UNIVERSITÀ DEGLI STUDI DI CATANIA

INFN-LNS

Anisotropic flows and the shear viscosity of the QGP within a kinetic approach

S. Plumari, A. Puglisi, L. Guardo,

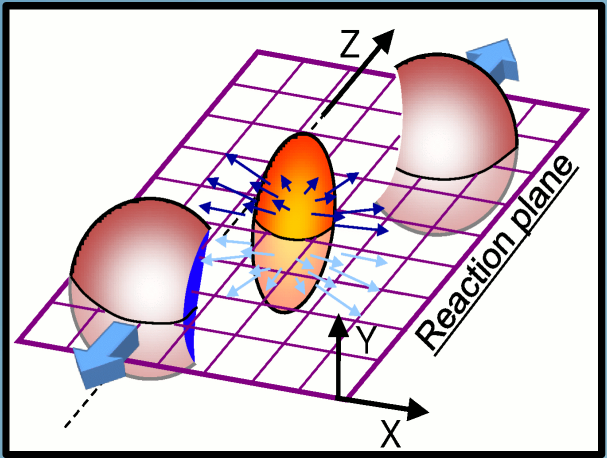
M. Ruggieri, F. Scardina, V. Greco

Outline

- **Transport approach at fixed η/s:**
  - **Motivation**
  - **How to fix locally η/s ↔ σ(θ), M, T -**

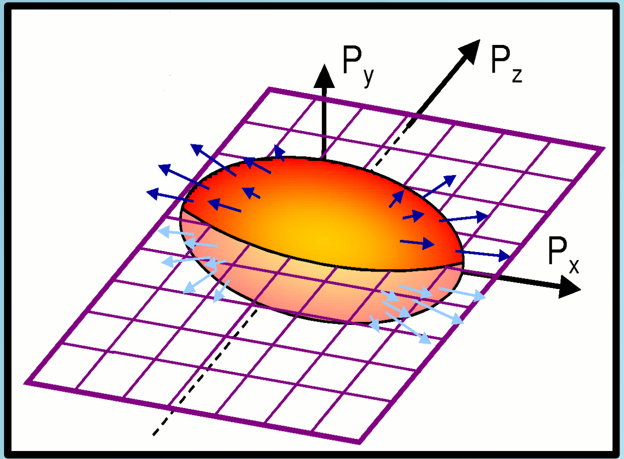
    Chapman-Enkog approach.
- **η/s and genration of v_2: from RHIC to LHC**
- **V_n from initial state fluctuations (preliminary)**
- **Conclusions**

Information from non-equilibrium: elliptic flow



$\lambda=(\sigma\rho)^{-1}$ or η/s viscosity

$c_s^2=dP/d\varepsilon$, EoS-lQCD



$$\varepsilon_x=\left\langle\frac{y^2-x^2}{y^2+x^2}\right\rangle$$

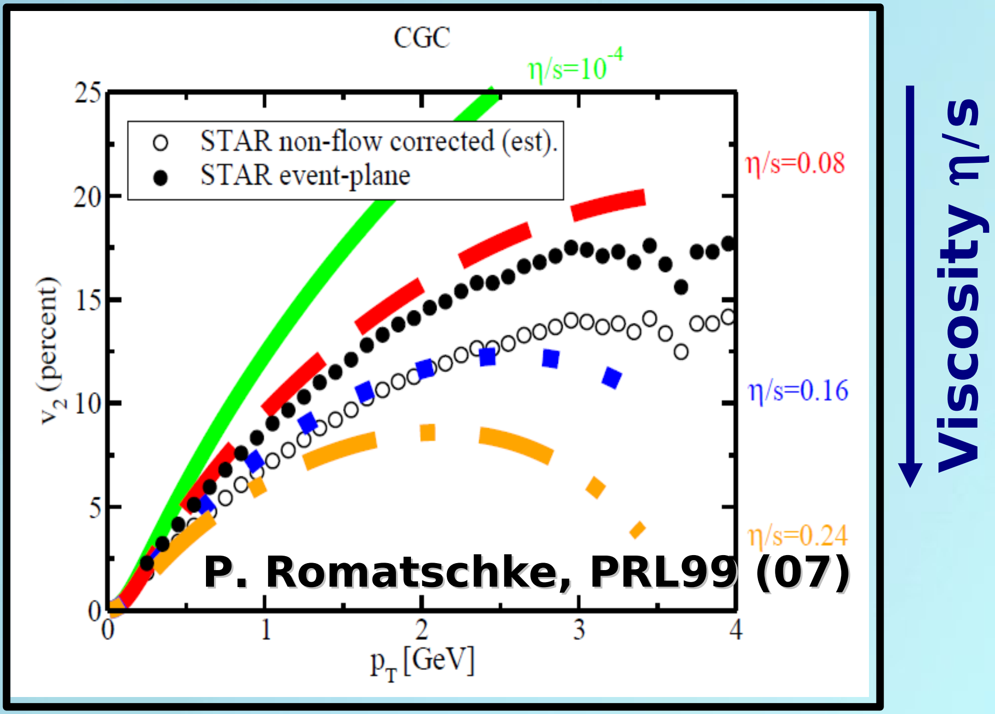
The v_2/ε measures efficiency in converting the eccentricity from Coordinate to Momentum space J.Y. Ollitrault, PRD 46 (1992).

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

Can be seen also as Fourier expansion

$$\frac{dN}{dp_T d\phi}=\frac{dN}{dp_T}\left[1+2v_2\cos(2\phi)+2v_4\cos(4\phi)+\ldots\right]$$

by symmetry v_n with n odd expected to be zero ... (but event by event fluctuations)



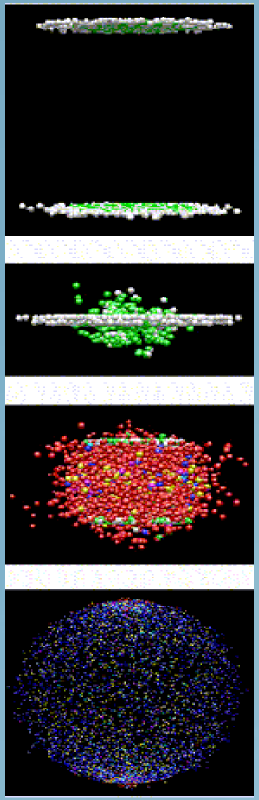
Motivation for a kinetic approach:

$$\{p^{\mu}\partial_{\mu}+[p_{\nu}F^{\mu\nu}+M\partial^{\mu}M]\partial_{\mu}^{p}\}f(x,p)=C_{22}+C_{23}+\ldots$$

Free streaming

Field Interaction → $\varepsilon \neq 3P$

Collisions → $\eta \neq 0$



- Starting from 1-body distribution function and not from $T^{\mu\nu}$: possible to include f(x,p) out of equilibrium.
- It is not a gradient expansion in η/s.
- Valid at intermediate p_T out of equilibrium.
- Valid at high η/s (cross over region): + self consistent kinetic freeze-out
- Include hadronization by coalescence + fragmentation.

Parton Cascade model

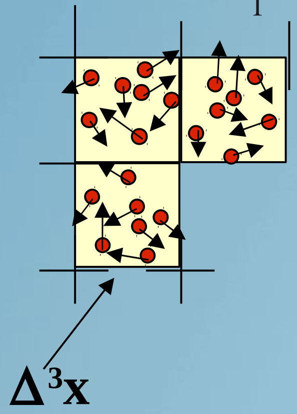
$$p^{\mu}\partial_{\mu}f(X,p)=C=C_{22}+C_{23}+\ldots$$

Collisions → $\begin{cases}\varepsilon-3p=0,\\ \eta\neq 0\end{cases}$

$$C_{22}=\frac{1}{2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int\frac{d^3p'_1}{(2\pi)^3 2E'_1}\frac{d^3p'_2}{(2\pi)^3 2E'_2}f'_1 f'_2\left|M_{1'2'\to 12}\right|^2(2\pi)^4\delta^{(4)}(p'_1+p'_2-p_1-p_2)$$

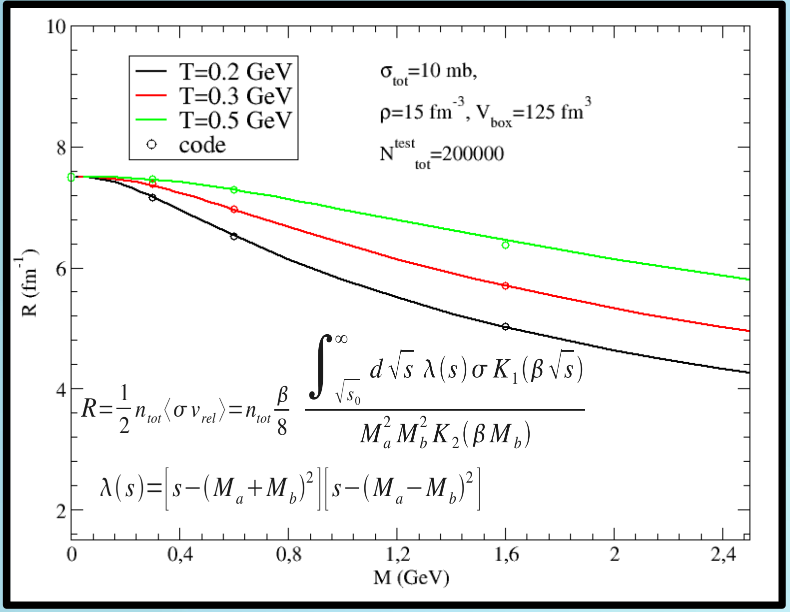
For the numerical implementation of the collision integral we use the stochastic algorithm. (Z. Xu and C. Greiner, PRC 71 064901 (2005))

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



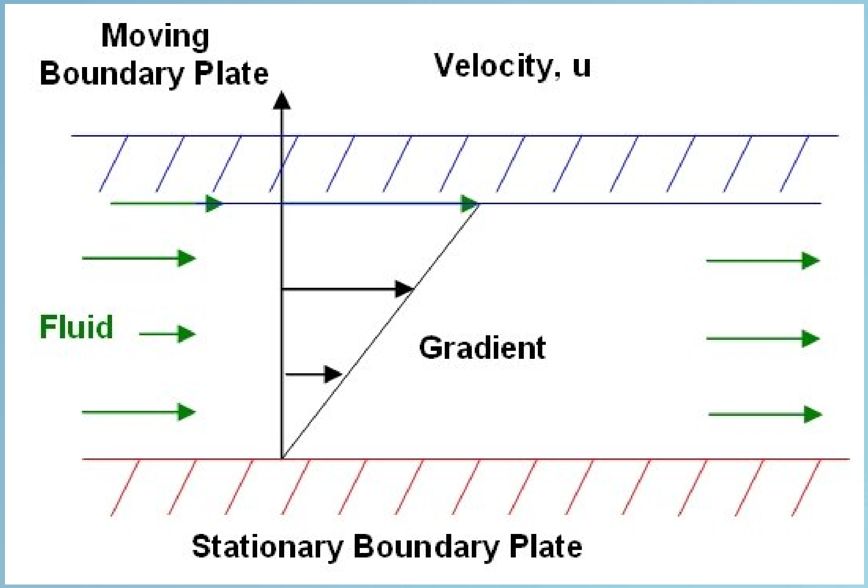
$\Delta t\to 0$

$\Delta^3 x\to 0$ ⇒ **right solution**



Do we really have the wanted shear viscosity η with the relax. time approx.?

- Check η with the Green-Kubo correlator



$$\frac{F}{A} = \eta \frac{\partial u}{\partial y}$$

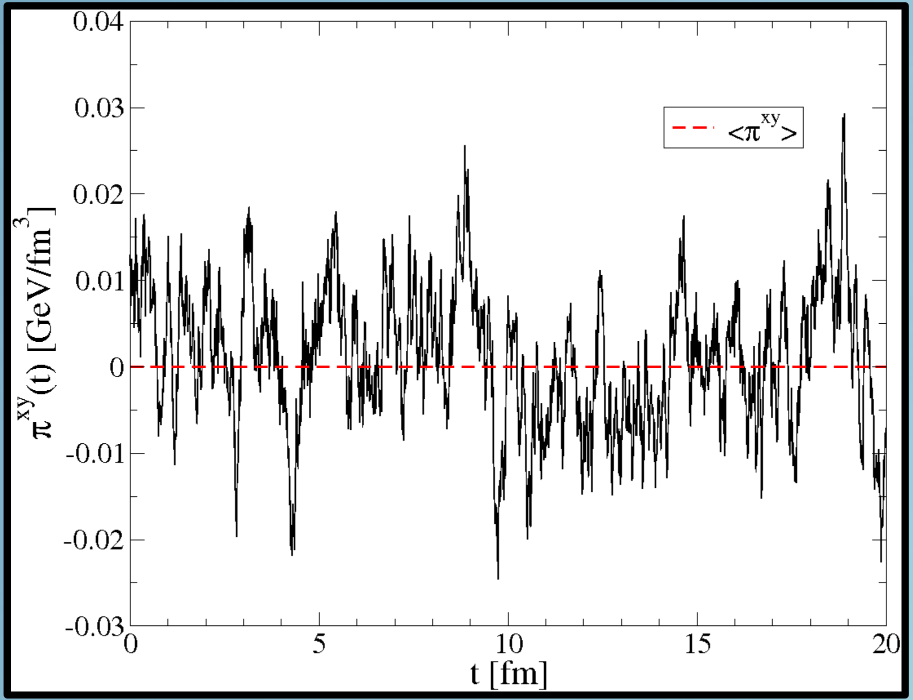
Extraction of the Shear Viscosity: Box calculation

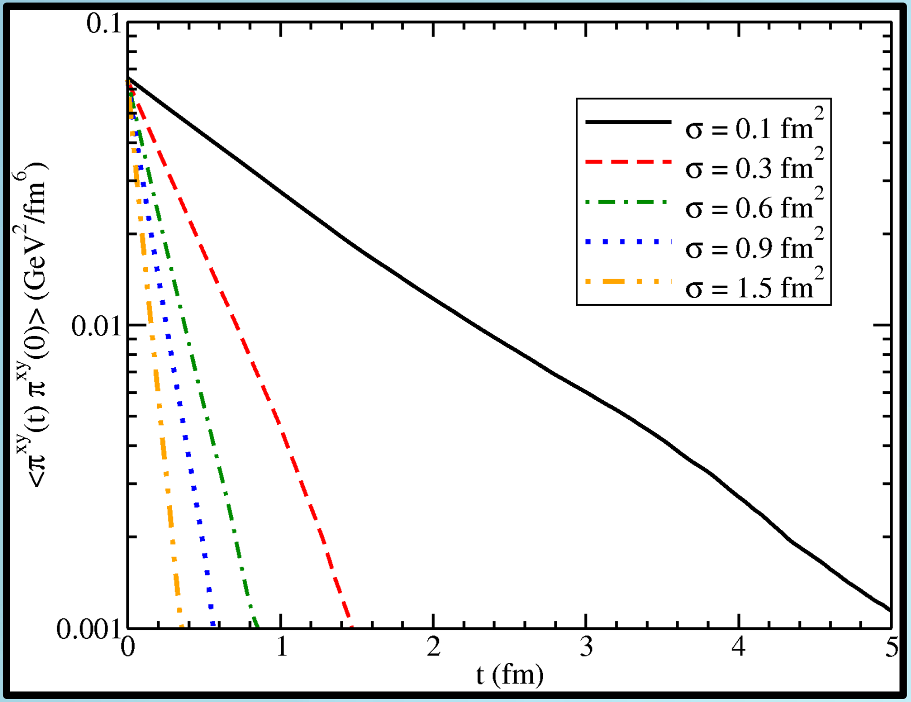
Green – Kubo relation

$$\eta = \frac{1}{T}\int_0^\infty dt \int_V d^3x \langle \pi^{xy}(x,t)\pi^{xy}(0,t)\rangle$$

$$\langle \pi^{xy}(\vec{x},t)\pi^{xy}(\vec{0},t)\rangle = \langle \pi^{xy}(0)\pi^{xy}(0)\rangle \cdot e^{-t/\tau}$$

$$\Rightarrow \quad \eta = \frac{V}{T}\langle \pi^{xy}(0)\pi^{xy}(0)\rangle \cdot \tau$$





S. Plumari et al.,Phys.Rev. C86 (2012) 054902.
C. Wesp et al., Phys. Rev. C 84, 054911 (2011).
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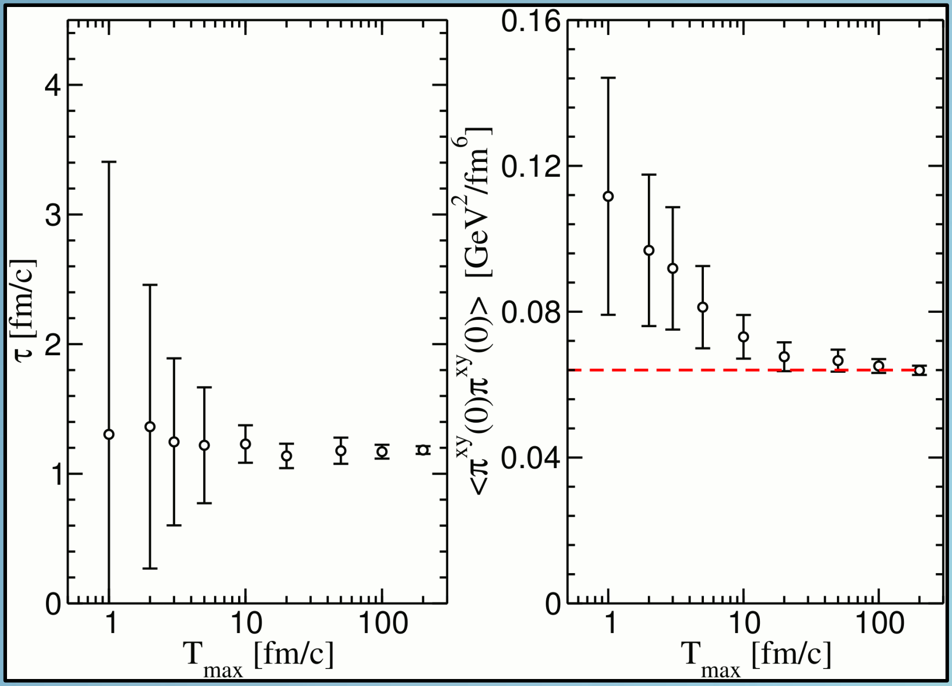
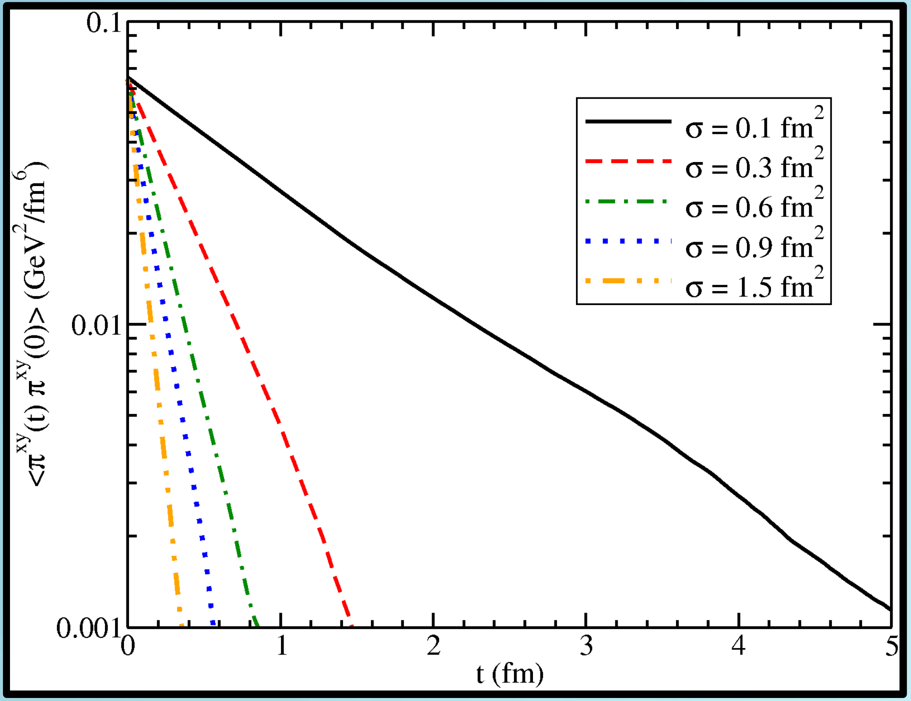
Depends on microscopical details: τ(σ)

$$\eta = \frac{V}{T}\langle \pi^{xy}(0)\pi^{xy}(0)\rangle \cdot \tau$$

Depends on macroscopical details:

$$= \frac{4}{15}\frac{eT}{V}$$





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Extraction of the Shear Viscosity: Box calculation

Relaxation Time Approximation

Kapusta, PRC(2010); Gavin NPA(1985);

$$\eta = \frac{1}{15T}\int_0^\infty \frac{d^3p}{(2\pi)^3}\frac{p^4}{E^2}\tau(E) f^{eq}(E) \qquad \tau^{-1}(E) = \rho\langle \sigma_{tot} v_{rel}\rangle$$

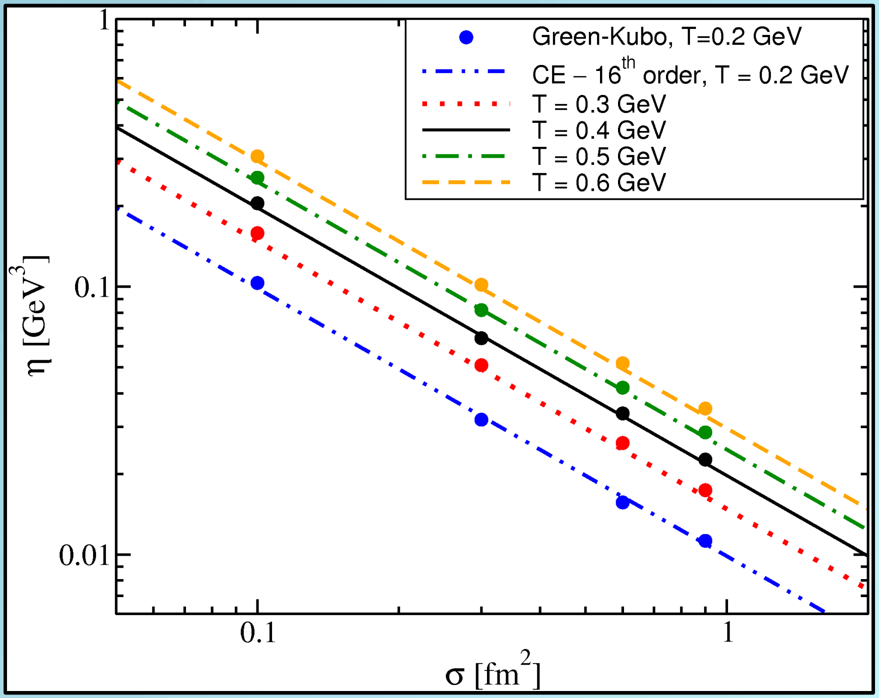
$$\eta_{relax} = 0.8\frac{T}{\sigma_{tot}} \Rightarrow \eta \sim \frac{1}{\sigma_{tot}}$$

Usual as Relax. Time Approx. - Israel Stewart $\sigma_{tot} \to \sigma_{tr} = (2/3)\sigma_{tot}$

$$\eta^{IS}_{relax} = 0.8\frac{T}{\sigma_{tr}} = 1.2\frac{T}{\sigma_{tot}}$$

Molnar-Huovenin PRC(2009),
G. Ferini PLB(2009),
Khvorostukhin PRC (2010)
....

