


Dr. Marco Ruggieri
Dipartimento di Fisica e Astronomia, Università degli Studi di Catania, Catania (Sicily)

Elliptic Flow and Shear Viscosity of Color Glass Condensate

Mainly based on collaboration with:
F. Scardina, S. Plumari and V. Greco

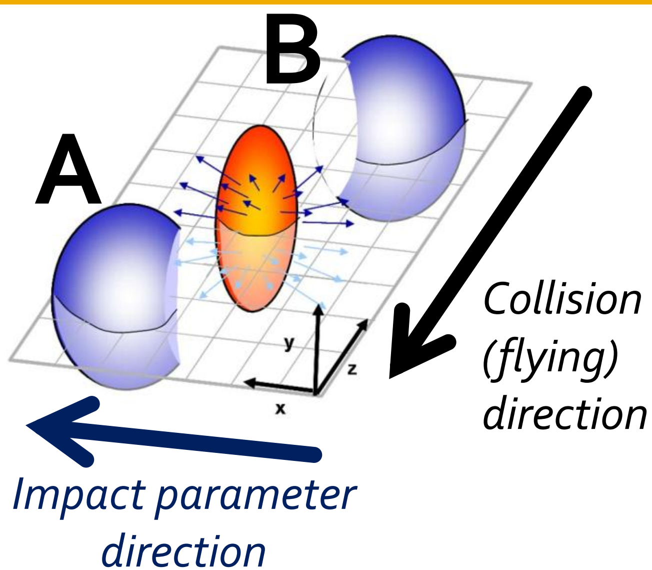
St Goar, 2013 March 19

Plan of the talk

- Elliptic flow in heavy ion collisions (HICs)
- Initial conditions: Glauber and Color Glass Condensate (CGC)
- *Elliptic flow and viscosity of CGC*
- Conclusions and Outlook

Elliptic flow in HICs, 1

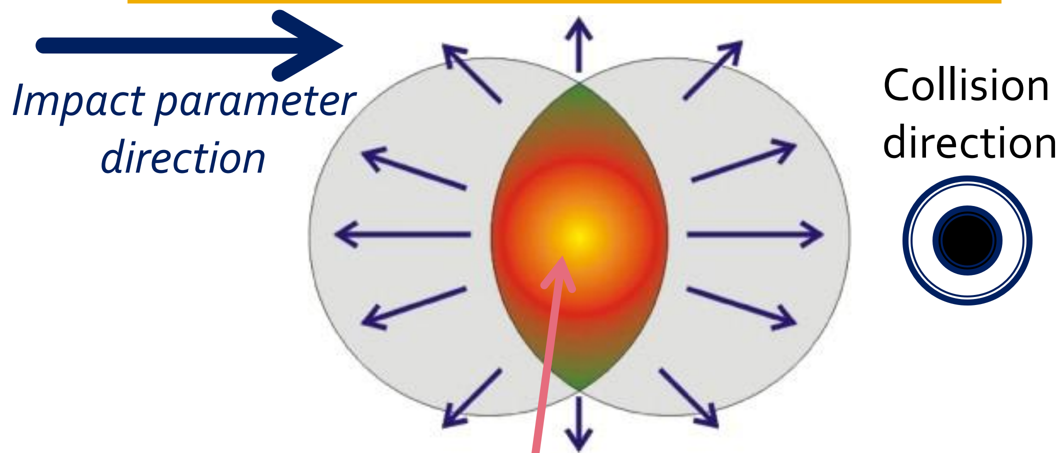
3D view of Heavy Ion Collision (HIC)



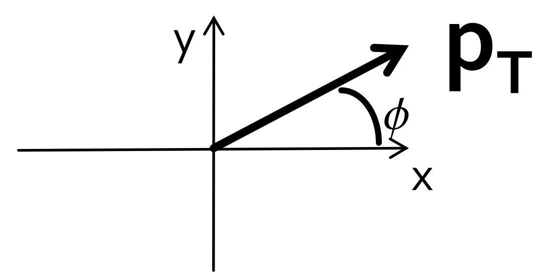
A,B: Cu, Au (RHIC)
Pb (LHC).

$$\sqrt{s}\ \text{up to}\ 200 \times A\ \text{GeV}\ , \qquad \text{RHIC}$$
$$\sqrt{s}\ \text{up to}\ 2.76 \times A\ \text{TeV}\ , \qquad \text{LHC}$$

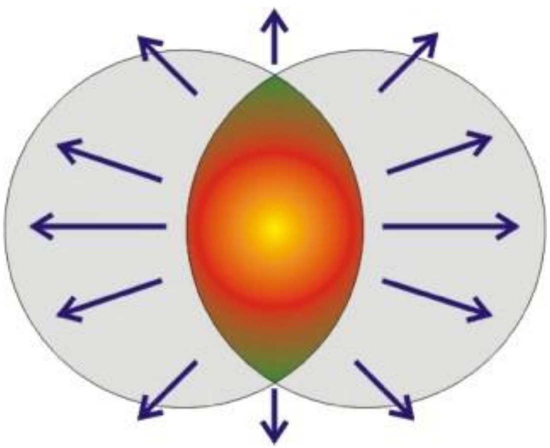
Projection of HIC on the transverse plane

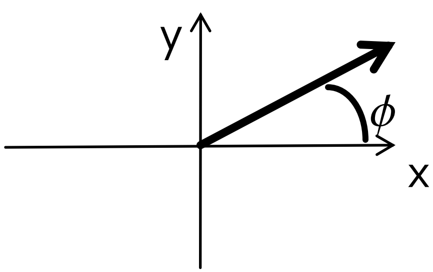


FIREBALL:
Hot and dense expanding parton mixture
QUARK-GLUON-PLASMA (QGP)



Elliptic flow in HICs, 1





Particle multiplicity

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

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

N.B.: STAR, PHENIX and ALICE collaborations report nonvanishing measured ***odd flows***, which are however due to *initial state fluctuations* which we neglect, see e.g.

G. Eyyubova, Acta Phys. Pol. B Proceedings Supplement 5 (2012)

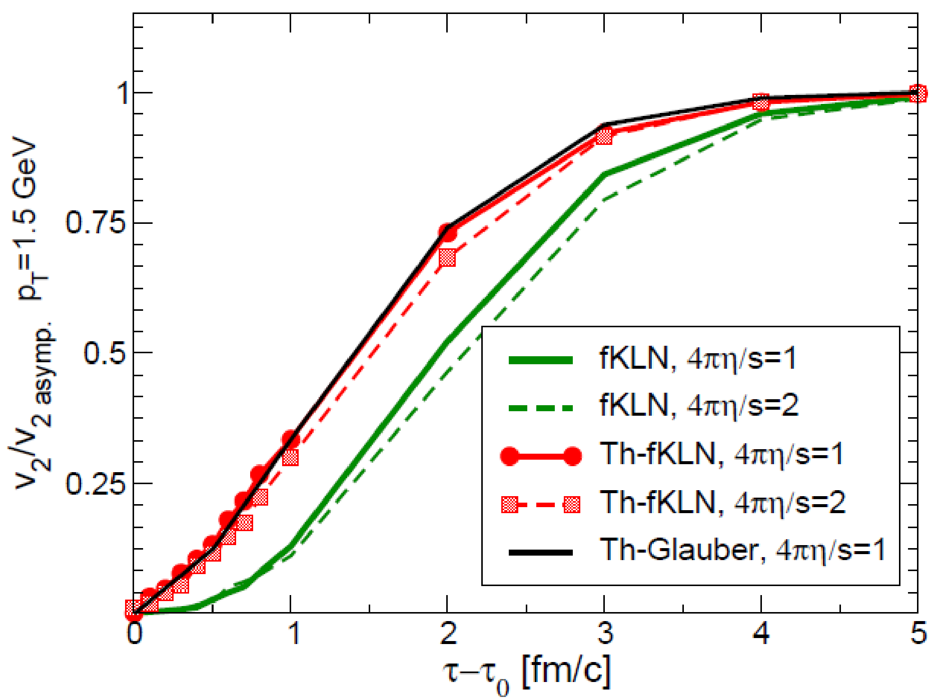
W. Cassing et al., 1202.3272 [nucl-th]

Thanks to Dr. Nan Su for pointing me out few details about this slide.

