UNIVERSITÀ DEGLI STUDI DI CATANIA
INFN-LNS

ANISOTROPIC FLOWS AND SHEAR VISCOSITY WITHIN A TRANSPORT APPROACH

S. PLUMARI, V. GRECO

- **Transport approach at fixed η/s.**
- **Effect of η/s(T) on the generation of v_2 at RHIC and LHC.**
- **Impact of high p_T partons on the build-up of v_2.**
    - **Scaling properties of $v_2(p_T)/\varepsilon$.**
    - **η/s(T): large $v_4/(v_2)^2$.**
- **Conclusions**

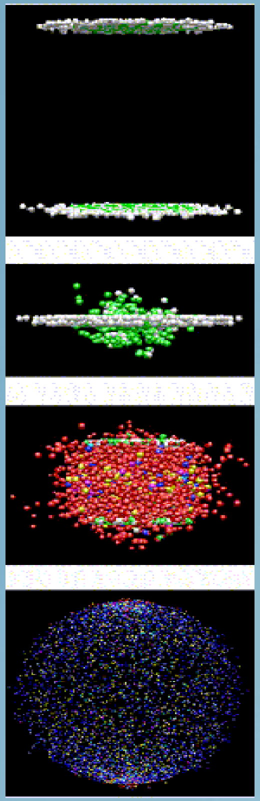
Motivation for a kinetic approach:

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

Free streaming

Field Interaction → ε≠3P

Collisions → η≠0



- 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).
- Include hadronization by coalescence + fragmentation.
- Allows to study the jet-bulk talk.

Parton Cascade model

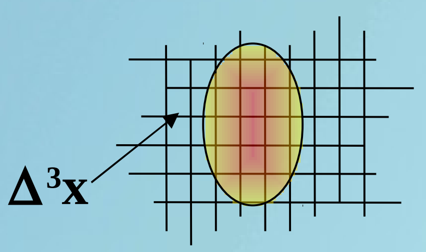
$$p^{\mu}\partial_{\mu} f(X,p) = C = C_{22} + C_{23} + \dots$$

Collisions → $\left\{ \begin{array}{l} \varepsilon - 3p = 0, \\ \eta \neq 0 \end{array} \right.$

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

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**

Passed several numerical test on the box.

Simulating a constant η/s

$$\eta(\vec{x},t)=\frac{4}{15}\lambda(\vec{x},t)\,n_{tot}(\vec{x},t)\,\langle p\rangle \;\Longrightarrow\; \sigma_{tr}^{\eta/s}=\frac{4}{15}\frac{\langle p\rangle}{n}\frac{1}{\eta/s}=K\,\sigma_{tr}^{pQCD}$$

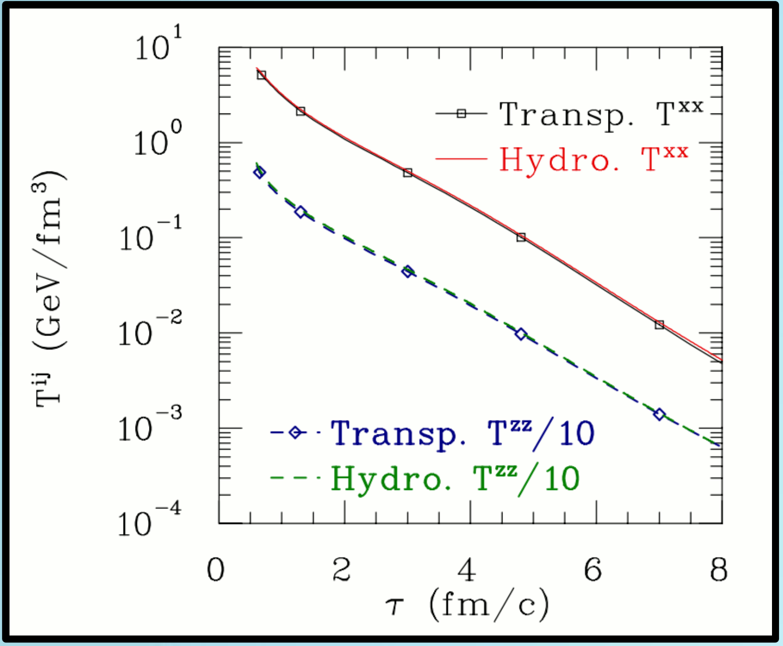
σ is evaluated in such way to keep the η/s=cost. during the dynamics.
(similar to D. Molnar, arXiv:0806.0026[nucl-th] but our approach is local.)

At low p_T equivalent to Hydro dynamics

With this approach we have large cross-section

$$\sigma_{Tot}=K\,\sigma_{pQCD}\gg\sigma_{pQCD}$$

V.Greco,et al. PLB 670 (2009), PPNP 62 (2009) 562.



D. Molnar et al., JPG 35, (2008). QM08

Take into account the non-perturbative effects

BUT NEVER REACH THE pQCD LIMIT WHATEVER IS THE p_T OF THE COLLIDING PARTICLE – EQUIVALENT TO HYDRO

Initial condition of our simulation

- In coordinate space we use a Glauber model
- In momentum space:
  - For $p_T < p_0$ GeV thermal distribution.

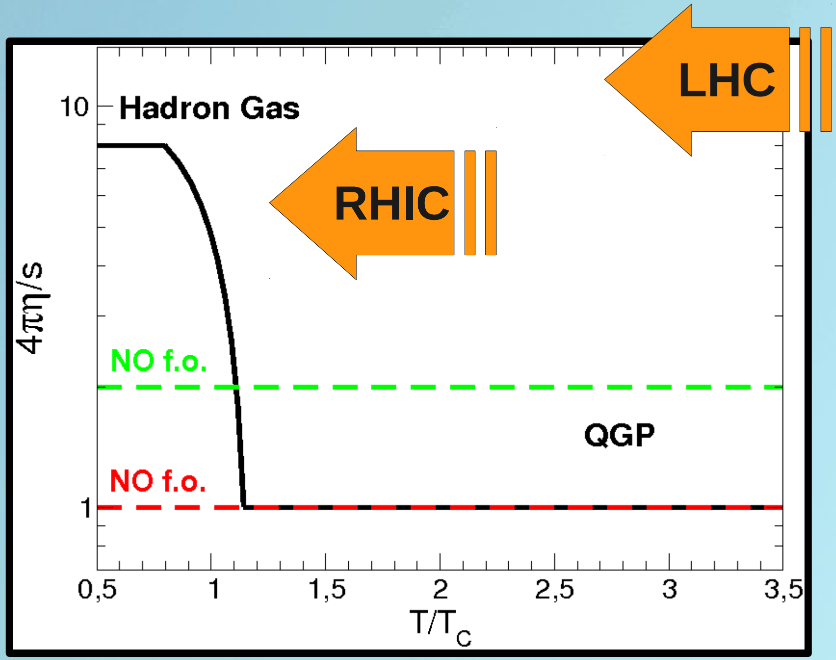
    2 T_C at RHIC for Au+Au @ 200 GeV

    3.5 T_C at LHC for Pb+Pb @ 2.76 TeV
  - For $p_T > p_0$ GeV spectra of minijets.

$$\frac{dN_i}{d^2 p_T} \approx \frac{A_i}{(1 + p_T / B_i)^n}$$

kinetic freeze-out scheme

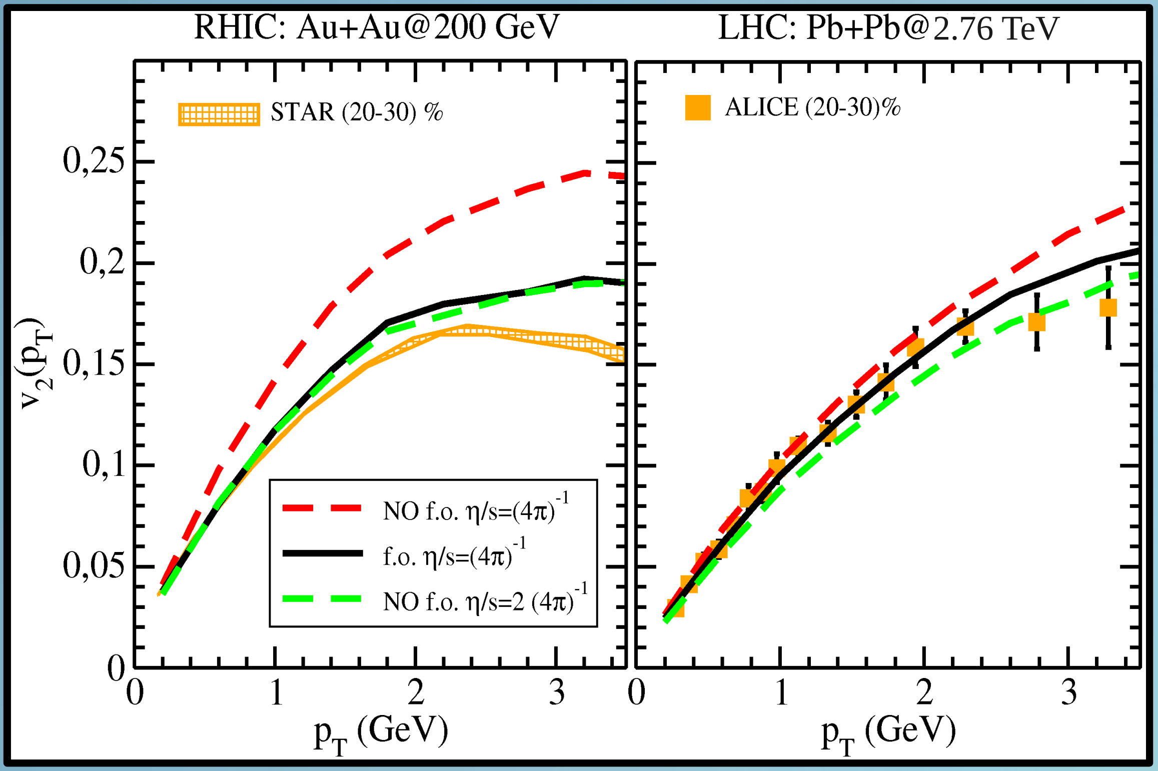
- η/s increases in the cross-over region, with a smooth transition between the QGP and the hadronic phase, the collisions are switched off.

