Elliptic Flow from Nonequilibrium Color Glass Condensate Initial Conditions

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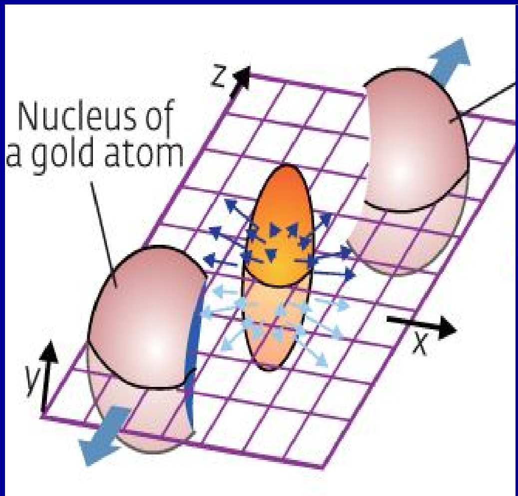
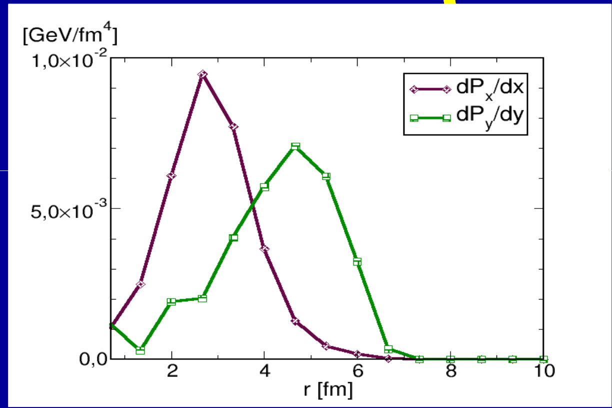
Outline

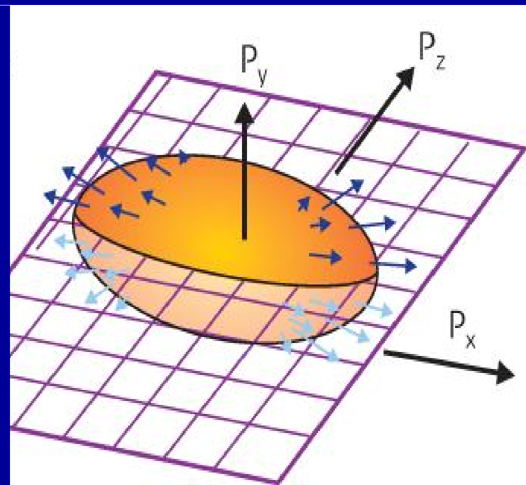
- Elliptic flow and η/s in the QGP
- Initial Condition (Glasma fKLN)
- Transport Kinetic Theory at Fixed η/s
- Results
- Conclusions and future developments

Elliptic flow and η/s in the QGP





Different gradient pressure



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$\frac{d^3N}{dy p_T dp_T d\phi} = \frac{1}{2\pi}\frac{d^2N}{dy p_T dp_T}\left[1 + 2v_2(y, p_T)\cos 2\phi\right]$$

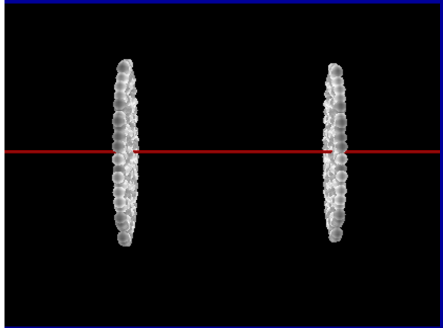
$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

v_2 is sensitive both to the initial condition in the overlap zone and to η/s of the evolving QGP

➢Initial Conditions :Glauber model

The initial profile of the fireball is given by the geometrical superposition of the profiles of the two colliding nuclei

➢Initial Conditions: Glasma



The two nuclei could be described as two tiny disks of Color Glass Condensate (CGC)

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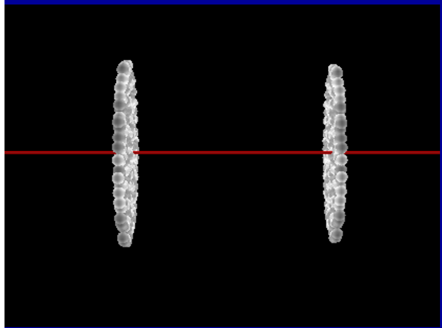

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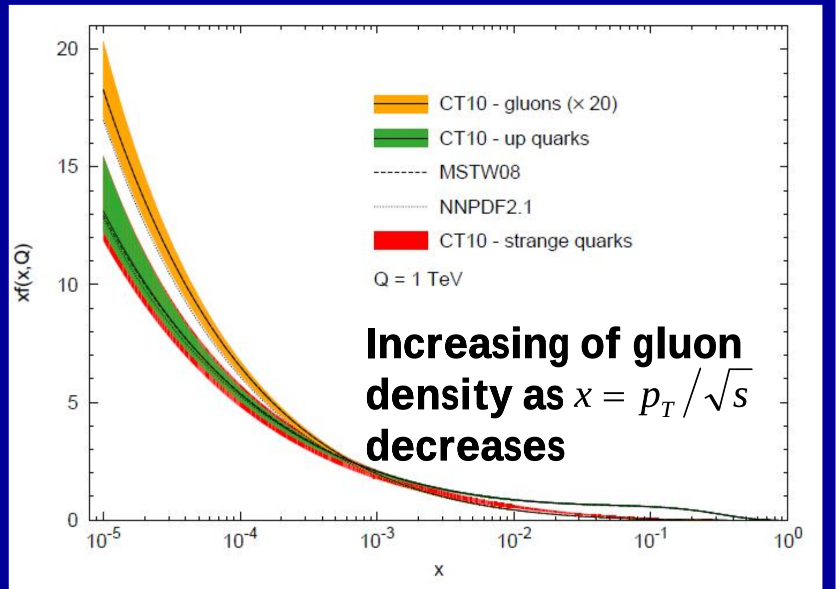


[Brandt and Klasen,arXiv:1305.5677]

Saturation scale

$$Q^2_{sat}(s) \propto \alpha_s(Q^2)\frac{xg(x,Q^2)}{\pi R^2} \propto A^{1/3}$$

At RHIC $Q_s^2 \sim$ 1-2 GeV^2
At LHC $Q_s^2 \sim$ 3-6 GeV^2 ?

