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

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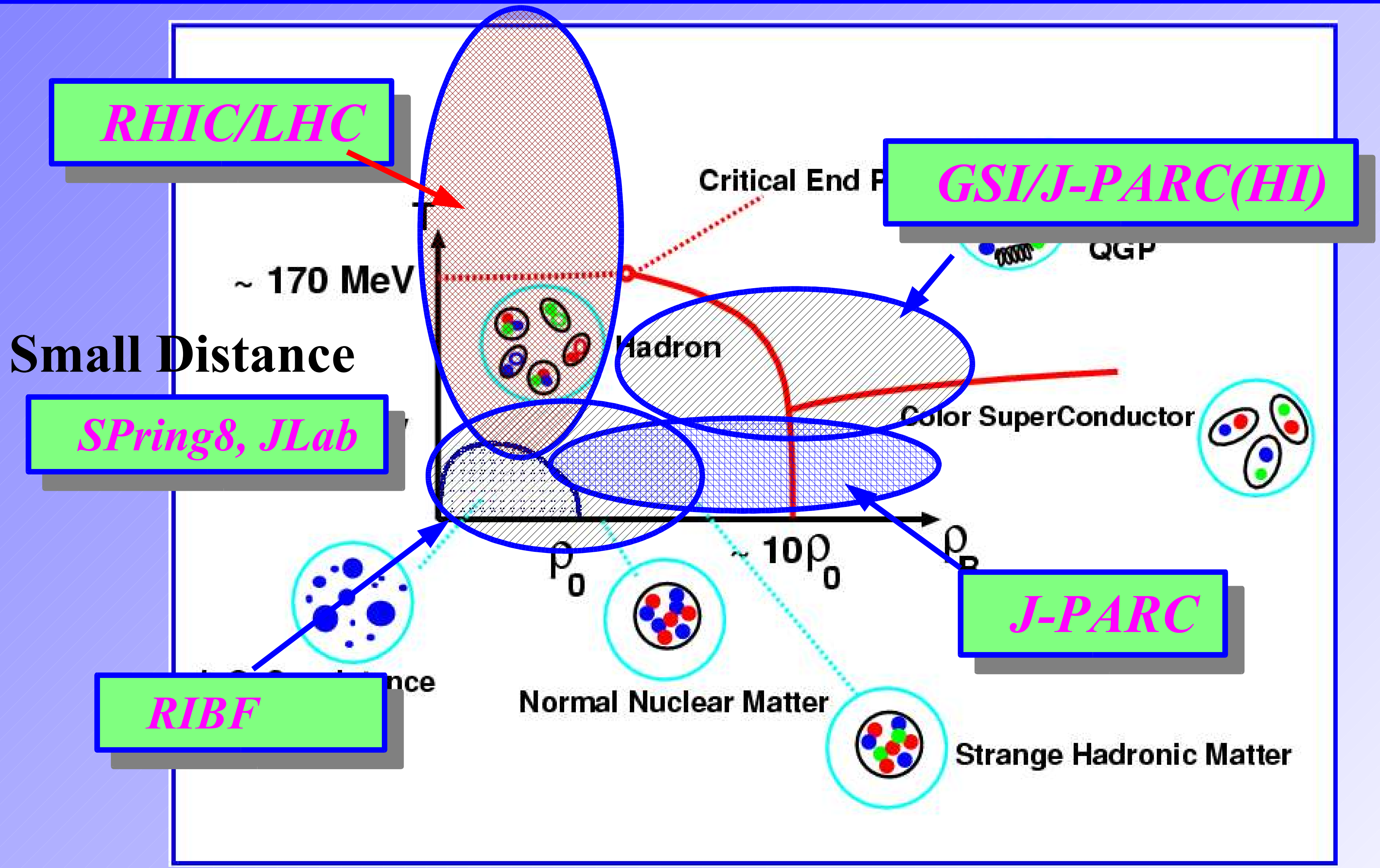
- Introduction
- Jet-Fluid String (JFS) model
- Results
- Summary

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/or 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

QGP Signals at RHIC

- **High pT: Jet Quenching**
  → *Independent* Fragmentation of Jet Partons which experienced Energy Loss in QGP.
  → *How about v_2 at high p_T ?*

- **Medium pT: Quark Number Scaling of v_2**
  → Quark Recombination suggests this scaling.
  → *Entropy reduces in "n → 1" process !*

- **Low pT: Strong Elliptic Flow**
  → Hydrodynamics explains string rise of v_2 at low p_T.
  → *Results depends on the later stages.*

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

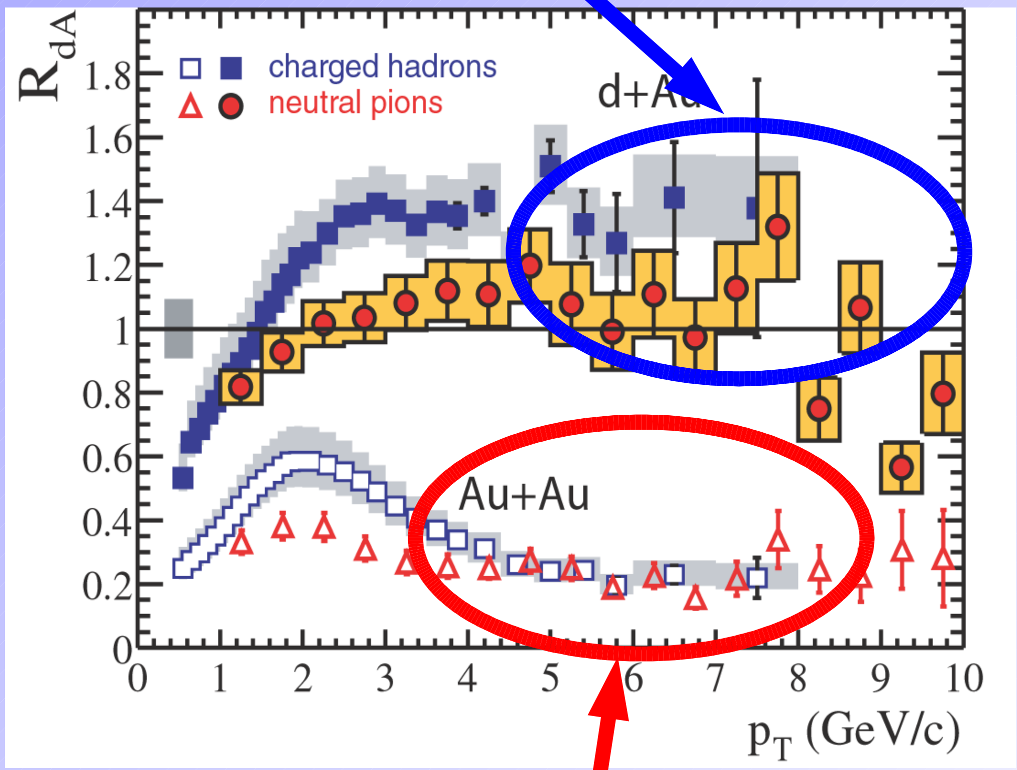
by Esumi, Matter03

Jet Quenching at RHIC (II)

d + Au: Initial State Effects

Do we really see suppression of high energy particles at RHIC ?
→ YES for Au+Au Collisions,
and NO for d+Au Collisions !

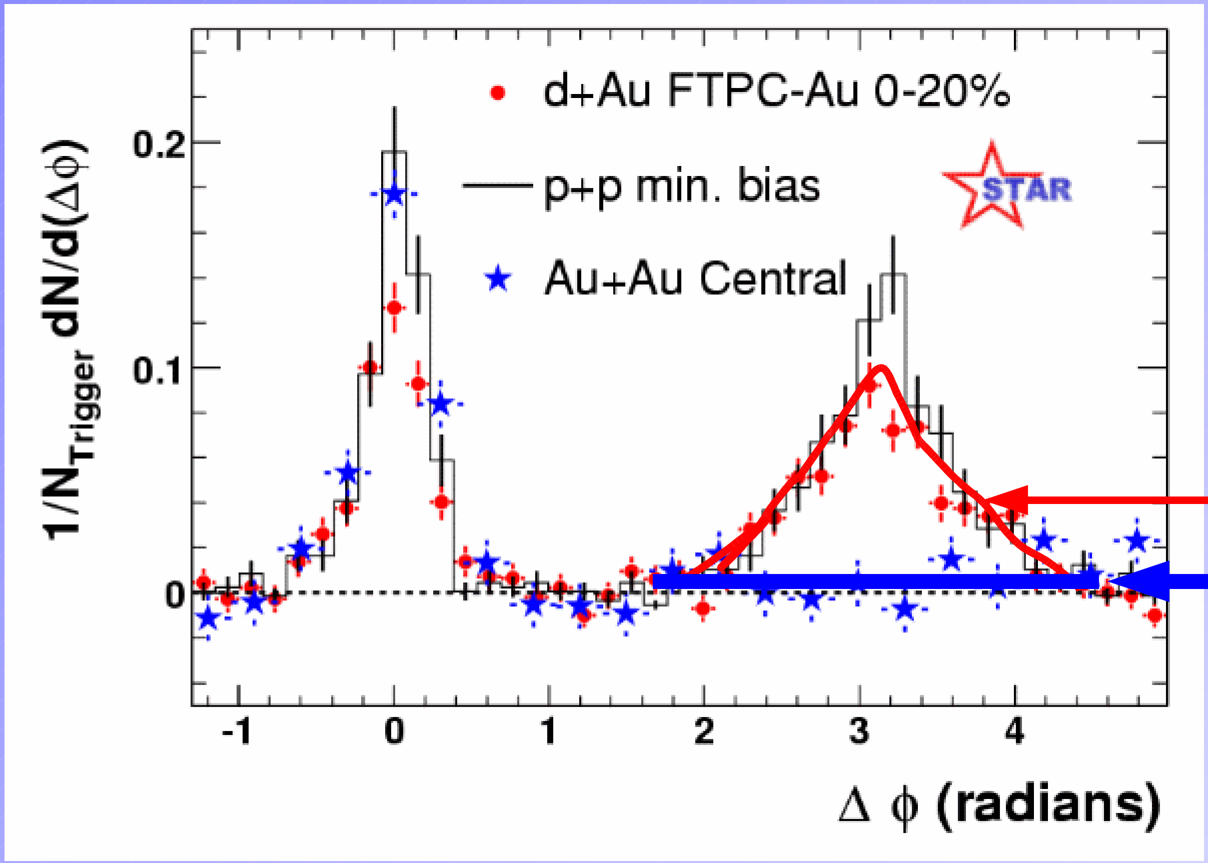
$$R_{AB}(p_T) = \frac{d^2N/dp_T d\eta}{T_{AB}\, d^2\sigma^{pp}/dp_T d\eta}$$

