GLV energy loss in realistic expanding medium

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CCNU, Wuhan, China

arXiv:1209.2430

Motivation

Line integrals, e.g.,

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

Gyulassy, Vitev, et al...

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

Shuryak & Liao

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

Betz et al

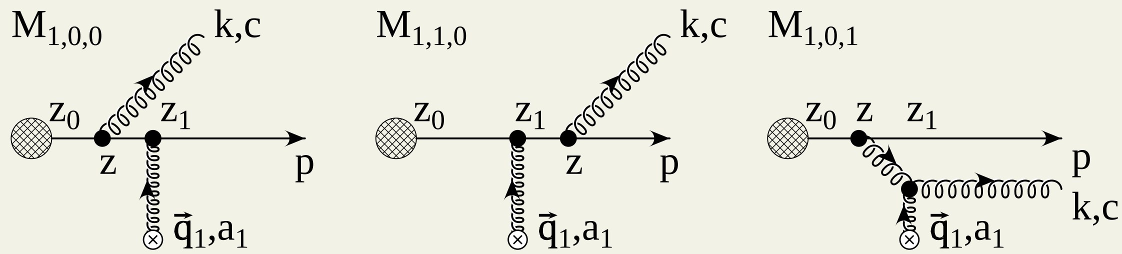
vs stochastic E-loss?

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

$\rightarrow$ **natural to combine (D)GLV with a parton transport model (MPC)**

GLV - opacity expansion

Gyulassy, Levai, Vitev NPB594 ('00)



$$x\frac{dN^{(n)}}{dx\,d^2\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\frac{\chi^n}{n!}\int\prod_{i=1}^{n}\left\{d\mathbf{q}_i\left(\frac{dz_i\rho_i\sigma_i}{\chi}\right)(\bar{v}_i^2(\mathbf{q}_i)-\delta^2(\mathbf{q}_i))\right\}$$

$$\times\left[-2\,\mathbf{C}_{(1,\cdots,n)}\cdot\sum_{m=1}^{n}\mathbf{B}_{(m+1,\cdots,n)(m,\cdots,n)}\left(\cos\left(\sum_{k=2}^{m}\omega_{(k,\cdots,n)}\Delta z_k\right)-\cos\left(\sum_{k=1}^{m}\omega_{(k,\cdots,n)}\Delta z_k\right)\right)\right]$$

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

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

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

Setup:

- **Bulk dynamics evolution computed from covariant transport (MPC code)**

DM & Gyulassy, PRC62 ('00)

- **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)**
- **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 (LO pQCD) to get some hadronic observables: R_{AA} **and** v_2

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,** $\Delta E(z)$

keep in mind, some ingredients are still missing:

- **fluctuations in radiated gluon momenta** $\Delta E(z, \vec{k}_T, x)$
- **multiple gluon emission**
- **elastic energy loss**
- **dynamical screening** $|V(q)|^2 \sim 1/(q^2+\mu^2)^2 \;\; \to \;\; 1/[q^2(q^2+\mu^2)]$

we crudely account for these by hand via rescaling $\chi \to \chi/Z$

but we do include transverse expansion (unlike Buzzatti et al, Horowitz et al, Betz et al**)**

first temptation: GLV "pocket formula"

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

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

$$\langle \Delta E \rangle = \int dz\, p(z)\, \Delta E(z) \qquad , \qquad p(z) = \frac{\sigma_{gg}(z) \rho(z, \tau{=}z{-}z_0)}{\chi}$$

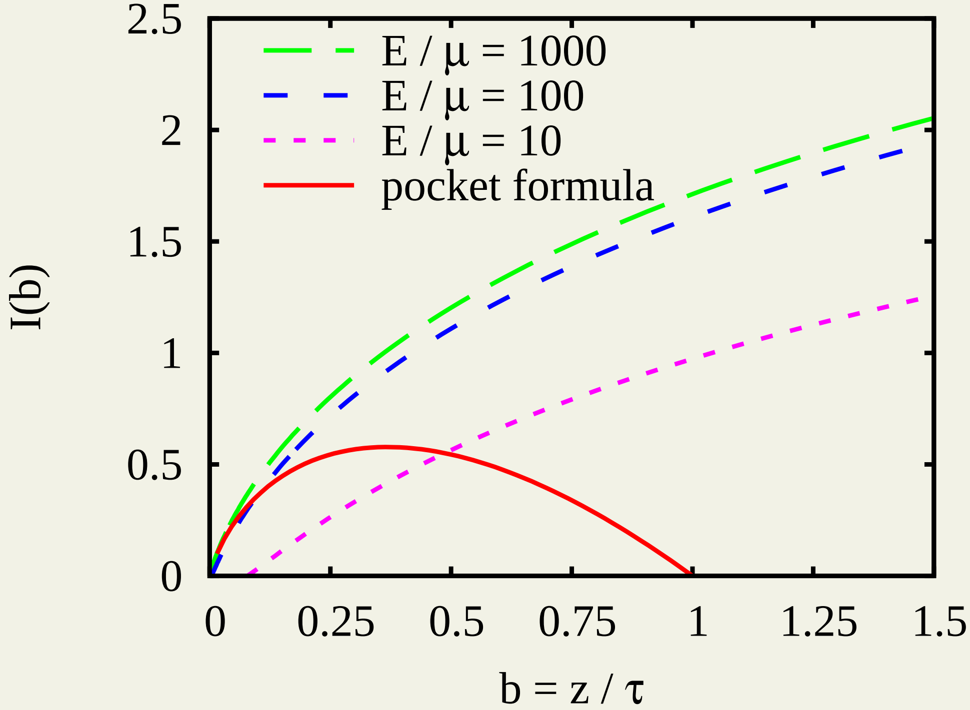
BUT: only valid for asymptotic energy $E/\mu \to \infty$

in practice, not reliable even qualitatively

Finite energy & kinematics crucial:

$$|k| \; < \sim xE$$
$$|q| \; < \sim \sqrt{s} \; \sim \; \sqrt{6ET}$$
$$xE \; > \sim \mu \qquad \textbf{(plasma)}$$

$$\Delta E^{(1)}_{GLV}(z) \;=\; \frac{C_R\alpha_s}{\pi^2}\chi \int dx\, d\mathbf{k}\, d\mathbf{q}\, \frac{\mu^2}{\pi(\mathbf{q}^2+\mu^2)^2}\frac{2\mathbf{k}\cdot\mathbf{q}}{\mathbf{k}^2(\mathbf{k}-\mathbf{q})^2}(1-\cos\omega\Delta z)$$
$$\equiv\; \frac{2C_R\alpha_s}{\pi} E\,\chi\, I(\Delta z/\tau(z), E/\mu(z)) \qquad , \qquad \omega \equiv \mu^2/(2Ex)$$



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

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

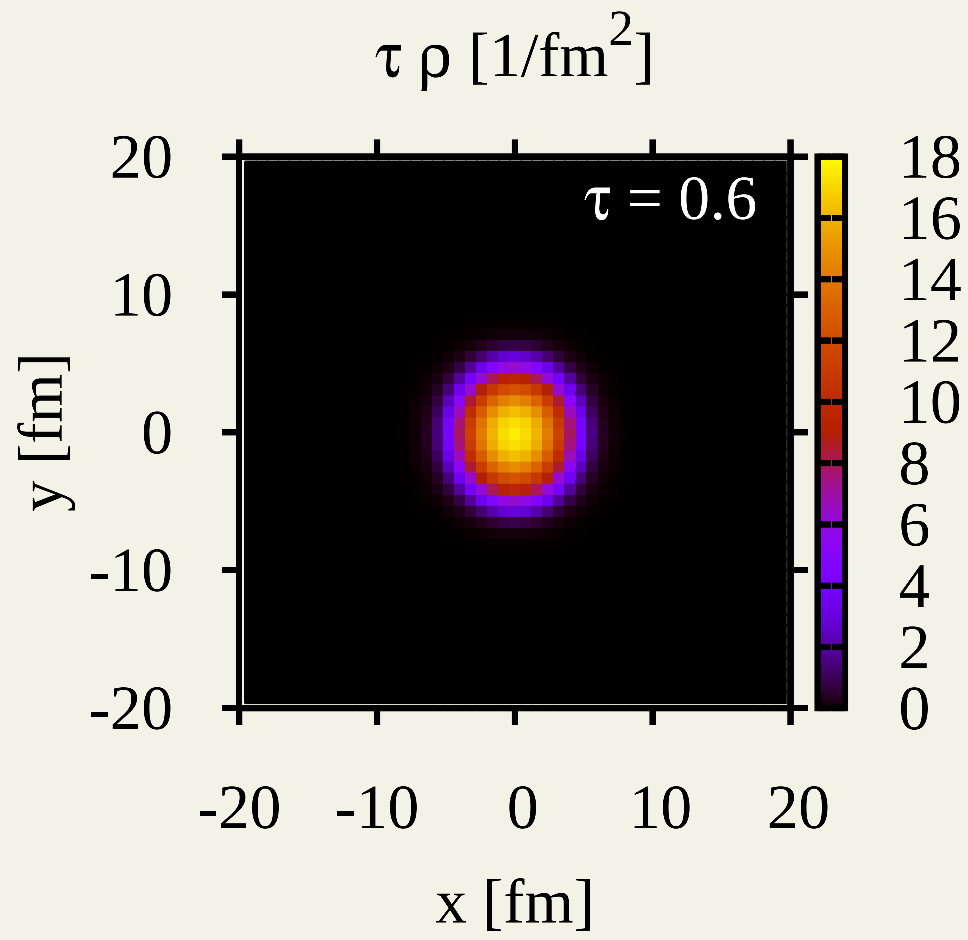
Medium evolution from kinetic theory (MPC transport code):

- $2 \to 2$ **with massless gluons**
- **opacity set to generate sufficient** $v_2(p_T) \sim 0.2$ **at RHIC / LHC**
- $\eta/s \approx 0.1$ **dynamics via** $\sigma_{gg} \sim 1/T^2 \sim \tau^{2/3}$ DM, arXiv:0806.0026
- **boost-invariant initial conditions in** $|\eta| < 5$ **window**

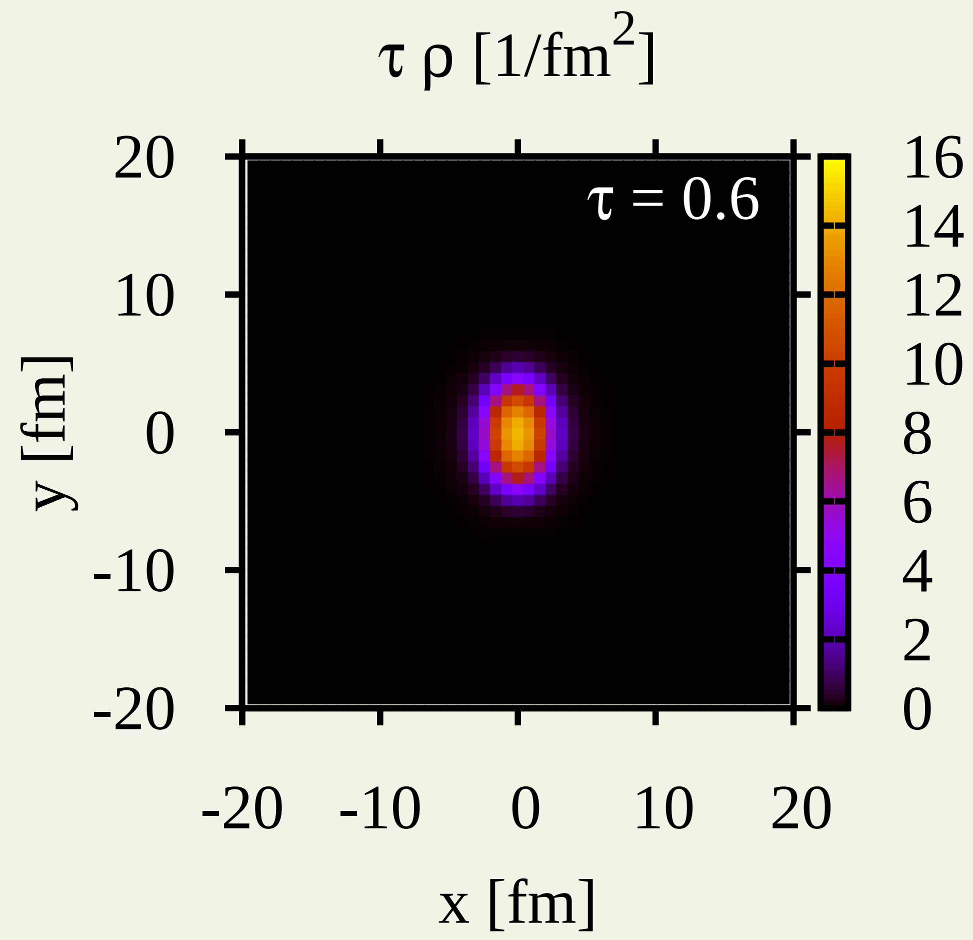
- **LO pQCD jet production & fragmentation (CTEQ5L, BKK95,** $K_{NLO} \approx 2.5$**)**
- **jet and bulk transverse profiles** $\propto \rho^{binary}(x_\perp)$**, with** $dN^{bulk}/dy \propto N_{part}$
- T **set by** $\rho(T)$ **for massless gluon gas,** $\mu_D = gT$
- $\tau_0 = 0.6$ **fm formation, and LINEAR density buildup** $\rho(\tau) \propto \tau$ **for** $\tau < \tau_0$

Two centralities: $0 - 10$**% (**$b \approx 3$ **fm) and** $25 - 35$**% (**$b \approx 8$ **fm)**