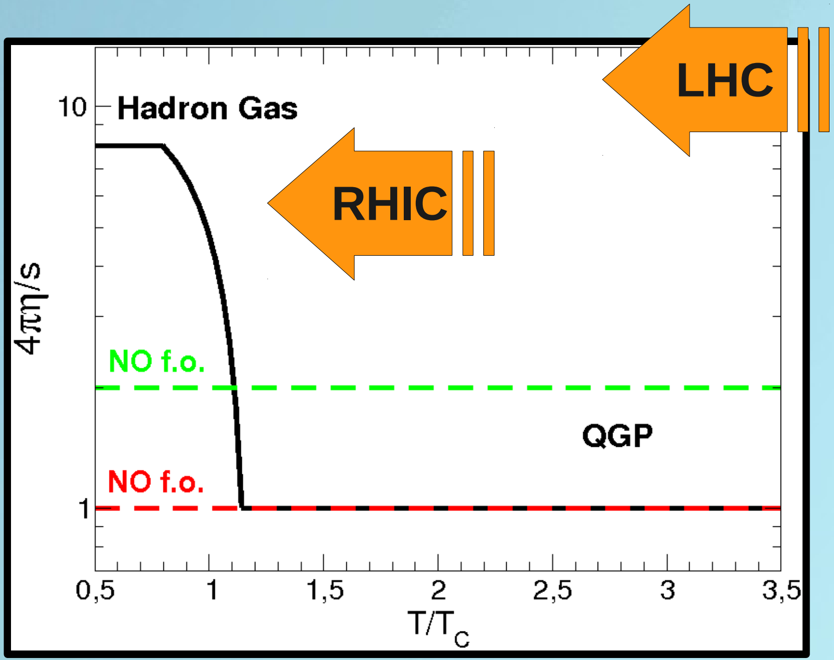


For the v_2 similar to cut-off at ε_0=0.7 GeV/fm^3

Effect of kinetic freeze-out

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



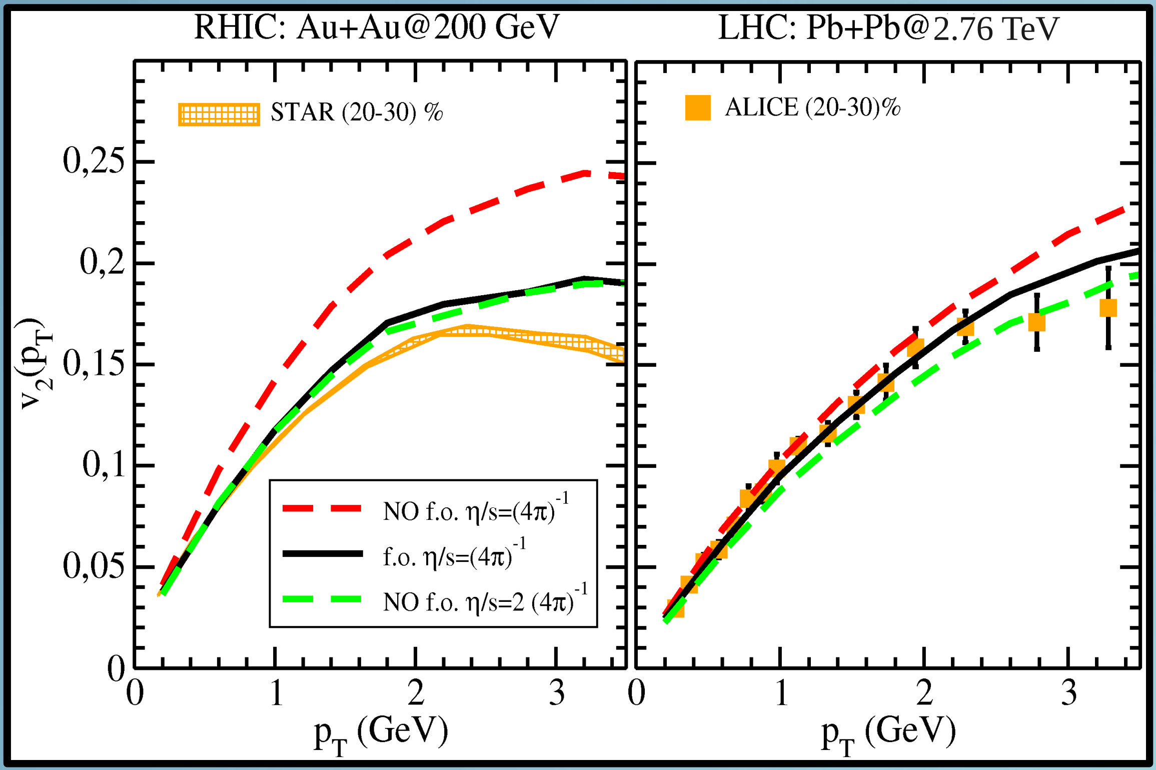


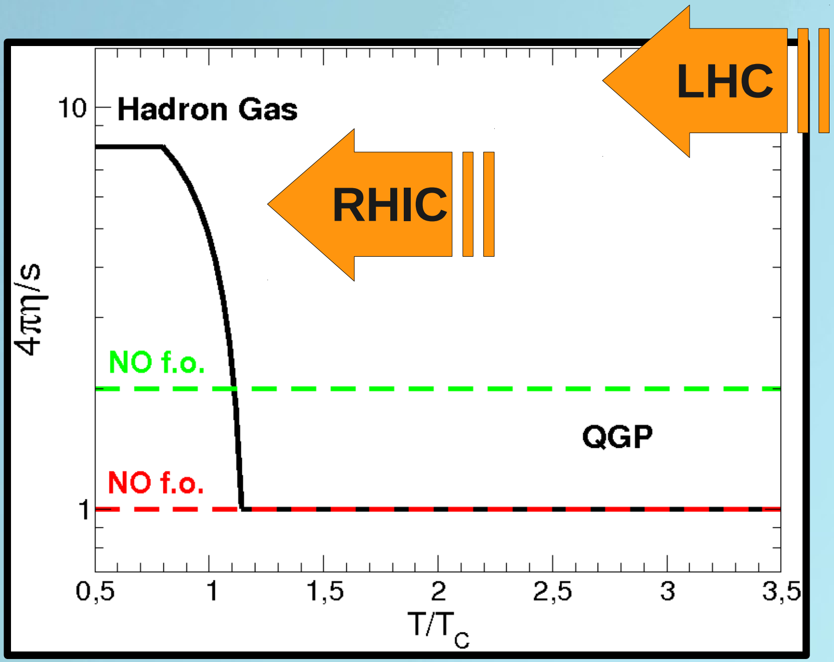
RHIC:

- **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 GeV v_2 decrease not explained (similar to hydro).**

Effect of kinetic freeze-out

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

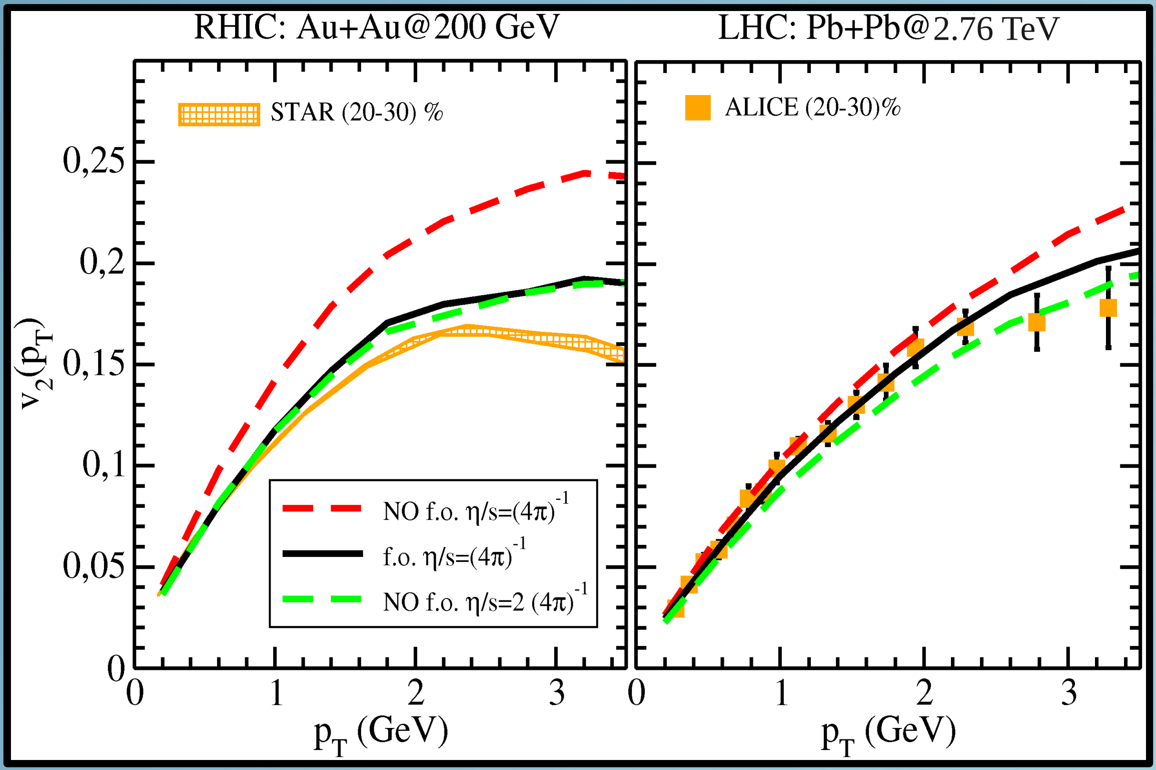




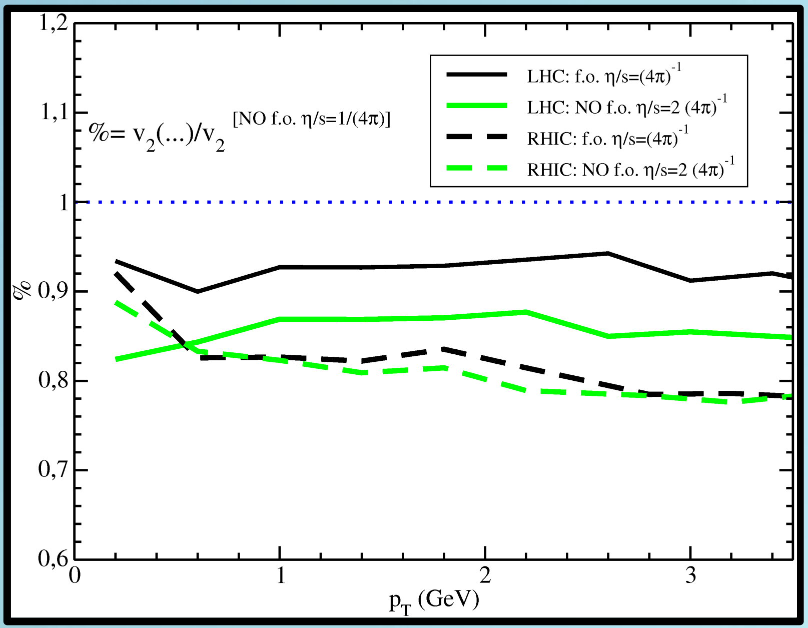
LHC:

- 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 10%.
- Without the kinetic freezout the effect of a constant $\eta/s=2(4\pi)^{-1}$ is to reduce the v_2 of 20%.

Effect of kinetic freeze-out



Suppression of v_2 respect to the ideal case $\eta/s=(4\pi)^{-1}$



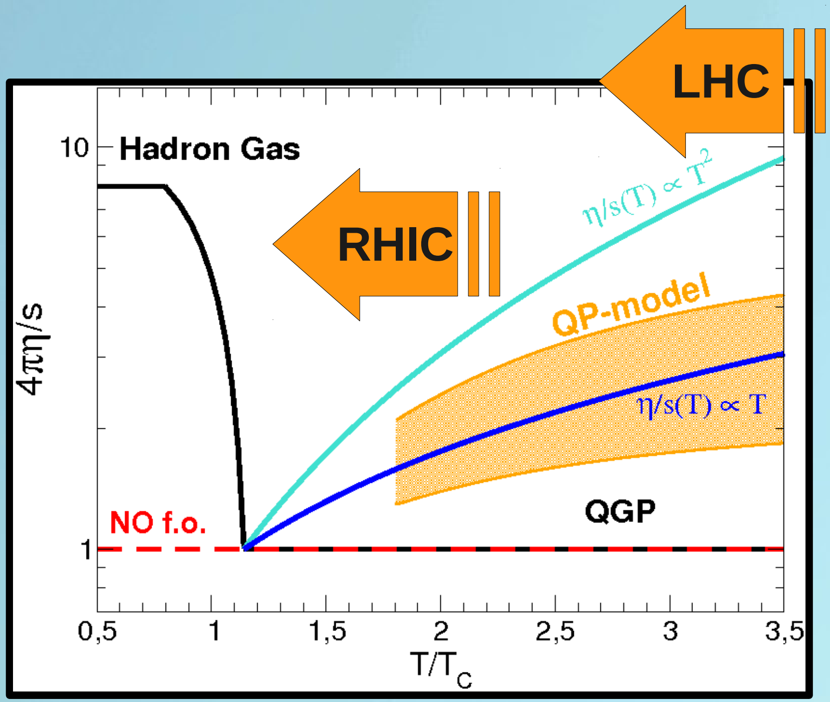
At LHC the contamination of mixed and hadronic phase becomes negligible

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

Temperature dependent η/s(T)

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

- **In the QGP phase η/s is expected to have a minimum value T_C.**
- **Quasi-particle models seem to suggest a $\eta/s \sim T^{\alpha}$ $\alpha \sim 1 - 1.5$.**



S.Plumari, W.M.Alberico, V.Greco, C.Ratti, arxiv:1103.5611[hep-ph].

