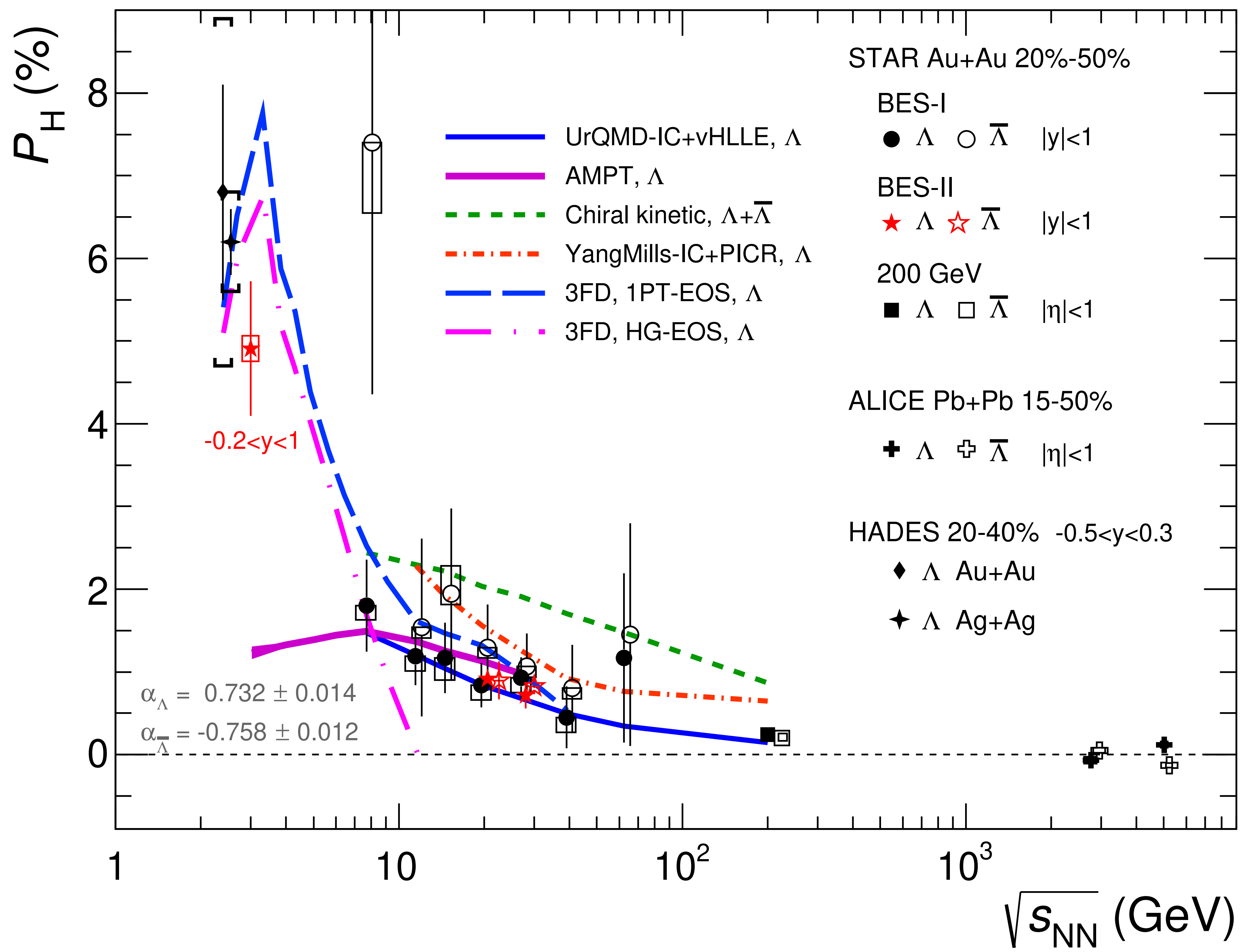
$$\omega_y \approx -\frac{\partial v_z}{\partial x} \neq 0$$

$$P = \frac{(S+1)(\boldsymbol{\omega} + \mu \boldsymbol{B}/S)}{3T}$$

The most vortical fluid ever observed! ω~10^{21} (s^{-1})

STAR, Nature 548.62(2017)

Reviews:
TN and S.Voloshin, Int.J.Mod.Phys.E33(2024)2430010
F.Becattini, M.Buzzegoli, TN, S.Pu, A.Tang, Q.Wang, Int.J.Mod.Phys.E33(2024)2430006



Energy dependence of P_H can be explained by models based on thermal vorticity

- Smaller velocity shear at higher energy due to longitudinal boost invariance
- Dilution effect due to longer system lifetime

I.Karpenko, F. Becattini, EPJ(2017)77.213
Y. Xie, D. Wang, L. P. Csernai, PRC95, 031901(R) (2017)

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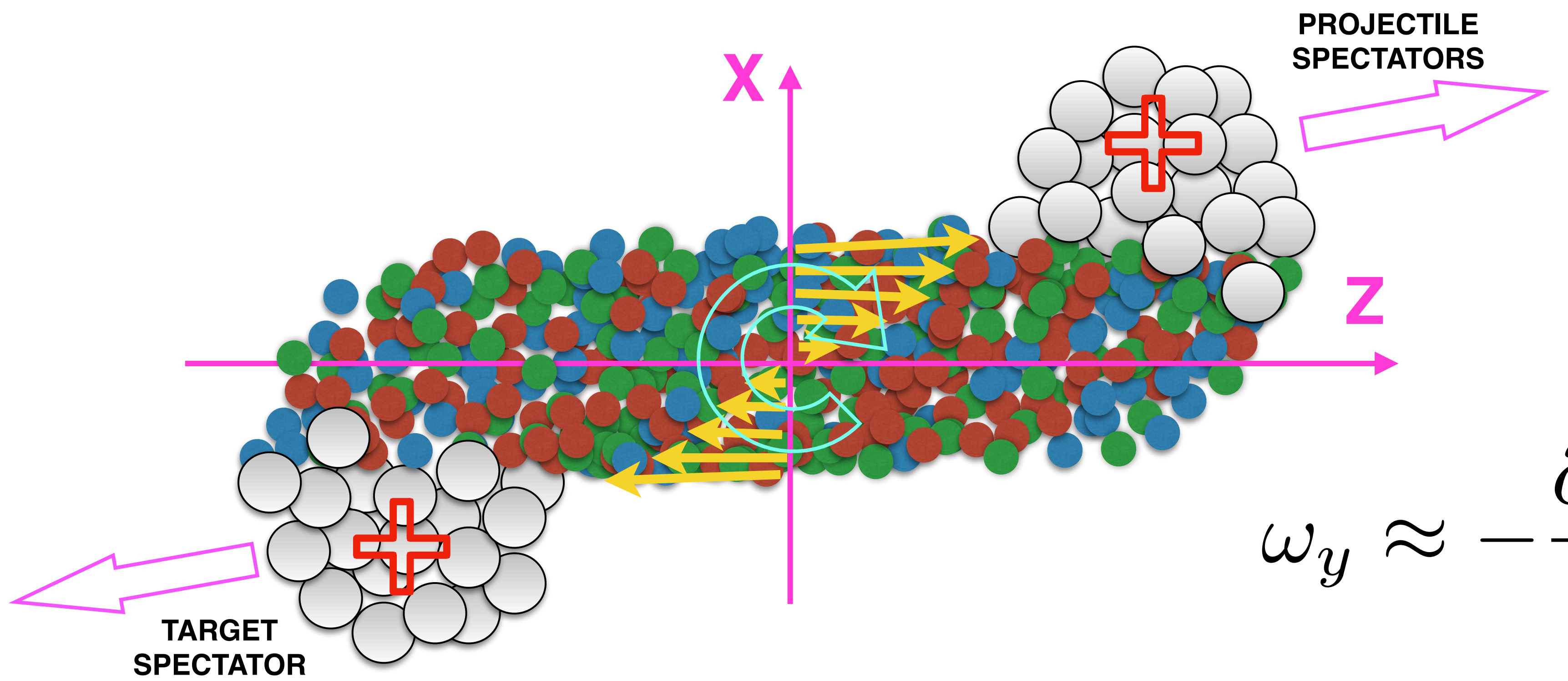

