E-loss, radiative transport, viscous δf

Purdue group (Denes Molnar, Deke Sun, Zack Wolff, Dustin Hemphill, & Mridula Damodaran)

JET Collaboration Meeting at UC Davis, June 17-18, 2014

GLV + bulk medium

DM & Deke Sun

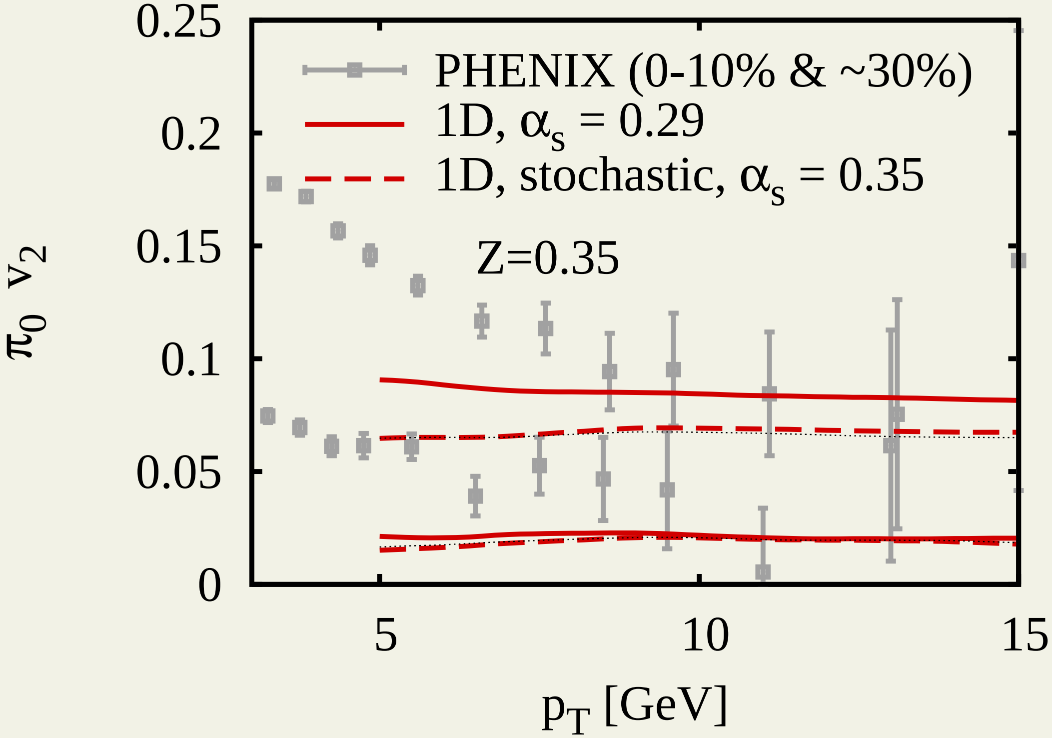
$$\Delta E^{(1)}_{GLV}(z) = \frac{C_R \alpha_s}{\pi^2}\chi \int dx\, d\mathbf{k}\, d\mathbf{q}\, \frac{\mu^2}{\pi(\mathbf{q}^2+\mu^2)^2}\frac{2\mathbf{k}\cdot\mathbf{q}}{\mathbf{k}^2(\mathbf{k}-\mathbf{q})^2}(1-\cos\omega\Delta z)$$

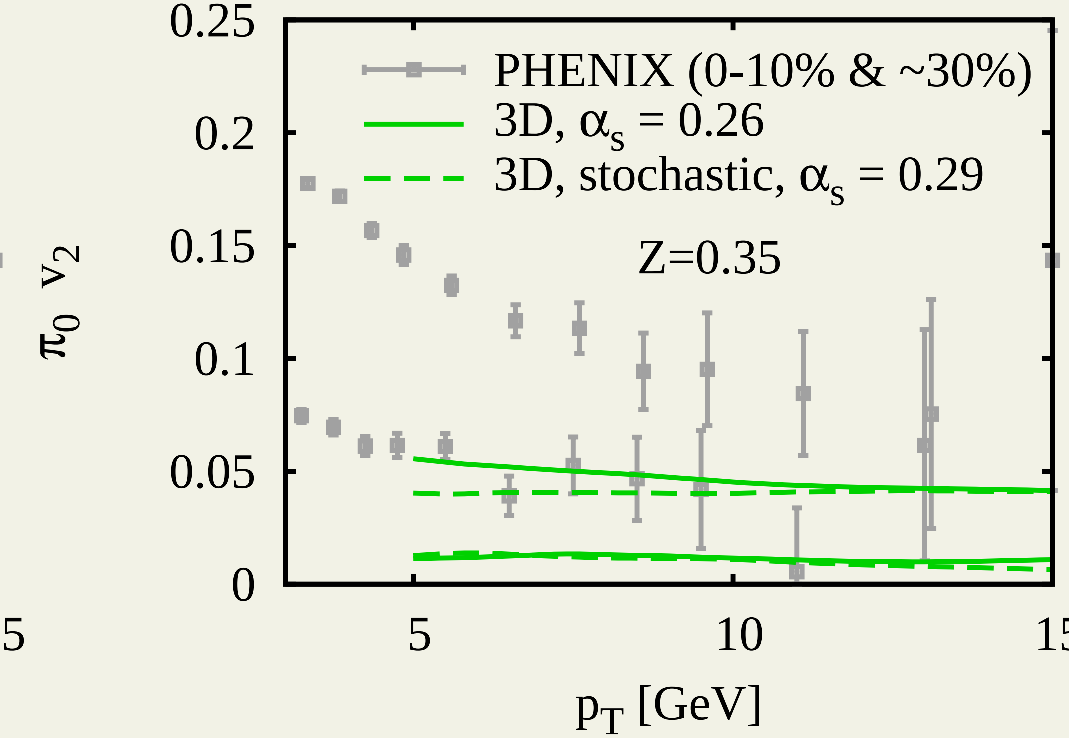
$$E_{GLV} = \int dz\, \rho\, \sigma_{gg\to gg} \Delta E_{GLV}(z)$$

- **transverse expansion halves v_2 at RHIC (also LHC)**

DM & Sun, NPA901-911 ('13) & 1305.1046

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





BUT claim: $R_{AA}(\phi)$ works in 200-GeV at RHIC Betz & Gyulassy, 1305.6458

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

with "pQCD-like" $a = 1/3$**,** $b = 1$**,** $c = 2 - a + b = 8/3$

Apparent contradiction, but calculations differ

- medium evolution

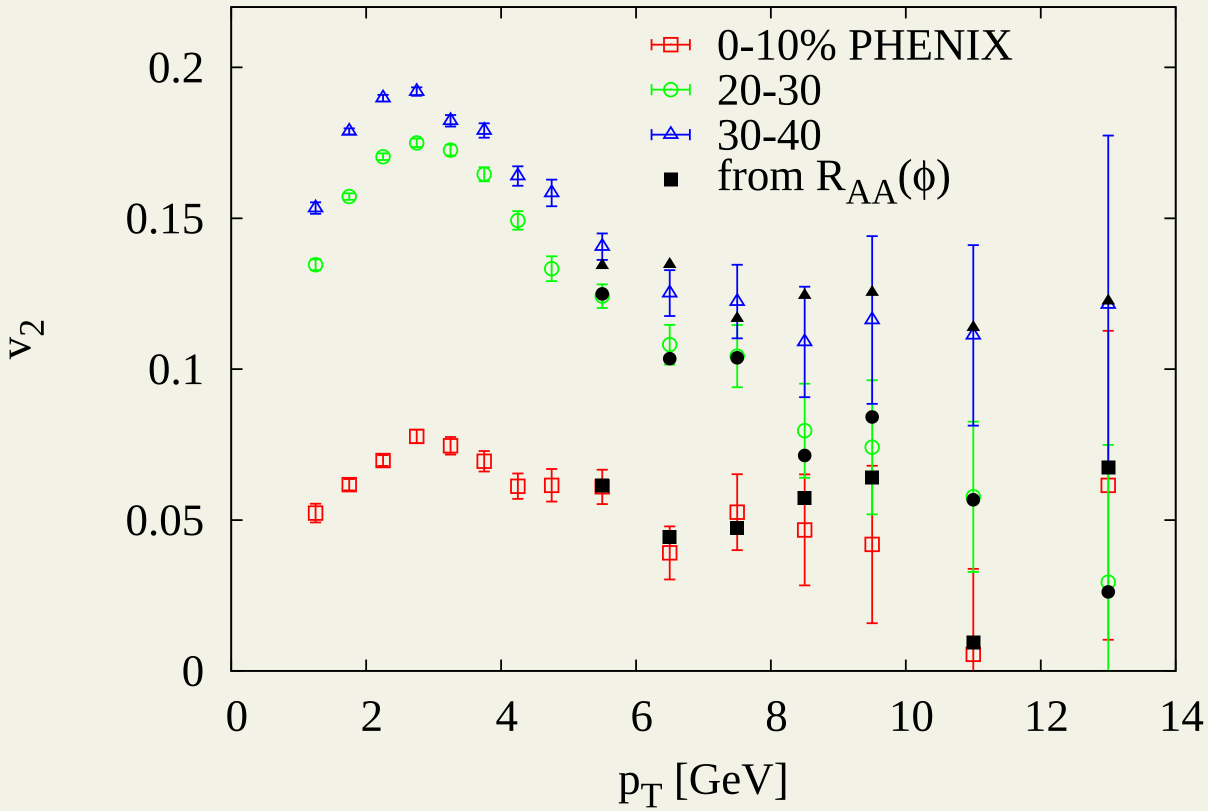
- energy loss model

[- observable studied]

we resolved this $\rightarrow$ hydro model/EOS(!) DM & Sun, arXiv:1405.4848

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

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



⇒ **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"

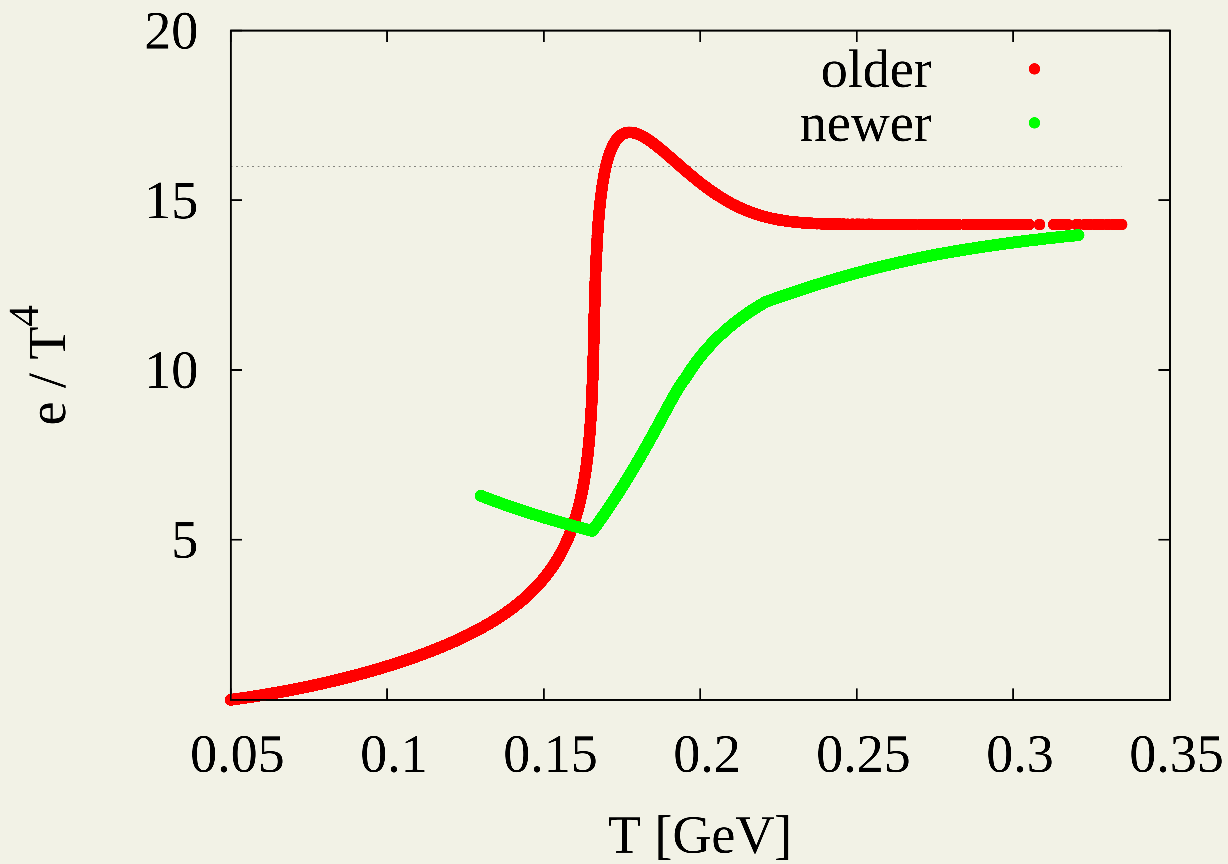
iv) $\eta/s = 0.08$, fKLN profile - "visc. fKLN"

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

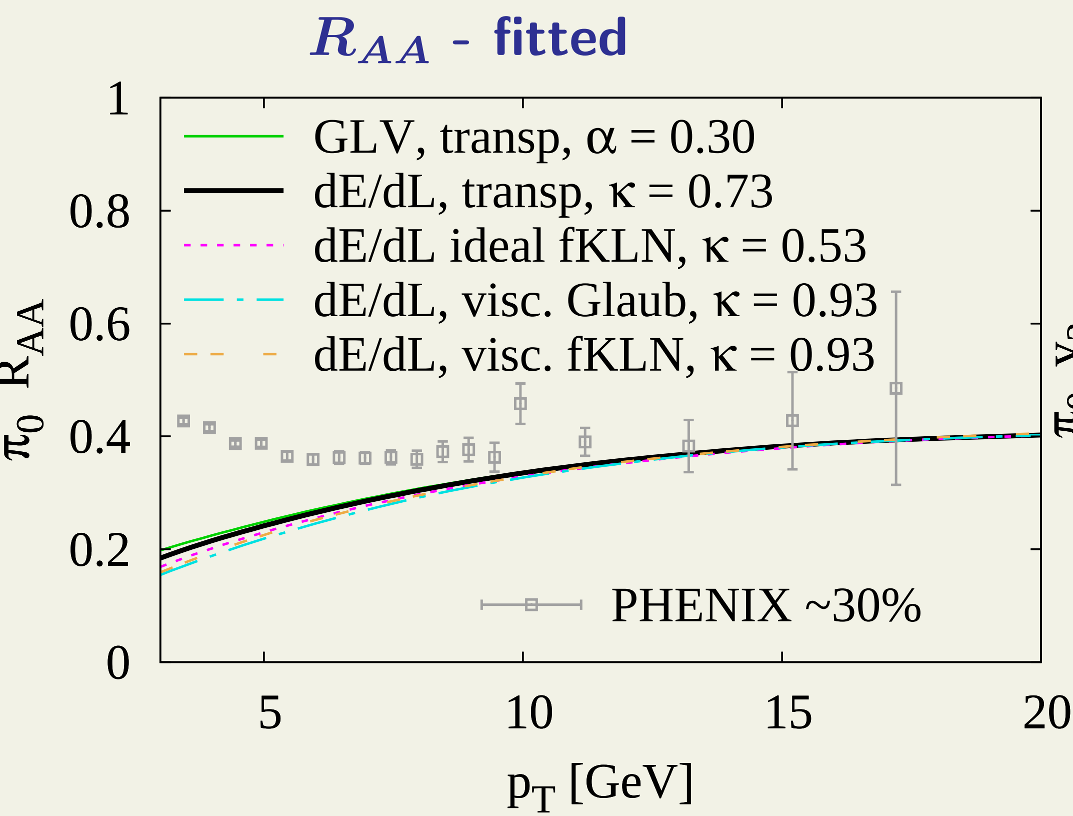
all cases Au+Au at fixed $b \approx 8$ fm, smooth geometry

