Color Glass Condensate, Hydrodynamics and the parton energy loss

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Collaboration with Tetsufumi Hirano (RIKEN-BNL)

CGC, hydrodynamics, and parton energy loss can be consistent each other?

- Success of CGC, hydrodynamics and parton energy loss at RHIC
- Some results from CGC+hydro+Jet model

  Nuclear modification factors.

  elliptic flow for identified hadrons.

  Dihadron spectra.

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Motivation

- **Parton saturation in the color glass condensate**

  KLN model (Kharzeev, Levin, Nardi), KNV............

  rapidity, centrality, energy dependence of hadron multiplicities

  initial state modification of the spectra (Cronin effect).

- **PQCD calculations with parton energy loss**

  (M.Gylassy, P.Levai, I.Vitev, X. N. Wang SW, BDPMS, AMY..........)

  high-pT spectra: suppression of single hadron spectra,

  back-to-back correlations.

  Elliptic flow at high pt.

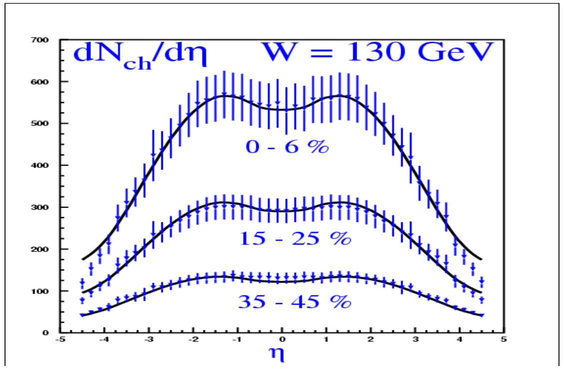
- **Hydrodynamics**

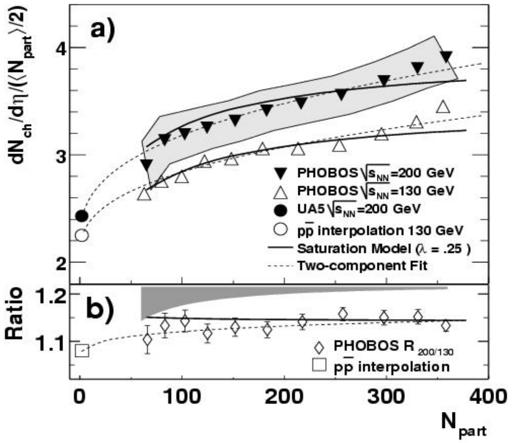
  P. F. Kolb, U. Heinz, T. Hirano, P. Huovinen.........

  explanation of large elliptic flow of pions, kaons, protons at low pt.

Parton saturation, collective effects, jet quenching

D. Kharzeev, E. Levin, M. Nardi

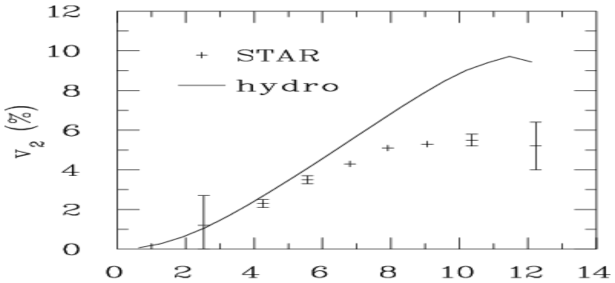


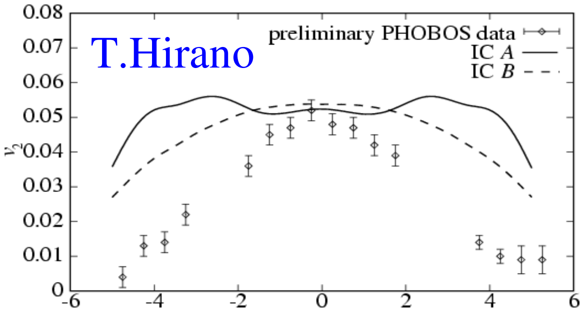


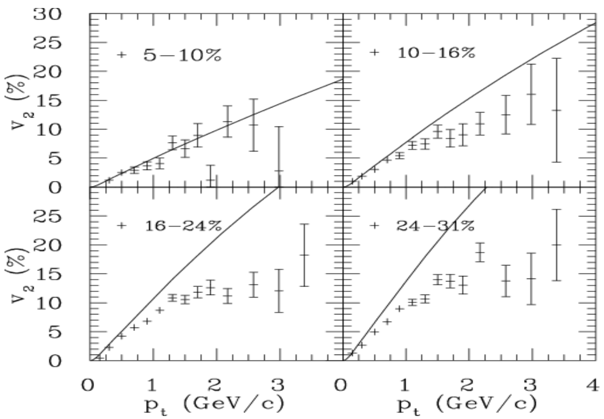
Rapidity, centrality and energy dep.

$$\frac{dN}{d\eta} \approx \frac{N_{part}}{\alpha_s(Q_s^2)} \qquad Q_s^2(x) \sim \left(\frac{x_0}{x}\right)^{\lambda}$$

