Hadrons from a Multi-Phase Transport Model

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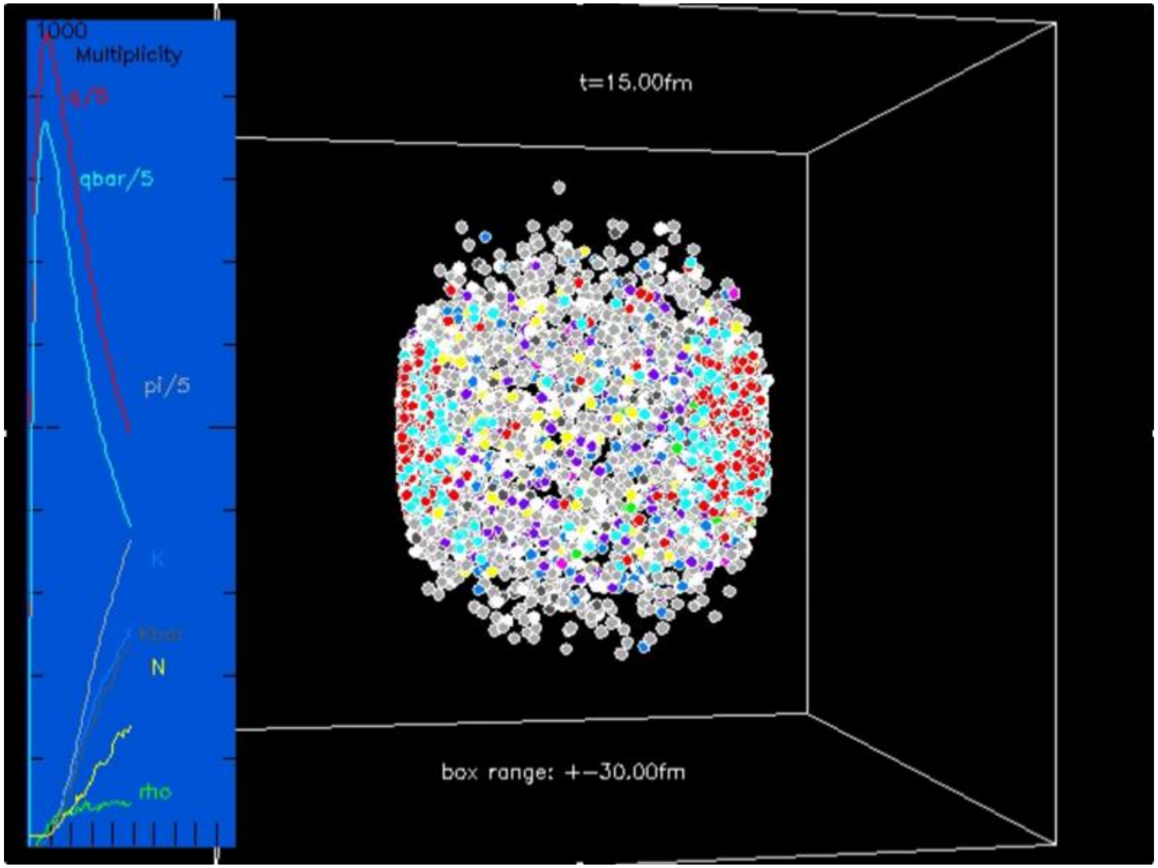


The Hadronic Interaction Workshop at CUHK, Hong Kong, 3/2025

Outline

1) A Multi-phase Transport (AMPT) Model

2) A baryon stopping puzzle

3) Some results of p+O collisions from AMPT

4) Summary

1) A Multi-phase Transport (AMPT) Model

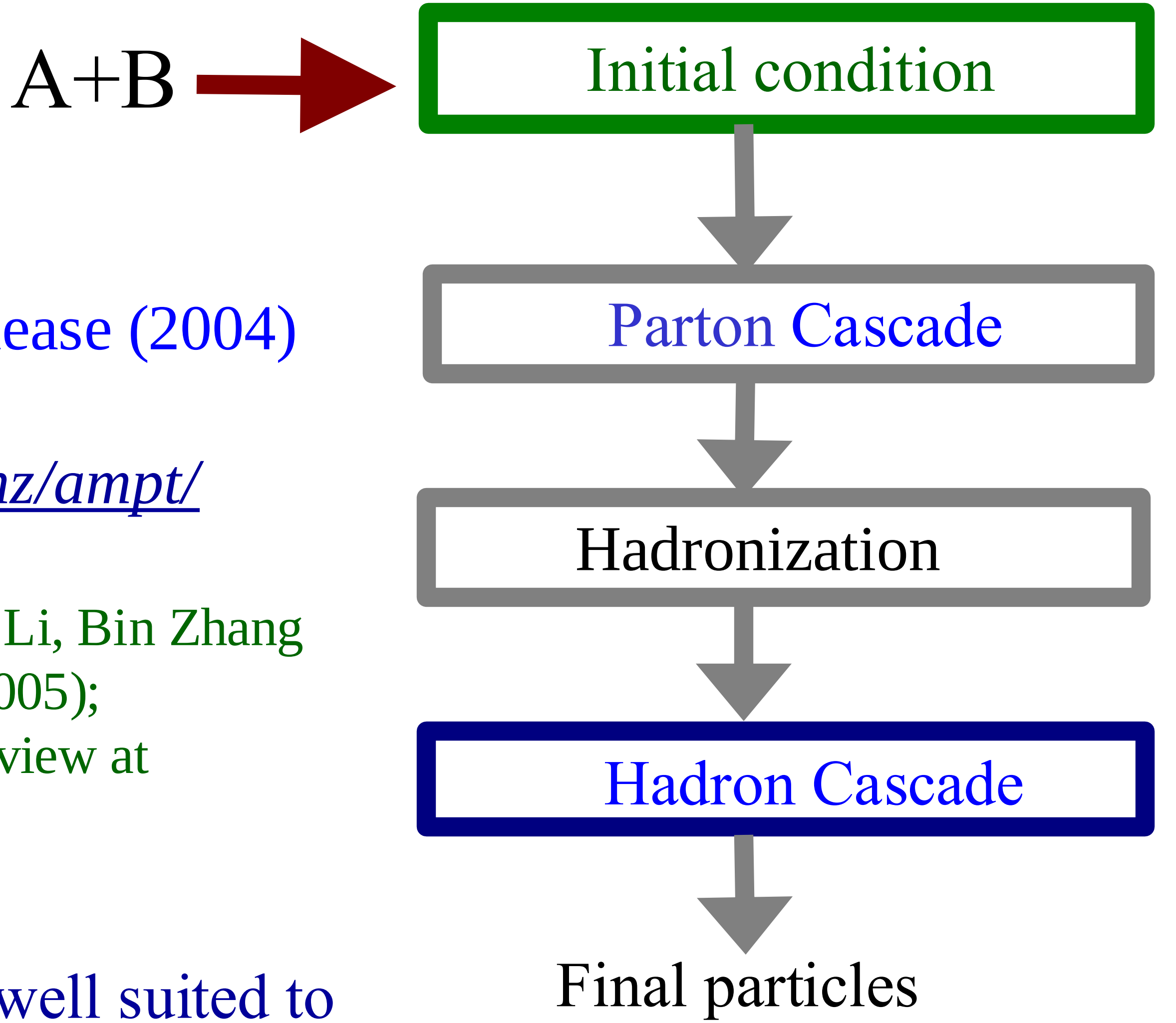
Transport models based on the Boltzmann equation have been developed to study and simulate high energy nuclear collisions.

They include

ART, HSD, UrQMD, SMASH (hadron transport)
ZPC, MPC (elastic parton transport)
AMPT (elastic parton transport + hadron transport)
PACIAE (2-body parton transport + hadron transport)
BAMPS (2-body plus 2 $\leftrightarrow$ 3 parton transport)
PHSD (off-shell parton transport + hadron transport)
...

There are also event generators without final state rescatterings:
PYTHIA, HIJING, ...

A multi-phase transport (AMPT) model
aims to provide a kinetic description of all essential stages of relativistic heavy ion collisions:

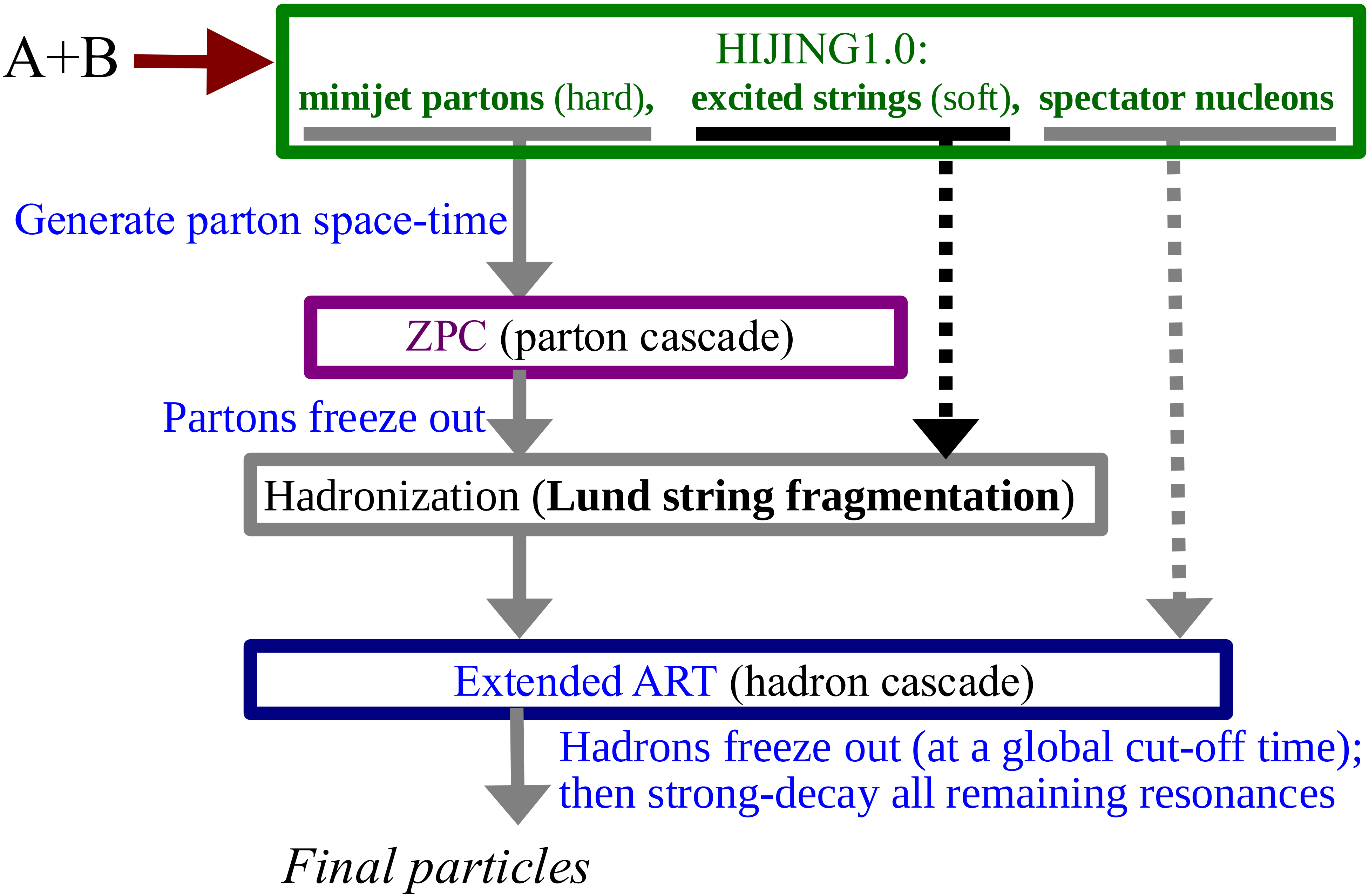


Source codes since 1st release (2004) are available at
https://myweb.ecu.edu/linz/ampt/

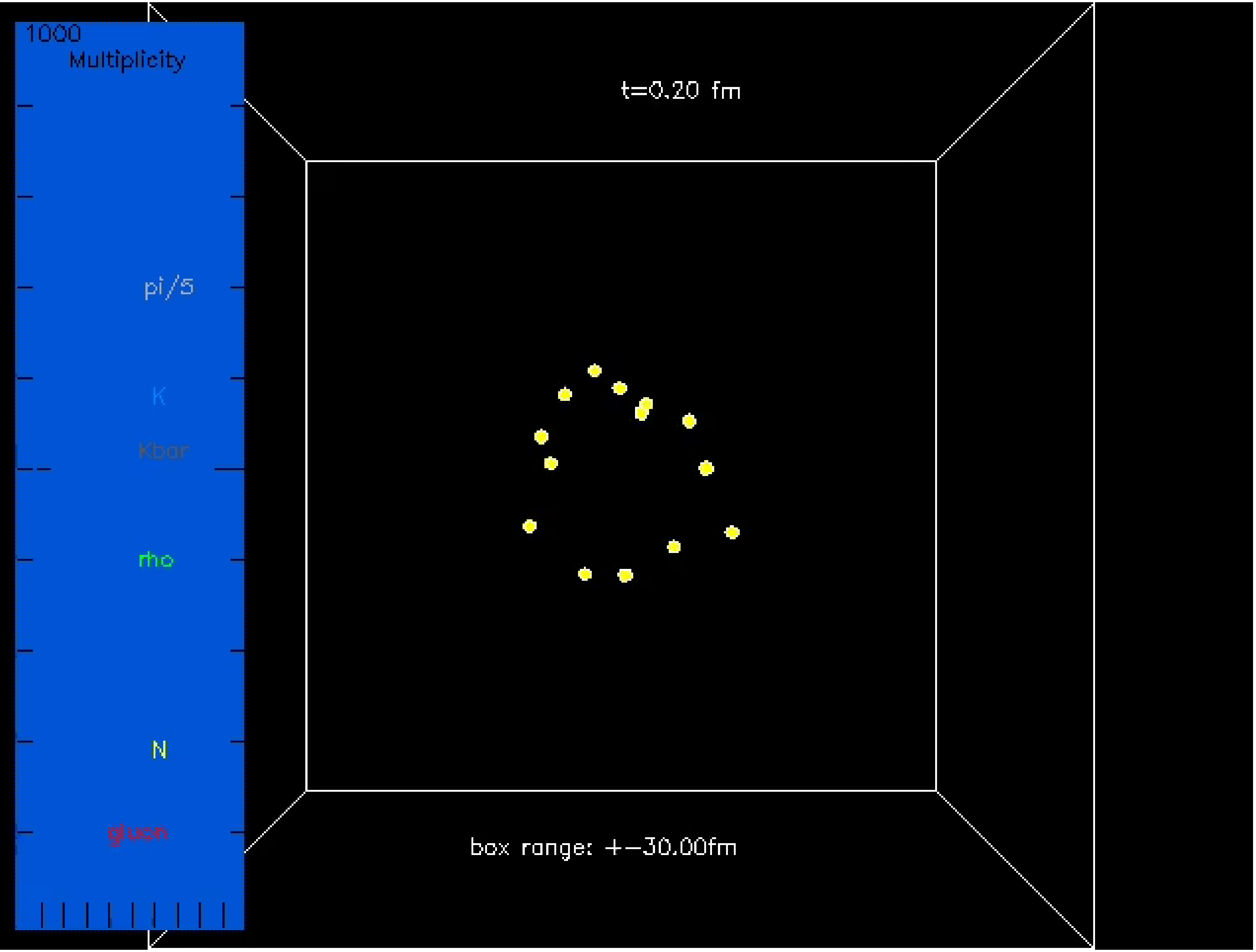
ZWL, Che-Ming Ko, Bao-An Li, Bin Zhang & Subrata Pal, Phys Rev C (2005);
ZWL & Liang Zheng, mini-review at Nucl Sci Tech (2021)

As a result, the model is well suited to describe non-equilibrium dynamics

Structure of AMPT v1.xx (AMPT-default)



A central Au+Au event at $\sqrt{s_{NN}} = 200$ GeV from AMPT-default



60fm-long box; shows only formed particles.

⊙

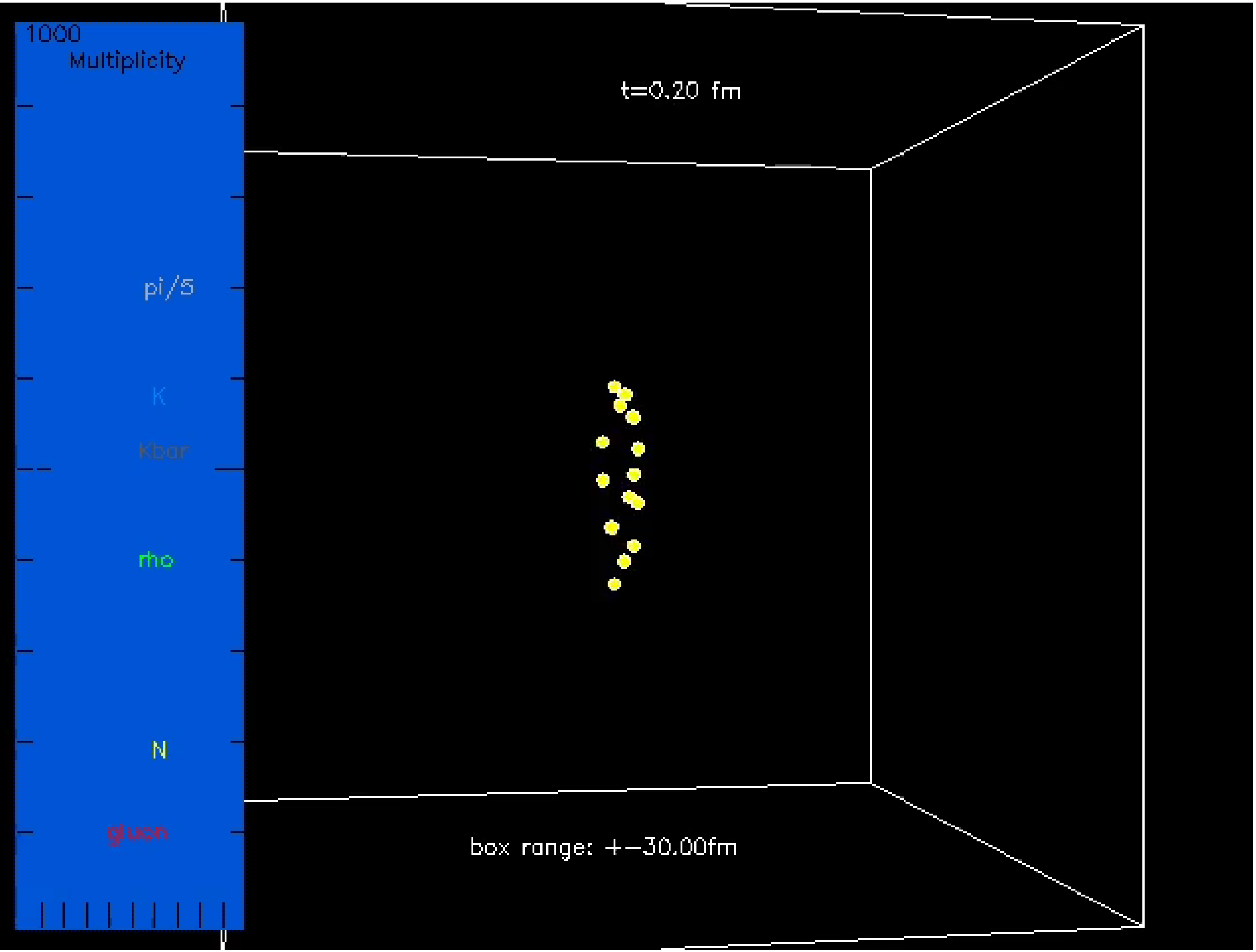
Beam axis

1st frame:
right after the primary collision, only spectator nucleons are formed.

At middle right:
a rho decays at 7.0 fm/c.

