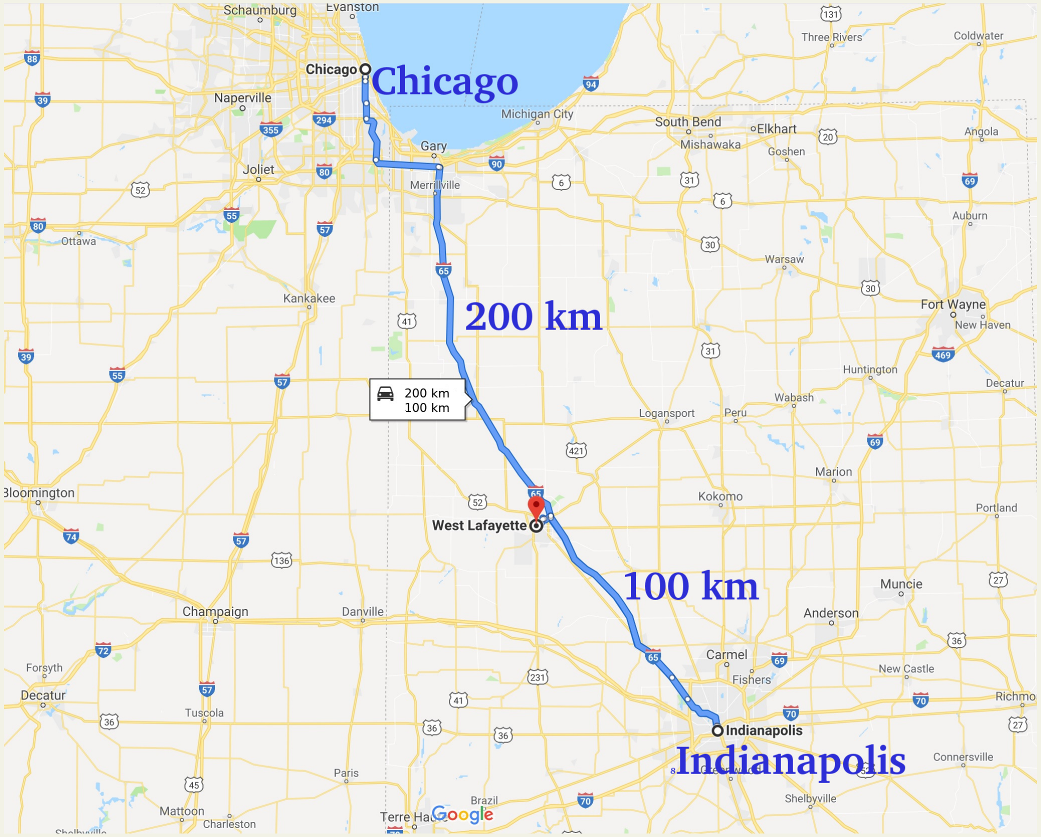
Large v_2 with small cross section

Denes Molnar, Purdue University & Wigner RCP

Balaton Workshop 2019
Tihany, Hungary, June 17-21, 2019

PURDUE
UNIVERSITY

U.S. DEPARTMENT OF
ENERGY
Office of
Science



Purdue University

→ www.purdue.edu

∼ 2 hrs to Chicago (QM2017)
∼ 1 hr to Indianapolis (F1 racing)

∼ 50 000 students

∼ 150 physics grad students

∼ 60 physics professors

High-E Nuclear Physics Group

→ Fuqiang Wang, Wei Xie, DM

Outline

I. AMPT puzzle (hydro vs small cross sections)

II. Covariant transport and MPC

III. Understanding AMPT through MPC comparisons

IV. Summary - how small cross sections can work

A Multi-Phase Transport

Lin, Ko et al, PRC72 ('05)

full-fledged multicomponent event generator

$$\begin{aligned}\textbf{AMPT} \approx\ & \textbf{Lund string model (HIJING)} \\ & + 2 \to 2\ \textbf{parton cascade (ZPC)} \\ & + \textbf{hadron transport (ART)}\end{aligned}$$

version with "string melting":

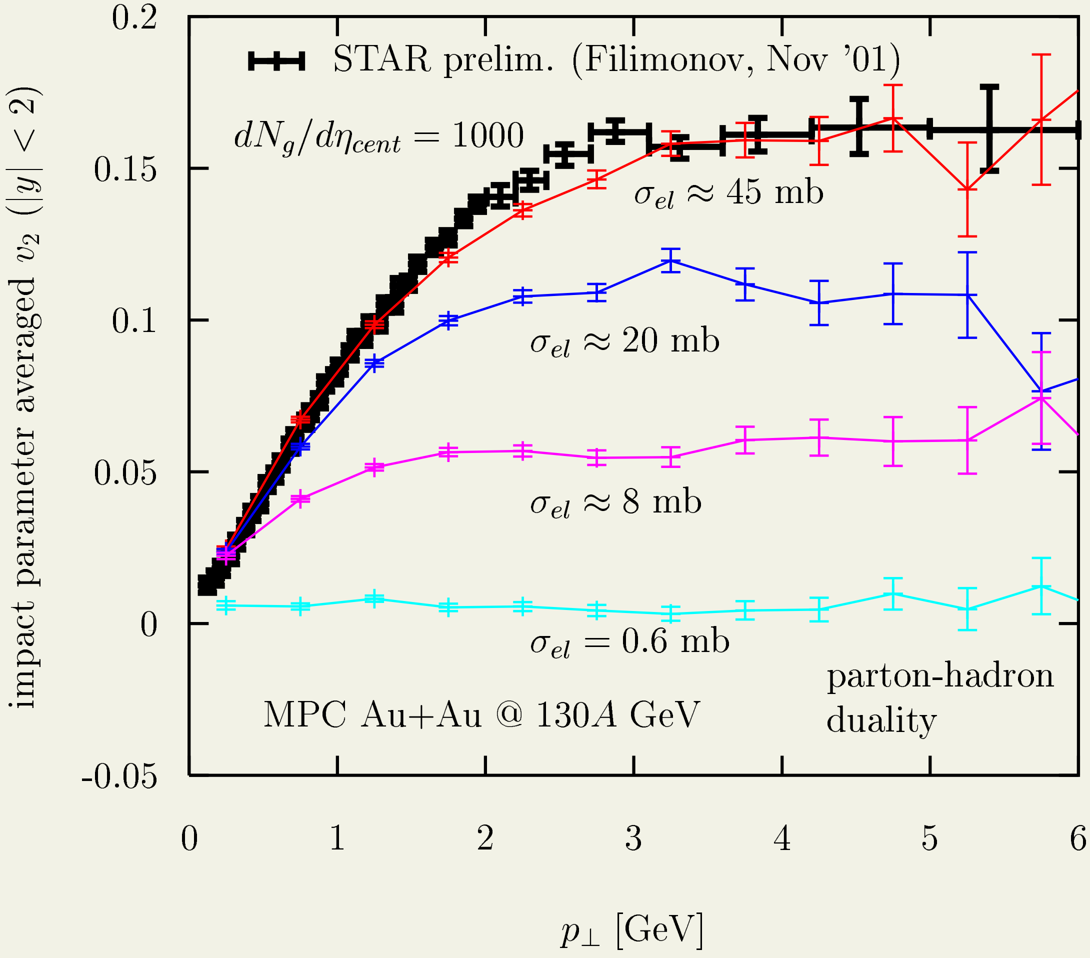
- **energy density in strings converted to quanta (quarks/antiquarks)**
- → **fluctuating initial geometry (random nucleon positions)**
- **hadronization via coalescence**

explains quite well a wide range of A+A observables

- **using small** ~ 3 **mb partonic cross sections (!?)**

Parton opacity puzzle

DM & Gyulassy, NPA 697 ('02): **$v_2(p_T, \chi)$ in Au+Au at RHIC**



parton transport model MPC

$2 \to 2$ **only, forward-peaked**

$\sigma_{tr} \approx 0.3\sigma_{tot}$

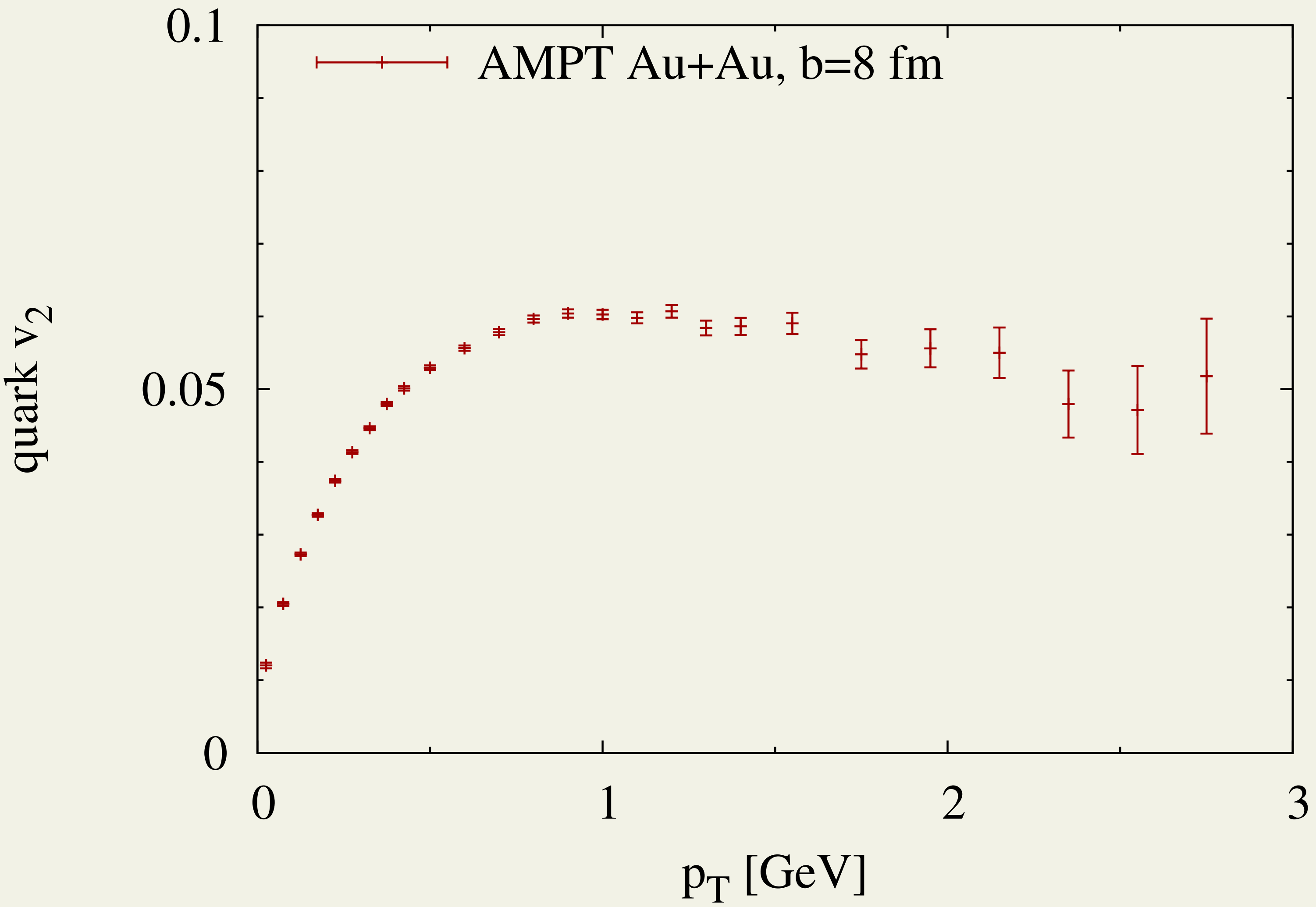
Au+Au @ 130 GeV, $b = 8$ fm

- minijet initconds
- 1 parton $\to$ 1 π hadronization

perturbative $\sigma_{gg\to gg} \approx 3$ mb gives $v_2 \approx 2\%$ → need $15\times$ higher opacity

radiative $gg \leftrightarrow ggg$ helps (e.g., BAMPS)... but AMPT has pure elastic $2 \to 2$

quark v_2 from AMPT for 200-GeV Au+Au, b=8 fm



$v_2 \approx 6\%$ with only $\sigma_{qq} = 3$ mb... yet $\sim$15% hadron v_2 (30% centrality)

v_2 amplified by coalescence

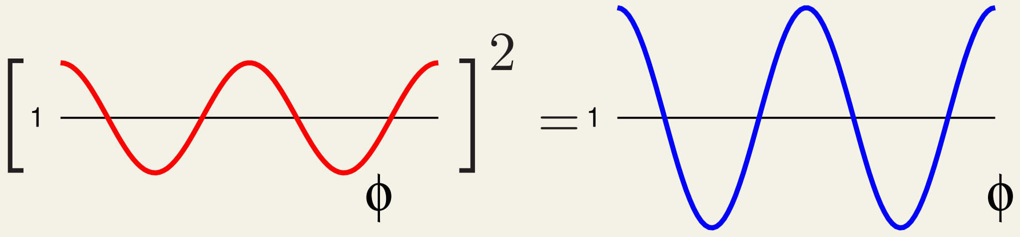
Ko, Lin, Voloshin, DM, Greco, Levai, Mueller, Fries, Bass, Nonaka, Asakawa ...

