UNIVERSITÀ DEGLI STUDI DI CATANIA

INFN-LNS

Initial state fluctuations in ultra-central collisions in an event-by-event transport approach

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

F. Scardina, M. Ruggieri, V. Greco

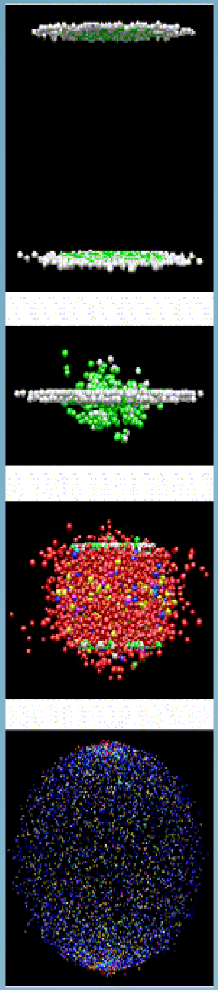
Outline

- **Transport approach at fixed η/s:**
  - **fix locally η/s ↔ σ(θ), M, T -> Chapman-Enkog approach.**
- **Initial state fluctuations:**
  - **η/s and generation of v_n(pT): from RHIC to LHC**
  - **Correlations between ε_n and v_n**
- **Conclusions**

Motivation for a kinetic approach:

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

Free streaming — Field Interaction → ε≠3P — Collisions → η≠0



- Starting from 1-body distribution function and not from $T^{\mu\nu}$:

  - possible to include f(x,p) out of equilibrium.

    M. Ruggieri et.al, PLB 727 (2013) 177

  - extract information about the viscous correction δf to f(x,p)

    S.Plumari,G.L. Guardo, V. Greco, J.Y. Ollitrault NPA 941 (2015) 87

- Valid at intermediate p_T out of equilibrium.
- Valid at high η/s (cross over region) + self consistent kinetic freeze-out

DISADVANTAGES ?!

- The relaxation times are those of kinetic theory
- Hadronizzation missing now but it will be possible to include:

  Coalescence + Fragmentation

Parton Cascade model

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

For the numerical implementation of the collision integral we use the stochastic algorithm.

Z. Xu and C. Greiner, PRC 71 064901 (2005)

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

Simulating a constant η/s

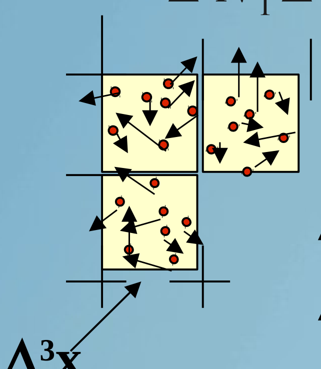
For anisotropic cross section and massless particles:

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

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]

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

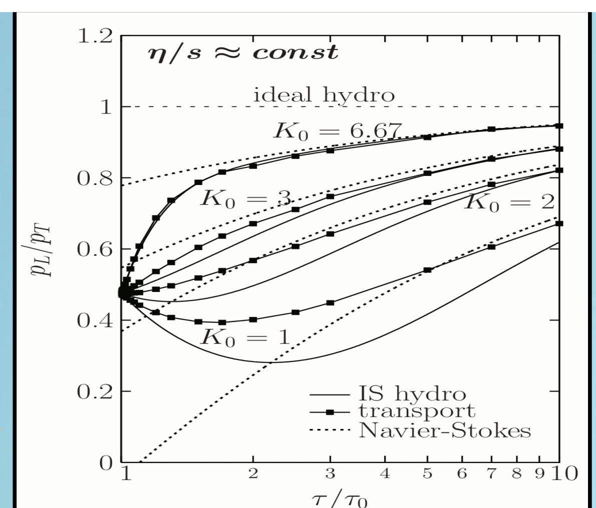


$\Delta t \to 0$

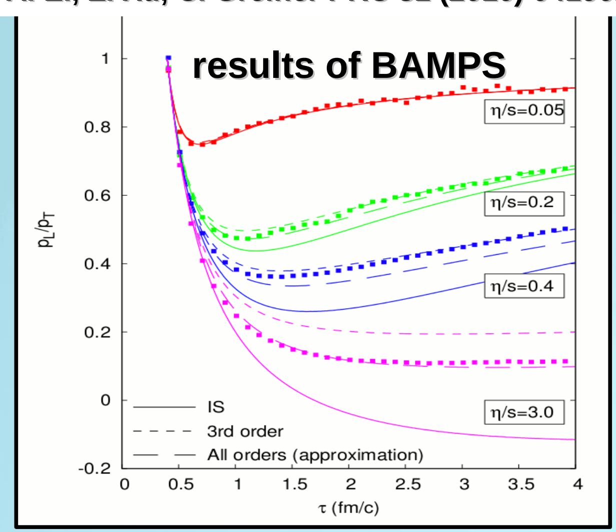
$\Delta^3 x \to 0$

right solution

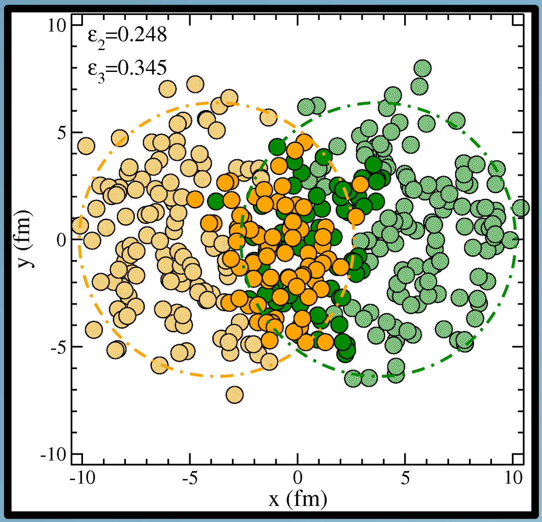
P. Huovinen and D. Molnar, PRC79(2009)



