Directed flow in heavy-ion collisions as a probe of the first order phase transition

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in collaboration with

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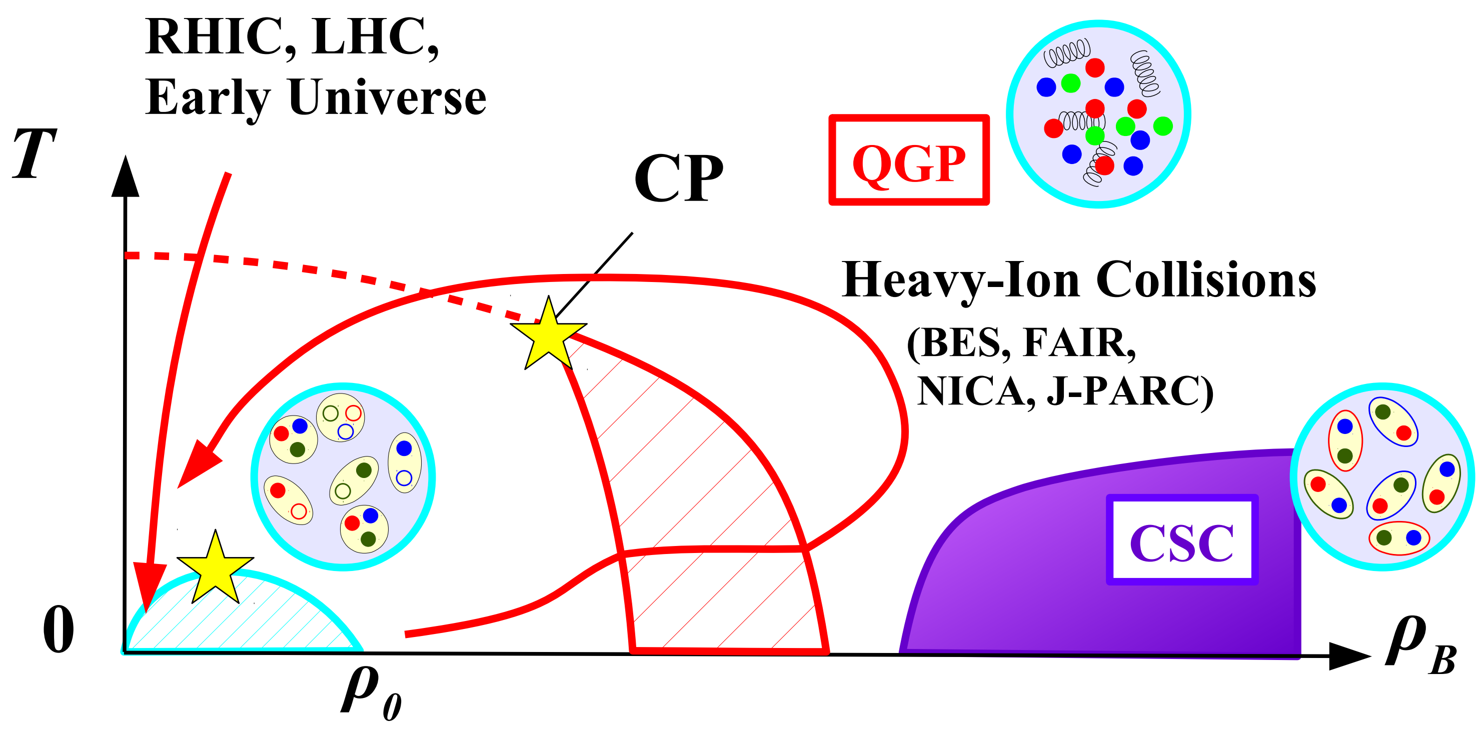
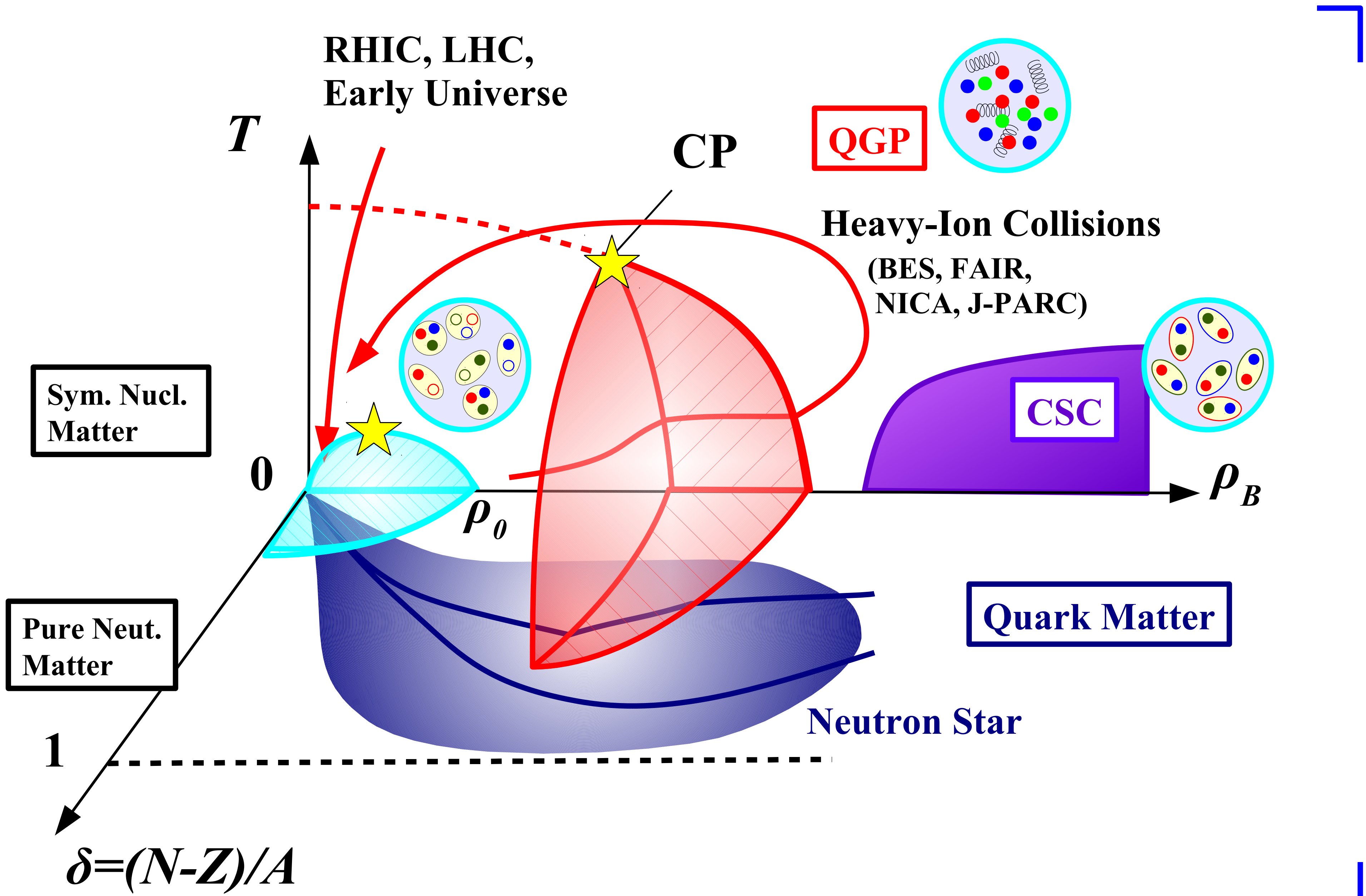
- **Introduction: Negative dv1/dy at $\sqrt{s_{NN}}$~10 GeV**
- **Hadronic transport model with Softening Effects**
- **Summary**

Y. Nara, A. Ohnishi, arXiv:1512.06299 [nucl-th] (QM2015 proc., to appear)
Y. Nara, H. Niemi, A. Ohnishi, H. Stoecker, arXiv:1601.07692 [hep-ph]

QCD Phase Diagram



QCD Phase Diagram



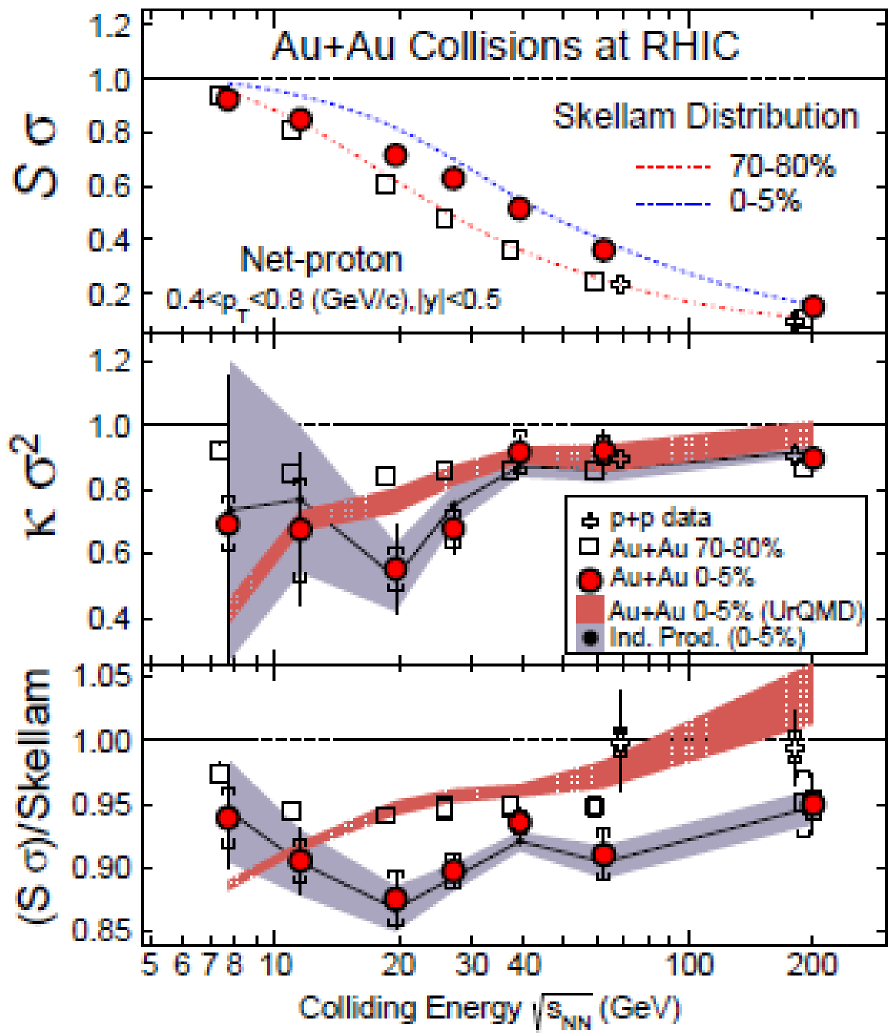
QCD phase transition

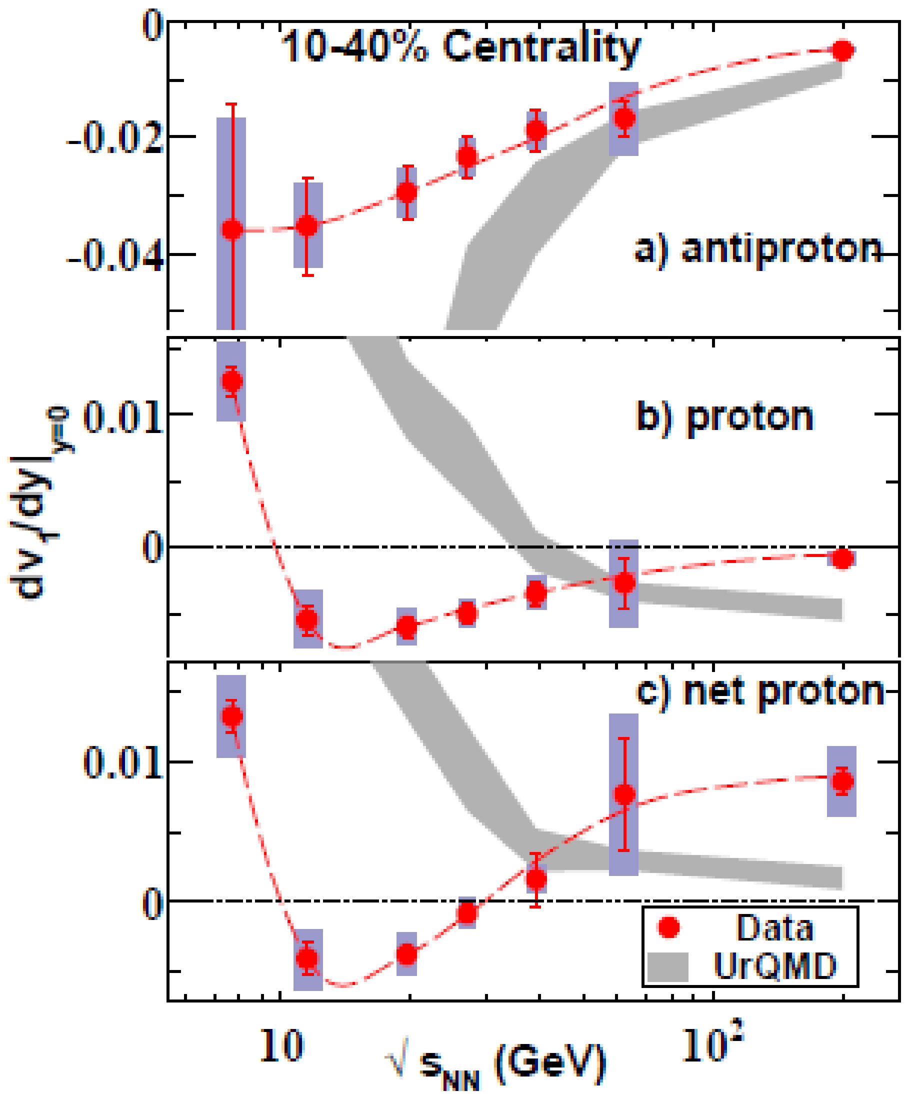
- **QCD phase transition at top RHIC & LHC energies = Crossover**
  → One of Next Grand Challenges
  =Discovery of 1st or 2nd order phase transition in QCD