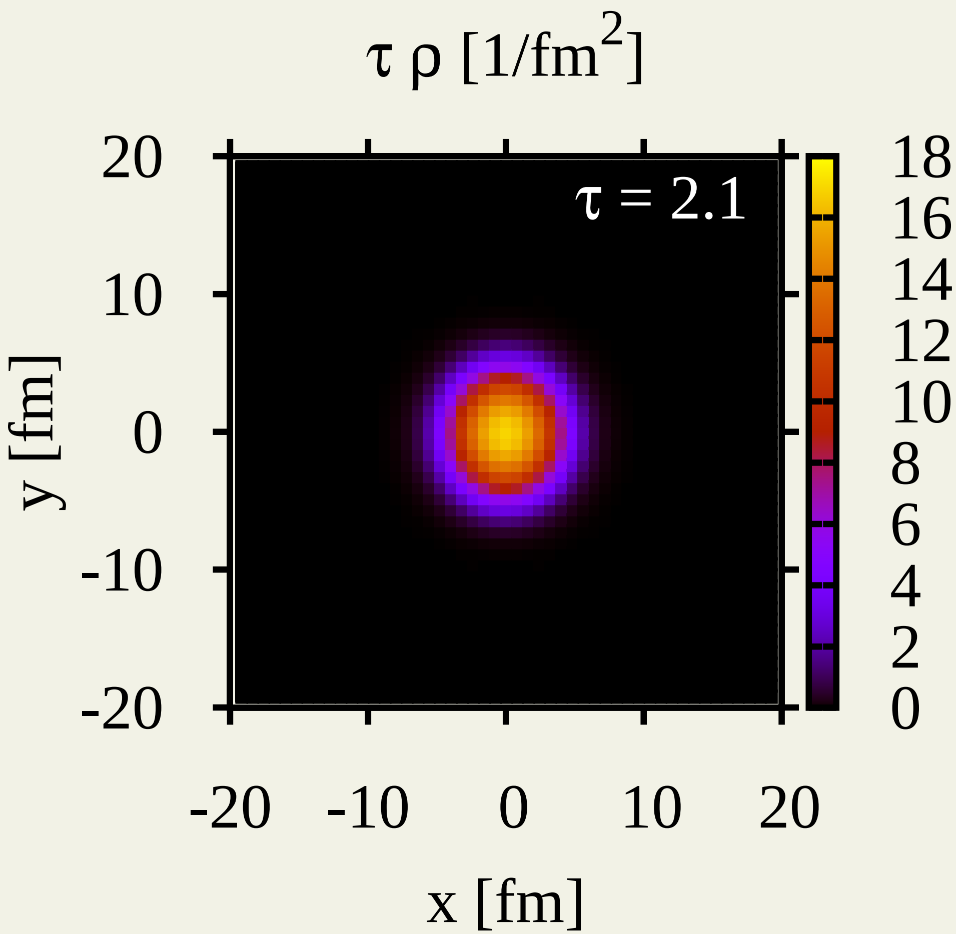
Au+Au, b=3 fm



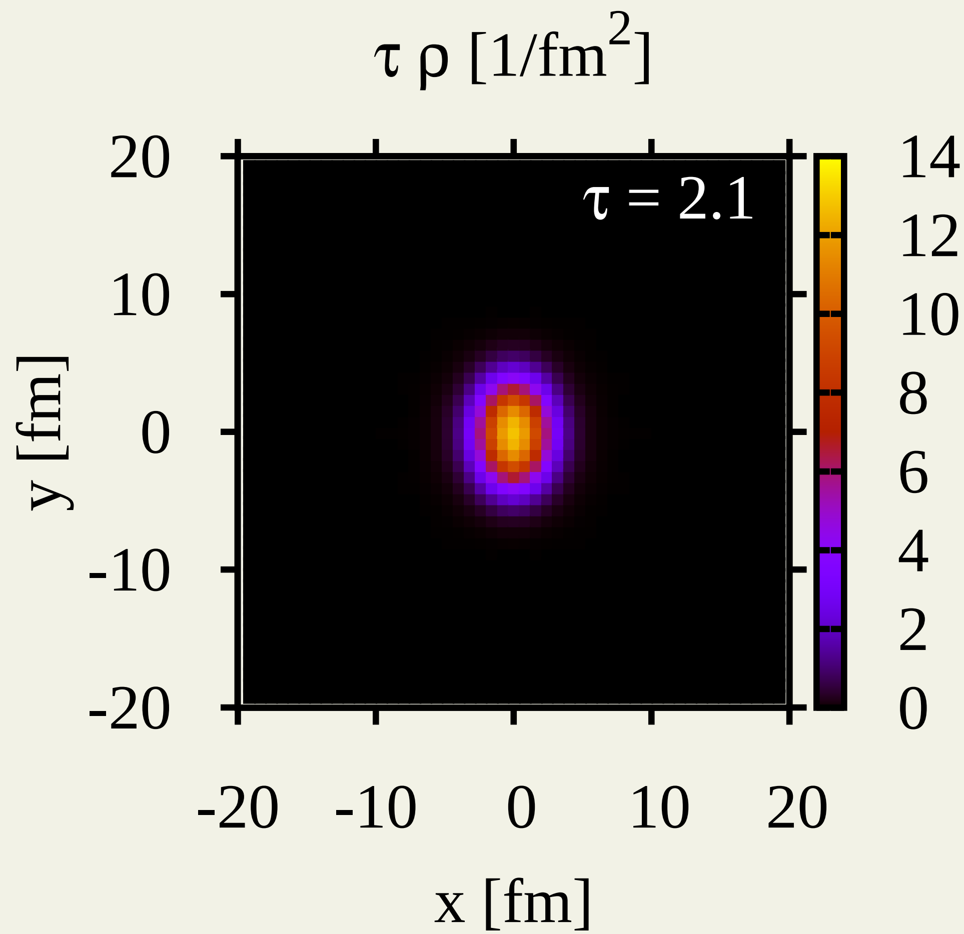
Au+Au, b=8 fm



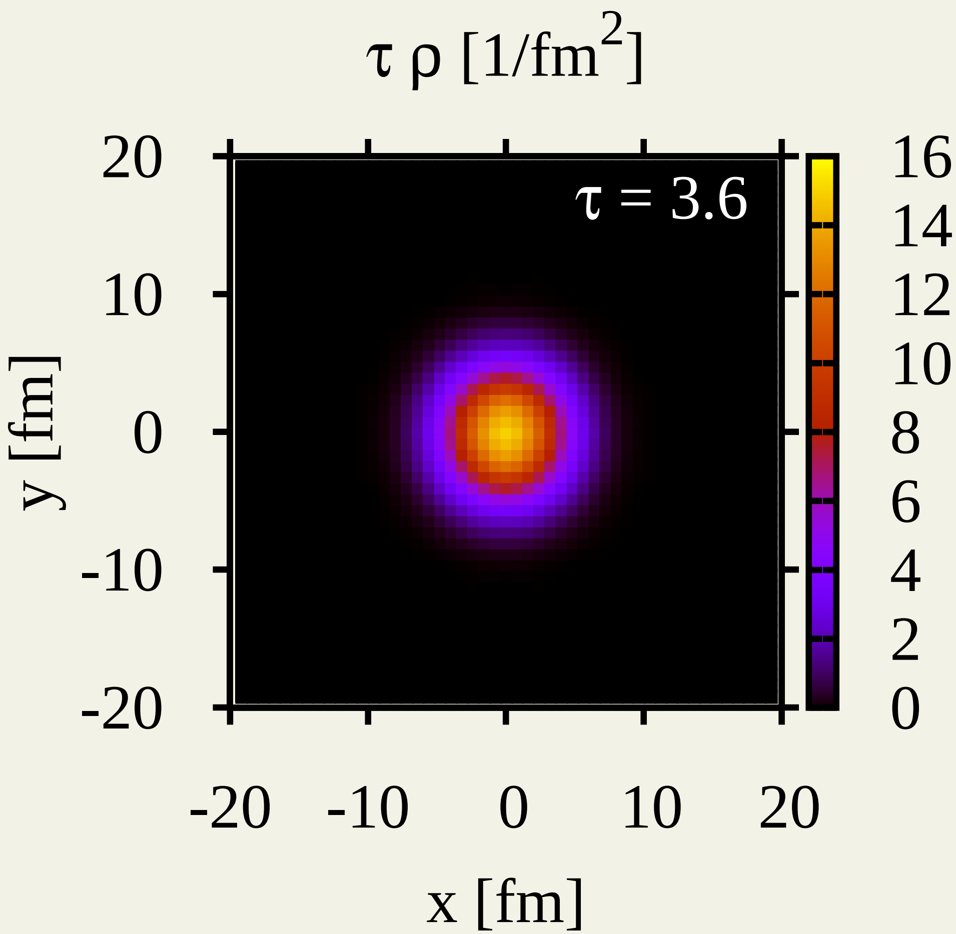
Au+Au, b=3 fm



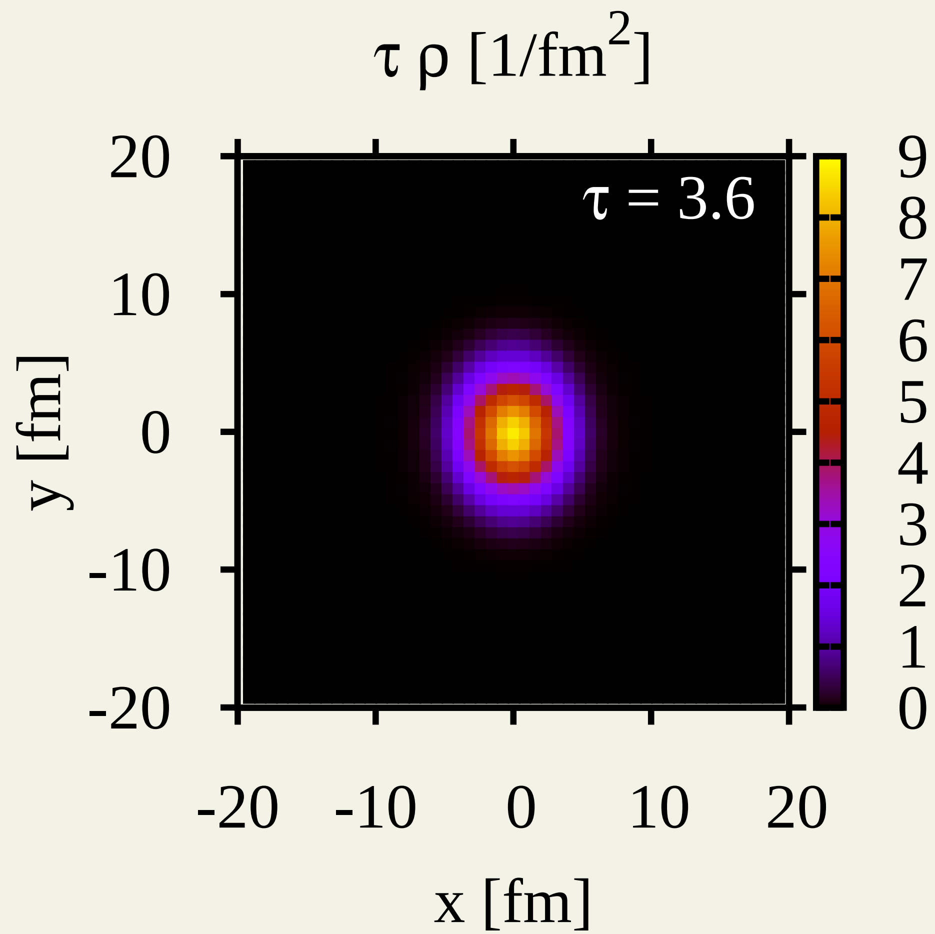
Au+Au, b=8 fm



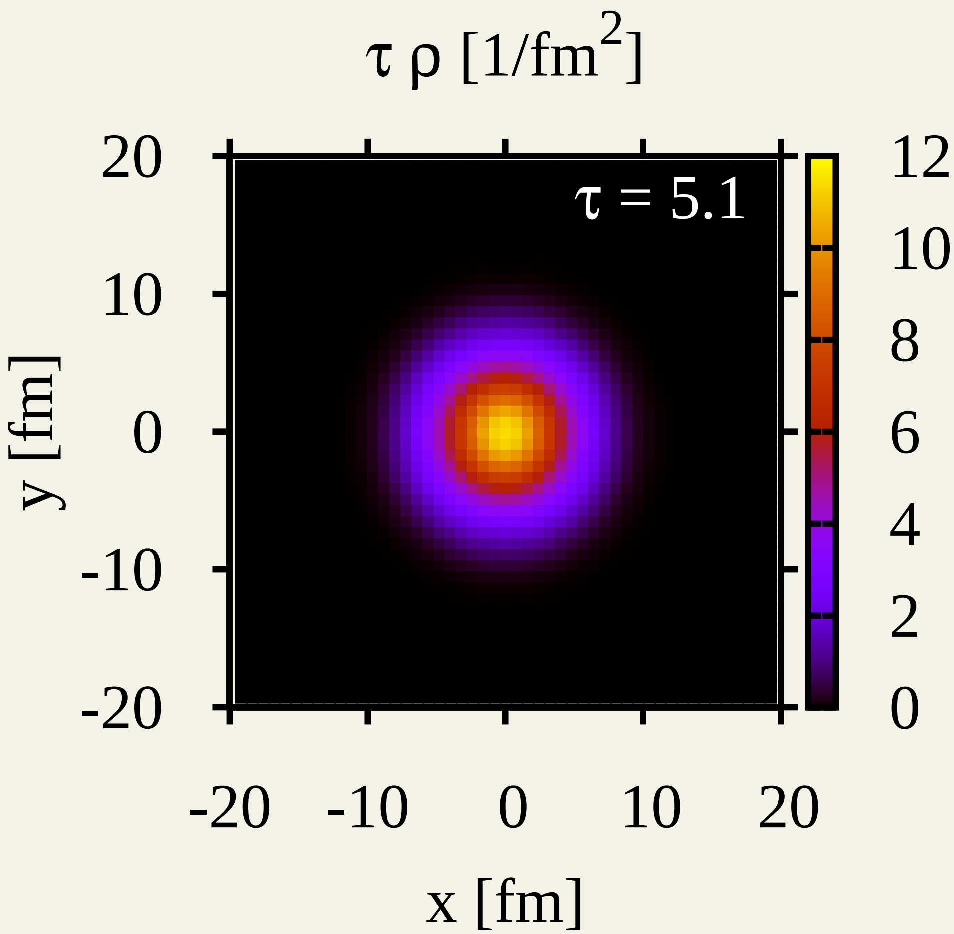
Au+Au, b=3 fm



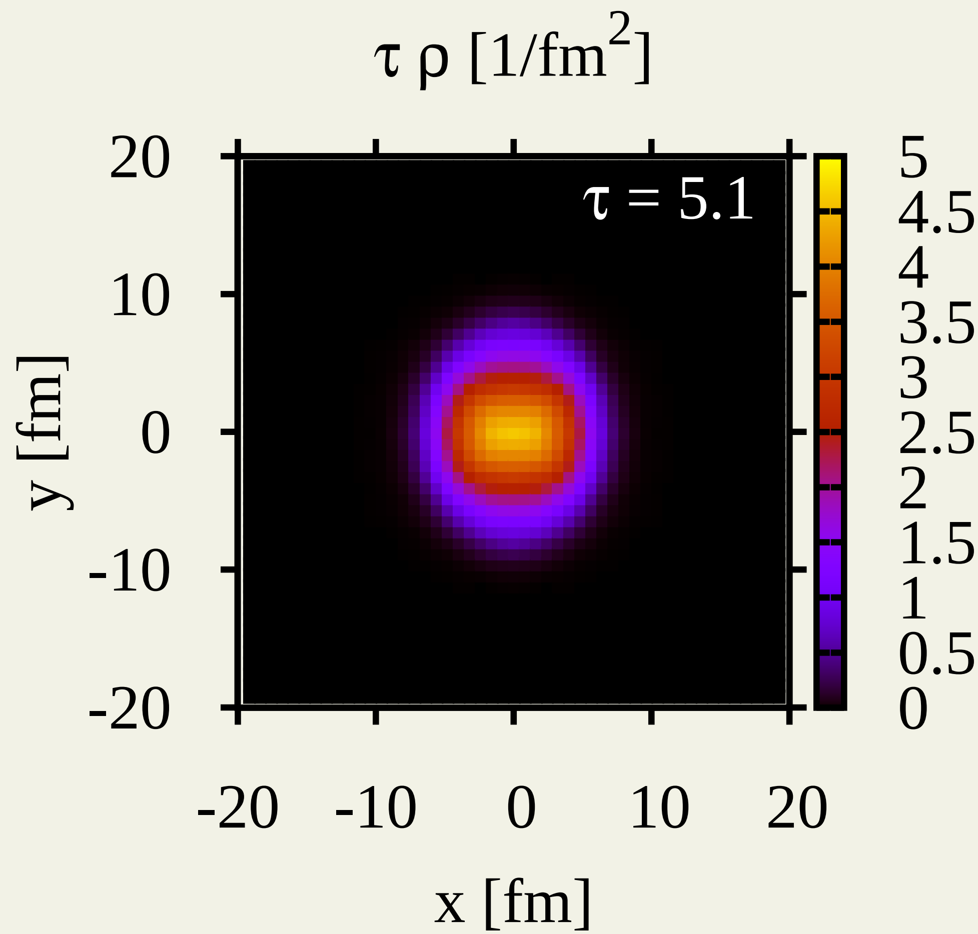
Au+Au, b=8 fm



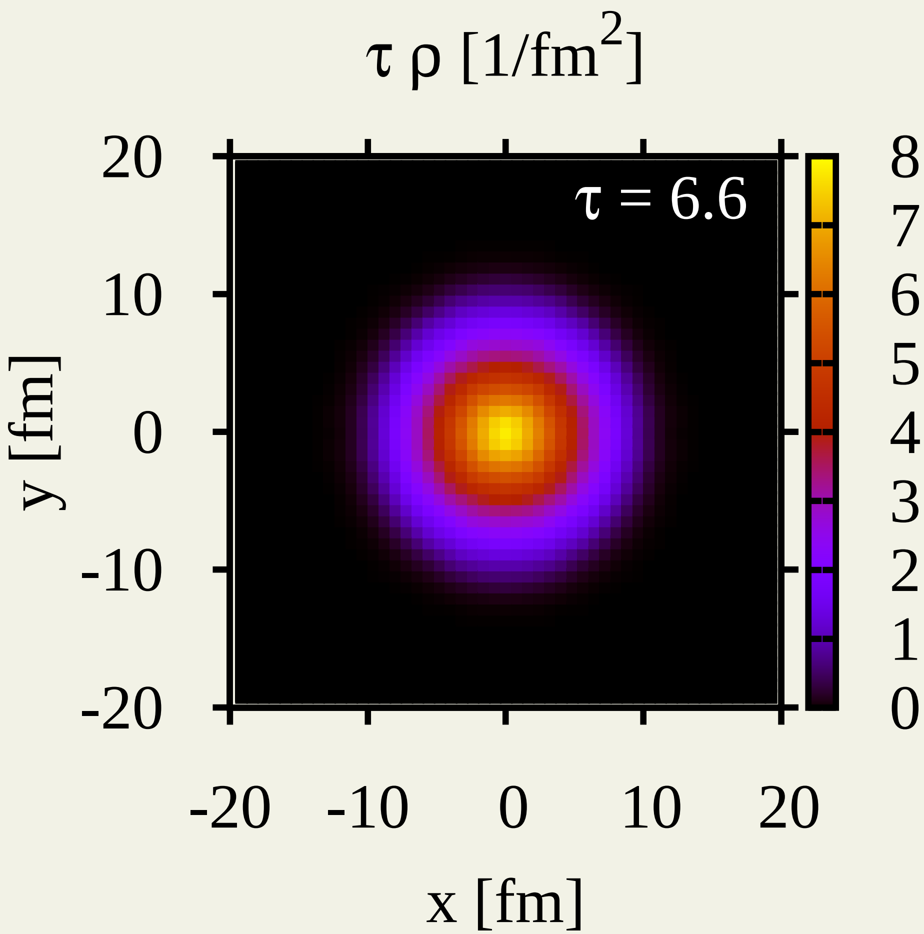
Au+Au, b=3 fm



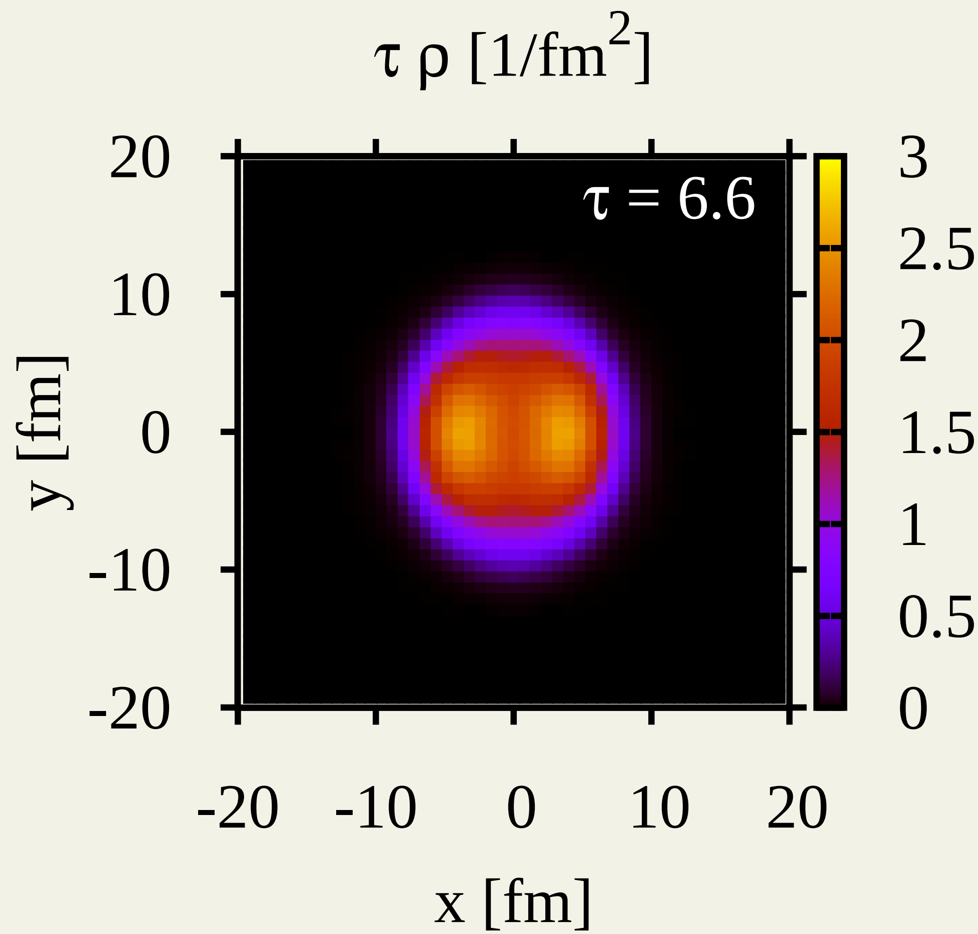
Au+Au, b=8 fm



