Transport at low and high opacity and the elliptic flow

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He, Edmunds, Lin, Liu, DM & Wang, PLB 753, 506 (2015) [arXiv:1502.05572]
Li, He, Lin, DM, Wang & Xie, PRC93, 051901 (2016) [arXiv:1601.05390v2]
Li, He, Lin, DM, Wang & Xie, 1604.07387

Outline

I. Elliptic flow in heavy-ion collisions

II. Hydrodynamics vs covariant transport

III. Anisotropic escape from AMPT and MPC/Cascade

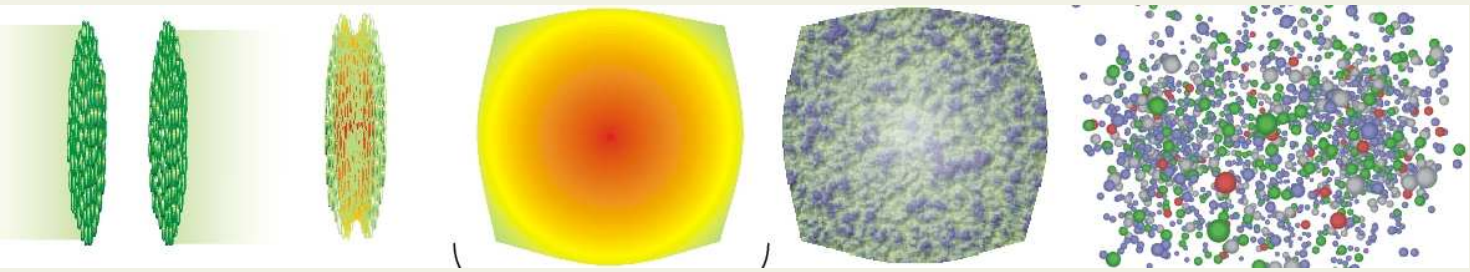
IV. Mass ordering for v2 in AMPT

V. Conclusions, open questions

Heavy ion physics

goal: study quark-gluon plasma (many-body QCD)

initial nuclei **quark-gluon plasma** **hadron gas**



[image: S. Bass]

$\uparrow$

$\mathcal{O}(10\ \mathrm{fm})$

$\downarrow$

$\longleftarrow\ \mathcal{O}(10\ \mathrm{fm}/c)\ \longrightarrow$

The bulk ($> 99\%$): $\rightarrow$ relativistic, dissipative hydrodynamics

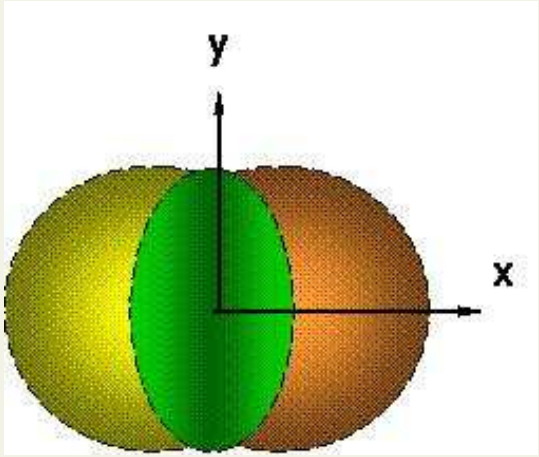
- **many-body QCD system, collectivity** $\sim$ **statistical physics, hydro**

Rare probes: $\rightarrow$ perturbative QCD

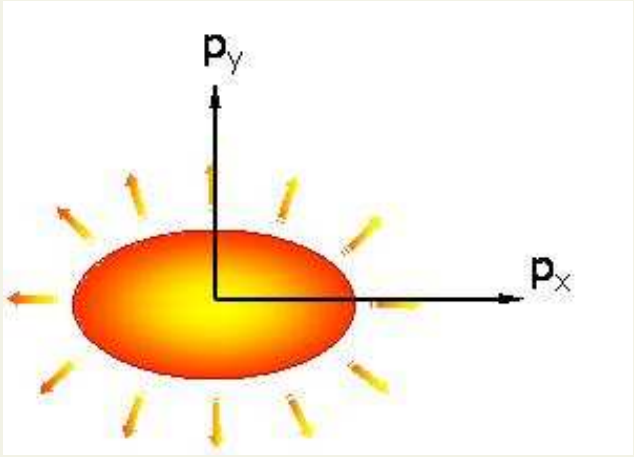
- **evolution inevitably reflects presence of medium $\Rightarrow$ Tomography**

Elliptic flow

initial spatial anisotropy converts to final momentum space anisotropy



$\longrightarrow$



$$\varepsilon \equiv \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$$

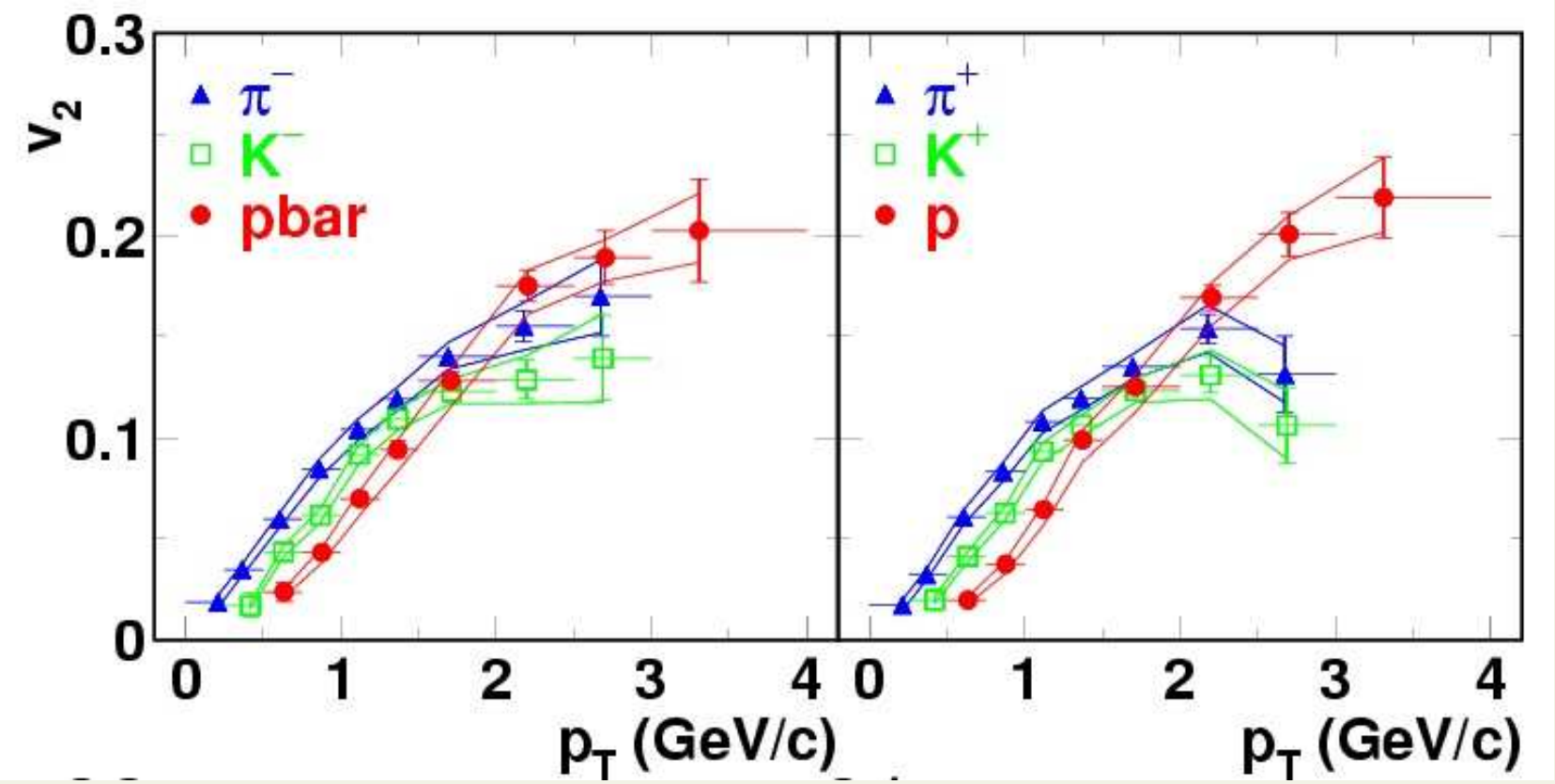
$$v_2 \equiv \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle} \equiv \langle \cos 2\phi_p \rangle$$

flow harmonics: $$\frac{dN}{p_T\, dp_T\, d\phi} \equiv \frac{1}{2\pi} \frac{dN}{p_T dp_T} \left[1 + \sum_{n=1} 2 v_n \cos n(\phi - \psi_n) \right]$$

- **quite large: v2(pT) $\sim 20\%$ at high pT means $\sim 2:1$ anisotropy**

- **"mass ordering": heavier particles v2 smaller at low pT ($\pi > K > p > ..$)**

e.g., Au+Au at RHIC PHENIX, PRL91, 182301 ('03)



Hydrodynamics paradigm

assumption of local thermalization quite successful in explaining observables

conserved currents:

$$\partial_\mu T^{\mu\nu}(x) = 0 \quad , \qquad \partial_\mu N_B^\mu(x) = 0$$

if dissipation - extra fields and equations of motion:

$$T^{\mu\nu}(x) = T^{\mu\nu}_{ideal}(x) + \delta T^{\mu\nu}(x)$$

$$N^\mu(x) = N^\mu_{ideal}(x) + \delta N^\mu(x)$$

$$\delta \dot{T}^{\mu\nu} = A^{\mu\nu}(\{T^{\alpha\beta}, N^\gamma\}) \quad , \qquad \delta \dot{N}^\mu = B^\mu(\{T^{\alpha\beta}, N^\gamma\})$$

= causal 2nd-order dissipative hydrodynamics (≠ Navier-Stokes)

Israel & Stewart '79; Muronga '04; Baier, Romatschke et al '06; Heinz, Song et al; Teaney et al

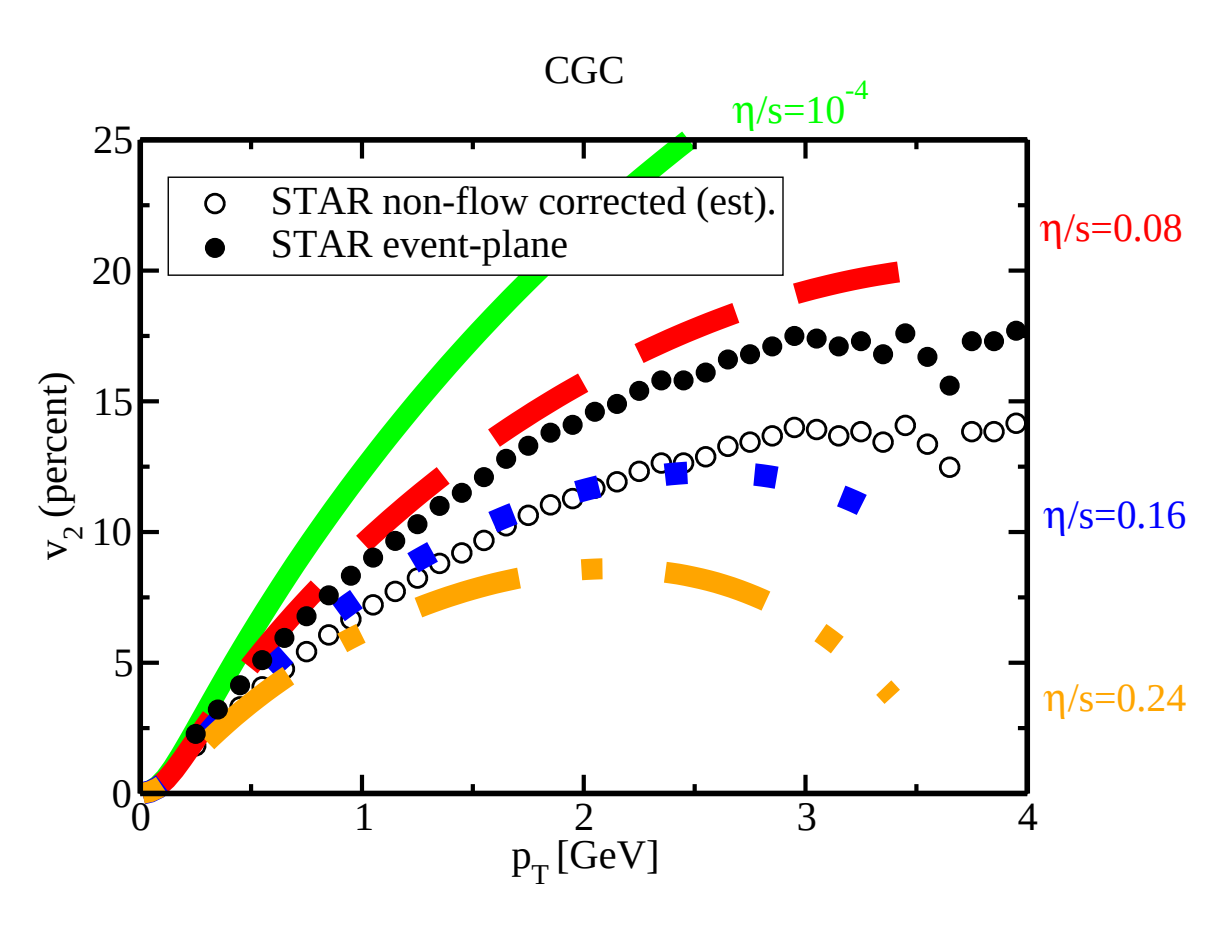
DM, Huovinen et al; Koide, Kodama et al; Schenke, Jeon et al; Denicol, Rischke et al; Strickland et al...

utilizes equation of state ($p(e, n_B)$, $T(e, n_B)$), transport coeffs (η, ζ, κ_B), relaxation times (τ_η, τ_ζ, τ_κ)

open questions remain (thermalization, freezeout, small systems,...)

- **hydrodynamic evolution does generate v2** e.g., Ollitrault, PRD46 ('92)
- **mass ordering is natural in hydro (at fixed p_T, velocities differ)**
  e.g., Huovinen, Kolb et al PLB 503 ('01)
- **v2 can be used to measure viscosity**

Romatschke & Luzum, PRC78 ('08):



→ **hydro implies opaque system**

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.,

$$C^i_{2\to 2} = \frac{1}{2}\sum_{jkl}\int_{234} (f^k_3 f^l_4 - f^i_1 f^j_2) W^{ij\to kl}_{12\to 34} \qquad \left(\int_j \equiv \int \frac{d^3p_j}{2E_j}\ , \quad f^k_a \equiv f^k(x,p_a) \right)$$

thermalizes (in box), fully causal and stable $\rightarrow$ **can derive hydro eqns**

e.g., Denicol, Rischke et al

handles both high or low opacities $\rightarrow$ **usable for fluid-to-particle conversion**

e.g., Teaney, Moore & Dusling; DM & Wolff, ...