coalescence of comoving quarks: $q\bar{q} \Rrightarrow\!\!\longrightarrow M \qquad 3q \Rrightarrow\!\!\Longrightarrow B$

DM & Voloshin, PRL91 ('03)

$$\frac{dN_M(p_T)}{d\phi} \propto \left[\frac{dN_q(p_T/2)}{d\phi}\right]^2$$

$$\frac{dN_B(p_T)}{d\phi} \propto \left[\frac{dN_q(p_T/3)}{d\phi}\right]^3$$

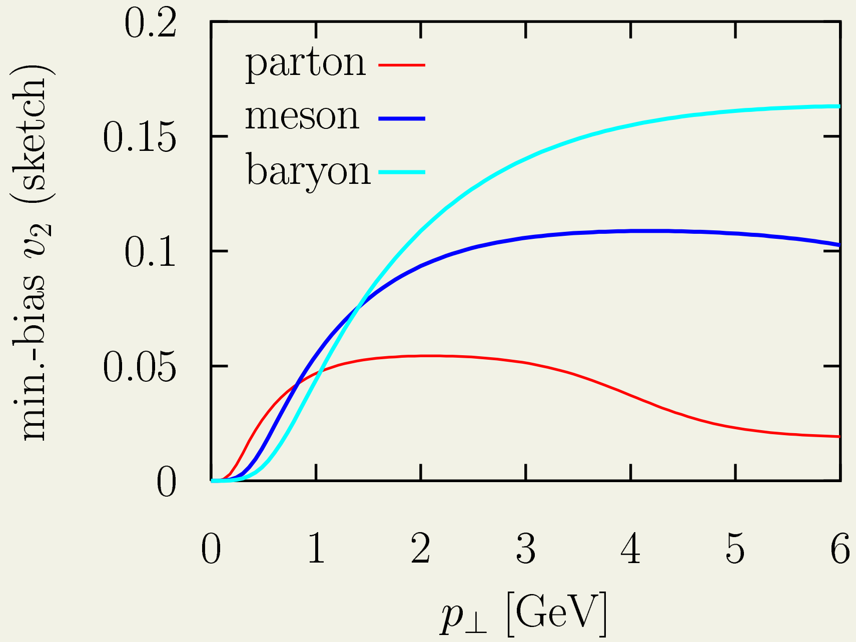


squared/cubed probability → amplified v_2

$$v_2^{hadron}(p_\perp) \approx n \times v_2^{quark}(p_\perp/n)$$

$\left.\begin{array}{l} 3\times \textbf{ for baryons} \\ 2\times \textbf{ for mesons} \end{array}\right\}$ **50% larger v_2 for baryons**

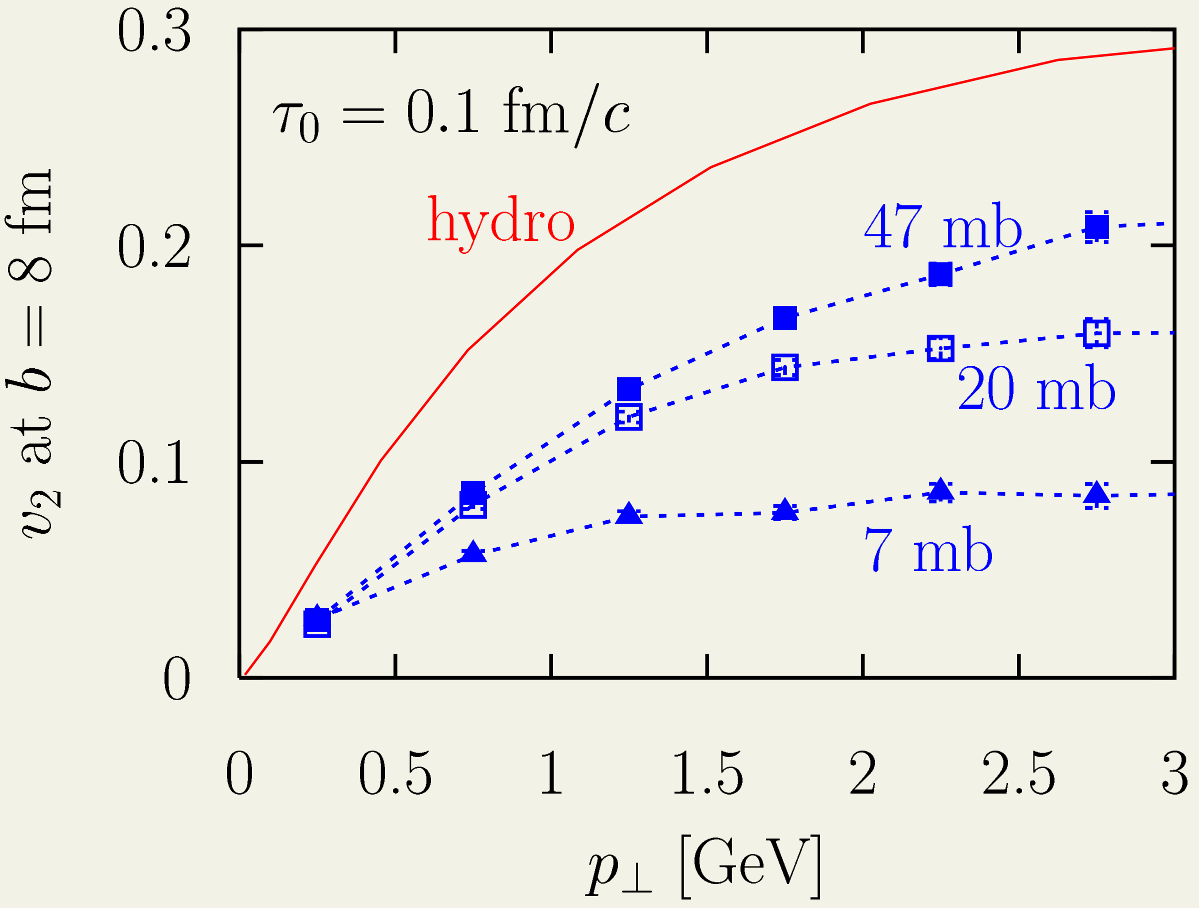
→ 5× **for pentaquark,** 6× **for deuteron**



⇒ AMPT can get hadron v_2 with lower opacity... in principle

could we be in or near the hydro limit? → No.

DM & Huovinen, PRL94 ('05)

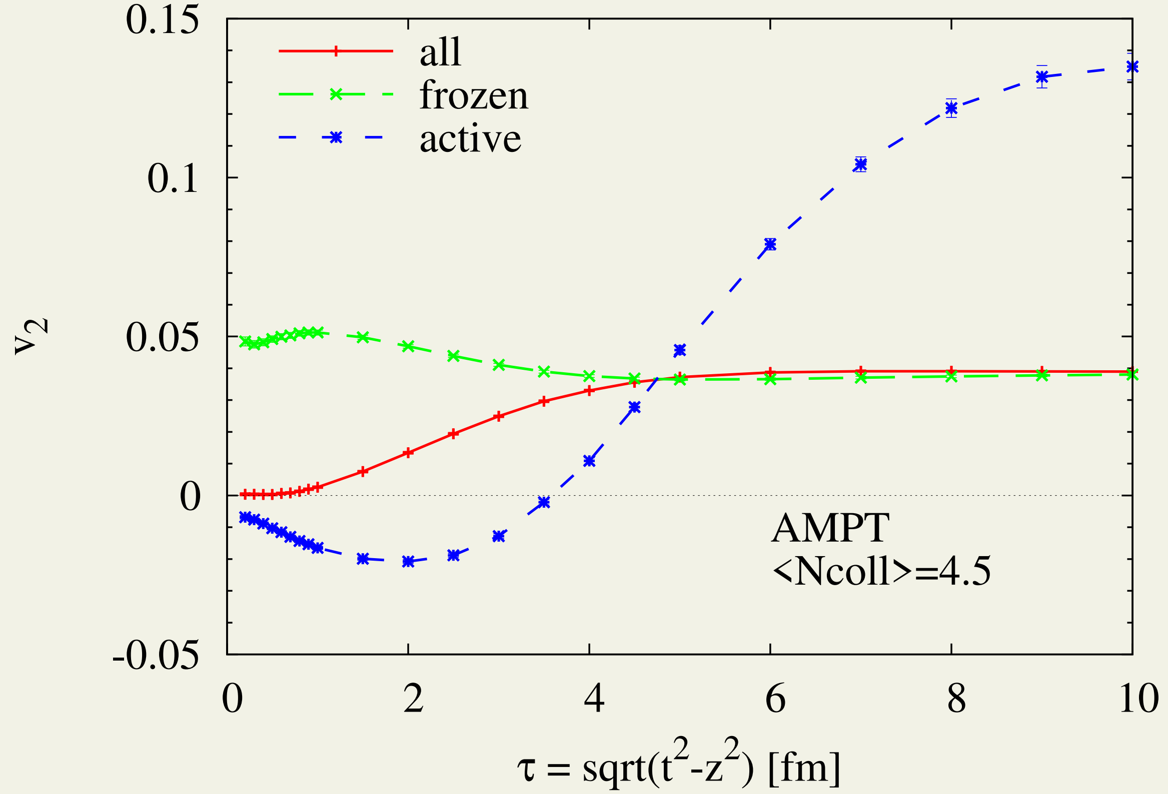


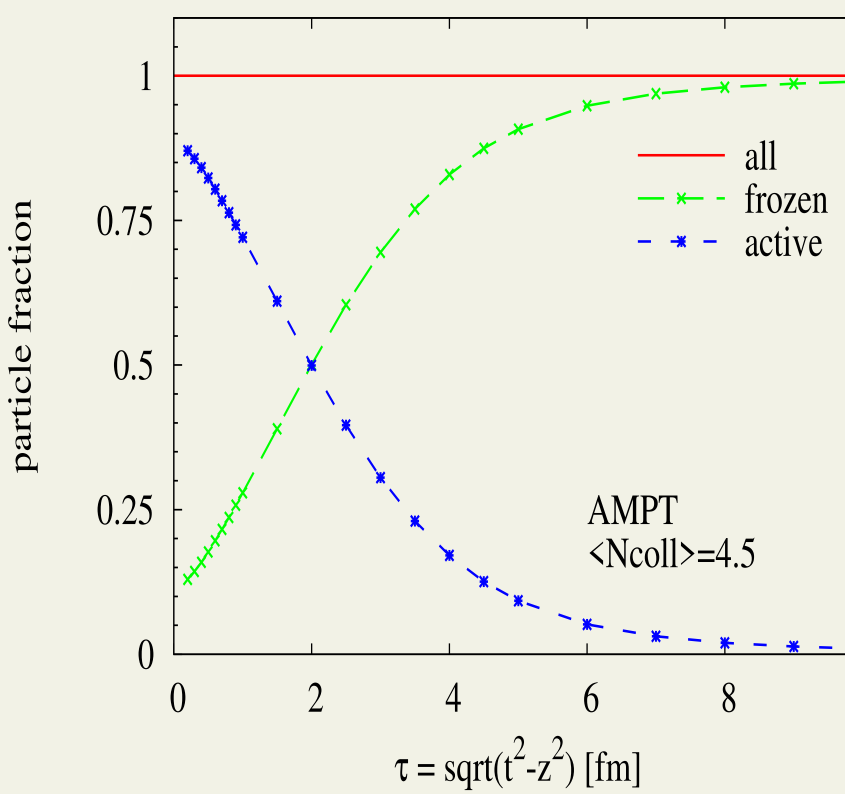
- $2 \to 2$ **parton kinetic theory is definitely not ideal hydro**
- **for large $\sigma \sim 40 - 50$ mb, viscous hydro is reachable** Huovinen & DM, JPG35 ('08)

AMPT $\neq$ Hydro

AMPT's v_2 comes from "anisotropic escape" He et al, PLB 753 ('15); Li et al, ...

DM et al ('15): **AMPT v_2 vs Bjorken τ**





- **for long time, still interacting partons carry nearly zero or even negative v_2**
- **almost all v_2 is carried by frozen-out partons**
- **the combined parton v_2 rises than saturates as expected** Ko, Zhang, Gyulassy ('99)

AMPT still gets $v_2 \sim 6$% for quarks with only 3 mb... but how?