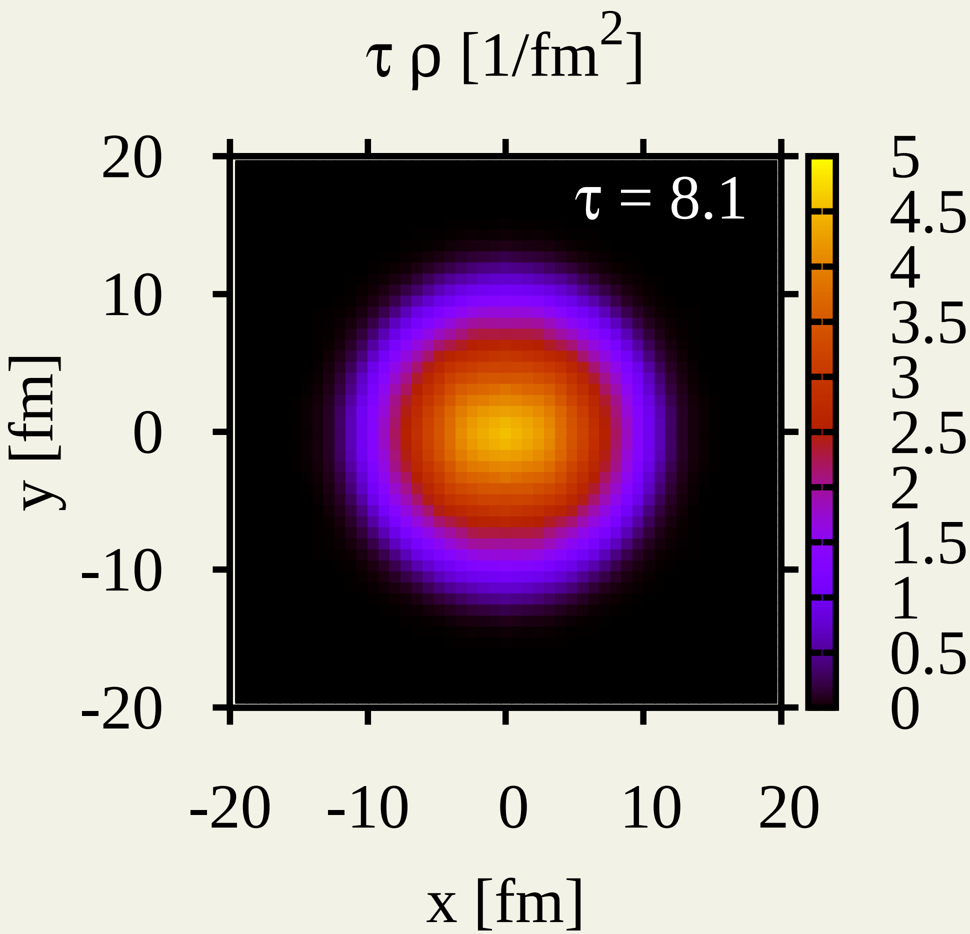
Au+Au, b=3 fm



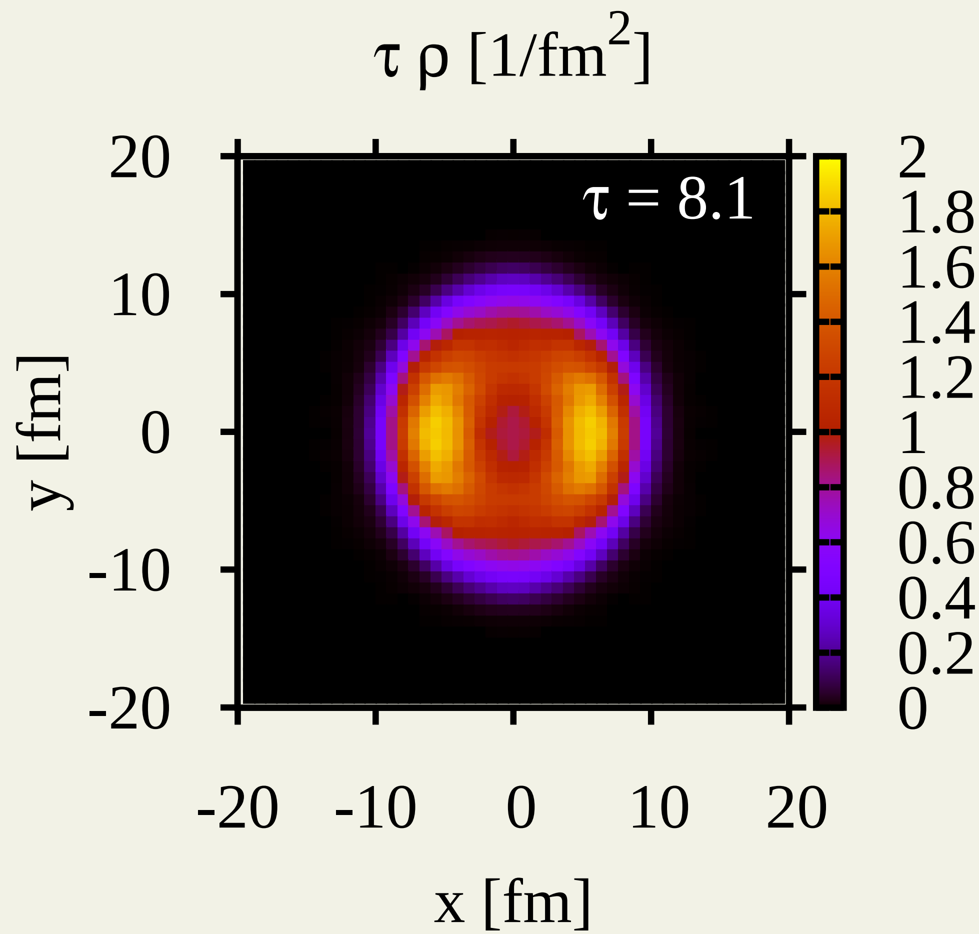
Au+Au, b=8 fm



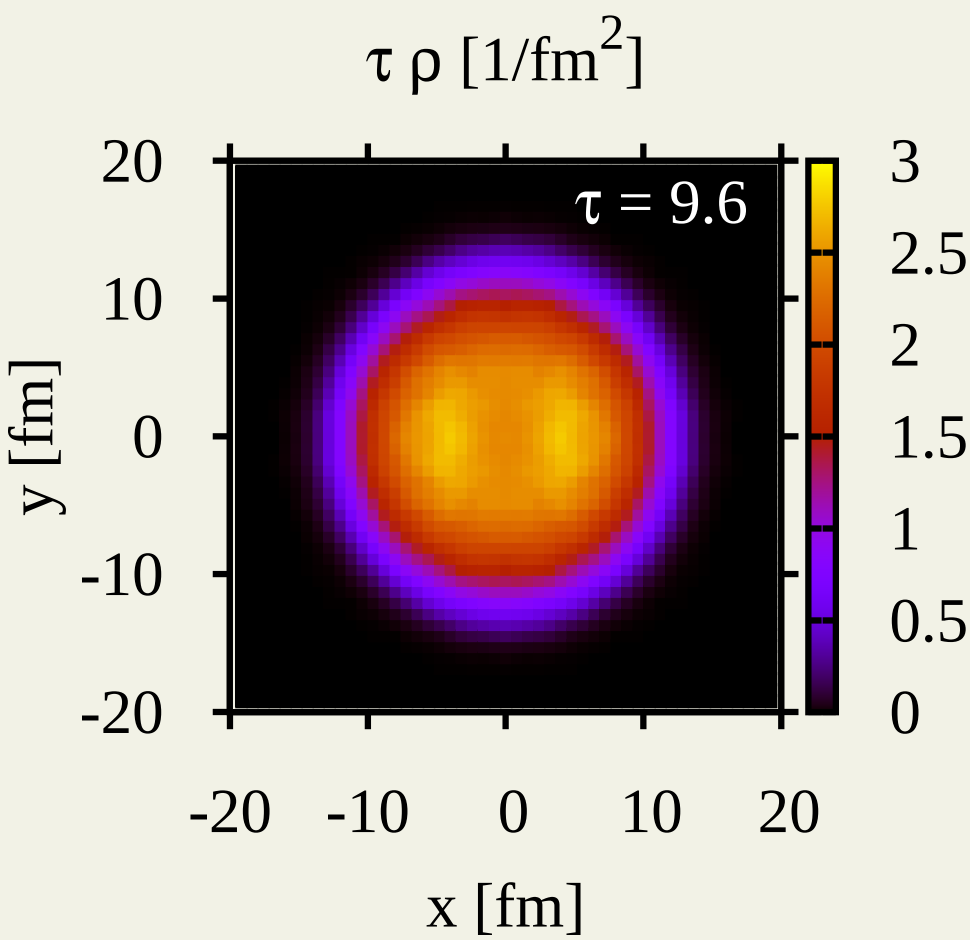
Au+Au, b=3 fm



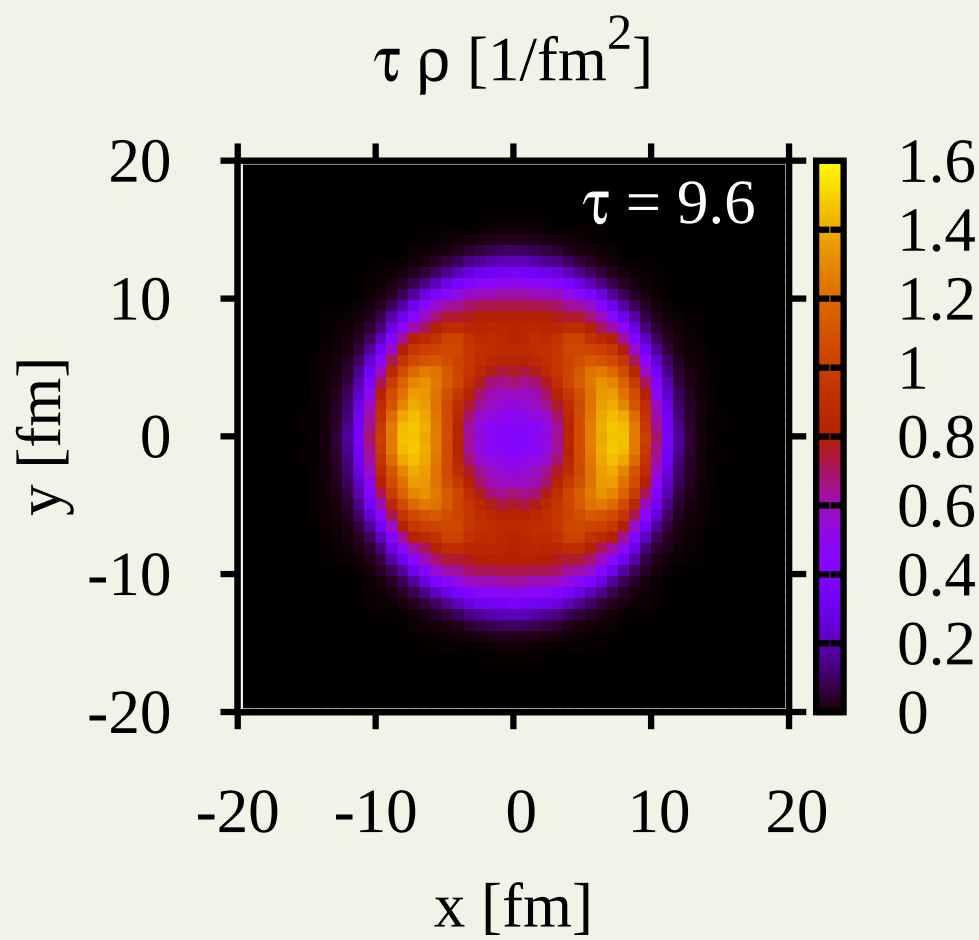
Au+Au, b=8 fm



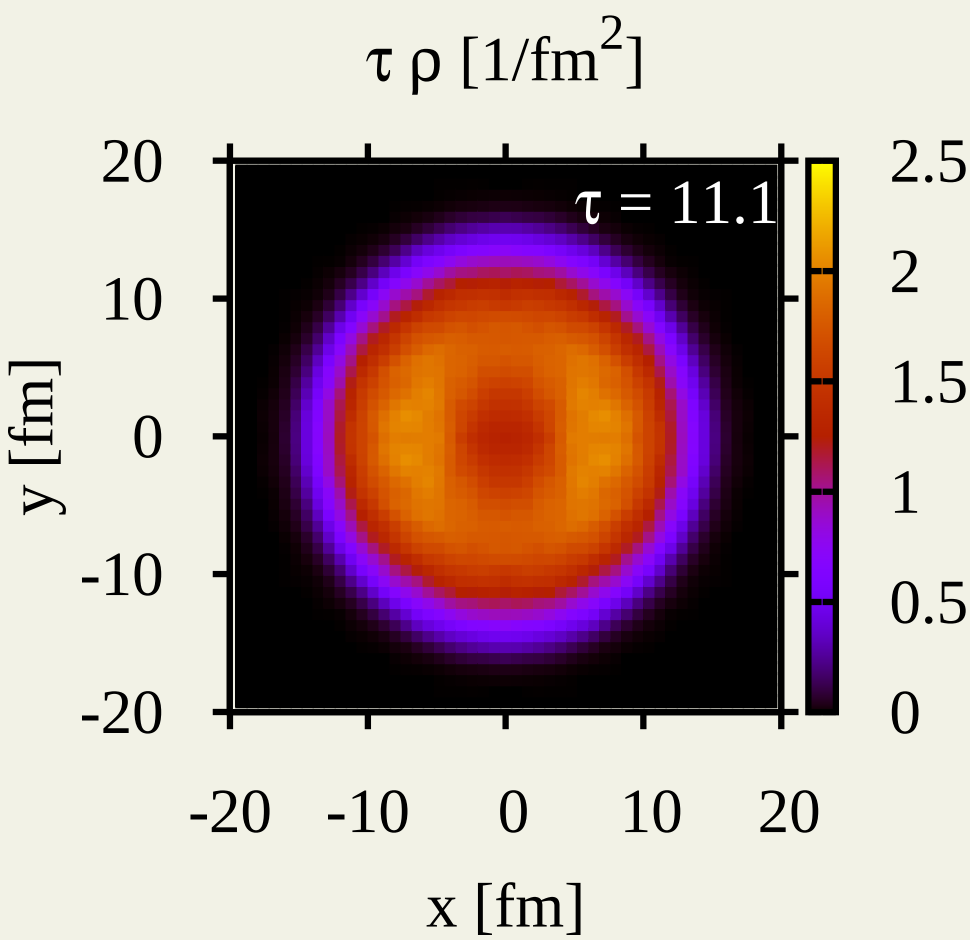
Au+Au, b=3 fm



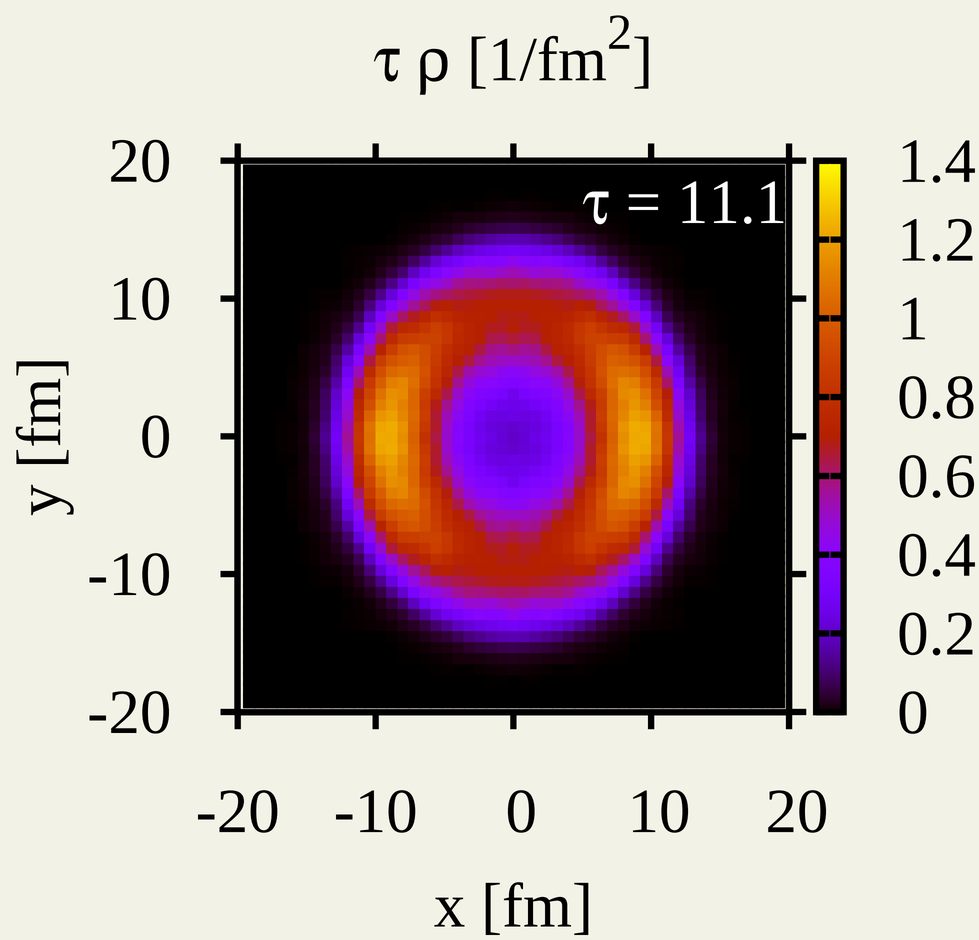
Au+Au, b=8 fm



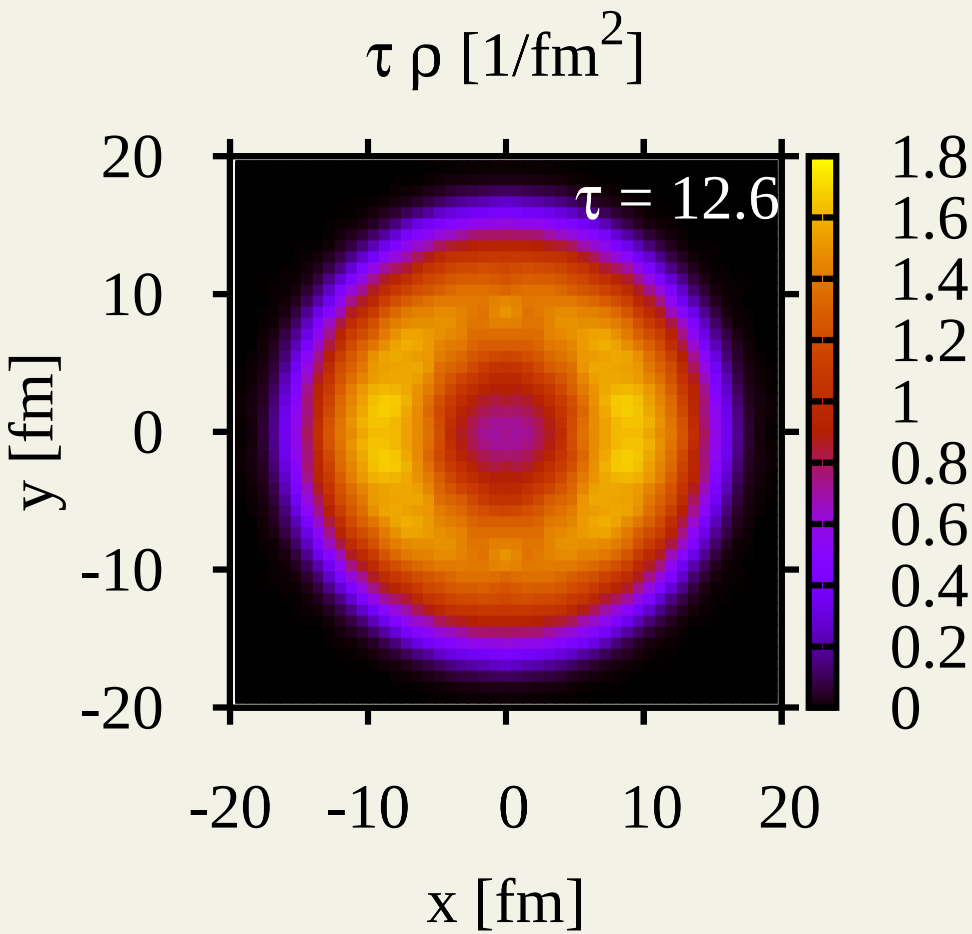
Au+Au, b=3 fm



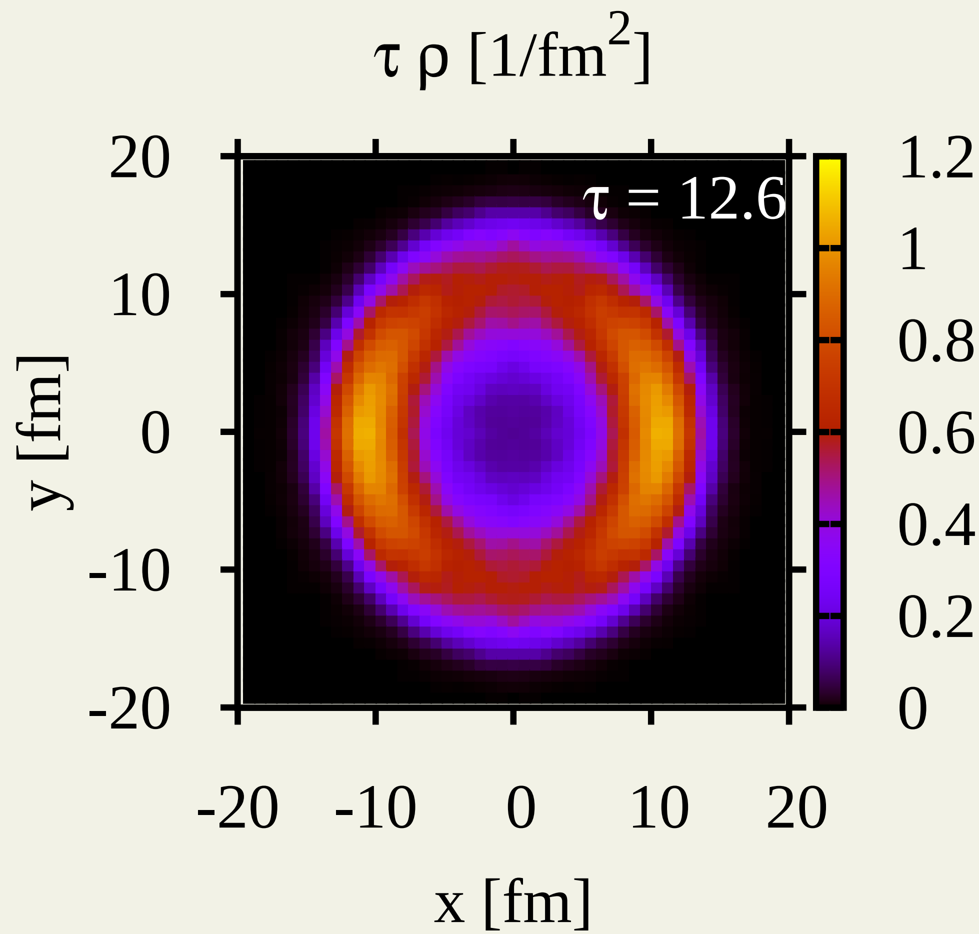
Au+Au, b=8 fm



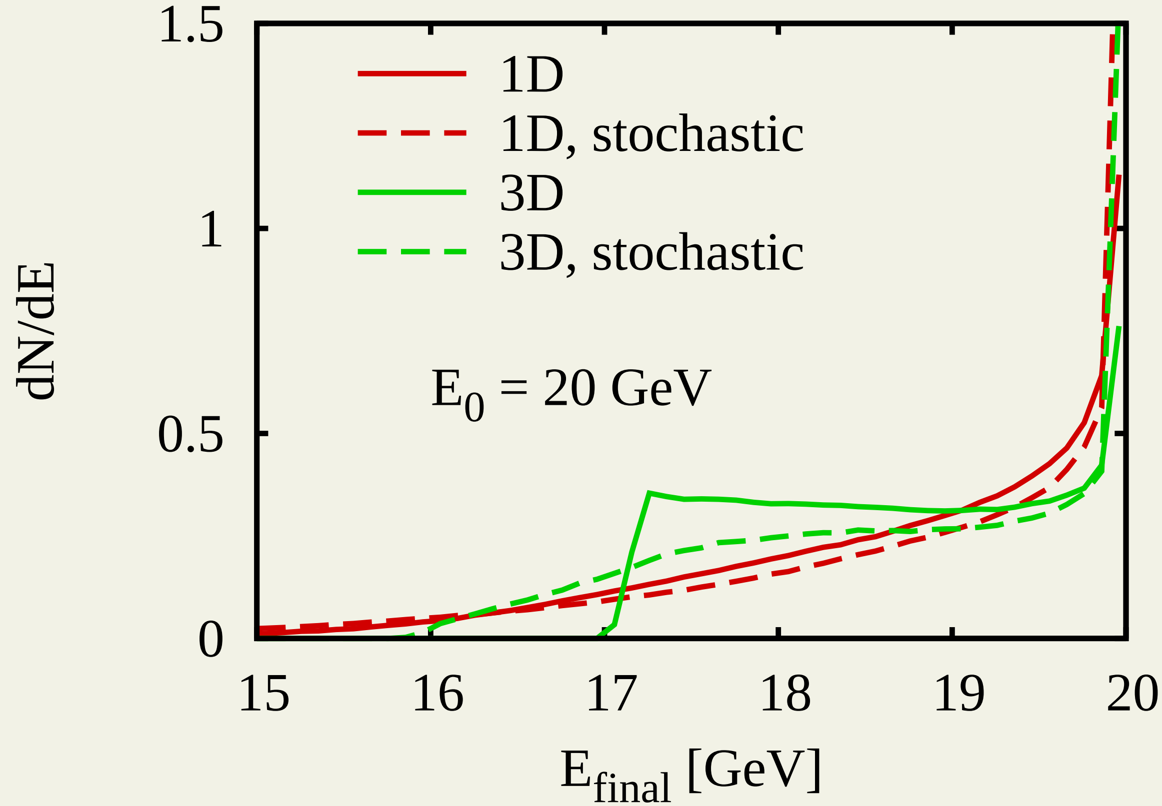