A. El, Z. Xu, C. Greiner PRC 81 (2010) 041901



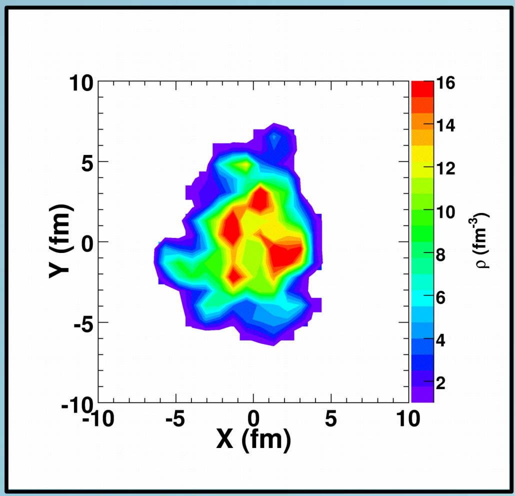
Initial State Fluctuations

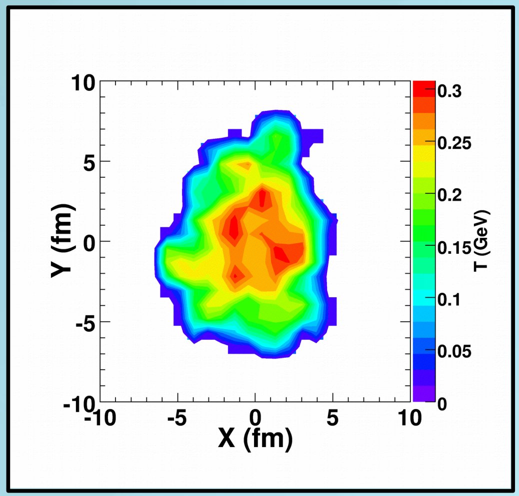


smooth distribution

Monte Carlo Glauber

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

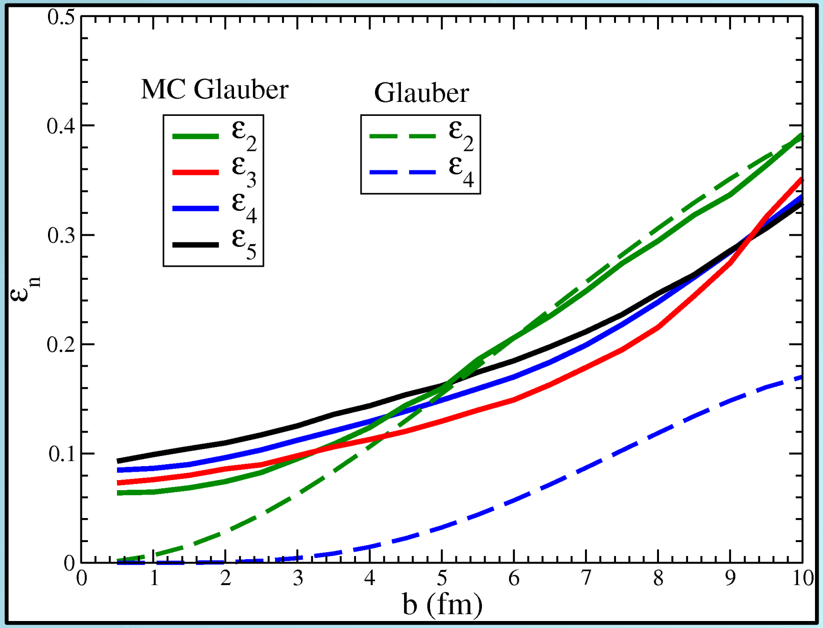




Characterization of the initial profile in terms of Fourier coefficients

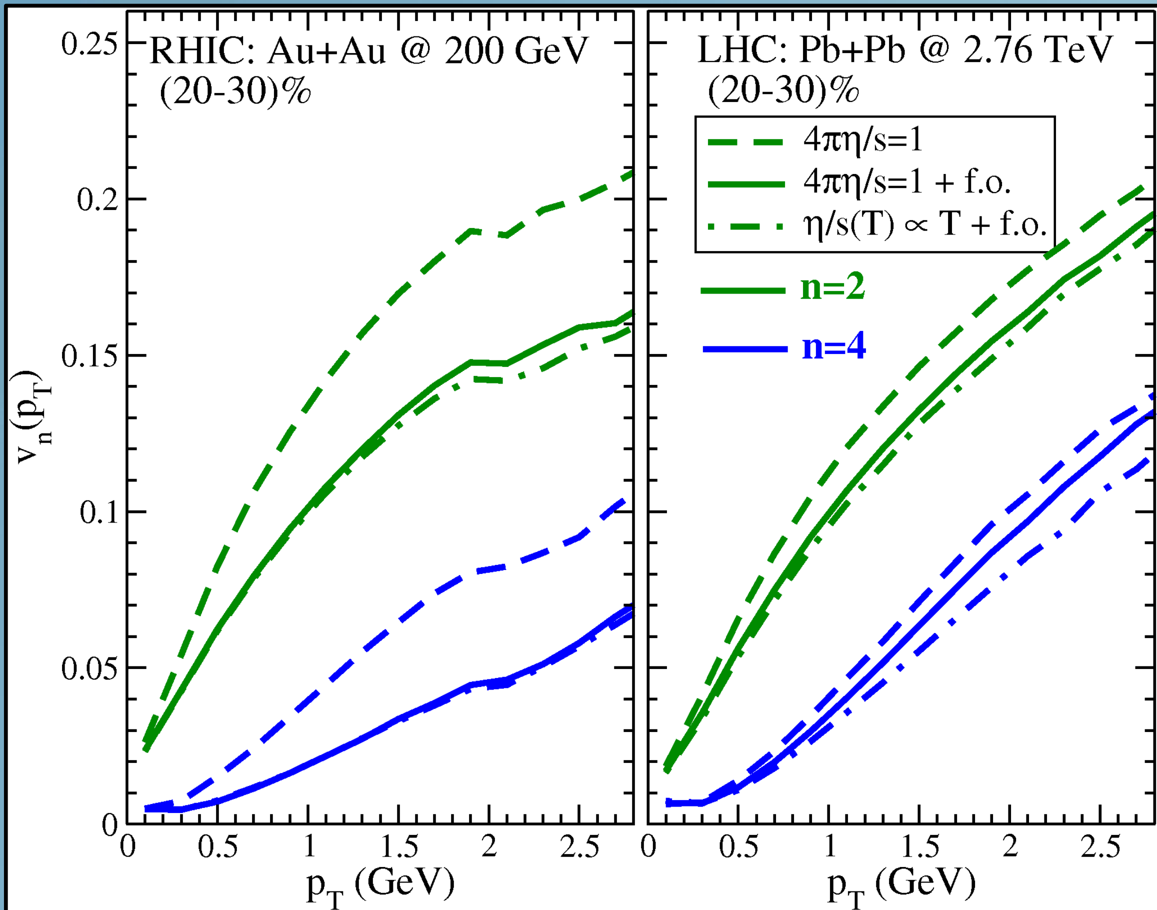
$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\varphi-\Phi_n)]\rangle}{\langle r_\perp^n\rangle} \qquad \Phi_n = \frac{1}{n}\arctan\frac{\langle r_\perp^n \sin(n\varphi)\rangle}{\langle r_\perp^n \cos(n\varphi)\rangle}$$

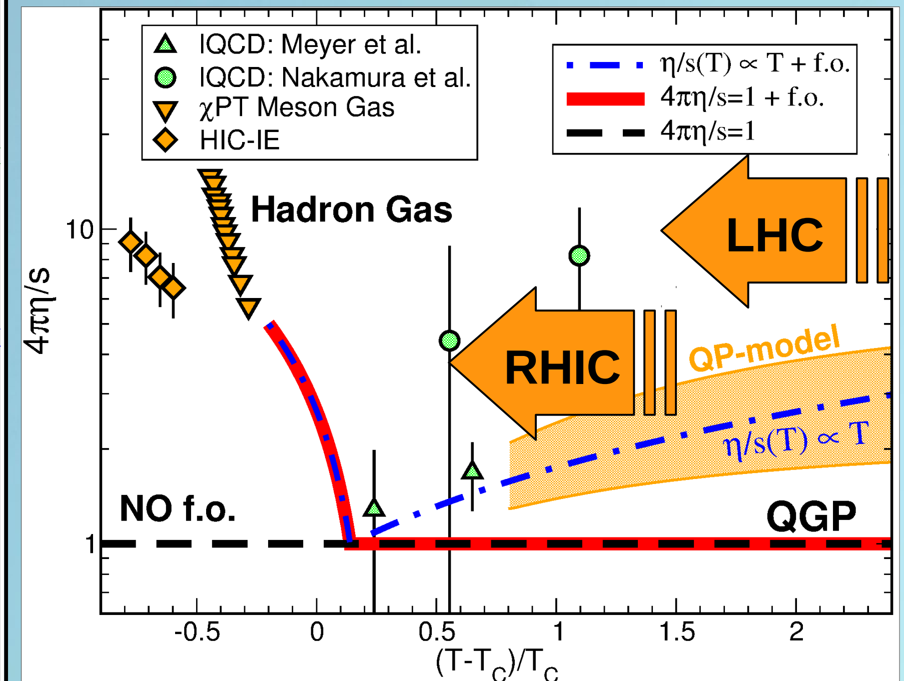
$$r_\perp = \sqrt{x^2+y^2}, \qquad \varphi = \arctan(y/x)$$



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).

Initial State Fluctuations: $v_n(p_T)$ and η/s

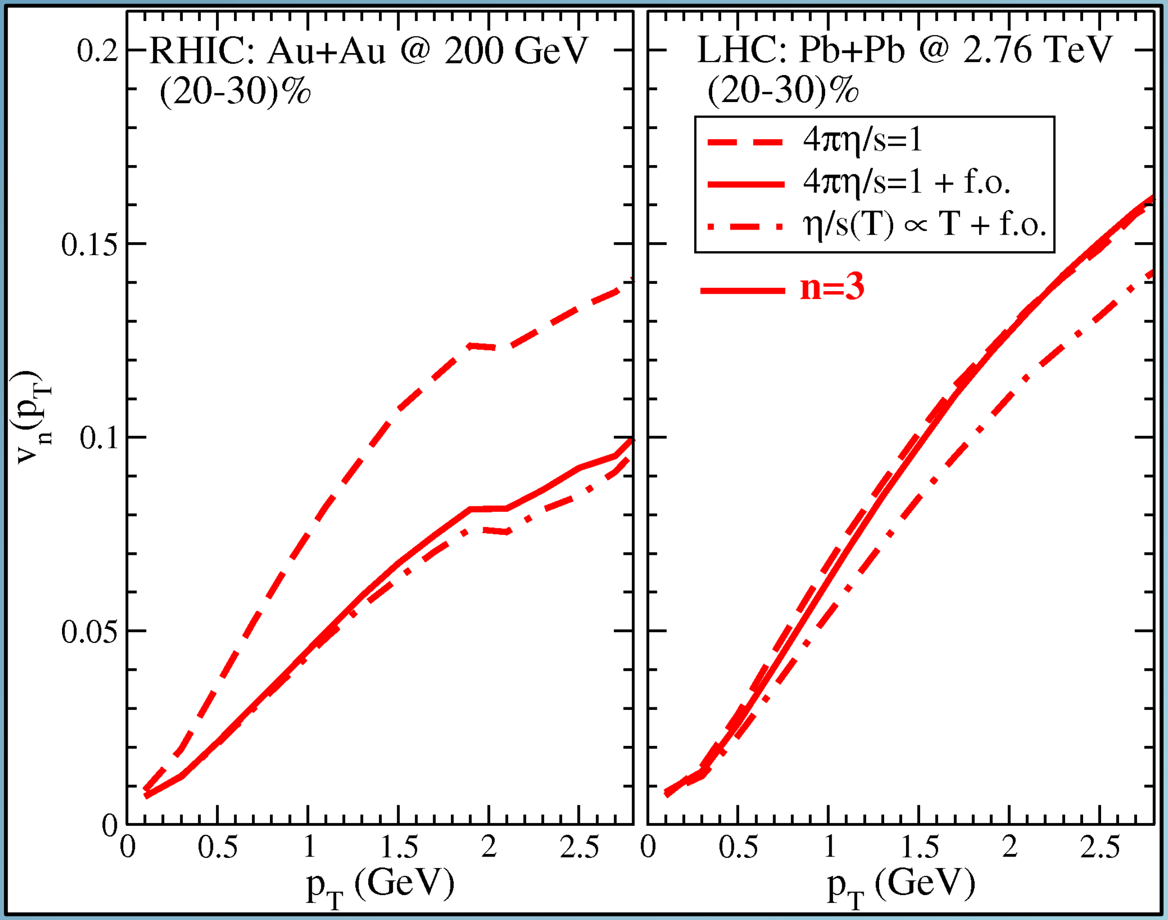


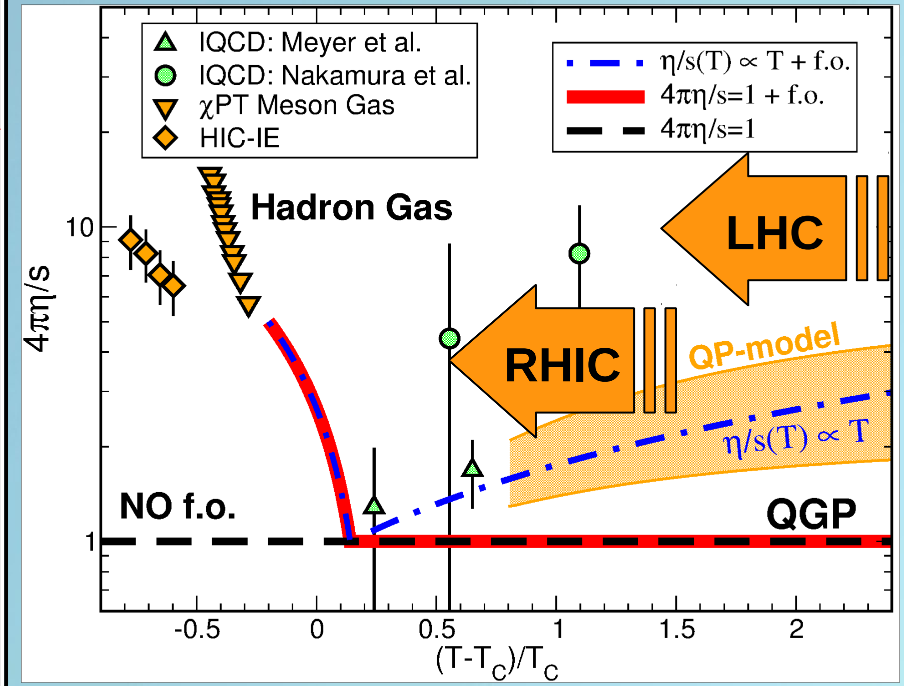


S. Plumari, G. L. Guardo, F. Scardina and V. Greco, arXiv:1507.05540

- $v_n(p_T)$ at RHIC is more sensitive to the value of the η/s at low temperature. $v_4(p_T)$ and $v_3(p_T)$ are more sensitive to the value of η/s than the $v_2(p_T)$.
- At LHC energies $v_n(p_T)$ is more sensitive to the value of η/s in the QGP phase (compare solid and dot-dashed lines).

