Baryon Production
in A Multi-Phase Transport (AMPT) Model

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Outline

- Introduction of the AMPT model
- Model results on baryon and electric charge stopping
- Relations to quark stopping
- On net-charge reconstruction
- Summary

Mostly based on work with PhD student Mason Ross

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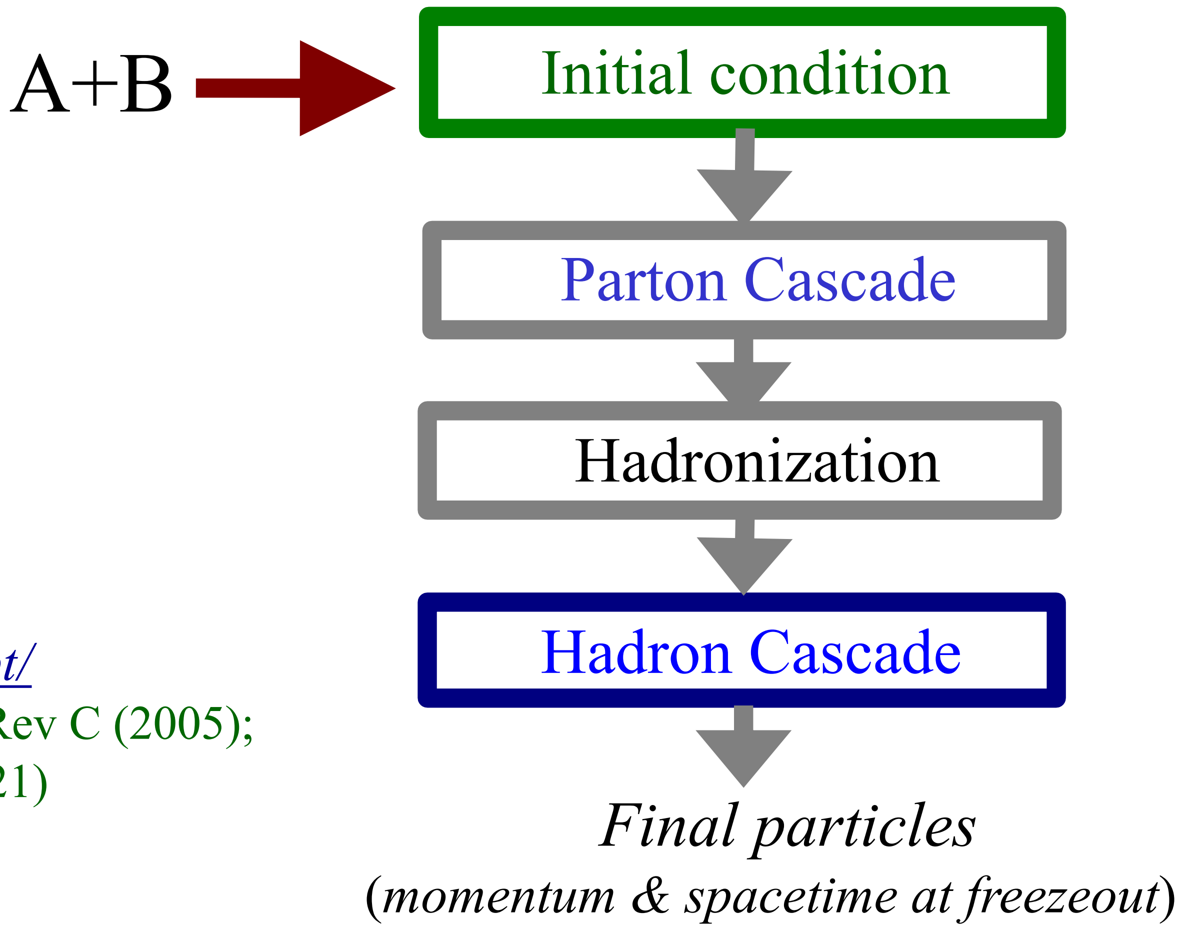
A multi-phase transport (AMPT) model

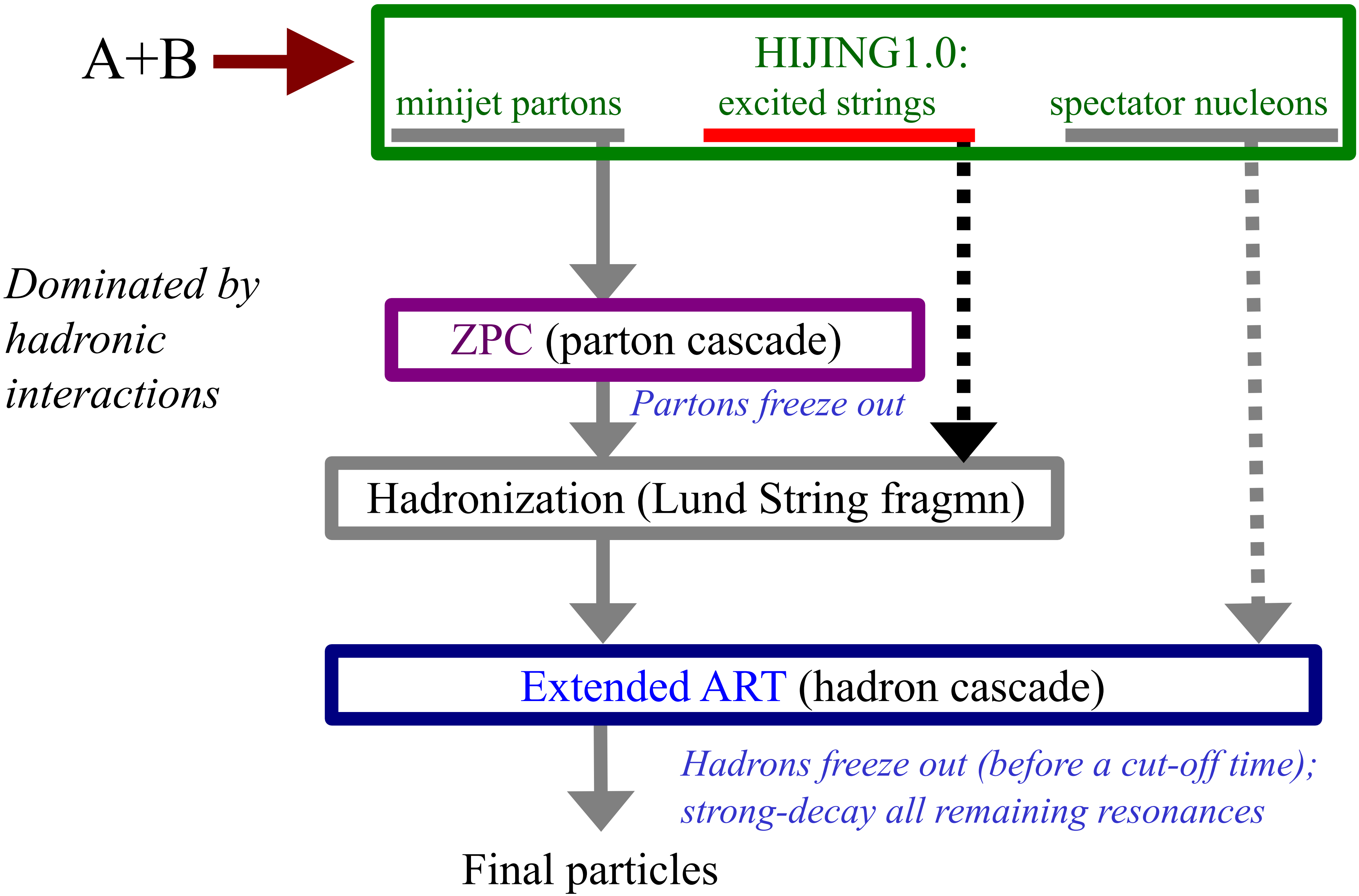
was constructed as a self-contained kinetic description of heavy ion collisions:

- evolves the system from initial condition to final observables;
- has explicit parton stage and hadron stage;
- includes productions of all quark flavors & conserved charges in 3D;
- can address initial condition & dynamics/evolution in non-equilibrium.

