J-PARC エネルギーにおける集団フロー
(Collective Flows at J-PARC Energies)

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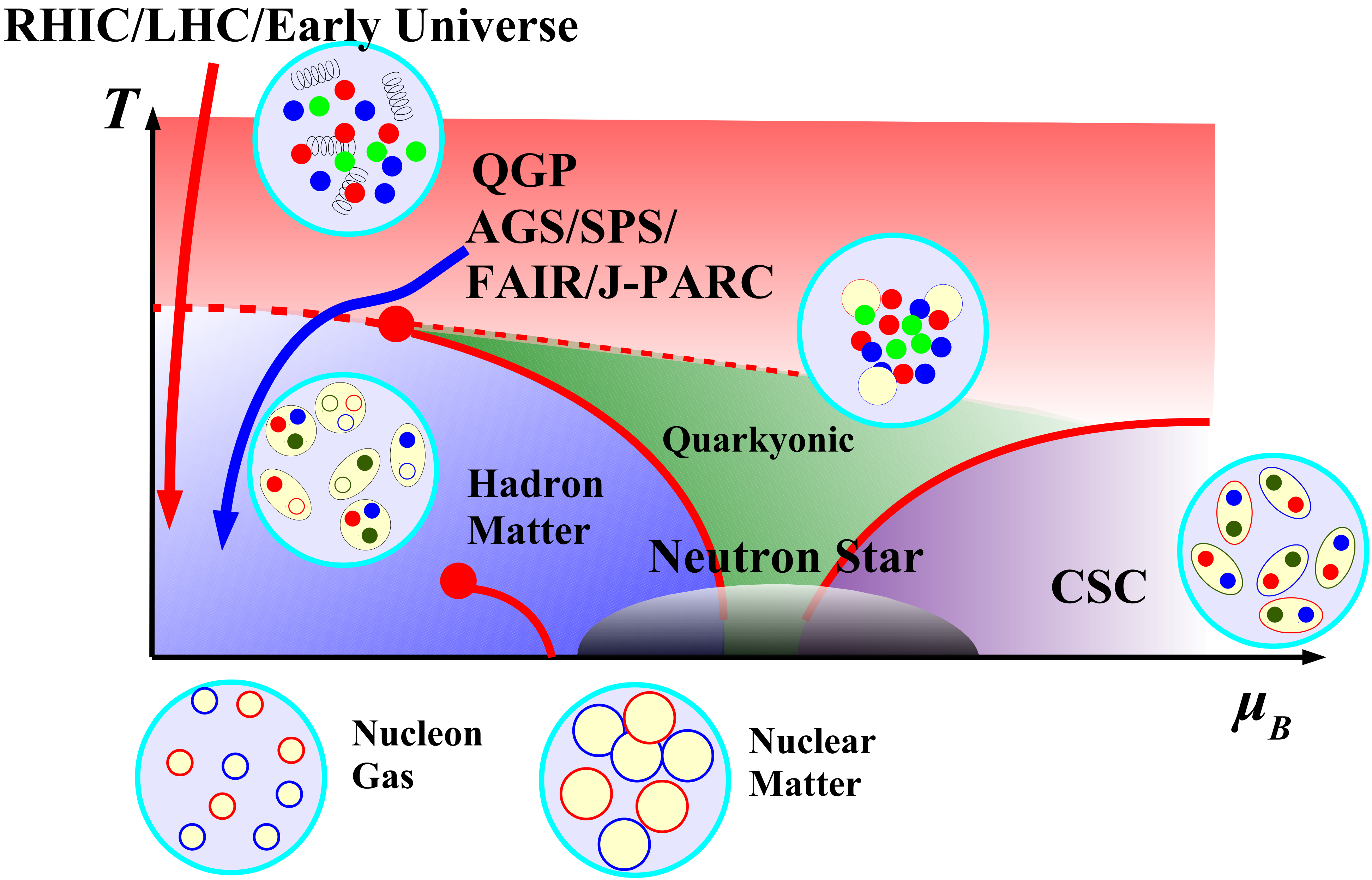
J-PARC における重イオン衝突実験が拓く新しい物理
11/26-27, 2014, KEK

- **Introduction**
- **A Hadronic Transport Model: JAM**
- **Collective Flows at J-PARC Energy**
- **Summary**

QCD Phase Diagram



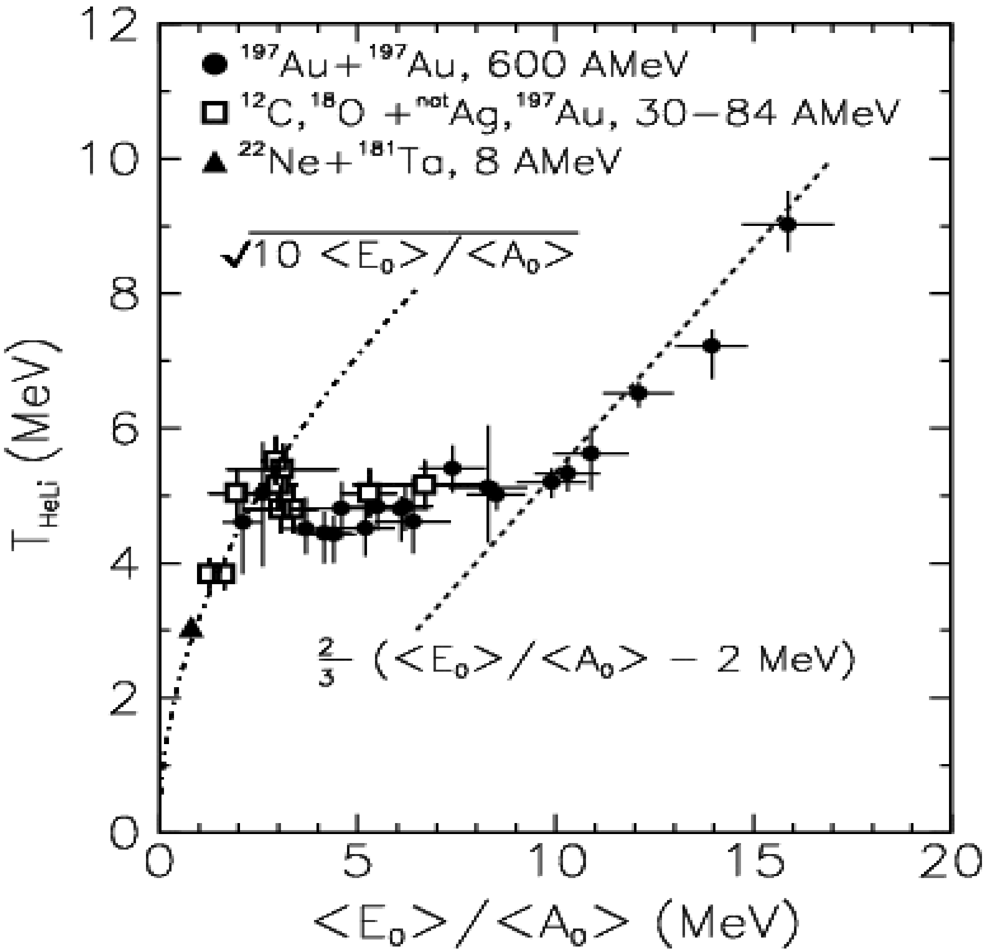
Signals of QGP formation & QCD phase transition

- Signals of QGP formation at $\sqrt{s_{NN}}$ = 200 GeV and above (RHIC, LHC)
  - Jet quenching in AA collisions (not in dA)
  - Large elliptic flow (success of hydrodynamics)
  - Quark number scaling (coalescence of quarks)

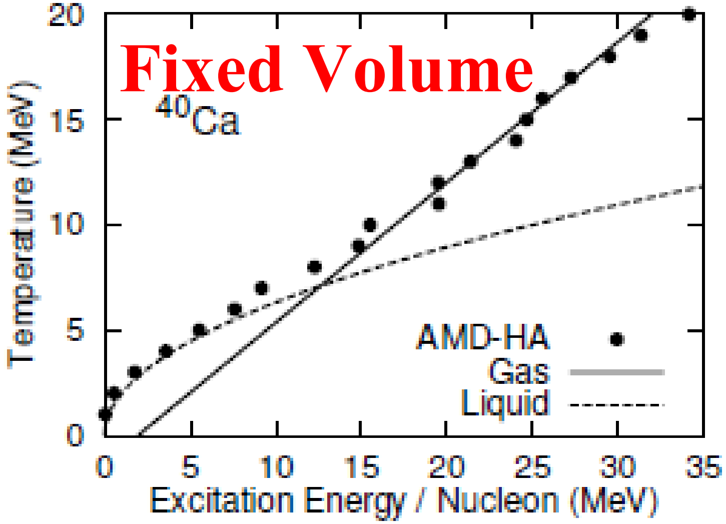
  Similar signals are observed at $\sqrt{s_{NN}} > 39$ GeV
- Signals of QCD phase transition at $\sqrt{s_{NN}}$ = 4-40 GeV (?)
  - Hint from Liquid-Gas phase transition: caloric curve
  - Horn, Step (Re-Hardening), Dale
  - Non-monotonic behavior of
    proton number moment ($\kappa\sigma^2$) and collective flow (dv_1/dy)

Nuclear Liquid-Gas Phase Transition

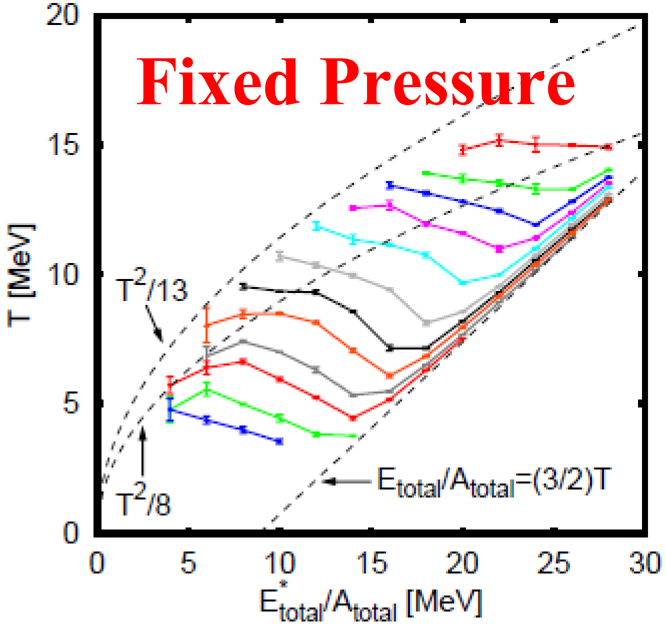
- **Caloric curve → LG phase transition (Smoking gun)**



J. Pochadzalla et al. (GSI-ALLADIN collab.), PRL 75 (1995) 1040.



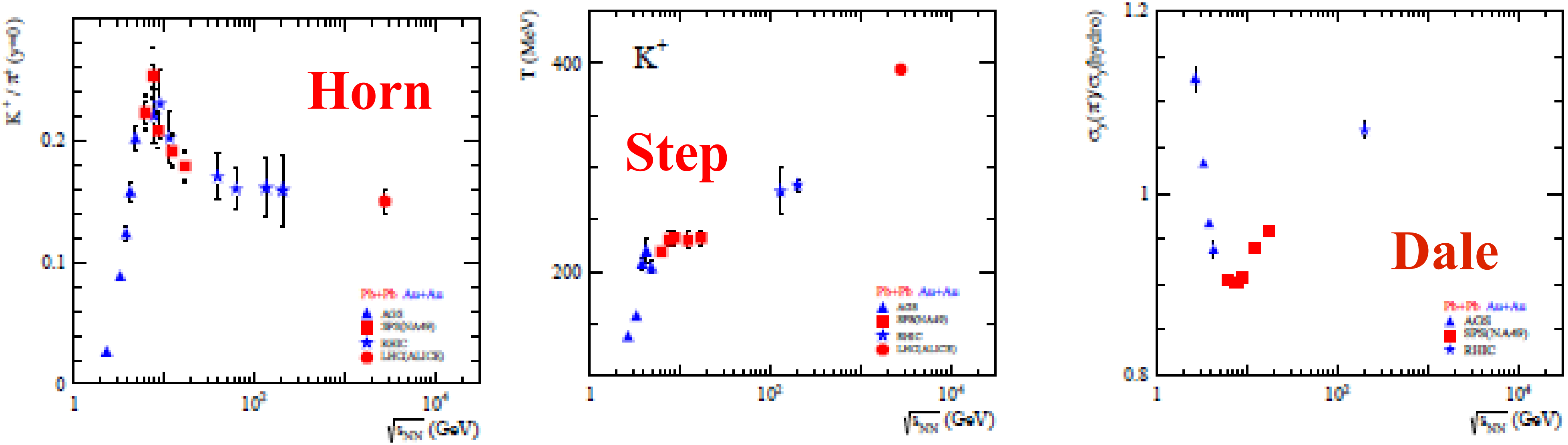
AO, Randrup ('98)



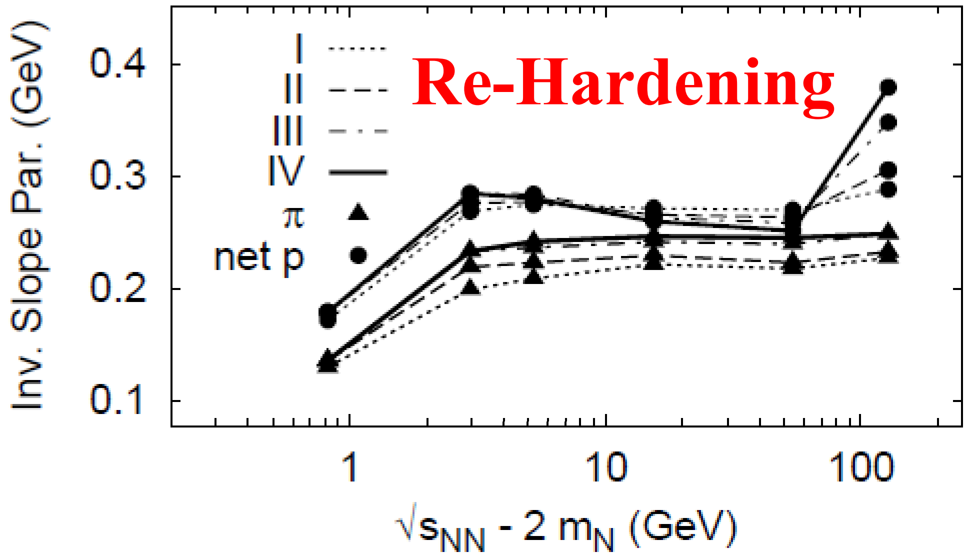
T. Furuta, A.Ono ('09)

Horn, Step and Dale

- **Non-monotonic behavior in K^+/π^+ ratio (Horn), m_T slope par. (Step or re-hardening), rapidity dist. width of π (Dale)**



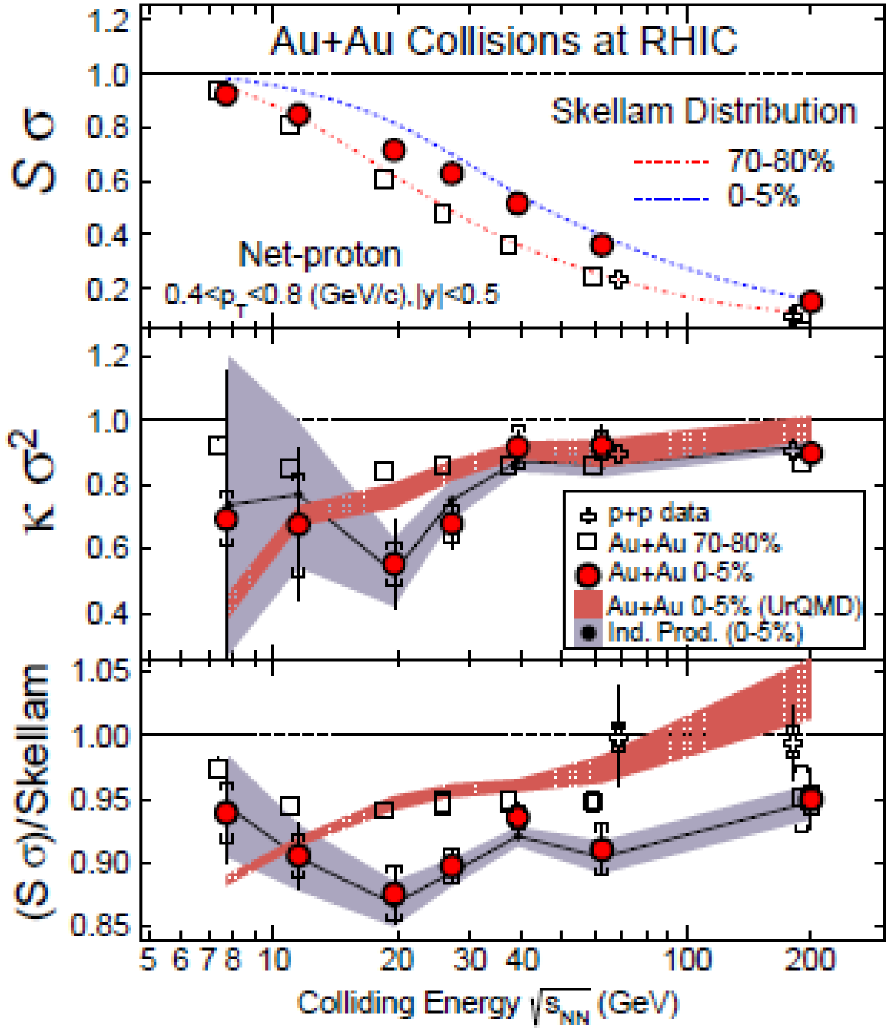
E.g. A. Rustamov (2012)