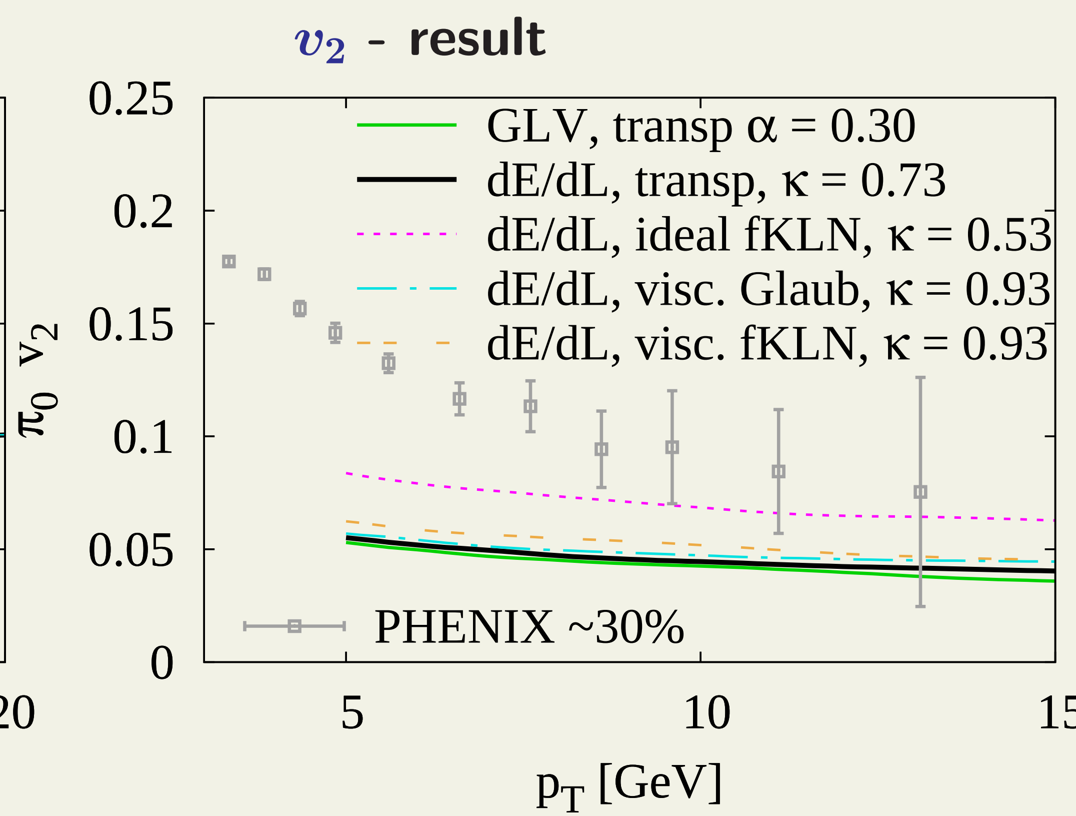
older set: **smoothed Bag Model EoS (SM-EOSQ)**

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



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



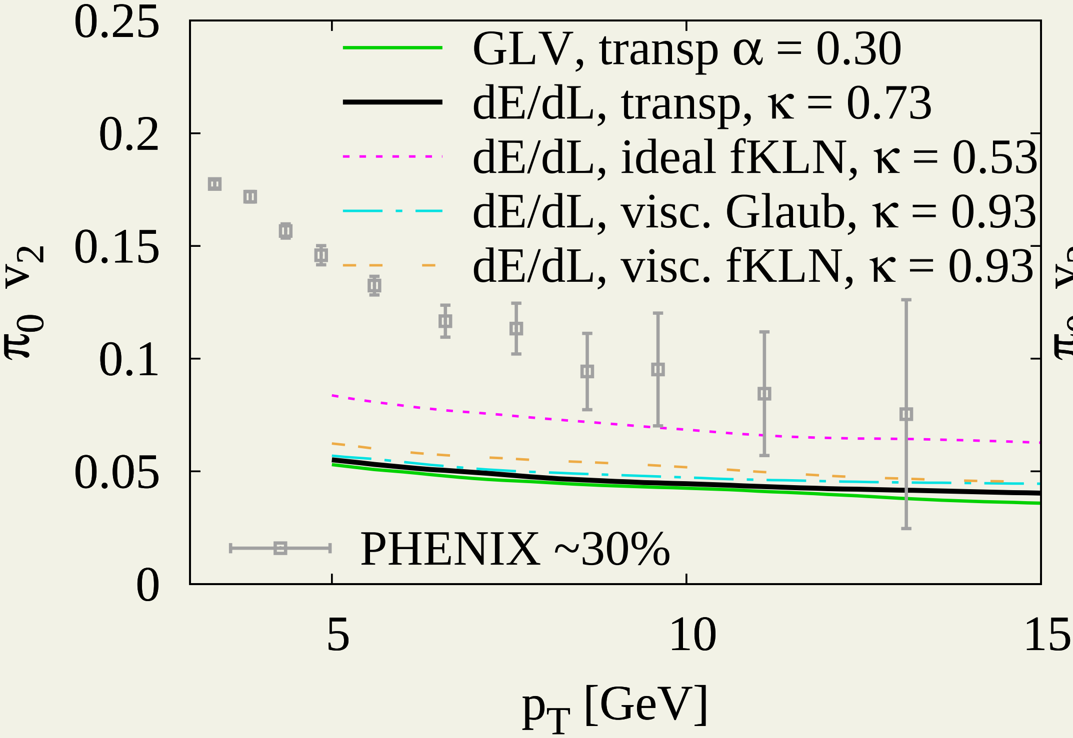


all medium models with dE/dL look very similar to GLV + transport

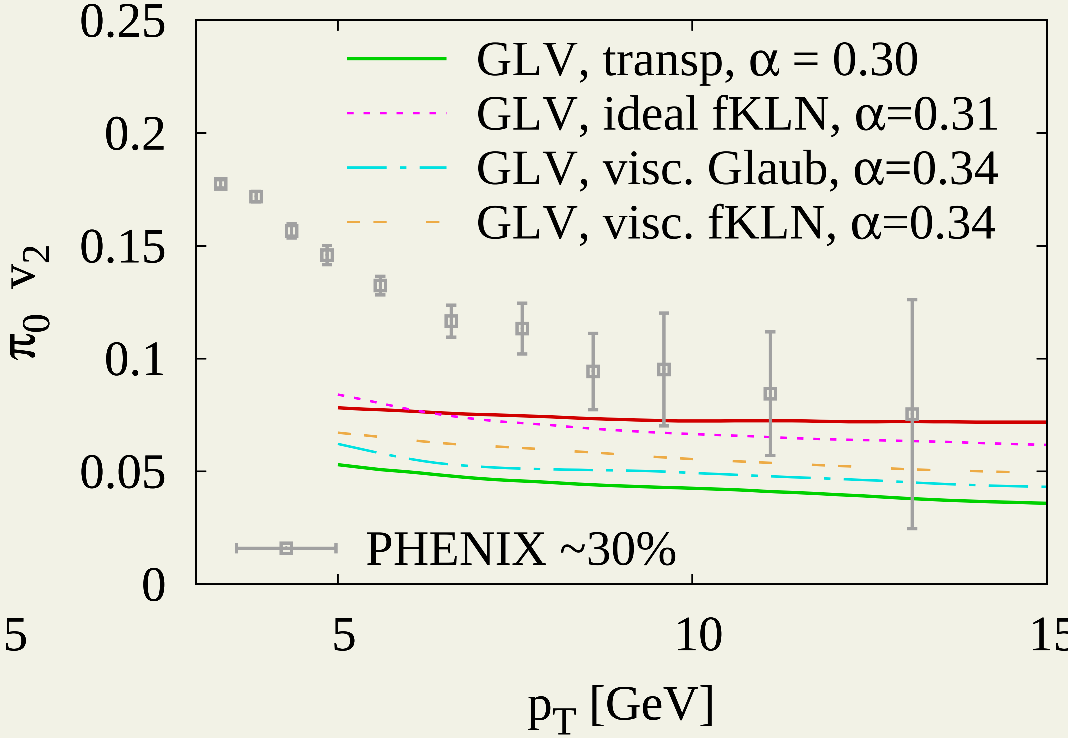
except "older" OSU hydro calculation that gives higher v_2

results for different media DM & Sun, 1405.4848

v_2 from dE/dL



v_2 from GLV



GLV and "pQCD-like" dE/dL quite similar

Covariance

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

Suppose holds in fluid rest frame ($u_F = (1, \vec{0})$), rewrite it in covariant form.
For massless particles ($|\vec{v}| = 1$):

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

so covariantly

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

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

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

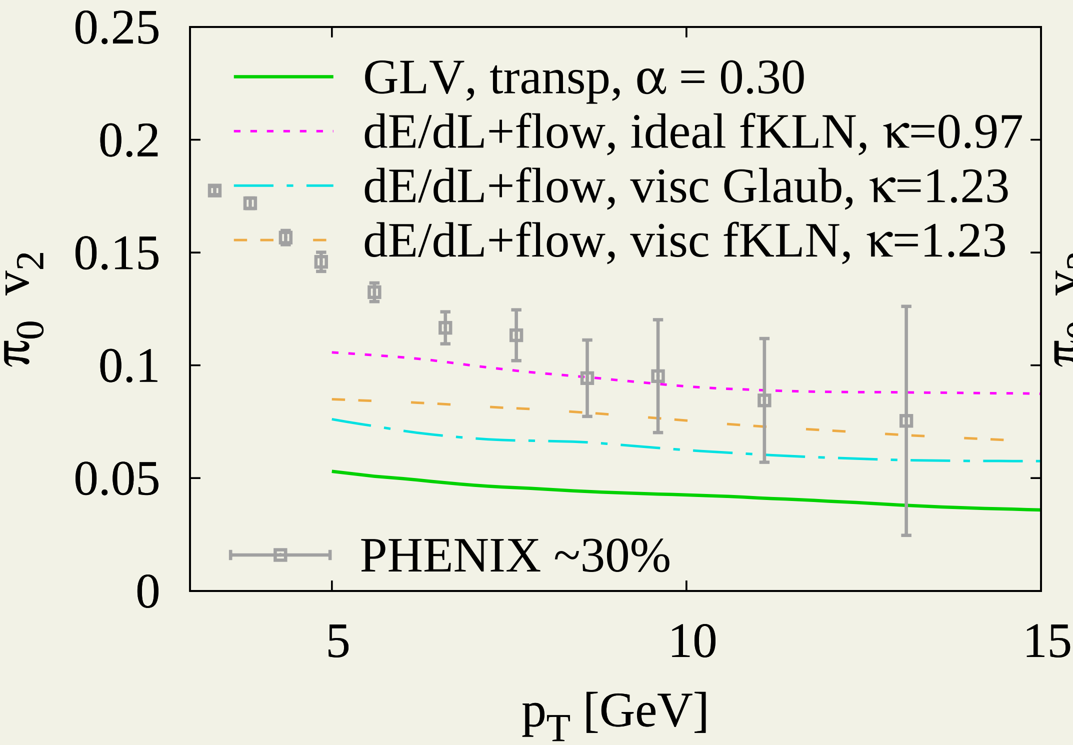
Same arises in GLV, in

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

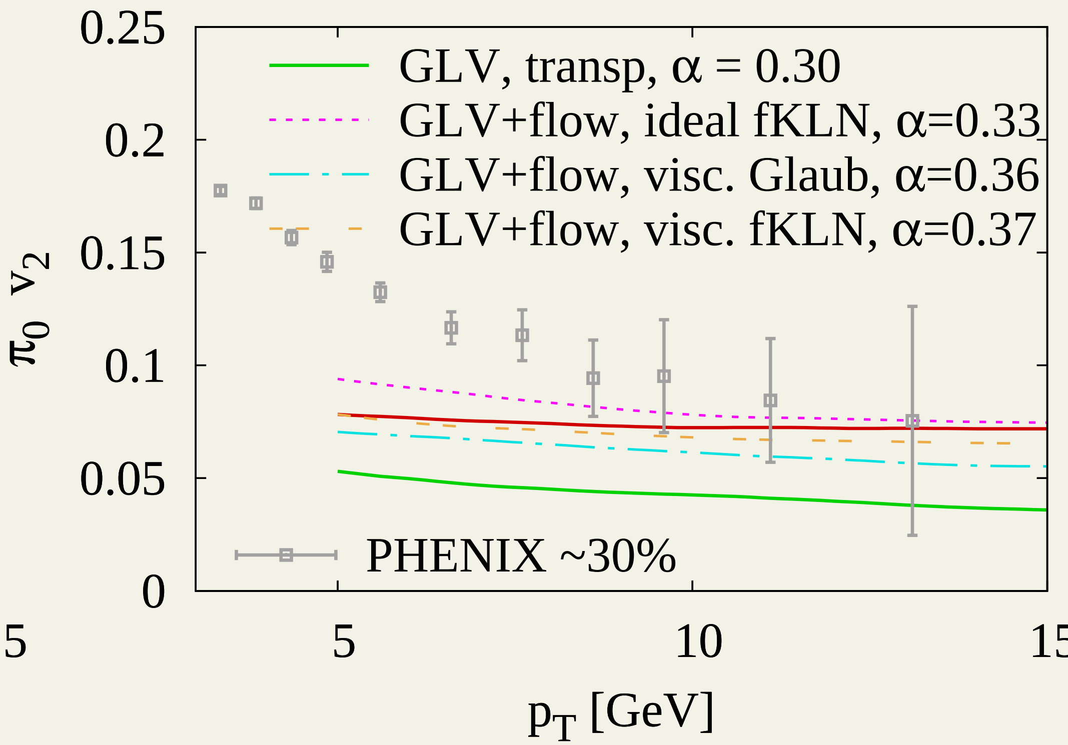
via $dL \, \rho \, \sigma \ \to \ dL_{LR} \, \rho_{LR} \, \sigma = dL \, \rho_{LR} \, \sigma \, \gamma_F (1 - \vec{v}\vec{v}_F) = dL \, \rho \, \sigma \, (1 - \vec{v}\vec{v}_F)$

covariant results for different media DM & Sun, 1405.4848

v_2 from dE/dL



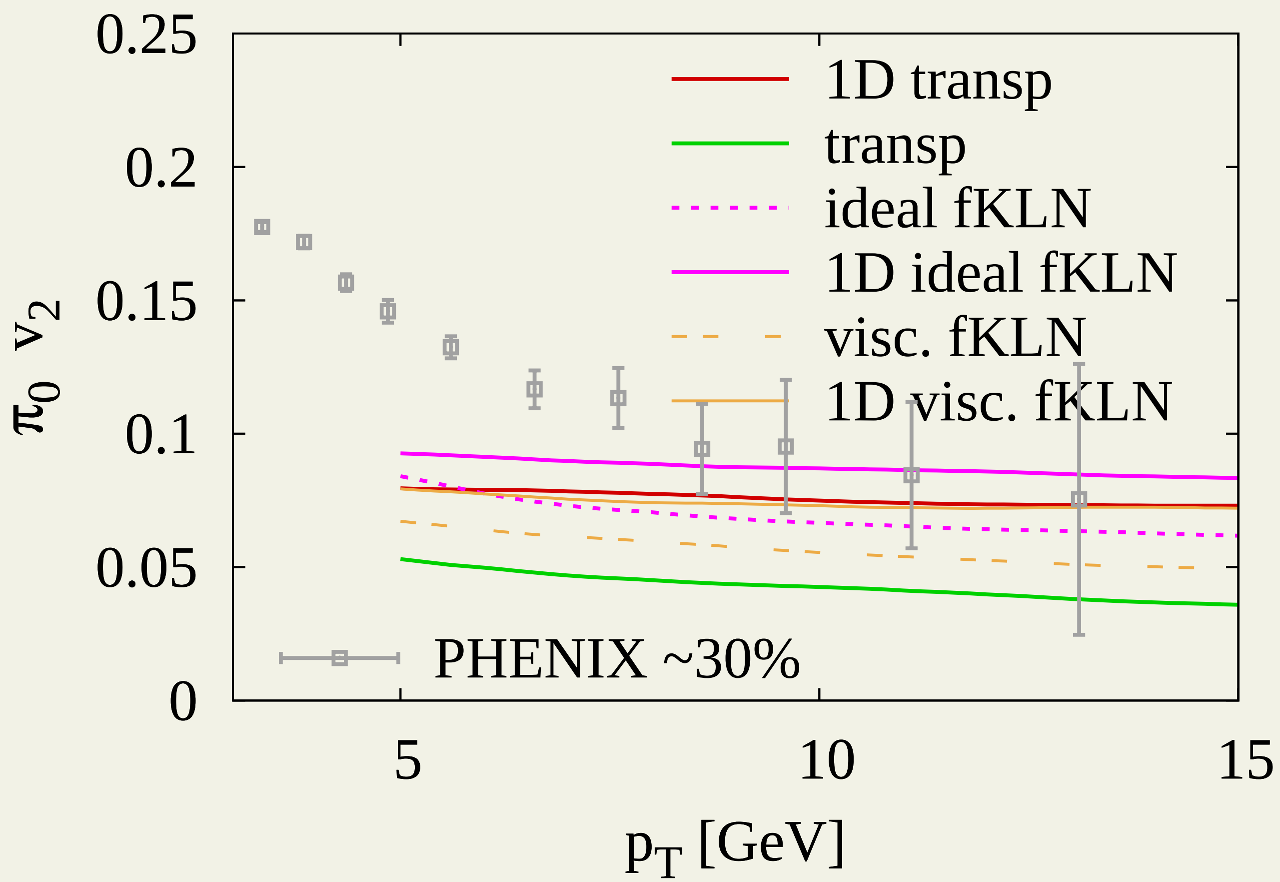
v_2 from GLV



GLV and "pQCD-like" dE/dL quite similar

1D vs 3D still matters with naive GLV

DM & Sun ('13)



Message:

- **nontrivial to get R_{AA} and v_2 simultaneously**
- **bulk medium background evolution matters**
- **covariance helps**

Radiative transport MPC/Grid

DM & Dustin Hemphill & Mridula Damodaran

Radiative transport:

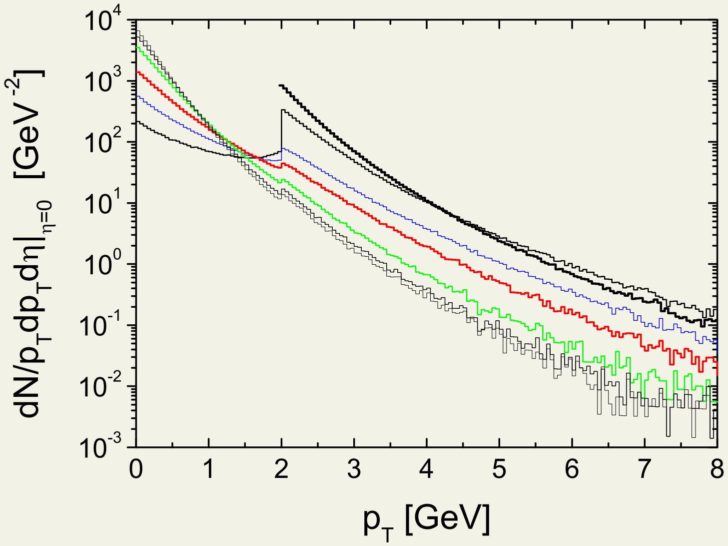
$$p\partial f = S + C_{2\to 2}[f] + C_{2\leftrightarrow 3}[f] + \ldots$$

- **Purdue code MPC/Grid for both single-CPU and parallel runs**

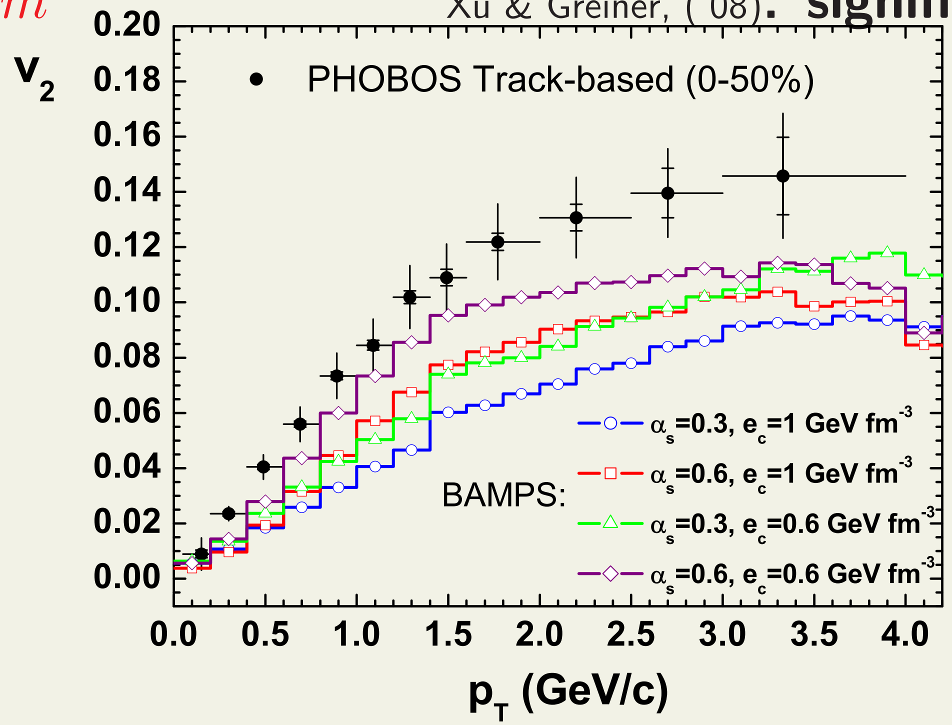
5 useful knobs: cell sizes (d_x, d_y, d_z/d_η), timestep Δt, subdivision ℓ

Big question: does pQCD really thermalize as BAMPS claims?

Xu& Greiner, PRC71 ('05): $\tau_{eq} \sim 1 fm$



Xu & Greiner, ('08): **significant** v_2



need QCD rates

***gg ↔ gg*:**

$$|\bar{\mathcal{M}}|^2_{LO} = \frac{9g^4}{2}\left(3 - \frac{us}{t^2} - \frac{ts}{u^2} - \frac{ut}{s^2}\right) \sim \frac{9g^4 s^2}{2}\left(\frac{1}{t^2} + \frac{1}{u^2}\right) \qquad (1)$$

Debye screening: $1/t^2 \;\; \to \sim 1/(t-\mu^2)^2$

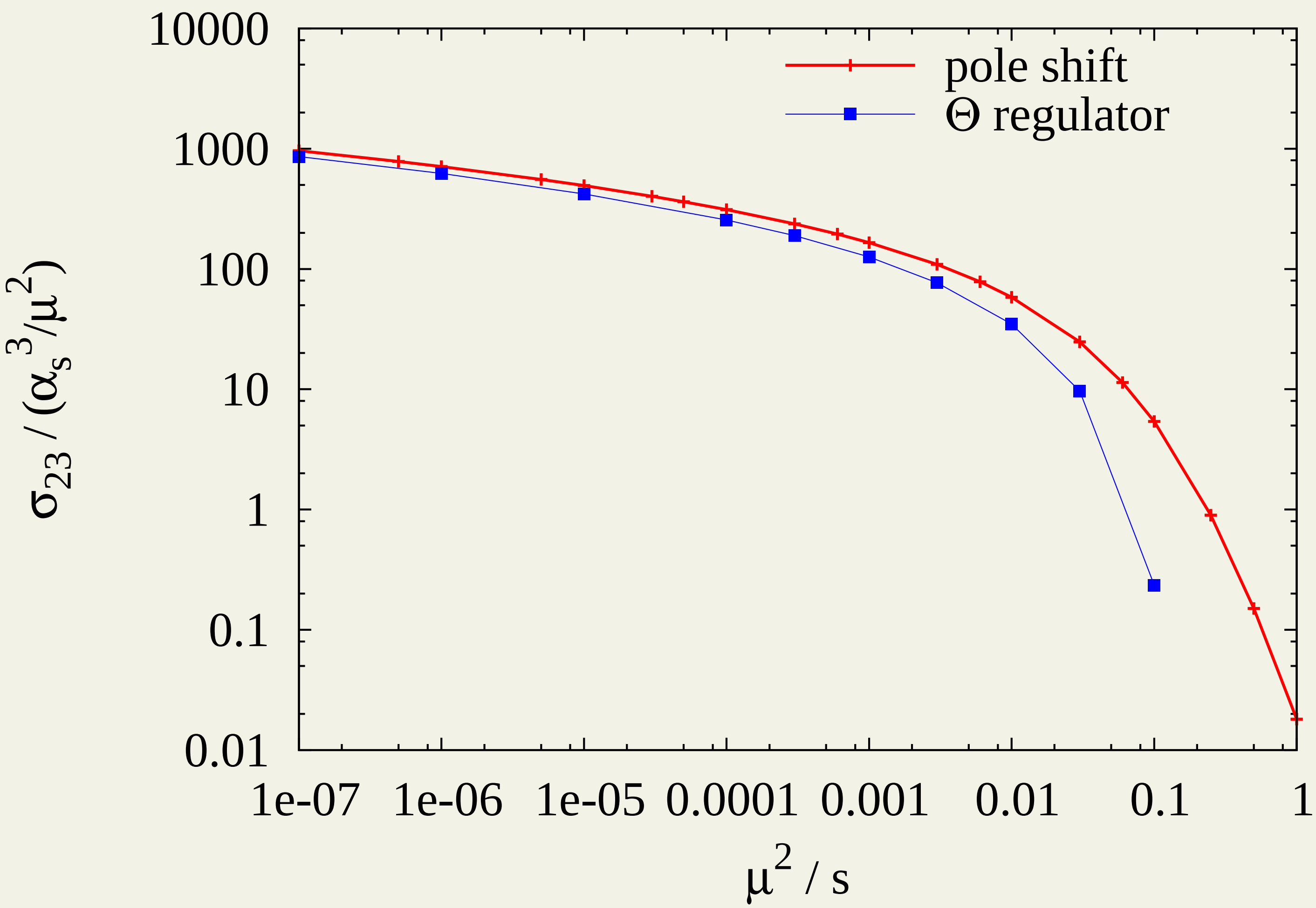
***gg ↔ ggg*:** e.g., Berends et al, PLB 103 ('81) **12 × 10 terms**

$$|\bar{\mathcal{M}}|^2_{LO} = \frac{g^6 N_c^3}{2(N_c^2-1)} \sum_{perms\{12345\}} \frac{1}{p_{12}\, p_{23}\, p_{34}\, p_{45}\, p_{51}} \times \sum_{i<j} p_{ij}^4 \;, \qquad p_{ij} \equiv p_i p_j \qquad (2)$$

screened by hand: $p_{ij} \to p_i p_j + \mu^2$ Chen et al, PRD83 ('11)

or $\Theta(p_i p_j - \mu^2)$ Fochler et al

DM & Hemphill ('13) **screened LO $gg \to ggg$**



$$\sigma_{2\to 2} = \frac{9\pi\alpha_s^2}{2\mu^2}$$

$$\sigma_{2\to 3} = \frac{\alpha_s^3}{\mu^2} f\left(\frac{\mu^2}{s}\right)$$

$$\frac{\mu^2}{s} \sim \frac{g^2T^2}{18T^2} \sim 0.7\alpha_s \sim 0.2\,(RHIC)$$

instead of LO pQCD $gg \leftrightarrow ggg$:

$$|\bar{\mathcal{M}}|^2_{LO} = \frac{g^6 N_c^3}{2(N_c^2 - 1)} \sum_{perms\{12345\}} \frac{1}{p_{12}\, p_{23}\, p_{34}\, p_{45}\, p_{51}} \times \sum_{i<j} p_{ij}^4 \,, \qquad p_{ij} \equiv p_i p_j \tag{3}$$

BAMPS has Bertsch-Gunion form (valid for $q_T, k_T \ll \sqrt{s}$, $\quad y \approx 0$)

$$|\bar{\mathcal{M}}|^2_{BG} = \frac{54 g^6 s^2}{\vec{q}_T^{\,2}\, \vec{k}_T^{\,2}\, (\vec{k}_T + \vec{q}_T)^2} \quad \to \quad \frac{54 g^6 s^2 q_T^2\, \Theta(k_T \mathrm{ch} y - 1/\lambda_{MFP})}{(q_T^2 + \mu^2)^2 k_T^2 [(\vec{k}_T + \vec{q}_T)^2 + \mu^2]} \tag{4}$$

[$p_3 = (k_T e^y, k_T e^{-y}, \vec{k}_T)$, $\quad p_4 = (q_T e^{y_i}, q_T e^{-y_i}, \vec{q}_T)$, $\quad p_5 = (\sqrt{s}, \sqrt{s}, 0_T) - p_3 - p_4$ **]**

many other choices possible, e.g., fully symmetric Bertsch-Gunion

$$|\bar{\mathcal{M}}|^2_{BG} = \frac{54 g^6 s^2}{(q_T^2 + \mu^2)(k_T^2 + \mu^2)[(\vec{k}_T + \vec{q}_T)^2 + \mu^2]} \tag{5}$$

Total $\sigma_{gg\to ggg}$

$$\sigma_{23}^{TOT} = \frac{1}{3!}\frac{1}{64\pi^5 s}\int \frac{d^3p_3}{2E_3}\frac{d^3p_4}{2E_4}\frac{d^3p_5}{2E_5}\left|M_{12\to 345}\right|^2 \delta^4(p_1+p_2-p_3-p_4-p_5)$$

$$= \frac{1}{3!}\frac{1}{128\pi^4 s}\int_{-\infty}^{\infty} dy \int_0^{\sqrt{s}/(2\,\mathrm{ch}y)} dk_T \int_0^{2\pi} d\varphi \int_0^{q_T^{max}} dq_T\, J(k_z, k_T, q_T, \varphi) \sum_{i=1}^{2} |M|^2_{(i)}$$

clear-cut calculation, of course depends on $|M_{gg\to ggg}|$ used

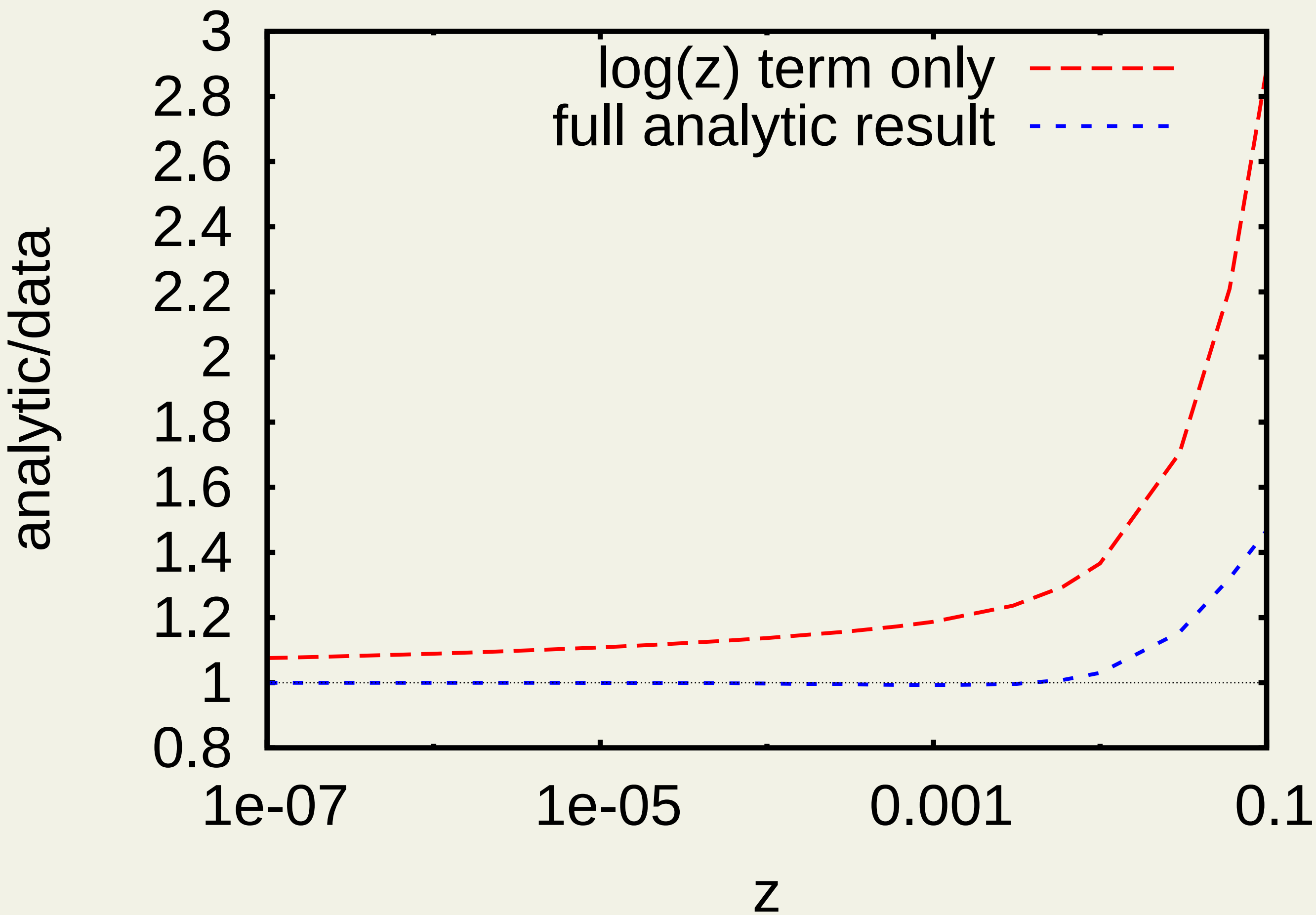
generically, for $\mu_D^2 \ll s$:

$$\sigma_{gg\to ggg} \sim \frac{\alpha_s^3}{\mu_D^2} \ln \frac{s}{\mu_D^2}$$

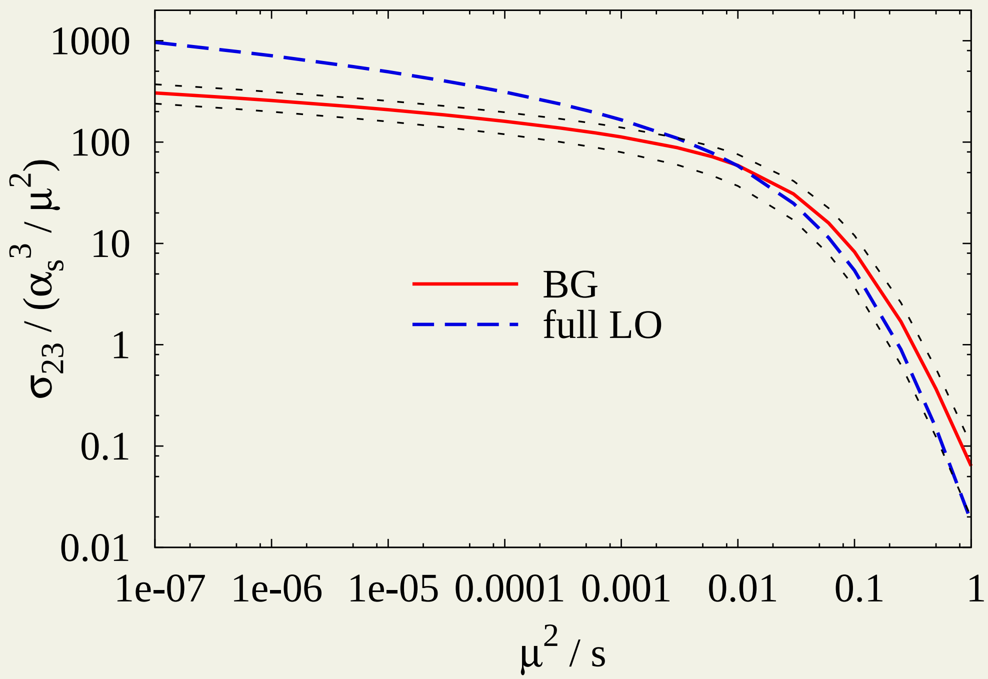
e.g., for fully symmetric BG: DM & Hemphill ('14):

