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Theoretical Overview of Initial State and Flow Physics

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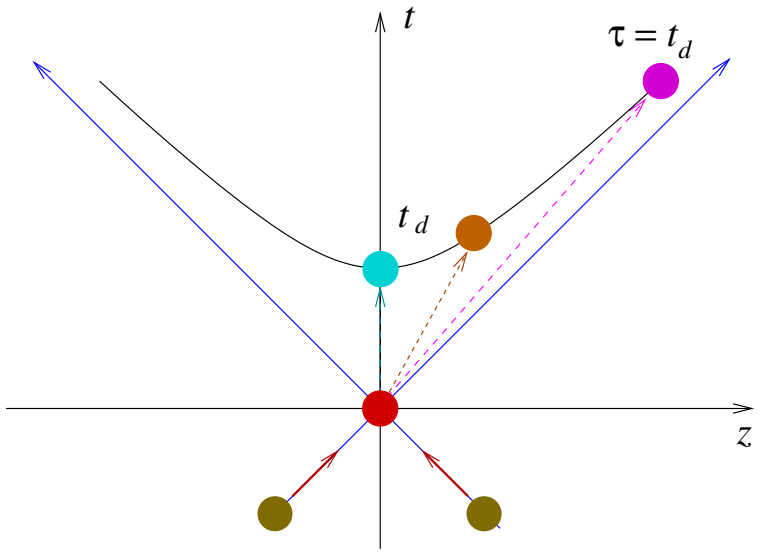
The issue of the day

$$T^{\mu\nu}(0) \Longrightarrow T^{\mu\nu}_{\rm id}(\tau_0) + \pi^{\mu\nu}(\tau_0)$$

- What do we have at $\tau = 0$?
  [Talks: R. Fries, G. Jackson, J. Casalderrey-Solana]
- What happens between $\tau = 0$ and $\tau = \tau_0$?
  [Talks: T. Epelbaum, W. Cassing]
- Is $T^{\mu\nu}(\tau_0)$ equilibrium or non-equilibrium?
  - If non-equilibrium, how big is $\pi^{\mu\nu}(\tau_0)$ and what effect does it have?
    [Talks: G. Vujanovic]
- Initial-condition-sensitive observables?
  [Talks: C. Shen, A. Kovner, M. Lubinsky, F. Scardina, R. Paatelainen, R. Vogt]
- Jet + Hydro?
  [Y. Tachibana]

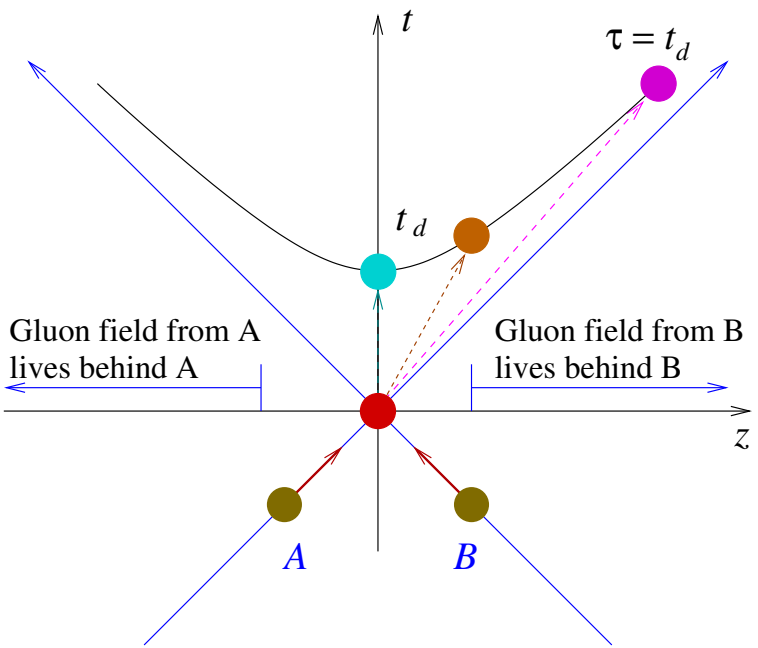
Initial condition in τ

- Why τ? – Time dilation



  - If the three fireballs all start out from $t = 0, z = 0$ and evolve exactly the same way (e.g. thermalization), the state of the cyan at $t = t_d$ is the same as the state of the brown and magenta at $\tau = t_d$
  - Appropriate "time" variable
    - Relativistic case: $\tau = \sqrt{t^2 - z^2} = t\sqrt{1 - v_z^2}$ is the most natural time variable – Local time at z
    - Non-relativistic case: $z = v_z t \ll t \implies t$ is the the most natural time variable.

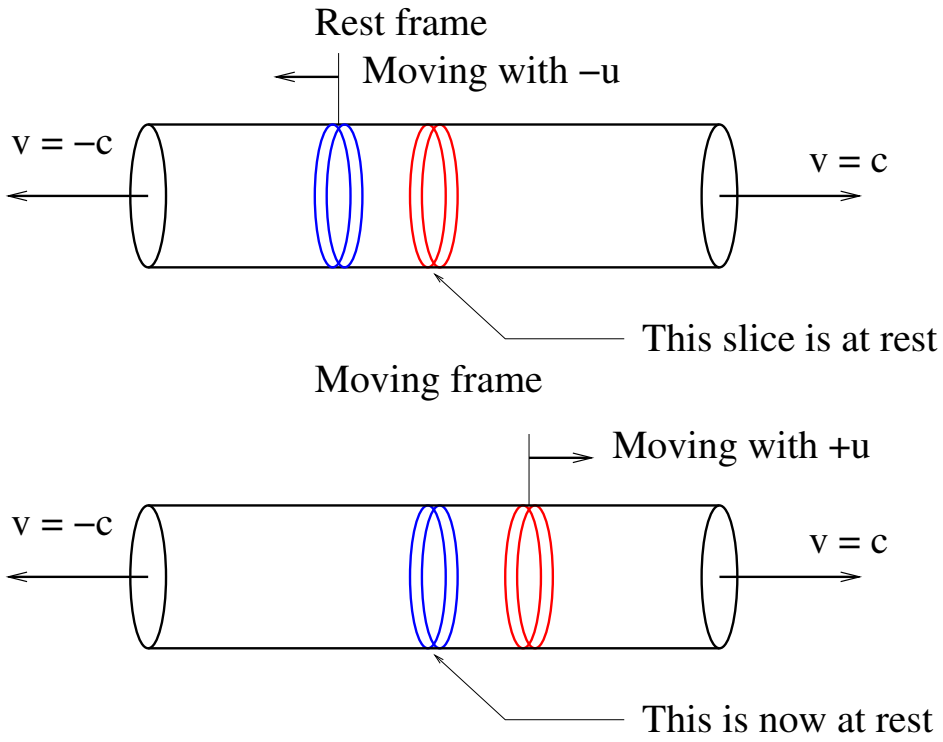
What do we know about $\tau = 0$?



- $t = 0, z = 0$: It is the "little-bang singularity".
- $t = |z|$: Transition line between the gluon field from individual nuclei (CGC, $t < |z|$) and the gluon field after the collision (Glasma, $t > |z|$)
- If the cyan, brown and the magenta fireballs starts out from $t = 0, z = 0$ with exactly the same at-rest conditions $\Longrightarrow$ Strong $\Delta\eta$ correlation
- Current formulation limited to $\sqrt{s} = \infty$, or the boost-invariant system

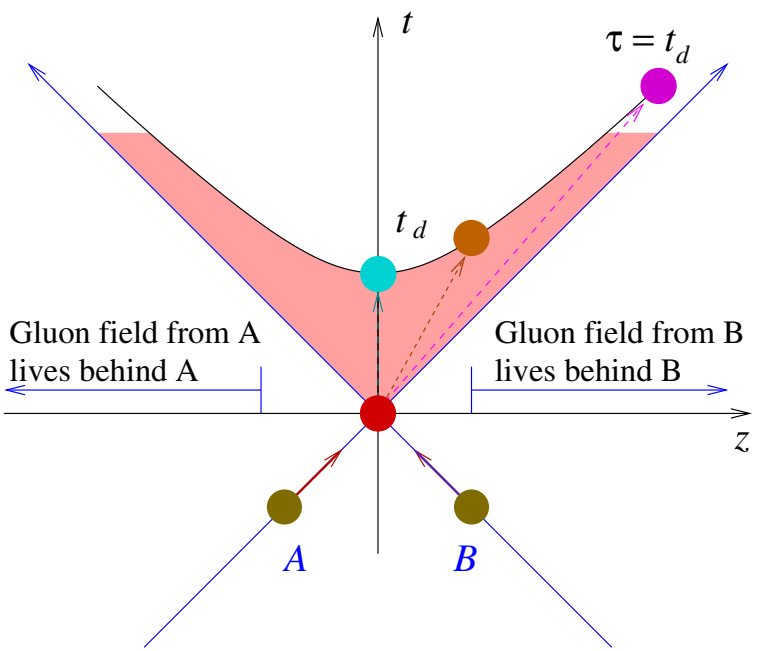
Boost invariance

- Idealized physical picture: Two infinitely energetic ($v = c$) pancakes pulling away from each other leaving energies behind:



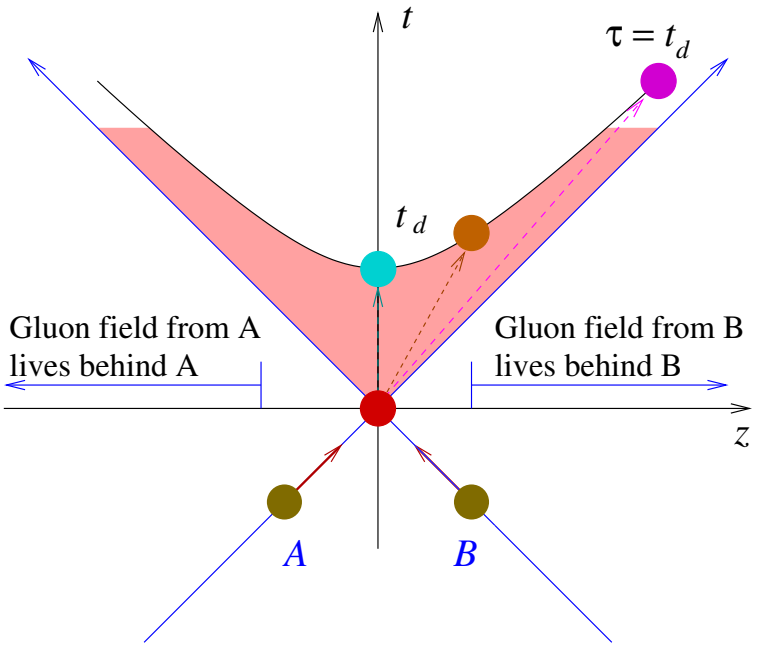
- In both frames, the system size $= 2ct$ at the local time t
- If the boundary condition decides the dynamics $\Longrightarrow$ Can't distinguish them $\Longrightarrow$ Boost invariance

What happens in $0 \leq \tau \leq \tau_0$?



- Thermalization, Hydrodynamization, Isotropization, Equilibration, ...
- What does that actually mean?

What happens in $0 \leq \tau \leq \tau_0$?



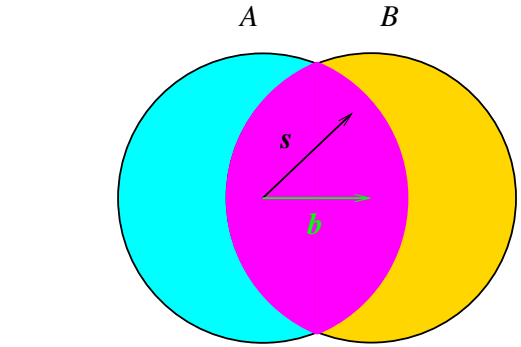
- $T^{\mu\alpha}(\tau_0) g_{\alpha\beta} u_0^{\beta} = \epsilon_0 u_0^{\mu}$: Always possible.
- Thermalization: EoS: $p_0 = p(\epsilon_0)$
  - Needed for $T^{\mu\nu}_{\rm id}(\tau_0) = (\epsilon_0 + p_0) u_0^{\mu} u_0^{\nu} - p_0 g^{\mu\nu}$
  - Equilibrium concept: Local equilibrium at τ_0?
- $\pi^{\mu\nu}(\tau_0) = T^{\mu\nu}(\tau_0) - T^{\mu\nu}_{\rm id}(\tau_0)$
- $\pi^{\mu\nu}(\tau_0)$ is *not* $\eta \nabla^{(\mu} u^{\nu)} + \zeta \Delta^{\mu\nu} \nabla_{\alpha} u^{\alpha}$
- What is $\pi^{\mu\nu}(\tau_0)$?
  - Hydro is agnostic about this
  - How big is too big?
  - Need microscopic models for $0 \leq \tau \leq \tau_0$ – From particles to $T^{\mu\nu}$?

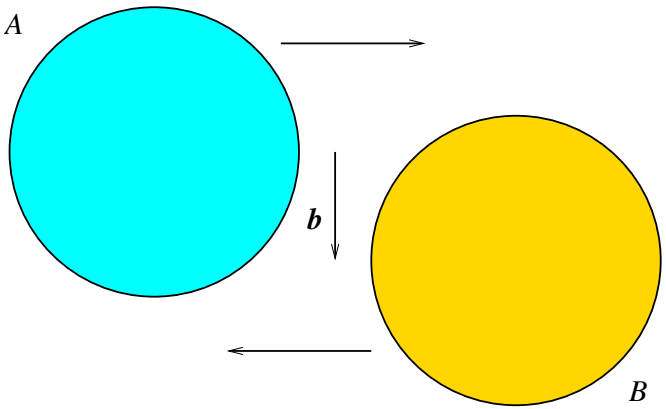
Initial State Models

- Optical Glauber
- MC-Glauber
- MC-KLN
- MC-rcBK
- IP-Glasma
- AMPT
- EPOS (NEXUS)