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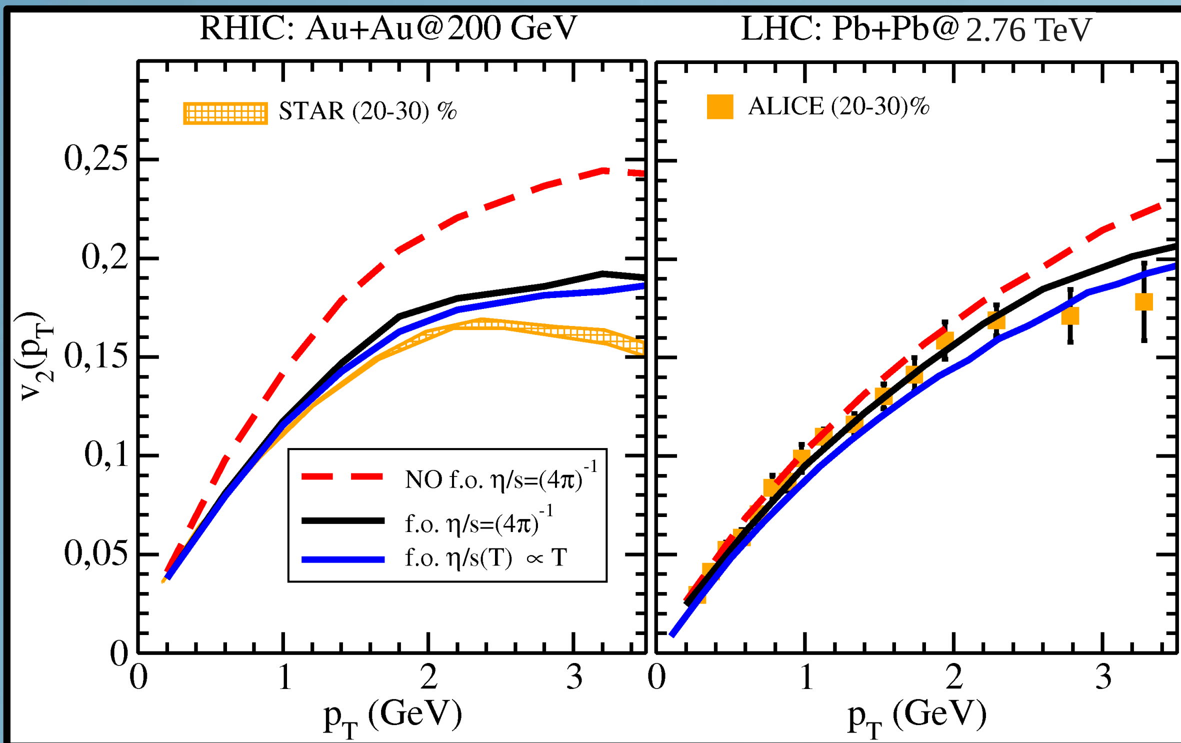

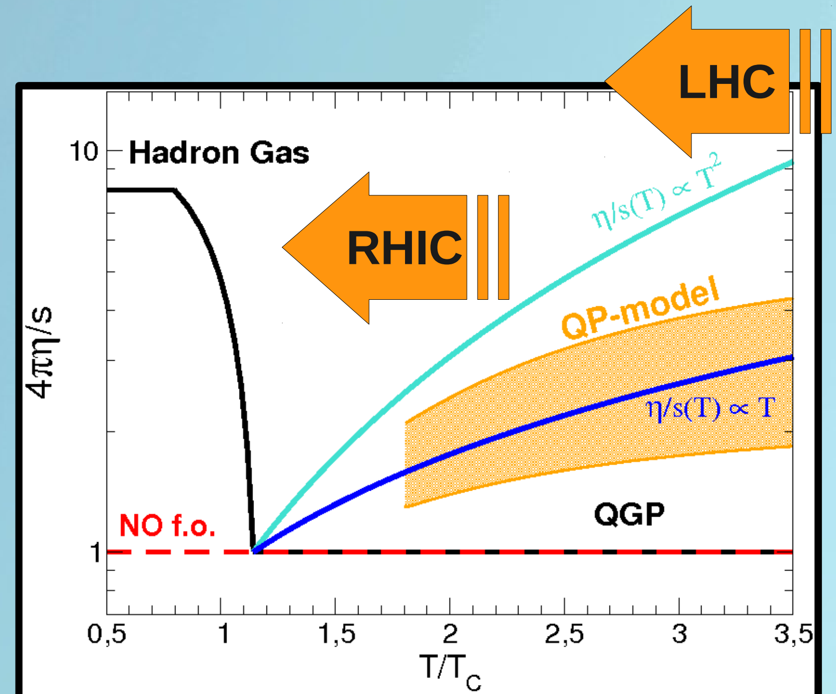

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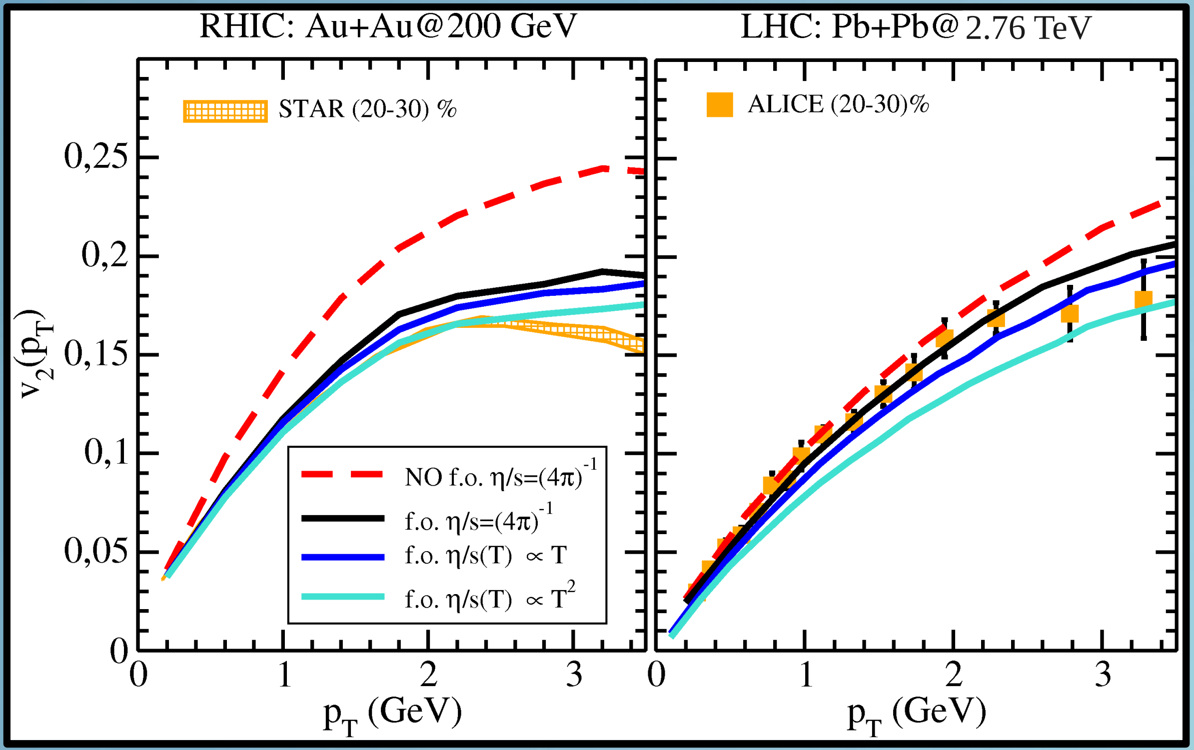

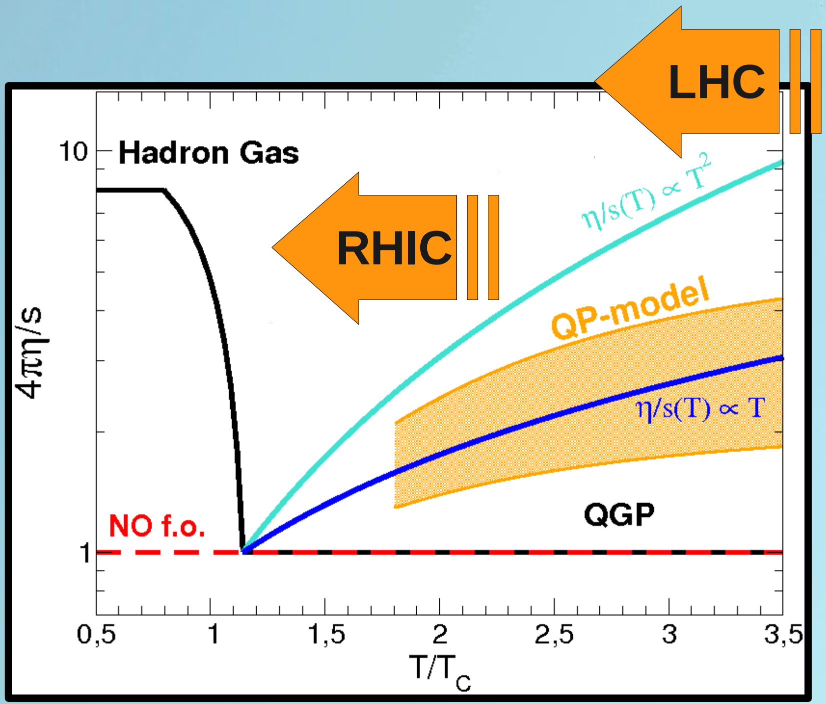

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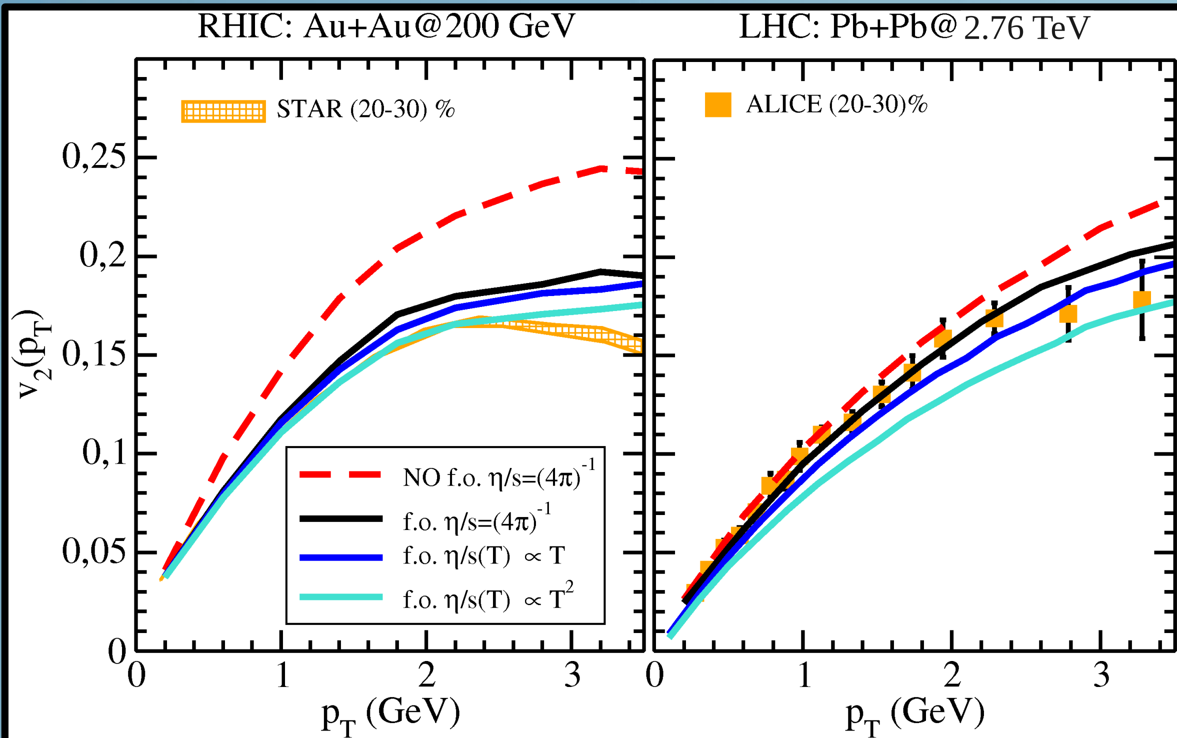
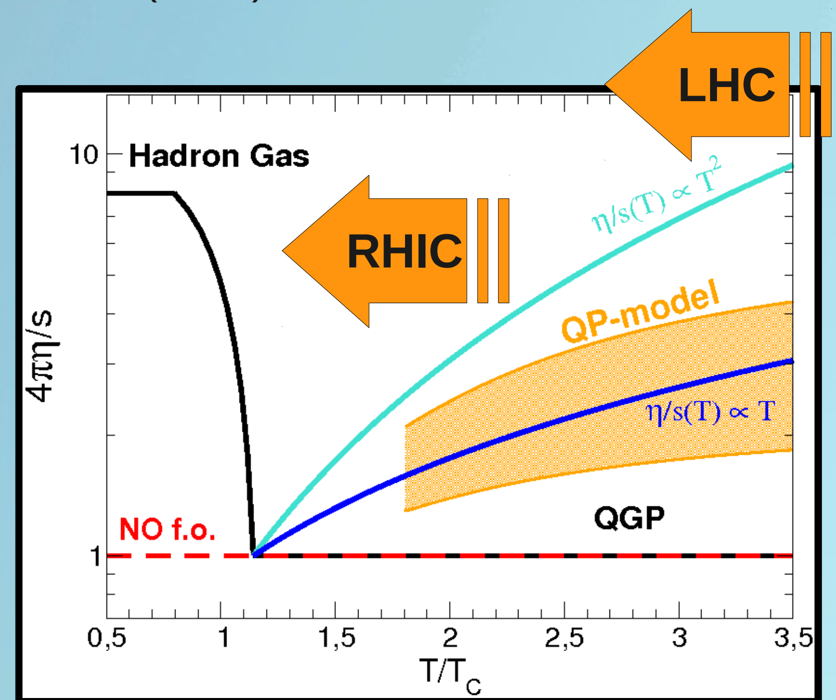