S. Plumari et al.,PRC86 (2012) 054902.



Isotropic cross section: massless case

- **At 1st order of approx. in the Chapman-Enskog:** $[\eta]^{CE}_{1st} = 1.2\frac{T}{\sigma_{tot}}$

- **successive approx. up to 16 order:** $[\eta]^{16th}_{CE} = 1.267\frac{T}{\sigma_{tot}}$

A. Wiranata, M. Prakash, PRC85 (2012) 054908.
O. N. Moroz, arXiv:1112.0277 [hep-ph].

Extraction of the Shear Viscosity: Box calculation

$$\eta^{IS}_{relax}/s = \frac{1}{15}\langle p\rangle \tau_r = \frac{1}{15}\frac{\langle p\rangle}{\sigma_{tot}\langle f(a) v_{rel}\rangle \rho}$$

$$\sigma_{tr} = \int d\Omega \sin^2(\theta_{cm}) \frac{d\sigma}{d\Omega_{cm}} = \sigma_{tot} f(a) \leqslant \frac{2}{3}\sigma_{tot}$$

Employed also for non-isotropic cross section:

G.Ferini, PLB(2009); D. Molnar, JPG35(2008); V.Greco, PPNP(2009);

For the standard pQCD-like cross section

$$\frac{d\sigma}{d\Omega_{cm}} = \frac{9\pi\alpha_S^2}{2}\frac{1}{(q^2+m_D^2)^2}\left(1+\frac{m_D^2}{s}\right)$$

m_D regulates the anisotropy of collision

$m_D \rightarrow \infty$ we recover the isotropic limit

$$f(a) = 4a(1+a)[(2a+1)\ln(1+a^{-1})-2], \quad a = m_D^2/s$$

1st Chapman-Enskog approximation

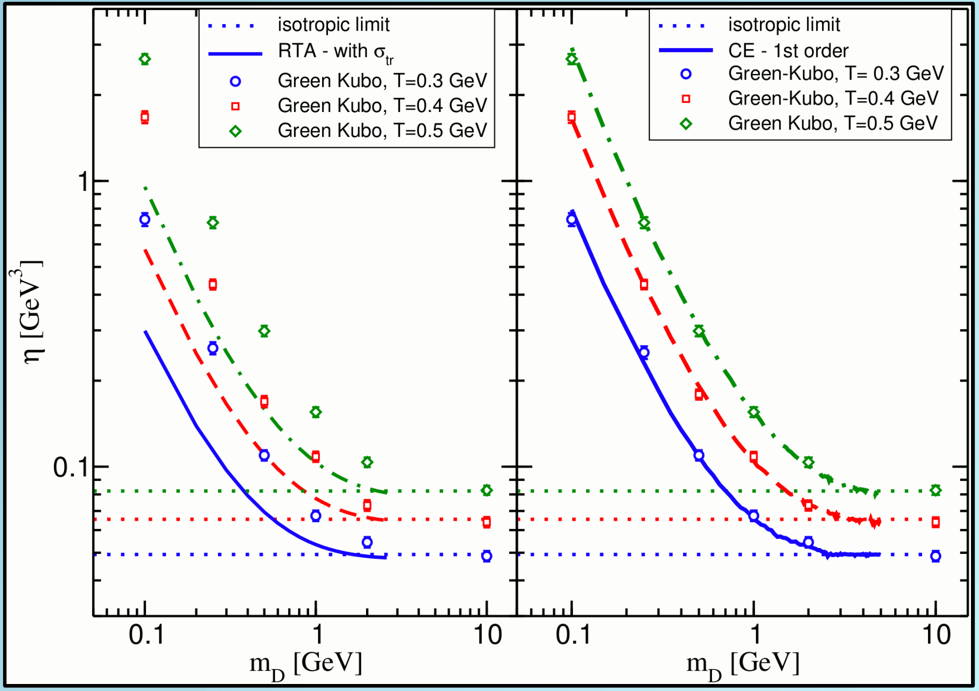
$$[\eta]_{1st}/s = \frac{1}{15}\langle p\rangle \tau_\eta = \frac{1}{15}\frac{\langle p\rangle}{\sigma_{tot}\, g(a)\, \rho}$$

$$g(a) = \frac{1}{50}\int_0^\infty dy\, y^6\left[\left(y^2+\frac{1}{3}\right)K_3(2y) - y K_2(2y)\right] f(a), \quad a = \frac{m_D}{2T}$$

- **CE and RTA can differ by a factor of 2**
- **Green-Kubo agree with CE (< 5%)**

A. Wiranata, M. Prakash, PRC85 (2012) 054908.
O. N. Moroz, arXiv:1112.0277 [hep-ph].

S. Plumari et al.,PRC86 (2012) 054902.



- **We know how to fix locally η/s(T)**
- **We have checked the Chapmann-Enskog:**

- CE good already at I° order ≈ 5% (≈ 3% at II° order)

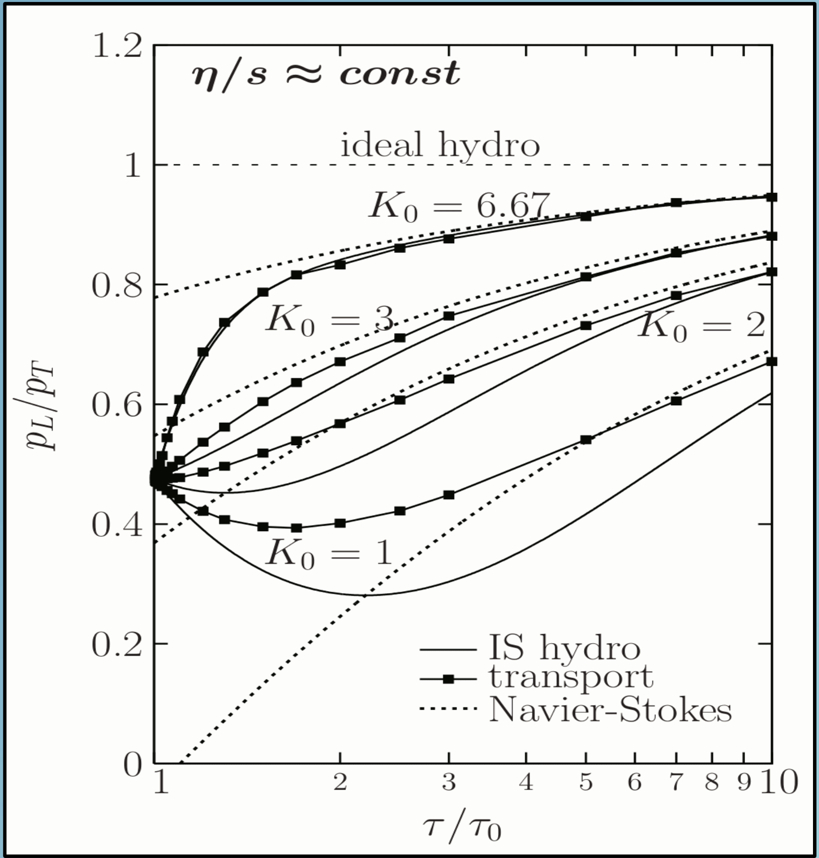
- RTA even with σ_{tr} severely underestimates η

Simulating a constant η/s

For the general case of anisotropic cross section and massless particles:

$$\eta(\vec{x},t)/s=\frac{1}{15}\langle p\rangle\,\tau_\eta \quad\Longrightarrow\quad \sigma_{tot}^{\eta/s}=\frac{1}{15}\frac{\langle p\rangle}{g(m_D/2T)\,n}\frac{1}{\eta/s}$$

σ is evaluated in such way to keep fixed the η/s during the dynamics according the Chapman-Enskog equation. (similar to D. Molnar, arXiv:0806.0026[nucl-th] but our approach is local.)



Huovinen and Molnar, PRC79(2009)

Knudsen number

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

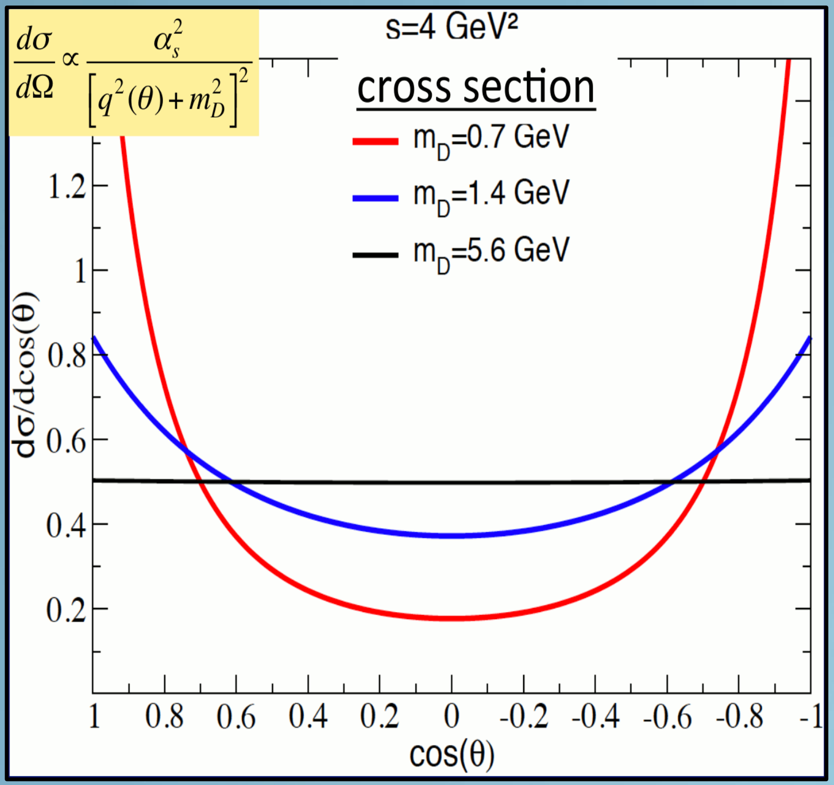
Large K small η/s

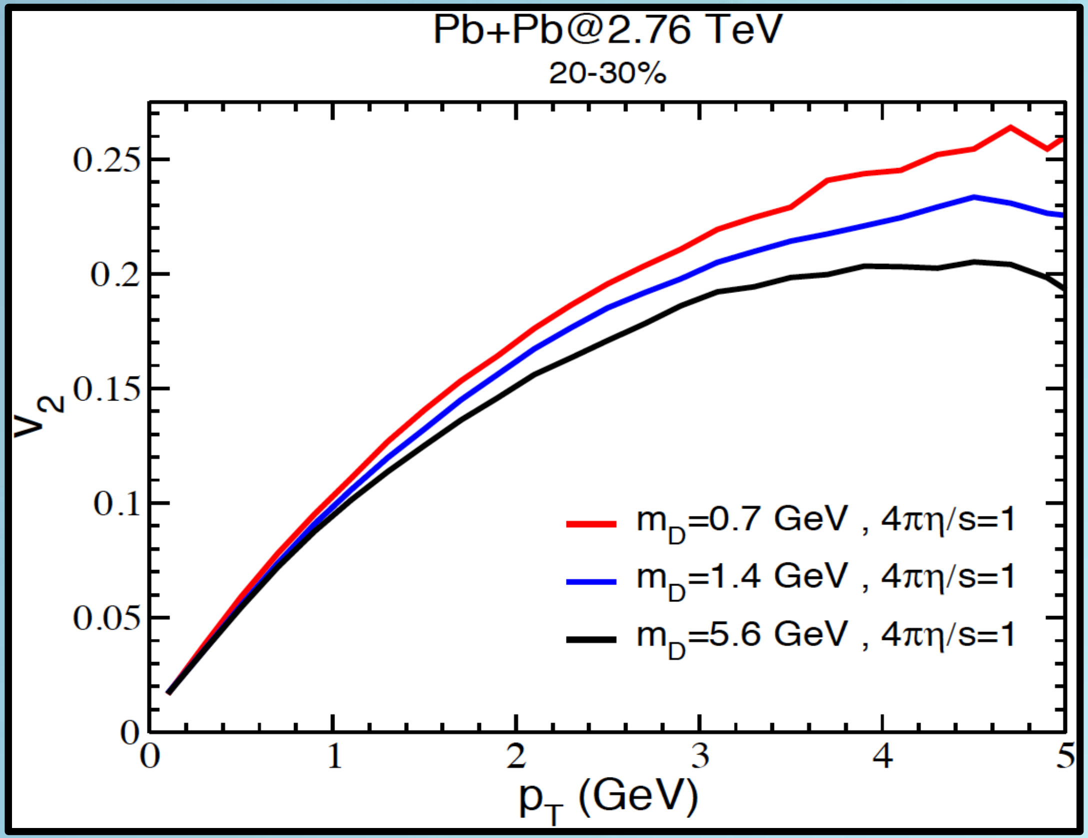
$$K=\frac{1}{5}\frac{T_0\tau_0}{\eta/s}$$

$$\frac{\eta}{s}=\frac{1}{5}T\cdot\lambda$$

In the limit of small η/s (<0.16) and for small pT equivalent viscous hydro

η/s or detail of the corss section





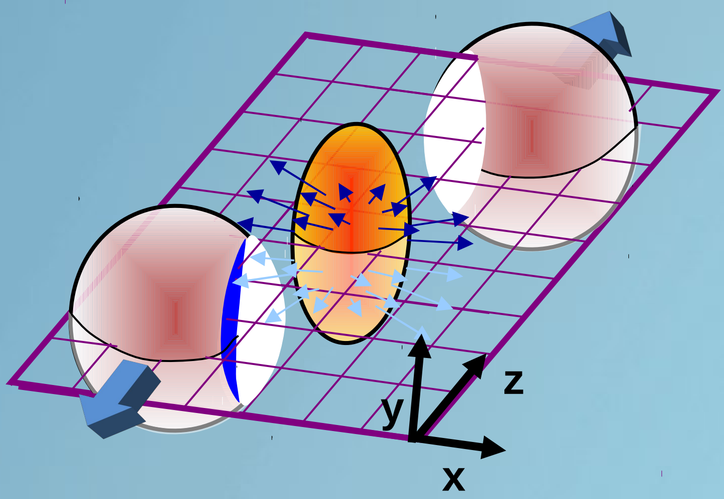
$$\frac{\eta}{s}=\frac{1}{15}\langle p\rangle \tau_\eta$$

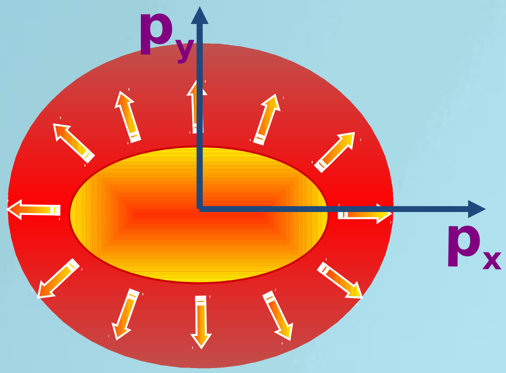
$$\tau_\eta=\frac{1}{\sigma_{tot}\, g(a)\rho}$$

- **η/s is the physical parameter determining the v_2 at least up to p_T 1.5 -2 GeV.**
- **microscopic details becomes important at higher p_T.**

Applying kinetic theory to A+A Collisions….

- Impact of $\eta/s(T)$ on the build-up of $v_2(p_T)$ vs. beam energy





Initial condition of our simulation

- r-space: standard Glauber model
- p-space: Boltzmann-Juttner Tmax=1.7-3.5 Tc
- [pT<2 GeV]+ minijet [pT>2-3GeV]

Discarded in viscous hydro

We fix maximum initial T at RHIC 200 AGeV

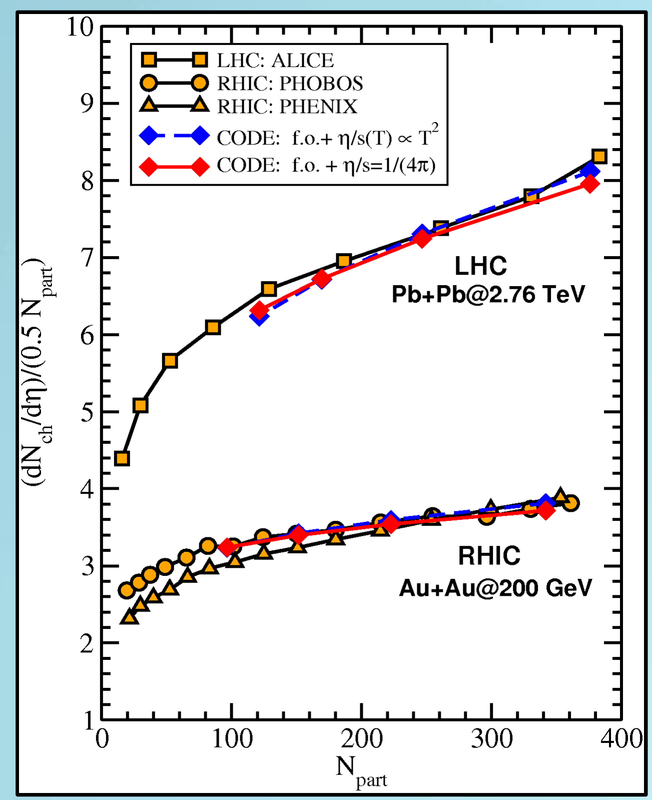
T_{max0} = 340 MeV

$T_0\ \tau_0$ =1 -> τ_0=0.6 fm/c

Typical hydro condition

Then we scale it according to $$\frac{1}{\tau A_T}\frac{dN_{ch}}{d\eta} \propto T^3$$

$\sqrt{s}$	62 GeV	200 GeV	2.76 TeV
T_0	290 MeV	340 MeV	590 MeV
τ_0	0.7 fm/c	0.6 fm/c	0.3 fm/c