- **Signals of QCD phase transition at J-PARC energies ($\sqrt{s_{NN}}$=5-10 GeV)?**
  - **(Partial) Chiral restoration → Modification of hadron properties**
  - **Critical Point → Large fluctuation of conserved charges**
  - **First-order phase transition → Softening of EOS**

  → Non-monotonic behavior of proton number moment ($\kappa\sigma^2$) and collective flow (dv_1/dy)

Net-Proton Number Cumulants & Directed Flow

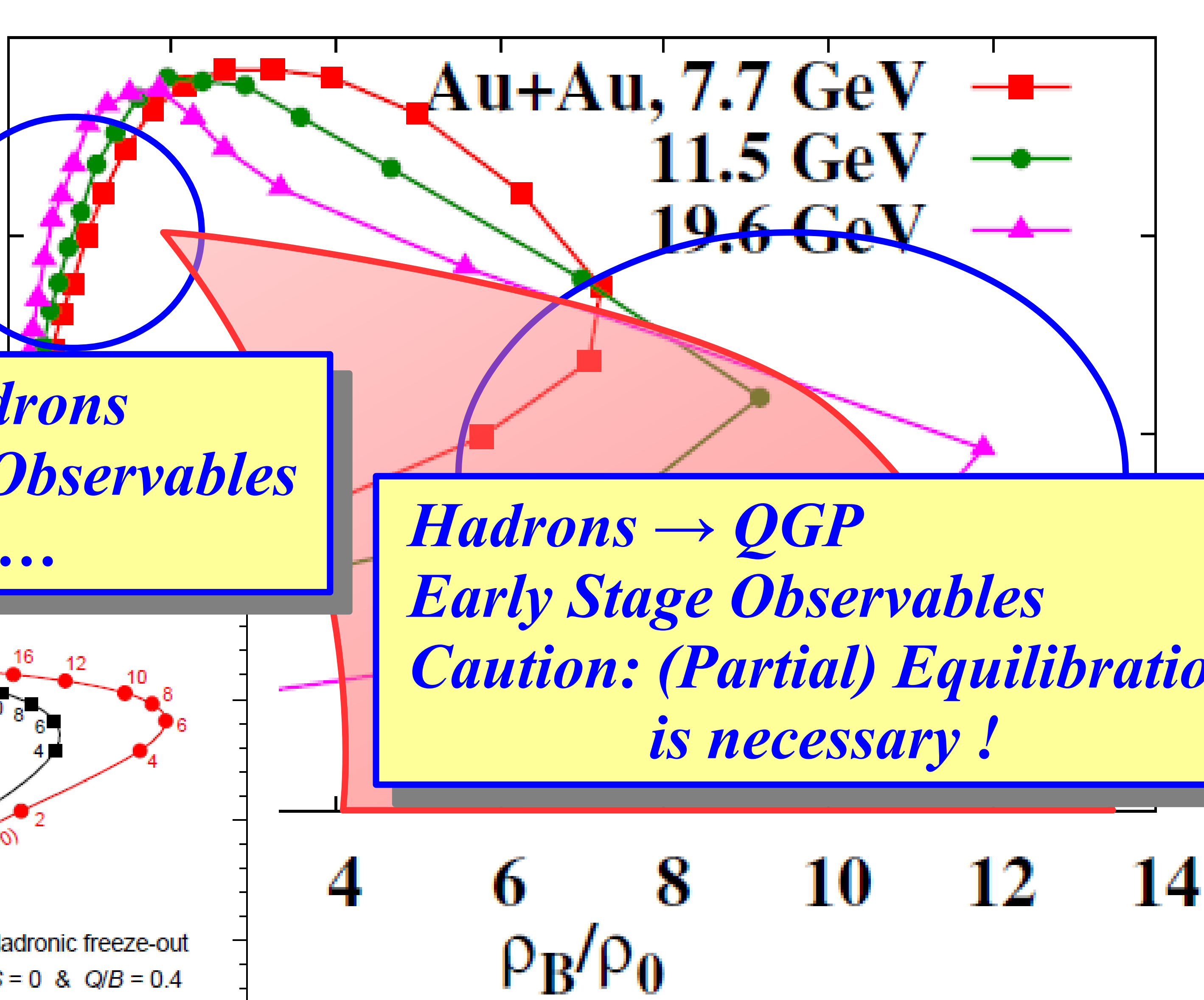




STAR Collab. PRL 112('14)032302

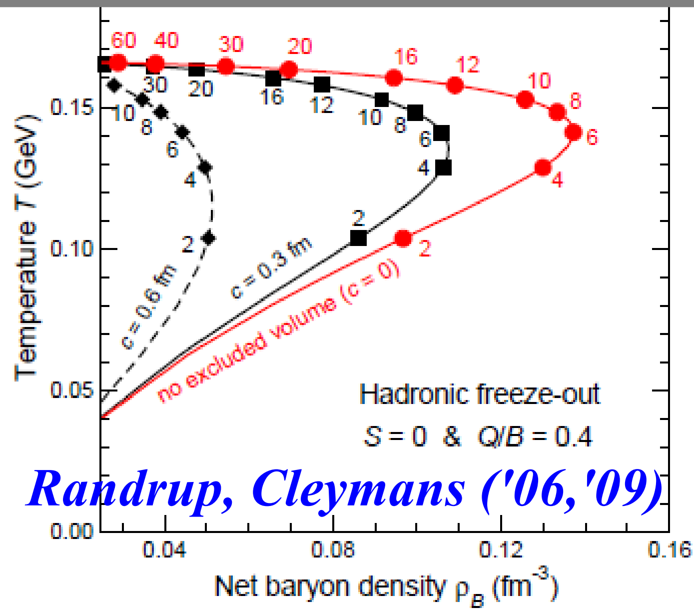
STAR Collab., PRL 112('14)162301.

Two ways to probe QCD phase transition



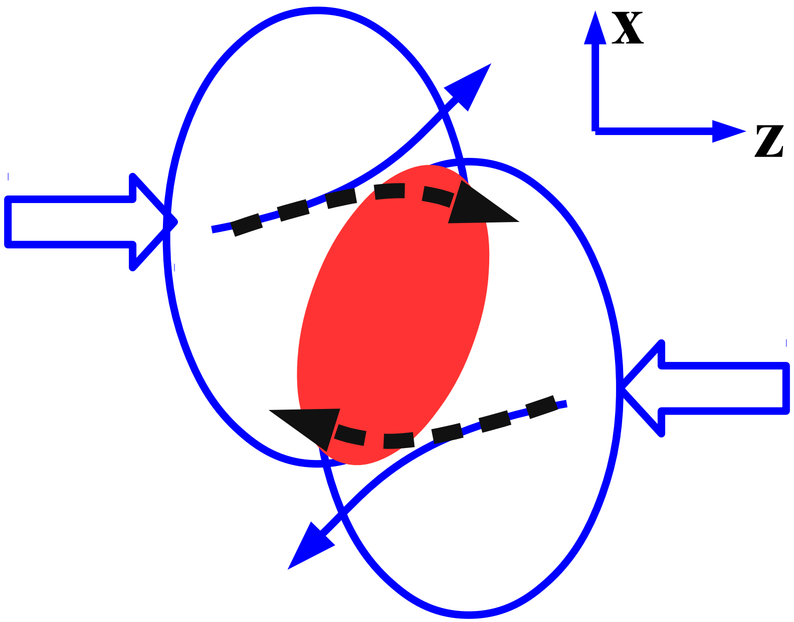
QGP → Hadrons
Final State Observables
Cumulants, …

Hadrons → QGP
Early Stage Observables
Caution: (Partial) Equilibration is necessary !

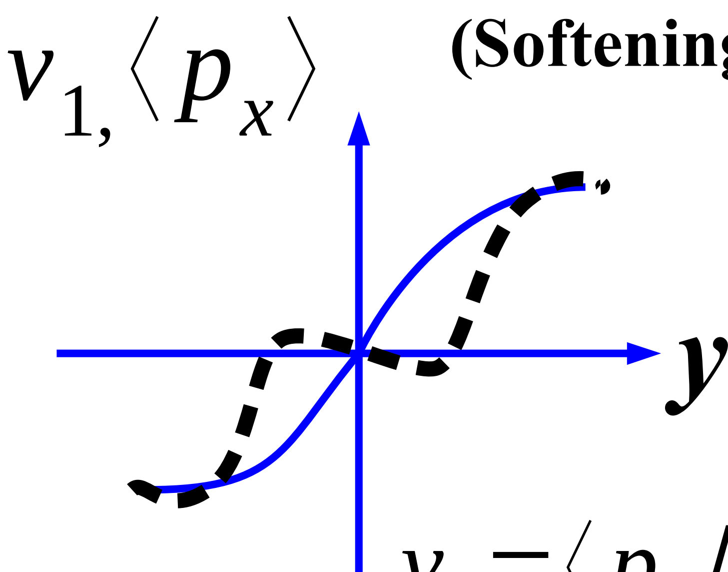


Randrup, Cleymans ('06,'09)

What is directed flow ?



Attraction
(Softening)



$$v_1 = \langle p_x / p \rangle = \langle \cos\varphi \rangle$$

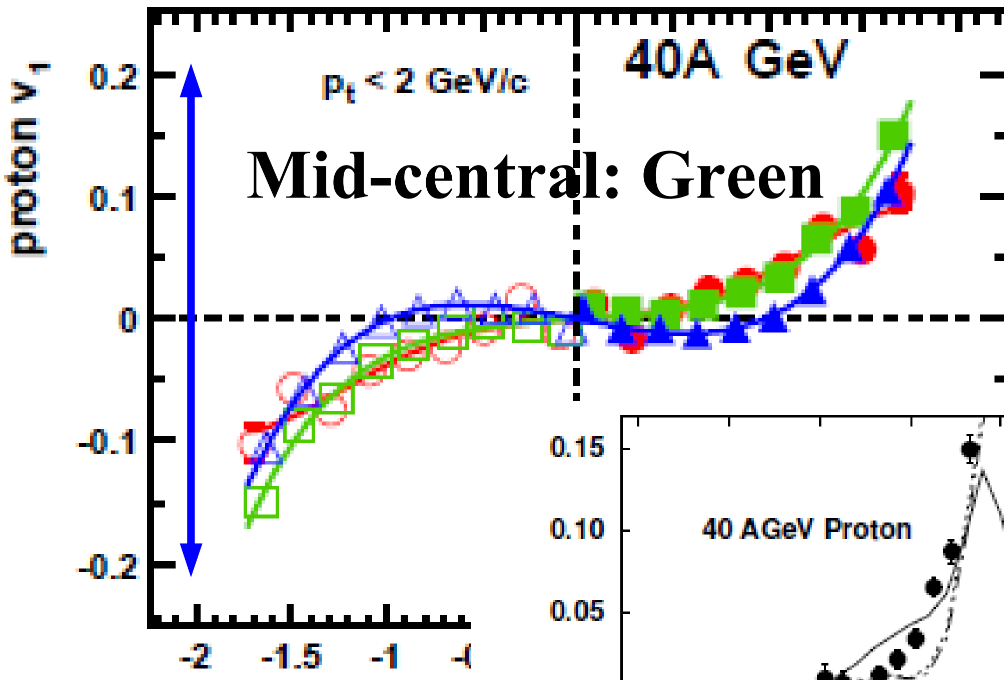
- v_1 or $\langle p_x \rangle$ as a function of y is called directed flow.
- Created in the overlapping stage of two nuclei
  → Sensitive to the EOS
  in the early stage.
- Becomes smaller at higher energies.

