UNIVERSITÀ DEGLI STUDI DI CATANIA
INFN-LNS

Correlazioni tra flussi collettivi ed eccentricità iniziali in collisioni ultra centrali

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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**

Parton Cascade model

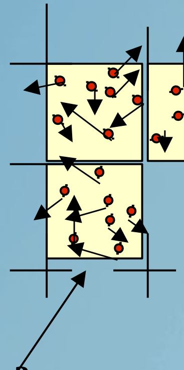
$$p^{\mu}\partial_{\mu}f(X,p)=C=C_{22}+C_{23}+\ldots$$

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

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

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

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

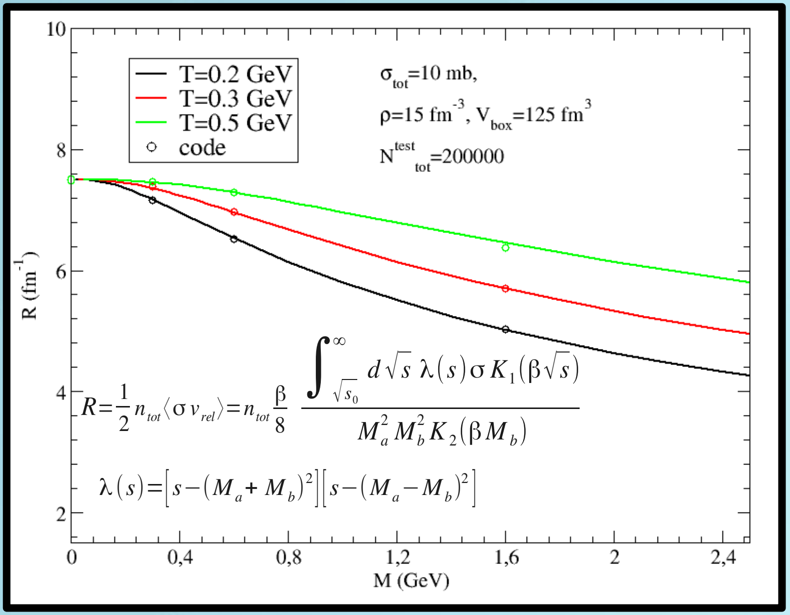


Δ^3x

Δt→0

Δ^3x→0

⇒ **right solution**



Simulating a constant η/s

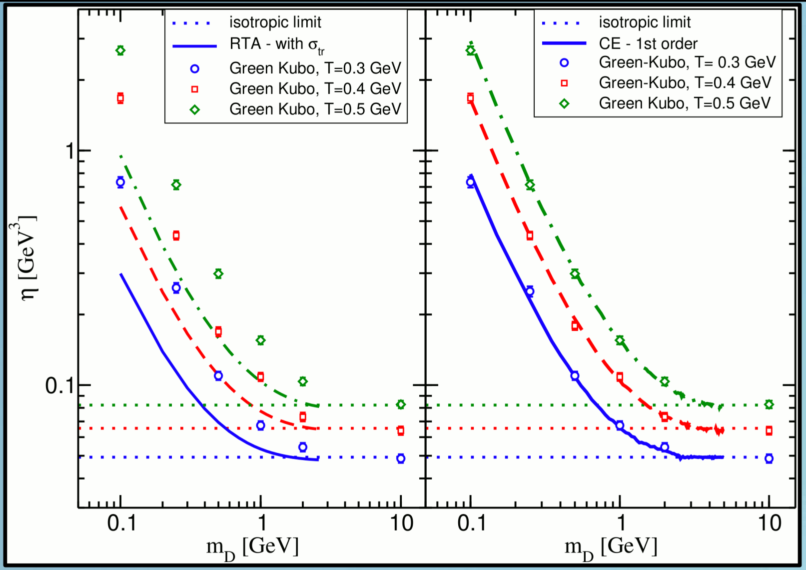
For the general case of anisotropic cross section and massless particles:

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

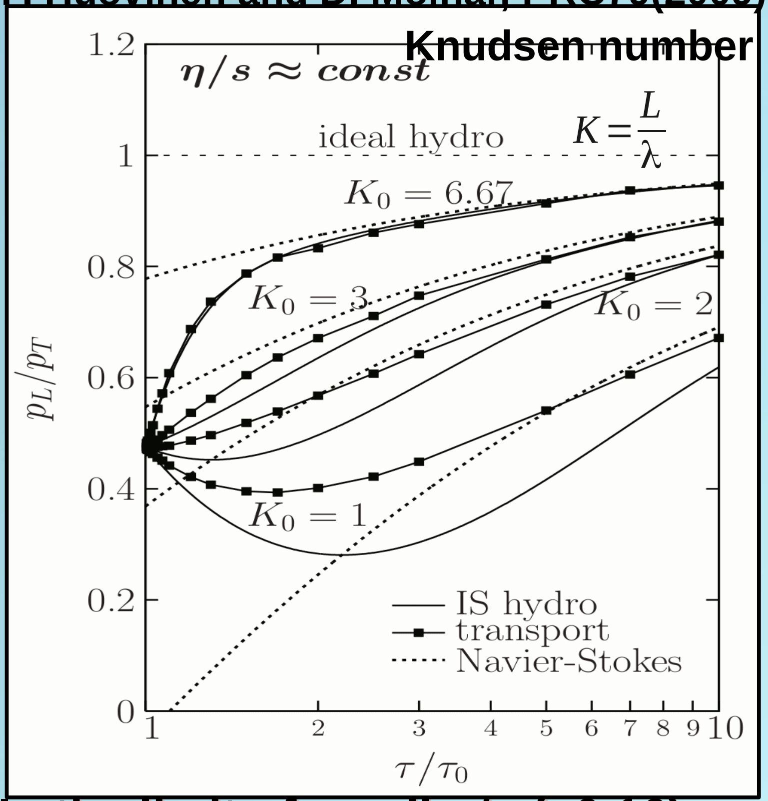
σ is evaluated in such way to keep fixed the η/s during the dynamics according the Chapman-Enskog equation. (similar to D. Molnar, arXiv:0806.0026[nucl-th] but our approach is local.)

- We know how to fix locally η/s(T)
- We have checked the Chapmann-Enskog (CE):
  - CE good already at 1st order ≈ *5%*
  - Relaxation Time Approx. severely understimates η

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

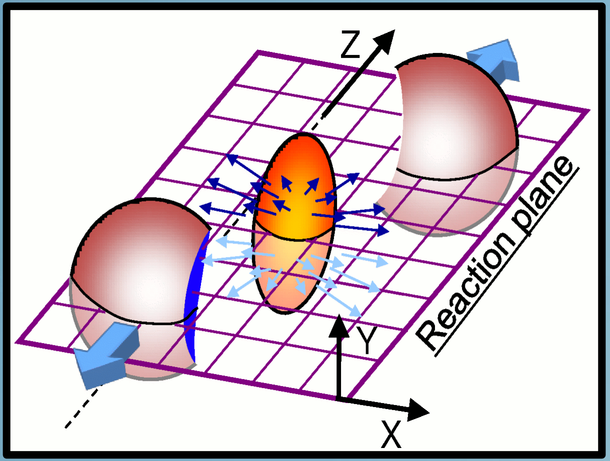


P. Huovinen and D. Molnar, PRC79(2009)

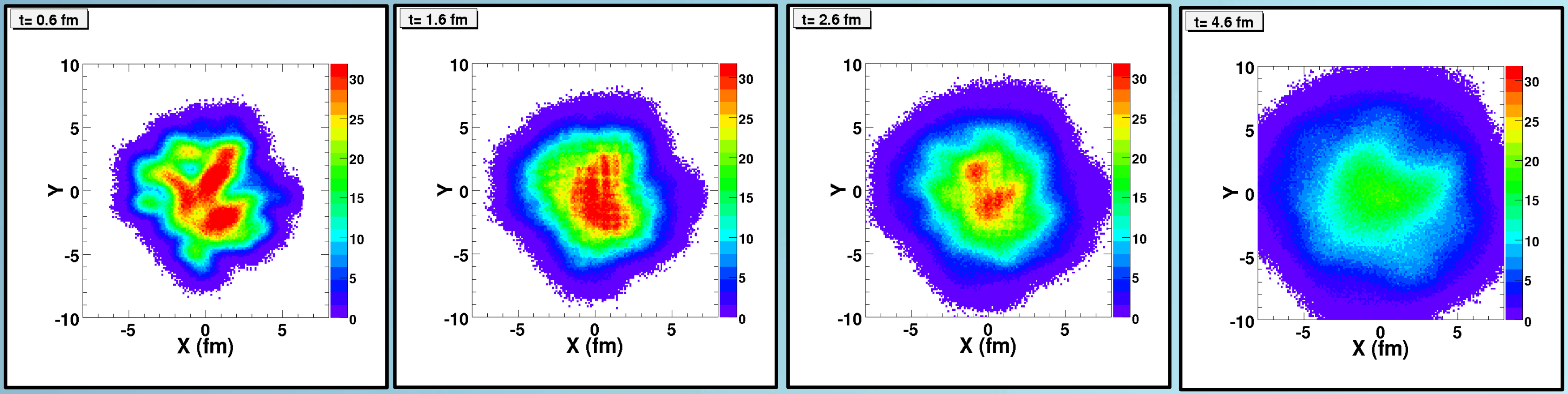


In the limit of small η/s (<0.16) and for small pT equivalent viscous hydro

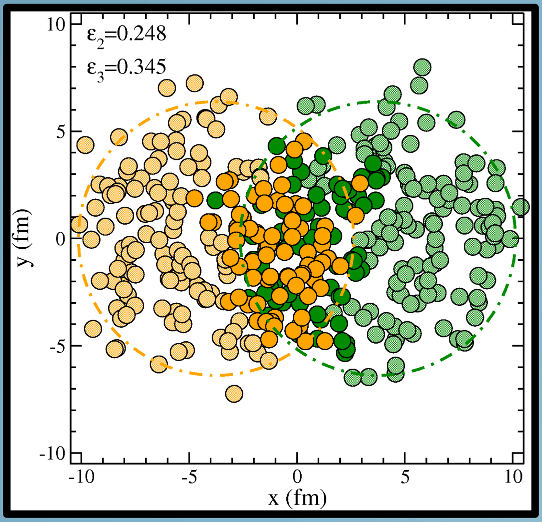
Applying kinetic theory to A+A Collisions….



- Impact of $\eta/s(T)$ on the build-up of $v_n(p_T)$ vs. beam energy.
- To include the Initial state fluctuations.



