Hard and soft responses from parton transport

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Workshop on Jet Quenching at RHIC vs LHC

in Light of Recent dAu vs pPb controls

Apr 15-17, 2013, Brookhaven National Laboratory, Upton, NY

in collaboration with Deke Sun

(parton) transport can give you:

- bulk medium evolution
- nonequilibrium effects
- fluctuations

Covariant transport

(on-shell) phase-space density $f(x,\vec{p}) \equiv \frac{dN(\vec{x},\vec{p},t)}{d^3x d^3p}$

transport equation:

$$p^\mu \partial_\mu f_i(x,p) = C^i_{2\to 2}[\{f_j\}](x,p) + C^i_{2\leftrightarrow 3}[\{f_j\}](x,p) + \cdots$$

with, e.g.,

$$C^i_{2\to 2} = \frac{1}{2}\sum_{jkl} \int\limits_{234} (f_3^k f_4^l - f_1^i f_2^j) W^{ij\to kl}_{12\to 34} \qquad \left(\int\limits_j \equiv \int \frac{d^3 p_j}{2E_j} \,, \quad f_a^k \equiv f^k(x, p_a) \right)$$

fully causal and stable, can handle large gradients

near hydrodynamic limit, transport coefficients and relaxation times:

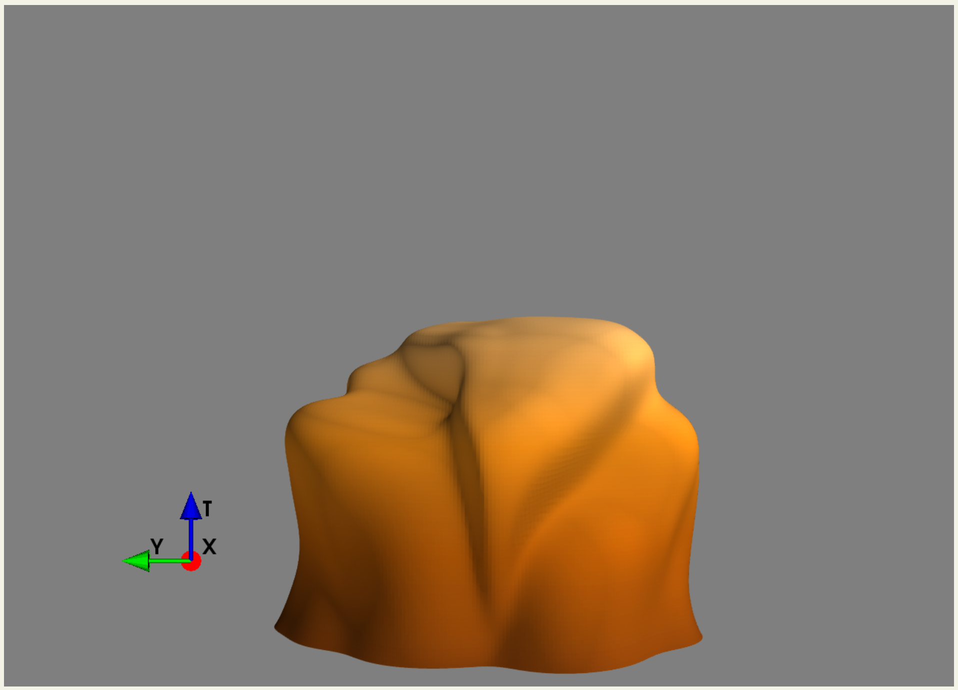
$\eta \approx 1.2 T/\sigma_{tr}$, $\qquad \tau_\pi \approx 1.2 \lambda_{tr}$

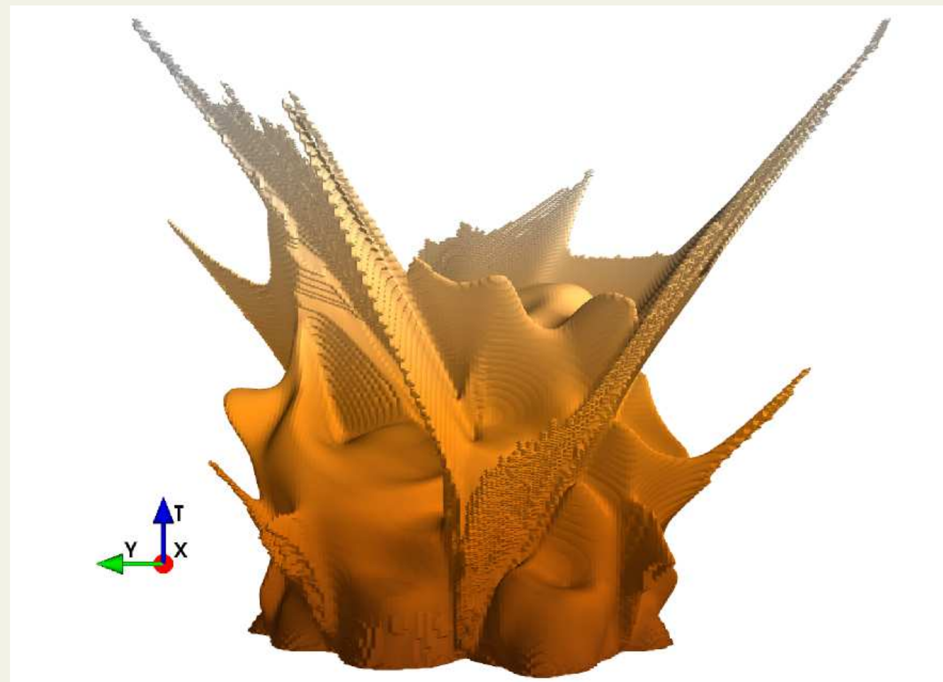
Freezeout

Cooper-Frye: <u>assumed</u> sudden transition to a gas on a 3D hypersurface

$$E\, dN = p^\mu d\sigma_\mu(x)\, d^3p\, f_{gas}(x, \vec{p})$$

Huovinen & Holopainen (QM2012): $\boldsymbol{T_{FO} = const}$ **vs** $\boldsymbol{\tau_{scatt}/\tau_{exp} = const}$ **?!**





also need viscous corrections $f_{gas} = f_{equil} + \delta f$ **(e.g.,** Wolff & Molnar @ QM2012**)**

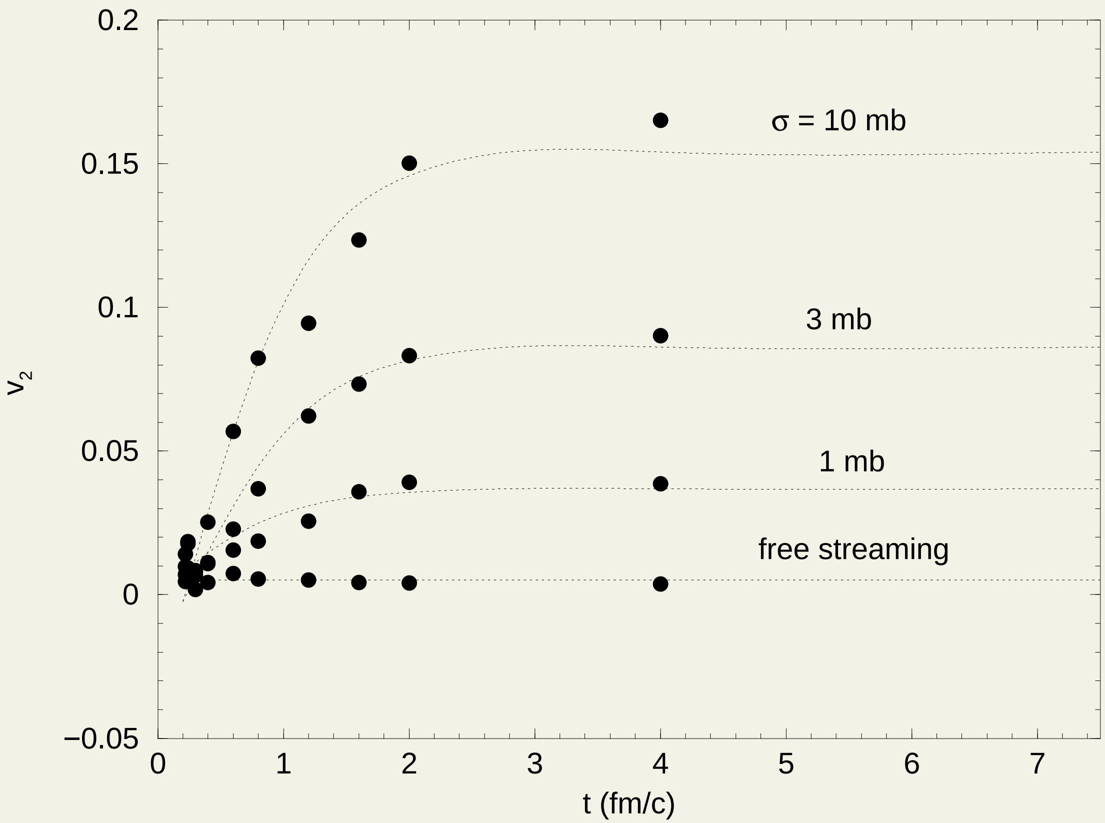
Collectivity with suitable rates

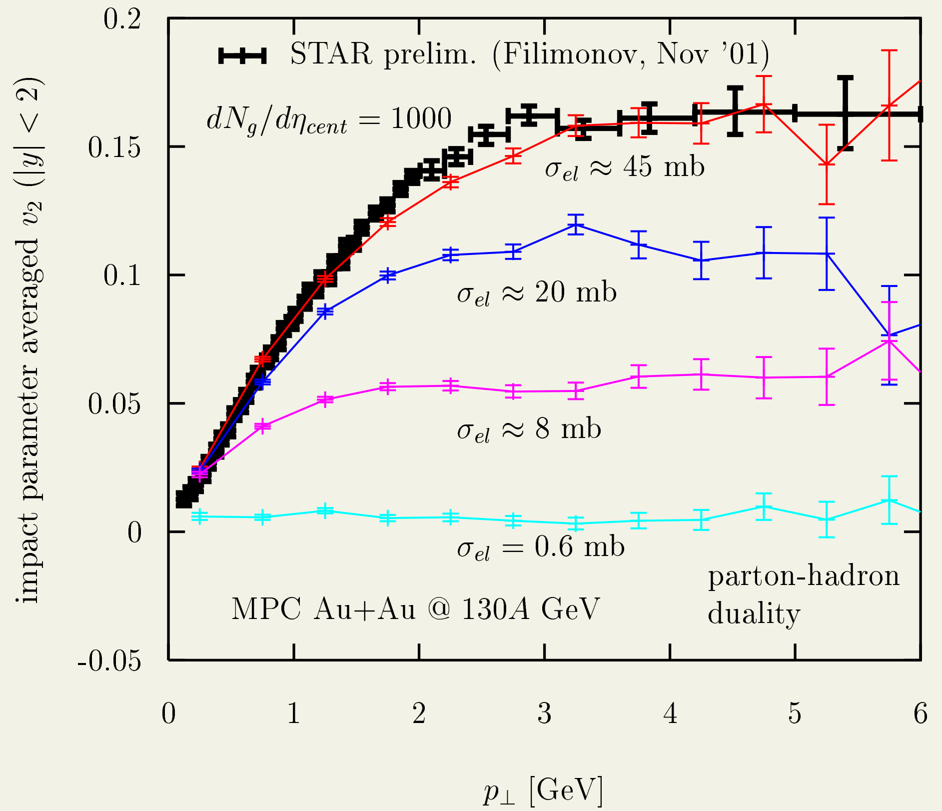
Zhang, Gyulassy & Ko ('99):

DM & Gyulassy, NPA 697 ('02):

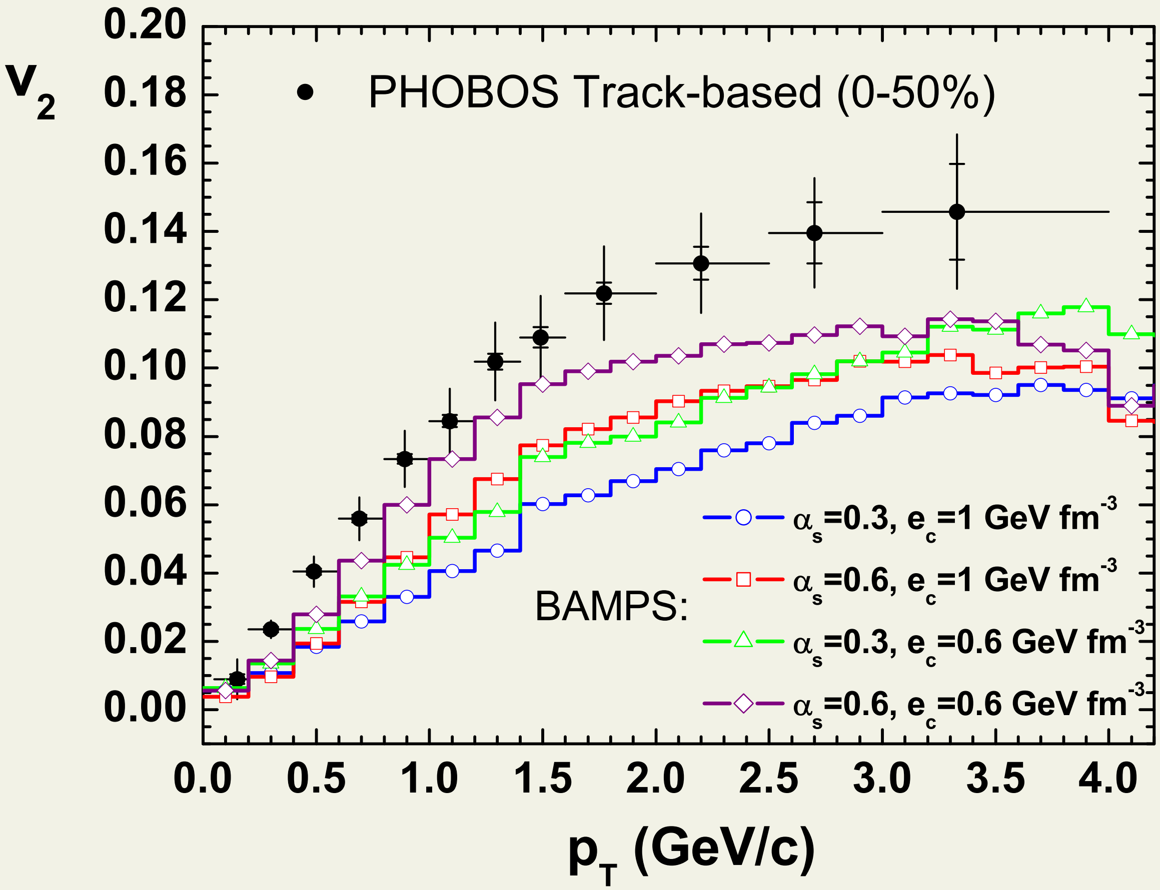
$2 \to 2$ **transport ZPC**

$2 \to 2$ **transport MPC**





Xu & Greiner, ('08) **BAMPS claim: perturbative $3 \leftrightarrow 2$ rates thermalize**



Still to be confirmed... **matrix elements?**

Application: bulk medium for jet quenching

E.g., line integrals

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

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

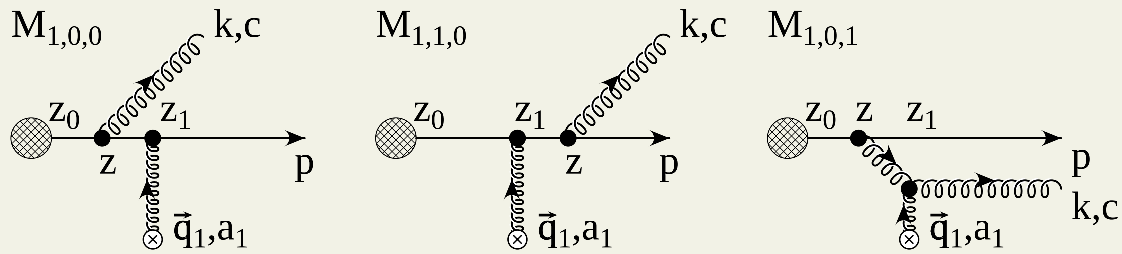
or stochastic E-loss

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)



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

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

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)

- **Here: only use the density $\rho(x_\perp, \tau)$**
  - **in principle, we could use spacetime location of scatterers for external jets embedded 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

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)**

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,** $\Delta E(z)$

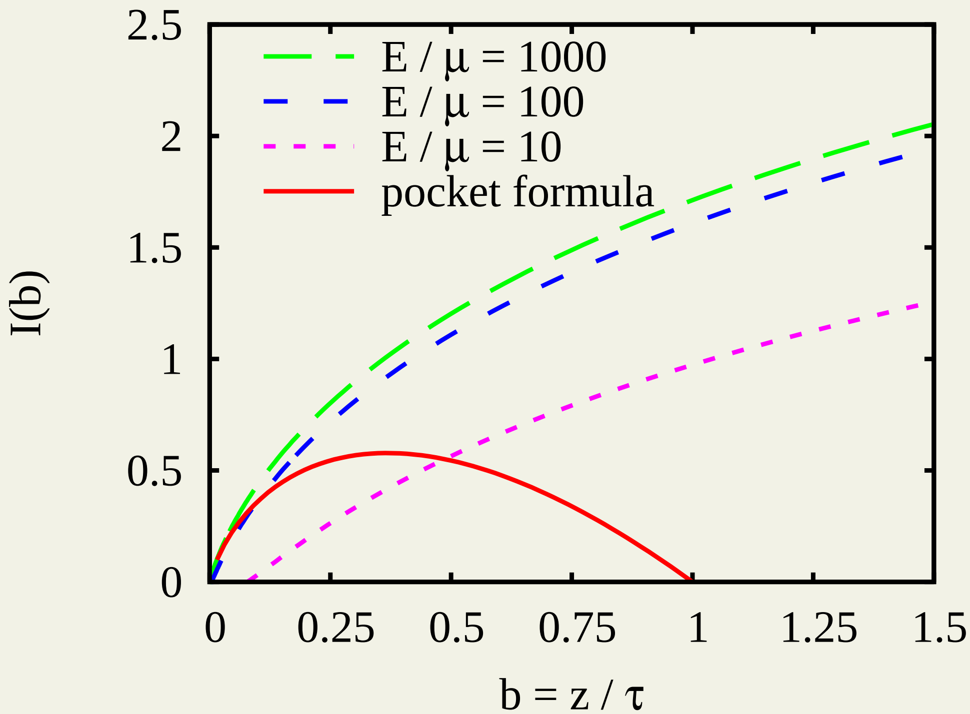
not the most sophisticated E-loss treatment

but we <u>did</u> include transverse expansion (unlike Buzzatti et al, Horowitz et al, Betz et al**)**

Finite energy & kinematics crucial:

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

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



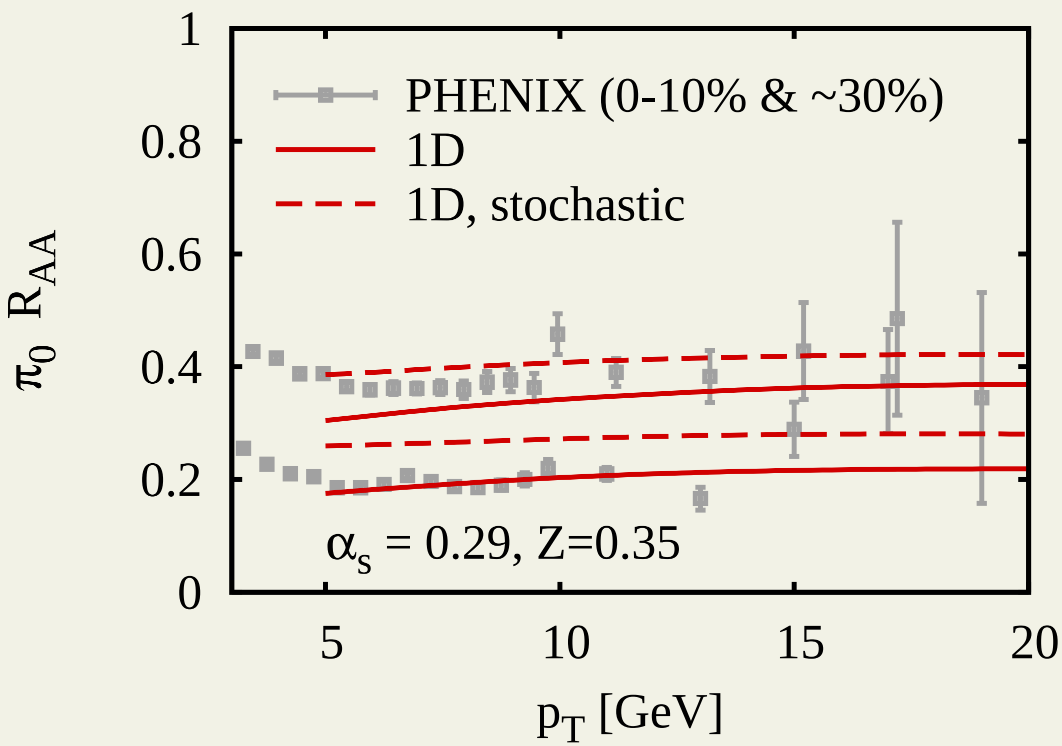
$$\tau(z) \equiv \frac{2E}{\mu^2(z)}$$

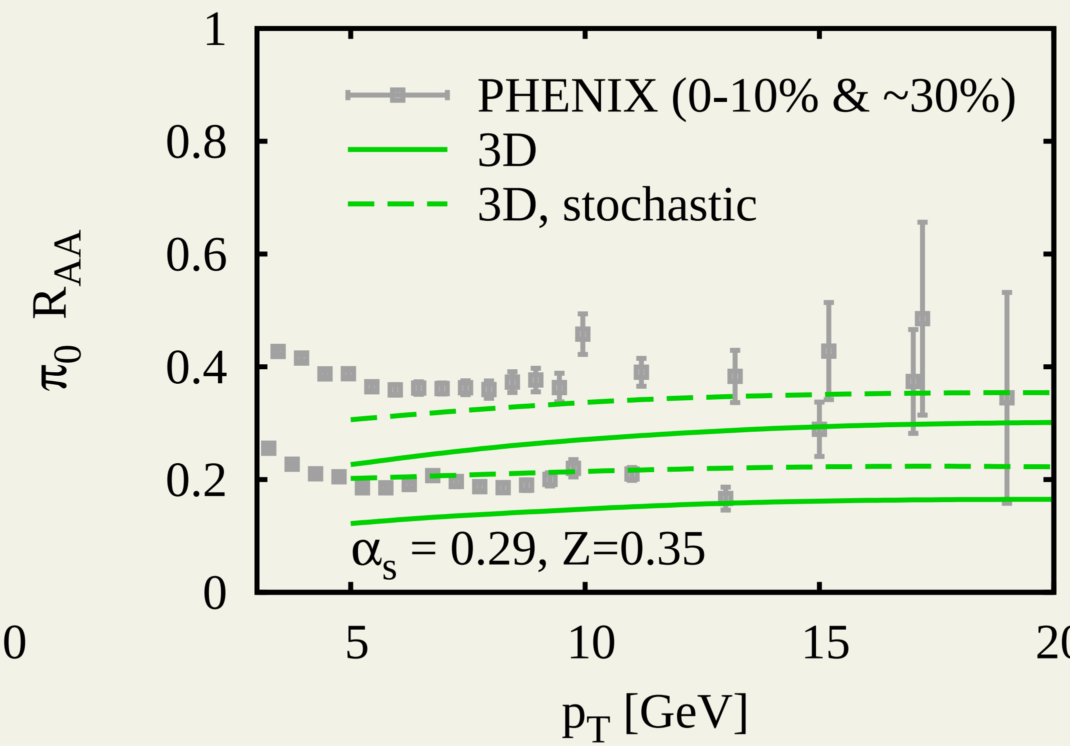
"pocket formula"

$$\langle \Delta E^{(1)}_{GLV} \rangle \sim \int \rho(z_0 + v\tau, \tau) \ln \frac{2E}{\mu^2 \tau}$$

