Improving the AMPT Model for Isobar Collisions

Zi-Wei Lin
East Carolina University

National Science Foundation

Outline

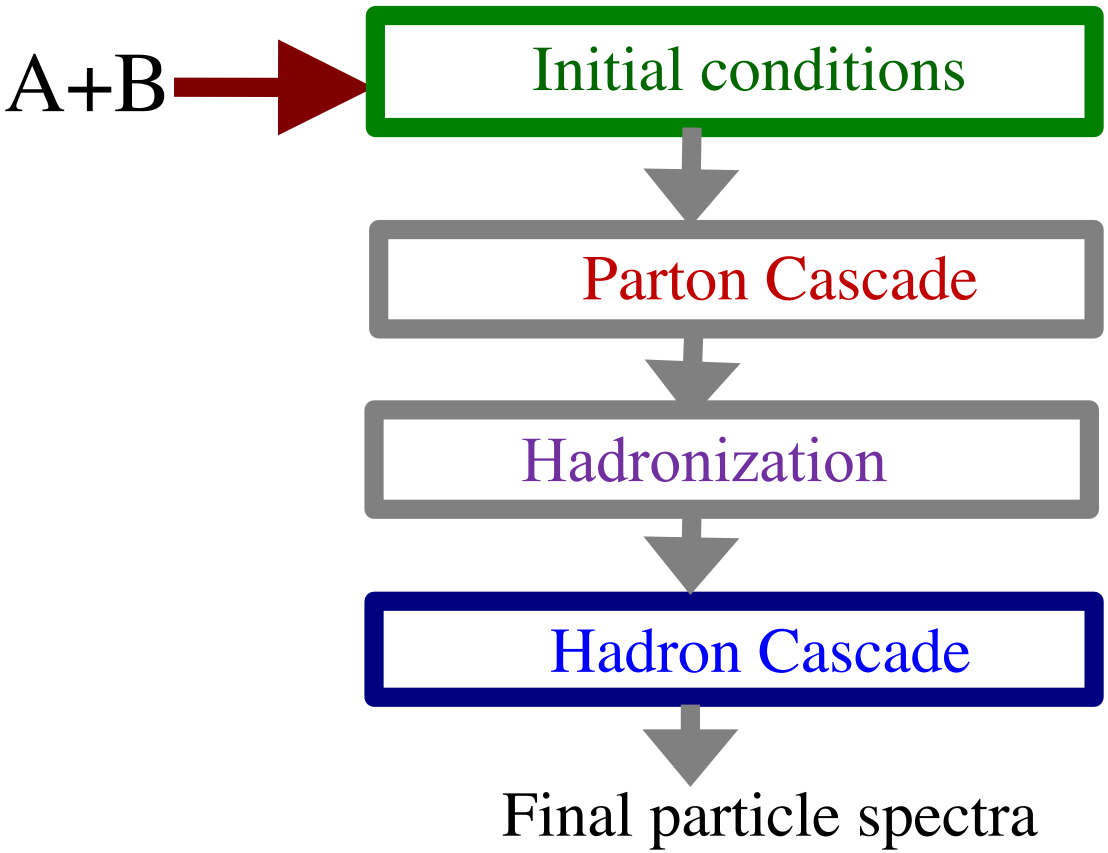
- Introduction of the AMPT model
- Improvements relevant for isobar collisions
  - Incorporation of nucleus of different shapes
  - Local nuclear scaling and self-consistent system size dependence
  - The new quark coalescence model
  - Implementation of charge conservation
  - Further developments
- Summary

Partly based on a mini-review of recent AMPT developments on Nucl. Sci. Tech. (2021)
and collaborations with Guo-Liang Ma, Bedangadas Mohanty, Md. Rihan Haque, Fuqiang Wang, Chao Zhang, Liang Zheng, et al.

A Multi-Phase Transport (AMPT)

Constructed as a self-contained kinetic description of heavy ion collisions

- evolves the system from fluctuating initial conditions to final observables;
- produces particles of all flavours at all P_T & y;
- includes non-equilibrium initial condition & dynamics.



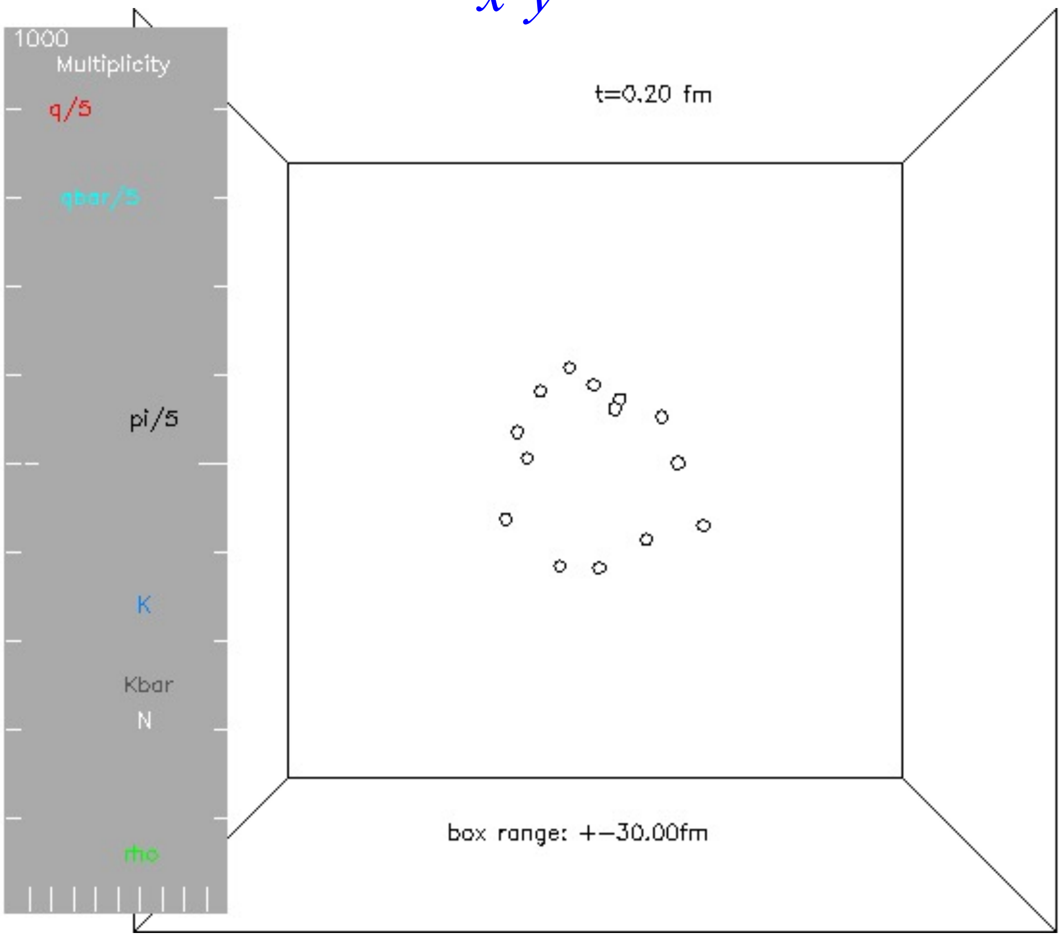
Source codes online since 2004, available at the ECU website *http://myweb.ecu.edu/linz/ampt/*

