Overview of a multi-phase transport (AMPT) model

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原子核结构与相对论重离子碰撞前沿交叉研讨会, 大连, 8/2023

Outline

- Introduction of the AMPT model
- Recent AMPT developments
- Outlook and Summary

Why do we need transport models?

- **For large systems at very high energies:**
  transport models are similar to hydrodynamics,
  transport models (using particles & scatterings) are complementary to
  hydrodynamics-based models (using $T_{\mu\upsilon}$, EoS & transport coefficients).

- **For finite/small systems at finite energies:**
  non-equilibrium effects are expected to be important.
  One example is the parton escape mechanism:
  interaction-induced response of kinetic theory
  to convert geometrical shape to flows.

  L. He et al. PLB (2016);
  ZWL et al. NPA (2016);
  H.L. Li et al. PRC (2019)

→ Transport models
and/or kinetic theory   Heiselberg & Levy, PRC (1999), Kurkela et al. EPJC (2019), …
are crucial as they address non-equilibrium dynamics.

Y Yin's talk on non-equilibrium

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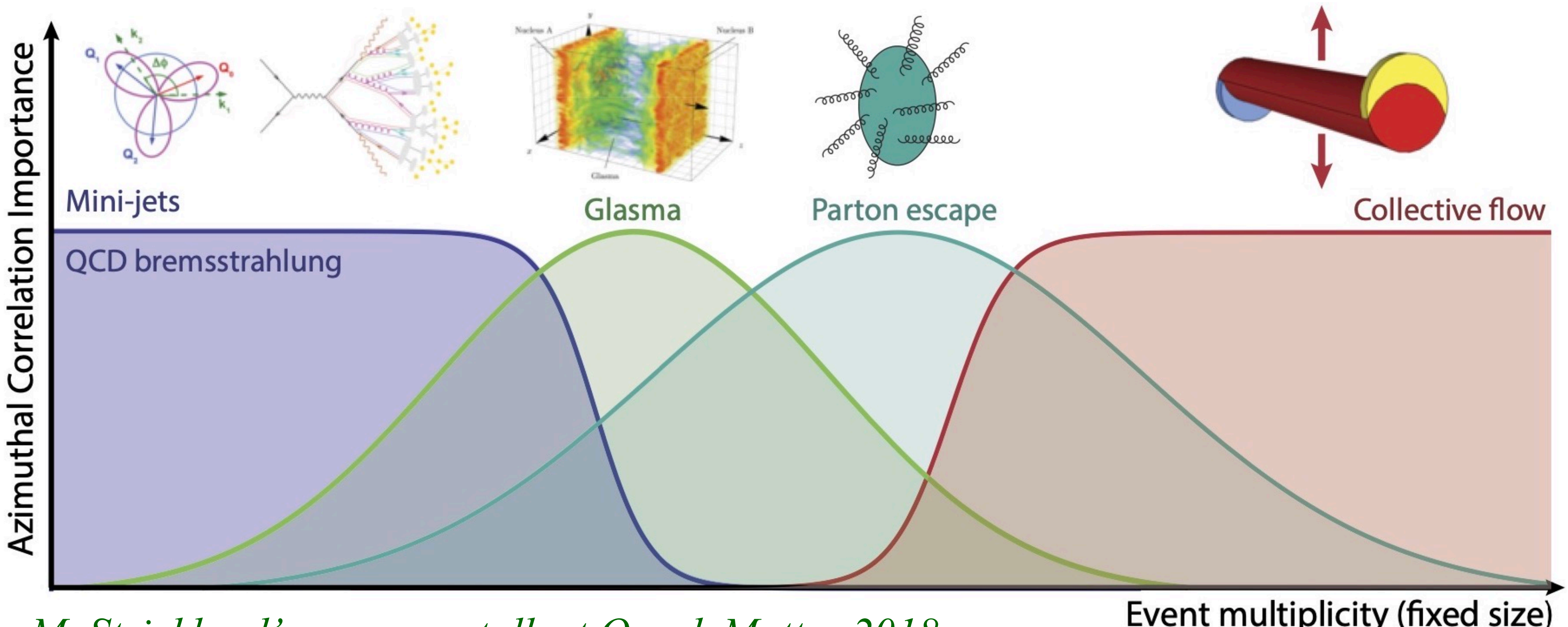


M. Strickland's summary talk at Quark Matter 2018

Fig. 1. Cartoon depicting the various different sources of azimuthal anisotropy. Height of each curve on the vertical axis is arbitrary.

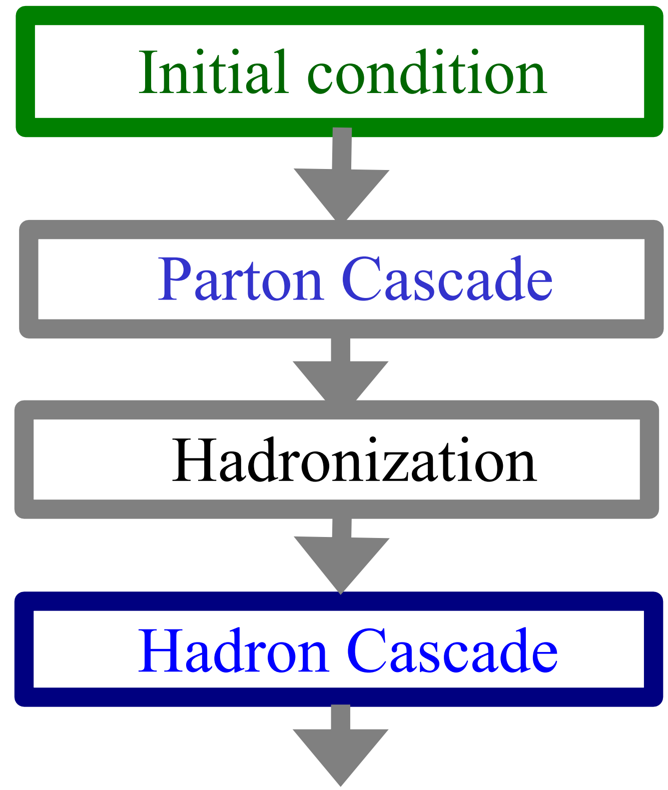
For a general transport model of relativistic heavy ion collisions

We need:	**Choice for each component:**
Initial condition	**HIJING soft+hard model (+string melting)**, nuclear structure (DFT, ...), CGC, pQCD, PYTHIA, …
Pre-equilibrium interactions: *thermalization,initial flow*	Parton cascade (**ZPC**, MPC, BAMPS), AdS/CFT, CGC, FRG, NJL, …
Space-time evolution of QGP	Parton cascade (**ZPC**, MPC, BAMPS), (ideal, viscous) hydrodynamics, ...
Hadronization /QCD phase transition	**Quark coalescence/parton recombination, string fragmentation**, Cooper-Frye, independent fragmentation, statistical hadronization,...
Hadronic interactions	Hadron cascade (**ART**, UrQMD, SMASH, …)

The AMPT model currently includes the ***green*** components.

A multi-phase transport (AMPT) model provides a self-contained kinetic description of heavy ion collisions:

- evolves the system from initial condition to final observables;
- automatically includes productions of all flavours, 3D, conserved charges;
- can study non-equilibrium initial condition & dynamics/evolution.



