UNIVERSITÀ DEGLI STUDI DI CATANIA
INFN-LNS

Anisotropic flows from initial state fluctuations in ultra-relativistic heavy ion collisions

S. Plumari, L. Oliva, A. Puglisi,
M. Ruggieri, F. Scardina, V. Greco

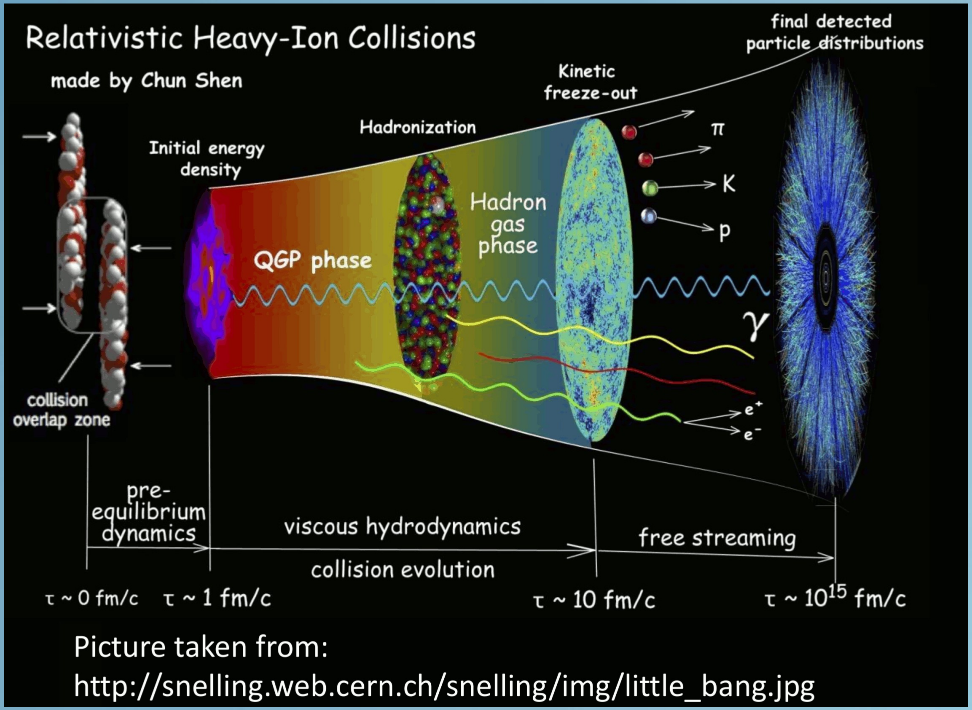
Outline

- **Transport approach at fixed η/s**
- **Abelian flux tube model for early stages of HIC**
- **Initial state fluctuations**

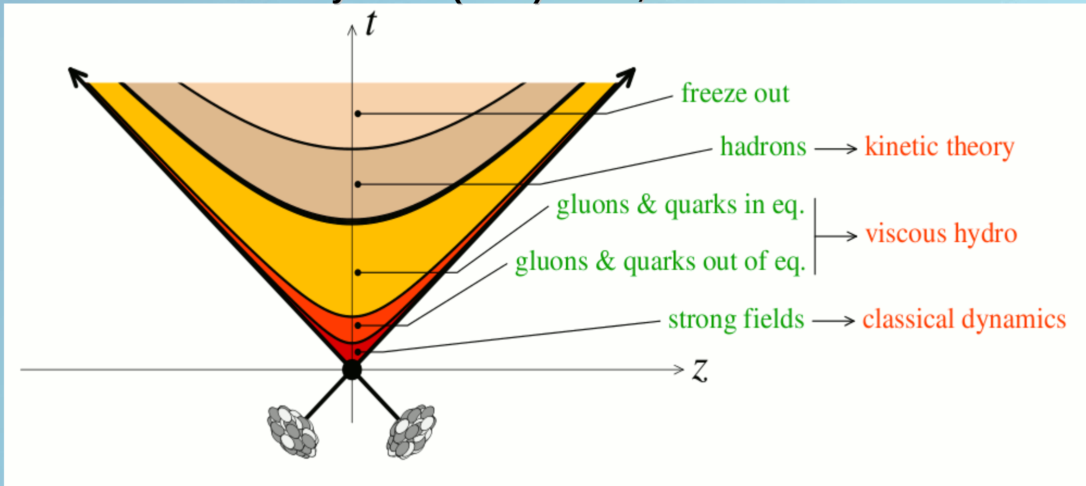
  - η/s and generation of v_n(pT): from RHIC to LHC

  - Correlations between ε_n (space eccentricities) and v_n (collective flows)
- **Conclusions**

sketch of evolution of a HIC



F. Gelis Int.J.Mod.Phys. E24 (2015) no.10, 1530008



Initial out-of-equilibrium state:
Glasma, namely, a configuration of longitudinal color–electric and color-magnetic flux tubes.

η/s(T) around to a phase transition

- **Quantum mechanism**

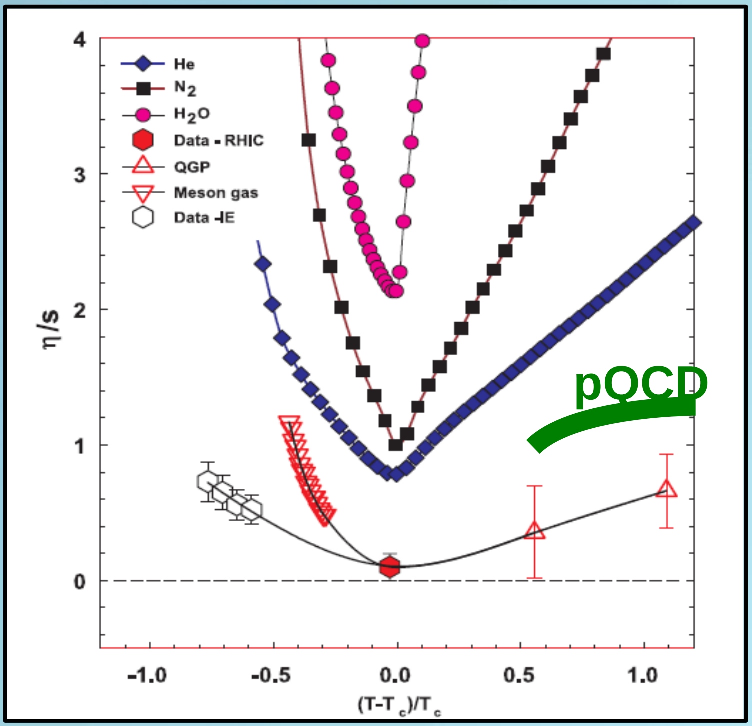
$$\Delta E \cdot \Delta t \geqslant 1 \;\rightarrow\; \eta/s \approx \frac{1}{15}\langle p\rangle \cdot \tau > \frac{1}{15}$$

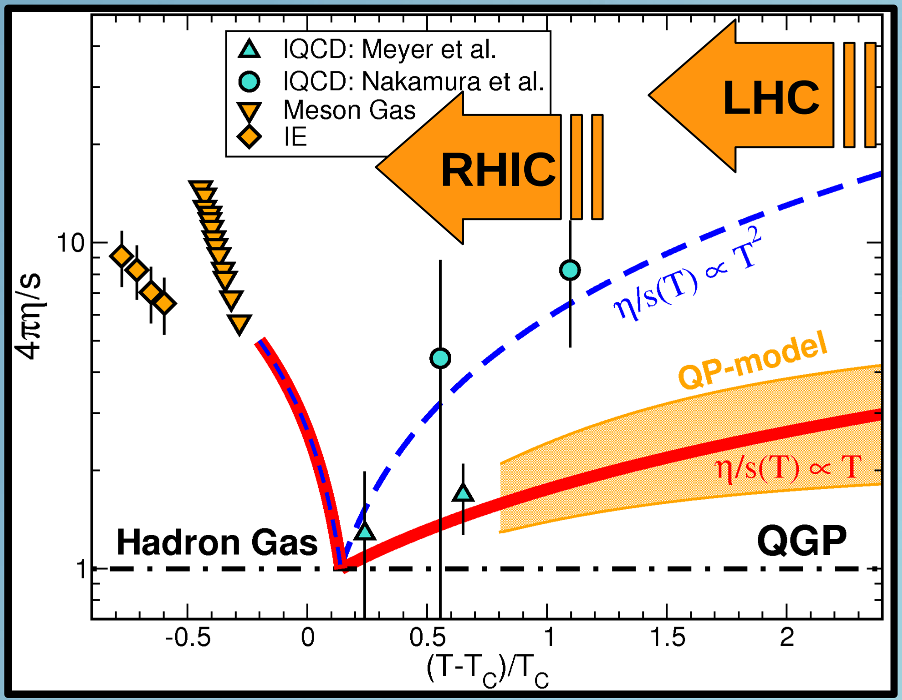
- **AdS/CFT suggest a lower bound η/s = 1/(4 π)~0.08**

- **From pQCD:** $\eta/s \sim \dfrac{1}{g^4 \ln(1/g)} \;\Rightarrow\; \eta/s \sim 1$

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.

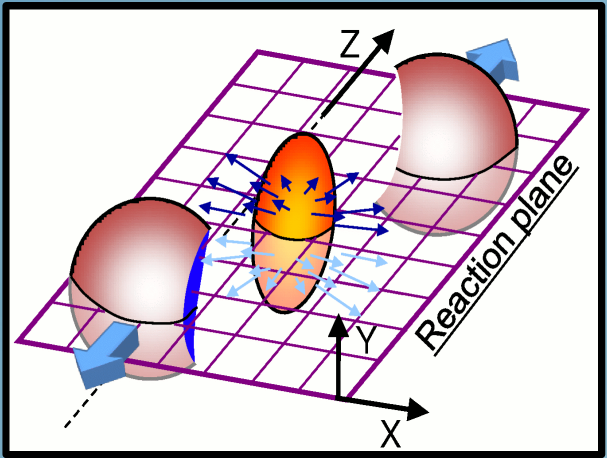




S. Plumari et al., J. Phys.: Conf. Ser. 420 012029 (2013). arXiv:1209.0601.

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

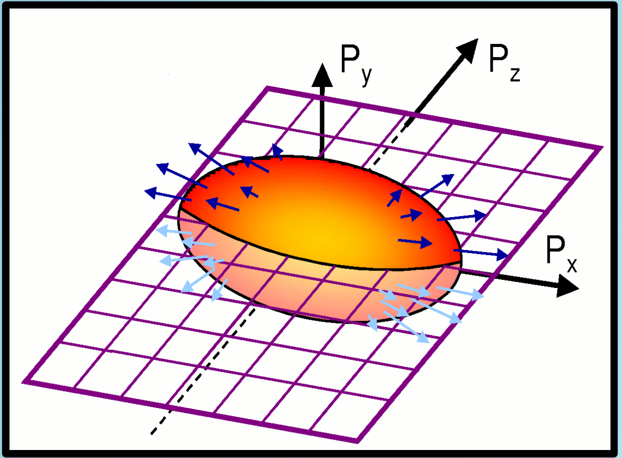
Information from non-equilibrium: elliptic flow



INITIAL OLD VIEW

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

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



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

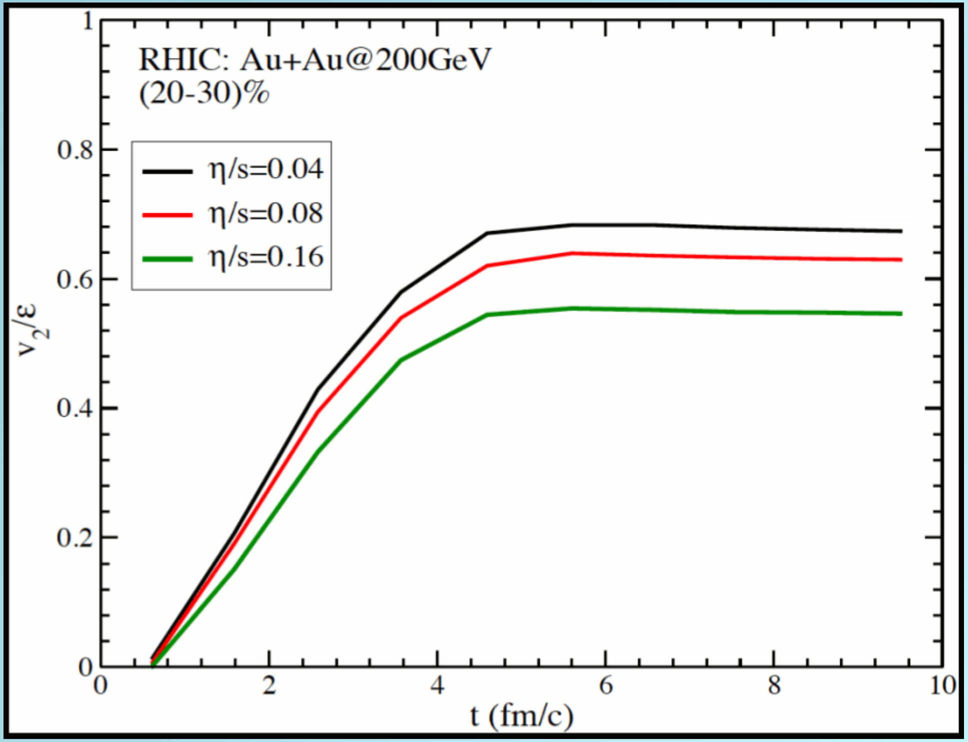
The v_2/ε measures efficiency in converting the eccentricity from Coordinate to Momentum space

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

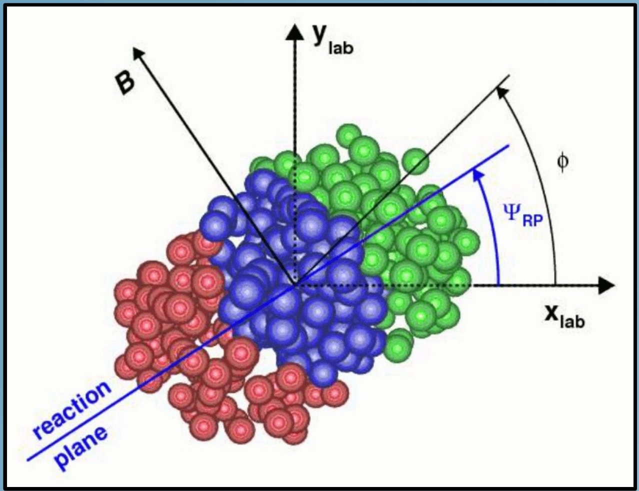
Can be seen also as Fourier expansion

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T d\eta}\left[1 + 2v_2\cos(2\phi) + 2v_4\cos(4\phi) + \ldots\right]$$