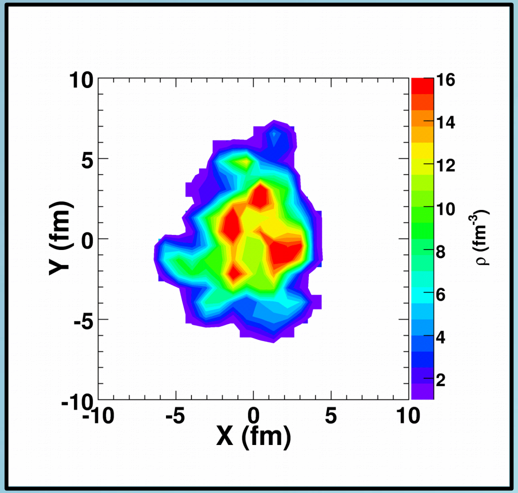
Initial State Fluctuations

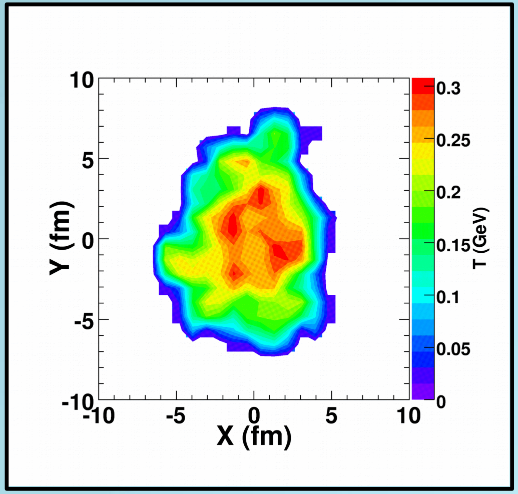


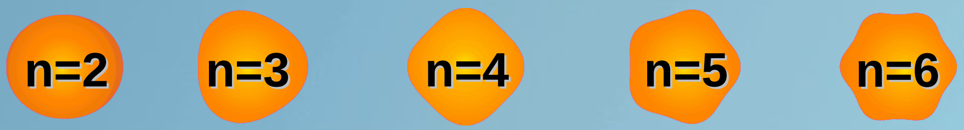
smooth distribution

Monte Carlo Glauber

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



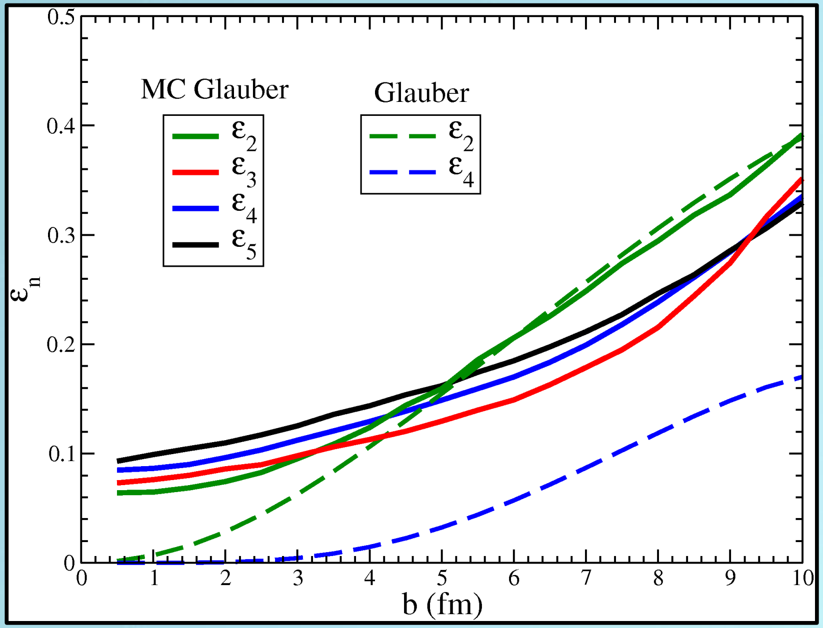




Characterization of the initial profile in terms of Fourier coefficients

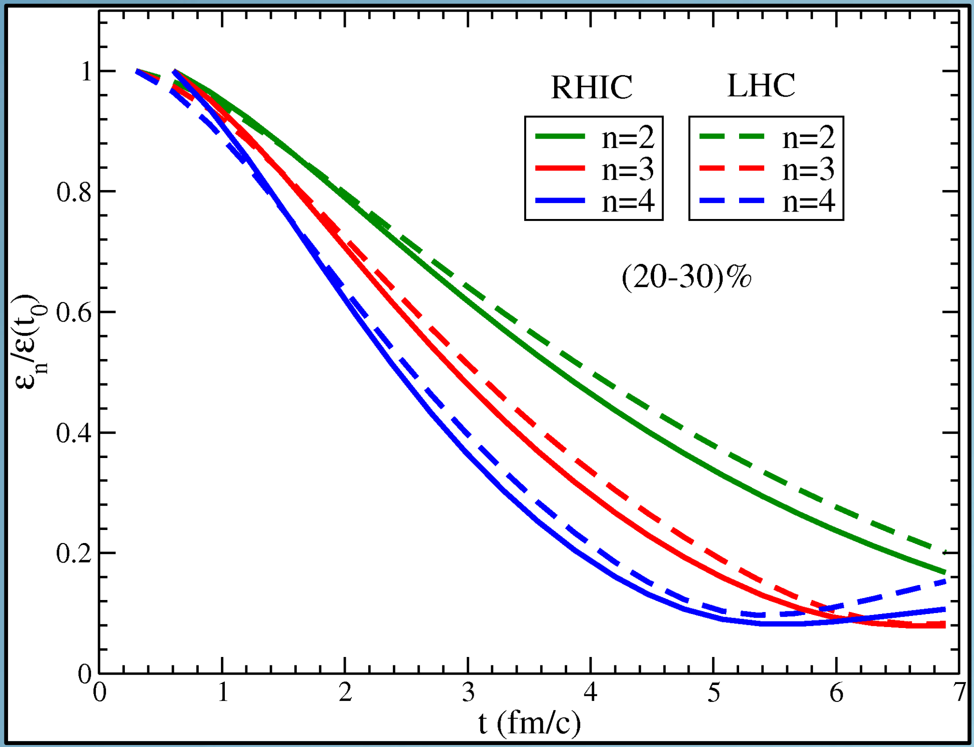
$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\varphi-\Phi_n)]\rangle}{\langle r_\perp^n\rangle} \qquad \Phi_n = \frac{1}{n}\arctan\frac{\langle r_\perp^n \sin(n\varphi)\rangle}{\langle r_\perp^n \cos(n\varphi)\rangle}$$

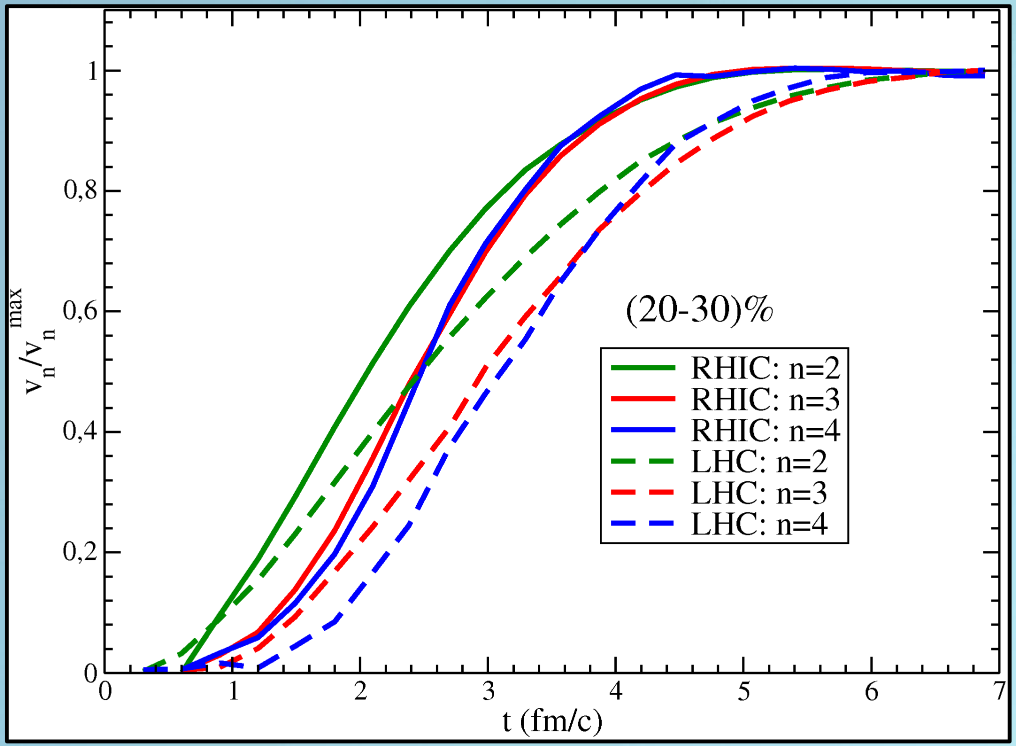
$$r_\perp = \sqrt{x^2+y^2}, \qquad \varphi = \arctan(y/x)$$



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).

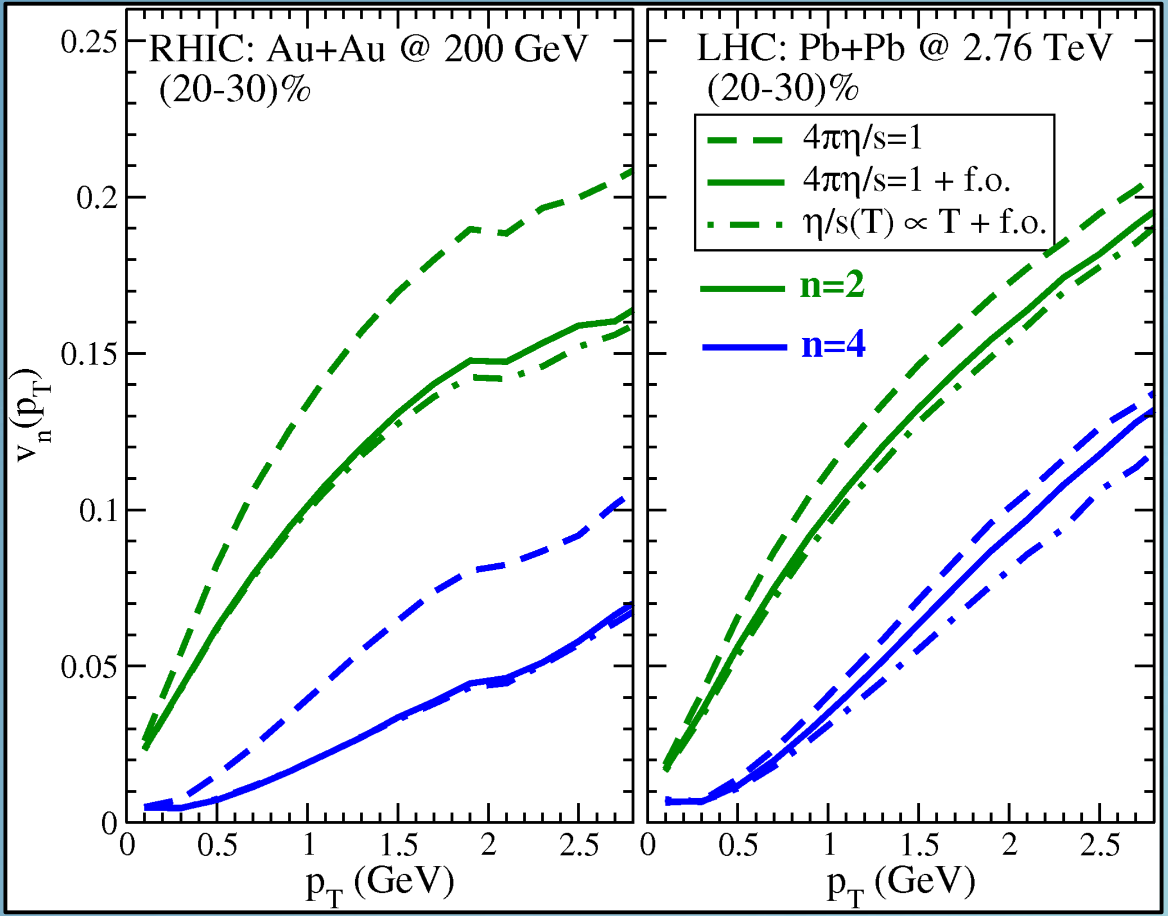
Initial State Fluctuations: time evolution of $\langle v_n \rangle$ and ε_n

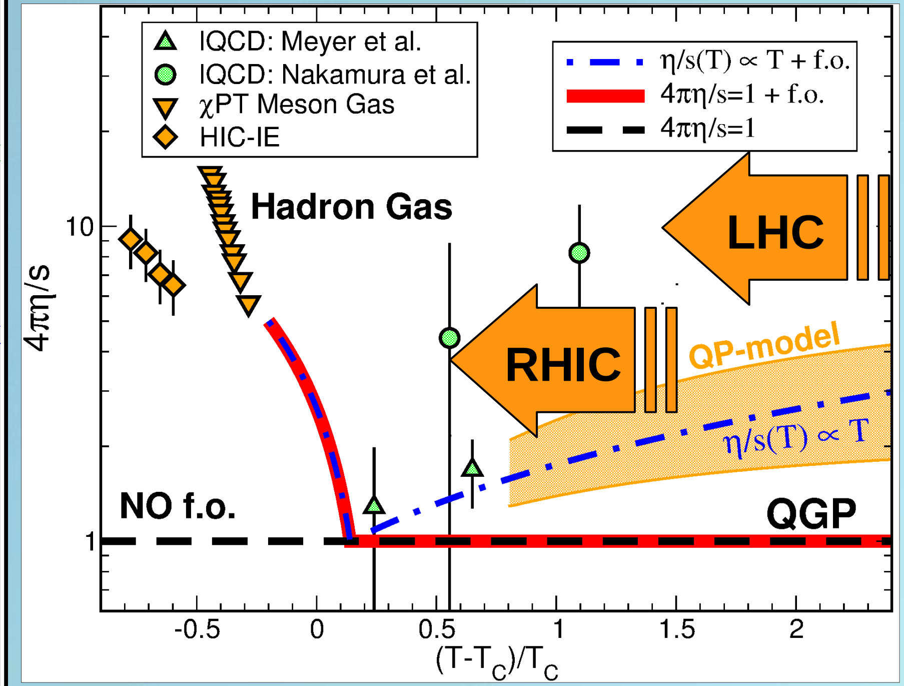




- **The time evolution for ε_n is faster for large n. At very early times $\varepsilon_n(t)=\varepsilon_n(t_0)-\alpha_n t^{n-2}$.**
- **$\langle v_n \rangle$ shows an opposite behaviour: $\langle v_n \rangle$ develops later for large n. At very early times $\langle v_n \rangle \propto t^{n+1}$.**
- **Different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