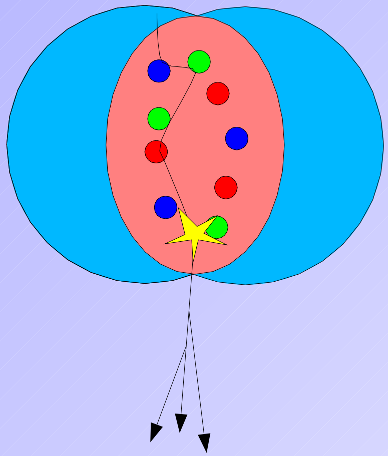


High Energy Particles are suppressed in
Au + Au Collisions
but NOT suppressed in
d + Au Collisions
at RHIC compared to p+p collisions !

Au + Au:
Initial State
+ Final State Effects

Jet Quenching at RHIC (III)





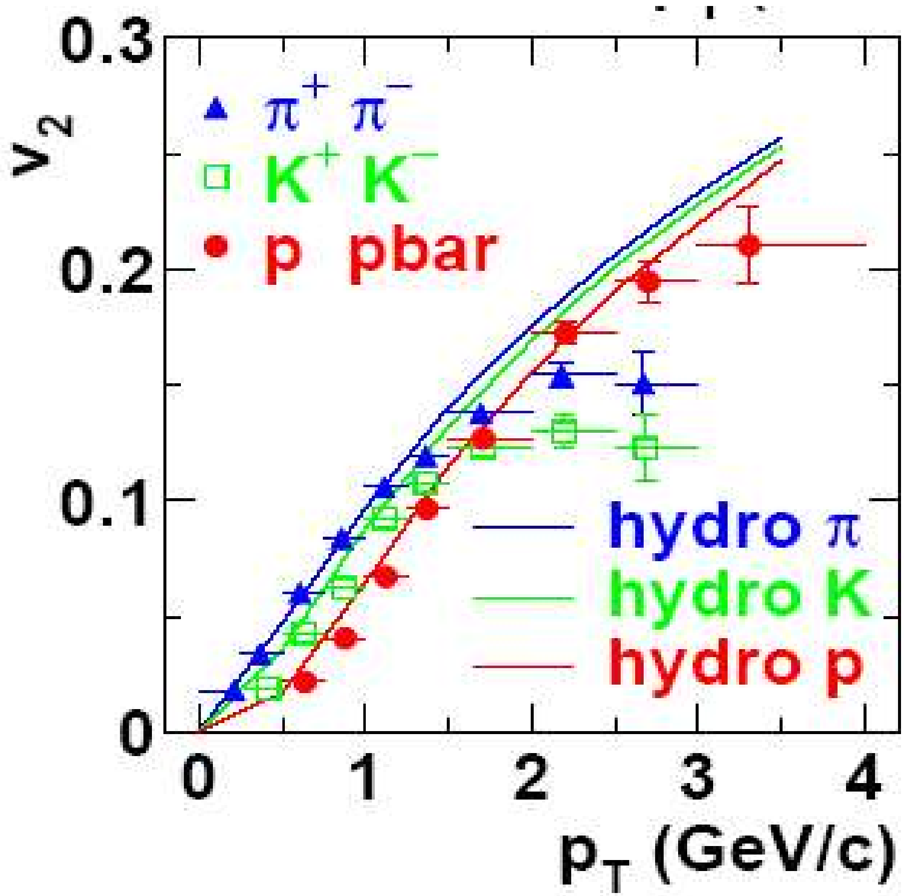
d + Au: Backward Peak

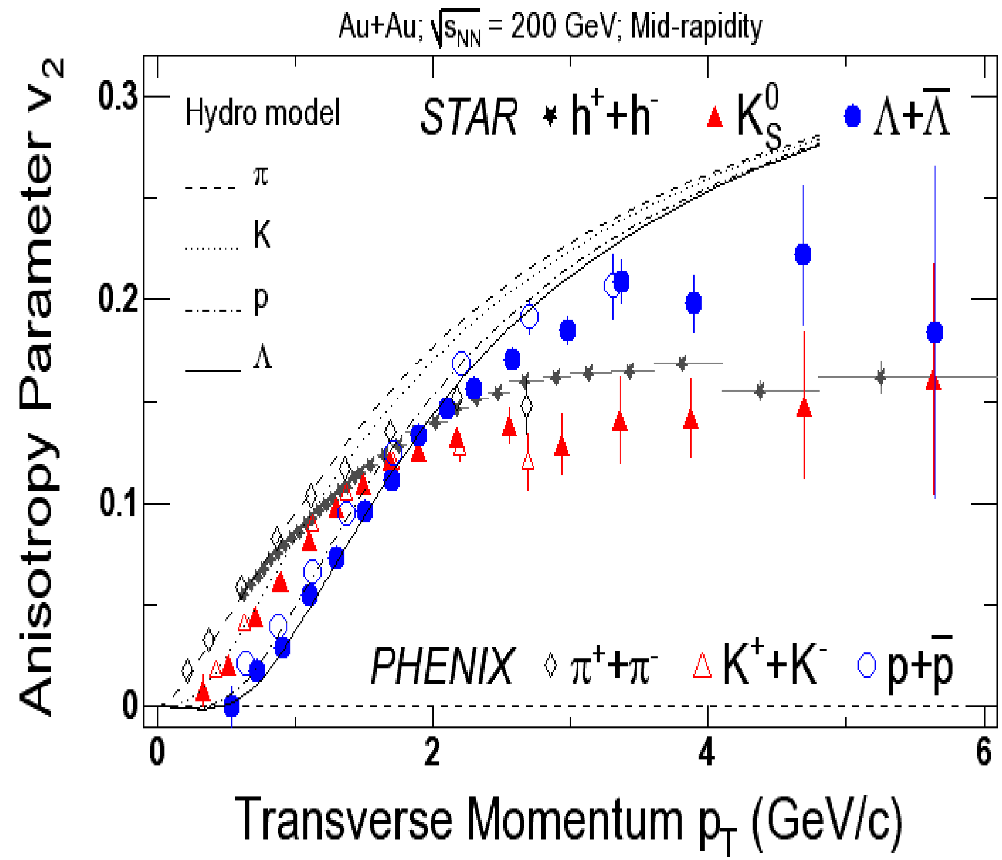
Au + Au:
No Backward Peak

STAR (nucl-ex/0306024)

