Dr. Marco Ruggieri
Università degli Studi di Catania, Catania (Italy)

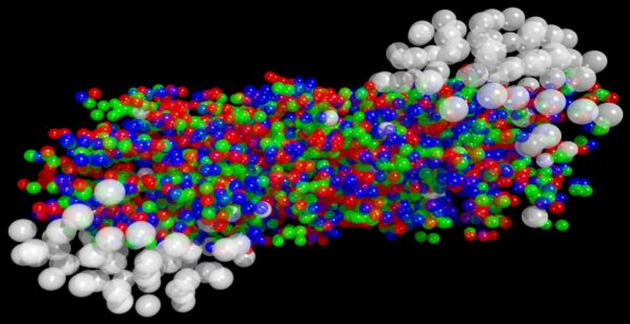
COLLECTIVE FLOWS AND VISCOSITY OF QUARK-GLUON PLASMA

QCD@work 2014

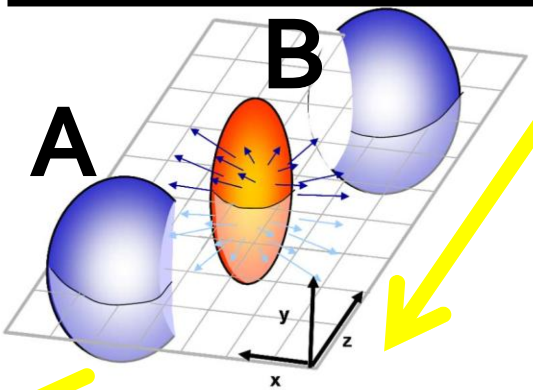
Collaborators:
- *Vincenzo Greco*
- *Salvatore Plumari*
- *Francesco Scardina*

In this talk:

- Transport theory for heavy ion collisions
- ***Thermalization and Isotropization***
- ***Collective Flows***
- Conclusions



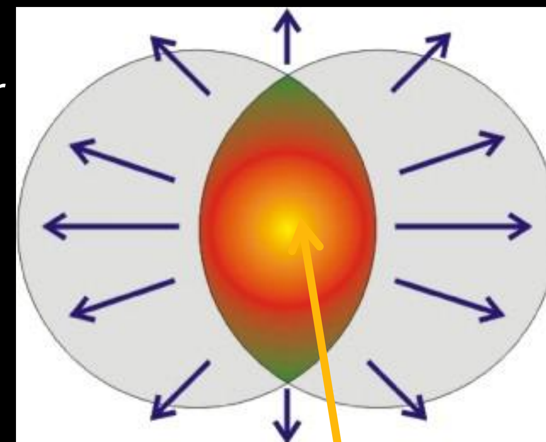
Heavy Ion Collisions



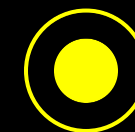
Impact parameter direction

Collision (flight) direction

Impact parameter direction



Collision direction

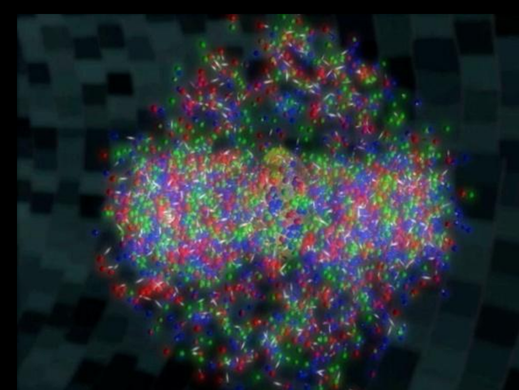


FIREBALL:
Hot and dense expanding ***parton mixture***
QUARK-GLUON-PLASMA (QGP)
T about 10^{12} K, t about 10^{-23} seconds

A,B: Cu, Au (RHIC@BNL)
Pb (LHC@CERN).

$$\sqrt{s} \text{ up to } 200 \times A \text{ GeV}\,, \qquad \text{RHIC}$$

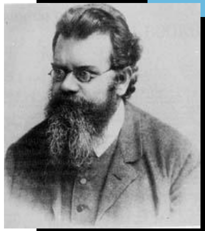
$$\sqrt{s} \text{ up to } 2.76 \times A \text{ TeV}\,, \qquad \text{LHC}$$



Boltzmann equation and QGP

In order to *simulate* the temporal evolution of the fireball we solve the ***Boltzmann equation*** for the parton distribution function ***f***:

$$\left\{p^{\mu}\partial_{\mu} + \left[p_{\nu}F^{\mu\nu} + m\partial^{\mu}m\right]\partial_{\mu}^{p}\right\}f(x,p) = C[f]$$



Field interaction (EoS)

Collision integral

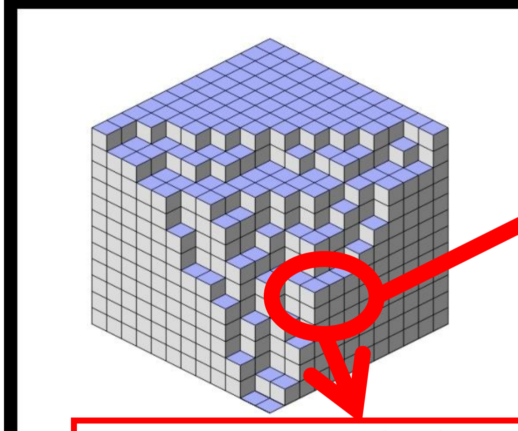
Collision integral: change of ***f*** due to collision processes in the phase space volume centered at (***x***,***p***).

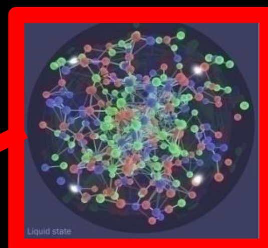
*We map by C[f] the phase space evolution of a fluid which **dissipates with a given value of η/s**, **like in hydrodynamics calculations.***

One can expand C[f] over microscopic details (2<->2,2<->3…), but in a hydro language this is irrelevant: ***only the global dissipative effect of C[f] is important.***

Transport *gauged* to hydro

We use ***Boltzmann equation*** to simulate a fluid at ***fixed eta/s*** rather than fixing a set of microscopic processes.
Total Cross section is ***computed*** in ***each configuration space cell*** according to ***Chapman-Enskog equation*** to give the ***wished value of eta/s***.





$$\boxed{\frac{\eta}{s} = \frac{\langle p \rangle}{g(m_D)\rho}\frac{1}{\sigma}}$$

(.) Collision integral is gauged in each cell to assure that the fluid dissipates according to the desired value of eta/s.

(.) Microscopic details are not important: the specific microscopic process producing eta/s is not relevant, only macroscopic quantities are, in analogy with hydrodynamics.

Transport ←  → ***Hydro***

Description in terms of parton distribution function

Dynamical evolution governed by macroscopic quantities

Why transport for uRHICs?

$$\left\{p^{\mu}\partial_{\mu} + \left[p_{\nu}F^{\mu\nu} + m\partial^{\mu}m\right]\partial_{\mu}^{p}\right\}f(x,p) = C[f]$$

- Starting from 1-body distribution function f(x,p) and not from $T_{\mu\nu}$:
  - Implement non-equilibrium implied by CGC-Qs scale (beyond ε_x)
  - Include off-equilibrium at high and intermediate p_T :

    Relevant at LHC due to large amount of minijet production
  - freeze-out self-consistently related with η/s(T)

- It's not an expansion in η/s:

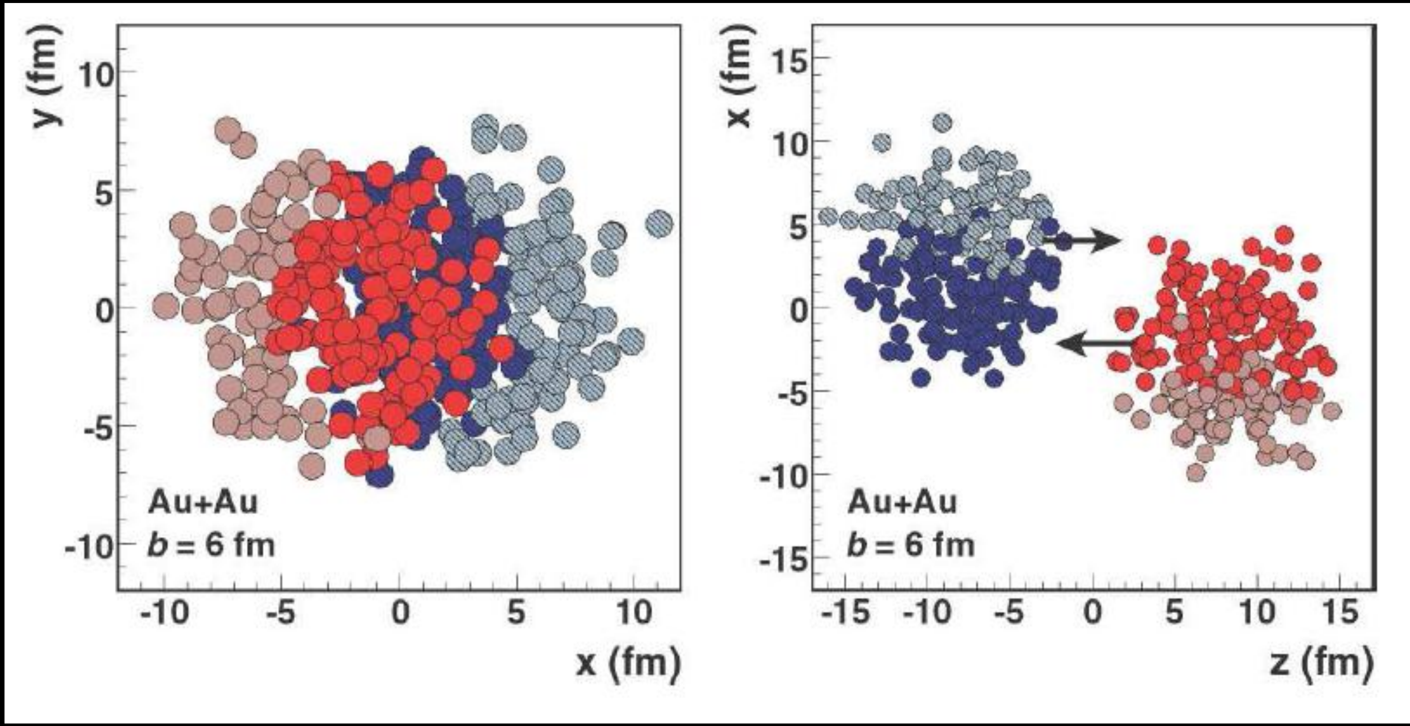
  - valid also at high η/s -> LHC ($T>>T_c$)

- Appropriate for heavy quark dynamics

- f(x,p) and kinetic equations are useful to grasp informations about early glasma evolution

Initial condition: Glauber

(Almost) Geometrical description of the fireball:



Assuming a nucleon distribution in the parents nuclei (typically a ***Woods-Saxon***), one counts ***how many particles*** from each nucleus are present in the ***overlap region***; among them, the ***participants*** are the nucleons that effectively can have an interaction (in fact, the particles that *are in the overlap region* but *do not interact*, are not considered).

For a review see: Miller *et al.*, Ann.Rev.Nucl.Part.Sci. **57, 205 (2007)**

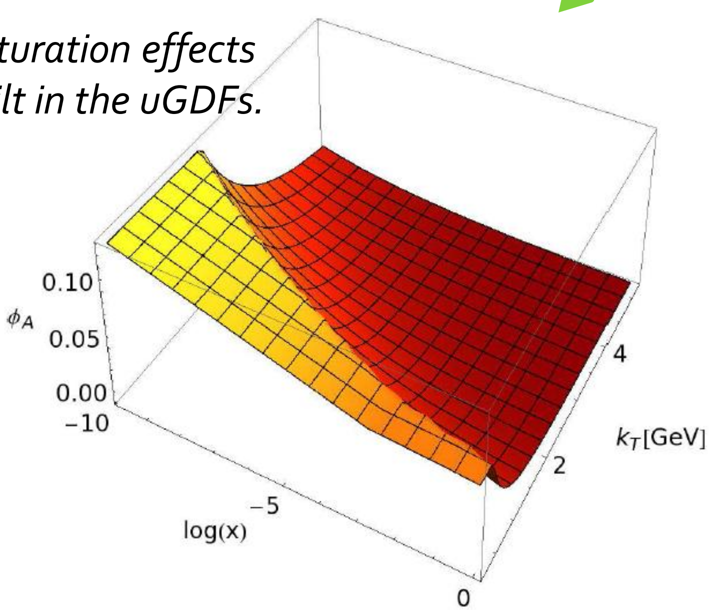
Initial condition: "CGC"-KLN

Nardi *et al.*, Nucl. Phys. A**747**, 609 (2005)
Kharzeev *et al.*, Phys. Lett. B**561**, 93 (2003)
Nardi *et al.*, Phys. Lett. B**507**, 121 (2001)
Drescher and Nara, PRC**75**, 034905 (2007)
Hirano and Nara, PRC**79**, 064904 (2009)
Hirano and Nara, Nucl. Phys. A**743**, 305 (2004)
Albacete and Dumitru, arXiv:1011.5161[hep-ph]

(f)KLN spectrum

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

Saturation effects built in the uGDFs.

