UNIVERSITÀ DEGLI STUDI DI CATANIA

INFN-LNS

Anisotropie v_n nello spazio degli impulsi e fluttuazioni di stato inziale nel plasma creato nelle collisioni ad energie ultra-relativistiche

S. Plumari, L. Oliva, A. Puglisi,

M. Ruggieri, F. Scardina, V. Greco

Outline

- Transport approach at fixed η/s
- Initial state fluctuations

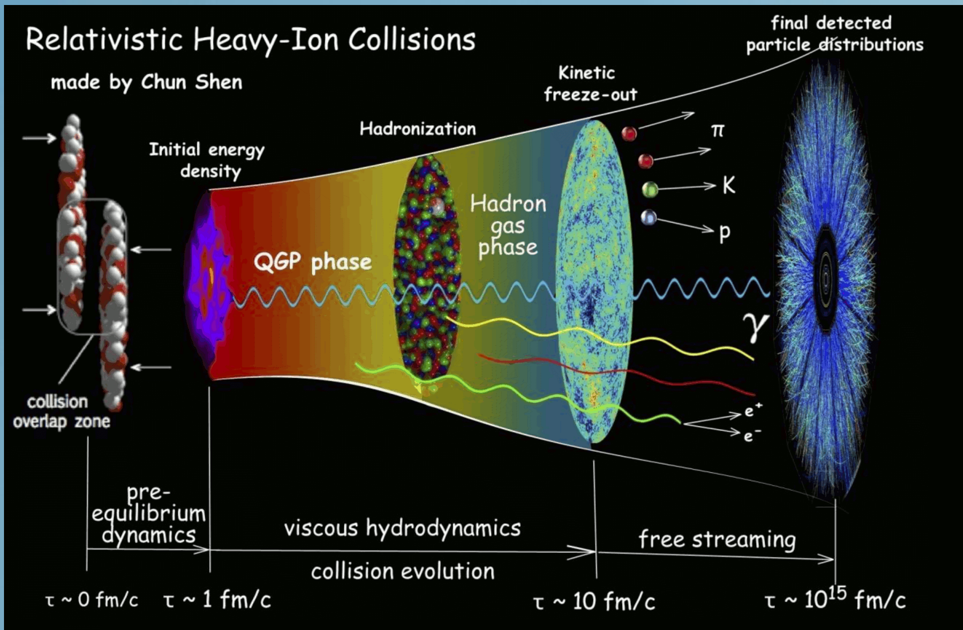
  - role of η/s on the build-up of v_n(pT): from RHIC to LHC

  - Correlations between ε_n (space eccentricities) and

    v_n (collective flows)

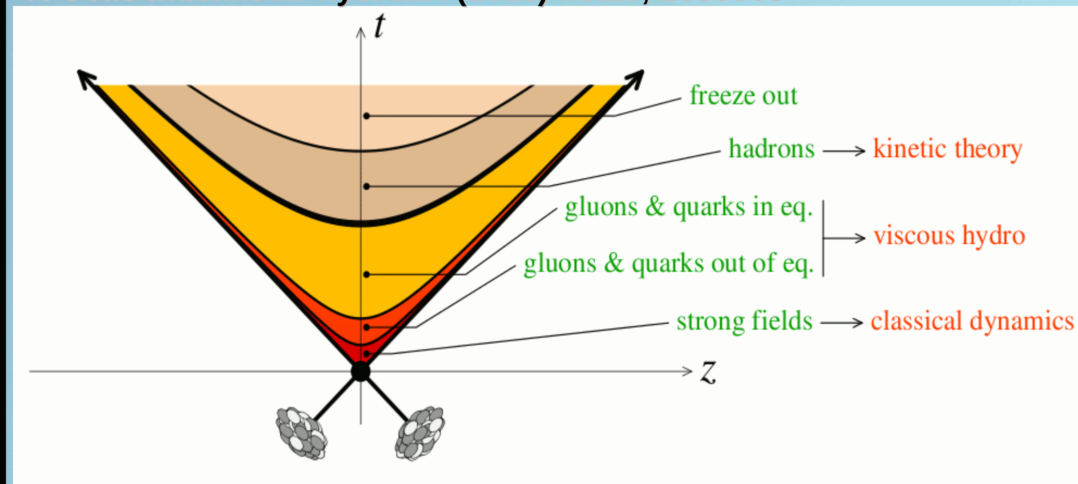
- Conclusions

sketch of evolution of a HIC



Picture taken from:
http://snelling.web.cern.ch/snelling/img/little_bang.jpg

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**

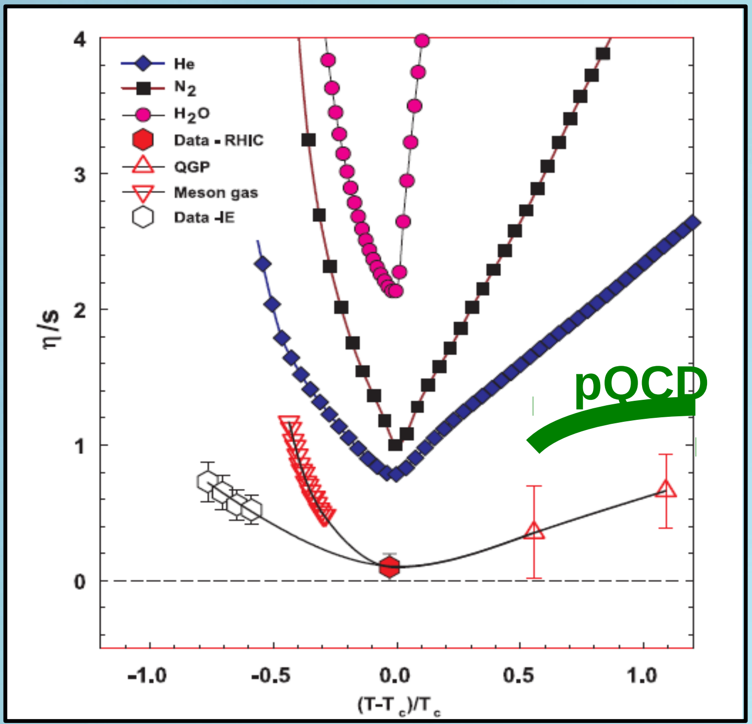
$$\Delta E \cdot \Delta t \geqslant 1 \rightarrow \eta/s \approx \frac{1}{15}\langle p \rangle \cdot \tau > \frac{1}{15}$$

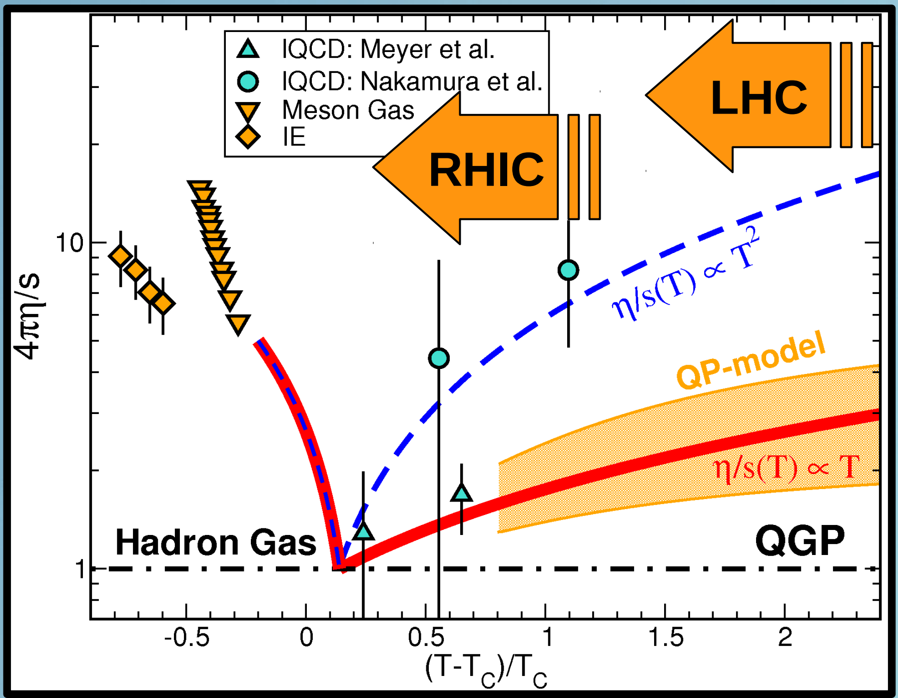
- **AdS/CFT suggest a lower bound $\eta/s = 1/(4\pi) \sim 0.08$**

- **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.

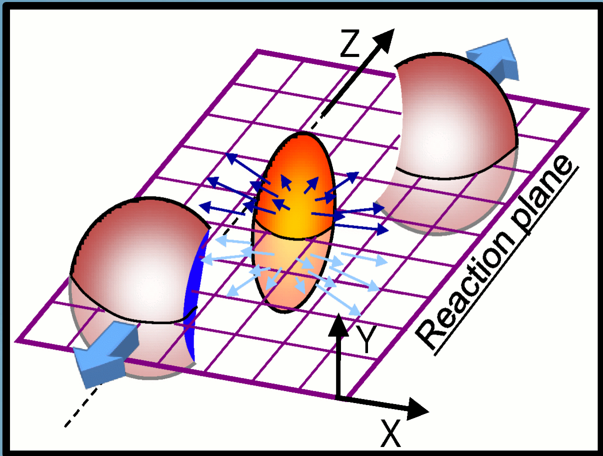




S. Plumari et al., J. Phys.: Conf. Ser. 420 012029 (2013). arXiv:1209.0601.

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

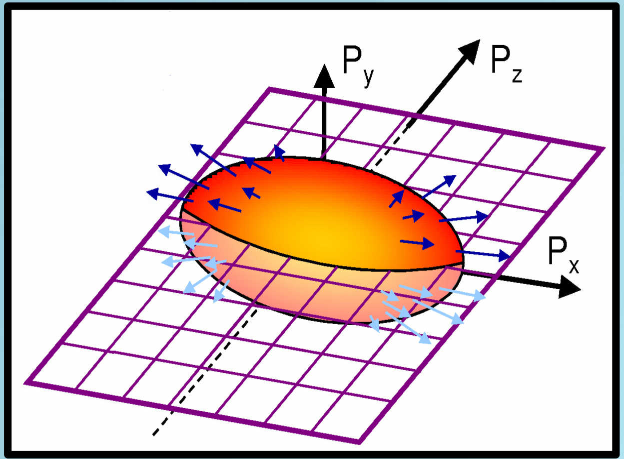
Information from non-equilibrium: elliptic flow