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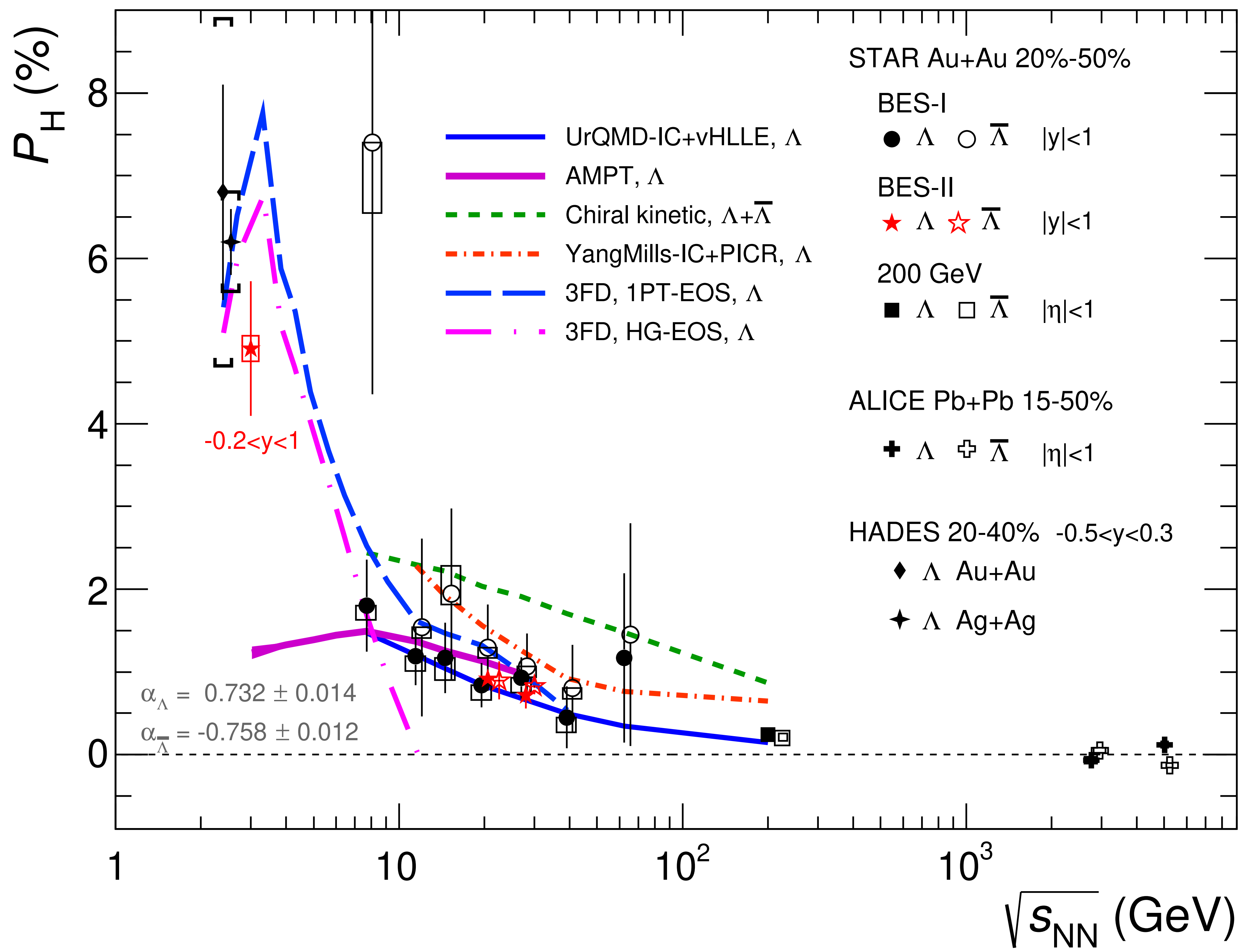

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I.Karpenko, F. Becattini, EPJ(2017)77.213
Y. Xie, D. Wang, L. P. Csernai, PRC95, 031901(R) (2017)

Transverse polarization (wrt production plane) coupled to v_1 may contribute at lower $\sqrt{s_{NN}}$

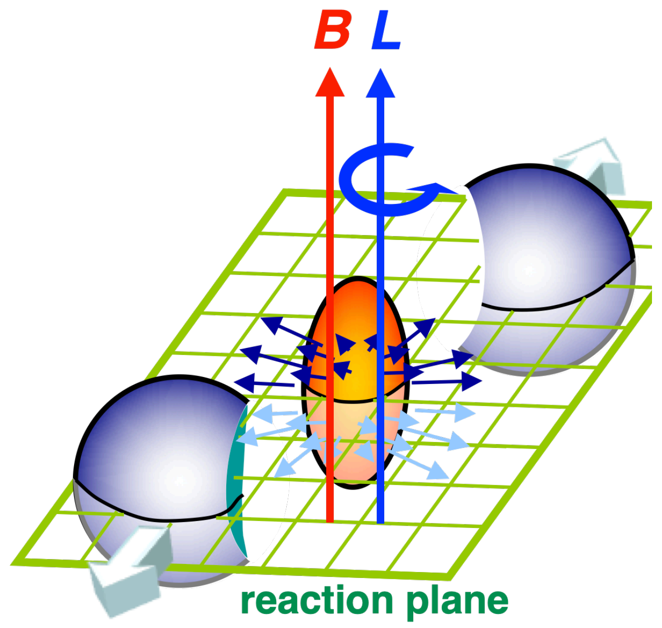
- Its origin is not understood since the first measurement in 1976