<u>not</u> reliable

pion RAA, RHIC

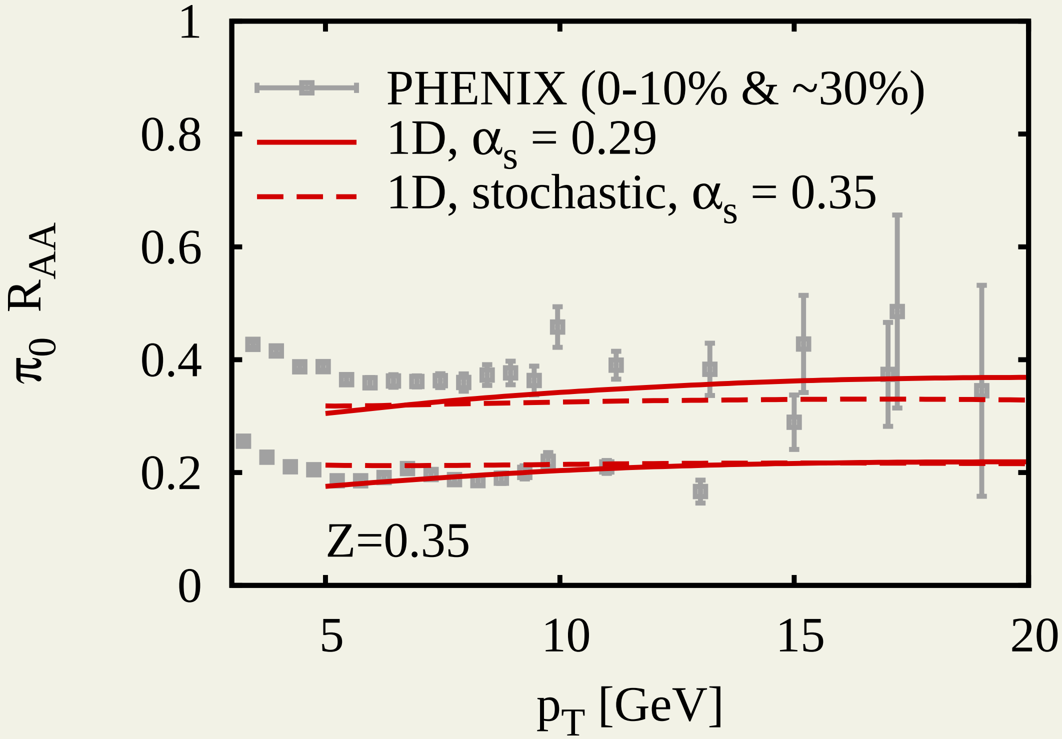


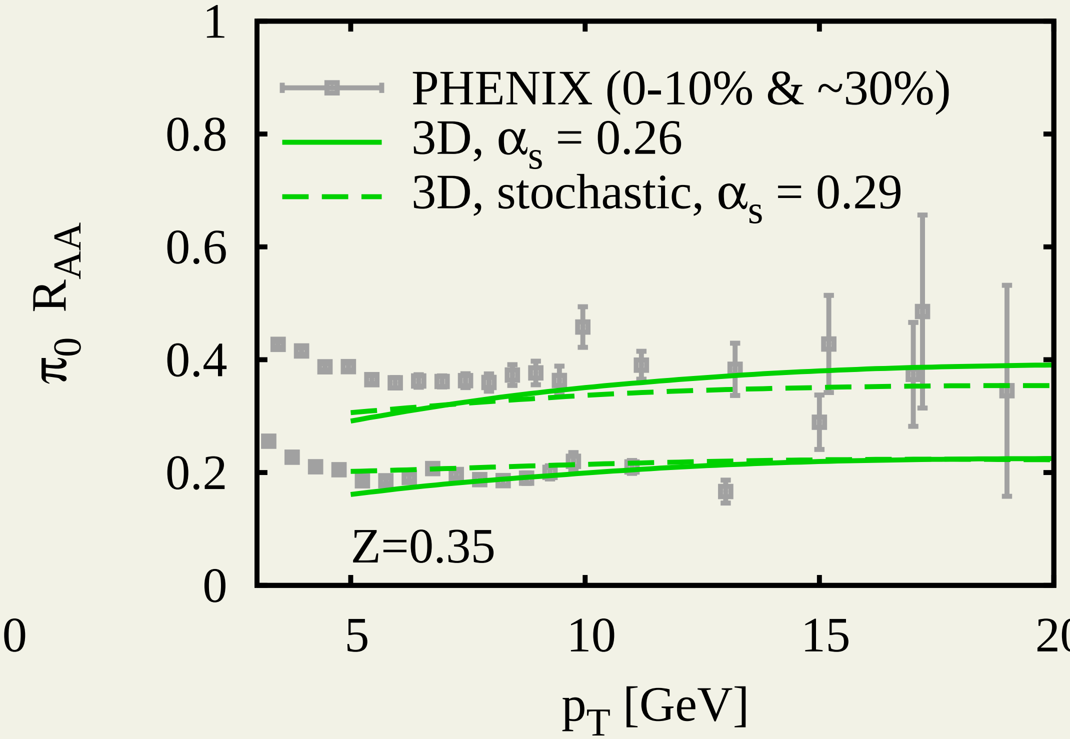


fluctuations and transverse expansion matter

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

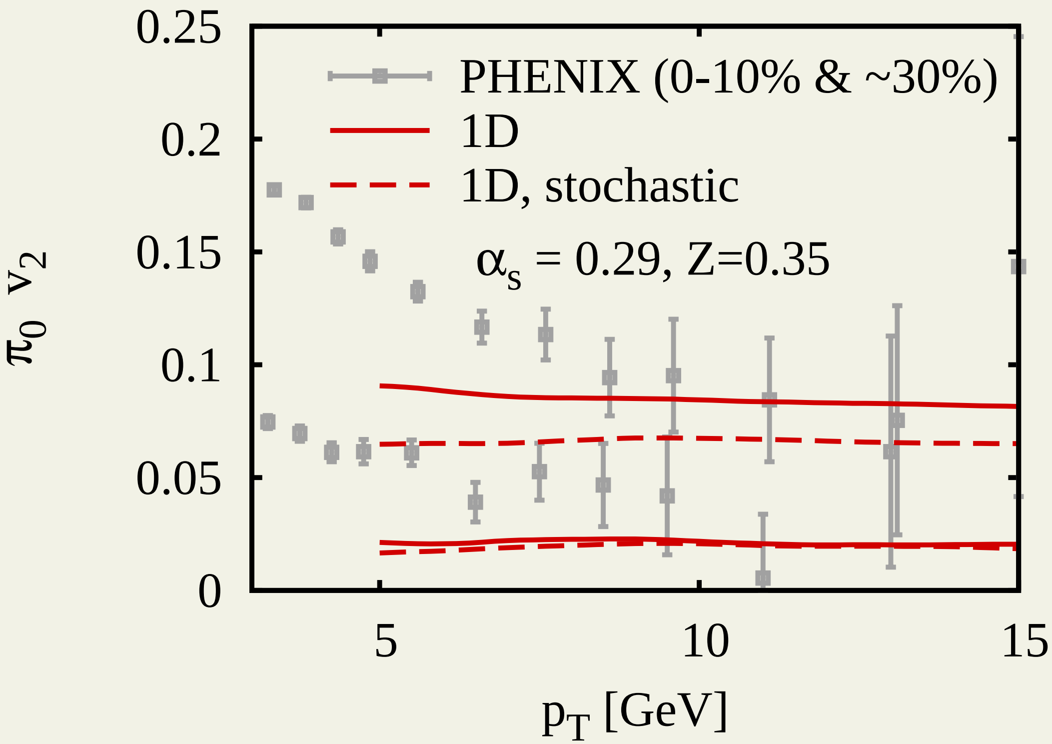
pion RAA, RHIC - α_s **scaled to RAA for central**



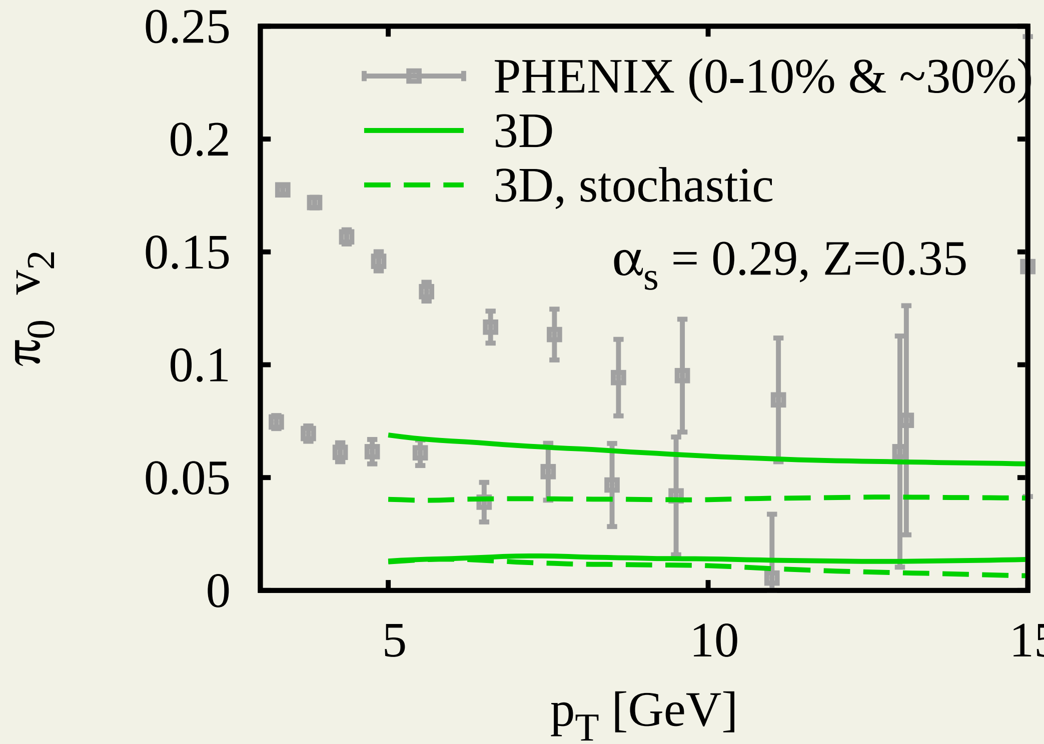


only small 10-15% differences after tuning parameters to central data

pion v2, RHIC

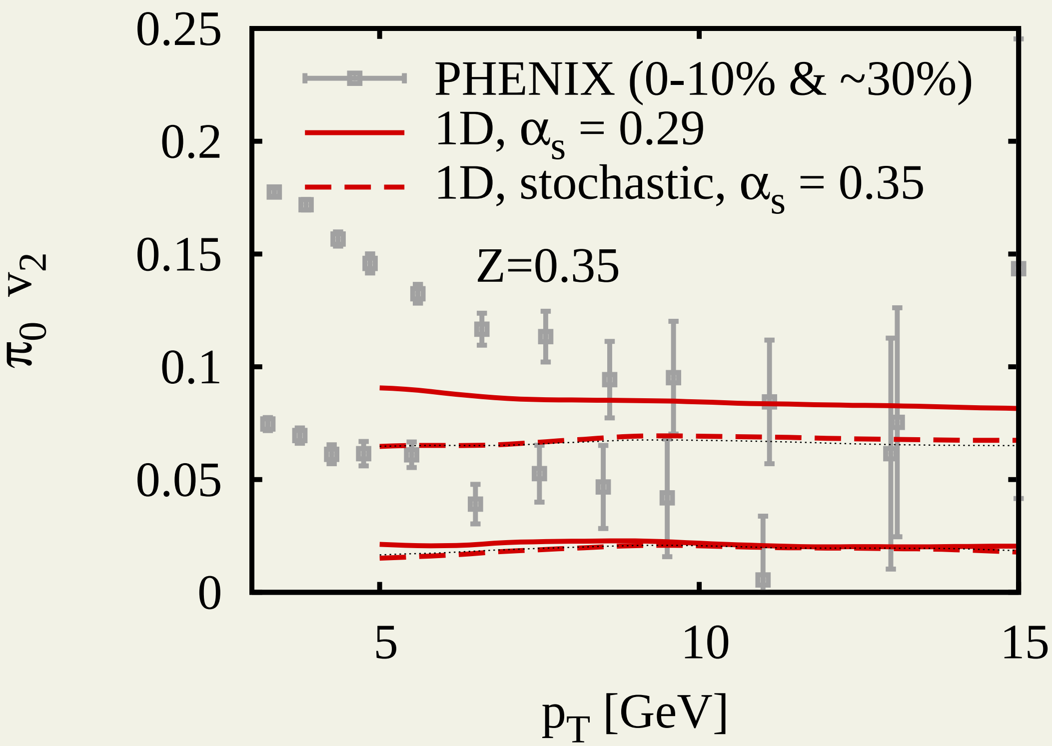


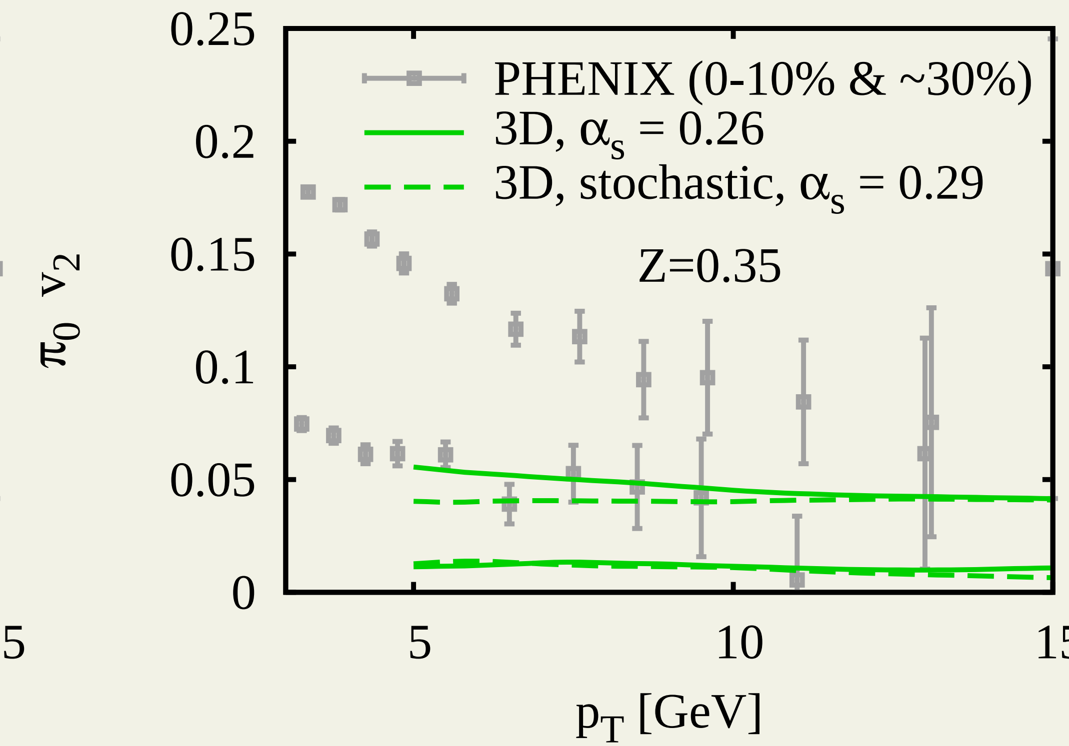
0.25
0.2
0.15
0.1
0.05
0
5
10
15
π_0 v_2
p_T [GeV]
PHENIX (0-10% & ~30%)
1D
1D, stochastic
α_s = 0.29, Z=0.35



0.25
0.2
0.15
0.1
0.05
0
5
10
π_0 v_2
p_T [GeV]
3D
3D, stochastic
α_s = 0.29, Z=0.35

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** $\Delta z/\tau_f$**)**

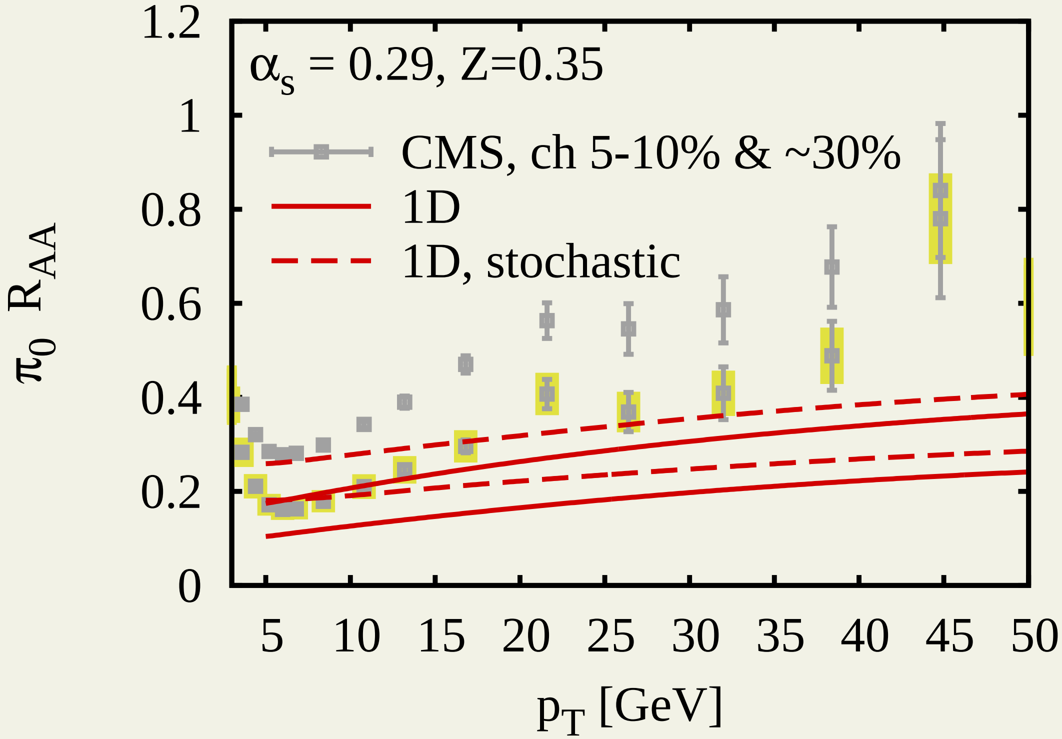
Now move to LHC energies. Simple assumption:

- higher $dN/d\eta = 2400$ in central collisions ($b = 0$)

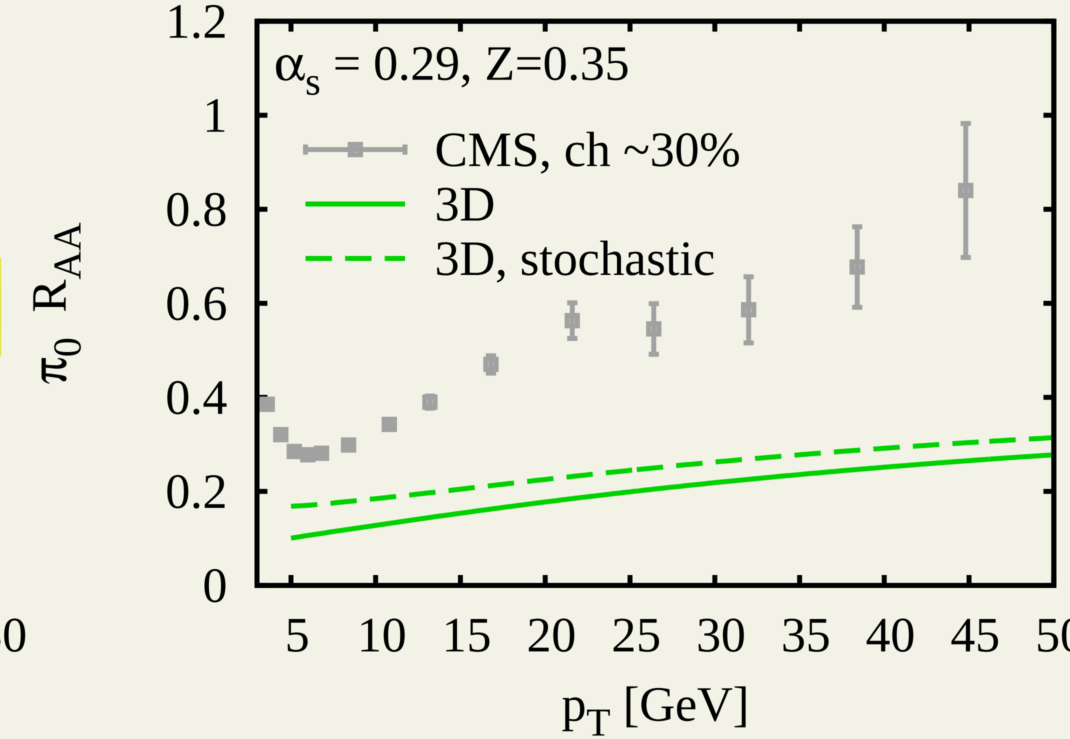
- all other ingredients stay same

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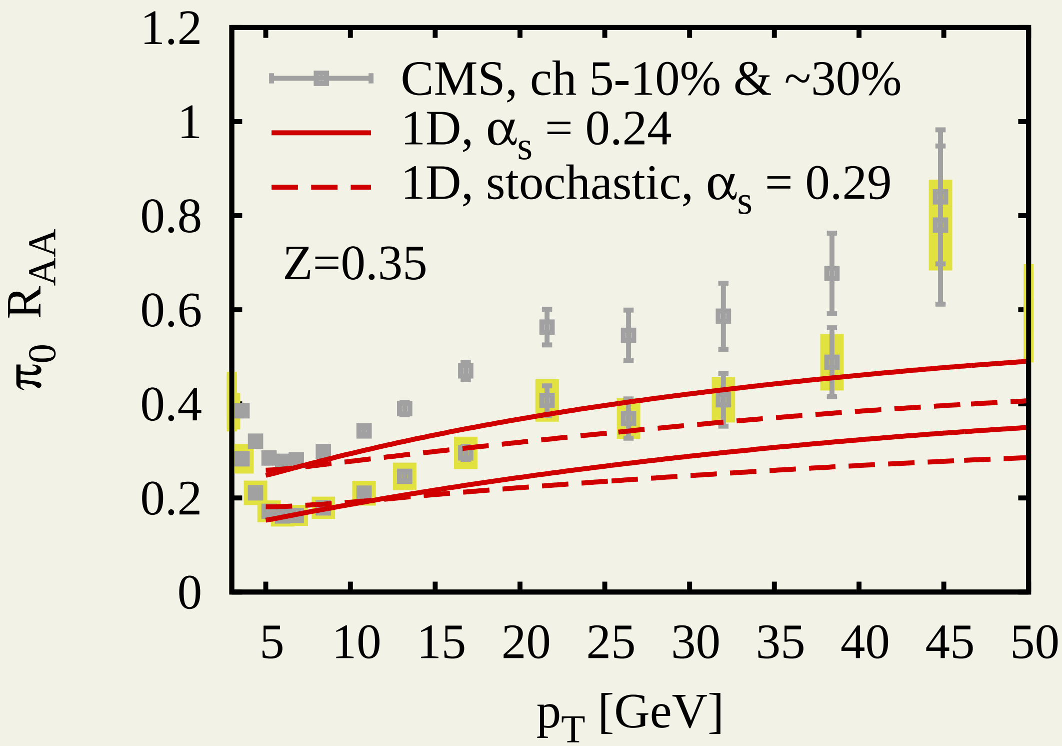
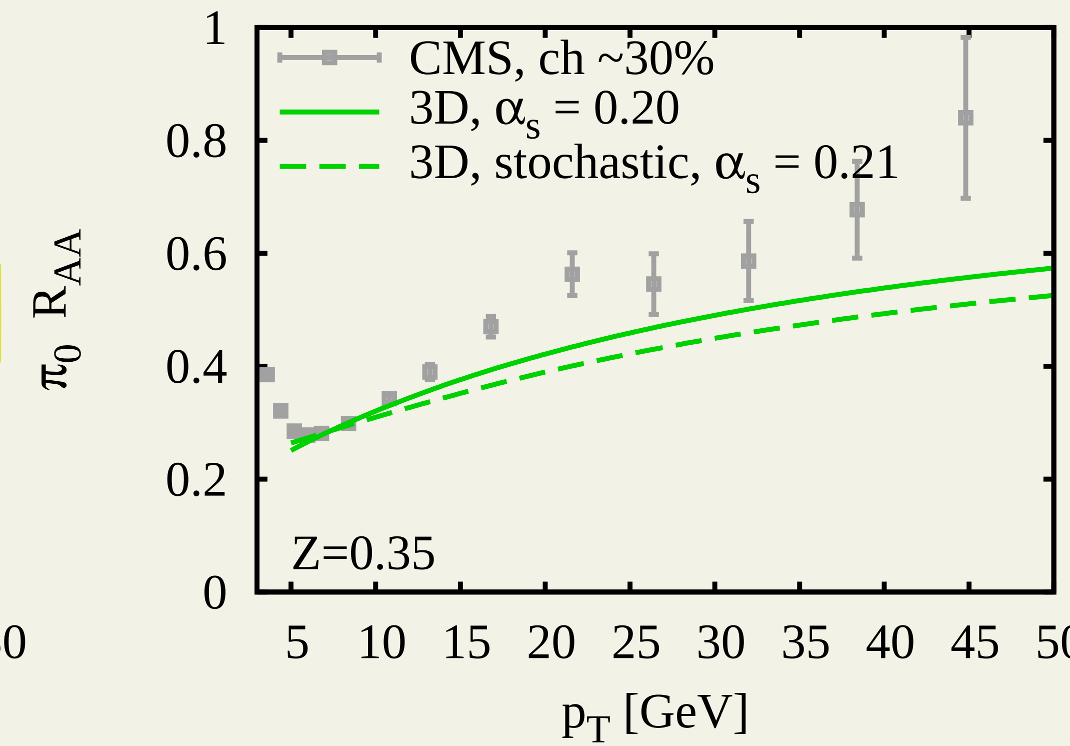
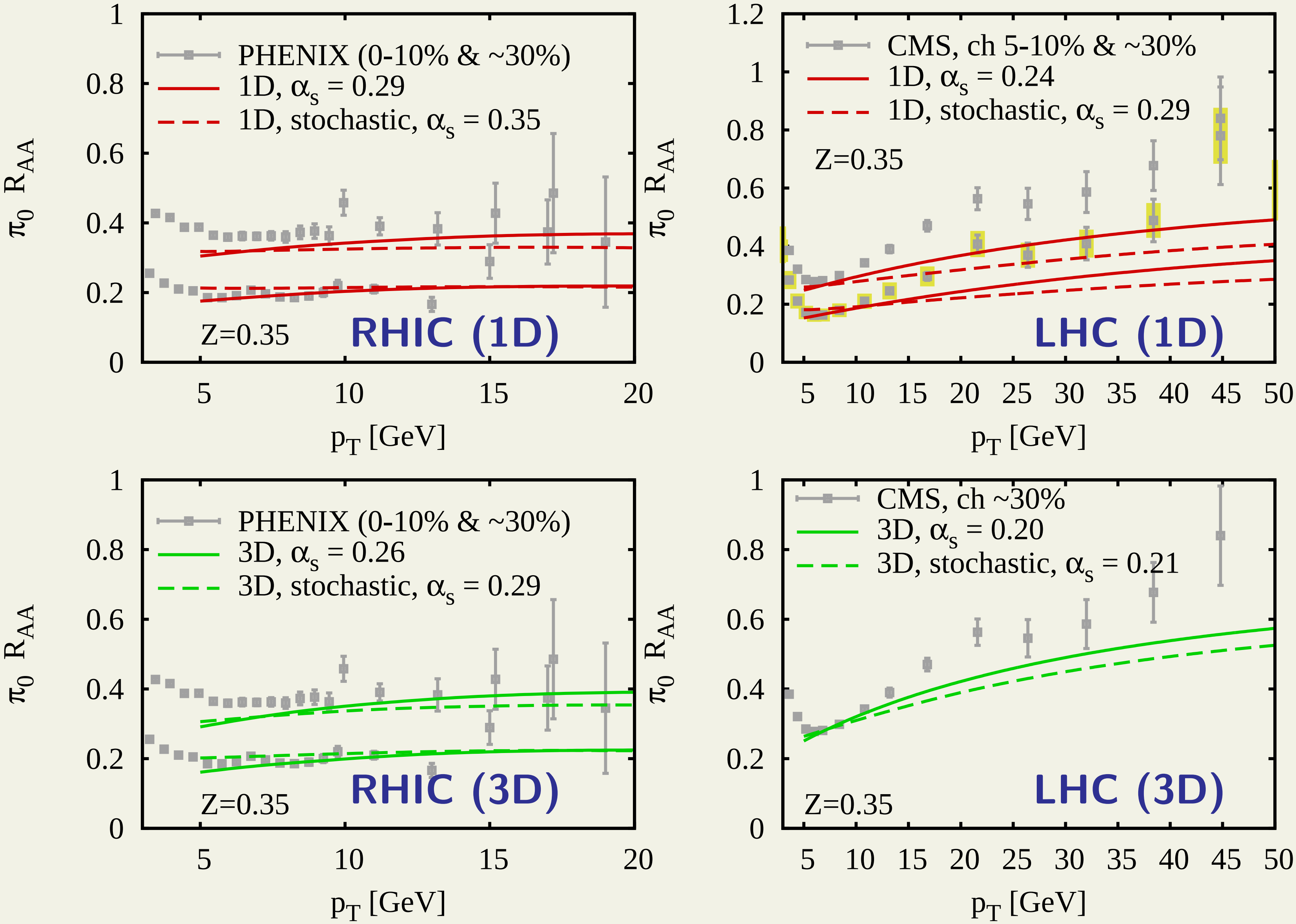
π_0 R_{AA}
α_s = 0.29, Z=0.35
CMS, ch ~30%
3D
3D, stochastic
5 10 15 20 25 30 35 40 45 50
p_T [GeV]