Final particles
(*momentum spectra & spacetime at freezeout*)

Source codes since 1st release (2004) are available at the ECU website
https://myweb.ecu.edu/linz/ampt/

ZWL, Che-Ming Ko, Bao-An Li, Bin Zhang & Subrata Pal, Phys Rev C (2005);
ZWL & Liang Zheng, mini-review at Nucl Sci Tech (2021)

AMPT codes have been made available online since 2004

Not Secure | myweb.ecu.edu/linz/ampt/

AMPT source codes

(updated December 25, 2018):

A Multi-Phase Transport (AMPT) model is a Monte Carlo transport model for nuclear collisions at relativistic energies.
Each of the following versions contains:
the source codes, an example input file, a Makefile, a readme, a required subdirectory for storing output files, and a script to run the code.

1. ampt-v1.11-v2.11.tgz (11/2004)
2. ampt-v1.21-v2.21.tgz (10/2008)
3. *Other older versions inbetween*
4. ampt-v1.26t5-v2.26t5.zip (4/2015)
5. ampt-v1.26t7-v2.26t7.zip (10/2016)
6. ampt-v1.26t7b-v2.26t7b.zip (5/2018)
7. ampt-v1.26t9-v2.26t9.zip (9/2018)
8. ampt-v1.26t9b-v2.26t9b.zip (12/2018)

String Melting AMPT since 4/2015 can reasonably describe bulk matter at high energies like RHIC/LHC.

This readme file lists the main changes up to version v1.26t9b-v2.26t9b ("t" means a version under test):

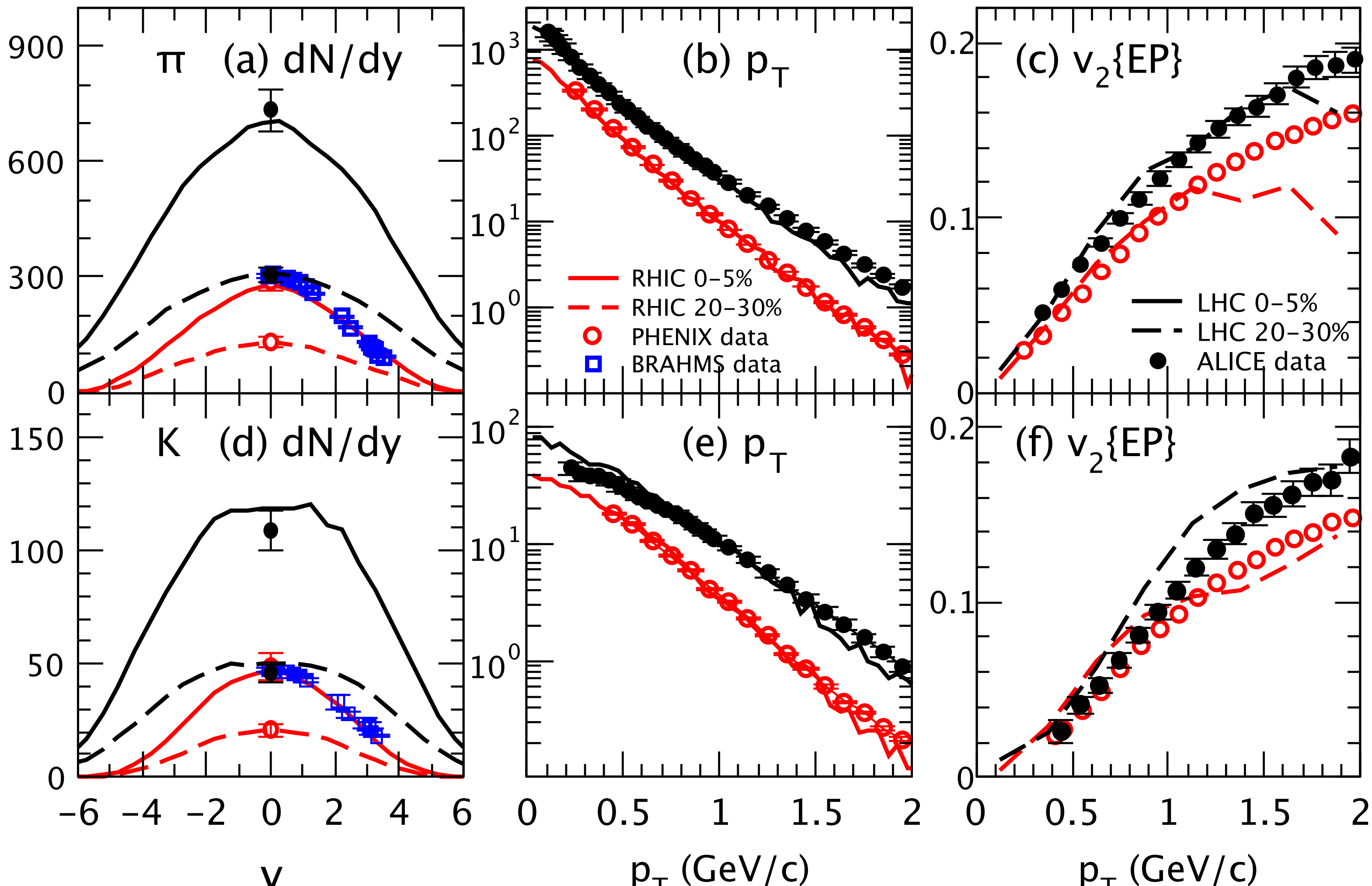
```
AMPT Users' Guide

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
12/2018 test version v1.26t9b/v2.26t9b:
     * Fixed bugs that can cause segmentation fault (especially for default
       AMPT at high energies):
       exclude endpoints of 0. and 1. in random values from RANART()
         in amptsub.f in order to avoid crash in case of 0 branching ratio,
```

