Jet-Fluid String Formation and Decay in High-Energy Heavy-Ion Collisions

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- **Introduction**
- **Jet-Fluid String (JFS) model**
- **Results**
- **Summary**

Hadronization Mechanism at RHIC

- *High p_T : Indep. Frag. of Jet Partons* *(E.g. Hirano-Nara)*

  O Explains pT spectrum when E-loss is included.

  X Elliptic Flow v_2 is small at high p_T *←This Talk*

- *Medium p_T : Recombination* *(E.g. Duke-Osaka-Nagoya)*

  O Explains Baryon Puzzle and Quark Number Scaling of v_2

  X Entropy decreases in "$n \rightarrow 1$" process

- *Low p_T : Equil. Fluid Hadronization* *(E.g. Hirano-Gyulassy)*

  O Explains p_T spec. and v_2 at low p_T

  X Results depends on the Freeze-Out Conditions

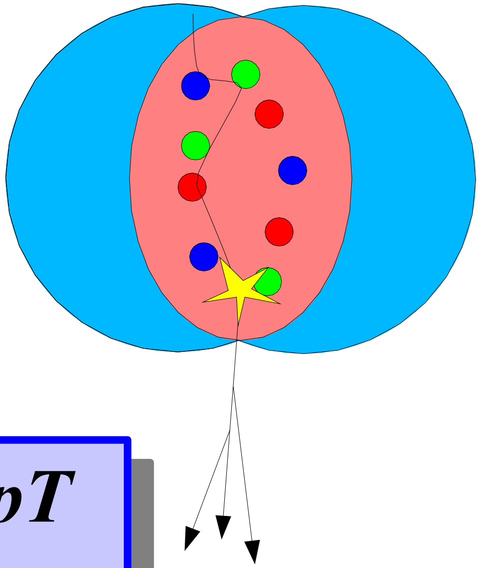
QGP Signals are understood separately,
and they are not necessarily consistent.
→ Further Ideas are required !

How can we get large v_2 at high p_T ?

- Quark Recombination → Combined Objects have larger v2

$$f(p, \varphi) = (1 + 2\, v_2(p/2) \cos\varphi) \times (1 + 2\, v_2(p/2) \cos\varphi)$$
$$\approx 1 + 2 \times 2\, v_2(p/2) \cos\varphi$$

- Energy Loss in QGP generates v2
  - Large/Small suppression in y/x directions



Plausible Hadronization giving large v2 at high pT
- *Combination of several partons*
- *Large Energy Loss*

→ Jet parton picks up Fluid parton
and forms a string (Jet-Fluid String)

Jet-Fluid String Formation and Decay

Jet production: **pQCD(LO) × K-factor (PYTHIA6.3, K=1.8, *pp* fit)**

$$\sigma_{jet} = K \sigma_{jet}^{pQCD(LO)}$$

Jet propagation in QGP

3D Hydro + Simplified GLV 1st order formula × *C*

(Hirano-Nara, NPA743('04)305, Hirano-Tsuda, PRC 66('02)054905. Web version!
Gylassy-Levai-Vitev, PRL85('00)5535)

$$\frac{dE}{d\tau} = 3\pi\alpha_s^3 F_{color} C (\tau - \tau_0) \log\left(\frac{2E_0}{\mu^2 L}\right)$$

Jet-Fluid String formation

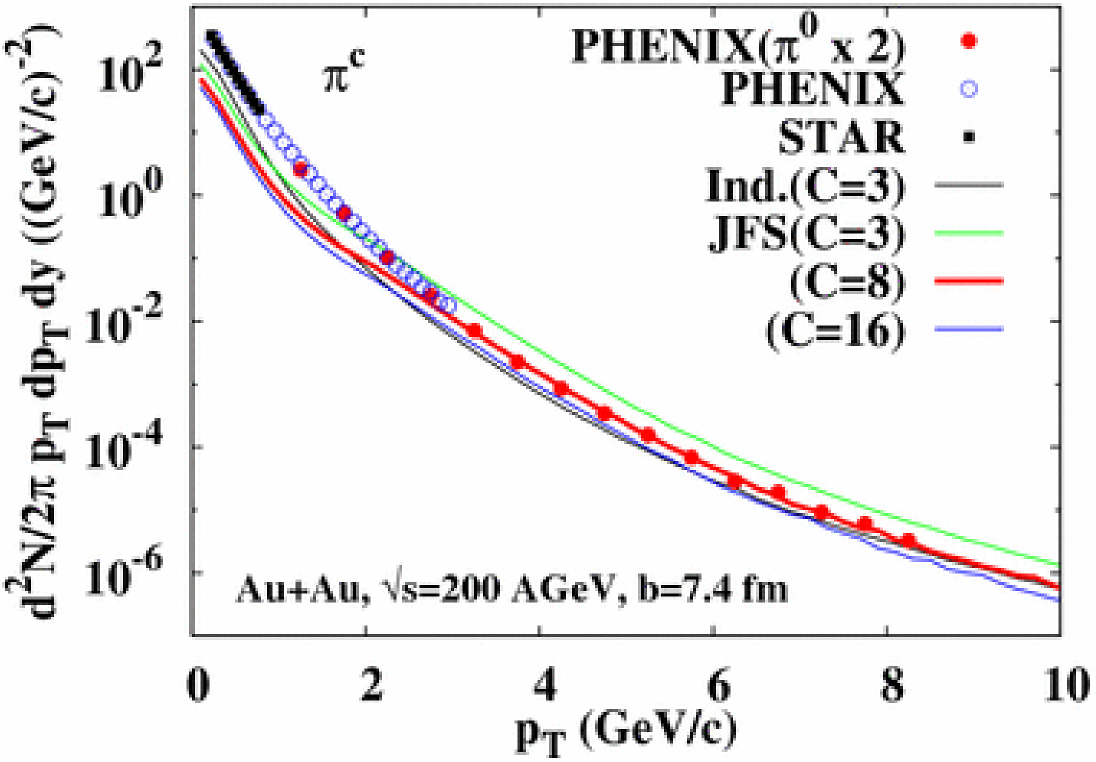
Fluid parton breaks color flux,
according to string spectral func.

