



Johann Wolfgang Goethe-Universität Frankfurt

Institut für Theoretische Physik

# Thermalization of gluons at RHIC including $gg \leftrightarrow ggg$ interactions in a parton cascade

Zhe Xu and Carsten Greiner

- Motivation
- Parton cascade with the **stochastic algorithm**
- Initial conditions
- Results
- Summary and outlook

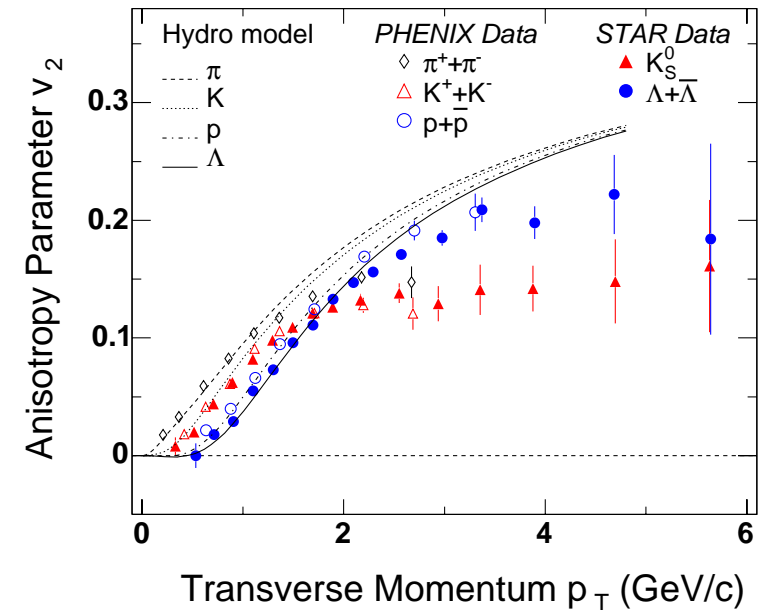
Wien, 2005

# Motivation

elliptic flow --- 'early signature' of QGP

$$\frac{dN_h}{dp_T^2 dy d\phi} = \frac{dN_h}{dp_T^2 dy} \frac{1}{\pi} (1 + 2v_1 \cos \phi + 2v_2 \cos 2\phi + \dots)$$

evidence for an early buildup of pressure and a fast thermalization of the quark-gluon system



- How can one describe the fast thermalization by the partonic collisions?
- How can one understand the hydrodynamical behavior by the partonic collisions?

transport simulation: on-shell parton cascade

Z. Xu and C. Greiner, PRC 71, 064901 (2005)

solving the Boltzmann-equations for quarks and gluons

$$p^\mu \partial_\mu f(x, p) = C_{gg \leftrightarrow gg}(x, p) + C_{gg \leftrightarrow ggg}(x, p)$$

(Z)MPC, VNI/BMS

new development

## parton scatterings in leading order pQCD

$$|M_{gg \rightarrow gg}|^2 = \frac{9g^4}{2} \frac{s^2}{(q_\perp^2 + m_D^2)^2},$$

$$|M_{gg \rightarrow ggg}|^2 = \left( \frac{9g^4}{2} \frac{s^2}{(q_\perp^2 + m_D^2)^2} \right) \left( \frac{12g^2 q_\perp^2}{k_\perp^2 ((\vec{k}_\perp - \vec{q}_\perp)^2 + m_D^2)} \right) \Theta_{LPM}$$

J.F.Gunion, G.F.Bertsch, Phys. Rev. D 25, 746(1982)

$$\alpha_s \approx \frac{12\pi}{(33-2n_f) \ln(s/\Lambda_{QCD})}$$

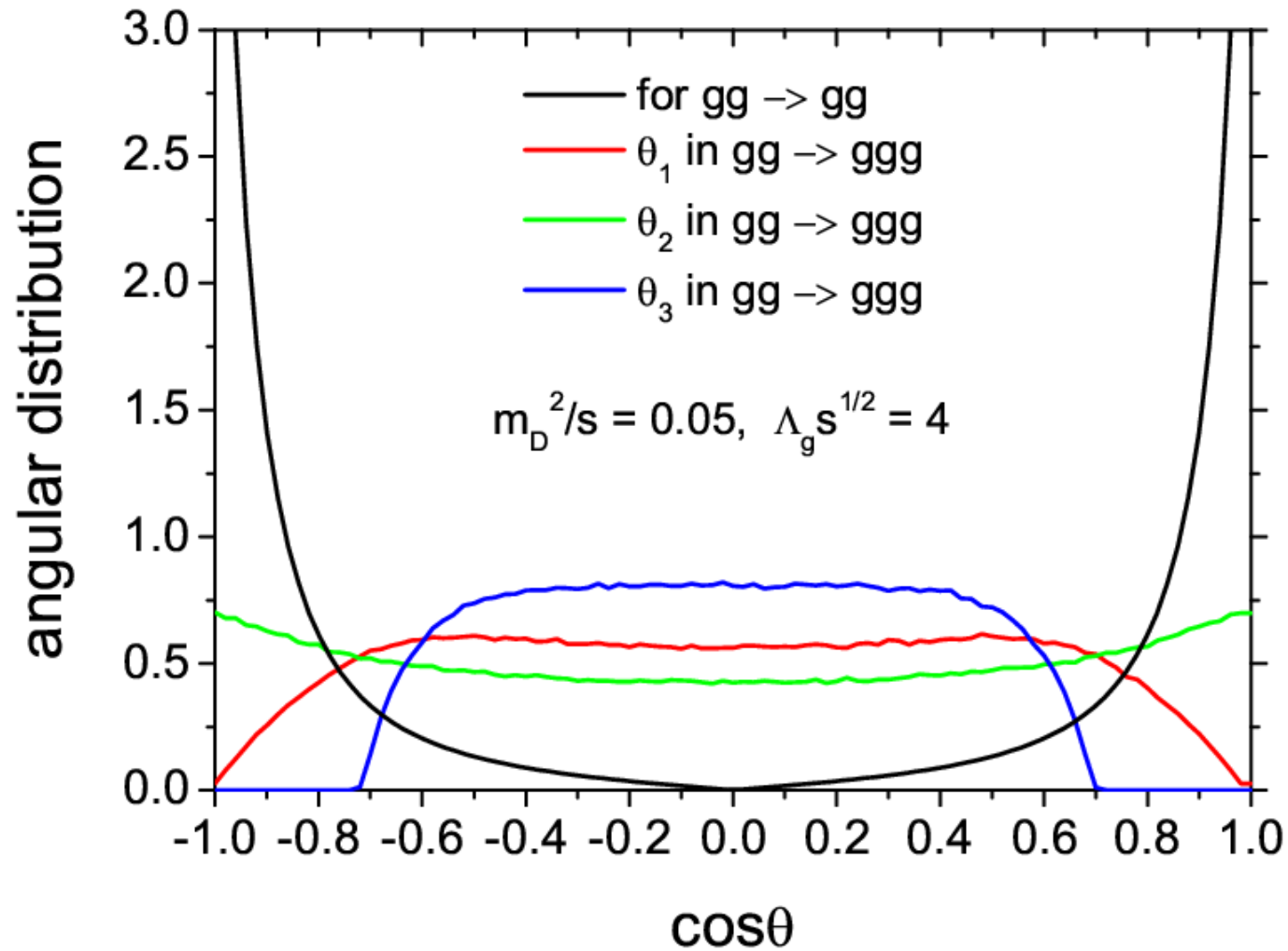
screening mass:  $m_D^2 = 16\pi\alpha_s \int \frac{d^3p}{(2\pi)^3} \frac{1}{p} (3f_g + n_f f_q),$

**LPM suppression:** the formation time  $\Delta\tau \approx \frac{1}{k_\perp} \cosh y < \Lambda_g$

$$\longrightarrow \Theta(k_\perp \Lambda_g - \cosh y)$$

## Example

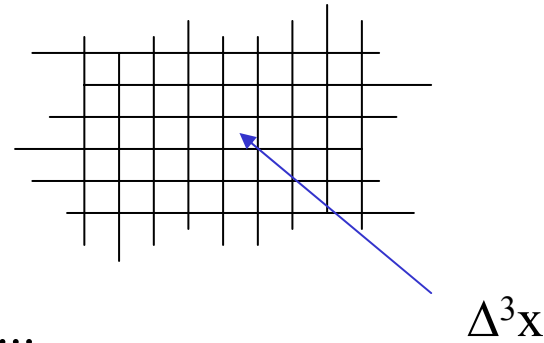
$$\alpha_s \sim 0.3 \quad \Lambda_g \sim 0.5 \text{ fm} \quad T \sim 400 \text{ MeV} \quad \text{fugacity} \sim 0.5$$



## Stochastic algorithm

P.Danielewicz, G.F.Bertsch, Nucl. Phys. A 533, 712(1991)  
A.Lang et al., J. Comp. Phys. 106, 391(1993)

cell configuration in space



for particles in  $\Delta^3x$  with momentum  $\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3 \dots$

collision probability:

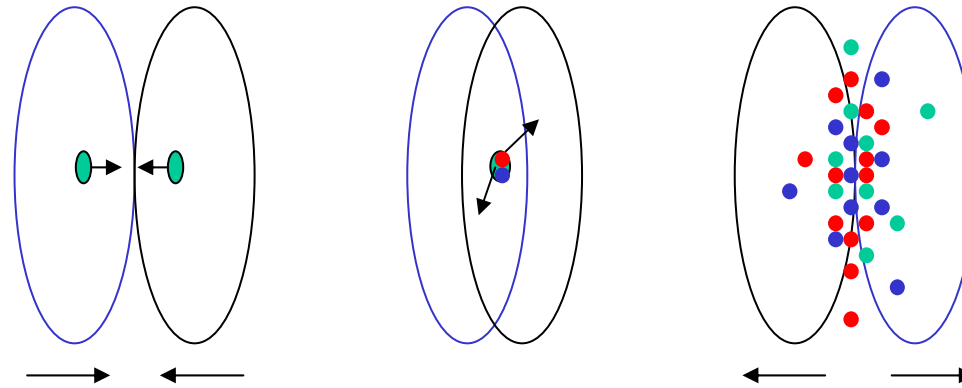
$$\text{for } 2 \leftrightarrow 2 \quad P_{22} = v_{rel} \sigma_{22} \frac{\Delta t}{\Delta^3 x}$$

$$\text{for } 2 \rightarrow 3 \quad P_{23} = v_{rel} \sigma_{23} \frac{\Delta t}{\Delta^3 x}$$

$$\text{for } 3 \rightarrow 2 \quad P_{32} = \frac{I_{32}}{8E_1 E_2 E_3} \frac{\Delta t}{(\Delta^3 x)^2}$$

$$I_{32} = \frac{1}{2} \int \frac{d^3 p_{1'}}{(2\pi)^3 2E_{1'}} \frac{d^3 p_{2'}}{(2\pi)^3 2E_{2'}} |M_{123 \rightarrow 1'2'}|^2 (2\pi)^4 \delta^{(4)}(p_1 + p_2 + p_3 - p_{1'} - p_{2'})$$