The production of particle HIC is controlled by the Q_s

Reviews

McLerran, 2011
Iancu, 2009
McLerran, 2009
Lappi, 2010
Gelis, 2010
Fukushima, 2011

➢Initial Conditions: fKLN-Glasma

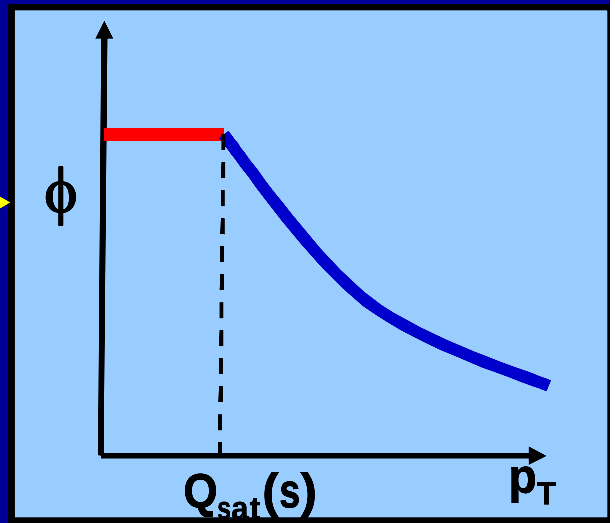
- **fKLN spectrum**

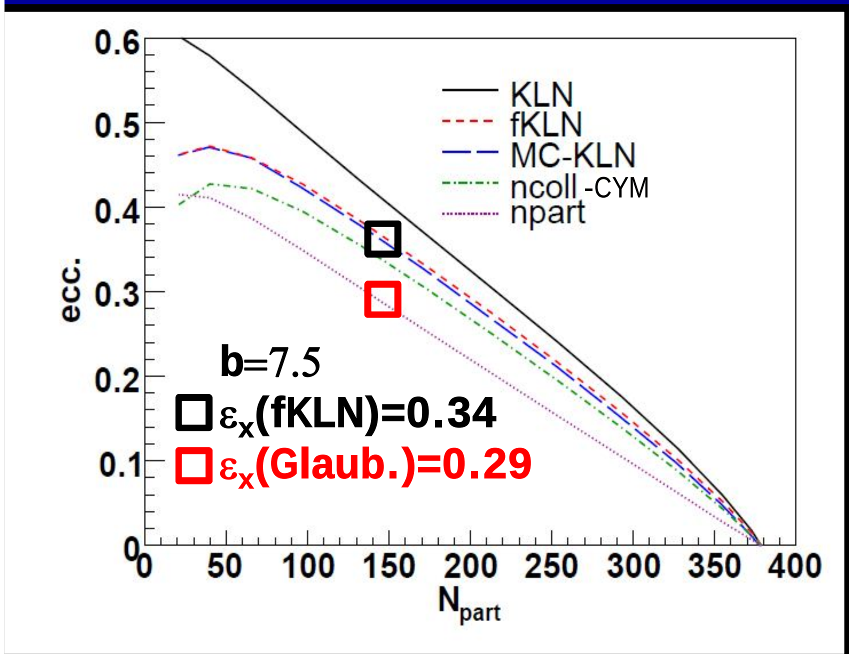
Kharzeev *et al.*, Phys. Lett. B561, 93 (2003)
Nardi *et al.*, Phys. Lett. B507, 121 (2001)
Drescher and Nara, PRC75, 034905 (2007)
Hirano and Nara, PRC79, 064904 (2009)
Albacete and Dumitru, arXiv:1011.5161[hep-ph]

$$\frac{dN_g}{d^2x_\perp dy} \propto \int \frac{d^2p_T}{p_T^2}\int_0^{p_T} d^2k_T\alpha_s(Q^2) \times\phi_A\left(x_A, \frac{(p_T+k_T)^2}{4}; \boldsymbol{x}_\perp\right) \times\phi_B\left(x_B, \frac{(p_T-k_T)^2}{4}; \boldsymbol{x}_\perp\right)$$

Saturation effects built in the ϕ.

$$\phi_A(x_1, k_T^2; \boldsymbol{x}_\perp) = \frac{\kappa Q_s^2}{\alpha_s(Q_s^2)}\left[\frac{\theta(Q_s - k_T)}{Q_s^2+\Lambda^2} + \frac{\theta(k_T - Q_s)}{k_T^2+\Lambda^2}\right]$$