INITIAL OLD VIEW

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

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



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

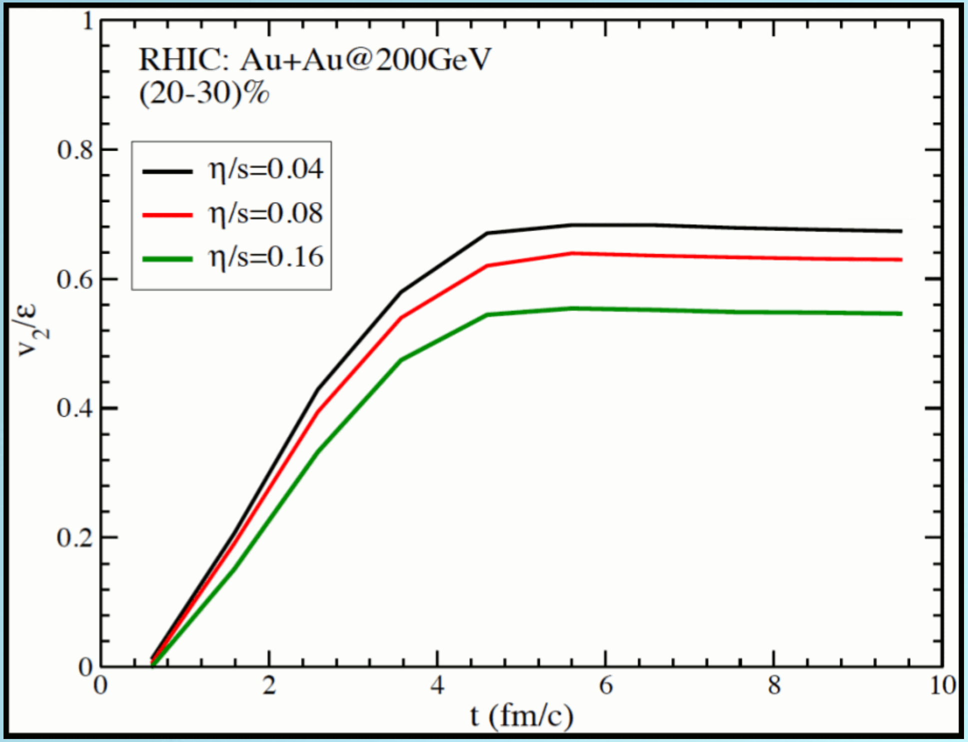
The v_2/ε measures efficiency in converting the eccentricity from Coordinate to Momentum space

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

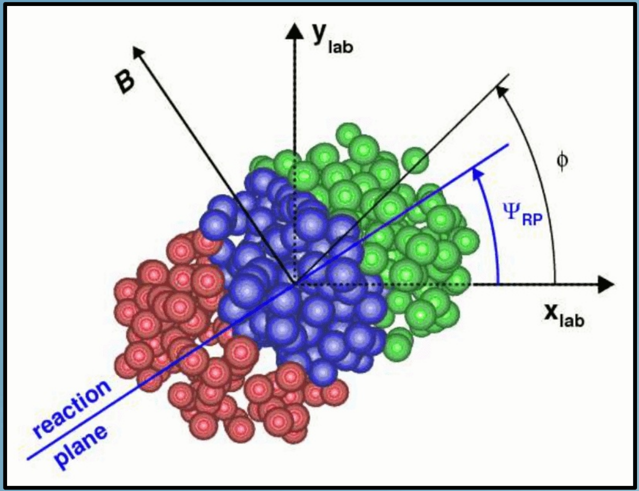
Can be seen also as Fourier expansion

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

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

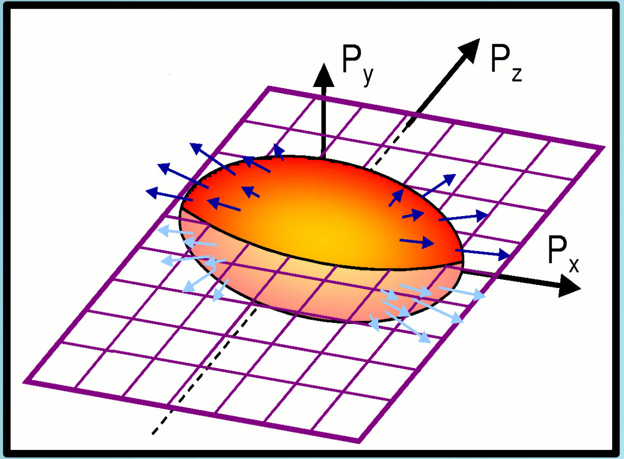


Information from non-equilibrium: $v_n(p_T)$



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

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



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

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

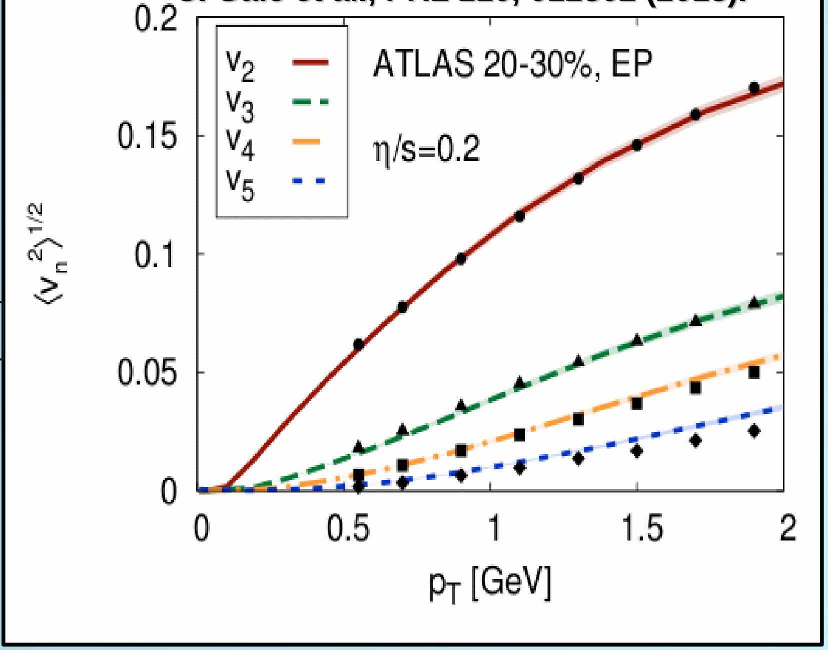
$$\langle v_n\rangle=\langle\cos[n(\varphi-\Psi_n)]\rangle$$

Can be seen also as Fourier expansion

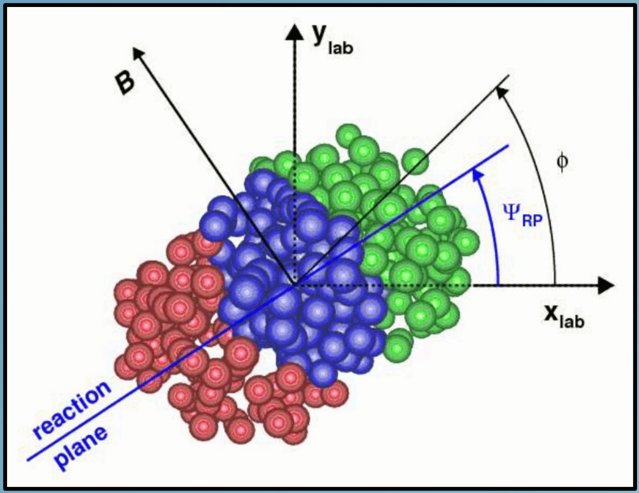
$$E\frac{d^3N}{dp^3}=\frac{d^2N}{2\pi p_T dp_T d\eta}\left[1+2v_2\cos 2(\varphi-\Psi_2)+2v_3\cos 3(\varphi-\Psi_3)+\ldots\right]$$

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

C. Gale et al., PRL 110, 012302 (2013).



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



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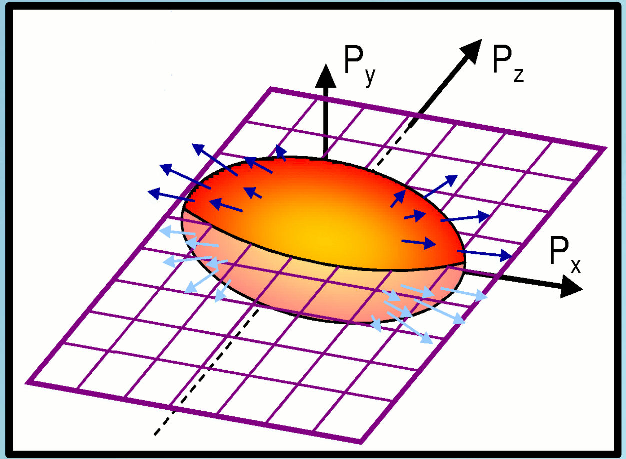

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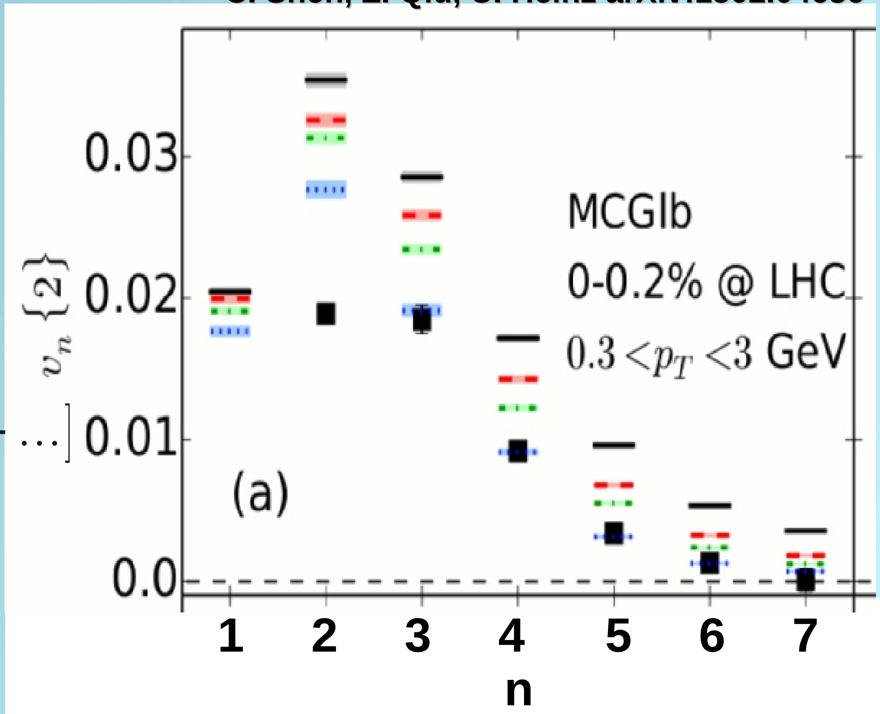
The v_2/ε measures efficiency in converting the eccentricity from Coordinate to Momentum space

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

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



Can be seen also as Fourier expansion

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

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

Motivation for a kinetic approach:

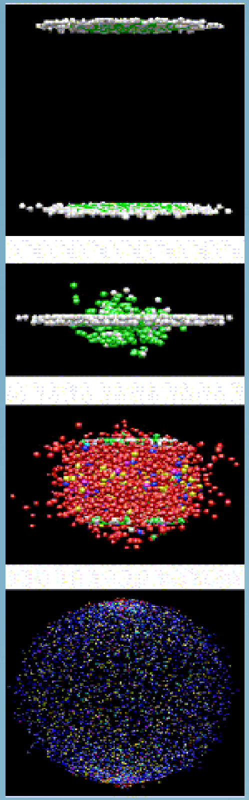
$$\{p^{\mu}\partial_{\mu} + [p_{\nu}F^{\mu\nu} + M\,\partial^{\mu}M]\,\partial_{\mu}^{p}\}\,f(x,p) = S_0 + C_{22} + \ldots$$

Free streaming

Field Interaction → ε≠3P

Souce term: particle creation

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

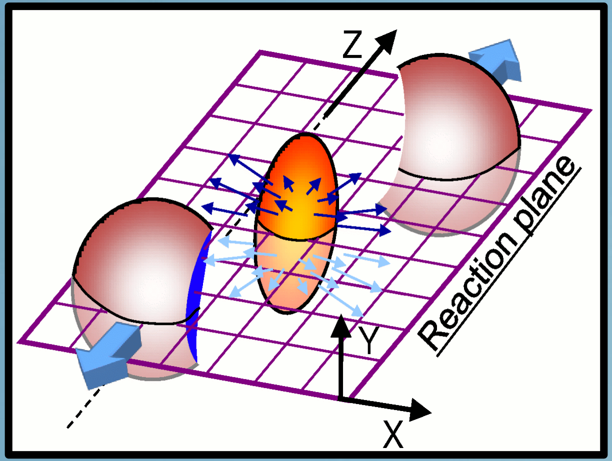
  M. Ruggieri, A. Puglisi, L. Oliva, S. Plumari, F. Scardina, V. Greco PRC 92 (2015) 064904.