Initial conditions: minijets production with  $p_t > p_0$



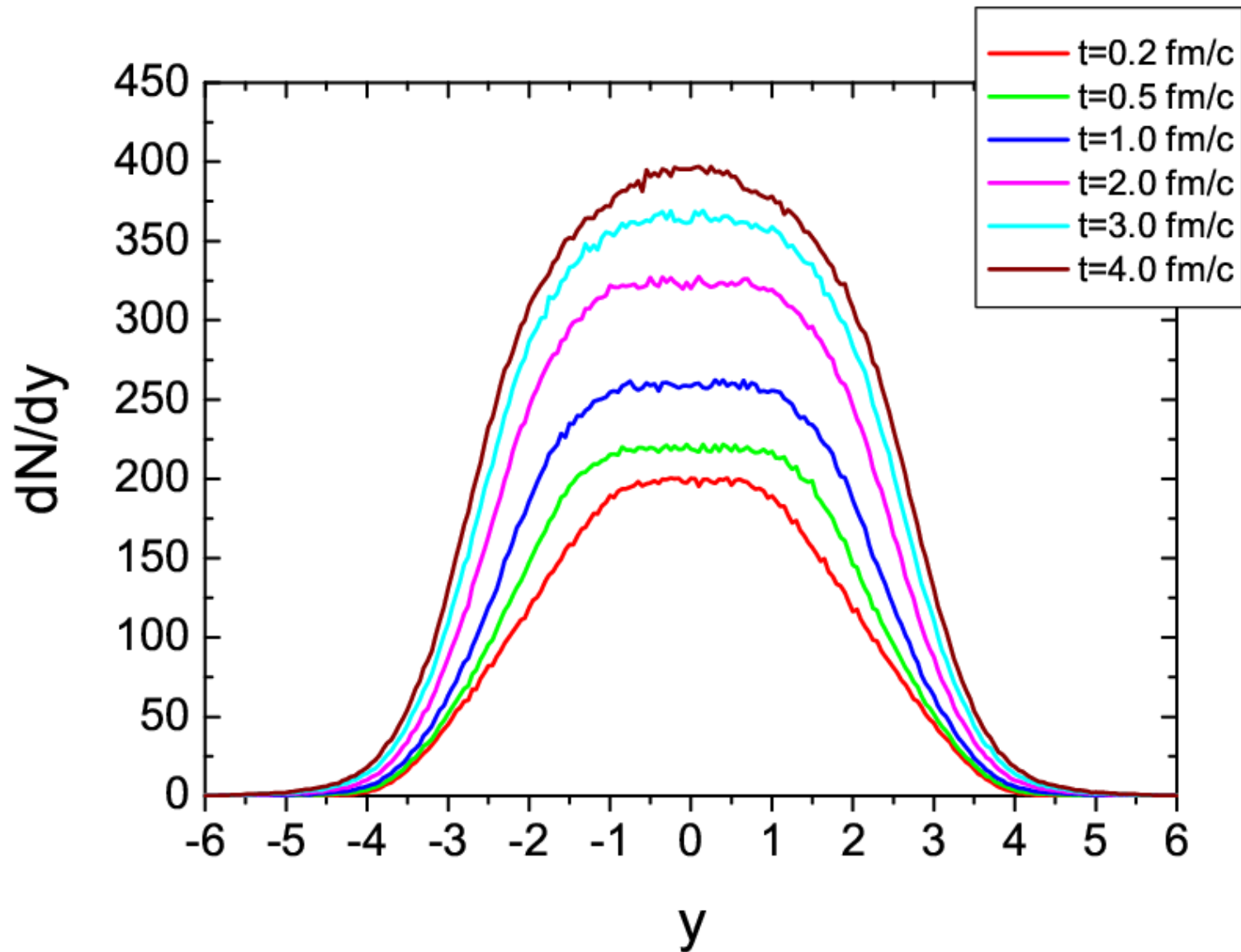
$$\frac{d\sigma_{jet}}{dp_T^2 dy_1 dy_2} = K \sum_{a,b;c,d} x_1 f_a(x_1, p_T^2) x_2 f_b(x_2, p_T^2) \frac{d\sigma^{ab \rightarrow cd}}{d\hat{t}}$$

binary approximation  $\Rightarrow N_{jet}^{AA} \approx 2 T_{AA}(b=0) \sigma_{jet}^{pp}$

$N_g \approx 830$  for a central Au+Au collision at **RHIC**  
at 200 AGeV using  **$p_0=2$  GeV**

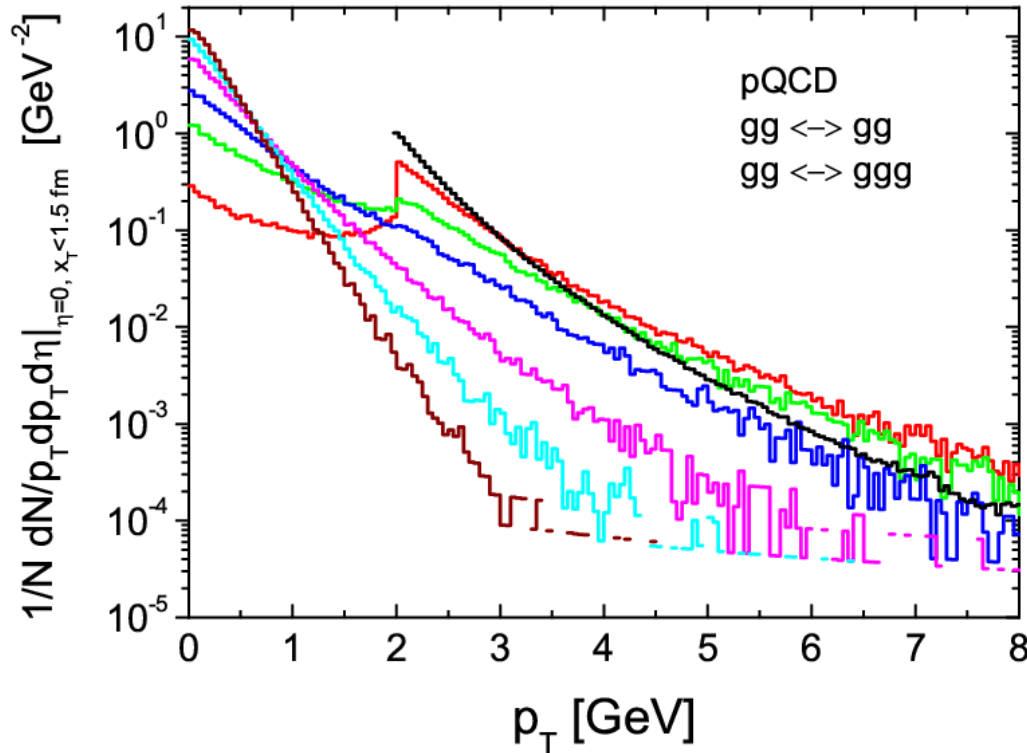
## Results

rapidity distribution



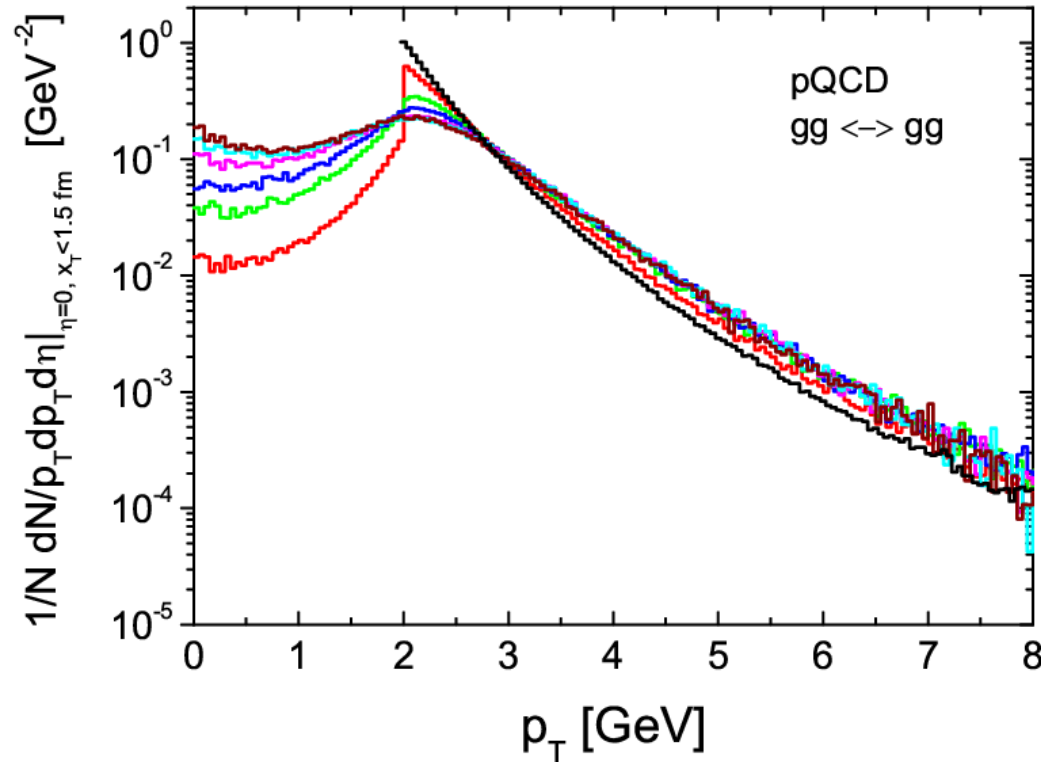
the central region:  
 $\eta: [-0.5:0.5]$  and  $x_t < 1.5$  fm