ZWL, Ko, Li, Zhang & Pal, PRC (2005);
ZWL & Zheng, NST (2021).

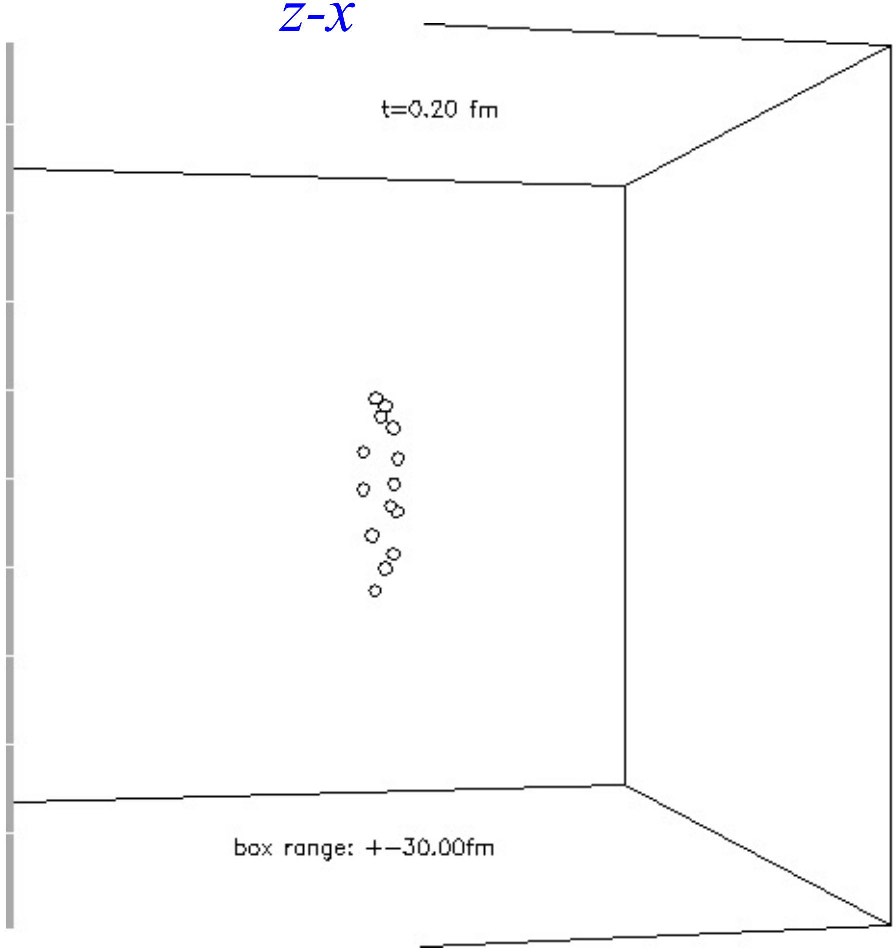
A Multi-Phase Transport (AMPT)

Time evolution of 1 central Au+Au event at 200AGeV
from AMPT-SM (*the String Melting version, applicable at high energies)*:

x-y



z-x



Animations at the ECU website
http://myweb.ecu.edu/linz/ampt/

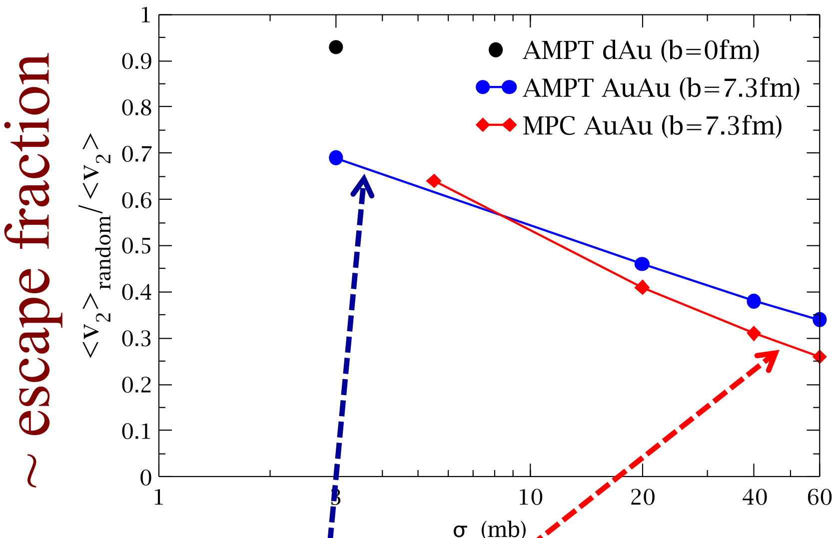
Transport models for finite systems

- **For large systems at very high energies:**
  transport model approaches hydrodynamics,
  transport model (particles, scatterings, microscopic picture) are complementary to hydrodynamics-based models ($T_{\mu\upsilon}$, EoS, transport coefficients).
- **For finite/small systems at finite energies:**
  non-equilibrium effects can be important,
  important to develop transport model/kinetic theory & compare with hydrodynamics to understand physics including collectivity of finite size systems.

