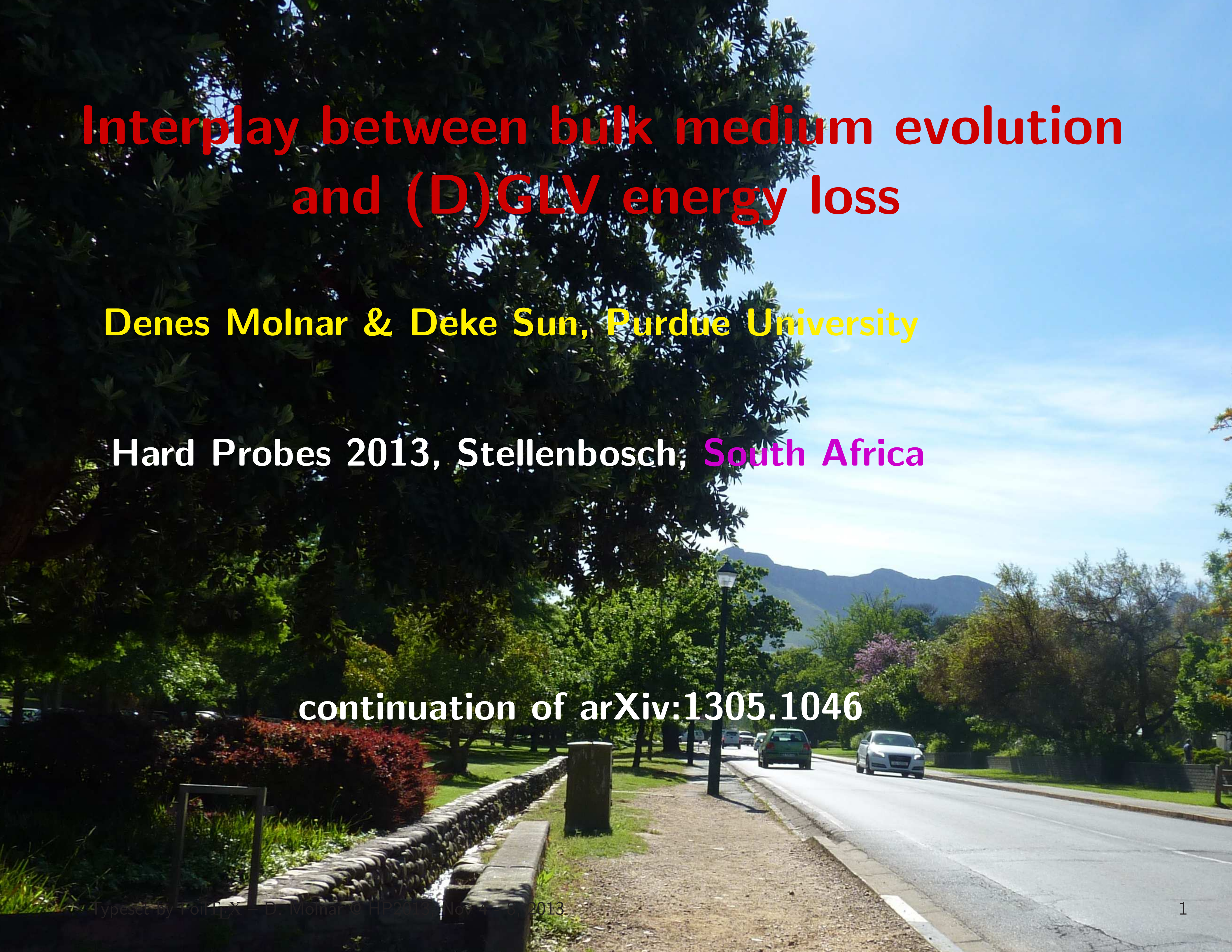


Interplay between bulk medium evolution and (D)GLV energy loss

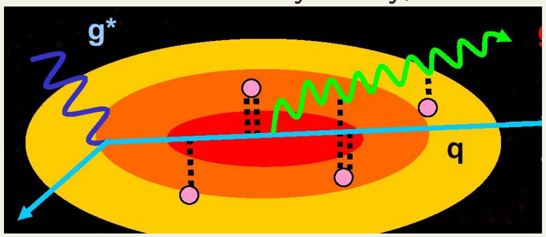
Denes Molnar & Deke Sun, Purdue University

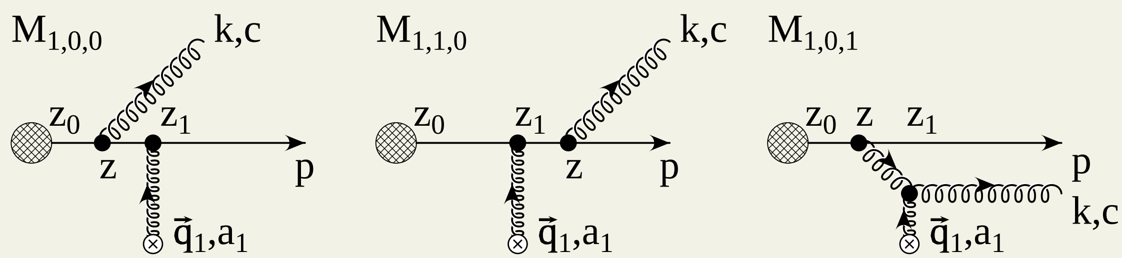
Hard Probes 2013, Stellenbosch, South Africa

continuation of arXiv:1305.1046

DGLV - opacity expansion

Gyulassy, Levai, Vitev NPB594 ('00)
Djordjevic PRC74 ('06)
Buzzatti & Gyulassy, PRL108 ('12)





$$x\frac{dN^{(1)}_{GLV}(L)}{dx\,d\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\chi\int\frac{d\mathbf{q}}{\pi}\,\frac{\mu^2}{\mathbf{q}^2(\mathbf{q}^2+\mu^2)}\frac{2\mathbf{Q}}{\mathbf{Q}^2+X}\left(\frac{\mathbf{Q}}{\mathbf{Q}^2+X}-\frac{\mathbf{k}}{\mathbf{k}^2+X}\right)(1-\cos\omega L)$$

$$\omega\equiv\frac{\mathbf{Q}^2+X}{2Ex}\,,\qquad \mathbf{Q}=\mathbf{k}+\mathbf{q}\,,\qquad X=x^2M^2+\frac{(1-x)\mu^2}{2}$$

usual challenge in practice: $\rho_i(\vec{x})\to\rho_i(\vec{x},t)$

we here use $\langle\Delta E^{(1)}\rangle=\int d\tau\,\rho(\tau,\vec{x}_{T,0}+\vec{v}\tau)\,\sigma_{gg\to gg}\,\chi^{-1}\,dx\,d\mathbf{k}\,E\;x\frac{dN^{(1)}_{GLV}}{dx\,d\mathbf{k}}$

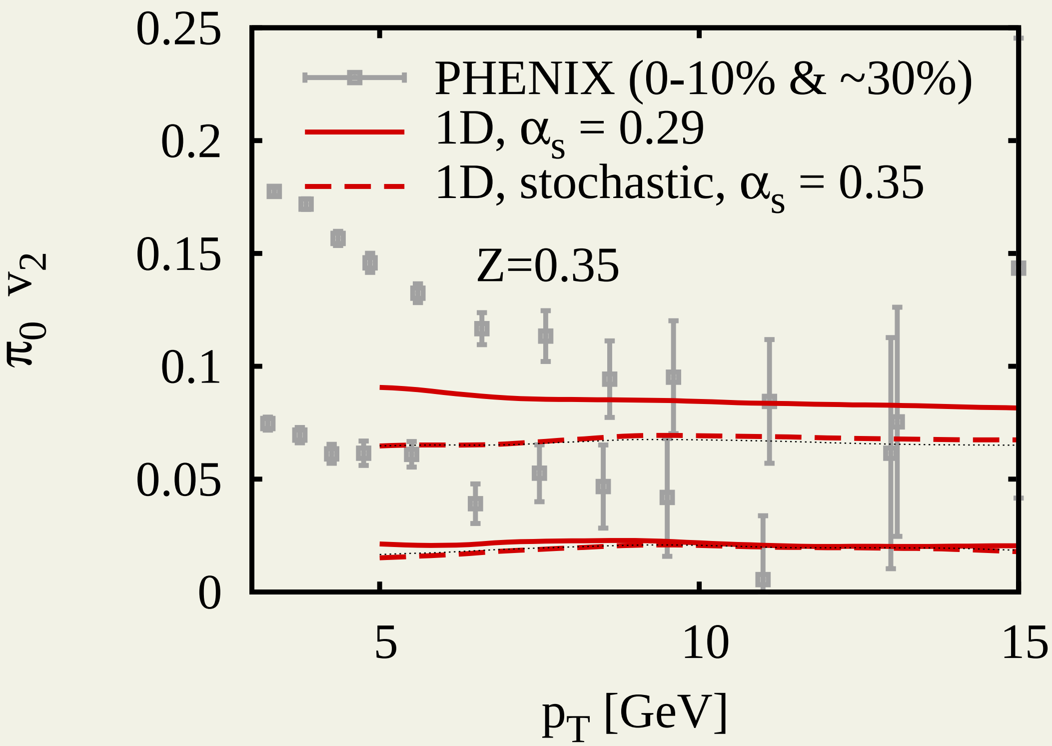
finite energy & kinematics $(|k|\lesssim xE,\ |q|\lesssim\sqrt{6ET},\ xE\gtrsim\mu)$

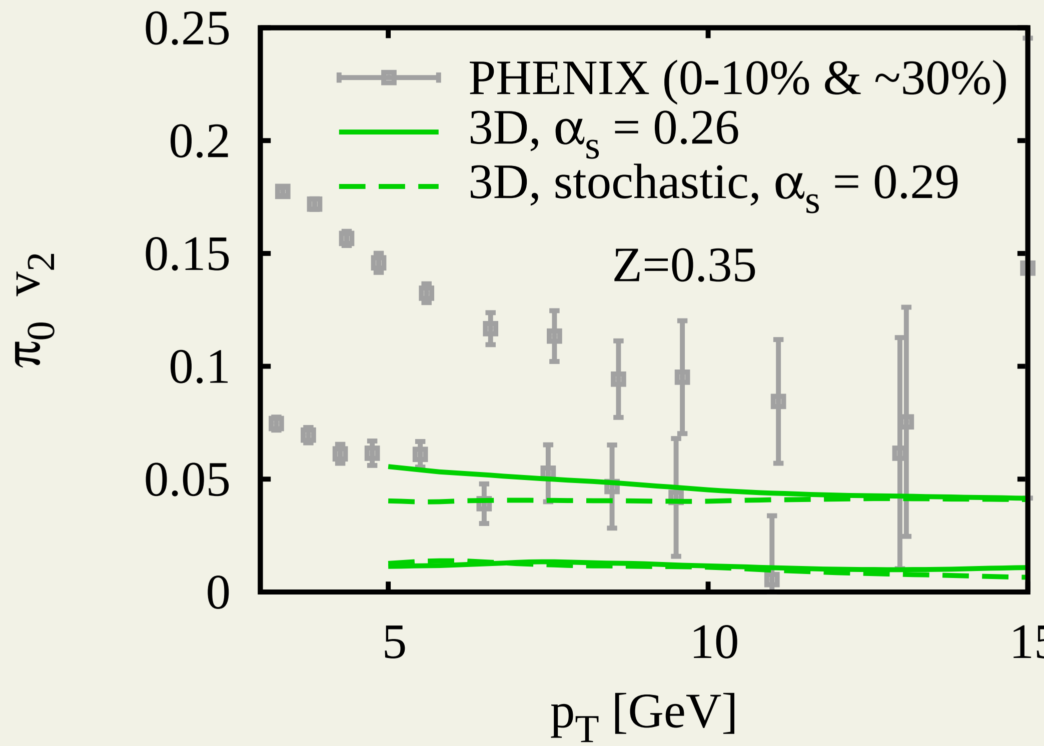
Motivation

HP2012: GLV gives much smaller v_2 with transversely expanding medium

DM & Sun 1305.1046:

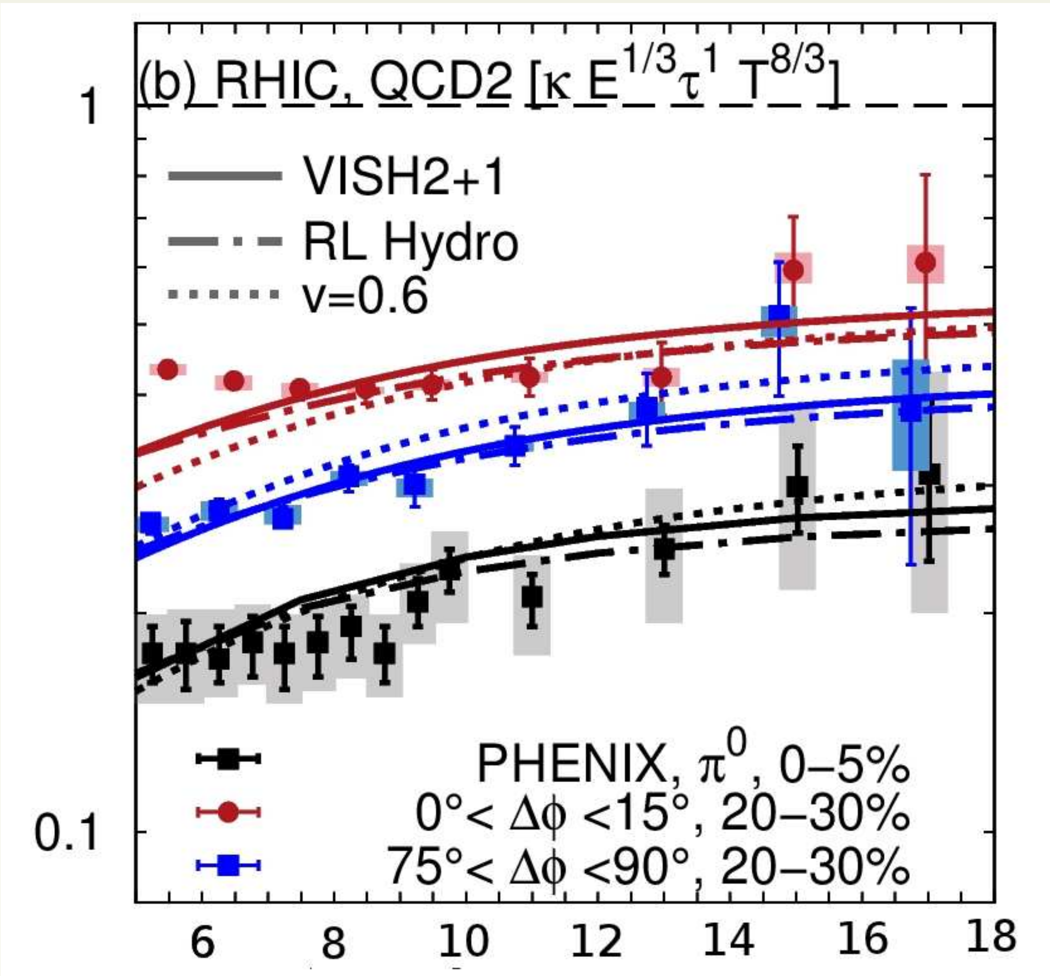
Bjorken expansion only vs **longitudinal + transverse expansion**