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



Information from non-equilibrium: $v_n(p_T)$



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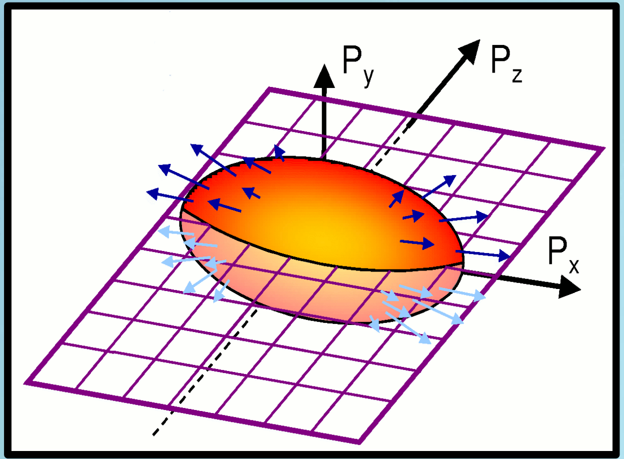

$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\phi - \Phi_n)]\rangle}{\langle r_\perp^n \rangle}$$

The v_2/ε measures efficiency in converting the eccentricity from Coordinate to Momentum space

$$\langle v_n \rangle = \langle \cos[n(\phi - \Psi_n)]\rangle$$

Can be seen also as Fourier expansion

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T d\eta}\left[1 + 2v_2\cos 2(\phi - \Psi_2) + 2v_3\cos 3(\phi - \Psi_3) + \ldots\right]$$

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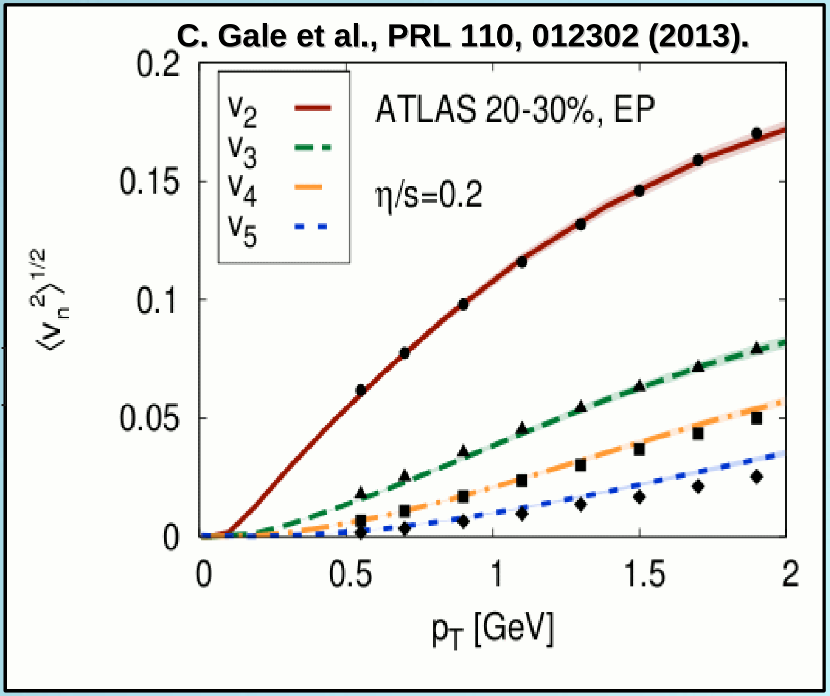
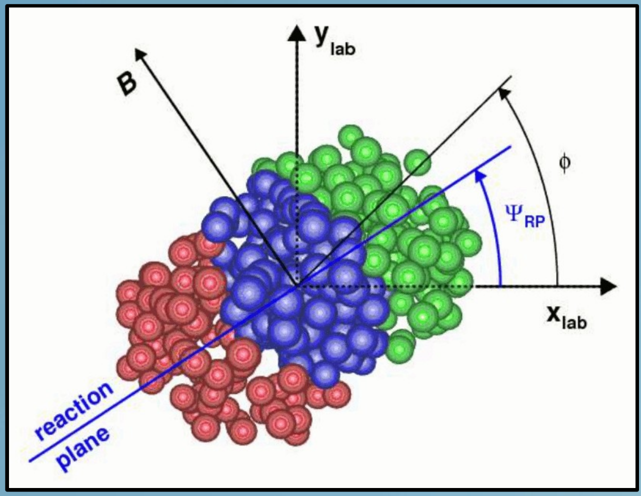
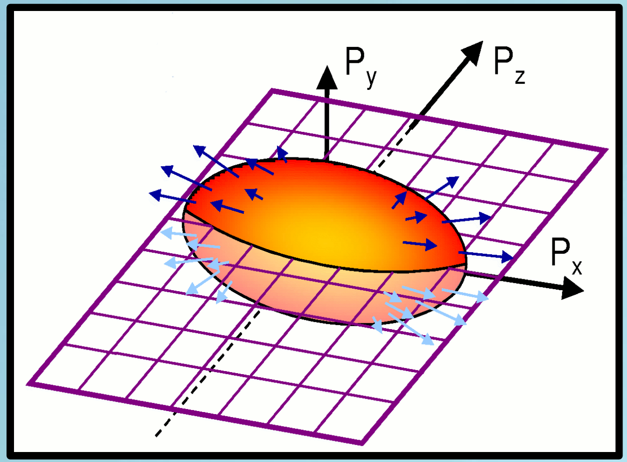


Information from non-equilibrium: $v_n(p_T)$



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

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



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The v_2/ε measures efficiency in converting the eccentricity from Coordinate to Momentum space

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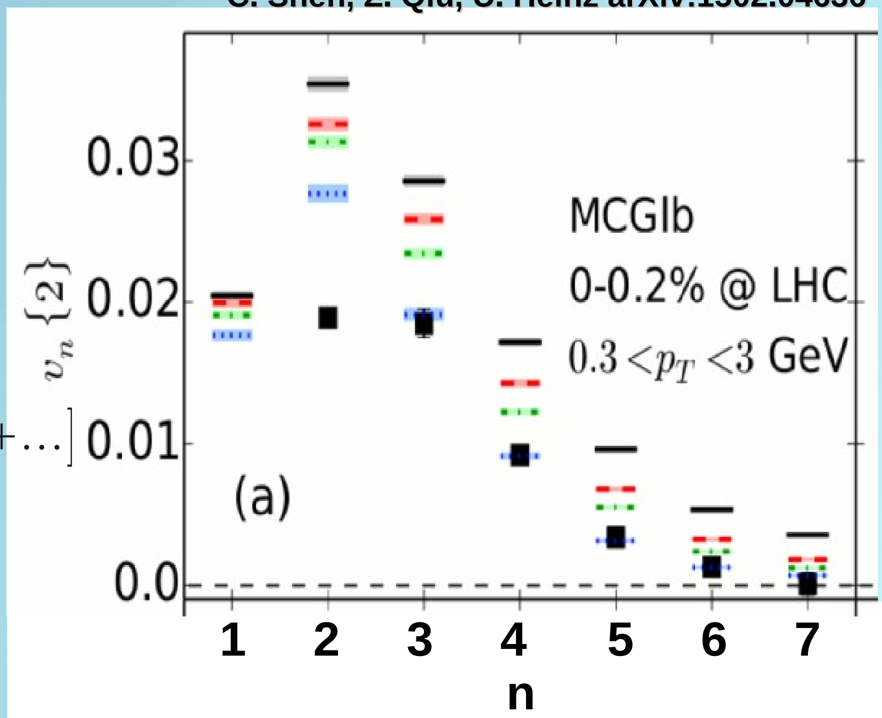
C. Shen, Z. Qiu, U. Heinz arXiv:1502.04636



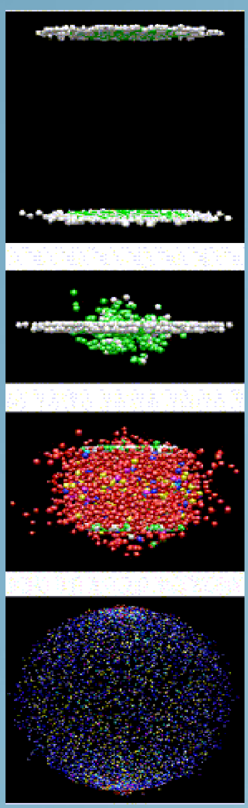
Can be seen also as Fourier expansion

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T d\eta}\left[1 + 2v_2\cos 2(\phi - \Psi_2) + 2v_3\cos 3(\phi - \Psi_3) + \ldots\right]$$

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

Motivation for a kinetic approach:

$$\Big\{\underbrace{p^{\mu}\partial_{\mu}}_{\text{Free streaming}}+\underbrace{\big[p_{\nu}F^{\mu\nu}+M\partial^{\mu}M\big]}_{\text{Field Interaction}\,\rightarrow\,\varepsilon\neq 3P}\partial^{p}_{\mu}\Big\}f(x,p)=\underbrace{S_{0}}_{\substack{\text{Souce term:}\\ \text{particle creation}}}+\underbrace{C_{22}+\;\ldots}_{\substack{\text{Collisions}\\ \eta\neq 0}}$$



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

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

  M. Ruggieri, F. Scardina, S. Plumari, V. Greco PLB 727 (2013) 177.

  M. Ruggieri, A. Puglisi, L. Oliva, S. Plumari, F. Scardina, V. Greco PRC 92 (2015) 064904.

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

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

- 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

Boltzmann Transport Equation

$$\{p^\mu \partial_\mu + [p_\nu F^{\mu\nu} + M \partial^\mu M] \partial_\mu^p\} f(x,p) = S_0 + C_{22} + \ \ldots$$

To solve numerically the Boltzmann-Vlasov eq. we use the test particle method

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

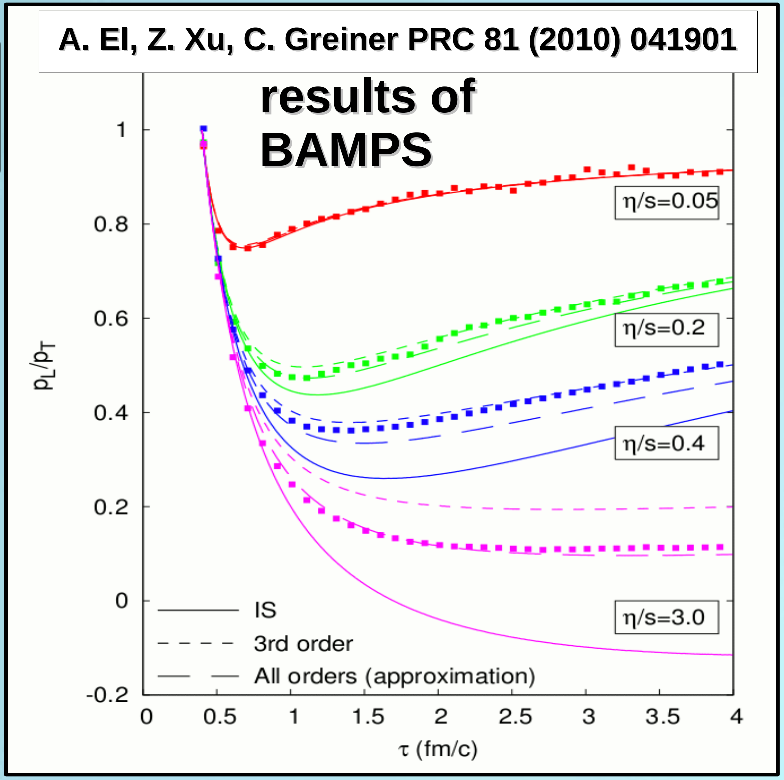
For the numerical implementation of the collision integral we use the stochastic algorithm.

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

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

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])

- **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.



From fields (Glasma) to particles (QGP): (1+1D evolution)

$$\begin{cases} [p^\mu \partial_\mu + p_\nu F^{\mu\nu} \partial^p_\mu] f(x,p) = \dfrac{dN}{d\Gamma} + C_{22} + \ \dots \\ \partial_\mu F^{\mu\nu} = J^\nu \end{cases}$$

We solve self-consistently Boltzmann-Vlasov and Maxwell eq. (abelian approx.)

SCHWINGER MECHANISM

Classical fields decay to particles pairs via tunneling due to vacuum instability

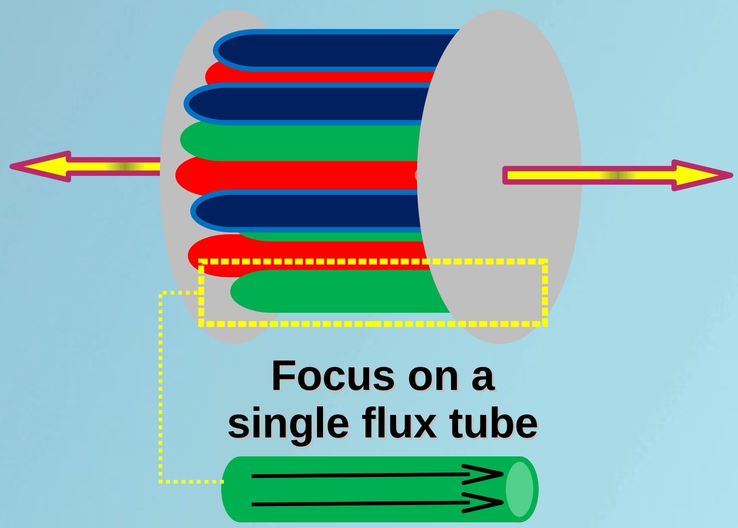
$$\frac{dN_{jc}}{d\Gamma} \equiv p_0 \frac{dN_{jc}}{d^4x\, d^2p_T\, dp_z} = \mathcal{R}_{jc}(p_T)\,\delta(p_z)\,p_0$$

$$\mathcal{R}_{jc}(p_T) = \frac{\mathcal{E}_{jc}}{4\pi^3} \left| \ln\left(1 \pm e^{-\pi p_T^2/\mathcal{E}_{jc}}\right)\right|$$

$$\mathcal{E}_{jc} = (g|Q_{jc}E| - \sigma_j)\,\theta\,(g|Q_{jc}E| - \sigma_j)$$

LONGITUDINAL CHROMO-ELECTRIC FIELDS DECAY IN GLUON PAIRS AND QUARK-ANTIQUARK PAIRS

Casher, Neuberger and Nussinov, PRD 20, 179 (1979)
Glendenning and Matsui, PRD 28, 2890 (1983)



ABELIAN FLUX TUBE MODEL

- **negligible chromo-magnetic field**
- **abelian dynamics for the chromo-electric field**
- **longitudinal initial field**
- **Schwinger mechanism**

From Glasma to Quark Gluon Plasma: (1+1D evolution)