At lower right:
*a K*bar is produced at 16.6 fm/c & vanishes at 20.8fm/c.*

The same Au+Au event from AMPT-default



Side view:

↔ Beam axes

Dynamics is time-dilated at large rapidities: for example, see hadronization of gluons

String Melting version of AMPT

If we use the Bjorken formula to estimate
the initial energy density in heavy ion collisions:

$$\epsilon_0 \sim \frac{dE_T/dy}{\pi R^2 \tau_0} \approx \frac{dE_T/dy}{150\, fm^3}$$

~ 2.5 SPS, 6 RHIC, 20 LHC GeV/fm^3

R: Nuclear radius

τ_0: Proper formation time, taken as *1 fm/c*

>>critical energy density
for QCD phase transition:
$\varepsilon_c \sim O(1/2)$ GeV/fm^3

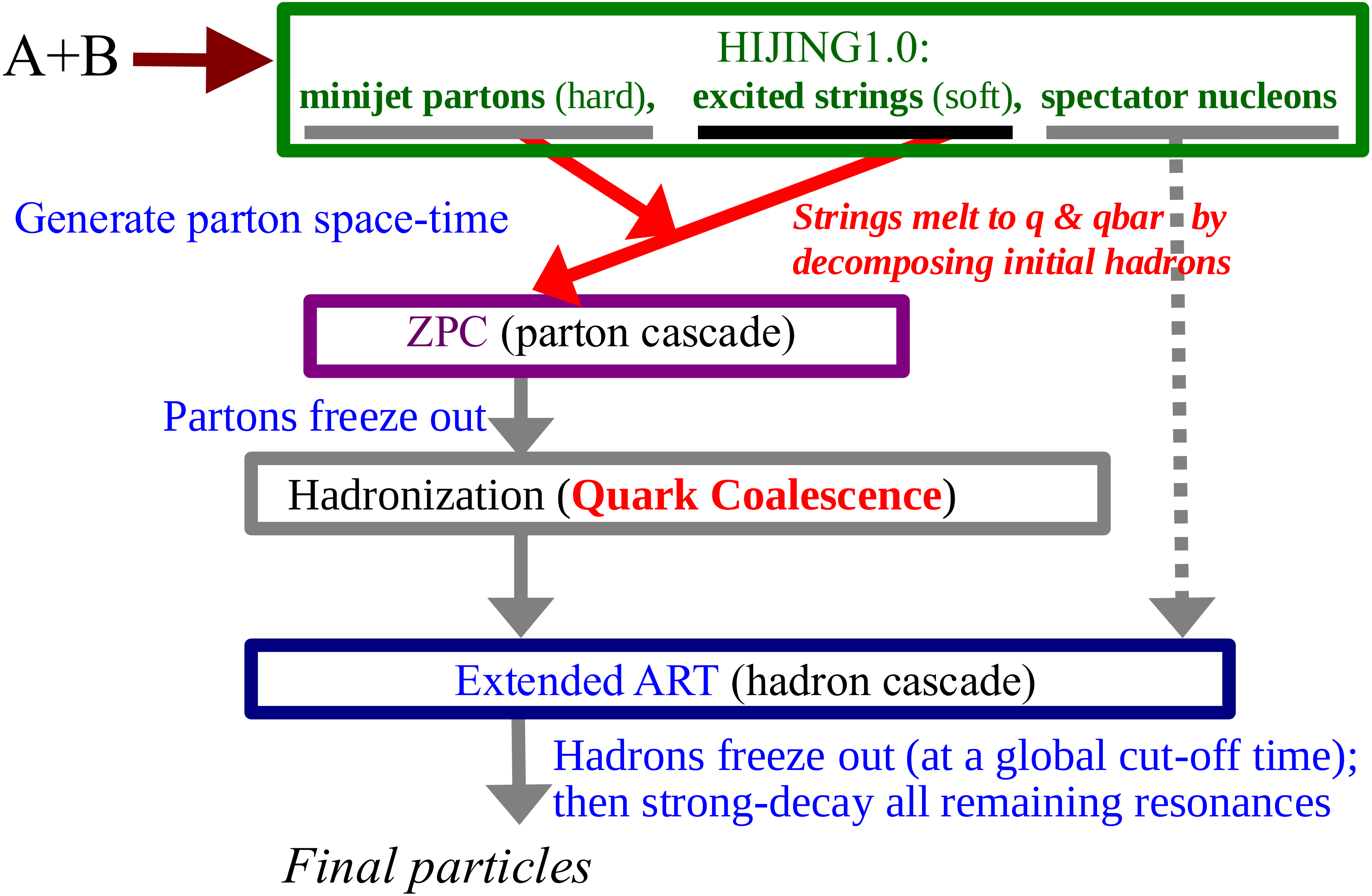
➔ At high-enough energies,

hadronic matter such as strings cannot exist at early times,

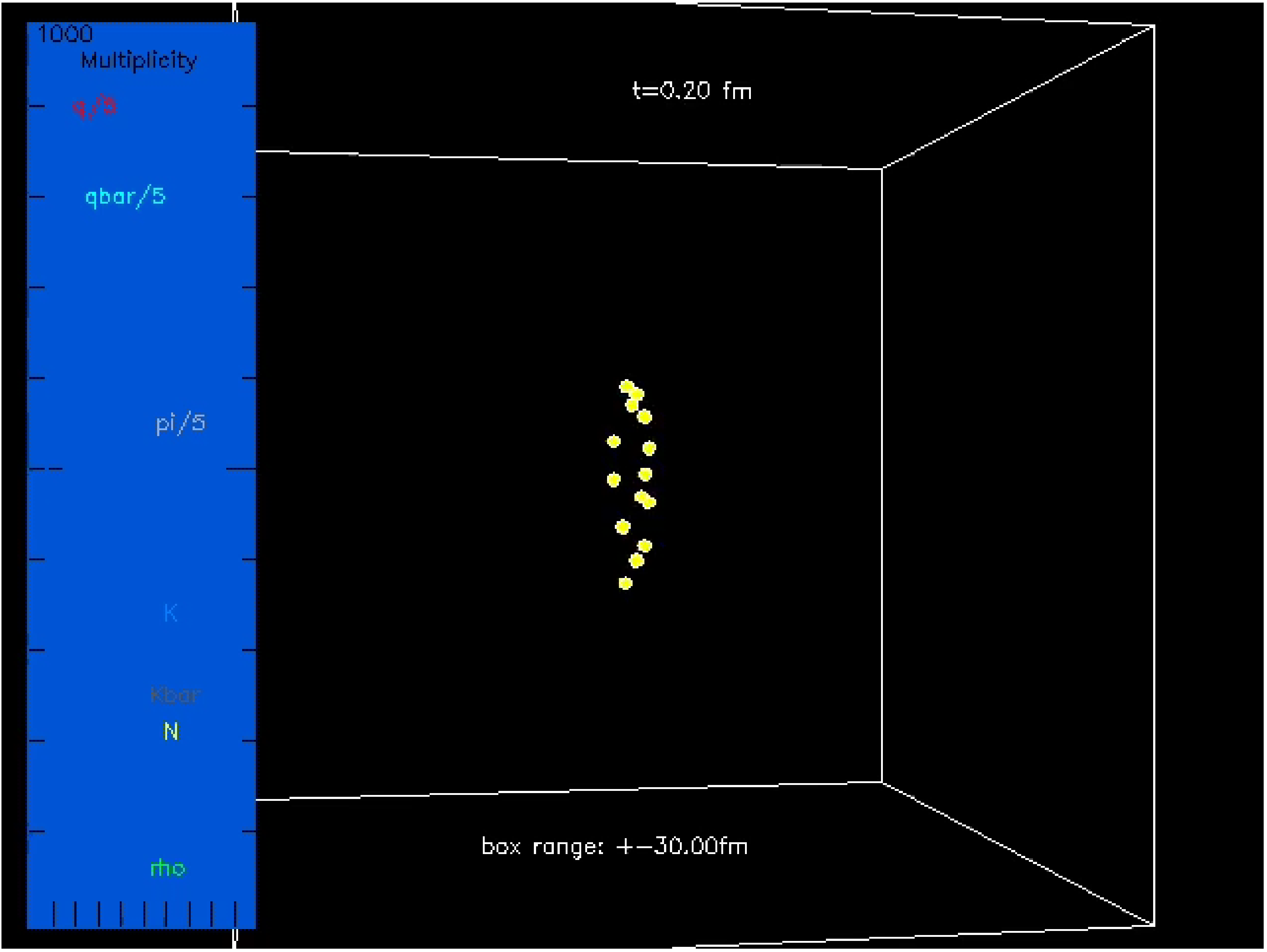
they should be represented by a dense partonic matter

➔ the string melting version of AMPT ZWL & Ko, PRC (2002)

Structure of AMPT v2.xx (AMPT-String Melting)



The same Au+Au event from AMPT-String Melting



Side view:

Beam axes

Middle region (near mid-rapidity):
coalescence of
q (red) and
qbar (cyan)
occurs earlier

Components of AMPT

HIJING1.0 — Two component model (*soft strings* + *hard minijets*)

ZPC — parton cascade (*elastic collisions only*)

Hadronization — Lund string fragmentation (*AMPT- default*)
or
Quark coalescence (*AMPT-String Melting*)

Extended ART — Hadron cascade,
including secondary interactions for
$p\ r\ w\ h\ K\ K^{*}\ f$

$n\ p\ \mathrm{D}\ N^{*}(1440)\ N^{*}(1535)\ \mathrm{L}\ \mathrm{S}\ \mathrm{X}\ \mathrm{W}$ *deuteron*

All other particles with PYTHIA flavor codes have no secondary interactions,
but they will be produced (*from HIJING or quark coalescence*),
e.g. $D\ D_s\ J/\mathrm{Y}\ \ B\ \Upsilon$.

Each hadron has an explicit isospin/charge.