due to bias for late scattering $\Delta E \sim \int dL ... (1 - \cos \omega L)$

However, Betz & Gyulassy, 1305.6458: $R_{AA}(\phi)$ in 200-GeV Au+Au at RHIC



$$\frac{dE}{dL} = \kappa \frac{C_{jet}}{C_g} E^a L^b T^c(L)$$

"pQCD-like"

$$a = 1/3,\ b = 1,$$
$$c = 2 - a + b = 8/3$$

Not apples-to-apples

- **comparison to** $R_{AA}(\phi)$ **vs** R_{AA} **&** v_2

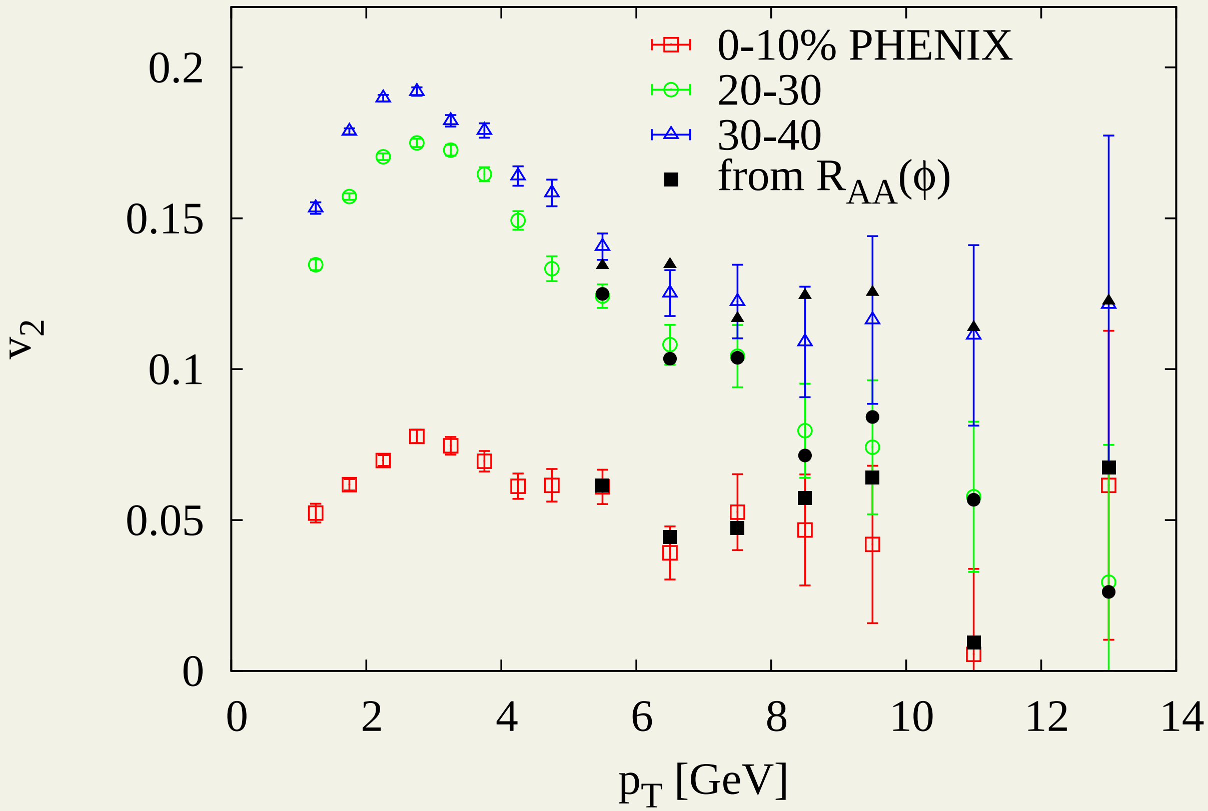
- **hydro vs** $2 \to 2$ **transport medium (**$e = 3p$**, conserved number)**

- **power-law** dE/dL **vs GLV energy loss**

...

$$\frac{dN_{AA}}{d^2p_T} = \frac{dN_{AA}}{2\pi\, p_T\, dp_T}(1+2v_2\cos 2\phi) \;\to\; R_{AA}(\phi,\Delta\phi) = R_{AA}\left(1 + 2v_2\cos 2\phi\,\frac{\sin\Delta\phi}{\Delta\phi}\right)$$

pion v_2 PHENIX PRL 105 ('10) **vs $R_{AA}(0,\pi/6)$, $R_{AA}(\pi/2,\pi/6)$** PHENIX PRC87 ('13)



$\Rightarrow$ **datasets are consistent**

Recheck results with four different hydro solutions...

from https://wiki.bnl.gov/TECHQM, computed VISH2+1 by OSU group

"older OSU" Song, Heinz, Moreland et al arXiv:0709.0742, 0712.3715, 0805.1756

i) ideal hydro, fKLN initial profile - "ideal fKLN"

ii) $\eta/s = 0.08$, fKLN profile - quite similar to i) in practice

"newer OSU" - Shen et al, arXiv:1010.1856; Renk et al, arXiv:1010.1635

iii) $\eta/s = 0.08$, Glauber profile - "visc. Glaub"

iv) $\eta/s = 0.08$, fKLN profile - "visc. fKLN"

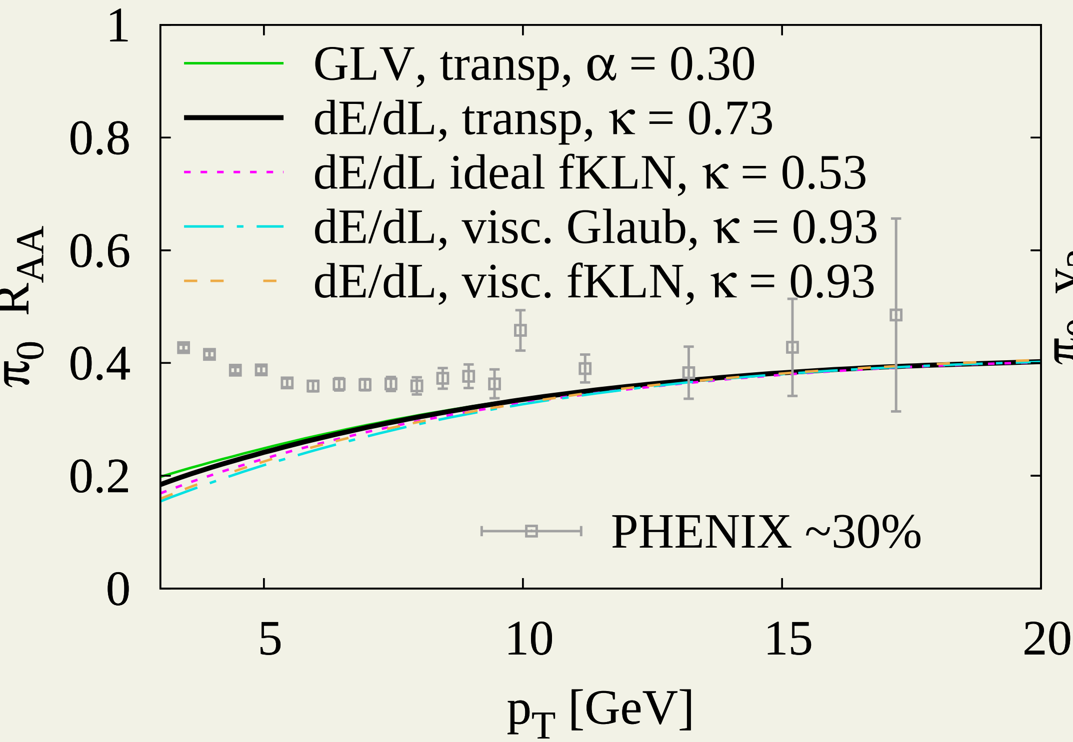
newer set has most realistic s95-PCE EOS by Huovinen & Petrecky

all cases Au+Au at fixed $b \approx 8$ fm, smooth geometry

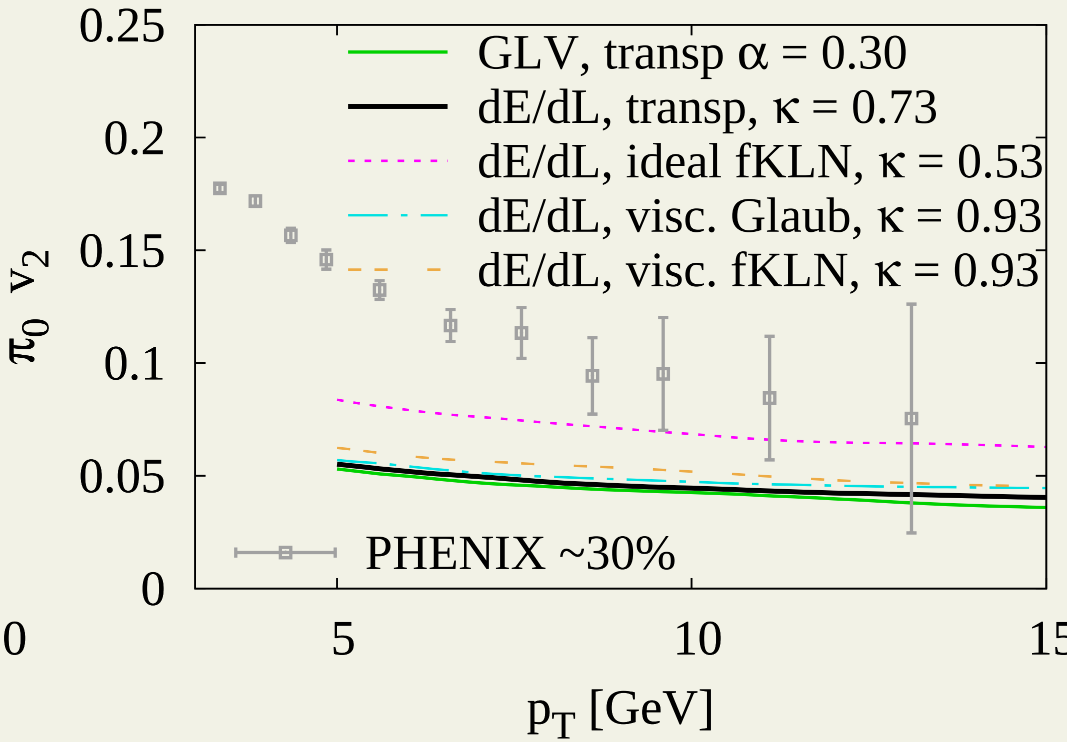
Start with dE/dL model

dE/dL model results for different media DM & Sun ('13)

R_{AA} - fitted



v_2 - result



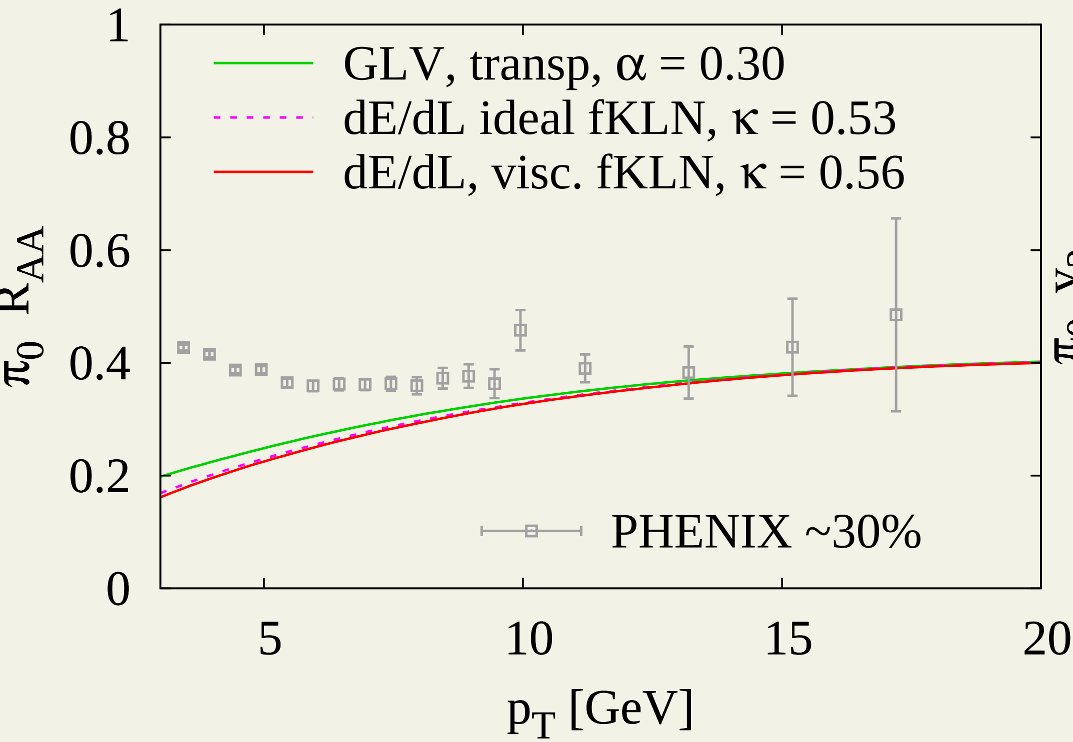
all medium models with dE/dL look very similar to GLV + transport

except "older" OSU hydro calculation that gives higher v_2

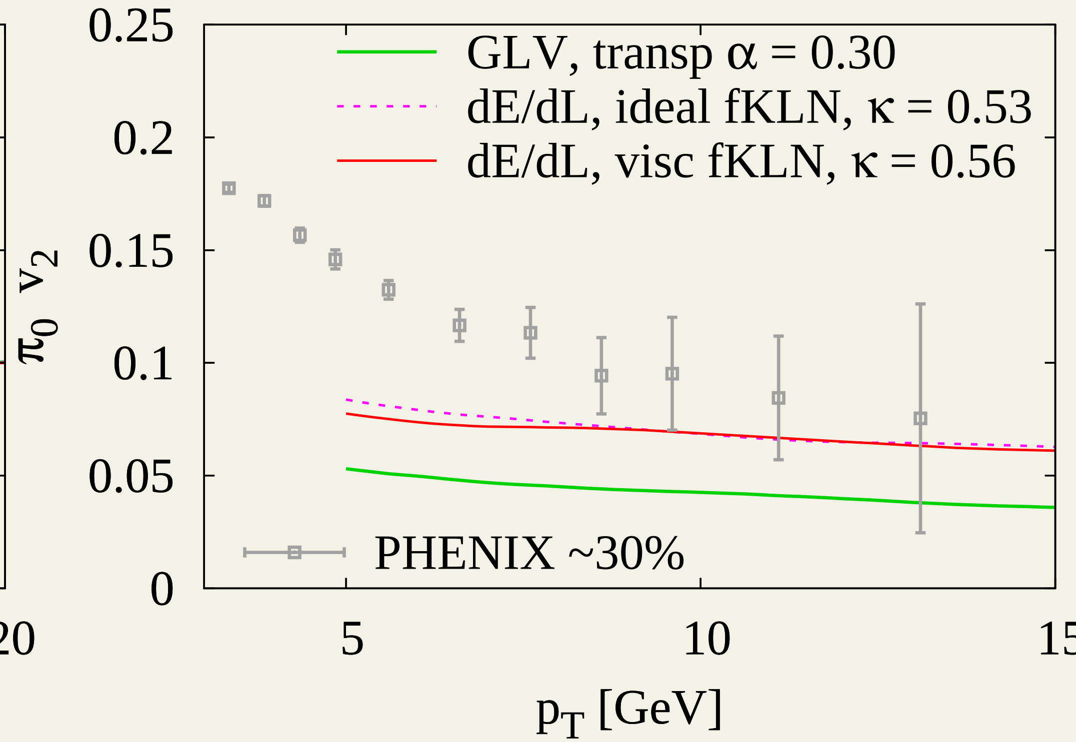
recheck "older OSU" profile with viscosity on, $\eta/s = 0.08$