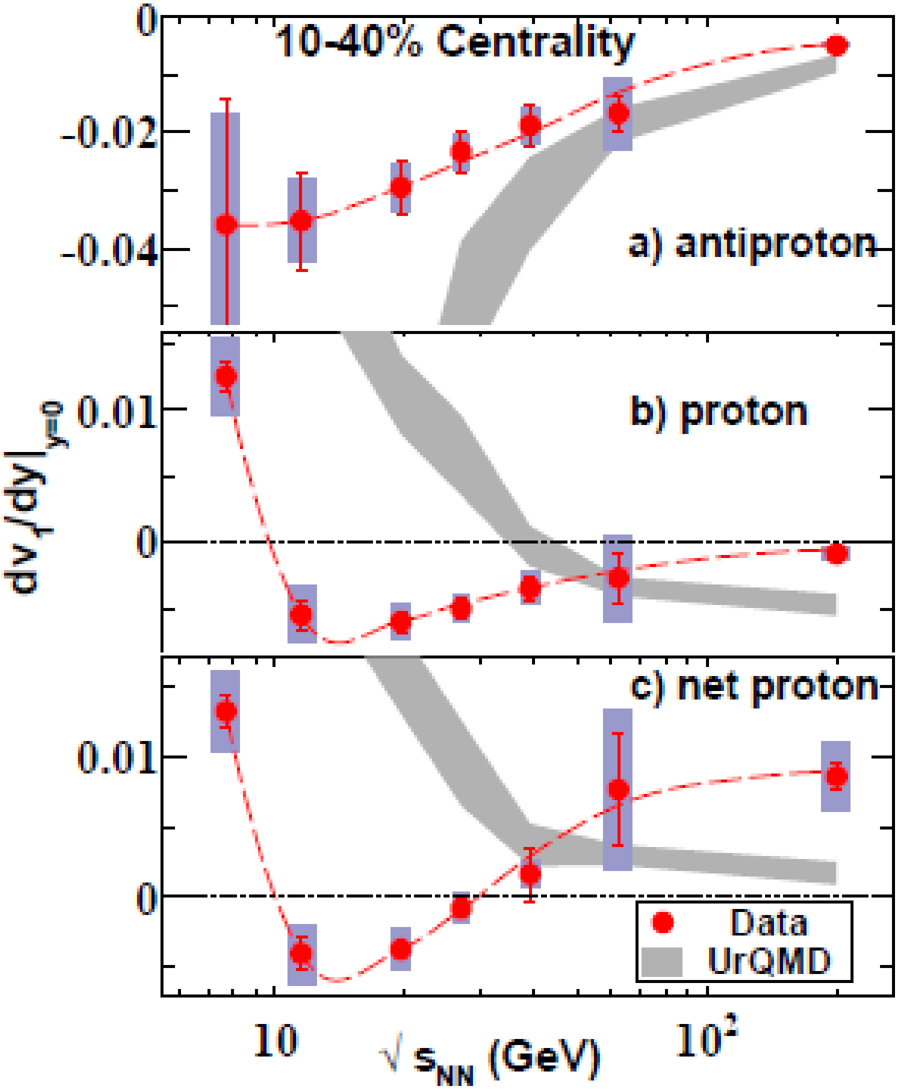


N. Otuka, P.K.Sahu, M. Isse, Y. Nara, AO, nucl-th/010205

Net-Proton Number Moments & Directed Flow

- **Non-monotonic behavior of $\kappa\sigma^2$ and dv_1/dy. CP signal ?**





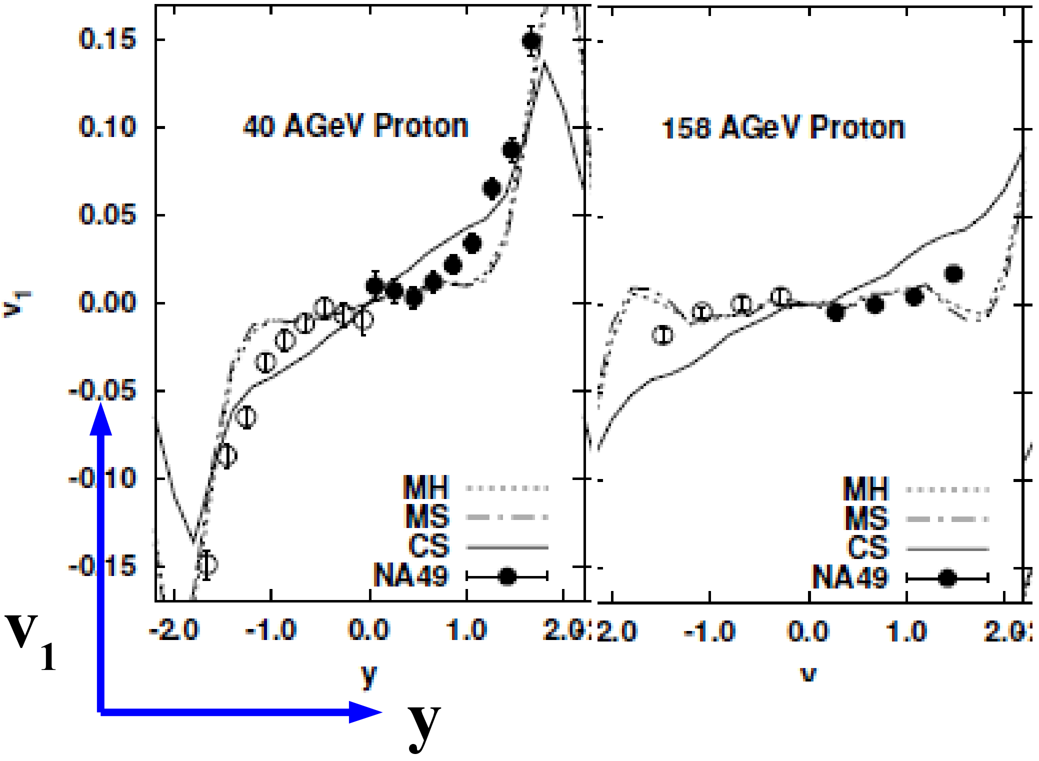
STAR Collab. (PRL 112('14)032302

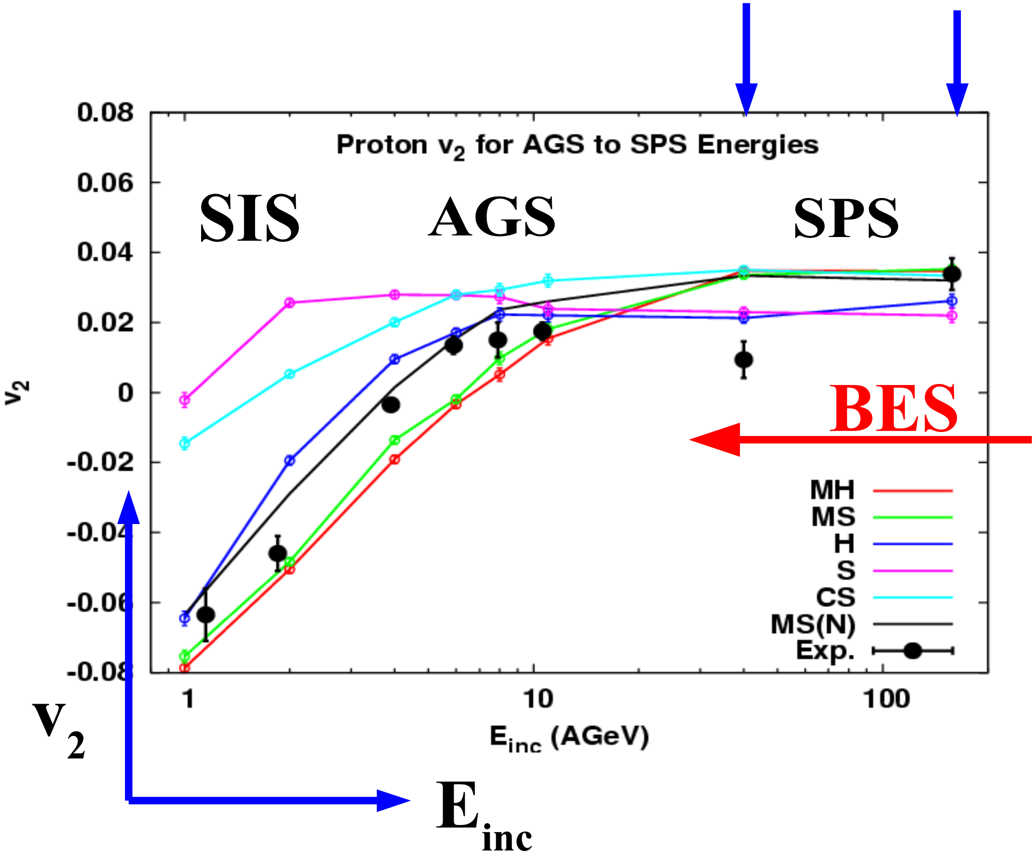
STAR Collab., PRL 112('14)162301.

JAM results at AGS and SPS Energies

- **JAM w/ Mean-Field effects roughly explains v_1 and v_2 at AGS & SPS (1-158 A GeV → $\sqrt{s_{NN}}$ = 2.5-20 GeV)**

$\sqrt{s_{NN}}$=8.9 GeV $\sqrt{s_{NN}}$=17.3 GeV



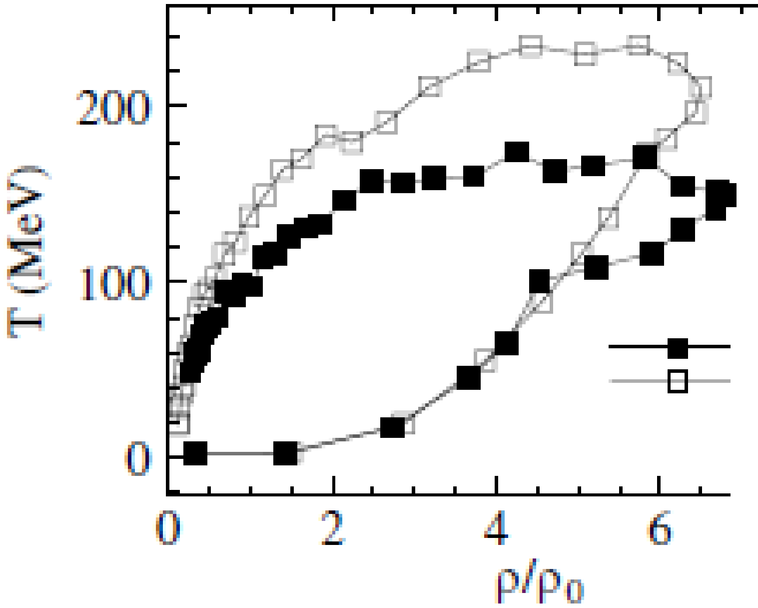


M. Isse, AO, N. Otuka, P. K. Sahu, Y. Nara, PRC72('05)064908

QCD phase transition at J-PARC Energies ?

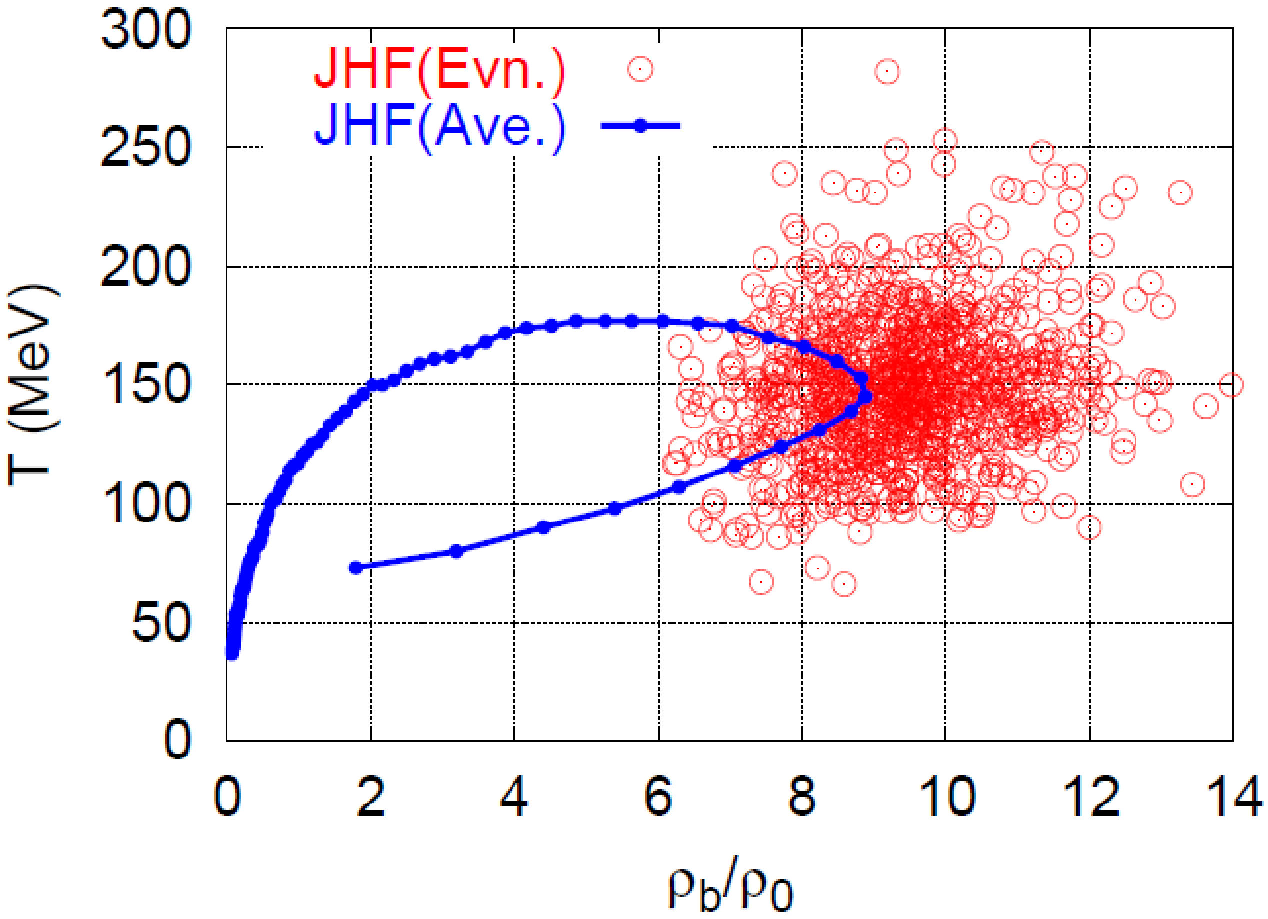
- *J-PARC Energies*: $\sqrt{s_{NN}}$ = 4-40 GeV (or $\sqrt{s_{NN}}$ = 1.9-6.2 GeV)
  - E(p)=30 GeV → E(Au) ~ 12 AGeV (full strip, $\sqrt{s_{NN}}$ = 5.1 GeV for Au+Au)
  - E(p)=50 GeV → E(Au) ~ 20 AGeV ($\sqrt{s_{NN}}$= 6.4 GeV)
  - E(p)=30 GeV (50 GeV) Collider → $\sqrt{s_{NN}}$= 26 GeV (42 GeV)
- Two Aspects of J-PARC energies
  - Formation of highest baryon density matter
  - Various non-monotonic behaviors → Onset of deconfinement

Highest Density Matter at J-PARC ?



