重イオン反応における集団運動流
--- AGS から RHIC まで ---

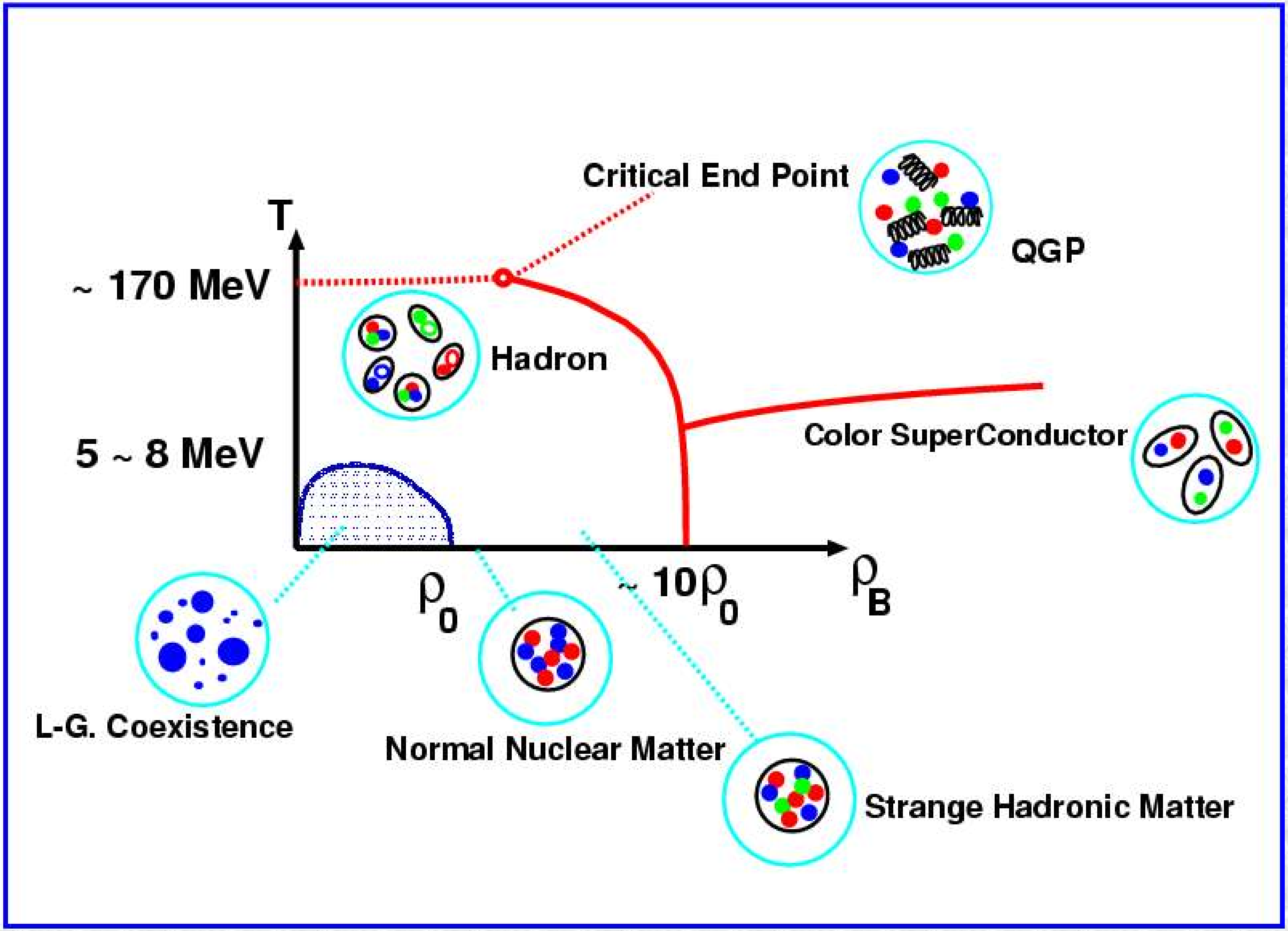
北海道大学・大学院理学研究科　大西　明

Contents

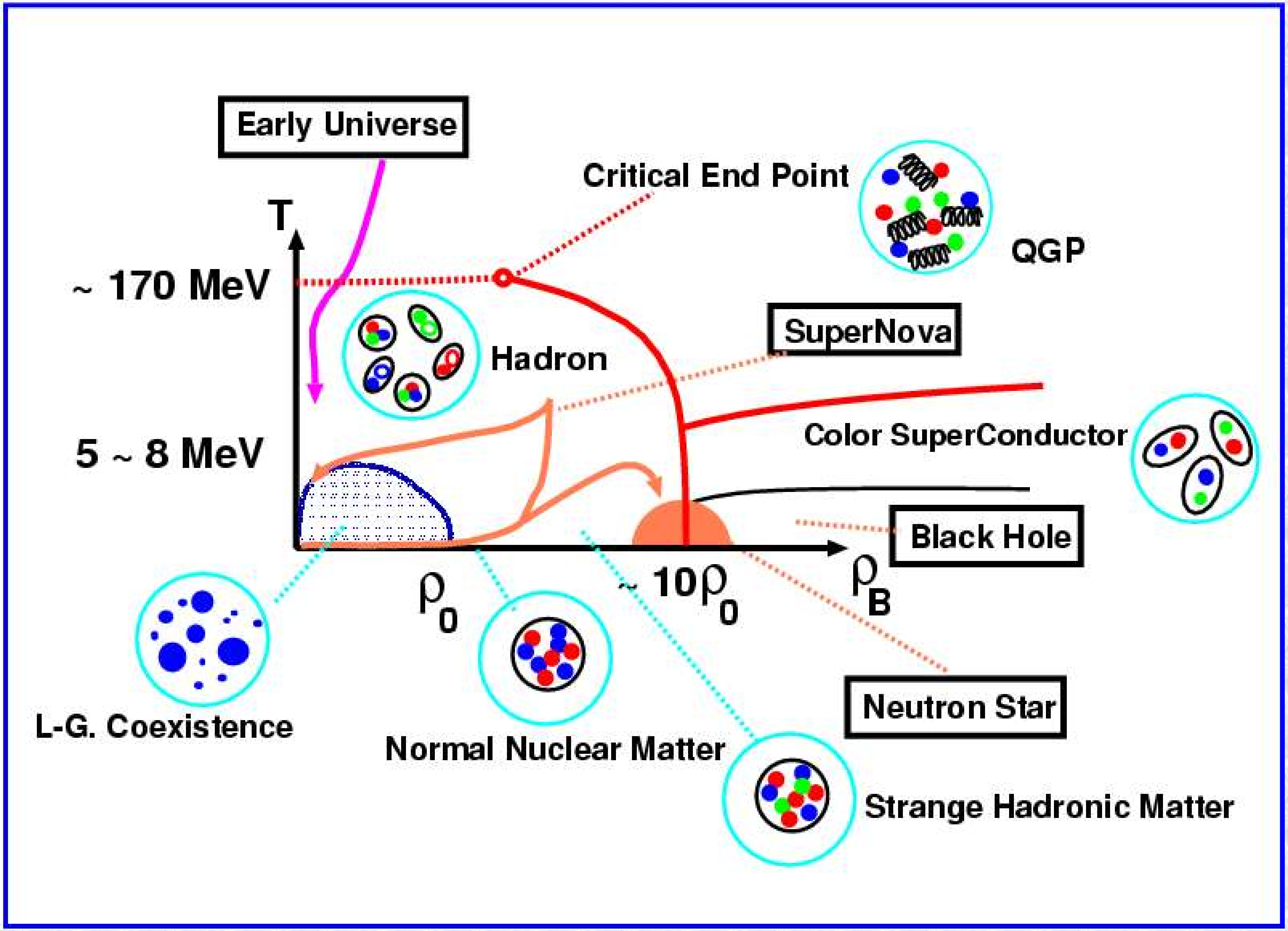
1. Introduction
   - Physics of High Temperature Matter
   - Nuclear / Hadronic Matter Phase Diagram
   - How Much do we understand ?
2. Collective Flows
   - Two Facets of Flow: EOS probe and QGP signal
3. Hadronic Models Study of Collective Flows from AGS to RHIC
   - Relativistic QMD, Simplified (RQMD/S)
   - Hadronic Cascade: JAM
   - AGS and SPS Energies: Success of Hadronic Description
   - RHIC Energy: Failure of Hadronic Model
   - Where does QGP formation start ?
4. Summary

Introduction

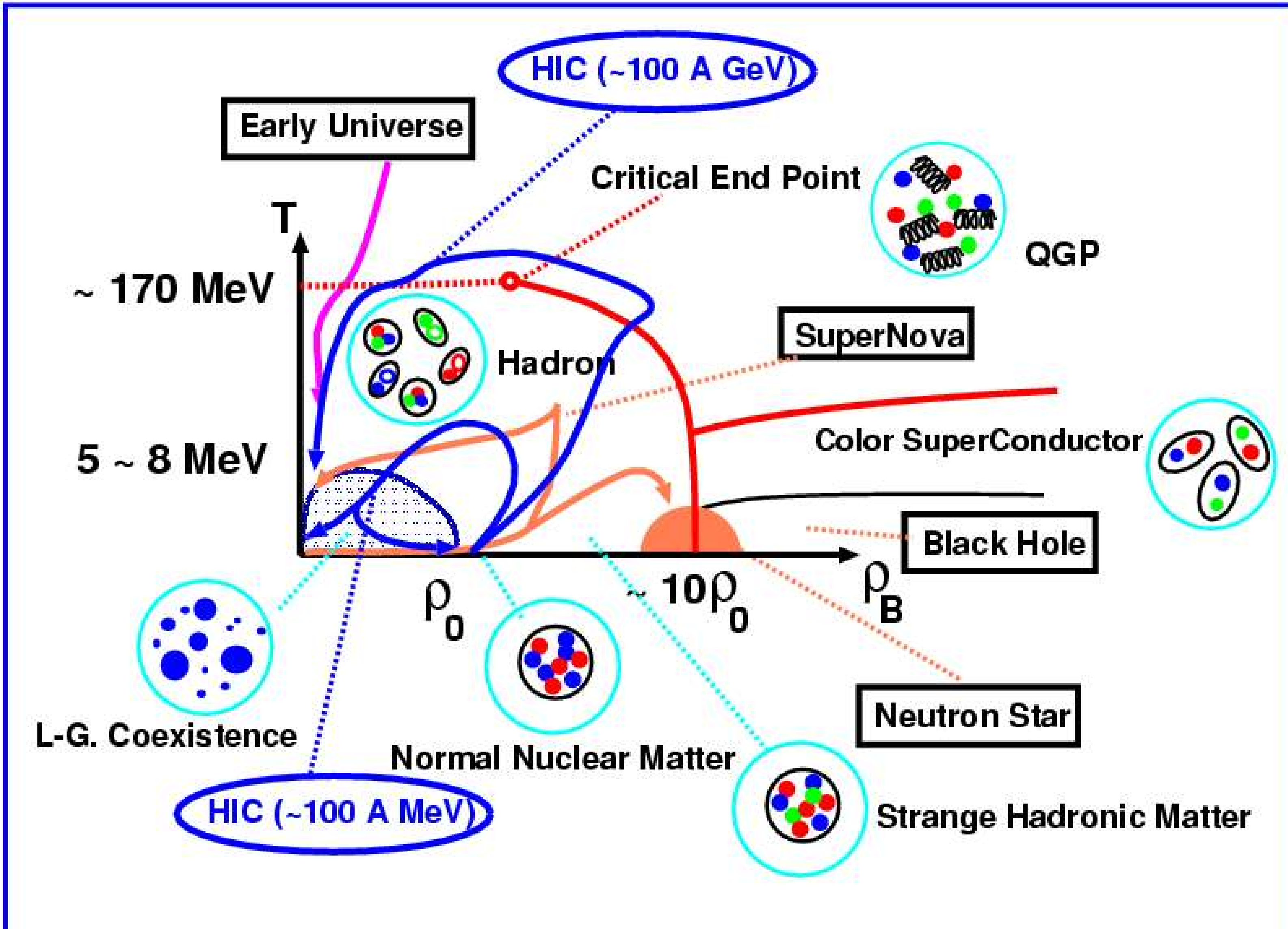
Hadronic Matter Phase Diagram



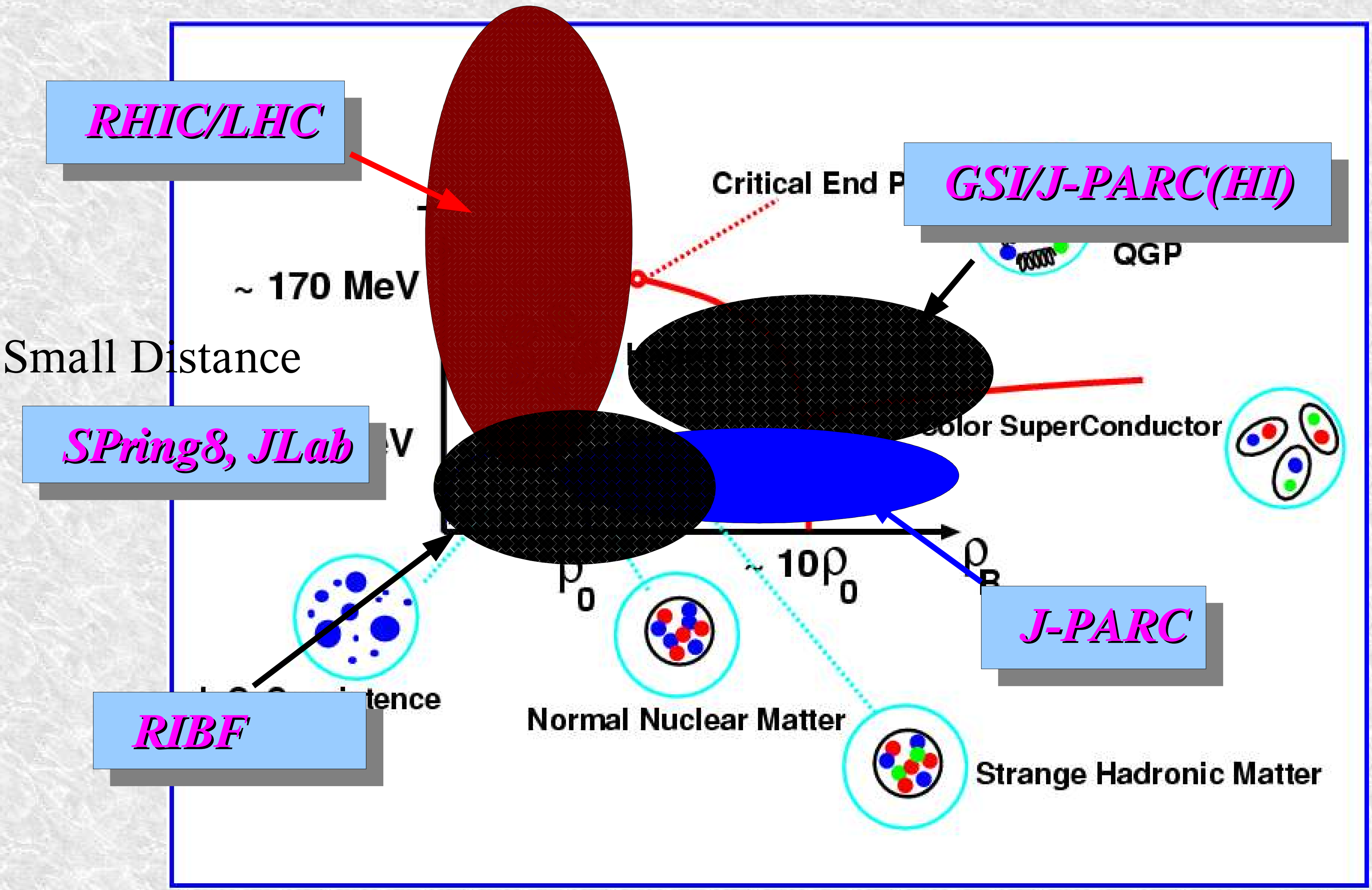
Hadronic Matter Phase Diagram



Hadronic Matter Phase Diagram



Hadronic Matter Phase Diagram

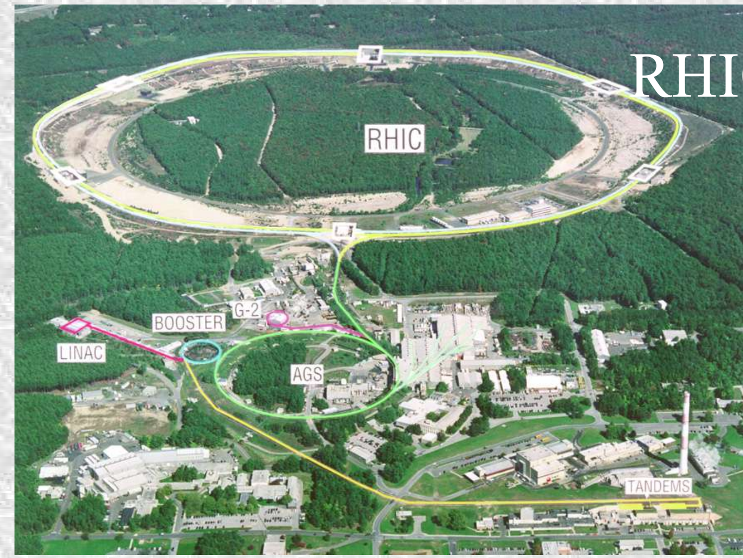


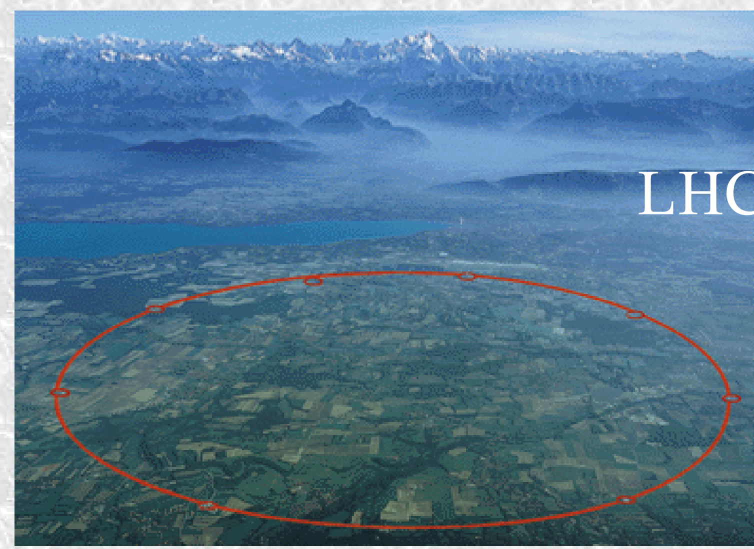
Physics of Hot Nuclear Matter

- *Why is it interesting ?*
  - *Lattice QCD: We should see QCD phase transition !*
  - *Modification of Hadrons in Hot Medium*
  - *Close relation to Compact Astrophysical Objects*
- *How do we heat the Nucleus ?*
  - *Hot but Not Dense: High-Energy proton (light ion) induced Reaction, Absorption of pbar, π^-, ...*
  - *Hot and Dense: High-Energy Heavy-Ion Collisions*
- *What do we want to know in High-E. HI Collisions ?*
  - *Formation and Confirmation of QGP*
  - *Hadron Properties in Hot Nuclear Matter*
  - *Equation of State*