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



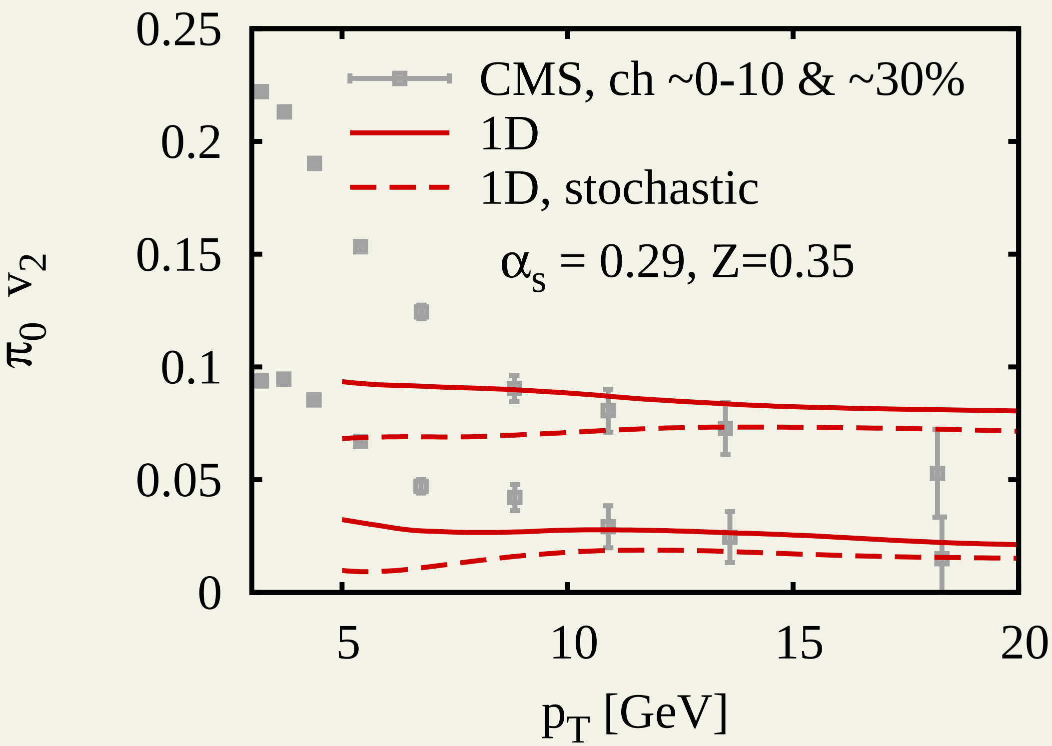


GLV implementation here is simplified, also $\alpha_s = const$ (no running)

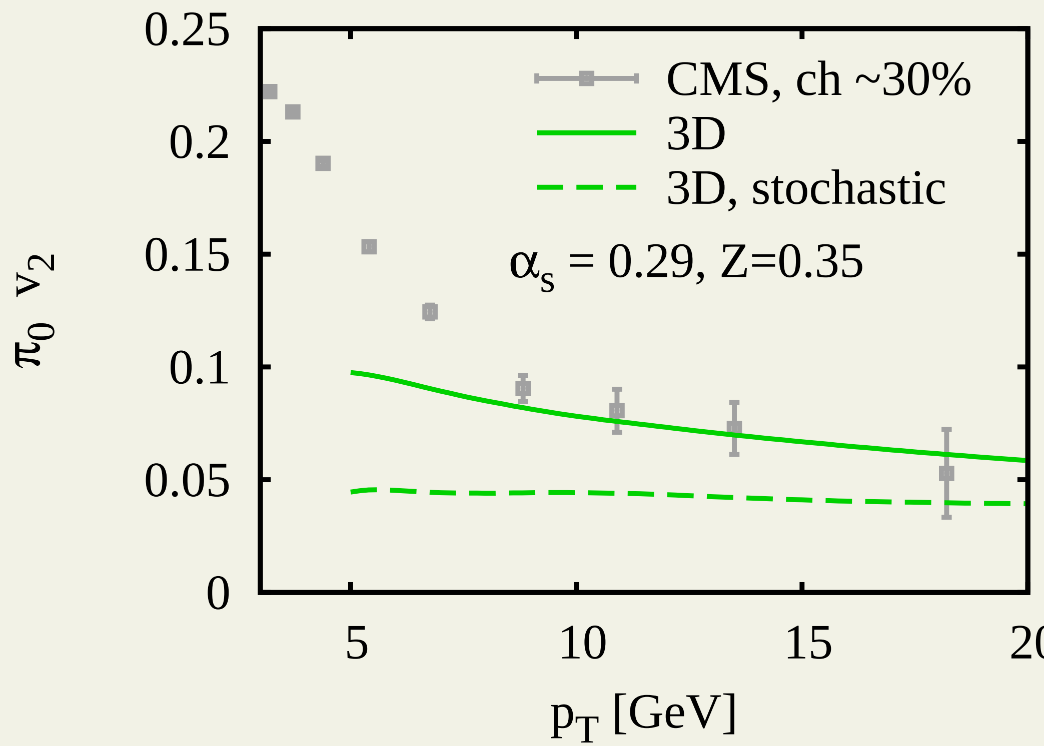


need $20-25$**% smaller** α_s **at LHC than at RHIC - similar to** Betz et al, 1201.0281

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



0.25
0.2
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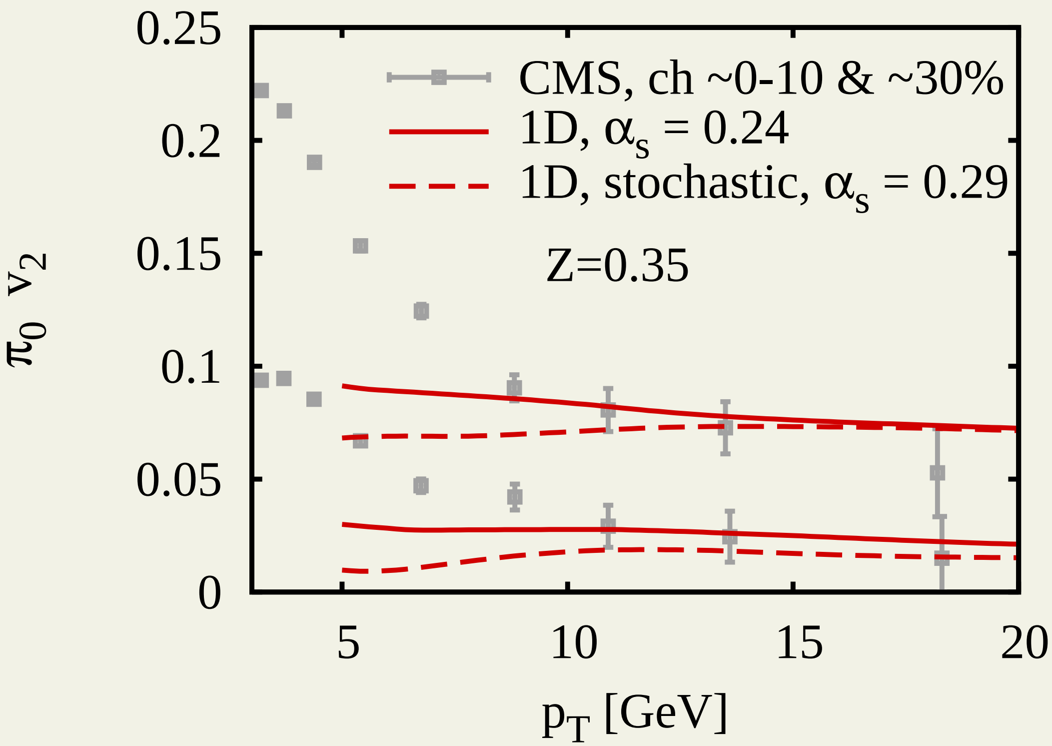
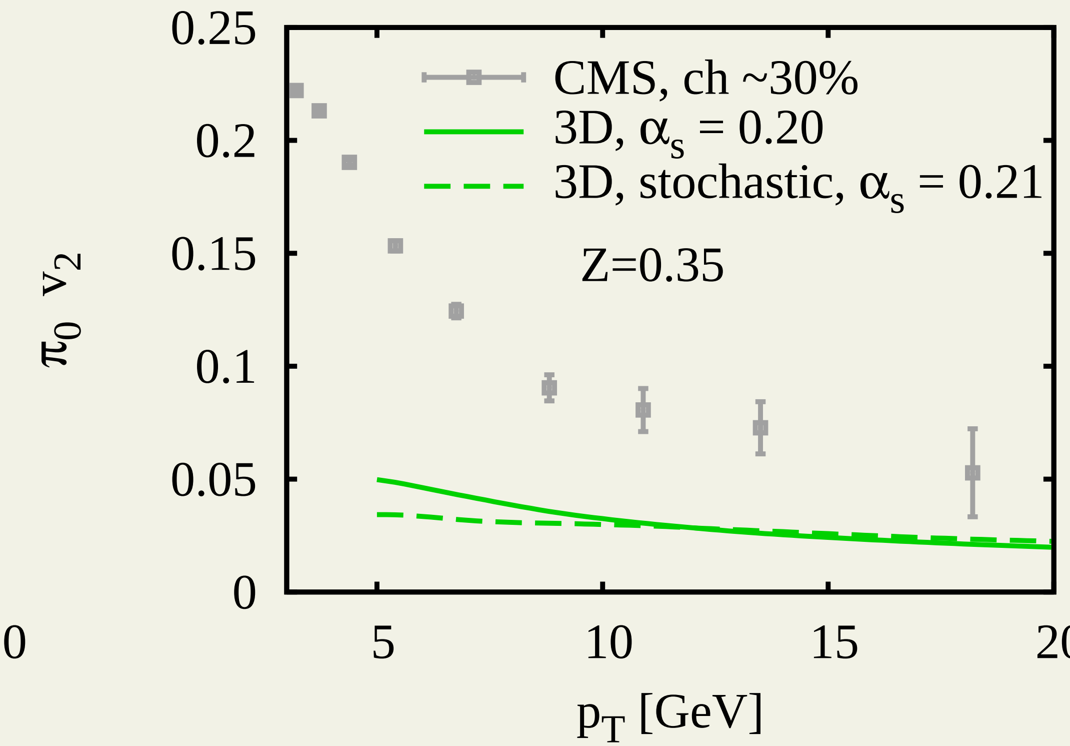
π_0 v_2
p_T [GeV]
CMS, ch ~30%
3D
3D, stochastic
α_s = 0.29, Z=0.35

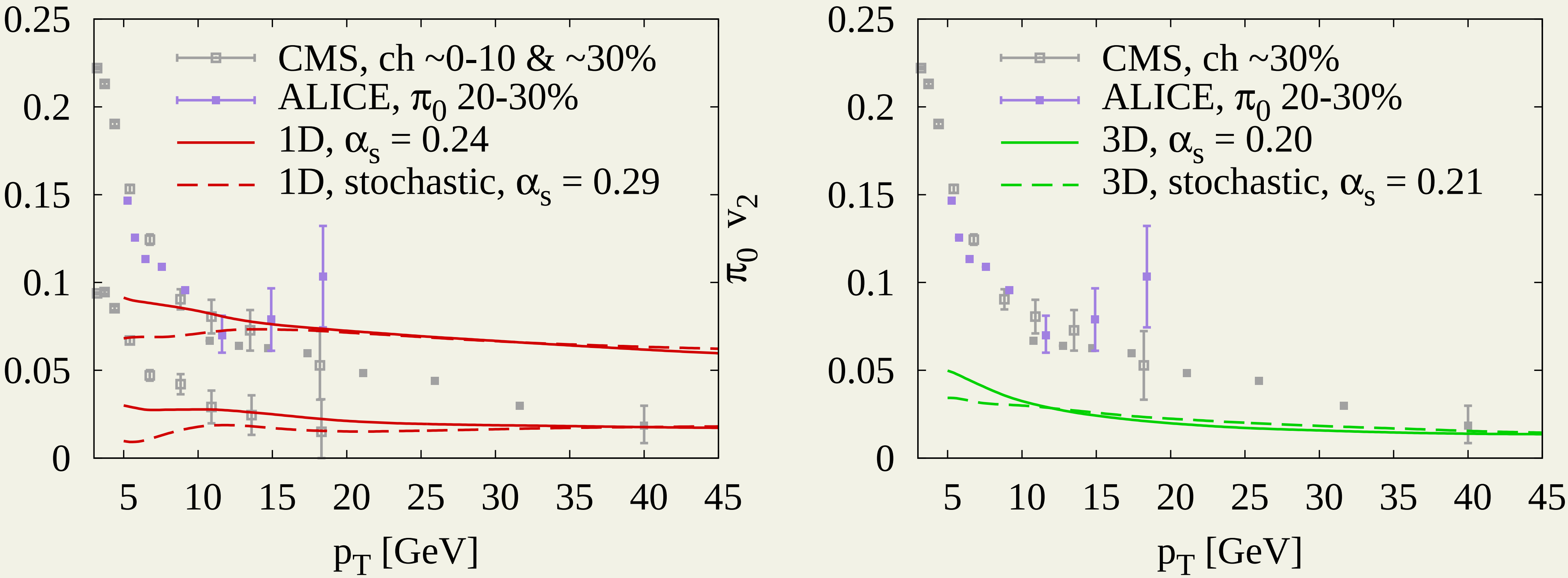
pion v2, LHC - α_s scaled to RAA at pT = 6 GeV





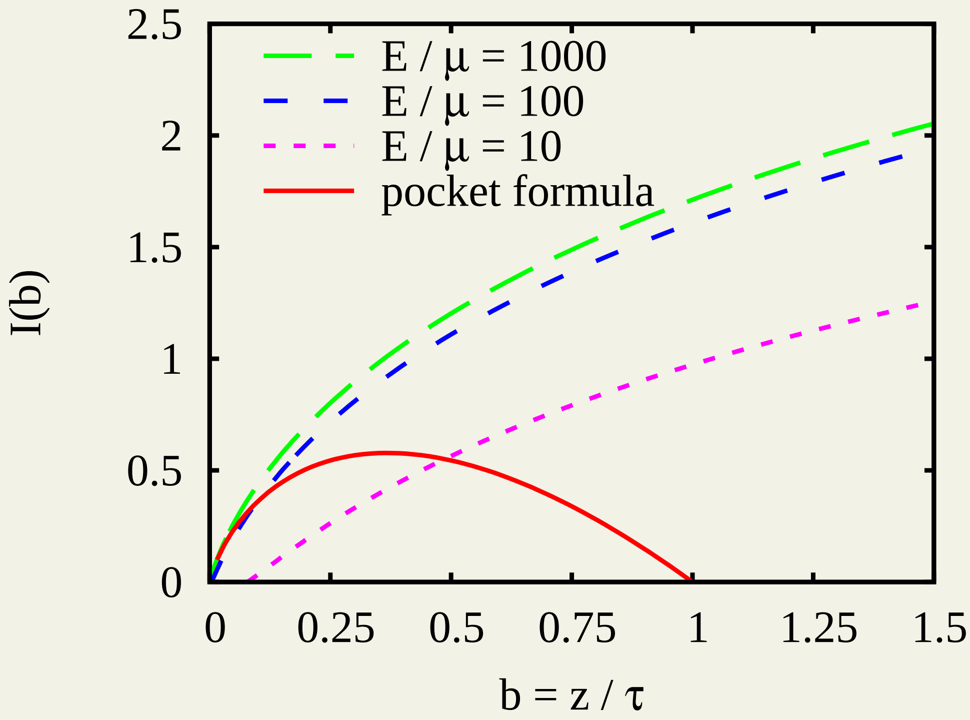
similar reduction in 3D case as at RHIC energies

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



In short: for transversely expanding medium, both R_{AA} and v_2 are smaller with GLV energy loss. LPM interference favors late scattering.

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

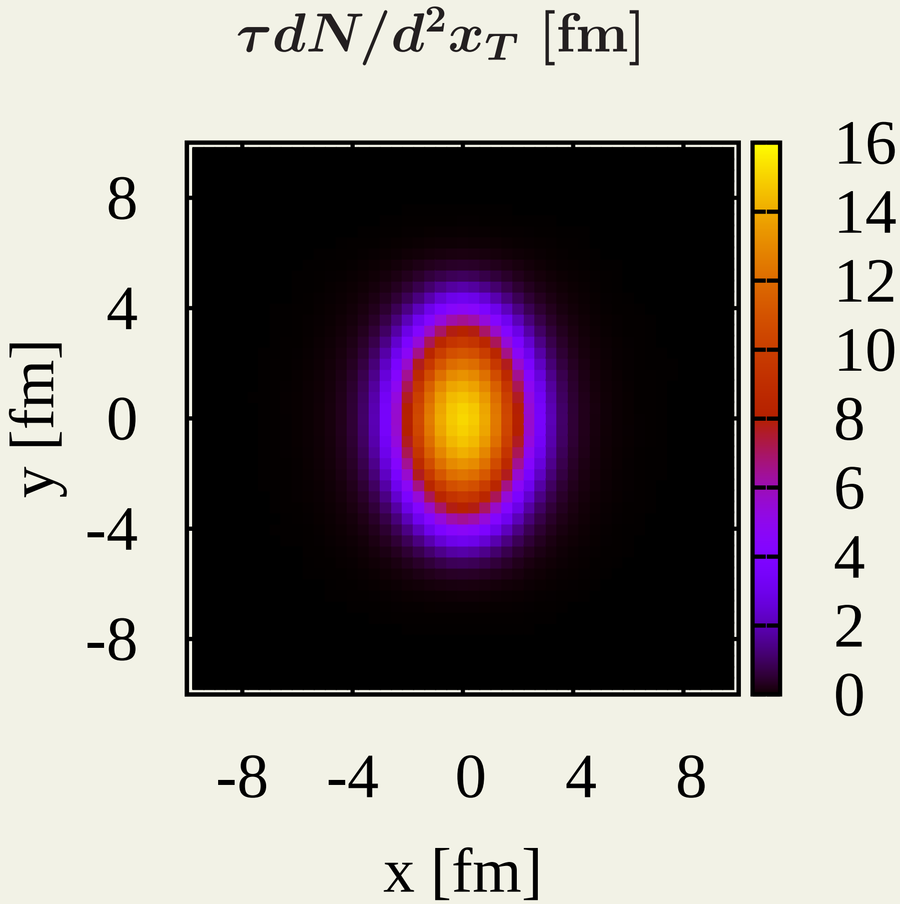


$$\tau(z) \equiv \frac{2E}{\mu^2(z)}$$

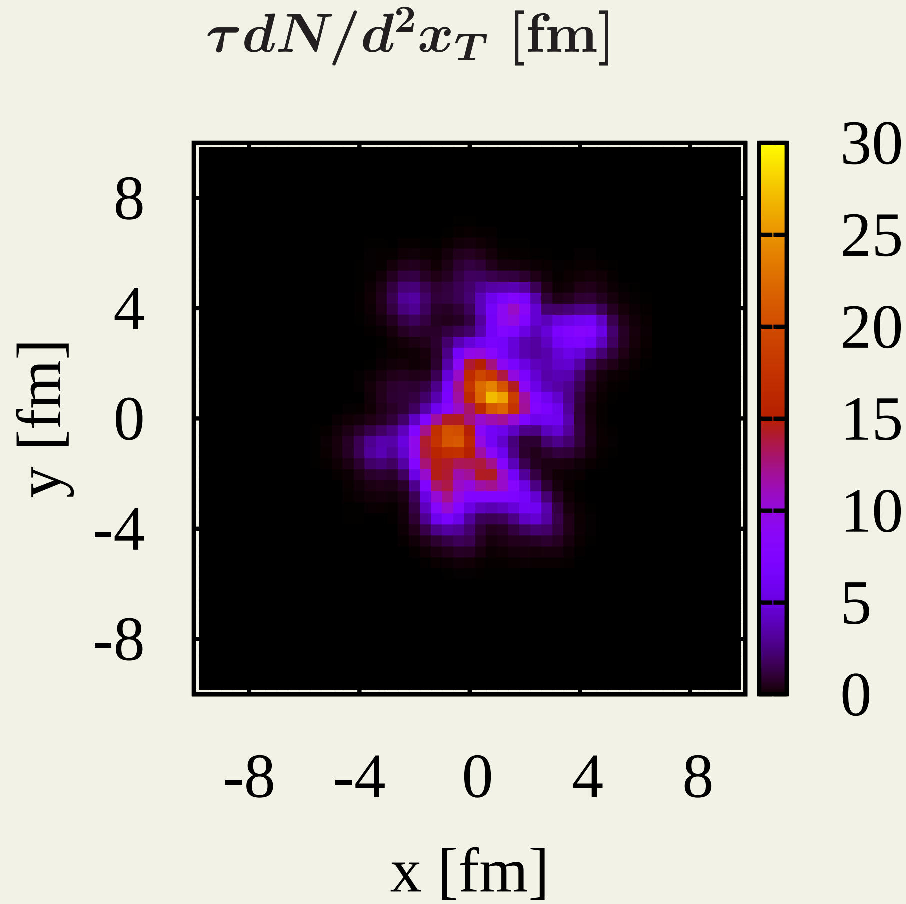
Could fluctuations help?

- **MC Glauber initconds (binary)**
- **RHIC Au+Au at $b = 8$ fm, 200A GeV**
- **same $2 \to 2$ transport (MPC)**