Test: use parton transport MPC to check AMPT's partonic stage

1) **dynamics - issue of parton subdivision**

2) **initconds - AMPT vs just minijets**

focus on 200-GeV Au+Au at RHIC, fixed $b = 8$ fm impact parameter

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 (BTE):

$$p^\mu \partial_\mu f_i(x,p) = C^i_{2\to2}[\{f_j\}](x,p) + C^i_{2\leftrightarrow3}[\{f_j\}](x,p) + \cdots$$

with, e.g.,

$$C^i_{2\to2} = \frac{1}{2}\sum_{jkl}\int_{234} (f^k_3 f^l_4 - f^i_1 f^j_2) W^{ij\to kl}_{12\to34} \qquad \left(\int_j \equiv \int \frac{d^3p_j}{2E_j}\,, \quad f^k_a \equiv f^k(x,p_a) \right)$$

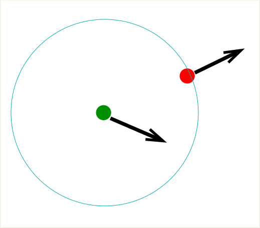
thermalizes (in box), fully causal and stable → can derive hydro eqns
e.g., Denicol, Rischke et al

handles both high or low opacities → usable for fluid-to-particle conversion
e.g., Teaney, Moore & Dusling; DM & Wolff, ...

hydro limit: transport coeffs & rel. times $(\eta \approx 1.2T/\sigma,\ \tau_\pi \approx 1.2\lambda_{tr}\ \ldots)$

$\exists$ **covariant transport codes: ZPC** (Zhang)**, MPC** (Molnar)**, BAMPS** (Xu)**, ...**

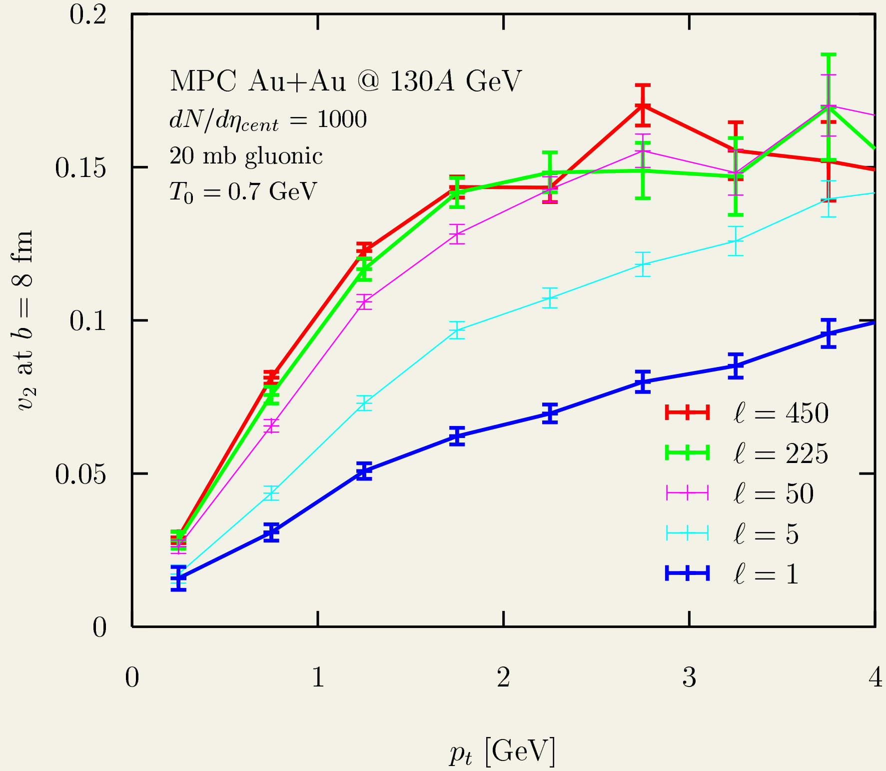
Parton subdivision



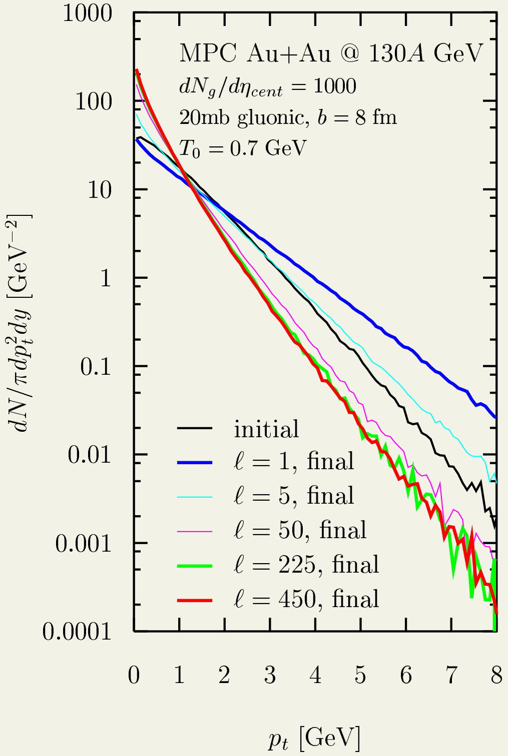
Nonlocal artifacts: **due to action at distance** $d < \sqrt{\frac{\sigma}{\pi}}$

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

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



spectra



- **ZPC could do subdivision, but AMPT runs it with $\ell = 1$**
- **high RHIC opacities: need subdivision $\ell \sim \mathcal{O}(100)$ to remove artifacts in v_2**

Initial conditions (Au+Au at RHIC)

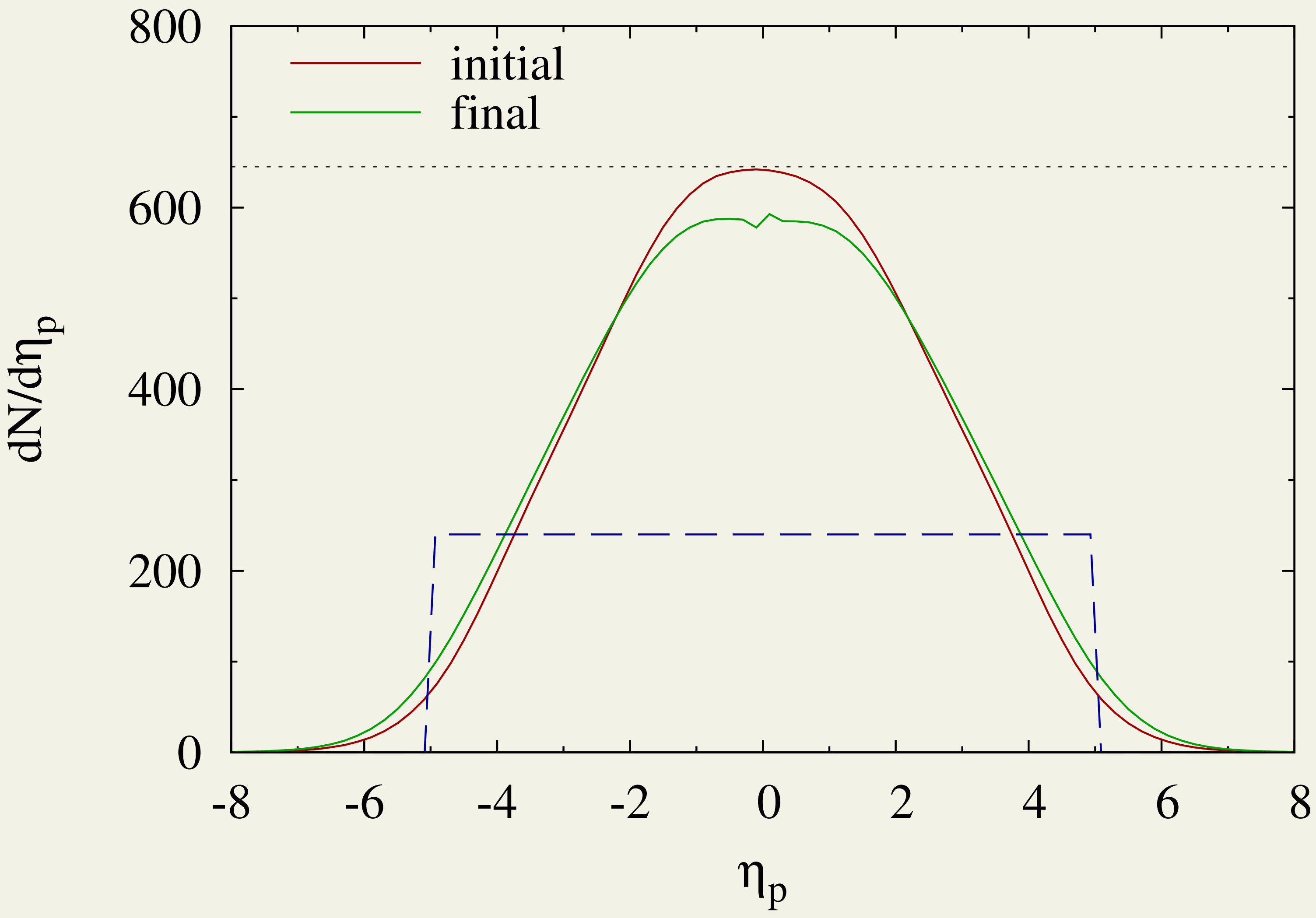
Molnar-Gyulassy study: boost-invariant fit to HIJING minijets

- massless gluons
- flat $dN_g/d\eta(b=0) = 1000 \Rightarrow dN/d\eta(b = 8\ \mathrm{fm}) \approx 240$
- locally thermal $T_0 = 0.7$ GeV, $f = N(\vec{x}_T)e^{-m_T\cosh(\eta-y)/T_0}$
- constant formation time $\tau_0 = 0.1$ fm $\sim 1/p_T$
- binary collision transverse profile for Au+Au at $b = 8$ fm
- $d\sigma/dt \propto 1/(t-\mu_D^2)^2$, $\sigma_{gg} = 9\pi\alpha_s^2/2\mu_D^2$, with $\mu_D = 0.7$ GeV

AMPT: v2.26t5d6

- massive quarks: $m_u = 5.6$ MeV, $m_d = 9.9$ MeV, $m_s = 199$ MeV
- enhanced $dN_q/d\eta \approx 2.5 \times dN_h/d\eta$ (string melting), nonuniform in η
- formation time distribution
- transverse profile close to wounded nucleons
- sizeable event-by-event fluctuations
- $\mu_D = 0.45$ GeV, $\alpha_s = 0.33 \ \Rightarrow\ \sigma = 3$ mb (quark Casimirs ignored)

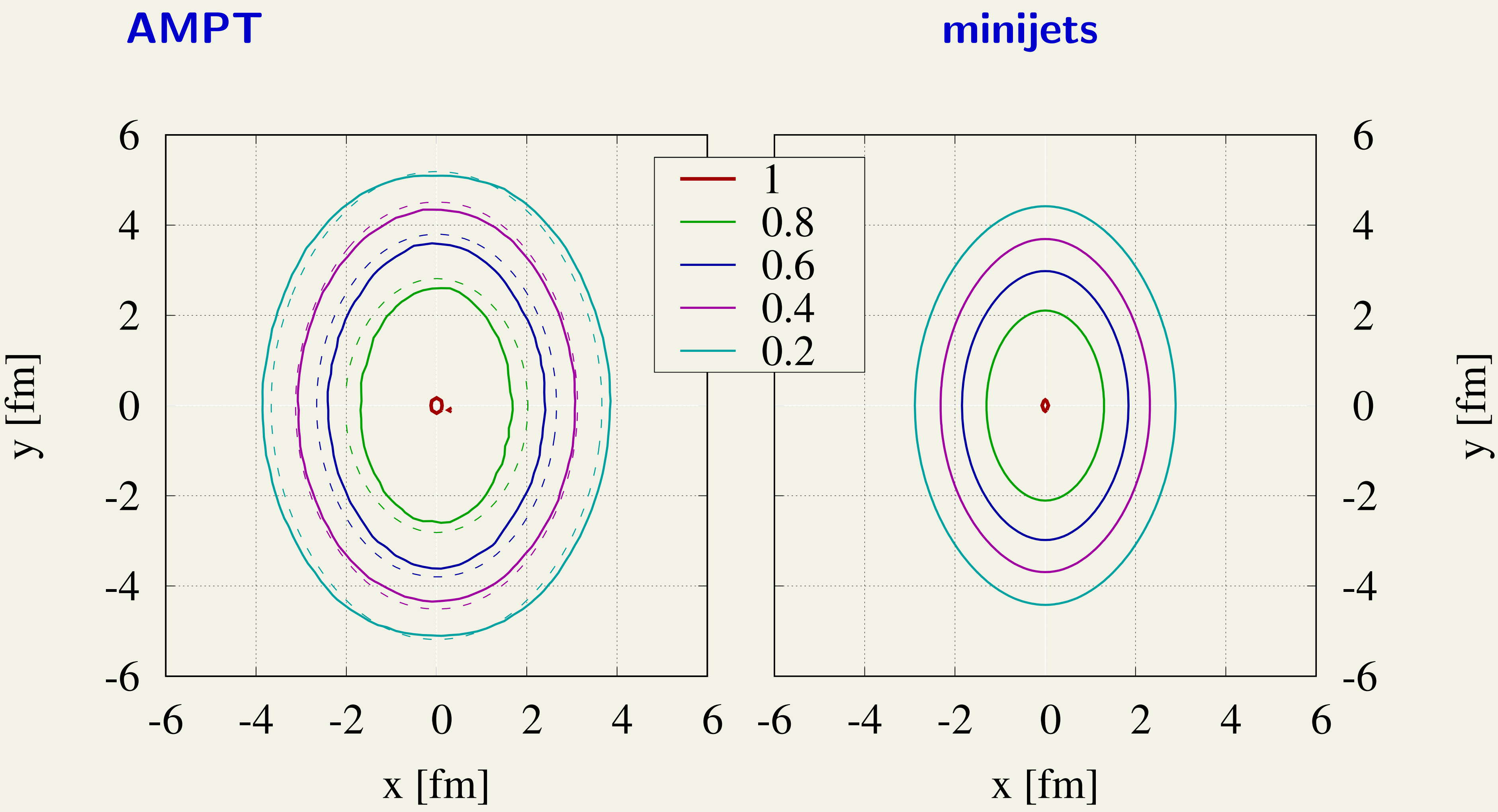
Au+Au, b=8 fm - AMPT pseudorapidity $dN/d\eta_p$