Nara, Otuka, AO, Maruyama ('97)

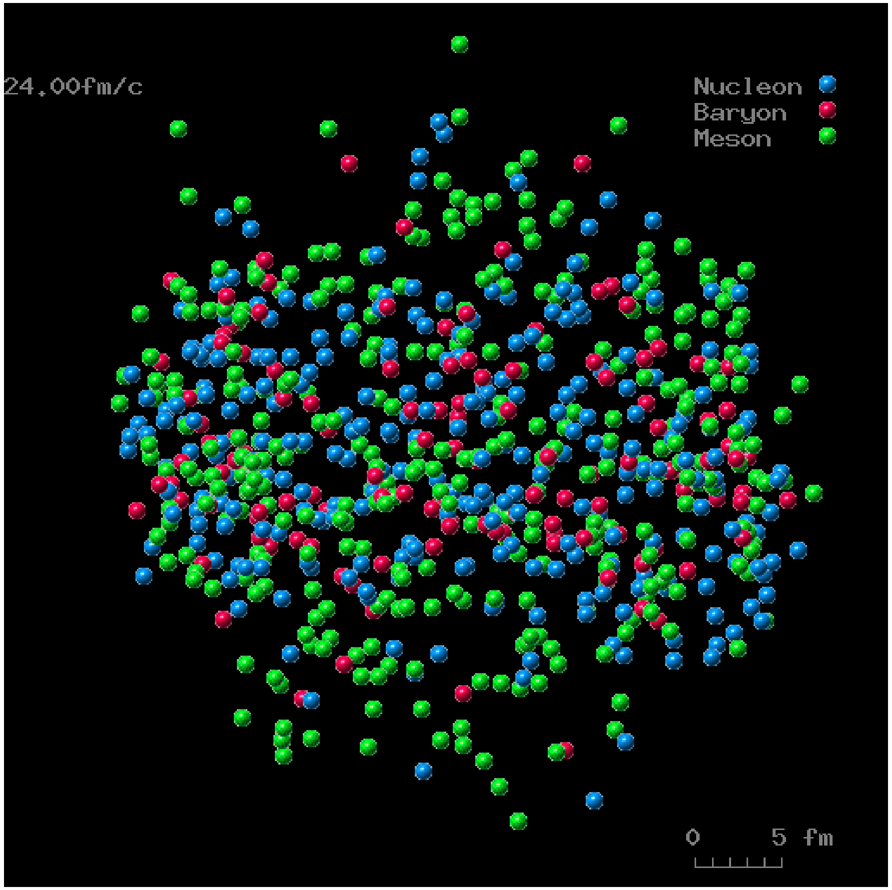
Central 1 fm^3 cube.



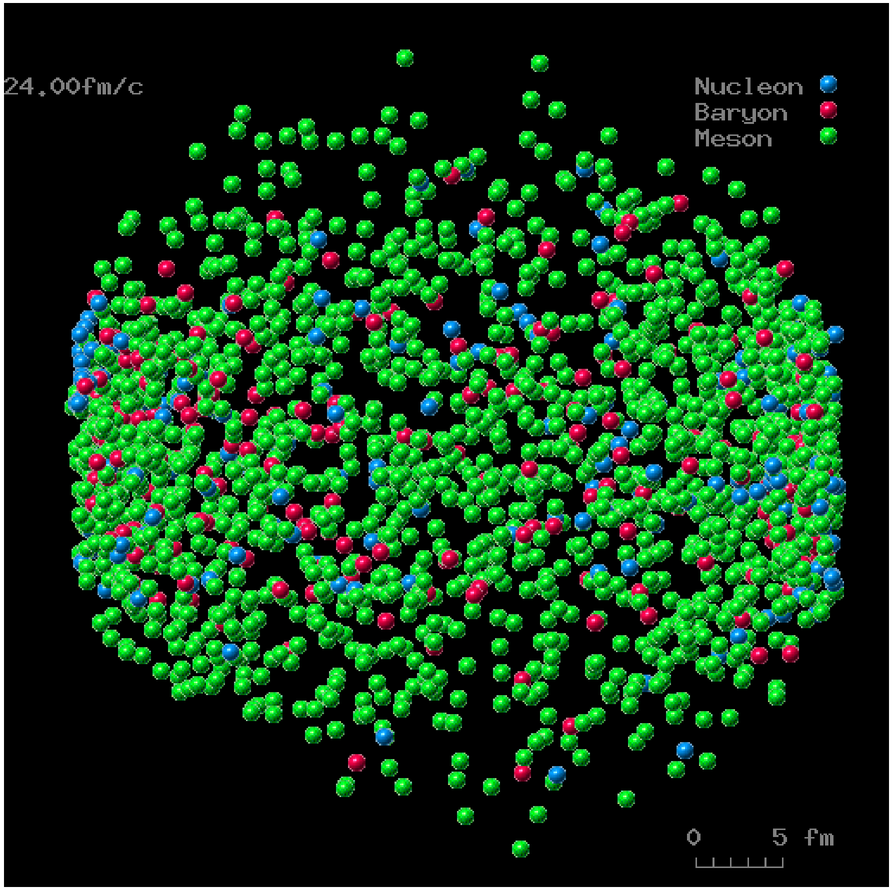
大西、JHF workshop (2002)

How do heavy-ion collisions look like ?

Au+Au, 10.6 A GeV

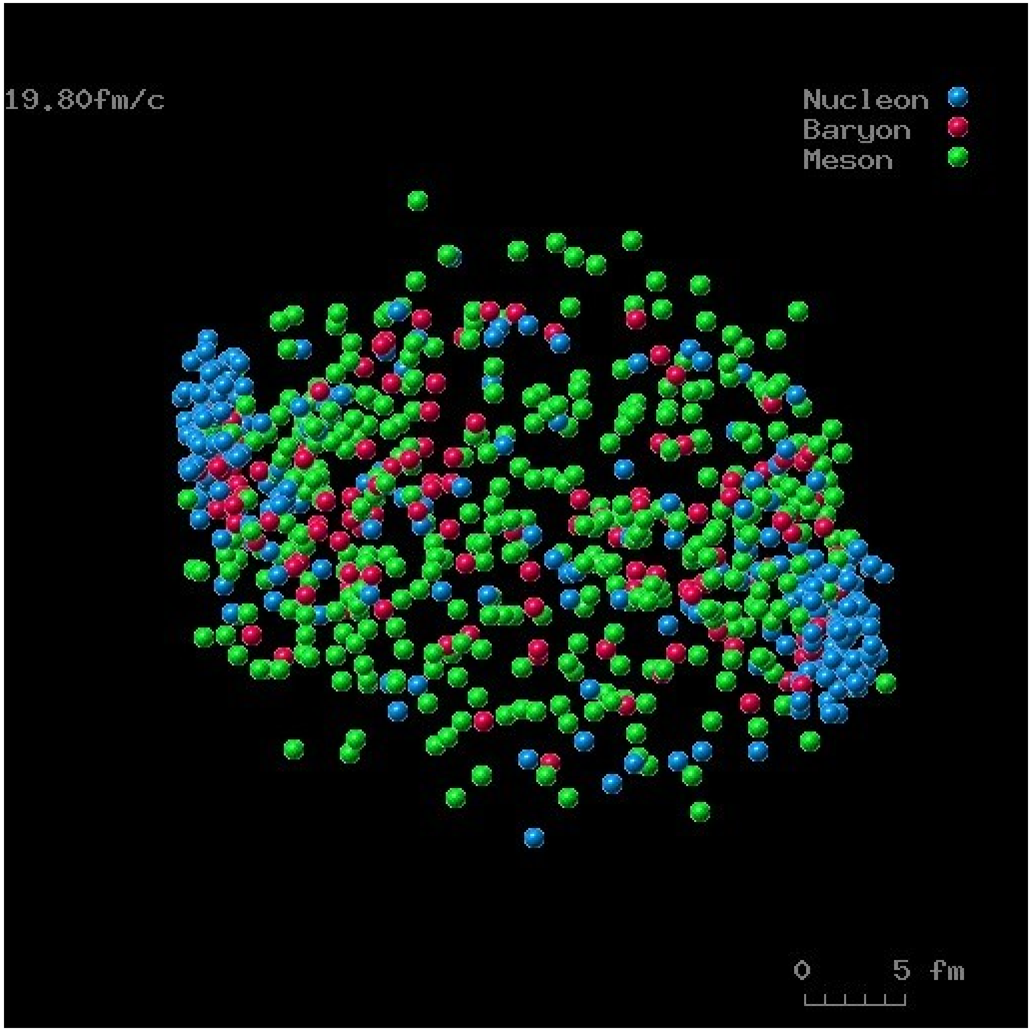


Pb+Pb, 158 A GeV



JAMming on the Web **http://www.jcprg.org/jow/**

J-PARC energy



Au+Au, 25 AGeV, b=5 fm (JOW)

QCD phase transition at J-PARC Energies ?

- ***J-PARC Energies***: $\sqrt{s_{NN}}$ = 4-40 GeV (or $\sqrt{s_{NN}}$ = 1.9-6.2 GeV)
  - E(p)=30 GeV → E(Au) ~ 12 AGeV (full strip, $\sqrt{s_{NN}}$ = 5.1 GeV for Au+Au)
  - E(p)=50 GeV → E(Au) ~ 20 AGeV ($\sqrt{s_{NN}}$= 6.4 GeV)
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- Two Aspects of J-PARC energies
  - Formation of highest baryon density matter
  - Various non-monotonic behaviors → Onset of deconfinement

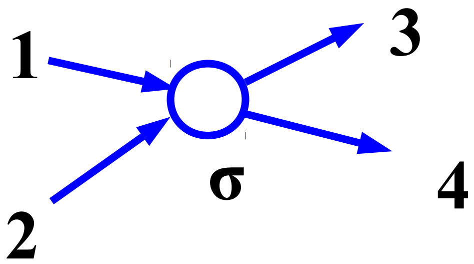
Question

Do these Non-mono. behaviors signal the onset of
QCD phase transition and/or QCD critical point ?
or Do they show some properties of hadronic matter ?
→ Let's examine in hadronic transport models !

A Hadronic Transport Model: JAM

Transport Equation

- **Boltzmann equation with potential effects (BUU Equation)**
  Bertsch, Das Gupta, Phys. Rept. 160(88), 190



$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\nabla f - \nabla U \cdot \nabla_p f = I_{\rm coll}$$

$$I_{\rm coll}(\mathbf{r},\mathbf{p}) = -\frac{1}{2}\int \frac{d\mathbf{p}_2}{(2\pi)^3} d\Omega\ v_{12}\ \frac{d\sigma}{d\Omega}\ [f f_2 (1-f_3)(1-f_4)) - (12 \leftrightarrow 34)]$$

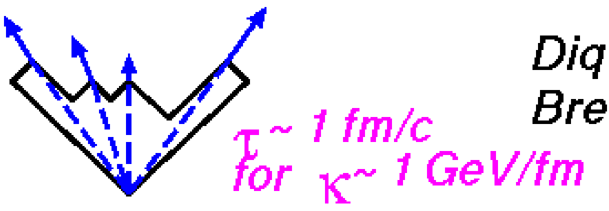
(NN elastic scattering case)

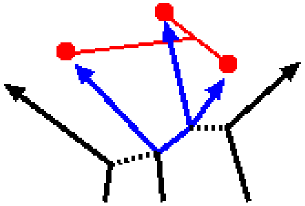
- **Inputs of Transport models**
  - **Cross section σ (c.f. Nara's talk)**
    - **Elementary cross section should be taken from data, if possible.**
    - **Unknown cross sections need to be given by a model.**
  - **Potential U**
    - **Hopefully, given by ab initio calc. Usually, given by phen. models.**
    - **U depends on ρ and p.**

JAM (Jet AA Microscopic transport model)

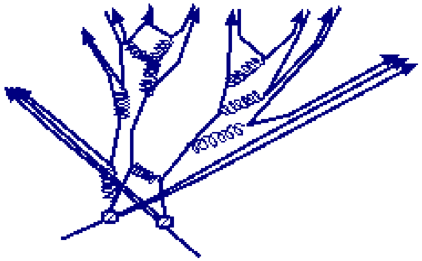
Nara, Otuka, AO, Niita, Chiba, Phys. Rev. C61 (2000), 024901.
Isse, AO, Otuka, Sahu, Nara, Phys.Rev. C 72 (2005), 064908.

- **Hadron-String Cascade with Jet production**
  - **Hadron Res. up to m < 2 GeV**
  - **String & Jet production and decay using Lund string model**
    T. Sjostrand et al., Comput. Phys. Commun. 135 (2001), 238 (PYTHIA).
  - **String-Hadron collisions are simulated by *hh* collisions in the formation time (~ RQMD)** *H. Sorge,PRC52 ('95)3291.*
  - **Mean field effects are included with density and momentum dependences.**
    Isse et al., ('05)
  - **NO Secondary partonic int.**
  - **Open to public**

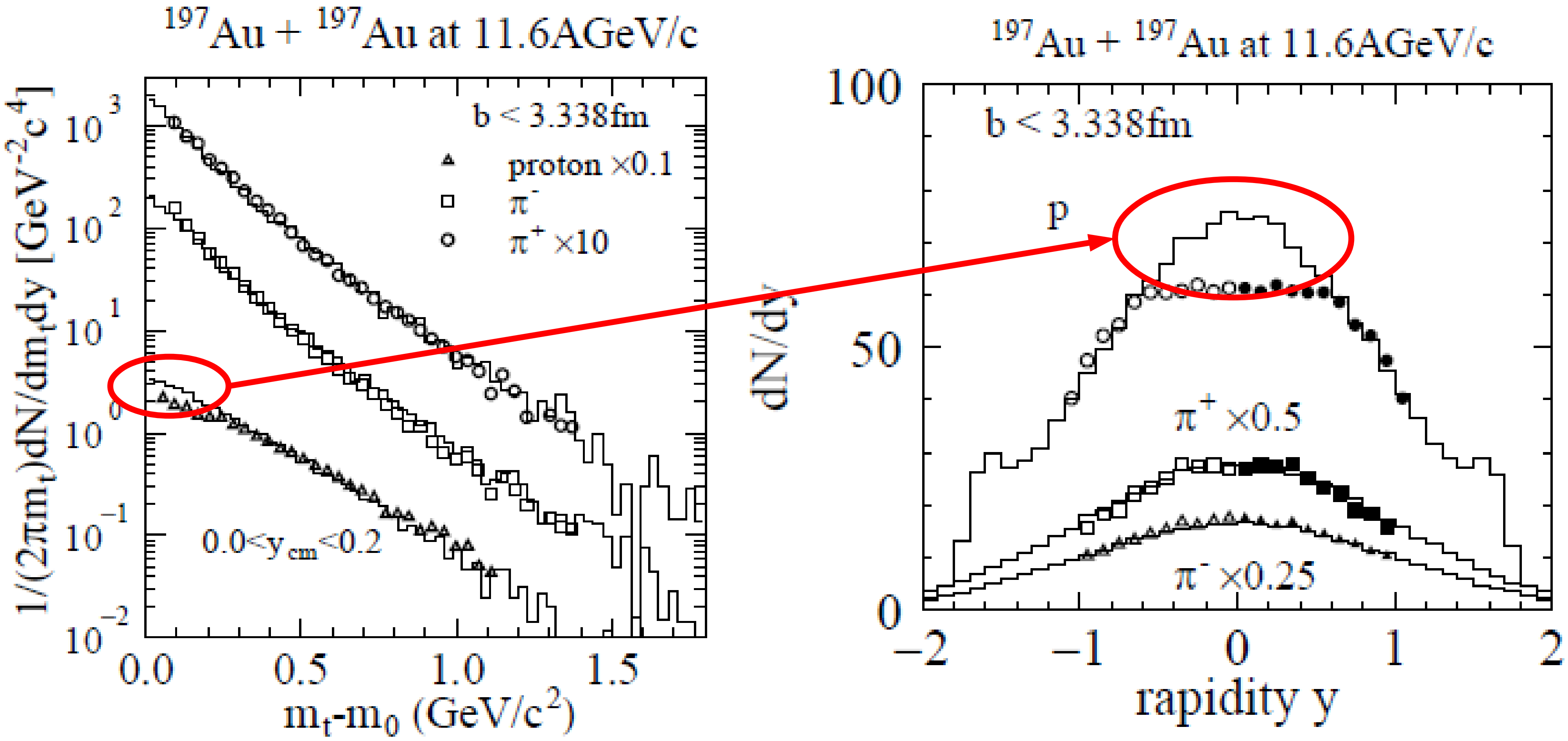




Resonance
+ String
+ Jet



Hadron spectra in Au+Au at AGS



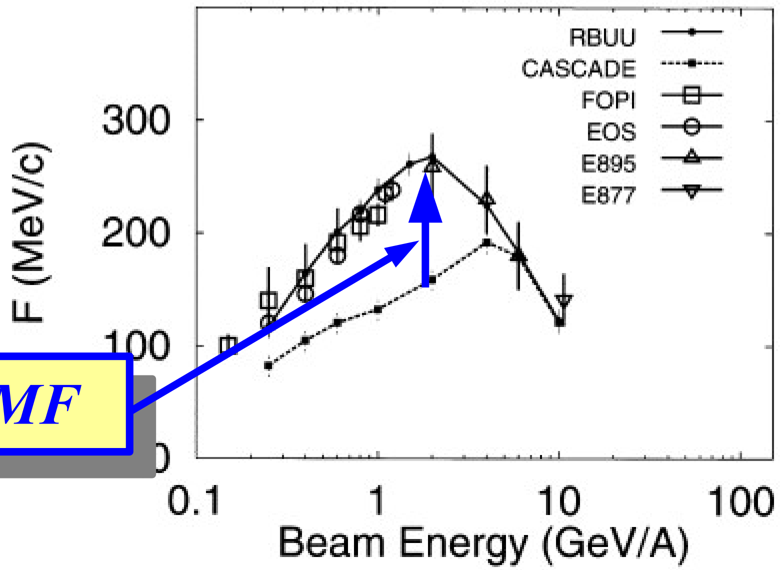
Hadron pT spectra at AGS are well described, except for low pT protons (→ Mean Field Effects).

