Overview on AMPT and Nuclear Structure

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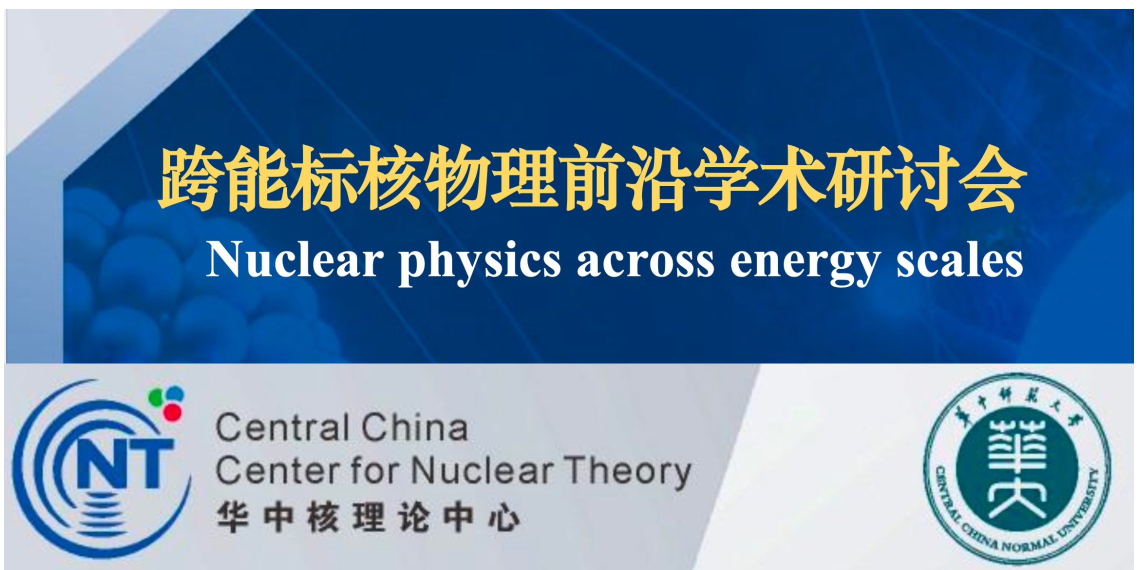


Sept. 19-21, 2025 CCNU, Wuhan, China

Outline

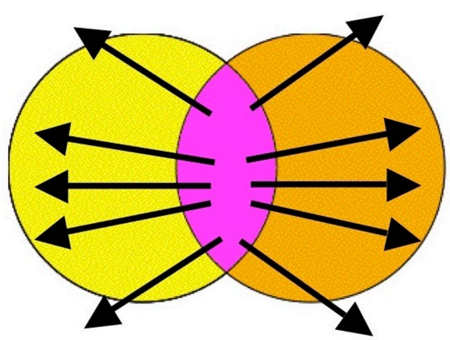
- Introduction to A Multi-Phase Transport (AMPT) model
- Selected AMPT results related to nuclear structure
- Outlook
- Summary

National Science Foundation

Transport models are suitable for non-equilibrium studies

- Hydro-based hybrid models are now the “standard model”
  for heavy ion collisions at high energies.
  EoS, η, ζ, …

- For finite/small systems at finite energies,
  or early time & hard probes of large systems at high energies:
  non-equilibrium effects are expected to be important.
  One example is **the parton escape mechanism**:
  interaction-induced response from kinetic theory
  to the anisotropic spatial geometry alone.



L He et al. PLB 753 (2016);
ZWL et al. NPA 956 (2016);
HL Li et al. PRC 99 (2019)

Transport models are suitable for non-equilibrium studies

Small system data show similar flow features as large systems:

are they real signals from collectivity?
is a parton matter formed in small systems?
is the matter close to equilibrium or far off equilibrium (core-corona)?
is the matter dominated by gluons or quarks?

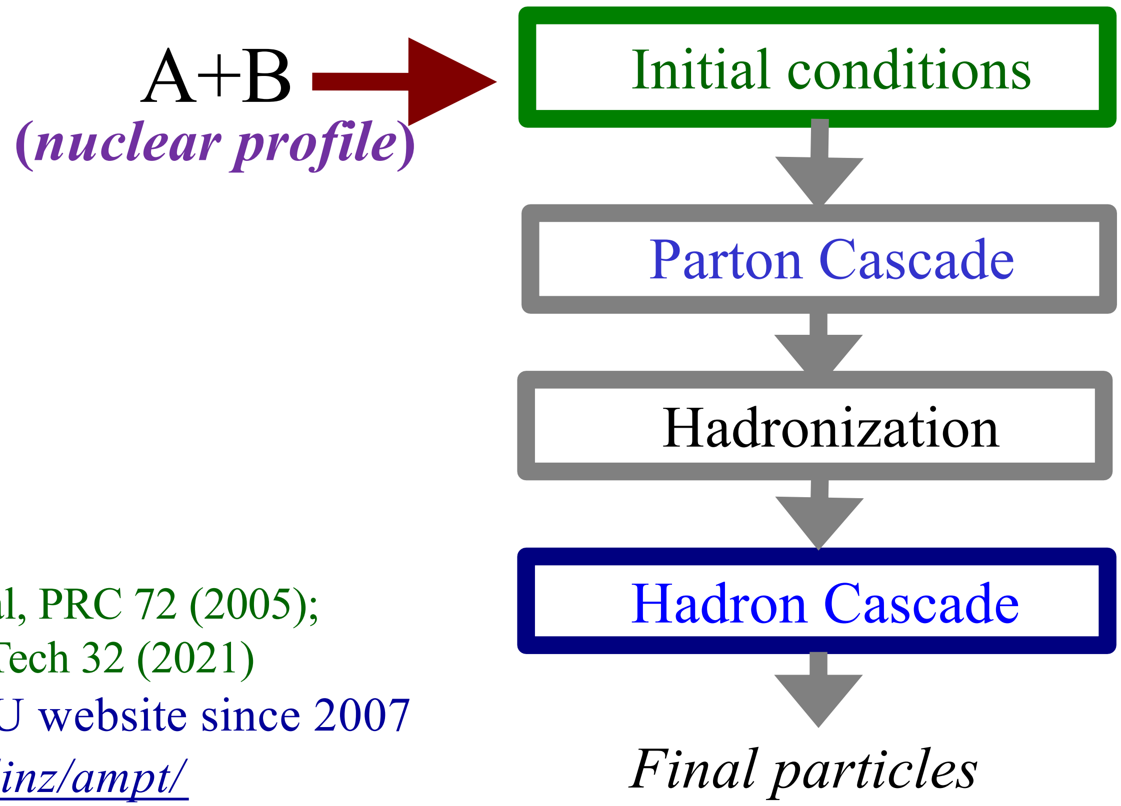
To answer these questions and better study properties of parton matter/QGP, transport models / kinetic theory are crucial
as they don't assume equilibrium & can address non-equilibrium dynamics.

B Zhang, CPC 109 (1998); Heiselberg & Levy, PRC 59 (1999);
ZWL & Ko, PRC 65 (2002); Z Xu & Greiner, PRC 71 (2005);
Bzdak & Ma, PRL 113 (2014);
Kurkela et al. PLB 783 (2018) & EPJC 79 (2019);
Kurkela, Törnkvist & Zapp, EPJC 84 (2024); ...