M. Ruggieri, et al., PRC 92 (2015) 064904.

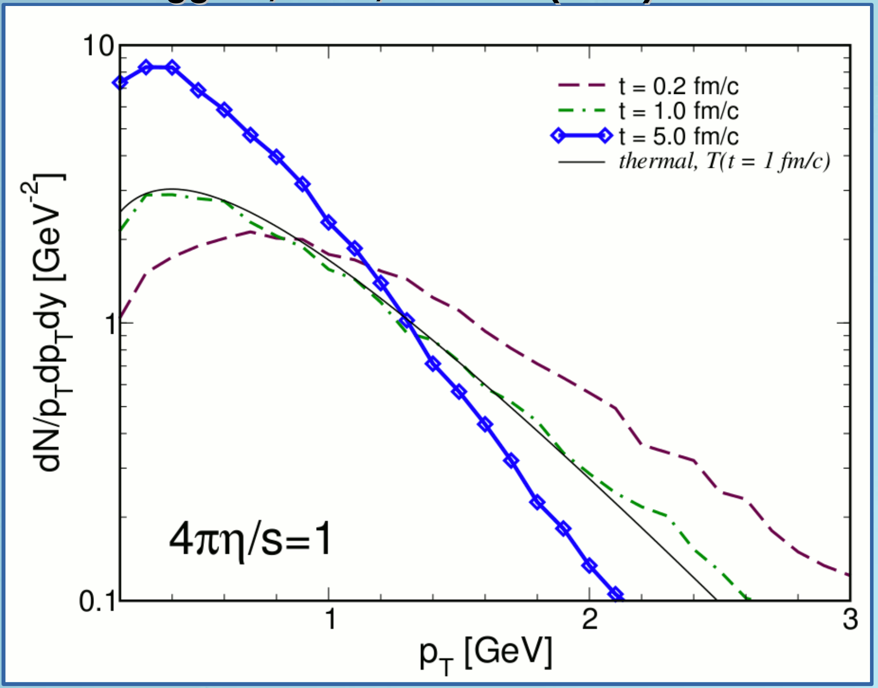
1+1 D expansion

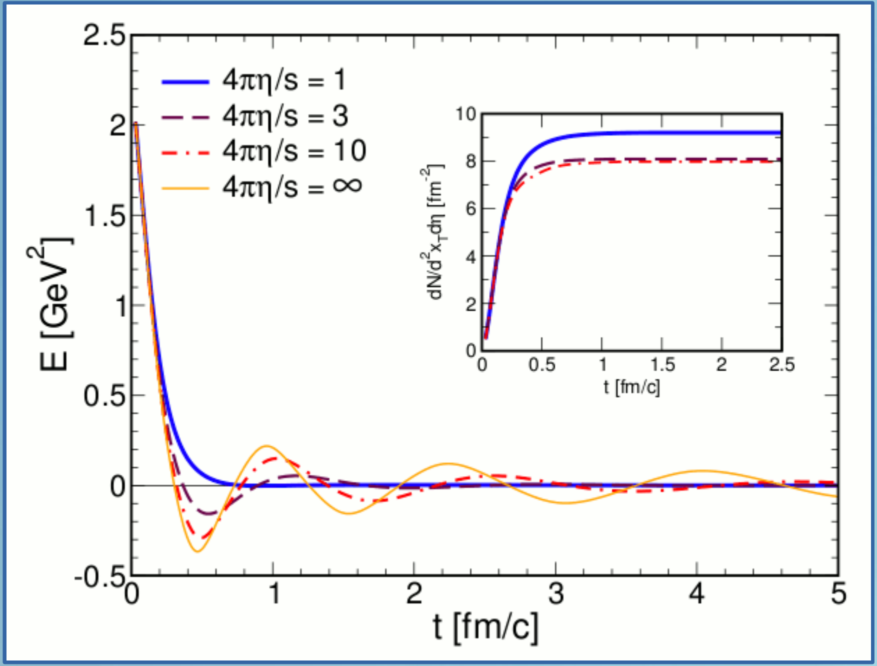
For $4\pi\eta/s=1$:

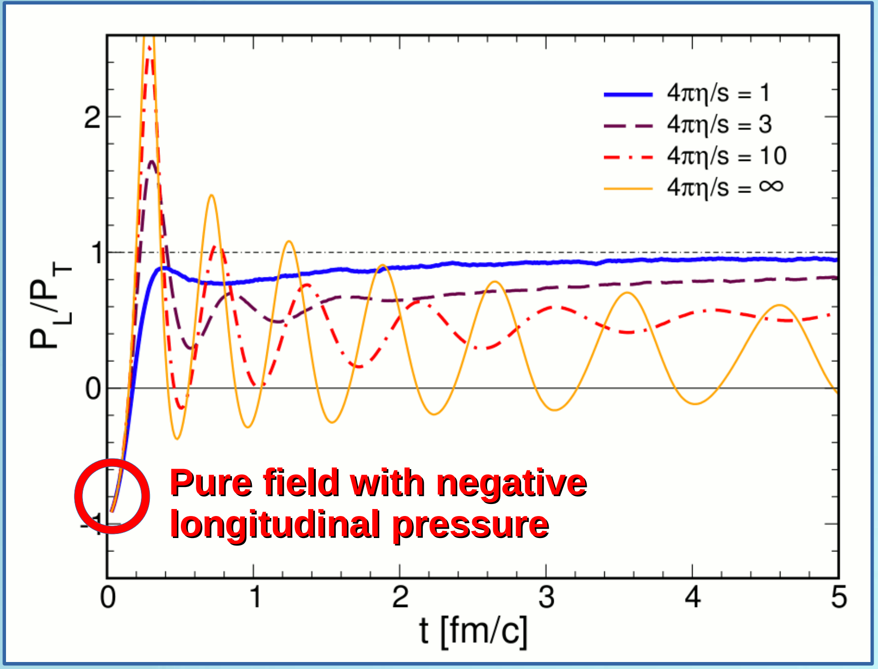
- Field decays quickly with a power law
- Fast thermalization in about 1 fm/c
- Pressure isotropization in about 1 fm/c

For large η/s:

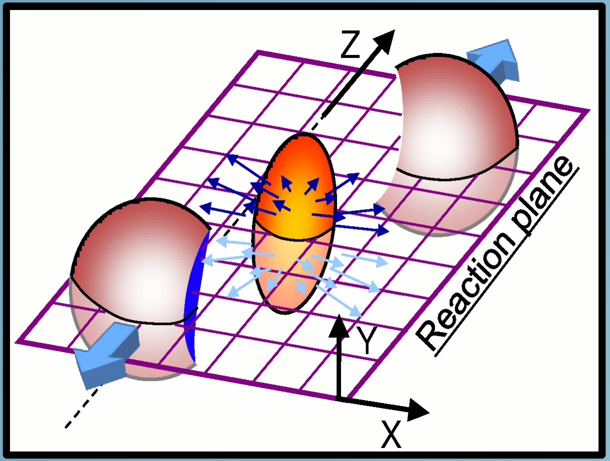
- Field decays faster in about 0.5 fm/c and for t > 0.5 fm/c plasma oscillations
- Particle spectra different from a thermal one
- Less efficient isotropization





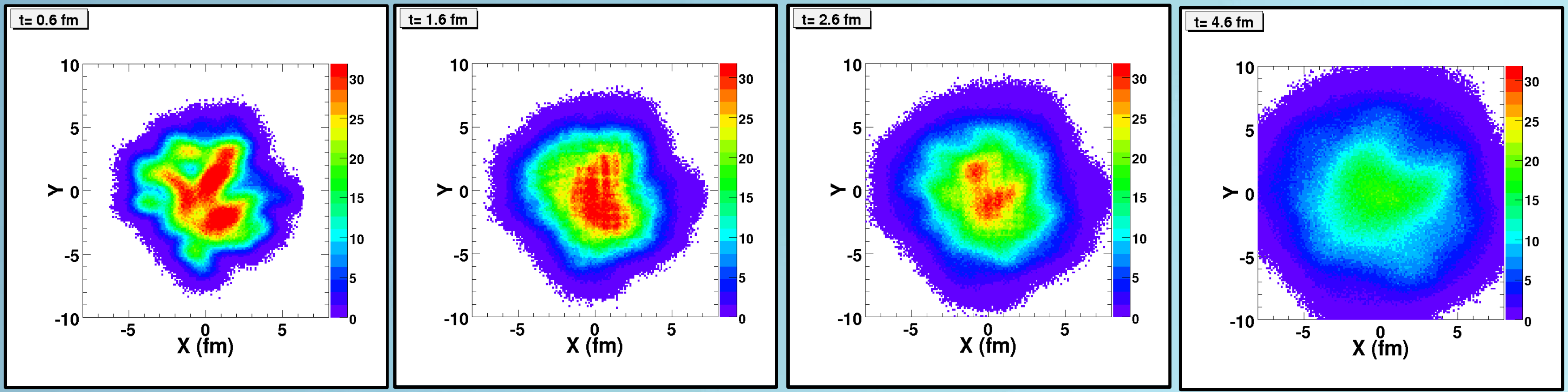


Applying kinetic theory to A+A Collisions….

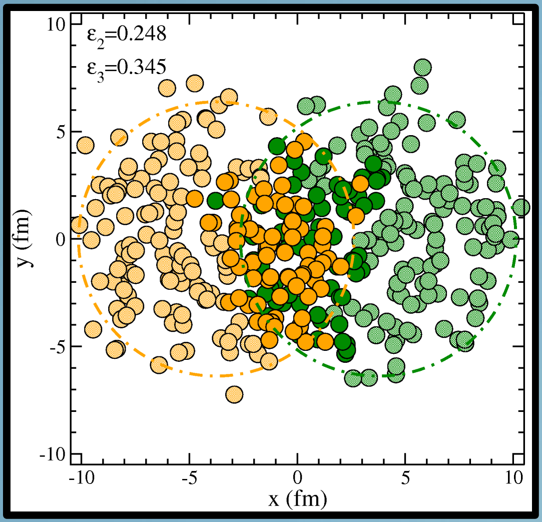


$$\{p^{\mu}\partial_{\mu}+M\,\partial^{\mu}M\,\partial^{p}_{\mu}\}f(x,p)=C_{22}+\ \ldots$$

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



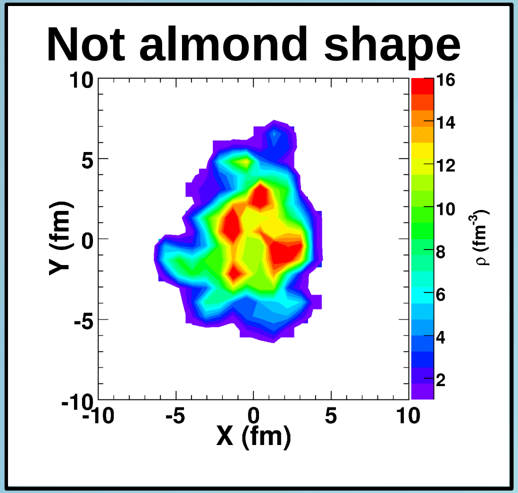
Initial State Fluctuations

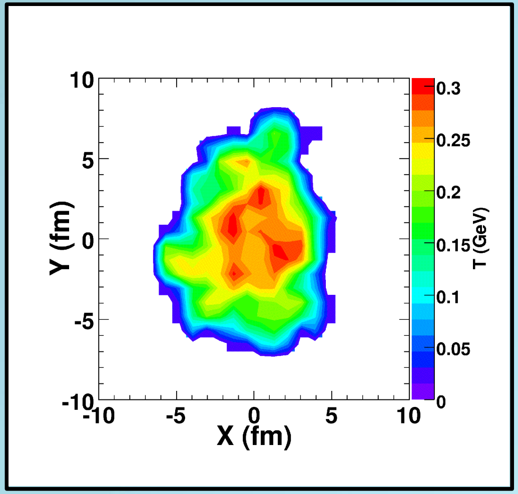


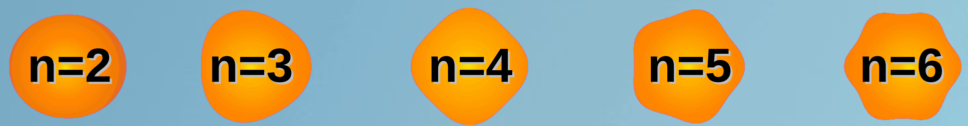
smooth distribution

Monte Carlo Glauber

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



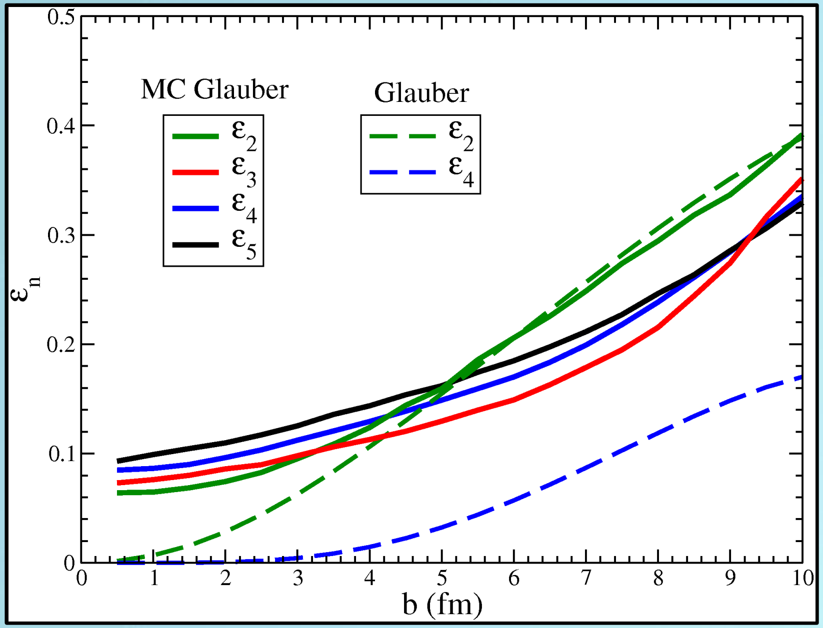




Characterization of the initial profile in terms of Fourier coefficients

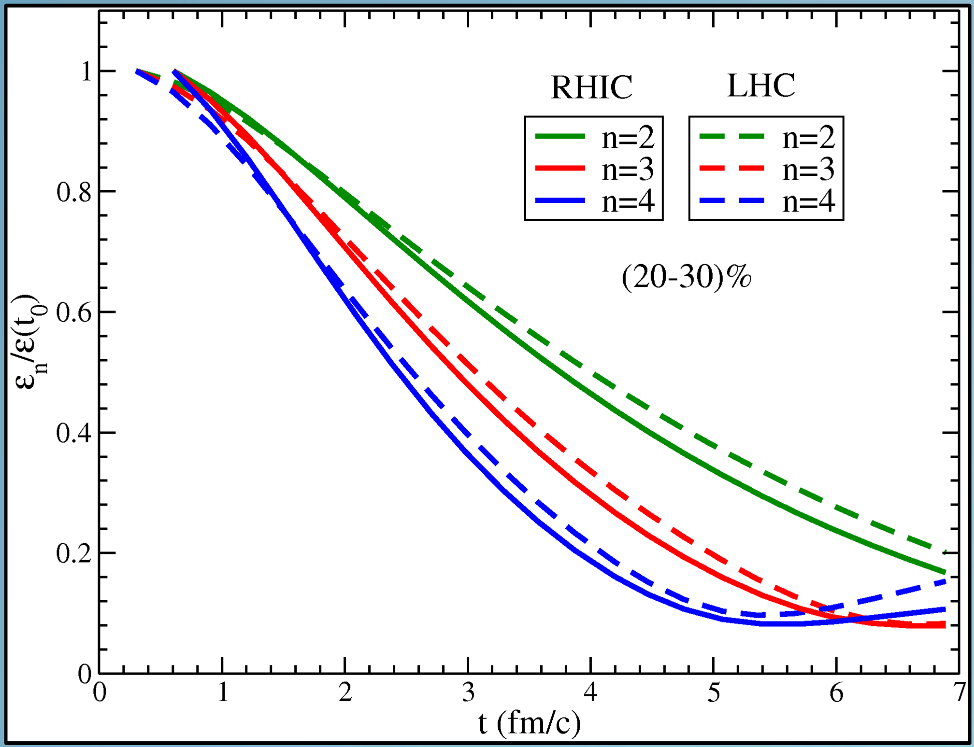
$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\phi-\Phi_n)]\rangle}{\langle r_\perp^n\rangle} \qquad \Phi_n = \frac{1}{n}\arctan\frac{\langle r_\perp^n \sin(n\phi)\rangle}{\langle r_\perp^n \cos(n\phi)\rangle}$$