Selected earlier results: particle yields

AMPT-default for p+p or p+pbar collisions:

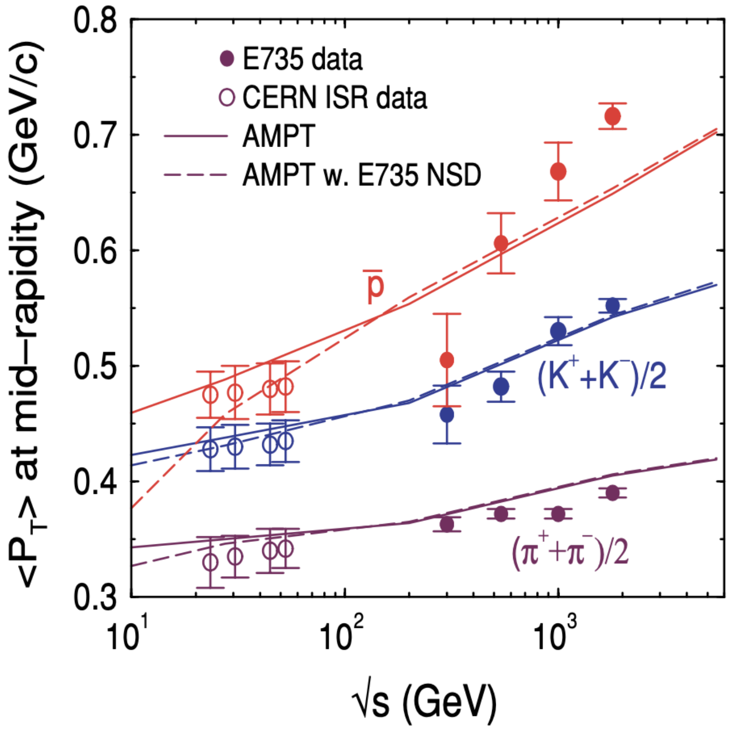
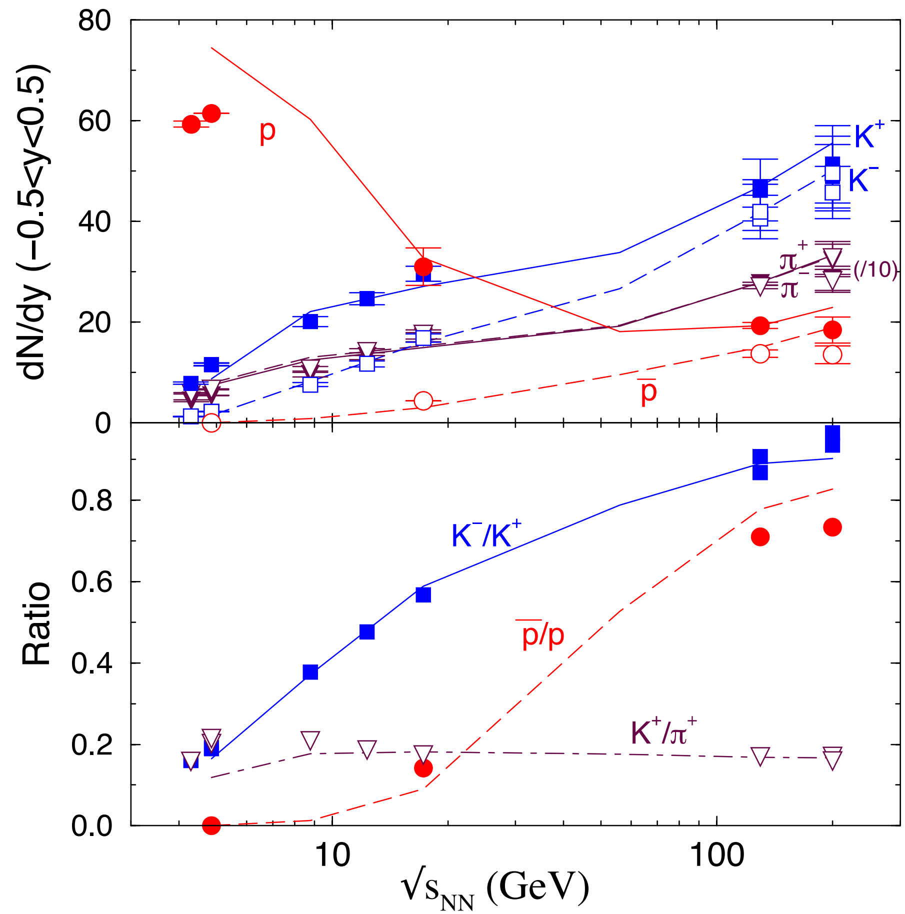


FIG. 15. (Color online) Energy dependence of the mean transverse momenta of pions, kaons, and antiprotons for *pp* and $p\bar{p}$ collisions.

AMPT-default for central Au+Au or Pb+Pb collisions:



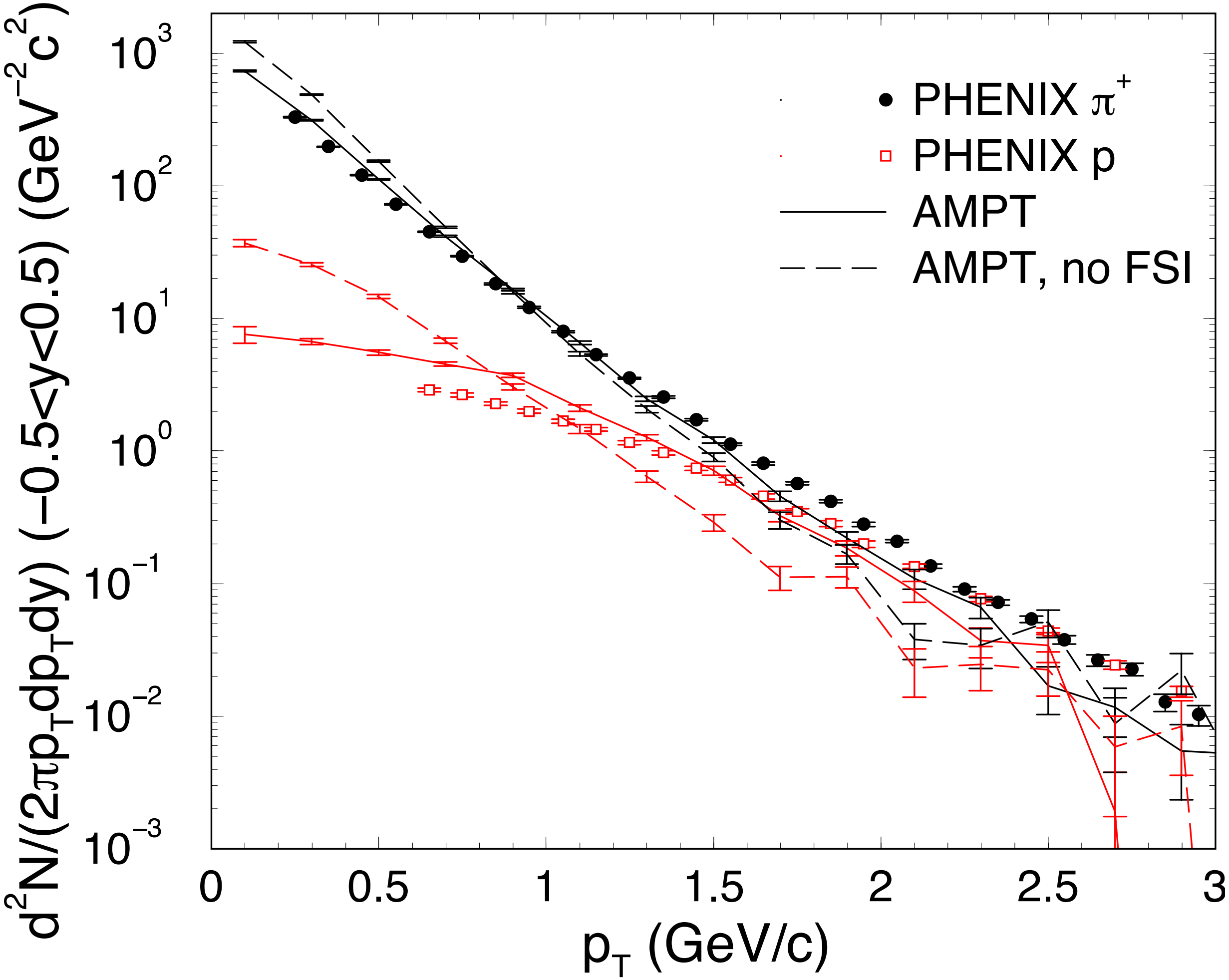
ZWL et al. PRC 72 (2005)

Selected earlier results: p_T spectra

AMPT-default for central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV:

FSI
=Final State Interactions:

lead to
more transverse flow
and a harder p_T spectrum



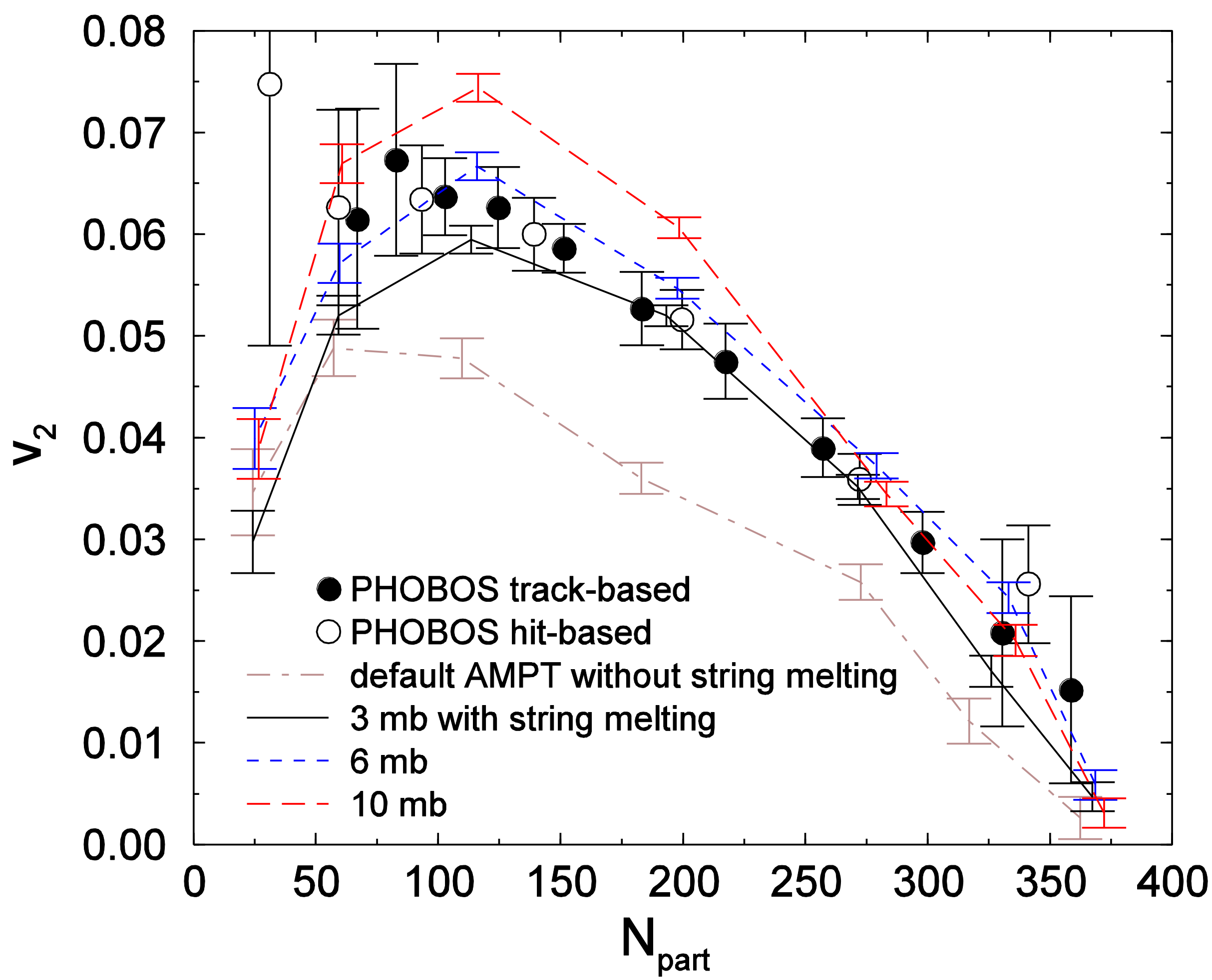
ZWL et al. PRC 72 (2005)