High Energy Heavy-Ion Collision Experiments

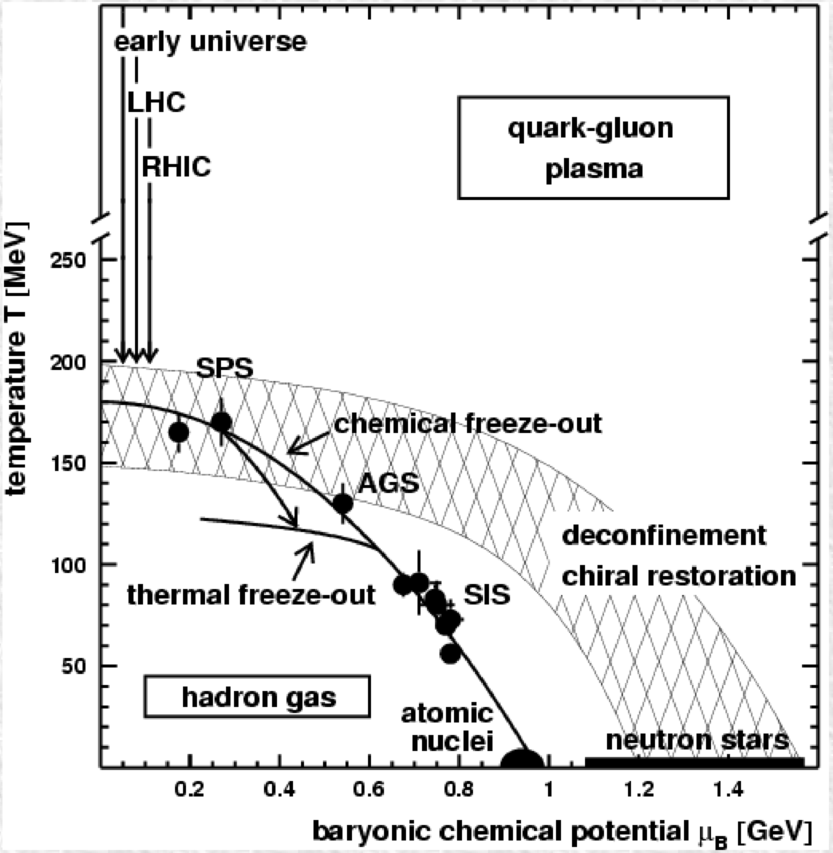
Heavy-ion physisists wanted
to create QGP for a long time ...



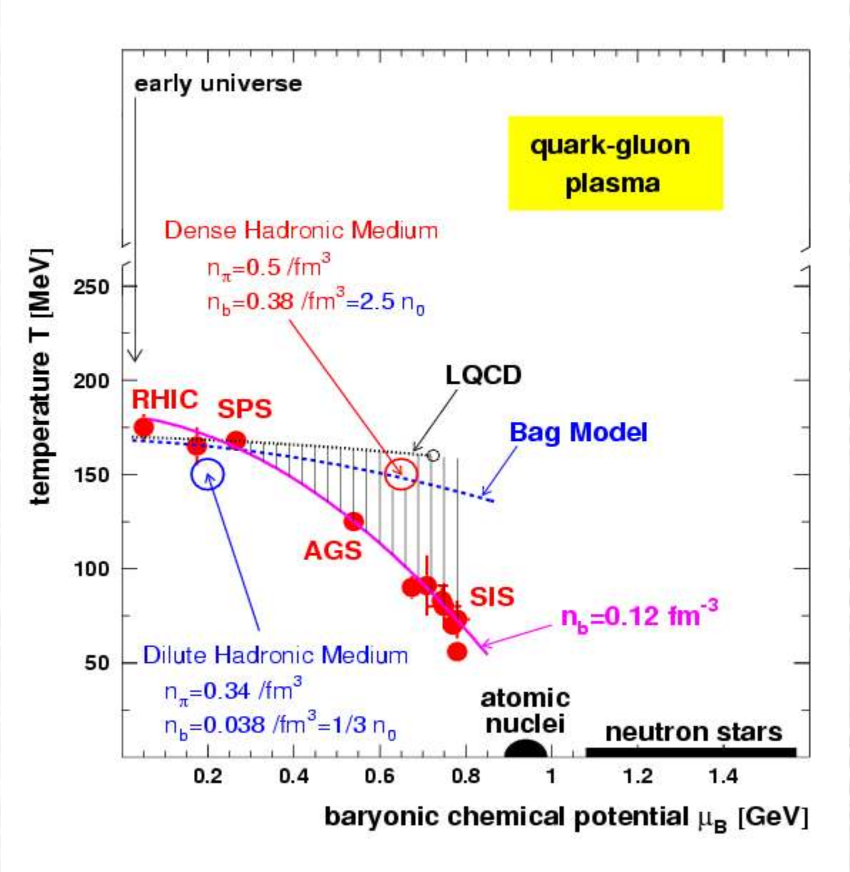


LBL-Bevalac: 800 A MeV
GSI-SIS: 1-2 A GeV
BNL-AGS (1987-): 10 A GeV
CERN-SPS (1987-): 160 A GeV
BNL-RHIC (2000-): 100+100 A GeV
CERN-LHC (2007(?)-): 3 + 3 A TeV

Experimentally Estimated Phase Diagram



1998 (J. Stachel et al.)

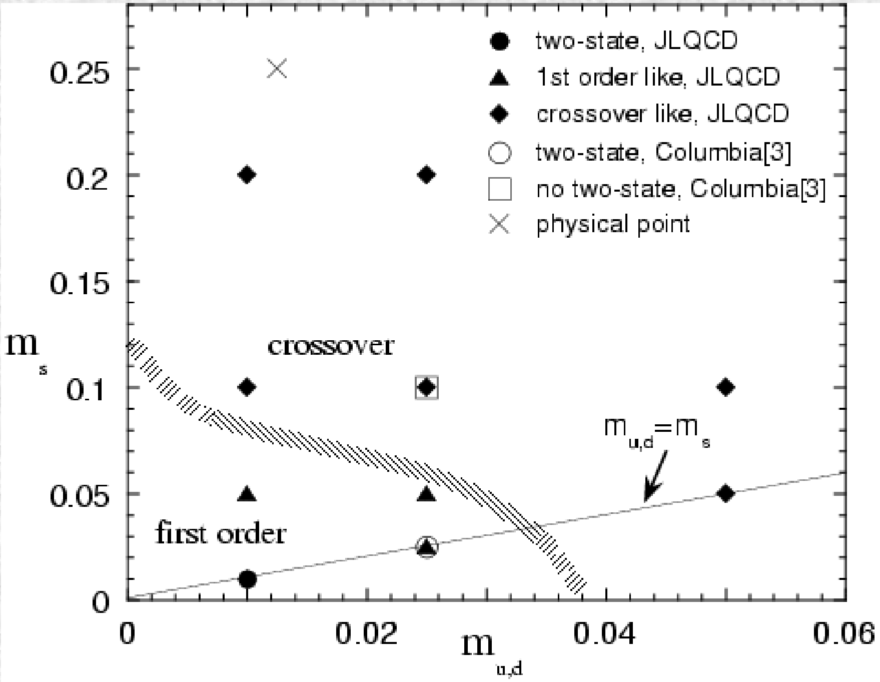


2002 (Braun-Munzinger et al.
J. Phys. G28 (2002) 1971.)

Chem. Freeze-Out Points are very Close to Expected QCD Phase Transition Boundary

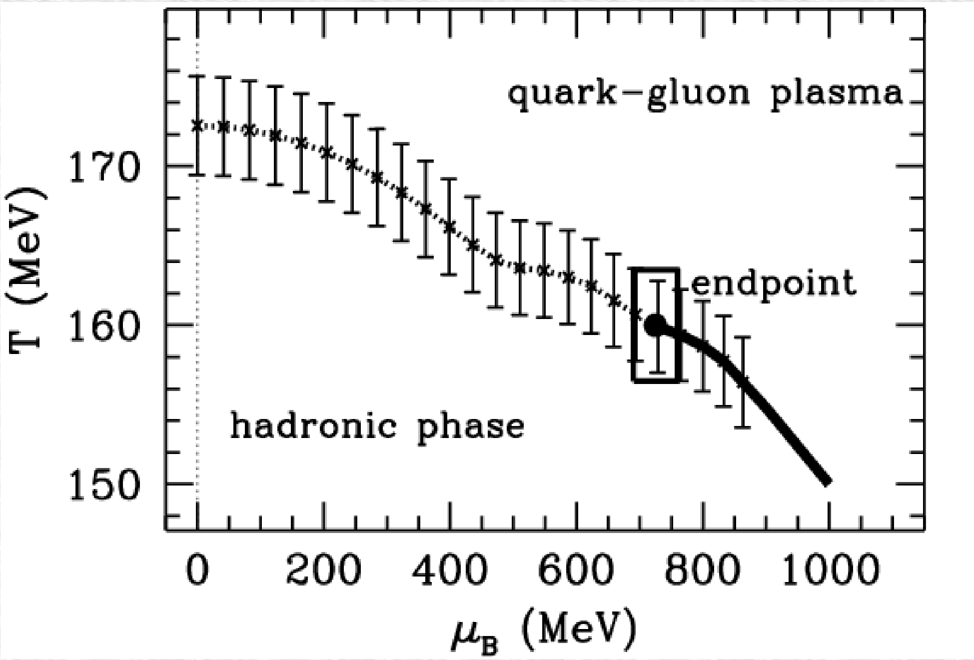
Theoretically Expected QCD Phase Diagram

Zero Chem. Pot.



JLQCD Collab. (S. Aoki et al.),
Nucl. Phys. Proc. Suppl. 73 (1999) 459.

Finite Chem. Pot.



Finite μ: Fodor & Katz,
JHEP 0203 (2002), 014.

Zero Chem. Pot. : Cross Over
Finite Chem. Pot.: Critical End Point

Collective Flows
in High-Energy Heavy-Ion Collisions

Collective Flows in Heavy-Ion Collisions

- *Signal of QGP Formation*
  - *Probe of Thermalization Degree / Pressure in the Early Stage at Low P_T.*
  - *Jet Energy Loss appears as Anisotropic Flow for High P_T.*
- *Sensitive to Equation of State*
  - *Flows are generated in the Early Stage where the Density is still High.*
  - *Various Densities and Temperatures*
    ↔ *Incident Energy, Impact Parameter, System Size*

What is Collective Flow ?

(Directed) Flow (dP_X/dY)

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

Elliptic Flow (V_2)

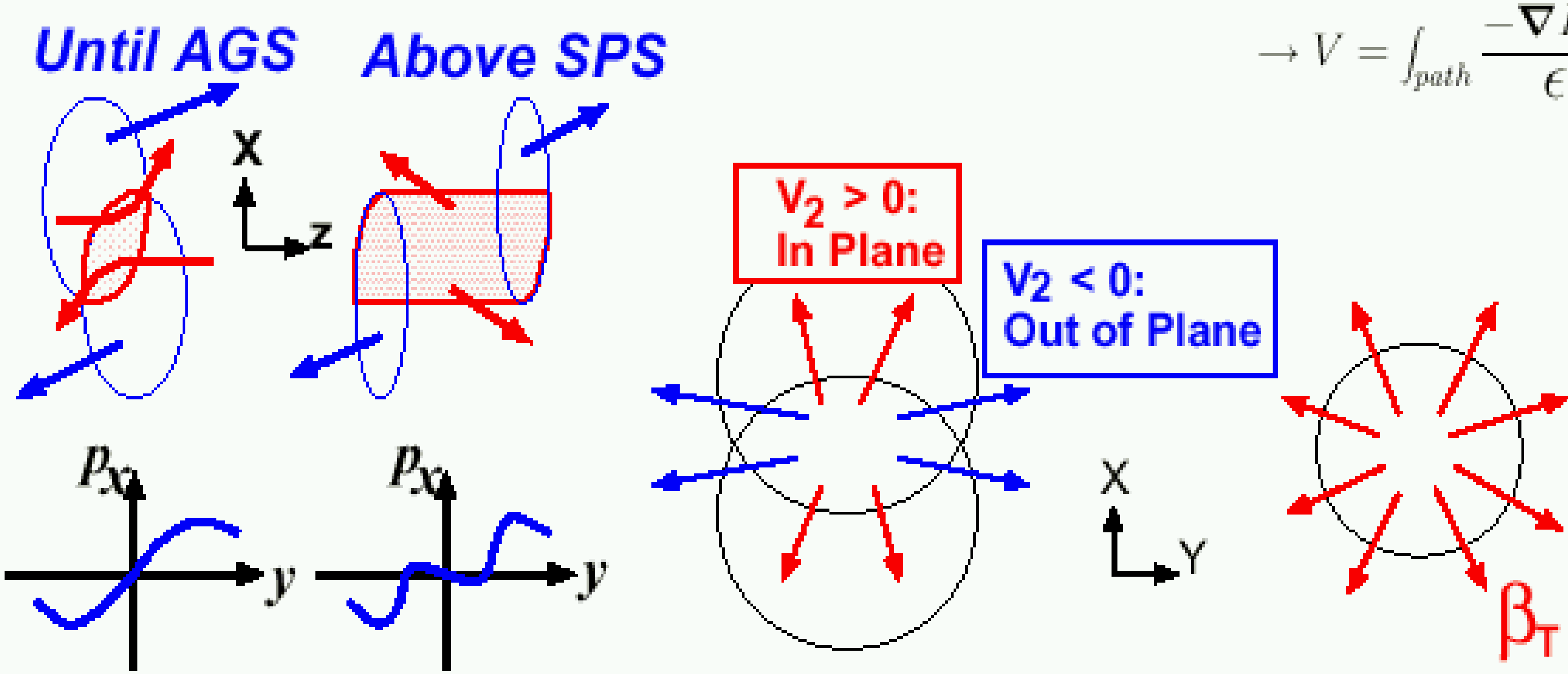
Thermalization
& Pressure Gradient

Radial Flow (β_T)