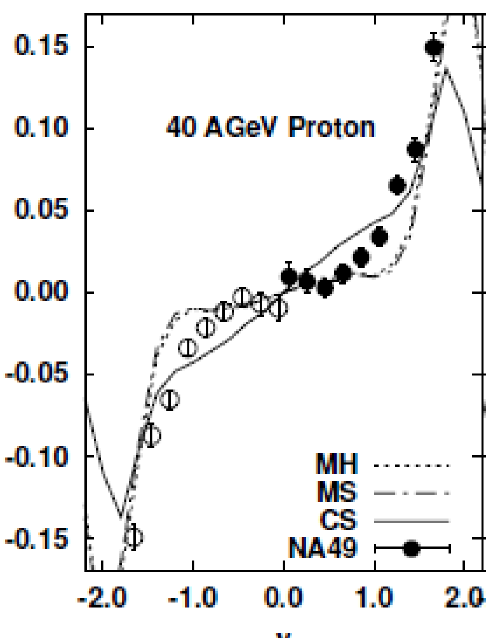
How can we explain non-monotonic dependence of dv_1/dy ?
→ Softening or Geometry

SPS(NA49) vs RHIC(STAR)

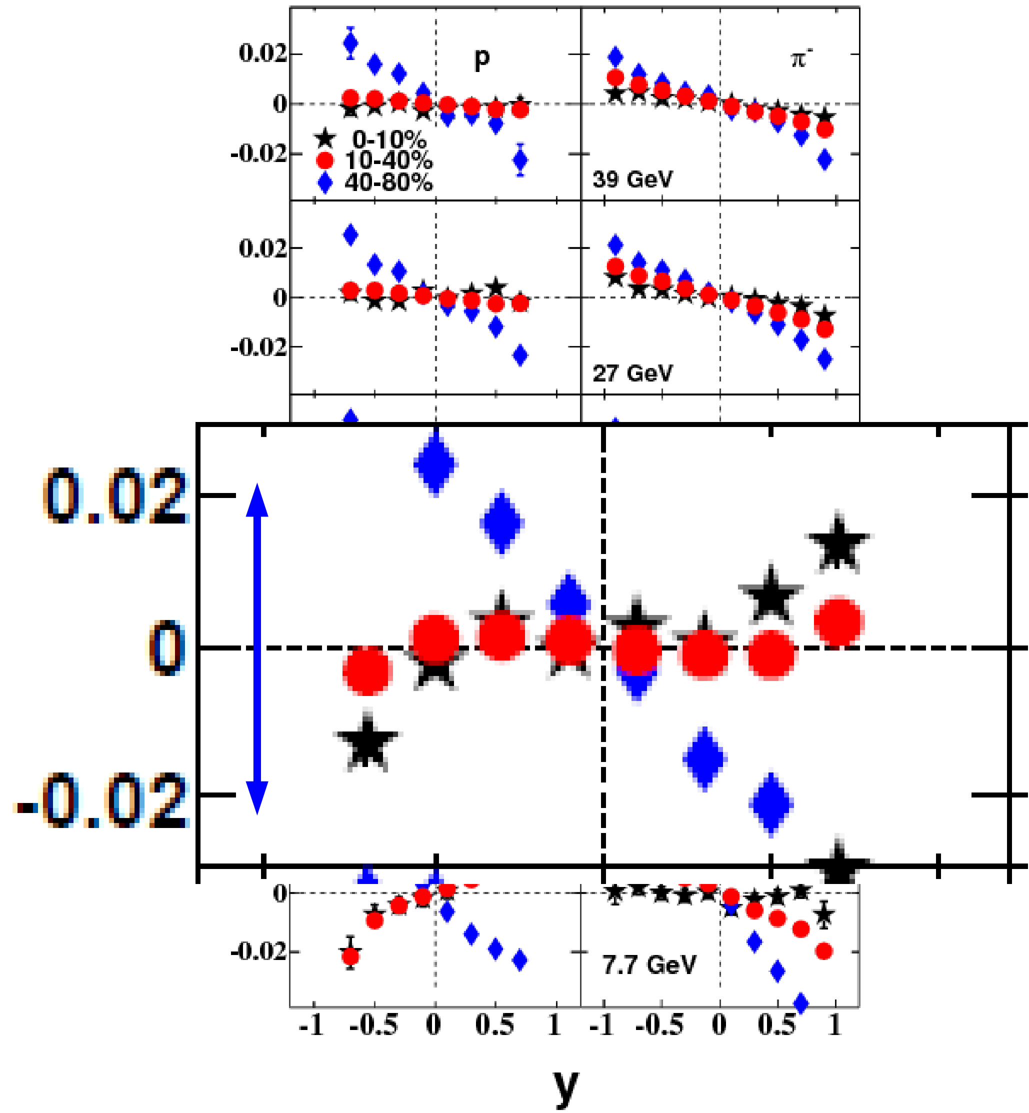
- SPS (NA49), $\sqrt{s_{NN}}$ = 8.9 GeV
- RHIC(STAR), 7.7-39 GeV

C. Alt et al. (NA49), PRC68 ('03) 034903





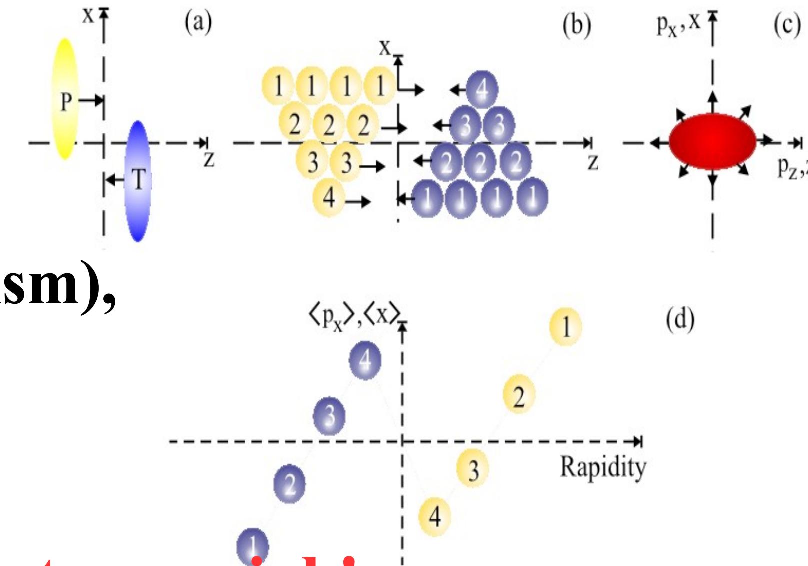
Hadronic Transport w/ MF



M.Isse,AO,N.Otuka,P.K.Sahu,Y.Nara, PRC72 ('05)064908

L. Adamczyk et al. (STAR), PRL 112(2014)162301

Does Directed Flow Collapse Signal Phase Tr. ?



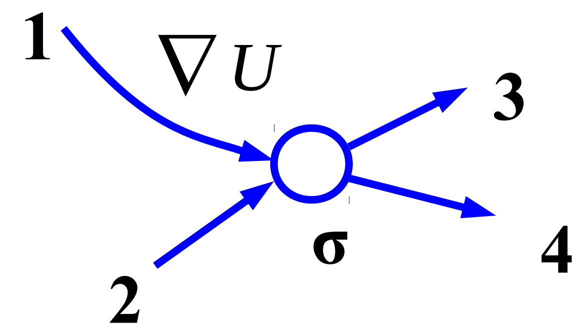
- **Negative dv_1/dy at high-energy ($\sqrt{s_{NN}} > 20$ GeV)**
  - **Geometric origin (bowling pin mechanism), not related to FOPT**
    R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL84,2803('00)
- **Negative dv_1/dy at $\sqrt{s_{NN}} \sim 10$ GeV → Controversial !**
  - **Yes, in three-fluid simulations. → Thermalization ?**
    Y. B. Ivanov and A. A. Soldatov, PRC91('15)024915; P. Batyuk et al., 1608.00965.
  - **No (for semi-central collisions), in transport models incl. hybrid.**
    E.g. J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher, H. Stoecker, PRC89('14)054913.
    Exception: *B.A.Li, C.M.Ko ('98) with FOPT EOS*

We investigate the directed flow at J-PARC energies in hadronic transport model with / without mean field effects and with / without softening effects via attractive orbit.

Hadronic Transport with Softening Effects

Transport Model

- **Microscopic Transport Models**
  = Boltzmann equation
  with (optional) potential effects
  E.g. Bertsch, Das Gupta, Phys. Rept. 160(88), 190



  - **UrQMD 3.4 (Frankfurt), PHSD Giessen (Cassing), GiBUU 1.6 Giessen (Mosel), AMPT (Texas A&M), JAM (Y. Nara)**

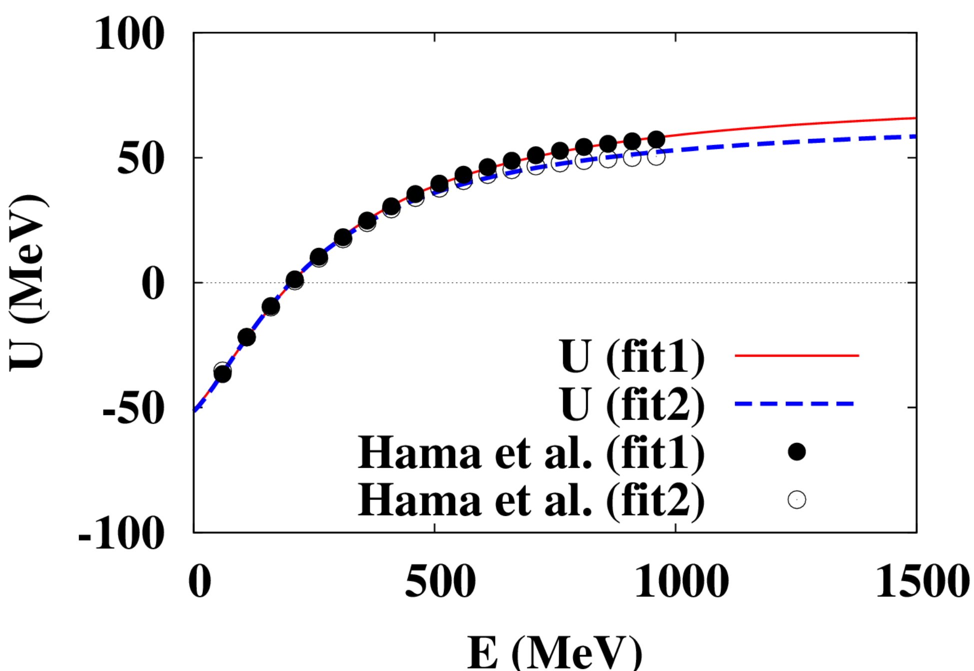
- **Hadron-string transport model JAM**
  - **Hadronic cascade with resonance and string excitation**
    Nara, Otuka, AO, Niita, Chiba, Phys. Rev. C61 (2000), 024901.
  - **Potential term → Mean field effects in the framework of RQMD/S**
    Sorge, Stocker, Greiner, Ann. of Phys. 192 (1989), 266.
    Tomoyuki Maruyama et al., Prog. Theor. Phys. 96(1996), 263.
    Isse, AO, Otuka, Sahu, Nara, Phys.Rev. C 72 (2005), 064908.