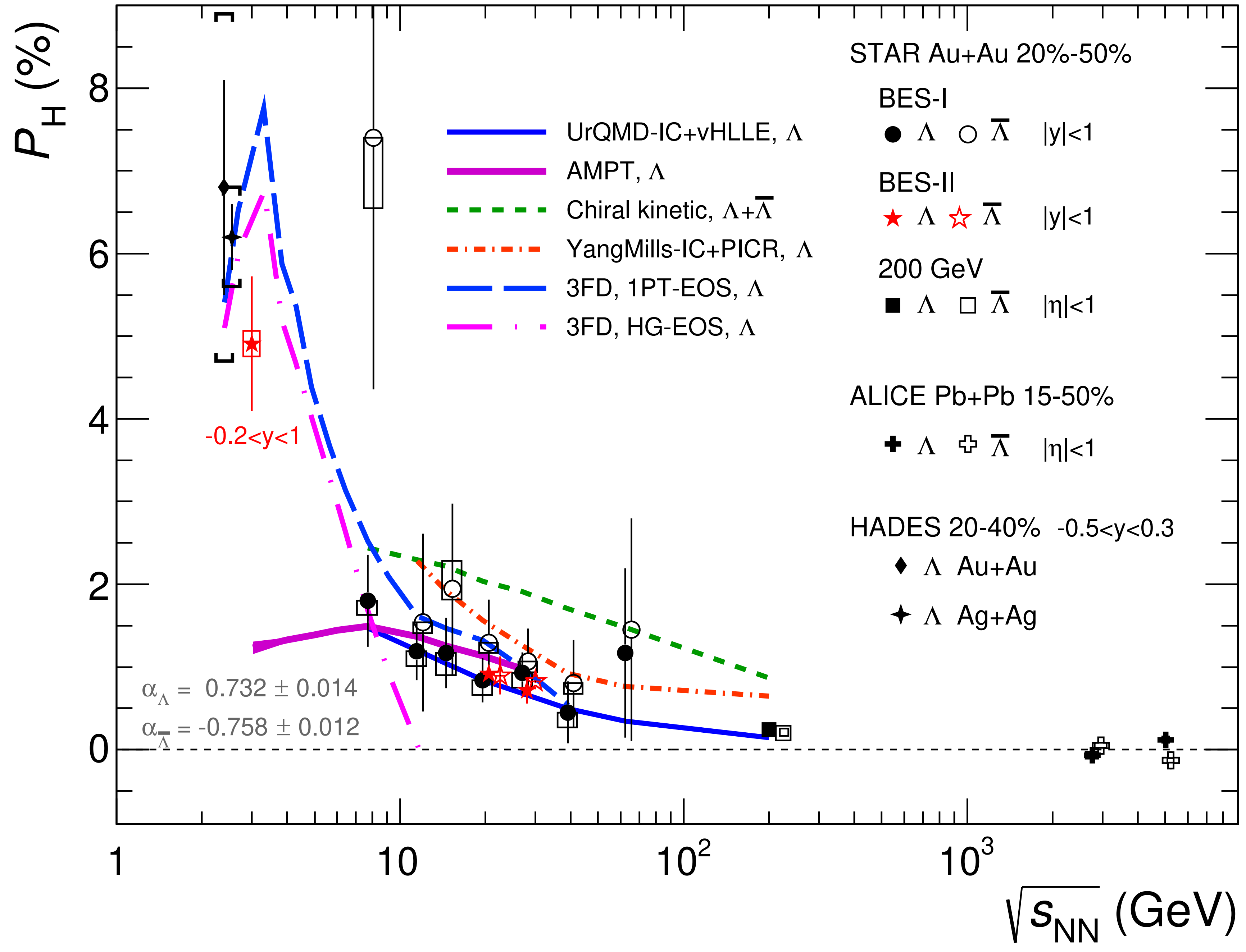
F.Liu and Z. Tu, arXiv:2603.19581

Polarization in HIC

Recent reviews
TN and S.Voloshin, Int.J.Mod.Phys.E33(2024)2430010
F.Becattini, M.Buzzegoli, TN, S.Pu, A.Tang, Q.Wang, Int.J.Mod.Phys.E33(2024)2430006