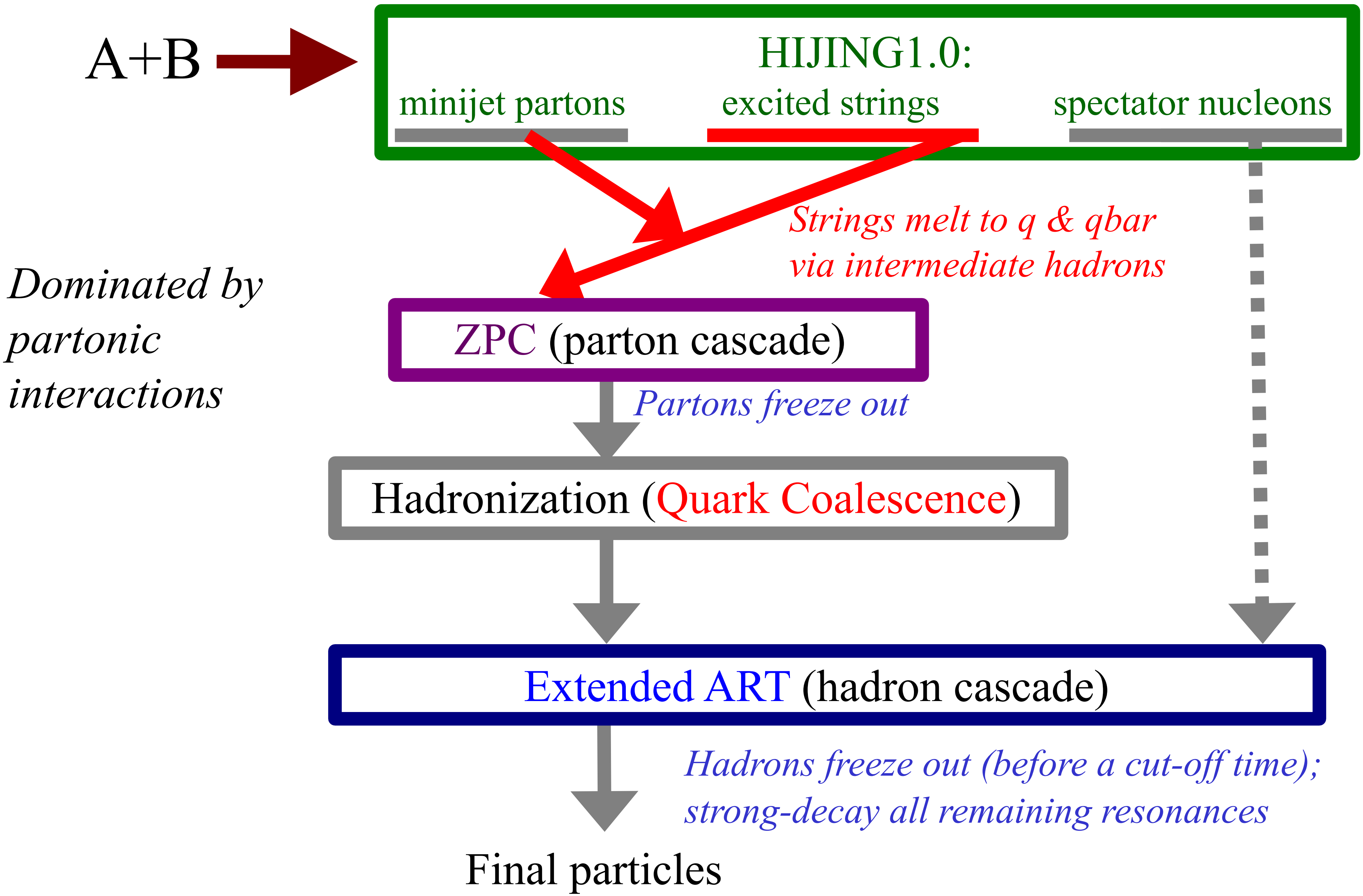


Source codes at
https://myweb.ecu.edu/linz/ampt/
ZWL, Ko, Li, Zhang & Pal, Phys Rev C (2005);
ZWL & Zheng, Nucl Sci Tech (2021)

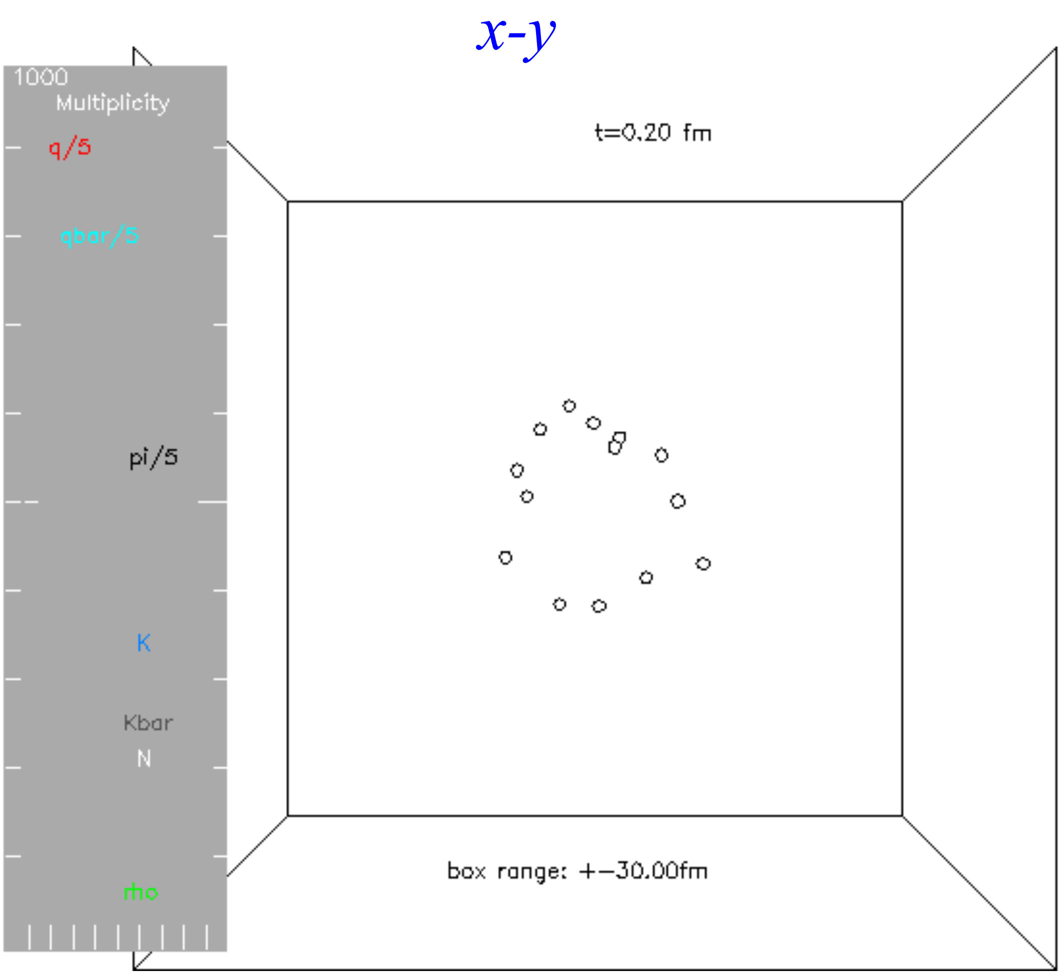
Structure of the default AMPT model

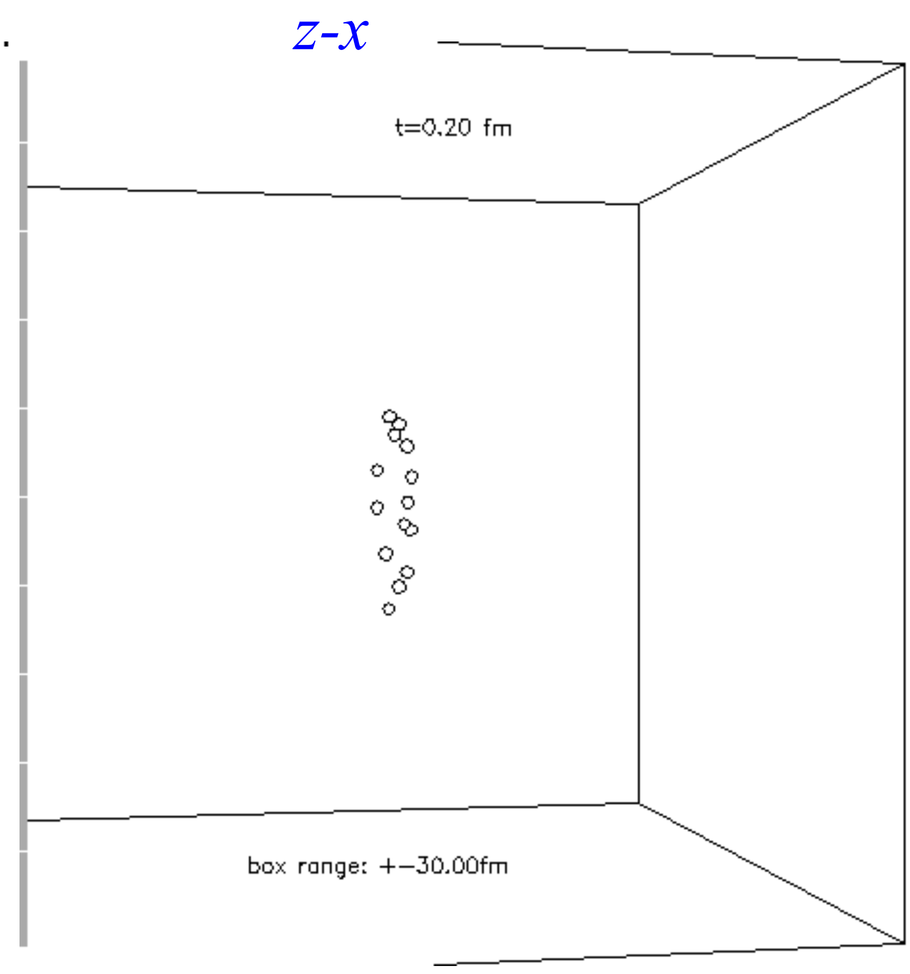


Structure of the string melting AMPT model



A central Au+Au event at 200 AGeV
from the String Melting AMPT model *(applicable at high energies)*:

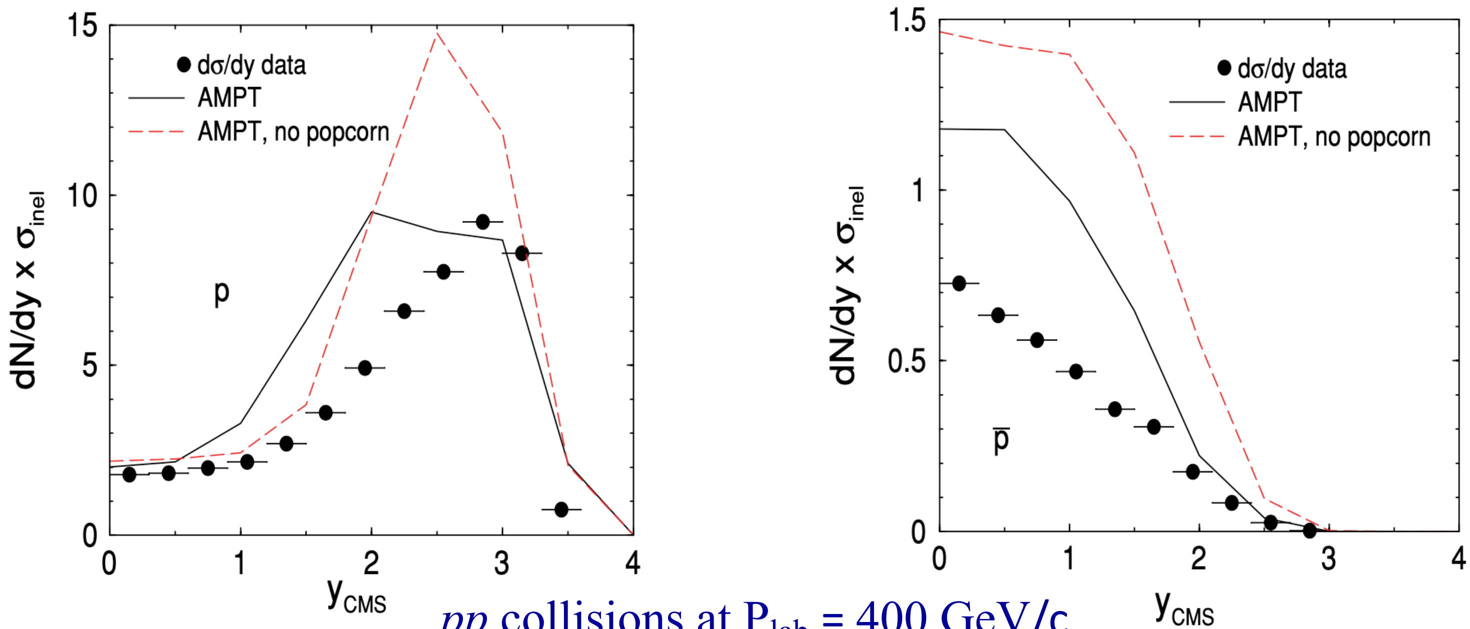




Baryon productions in AMPT

In both versions of AMPT, the initial baryon stopping is described by HIJING1.0 via the Lund string fragmentation in PYTHIA.

To have more freedom for adjusting the baryon stopping in AMPT, we have included the popcorn mechanism:
this introduces two additional baryon-antibaryon pair production channels:
the $B\bar{B}$ and $BM\bar{B}$ configurations; with a parameter controlling their ratio.

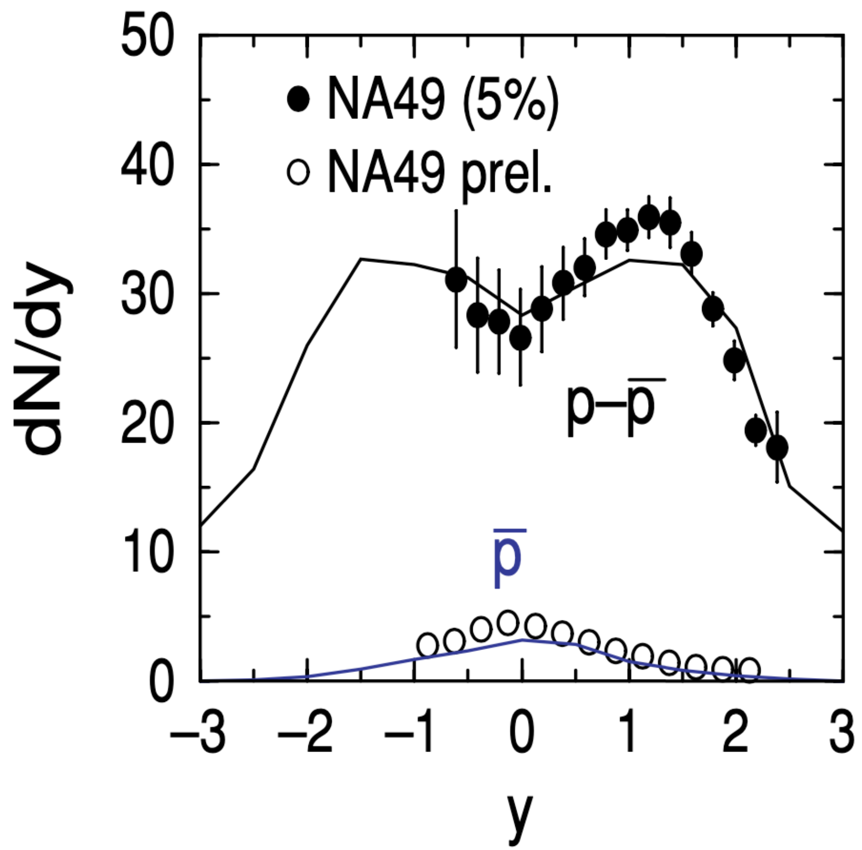


pp collisions at P_{lab} = 400 GeV/c

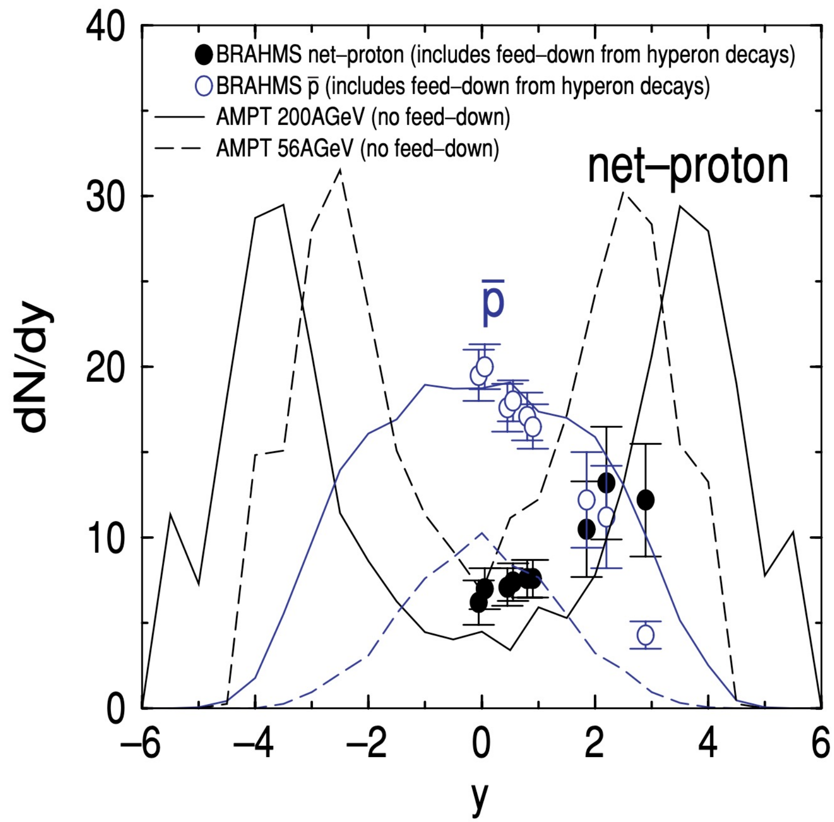
The popcorn mechanism can help but is not enough.

Baryon stopping in the default AMPT model for AA collisions are often reasonable.