R_{AA} - fitted

DM & Sun ('13)

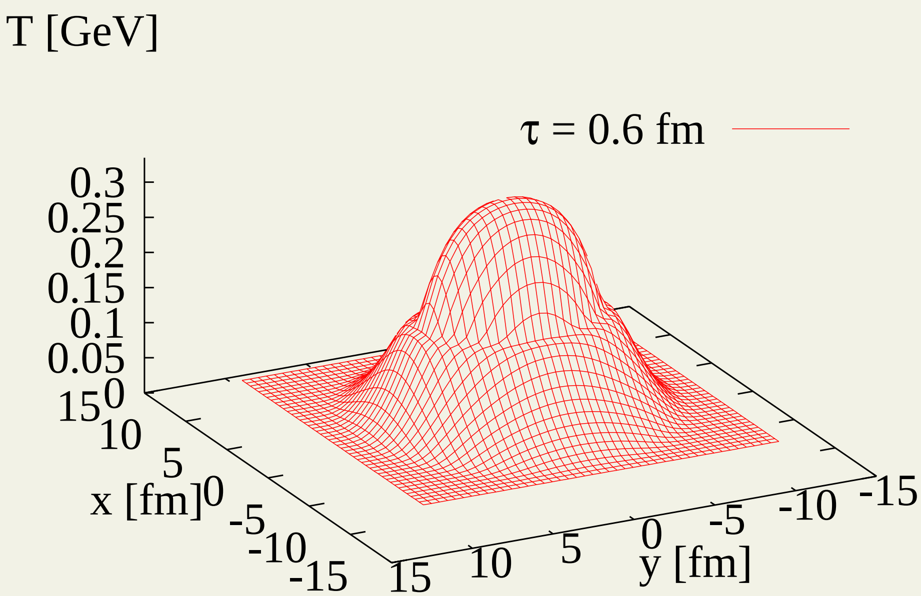


v_2 - result

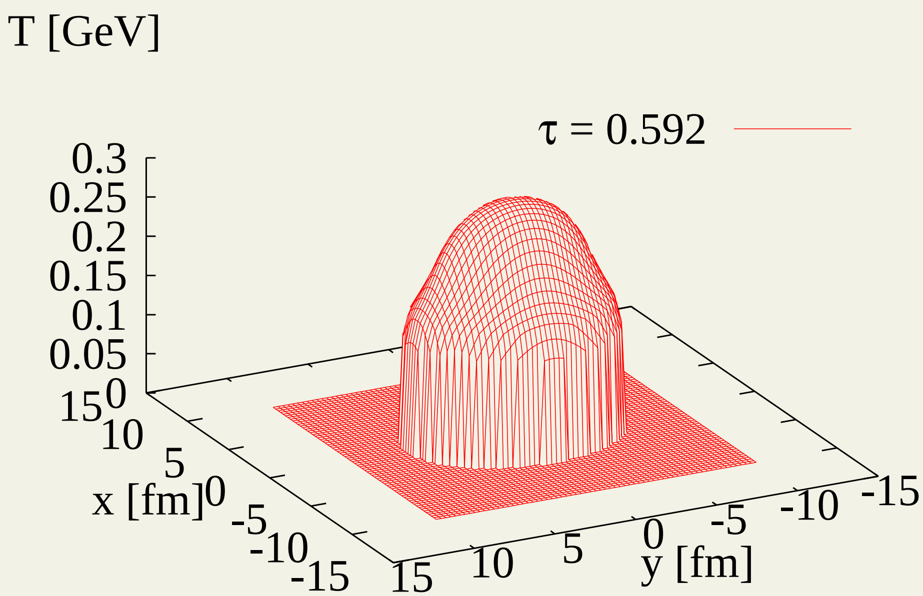


after κ adjusted to match R_{AA}, we get much the same(!) v_2

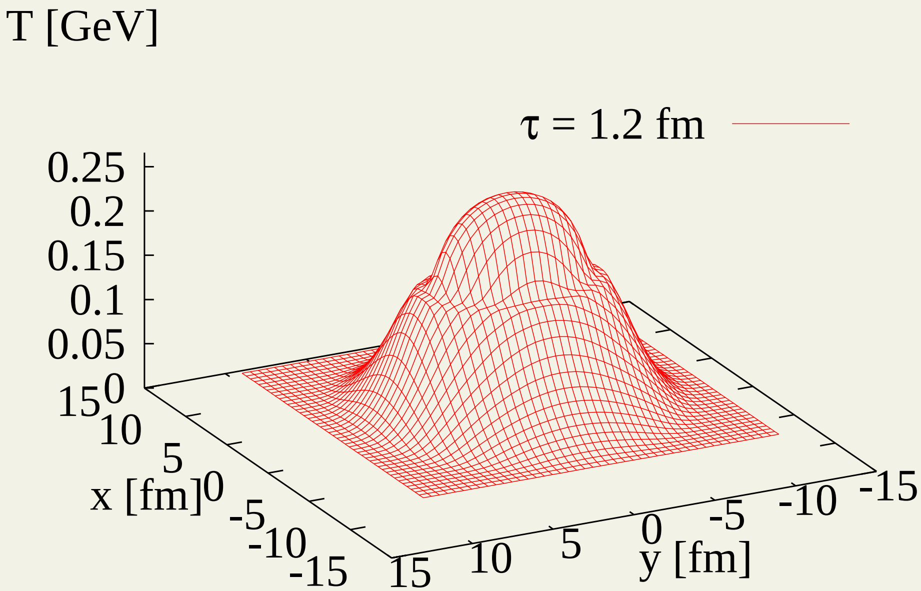
“old OSU”, fKLN, ideal

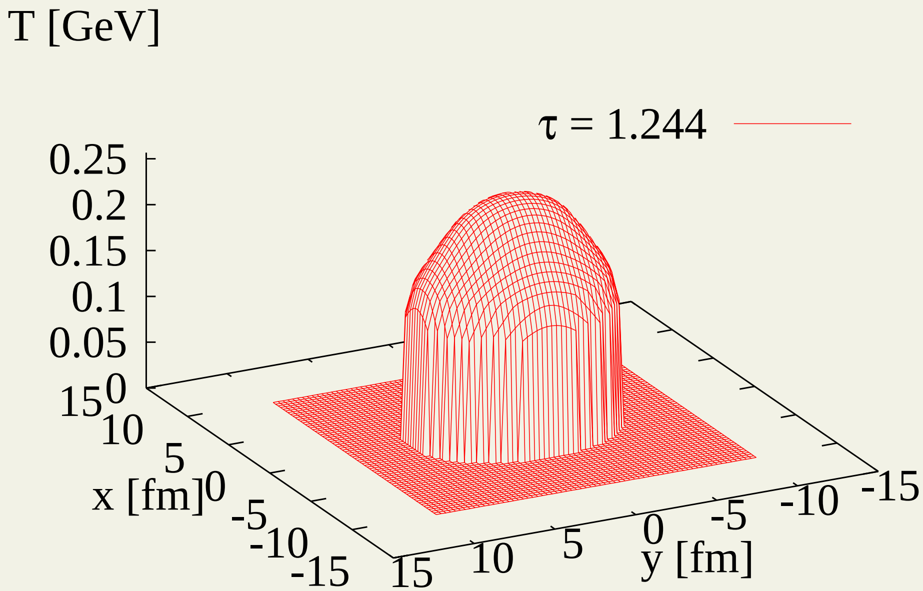


“new OSU”, fKLN, $\eta/s = 0.08$

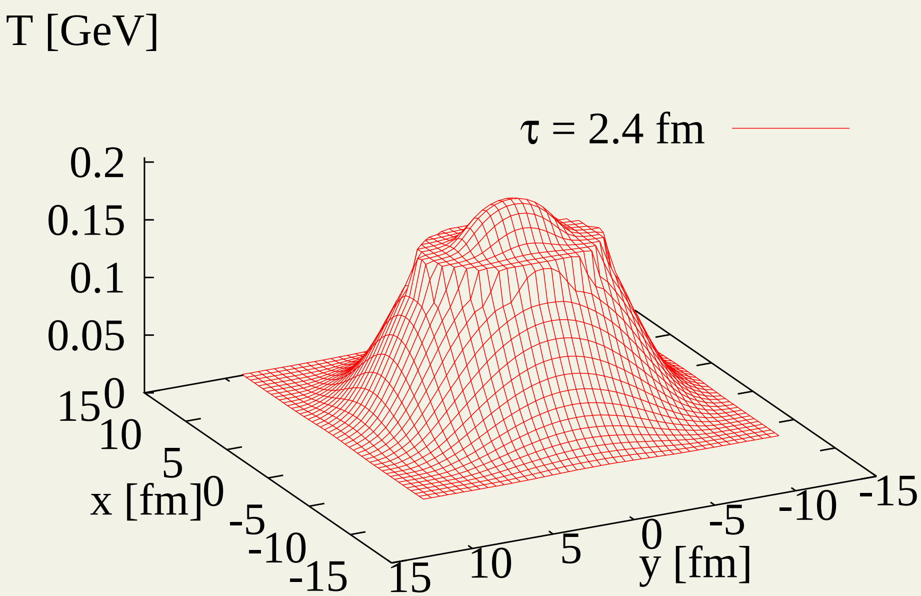


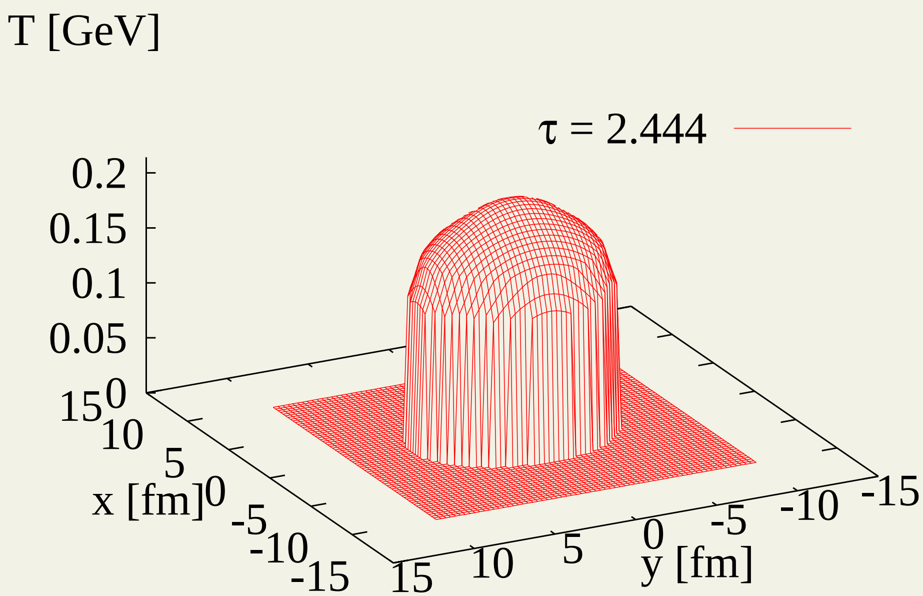
"old OSU", fKLN, ideal **"new OSU", fKLN, $\eta/s = 0.08$**



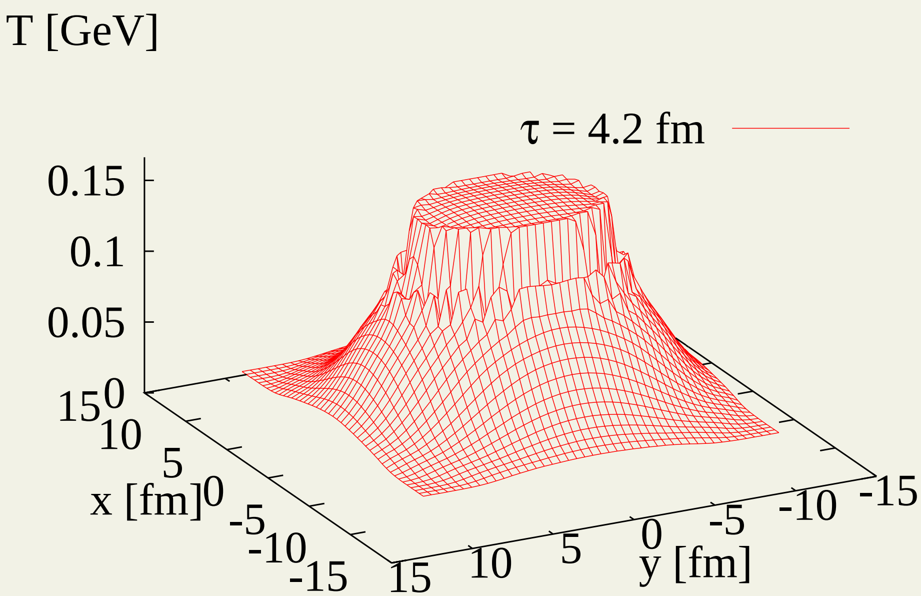


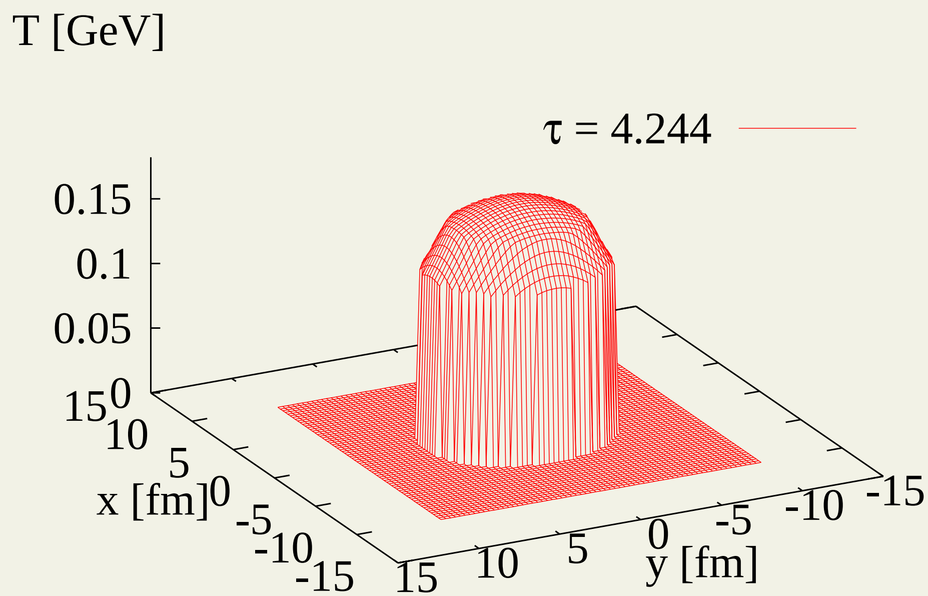
“old OSU”, fKLN, ideal **“new OSU”, fKLN, $\eta/s = 0.08$**