Heiselberg & Levy, PRC (1999), Borghini et al. EPJC (2018), Kurkela et al. PLB (2018) & EPJC (2019), …

On example is
the escape mechanism:
interaction-induced response to anisotropic geometry from kinetic theory.

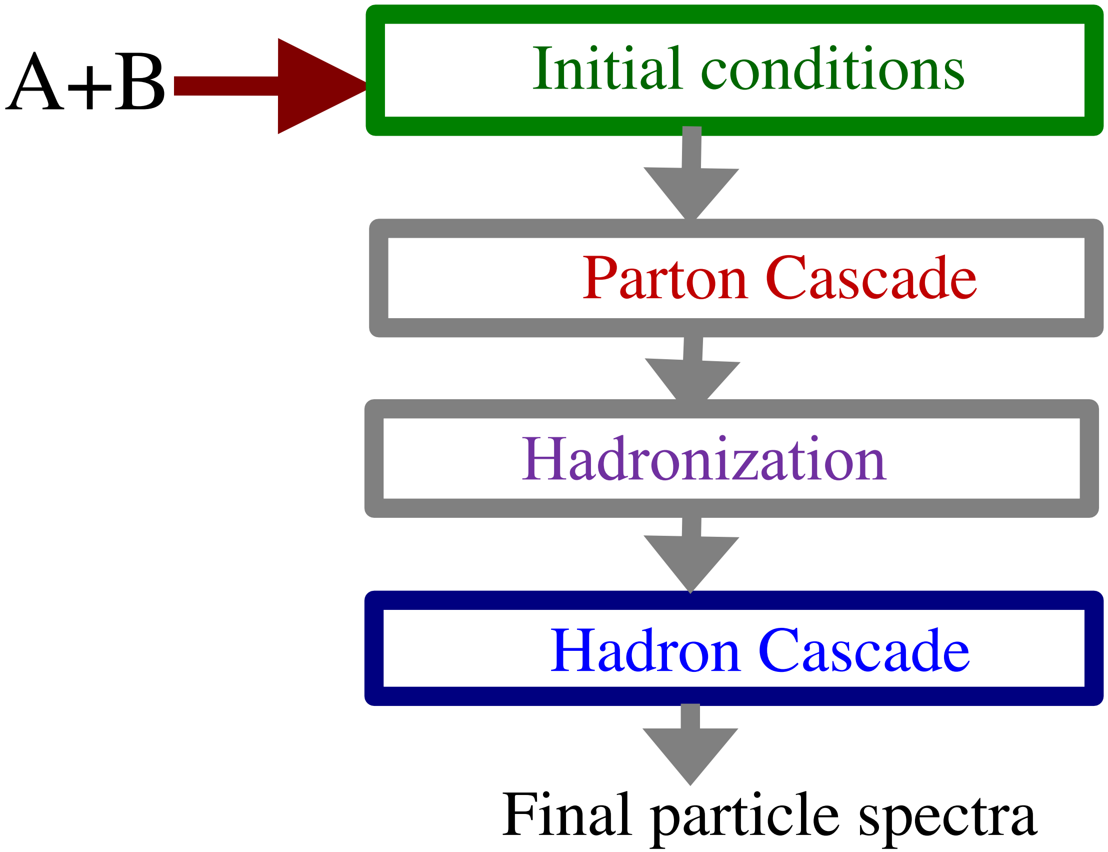
L He et al. PLB (2016);
ZWL et al. NPA (2016);
H.L. Li et al. PRC (2019).



- At very large opacity (large system/energy/σ), hydrodynamic collective flow will dominate v_2
- Escape mechanism dominates v_2 for small systems & even semi-central AuAu @200 GeV.

Improvements relevant for isobar collisions

They cover the following AMPT components:



Initial conditions:
- Incorporation of nucleus of different shapes
- Local nuclear scaling and self-consistent system size dependence

Hadronization:
- The new quark coalescence model

Hadron Cascade:
- Implementation of charge conservation

ZWL & Zheng, NST (2021)

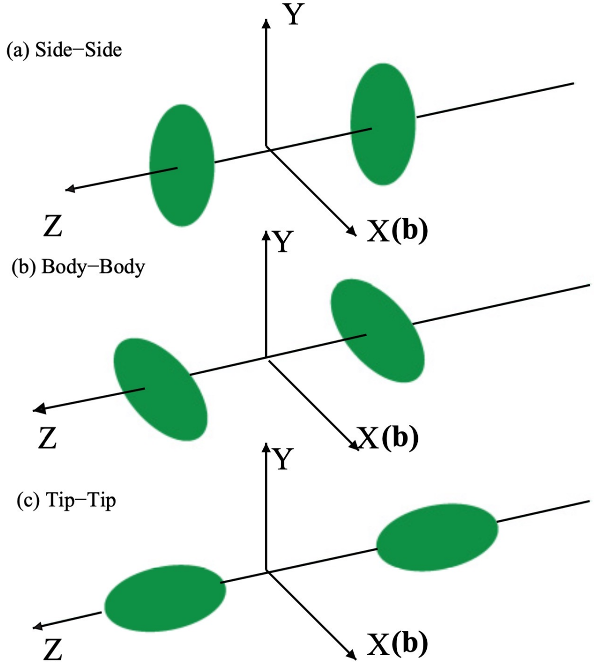
Improvements not covered in this talk: *updates with modern nPDFs, heavy flavor productions, finite nuclear thickness, pythia8 initial condition with sub-nucleon structure, parton cascade.*

Rihan Haque, ZWL & Mohanty, PRC (2012)