Smooth (or Average) Initial Conditions

Optical Glauber



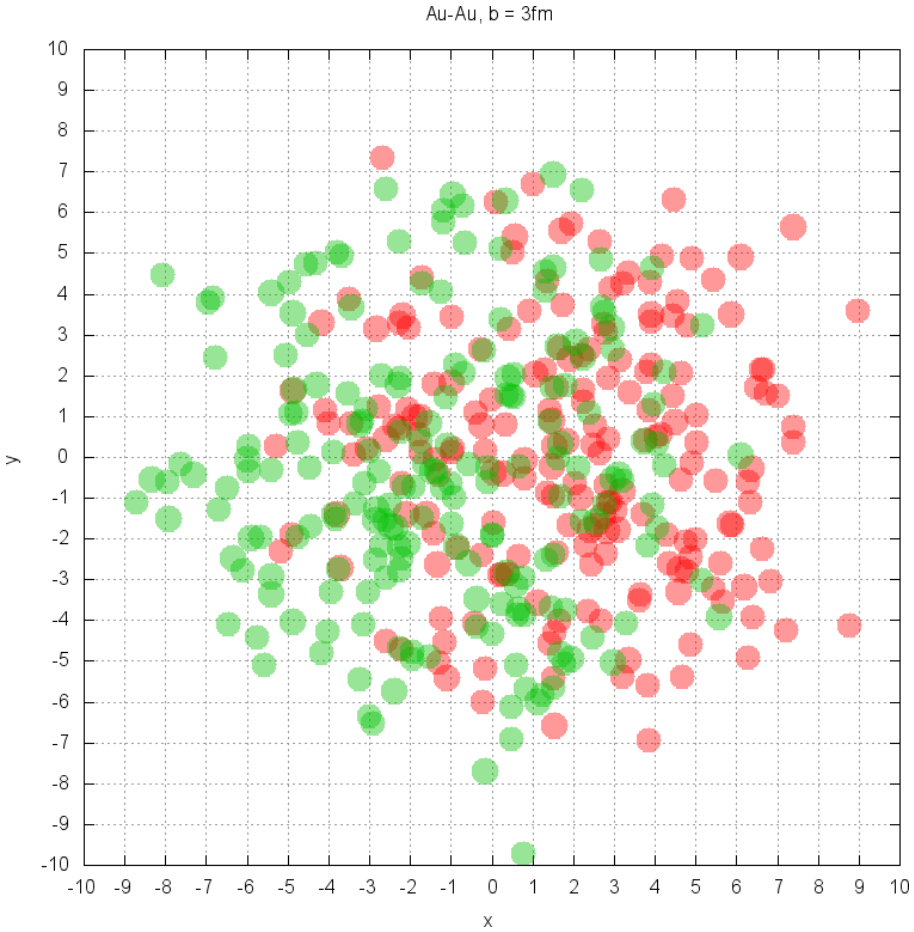


- Thickness functions: $T_{A,B}(\mathbf{s}) = \int_{-\infty}^{\infty} dz\, \rho_{A,B}(z, \mathbf{s})$
- Overlap function: $T_{AB}(\mathbf{b}) = \int d^2s\, T_A(\mathbf{s}) T_B(\mathbf{s} - \mathbf{b})$
- Number of collisions: $N_{\rm coll}(\mathbf{b}) = ABT_{AB}(\mathbf{b})\sigma_{\rm inel}^{\rm NN}$
- Number of participants:

$$N_{\rm part}(\mathbf{b}) = A \int d^2s\, T_A(\mathbf{s}) \left(1 - \left[1 - T_B(\mathbf{s} - \mathbf{b})\sigma_{\rm inel}^{\rm NN}\right]^B\right) + B \int d^2s\, T_B(\mathbf{s} - \mathbf{b}) \left(1 - \left[1 - T_A(\mathbf{s})\sigma_{\rm inel}^{\rm NN}\right]^A\right)$$

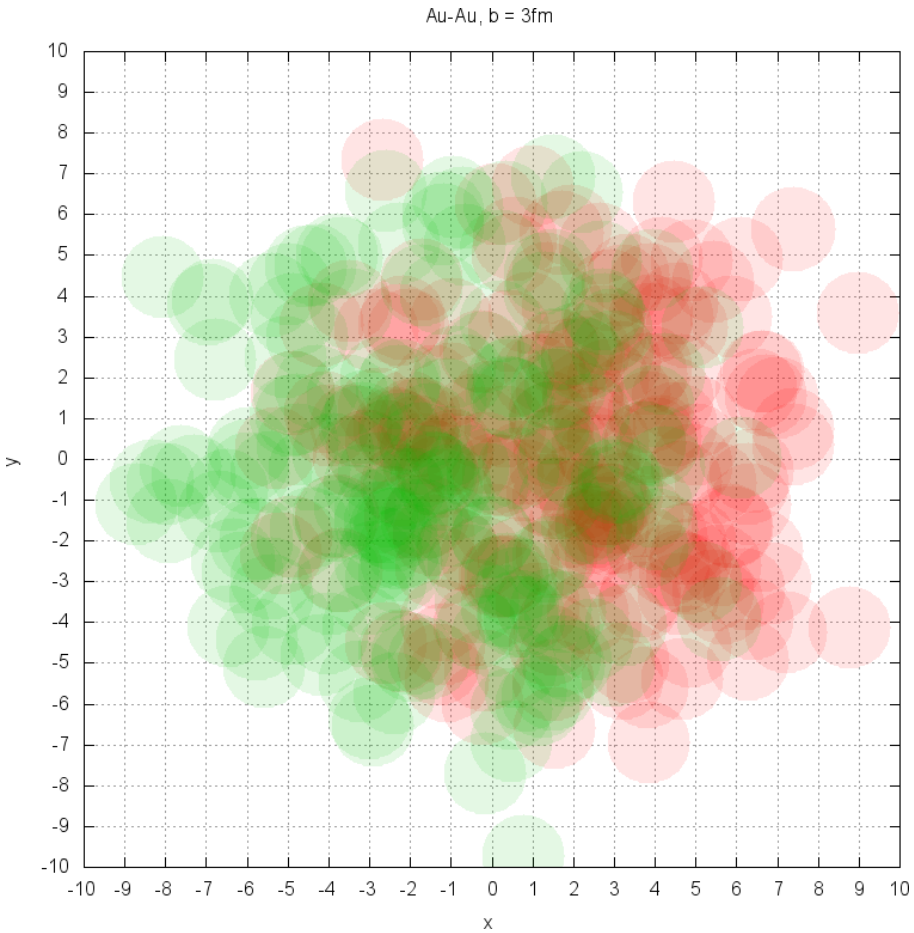
- Smooth distribution $\Longrightarrow$ No fluctuations.
  No $\epsilon_{\rm odd}$ nor $v_{\rm odd}$

Fluctuating Initial Conditions



1. Sample nucleon positions

Fluctuating Initial Conditions



1. Sample nucleon positions
2. Decide what collides with what
3. Decide how much energy is deposited
4. Calculate the energy density in the hydro cells

MC-Glauber

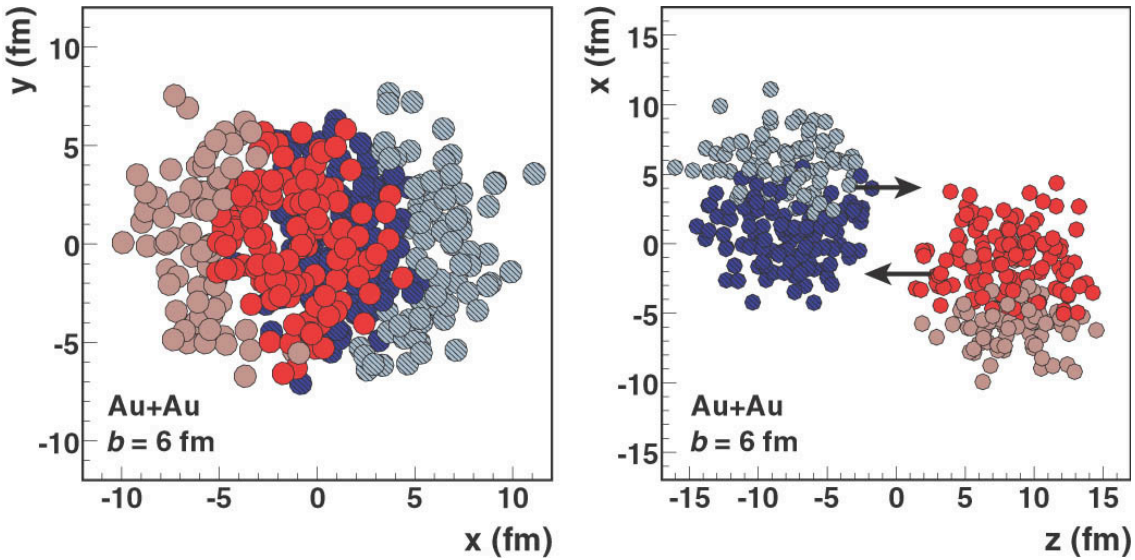
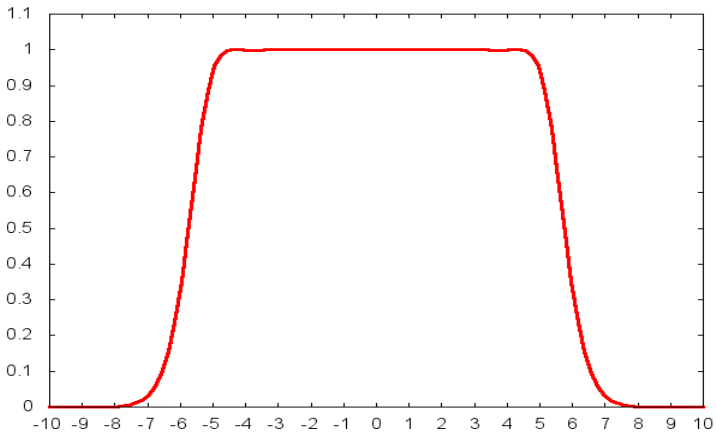


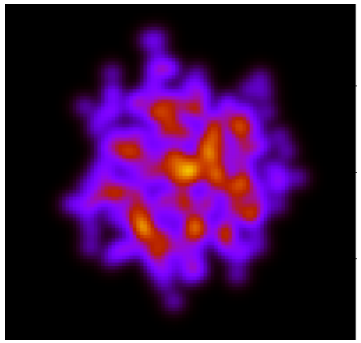
Figure from [Miller, Reygers, Sanders and Steinberg, Ann. Rev. Nucl. Part. Sci. 57 (2007) 205-243]

- Nucleon positions sampled from $T_{A,B}(\mathbf{s})$
- Collision if $d \leq \sqrt{\sigma_{\text{inel}}^{NN}/\pi}$

MC-Glauber



Profile in η



Transverse profile

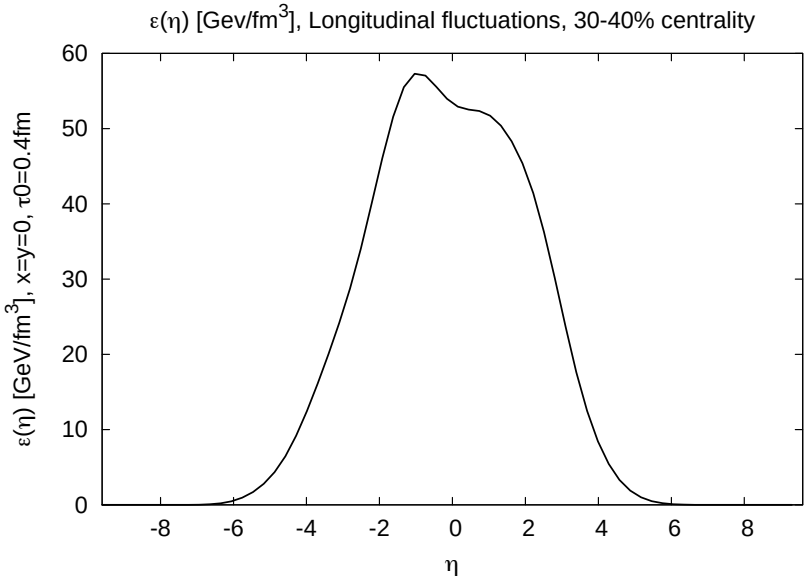
- Energy density in a hydro cell positioned at $\mathbf{x}_\perp^K$

$$\epsilon_\perp(\mathbf{x}_\perp^K) = \sum_{J=1}^{N_w} \frac{\epsilon_0}{2\pi\sigma^2} e^{-(\mathbf{x}_\perp^K - \mathbf{x}_\perp^J)^2/2\sigma^2}$$

- The sum is over all wounded nucleons (usually truncated) with $\sigma \sim \tau_0$.
- η profile: Smooth. An Wood-Saxon or a stretch-Gaussian

AMPT

[L. Pang, Q. Wang and X-N. Wang, Phys.Rev. C86 (2012) 024911], Figure by Khadija El Berhoumi

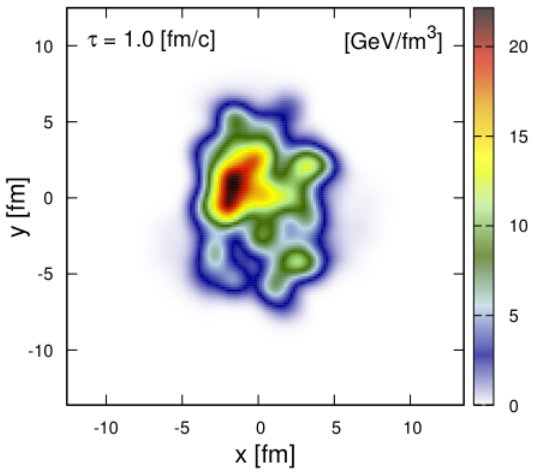


- Sample nucleon positions
- Mini-Jets and string melt produces partons
- Energy-Momentum tensor at τ_0
- HIJING initial conditions
- ZPC in the AMPT evolves partons
- Fluctuations in η

$$T_0^{\mu\nu}(\mathbf{x}_\perp,\eta) = \sum_{i=1}^{N_{\rm parton}} \frac{p_i^\mu p_i^\nu}{p_i^0} \frac{e^{-(\mathbf{x}_\perp-\mathbf{x}_\perp^i)^2/2\sigma_T^2} e^{-(\eta-\eta_i)^2/2\sigma_\eta^2}}{\tau_0 2\pi\sigma_T^2\sqrt{2\pi\sigma_\eta^2}}$$

NEXUS & NeXSpheRIO

[Qian, Mota, Andrade, Gardim, Grassi, Hama and Kodama, arXiv:1305.4673]



An events in the $0-5\,\%$ centrality

- Pomeron $\Longrightarrow$ String with piecewise constant $\dot{X}^\mu$
- Each segment carries

$$\Delta P^\mu_{\rm lab} = \int_A^B \{(\partial_t X^\mu) dr + (\partial_r X^\mu) dt\}$$

- Energy-Momentum tensor at τ_0

$$T_0^{\mu\nu}(\mathbf{x}_\perp, \eta) = \sum \frac{\Delta P^\mu \Delta P^\nu}{\Delta P^0} W(\mathbf{x}_\perp, \eta)$$

- Solve $T_0^{\mu\nu} u_\nu = \epsilon_0 u^\mu$ to get local ϵ and u^μ

[Drescher and Nara, Phys.Rev.C75:034905,2007]

- Based on k_T factorization: Energy density at $\mathbf{x}_\perp^K$ and y:

$$\frac{dE_g}{d^2x_\perp dy} = \frac{4N_c}{N_c^2-1}\int^{p_\perp^{\max}}\frac{d^2p_\perp}{p_\perp^2}p_\perp\int^{p_\perp}\frac{d^2k_\perp}{4}\alpha_s \times\phi_A(x_A,(\mathbf{p}_\perp+\mathbf{k}_\perp)^2/4)\phi_B(x_b,(\mathbf{p}_\perp-\mathbf{k}_\perp)^2/4)$$

  with $x_{A,B}=p_\perp e^{\pm y}/\sqrt{s}$

- Unintegrated gluon distribution function

$$\phi_A(x_A,k_\perp^2;\mathbf{x}_\perp)\sim\frac{1}{\alpha_s(Q_s^2)}\frac{Q_s^2(x_A,\mathbf{x}_\perp)}{\max(Q_s^2(x_A,\mathbf{x}_\perp),k_\perp^2)}$$

MC-KLN

- Sample nucleon positions
- In each hydro cell, determine the thickness at $\mathbf{x}_\perp^K$:
  $t_{A,B}(\mathbf{x}_\perp^K) = (\text{number of nucleons})/S$
- Determine the saturation scale

$$Q^2_{s,A}(x, \mathbf{x}_\perp) = 2\,\text{GeV}^2 \left(\frac{t_A(\mathbf{x}_\perp^K)/p_A(\mathbf{x}_\perp^K)}{1.53} \right) \left(\frac{0.01}{x} \right)^\lambda$$

with $x_{A,B} = p_\perp e^{\pm y}/\sqrt{s}$.
$p_A(\mathbf{x}_\perp)$: Prob. to find at least one nucleon at $\mathbf{x}_\perp$

$$p_A(\mathbf{x}_\perp) 1 - (1 - S T_A(\mathbf{x}_\perp)/A)^A$$

and $S \approx \sigma_{\text{inel}}^{NN}$

MC-rcBK

[Dumitru and Nara, Phys. Rev. C 85, 034907 (2012)]