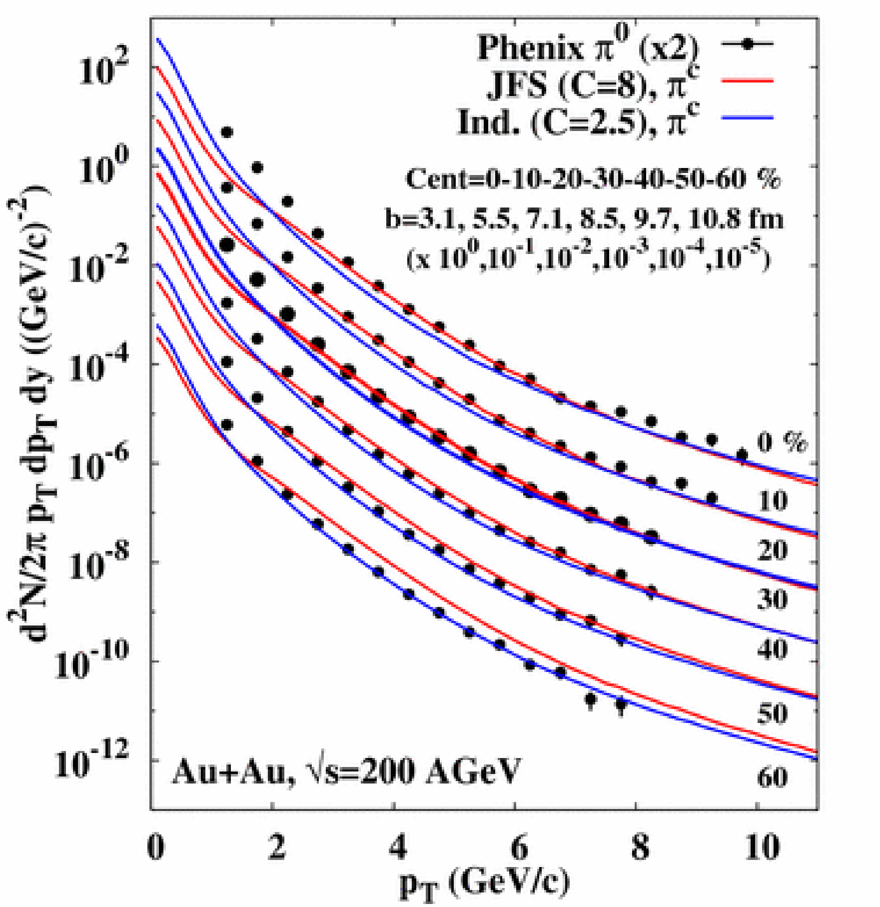
$$P(\sqrt{s}) \propto \Theta(\sqrt{s} - \sqrt{s_0}) \quad (\sqrt{s_0} = 2GeV)$$

Only g and light q (qbar) are considered.

Energy Loss Factor C : p_T Spectrum Fit

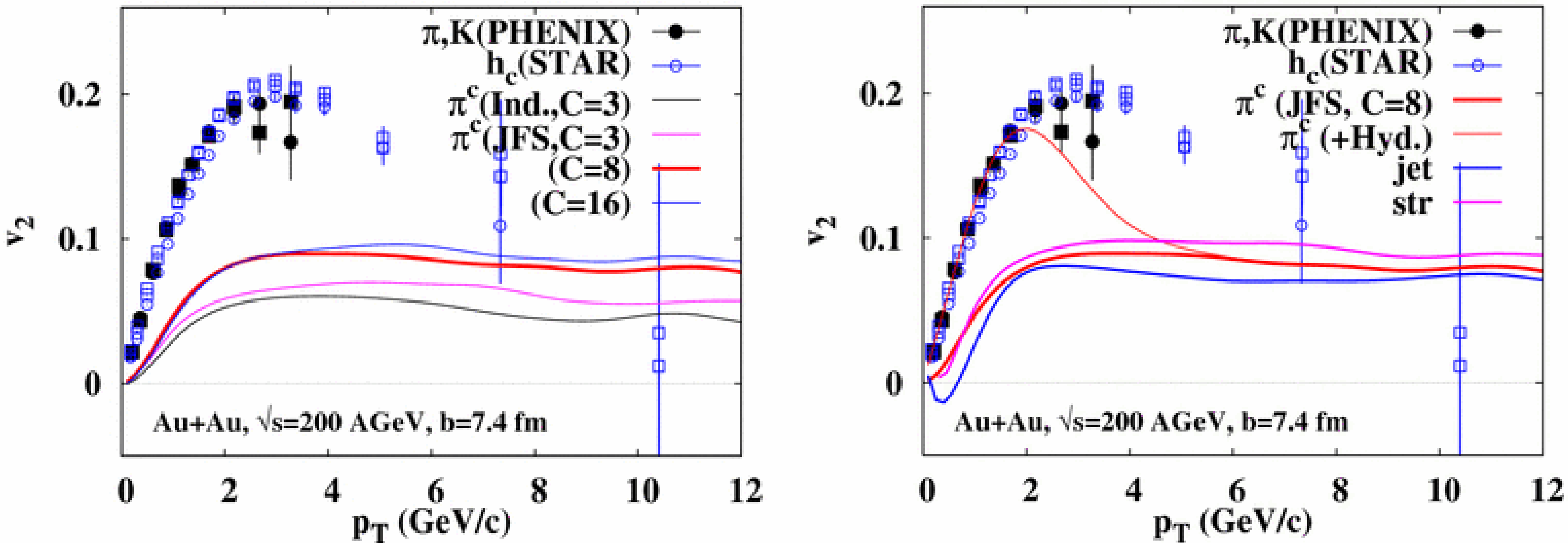
- **For the same C →** $dN_{JFS}(\text{high } p_T) > dN_{Ind}(\text{high } p_T)$
- p_T **spec. fit → Ind. Frag.:** $C \approx (2.5\text{-}3)$**, JFS:** $C \approx 8$
  → *Large Energy Loss is necessary / allowed in JFS*





Elliptic Flow: p_T Deps.

