Sep.30-Oct.04, 2002 @ PANIC02

Systematic Study of Radial and Elliptic Flows in High-Energy Heavy-Ion Collisions

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Our Refs.

- Y. Nara, N. Otuka, A. Ohnishi, T. Maruyama, Prog. Theor. Phys. Suppl. 129 (1997) 33.
- Y. Nara, N. Otuka, A. Ohnishi, K. Niita, S. Chiba, Phys. Rev. C **61** (2000), 024901. (JAM)
- P. K. Sahu, W. Cassing, U. Mosel and A. Ohnishi, Nucl. Phys. **A672** (2000), 376. (RBUU, Flow)
- N. Otuka, P.K. Sahu, M. Isse, Y. Nara and A. Ohnishi, nucl-th/0102051 (RHIC, radial flow)
- P.K. Sahu, N. Otuka, N. Ohnishi, Pramana-J. Phys., in press; nucl-th/0206010 (RHIC, v2)

Contents

⋆ Hydrodynamical Signals of QGP at RHIC

- Proposed and Observed Signals of QGP

  ⋆ Anomalous J/ψ supression: Uncertain $\sigma(hh)$

  ⋆ Strangeness Enhancement: Uncertain $\sigma(hh)$

  ⋆ Low-E Dilepton Enh.: Partial Chiral Restoration

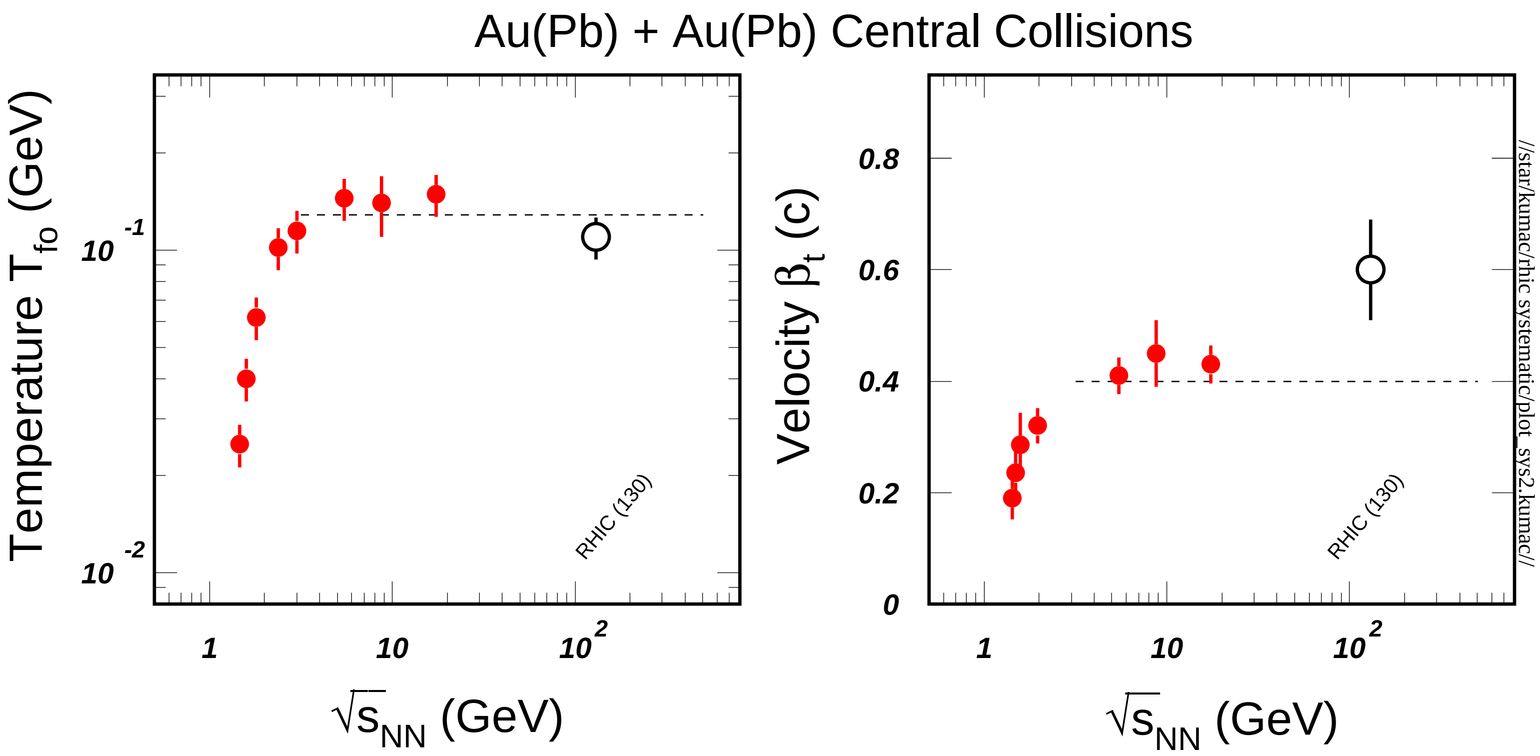
  ⋆ Softening of particle spectra: Hagedorn Gas

  ⋆ Jet Energy Loss: Dense Partonic Gas (not fixed yet ?)