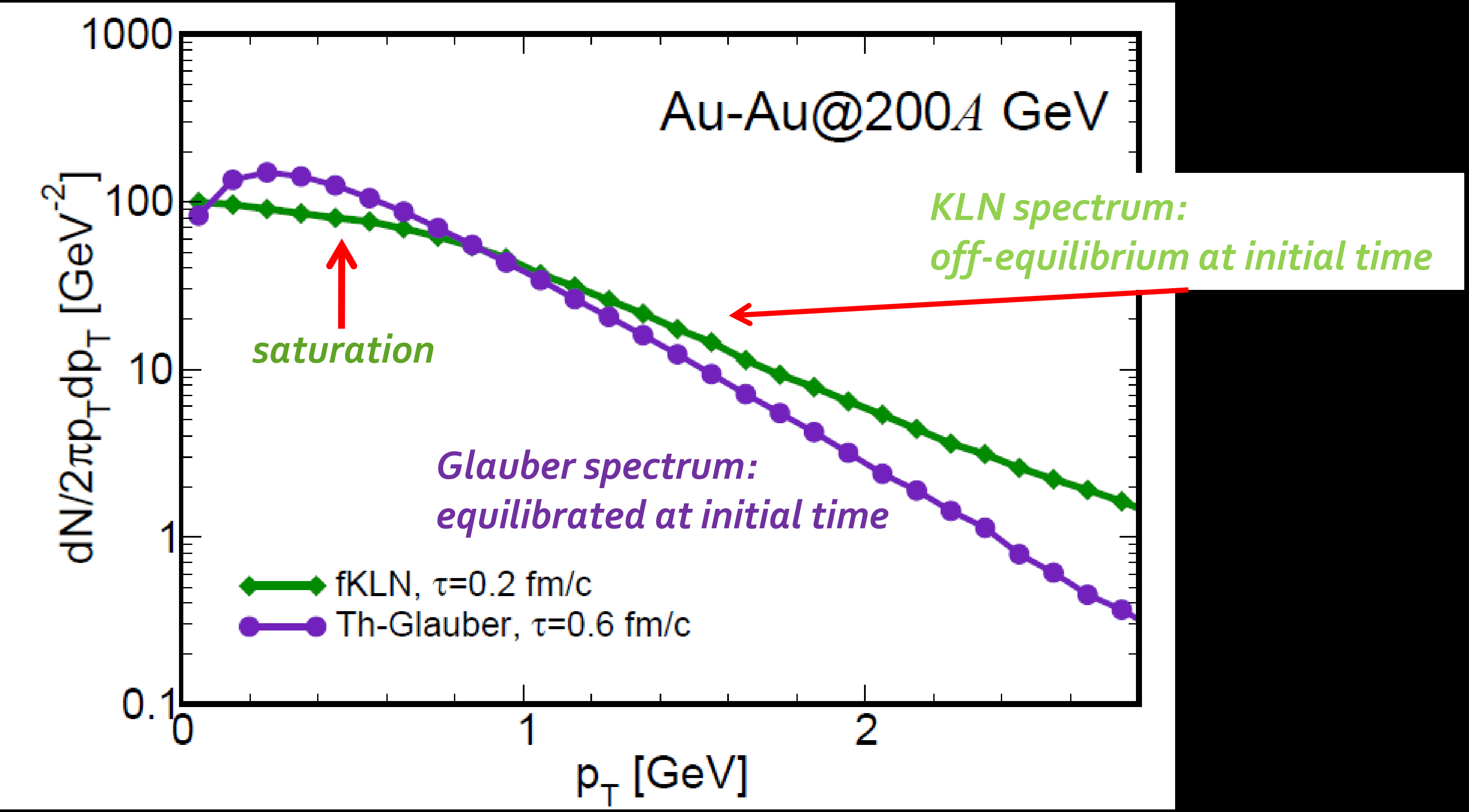


Gluon production is ***damped*** for momenta ***below the saturation scale***

This spectrum models ***gluons produced*** after the ***shattering of the color glass condensate***

M. R. *et al.*, PLB727 (2013)
M. R. *et al.*, PRC 89 (2014)

Initial spectra



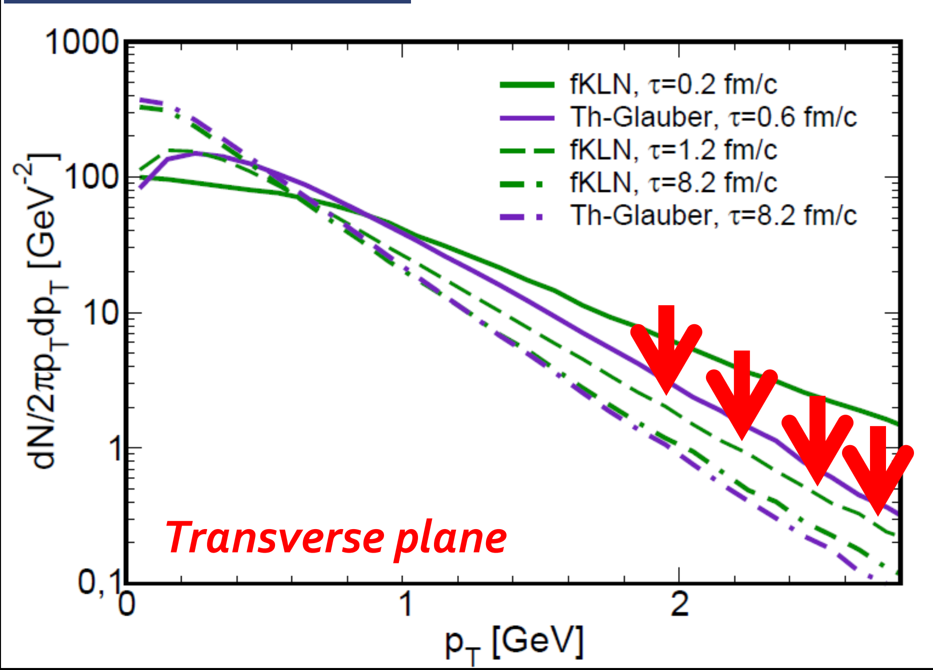
Our novelty:

For fKLN we consider the ***initial spectrum given by the theory at small transverse momenta.***

M. R. *et al.*, PLB727 (2013)
M. R. *et al.*, PRC 89 (2014)

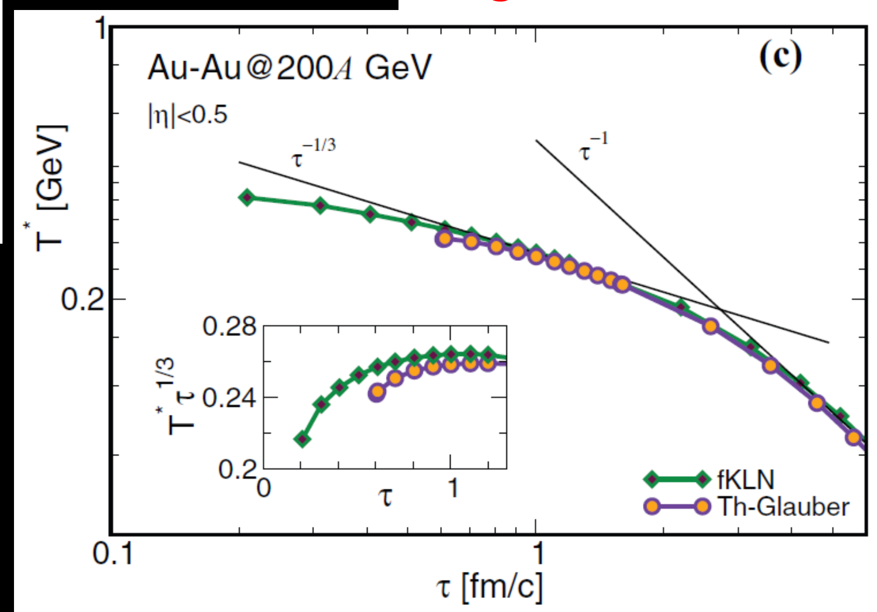
Thermalization

AuAu@200A GeV



Thermalization in *about 1 fm/c*,
in agreement with:
Greiner *et al.*, Nucl. Phys. A**806**, 287 (2008).

Longitudinal direction



We have dynamics in the early stages of the simulation, which prepares the momentum distribution to build up the elliptic flow.

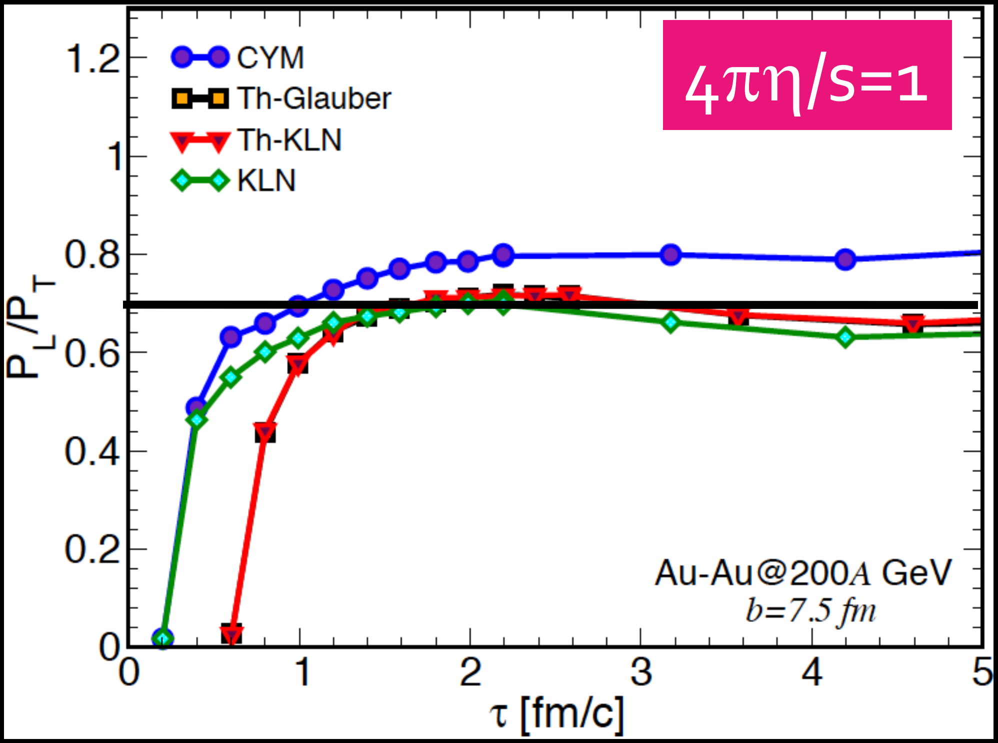
Similar results for Pb-Pb collisions

M. R. *et al.*, PRC 89 (2014)

Pressure isotropization

$$T^{\mu\nu} = \int \frac{d^3p}{(2\pi)^3}\frac{p^\mu p^\nu}{E} f(x,p)$$

$$P_T = \frac{1}{V}\int_\Omega d^2x_\perp d\eta\, \frac{T_{xx}+T_{yy}}{2}\,,$$
$$P_L = \frac{1}{V}\int_\Omega d^2x_\perp d\eta\, T_{zz}\,,$$



t=1/Qs≈0.1-0.2 fm/c -> P_L/P_T > 0
Gelis & Epelbaum
arXiV:1307.2214

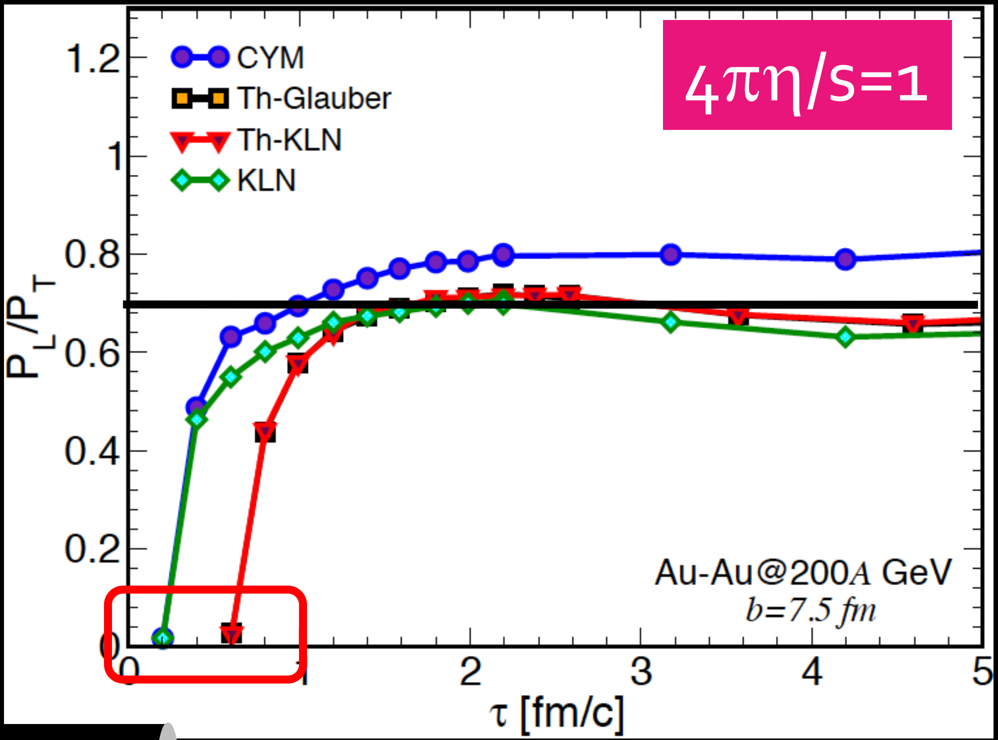
CYM (IP-Glasma) spectrum:
Courtesy of B. Schenke
& R. Venugopalan

M. R. *et al.*, PRC 89 (2014)

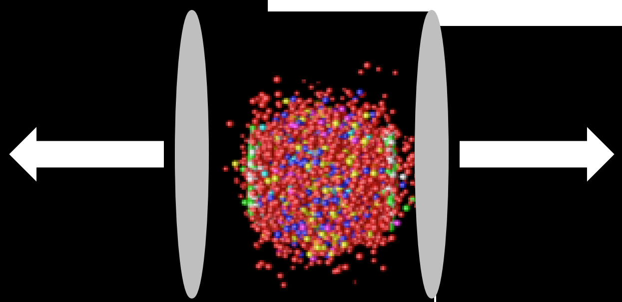
Pressure isotropization

$$T^{\mu\nu} = \int \frac{d^3p}{(2\pi)^3}\frac{p^\mu p^\nu}{E} f(x,p)$$

$$P_T = \frac{1}{V}\int_\Omega d^2x_\perp d\eta \, \frac{T_{xx}+T_{yy}}{2} \, ,$$
$$P_L = \frac{1}{V}\int_\Omega d^2x_\perp d\eta \, T_{zz} \, ,$$



$t=1/Q_s \approx 0.1$-0.2 fm/c -> $P_L/P_T > 0$
Gelis & Epelbaum
arXiV:1307.2214



CYM (IP-Glasma) spectrum:
Courtesy of B. Schenke
& R. Venugopalan

Free longitudinal streaming : zero longitudinal pressure

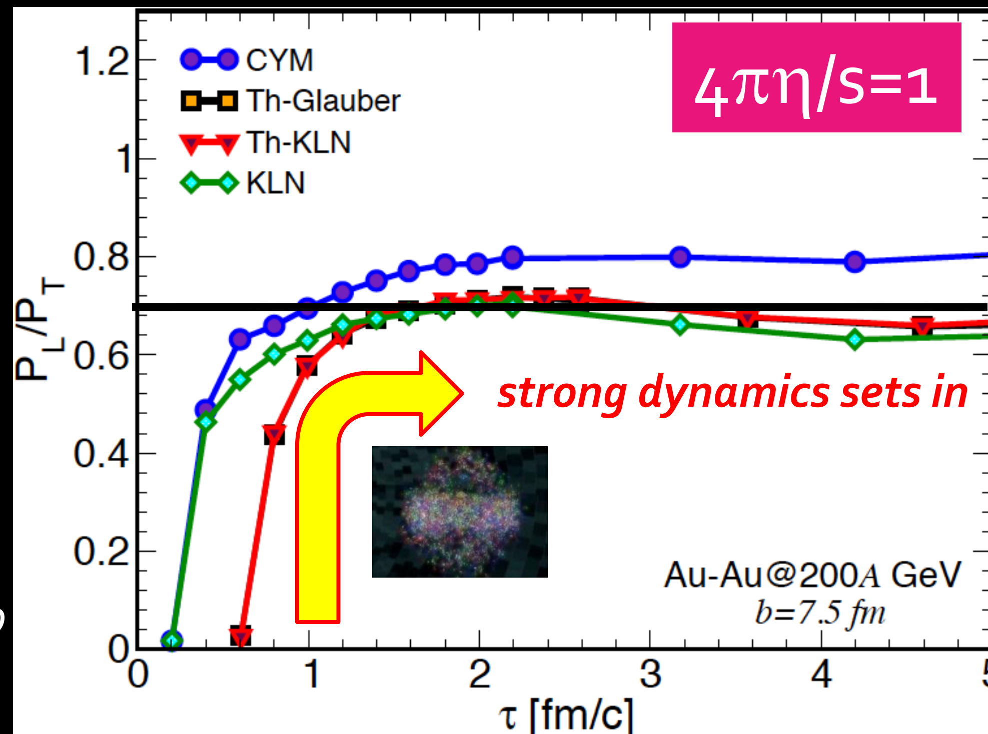
M. R. *et al.*, PRC 89 (2014)