Mean Field and Particle DOF Effects @ AGS

- **Mean Field Effects at AGS**
  → Visible but small for p_T spectrum
  Essential for Flow
- **Particle DOF Effects**
  → Seen at high p_T

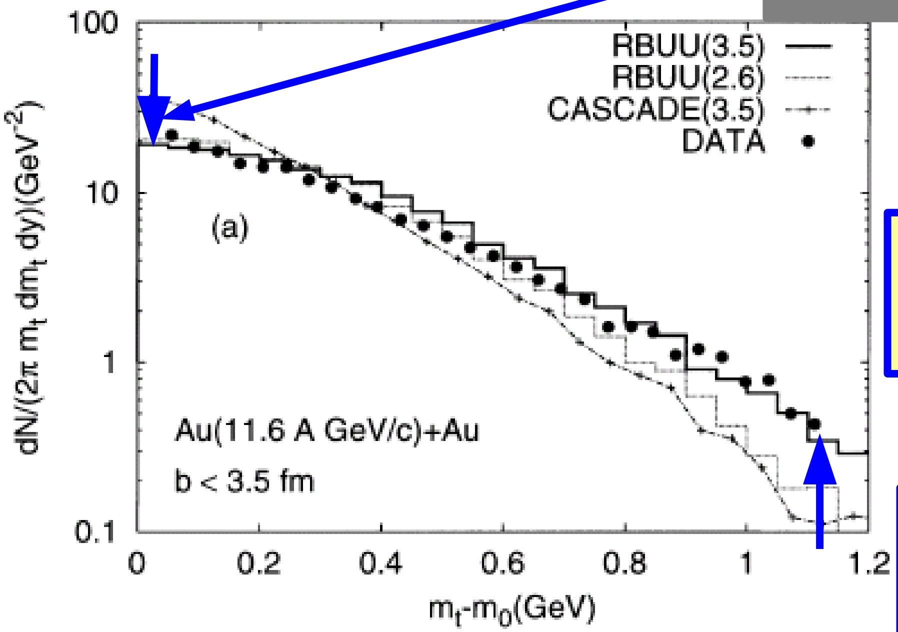
Sahu, Cassing, Mosel, Ohnishi (2000)

P.K. Sahu et al. / Nuclear Physics A 672 (2000) 376–386



Repulsive MF

P.K. Sahu et al. / Nuclear Physics A 672 (2000) 376–386



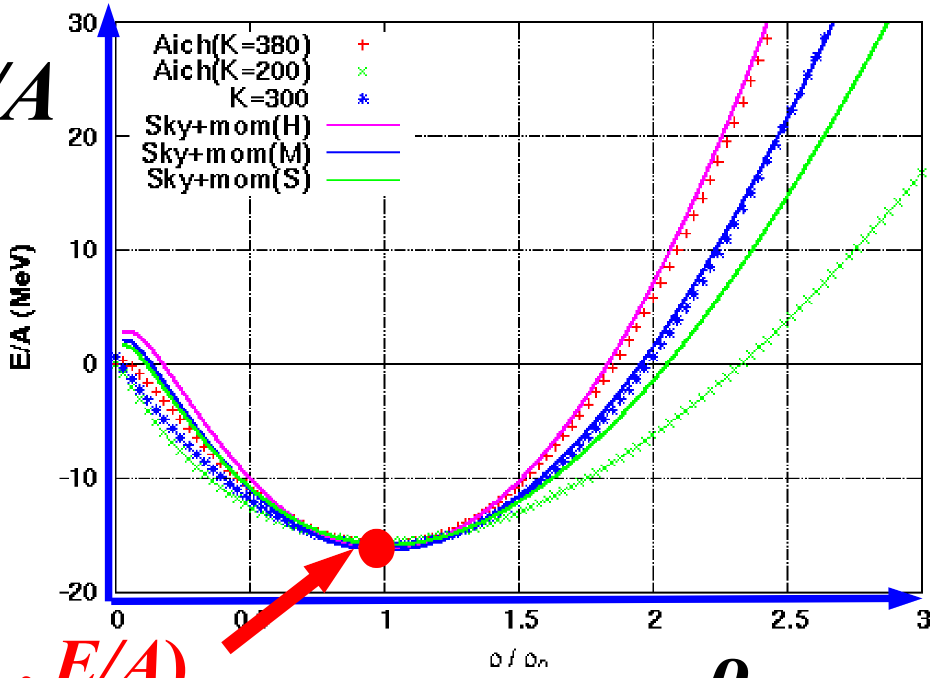
Switching √s = 3.5 GeV (JAM fit)

Switching √s = 2.6 GeV (HSD default)

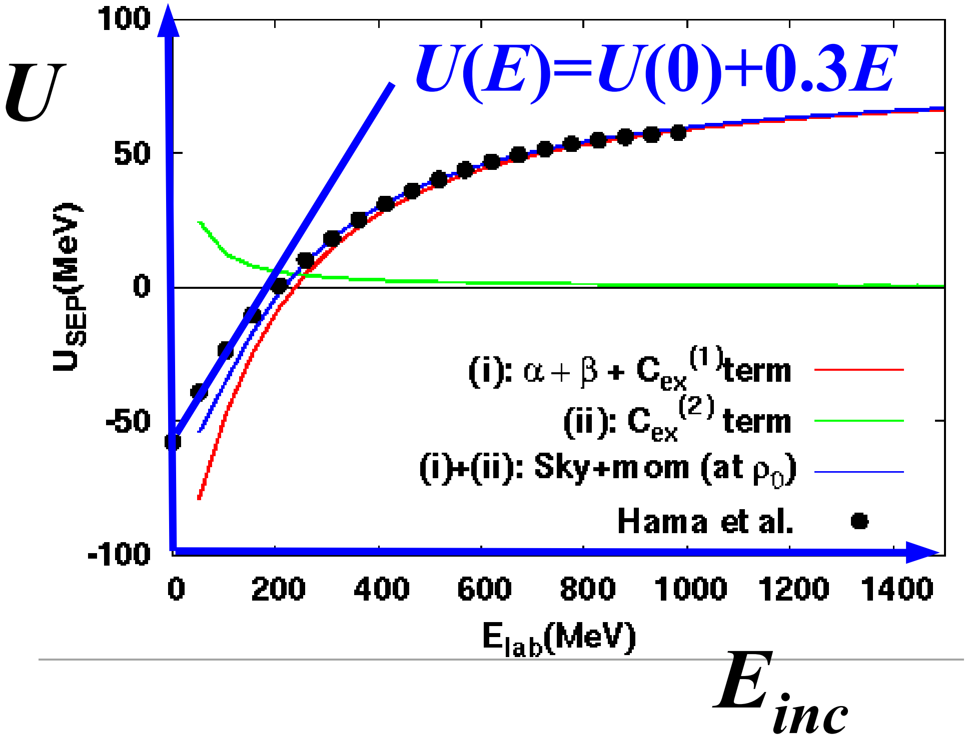
Nuclear Mean Field

- **MF has ρ and p-deps.**
  - **ρ dep.: Saturation point (ρ_0, *E/A*) = (0.15 fm^{-3}, -16.3 MeV)**
  - **p dep.: Global potential up to E=1 GeV is known from pA scattering**

    $$U(\rho_0, E) = U(\rho_0, E=0)+0.3\,E$$



$(\rho_0\ , E/A)$
$=(0.15\ \mathrm{fm}^{-3}\ , -16.3\ \mathrm{MeV})$

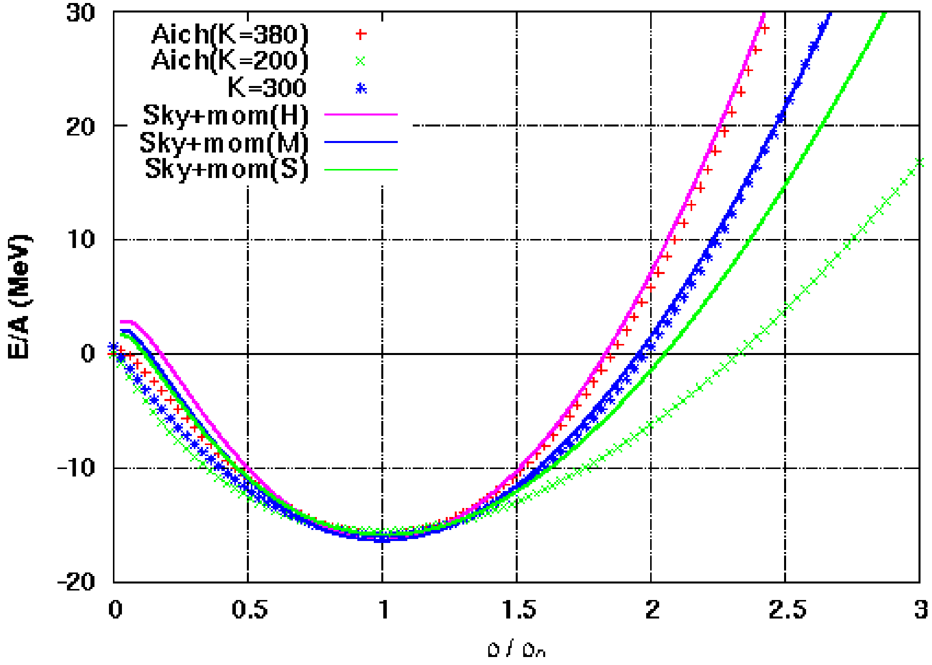


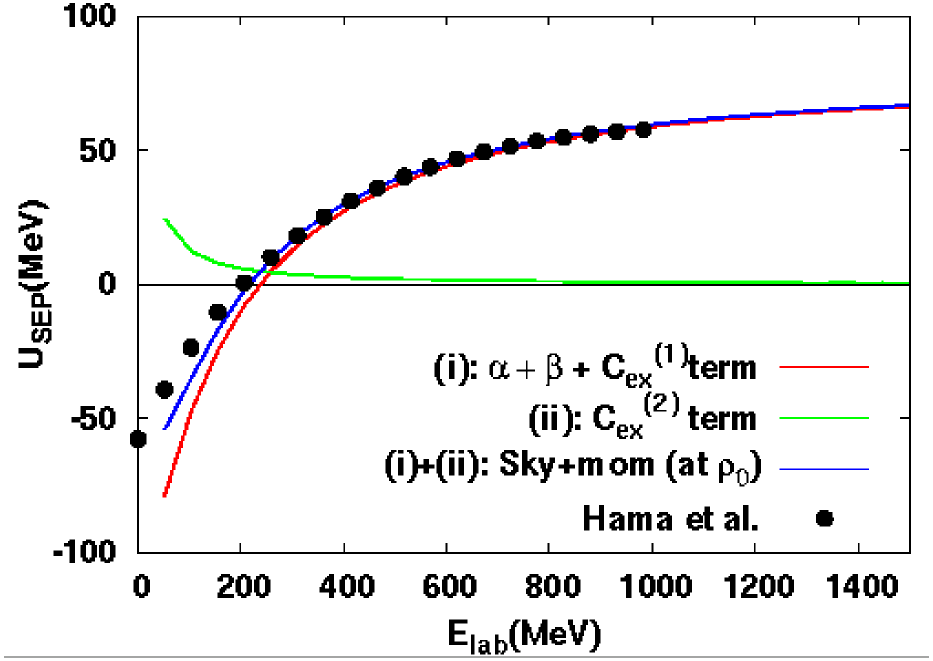
Phenomenological Mean Field

- **Skyrme type ρ-Dep. + Lorentzian p-Dep. Potential**

$$V=\sum_i V_i=\int d^3r\left[\frac{\alpha}{2}\left(\frac{\rho}{\rho_0}\right)^2+\frac{\beta}{\gamma+1}\left(\frac{\rho}{\rho_0}\right)^{\gamma+1}\right]$$

$$+\sum_k\int d^3r\,d^3p\,d^3p'\,\frac{C_{ex}^{(k)}}{2\rho_0}\,\frac{f(r,p)\,f(r,p')}{1+(p-p')^2/\mu_k^2}$$





Simplified RQMD treatment of p- and ρ-dep. mean field in JAM

Isse, AO, Otuka, Sahu, Nara, Phys.Rev. C 72 (2005), 064908

Relativistic QMD/Simplified (RQMD/S)

- **RQMD = Constraint Hamiltonian Dynamics**
  (Sorge, Stocker, Greiner, Ann. of Phys. 192 (1989), 266.)
- **Constraints: $\varphi \approx 0$ (Satisfied on the realized trajectory, by Dirac)**
  - **Variables in Covariant Dynamics = 8N phase space: (q_μ, p_μ)**
  - **Variables in EOM = 6N phase space**
    → We need 2N constraints to get EOM
- **On Mass-Shell Constraints**

$$H_i \equiv p_i^2 - m_i^2 - 2m_i V_i \approx 0$$

- **Time-Fixation in RQMD/S**

$$\chi_i \equiv \hat{a} \cdot (q_i - q_N) \approx 0 \, (i = 1, \sim N-1) \quad , \quad \chi_N \equiv \hat{a} \cdot q_N - \tau \approx 0$$

$$\hat{a} = \text{Time-like unit vector in the Calculation Frame}$$

(Tomoyuki Maruyama et al., Prog. Theor. Phys. 96(1996), 263.)

RQMD/S (cont.)

- **Hamiltonian is made of constraints**

$$H=\sum_i u_i \phi_i \quad (\phi_i = H_i (i=1\sim N), \chi_{i-N} (i=N+1\sim 2N))$$

- **Time Development** $\dfrac{df}{d\tau}=\dfrac{\partial f}{\partial \tau}+\{f, H\} \quad , \quad \{q_\mu, p_\nu\}=g_{\mu\nu}$
- **Lagrange multipliers are determined to keep constraints**
  → *We can obtain the multipliers analytically in RQMD/S*

$$\frac{d\phi_i}{d\tau}\approx 0 \quad \rightarrow \quad \delta_{i,2\mathrm{N}}+\sum_j u_j \{\phi_i, \phi_j\}\approx 0$$

- **Equations of Motion**

$$H=\sum_i (p_i^2-m_i^2-2m_i V_i)/2p_i^0 \quad , \quad p_i^0=E_i=\sqrt{\vec{p}_i^2+m_i^2+2m_i V_i}$$

$$\frac{d\vec{r}_i}{d\tau}\approx -\frac{\partial H}{\partial \vec{p}_i}=\frac{\vec{p}}{p_i^0}+\sum_j \frac{m_j}{p_j^0}\frac{\partial V_j}{\partial \vec{p}_i} \quad , \quad \frac{d\vec{p}_i}{d\tau}\approx \frac{\partial H}{\partial \vec{r}_i}=-\sum_j \frac{m_j}{p_j^0}\frac{\partial V_j}{\partial \vec{r}_i}$$

We can include MF in an almost covariant way in molecular dynamics

Particle "DISTANCE"

$$r_{Tij}{}^2 \equiv r_\mu r^\mu - \left(r_\mu P^\mu_{ij}\right)^2 / P^2_{ij} = \vec{r}^{\,2} \qquad \left(in\ CM\right)$$

$$P_{ij} \equiv p_i + p_j \quad , \qquad r \equiv r_i - r_j$$

Particle "Momentum Difference"

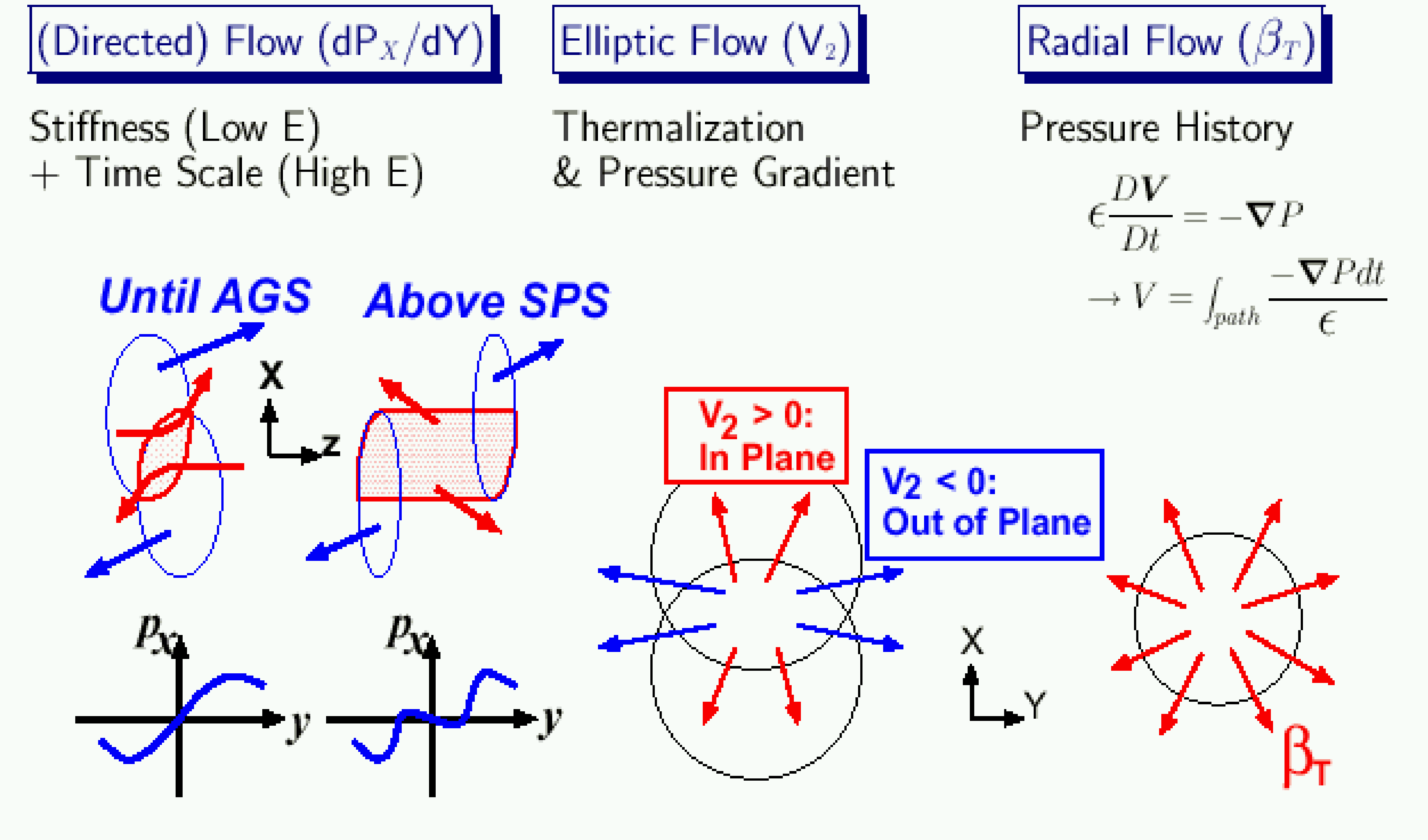
$$p_{Tij}{}^2 \equiv p_\mu p^\mu - \left(p_\mu P^\mu_{ij}\right)^2 / P^2_{ij} = \vec{p}^{\,2} \qquad \left(in\ CM\right)$$

$$p \equiv p_i - p_j$$

Lorentz Invariant, and Becomes Normal Distance in CM !