$$\eta_p \equiv \frac{1}{2} \ln \frac{|p| + p_z}{|p| - p_z}$$

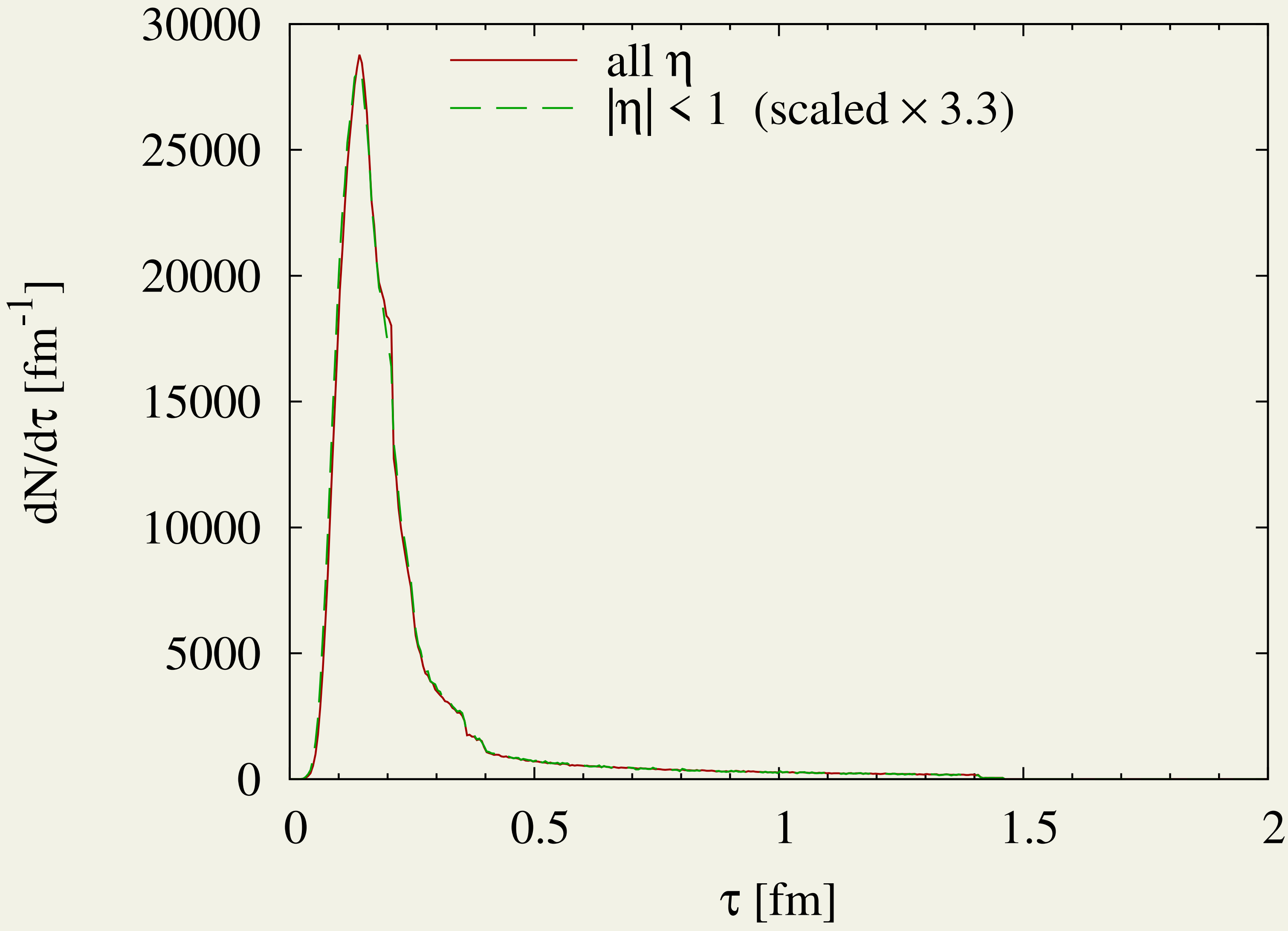
evidently not boost invariant, peak around $dN/d\eta_p \sim 650$

Au+Au, b=8 fm - transverse profile dN/d^2x_T for $|\eta_p| < 1$



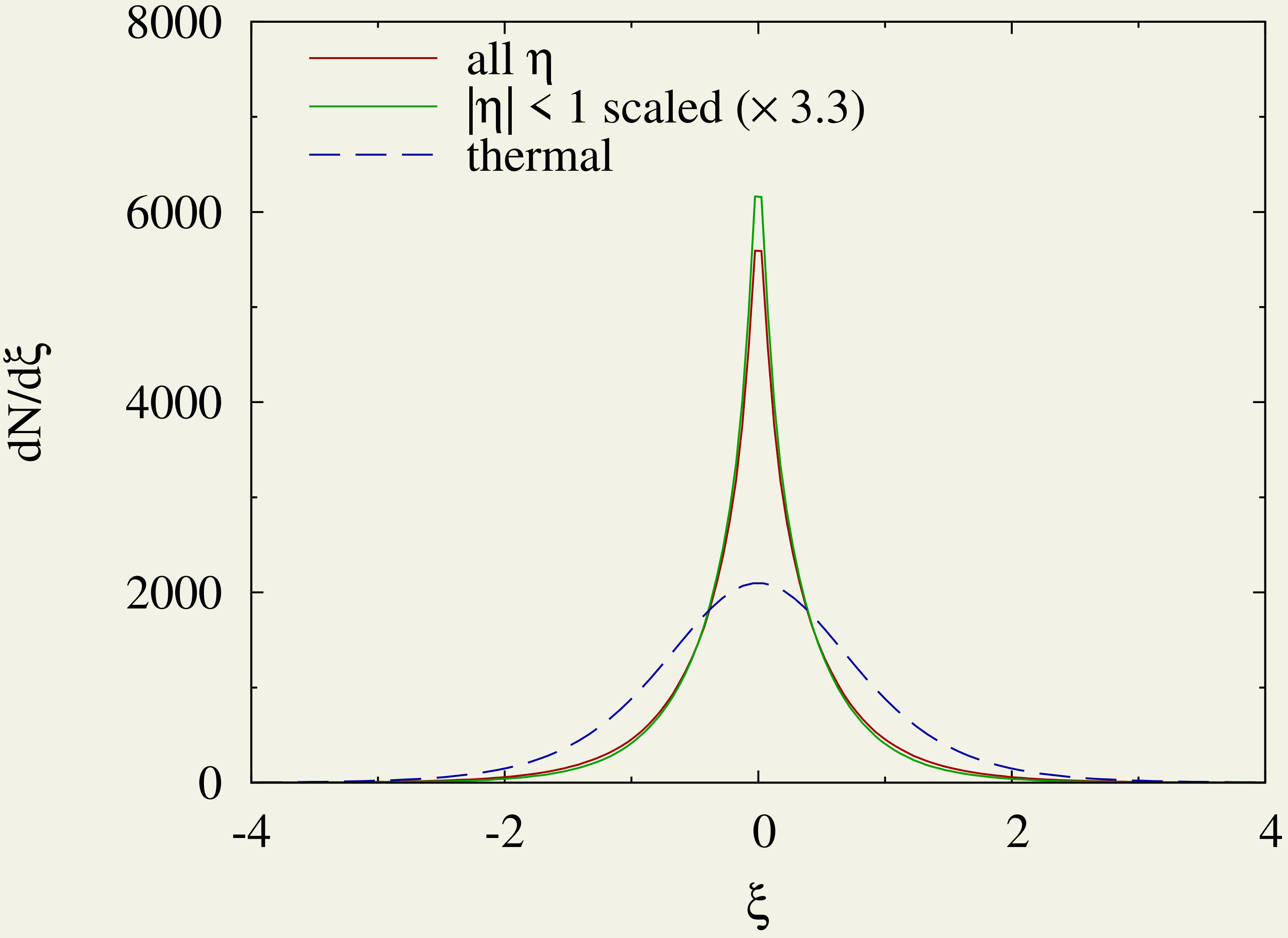
AMPT: close to wounded nucleons (dashed); minijets: binary coll profile

Au+Au, b=8 fm - **AMPT formation time** $\tau = \sqrt{t^2 - z^2}$



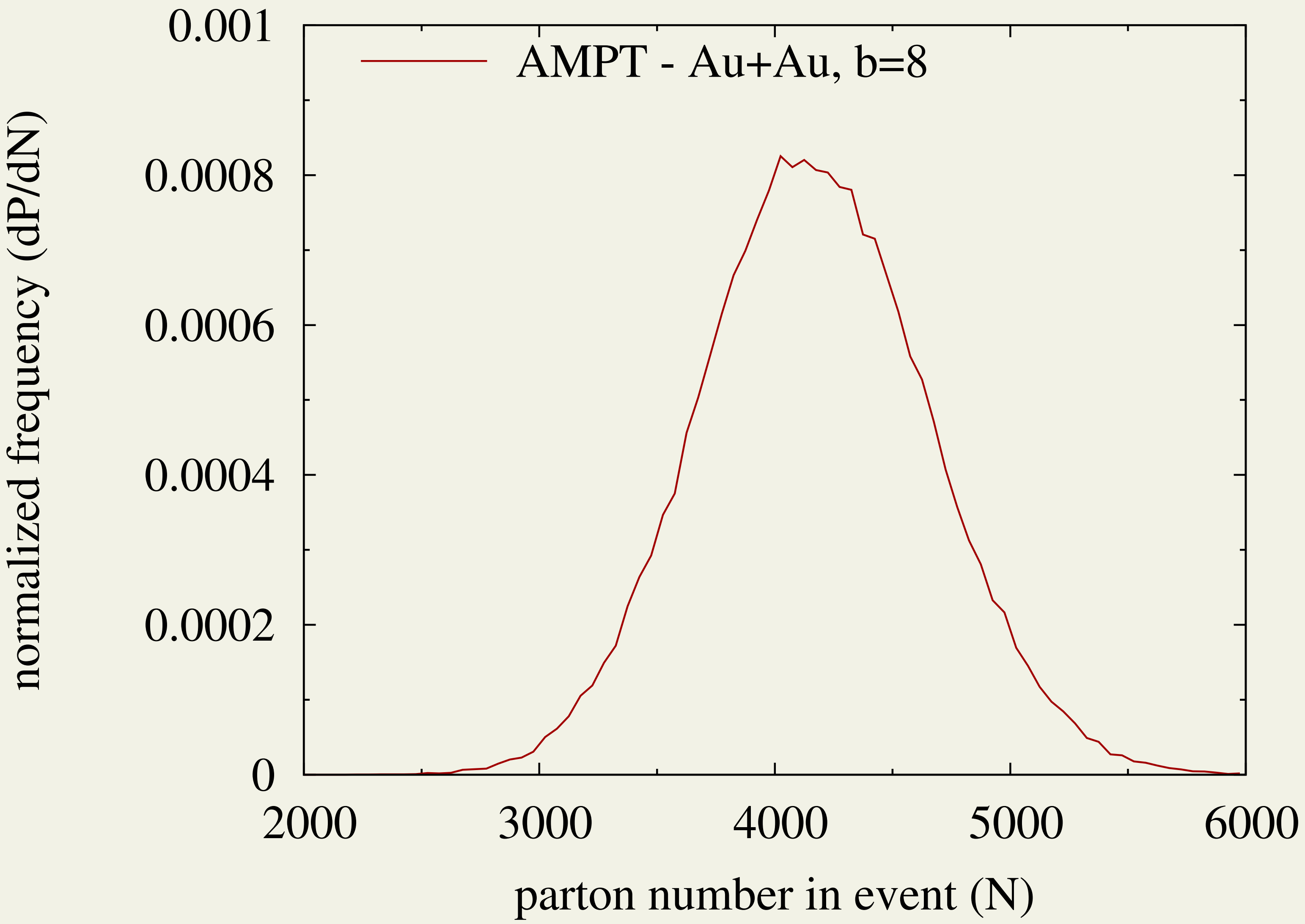
broad distribution, peaks around $\boldsymbol{\tau \sim 0.2}$ fm (average $\tau \approx 0.23$ fm)