Pressure History

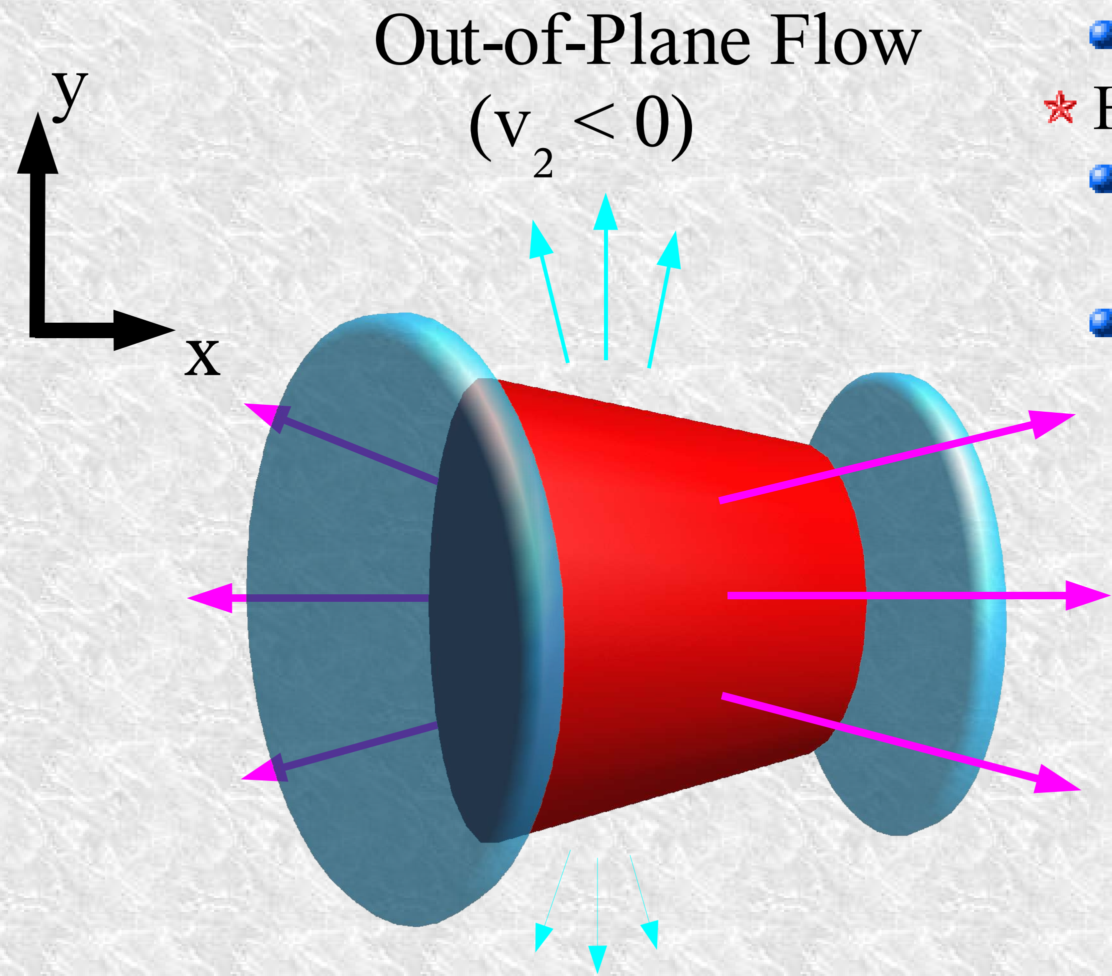
$$\epsilon \frac{D\mathbf{V}}{Dt} = -\nabla P$$

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



Elliptic Flow (I)

- 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 V_2



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

Is QGP Formed at AGS, SPS and/or RHIC ?

Proposed and/or Measured Signals

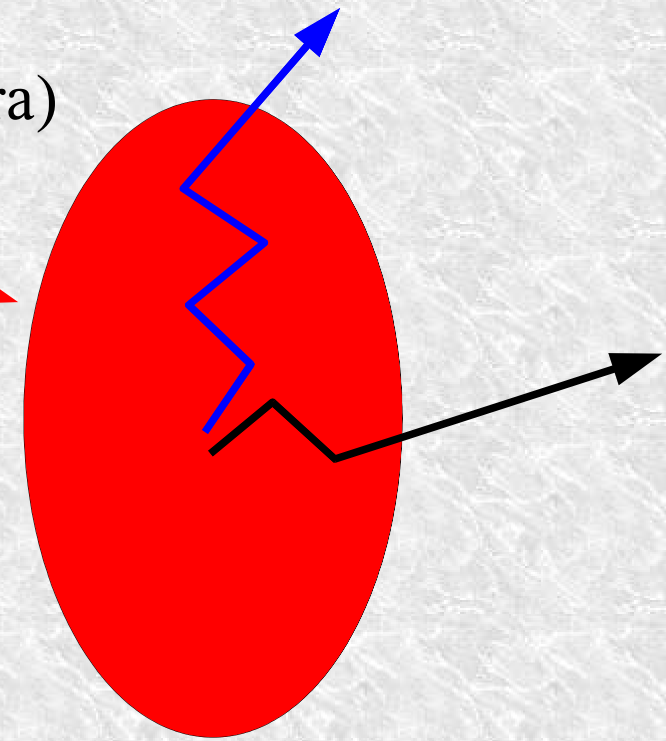
This Talk

- Collective Flow (AGS, SPS, RHIC)
  - → *EOS modification / Thermalization Degree*
- Low-Mass Lepton Pair (Yes @ SPS, Not Yet @ RHIC)
  - → *Partial Restoration at High Temperature/Density*
- High-Mass Lepton Pair (Yes @ SPS, Preliminary @ RHIC)
  - → *J/Ψ Suppresion at High Temperature*
- Jet Energy Loss (@ RHIC)
  - → *Parton Dynamics at High (Freed) Gluon Density*
- Strangeness Enhancement (Yes @ AGS, Lower E. SPS, No @ RHIC)
  - → *Rescattering or Potential at High Density or QGP*

Elliptic Flow (II)

- What is the Origin of Elliptic Flow ?
  - Hydrodynamics
  - Jet Energy Loss
  - Coalescence

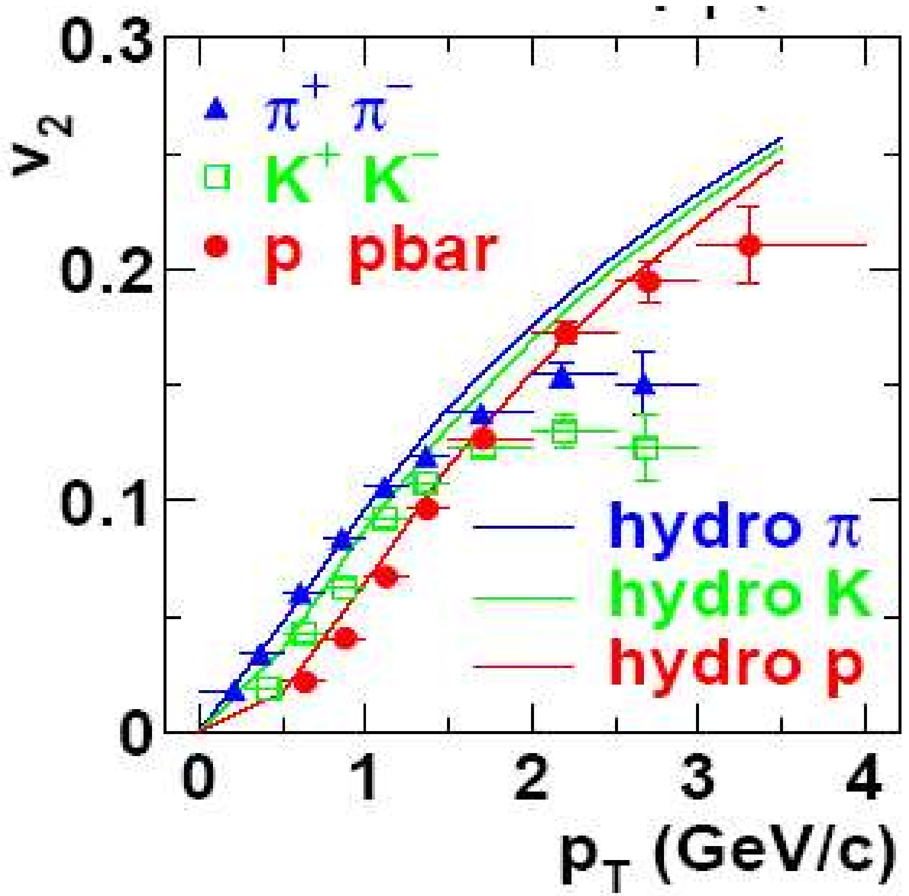
Jet + Hydro
(Hirano and Nara)

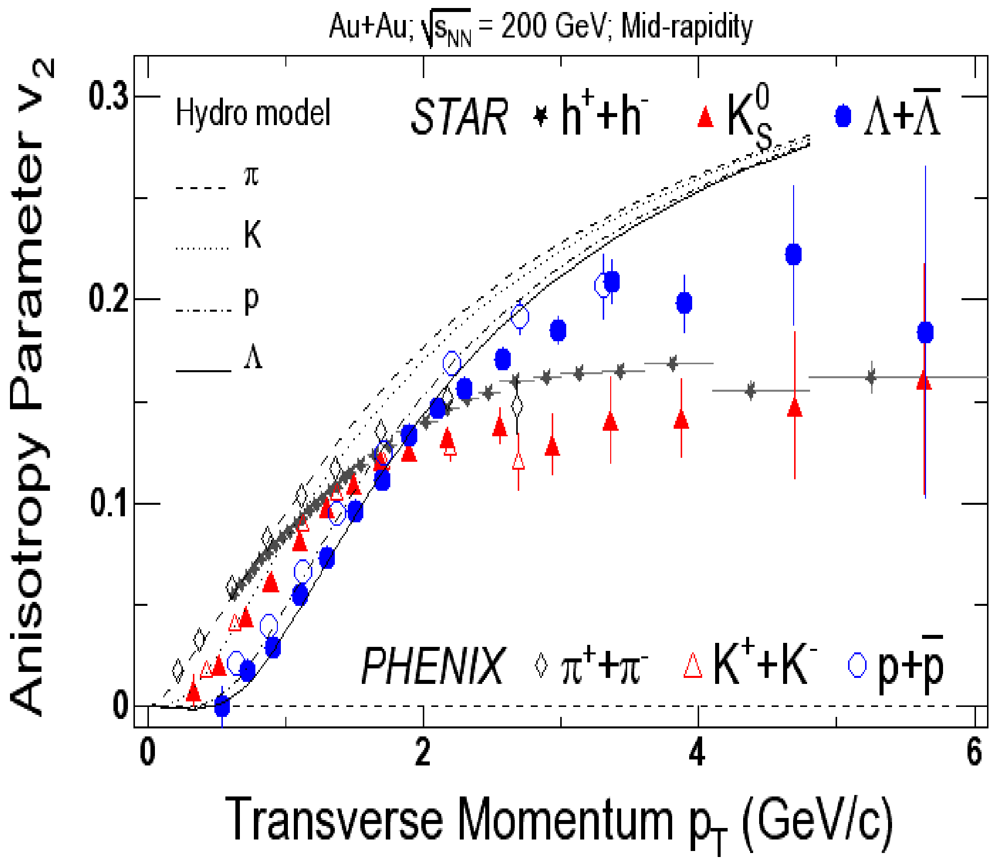


Fragmentation & Recombination
Fries, Nonaka, ...

$$f(\phi) \simeq f_1(\phi) f_2(\phi)$$
$$\propto (1 + 2v_2 \cos\phi) \times (1 + 2v_2 \cos\phi)$$
$$= 1 + 2 \times 2 v_2 \cos\phi$$

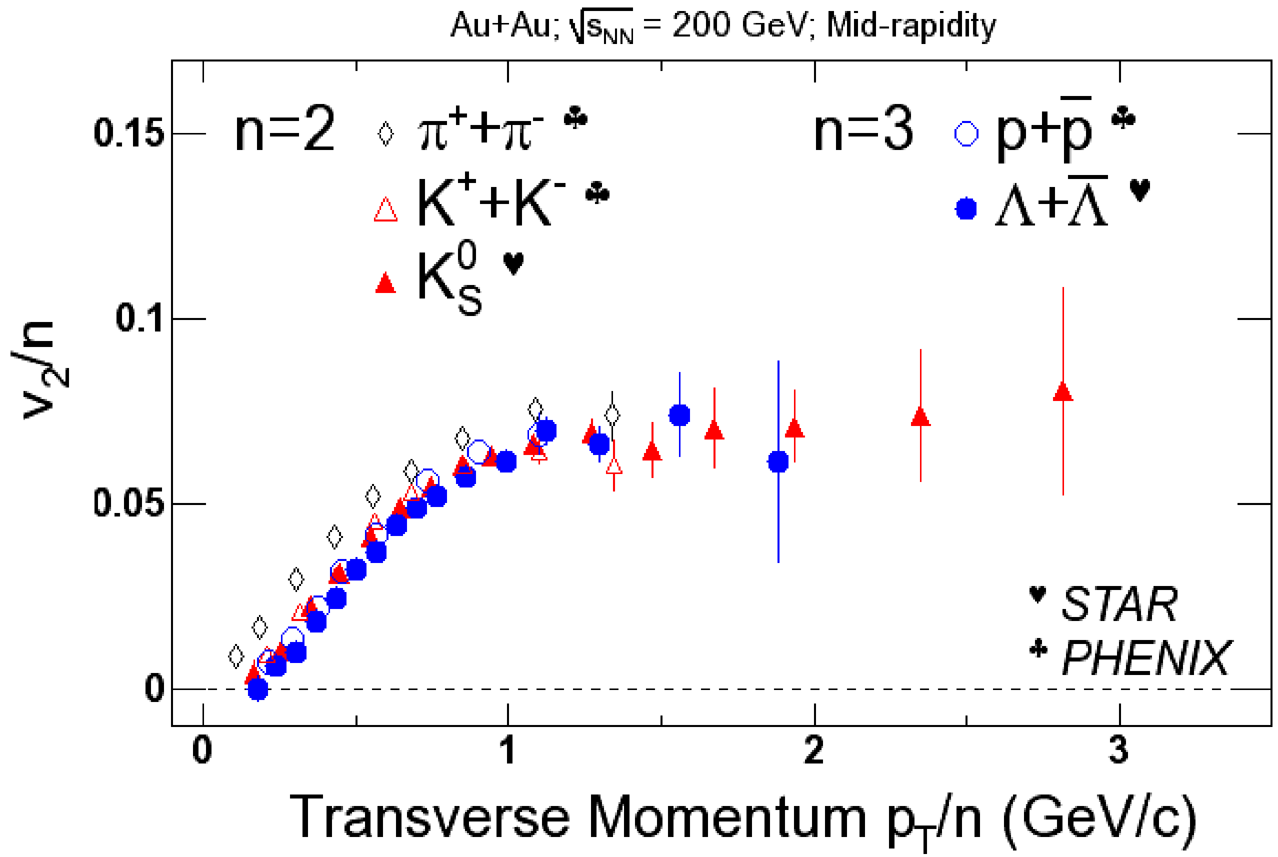
by Esumi, Matter03





Low Momentum : Hydrodynamical calc. with Early Thermalization
High Momentum : Reduction from Hydro. calc.