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

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

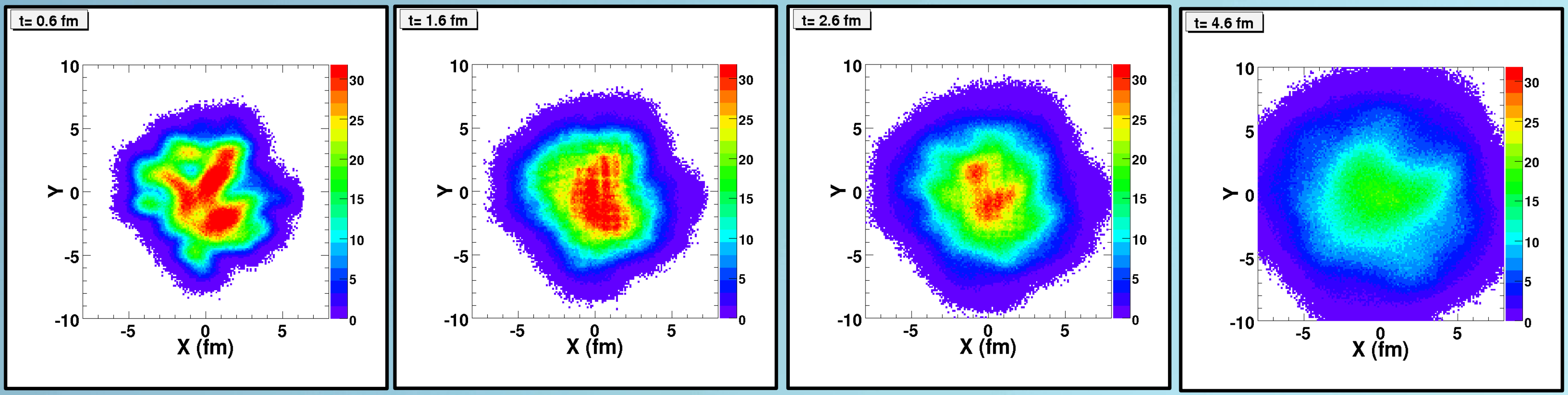
- It is not a gradient expansion in η/s.
- Valid at intermediate p_T out of equilibrium.
- Valid at high η/s (cross over region): + self consistent kinetic freeze-out

Applying kinetic theory to A+A Collisions....

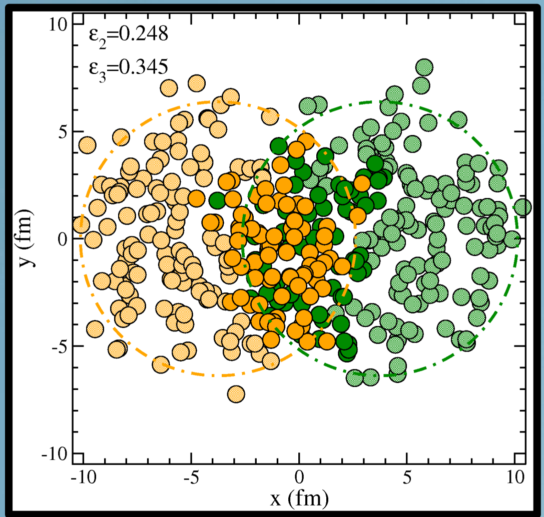


$$\left\{ p^{\mu} \partial_{\mu} + M \partial^{\mu} M \partial_{\mu}^{p} \right\} f(x,p) = C_{22} + \quad \ldots$$

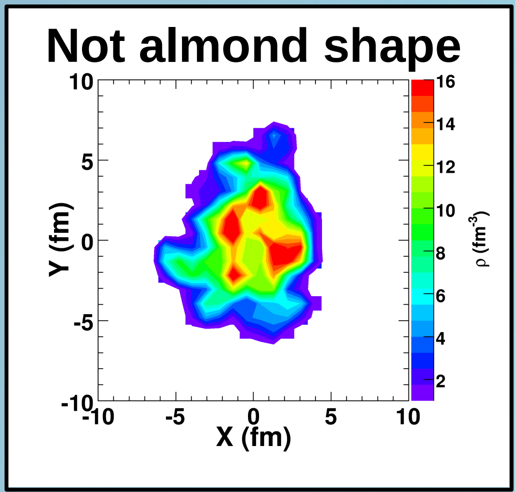
- Impact of $\eta/s(T)$ on the build-up of $v_n(p_T)$ vs. beam energy
- role of EoS on the $v_n(p_T)$
- including the Initial state fluctuations

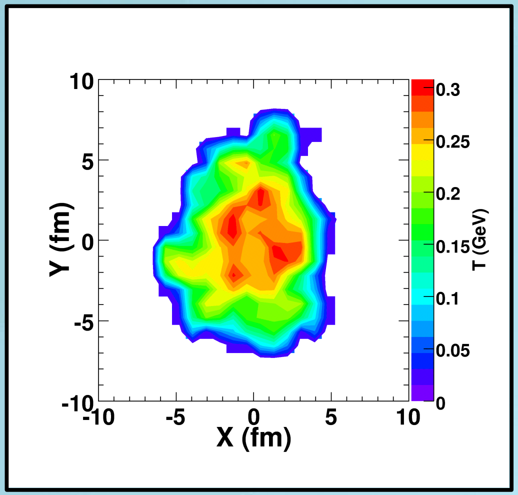


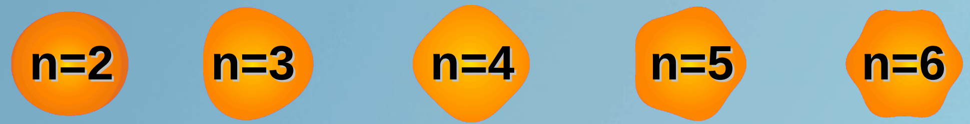
Initial State Fluctuations: Monte Carlo Glauber



smooth distribution



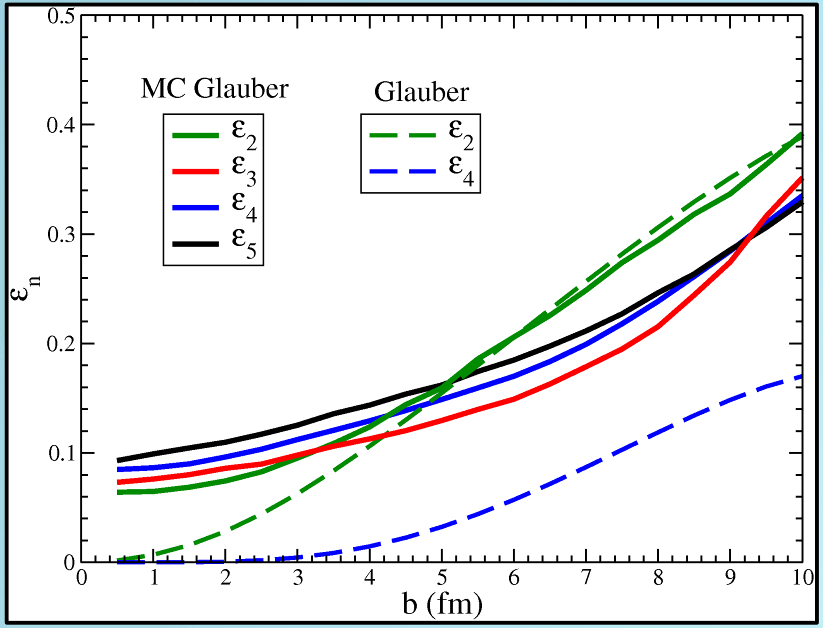




Characterization of the initial profile in terms of Fourier coefficients

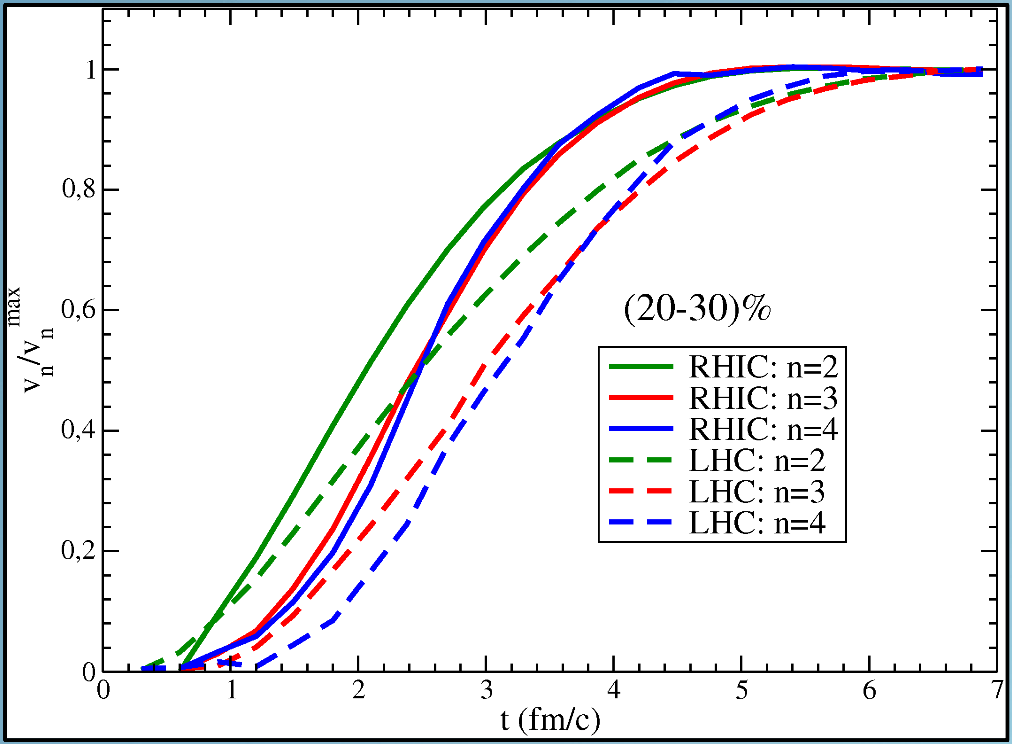
$$\epsilon_n = \frac{\langle r_\perp^n \cos[n(\varphi - \Phi_n)]\rangle}{\langle r_\perp^n \rangle} \qquad \Phi_n = \frac{1}{n}\arctan\frac{\langle r_\perp^n \sin(n\varphi)\rangle}{\langle r_\perp^n \cos(n\varphi)\rangle}$$