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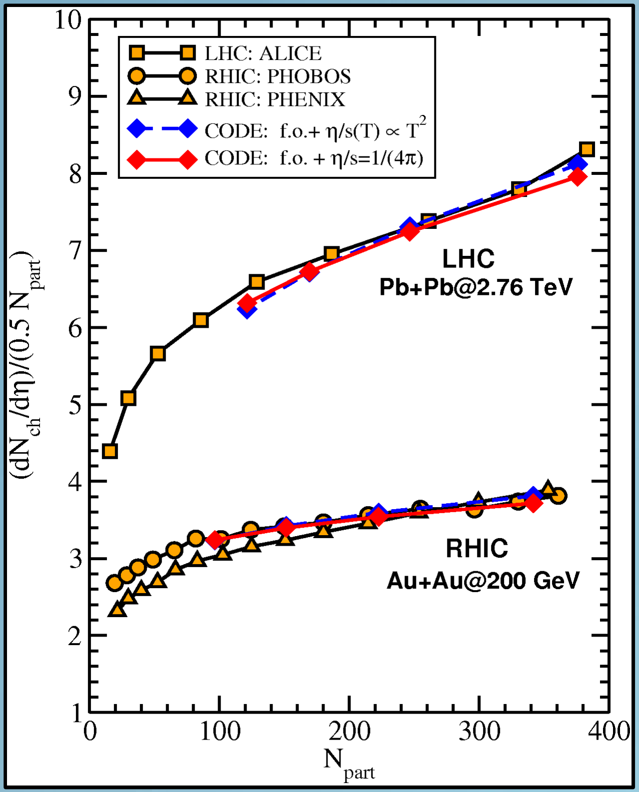
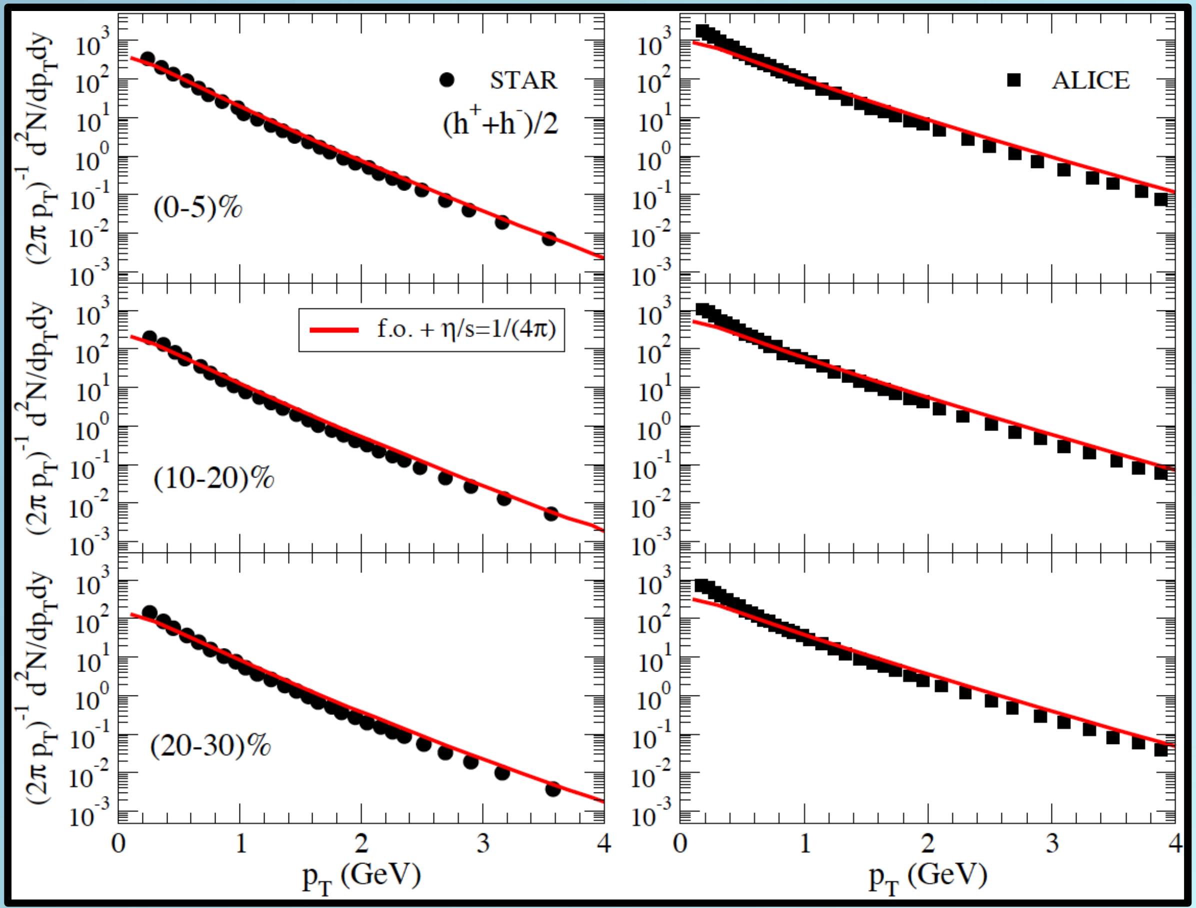
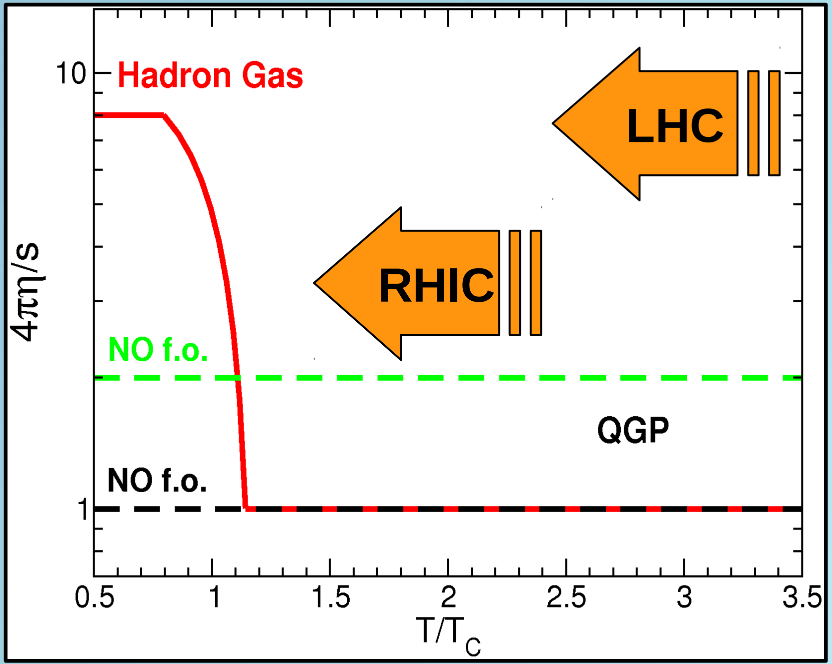




kinetic freeze-out scheme

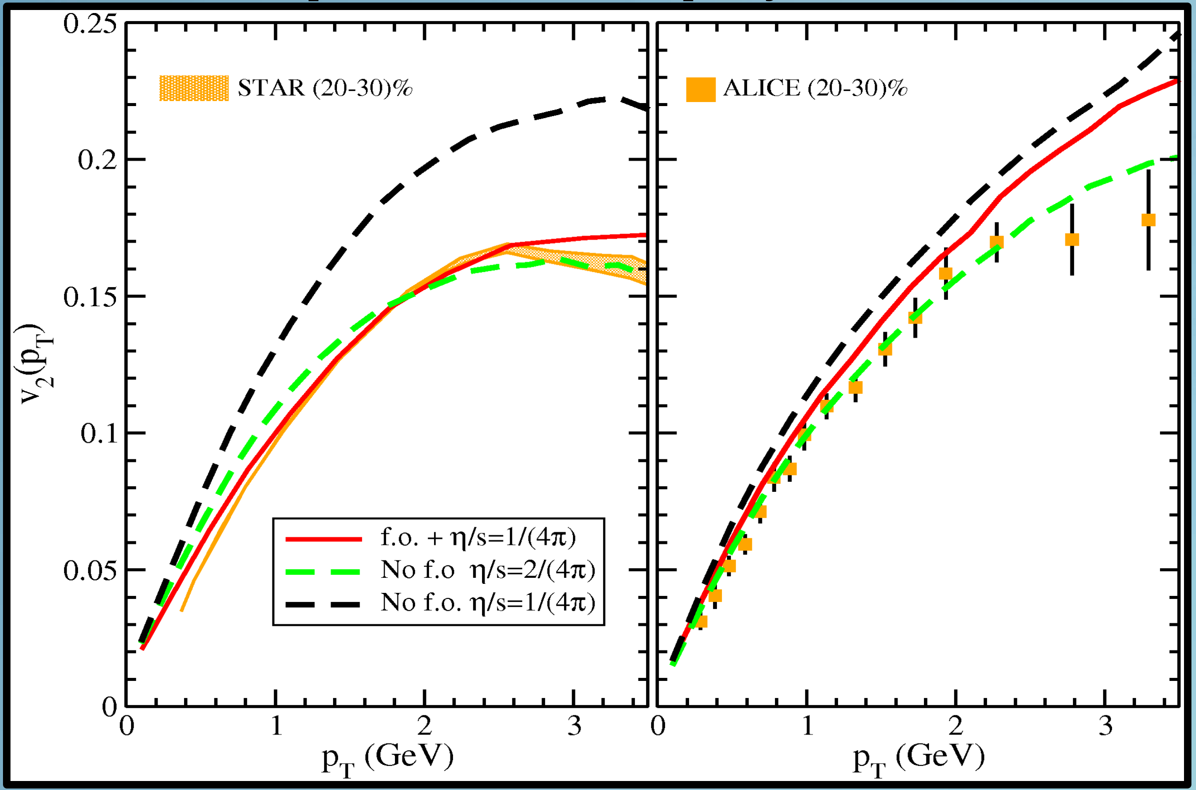
- The f.o. Is the increase of η/s in the cross-over region, with a smooth transition between the QGP and the hadronic phase, the collisions are switched off.

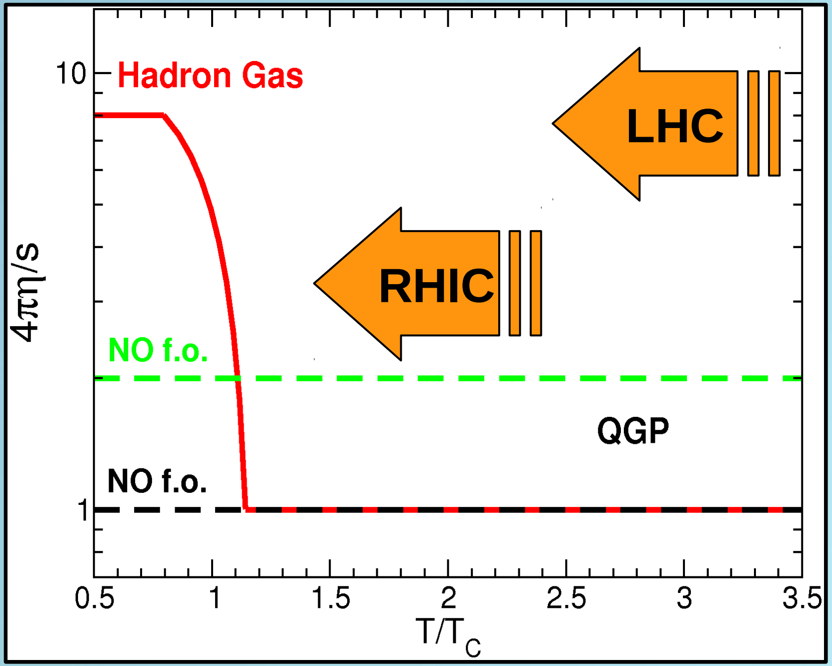


For the v_2 similar to cut-off at ε_0=0.7 GeV/fm^3

kinetic freeze-out scheme

K. Aamodt et al. [ALICE Collaboration], Phys. Rev.Lett. 105, 252302 (2010).





S. Plumari et al., J. Phys.: Conf. Ser. 420 012029 (2013). arXiv:1209.0601.

RHIC:

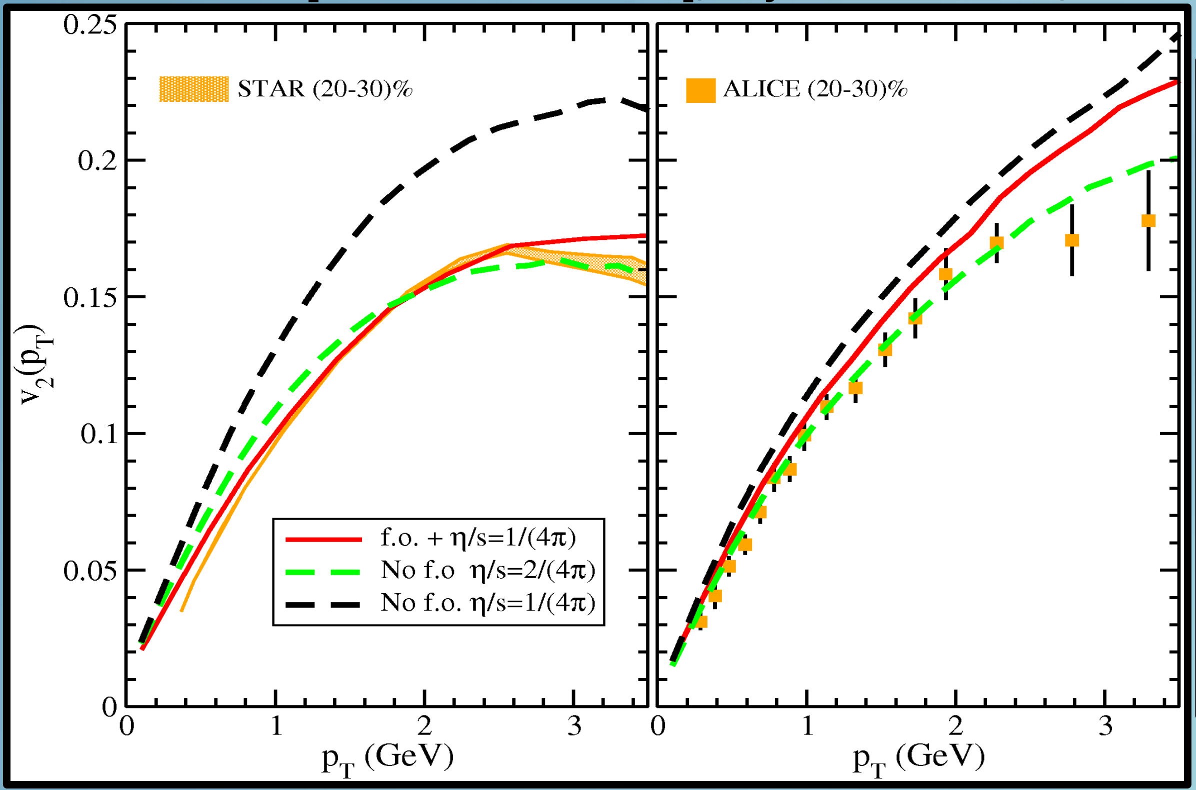
- Like viscous hydro the data are close to $\eta/s=1/(4\pi)$ + f.o.
- Sensitive reduction of the v_2 when the f.o. is included the effect is about of 20%.
- p_T < 2.5 GeV good agreement with the experimental data.

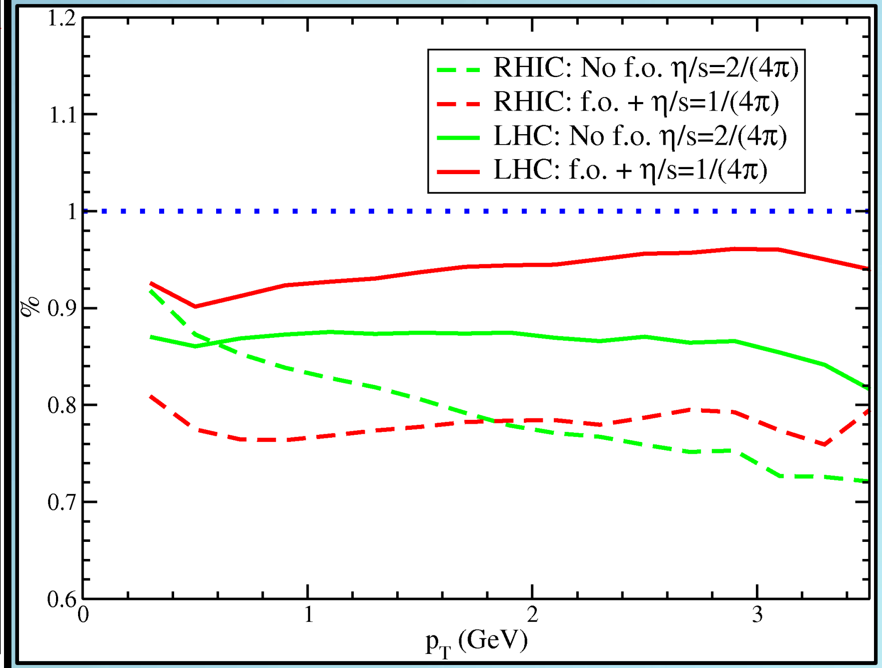
LHC:

- p_T< 2 GeV like hydro data described with $\eta/s=1/(4\pi)$ + f.o.
- Smaller effect on the reduction of the v_2 when the f.o. is included an effect of about 5%.
- Without the kinetic freezout the effect of a constant $\eta/s=2(4\pi)^{-1}$ is to reduce the v_2 of 15%.

kinetic freeze-out scheme

K. Aamodt et al. [ALICE Collaboration], Phys. Rev.Lett. 105, 252302 (2010).





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At LHC the contamination of mixed and hadronic phase becomes negligible

Longer life time of QGP → v_2 completely developed in the QGP phase (at least up to 3 GeV)

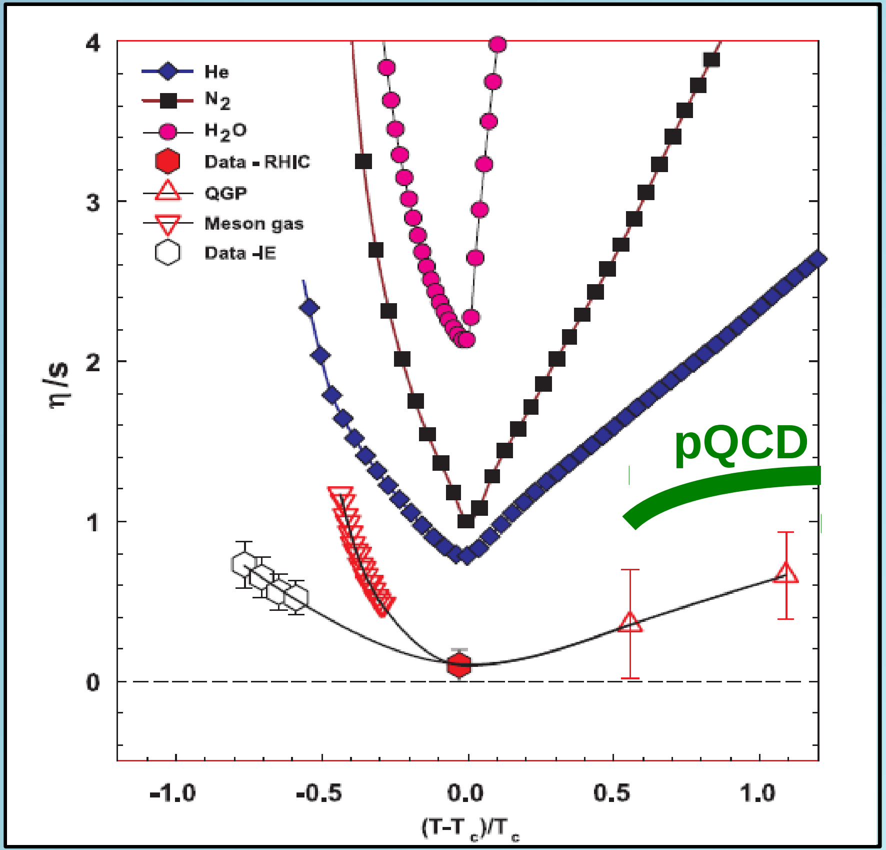
η/s(T) around to a phase transition

P. Kovtun et al.,Phys.Rev.Lett. 94 (2005) 111601.
L. P. Csernai et al., Phys.Rev.Lett. 97 (2006) 152303.
R. A. Lacey et al., Phys.Rev.Lett. 98 (2007) 092301.

- **Quantum mechanism**

$$\Delta E \cdot \Delta t \geqslant 1 \rightarrow \eta/s \approx \frac{1}{15} \langle p \rangle \cdot \tau > \frac{1}{15}$$

- **AdS/CFT suggest a lower bound η/s = 1/(4 π)~0.08**



The QGP viscosity is close to this bound!

Do we have signature of a 'U' shape of η/s(T) for the QCD matter ?