Au+Au, b=3 fm



Au+Au, b=8 fm



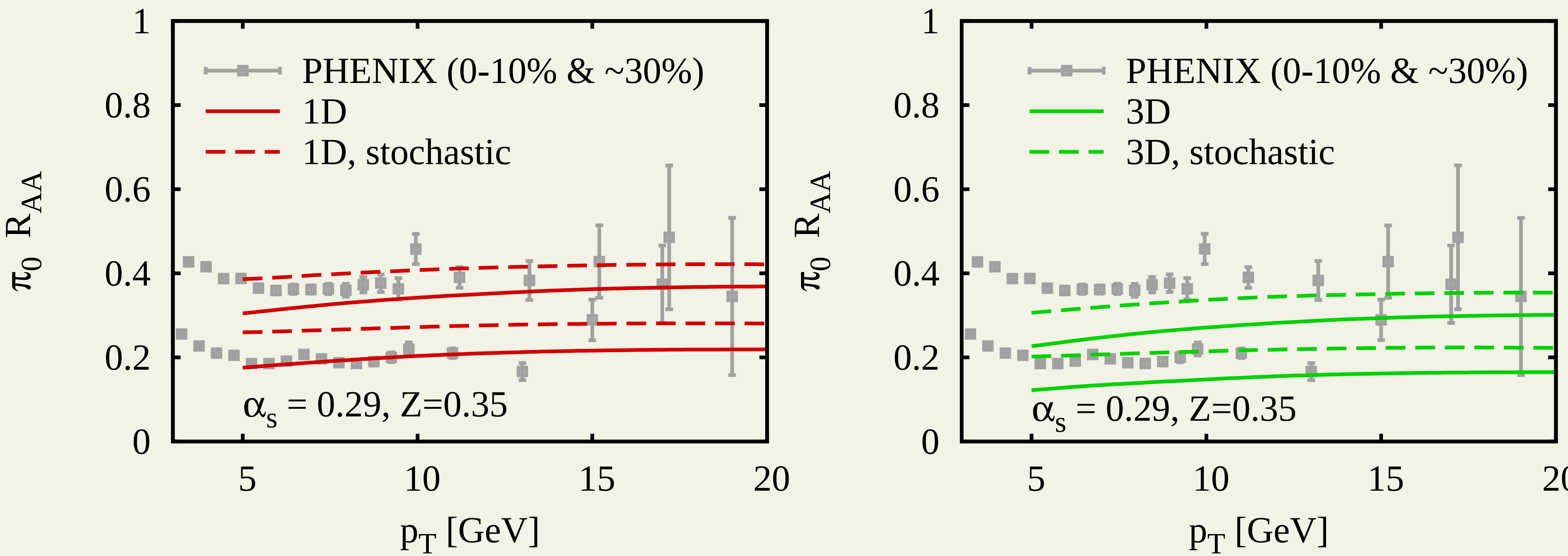
E-loss for 20 GeV gluons - Au+Au, b=8 fm



$\rightarrow$ **more fluctuation with stochastic**

$\rightarrow$ **less(!) fluctuation with expansion**

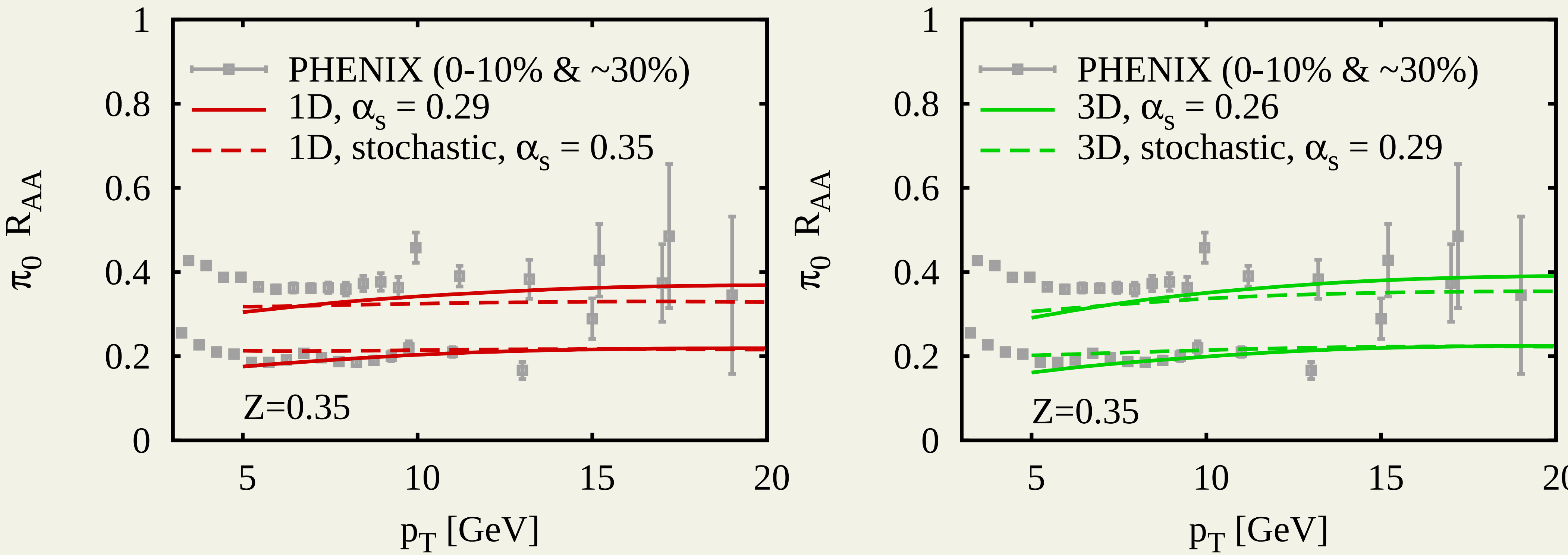
pion RAA, RHIC



significant effect from fluctuations and transverse expansion

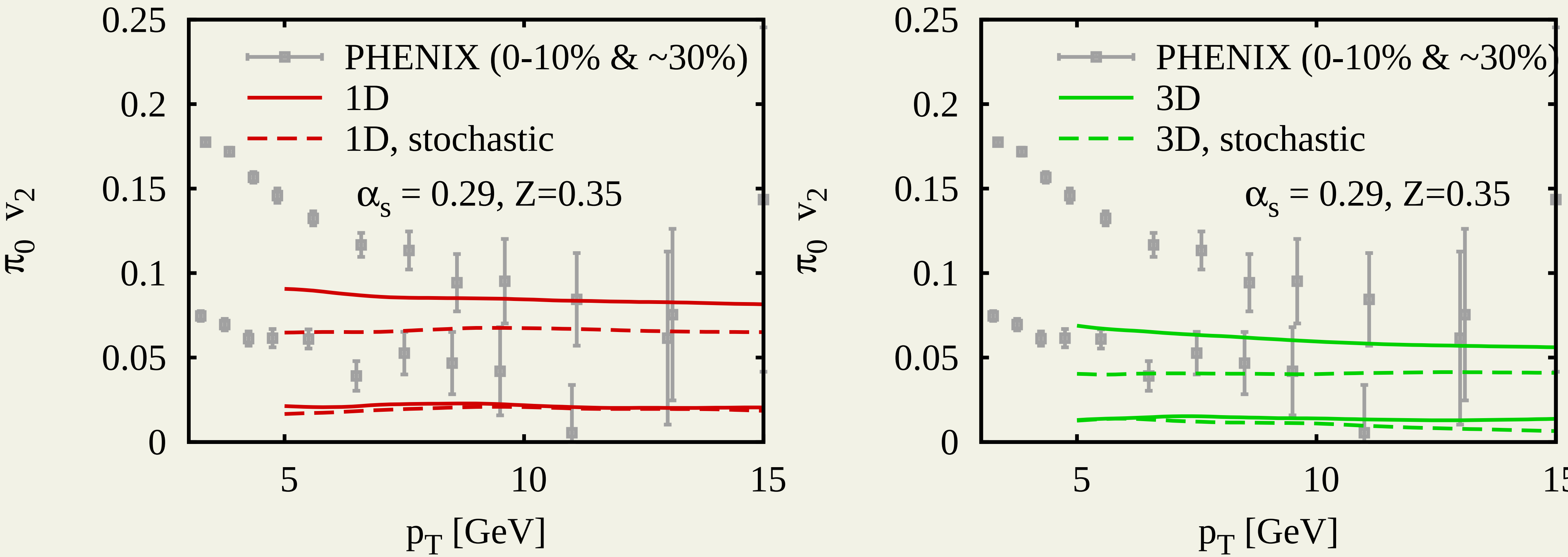
more energy loss with transverse expansion because GLV favors large $\Delta z/\tau_f$