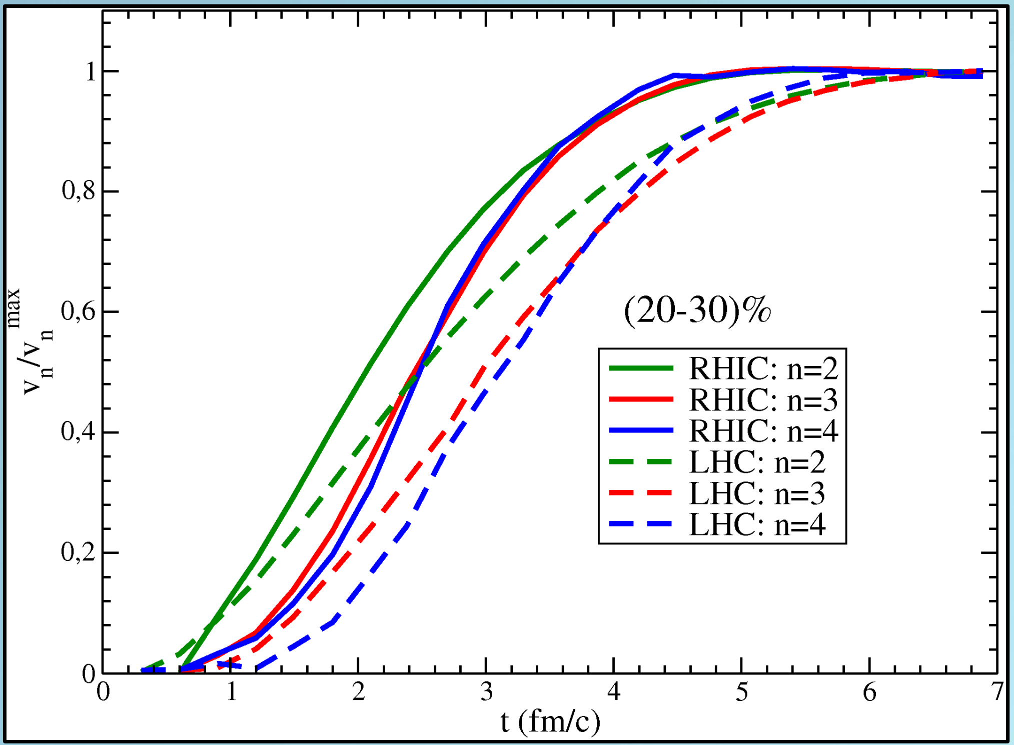
$$r_\perp = \sqrt{x^2+y^2}, \qquad \phi = \arctan(y/x)$$



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).

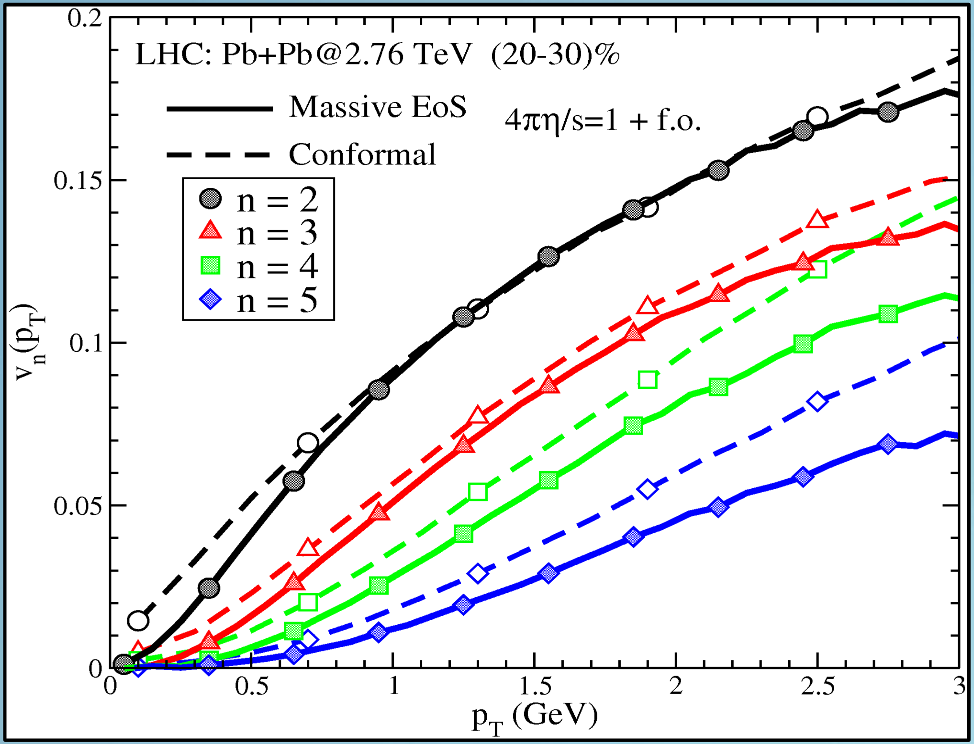
Initial State Fluctuations: time evolution of $\langle v_n \rangle$ and ε_n

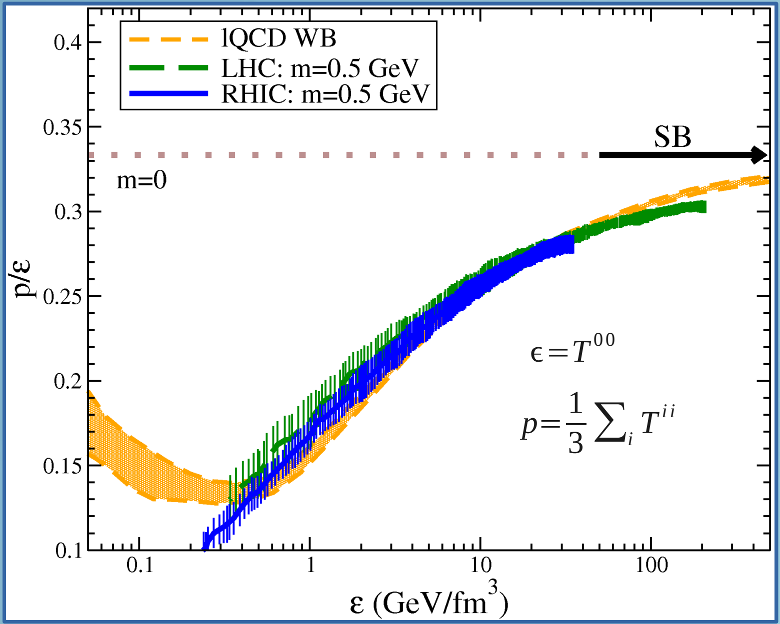




- **The time evolution for ε_n is faster for large n. At very early times $\varepsilon_n(t)=\varepsilon_n(t_0)-\alpha_n t^{n-2}$.**
- **$\langle v_n \rangle$ shows an opposite behaviour: $\langle v_n \rangle$ develops later for large n. At very early times $\langle v_n \rangle \propto t^{n+1}$.**
- **Different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

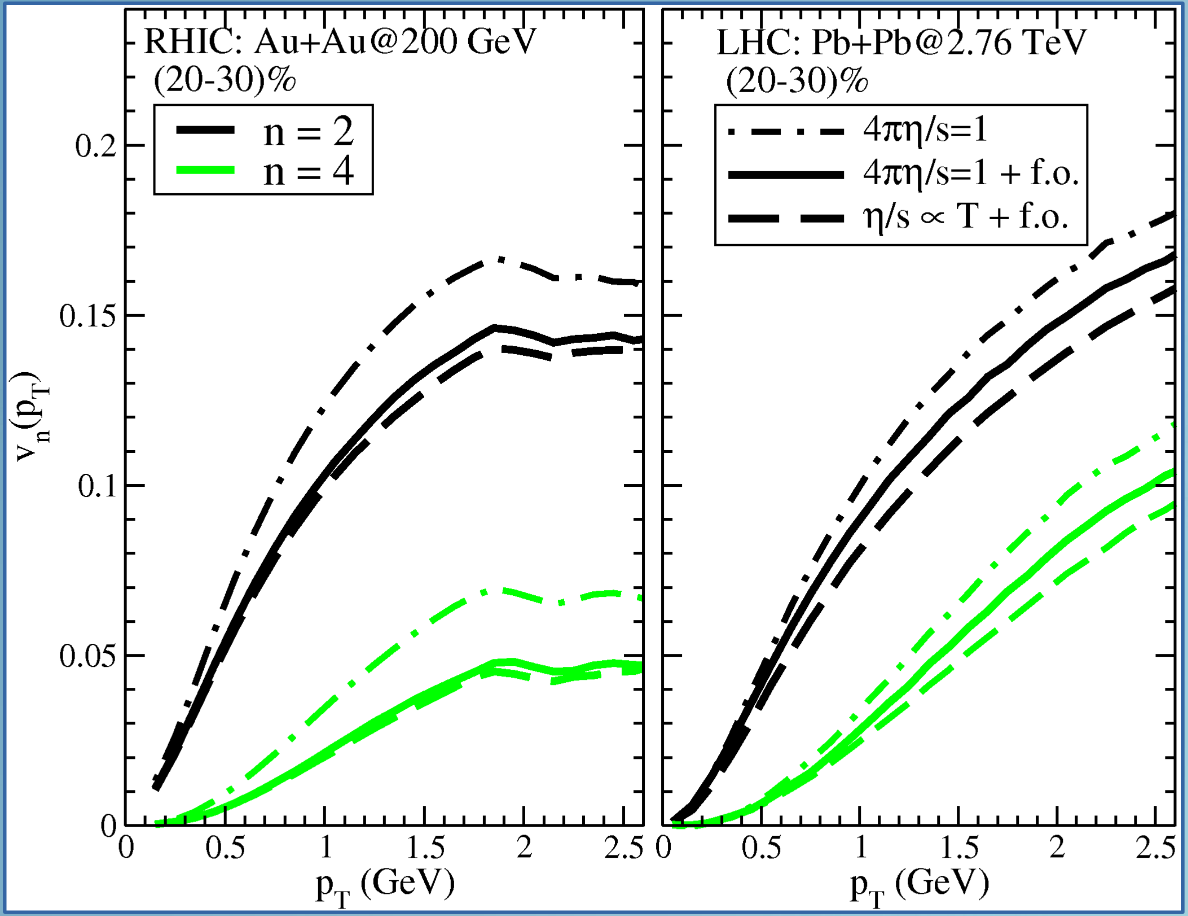
Initial State Fluctuations: role of the EoS on $<v_n>$ and $v_n(p_T)$

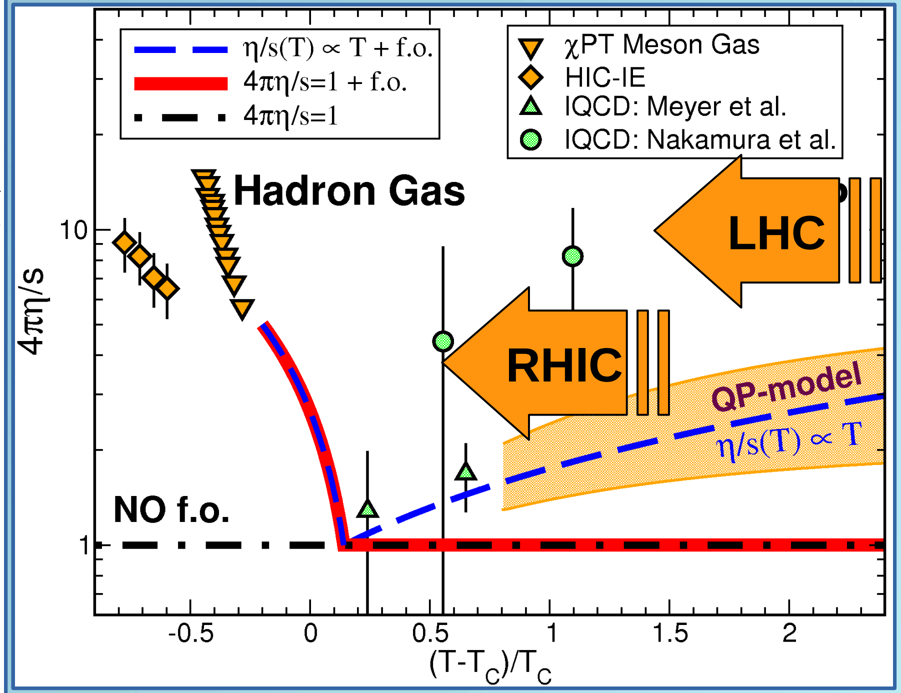




- **For massless case the system is more efficient in converting the initial anisotropy in coordinate space.**
- **The effect of the EoS is to reduce the $<v_n>$.**
- **The elliptic flow show a mass ordering typical of hydro expansion where at low p_T the $v_2(p_T) \propto p_T - <\beta_T> m_T$**
- **Different $<v_n>$ probes different value of p/ε during the expansion of the fireball.**