Pressure isotropization

$$T^{\mu\nu} = \int \frac{d^3p}{(2\pi)^3}\frac{p^\mu p^\nu}{E} f(x,p)$$

$$P_T = \frac{1}{V}\int_\Omega d^2x_\perp d\eta \, \frac{T_{xx}+T_{yy}}{2} \; ,$$
$$P_L = \frac{1}{V}\int_\Omega d^2x_\perp d\eta \, T_{zz} \; ,$$

$t=1/Qs \approx 0.1$-0.2 fm/c -> $P_L/P_T > 0$
Gelis & Epelbaum
arXiV:1307.2214



CYM (IP-Glasma) spectrum:
Courtesy of B. Schenke
& R. Venugopalan

Strong dynamics removes pressure anisotropy

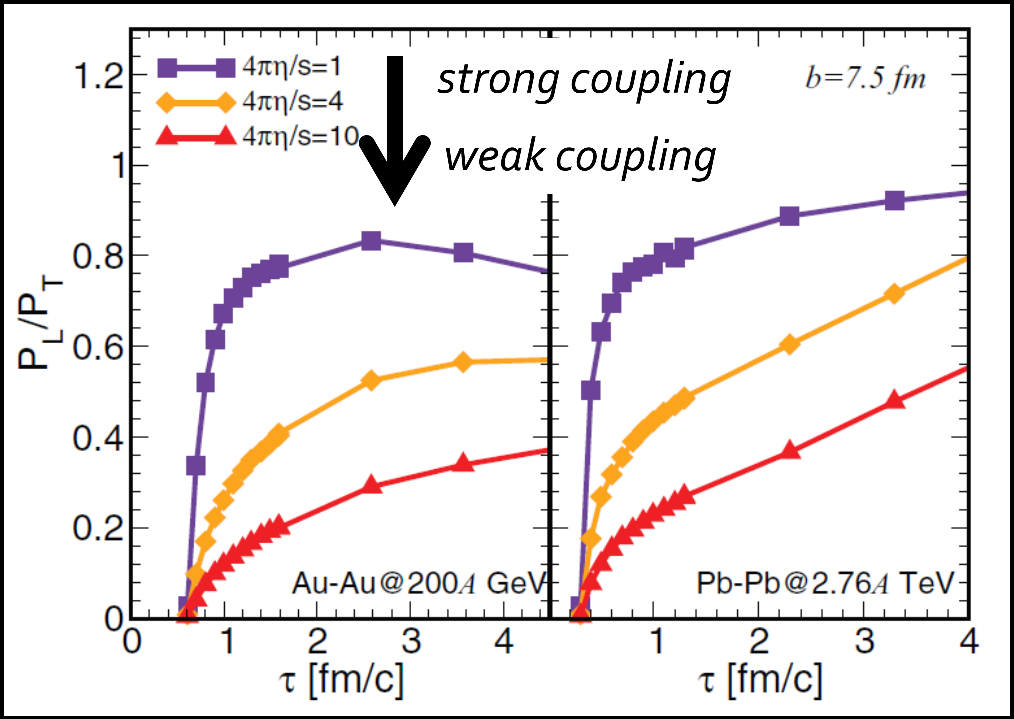
Fast isotropization: τ around 1 fm/c

M. R. *et al.*, PRC 89 (2014)

Pressure isotropization

$$T^{\mu\nu} = \int \frac{d^3p}{(2\pi)^3} \frac{p^\mu p^\nu}{E} f(x,p)$$

$$P_T = \frac{1}{V}\int_\Omega d^2x_\perp d\eta \, \frac{T_{xx}+T_{yy}}{2} \,,$$
$$P_L = \frac{1}{V}\int_\Omega d^2x_\perp d\eta \, T_{zz} \,,$$



- For $\eta/s > 0.3$ one misses fast isotropization in P_L/P_T (τ about 2-3 fm/c)
- For $\eta/s \approx$ pQCD no isotropization

For large viscosity the system is not able to remove anisotropy efficiently

Elliptic flow in RHICs

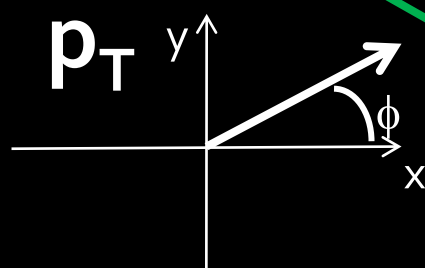
Particle multiplicity in phase space

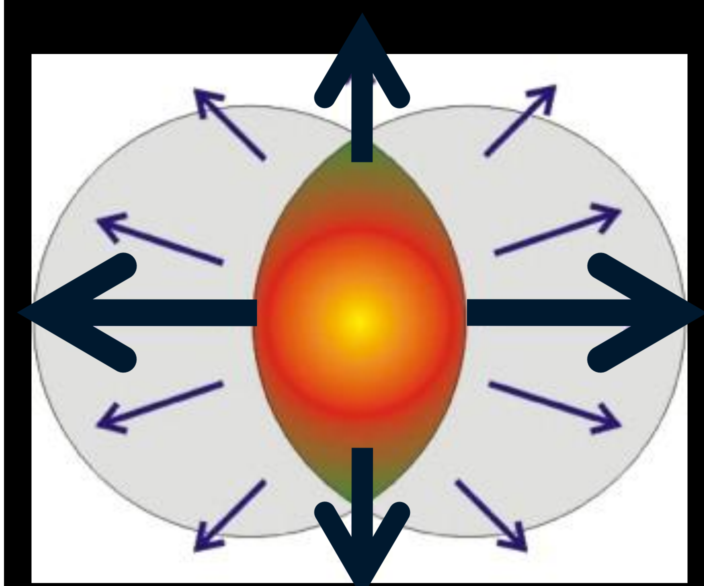
$$\frac{d^3N}{dyp_Tdp_Td\phi} = \frac{1}{2\pi}\frac{d^2N}{dyp_Tdp_T}[1 + 2v_2(y,p_T)\cos 2\phi]$$

Elliptic flow:
leading contribution to anisotropy in momentum space

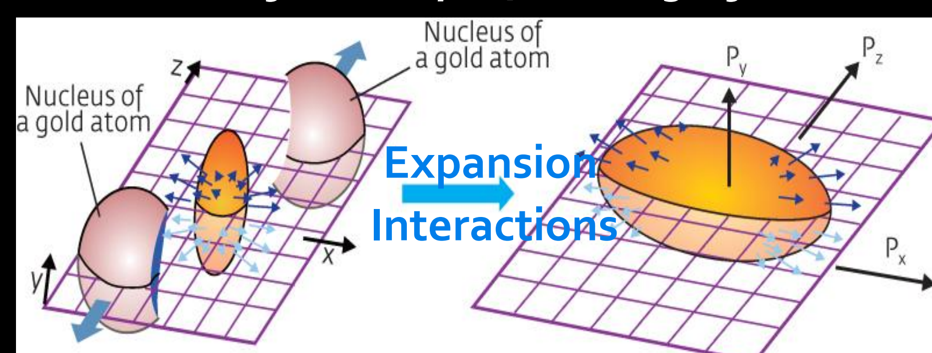
$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$$

Fourier decomposition in terms of *harmonics* in the *transverse plane*.





*Immediately after the collision, **pressure gradient** along **X** is larger than that along **Y**.*
*As a consequence, **the medium expands preferentially along the short axis of the ellipse,** creating a **flow.***



Ollitrault, PRD46 (1992)

Elliptic flow in RHICs

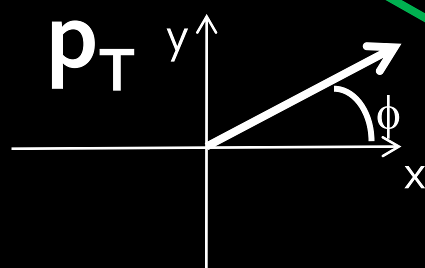
Particle multiplicity in phase space

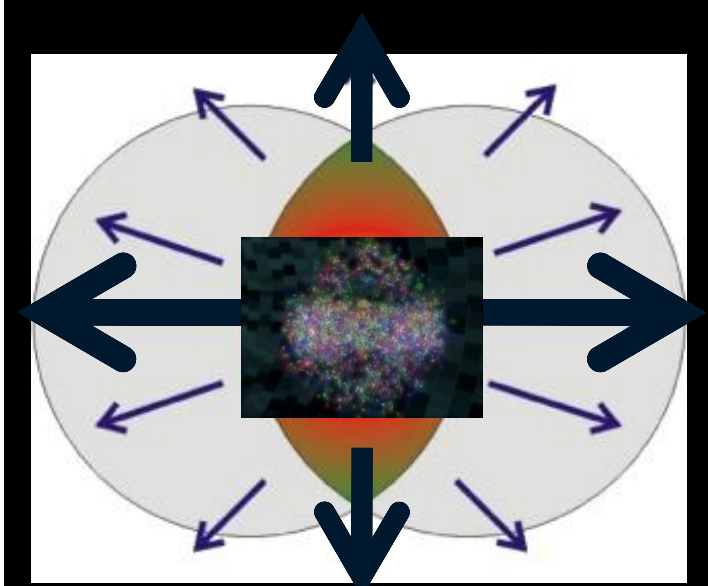
$$\frac{d^3N}{dy p_T dp_T d\phi} = \frac{1}{2\pi}\frac{d^2N}{dy p_T dp_T}\left[1 + 2v_2(y, p_T)\cos 2\phi\right]$$

Elliptic flow:
leading contribution to anisotropy in momentum space

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

Fourier decomposition in terms of *harmonics* in the *transverse plane*.



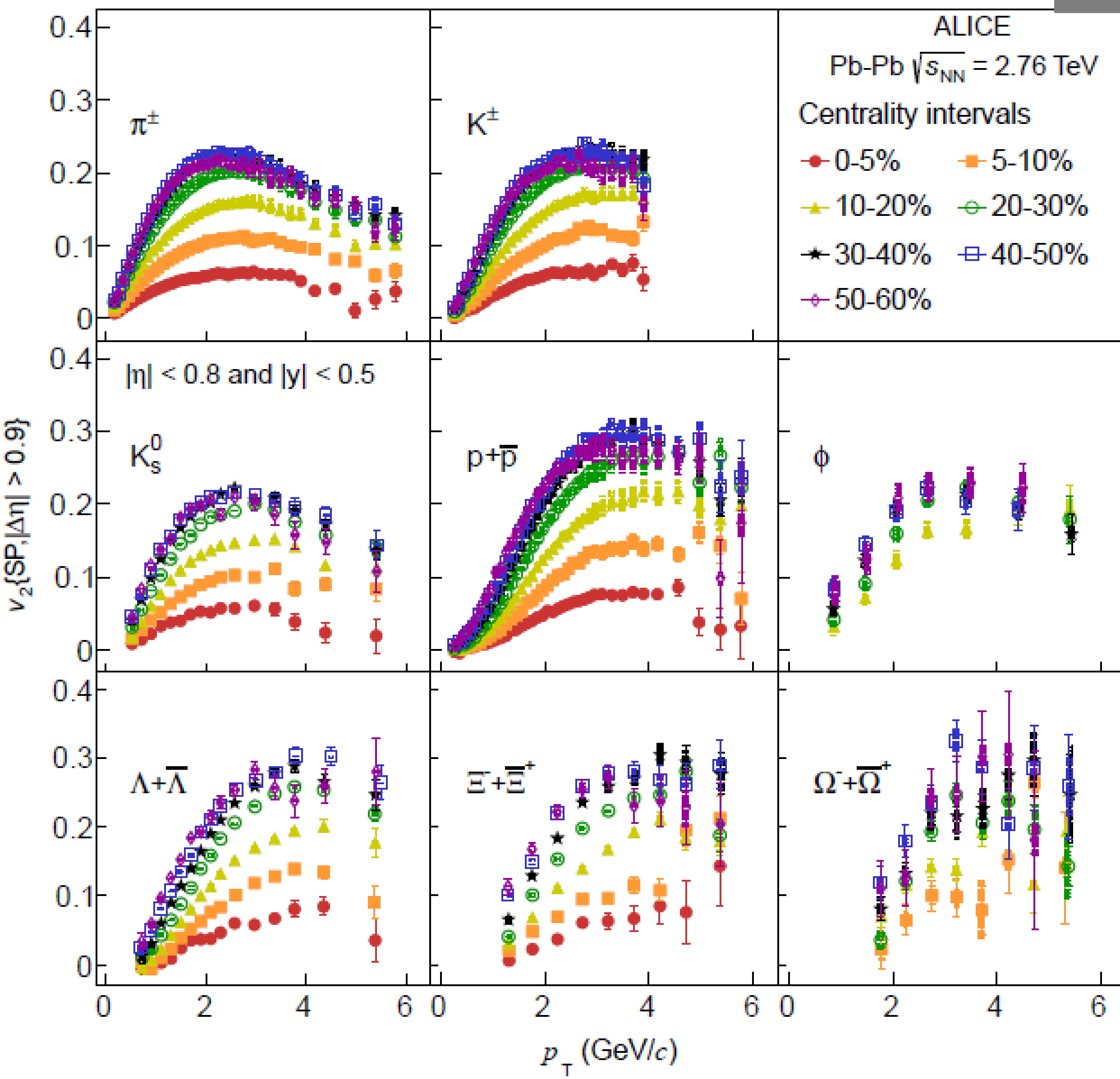


Immediately after the collision, ***pressure gradient*** *along* ***X*** *is larger than that along* ***Y****.*
As a consequence, ***the medium expands preferentially along the short axis of the ellipse,*** *creating a* ***flow.***

Strong coupling (liquid behaviour) is mandatory to develop such a flow: a perfect gas would not develop any flow.