Collective Flows at J-PARC Energies

What is Collective Flow ?



(Directed) Flow (dP_X/dY)

Stiffness (Low E)
+ Time Scale (High E)

Elliptic Flow (V_2)

Thermalization
& Pressure Gradient

Radial Flow (β_T)

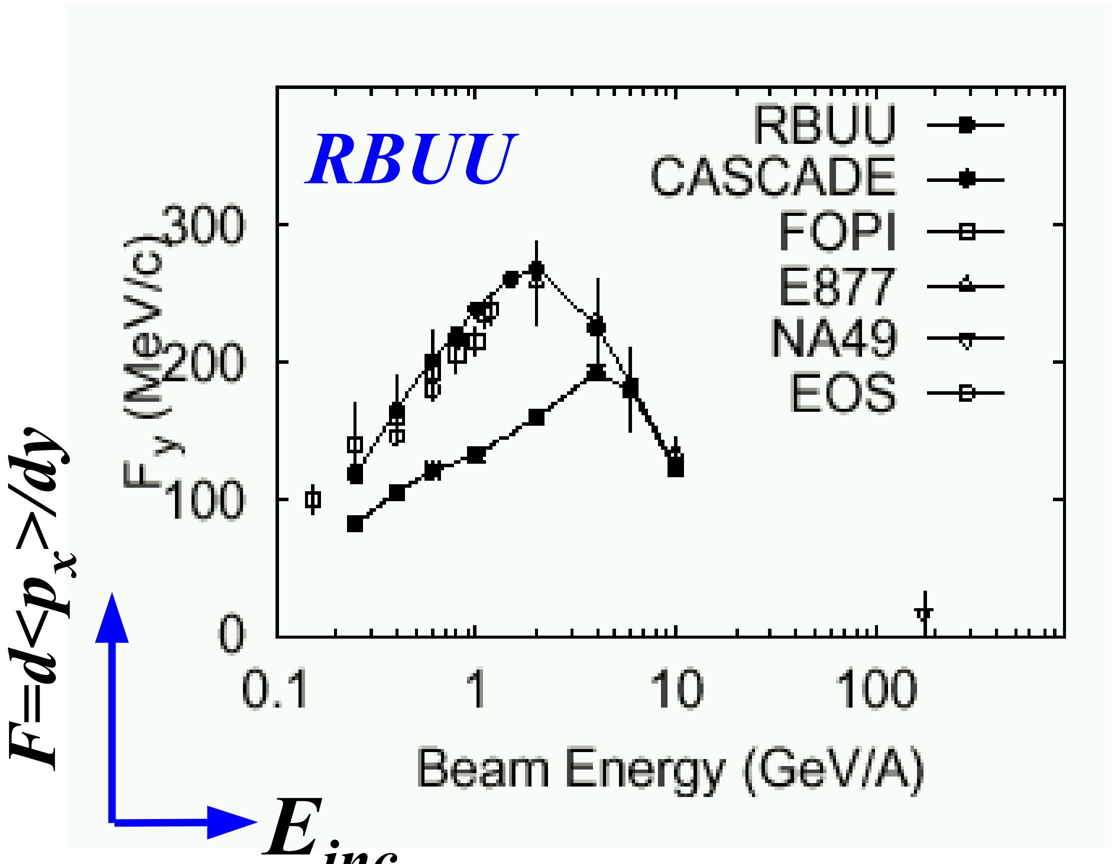
Pressure History

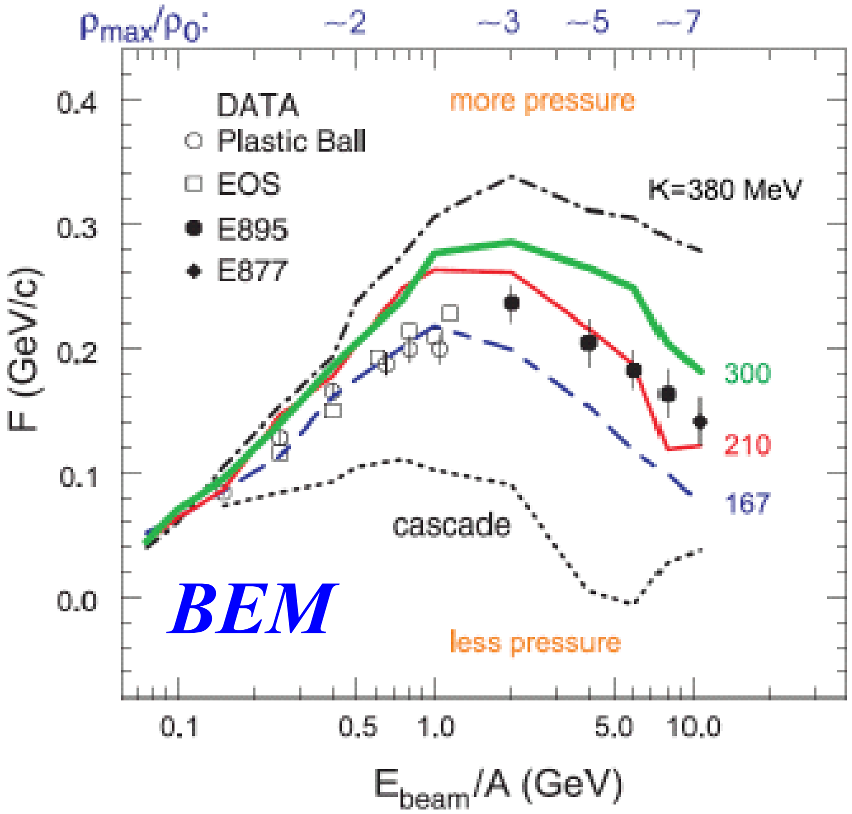
$$\epsilon \frac{D\mathbf{V}}{Dt} = -\nabla P$$

$$\rightarrow V = \int_{path} \frac{-\nabla P dt}{\epsilon}$$

Side Flow at AGS Energies

- **Relativistic BUU (RBUU) model: *K ~ 300 MeV***
  (Sahu, Cassing, Mosel, AO, Nucl. Phys. A672 (2000), 376.)
- **Boltzmann Equation Model (BEM): *K=167~210 MeV***
  (P. Danielewicz, R. Lacey, W.G. Lynch, Science 298(2002), 1592.)

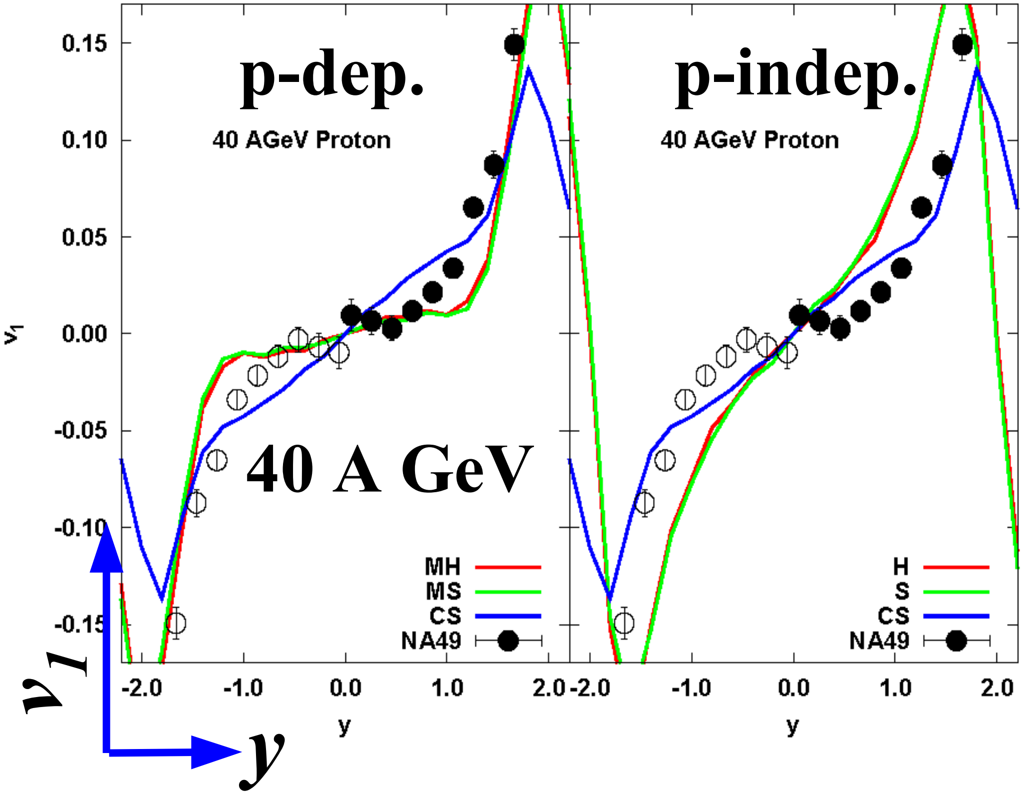


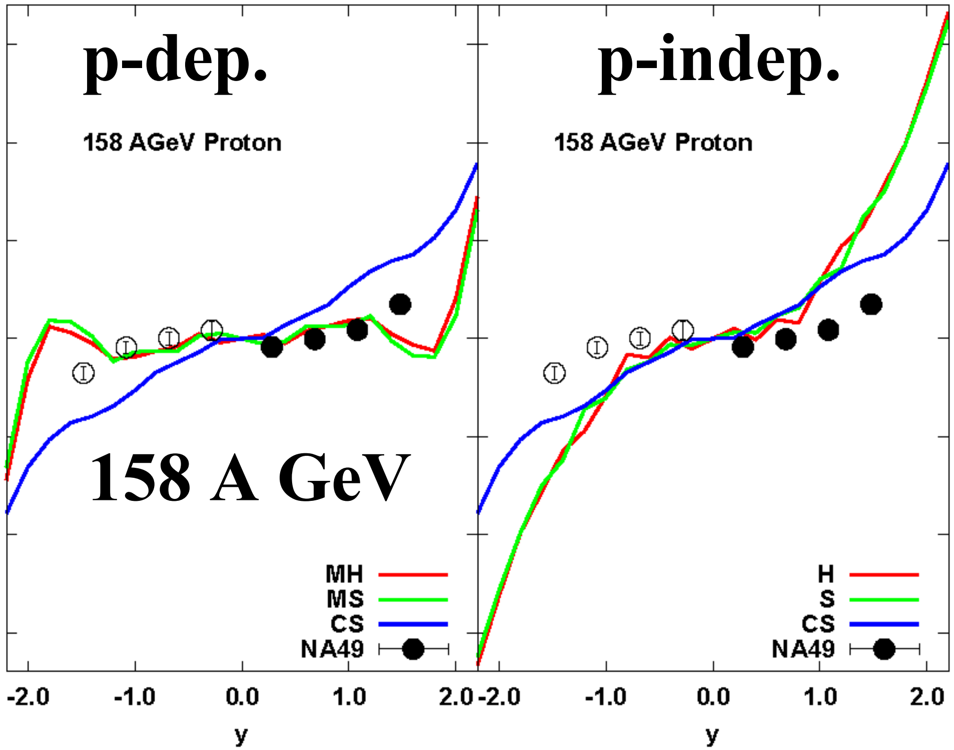


Directed flow v_1 at SPS

Isse, AO, Otuka, Sahu, Nara, PRC 72 (2005), 064908

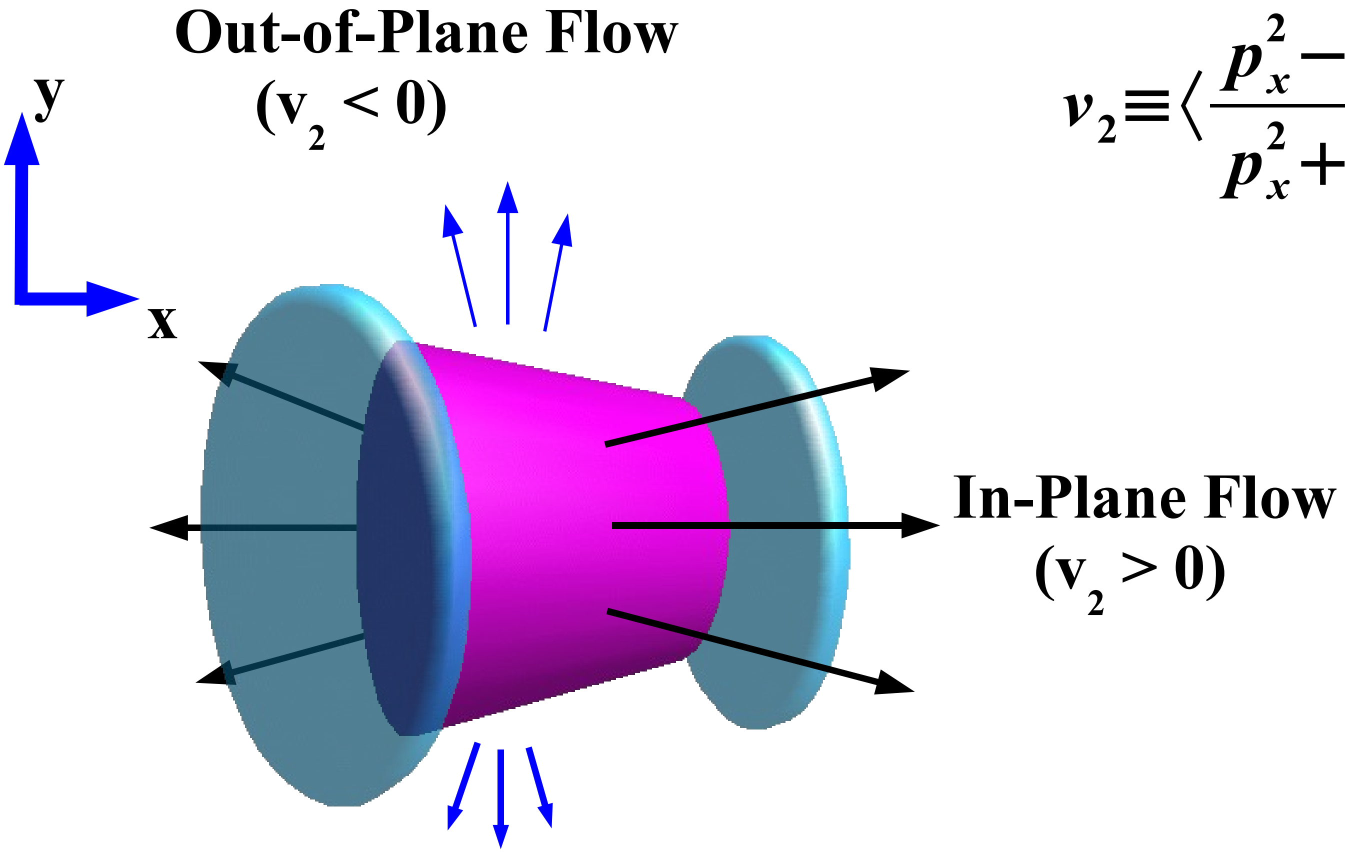
- **JAM-RQMD/S**
  - **p-dep. (indep.) MF suppresses (enhances) v_1.** $v_1=\langle\cos\phi\rangle=\langle p_x/p_T\rangle$
  - **“Wiggle” behavior appears with p-dep. MF at 158 A GeV.**