Initial State Fluctuations: $v_n(p_T)$ and η/s





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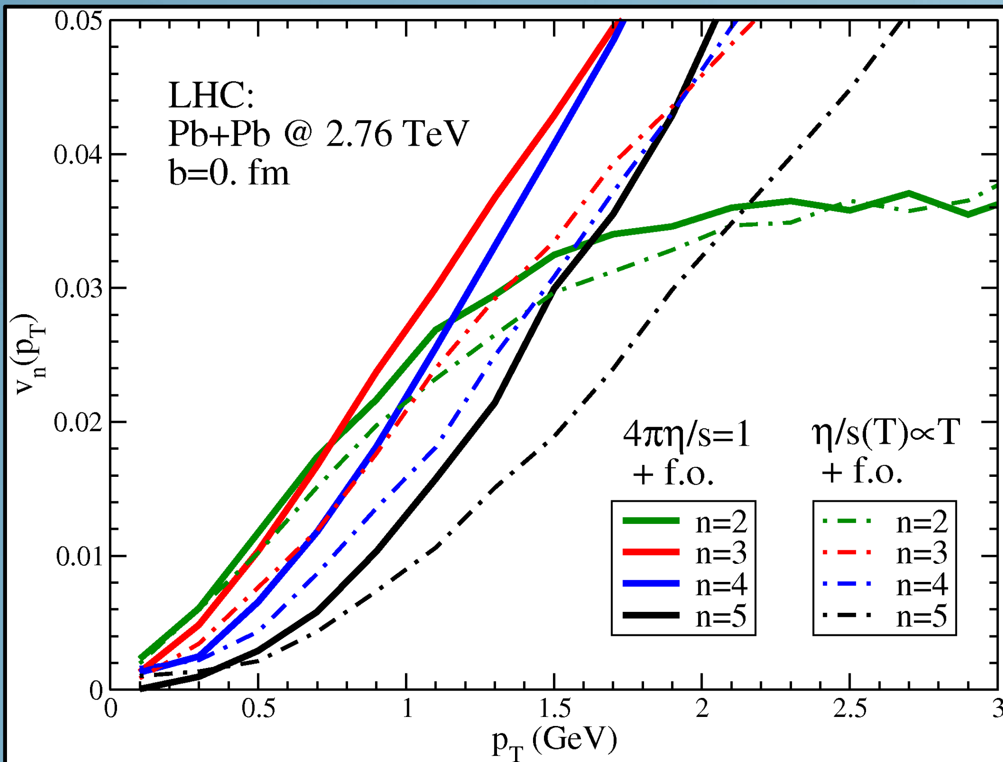
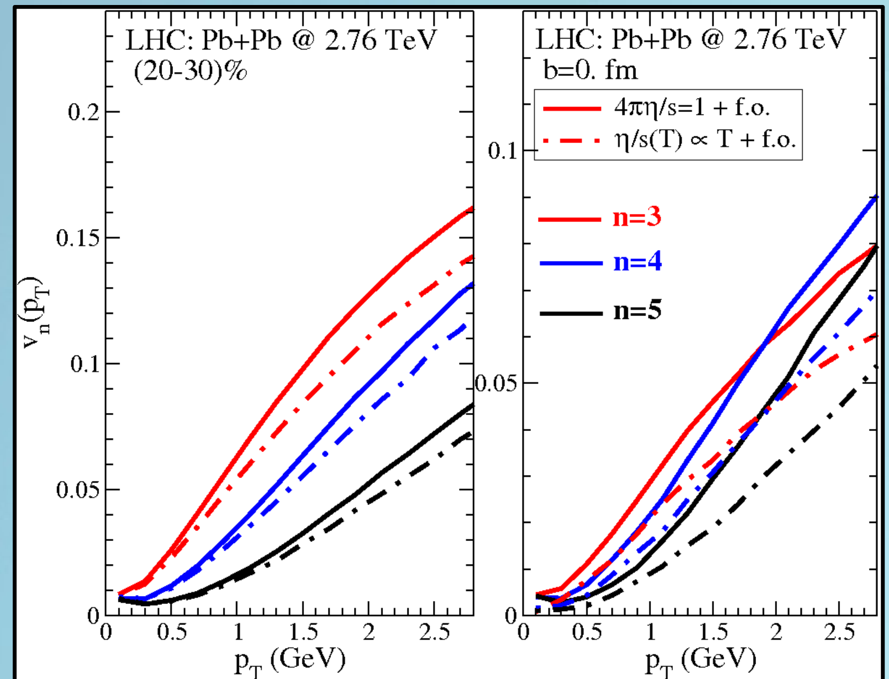
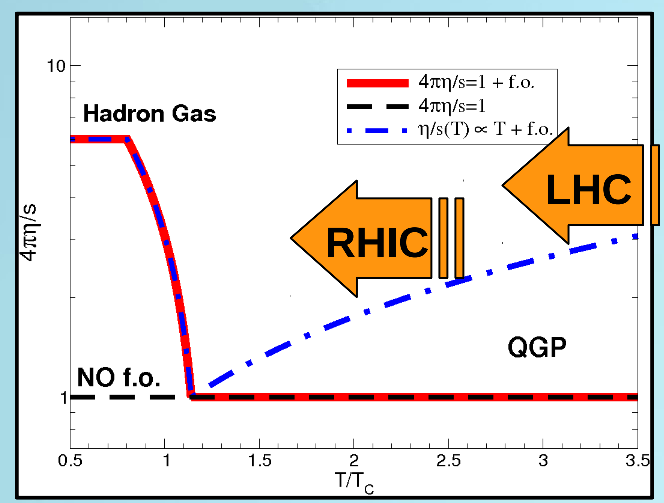
Initial State Fluctuations: $v_n(p_T)$ for central collisions



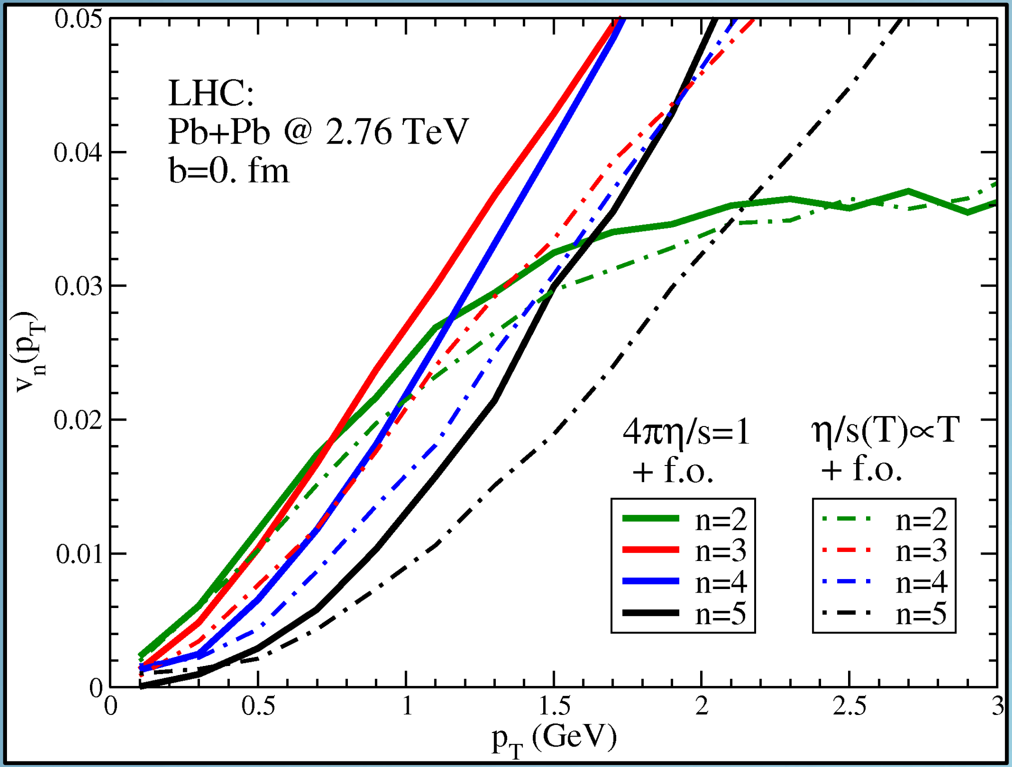


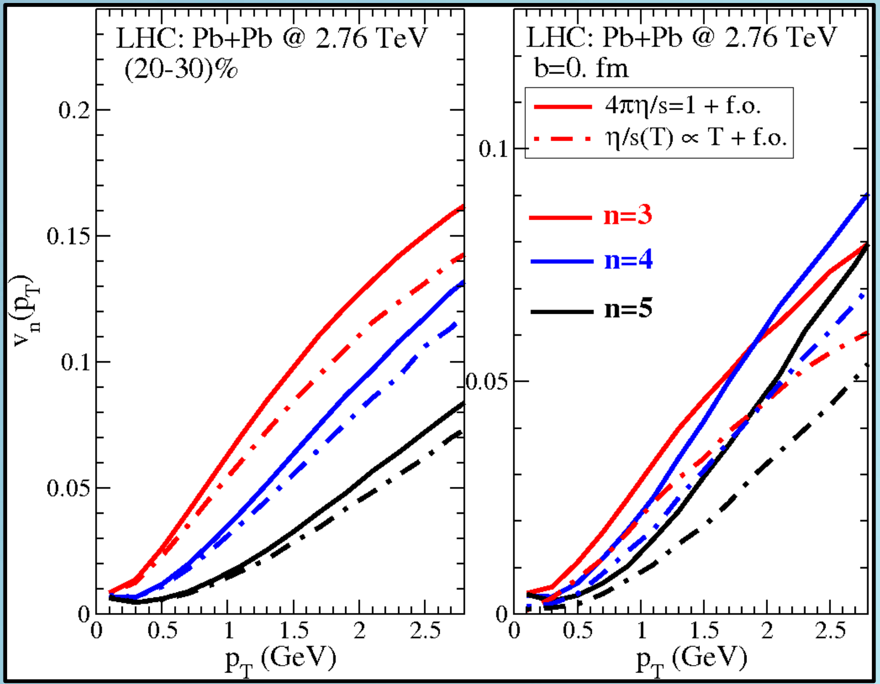
- At low p_T $v_n(p_T) \propto p_T^n$. v_2 for higher p_T saturates while v_n for n>3 increase linearly with p_T.
- For central collisions viscous effect are more relevant. For n>2 the $v_n(p_T)$ are more sensitive to the η/s ratio in the QGP phase.