Selected earlier results: v_2

Anistropic distributions in the transverse plane:

elliptic flow v_2
in Au+Au collisions
at $\sqrt{s_{NN}} = 200$ GeV

AMPT-String Melting:
partonic interactions are essential for reproducing the v_2 data



ZWL & Ko, PRC 65 (2002);
ZWL et al. PRC 72 (2005)

Improvement with modern PDFs of nuclei

Use modern nuclear parton distribution functions (nPDFs) to improve heavy flavor & high p_T observables:

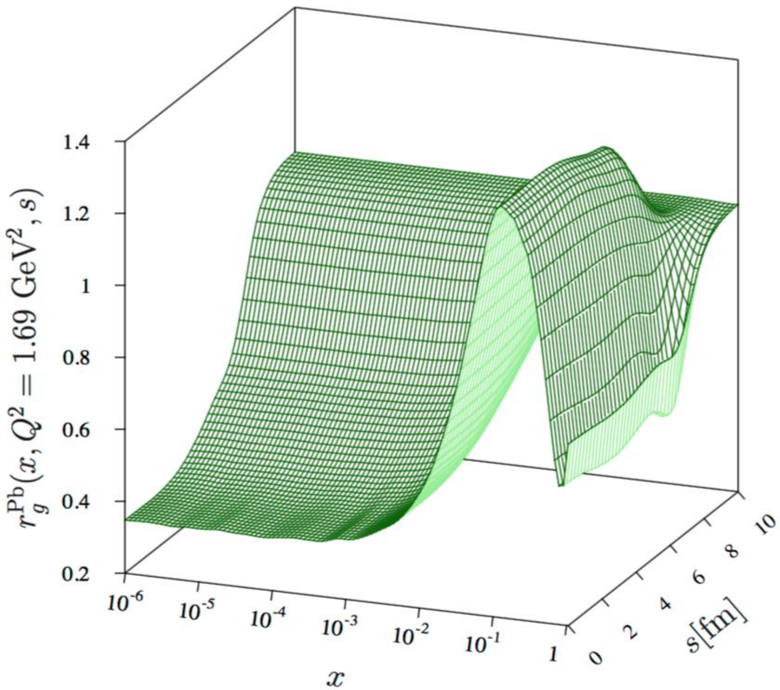
C. Zhang et al., PRC 99 (2019)

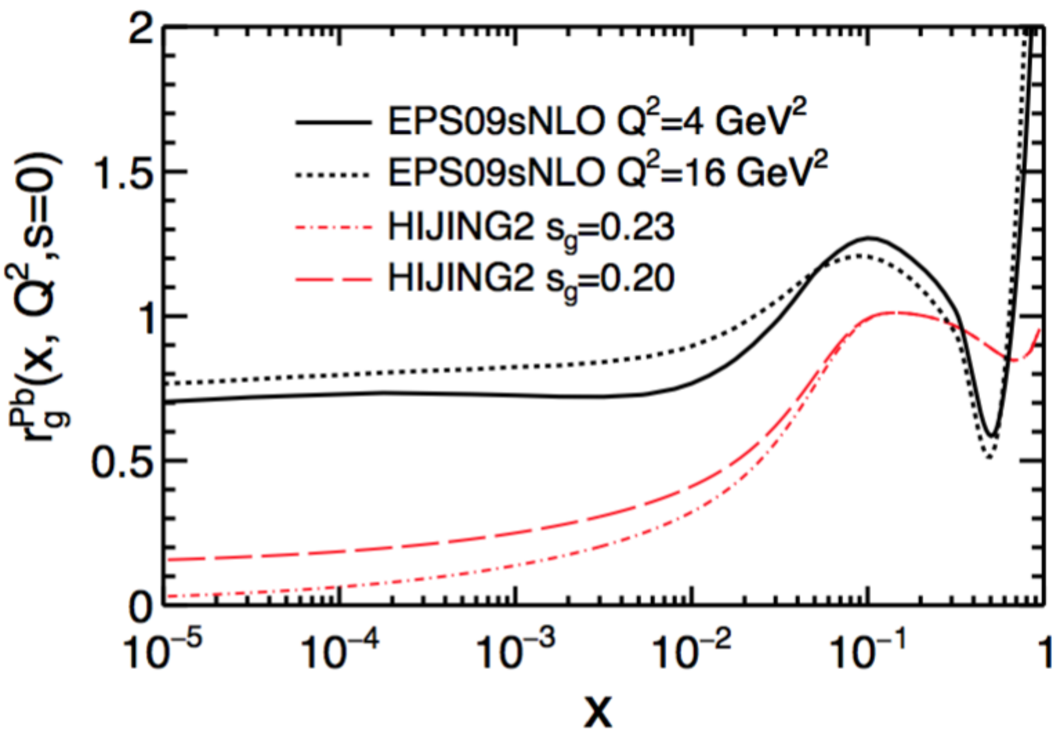
$$\frac{d\sigma^{Q\bar{Q}}}{dp_T^2 dy_1 dy_2} = K \sum_{a,b} x_1 f_a(x_1,\mu_F^2) x_2 f_b(x_2,\mu_F^2) \frac{d\sigma^{ab\to Q\bar{Q}}}{d\hat{t}}$$

Here we use
CTEQ6.1M PDFs for free nucleon;
EPS09s: spatial-dependent nuclear shadowing, has Q^2 evolution.

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

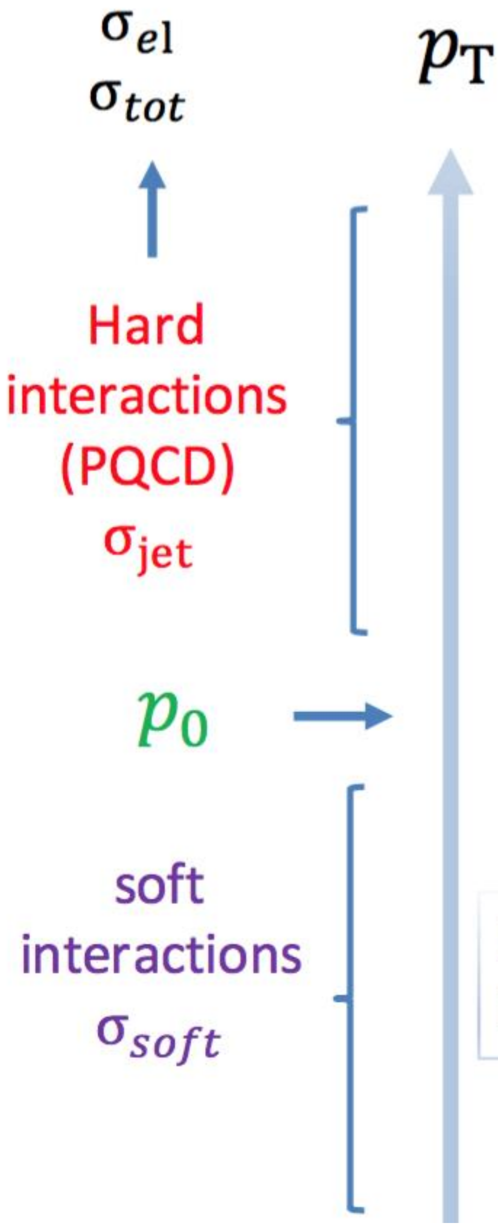
Nuclear Shadowing for Pb:





Improvement with modern PDFs of nuclei

Initial condition from the HIJING1.0 model:



$$\sigma_{jet} = \int_{p_0^2}^{s/4} dp_T^2 dy_1 dy_2 \frac{1}{2} \frac{d\sigma_{jet}}{dp_T^2 dy_1 dy_2},$$

$$\frac{d\sigma_{jet}}{dp_T^2 dy_1 dy_2} = K \sum_{a,b} x_1 f_a(x_1, p_T^2) x_2 f_b(x_2, p_T^2) \frac{d\sigma^{ab}(\hat{s}, \hat{t}, \hat{u})}{d\hat{t}}$$

$$\chi(b,s) \equiv \chi_s(b,s) + \chi_h(b,s) = \frac{1}{2}\left[\sigma_{soft} T_{NN}(b) + \sigma_{jet} T_{NN}(b)\right],$$