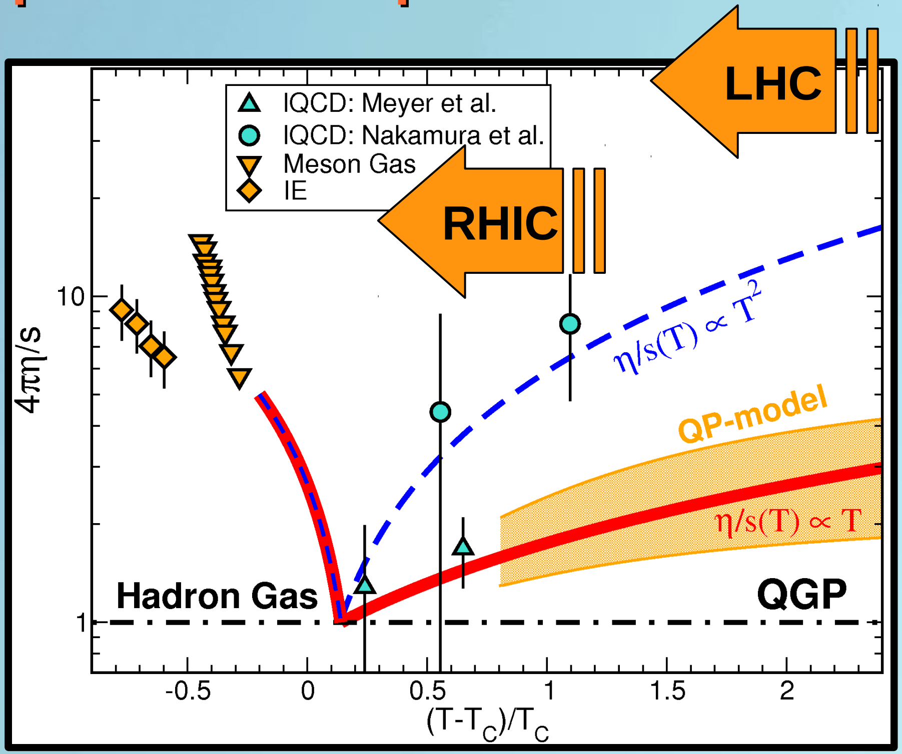
From pQCD: $\eta/s \sim \frac{1}{g^4 \ln(1/g)} \Rightarrow \eta/s \sim 1$

P.Arnold et al., JHEP 0305 (2003) 051.

Temperature dependent η/s(T)

Phase transition physic suggest a T dependence of η/s also in the QGP phase

- **LQCD some results for quenched approx. large error bars**
- **Quasi-Particle models seem to suggest a $\eta/s \sim T^{\alpha}$ $\alpha \sim 1 - 1.5$.**
- **Chiral perturbation theory → Meson Gas**
- **Intermediate Energies – IE ($\mu_B > T$)**



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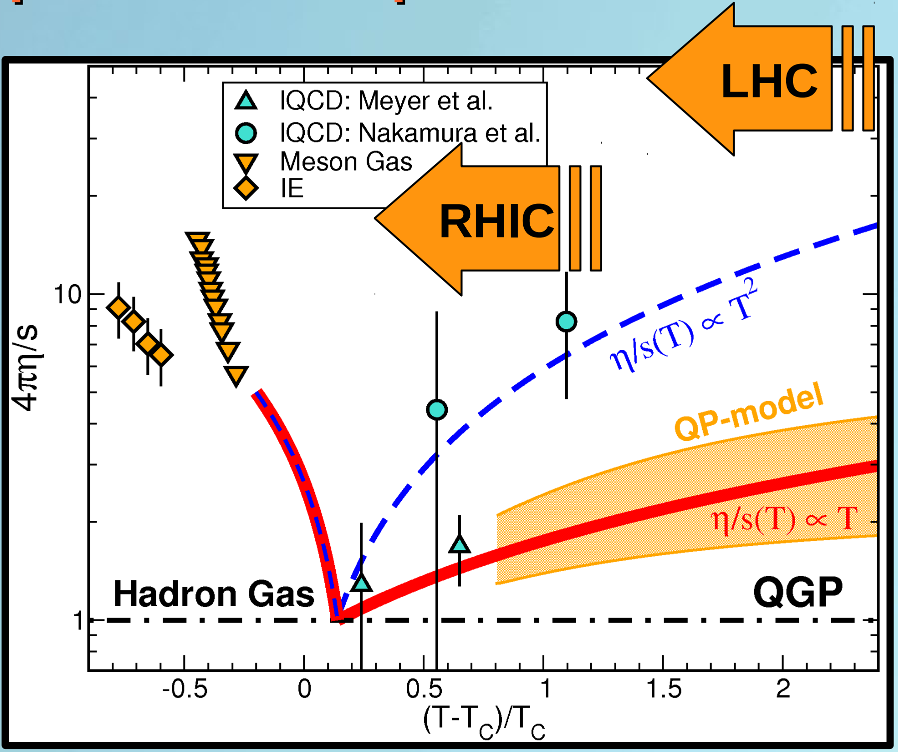

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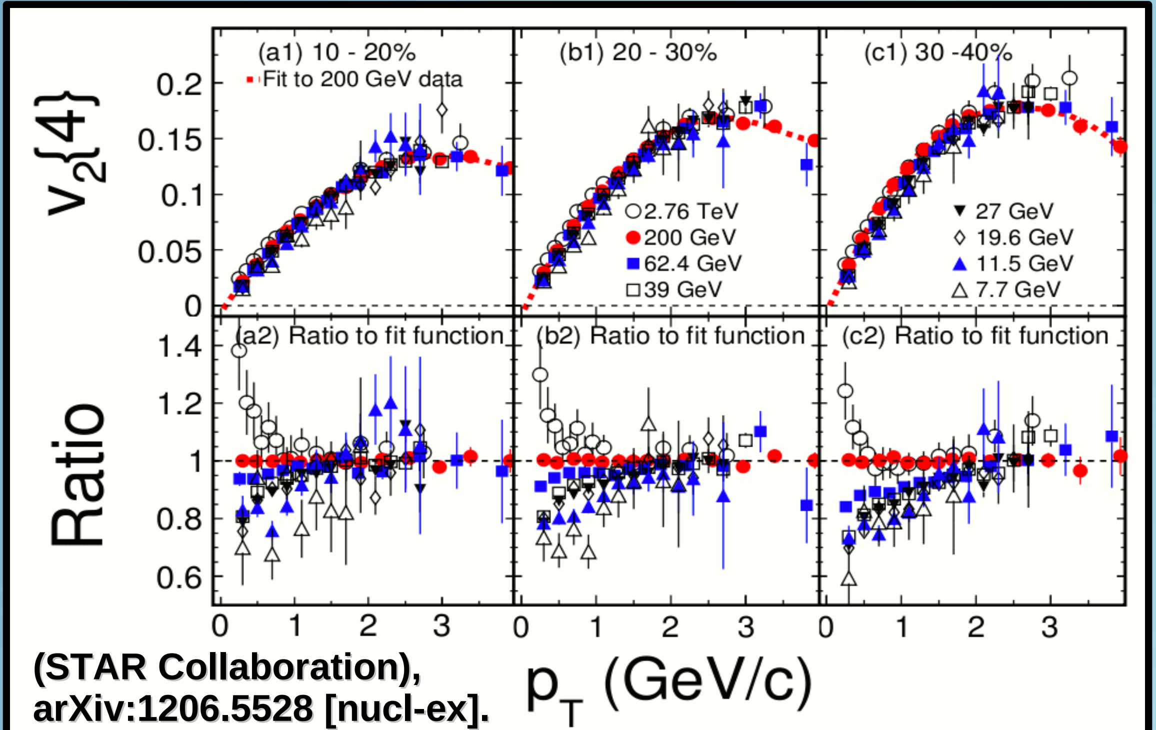
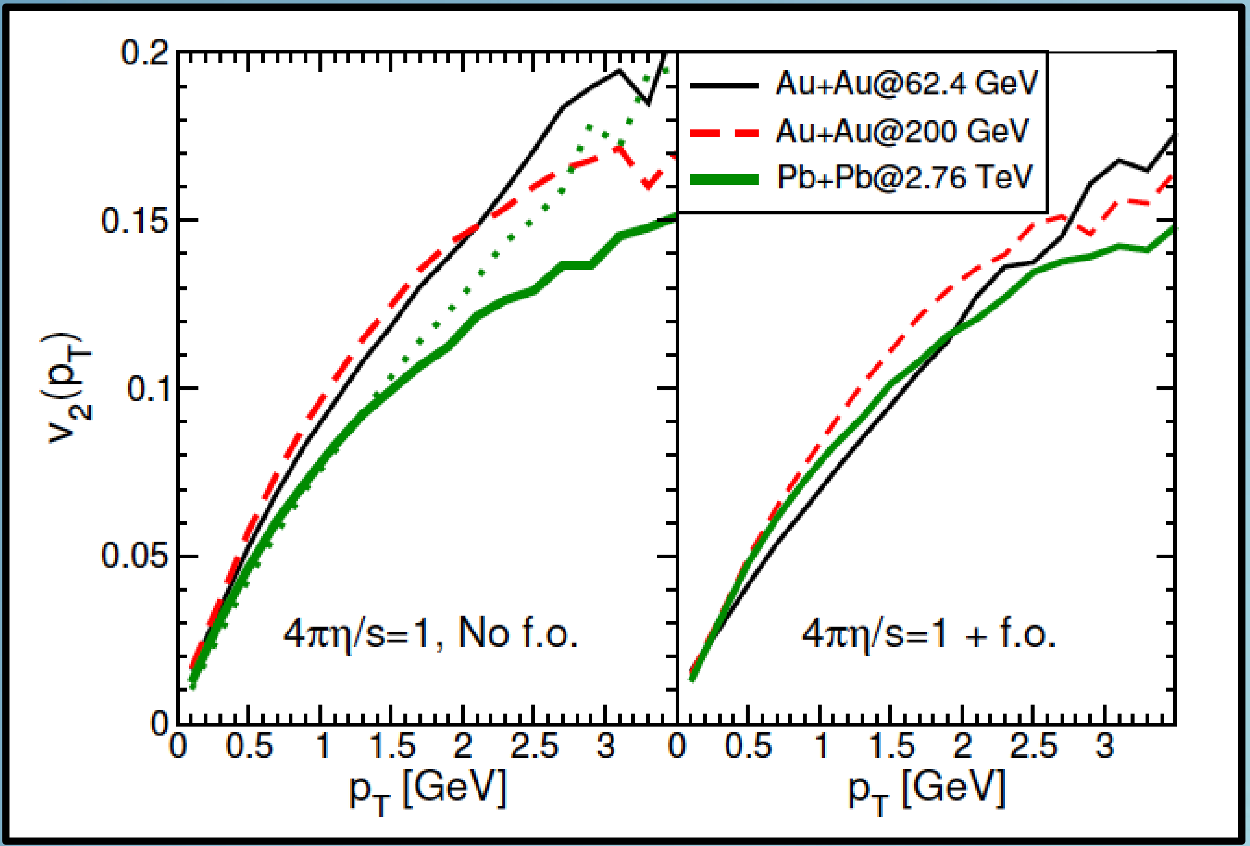
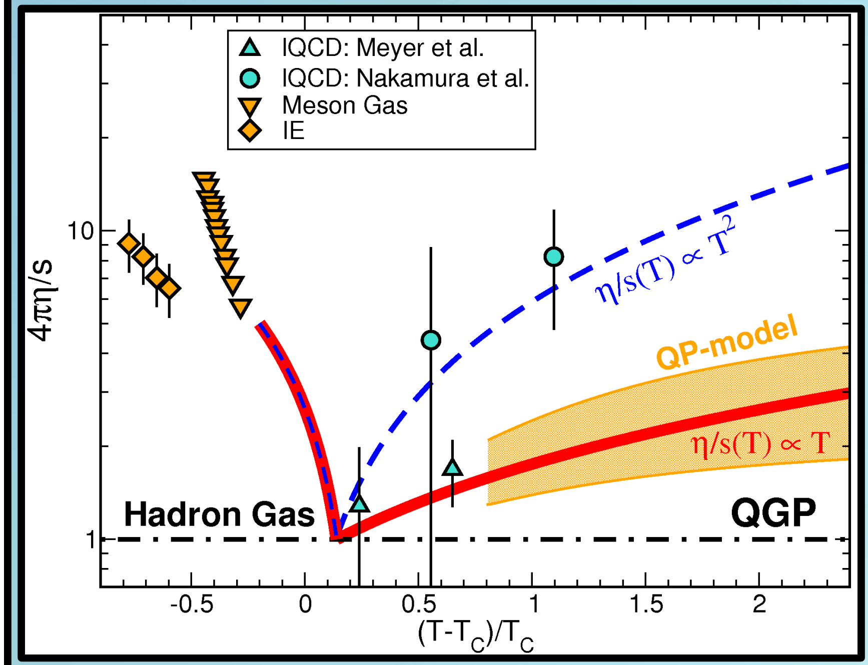


(STAR Collaboration), arXiv:1206.5528 [nucl-ex].

Temperature dependent η/s(T)

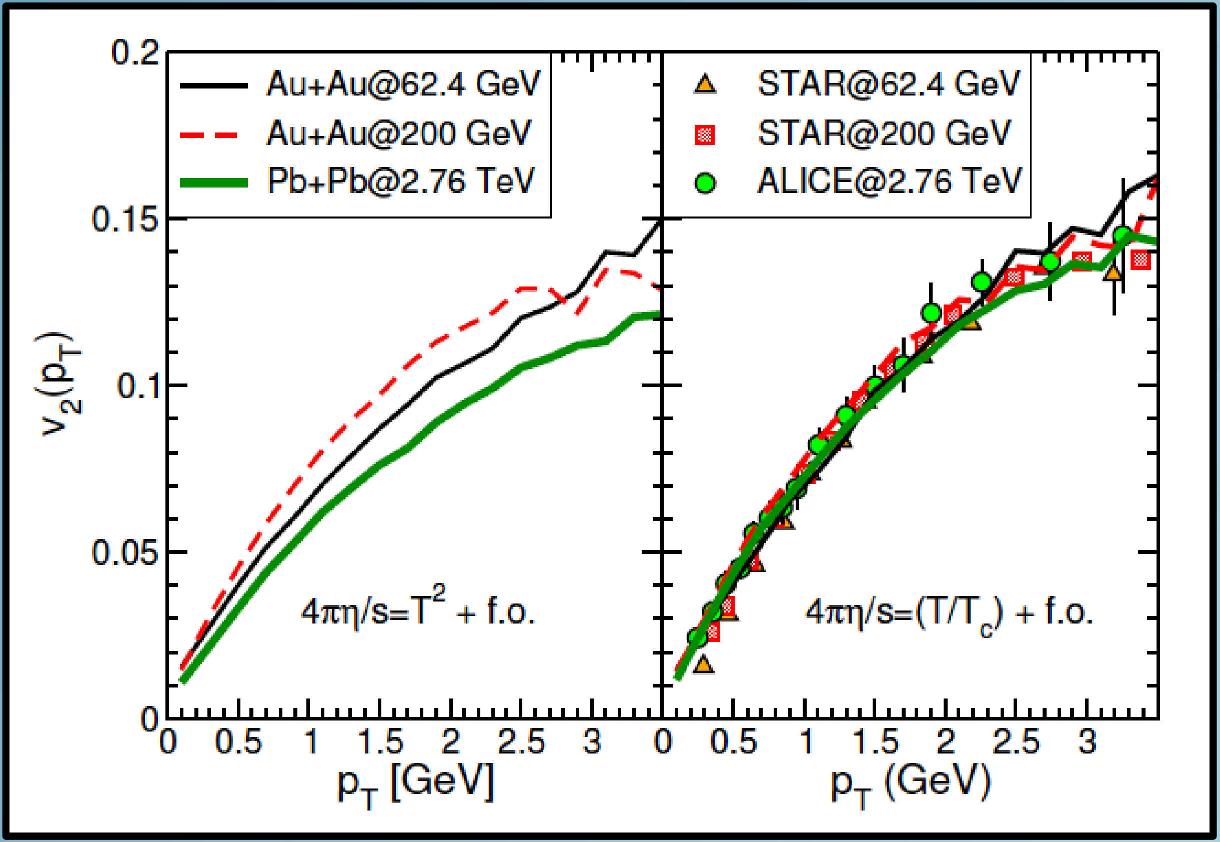


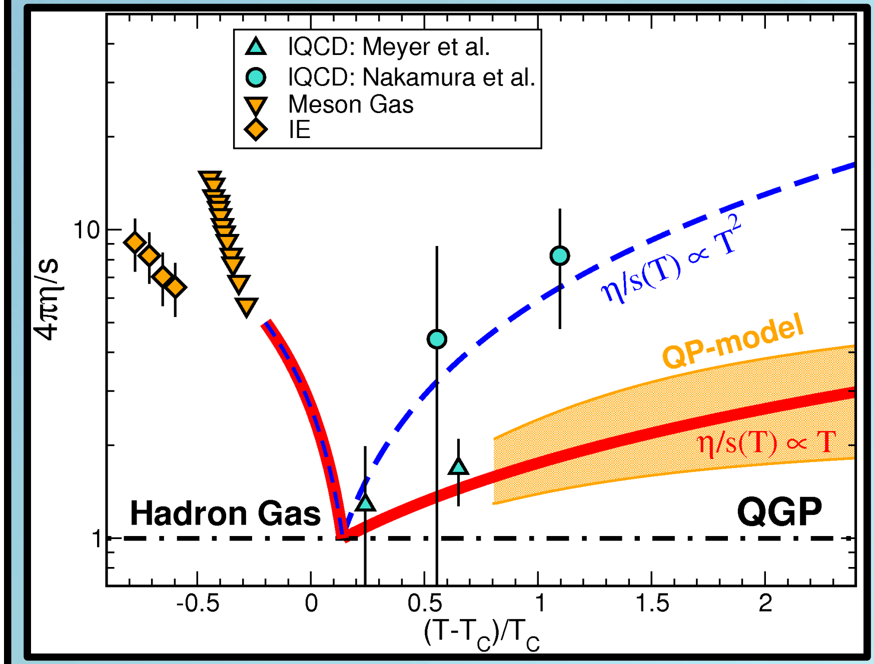


Plumari, Greco, Csernai, arXiv:1304.6566

- **For 4πη/s=1 during all the evolution of the fireball we get a discrepancy for the $v_2(p_T)$, in particular we observe a smaller $v_2(p_T)$ at LHC.**
- **Similar results for η/s∝ T² → a discrepancy about 20%.**
- **Notice only with RHIC → scaling for 4πη/s=1 LHC data play a key role**

Temperature dependent η/s(T)





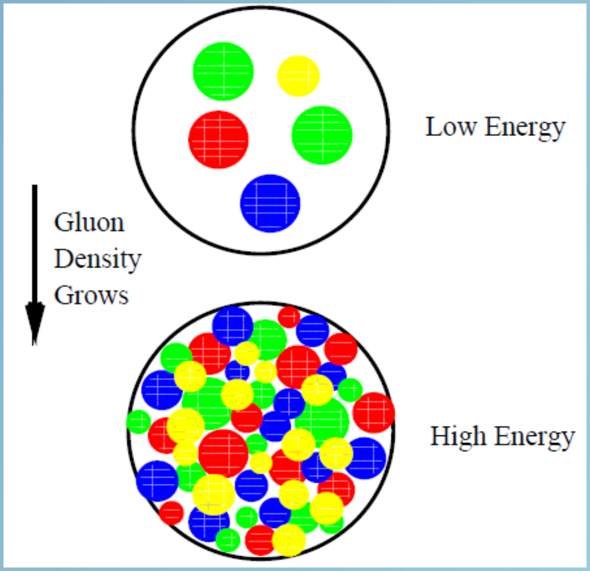
Plumari, Greco, Csernai, arXiv:1304.6566

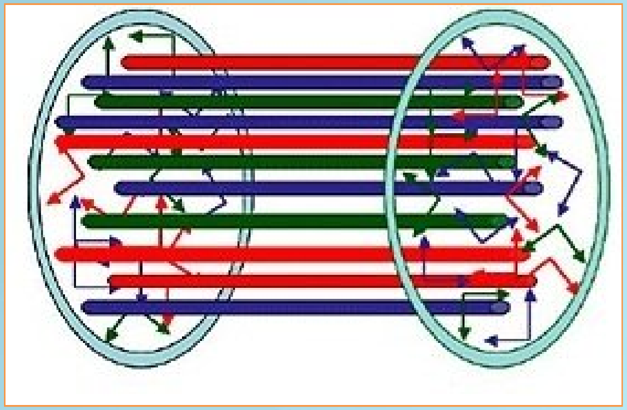
- **Invariance of $v_2(p_T)$ in BES suggest that the system goes through a phase transition.**
- **Hope: v_n, n>3 with an event-by-event analysis will put even stronger consstraint**
- **Implementation of local fluctuation under development**

- **Similar results: R. A. Lacey et al., arXiv:1305.3341 [nucl-ex].**

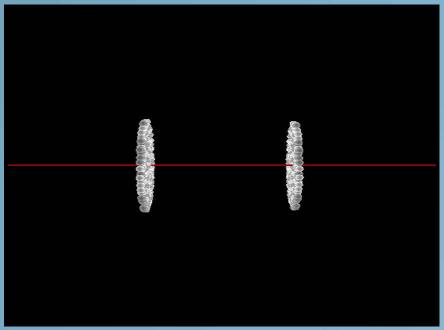
What about Color Glass condensate initial stat