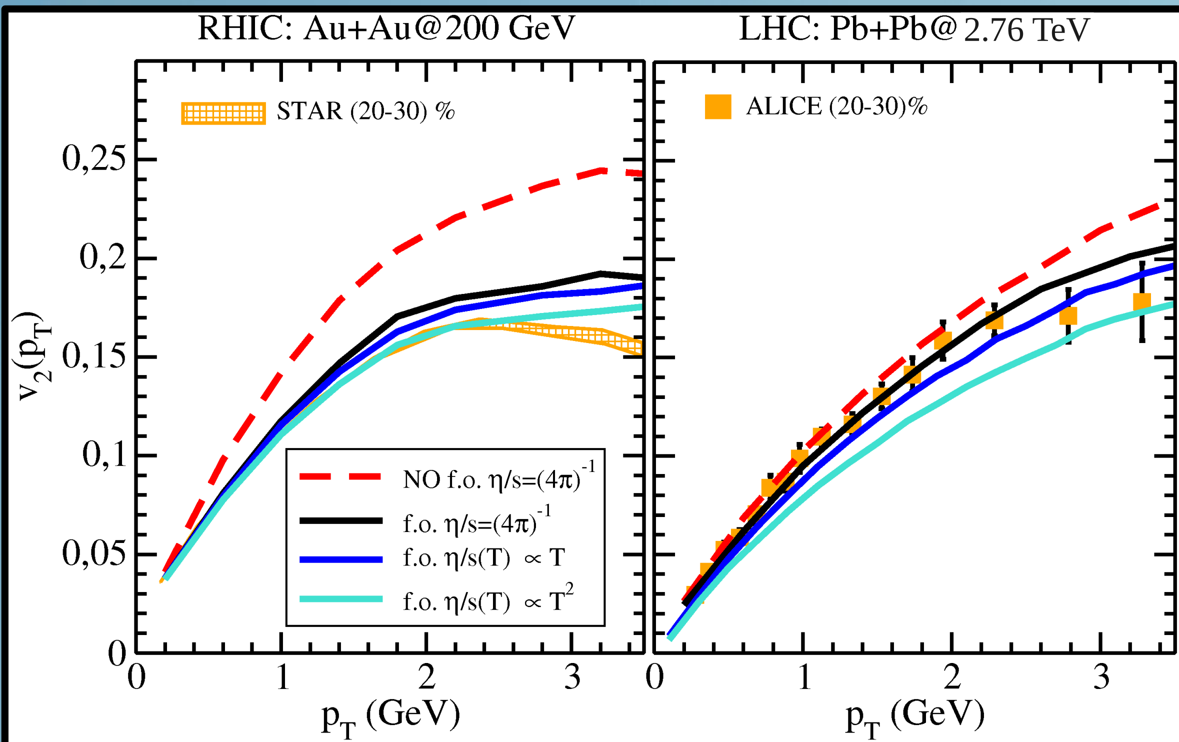
S.Plumari, W.M.Alberico, V.Greco, C.Ratti, arxiv:1103.5611[hep-ph].

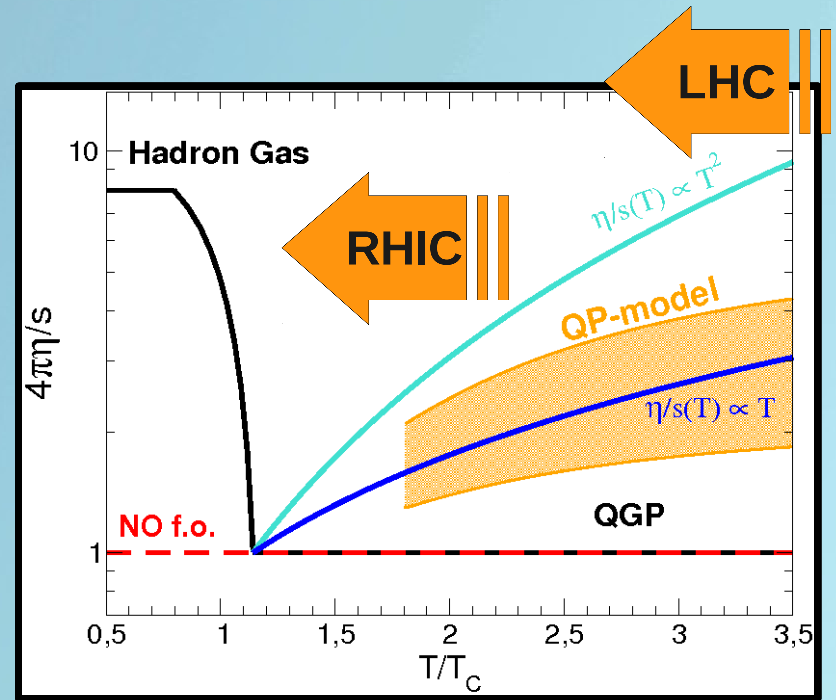
RHIC:

- **The v_2 is insensitive to the value of η/s in the QGP phase**
- **η/s~T² cannot account for the v_2 decrease fot p_T< 2 GeV.**

Temperature dependent η/s(T)

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





S.Plumari, W.M.Alberico, V.Greco, C.Ratti, arxiv:1103.5611[hep-ph].

LHC:

- **The v_2 more sensitive to the QGP phase but still a strong temperature dependence in η/s has a small effect in the $v_2(p_T)$.**

What happens in a wider pt range?
Transport approach allows for such an extension naturally

Of course there is a minimal consideration to do ...

$$\sigma_{Tot}(s) = K\,\sigma_{pQCD}(s)$$

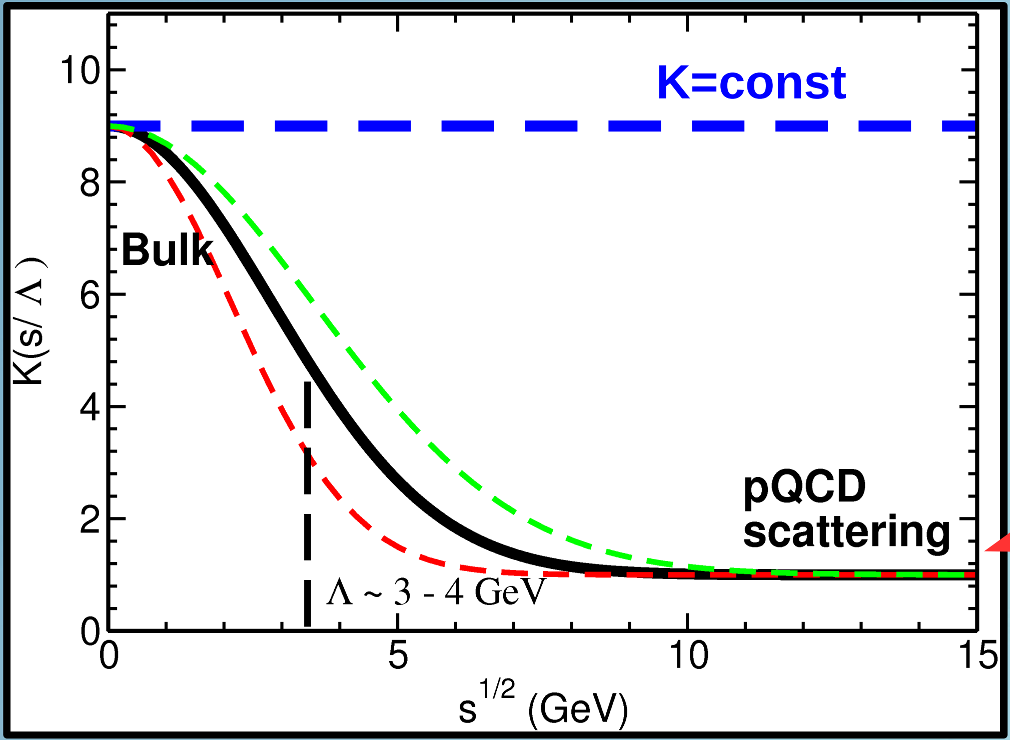
→ **Some non perturbative effect also for high p_T particles**

and high p_T particle should collide with σ_{pQCD} →

$$K = K(s/\Lambda^2)$$

$$\sigma_{Tot}(s) = K(s/\Lambda^2)\,\sigma_{pQCD}(s)$$

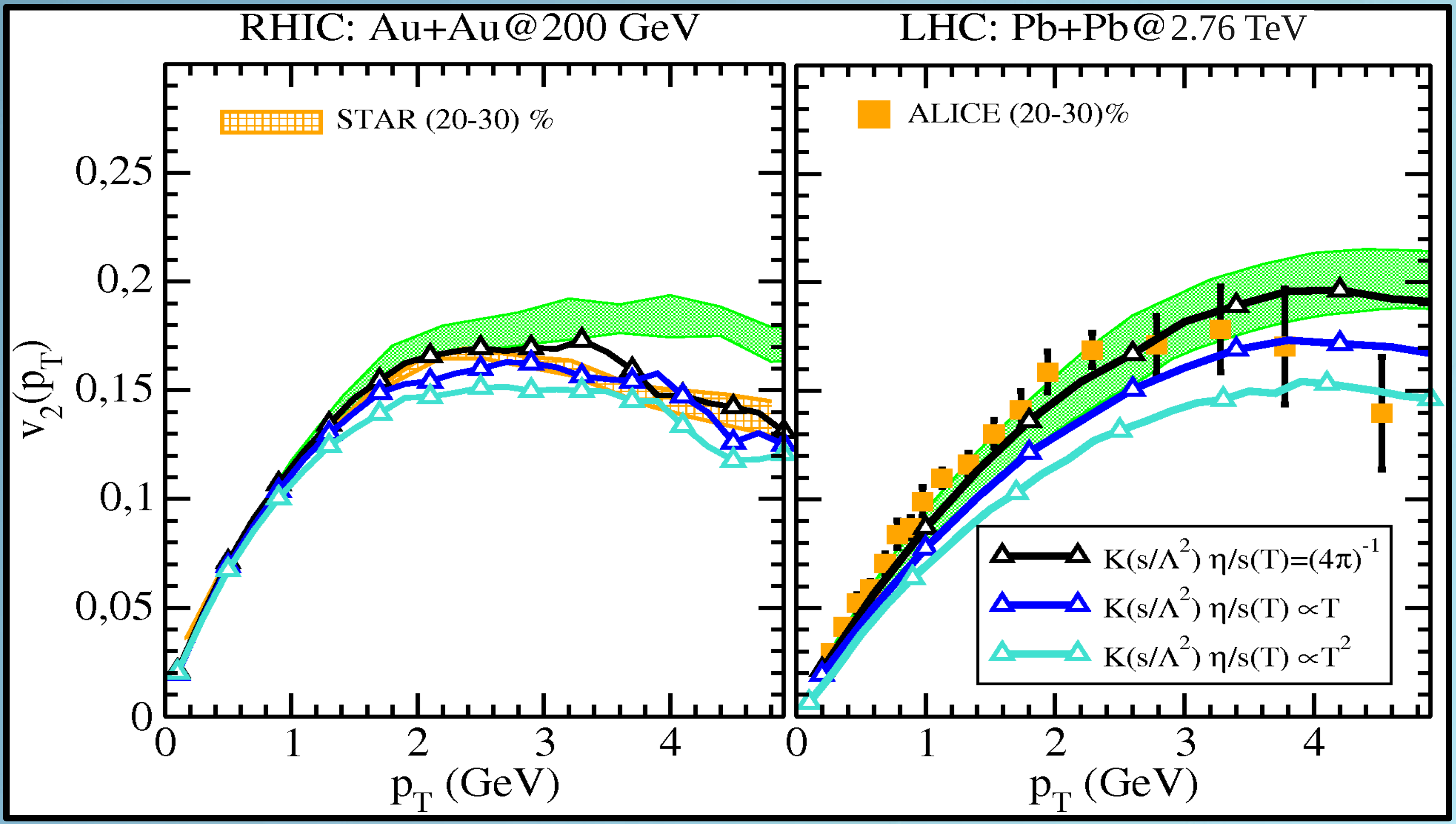
K(s) is such that $\sqrt{s} >> \Lambda$ (~ 3 – 4 GeV) K(s) → 1