Elliptic flow: exp. data

arXiv:1405.4632

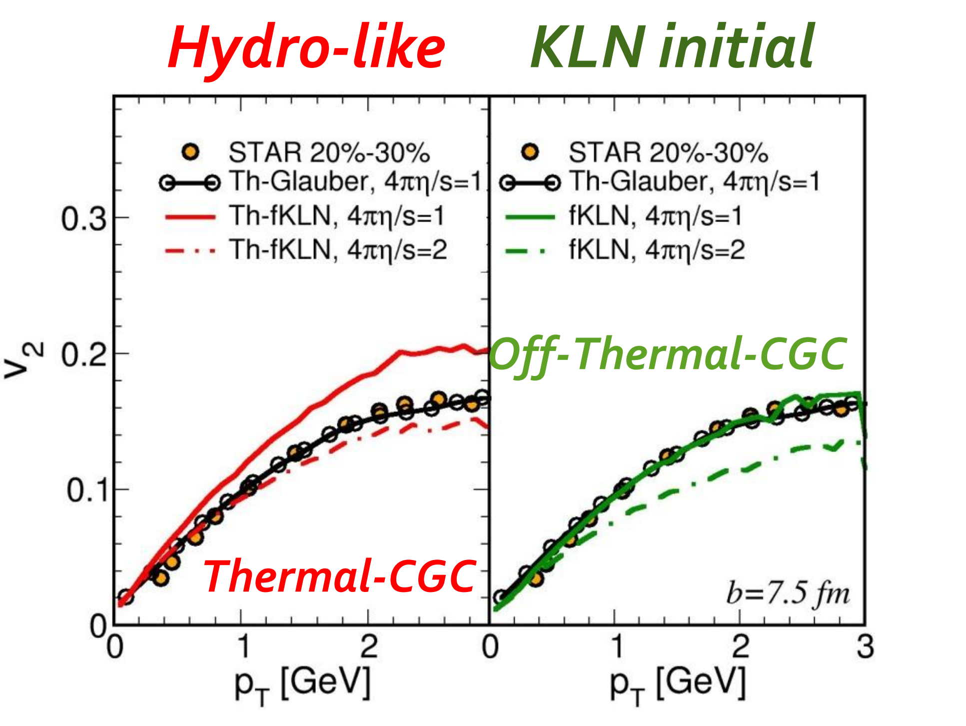


CERN-PH-EP-2014-104
May 20, 2014

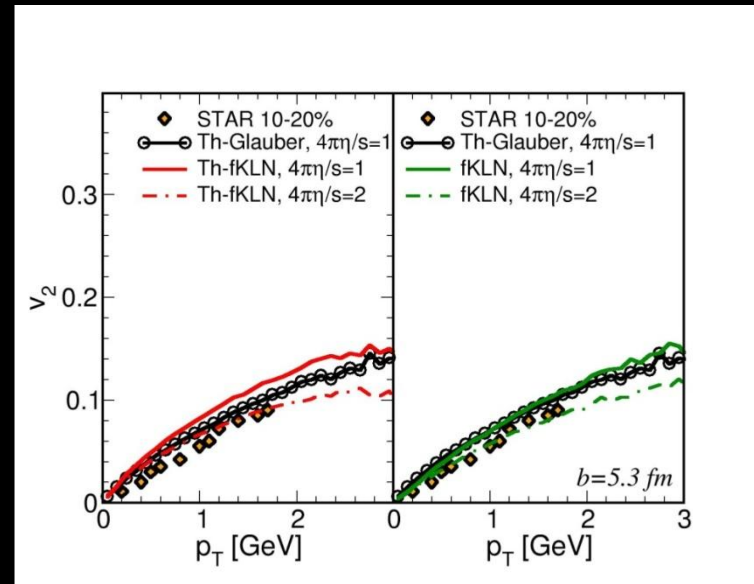
M. R. *et al.*, PLB727 (2013)
M. R. *et al.*, PRC 89 (2014)

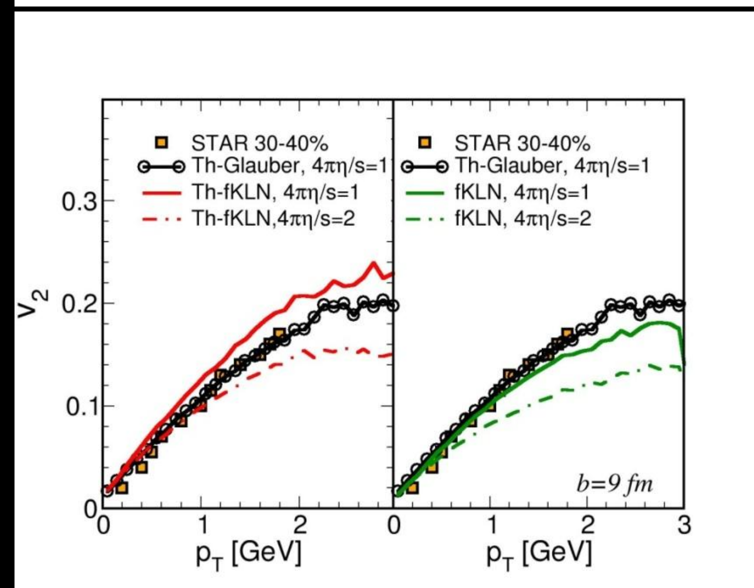
Elliptic flow from Transport

Au-Au collision
RHIC energy



Larger eccentricity of KLN implies larger v_2



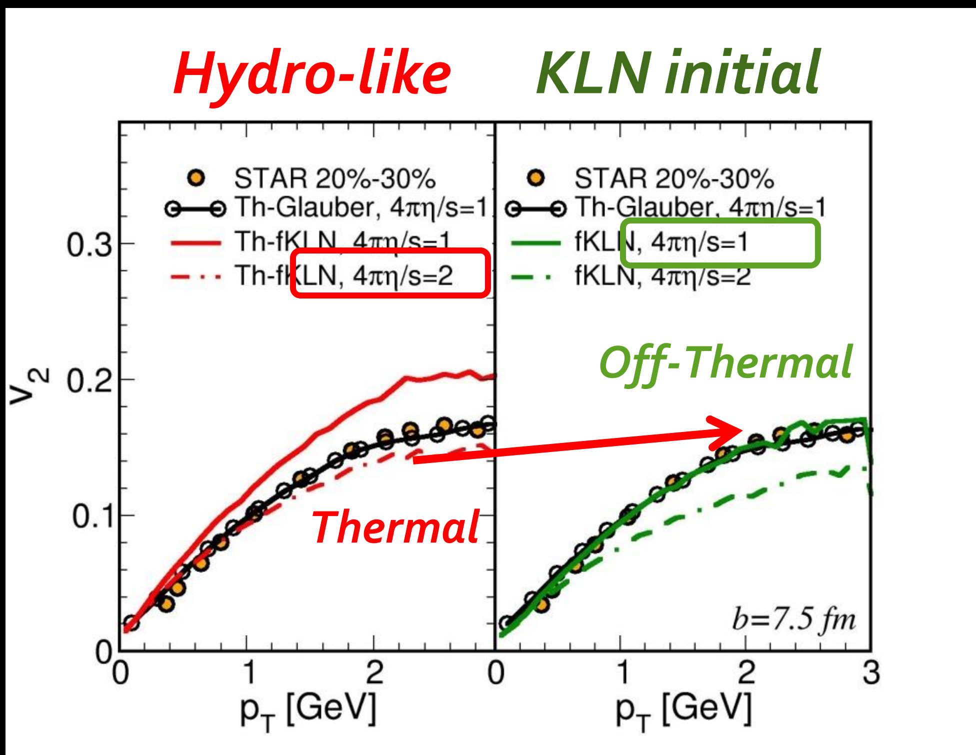


Results in fair agreement with hydro:
Song *et al.*, PRC83 (2011)

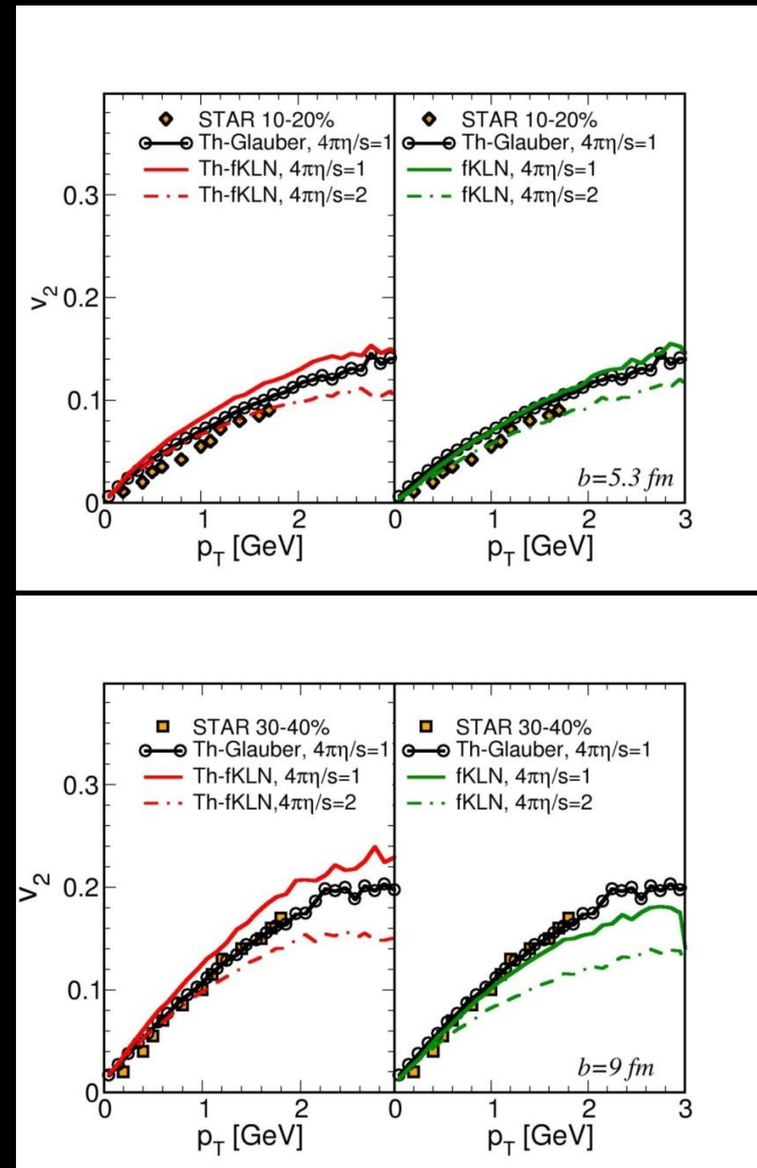
M. R. *et al.*, PLB727 (2013)
M. R. *et al.*, PRC 89 (2014)

Elliptic flow from Transport

Au-Au collision
RHIC energy



Larger eccentricity of KLN implies larger v_2

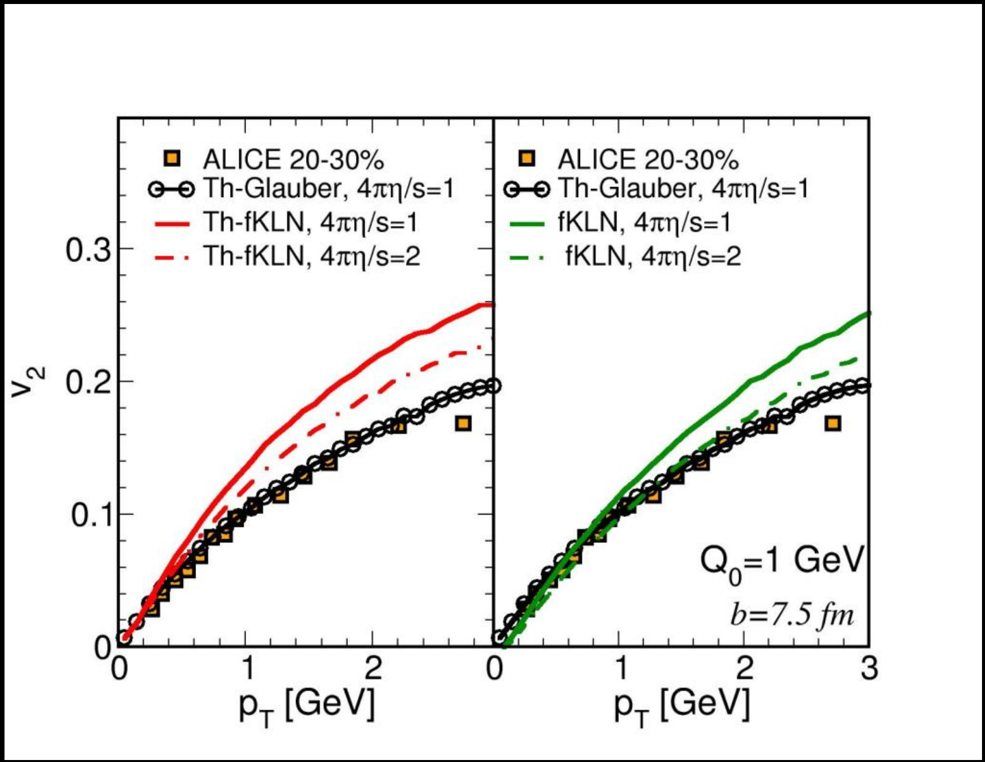


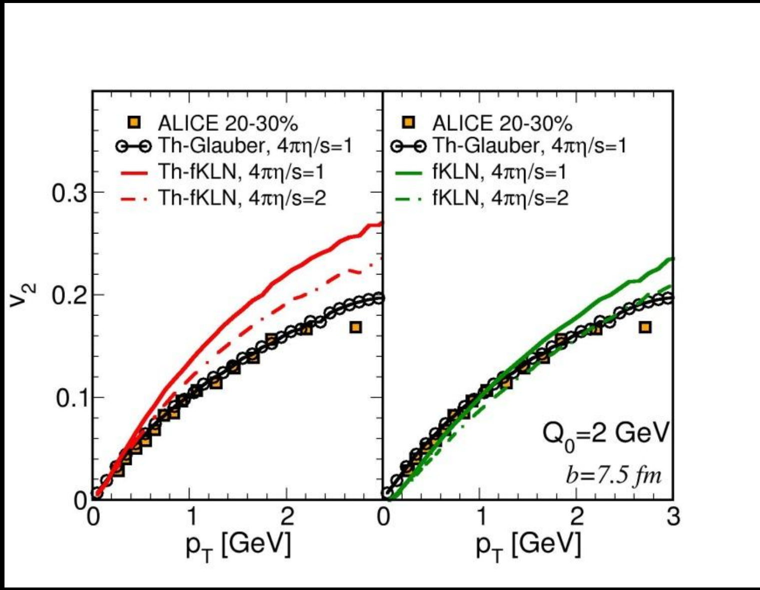
Results in fair agreement with hydro:
Song *et al.*, PRC83 (2011)

M. R. *et al.*, PRC 89 (2014)

Elliptic flow from Transport

Pb-Pb collision
LHC energy





Elliptic flow computations show this quantity is ***very sensitive*** *to the* ***initial conditions:***

.) Initial anisotropy (eccentricity)

.) Initial momentum distribution

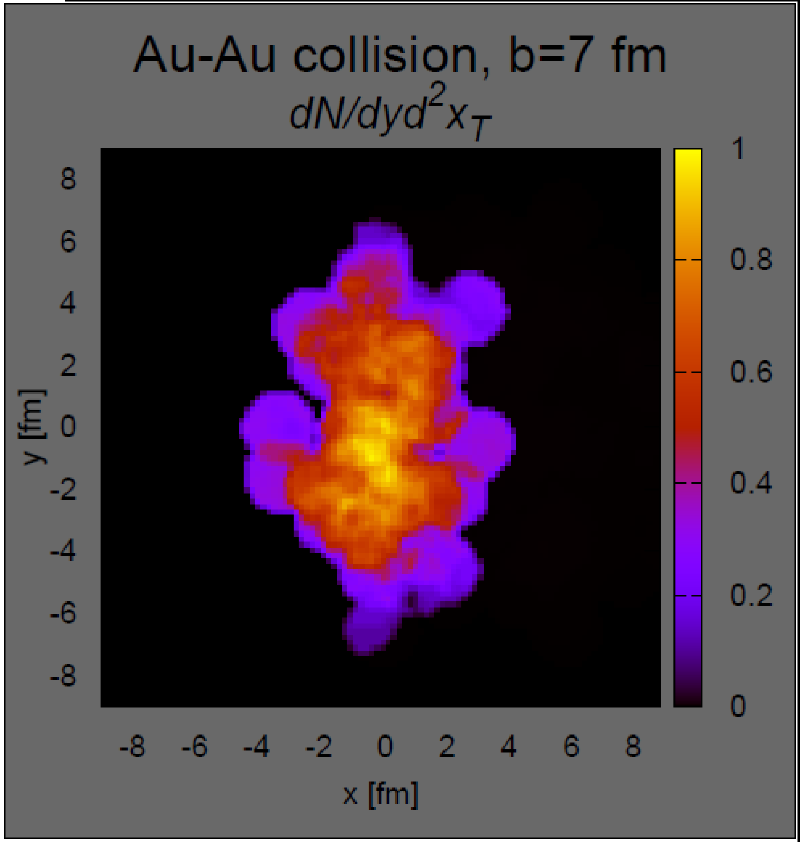
Measurements of elliptic flow in experiments might permit to identify the best theoretical initial conditions.