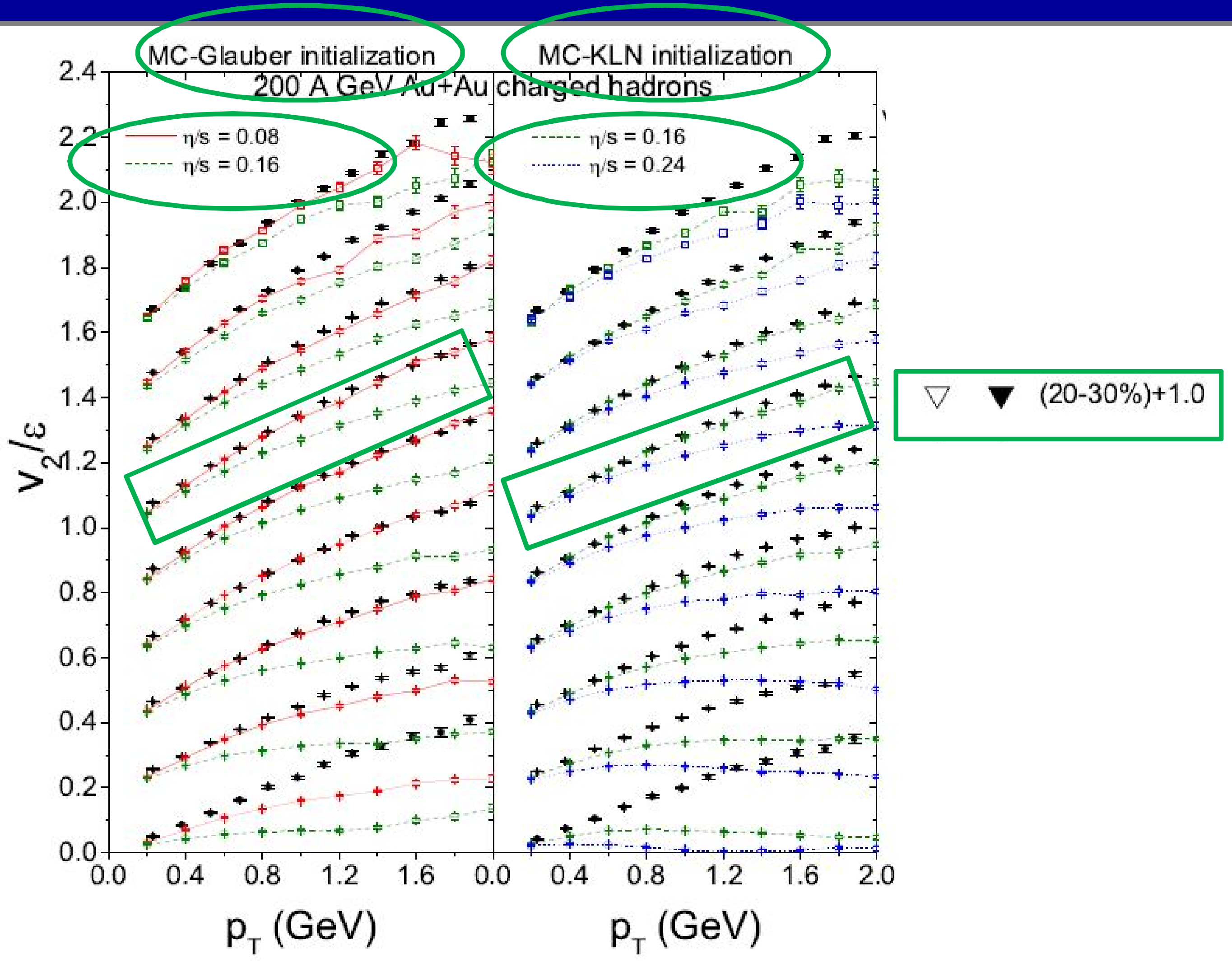


$$Q_{s,A}^2(x, \boldsymbol{x}_\perp) \propto Q_s^2 T_A(\boldsymbol{x}_\perp) x^{-\lambda}$$

***Universal saturation scale*, in agreement with:**
Lappi and Venugopalan, PRC 74 054905 (2006)

V_2 from KLN in Hydro

[Heinz *et al.*, PRC 83, 054910 (2011)]



Glauber $\eta/s \cong 1/4\pi$

fKLN $\eta/s \cong 2/4\pi$

Similar conclusion in Drescher et al., PRC (2011)

Larger ε_x - > higher η/s to get the same $v_2(p_T)$

Transport theory

$$p^{\mu}\partial_{\mu} f(x,p) + M(X)\partial_{\mu} M(X)\partial_{p}^{\mu} f(X,p) = C[f]$$

Free streaming — Mean Field — Collisions

f(x,p) is a one body distribution function

We map with C[f] the local phase space evolution of a fluid with a fixed η/s

$$\mathcal{C}_{22} = \frac{1}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int \frac{d^3p'_1}{(2\pi)^3 2E'_1}\frac{d^3p'_2}{(2\pi)^3 2E'_2} f'_1 f'_2 |\mathcal{M}_{1'2'\to 12}|^2 (2\pi)^4 \delta^{(4)}(p'_1+p'_2-p_1-p_2)$$
$$-\frac{1}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int \frac{d^3p'_1}{(2\pi)^3 2E'_1}\frac{d^3p'_2}{(2\pi)^3 2E'_2} f_1 f_2 |\mathcal{M}_{12\to 1'2'}|^2 (2\pi)^4 \delta^{(4)}(p_1+p_2-p'_1-p'_2)$$

Collision integral is solved with a **local stochastic sampling**

[Z. Xhu, C. Greiner, PRC71(04)]
[G. Ferini et al Phys.Lett.B670:325-329,2009]

$$P_{22} = \frac{\Delta N_{\rm coll}^{2\to 2}}{\Delta N_1 \Delta N_2} = v_{\rm rel}\sigma_{22}\frac{\Delta t}{\Delta^3 x}$$

- **valid also at intermediate and high p_T out of equilibrium**
- **CGC p_T non-equilibrium distribution (beyond the difference in ε_x)**

Simulate a fixed shear visosity

Usually a key input ingredient of a transport approach is the knowledge of the cross section σ but here we reverse it and start from η/s with aim of creating a more direct link to viscous hydro.