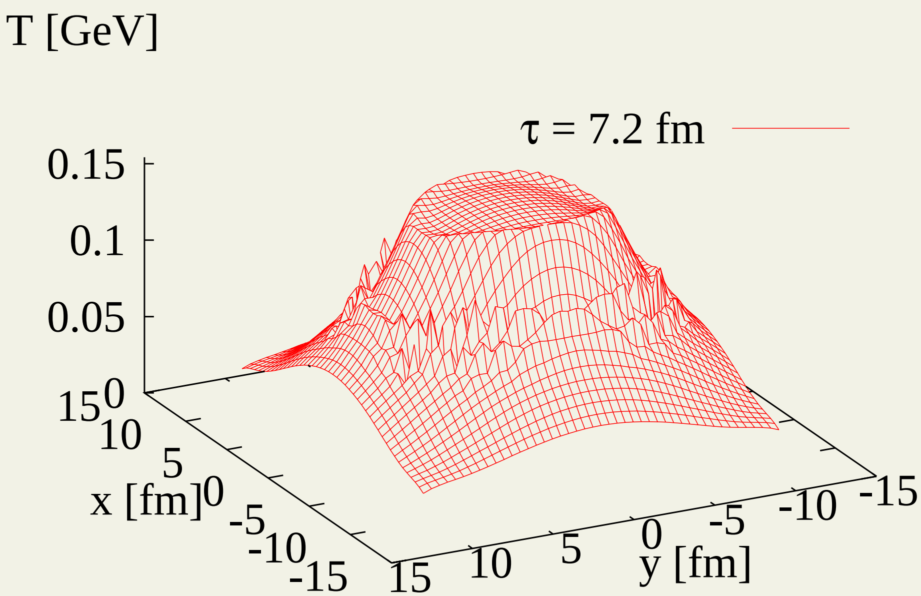
“old OSU”, fKLN, ideal   “new OSU”, fKLN, $\eta/s = 0.08$

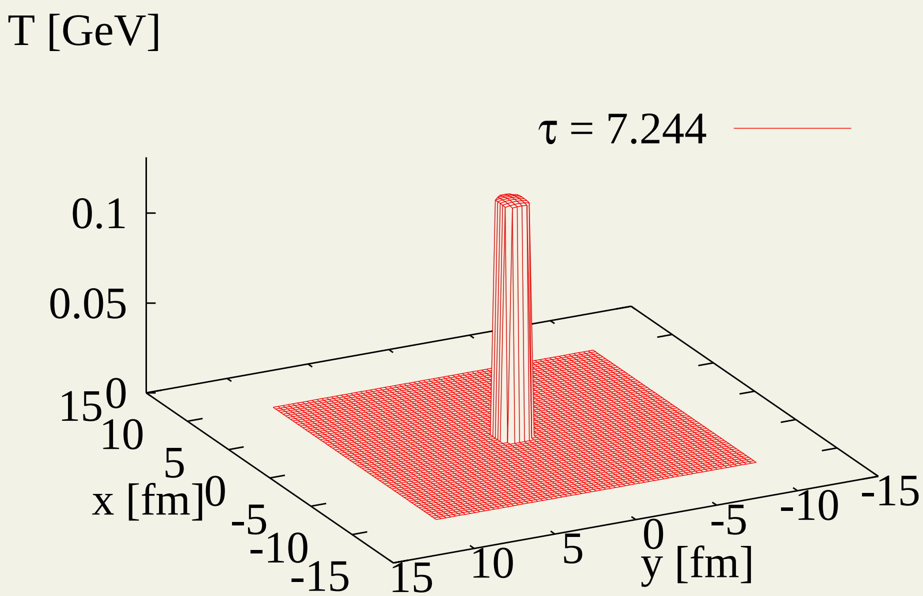




“Table Mountain”   vs   “basalt dome”

“old OSU”, fKLN, ideal **“new OSU”, fKLN, $\eta/s = 0.08$**

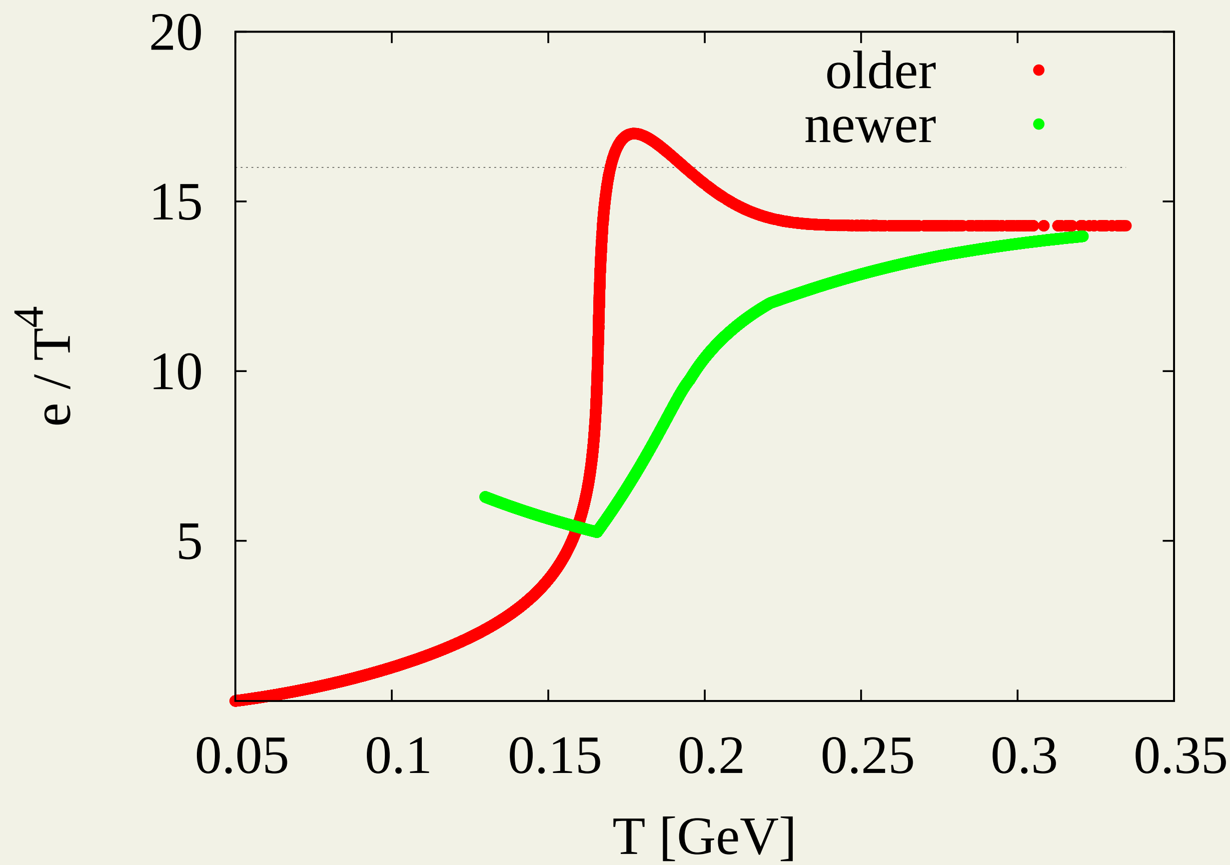




(new dataset strictly contains only $T \geq 130$ MeV points)

older set: smoothed Bag Model EoS (SM-EOSQ)

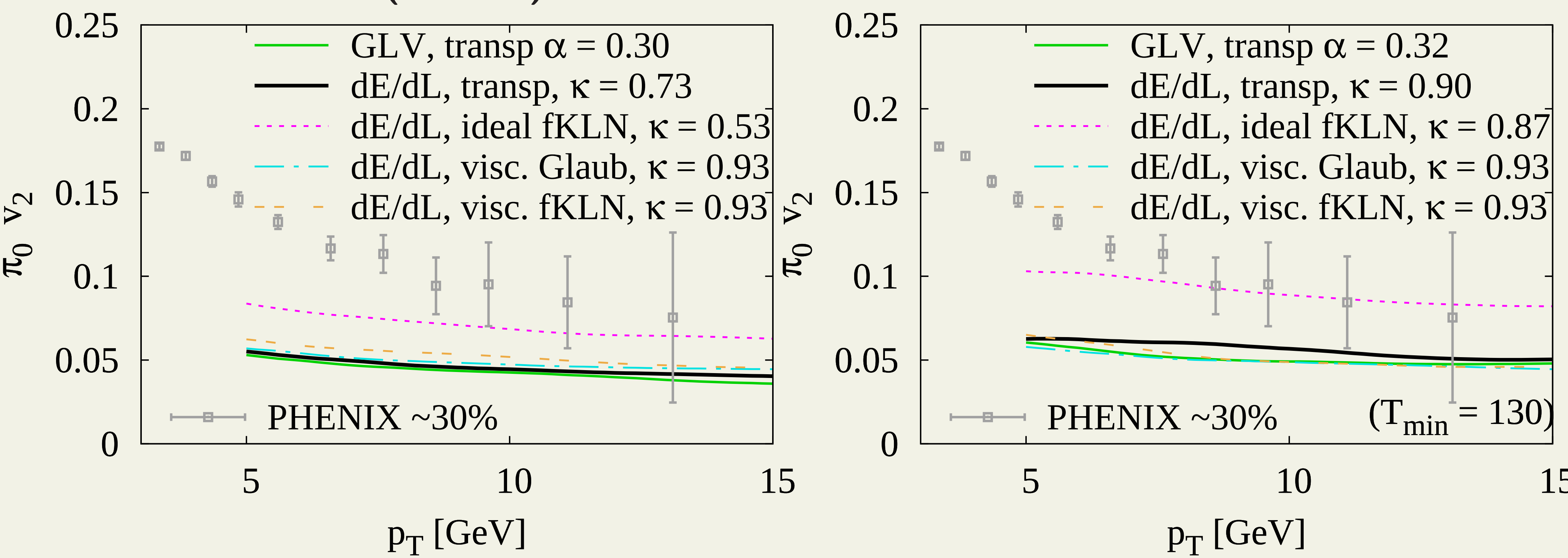
newer set: lattice QCD merged onto hadron gas (s95-PCE)



sensitivity to $T > T_{min}$ cutoff of line integrals

DM & Sun ('13)

$T > 100$ **MeV (default)** vs $T > 130$ **MeV**



matters little, except for "older OSU" grids

but those are missing evolution when $130 > T_{center} > 100$ **MeV..**

Covariance

Problem: $dE/dL = const \times E^a L^b T^c$ **encodes frame dependent physics**

Suppose holds in fluid rest frame ($u_{LR} = (1, \vec{0})$**), rewrite it in covariant form**

$$E_{LR} \to p^\mu u_\mu = p \cdot u \ , \quad \Delta E_{LR} \to \Delta p \cdot u \ , \quad \Delta L_{LR} \to \sqrt{-(\Delta L - (u \cdot \Delta L) u)^2}$$

where $\Delta L^\mu = (L^0, \vec{L}) = \Delta t (1, \vec{v})$**,** $\qquad u^\mu = \gamma_F (1, \vec{v}_F)$

For massless particles ($|\vec{v}| = 1$**)**

$$\Delta E_{LR} = \Delta E \, \gamma_F (1 - \vec{v}\vec{v}_F)$$

$$\Delta L_{LR} = \Delta L \, \gamma_F (1 - \vec{v}\vec{v}_F)$$

so covariantly

$$\frac{dE}{dL} = \frac{dE_{LR}}{dL_{LR}} = \kappa \left[\gamma_F (1 - \vec{v}\vec{v}_F)\right]^{a+b} E^a L^b T^c$$