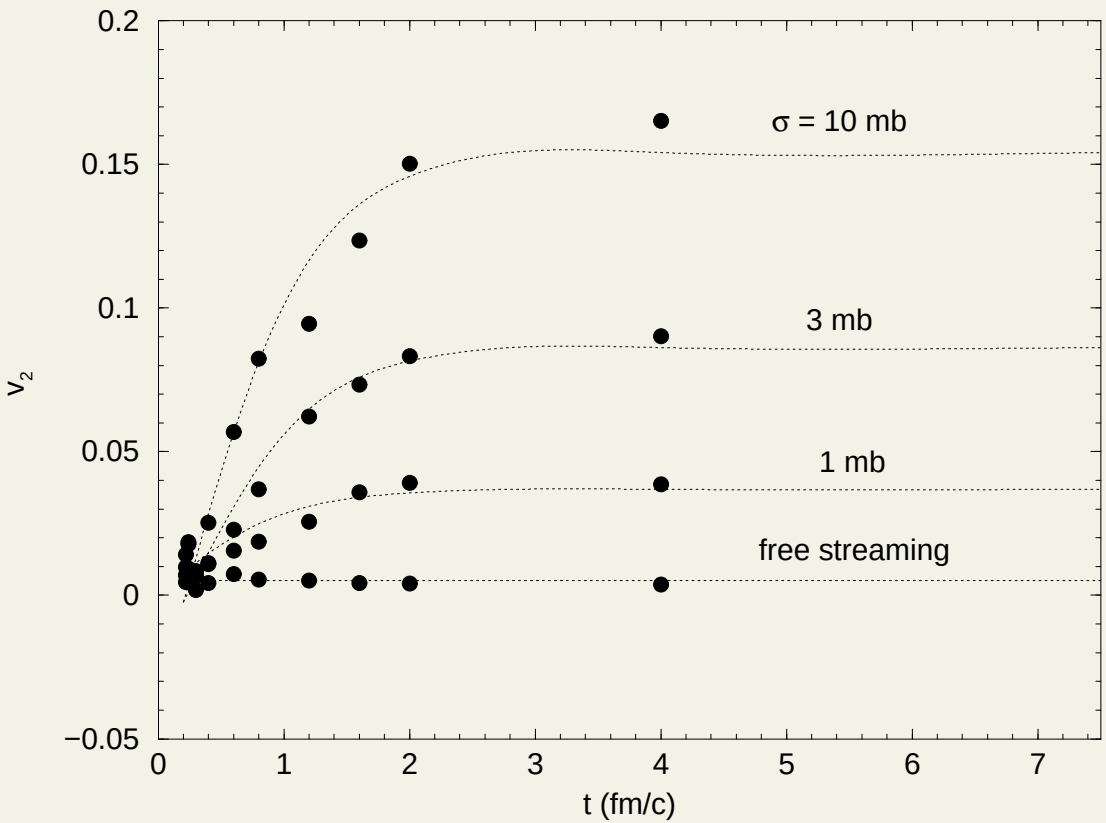
high opacity (hydro) limit: transport coeffs & relaxation times

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

v_2 builds up early

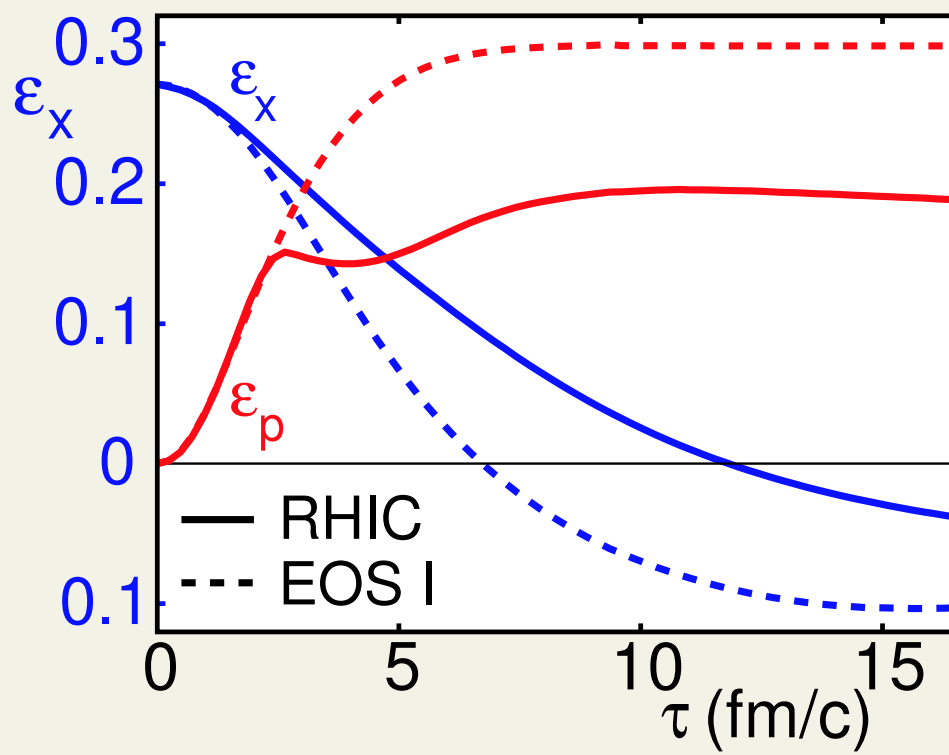
both in transport

Zhang, Gyulassy & Ko ('99):



and in hydro

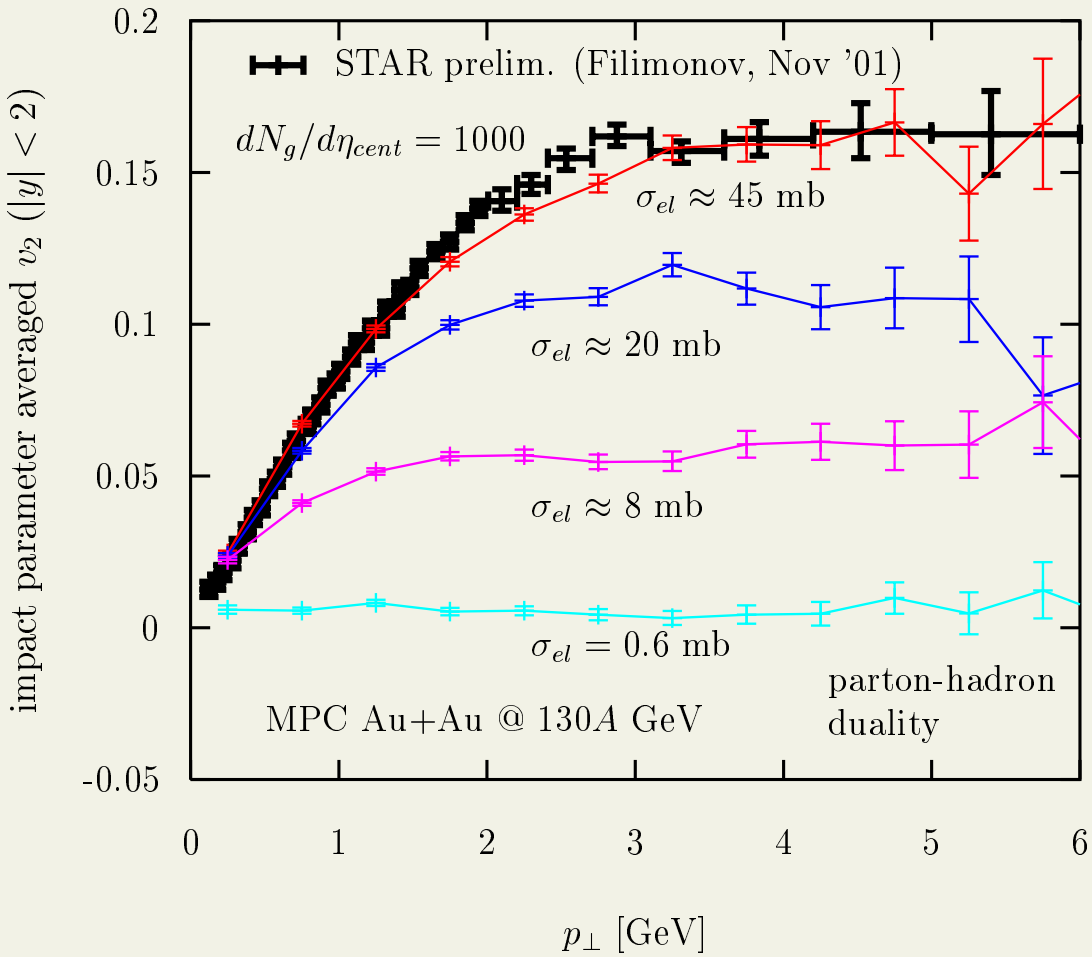
Kolb & Heinz, nucl-th/0305084v2



as system expands, spatial eccentricity reduces $\rightarrow v_2$ "self-quenches" itself

Opacity at RHIC

DM & Gyulassy, NPA 697 ('02): $v_2(p_T, \chi)$



parton transport model MPC

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

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

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

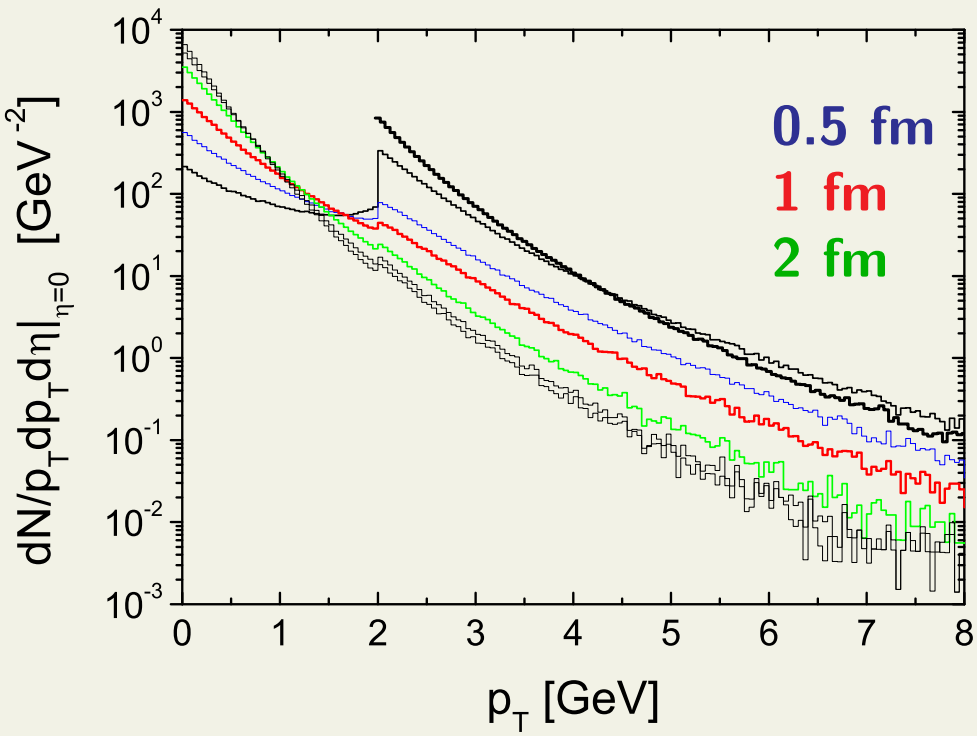
- minijet initconds
- 1 parton $\to$ 1 π hadronization

$\langle N_{coll} \rangle \sim 40 - 70$: **i.e.,** $10 - 15\times$ **higher opacity than from perturbative** $2 \to 2$

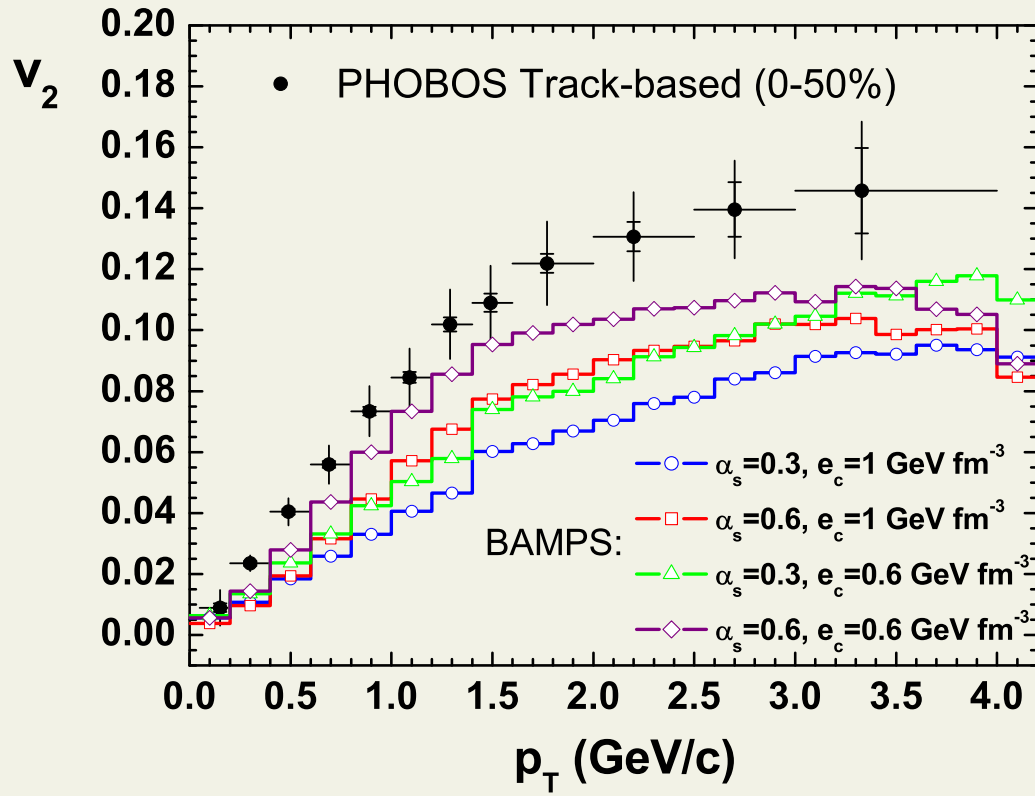
One way out: include perturbative $ggg \leftrightarrow gg$

e.g., Frankfurt/BAMPS (2005-), or MPC/Grid (2015-)

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



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



some challenges remain: e.g., treatment of LPM and sensitivity to screening

A Multi-Phase Transport

Lin, Ko et al, PRC72 ('05)

also quite successful with observables

AMPT $\approx$ Lund string model (HIJING)
$+$ $2 \to 2$ parton cascade (ZPC)
$+$ hadron transport (ART)

version with "string melting":

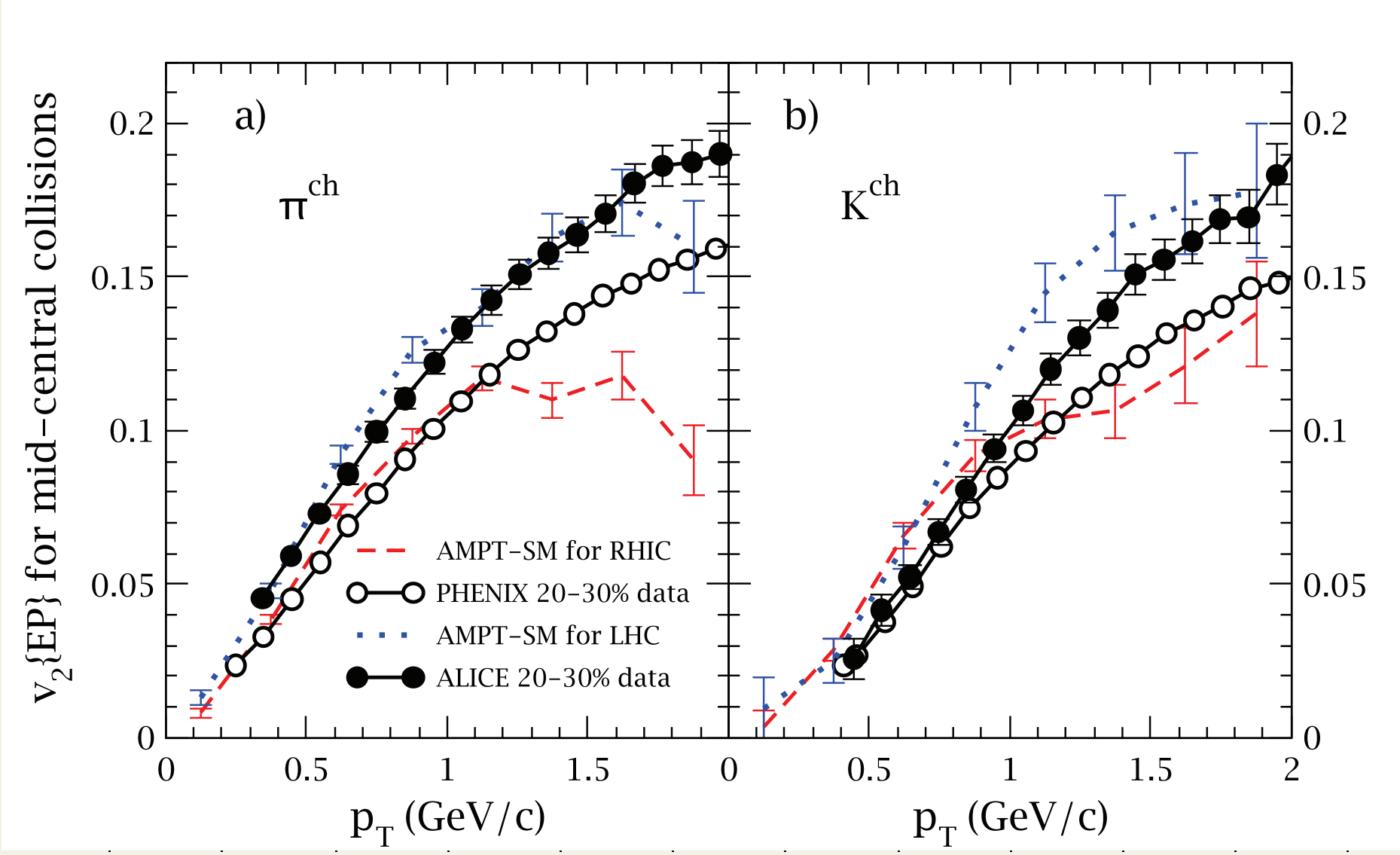
- **energy density in strings converted to quanta (quarks/antiquarks)**
- **$\to$ fluctuating initial geometry (random nucleon positions)**
- **hadronization via coalescence**

$\to$ higher parton density, enhanced collectivity

HERE: use it to study elliptic flow in 200-GeV Au+Au arXiv:1502.05572

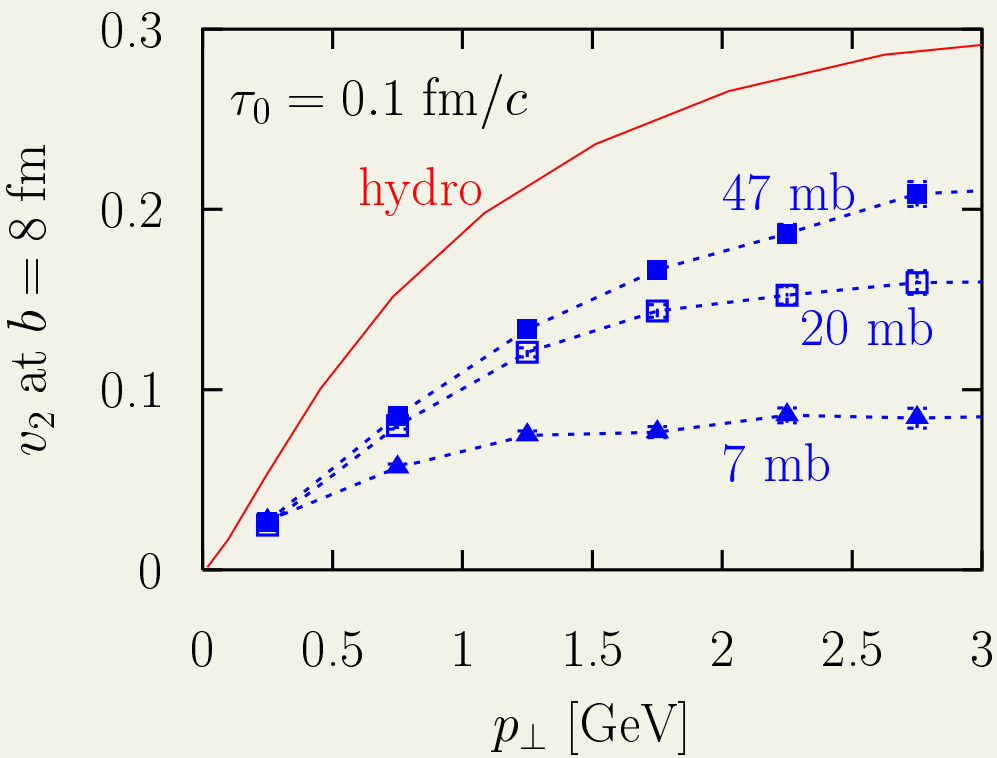
AMPT also gets low-pT v2

Z.-W. Lin, PRC90 ('14)