The AMPT model

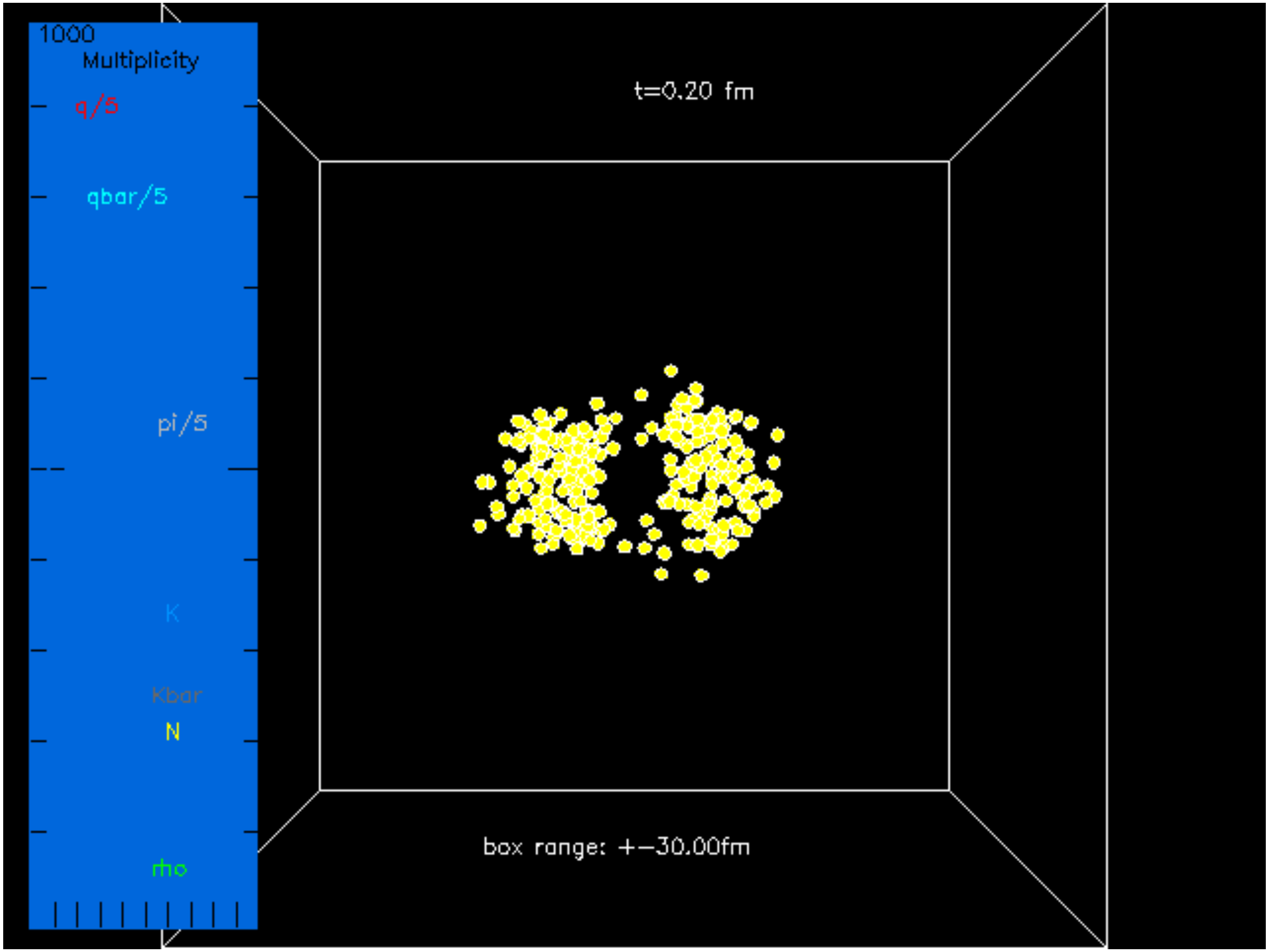
A multi-phase transport (AMPT) model
was constructed as a self-contained kinetic description of nuclear collisions:

- evolves the system from initial condition to final observables
- includes 3D productions of all flavours & conserved charges (B/Q/S/C...)
- includes fluctuating initial conditions & non-equilibrium dynamics/evolution



ZWL, Ko, Li, Zhang & Pal, PRC 72 (2005);
ZWL & Zheng, Nucl Sci Tech 32 (2021)
Source codes at the ECU website since 2007
https://myweb.ecu.edu/linz/ampt/

A b=10fm Au+Au event at 200A GeV from string melting AMPT



x-*y* plane

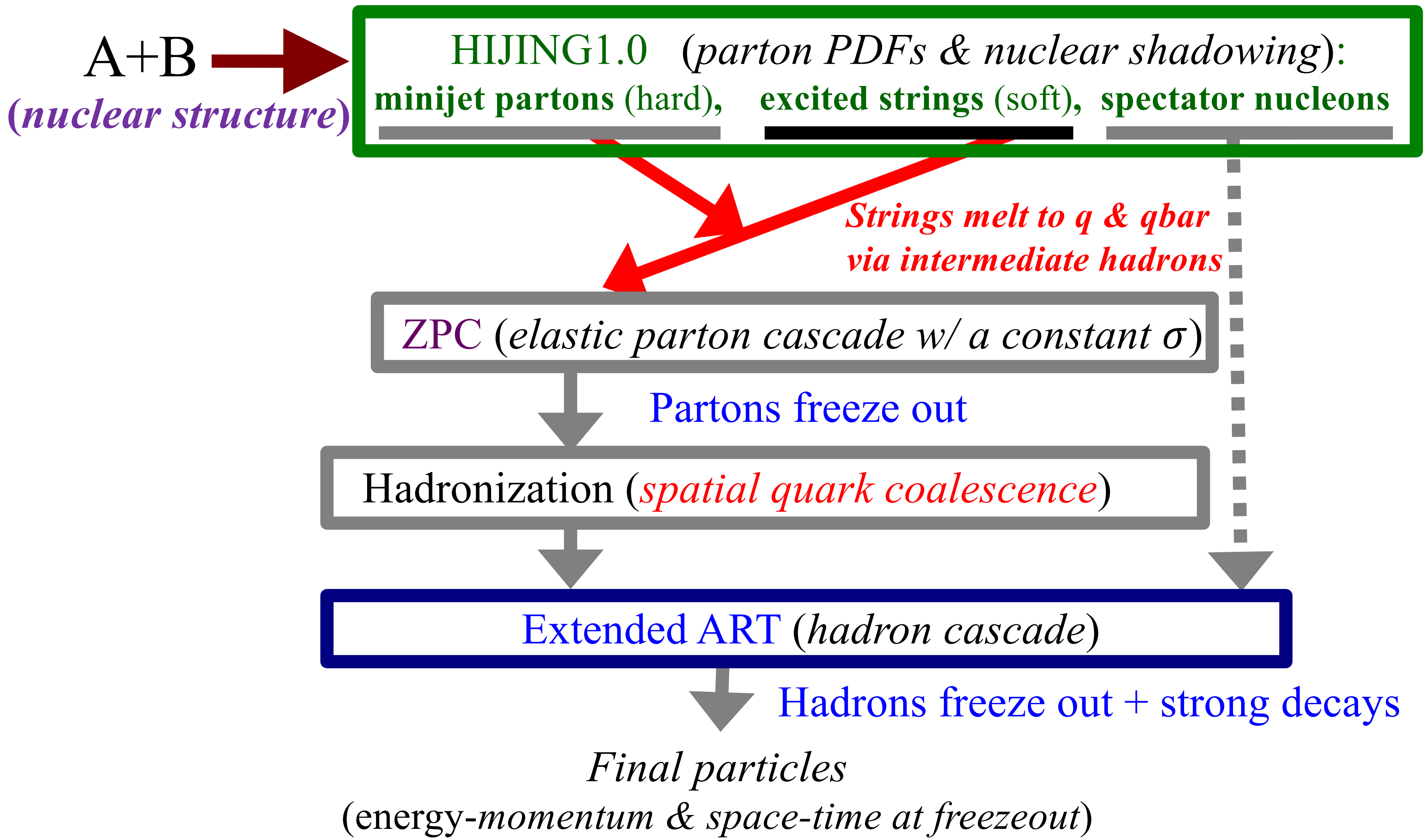
⊙

Beam axis

Initial overlap region has an irregular geometry (*will develop into triangular flow* v_3)

The AMPT model: string melting version:

applicable when we expect the formation of a parton matter



Main developments of the AMPT model

AMPT-string melting model to describe the bulk matter	ZWL, PRC 90 (2014)
New quark coalescence to allow freedom to form M or B	He & ZWL, PRC 96 (2017)
Modern PDFs & b-dependent nuclear shadowing	C Zhang, Zheng, Liu, Shi & ZWL, PRC 99 (2019)
Improvements of heavy flavors	Zheng, C Zhang, Shi & ZWL, PRC 101 (2020); C Zhang, Zheng, Shi & ZWL, PLB 846 (2023)
Local nuclear scaling for self-consistent size dependence	C Zhang, Zheng, Shi & ZWL, PRC 104 (2021)
AMPT-HC: pure hadron cascade with mean fields	Yong, Xiao, Gao & ZWL, PLB 820 (2021); Yong, Li, Xiao & ZWL, PRC 106 (2022)
Include sub-nucleon structure of proton	Zheng, C Zhang, Liu, ZWL, Shou & Yin, EPJC 81 (2021); XL Zhao, ZWL, Zheng & GL Ma, PLB 839 (2023), …
Benchmark and improve ZPC parton transport	XL Zhao, GL Ma, YG Ma & ZWL, PRC 102 (2020); Mendenhall & ZWL, 2507.23107