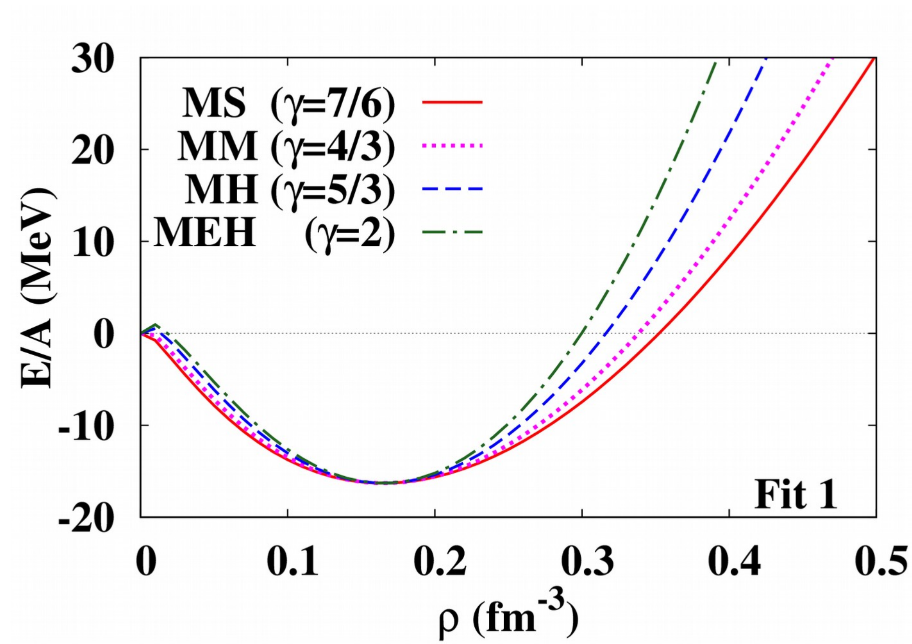
Mean Field Potential

- **Skyrme type density dependent + momentum dependent potential**

$$V = \sum_i V_i = \int d^3r \left[\frac{\alpha}{2} \left(\frac{\rho}{\rho_0} \right)^2 + \frac{\beta}{\gamma+1} \left(\frac{\rho}{\rho_0} \right)^{\gamma+1} \right] + \sum_k \int d^3\boldsymbol{r} d^3\boldsymbol{p} d^3\boldsymbol{p}' \frac{C_{ex}^{(k)}}{2\rho_0} \frac{f(\boldsymbol{r},\boldsymbol{p}) f(\boldsymbol{r},\boldsymbol{p}')}{1 + (\boldsymbol{p}-\boldsymbol{p}')^2/\mu_k^2}$$

Type	α (MeV)	β (MeV)	γ	$C_{\rm ex}^{(1)}$ (MeV)	$C_{\rm ex}^{(2)}$ (MeV)	μ_1 (fm^{-1})	μ_2 (fm^{-1})	K (MeV)
MH1	-12.25	87.40	5/3	-383.14	337.41	2.02	1.0	371.92
MS1	-208.89	284.04	7/6	-383.14	337.41	2.02	1.0	272.6



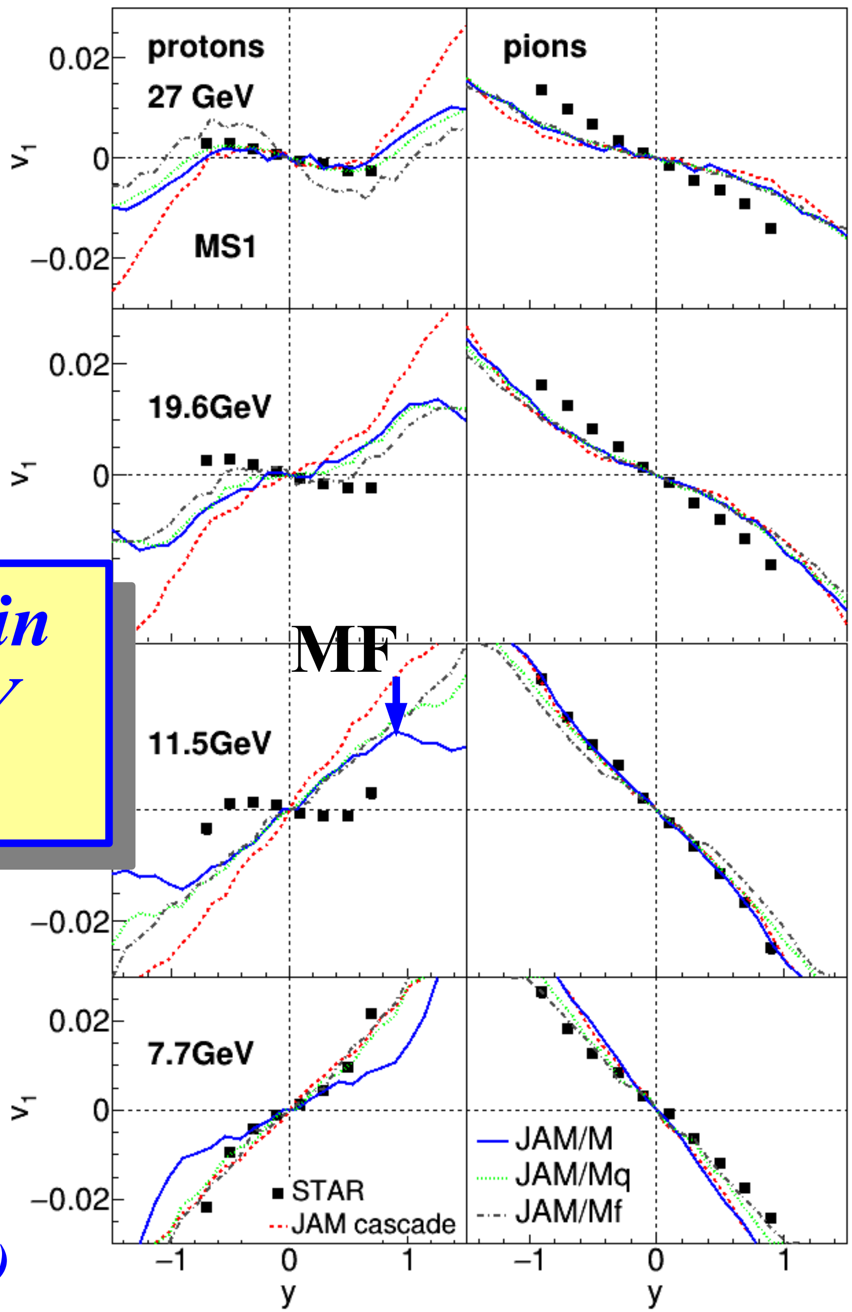


Y. Nara, AO, arXiv:1512.06299 [nucl-th] (QM2015 proc.)
Isse, AO, Otuka, Sahu, Nara, PRC 72 (2005), 064908.

Comparison with RHIC data on v_1

- **Pot. Eff. on the v_1 is significant, but dv1/dy becomes negative only at $\sqrt{s_{NN}} > 20$ GeV.**

Hadronic approach does not explain directed flow collapse at 10-20 GeV even with potential effects.

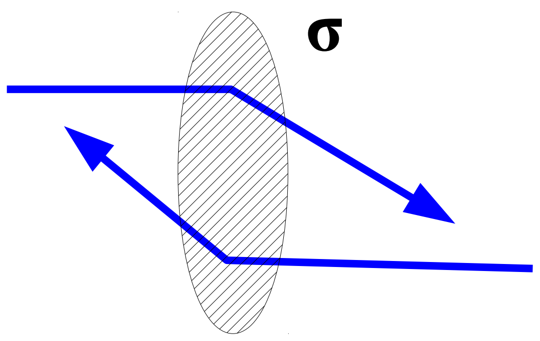


JAM/M: only formed baryons feel potential forces
JAM/Mq: pre-formed hadron feel potential with factor 2/3 for diquark, and 1/3 for quark
JAM/Mf: both formed and pre-formed hadrons feel potential forces.

Y. Nara, AO, arXiv:1512.06299 [nucl-th] (QM2015 proc.)

Softening Effects via Attractive Orbit Scattering

- **Attractive orbit scattering simulates softening of EOS**
  P. Danielewicz, S. Pratt, PRC 53, 249 (1996)
  H. Sorge, PRL 82, 2048 (1999).



$$P = P_f + \frac{1}{3TV}\sum_{(i,j)}(q_i \cdot r_i + q_j \cdot r_j)$$

(Virial theorem)

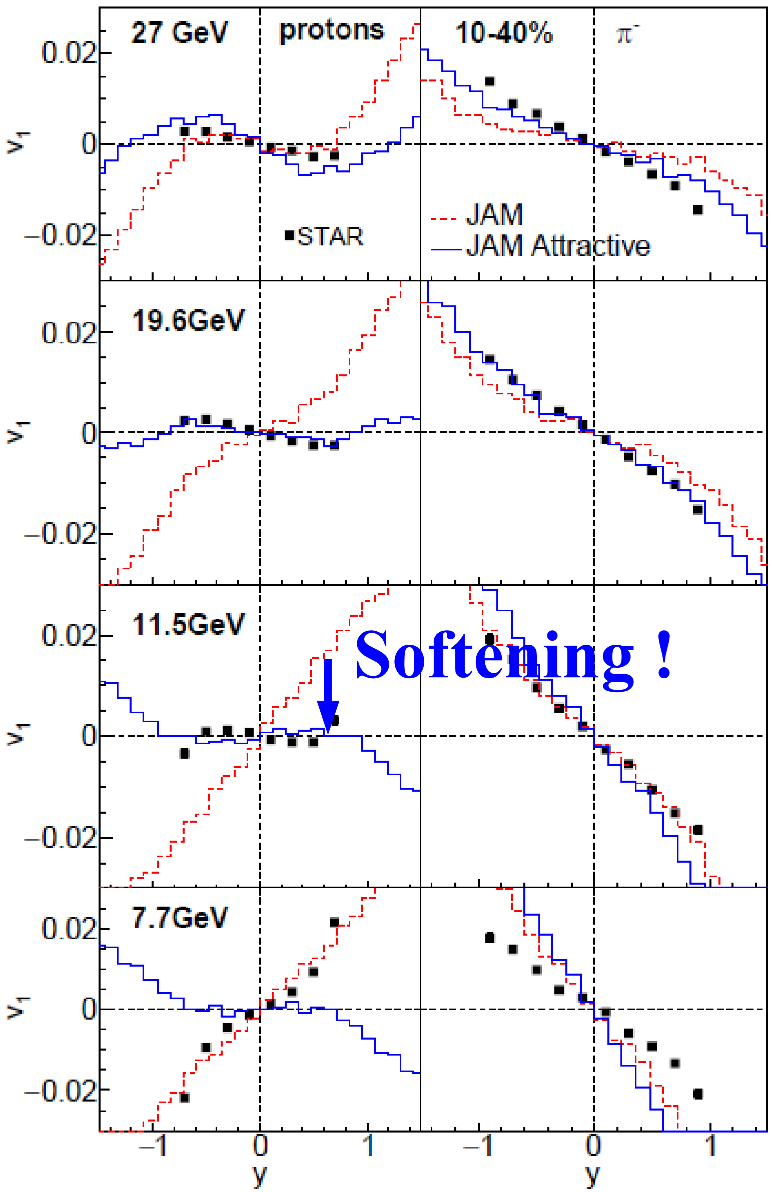
- **With attractive orbit, particle trajectories are bended toward denser region.**
  → ***Attractive orbit scattering simulates time evolution with softer EOS !***

Let us examine the EOS softening effects, which cannot be explained in hadronic mean field potential, by using attractive orbit scatterings !