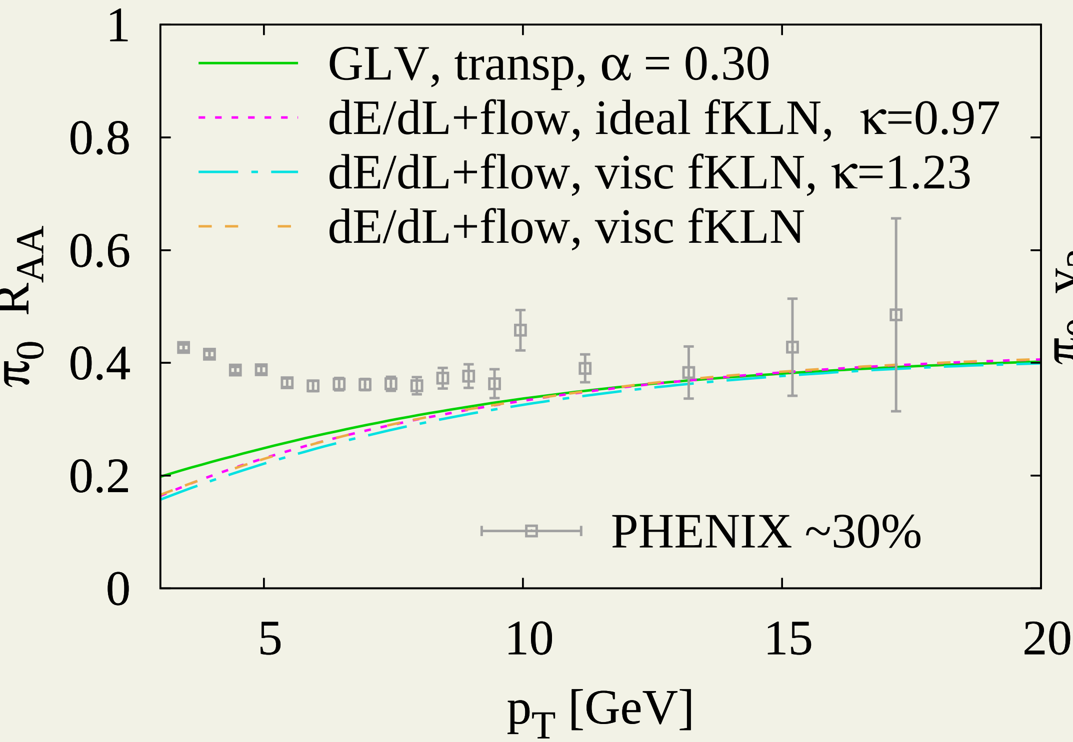
$\Rightarrow$ **couples E-loss and medium flow**

similar effect argued, e.g., in Baier, Mueller, Schiff nucl-th/0612068v3

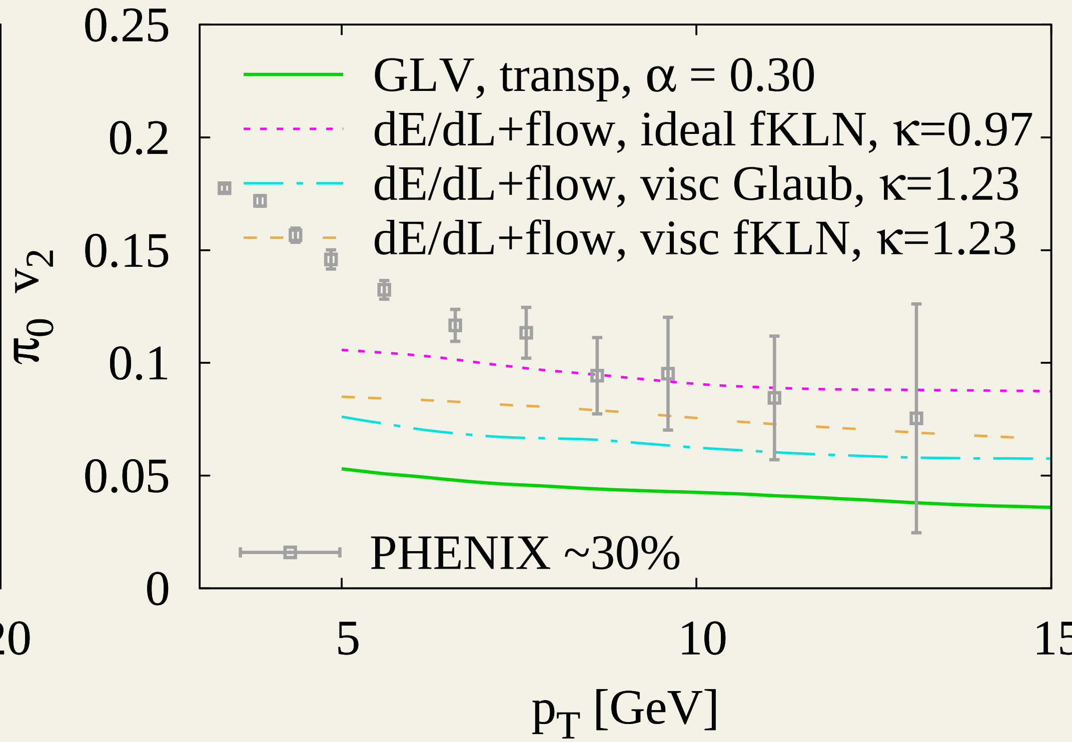
covariant dE/dL - flow effect

R_{AA} - fitted

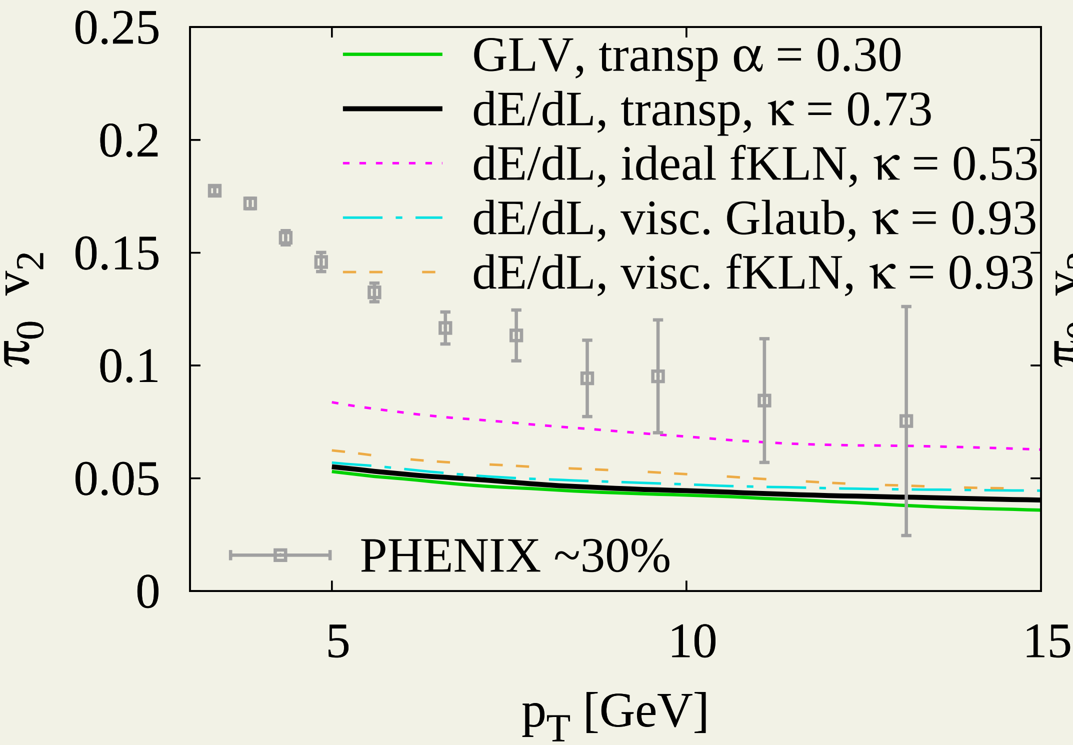
DM & Sun ('13)

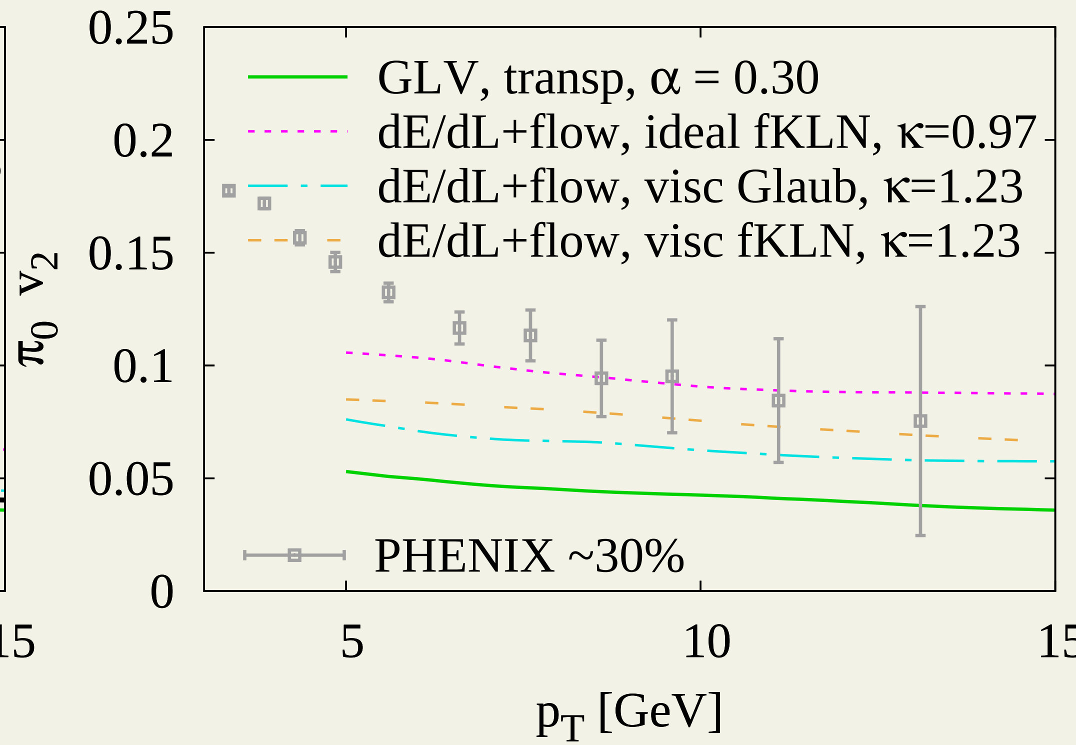


v_2 - result



“vanilla” dE/dL vs **covariant dE/dL**





need larger κ to match R_{AA}, but also get larger v_2

Now check GLV

- **hydro medium vs transport medium**

  set $\rho = e/(3T)$ **from hydro (other possibilities:** $\rho \sim e^{3/4}$**,** $\rho \sim T^3$**, ...)**

- **frame dependence**

$$\Delta E = \frac{C_R \alpha_s}{\pi^2} \int dL \, \rho \, \sigma_{gg\to gg} \, I\left(\frac{\mu^2 L}{E}, \frac{E}{\mu}, \frac{M}{\mu}\right)$$

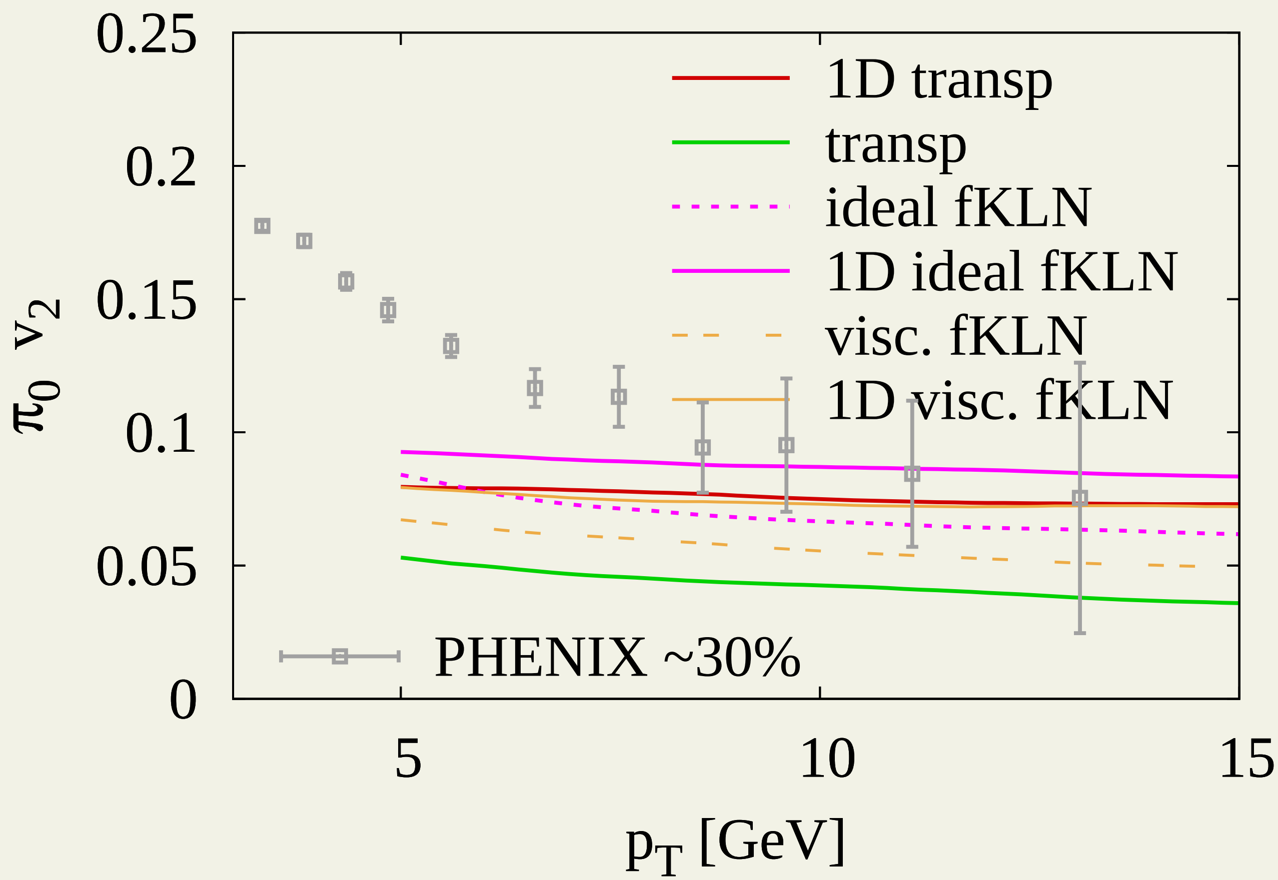
based on earlier discussion: L/E **is invariant**

and covariantly (for massless at least)

$$dL_{LR} \, \rho_{LR} \, \sigma = dL \, \rho_{LR} \, \sigma \, \gamma_F (1 - \vec{v}\vec{v}_F) = dL \, \rho \, \sigma \, (1 - \vec{v}\vec{v}_F)$$

1D vs 3D still matters with naive GLV

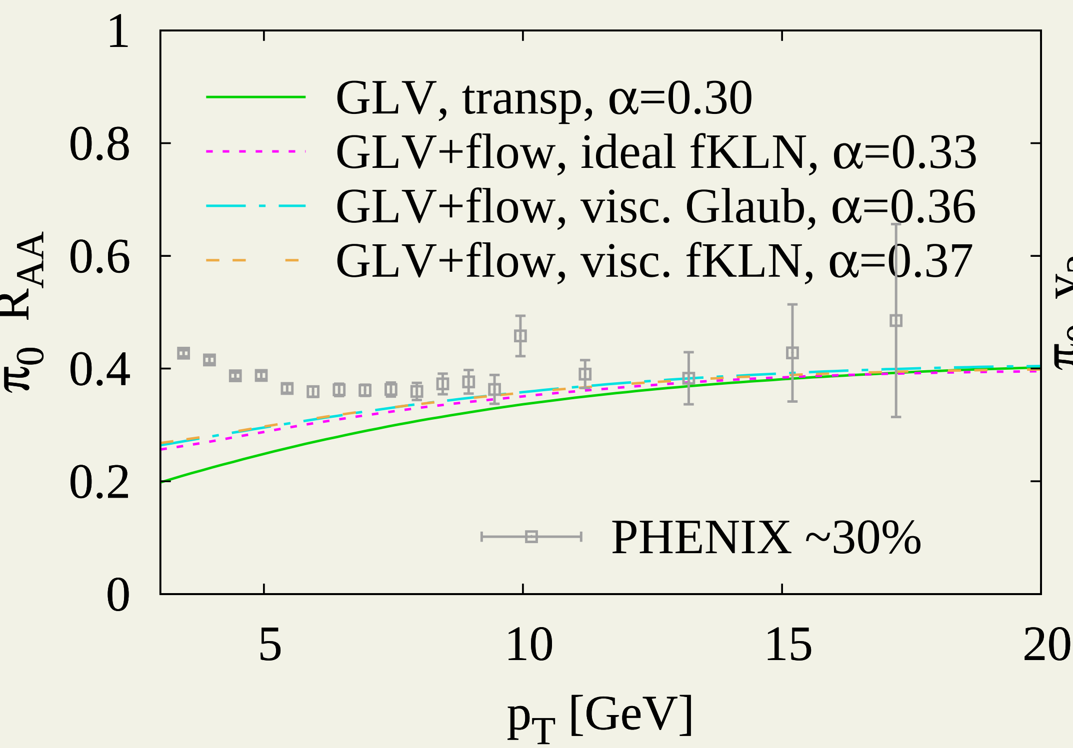
DM & Sun ('13)