☞ Clear Bulk/Hydrodynamical Signal is desired.
$\rightarrow$ Strong Radial and Elliptic Flows at RHIC

- Observed "Re-Hardening" Signature

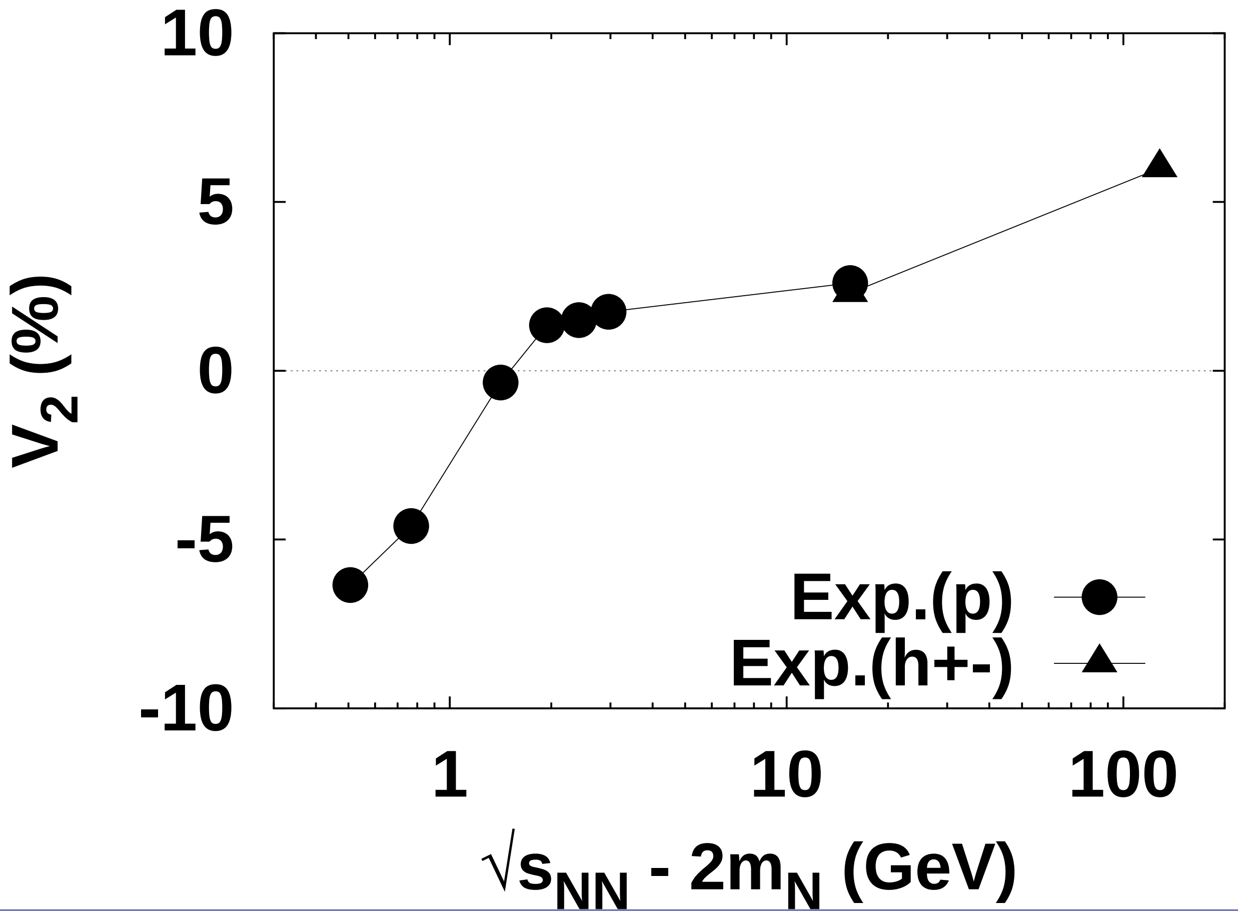
Nu Xu and M. Kaneta, NPA698(2002),306; nucl-ex/0104021



Strong Radial Flow Appears at RHIC !

- <u>Strong Elliptic Flow</u>

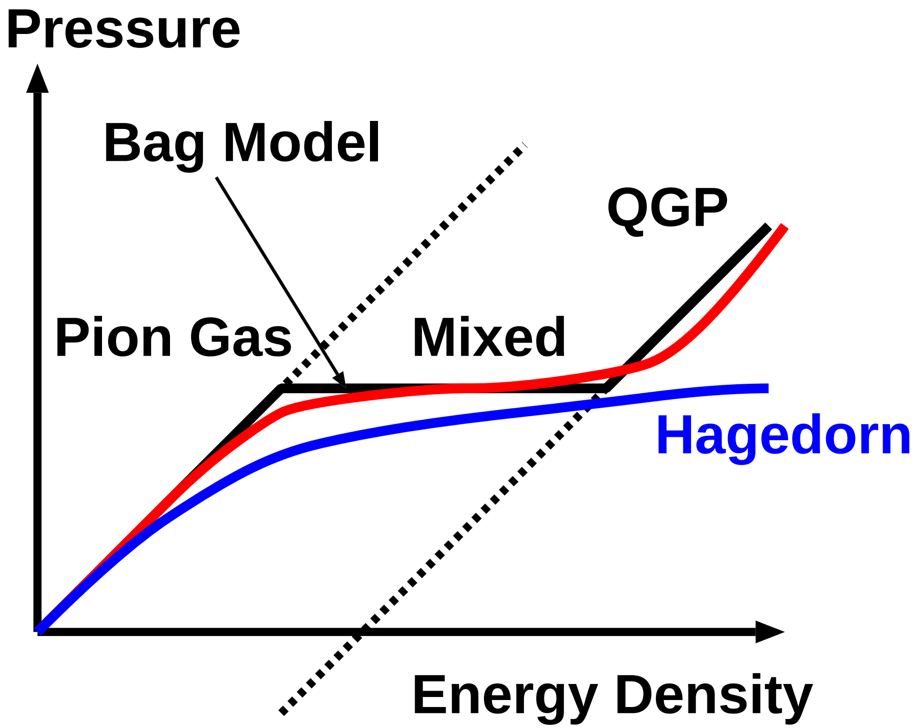
EOS,E895,E877,NA49,STAR



☞ Elliptic Flow Also Grows between SPS and RHIC Rapidly

→ Do These Strong Flows really signal QGP ?