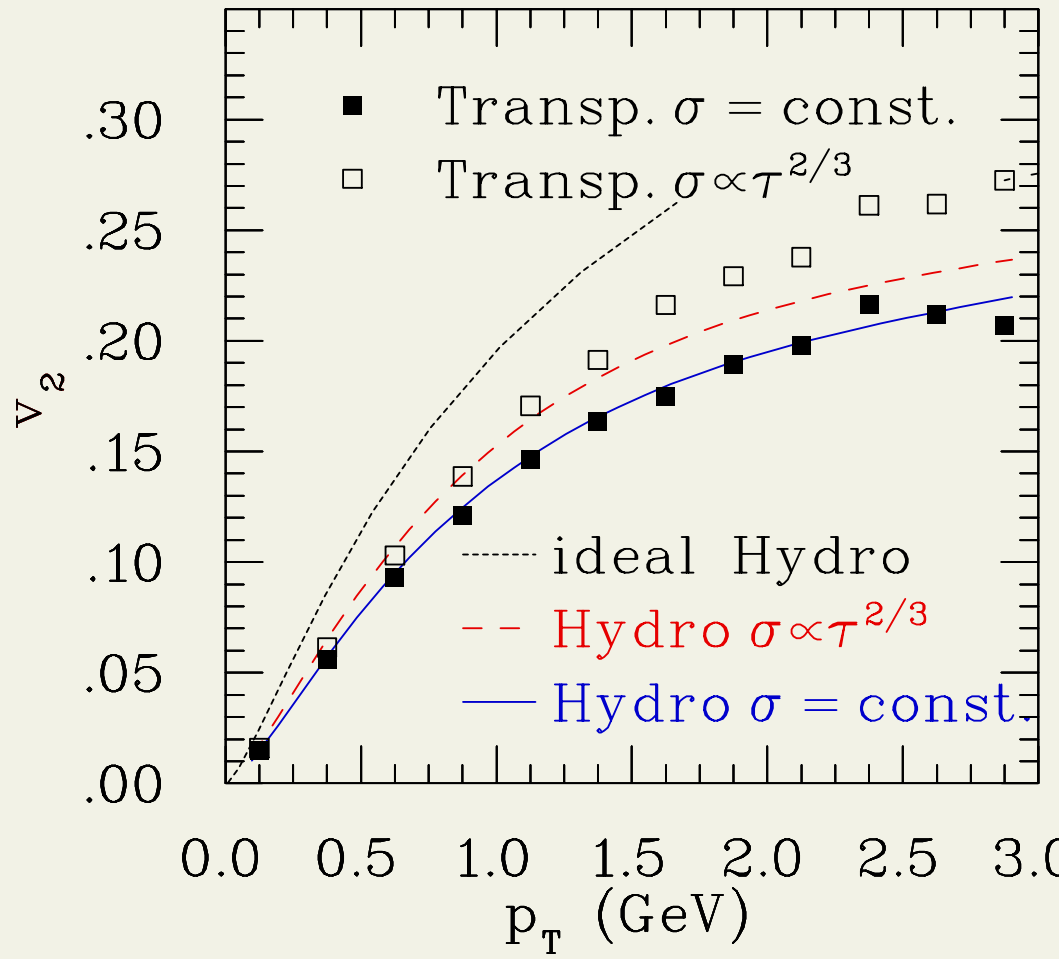


ideal hydro needs $\sigma \to \infty$ (hard) though viscous hydro could be reachable

DM & Huovinen, PRL94 ('05)



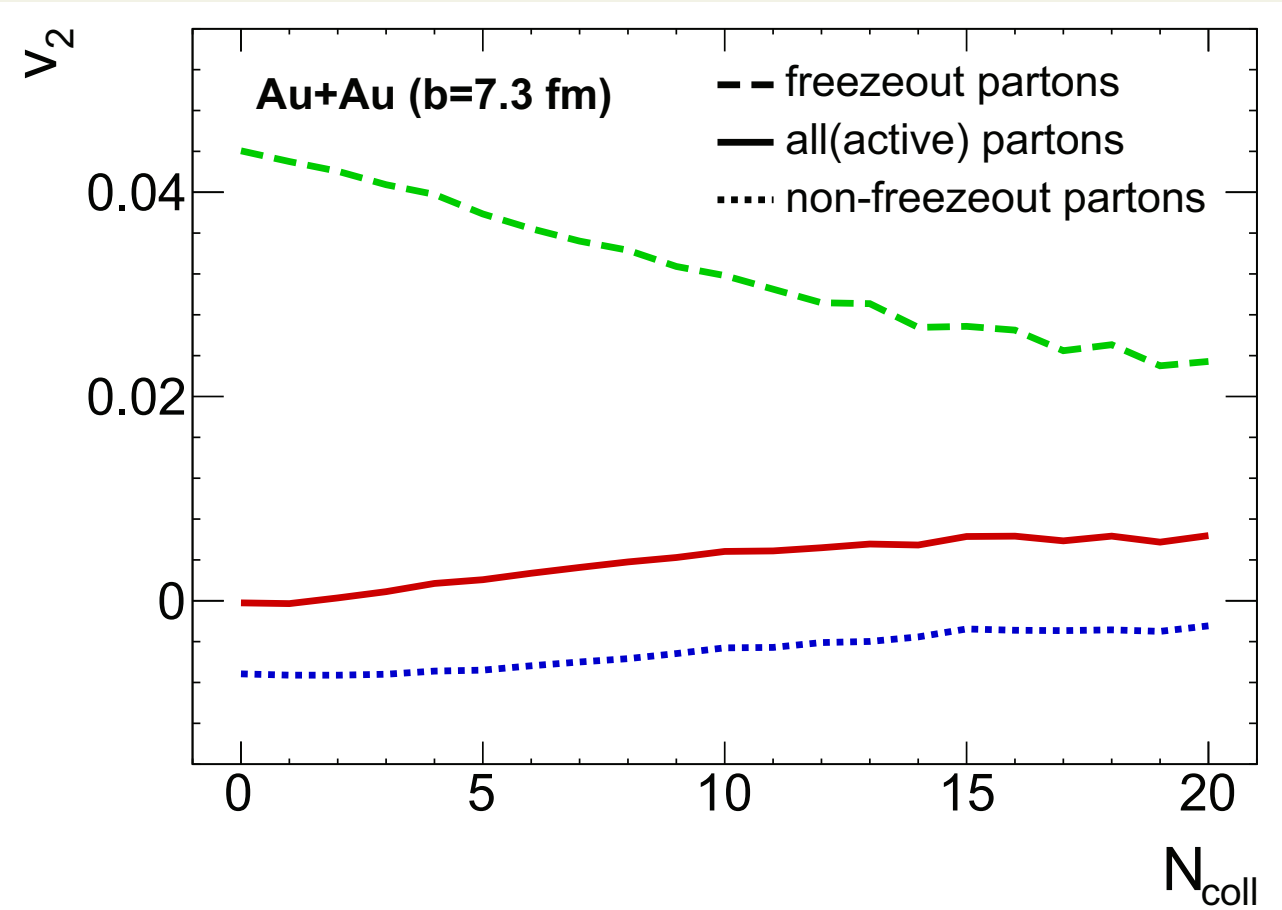
Huovinen & DM, JPG35 ('08)



Is AMPT just hydro?? → No.

v_2 from AMPT - vs N_{coll}

He et al, PLB 753 ('15)



$$\frac{d\sigma}{dt} \propto \frac{1}{(t-\mu_D^2)^2}$$

$$\mu_D^2 = 0.2 \text{ GeV}^2$$

$$\sigma_{TOT} = \frac{9\pi\alpha_s^2}{2\mu_D^2} = 3 \text{ mb}$$

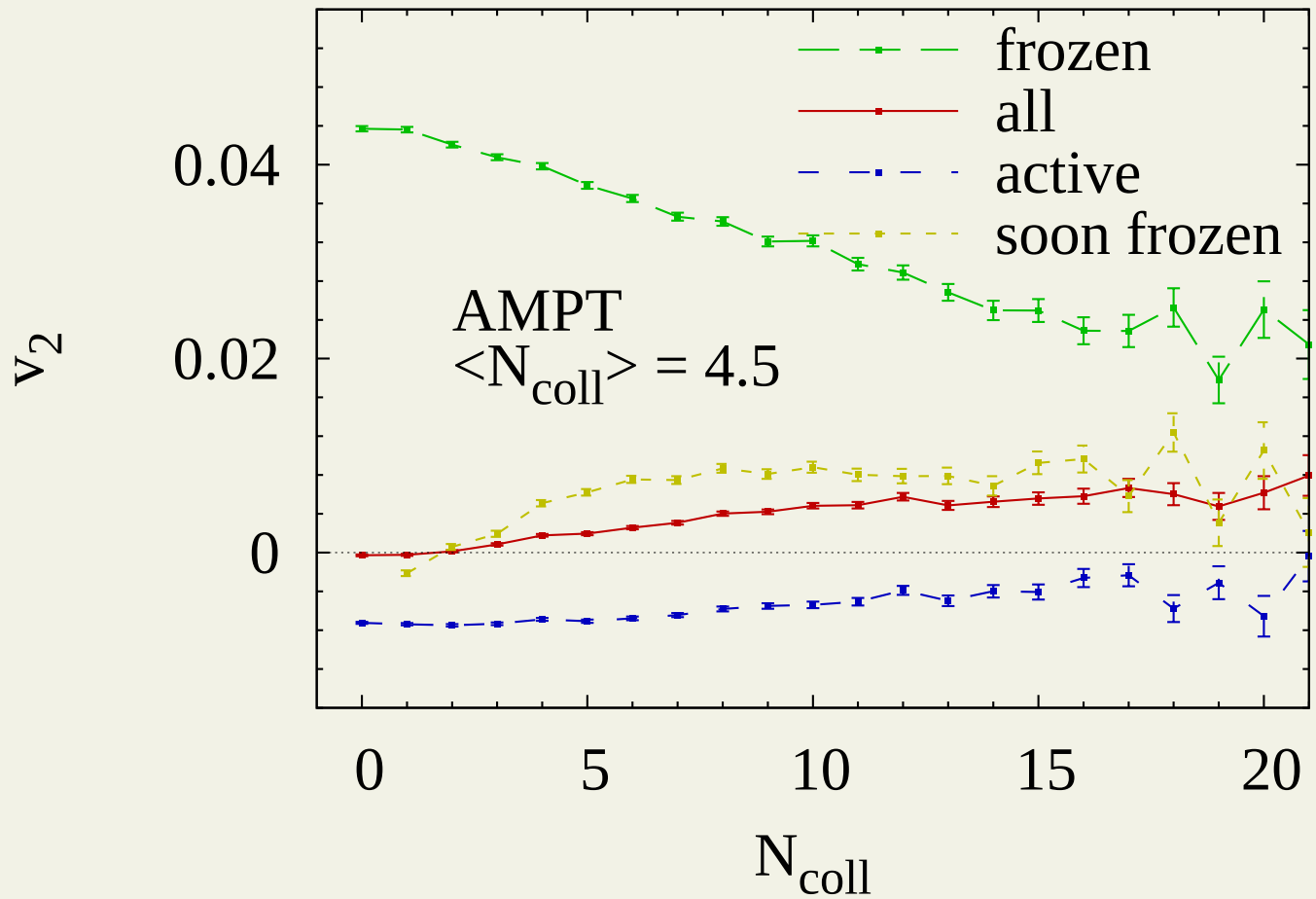
$$\Rightarrow \langle N_{coll} \rangle \approx 4.5$$

solid: all - all partons right after their N_{coll}-th collision

dashed: frozen out - partons that do not interact after the N_{coll}-th collision

dotted: non-freezeout - these will have more than N_{coll} collisions in future

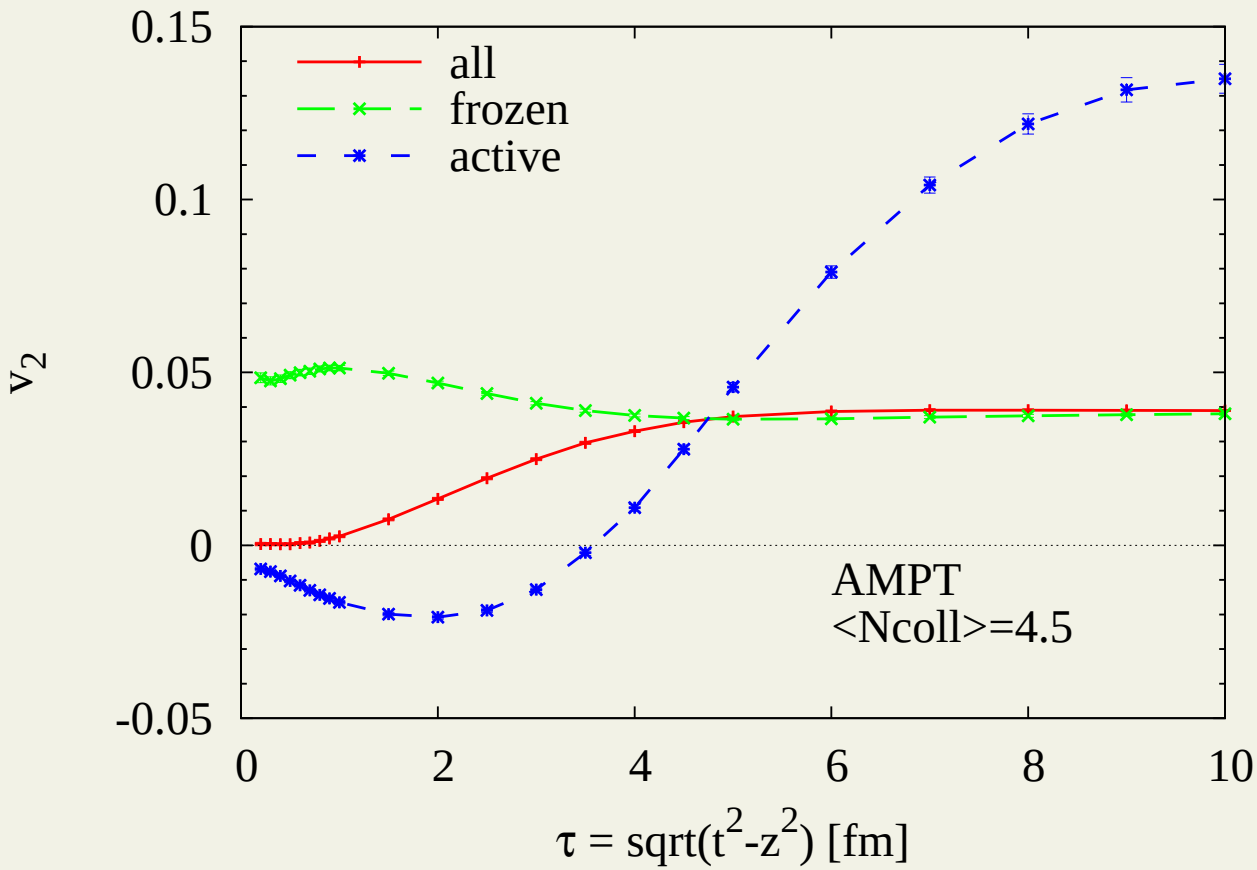
DM et al ('15): v_2 **vs** N_{coll}



yellow: same partons as green curve but their v_2 plotted right before N_{coll}

v_2 from AMPT - vs (proper) time

DM et al ('15):