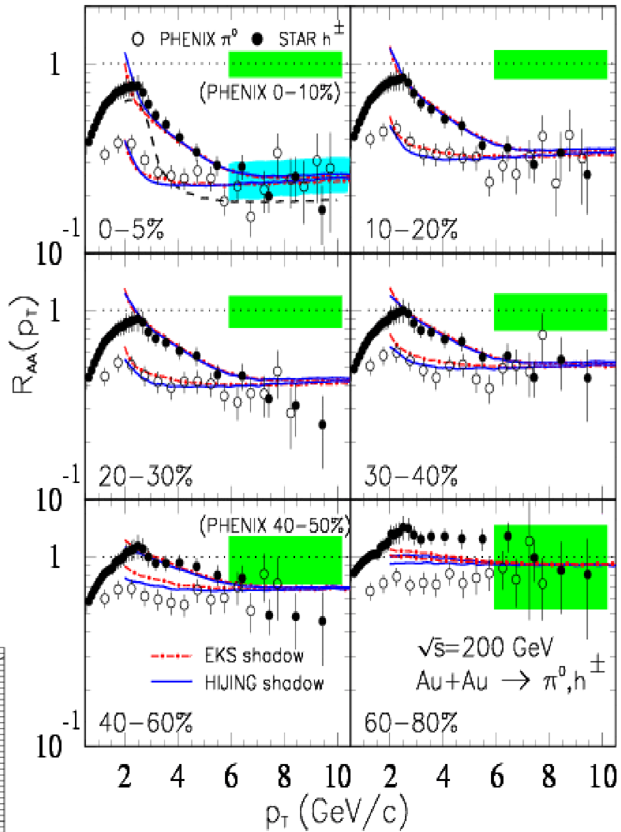
Pasi Huovinen







X.N.Wang



Hydrodynamics

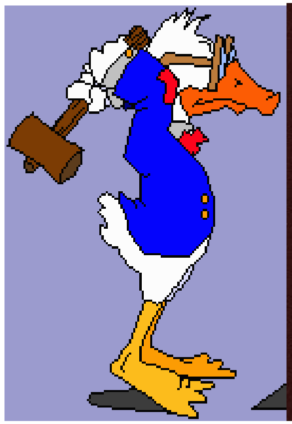
- b<5fm
- Mid-rapidity
- pT<2GeV/c

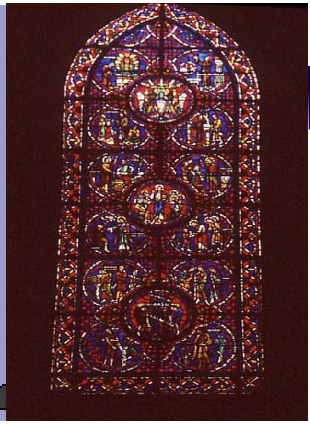
These three independent physics are closely related each other?

- **Parton saturation in color glass condensate**
  provide initial parton productions
  Need final state interactions (can not explain collective effects, eT/n)
- **PQCD parton energy loss of high pt jets**
  high-pT spectra: suppression of hadron spectra,
  Need time evolution of the matter density for the input of energy loss
- **Hydrodynamics**
  provide time evolution of the system for the soft sector
  explanation of large collective effect.
  Need initial conditions, can not apply high-pT

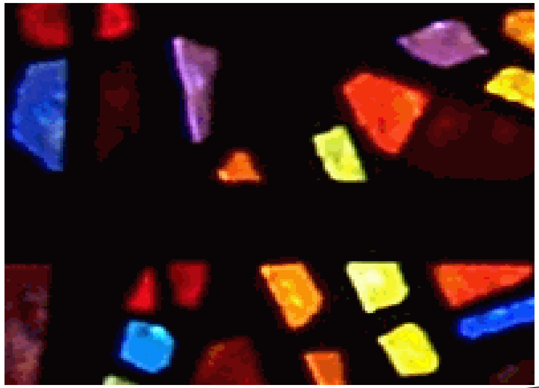
Different physics talk to each other

CGC dense parton at small-x



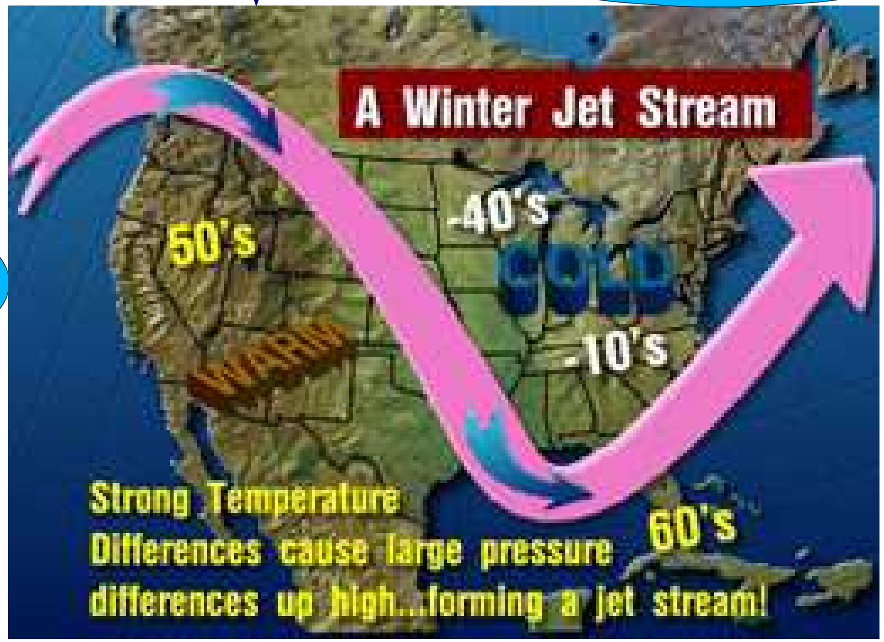


Shattering CGC



So far unknown

Hydrodynamics



High x partons generate low x parton

Jet propagation

PQCD high-x dilute

The model

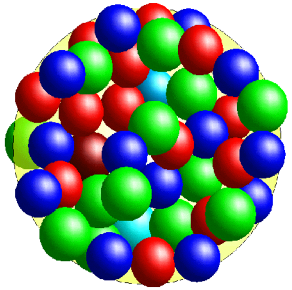
High density

CGC

Local thermal →

Full 3D Hydrodynamics

Collective Flow



Kt factrization approach (KLN)