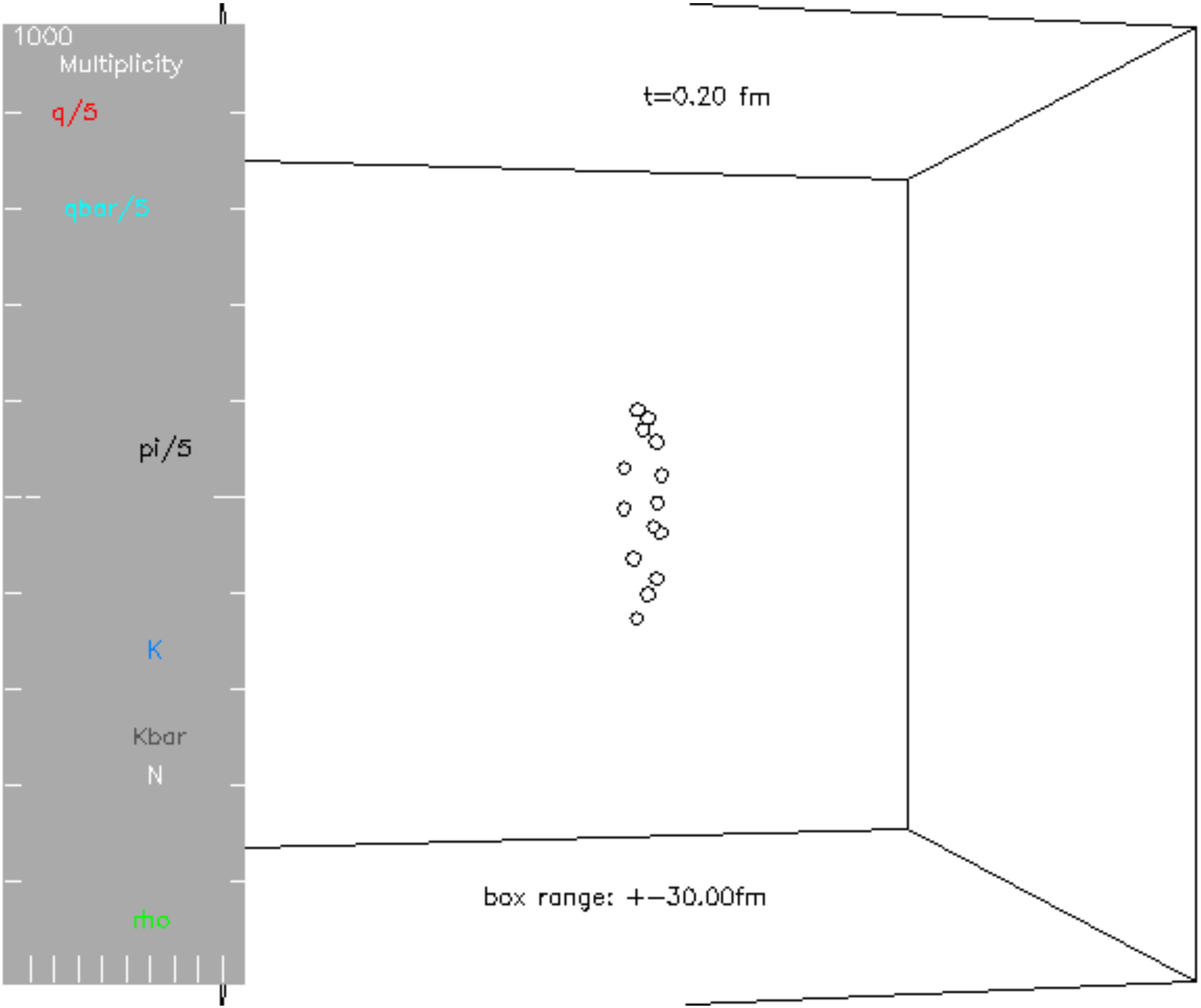
The string melting version of AMPT

- The string melting version is applicable
  when we expect the formation of a parton matter.
- It can reasonably describe the bulk matter observables
  at low p_T in high energy A+A collisions
  (after using a very small Lund parameter b_L=0.15/GeV^2):

ZWL, PRC (2014)



A b=0fm Au+Au event at 200A GeV from String Melting AMPT

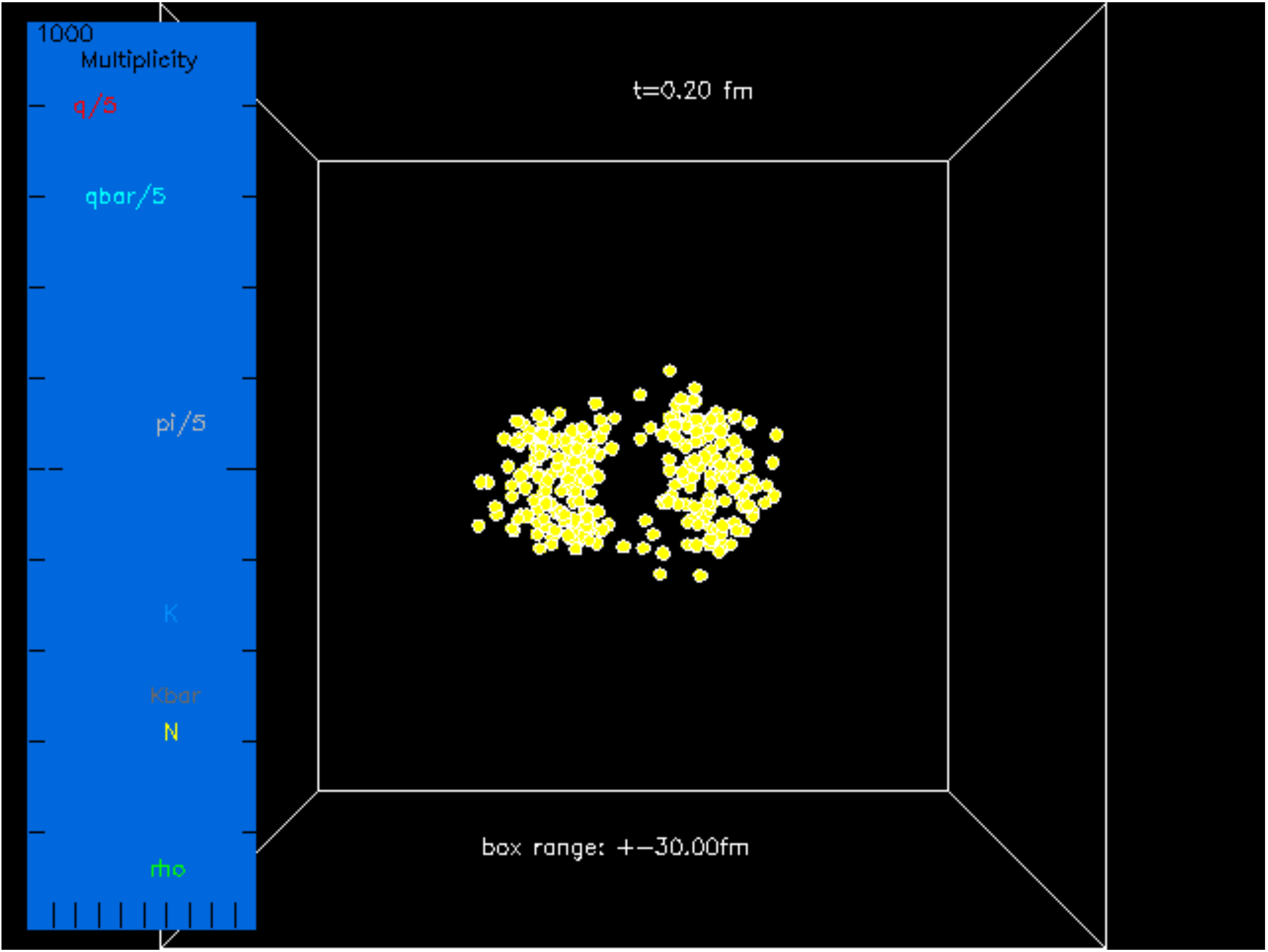


60fm-long box

Beam axis

Left panel shows time evolution of various particle numbers

A b=10fm Au+Au event at 200A GeV from String Melting AMPT



60fm-long box

⊙

Beam axis

Initial overlap region has an irregular geometry (*will lead to triangular flow* v_3)