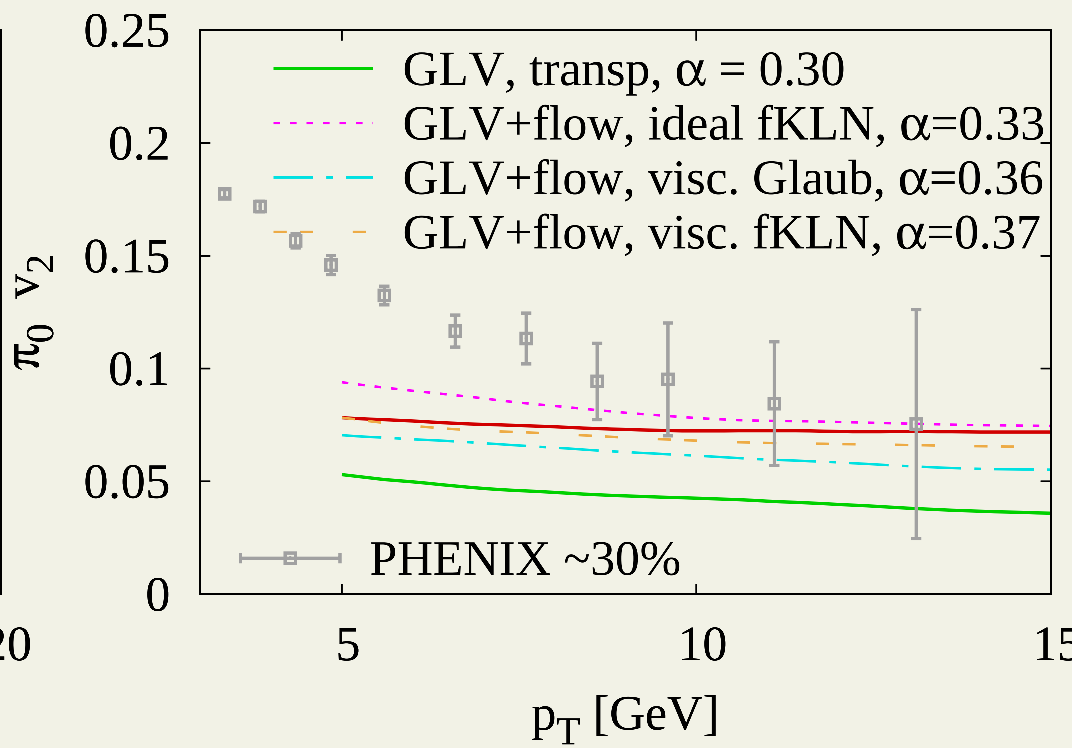
covariant GLV - flow effect

R_{AA} - fitted

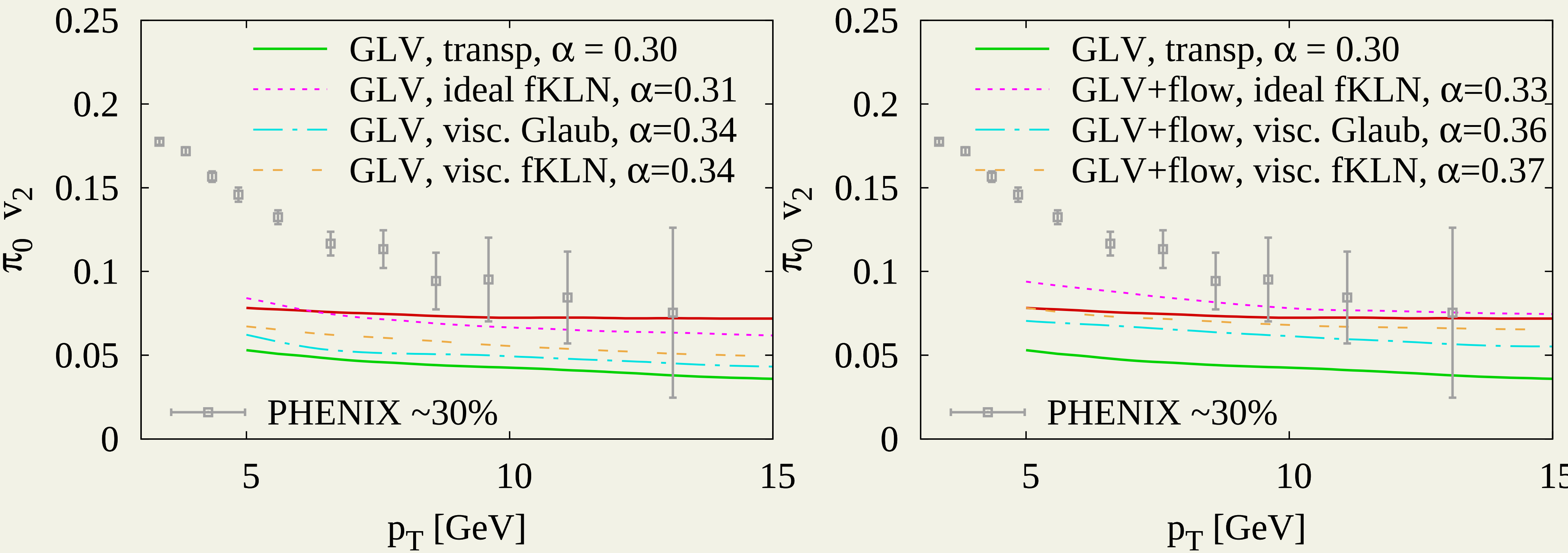
DM & Sun ('13)



v_2 - result



“vanilla” GLV **vs** **covariant GLV**



hydro media give more v_2 than transport medium

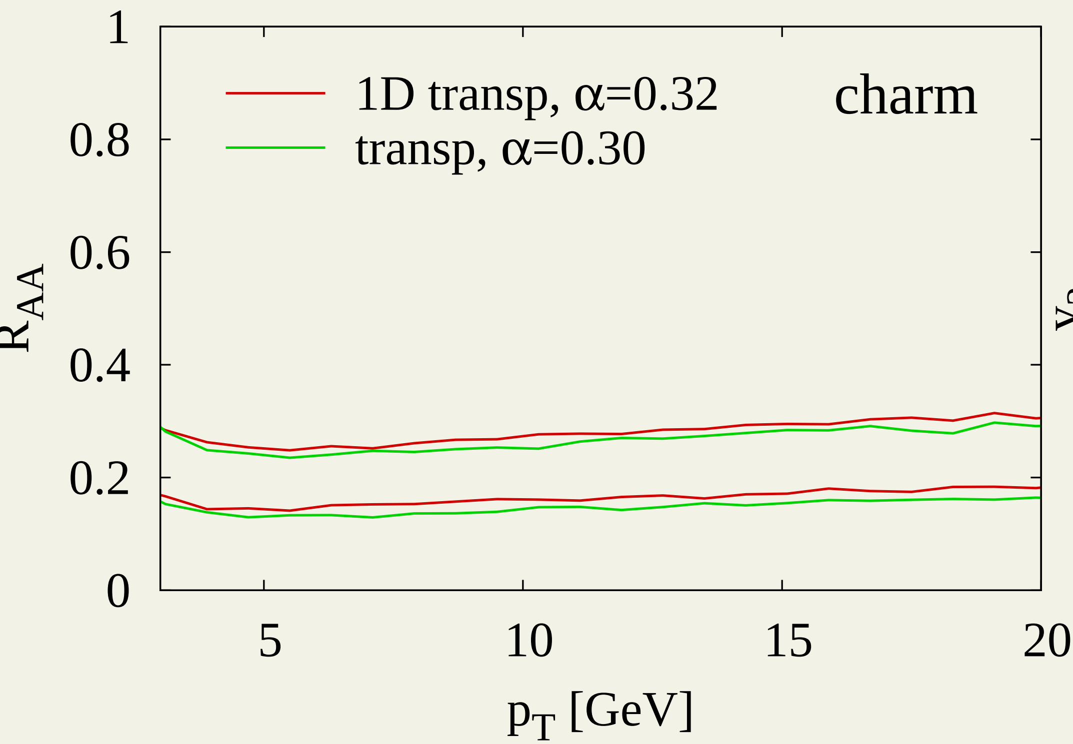
additional v_2 increase through Eloss-flow coupling (covariant Eloss)

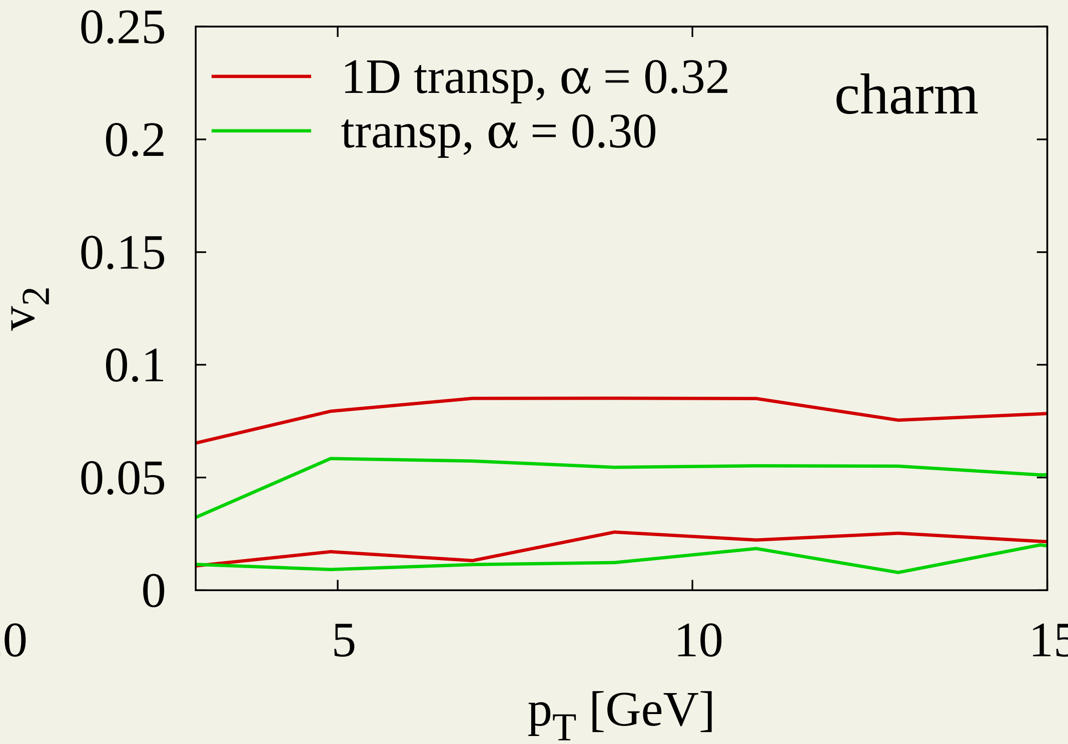
charm from DGLV - parameters fixed by light sector

R_{AA} - result

v_2 - result

DM & Sun ('13)