Au+Au, b=8fm - AMPT coord rapidity - pseudorapity correlation $\xi \equiv \eta - \eta_p$



much sharper than boost-invariant thermal $\propto 1/\cosh^2\xi$ **correlation**

Au+Au, b=8fm - AMPT total quark number in event

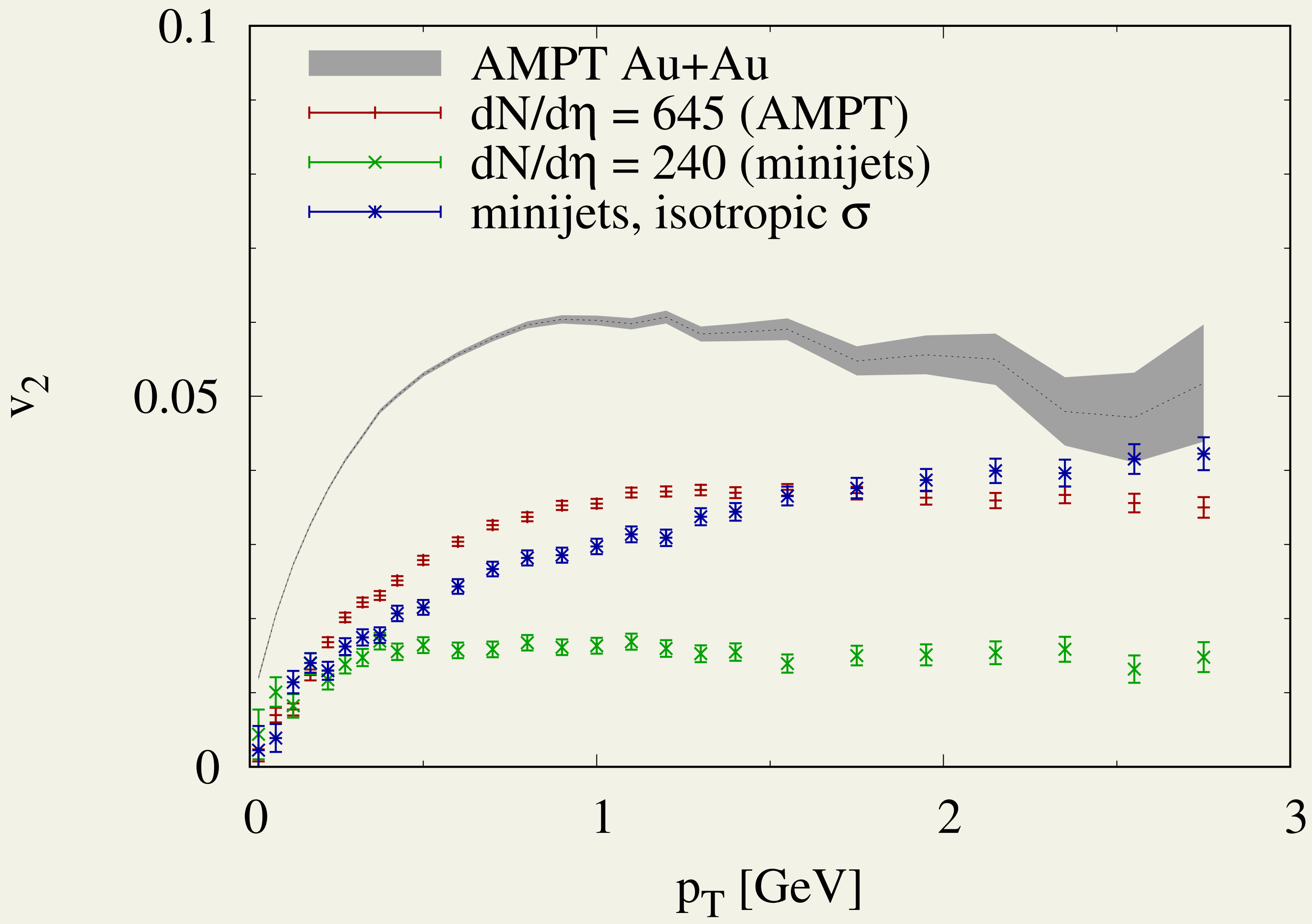


large event-by-event fluctuations, $\langle N_{quark} \rangle \approx 4200$

MPC v1.9 comparison strategy: go from simple to complicated

- take boost-invariant minijet study as baseline
- gradually include features of AMPT initconds
- use wounded nucleon profile, and the same $d\sigma/dt$ as AMPT

1) set $dN/\eta_p \approx 650$ to match AMPT (at midrapidity), use AMPT $d\sigma/dt$

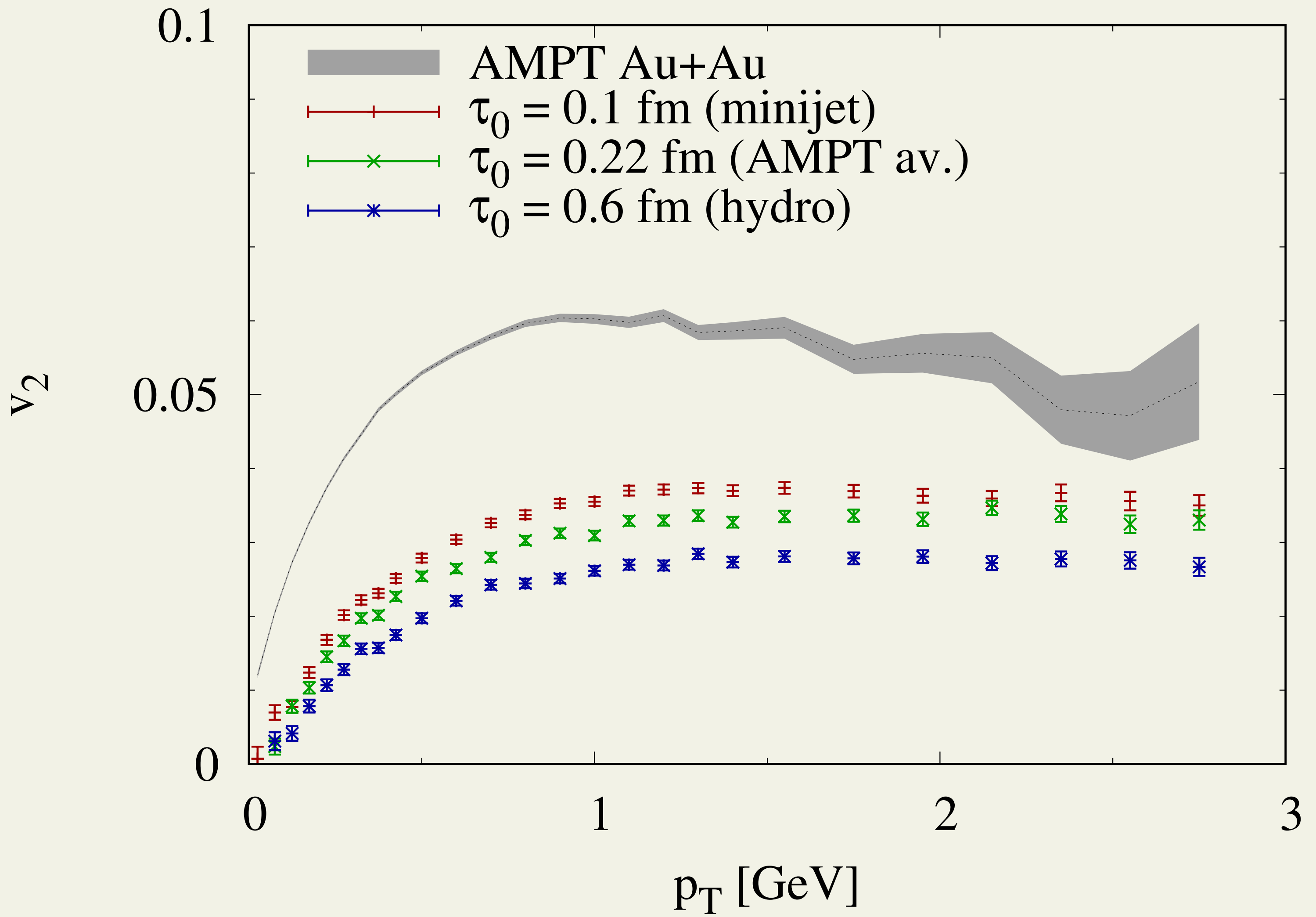


$\tau_0 = 0.1$ fm

$T_0 = 0.7$ GeV

2.7× larger density, but only gets v_2 to $\approx 3.5\%$... (need $5\times$ more opacity)