Jet propagation in the QGP fluids

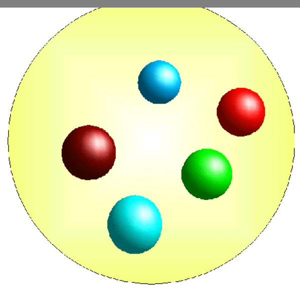
Pythia

Jet production

Energy loss using GLV 1st formula →

Quenched jet

Independent fragmentation



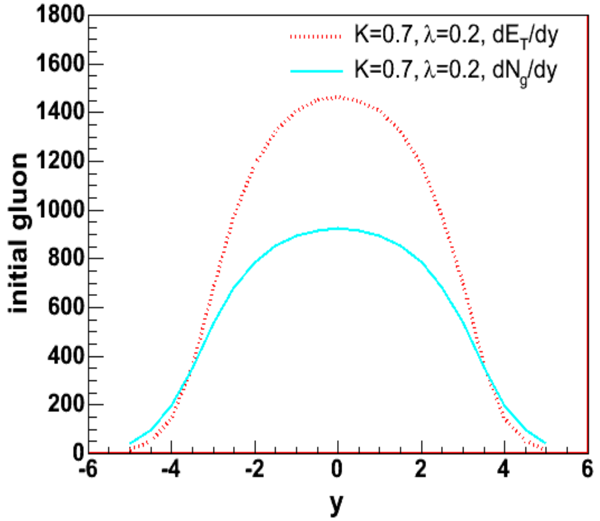
- LO pQCD matrix element
- Initial state radiations
- Final state radiations.

Understanding the processes to thermalization is
the final piece of the jigsaw puzzle at RHIC
(L. McLerran)

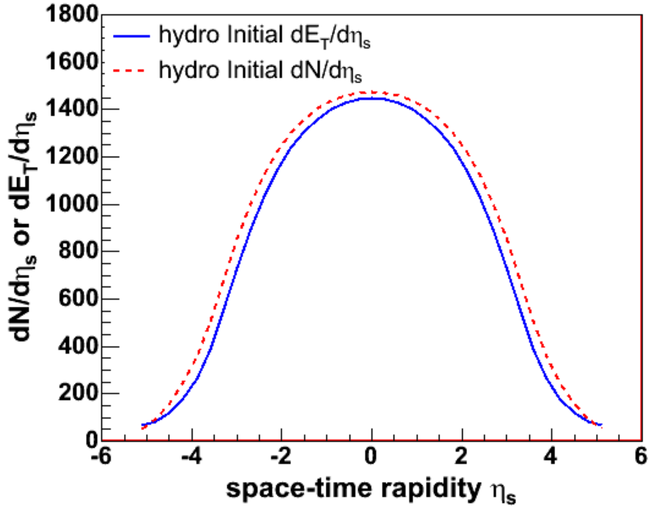
flow is generated.

Three steps to the final hadrons

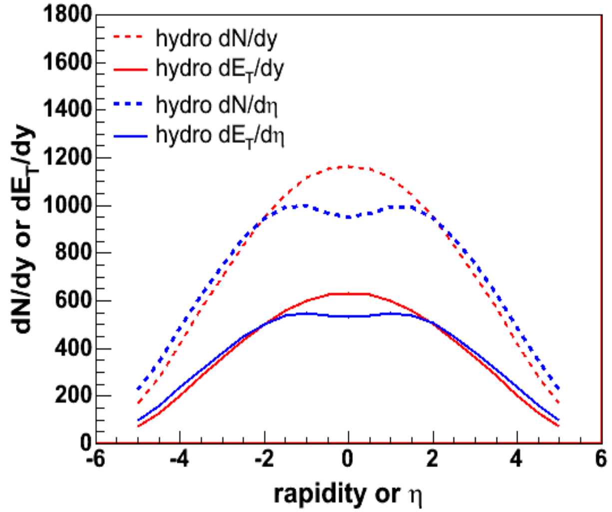
dEt/dy or dN/dy from CGC



Assume local thermal



Hydro evolution



Transverse energy per particle:

e/n = 1.6 GeV **0.98GeV** **0.55GeV**

Based on KLN

$$\frac{dE_t}{d^2x_t dy} = \frac{4\pi N_c}{N_c^2-1}\int p_t \frac{d^2 p_t}{p_t^2}\int d^2 k_t \alpha_s \phi(x_1, k_t^2)\phi(x_2,(p_t-k_t)^2)$$

Bjorken's ansatz + thermal

$$e = \frac{dE_T}{\tau_0 d^2 x_T d\eta_s} \qquad n = \frac{dN}{\tau_0 d^2 x_T d\eta_s}$$

