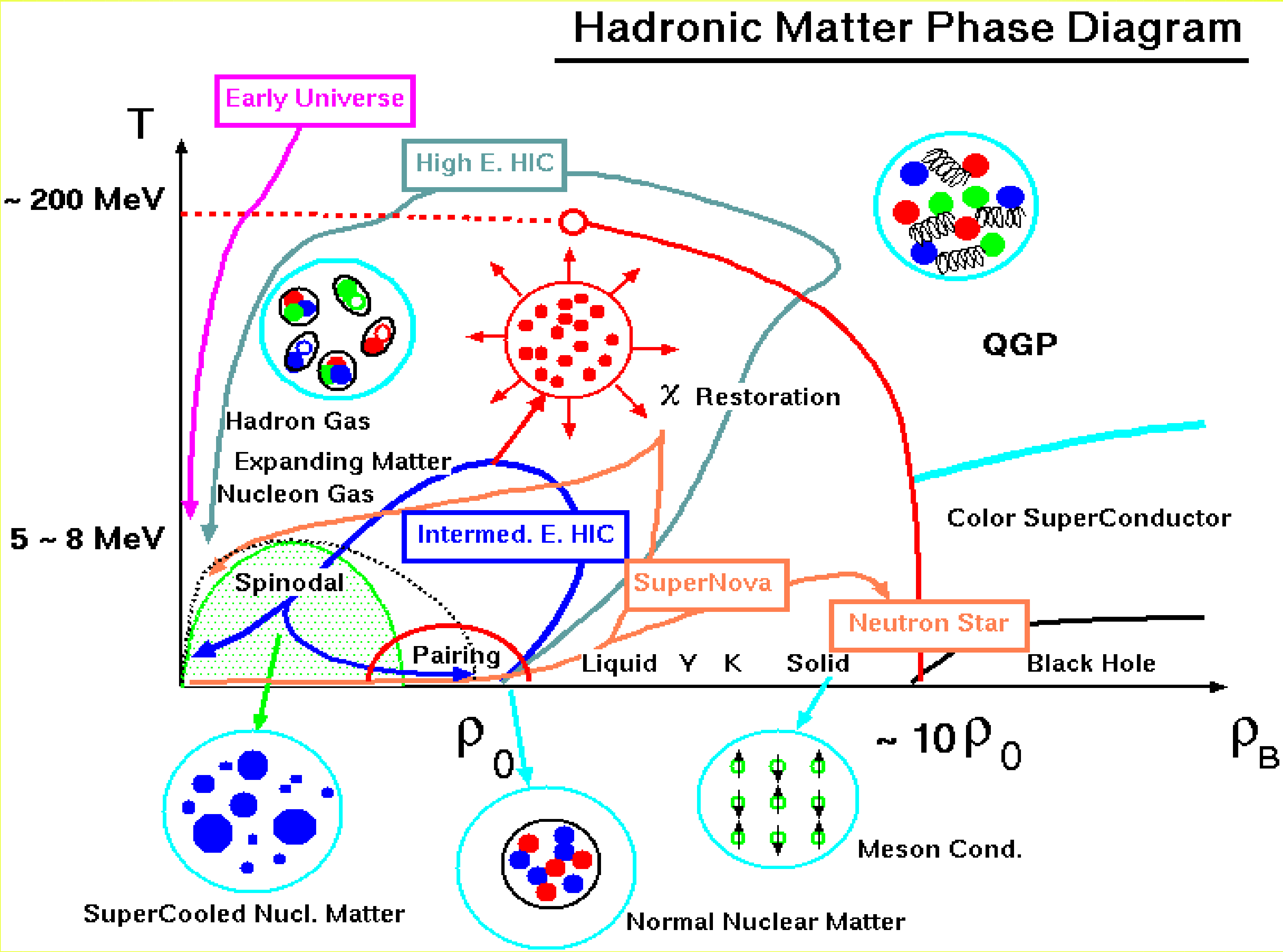
# RHIC エネルギーでの粒子相関

Akira Ohnishi (Hokkaido Univ.)

1. Introduction
2. Hadronic Cascade Study at AGS Energy
3. Elliptic Flow at RHIC Energy
4. Two Particle Momentum Correlation (Status Report)
5. Summary

In Collaboration with
***M. Isse, N. Otuka, P.K. Sahu, C. Phatak, Y. Nara***

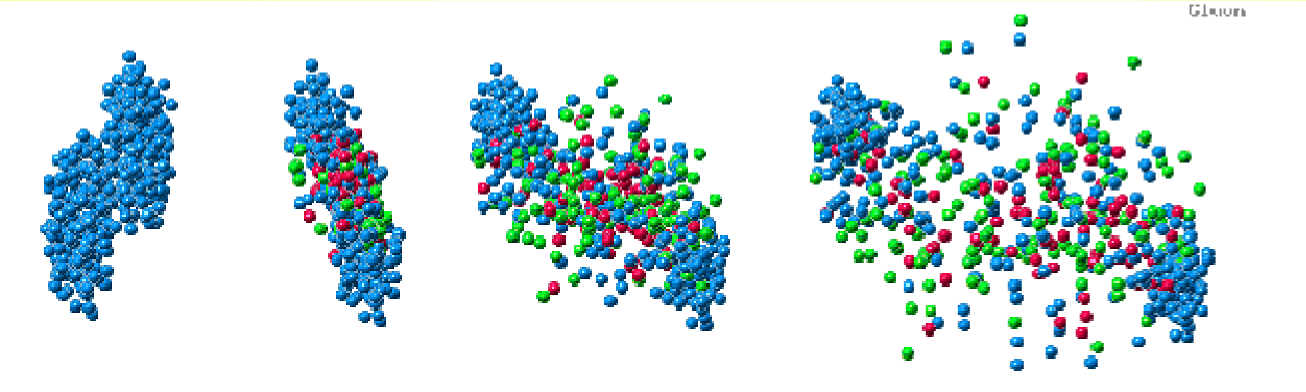
Sec. 4: In Future collaboration with
***Asakawa, Kitazawa, Ikeji, Tsumura***


Hadronic Matter Phase Diagram
Early Universe
T
High E. HIC
~ 200 MeV
QGP
Hadron Gas
χ Restoration
Expanding Matter
Nucleon Gas
5 ~ 8 MeV
Intermed. E. HIC
Color SuperConductor
Spinodal
SuperNova
Neutron Star
Pairing
Liquid Y K Solid
Black Hole
ρ0
~ 10ρ0
ρB
Meson Cond.
SuperCooled Nucl. Matter
Normal Nuclear Matter

