

Realistic medium-averaging in radiative energy loss

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Motivation

Line integrals, e.g.,

$$\Delta E_{GLV}^{(1)} \approx \frac{9\pi C_R \alpha_s^3}{4} \int d\tau \tau \rho(z_0 + v\tau, \tau) \ln \frac{2E}{\mu^2 \tau}$$

Gyulassy, Vitev, et al...

$$\frac{dE}{dL} = \kappa[s(L)]s(L)L$$

Shuryak & Liao

$$\frac{dE}{dL} = \text{const} \times E^\alpha L^\beta T^{2-\alpha+\beta}(L)$$

Betz et al

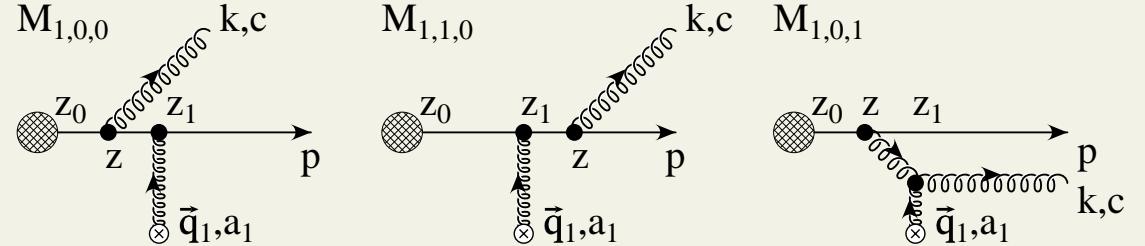
vs stochastic E-loss?

ΔE depends on the medium. E.g, GLV needs scattering center information

→ natural to combine (D)GLV with a parton transport model (MPC)

GLV - opacity expansion

Gyulassy, Levai, Vitev NPB594 ('00)



$$\begin{aligned}
 x \frac{dN^{(n)}}{dx d^2k} = & \frac{C_R \alpha_s}{\pi^2} \frac{\chi^n}{n!} \int \prod_{i=1}^n \left\{ d\mathbf{q}_i \left(\frac{dz_i \rho_i \sigma_i}{\chi} \right) (\bar{v}_i^2(\mathbf{q}_i) - \delta^2(\mathbf{q}_i)) \right\} \\
 & \times \left[-2 \mathbf{C}_{(1,\dots,n)} \cdot \sum_{m=1}^n \mathbf{B}_{(m+1,\dots,n)(m,\dots,n)} \right. \\
 & \left. \left(\cos \left(\sum_{k=2}^m \omega_{(k,\dots,n)} \Delta z_k \right) - \cos \left(\sum_{k=1}^m \omega_{(k,\dots,n)} \Delta z_k \right) \right) \right]
 \end{aligned}$$

$$\text{formation time } \omega_{n\dots m} = \frac{2xE}{(k-\mathbf{q}_n-\dots-\mathbf{q}_m)^2}$$

key assumptions: static Yukawa scatterers, soft emission, $\lambda_{MFP} \gg 1/\mu_D$

as usual, in the end interpret $\rho_i(\vec{x}) \rightarrow \rho_i(\vec{x}, t)$ along jet trajectory

Setup:

- Bulk dynamics evolution computed from covariant transport (MPC code)
- GLV⁽¹⁾ jet energy loss using medium from transport
 - either using the density $\rho(x_\perp, \tau)$
 - or spacetime location of scatterings for embedded external jets in transport (no jet recoil, forward scattering)
 - crude account for multi-gluon emission via rescaling $\rho \rightarrow \rho/Z$
- Keep energy loss stochastic (no averaging over scattering location)
- Radiated glue considered “lost” and feedback on medium ignored - focus on high p_T
- After E-loss, fragment as in vacuum to get some hadronic observables (LO pQCD)

$$R_{AA} \equiv \frac{\text{yield in } A+A}{\text{binary scaled } p+p \text{ yield}} \quad , \quad v_2(p_T) \equiv \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

4 scenarios:

1D = longitudinal Bjorken expansion, $\langle \Delta E \rangle$

1D, stochastic = longitudinal Bjorken expansion, $\Delta E(z)$

3D = Bjorken AND transverse expansion, $\langle \Delta E \rangle$

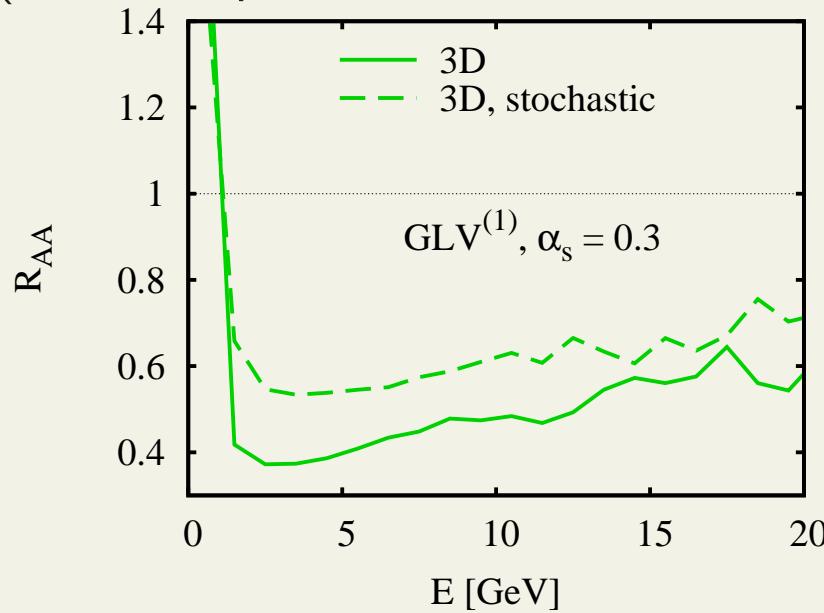
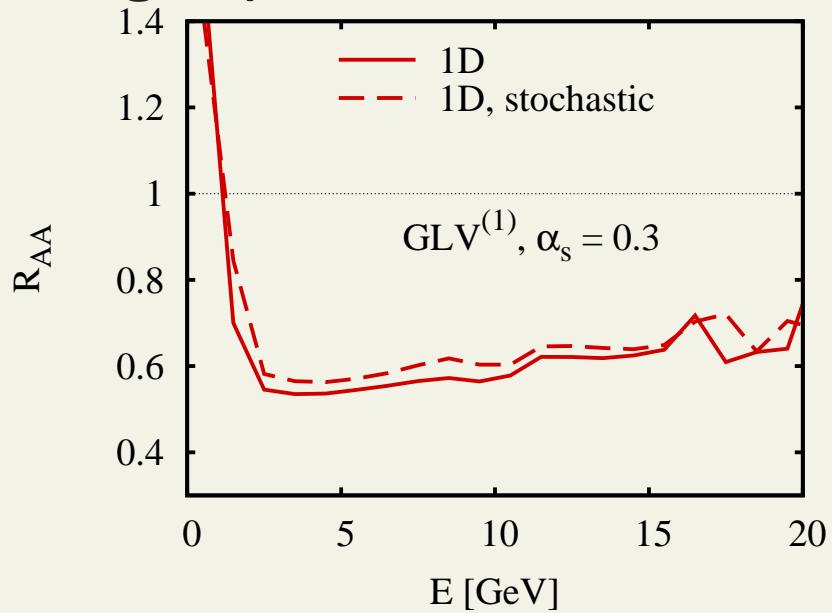
3D, stochastic = Bjorken AND transverse expansion, $\Delta E(z)$

first exploration: parametrized medium evolution, and

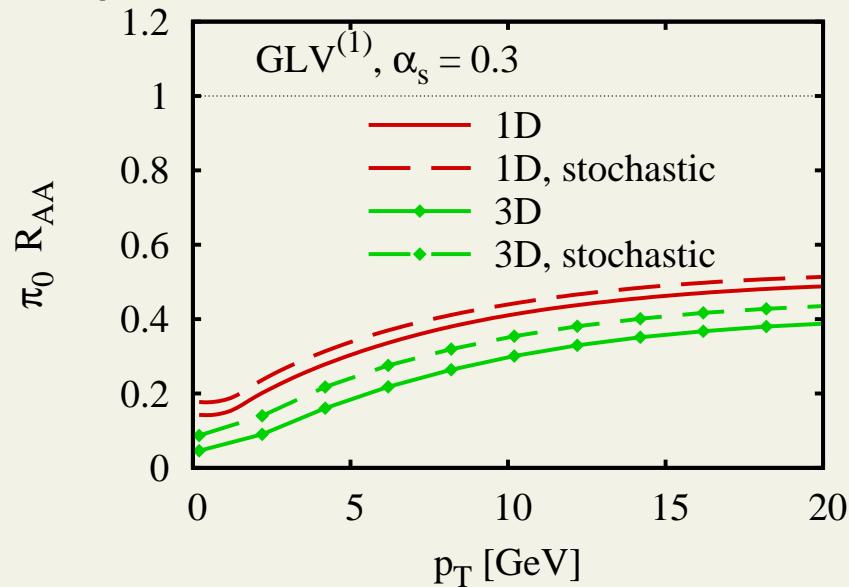
$$\langle \Delta E_{GLV}^{(1)} \rangle \approx \frac{9\pi C_R \alpha_s^3}{4} \int d\tau \tau \rho(z_0 + v\tau, \tau) \ln \frac{2E}{\mu^2 \tau}$$

$$\rightarrow \Delta E(z) = \frac{C_R \alpha_s}{2} \chi \mu^2(z)(z-z_0) \ln \frac{2E}{\mu^2(z)(z-z_0)} \quad , \quad p(z) = \frac{\sigma_{gg}(z)\rho(z, \tau=z-z_0)}{\chi}$$

light quark E-loss - Au+Au, 7fm (Gaussian profile as in Gyulassy et al PLB626 ('02))



pion R_{AA} , Glauber Au+Au, 8fm (linear stretching for transverse exp.)

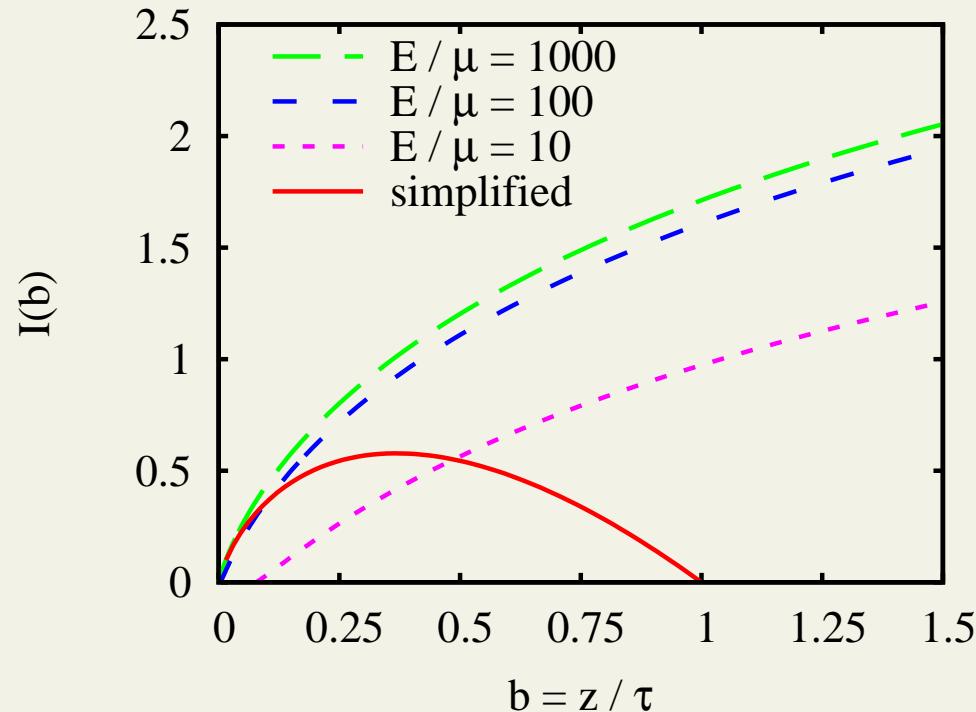


→ dynamics and fluctuations matter

Finite energy & kinematics also matter:

$$\begin{aligned} |k| &< \sim xE \\ |q| &< \sim \sqrt{s} \sim \sqrt{6ET} \\ xE &> \sim \mu \quad (\text{plasma}) \end{aligned}$$

$$\begin{aligned} \Delta E_{GLV}^{(1)}(z) &= \frac{C_R \alpha_s}{\pi^2} \chi \int dx dk dq \frac{\mu^2}{\pi(q^2 + \mu^2)^2} \frac{2k \cdot q}{k^2(k - q)^2} (1 - \cos \omega \Delta z) \\ &\equiv \frac{2C_R \alpha_s}{\pi} E \chi I(\Delta z/\tau(z), E/\mu(z)) , \quad \omega \equiv \mu^2/(2Ex) \end{aligned}$$



$$\tau(z) \equiv \frac{2E}{\mu^2(z)}$$

$$I(\Delta z \ll \tau, \infty) \approx \frac{\pi \mu^2 \Delta z}{4E} \ln \frac{2E}{\mu^2 \Delta z}$$

Same 4 scenarios:

1D = Bjorken $\rho(\tau) \propto 1/\tau$ expansion, $\langle \Delta E \rangle$

1D, stochastic = Bjorken $\rho(\tau) \propto 1/\tau$ expansion, $\Delta E(z)$

3D = Bjorken AND transverse expansion, $\langle \Delta E \rangle$

3D, stochastic = Bjorken AND transverse expansion, $\Delta E(z)$

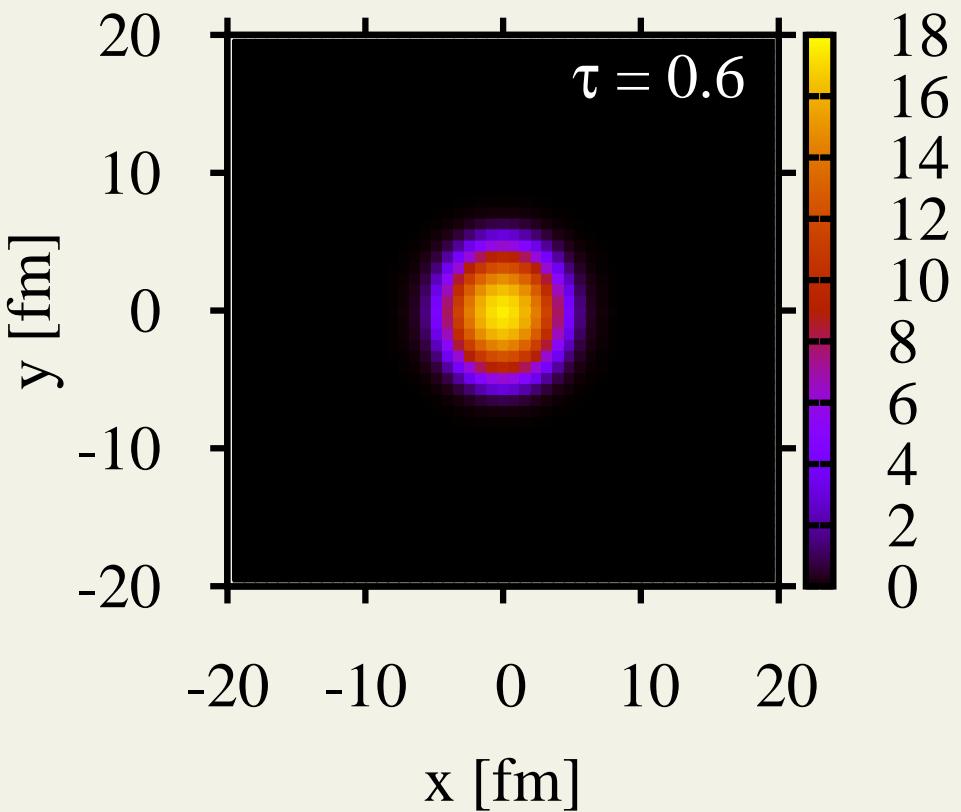
but now GLV with kinematic cutoffs.