Elliptic flow in HICs, 1

Elliptic flow is mostly generated early in the nucleus-nucleus collision, and is present at the ***partonic level*** before partons hadronize.

Generation of elliptic flow (simulation)



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

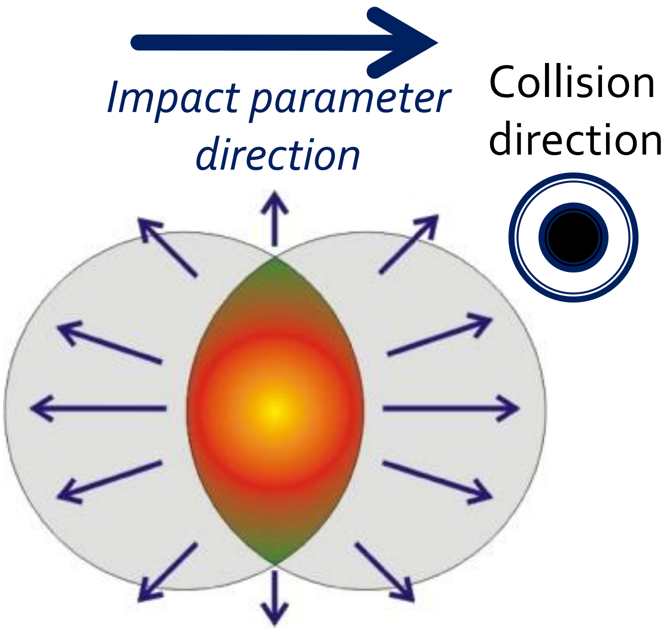
Elliptic flow acts as a **messenger**:
it brings us the properties of the hot and dense state of partonic matter created after the collision.

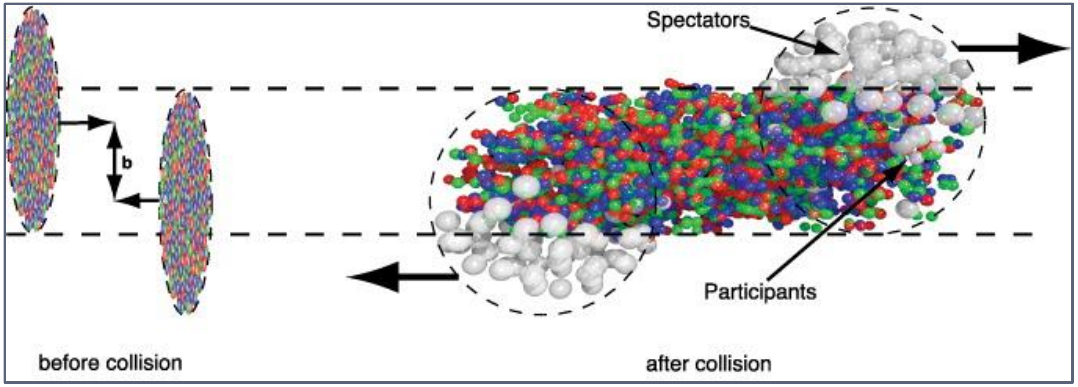
Scenario in agreement with several independent computations, e.g.:

Csernai *et al.*, PRL **97**, 152303 (2006)
Molnar *et al.*, PRL **91**, 092301 (2003)
Greco *et al.*, PRC **68**, 034904 (2003)
Fries *et al.*, PRC **68**, 044902 (2003)
Peschanski and Saridakis, PRC **80** (2009)

Initial condition: Glauber (briefly)

Geometrical description of the fireball:





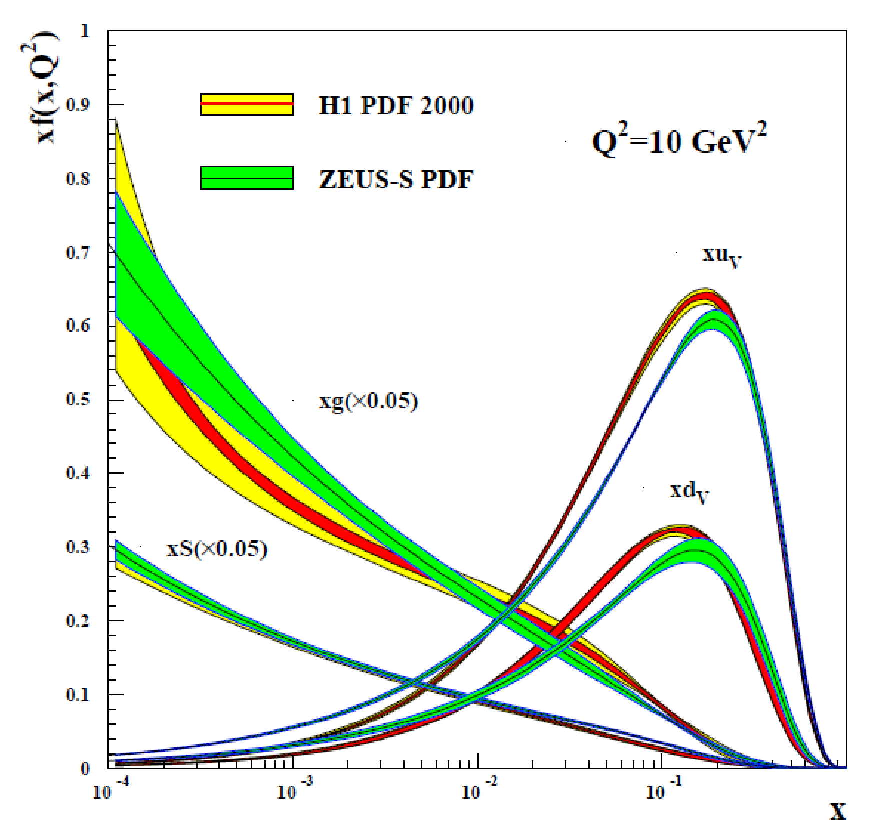
Assuming a nucleon distribution in the parents nuclei (typically a Woods-Saxon), one counts how many particles from each nucleus are present in the overlap region; among them, the ***participants*** are the nucleons that effectively can have an interaction
(in fact, the particles that *are in the overlap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

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

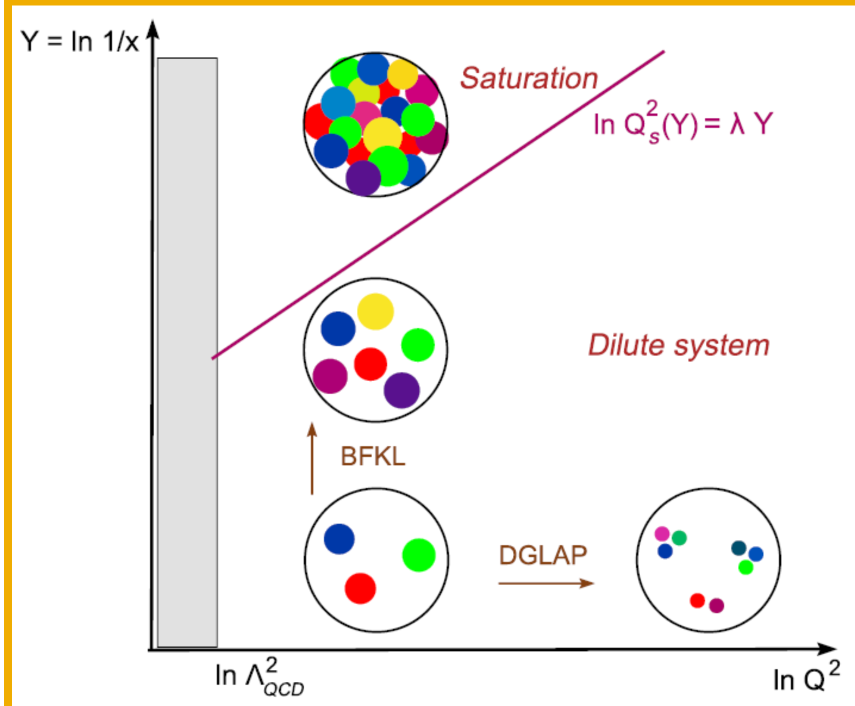
Iancu, **Nucl.Phys.Proc.Suppl. 191 (2009) 281-294**