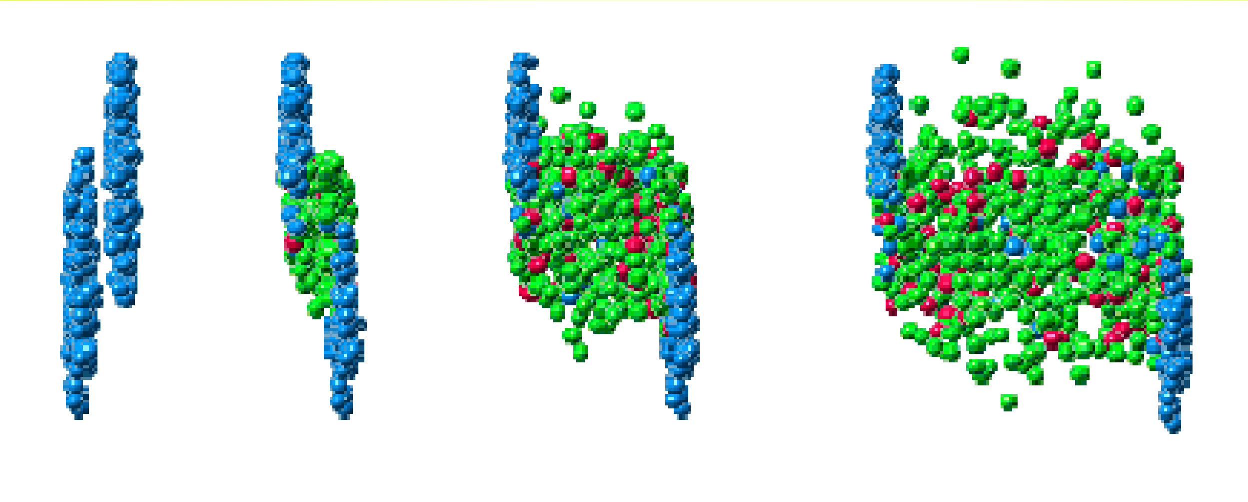
# JAMming on the Web

**http://nova.sci.hokudai.ac.jp/~ohtsuka/**

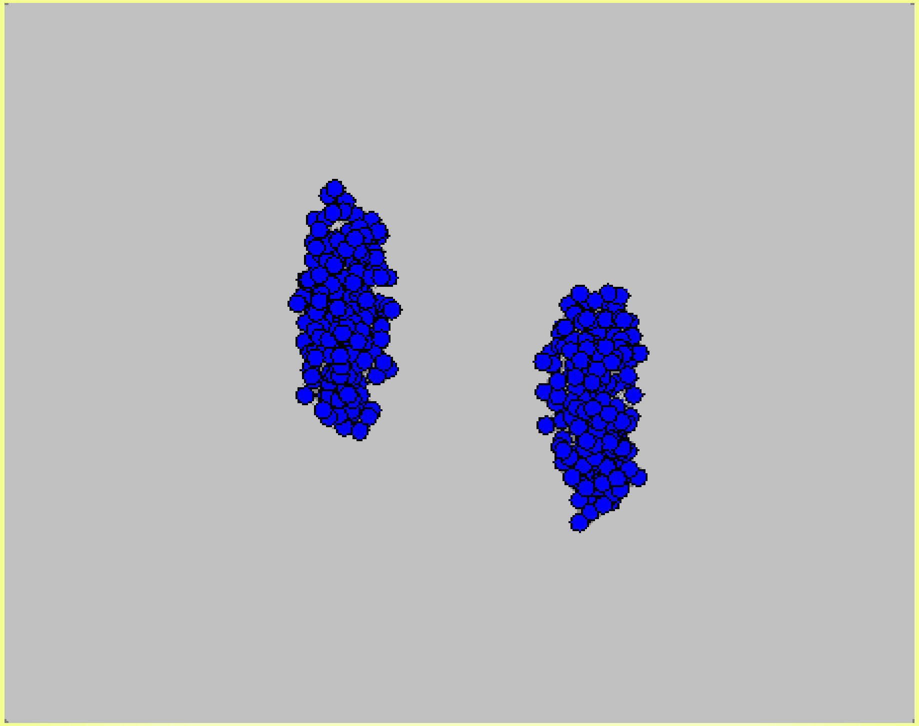
## AGS




## SPS



Collision Examle



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

## Proposed and/or Measured Signals

- 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*

*Do these "SIGNALS" really signal QGP formation ?*

# Hadronic Cascade Study of Collective Flows at AGS Energy

# What is Collective Flow ?

**(Directed) Flow ($dP_X/dY$)**

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

**Elliptic Flow ($V_2$)**

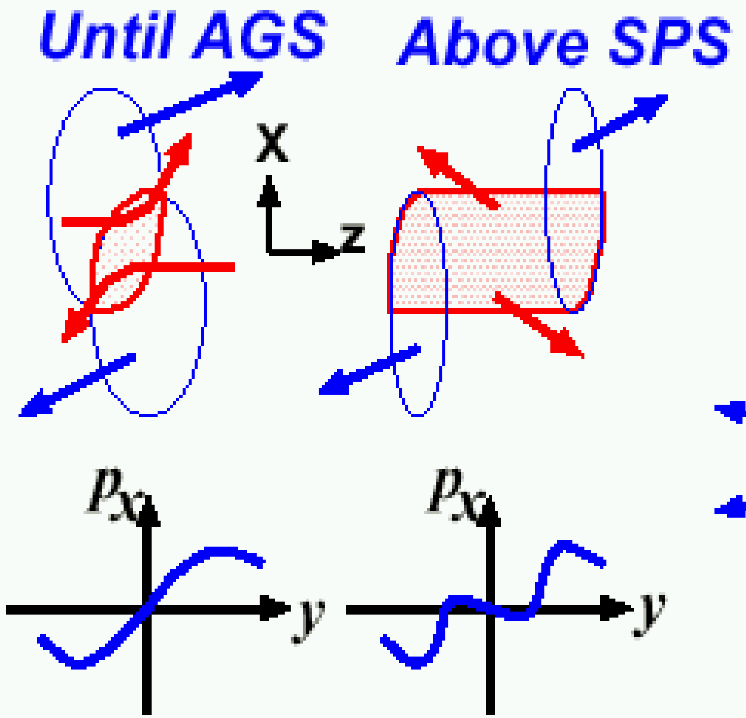
Thermalization
& Pressure Gradient

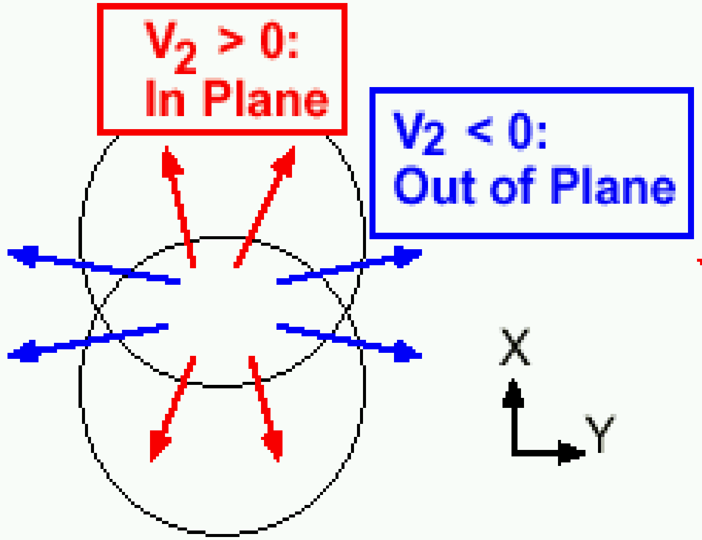
**Radial Flow ($\beta_T$)**

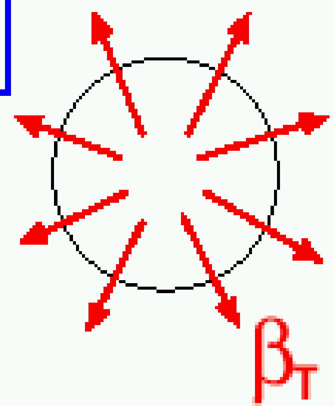
Pressure History

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

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




**Complex Observables, but Closely Related to EOS**

# JAM (Jet AA Microscopic transport model)

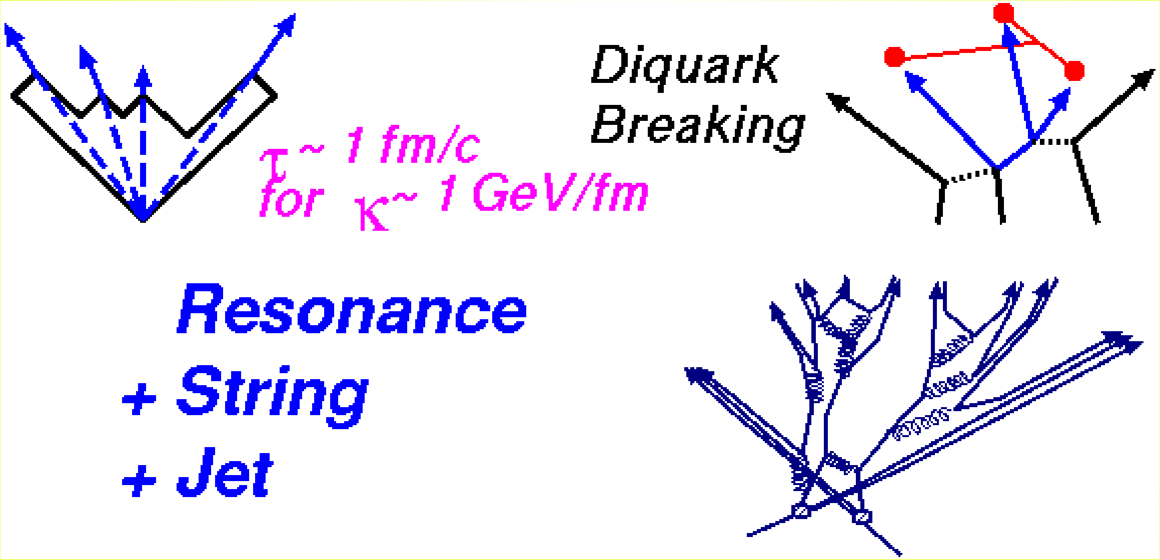
Y. Nara et al., Phys. Rev. C61 (2000), 024901.

**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

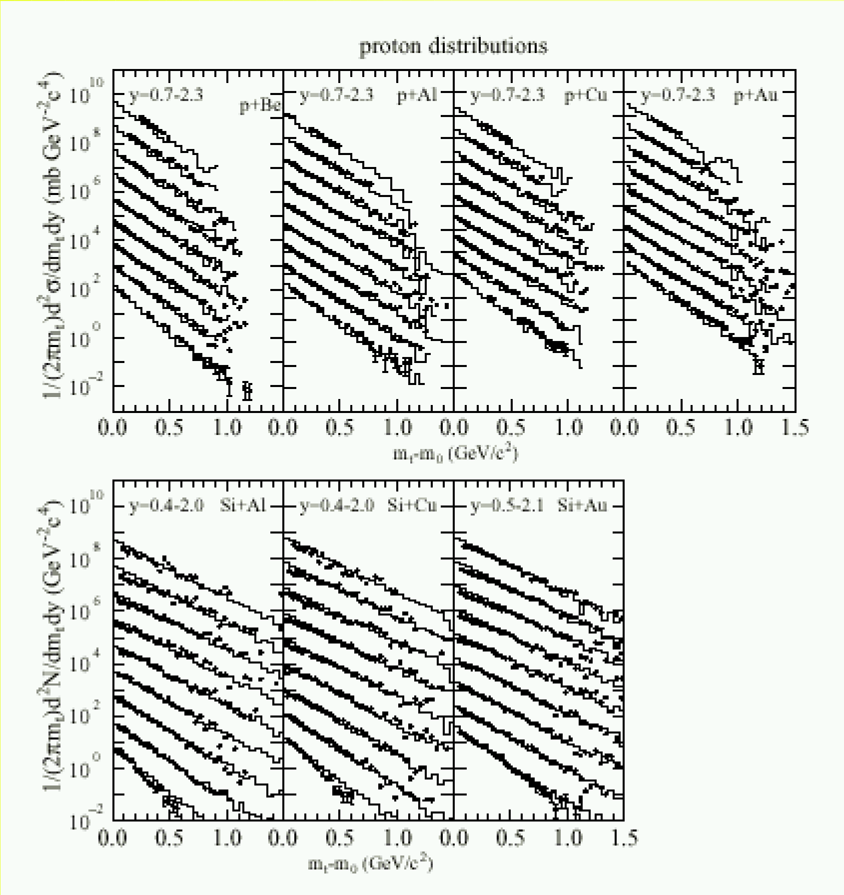
[2] Consituent Rescattering (~ RQMD)

# Followings are NOT included in JAM

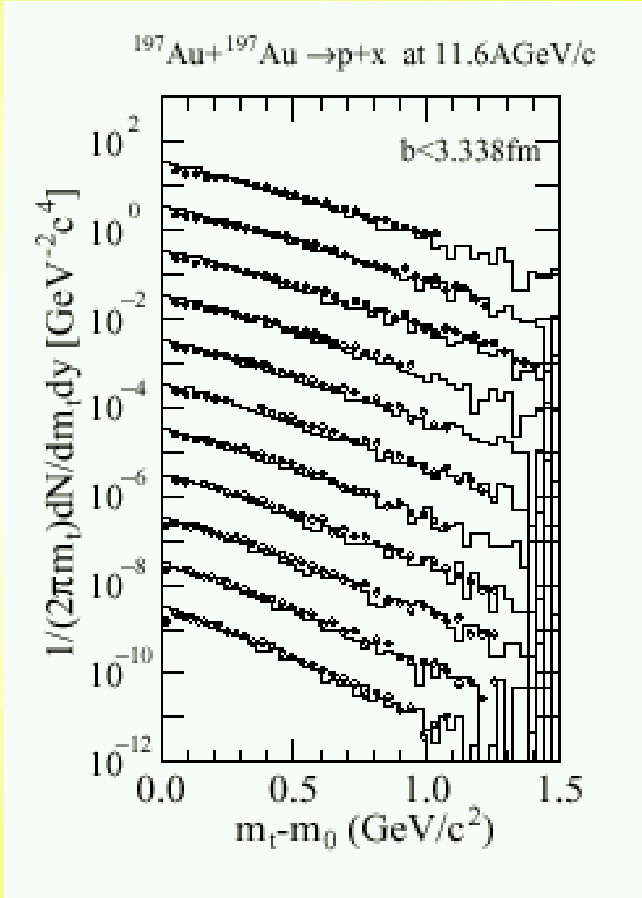
Mean Field (in progress)
Medium Modification
Secondary Interaction of Partons
with Other Hadrons, String and Partons from Other Jets

# JAM Results @ AGS Energy

## p-A Collision




## Au+Au Collision



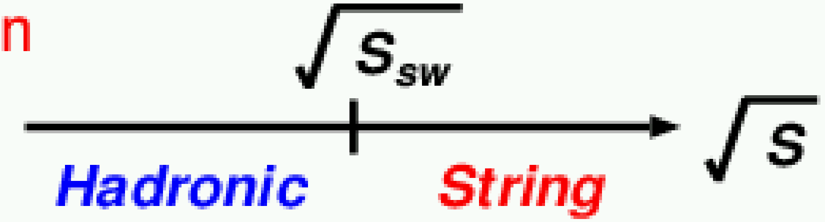

*JAM explains AA collisions as well as pA collisions:*
*→ Good Elementary Cross Sections for MM, MN and NN*