Most of these were summarized in a mini-review: ZWL & Zheng, Nucl Sci Tech 32 (2021)

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

- Discovery of triangular flow v_3 — Alver & Roland, PRC 81 (2010)
- Early study of flows in small systems — Bzdak & Ma, PRL 113 (2014), ...
- Longitudinal decorrelations of flows — Pang et al. PRC 91 (2015) & EPJA 52 (2016); ...
- Non-equilibrium parton escape for finite systems/energies — L He et al. PLB 753 (2016); ZWL et al. NPA 956 (2016); 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, PRC 109 (2024); ...
- Vorticity & polarization observables — Jiang, ZWL & Liao, PRC 94 (2016); Pang et al, PRL 117 (2016); H Li et al. PRC 96 (2017); ...
- Effects of nuclear structure — HJ Xu et al. PRL 121 (2018), CPC 42 (2018); HL Li et al. PRL 125 (2020); Jia, Giacalone & Zhang, PRL 131 (2023); ...

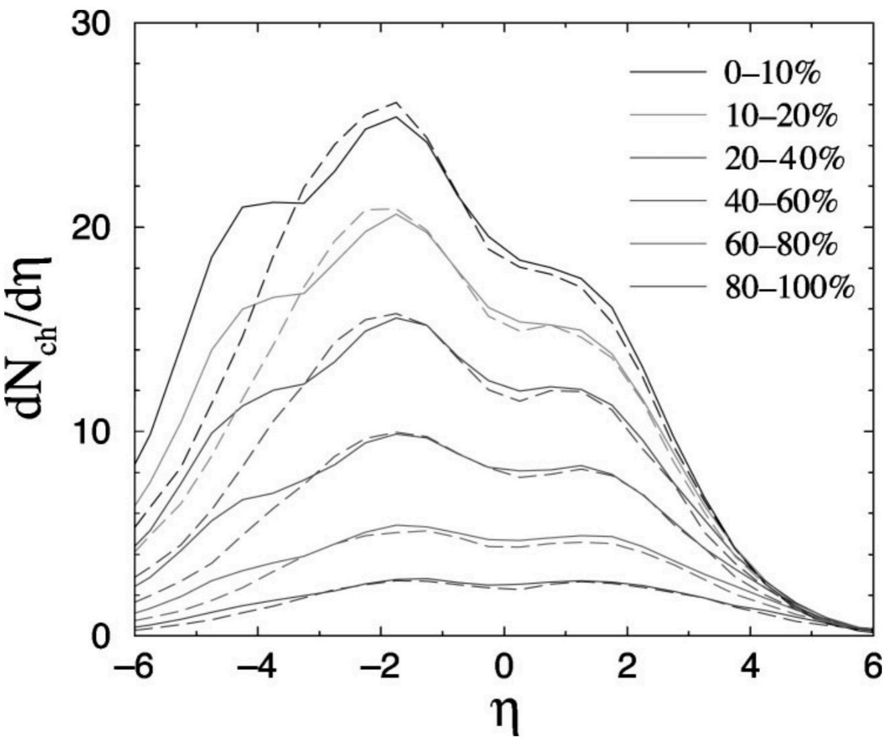
Incorporation of nucleus structure: d+Au

The first AMPT study that considered nuclear structure
(beyond the Woods-Saxon shape) is on dAu:

ZWL & Ko, PRC 68 (2003)

In this study, we use the Hulthen wave function [29] to model the structure of a deuteron [30]:

$$u(r) = Ce^{-\alpha r}(1 - e^{-\mu r}), \qquad (1)$$



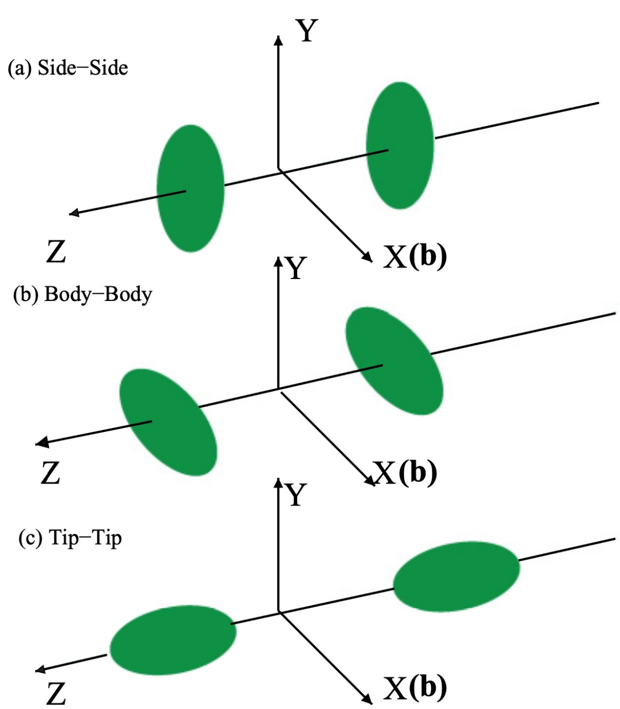
d+Au at 200A GeV
effect of final-state interactions:

dashed: HIJING
solid: AMPT-default

Incorporation of nucleus structure: U+U

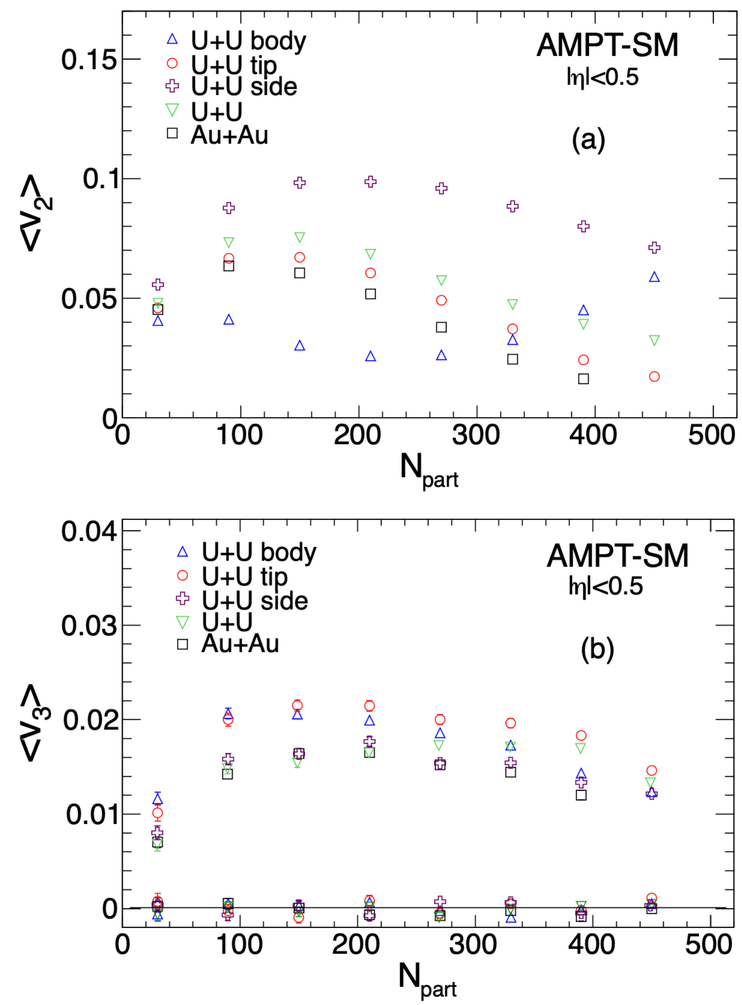
Nucleon density of ^{238}U is parametrized as a deformed Woods-Saxon:

$$\rho = \frac{\rho_0}{1+\exp([r-R']/a)},$$
$$R' = R\left[1+\beta_2 Y_2^0(\theta)+\beta_4 Y_4^0(\theta)\right]$$