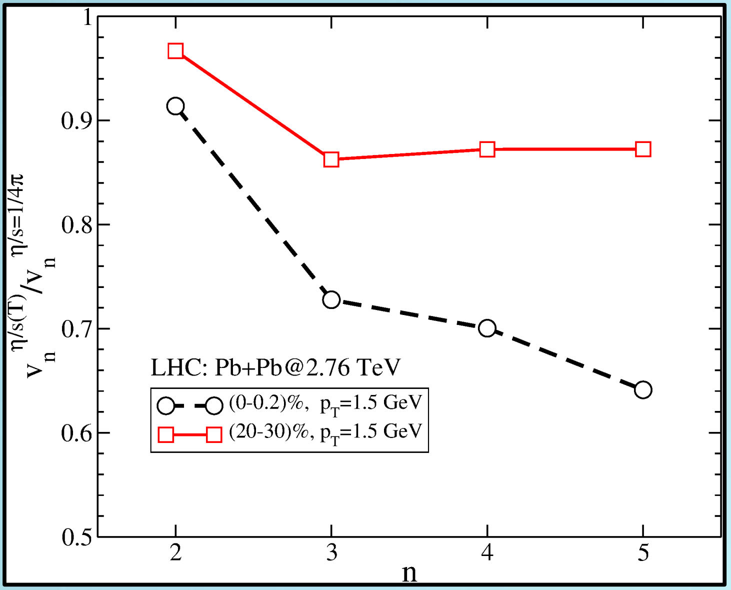


S. Plumari, G. L. Guardo, F. Scardina and V. Greco, arXiv:1507.05540

Initial State Fluctuations: $v_n(p_T)$ for central collisions







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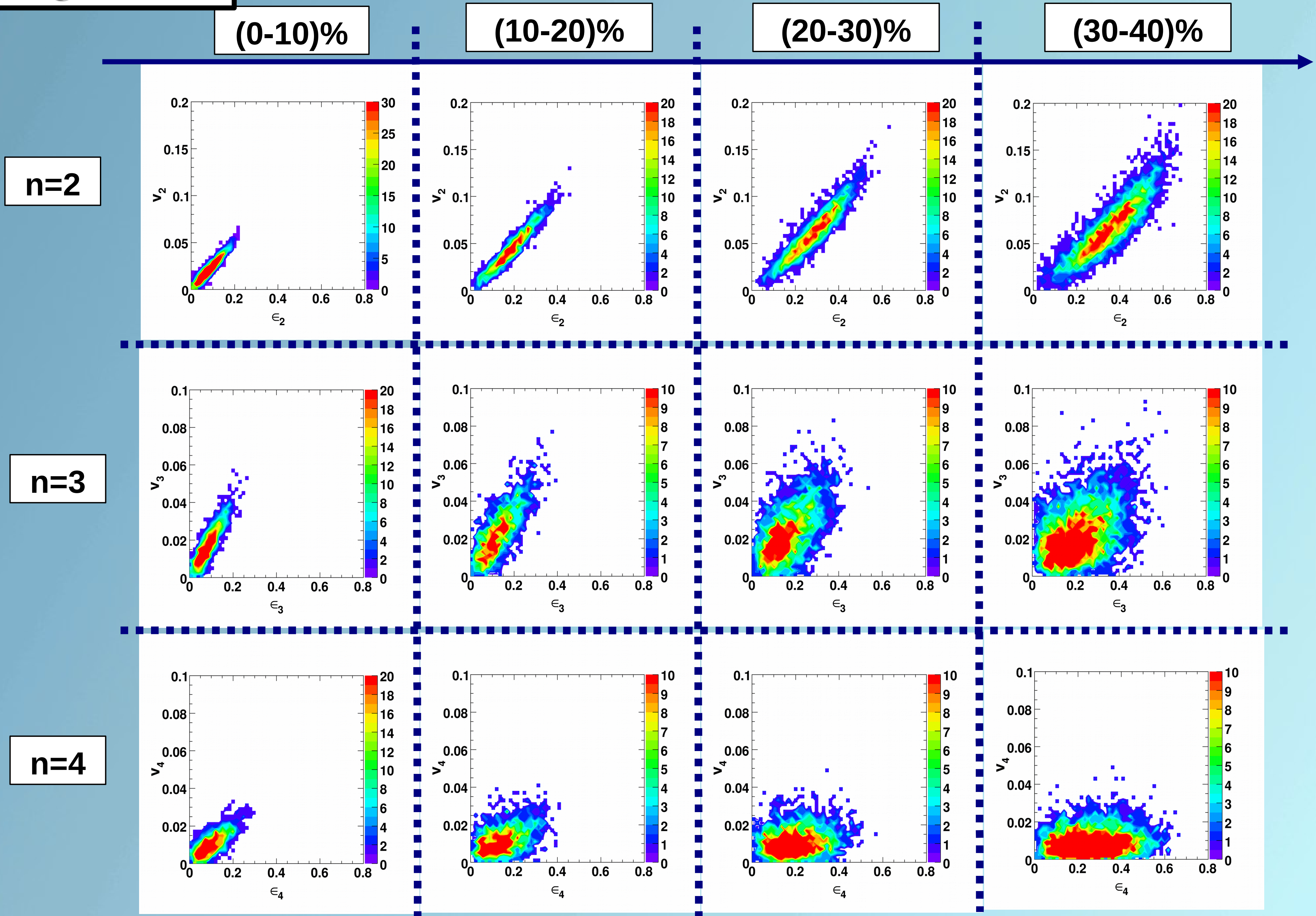
S. Plumari, G. L. Guardo, F. Scardina and V. Greco, arXiv:1507.05540

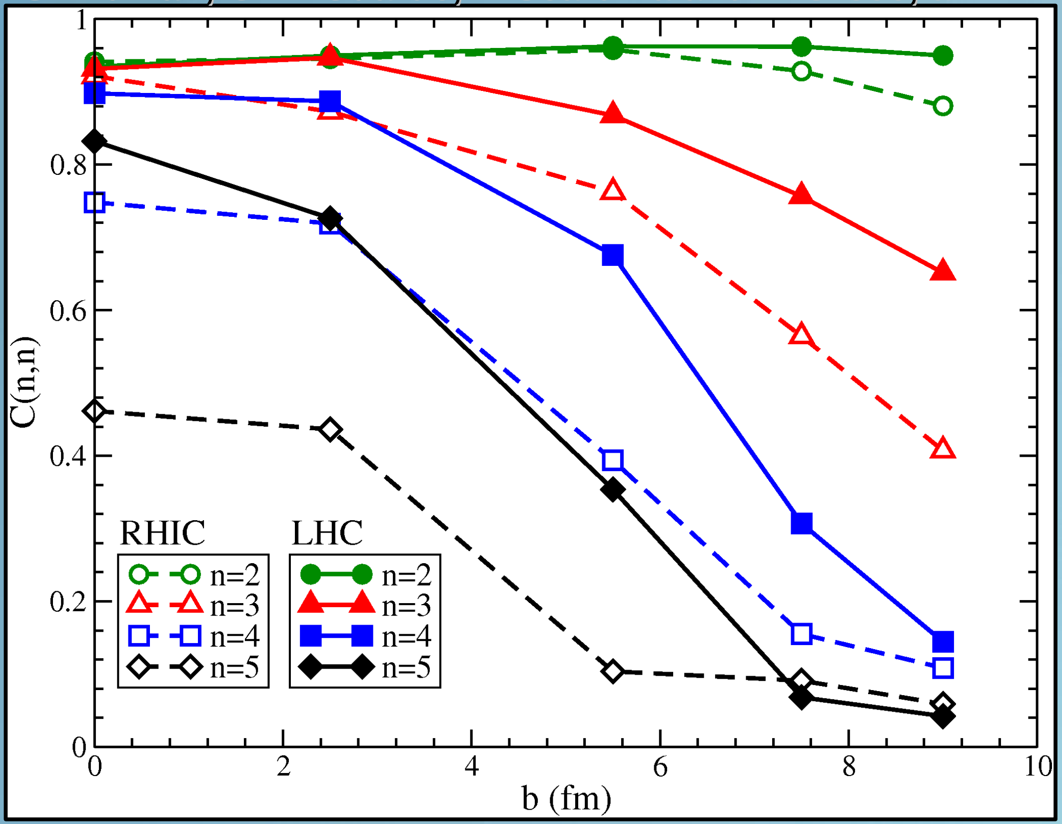
RHIC:
Au+Au @ 200 GeV

Initial State Fluctuations: v_n vs ε_n



Initial State Fluctuations: v_n vs ε_n

S. Plumari, G. L. Guardo, F. Scardina and V. Greco, arXiv:1507.05540



$$C(n,m)=\left\langle \frac{(v_n-\langle v_n\rangle)(\epsilon_m-\langle \epsilon_m\rangle)}{\sigma_{v_n}\sigma_{\epsilon_m}}\right\rangle$$

B.H. Alver, C. Gombeaud, M. Luzum and J.-Y. Ollitrault, Phys.Rev. C82 (2010) 034913.