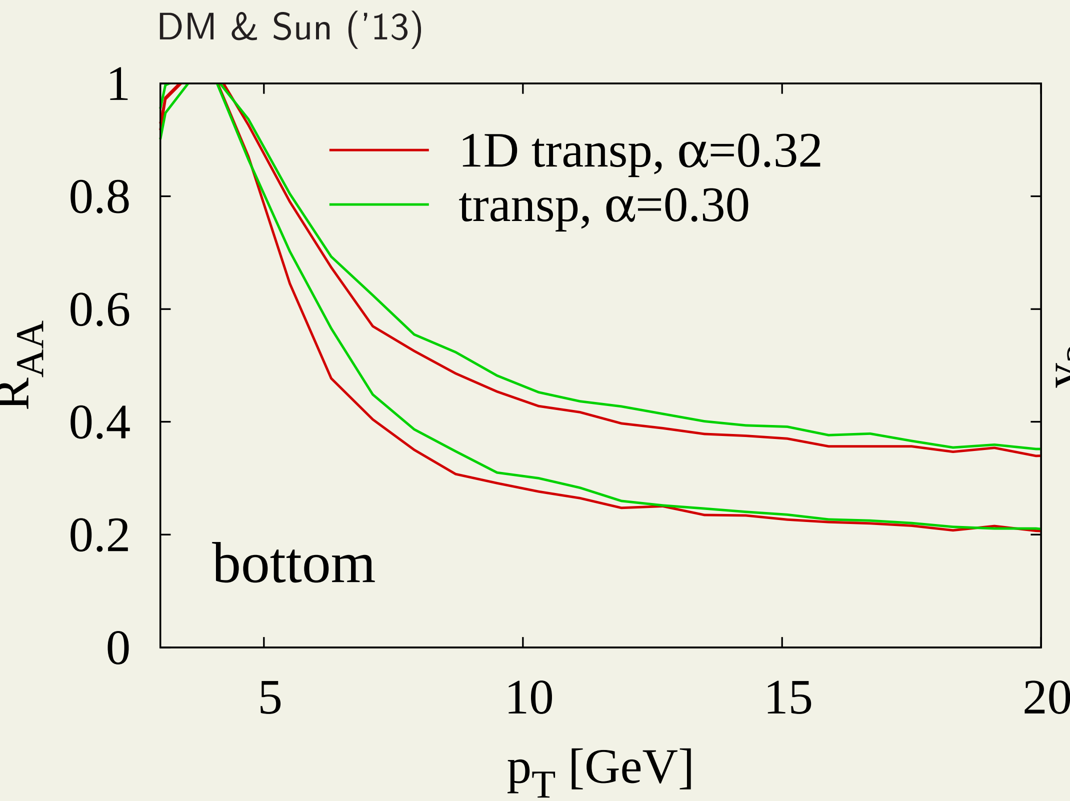


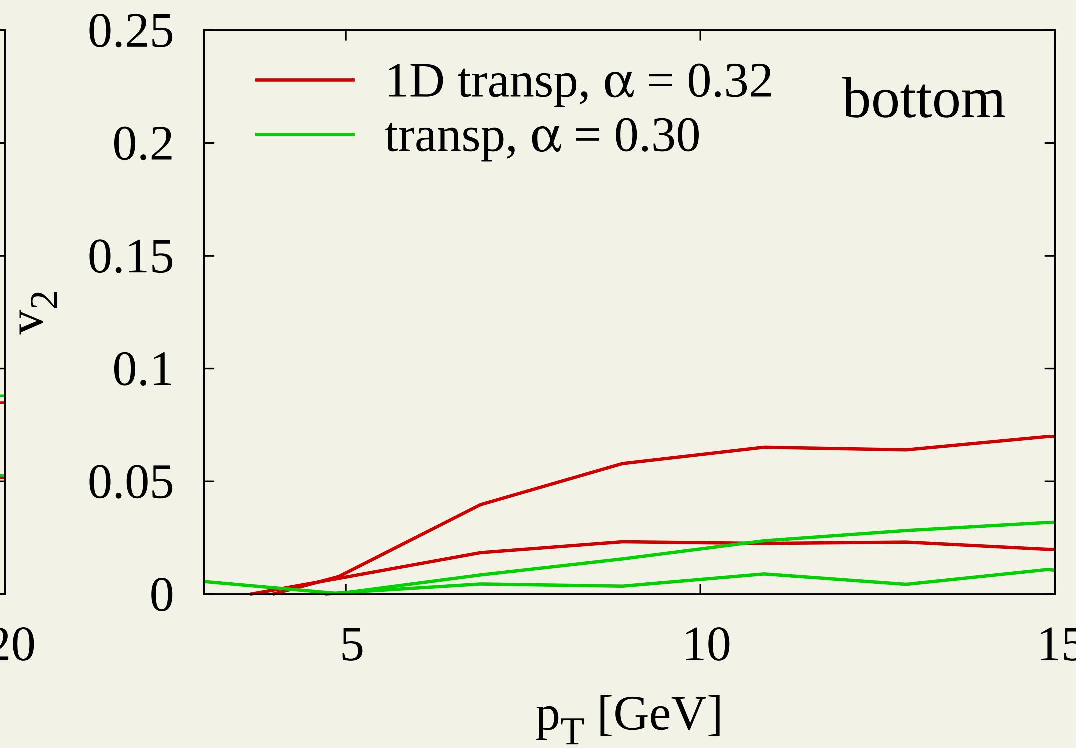


bottom from DGLV - parameters fixed by light sector

R_{AA} - result

v_2 - result



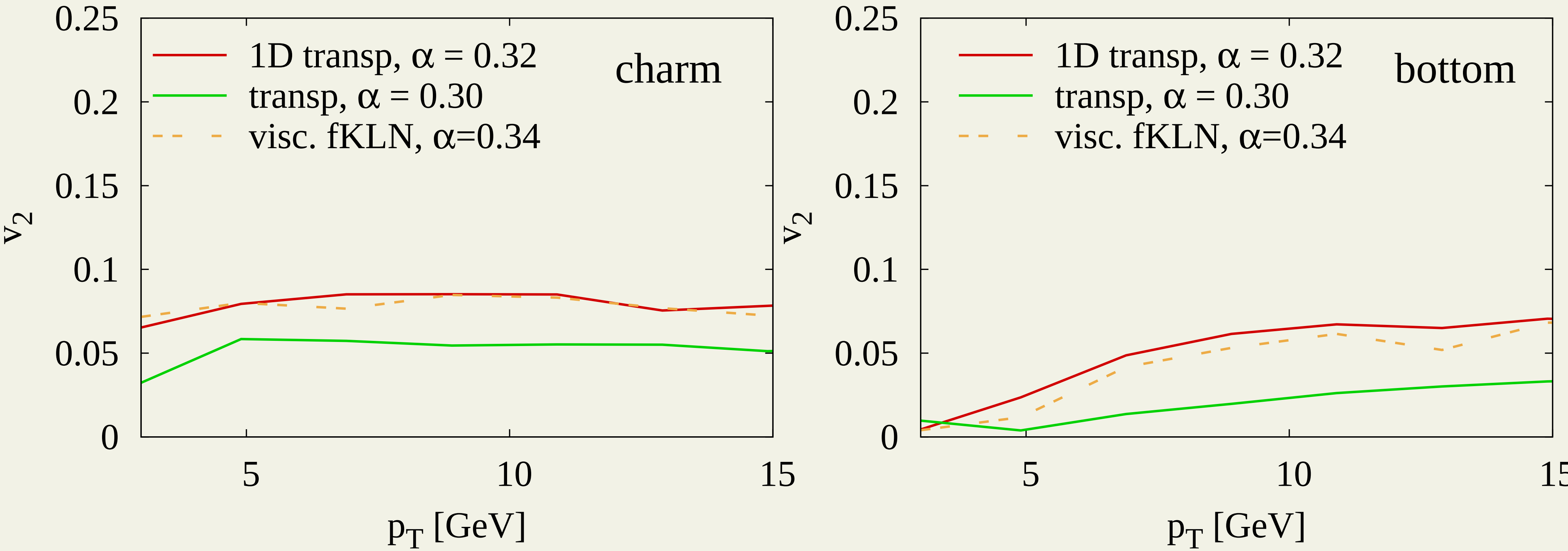


Steps in progress:

- **heavy quark Eloss results with hydro medium evolution**

- **Eloss-flow coupling for heavy quarks**

VERY preliminary: hydro vs transport medium matters more



Summary

We investigated GLV radiative energy loss and the power law dE/dL model by Betz et al at RHIC using various bulk medium models ($2 \to 2$ transport and hydro).

With parameters set to reproduce R_{AA}, both models give about the same v_2 for a variety transport and hydro backgrounds, with the one exception of larger v_2 for hydro with smoothed bag model equation of state (SM-EOSQ).

Frame-independent formulation of dE/dL or GLV gives rise to coupling between flow and energy loss through $(1-\vec{v}_{jet}\vec{v}_{fluid})$ factors. These generally increase elliptic flow, largely compensating for v_2 reduction seen earlier due to interference bias towards later scatterings. We see indication that this interplay depends on quark mass.

Some future steps:

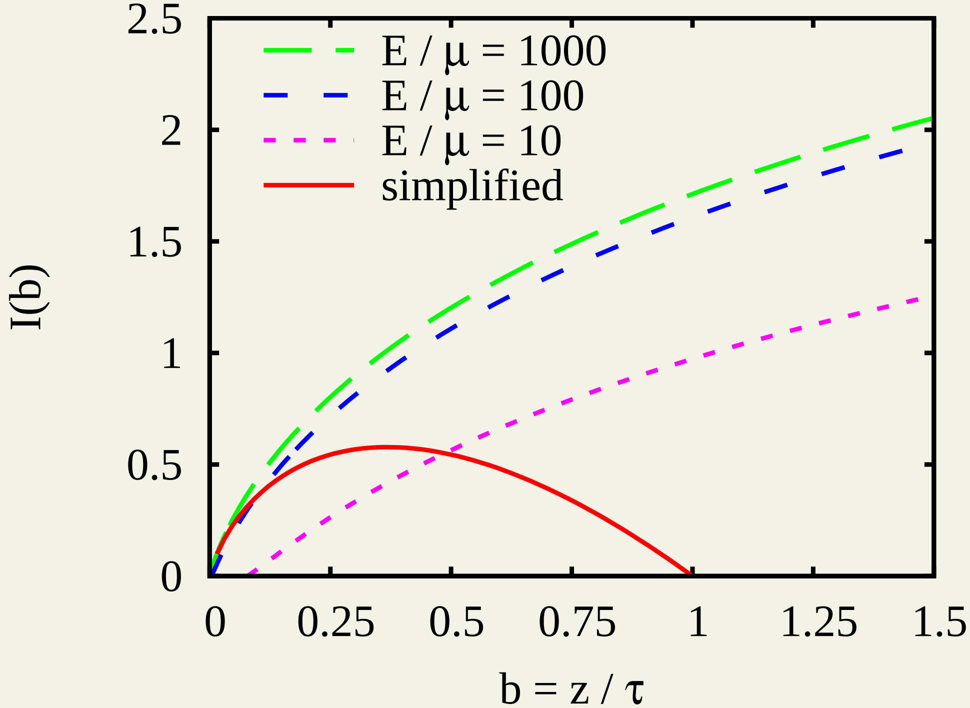
- heavy quark observables
- cross-check at LHC energies
- refine E-loss treatment (fluctuations, elastic, $\alpha_s(Q^2)$...)

Backup slides

Finite energy & kinematics also matter:

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

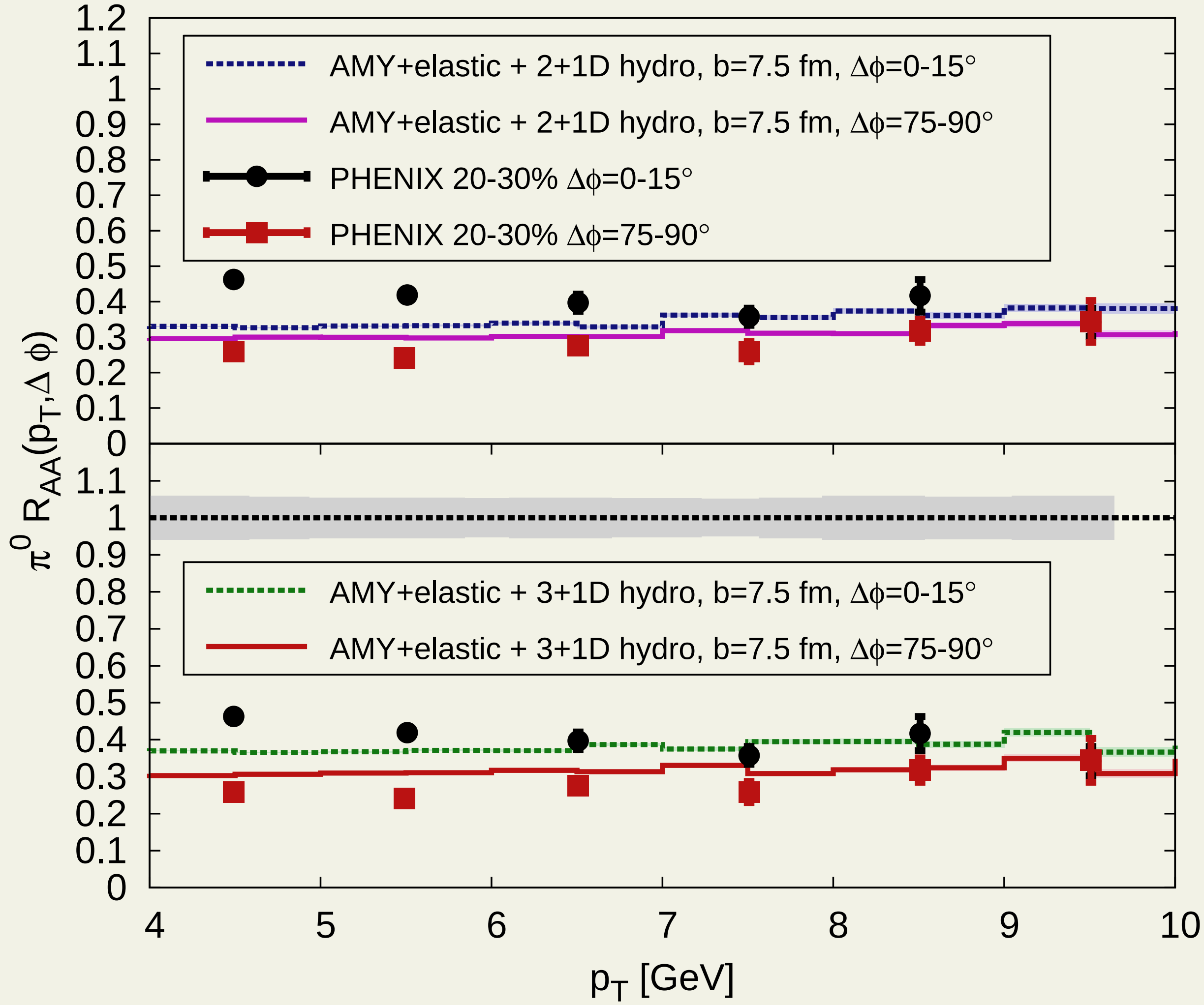
$$\Delta E^{(1)}_{GLV}(z) \;=\; \frac{C_R\alpha_s}{\pi^2}\chi \int dx\, d\mathbf{k}\, d\mathbf{q}\, \frac{\mu^2}{\pi(\mathbf{q}^2+\mu^2)^2}\frac{2\mathbf{k}\cdot\mathbf{q}}{\mathbf{k}^2(\mathbf{k}-\mathbf{q})^2}(1-\cos\omega\Delta z)$$
$$\equiv\; \frac{2C_R\alpha_s}{\pi} E\,\chi\, I(\Delta z/\tau(z),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