- Naive Expectations



If QGP is formed,

⋆ Pressure is expected to Grow Again (Bag Model).
$\rightarrow$ Larger Radial Flow

⋆ Thermalization Time would be Much Shorter
(Free from Hadronic Formation Time, $\tau \sim 1$ fm/c).
$\rightarrow$ Larger Elliptic Flow

In this work,

- ⋆ We analyze radial and elliptic flows from SIS to RHIC energies systematically in a realistic dynamical hadron-string cascade model including mini-jet production (JAM).
- ⋆ We will show that Hadron Rapidity and m_T Spectra are well explained EXCEPT for very stiff proton and anti-proton m_T spectra at RHIC,
- ⋆ and that Elliptic Flows are in the Range of Hadron-String Cascade when Mean Field Effects are included up to SPS energies, but we CANNOT explain Strong Elliptic Flow at MID-RAPIDITIES in RHIC.

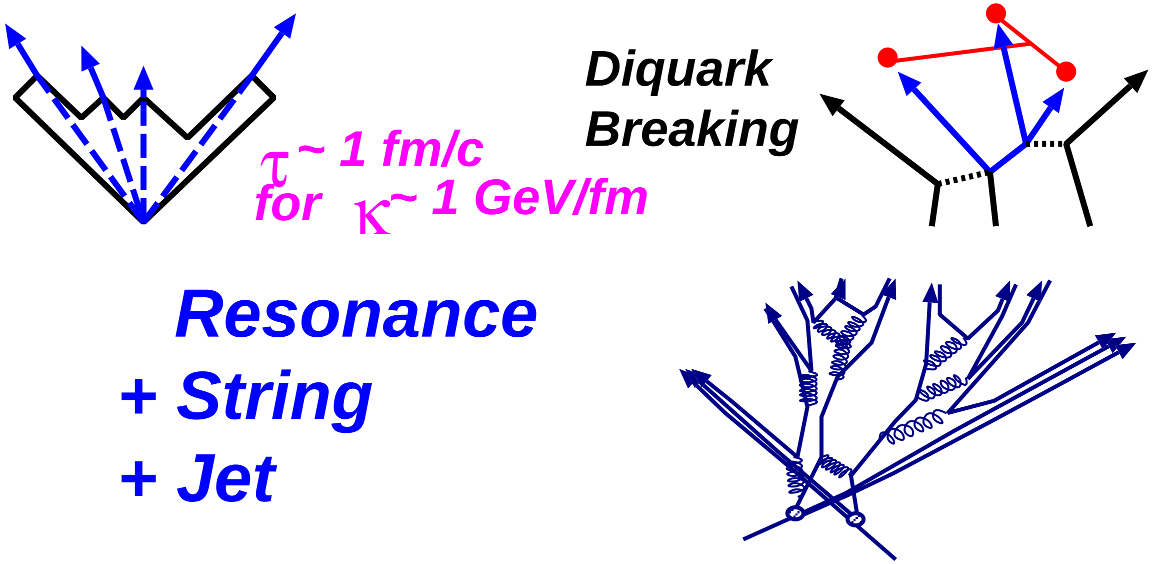
⋆ Hadron-String Cascade Model from SIS to RHIC

JAM (Jet Aa Microscopic transport model)

Y. Nara et al., PRC61('00), 024901.

DOF: h(B, B*, M, M* (m $\leq$ 2 GeV)) + s(Strings) + Mini-Jet Partons

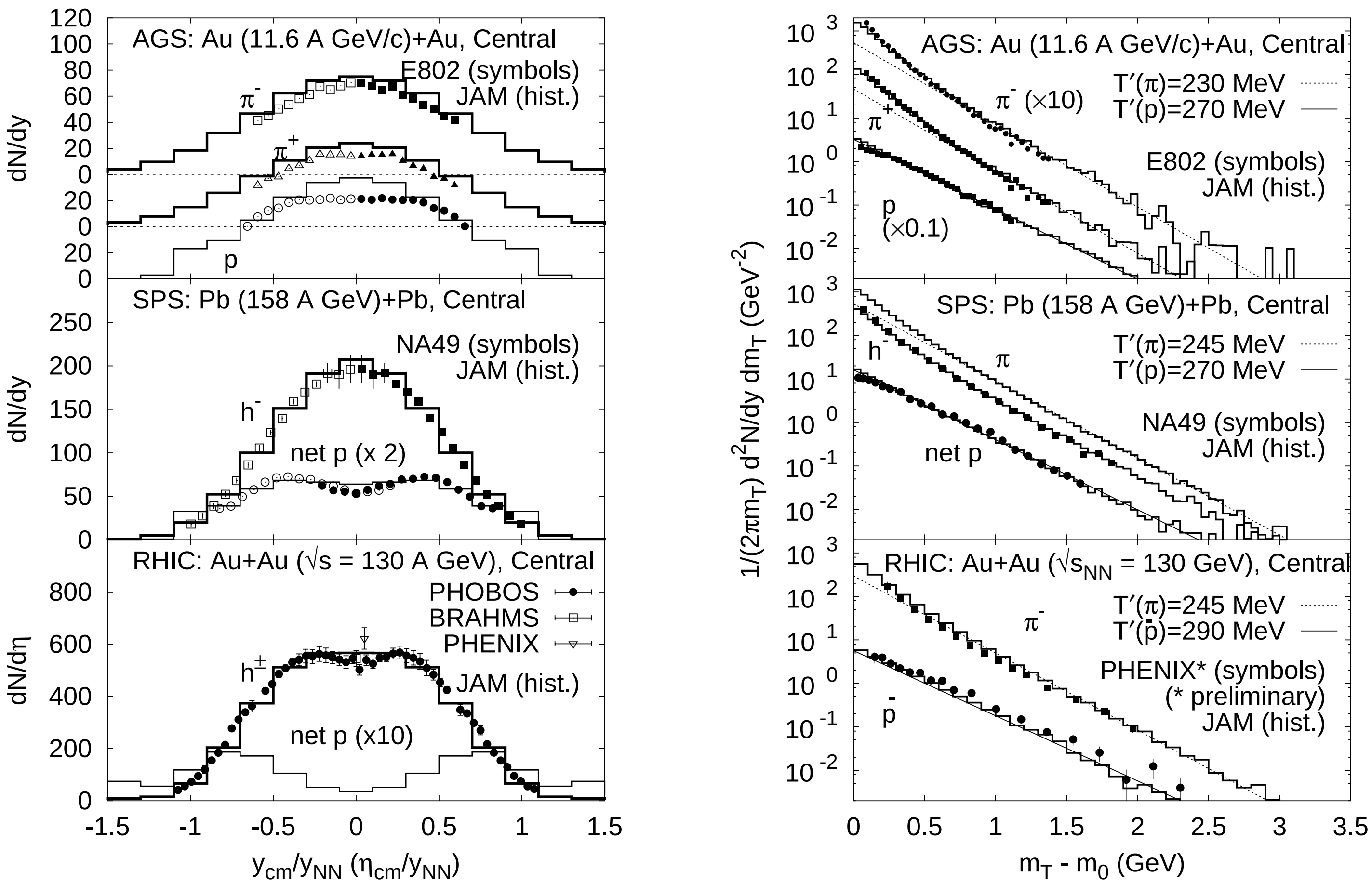
σ: Hadronic ($hh \leftrightarrow hh$, $hh \leftrightarrow h$) + Soft [1,2] + Hard [3]