Medium evolution from kinetic theory (MPC transport code):

- $2 \rightarrow 2$ with massless gluons
- opacity set to generate sufficient $v_2(p_T) \sim 0.2$ at RHIC
- $\eta/s \approx 0.1$ dynamics via $\sigma_{gg} \sim 1/T^2 \sim \tau^{2/3}$
- jet and bulk transverse profiles $\propto \rho^{binary}(x_\perp)$, with $dN^{bulk}/dy \propto N_{part}$
- T set by $\rho(T)$ for massless gluon gas, $\mu_D = gT$
- $\tau_0 = 0.6$ fm formation, and LINEAR $\rho(\tau) \propto \tau$ for $\tau < \tau_0$

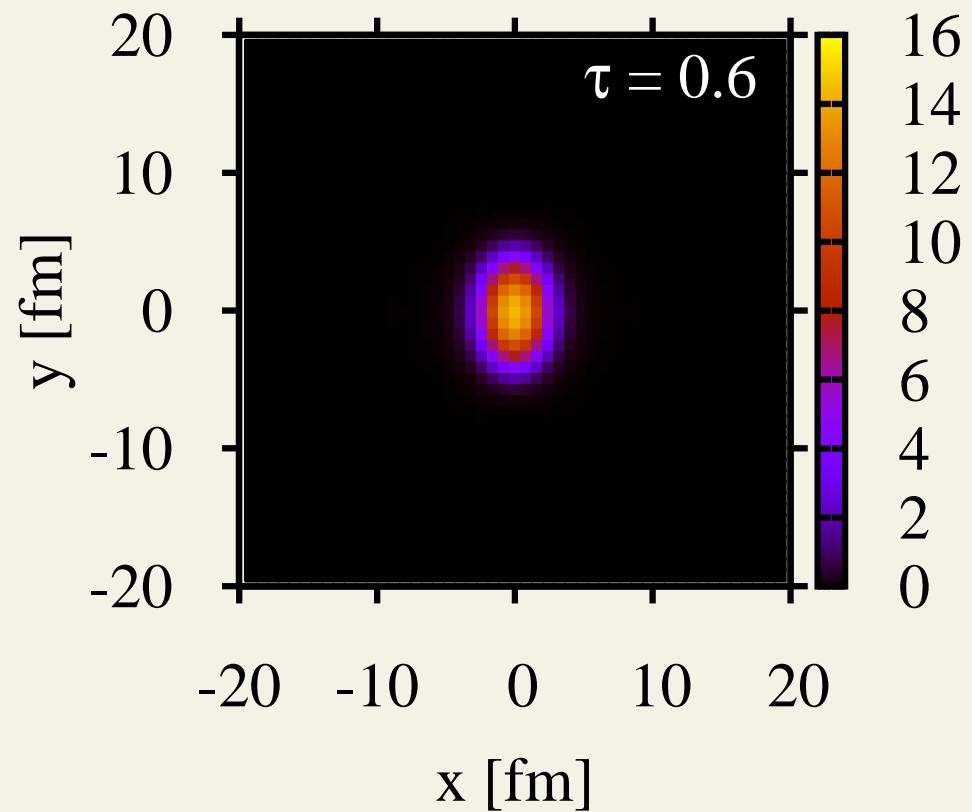
Au+Au, $b=3$ fm

$$\tau \rho [1/\text{fm}^2]$$



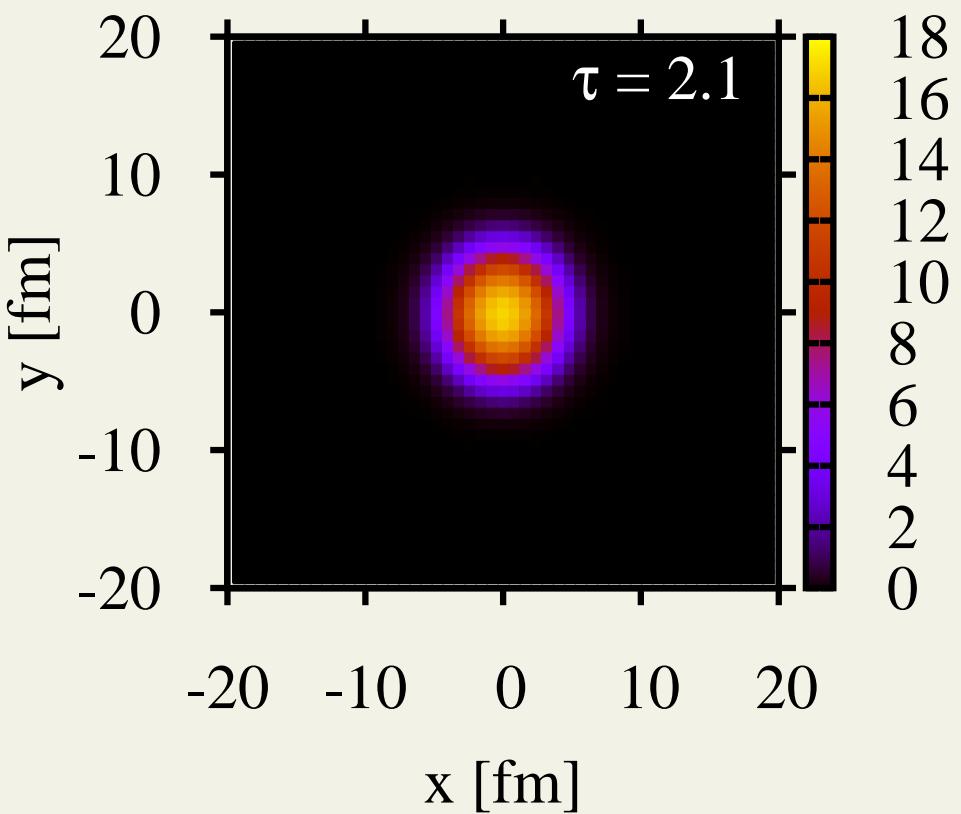
Au+Au, $b=8$ fm

$$\tau \rho [1/\text{fm}^2]$$



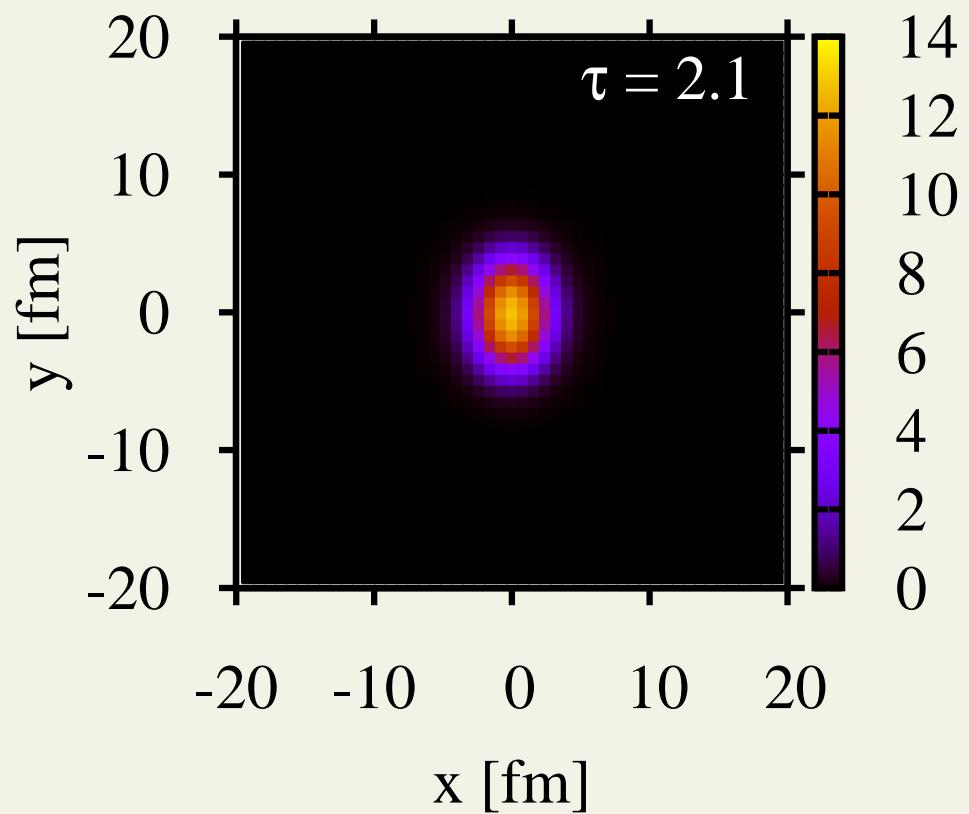
Au+Au, $b=3$ fm

$$\tau \rho [1/\text{fm}^2]$$



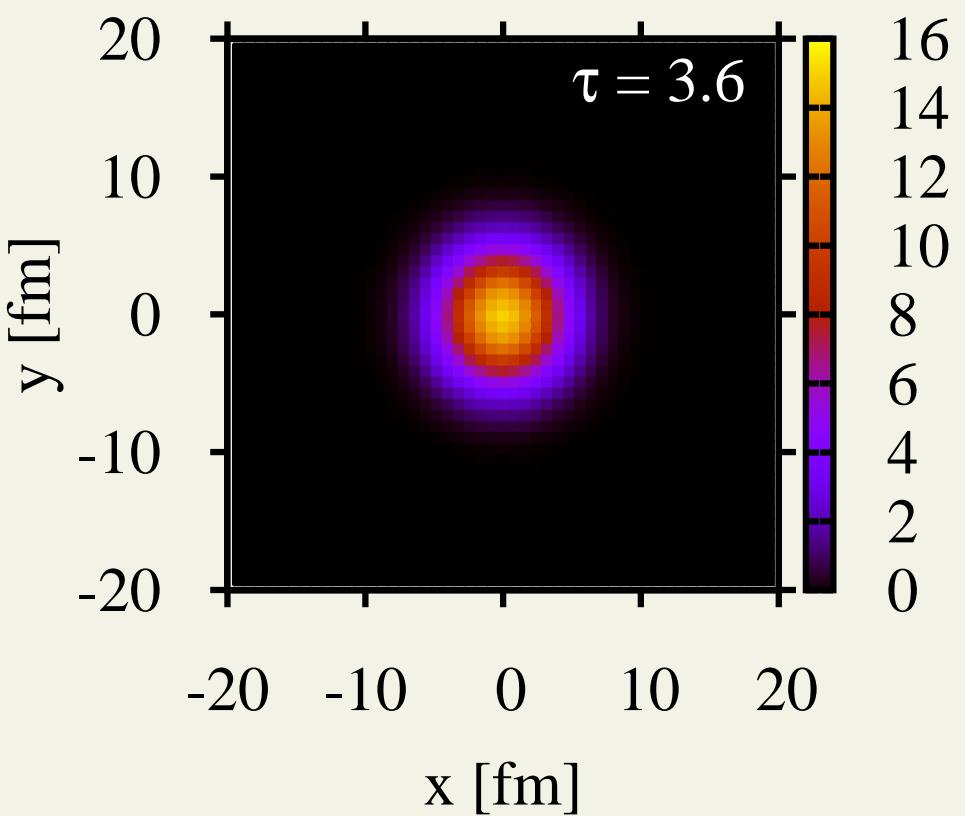
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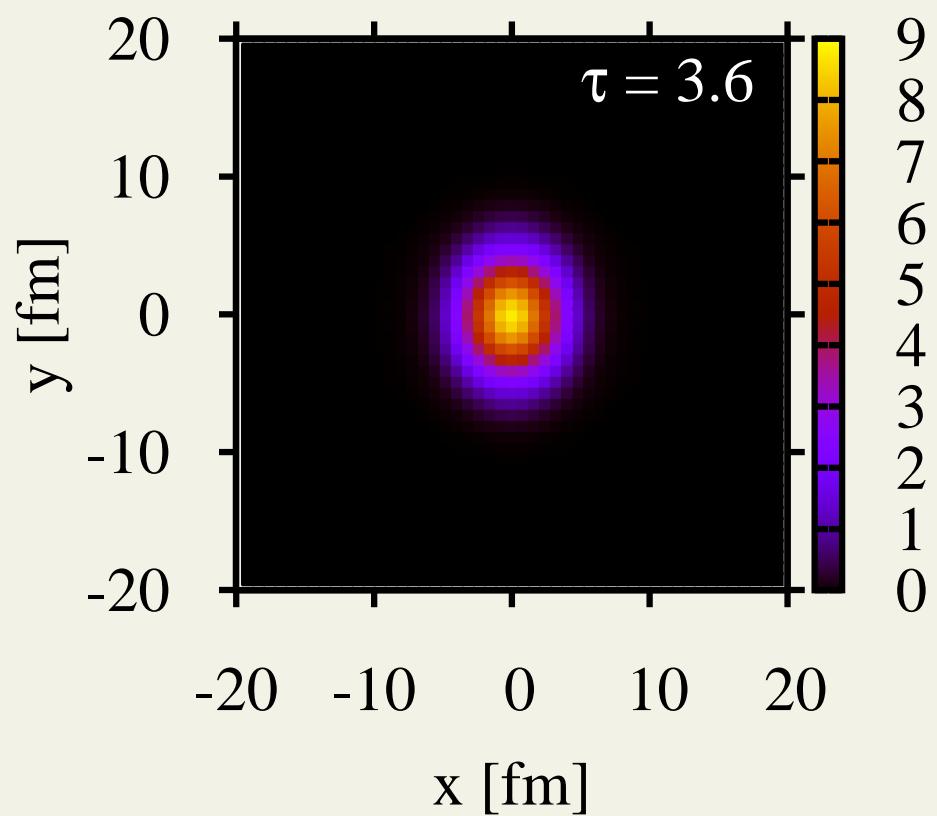
Au+Au, $b=3$ fm

$\tau \rho [1/\text{fm}^2]$



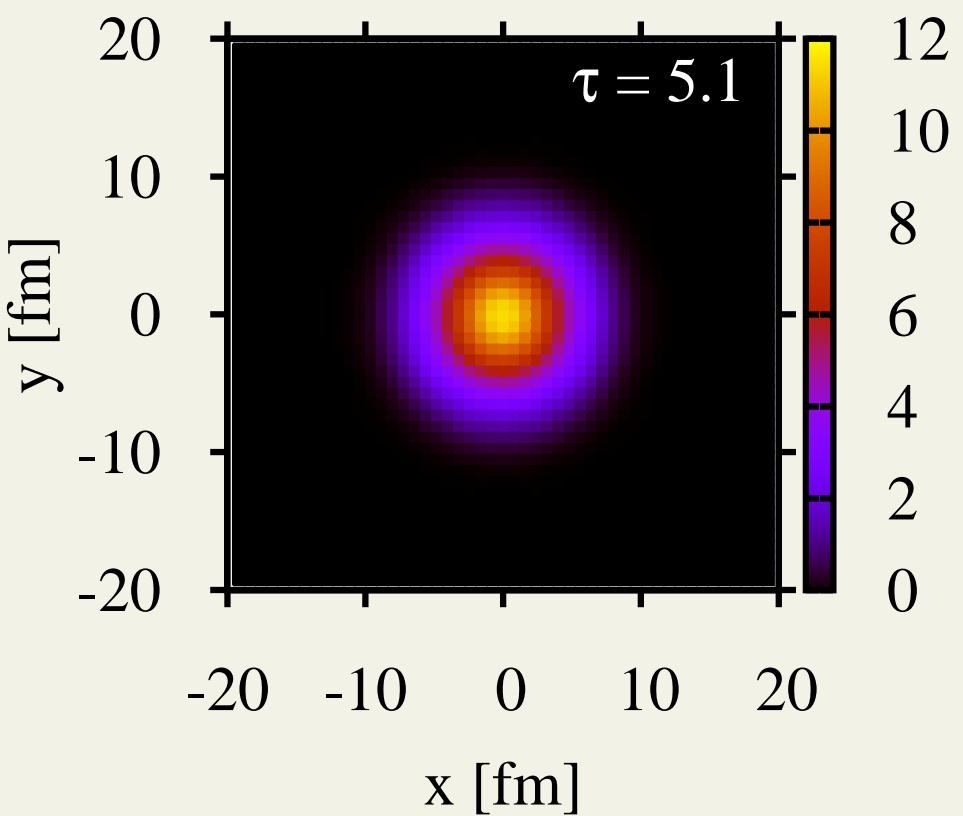
Au+Au, $b=8$ fm

$\tau \rho [1/\text{fm}^2]$



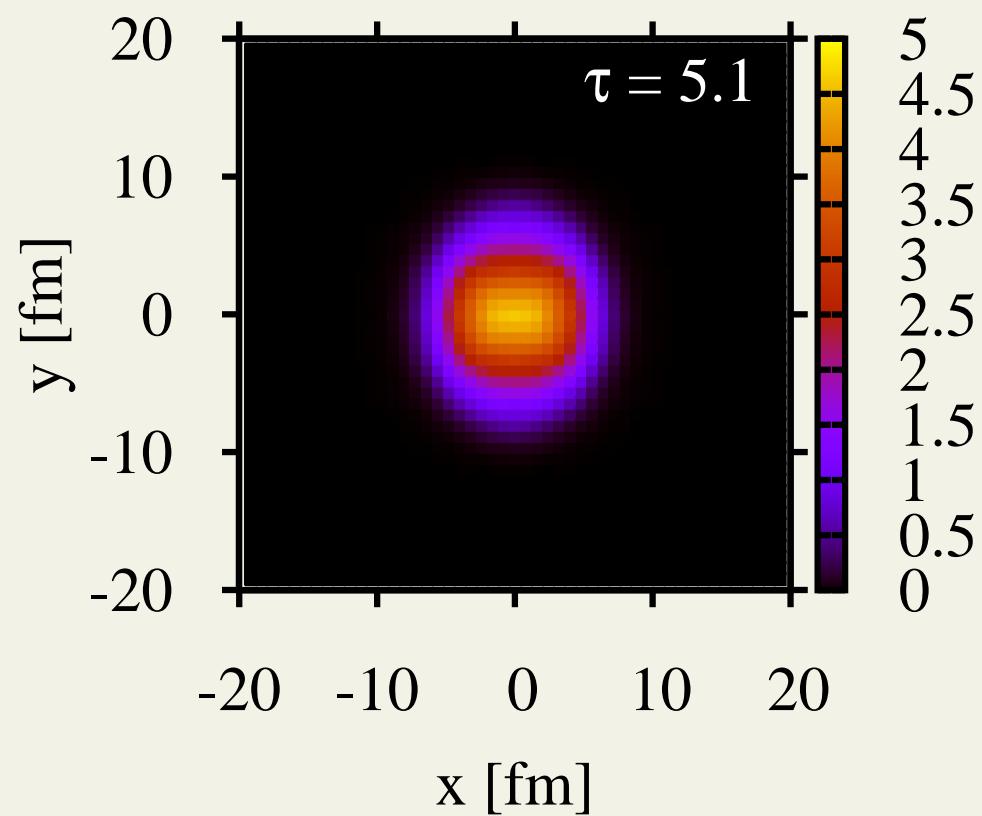
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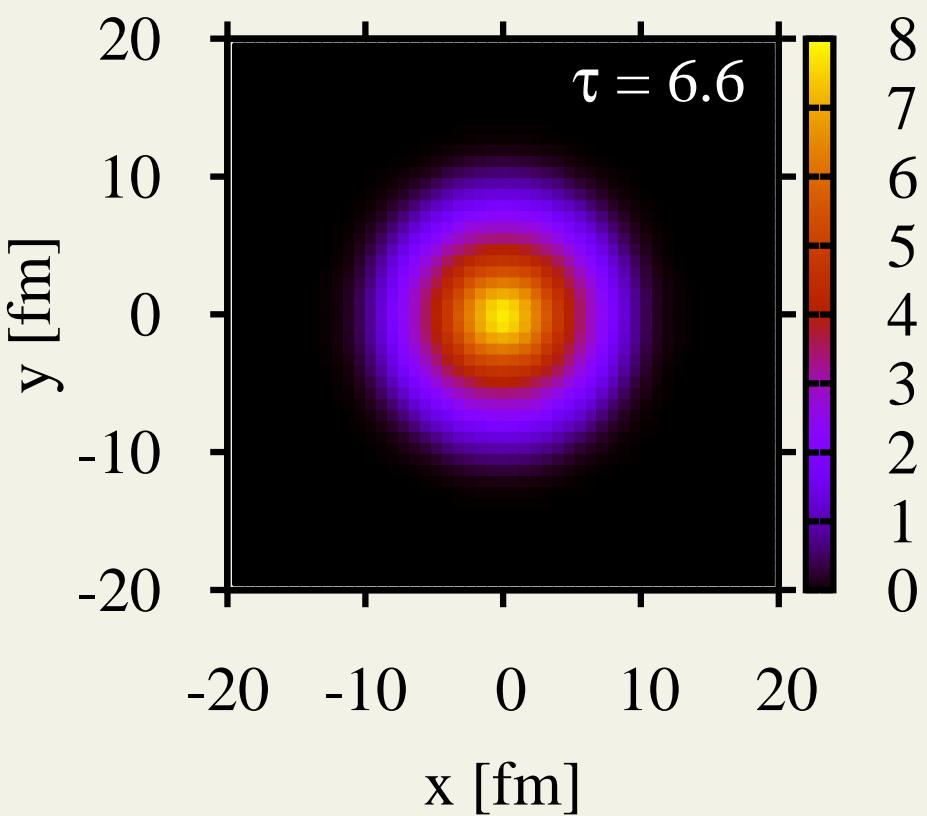
Au+Au, $b=8$ fm