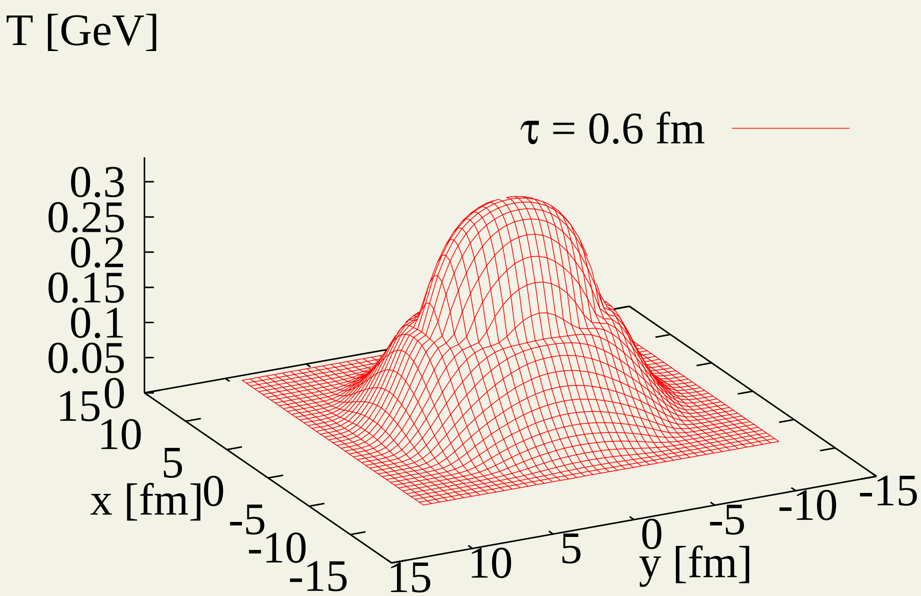
$$\tau(z) \equiv \frac{2E}{\mu^2(z)}$$

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

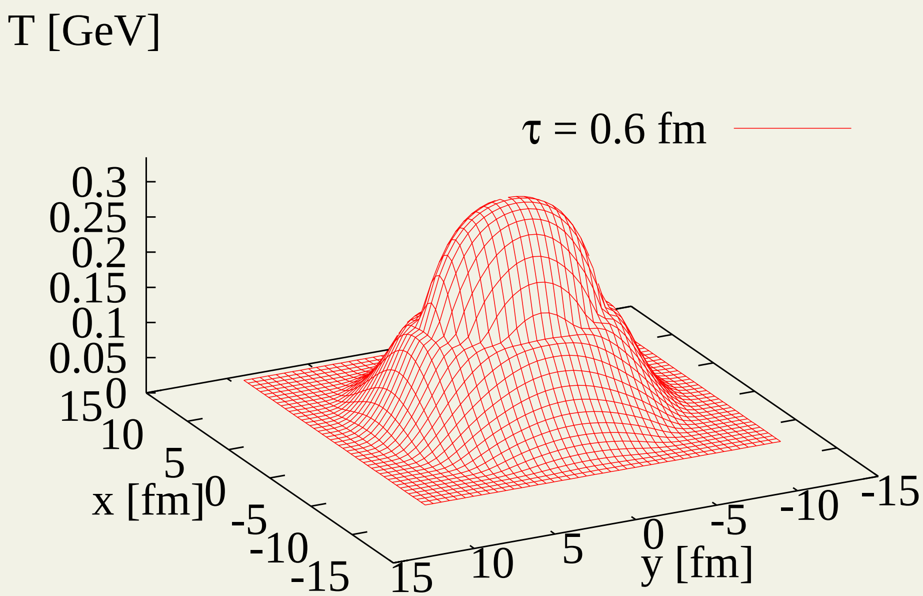
MARTINI $R_{AA}(\phi)$ Schenke et al, PRC80 ('09):



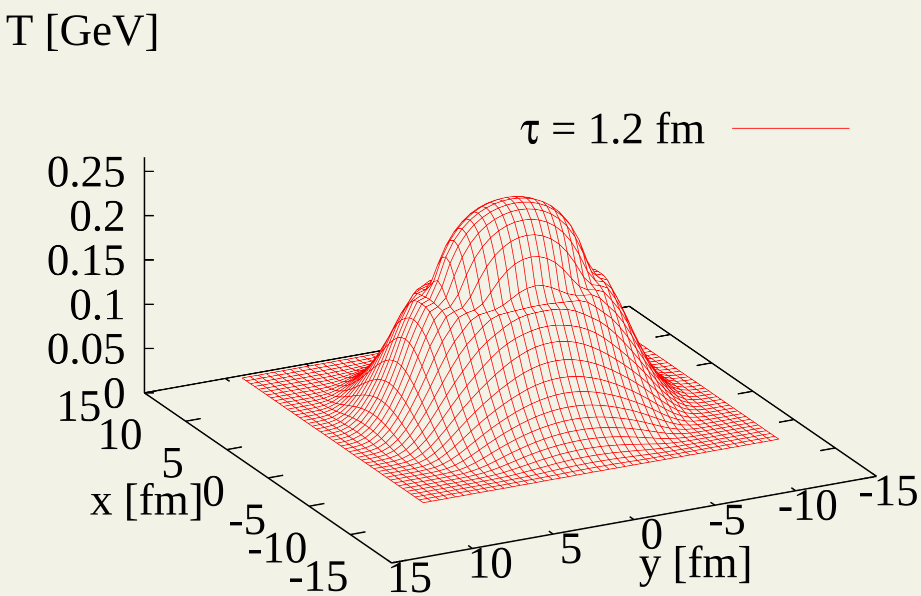
“old OSU”, fKLN, ideal



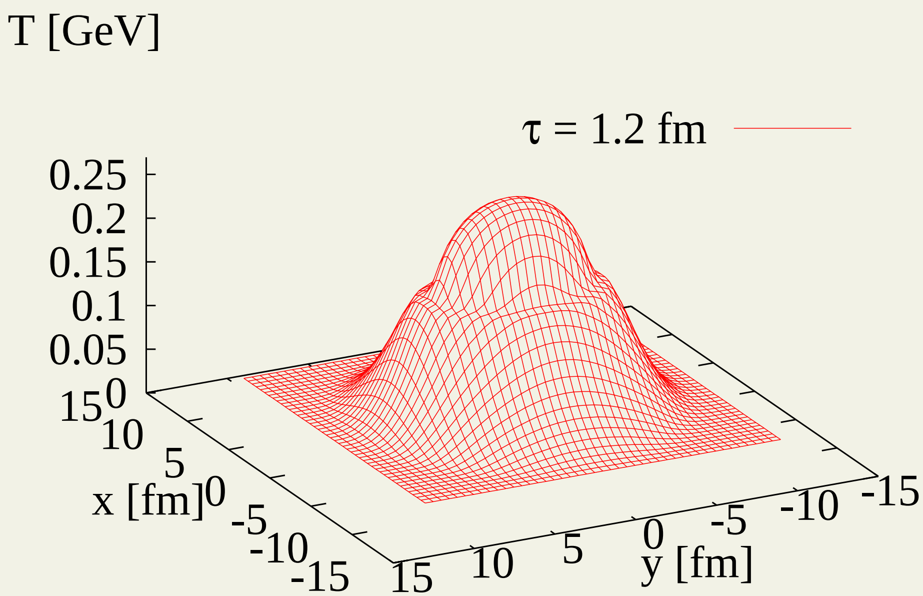
“old OSU”, fKLN, $\eta/s = 0.08$



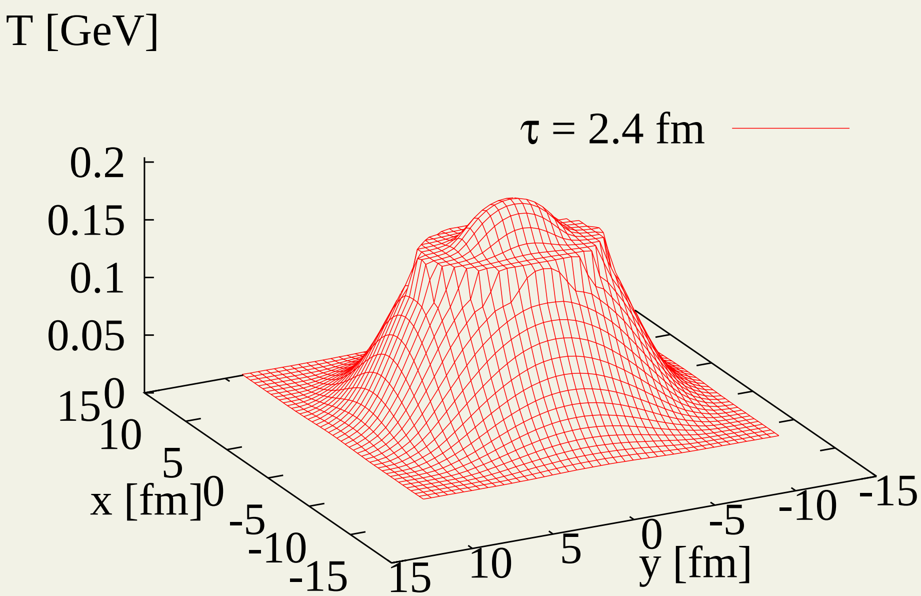
“old OSU”, fKLN, ideal



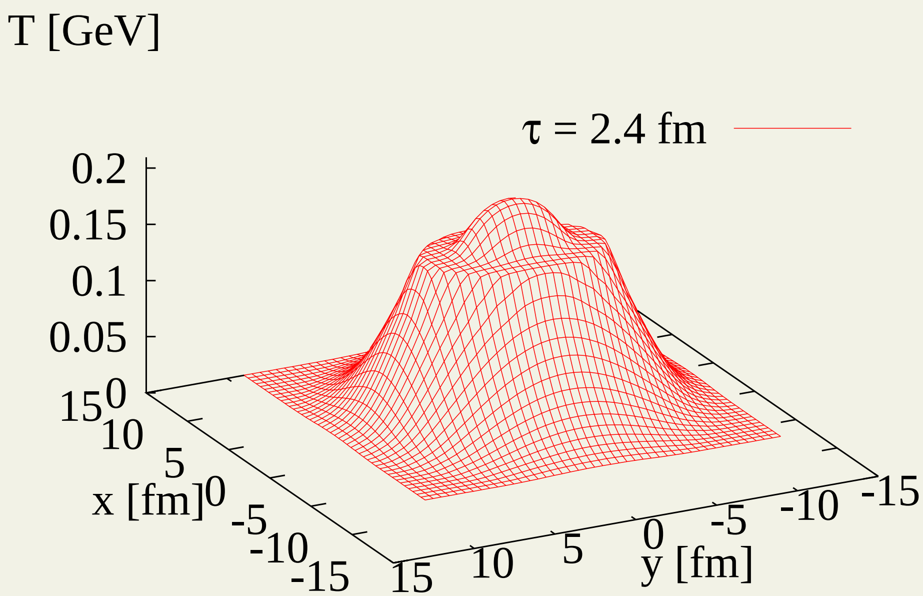
“old OSU”, fKLN, $\eta/s = 0.08$



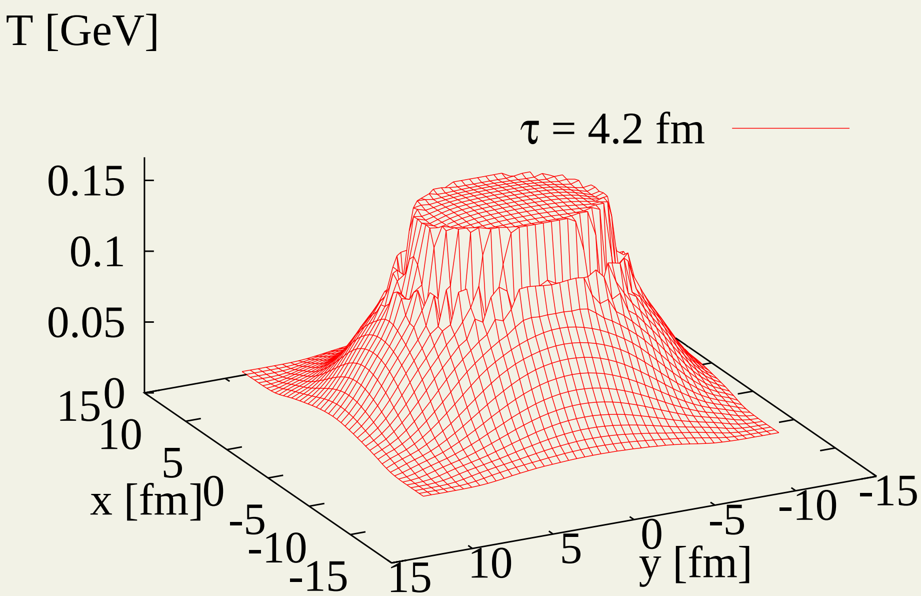
“old OSU”, fKLN, ideal



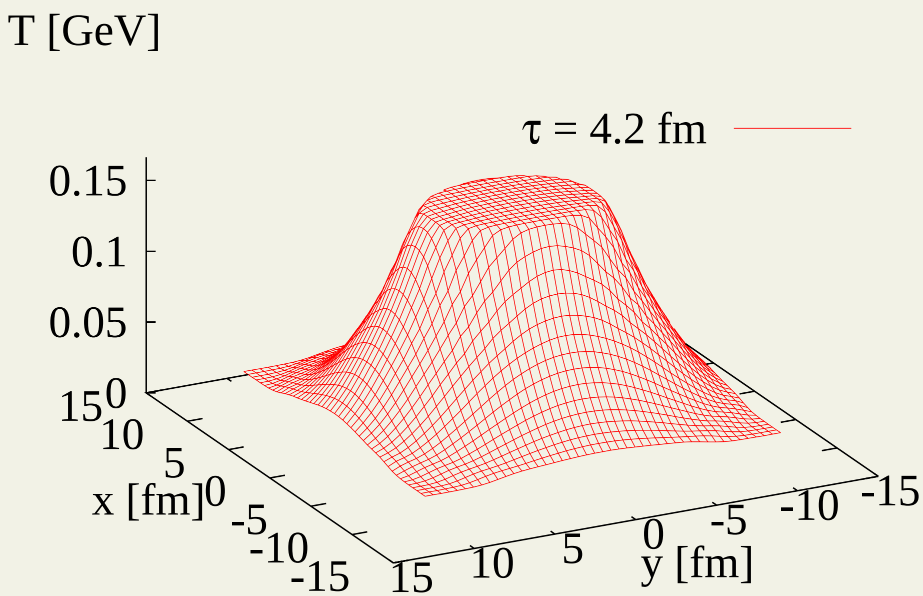
“old OSU”, fKLN, $\eta/s = 0.08$



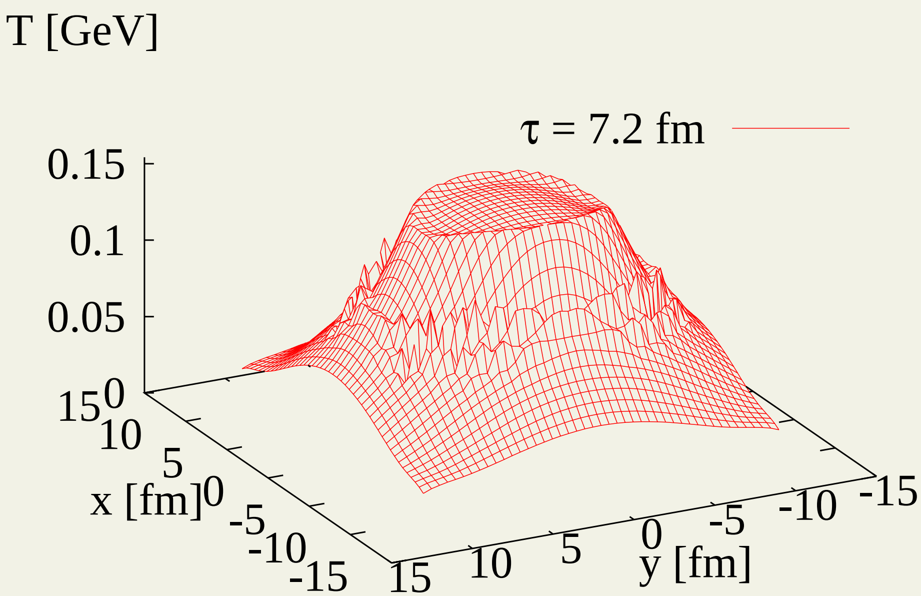
“old OSU”, fKLN, ideal



“old OSU”, fKLN, $\eta/s = 0.08$



“old OSU”, fKLN, ideal



“old OSU”, fKLN, $\eta/s = 0.08$