H. Petersen, G.-Y. Qin, S.A. Bass and B. Muller, Phys.Rev. C82 (2010) 041901.

Z. Qiu and U. W. Heinz, Phys.Rev. C84 (2011) 024911.

H. Niemi, G.S. Denicol, H. Holopainen and P. Huovinen, Phys.Rev. C87 (2013) 5, 054901.

- At LHC v_n are more correlated correlated to ε_n than at RHIC.
- v_2 and v_3 linearly correlated to the corresponding eccentricities ε_2 and ε_3 rispectively.
- C(4,4) < C(2,2) for all centralities. 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.
  H. Niemi, G.S. Denicol, H. Holopainen and P. Huovinen PRC87(2013) 054901.
- For central collisions v_n are strongly correlated to ε_n: $v_n \propto \varepsilon_n$ for n=2,3,4.

Initial State Fluctuations: v_n vs ε_n

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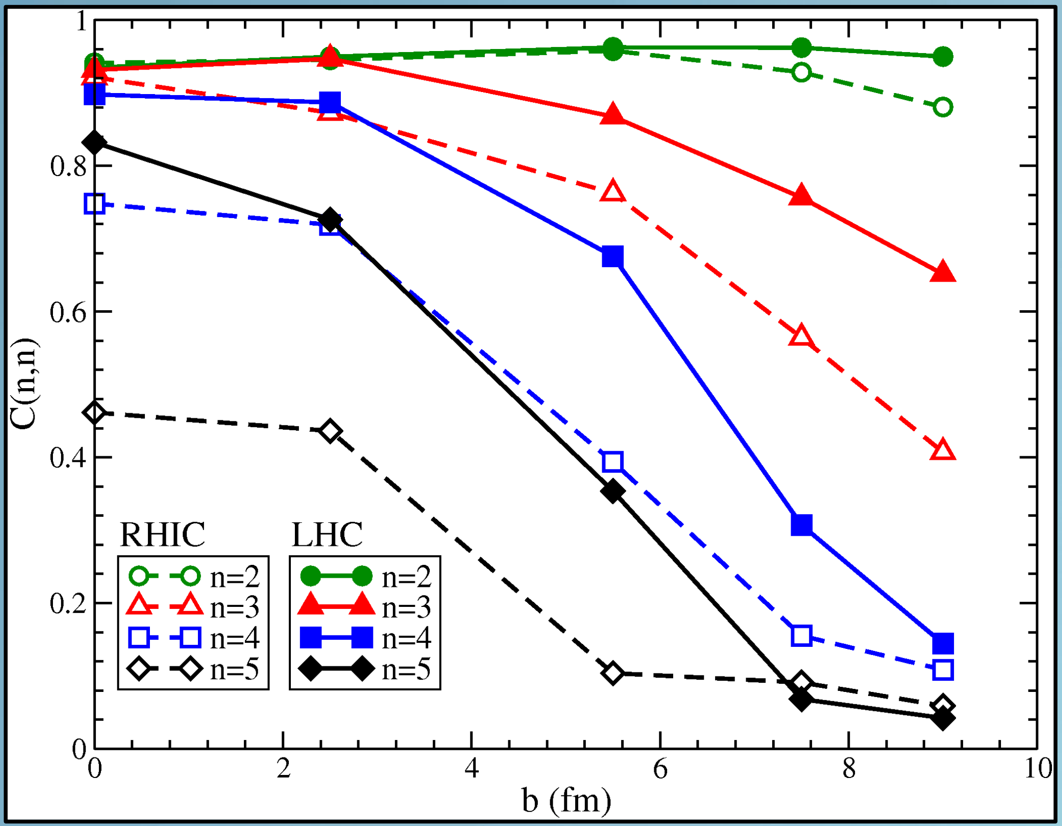

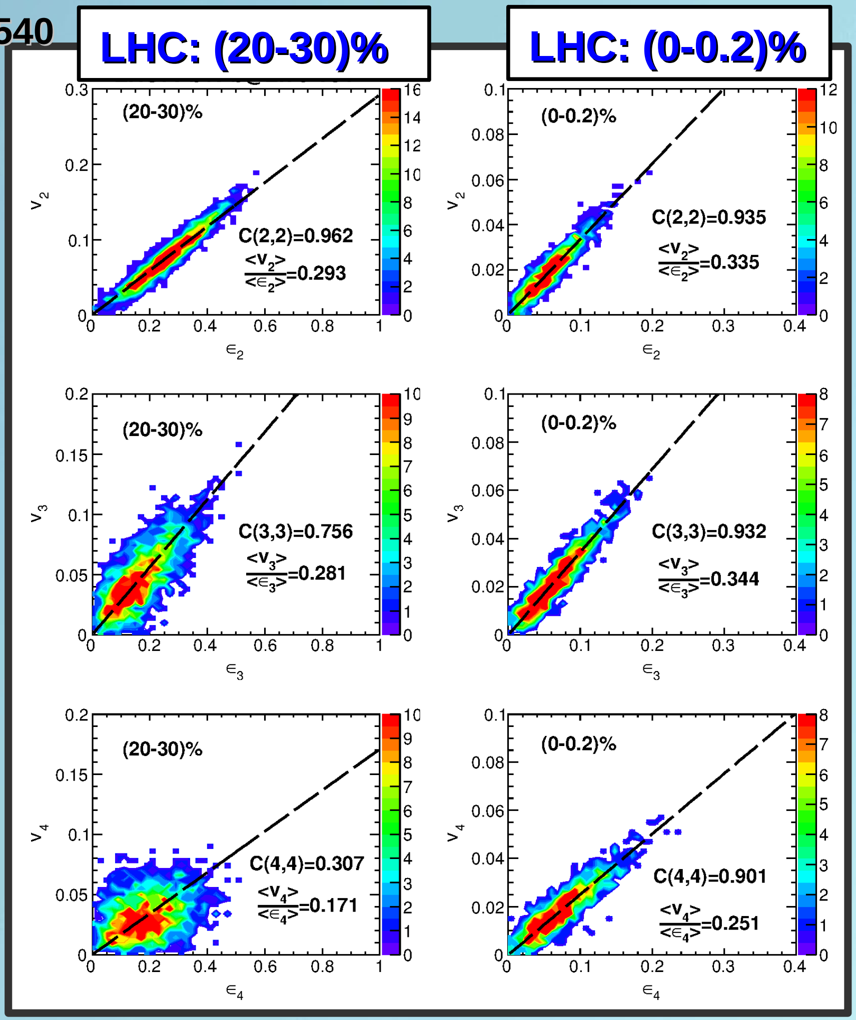

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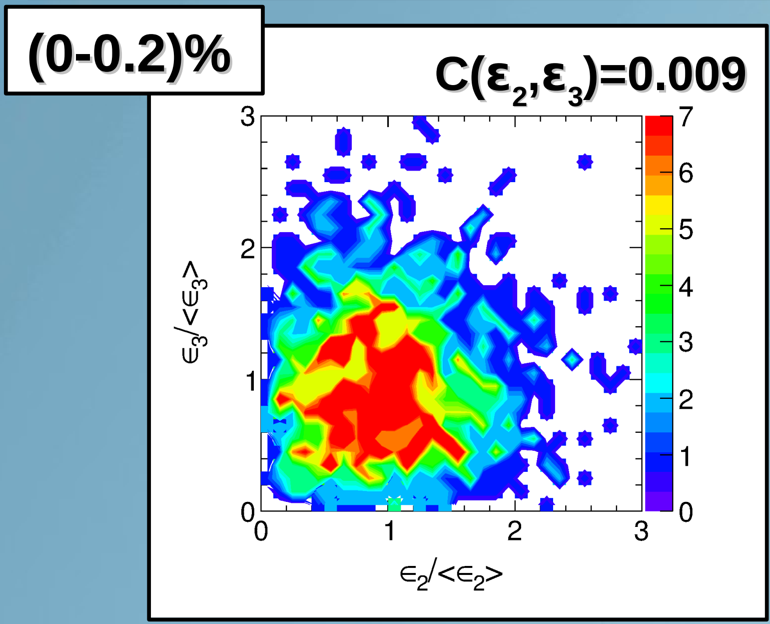
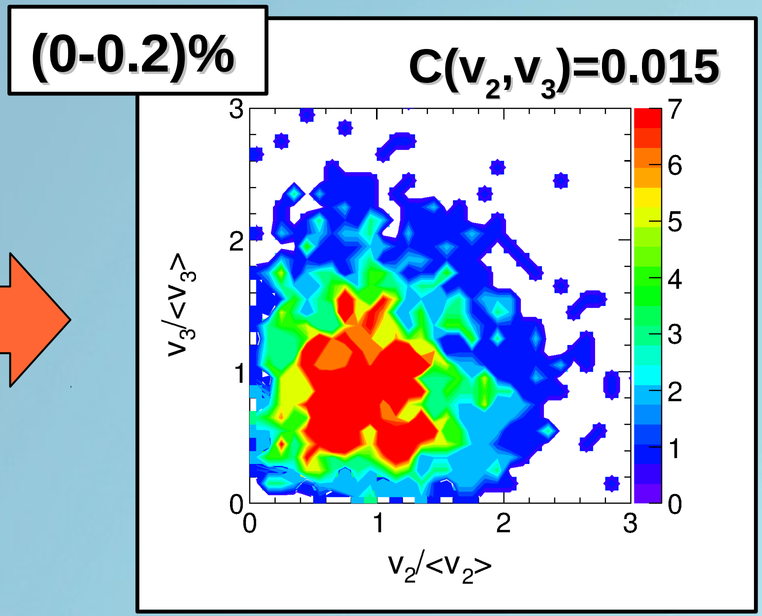
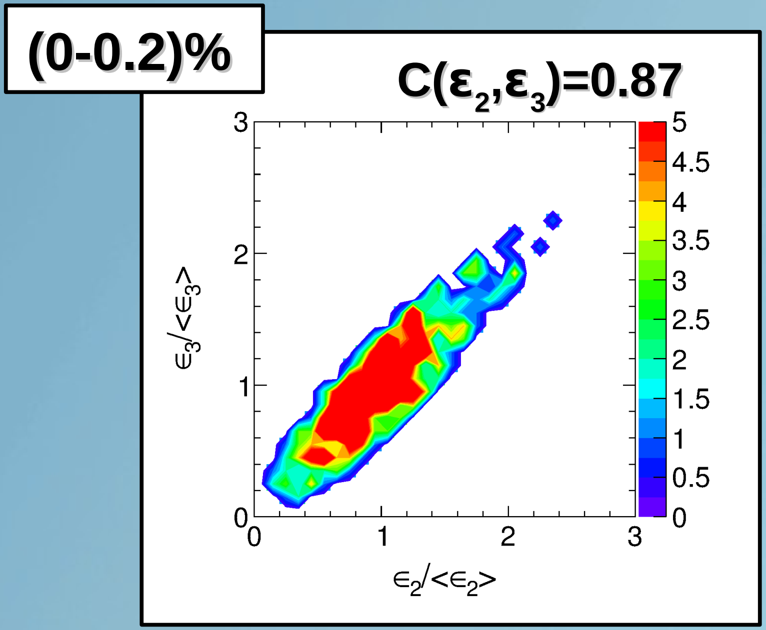
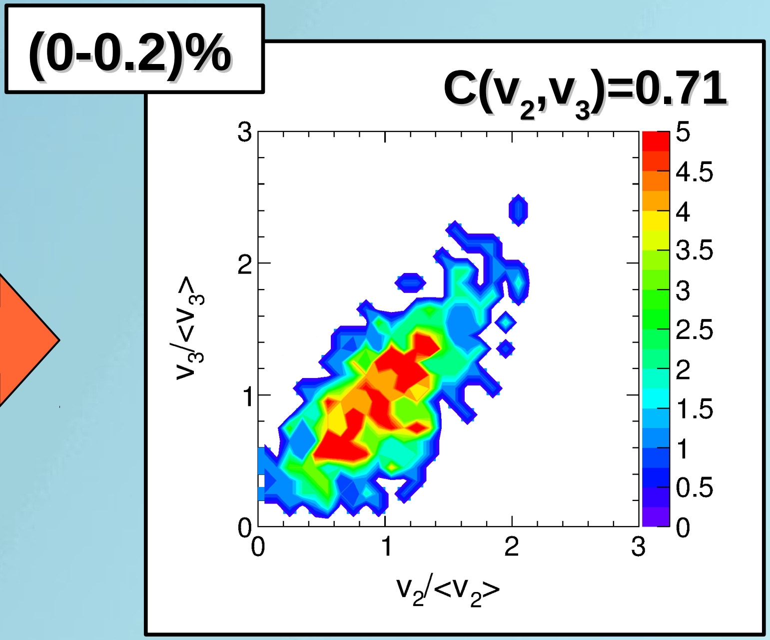
Correlations: $(\varepsilon_n,\varepsilon_m)$ vs (v_n,v_m) in (0-0.2)%