Jet Energy Loss also lead
to reduction of back-to-back correlation

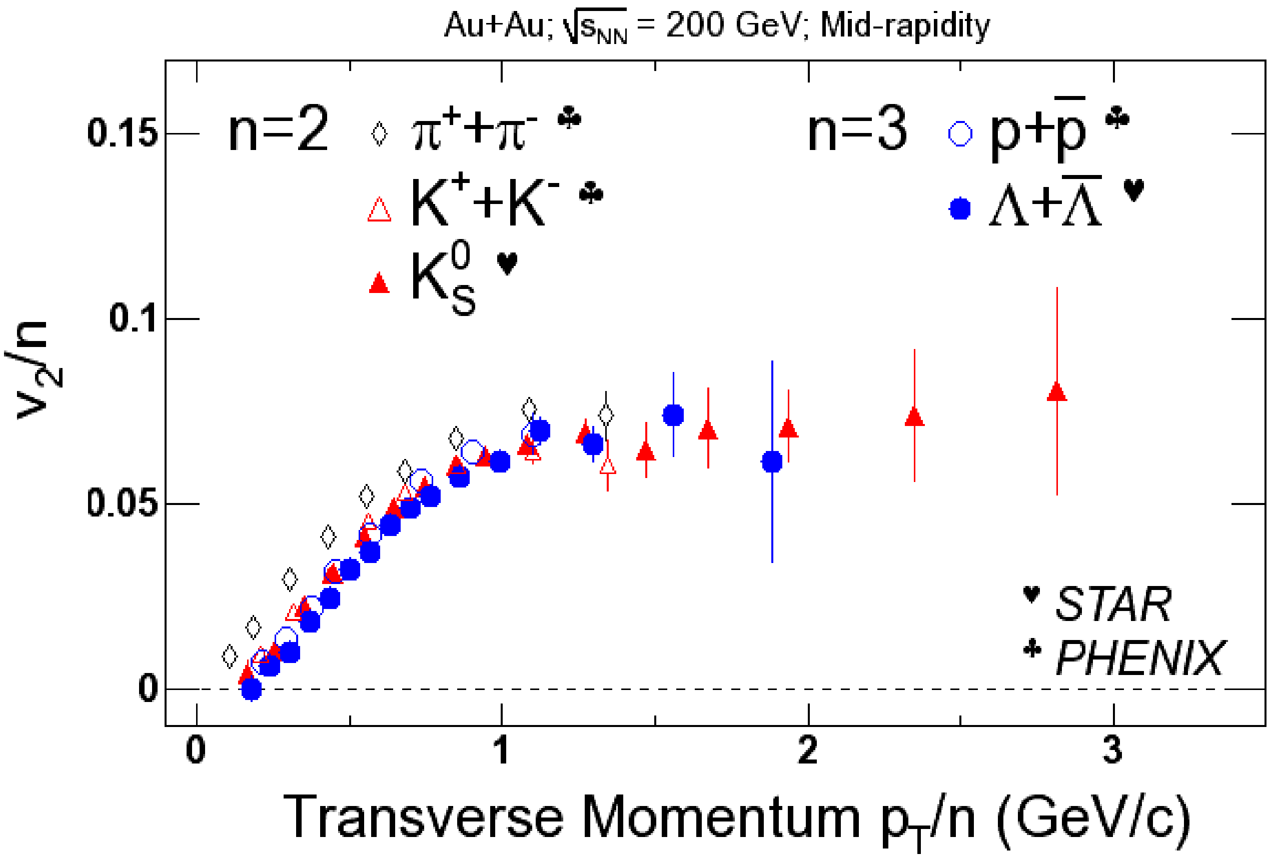
by Esumi, Matter03





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

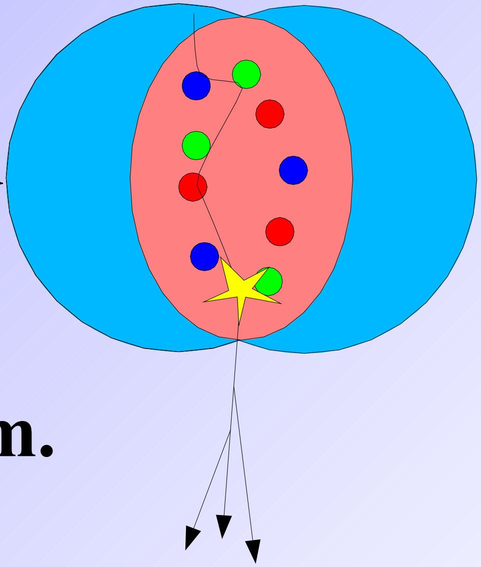
How can we get large v_2 at high p_T ?

- **Essense in Quark Recombination Model**
  → When two or three quarks make an object,
  that object will have an momentum anisotropy of their sum.

$$f(\varphi)=(1 + 2\,v_2(q)\cos\varphi) \times (1 + 2\,v_2(q)\cos\varphi)$$

$$\approx 1 + 2 \times 2\,v_2(q)\cos\varphi$$

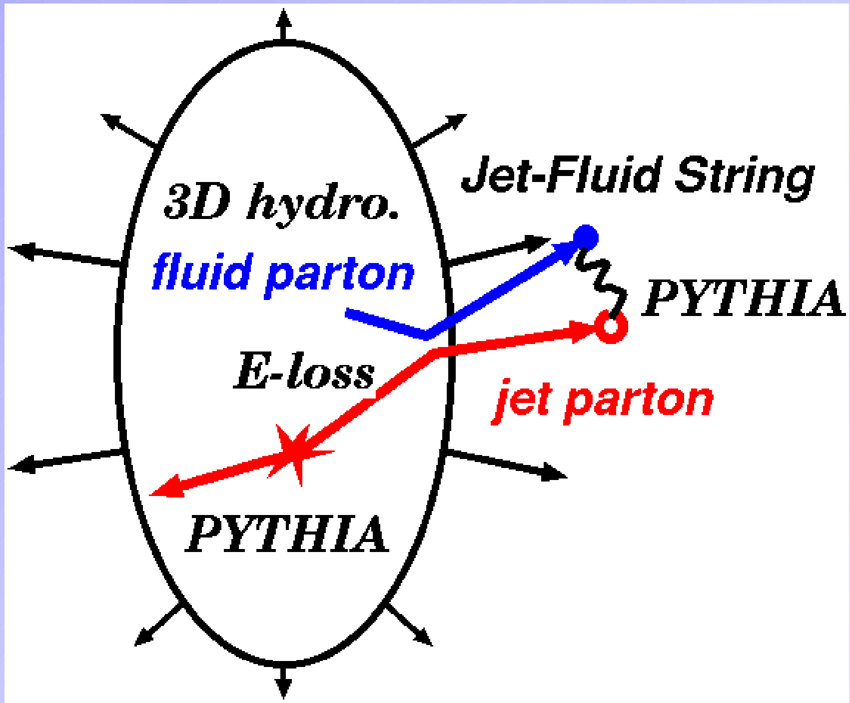
- **Elliptic Flow of High pT particles is generated by the Energy Loss in QGP.**
  → Larger Energy Loss gives Larger v_2
  but they are not consistent with p_T spectrum.



Let's consider a possibility of New Hadronization Scheme to generate Larger v2 at high pT by combining the above two ideas !

Jet-Fluid String Formation and Decay

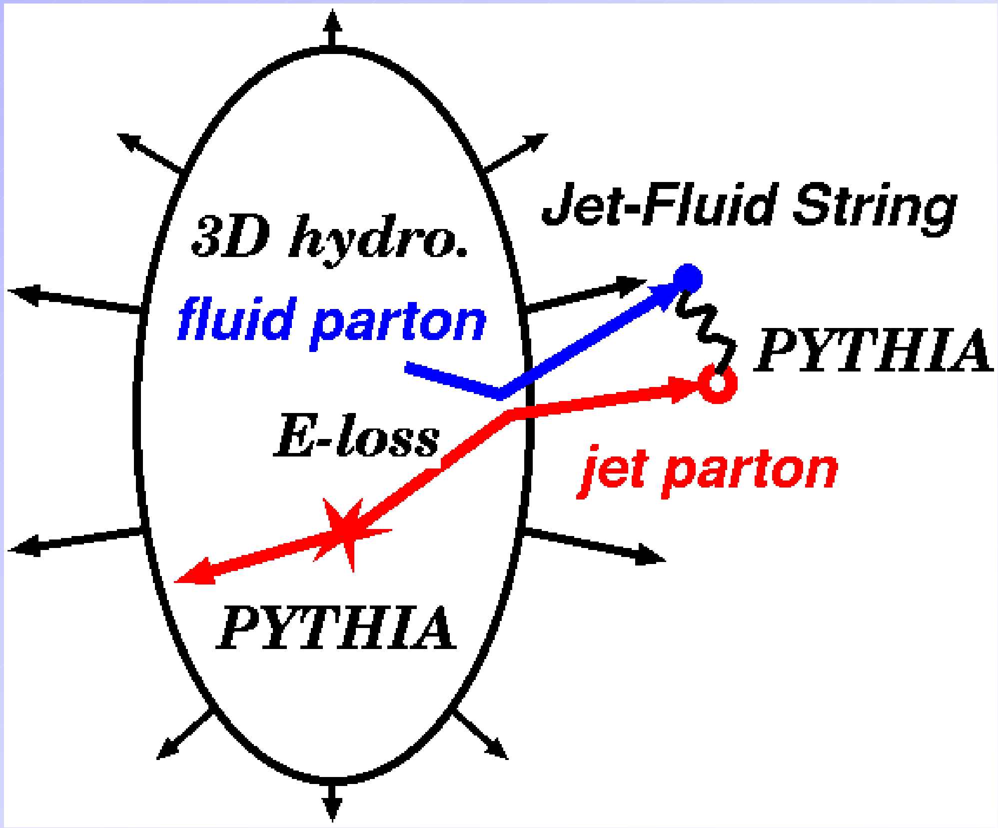
- Jet parton picks up a fluid parton **to make a color singlet object**.
  ↔ Independent Fragmentation
  (No explicit color flux specified)
- Color singlet string will **break up into many (several) hadrons**.
  → Entropy does not decrease.
  ↔ Quark Recombination
- Momenta of jet and fluid partons are **positively correlated**.
  → String will have large p_T and v_2.