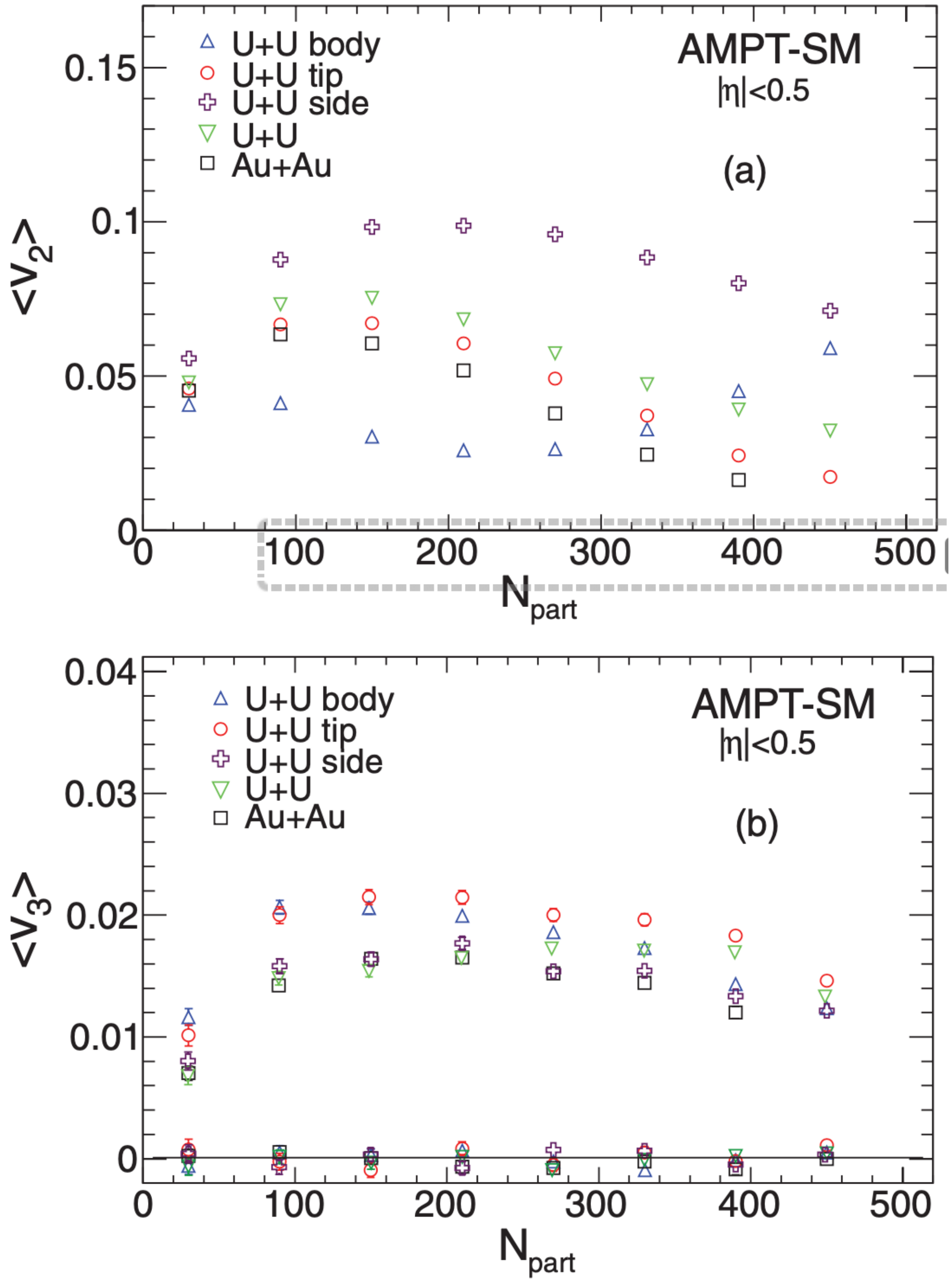
AMPT is also a test-bed of different ideas for the community

- Discovery of triangular flow v_3 — Alver & Roland, PRC 81 (2010)
- Longitudinal (de)correlations of flows — Pang et al. PRC 91 (2015) & EPJA52 (2016); ...
- Flows can be dominated by non-equilibrium parton escape for finite systems/energies — L He et al. PLB 753 (2016); ZWL at QM2015 & SQM2017; HL Li et al. PRC 99 (2019)
- CME signal & background — Shou, Ma & Ma, PRC 90 (2014); Huang, Ma & Ma, PRC 97 (2018); XL Zhao & Ma, PRC 106 (2022); Chen, Zhao & Ma, 2301.12076; ...

  Guo-Liang Ma's talk
- Vorticity & polarization observables — Jiang et al. PRC 94 (2016); H Li et al. PRC 96 (2017); Lan et al. PLB 780 (2018); ...
- Incoming nuclei with nuclear structure — Haque, ZWL & Mohanty, PRC (2012); HJ Xu et al. PRL 121 (2018), CPC 42 (2018), HL Li et al. PRL 125 (2020); Jia, Giacalone & Zhang, PRL 131 (2023); ...

  Jiangyong Jia's talk

First AMPT study with nuclear structure



Incoming ^{238}U+U at 200A GeV:

$$\rho = \frac{\rho_0}{1+\exp([r-R']/a)},$$

$$R' = R\left[1+\beta_2 Y_2^0(\theta)+\beta_4 Y_4^0(\theta)\right]$$

Md. Rihan Haque, ZWL &
Bedangadas Mohanty, PRC (2012)

Recent development: modern PDF and nuclear shadowing

Chao Zhang, Liang Zheng, Feng Liu, Shusu Shi & ZWL, PRC (2019)

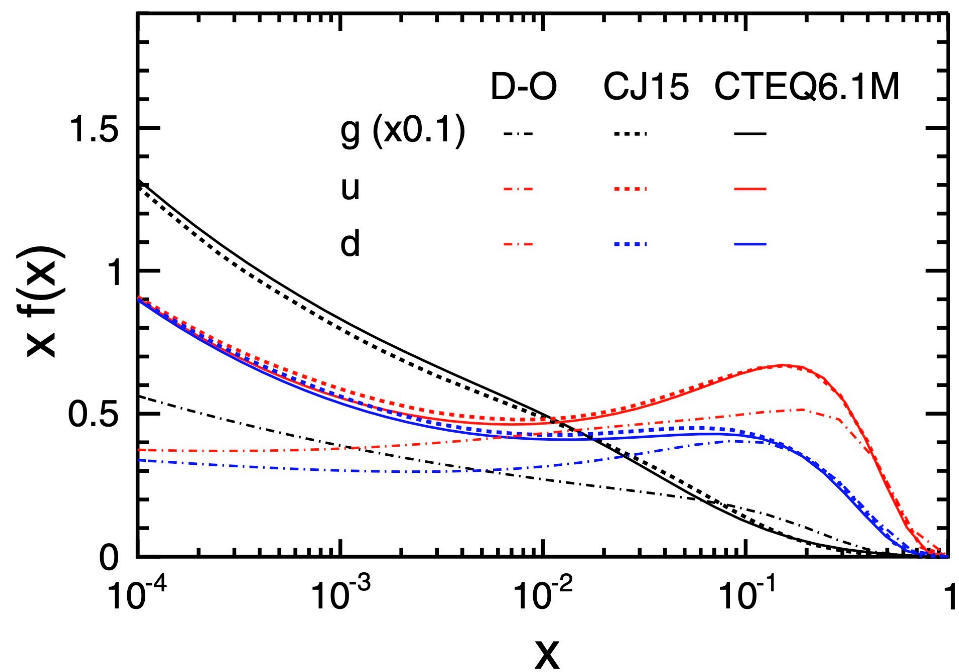
Modern nPDFs will improve pQCD observables like heavy flavor & high p_T:

$$\frac{d\sigma^{Q\bar{Q}}}{dp_T^2 dy_1 dy_2} = K \sum_{a,b} x_1 f_a(x_1,\mu_F^2) x_2 f_b(x_2,\mu_F^2) \frac{d\sigma^{ab\to Q\bar{Q}}}{d\hat{t}}$$