$$P_{22} = \frac{\Delta N^{2\to 2}_{\text{coll}}}{\Delta N_1 \Delta N_2} = v_{\text{rel}}\sigma_{22}\frac{\Delta t}{\Delta^3 x}$$

The total Cross section is computed in each configuration space cell according to Chapman-Enskog approximation

$$\frac{\eta}{s} = \frac{1}{15}\langle p \rangle \cdot \tau_\eta = \frac{1}{15}\frac{\langle p \rangle}{g(\frac{m_D}{T})\sigma_{TOT}\rho}$$

$$\Rightarrow \quad \sigma_{tot}(n(\vec{r}),T) = \frac{1}{15}\frac{\langle p_\alpha \rangle}{g(a)n_\alpha}\frac{1}{\eta / s}$$

Space-Time dependent cross section evaluated locally

$$g(a) = \frac{1}{50}\int dy y^6 \left[(y^2+\frac{1}{3})K_3(2y)-yK_2(2y)\right] h\left(\frac{a^2}{y^2}\right)$$

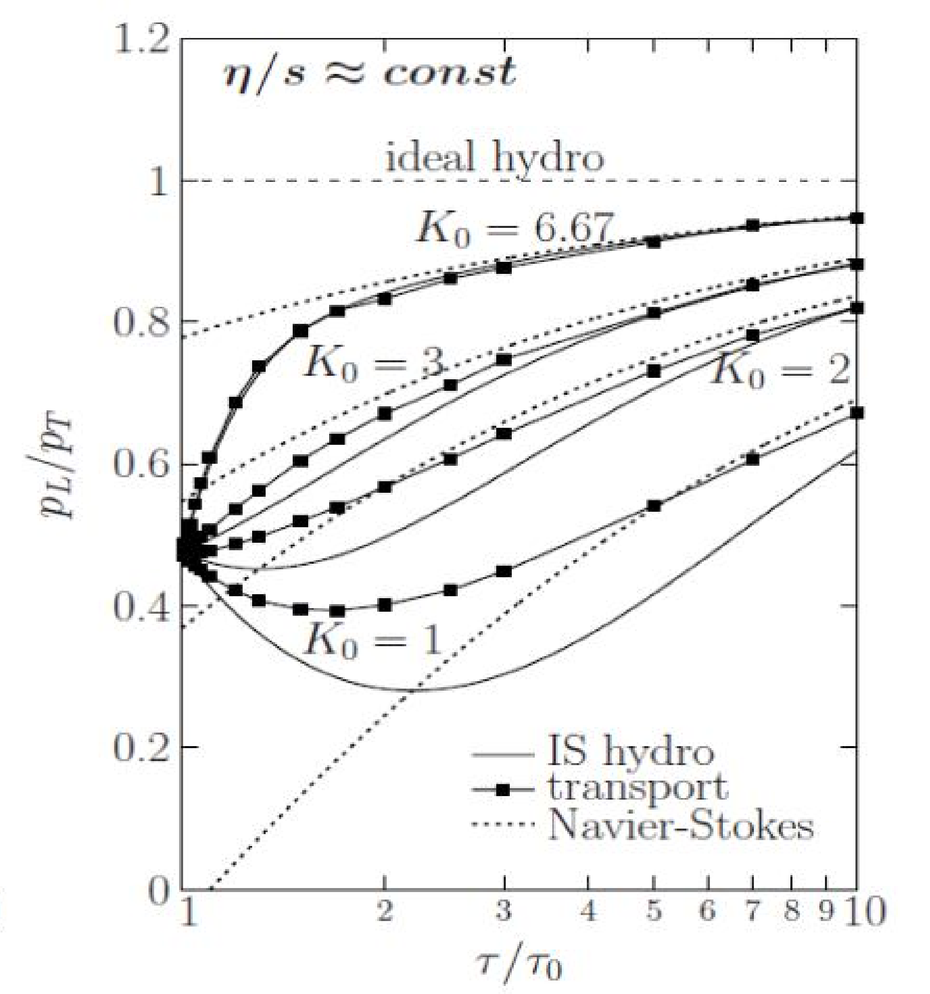
α=cell index in the r-space

Plumari *et al.*, Phys. Rev. C86 (2012)
Greco *et al.*, Phys. Lett. B670 (2009)
Plumari *et al.*, J.Phys.Conf.Ser. 420 (2013)

Transport vs Viscous Hydrodynamics in 1+1D

Comparison for the relaxation of pressure anisotropy P_L/P_T

Huovinen and Molnar, PRC79(2009)