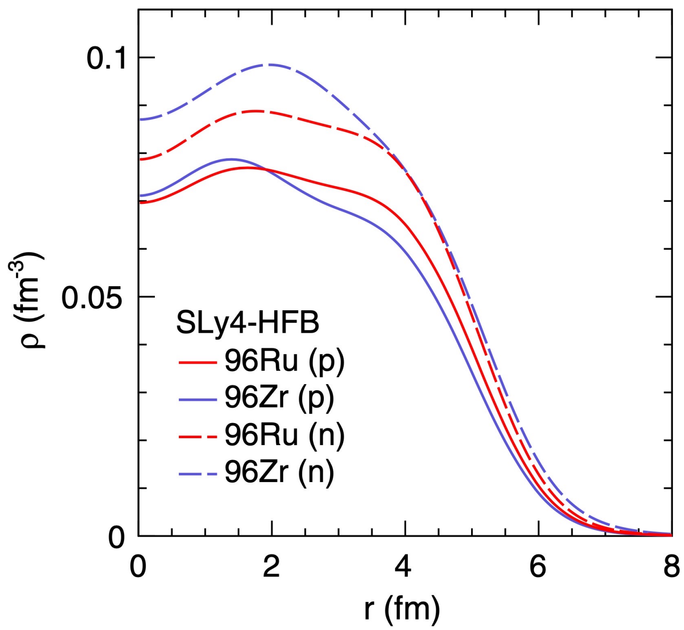
Rihan Haque, ZWL & Mohanty, PRC 85 (2012)

v_2 are very sensitive to orientation; v_3 less so:



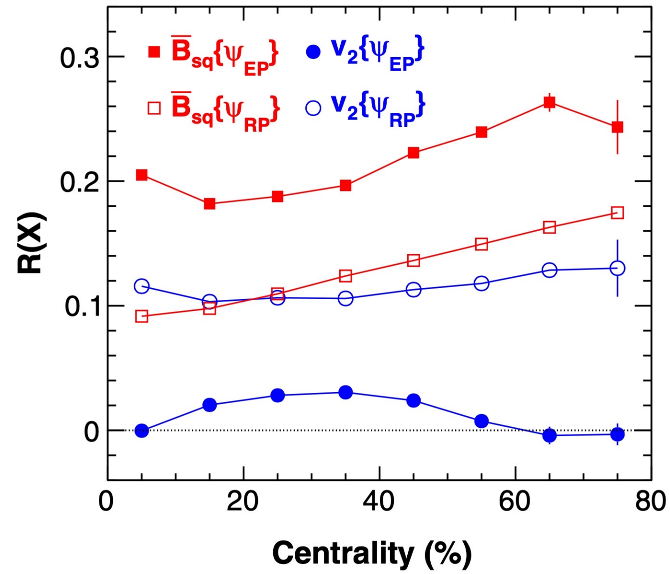
Incorporation of nucleus structure: isobars

For isobar calculations, protons & neutrons are sampled according to radial density distributions from density functional theory (DFT):



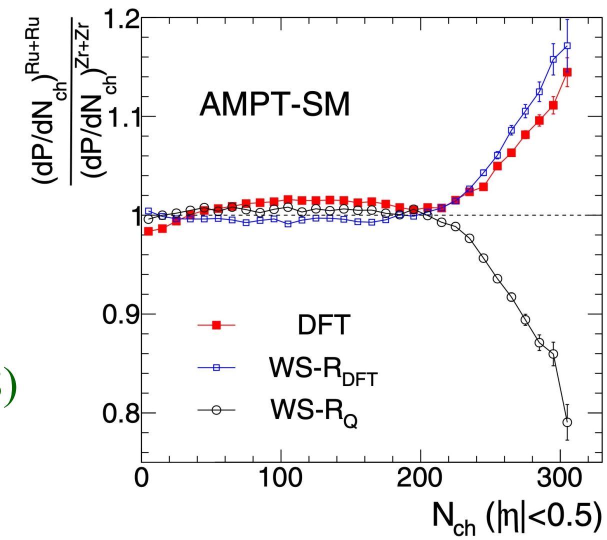
H.J. Xu, Wang, Li, Zhao, ZWL, Shen & Wang, PRL 121 (2018)

Sizable relative difference of v_2 is found for isobar systems:

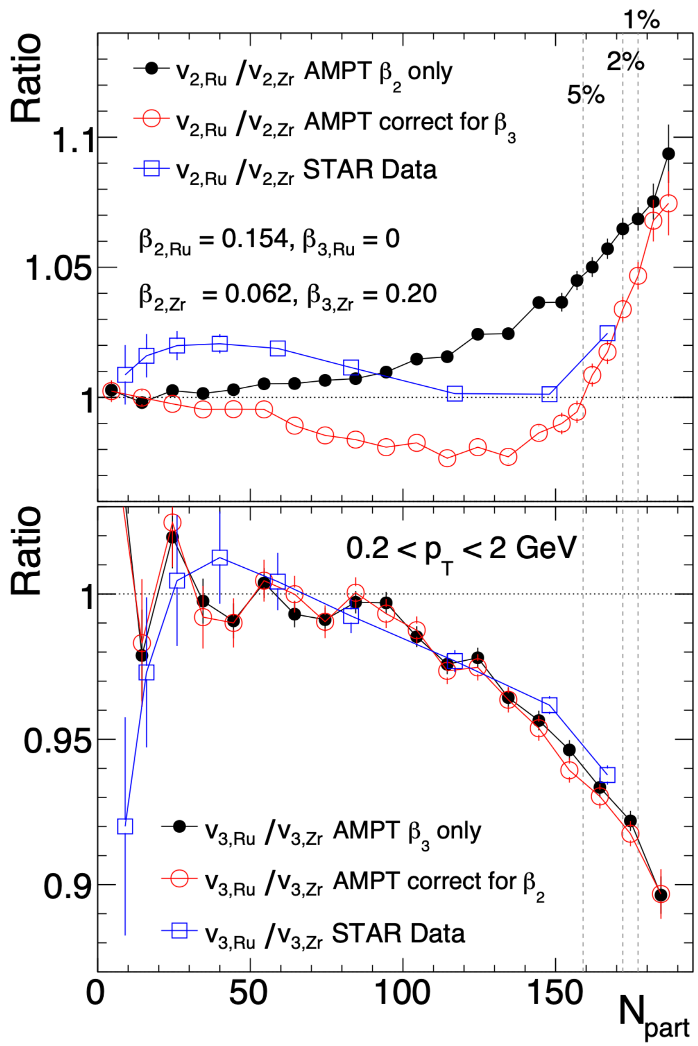


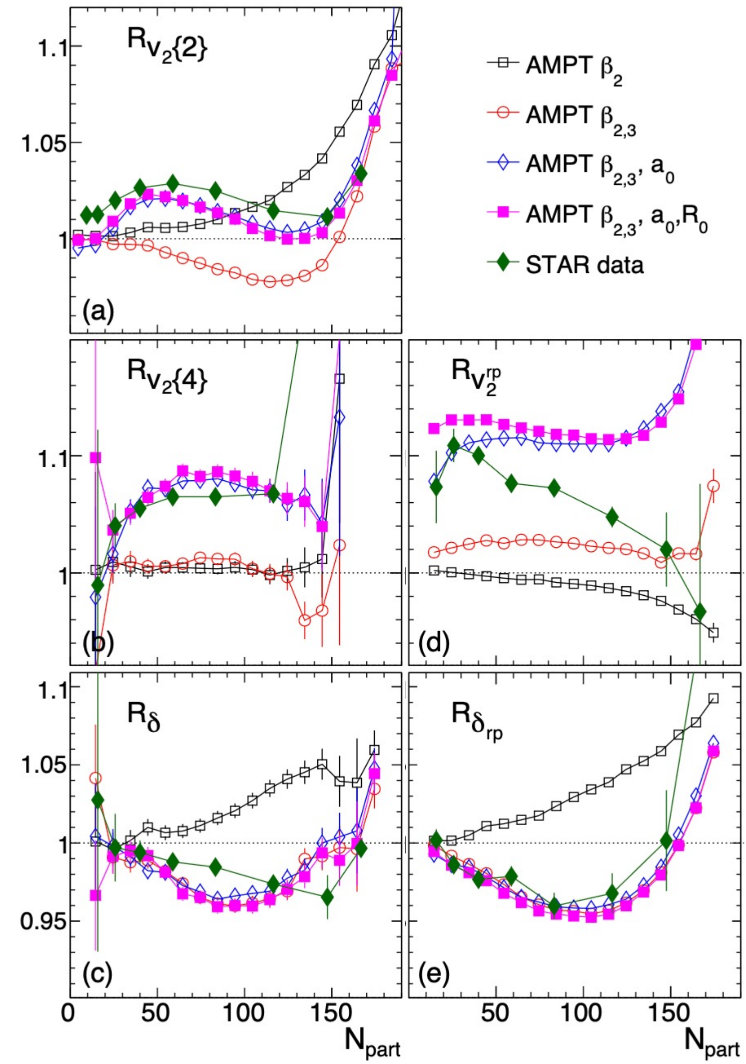
Ratio of N_{ch} distributions probes the nuclear mass radii:

H.L. Li, Xu, Zhao, ZWL, Zhang, Wang, Shen & Wang, PRC 98 (2018)



Incorporation of nucleus structure: deformations





Quadrupole and octupole deformations could be extracted from v_2 & v_3

CJ Zhang & Jia, PRL 128 (2022)

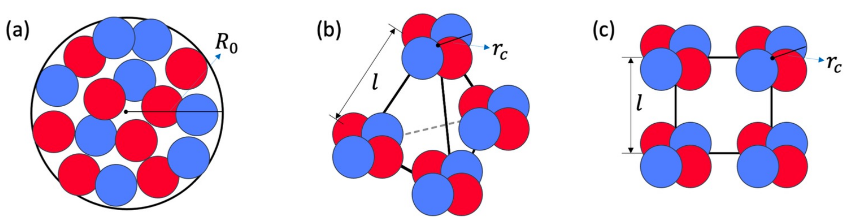
Effects of nuclear skin and nuclear deformations can be disentangled

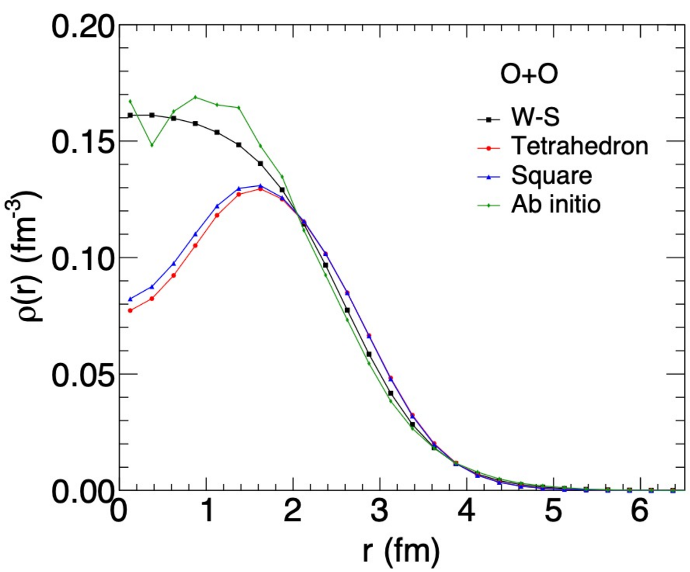
Jia, Giacalone & Zhang, PRL 131 (2023)

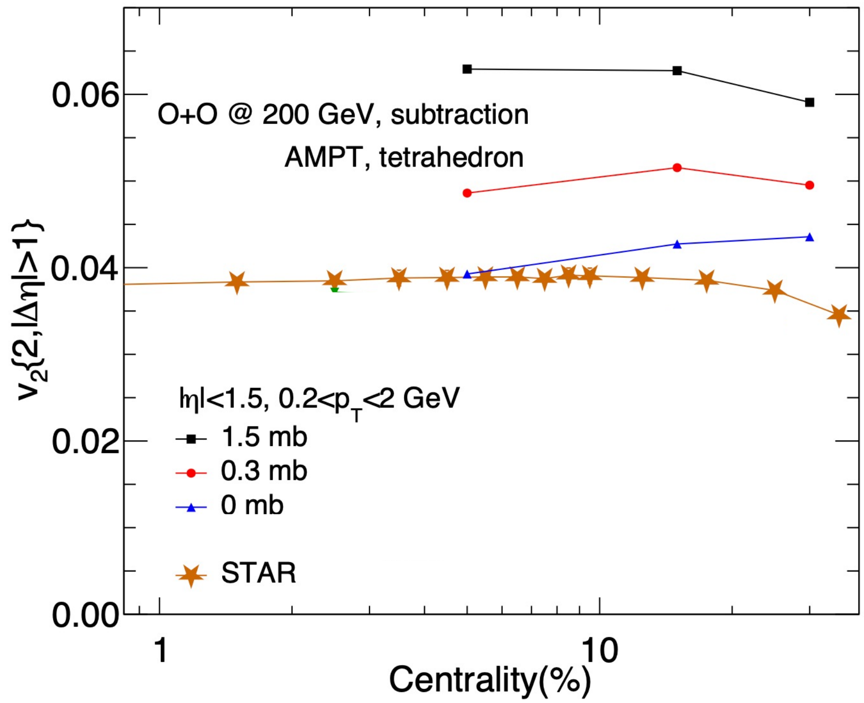
Incorporation of nucleus structure: O+O

Nuclear cluster structures in ^{16}O:

Xin-Li Zhao, Ma, Zhou, ZWL & Zhang, 2404.09780







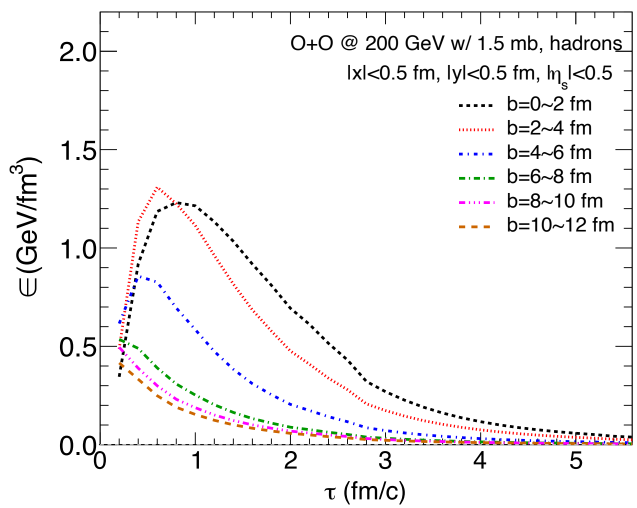
A problem:

the model v_2 is higher than STAR data, even at 0 parton cross section σ

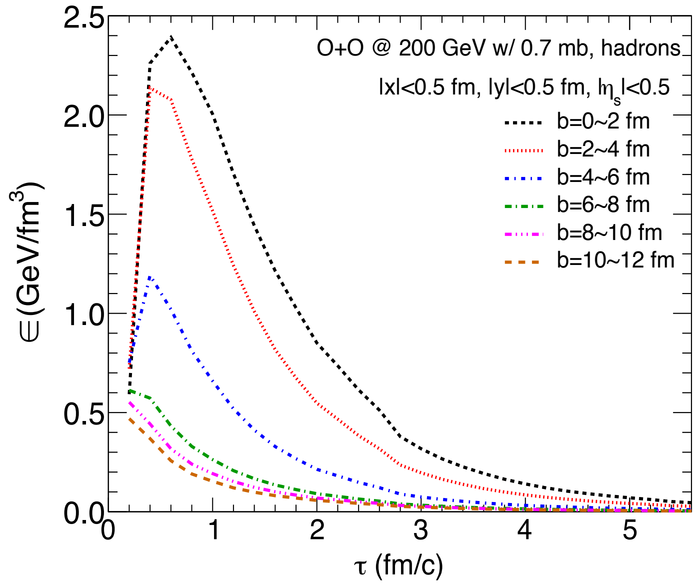
Incorporation of nucleus structure: O+O

A problem for O+O at 200A GeV:
→ flow from the hadron phase is too big
→ hadron phase starts too early?

Indeed the case:
peak energy density of hadron phase in AMPT-SM
$> 1\ \mathrm{GeV/fm^3}$ (for the central cell in O+O collisions)



O+O at 1.5mb



O+O at 0.7mb

Incorporation of nucleus structure: O+O

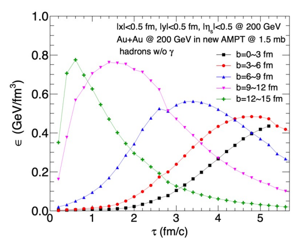
This is because hadronization (quark coalescence) in AMPT-SM starts when parton interactions stop, not at a given energy density.