2) match formation time to AMPT average, $\langle\tau_0\rangle = 0.22$ fm

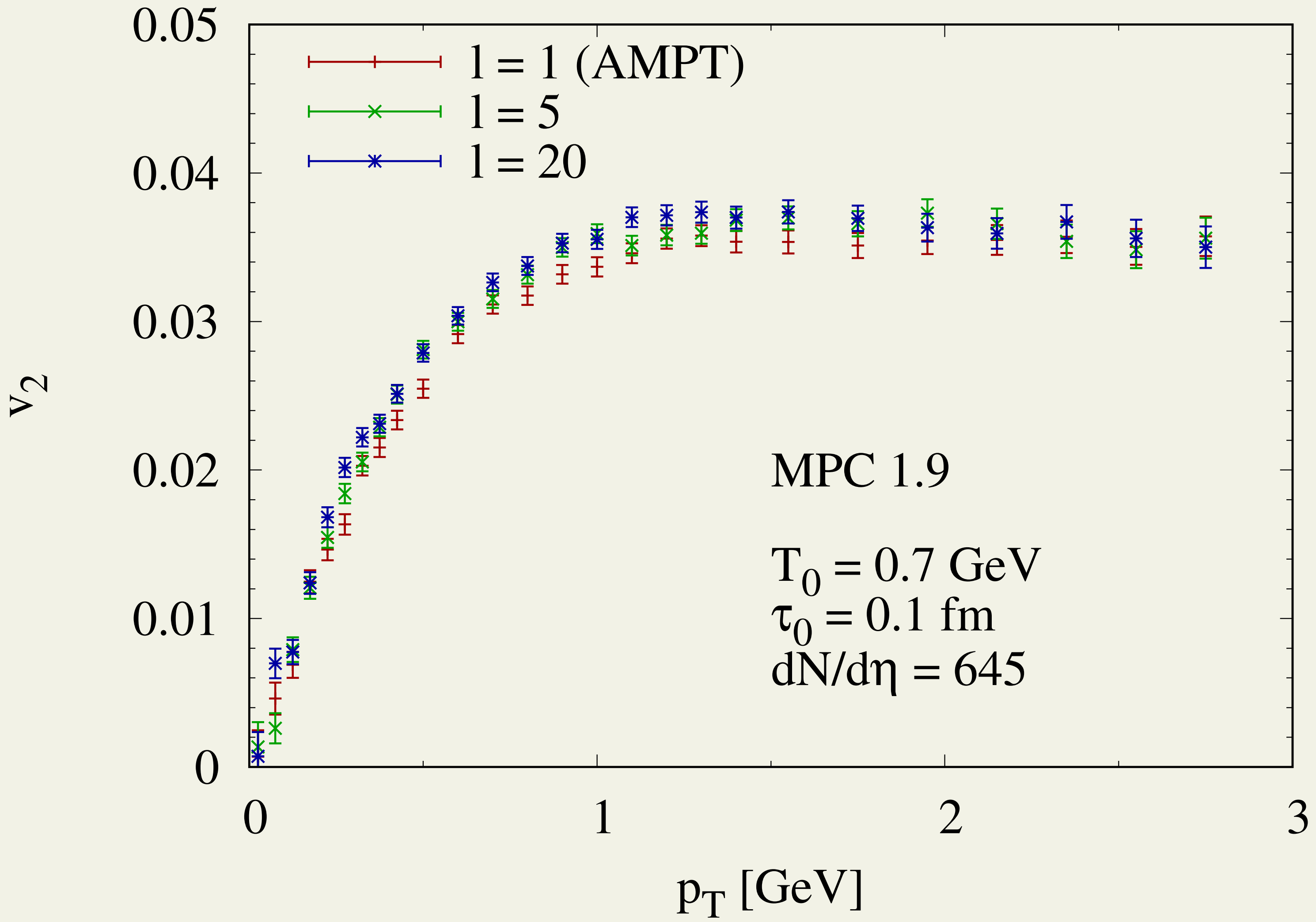


$dN/d\eta = 645$

$T_0 = 0.7$ GeV

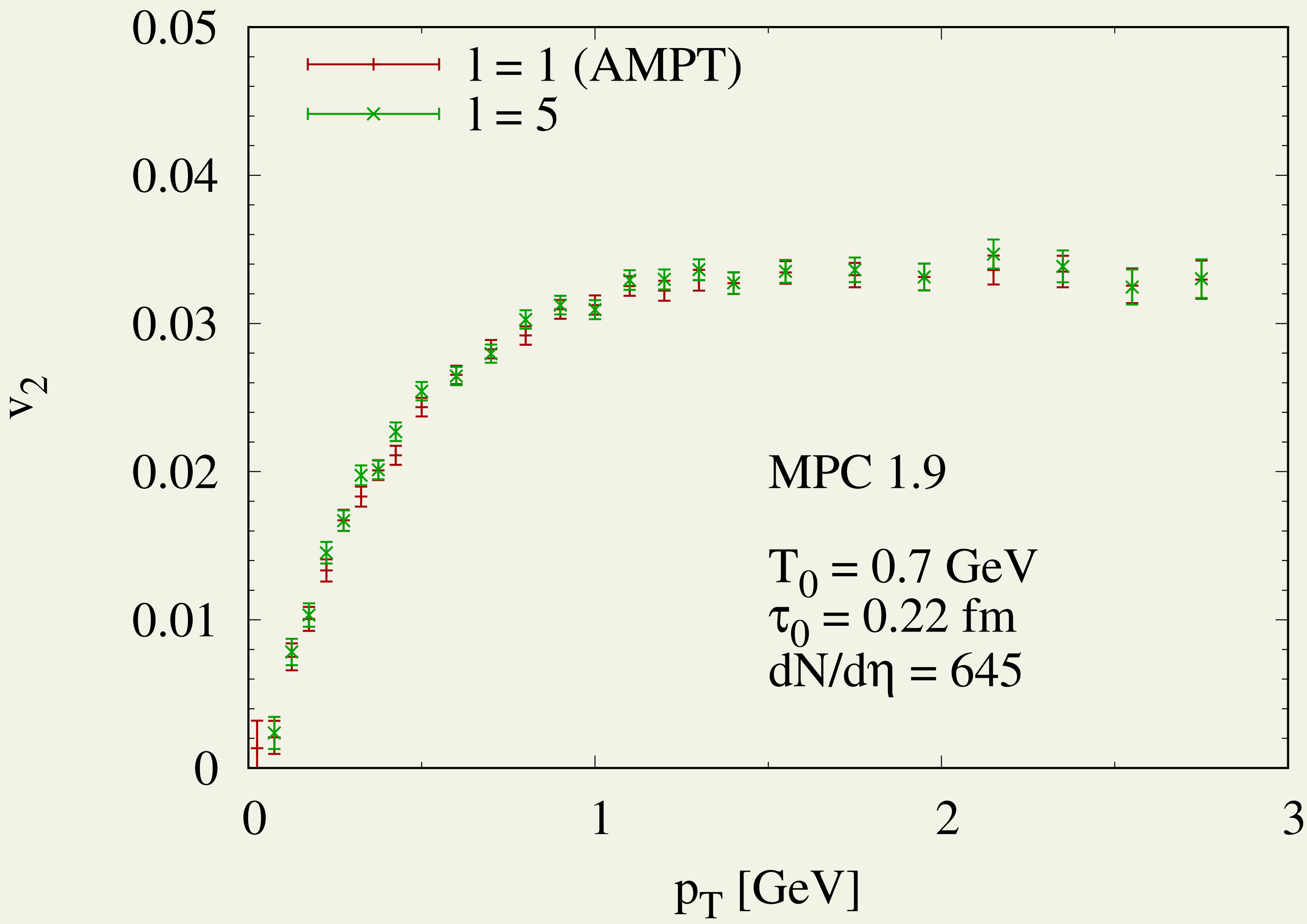
larger $\tau_0 \Rightarrow$ smaller v_2 (lower density $n \sim 1/\tau$, also shorter evolution)

3) decrease parton subdivision, down to $\ell = 1$



modest $\lesssim 10$**% effect on** $v_2(p_T)$**, for short** $\tau_0 = 0.1$ **fm**

same, but now match $\langle\tau_0\rangle$ from AMPT



less than 5% distortion in $v_2(p_T)$, removable with subdivision $\ell = 5$

So far we...

- **matched initial $dN/d\eta$, formation time, transverse profile, interactions**

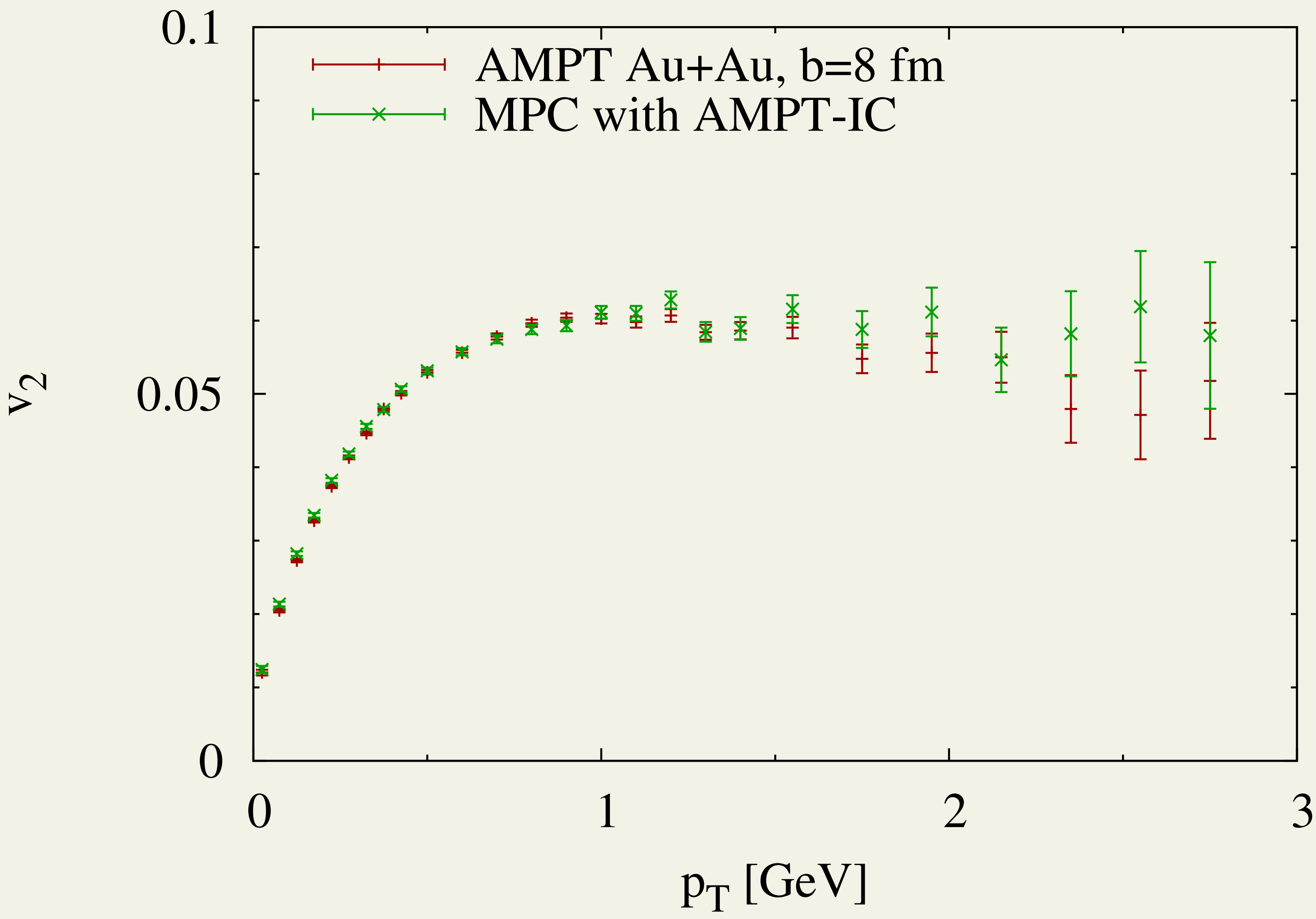
- **ruled out too low parton subdivision**

  (effectively, AMPT runs at subdivision ~ 10 relative to $\sigma \sim 30$ mb, and another factor of ~ 5 would be sufficient)

still, v_2 is too small.

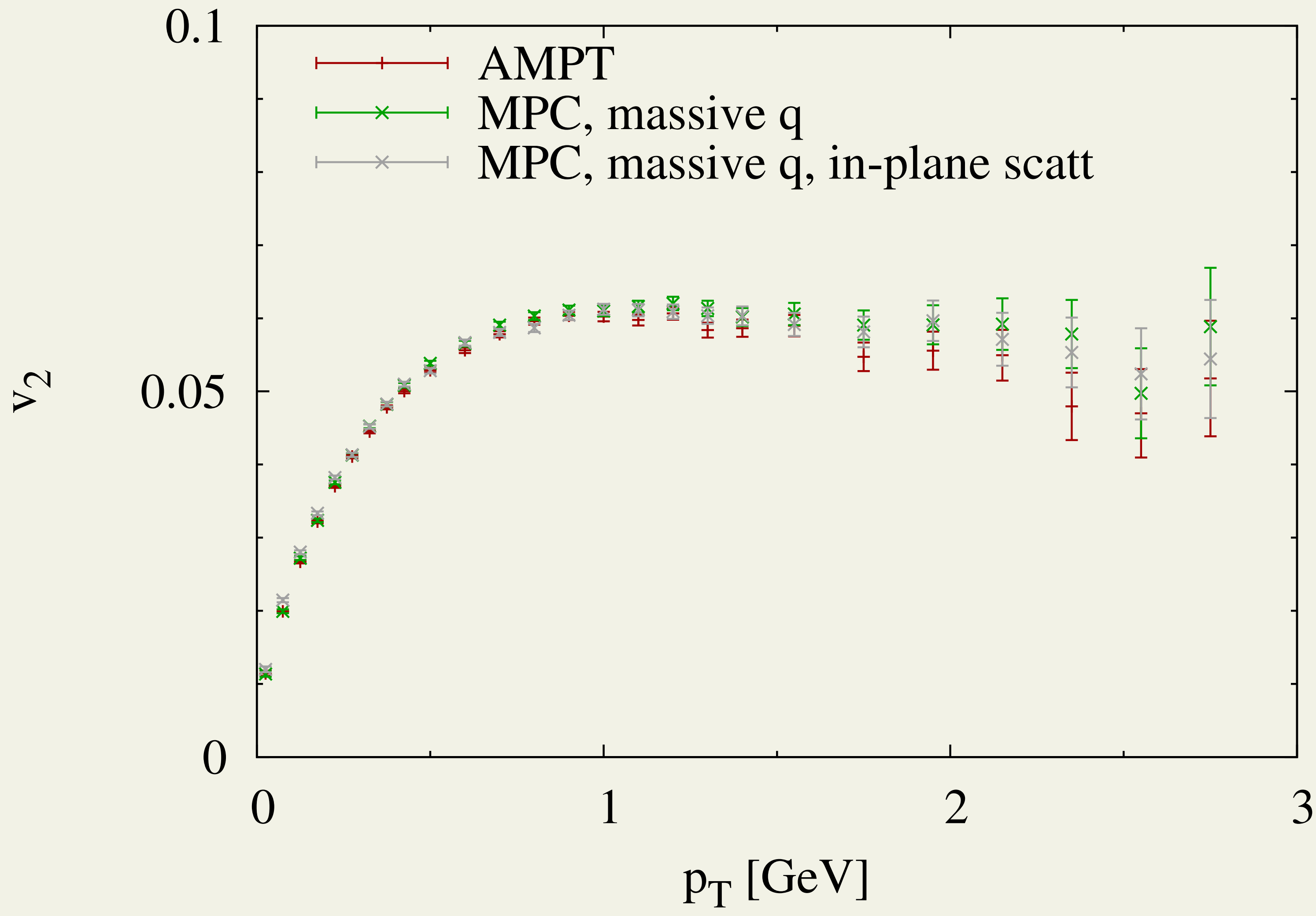
what if we use the exact same initial conditions?