Knudsen number^{-1}

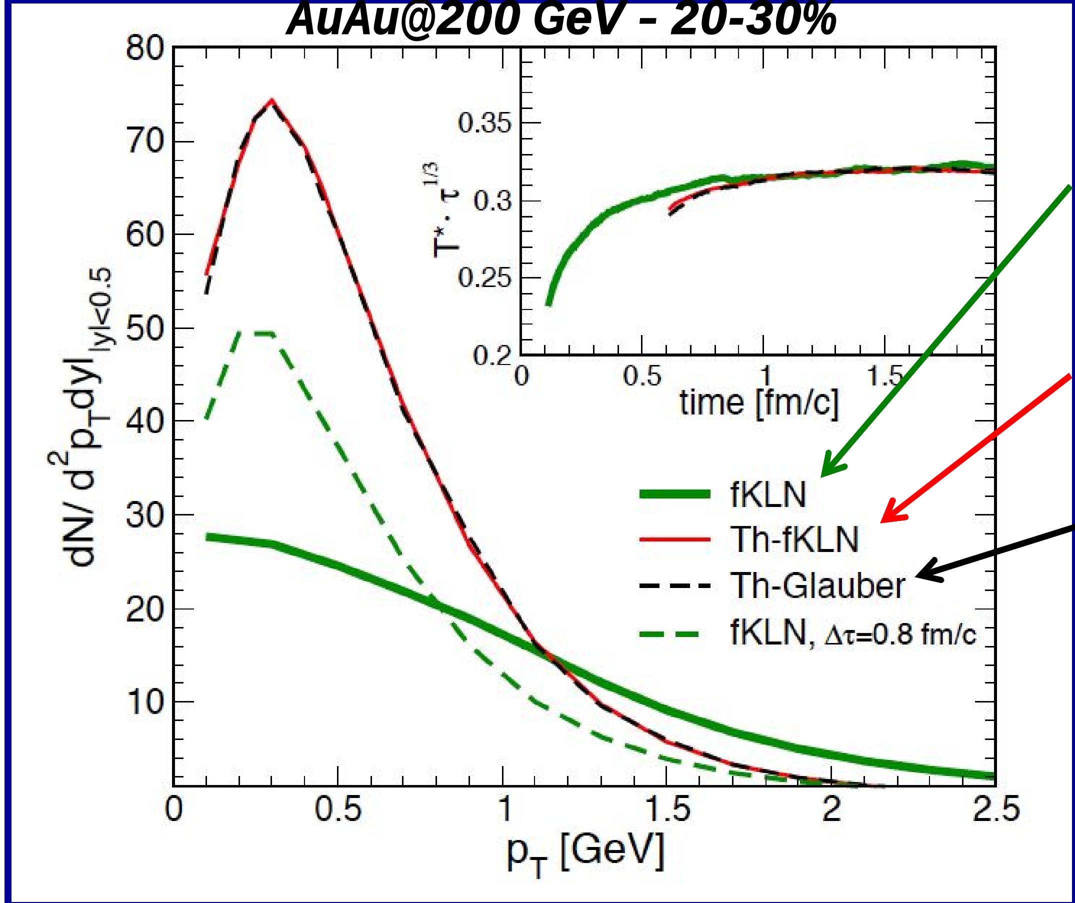
$$K = \frac{L}{\lambda} \to \frac{\tau}{\lambda}$$

Large K small η/s

$$K \propto \frac{1}{\eta / s}$$

In the limit of small η/s (<0.16) transport reproduce viscous hydro

Implementing fKLN p_T distribution



Using kinetic theory at finite η/s we can implement full KLN (x & p space) - ε_x=0.34, Qs =1.44 GeV

KLN only in x space (like in Hydro) ε_x=0.34, Qs=0

Glauber in x and thermal in p ε_x=0.289 , Qs=0

F. S. *et al.*, 1303.3178 [nucl-th]

Thermalization in less than 1 fm/c, in agreement with Andrej El, Greiner *et al.*, NPA806, 287 (2008).
Not so surprising: η/s is small -> large effective scattering rate -> fast thermalization.

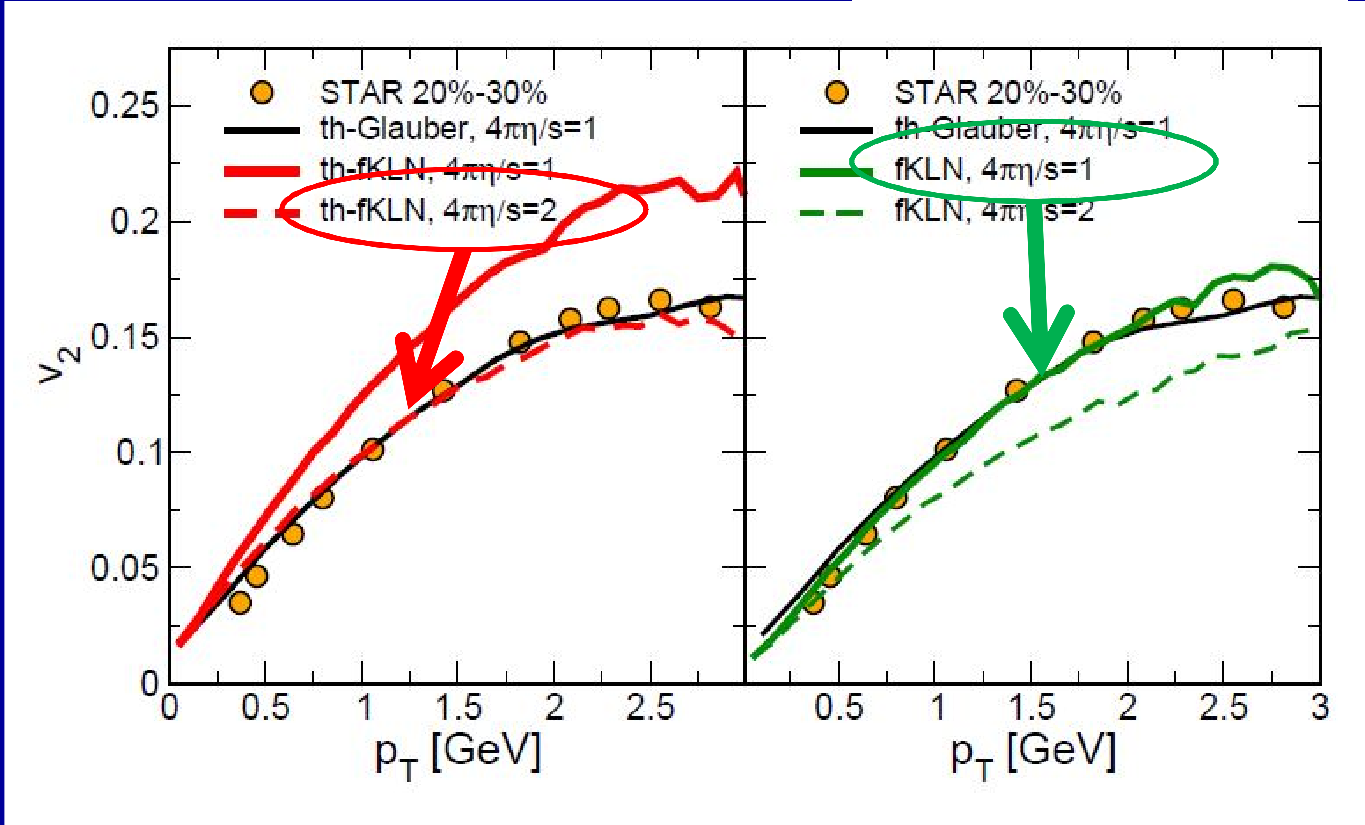
$$\sigma_{tot} = \frac{\langle p \rangle}{\rho\, g(a)} \frac{1}{\eta/s}$$