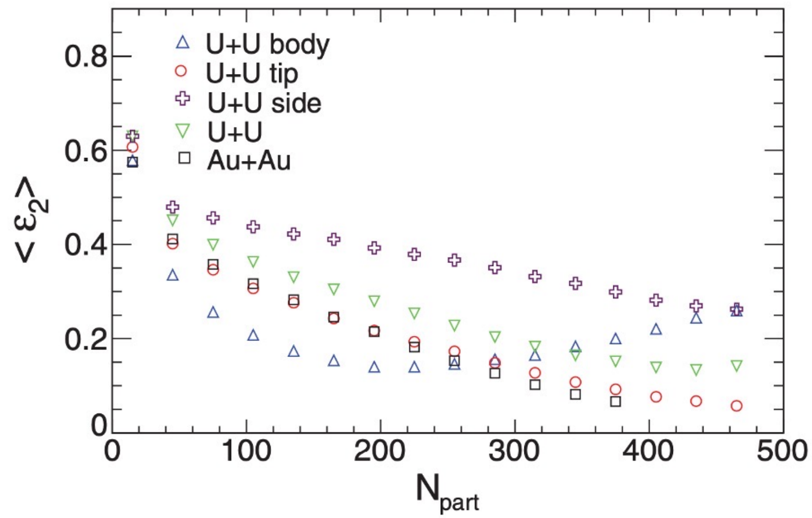
Nucleon density distribution of ^{238}U in AMPT is parametrized as deformed Woods-Saxon:

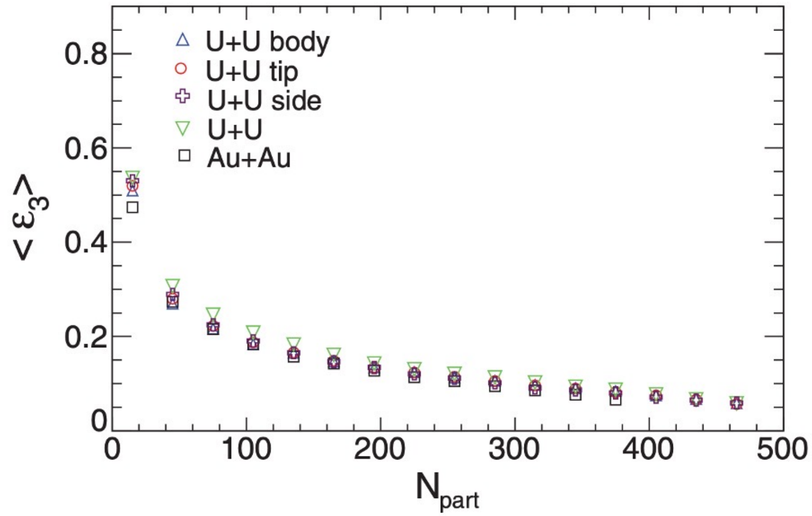
$$\rho = \frac{\rho_0}{1+\exp([r-R']/a)},$$

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



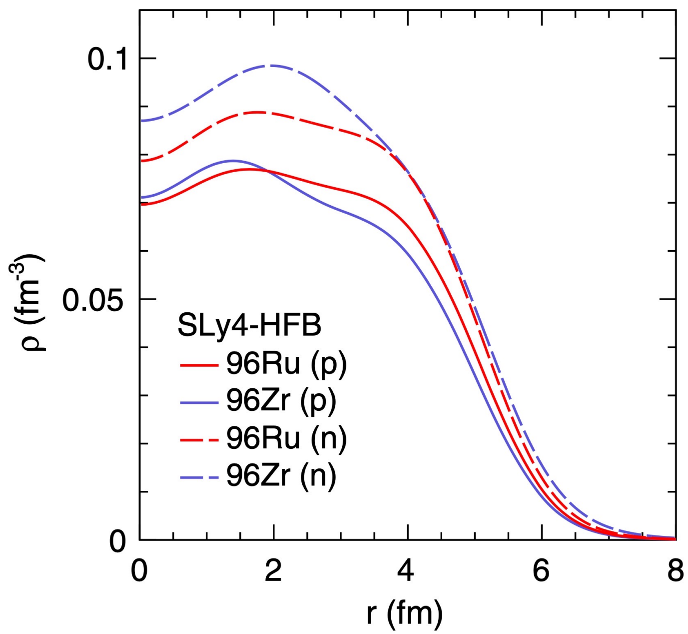
Eccentricity ε_2 and triangularity ε_3:
ε_2 and v_2 are very sensitive to orientation.





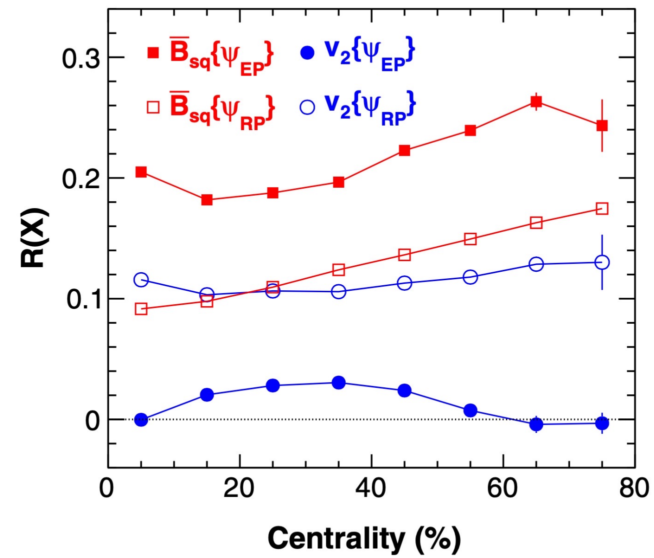
Incorporation of nucleus of different shapes

For isobar nuclei in the AMPT initial condition, protons & neutrons are sampled according to radial density distributions from density functional theory (DFT):