[1] "DPM + Lund" (∼ HIJING) + Phase Space ($hh \leftrightarrow s$, $hh \rightarrow hs$, $hh \rightarrow ss$, $s \rightarrow hhh$...)
[2] Consituent Rescattering (∼ RQMD)
(c= (qq), q, q̄ $ch \leftrightarrow ch$, $ch \rightarrow cs$ (c= (qq), q, q̄))
[3] Jetset: Pythia (Mini-Jet Production)

⋆ Hadronic Spectra from SIS to RHIC

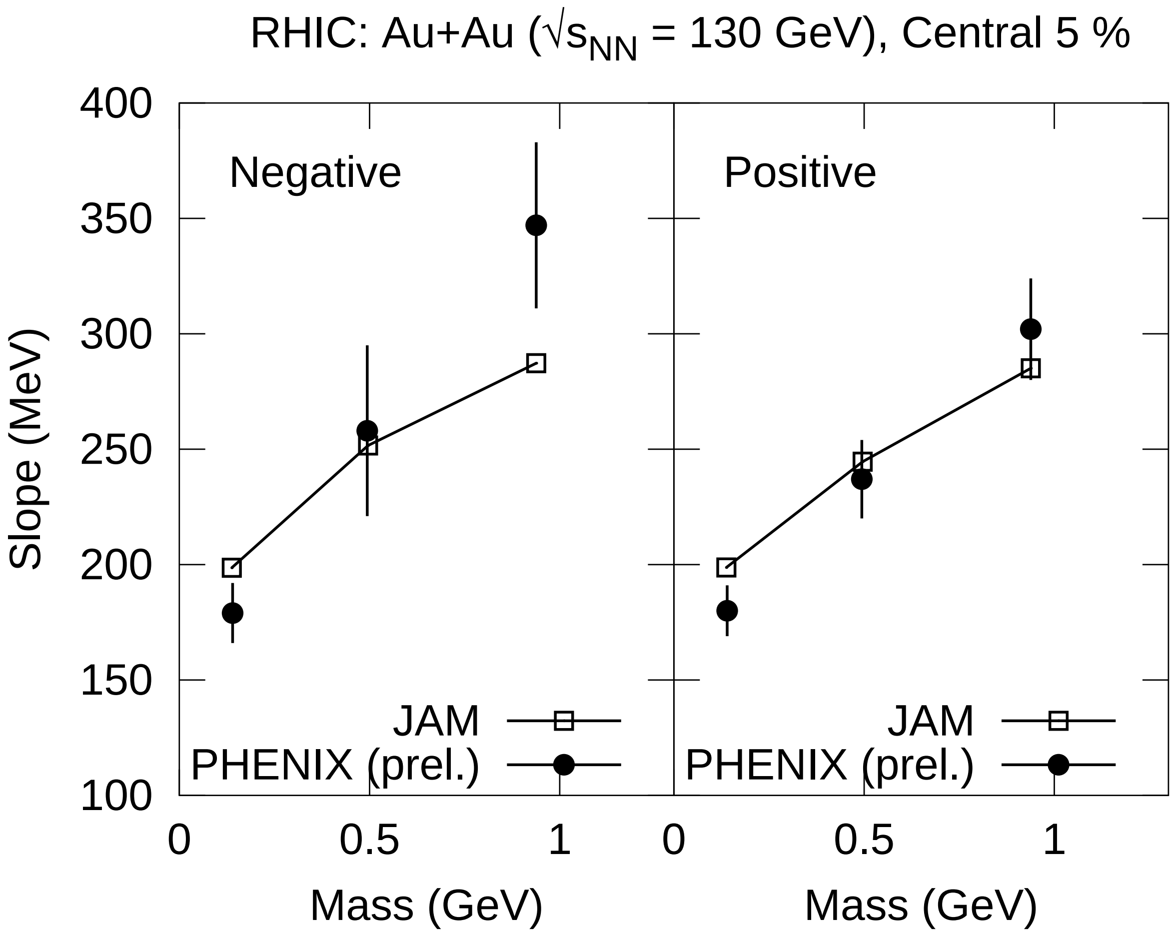
- Rapidity and m_T Distributions (N. Otuka et al. nucl-th/0102051)