# 高エネルギー重イオン反応による状態方程式の探索

**RBUU (Relativistic Boltzmann-Uehling-Uhlenbeck model)**

P. K. Sahu et al., NPA672('00)376.

- ⋆ DOF: $h$(B, B$^*$, M, M$^*$ (m $\leq$ 2 GeV)) + $s$(Strings)
- ⋆ $\sigma$: Hadronic (BB $\leftrightarrow$ BB$^*$, NN $\leftrightarrow$ $\Delta\Delta$, MB $\leftrightarrow$ B$^*$, ...) + String Form. and Frag. (HSD by Cassing)
- ⋆ Energy Domain Separation




- ⋆ Relativistic Mean Field ($\sigma\omega$ + U($\sigma$) + Form Factor)
- ⋆ Medium Modifications

# Equation of State at High Densities/High Momentum

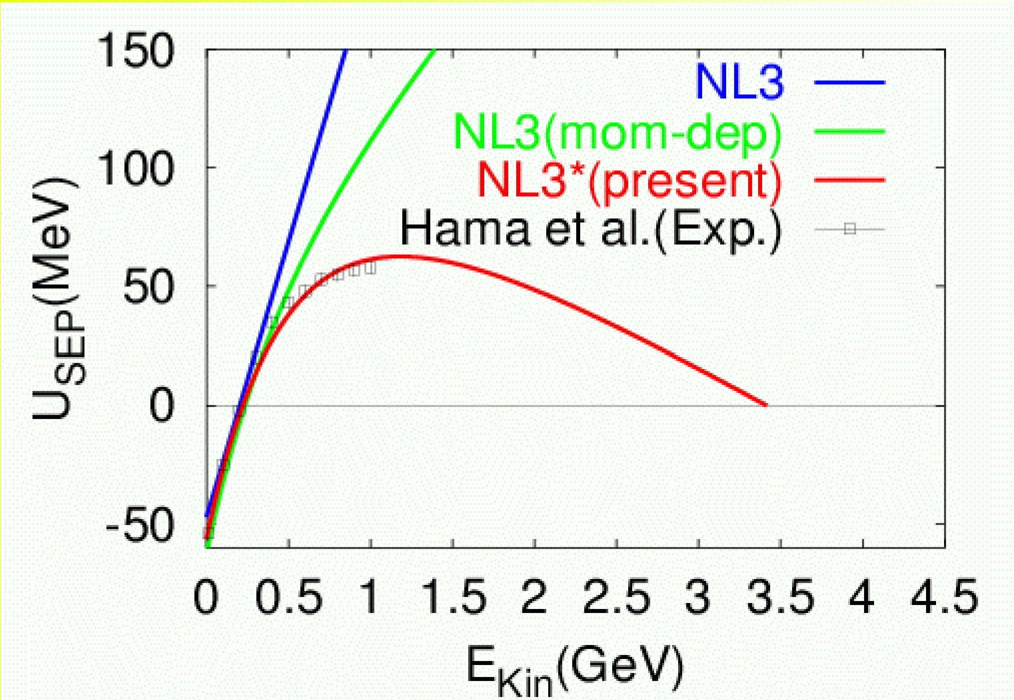
- Energy Dependence: Form Factor of MB Coupling

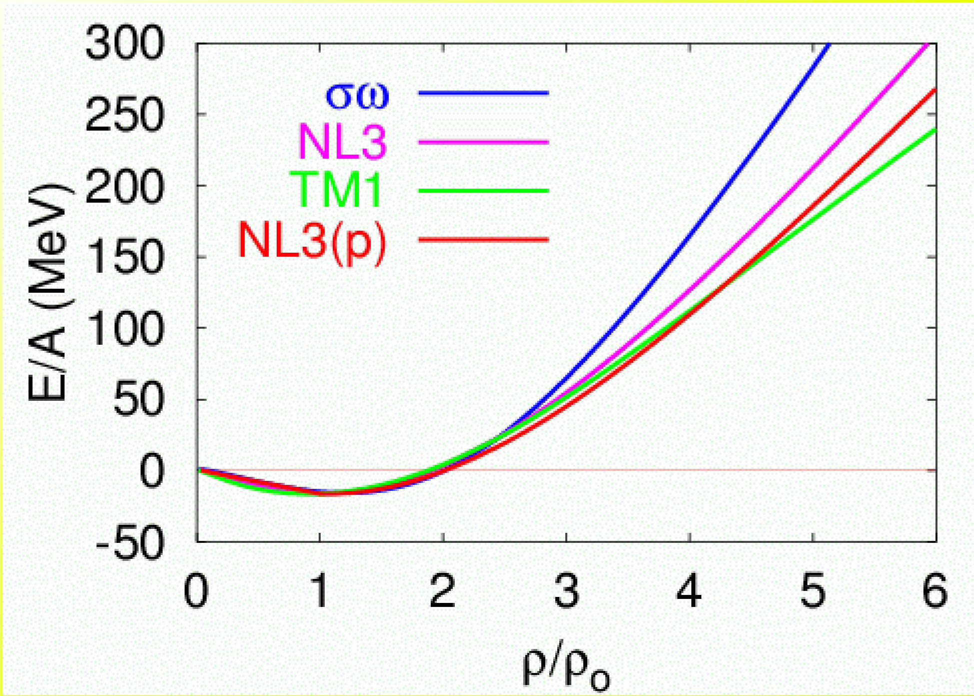
Schrödinger Equivalent Potential

$$U_{sep}(E_{kin}) = U_S + U_0 + \frac{1}{2M}(U_S^2 - U_0^2) + \frac{U_0}{M} E_{kin}$$

Form Factor: Reduce MB Coupling at High Momentum

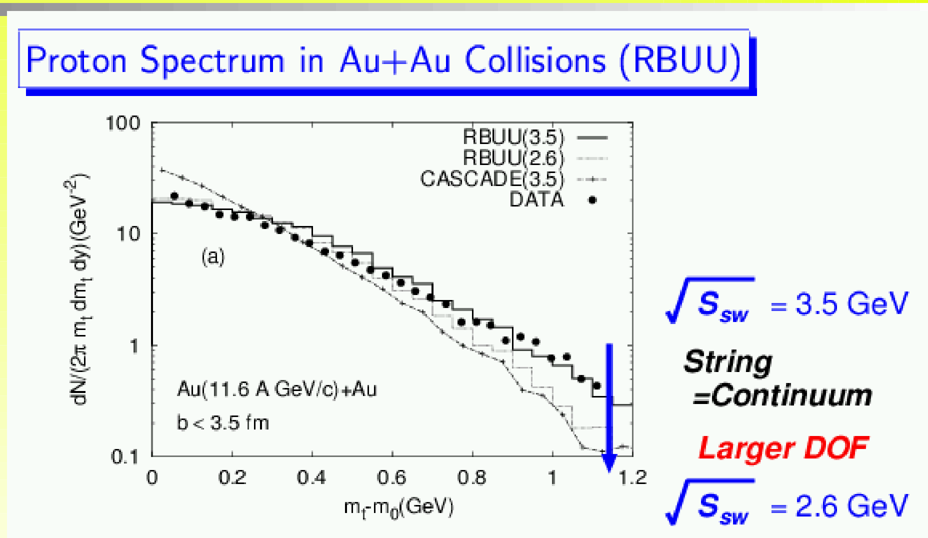
$$f_S(\mathbf{p}) = \frac{\Lambda_S^2 - \alpha \mathbf{p}^2}{\Lambda_S^2 + \mathbf{p}^2} \quad \text{and} \quad f_V(p) = \frac{\Lambda_V^2 - \beta \mathbf{p}^2}{\Lambda_V^2 + \mathbf{p}^2} \ ,$$



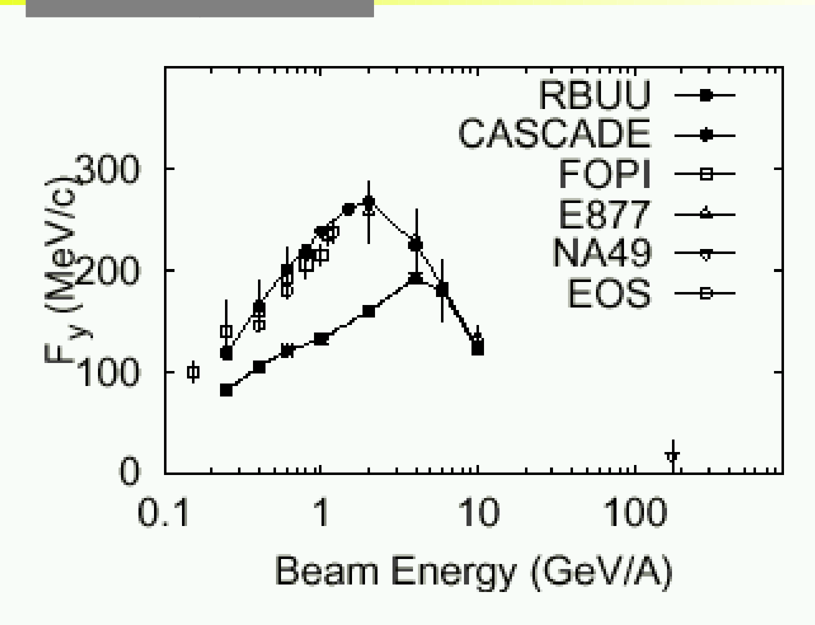



# RBUU Results

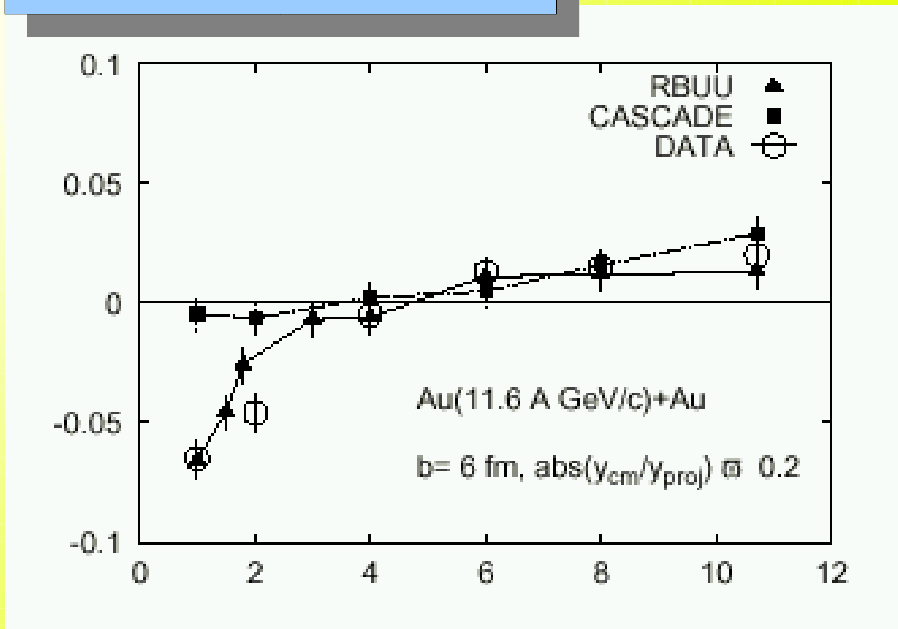
## (Sahu,Cassing,Mosel,AO, 2000)