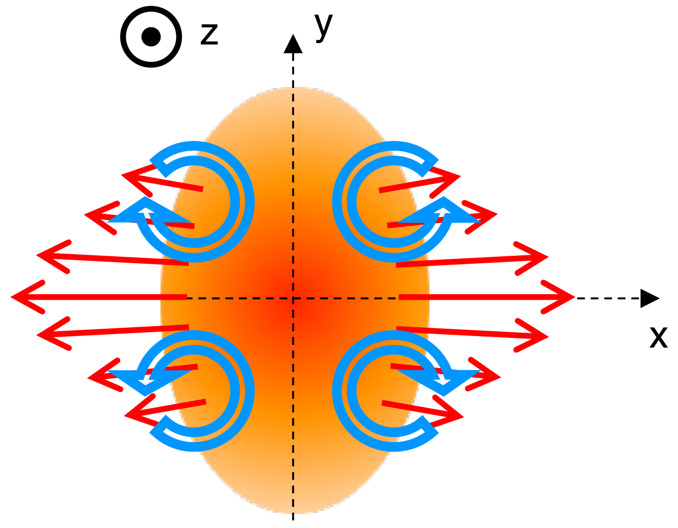
$P_J = P_{-y}$

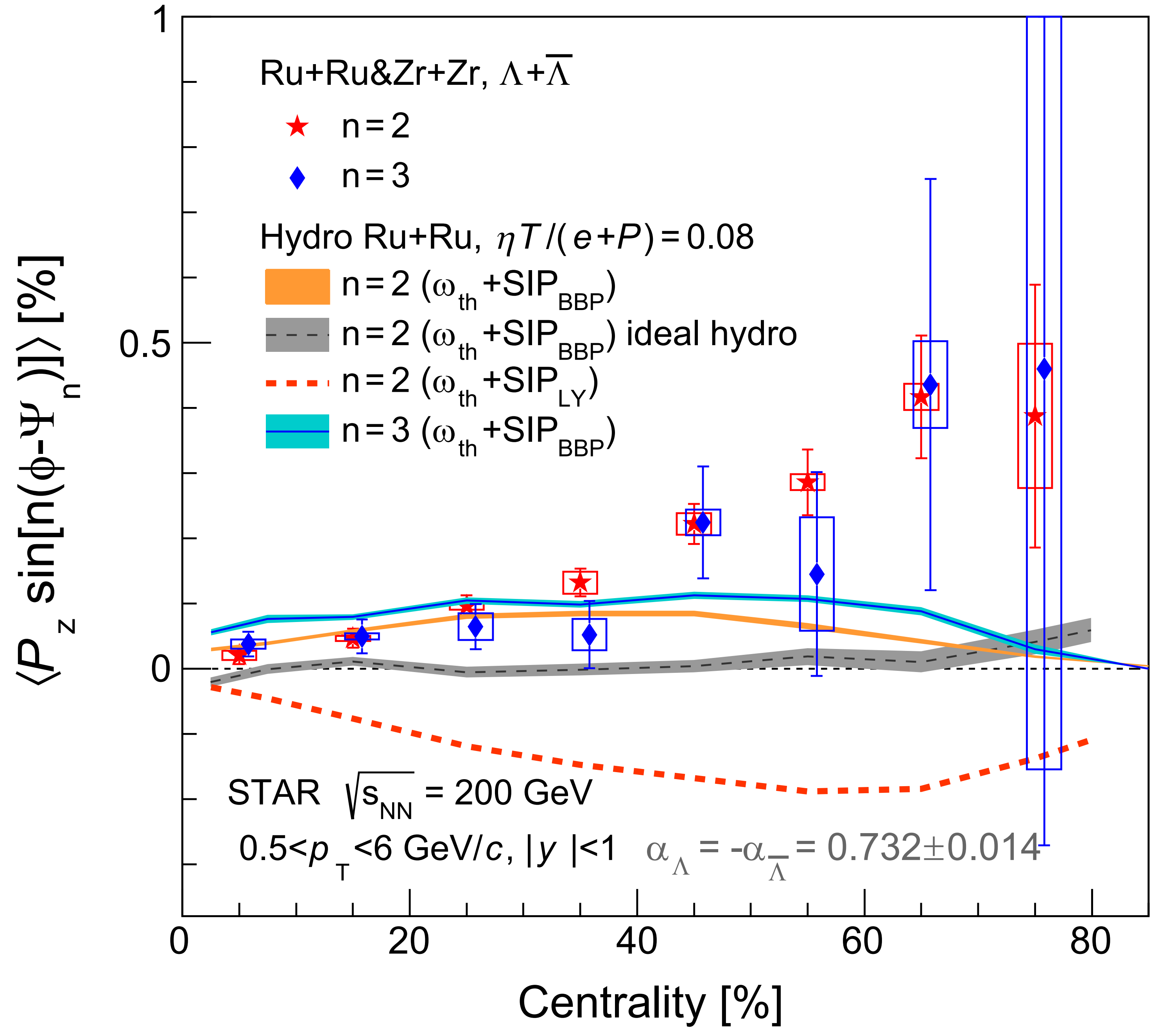




Driven by the initial orbital angular momentum

P_z





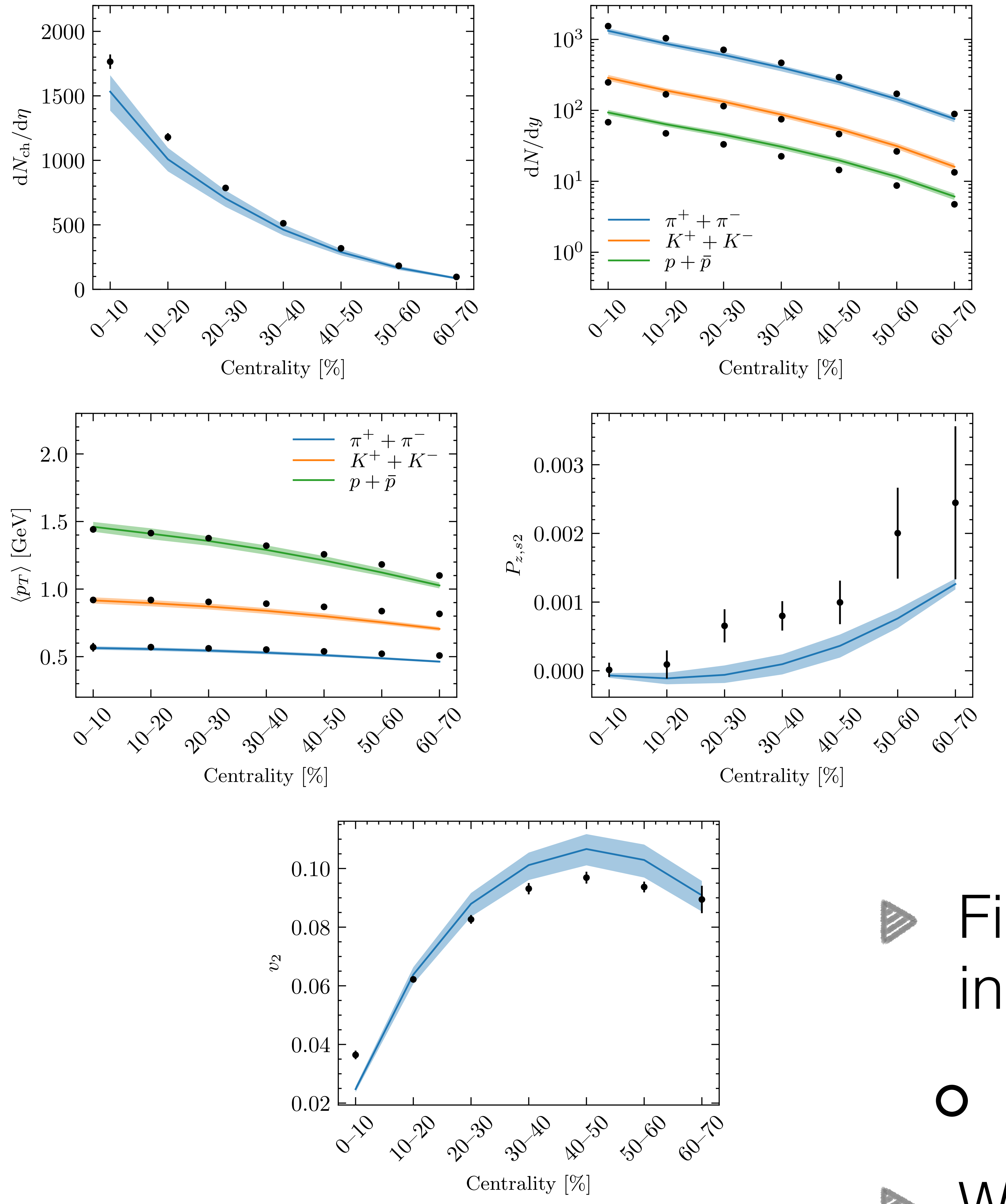
Driven by anisotropic flow

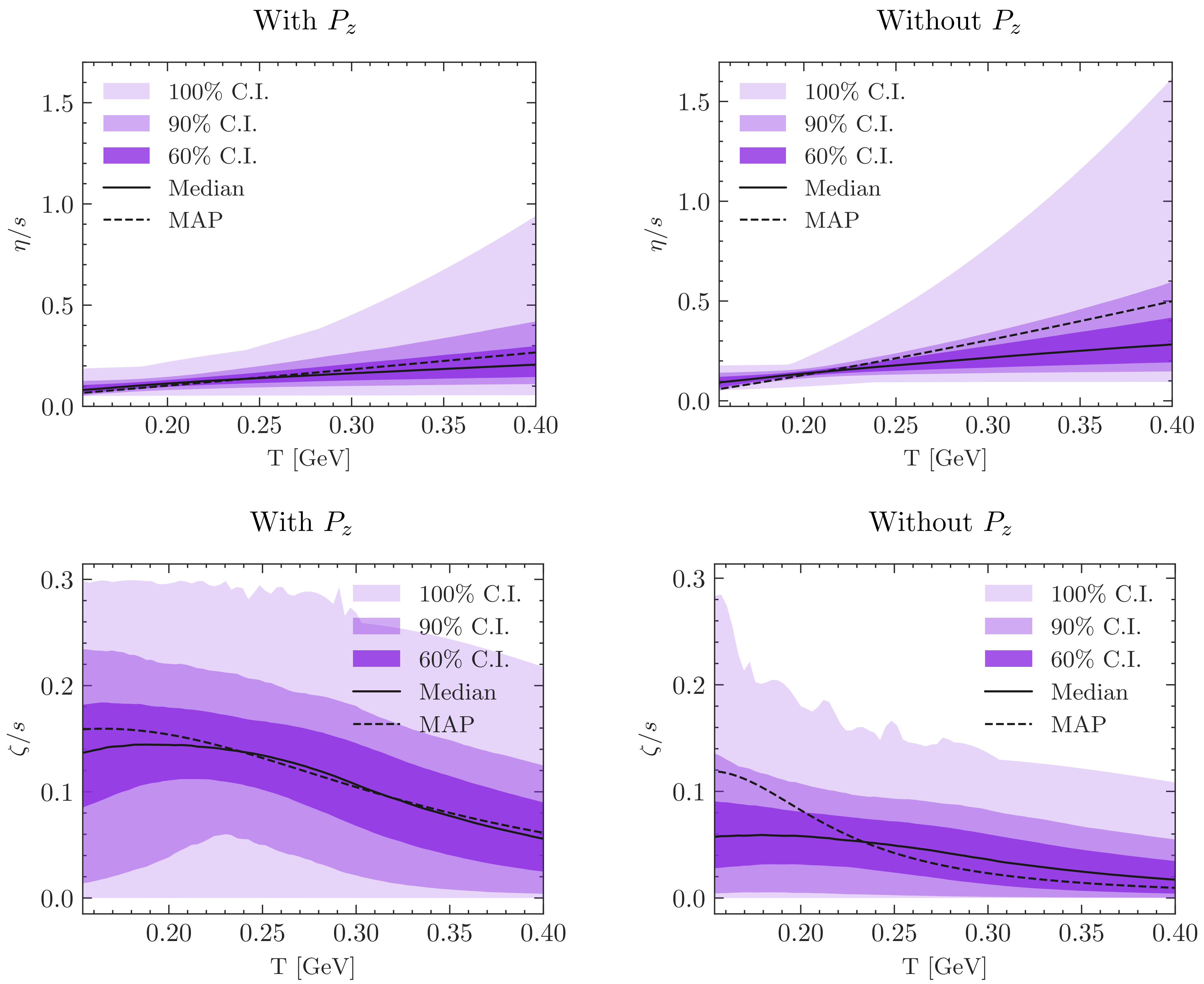
- Spin observables seem to have sensitivity to the medium properties such as the shear/bulk viscosities and EOS