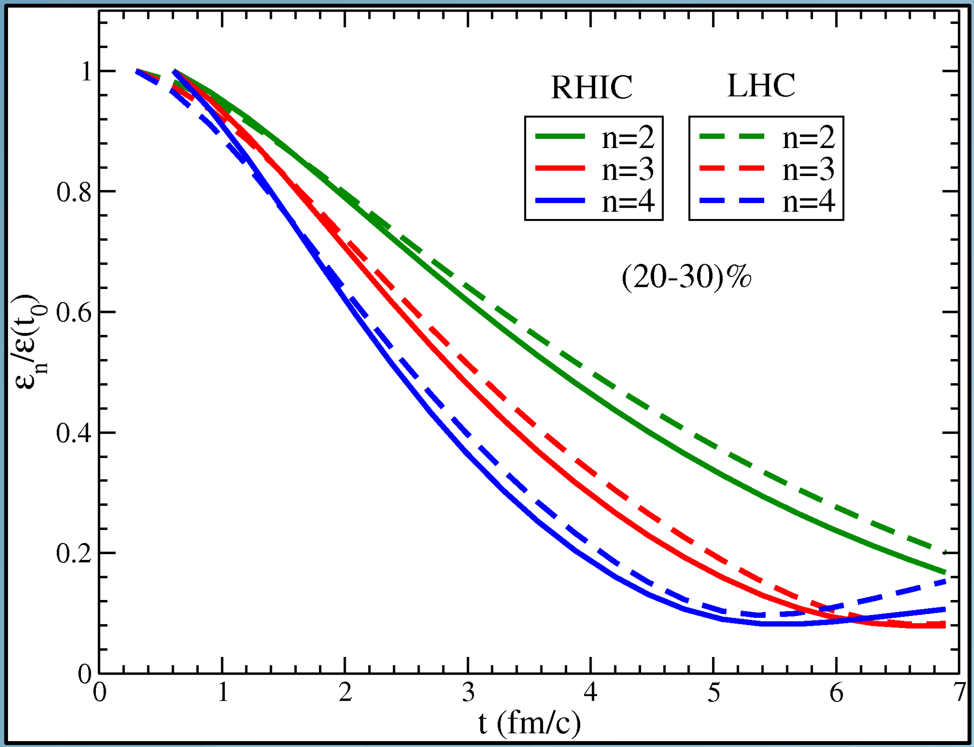
- **Final correlations in (v_n,v_m) reflect initial correlations in $(\varepsilon_n,\varepsilon_m)$**
- **For (20-30)%: $C(v_n,v_m)=0.38$ and $C(\varepsilon_n,\varepsilon_m)=0.78$ differ a factor 2**

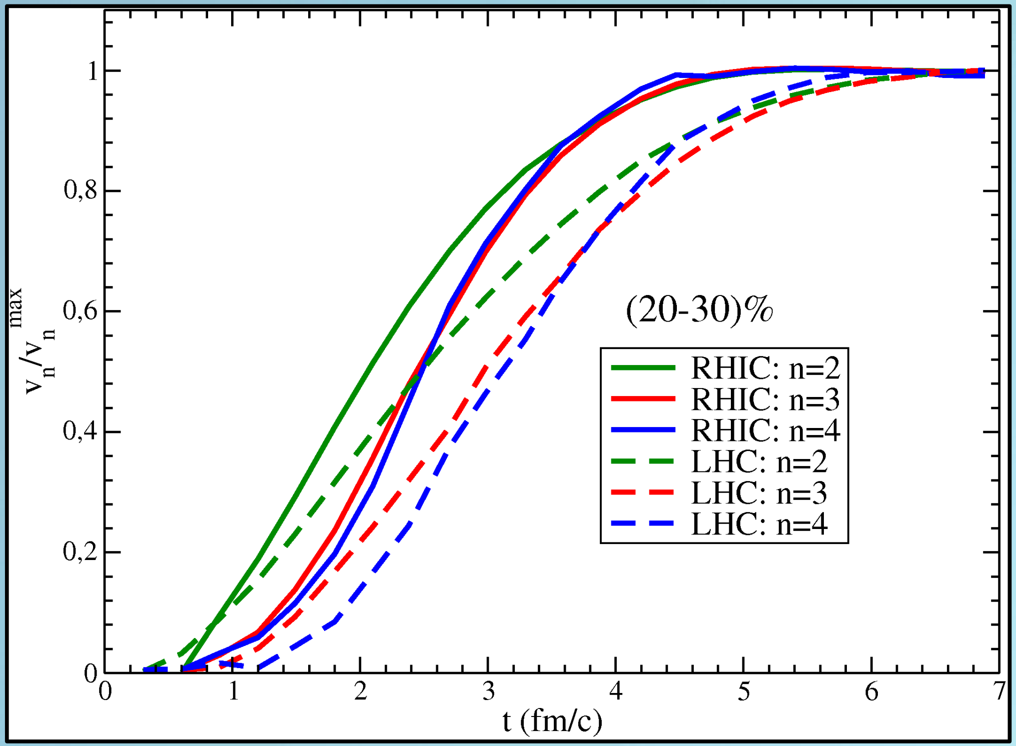
Conclusions

Transport at fixed η/s:

- Enhancement of η/s(T) in the cross-over region affect differently the expanding QGP from RHIC to LHC. LHC nearly all the v_n from the QGP phase.
- At LHC there is a stronger correlation between v_n and ε_n than at RHIC for all n.
- Ultra central collisions:
  - $v_n \propto \varepsilon_n$ for n=2,3,4 strong correlation C(n,n)≈1
  - $v_n(p_T)$ much more sensitive to η/s(T)
  - degree of correlation increase with the collision energy
  - correlations in (v_n, v_m) reflect the initial correlations in $(\varepsilon_n, \varepsilon_m)$

Initial State Fluctuations: time evolution of $\langle v_n \rangle$ and ε_n





- **The time evolution for ε_n is faster for large n. At very early times $\varepsilon_n(t)=\varepsilon_n(t_0)-\alpha_n t^{n-2}$.**
- **$\langle v_n \rangle$ shows an opposite behaviour: $\langle v_n \rangle$ develops later for large n. At very early times $\langle v_n \rangle \propto t^{n+1}$.**
- **Different v_n can probes different value of $\eta/s(T)$ during the expansion of the fireball.**

η/s(T) around to a phase transition

- **Quantum mechanism**

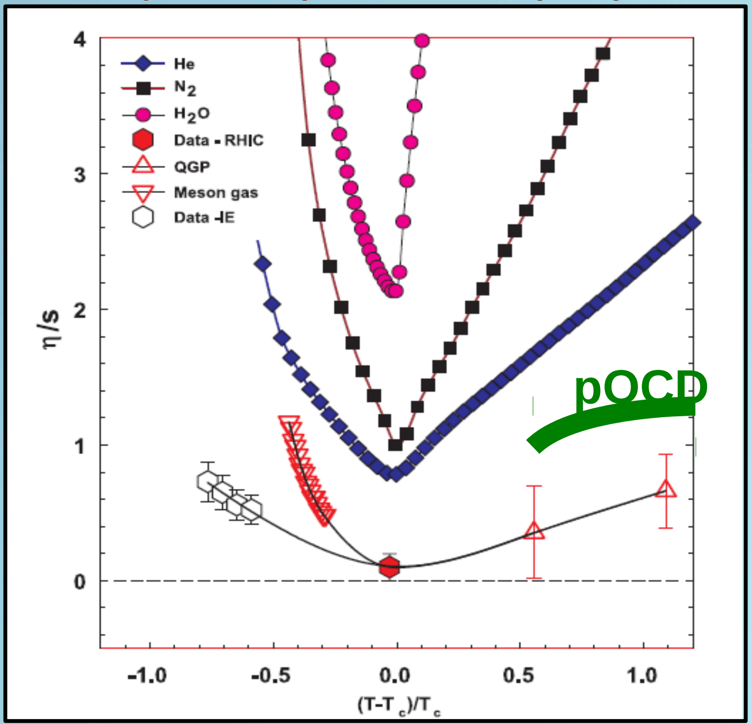
$$\Delta E \cdot \Delta t \geqslant 1 \rightarrow \eta/s \approx \frac{1}{15}\langle p \rangle \cdot \tau > \frac{1}{15}$$