Gluon saturation

Parton distribution functions



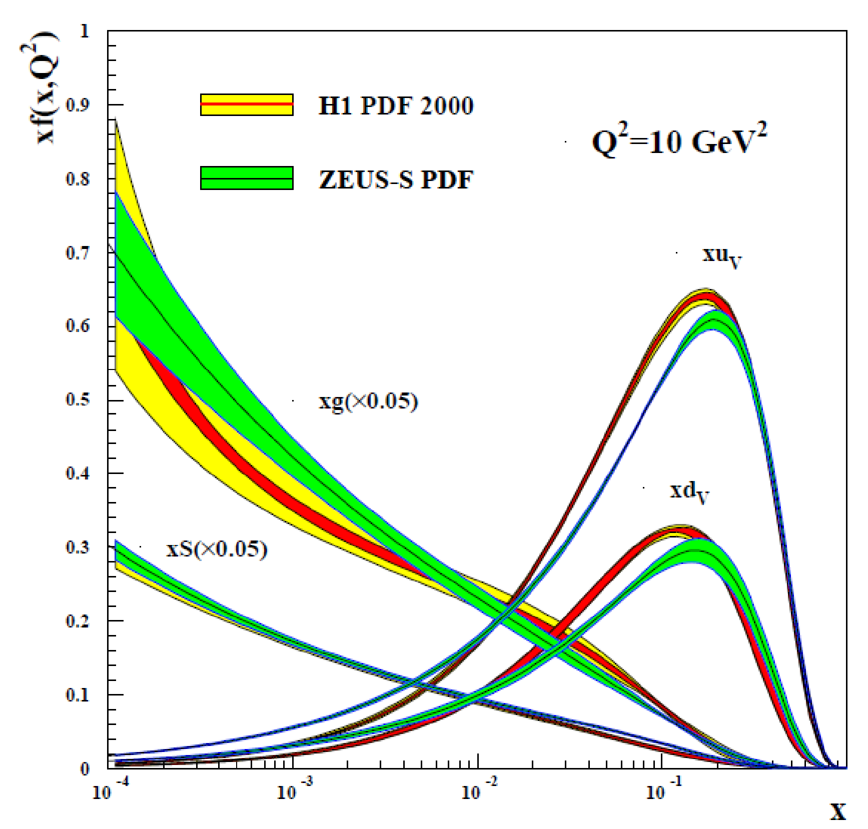
Phase Diagram



Iancu, **Nucl.Phys.Proc.Suppl. 191 (2009) 281-294**

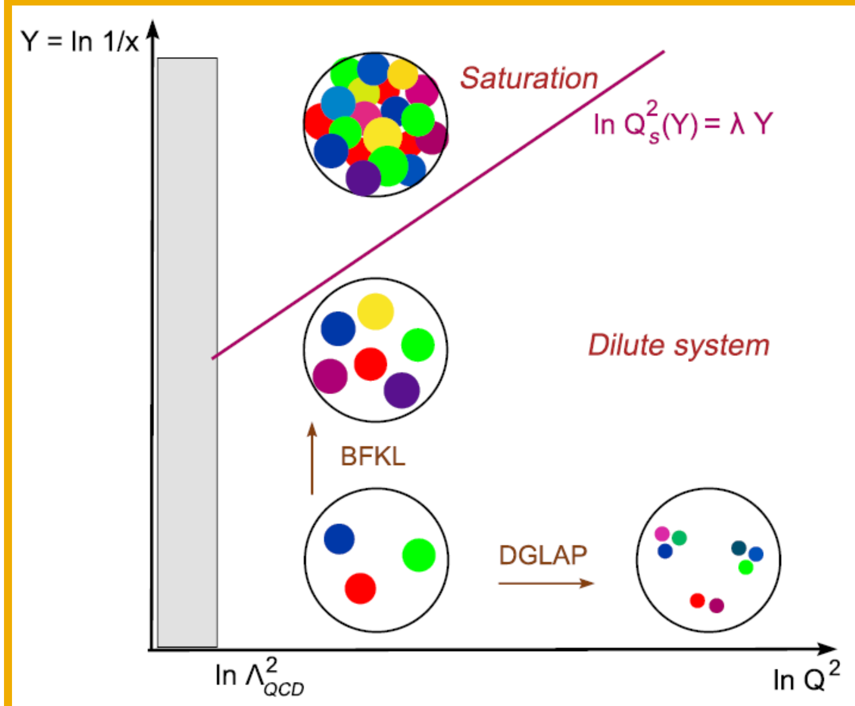
Gluon saturation

Parton distribution functions



Direction of decreasing transverse partons area ($1/Q^2$)