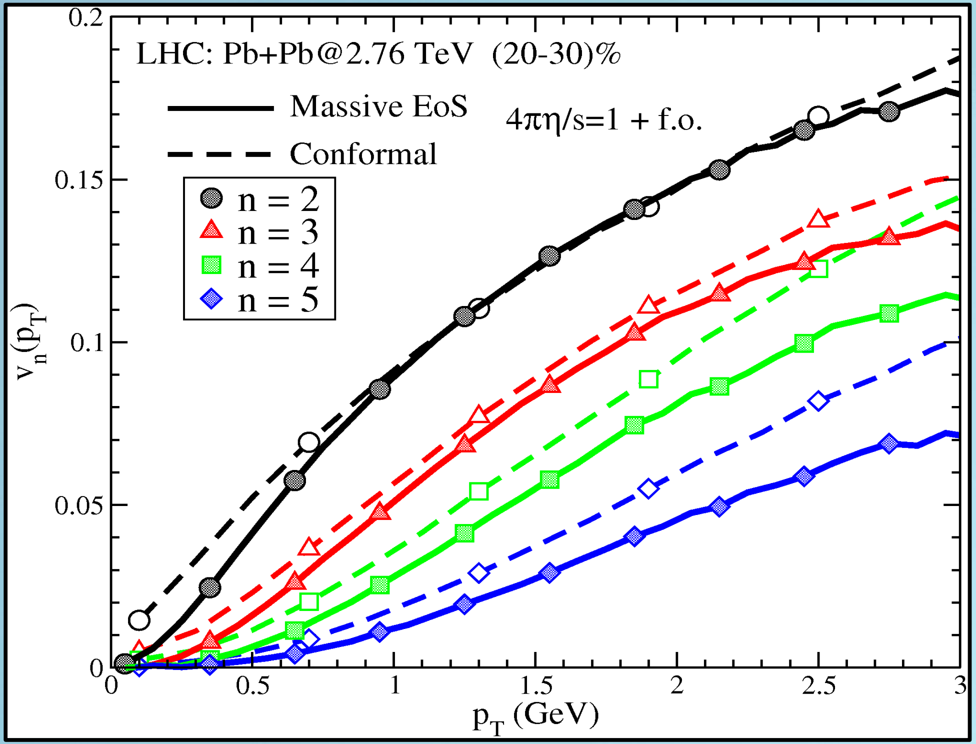
$$r_\perp = \sqrt{x^2 + y^2}, \qquad \varphi = \arctan(y/x)$$

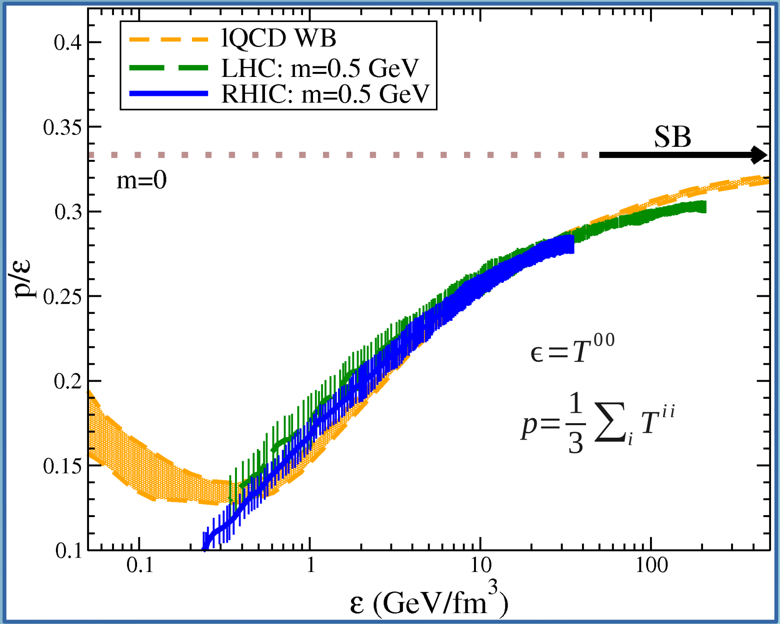


G-Y. Qin, H. Petersen, S.A. Bass and B. Muller, PRC82,064903 (2010).
H.Holopainen, H. Niemi and K.J. Eskola, PRC83, 034901 (2011).

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

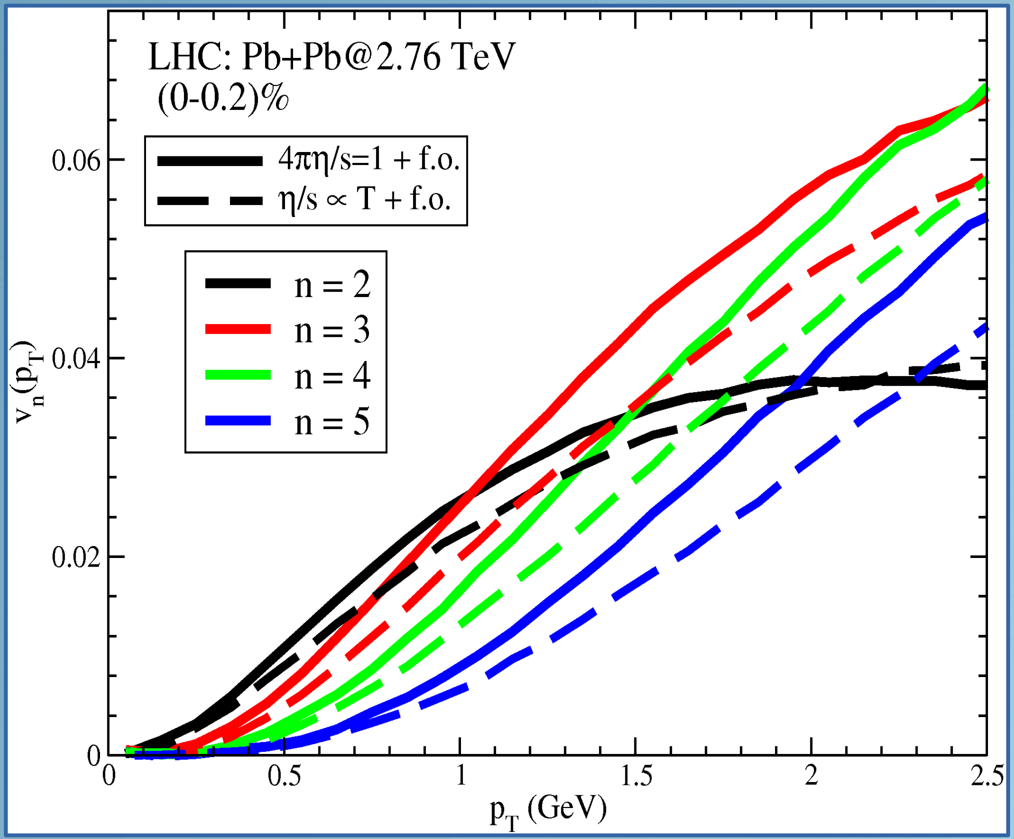


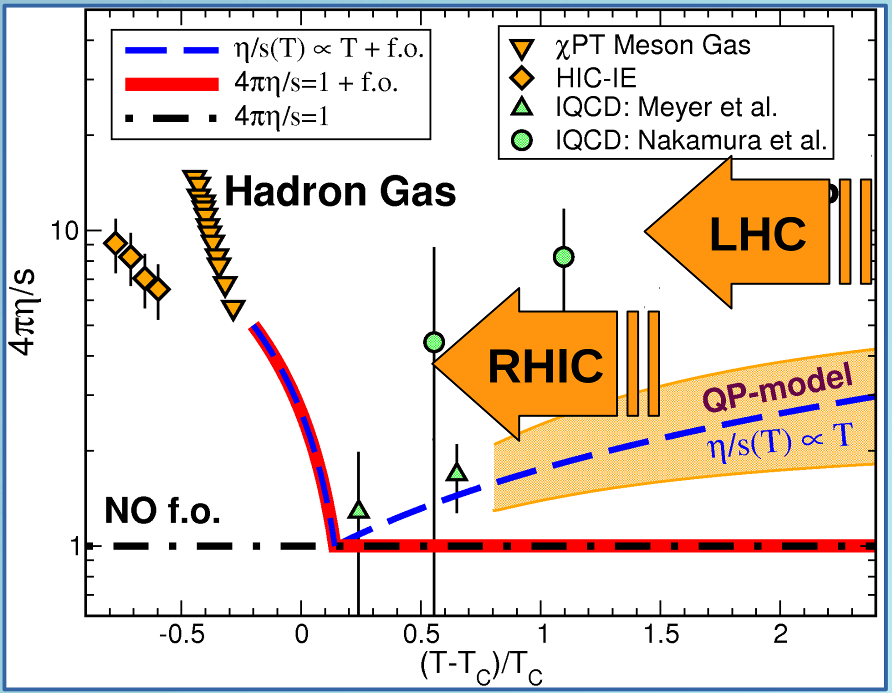


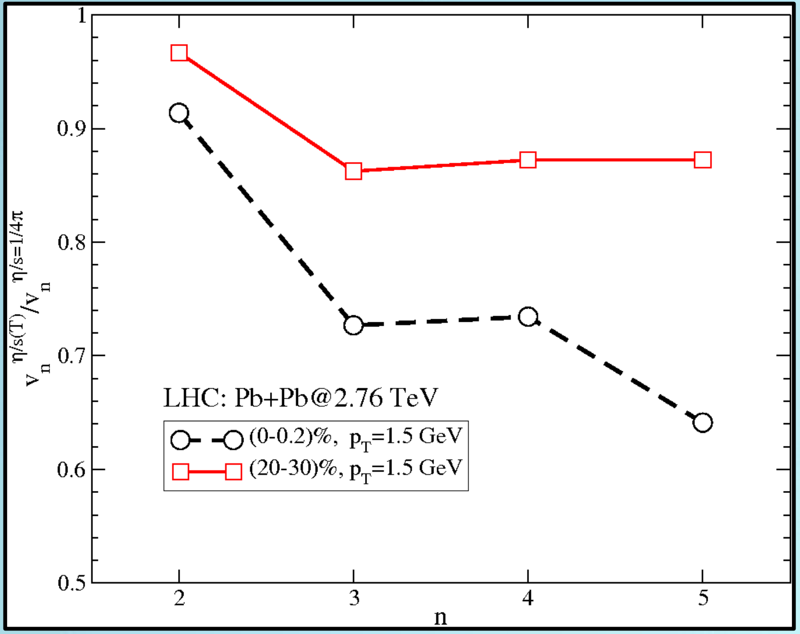


- **For massless case the system is more efficient in converting the initial anisotropy in coordinate space.**
- **The effect of the EoS is to reduce the $<v_n>$.**
- **The elliptic flow show a mass ordering typical of hydro expansion where at low p_T the**
  $v_2(p_T) \propto p_T - <\beta_T> m_T$
-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