4) MPC with full AMPT initconds (same $\vec{p}$, $\vec{x}$, t for each massless parton)



MPC with $\sigma = 3$ mb ($\ell = 1$) **reproduces the elliptic flow from AMPT!**

MPC with full AMPT initconds (same $\vec{p}$, $\vec{x}$, t) - including correct m_q



same result: MPC with $\sigma = 3$ mb ($\ell = 1$) reproduces AMPT's v2

Missing link: momentum distribution

- for thermal minijets, $\langle p_T \rangle = 3\pi T/4 \approx 1.6$ **GeV for** $T_0 = 0.7$ **GeV**

$$\frac{dN}{d^2p_T dy} = E\frac{dN}{d^3p} = p_\mu d\sigma^\mu f \propto m_T \tau\, \cosh\xi\, e^{-m_T \cosh\xi / T}$$

- for AMPT quarks, $\langle p_T \rangle \approx 0.54$ **GeV** $\Rightarrow$ $T_{eff} = 0.23$ **GeV only**

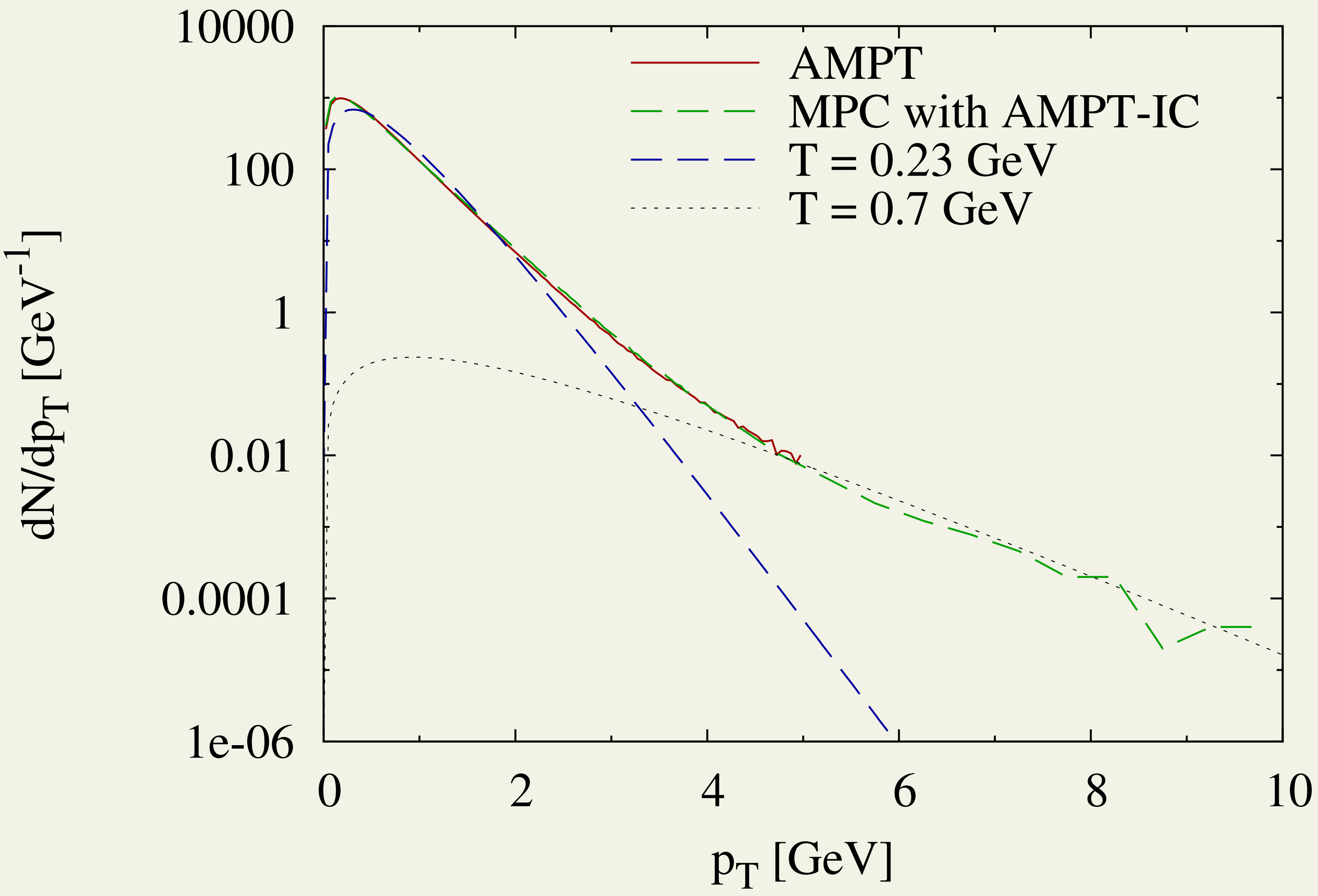
at lower temperature, the cross section is more isotropic (with μ_D fixed)

$\Rightarrow$ more effective v_2 generation

$$\sigma_{tr} = 4\sigma_{TOT}\, z(1+z)\left[(2z+1)\ln\left(1+\frac{1}{z}\right) - 2\right] , \qquad z \equiv \frac{\mu^2}{s} \approx \frac{\mu^2}{18T^2}$$

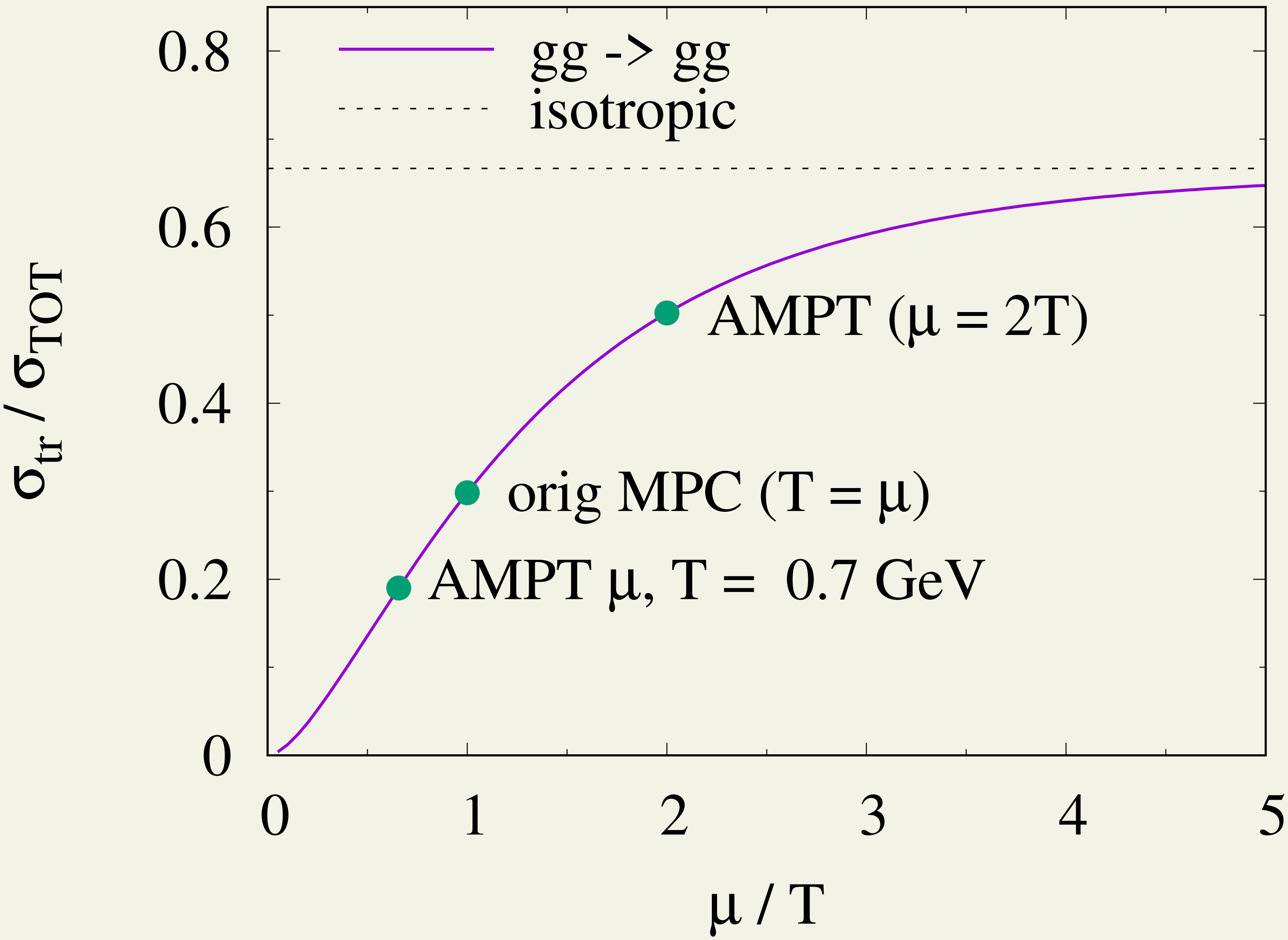
so $\dfrac{\sigma_{tr}(T = 0.23\,\mathrm{GeV})}{\sigma_{tr}(T = 0.7\,\mathrm{GeV})} \approx 2.6$ **(!)**

initial **parton spectrum** in Au+Au at RHIC, b=8 fm ($|\eta_p| < 1$)



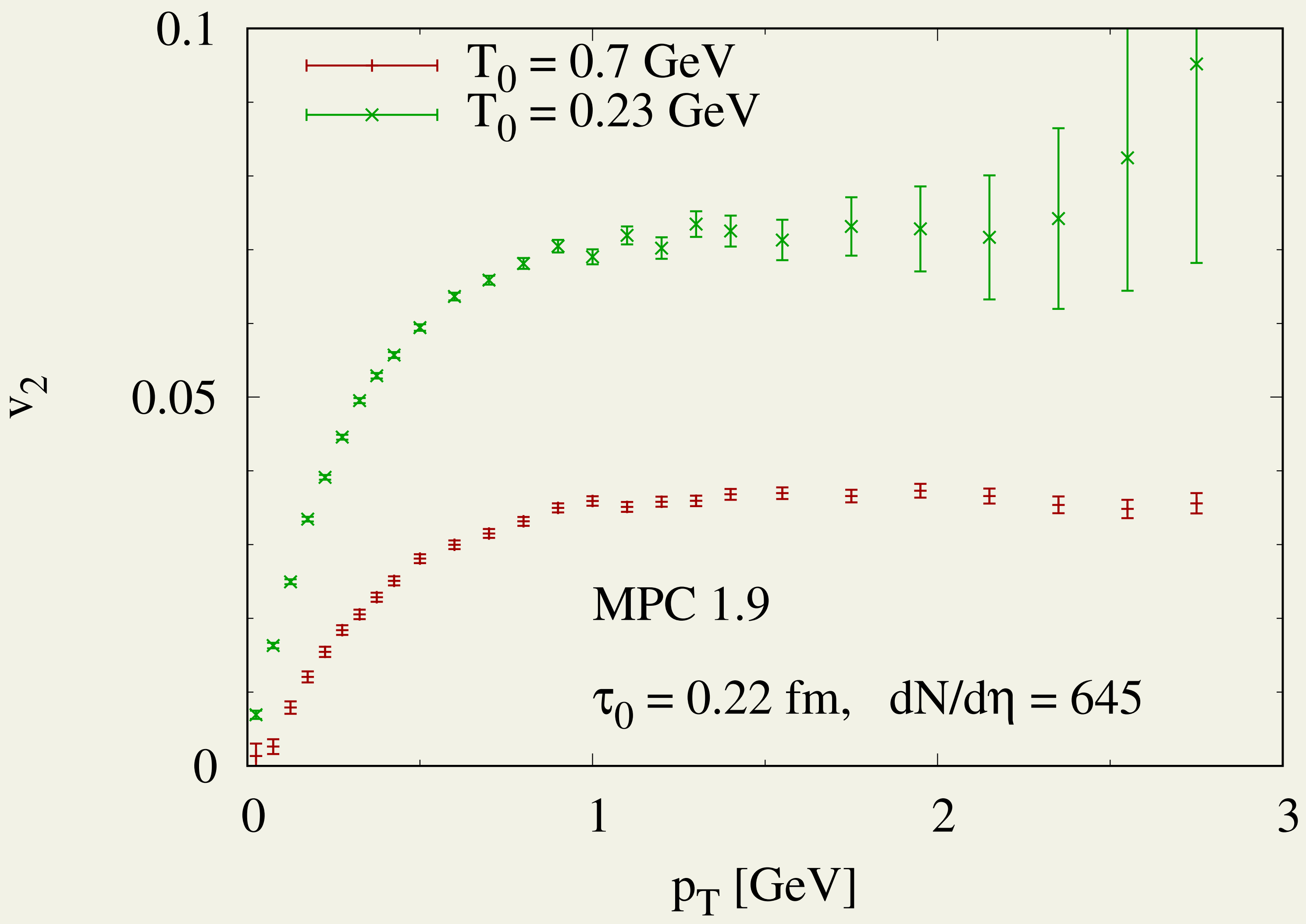
$T = 0.7$ GeV captures minijet tail, but string melting plasma is $3\times$ colder