Elliptic Flow

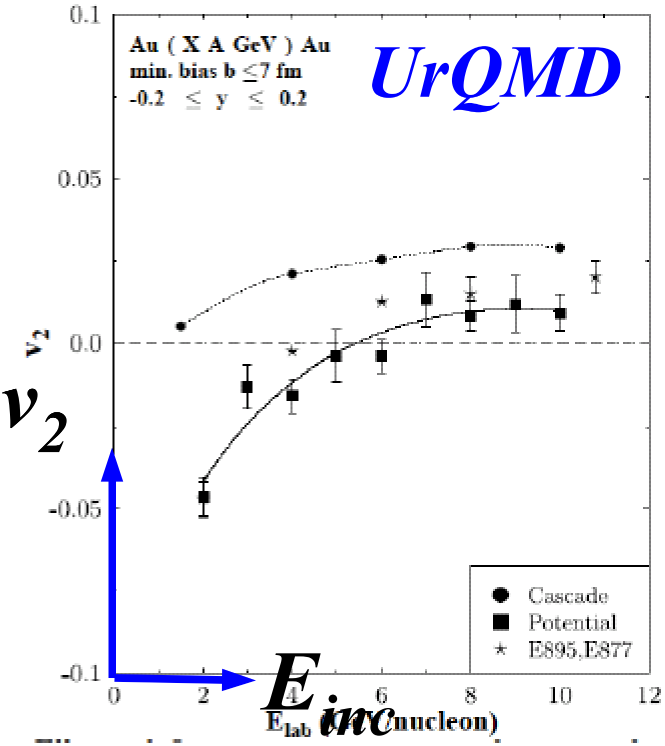
- **What is Elliptic Flow ? → Anisotropy in P space**
- **Hydrodynamical Picture**
  - **Sensitive to the Pressure Anisotropy in the Early Stage**
  - **Early Thermalization is Required for Large V2**

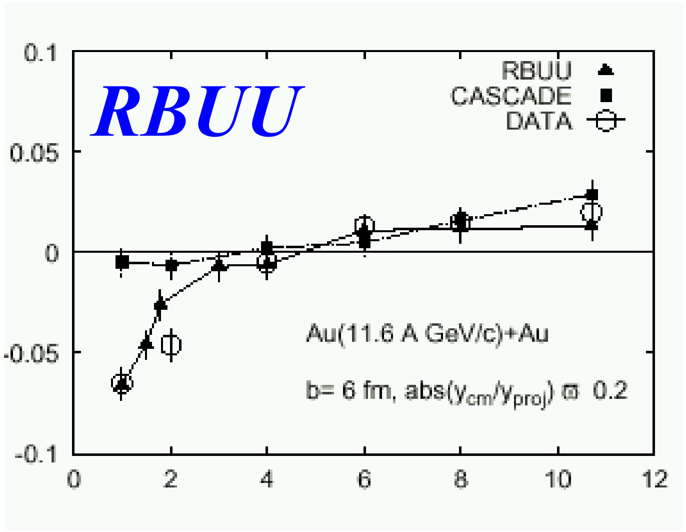


$$v_2 \equiv \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \langle \cos 2\phi \rangle$$

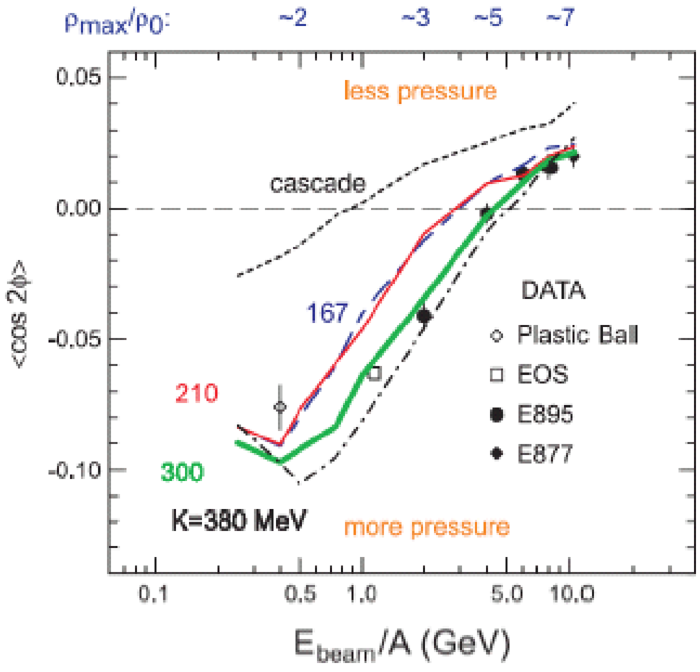
Elliptic Flow at AGS

- **Strong Squeezing Effects at low E (2-4 A GeV)**
  - **UrQMD: Hard EOS (S.Soff et al., nucl-th/9903061)**
  - **RBUU (Sahu-Cassing-Mosel-AO, 2000): K ~ 300 MeV**
  - **BEM(Danielewicz2002): K = 167 → 300 MeV**



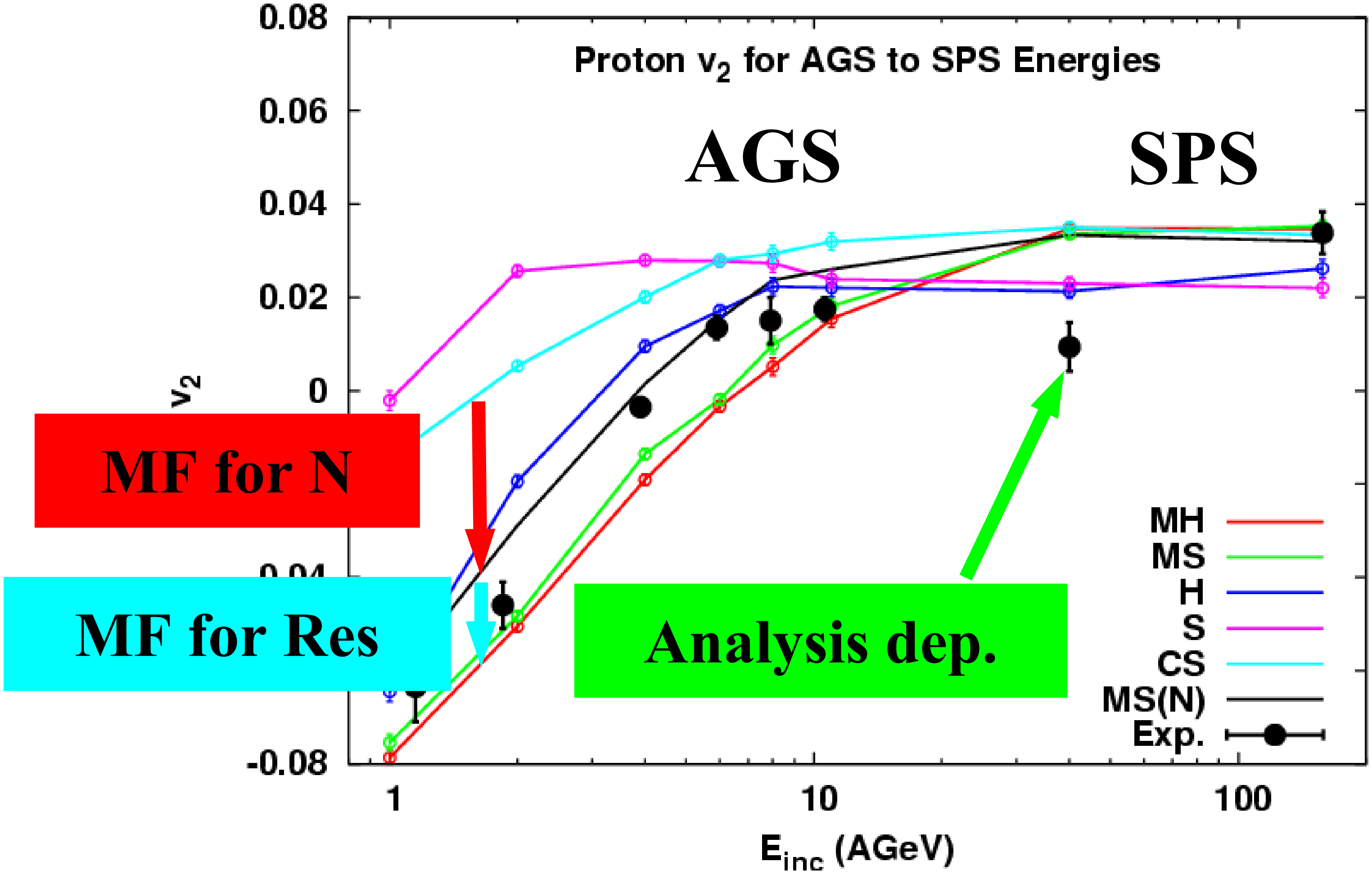


BEM



Elliptic Flow from AGS to SPS

- **JAM-MF with p dep. MF explains proton v2 at 1-158 A GeV**
  - **v2 is not very sensitive to K (incompressibility)**
  - **Data lies between MS(B) and MS(N)**

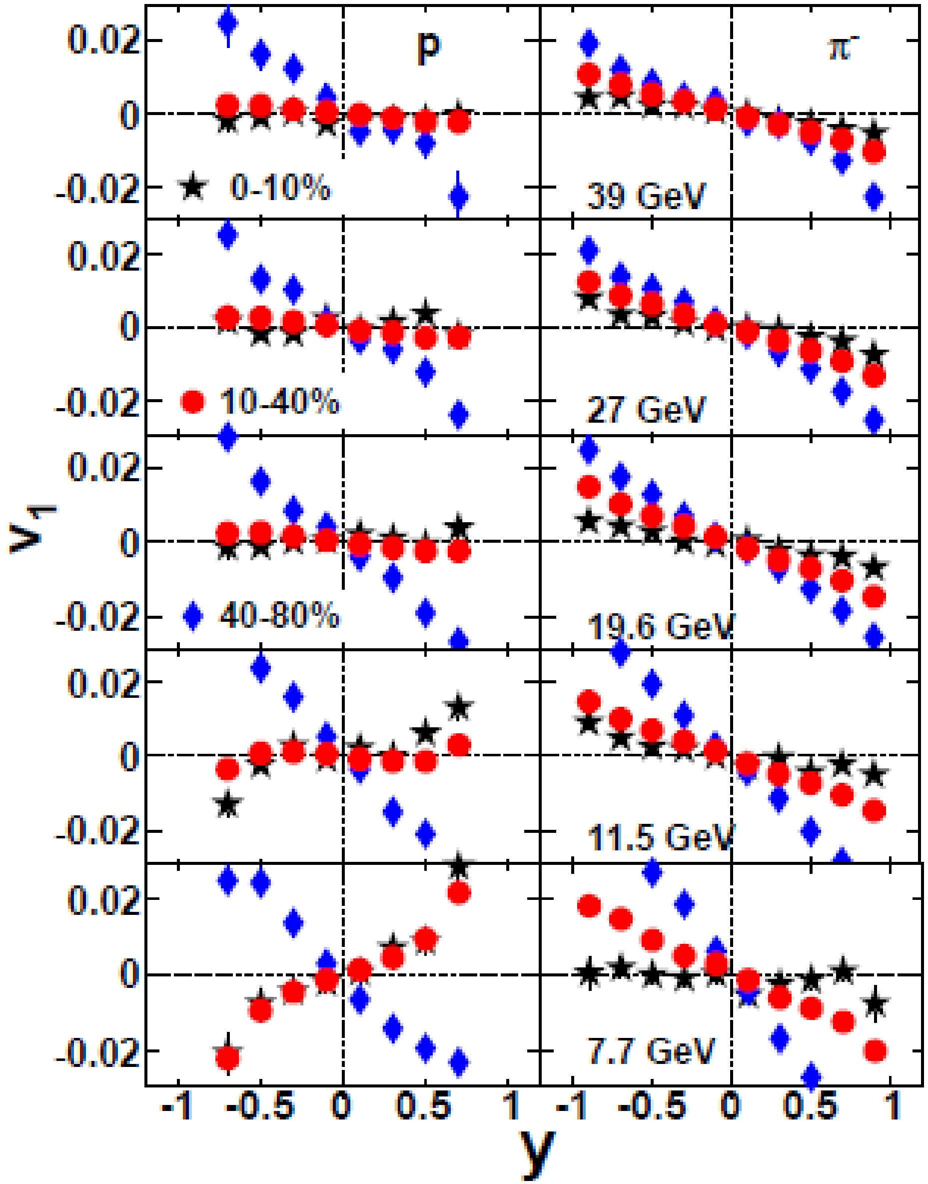


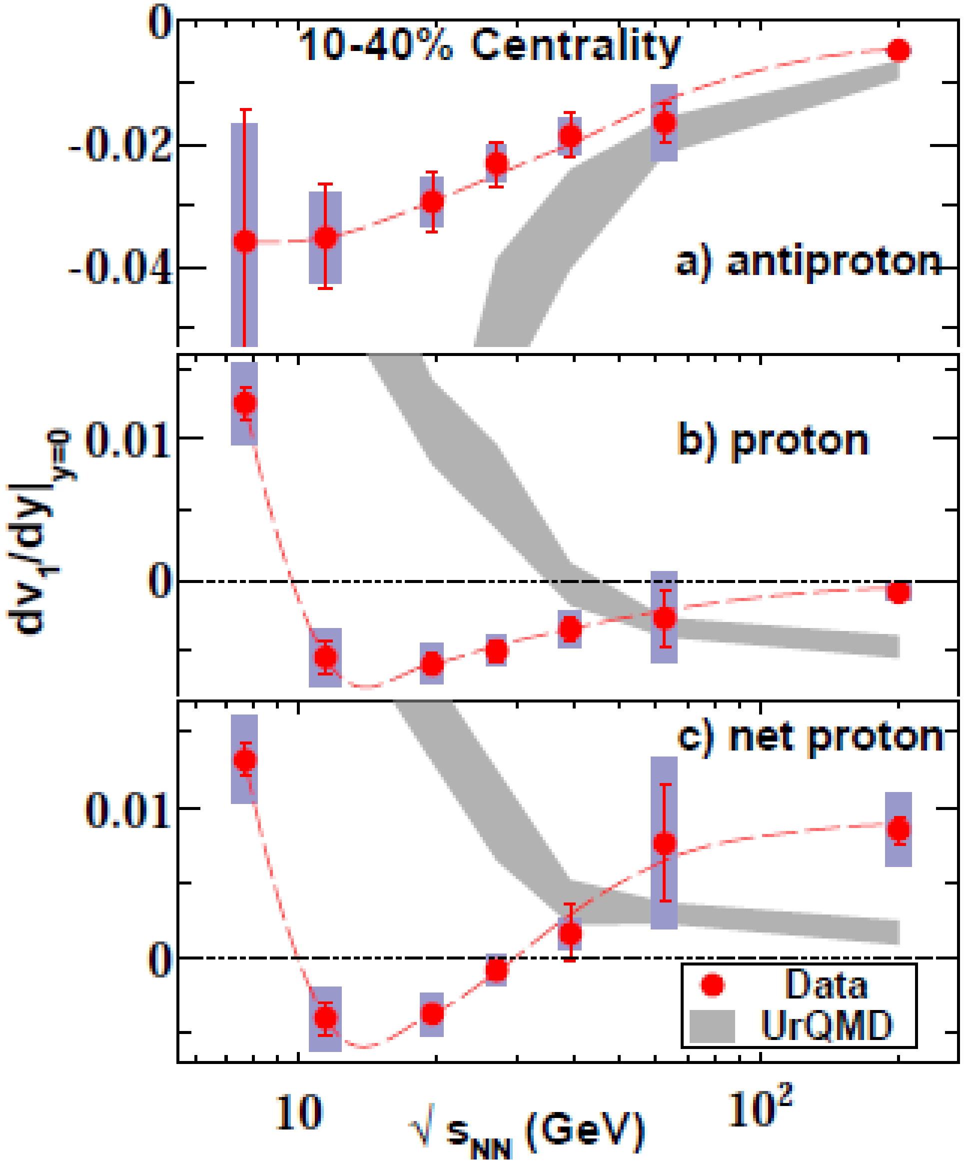
MF for N

MF for Res

Analysis dep.