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

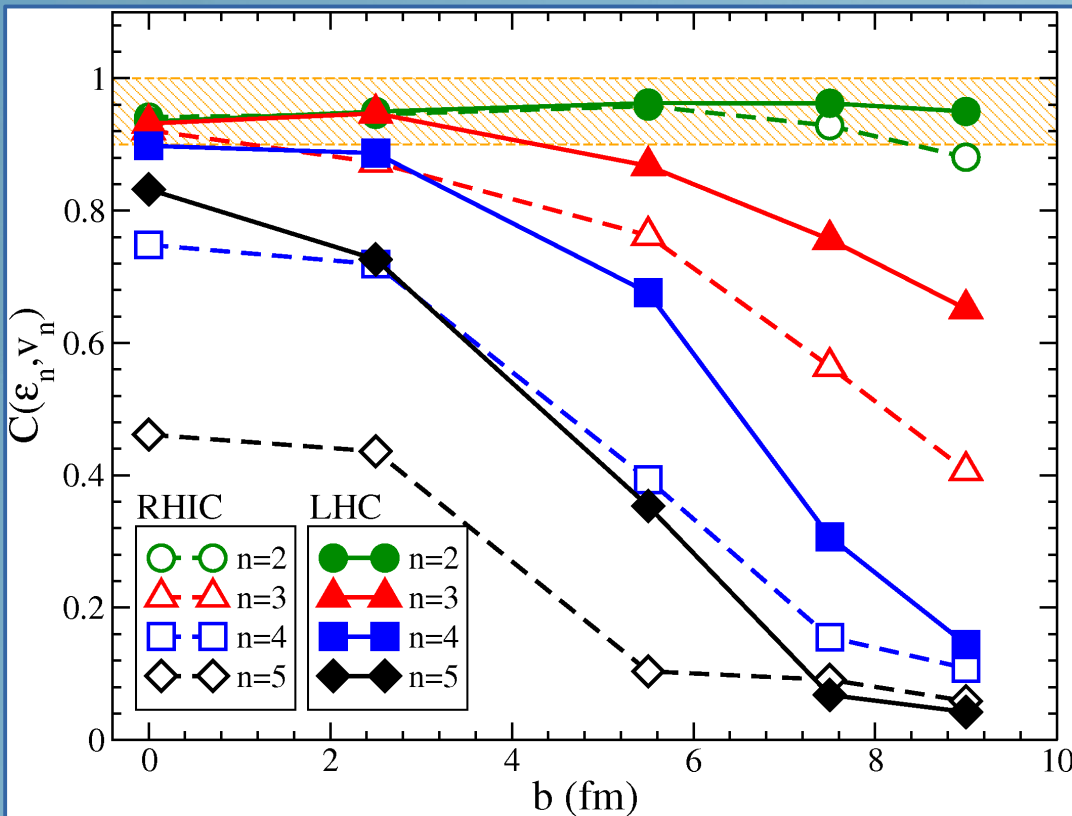




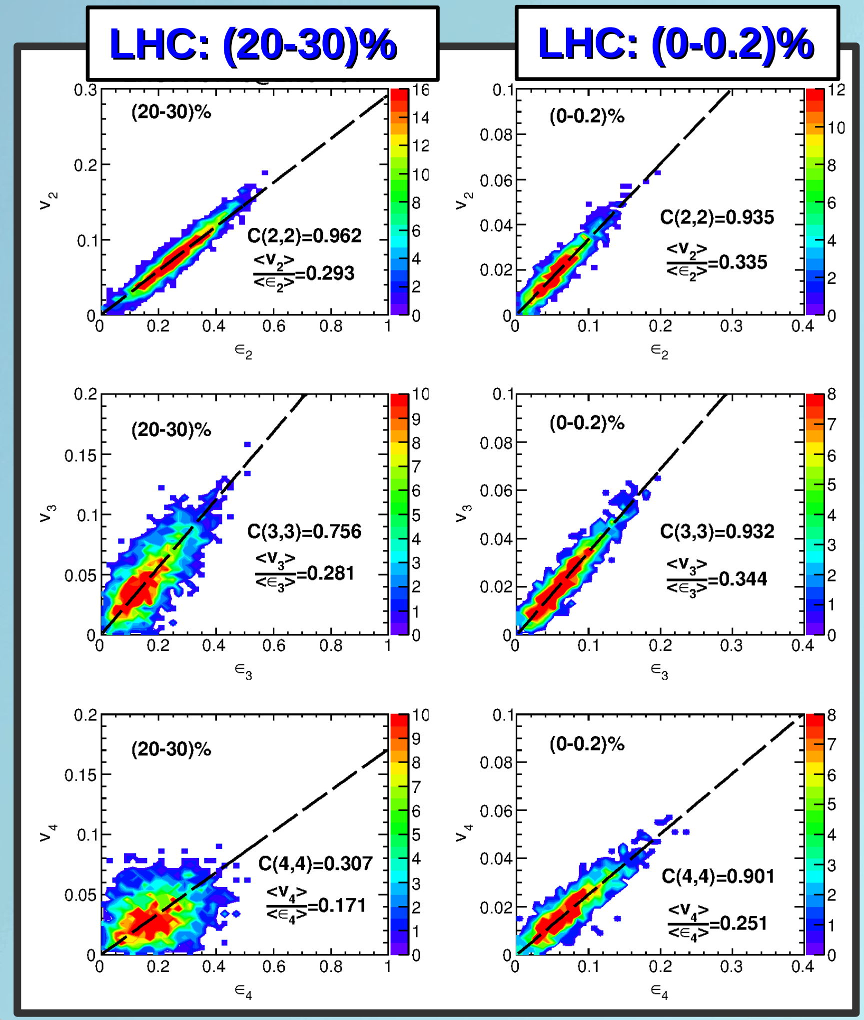


- At low p_T $v_n(p_T) \propto p_T^n$. v_2 for higher p_T saturates while v_n for n>3 increase linearly with p_T.
- For central collisions viscous effect are more relevant. For n>2 the $v_n(p_T)$ are more sensitive to the η/s ratio in the QGP phase.

Initial State Fluctuations: v_n vs ε_n



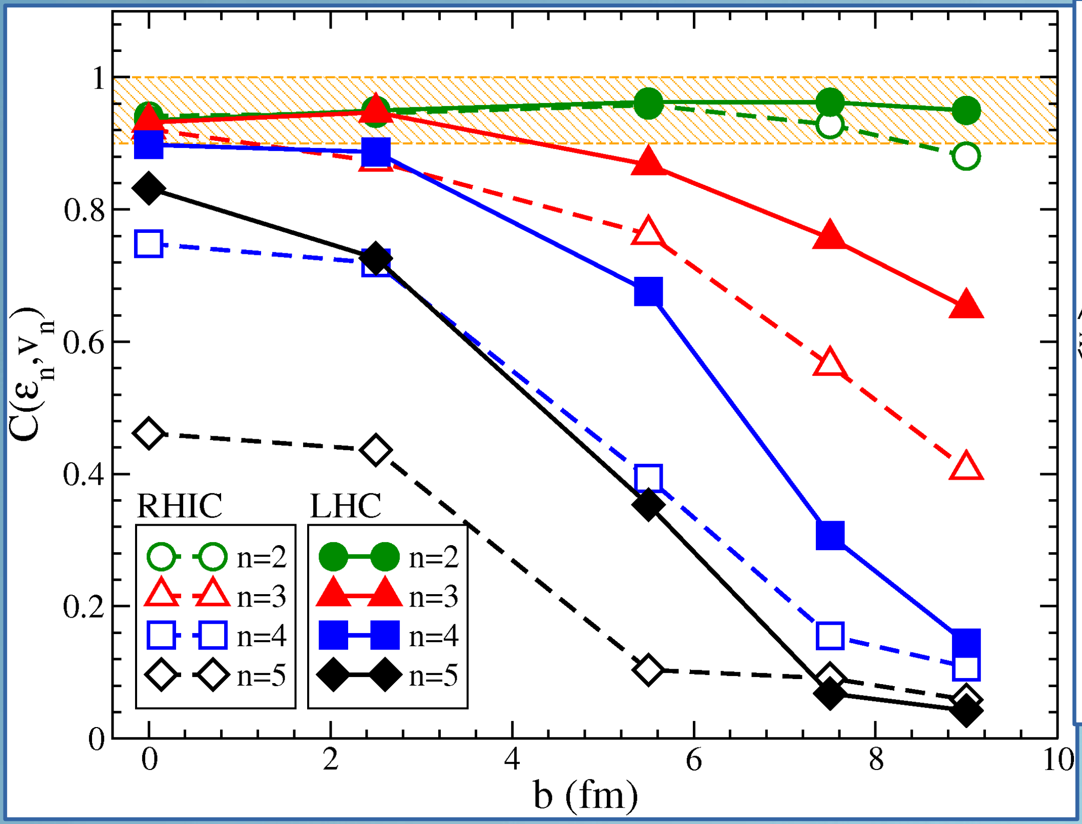
S. Plumari, G. L. Guardo, F. Scardina, V. Greco Phys.Rev. C92 (2015) no.5, 054902.

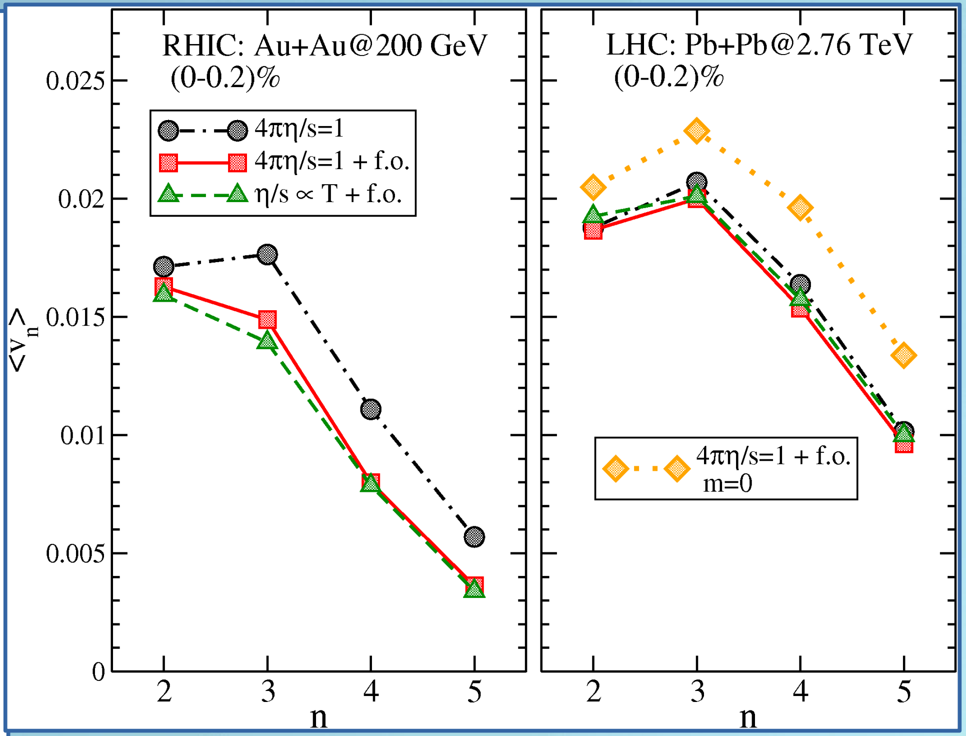


- At LHC v_n are more correlated to ε_n than at RHIC.
- v_2 and v_3 linearly correlated to the corresponding eccentricities ε_2 and ε_3 rispectively.
- C(4,4) < C(2,2) for all centralities. v_4 and ε_4 weak correlated similar to hydro calculations:

  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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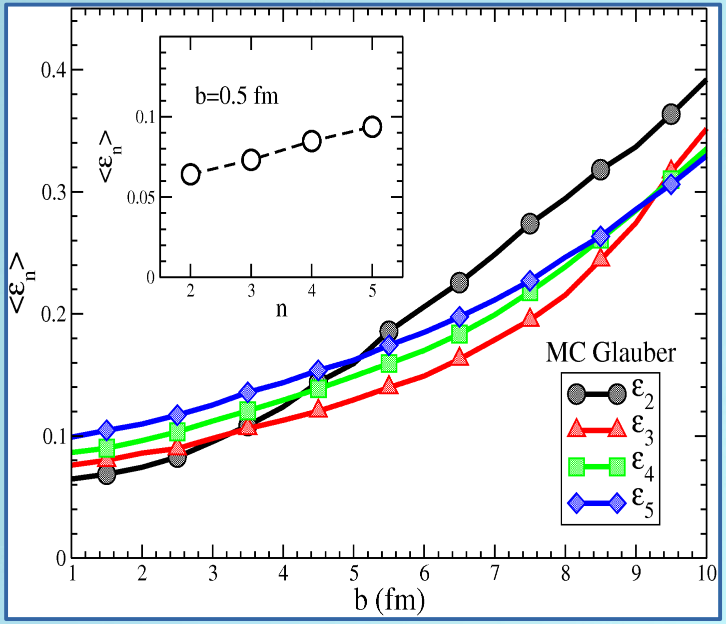
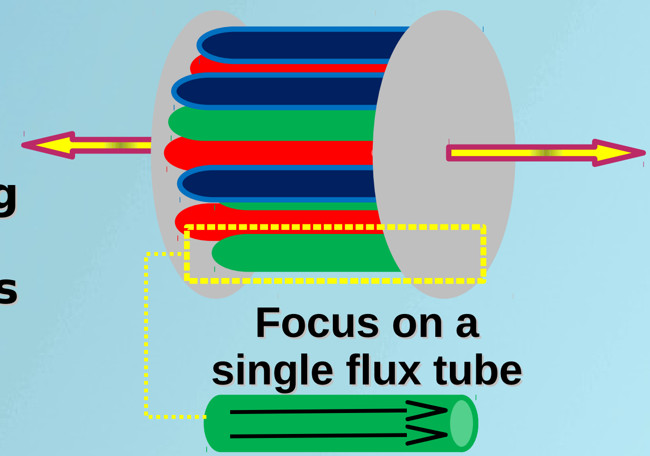


- **Equation of State and collision energy play a role on the build up of $\langle v_n \rangle$ in central collisions. The effect of the EoS is to reduce the final $\langle v_n \rangle$.**
- **At RHIC energies the $\langle v_n \rangle$ are smaller than those LHC and for more realistic $\eta/s(T)$ $v_2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

From fields (Glasma) to particles (QGP)

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

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

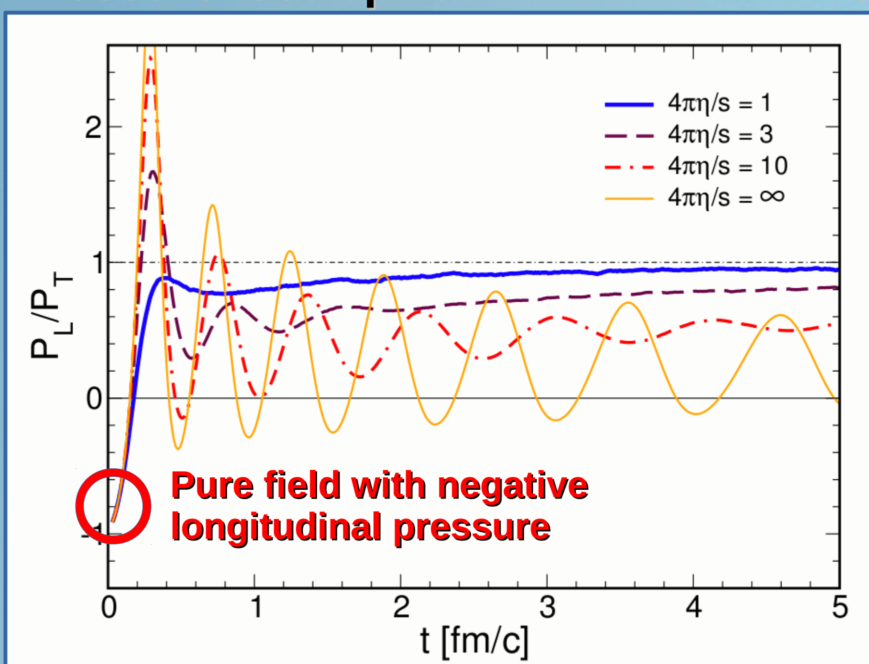


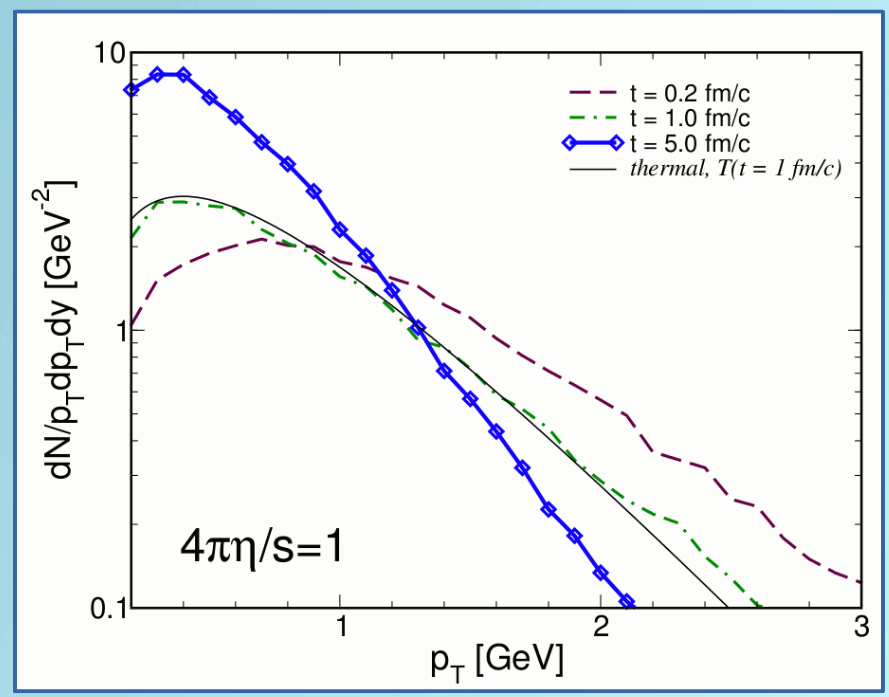
SCHWINGER MECHANISM

Classical fields decay to particles pairs via tunneling due to vacuum instability.
Longitudinal Chromo-Electric fields decay in gluon pairs and quark-antiquark pairs.

For 4πη/s=1:

- Fast thermalization in about 1 fm/c
- Pressure isotropization in about 1 fm/c





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 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 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 $(\varepsilon_n, \varepsilon_m)$

- **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

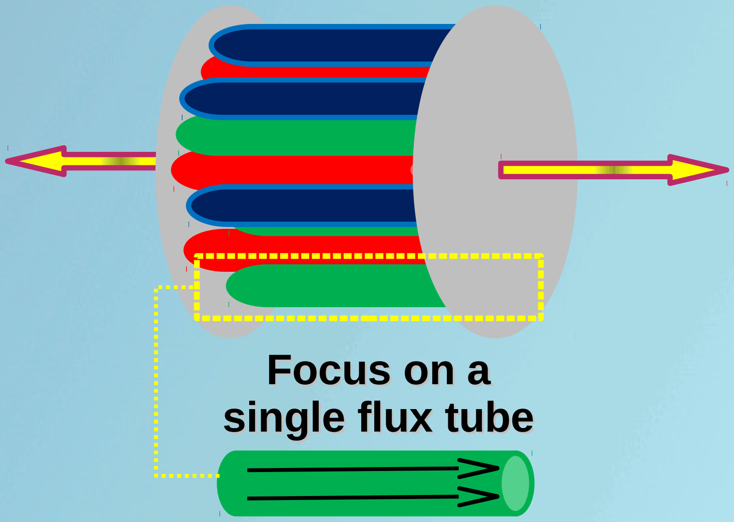
From fields (Glasma) to particles (QGP): (1+1D evolution)

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

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

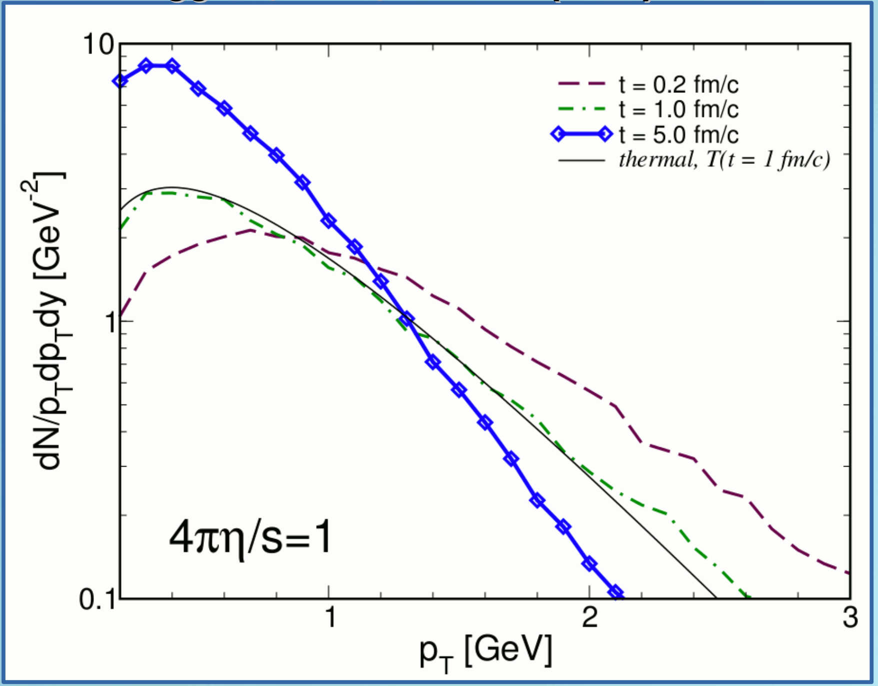
Casher, Neuberger and Nussinov, PRD 20, 179 (1979)
Glendenning and Matsui, PRD 28, 2890 (1983)

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.