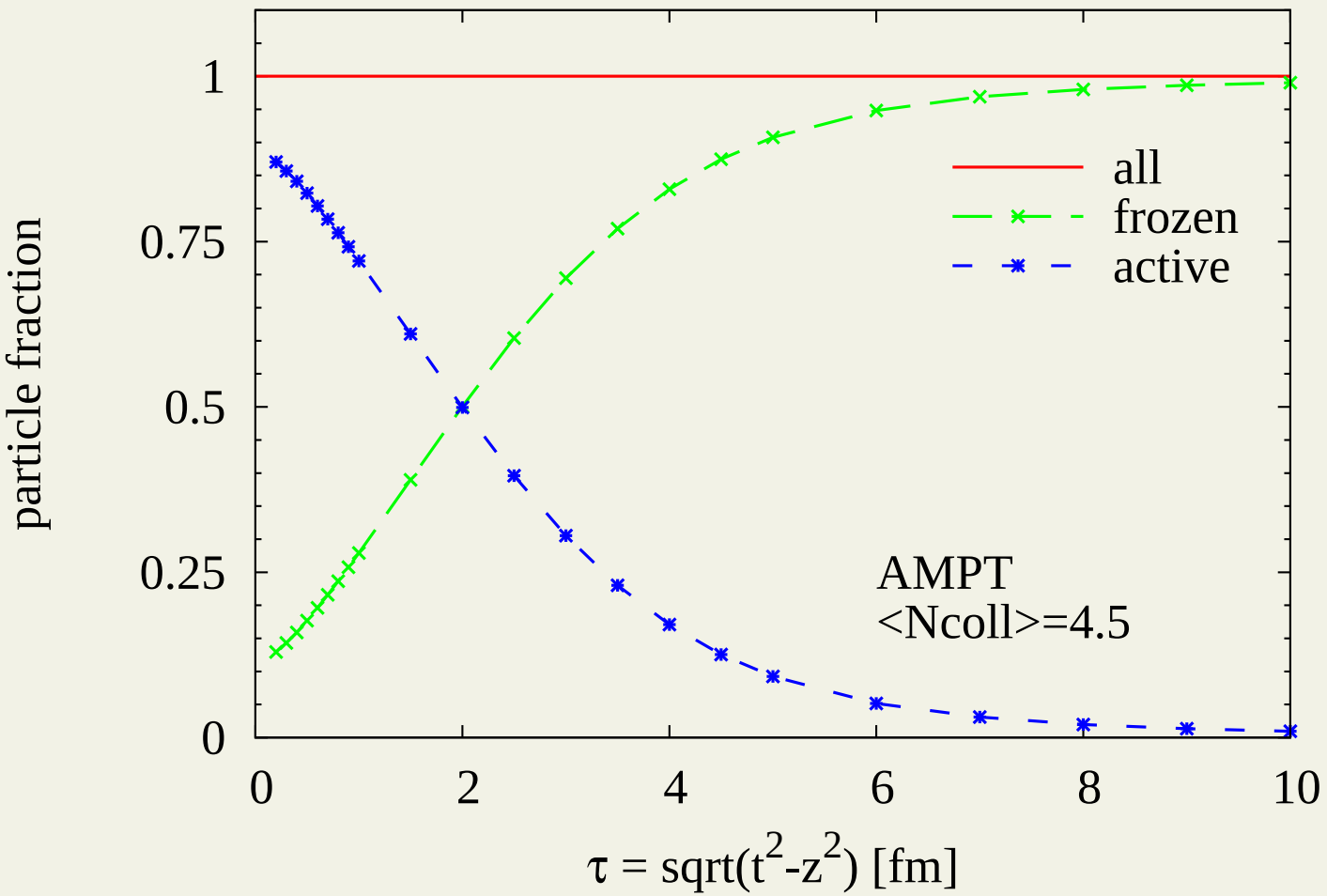


all - **all partons at the given** $\tau = \sqrt{t^2 - z^2}$

frozen out - **partons that had their last collisions before given** τ

active - **partons that will have collision after** τ **(still interacting part)**

DM et al ('15): **frozen/active/all fraction vs time**



So far:

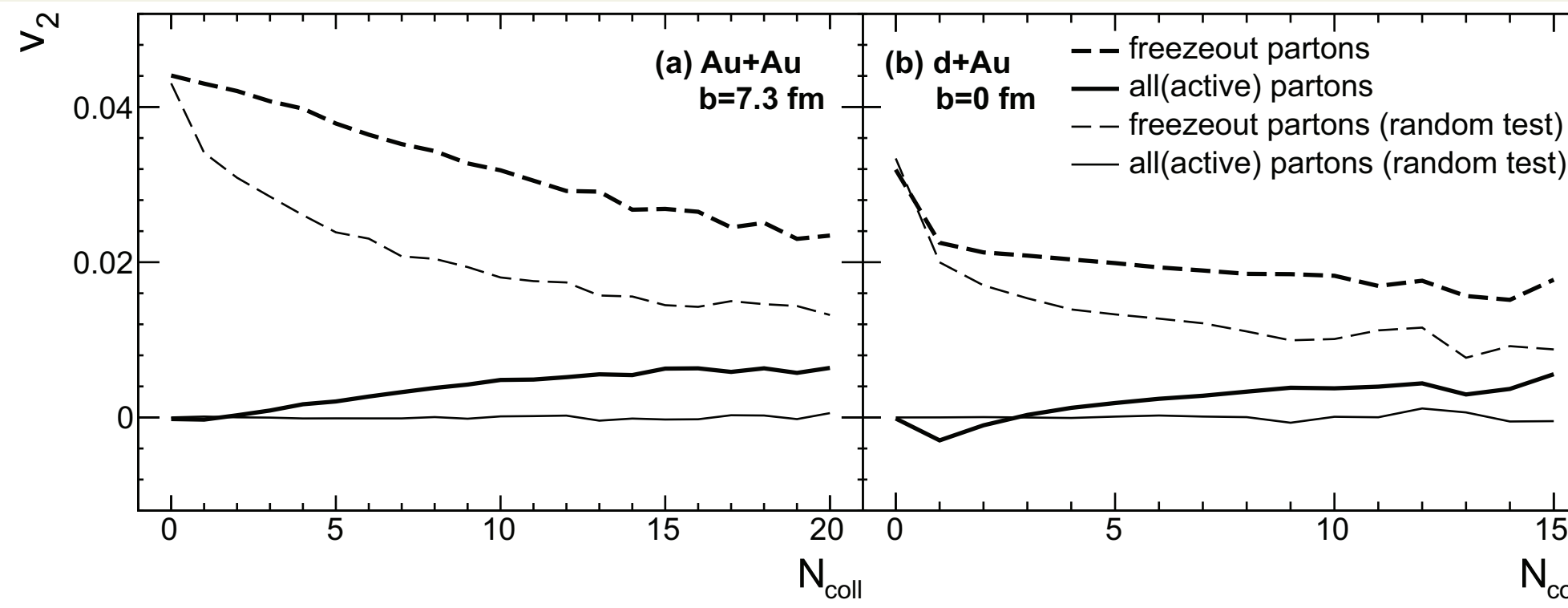
- interacting "hydro" component has low v_2 during most of the flow buildup

- large $\mathcal{O}(1)$ change in v_2 near the very last collision

$\rightarrow$ is it the collision (change in momenta)?
or that there will be no further collisions (escape probability)?

Test: randomize azimuth after each $2 \rightarrow 2$ collision (rotate outgoing momenta by random angle uniformly sampled over $[0, 2\pi]$)

He et al, PLB 753 ('15)



thick lines: standard AMPT, thin lines: AMPT with φ-randomization

dashed: frozen out, solid: all

$\rightarrow$ **escape v_2 largely survives randomization $\Rightarrow$ azimuthal escape bias**

It is general, not just AMPT

Recheck with MPC/Cascade DM & Gyulassy, PRC62 ('00)

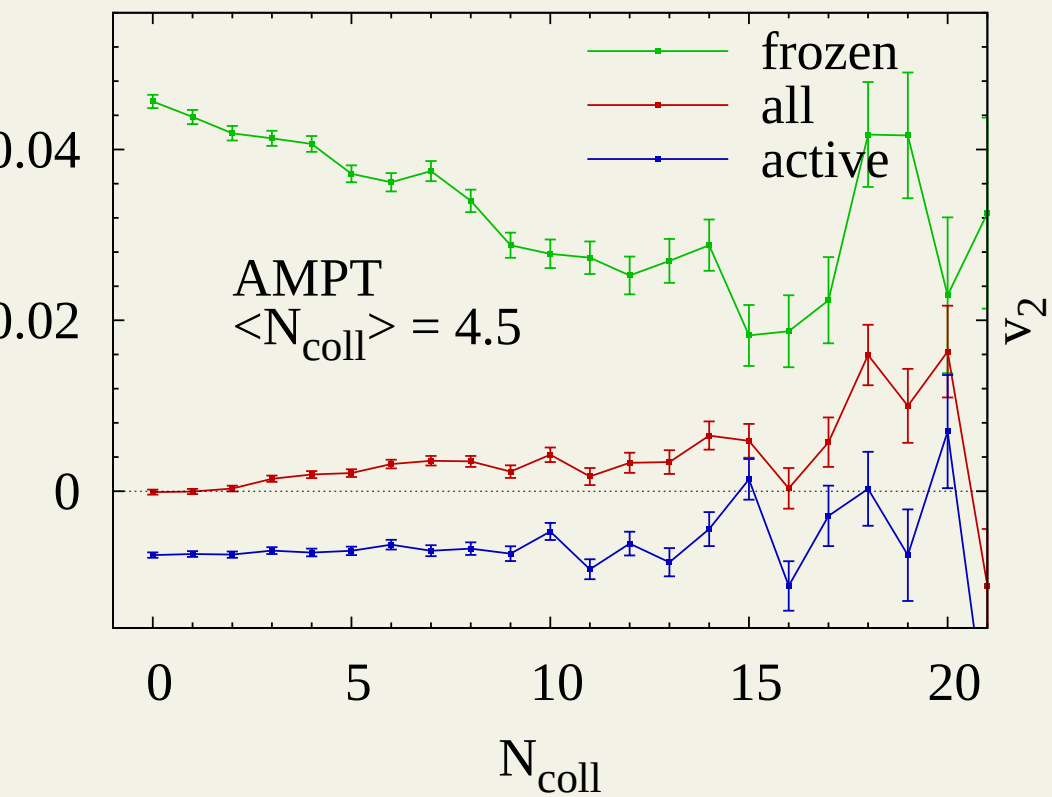
- parameters like in DM & Huovinen, PRL 94 ('05):

$$\begin{aligned}&\text{Au+Au, } b = 8 \text{ fm, smooth binary collision profile,}\\&\text{uniform } \frac{dN}{d\eta} \text{ for } |\eta| < 5\text{, with } \left.\frac{dN}{d\eta}\right|_{b=0} = 1000\\&\tau_0 = 0.6 \text{ fm, } T_0 = 385 \text{ MeV}\\&\sigma = const\text{, isotropic}\end{aligned}$$

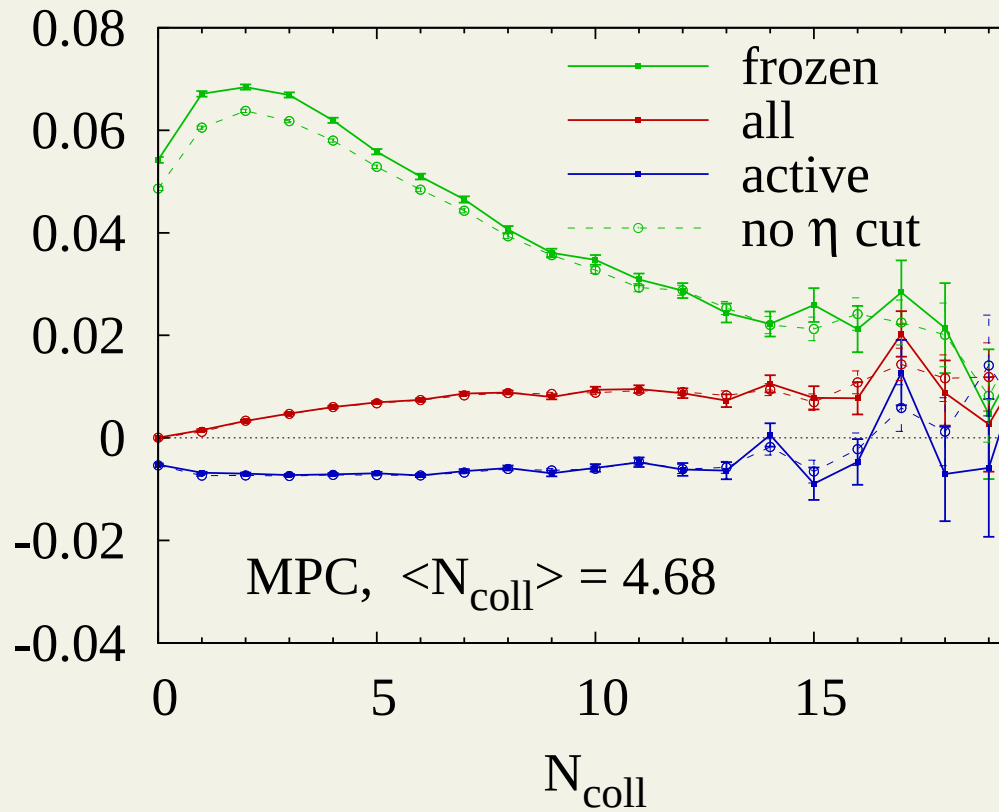
study 3 different opacities $\langle N_{coll} \rangle \approx 4.5$, 17, and 35

DM ('15): **v2 vs Ncoll comparison**

AMPT



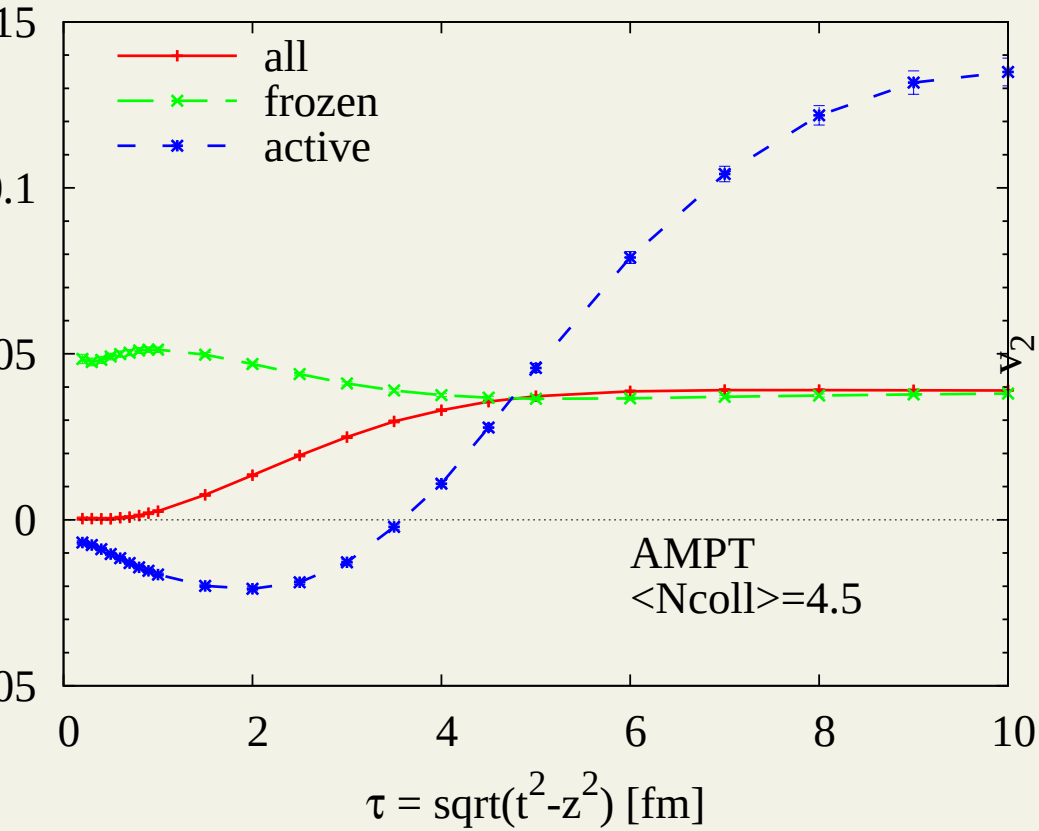
MPC/Cascade



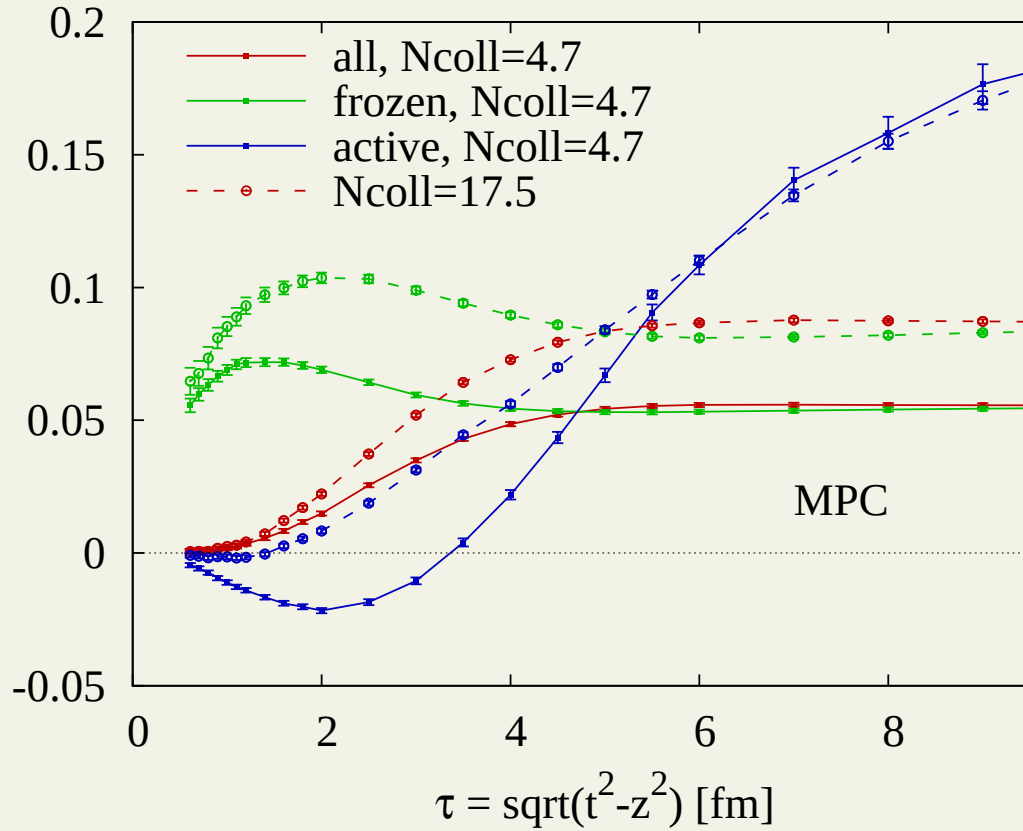
very similar at the same opacity $\langle N_{coll} \rangle \sim 4.5$