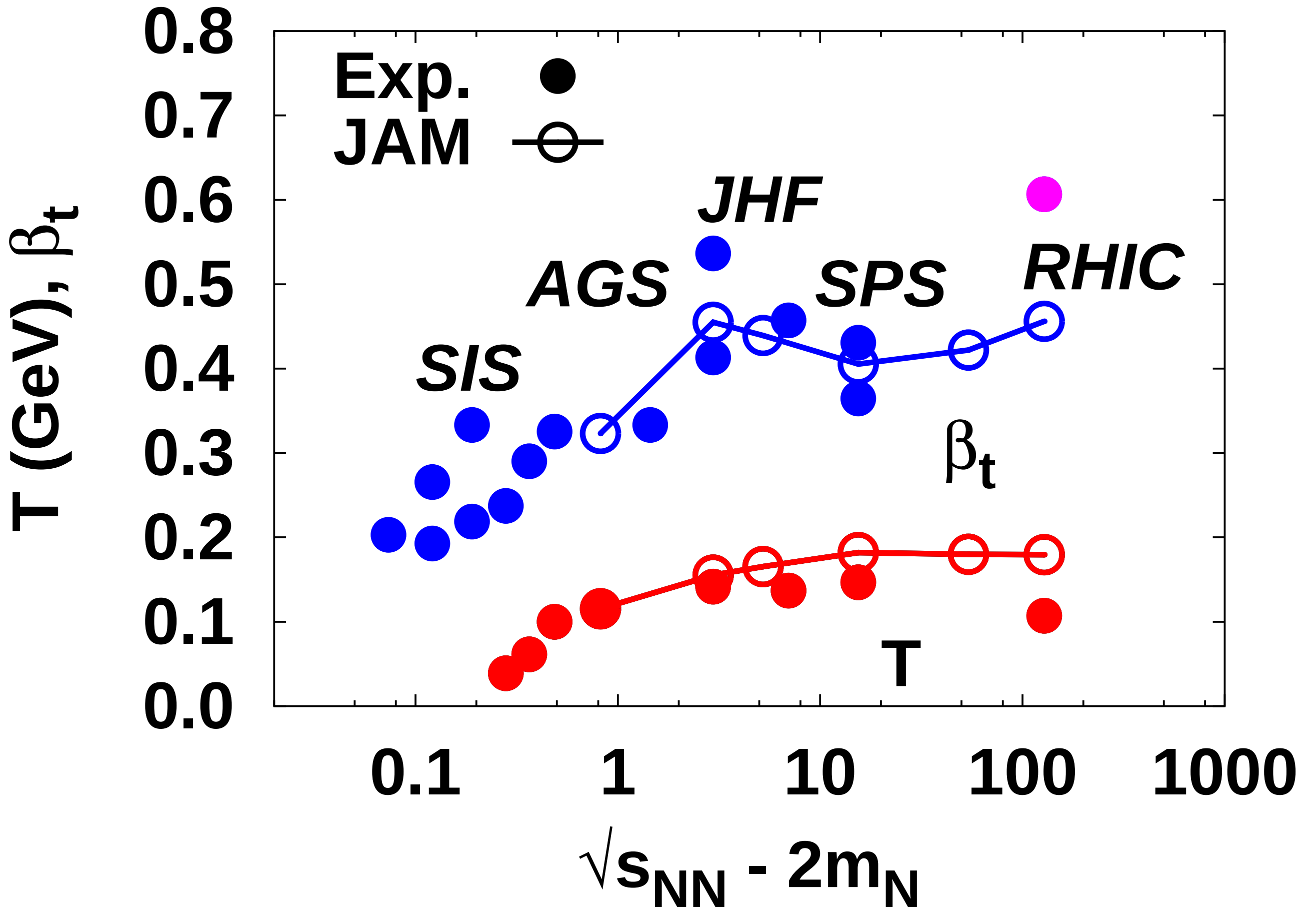
☞ Good EXCEPT FOR anti-proton (and proton) m_T spectra at RHIC

- Decomposition to T and β

$$\frac{d^2N}{M_t dM_t dY d\phi} \propto \exp(-M_t/T'), \qquad T'(M) = T + \frac{1}{2} M\,\beta^2$$