pion RAA, RHIC - α_s scaled to RAA for central

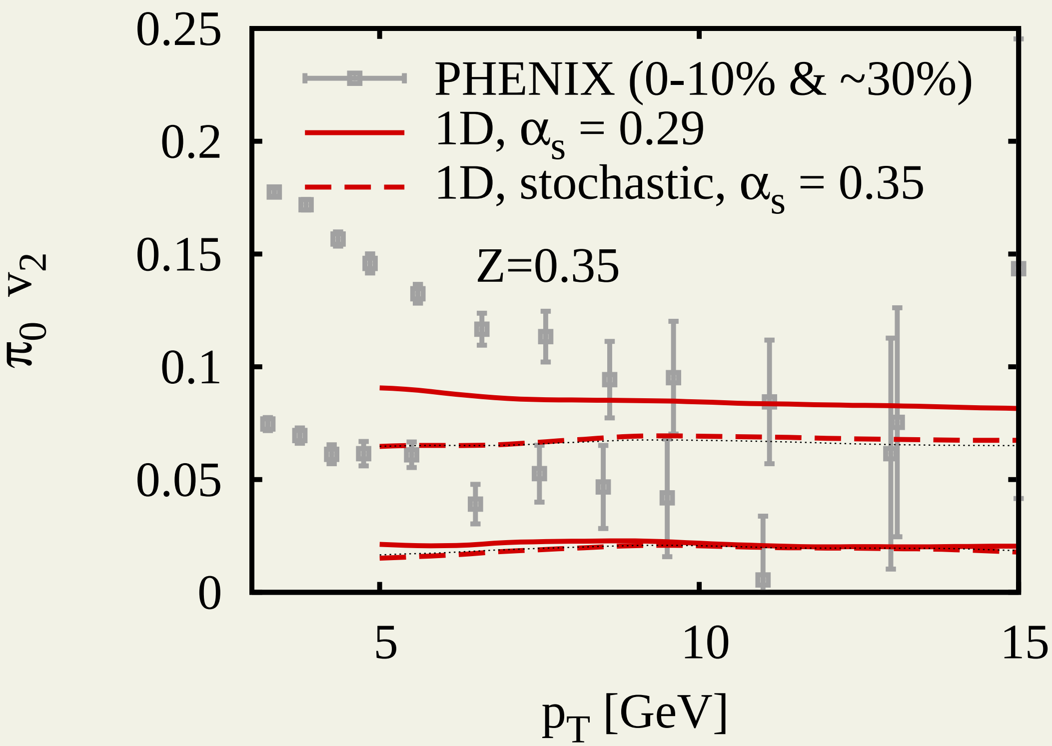


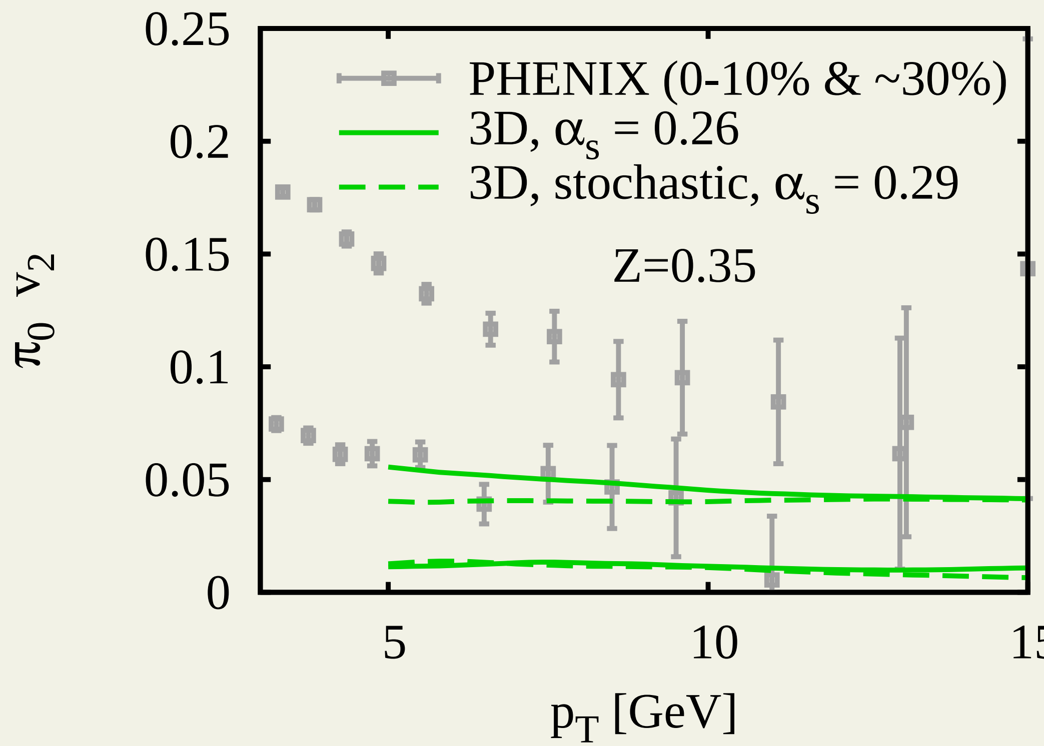
only small 10-15% differences after tuning parameters to central data

pion v2, RHIC


PHENIX (0-10% & ~30%)
1D
1D, stochastic
αs = 0.29, Z=0.35
π0 v2
pT [GeV]
0.25
0.2
0.15
0.1
0.05
0
5
10
15
PHENIX (0-10% & ~30%)
3D
3D, stochastic
αs = 0.29, Z=0.35
π0 v2
pT [GeV]

pion v2, RHIC - α_s scaled to RAA for central





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

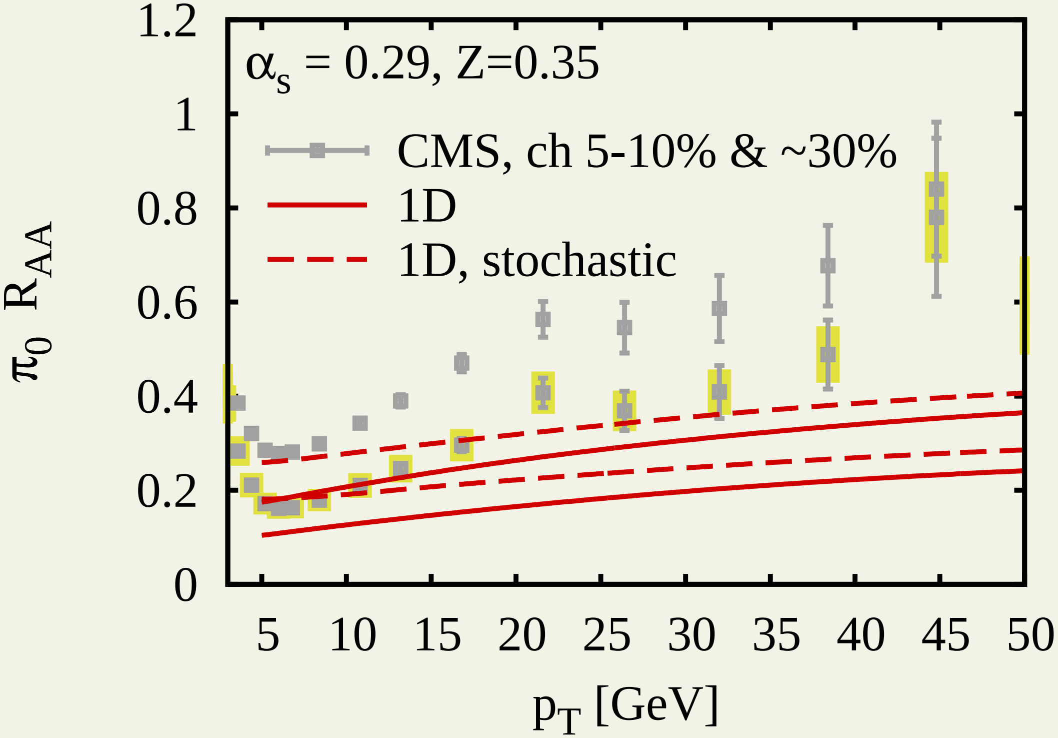
smaller v_2 with transverse expansion - GLV favors later times (large $\Delta z/\tau_f$)

Now move to LHC energies. Simple assumption:

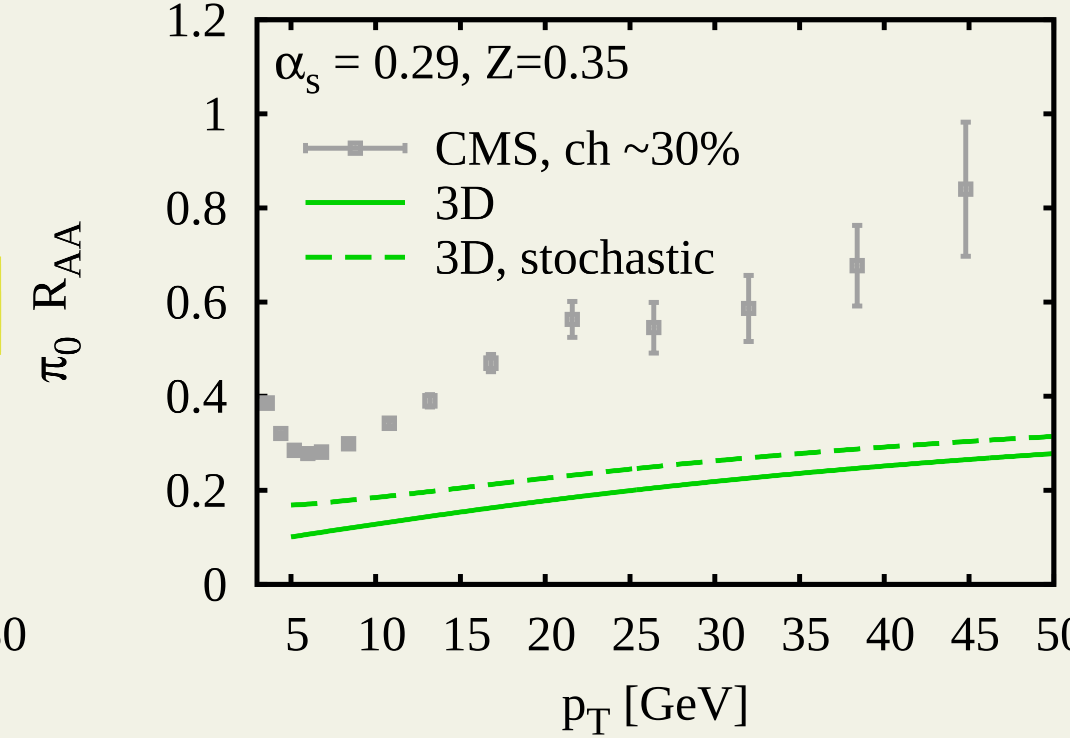
- **higher** $dN/d\eta = 2400$ **in central collisions (**$b = 0$**)**
- **all other ingredients stay same**

at present we only have mid-peripheral results in the 3D case

pion RAA, LHC

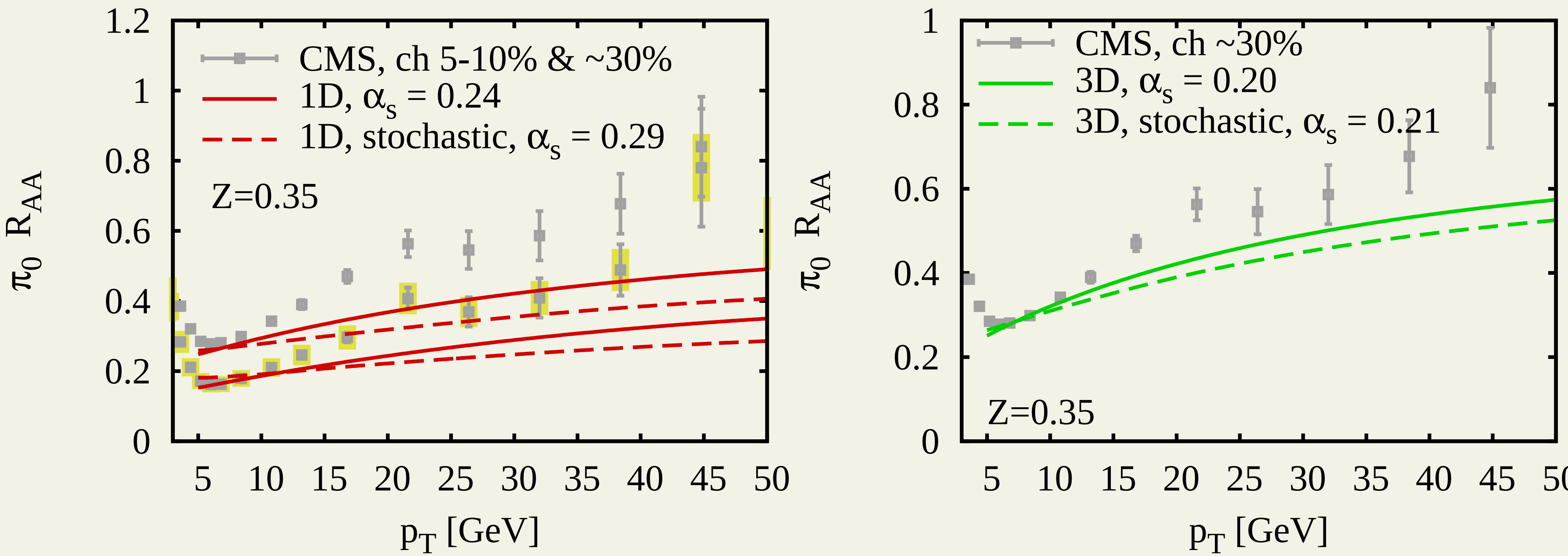


1.2
1
0.8
0.6
0.4
0.2
0
π_0 R_{AA}
α_s = 0.29, Z=0.35
CMS, ch 5-10% & ~30%
1D
1D, stochastic
5 10 15 20 25 30 35 40 45 50
p_T [GeV]

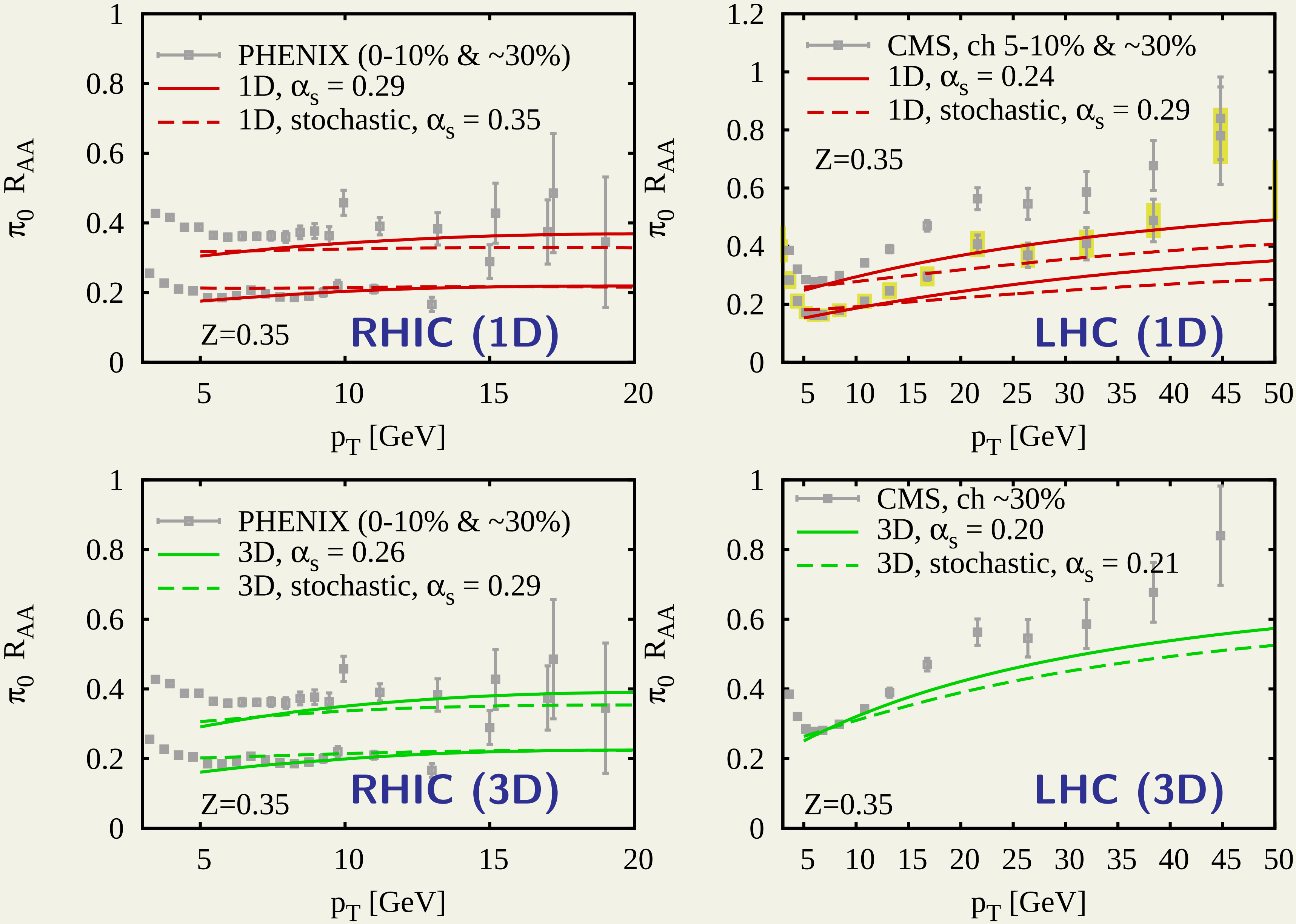


1.2
1
0.8
0.6
0.4
0.2
0
π_0 R_{AA}
α_s = 0.29, Z=0.35
CMS, ch ~30%
3D
3D, stochastic
5 10 15 20 25 30 35 40 45 50
p_T [GeV]