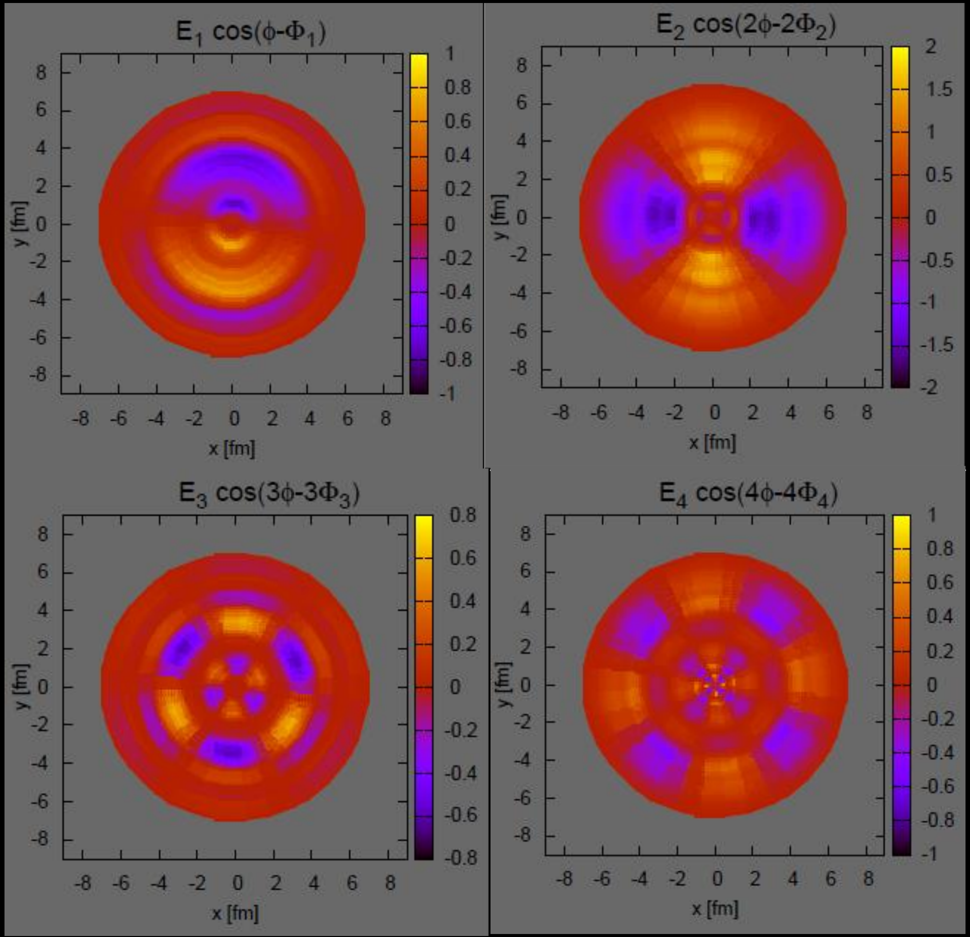
M. R. *et al.*, in preparation

Triangular flow from Transport

Initial state anisotropy parametrization

$$\frac{dN}{x_\perp dx_\perp d\phi} = \frac{dN}{x_\perp dx_\perp}\left[1 + 2\sum_{n=1}^{\infty} E_n(x_\perp)\cos\left(n(\phi - \Psi_n)\right)\right]$$

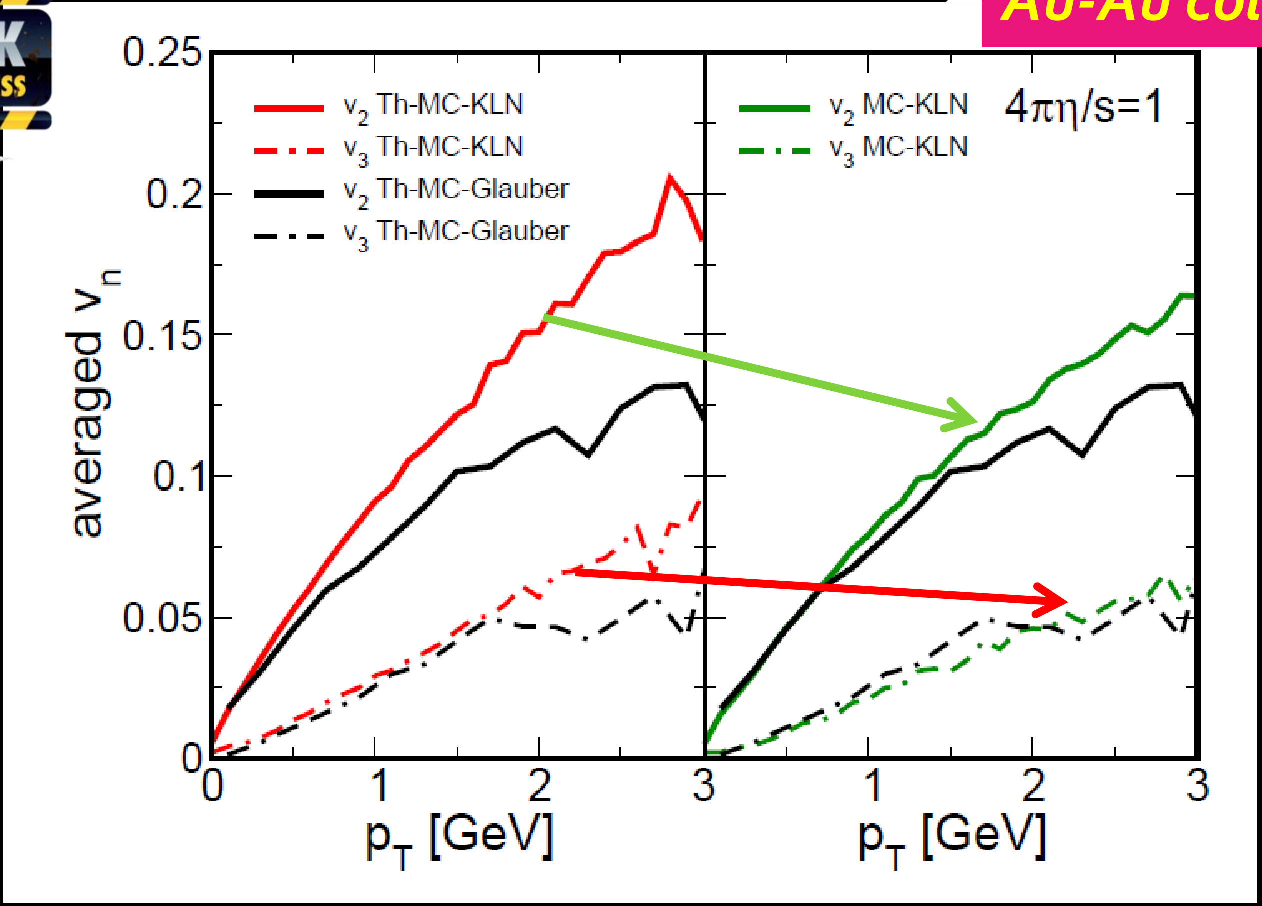




M. R. *et al.*, in preparation

Triangular flow from Transport

Au-Au collision



Elliptic and Triangular flows of MCKLN turns out to be in agreement with the MCGlauber ones, both with minimal viscosity.

Conclusions

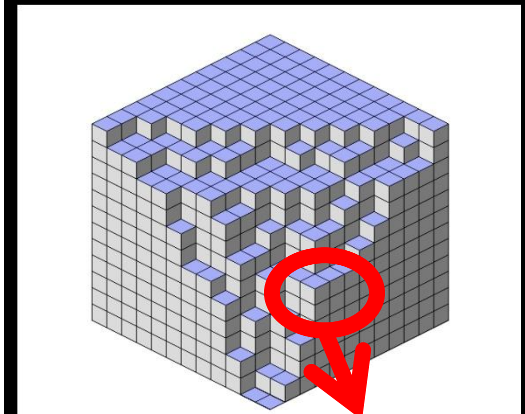
- ***Kinetic Theory*** permits to compute ***elliptic flow*** of plasma**,** as well as its ***thermalization times*** and ***isotropization efficiency***.
- ***Initial distribution in momentum space affects the flow and the building up of momentum anisotropy.***
- ***Elliptic and Triangular flows of MCKLN turns out to be in agreement with the one of MCGlauber, both with the same viscosity.***

Thanks for your attention

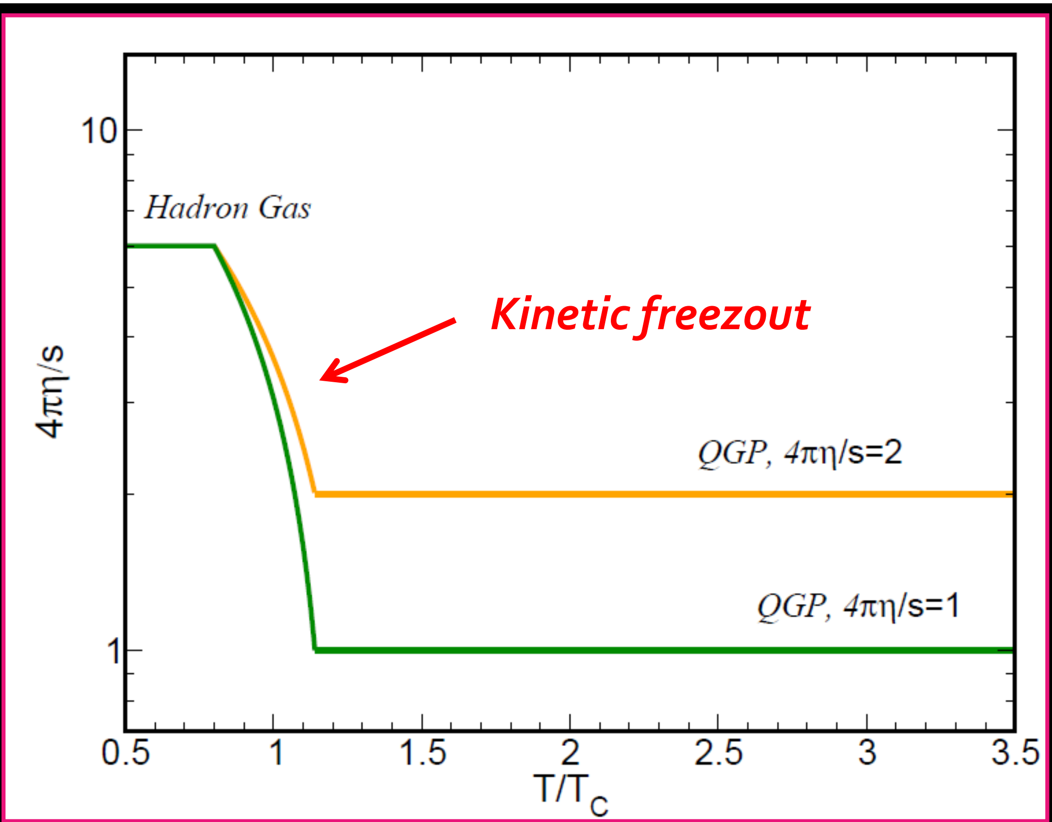
Good wood does not grow in comfort:
the stronger the wind, the stronger the tree is.

Transport *gauged* to hydro

We use ***Boltzmann equation*** to simulate a fluid at ***fixed eta/s*** rather than fixing a set of microscopic processes.
Total Cross section is ***computed*** in ***each configuration space cell*** according to ***Chapman-Enskog equation*** to give the ***wished value of eta/s***.



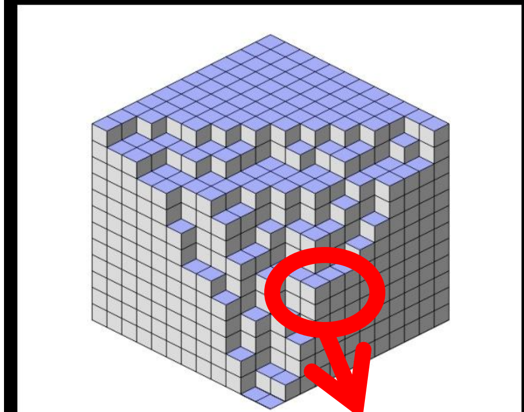
$$\boxed{\frac{\eta}{s} = \frac{\langle p \rangle}{g(m_D)\rho}\frac{1}{\sigma}}$$



A ***smooth kinetic freezout*** is implemented in order to gradually reduce the strength of the interactions as the temperature decreases below the critical temperature.