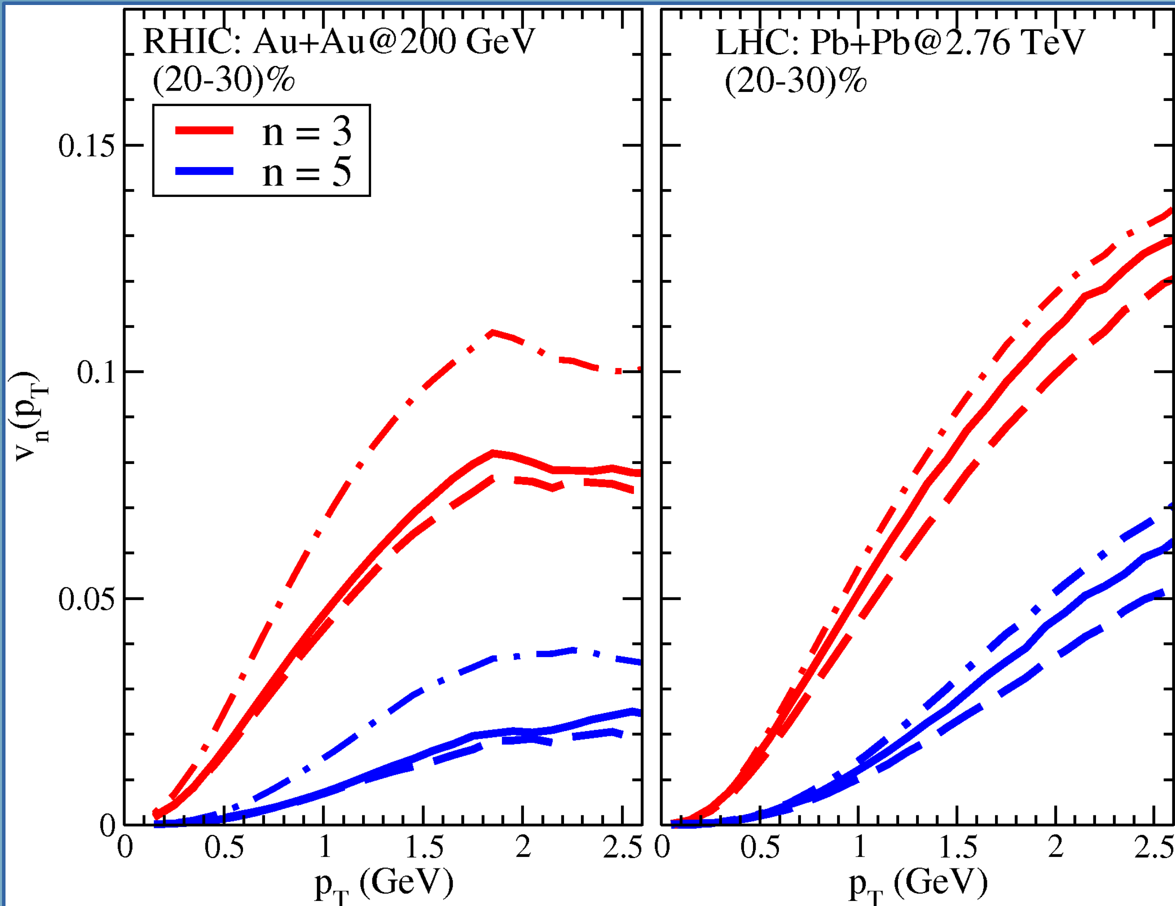
Initial State Fluctuations: $v_n(p_T)$ and η/s

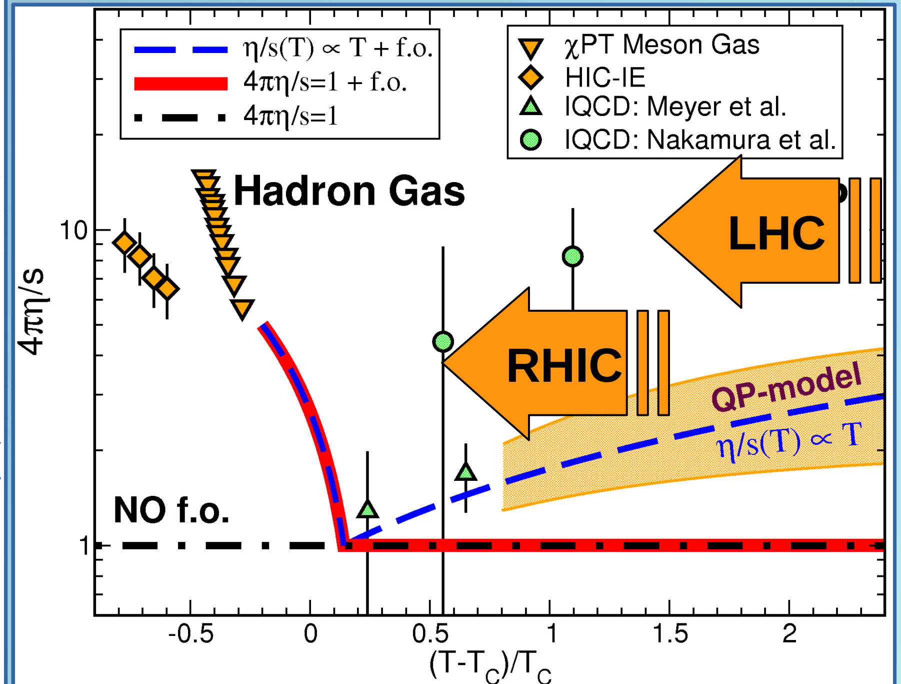




- $v_n(p_T)$ at RHIC is more sensitive to the value of the η/s at low temperature. $v_4(p_T)$ and $v_3(p_T)$ are more sensitive to the value of η/s than the $v_2(p_T)$.
- At LHC energies $v_n(p_T)$ is more sensitive to the value of η/s in the QGP phase (compare solid and dot-dashed lines).

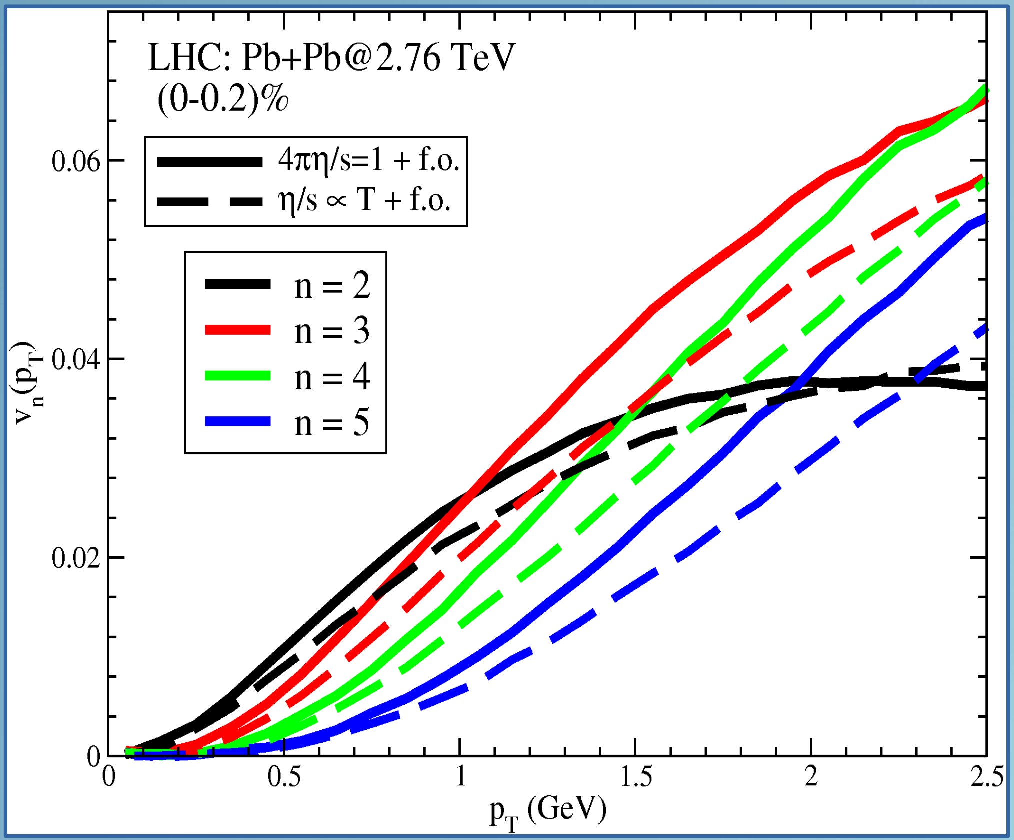
Initial State Fluctuations: $v_n(p_T)$ and η/s

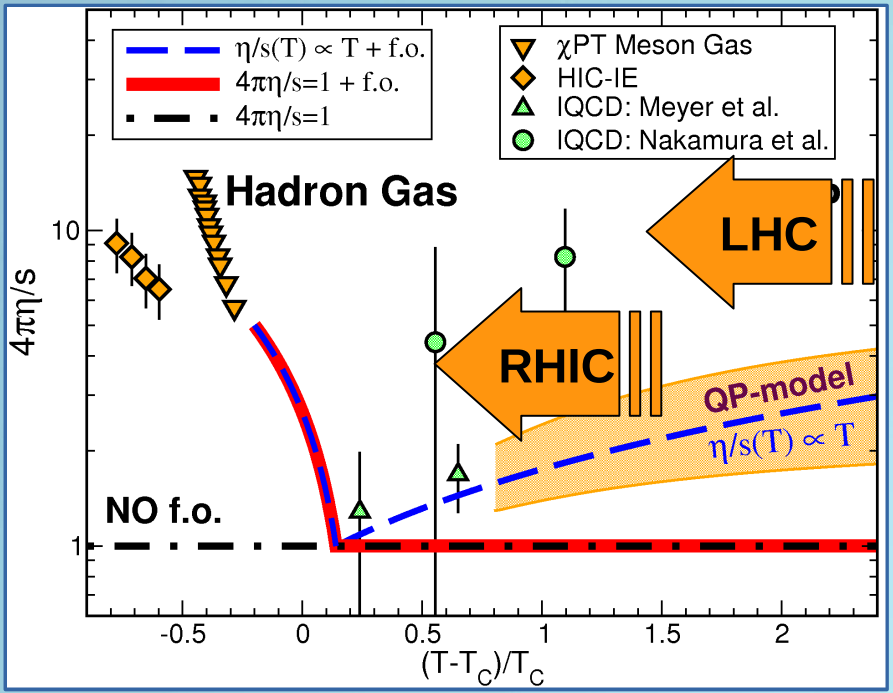




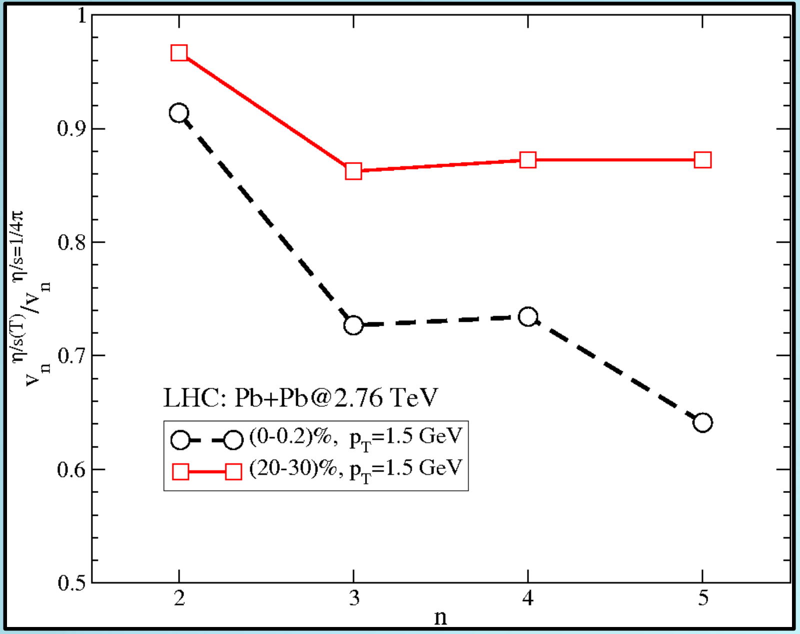
- $v_n(p_T)$ at RHIC is more sensitive to the value of the **η**/s at low temperature. $v_4(p_T)$ and $v_3(p_T)$ are more sensitive to the value of **η**/s than the $v_2(p_T)$.
- At LHC energies $v_n(p_T)$ is more sensitive to the value of **η**/s in the QGP phase (compare solid and dot-dashed lines).

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



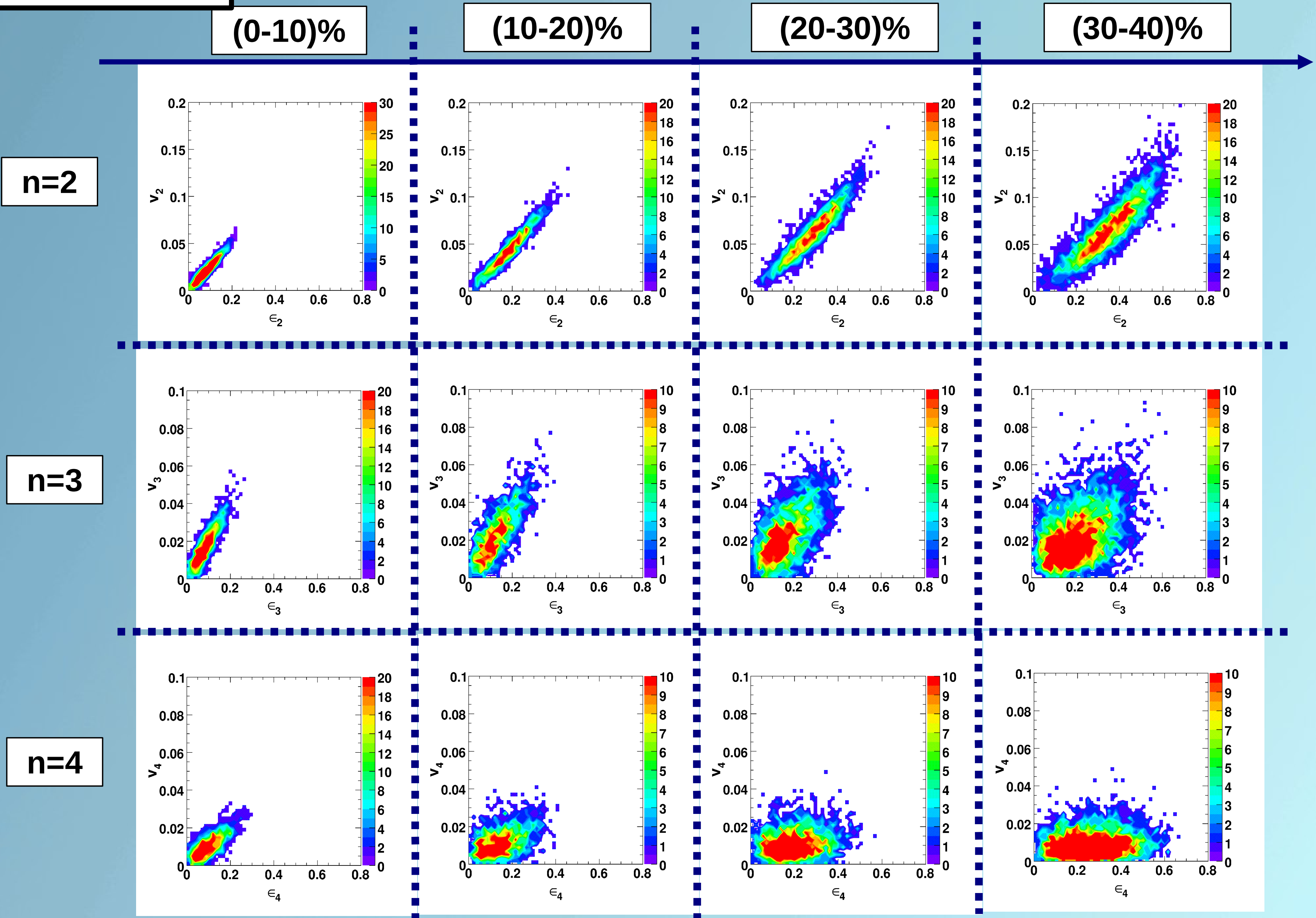


- At low p_T $v_n(p_T) \propto p_T^{\,n}$. v_2 for higher p_T saturates while v_n for n>3 increase linearly with p_T.
- For central collisions viscous effect are more relevant. For n>2 the $v_n(p_T)$ are more sensitive to the η/s ratio in the QGP phase.