by Esumi, Matter03

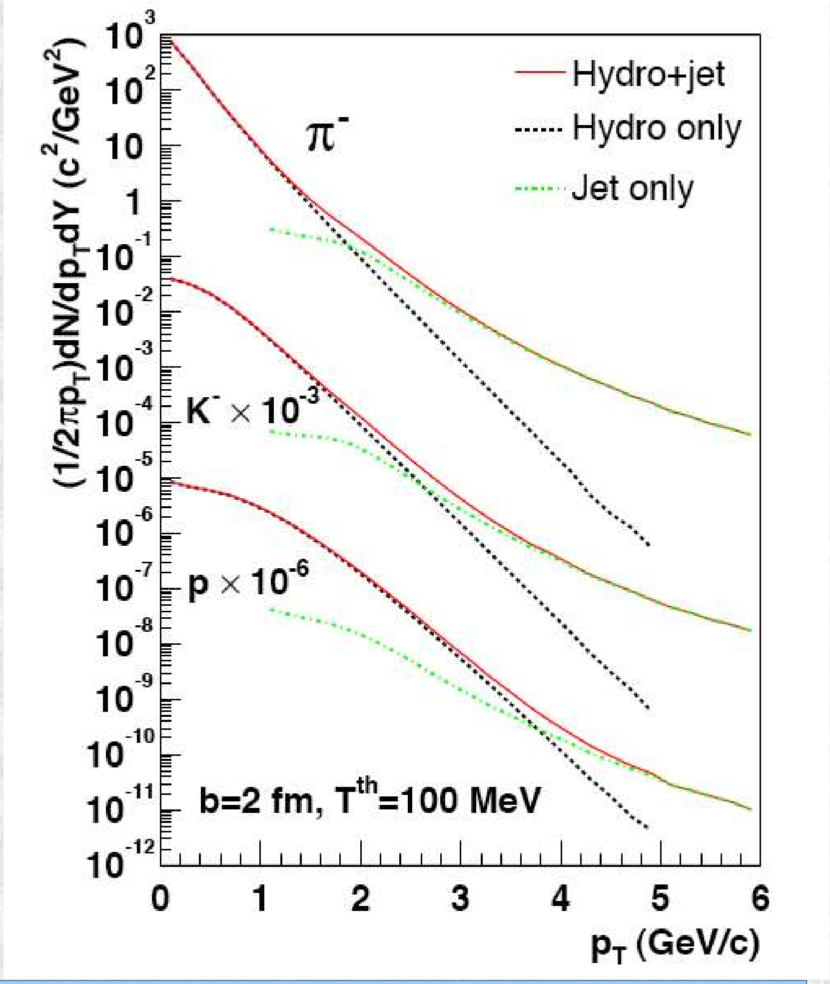


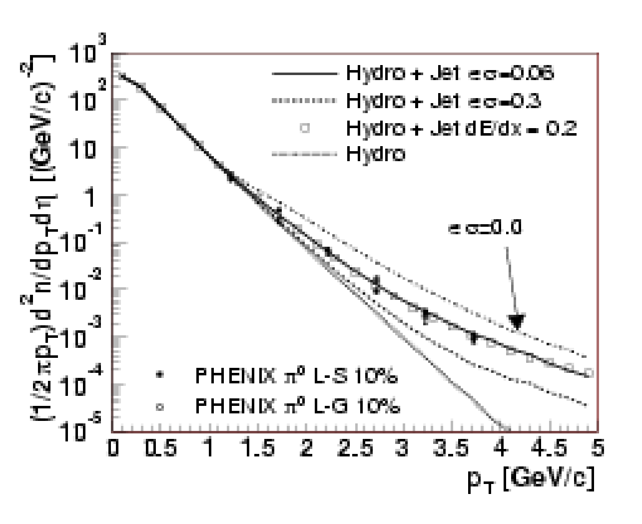
Coalescence (Recombination) Picture

$$v_2^{Hadron}(P_T) = n\, v_2^{Parton}(P_T/n)$$

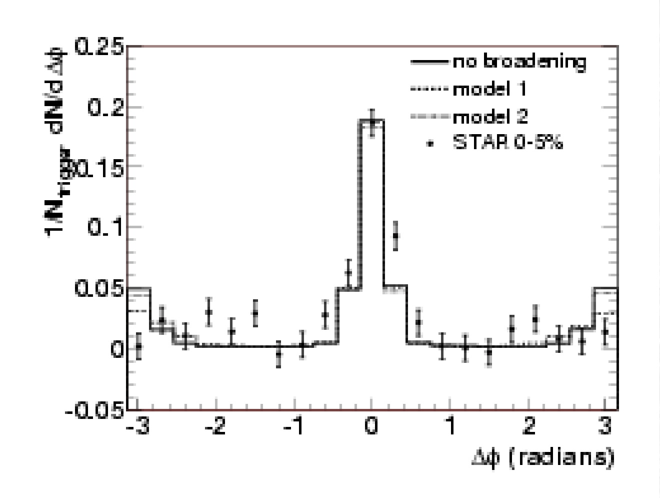
Recombination Picture seems to work well
... Parton Elliptic Flow

Hydro + Jet Model (Hirano and Nara)





PRC66 (2002) 041901.

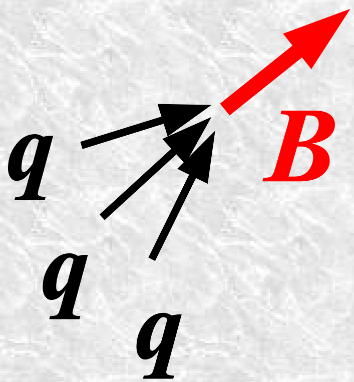


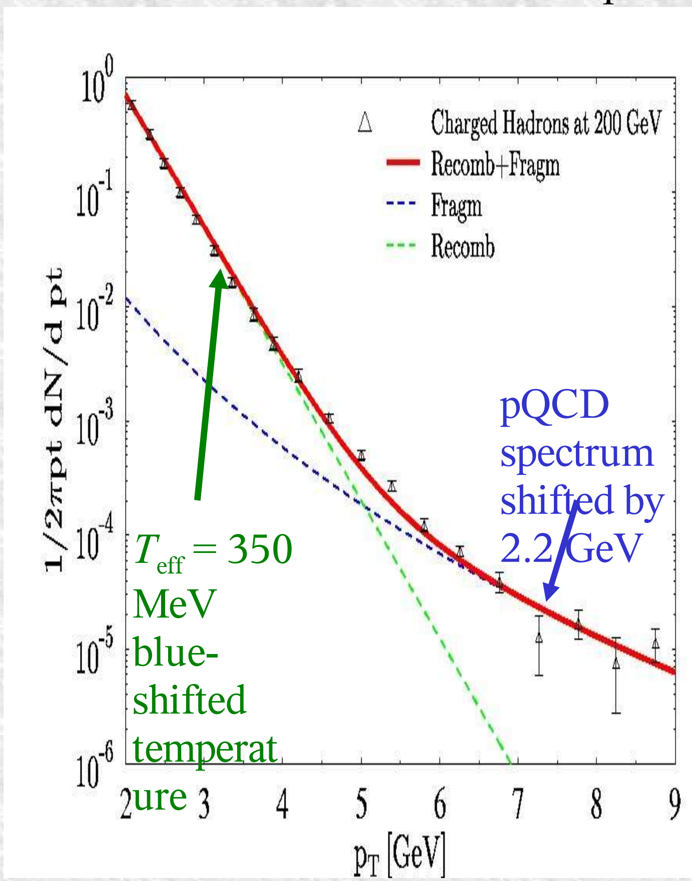
PRL 91 (2003) 082301.

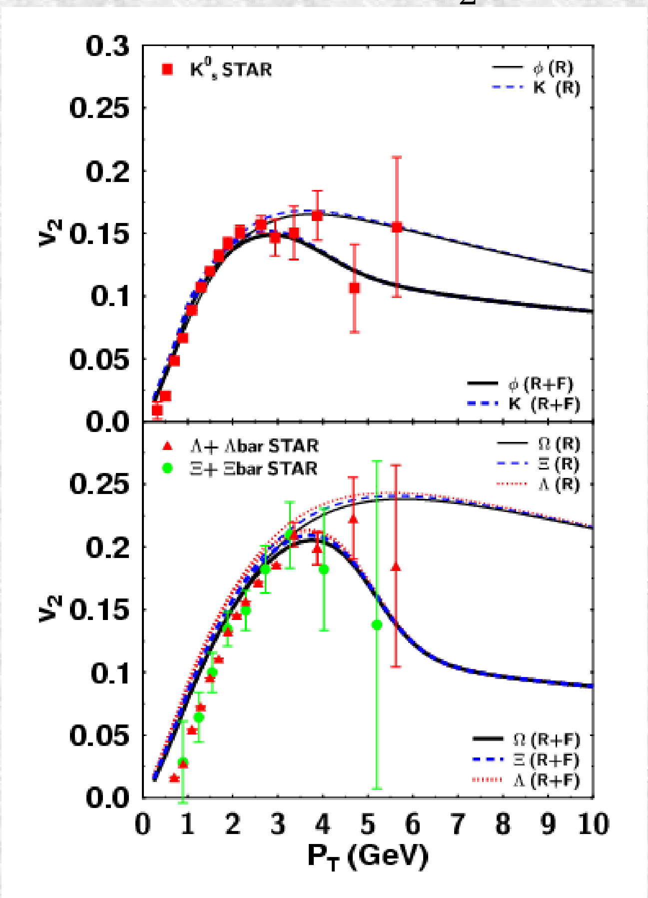
Heavy-Particles are affected by Hydro. Flow until Larger P_T

Fragmentation and Recombination (Duke U. Group)

Recombination Enhances Intermed. P_T Hadrons and Baryon V_2.







$$v_2^{Hadron}(P_T/n) = n\, v_2^{Parton}(P_T/n)$$

Fries et al. PRL 90 (2003), 202303, Nonaka et al., nucl-th/0308051

The Nuclear Equation of State

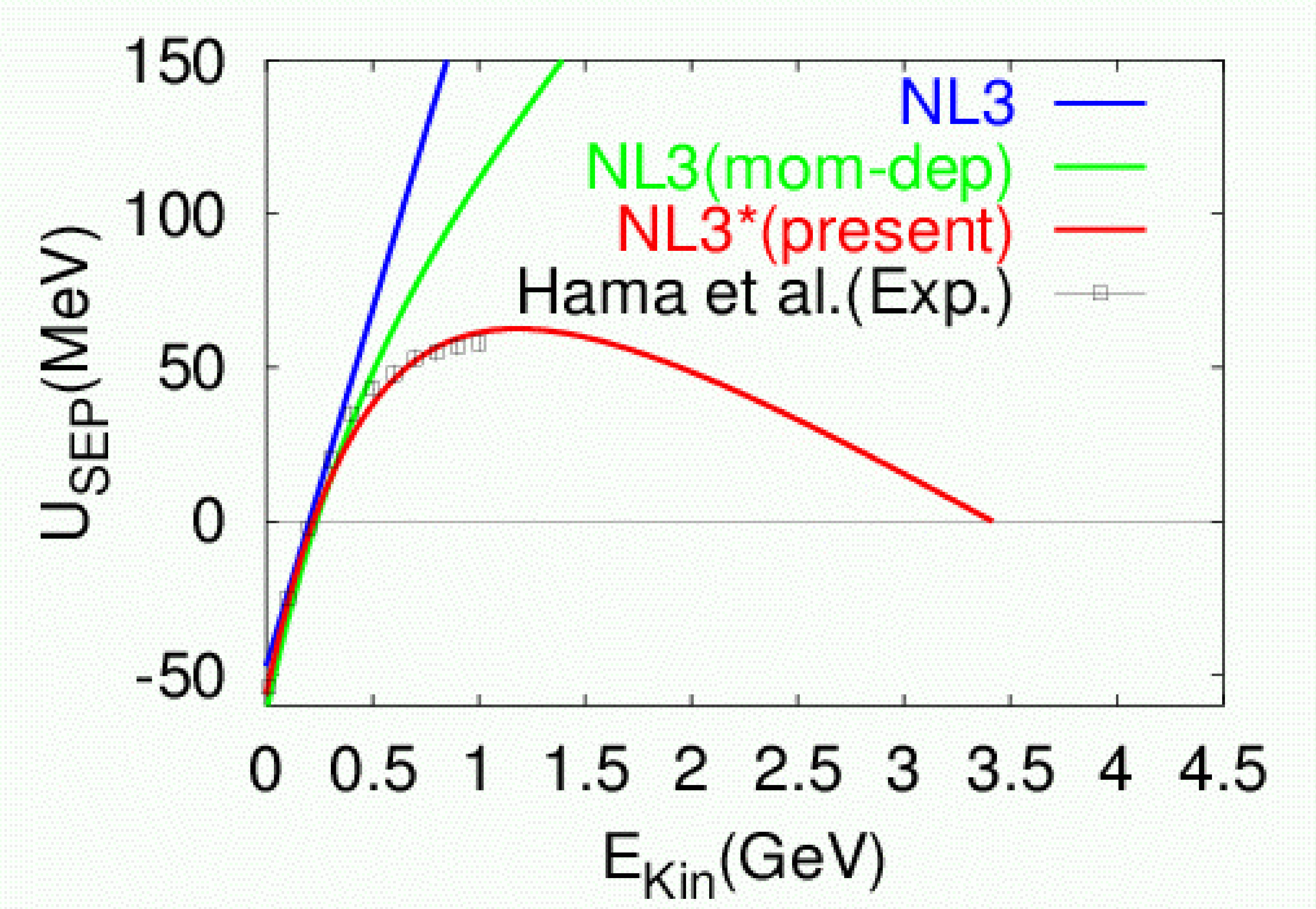
- Nuclear Equation of State (EOS)
  - gives the bulk properties of Nuclei
  - determines the properties of Neutron Stars
  - EOS is crucial in Supernova Explosion
- How to obtain EOS ?
  - Asymmetric Nuclear Matter: Unstable Nuclear Phys.
  - Cold Dense Matter: Hypernuclear Phys.
  - Nuclear Matter at Subsaturation Densities:
    - Low-E Reaction with unstable nuclei (nucleosynthesis)
    - Nuclear Pasta, Fragmentation
  - Hot and/or Dense Matter: High-Energy Heavy-Ion

Collective Flow and EOS: Old Problem ?

- *1980's: First Suggestions and Measurement*
  - *Hydrodynamics suggested the Exsitence of Flow.*
  - *Strong Collective Flow suggests Hard EOS*
- *1990's: Deeper Discussions in Wider Einc Range*
  - *Momentum Dep. Pot. can generate Strong Flows.*
  - *Einc deps. implies the importance of Momentum Deps.*
  - *Flow Measurement up to AGS Energies.*
- *2000's: Extention to SPS and RHIC Energies*
  - *EOS is determined with Mom. AND Density Dep. Pot. ?*

Old but New (Continuing) Problem !

Momentum Dependence of N-A Potential

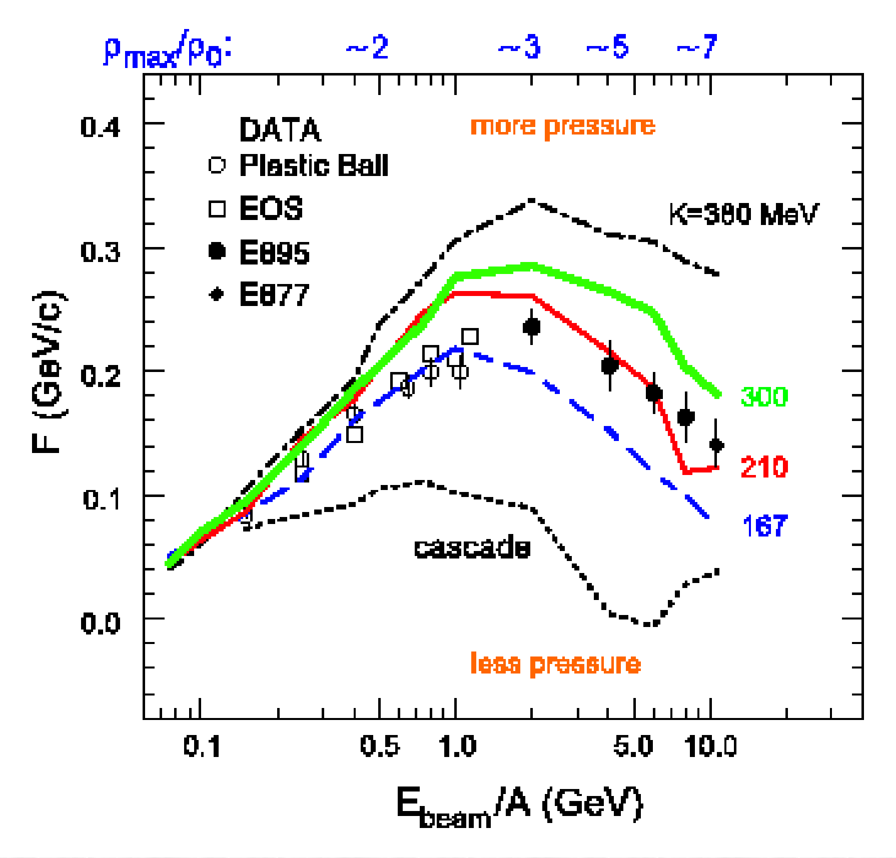


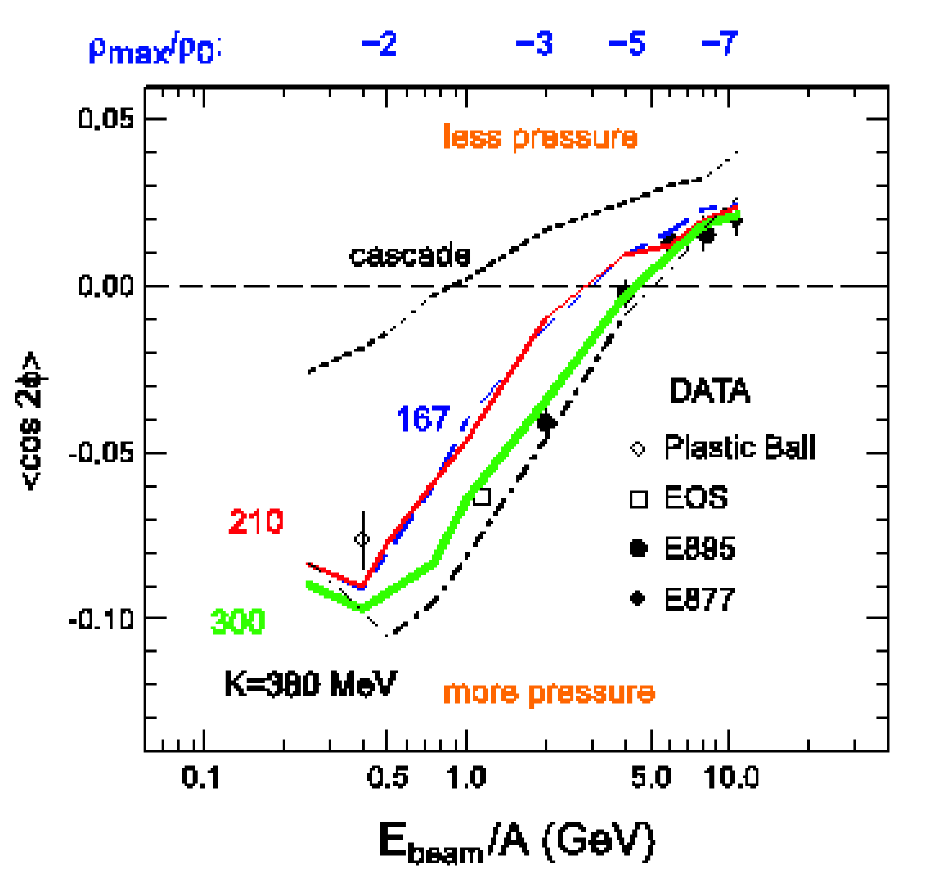
(Sahu, Cassing, Mosel, AO, Nucl. Phys. A672 (2000), 376.)