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

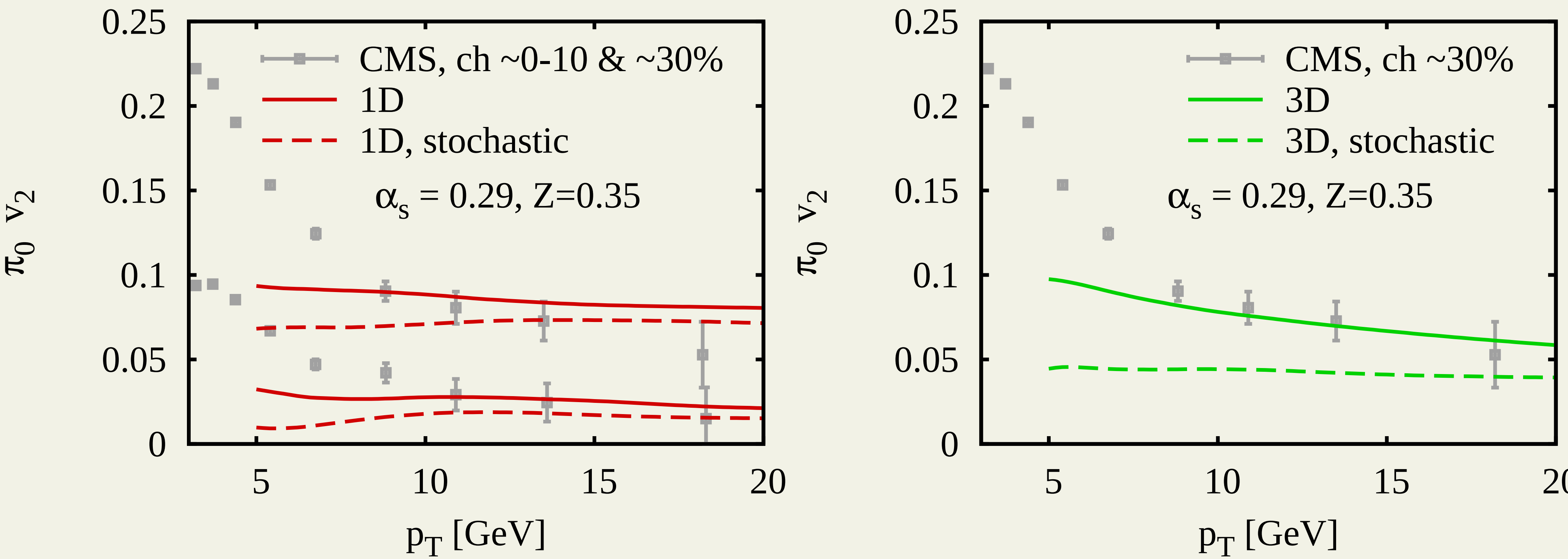


GLV implementation here is simplified, also $\alpha_s = const$ (no running)



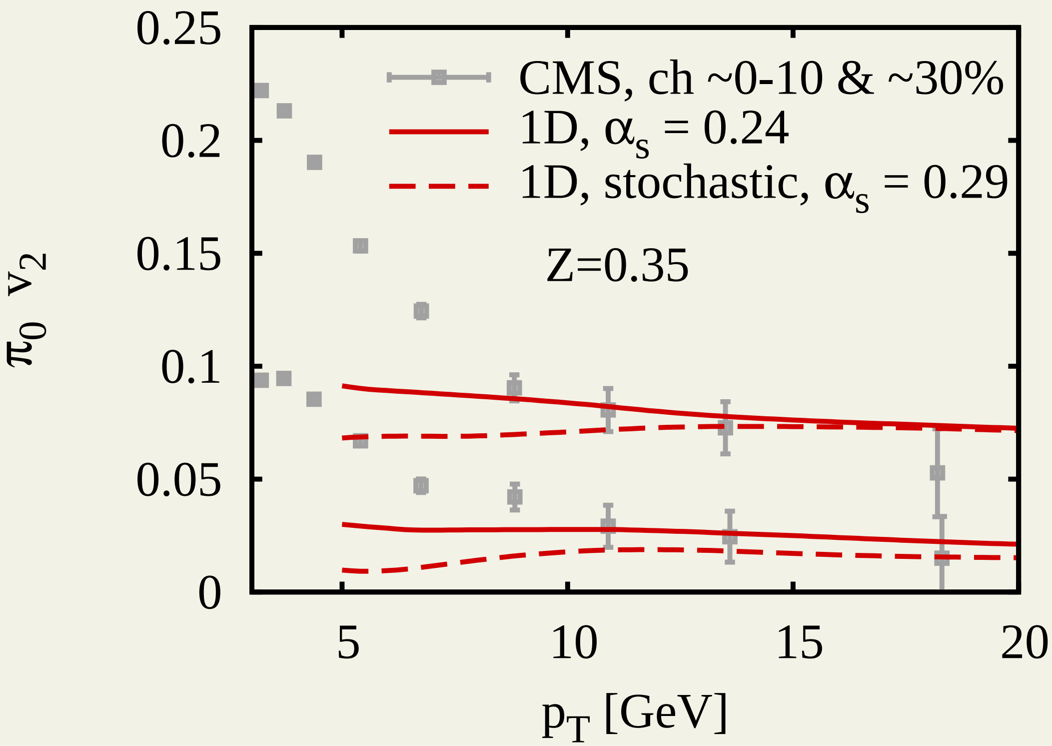
need $20 - 25$% smaller α_s at LHC than at RHIC - similar to Betz et al, 1201.0281

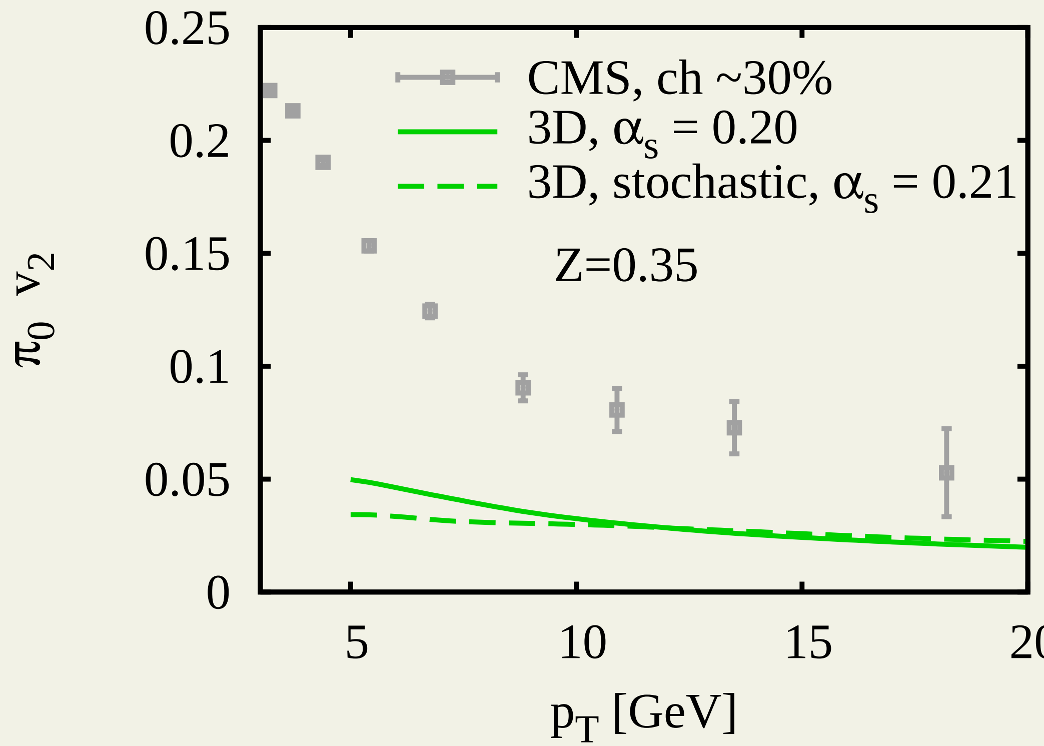
pion v2, LHC



0.25
0.2
0.15
0.1
0.05
0
5
10
15
20
π_0 v_2
p_T [GeV]
CMS, ch ~0-10 & ~30%
1D
1D, stochastic
α_s = 0.29, Z=0.35
CMS, ch ~30%
3D
3D, stochastic
α_s = 0.29, Z=0.35

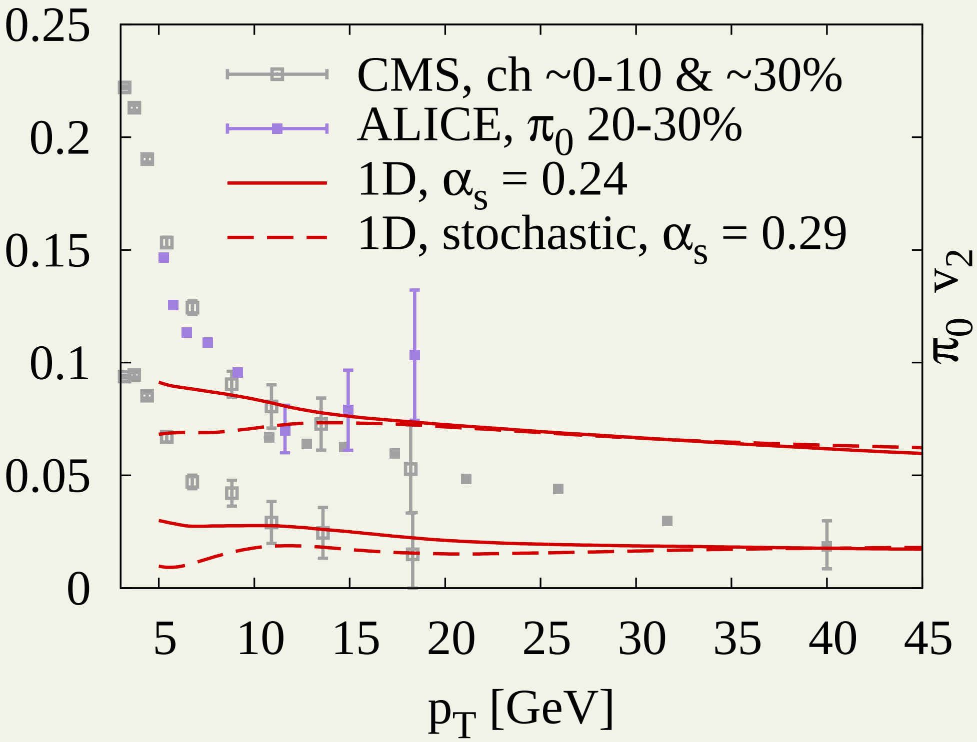
pion v2, LHC - α_s scaled to RAA at pT = 6 GeV

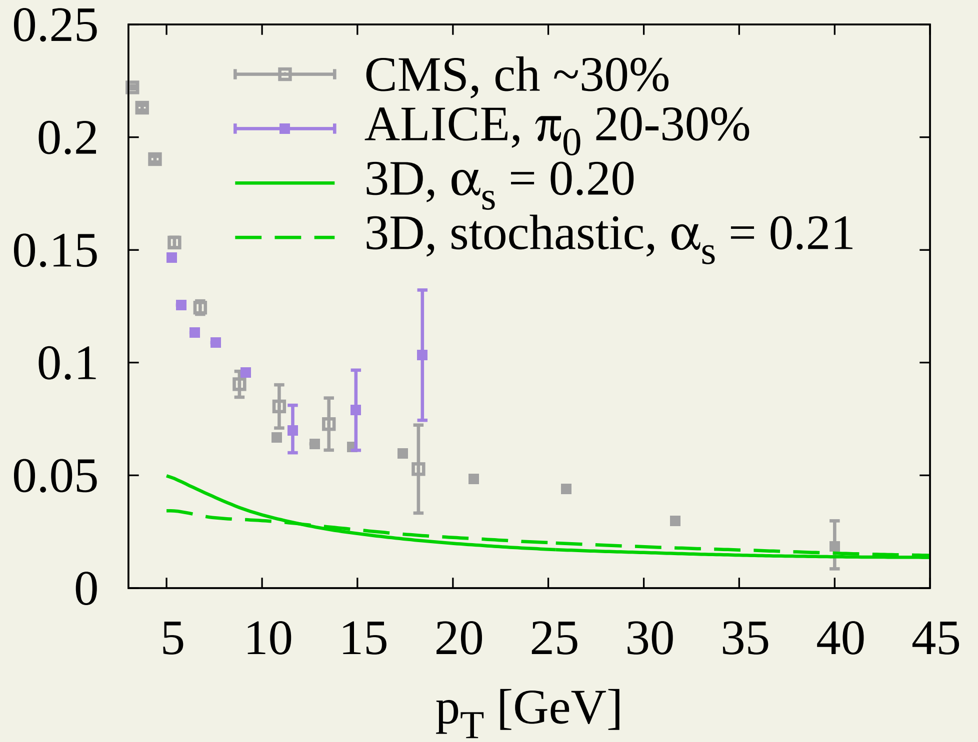




similar reduction in 3D case as at RHIC energies

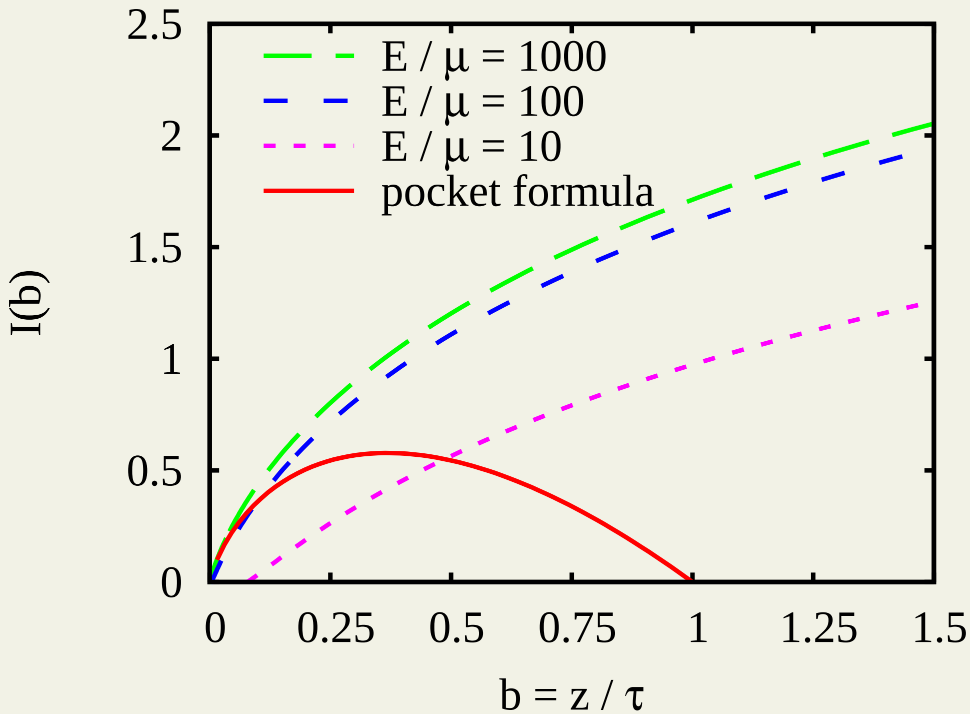
high-pT pion v2, LHC (α_s scaled to RAA at pT = 6 GeV)





__In a nutshell:__ **for transversely expanding medium, both R_{AA} and v_2 are smaller with GLV energy loss. LPM interference favors late scattering.**

$$\Delta E^{(1)}_{GLV}(z) \quad \propto \quad \int dx\, d\mathbf{k}\, d\mathbf{q}\, \frac{\mu^2}{\pi(\mathbf{q}^2+\mu^2)^2}\frac{2\mathbf{k}\cdot\mathbf{q}}{\mathbf{k}^2(\mathbf{k}-\mathbf{q})^2}(1-\cos\omega\Delta z) \;\; \propto \;\; I(\Delta z/\tau(z), E/\mu(z))$$



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

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)**

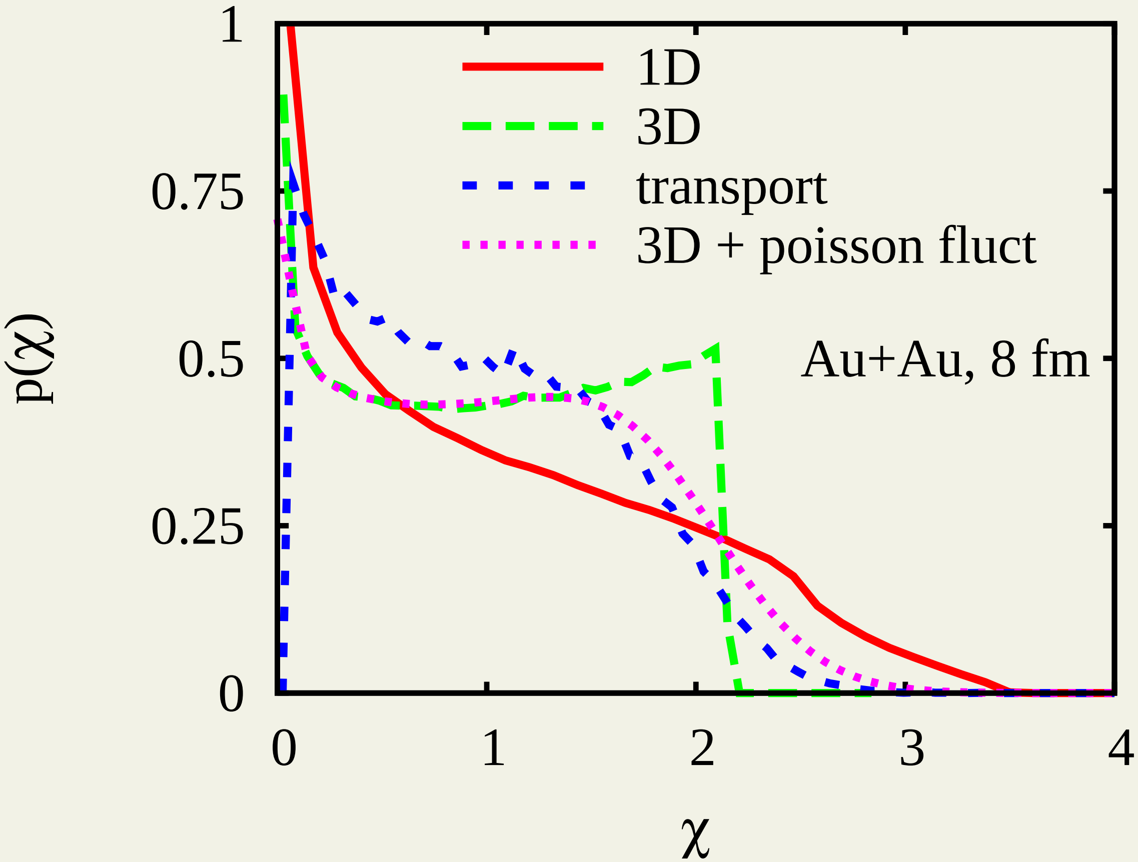
[our current numerical setup suppresses fluctuations by $\sim 4-5$ (we oversample to improve statistics)]