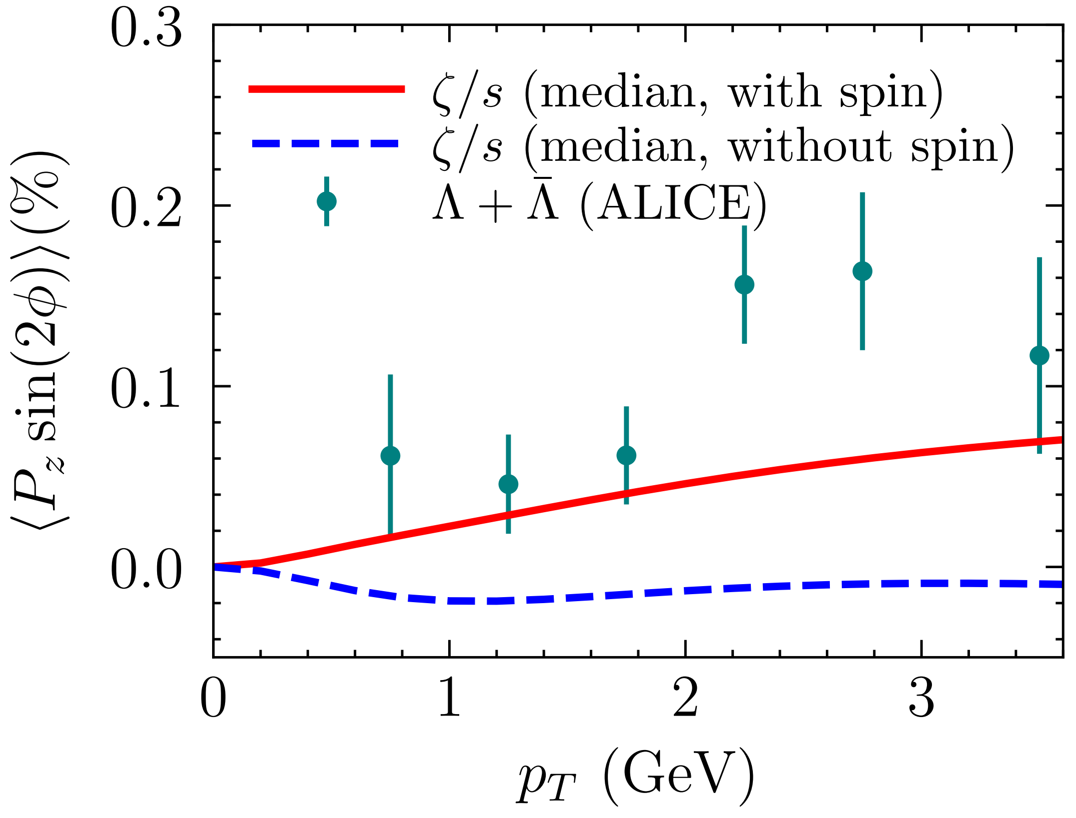
S. Alzharani et al., PRC106.014905 (2022)
A. Palermo et al., EPJC84(2024)920