Equivalent to viscous hydro

At high p_T "correct" pQCD limit to be defined but certainly far from η/s ~ 0.1

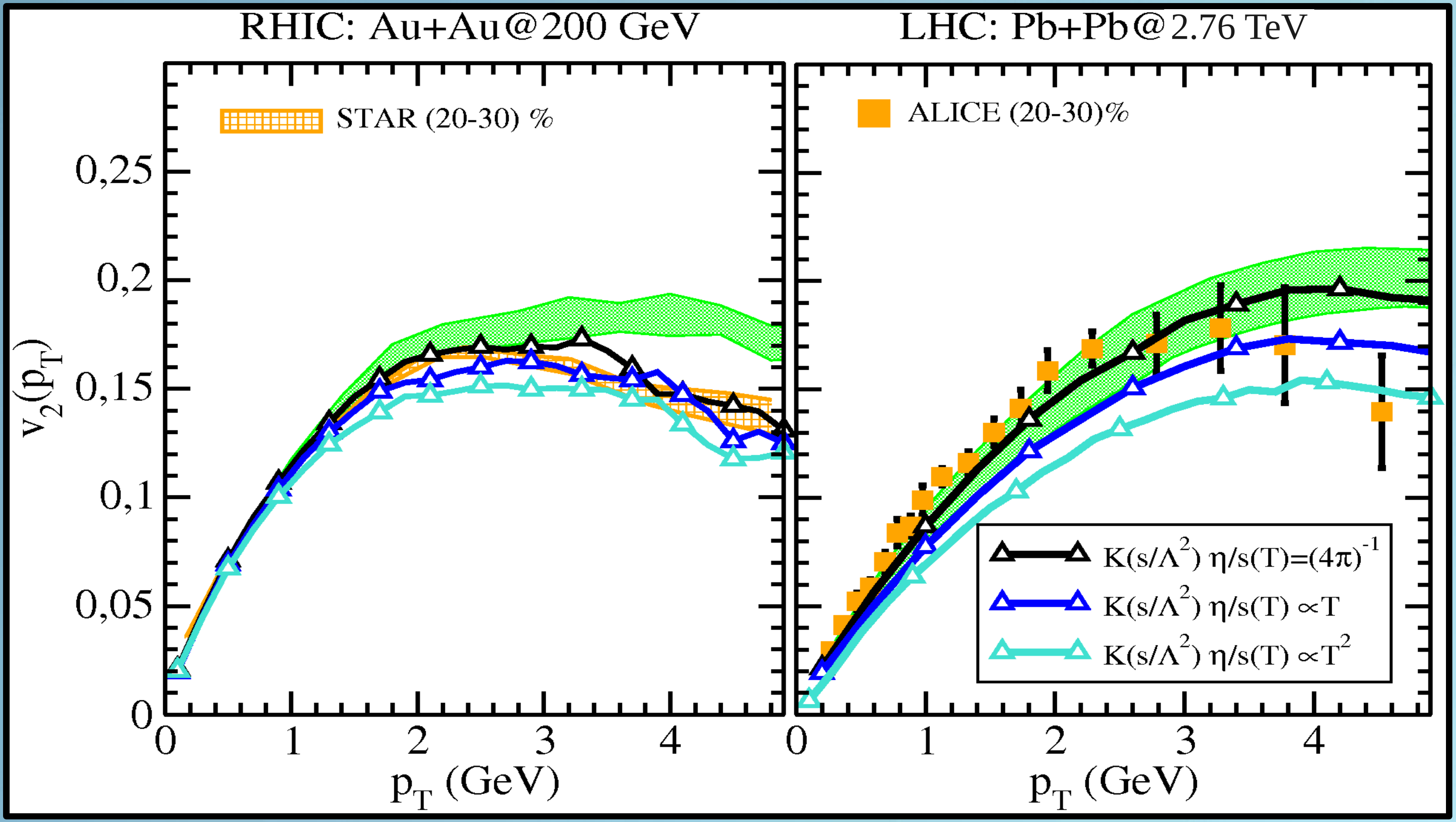
K. Aamodt et al. [ALICE Collaboration], Phys. Rev.Lett. 105, 252302 (2010).



RHIC:

- For Λ >3 GeV the v_2 is not very sensitive to the scale parameter Λ.
- K(s/Λ) does not affect v_2 for p_T < 2.5 GeV and high p_T does not affect the bulk.
- A reduction of v_2 only for p_T< 3 GeV .

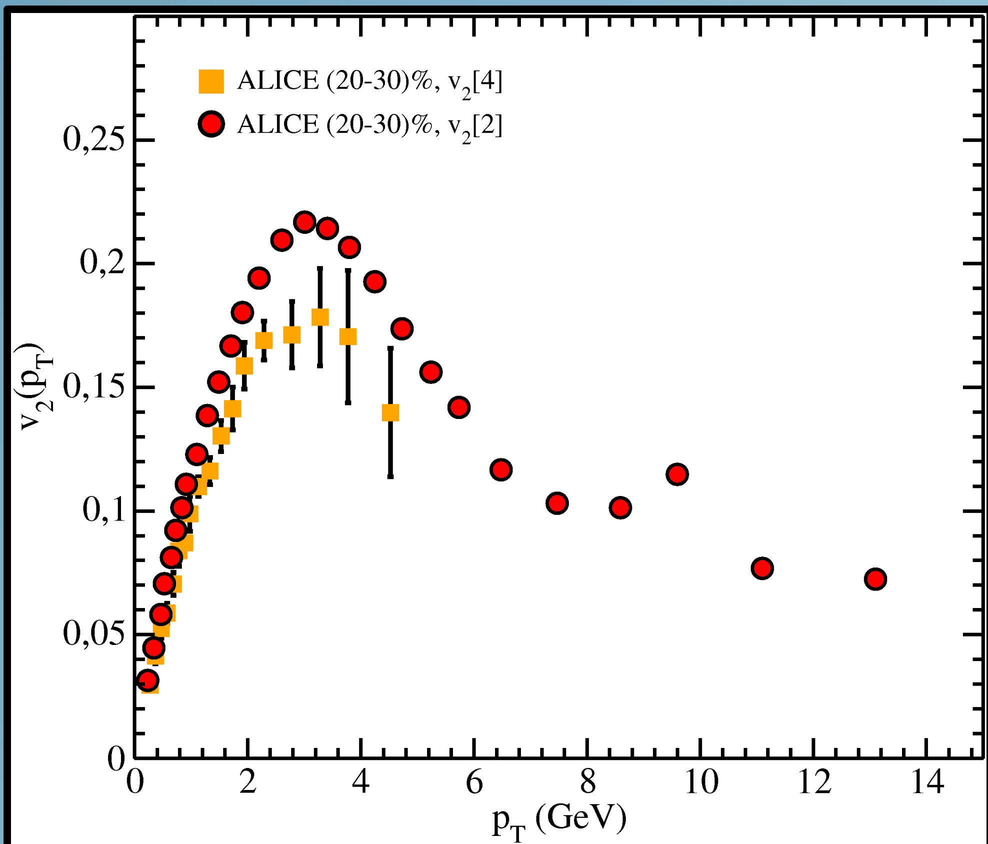
K. Aamodt et al. [ALICE Collaboration], Phys. Rev.Lett. 105, 252302 (2010).

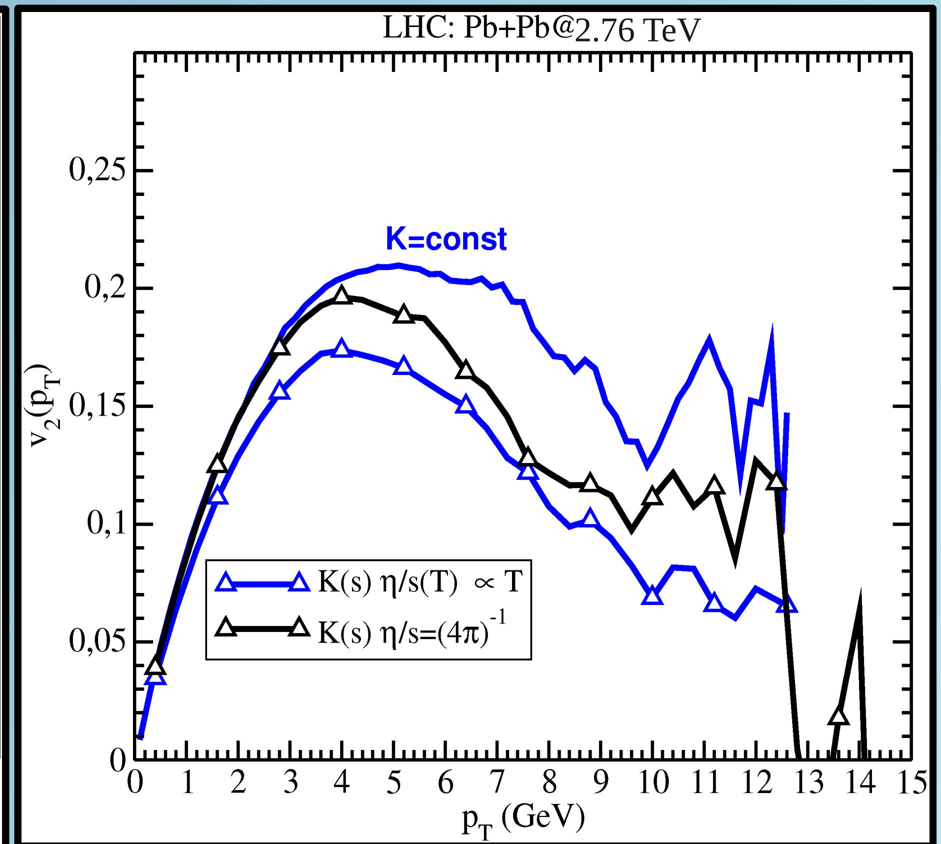


LHC:

- **The effect of K(s/Λ) even at p_T ~ 1 – 3 GeV (much more high partons that affect also the bulk).**
- **v_2 remains sensitive to the η/s(T) in the QGP phase.**