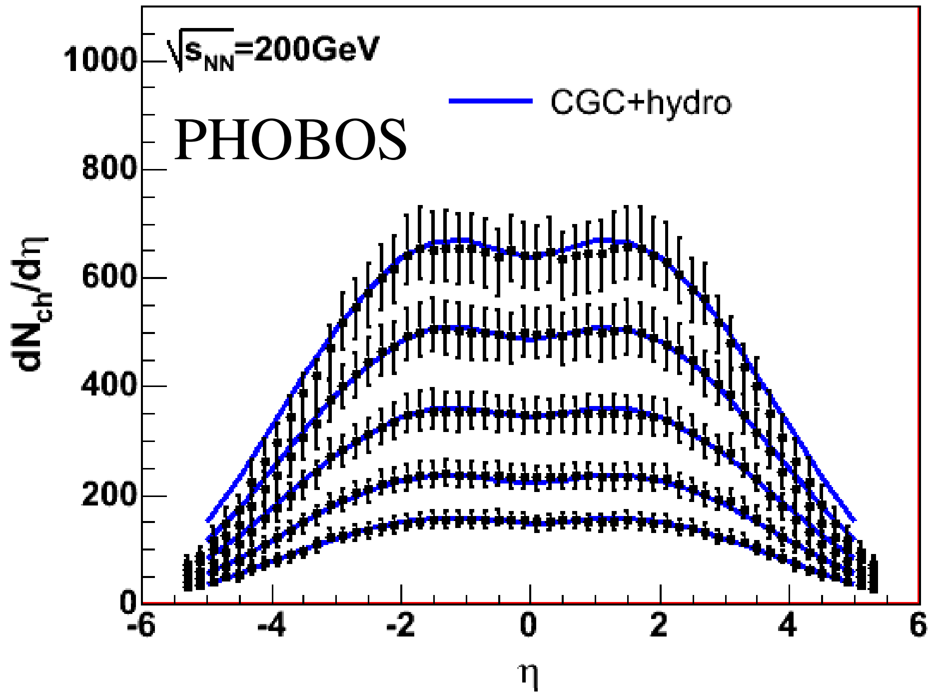
$$n = aT^3 \qquad e = bT^4 + B$$

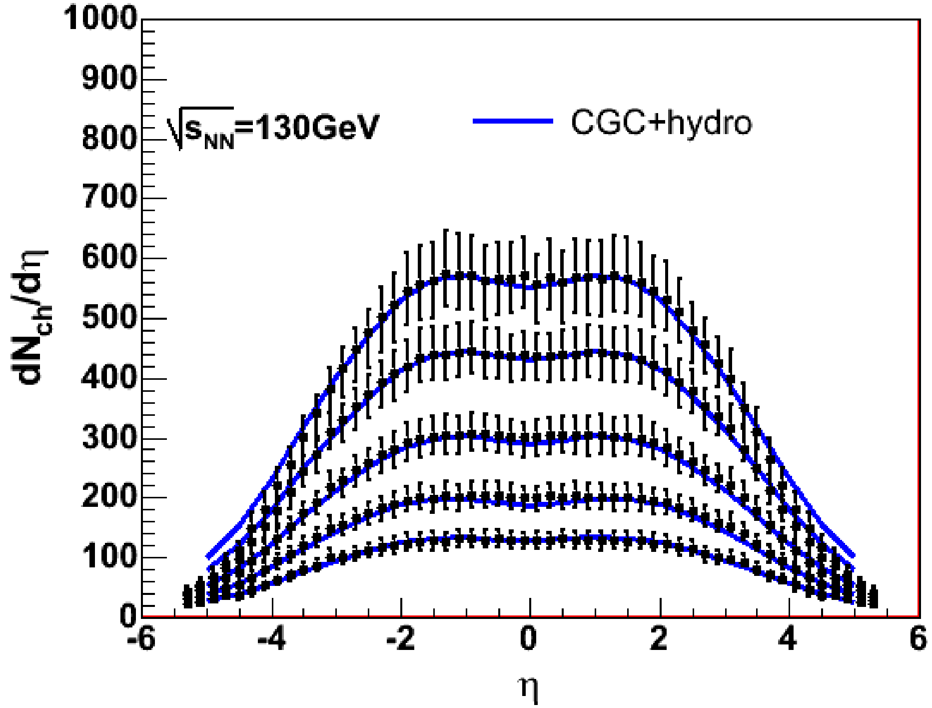
$$\phi(x_1, k_t^2) \sim \theta(Q_s - k_T) + \frac{Q_s^2}{k_T^2}\theta(k_T - Q_s)$$