$\tau \rho [1/\text{fm}^2]$



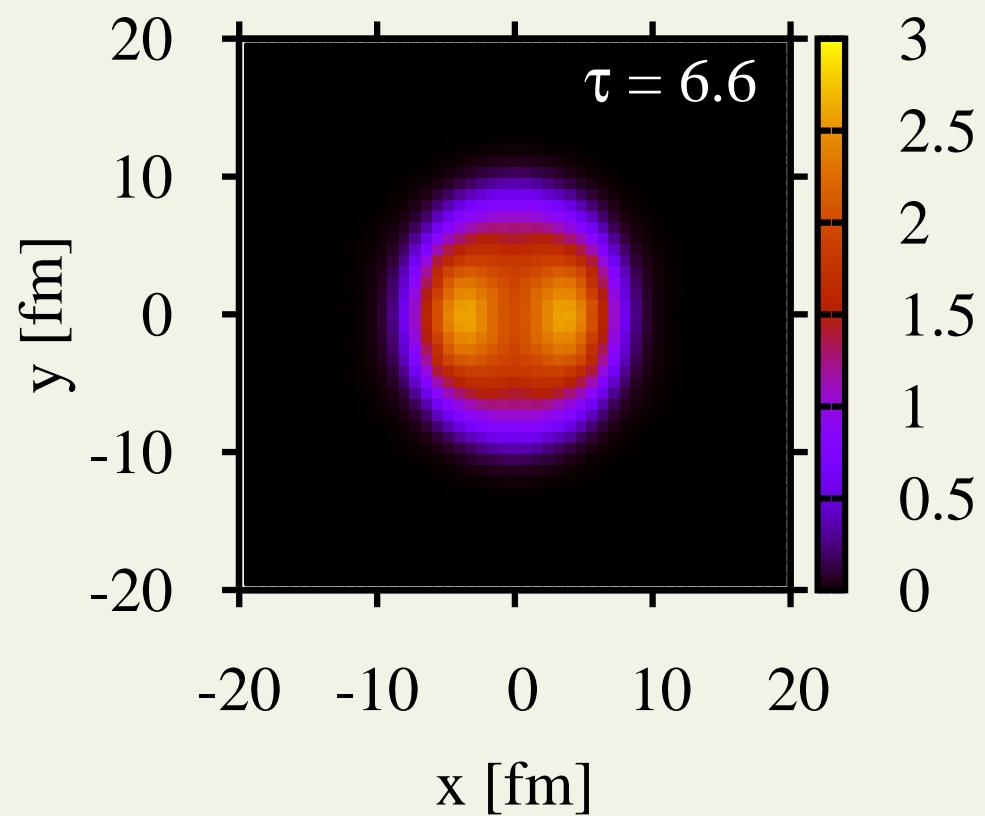
Au+Au, $b=3$ fm

$$\tau \rho [1/\text{fm}^2]$$



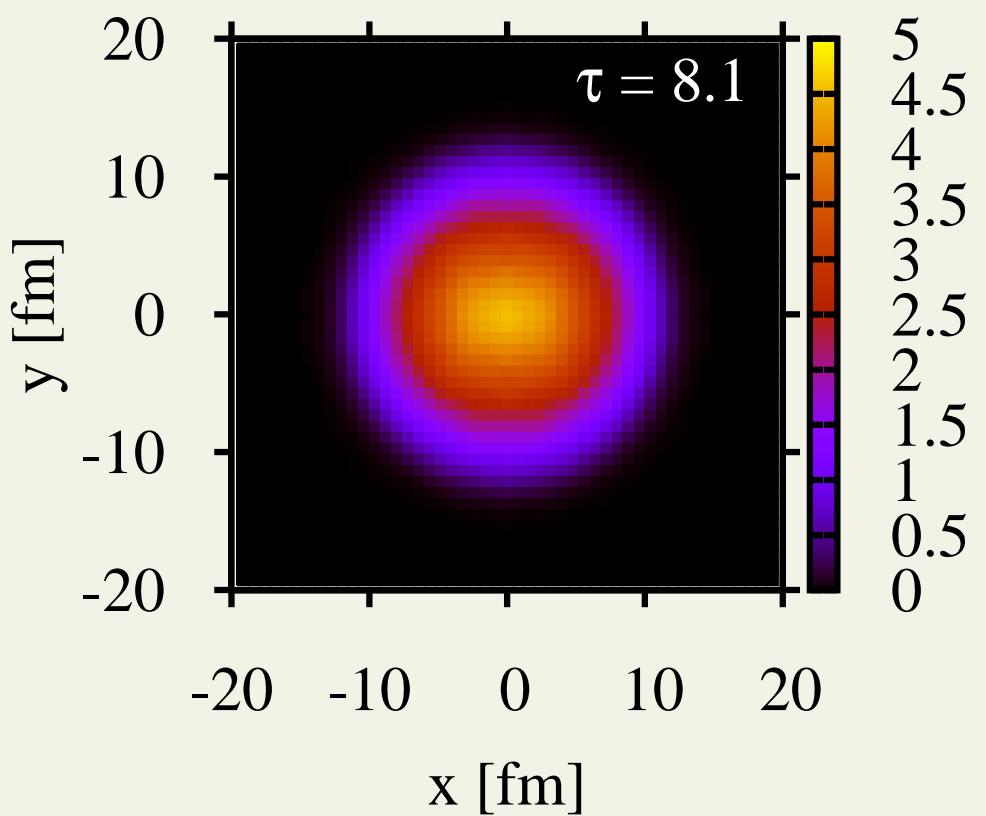
Au+Au, $b=8$ fm

$$\tau \rho [1/\text{fm}^2]$$



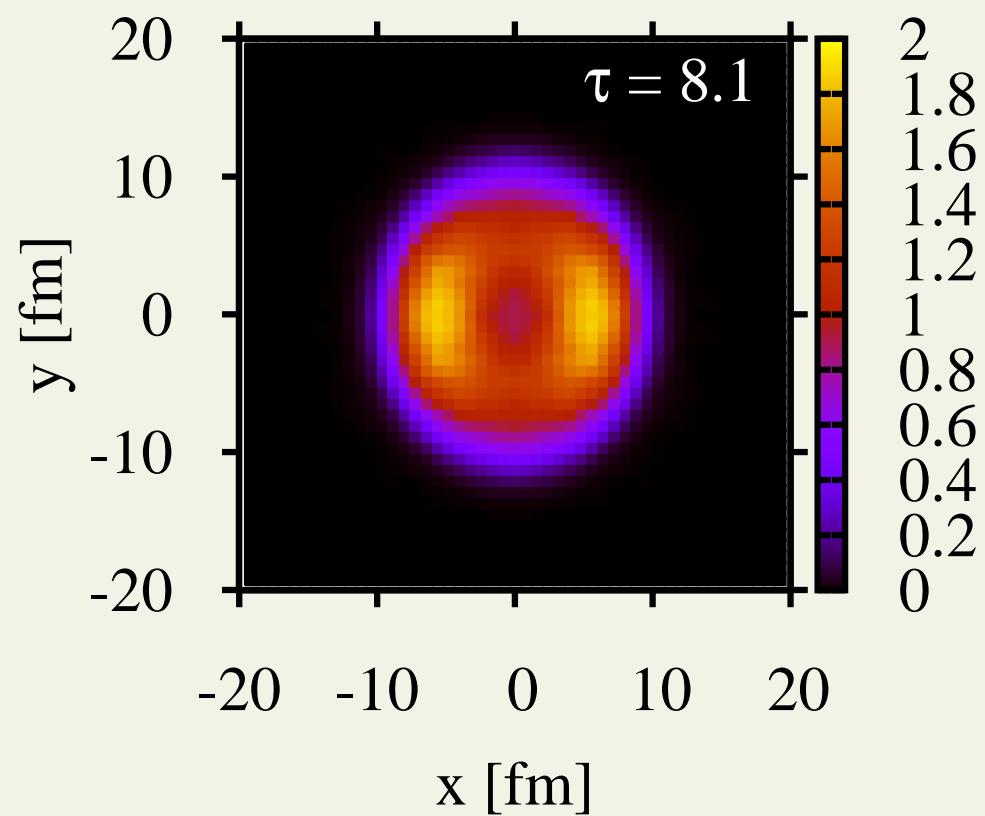
Au+Au, $b=3$ fm

$$\tau \rho [1/\text{fm}^2]$$



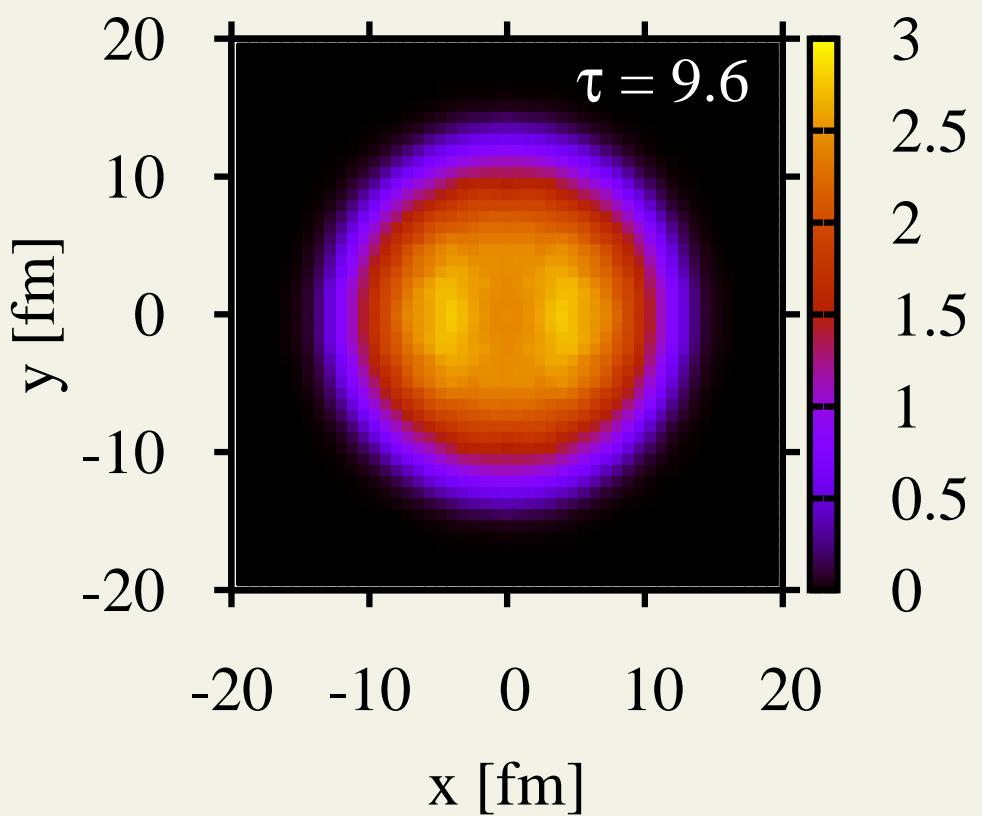
Au+Au, $b=8$ fm

$$\tau \rho [1/\text{fm}^2]$$



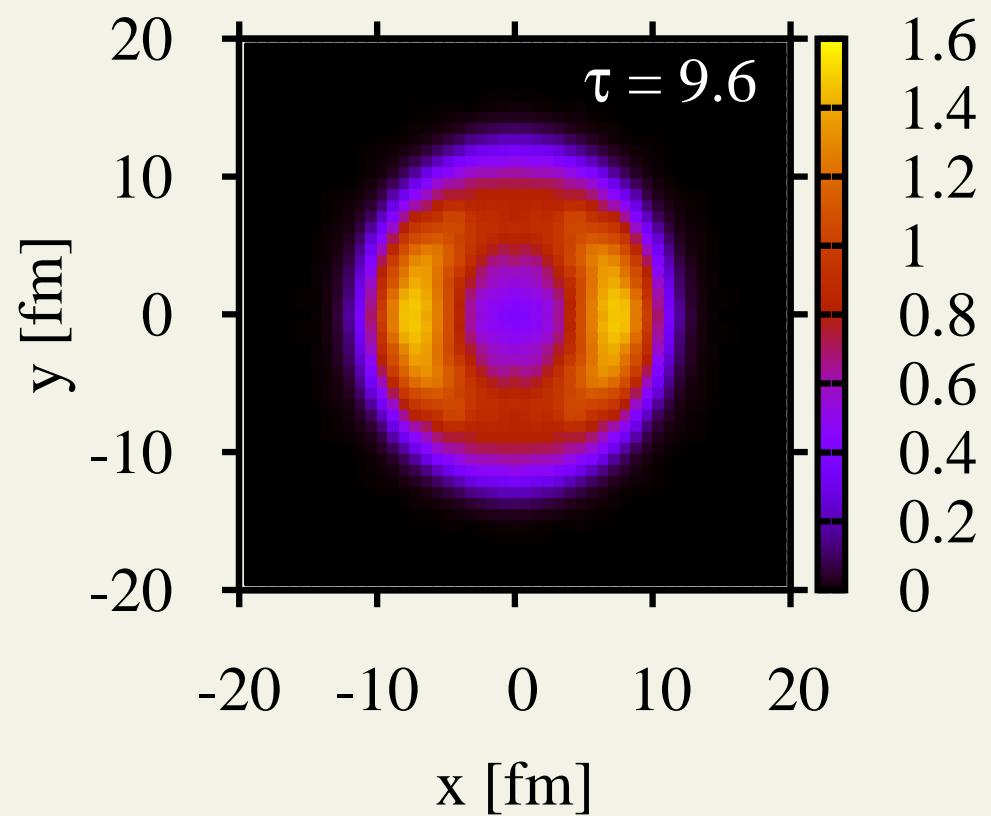
Au+Au, $b=3$ fm

$\tau \rho [1/\text{fm}^2]$



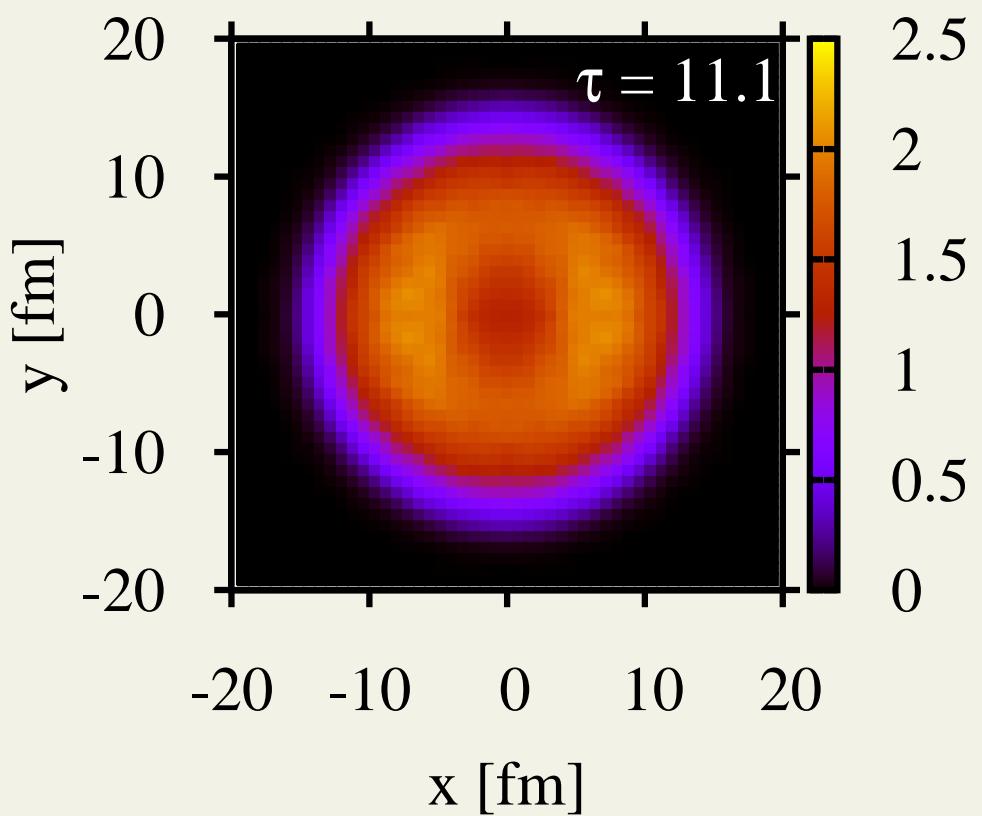
Au+Au, $b=8$ fm

$\tau \rho [1/\text{fm}^2]$



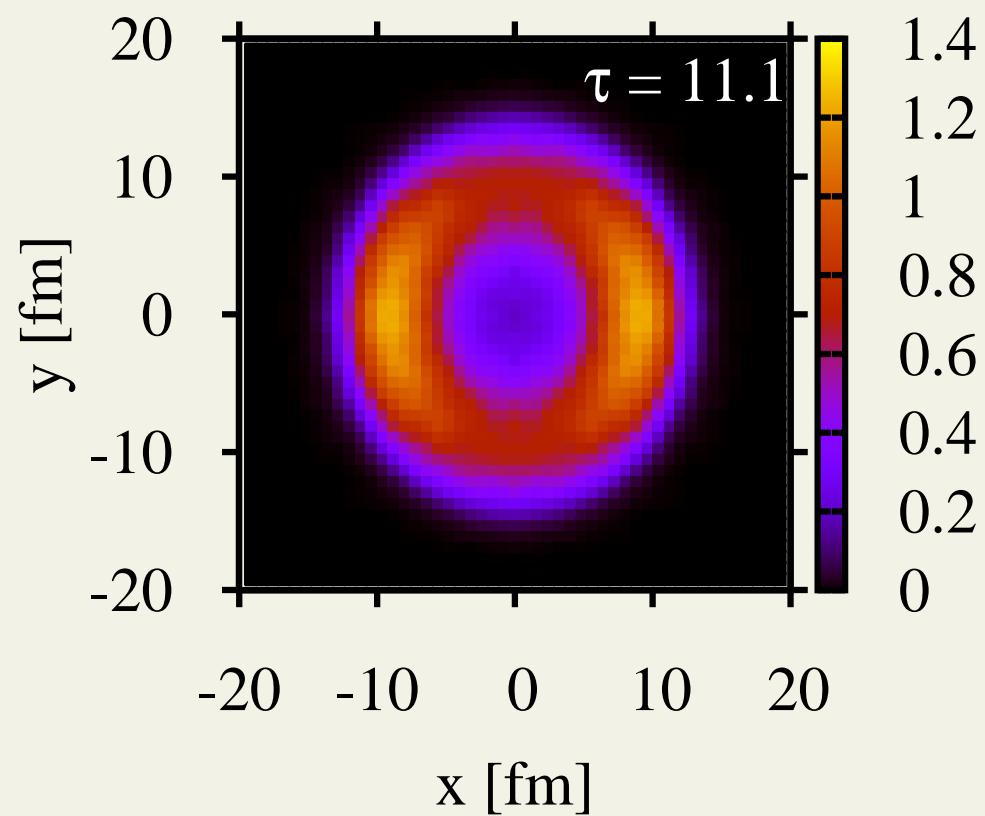