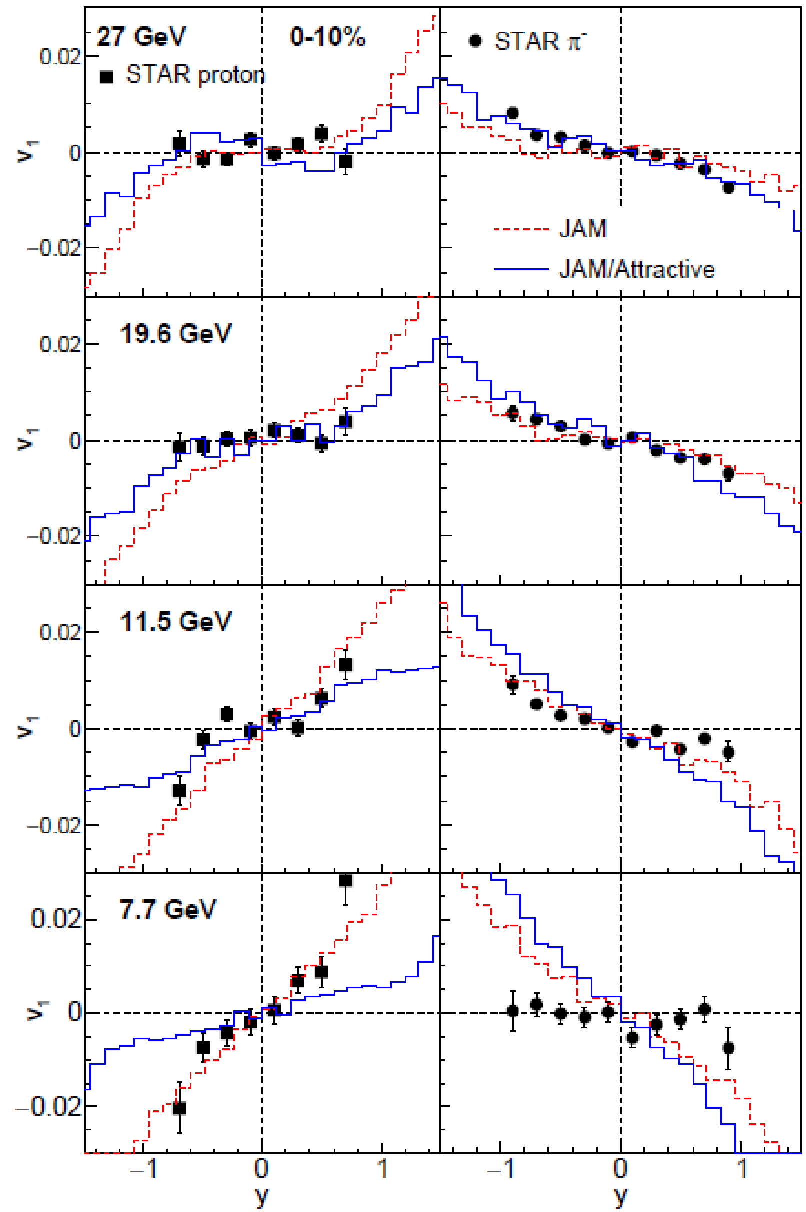
Y. Nara, H. Niemi, AO, H. Stöcker, arXiv:1601.07692 [hep-ph]

Directed Flow with Attractive Orbits

Nara, Niemi, AO, Stöcker ('16)

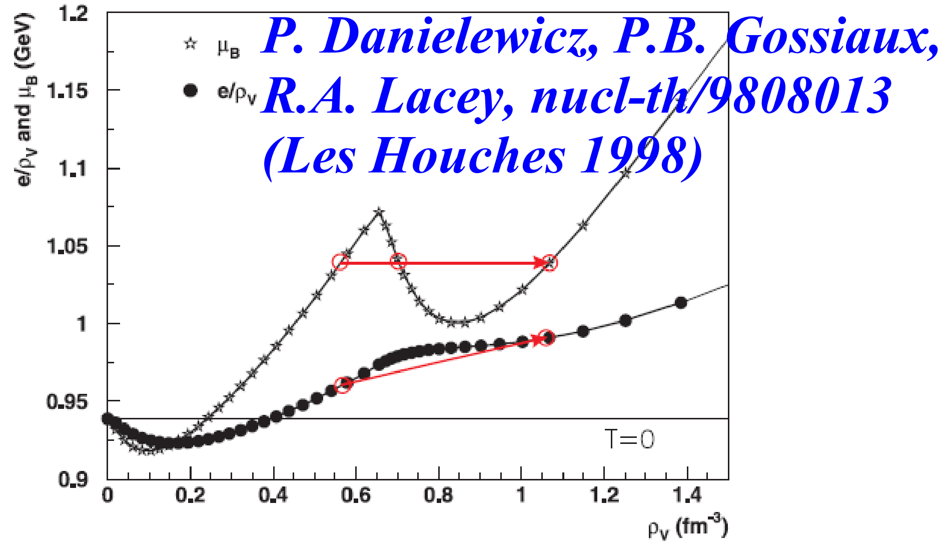


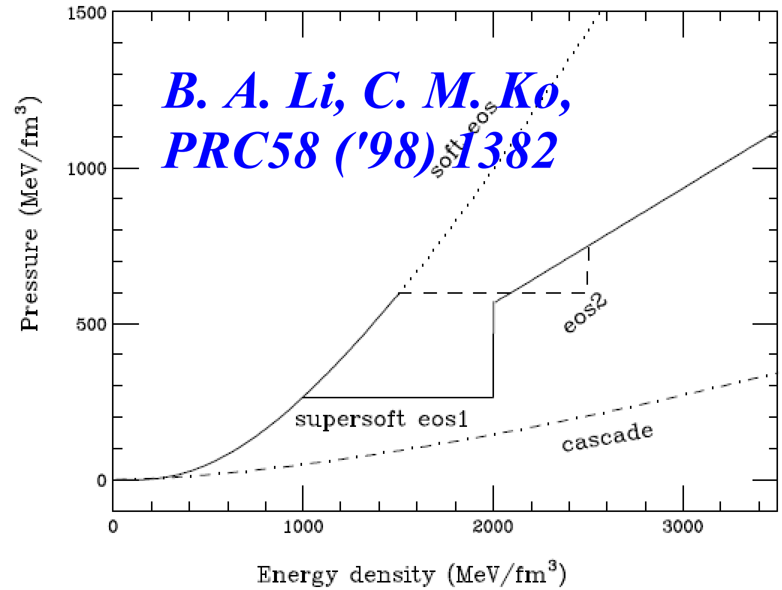
mid-central (10-40 %)

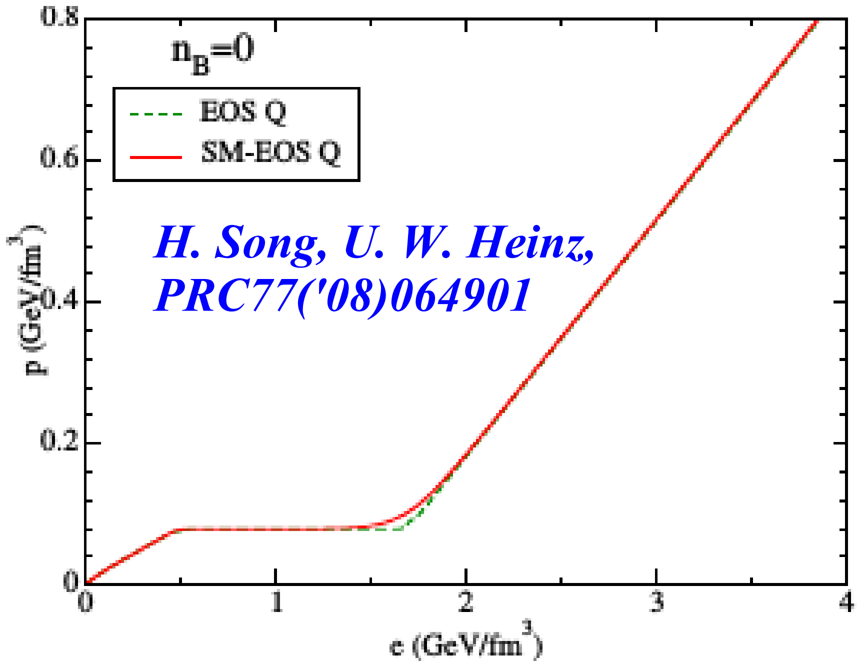


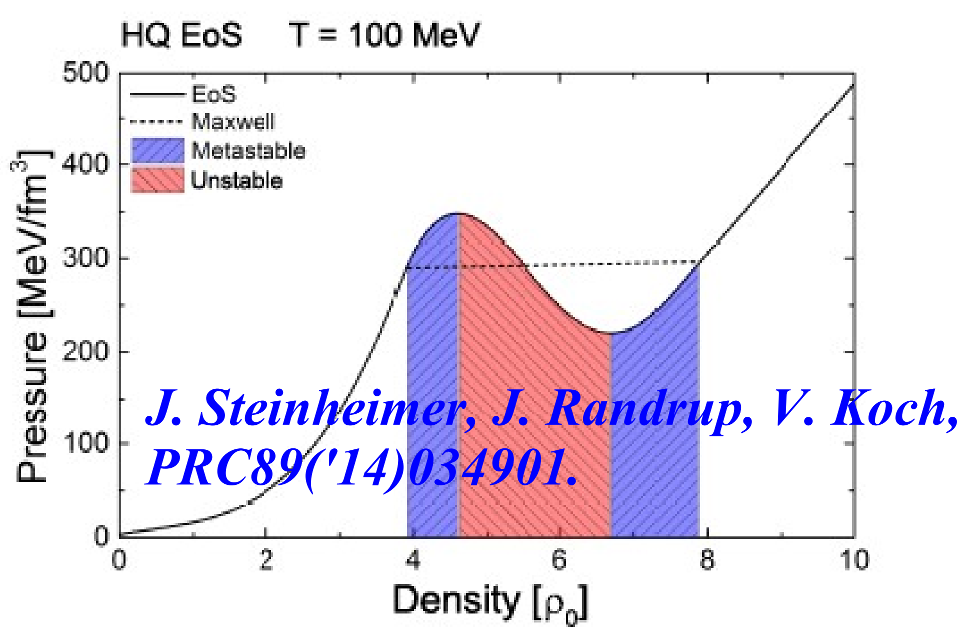
central (0-10 %)

Softening: Where and How much ?







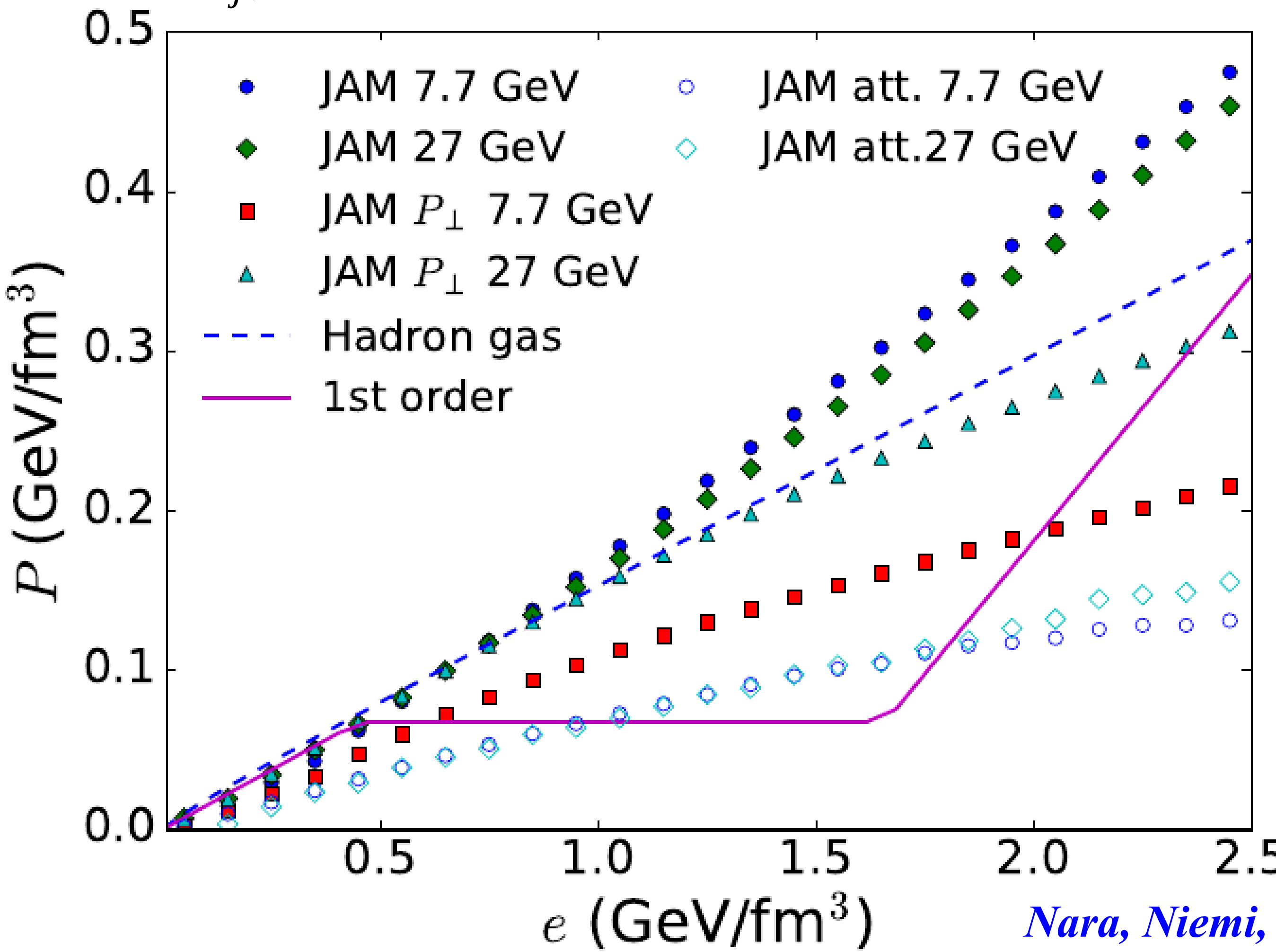


Previous analyses: ρ_B=(3-10) ρ_0, P=(80-700) MeV/fm^3

Softening of EOS by Attractive Orbits

$$\Delta P = -\frac{\rho}{3(\delta\tau_i + \delta\tau_j)}(p_i' - p_i)^\mu (x_i - x_j)_\mu$$