## Side Flow



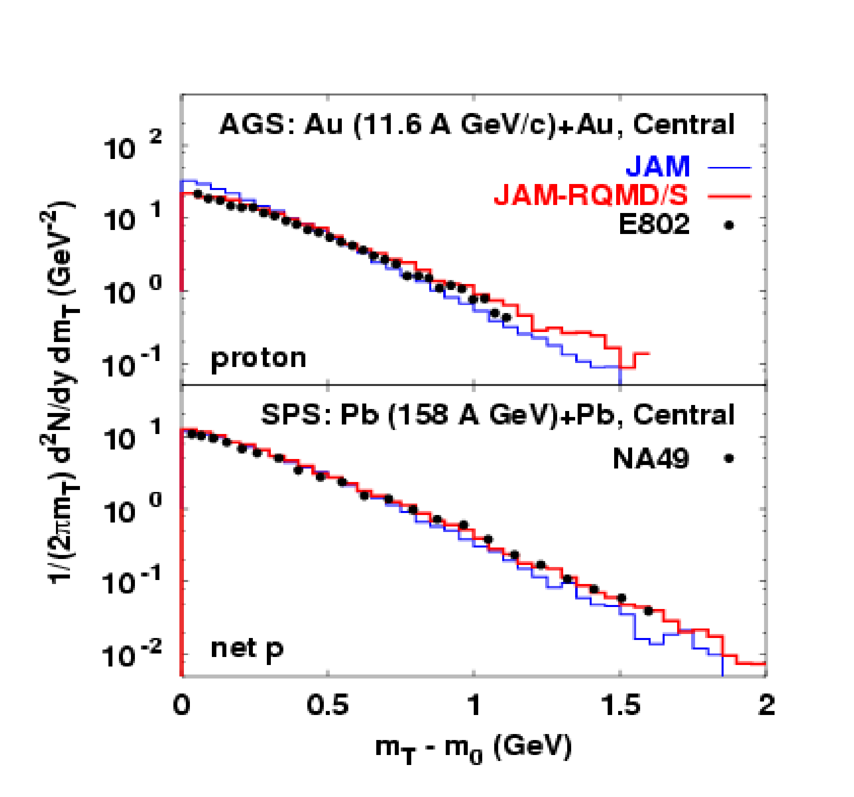

## Elliptic Flow ($v_2$)



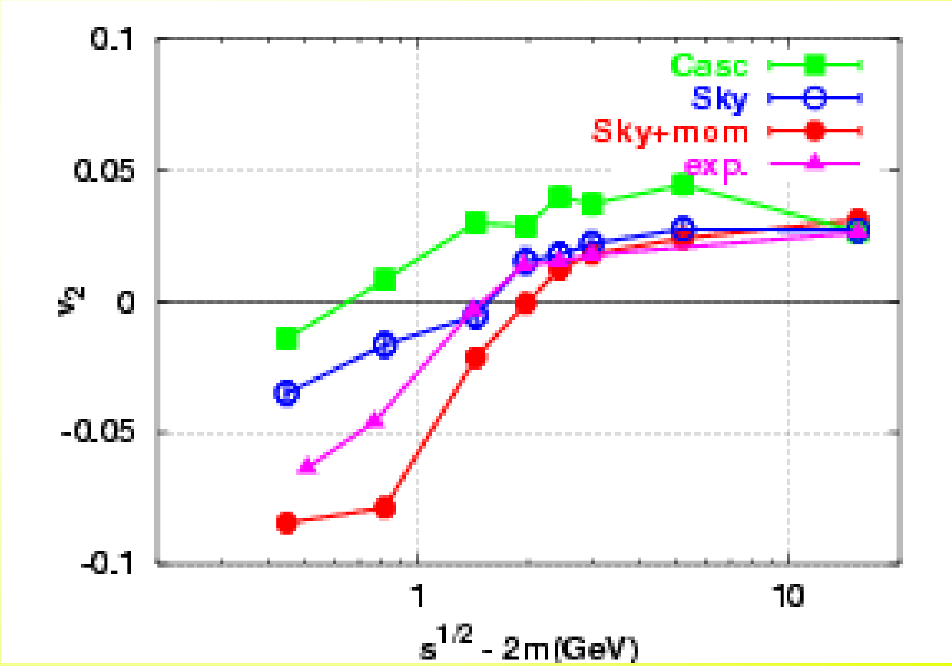

**Three kind of flows can be explained by choosing EOS and DOF**

# Incident Energy Deps. of V2

## Mean Fields Effects (JAM-RQMD/S)




## M. Isse, Master Thesis




**Mean Field Effects → Downward Shift in V2**

# Short Summary at AGS Energies

- Hadronic cascade gives good description of Hadron Spectra from pA to AA collision upto AGS (or SPS) energies.
- Mean Field Effects are important up to SPS Energies.
- Especially, in understanding
  Side flow and Elliptic flow,
  Mean Field Effects are essential.
- In the present Hadronic Cascade models, Resonance and String DOF seems to be NOT continuous. I.e., when we modify the switching mass, calculated results change.

**How about at RHIC ?**

# Elliptic Flow at RHIC Energy

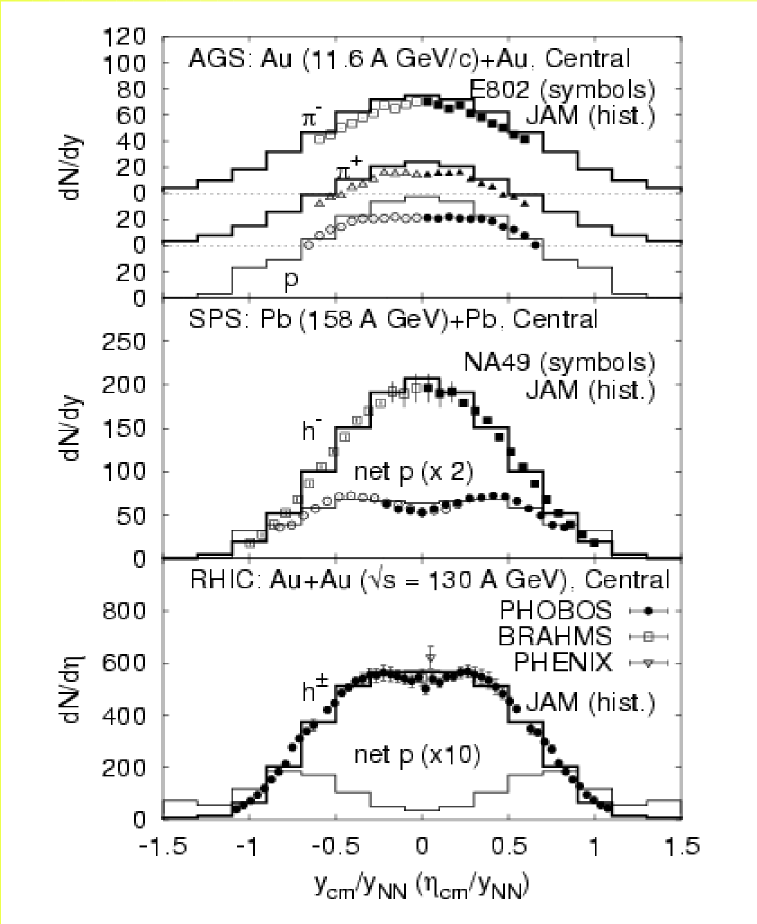
# What is Suggested from Collective Flows at RHIC

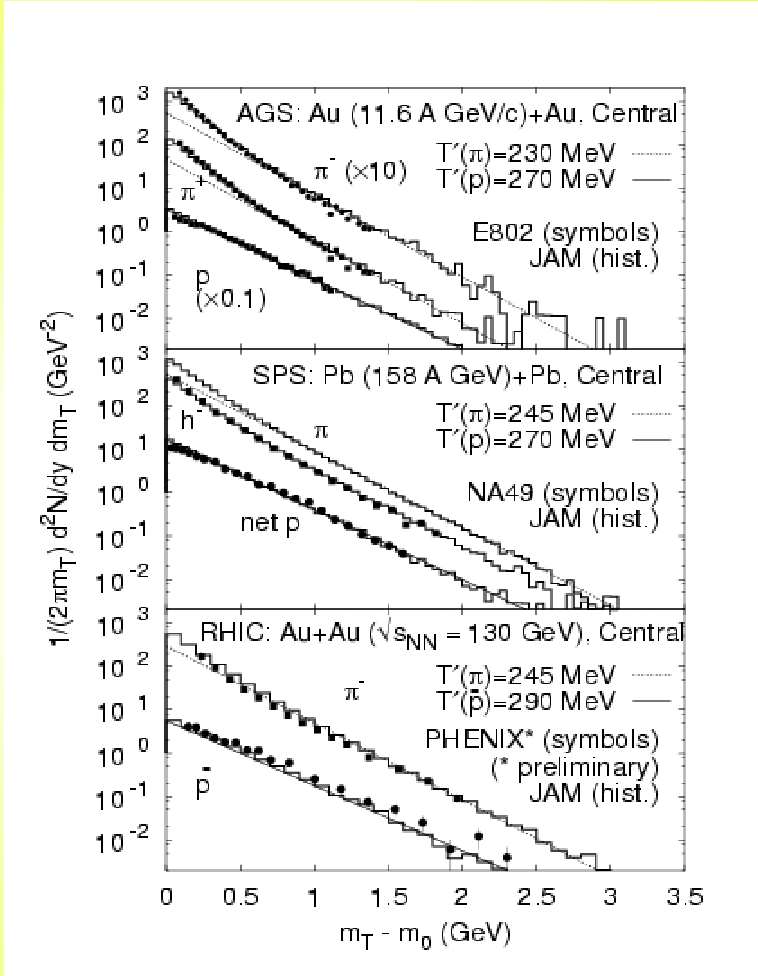
- Hard Proton Spectrum
  → Large Pressures during expansion
- Elliptic Flow
  → Early Thermalization (=Pre-Hadronic Interaction)
- Jet Observation ($\phi$ Correlation, Energy Loss)
  → Partons are Propagating