Can we understand p_T spectrum and v_2 consistently ?

Model Details (1)

- Model Components
  - (Mini-)Jet Production: Pythia
  - Parton Energy Loss in QGP:
    GLV first order formula
    + 3D Hydrodynamics results
  - String formation Prob.:
    Use parameterized form
  - String Fragmentation: Pythia



Model Details (2)

- **Relevant Model Parameters**
  - **Jet production: K-factor**

$$\sigma_{jet} = K\,\sigma_{jet}^{pQCD(1\,st\,order)}$$

(c.f. JAM → K=3)

  - **Energy Loss**

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

(c.f. Hydro+Jet model C ≈ 2.7)

  - **Parameterized String Formation Probability**

$$P(\sqrt{s}) \propto \Theta(\sqrt{s}-\sqrt{s_0})\,s^{-n/2}$$

(This should be evaluated by pQCD matrix element + string level density)
Current Choice: $\sqrt{s_0}$ = 1.0 GeV, n = 1

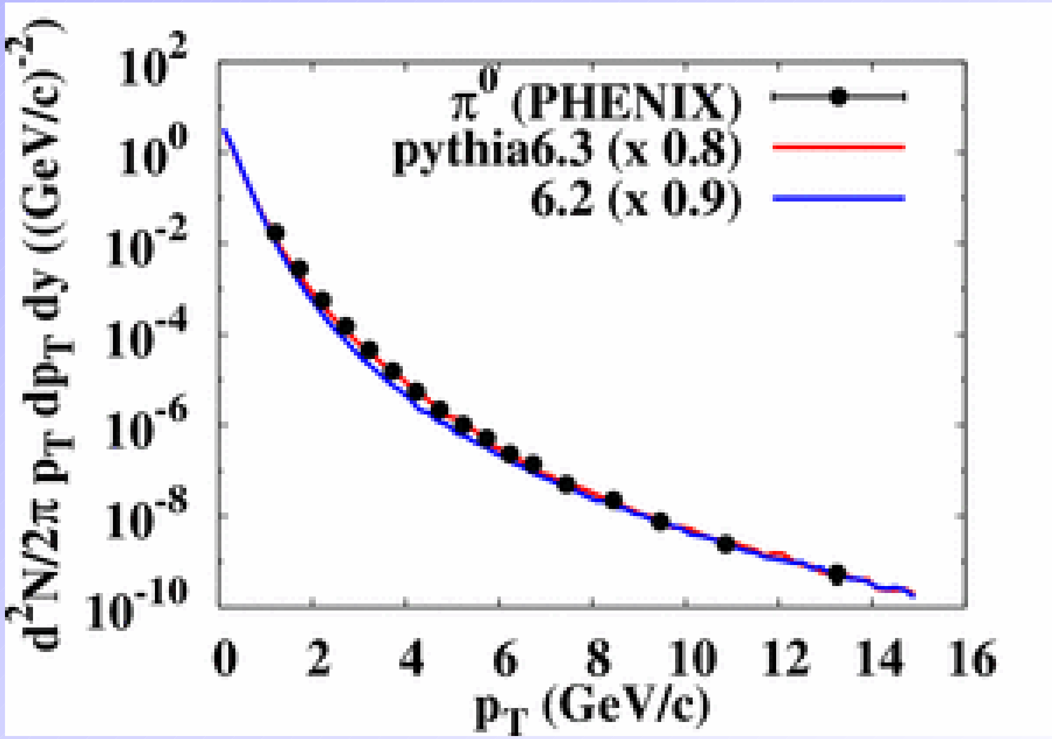
K-factor

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

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

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

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



Energy Loss Factor (1)

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

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

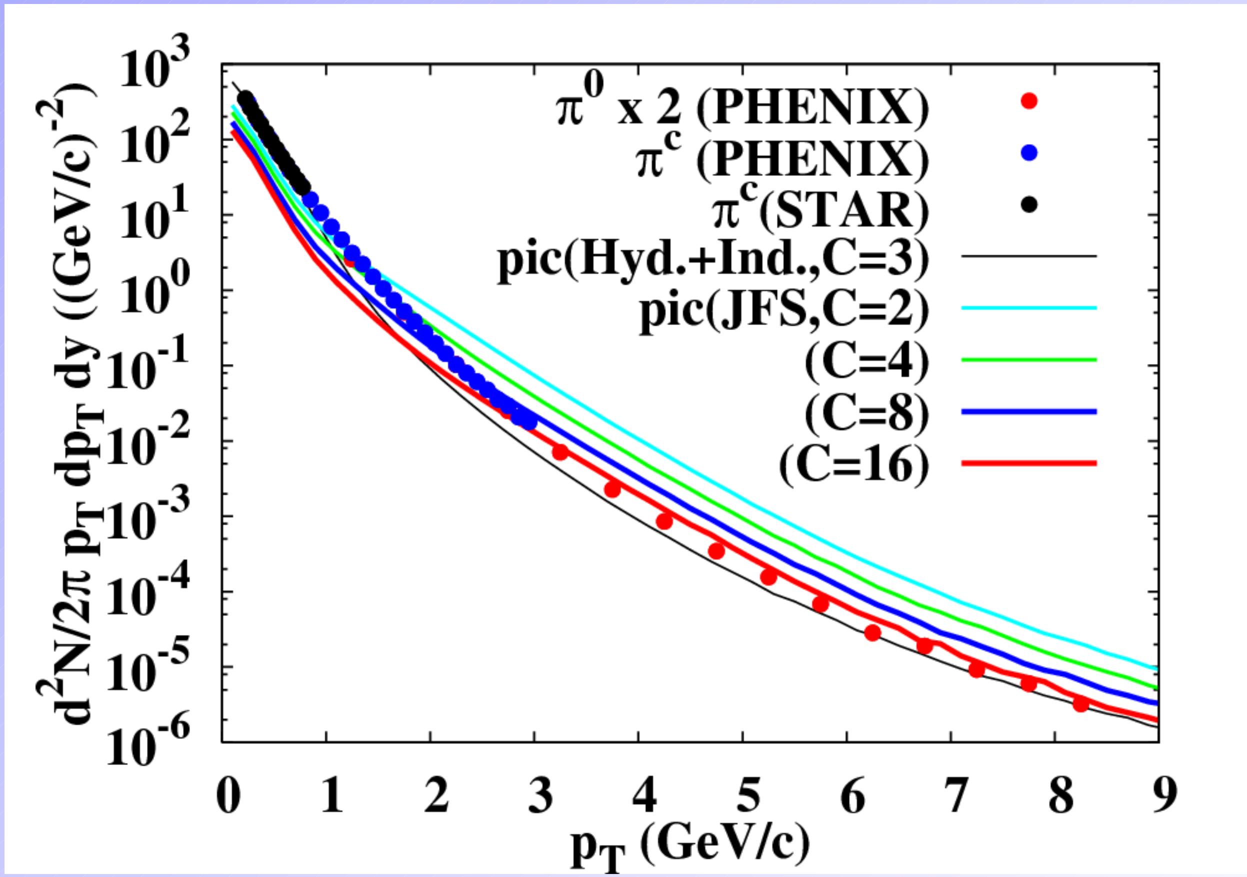
→ Determining N_{jet} is important !
Ncoll = 373 @ b=7.4 fm (PHENIX estimate)
σ^{NN}_{jet} = 17.5 mb (pp fit pythia 6.3), σ^{NN}_{tot} = 47. 4 mb (JAM)