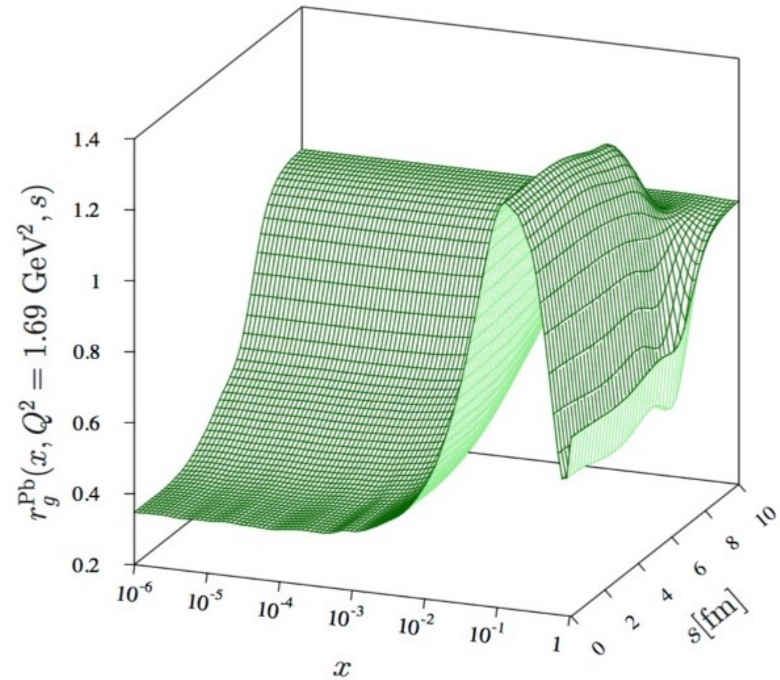
$$f_i^{p/A}(x,Q^2) \equiv R_i^A(x,Q^2) \underline{f_i^p(x,Q^2)}$$

$$R_i^A(x,Q^2) \equiv \frac{1}{A}\int d^2\mathbf{s}\, T_A(\mathbf{s})\, \underline{r_i^A(x,Q^2,\mathbf{s})}$$

We have incorporated CTEQ6.1M PDFs for the free nucleon & EPS09s nuclear shadowing



Free proton PDFs vs x from the old Duke-Owens set and newer sets



Shadowing function for Pb vs x and s (transverse position)

Recent development: heavy flavor (HF)

$gg \to gg$ cross section in pQCD
is divergent for massless g,
so HIJING uses a minijet cutoff $\boldsymbol{p_0}$ (for minijets of ALL flavours).

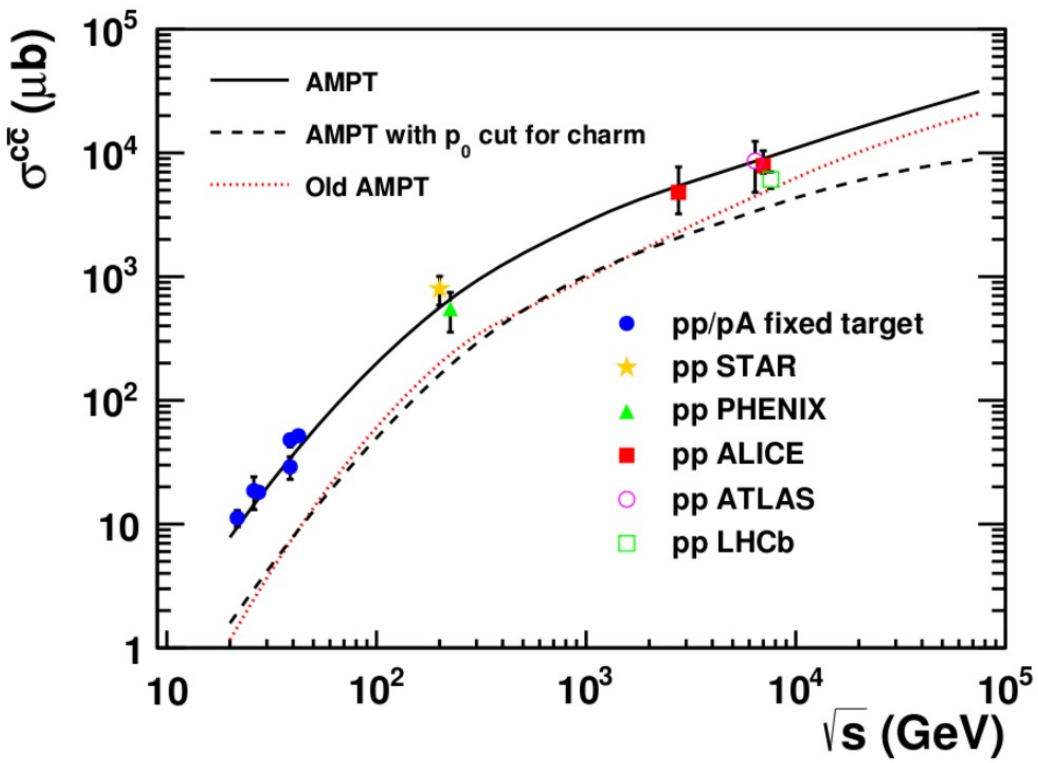
$$\frac{d\sigma}{dt} \sim \frac{9\pi\alpha_s^2}{2t^2}$$

But due to heavy quark mass, heavy flavor production
has a finite cross section and does not need a cutoff, (e.g. in FONLL):

$$g + g \to Q + \bar{Q}, \quad q + \bar{q} \to Q + \bar{Q}, \ \ldots$$

→ We remove the unnecessary $\boldsymbol{p_0}$ cut
on HF productions in HIJING/AMPT

→ AMPT with modern nPDFs
now well describes world *pp* data
on total $c\bar{c}$ cross section:



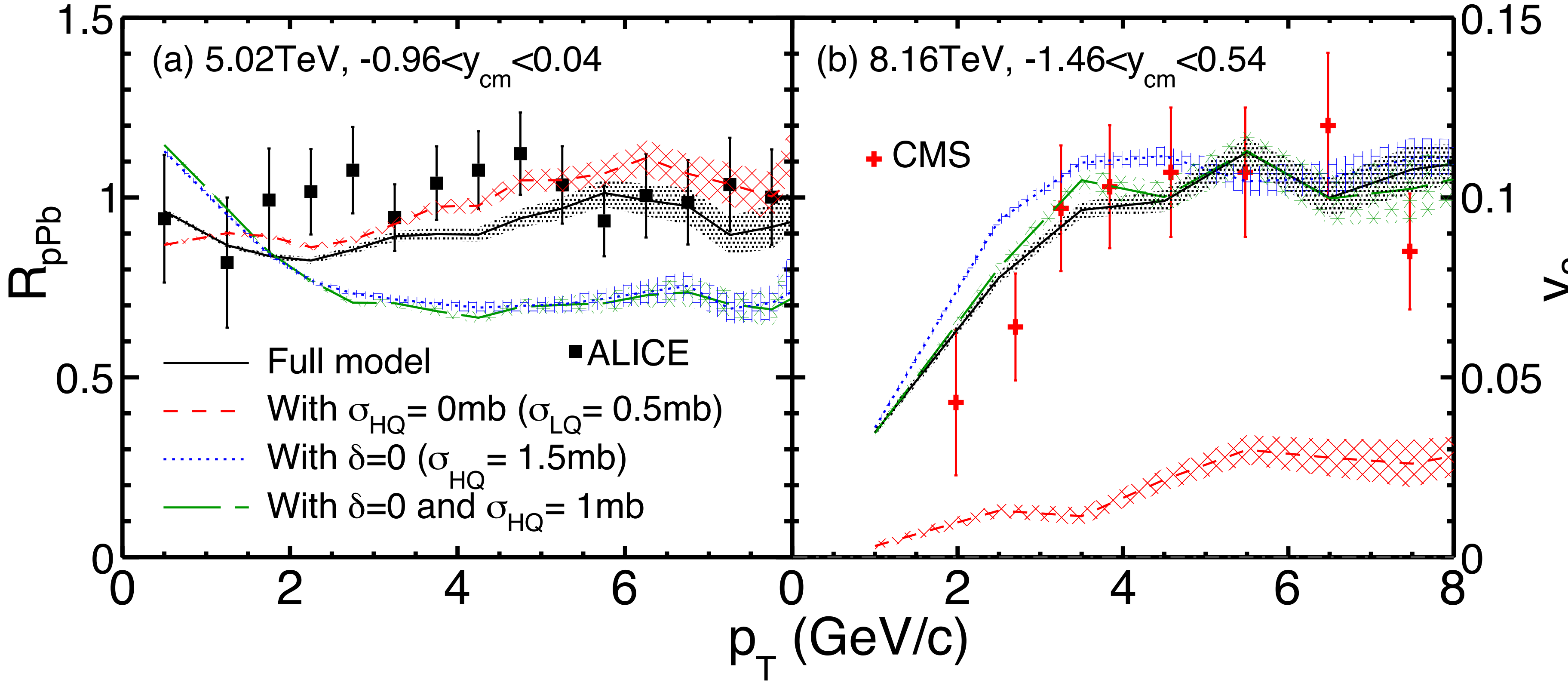
Liang Zheng, Chao Zhang,
Shusu Shi & ZWL, PRC (2020)