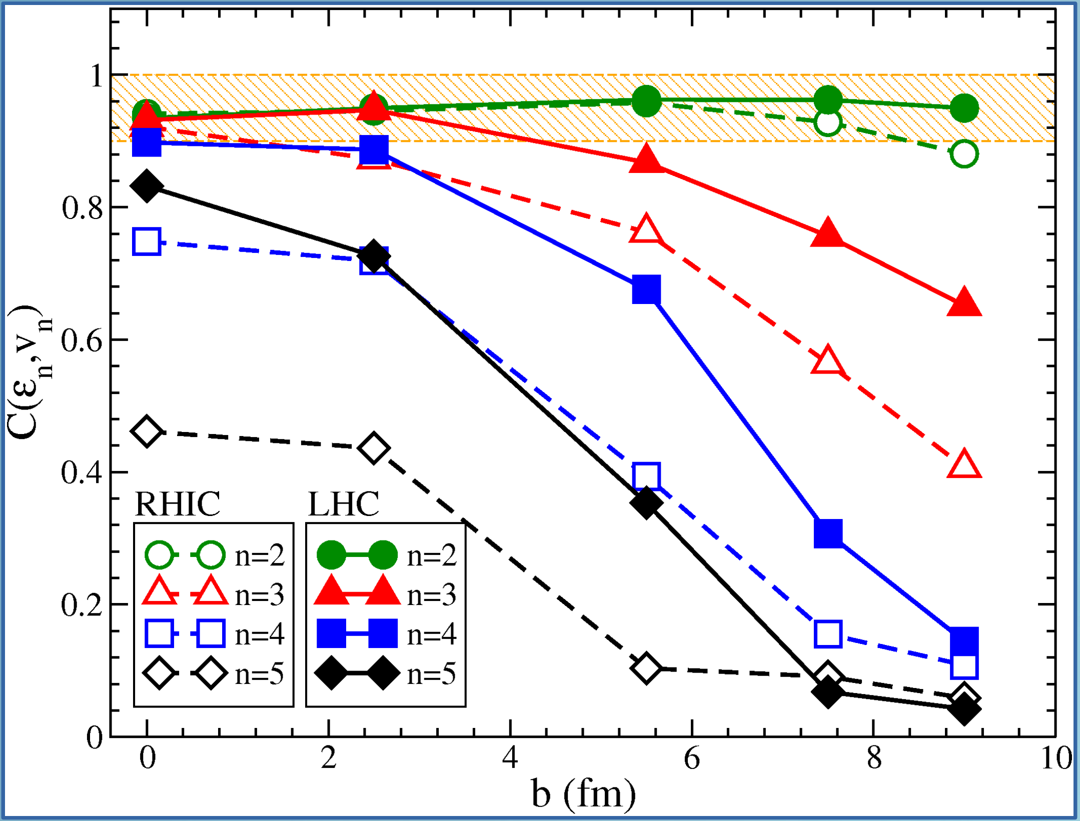


Initial State Fluctuations: v_n vs ε_n

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.

S. Plumari, G. L. Guardo, F. Scardina, V. Greco Phys.Rev. C92 (2015) no.5, 054902.

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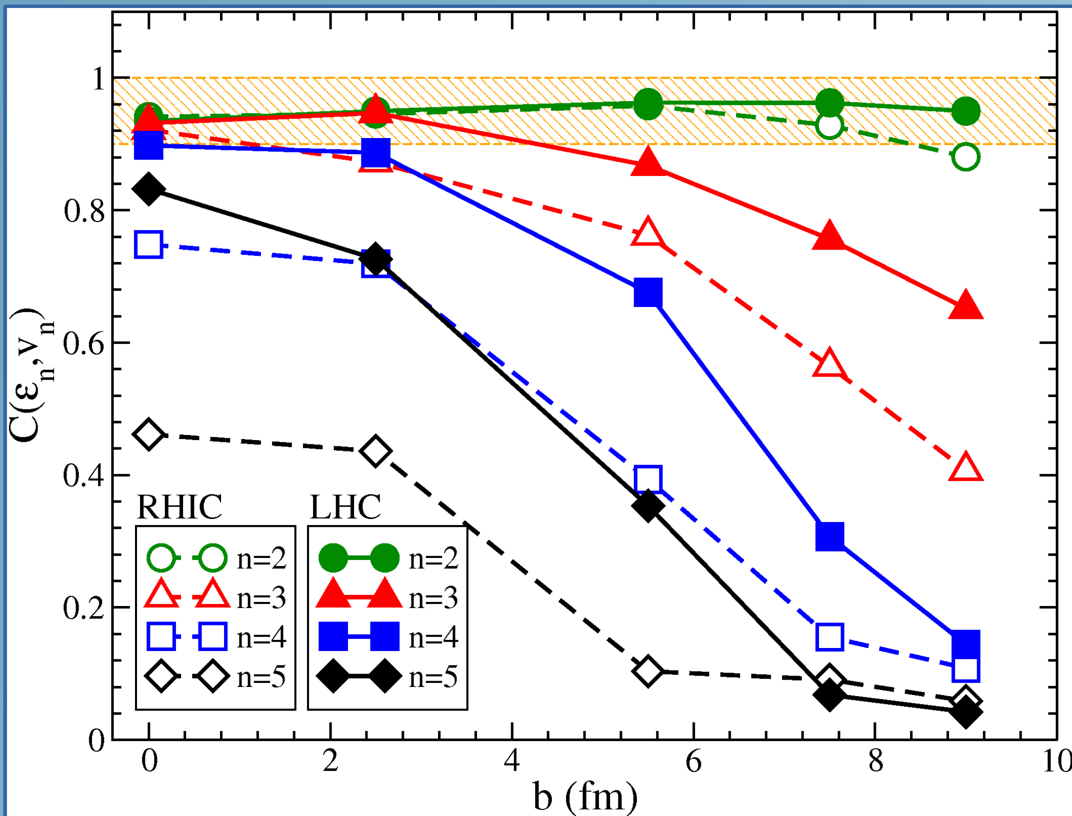
Initial State Fluctuations: v_n vs ε_n



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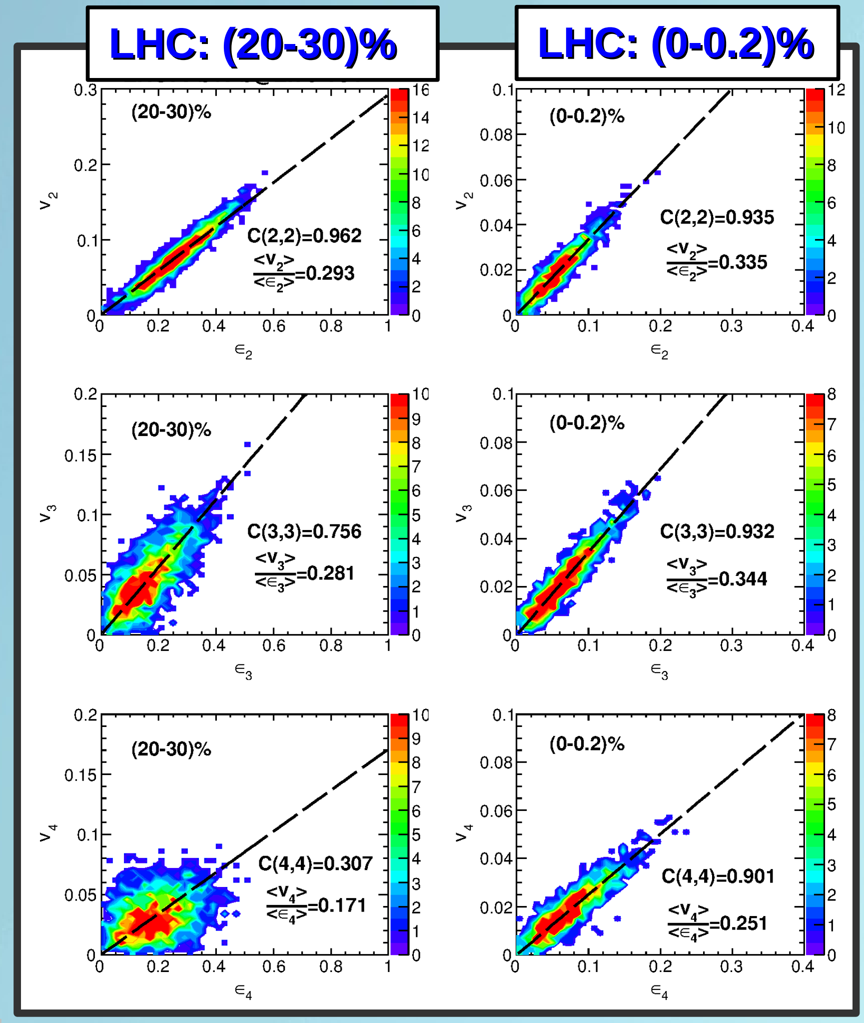

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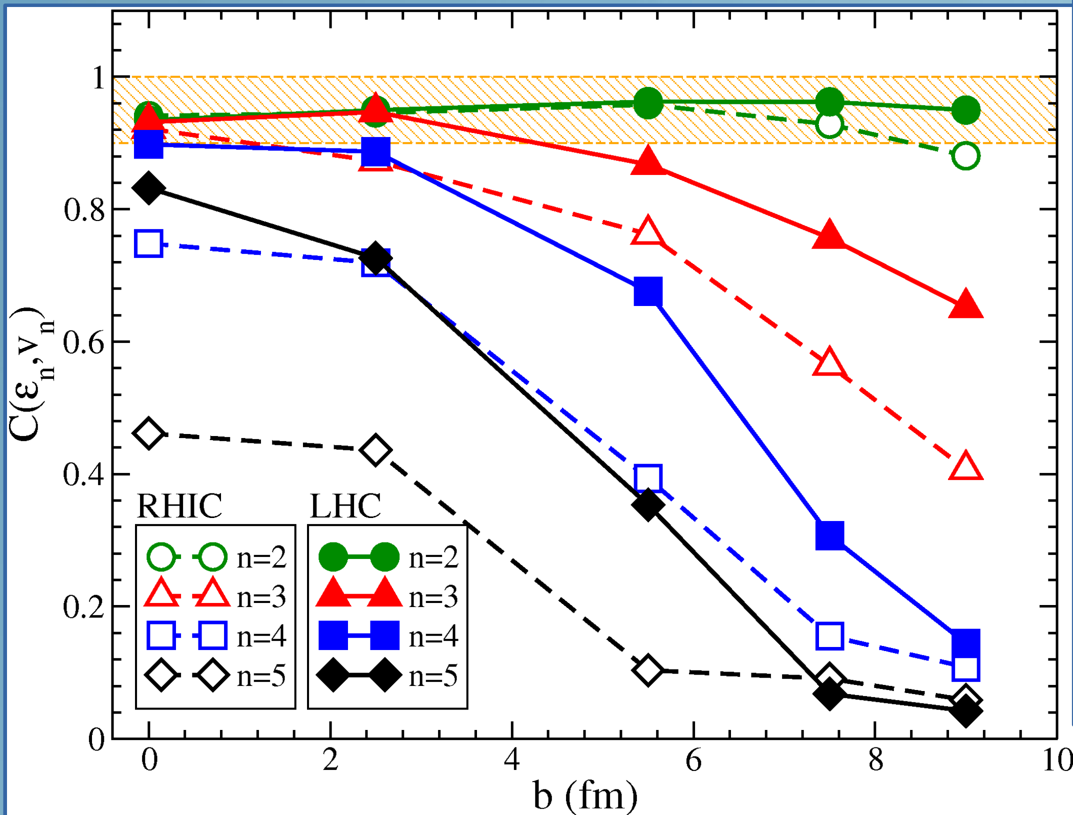

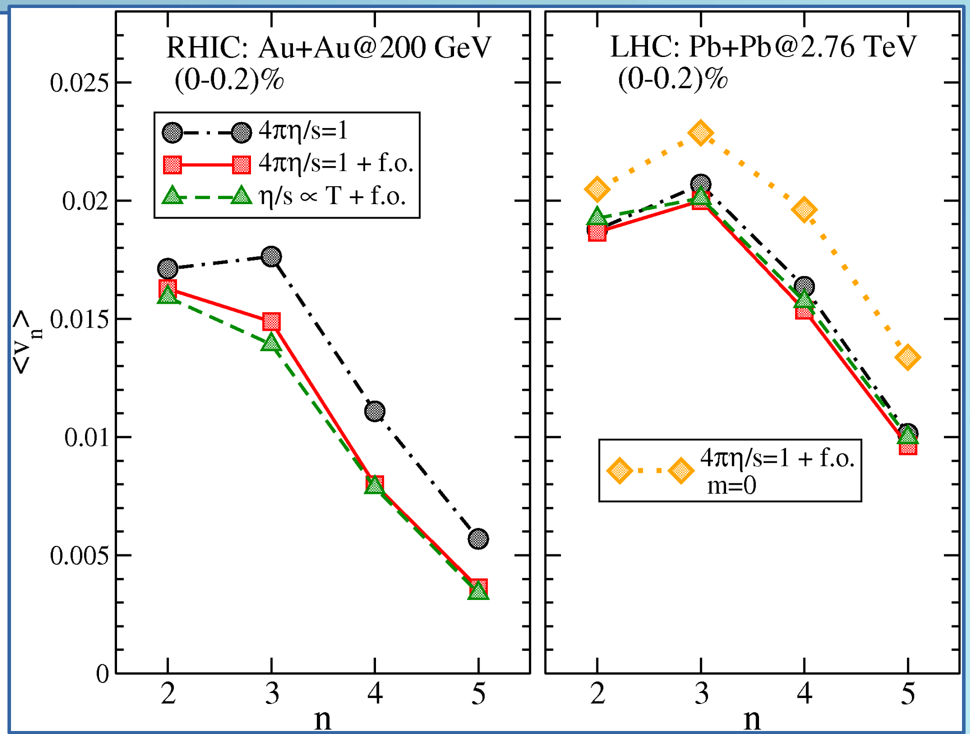

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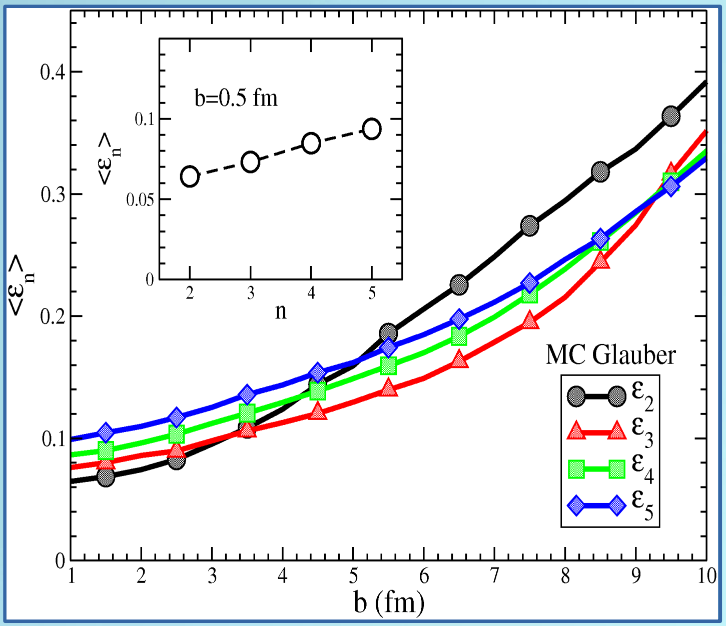


- Equation of State and collision energy play a role on the build up of $<v_n>$ in central collisions. The effect of the EoS is to reduce the final $<v_n>$.
- At RHIC energies the $<v_n>$ are smaller than those LHC and for more realistic $\eta/s(T)$ $v_2 > v_3 > v_4$ ...
- At LHC energies and ultra-central collisions the $<v_n>$ keep more information about the initial eccentricities $<\varepsilon_n>$.