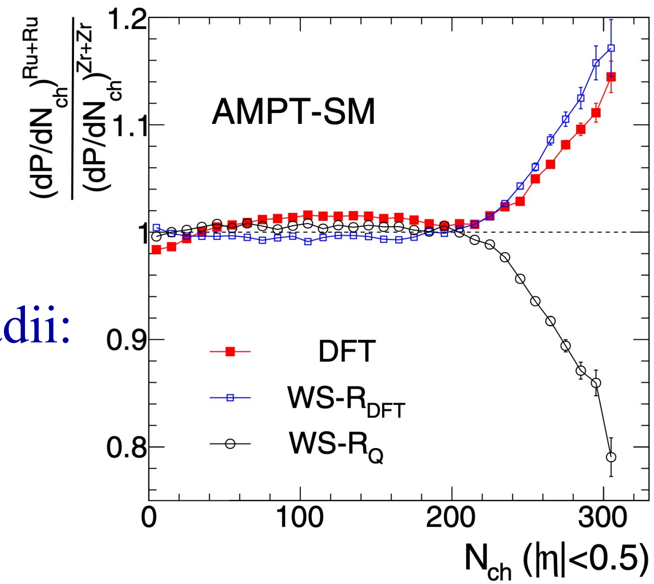


H.J. Xu et al. PRL (2018);
H.J. Xu's talk on Tuesday

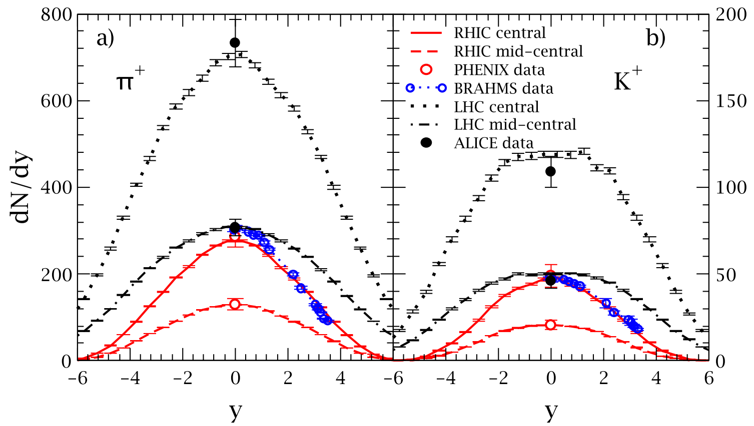
Sizable v_2 difference is found for isobar systems:

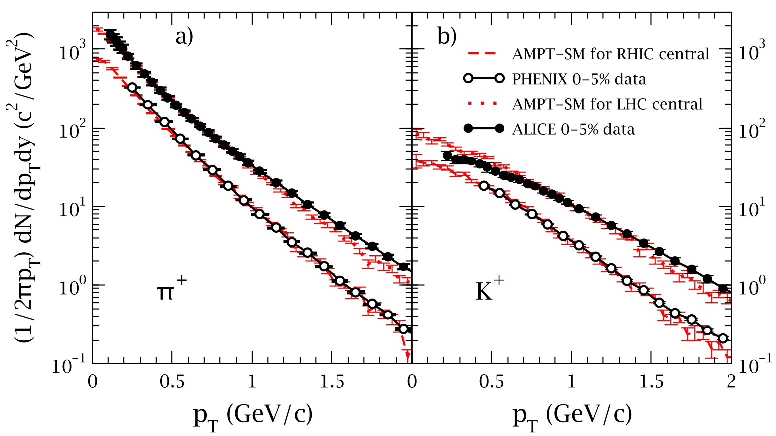


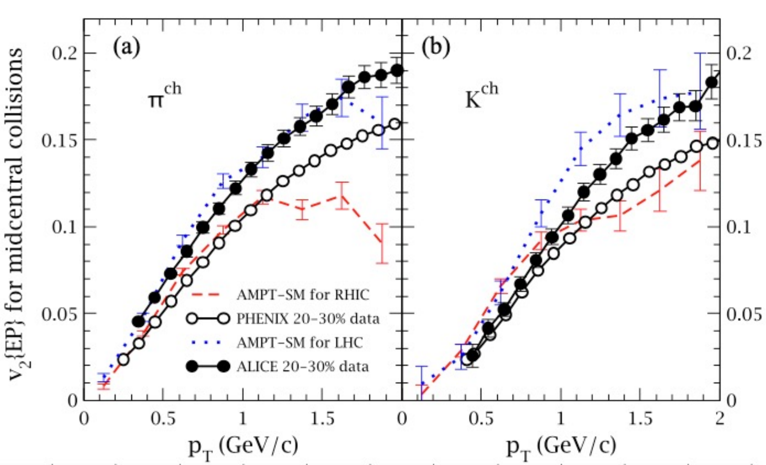
Ratio of N_{ch} distributions probes the nuclear mass radii:
H.L. Li et al. PRC (2018)



Local nuclear scaling and self-consistent size dependence







String Melting AMPT describes flows and HBT
but used to (*before 2014*) fail badly in hadron spectra.

We later realized that the model
can simultaneously describe dN/dy, p_T –spectra & v_2
(for bulk matter at low-p_T) in central and
mid-central high energy AA collisions,
as long as a very small Lund b_L parameter is used.

ZWL, PRC (2014)

Lund symmetric string fragmentation function:

$$f(z) \propto z^{-1}(1-z)^{a_L} e^{-b_L m_T^2/z}$$

b_L typical values (in 1/GeV^2):
0.5 (AMPT-def), ~0.58 (PYTHIA6.2), 0.9 (HIJING1)

b_L ~0.15 is needed for AMPT-SM for high energy AA,
corresponds to a much higher string tension:

$$\kappa \propto \frac{1}{b_L(2+a_L)}$$

ZWL et al. PRC (2005)

Local nuclear scaling and self-consistent size dependence

Different values of $\mathbf{b_L}$ are needed for pp and central AA, same for the minijet cutoff scale $\mathbf{p_0}$ (*related to saturation scale Q_s in the AMPT model updated with modern nPDFs*).