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

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

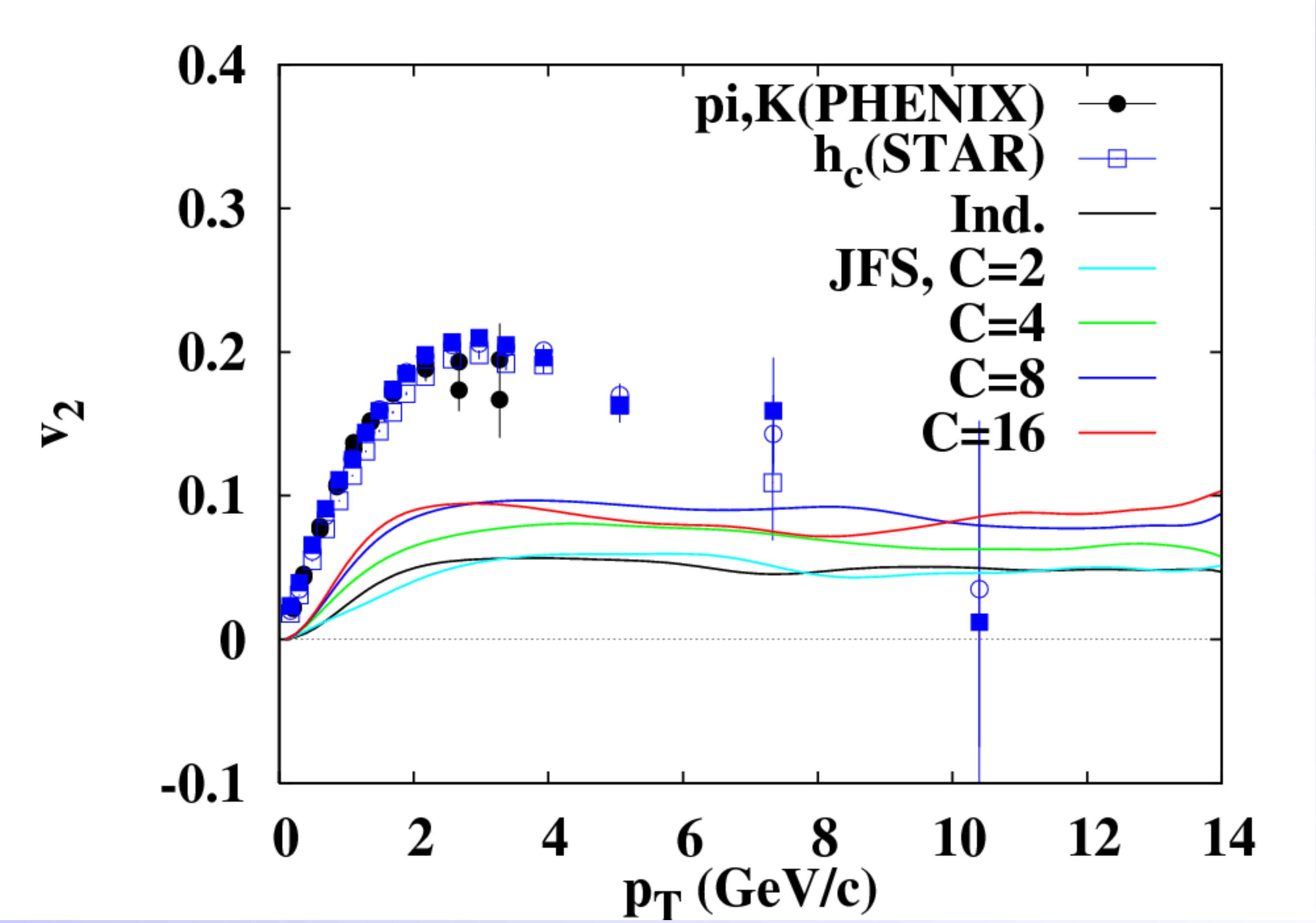
Energy Loss Factor (2)

- **Comparison with pion pT spectrum in Au+Au @ RHIC**
  Ind. Frag.: C ≈ 3, JFS: C > 8
  → Large Energy Loss is allowed in JFS



Elliptic Flow

- **JFS with large energy loss factor, C**
  → Enhanced Elliptic Flow (~ 10 %) is generated even at high p_T (~ 10 GeV/c).
- **Independent Frag.**
  → v_2 ~ 5 %
  at high pT

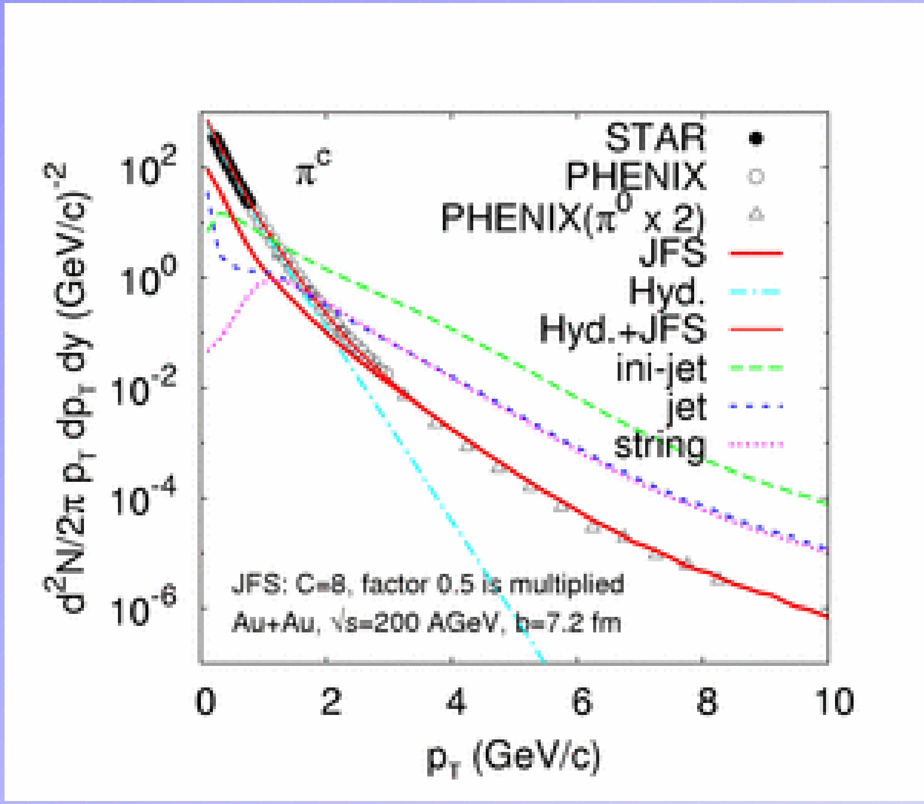


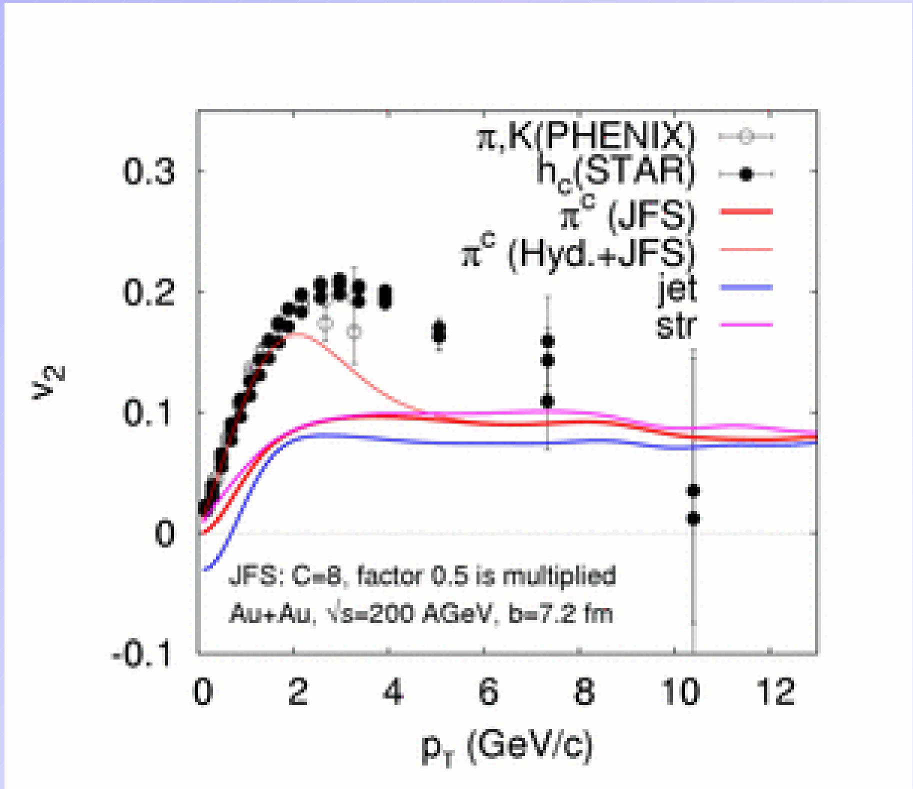
Combined with Low p_T spectrum

- Low pT spectrum is assumedand combined.

$$F^{Hyd}(p_T) = A \exp(-p_T/T)(1 + B/(1 + (p_T/p_0)^8))$$

$$v_2^{Hyd}(p_T) = 0.13\, p_T$$



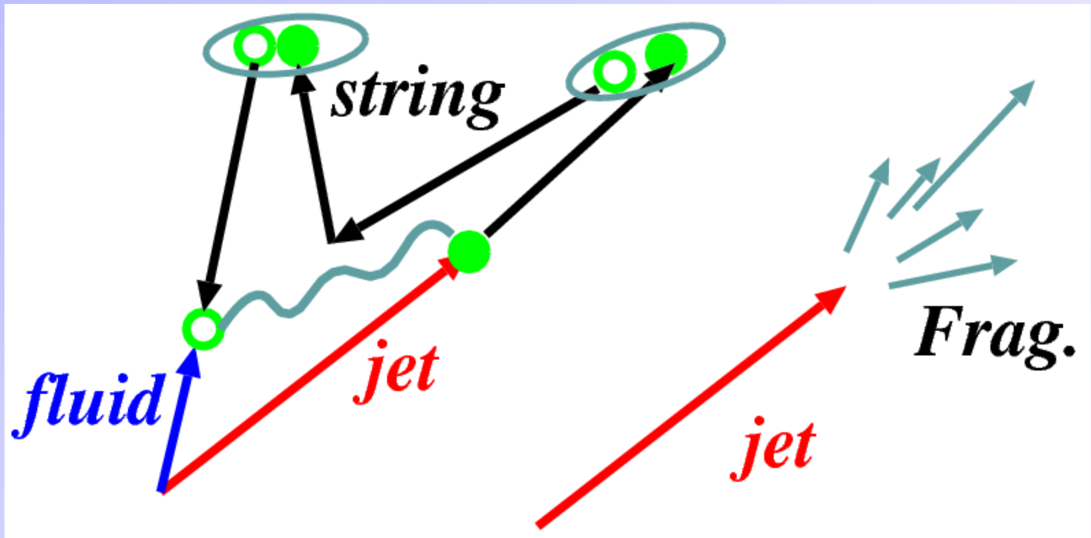


Discussion

- **Mechanism to produce high p_T hadrons in JFS**
  - **Jet and Fluid partons are correlated in momentum**
    → large transverse VELOCITY (p_T) of formed Strings
  - **Relative momentum is relatively small**
    → Smaller number of hadrons with high p_T are formed