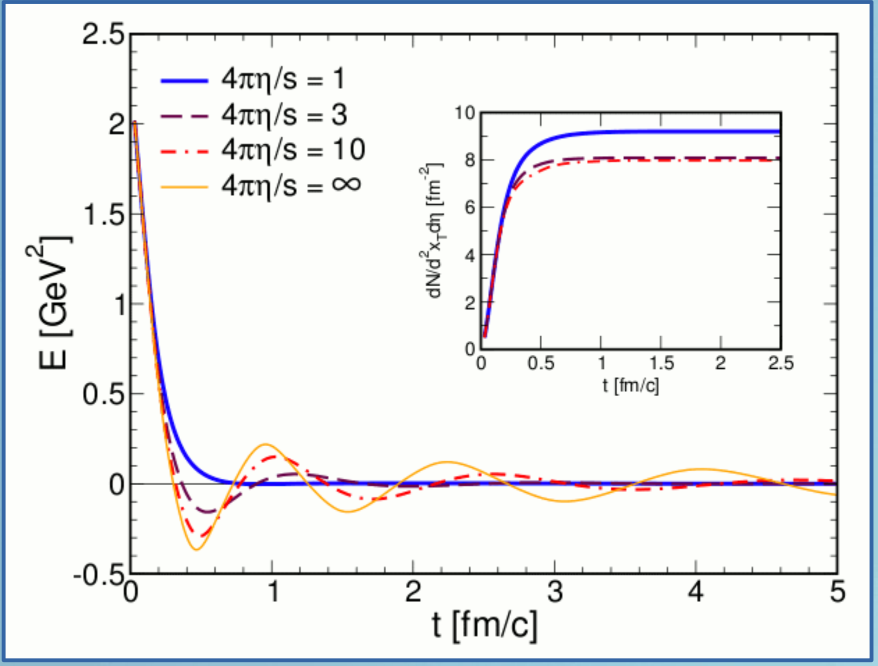
1+1 D expansion

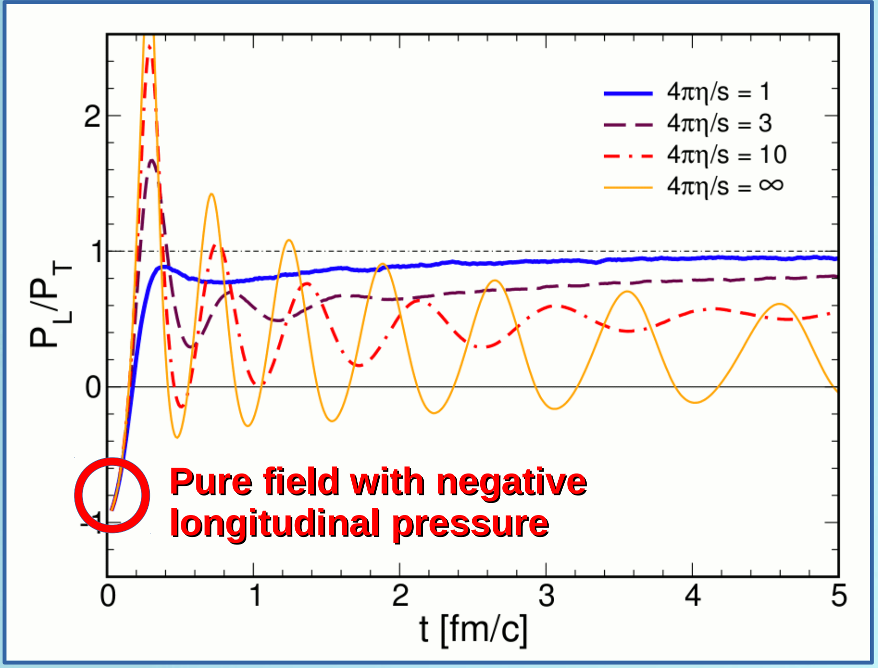
For $4\pi\eta/s=1$:

- **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:

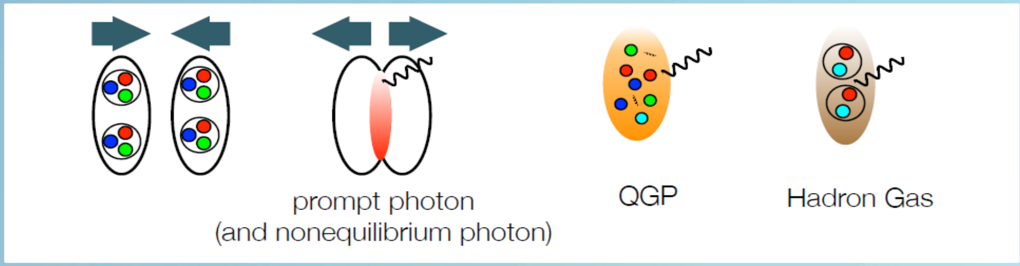
- **Field decays faster in about 0.5 fm/c and for t > 0.5 fm/c plasma oscillations**
- **Particle spectra different from a thermal one**
- **Less efficient isotropization**





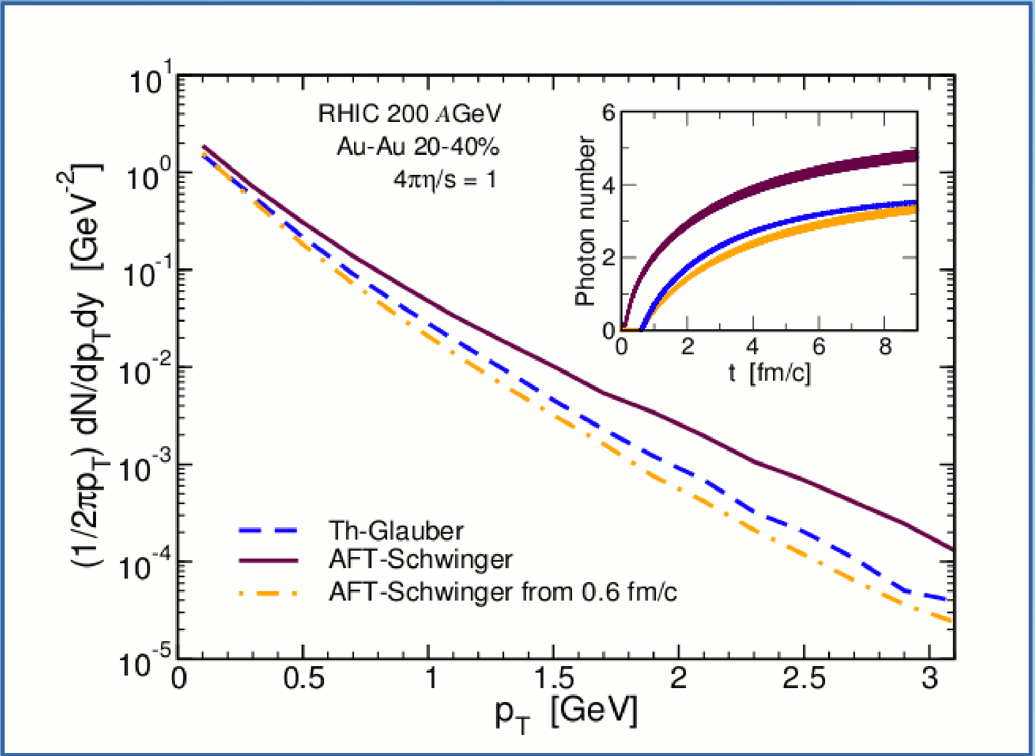
From Glasma to Quark Gluon Plasma: (3+1D evolution)

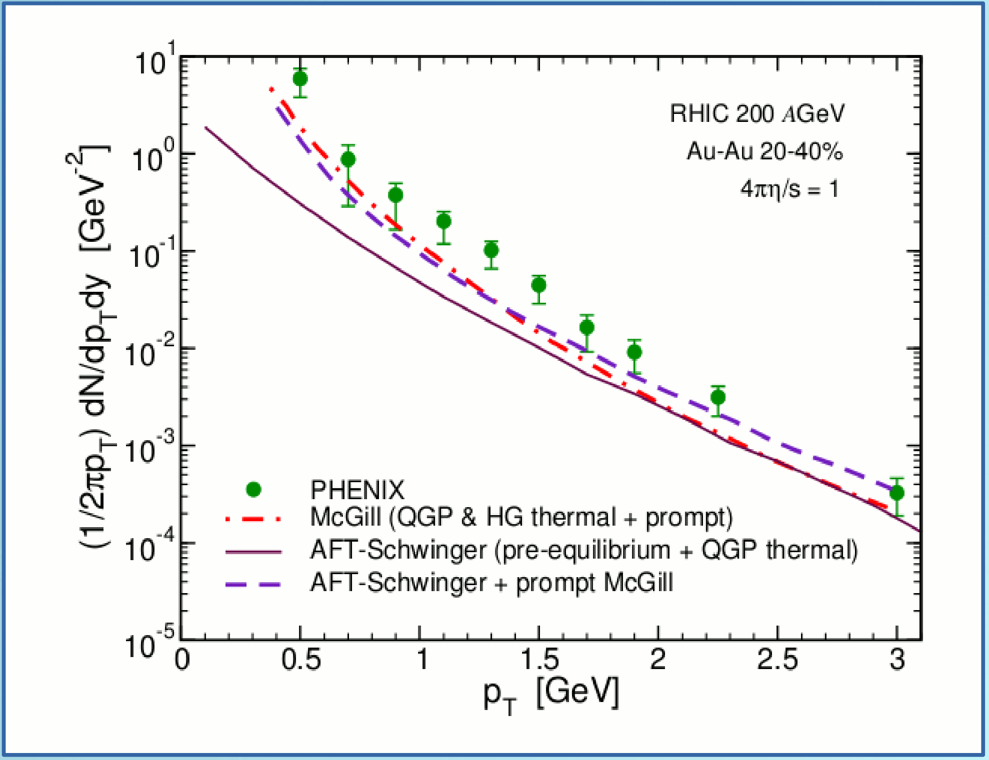
Electromagnetic probes are an efficient tool to investigate the initial state of heavy ion collisions and the properties of quark-gluon plasma.



- **Schwinger simulations take into account of pre-equilibrium effects: Total photon number enhanced of 30% mainly at high pT**

Theoretical models can be used to identify these sources and their relative importance in the spectrum





Boltzmann Transport Equation

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

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

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

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

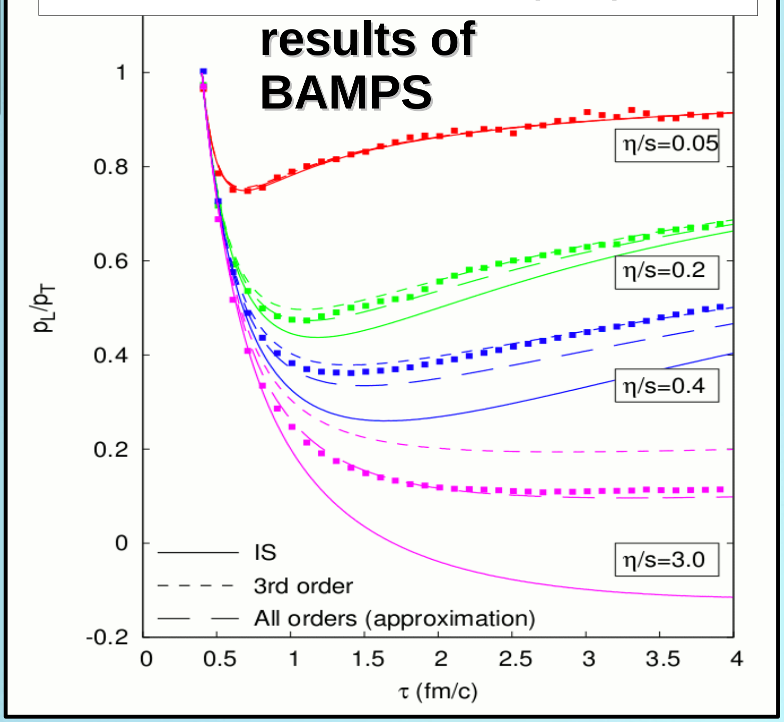
(Z. Xu and C. Greiner, PRC 71 064901 (2005))