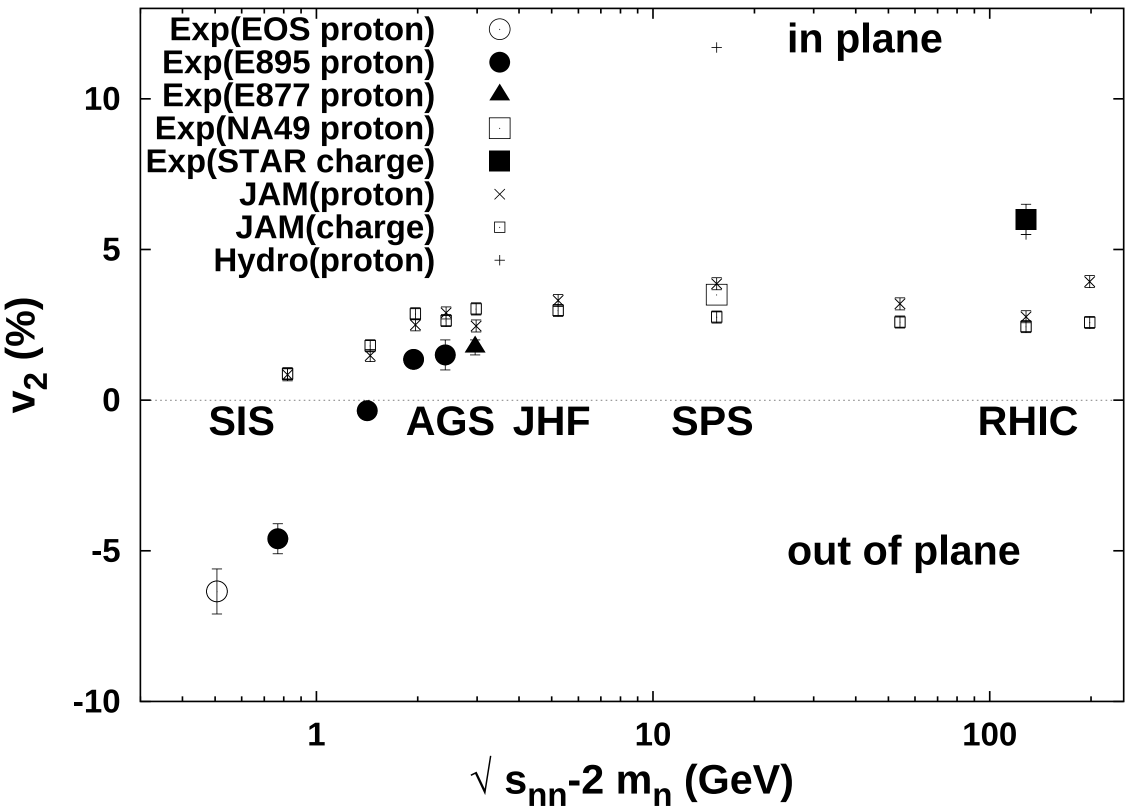
- Temperature and Radial Flow from SIS to RHIC



Re-Hardening in JAM is Too WEAK.

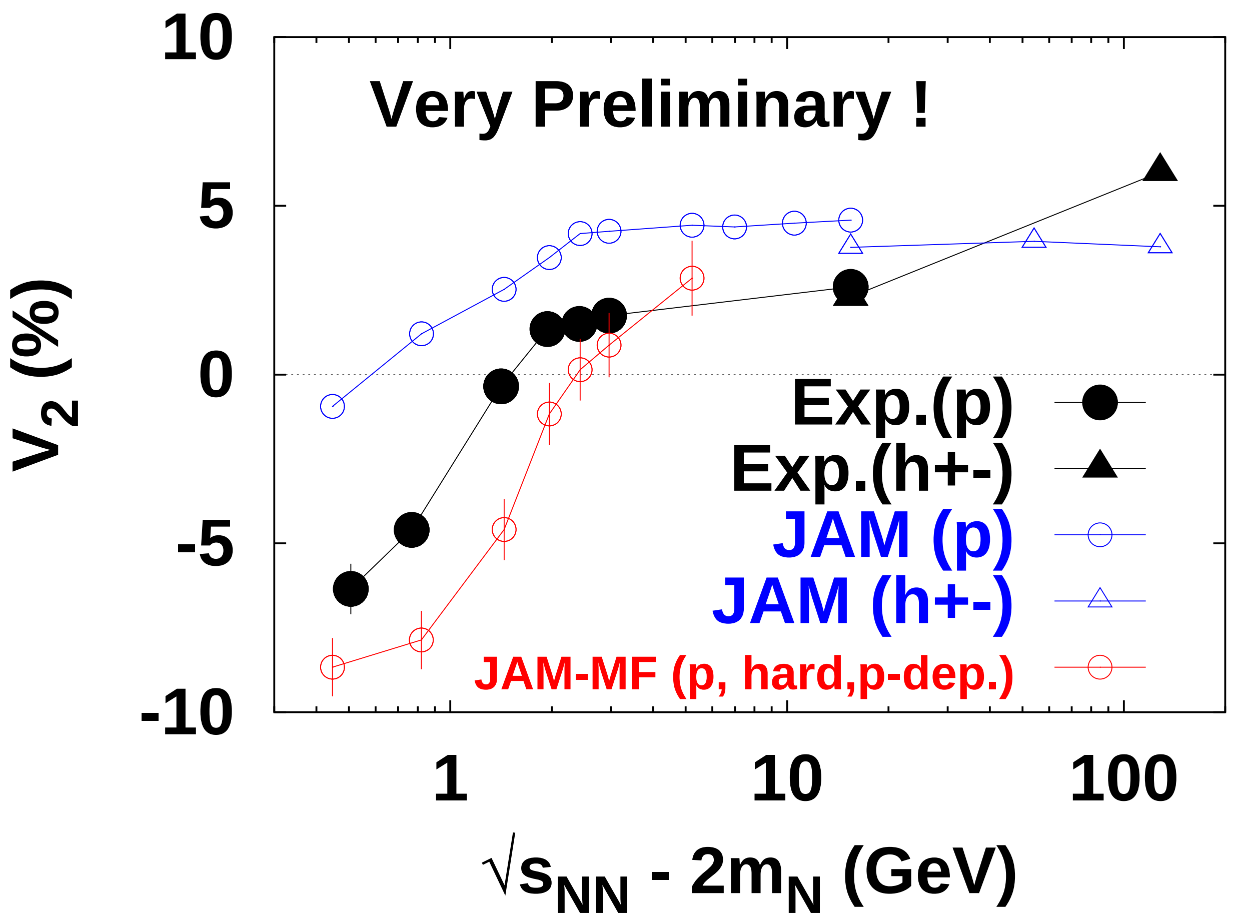
⋆ Elliptic Flow from SIS to RHIC

- Incident Energy Dependence (P.K.Sahu et al., nucl-th/0206010)



☞ Larger than Data up to SPS → Mean Field Effects ?