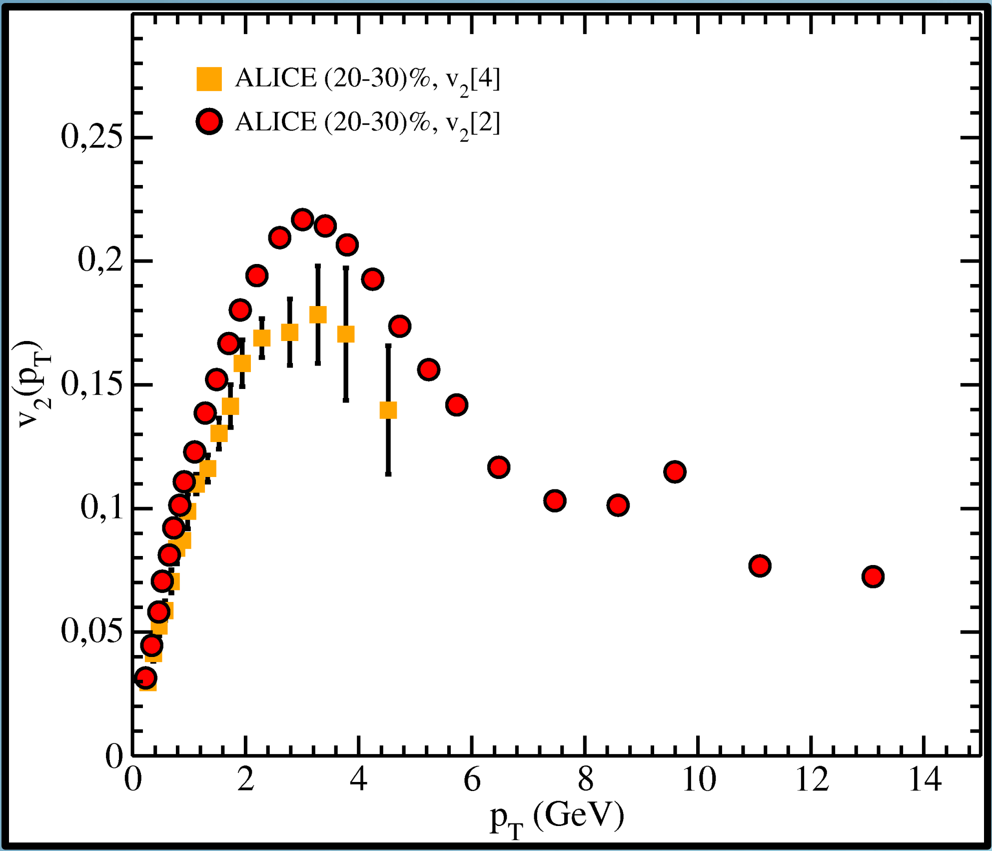
Going to high p_T

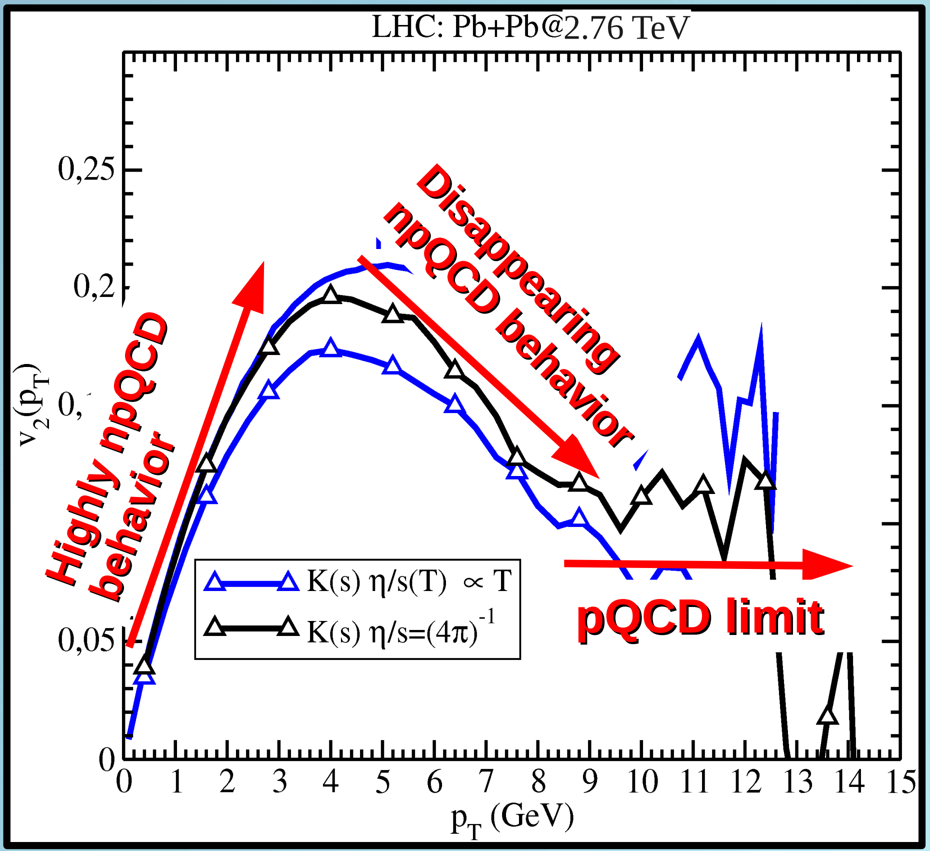




- We get a sizeable v_2 from collisional energy loss (v_2~7%) (and a behaviour similar to the one observed experimental).
- Above 10 GeV sets in flat behavior typical of path lengh.
- This is not hydro+jet model, because we have only collisional energy loss and we treat on the same footing the high and low energy particles.

Going to high p_T





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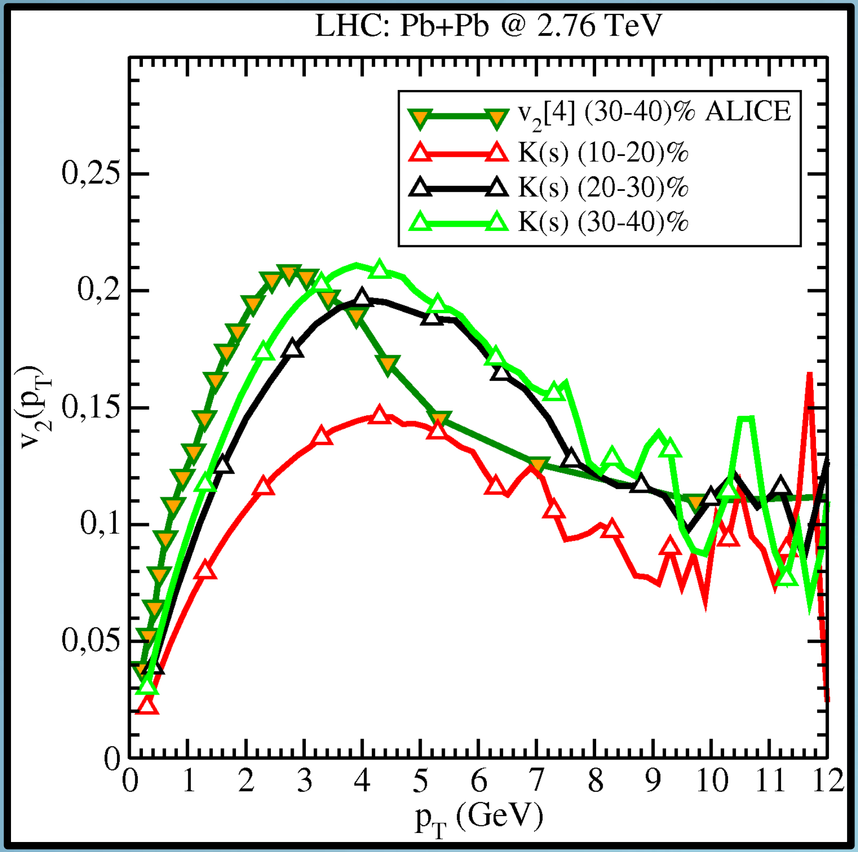

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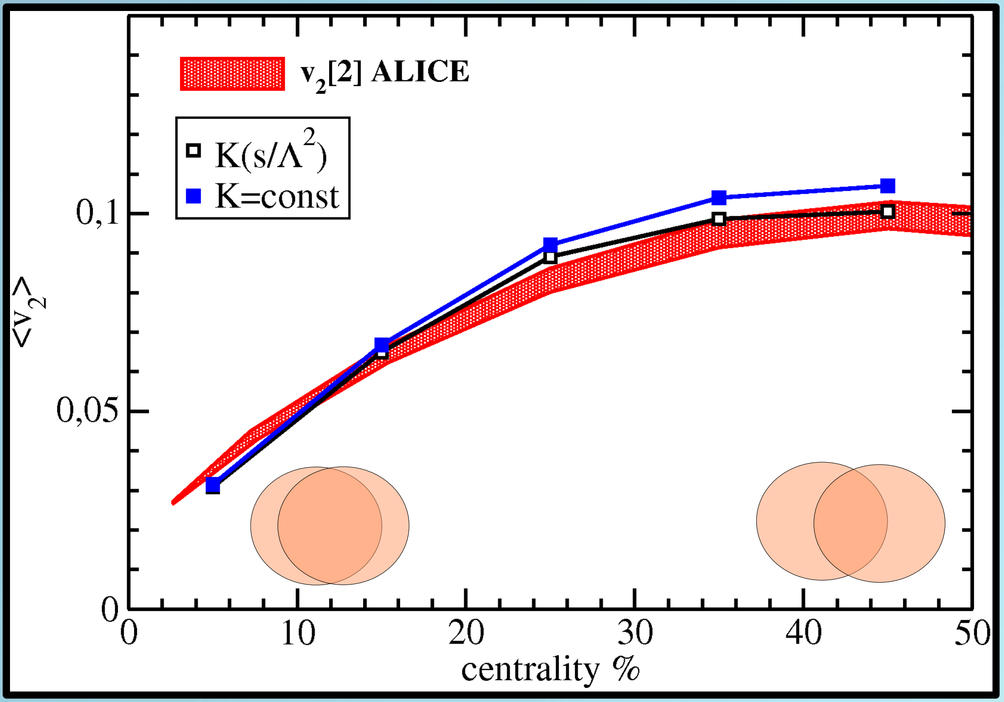
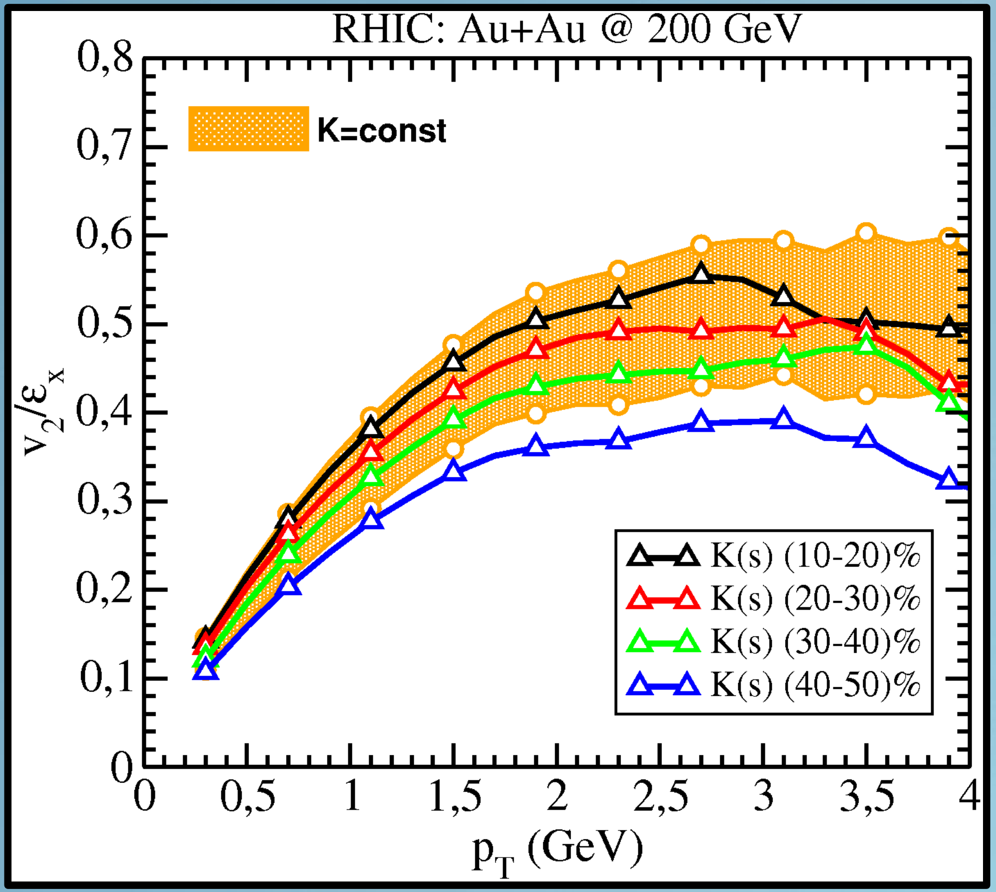
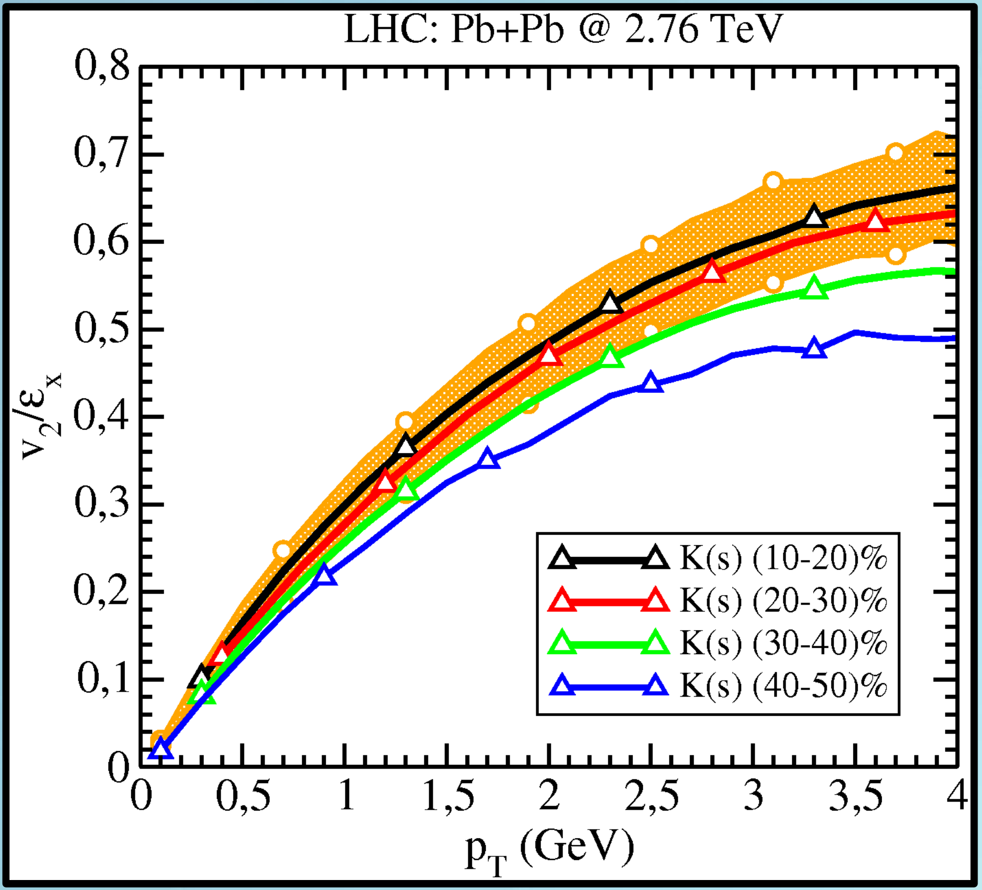


- **Shift of v_2 to low p_T expected for fragmentation.**
- **The saturation persist also for more central collisions.**
- **Good agreement with the experimental data for the $\langle v_2 \rangle$ as function of the centrality. The effect of K(s) is to reduce the $\langle v_2 \rangle$.**

Effect on the breaking of the v_2/ε scaling





RHIC

Similar breaking w/o K(s): the amplitude is of about 30 % (from f.o.).