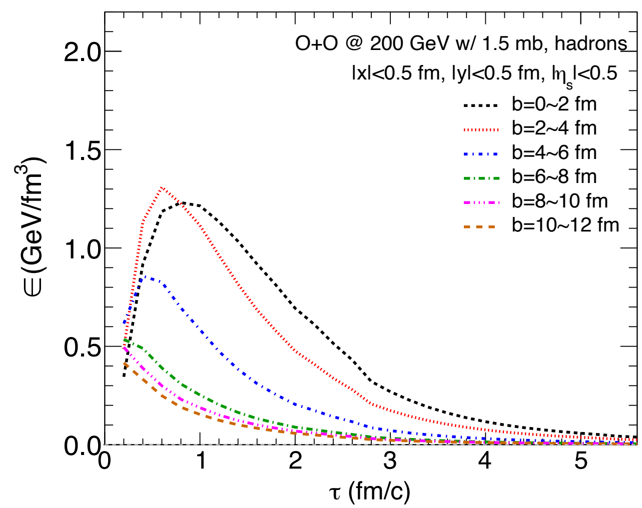
Qualitative estimate: parton interactions stop when $\sigma n L \sim 1$

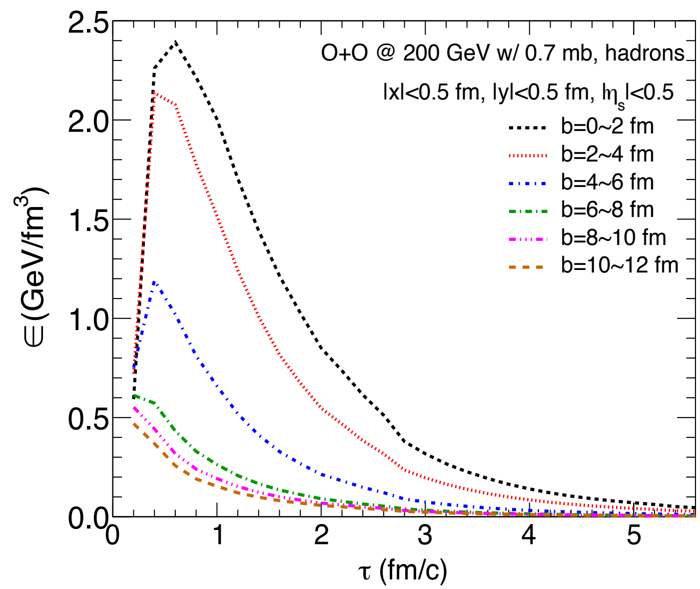
n: parton density;
L: system size.

$\rightarrow n \sim \dfrac{1}{\sigma L}$ is higher for a smaller system.

$\rightarrow$ peak hadron density is higher at $\sigma = 0.7$mb than at 1.5mb;
and higher in O+O than in Au+Au.





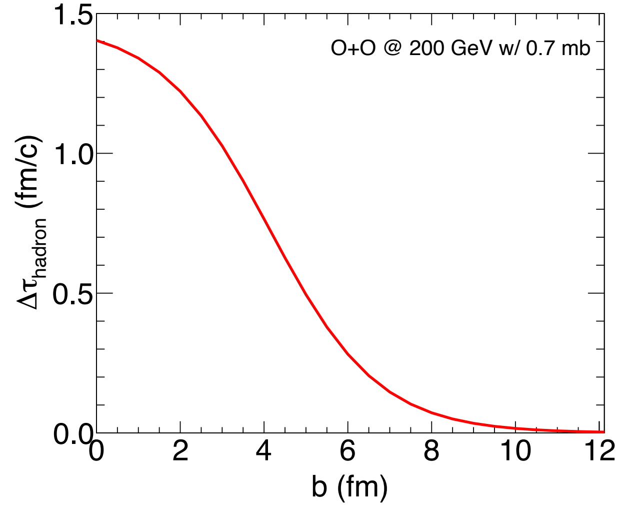


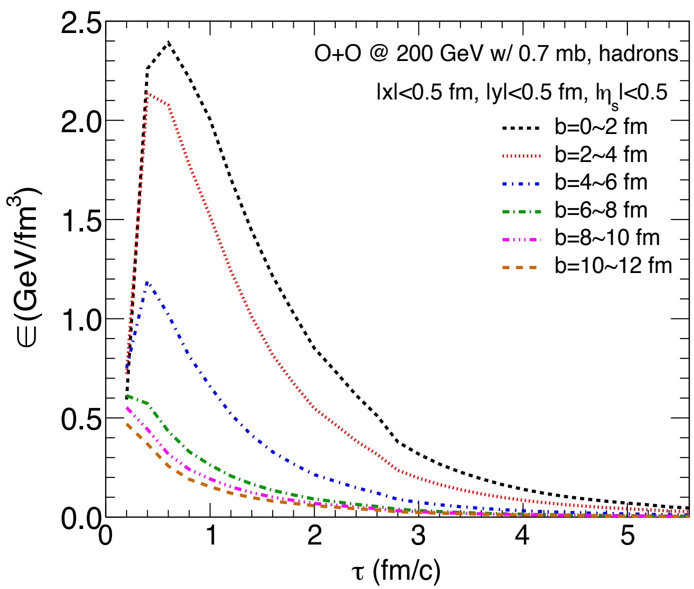
Au+Au at σ=1.5mb O+O at 1.5mb O+O at 0.7mb

Incorporation of nucleus structure: O+O

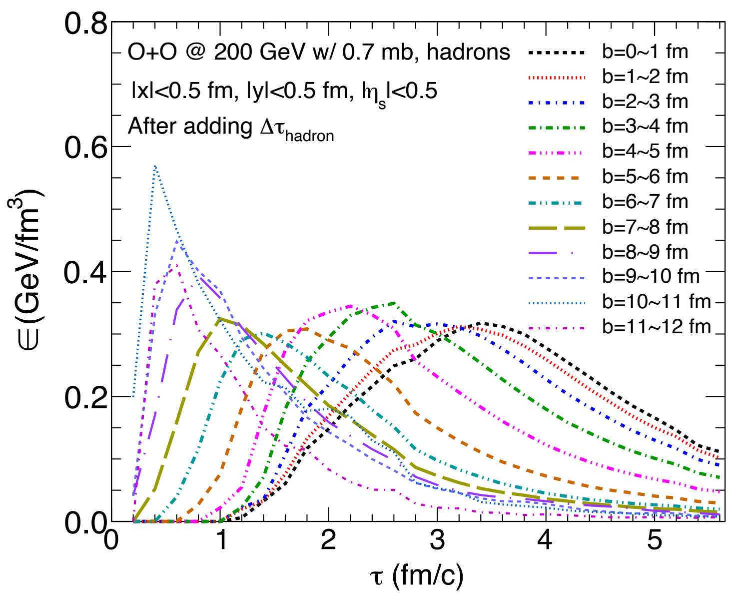
Current solution of the problem:

increase hadron proper formation time by $\Delta\tau_{hadron}$ so that the peak hadronic energy density is around a fixed ϵ_c (0.3 $\mathrm{GeV/fm^3}$ here)