- Kinetic Theory with a Q_s saturation scale

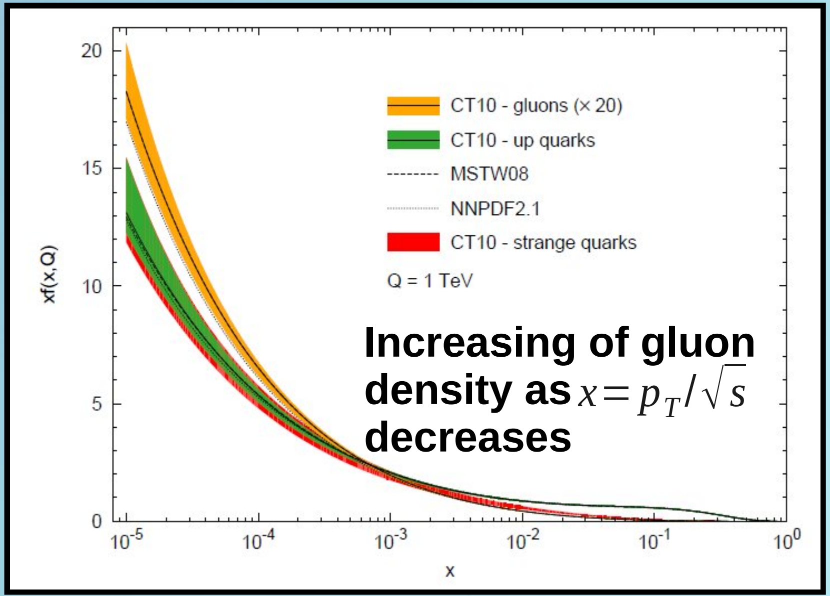




Initial Conditions: Glasma



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



[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^2_s ~ 1-2 GeV^2

At LHC Q^2_s ~ 2-5 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

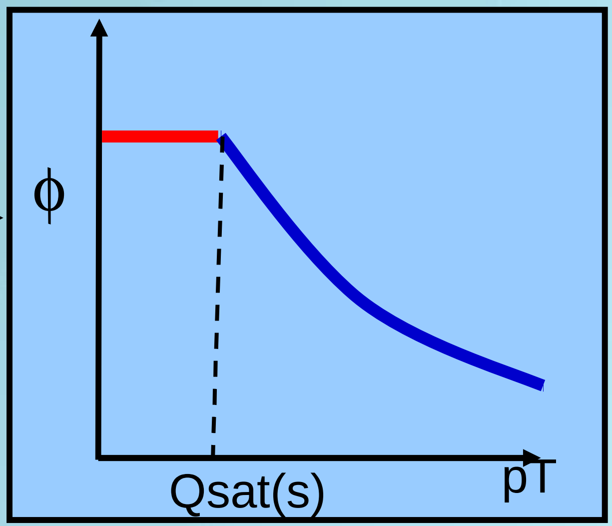
Initial Conditions: fKLN

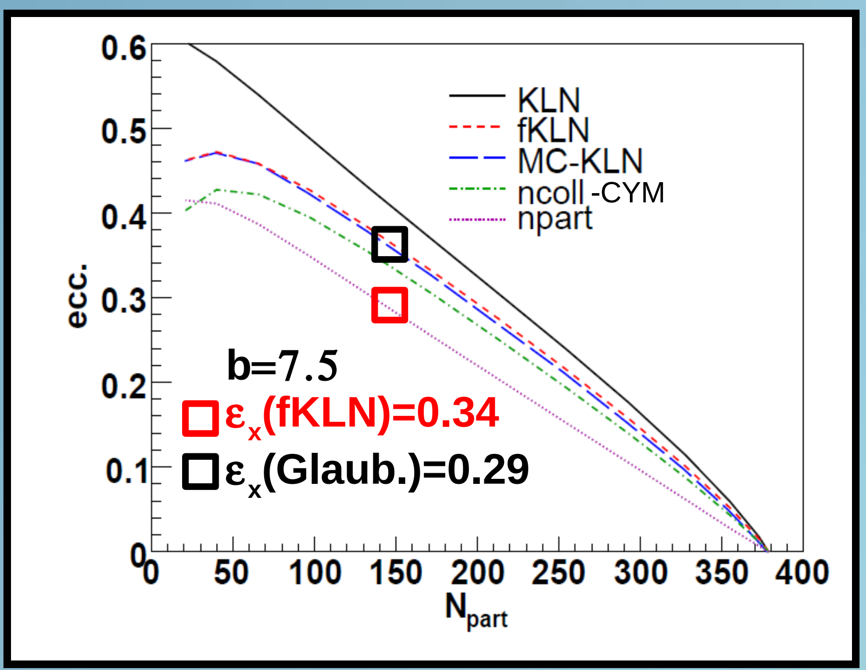
Kharzeev *et al.*, Phys. Lett. B561, 93 (2003)
Nardi *et al.*, Phys. Lett. B507, 121 (2001)
Drescher and Nara, PRC75, 034905 (2007)
Hirano and Nara, PRC79, 064904 (2009)
Albacete and Dumitru, arXiv:1011.5161[hep-ph]

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

Saturation effects built in the ϕ.

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





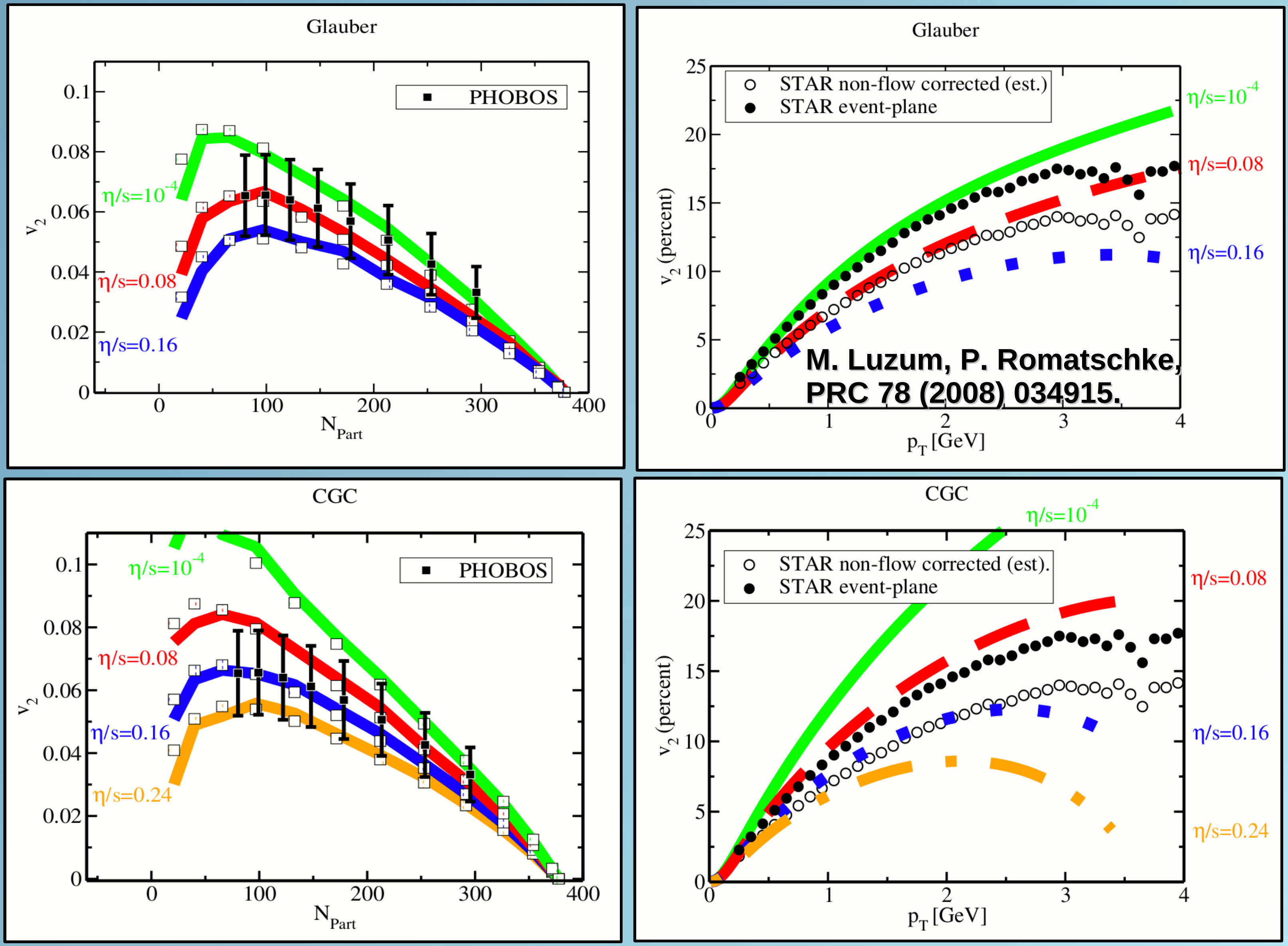
$$Q_{s,A}^2(x, \boldsymbol{x}_\perp) \propto Q_s^2 T_A(\boldsymbol{x}_\perp) x^{-\lambda}$$

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

V2 from fKLN in viscous hydro

1) r-space from KLN (larger ε_x)

2) p-space thermal at $t_0 \approx 0.6$ fm/c - we call it <u>fKLN-Th</u>



Glauber

$$\eta/s \approx \frac{1}{4\pi}$$

CGC

$$\eta/s \approx \frac{2}{4\pi}$$

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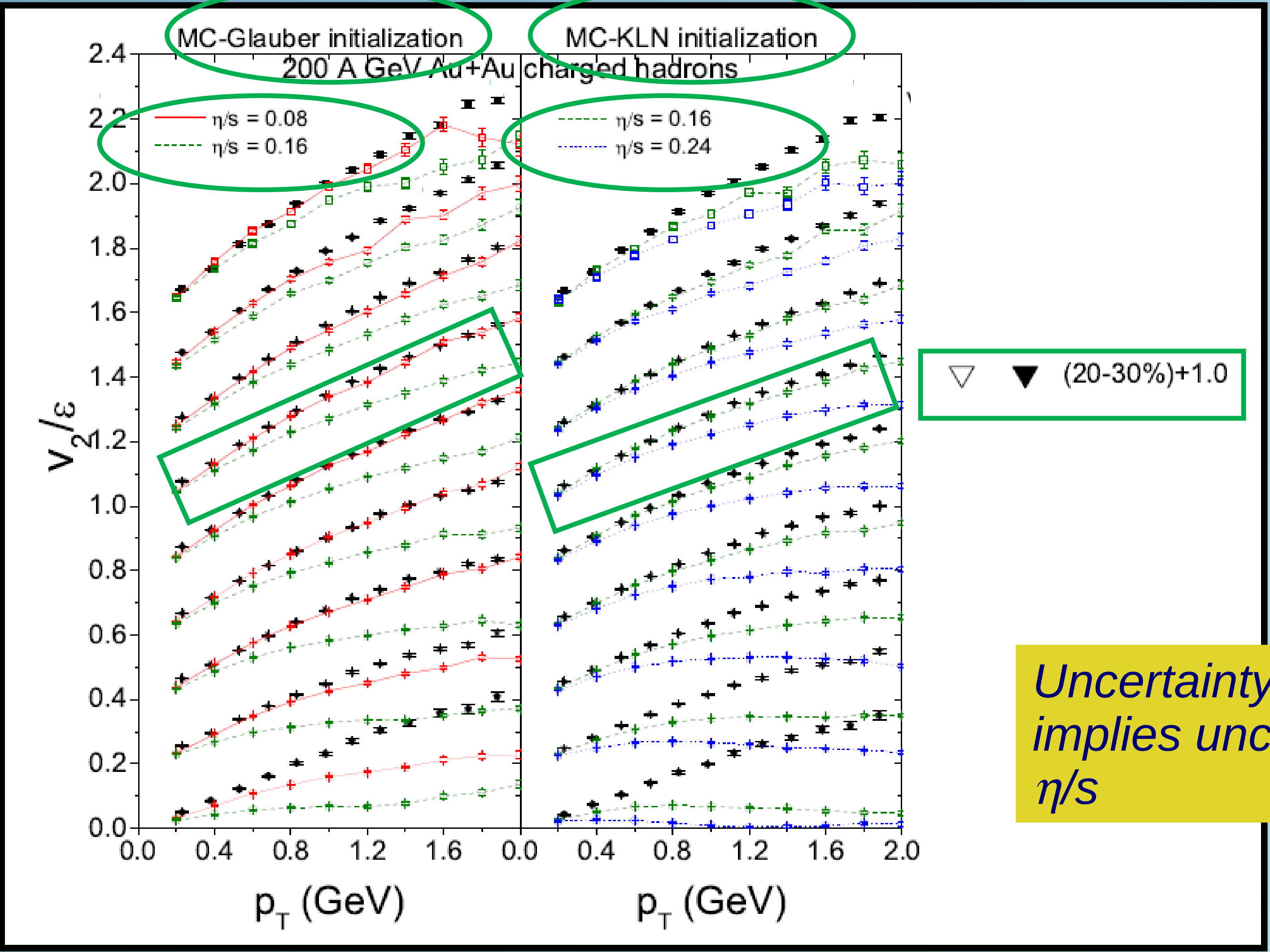


Larger ε_x - > higher η/s to get the same $v_2(p_T)$

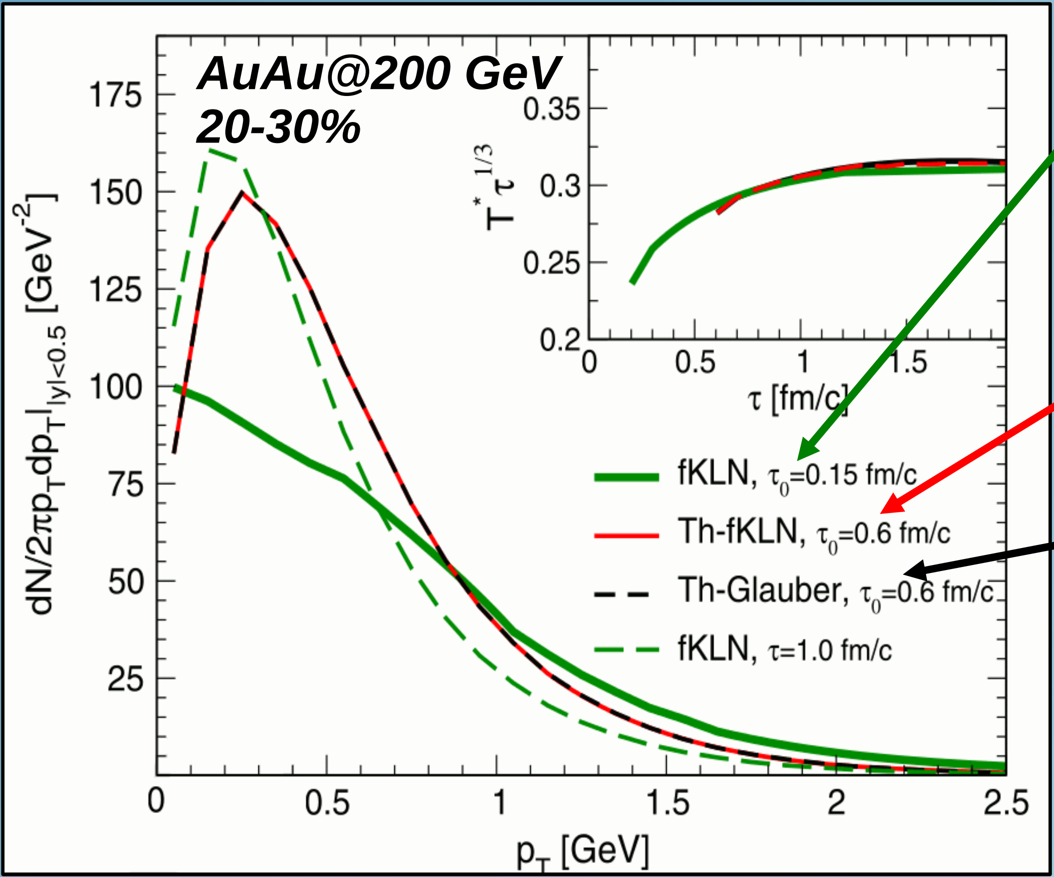
Glauber: $\eta/s \approx \frac{1}{4\pi}$

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

Uncertainty on initial conditions implies uncertainty of a factor 2 on η/s

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

Implementing fKLN pT disstribution



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

fKLN only in x space (like in Hydro) ε_x=0.34, Q_s=0

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

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

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

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

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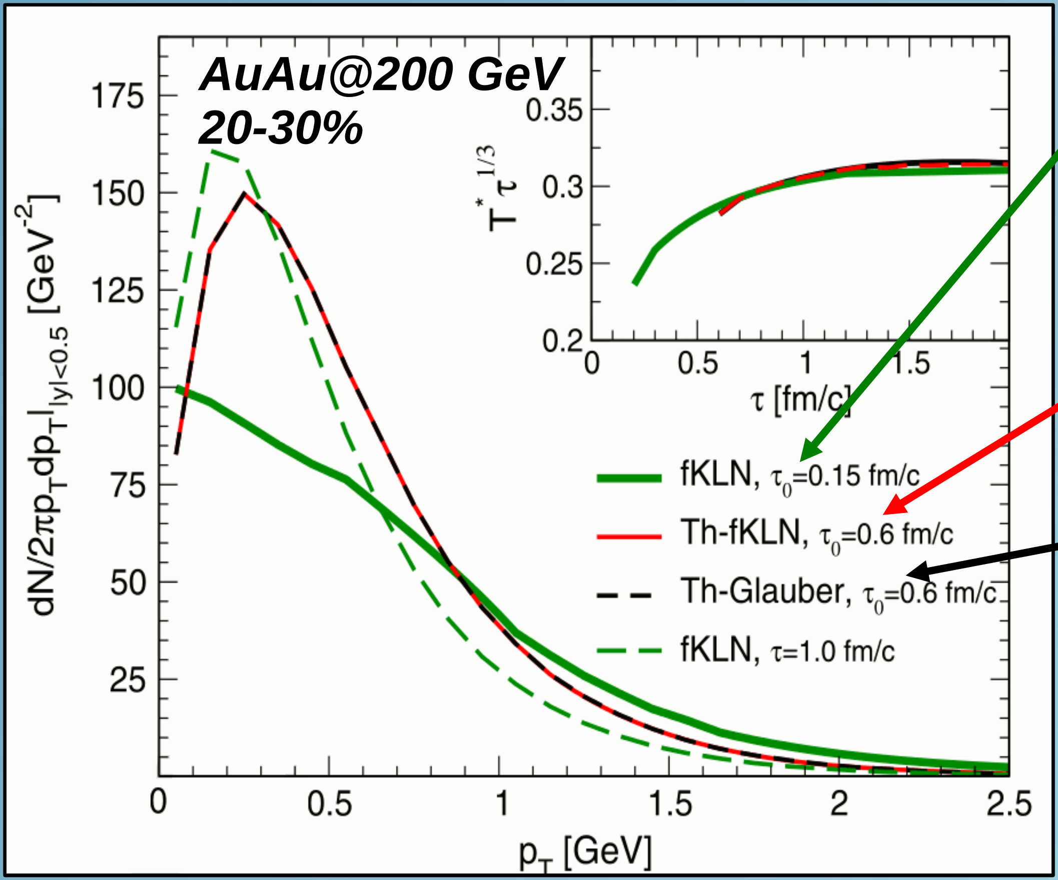

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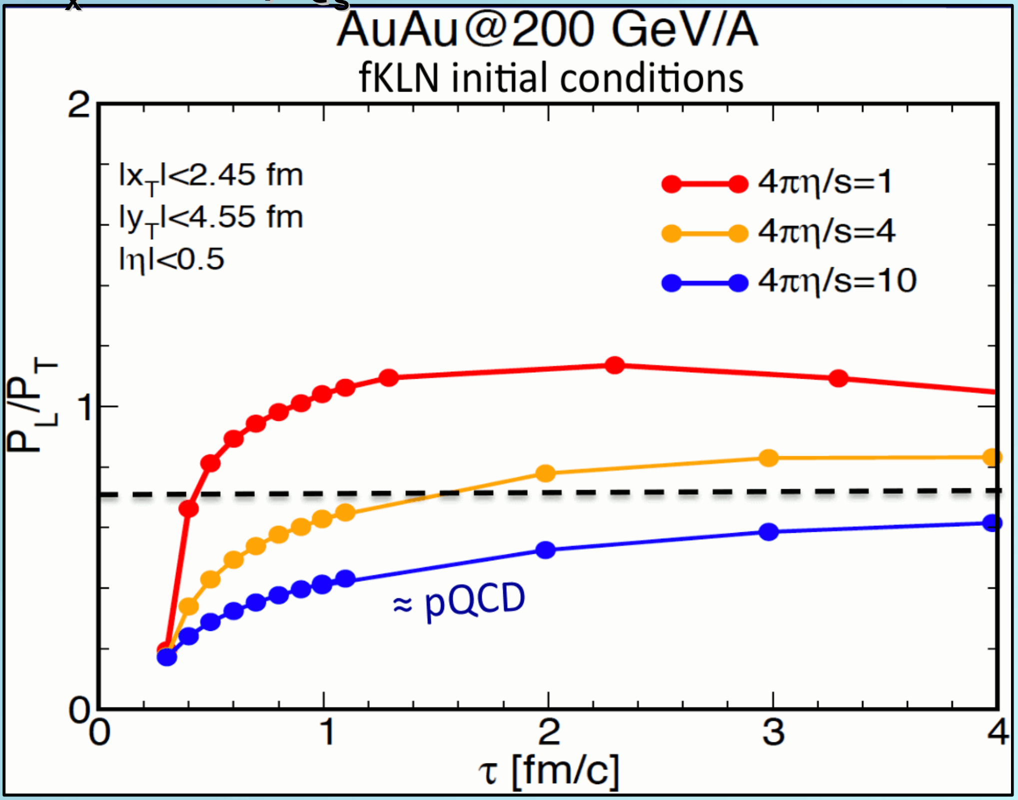