Elliptic flow at RHIC from: fKLN Glasma

F. S. *et al.*, 1303.3178 [nucl-th]

In agreement with:
[Heinz *et al.*, PRC 83, 054910 (2011)]

AuAu@200 GeV

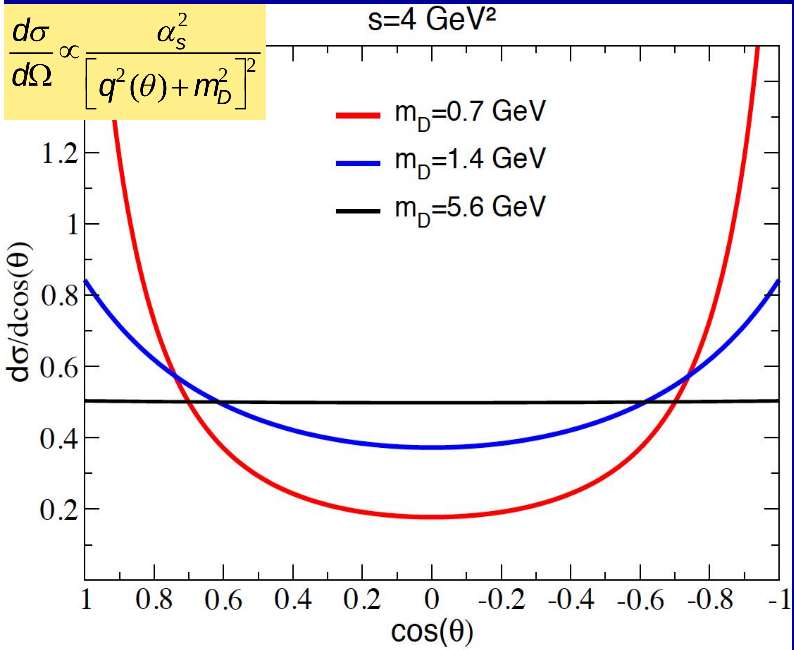


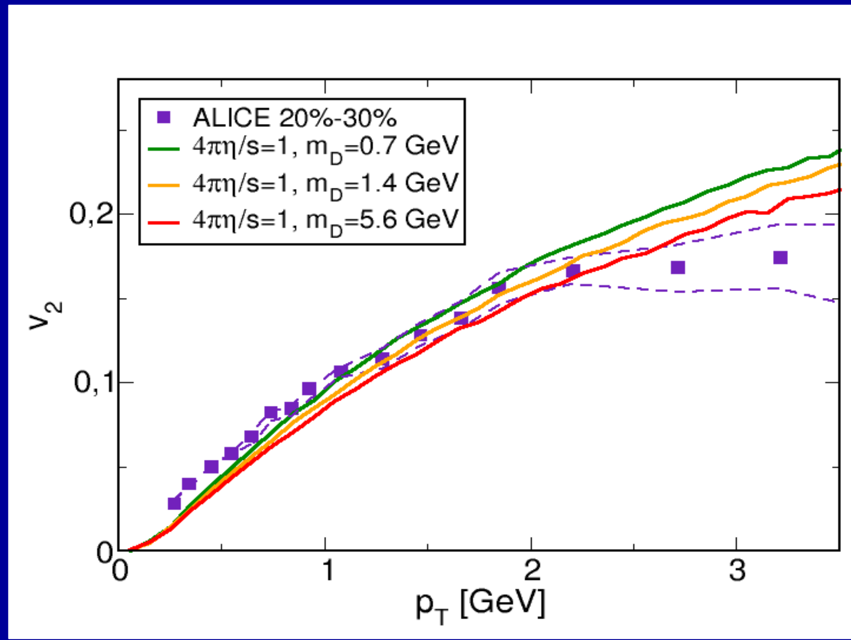
When implementing KLN and Glauber like Hydro we get the same results

When implementing the full fKLN we get close to the data with $4\pi\eta/s=1$: larger ε_x compensated by the nonequilibrium distribution

Are micro-details important?

$$\frac{d\sigma}{d\Omega} \propto \frac{\alpha_s^2}{\left[q^2(\theta)+m_D^2\right]^2}$$





Increasing m_D makes the σ isotropic

We keep the same η/s

$$\frac{\eta}{s} = \frac{1}{15}\langle p\rangle \cdot \tau_\eta = \frac{1}{15}\frac{\langle p\rangle}{g(\frac{m_D}{T})\sigma_{TOT}\rho}$$

$$\frac{\sigma_{TOT}(m_{1D})}{\sigma_{TOT}(m_{2D})} = \frac{g(m_{2D})}{g(m_{1D})}$$

for m_D=1.4 GeV -> 25% smaller σ_{tot}

for m_D=5.6 GeV -> 40% smaller σ_{tot}

- **Strong change in the angular dependence of σ result in a very little change of the elliptic flow at low p_T**