transport cross section vs Debye mass



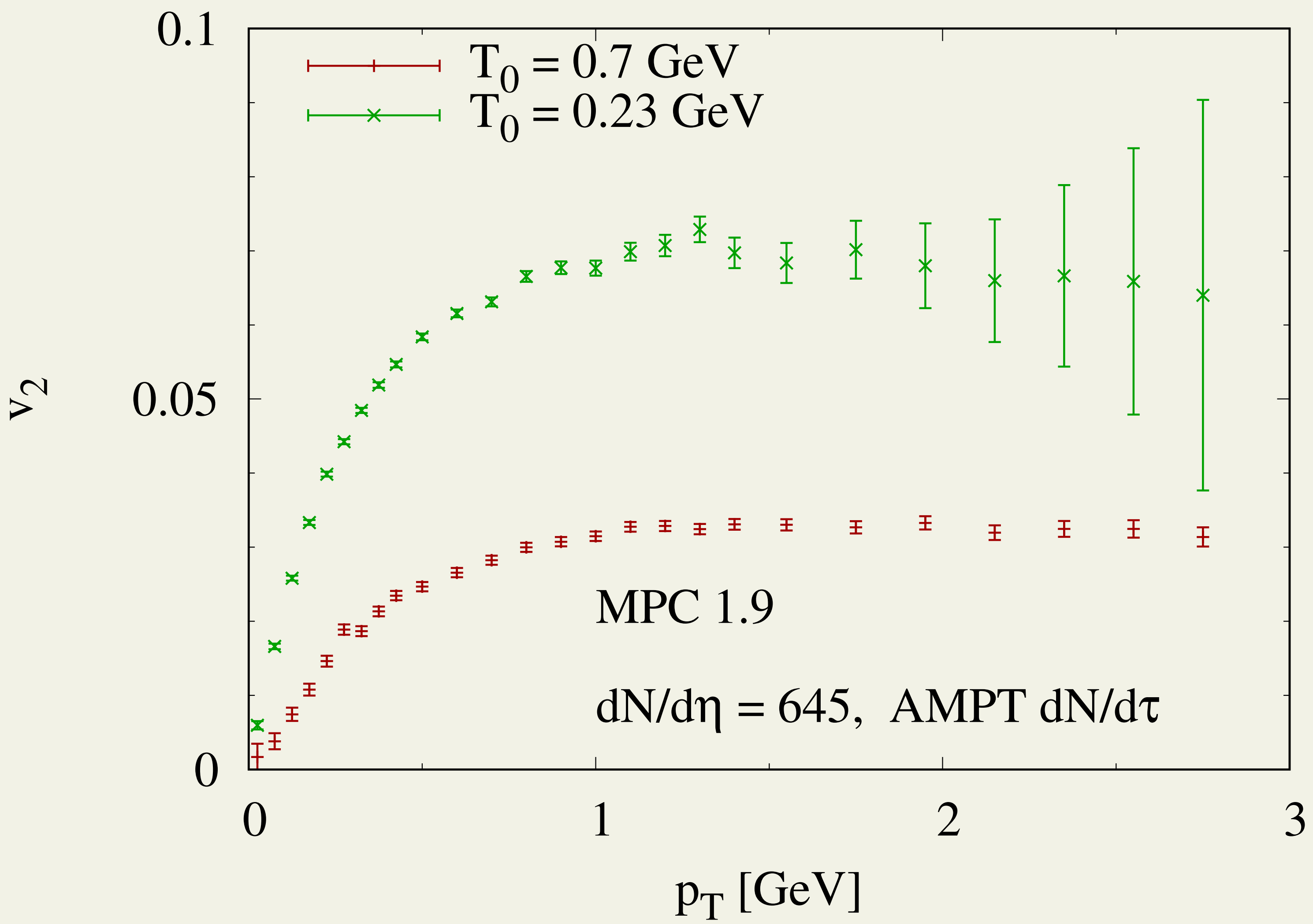
much more efficient transport at same $\sigma_{TOT} = 3$ mb for AMPT

4) now set T_{eff} to AMPT $\langle p_T \rangle$



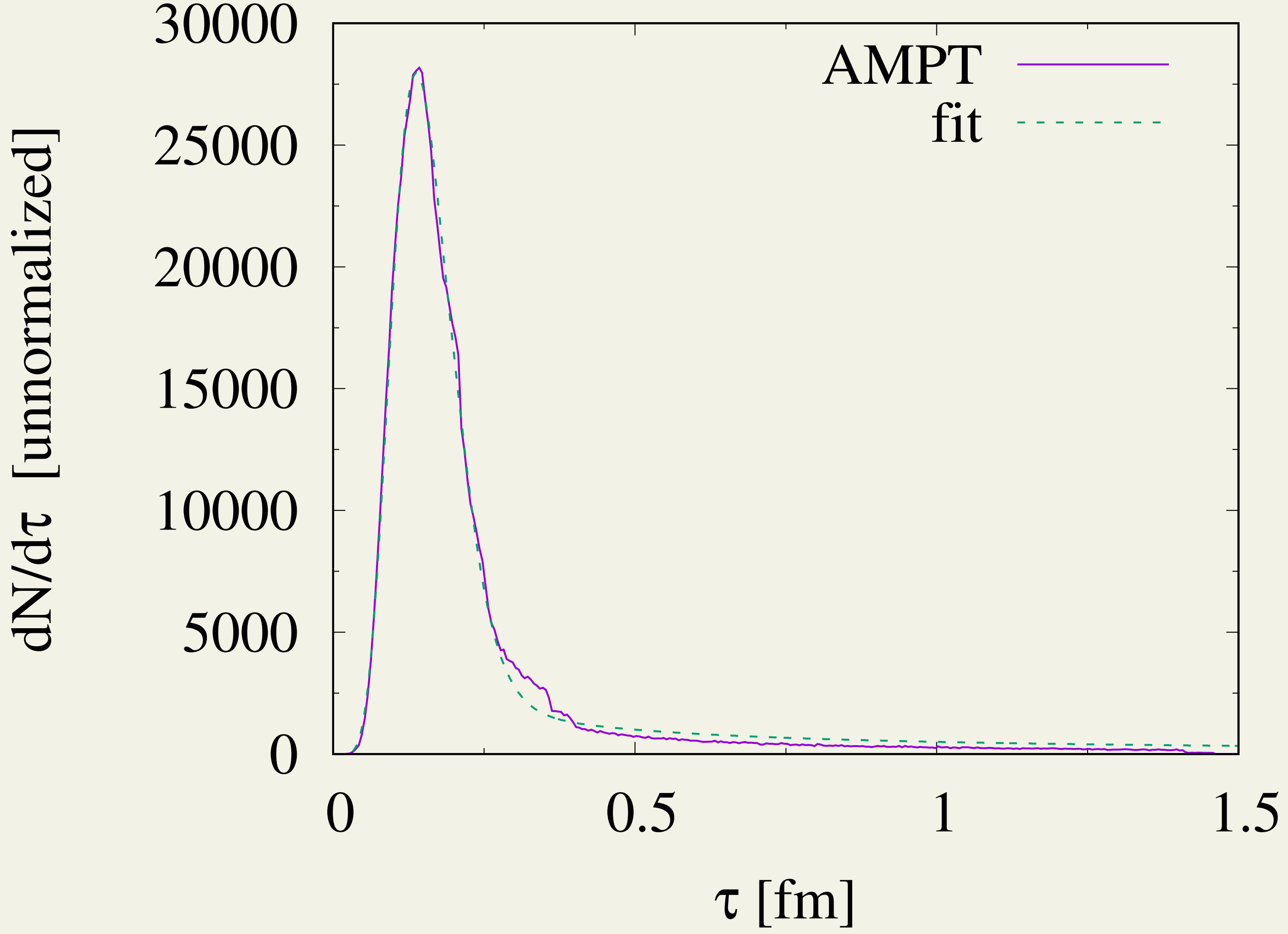
large $6-7$% v_2, even slightly higher than from AMPT

same comparison but also include AMPT formation time distribution



practically same v2 as for constant $\tau_0 = \langle \tau_{form} \rangle$

fit to AMPT $dN/d\tau$: $$\frac{dN}{d\tau} = \left(\frac{\tau}{a}\right)^8 e^{-\tau/c} + \frac{b}{\tau}\tanh\left[\left(\frac{\tau}{d}\right)^9\right]$$



Summary

- Using the covariant Molnar's Parton Cascade, we pinpoint how AMPT generates enough elliptic flow (v_2) in Au+Au at RHIC with only 3-mb cross sections:

  1) **about $2.5\times$ higher parton densities** via string melting, and

  2) **cold initial plasma** with effective temperature $T_{eff} \sim 0.2 - 0.25$ GeV; thus $\mu_D \approx 2T \Rightarrow$ more isotropic partonic cross sections

- The partonic stage of AMPT approximates well solutions of the covariant Boltzmann transport equation. **Artifacts due to lack of parton subdivision were below 5%** for $v_2(p_T)$ in Au+Au at RHIC. Compared to studies that generated high opacities with large $\sigma \sim 30$ mb, AMPT effectively incorporates a subdivision $\ell \sim 10$ already.

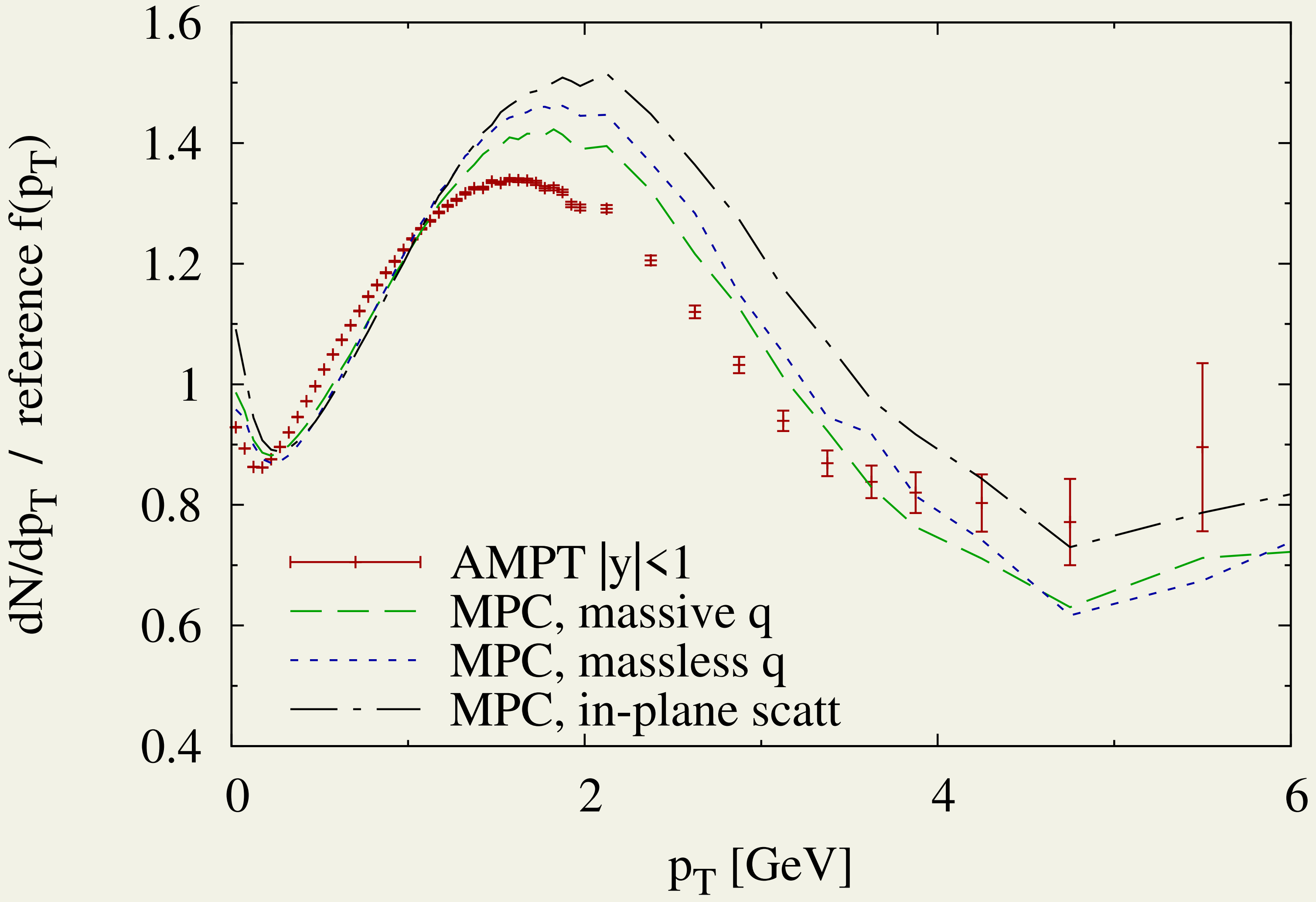
- With 3 mb cross section, AMPT still generates $2 - 3\times$ smaller partonic v_2 than that of hadrons. But it makes up for the difference with quark coalescence - the algorithm of which needs to be tested in detail.

Next steps:

- include fluctuations in N_{quark}, initial profile
- check v_2 distribution, not just event average

Backup slides

On log plot, AMPT and MPC spectra also agree. But on linear scale...



quark spectra
divided by
Tsallis reference

$$\frac{dN}{d^2p_T} \propto (1 + ap_T)^{-b}$$

up to ~ 10% deviations - i.e., MPC with $\ell = 1$ is <u>not</u> same as AMPT