Conclusions

Transport at fixed η/s:

- Relativistic transport theory permit to study early dynamics of HIC
  - Initial color-electric field decays in about 1 fm/c
  - Thermalization and Isotropization in about 1 fm/c

- 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 stronger correlation between v_n and ε_n than at RHIC for all n.

  Ultra central collisions:

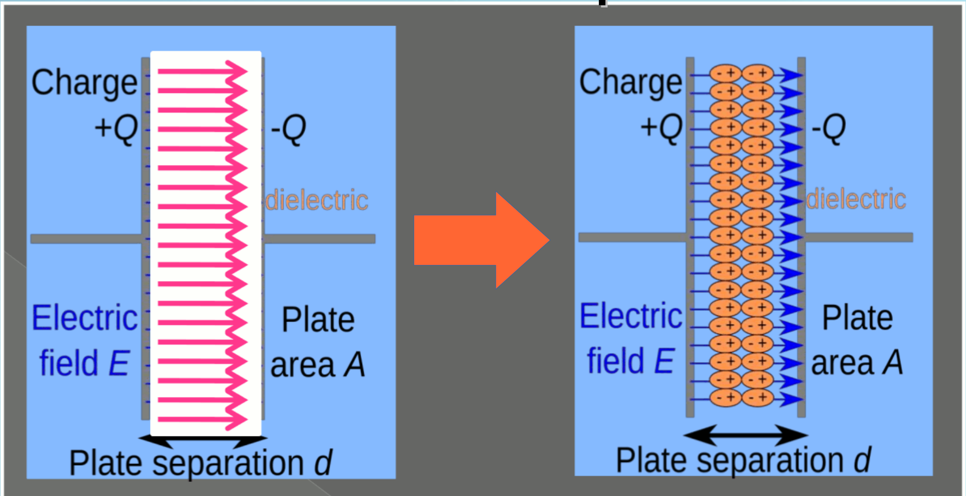
  - $v_n \propto \varepsilon_n$ for n=2,3,4 strong correlation $C(n,n) \approx 1$
  - $v_n(p_T)$ much more sensitive to η/s(T)
  - degree of correlation increase with the collision energy and the relative strenght of $\langle v_n \rangle$ depend on the colliding energies.
  - correlations in (v_n, v_m) reflect the initial correlations in $(\varepsilon_n, \varepsilon_m)$

From Glasma to Quark Gluon Plasma: (1+1D evolution)

$$\begin{cases} [p^\mu \partial_\mu + p_\nu F^{\mu\nu} \partial^p_\mu] f(x,p) = \dfrac{dN}{d\Gamma} + C_{22} + \ \ldots \\ \partial_\mu F^{\mu\nu} = J^\nu \end{cases}$$

We solve self-consistently Boltzmann-Vlasov and Maxwell eq. (abelian approx.)

Vacuum with electric field
Unstable toward pair creation



Schwinger effect in Electrodynamics

Field interaction + source term
Link between parton distribution function and classical color fields

$$\frac{dE}{d\tau} = -j_M - j_D$$

Conductive current due to charge movement

Polarization current Dipole moment formed in vacuum by Schwinger effect

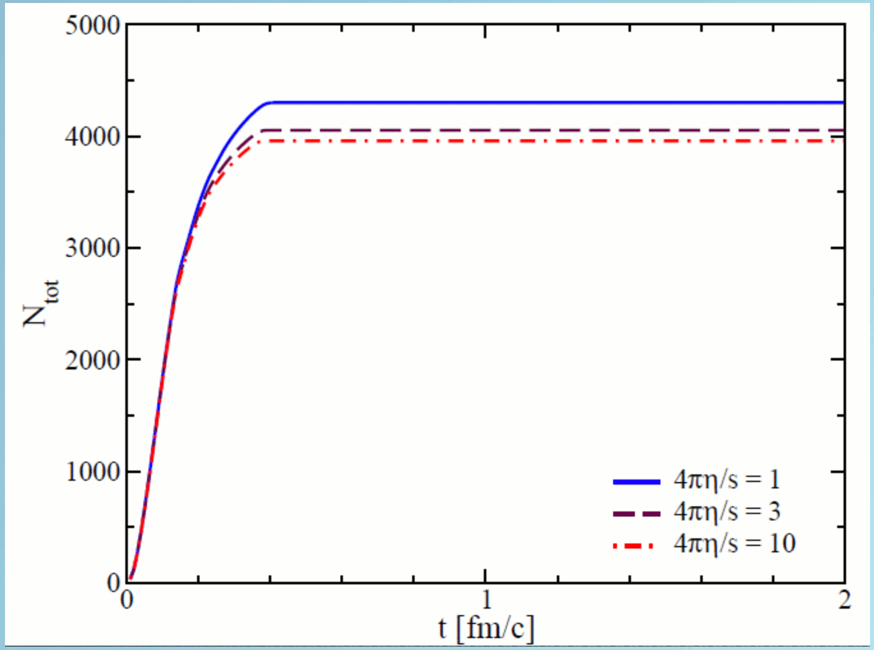
$$\frac{dN_{jc}}{d\Gamma} \equiv p_0 \frac{dN_{jc}}{d^4x d^2p_T dp_z} = \mathcal{R}_{jc}(p_T)\delta(p_z)p_0$$

$$\mathcal{R}_{jc}(p_T) = \frac{\mathcal{E}_{jc}}{4\pi^3}\left|\ln\left(1 \pm e^{-\pi p_T^2/\mathcal{E}_{jc}}\right)\right|$$

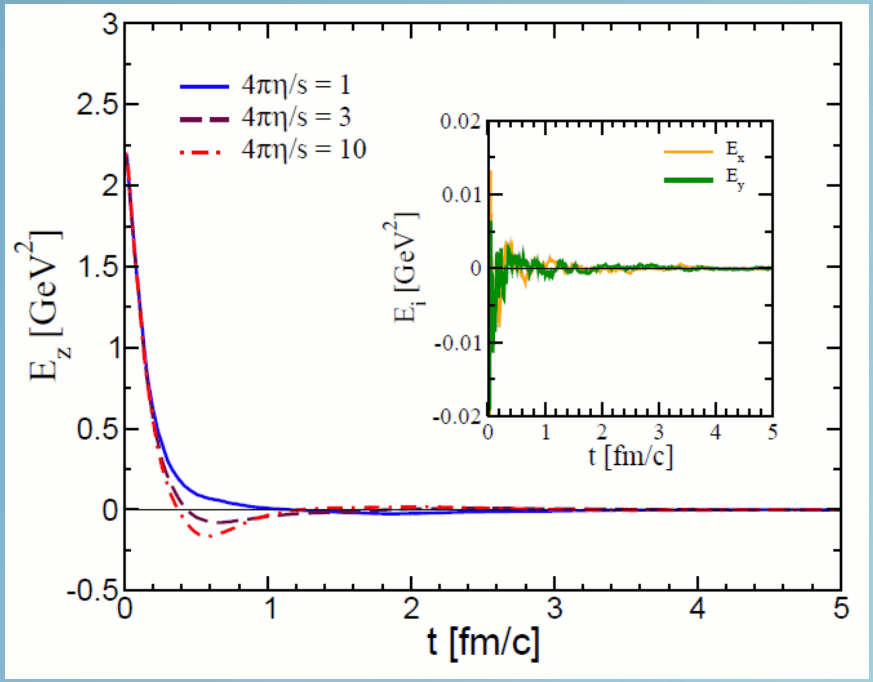
$$\mathcal{E}_{jc} = (g|Q_{jc}E| - \sigma_j)\,\theta\,(g|Q_{jc}E| - \sigma_j)$$

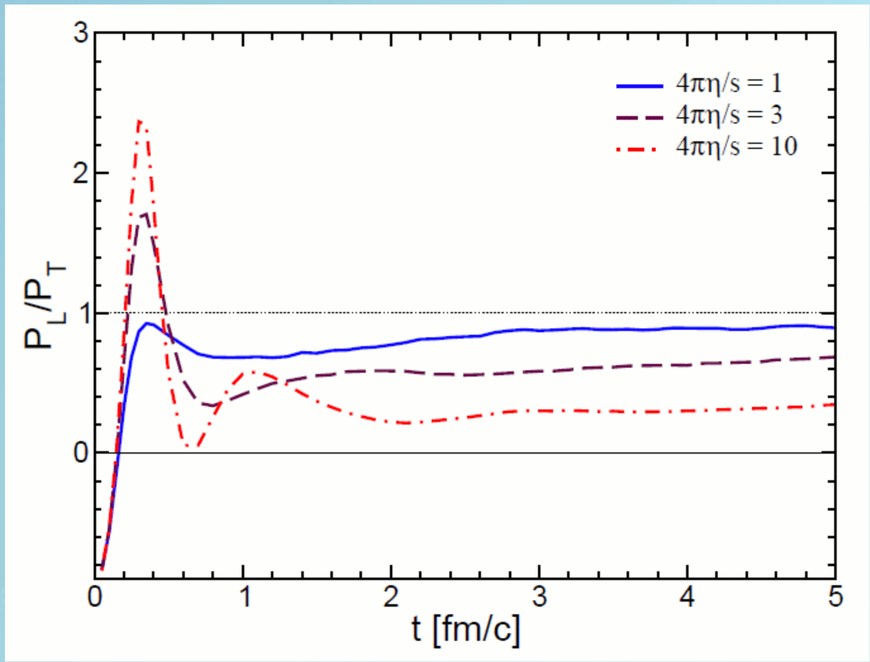
From Glasma to Quark Gluon Plasma: (3+1D evolution)

PRELIMINARY RESULTS



AGREEMENT WITH 1+1D CALCULATION

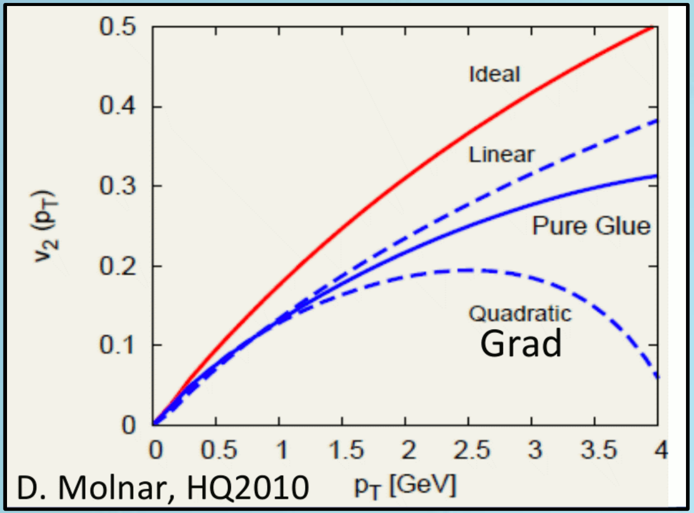




From Transport to Hydro: extraction of viscous corrections to f(x,p) and $v_n(p_T)$. (work in collaboration with J.Y. Ollitrault)

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

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



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.

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

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)

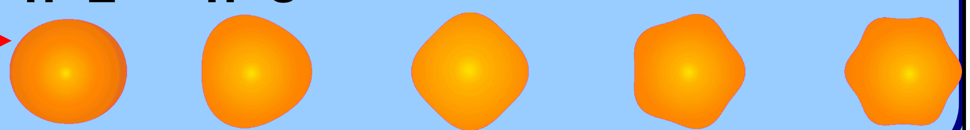
- We start with an initial azimuthally symmetric profile (optical Glauber model).
- Then we deform the initial distribution (α<<1)

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

2π/n symmetry

This Creates only

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



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 $T^{\mu\nu}(x)$

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

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

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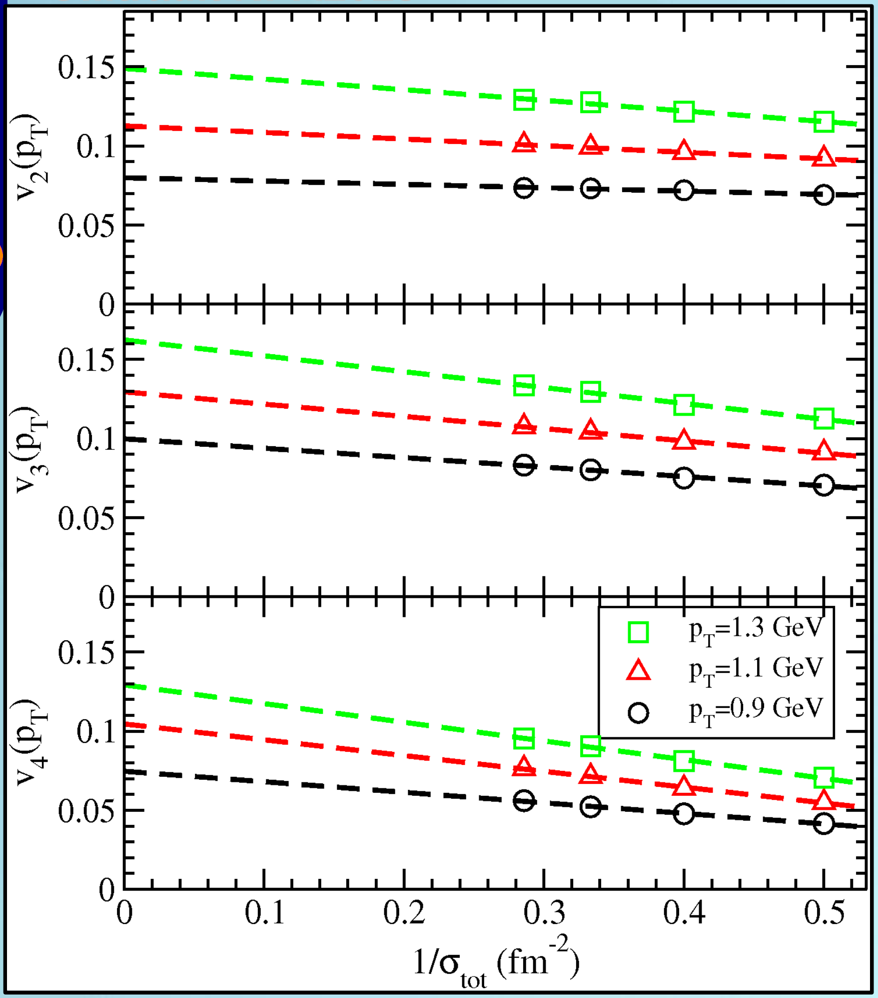