Is the EOS determined ?

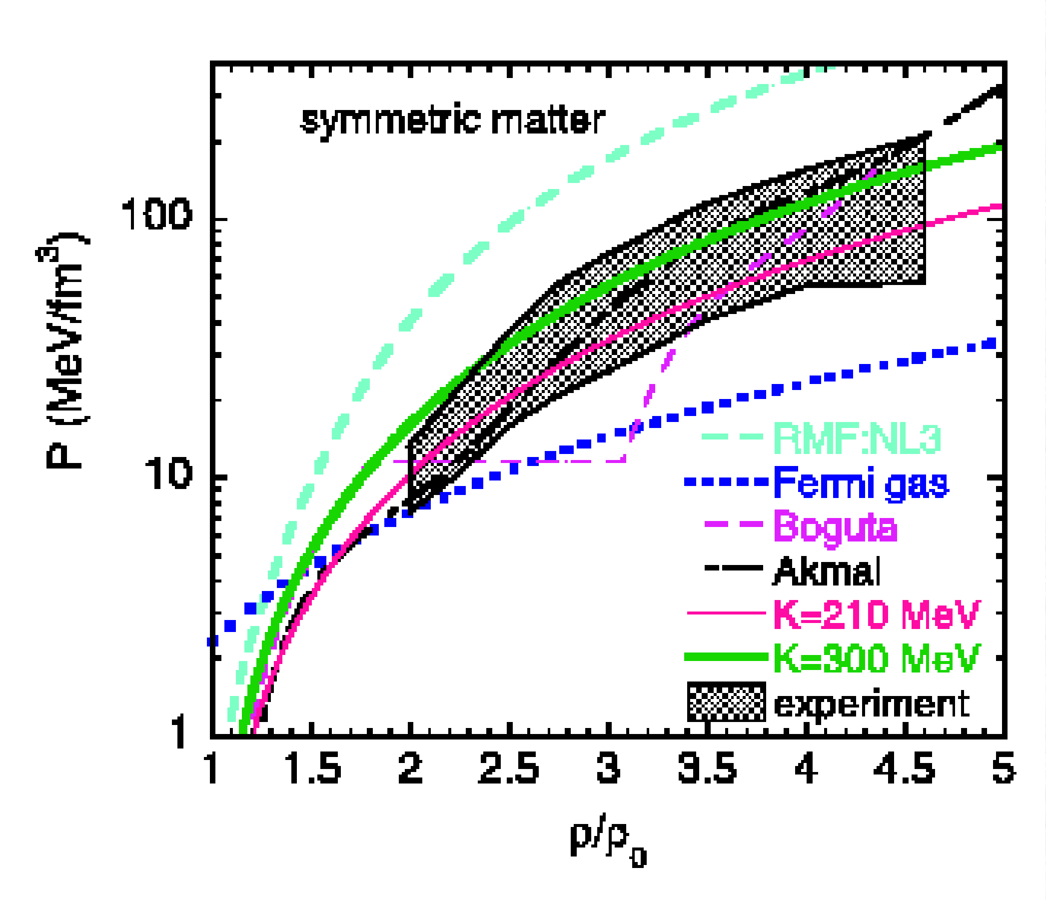
(Directed) Flow and Elliptic Flow up to AGS

(P. **Danielewicz, R. Lacey, W.G. Lynch, Science 298(2002), 1592.)**





Constraint of EOS



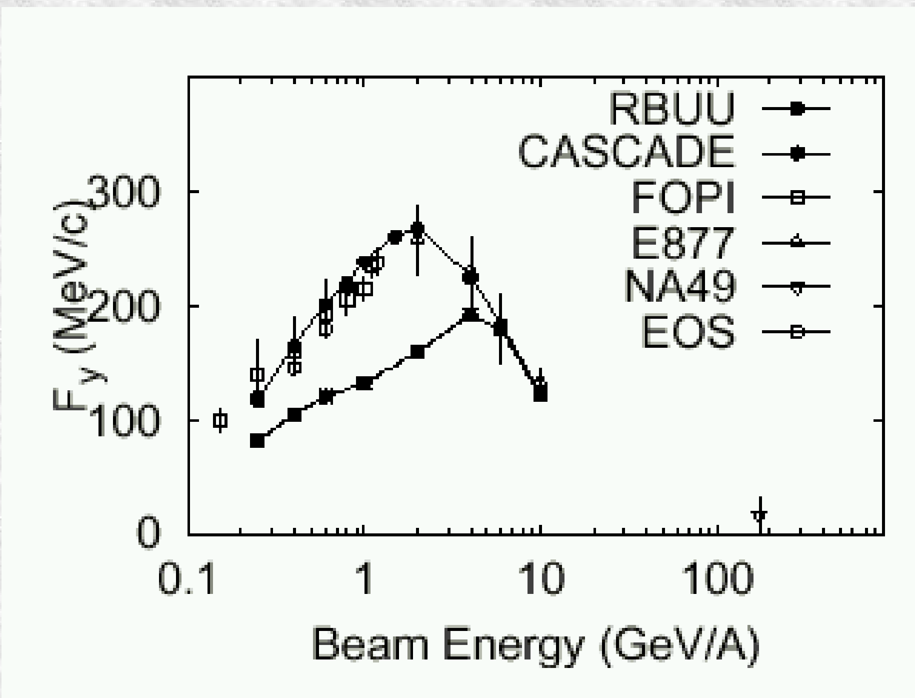
Allowed Pressure range
as a function of density
is constraint by “EXPERIMENTS”
→ Is it true ?

(P. **Danielewicz et al., Science 298(2002), 1592.)**

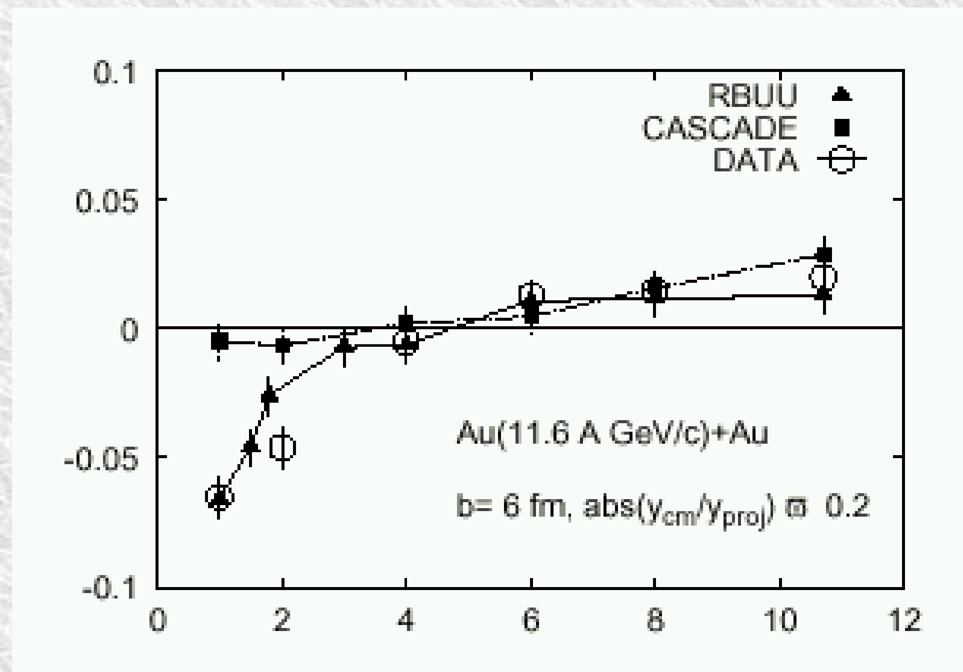
Our Results

(Sahu, Cassing, Mosel, AO, Nucl. Phys. A672 (2000), 376.)

Side Flow

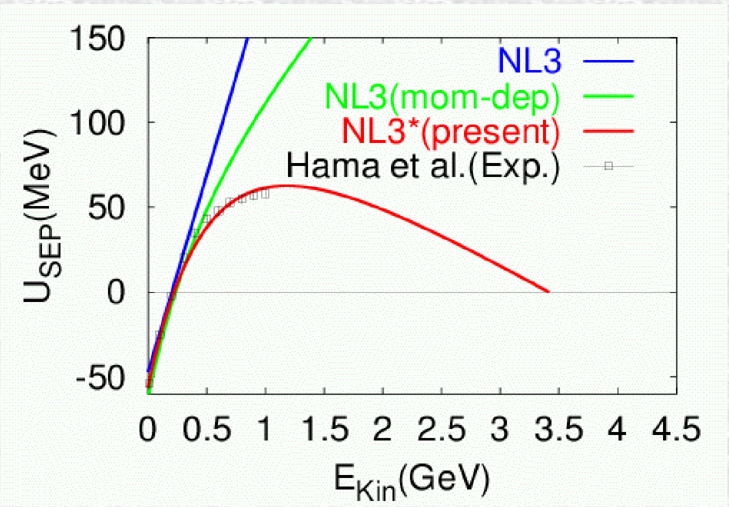


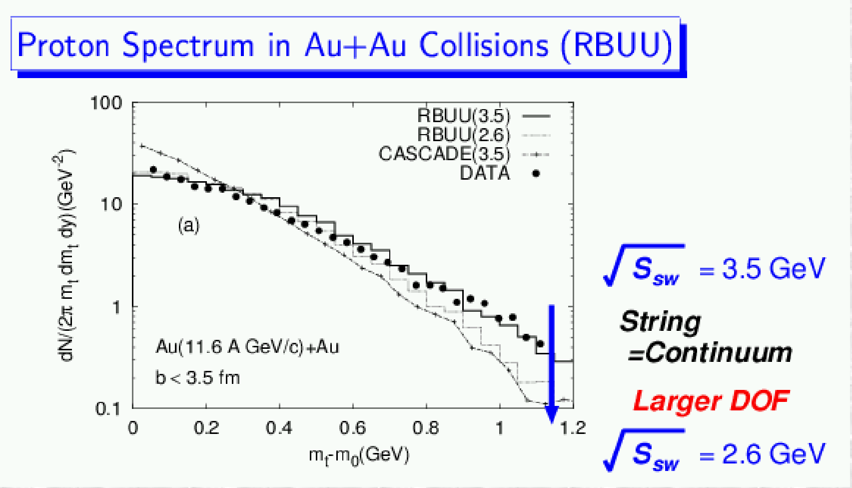
Elliptic Flow (v_2)



What is Essential in Collective Flows ?

- ***Equation of State***
- ***Momentum Dependence***
  - ***In Relativistic Mean Field Model, the reduction of the Coupling to Vector meson is important.***
- ***Particle Degrees of Freedom in Cascade (w.o. Mean Field)***
  - ***Strings (Continuum Hadron) Reduces the pressure***





What should be done ?

- *Success of Hadronic Description at AGS*
- *Success of Hydrodynamic Description at RHIC*
- *Resulting EOS can be MODEL-DEPENDENT*

  → *Flows at SPS energies*

  - *Lower SPS energy HI Collisions (20-80 A GeV) have been measured recently.*
  - *Not Very Seriously Investigted in relation to EOS*
  - *High T but relatively Low Density → Sensitive to Mom. Dep. Potential*

We study Collective Flows from AGS to RHIC energies systematically, by using a Hadronic Cascade Model (JAM) with Mean Field Effects.

Hadronic Model Study of Collective Flows from AGS to RHIC

Mean Field in High-E. Heavy-Ion Collisions

- *Mean Field in High Energy Heavy-Ion Collisions*
  → Must be treated in a Covariant Way !
  - *RMF: Formally Good, but Large Cancellation of Scalar and Vector Potential makes Large Fluctuations.*
  - *RQMD has been applied to SPS energies, but mainly only with Mom. Indep. Potential.*

We analyze Collective Flows in RQMD/S with Momentum Dependent Potentials !

Relativistic QMD/Simplified (RQMD/S)

Constraint Hamiltonian Dynamics
(Sorge, Stocker, Greiner, Ann. of Phys. 192 (1989), 266.)

Constraints

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

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

- Time-Fixation in RQMD/S

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

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

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

RQMD/S (cont.)

Equation of Motion

- Hamiltonian

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

- Time Development

$$\frac{df}{d\tau} = \frac{\partial f}{\partial \tau} + \{f, H\} \quad , \quad \{q_\mu, p_\nu\} = g_{\mu\nu} \quad , \quad \frac{d\phi_i}{d\tau} \approx$$

After determining the Lagrange multipliers, we finally get EOM

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

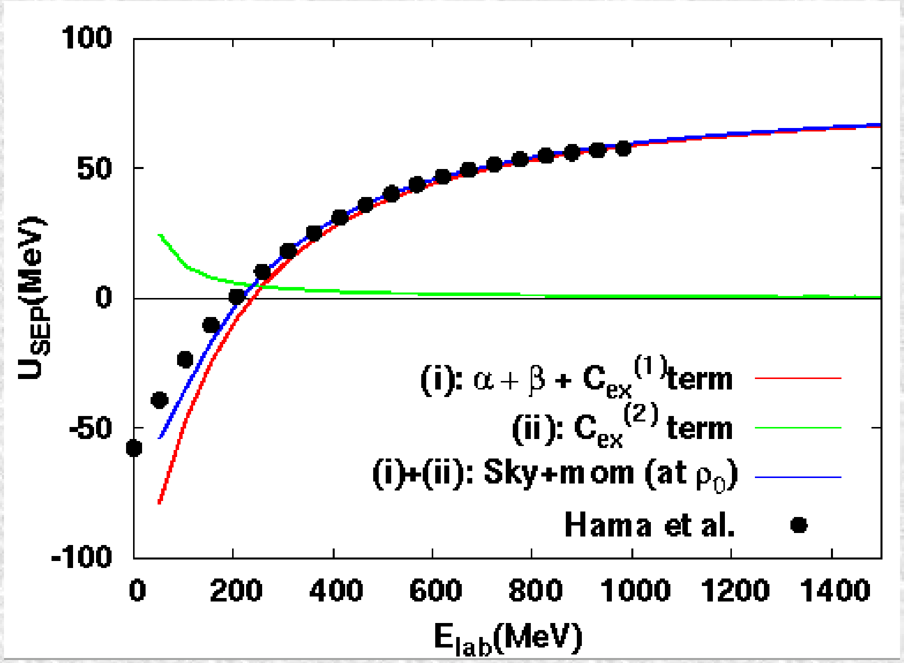
$$\frac{d\vec{r}_i}{d\tau} \approx -\frac{\partial H}{\partial \vec{p}_i} = \frac{\vec{p}}{p_i^0} + \sum_j \frac{m_j}{p_j^0} \frac{\partial V_j}{\partial \vec{p}_i} \quad , \quad \frac{d\vec{p}_i}{d\tau} \approx \frac{\partial H}{\partial \vec{r}_i} = -\sum_j \frac{m_j}{p_j^0} \frac{\partial V}{\partial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

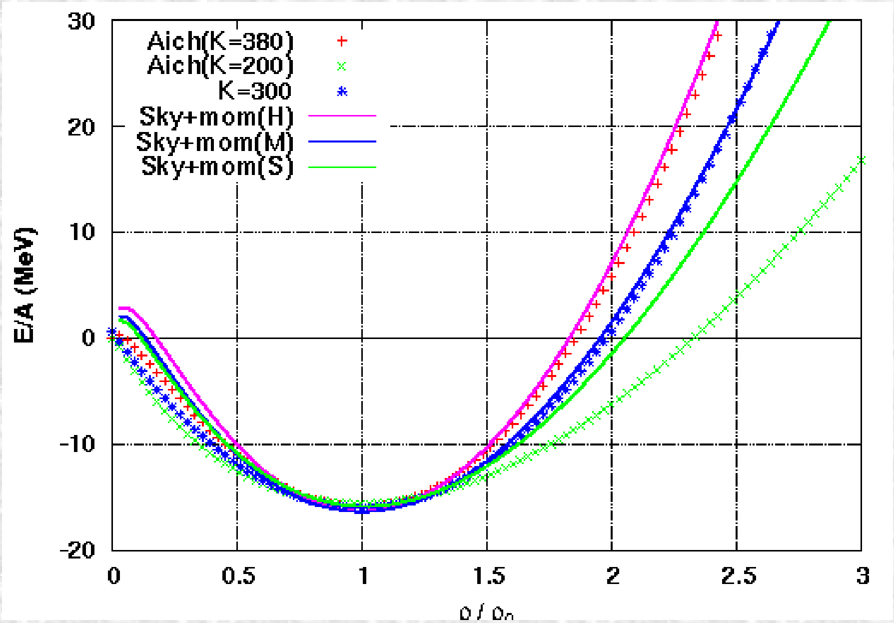
Choice of Potential

Skyrme type Density Dep. Potential + Momentum Dep. Potential

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

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





Particle “DISTANCE”

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

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

Particle “Momentum Difference”

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

$$p \equiv p_i - p_j$$

Lorentz Invariant, and Becomes Normal Distance in CM !