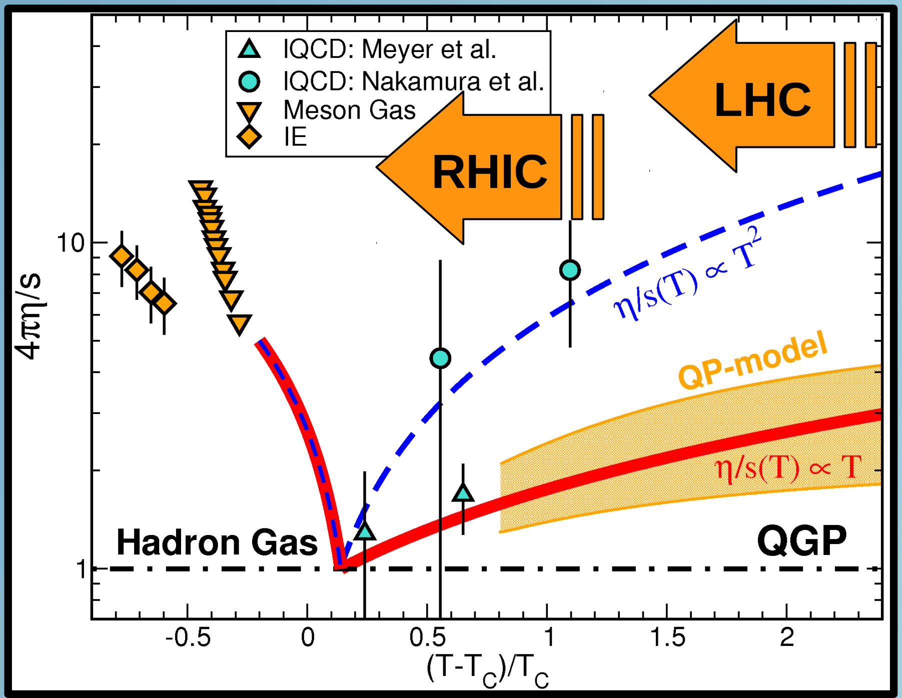
- **AdS/CFT suggest a lower bound $\eta/s = 1/(4\pi) \sim 0.08$**

- **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.

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.





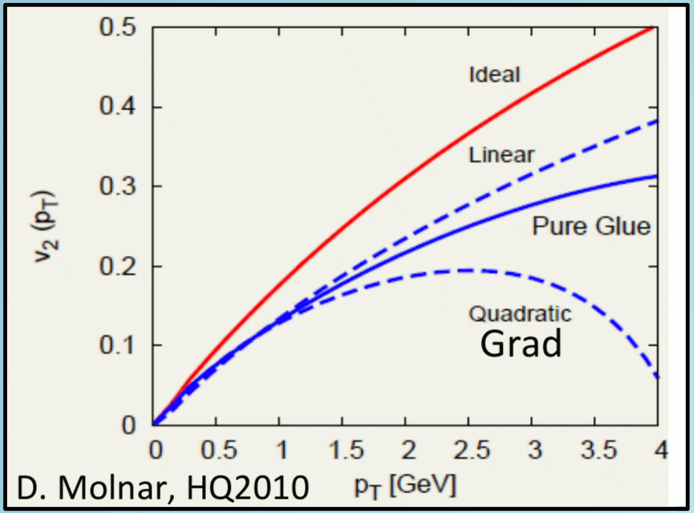
S. Plumari et al., J. Phys.: Conf. Ser. 420 012029 (2013). arXiv:1209.0601.

- **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 ($\mu_B > T$)**

From Transport to Hydro: extraction of viscous corrections to f(x,p) and $v_n(p_T)$. (work in collaboration with J.Y. Ollitrault)

$$f(x,p)=f^{(0)}(x,p)+\delta f(x,p)$$

$$T^{\mu\nu}=T^{(0)\mu\nu}+\delta T^{\mu\nu}\leftarrow f^{(0)}+\delta f$$



A common choice for δf – the Grad ansatz

$$\delta f\propto\Gamma_s f^{(0)}p^{\alpha}p^{\beta}\langle\nabla_{\alpha}u_{\beta}\rangle\propto p_T^2$$

BUT it doesn't care about the microscopic dynamics

In general in the limit σ→∞, f(σ) can be expanded in power of 1/σ.

$$f(\sigma)\underset{\sigma\to\infty}{\approx}f^{(0)}+\frac{1}{\sigma}\delta f+O\left(\frac{1}{\sigma^2}\right)\quad\Rightarrow\quad v_n(p_T)\underset{\sigma\to\infty}{\approx}v_n^{(0)}(p_T)+\frac{1}{\sigma}\delta v_n+O\left(\frac{1}{\sigma^2}\right)$$

PURPOSE: evaluate the ideal hydrodynamics limit $f^{(0)}$, $v_n^{(0)}$ and the viscous corrections δf and δv_n solving the Relativistic Boltzmann eq for large values of the cross section σ

From Transport to Hydro: extraction of viscous corrections to f(x,p) and $v_n(p_T)$. (work in collaboration with J.Y. Ollitrault)

Coodinate space (x,y)

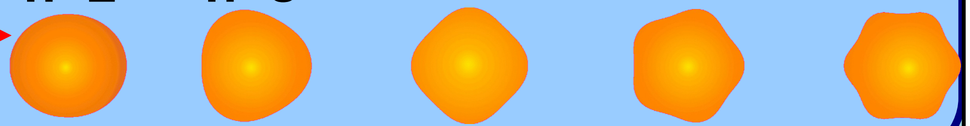
- We start with an initial azimuthally symmetric profile (optical Glauber model).
- Then we deform the initial distribution (α<<1)

$$z = x + iy \rightarrow z + \delta z \equiv z - \alpha \bar{z}^{n-1}$$

2π/n symmetry

This Creates only

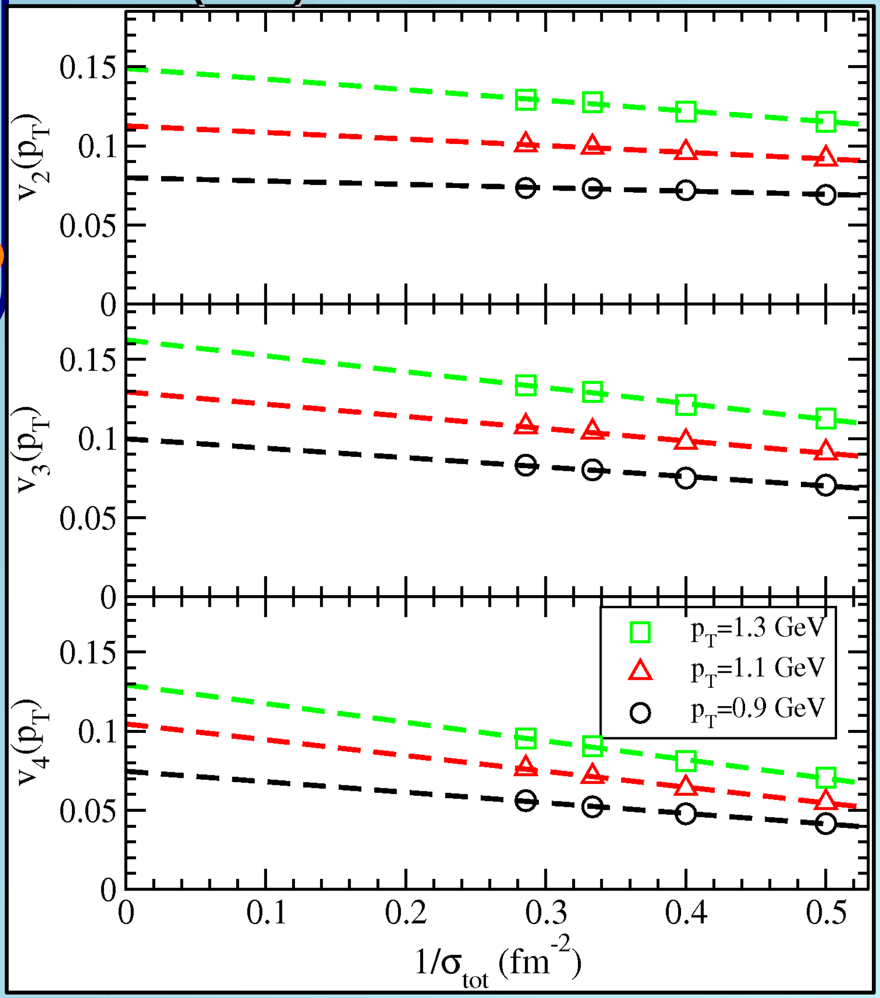
n=2 n=3 n=4 n=5 n=6



$$f(\sigma) \underset{\sigma\to\infty}{\approx} f^{(0)} + \frac{1}{\sigma}\delta f + O\left(\frac{1}{\sigma^2}\right)$$

$$v_n(p_T) \underset{\sigma\to\infty}{\approx} v_n^{(0)}(p_T) + \frac{1}{\sigma}\delta v_n + O\left(\frac{1}{\sigma^2}\right)$$

S.Plumari,G.L. Guardo,V. Greco,J.Y.Ollitrault NPA 941 (2015) 87



Momentum space

- Thermal distribution:

$$dN/d^3p \propto \exp(-p/T)$$

- Constant distribution:

$$dN/d^3p \propto \theta(p_0 - p)$$

We assume initially the same local $T^{\mu\nu}(x)$

From Transport to Hydro: extraction of viscous corrections to f(x,p) and $v_n(p_T)$. (work in collaboration with J.Y. Ollitrault)