C Zhang et al. PRC (2019); Zheng et al. PRC (2020)

We propose to scale them with local nuclear densities:

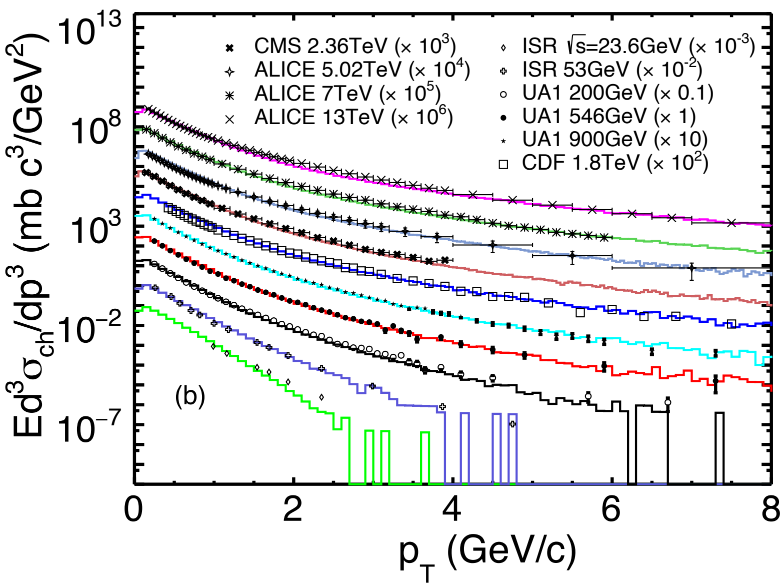
C Zhang et al. PRC (2021)

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

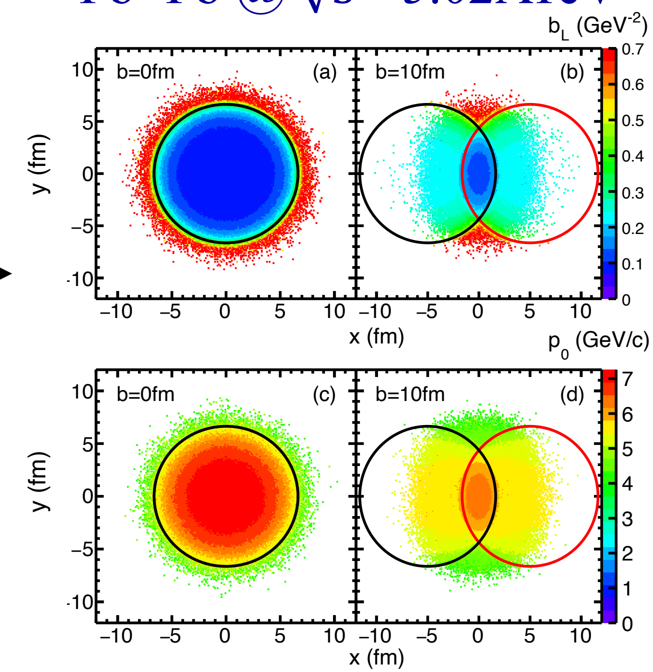
$$p_0(s_A, s_B, s) = p_0^{pp}(s)[\sqrt{T_A(s_A)T_B(s_B)}/T_p]^{\alpha(s)}.$$

Similar geometric form preferred for initial entropy deposition: Bernhard et al. PRC (2016)

We fit charged hadrons in *pp* to determine $b_L^{pp}=0.7$, then used central AuAu/PbPb data to get $\alpha(s)$, $\beta(s)$:



Pb+Pb @ $\sqrt{s}$= 5.02ATeV

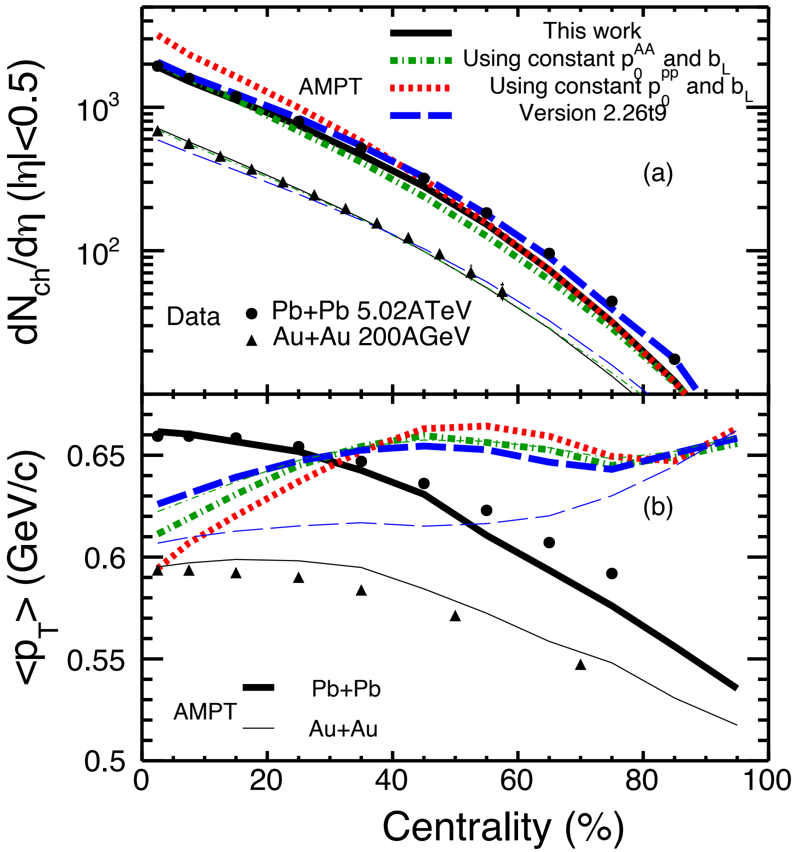


Local nuclear scaling and self-consistent size dependence

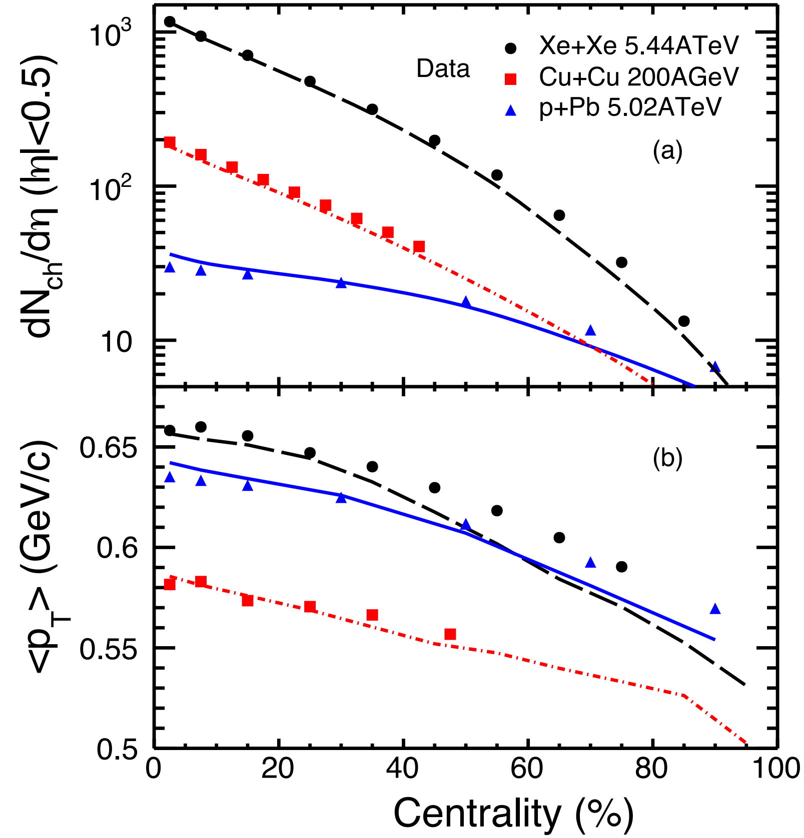
The scaling allows AMPT-SM to self-consistently describe the system size dependence, including centrality dependences of AuAu & PbPb and smaller systems.

C Zhang et al. PRC (2021)

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



Also works for smaller systems:



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

No longer free parameters **→ *η* … can be better studied**

The new quark coalescence model

Old Coalescence

(*in public AMPT)*

$q_{\overline{B}}$ q_m q_B $\overline{q}_m$ ....

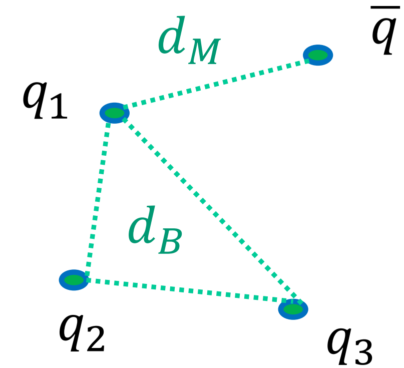
There is an artificial constraint that forces the separate conservation of the numbers of mesons, baryons and antibaryons for each event (*while only net-baryon conservation is necessary*):

- Quarks from the melting of mesons search all antiquarks and choose the closest antiquark to form mesons.
- Then quarks from the melting of baryons search all remaining quarks and choose the closest two quarks to form baryons (*same for anti-baryons*).

New coalescence

Y. He & ZWL, PRC (2017)

We remove the artificial constraint, **quarks now have freedom to form either meson or baryon**:

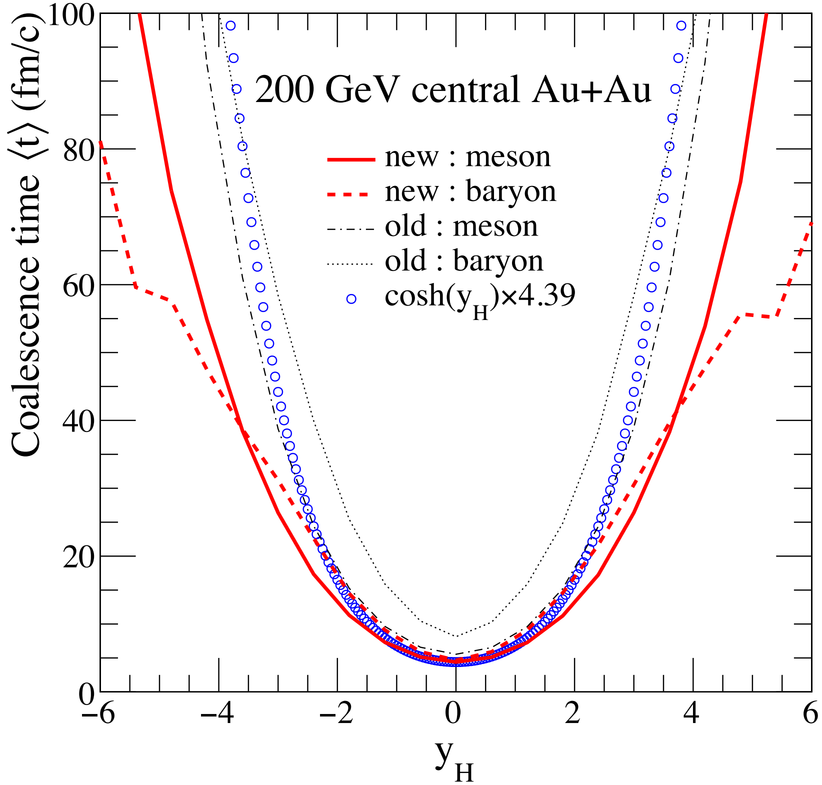


For example, for a quark q_1:
d_M: closest distance to an antiquark *(in rest frame)*
d_B: average distance among the 3 quarks after finding closest q_2 & q_3

If $d_B < d_M * r_{BM}$, q_1 will coalesce to a baryon;
otherwise, q_1 will coalesce to a meson.