DM ('15): **v2 vs tau comparison**

AMPT

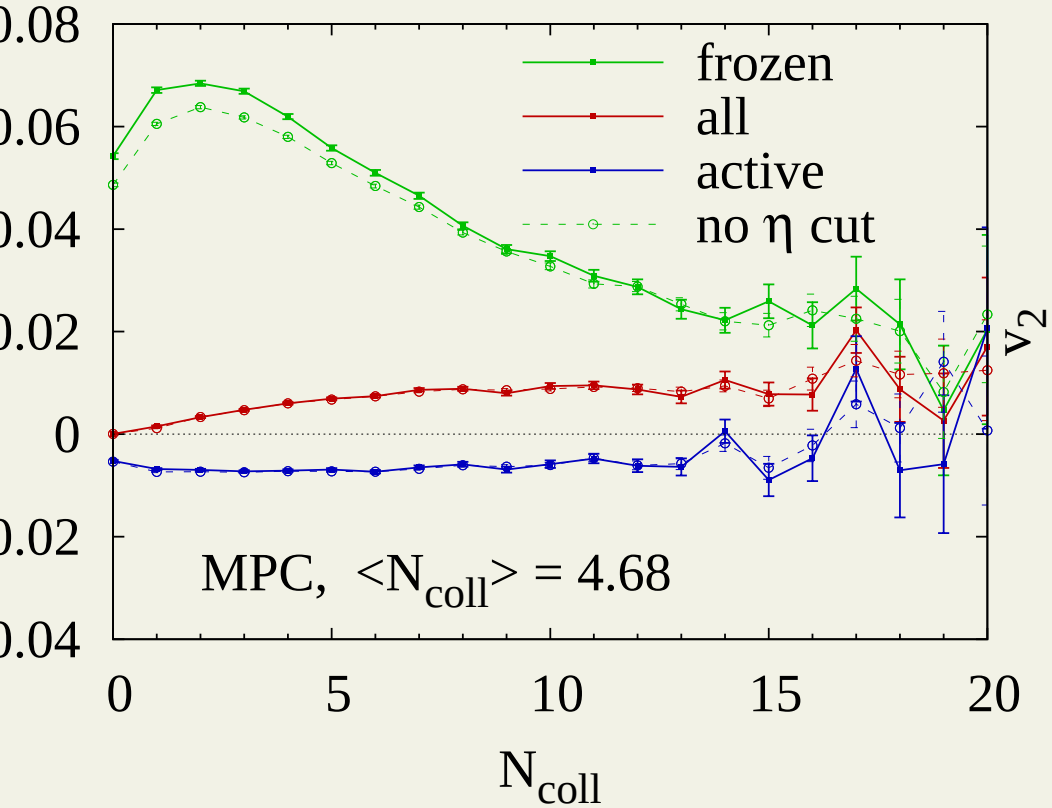


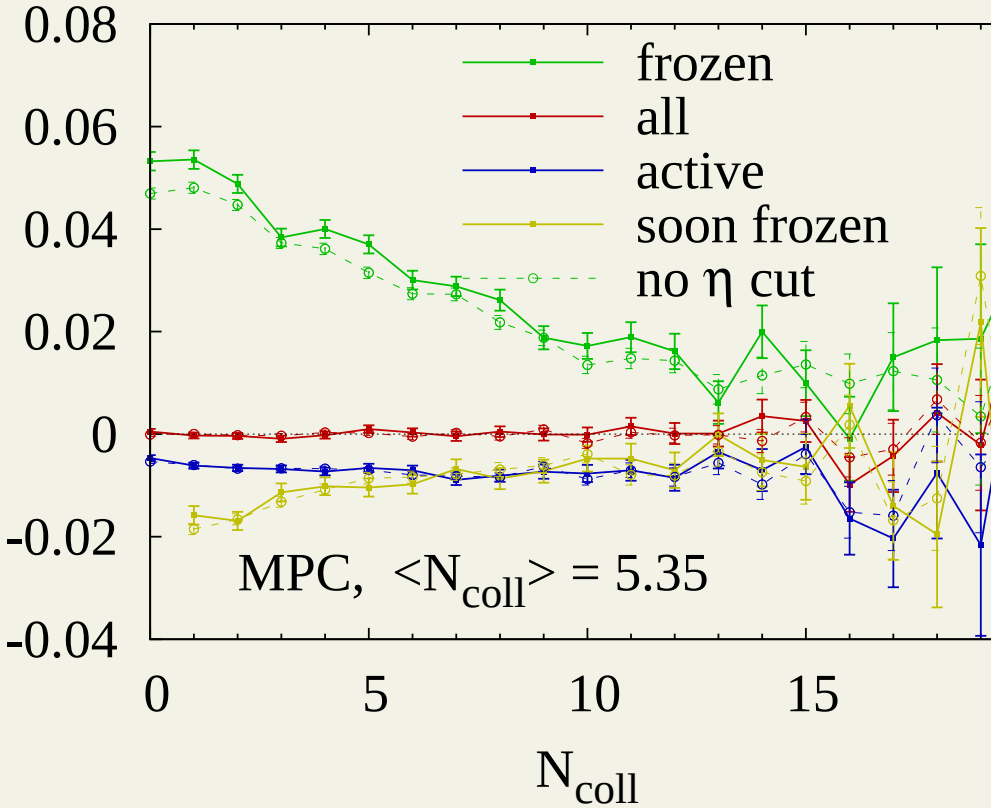
MPC/Cascade



very similar at the same opacity $\langle N_{coll} \rangle \sim 4.5$

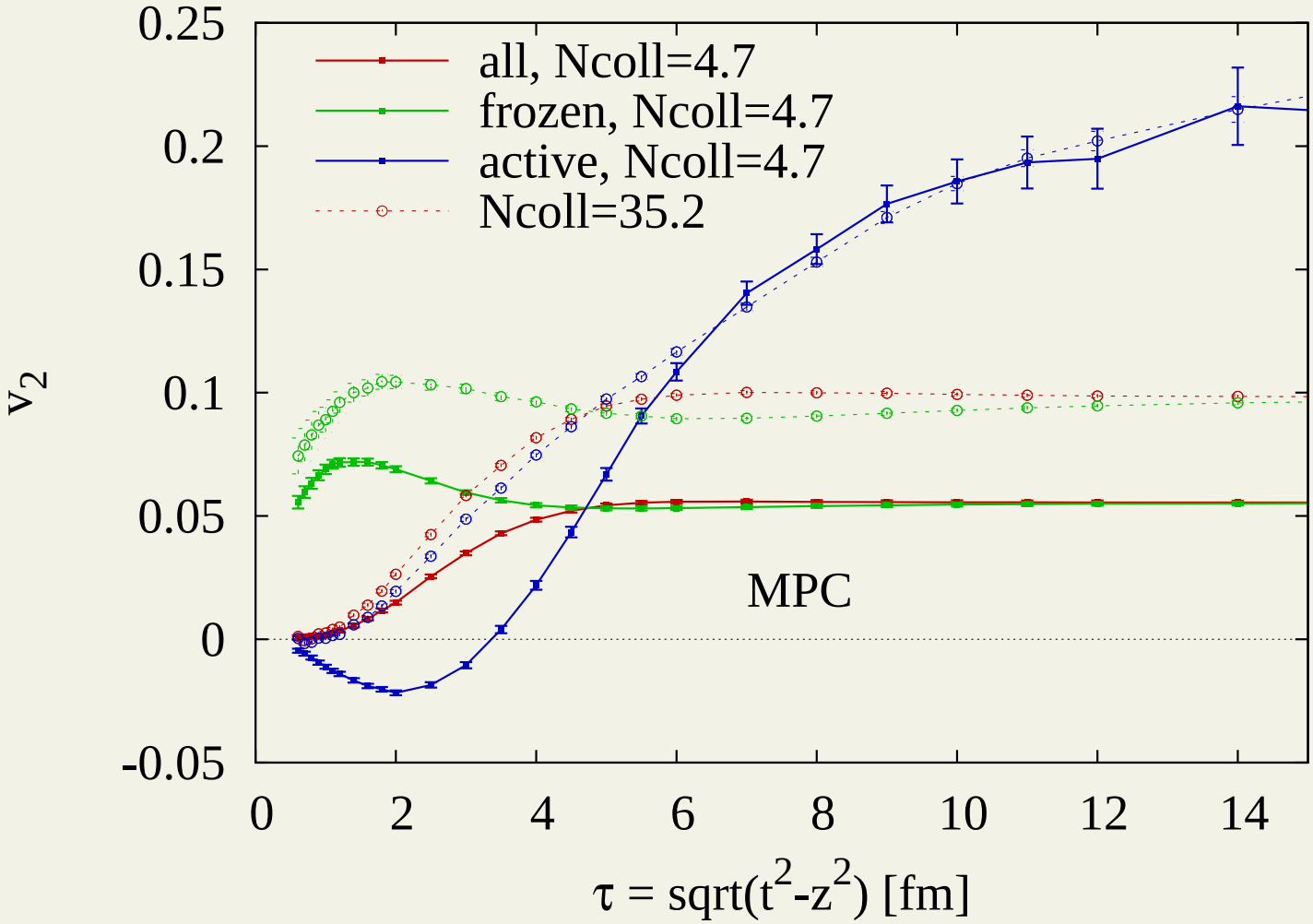
DM ('15): **standard** **vs** **phi-randomized** **MPC/Cascade**





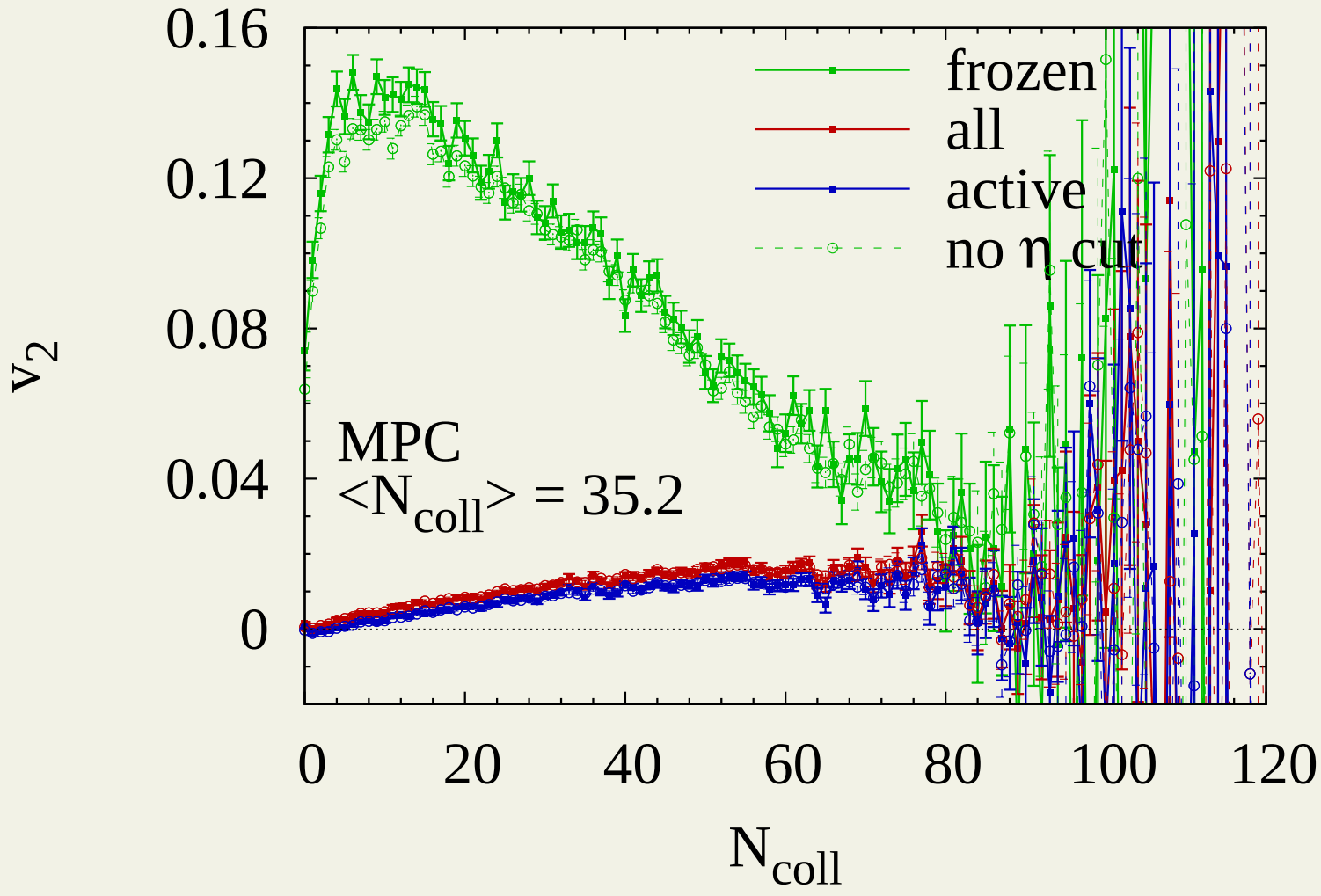
qualitative picture unaffected by randomization (like for AMPT)