$$xG(x, Q^2) = K x^{-\lambda}(1-x)^4 \ln(Q^2/\Lambda_{QCD}^2)$$

$$Q_s^2 \sim \alpha(Q_s^2) xG(x, Q_s^2)\rho_{part}^A$$

Pseudo rapidity distribution

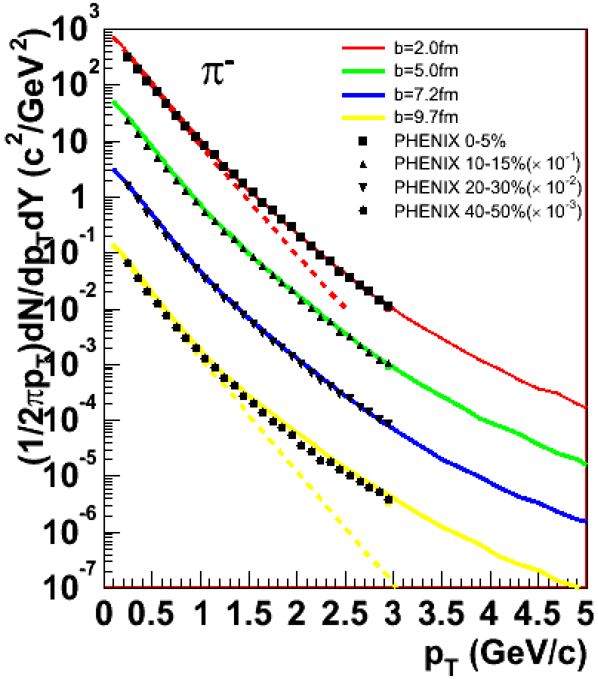


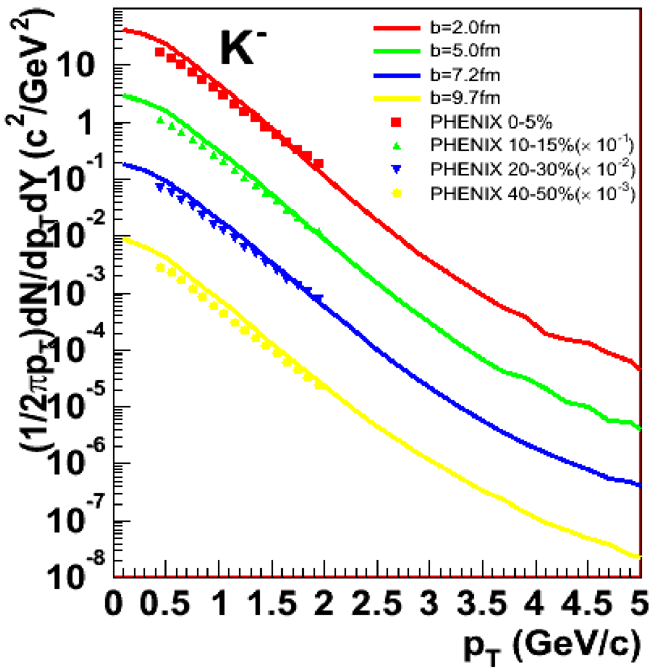


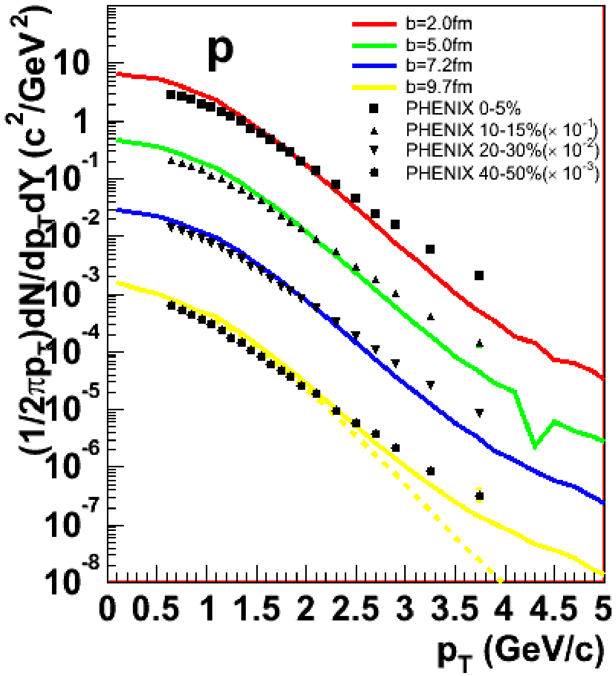
We have to specify a hydro initial condition from infinite number of candidates

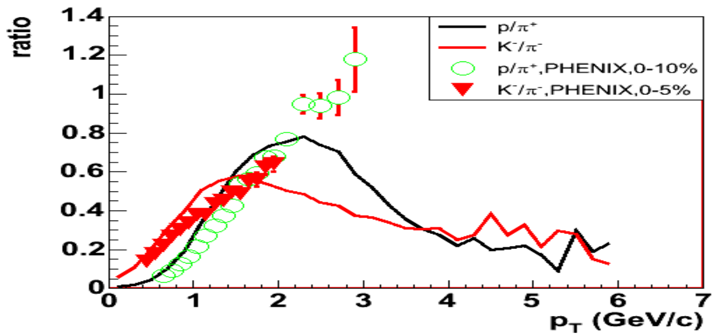
CGC provides a good initial condition for hydrodynamics