average **Au+Au, b=8 fm**

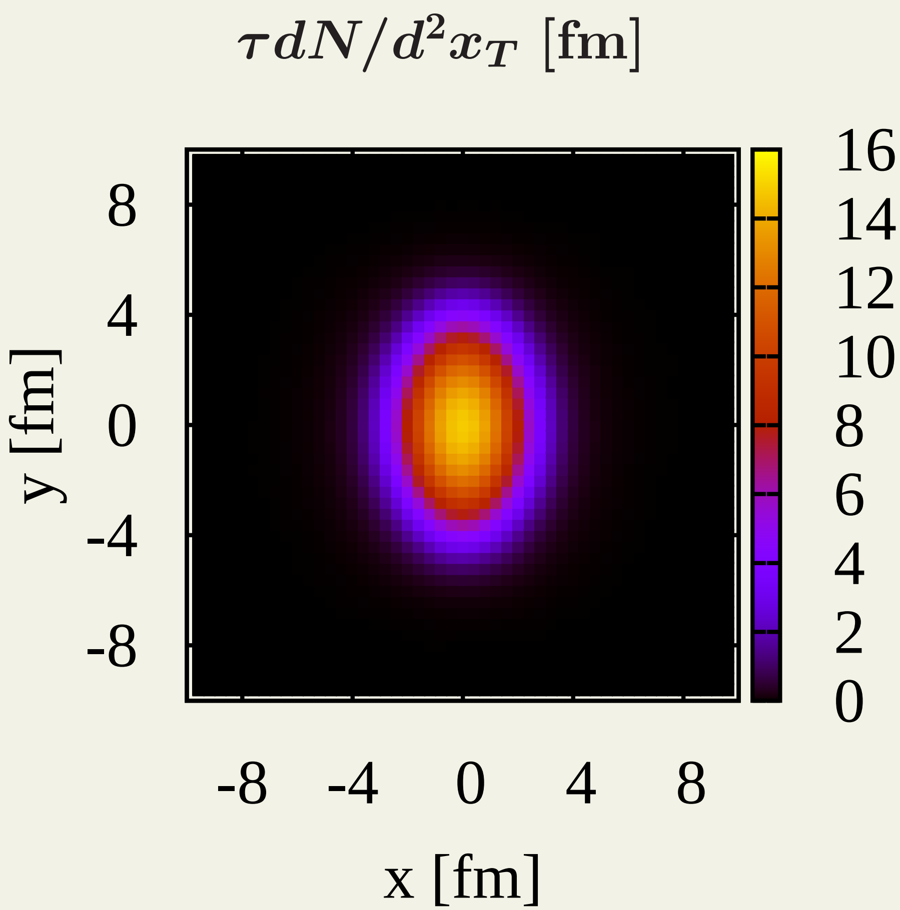


single **MC Glauber**

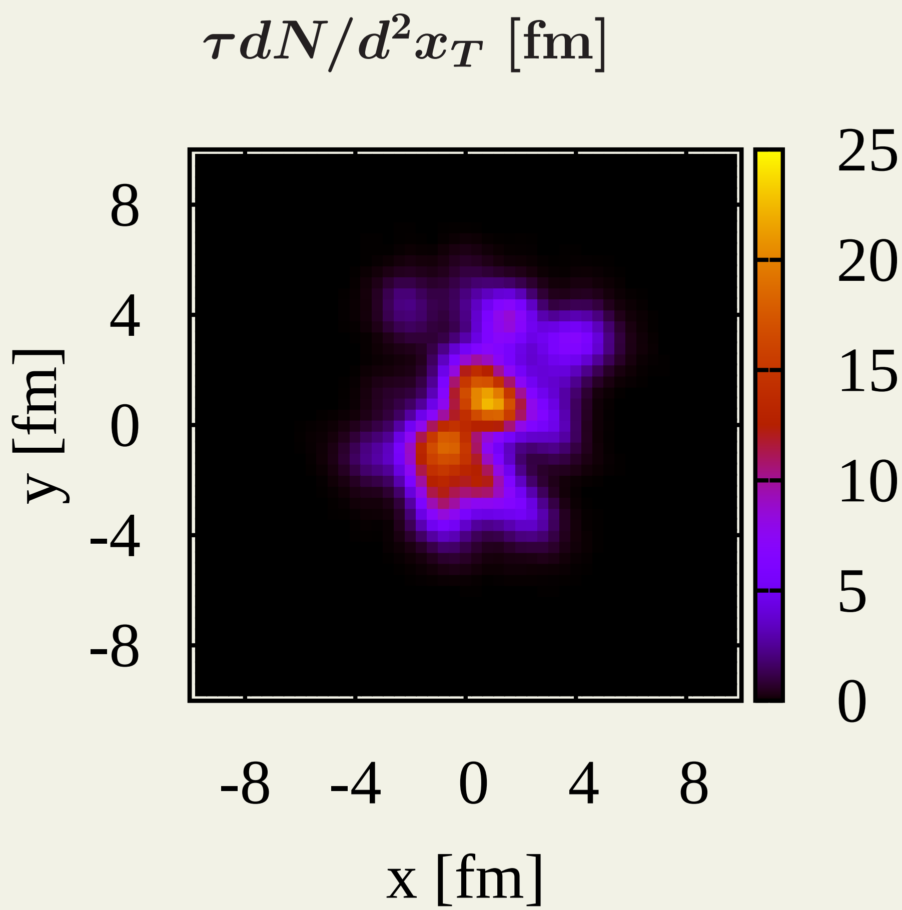


$\boldsymbol{\tau = 0.6}$ **fm**

average Au+Au, b=8 fm

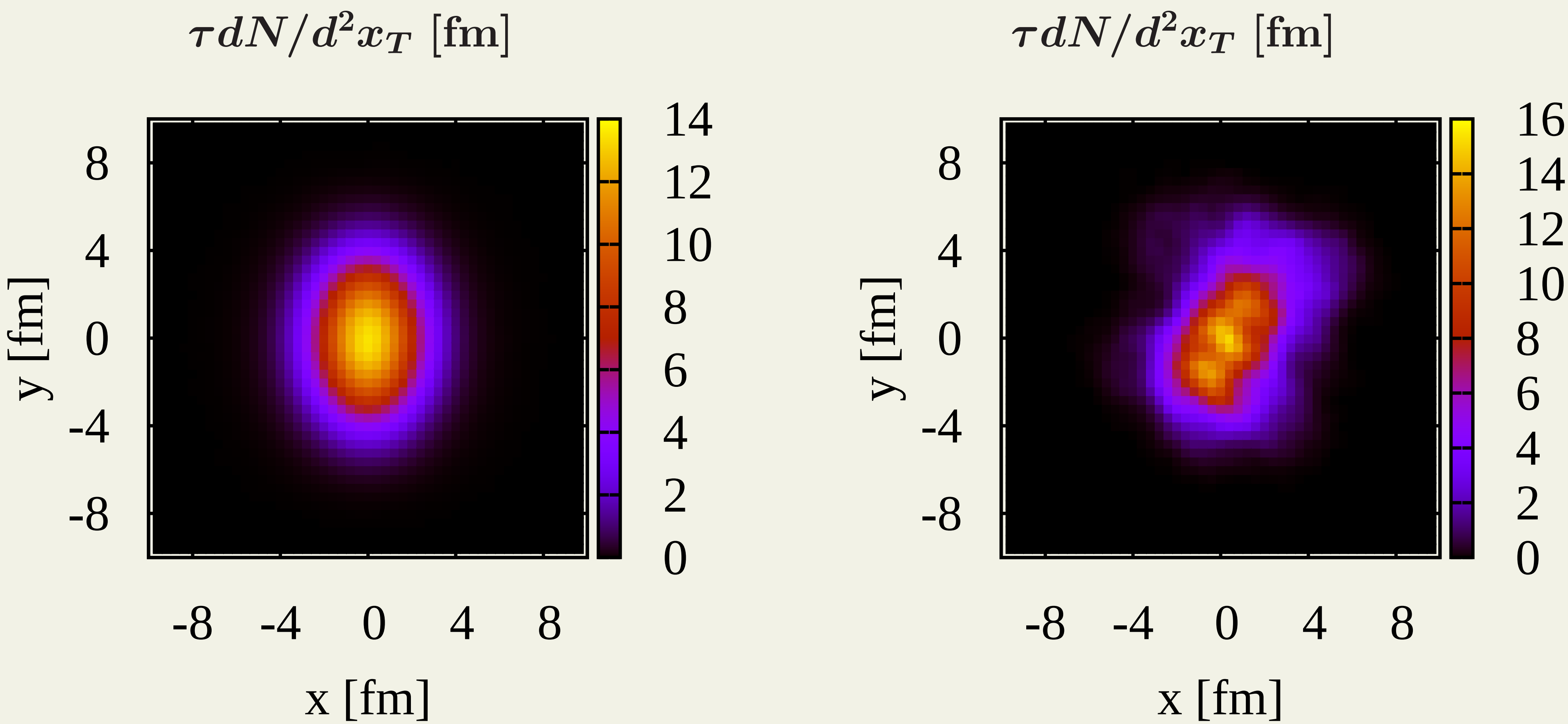


single MC Glauber



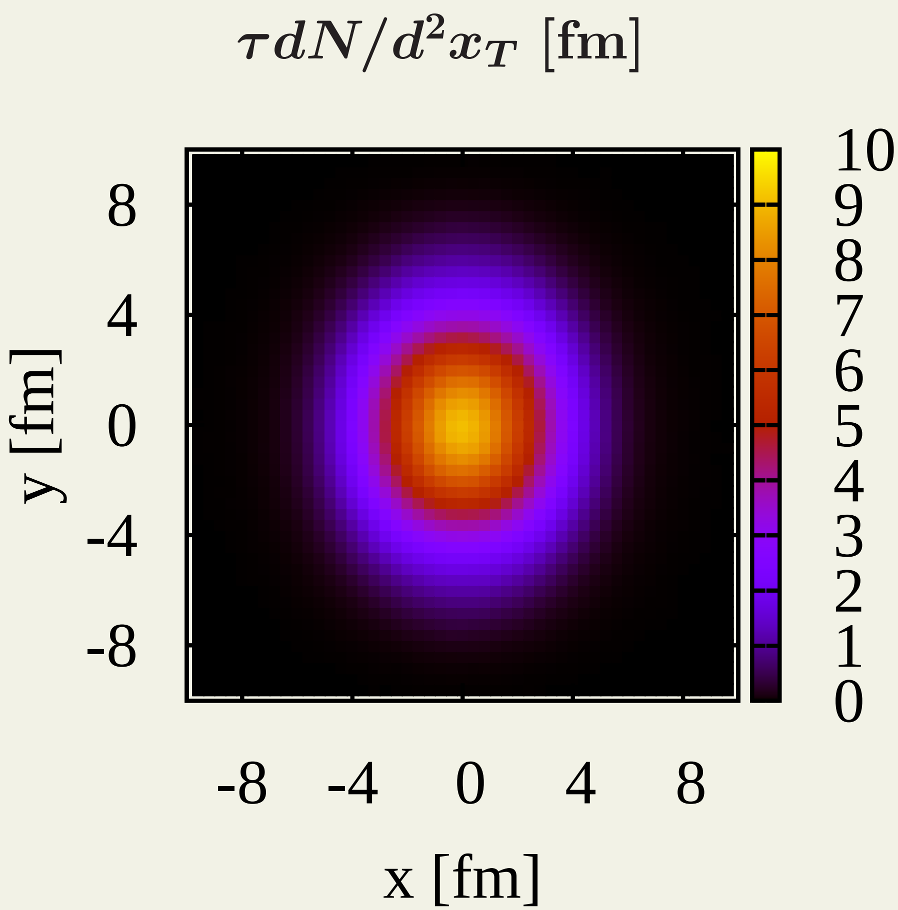
$\tau = 1.2$ fm

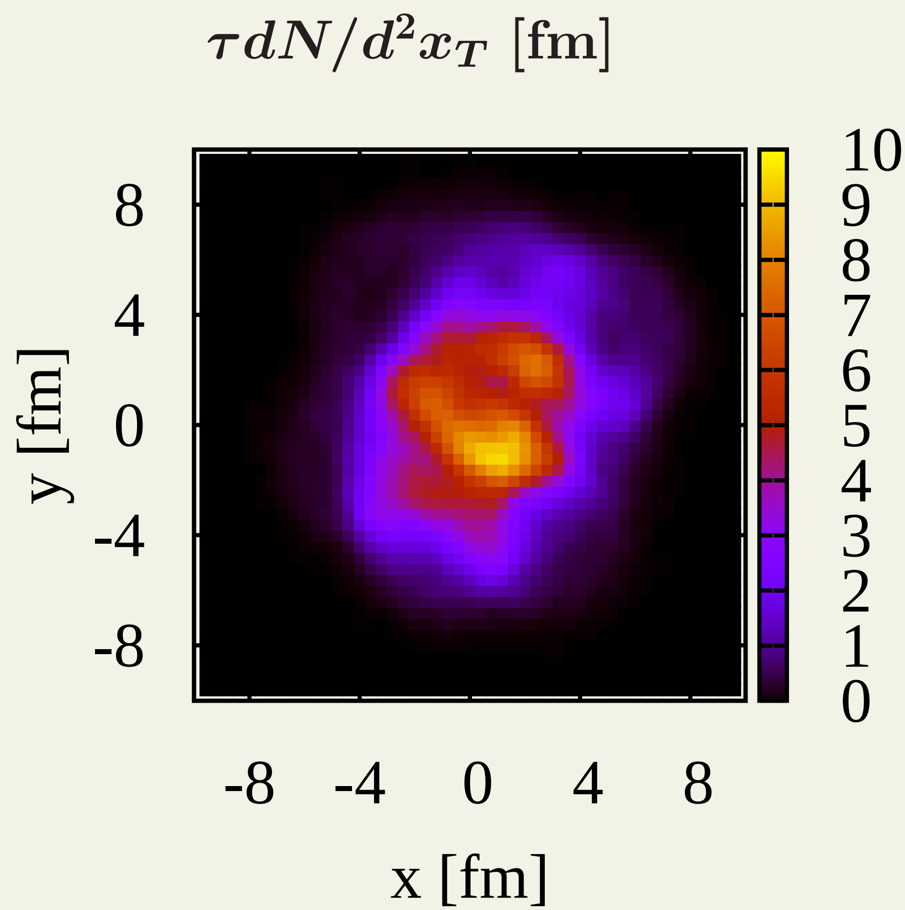
average **Au+Au, b=8 fm** **single** **MC Glauber**



$\tau = 2.1$ **fm**

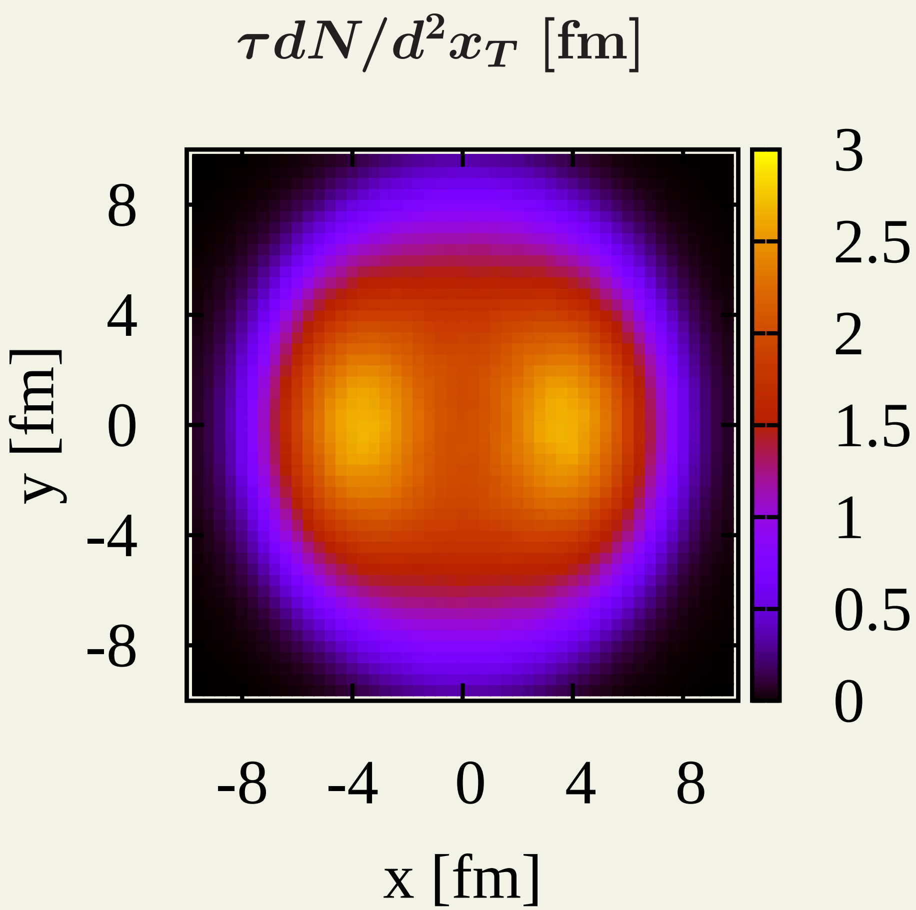
average Au+Au, b=8 fm **single MC Glauber**



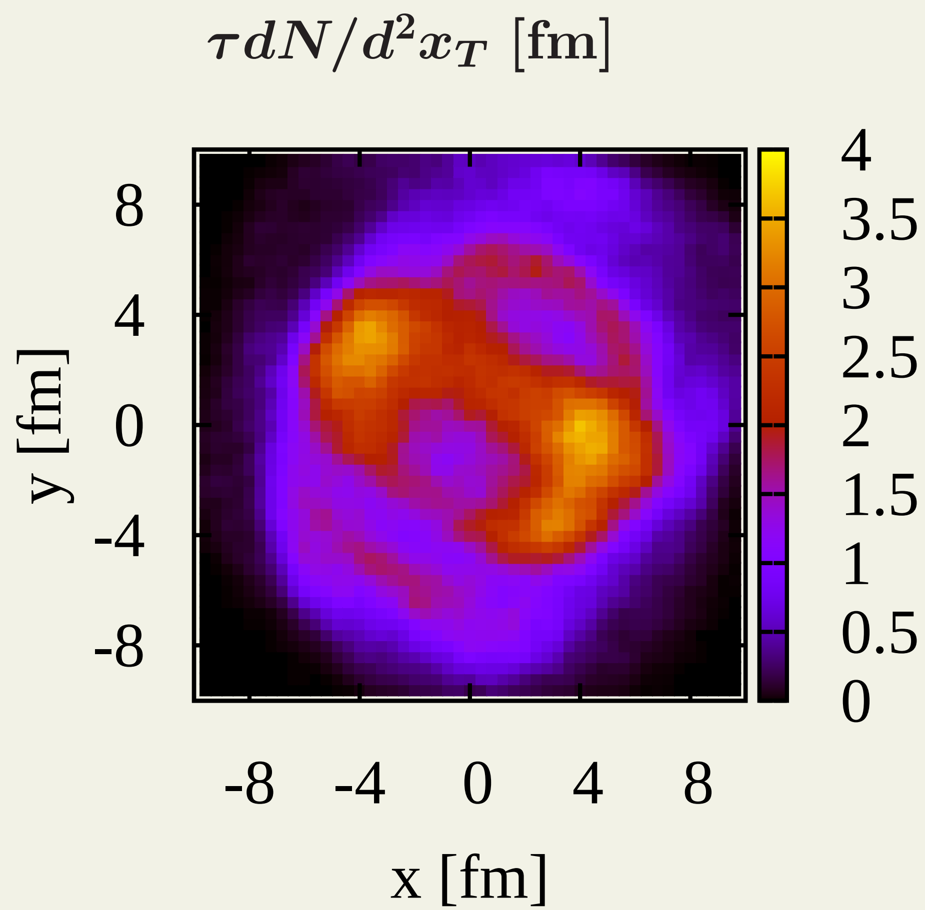


$\boldsymbol{\tau = 3.6}$ **fm**

average **Au+Au, b=8 fm**

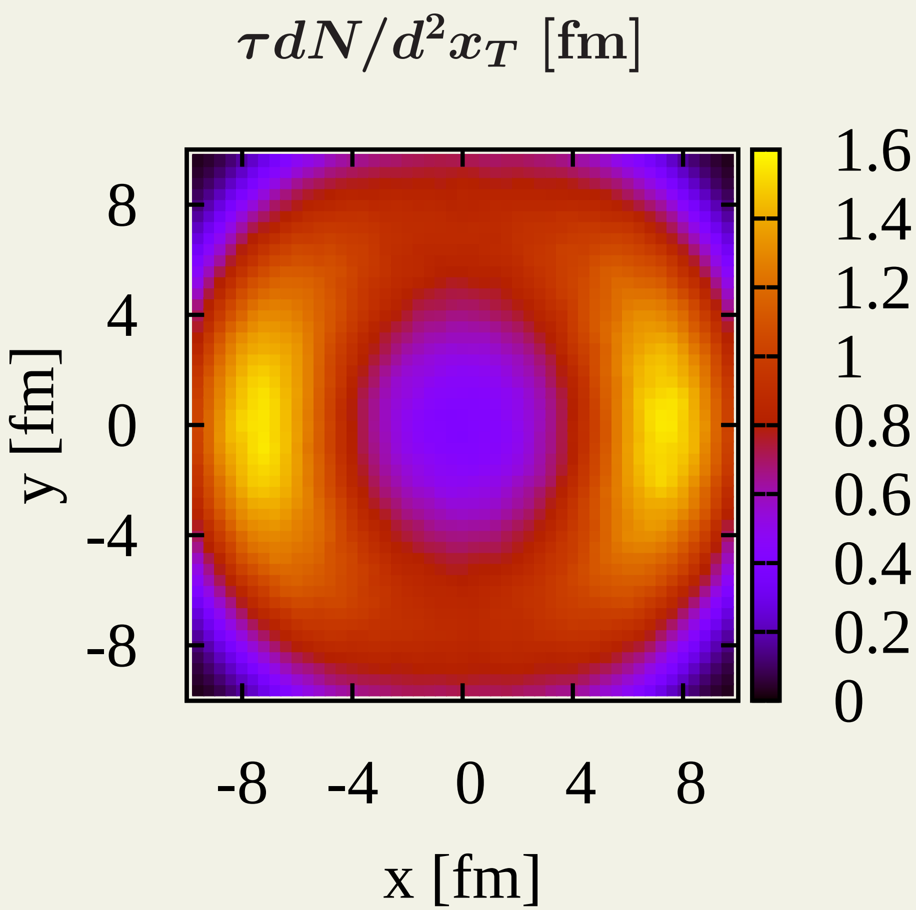


single **MC Glauber**

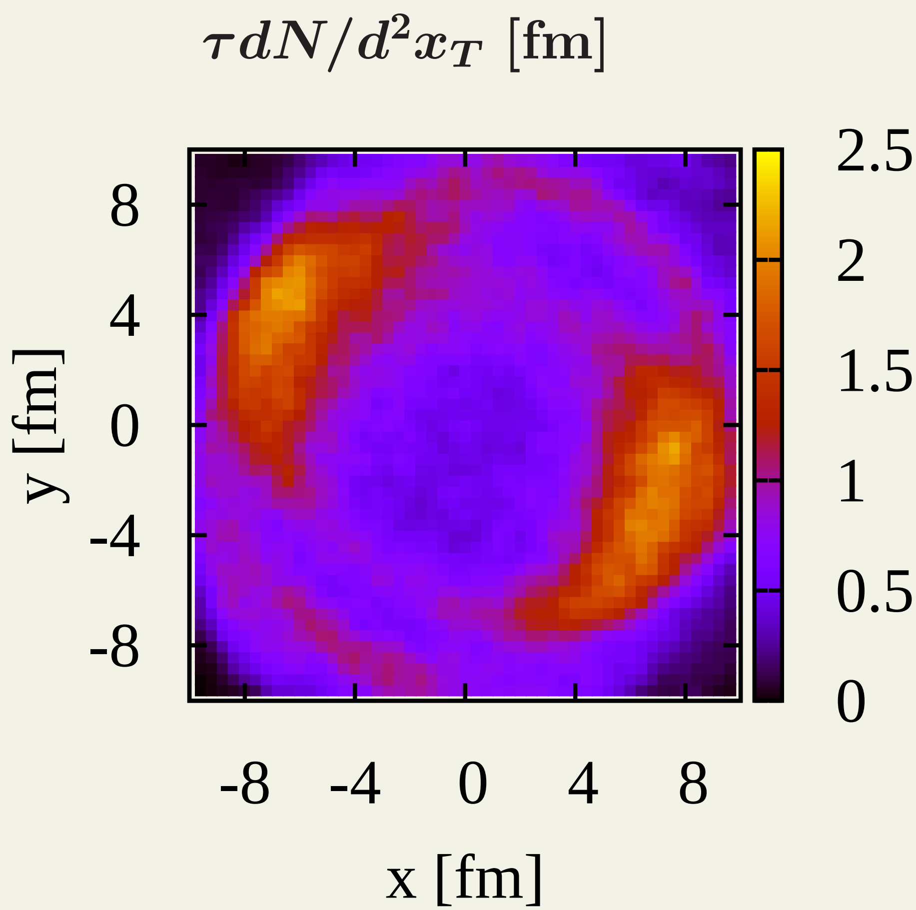


$\tau = 6.6$ **fm**

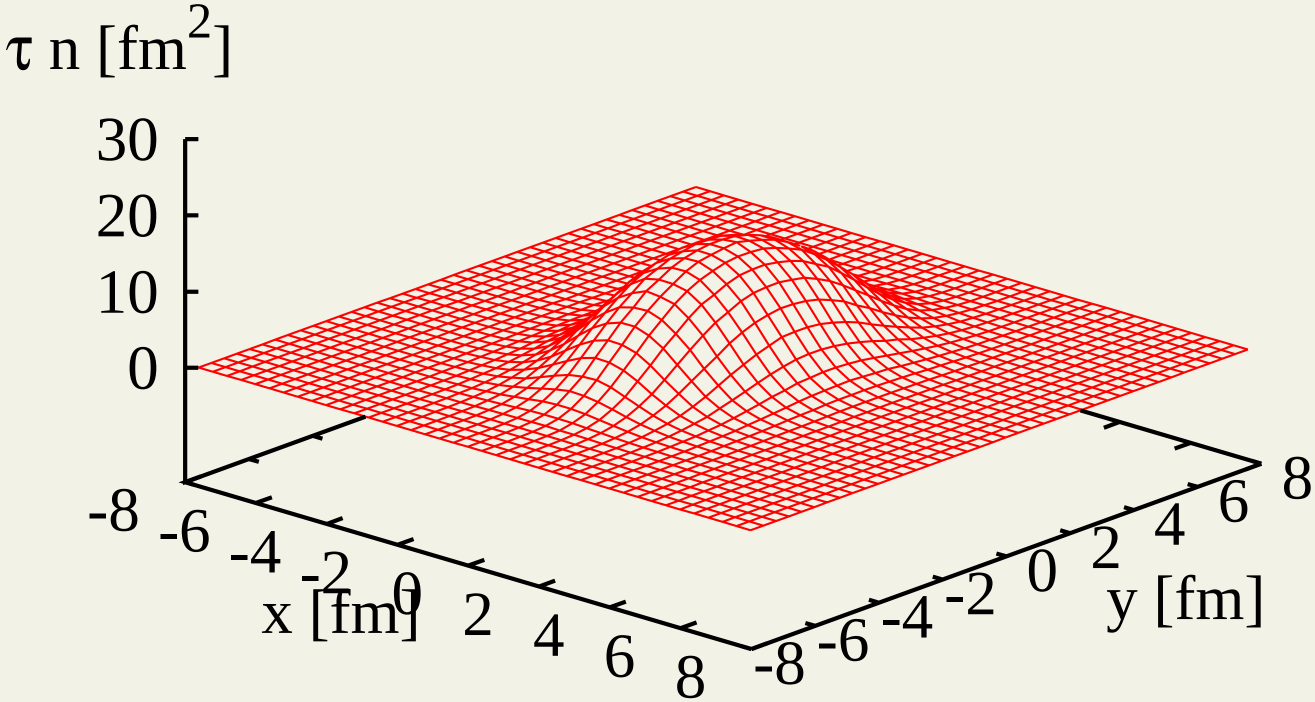
average **Au+Au, b=8 fm**

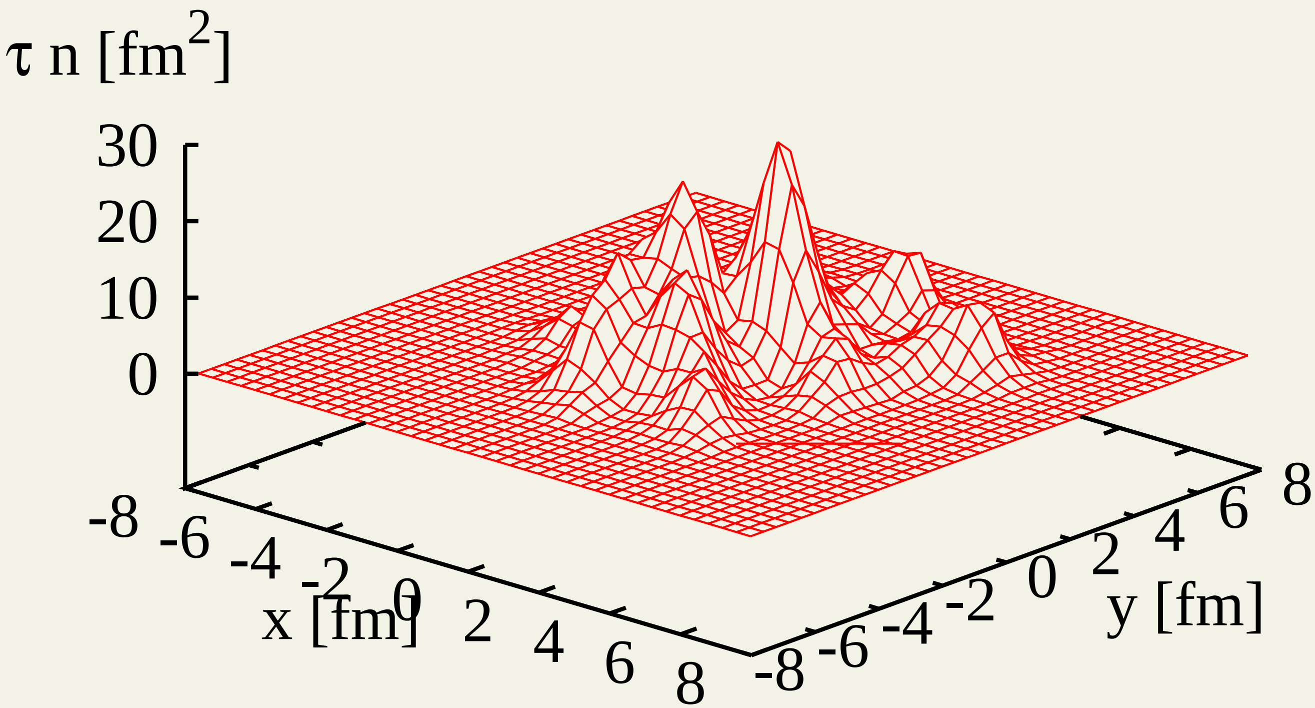


single **MC Glauber**



$\boldsymbol{\tau = 9.6}$ **fm**


τ n [fm2]
30
20
10
0
-8 -6 -4 -2 0 2 4 6 8
x [fm]
-8 -6 -4 -2 0 2 4 6 8
y [fm]


τ n [fm2]
30
20
10
0
-8 -6 -4 -2 0 2 4 6 8
x [fm]
-8 -6 -4 -2 0 2 4 6 8
y [fm]