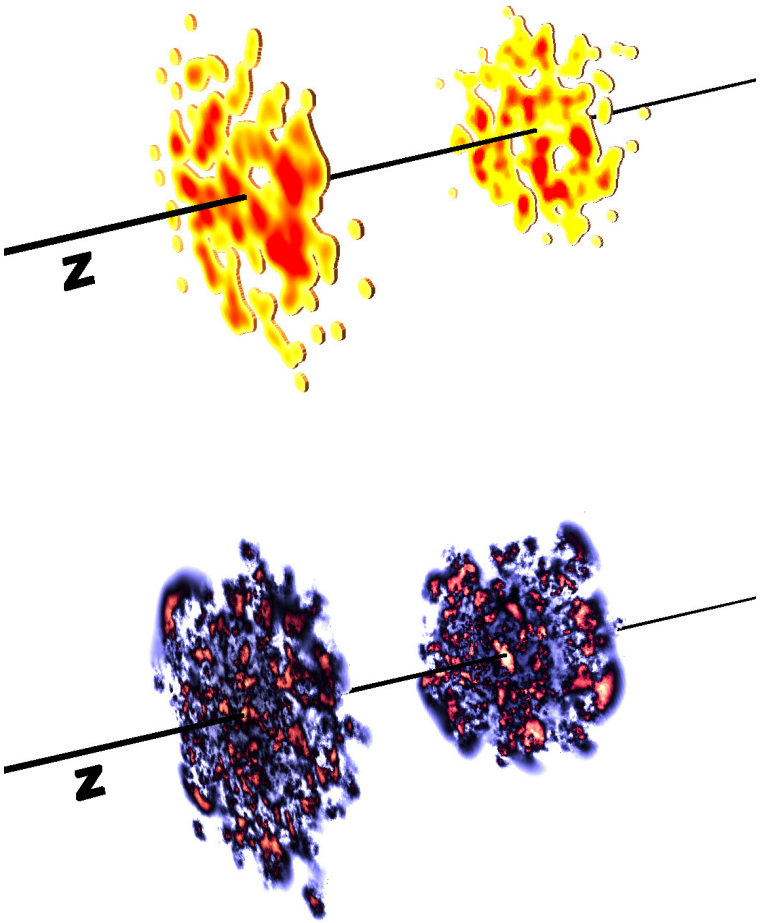
- k_T factorization again:

$$\left\langle \frac{dN_g}{d^2 r_\perp dy} \right\rangle = \frac{4N_c}{N_c^2 - 1} \int^{p_\perp^{\max}} \frac{d^2 p_\perp}{p_\perp^2} \int^{p_\perp} \frac{d^2 k_\perp}{4} \alpha_s(Q_R) \times \phi_A(x_A, (\mathbf{p}_\perp + \mathbf{k}_\perp)^2/4) \phi_B(x_A, (\mathbf{p}_\perp - \mathbf{k}_\perp)^2/4)$$

- Unintegrated gluon distribution function evolves with rcBK in x
- NBD multiplicity fluctuations added
- $Q_R = \max(|\mathbf{p}_\perp + \mathbf{k}_\perp|, |\mathbf{p}_\perp - \mathbf{k}_\perp|)/2$

IP-Glasma

[Schenke, Tribedy and Venugopalan (STV), Phys.Rev. C86 (2012) 034908]



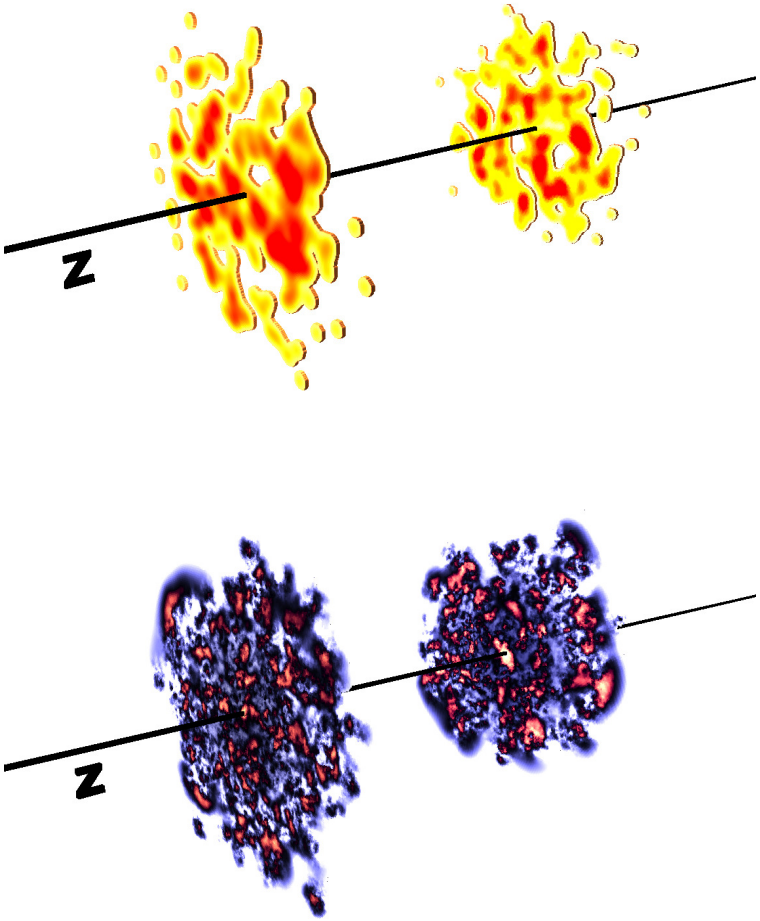
Color charge density and correlation

- Based on $[D_\mu, G^{\mu\nu}] = J^\nu$ with $J^\nu = \rho_A(x^-, \mathbf{x}_\perp)\delta^{+\nu} + \rho_B(x^+, \mathbf{x}_\perp)\delta^{-\nu}$
- Calculate gluon density from the classical gluon field A^μ in the forward light-cone
- This part is Glasma

  [Lappi and McLerran, Nucl.Phys.A772:200-212, 2006]
- Need to know the color charge densities $\rho_{A,B}(x^\pm, \mathbf{x}_\perp)$
- This part is IP-Sat

  [Kowalski and Teaney, Phys. Rev. D 68, 114005 (2003)]

IP-Glasma



Color charge density and correlation

- Sample nucleon positions
- At each lattice position $\mathbf{x}_\perp^K$, determine the distance $\mathbf{b}_J$ from each nucleon.
- For each nucleon, get $Q_{s,p}^2(x, \mathbf{b}_\perp^J)$ from the IP-Sat model
- Determine the color fluctuation by $(0.75g^2)^2\mu_A^2 = \sum Q_{s,p}^2$
- Solve the classical YM equation
- Get $T_{\rm id}^{\mu\nu}$ from A_μ.
- Correlation scale: $1/Q_s$
- NBD: natural consequence

What are we *really* trying to learn?

Properties of QGP

- Transport coefficients
  (shear and bulk viscosities, susceptibilities, ...)
- Equation of state
- Nature of the phase transition
- ...
- Initial condition is a *probe* just as a *jet* is a probe

Problem

- No clear equivalent of *pp* jets for initial conditions
- Need to extract properties of QGP (such as η/s) as well as the nature of the initial conditions at the same time

What are we *really* trying to learn?

Nature of initial conditions

- Dynamics $\tau = 0$ and $\tau = \tau_{\rm hydro}$?
- $T_{\rm max}$?
- Spectrum of fluctuations?
- Inherent or emergent correlations?
- ...
- This is soft physics
- How do we probe this?

Determining QGP prop's and initial state prop's

To do both:

- Needs tension
  - If $\Delta_{QGP} O + \Delta_{\text{hydro}} O + \Delta_{\text{init}} O = 0$, out of luck
    (for example, charged hadron spectra)
  - Need observables for which $\Delta_{QGP} O + \Delta_{\text{hydro}} O + \Delta_{\text{init}} O \neq 0$

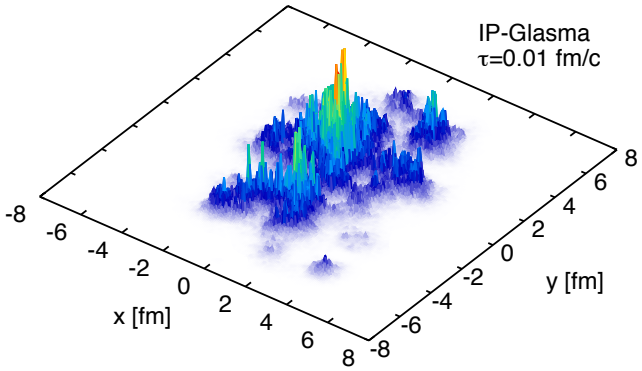
Flow coefficients

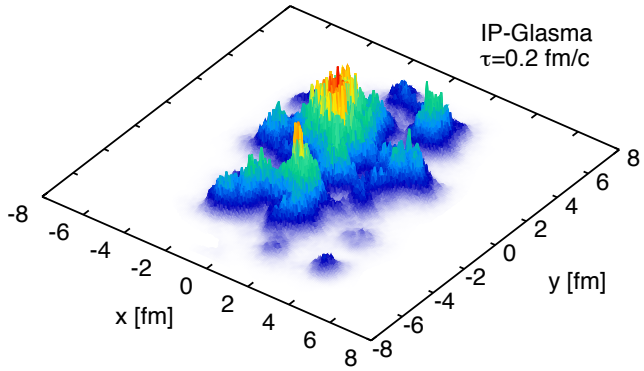
- Determined by *initial* ϵ_n at τ_0: e-by-e
- Moments of v_n distributions available
- Ultra-central: *Fluctuation driven* instead of geometry
  Provides the necessary tension: Difficult to get all v_n's right without getting all ϵ_n's right
- Photon and dilepton spectra and v_n
  [Talks: G. Vujanovic, C. Shen, I. Helenius, J. Ghiglieri, U. Heinz]

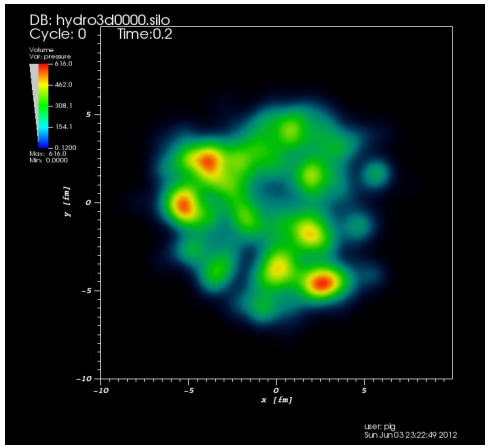
Initial state imprints in the final states

Initial Energy Density Comparison

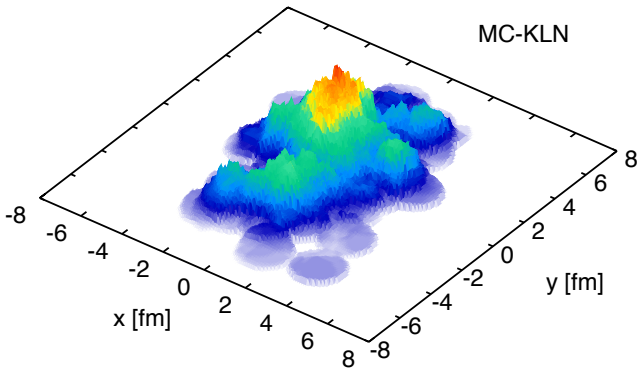
Figures from [STV, Phys.Rev.Lett.108.252301], [Gale, Jeon and Schenke, Int. J. of Mod. Phys. A, Vol. 28, 1340011 (2013)], [L. Pang, Q. Wang and X-N. Wang, Phys.Rev. C86 (2012) 024911], and [Drescher, Liu, Ostapchenko, Pierog and Werner, Phys.Rev. C65 (2002) 054902]

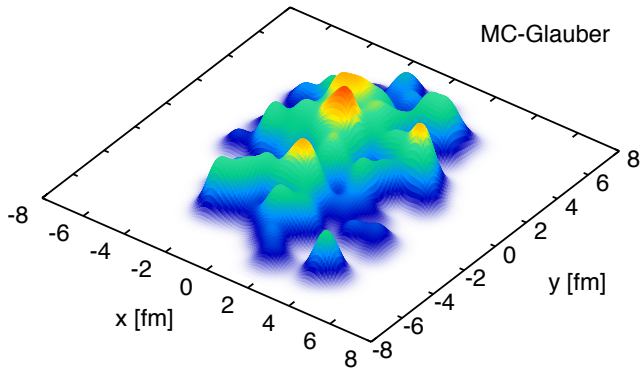


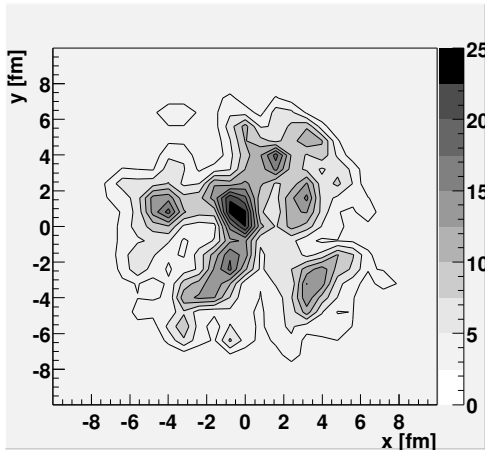




AMPT at $\tau = 0.2\,\mathrm{fm}$







NeXSpheRIO

Eccentricity Comparison 1

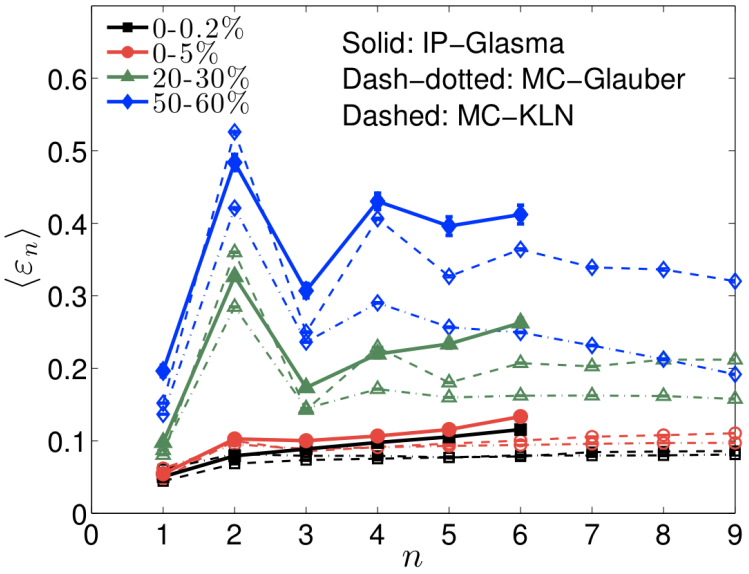


Figure from [Heinz and Snelling, Annu. Rev. Nucl. Part. Sci. 63 (2013) 123-151]