DM ('15): **v2 vs tau at lowest and highest opacity**

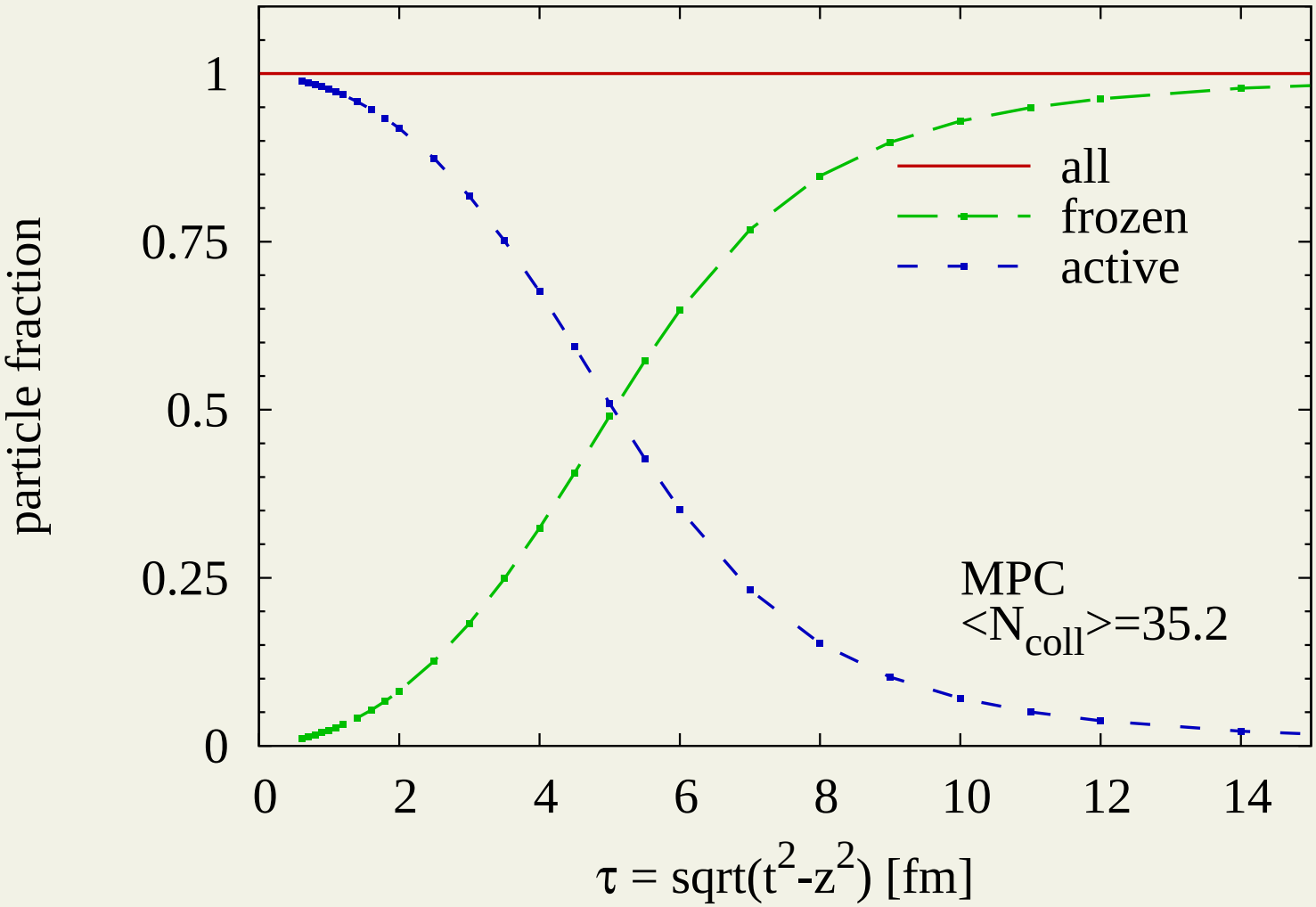


low opacity: escape dominates; high opacity: active part carries most of v_2

DM ('15): **v2 vs Ncoll at highest opacity**

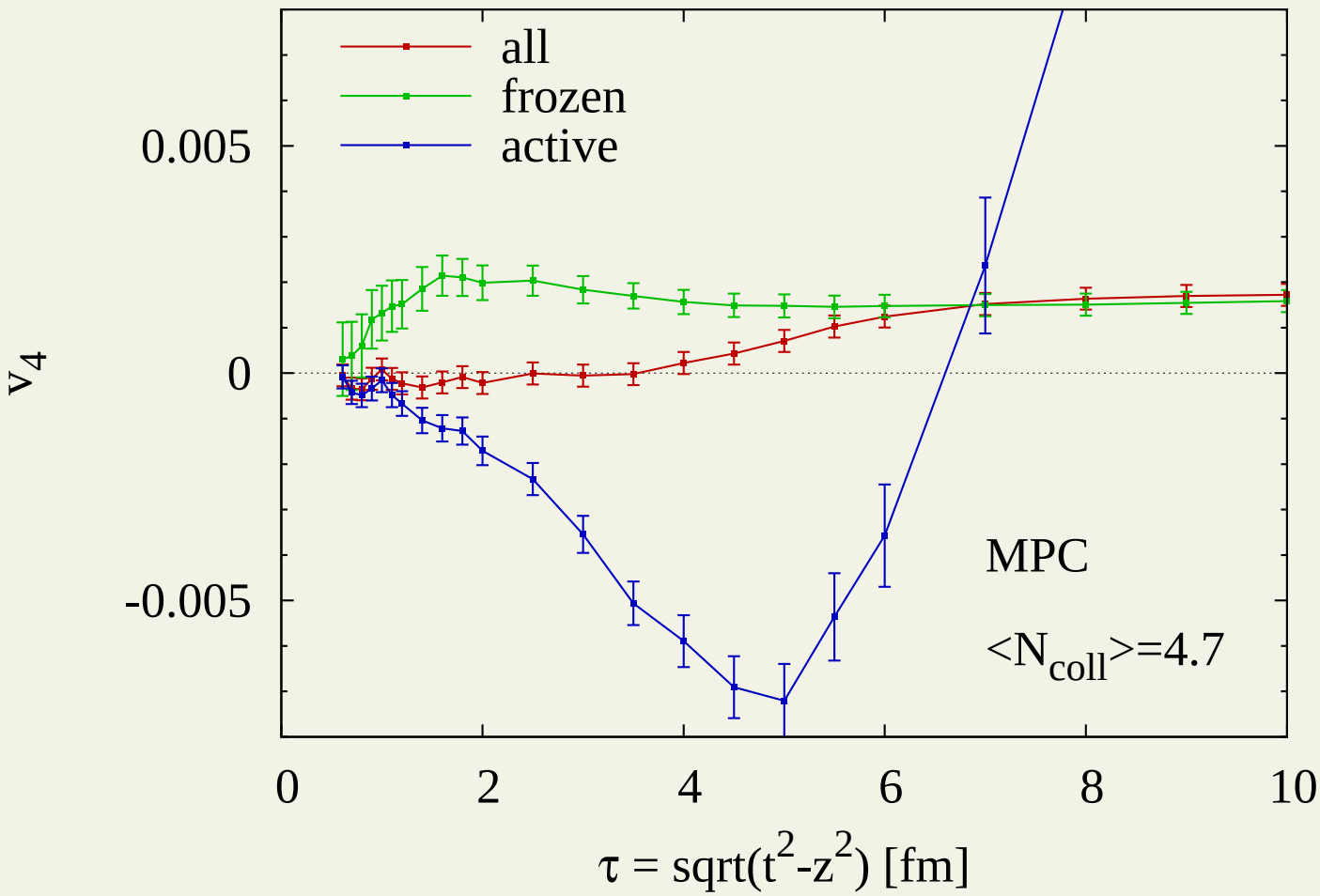


DM ('15): **active/frozen/all fraction vs tau**

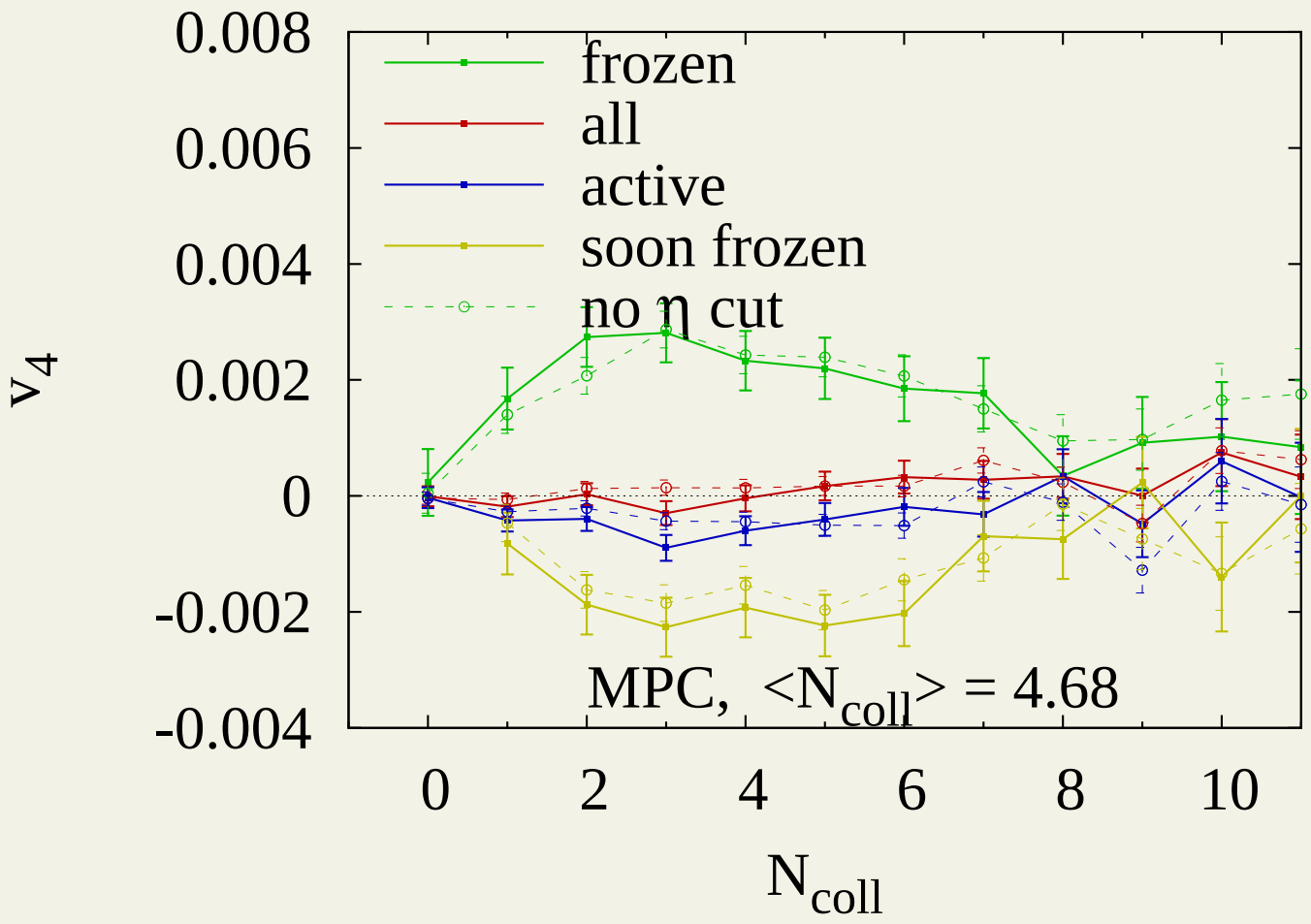


v_4 also similar...

v4 vs tau DM ('15)



v4 vs Ncoll DM ('15)



need more statistics but qualitatively similar behavior to v_2 (escape)

Anisotropic escape is a generic feature of transport models, as long as opacities are not very large

- **not captured by standard hydro + Cooper-Frye**
- **Fokker-Planck also lacks chance for no interaction**

- **revive continuous emission hydro that weights by $P_{escape} = e^{-\int dz \sigma \rho}$?**

Socolowski, Grassi, Hama & Kodama PRL 93, 182301 (2004)

Alright, escape gives v2 - but a mass-ordered one??

standard hydro explanation: flow boost effect Huovinen, Kolb et al PLB 503 ('01)

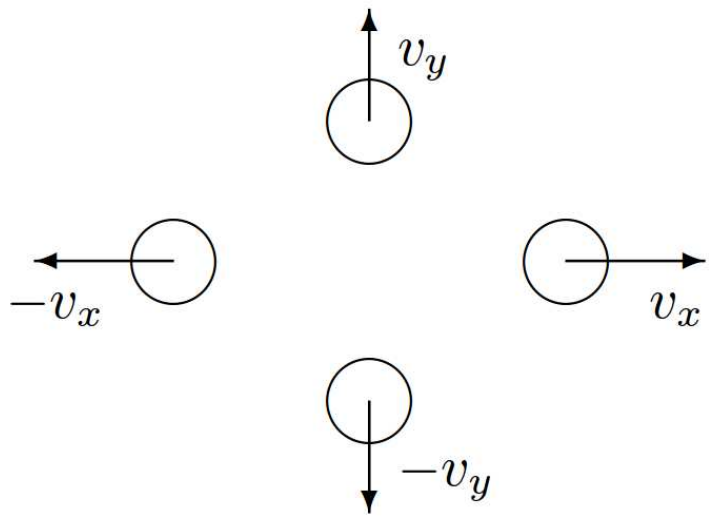
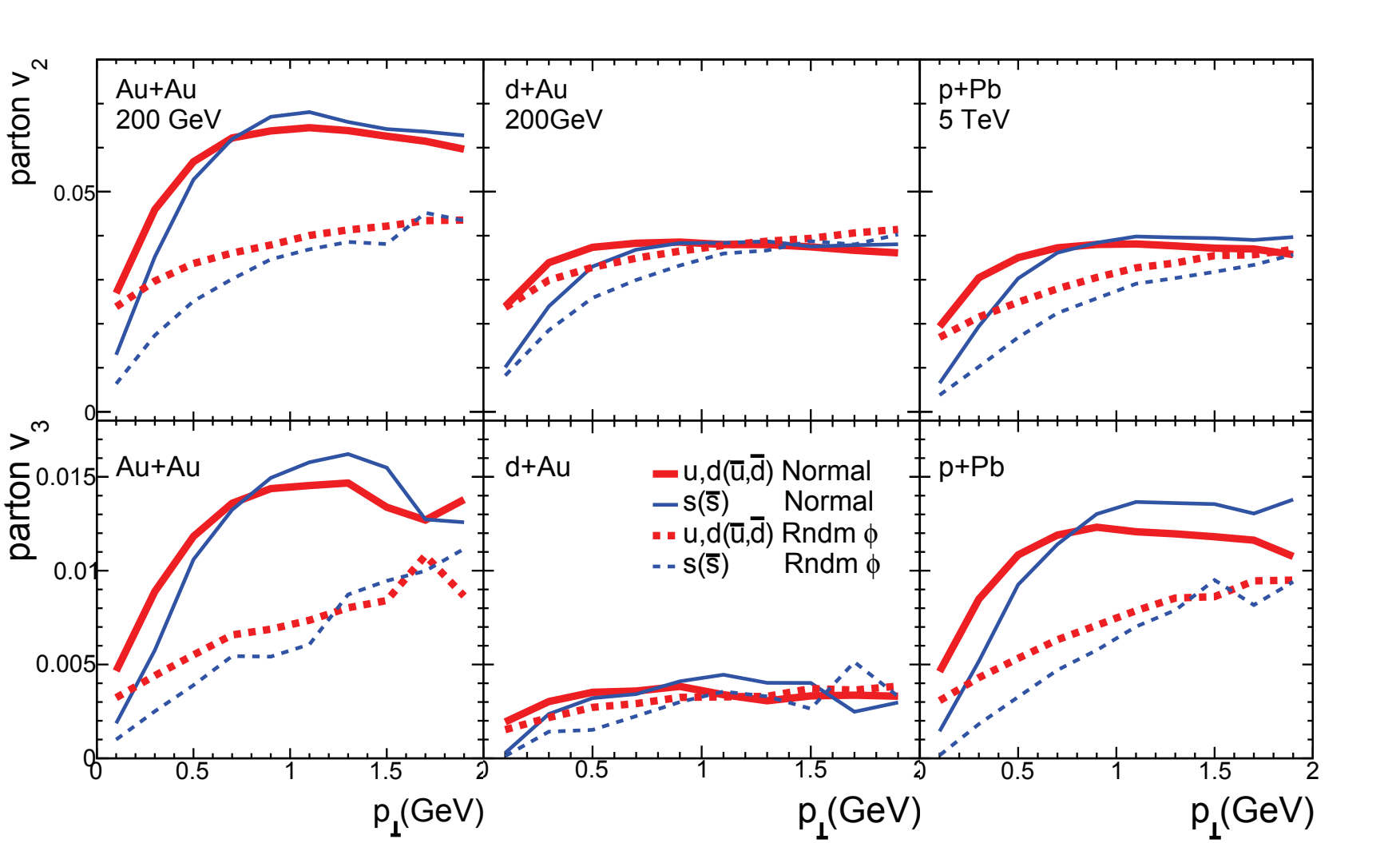


FIG. 6. Simple source of four fireballs.

AMPT: parton cascade + hadronization + rescatterings (+ decays)

AMPT - partonic flow (AA, dA, pA)

Li et al, 1601.05390v2:



weak mass ordering at low pT, even with ϕ-randomization

Hadronization (coalescence)

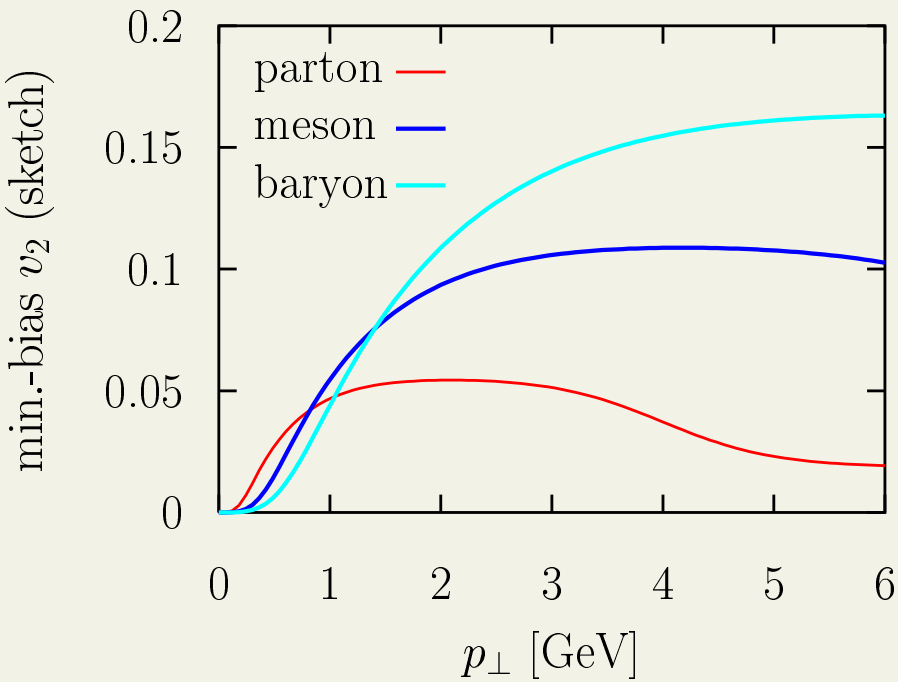
in AMPT, meson and baryons form via $q\bar{q} \rightarrow M$, $qqq \rightarrow B$

whereas in hydro hadronization built into EoS ($p(e, n_B)$)

fusion nearby in phase space $\Rightarrow$ **helps "amplify" elliptic flow**

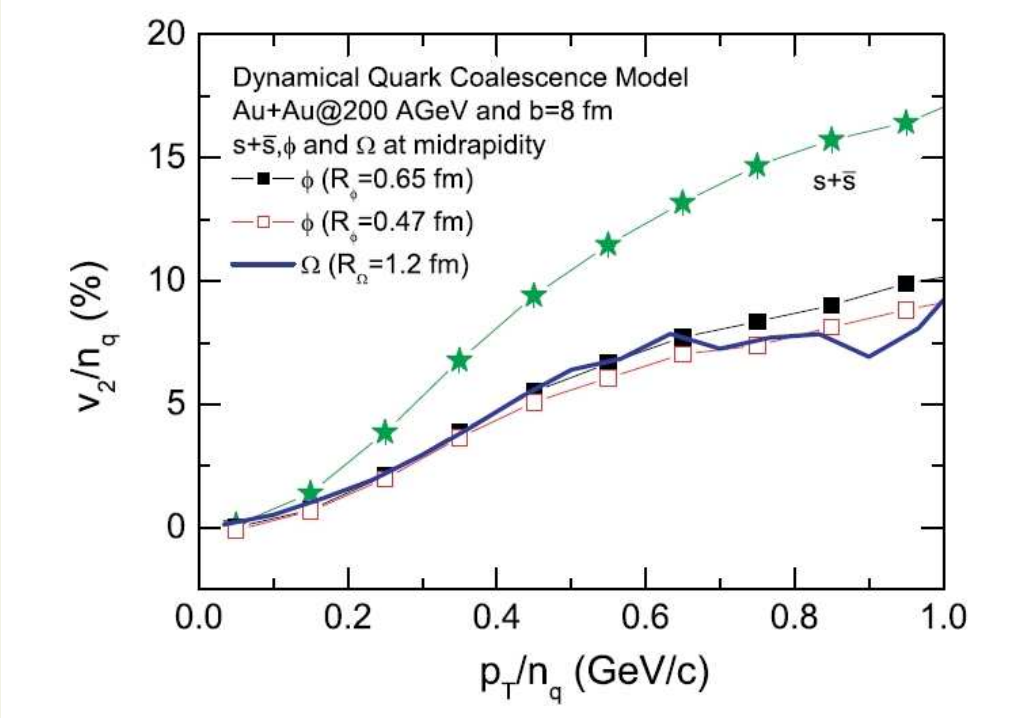
naively $v_{2,n}(p_T) \approx n v_{2,q}(p_T/n)$