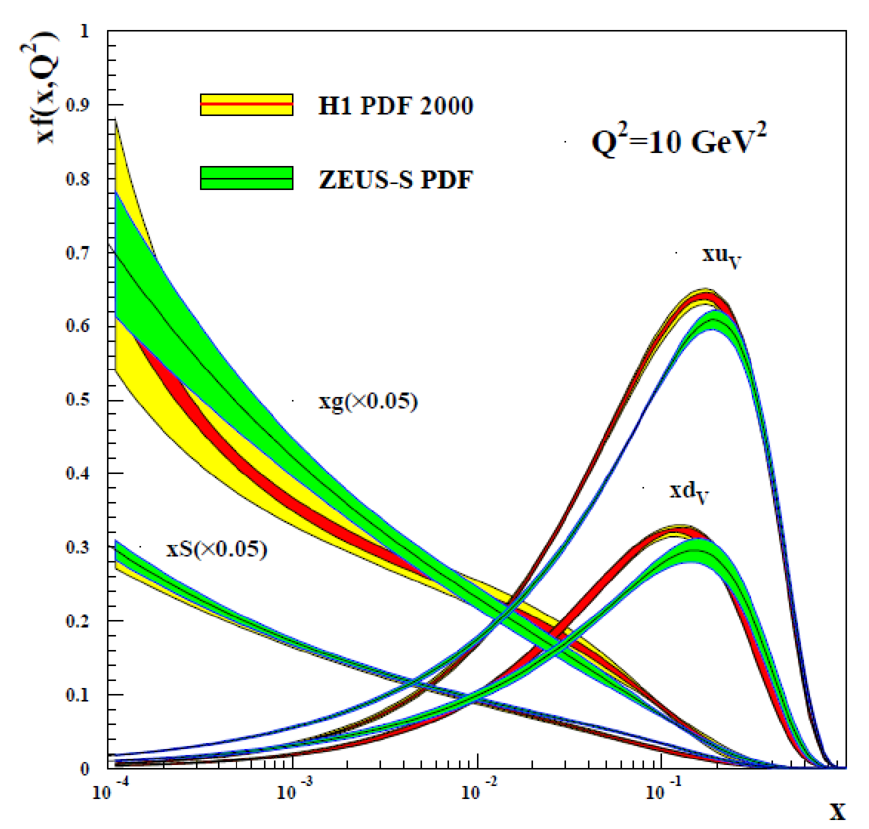
Phase Diagram



Iancu, **Nucl.Phys.Proc.Suppl. 191 (2009) 281-294**

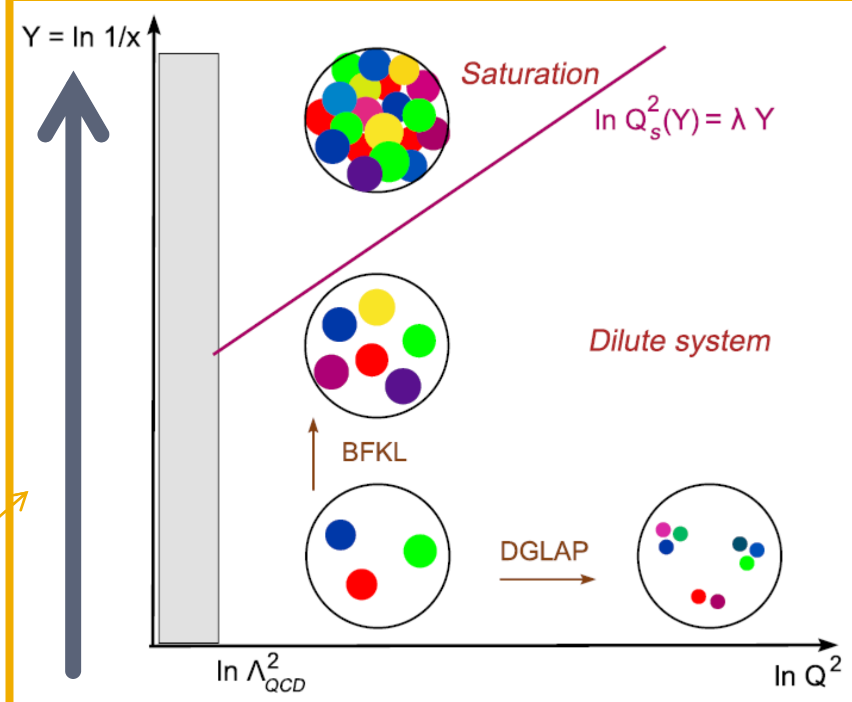
Gluon saturation

Parton distribution functions



Direction of decreasing transverse partons area (1/Q²)

Phase Diagram

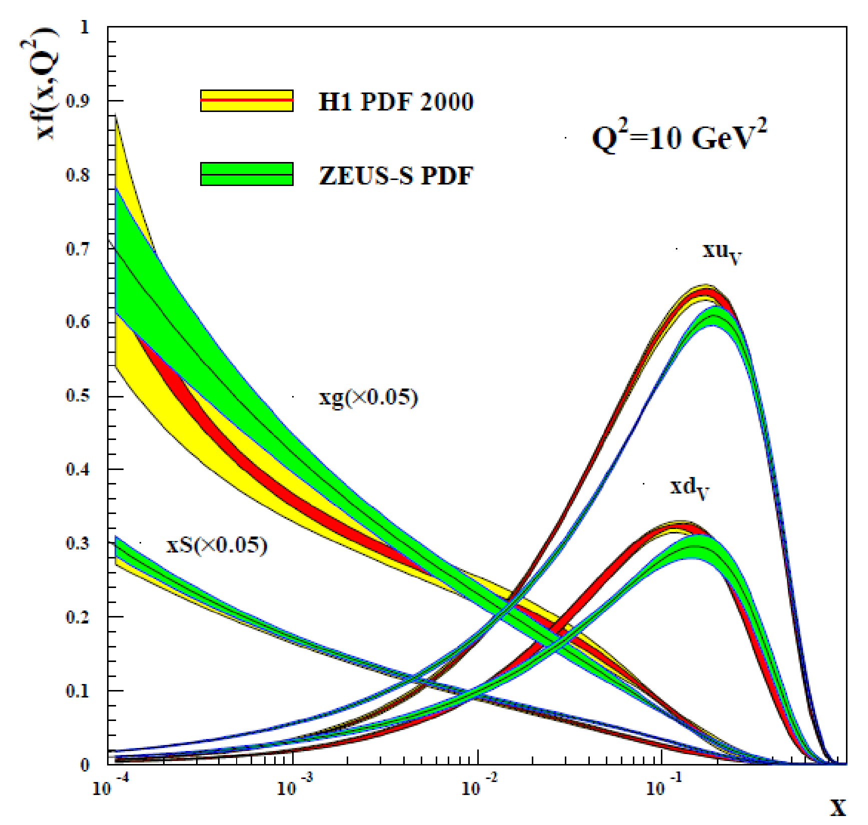


Direction of increasing gluon number

Iancu, **Nucl.Phys.Proc.Suppl. 191 (2009) 281-294**

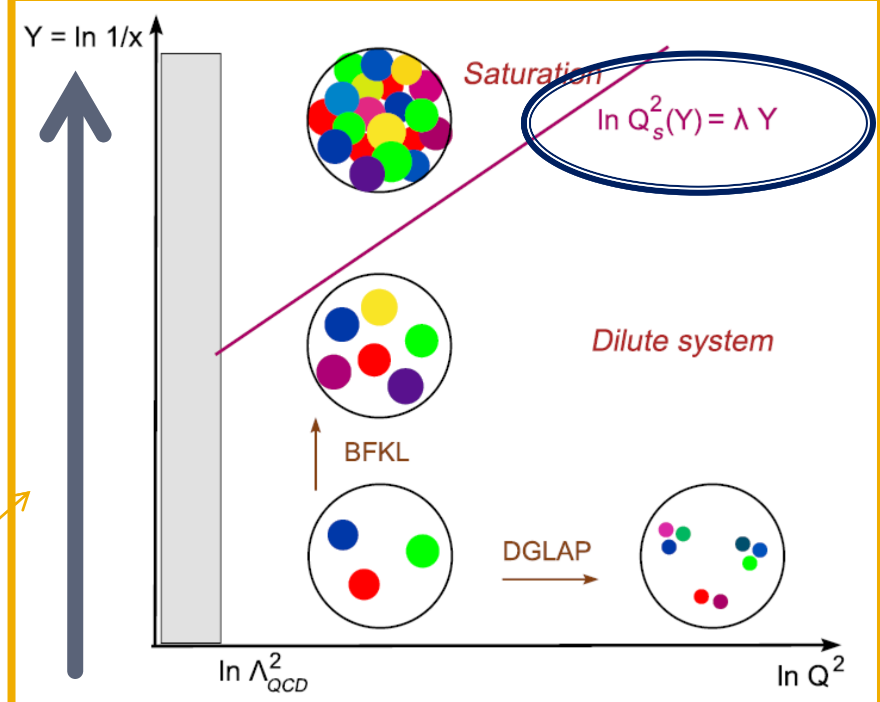
Gluon saturation

Parton distribution functions



Direction of decreasing transverse partons area ($1/Q^2$)

Phase Diagram

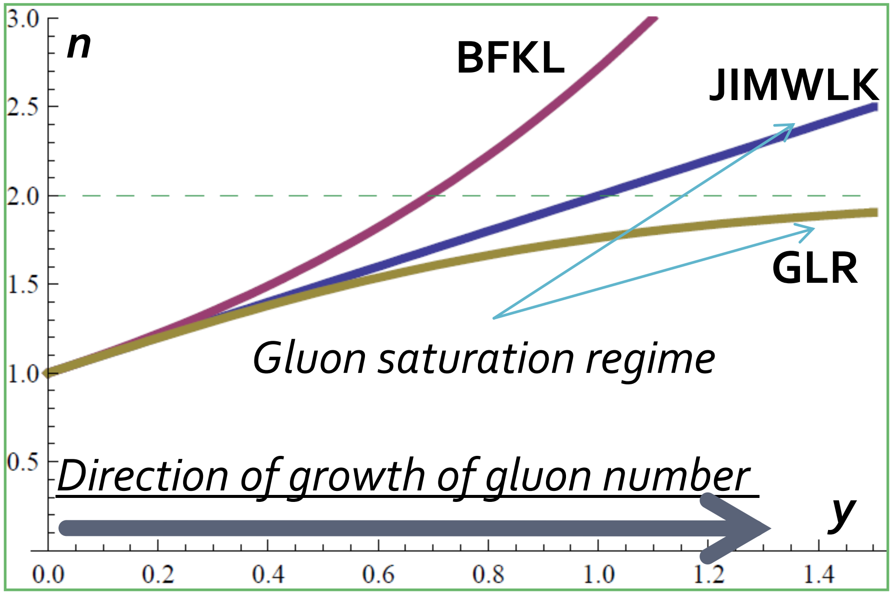


Direction of increasing gluon number

McLerran and Venugopalan, PRD **49**, 2233 (1994)
McLerran and Venugopalan, PRD **49**, 3352 (1994)

Gluon saturation

Small x (i.e. slow) gluon dynamics:
high density boson system,
living in the background of ***large x (i.e. fast) color sources***, the latter being ***randomly distributed*** in the nucleus.