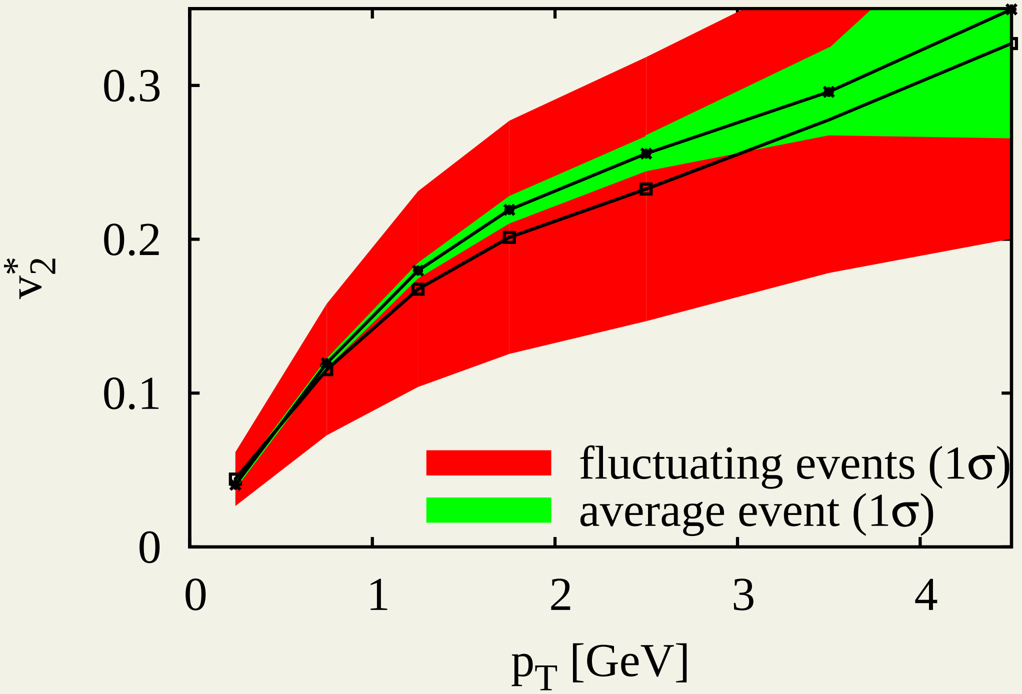
"./flu

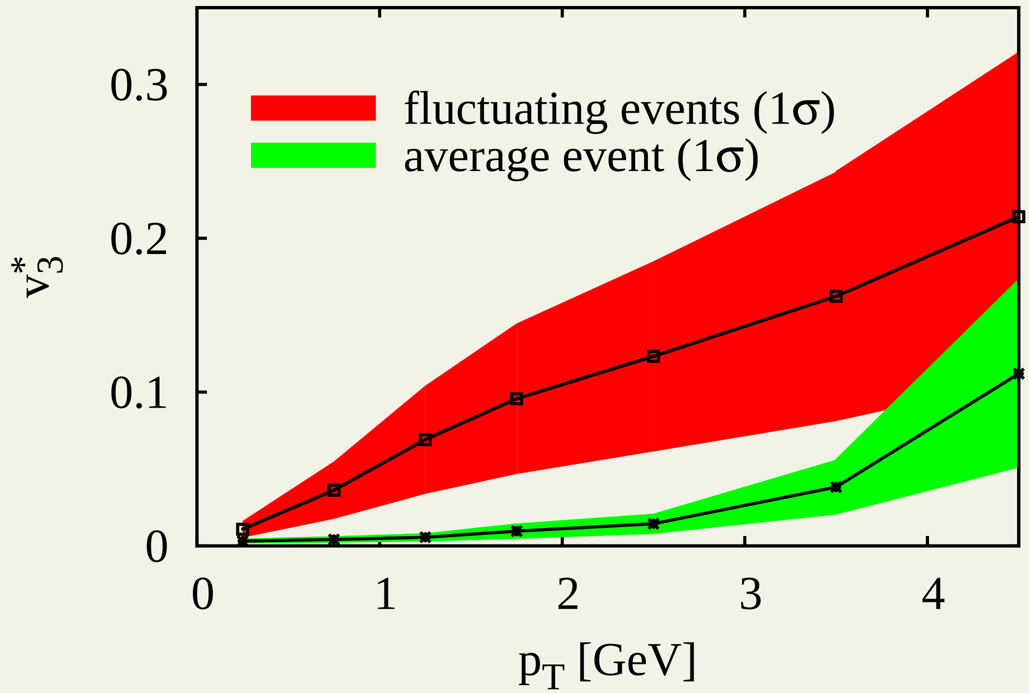
Analyze MEDIUM and JET response using eccentricity coefficients

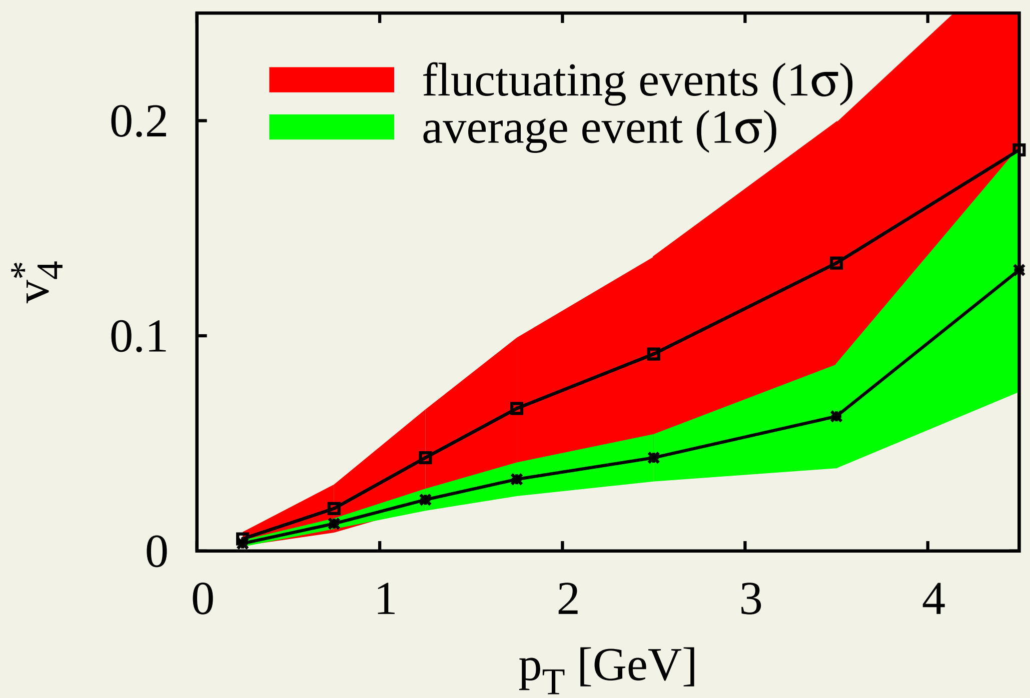
$$\begin{aligned}\vec{\epsilon}_{n,k} &\equiv \frac{1}{\langle r^k\rangle}\left(\langle r^k\cos(n\phi_x)\rangle, \langle r^k\sin(n\phi_x)\rangle\right)\\ &= \epsilon^*_{n,k}\left(\cos\Phi_{n,k}, \sin\Phi_{n,k}\right)\end{aligned}$$

and similar decomposition for transverse momenta (v_n, Φ_n)

$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\varphi - \Phi_n)$$



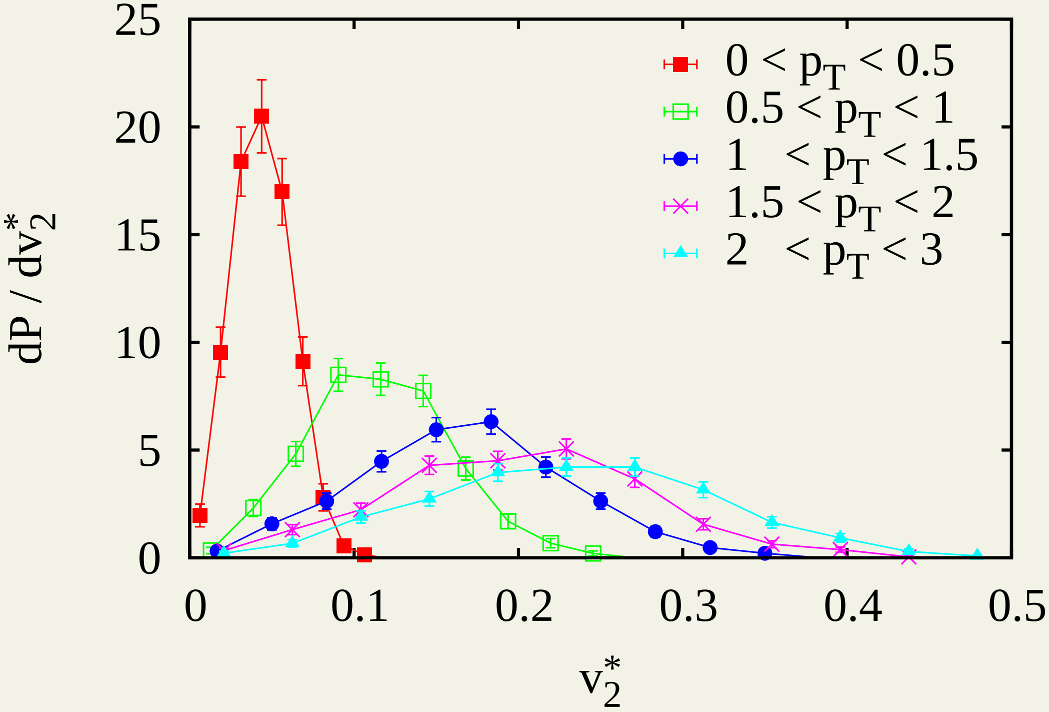


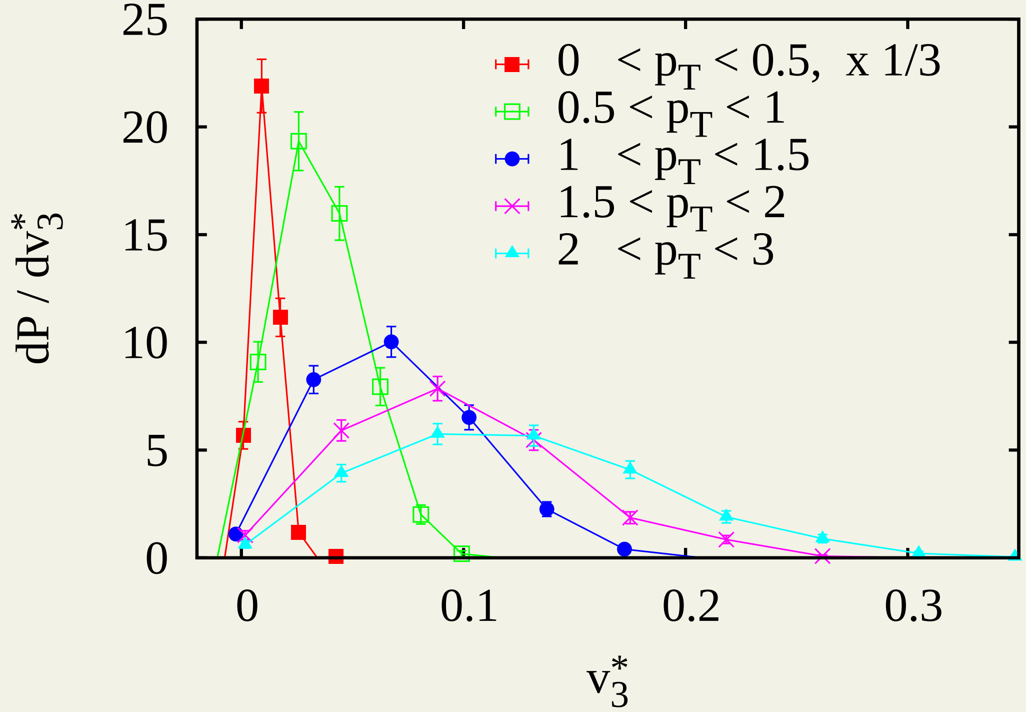


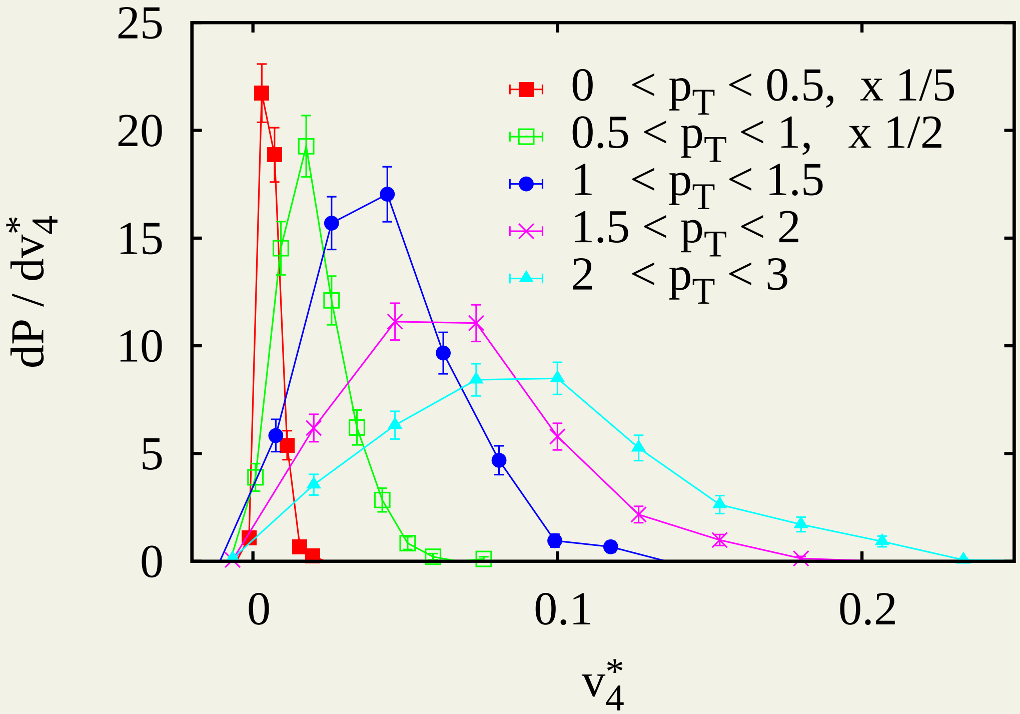
average v_2 essentially same as from averaged initcond

v_n **increase with** p_T

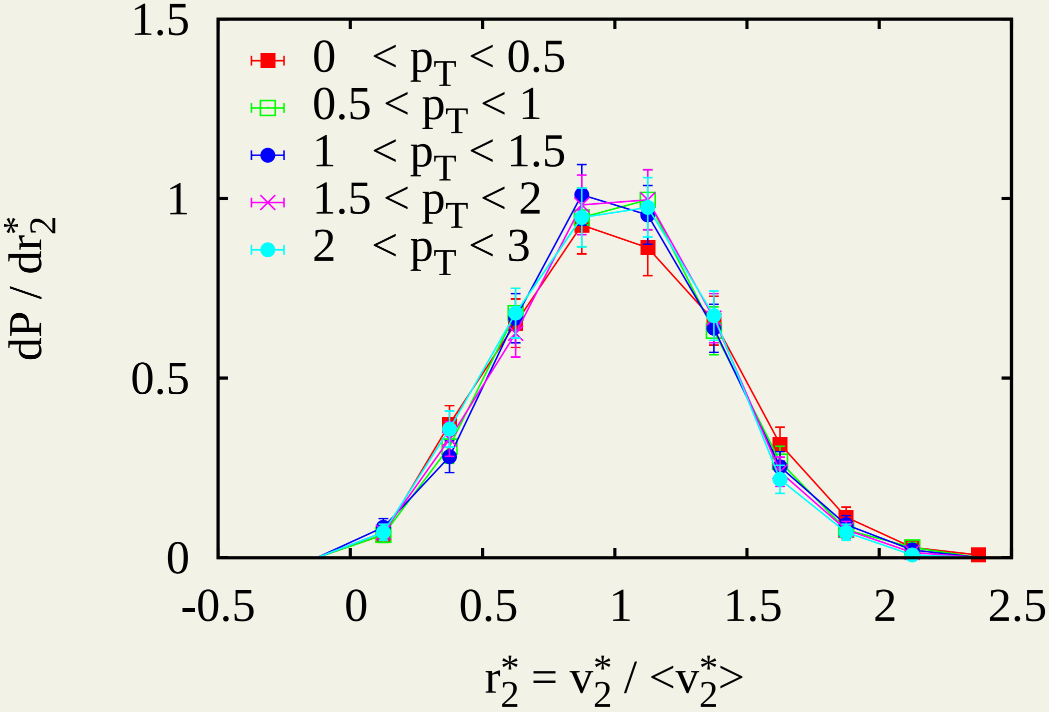
(shades represent $\sqrt{\langle \delta v_n^2 \rangle}$)

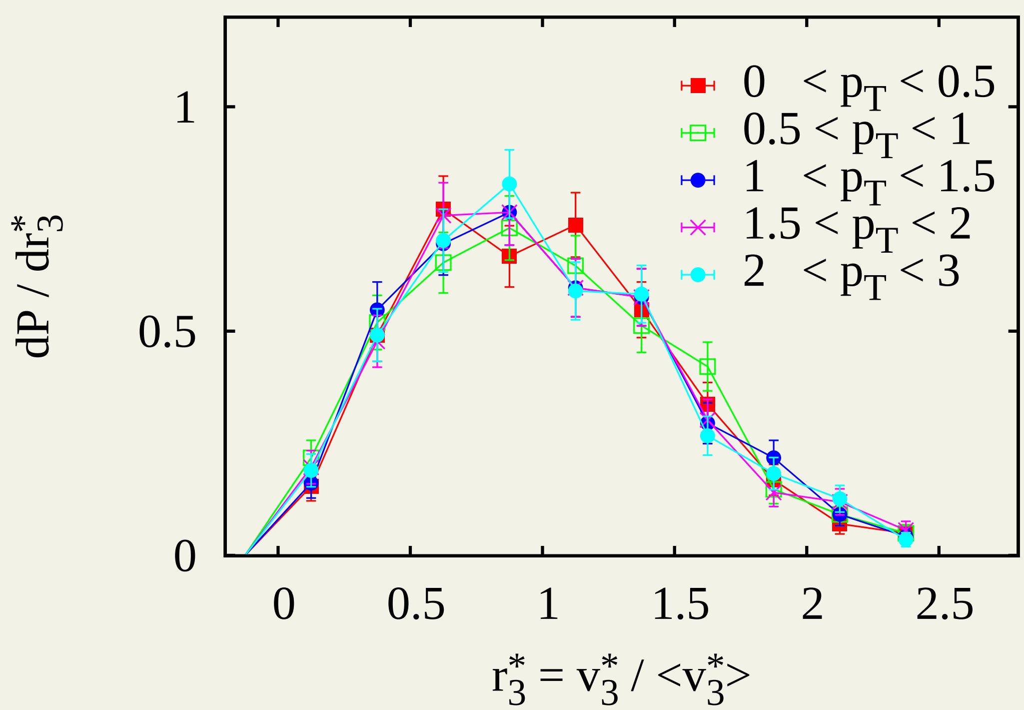


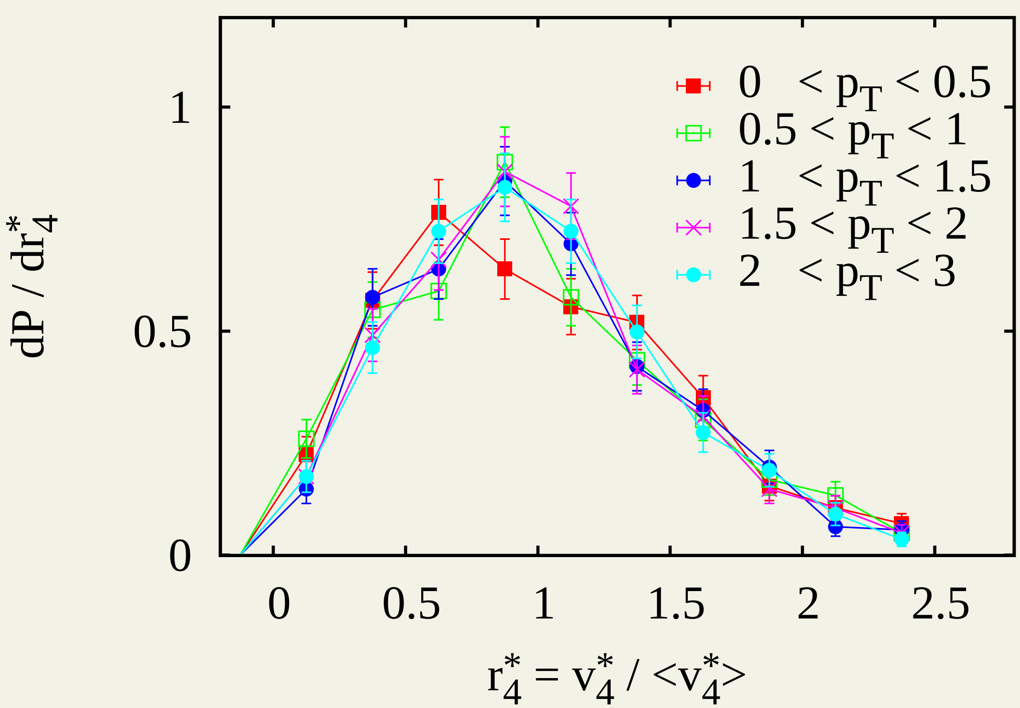




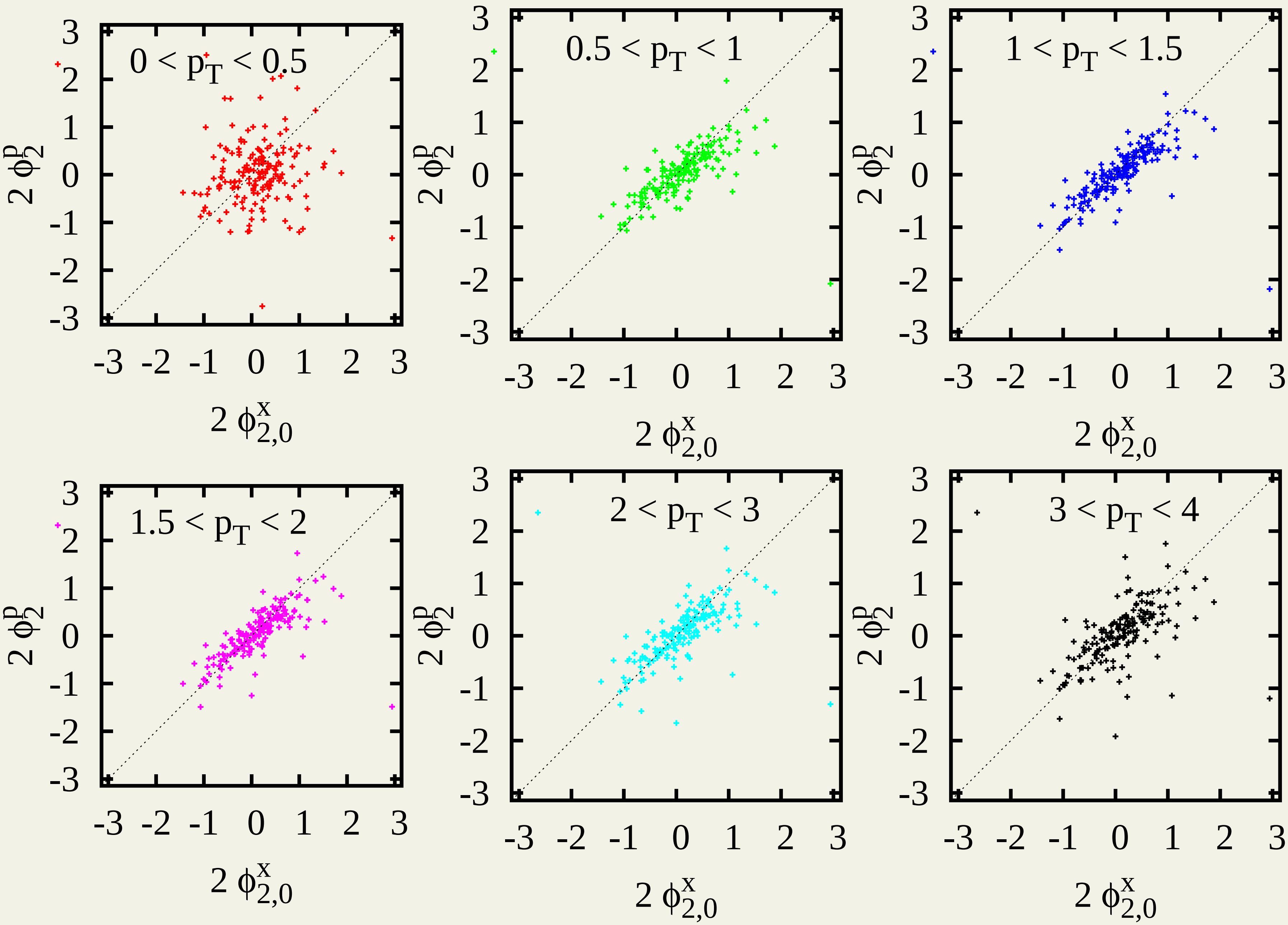
MC Glauber initial conditions induce large v_2, v_3, v_4 fluctuations in bulk transport medium