$$\sigma_{tot} = 2\pi \int_0^\infty db^2 \left[1 - e^{\chi(b,s)}\right]$$

Key input parameters in the model

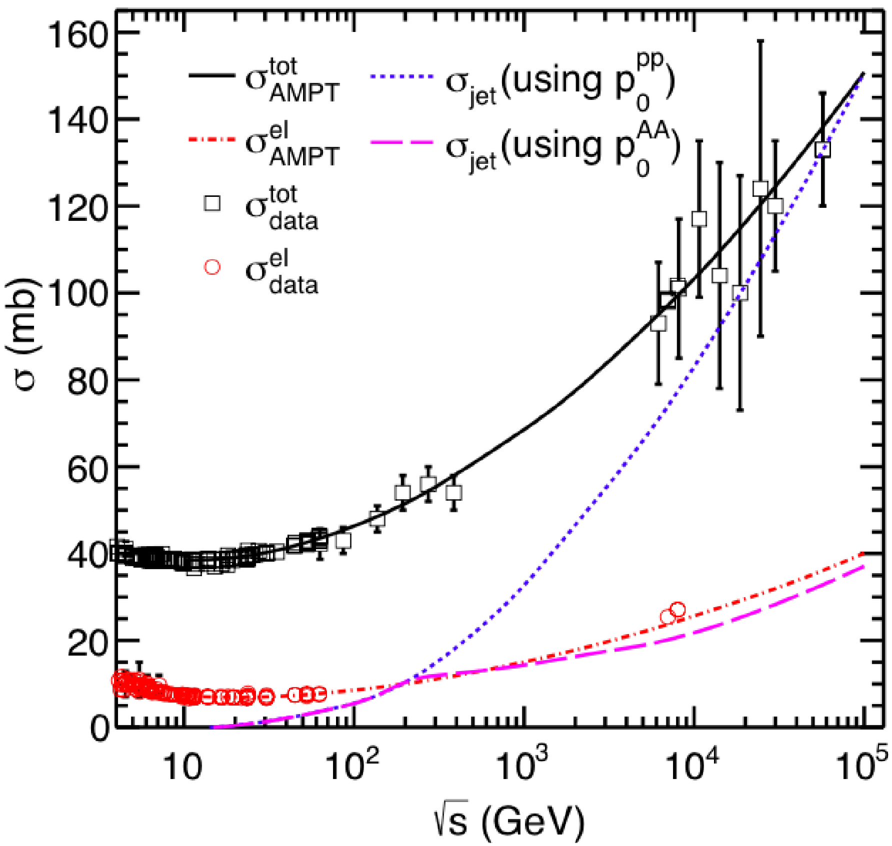
$$\sigma_{el} = \pi \int_0^\infty db^2 \left[1 - e^{\chi(b,s)}\right]^2$$

$$\sigma_{in} = \pi \int_0^\infty db^2 \left[1 - e^{2\chi(b,s)}\right]$$

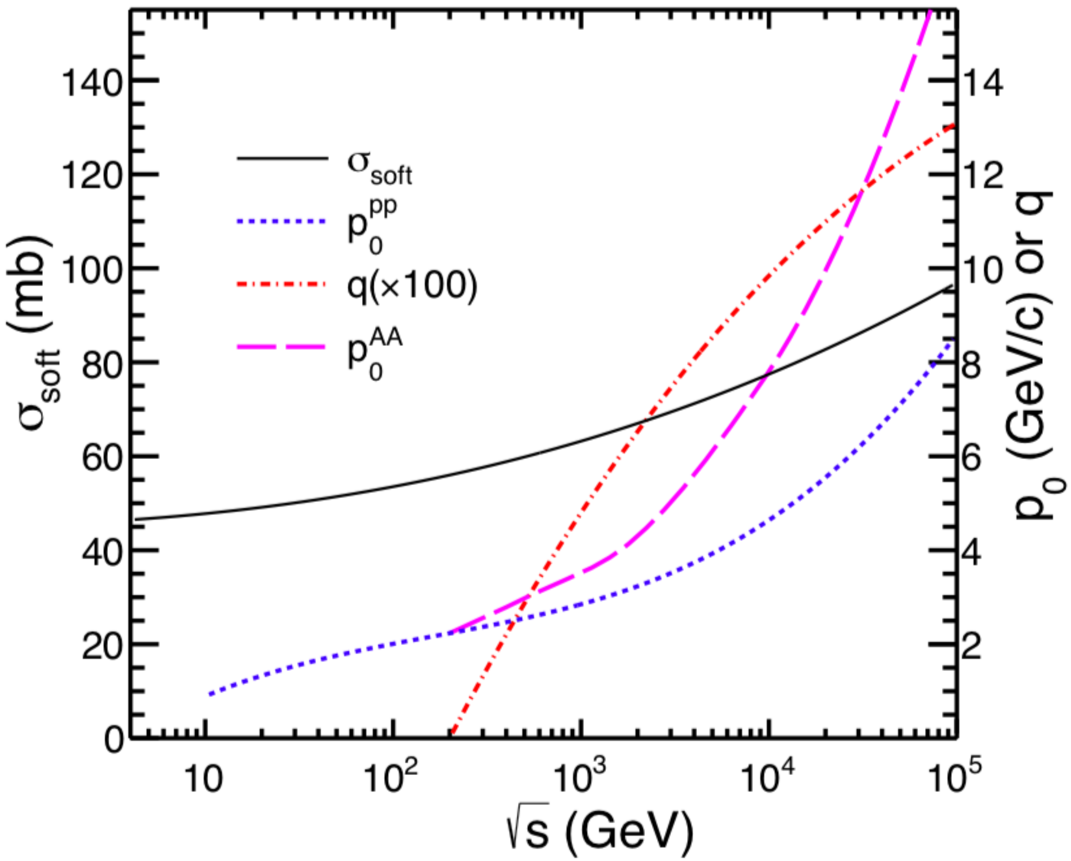
$$\sigma_{tot} = 2\pi \int_0^\infty db^2 \left[1 - e^{\chi(b,s)}\right]$$

Improvement with modern PDFs of nuclei

Fitting p_0 & σ_{soft} in the HIJING1.0 model:



We determine p_0 & σ_{soft} at different energies (4, ~10^5) GeV by fitting data on total and elastic *pp* cross sections.



→ p_0 for *pp* collisions (p_0^{pp}) increases strongly with energy (*like in HIJING 2.0*).

Note: $p_0 = 2GeV/c$ *in HIJING 1.0*

Improvement of heavy flavor productions

L. Zheng et al., PRC 101 (2020)

gg® *gg* cross section
in leading-order pQCD
is divergent for massless g,
so HIJING uses a
minijet cutoff p_0,
but for minijets of ALL flavors.

$$\frac{d\sigma_{gg}}{dt} = \frac{9\pi\alpha_s^2}{2s^2}\left(3 - \frac{ut}{s^2} - \frac{us}{t^2} - \frac{st}{u^2}\right)$$
$$\simeq \frac{9\pi\alpha_s^2}{2}\left(\frac{1}{t^2} + \frac{1}{u^2}\right) \simeq \frac{9\pi\alpha_s^2}{2t^2}$$

But heavy flavor production may NOT be subject to this cutoff
due to heavy quark mass >> Λ_{QCD} (e.g. in FONLL)

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

1) So we now remove the p_0 cut on HF productions
in the two-component model HIJING & AMPT.

Improvement of heavy flavor productions

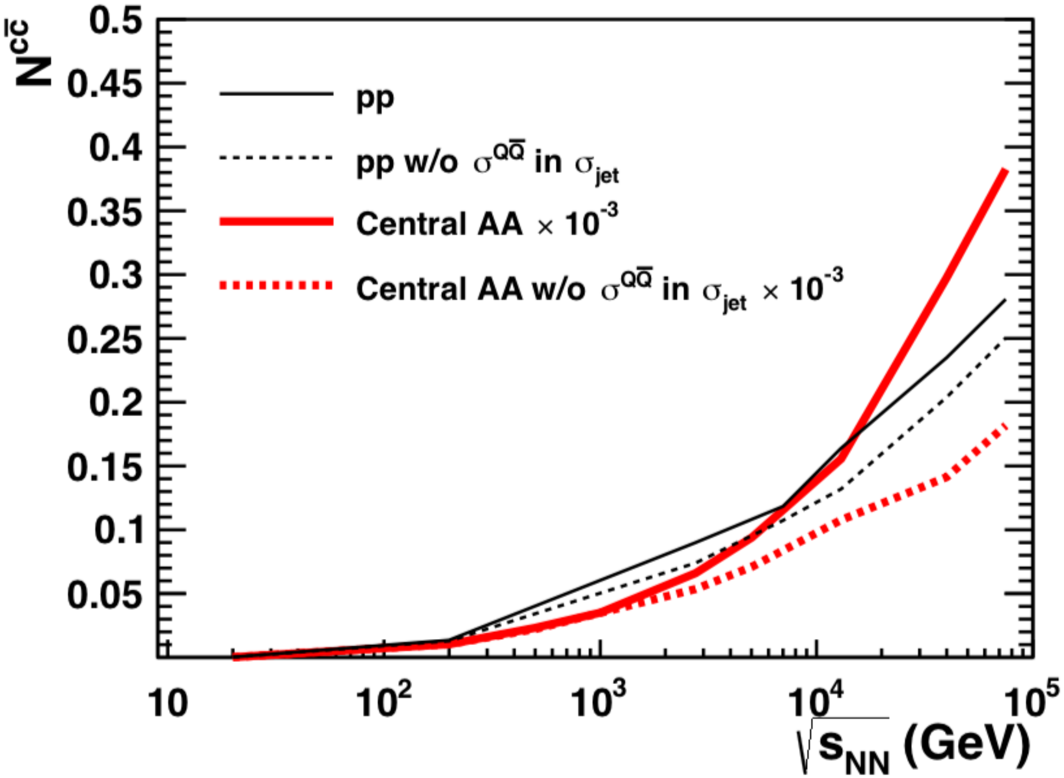
σ_{jet} in the HIJING model
currently only includes light flavor (LF: u/d/s) minijets,
then HF & LF minijets are generated according to
their relative cross sections.

2) We now include HF in σ_{jet}:

$$\sigma_{jet} = \sigma_{jet}^{LF} + \sigma^{HF}$$

sizable effect above a few TeV.