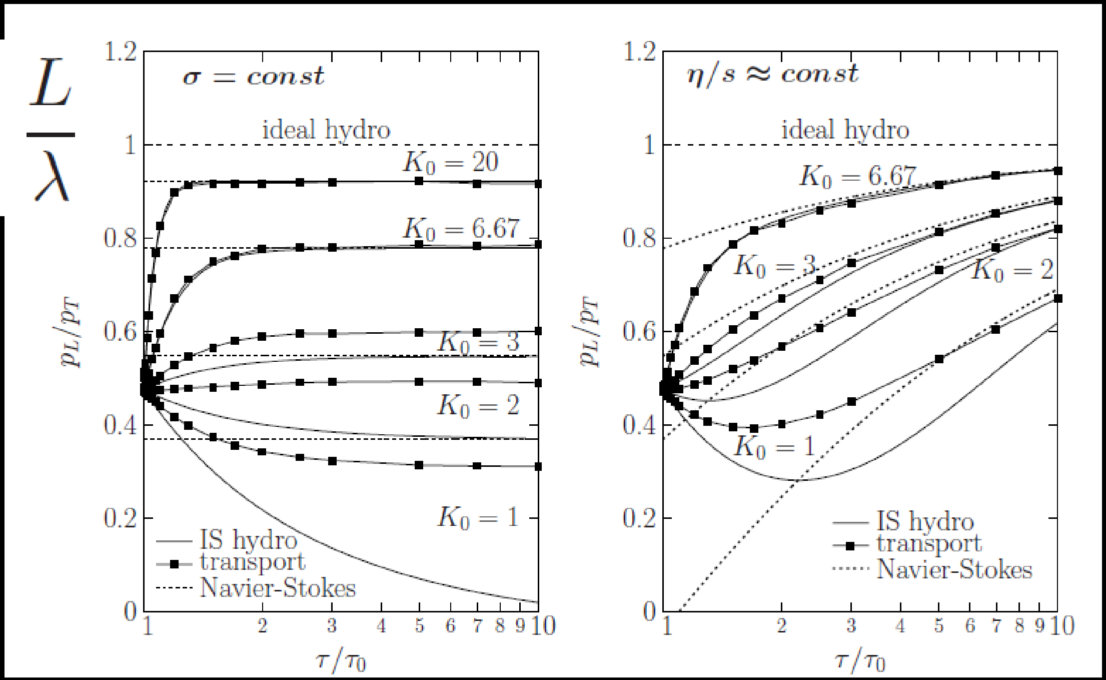
Transport *gauged* to hydro

We use ***Boltzmann equation*** to simulate a fluid at ***fixed eta/s*** rather than fixing a set of microscopic processes.
Total Cross section is ***computed*** in ***each configuration space cell*** according to ***Chapman-Enskog equation*** to give the ***wished value of eta/s***.



$$K_0 = \frac{L}{\lambda}$$

$$\frac{\eta}{s} = \frac{\langle p \rangle}{g(m_D)\rho}\frac{1}{\sigma}$$

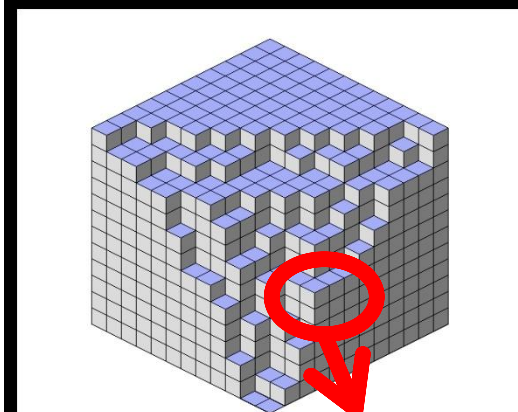


Huovinen and Molnar, PRC79 (2009)

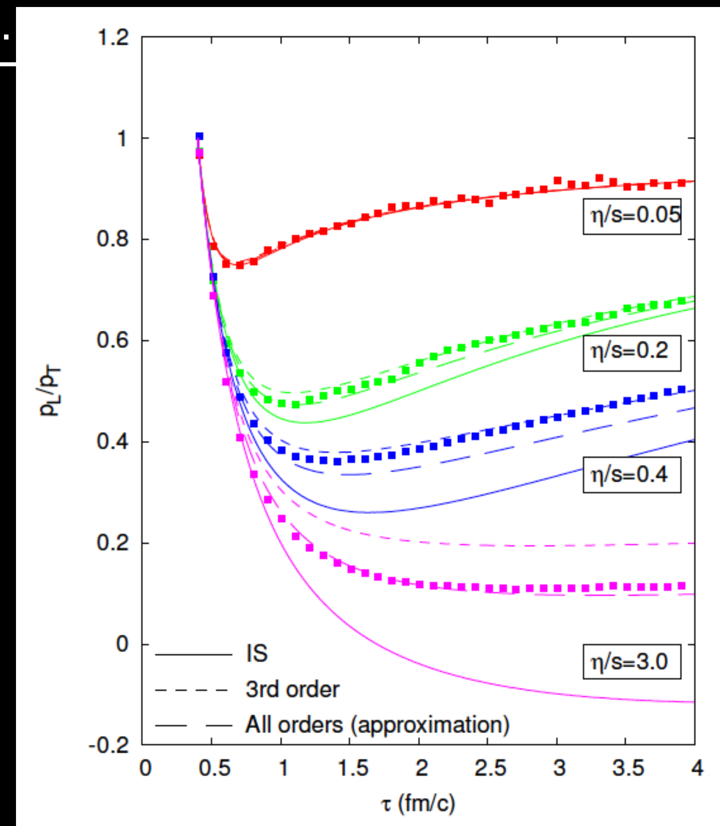
There is agreement of hydro with transport also in the non dilute limit

Transport *gauged* to hydro

We use ***Boltzmann equation*** to simulate a fluid at ***fixed eta/s*** rather than fixing a set of microscopic processes.
Total Cross section is ***computed*** in ***each configuration space cell*** according to ***Chapman-Enskog equation*** to give the ***wished value of eta/s***.



$$\boxed{\frac{\eta}{s} = \frac{\langle p \rangle}{g(m_D)\rho}\frac{1}{\sigma}}$$

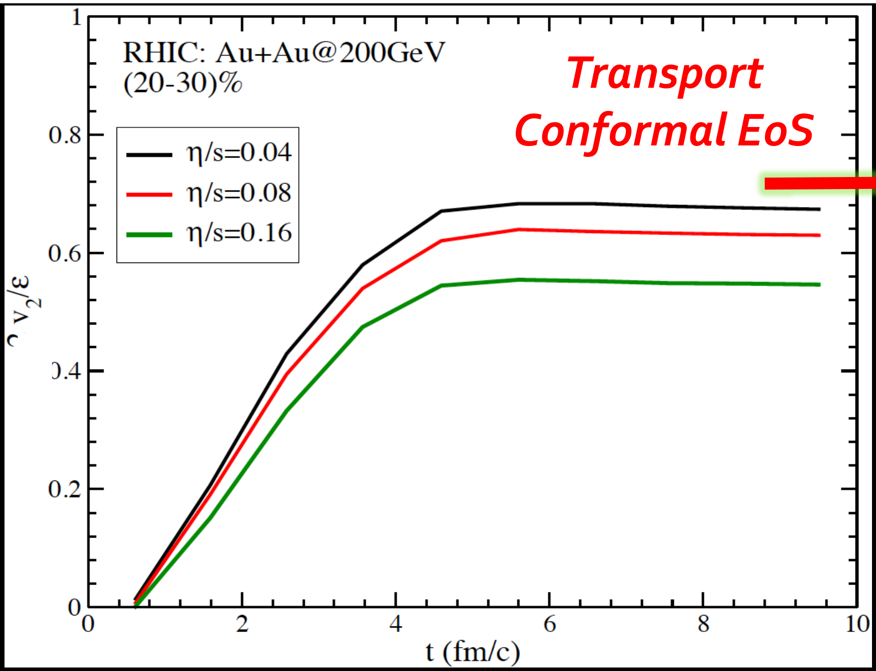


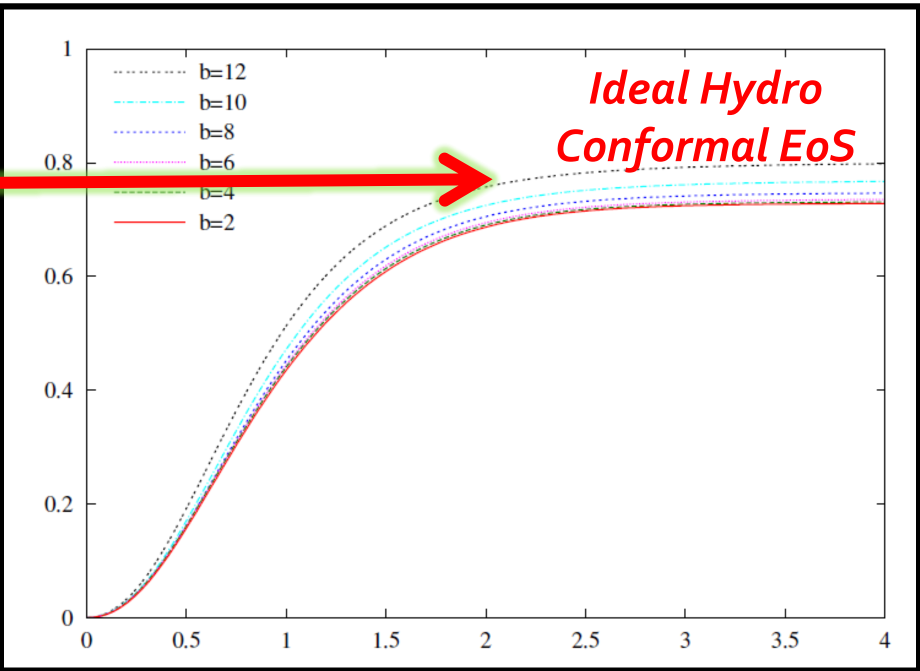
El, Xu, Greiner, Phys.Rev. C81 (2010) 041901

There is agreement of hydro with transport also in the non dilute limit

Transport *gauged* to hydro

We use ***Boltzmann equation*** to simulate a fluid at ***fixed eta/s*** rather than fixing a set of microscopic processes.
Total Cross section is ***computed*** in ***each configuration space cell*** according to ***Chapman-Enskog equation*** to give the ***wished value of eta/s***.





Bhalerao *et al.*, PLB627 (2005)

There is agreement of hydro with transport also in the non dilute limit

Few remarks on fKLN

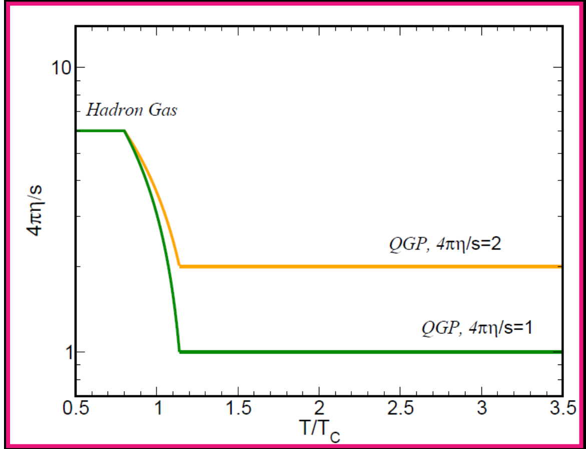
- fKLN is not glasma [Blaizot et al., NPA846 (2010)]
- We neglect initial field dynamics, which however ***should decay*** within $1/Q_s$
- It is not our purpose to insist on exact reproduction of experimental data [See instead IP-Glasma calculations, Gale *et al.*, PRL110 (2013)]

Rather, we want to solve another problem, namely compute the role of the initial nonequilibrium distribution in momentum space, often neglected in hydro and hybrid calculations

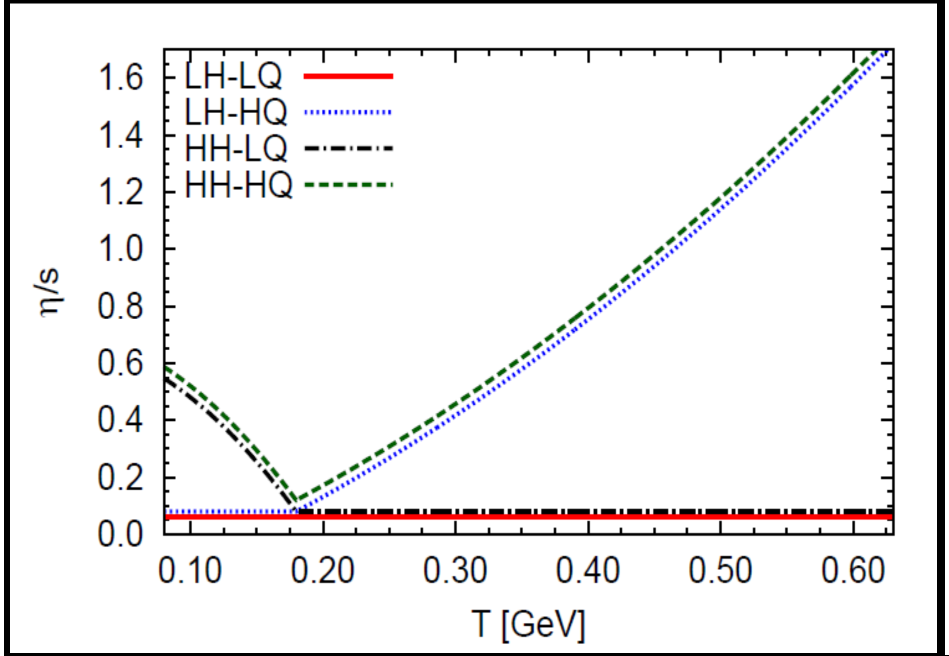
- Hydro widely uses KLN, and we are interested to compare the two approaches

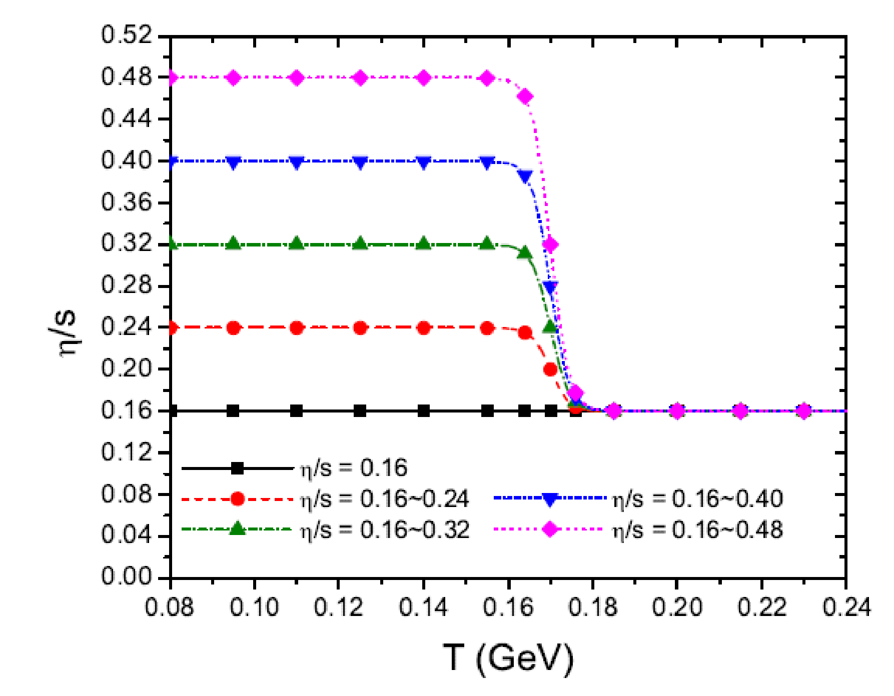
Viscometer: Schen et al., arXiv1308:2111
Thermometer: Schen et al., arXiv1308:2440
Flow computations: Hirano and Nara, PRC**79** (2009)
Hirano and Nara, NPA**743** (2004)

Various η/s used in hydro



Temperature dependence of eta/s already used in hydro simulations recently.