***Do these really require QGP formation ?***

→ *Verification in Hadron-String Cascade Model is Necessary*

# Hadron Spectra at AGS-SPS-RHIC



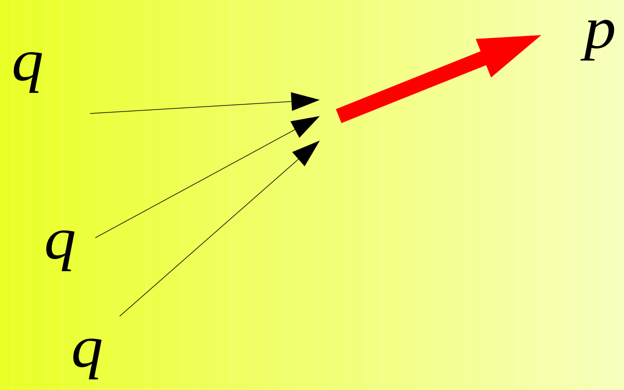



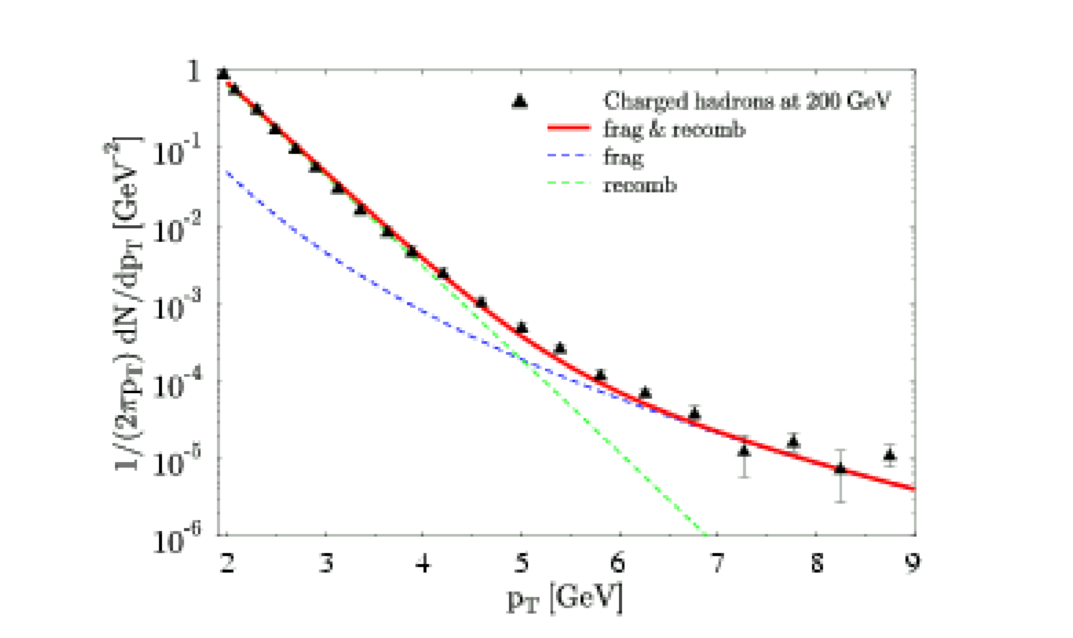

**Proton Spectra @ RHIC is too soft in JAM (Proton Puzzle).**

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

# Another Interpretation of Proton Enhancement: Quark Recombination

**(Fries, Bass, Mueller, Nonaka, nucl-th/0301087; PRC(2003))**

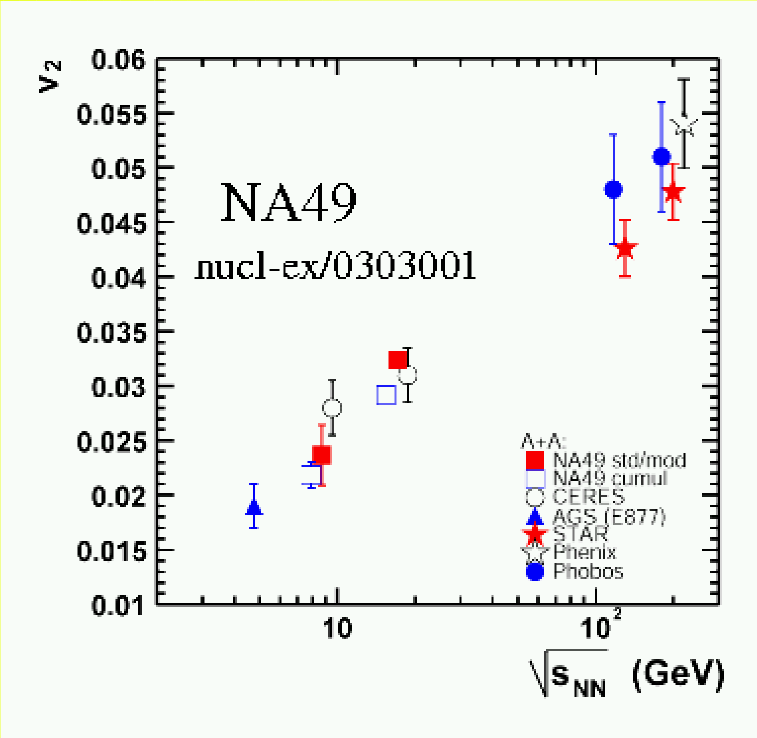


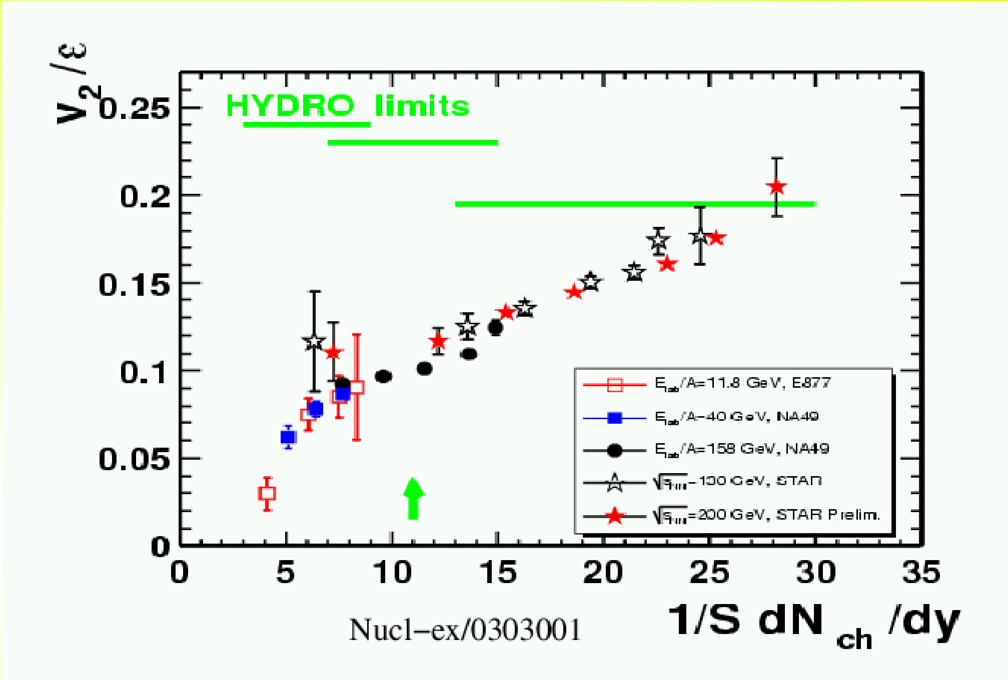




***Quark Recombination model also requires that quarks move freely.***

**Another interpretation: Difference of Hydro. & Jet dominating $p_T$.**
**(Hirano & Nara)**

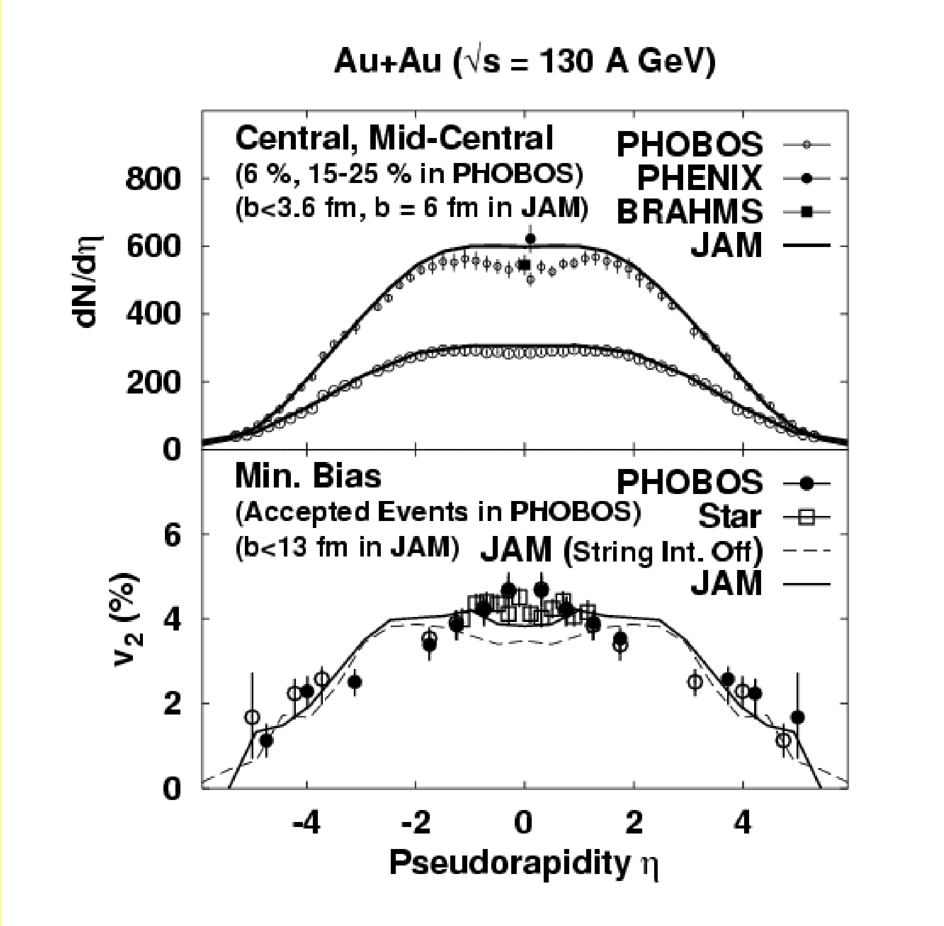
# Elliptic Flow from AGS to RHIC



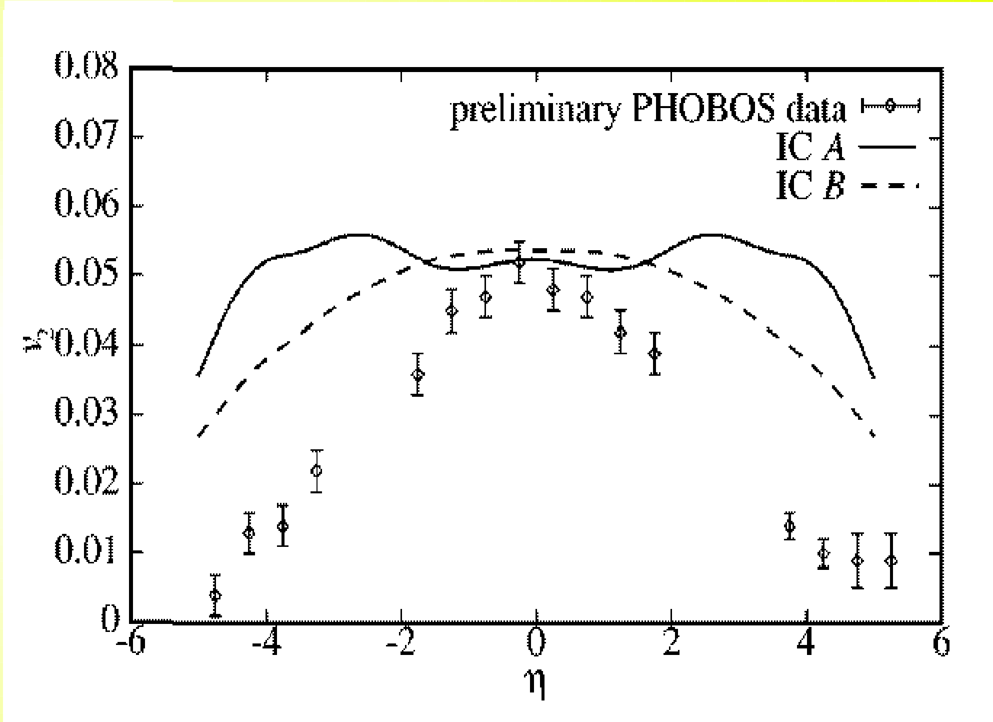




- Anisotropic Pressure is close to Hydrodynamical Values @ RHIC
  → Particles should interact before Almond Shape is obscured.
- ? Incident Energy Dependence is Smooth. Why ?