Central Pb+Pb collisions at top SPS energy (17.3GeV)



Central Au+Au collisions at RHIC energies

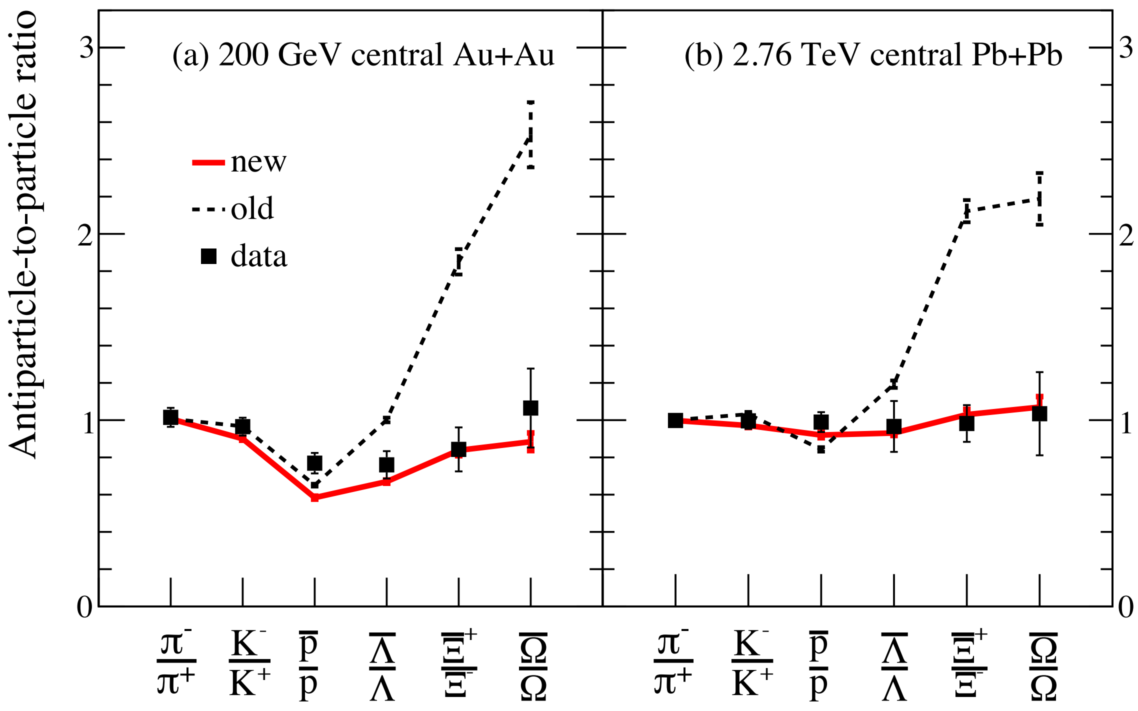


Baryon stopping in the string melting AMPT model also depends on quark coalescence.

We have improved the quark coalescence model in AMPT, it is more physical and efficient, especially for (anti)baryons.

Y He & ZWL, Phys Rev C (2017)

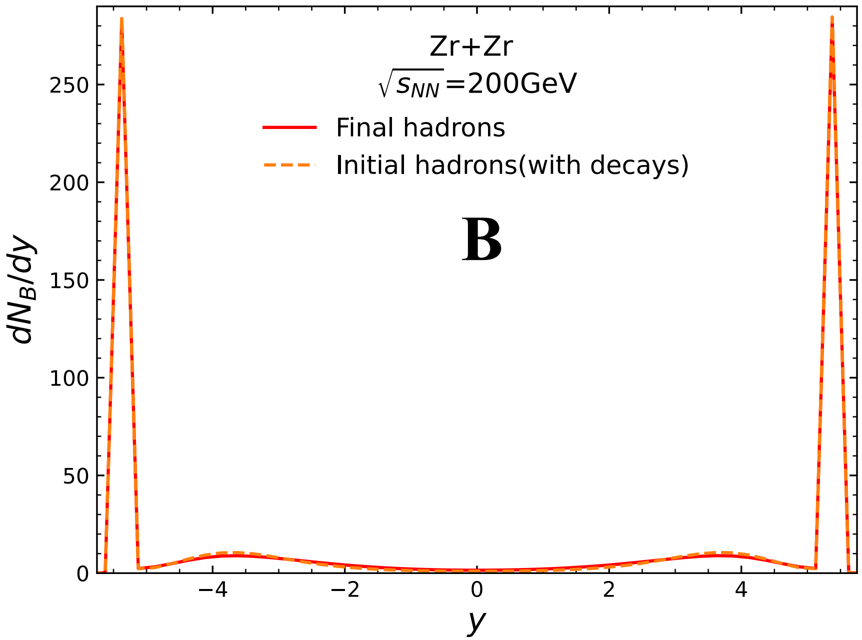
It improves (anti)baryon observables including p & $\bar{p}$ yield & p_T–spectra and multi-strange $\bar{B}/B$ ratios:

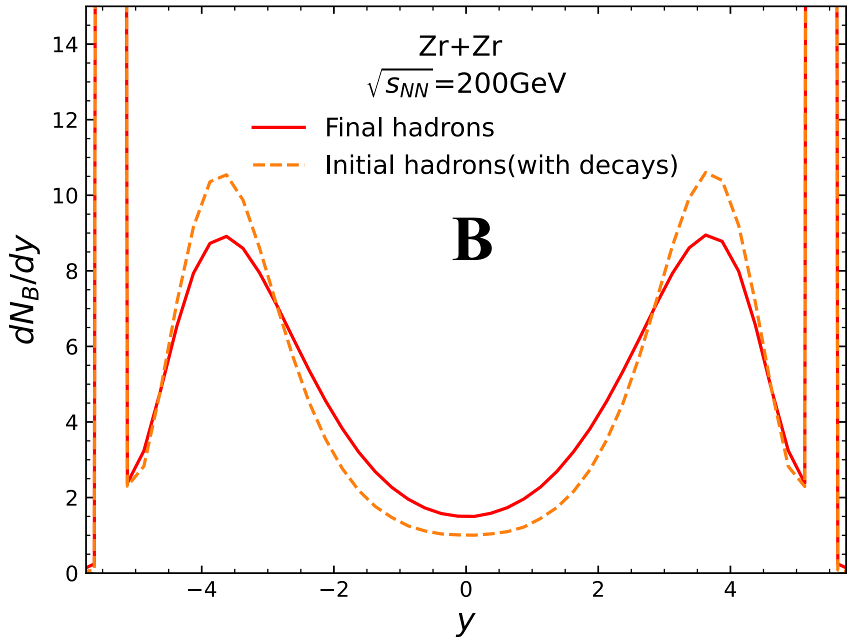


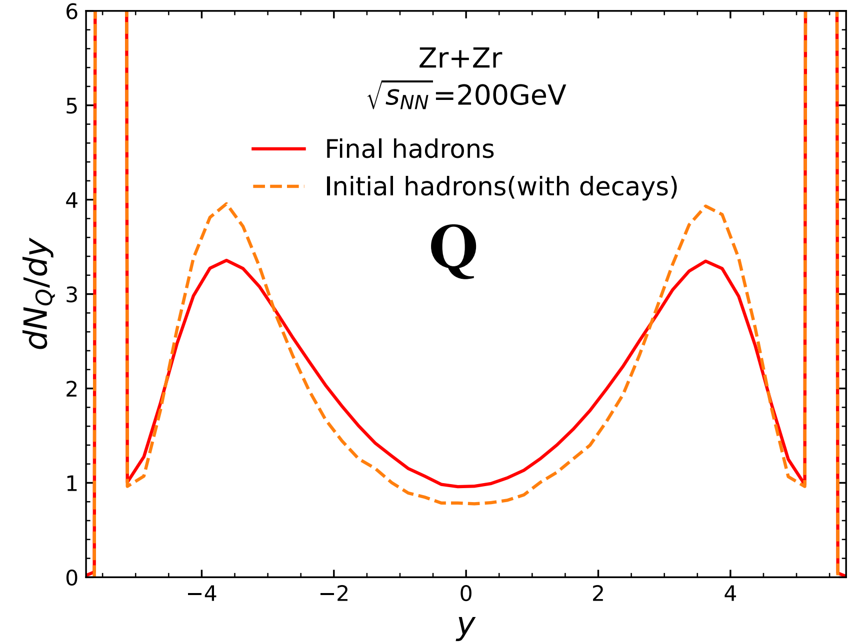
There are still challenges, such as the low $\bar{p}/p$ ratio at/below 200A GeV.