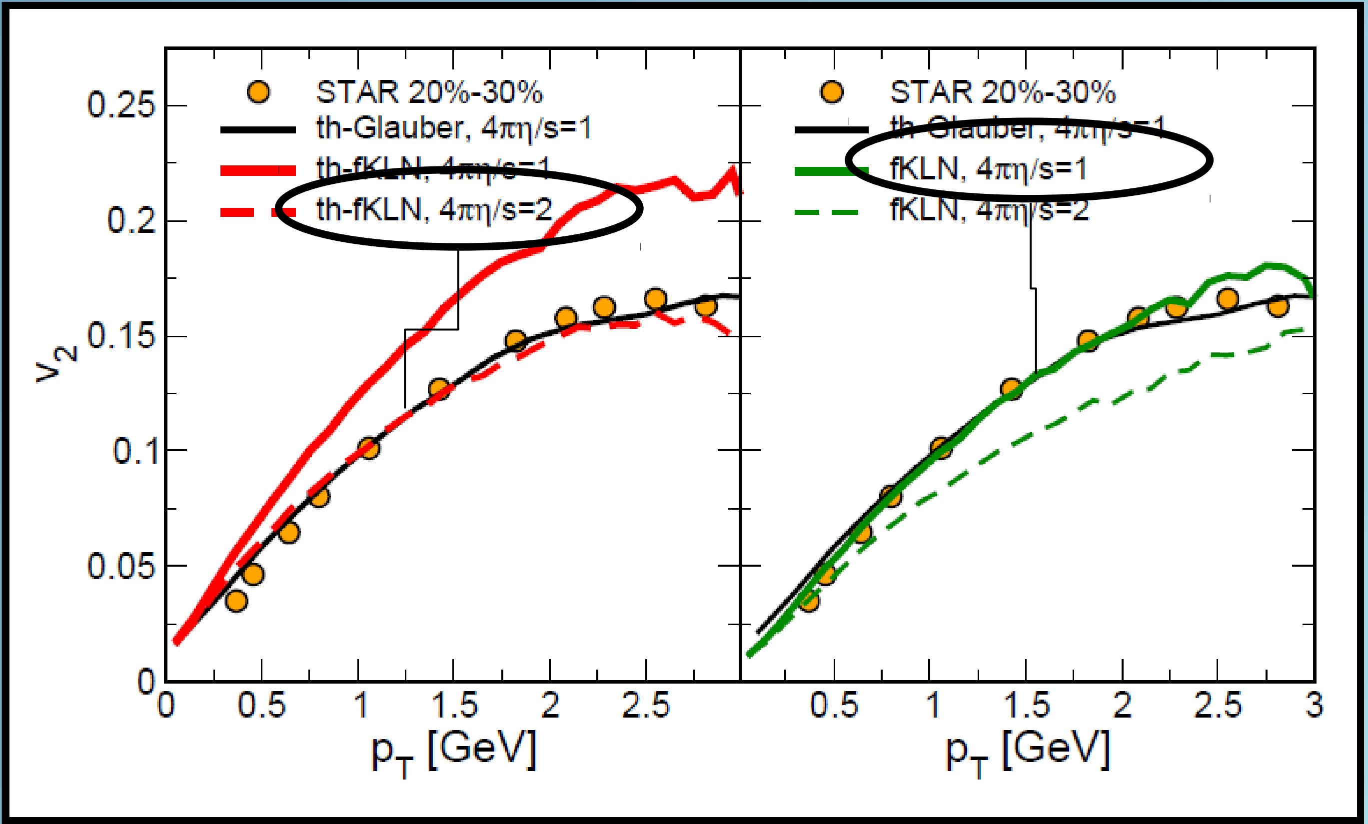
- **Semi-quantitative agreement with Florkowski PRD88 (2013) 034028.**

our approach is 3+1D no relaxation time approximation but no field

Elliptic flow at RHIC from: fKLN Glasma

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

Au+Au@200 GeV

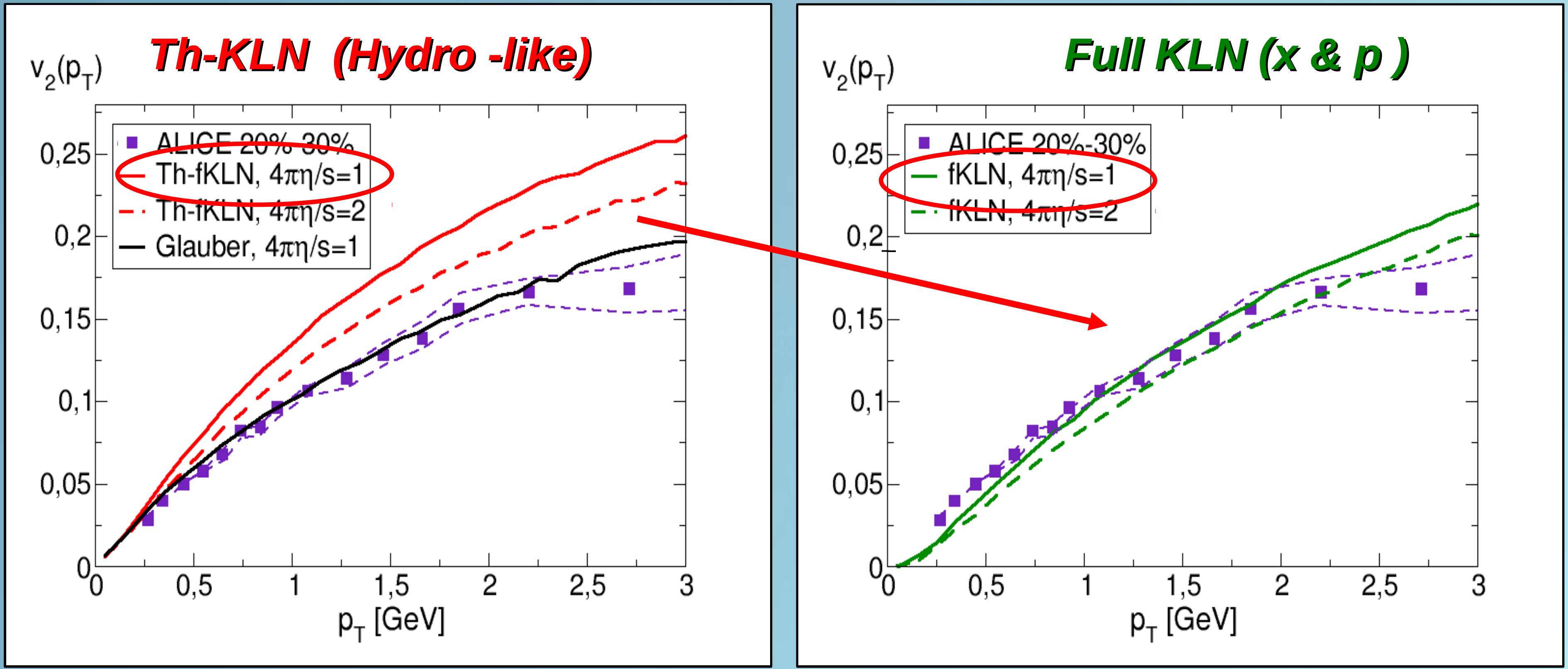


M. Ruggieri *et al.*, 1303.3178 [nucl-th]

- **When implementing KLN and Glauber like in Hydro we get the same of Hydro**
- **When implementing full KLN we get close to the data with $4\pi\eta/s = 1$:**
  larger ε_x compensated by Q_s saturation scale (non-equilibrium distribution)

Elliptic flow at LHC from: fKLN Glasma

Pb+Pb@2.76 TeV



At LHC the larger saturation Q_s (≈ 2.4 GeV) scale makes the effect larger:

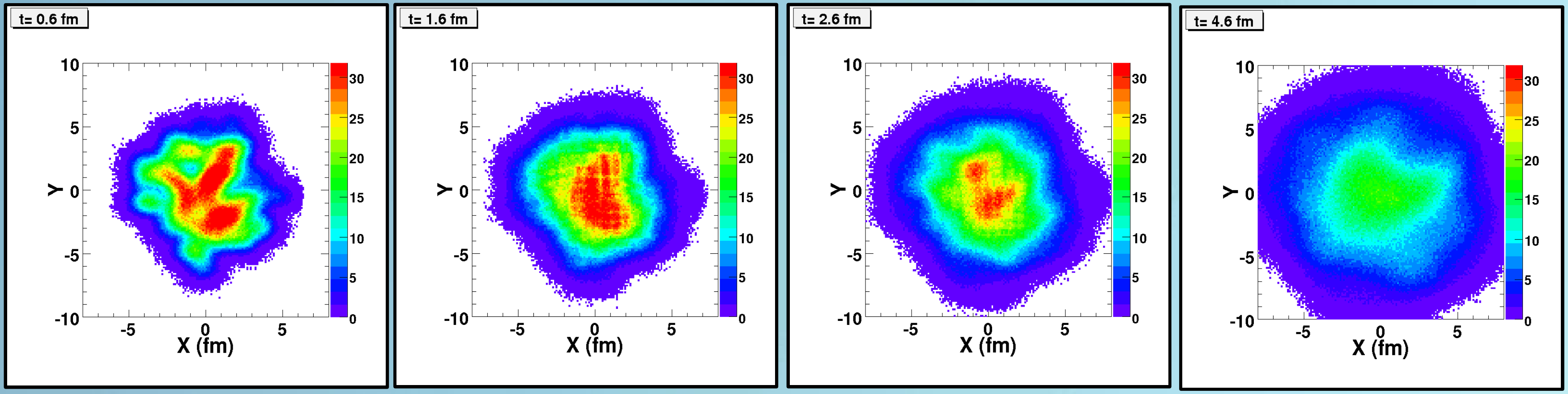
- $4\pi\eta/s$= 2 not sufficient to get close to the data for Th-KLN

- $4\pi\eta/s$=1 it is enough if one implements both x &p

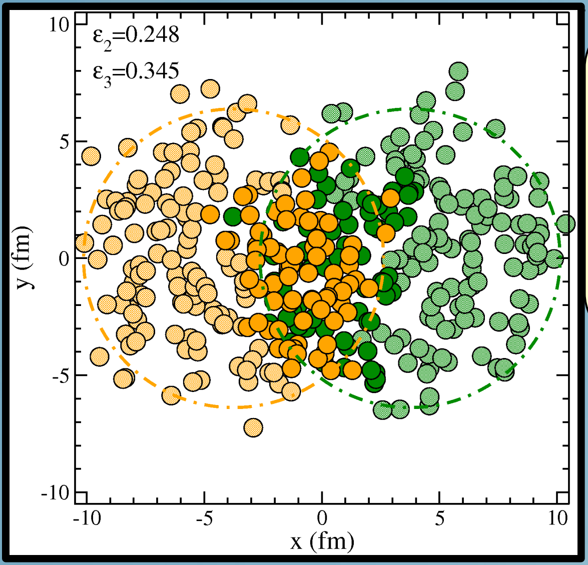
Next step –

To include the Initial State Fluctuations

(Preliminary results)

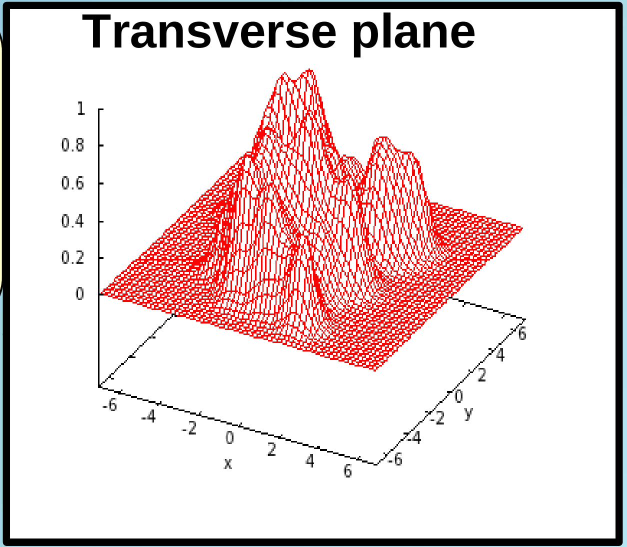


Initial State Fluctuations (Preliminary)



Monte Carlo Glauber

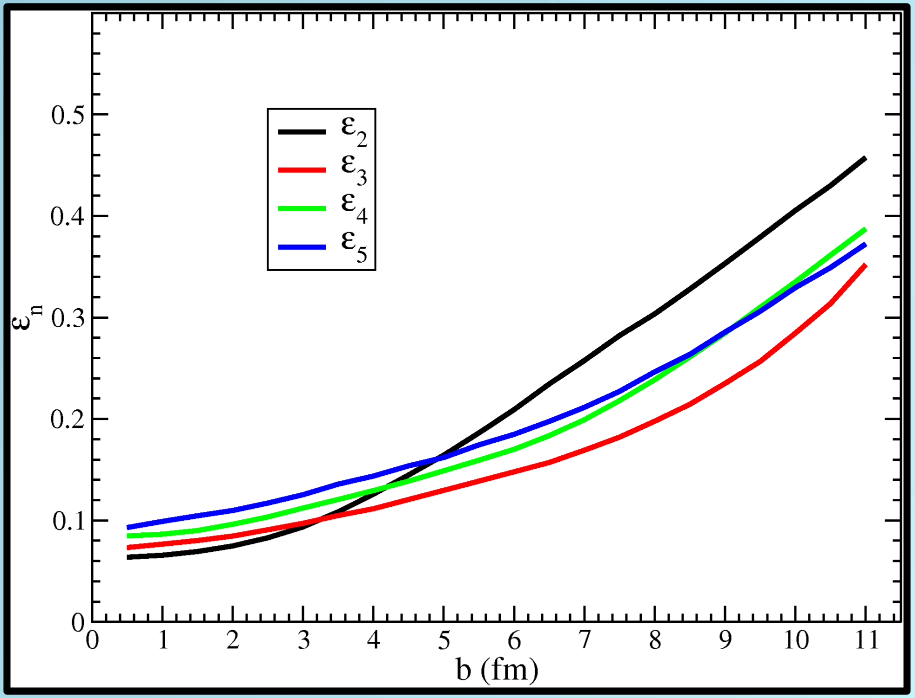
$$\rho_\perp(x,y) \propto \sum_{i=1}^{N_{part}} \exp\{-[(x-x_i)^2+(y-y_i)^2]/(2\sigma^2)\}$$



Characterization of the initial profile in terms of Fourier coefficients

$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\phi-\Phi_n)]\rangle}{\langle r_\perp^n\rangle} \qquad \Phi_n = \frac{1}{n}\arctan\frac{\langle r_\perp^n \sin(n\phi)\rangle}{\langle r_\perp^n \cos(n\phi)\rangle}$$

$$r_\perp = \sqrt{x^2+y^2}, \qquad \phi = arct(y/x)$$



G-Y. Qin, H. Petersen, S.A. Bass and B. Muller, PRC82,064903 (2010).
H.Holopainen, H. Niemi and K.J. Eskola, PRC83, 034901 (2011).

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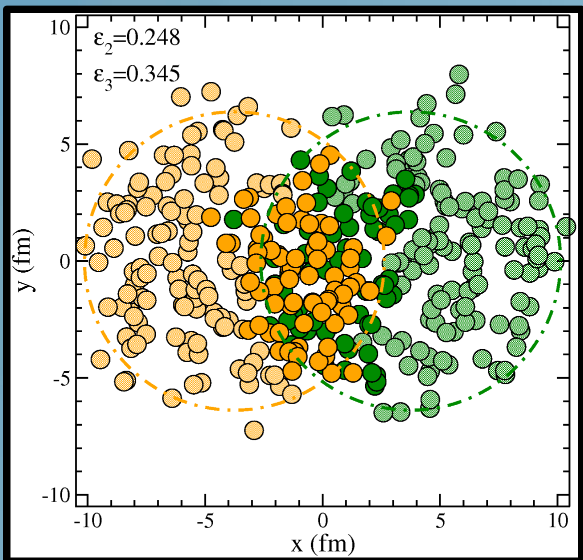

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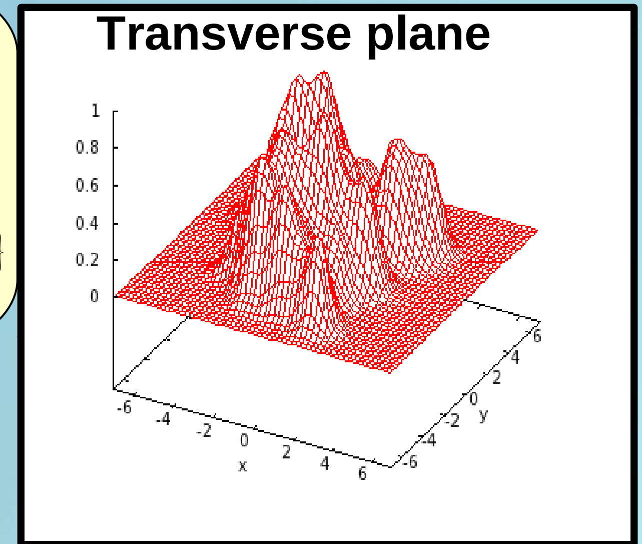

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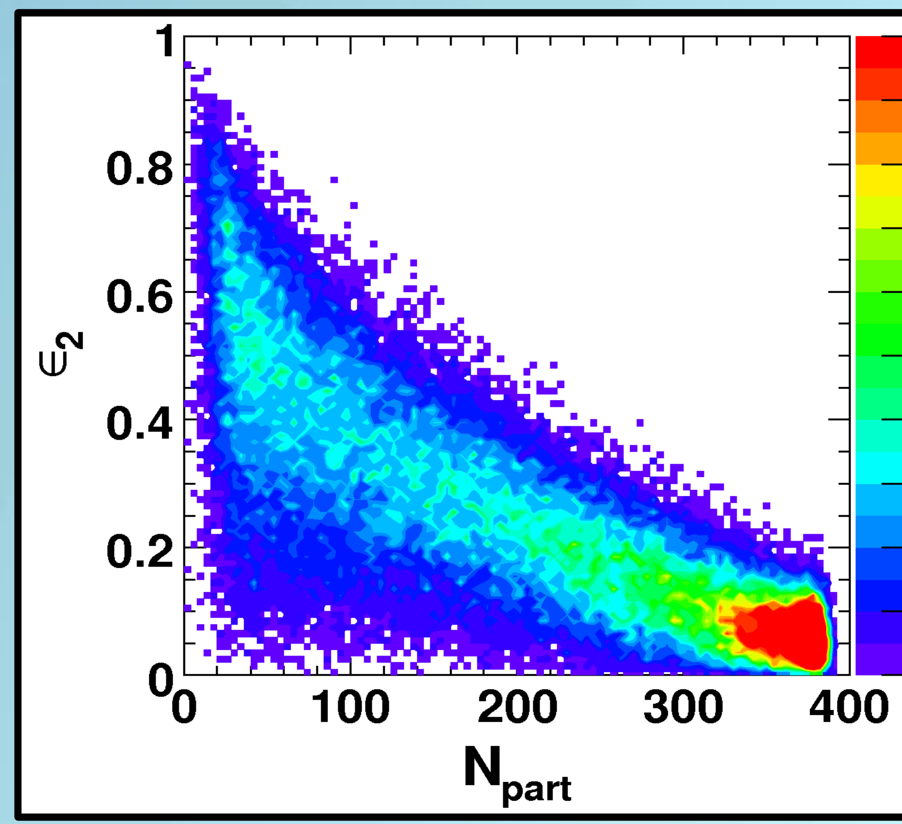

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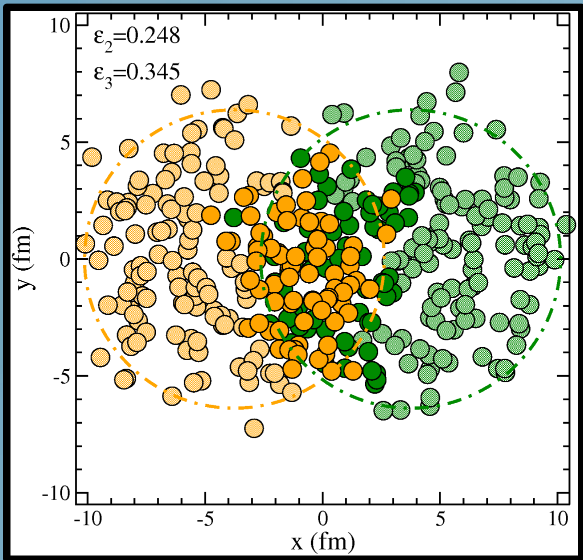