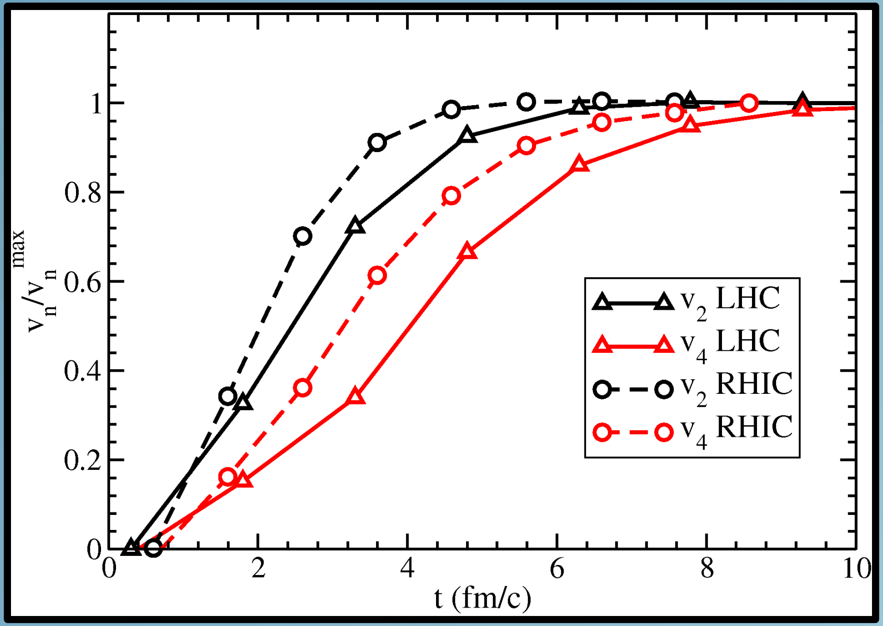
The effect of K(s) is in general to reduce the value of v_2/ε.

LHC

For K=const the system is more efficent and the breaking is of about 17 %.

The effect of K(s) is in general to increase the value of the breaking of about 25 %.

Effect of η/s(T) and K(s) on the ratio $v_4/(v_2)^2$



- V_2 develops earlier at higher η/s.
- V_4 develops later at lower η/s.

S. Plumari et al., J.Phys.: Conf. Ser. 270 (2011) 012061

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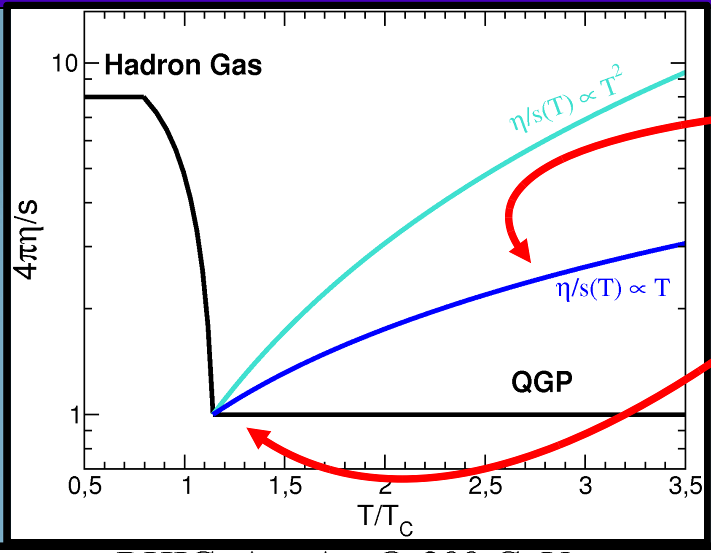
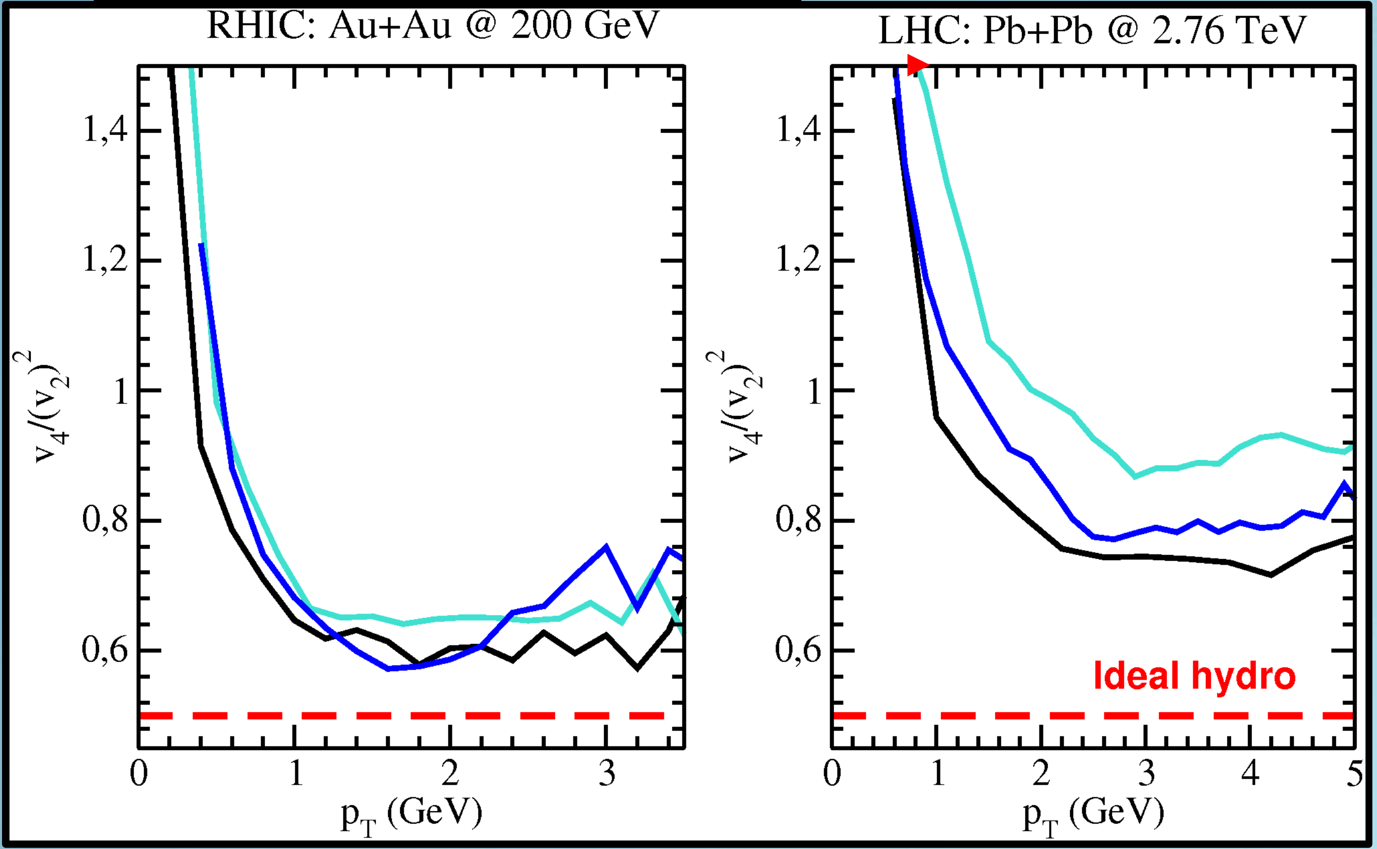


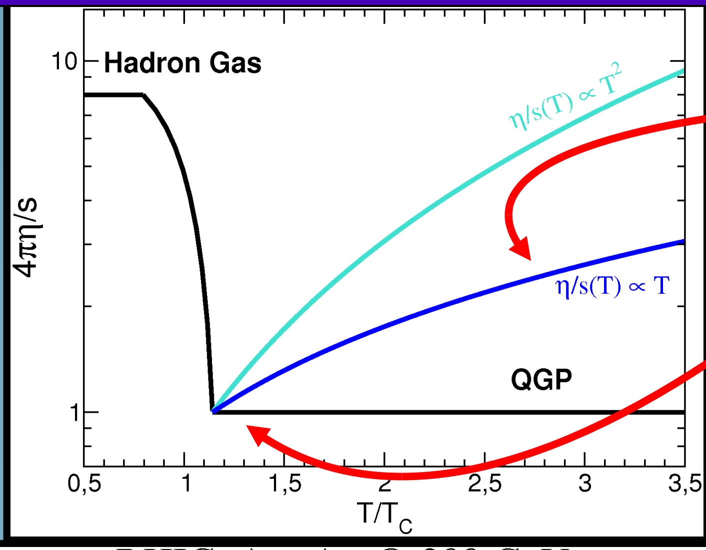
- V_2 develops earlier at higher η/s.
- V_4 develops later at lower η/s.
- This gives an higher value of the ratio $V_4/(V_2)^2$.

S. Plumari et al., J.Phys.: Conf. Ser. 270 (2011) 012061



At LHC the $v_4/(v_2)^2$ is more sensitive to the QGP phase then at RHIC energies

Effect of η/s(T) and K(s) on the ratio $v_4/(v_2)^2$



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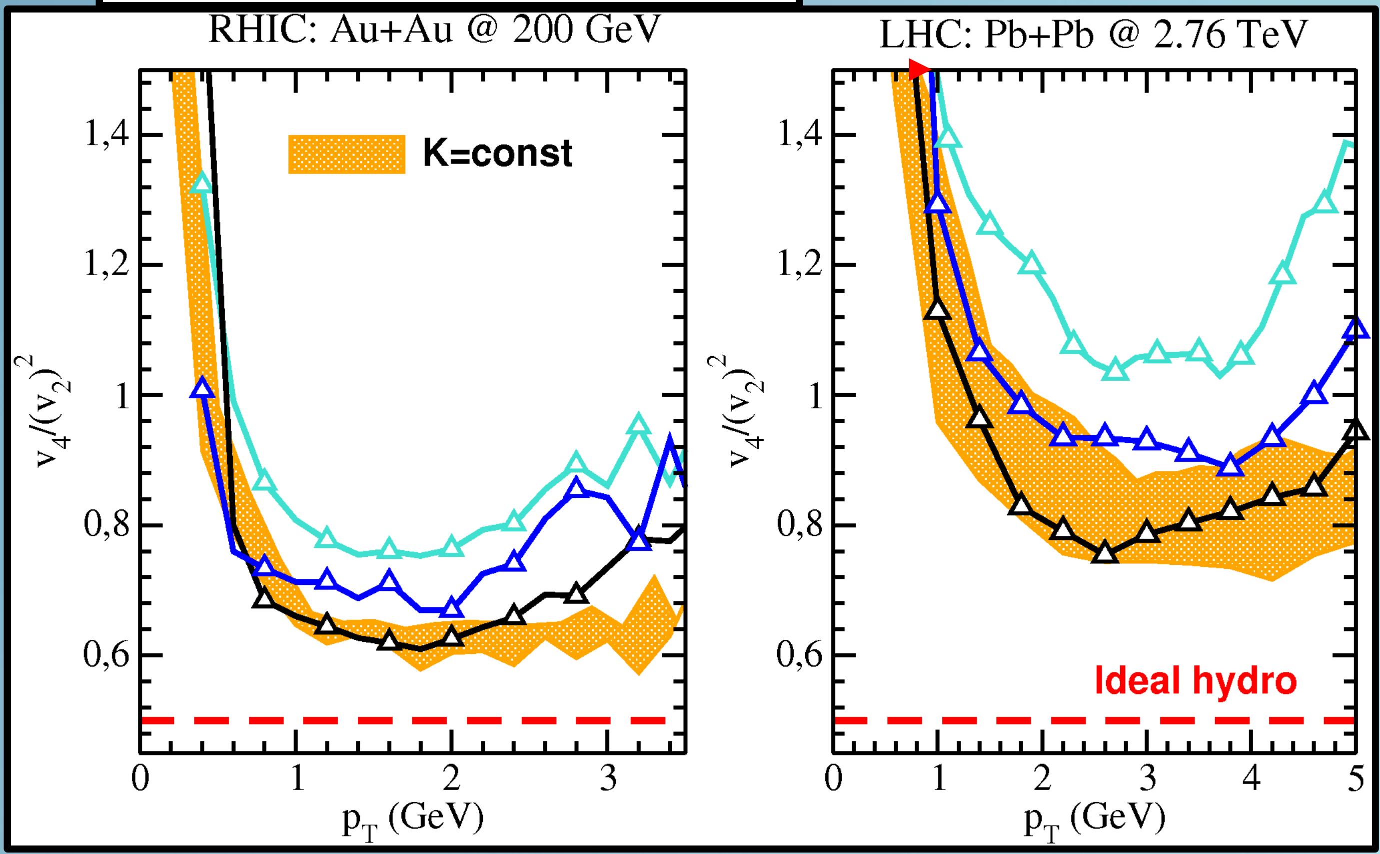