Results from string melting AMPT

Minimum-bias Zr+Zr collisions







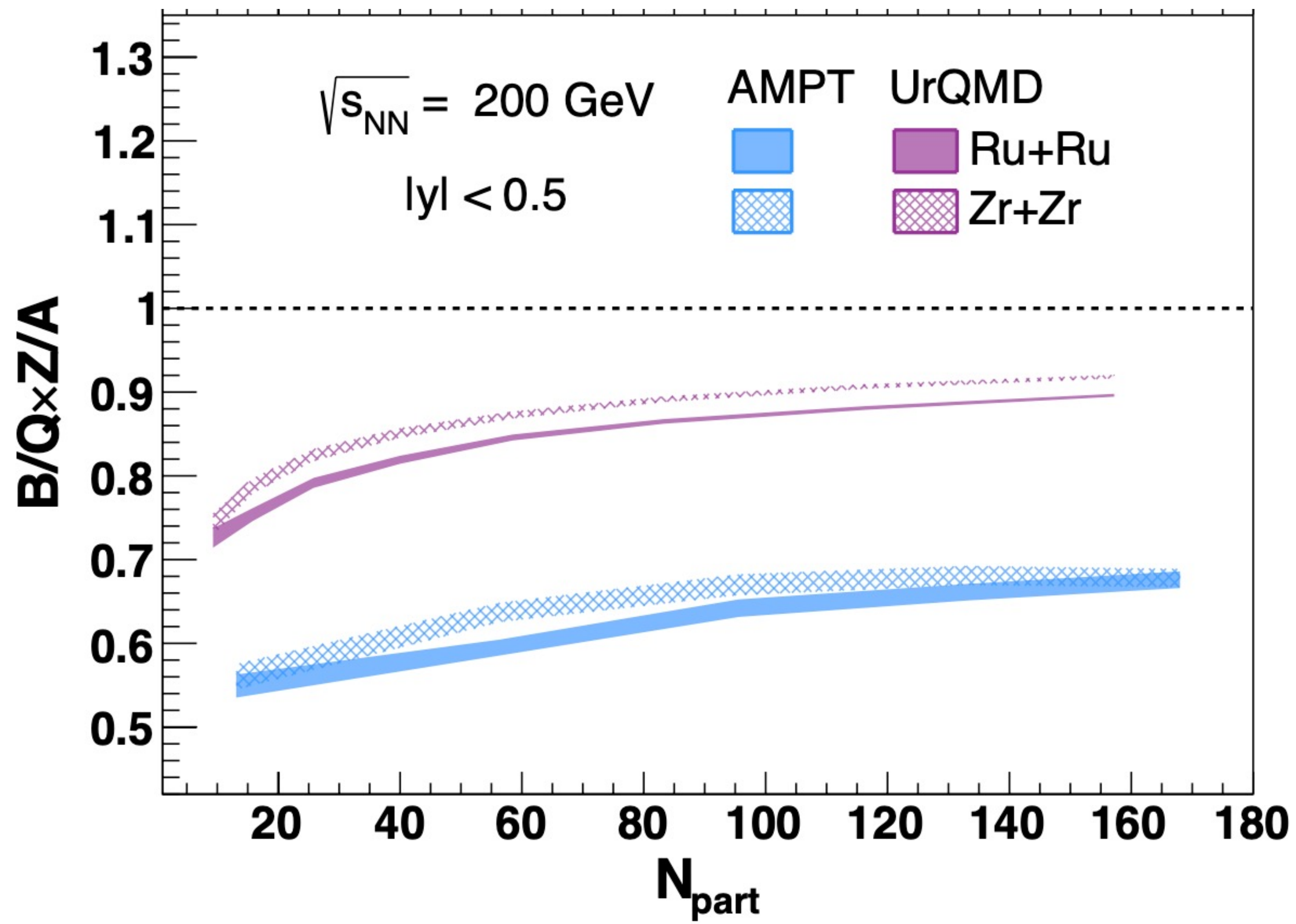
N_B or B: net-baryon number.

N_Q or Q: net-electric charge number.

Ratio **B/Q*Z/A** has been proposed to study baryon stopping.

Z. Xu, RBRC workshop on Physics Opportunities from isobar run (2022)

Ratio at mid-rapidity:
B/Q*Z/A < 1 in both models, for every centrality.



N. Lewis et al., 2205.05685 [hep-ph]

More UrQMD results in
W. Lv et al., 2309.06445 [nucl-th]

Naive expectation for B/Q*Z/A

When we include all particles at all rapidities, conservation laws give B = 2A and Q = 2Z,

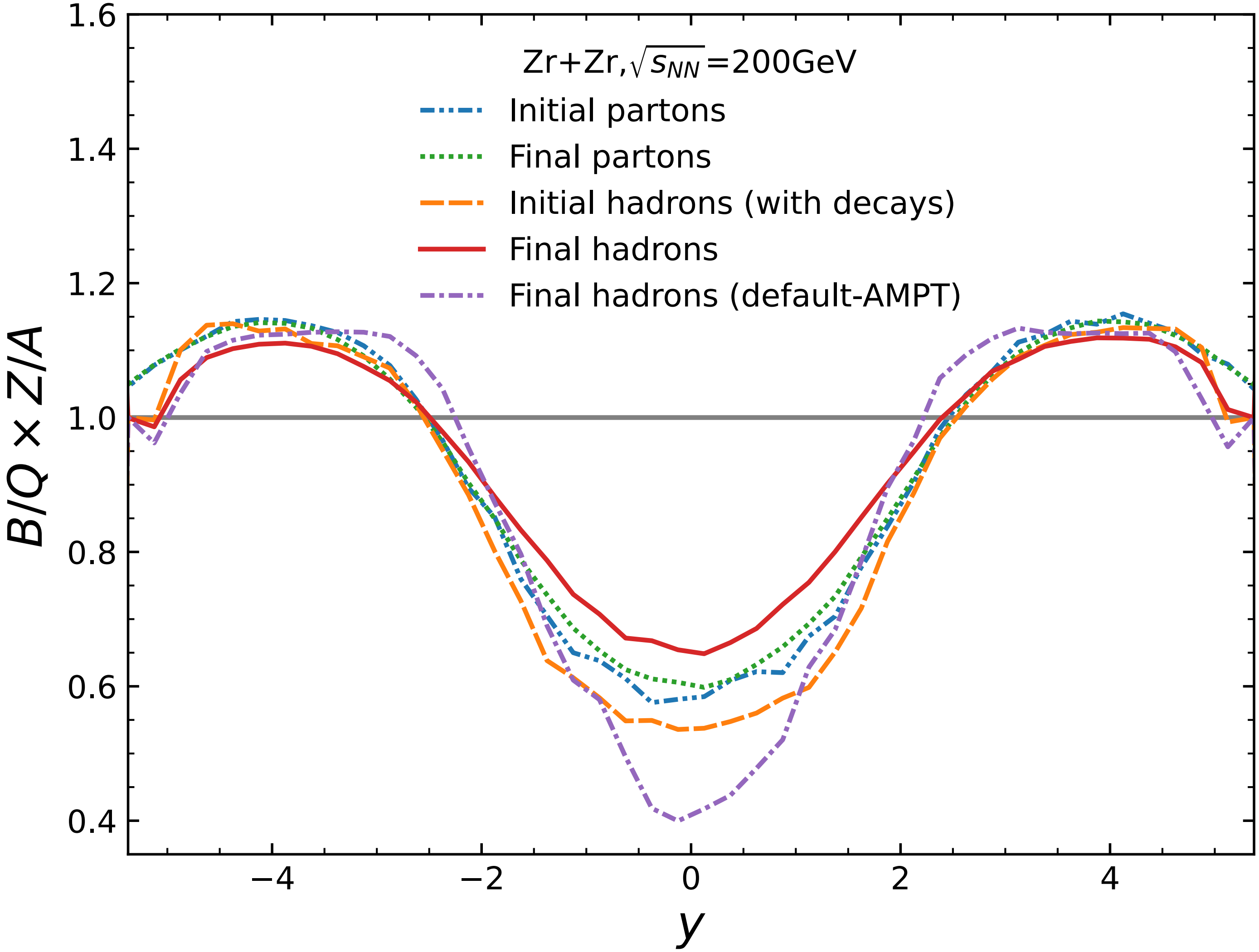
so B/Q*Z/A=1.

This can be called the naive expectation.

It's tempting to expect this to be true at any rapidity *y*, but we already see strong deviations.