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

- **Allowed large energy loss and Momentum anisotropy correlation of jet-fluid makes v_2 larger.**



Summary

- **A new mechanism to produce high pT hadrons (Jet-Fluid String formation and decay) is proposed.**
  - **This would be better than Indep. Frag. where Energy-Momentum conservation is satisfied only in average.**
  - **Low pT hadrons are suppressed than in Indep. Frag.**
  - **Entropy does not decrease, but increases.**
- **When we FIT p_T spectrum (roughly), large v_2 is found to be generated.**
  - **Easy to form high p_T hadrons, and then large energy loss is requred to explain p_T spectrum data.**
  - **Momentum anisotropy correlation of jet-fluid is expected to help.**

Further Problems

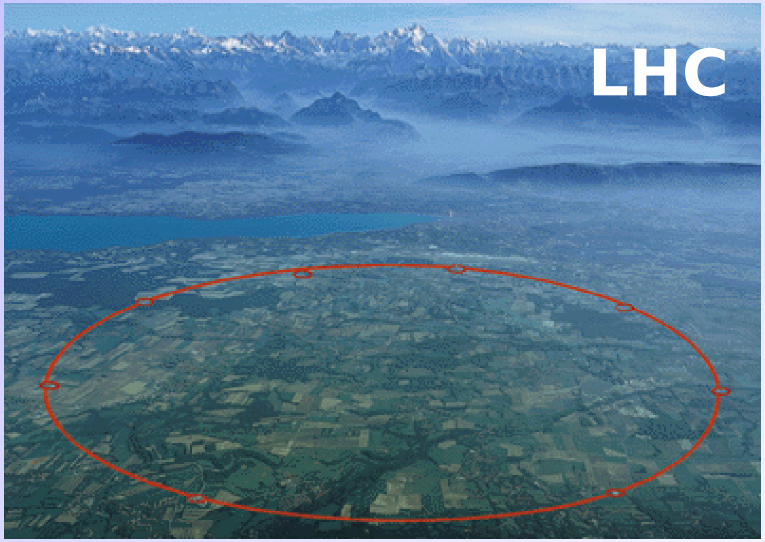
- Very large energy loss is required to explain p_T spectrum.
  - C > 8 in JFS ↔ C ≈ 2.7 in Hydro+Jet model (Hirano-Nara)

  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.
  → Yoshino's Master thesis ?
- and Many.

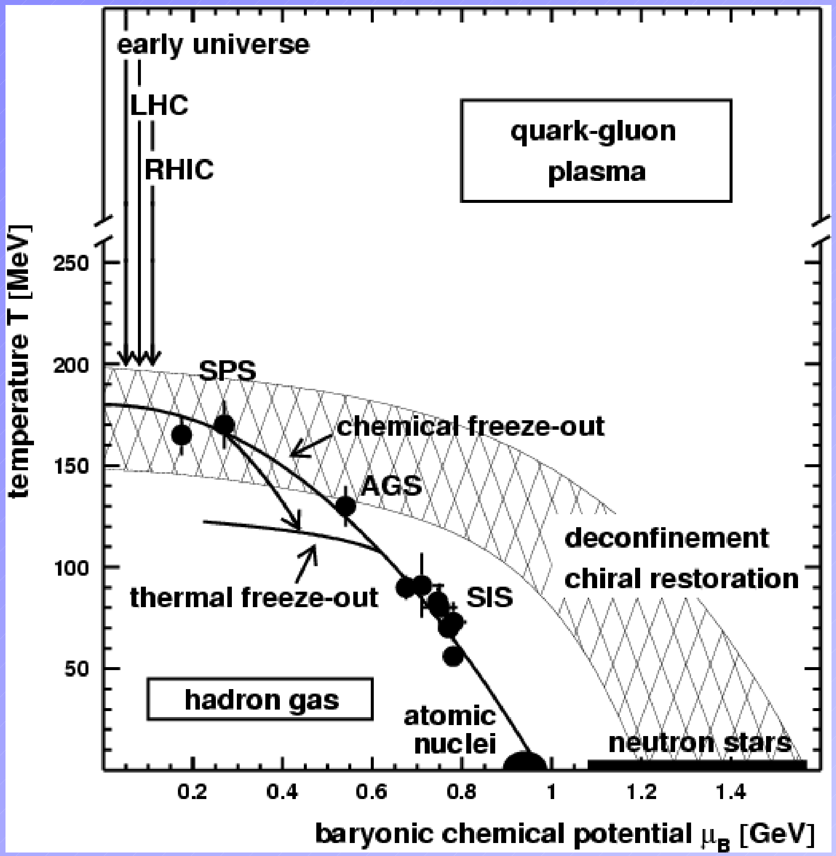
High-Energy Heavy-Ion Collision Experiments

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

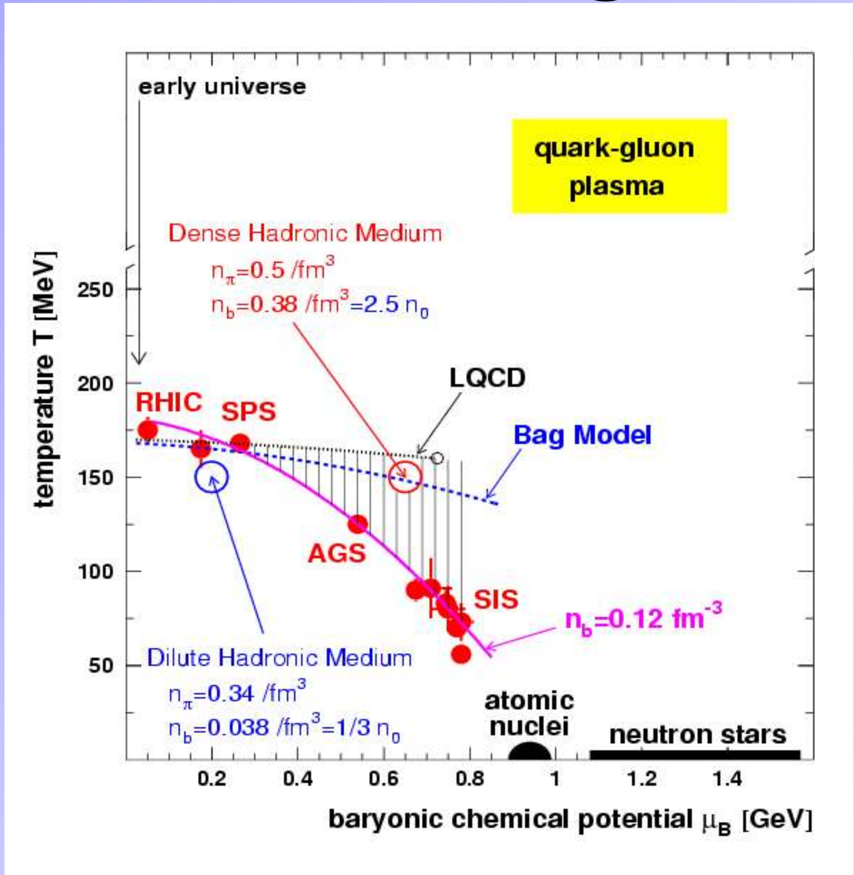
LBL-Bevalac:
800 A MeV
GSI-SIS:
1-2 A GeV
BNL-AGS (1987-):
10 A GeV
CERN-SPS (1987-):
160 A GeV
BNL-RHIC (2000-):
100+100 A GeV
CERN-LHC (2007(?)-):
3 + 3 A TeV



Experimentally Estimated Phase Diagram



1998 (J. Stachel et al.)