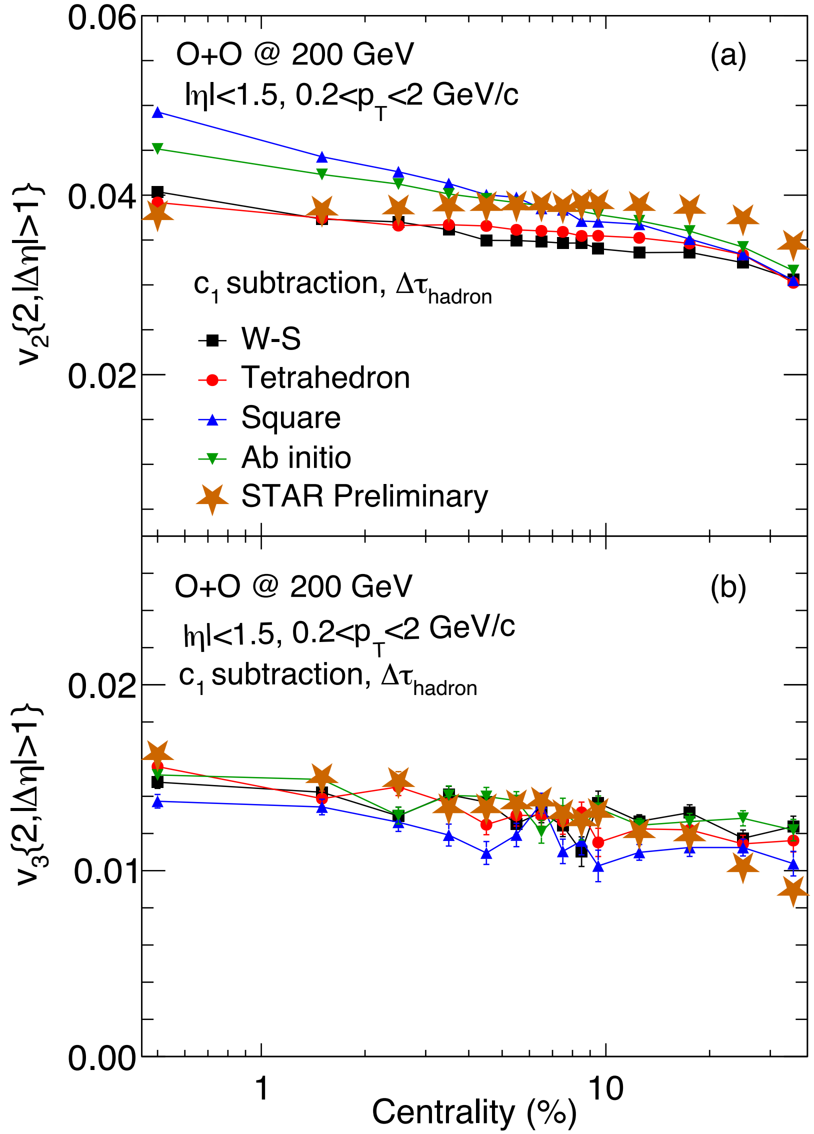
$+\Delta\tau_{hadron}$



Incorporation of nucleus structure: Ne+Ne & O+O

We then calculated flows at RHIC and LHC energies.

O+O at RHIC

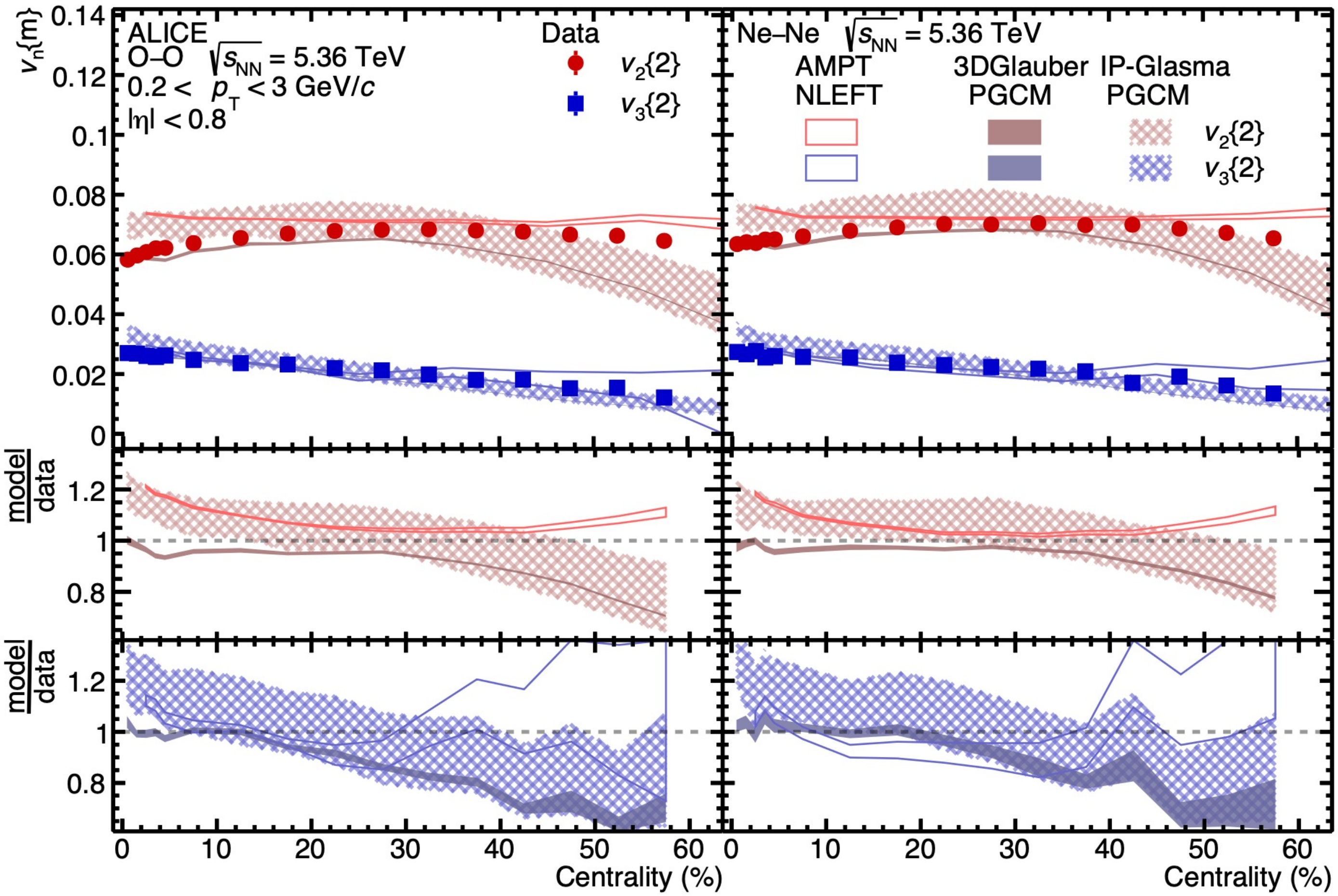


Cluster structures in ^{16}O affect flow, especially v_2

Xin-Li Zhao, Ma, Zhou, ZWL & Zhang, 2404.09780v2

Incorporation of nucleus structure: Ne+Ne & O+O

v_2 and v_3 at LHC — O+O — Ne+Ne



AMPT results:

overall magnitudes are reasonable;

v_2 is too flat versus centrality.

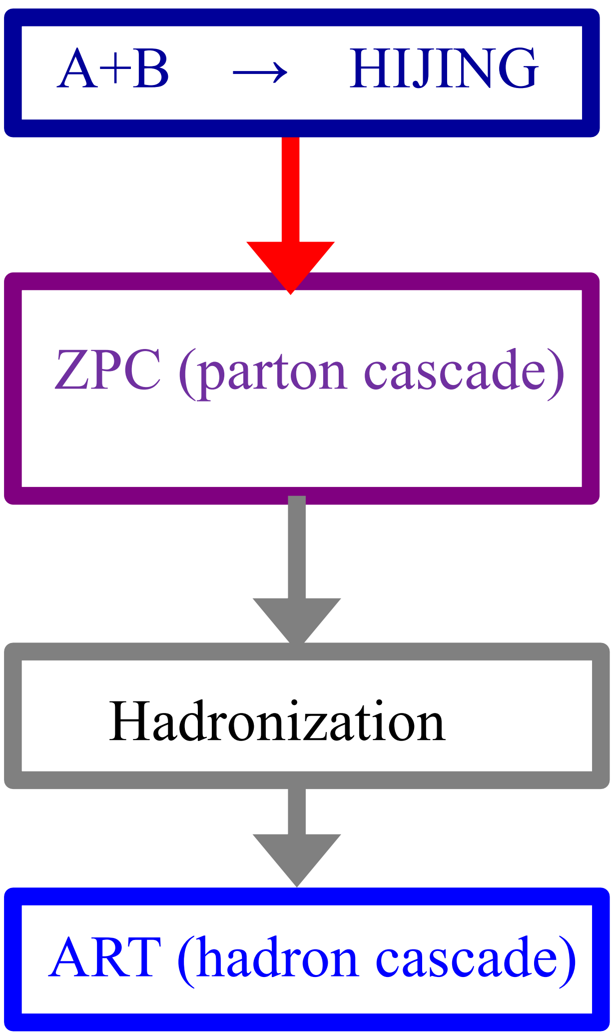
Note: the AMPT band only includes statistical error bars

ALICE 2509.06428v1

Outlook

Further developments are needed,
with many possible directions:

* = **Done**



*** Modern PDF & nuclear shadowing**
*** Size dependence of initial condition**
Nonzero nuclear thickness for lower energies
Gluons in initial condition for high energies

Parton cross sections from finite-T pQCD
2 ←→ 3 or 2 ←→ 1 parton interactions
QCD equation of state & CEP
E&M fields
Spin/angular momentum transport

*** Improved quark coalescence**
Hadronization at phase transition density
Gluons in hadronization
Include fragmentation **(* for heavy flavor)**

*** Hadron mean fields**
More resonances

Outlook

ZPC (parton cascade)	Parton cross sections from finite-T pQCD
Hadronization	Hadronization at phase transition density

Currently, AMPT treats the parton σ & screening mass μ as constant, *independent of density or temperature T*:

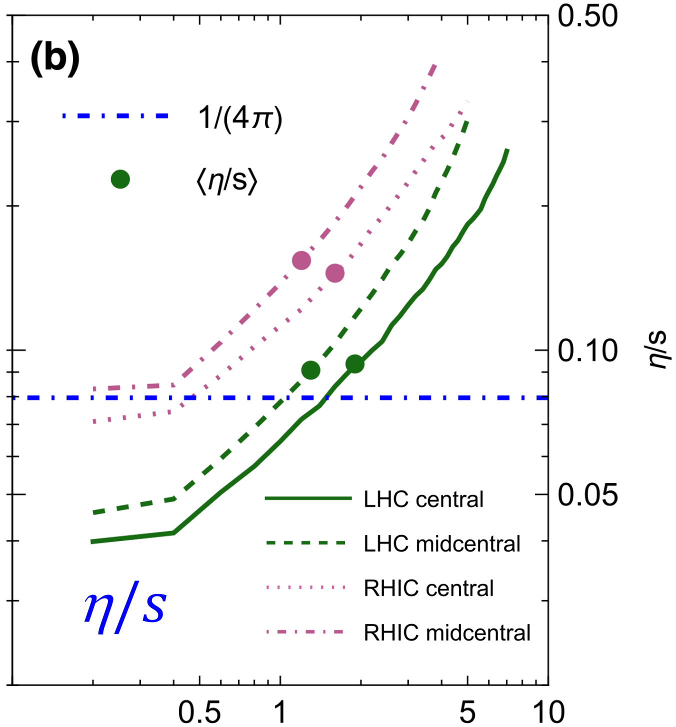
$$\frac{d\sigma}{dt} \sim \frac{9\pi\alpha_s^2}{2(t-\mu^2)^2}$$

We have calculated parton η/s in AMPT-SM:

average value is very small ~(1-3)/(4π),

but has *T*- & *t*-dependences opposite to pQCD

MacKay & ZWL, EPJC 82 (2022)

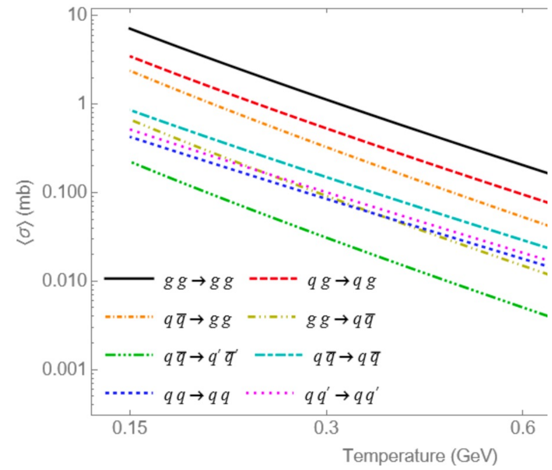


Outlook

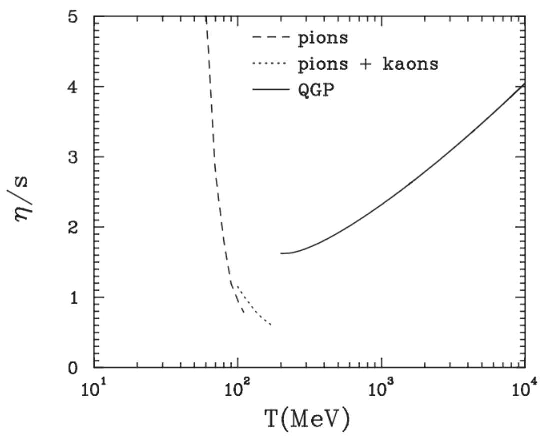
Finite-T pQCD $\rightarrow \mu \propto gT$

$\rightarrow \sigma \propto g^4/\mu^2 \propto g^2/T^2$

will be larger at lower T



Ohanaka & ZWL, in preparation; Ross & ZWL, ongoing



$\rightarrow \eta/s \propto \frac{1}{T^2\sigma} \propto \frac{1}{g^2}$

will be ~ the lowest around T_c

Csernai, Kapusta & McLerran, PRL 97 (2006)

Along this direction, we are developing ZPC/AMPT as a dynamical model of finite-T kinetic theory:

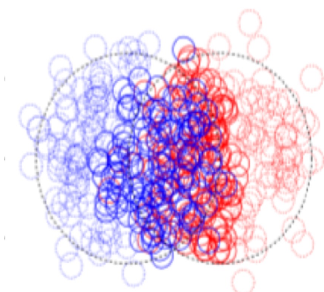
→ *parton-to-hadron phase transition according to local energy density*

→ *T- and t-dependences of η/s consistent with pQCD*

→ *extract η/s from the non-equilibrium transport approach*

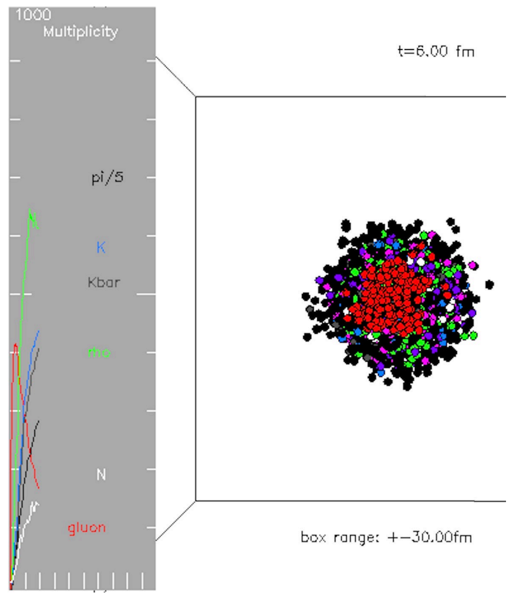
The AMPT model across energy scales

Incoming nuclei
+ hadron cascade
& mean fields



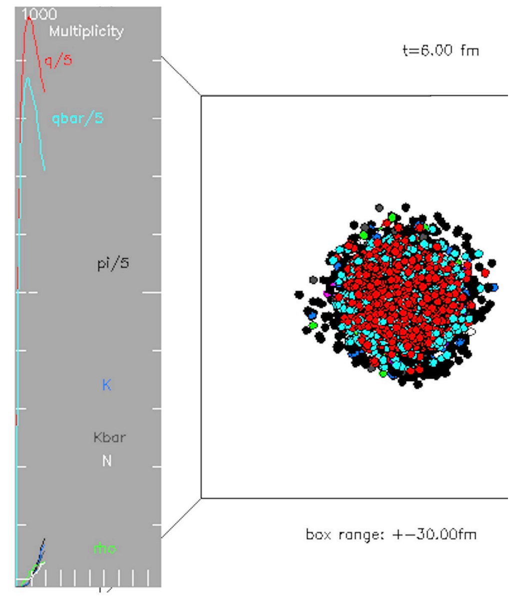
AMPT-HC

≈ HIJING initial condition
+hadron cascade



AMPT-Default

HIJING initial condition
melt to initial parton matter
+parton cascade
+hadron cascade



AMPT-StringMelting

?

AA: *2A GeV* *5A GeV* *20A GeV* *200A GeV* *5A TeV*

?

Summary

The AMPT model aims to provide
a self-contained kinetic description of heavy ion collisions;
especially suitable for studies of non-equilibrium dynamics.

Recent improvements have made AMPT more accurate and consistent.

Nuclear structures incorporated into the AMPT initial condition
have shown direct effects on certain observables;
this opens up new ways to study nuclear structure & origin of collectivity.

Further developments are necessary, including
developing ZPC/AMPT into a model for finite-T pQCD kinetic theory.

Thank you!