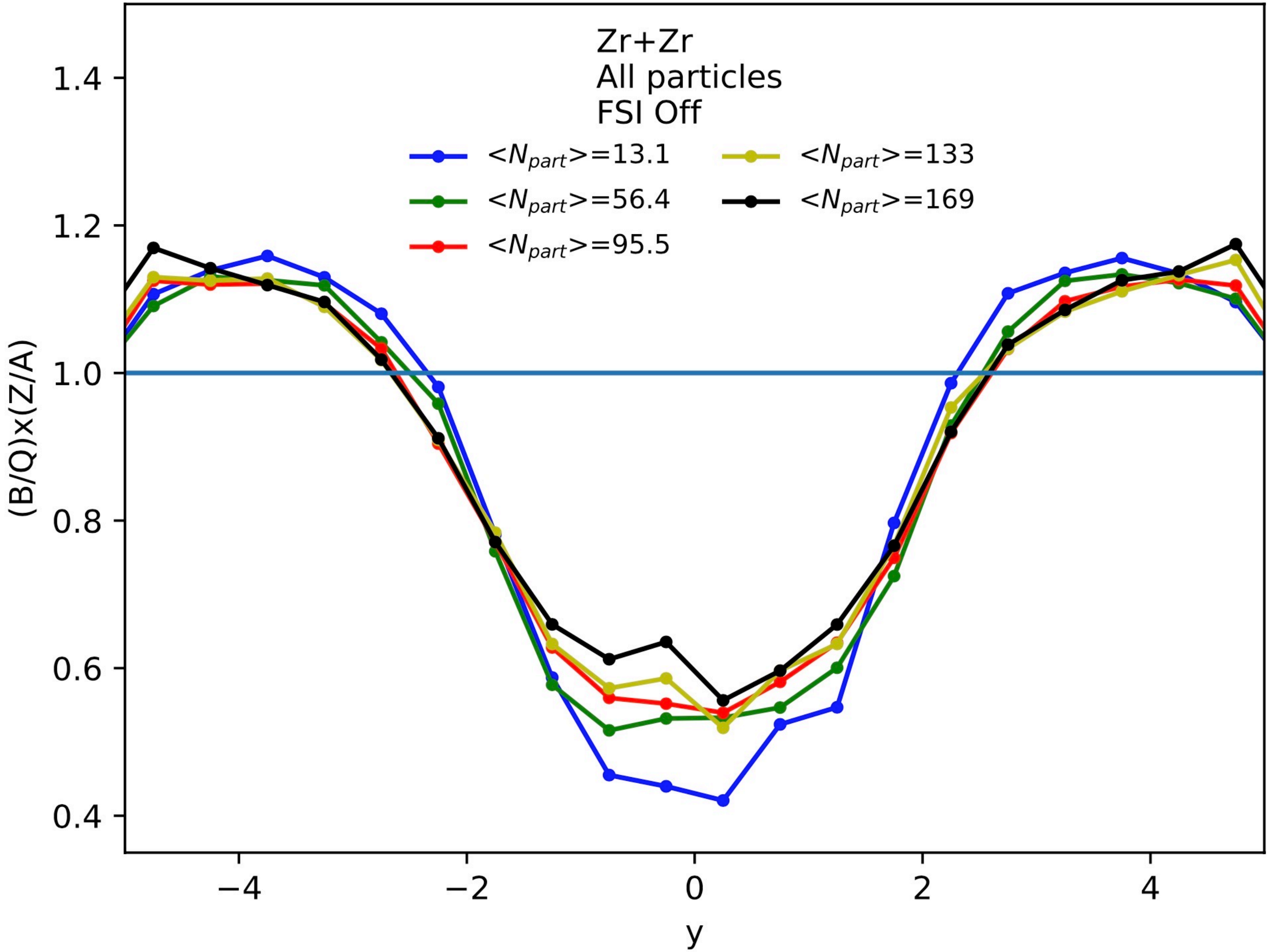
Ratio versus rapidity (for minimum bias events):

- B/Q*Z/A changes strongly with *y*
- Rescatterings and hadronization only modestly change the ratio
- Default AMPT and string melting AMPT are qualitatively similar

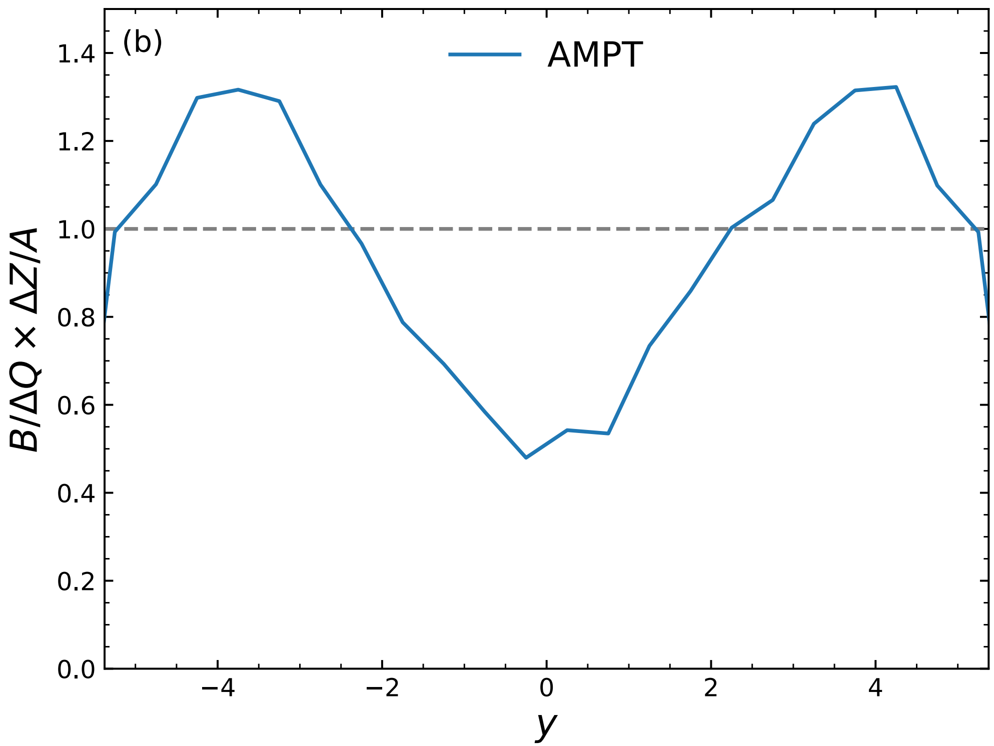


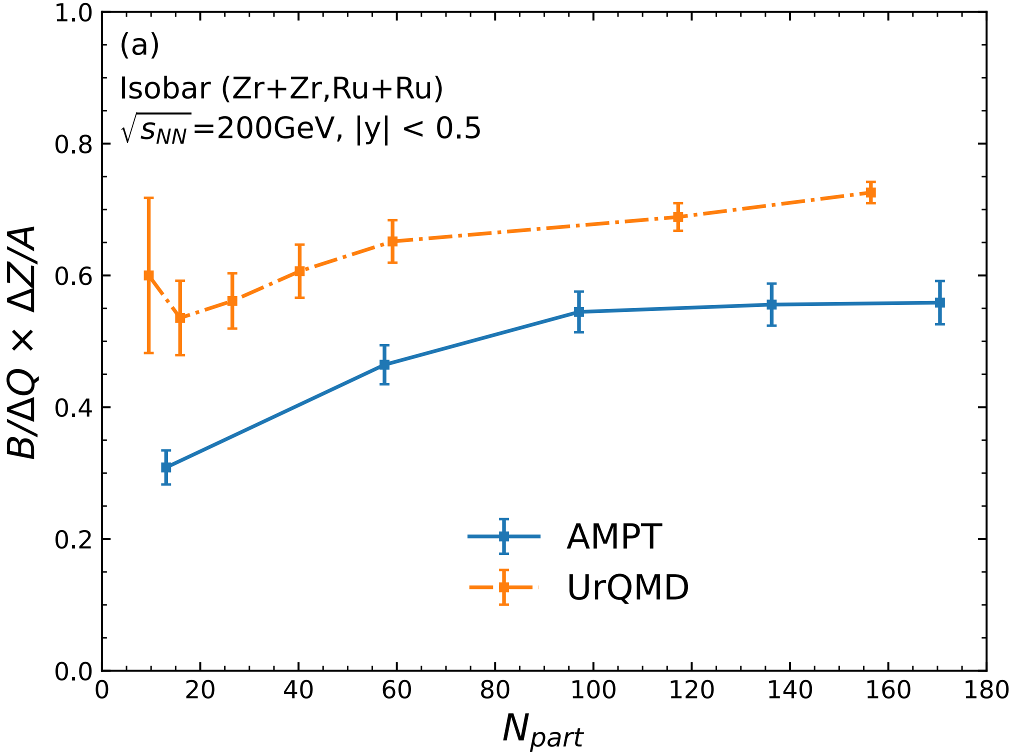
Ratio versus rapidity:

B/Q*Z/A changes only modestly with centrality



For the difference between Zr and Ru isobars:
B/ΔQ*ΔZ/A
is qualitatively similar to B/Q*Z/A





UrQMD results from
N. Lewis et al., 2205.05685 [hep-ph]

Relate B/Q*Z/A to quark stopping

We consider a quark matter under the conventional scenario:
baryon and electric charge are carried by quarks and antiquarks while neglecting the baryon junction.

Let $f_i \equiv f_i(y) \equiv dN/dy$ of quark flavor i, we then have

$$f_B \equiv \frac{dN_B}{dy} = \frac{1}{3}(f_u - f_{\bar{u}} + f_d - f_{\bar{d}} + f_s - f_{\bar{s}}),$$
$$f_Q \equiv \frac{dN_Q}{dy} = \frac{1}{3}(2f_u - 2f_{\bar{u}} - f_d + f_{\bar{d}} - f_s + f_{\bar{s}}).$$

Let's separate the dN/dy shape from the magnitude by writing

$$N_i = \int f_i(y)dy, \text{ and } s_i(y) \equiv f_i(y)/N_i,$$

$s_i(y)$ is the normalized dN/dy
& represents the stopping of quark flavor i

Consider "central" collisions, conservation laws give

$$\rightarrow \qquad N_u = 2A + 2Z + N_{\bar{u}}, \quad N_d = 4A - 2Z + N_{\bar{d}}.$$

Due to isospin symmetry of the strong interaction (& ignore neutron skin), we assume that the relative stopping of *u* is the same as *d* :

$$s_u(y) = s_d(y) \equiv s_q, \text{ similarly } s_{\bar{u}}(y) = s_{\bar{d}}(y) \equiv s_{\bar{q}}.$$

Then we have

$$\begin{aligned} 3f_B &= 6As_q + (N_{\bar{u}} + N_{\bar{d}})(s_q - s_{\bar{q}}) + N_s(s_s - s_{\bar{s}}), \\ 3f_Q &= 6Zs_q + (2N_{\bar{u}} - N_{\bar{d}})(s_q - s_{\bar{q}}) - N_s(s_s - s_{\bar{s}}). \end{aligned}$$

Note: N_u can still be different from N_d.