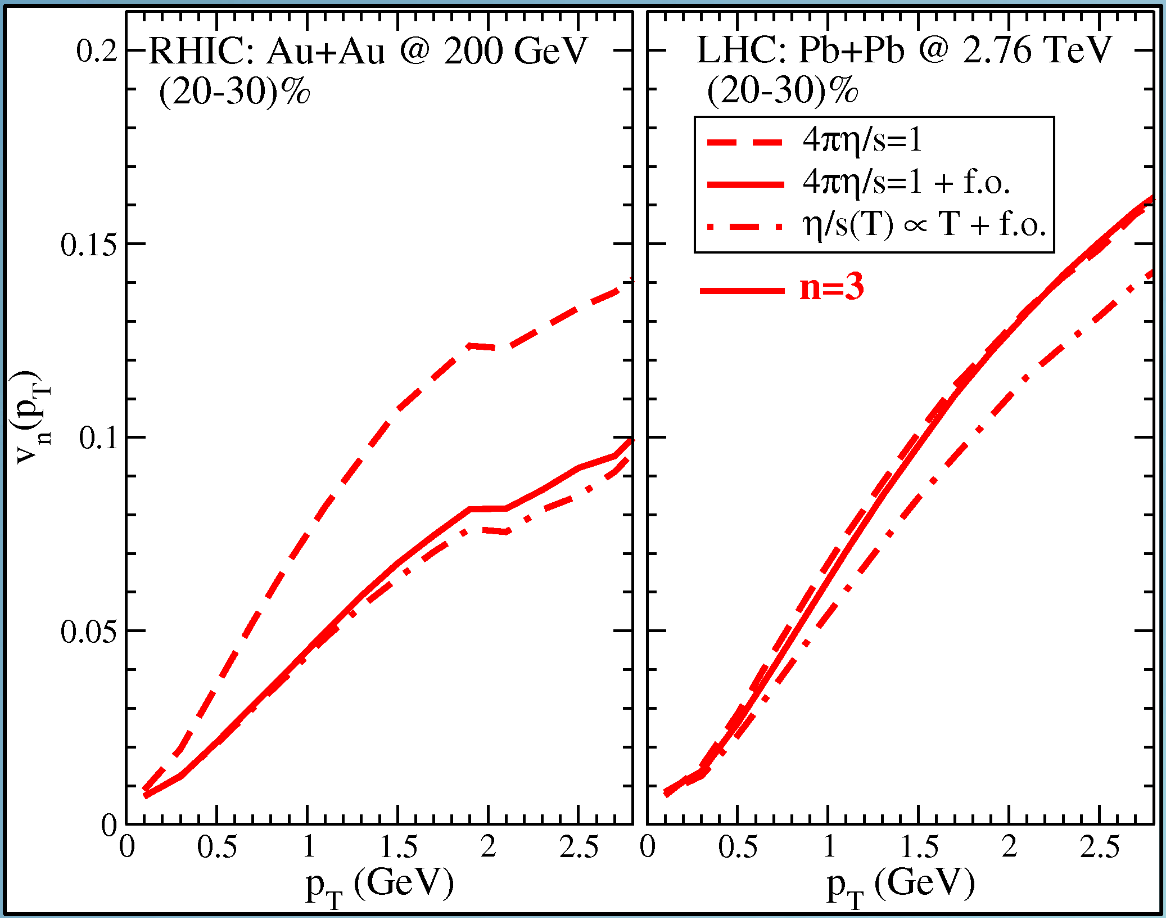
Initial State Fluctuations: $v_n(p_T)$ and η/s

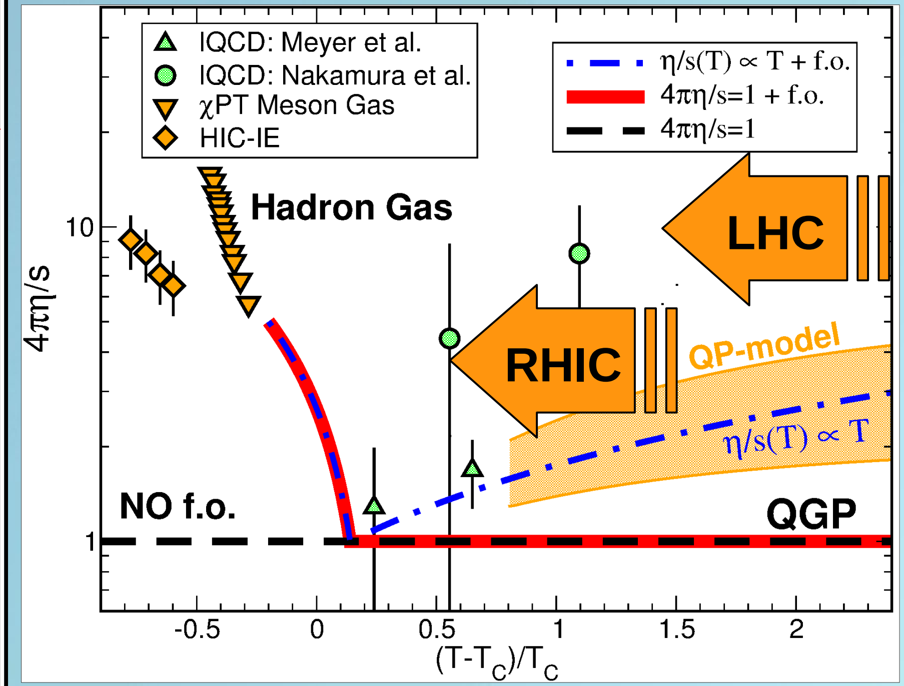




- $v_n(p_T)$ at RHIC is more sensitive to the value of the η/s at low temperature. $v_4(p_T)$ and $v_3(p_T)$ are more sensitive to the value of η/s than the $v_2(p_T)$.
- At LHC energies $v_n(p_T)$ is more sensitive to the value of η/s in the QGP phase (compare solid and dot-dashed lines).

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





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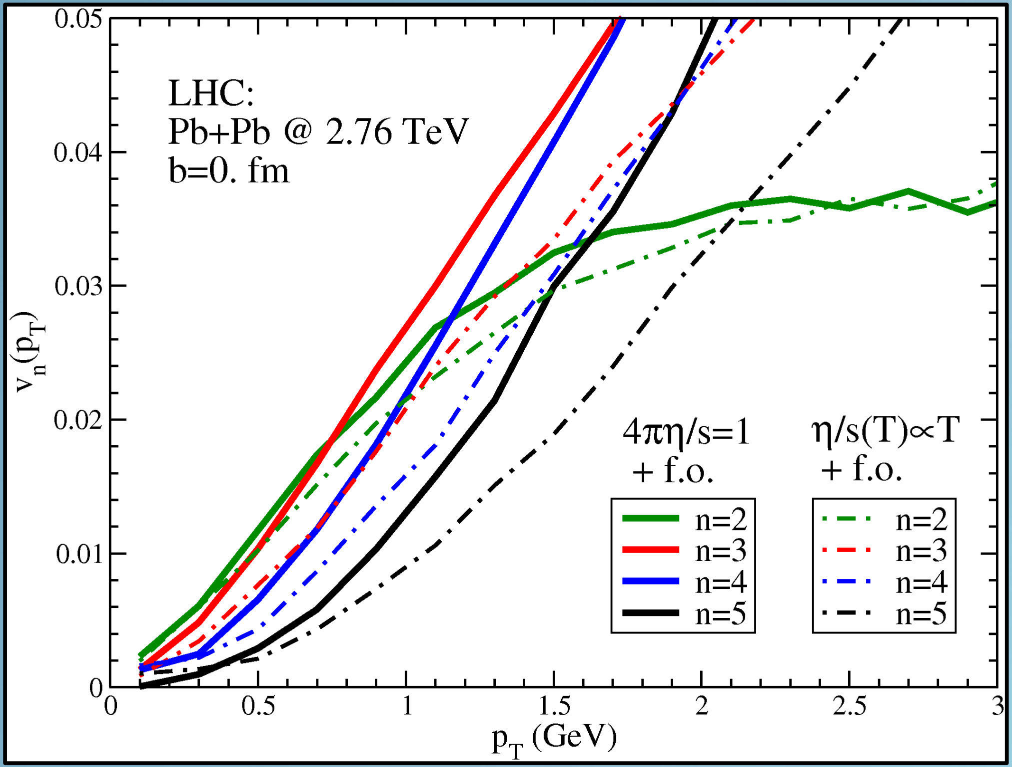
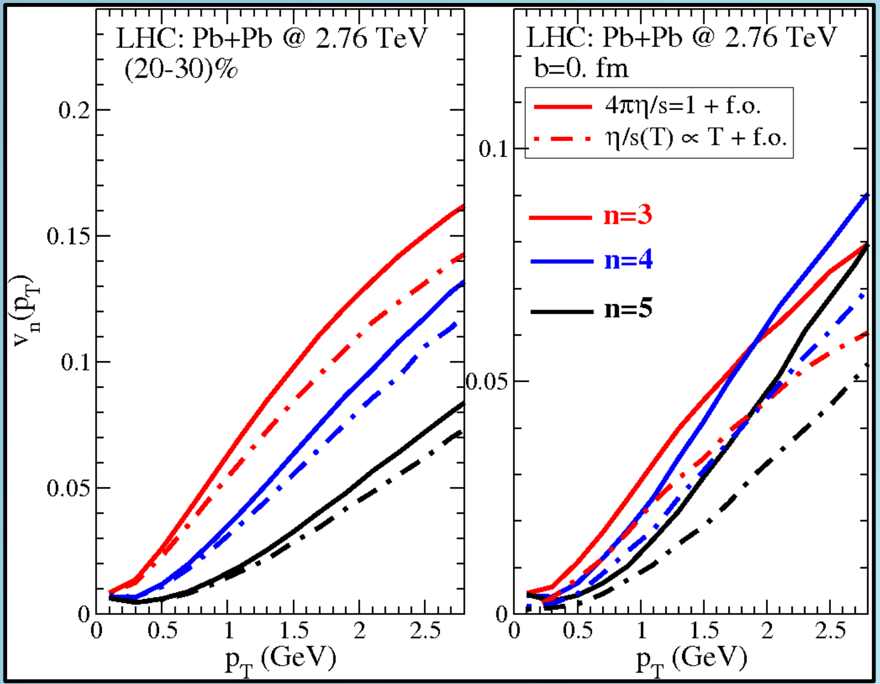
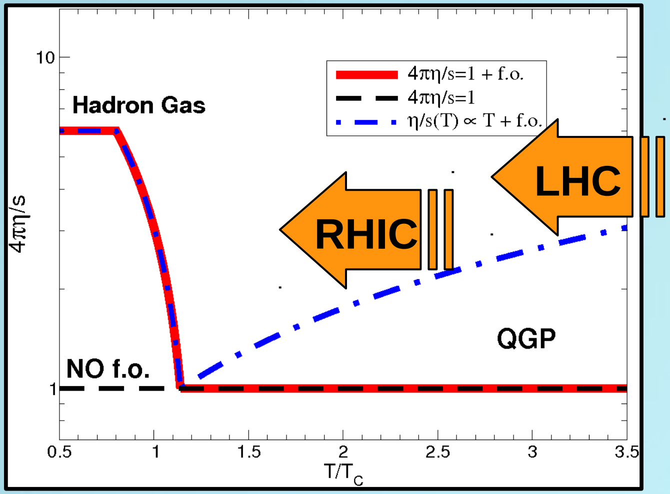
- At LHC energies $v_n(p_T)$ is more sensitive to the value of η/s in the QGP phase (compare solid and dot-dashed lines).