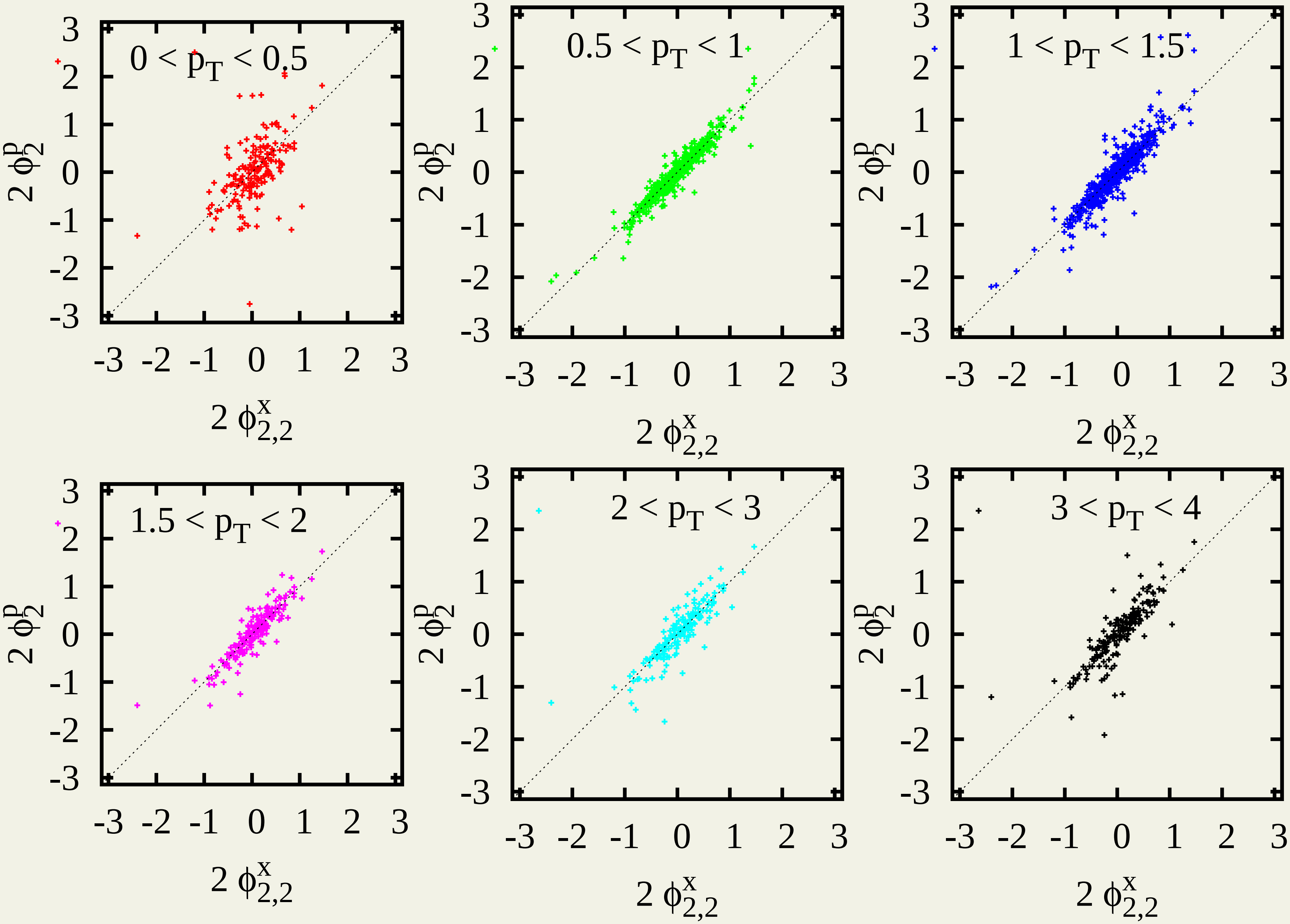




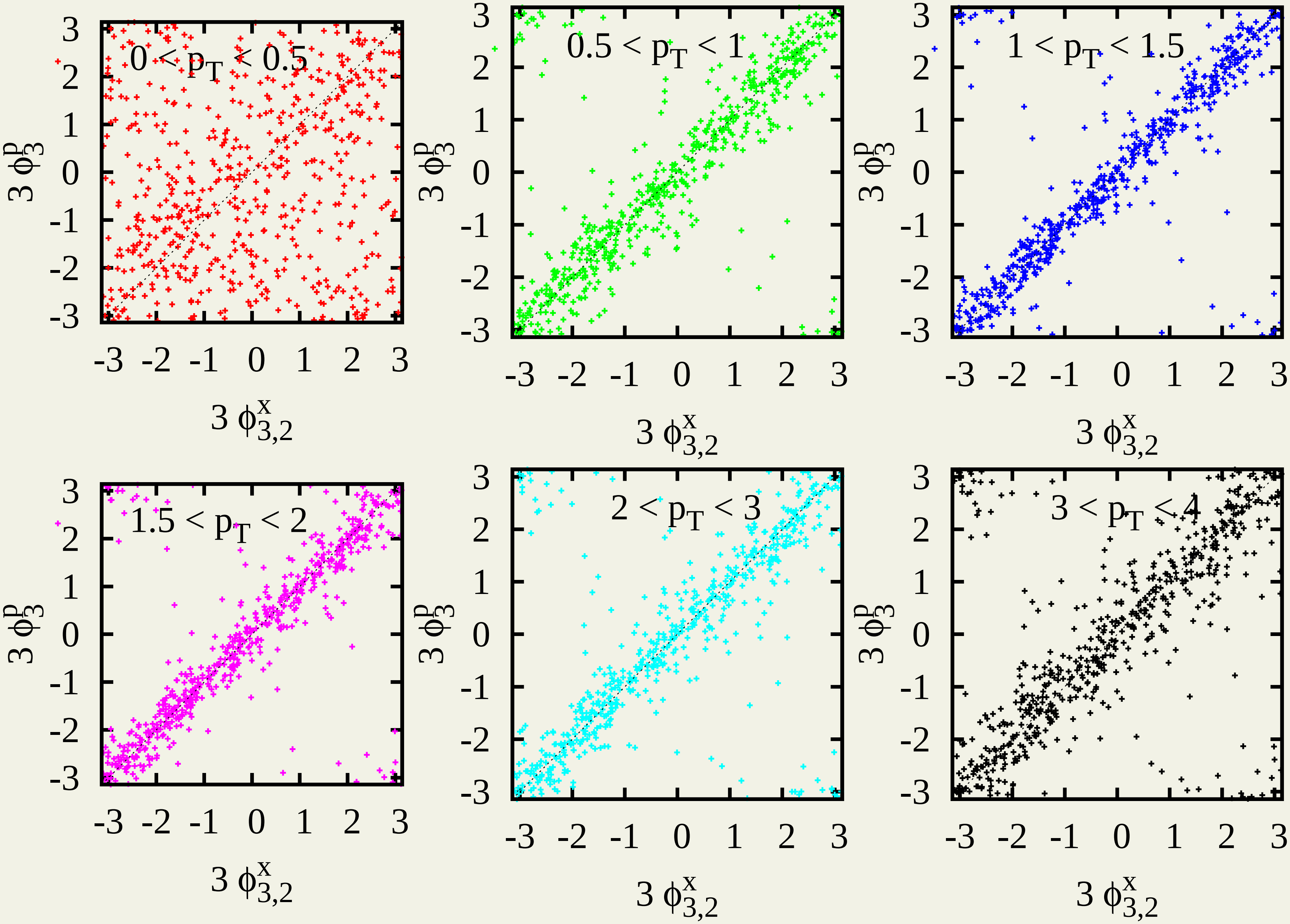
$v_n/\langle v_n\rangle$ **nearly universal independent of** p_T



$0 < p_T < 0.5$
$0.5 < p_T < 1$
$1 < p_T < 1.5$
$1.5 < p_T < 2$
$2 < p_T < 3$
$3 < p_T < 4$
$2\ \phi_2^p$
$2\ \phi_{2,0}^x$
-3 -2 -1 0 1 2 3



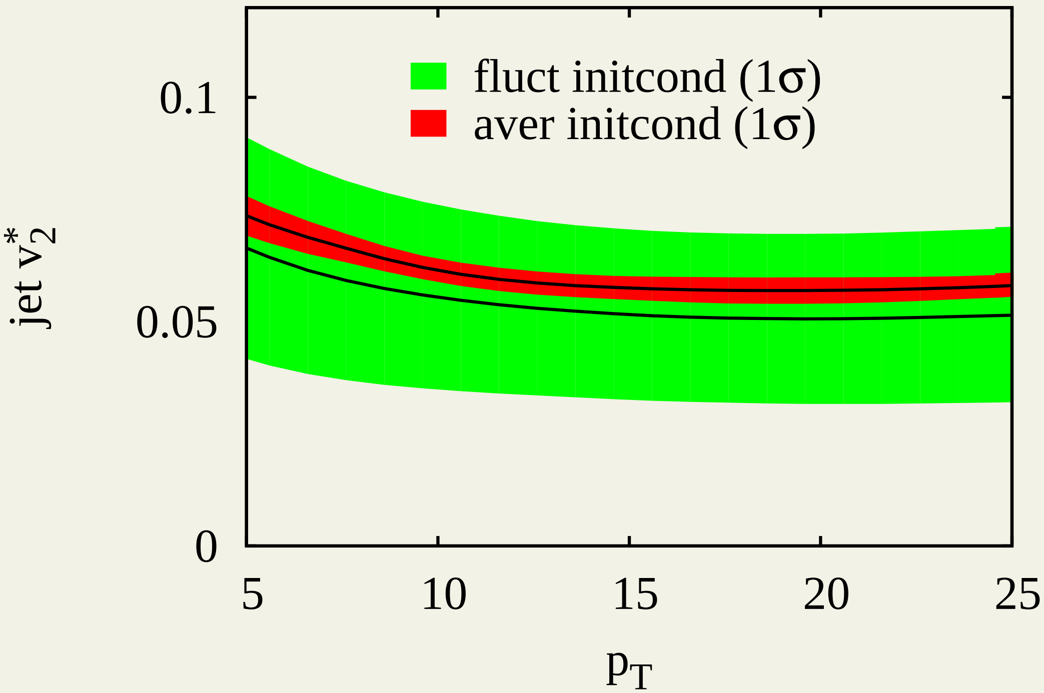
$\epsilon_{2,2}$ orientation correlates best with v_2 orientation

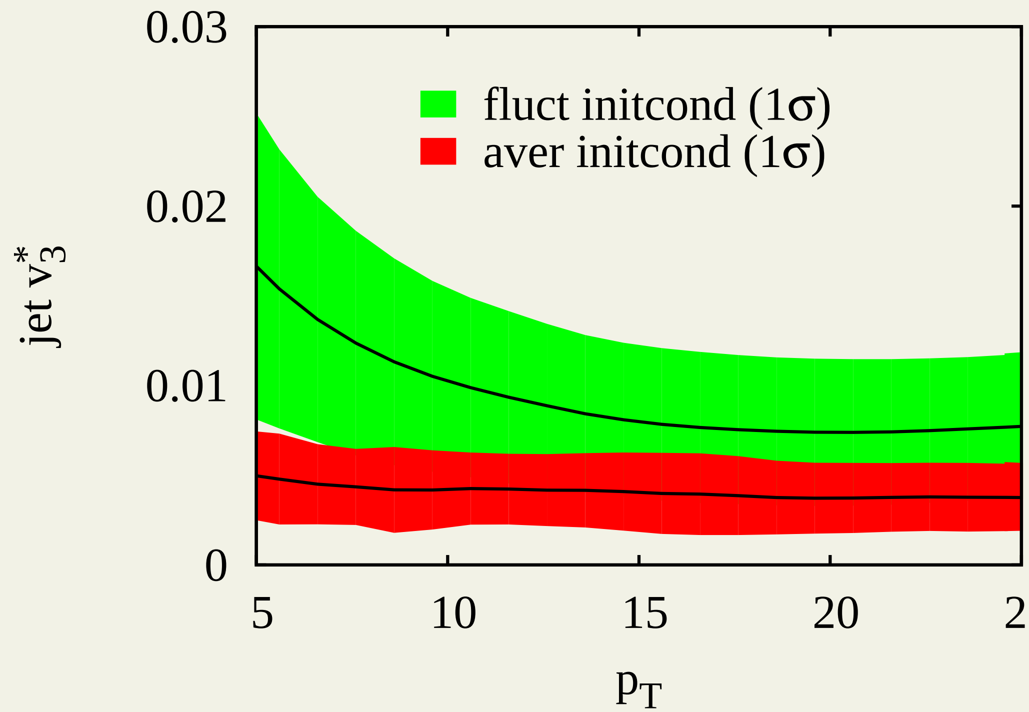


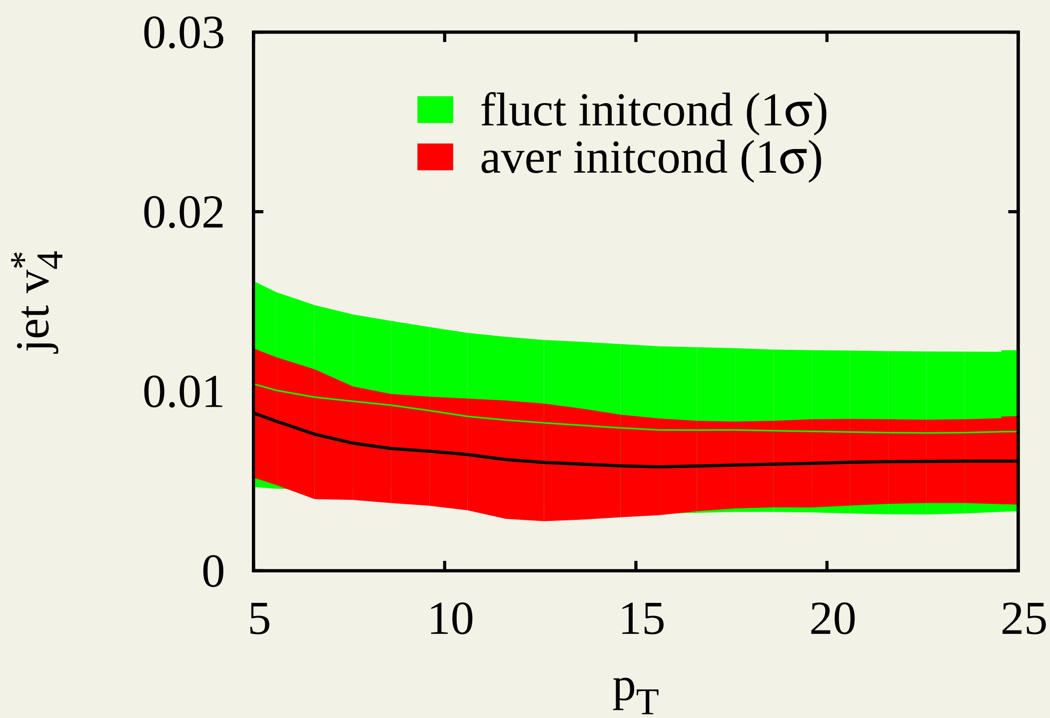
$\epsilon_{3,2}$ **correlates strongly with** v_3 **orientation**

Bulk medium response qualitatively similar to hydrodynamics.

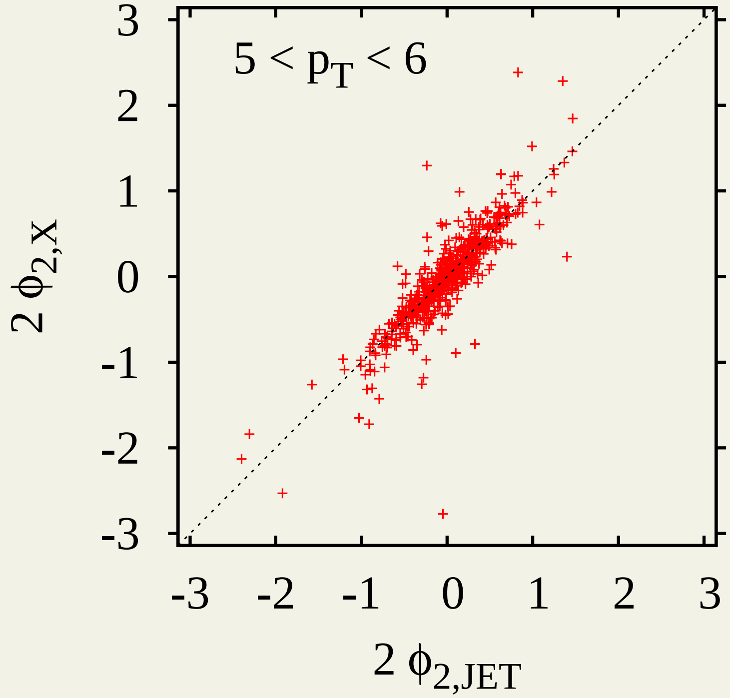
What about the jets?

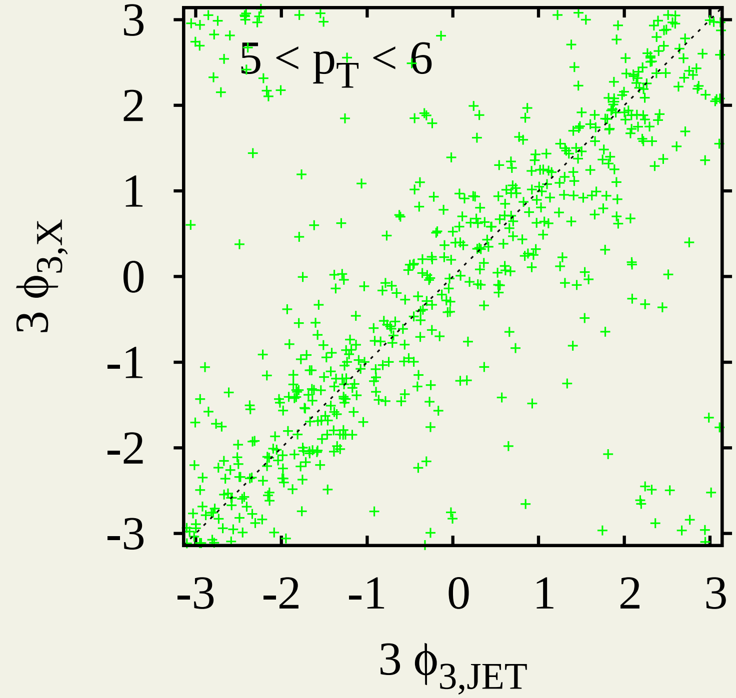


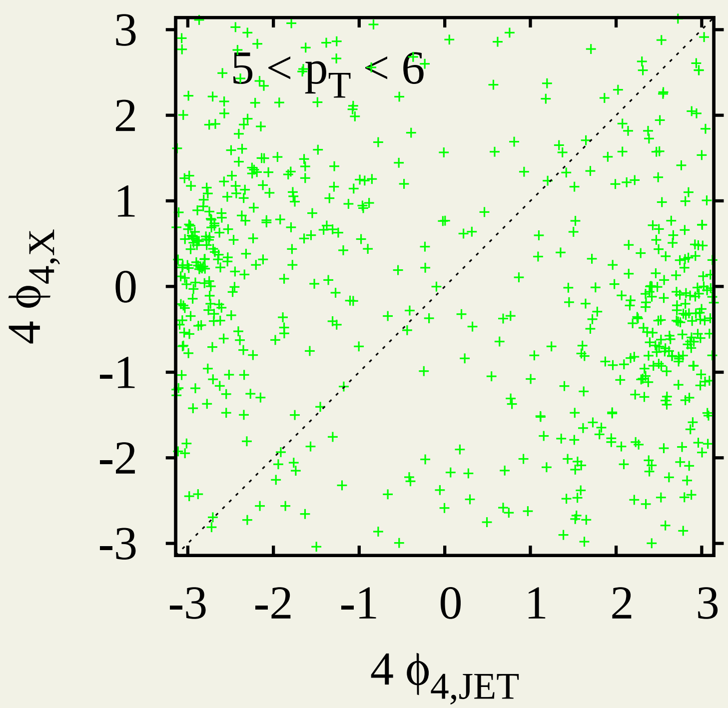




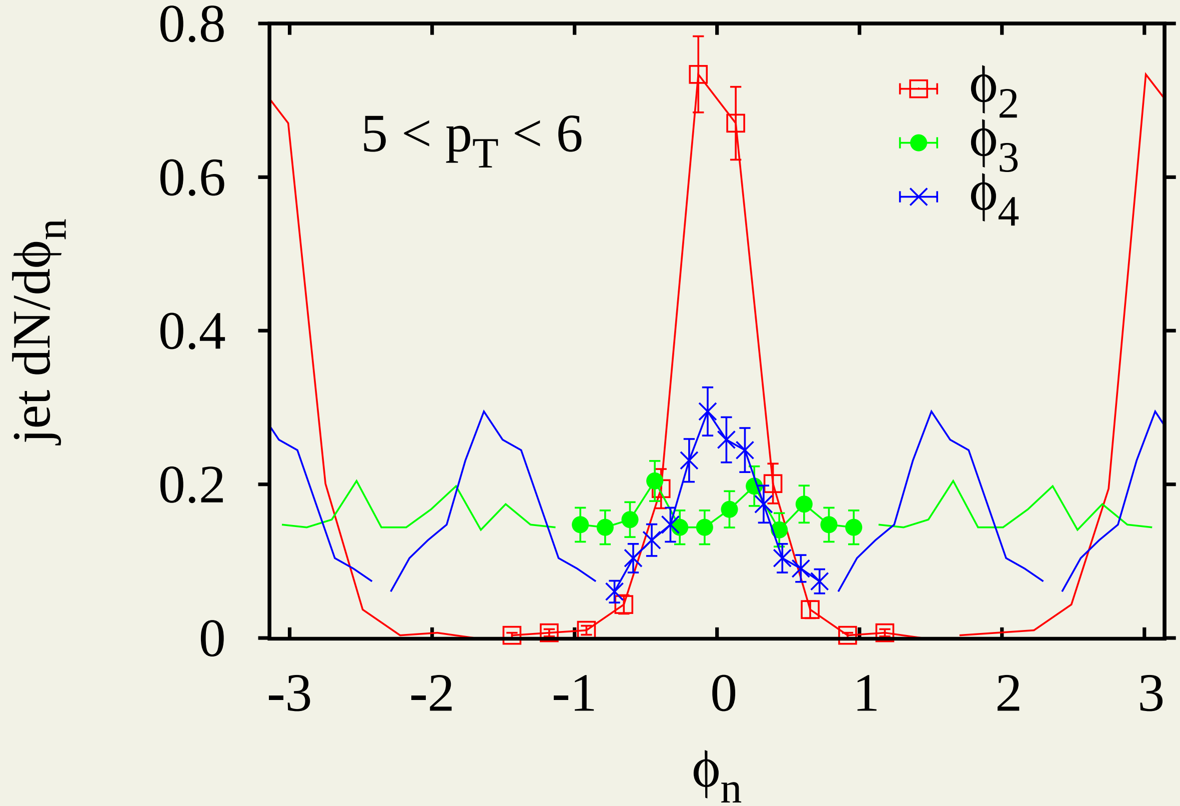
noticeable fluctuations in jet v_n







JET v_2 and v_3 correlate with orientation of $\epsilon_{2,3}$



angles relative to theorist's reaction plane $\rightarrow$ positive v_4

Summary

Parton transport can serve as bulk medium model. It responds to fluctuating initial conditions similarly to hydrodynamics.

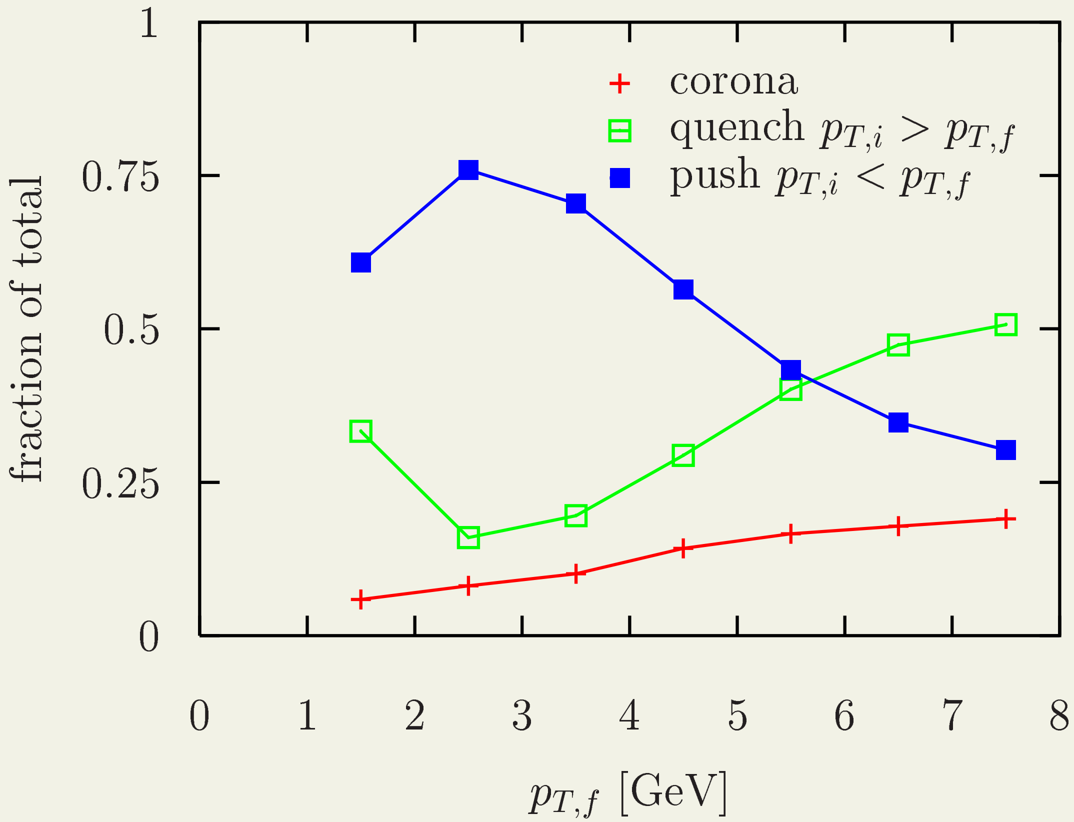
Though initial fluctuations NOT small perturbations, jet and medium $v_{2,3,4}$ correlate well with initial $\vec{\epsilon}_{2,3,4}$. For basic observables averaging even appears to nearly commute with evolution. (Where is the nonlinearity??)

We also find that, with GLV energy loss, transverse expansion reduces both R_{AA} and v_2 at high p_T.