- Mean Field Effects (M. Isse et al.)

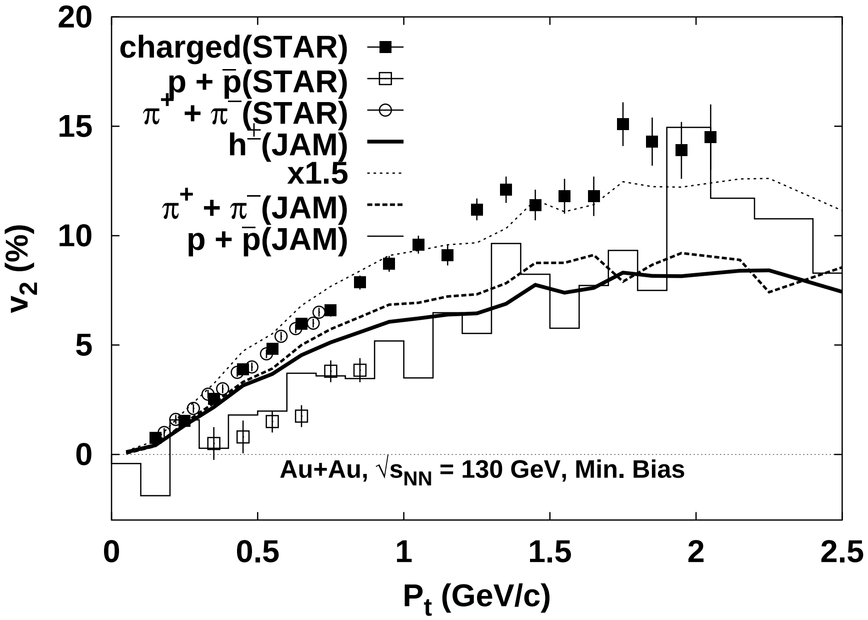


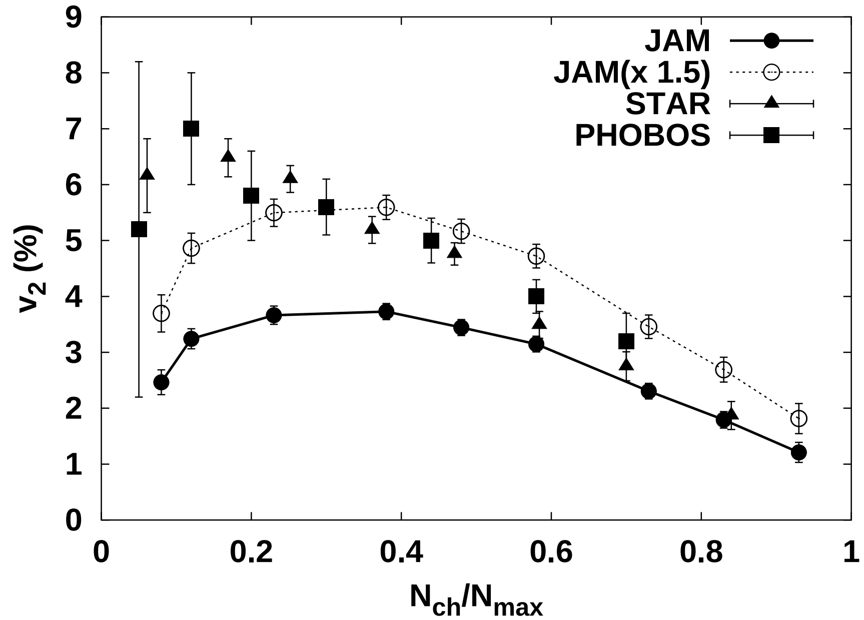
(* Stronger P_t are introduced)

☞ Mean Field Shifts V_2 Downwards

→ Upward Shift at RHIC cannot be explained by Hadronic Mean Field

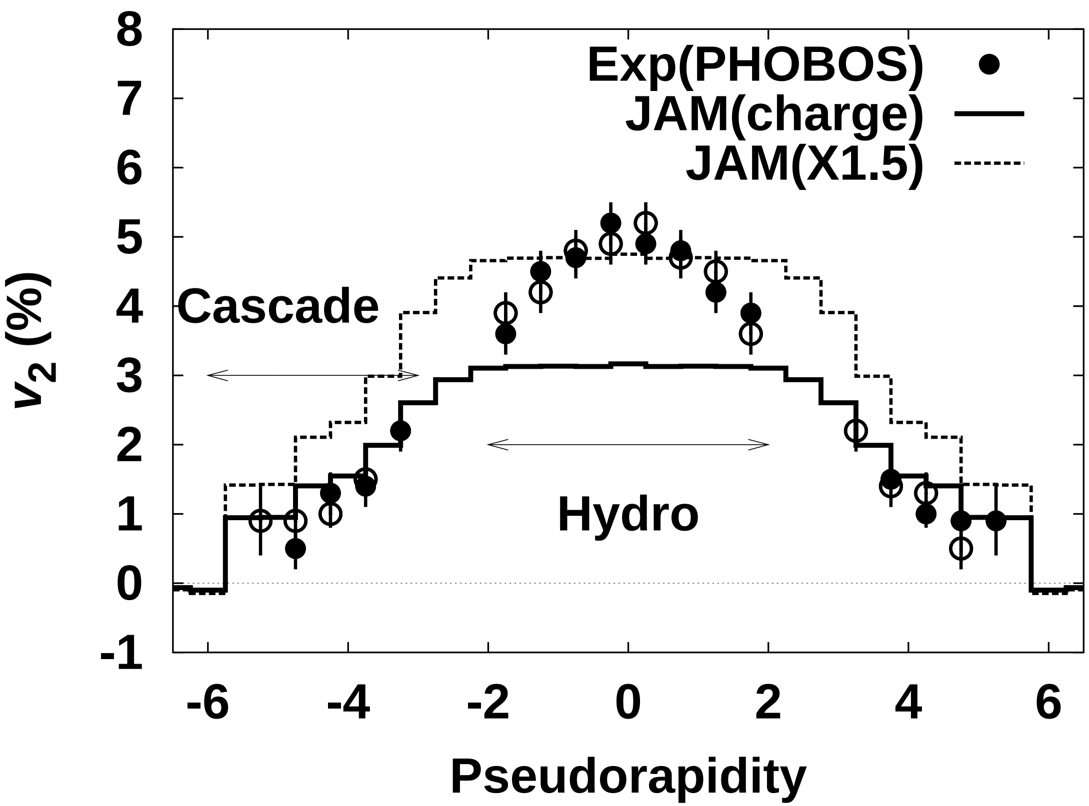
- P_T and Impact Parameter Dependence (P.K.Sahu et al., nucl-th/0206010)