We consider two simple limits below.

A)
If we can neglect sea-quarks and strange quarks (e.g., at very low energies):

$$3f_B = 6As_q + (N_{\bar{u}} + N_{\bar{d}})(s_q - s_{\bar{q}}) + N_s(s_s - s_{\bar{s}}),$$

$$3f_Q = 6Zs_q + (2N_{\bar{u}} - N_{\bar{d}})(s_q - s_{\bar{q}}) - N_s(s_s - s_{\bar{s}}).$$

we get the naive expectation (at any y):

$$\frac{f_B}{f_Q}\frac{Z}{A} \equiv B/Q \times Z/A = 1$$

B)

For heavy ion collisions with A=2Z (like isobar ^{96}Cd+Cd), isospin symmetry gives $N_{\bar{u}} = N_{\bar{d}} \equiv N_{\bar{q}}$,

so we have

$$3f_B = 12Zs_q + 2N_{\bar{q}}(s_q - s_{\bar{q}}) + \underline{N_s(s_s - s_{\bar{s}})},$$

$$3f_Q = 6Zs_q + N_{\bar{q}}(s_q - s_{\bar{q}}) - \underline{N_s(s_s - s_{\bar{s}})}.$$

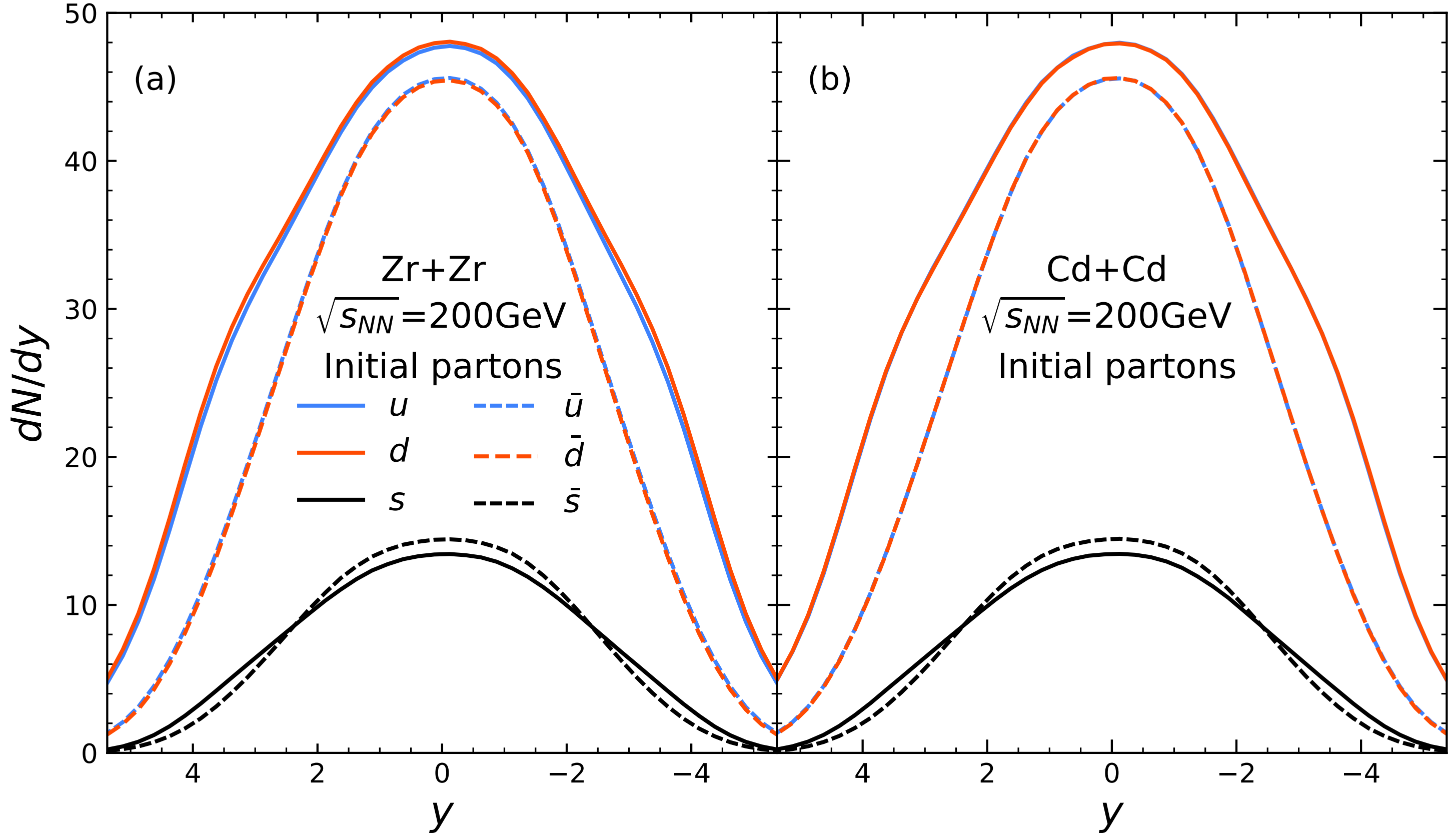
- Without the strangeness terms, we have (at any *y*)

$$f_B/f_Q = 2, \text{ or } B/Q \times Z/A = 1$$

- $B/Q*Z/A \neq 1$ (for isospin symmetric nucleus)
  is due to (anti)strange quarks
  and it means $s_s \neq s_{\bar{s}}$

Note: same conclusion for non-central events (when ignoring neutron skin)

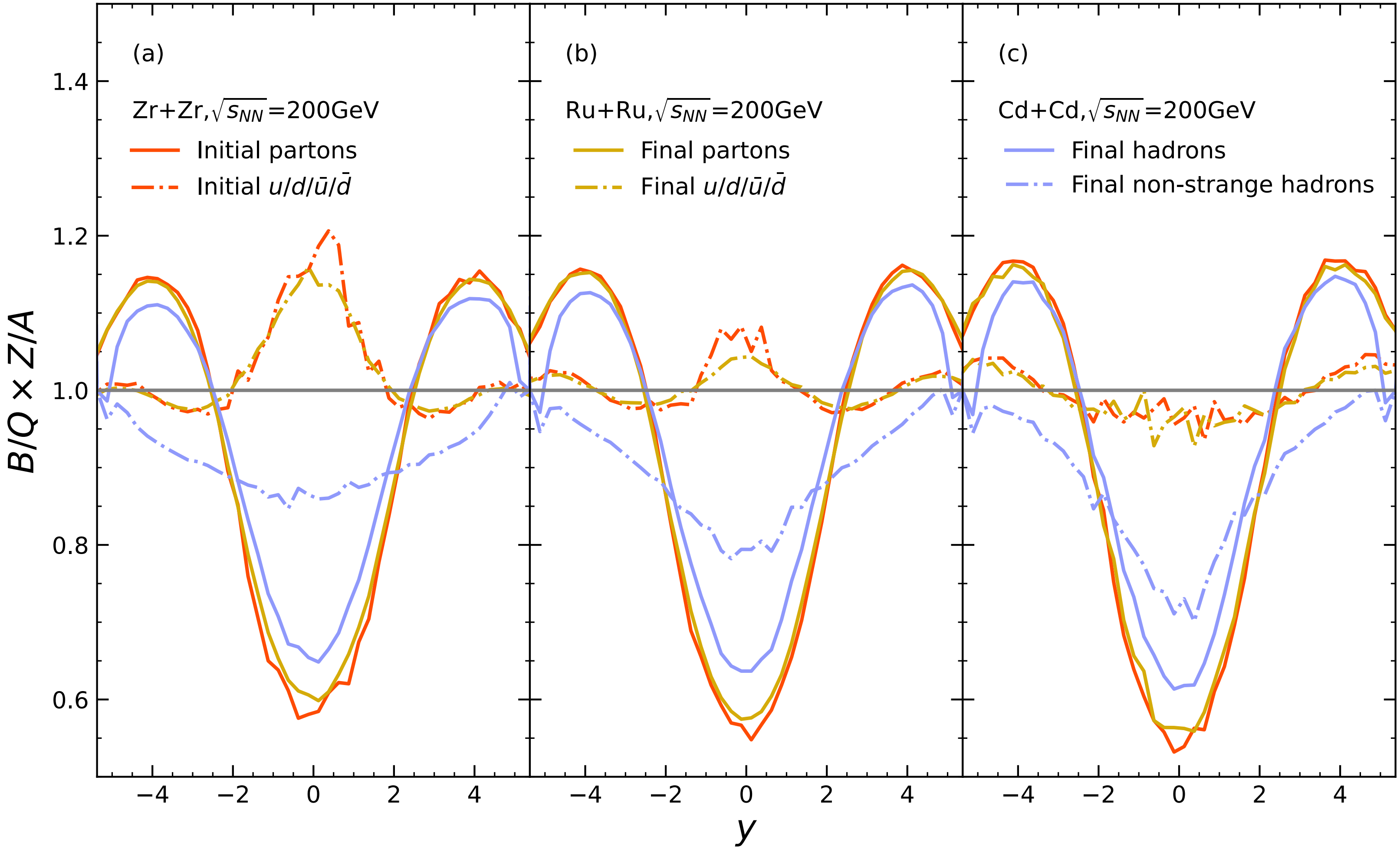
Quark results from string melting AMPT for minimum-bias ^{96}Zr+Zr & ^{96}Cd+Cd