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

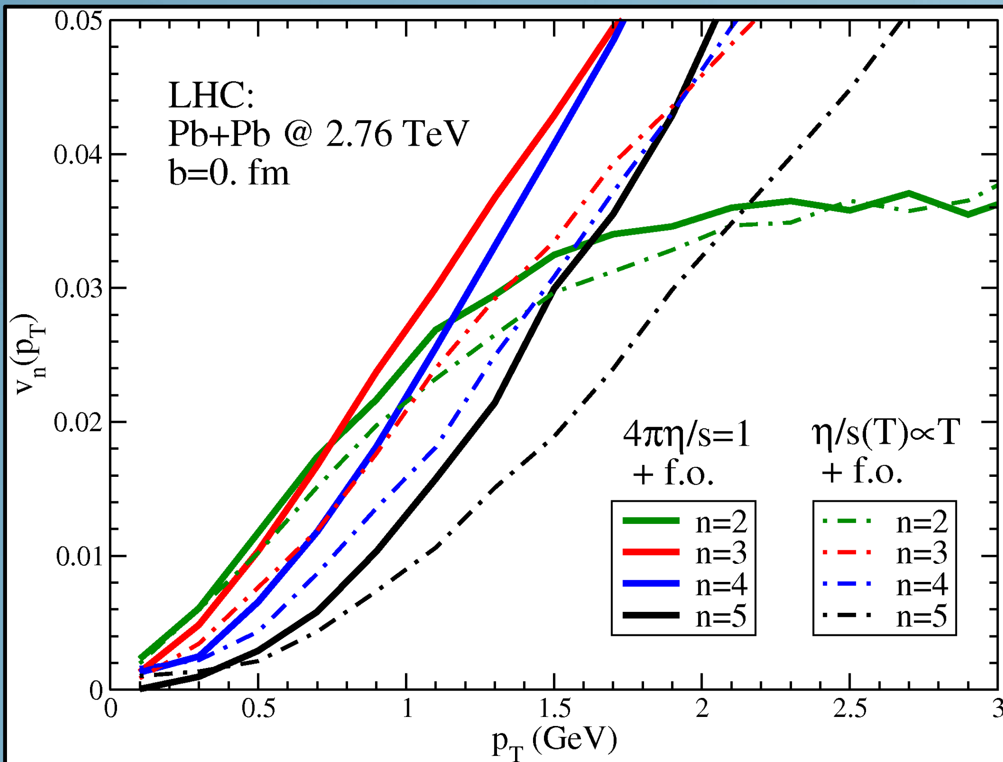


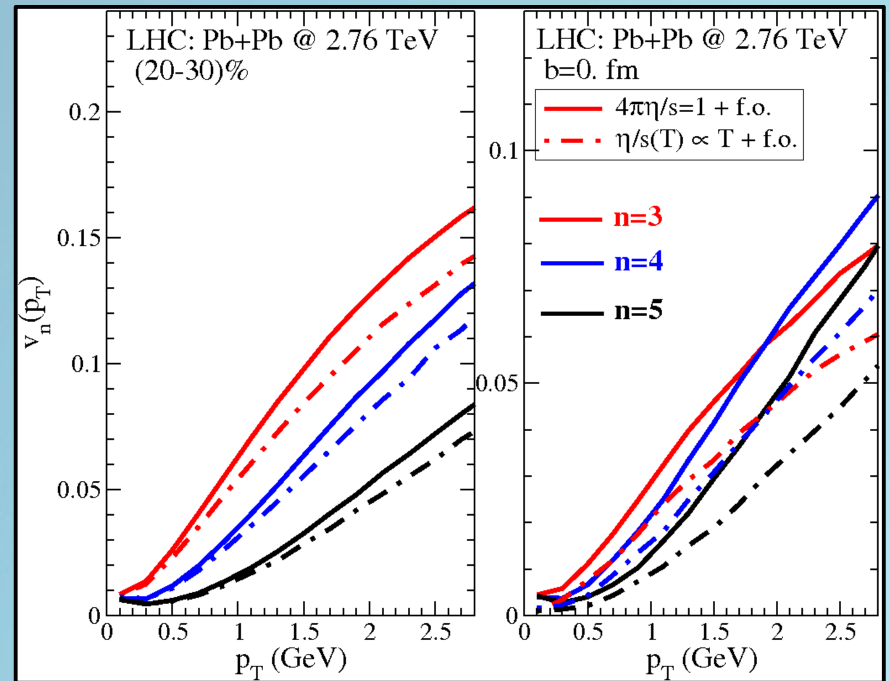


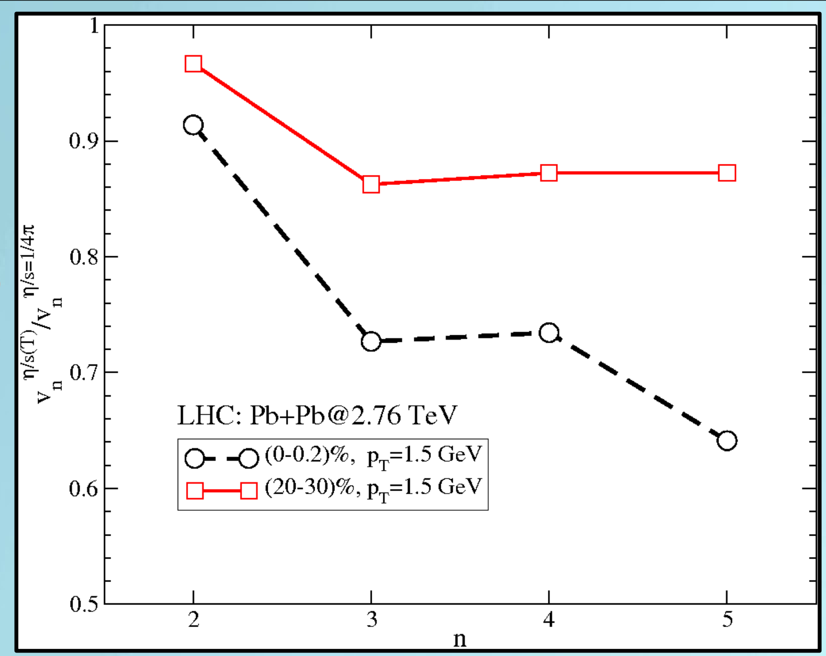


- At low p_T $v_n(p_T) \propto p_T^n$. v_2 for higher p_T saturates while v_n for n>3 increase linearly with p_T.
- For central collisions viscous effect are more relevant. For n>2 the $v_n(p_T)$ are more sensitive to the η/s ratio in the QGP phase.

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







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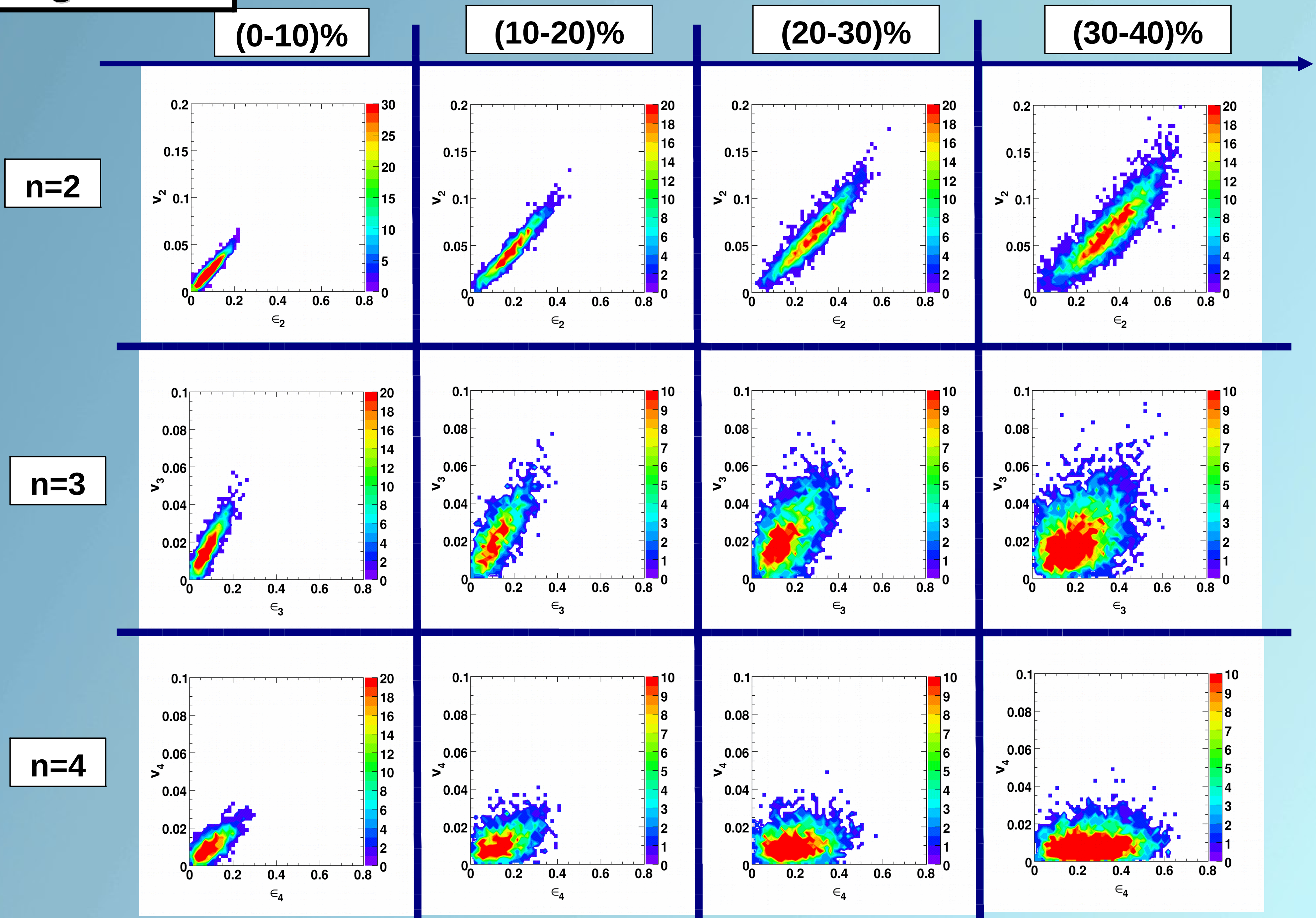
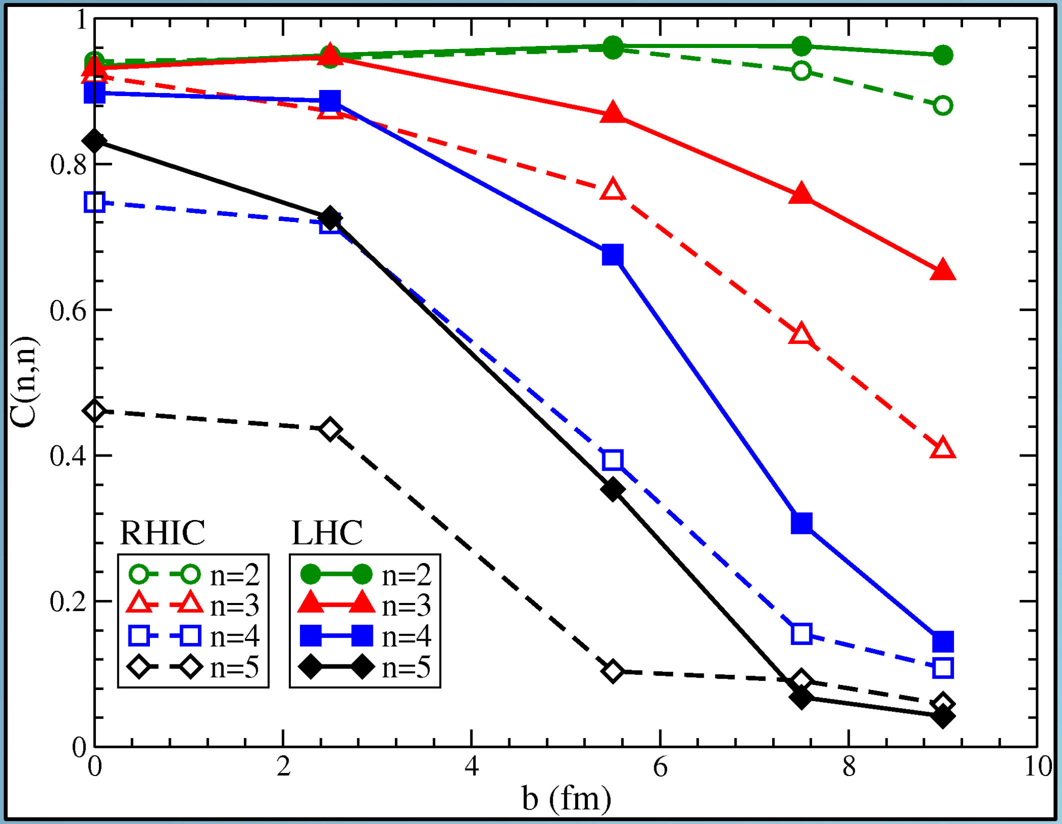
Initial State Fluctuations: v_n vs ε_n