Conclusions

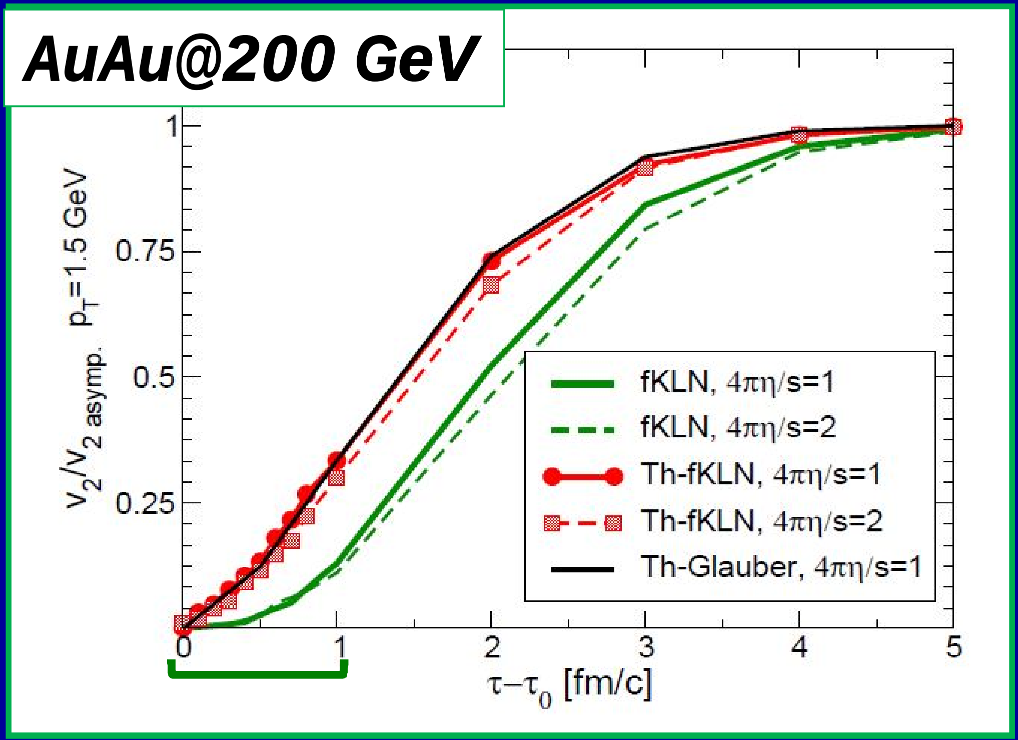
- ✓ We have used Kinetic Theory to compute the elliptic flow of a fireball produced in heavy ion collisions, both at RHIC and LHC energies
- ✓ Initial non-equilibrium Glasma distribution damps the $v_2(p_T)$ compensating the larger ε_x

Outlook

- ✓ Using also the Classic Yang-Mills initial condition
- ✓ Including the initial state fluctuations in order to study also the impact on the v3

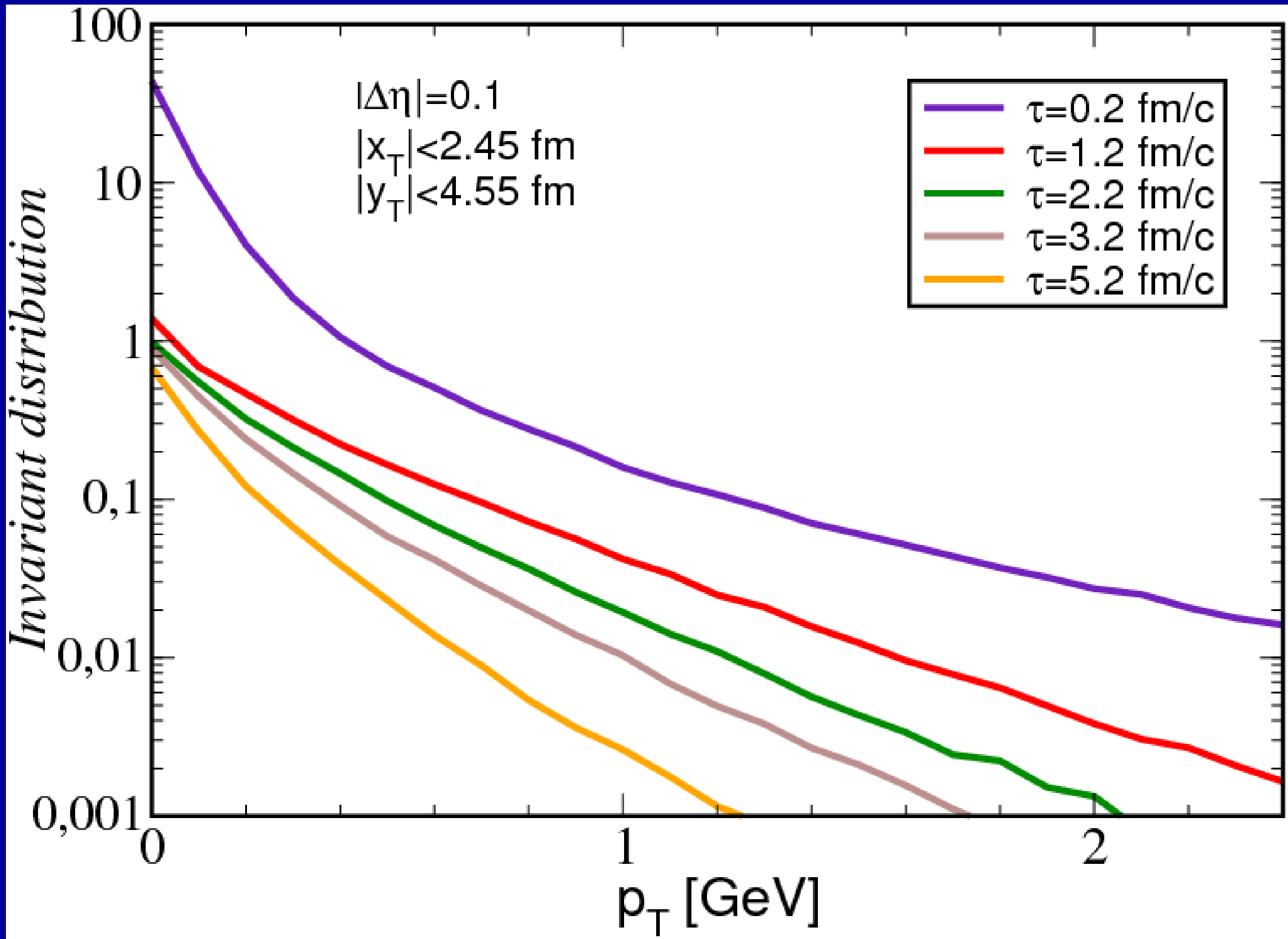
What is going on?