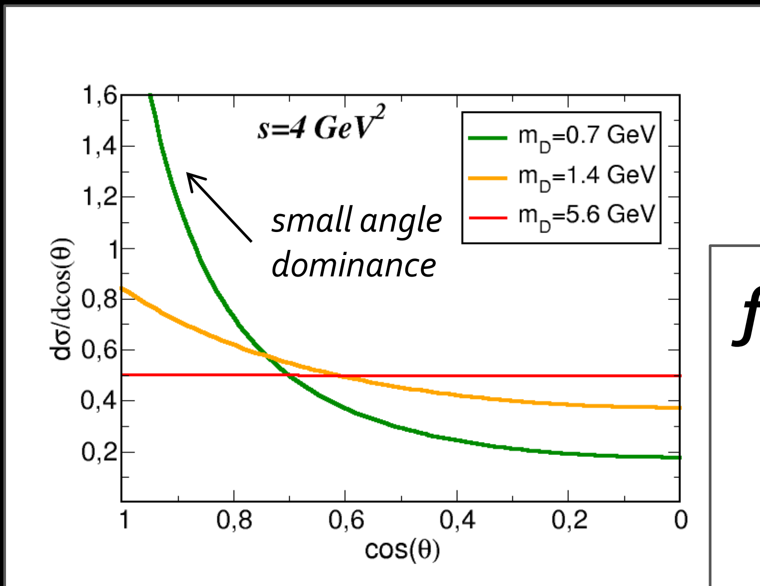




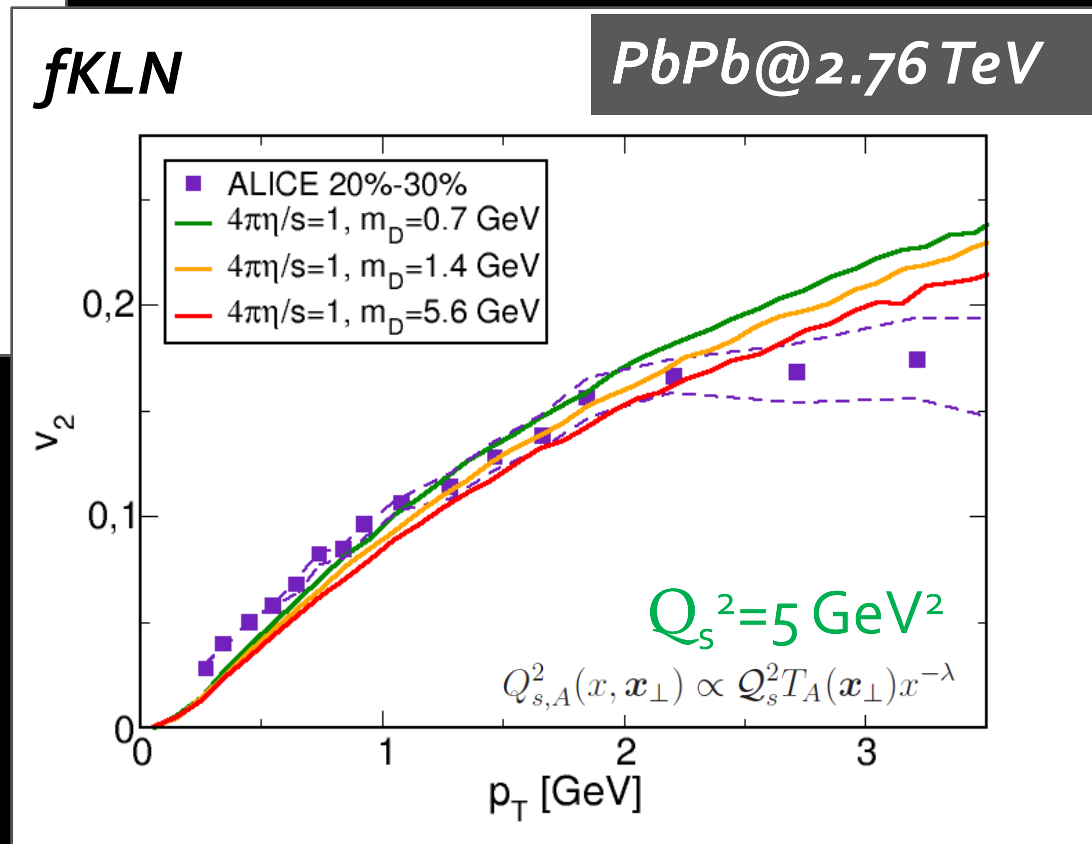
H. Niemi *et al.*, PRC86 (2012), PRL106 (2011)

Shen and Heinz, PRC83 (2011)

Are micro-details important?



$$\frac{d\sigma_{gg\to gg}}{dt} = \frac{9\pi^2\alpha_s^2}{2}\frac{1}{(t-m_D^2)^2}\left(1+\frac{m_D^2}{s}\right)$$



Same cross section used in:

Zhang *et al.*, PLB 455 (1999)

Molnar and Gyulassy, NPA 697 (2002)

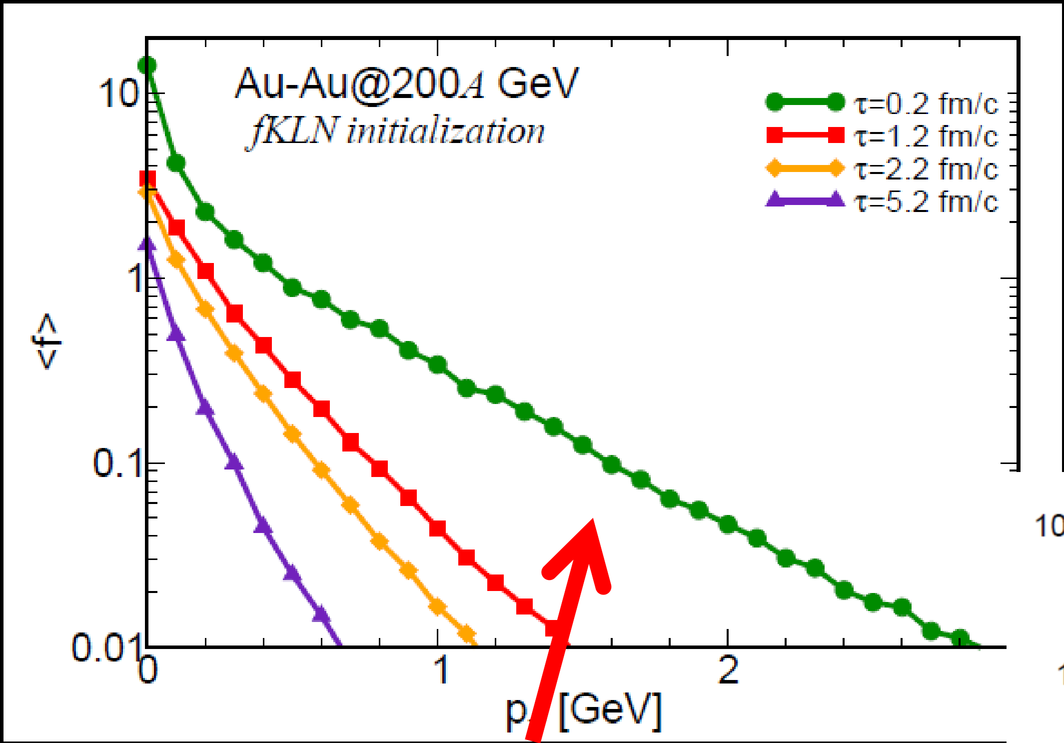
Greco et al., PLB 670 (2009)

Increasing m_D makes the cross section isotropic. However: ***Strong change of the cross section does not result in a strong change of the elliptic flow.***

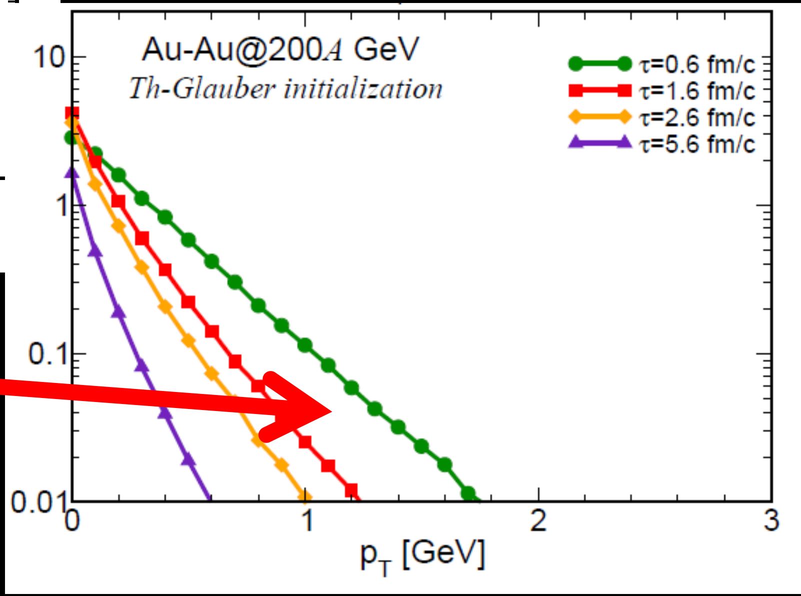
M. R. *et al.*, in preparation

M. R. *et al.*, in preparation
M. R. *et al.*, work in progress

Invariant distributions



$$f = \frac{(2\pi)^3}{g} \frac{\Delta N}{\Delta^2 x_\perp \Delta^2 p_T} \frac{1}{\Delta z \Delta p_z}$$



Longitudinal and transverse expansions help to dilute the system, lowering the invariant distribution functions

1+f factors in the collision integral, arising from the bosonic nature of gluons, should not modify in a substantial way our results on elliptic flow

Preliminary result: no change due to 1+f (at RHIC energy).

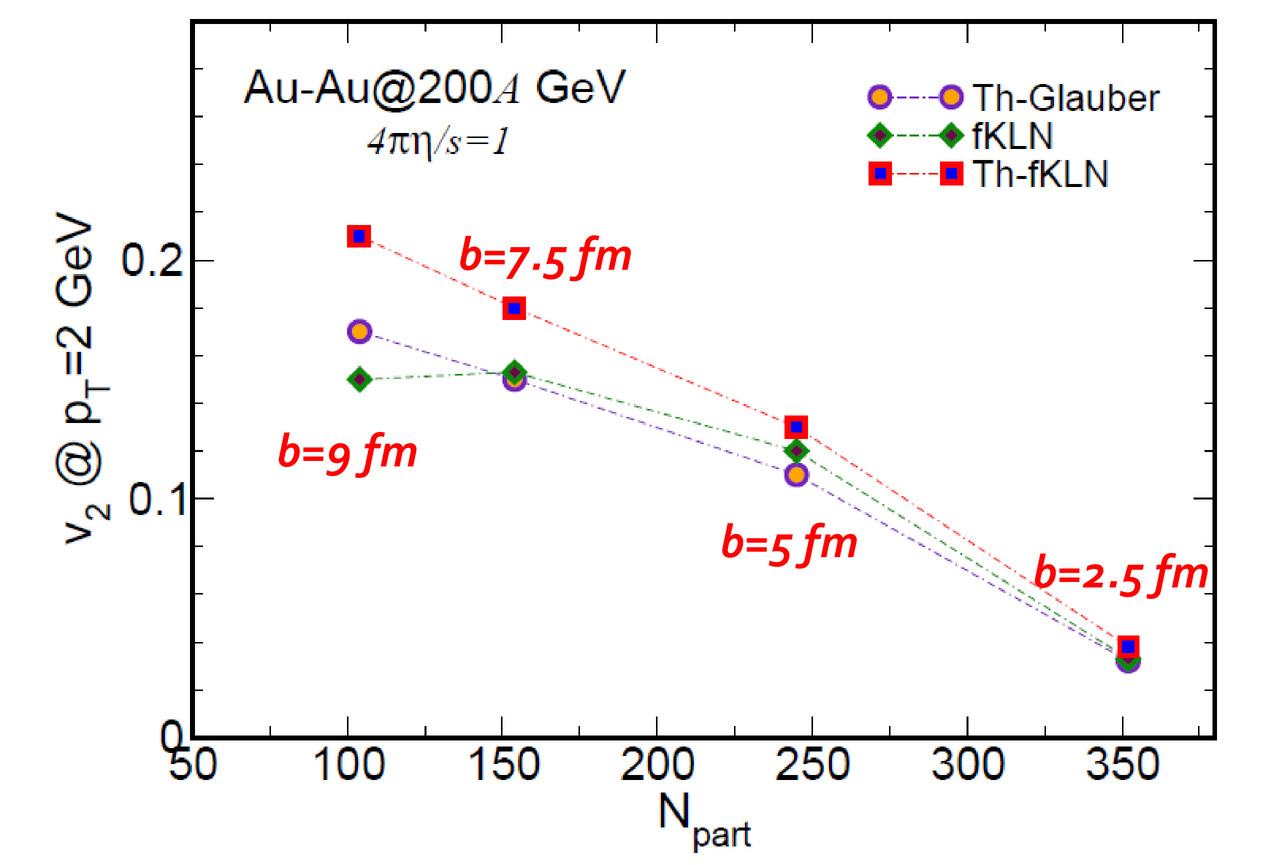
M. R. *et al.*, in preparation

Elliptic flow from Transport

Au-Au collision

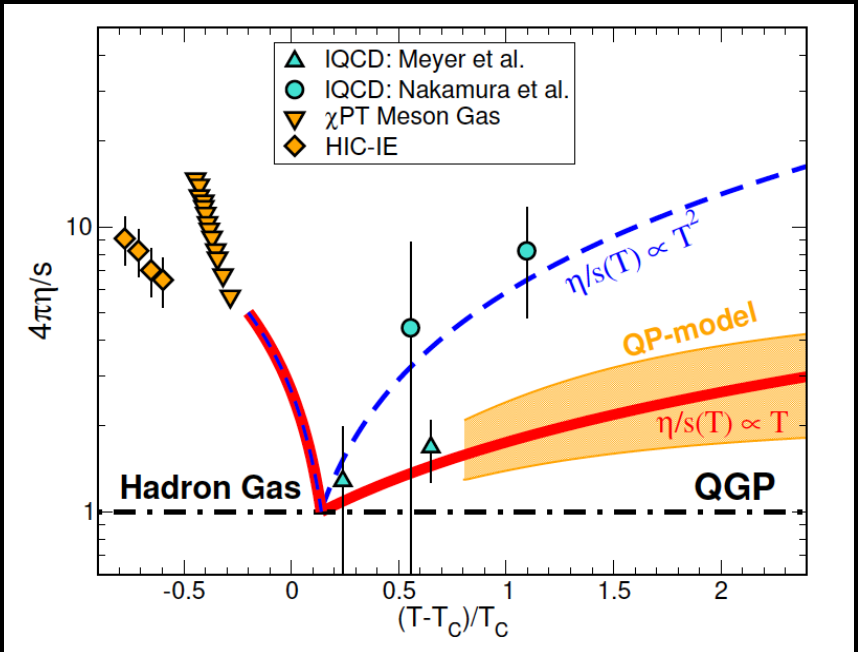
RHIC energy

Summary of the effect on differential v_2

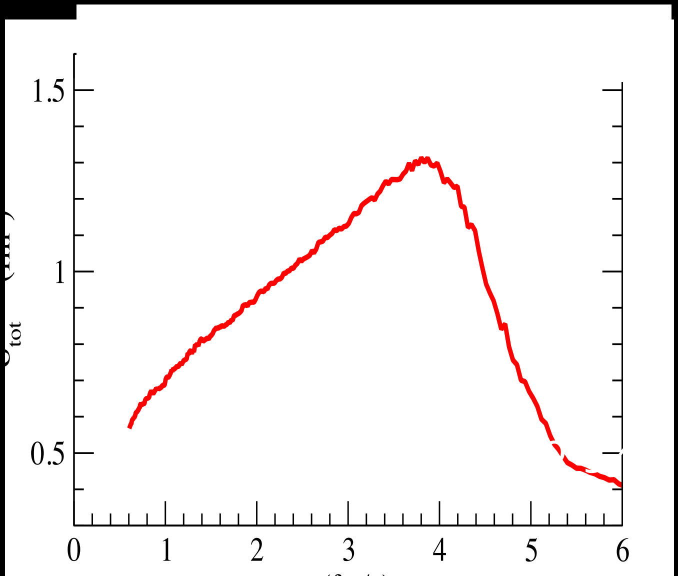


For more central collisions the effect on v2 becomes milder.