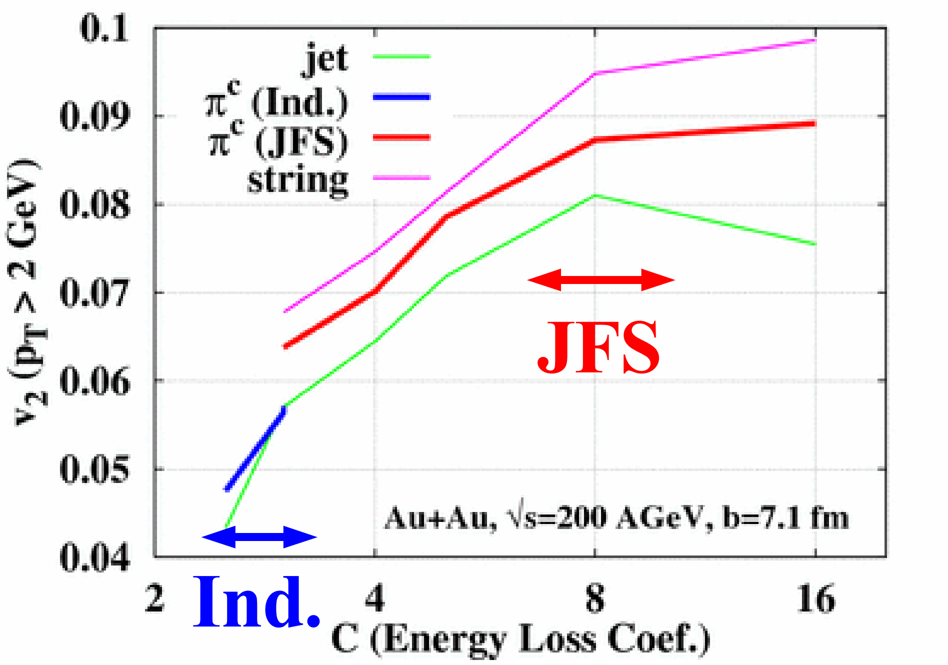
- **High pT v_2 : ~ 5 % in Ind. ($C = 3$) ↔ ~ 8 % in JFS ($C = 8$)**



Origin of Large v_2 = Large E-loss factor C + Fluid parton v_2

Elliptic Flow: Parameter Deps.

- v_2(jet): saturating behavior
  (large E-loss limit) ~ 8 %
- v_2 (string): grows up to ~ 10 %
  larger than v_2(jet, limit)
- v_2 (h): string decay reduces v_2
  → v_2(jet) < v_2 (h) < v_2 (string)



For p_T>2GeV ($p_T \approx$ 10 GeV)

Ind. Frag. with C = 2.5 → $v_2 \approx 5\ \%\ (4\ \%)$

Large E-loss factor C → + 3 %

Fluid parton v_2 → + 1 %

JFS with C = 8 → $v_2 \approx 9\ \%\ (8\ \%)$

Summary

- ***Jet-Fluid String (JFS) formation and decay*** **is proposed as a mechanism to produce high p_T hadrons.**
    - **Effecitve to produce high p_T hadrons**
    - **Event-by-Event Energy-Mom. conservation ↔ Ind. Frag.**
    - **Entropy does not decreases, but increases. ↔ Reco.**
- **When we FIT p_T spectrum,** ***large v_2 emerges at high p_T.***
    - **Large E-loss+fluid parton v_2**
- **Problems and Homeworks**
    - **Mechanism of large E-loss**
    - **d+Au fit → Cronin Effects**
    - **s-quarks, string spectral func.**

Comparison with Previous Works

- **J. Casalderrey-Solana, E.V. Shuryak, hep-ph/0305160**
  - **Quarks, diquarks and gluons in QGP cut color flux (~ JFS).**
  - **Large E-loss is generated by “phaleron”**
  - ***Large E-loss leads “surface emission” → large v_2***
- **Recombination (Duke-Osaka-(Minesota)-Nagoya)**
  - **Predicts large v_2 (~ 10 %) at high-pT**
    - ➢ **Sharply edged density dist. → E-loss $\propto L$ → $v_2 \approx 10$ %**
    - ➢ **Woods-Saxon density dist. → $v_2 \approx 5$ %**
  - **Entropy problem: S(QGP) ≈ S(H) requires Res. and Strings**
  - ***Spectral Func.: δ func. ↔ θ func. in JFS***

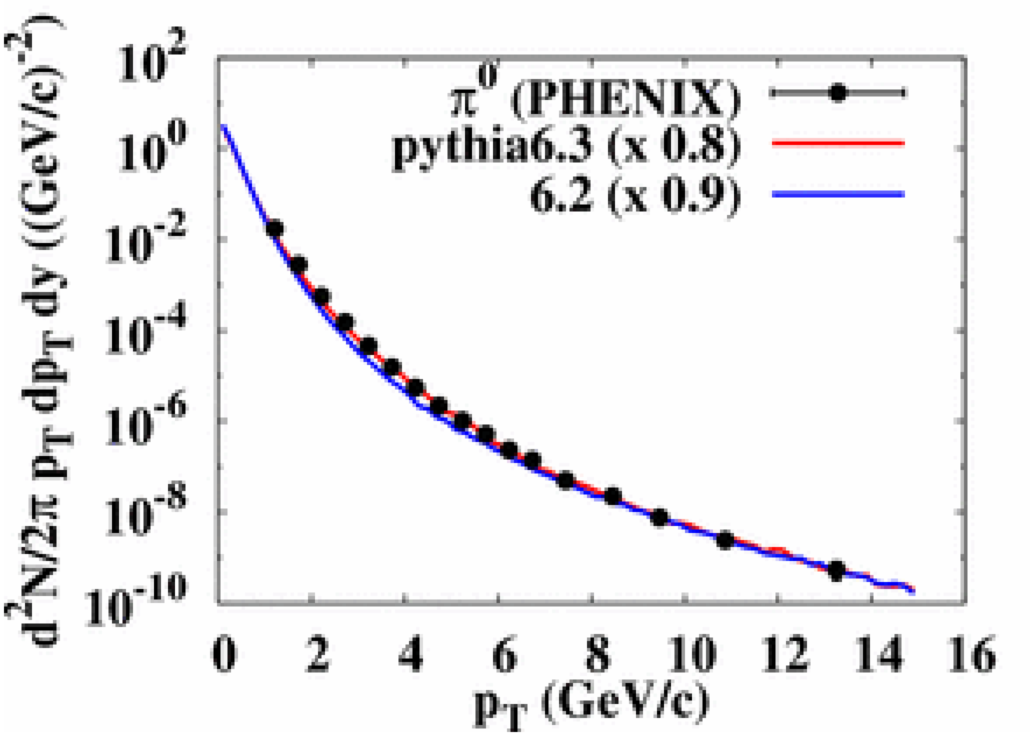
K-factor

- K-factor → absolute value of σ_{jet}
- Experimental Data: $pp \rightarrow \pi^0$ @ $\sqrt{s_{NN}} = 200$ GeV (PHENIX)