Recent development: heavy flavor (HF)

We have included the Cronin effect (k_T broadening) and independent fragmentation for charm (anti)quarks:

Chao Zhang, Liang Zheng, Shusu Shi & ZWL, 2210.07767

Without the Cronin effect (δ=0): we can get the D^0 v_2,
but R_{pA} is underestimated due to charm scatterings with medium (via σ_{HQ}).



The Cronin effect enhances charm R_{pA} at moderate/high p_T
but has little effect on charm v_2 $\rightarrow$ can resolve the R_{pA}/v_2 puzzle

Recent development: local nuclear scaling

For pp & central AA, we need different values for minijet cutoff p_0 (& Lund b_L)

→ we relate them to local nuclear thickness function $T_A(s)$

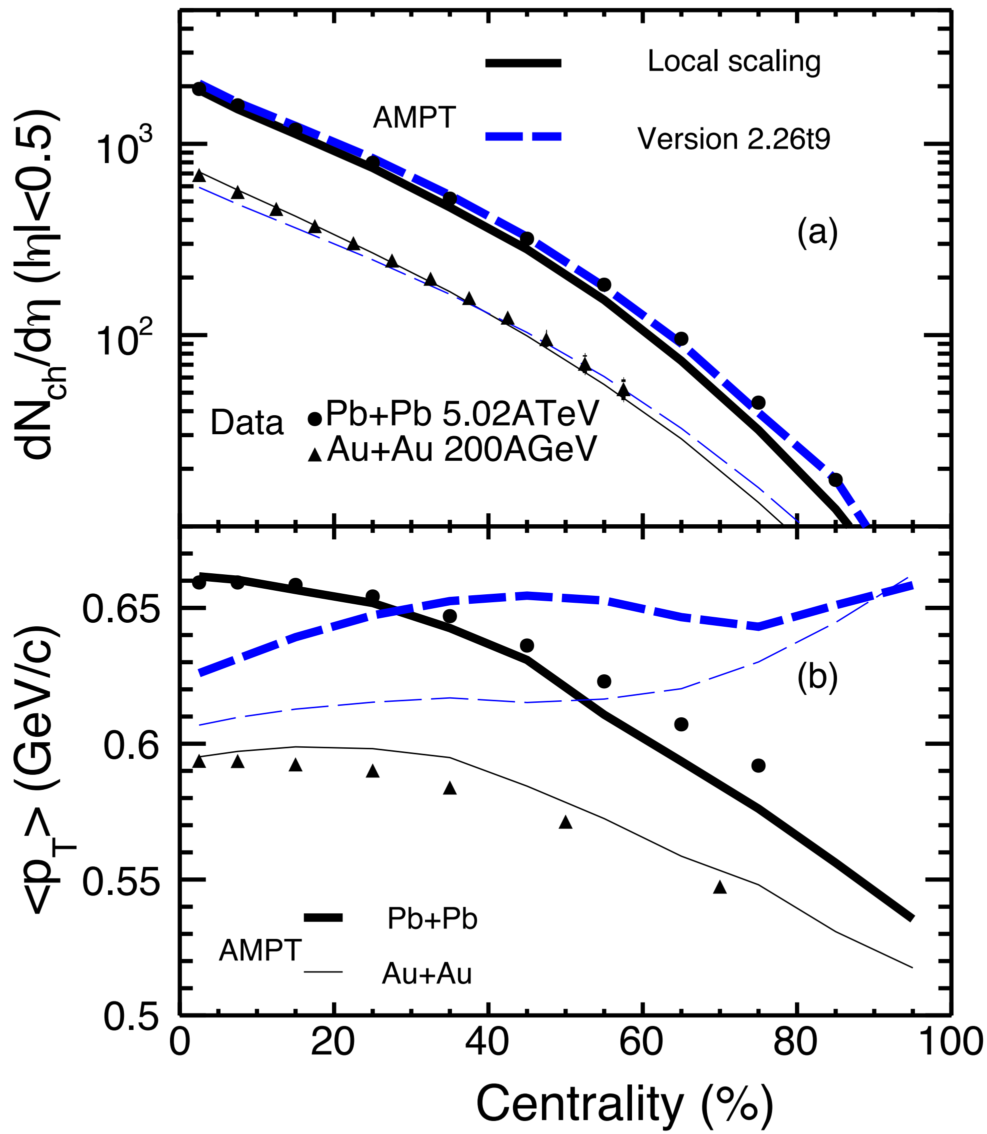
to self-consistently describe the system size or centrality dependence,

$$b_L(s_A, s_B, s) = \frac{b_L^{pp}}{[\sqrt{T_A(s_A)T_B(s_B)}/T_p]^{\beta(s)}}$$

$$p_0(s_A, s_B, s) = p_0^{pp}(s)[\sqrt{T_A(s_A)T_B(s_B)}/T_p]^{\alpha(s)}.$$

Centrality dependences of <p_T> are now correct, much better than public AMPT (v2.26t9)

Chao Zhang, Liang Zheng, Shusu Shi & ZWL, PRC (2021)