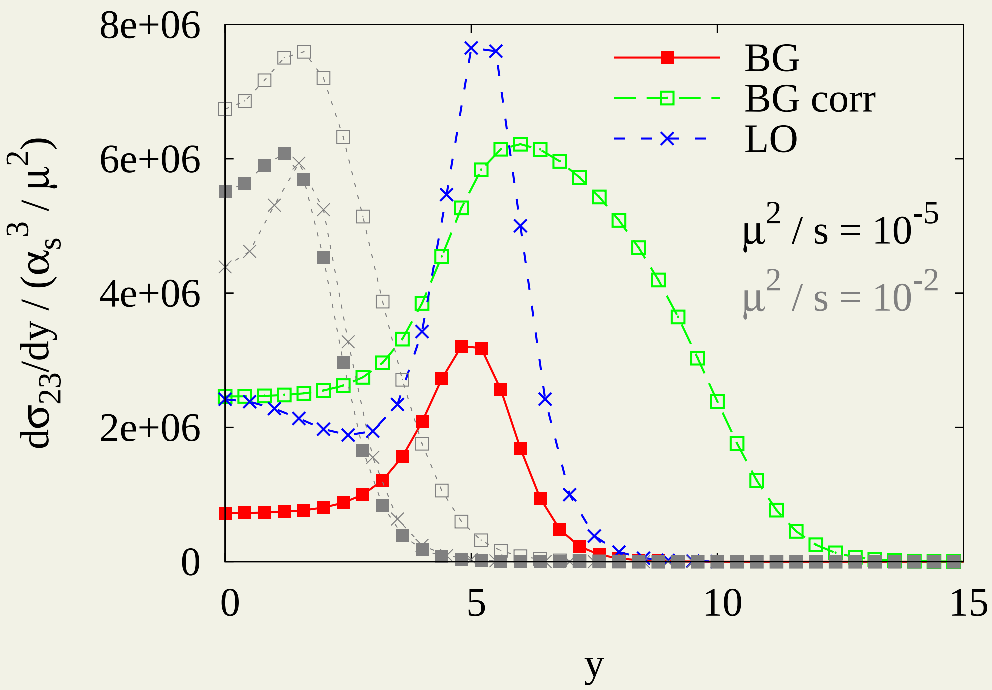
$$\sigma_{gg\to ggg} = \frac{\alpha_s^3}{\mu_D^2}\left[31.64 \ln\frac{1}{z} - 35.80 z^0 + \ldots\right] \qquad (z \equiv \mu_D^2/s)$$

DM & Hemphill ('14): **analytic / numerical $\sigma_{gg\to ggg}$ for fully symmetric BG**



$2 \leftrightarrow 3$ Bertsch-Gunion (e.g., BAMPS) not so accurate, large rapidities matter





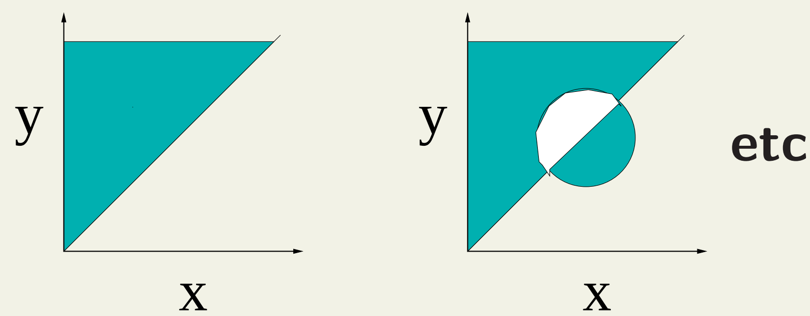
$$|\bar{M}|^2_{BG} = \frac{54 g^6 s^2 \vec{q}_T^{\,2}}{(\vec{q}_T^{\,2}+\mu^2)^2\,(\vec{k}_T^{\,2}+\mu^2)\,(\vec{r}_T^{\,2}+\mu^2)} \qquad \sigma_{23}^{TOT} = \frac{\alpha_s^3}{\mu^2} f\left(\frac{\mu^2}{s}\right)$$

$$|\bar{M}|^2_{LO} = \frac{g^6 N_c^3}{2(N_c^2-1)} \sum_{perms\{12345\}} \frac{1}{p_{12}\,p_{23}\,p_{34}\,p_{45}\,p_{51}} \times \sum_{i<j} p_{ij}^4\,, \qquad p_{ij} \equiv (p_i p_j)^2 + \mu^2$$

Permutation symmetry can be tricky if $|M|^2$ is approximated. E.g., in 2D:

$$\frac{1}{2!}\int_0^1 dx \int_0^1 dy\, |M|^2(x,y) \equiv \int_0^1 dx \int_x^1 dy\, |M|^2(x,y) \qquad \text{if } |M|^2(x,y) = |M|^2(y,x)$$

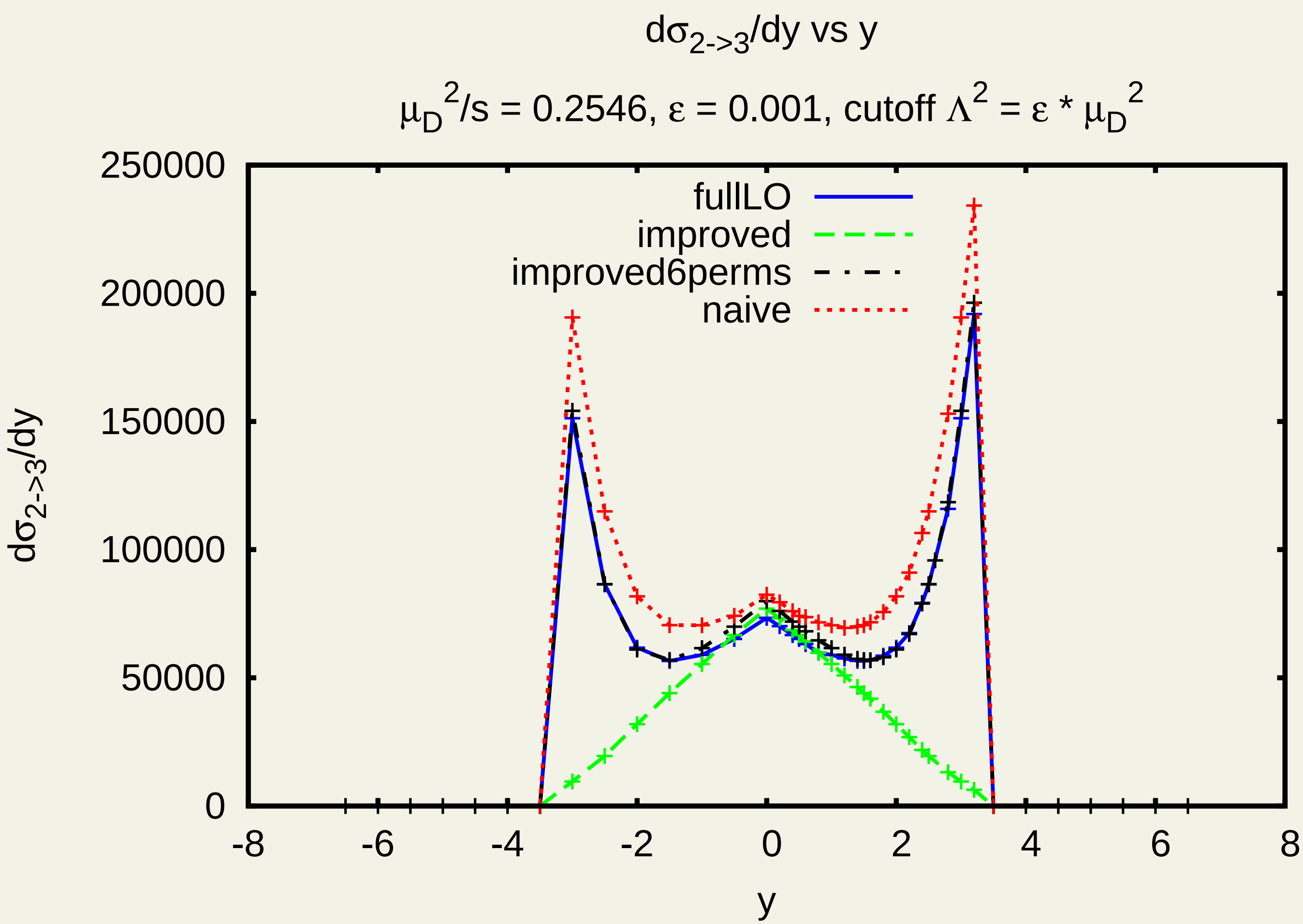
infinitely many equivalent ways to integrate over "half" space



But it does matter which one you take, if your $|M|^2$ breaks permutation symmetry - like Bertsch-Gunion. However, if approximation is valid over one half, and contributes little over the other half, then 2! may be dropped approximately.

"improved" Bertsch-Gunion Fochler et al, 1302.5250

$$|M|^2_{BG} \to |M|^2_{BG} \left(1 - \frac{p_T}{\sqrt{s}} e^{-|y|}\right)^2$$



Hemphill ('13)

$d\sigma_{2\to3}/dy$

naive BG

vs improved BG

vs full LO

vs permuted improved BG

sum of all 6 improved BG permutations divided by 3 works at $\mu^2/s \approx 0.25$.

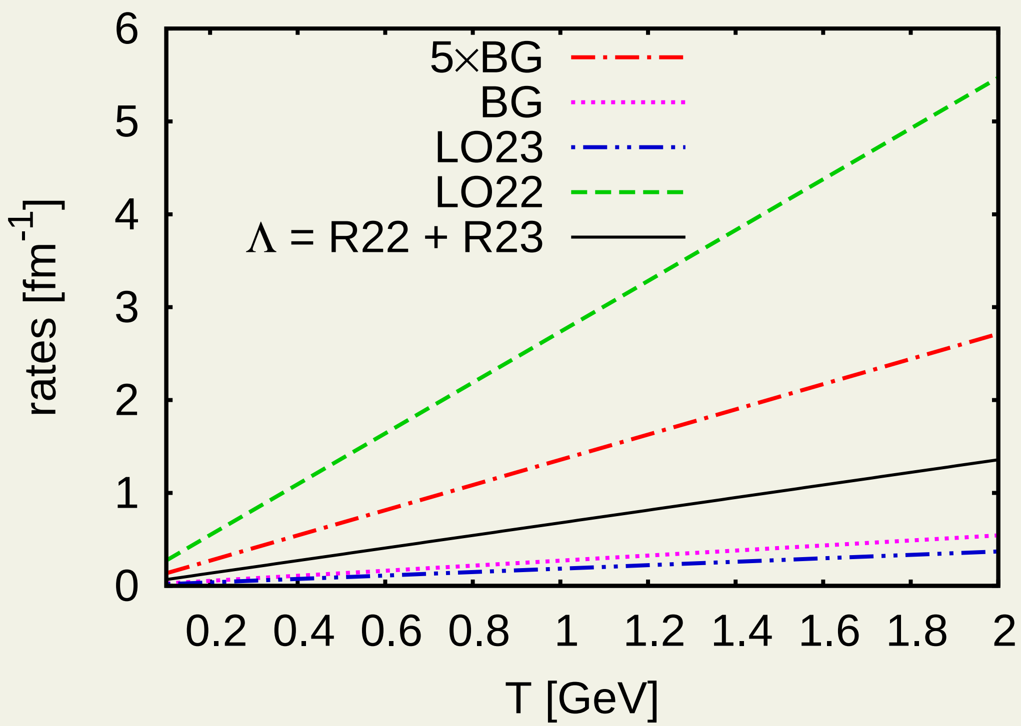
Thermal rates vs BAMPS

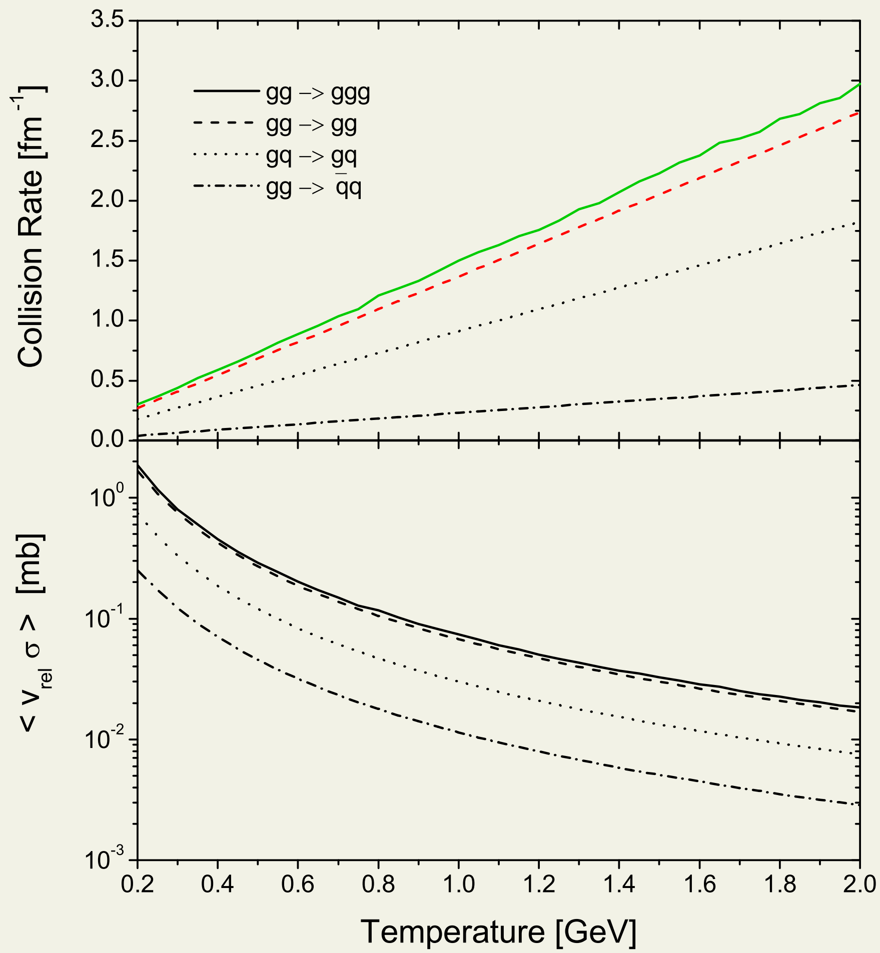
$$\gamma_{2\to X} = (2/n) \int d^3p_1 d^3p_2 f_1 f_2 v_{rel} \sigma_{2\to X}(s)$$

DM & Hemphill ('13) & ('14)