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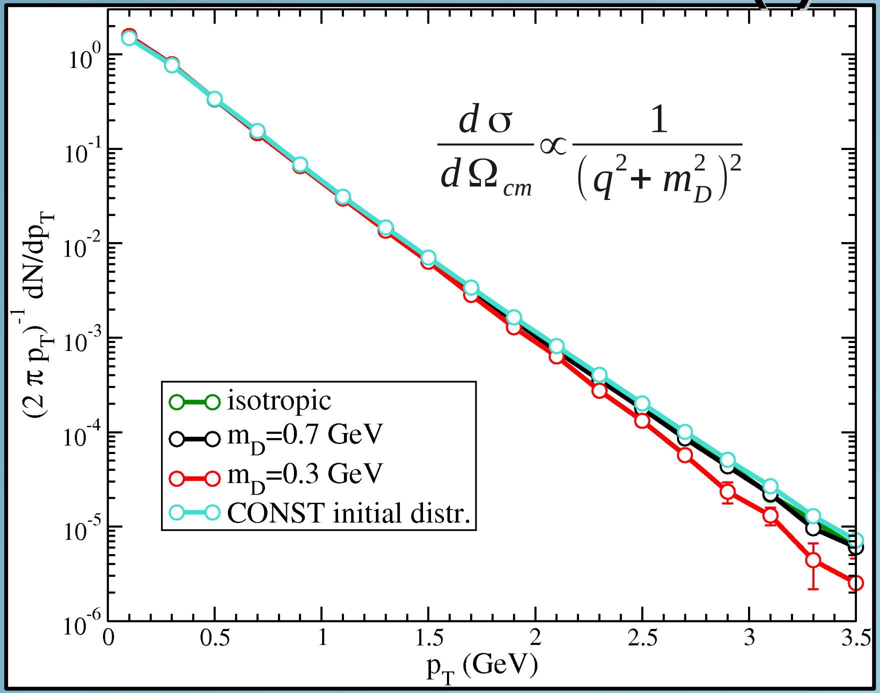
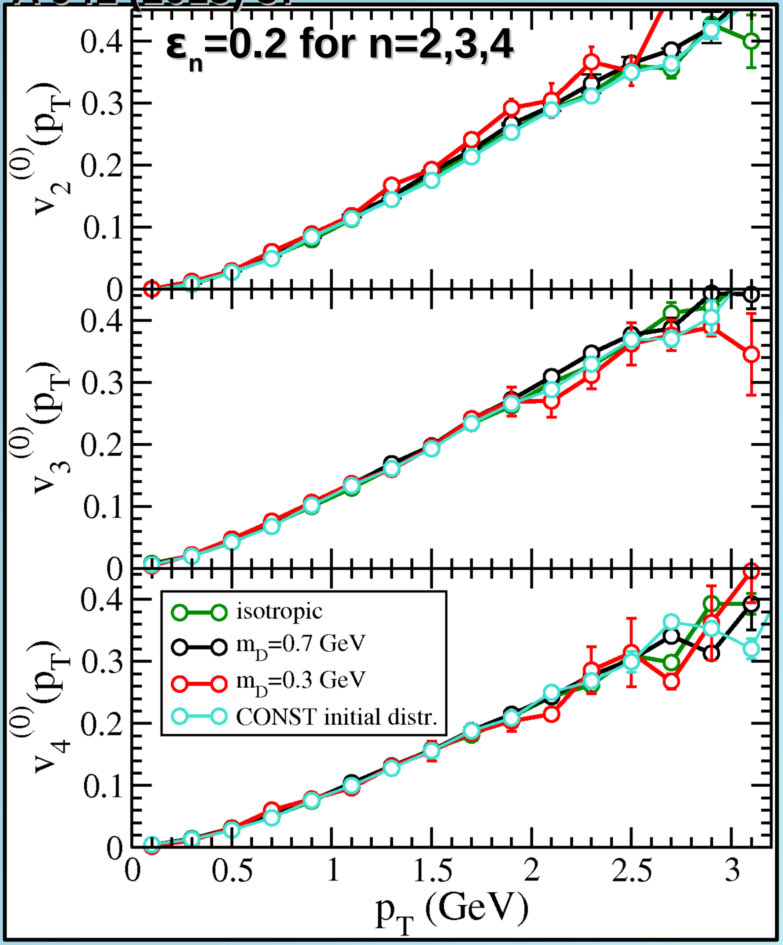
For the same initial local $T^{\mu\nu}(x)$:





For $\sigma \to \infty$ we find the ideal Hydro limit:

- $f^{(0)}$ is an exponential decreasing function.
- $f^{(0)}$ doesn't depends on microscopical details (i.e. mD).

- Universal behavior of $v_n^{(0)}(p_T)$
- $v_n^{(0)}(p_T)/\varepsilon_n$ is approximatively the same for all n and p_T.

From Transport to Hydro: extraction of viscous corrections to f(x,p) and $v_n(p_T)$. (work in collaboration with J.Y. Ollitrault)

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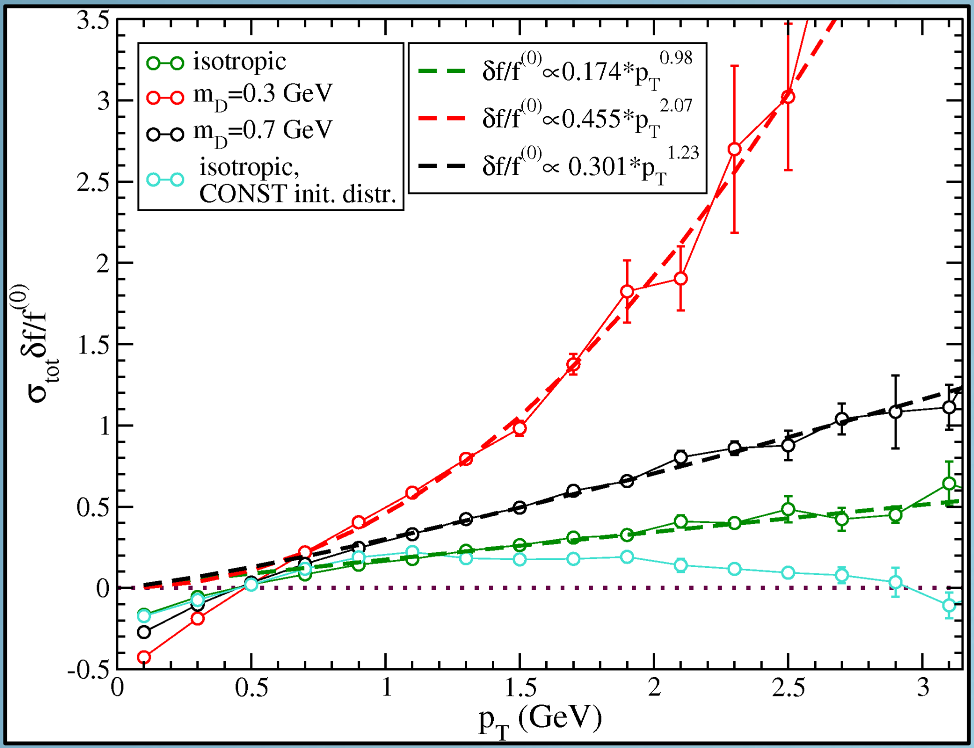

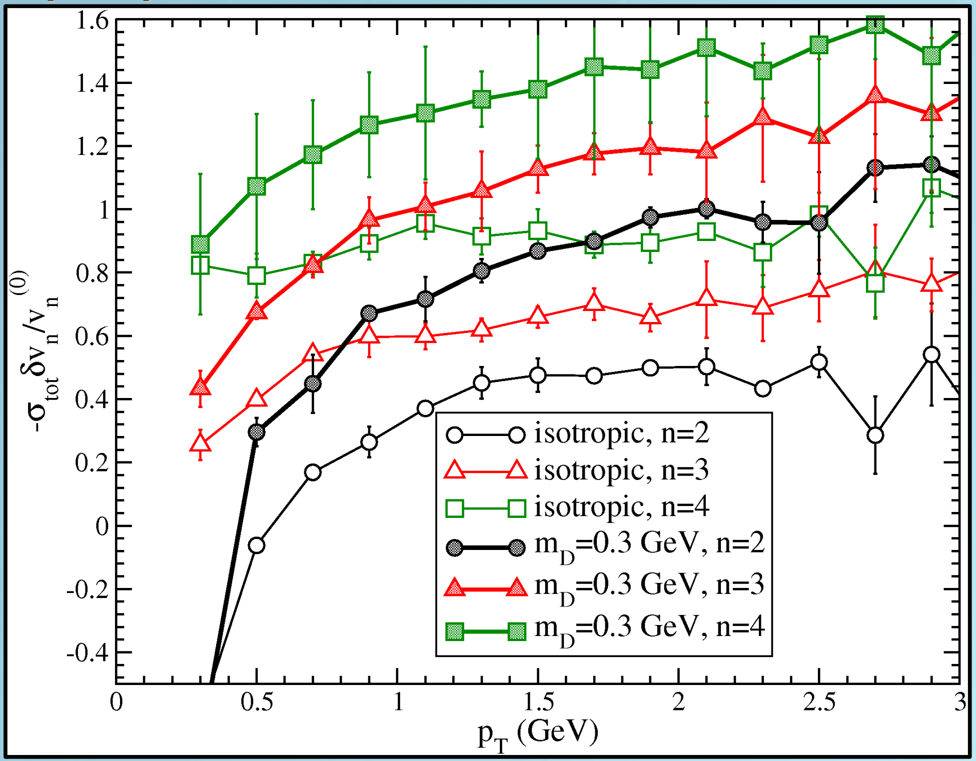

In δf and δv_n it is encoded the information about the microscopical details

- $\delta f(p_T)/f^{(0)} \propto p_T^{\alpha}$ with α = 1. - 2. and $\alpha(m_D)$.

For isotropic σ similar to R.S. Bhalerao et al. PRC 89, 054903 (2014)

- Larger is n larger is the viscous correction to $v_n(p_T)$
- Scaling: for p_T > 1.5 GeV → $-\delta v_n(p_T)/v_n^{(0)} \propto n$