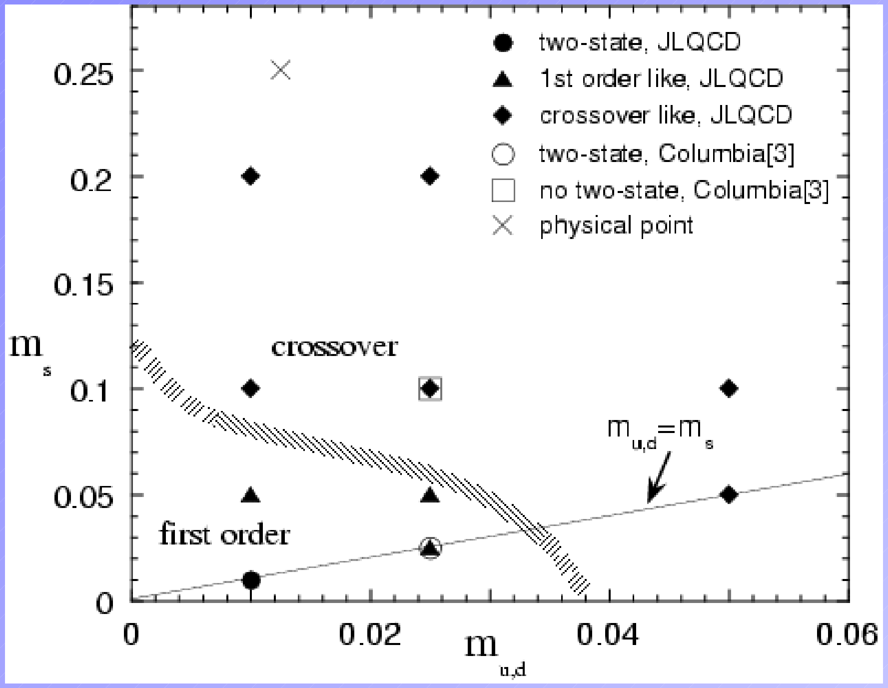


2002 (Braun-Munzinger et al. J. Phys. G28 (2002) 1971.)

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

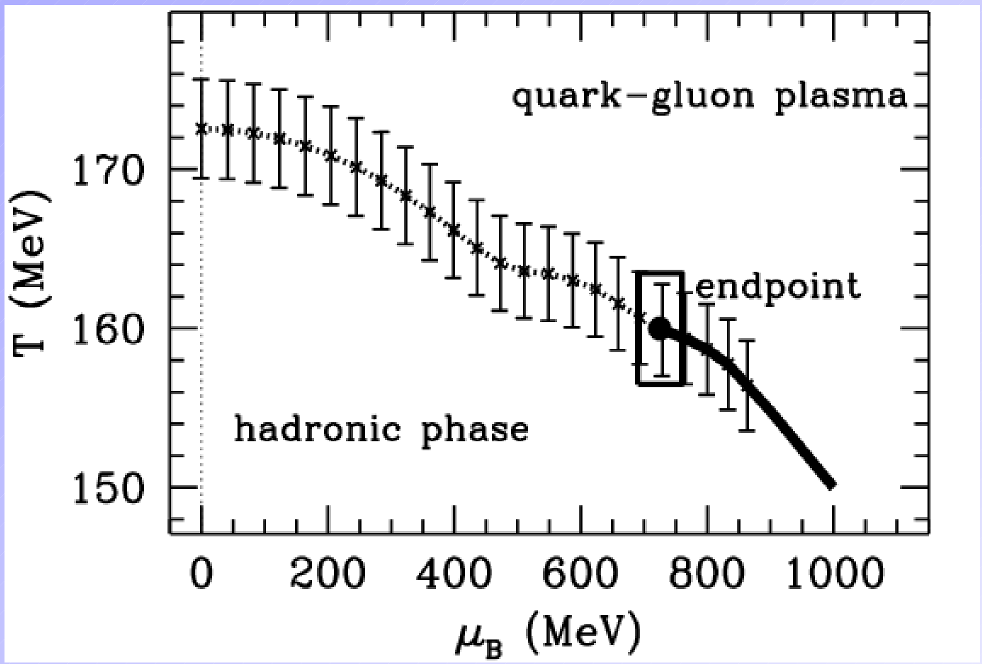
Theoretically Expected QCD Phase Diagram

Zero Chem. Pot.



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

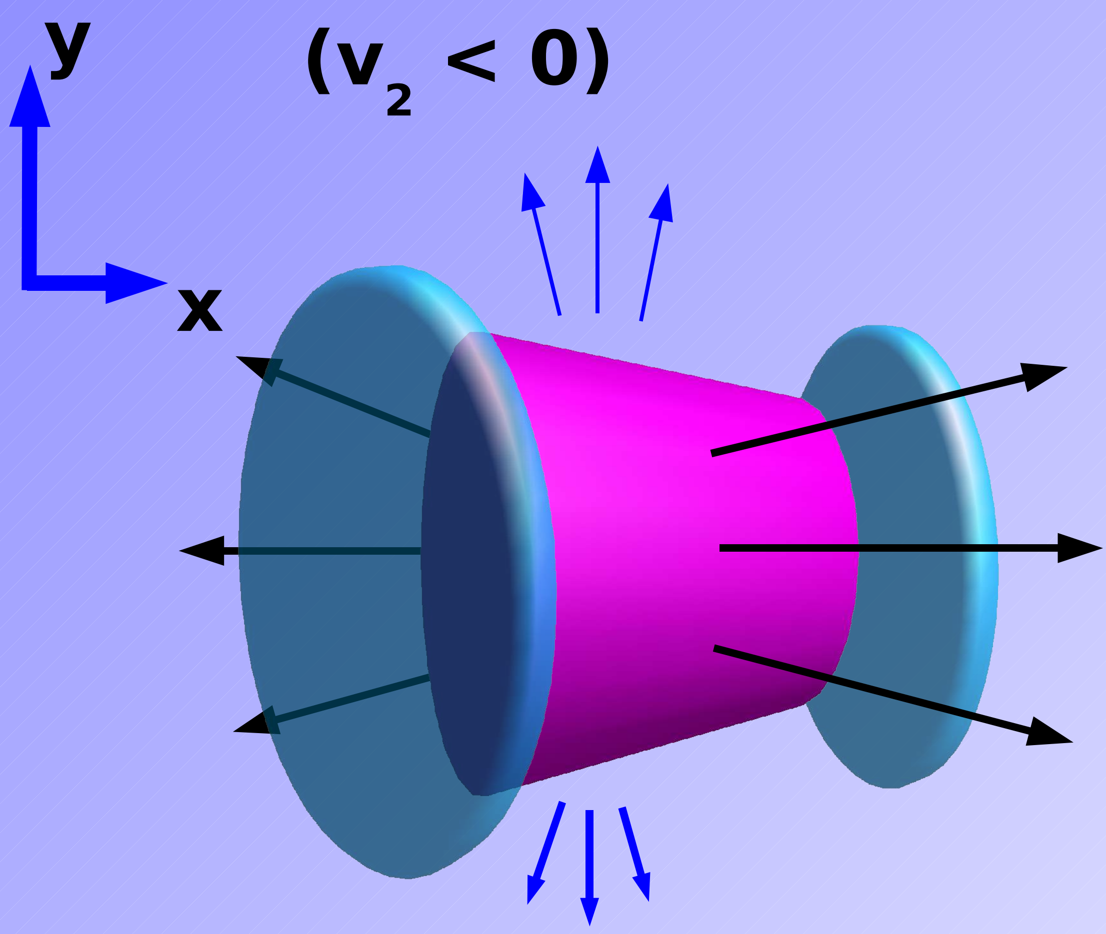
Finite Chem. Pot.



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

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

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

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

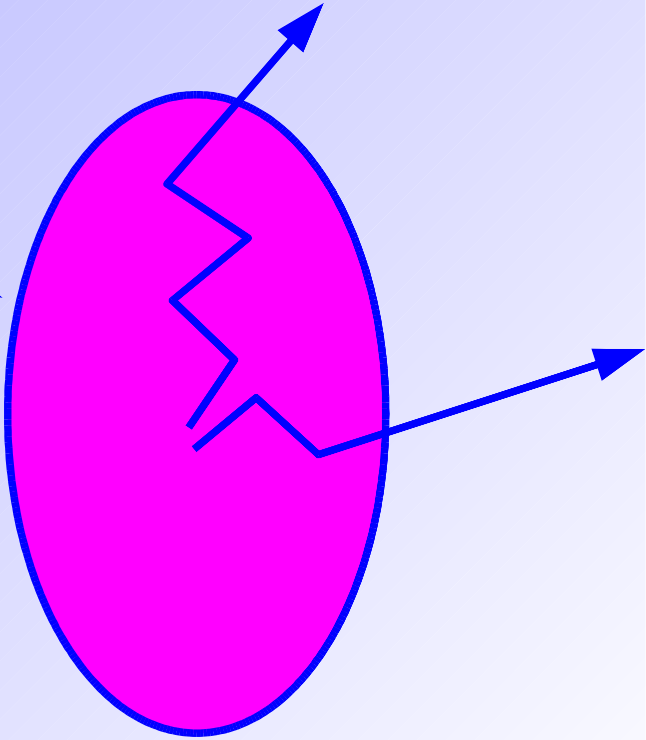
Elliptic Flow (II)