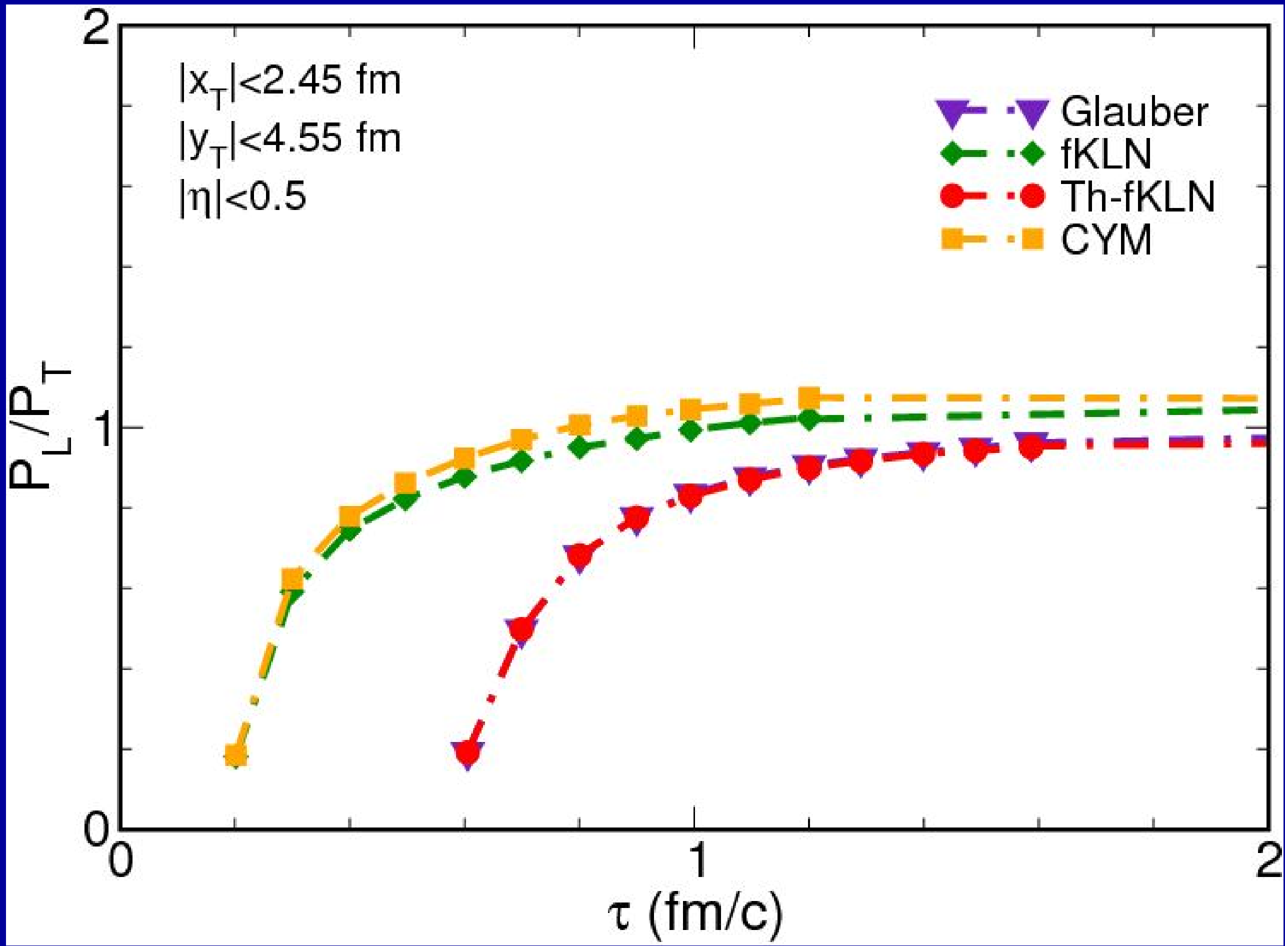
V_2 normalized time evolution



[M. Ruggieri *et al.*, 1303.3178 [nucl-th]]

We clearly see that when non-equilibrium distribution is implemented in the initial stage (≈ 1 fm/c) v_2 grows slowly respect to thermal one


|Δη|=0.1
|x_T|<2.45 fm
|y_T|<4.55 fm
τ=0.2 fm/c
τ=1.2 fm/c
τ=2.2 fm/c
τ=3.2 fm/c
τ=5.2 fm/c
Invariant distribution
p_T [GeV]
100
10
1
0,1
0,01
0,001
0
1
2


|x_T|<2.45 fm
|y_T|<4.55 fm
|η|<0.5
Glauber
fKLN
Th-fKLN
CYM
P_L/P_T
τ (fm/c)
0
1
2
0
1
2