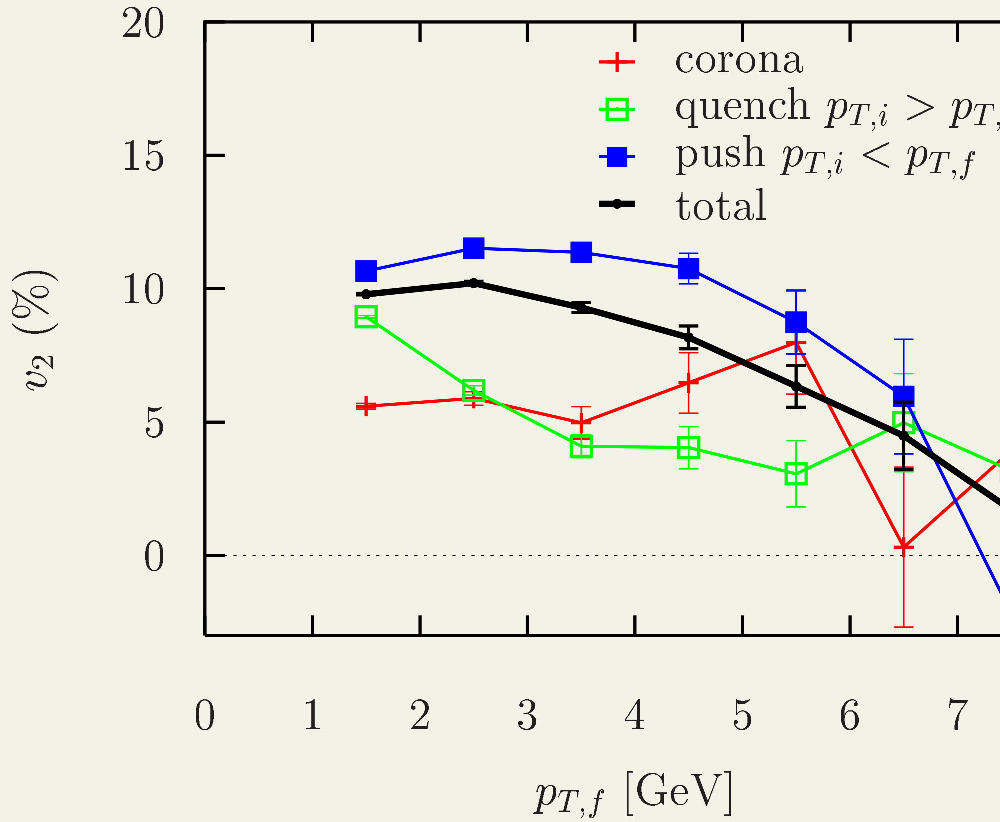
Some interesting avenues to investigate:

- dynamical fluctuations in transport
- migration in p_T ("plasma push" DM nucl-th/0503051)
- corona

DM ('05):

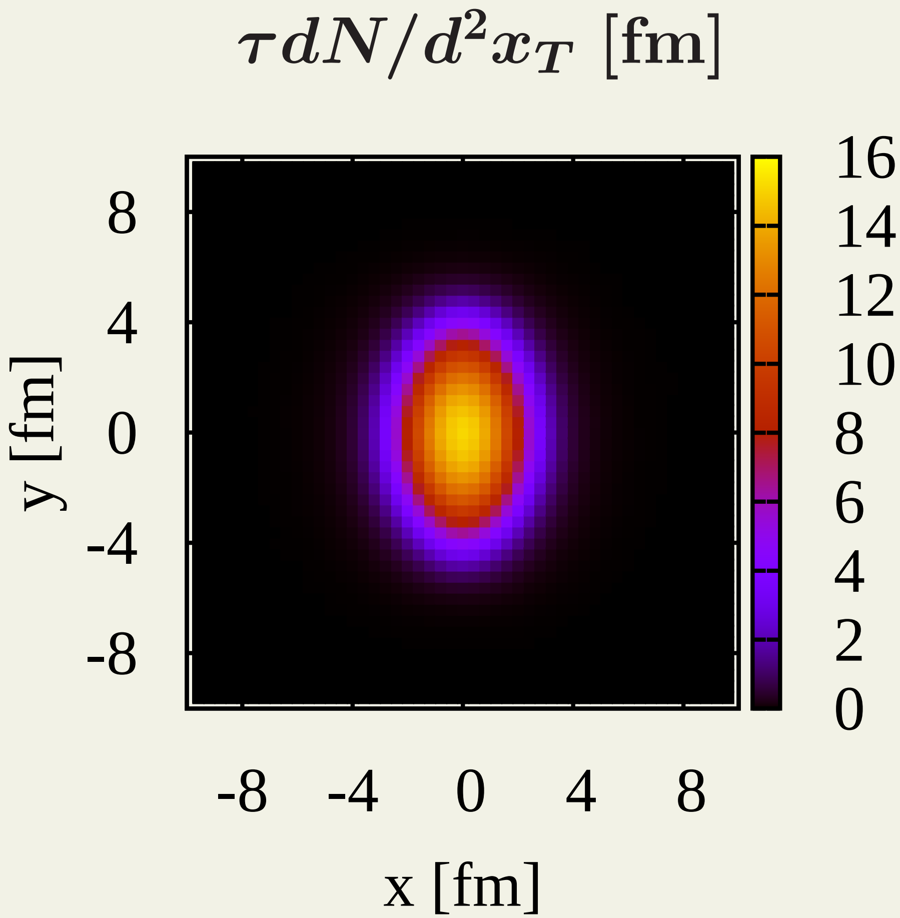


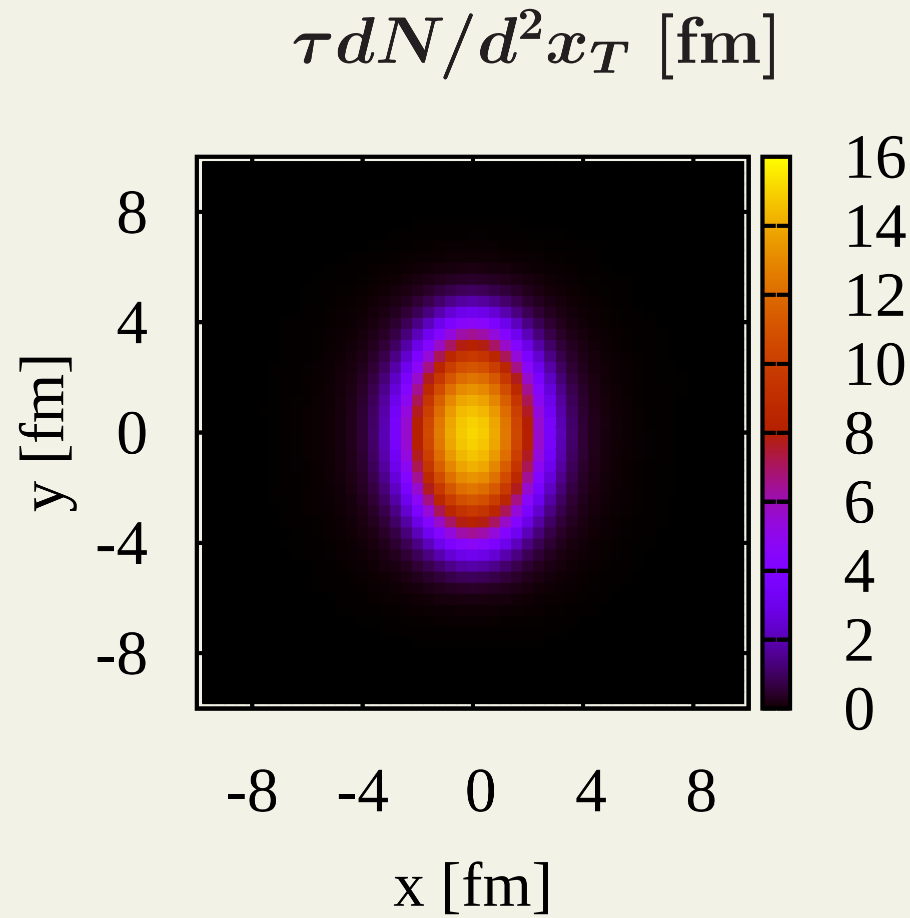
fraction of total
corona
quench $p_{T,i} > p_{T,f}$
push $p_{T,i} < p_{T,f}$
$p_{T,f}$ [GeV]
0
0.25
0.5
0.75
1
0
1
2
3
4
5
6
7
8



v_2 (%)
corona
push $p_{T,i} < p_{T,f}$
total
$p_{T,f}$ [GeV]
0
5
10
15
20
0
1
2
3
4
5
6
7

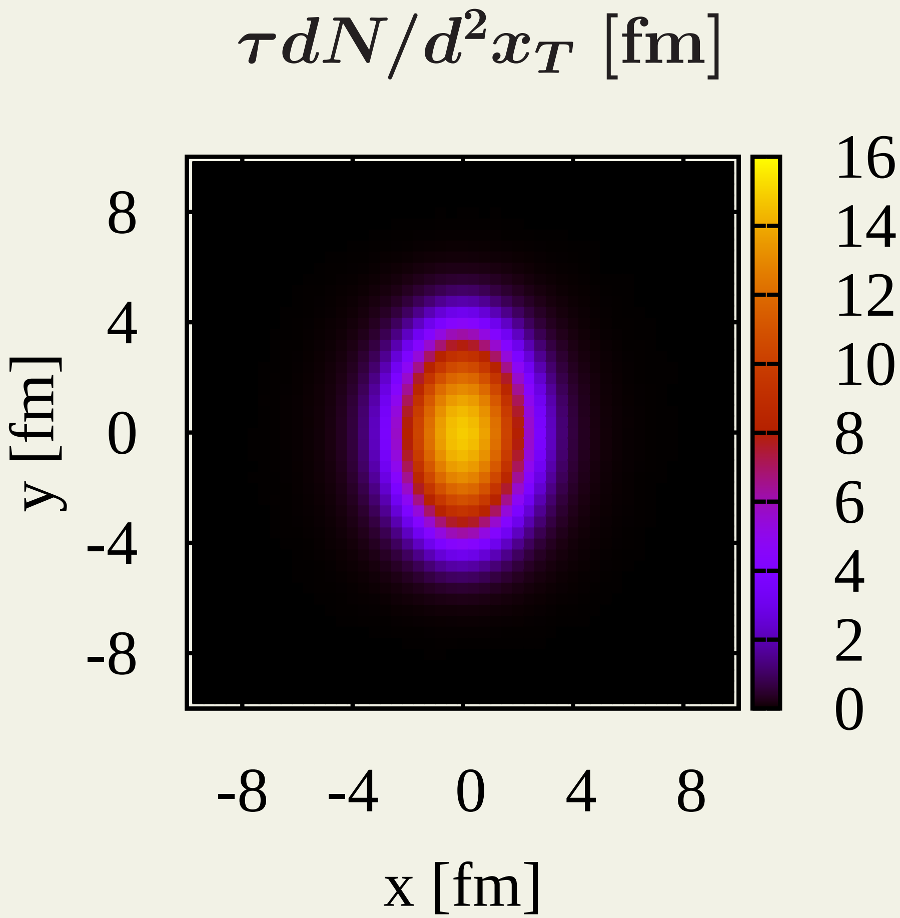
average Au+Au, b=8 fm **600 averaged MC Glauber runs**

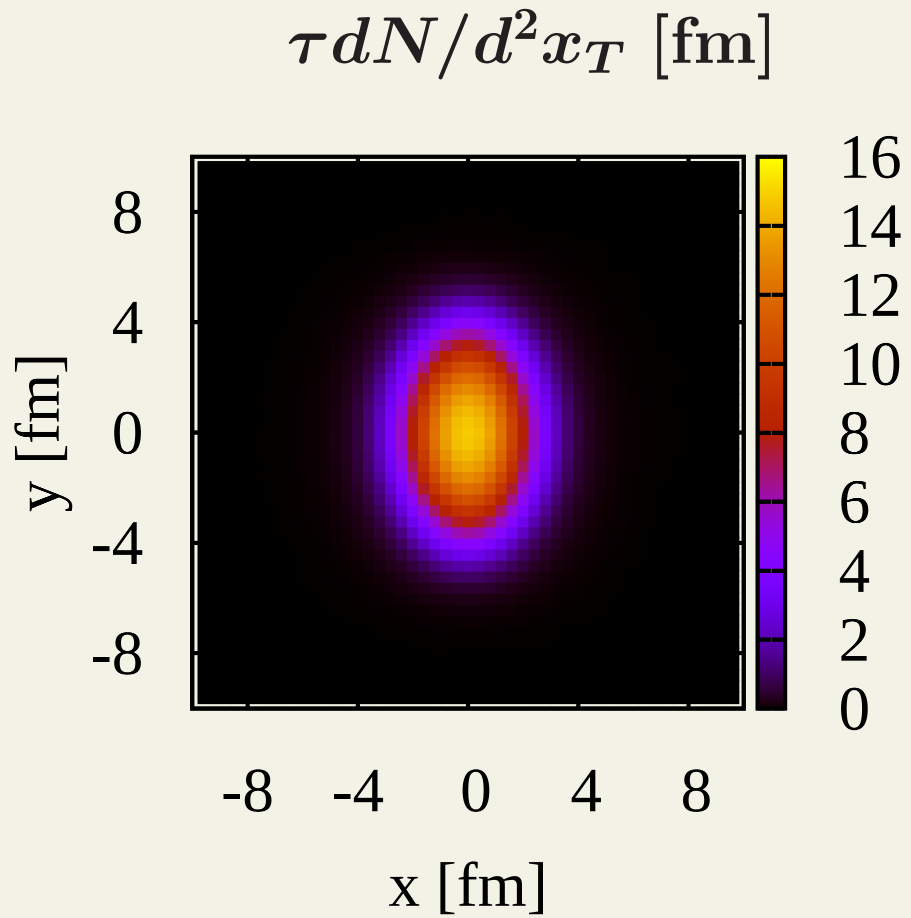




$\tau = 0.6$ fm

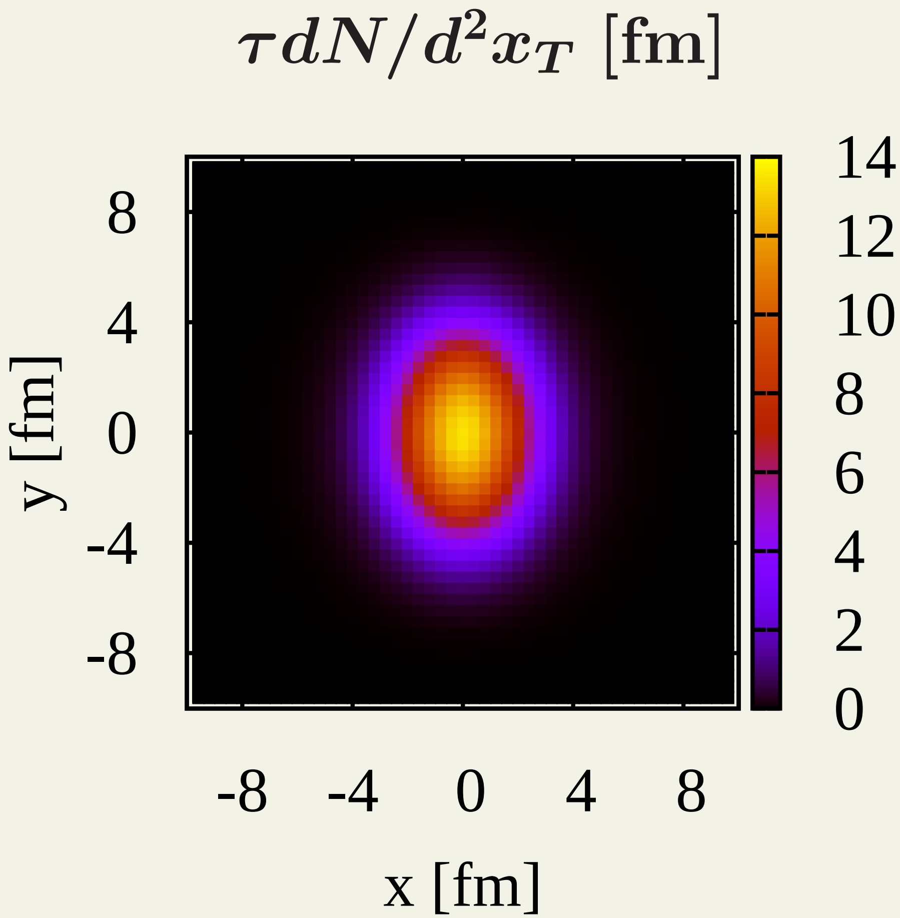
average Au+Au, b=8 fm **600 averaged MC Glauber**

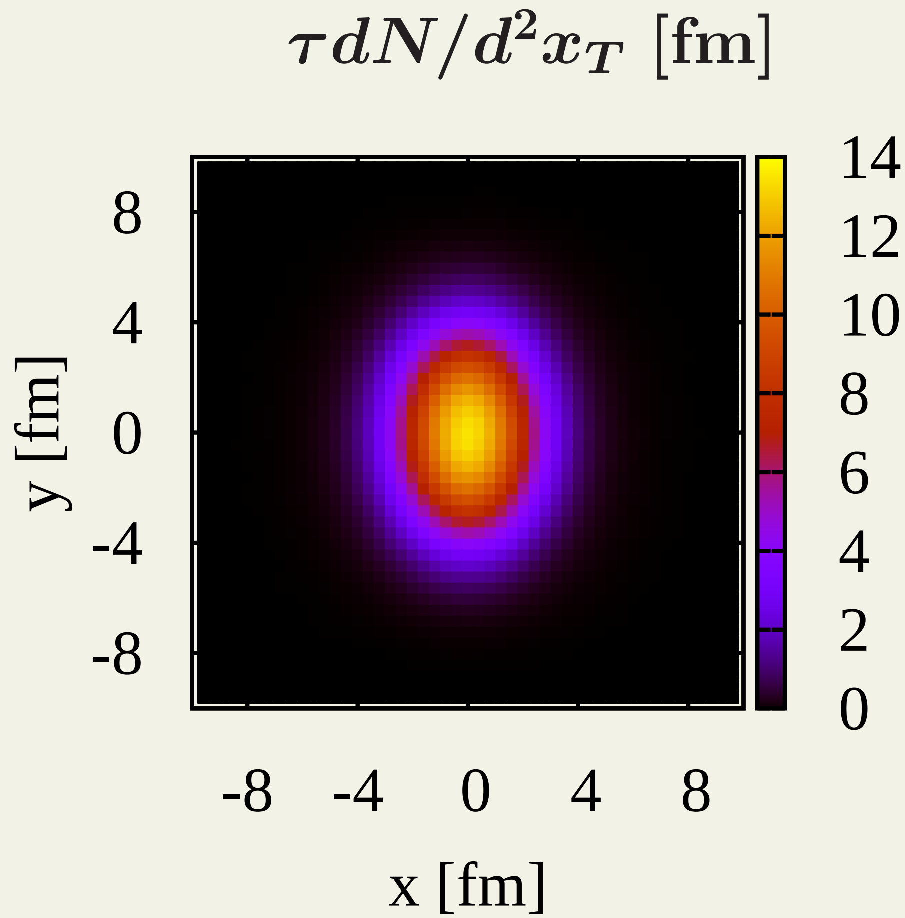




$\tau = 1.2$ fm

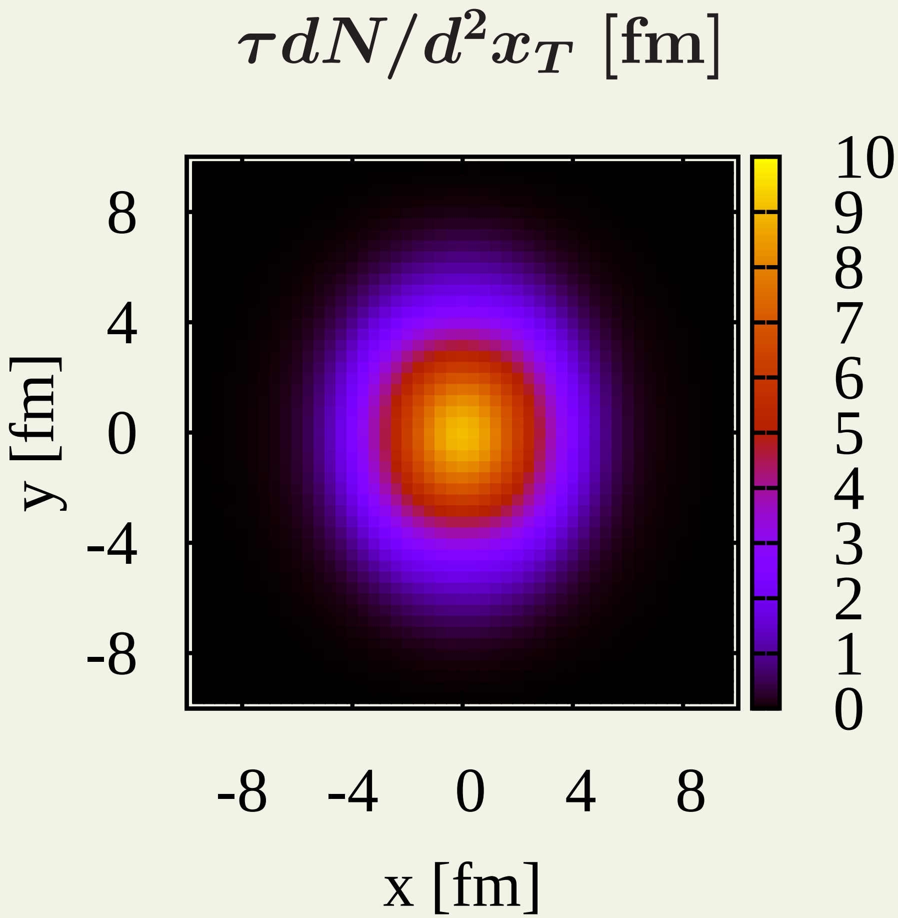
average **Au+Au, b=8 fm** **600 averaged** **MC Glauber**

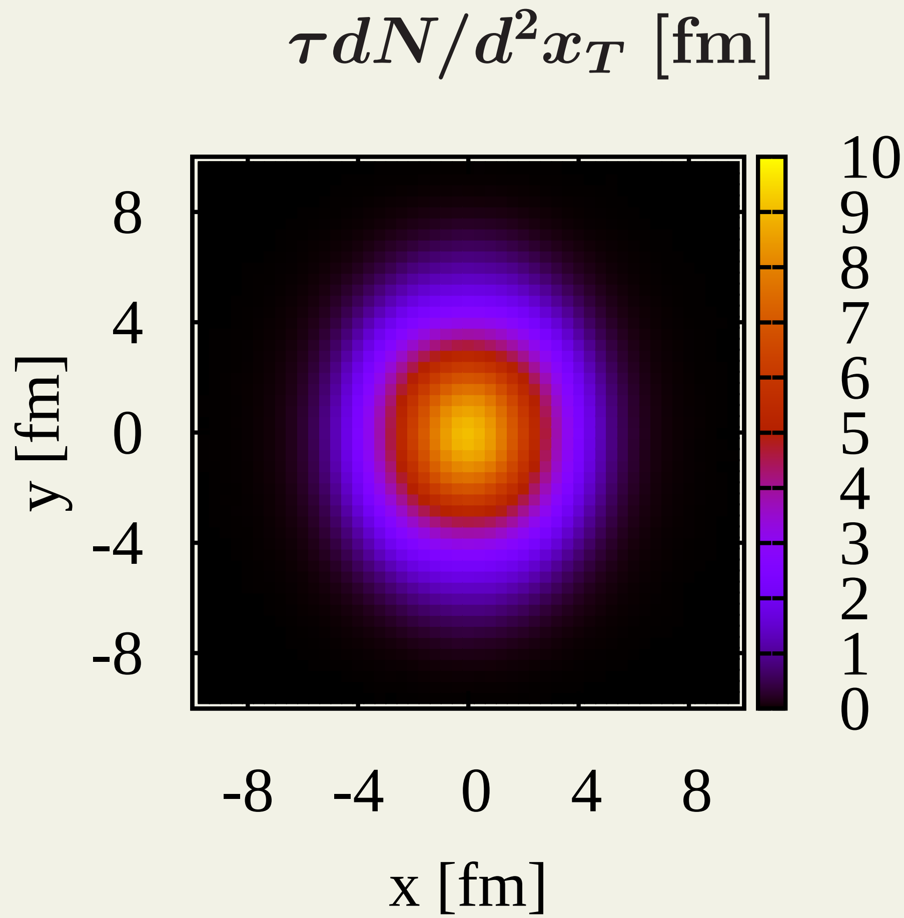




$\boldsymbol{\tau = 2.1}$ **fm**

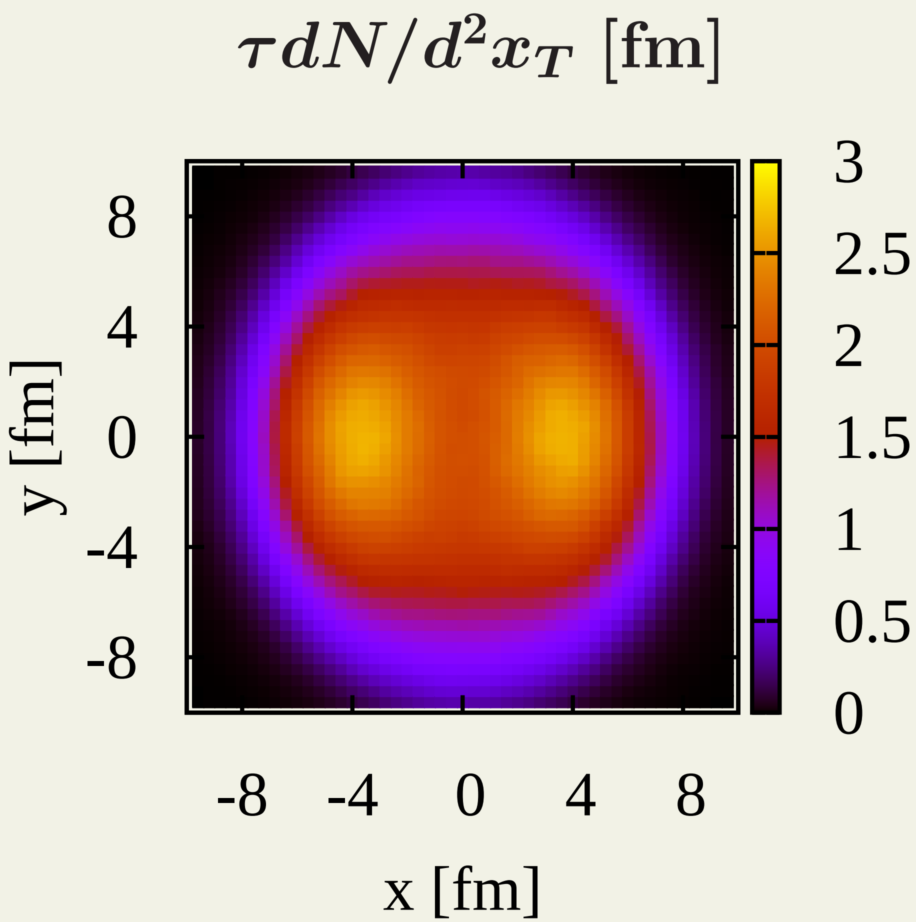
average Au+Au, b=8 fm | **600 averaged MC Glauber**

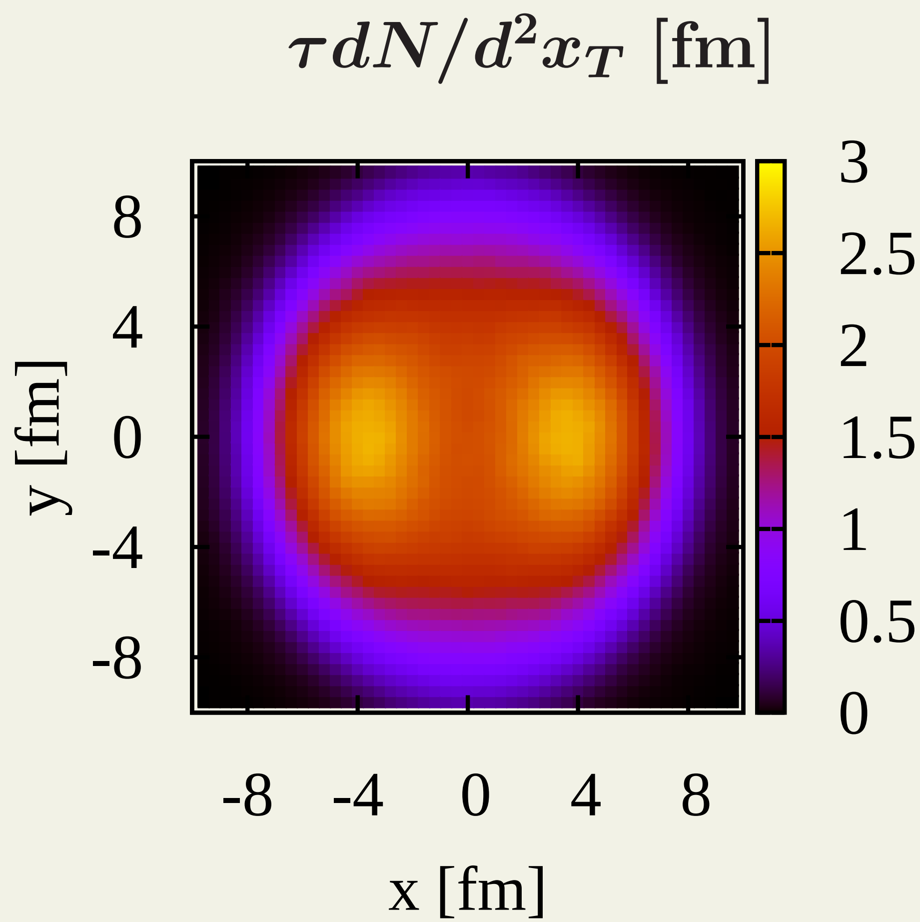




$\tau = 3.6$ fm

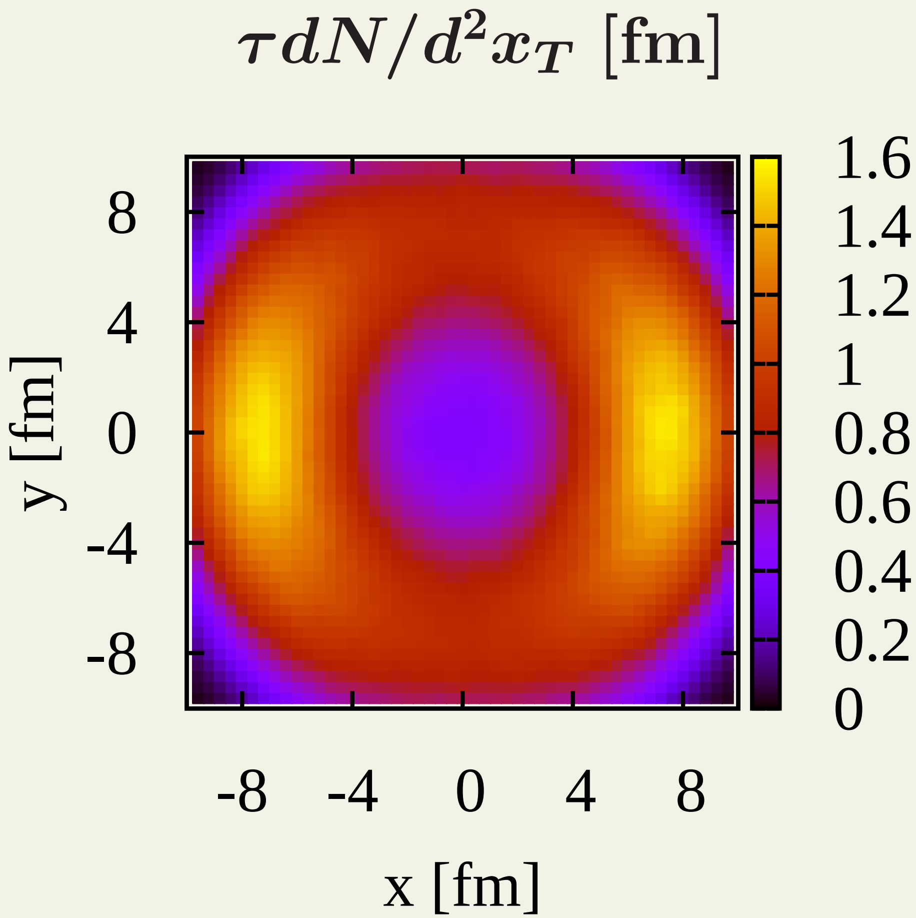
average Au+Au, b=8 fm **600 averaged MC Glauber**