RHIC:
Au+Au @ 200 GeV



Initial State Fluctuations: v_n vs ε_n



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

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.
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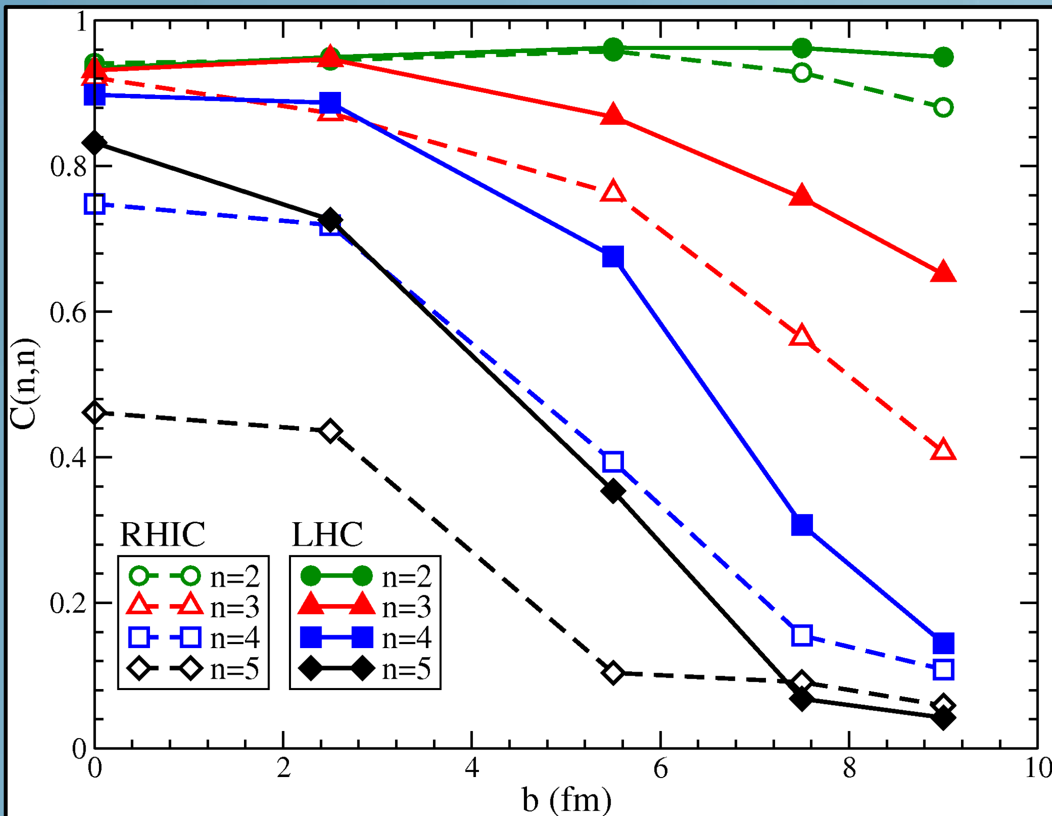
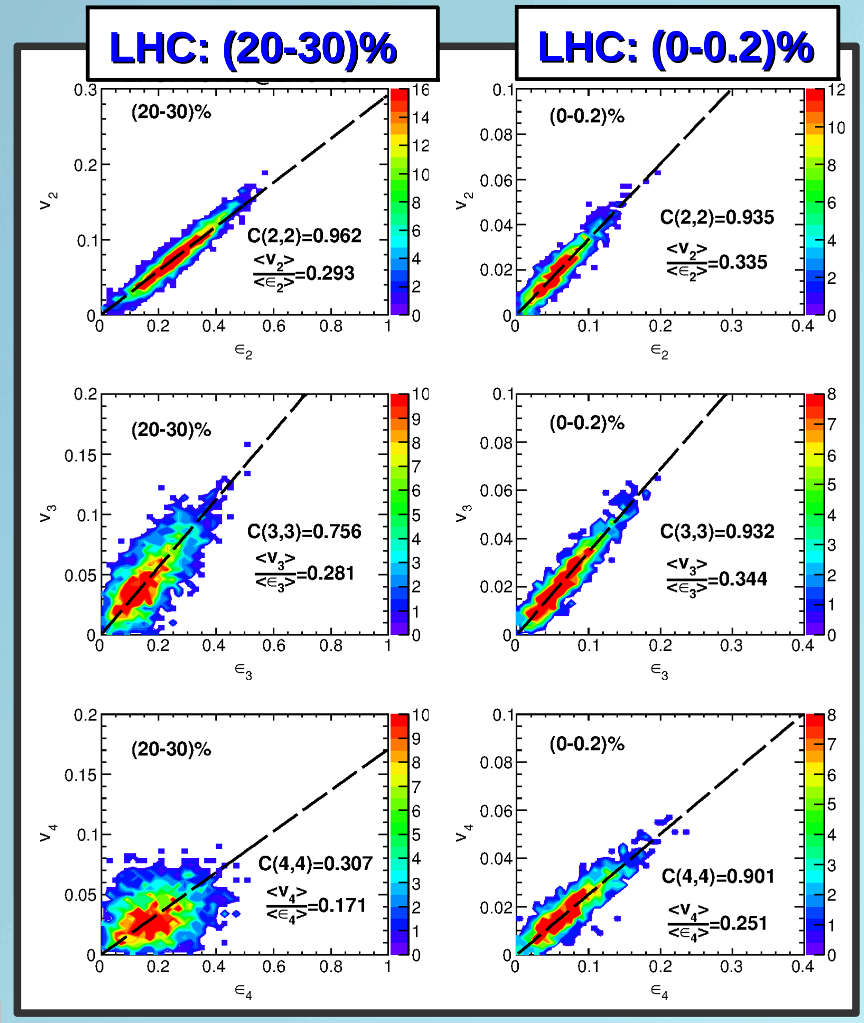
- For central collisions v_n are strongly correlated to ε_n: $v_n \propto \varepsilon_n$ for n=2,3,4.

Initial State Fluctuations: v_n vs ε_n





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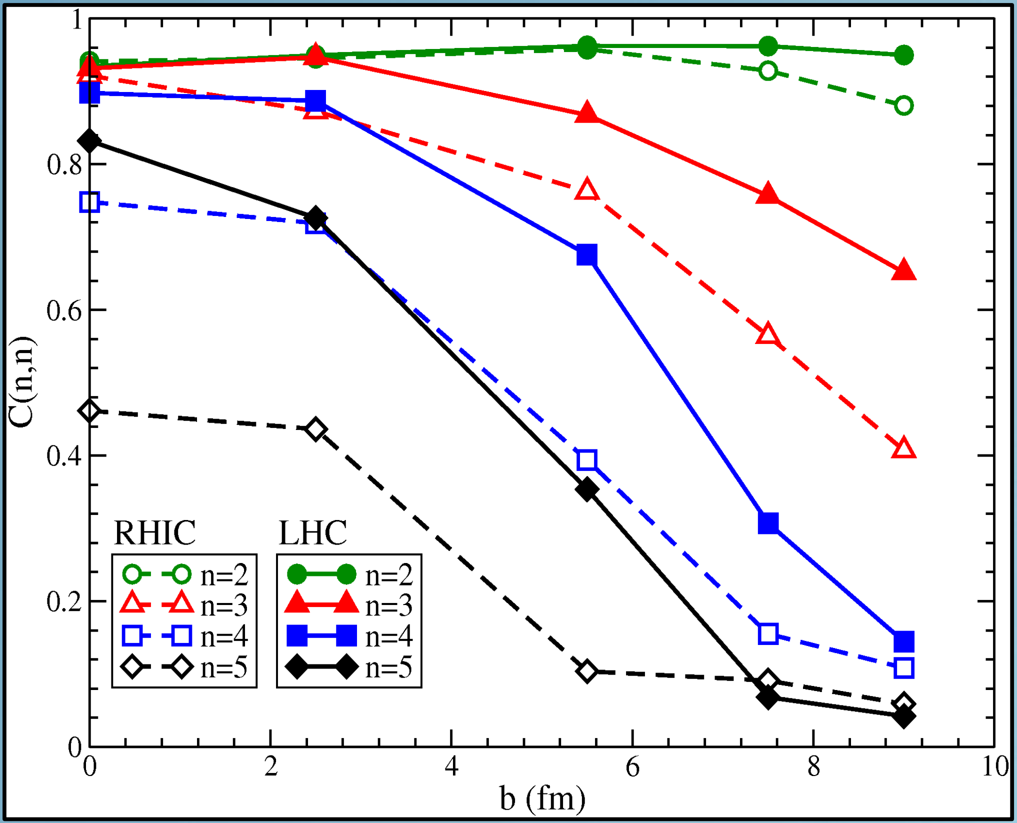
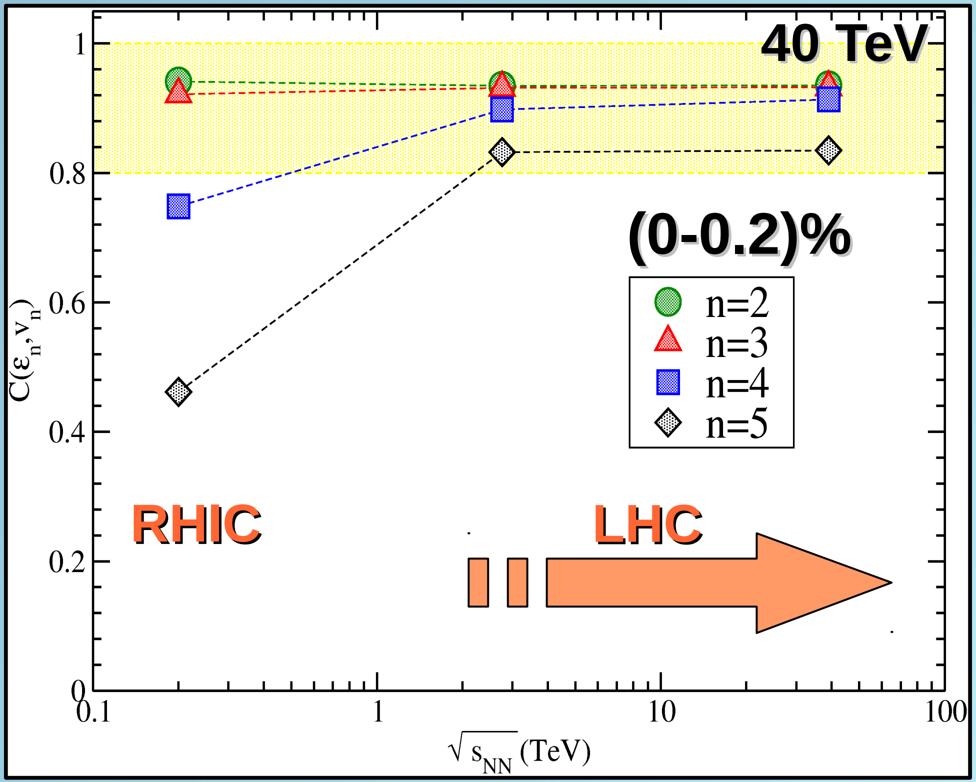
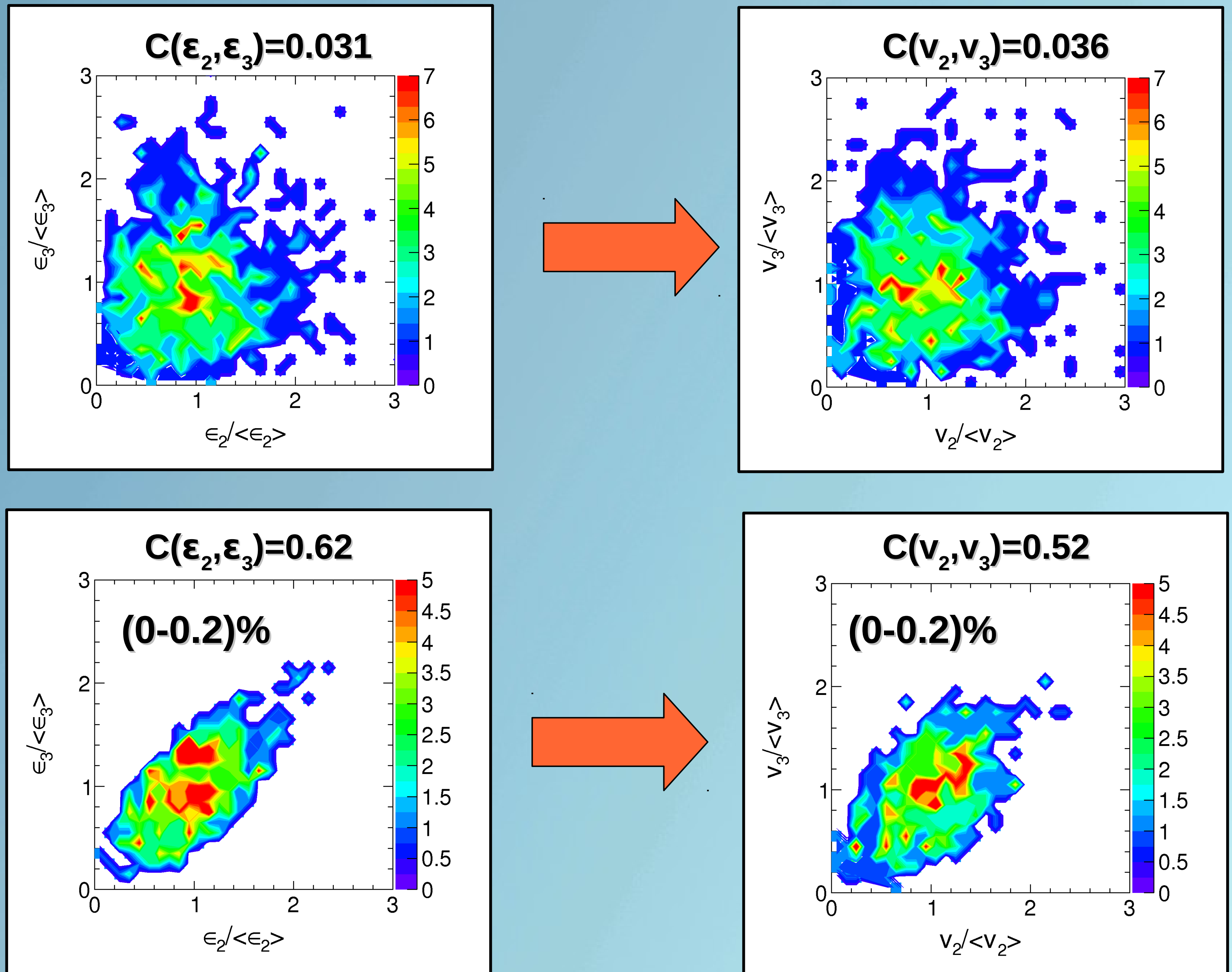
Correlations v_n and ε_n with the collision energy