DM & Voloshin, PRL91 ('03)



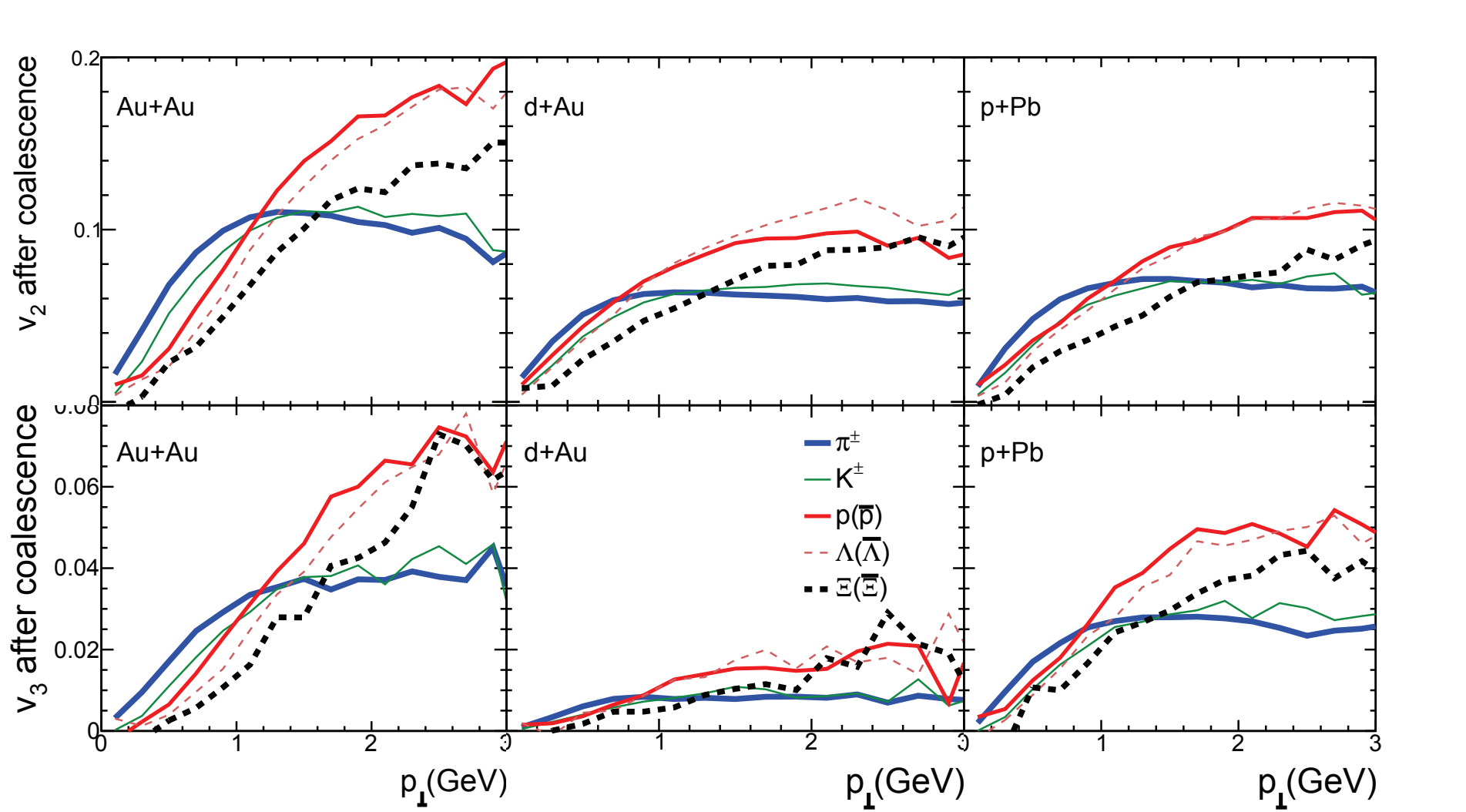
while in AMPT

Chen & Ko, PRC73 ('06)



AMPT - flow after coalescence

Li et al, 1601.05390v2:

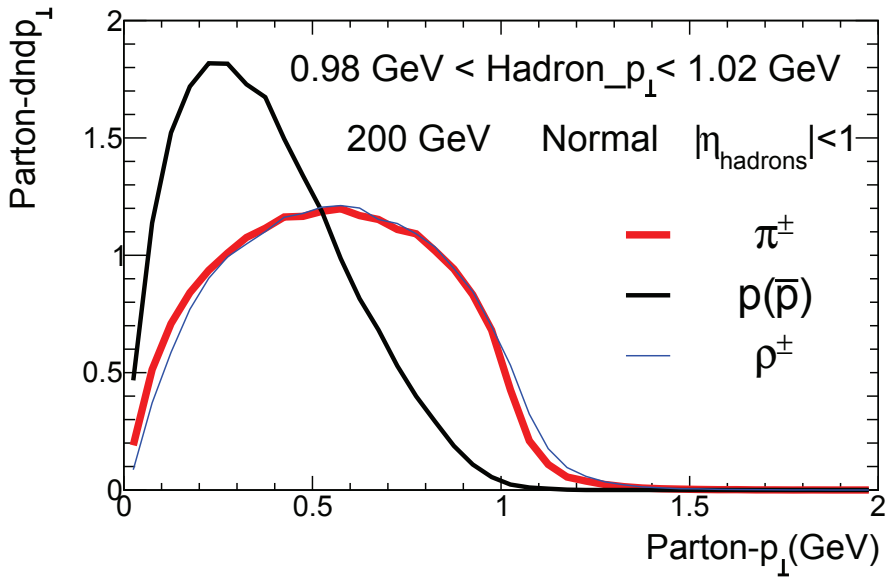


clear mass ordering, mainly from coalescence

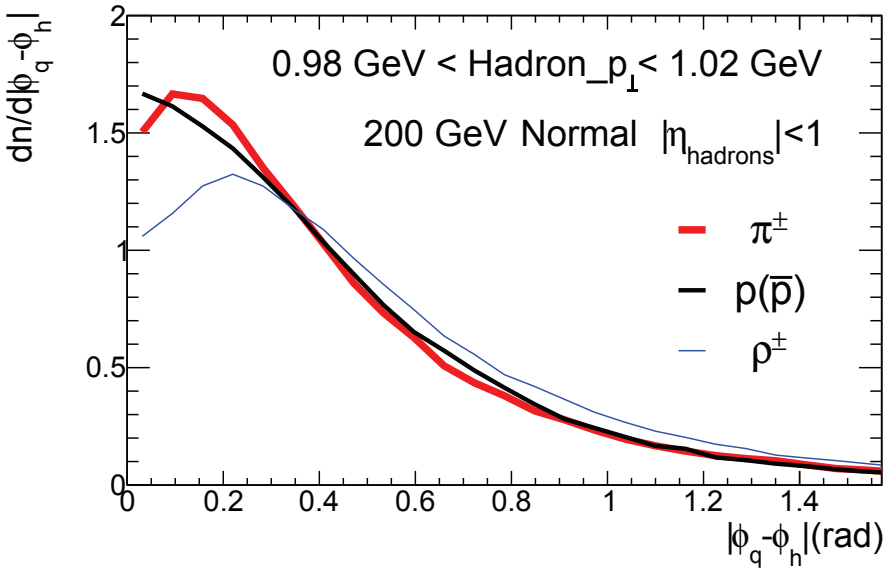
quark momenta and opening angles in coalescence depend on species

Li et al, 1601.05390v2:

parton pT for given hadron pT



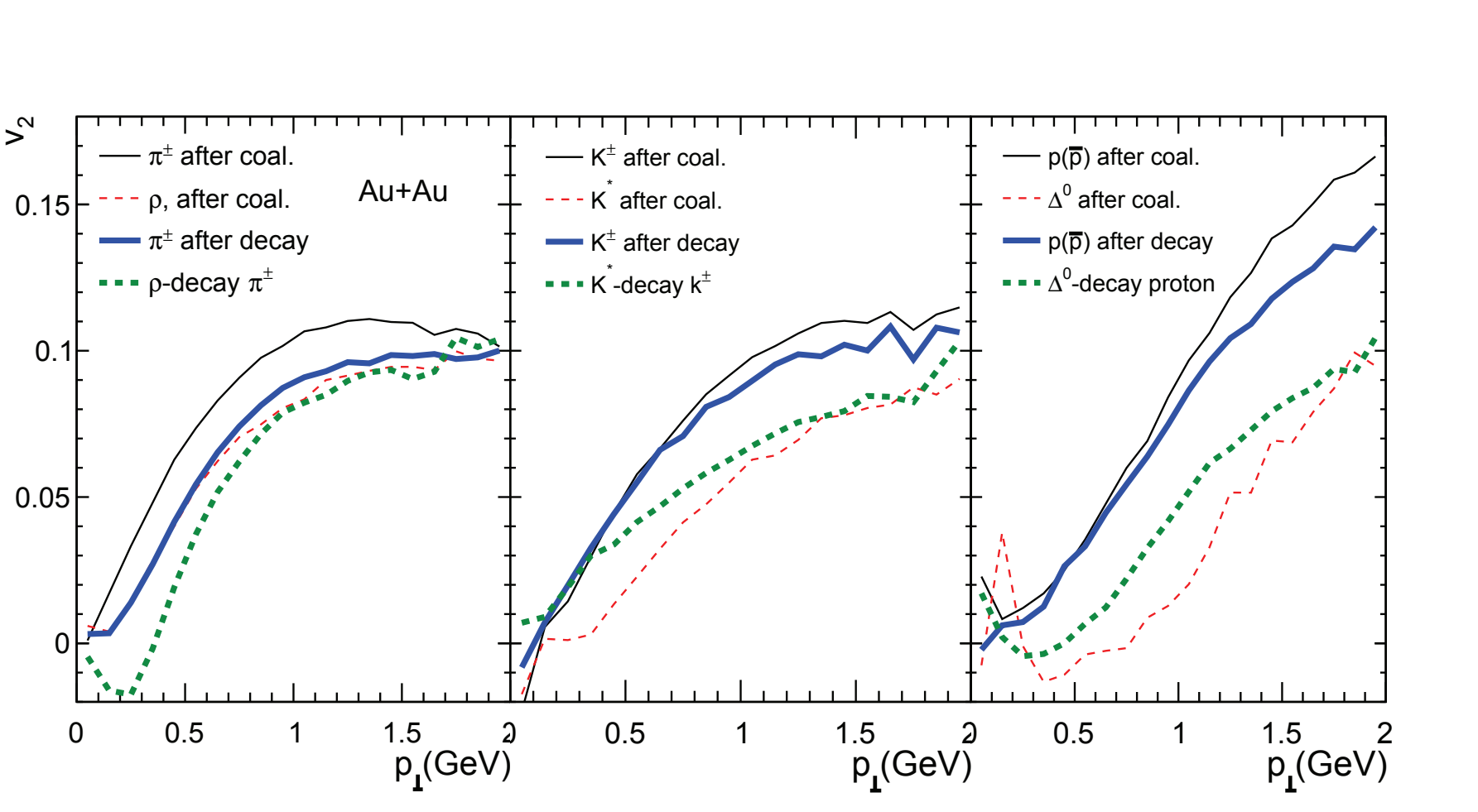
hadron-parton momentum opening angle



→ **opening angle varies within same meson/baryon group**

AMPT - effect of decays

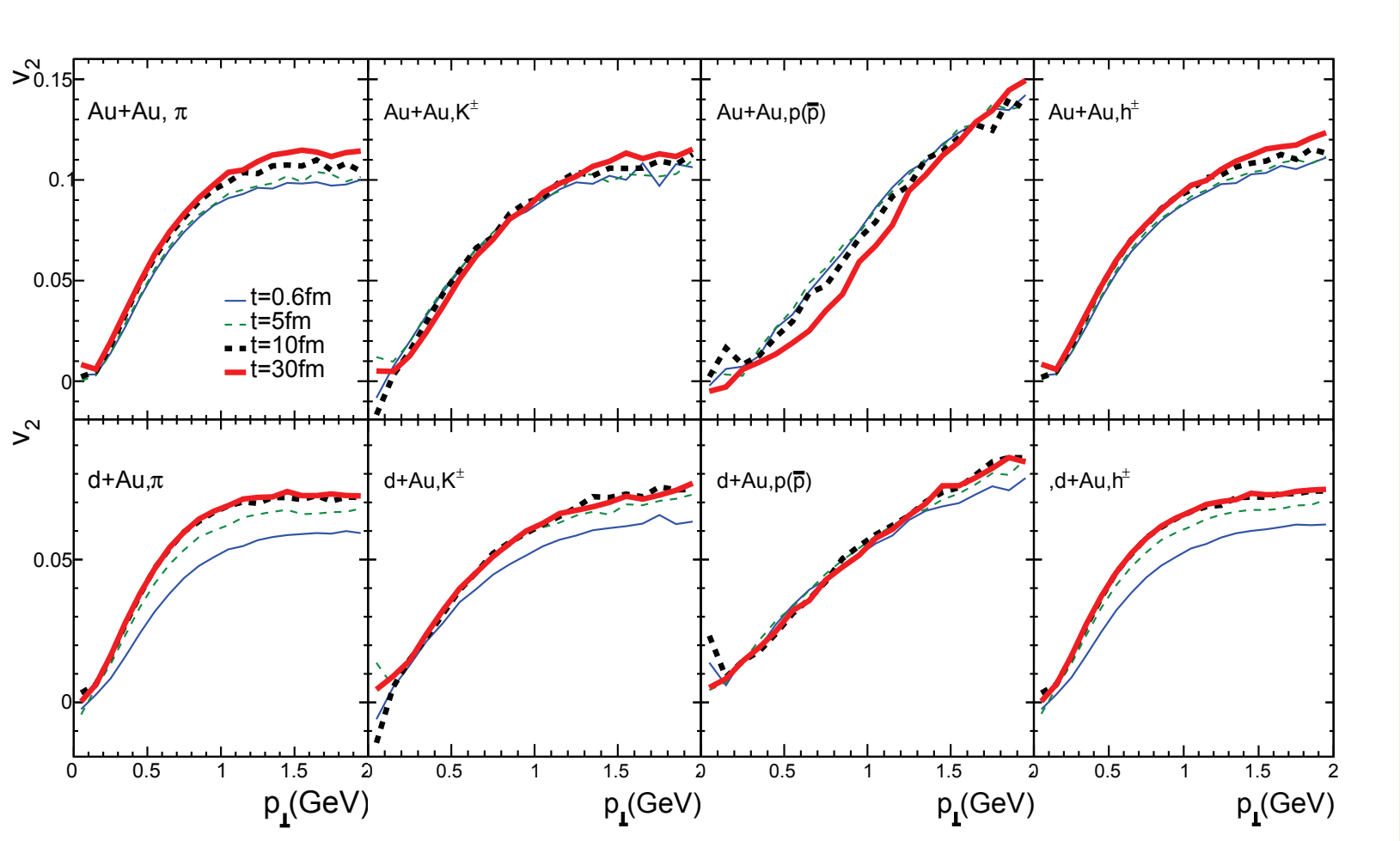
Li et al, 1601.05390v2:



→ **decays reduce v2 but effect varies with species**

AMPT - hadronic rescatterings

Li et al, 1601.05390v2:



→ **enhancement/reduction based on species, system size also matters**

Summary

Anisotropic escape is a generic feature of transport models. At modest $N_{coll} \sim 5$, most of the v_2 in mid-peripheral Au+Au is built up via escape and carried by already frozen out partons in both AMPT and MPC/Cascade, while the still interacting component has zero or even negative v_2. At very high opacities $N_{coll} \sim 30$, the interacting ("hydrodynamic") part does dominate the evolution of v_2.

Therefore, **application of hydrodynamics** to extract medium properties from elliptic flow (such as shear viscosity) **gets entangled with decoupling physics**. Ignoring escape can lead to an underestimate of v_2 from the theory, and thus a systematic bias towards smaller shear viscosities inferred from data.

Flow mass ordering arises in AMPT as an interplay among hadronization via coalescence, hadronic rescatterings, and decays. Most mass difference is generated by rescatterings and coalescence.