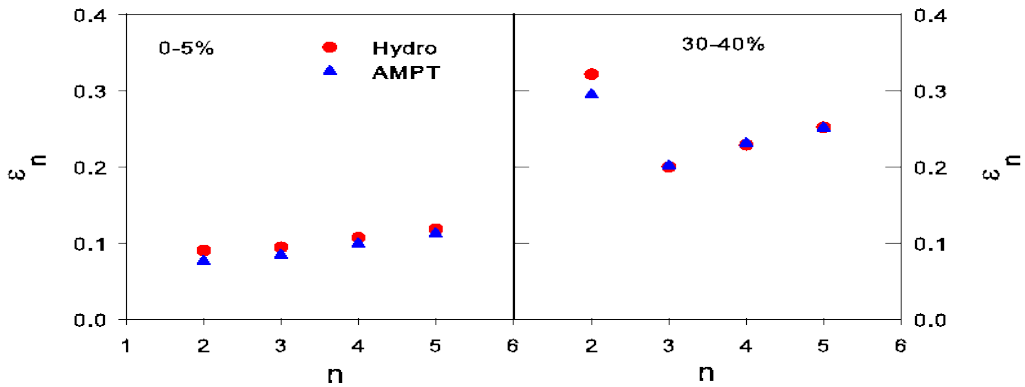
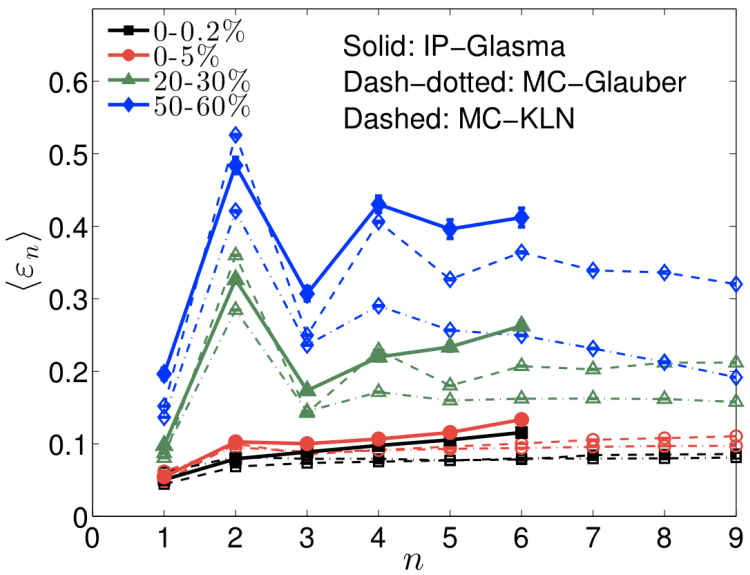


Figure from LongGang Pang, Private Comm.

- Obvious conclusion: Finer scale fluctuations induce larger higher order ϵ_n
- Not so obvious conclusion: Magnitude of ϵ_n all comparable for ultra-central collisions

Eccentricity Comparison 1



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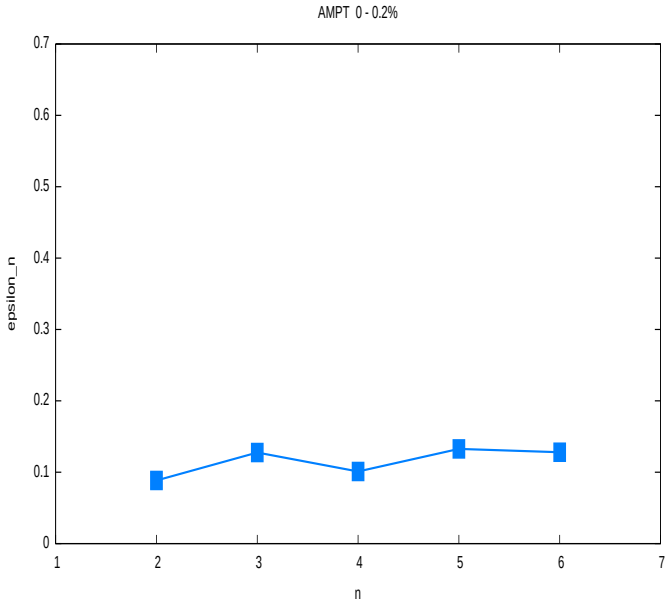
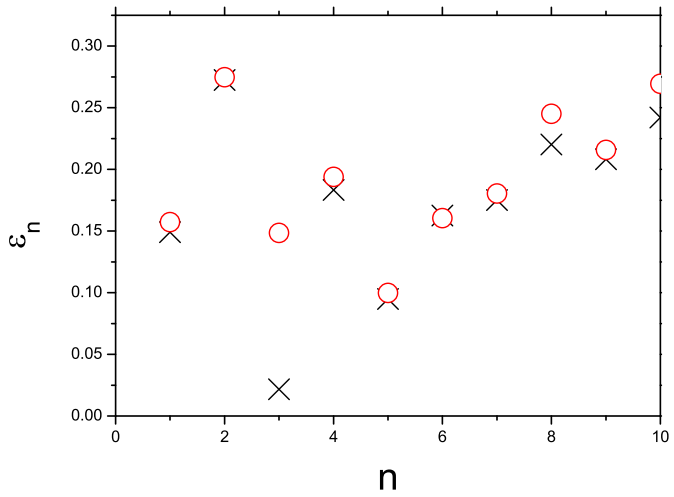


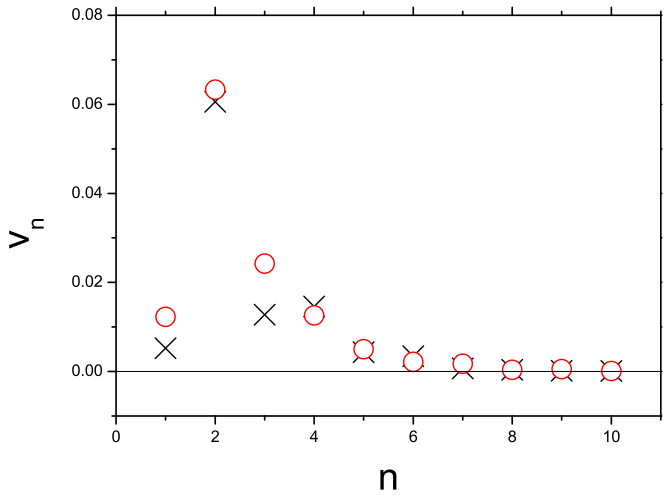
AMPT ultra-central. Data from LongGang Pang, Private Comm. Preliminary.

- Obvious conclusion: Finer scale fluctuations induce larger higher order ϵ_n
- Not so obvious conclusion: Magnitude of ϵ_n all comparable for ultra-central collisions

Eccentricity Comparison 2

NeXSpheRIO single event (0 – 5 %, red circles)

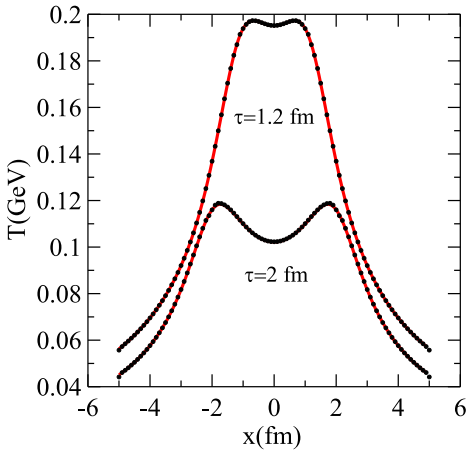


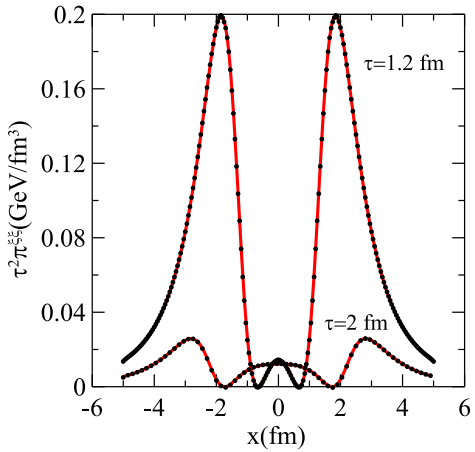


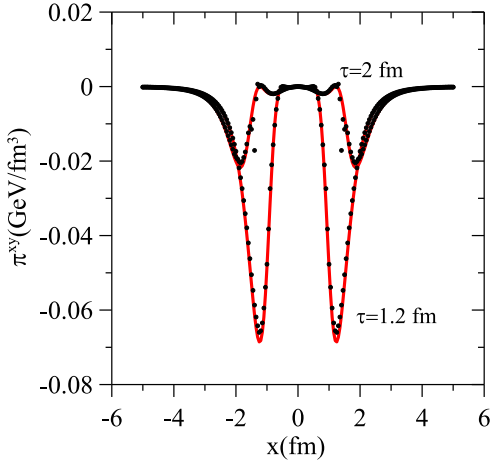
- Obvious conclusion: Finer scale fluctuations induce larger higher order ϵ_n
- Not so obvious conclusion: Magnitude of ϵ_n all comparable for ultra-central collisions

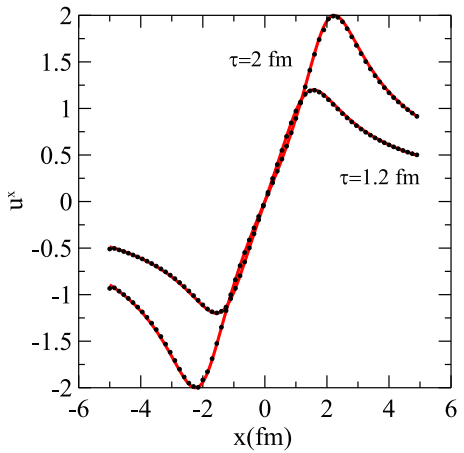
Confidence in viscous-hydro solutions

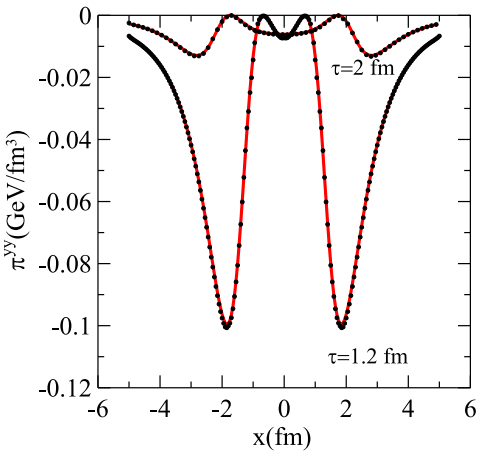
- Comparison with the viscous-Gubser flow and MUSIC
- Analytic ideal-hydro solution by [Gubser, Phys. Rev. D 82, 085027 (2010), Gubser and A. Yarom, Nucl. Phys. B 846, 469 (2011)]
- Semi-analytic Viscous-hydro solution by [Marrochio, Noronha, Denicol, Luzum, Jeon and Gale, arXiv:1307.6130].









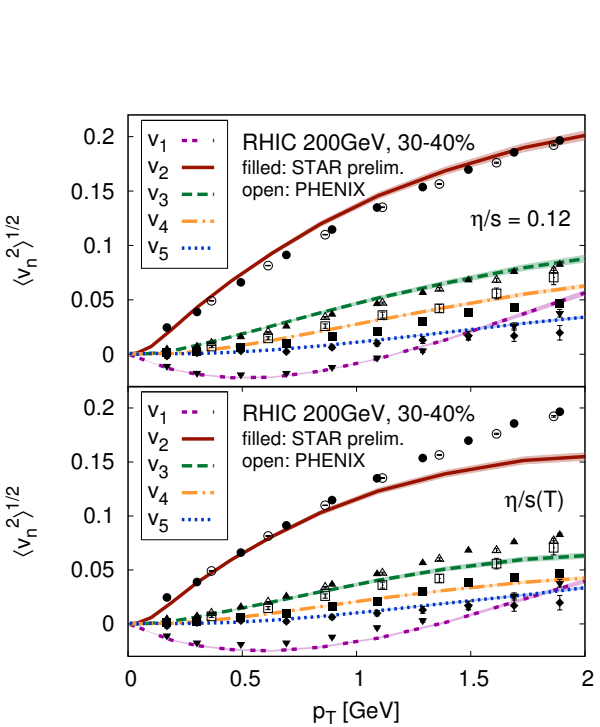


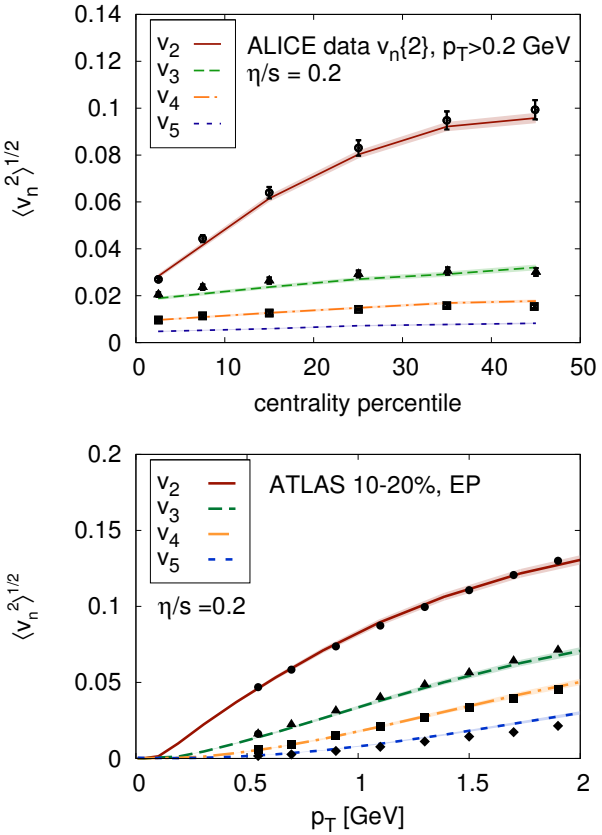
Figures from MNDLJG with

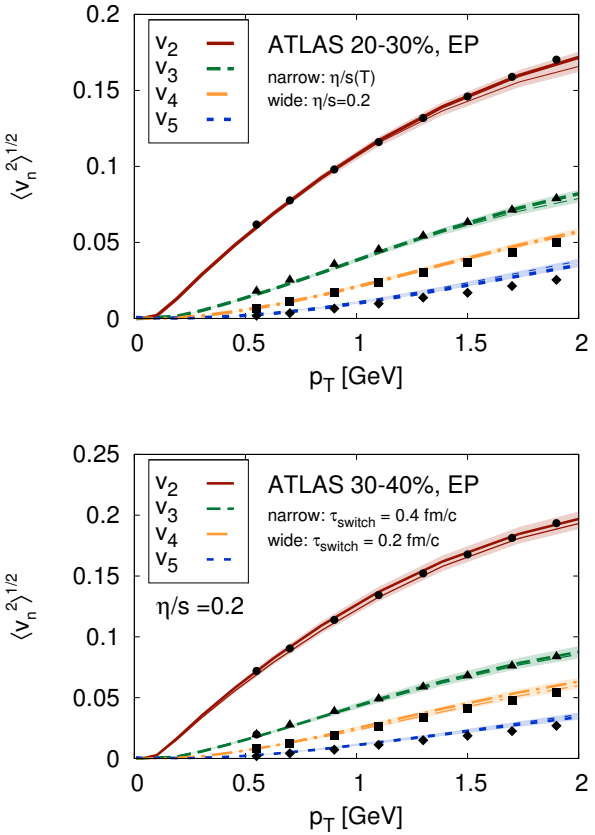
$\eta/s = 0.2, \tau_R T = 5\eta/s$.