- $v_4/(v_2)^2$ becomes more sensitive to the QGP phase also at RHIC
- $v_4/(v_2)^2$ becomes an increasing function at high p_T

BEFORE A QUANTITATIVE ESTIMATE

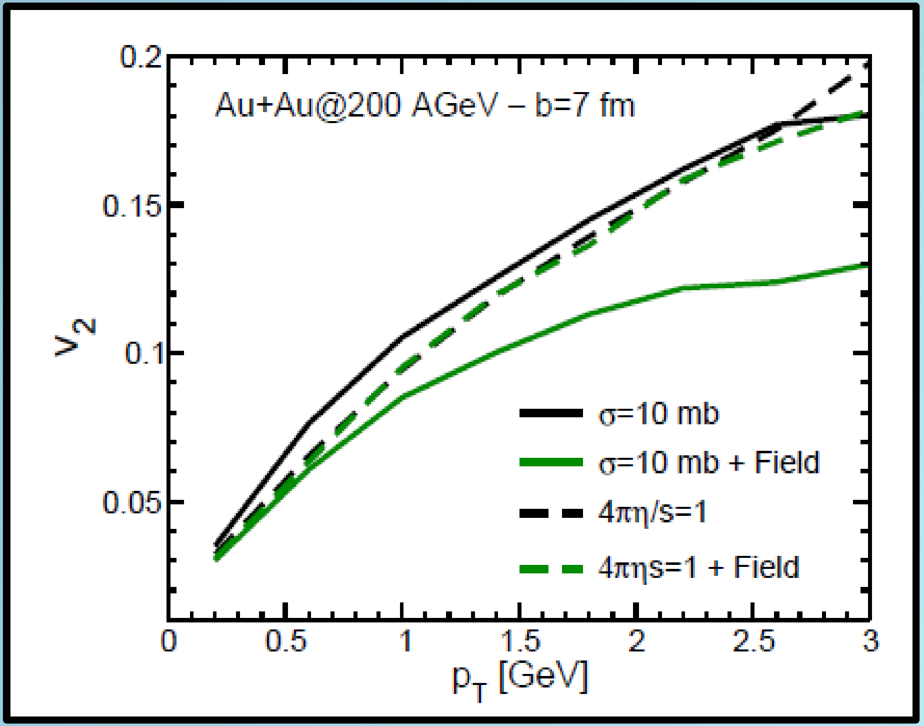
- Include lattice QCD-EoS P(ε)
  → quasi particle model (Near FUTURE)
- Include fragmentation (of high p_T) + coalescence
- At high p_T gluon radiation

Conclusions and Outlook

- We have investigate within a parton cascade model the effect of a $\eta/s(T)$ at RHIC and LHC energies.
  - At RHIC v_2 still 20% of v_2 depend on the cross-over region.
  - At LHC nearly all the v_2 from the QGP phase.
  - Agreement with Viscous Hydrodynamics $\eta/s \sim 0.1$ but not large sensitivity to T dependence ($\eta/s \sim T^2$ could be excluded)

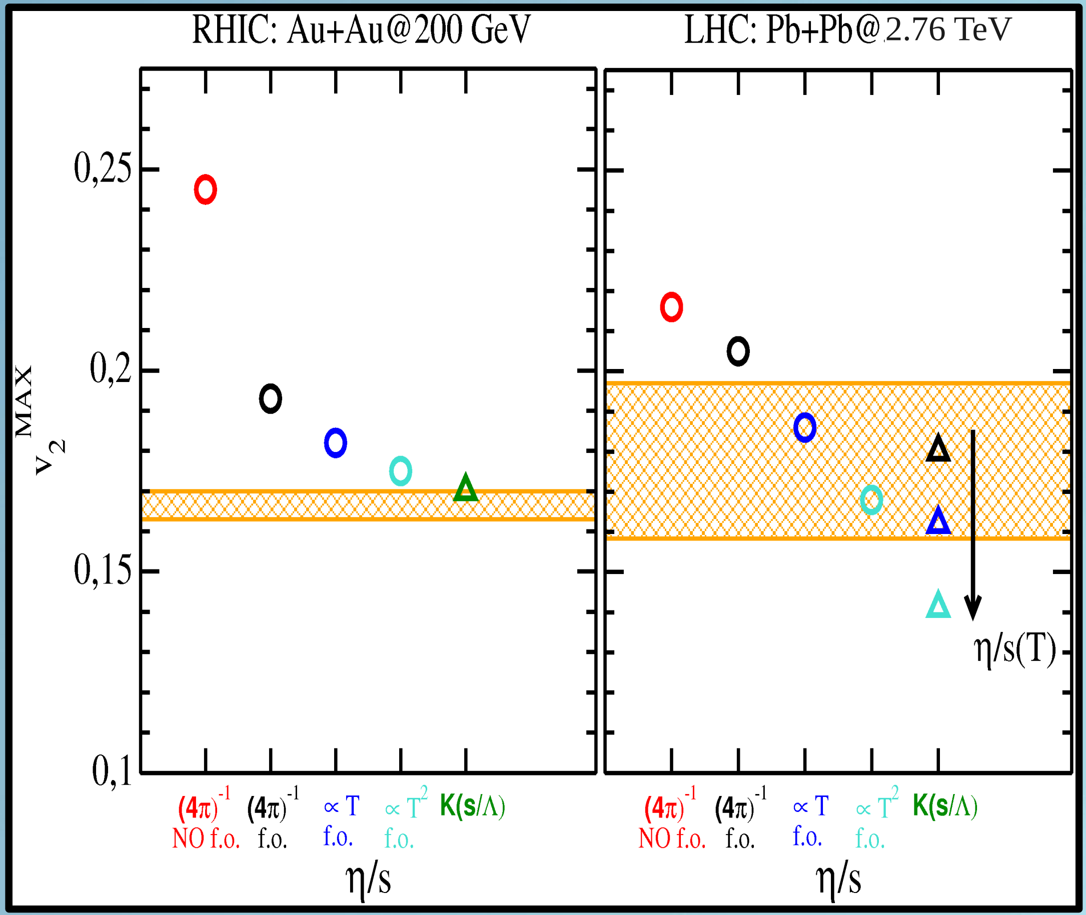
- At LHC the large ammount of particle with $p_T > 4$ GeV interacting nearly perturbatively cannot be neglected.
  - Affect the η/s estimates (v_2 at $p_T < 3$ GeV).
  - Could explain the rise and fall of $v_2(p_T)$ in $0 < p_T < 8$ GeV.
  - Breaking of v_2/ε similar to RHIC .
  - Signature of η/s (T) and K(s): large $v_4/(v_2)^2$ and increasing function of p_T at higher p_T.

Does the NJL chiral phase transition affect the elliptic flow of a fluid at fixed η/s?



S. Plumari et al., PLB689(2010)

- The NJL mean field reduce the v_2: attractive field (the effect is about 15 %).
- if η/s is fixed the effect of NJL mean field is compensed by the increase of σ.
- $V_2 \leftrightarrow \eta/s$ not modified by the NJL mean field dynamics.



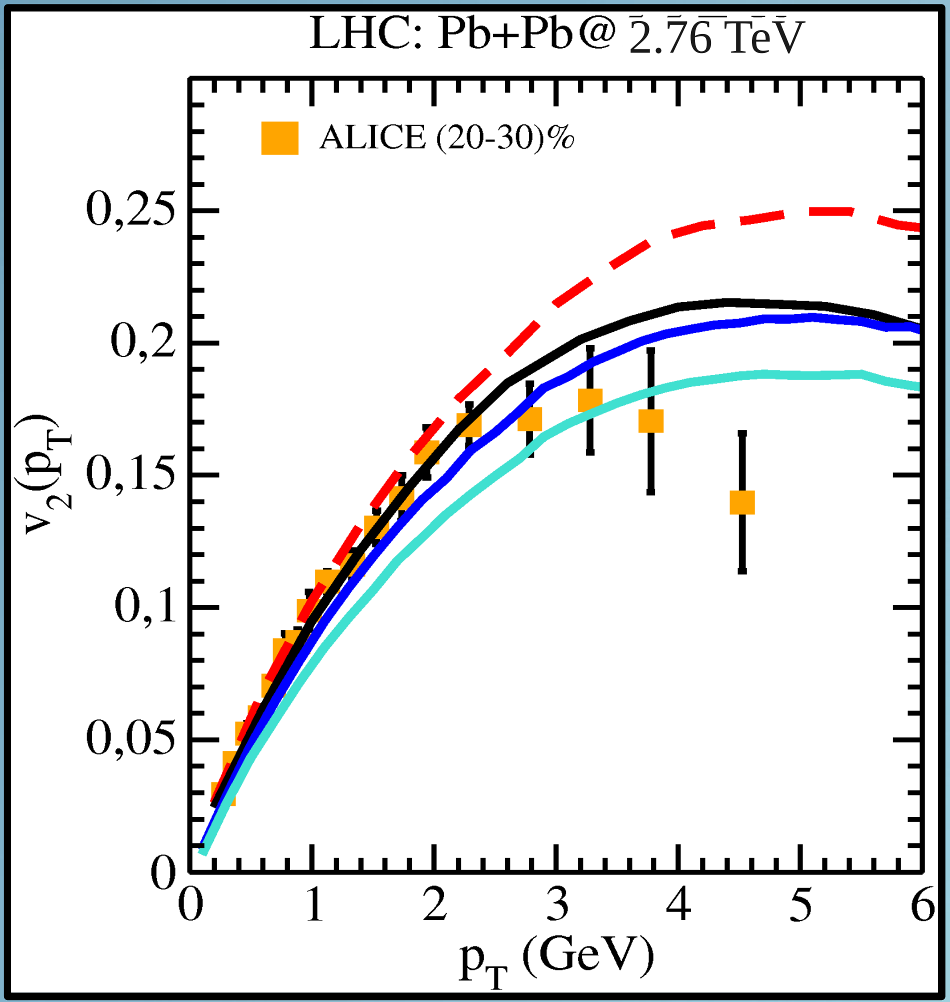
RHIC: Au+Au@200 GeV
LHC: Pb+Pb@2.76 TeV
v_2^{MAX}
0,25
0,2
0,15
0,1
$(4\pi)^{-1}$ NO f.o.
$(4\pi)^{-1}$ f.o.
$\propto T$ f.o.
$\propto T^2$ f.o.
$K(s/\Lambda)$
$\eta/s(T)$
η/s

Simulating a constant η/s

$$\eta(\vec{x},t)=\frac{4}{15}\lambda(\vec{x},t)\, n_{tot}(\vec{x},t)\,\langle p\rangle \;\Rightarrow\; \sigma_{tr}^{\eta/s}=\frac{4}{15}\frac{\langle p\rangle}{n}\frac{1}{\eta/s}=K\,\sigma_{tr}^{pQCD}$$

$$\sigma_{Tot}=K\,\sigma_{pQCD}\gg\sigma_{pQCD}$$

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



At LHC the maximum of the v_2 is at p_T~ 5.5 GeV strong efficency in converting the initial asymmetry also at large p_T.