L. V. Gribov et al., Phys. Rept. **100** (1983) 1.
A. H. Mueller and J. Qiu, Nucl. Phys. **B268** (1986) 427.
J. Jalilian-Marian et al., Nucl. Phys. **B504** (1997) 415.
E. Iancu et al., Nucl. Phys. **A692** (2001) 583.
A. Leonidov et al.,Nucl. Phys. **A703** (2002) 489.

Color: gluons carry color charge
Glass: fast partons randomly distributed in the hadron, with frozen dynamics (by Lorentz time dilatation).
Condensate: small x gluons are correlated for $\Delta x_\perp \approx 1/Q_s$

Initial condition: CGC

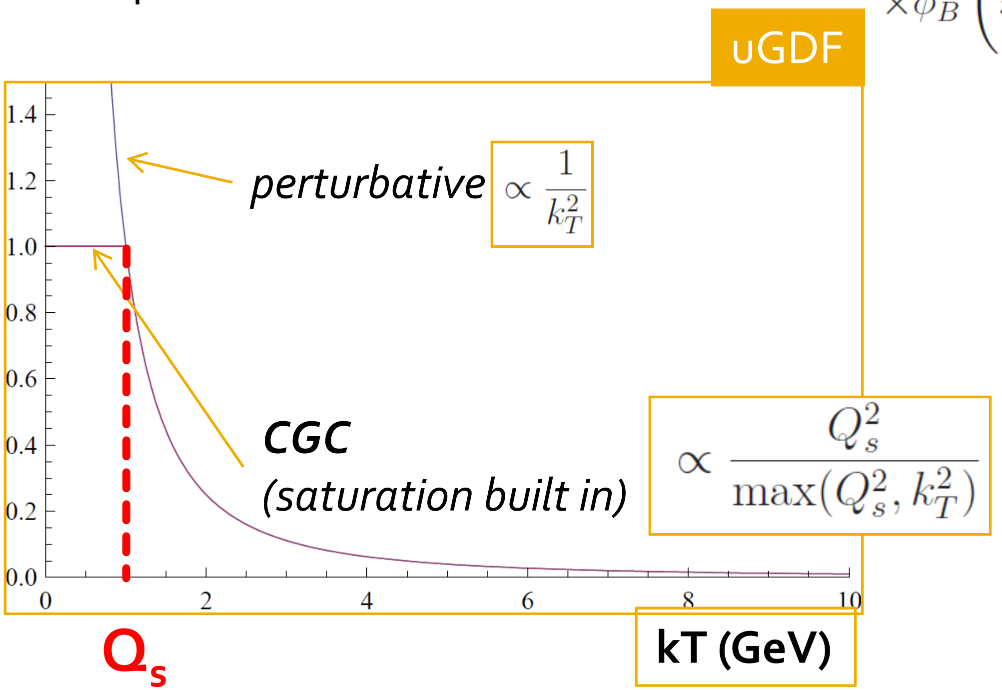
(f)KLN model

Factorization hypothesis: convolution of distribution functions, assuming each one equal to the one the partons had in the parent nucleus.

Melting of the CGC leads to **gluon production** in the fireball:

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

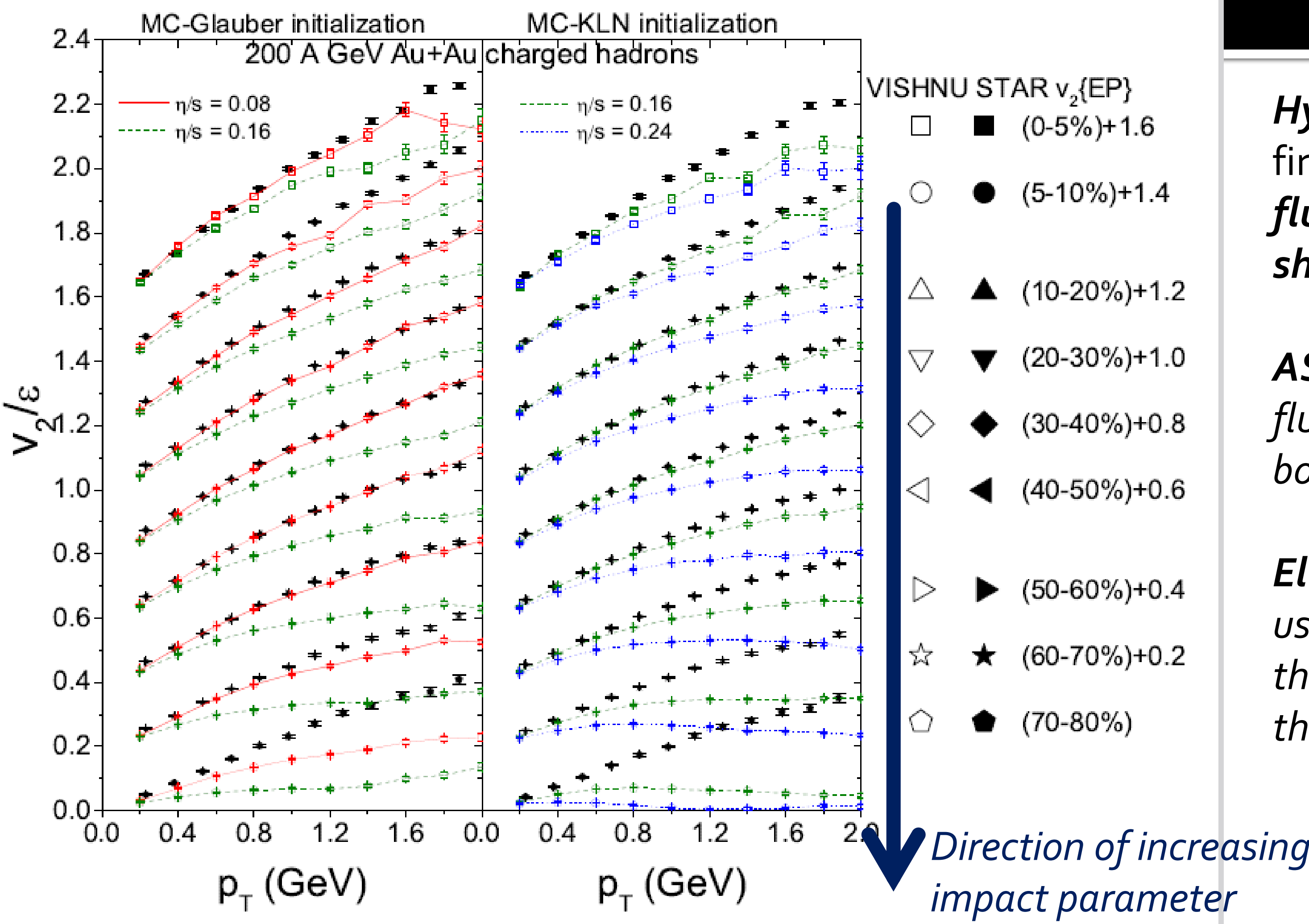
Unintegrated distribution functions (uGDFs)



Saturation scale ***Qs*** depends on:
1.) ***position in transverse plane***;
2.) ***gluon rapidity***.