# Pseudo Rapidity Dep. of Elliptic Flow




## Hydro Results (Hirano, 2001)

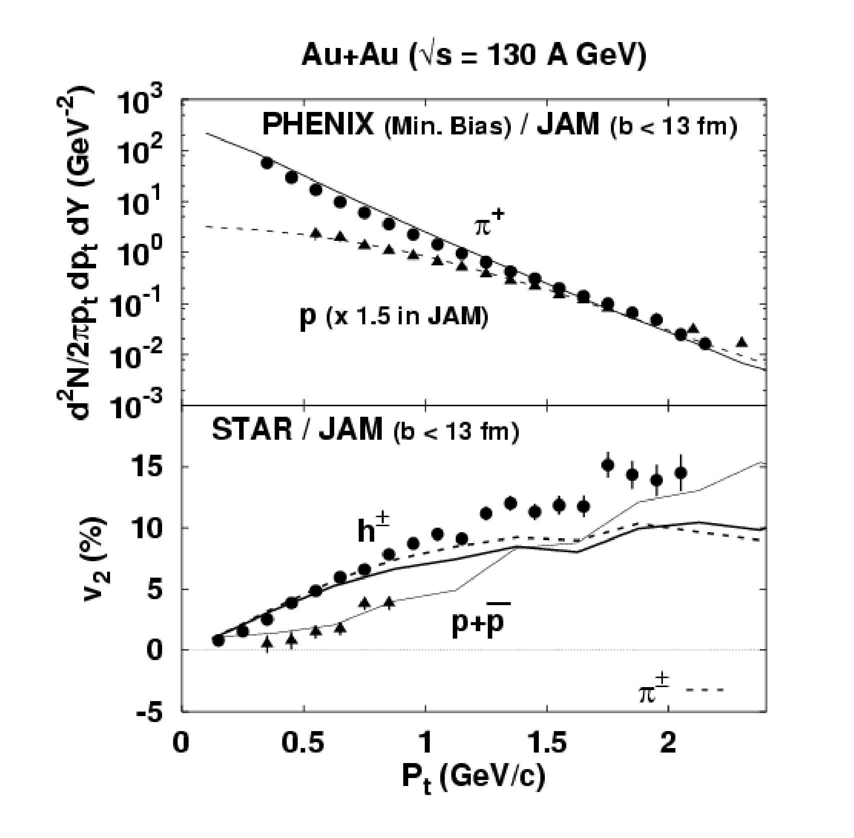


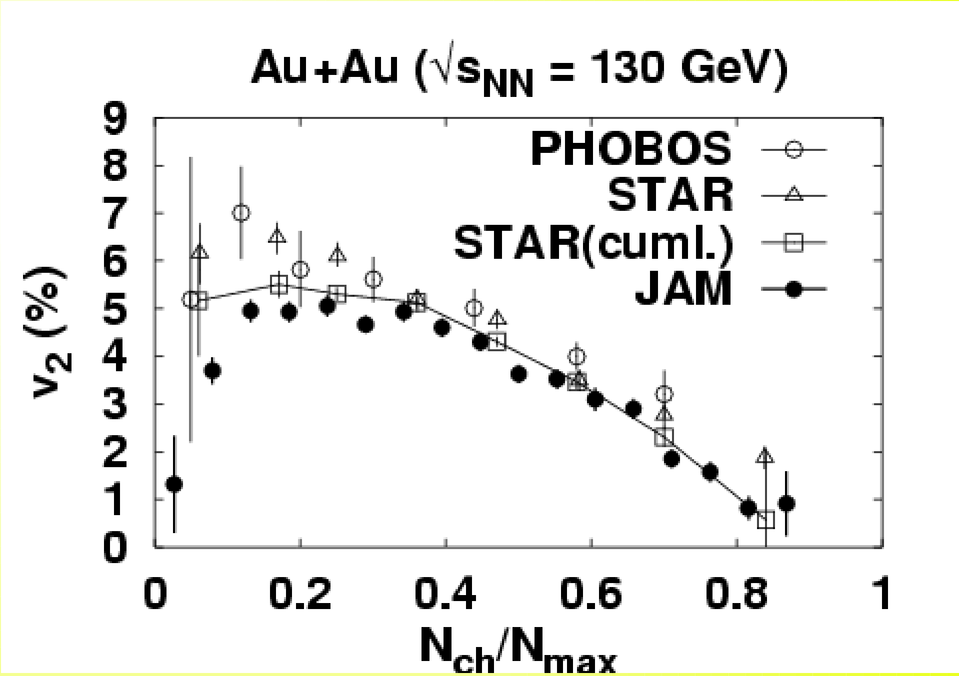

*Flat $v_2$ in JAM as well as in Hydrodynamical model.*

*→ What is the origin of $v_2$ enhancement at Mid-Rapidity ?*

# Pt and Impact Par. Dep. of Elliptic Flow
# Where Do We Underestimate ?

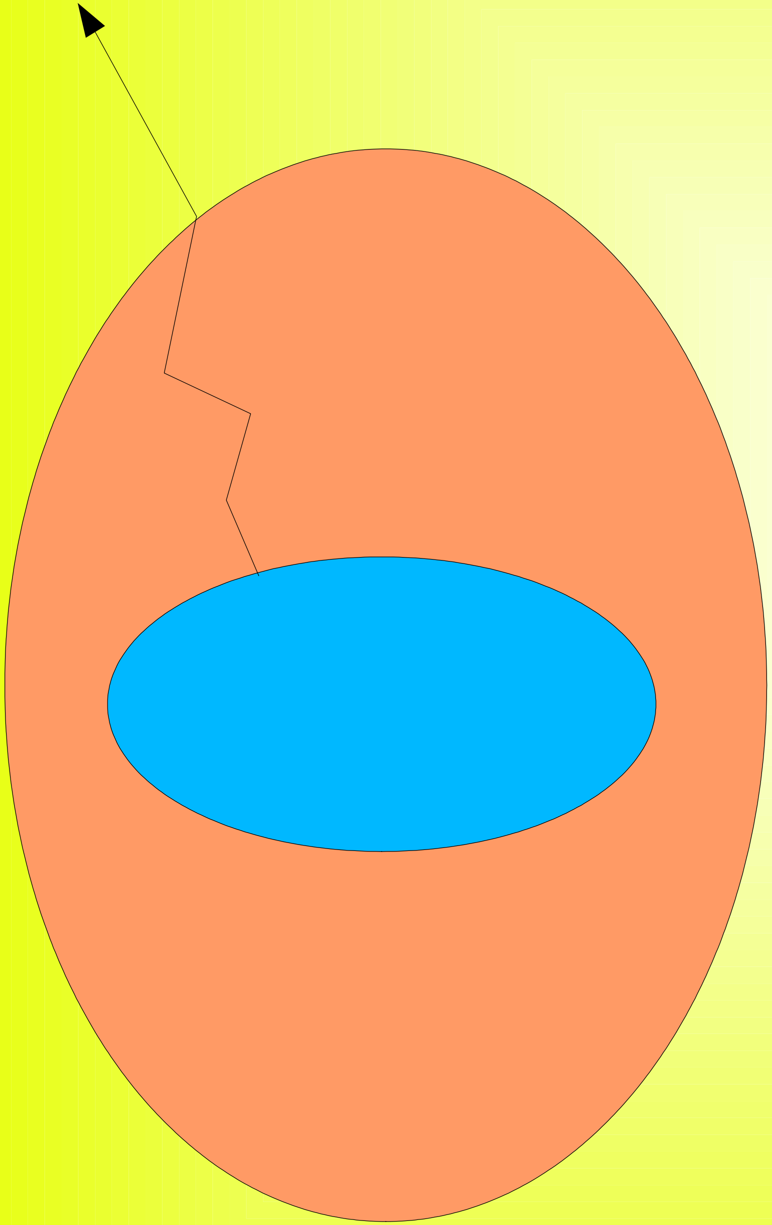
**(Ohnishi, Sahu, Isse, Otuka, Phatak, in preparation.)**



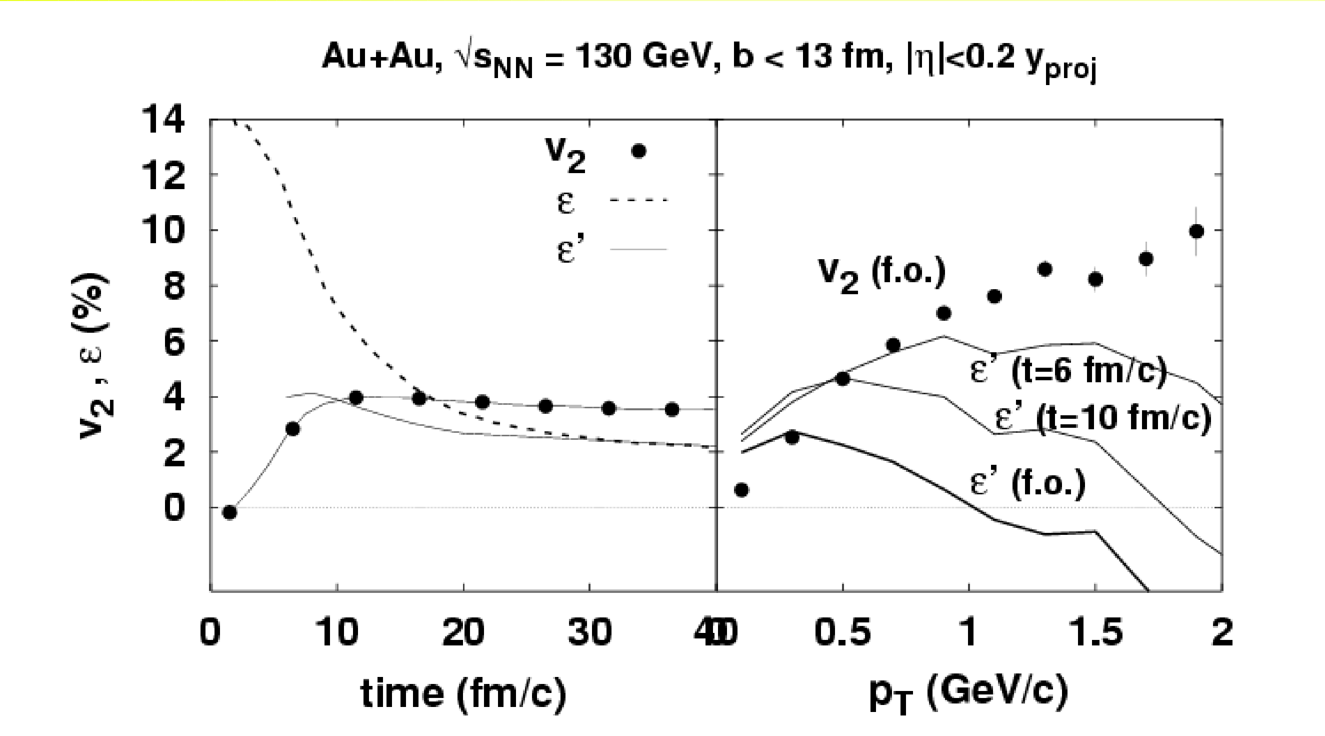

**Good for Pt integrated Values.**
**Underestimate at High Pt !**

# Why do we have large v2 at low $p_T$ ?



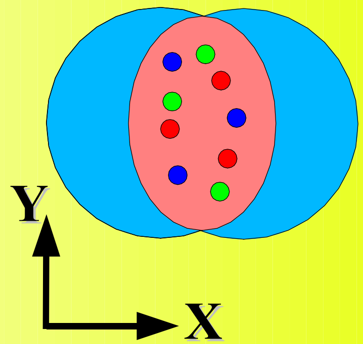
For v2 to grow, spatial eccentricity is necessary to be positively large.
However at Freeze-Out,
spatial eccentricity would be negative !
→ Let's go back in time
(with straight path approx.)