Not-so-ultra-central v_n

IP-Glasma RHIC and LHC:



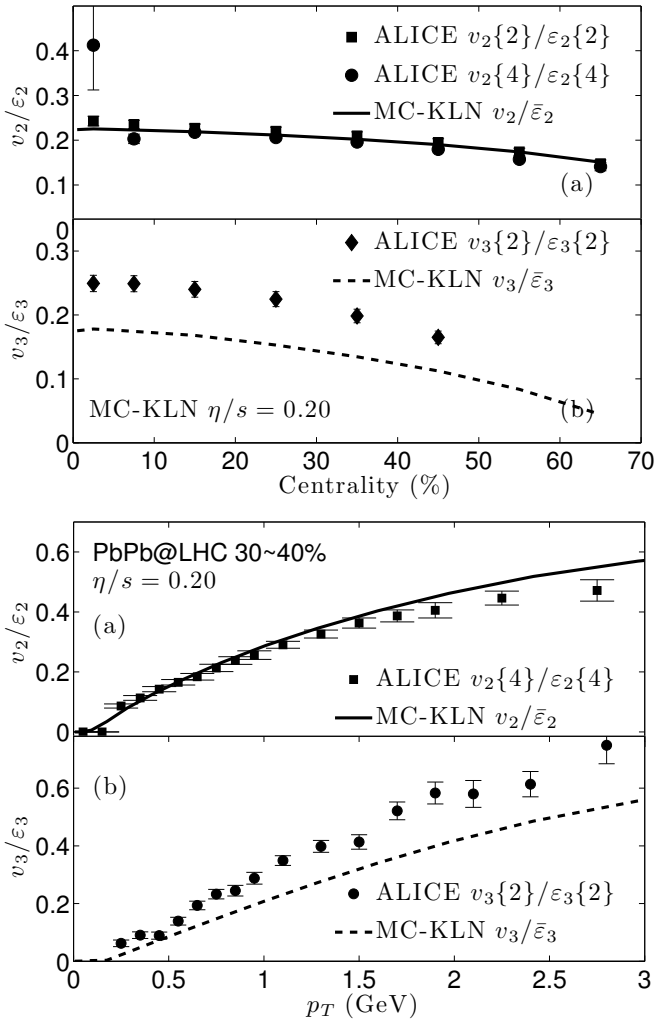


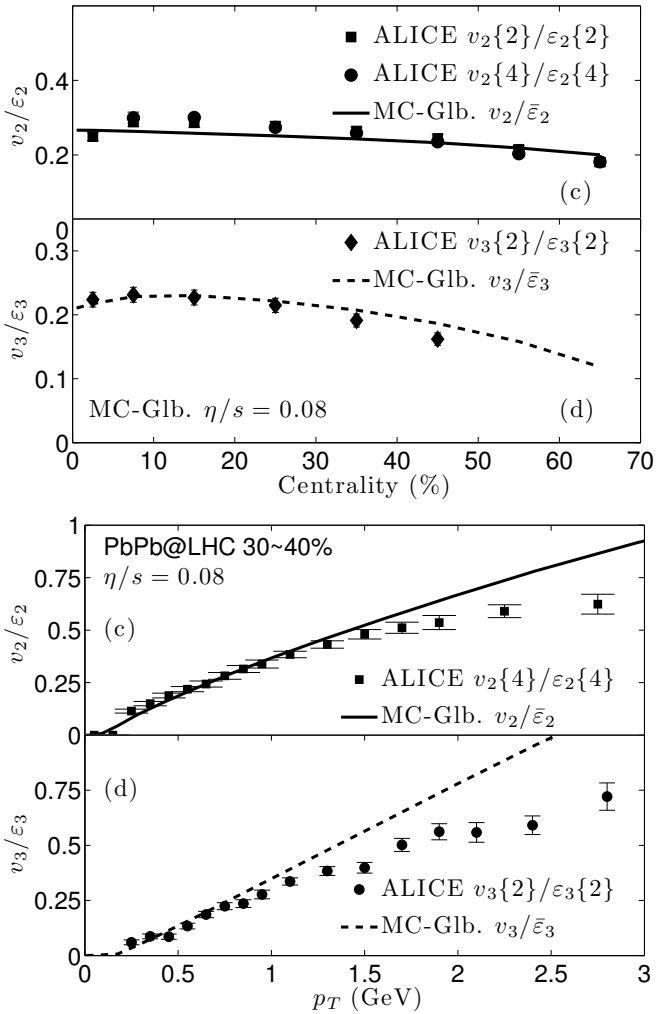


Figures from [Gale, Jeon, Schenke, Tribedy and Venugopalan (GJSTV), Phys.Rev.Lett.110.012302]

Not-so-ultra-central v_n

MC-Glauber and MC-KLN:





Figures from [Qiu, Shen and Heinz, Phys.Lett. B707 (2012) 151-155]

Not-so-ultra-central v_n

NeXSpheRIO:

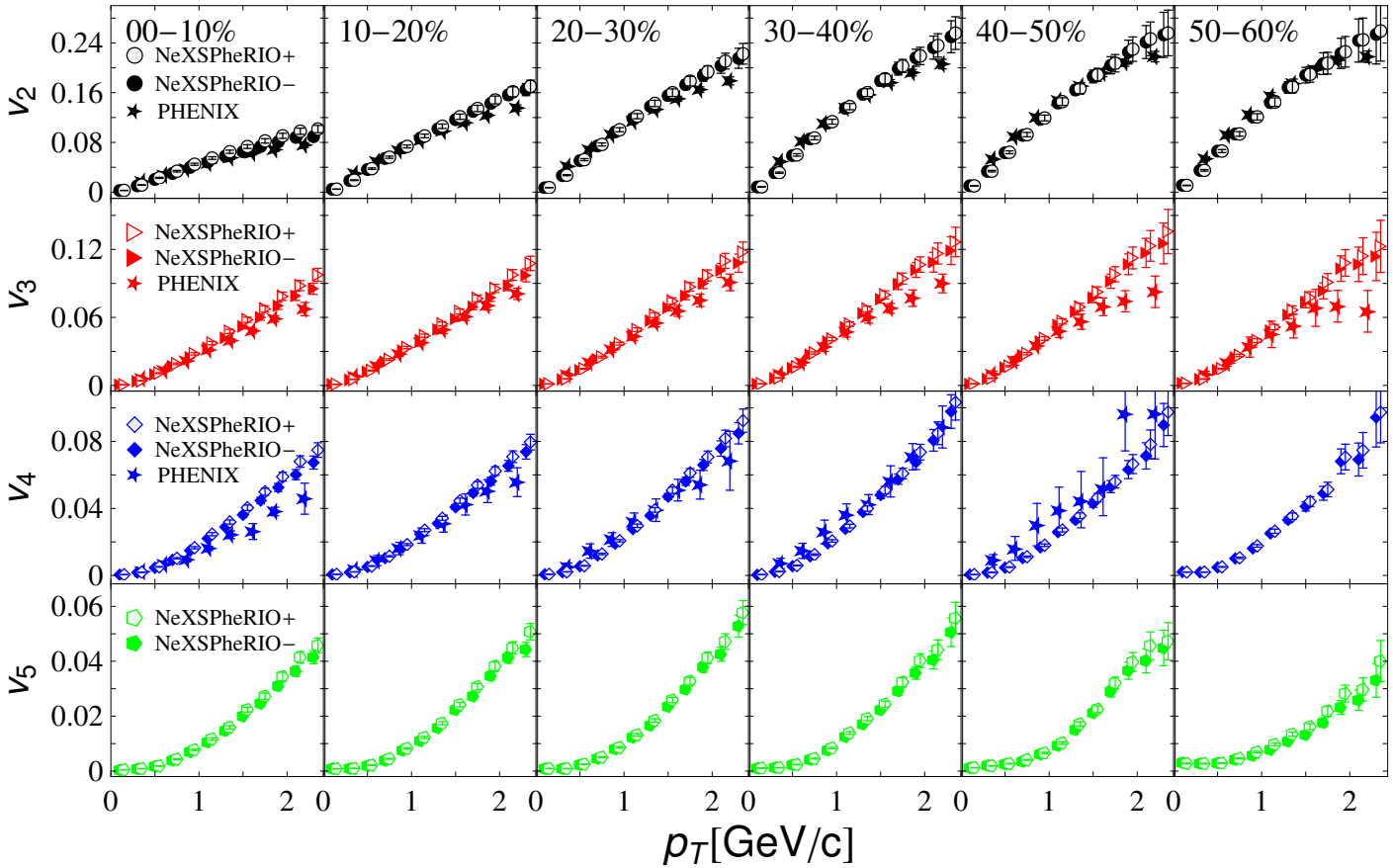
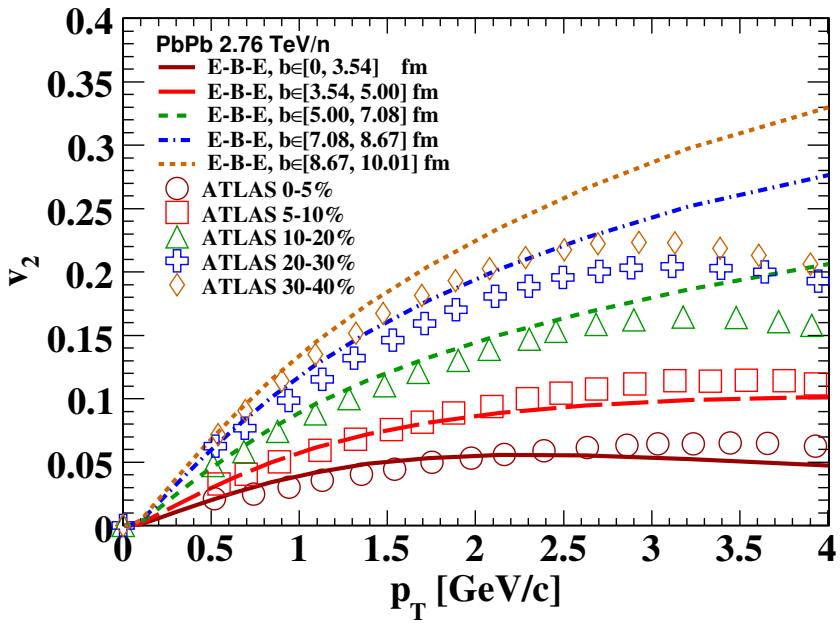
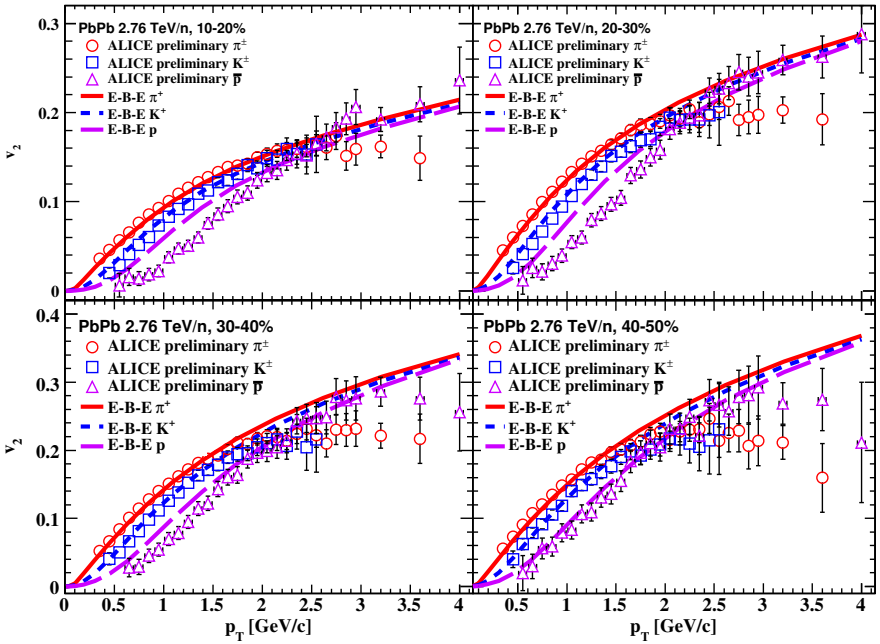


Figure from [Gardim, Grassi, Luzum and Ollitrault, Phys.Rev.Lett.109:202302, 2012]

Not-so-ultra-central v_n

AMPT Initial Condition:





Figures from [Pang, Q. Wang and X-N. Wang, Phys.Rev. C86 (2012) 024911]