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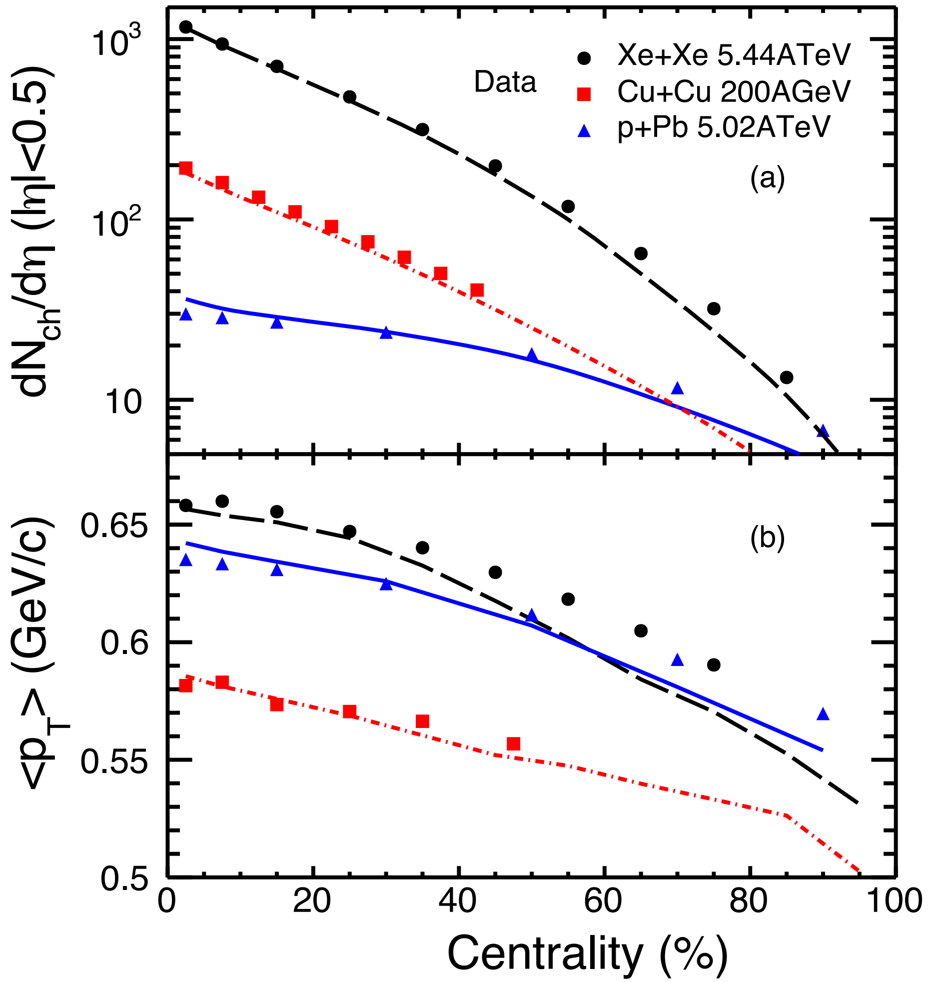
Scaling also works
for smaller systems:



Chao Zhang, Liang Zheng,
Shusu Shi & ZWL, PRC (2021)

Key AMPT input parameters: a_L b_L p_0 σ (parton cross section)

No longer free parameters → we can focus on QGP properties like σ & η/s

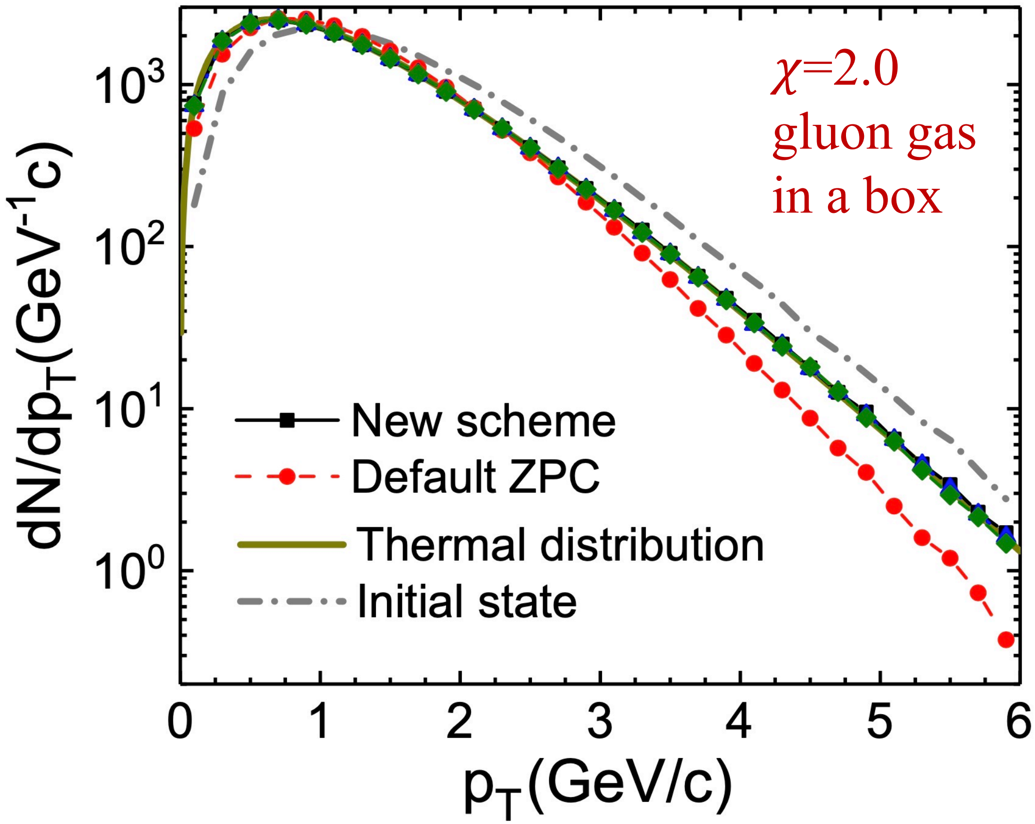
Recent development: parton transport

We have tested ZPC for partons in a box:

Xin-Li Zhao, Guo-Liang Ma, Yu-Gang Ma & ZWL, PRC (2020)

$$\partial_t f + \frac{\partial \boldsymbol{x}}{\partial t} \cdot \nabla_x f = C[|M^2| f_1 f_2] \propto \sigma f_1 f_2$$

- Parton cascade has freedom in choosing collision time (*ct*) and/or collision ordering time
- Default ZPC (t-average scheme) fails to maintain thermal equilibrium at high opacities
- A new choice (t-minimum scheme) gives the expected thermal distribution