Transverse momentum spectra CGC+hydro+jet





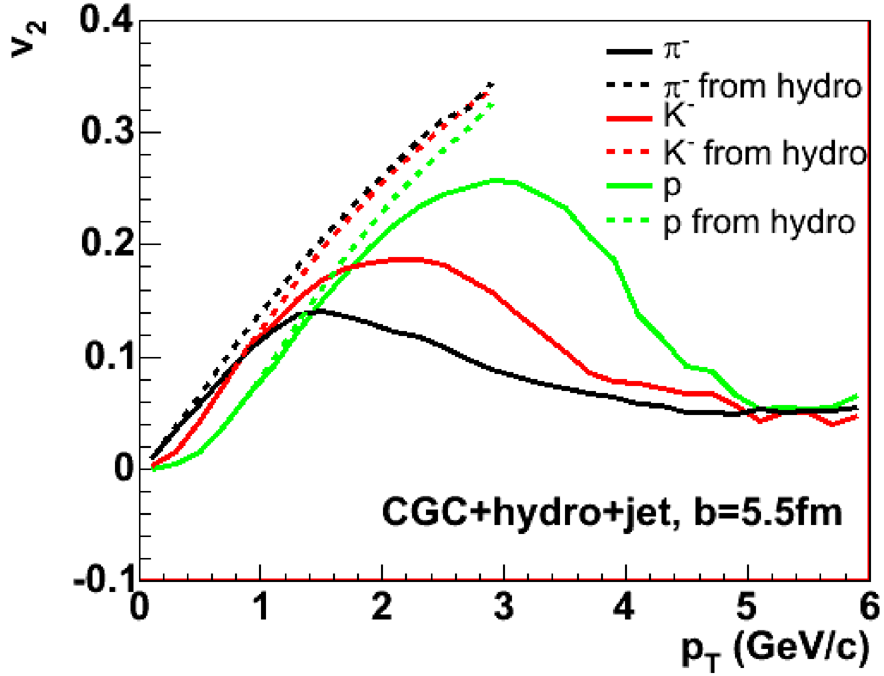


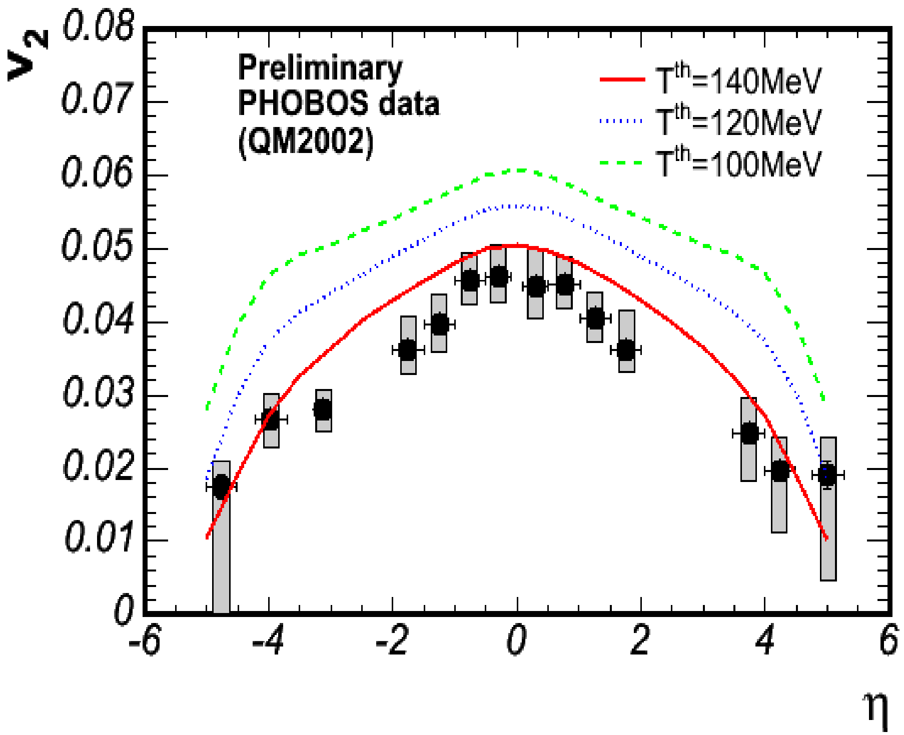


$$T_{chemical} = 170MeV\ ,\ T_{kinetic} = 100MeV$$

p/pi > 1 can be explained by hydrodynamic radial flow.

Elliptic flow for pi, K, p

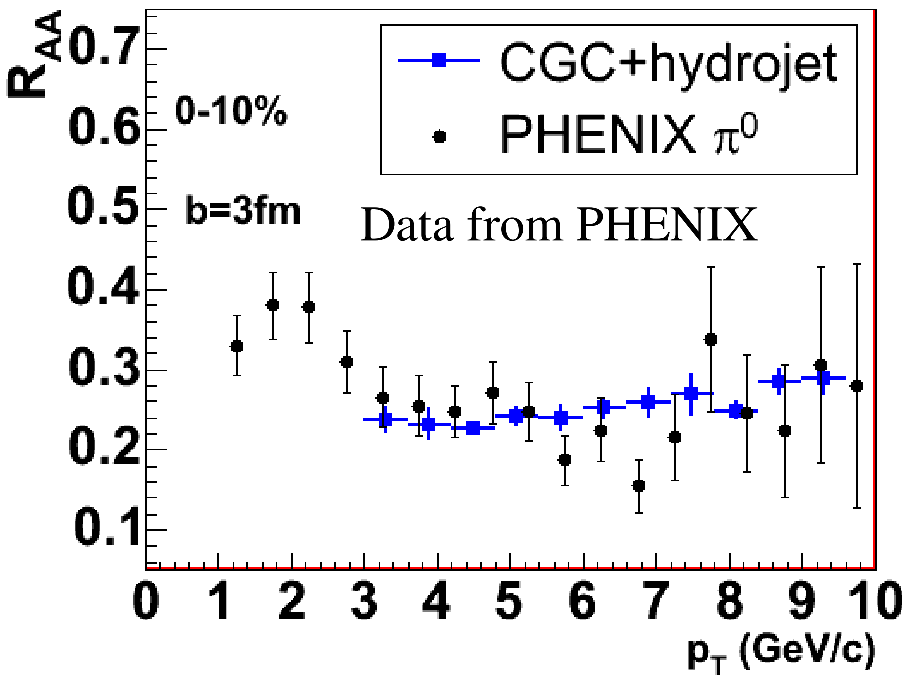




hydro+jet (flow + quenched jets)
explains the crossing behavior of v2 for identified particle.

$v_{2\pi} > v_{2K} > v_{2p}$ At low pt $v_{2\pi} < v_{2K} < v_{2p}$ At high pt

Suppression Factor @200GeV



GLV: Gyulassy, Levai, Vitev

Simple GLV 1st order formula

$$\Delta E = C \int_{\tau_0}^{\tau_f} d\tau \rho(\tau, x(\tau))(\tau - \tau_0) \ln\left(\frac{2E}{L\mu^2}\right)$$