H. Sorge, PRL82('99)2048.



Nara, Niemi, AO, Stöcker ('16)

Pressure in simulated EOS ~ EOS-Q (e.g. Song, Heinz ('08))

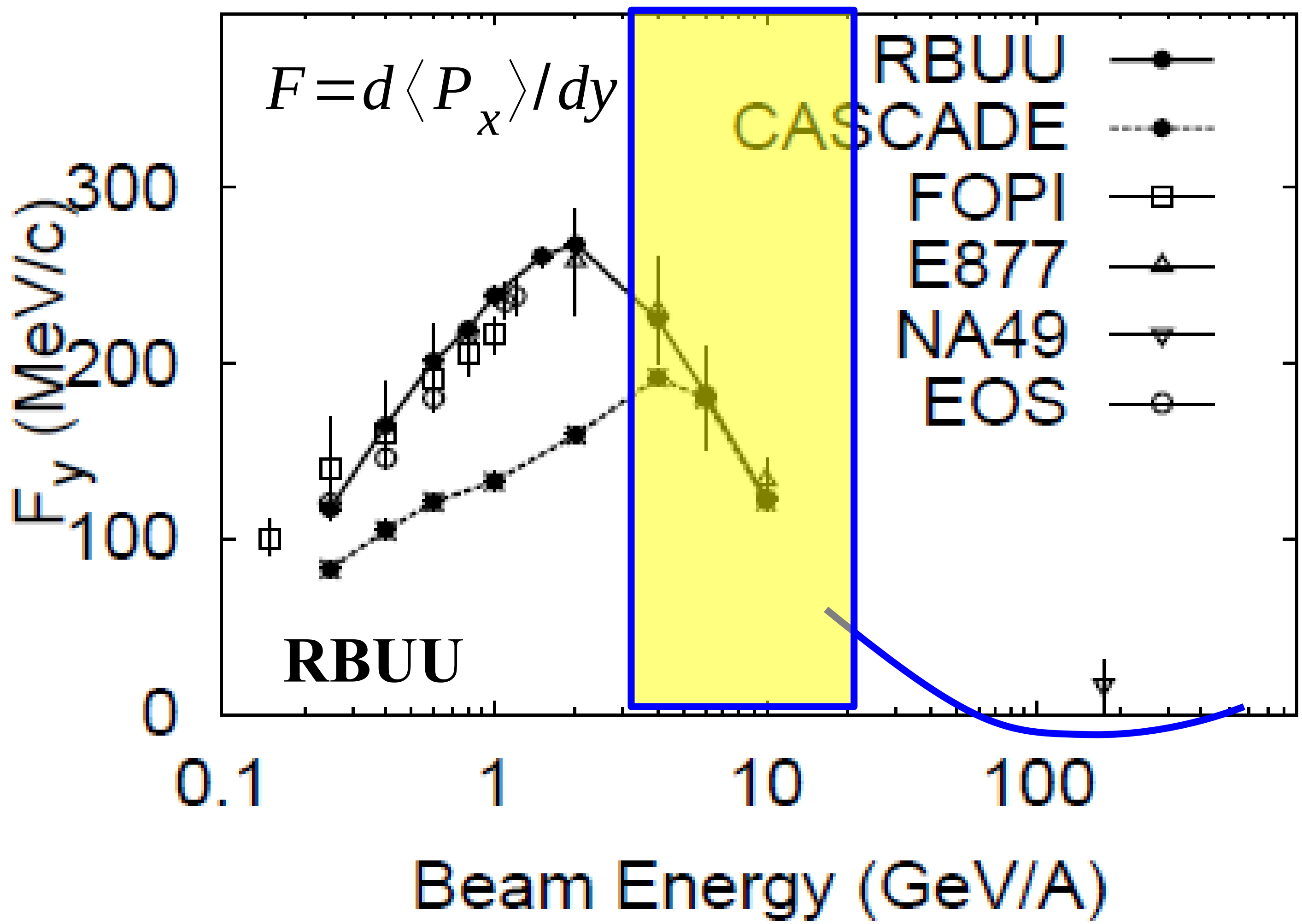
Summary

- **We may see QCD phase transition (1st or 2nd) signals at BES (or J-PARC) energies in baryon number cumulants and v_1 slope.**
- **Hadronic transport models cannot explain negative v_1 slope below $\sqrt{s_{NN}} = 20$ GeV.**
  - **Geometric (bowling pin) mechanism becomes manifest at higher energies (JAM, JAM-MF, HSD, PHSD, UrQMD, ….).**
- **Hadronic transport with EOS softening can describe negative v_1 slope below $\sqrt{s_{NN}} = 20$ GeV.**

  Y. Nara, H. Niemi, A. Ohnishi, H. Stoecker, arXiv:1601.07692 [hep-ph]
  - **Attractive orbit scattering simulates EOS softening (virial theorem).**
  - **We need more studies to confirm its nature.**
    First-order phase transition ? Crossover ? Forward-backward rapidities ? MF leading to softer EOS ?
- ***We need "re-hardening" at higher energies, e.g. $\sqrt{s}_{NN} = 27$ GeV.***

Thank you !