Ultra-central collisions

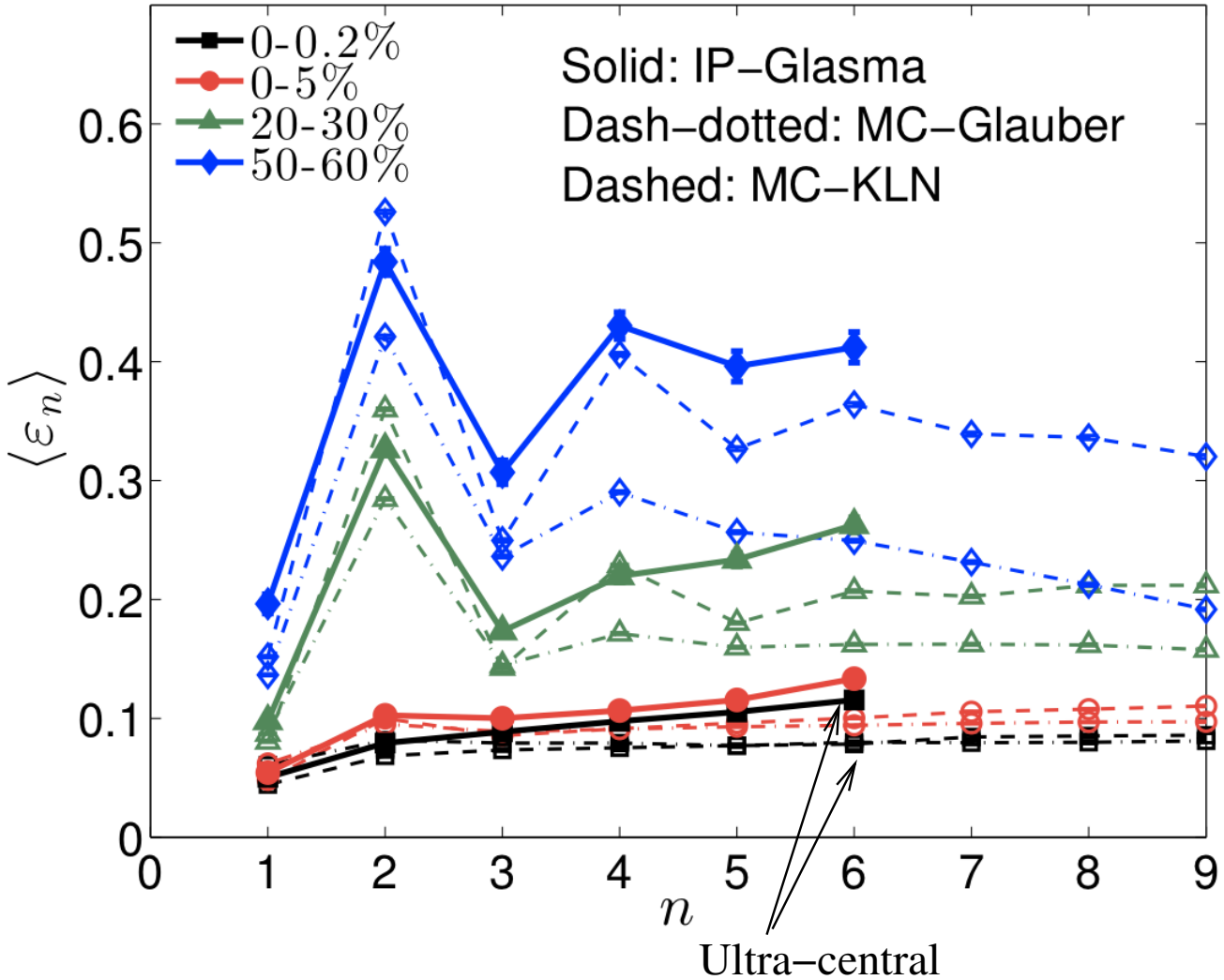
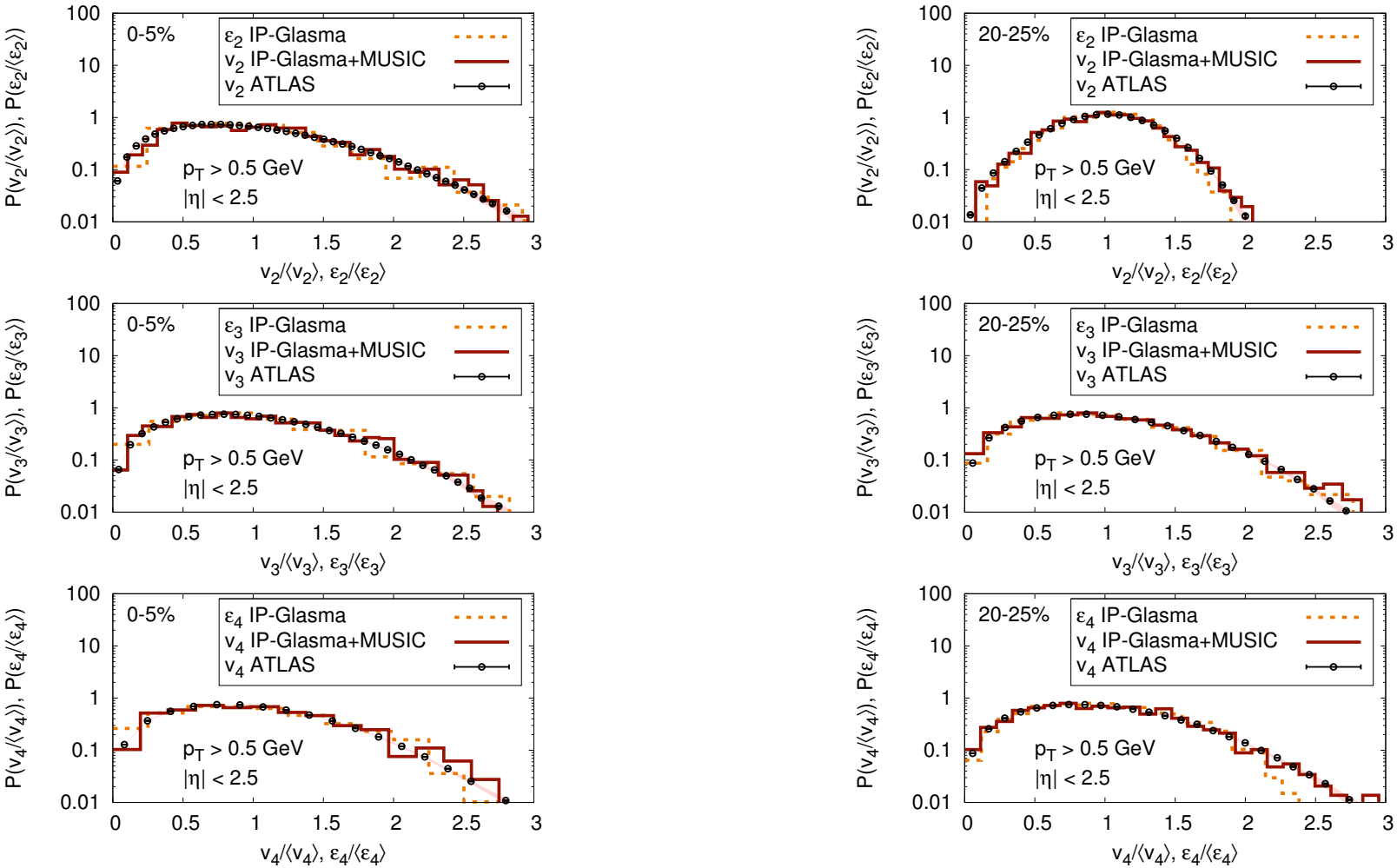


Figure from [Heinz and Snelling, Annu. Rev. Nucl. Part. Sci. 63 (2013) 123-151]

Lesson from the E-by-E v_n distributions

- E-by-E v_n is senstive to E-by-E ϵ_n



Figures from [GJSTV, Nucl.Phys.A904-905 2013 (2013) 409c-412c]

How Central is Ultra-Central?

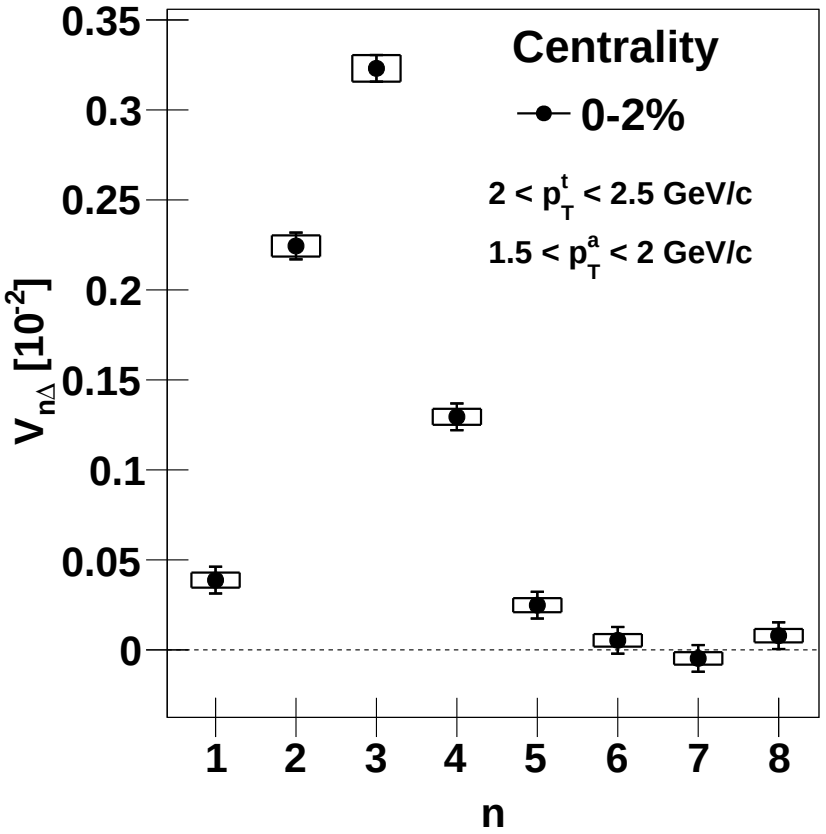
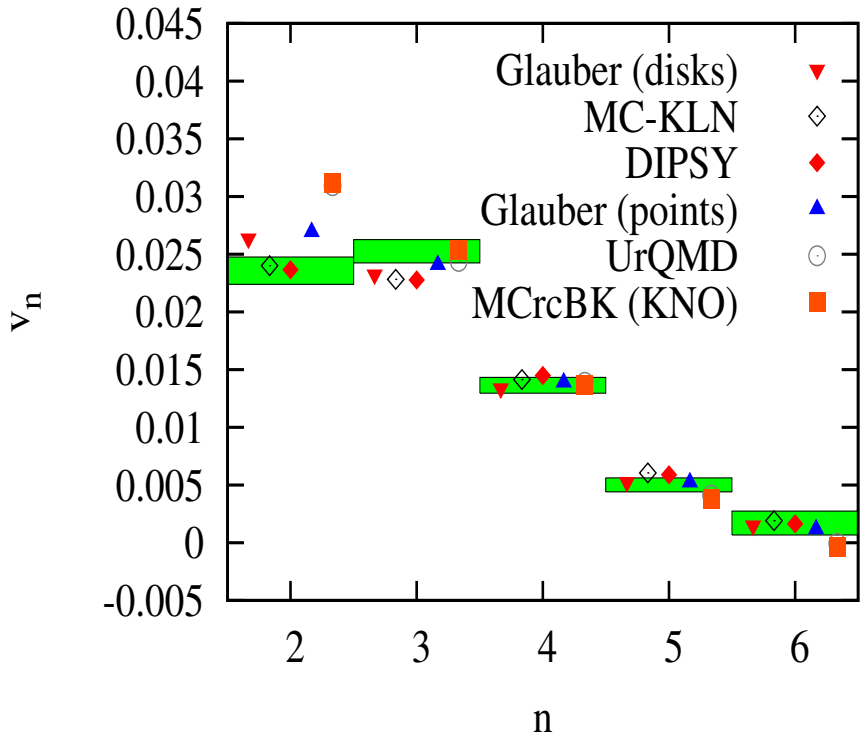


Figure from [ALICE, Phys.Lett. B708 (2012) 249-264]

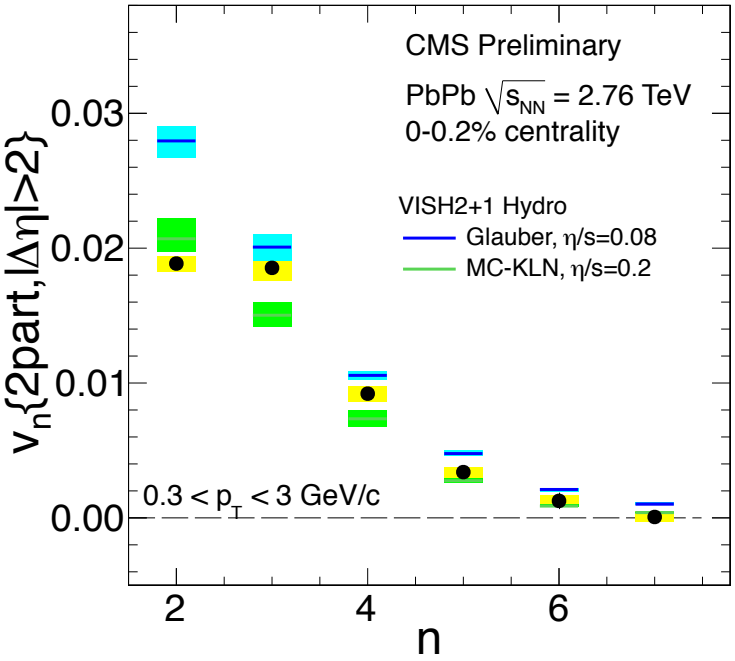


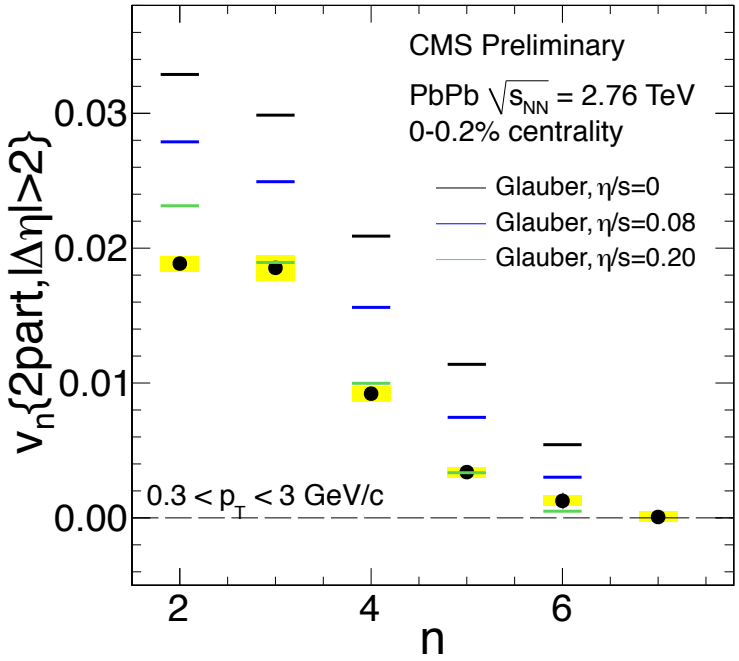
[Green bars: $0-1\,\%$ ATLAS]. Figure from [Luzum and Ollitrault, Nuclear Physics A 904-905 (2013) pp. 377-380]

- As Centrality $\to 0$, $v_3 \to v_2$
- At $0-1\,\%$, $v_3 \approx v_2$

Ultra-Central v_n

MC-Glauber & MC-KLN



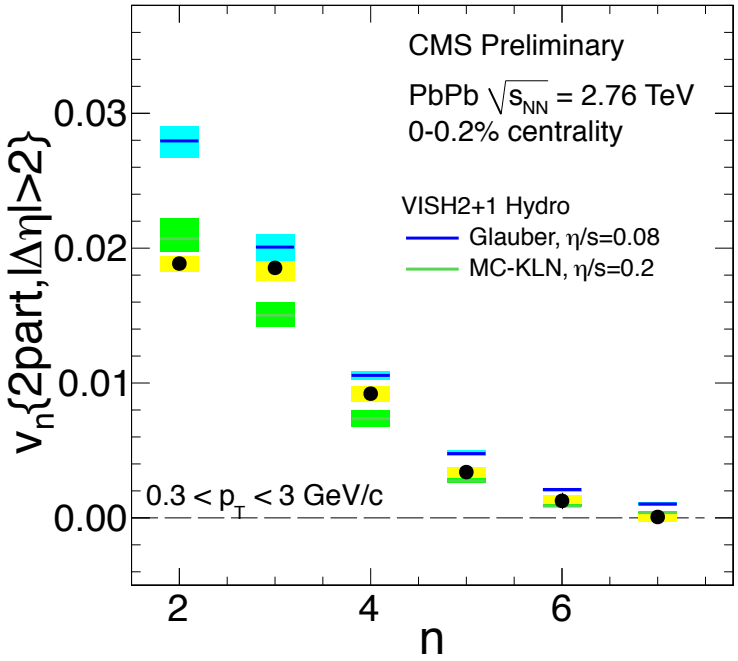


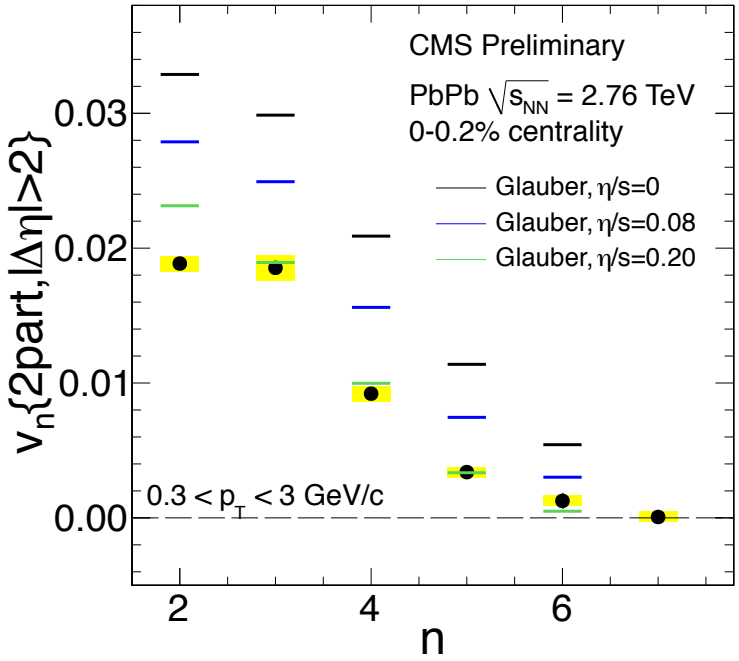
Figures from CMS-PAS HIN-12-011 and also [Harris, Kharzeev and Ullrich, 2012 CERN Courier 52 (no. 9) 17] and [Luzum and Ollitrault, Nuclear Physics A 904-905 (2013) pp. 377-380]

- Resolution power
- The tension: Exp. $v_2 \approx v_3$ but Theo. $v_2 > v_3$
- Promising: May be able to pin down both the initial state and the transport coefficients

Ultra-Central v_n

MC-Glauber & MC-KLN





Figures from CMS-PAS HIN-12-011 and also [Harris, Kharzeev and Ullrich, 2012 CERN Courier 52 (no. 9) 17] and [Luzum and Ollitrault, Nuclear Physics A 904-905 (2013) pp. 377-380]

- Resolution power
- The tension: Exp. $v_2 \approx v_3$ but Theo. $v_2 > v_3$
- Initial state fluctuations imprinted on final state hadrons

Direct access to the initial state?