Au+Au, $b=3$ fm

$$\tau \rho [1/\text{fm}^2]$$



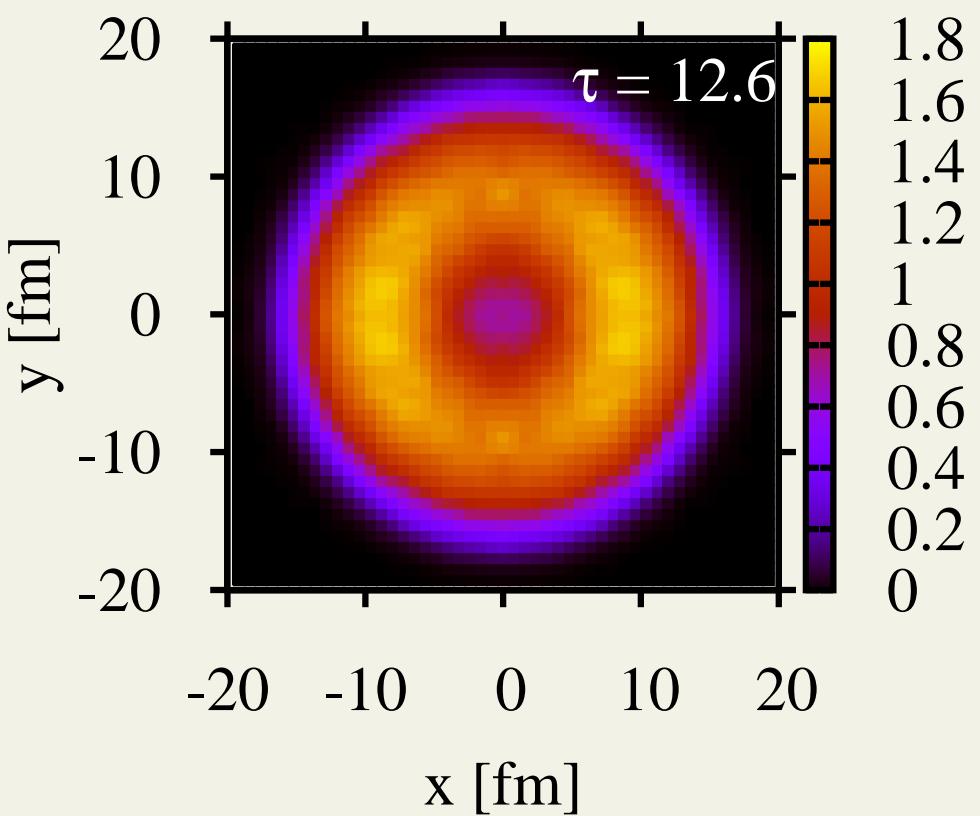
Au+Au, $b=8$ fm

$$\tau \rho [1/\text{fm}^2]$$



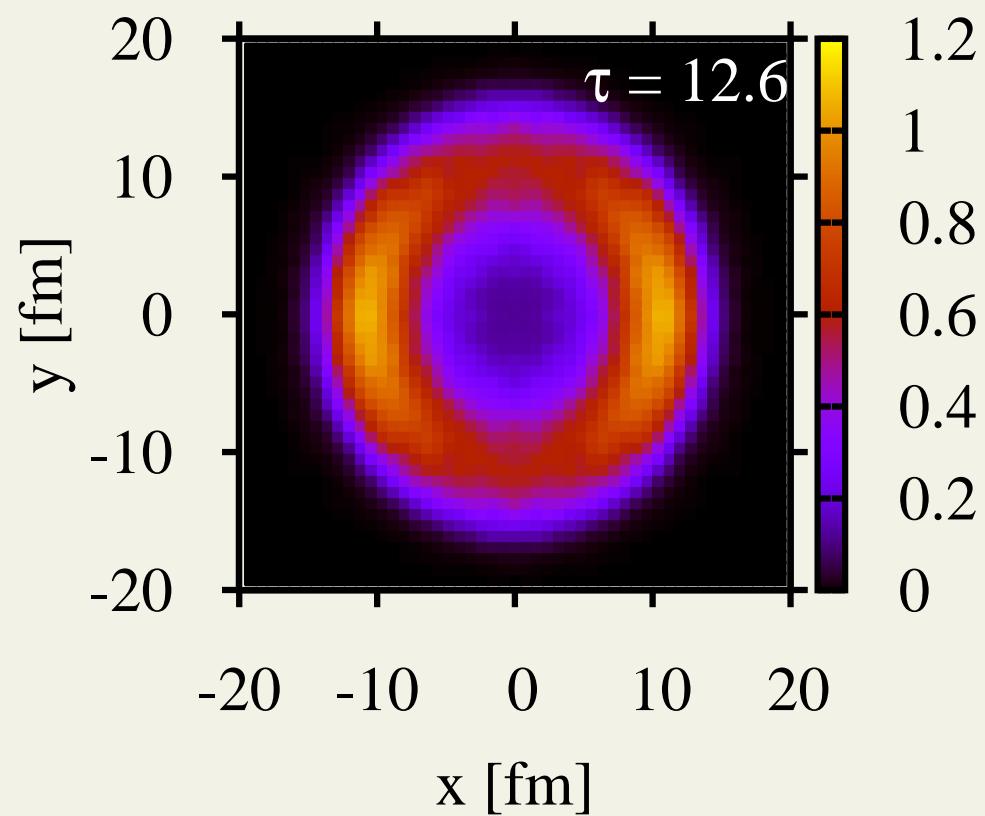
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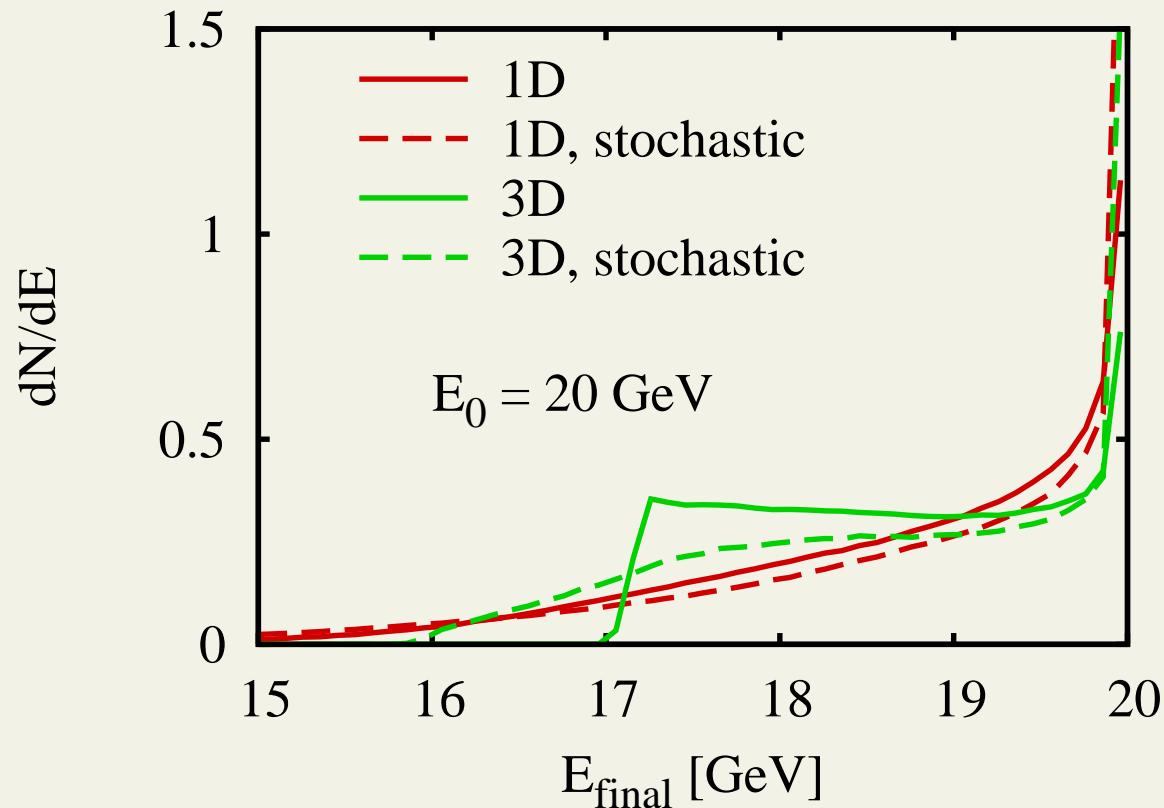


Au+Au, $b=8$ fm

$$\tau \rho [1/\text{fm}^2]$$



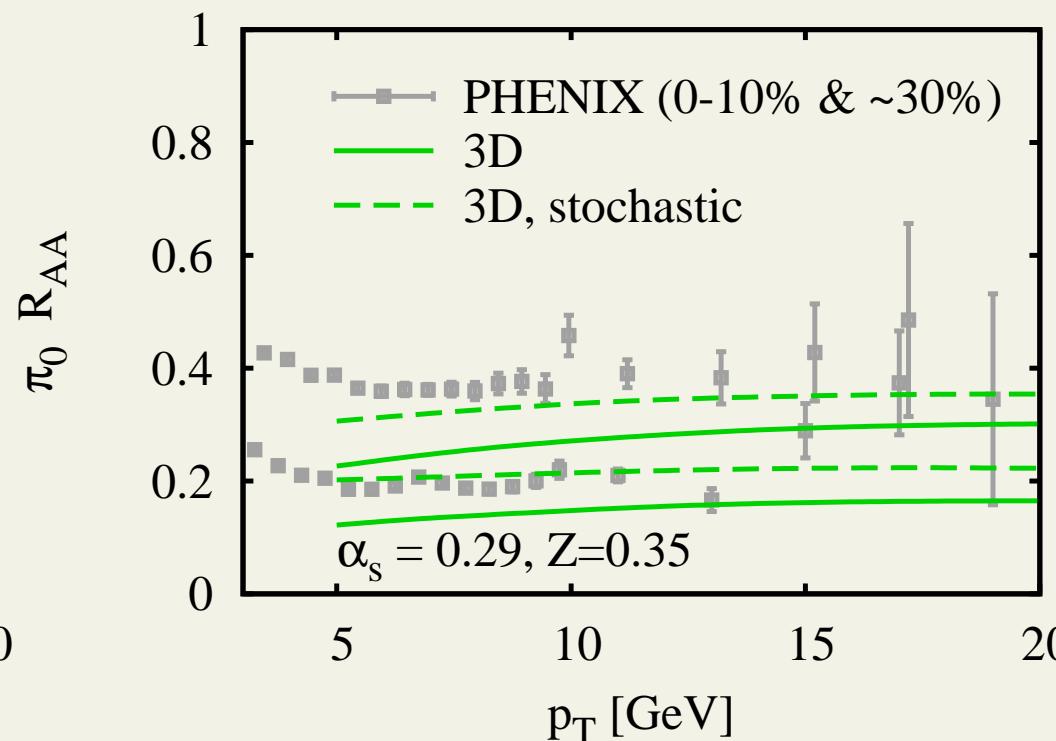
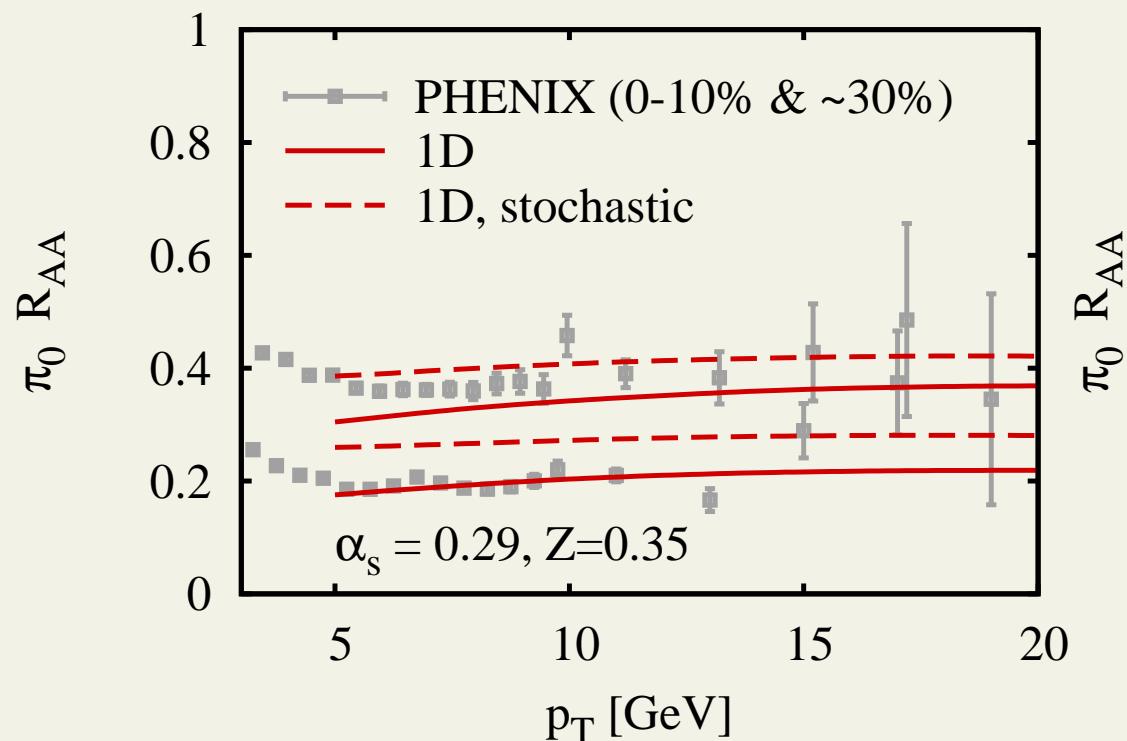
E-loss for 20 GeV gluons - Au+Au, b=8 fm



→ **more fluctuations with stochastic**

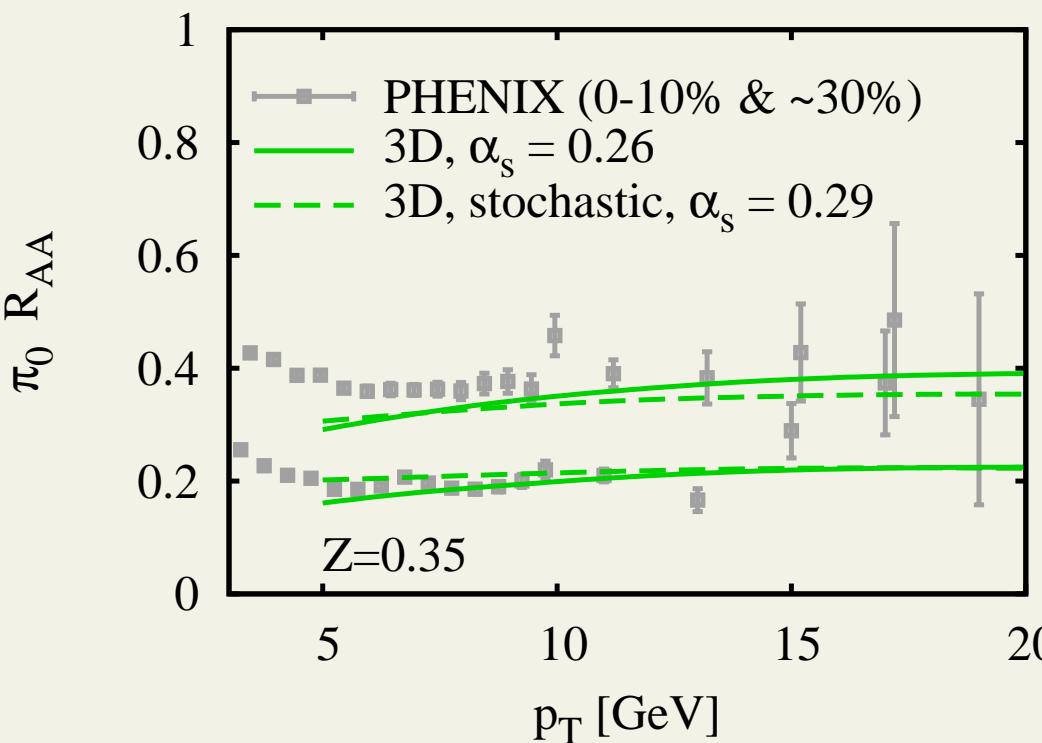
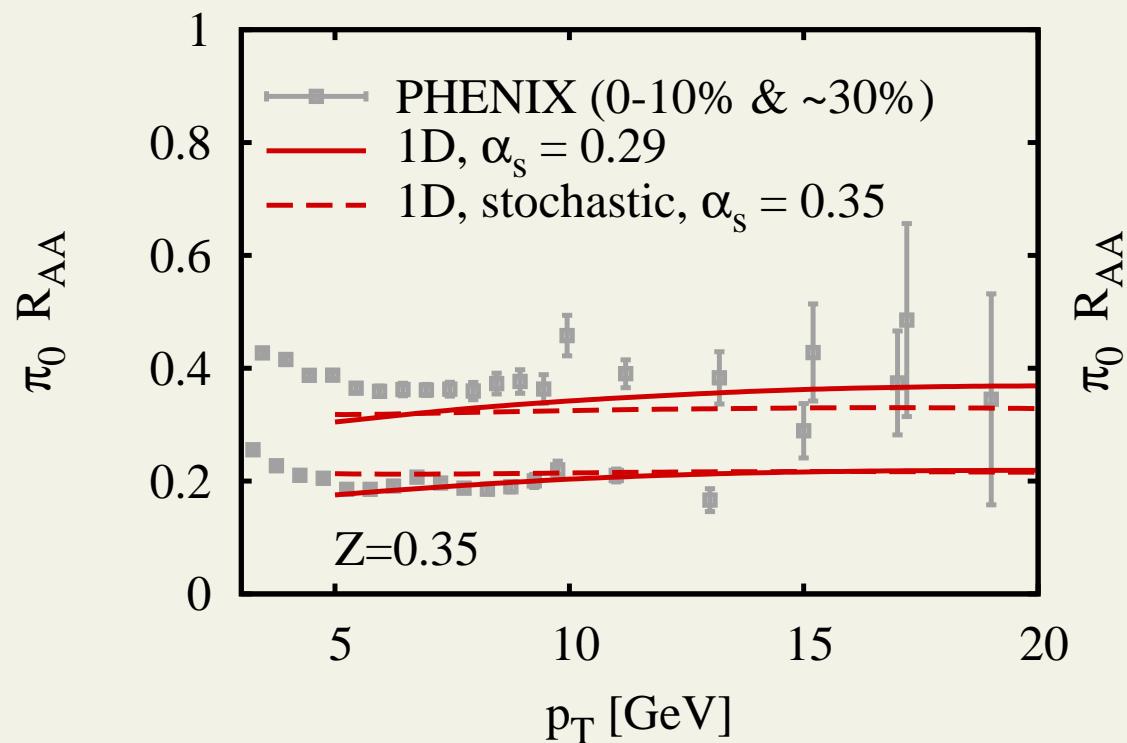
→ **less(!) fluctuations with expansion**