Cross section and freeze-out



- ✓ η/s increases in the cross-over region, realizing a smooth f.o. self-consistently dependent on h/s:
- ✓ Different from hydro that is a sudden cut of expansion at some $T_{f.o.}$



$$\sigma^* = g(a)\sigma_{tot} \approx \frac{1}{15}\frac{\bar{p}}{\rho}\frac{1}{\eta/s}$$

$\rho(\tau_o)$=23 fm^{-3}, η/s=0.08 → σ_{ToT}= 6 mb

$$\sigma_{pQCD} = \frac{9\pi\alpha_s^2}{m_D^2}, \quad \alpha_s = \frac{4\pi}{11\,ln\left(\frac{2\pi T}{\Lambda}\right)}, \quad m_D^2 = 4\pi\alpha_s(T)T$$

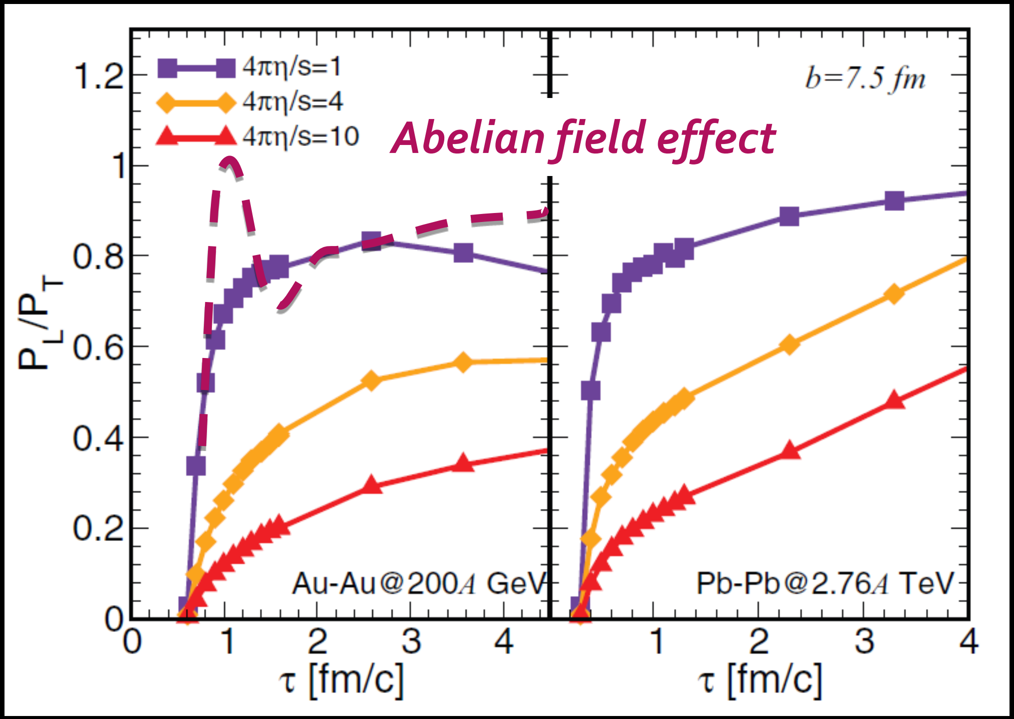
T_o=340 MeV → σ_{pQCD}= 3.6 mb

M. R. *et al.*, PRC 89 (2014)

Pressure isotropization

$$T^{\mu\nu} = \int \frac{d^3p}{(2\pi)^3} \frac{p^\mu p^\nu}{E} f(x,p)$$

$$P_T = \frac{1}{V}\int_\Omega d^2x_\perp d\eta \, \frac{T_{xx}+T_{yy}}{2} \; ,$$
$$P_L = \frac{1}{V}\int_\Omega d^2x_\perp d\eta \, T_{zz} \; ,$$

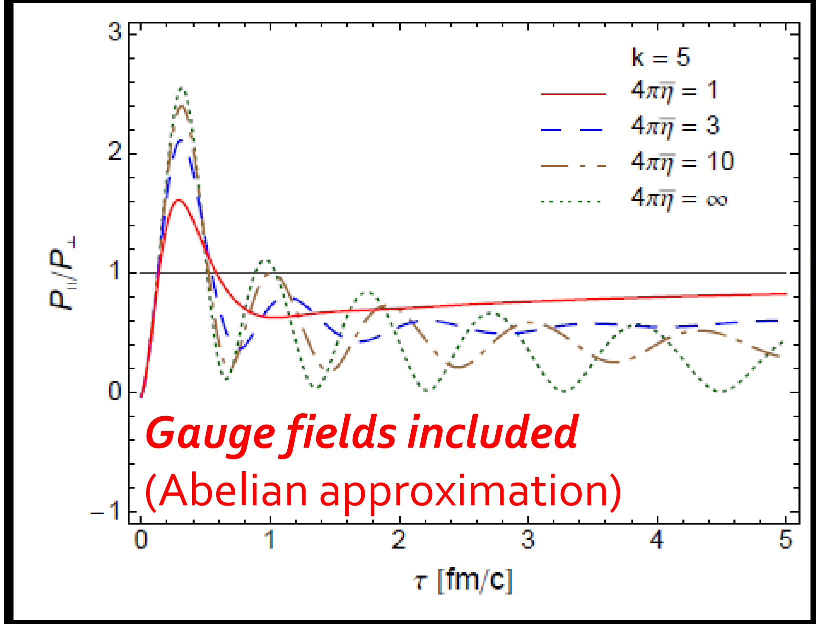


- For η/s > 0.3 one misses fast isotropization in P_L/P_T (τ about 2-3 fm/c)
- For η/s ≈ pQCD no isotropization
- Semi-quantitative agreement with Florkowski *et al.*, PRD88 (2013) 034028

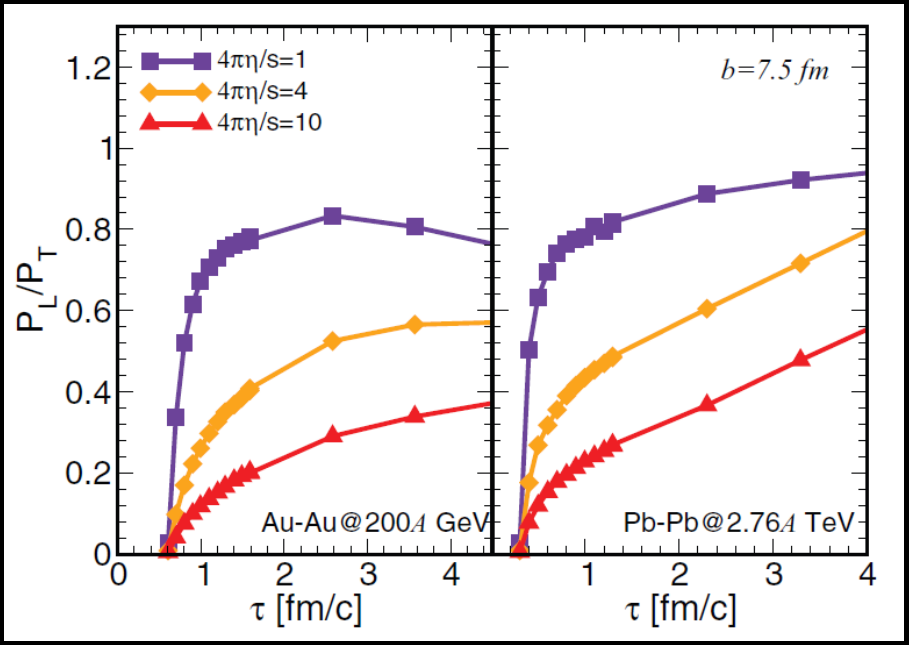
  ours is ***3+1D*** and ***full collision integral***; however ***no gauge fields***

Comparisons

Ryblewski and Florkowski, PRD88 (2013)

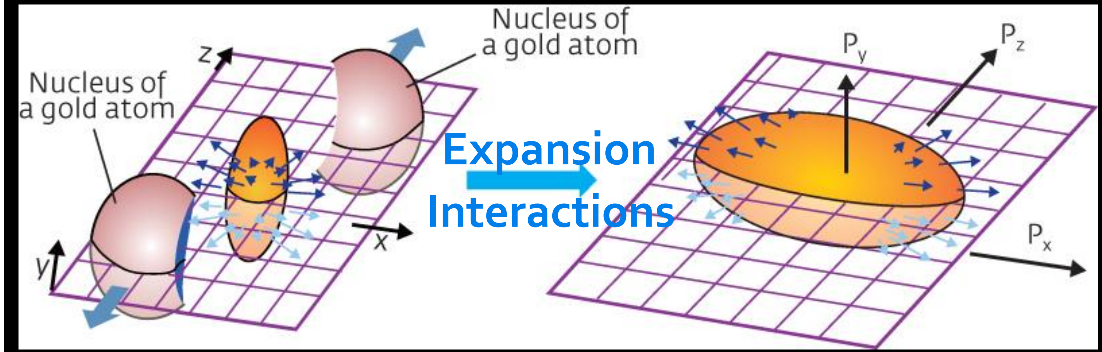


M. R. *et al.*, PRC 89 (2014)

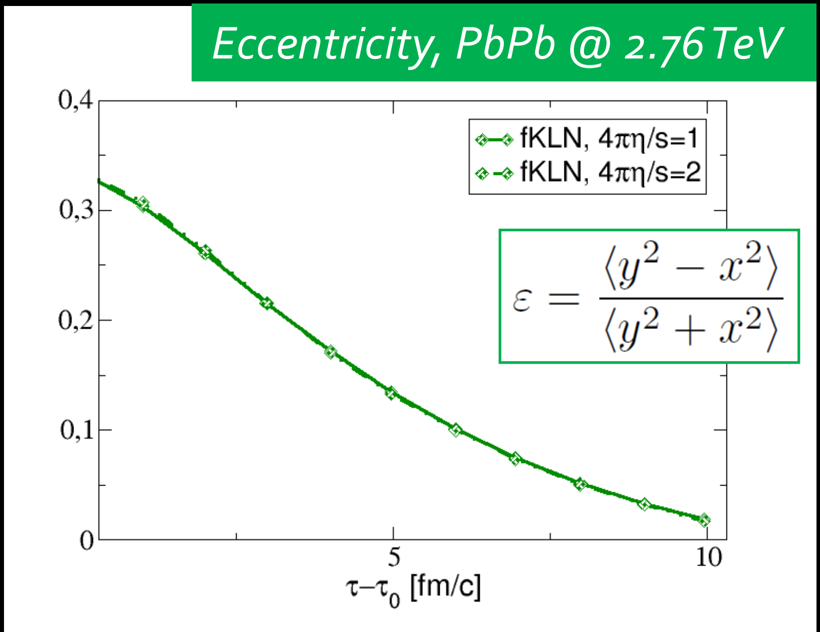


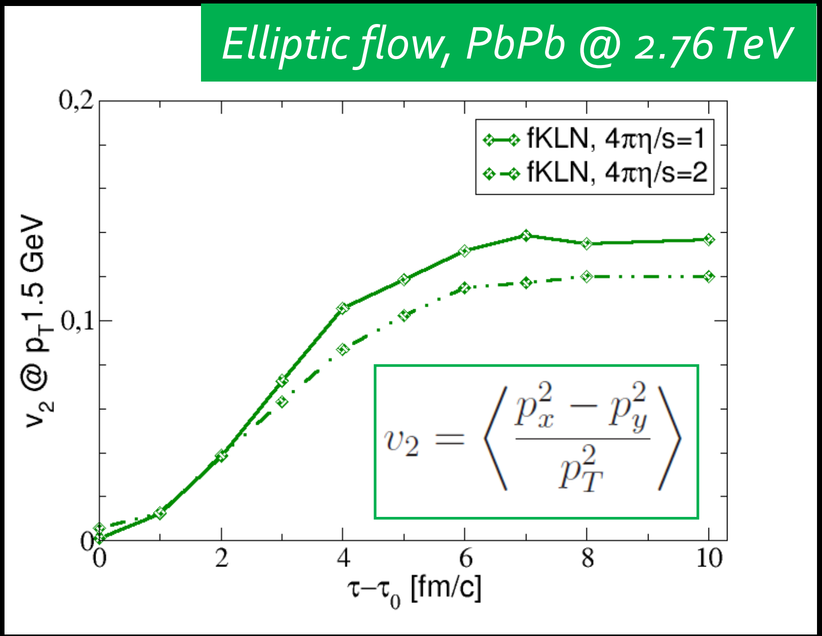
M. R. *et al.*, PLB727 (2013)
M. R. *et al.*, PRC 89 (2014)

Elliptic flow in RHICs



v2 measures how efficiently the <u>anisotropy of configuration in the initial state</u> is transmitted to <u>momenta in final states</u>.





Theoretical computation of elliptic flow depends on viscosity.
Comparison with experimental data leads to estimate of the viscosity of the QGP.