- For central collisions v_n are strongly correlated to ε_n: $v_n \propto \varepsilon_n$ for n=2,3,4 and 5.
- The correlation increase with $\sqrt{s_{NN}}$

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



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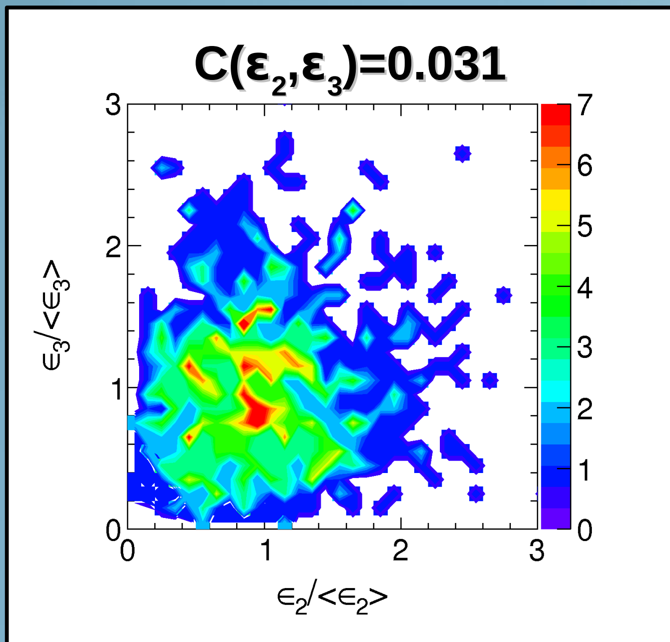
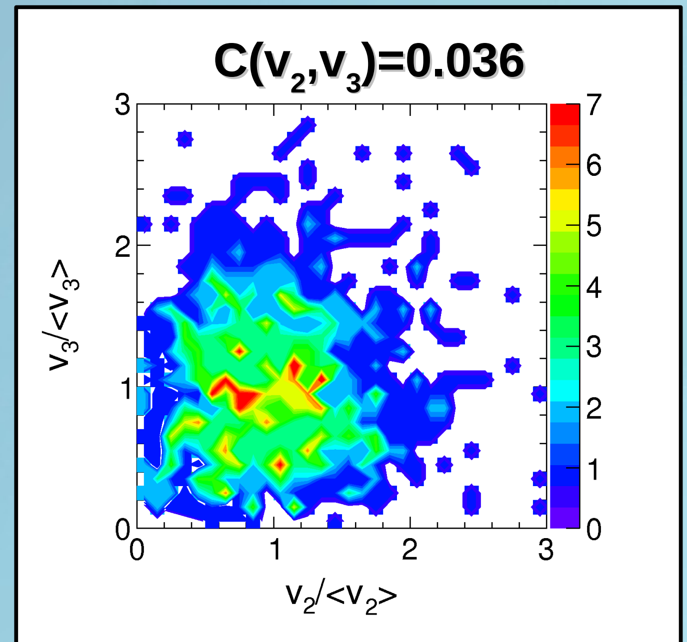
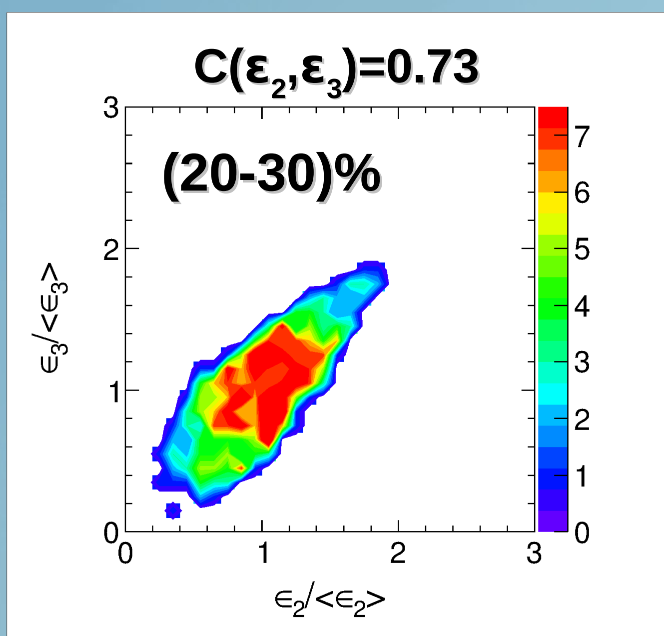
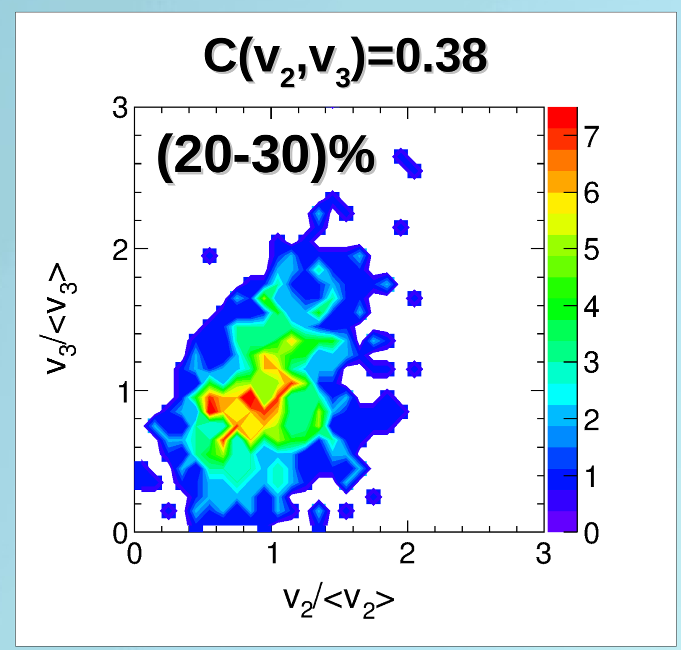