Hadronic Cascade Part: JAM

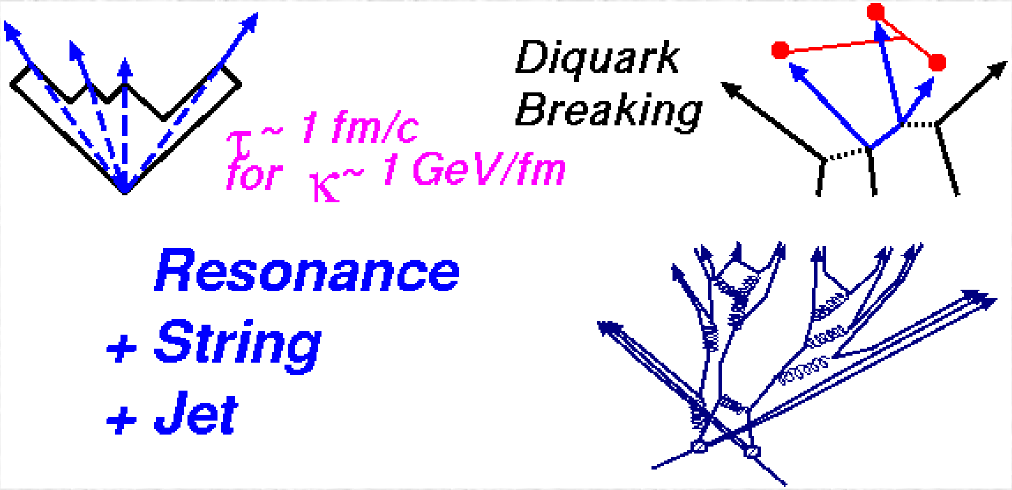
(Y. Nara et al., Phys. Rev. C61 (2000), 024901.)

DOF

Hadrons (h, m < 2 GeV) + Strings (s) + Partons (in Jet)

Cross Sections

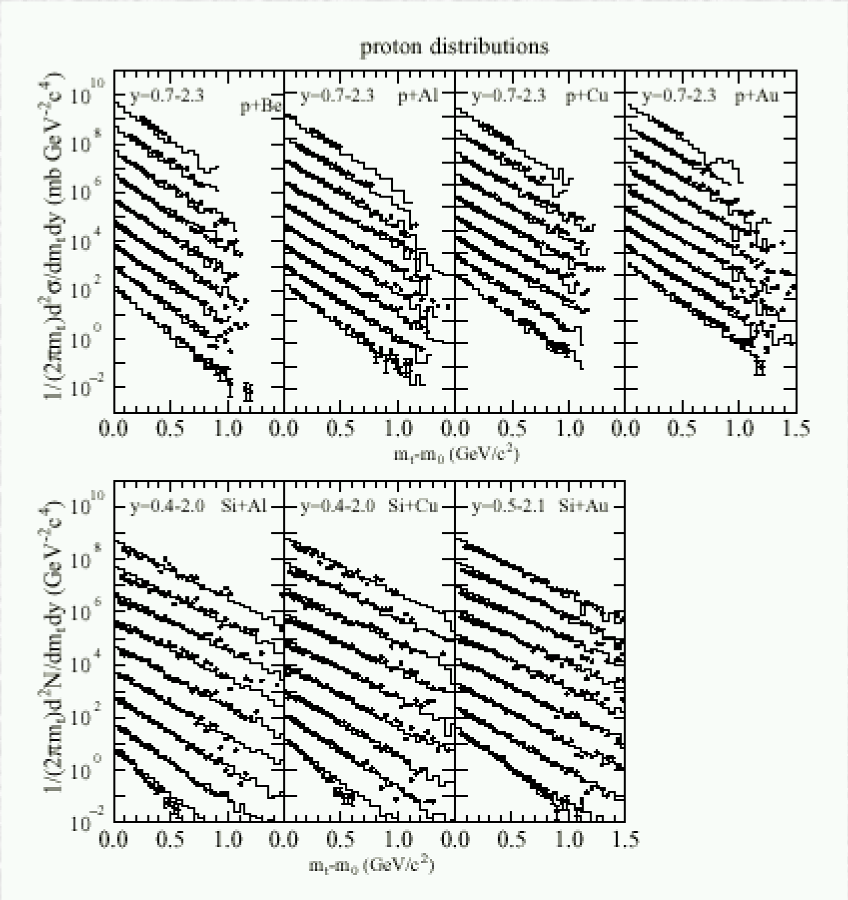
Hadronic (hh → hh, hh → h, h → hh)
+ Soft (hh → s, hh → ss, s → hh, hh → hs [1] ,
sh → s'h, ...[2])
+ Hard (Jet Production)



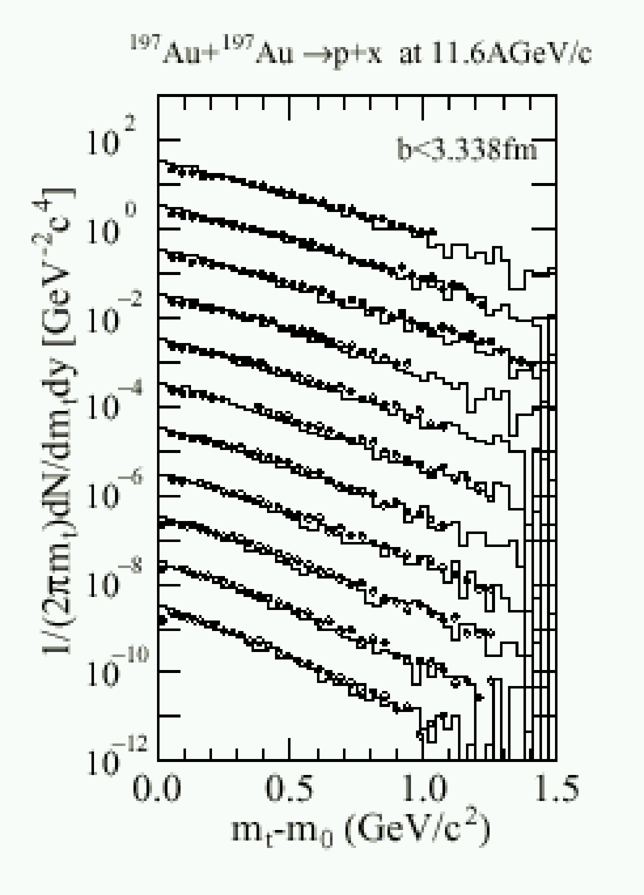
[1] "DPM + Lund" (~ HIJING) + Phase Space [2] Consituent Rescattering (~ RQMD)

JAM Results @ AGS Energy

p-A Collision



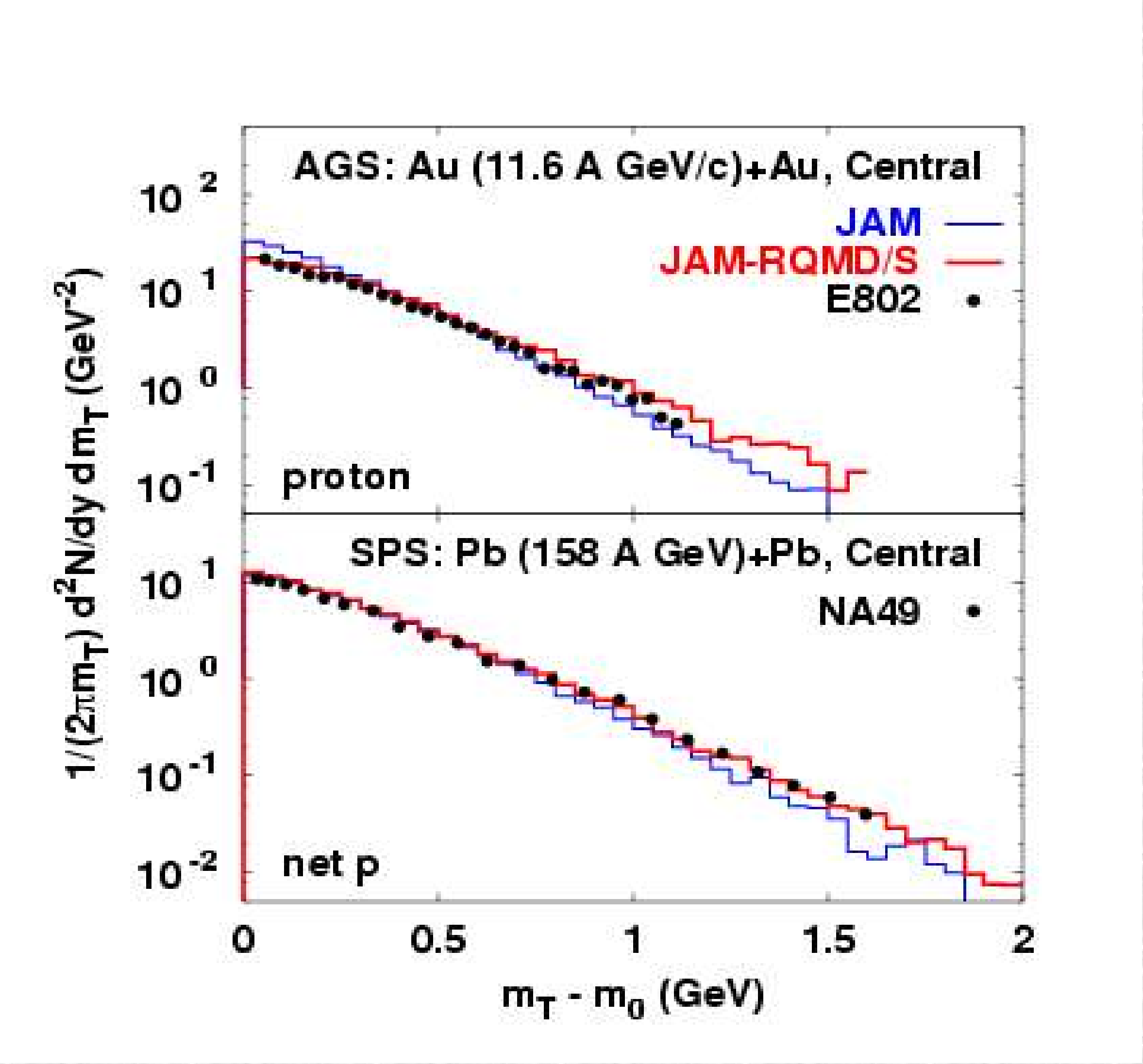
Au+Au Collision



JAM explains AA collisions as well as pA collisions:

→ Good Elementary Cross Sections for MM, MN and NN

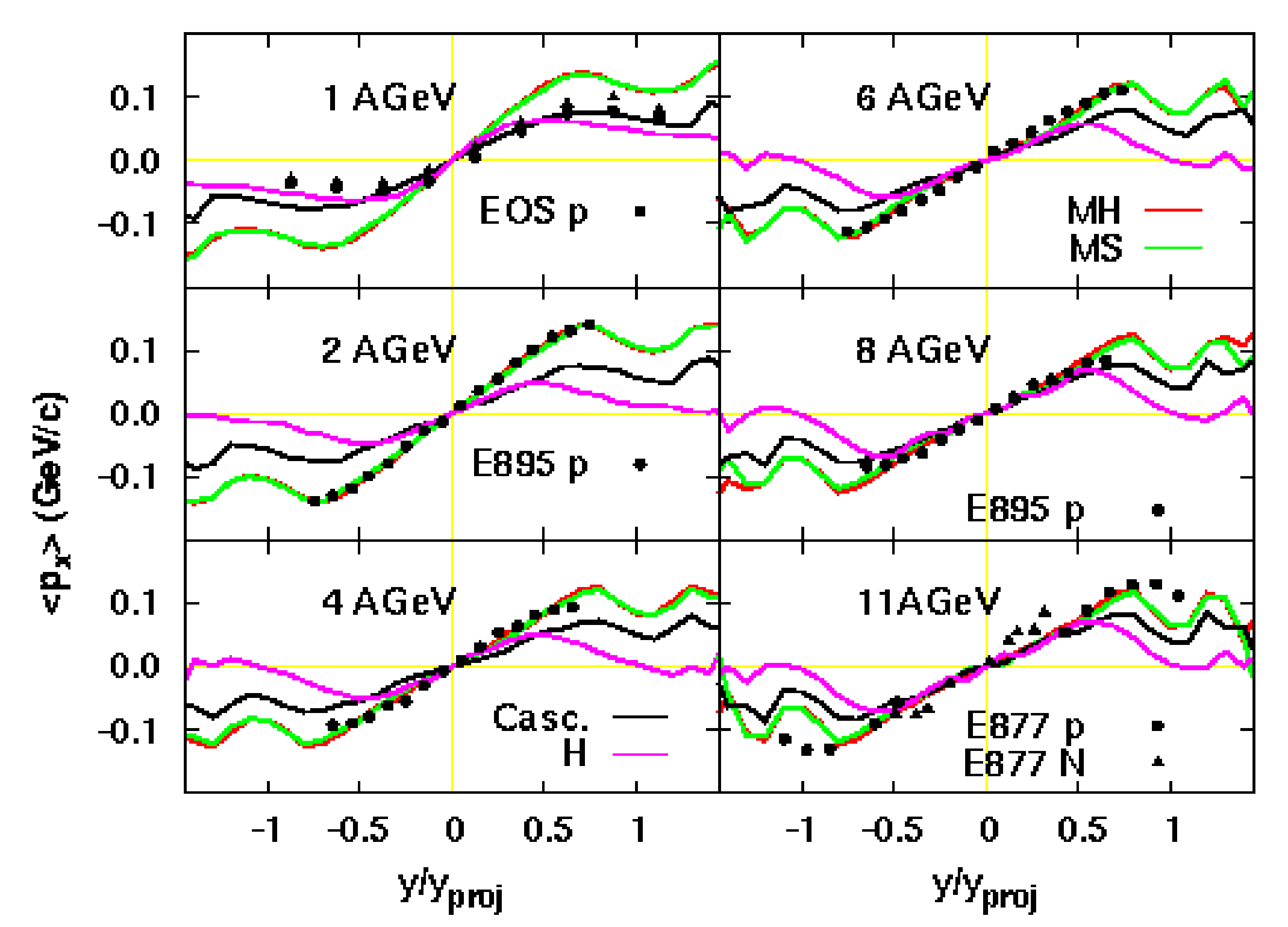
Mean Field Effects in Mt Spectrum



Mean Field affects
the Mt Spectra
even at SPS energy.
→ How about other Flows ?

(Directed) Sideflow at AGS Energies

(Ohnishi, Isse, Otuka, Nara, Sahu, JCNP04 Proc.,
Isse, Ohnishi, Otuka, Nara, Sahu, to be

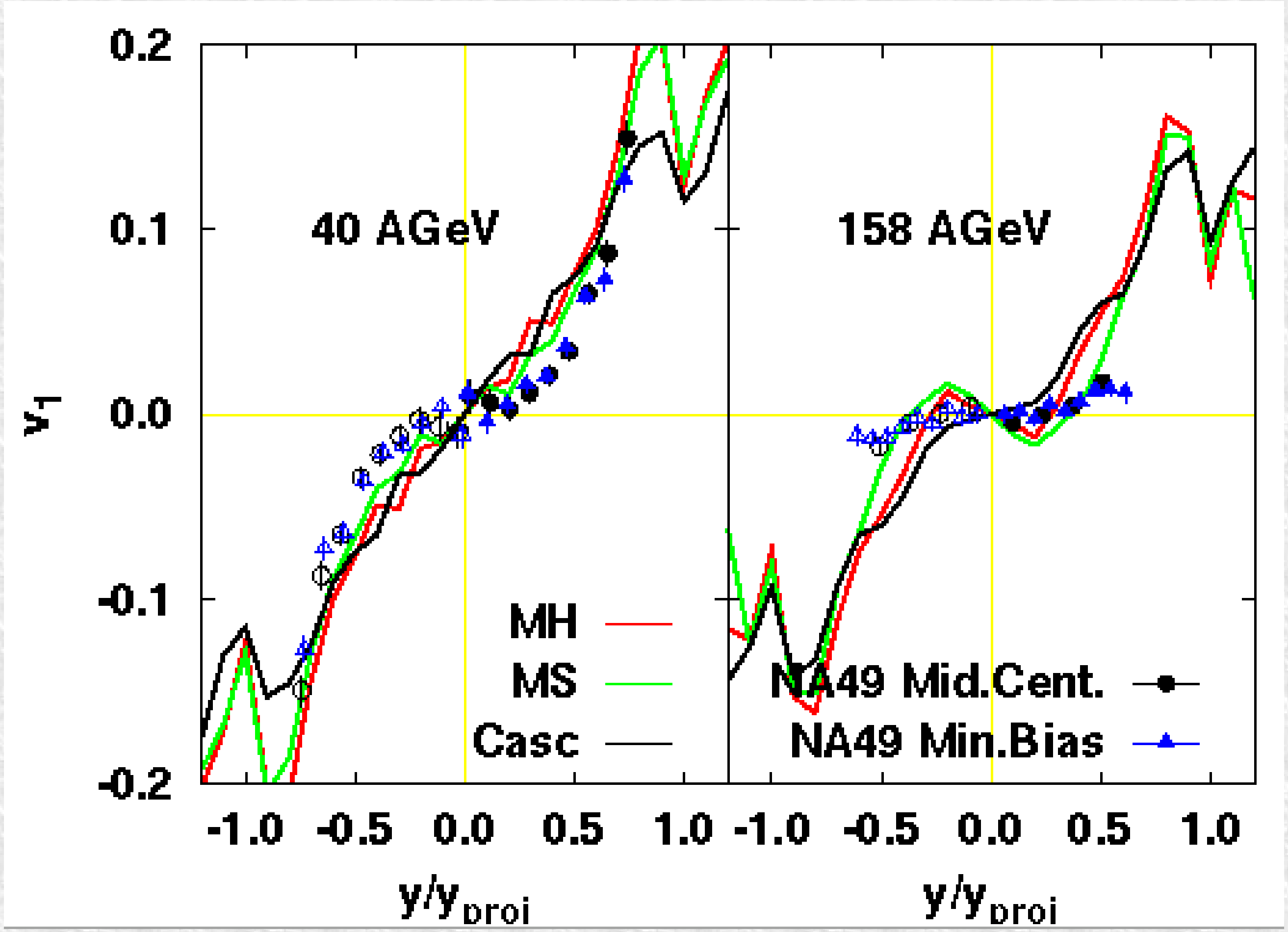


Isse

Momentum Dep. Pot. generally give good description of Data.