Xu&Greiner, PRC71 ('05)

smooth μ_D^2 or LPM cutoff $\Lambda = 1/MFP$





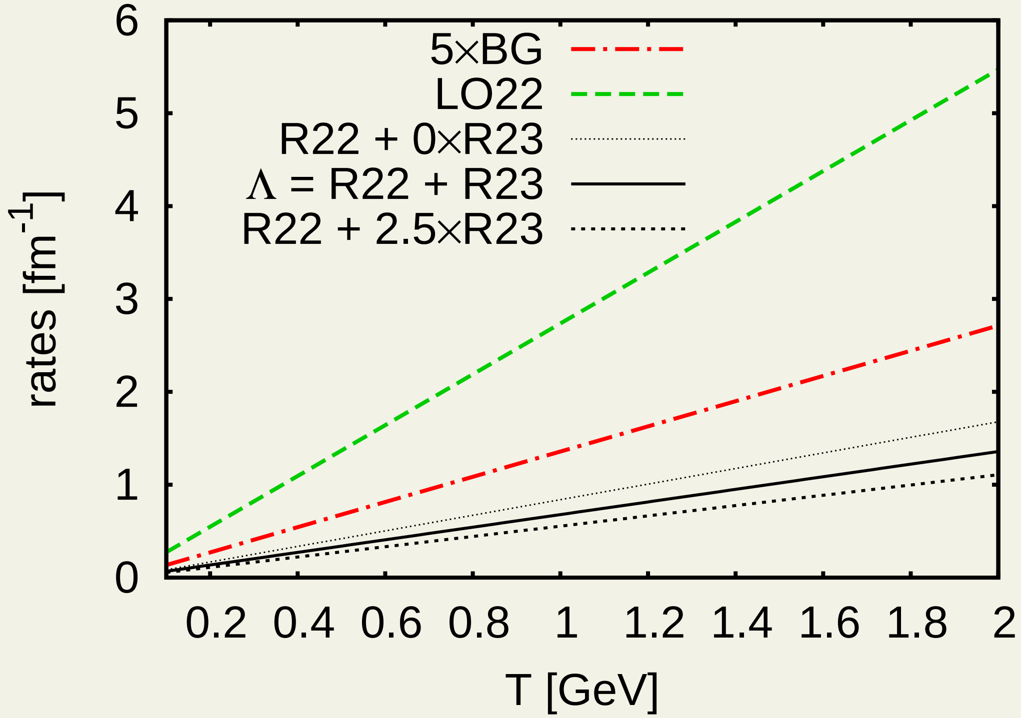
Thermal rates vs BAMPS

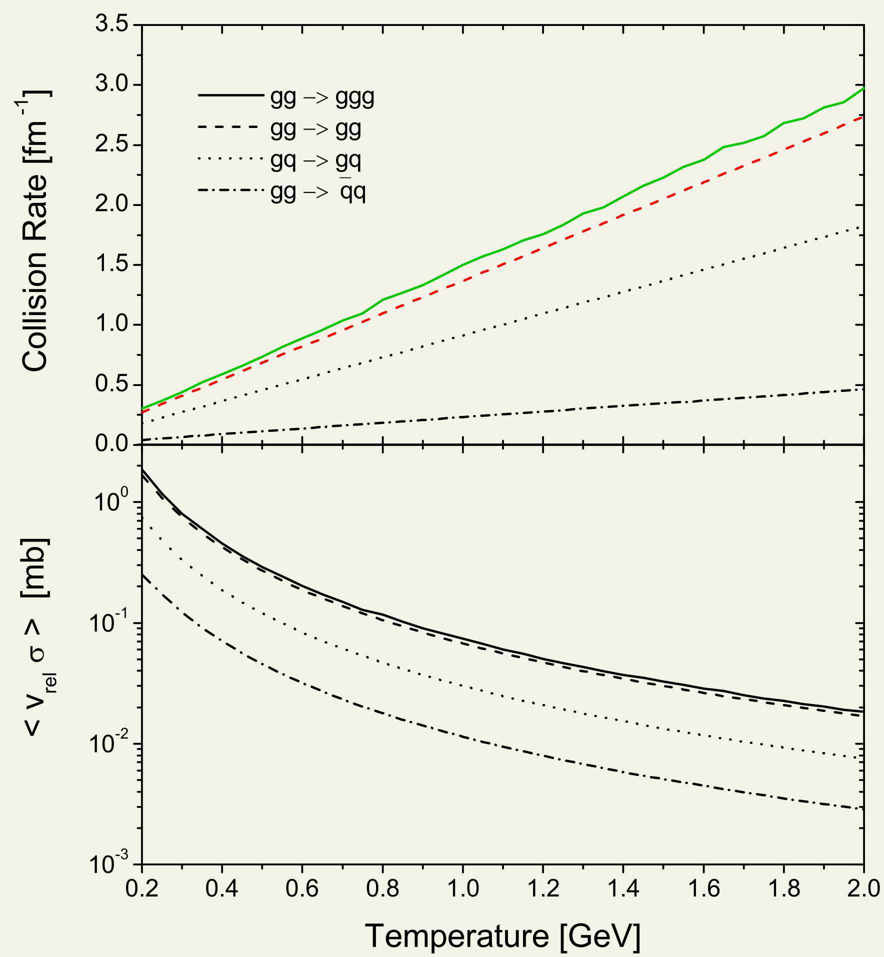
$$\gamma_{2\to X} = (2/n) \int d^3p_1 d^3p_2 f_1 f_2 v_{rel} \sigma_{2\to X}(s)$$

DM & Hemphill ('13) & ('14)

Xu&Greiner, PRC71 ('05)

LPM cutoff $\Lambda = 1/MFP$ dependence





Equilibration in static box

- **density estimate for central Au+Au (Glauber binary coll) at $\tau_0 = 0.6$ fm**

$$n = \frac{1}{\tau_0}\frac{dN}{d\eta d^2x_T} = \frac{1}{\tau_0}\frac{dN}{dy}\frac{T_A(\vec{x}_T)T_A(\vec{x}_T)}{T_{AB}(b=0)} \qquad \sim 25\,\mathrm{fm}^{-3}\ \text{for}\ x_T = 0$$

[with thickness function $T_A(\vec{x}) = \int dz\,\rho_A(\sqrt{x^2+z^2})$]

- **momentum distribution: pQCD minijets $p_T > p_0$, with $y = 0$**

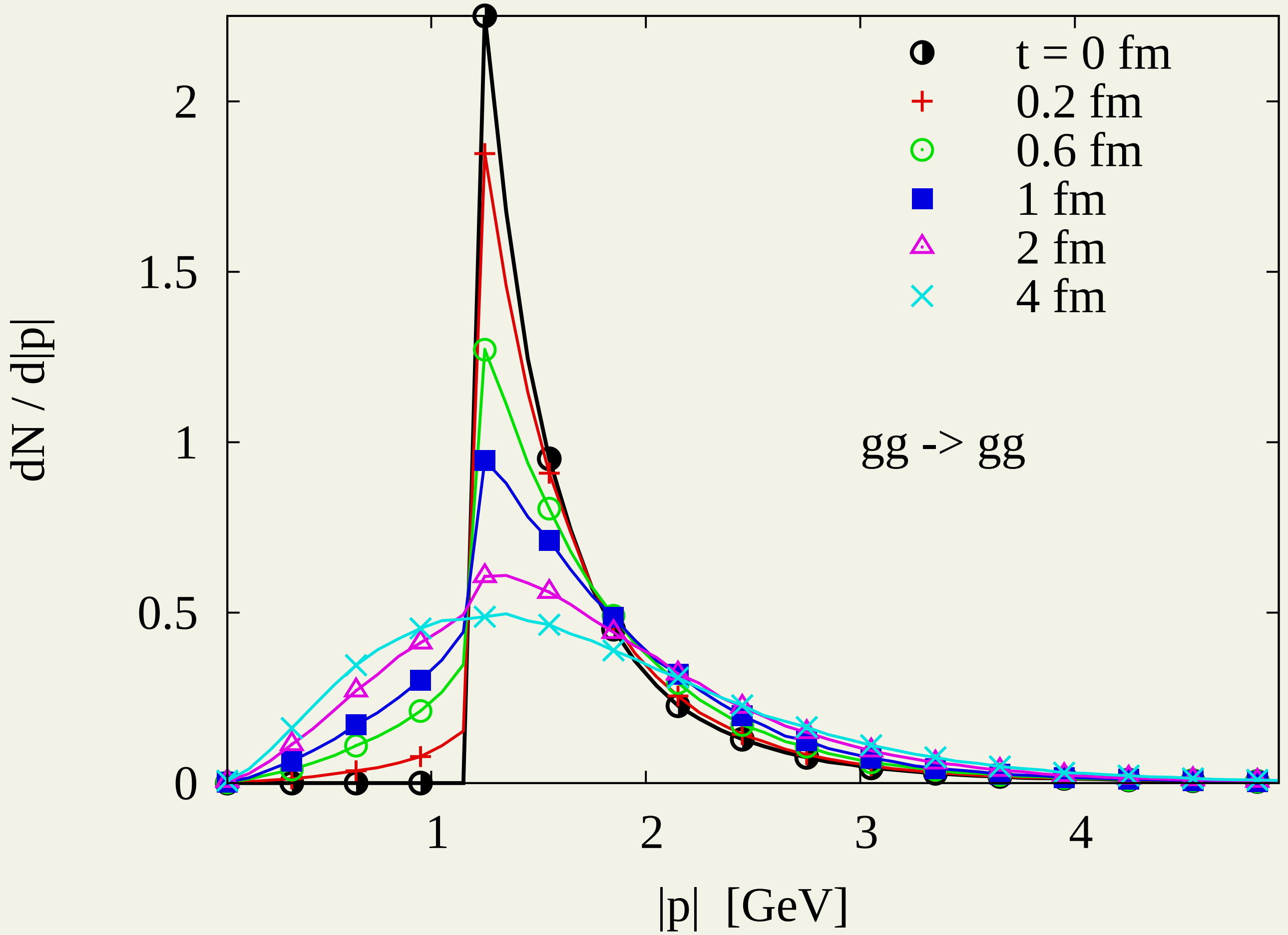
$$\frac{dN}{dy} \approx 1100 \qquad \to \qquad p_0 = 1.2\,\mathrm{GeV}$$

('a la' old saturation model Eskola, Kajantie ('98)**)**

- **LO σ_{23} with fixed $\mu_D = gT_{fin} = gE_{TOT}/3N_{fin}$, $\alpha_s = 0.4$**

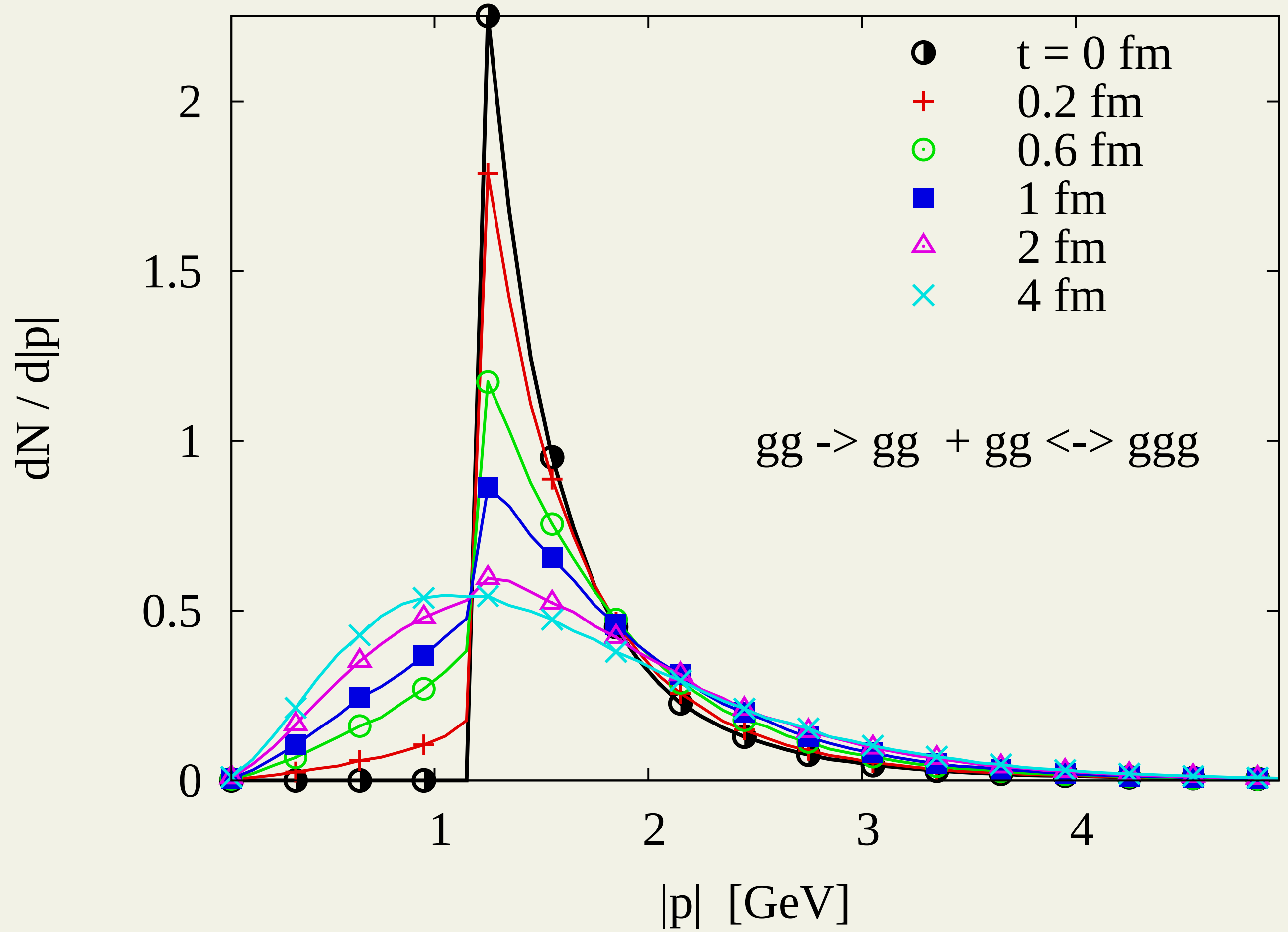
for simplicity: use correct $\sigma_{23}(s)$ but isotropic outgoing momenta

DM & Hemphill ('13): **energy distribution in box ($\propto p^2 e^{-p/T}$ in equilibrium)**



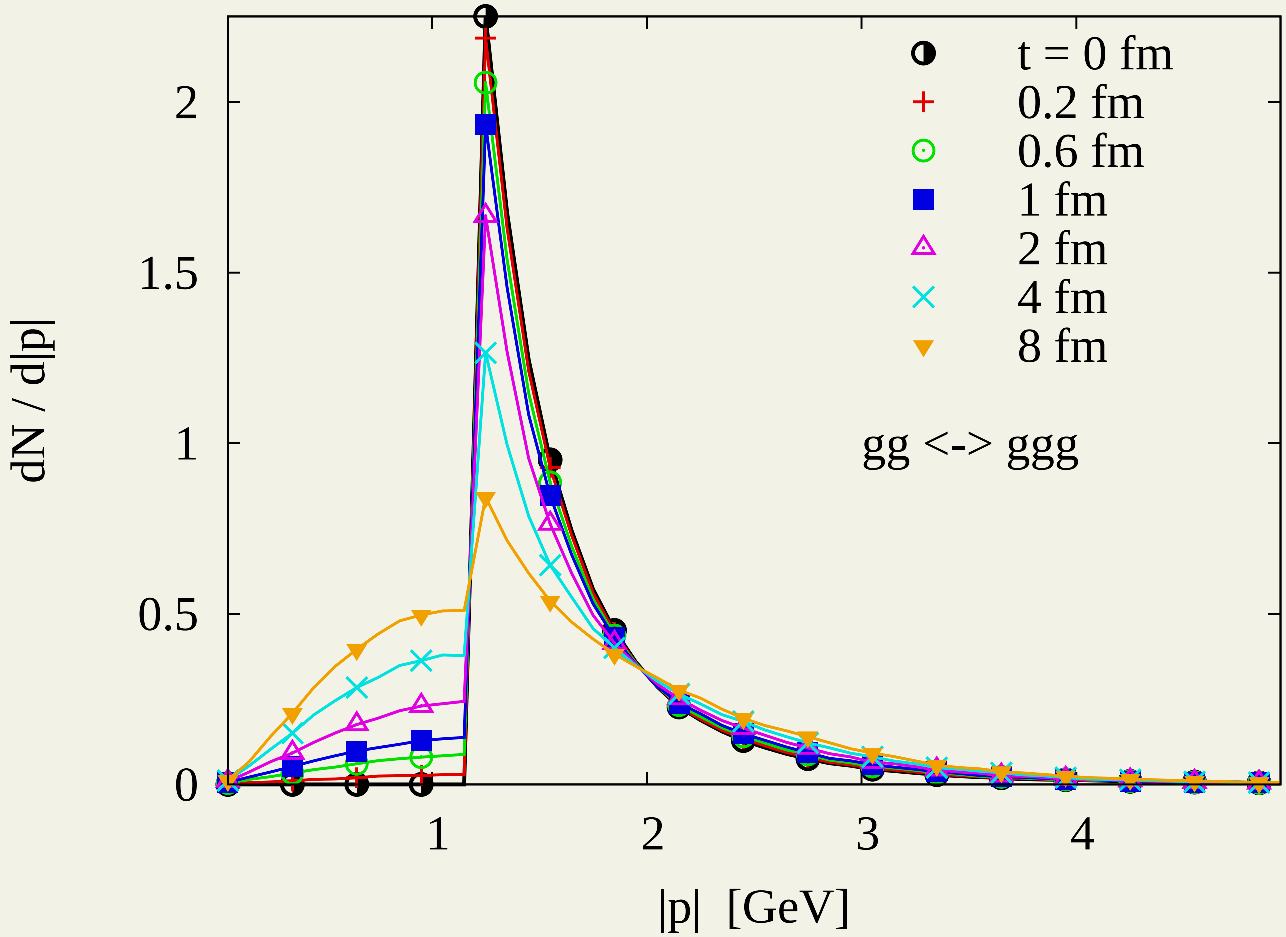
$\tau_{eq} \sim 1 - 2$ **fm**

DM & Hemphill ('13): **energy distribution in box ($\propto p^2 e^{-p/T}$ in equilibrium)**