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)

Elliptic flow in HICs, 2



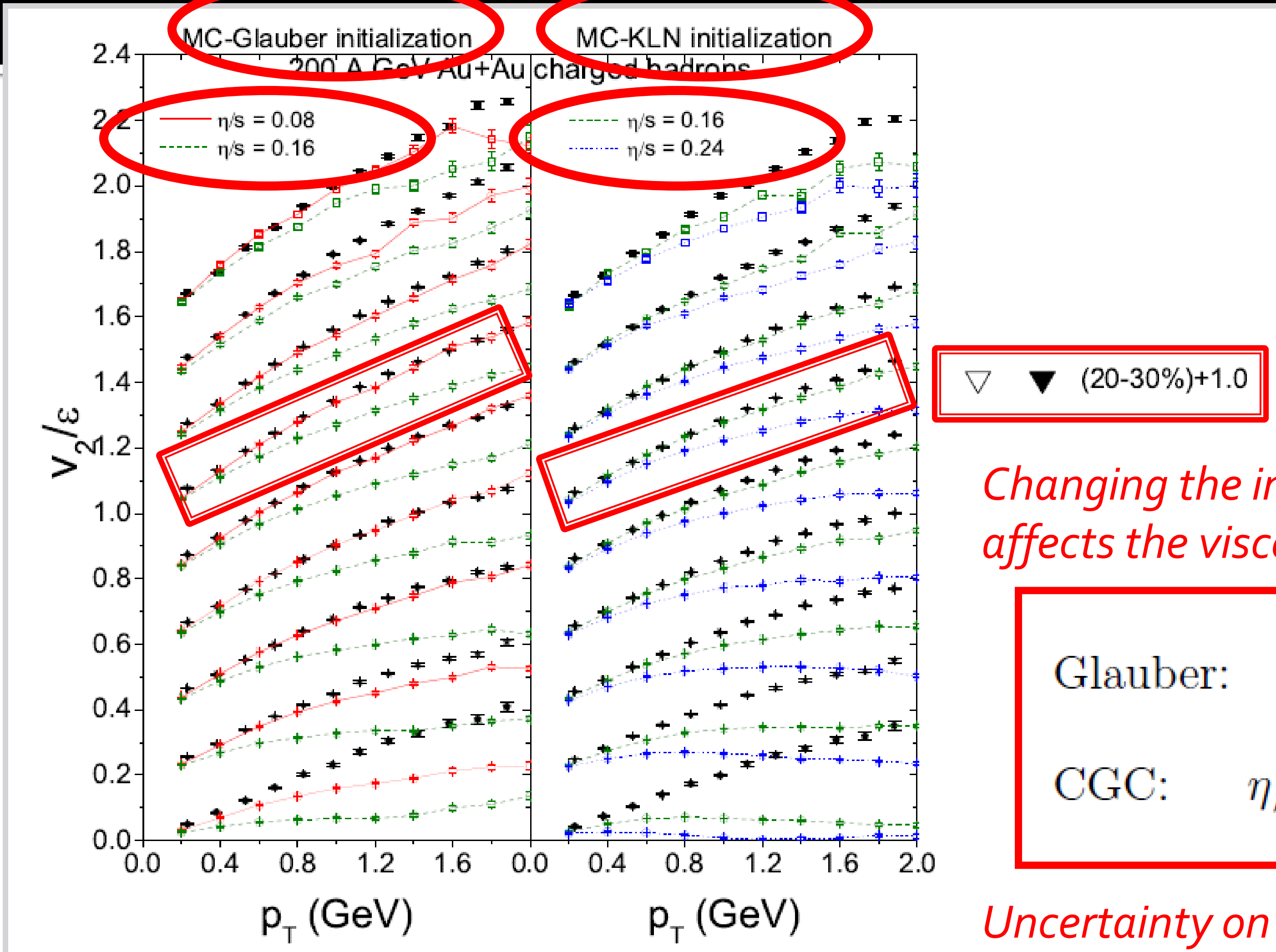
Hydro simulations: fireball treated as a ***fluid*** with a given ***shear viscosity.***

ASSUMPTION:
fluid is thermalized in both cases.

Elliptic flow data *are useful to estimate the* ***shear viscosity*** *of the QGP.*

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

Elliptic flow in HICs, 2



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

Hydro simulations: fireball treated as a ***fluid*** with a given ***shear viscosity.***

Changing the initial condition affects the viscosity of the fireball:

$$\text{Glauber:} \quad \eta/s \approx \frac{1}{4\pi}$$

$$\text{CGC:} \quad \eta/s \approx \frac{2}{4\pi}$$

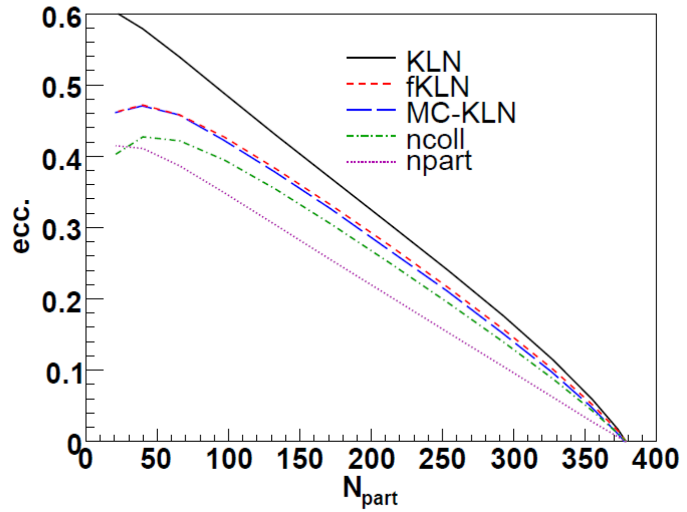
Uncertainty on the initial condition implies uncertainty on the ratio η/s of the produced quark-gluon plasma.

Elliptic flow in HICs, 2

$$\text{Glauber:} \quad \eta/s \approx \frac{1}{4\pi}$$

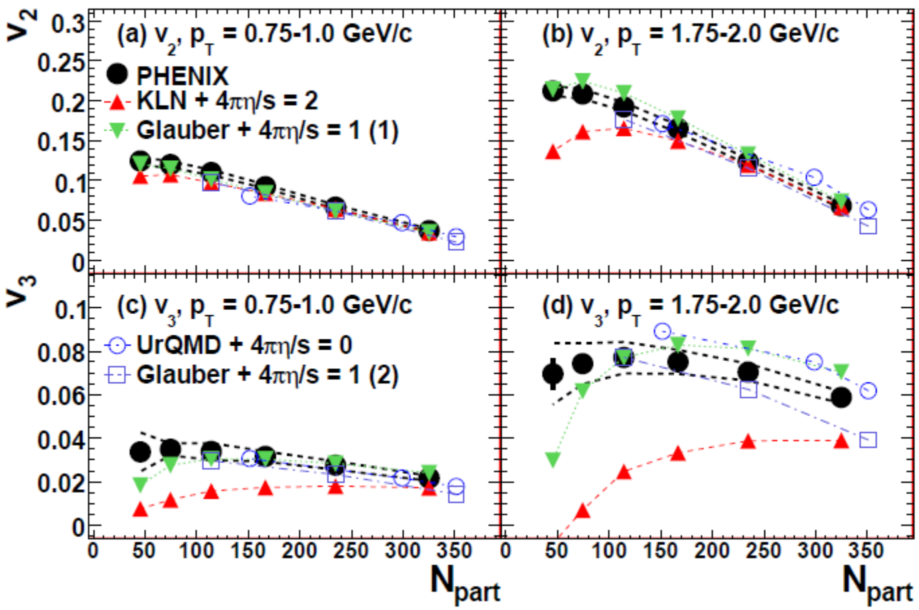
$$\text{CGC:} \quad \eta/s \approx \frac{2}{4\pi}$$

Eccentricity



Drescher and Nara, PRC **75** (2007) 034905

Adare *et al.*, [PHENIX Collaboration], PRL **107**, 252301 (2011).



The value of η/s affects the theoretical estimate of the higher harmonics.