(Directed) Sideflow at SPS Energies

$$v_1 \equiv \langle \cos\phi \rangle = \langle p_x / p_T \rangle$$

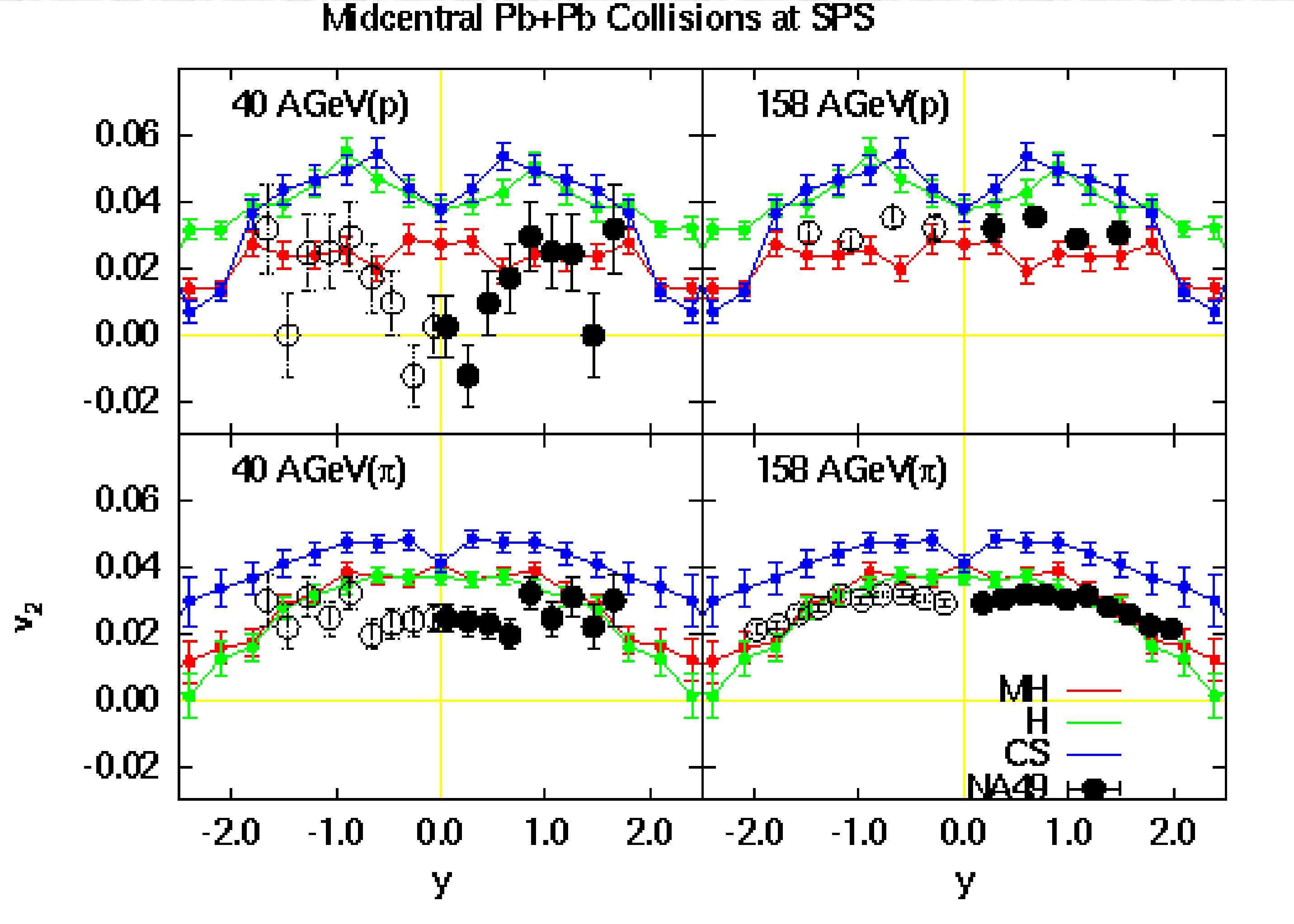


Isse

At 158 A GeV, Reverse Pressure from Spectator can be seen.

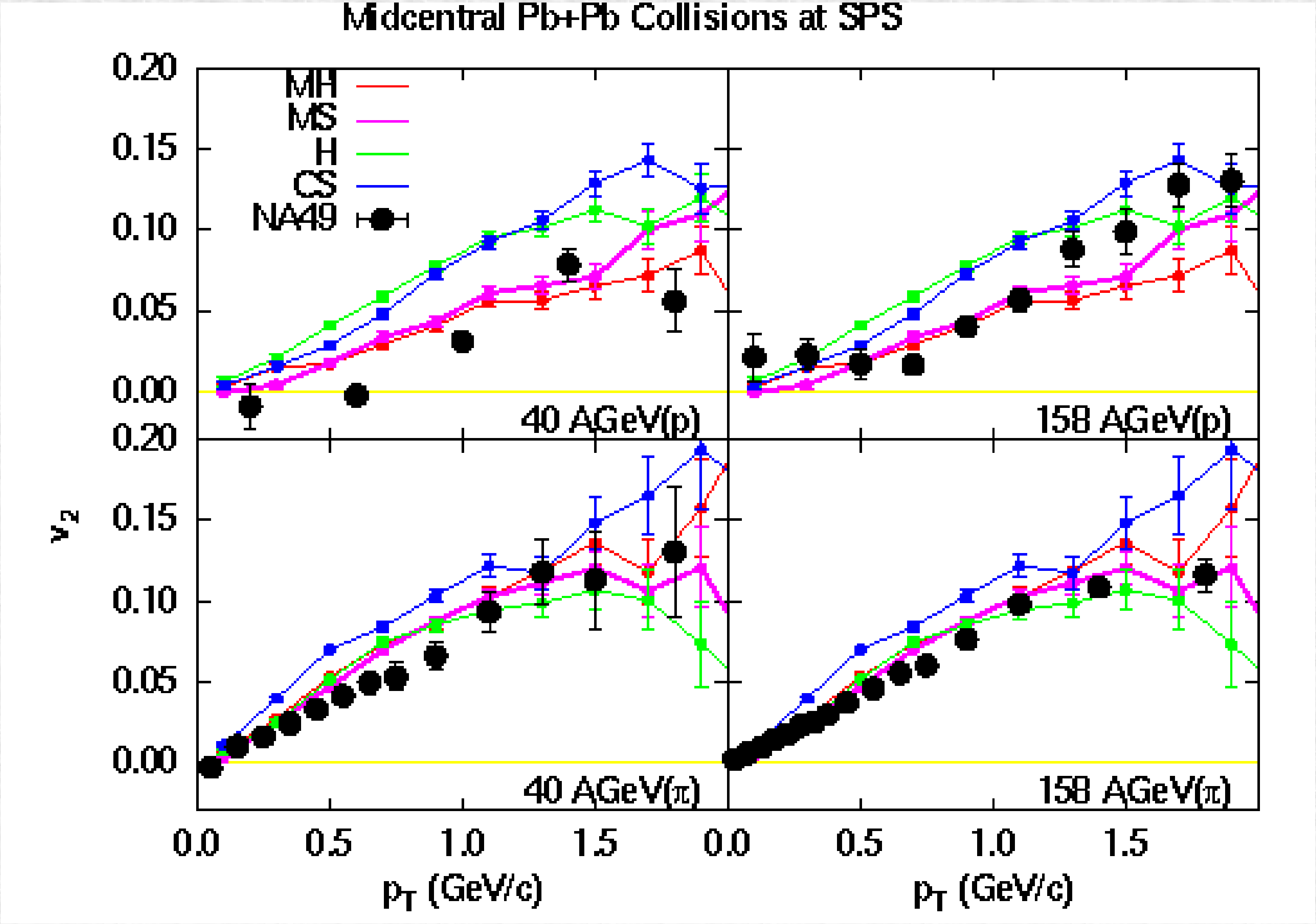
Elliptic Flow at SPS Energies (I)

Isse



158 A GeV: Good with MF / 40 A GeV: ? at Mid-Rapidity

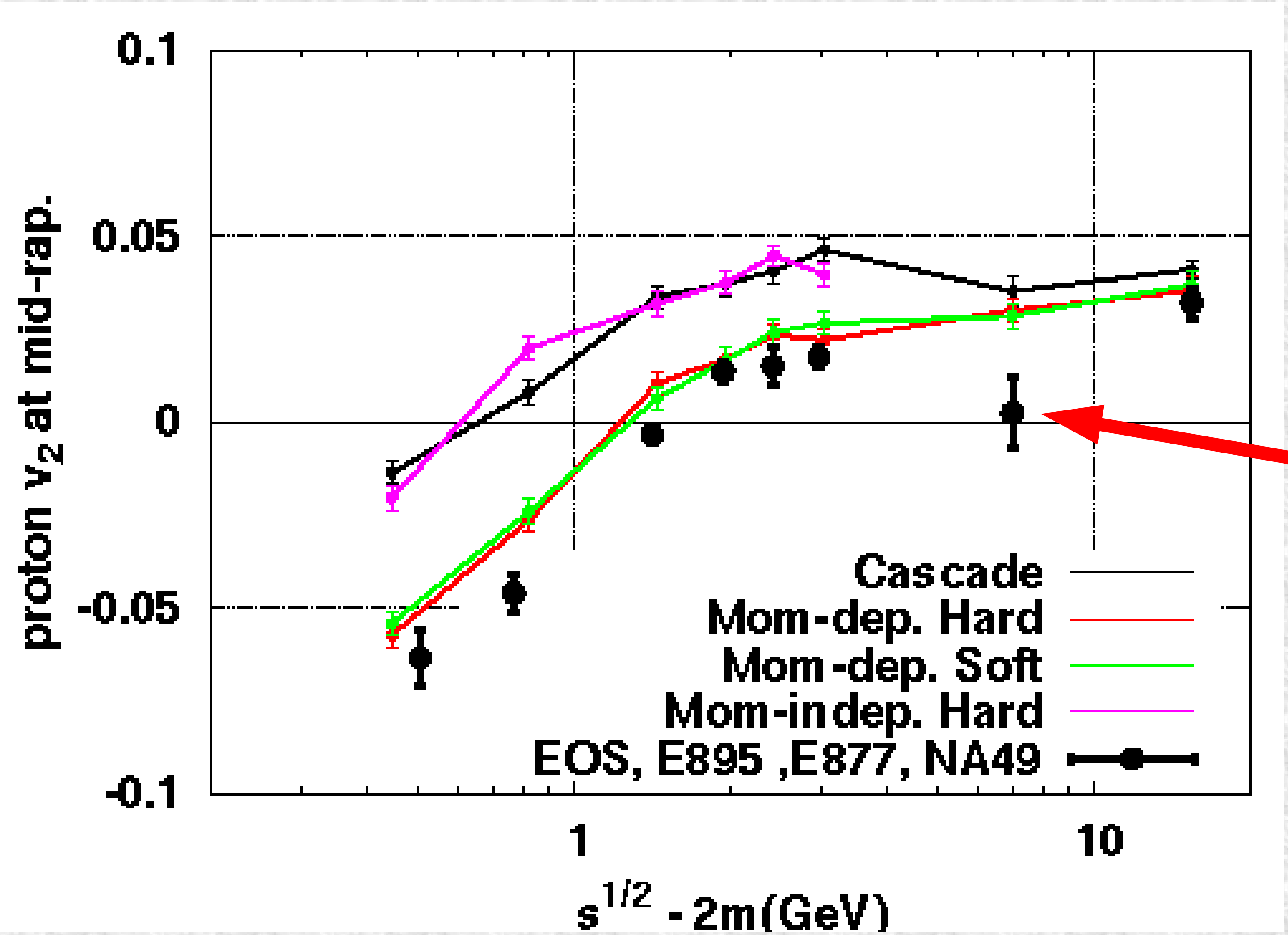
Elliptic Flow at SPS Energies (II)



Isse

Soft EOS may be better .....???