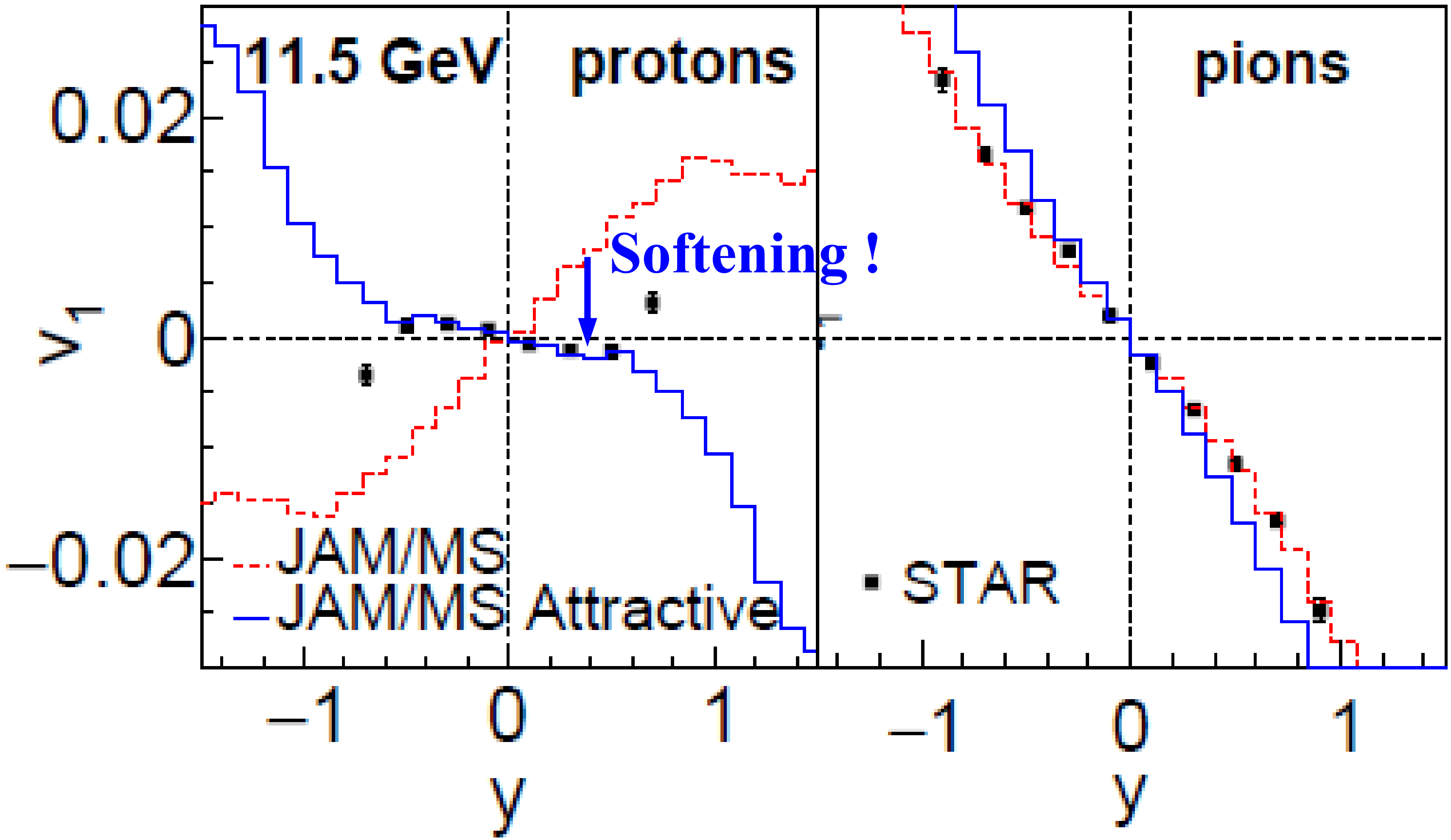
Directed Flow



P. K. Sahu, W. Cassing, U. Mosel, AO, Nucl. Phys. A 672 (2000),376

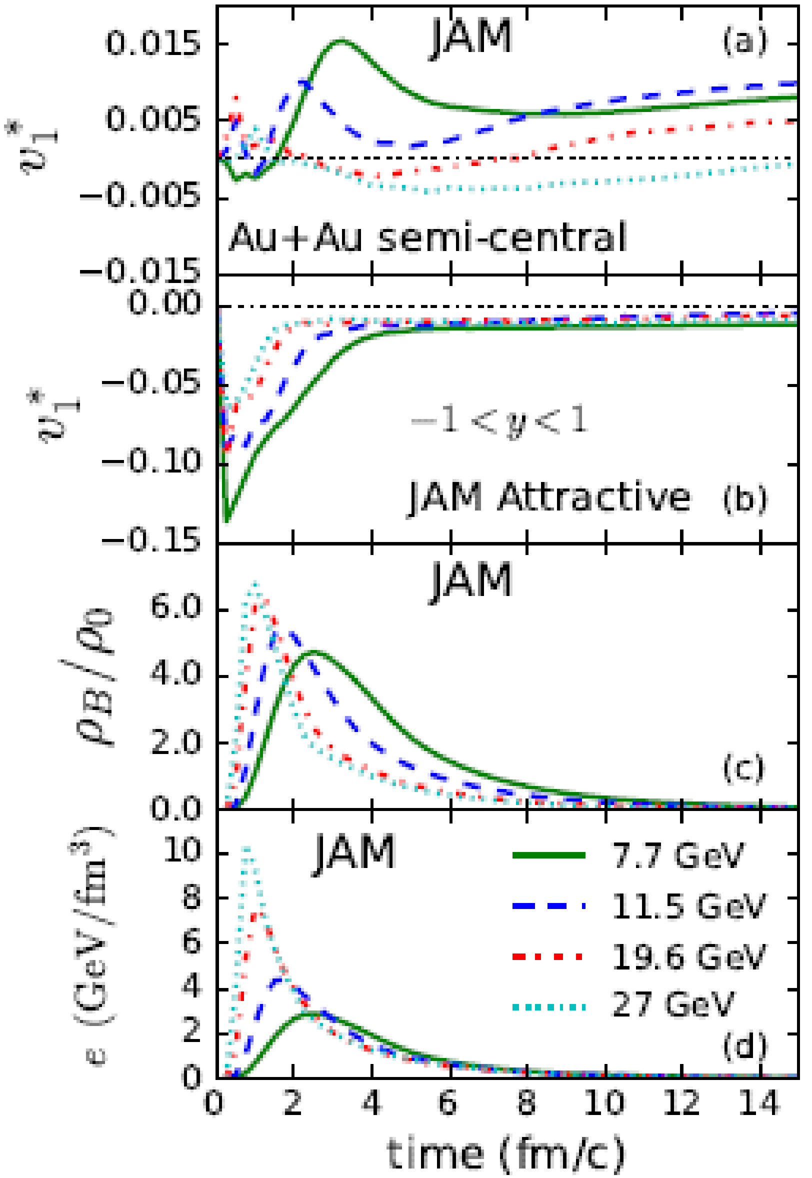
Mean Field + Attractive Orbit

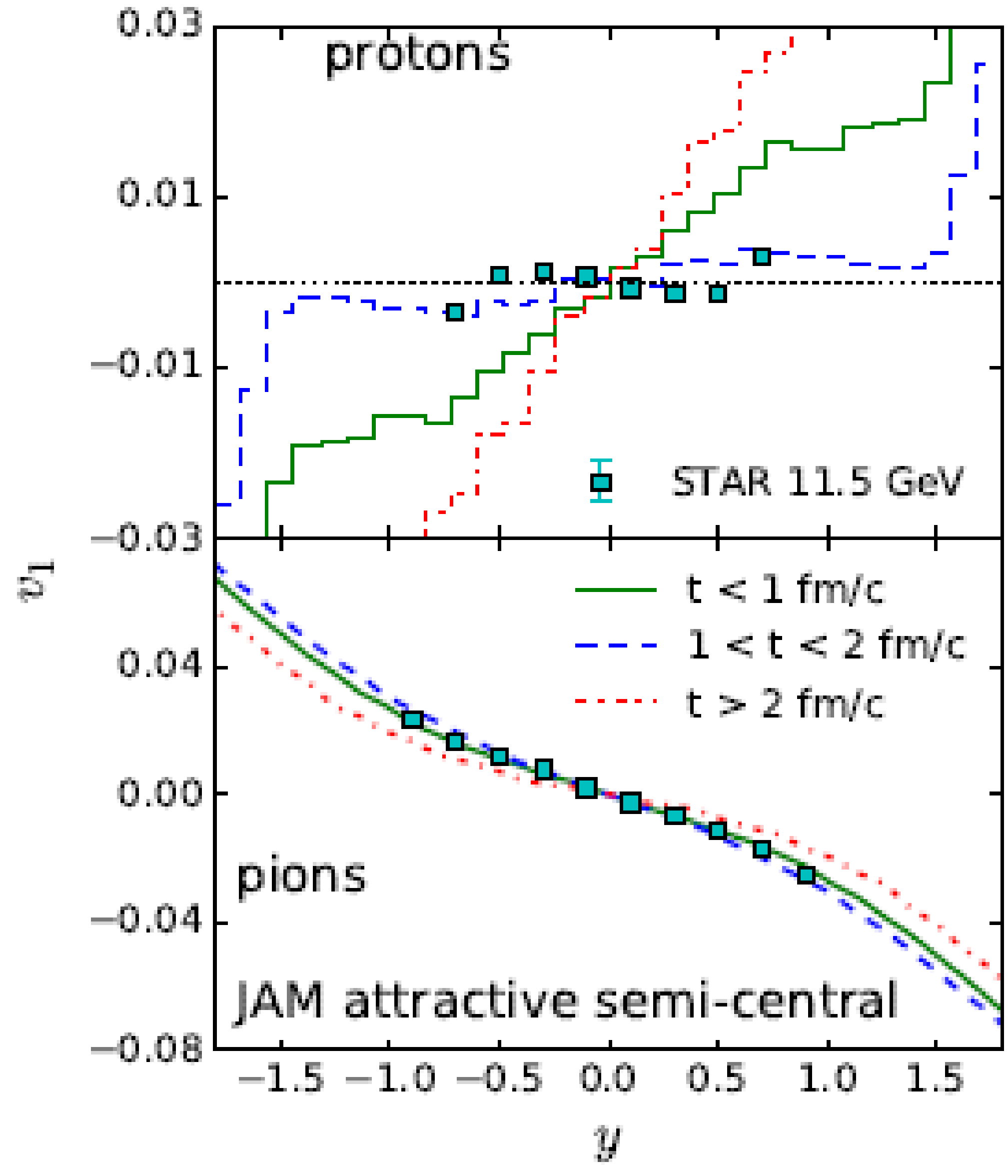
Nara, Niemi, AO, Stöcker ('16)



MF+Attractive Orbit make dv_1/dy negative at $\sqrt{s_{NN}} \sim 10$ GeV

v1 is sensitive to highest density regime

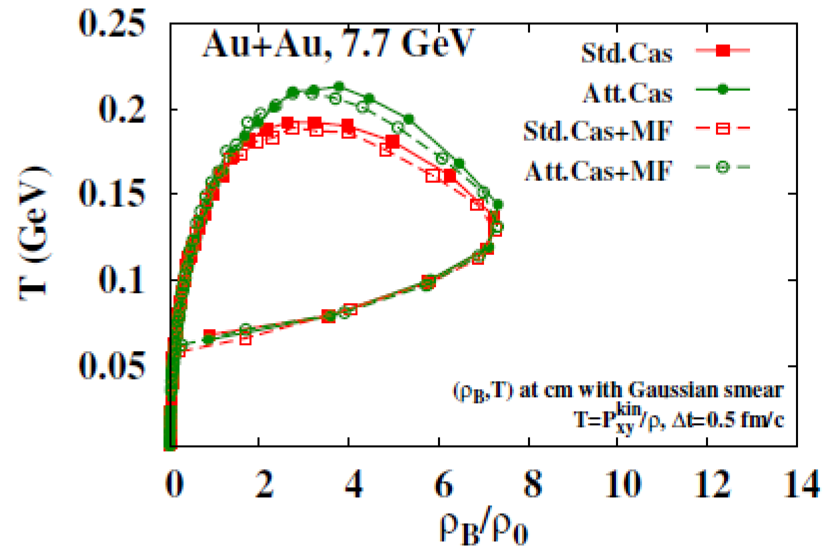


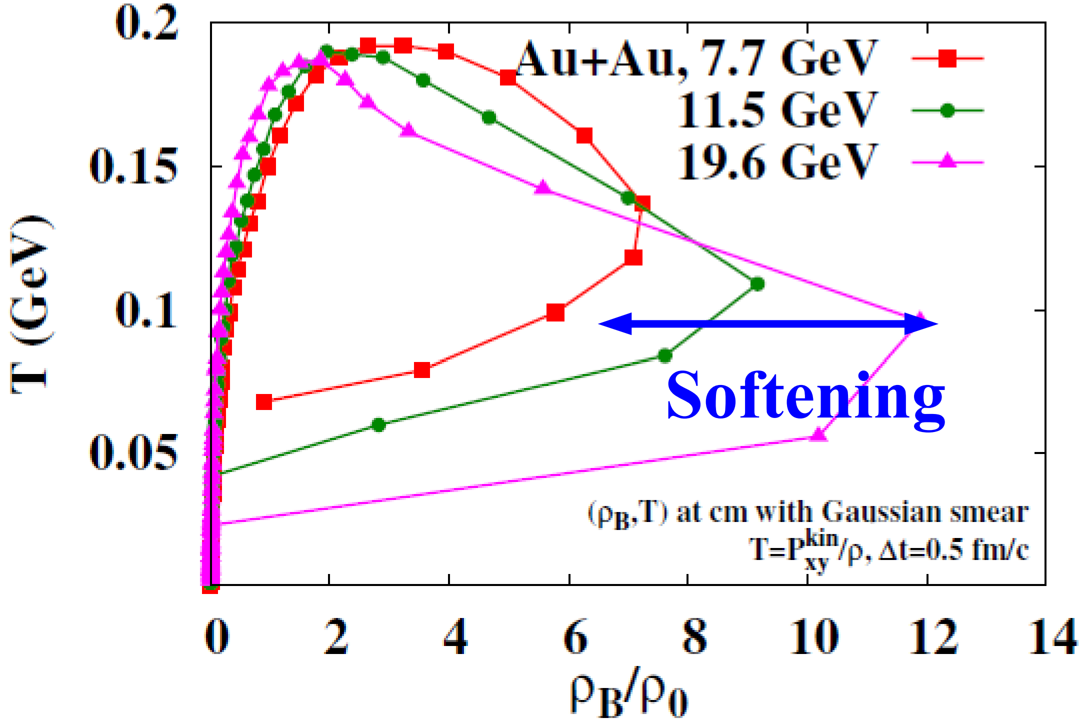


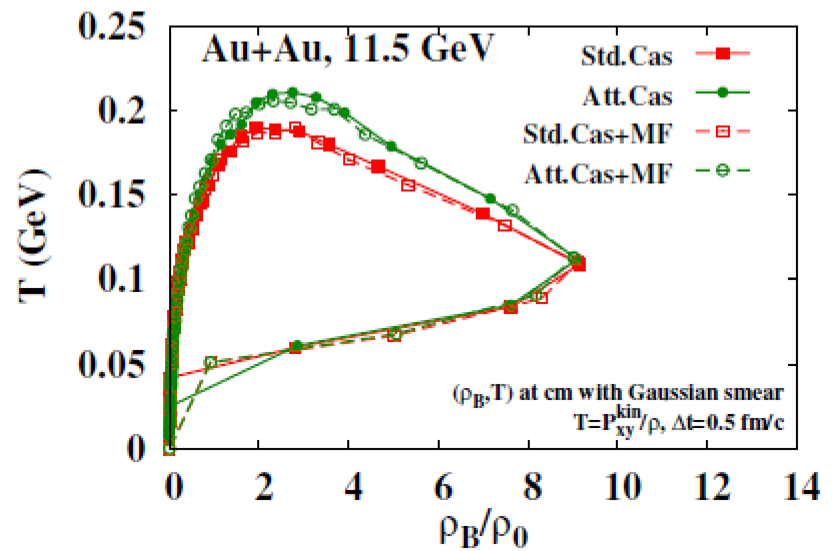
Nara, Niemi, AO, Stöcker ('16)

Softening of EOS: Where and How much ?

- "Softening" should take place at $\sqrt{s_{NN}}$=11.5 GeV → ρ/ρ_B ~ (6-10)
- Attractive orbit
  → Larger interactions
  & Higher T at later times