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

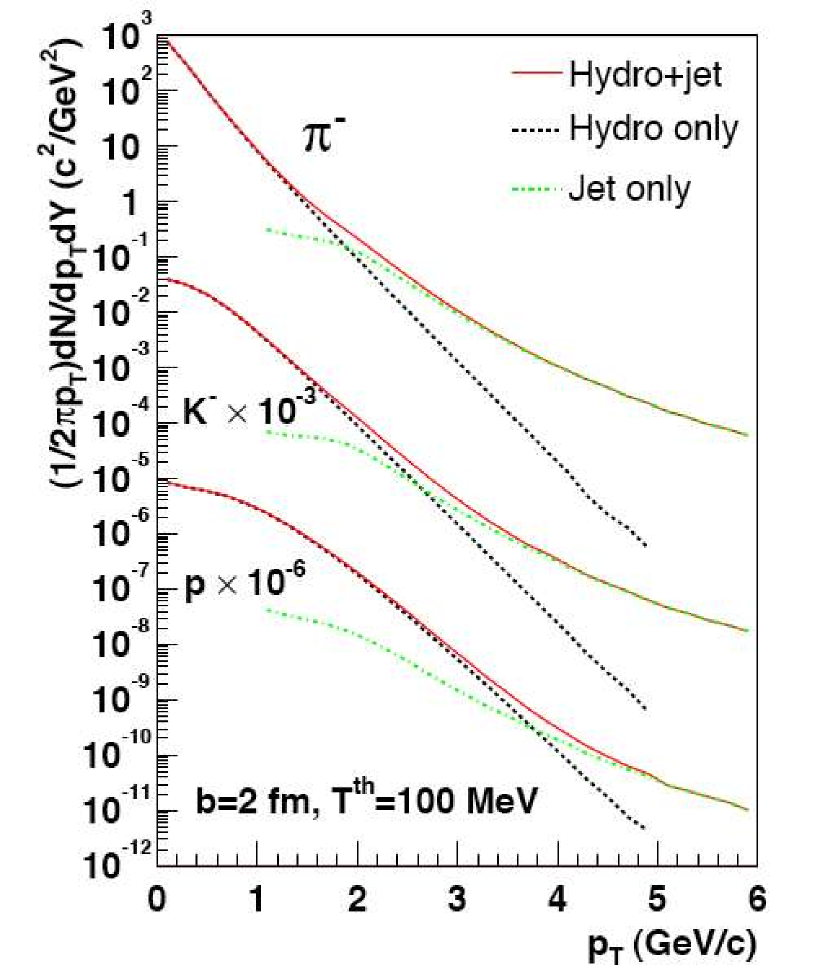
Hydro+Jet
(Hirano and Nara)

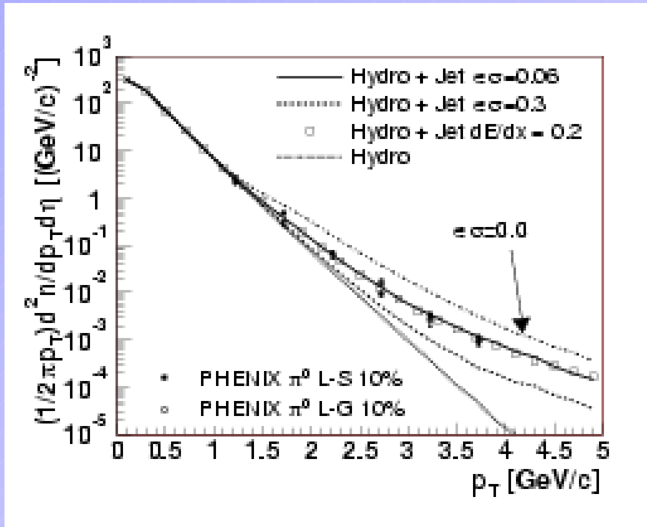
Fragmentation
& Recombination
Fries, Nonaka, ...

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

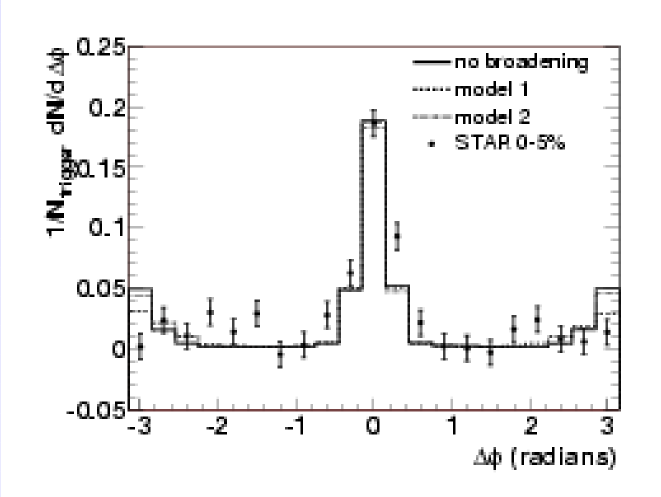


Hydro + Jet Model (Hirano and Nara)





PRC66 (2002) 041901.

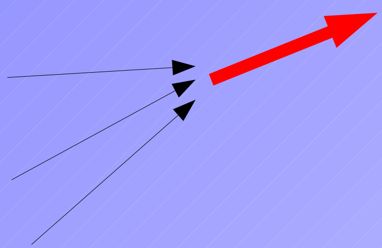


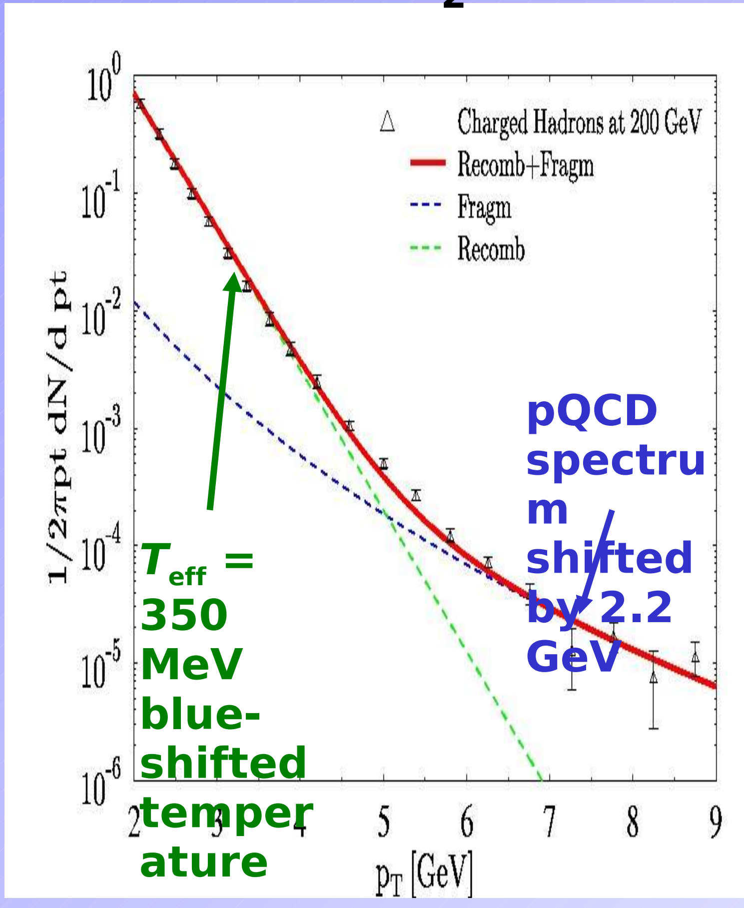
PRL 91 (2003)082301.

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

Fragmentation and Recombination (Duke U. Group)

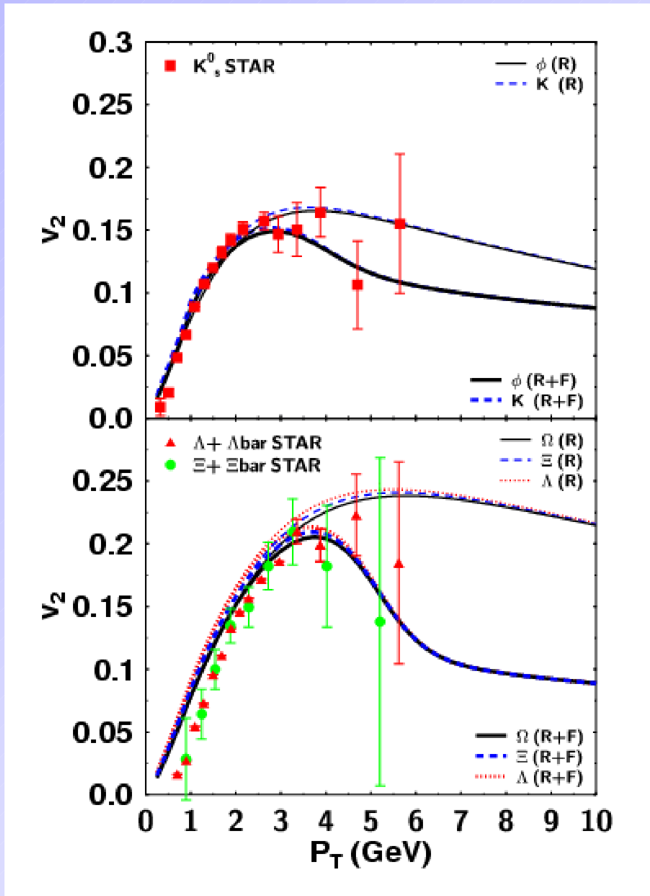
Recombination Enhances Intermed. P_T Hadrons and Baryon V_2.





T_{eff} = 350 MeV blue-shifted temperature

pQCD spectrum shifted by 2.2 GeV



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