Elliptic Flow from AGS to SPS Energies



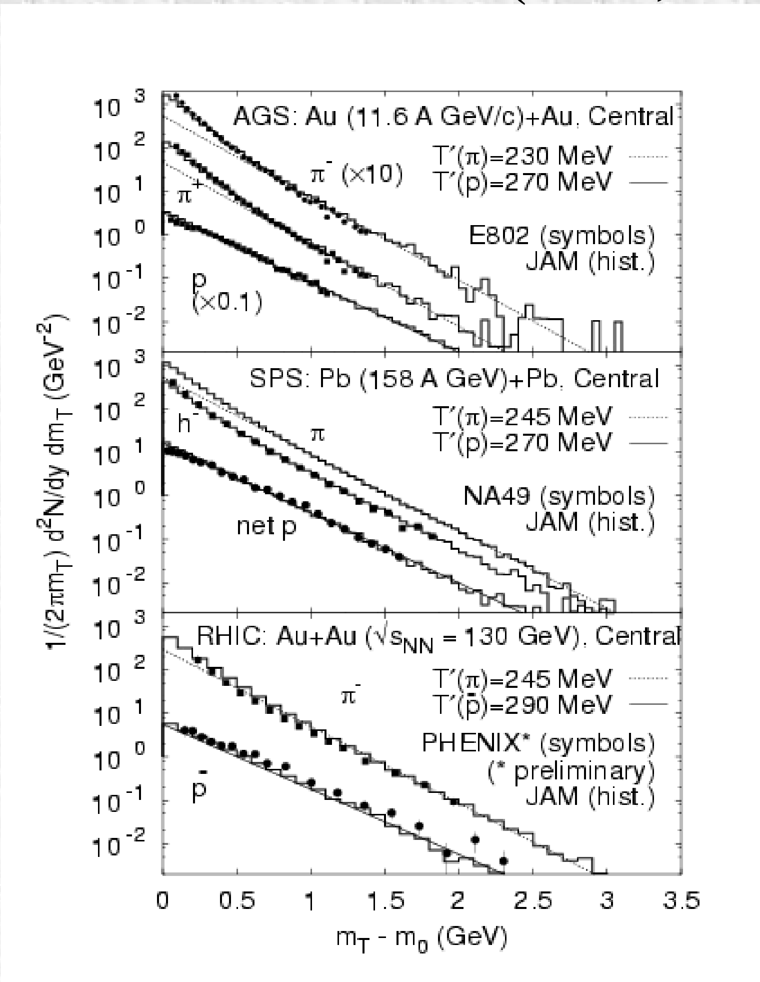
Largely Depends on Analysis Method

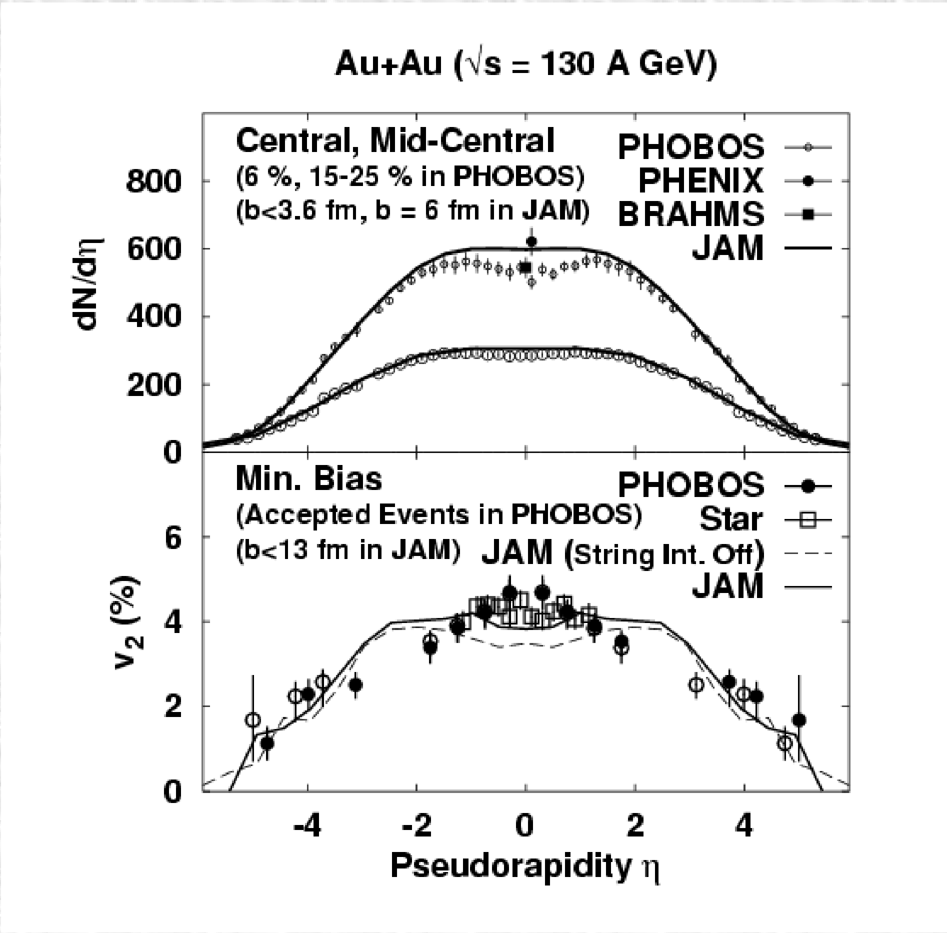
Isse

Potential Effects: Reduces V2 to Some Extent even at SPS

Global Observables at RHIC

(Sahu, Ohnishi, Isse, Otuka, Phatak, to be

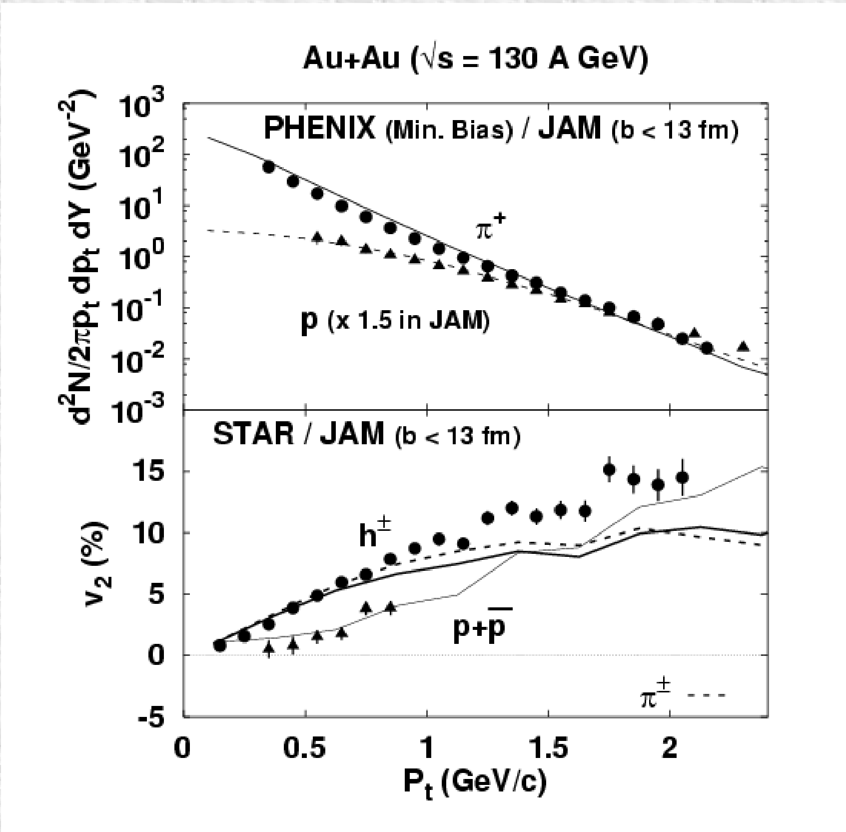




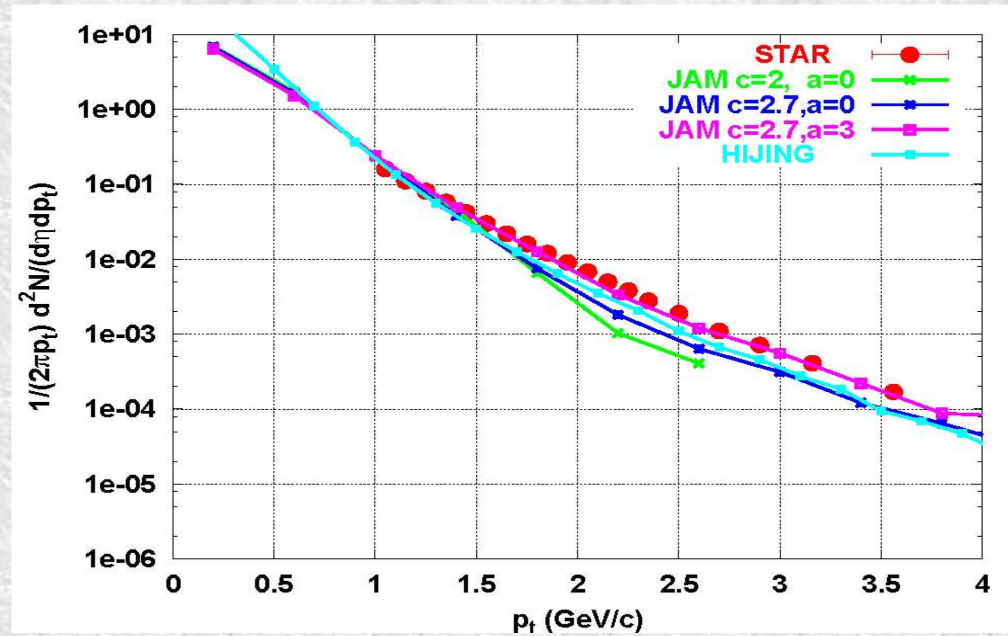
Proton Spectra @ RHIC is too soft in JAM (Proton Puzzle).

** Mean Field Effects are included for AGS and SPS energies*

Elliptic Flow at RHIC (I)



Isse

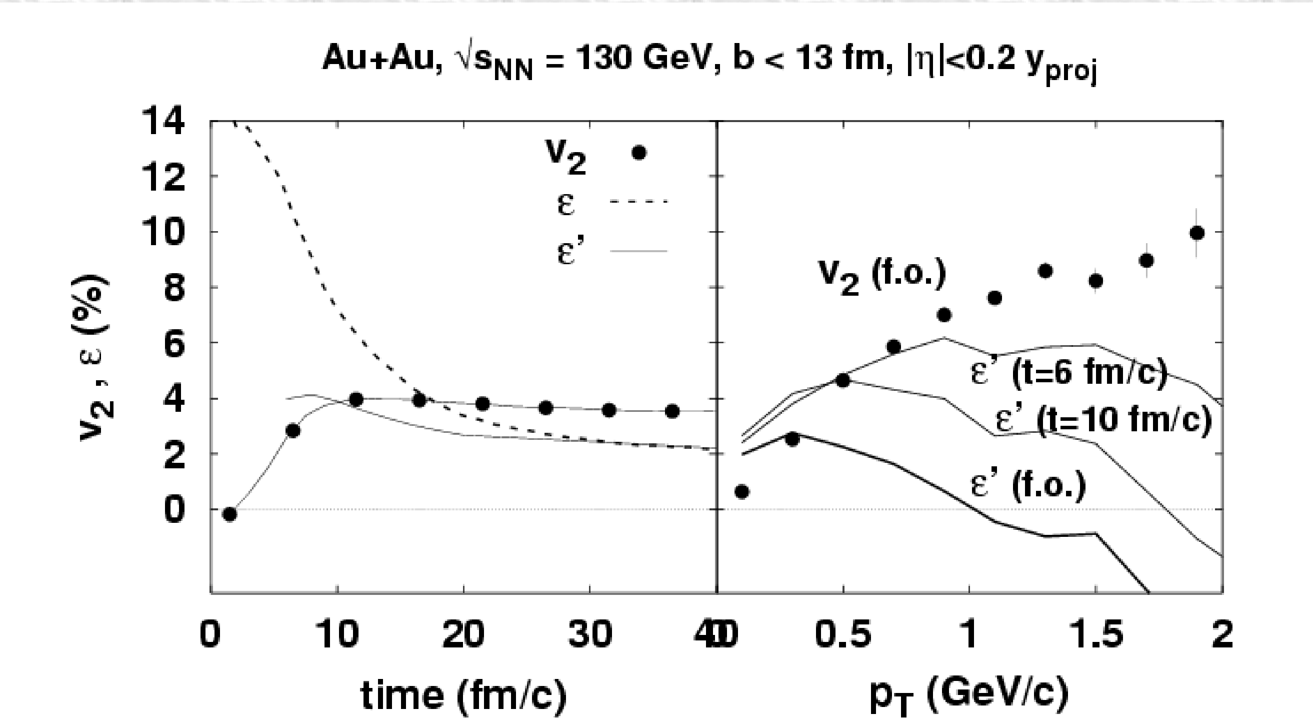


We can fit P_T spectra

by changing the "Thickness" of Nuclei,

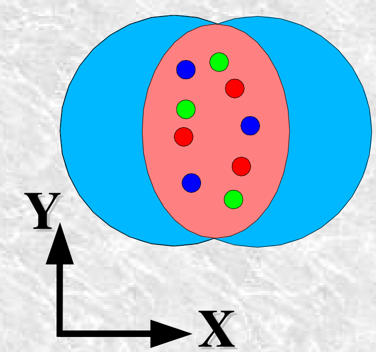
but we cannot Reproduce High P_T Elliptic Flow

When are Collective Flows Generated ?



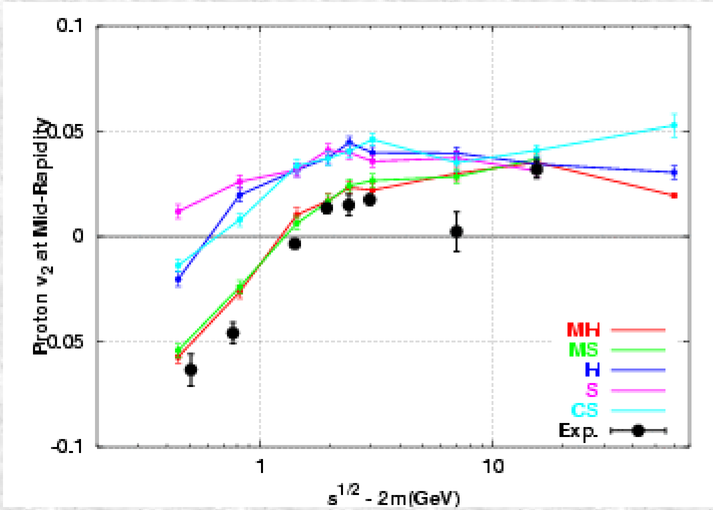
For v2 to grow,
spatial eccentricity
is necessary.

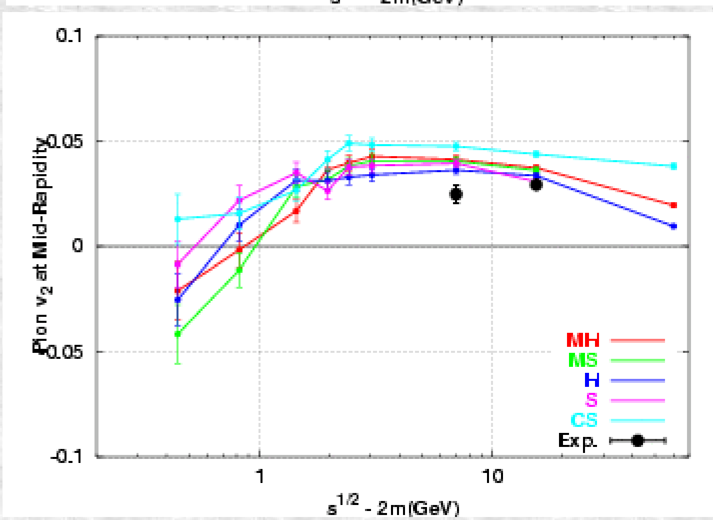
$$\epsilon = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$

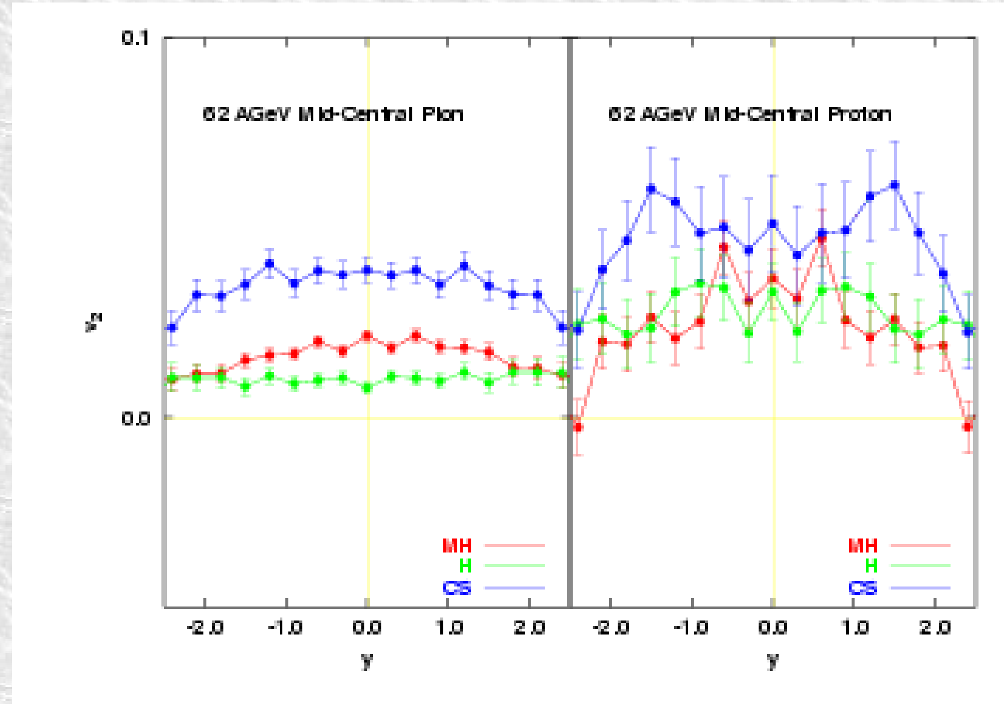


V2 is Generated at a long time scale in Hadron-String Cascade.
After formation time, Almond shape still seems to be kept
Due to forward emission of strings.

Where Does Hadronic Description Fail ?







Isse

√s = 62 GeV: V2 is smaller than that at SPS ?

Summary (I)

- *Collective Flows are sensitive to EOS. Determination of EOS from Flows is an Old but Current (i.e. Long Standing) Problem.*
- *Momentum Dep. of Potential is Essential to understand Flows at High Energies, esp. above 1 A GeV.*
- *Hadronic Cascade with Momentum Dependent Mean Field works systematically up to SPS energies. Precise estimate is still required to determine EOS.*

Summary (II)

- Partons seems to lose energy in the matter formed in Au+Au Collisions at RHIC, but not in d+Au Collisions.
  - Jet Energy Loss: Suppression of High PT particles relative to pp collision
  - Jet Quenching: Suppression of Backward Correlation
- Elliptic Flow at RHIC grows almost linearly up to around P_T = 2 GeV/c, suggesting early thermalization.
- These can be understood in models based on QGP picture, such as Hydro+Jet or Quark Recombination.
- High P_T Elliptic Flow is underestimated in the present Hadronic Cascade. Interactions in the Early Stages seems to be Necessary.

Summary (III)

- ***Where does the BULK QGP FORMATION start ?***
  - ***Up to top SPS, Hadronic Cascade (with Mean Field) seems to work.***
  - ***At $\sqrt{s} \geq 130$ GeV, Hydrodynamics (with Jet Energy Loss) works well.***
  - ***Between SPS and RHIC at $\sqrt{s} \geq 130$ GeV ?***
- ***Smooth Connection of Hadronic and Partonic DOF is necessary at around $\sqrt{s} = 20$-100 GeV !***

Collaborators

- *T. Ohnuma (M1)*
- *M. Isse (D2)*
- *N. Otuka (JAERI)*
- *Y. Nara (Arizona)*
- *P.K. Sahu (India)*

Thank You !

Hadronic Matter Phase Diagram