pion RAA, RHIC



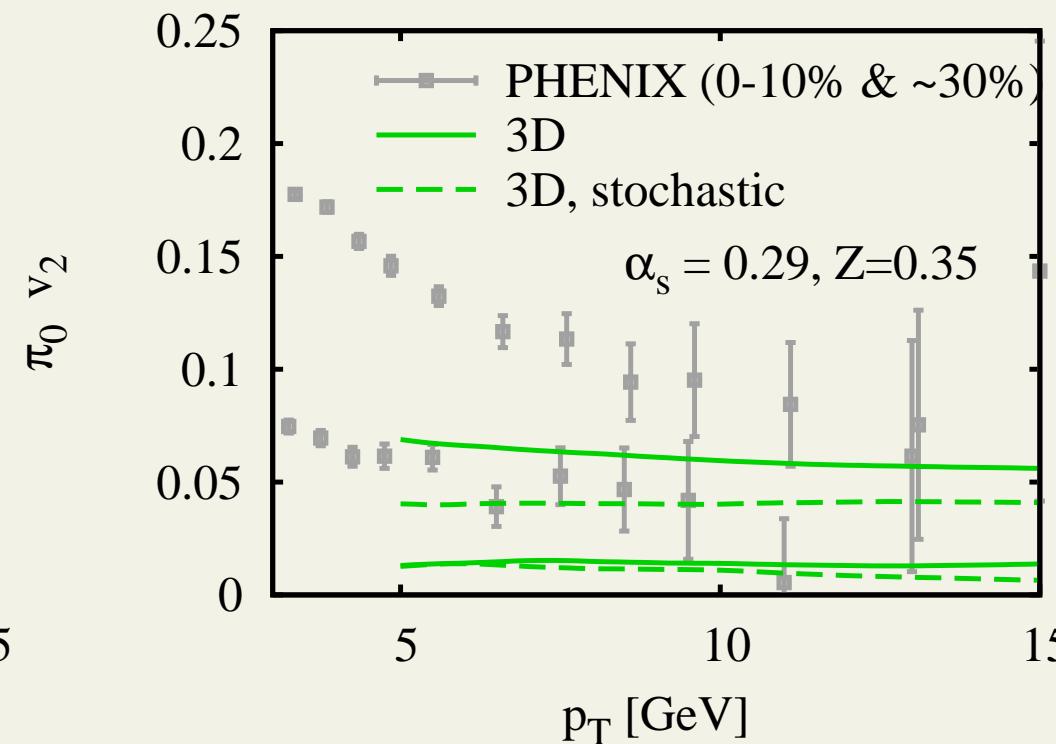
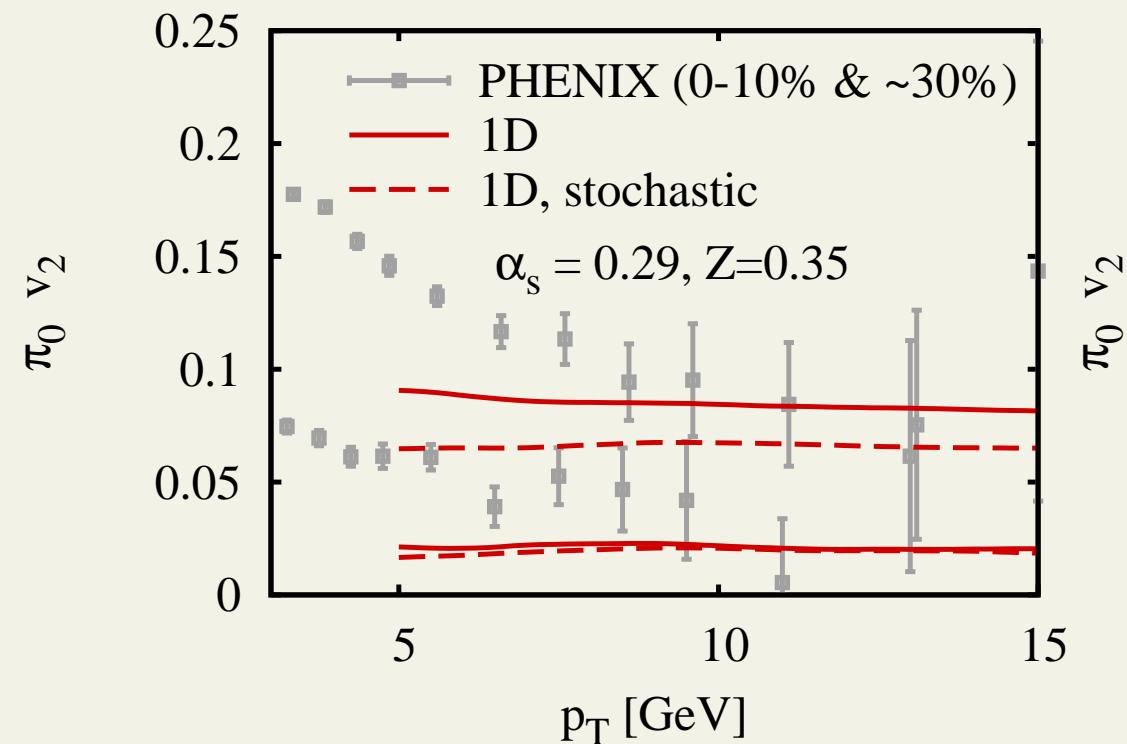
significant effect from fluctuations and transverse expansion

pion RAA, RHIC - α_s scaled to RAA for central

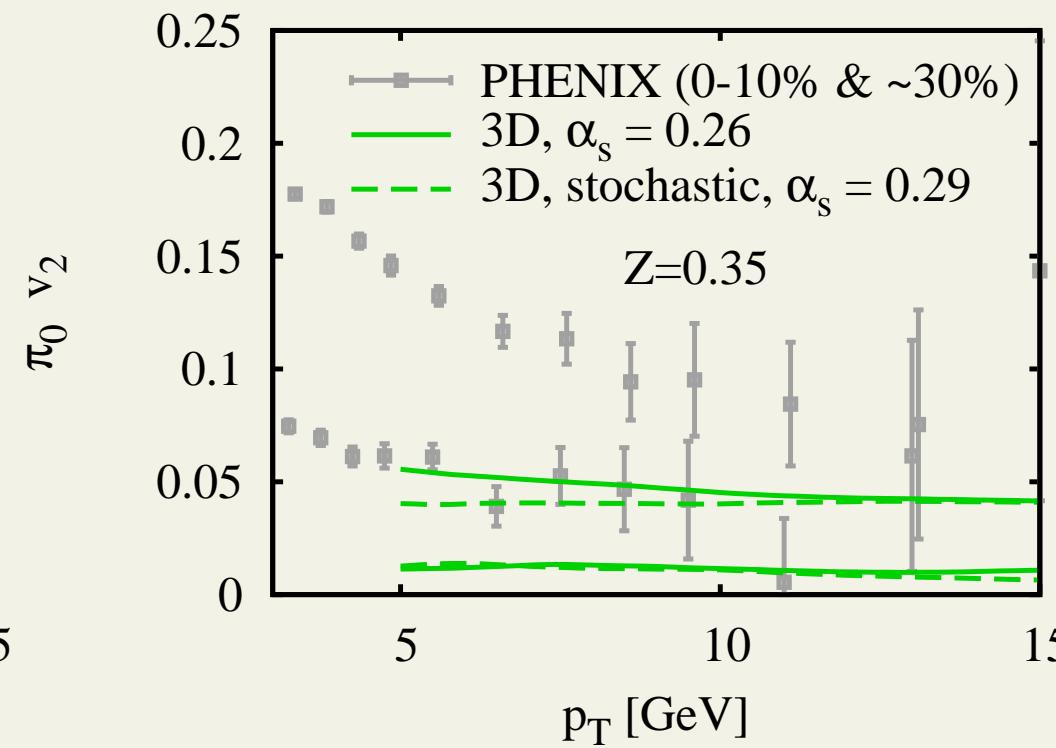
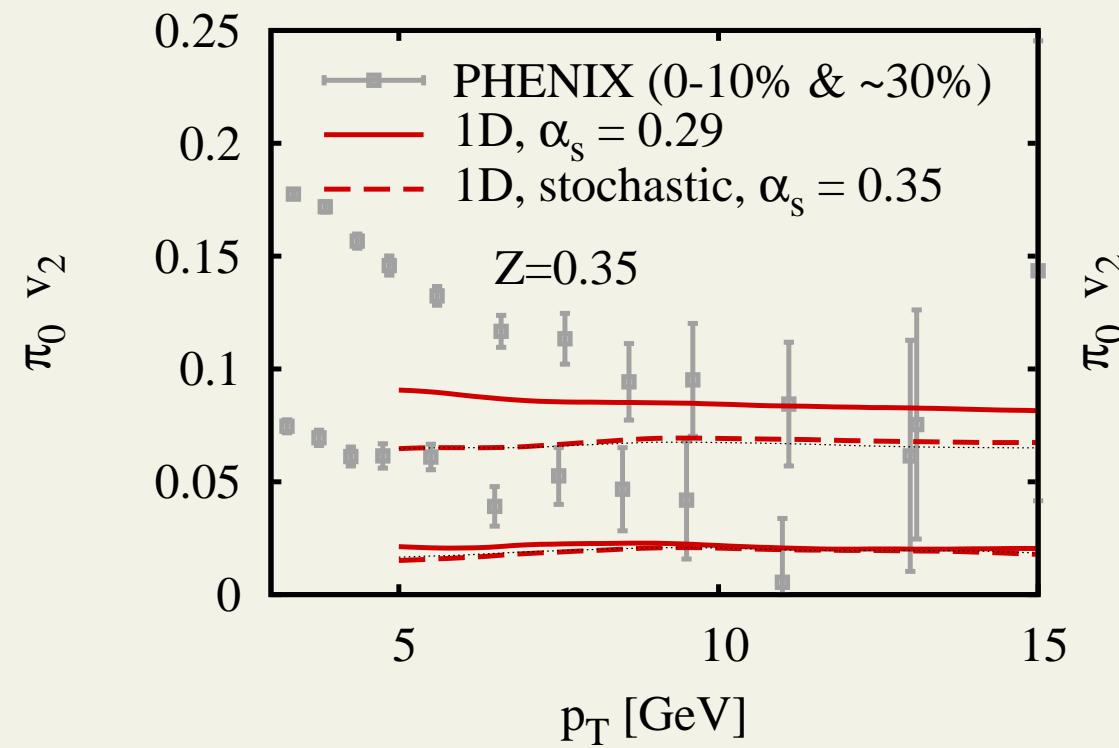


only small 10-15% differences after tuning parameters to central data

pion v_2 , RHIC



pion v_2 , RHIC - α_s scaled to RAA for central

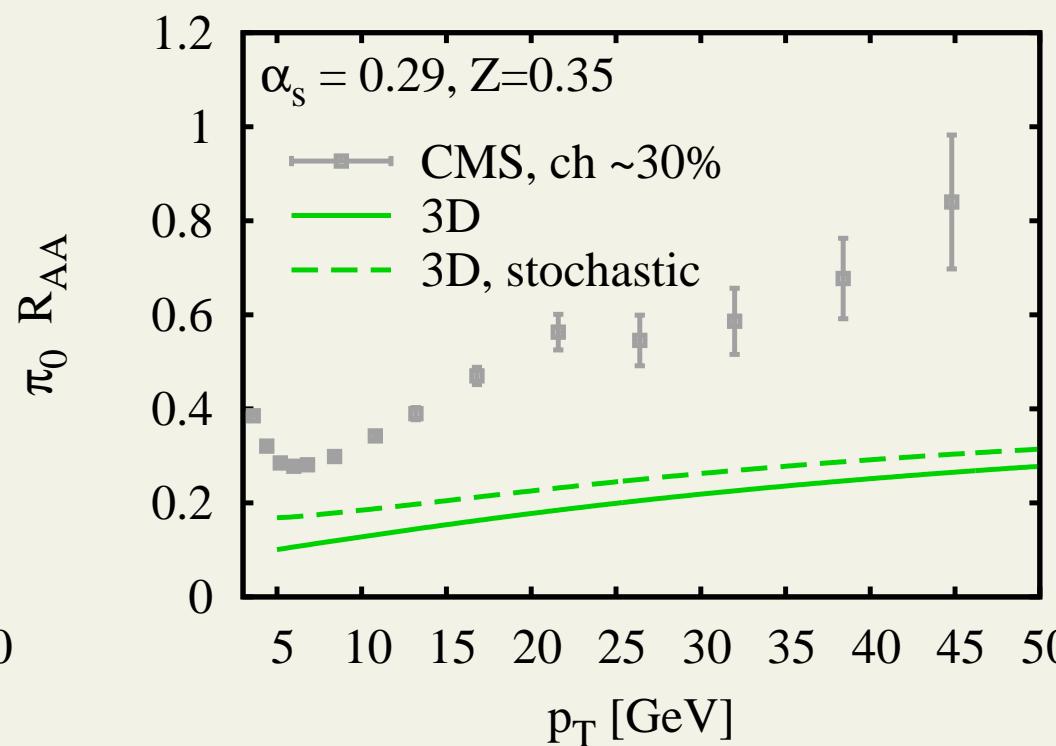
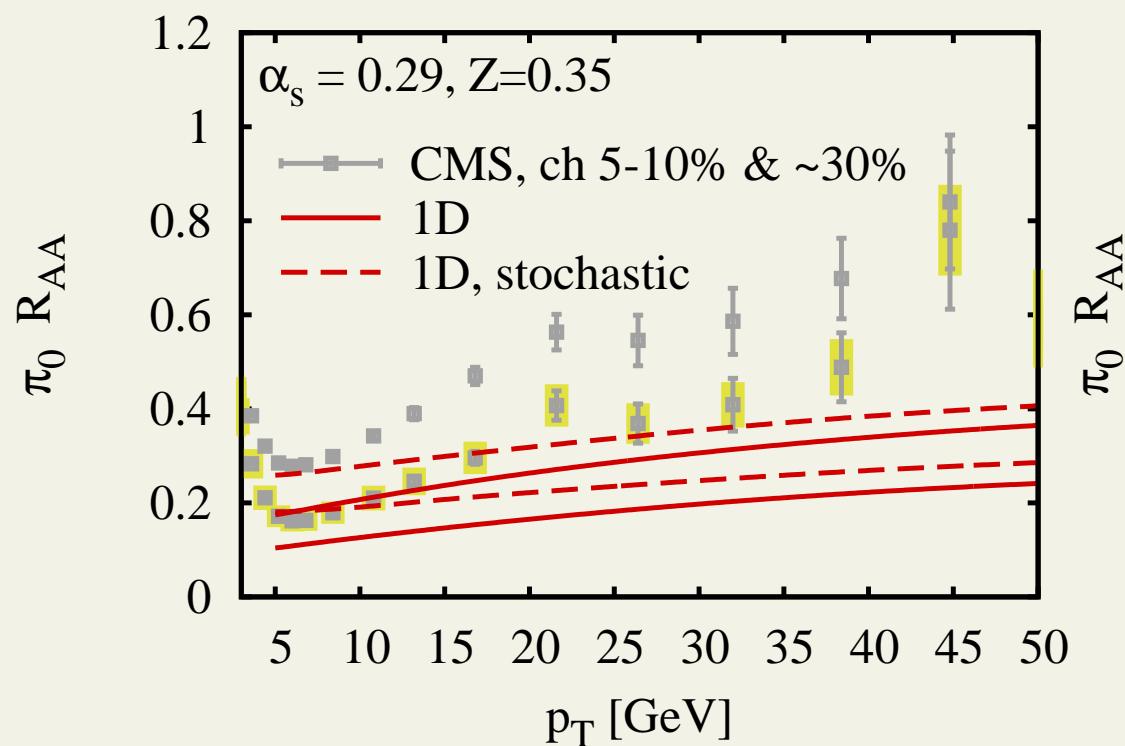