→ Single coalescence parameter r_{BM}, ~0.6

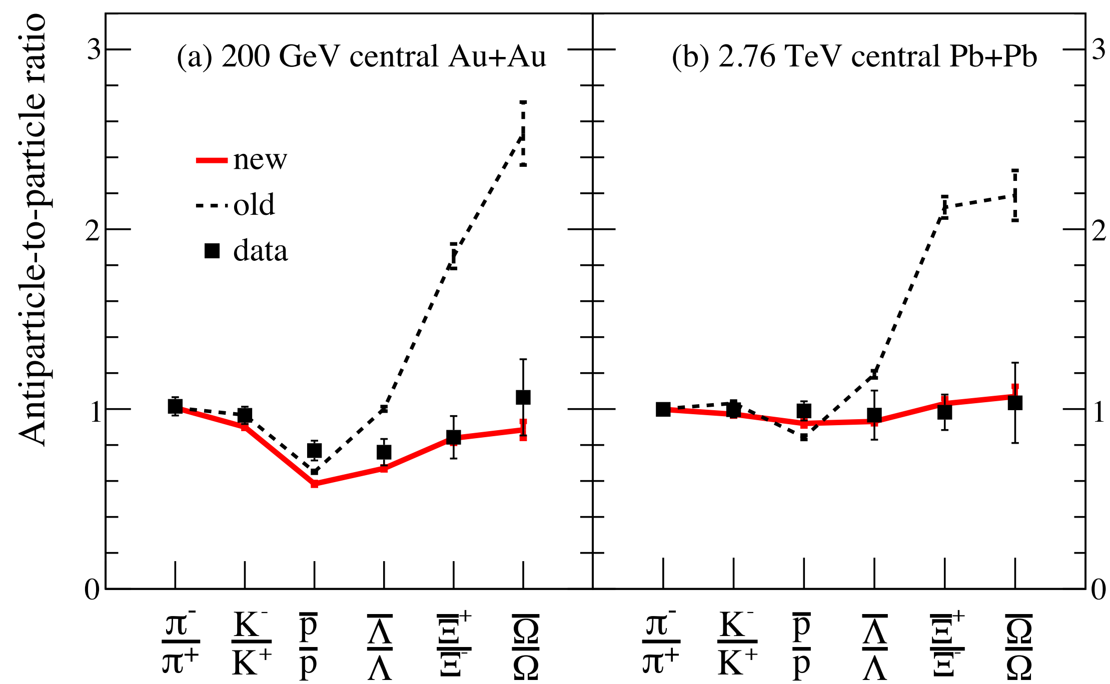
The new quark coalescence model



Y. He & ZWL, PRC (2017)

New quark coalescence is more efficient,
especially for (anti)baryons.

Improves (anti)baryon observables,
including p & pbar yield & p_T –spectra and multi-strange Bbar/B ratios:



Implementation of charge conservation

Why is charge conservation violated in public AMPT?

First reason: The hadron cascade has K^+ and K^- as explicit particles, **but not K^0 and K^0-bar.**

Currently, to let all kaons interact:

- before hadron cascade,

we change K^0 to K^+ *(also: K^0-bar to K^-)*

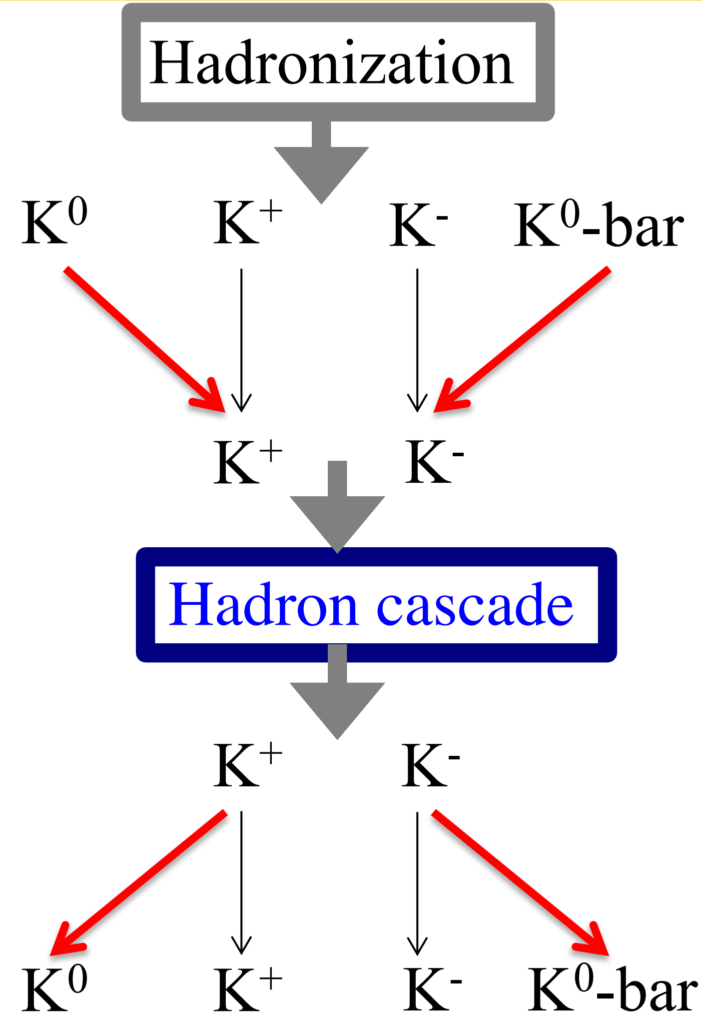
- after hadron cascade,

we change half of final K^+ into K^0.

Second reason:

Many reactions in the hadron cascade are not implemented for each possible isospin/charge state

→ **Need to identify & correct each such reaction while respecting detailed balance relations**



This work has been done in a version of AMPT:

Z.W. Lin & G.L. Ma, unpublished (2018).

This charge-conserved version has been shared with some colleagues for CME studies: Tang, CPC (2020); Choudhury et al. EPJC (2020).

Further developments relevant for isobar collisions

- Further improve the initial condition from HIJING:

  There is a small p_z-asymmetry of hadrons in symmetric collisions:
  this leads to rapidity-asymmetry of final state hadrons,
  especially antibaryons from public AMPT-SM at low energies
  (thanks to H.Z. Huan's group for pointing out this issue).

  There is an artificial ordering of initial protons and neutrons
  in the nucleus along the z direction when sampling Woods-Saxon
  (protons take ~half of the z range & neutrons take the other ~half):
  this affects the initial net-charge distribution
  and could affect charge-dependent observables.

- Self-consistent parton transport under electromagnetic fields

- Update the public AMPT model with recent improvements

Summary

AMPT provides a self-contained kinetic description of heavy ion collisions

Recent improvements make AMPT more versatile and reliable:

- Incorporation of deformed or arbitrary nucleon distributions

  enables studies of isobar collisions.

- New quark coalescence

  improves baryon & antibaryon productions.

- Implementation of charge conservation

  improves studies of charge-dependent observables.

- **Local nuclear scaling of initial condition parameters**

  significantly reduces uncertainty from free model parameters
  and enables us to focus on QGP properties like
  σ (parton cross section, or m_D) and its T-dependence $\leftrightarrow$ $\eta(T)$

Thanks for your attention!