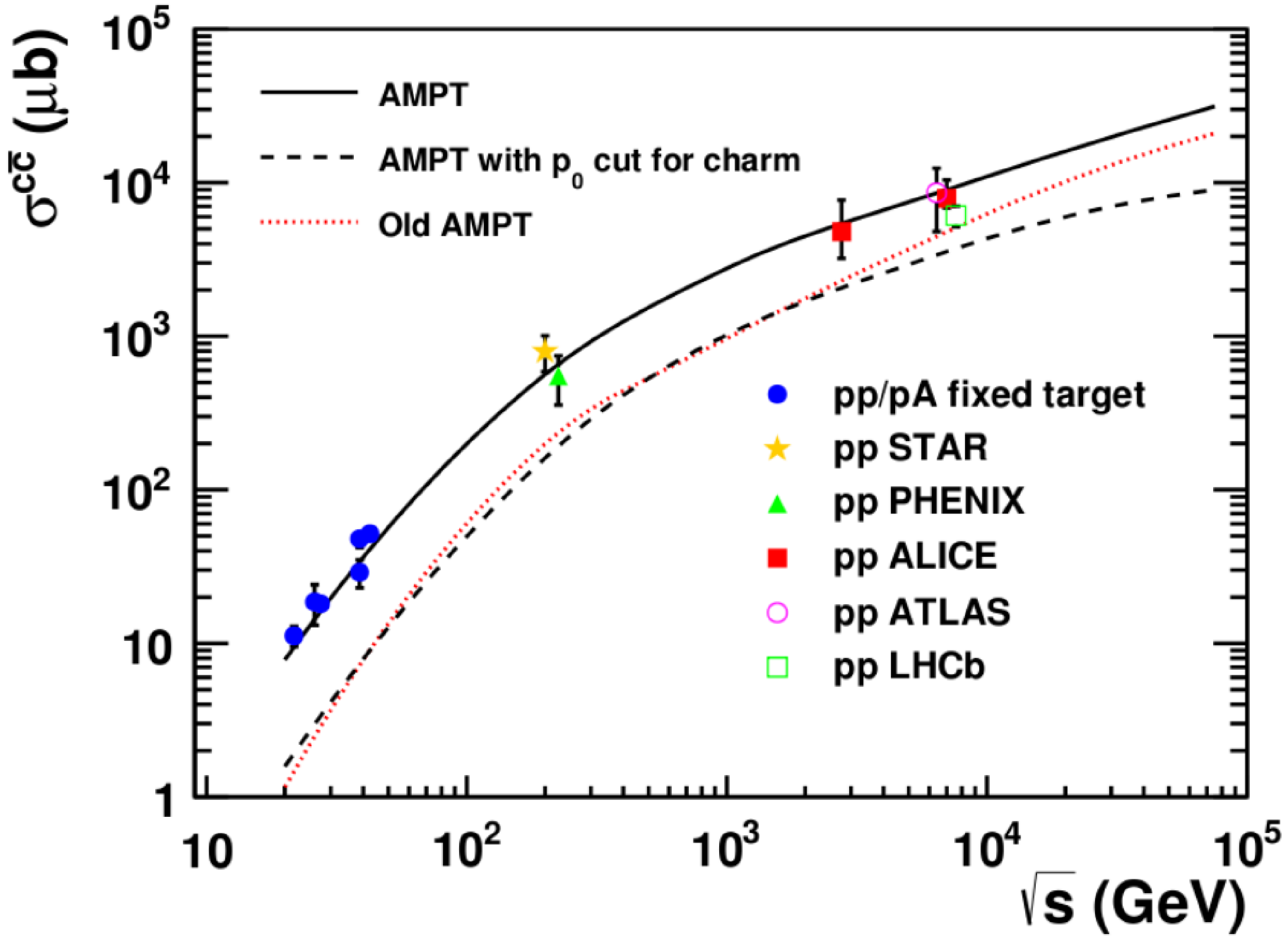
3) We also make correction
of factor of ½
for certain σ_{jet} channels



L. Zheng et al., PRC 101 (2020)

Improvement of heavy flavor productions

Charm quark yields in *pp* collisions:

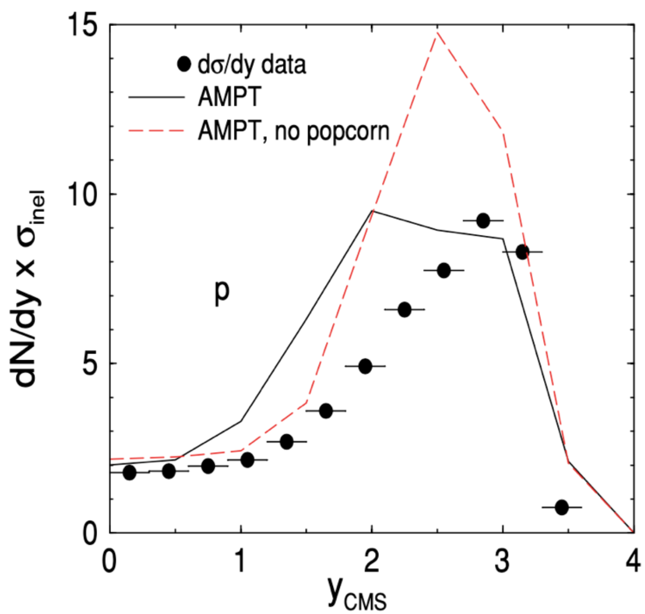


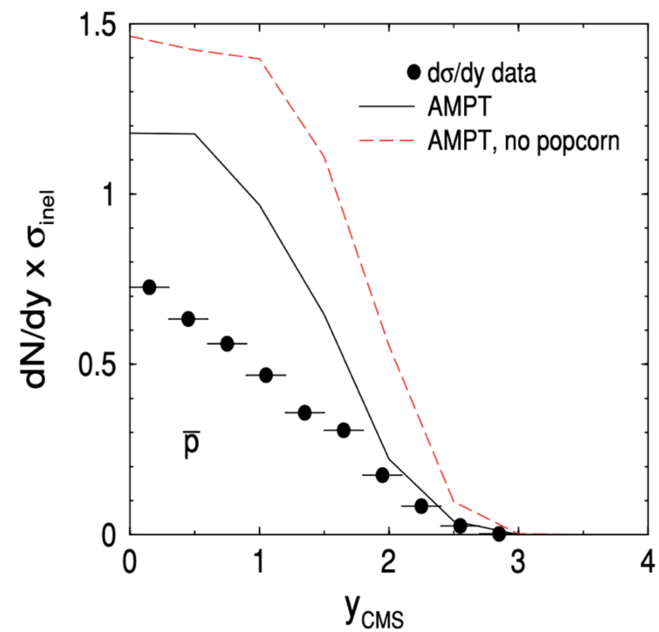
- Old/public AMPT charm yield << data
- Removing p_0 greatly enhances charm yield
- Updated AMPT model well describes the world data

2) A baryon stopping puzzle

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 2 additional baryon-antibaryon production channels:
the $B\bar{B}$ and $BM\bar{B}$ configurations.





ZWL et al. PRC 72 (2005)

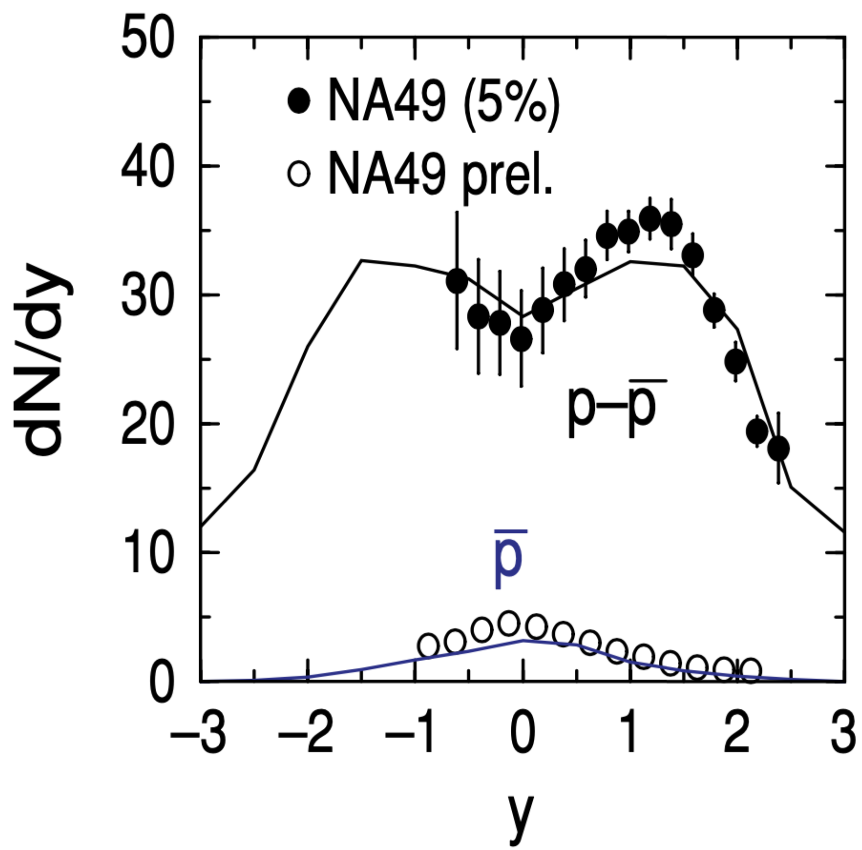
pp collisions at P_{lab} = 400 GeV/c

The popcorn mechanism can help but is often not enough.

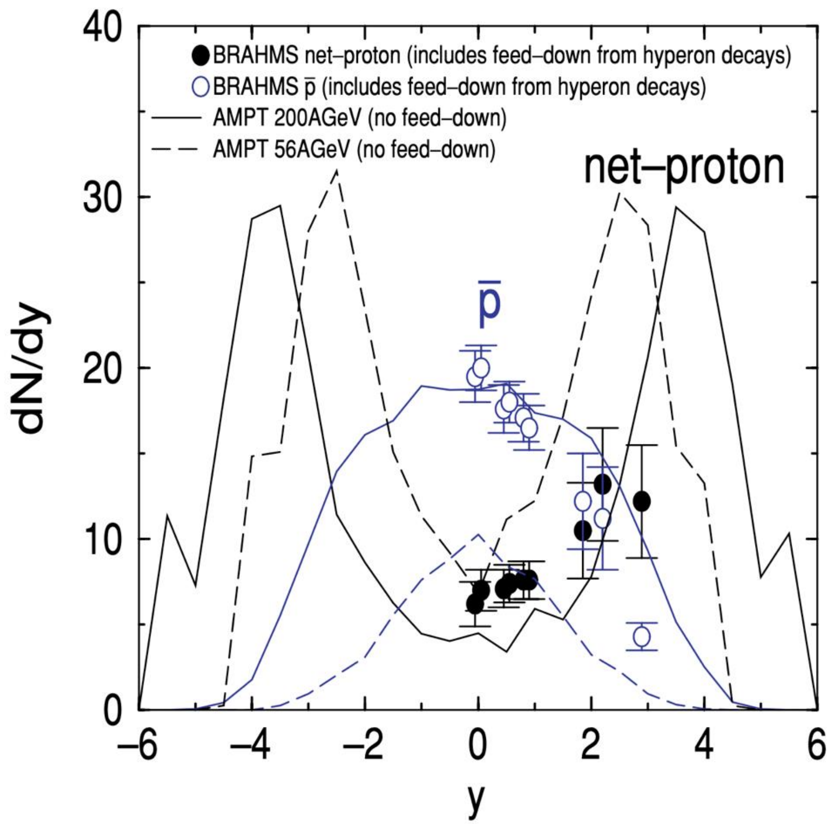
2) A baryon stopping puzzle

Baryon stopping in the AMPT-default model
for heavy ion collisions are often reasonable,
but good comparisons at large rapidities are limited.