challenging to get enough $v_2 > 4 - 5\%$ with expanding medium

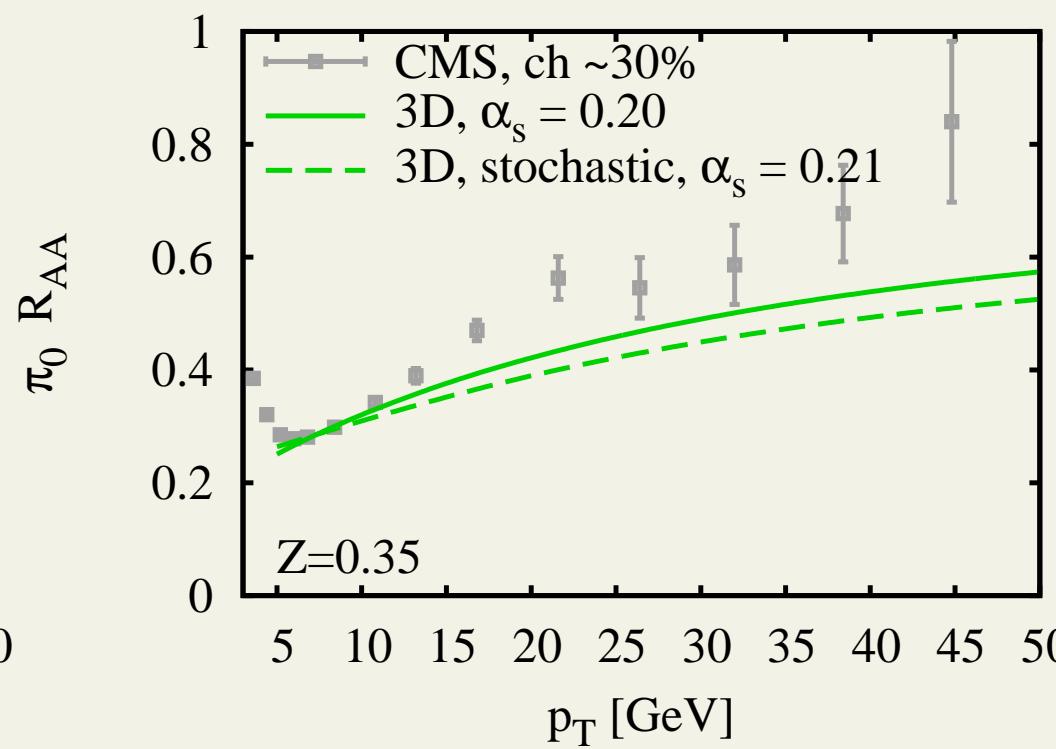
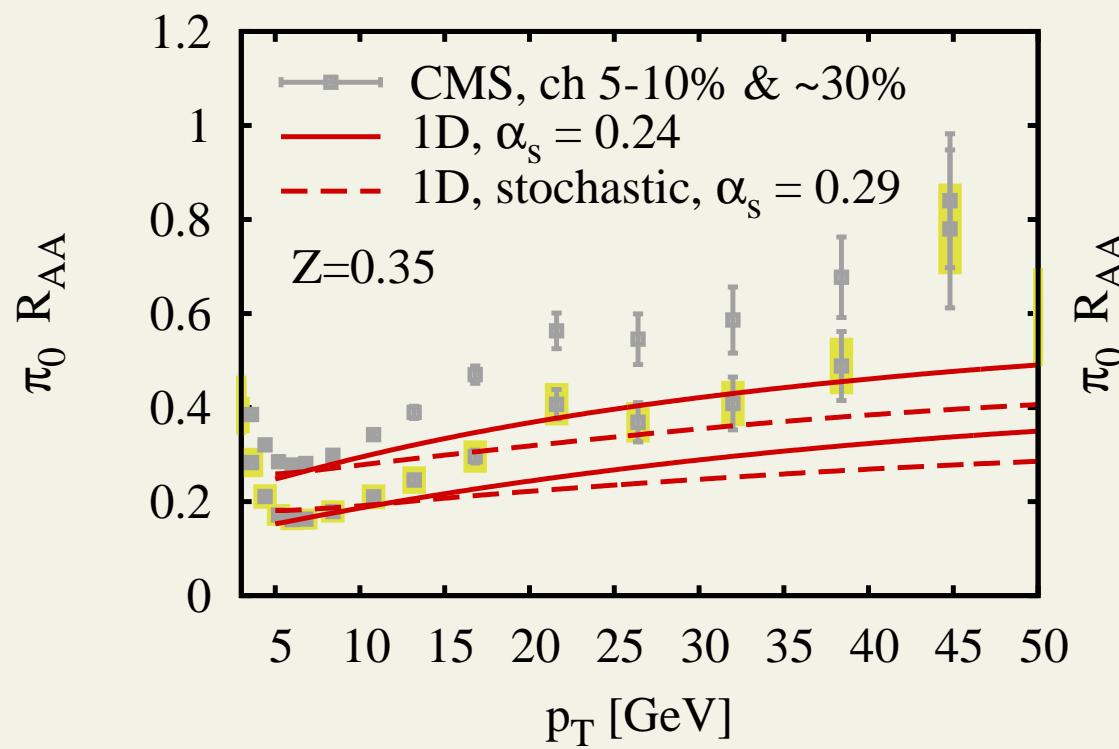
Now move to LHC energies. Simple assumption:

- higher $dN/d\eta = 2400$ in central collisions ($b = 0$)
- all other ingredients stay same

pion RAA, LHC

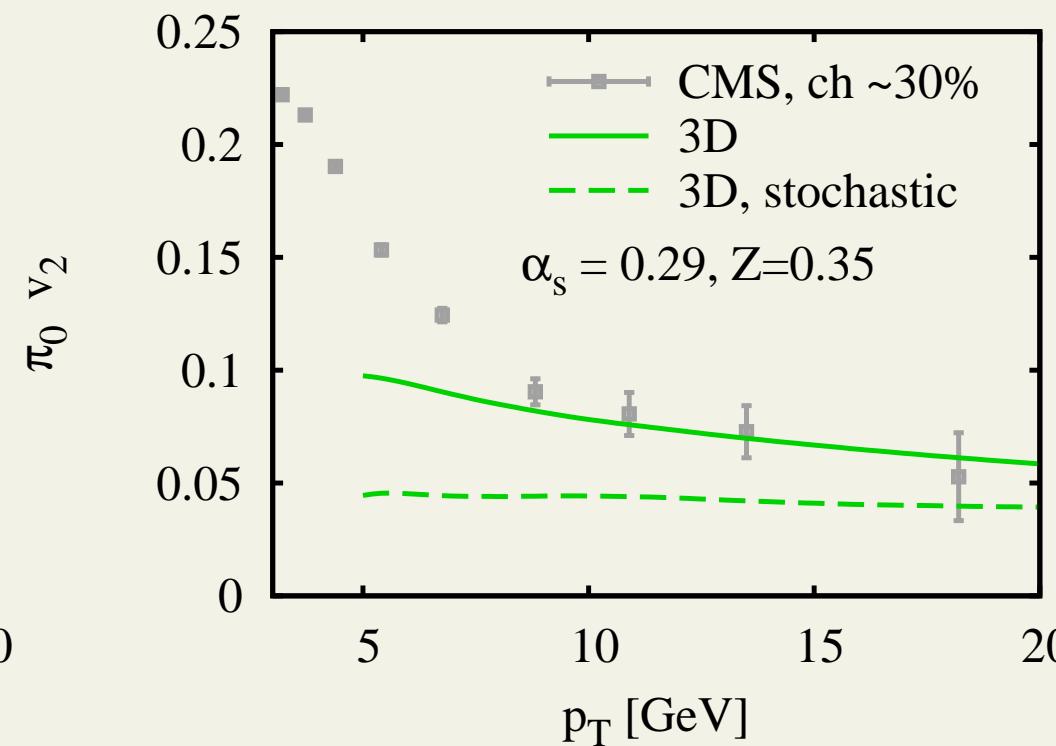
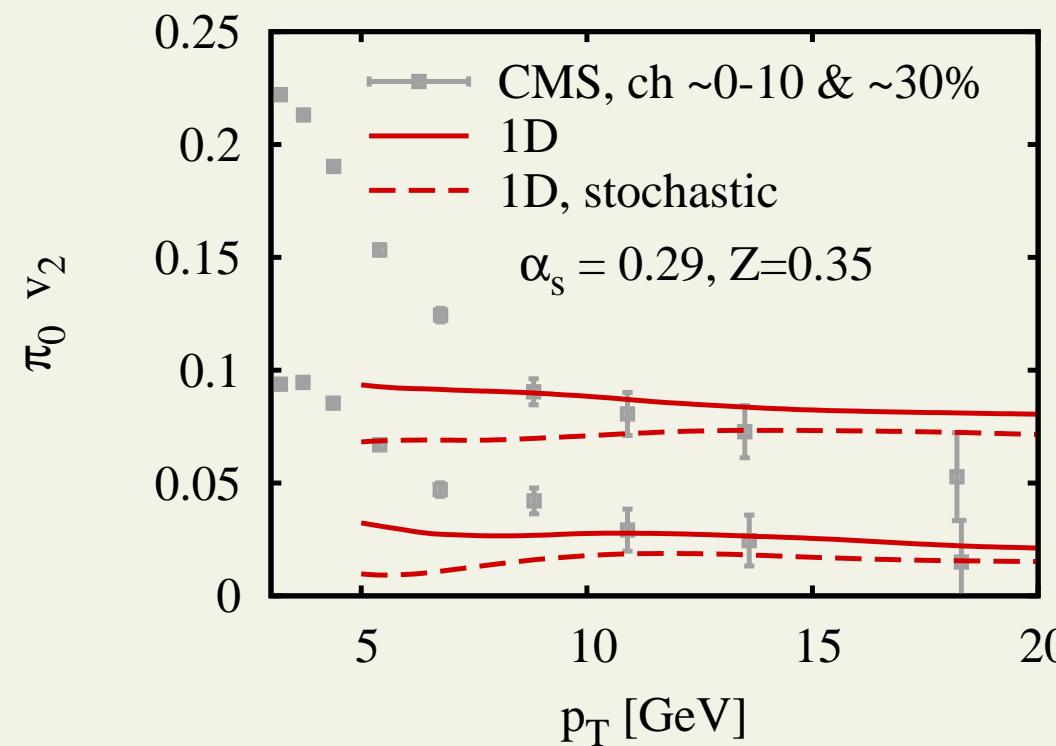


pion v2, RHIC - α_s scaled to RAA for central at $pT = 6$ GeV

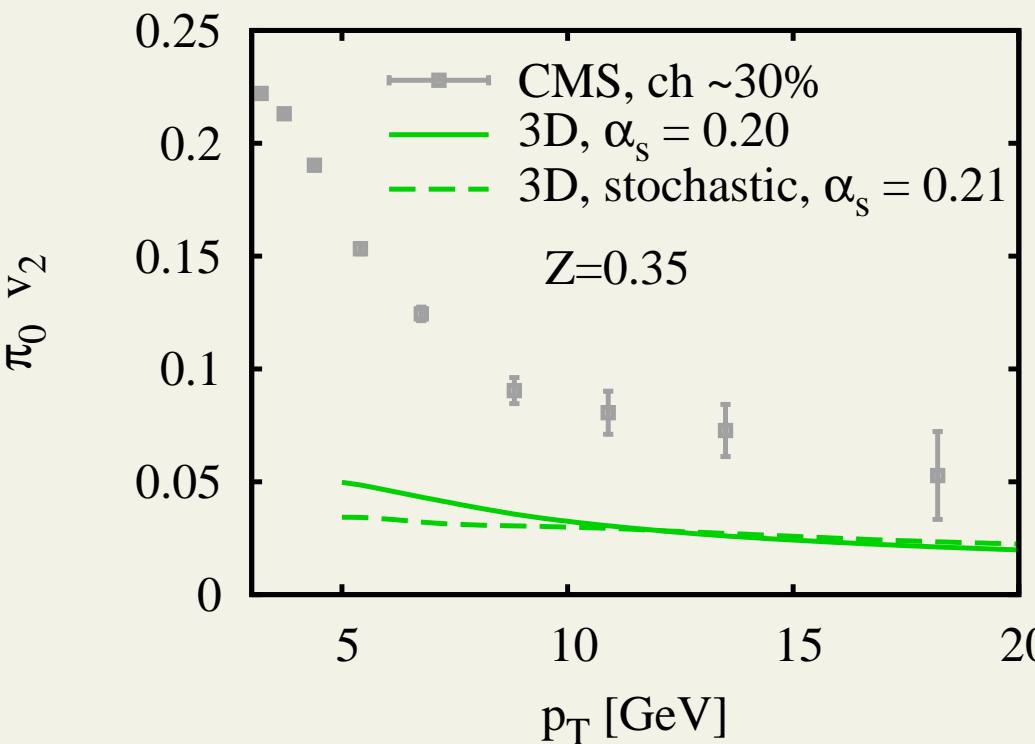
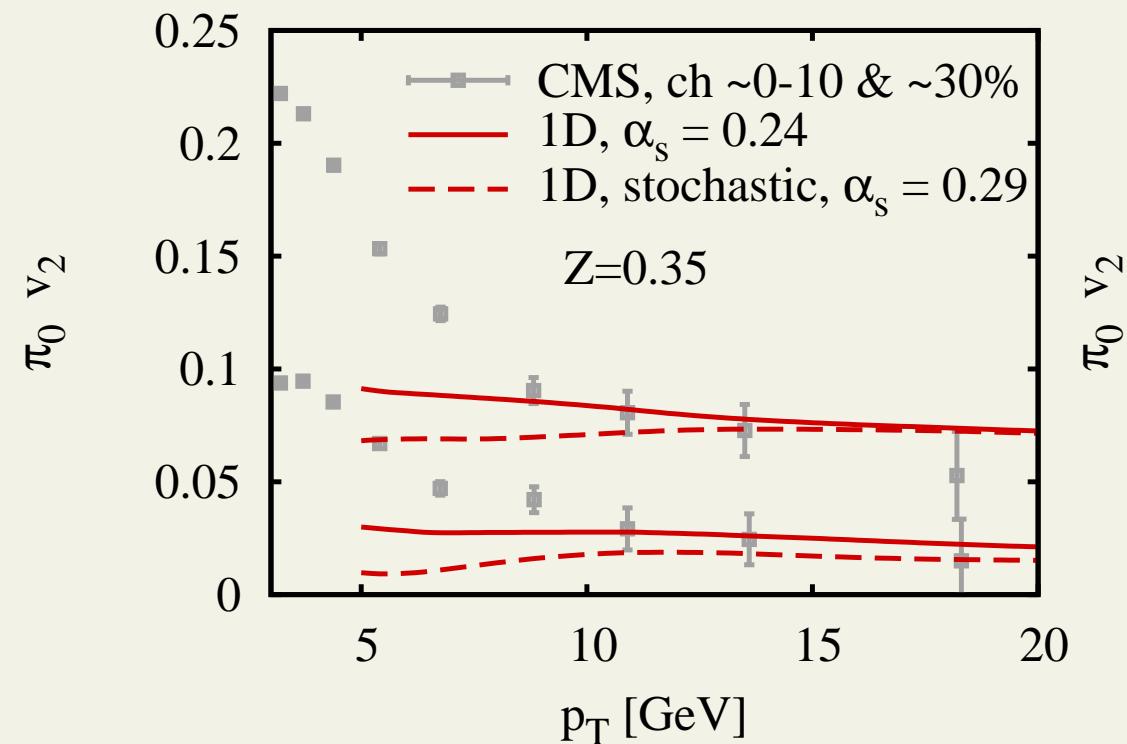


GLV implementation here is too simple (Columbia calculation looks better)

pion v2, LHC



pion v2, LHC - α_s scaled to RAA for central at $pT = 6$ GeV



same difficulty as at RHIC energies

Scenario “Transport”: instead of just the density, use directly the spacetime locations of jet-medium scatterings from MPC.

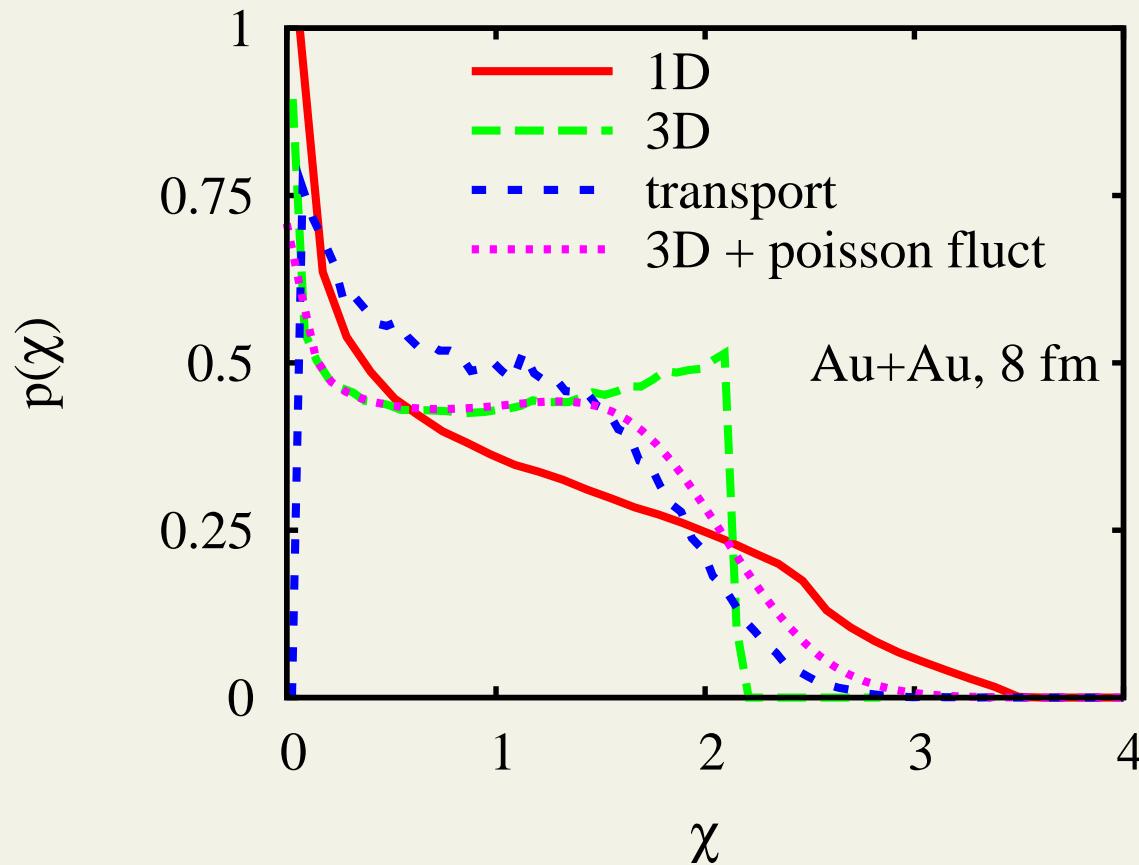
- includes flow effects $\chi \equiv \int dz \rho \sigma v_{rel}$
- opacity fluctuations
- correlations between scatterings (for GLV⁽²⁾ and beyond)

[our current numerical setup suppresses fluctuations by $\sim 4 - 5$ (we oversample to improve statistics)]

For apples-to-apples comparison, we need some adjustments:

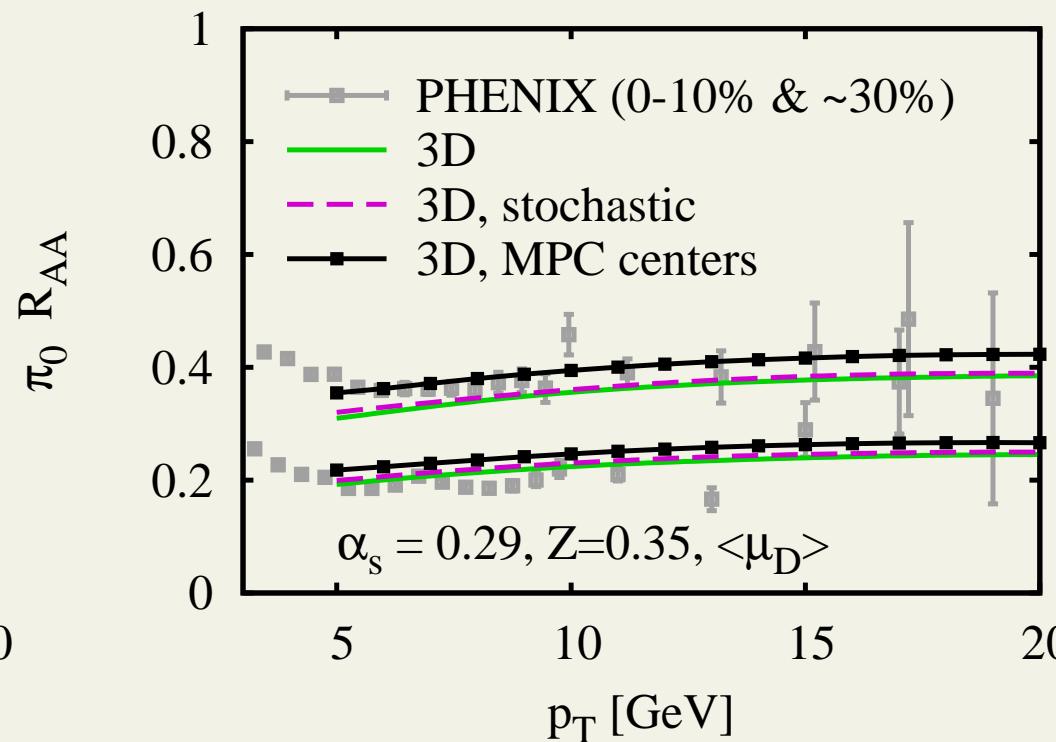
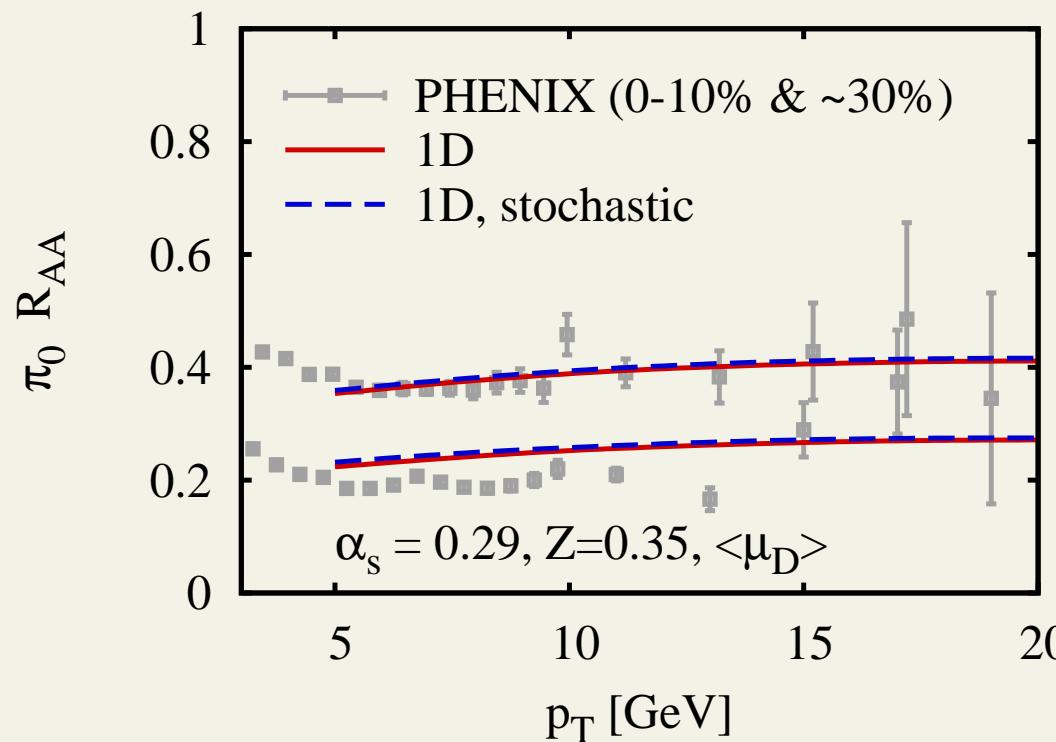
- instead of local $\mu_D(x_\perp, \tau)$, transversely averaged $\langle \mu_D \rangle \sim \langle T \rangle(\tau) \sim \tau^{-1/3}$
[spatial distribution is challenging to sample numerically]
- use $\rho(x_\perp, \tau) \equiv 0$ for $\tau < \tau_0$

opacity distribution for Au+Au, $b = 8$ fm



estimate from **density alone** is not too bad actually

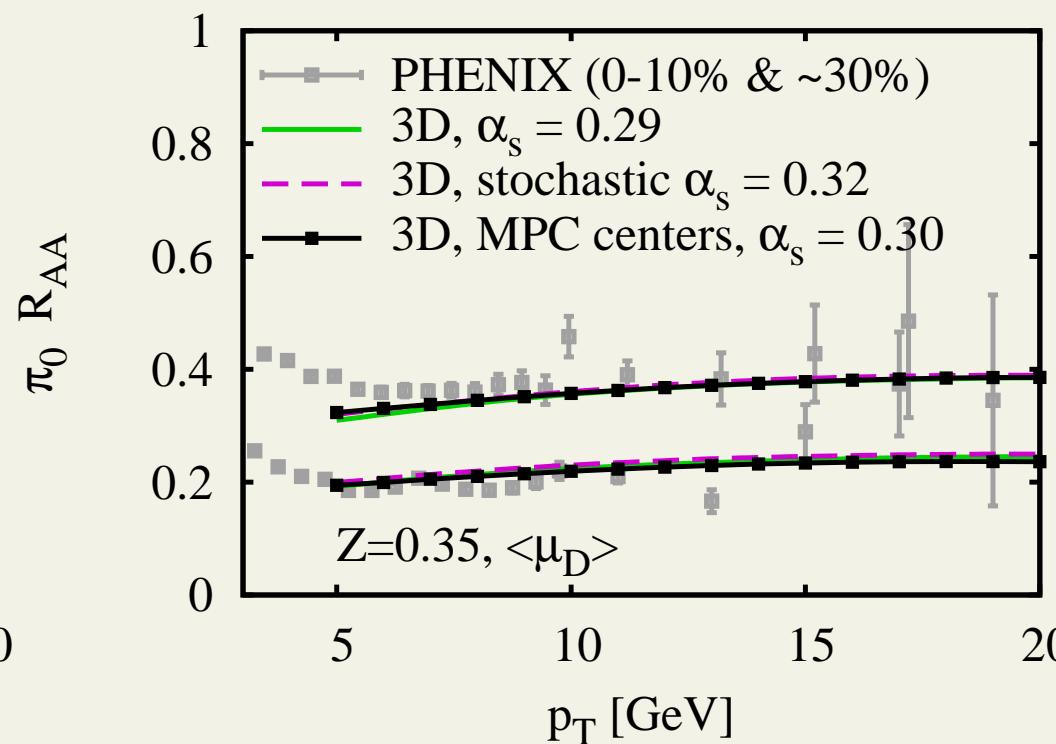
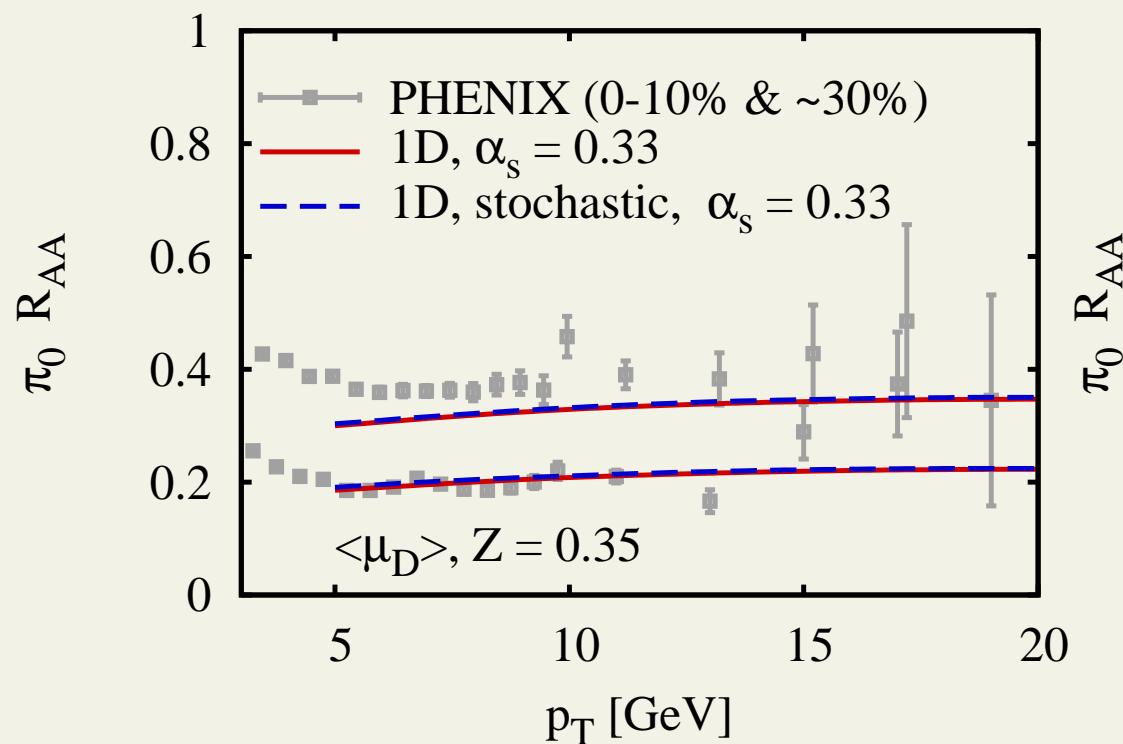
pion RAA, RHIC, $\langle \mu_D \rangle$



because no E-loss for $\tau < \tau_0$, E-loss fluctuations are MUCH reduced

realistic scattering positions from transport make a modest difference

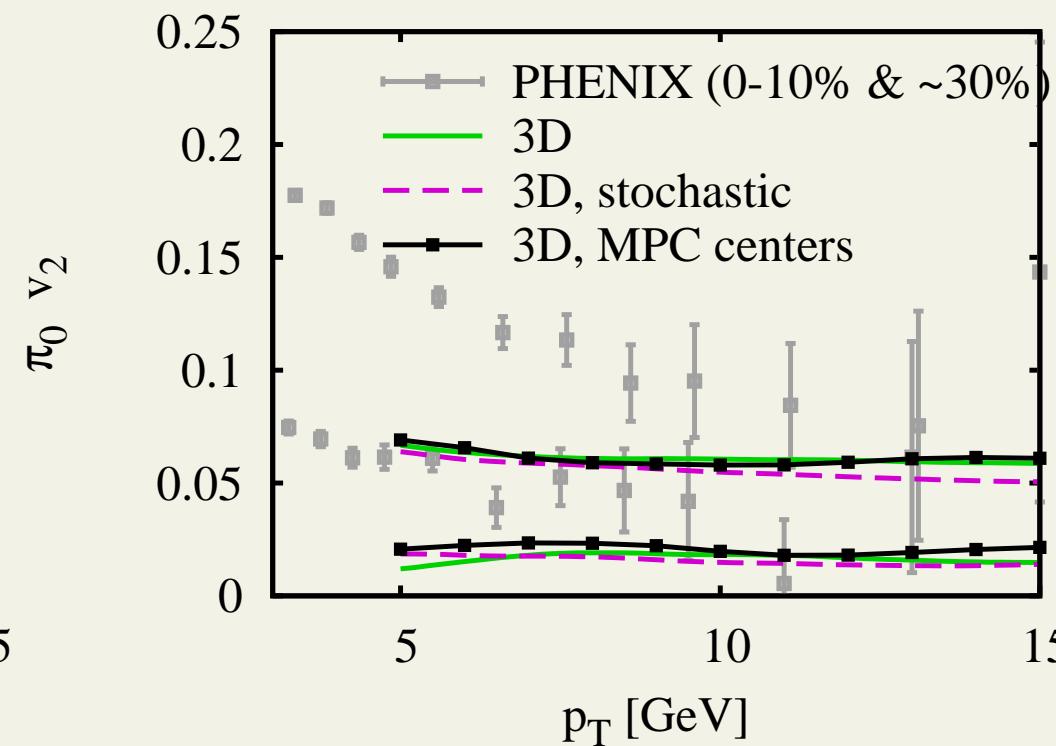
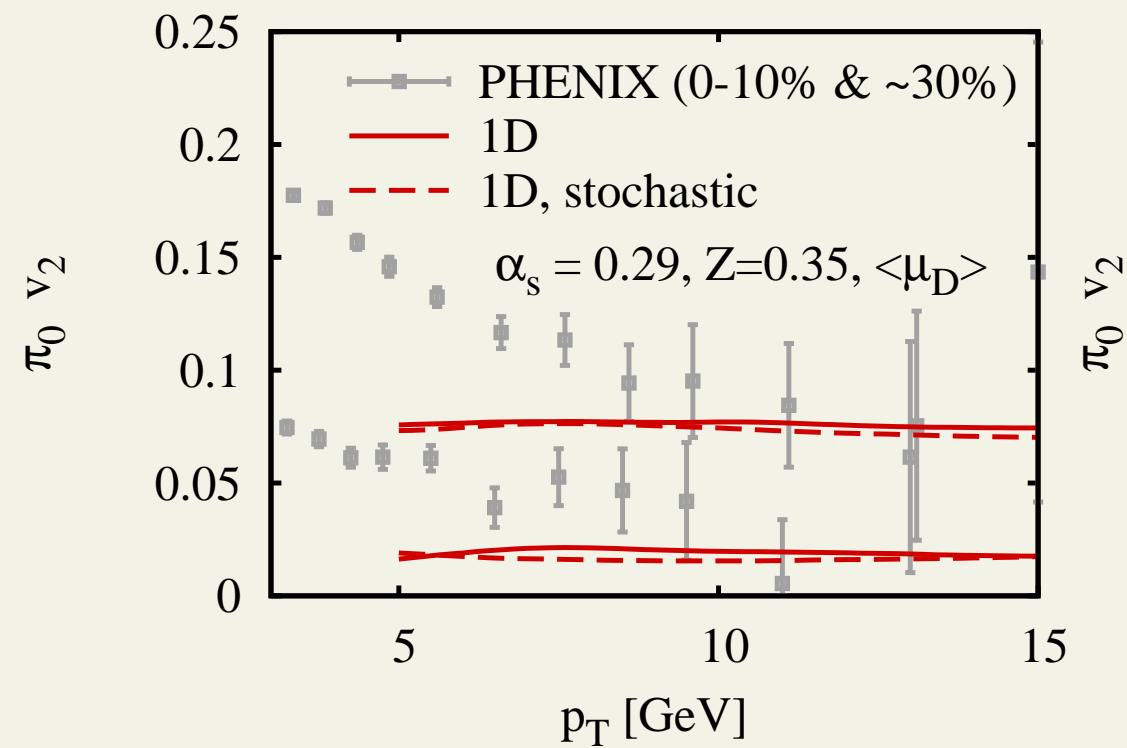
pion RAA, RHIC, $\langle \mu_D \rangle$ - α_s scaled to RAA for central