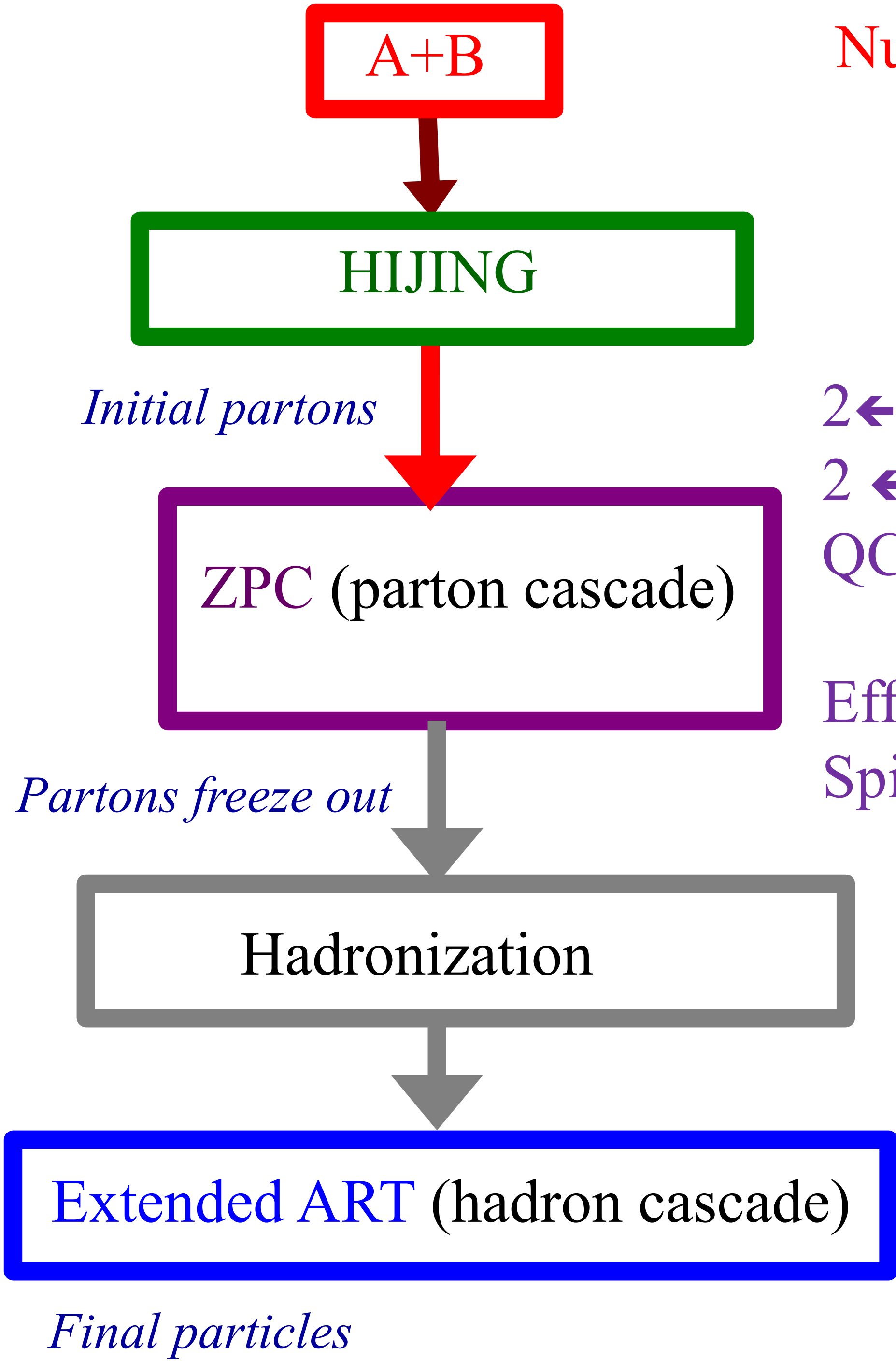
A more general collision scheme further improves the ZPC accuracy by a factor of 2 to 5

Todd Mendenhall & ZWL, in preparation

Recent development: other works

Implement electric charge conservation	ZWL & Guo-Liang Ma, unpublished (~2018)
Include nonzero nuclear thickness *for RHIC-BES energies and below*	ZWL, PRC (2018); Todd Mendenhall & ZWL, PRC (2021 & 2023); Han-Sheng Wang, Guo-Liang Ma, ZWL & Wei-Jie Fu, PRC (2022)
Include subnucleon structure of proton	Liang Zheng, Guang-Hui Zhang, Yun-Fan Liu, ZWL, Qi-Ye.Shou & Zhong-Bao Yin, EPJC (2021); Xin-Li Zhao, ZWL, Liang Zheng & Guo-Liang Ma, PLB (2023)
New version AMPT-HC: pure hadron cascade with mean fields *for low energies up to* $\sqrt{s}$*~5A GeV*	Gao-Chan Yong, Zhi-Gang Xiao, Yuan Gao & ZWL, PLB (2021); Gao-Chan Yong, Bao-An Li, Zhi-Gang Xiao & ZWL, PRC (2022)

Outlook: some future directions



Nuclear structure/deformation/Nskin

- *** modern PDF & nuclear shadowing**
- *** Size dependence of initial <p_T>**, <p_T^2>?
- **~* Nonzero nuclear thickness**
- gluons in initial condition

2↔2 inelastic parton reactions

2 ↔ 3or1 parton reactions

QCD equation of state & CEP

(via dynamical parton mass, FRG?)

Effect of E&M fields and QGP response

Spin/angular momentum transport

*** improved coalescence/hadronization**

hadronization at phase transition boundary

gluons in hadronization

independent fragmentation **(* for HF)**

*** hadron mean fields**

* *~Done*

Outlook: example with parton transport

Current AMPT treats parton σ or screening mass μ as constant parameter.

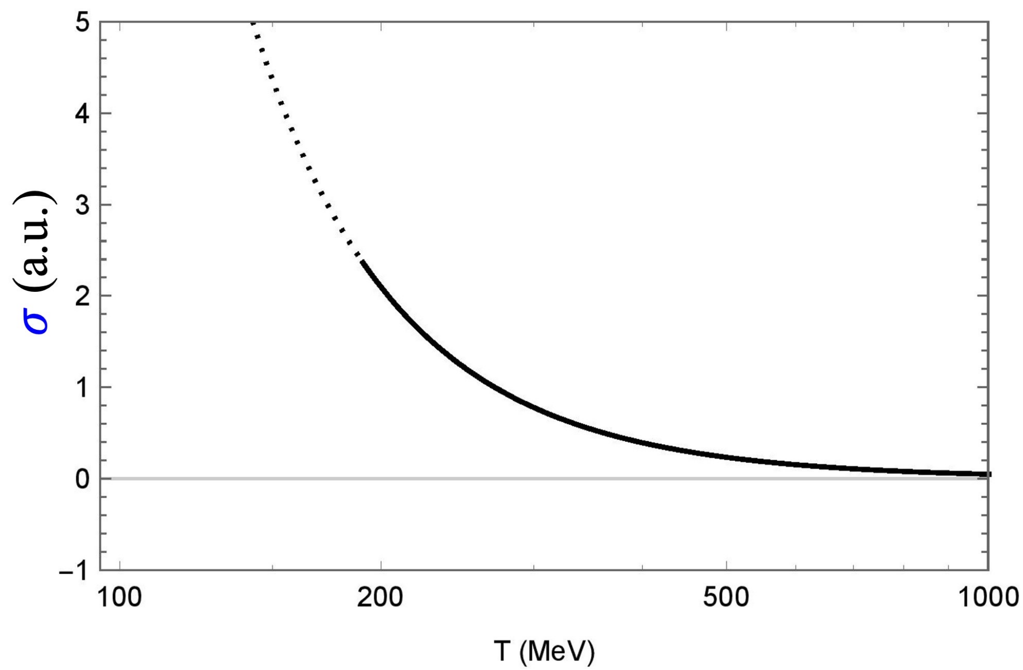
But finite-T pQCD → $\mu \propto gT$
this leads to QGP η/s(T)

Arnold, Moore & Yaffe, JHEP (2003);
Csernai, Kapusta & McLerran, PRL (2006)

→ $\sigma \propto 1/\mu^2$
will be larger at lower T

→ $\eta \propto \frac{T}{\sigma}$, $\eta/s \propto \frac{1}{T^2\sigma}$
will have the expected
T- & *time*-dependences

Noah MacKay and ZWL, EPJC (2022)



+ 2←→2 inelastic parton reactions
2 ←→ 1 parton reactions

→ will enable ZPC/AMPT to solve finite-T kinetic theory for studies of nonequilibrium dynamics

Summary

A multi-phase transport (AMPT) model
provides a self-contained kinetic description of heavy ion collisions and is thus especially suitable for studies of non-equilibrium dynamics.

Recent developments have made AMPT more versatile and accurate, for example:

- Incoming nuclei with nuclear structure:
  $\longleftrightarrow$ imprints in observables in high energy collisions
- Local nuclear scaling of key input parameters:
  significantly reduces uncertainty from free model parameters
  and enables us to focus on QGP properties like η/s
- Improved parton transport in a box is now accurate at high opacities:
  lays the foundation to develop ZPC/AMPT into
  a dynamical model of finite-temperature kinetic theory

There is more work to do…

Thanks for your attention!