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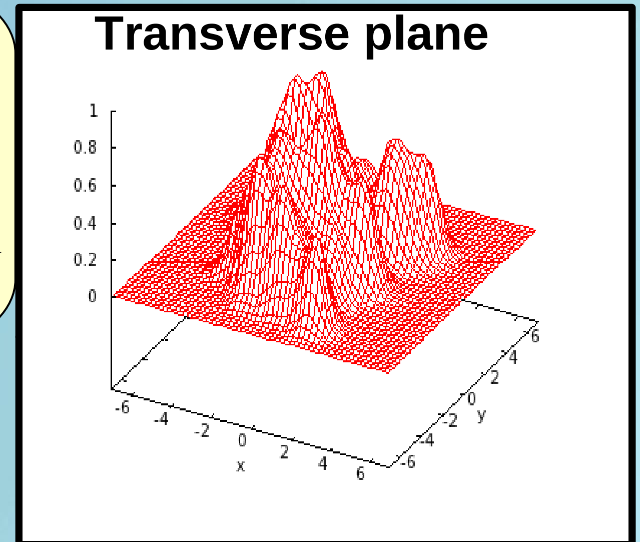

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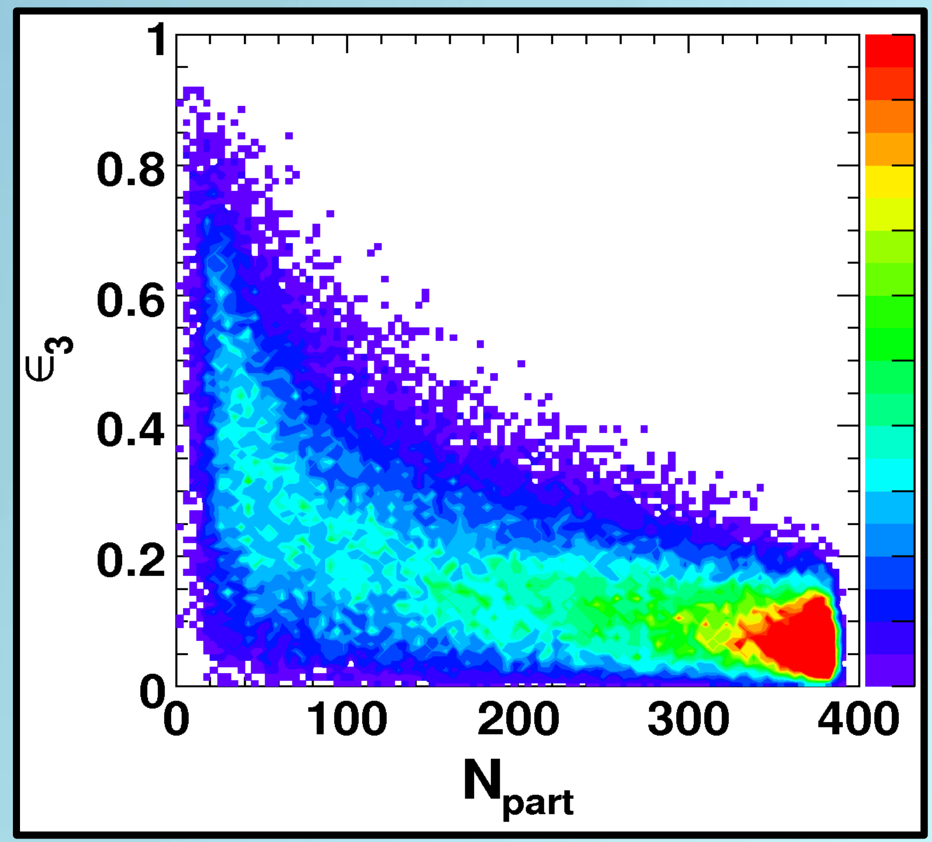

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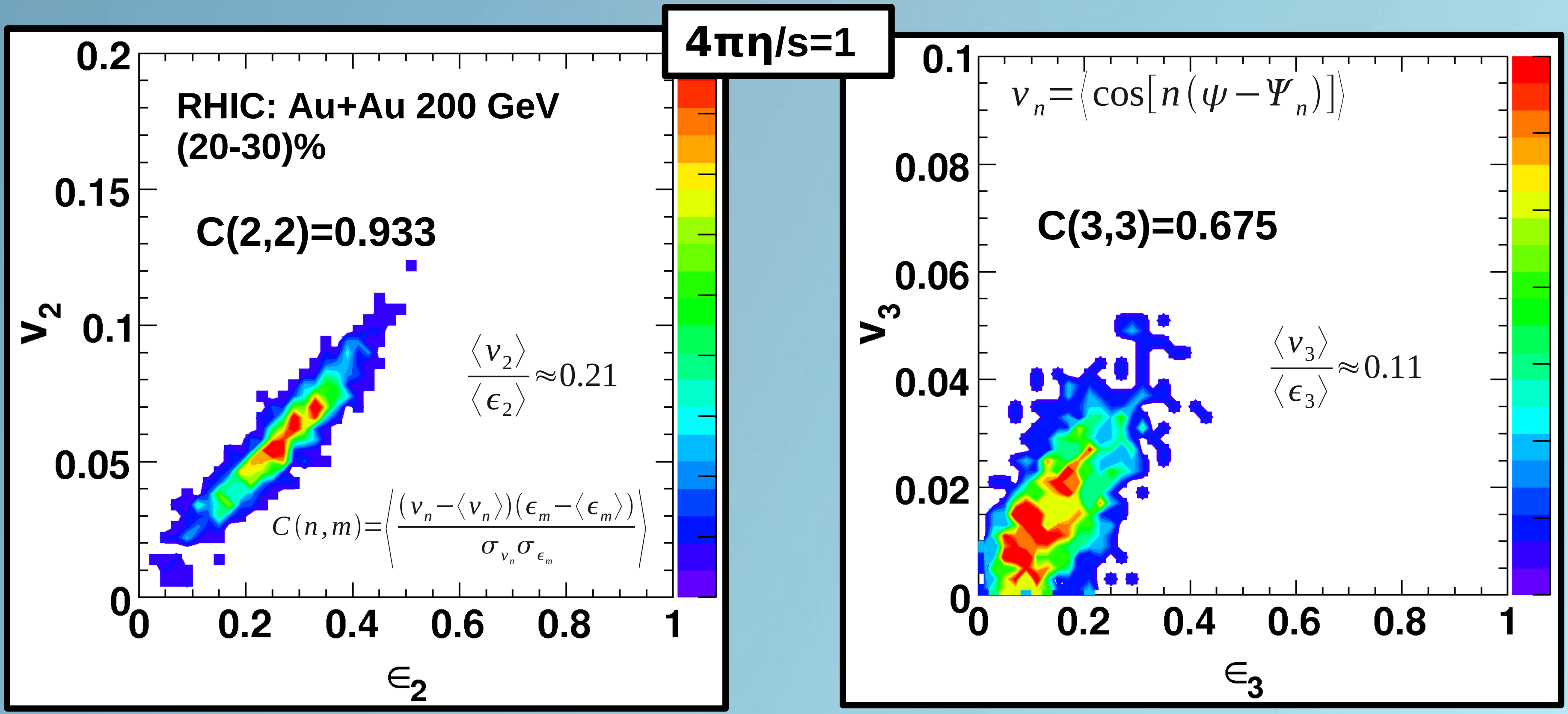
Initial State Fluctuations: v_n vs ε_n (Preliminary)



- v_2 and v_3 linearly correlated to the corresponding eccentricities ε_2 and ε_3 rispectively.
- v_4 and ε_4 weak correlated similar to hydro calculations:

F.G.Gardim,F.Grassi,M.Luzum and J.Y.Ollitrault NPA904 (2013) 503.
Niemi, Denicol, Holopainen and Huovinen PRC87(2013) 054901.

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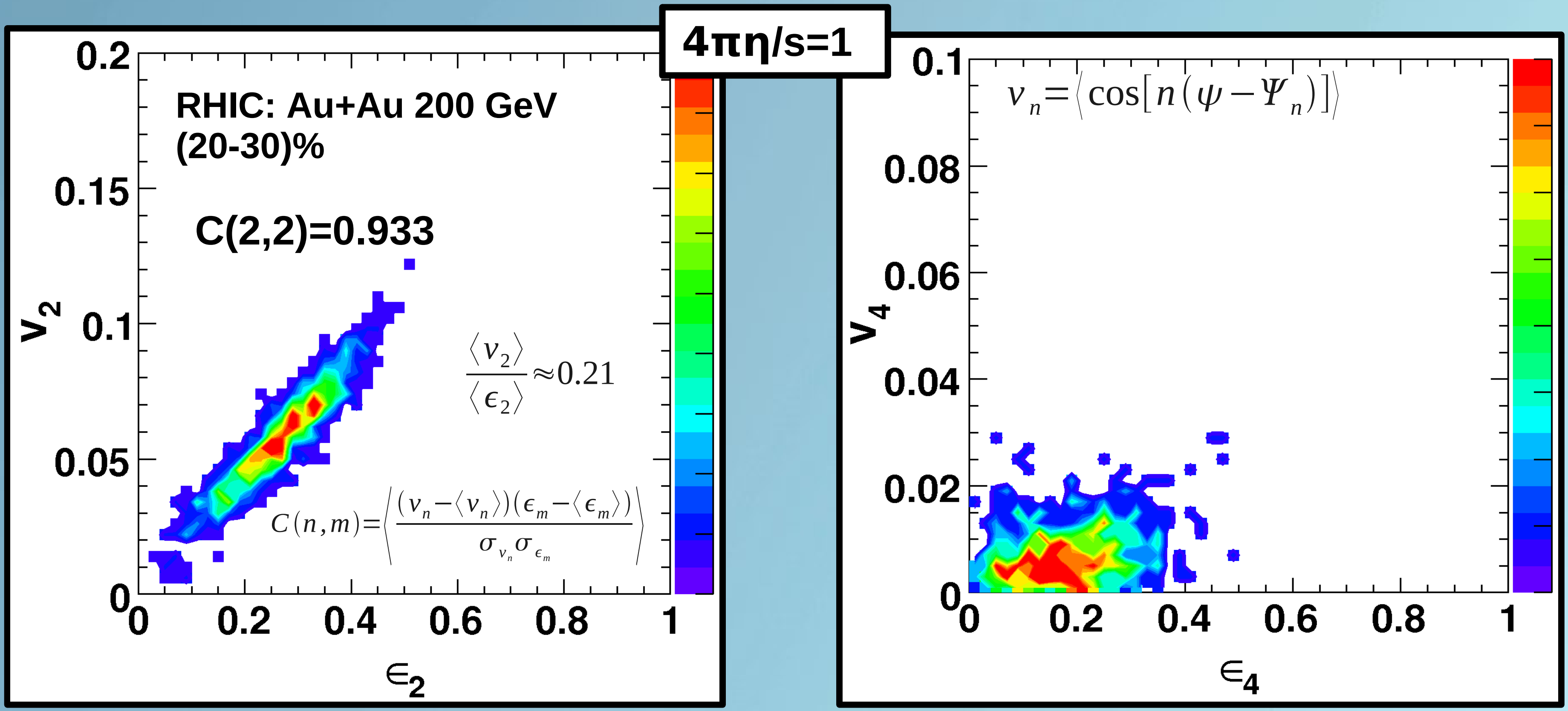

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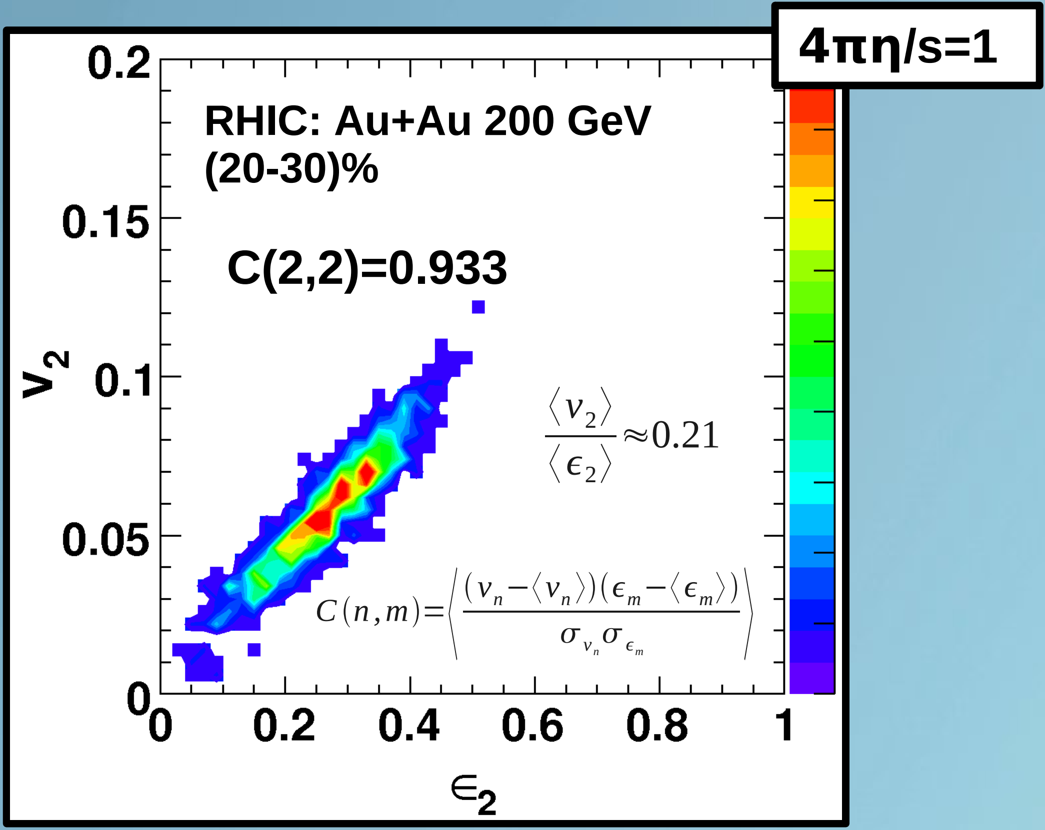

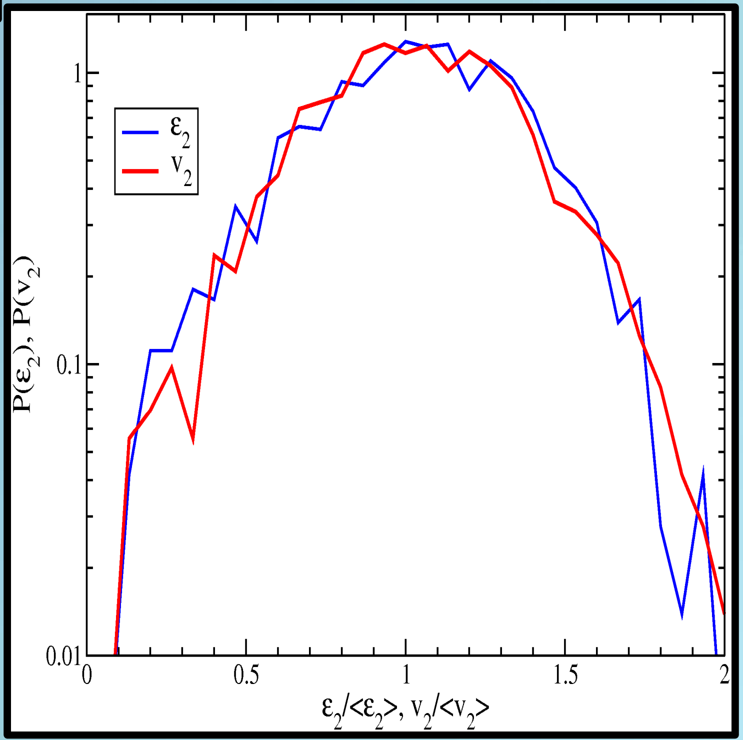

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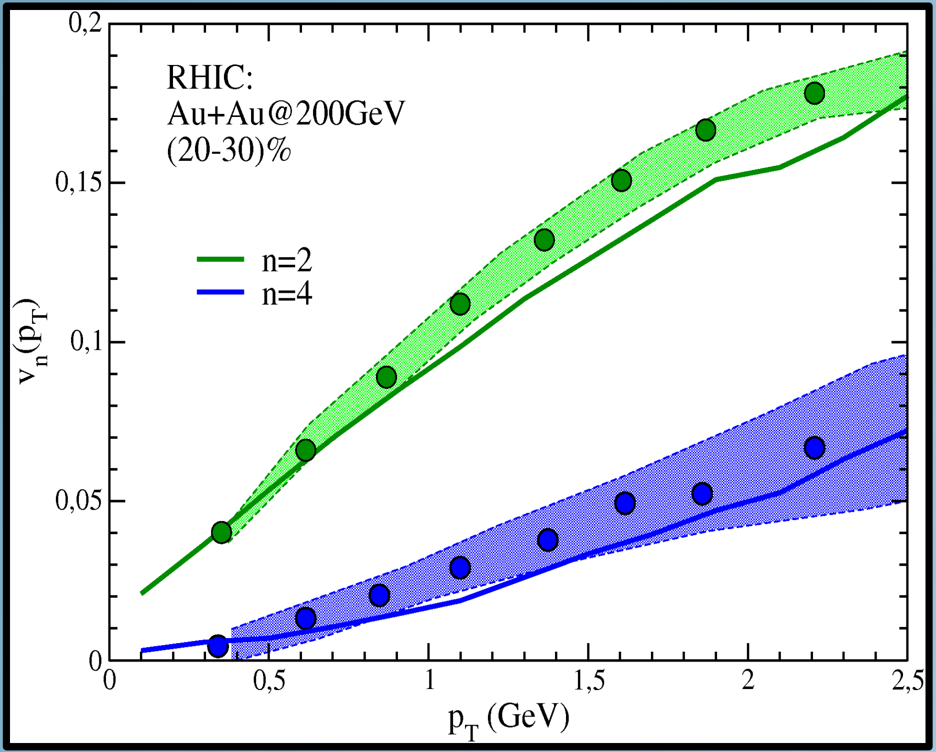
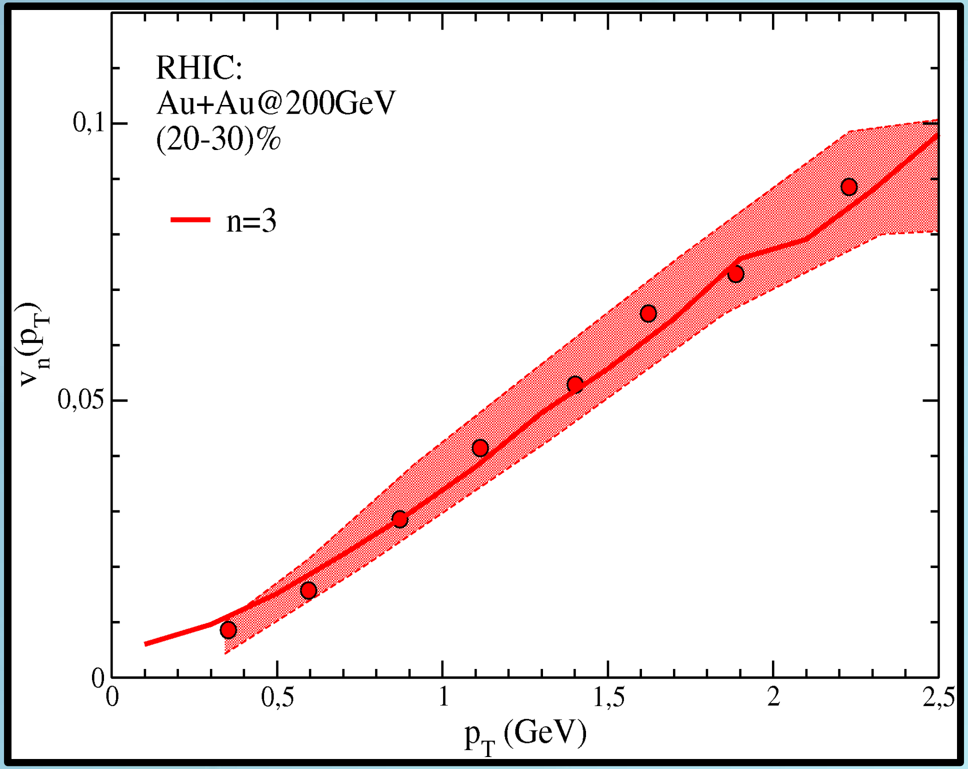
Niemi, Denicol, Holopainen and Huovinen PRC87(2013) 054901.

Initial State Fluctuations: $v_n(p_T)$ (Preliminary)

Data taken from: A. Adare et al. [PHENIX collaboration], Phys.Rev. Lett. 107, 252301 (2011).





- **Like in viscous hydro the data of $v_n(p_T)$ at RHIC energies are described with $4\pi\eta/s=1$.**

Conclusions

Enhancement of $\eta/s(T)$ in the cross-over region affect differently the expanding QGP from RHIC to LHC.

At LHC nearly all the v_2 from the QGP phase.