$$\frac{1}{\sigma^{exp}}\frac{d^2\sigma^{exp}}{2\pi p_T\, d\, p_T\, dy} = K\frac{\sigma^{pQCD(1st)}}{\sigma^{exp}}\frac{d^2N^{pQCD(1st)}}{2\pi p_T\, d\, p_T\, dy} \qquad A = K\frac{\sigma^{pQCD(1st)}}{\sigma^{exp}}$$

$\sigma^{Exp.} = 21.8$ mb (trigger)
$\sigma^{pQCD(1st)} = 9.9$ mb

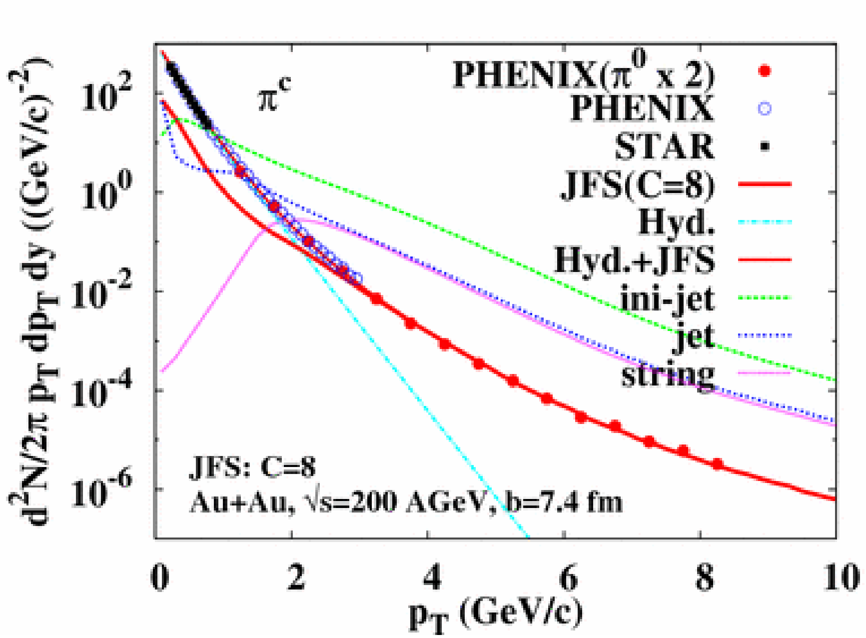
- pythia6.3 fit:
  $A \approx 0.8 \rightarrow K = 1.8$
  (σ_{jet} (p_T^{hard}>2Gev/c)≈ 17.5 mb)
- pythia6.2 fit:
  $A \approx 0.9 \rightarrow K = 2.0$
  ($\sigma_{jet} \approx 19.6$ mb)

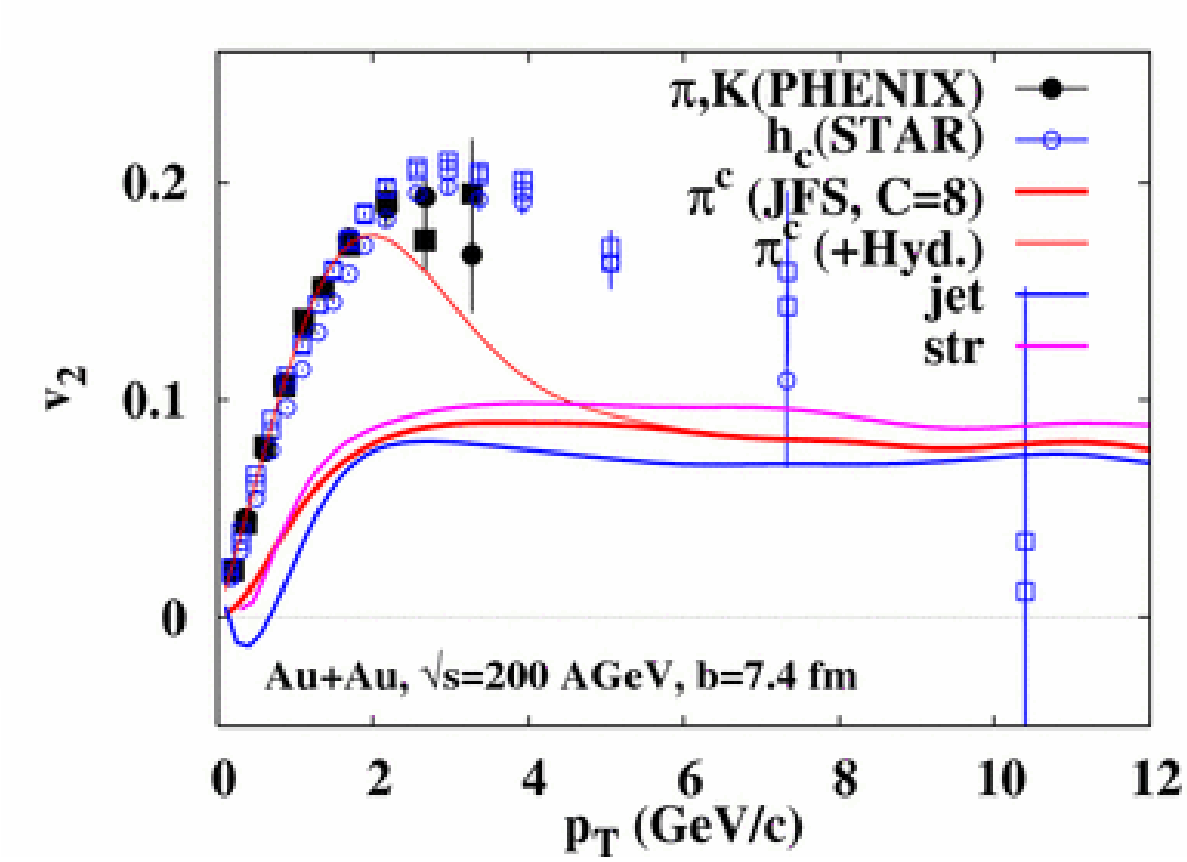


Combined with Low p_T spectrum

- Low pT spectrum is assumed and combined.