including  $gg \leftrightarrow ggg$



**thermalization** and  
**hydrodynamical** behavior

without  $gg \leftrightarrow ggg$

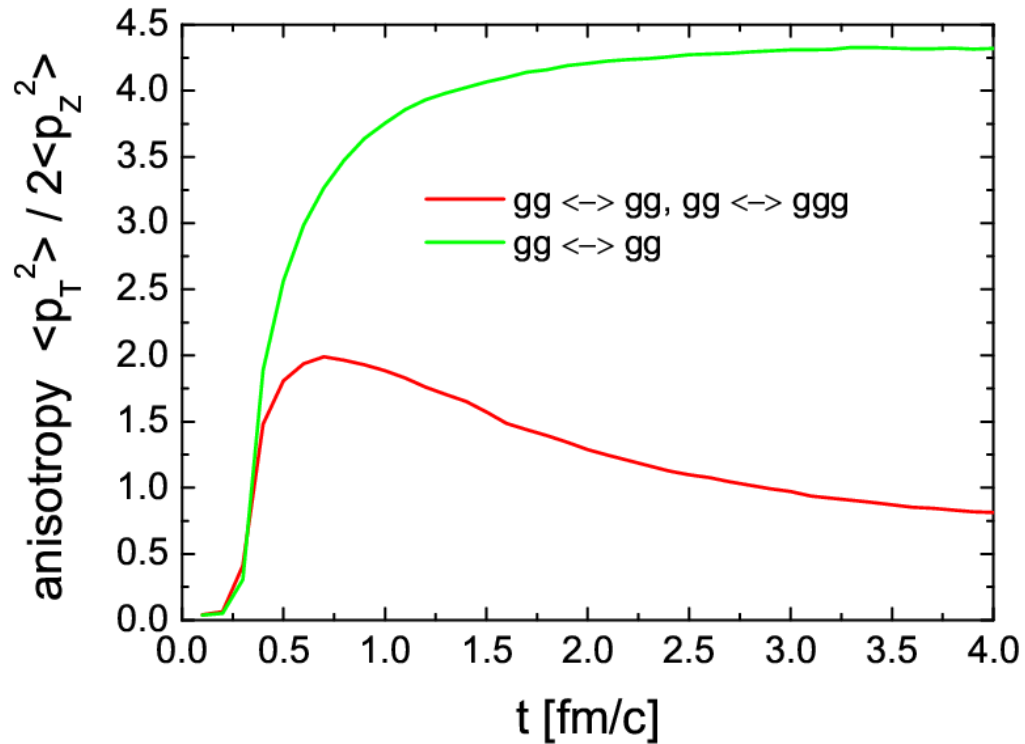


**NO thermalization** and  
**free streaming**

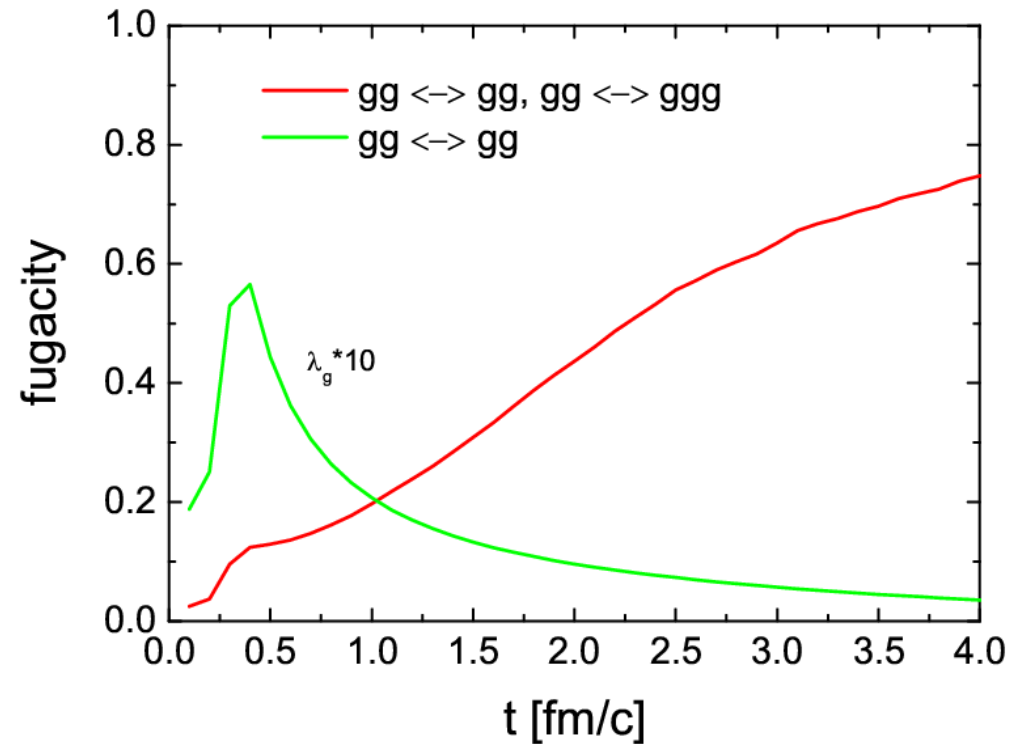


# Kinetic and chemical equilibration

in the central region:  $\eta: [-0.5:0.5]$  and  $x_t < 1.5$  fm



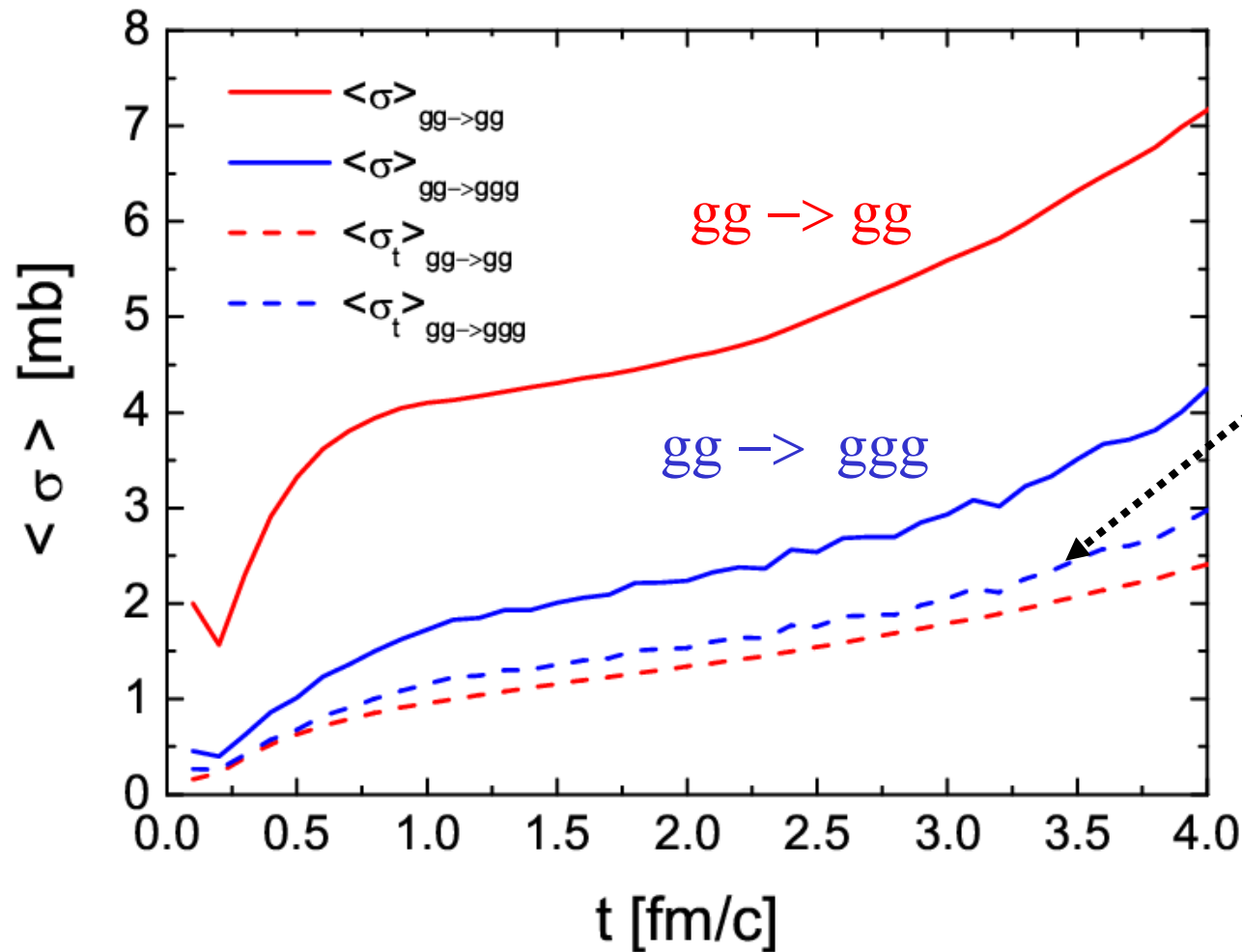
1~2 fm/c for the **kinetic** equilibration