# 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.***

# Short Summary of Collective Flows at RHIC

- **Collective Flow Data at RHIC seems to suggest QGP formation.**

  *Large V2 : Early Thermalization*
  *Strong Radial Flow : Re-Hardening and Strong Pressures*
  *Jet Quenching : Partonic Interaction*

- **Objections ! from Hadronic Cascade**

  *Large V2 :*
  *If integrated in $p_T$, large V2 can be achieved in Hadronic Cascade, because of the later formation of large eccentricity after hadronization.*
  *Strong Radial Flow : ?*
  *Jet Quenching :*
  *If each NN collision is treated as independent, it is necessary to have Enhancement rather than Quenching.*

*Hadronic Cascade gives good description at low $p_T$ ?*
*→ How about HBT effects ?*

# Two Particle Interferometry at RHIC

# Two Particle Correlation (1)

- Two Particle Correlation Function

$$C(p,q) \equiv \frac{P(p_1,p_2)}{P(p_1)P(p_2)} \quad , \qquad p_1 = p + q/2 \quad , \quad p_2 = p - q/2$$

- Bose-Einstein Correlation in Two Particle Production Prob.

$$P(p_1,p_2) = \int d^4x_1 d^4x_2 S(x_1,p_1) S(x_2,p_2) |\phi|^2$$

$$\phi = \left(\exp\left(i\,p_1 x_1 + i\,p_2 x_2\right) + \exp\left(i\,p_1 x_2 + i\,p_2 x_1\right)\right)/\sqrt{2}$$

$$|\phi|^2 = 1 + 2\cos q(x_1 - x_2)$$

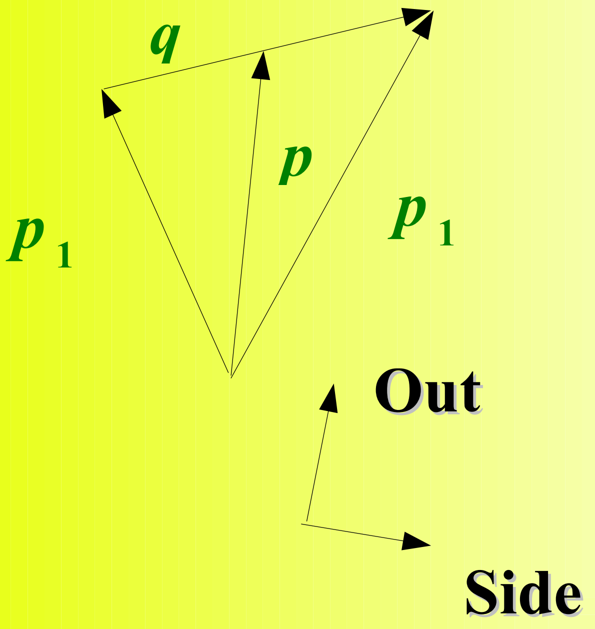
$$\rightarrow \quad C(p,q) = 1 + \frac{\int d^4x_1 d^4x_2 S(x_1,p_1) S(x_2,p_2) \cos q(x_1 - x_2)}{\int d^4x_1 S(x_1,p_1) \int d^4x_2 S(x_2,p_2)}$$

**Two Particle correlation probes source size and lifetime.**

# Two Particle Correlation (2)

- **Gaussian Source Fit**

$$C(p,q) = 1 + \lambda \exp\left(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2\right)$$




$$q = q_{long}\, e_z + q_{out} \frac{p_T}{|p_T|} + q_{side} \frac{p_T \times e_z}{|p_T|}$$

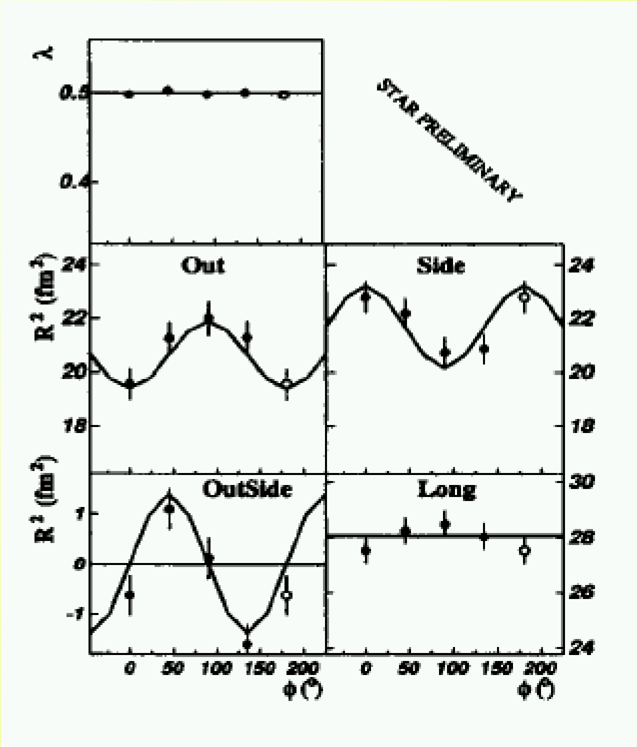
**Relation to the Source Lifetime**

$$R_{out} = \sqrt{R_T^2 + \beta^2 \tau^2} \quad , \quad R_{side} = R_T$$

***HBT puzzle at RHIC: $R_{out} < R_{side}$, especially at High $p_T$***

# HBT Puzzle: Present Consideration and Hints

- Hirano & Tsuda/Morita: Hydro., Size is not bad, but $R_{out} > R_{side}$.
- Heinz & Kolb: Hydro.,
  Freeze-Out at PHASE TRANSITION → $R_{out} < R_{side}$.
- PHENIX Analysis @ Miyazaki (Hiroshima U.):
  Coulomb effects may increase $R_{side}$, but not at high $p_T$.
- Data @ RHIC (STAR):
  Elliptic Flow Effects
  $R_{out} < R_{side}$ in plane !



# HBT analysis in Cascade-Type Models

- S. Pratt et al. (PRC 42 (1990), 2646.)

$$r_1(C) = R + r/2 - v(p)(t_2 - t_1) \quad , \quad r_2 = R - r/2.$$

- J.P. Sullivan et al. (RQMD @ SPS) (PRL 70 (1993), 3000.)

$$r_1(C) = r_1(F) + v_1(\tau - t_1) \quad , \quad r_2(C) = r_2(F) + v_2(\tau - t_2).$$

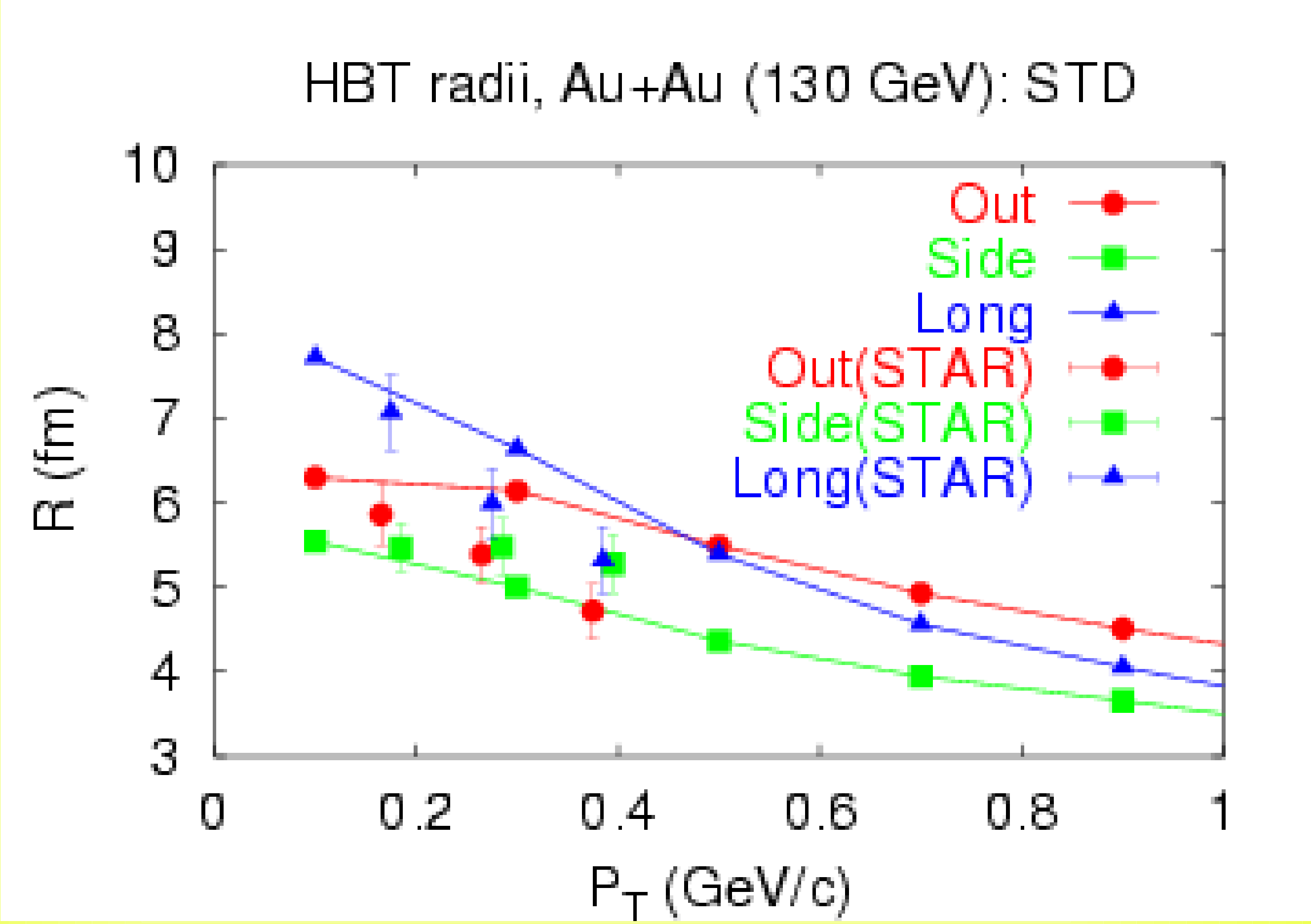
$$\tau = (t_1 + t_2)/2$$

- Zhang-Wiedemann-Slotta-Heinz (PLB 407 (1997), 33.)