———

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

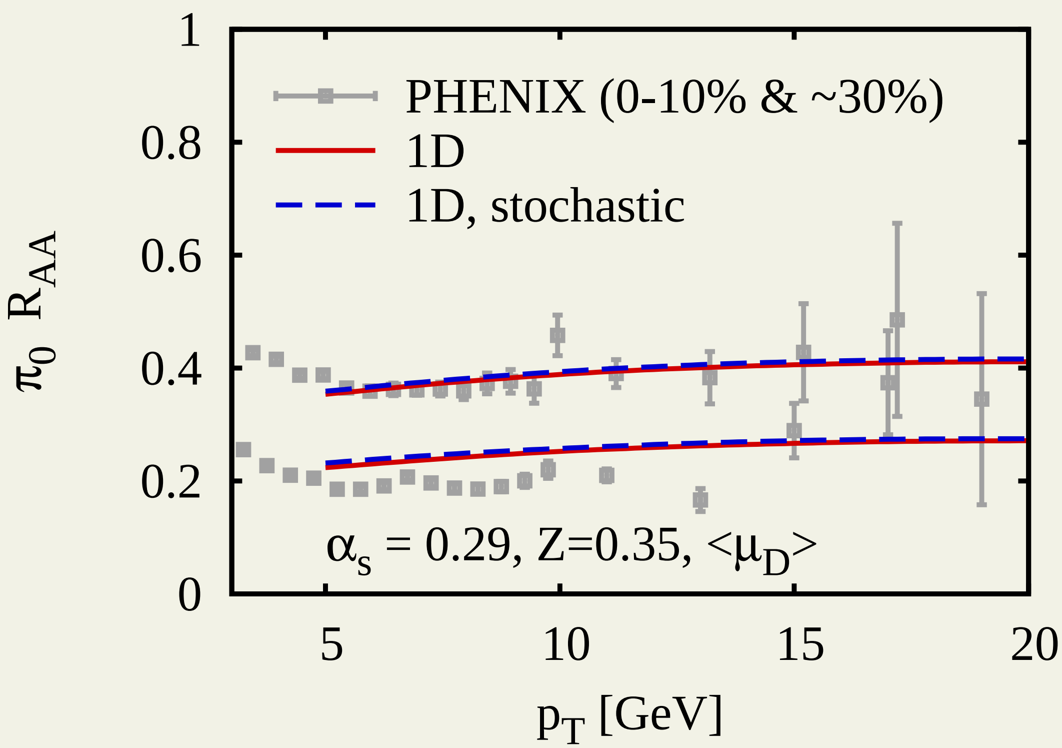
- **instead of local** $\mu_D(x_\perp, \tau)$**, transversely averaged** $\langle \mu_D \rangle \sim \langle T \rangle(\tau) \sim \tau^{-1/3}$
  [spatial distribution is challenging to sample numerically]
- **use** $\rho(x_\perp, \tau) \equiv 0$ **for** $\tau < \tau_0$

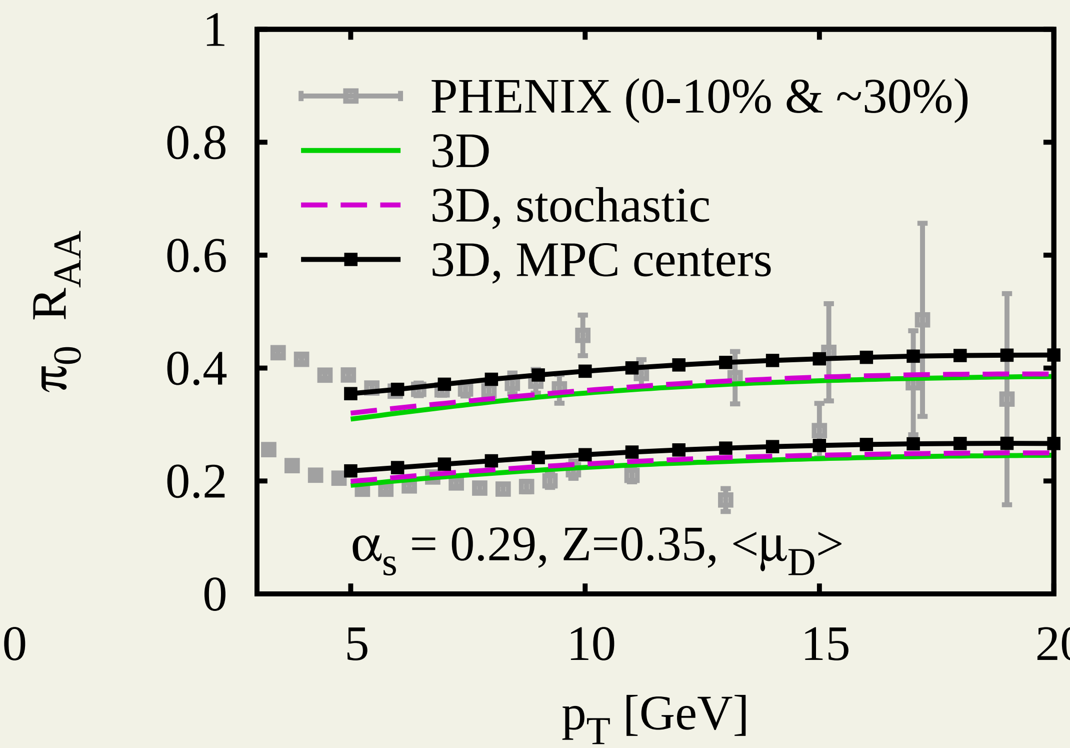
opacity distribution for Au+Au, b = 8 fm



estimate from density alone is not too bad actually

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

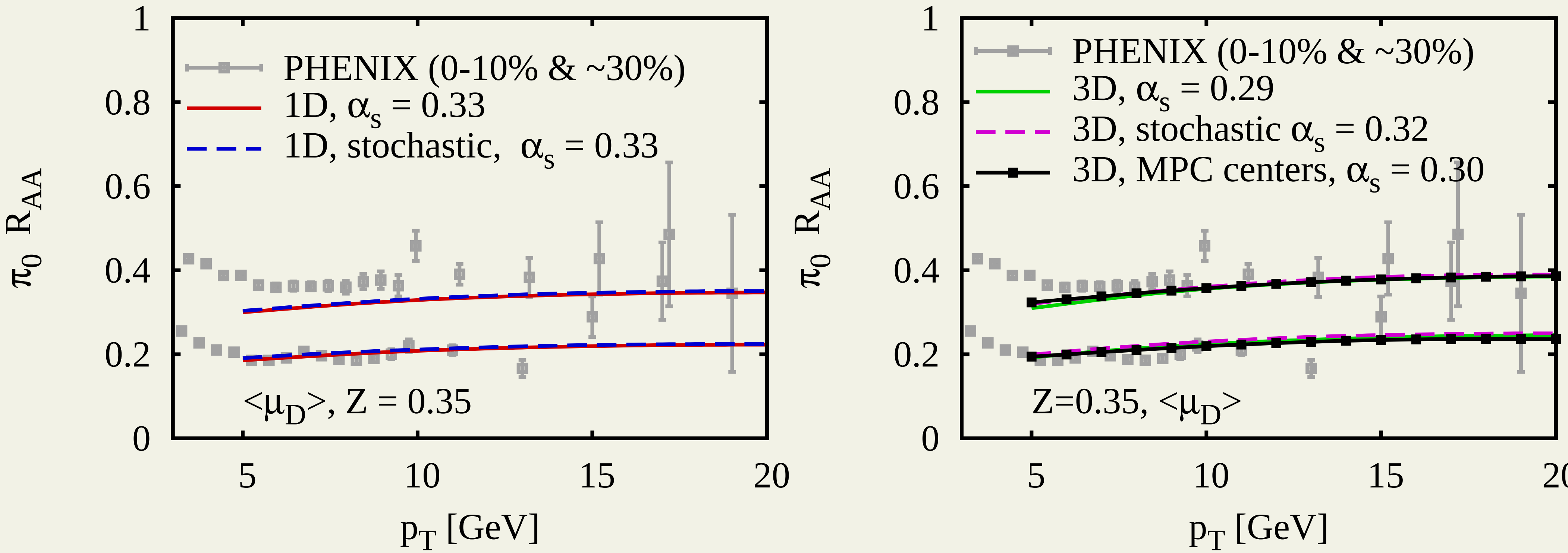




because no E-loss for $\tau < \tau_0$, E-loss fluctuations are MUCH reduced

realistic scattering positions from transport make a modest difference

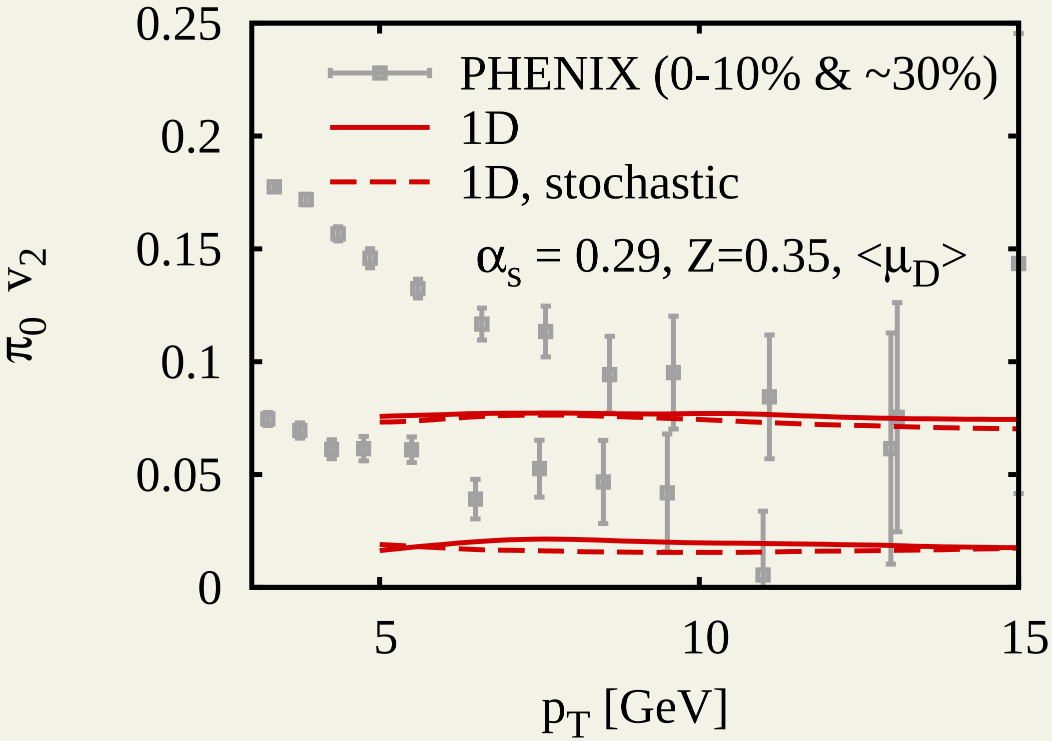
pion RAA, RHIC, $\langle \mu_D \rangle$ - α_s scaled to RAA for central