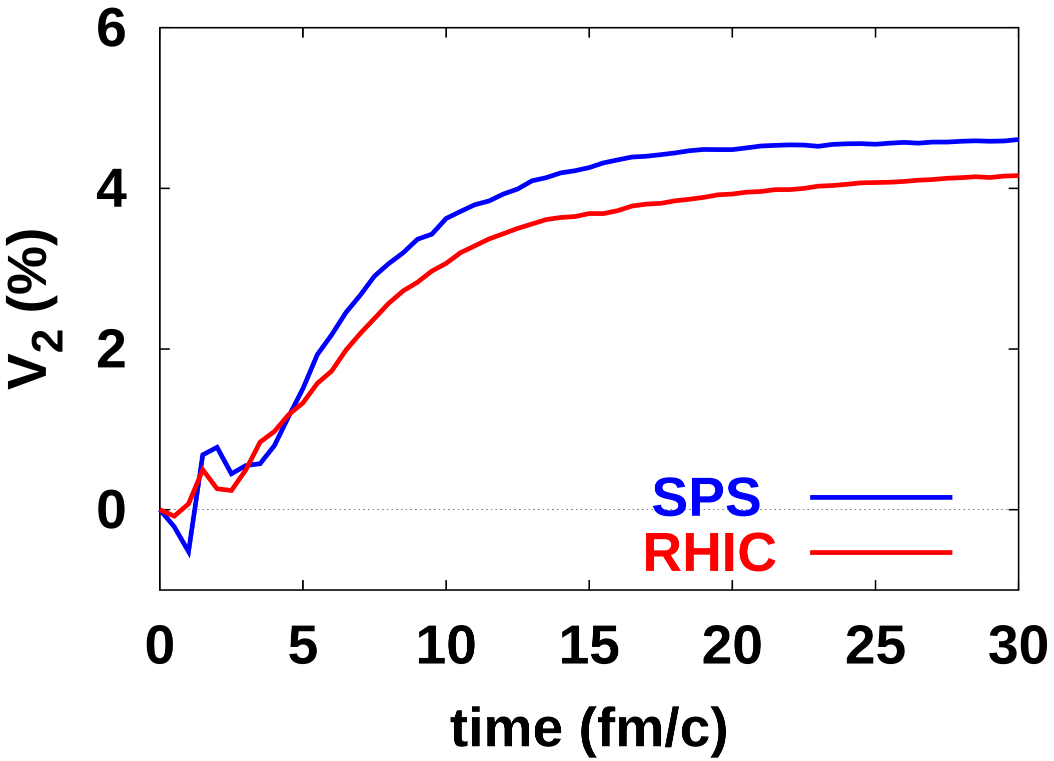
• Where Do We Underestimate V_2 ? : Pseudo-Rapidity Dependence

(P.K.Sahu et al., nucl-th/0206010)



☞ MID-RAPIDITY V_2 is Underestimated !

- Why Do We Underestimate V_2 ? : Time Dependence



In Hadron-String Scenario,
Formation Time and Interaction Suppression before String Decay
Make V_2 to Grow Later !
$\rightarrow$ Almond Shape is Already Obscured due to Large γ !

⋆ Summary

- ⋆ RHIC data show
  RE-HARDENING and EARLY THERMALIZATION
  at mid-rapidities.
- ⋆ Hadron-String Gas
  CANNOT BE STIFFER again
  at Higher Energy Densities.
  (Reduction of Repul. Int./Increase of Hadronic DOFs)
- ⋆ In Hadron-String Scenario,
  - ◦ Re-Hardening Signature is TOO WEAK,
  - ◦ and Thermalization is TOO SLOW,
- ⋆ The above observations suggest the necessity of
  Extra Pressure Generation in the Early Stage of Collisions
  such as that from QGP formation at mid-rapidities for RHIC.
- ⋆ Several Theoretical Supports
  - ◦ Success of Hydrodynamical description of V_2 at mid-rapidities
    (Hirano PRC65(2001)011901; P.F. Kolb et al., NPA696(2001)175.)
  - ◦ AMPT: Partonization of Strings + Parton Cascade

⋆ Problems to be solved

- ∘ Multiple Scattering Scheme
- ∘ Partonization: Initial Condition
- ∘ Hadronization $\cdots$ String/Parton Coalescence
- ∘ Parton Cascade incl. Inelastic Scattering