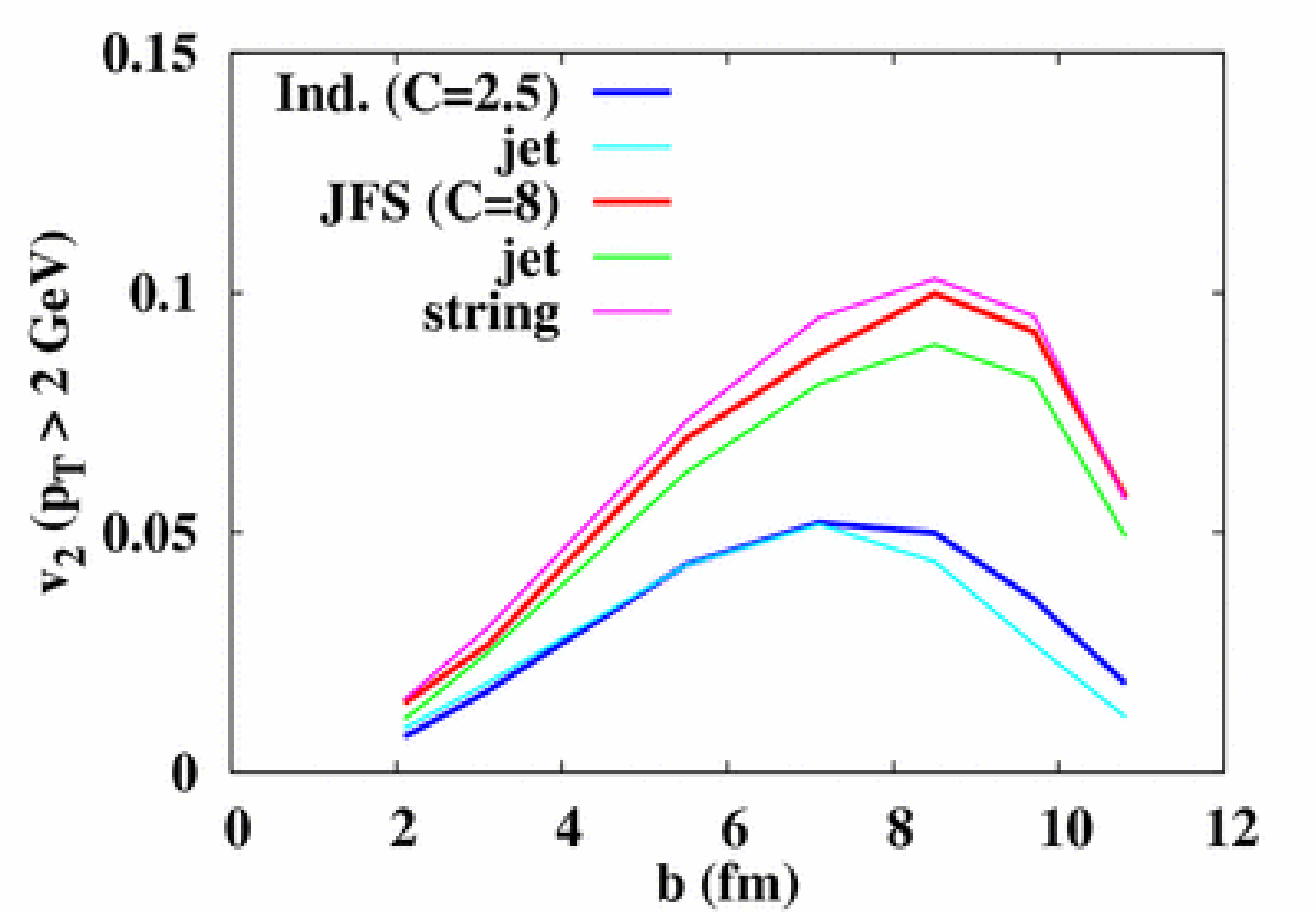
$$E\frac{d^3N_{Hyd}}{dp^3}(p_T)=A\exp(-p_T/T)(1+B/(1+(p_T/p_0)^8)) \qquad v_2^{Hyd}(p_T)=0.14\,p_T$$