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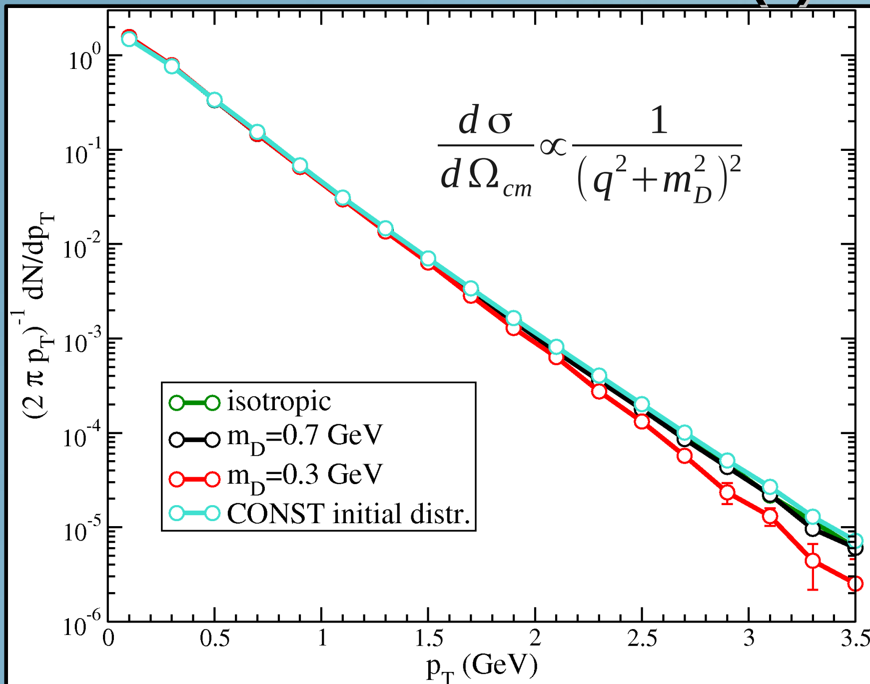
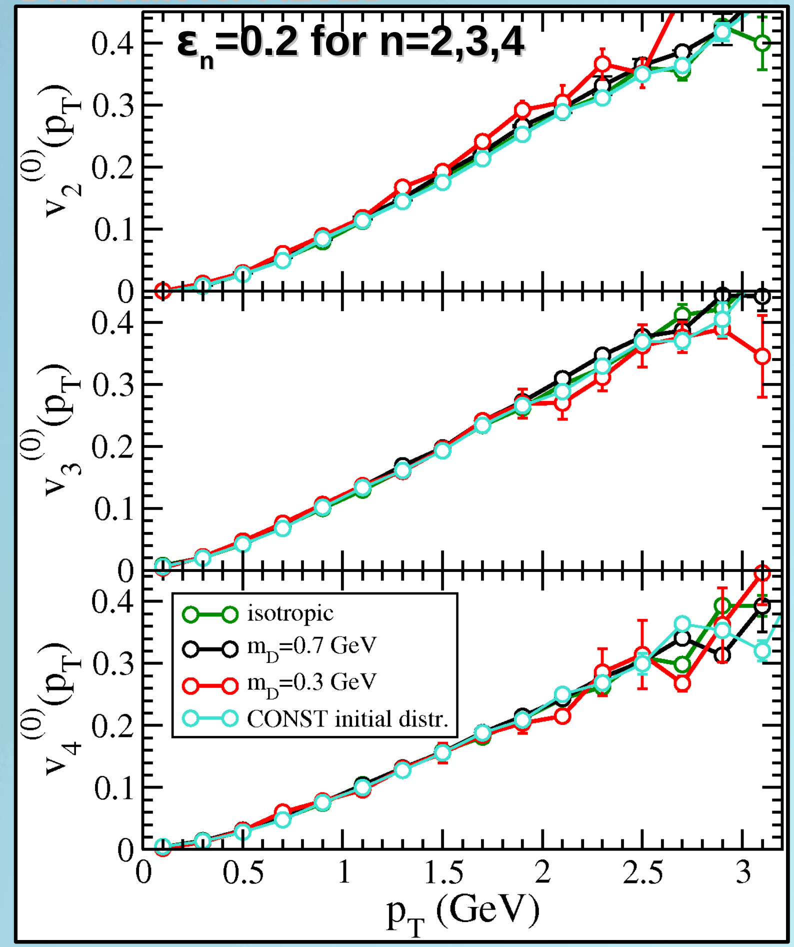
For the same initial local $T^{\mu\nu}(x)$:





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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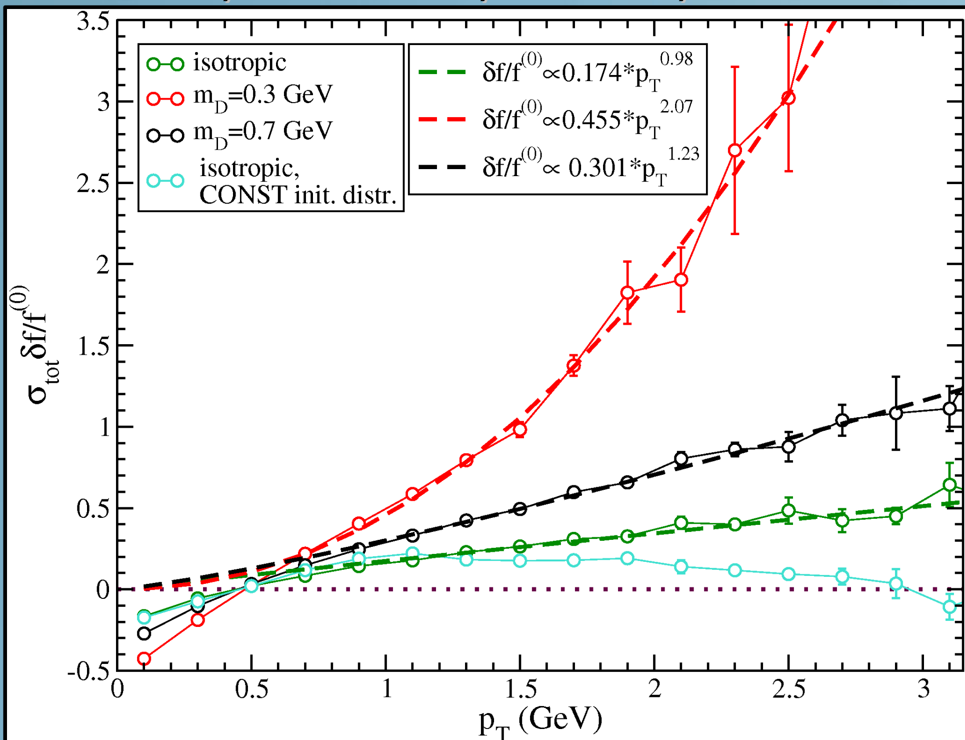
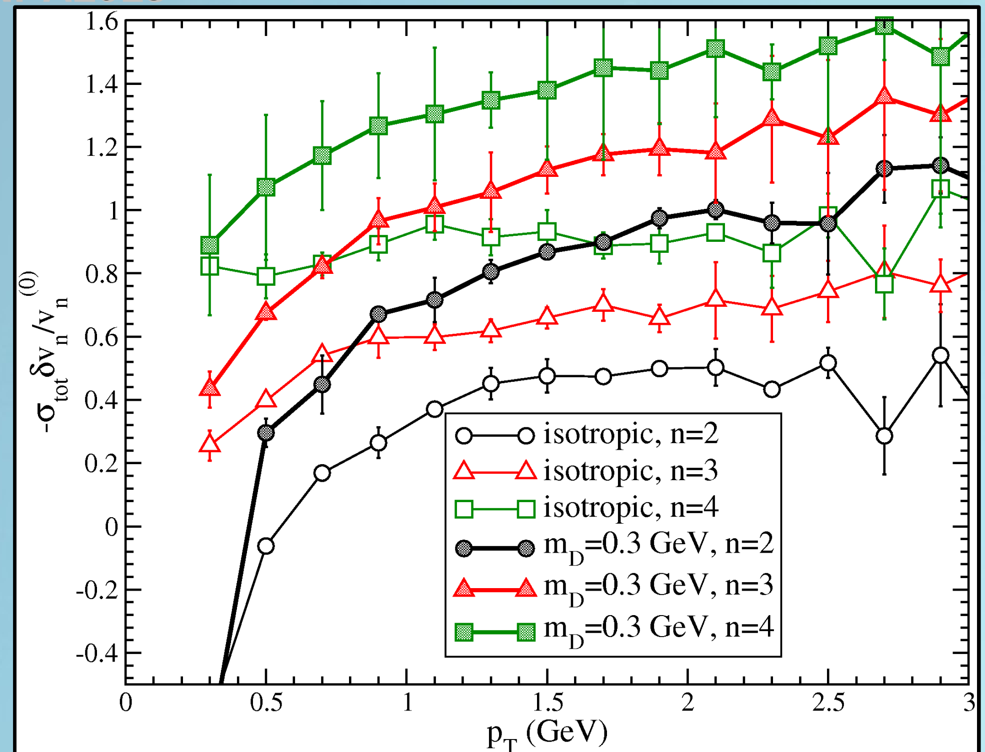




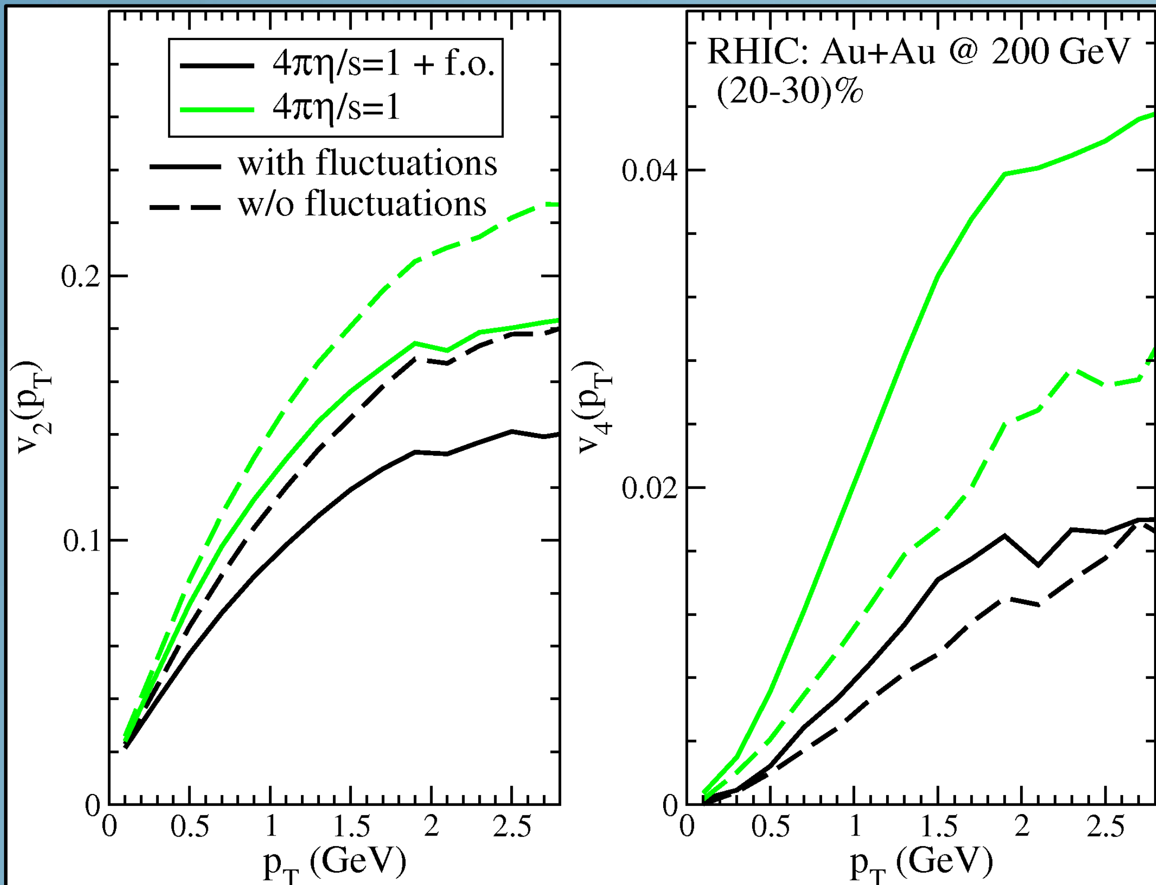
In δf and δv_n it is encoded the information about the microscopical details

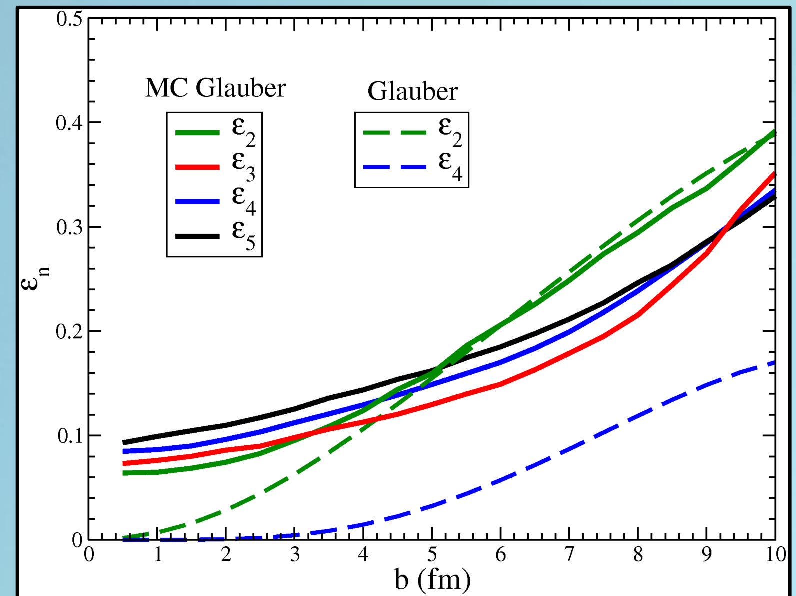
- **$\delta f(p_T)/f^{(0)} \propto p_T^{\alpha}$ with α = 1. - 2. and $\alpha(m_D)$.**

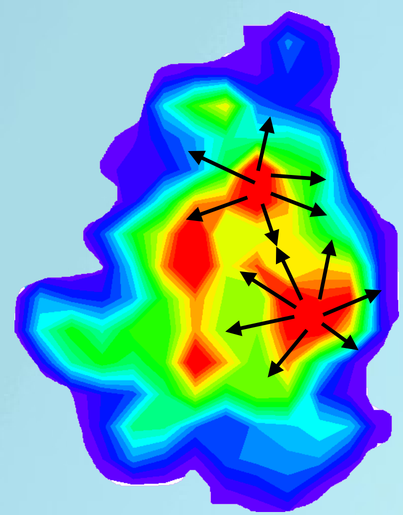
For isotropic σ similar to R.S. Bhalerao et al. PRC 89, 054903 (2014)

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

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.