$\sim 4$  fm/c for the **chemical** equilibration

## cross sections

in the central region:  $\eta: [-0.5:0.5]$  and  $x_t < 1.5$  fm



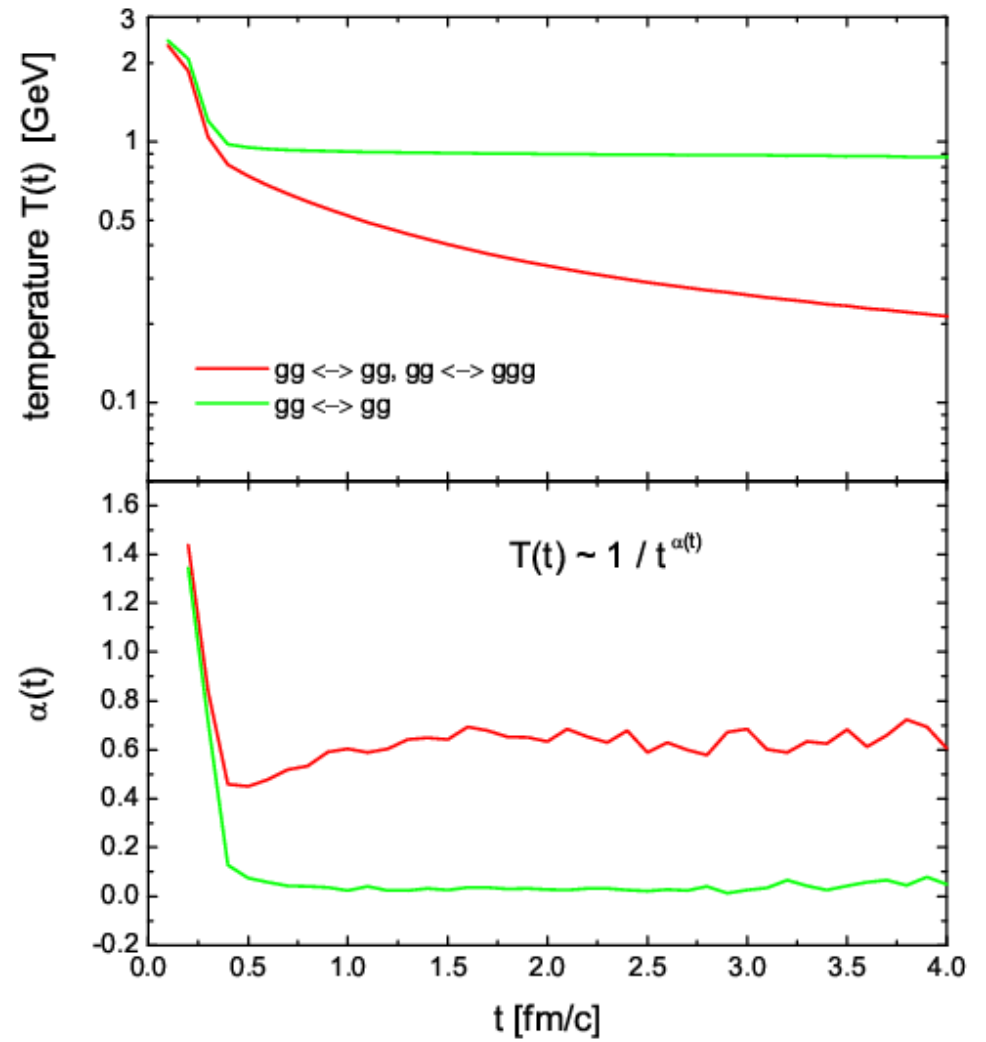
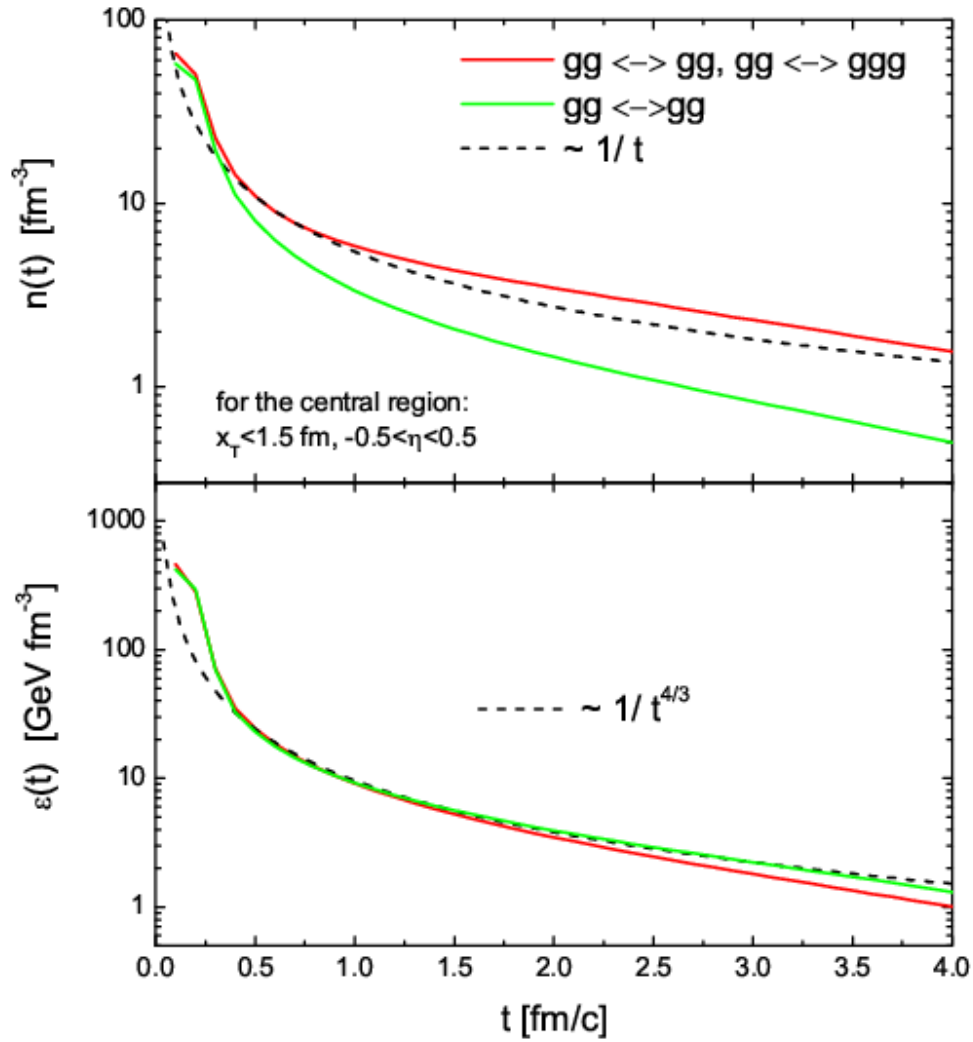
transport cross section:

$$\sigma_t = \int d\sigma \sin^2 \theta_{cm}$$

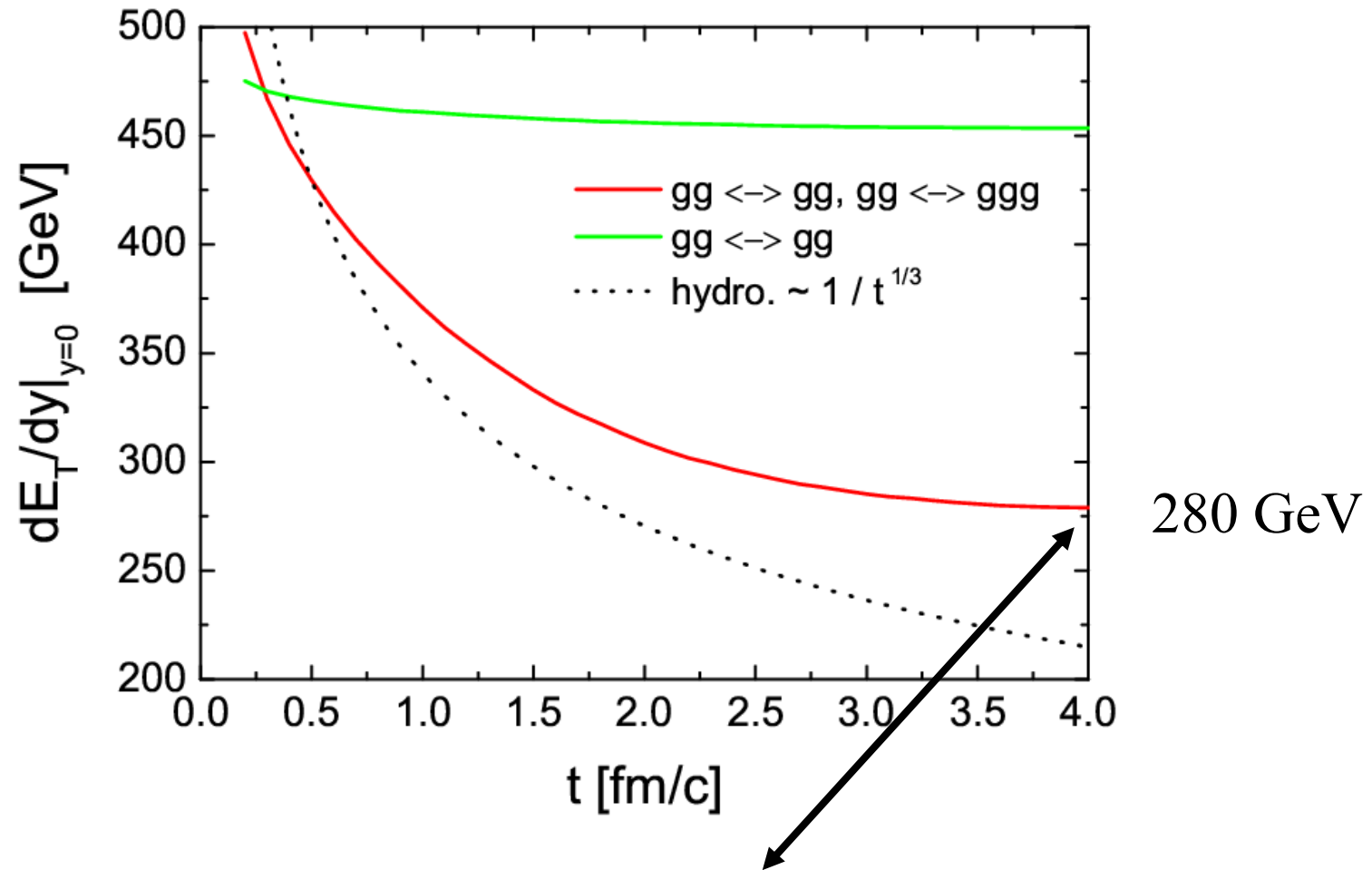
The **inelastic** collisions are the dominant processes to drive the system to kinetic equilibrium.