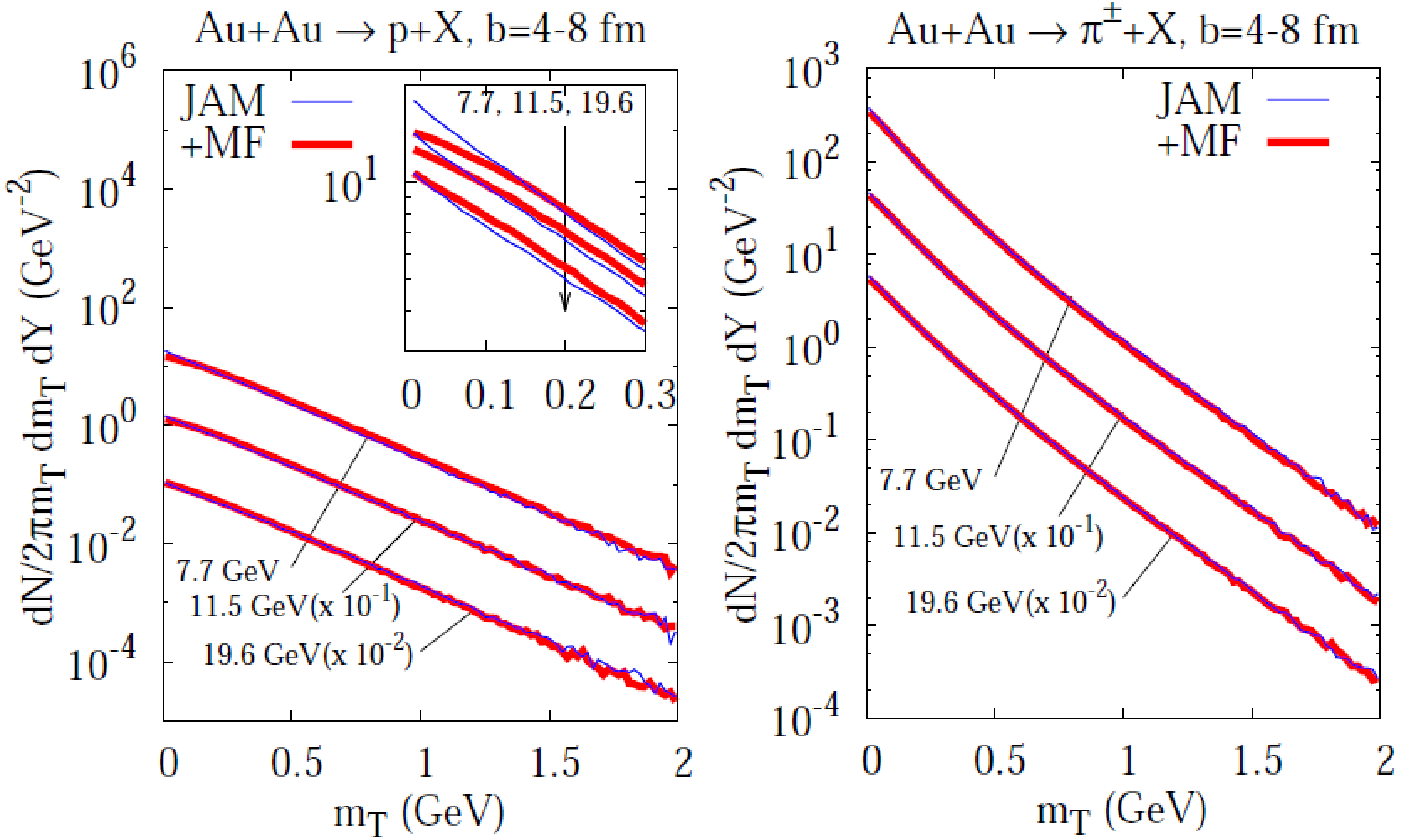
New Data from RHIC-BES





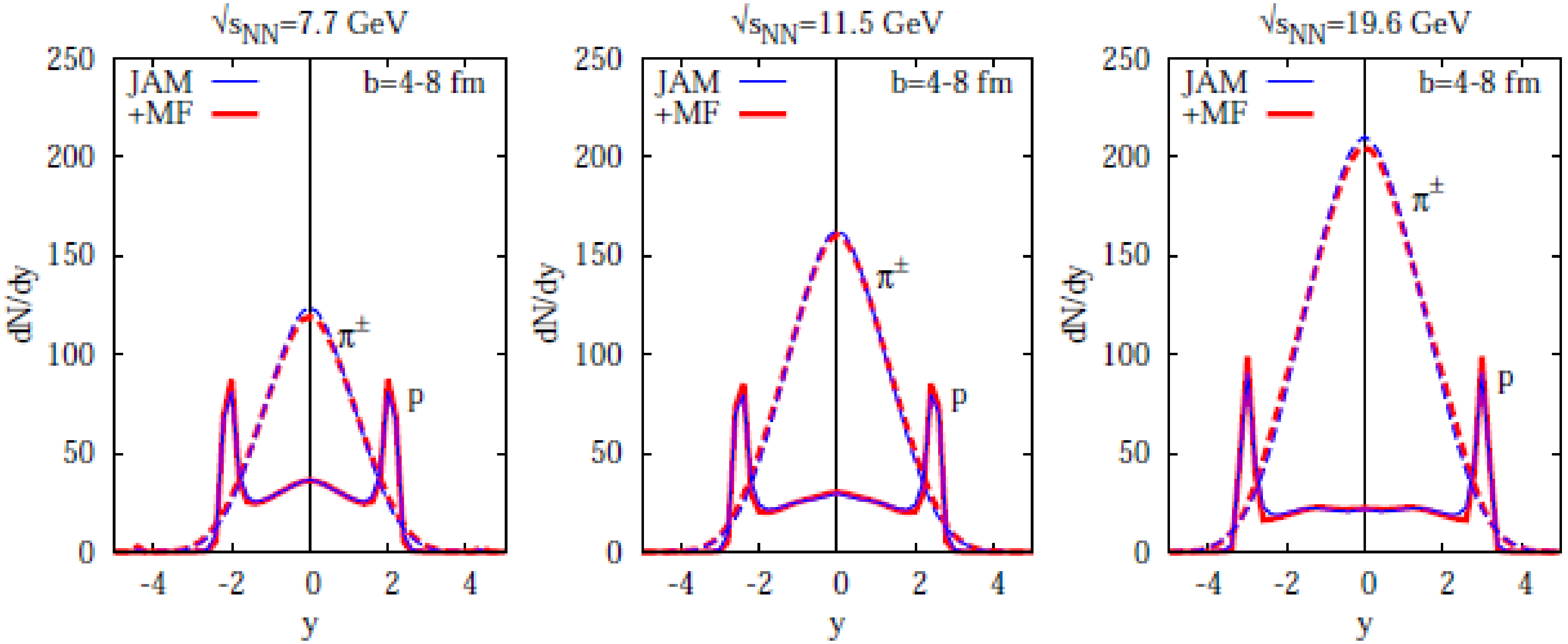
L. Adamczyk et al. (STAR Collab.), PRL 112('14)162301.

JAM Results at $\sqrt{s_{NN}}$=7.7, 11.5 and 19.6 GeV



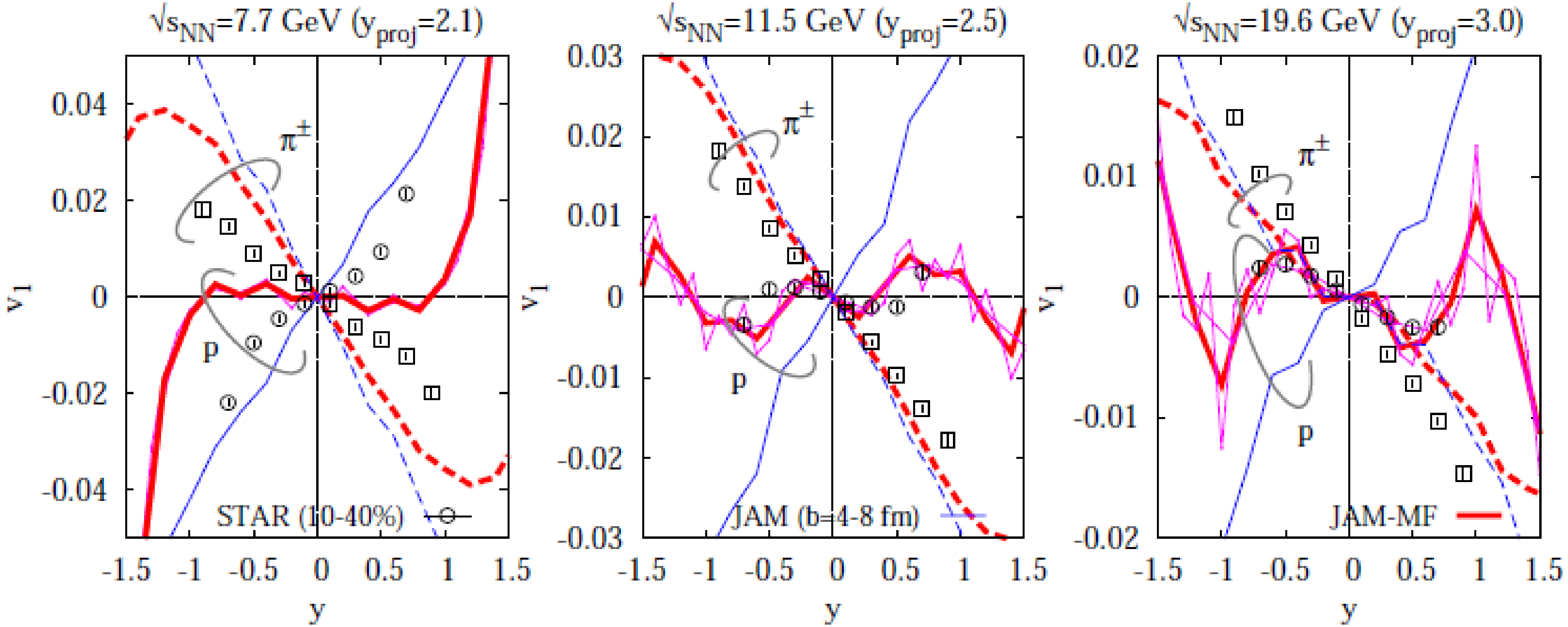
preliminary, Nara, AO, work in progress

JAM Results at $\sqrt{s_{NN}}$=7.7, 11.5 and 19.6 GeV



preliminary, Nara, AO, work in progress

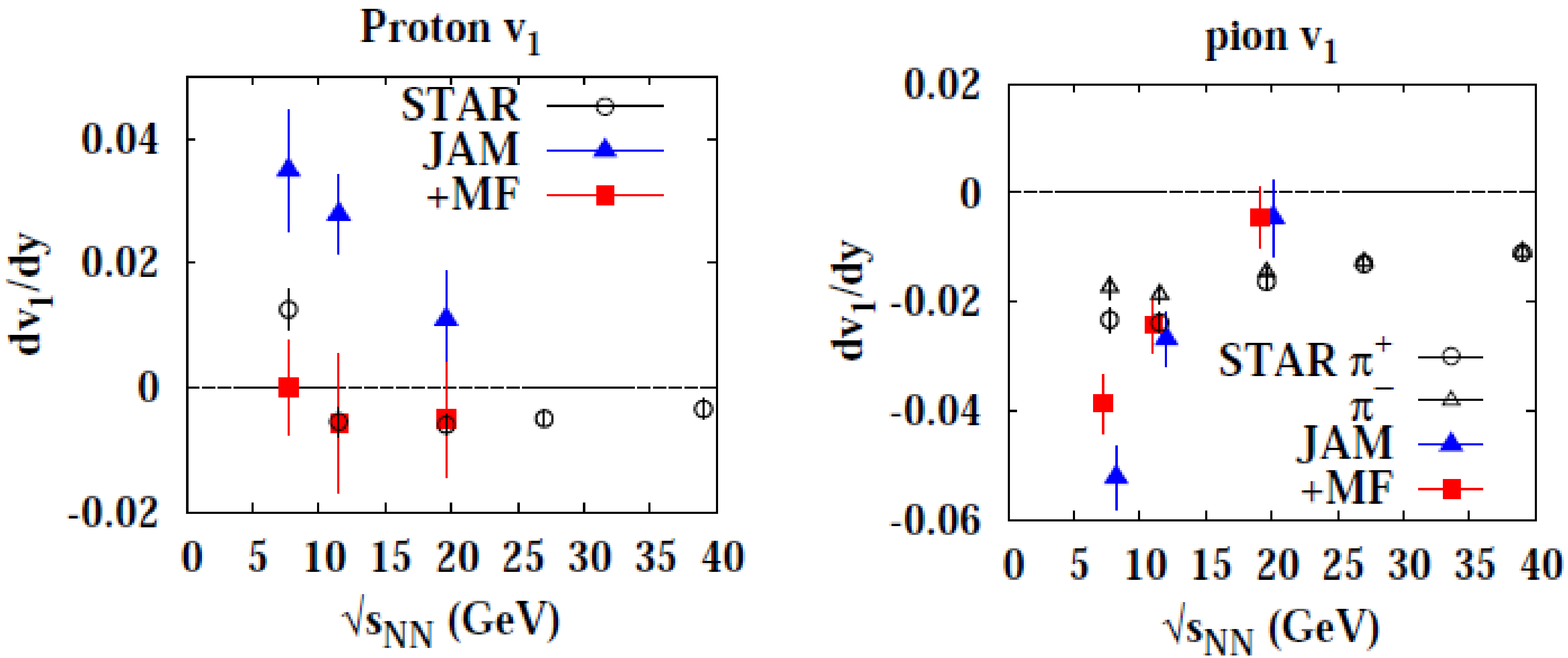
JAM Results at $\sqrt{s_{NN}}$=7.7, 11.5 and 19.6 GeV



preliminary, Nara, AO, work in progress

JAM Results at $\sqrt{s_{NN}}$=7.7, 11.5 and 19.6 GeV

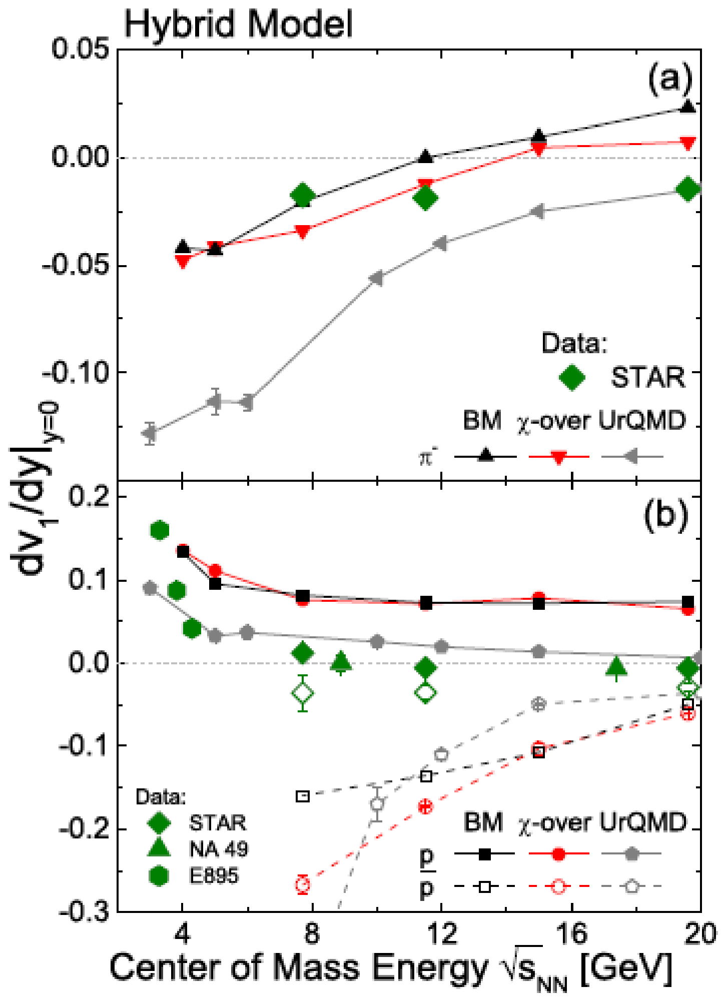
- **Incident E. dependence of dv_1/dy**
  - **proton:JAM (w/o MF) ~ UrQMD,
JAM (w/ MF) ~ STAR (underestimate at 7.7 GeV)**
  - **pion: energy dep. is too much (Note: No direct potential effects on pions.)**

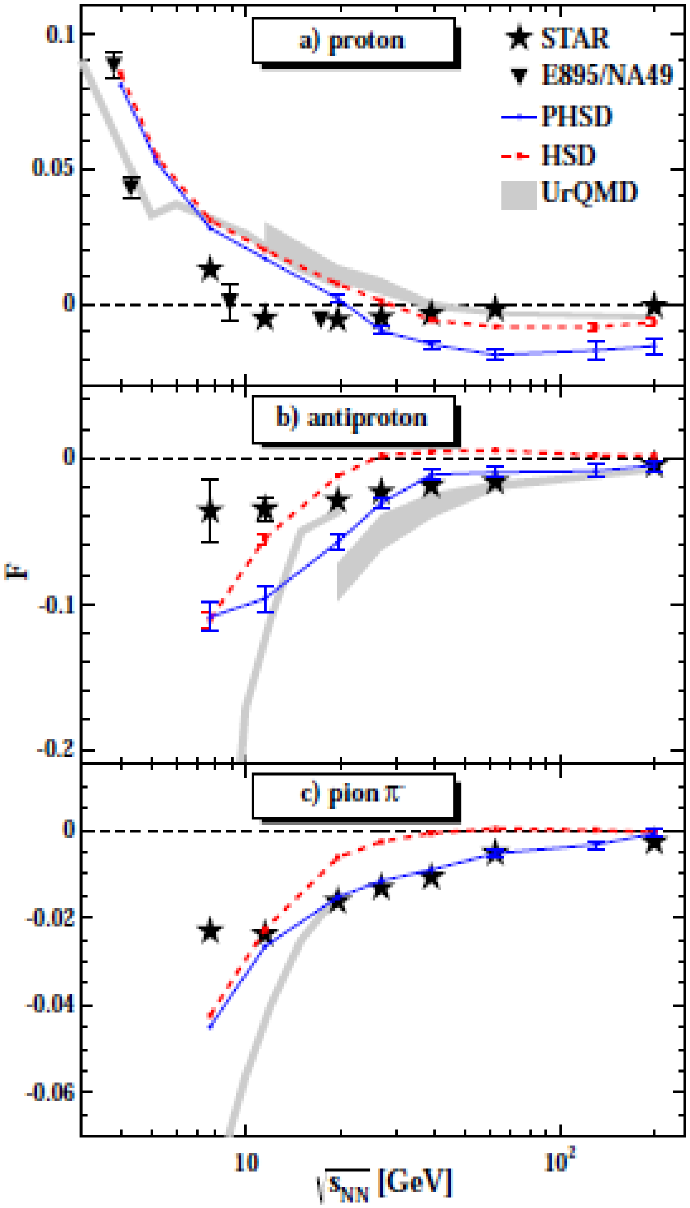


preliminary, Nara, AO, work in progress

Comparison with other approaches

- **Both Hybrid model (Frankfurt), PHSD (Giessen) show higher balance E.**





J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher, H. Stöcker, PRC89 ('14) 054913