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

Boltzmann equation

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

$$\boxed{p^\mu \partial_\mu f(x,p) = \mathcal{C}[f]}$$

f: distribution function of gluons
C[f]: collision integral, computed stochastically

In C[f] we consider only the ***elastic massless gluon scattering*** process:

$$\boxed{gg \to gg}$$

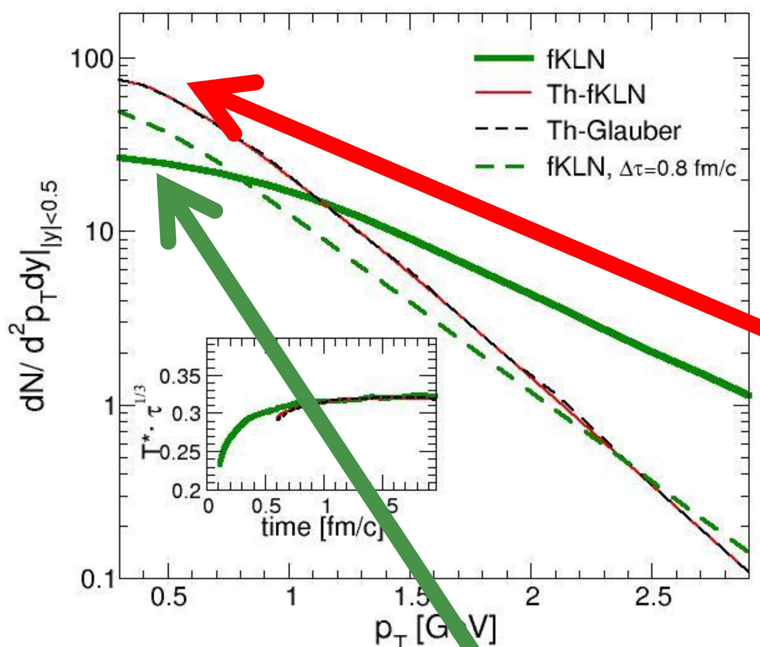
Distribution function is sampled at each time step by means of ***test particles*** which evolve according to the classical Hamilton equations of motion:

$$\boxed{\frac{d\boldsymbol{r}_i}{dt} = \frac{\boldsymbol{p}_i}{E_i}\,, \qquad \frac{d\boldsymbol{p}_i}{dt} = \text{coll}}$$

We use Boltzmann equation to simulate a fluid at ***fixed*** η/s; the ***cross section*** is ***computed*** in ***each phase space cell*** to give the wished value of η/s.

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

Initial condition and thermalization



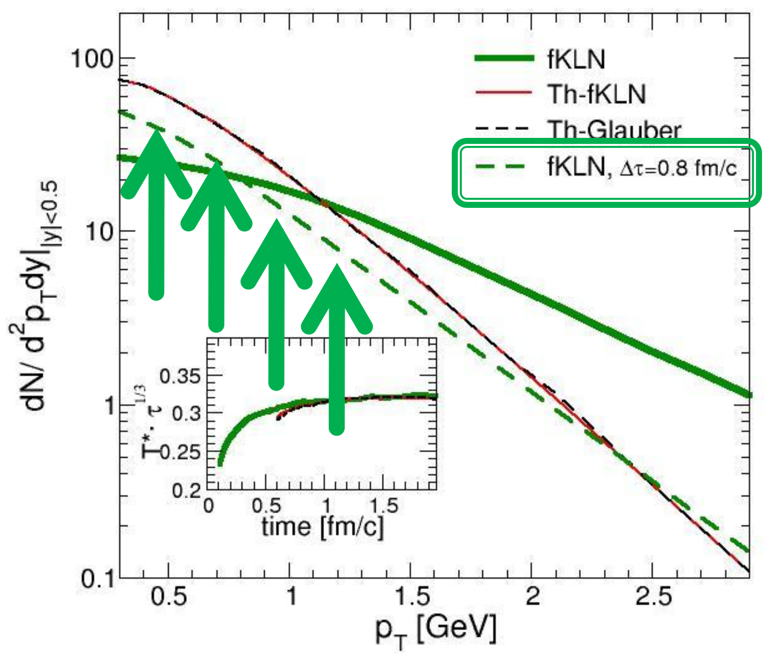
We use Transport to simulate a fluid at ***fixed*** η/s; the ***cross section*** is ***computed*** in ***each phase space cell*** to give the wished value of η/s.

Initial conditions as in hydro simulations:
thermalized distribution, to=0.6 fm/c,
free streaming

CGC initial conditions,
with saturation at low p_T built in,
to=0.1 fm/c,
no free streaming.

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

Initial condition and thermalization

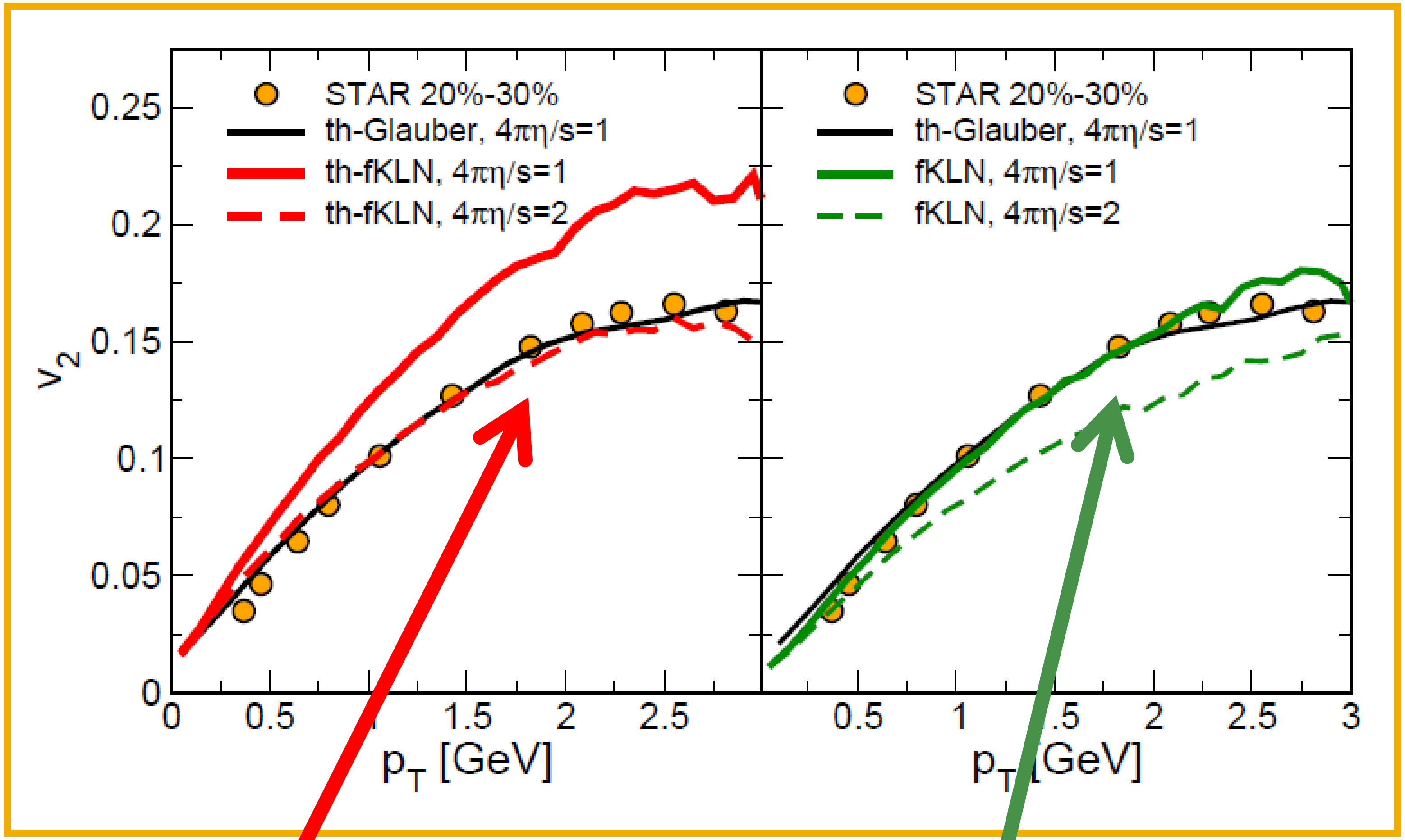


We use Transport to simulate a fluid at ***fixed*** η/s; the ***cross section*** is ***computed*** in ***each phase space cell*** to give the wished value of η/s.