- We see $s_u = s_d$, $s_{\bar{u}} = s_{\bar{d}}$ (previous assumptions)

- $s_s \neq s_{\bar{s}}$ even for isospin symmetric ^{96}Cd+Cd
- More $\bar{s}$ than s at mid-rapidity
  ⇢ this decreases B, increases Q & causes B/Q*Z/A < 1

Results from string melting AMPT
for MB ^{96}Zr+Zr ^{96}Ru+Ru ^{96}Cd+Cd



When excluding $\bar{s}$ and s quarks

- ^{96}Cd+Cd gives parton B/Q*Z/A ≈ 1.0 (as expected)
- Parton B/Q*Z/A is closer to 1.0 for Ru+Ru than Zr+Zr (as expected)

⇢ B/Q*Z/A ≠ 1 is mainly due to $s_s \neq s_{\bar{s}}$

On reconstruction of net charges

Using AMPT results, we check the experimental reconstruction method by comparing "Reconstructed" charge with the direct model result.

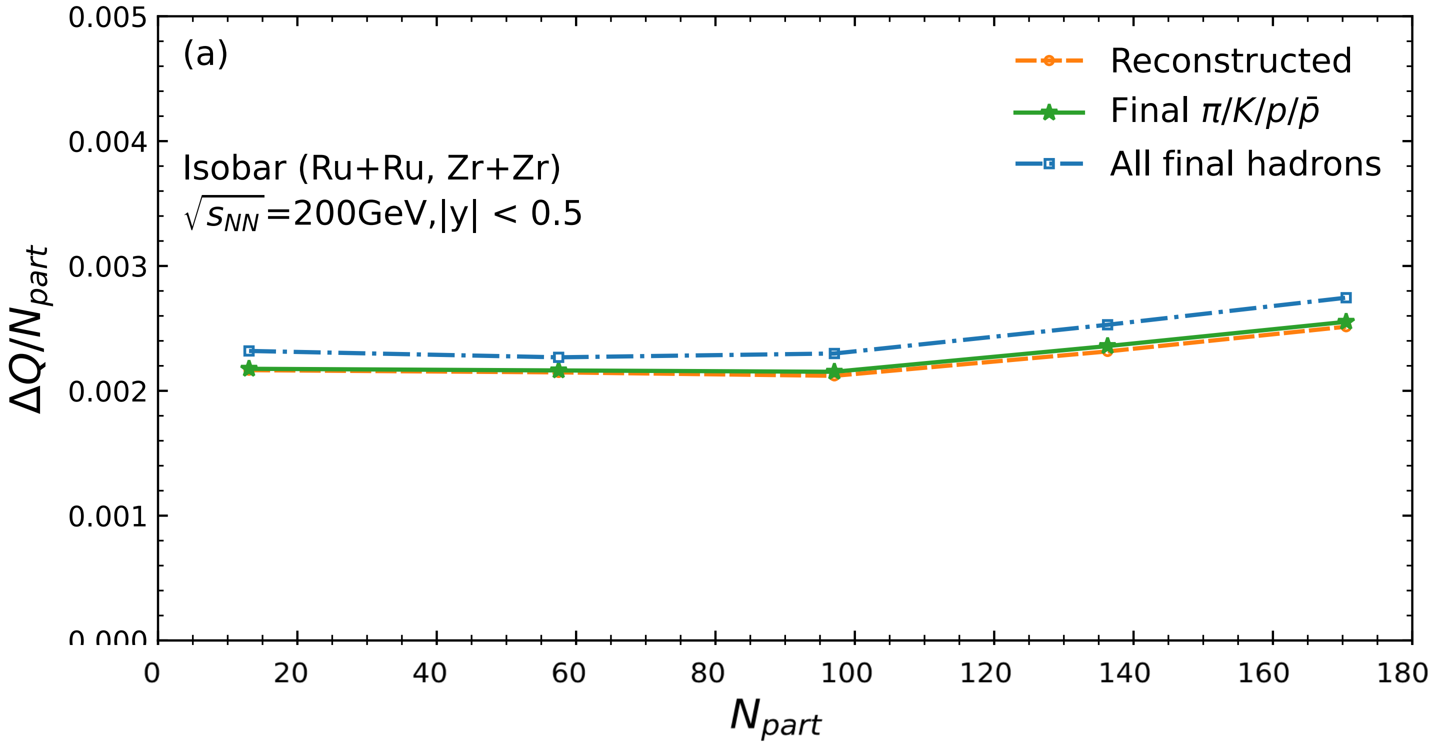
Net-electric charge reconstruction:

CY Tsang (for STAR) at GHP 2023 & Quark Matter 2023

$$\Delta Q = N_\pi[(R2_\pi - 1) + \frac{N_K}{N_\pi}(R2_K - 1) + \frac{N_p}{N_\pi}(R2_p - 1)].$$

$$R2_\pi = (N^{\mathrm{Ru}}_{\pi^+}/N^{\mathrm{Ru}}_{\pi^-})/(N^{\mathrm{Zr}}_{\pi^+}/N^{\mathrm{Zr}}_{\pi^-})$$

⇢ Reconstructed ΔQ is accurate (from π/K/p/p̄)



Net-baryon reconstruction:

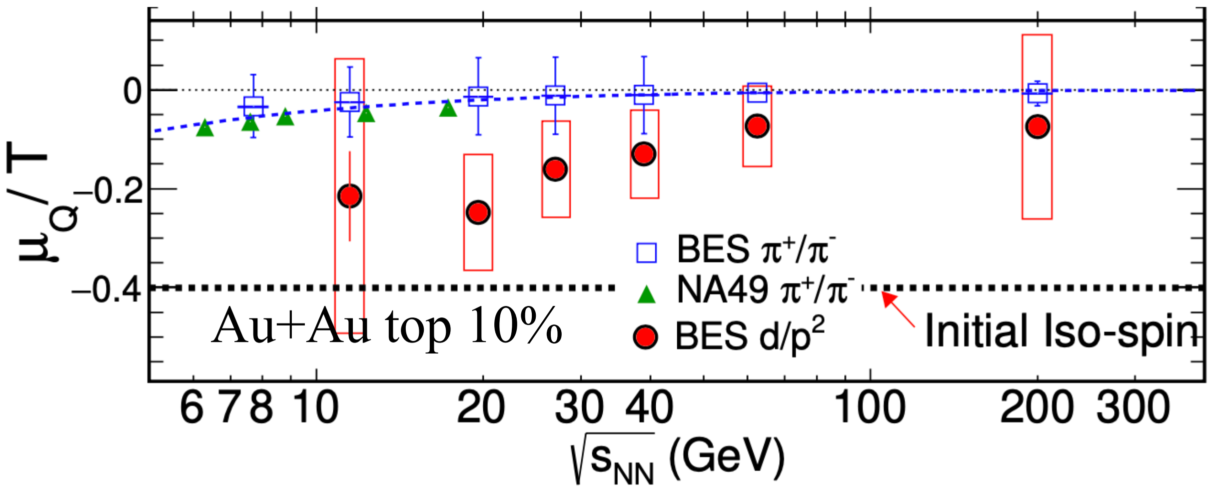
$$B_{net} = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}})$$
$$\approx (N_p - N_{\bar{p}}) + \bar{p}\sqrt{\frac{d}{\bar{d}}} - p\sqrt{\frac{\bar{d}}{d}}$$

CY Tsang (for STAR) at GHP 2023 & Quark Matter 2023

This is based on the thermal model:

$$\frac{\mu_Q}{T} = \frac{1}{2}\ln\left(\frac{\pi^+}{\pi^-}\right),$$
$$\frac{\mu_Q}{T} = \frac{1}{2}\ln\left(\frac{\bar{d}/\bar{p}^2}{d/p^2}\right).$$

STAR Collaboration, Phys Rev C 99, 064905 (2019)



However, " The μ_Q/T values extracted from π+/π− are systematically larger than those from $(\bar{d}/\bar{p}^2)/(d/p^2)$ at small $\sqrt{s_{NN}}$ "

⇢ Using $d\&\bar{d}$ data reconstructs more net-neutrons than using π+&π− data due to the uncertainty of μ_Q/T values

Summary

A Multi-Phase Transport (AMPT) model
enables us to study baryon production at both parton and hadron phases

Model results for isobars show
B/Q*Z/A   is strongly y-dependent & < 1 at mid-rapidity

Simple analysis shows
s-stopping $\neq$ $\bar{s}$-stopping
  is the main reason why parton $B/Q*Z/A \neq 1$,
  is the only reason for isospin symmetric A+A collisions

Reconstruction of the net-baryon number suffers from
the uncertainty of μ_Q/T values extracted from different observables

Thanks for your attention!