Bjorken:  $n \sim 1/t$ ,  $\varepsilon \sim 1/t^{4/3}$ ,  $T \sim 1/t^{1/3}$

$$T_g = \frac{\varepsilon_g}{3n_g}$$



transverse energy at  $y=0$

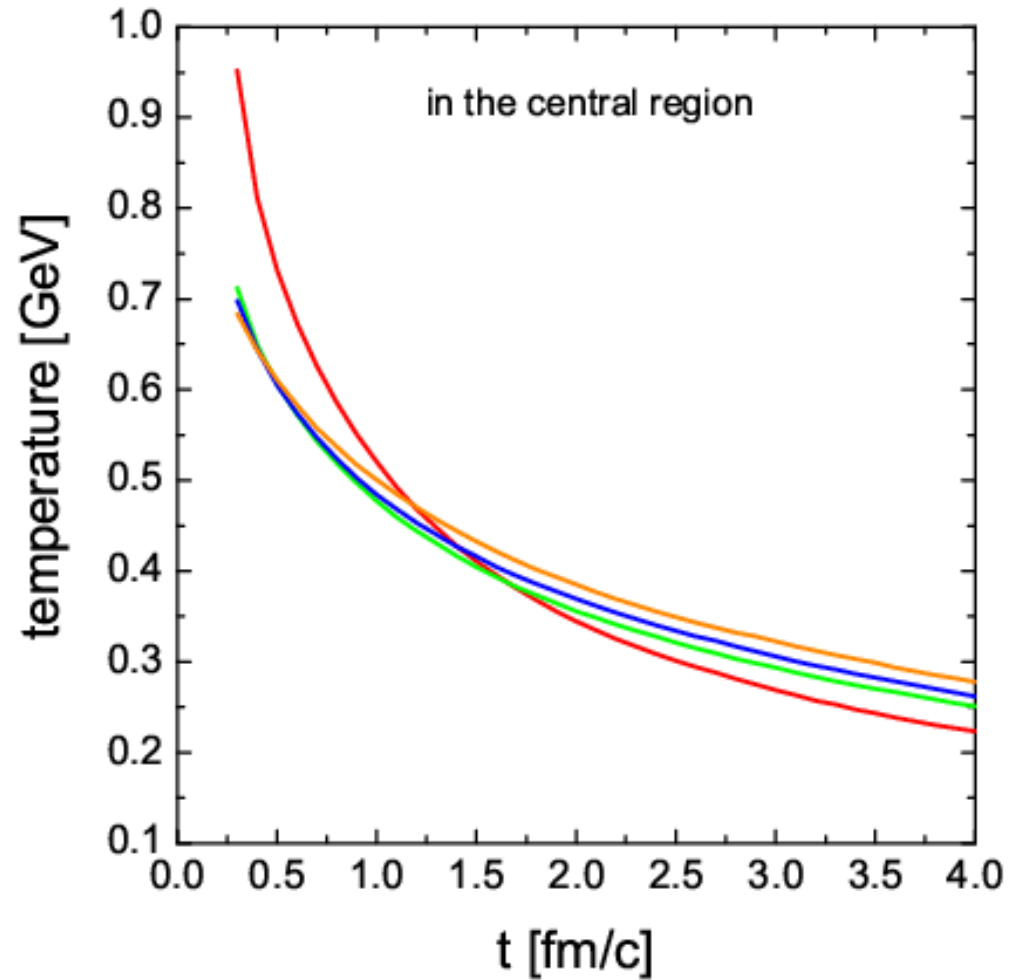
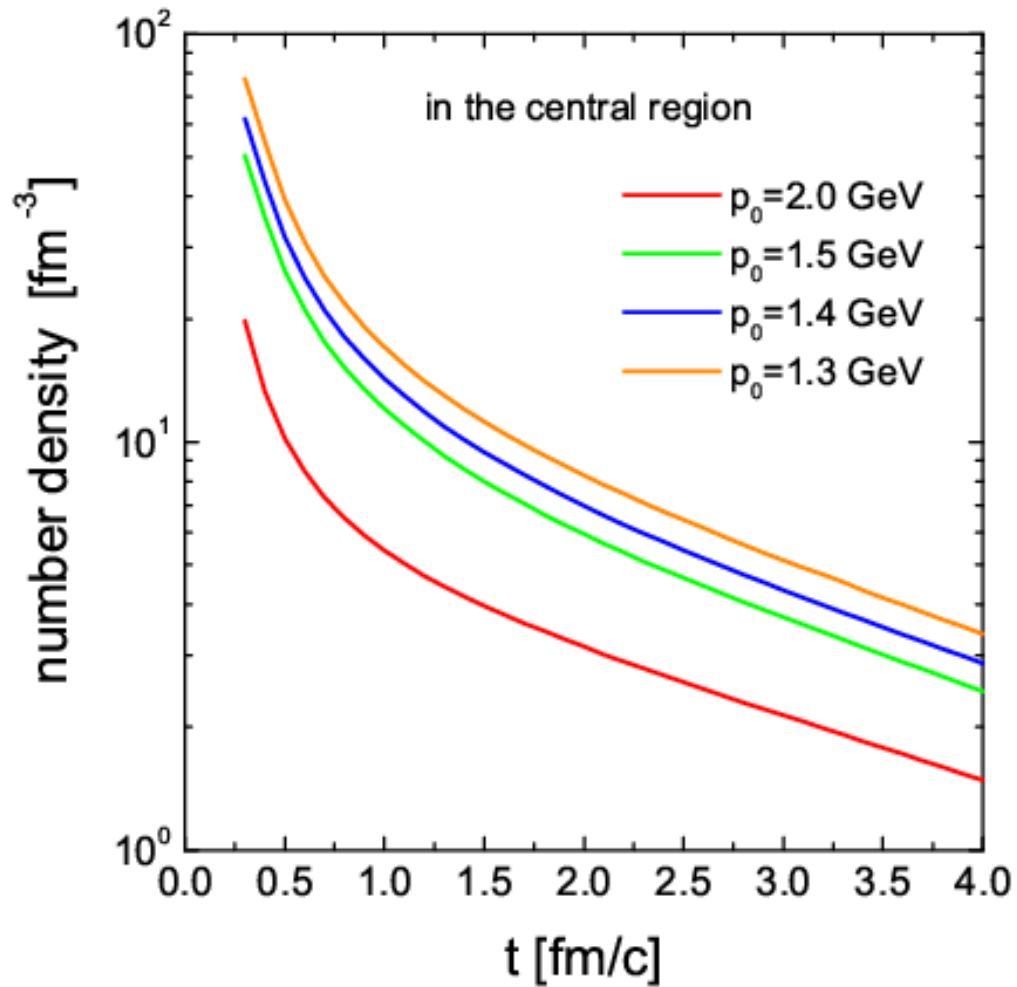


experimental data:

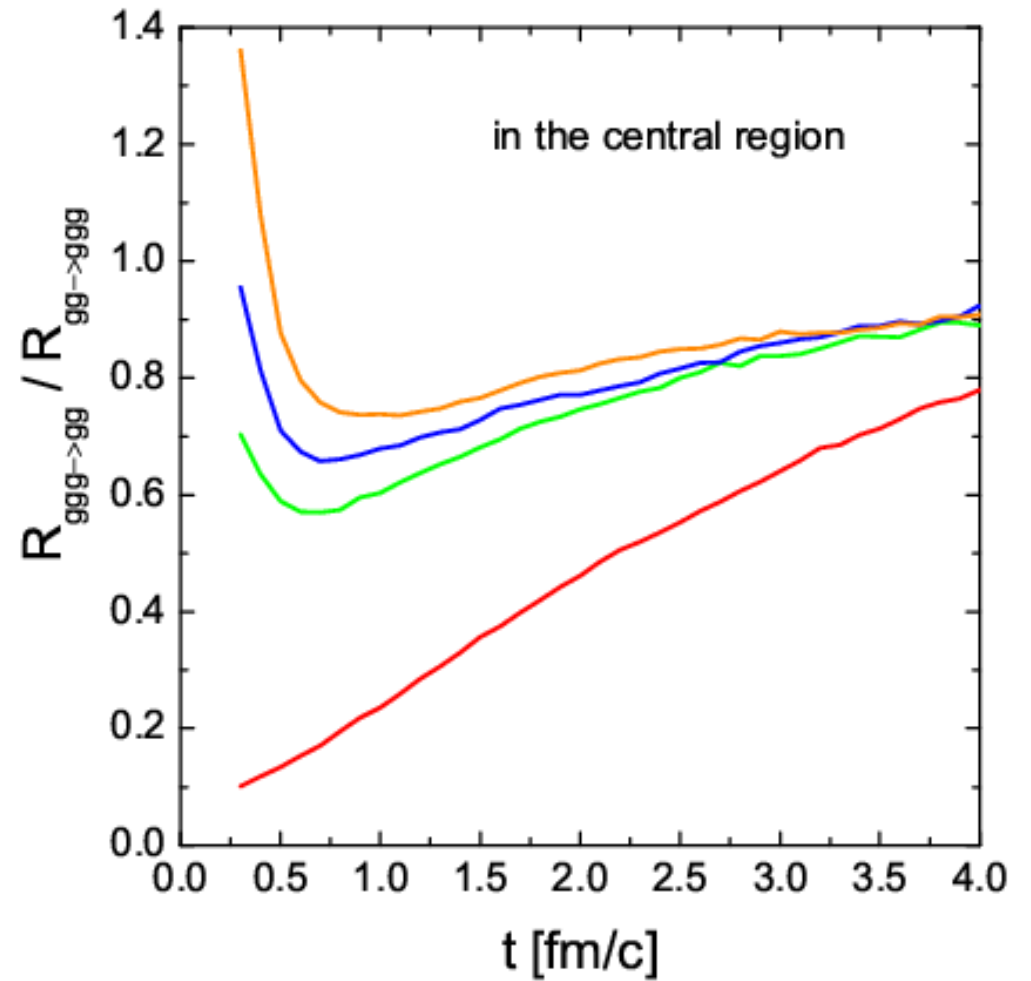
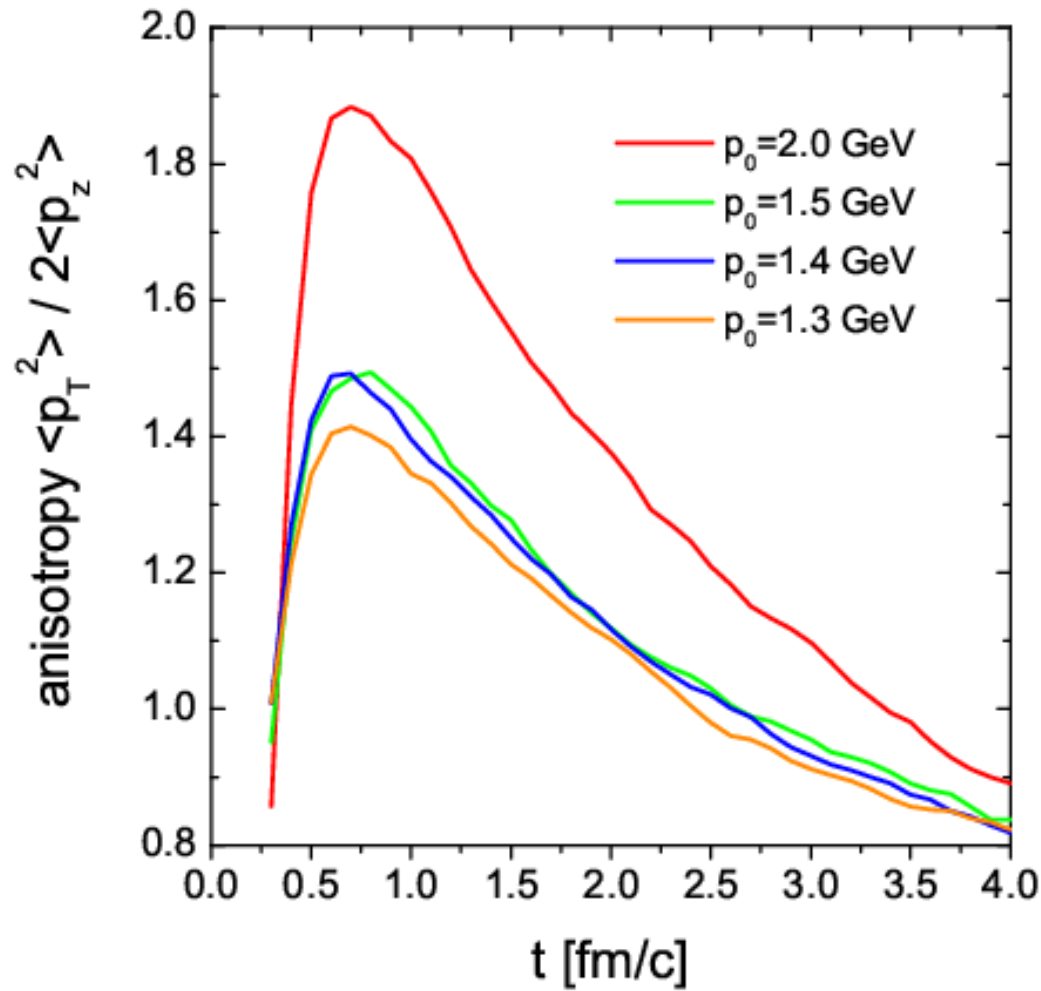
$$\frac{dE_T}{dy} \Big|_{y=0} = 620 \pm 33 \text{ GeV} \quad \text{STAR}$$