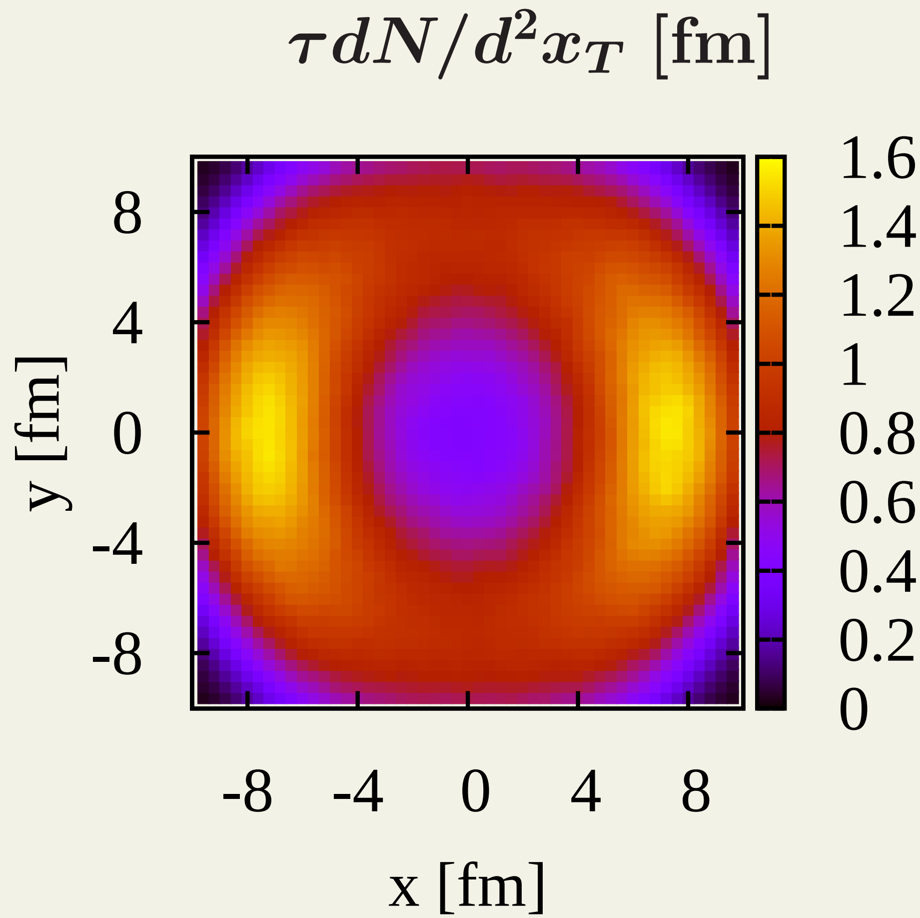




$\tau = 6.6$ fm

average Au+Au, b=8 fm **600 averaged MC Glauber**

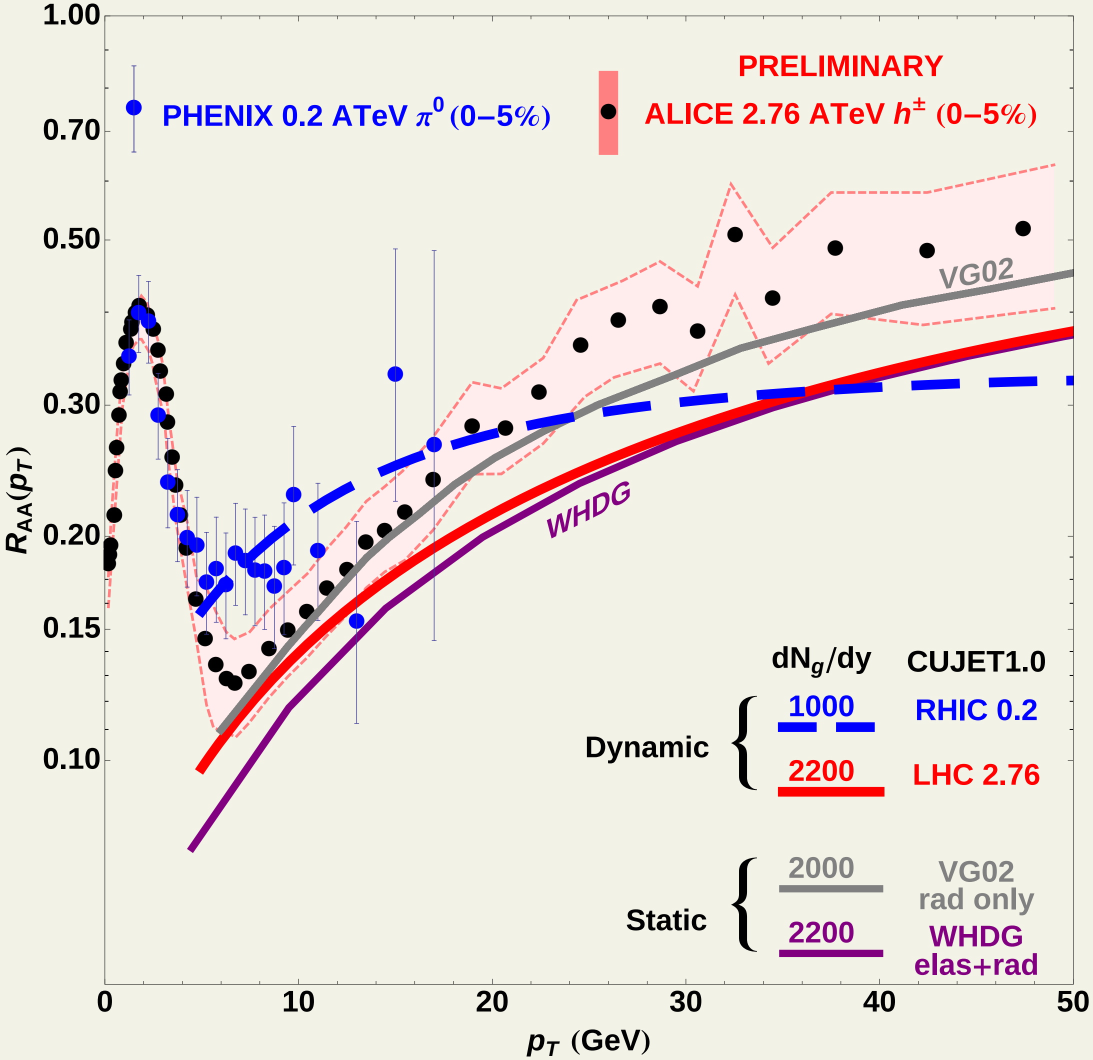




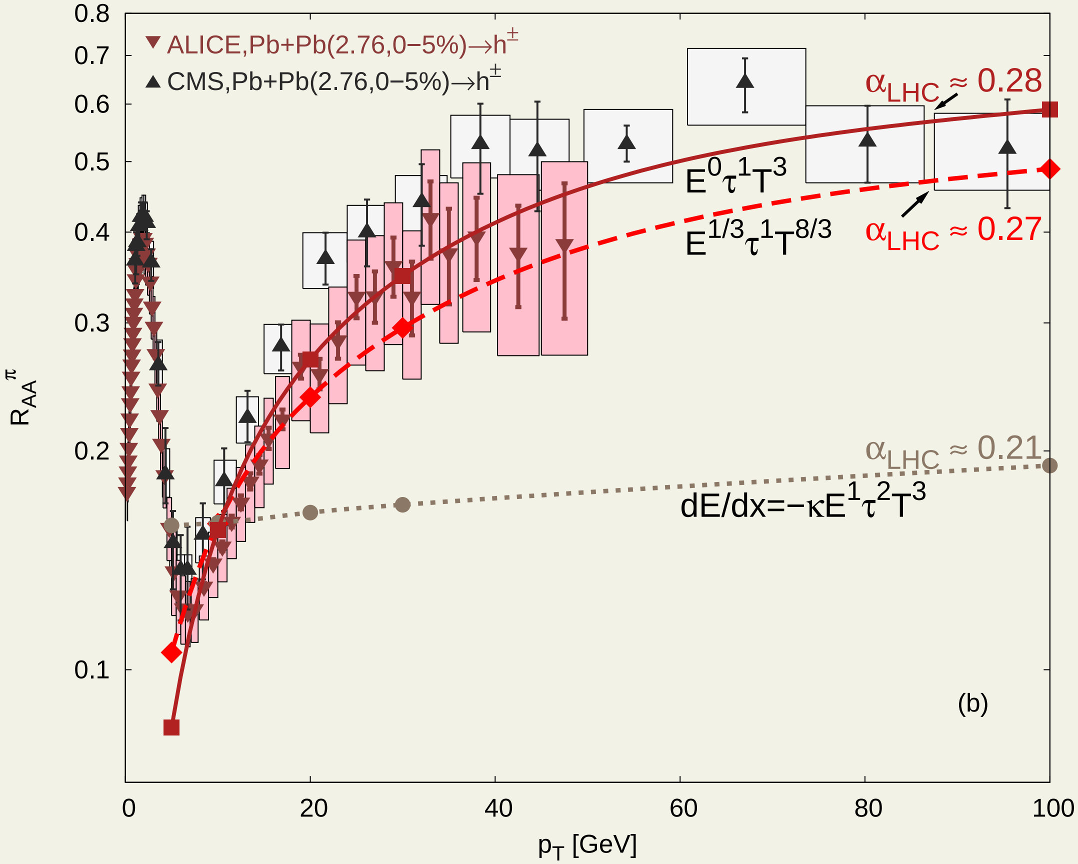
$\boldsymbol{\tau = 9.6}$ **fm**

Backup slides

CUJET 1.0 Buzzatti et al ('11)

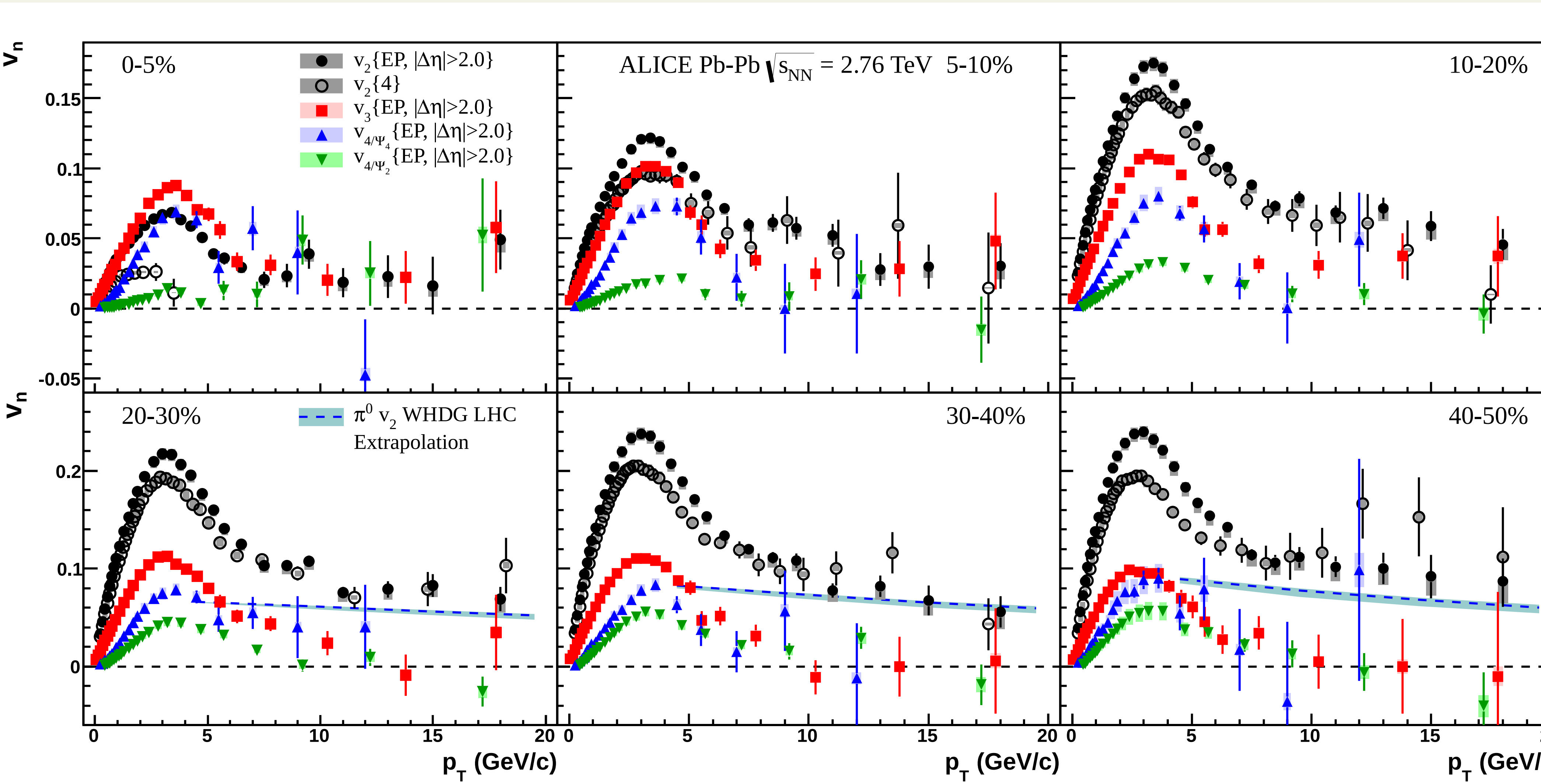


Betz & Gyulassy, arXiv:1201.0281

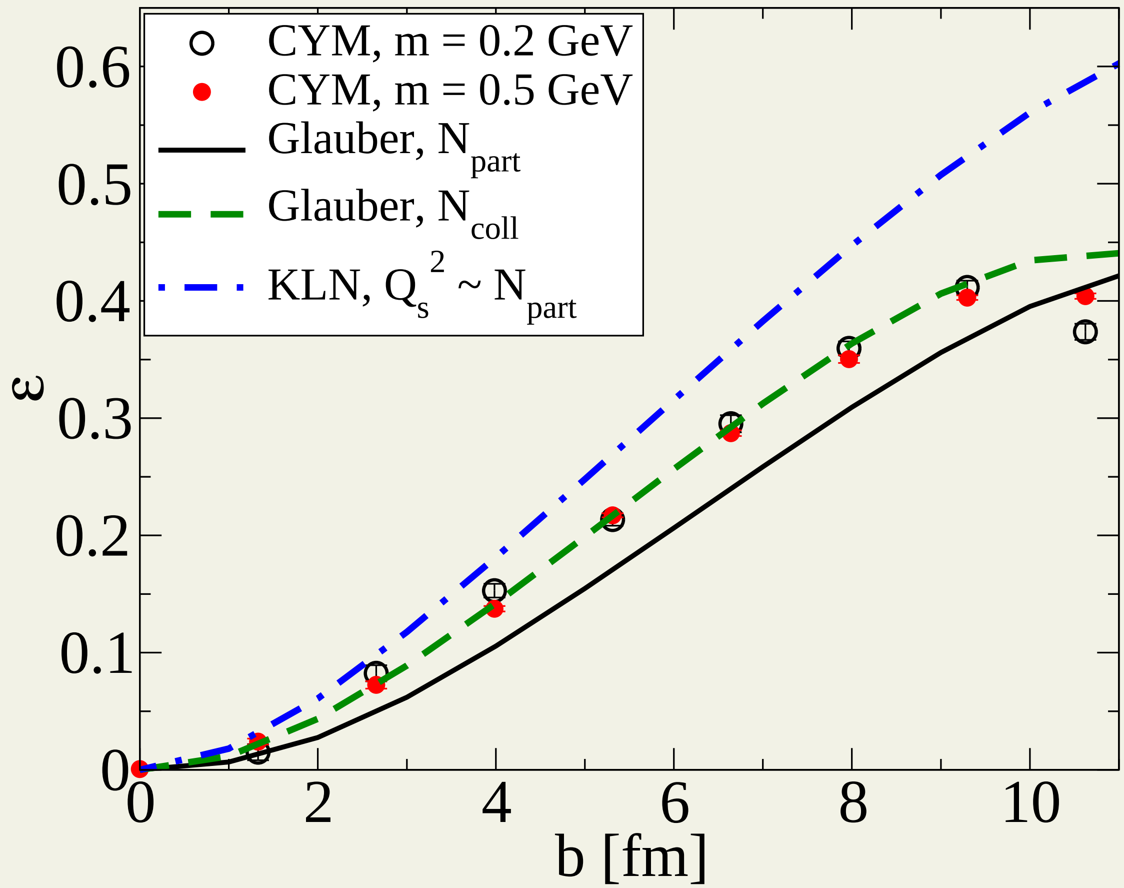


$$\alpha_s^{RHIC} = 0.3$$

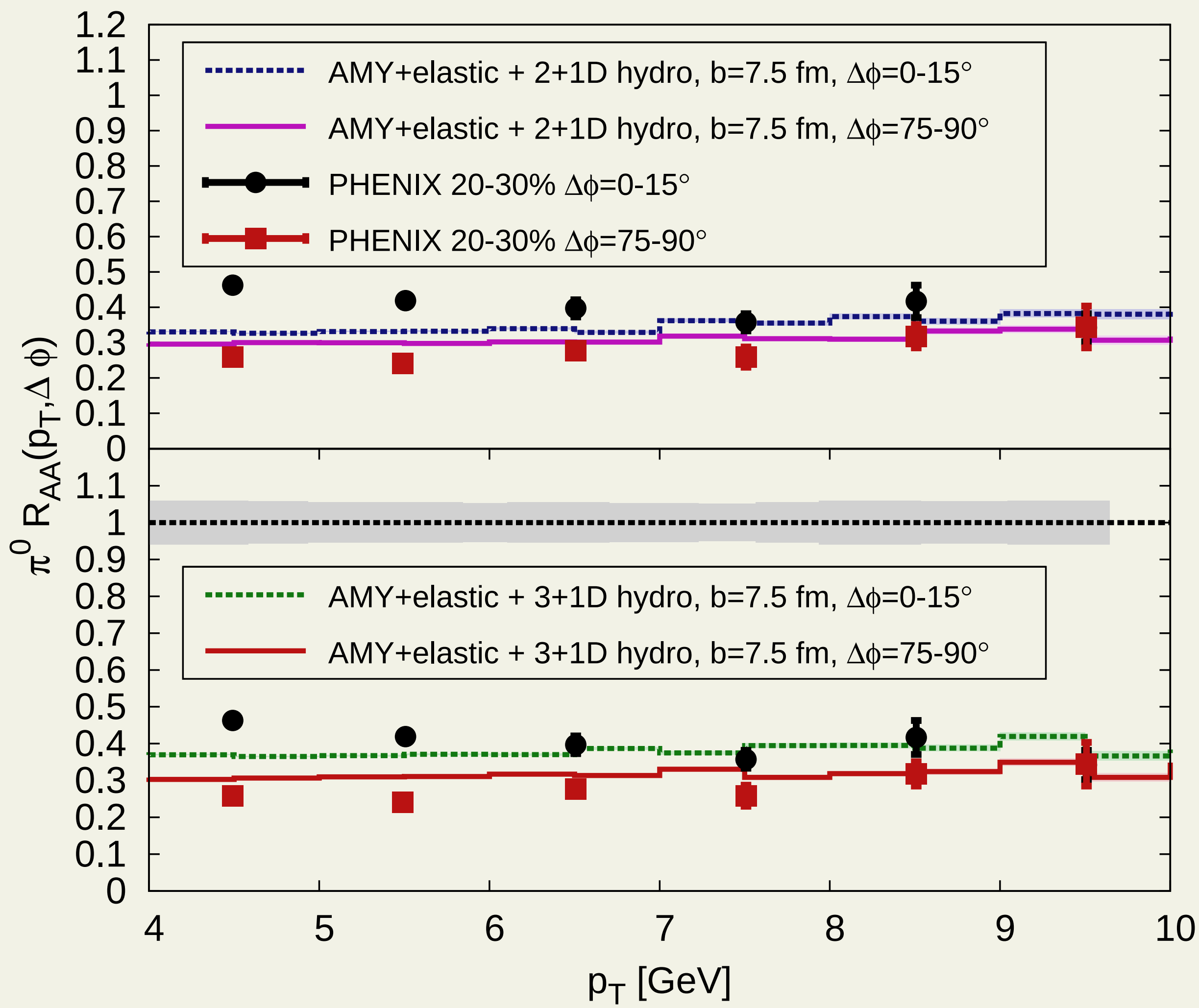
ALICE v2,v3,v4 arXiv:1205.5761v2



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

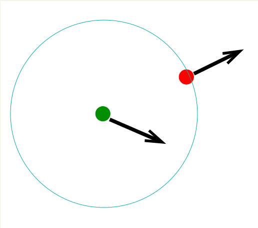


MARTINI $R_{AA}(\phi)$ Schenke et al, PRC80 ('09):



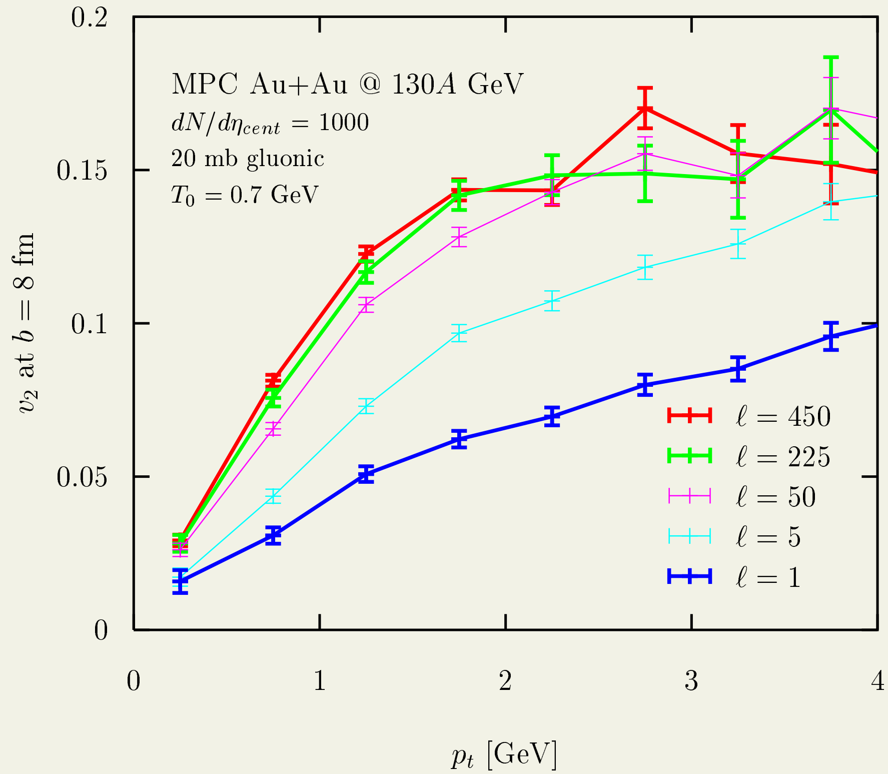
Parton subdivision

Naive $2 \to 2$ cascade nonlocal - action at distance $d < \sqrt{\frac{\sigma}{\pi}}$

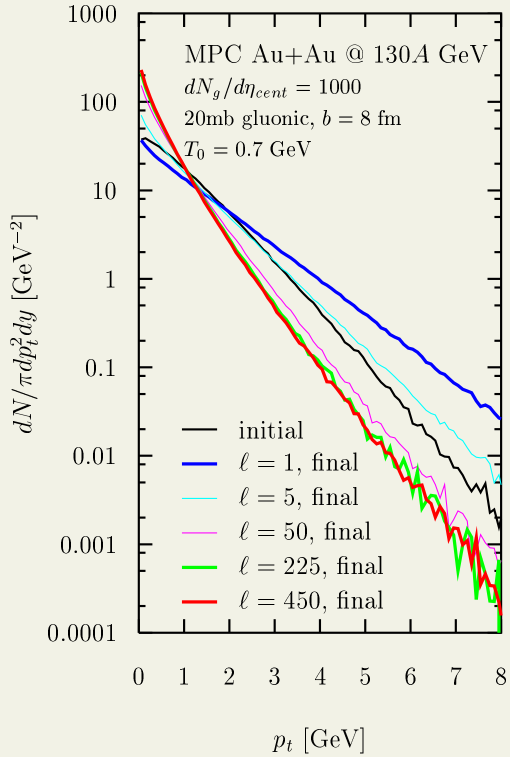


subdivision: rescale $f \to f \cdot \ell$, $\sigma \to \sigma/\ell$ $\Rightarrow$ $d \propto \ell^{-1/2}$ local as $\ell \to \infty$

DM & Gyulassy ('02): $v_2(p_T)$



spectra



at RHIC: need subdivision $\ell \sim 200$ to eliminate large artifacts

$\to$ computational challenge - CPU time scales as $\ell^{\sim 3/2}$ per run $\to$ barely fits on PC