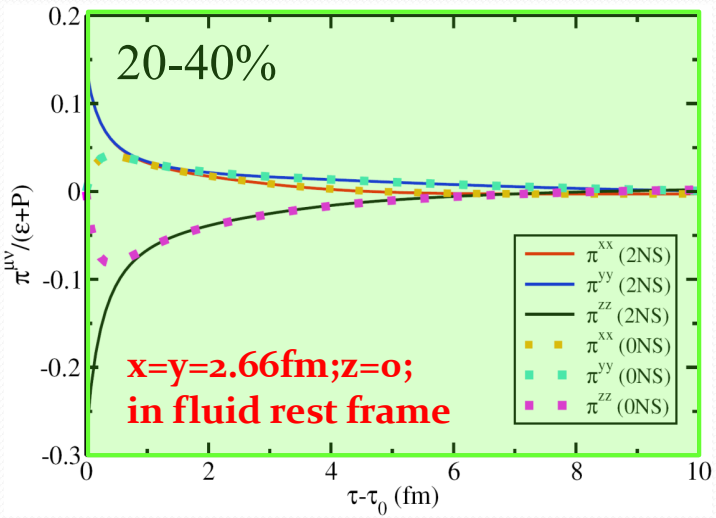
Non-zero $\pi^{\mu\nu}(\tau_0)$

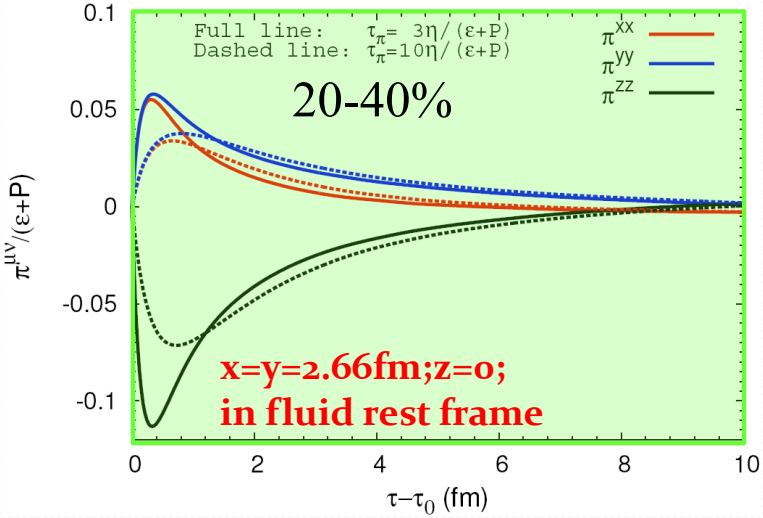
[Gojko Vujanovic's Talk, Tuesday]

- Observables sensitive to the initial state?

Motivation

- Hadronic observables have limited sensitivity to departures from equilibrium in the evolution the medium (τ_π) and to init. cond. ($\pi^{\mu\nu}$) .



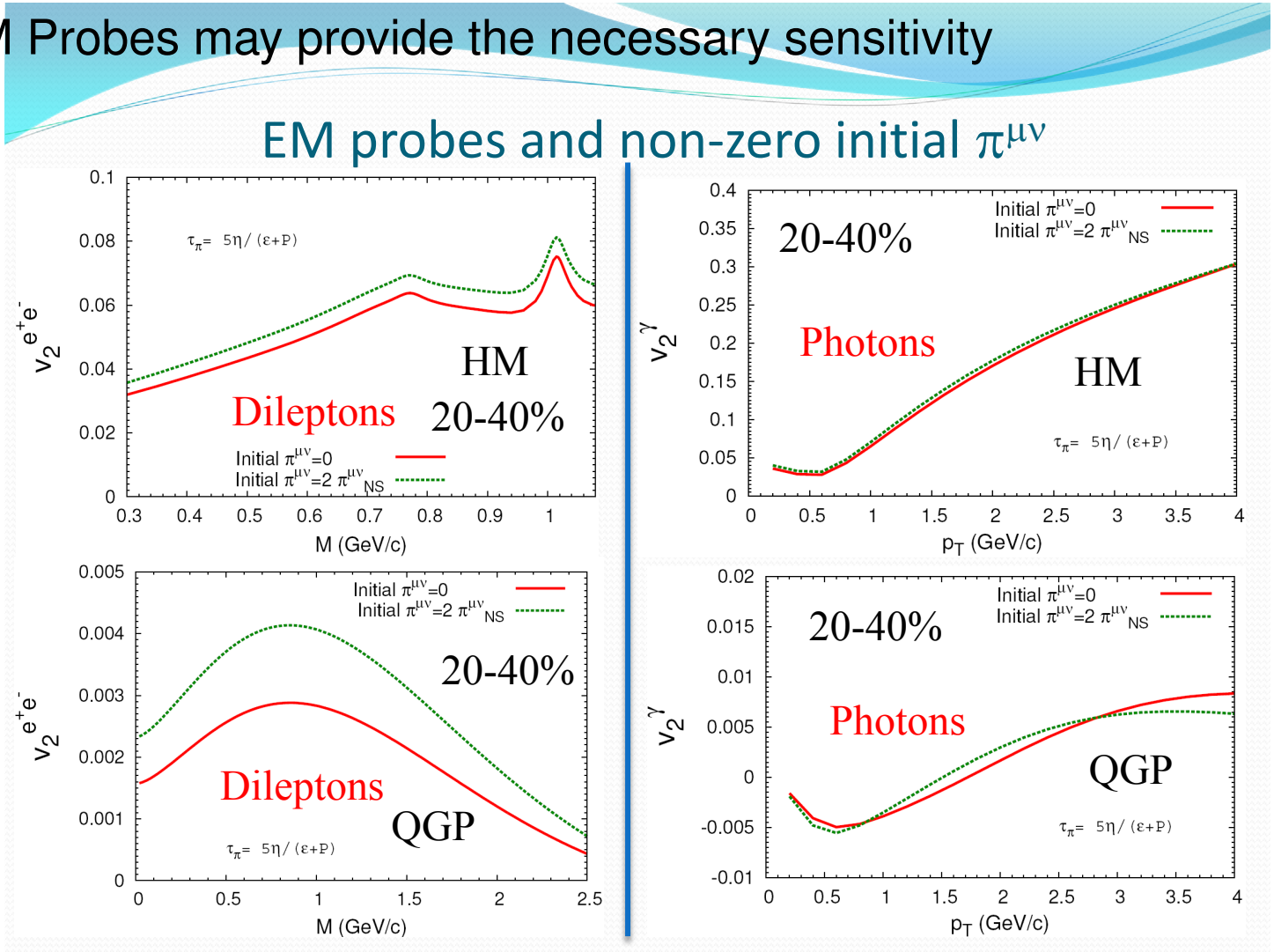


- EM probes on the other hand can escape the medium at any time hence are more sensitive to the evolution of the medium (in particular to the size of τ_π) and initial conditions (init. $\pi^{\mu\nu}$). Question: how much?

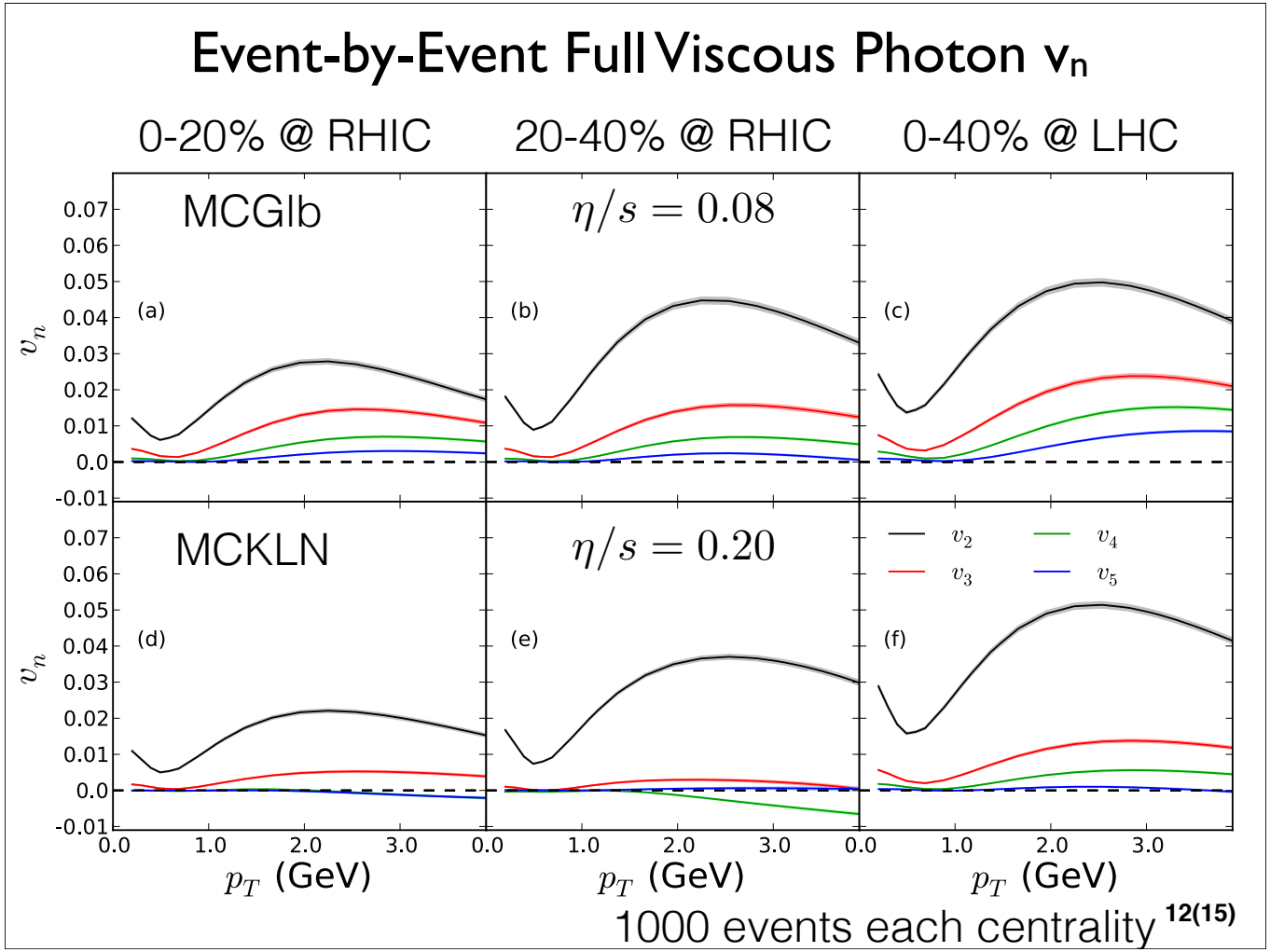
Effect of non-zero $\pi^{\mu\nu}(\tau_0)$ on EM Probes

[Gojko Vujanovic's Talk, Tuesday]

- EM Probes may provide the necessary sensitivity



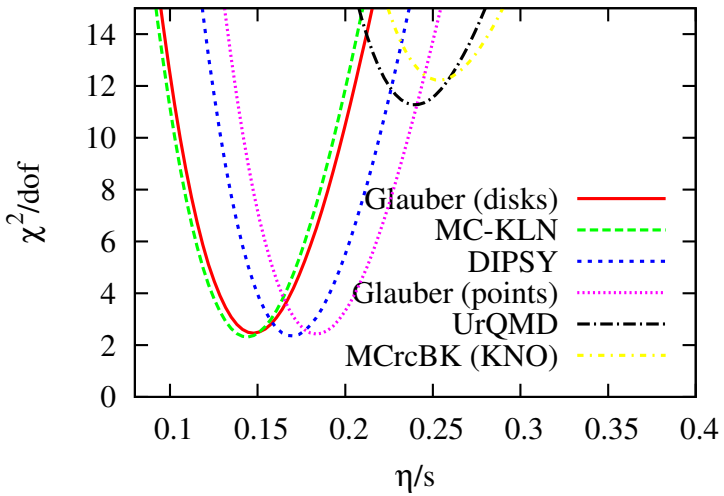
Initial state fluctuations in EM Probes



[Chun Shen's Talk, Monday.

Based on arXiv:1308.2111 by Shen, Heinz, Paquet, Kozlov and Gale]

Where do we stand?



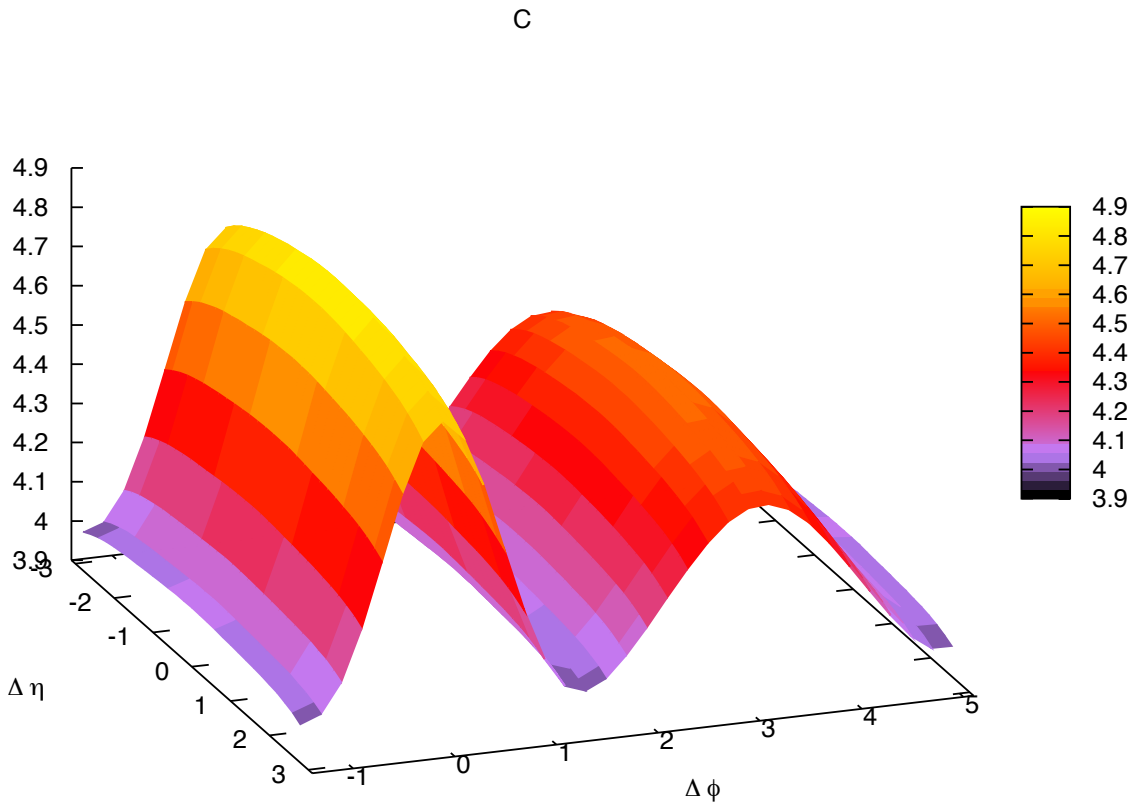
The χ^2 fit of η/s.