Bayesian analysis with spin

S. Singh, E. Grossi, and F. Becattini, arXiv:2605.29383

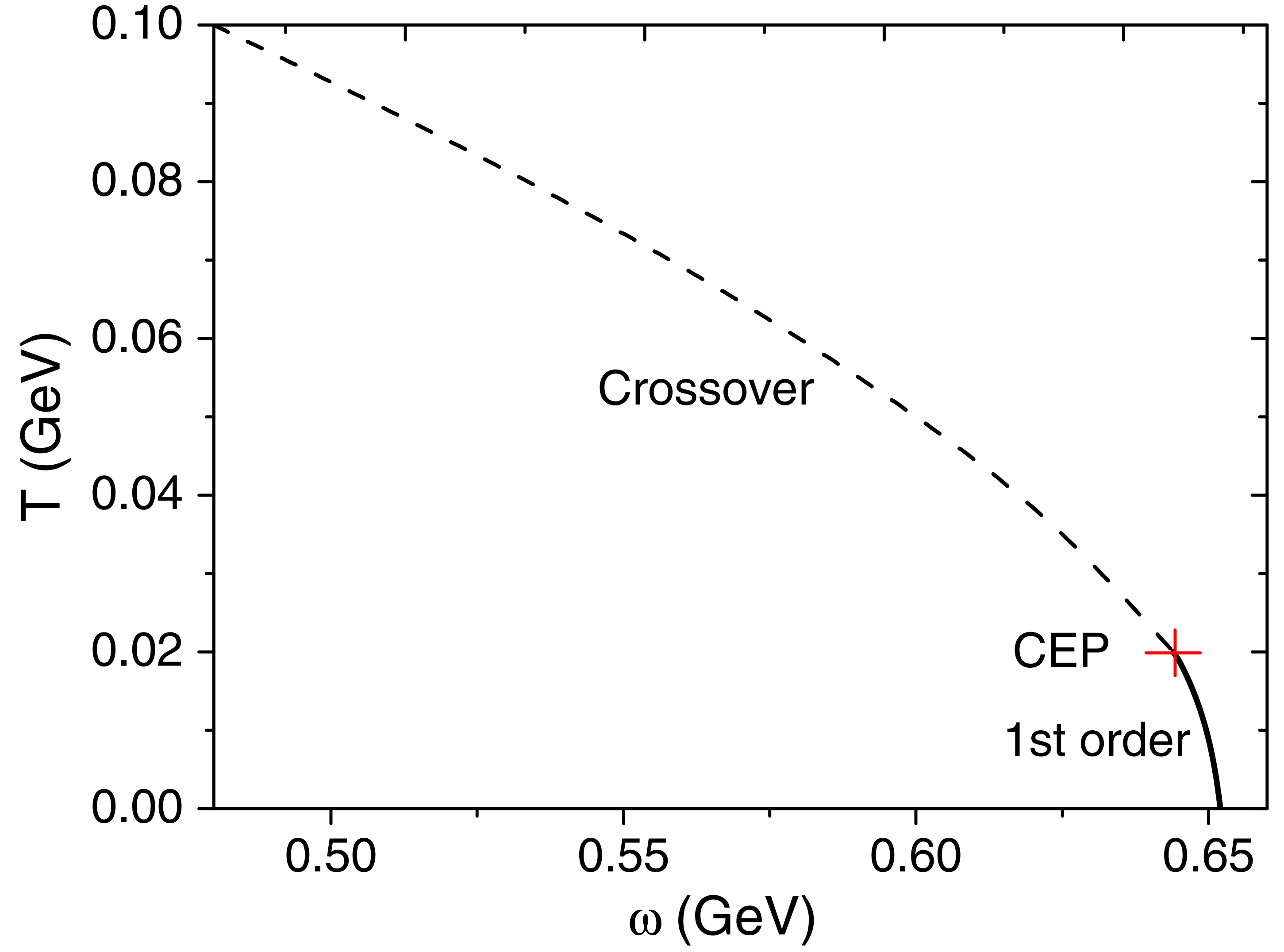




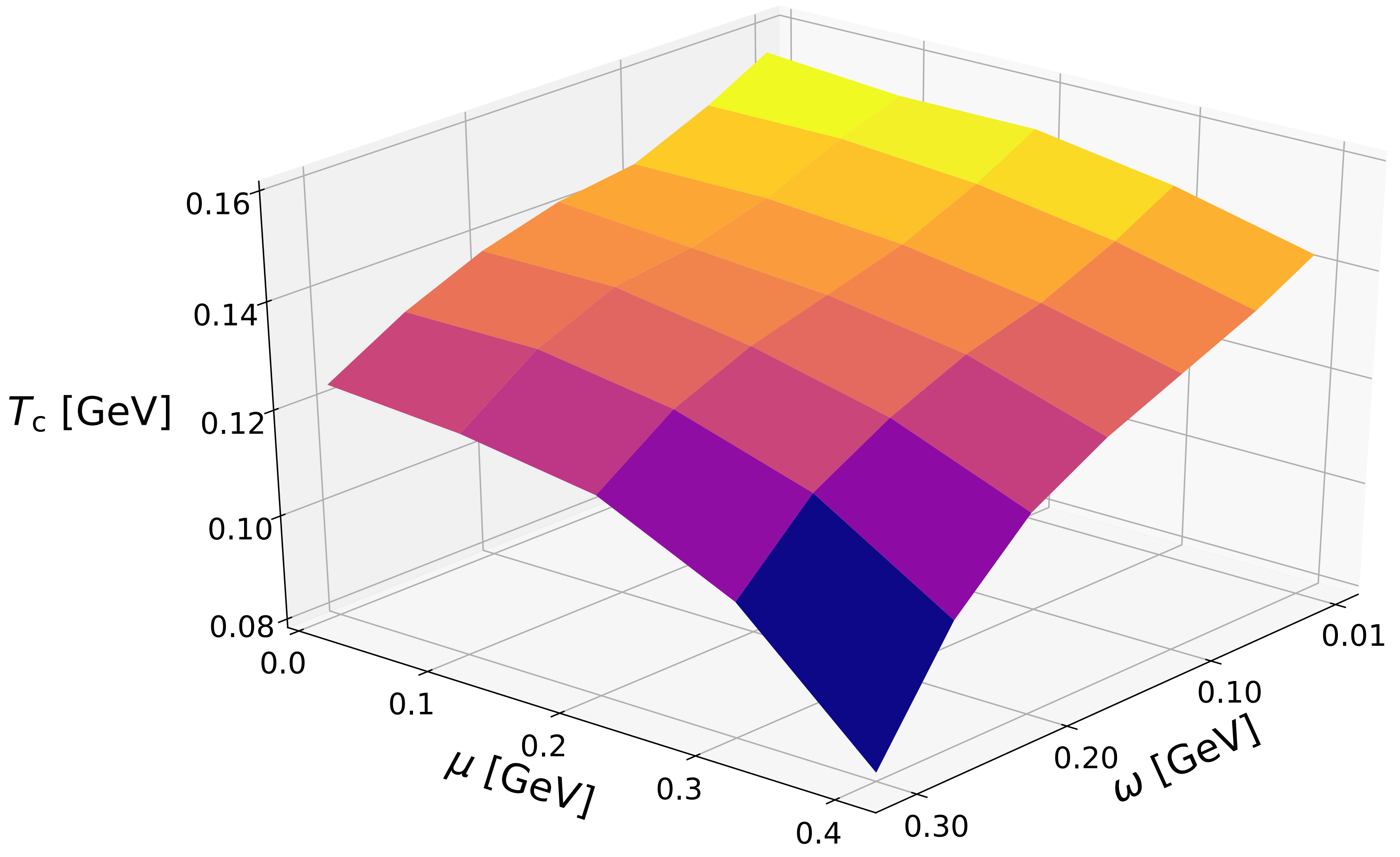


- First attempt to constrain η/s and ζ/s using the spin observable ($P_{z,2}$) in Bayesian analysis
  - Leading to larger bulk viscosity
- Without spin, the sign of $P_{z,2}$ becomes the opposite