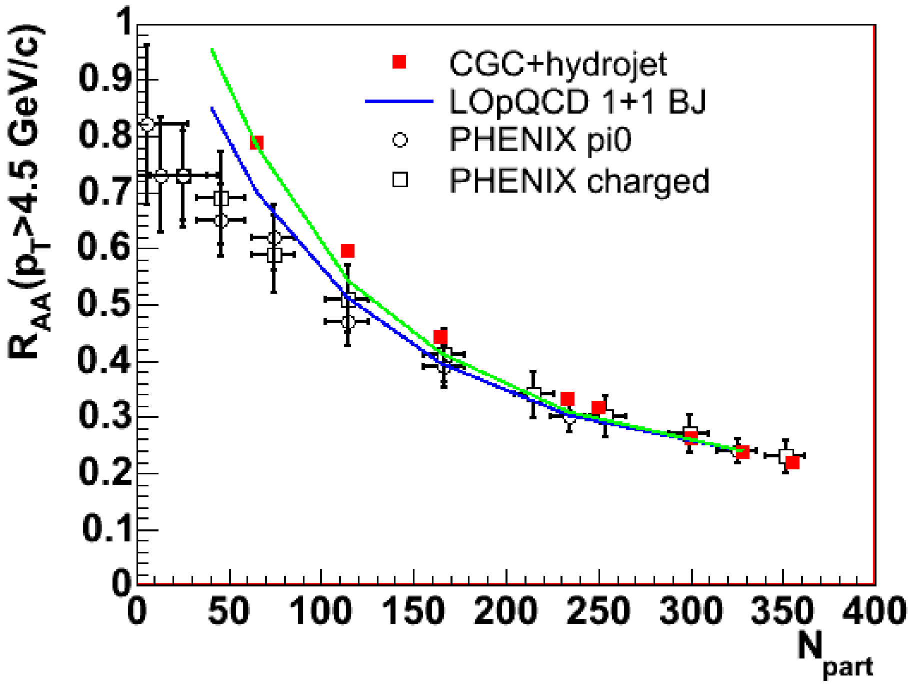
L=3fm, $\mu = 0.5\,GeV$

Improvement is necessary to get rid of the free parameter C

$$R_{AA}(p_T) = \frac{dN^{AA}/d^2 p_T d\eta}{\langle N_{coll}\rangle dN^{NN}/d^2 p_T d\eta}$$

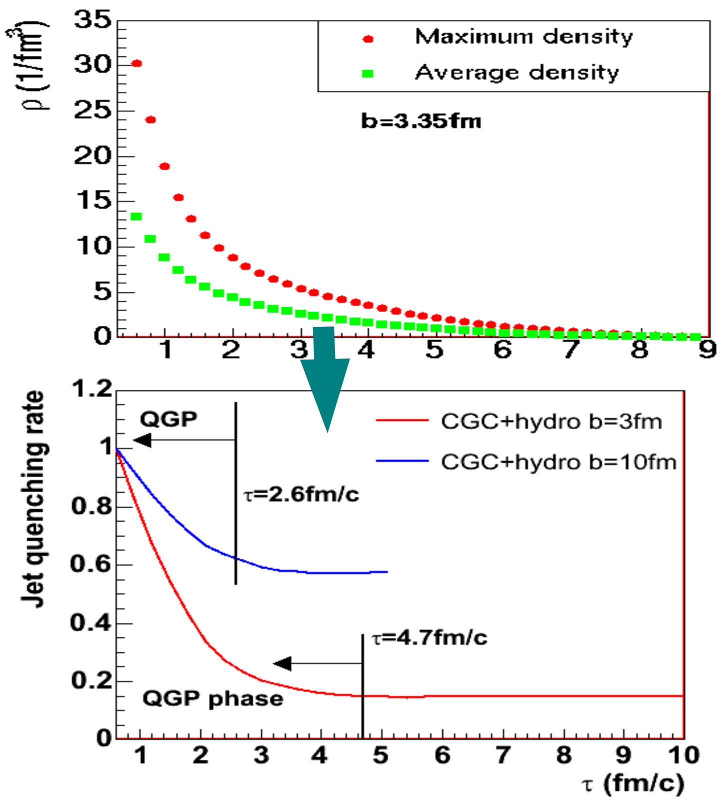
- C contains strong couping and color factor.
- More realistic energy loss formula.
- Hydro-> QGP, not gluon plasma.
- Fluctuations are not included in the energy loss.

Centrality dependence of nuclear modification factors



LO pQCD: 1+1D BJ expansion:

$$\rho(\tau)=\rho_0\frac{\tau_0}{\tau}$$ No phase transition



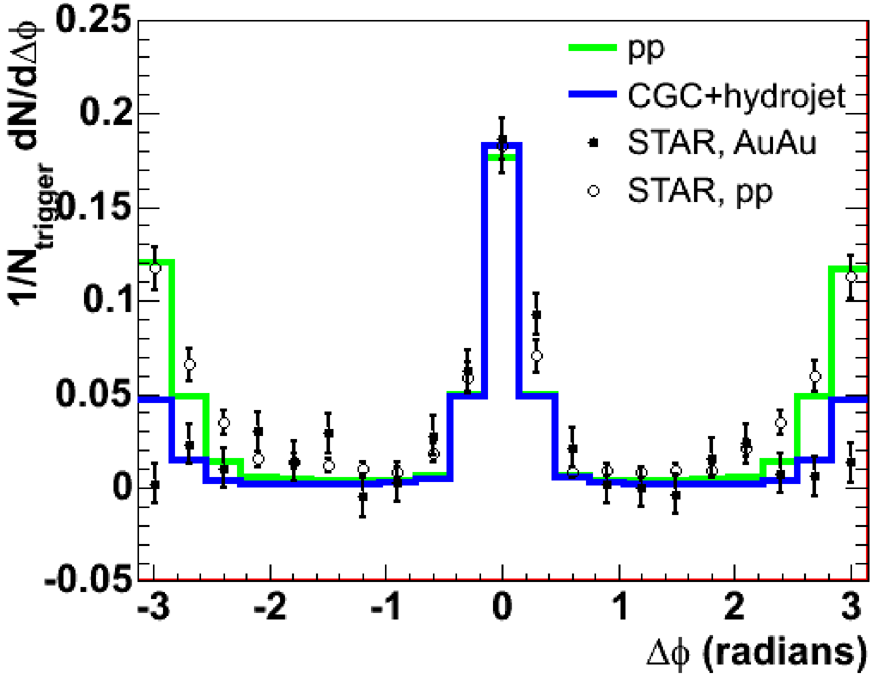
Jets are quenched in early times, but milder at peripheral collisions