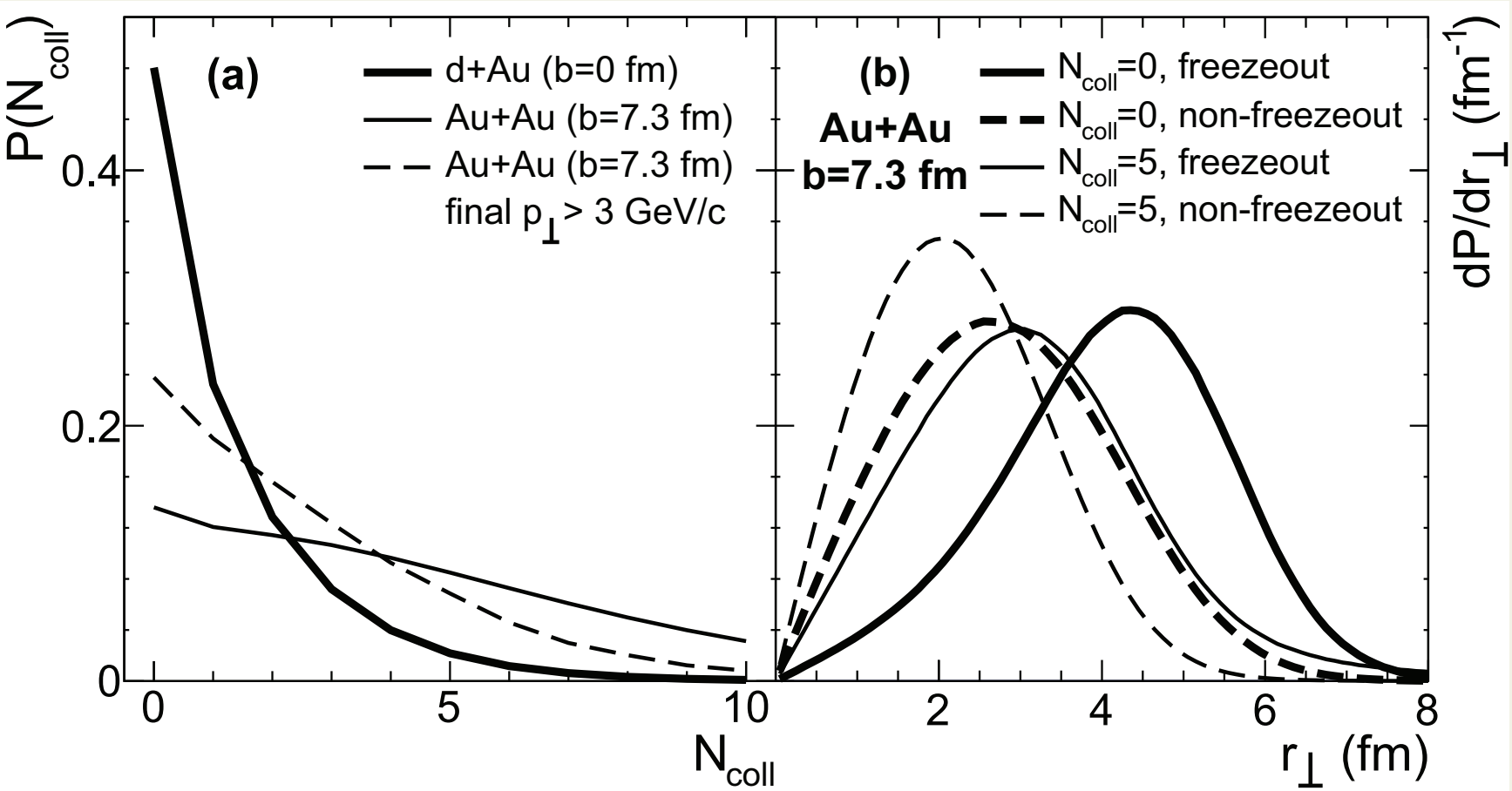
Open questions remain, such as how to properly incorporate escape into hydrodynamics or Fokker-Plank theory, and how anisotropic escape affects heavy quark v2.

Backup slides

spacetime picture looks like evaporation - “outside-in”

He et al, PLB 753 ('15)

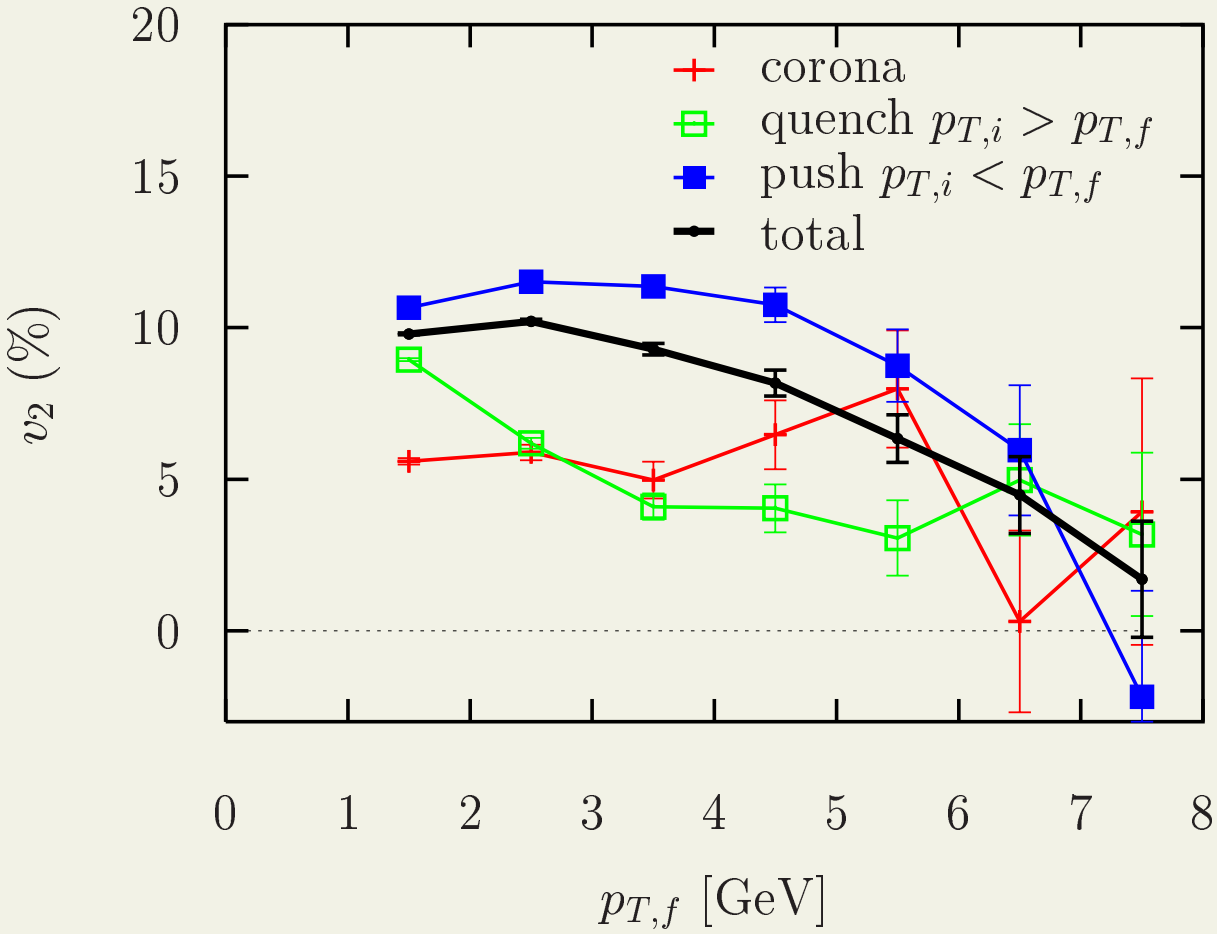
N_{coll} **distribution** **position distribution vs** N_{coll}



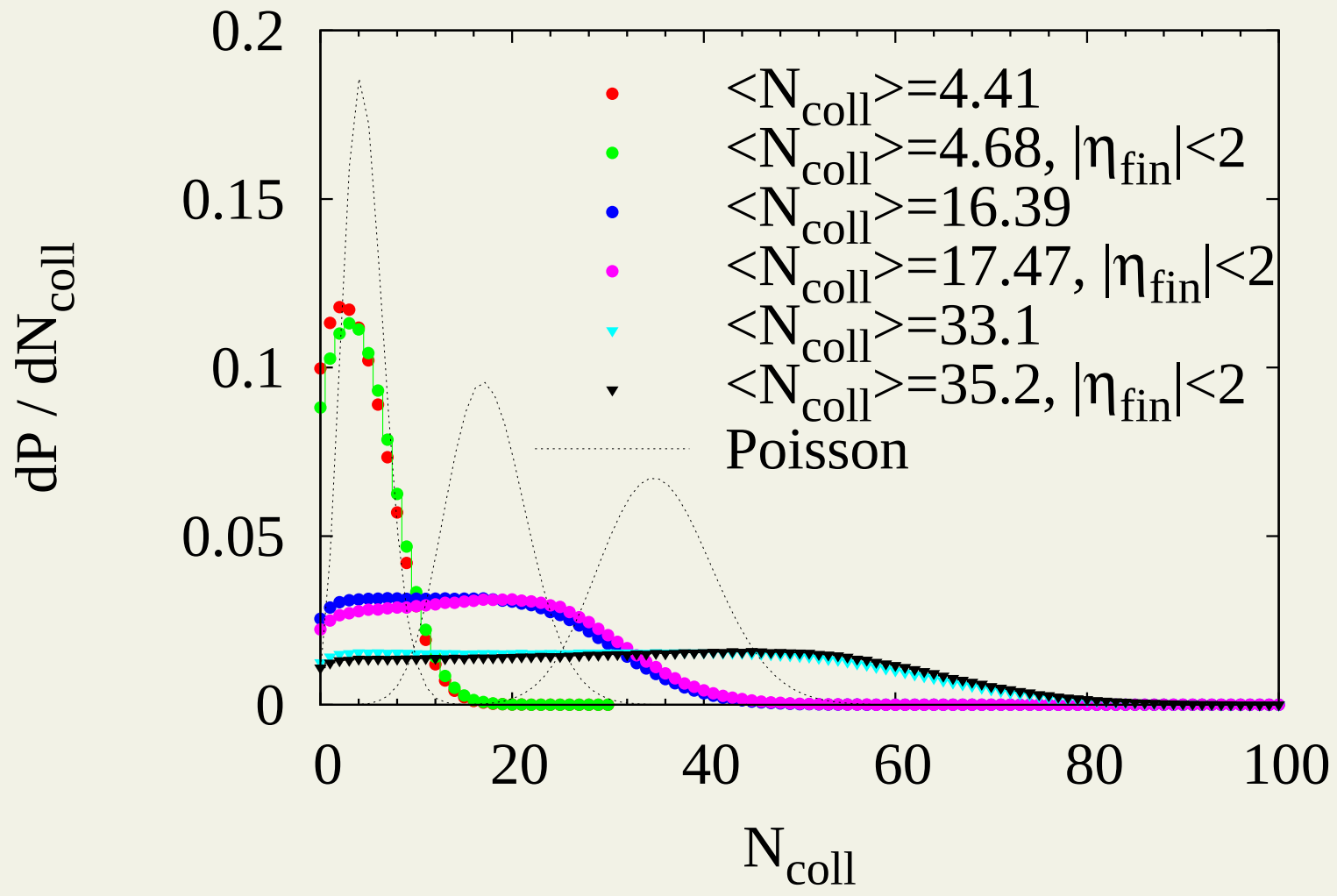
i) for all N_{coll}, the frozen-out component carries most of the v_2

ii) even escapees with $N_{coll} = 0$ show sizable "corona" v_2

- **confirms** DM, nucl-th/0503051

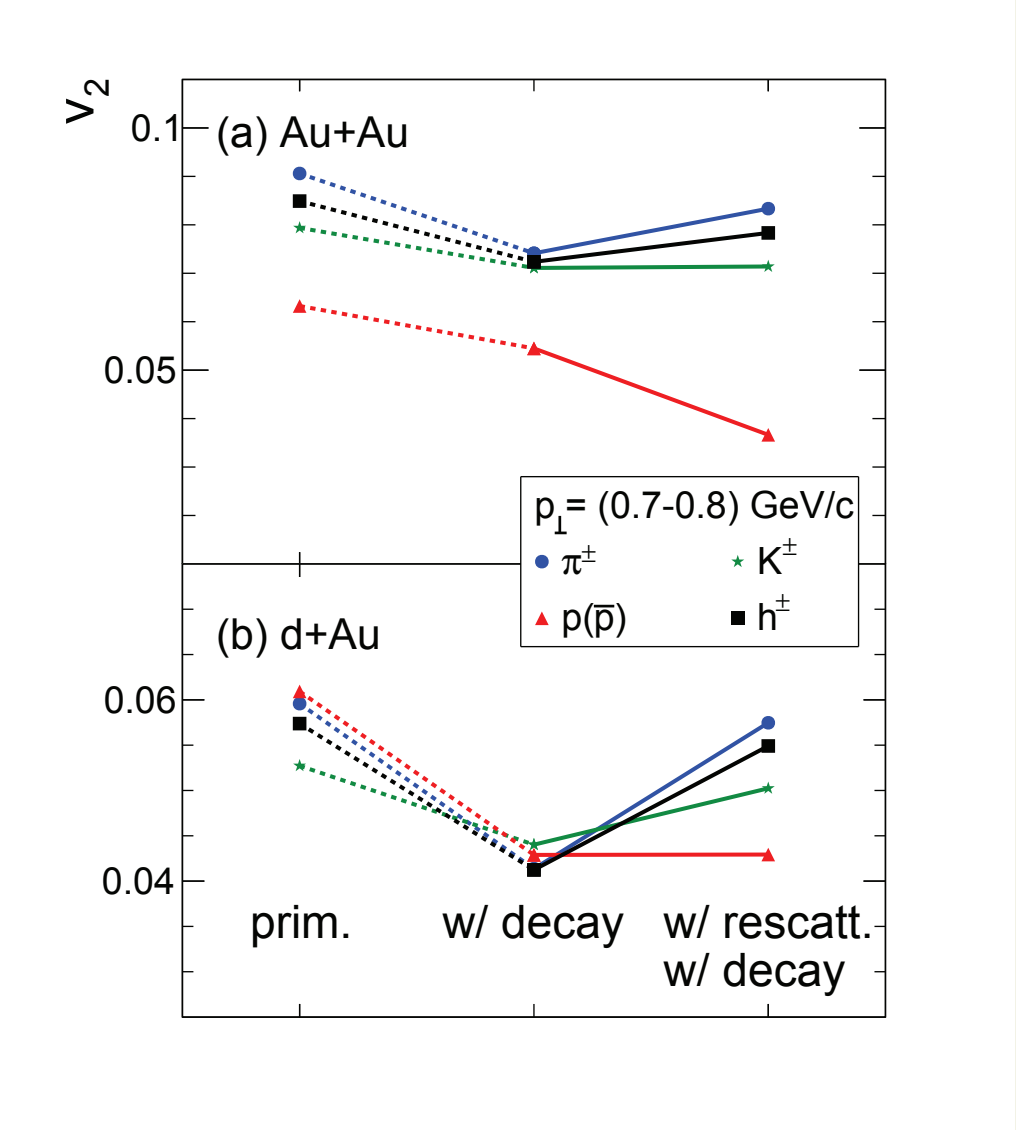


DM ('15): **Ncoll distribution from MPC/Cascade**



AMPT - mass ordering evolution

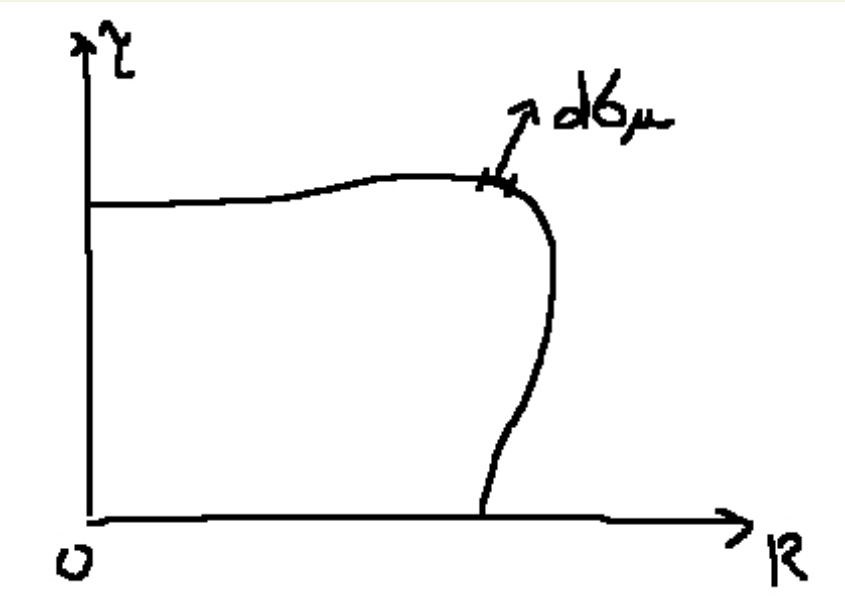
Li et al, 1601.05390v2, soon in PRC



Cooper-Frye freezeout

Not a very satisfactory solution (still open problem)

<u>Assume</u> sudden transition to a gas on a 3D hypersurface (typically $T = const$ or $\varepsilon = const$)



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

(covariant analog of $t = const$ freezeout $dN/d^3x d^3p = f(\vec{x}, \vec{p}, t_{fo})$)

Good: - conserves energy-momentum and charges locally

Bad: - negative contributions possible $p \cdot d\sigma < 0$
- arbitrariness in choice of HS & self-consistency problem

For panel discussion on small systems

Re: hydro/kinetic theory applied to systems of $\mathcal{O}(1\ \mathrm{fm})$ size with sub-fermi structures...

one intriguing question: **how/when quantum mechanics (wave physics) enters - e.g., cannot localize both in x and p**

$\Rightarrow$ **inherent momentum anisotropies** e.g. DM, Wang & Greene 1404.4119

Also, if these systems are opaque enough for hydro, there should be energy loss (jet quenching) signatures. E.g., p+Pb @ 5.02 TeV (top 3.4% cent):

DM & Sun at QM2015