Phase diagram of rotating nuclear matter



Y. Jiang and J. Liao, PRL117.192302(2016)

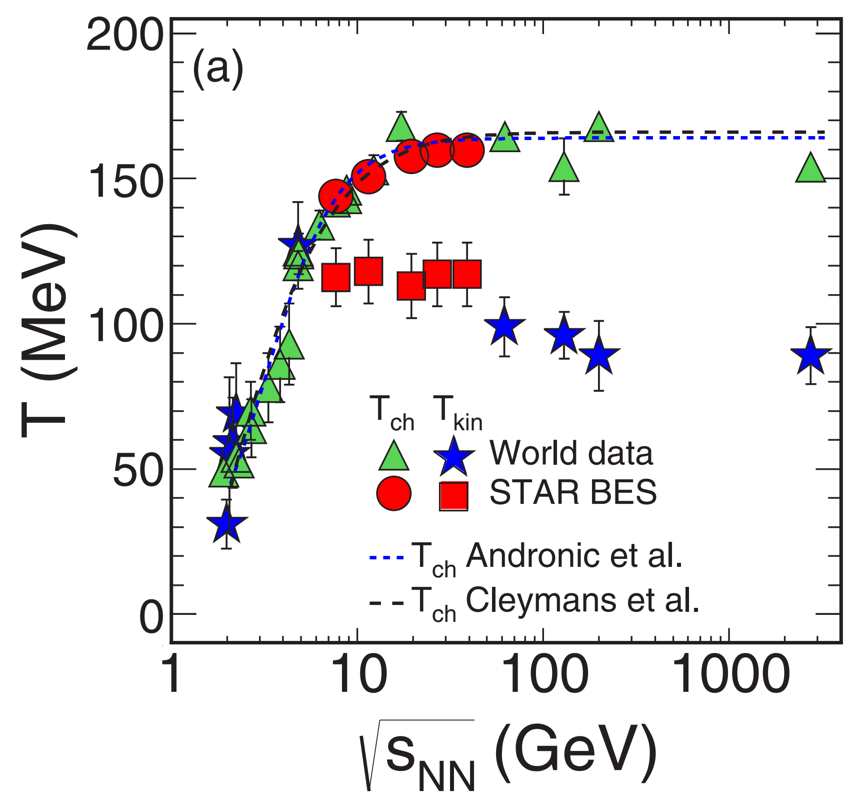


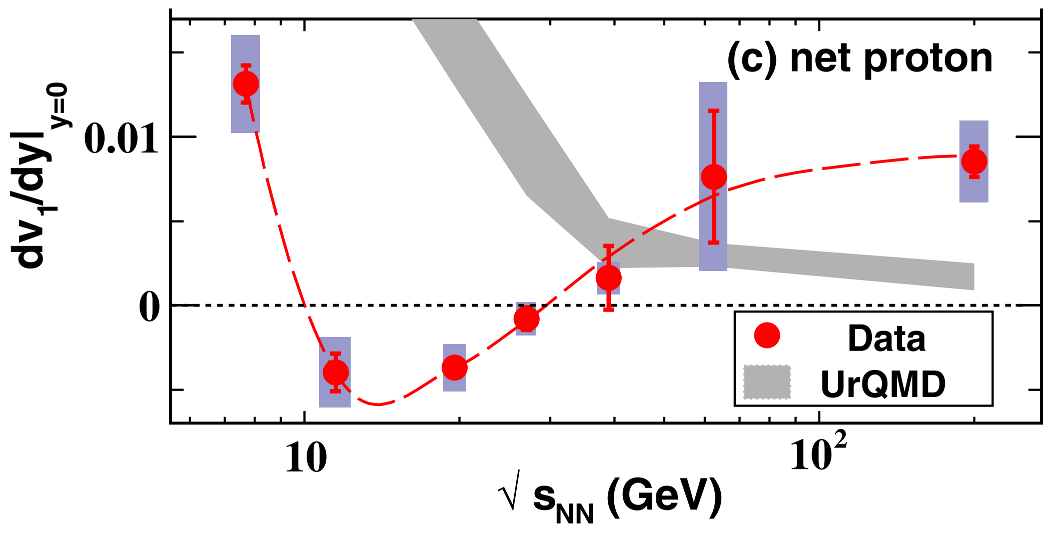
Y. Fujimoto, K. Fukushima, Y. Hidaka, PLB816(2021)136184

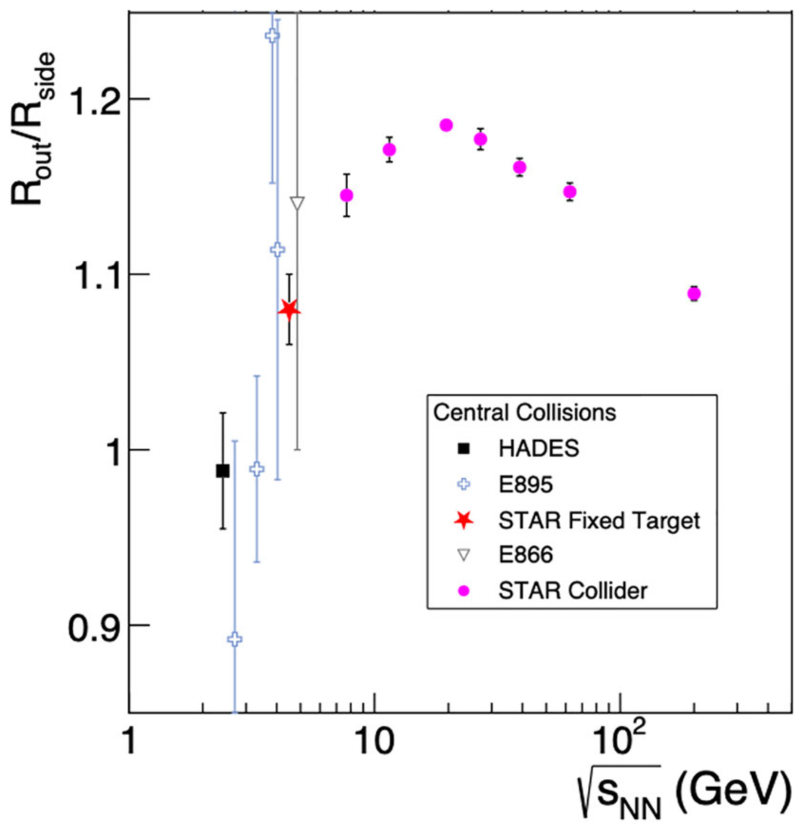
- Vorticity ω acts like baryon chemical potential μ_B and lower deconfinement transition temperature

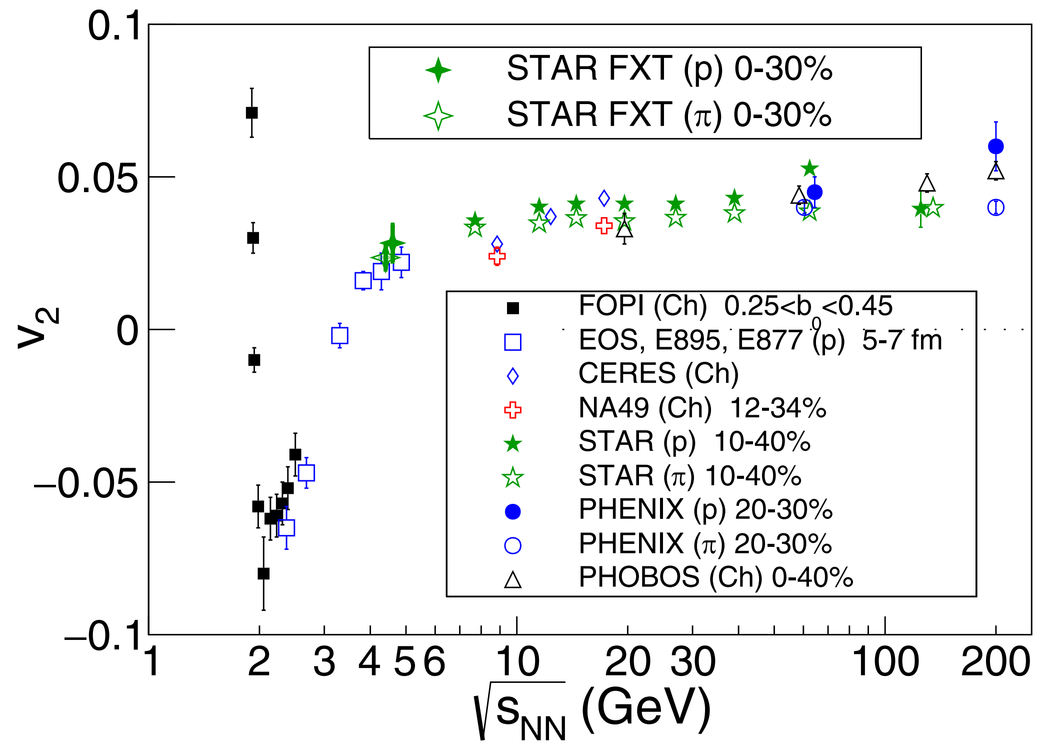
Summary

- Different observables show non-monotonicity or peak or dip in their energy dependence, which may or may not be related to the softening of EOS or 1st-PT
- Complexity in the interpretation due to other contributions, e.g. spectator shadowing, which need to be disentangled/understood
- Spin observables could be useful to constrain the medium properties and to study phase structure