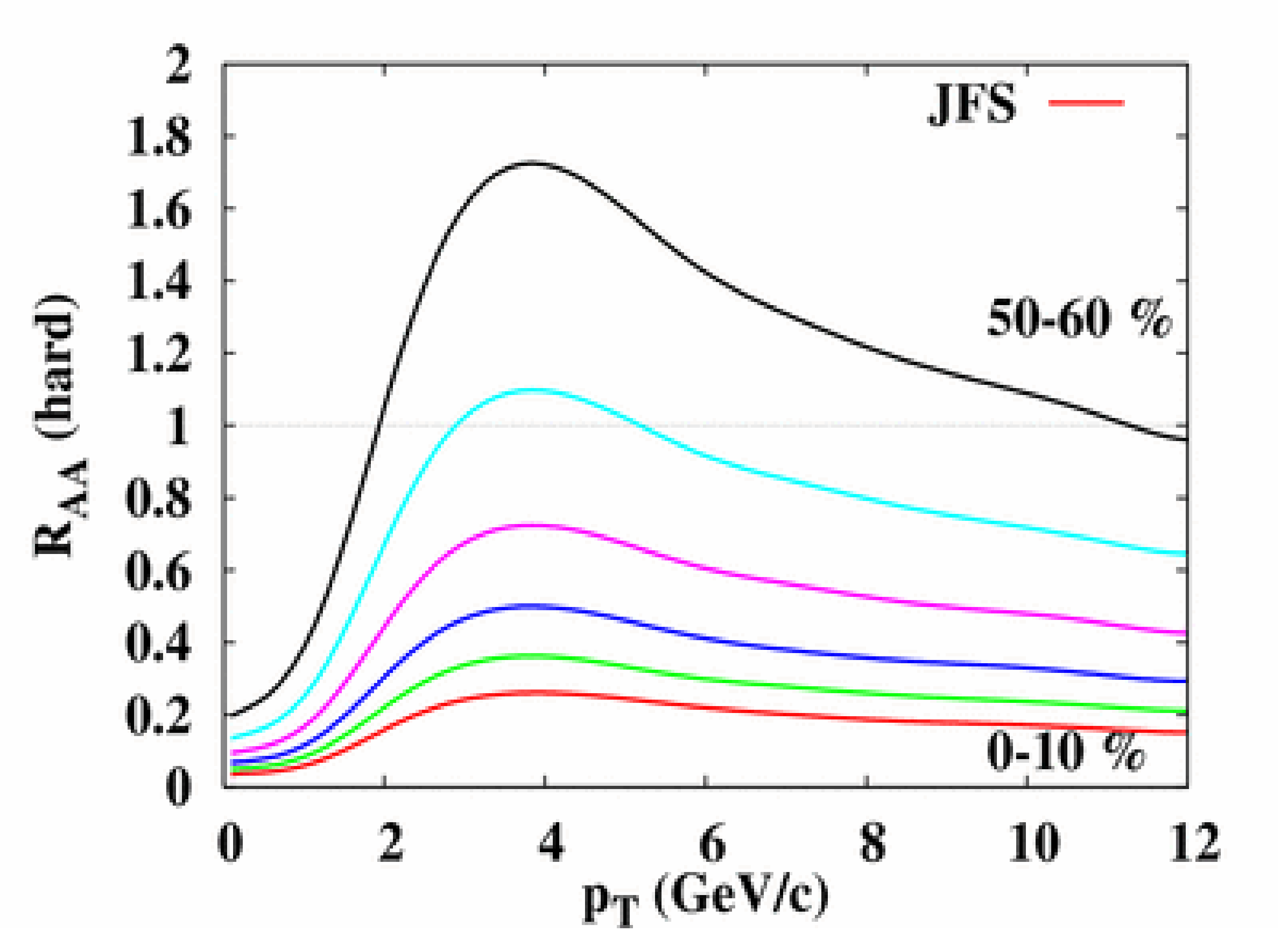
Elliptic Flow: Centrality Deps.

- Ind. (C=3): $v_2 \sim 5$ % at b ≈ 7 fm
- JFS (C=8): $v_2 \sim 10$ % at b ≈ 8.5 fm



Nuclear Modification Factor

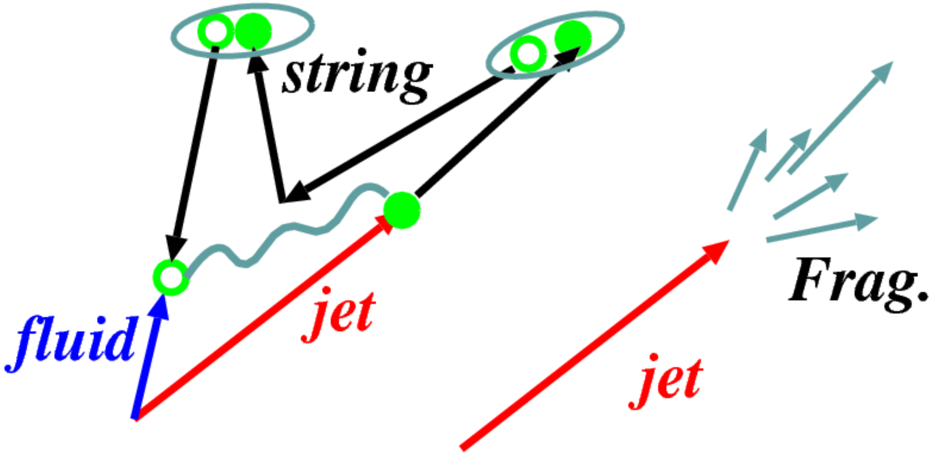
- Centrality Deps.



Discussion

- Mechanism to produce high p_T hadrons in JFS
  - String Decay from Lorenz boosted fluid
  - Relative momentum is relatively small
    → Smaller number of hadrons with high p_T are formed

  ↔ Independent Frag. (Large no. of Low p_T hadrons)



Energy Loss Factor

- **Additional Factor for Energy Loss → High p_T hadron yield**
- **Exp. Data: p_T spectra of π in Au+Au (PHENIX,STAR)**

$$\frac{d^2 N^{Exp.}}{2\pi p_T d p_T dy} = N_{jet} \frac{1}{N_{jet}} \frac{d^2 N^{JFS}(C)}{2\pi p_T d p_T dy}$$

→ Determining N_{jet} is important !

Ncoll = 373 @ b=7.4 fm (PHENIX estimate)

σ^{NN}_{jet} = 17.5 mb (pp fit pythia 6.3), σ^{NN}_{tot} = 47. 4 mb (JAM)

$$N_{jet} = \sigma^{NN}_{jet} \int d_T^{2r} T_A(r_T + b/2) T_B(r_T - b/2) = \frac{\sigma^{NN}_{jet}}{\sigma^{NN}_{tot}} N_{coll}$$