$$P(p_1, p_2) = \sum_{i,j \sim p} \cos(q \cdot (x_i - x_j)) \quad , \quad (q \neq p_1 - p_2)$$

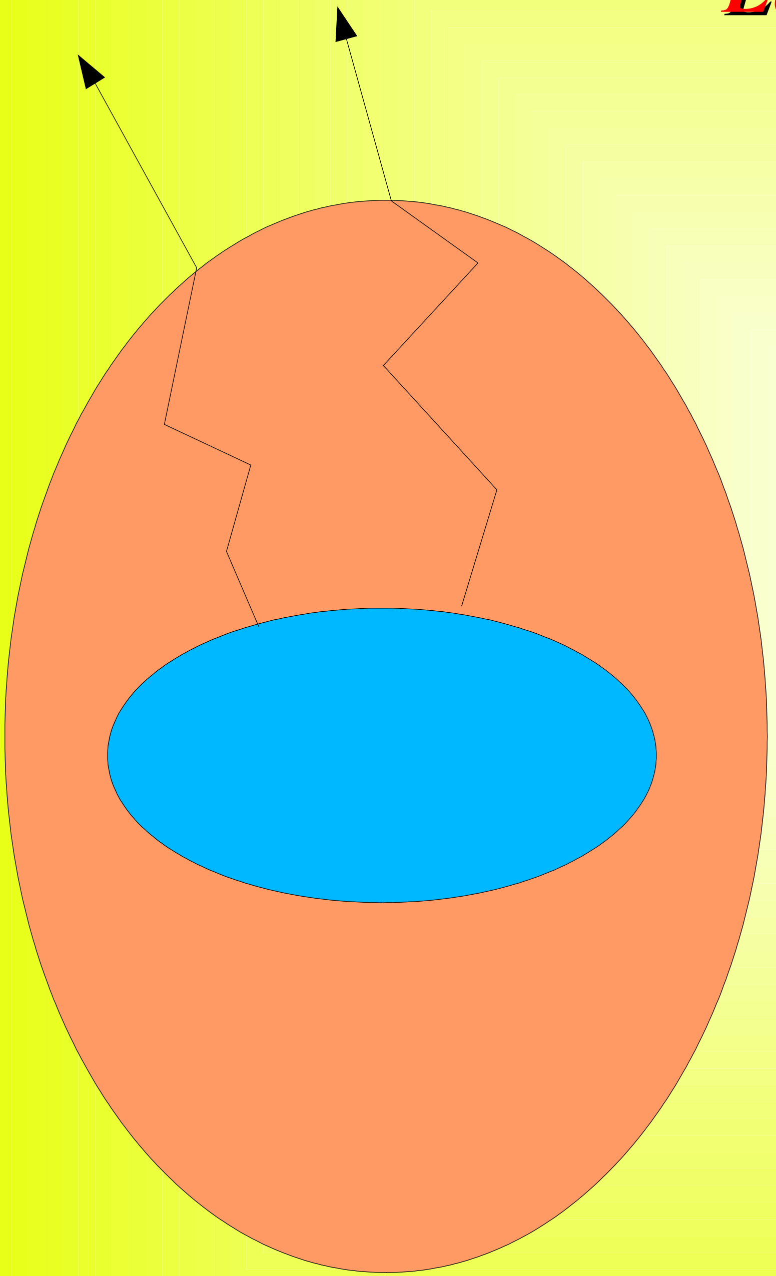
*Here we follow the prescription of Sullivan et al.*

# Standard Analysis of JAM results




**HBT puzzle remains !**

# Early Correlation ?

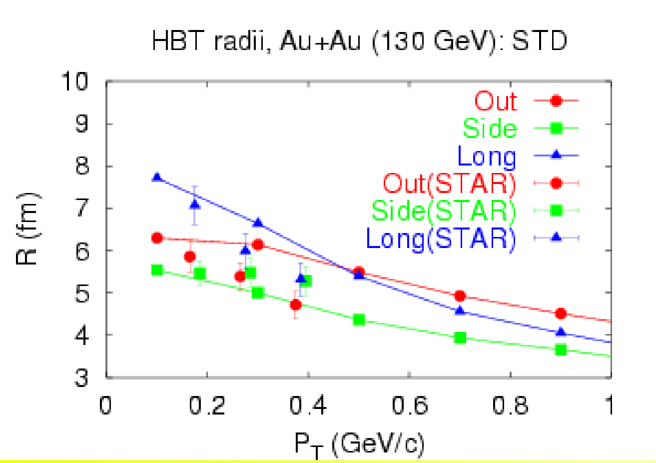


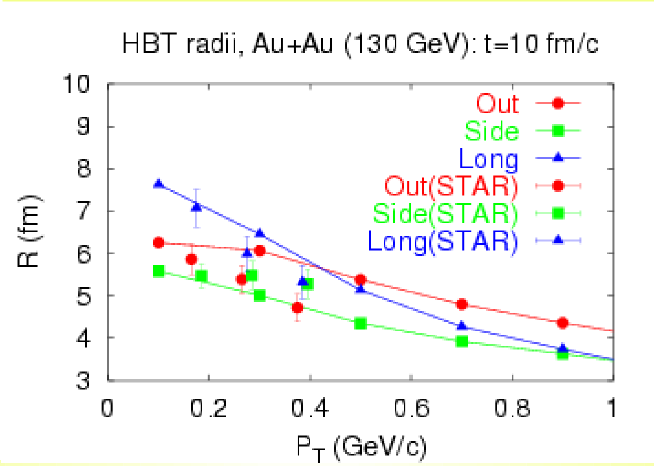
If the time at which the correlation is made corresponds to
the "LAST COLLISION" point,
we see larger Rout, and the effects of eccentricity is in reverse.

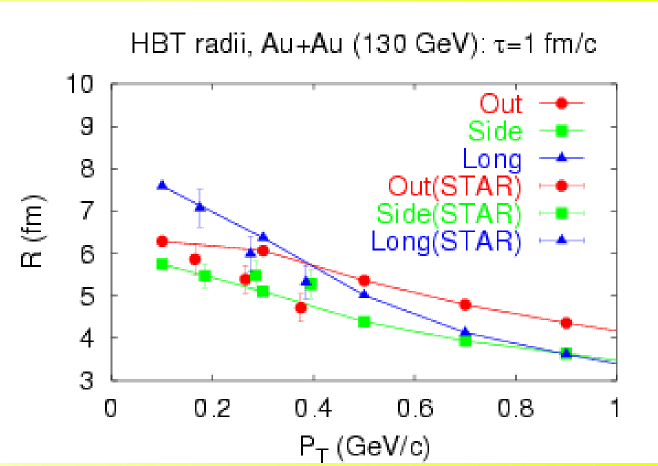
→ Let's go back in time
(with straight path approx.)

(Asakawa-san's idea)

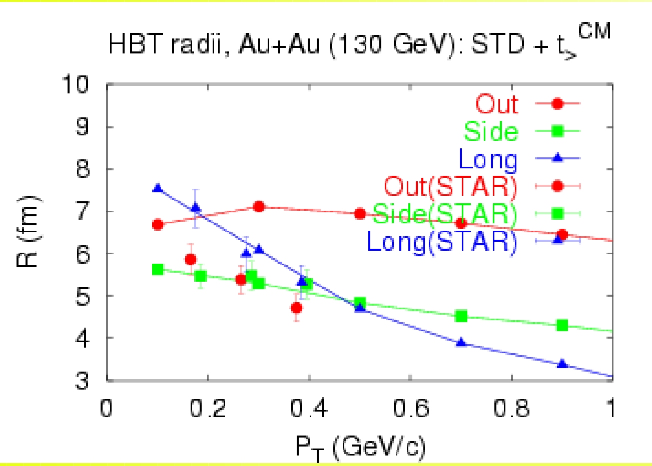
## Correlation at t = 10 fm/c and $\tau$ = 1 fm/c

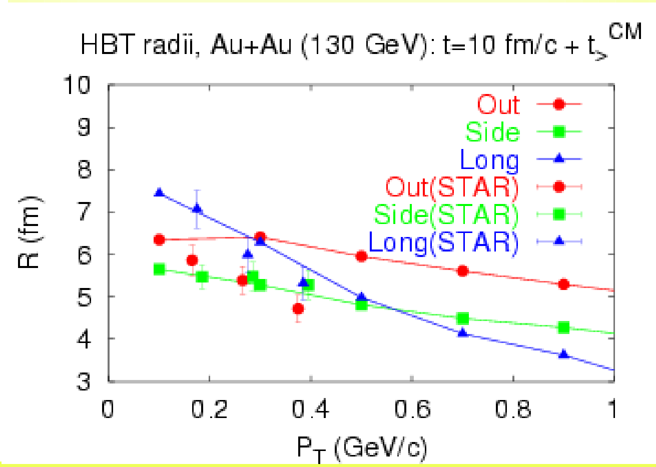


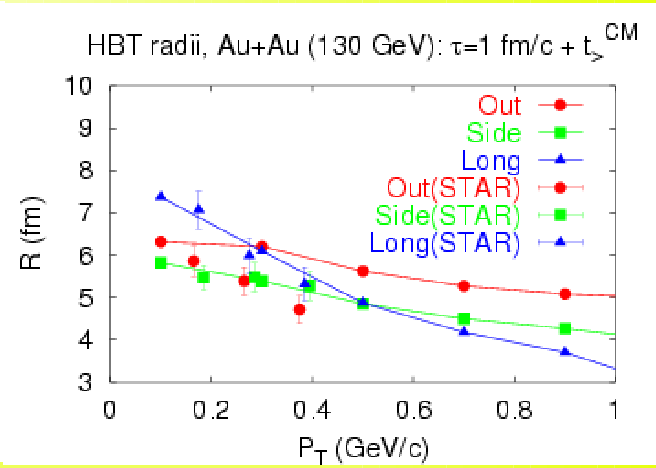




## Correlation at t = 10 fm/c and $\tau$ = 1 fm/c, and with $t_>^{CM}(1) = t_>^{CM}(2)$



# Summary

- Hadronic Cascade Models at RHIC

  Generally good at low $p_T$ ($p_T$ < 0.5 GeV/c),
  except for radial flow and HBT source size, $R_{out}$.

- Problems.
  - Underestimate of hadron yield at higher $p_T$
  - Underestimate of elliptic flow at higher $p_T$
  - We cannot see disappearance of back-to-back correlation in Au+Au (Isse)
  - HBT puzzle is not solved yet.
- Way to solve these problems.
  - Elementary Cross Section
  - "Classical Independent" hadron-hadron collision picture
  - "FREEZE OUT" condition at HBT.
  - *Partonic Interactions*