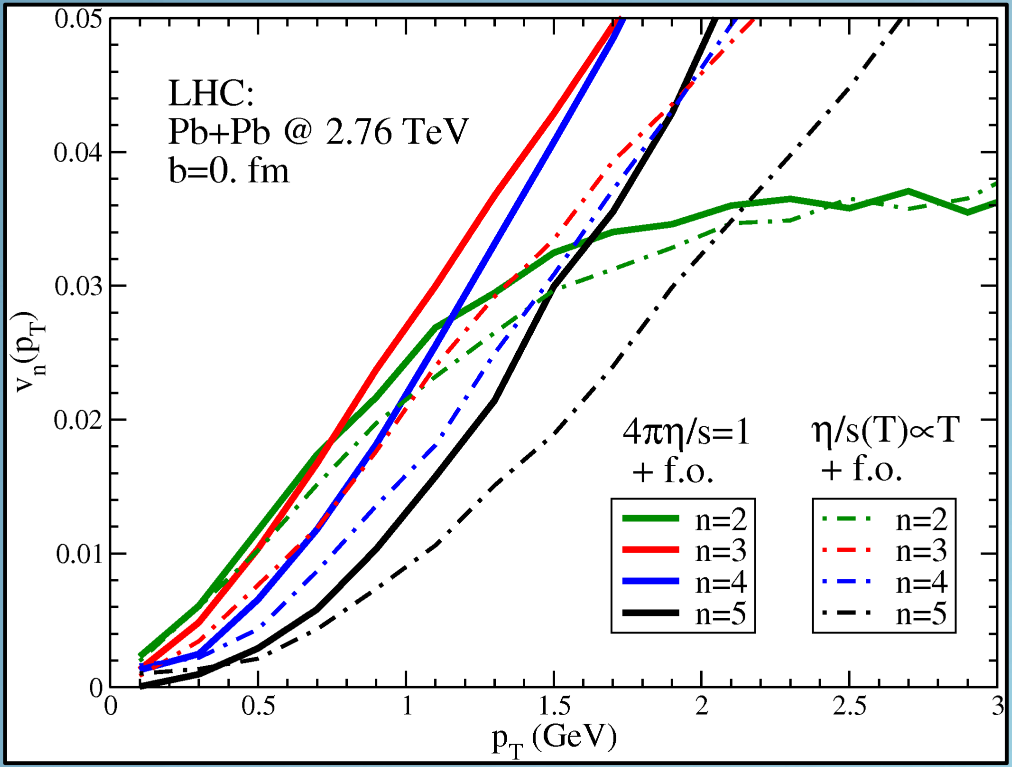
Conclusions

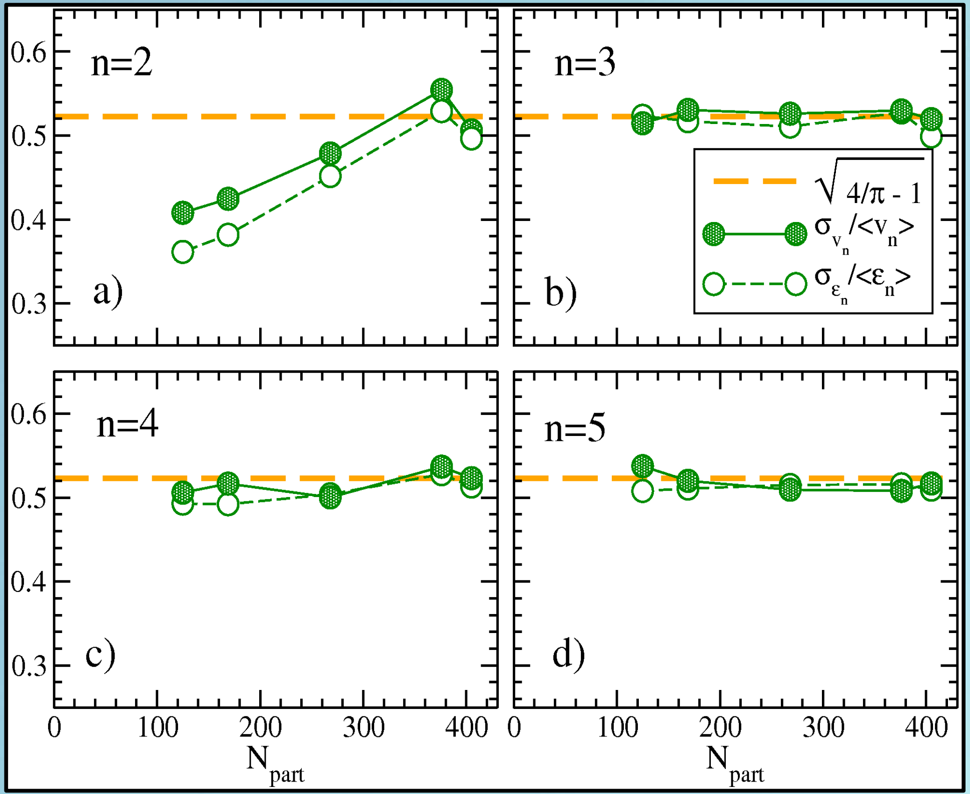
Transport at fixed η/s:

- **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.**

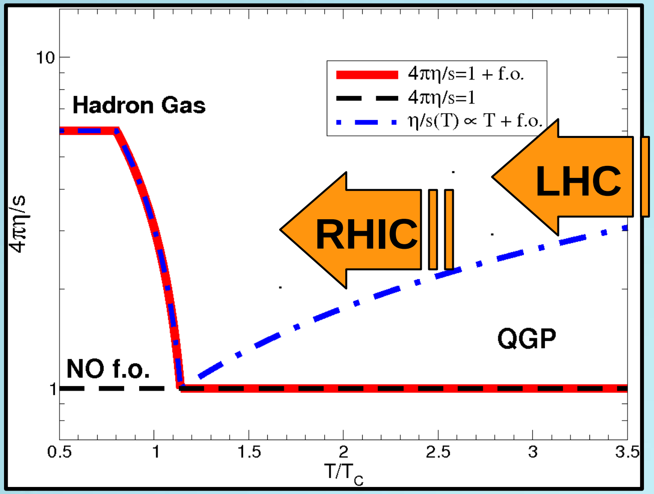
- **At LHC there is a stronger correlation between v_n and ε_n than at RHIC for all n.**
- **Ultra central collisions:**
  - **$v_n \propto \varepsilon_n$ for n=2,3,4 strong correlation C(n,n)≈1**
  - **$v_n(p_T)$ much more sensitive to η/s(T)**
  - **degree of correlation increase with the collision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

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

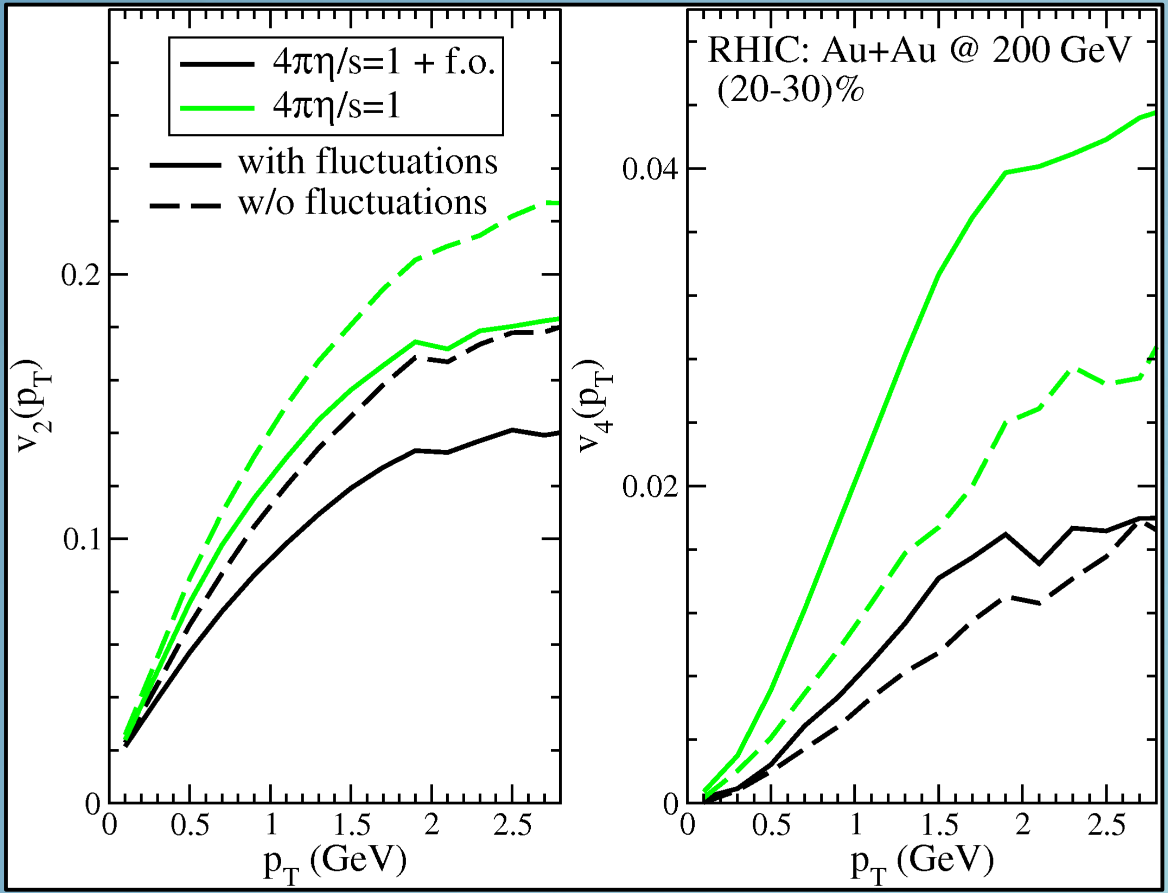


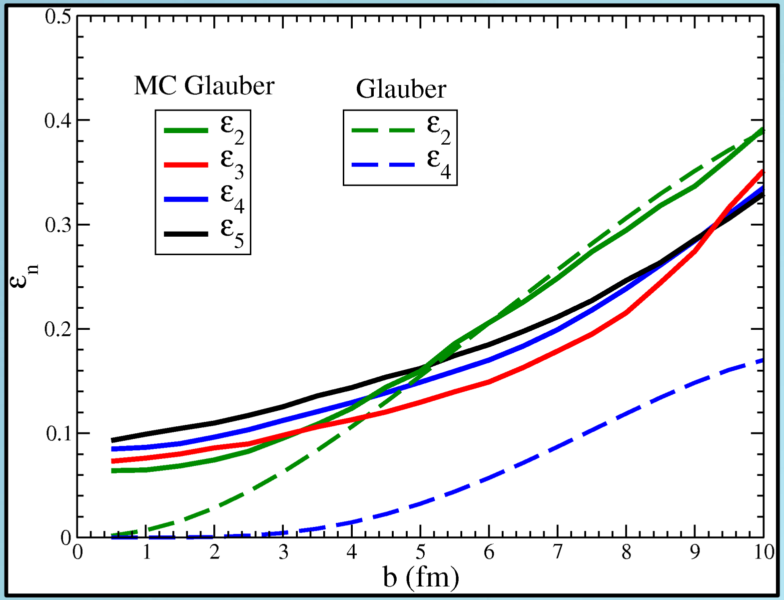


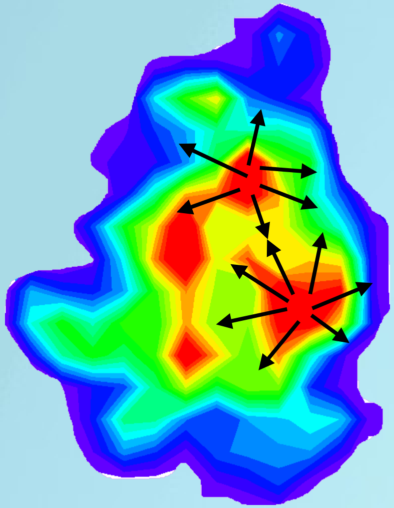
- At low p_T $v_n(p_T) \propto p_T^n$. v_2 for higher p_T saturates while v_n for n>3 increase linearly with p_T.
- For central collisions viscous effect are more relevant. For n>2 the $v_n(p_T)$ are more sensitive to the η/s ratio in the QGP phase.



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







- **The initial state fluctuations reduce the $v_2(p_T)$.**
- **$v_4(p_T)$ increase by the initial state fluctuations and it becomes more sensitive to the viscosity of the QGP. Larger ε_4 gives larger v_4.**

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

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

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

Coodinate space (x,y)

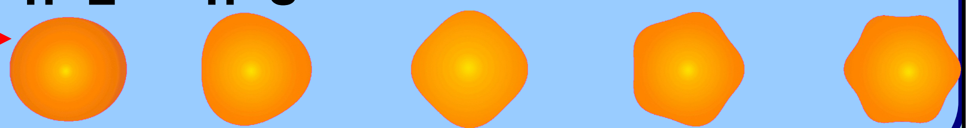
- We start with an initial azimuthally symmetric profile (optical Glauber model).
- Then we deform the initial distribution (α<<1)

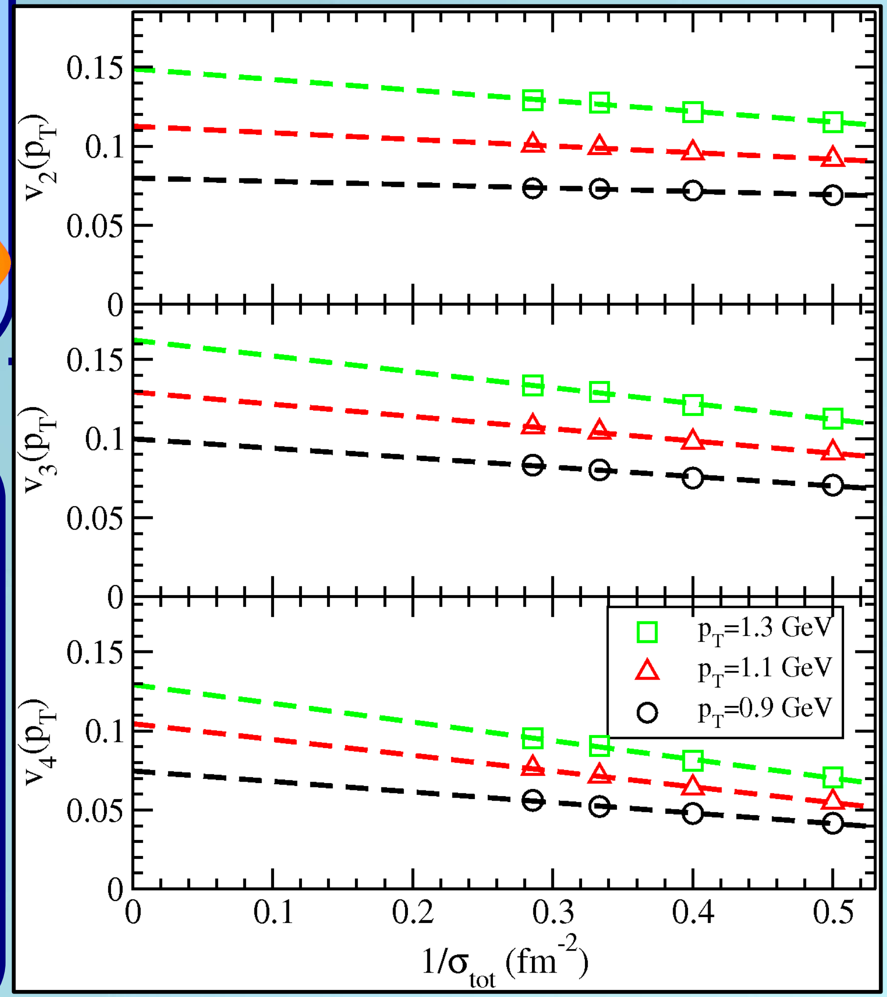
$$z = x + iy \rightarrow z + \delta z \equiv z - \alpha \bar{z}^{n-1}$$