$\tau_{eq} \sim 1 - 2$ **fm**

DM & Hemphill ('13): **energy distribution in box ($\propto p^2 e^{-p/T}$ in equilibrium)**



$4 - 8$ **fm(??)**

but BAMPS has local Debye mass from linear response e.g., Biro et al, PRC48

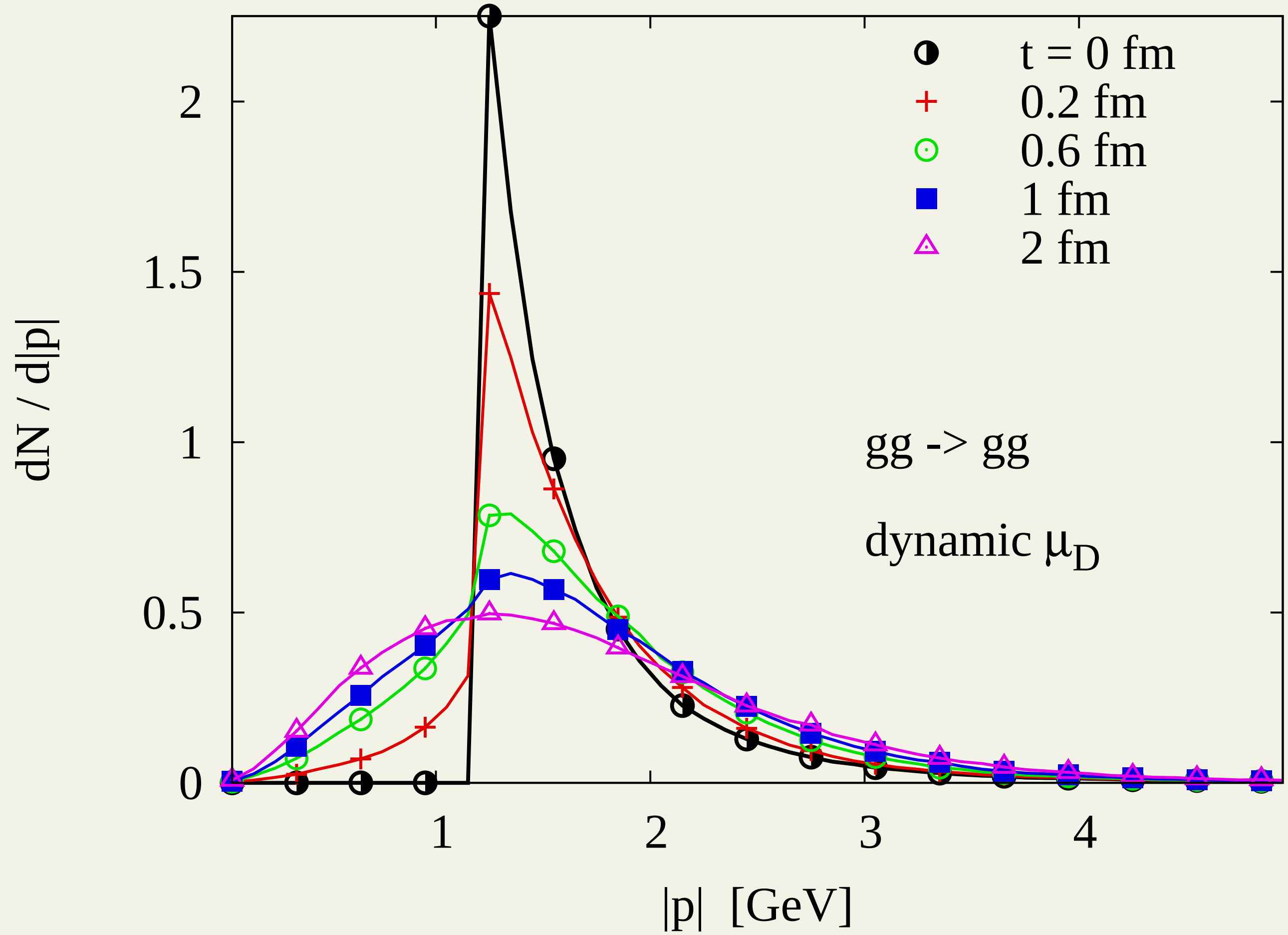
$$\mu_D^2[f] = 3\pi\alpha_s \int d^3p \, \frac{1}{p} \, f_g(\vec{p}) \qquad\qquad [\, f_{eq} = 16/(2\pi)^3 \times e^{-p/T} \,]$$

could matter out of equilibrium, so put it in (transverse $\vec{x}_T$ average for statistics)

Watch out, this reproduces $\mu_D = gT$ with Bose distribution, but for Boltzmann:

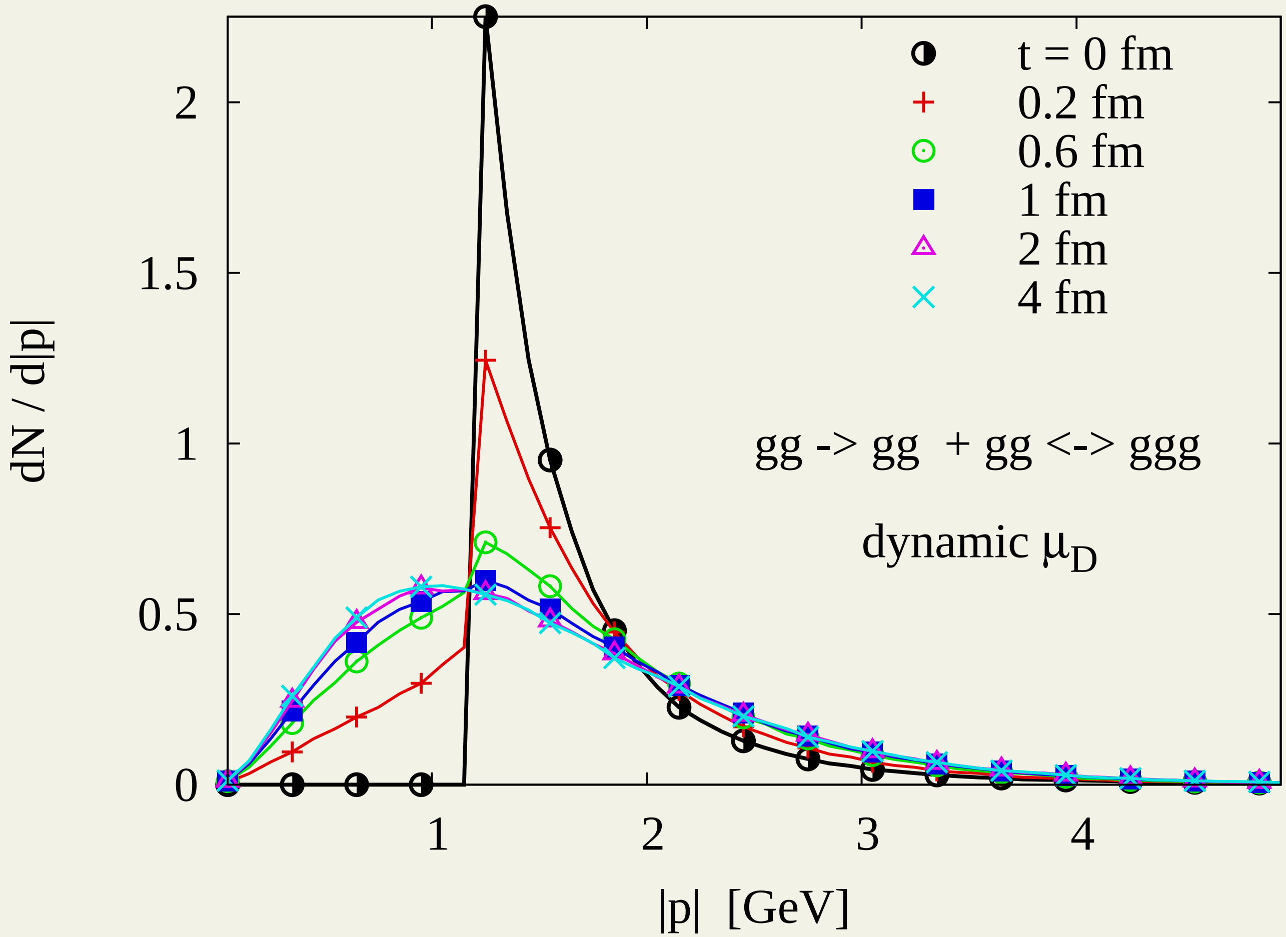
$$\mu_D^2 = \frac{6}{\pi^2} g^2 T^2 \quad < \quad g^2 T^2 \quad \Rightarrow \quad \text{larger rates(!)}$$

DM & Hemphill ('13): **energy distribution in box ($\propto p^2 e^{-p/T}$ in equilibrium)**



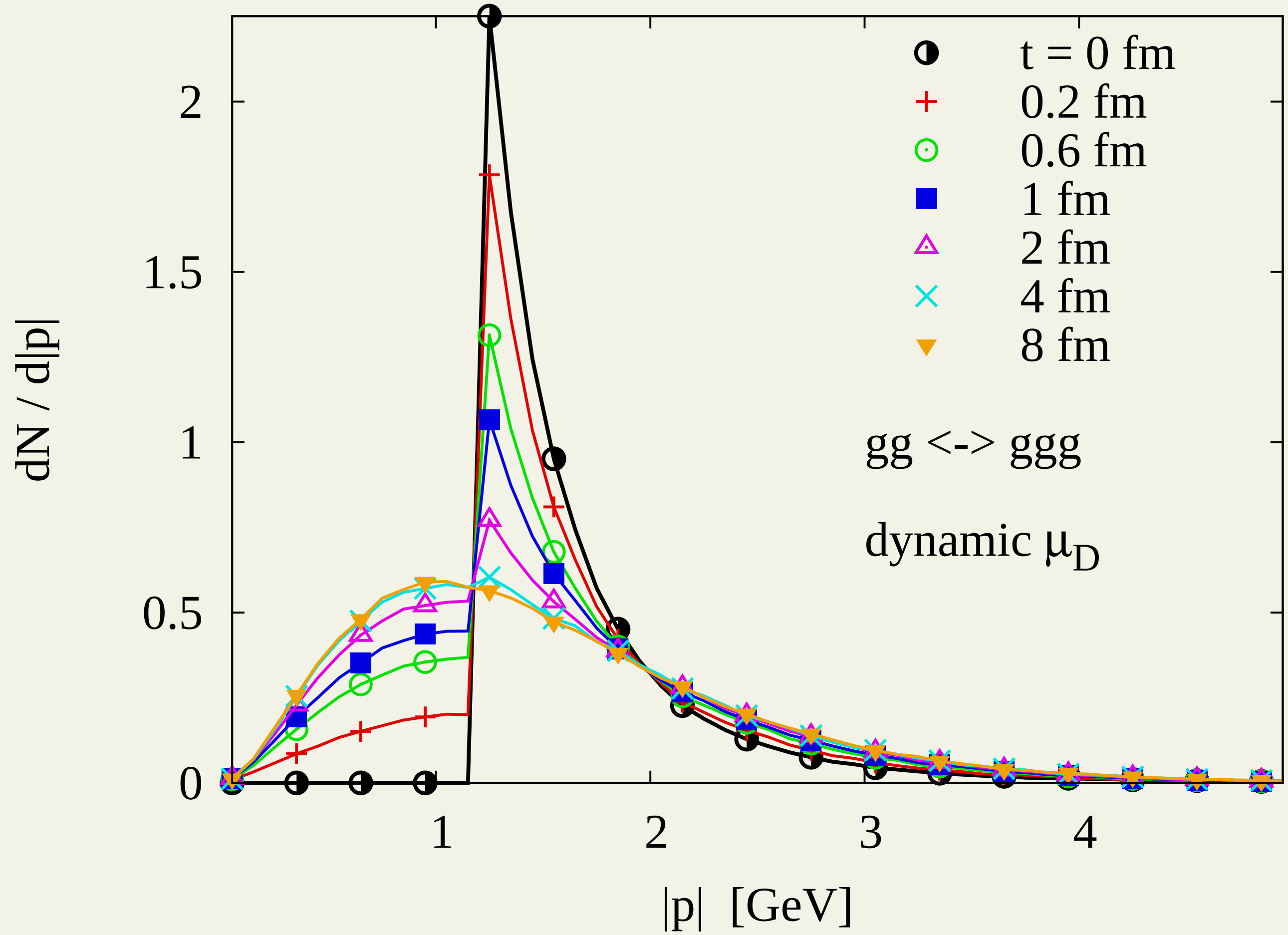
$\tau_{eq} \sim 0.5 - 1$ **fm**

DM & Hemphill ('13): **energy distribution in box ($\propto p^2 e^{-p/T}$ in equilibrium)**



$\tau_{eq} \sim 0.3 - 0.5$ **fm**

DM & Hemphill ('13): **energy distribution in box ($\propto p^2 e^{-p/T}$ in equilibrium)**



$1 - 1.5$ **fm(!)**

$6\times$ **higher rate due to smaller** μ_D **because** $\sigma_{gg\to ggg}$ **is very sensitive to** μ_D

Elliptic flow

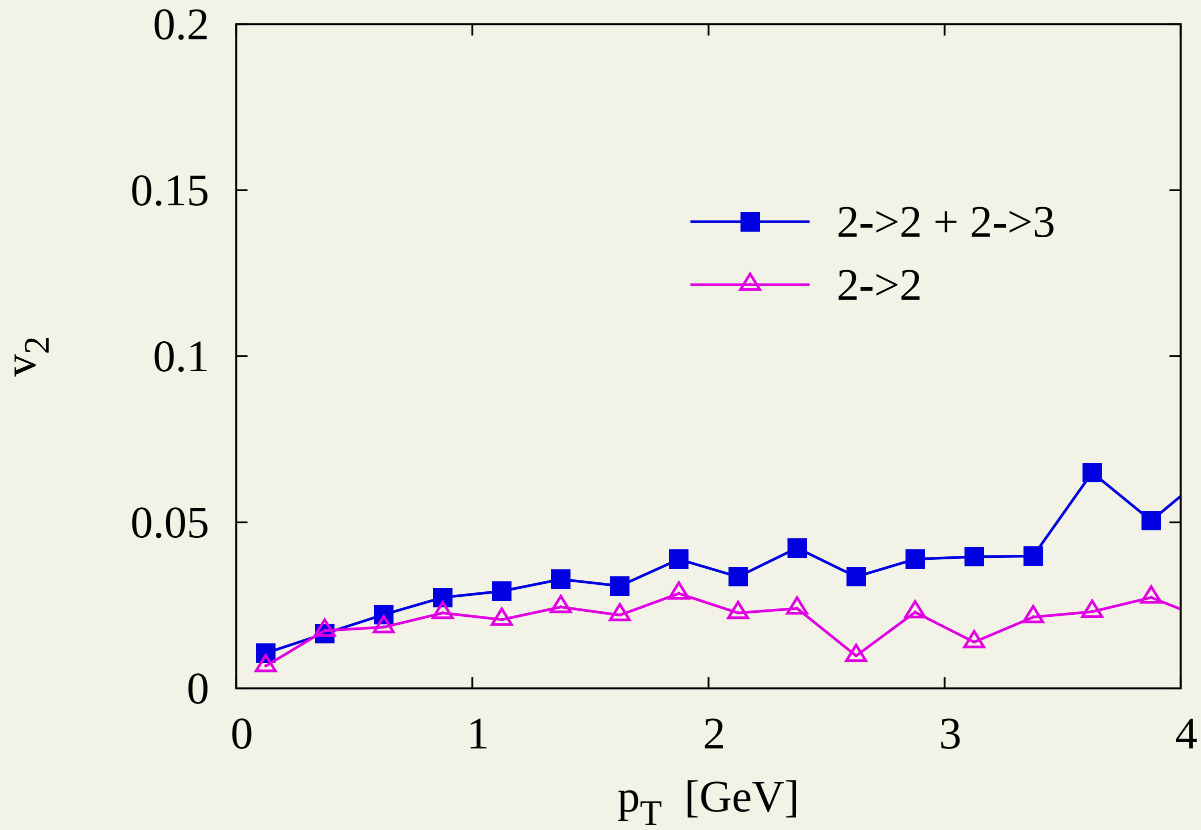
- longitudinal boost Bjorken invariance
- $\tau_0 = 0.6$ fm
- transverse density: Glauber (binary coll) profile

$$\frac{dN}{d\eta d^2 x_T} = \frac{dN}{d\eta} \times \frac{T_A(\vec{x}_T - \vec{b}/2) T_A(\vec{x}_T + \vec{b}/2)}{T_{AB}(b)}$$