but the effect can be absorbed via re-adjusting α_s

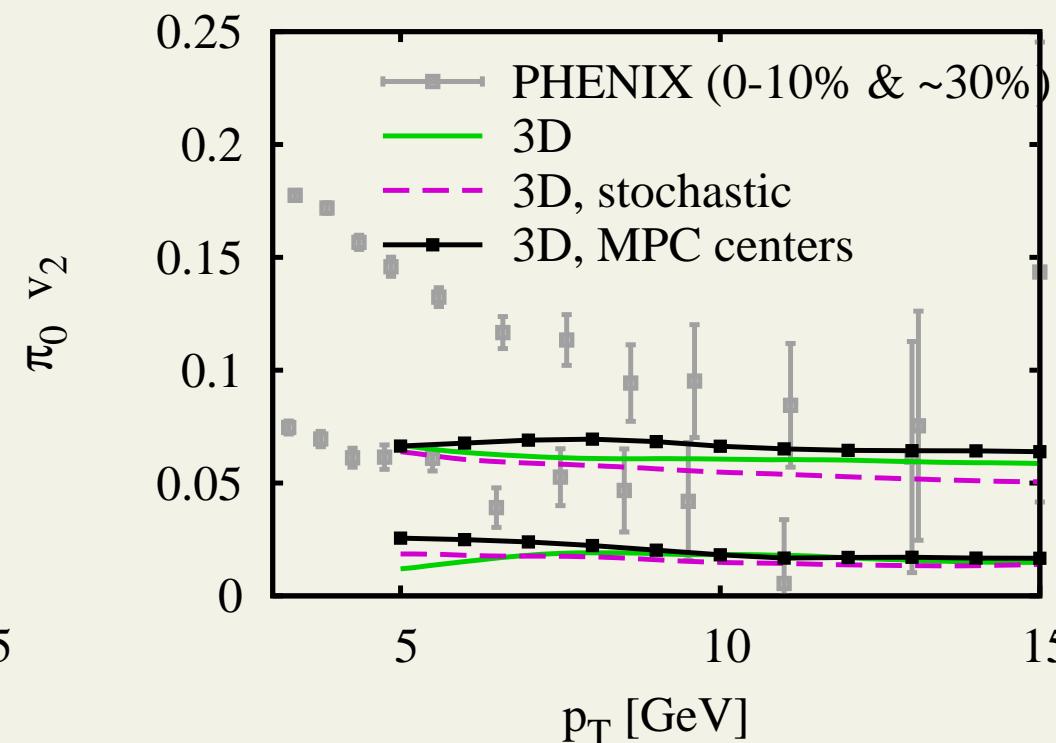
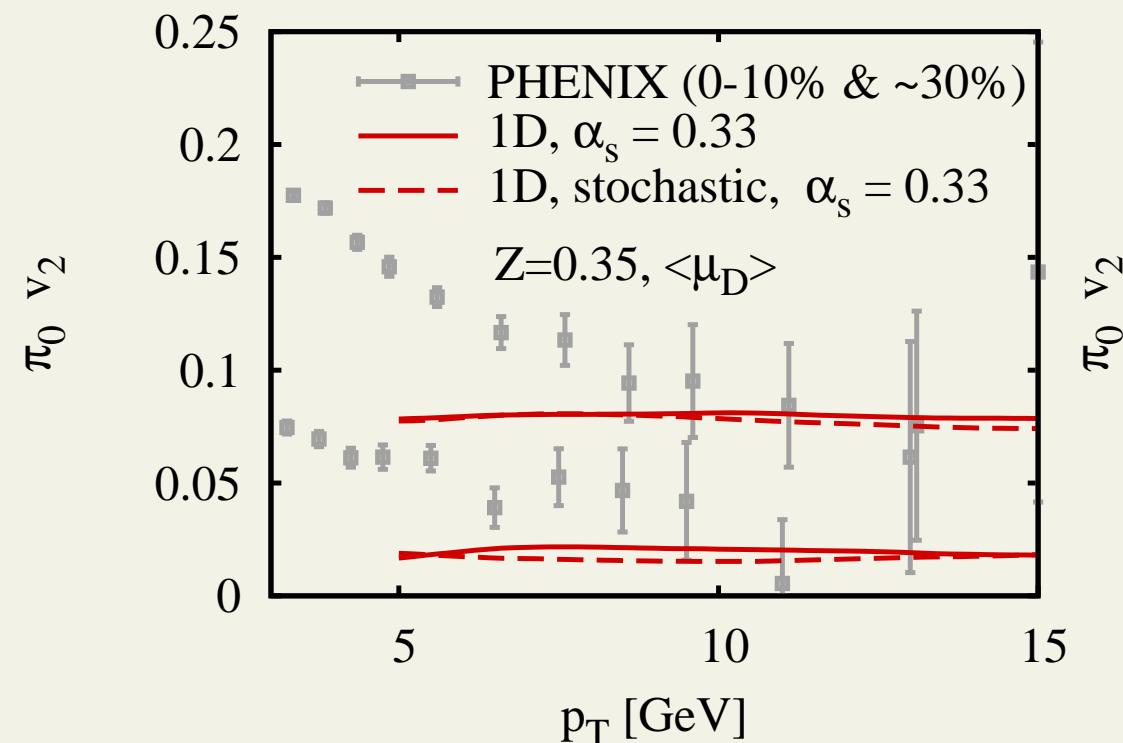
[in this $\rho(\tau < \tau_0) = 0$ scenario, E-loss fluctuations are much reduced]

pion v2, RHIC



but elliptic flow works better(!) in this scenario $\sim 6\%$

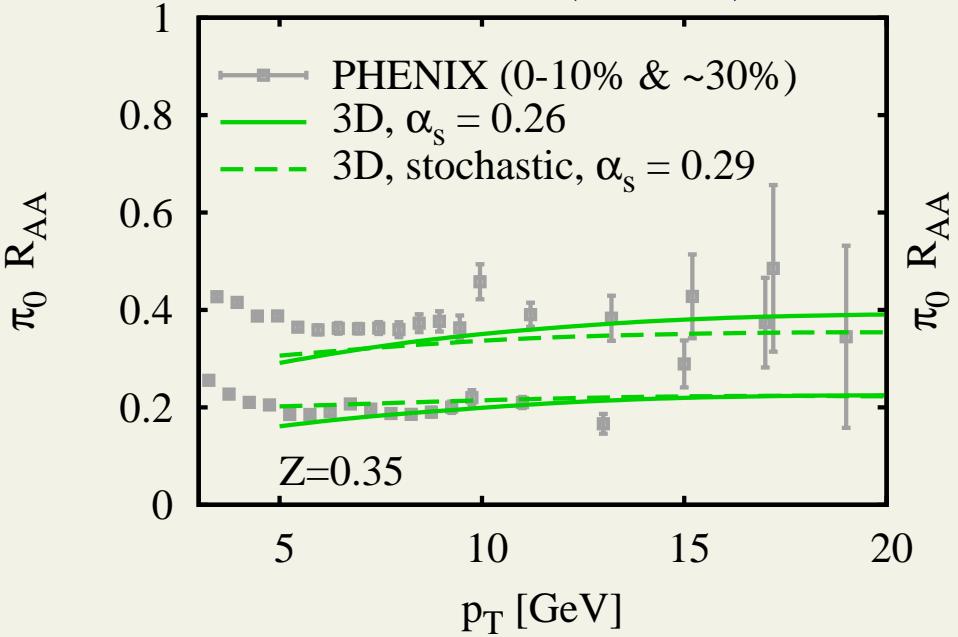
pion v2, RHIC - α_s scaled to RAA for central



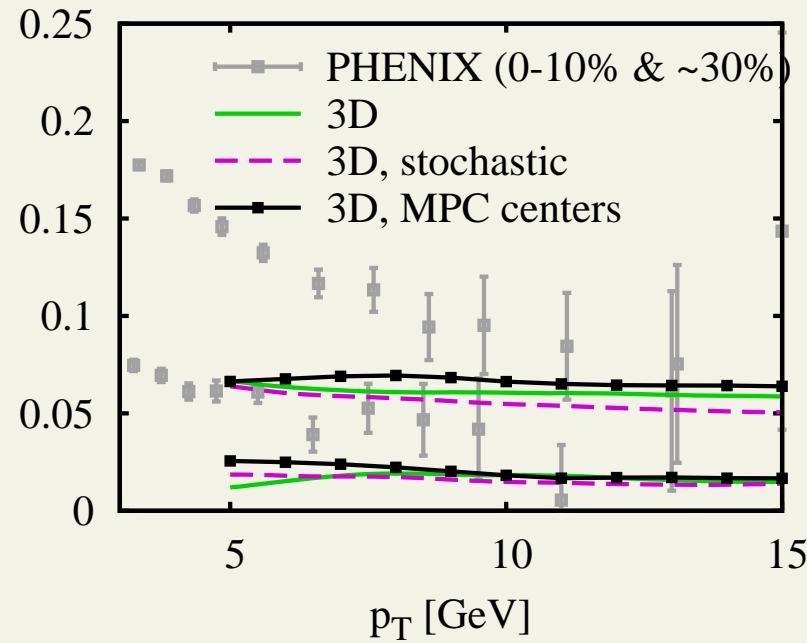
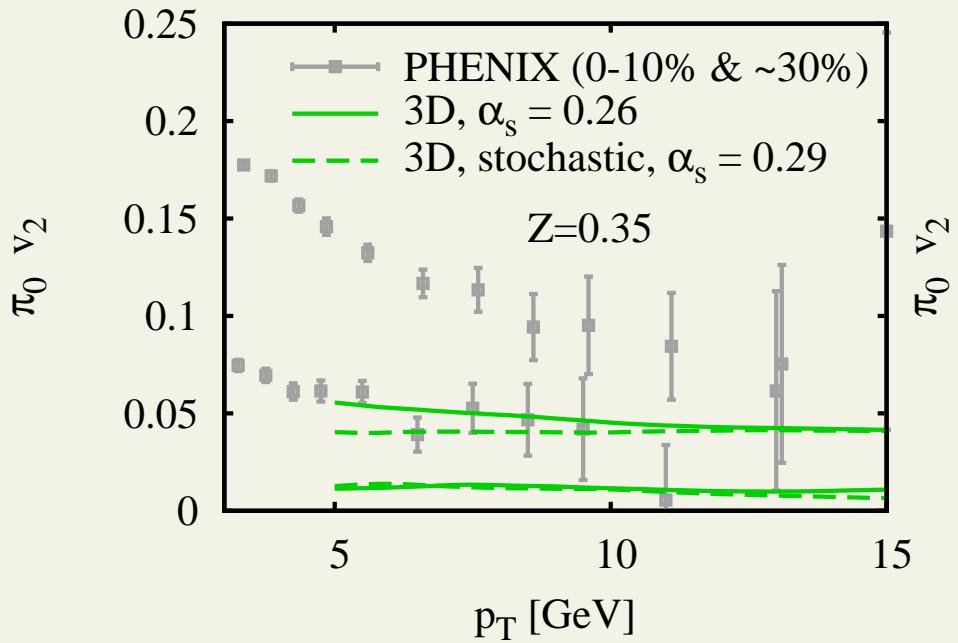
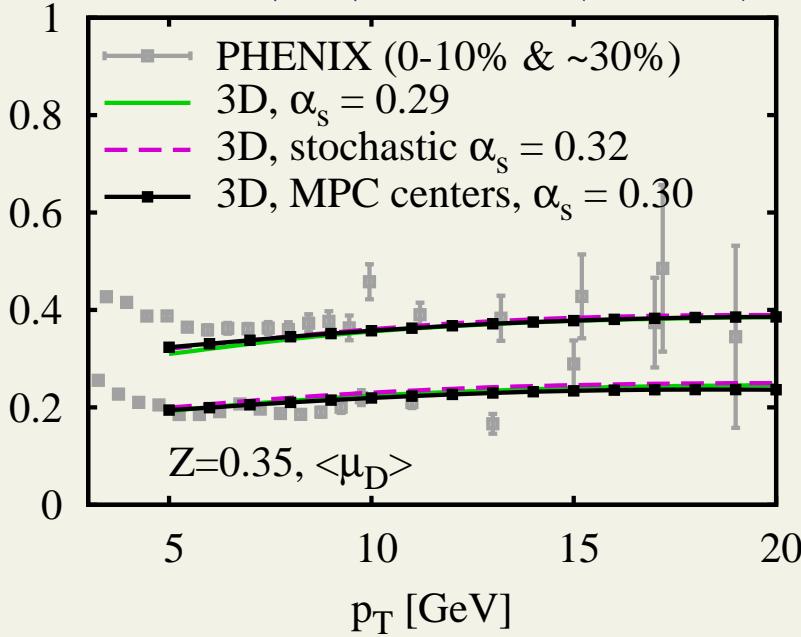
elliptic flow works better(!) in this scenario $\sim 6\%$

only small $< 10 - 15\%$ residual effects from stochastic E-loss

local μ_D , with $\rho(\tau < \tau_0) \propto \tau$



averaged $\langle \mu_D \rangle$, with $\rho(\tau < \tau_0) = 0$



Summary

We investigated GLV radiative energy loss using covariant transport (MPC) to model the bulk medium evolution.

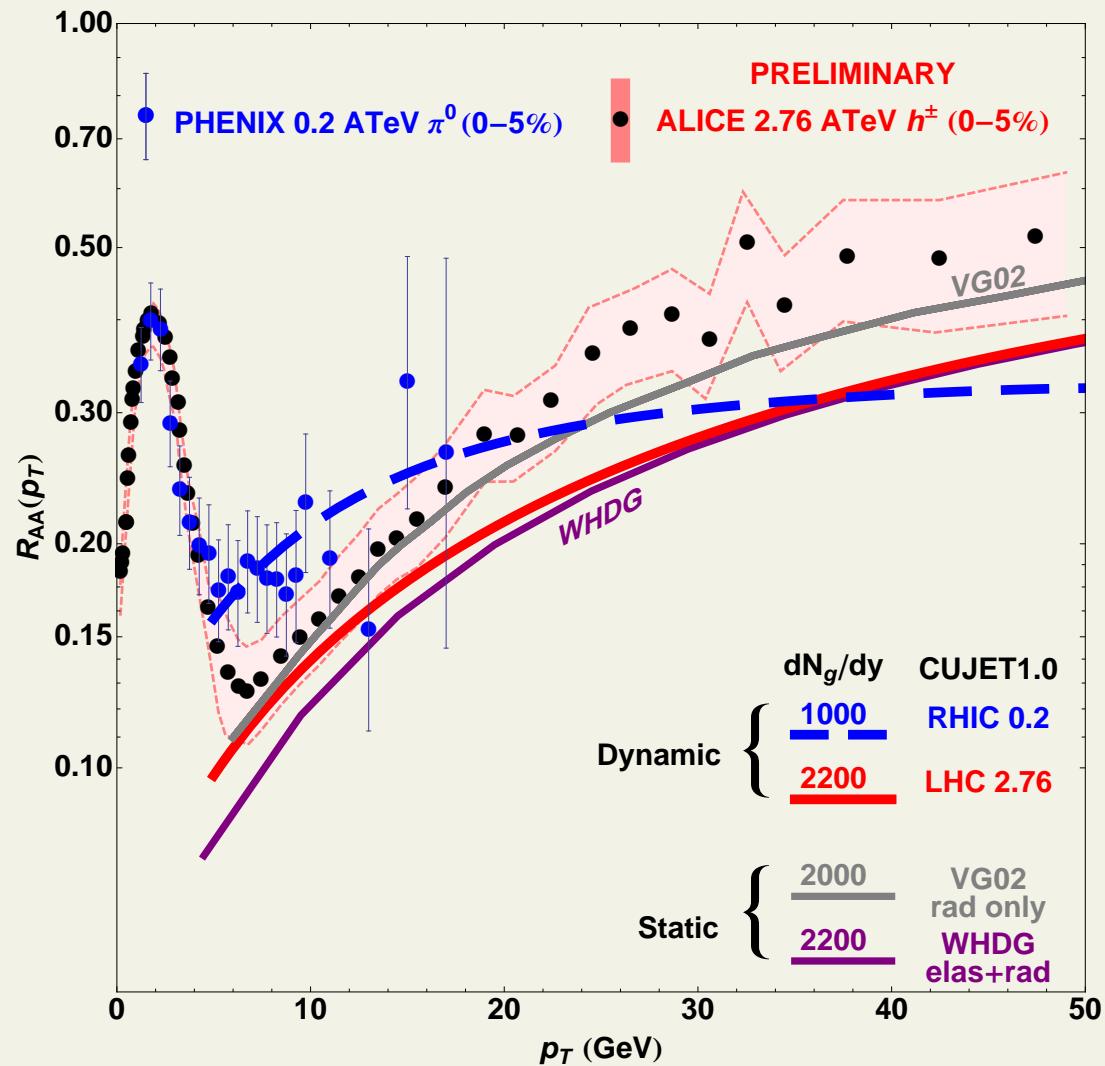
- Both the stochastic nature of energy loss and 3D expansion affect observables (R_{AA} , v_2). The effects can largely be absorbed by adjusting α_s . But a general reduction of v_2 due to 3D expansion seems robust, posing a challenge w.r.t. to data.
- The role of fluctuations is sensitive to assumptions about early opacities $\rho(\tau < \tau_0)$. We find that E-loss fluctuations are well captured with just the density information from the transport, so the full spacetime ensemble of jet-medium scattering points may not be necessary - albeit the comparison was in a scenario in which fluctuations already play a diminished role in the traditional density-based calculation.

Some future steps:

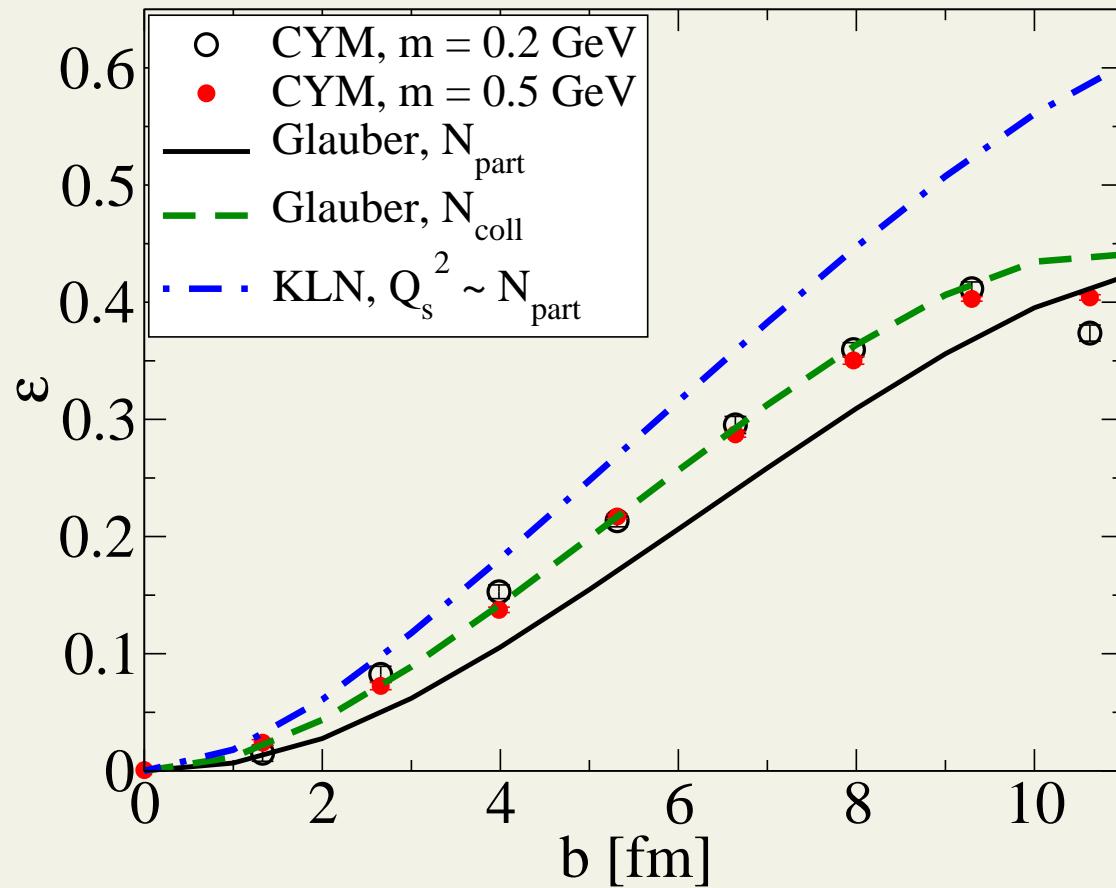
- refinements to E-loss treatment and the transport
- heavy quarks
- investigate GLV⁽²⁾

Backup slides

CUJET 1.0 Buzzatti et al ('11)



CYM eccentricity Venugopalan & Lappi, PRC74 ('06):



MARTINI $R_{AA}(\phi)$ Schenke et al, PRC80 ('09):