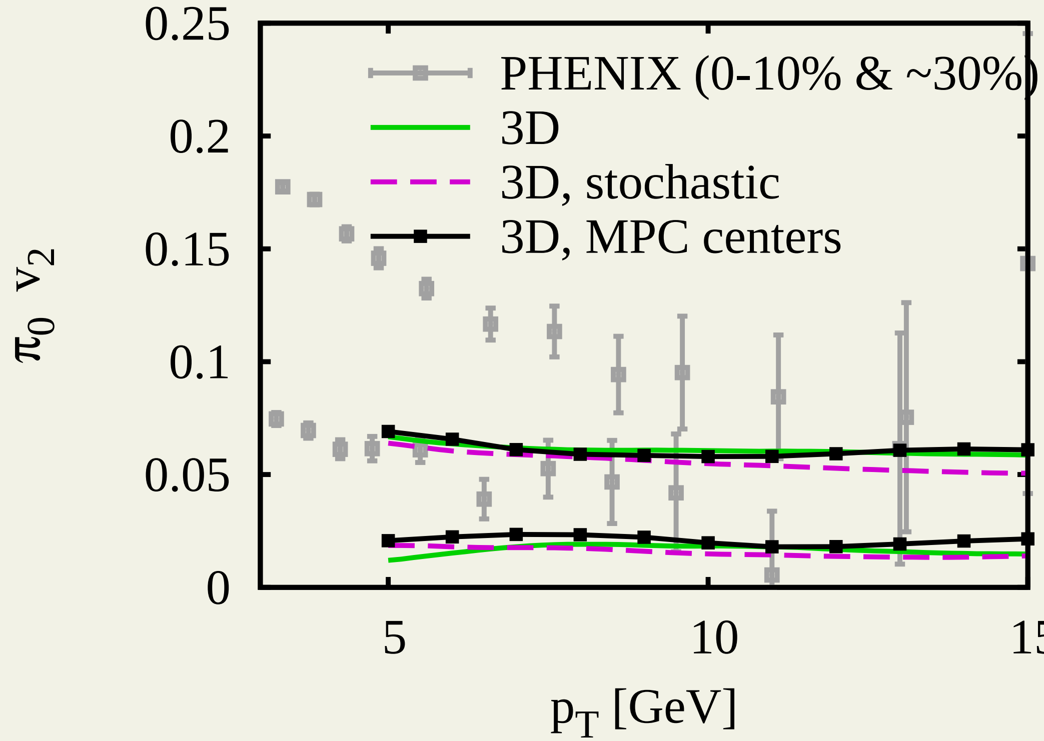


but the effect can be absorbed via re-adjusting α_s

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

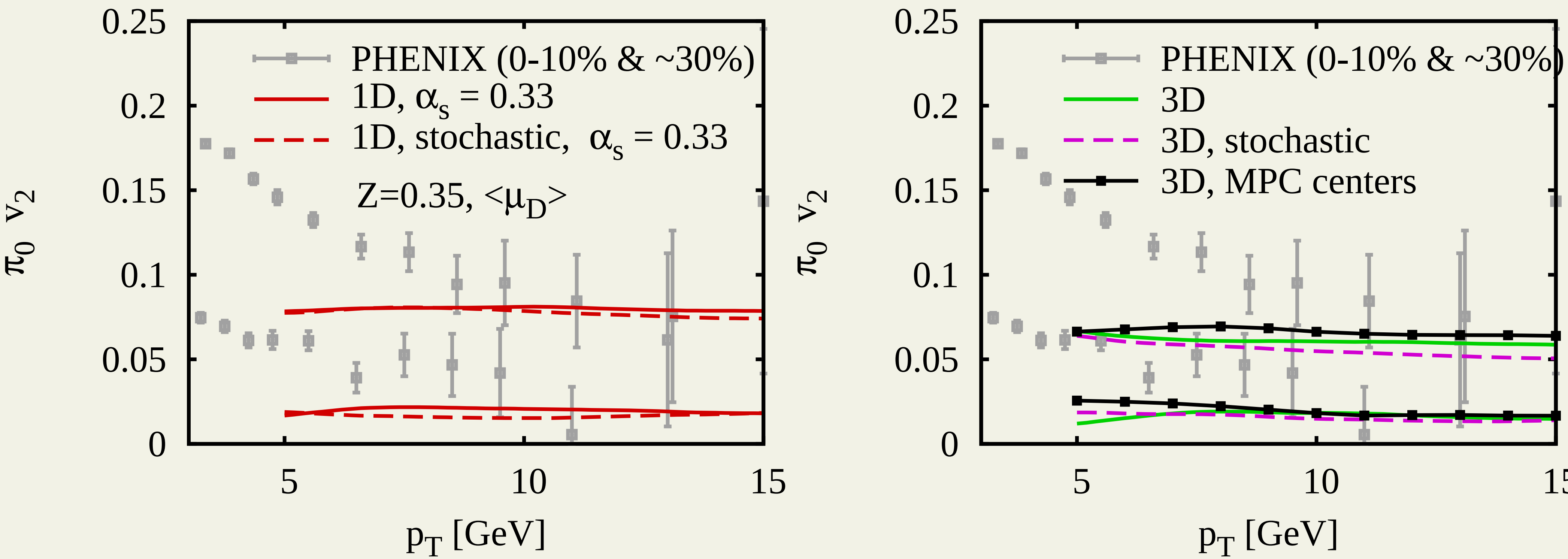
pion v2, RHIC





but elliptic flow works better(!) in this scenario ~ 6%

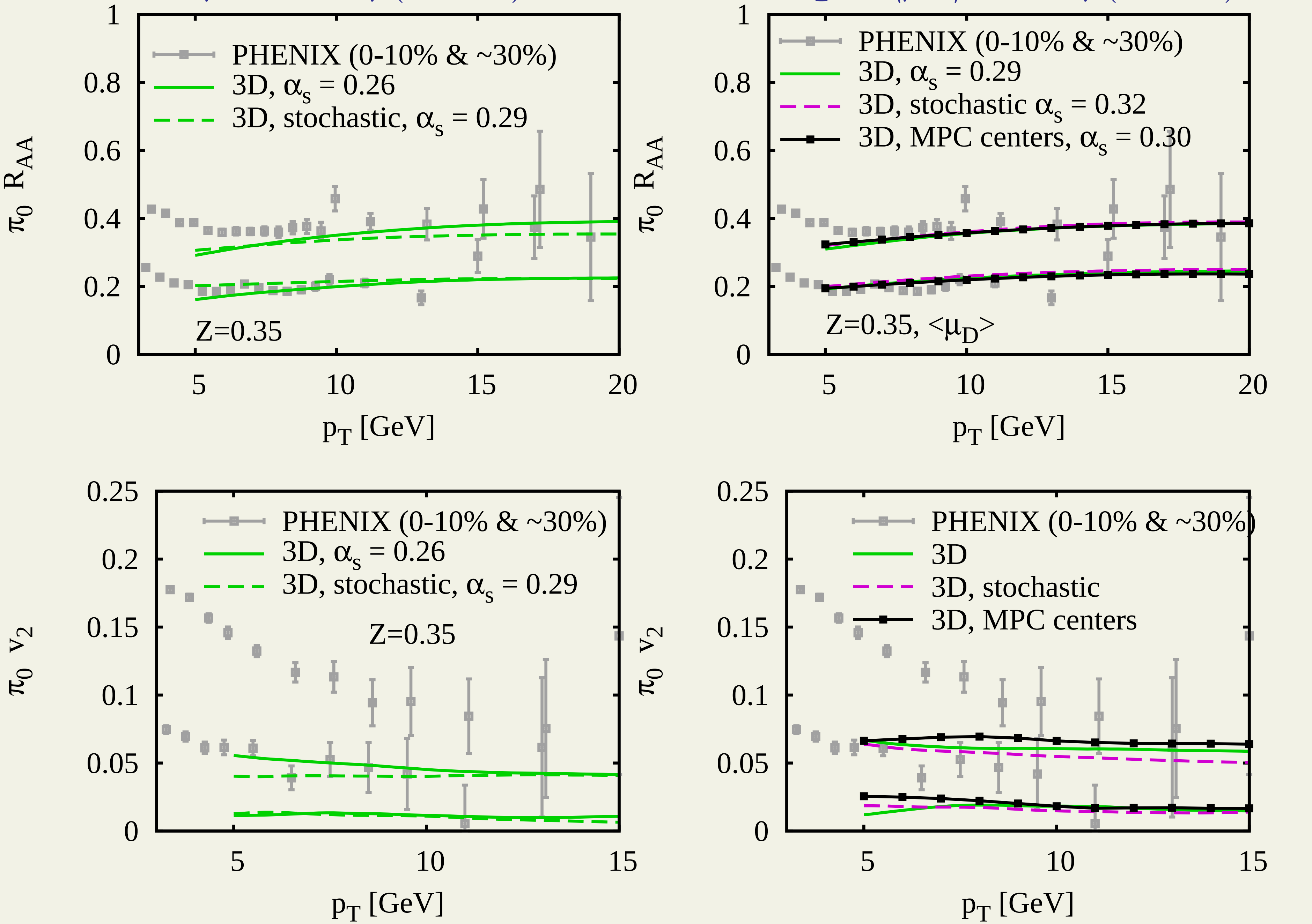
pion v2, RHIC - α_s scaled to RAA for central



elliptic flow works better(!) in this scenario ~ 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.

- transverse expansion reduces both R_{AA} and v_2. This is a generic feature of GLV energy loss.
- Energy loss fluctuations with scattering location are important but can largely be absorbed into an adjusted α_s.
- Fluctuations are sensitive to early opacity evolution $\rho(\tau < \tau_0)$.
  Fluctuations seem to be well captured with just the density information from the transport (instead of the full spacetime ensemble of jet-medium scatterings), albeit we only investigated a limited scenario where fluctuations had a diminished role.

Some future steps:

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

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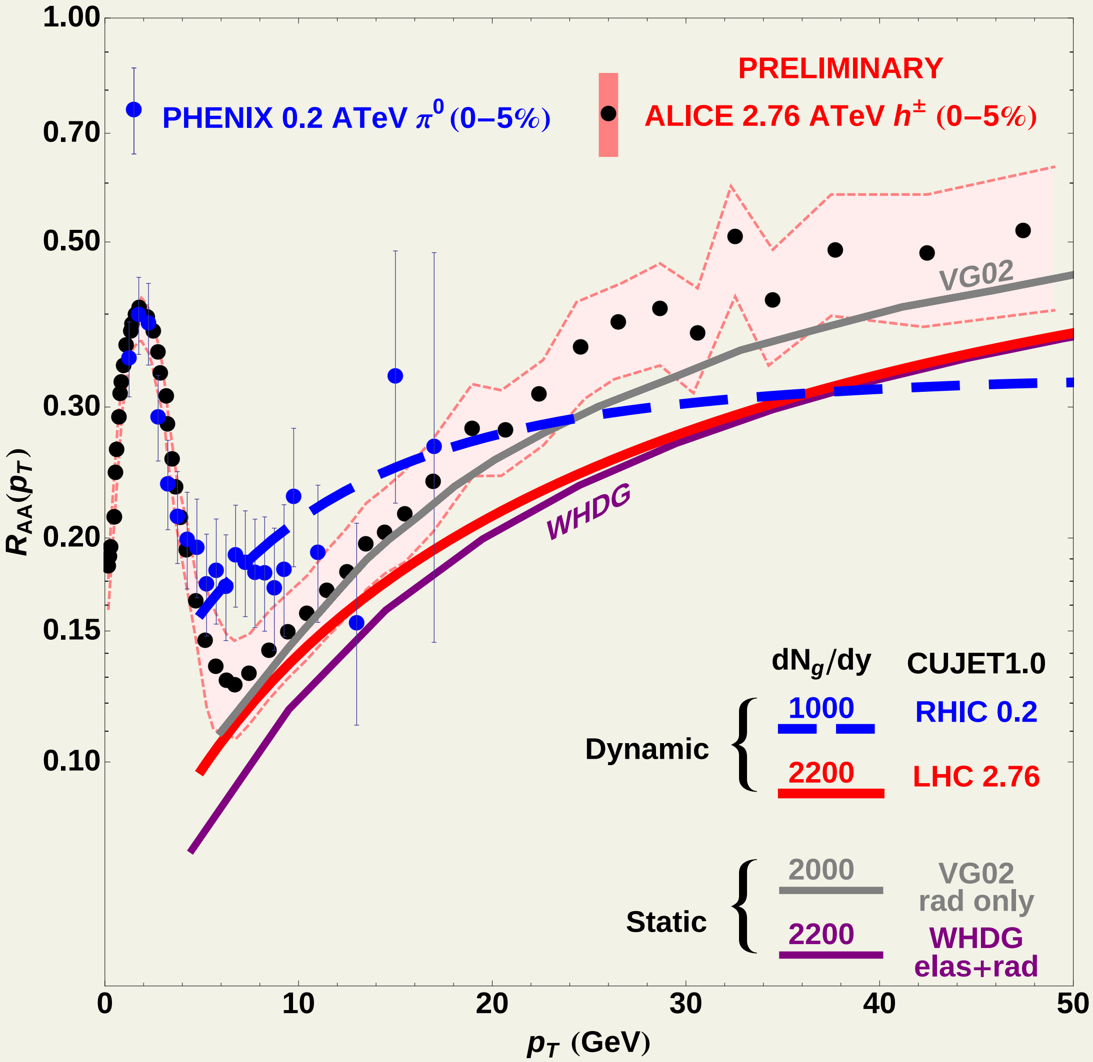
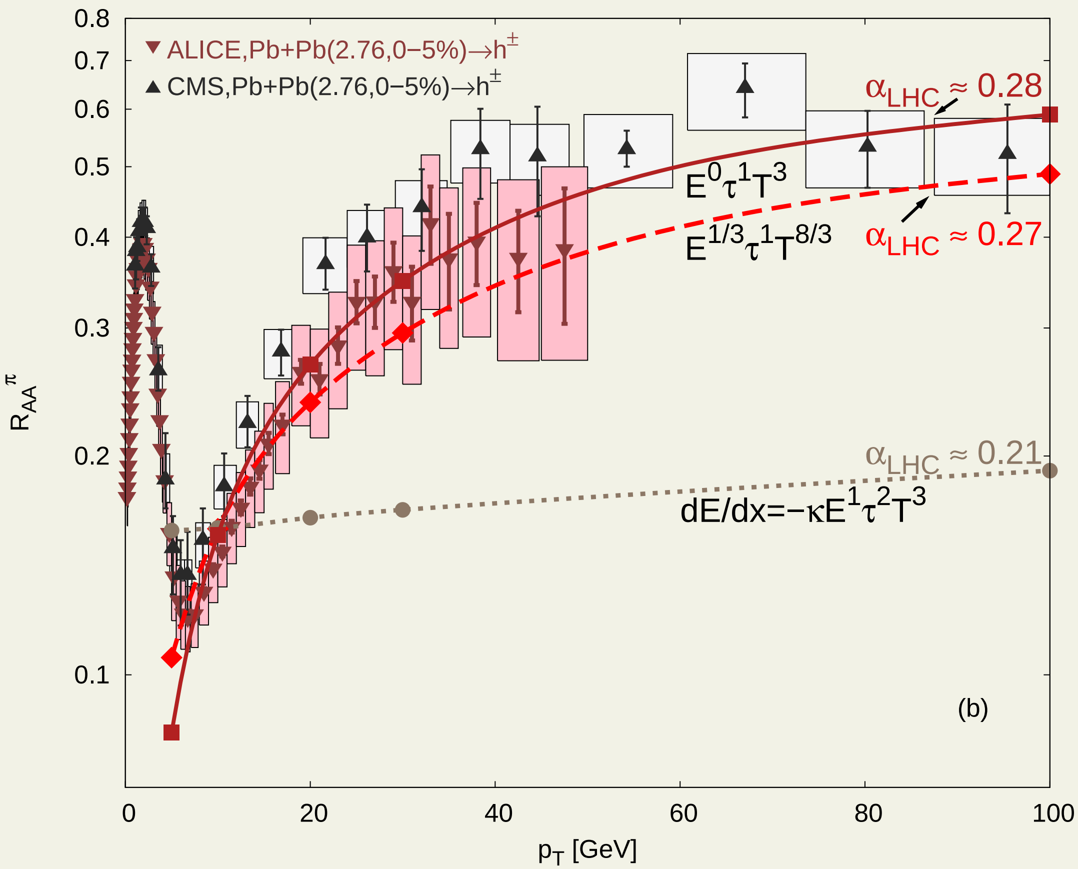
感謝大家的關注!

Backup slides

CUJET 1.0 Buzzatti et al ('11)

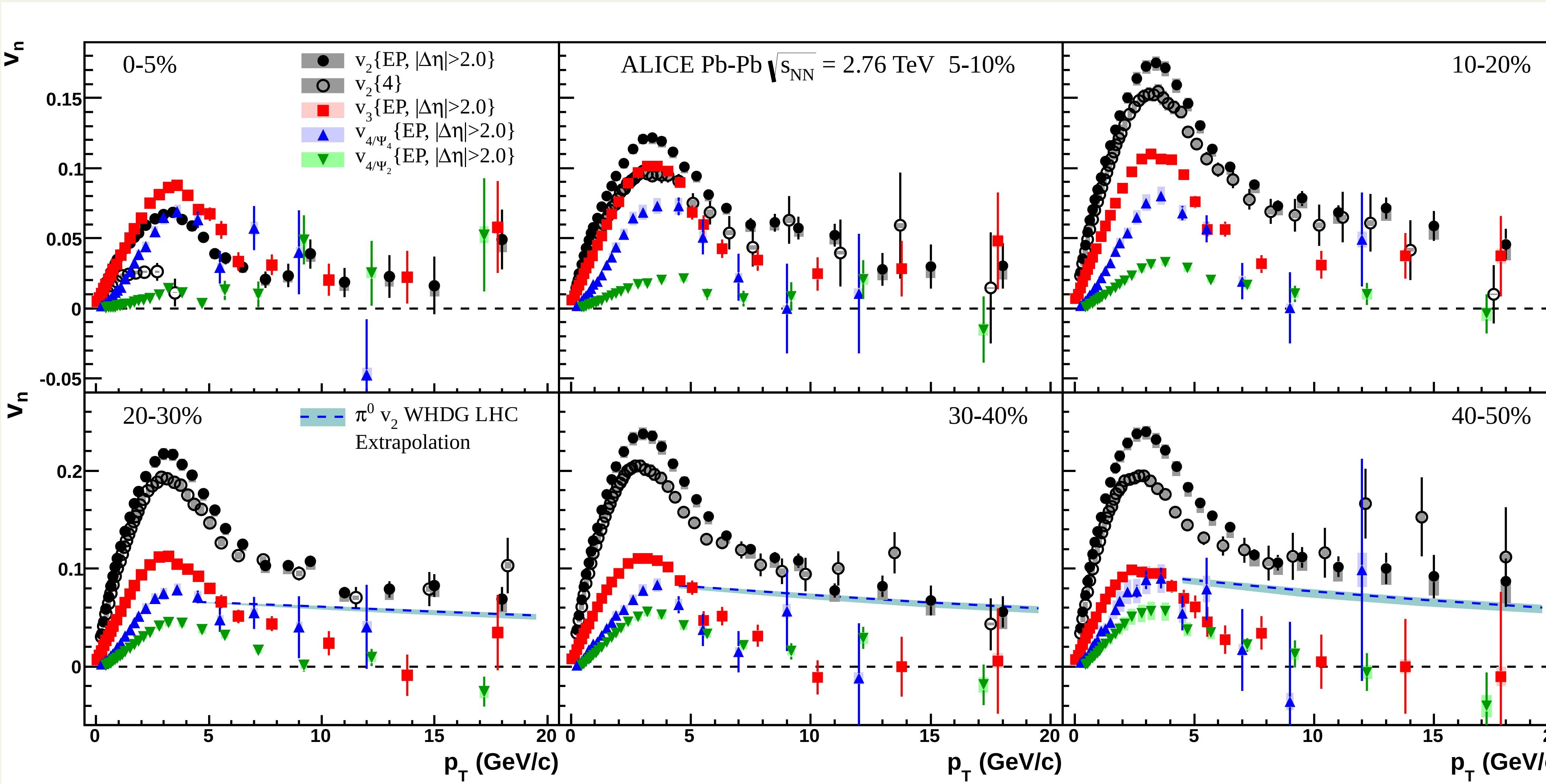


Betz & Gyulassy, arXiv:1201.0281

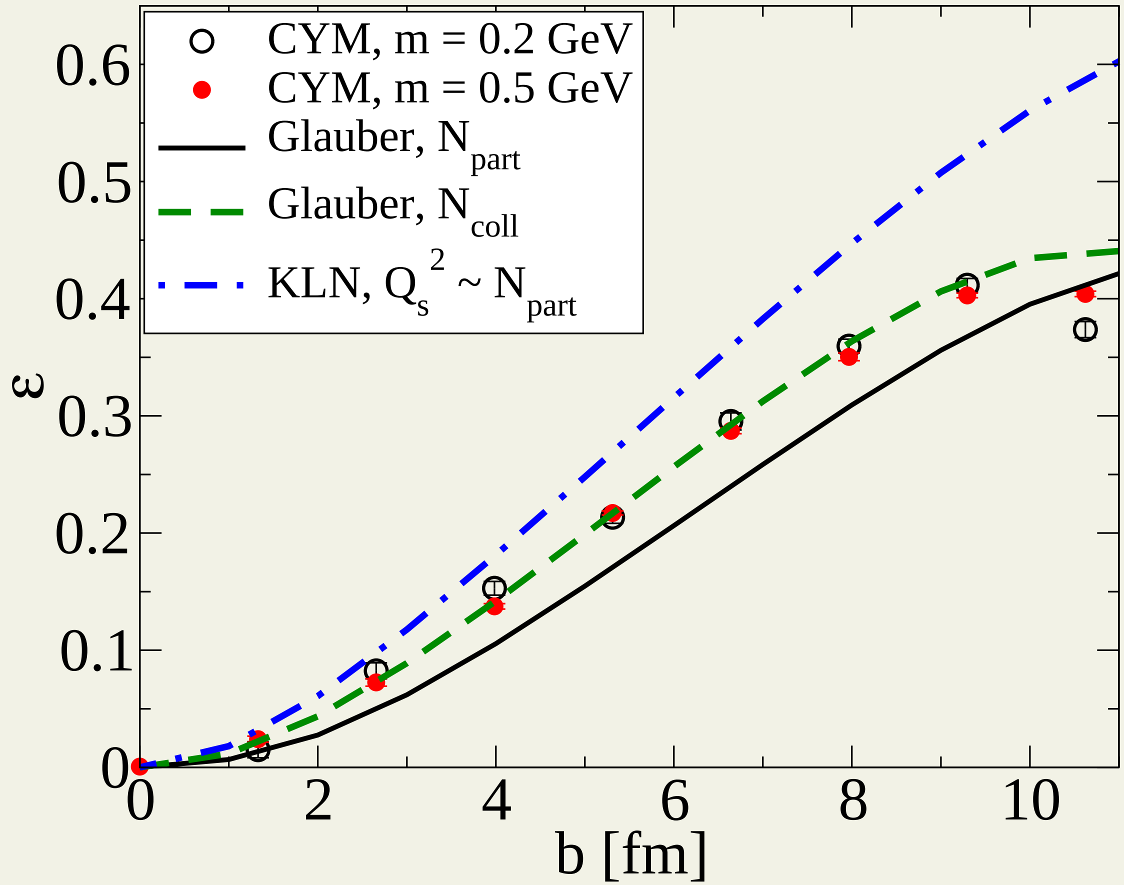


$$\alpha_s^{RHIC} = 0.3$$

ALICE v2,v3,v4 arXiv:1205.5761v2



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



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