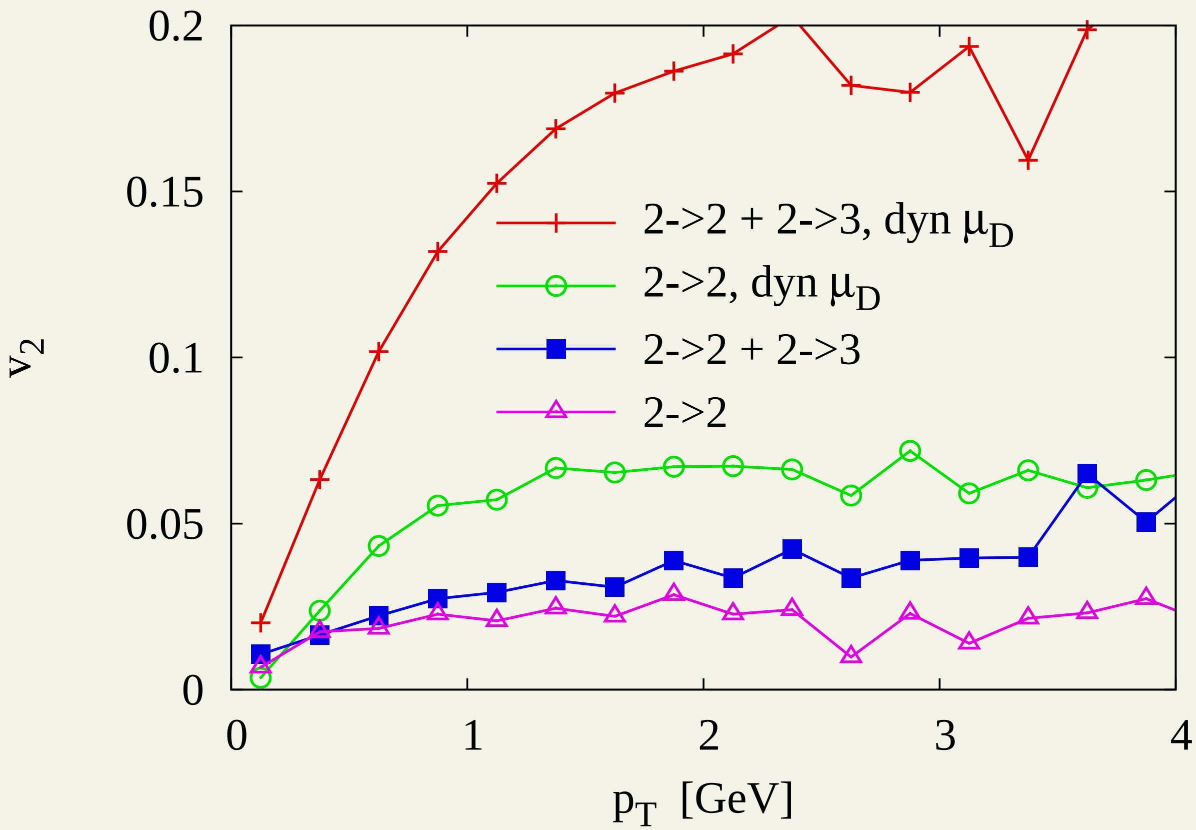
- momentum distribution: locally thermal at $T_0 = 0.5$ GeV
- fixed $\alpha_s = 0.4$, and dynamic $\mu_D[f]$ or $\mu_D \propto \tau^{-1/3}$

apply to RHIC Au+Au at $b = 8$ fm

RHIC Au+Au at $b = 8$ fm, with $\mu_D = gT_0(\tau_0/\tau)^{1/3}$

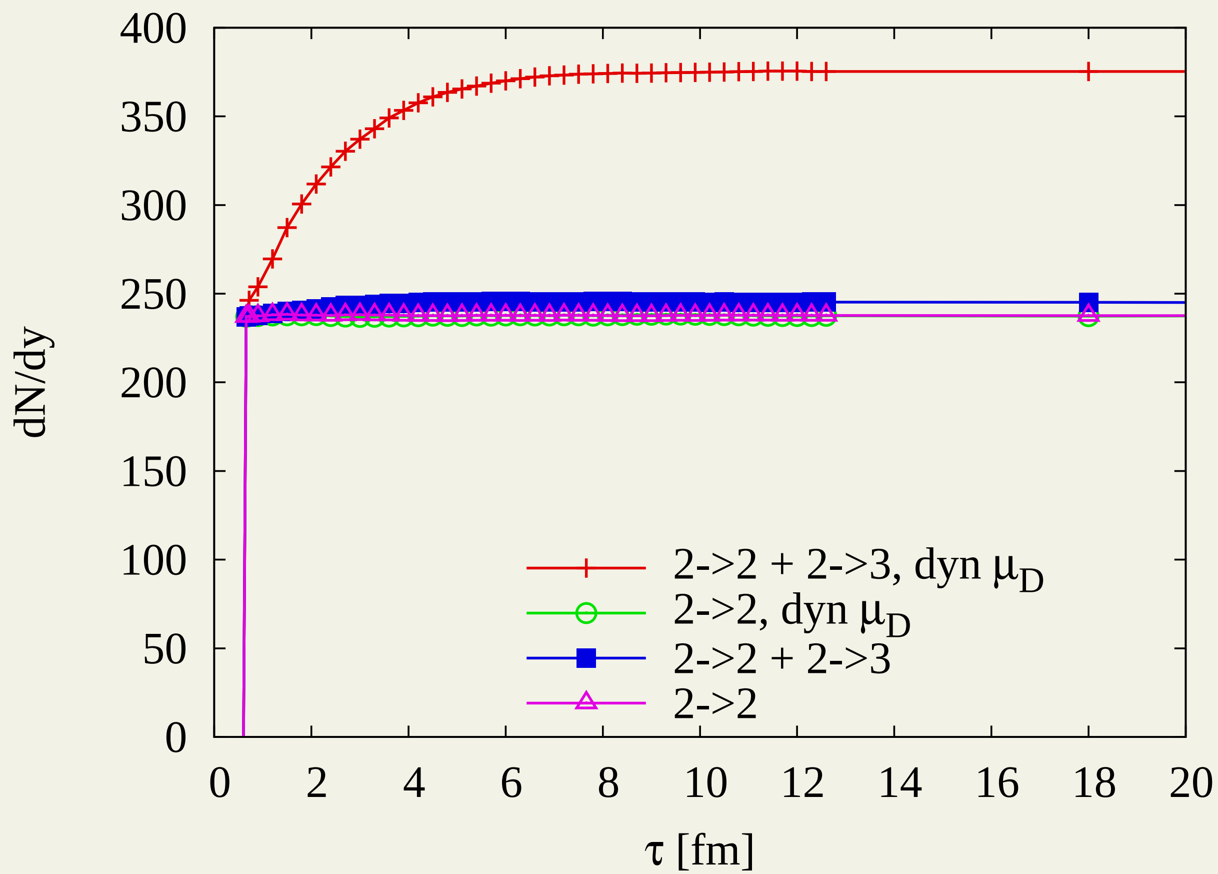


RHIC Au+Au at $b = 8$ fm, dynamical μ_D vs $\mu_D = gT_0(\tau_0/\tau)^{1/3}$



dynamical μ_D helps a lot

result with dynamically screened $gg \to ggg$ is not the final word because



$\Rightarrow$ **will need better constrained initconds (chemically better saturated)**

Message:

- **hard to reproduce BAMPS results, not clear what they did**
- **big sensitivity to screening, dynamical μ_D looks crucial**
- **we get significantly smaller thermal rates than BAMPS**

Self-consistent viscous δf

DM & Zack Wolff (& Qiang Zhang)

Hydro $\to$ particles

$$T^{\mu\nu}(x) \equiv \sum_i \int \frac{d^3p}{E} p^\mu p^\nu f_i(p,x)$$

- **in local equilibrium (ideal hydro) - "one to one"**

$$T^{\mu\nu}_{LR}(x) = diag(e,p,p,p) \qquad \Leftrightarrow \qquad f_{eq,i}(x,p) = \frac{g_i}{(2\pi)^3} e^{-p^\mu u_\mu / T}$$

- **near local equilibrium (viscous hydro) - "few to many"**

$$T^{\mu\nu}(x) = T^{\mu\nu}_{ideal}(x) + \pi^{\mu\nu}(x) \qquad \Leftarrow \qquad f(x,p) = f_{eq,i}(x,p) + \delta f_i(x,p)$$

common choice - "democratic" Grad ansatz: $\delta f_i \equiv f_i^{eq} \times \frac{\pi^{\mu\nu}}{2(e+p)} \frac{p_{\mu,i} p_{\nu,i}}{T^2}$

2 dissipative effects: - **corrections to equilibrium values** u^μ, T, n
- **corrections to thermal distributions** $f \to f_0 + \delta f$

Problem: “democratic Grad” ignores microscopic dynamics

$$\delta f_i \equiv f_i^{eq} \times \frac{\pi^{\mu\nu}}{2(e+p)} \frac{p_{\mu,i} p_{\nu,i}}{T^2}$$

instead of

$$\delta f_i \equiv f_i^{eq} \times \chi_i\left(\frac{\tilde{p}}{T}\right) \pi^{\mu\nu} \frac{p_{\mu,i} p_{\nu,i}}{T^2}$$

$\rightarrow$ **use instead a nonequilibrium approach: linearized kinetic theory**

DM, JPG38 ('11); DM & Wolff, arXiv:1404.7850

$$p^\mu \partial_\mu f_{eq,i} = \sum_j C_{ij}[f_{eq,i}, \delta f_j] + C_{ij}[\delta f_i, f_{eq,j}]$$

$$\delta f_j = \chi_j(p/T) \frac{p^\mu p^\nu \pi_{\mu\nu}}{2(e+p)T^2} f_{eq,j}$$

democratic: $\chi_j = \frac{\eta}{2s}$, **dynamical Grad:** $\chi_j = C_j \frac{\eta}{2s}$ **($\mu_B = 0$)**

Dynamics of hadron gas matters $\Rightarrow$ species dependent correction factors

σ_{ij} = const

	T = 100	120	140	165 MeV
π	1.08	1.13	1.17	1.21
K	0.89	0.96	1.02	1.08
η	0.87	0.94	1.00	1.06
f_0	0.85	0.92	0.98	1.04
ρ	0.80	0.87	0.93	0.99
ω	0.80	0.86	0.93	0.99
K^*892	0.77	0.83	0.90	0.96
N	0.76	0.82	0.88	0.94
η'(958)	0.75	0.82	0.88	0.94
f_0(980)	0.75	0.81	0.87	0.93
a_0(980)	0.75	0.81	0.87	0.93
ϕ(1020)	0.74	0.81	0.86	0.92
Λ	0.72	0.79	0.84	0.90
...				

$\sigma_{MM} : \sigma_{MB} : \sigma_{BB}$ = 4 : 6 : 9

	T = 100	120	140	165 MeV
π	1.08	1.15	1.21	1.27
K	0.90	0.98	1.06	1.14
η	0.88	0.95	1.03	1.12
f_0	0.86	0.94	1.01	1.10
ρ	0.80	0.88	0.96	1.04
ω	0.80	0.88	0.95	1.04
K^*892	0.77	0.85	0.92	1.01
N	0.56	0.62	0.68	0.74
η'(958)	0.76	0.83	0.91	0.99
f_0(980)	0.75	0.83	0.90	0.98
a_0(980)	0.75	0.83	0.90	0.98
ϕ(1020)	0.75	0.82	0.89	0.97
Λ	0.53	0.59	0.64	0.70
...				

corrections drop with mass even for $\sigma_{ij} = const$(!)

one-component system in NR limit:

$$\chi^{Grad} = \frac{5\sqrt{\pi}}{32}\sqrt{\frac{T}{m}}\frac{T}{n\sigma_{TOT}} \qquad \eta_s^{Grad} = \frac{5\sqrt{\pi}}{16}\frac{\sqrt{mT}}{\sigma_{TOT}}$$

two-component system in NR limit, with $n_B \ll n_A$:

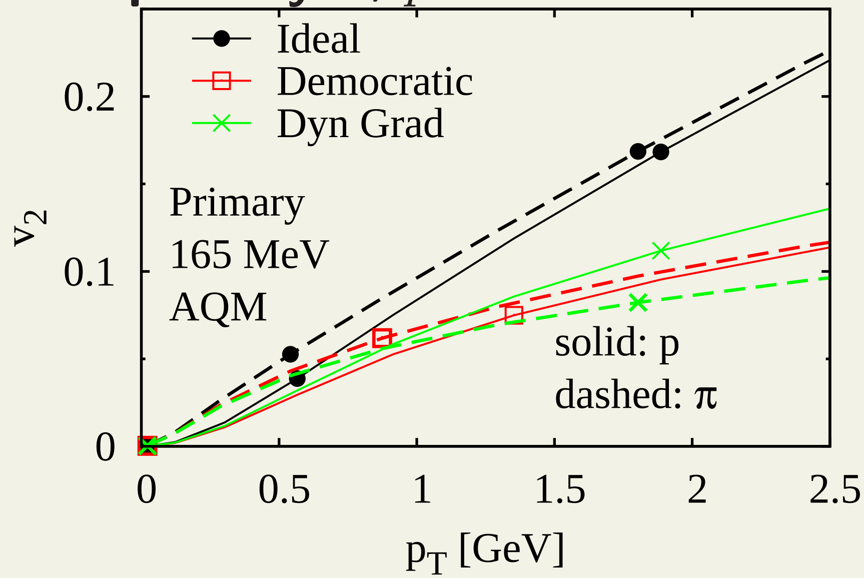
$$\chi_A^{Grad}\Big|_{n_B\to 0} = \frac{5\sqrt{\pi}}{32}\sqrt{\frac{T}{m_A}}\frac{T}{\sigma_{AA}n_A} \quad ,$$

$$\chi_B^{Grad}\Big|_{n_B\to 0} = \chi_A^{Grad}\frac{3(\mu+1)^2\sigma_{AA} + 2\sqrt{2\mu(1+\mu)}\sigma_{AB}}{\sqrt{2\mu(1+\mu)}(3+5\mu)\sigma_{AB}} \qquad \left(\mu = \frac{m_B}{m_A}\right) \ .$$

[DM & Wolff, arXiv:1404.7850]