## Initial conditions with smaller $p_0$

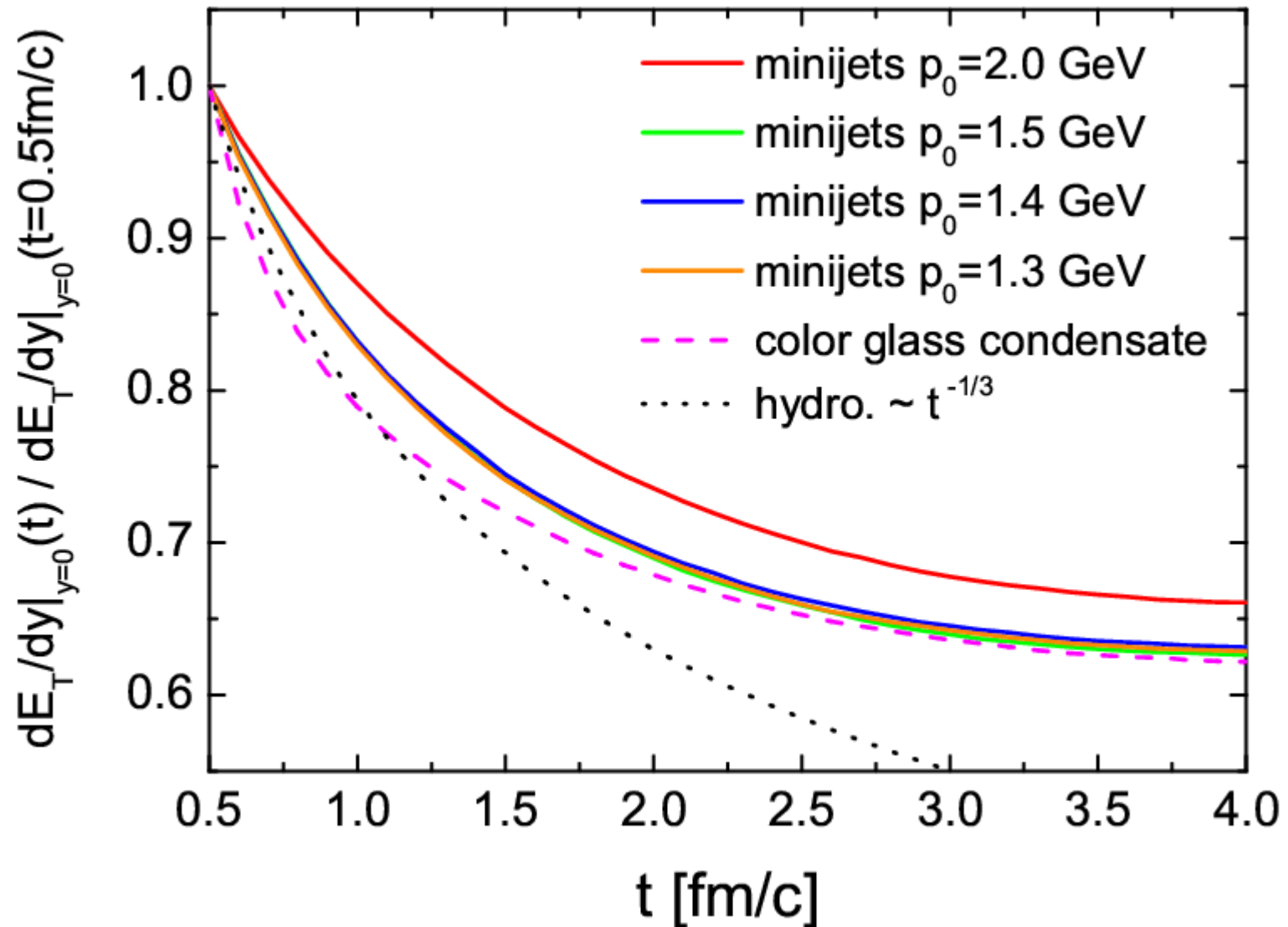
in the central region:  $\eta: [-0.5:0.5]$  and  $x_t < 1.5$  fm



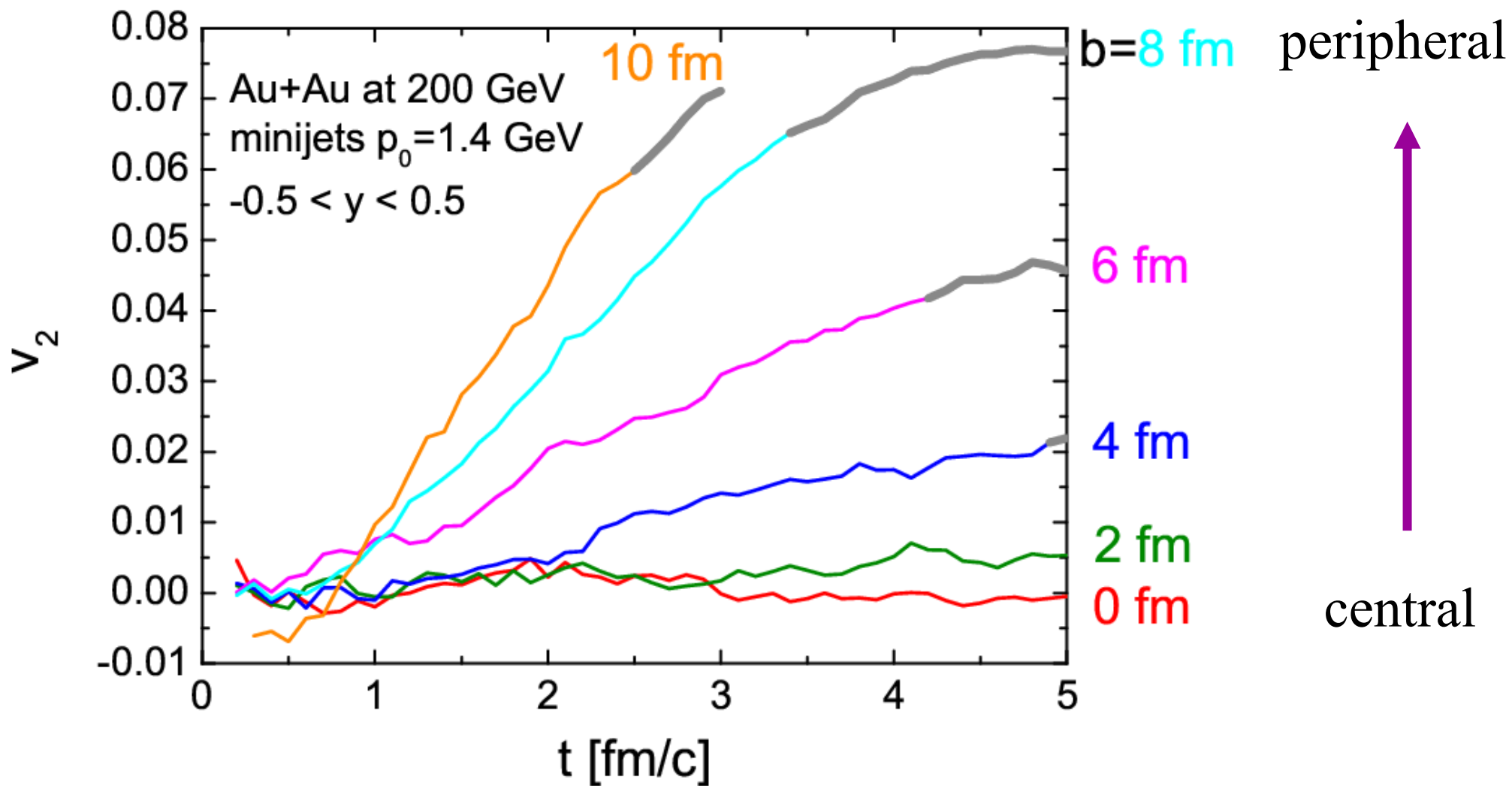
# Kinetic and chemical equilibration



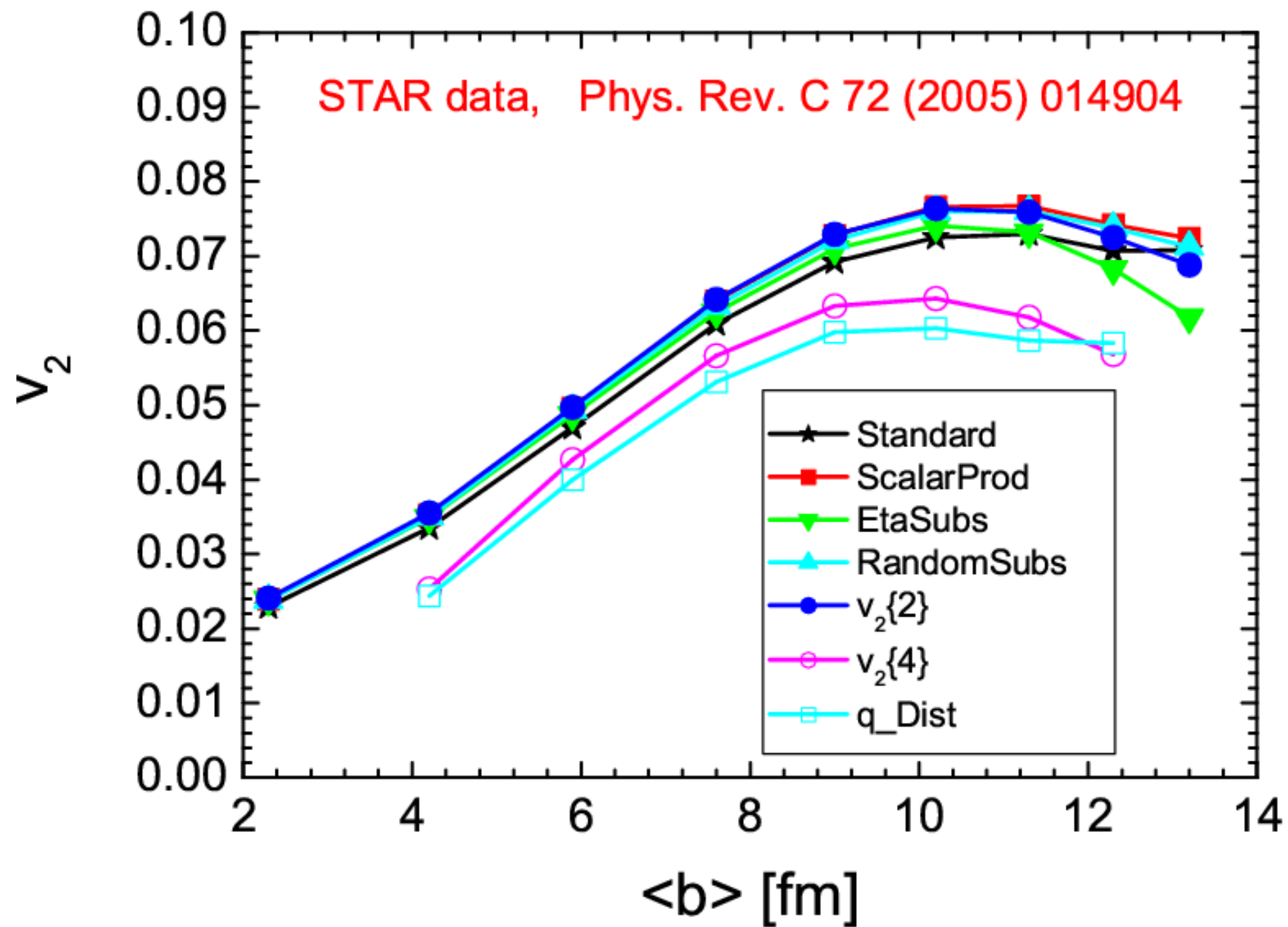
transverse energy at  $y=0$  in Au+Au central collision