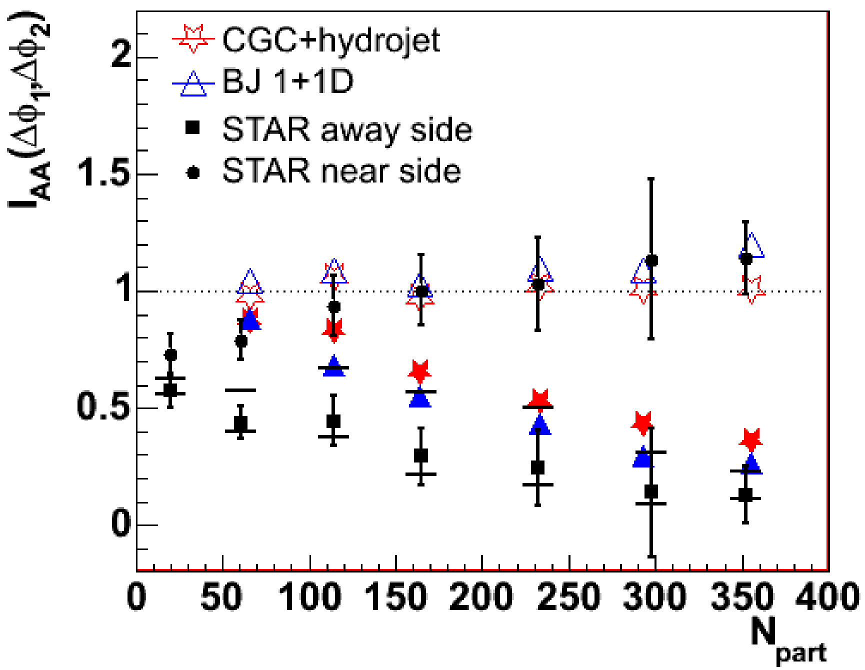
Parton energy loss in the partonic phase works up to b=5-7fm.

Energy loss in the hadronic phase may be important at peripheral collisions?

(Neither CGC nor hydro is applicable at very peripheral collisions.)

Back-to-Back correlations





$$D(\Delta\phi)=\frac{1}{N_{trig}}\frac{dN}{d\Delta\phi}$$

$$I_{AA}(\Delta_1\phi,\Delta_2\phi)=\frac{\int_{\Delta_1}^{\Delta_2} d(\Delta\phi) D^{AuAu} - B.G.}{\int_{\Delta_1}^{\Delta_2} d(\Delta\phi) D^{pp}}$$

mean pT times # of collision

$$\langle p_{\perp}^2\rangle \approx \mu^2 \frac{L}{\lambda} \approx \int \rho\, d\tau$$

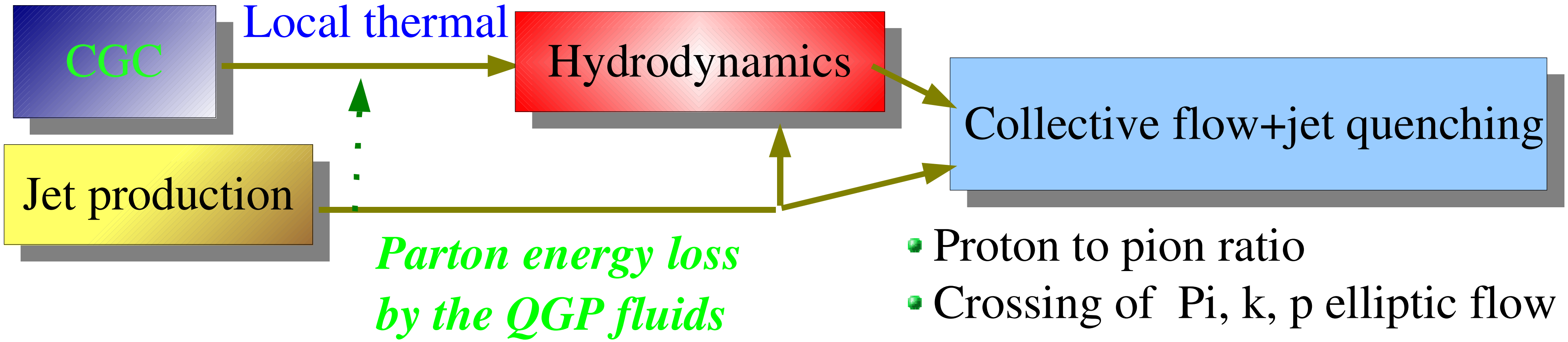
Effect is small

$$near\ side: |\Delta\phi| < 0.75$$

$$away\ side: |\Delta\phi| > 2.24$$

Summary and conclusions

CGC, hydrodynamics and jet propagation have been combined



- Proton to pion ratio
- Crossing of Pi, k, p elliptic flow

This picture works well at midrapidity |y|<2-3 and centrality b<7fm for the description of the bulk properties of the RHIC data.

Outlook and open questions

- Improve each component: CGC, hydro, energy loss
- Understanding the processes to the thermalization by non-equilibrium theory