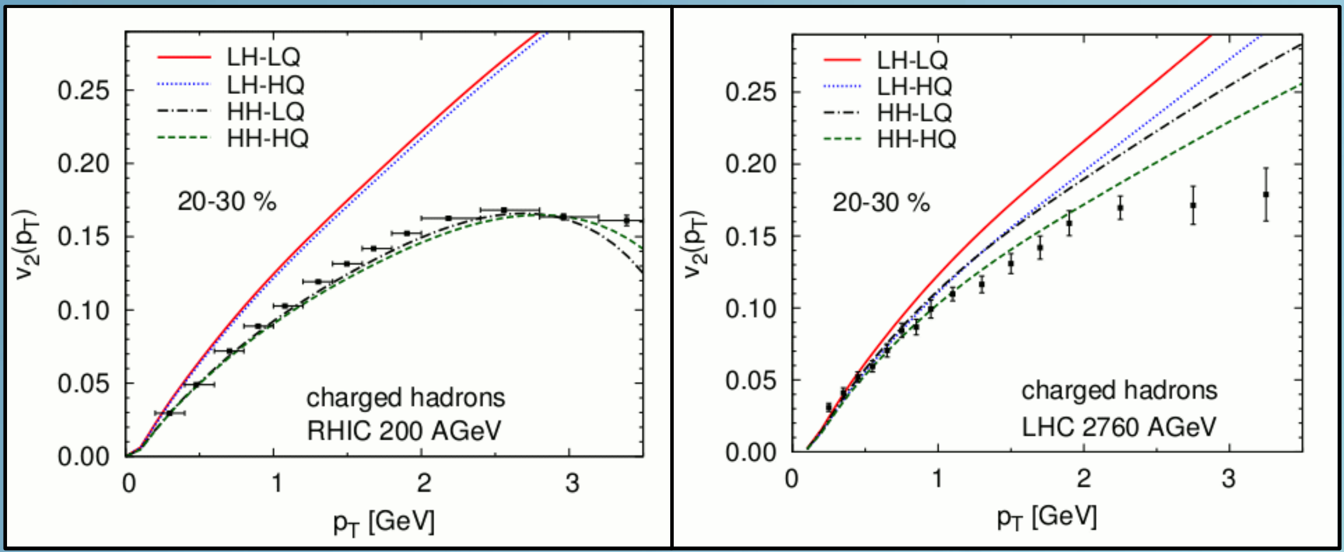
The scaling of $v_2(p_T)$ from Beam Energy Scan indicate a 'U' shape of $\eta/s(T)$ this would be a signature of $\eta/s(T)$ behavior typical of a phase transition.

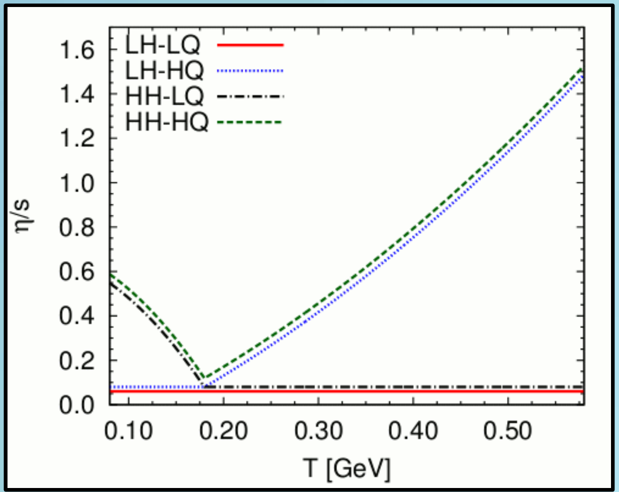
For $4\pi\eta/s=1$ v_2 and v_3 are linearly correlated to the corresponding eccentricities ε_2 and ε_3. While v_4 and ε_4 are weakly correlated similar to hydro calculation. (More detailed study is going on)

Outlook

To study the role of $\eta/s(T)$ on the v_n and their correlation on the initial eccentricities ε_n.
To study the effect of different initial condition (glasma) on $v_n \leftrightarrow \varepsilon_n$ correlation.

Effect of η/s(T) in Hydro: Niemi et al.





Niemi et al., PRL 106 (2011).

$$T^{\mu\nu} = T^{\mu\nu}_{eq} + \delta T^{\mu\nu} \leftarrow f_{eq} + \delta f$$

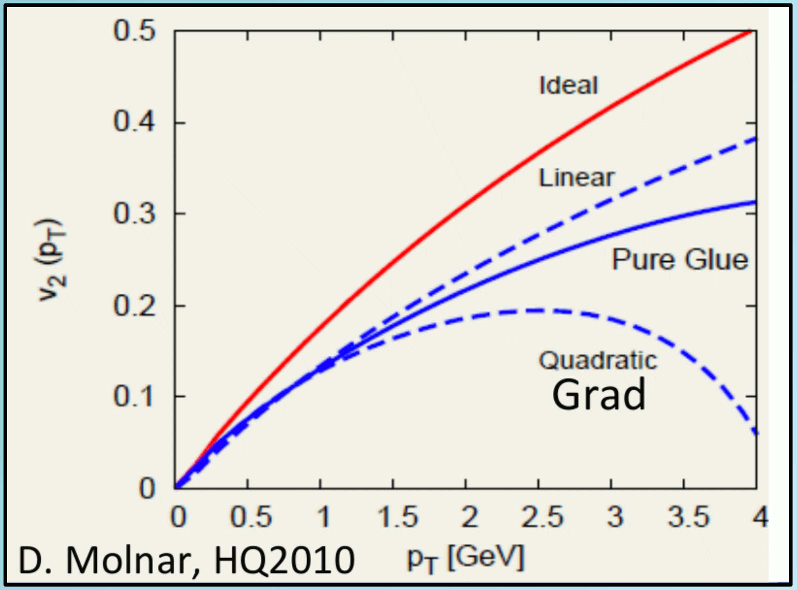
Grad ansantz

R. Lacey et al., PRC82

$$\delta f = \underbrace{\frac{\pi^{\mu\nu} p_\mu p_\nu}{(\epsilon + p) T^2} f_{eq} \approx \frac{\eta}{3s} \frac{p_T^2}{\tau T^2} f_{eq}}$$

- This inplies that the η is in Relaxation Time Approximation
  D. Teaney,Phys.Rev. C68 (2003) 034913

- Hydro is valid up to p_T~3 GeV



Extraction of the Shear Viscosity: Box calculation

Isotropic cross section: massive case

Massive case is relevant in quasi-particle models where M(T).
Good agreement with CE 1st order for isotropic cross section and massive particles.

1st Chapman-Enskog approximation

$$[\eta]_{1st} = 10\,T \left[\frac{K_3(z)}{K_2(z)}\right]^2 \frac{1}{c_{00}} = g(m_D, T)\frac{T}{\sigma_{tot}}$$

$$c_{00} = 16\left[\omega_2^{(2)} - z^{-1}\omega_1^{(2)} + (3z^2)^{-1}\omega_0^{(2)}\right]$$

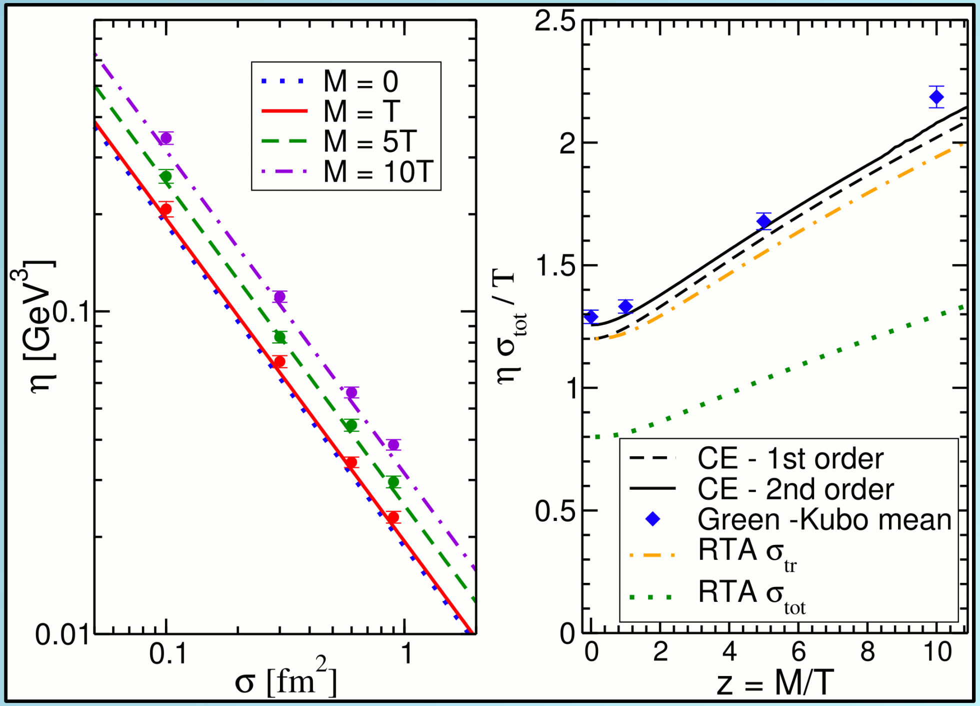
$$\omega_i^{(s)} = \frac{2\pi z^3}{[K_2(z)]^2}\int_1^\infty dy\,(y^2-1)^3 y^i K_j(2zy)\int_0^\pi d\Theta \sin\Theta \frac{d\sigma}{d\Omega}(1-\cos^s\Theta)$$

for $s=2 \;\propto \sigma_{tr}$

$$[\eta]_{1st}^{CE} = f(z)\frac{T}{\sigma_{tot}}$$

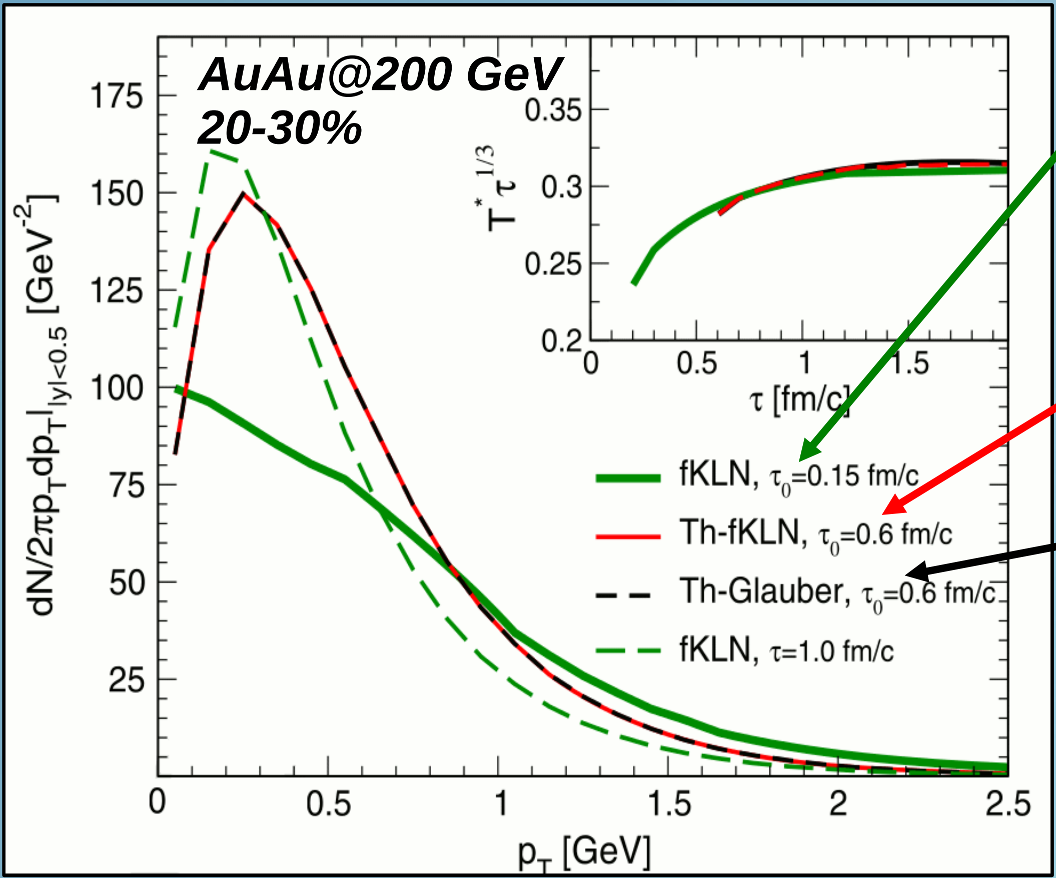
$$f(z) = \frac{15}{16}\frac{z^4 K_3^2(z)}{(15z^2+2)K_2(2z) + (3z^3+49z)K_3(2z)}$$

S. Plumari et al., arXiv:1208.0481 [nucl-th].



A. Wiranata, M. Prakash, arXiv:1203.0281 [nucl-th].
O. N. Moroz, arXiv:1112.0277 [hep-ph].

Implementing fKLN pT disstribution



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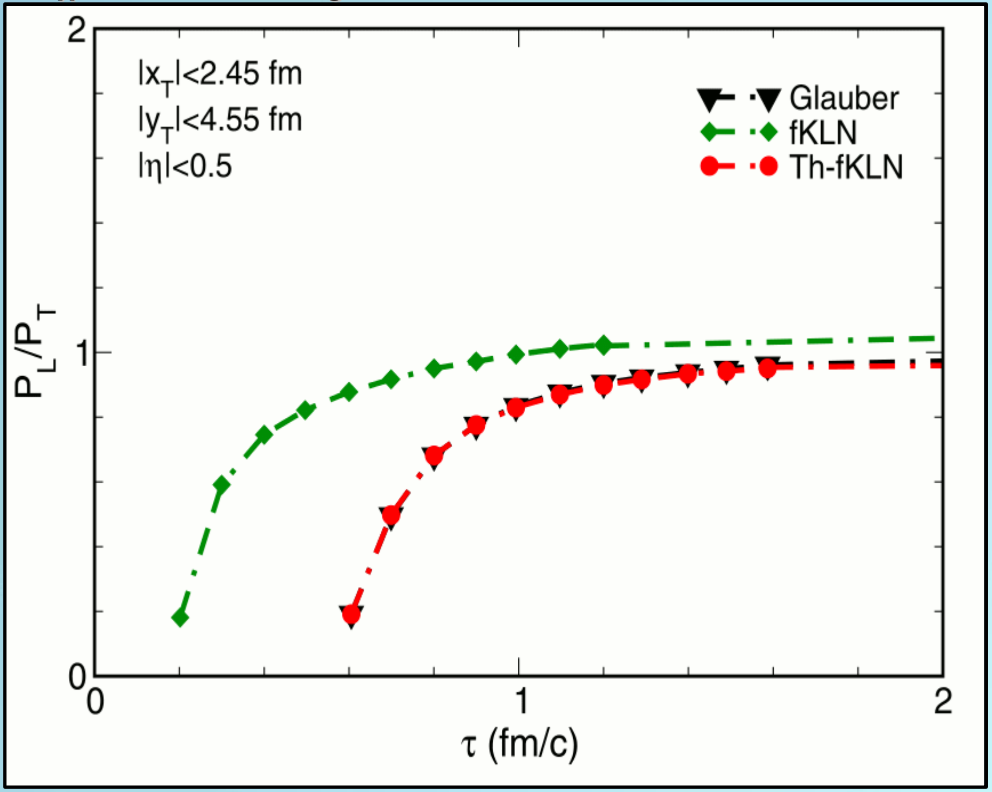
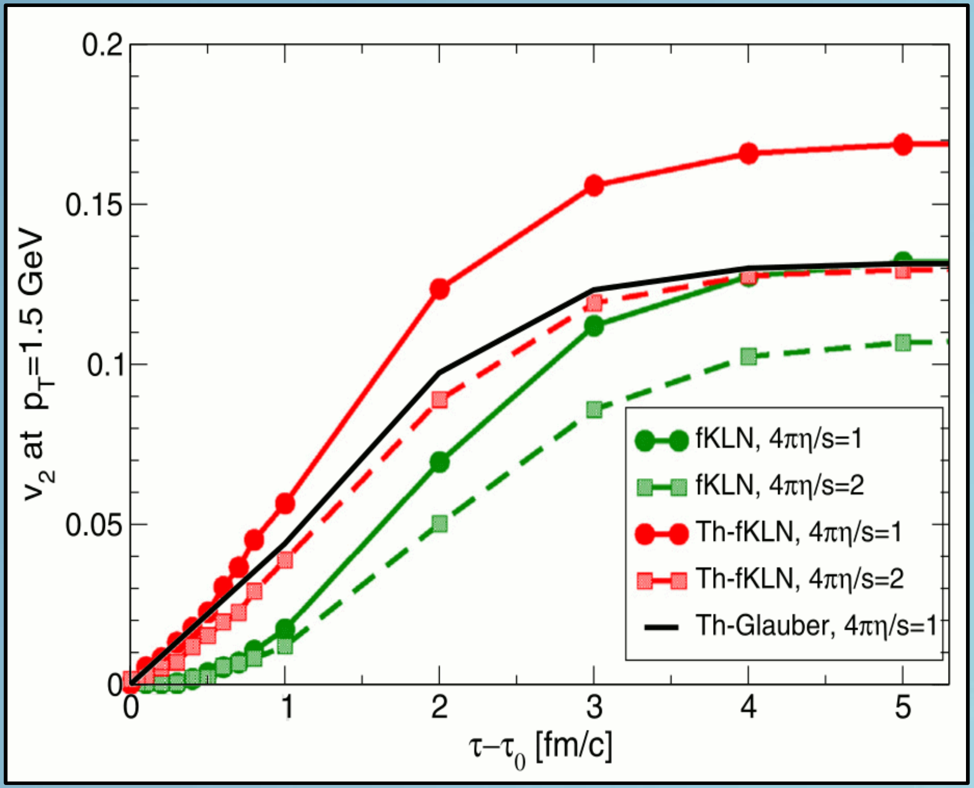


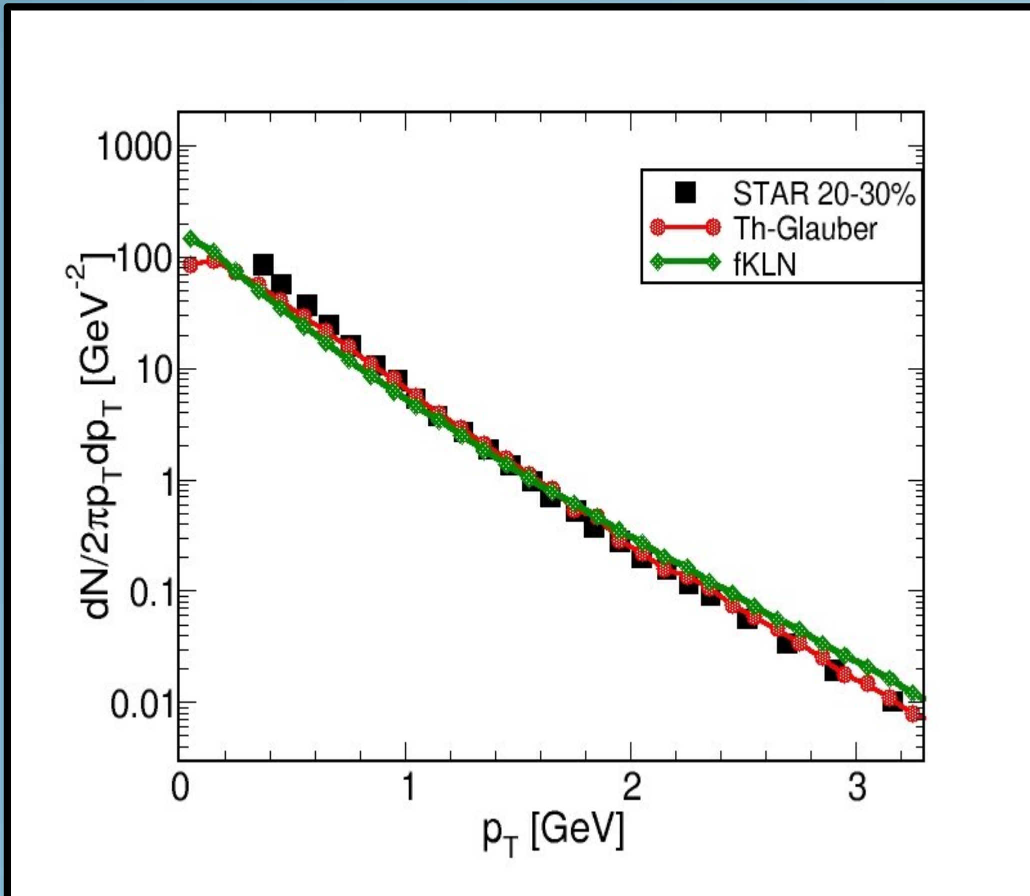
- **Thermalization in less than 1 fm/c, in agreement with Greiner *et al*., NPA806, 287 (2008).**
- **Not so surprising: η/s is small -> large effective scattering rate -> fast thermalization.**

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

Time evolution of v_2



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



STAR 20-30%
Th-Glauber
fKLN
1000
100
10
1
0.1
0.01
0
1
2
3
p_T [GeV]
$dN/2\pi p_T dp_T$ [GeV^{-2}]

Finite masses and EoS

$$p^{\mu}\partial_{\mu}f(x,p)=C_{22}$$

$$M\neq 0 \rightarrow \begin{cases} \epsilon-3p\neq 0 \\ C_s^2\leqslant\frac{1}{3} \end{cases}$$