$$T_A(r_T) = \int dz\, \rho(r_T, z)$$

Further Problems

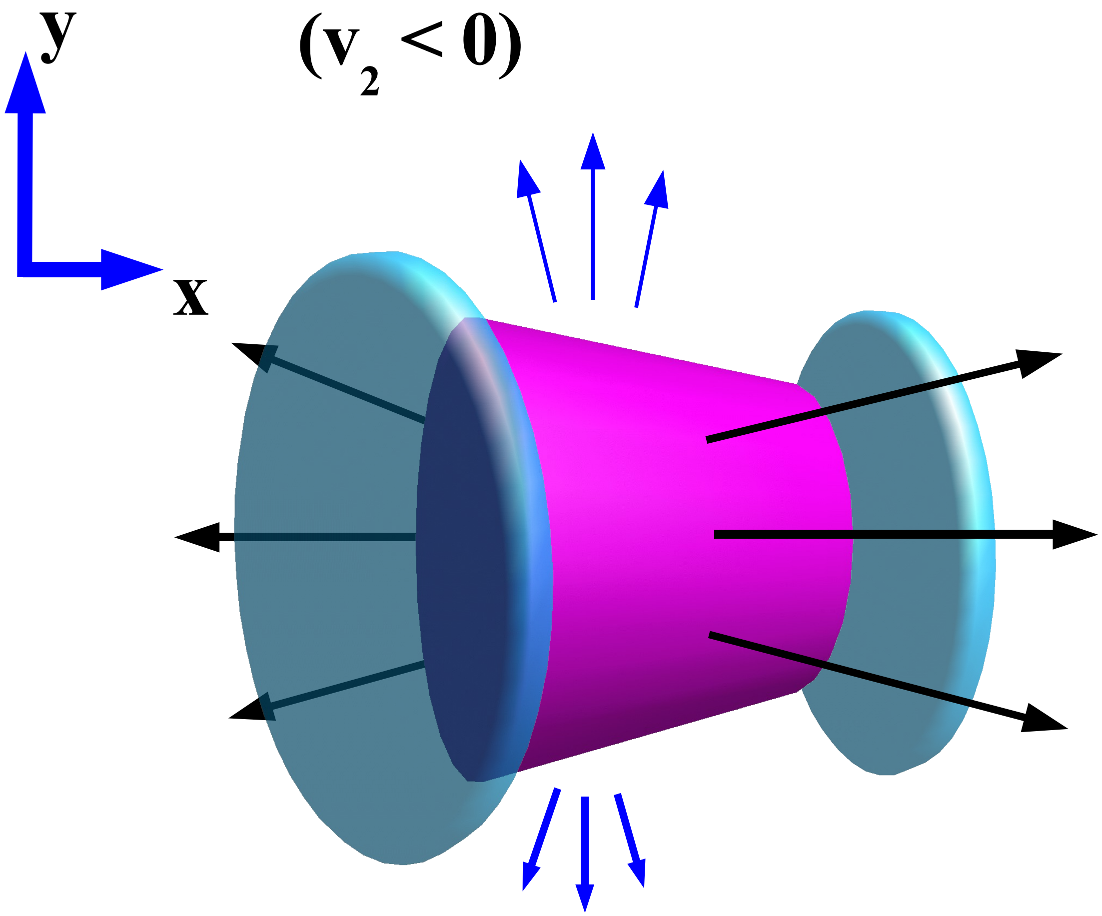
- Very large energy loss is required to explain p_T spectrum.
  - $C \approx 8$ in JFS ↔ $C \approx 2.7$ in Hydro+Jet model (Hirano-Nara)

Is it possible to justify this large energy loss ?

- Elliptic flow at medium pT is underestimated.
  → Fluid-Fluid String would be necessary to consider.
- Large baryon yield at medium pT may not be explained.
  → Three parton string ? (Jet-Fluid-Fluid, Fluid-Fluid-Fluid)
- String formation probability should be evaluated
  in pQCD matrix element + string level density.
- Strange hadrons

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 V_2**



Out-of-Plane Flow
($v_2 < 0$)

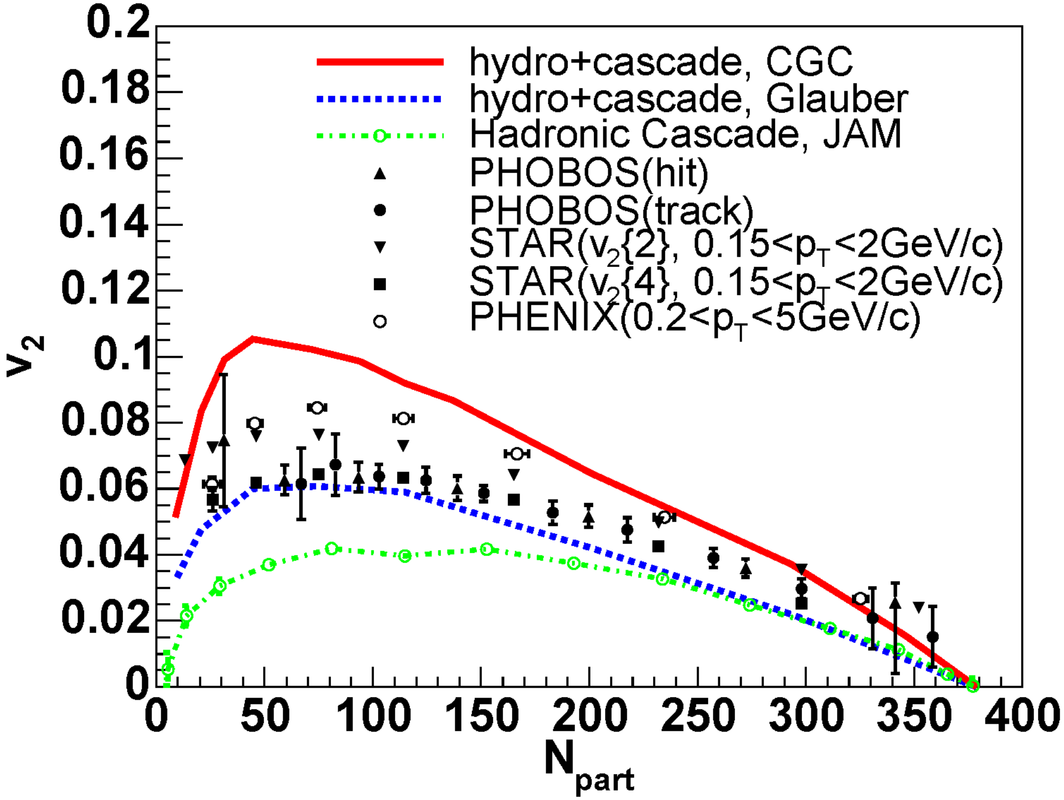
In-Plane Flow
($v_2 > 0$)

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

v_2(Centrality) @RHIC 200GeV, Au+Au

- カスケード模型 **JAM** は、周辺衝突になるにつれて (図の左側) 、小さくなってしまう。
- 実験値は、流体模型＋カスケードに **CGC** または **Glauber** 近似を仮定したものの間に位置する。