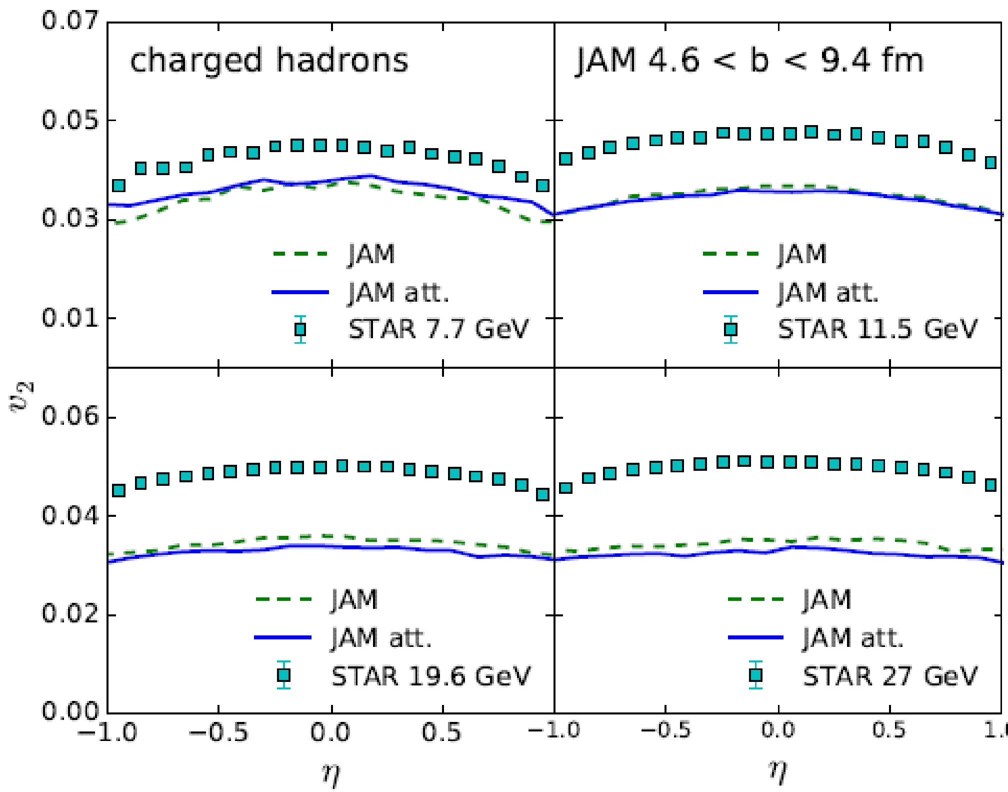


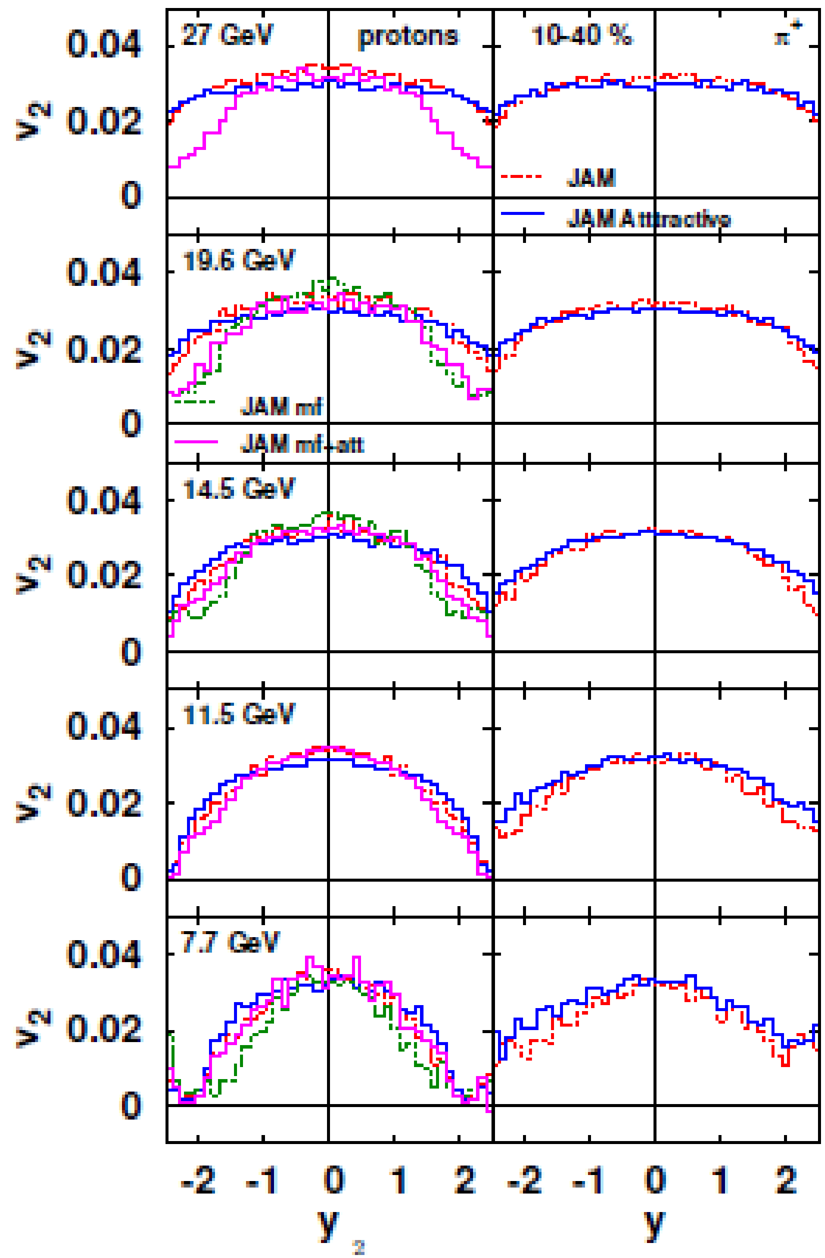




How about v_2 ?

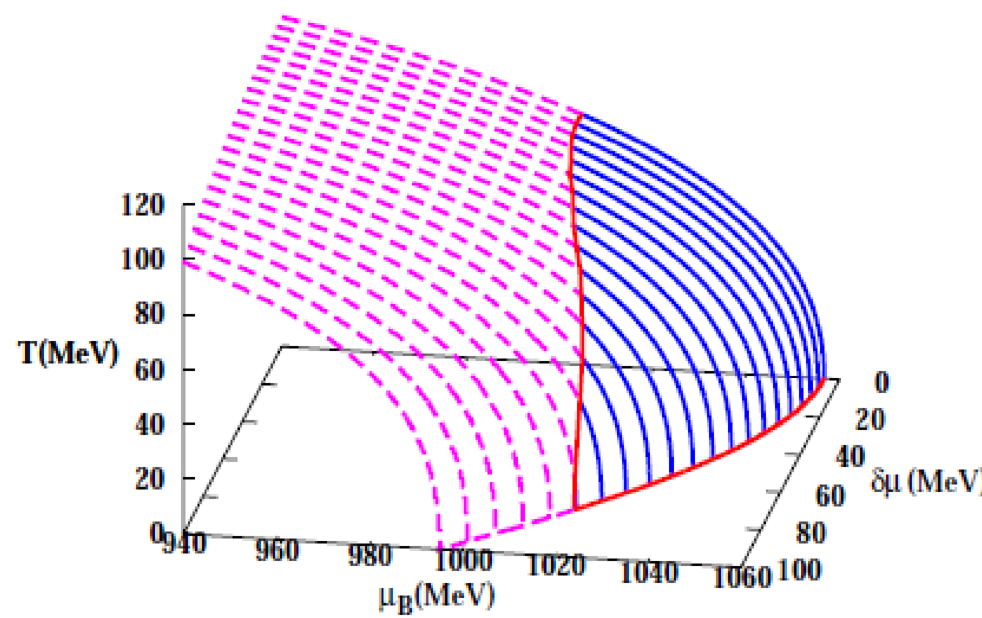
- **Do we see softening effects in other observables, e.g. v_2 ?**
- **Yes, attractive orbits reduces proton v_2 by ~ 0.2 %. (but there is no qualitative change.)**





Relation to Neutron Star Matter

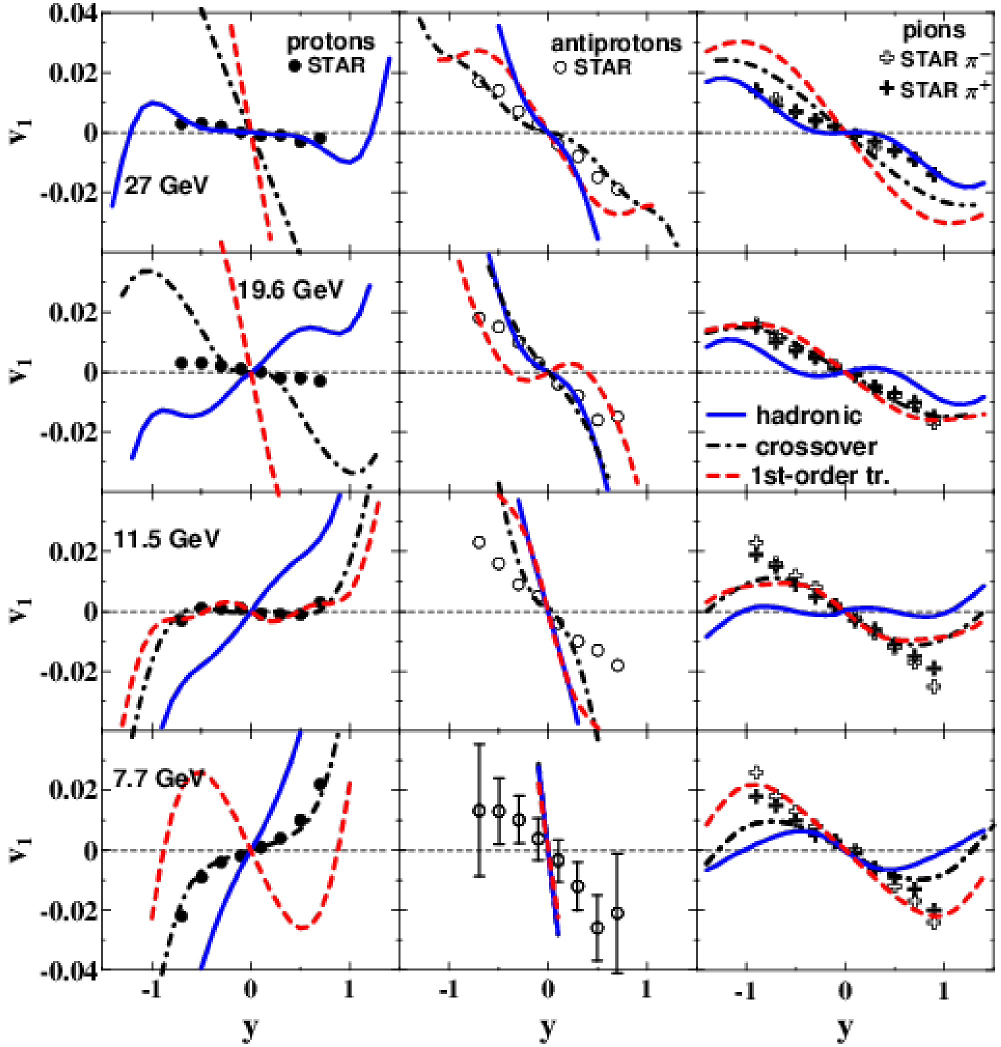
- **We may need early transition (2-5 ρ_0) to quark matter to solve the hyperon puzzle. Contradicting ?**
  → Temperature effects (T ~ 0 MeV & 100 MeV)
  Isospin chem. pot. (Weaker transition with finite $\delta\mu$)
  Hyperon repulsion may push up the transition density.



AO, Ueda, Nakano, Ruggieri, Sumiyoshi, PLB704('11),284
H. Ueda, T. Z. Nakano, AO, M. Ruggieri, K. Sumiyoshi, PRD88('13),074006

Negative dv_1/dy around $\sqrt{s_{NN}} \sim 10$ GeV

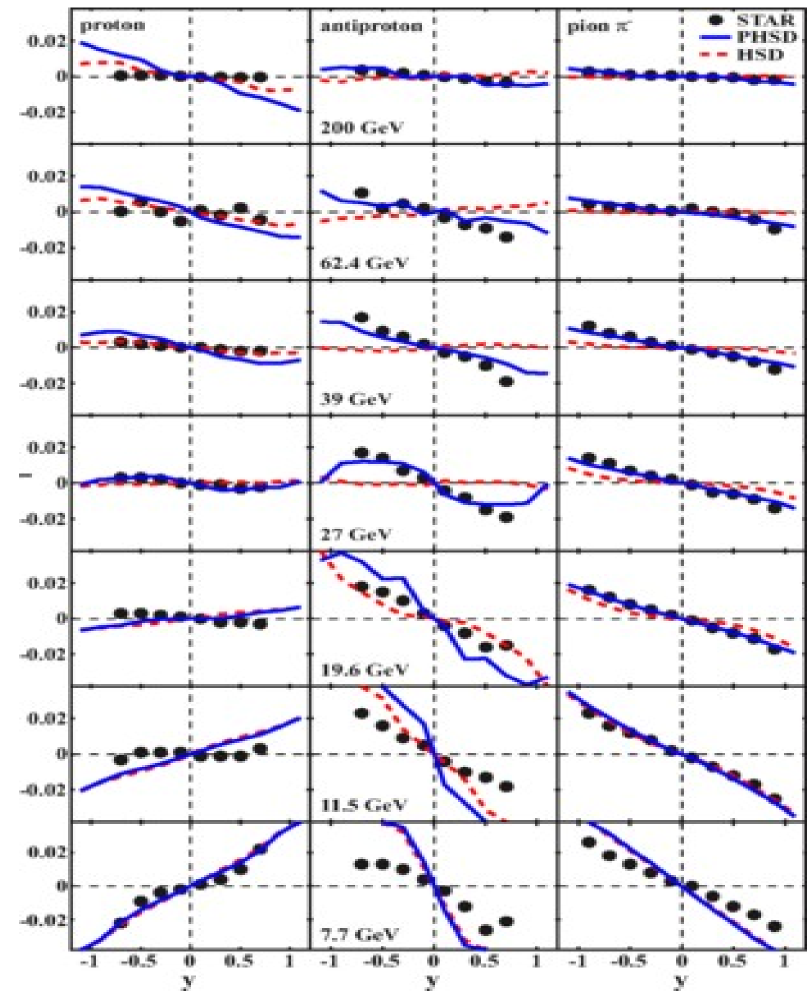
- **Yes in Hydrodynamics**



Black: Crossover, Red: 1st

Y. B. Ivanov and A. A. Soldatov, PRC91 (2015)024915

- **No at around $\sqrt{s_{NN}} \sim 10$ GeV in transport models.**



V. P. Konchakovski, W. Cassing, Y. B. Ivanov, V. D. Toneev, PRC90('14)014903