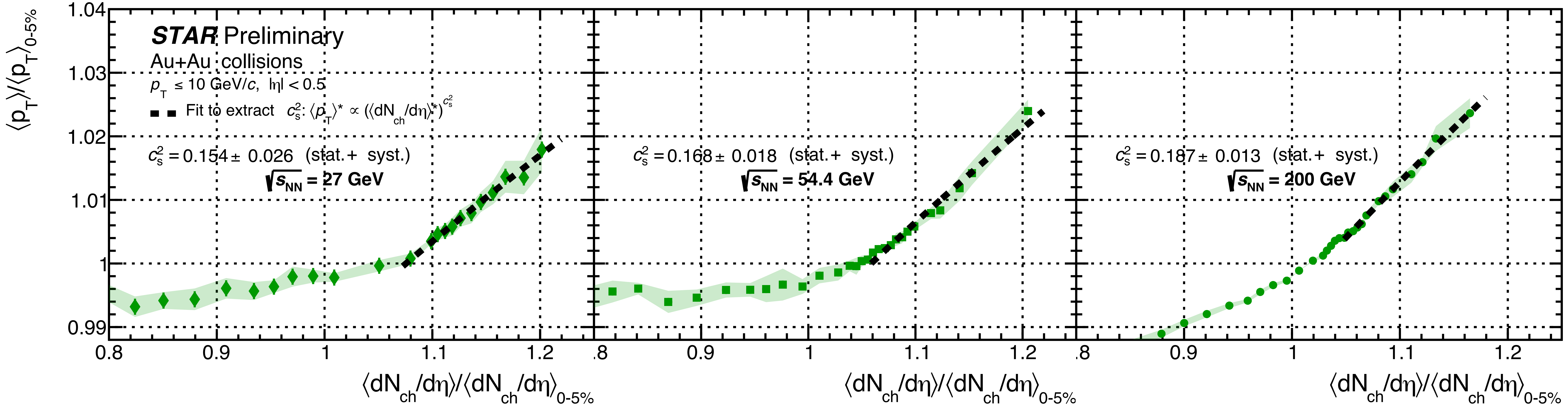
Outlook

- Stay tuned for completing BES-II FXT analyses
- Future experiments: CBM, CEE, JPARC-HI

Backup

C. Broodo(STAR), SQM2026

c_s^2 increases with $\sqrt{s_{NN}}$ →



ALICE, JHEP11(2025)076

ATLAS, PRL133, 252301 (2024)

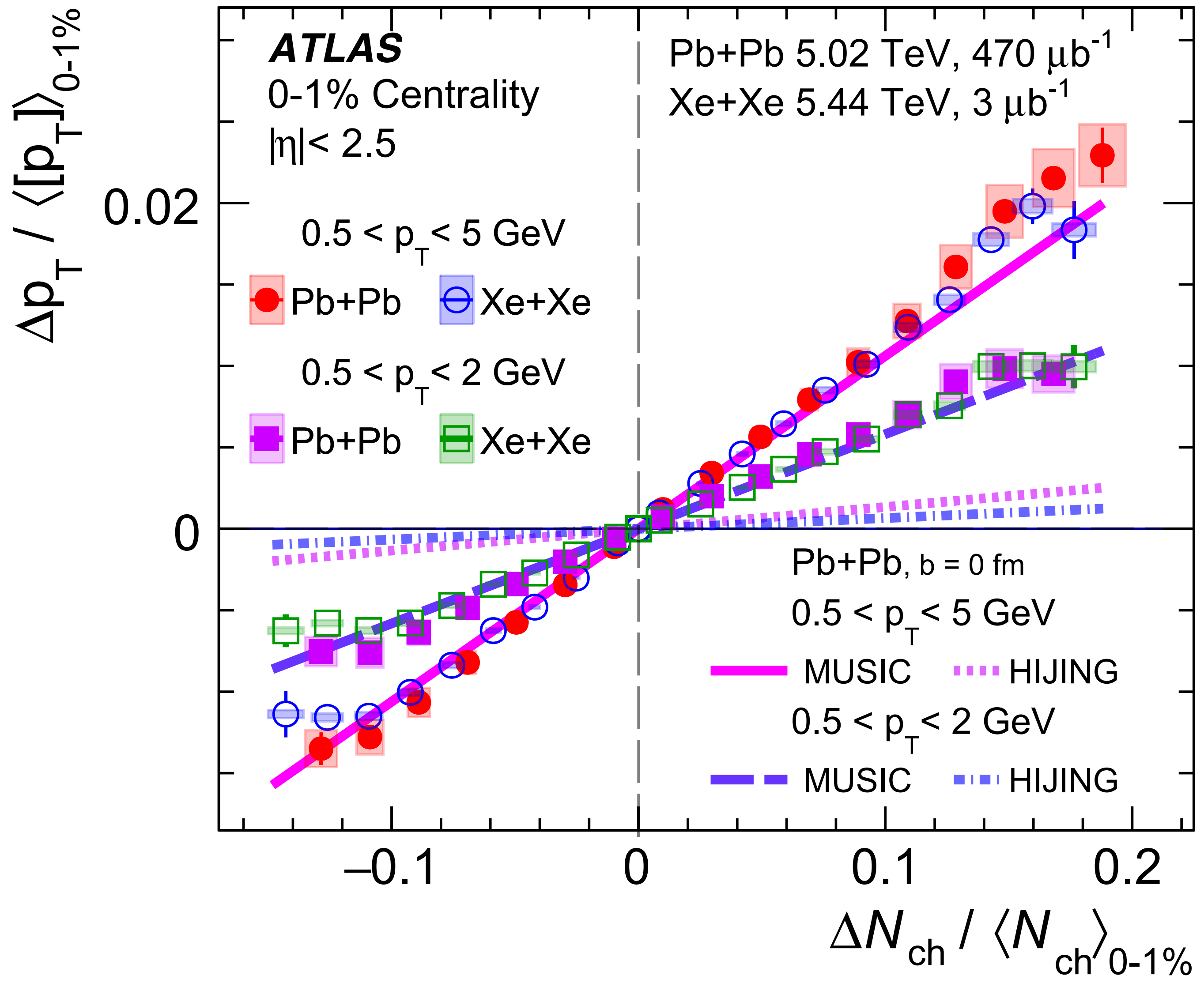


FIG. 4. Correlation between $\Delta p_T/\langle[p_T]\rangle_{0\%\text{–}1\%}$ and $\Delta N_{ch}/\langle N_{ch}\rangle_{0\%\text{–}1\%}$ in the 0%–1% most central Pb + Pb and Xe + Xe collisions for two p_T ranges. The error bars represent the statistical uncertainties of the measurement, whereas the shaded boxes represent the systematic uncertainties of the data along the x and y axes. The data are compared to the MUSIC hydrodynamic model with $c_s^2 \approx 0.23$ at $T_{eff} \approx 222$ MeV and the HIJING model, both at zero impact parameter ($b = 0$ fm) [11].