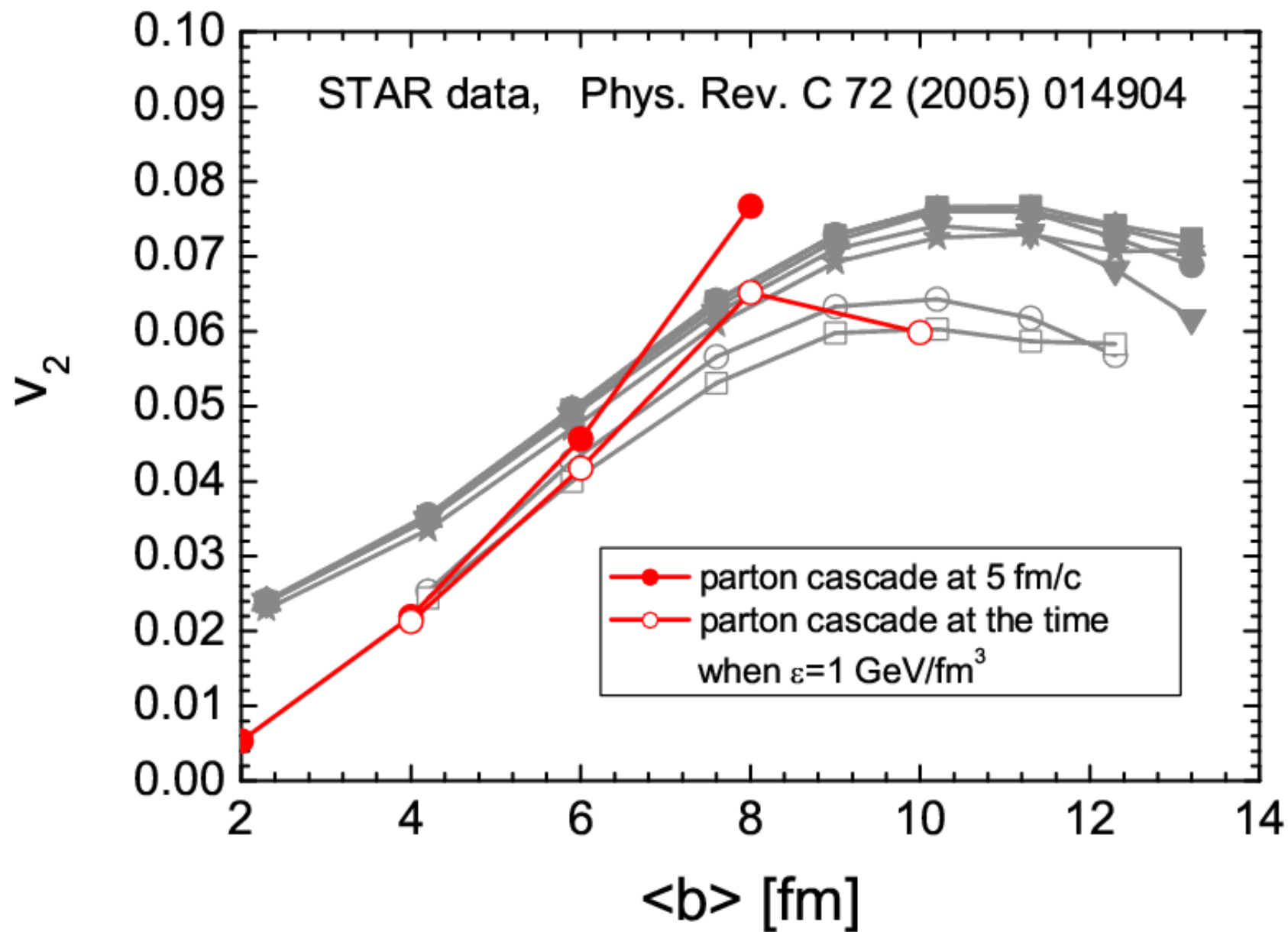
elliptic flow in noncentral Au+Au collisions at RHIC: preliminary results







## Comparison with RHIC data



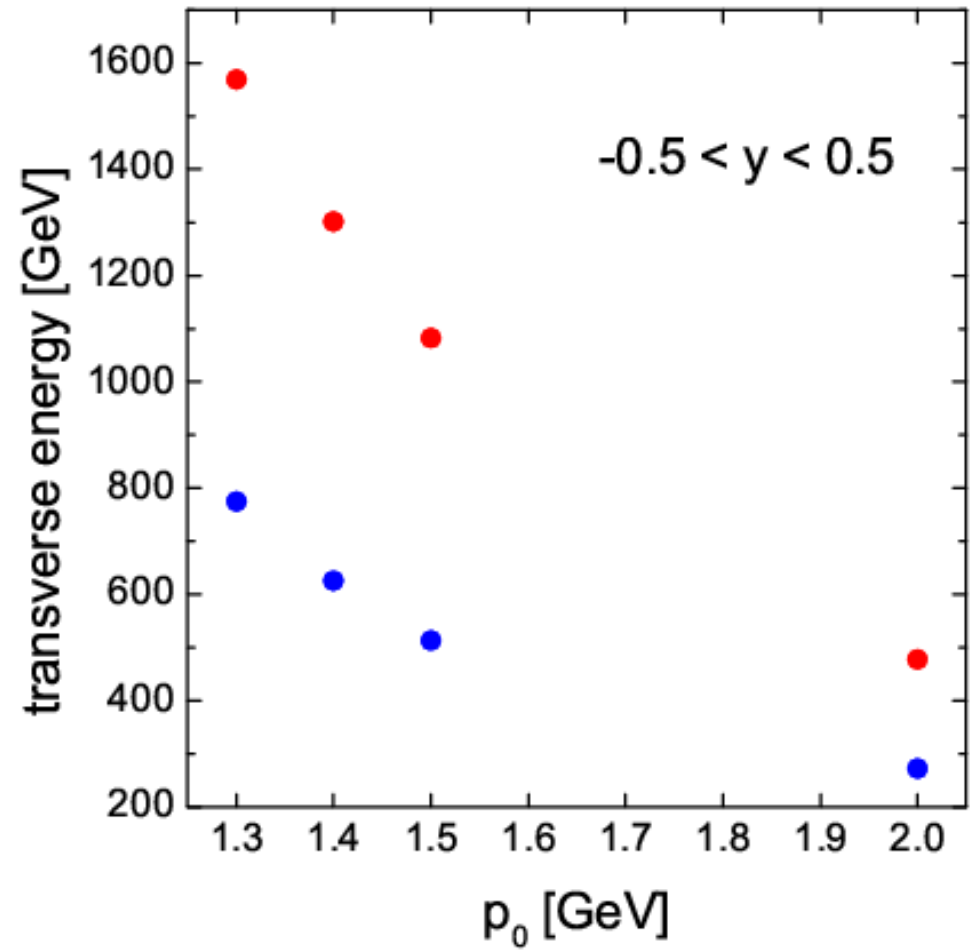
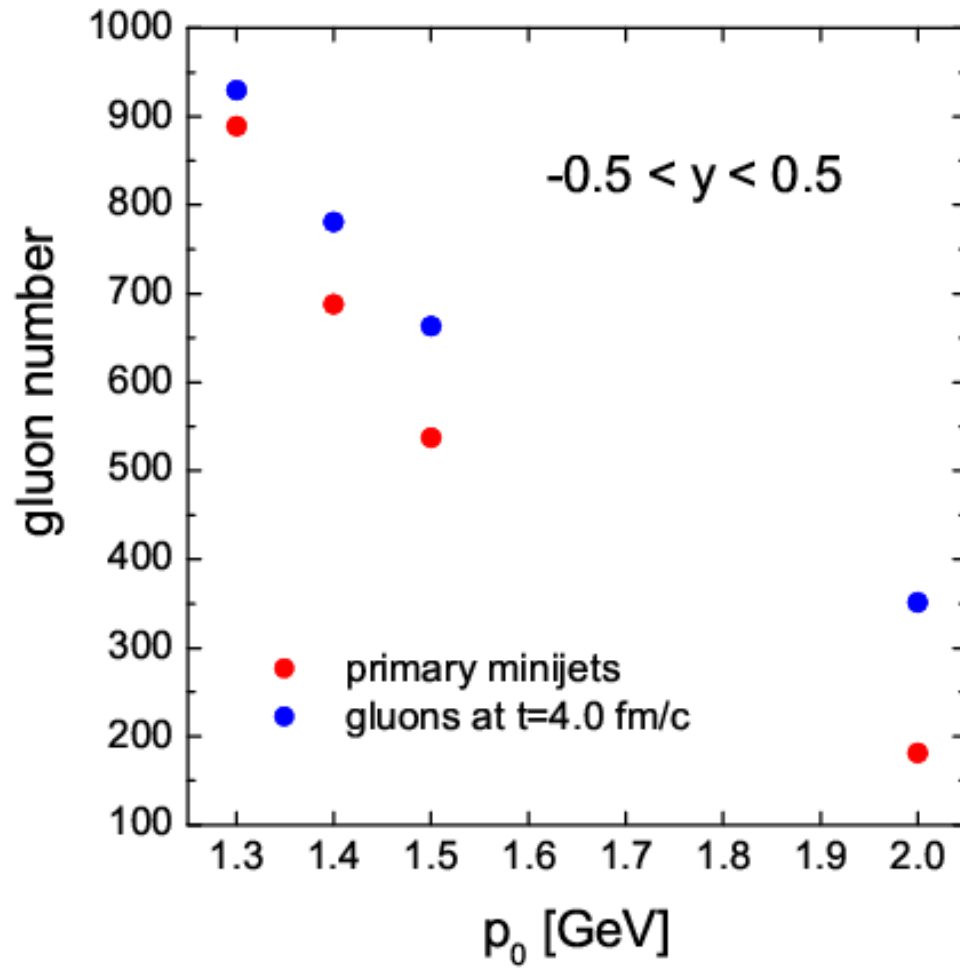
## Summary

- A new parton cascade including inelastic multiparton scatterings  $gg \leftrightarrow ggg$
- Hints of thermalization and hydrodynamical expansion at RHIC
- PQCD  $gg \leftrightarrow ggg$  are important for the thermalization.
- PQCD  $gg \leftrightarrow ggg$  generate the elliptic flow in noncentral collisions.