2π/n symmetry

This Creates only

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





Momentum space

- Thermal distribution:

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

- Constant distribution:

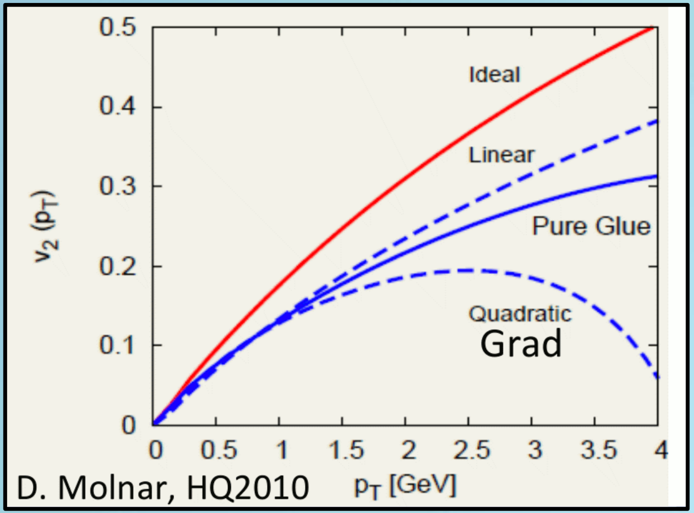
$$dN/d^3p \propto \theta(p_0 - p)$$

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)

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

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



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

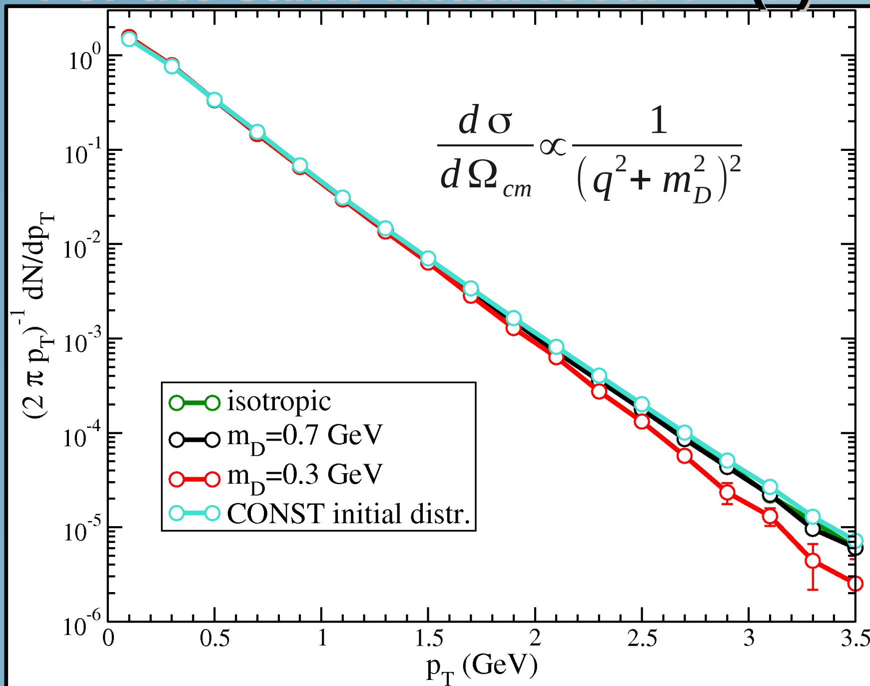
In general in the limit σ→∞, f(σ) can be expanded in power of 1/σ.

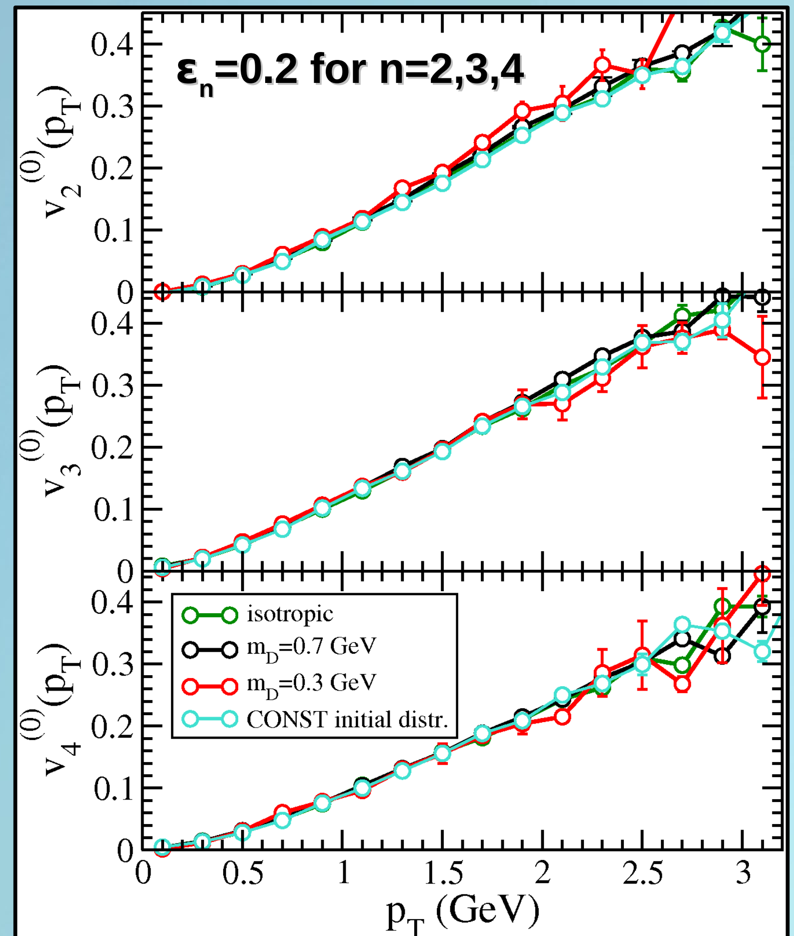
$$f(\sigma) \underset{\sigma\to\infty}{\approx} f^{(0)} + \frac{1}{\sigma}\delta f + O\left(\frac{1}{\sigma^2}\right) \quad \Rightarrow \quad v_n(p_T) \underset{\sigma\to\infty}{\approx} v_n^{(0)}(p_T) + \frac{1}{\sigma}\delta v_n + O\left(\frac{1}{\sigma^2}\right)$$

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)

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.

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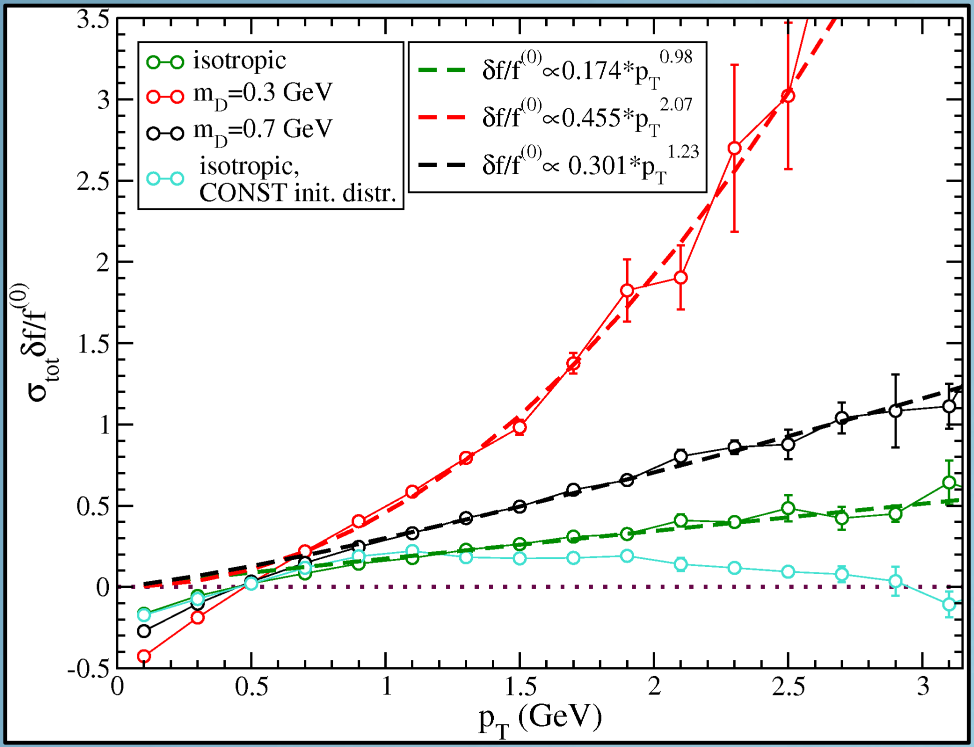

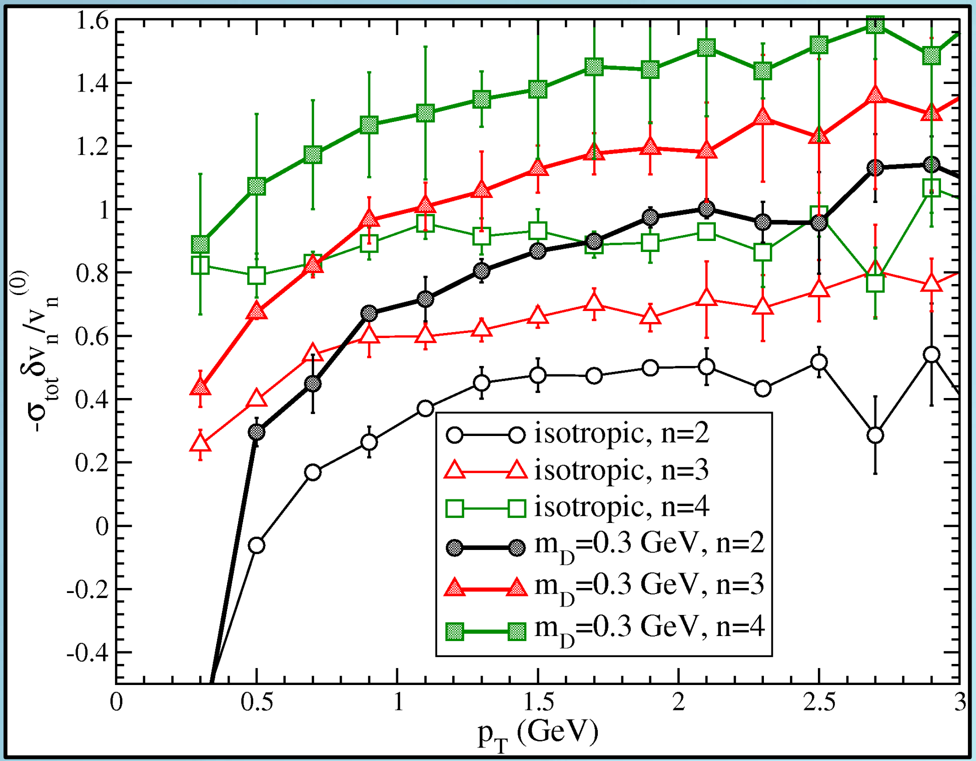

In δf and δv_n it is encoded the information about the microscopical details

- **$\delta f(p_T)/f^{(0)} \propto p_T^{\alpha}$ 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 → $-\delta v_n(p_T)/v_n^{(0)} \propto n$**