Figure from [Luzum and Ollitrault, Nuclear Physics A 904-905 (2013) pp. 377-380]

- Distinguishing initial state models
  - Ultra-Central flow data may be able to pin down QGP properties and the initial-state model
  - QCD based/inspired models may provide the best initial states
- QGP properties
  - See above
- EM probes
  - Promising probes of initial state & initial evolution
- Exciting times ahead

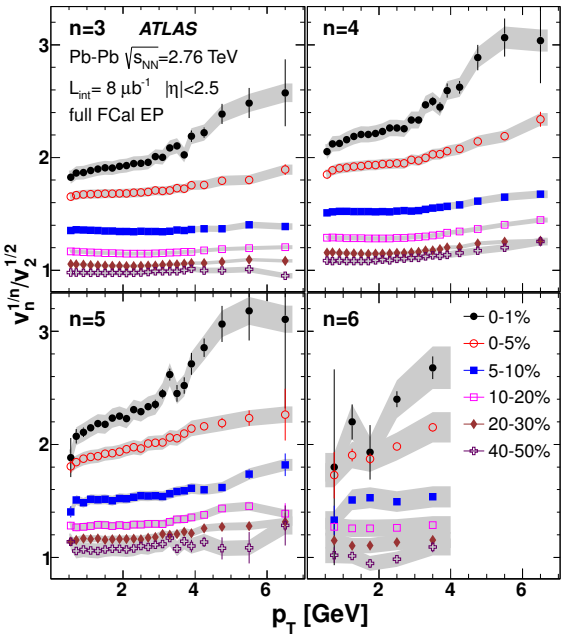
Backup Slides

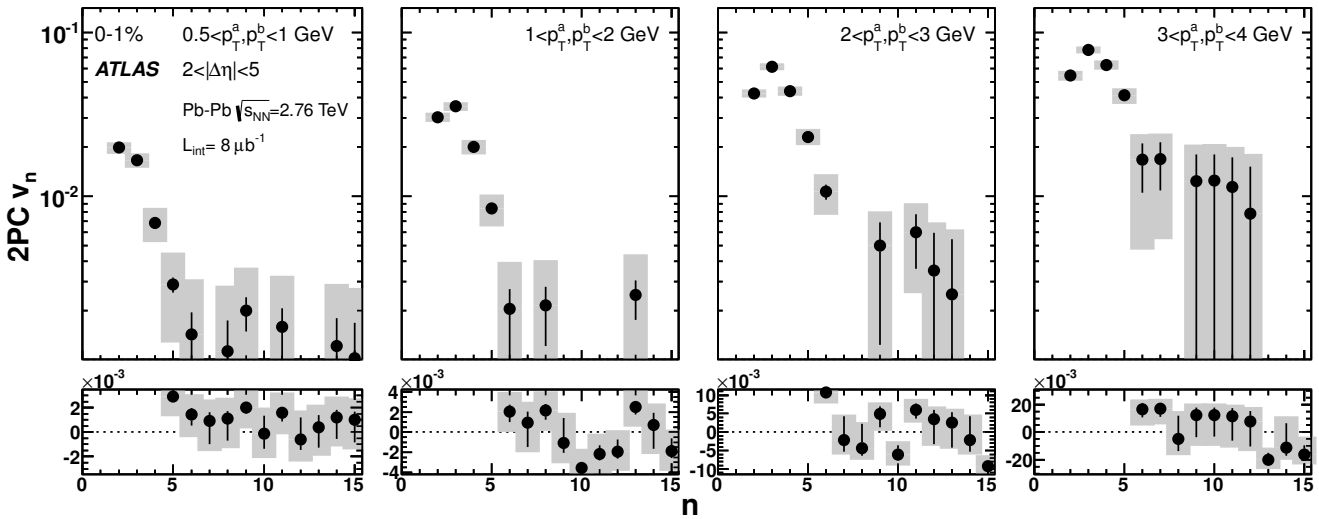
Hydro without Jets (MUSIC)



- 3D hydro initialized with a long plateau initial condition

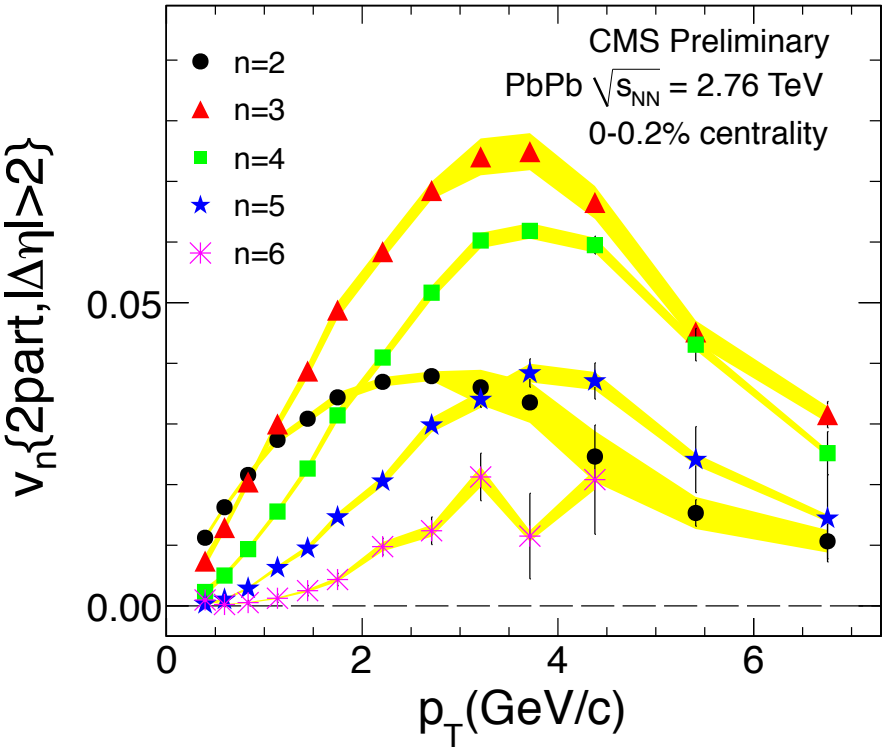
ATLAS Ultra-Central results

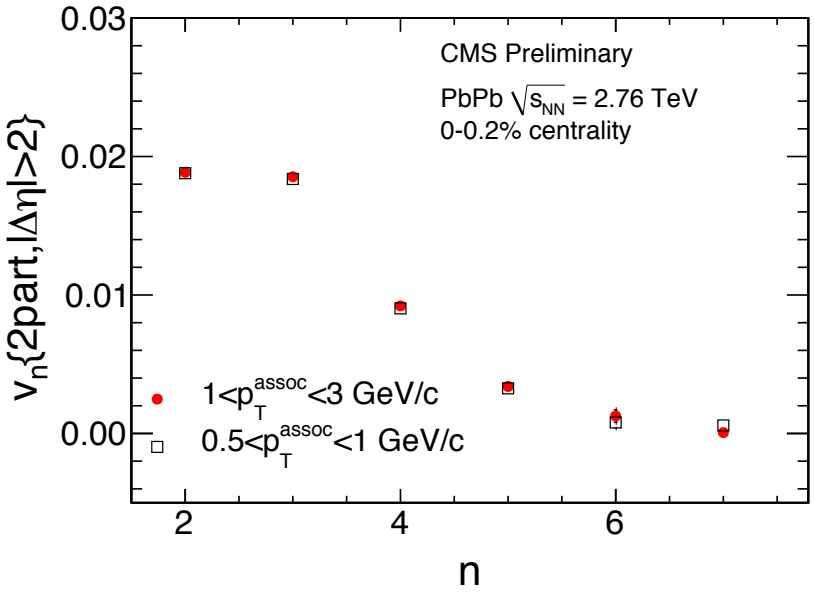




Figures from [ATLAS, Phys.Rev. C86 (2012) 014907]

CMS Ultra-Central results

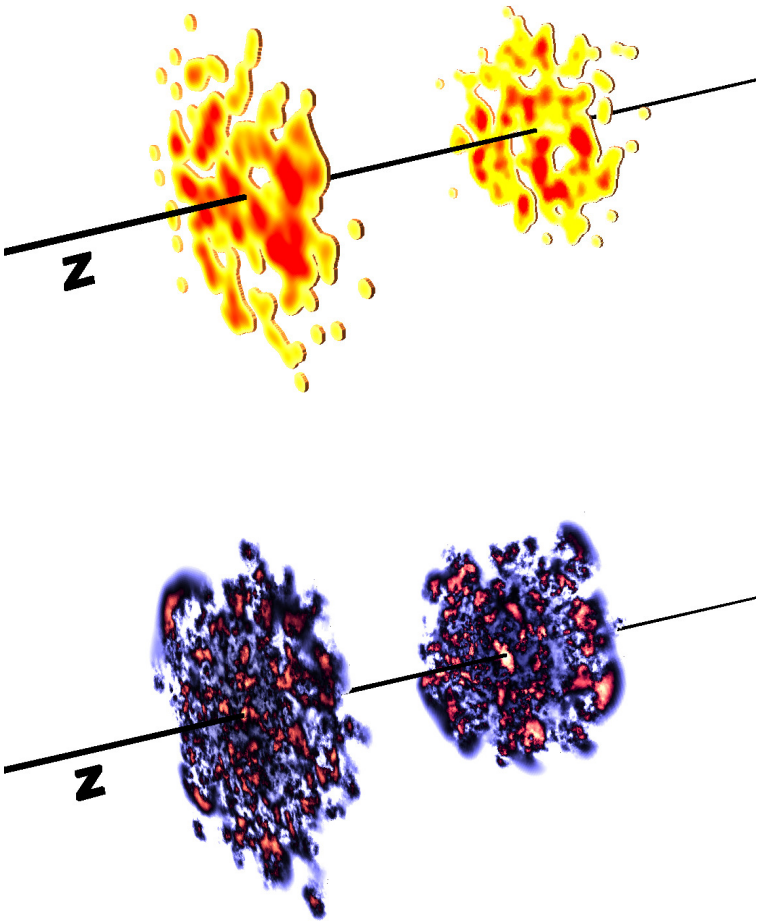




Figures from [CMS, CMS-PAS-HIN-12-011]

IP-Glasma

[Schenke, Tribedy, Venugopalan, Phys.Rev. C86 (2012) 034908]



Color charge density and correlation

- Sample nucleon positions
- At each lattice position $\mathbf{x}_\perp^K$, determine the distance $\mathbf{b}_J$ from each nucleon.
- For each nucleon, get $Q_{s,p}^2(x, \mathbf{b}_\perp^J)$:

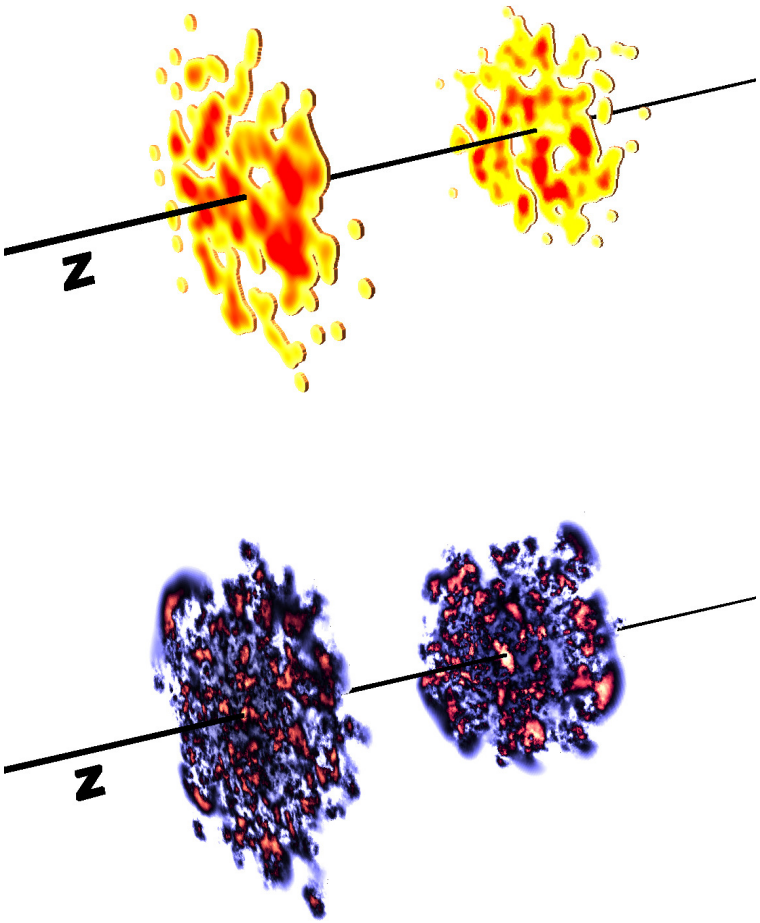
$$\frac{d\sigma^P_{\rm dipol}}{d^2\mathbf{b}_\perp} = 2(1 - \exp(-F(\mathbf{r}_\perp^d, x, \mathbf{b}_\perp))$$

$$F(\mathbf{r}_\perp^d, x, \mathbf{b}_\perp) = \frac{\pi}{2N_c}(r_\perp^d)^2 \alpha_s(\tilde{\mu}^2) x g(x, \tilde{\mu}^2) T_p(\mathbf{b}_\perp)$$

With $\tilde{\mu}^2 = 4/(r_\perp^d)^2 + \tilde{\mu}_0^2$,
determine r_S^2 from $F = 1/2$
Then, $Q_{s,p}^2 = 2/r_S^2$: a function of $x, \mathbf{b}_\perp$

IP-Glasma

[Schenke, Tribedy, Venugopalan, Phys.Rev. C86 (2012) 034908]



Color charge density and correlation

- Determine the color fluctuation scale in $\left\langle \rho^a_{A,B}(\mathbf{x}_\perp)\rho^b_{A,B}(\mathbf{y}_\perp)\right\rangle = g^2\mu^2_{A,B}(x,\mathbf{x}_\perp)\delta^{ab}\delta(\mathbf{x}_\perp-\mathbf{y}_\perp)$ by $(0.75g^2)^2\mu_A^2 = \sum Q^2_{s,p}$
- Instead of using KLN, solve the classical Yang-Mills in the forward light-cone with the sampled $\rho_a(x,\mathbf{x}^K_\perp)$
- Get $T^{\mu\nu}$ from A_μ.
- Correlation scale: $1/Q_s$