## Outlook

- viscous hydro.
- bottom-up thermalization with CGC
- including quarks, heavy quark production
- Jet quenching

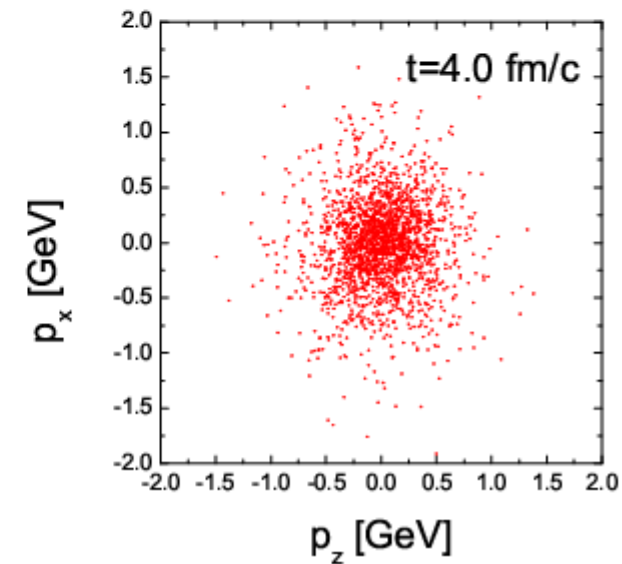
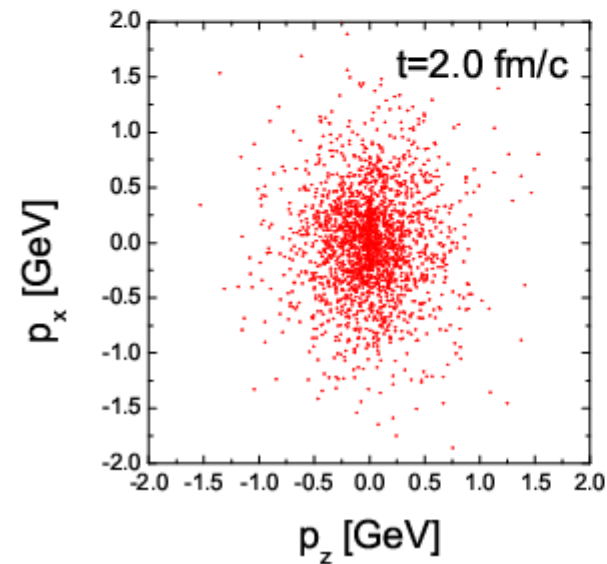
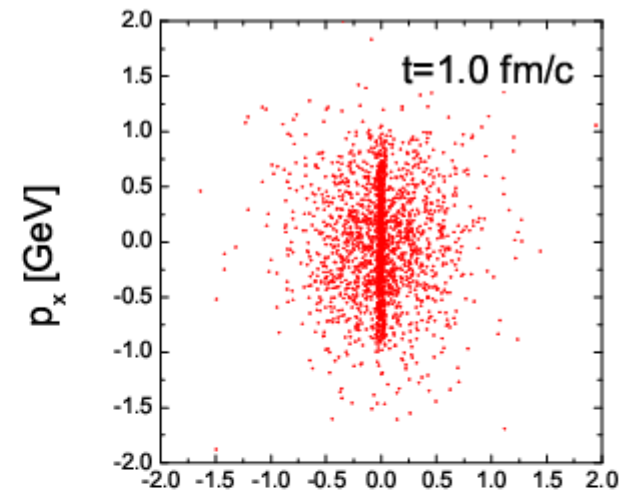
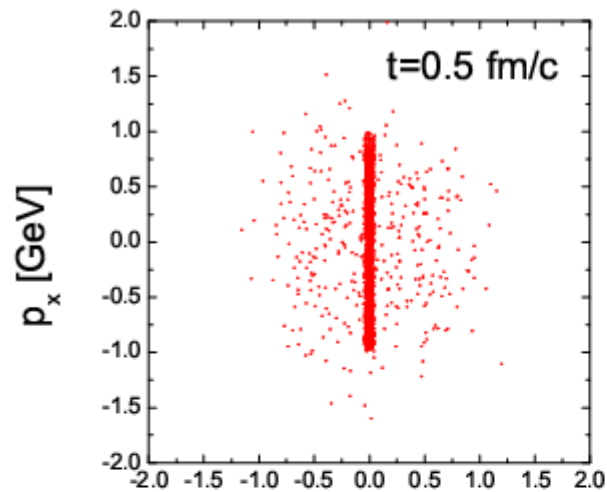
## Initial conditions with smaller $p_0$



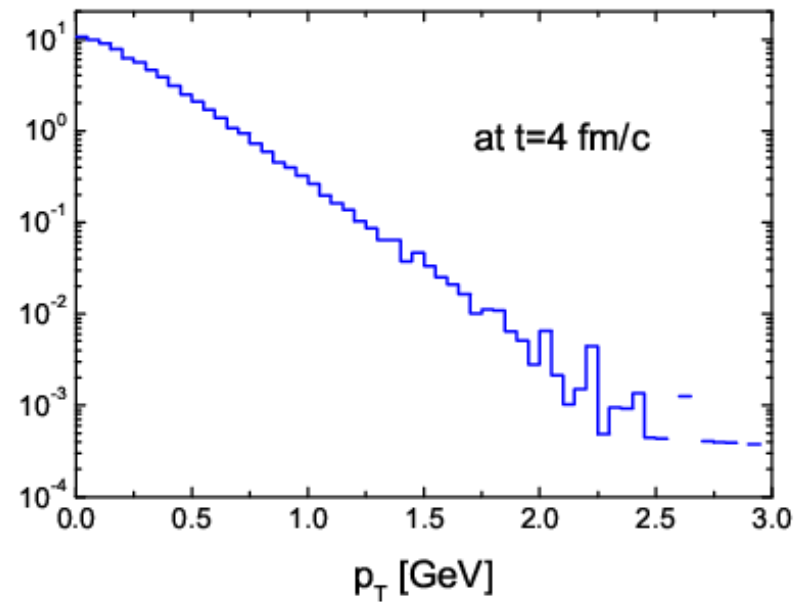
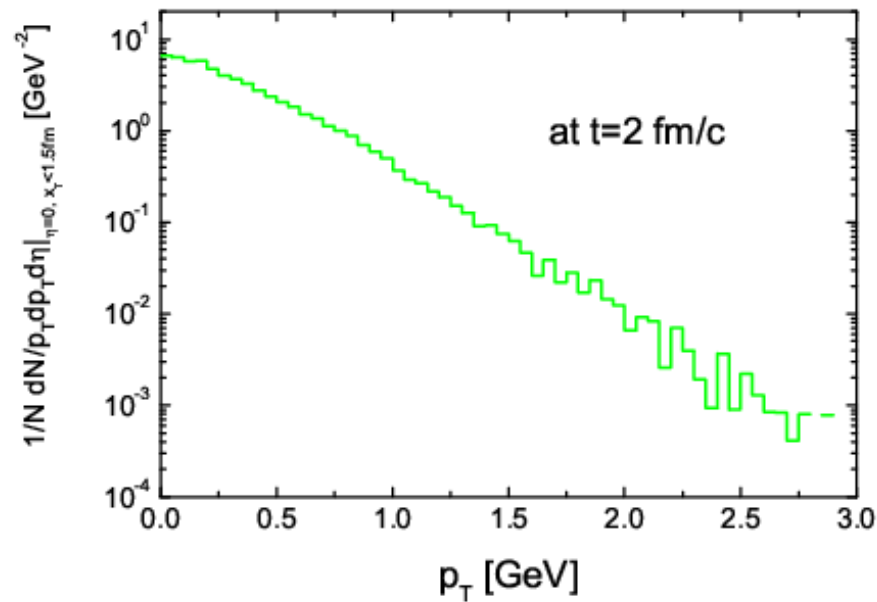
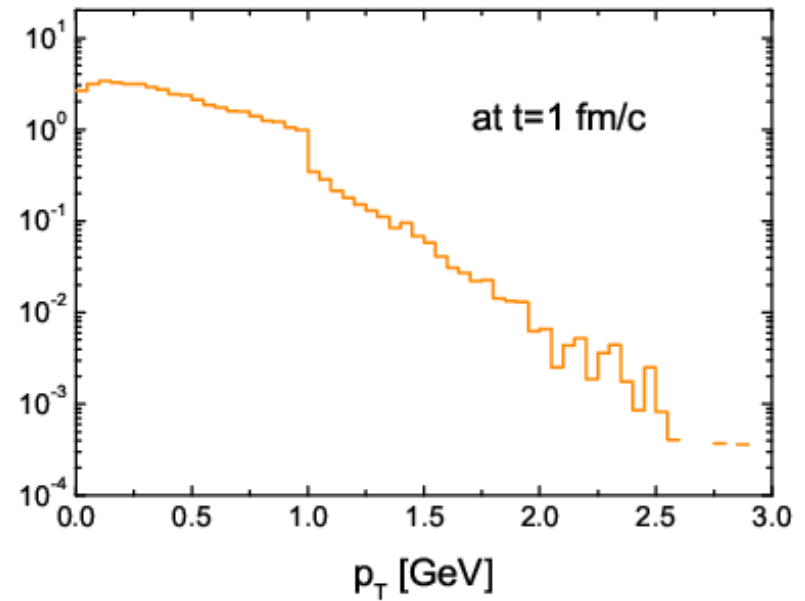
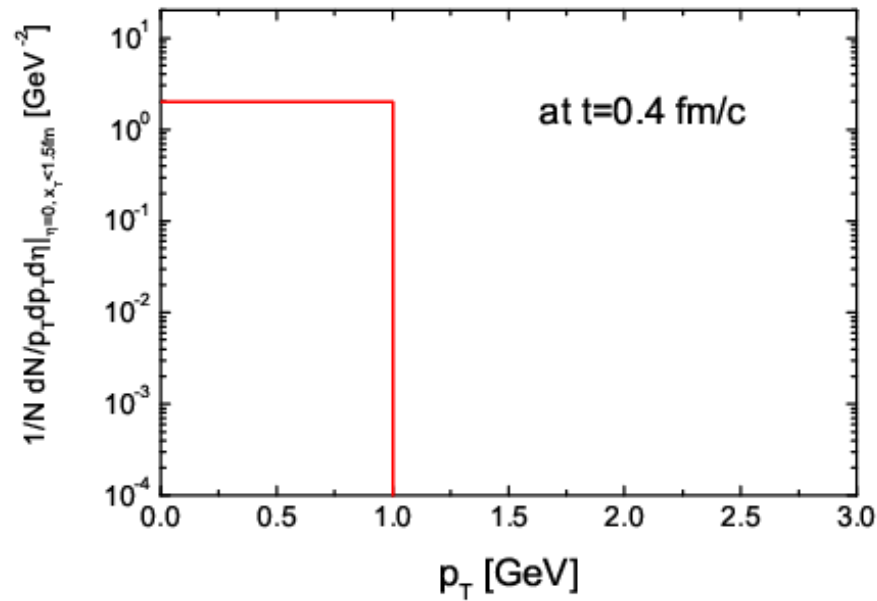
# Initial condition with Color Glass Condensate

$$f(x, p) \sim \delta(p_z) \Theta(Q_s^2 - p_T^2)$$

$\eta: [-0.05:0.05]$  and  $x_t < 1.5$  fm



in the central region:  $\eta: [-0.5:0.5]$  and  $x_t < 1.5$  fm



## Kinetic and chemical equilibration