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

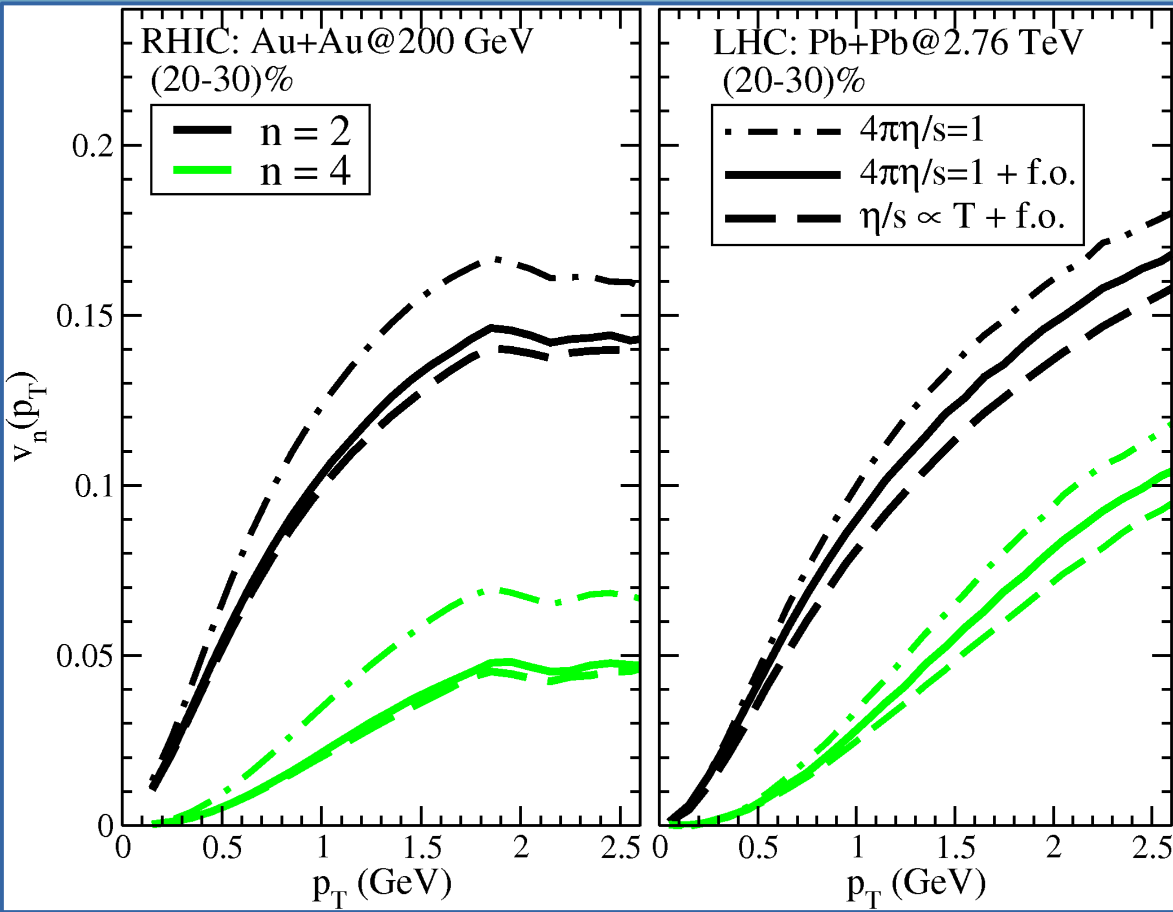
σ is evaluated in such way to keep fixed the η/s during the dynamics according the Chapman-Enskog equation.
(similar to D. Molnar, arXiv:0806.0026[nucl-th])

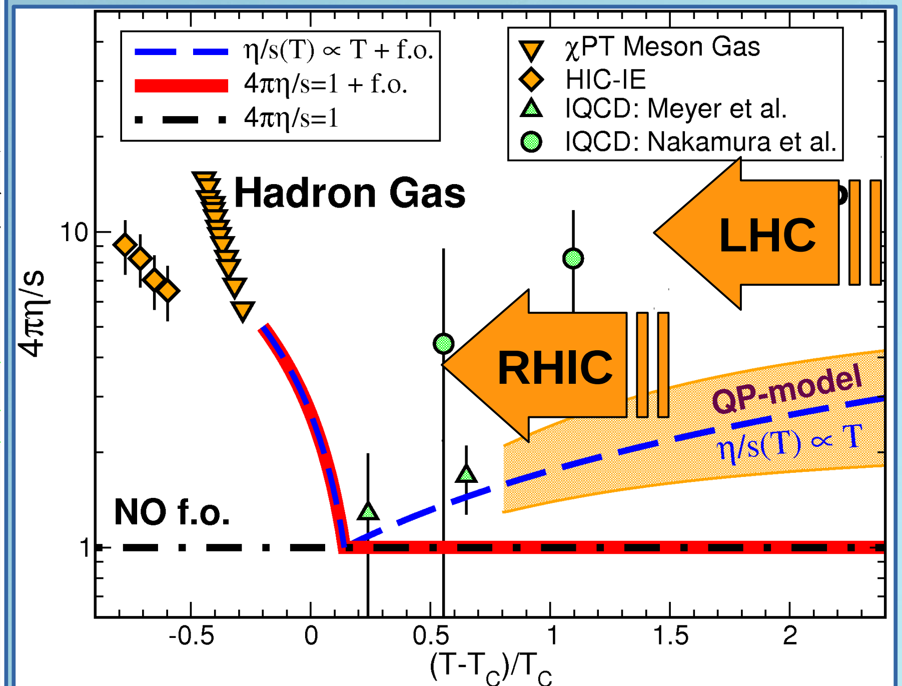
- **We know how to fix locally η/s(T)**
- **We have checked the Chapmann-Enskog (CE):**
  - **CE good already at 1st order ≈ *5%***
  - **Relaxation Time Approx. severely understimates η**
    S. Plumari et al.,PRC86 (2012) 054902.

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



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).

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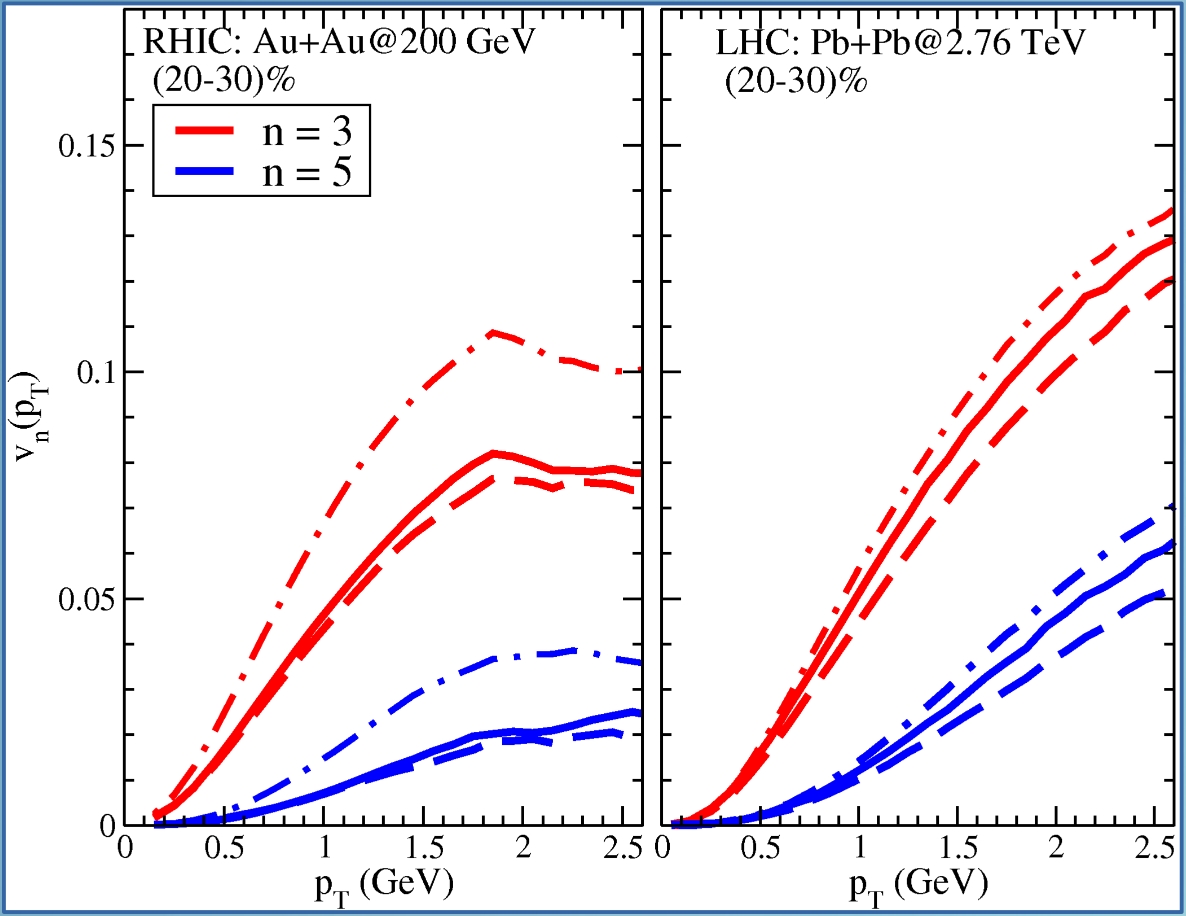

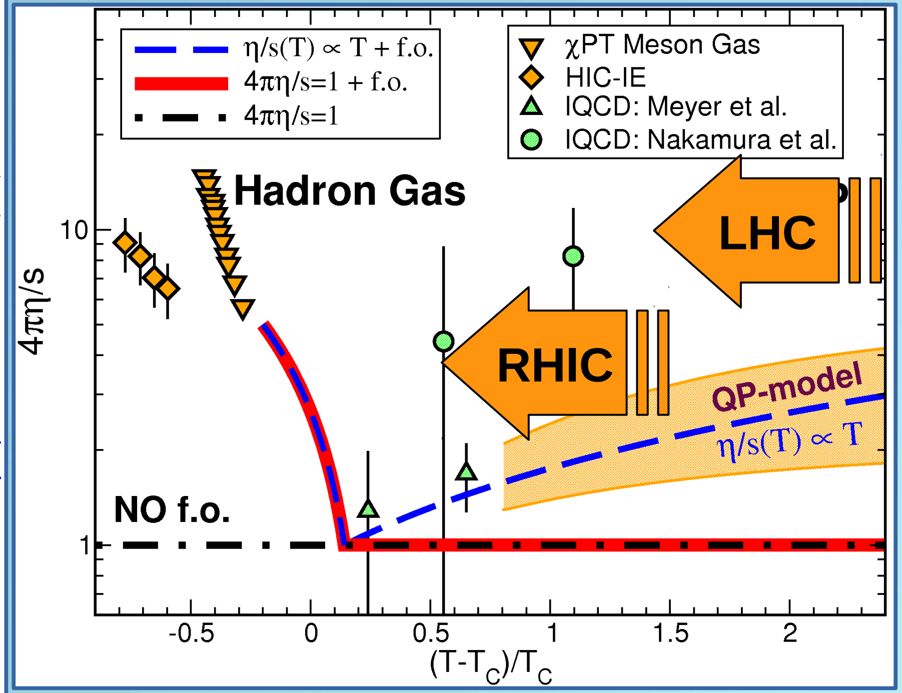

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