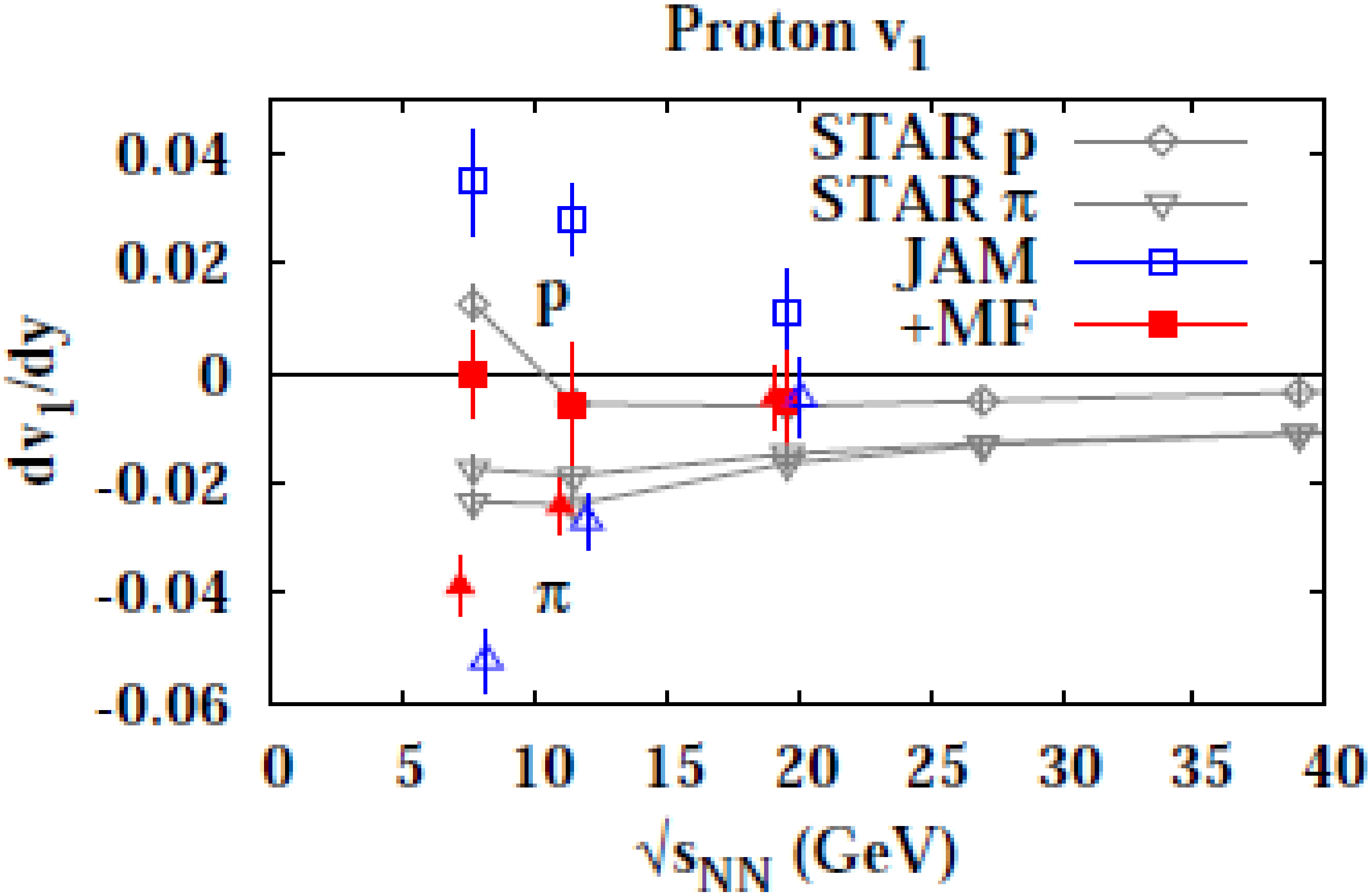
V. P. Konchakovski, W. Cassing, Yu. B. Ivanov, V. D. Toneev, PRC90('14)014903

Summary

- J-PARC energy での重イオン衝突では超高密度の物質が作られ、かつ解かれていない問題が多く残されている。
  - Horn, Step, Dale, proton # fluc., Collective flows, …
- ハドロン輸送模型により、E/A=1-158 GeV ($\sqrt{s_{NN}}$=2.5-20 GeV) における集団フローは定性的に説明される。
  - カスケード模型により、ハドロンスペクトルはほぼ説明可能。
  - v1, v2 などの集団フローは平均場に敏感である。
E/A > 300 MeV では低密度でも核子・核ポテンシャルは斥力なので、
運動量依存ポテンシャルを用いることが決定的。
  - RHIC-BES で見られる非単調な dv_1/dy は定性的 (半定量的) に説明される。(Isse et al. (2005) のプログラムをそのまま利用)
- To do
  - 素過程断面積の改善、π, Δ, N*, K, Y… への平均場効果、quark-gluon 自由度の導入、(viscous)hydro との結合、...
  - 興味のある方はやってみませんか？

Thank you for your attention.

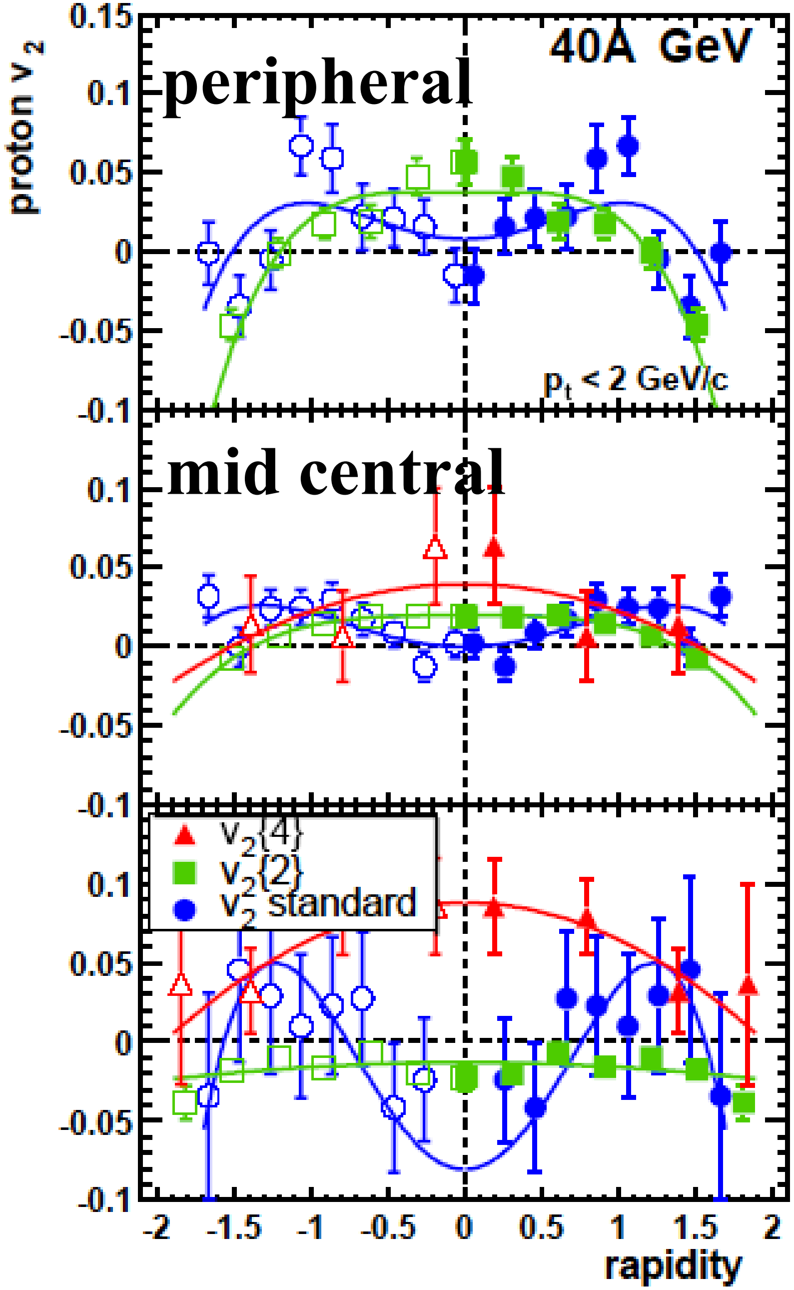
JAM Results at $\sqrt{s_{NN}}$=7.7, 11.5 and 19.6 GeV



Nara, AO, work in progress

Dip of V_2 at 40 A GeV: Phase Transition ?

- Dip of V_2 at 40 A GeV may be a signal of QCD phase transition at high baryon density.
  (Cassing et al.)
- However, the data is too sensitive to the way of the analysis (reaction plane/two particle correlation).
  - We have to wait for better data.



Flow and EOS; to be continued

- **In addition to the ambiguities in in-medium cross sections, Res.-Res. cross sections, we have model dependence.**
  - **RBUU** *(e.g. Sahu, Cassing, Mosel, AO, Nucl. Phys. A672 (2000), 376.)*
    - **In RMF, Strong cut-off for meson-N coupling in RMF → Smaller EOS dep.**
  - **Scalar potential interpretation in BUU** *Larionov,Cassing,Greiner,Mosel, PRC62,064611('00), Danielewicz, NPA673,375('00)*

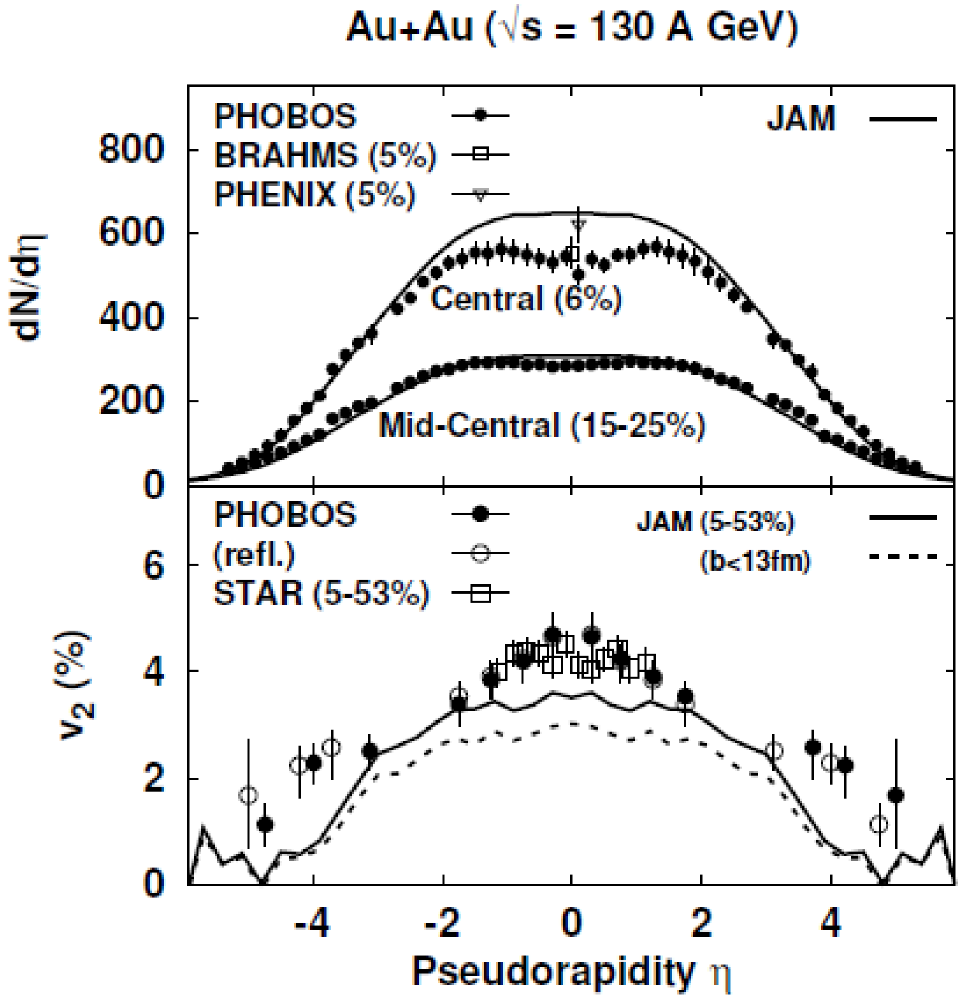
$$\varepsilon(\boldsymbol{p},\rho)=\sqrt{[m+U_s(\boldsymbol{p},\rho)]^2+\boldsymbol{p}^2} \quad =\sqrt{m^2+\boldsymbol{p}^2}+U(\boldsymbol{p},\rho)$$

    - **Due to the Scalar potential nature, EOS dependence is smaller.**
  - **Scalar/Vector Combination** *Danielewicz, Lacey, Lynch, Science 298('02), 1592*

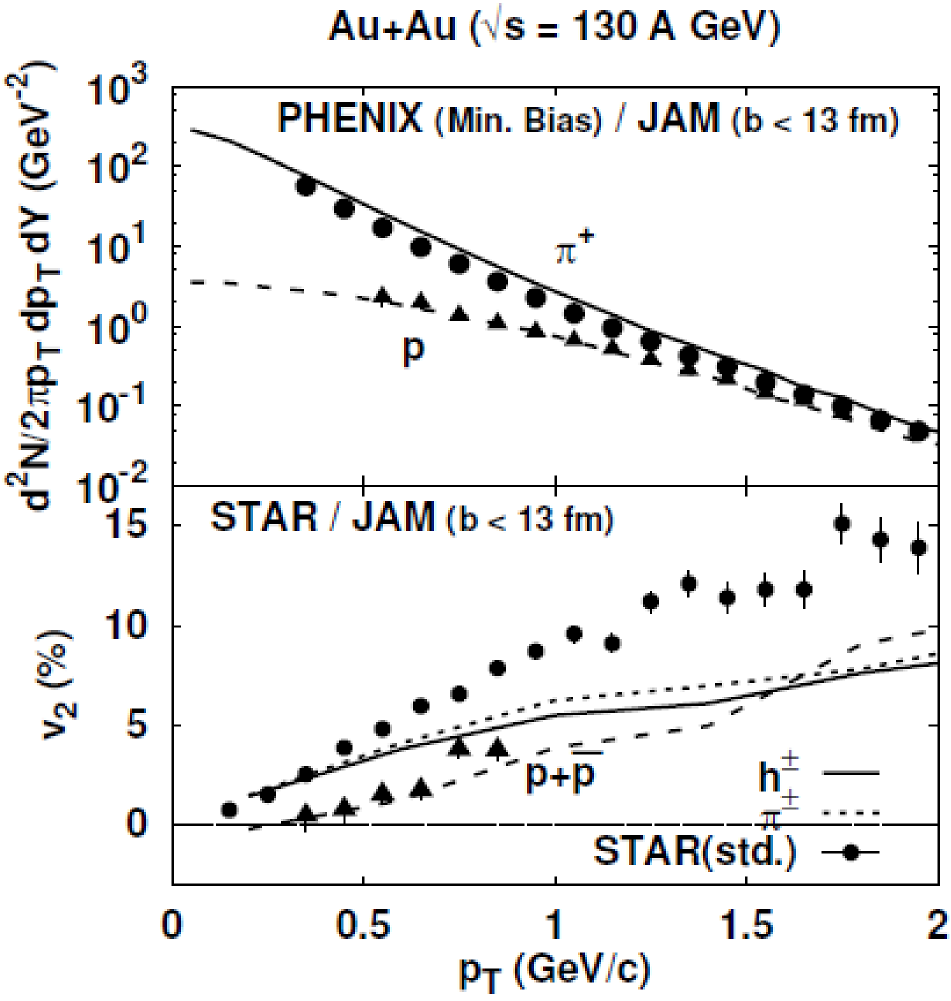
$$\varepsilon(p,\rho)=m+\int_0^p dp' v^*(p',\rho)+\tilde{U}(\rho), \quad v^*(p,\rho)=\frac{p}{\sqrt{p^2+[m^*(p,\rho)]^2}}.$$

    - **Relatively Strong EOS dependence even at high energy**
  - **JAM-RQMD/S** *Isse, AO, Otuka, Sahu, Nara, PRC 72 (2005), 064908*
    - **Similar to the Scalar model BUU**

JAM at RHIC



Au+Au ($\sqrt{s}$ = 130 A GeV)



Au+Au ($\sqrt{s}$ = 130 A GeV)

Sahu, AO, Isse, Otuka, Phatak (2006)