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

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

Elliptic flow from Transport

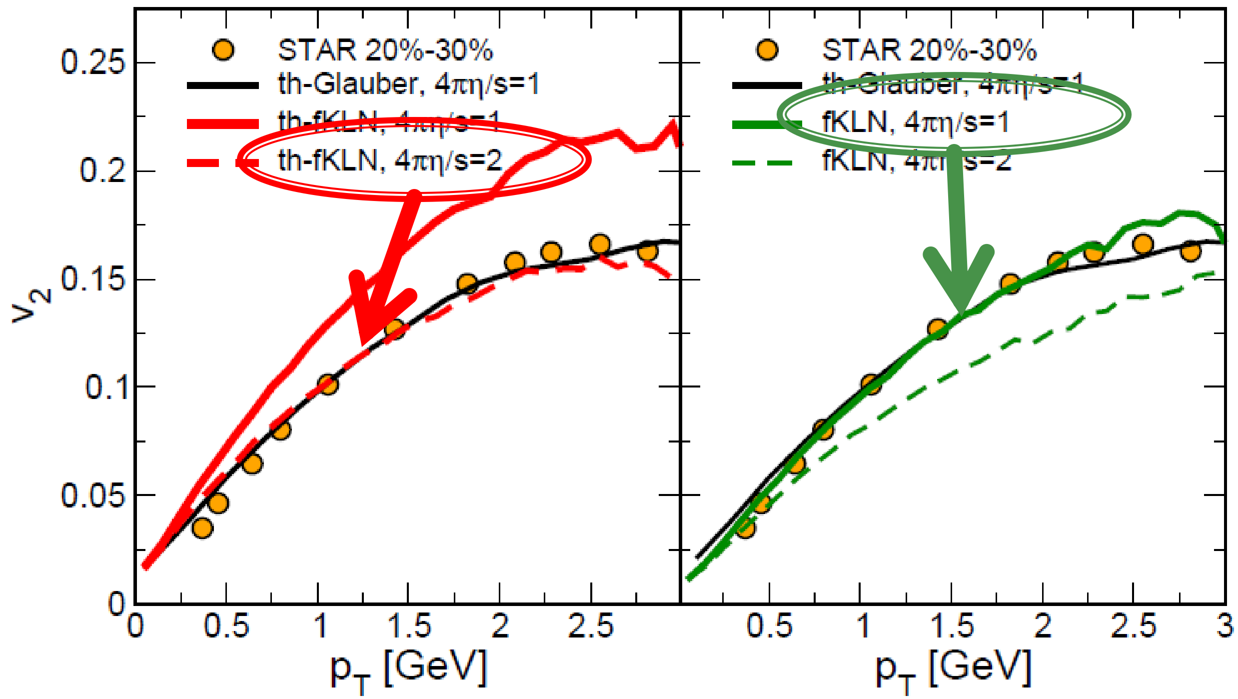


Hydro initial condition

CGC initial condition

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

Elliptic flow from Transport



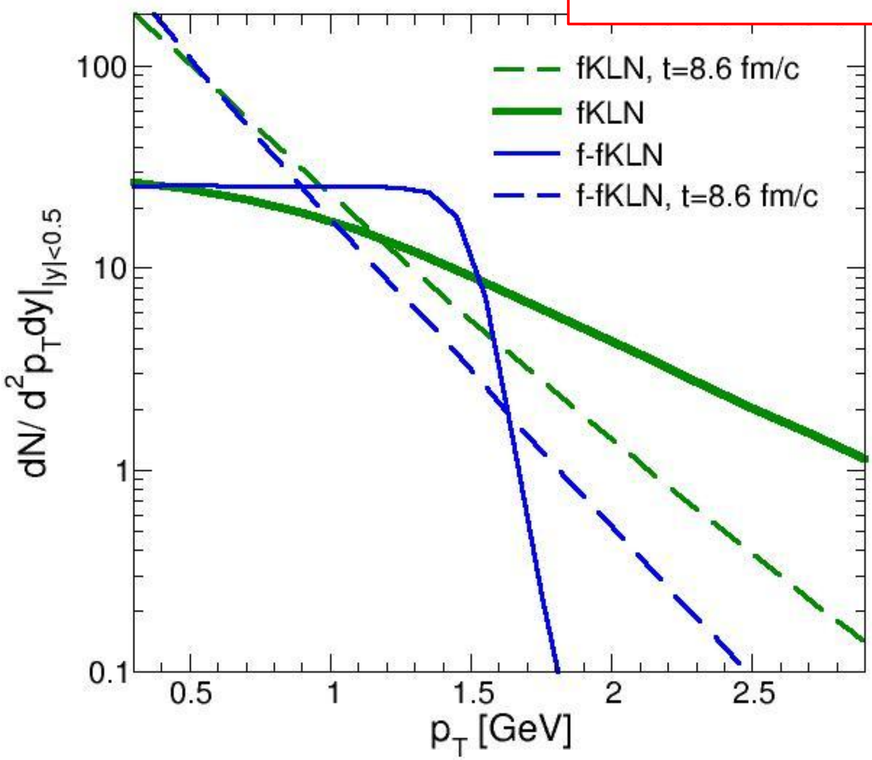
Implementing the proper initial condition in momentum space, which embeds saturation proper of a CGC, leads to the ***estimate of η/s in agreement with the Glauber initial condition.***

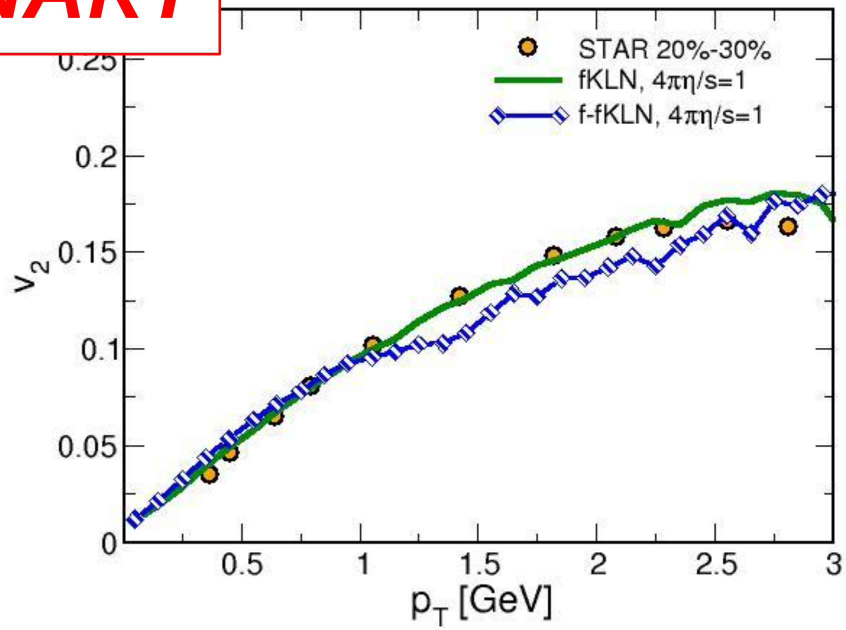
Incidentally, η/s turns out to be of the order of the ***universal lower limit*** conjectured in: Kovtun *et al.* in PRL **94**, 111691 (2005).

Hence, the expanding fireball behaves as an ***almost perfect fluid.***

Elliptic flow from Transport

PRELIMINARY





Taking the initial spectrum artificially flat leads to a further reduction of the elliptic flow.

Conclusions and Outlook

- Transport approach allows to study collective flow of CGC.
- Proper initial distribution in momentum space, which embeds saturation, has an important effect on the formation of the CGC v2.

Outlook

- Inclusion of inelastic processes and of thermal masses.
- *Detailed study of pre-equilibration times.*
- *Computation of higher order harmonics.*
- Extension to the LHC energies.

There are two breeds of fools: those who do not doubt anything, those who doubt everything.

(Charles-Joseph de Ligne)