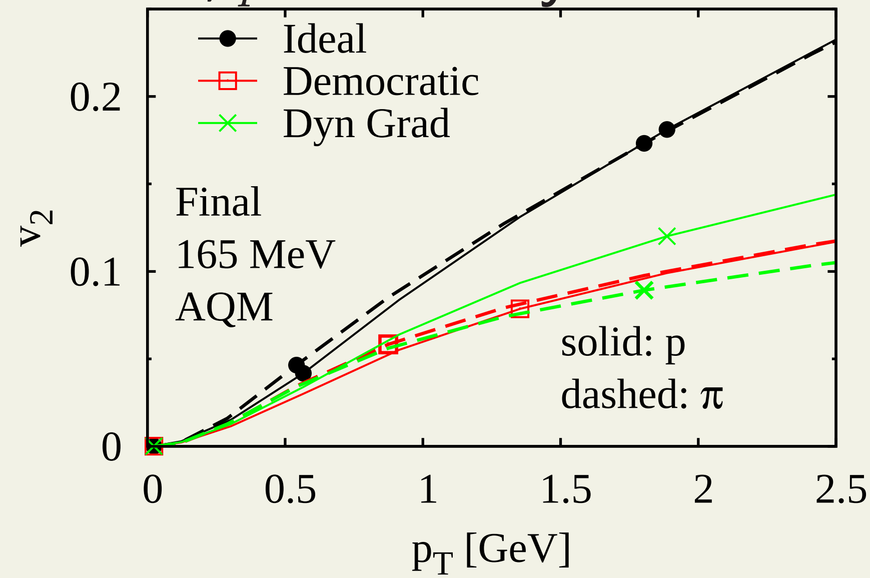
Affects v_2 at RHIC

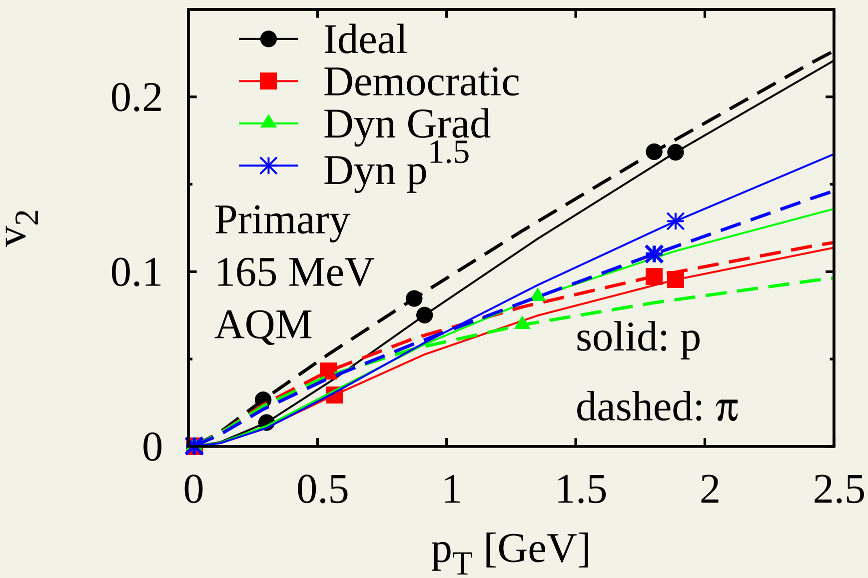
primary π, p



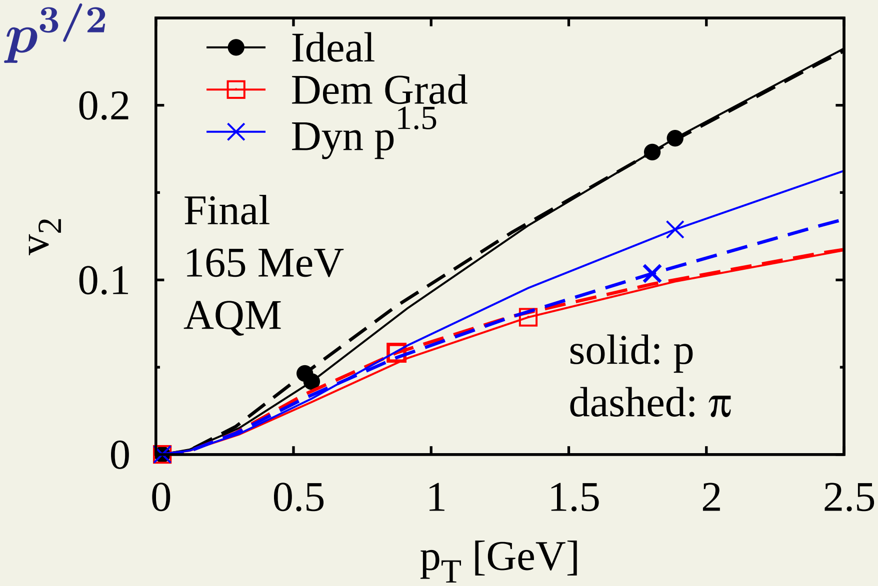
Grad

π, p **after decays**



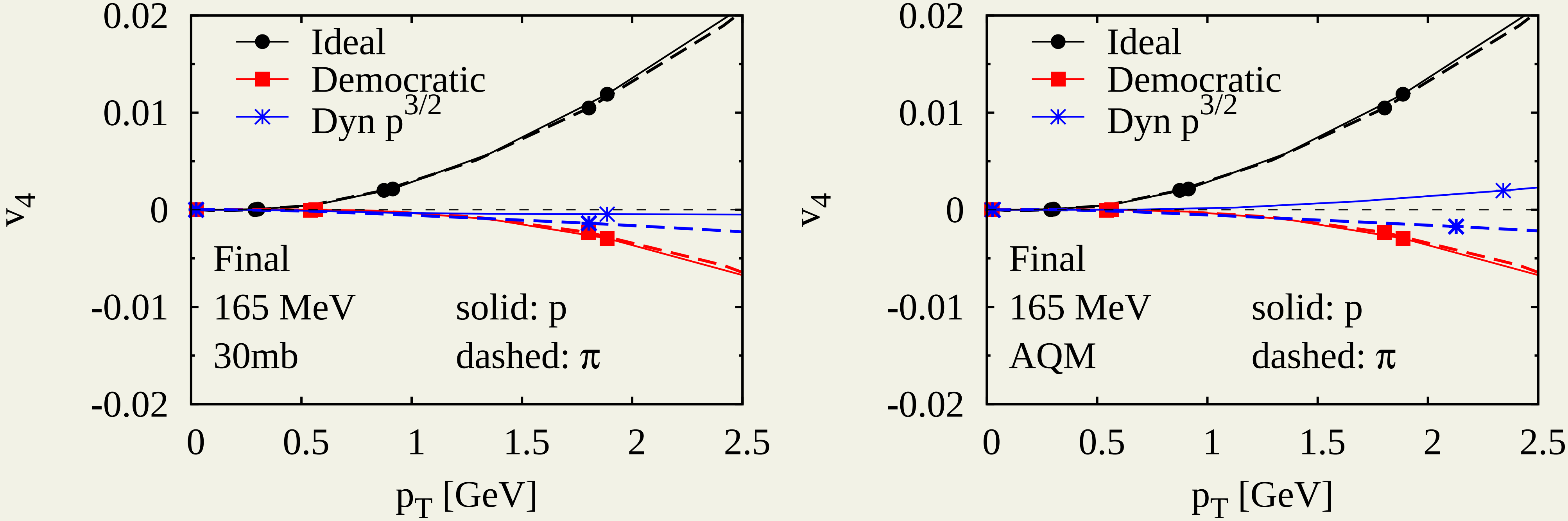


$\delta f \propto p^{3/2}$



Also affects v_4 (and v_6)

v_4 **after resonance decays, with** $\delta f \propto p^{3/2}$

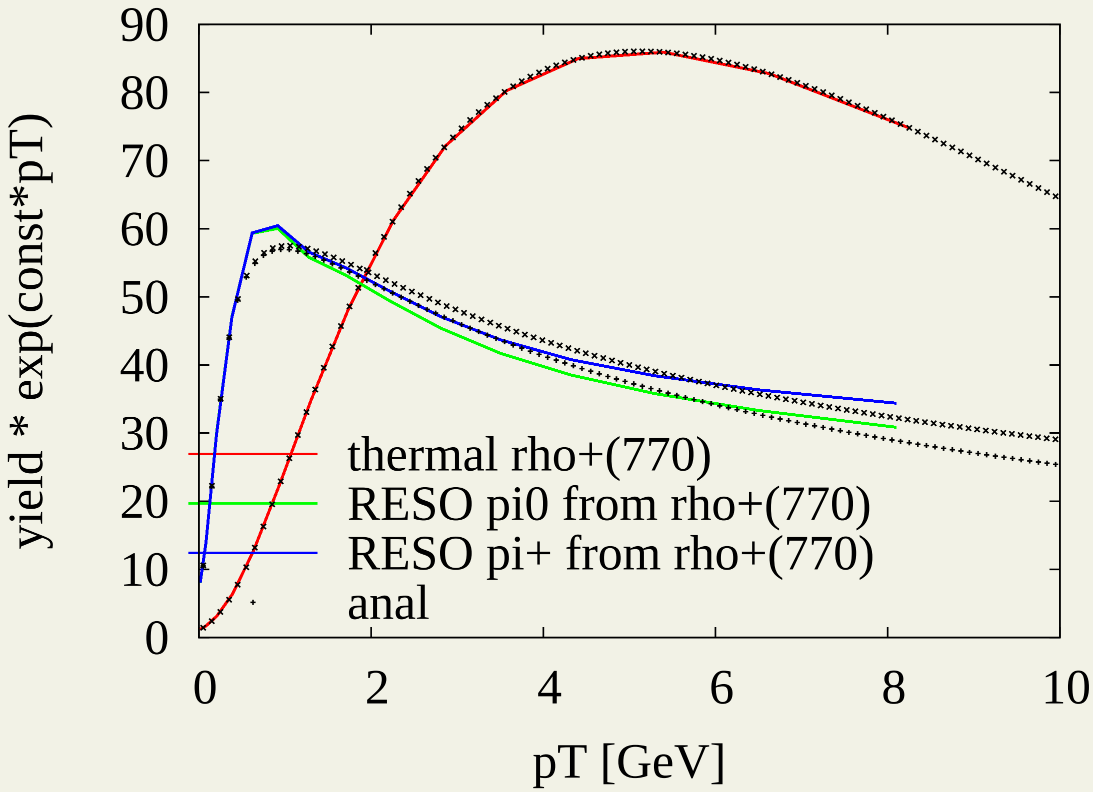


RESO not super accurate

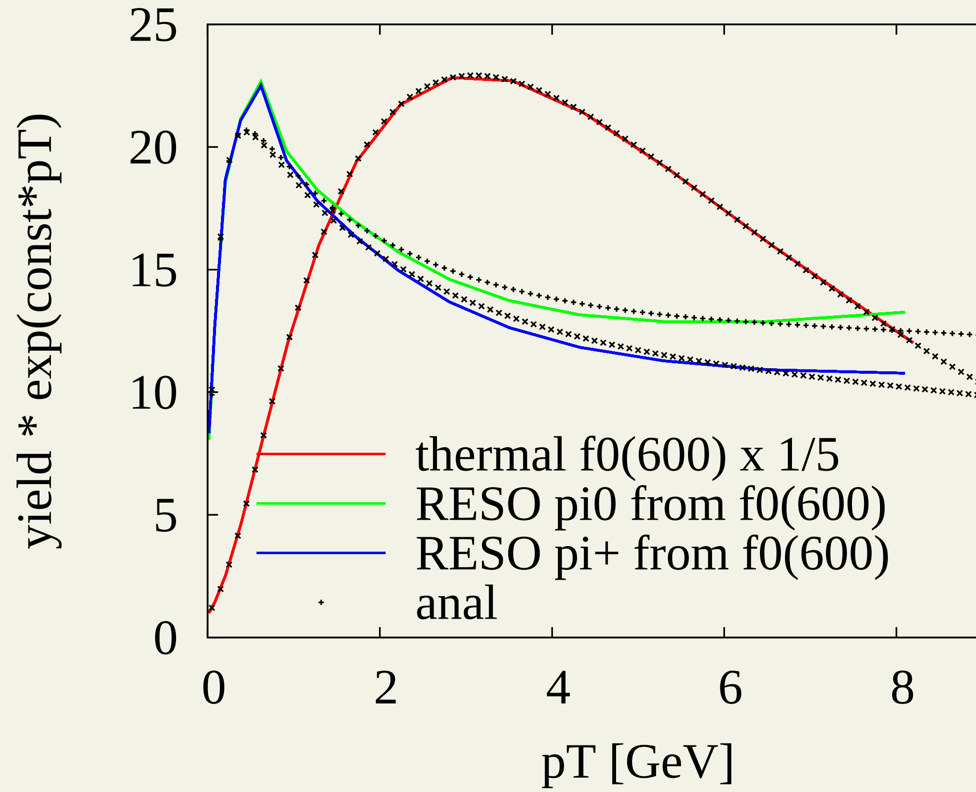
test of AZHYDRO/RESO, anno 1994 Sollfrank, Heinz et al

daughter spectra for static thermal resonance input, divide by convenient $\exp(const \times pT)$ **factor**

$\rho \to \pi\pi$



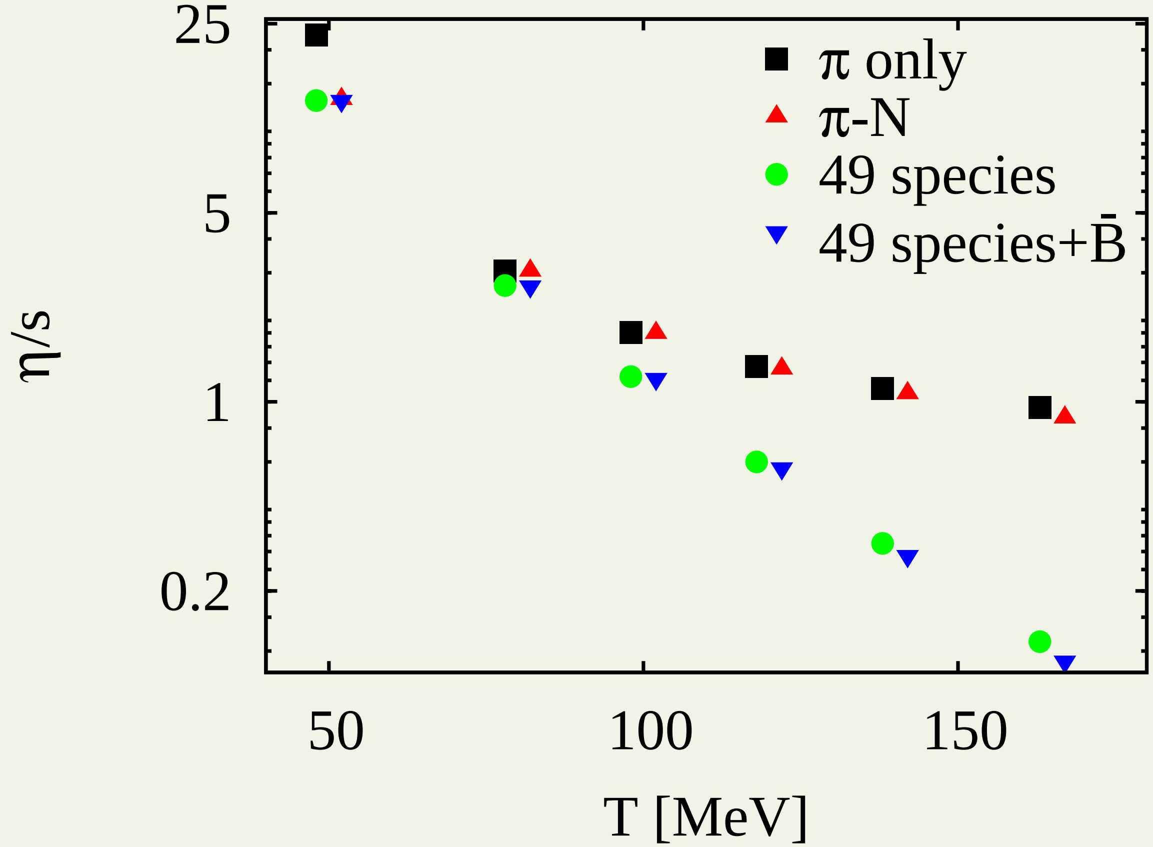
$f_0 \to \pi\pi$



Hadron gas viscosity

with realistic $\sigma(s)$ **for** $\pi - \pi$ **and** $\pi - N$

or $\sigma_{MM} = 30$ **mb for all hadrons up to** ~ 1.7 **GeV**



Message:

- viscous corrections depend on hadron species
- self-consistent δf_i can be obtained from kinetic theory
- dynamical treatment affects harmonic flow
- should explore more in hydro and hydro+transport models

  $\rightarrow$ use our tabulated corrections in Appendix F of arXiv:1404.7850 available for $\delta f \propto p^n$ with $n = 1$, 1.5, 2

Year 5

- **GLV + bulk dynamics (MPC/Eloss)**

- running α_s, fluctuations in emission momenta/number

  $\rightarrow$ ideally merge forces with Columbia

- heavy quarks with covariance

- **radiative transport MPC/Grid**

- shear viscosity

- truly local $\mu_D(x_T, \eta)$

- initconds/dynamics that reproduces basic RHIC/LHC observables

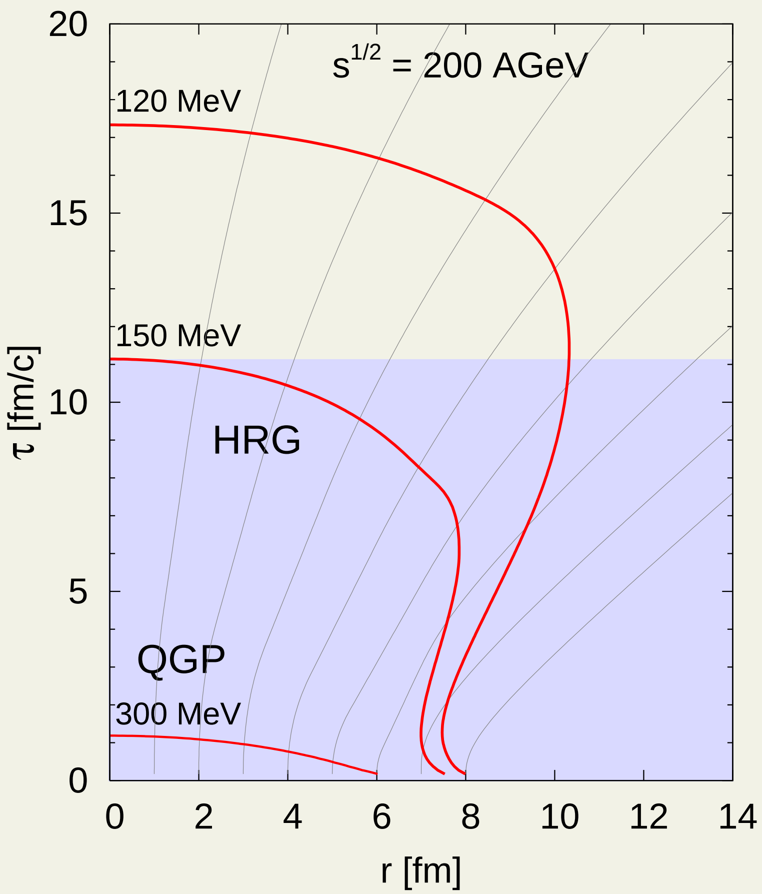
- **viscous fluid-particle conversion (δf)**

- bulk viscous δf

- self-consistent δf in hybrid hydro+transport approach

- dynamical hydro-transport coupling

MUST couple hydro and transport dynamically in shaded region below. From pure hydro, $T = const$ hypersurface is physically inconsistent (ignores breakdown of hydro outside hypersurface).



[adapted from Fig. 2 of Huovinen & Ruuskanen, Ann. Rev. Nucl. Part. Sci. 56 ('06)]