⇒流体描像が妥当
⇒部分的に **CGC**



Relativistic Hydrodynamics

- **EOM: Conservation Laws**

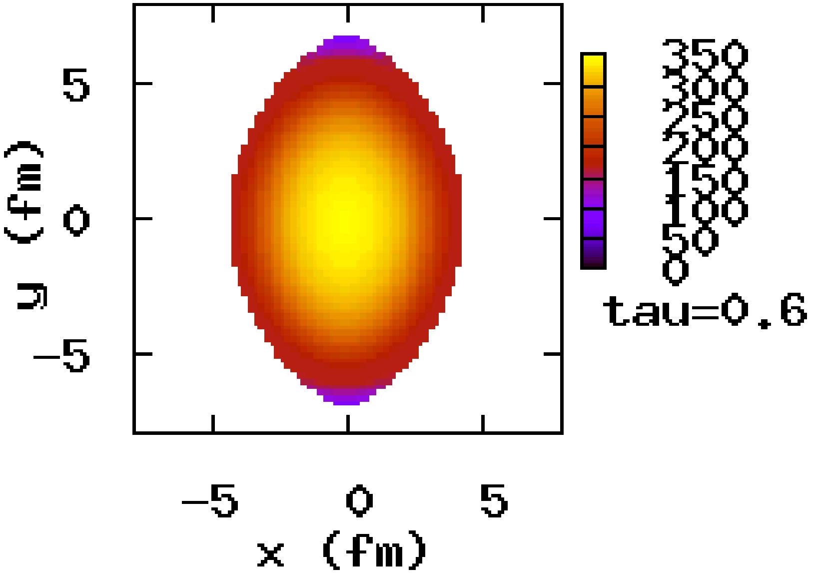
$\partial_\mu T^{\mu\nu} = 0$ **Energy Momentum Conservation**

$\partial_\mu n_i u^\mu = 0$ **Conservation of Charge (Baryon, Strangeness, ...)**

$$T^{\mu\nu} = (e+P)u^\mu u^\nu - P g^{\mu\nu}$$

e **: energy density, *P: pressure,***

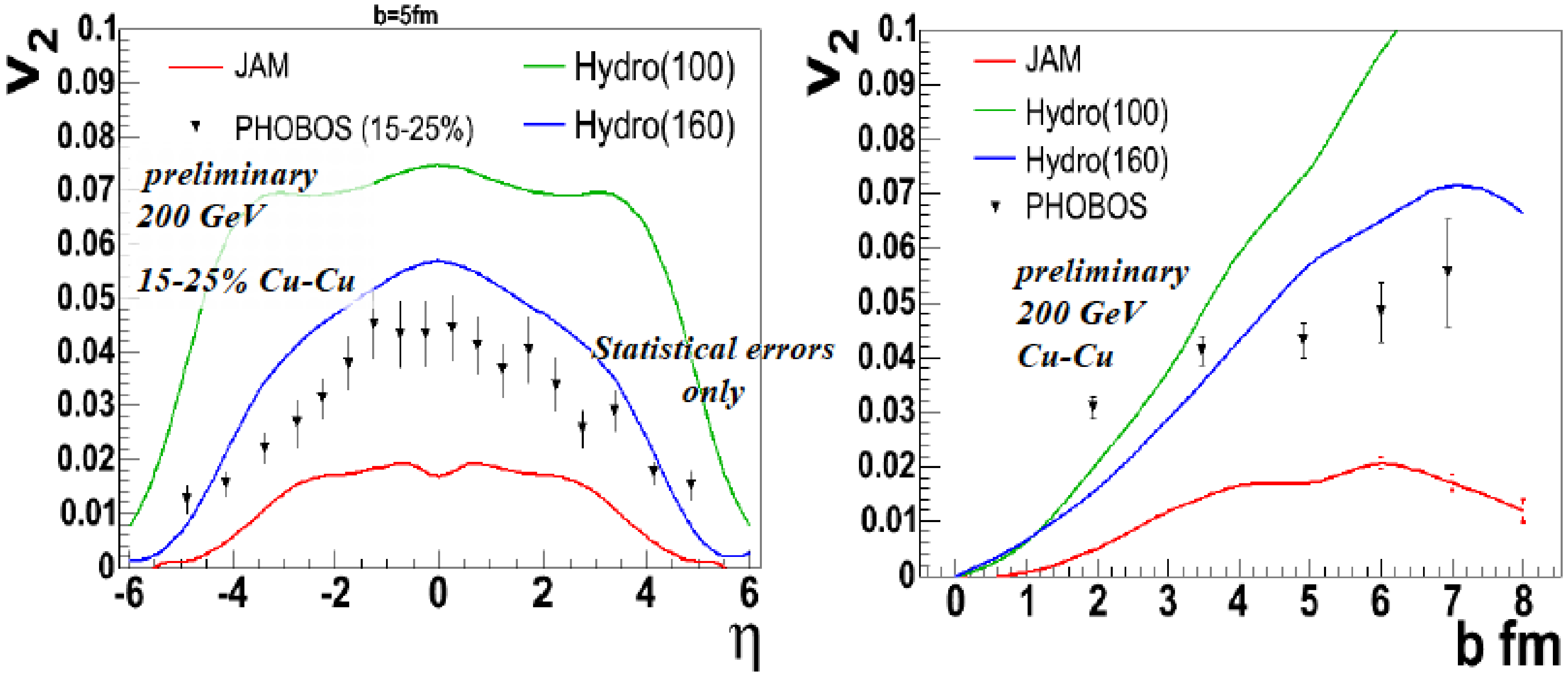
u^μ: **:four velocity $\gamma(1,v)$, n_i: :number density**



T. Hirano, Y. Nara,
Nucl. Phys. A743, 305 (2004)
T. Hirano, K. Tsuda,
Phys. Rev. C 66, 054905(2002)

PHOBOSの講演より

Compared to JAM Model



Cu-Cu more like Hydro than JAM hadron string cascade model

Here JAM uses a 1 fm/c formation time. Hydro (160) has kinetic freezeout temperature at 160 MeV

Division of Nuclear Phys

v_2は、両模型の違いが顕著。

流体模型でもT^{th} (⇔Freeze outの早さ) で違いがある。