Central Pb+Pb collisions
at SPS $\sqrt{s_{NN}}$ =17.3GeV

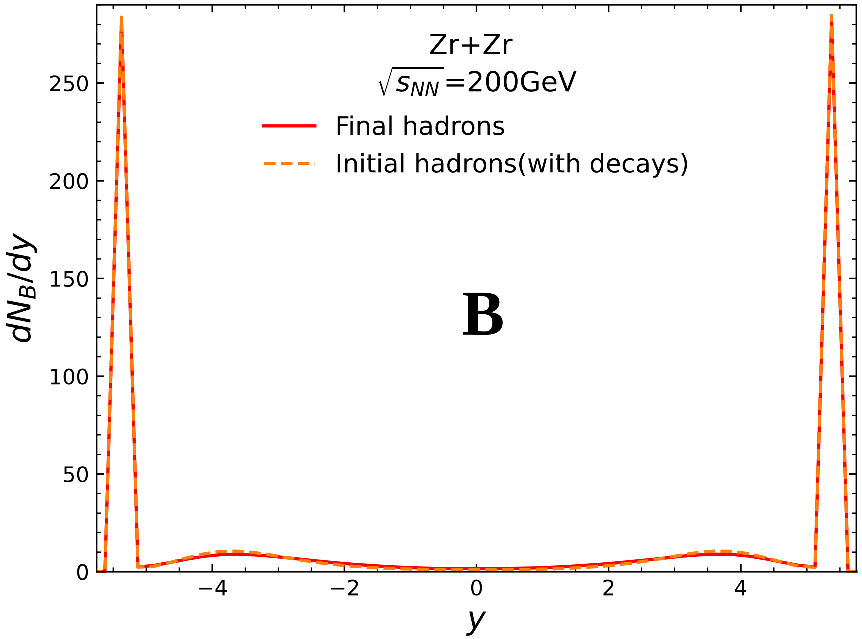


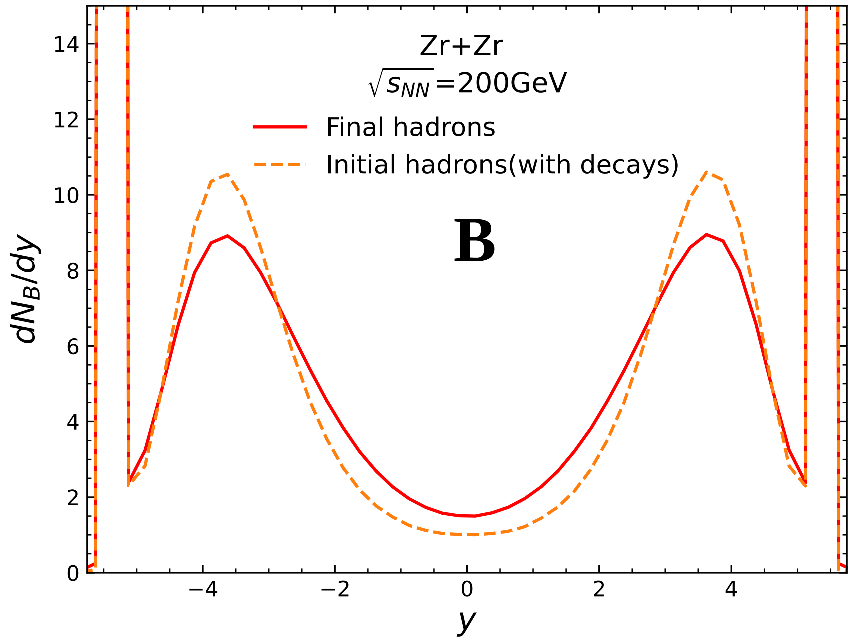
Central Au+Au collisions
at RHIC $\sqrt{s_{NN}}$ =56 & 200 GeV

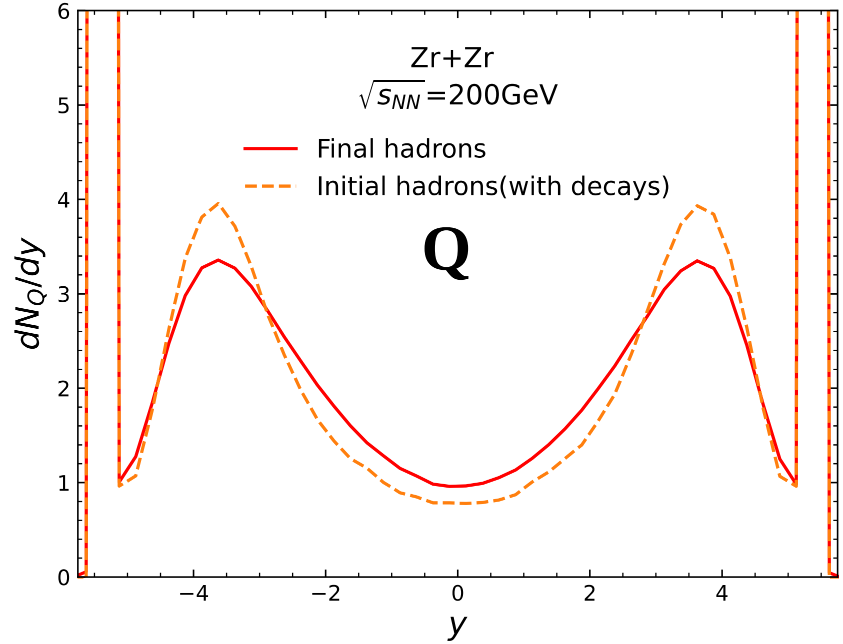


2) A baryon stopping puzzle

Results from AMPT-String Melting for minimum-bias Zr+Zr collisions:







N_B or B: net-baryon number.

N_Q or Q: net-electric charge number.

ZWL at the Baryon Dynamics workshop, Jan 2024.

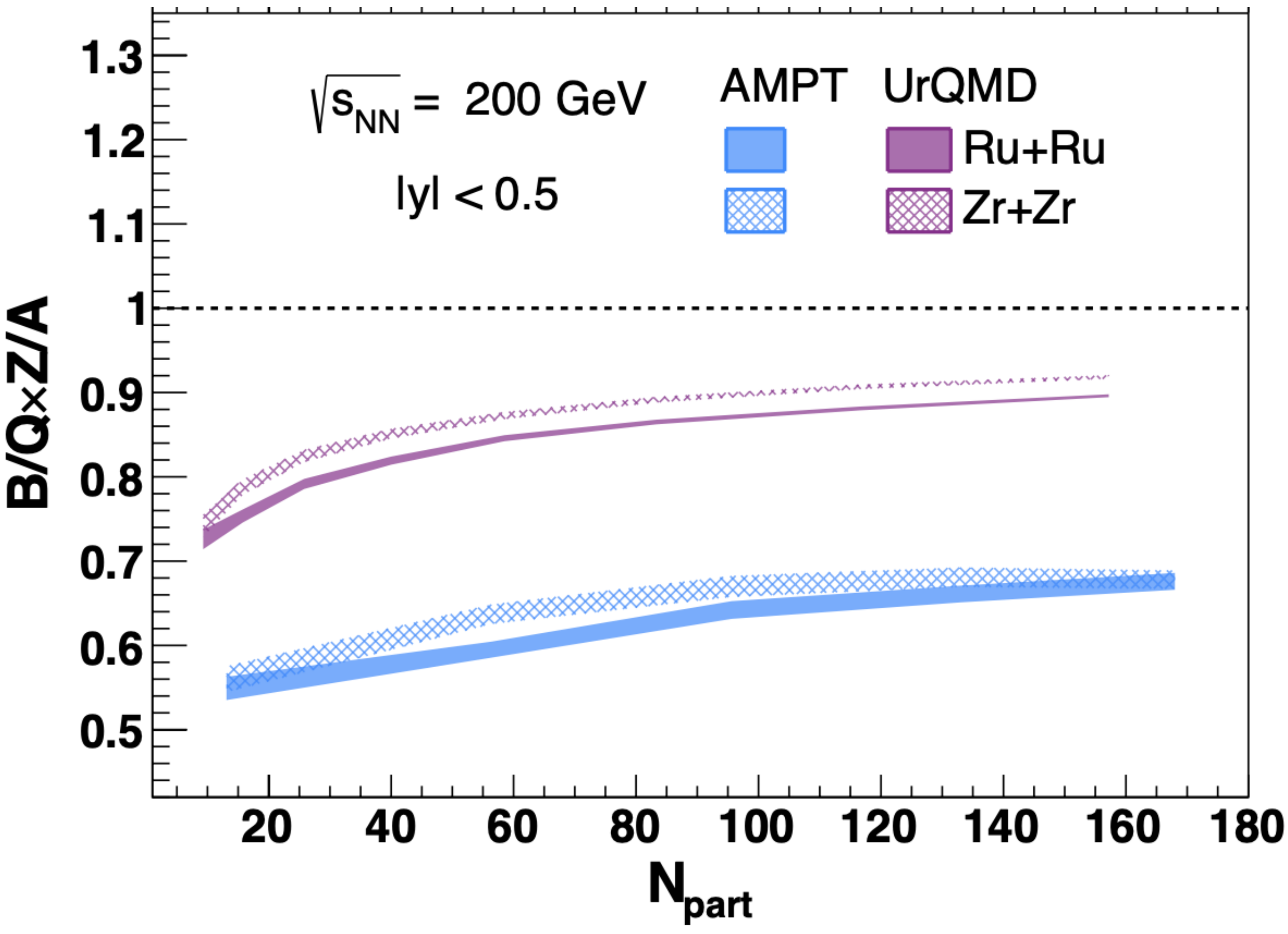
2) A baryon stopping puzzle

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

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

Both AMPT & UrQMD models give B/Q*Z/A < 1 at mid-rapidity, for every centrality of isobar collisions:

Lewis et al., EPJC 84 (2024)



More UrQMD results in Lv et al., CPC 48 (2024)

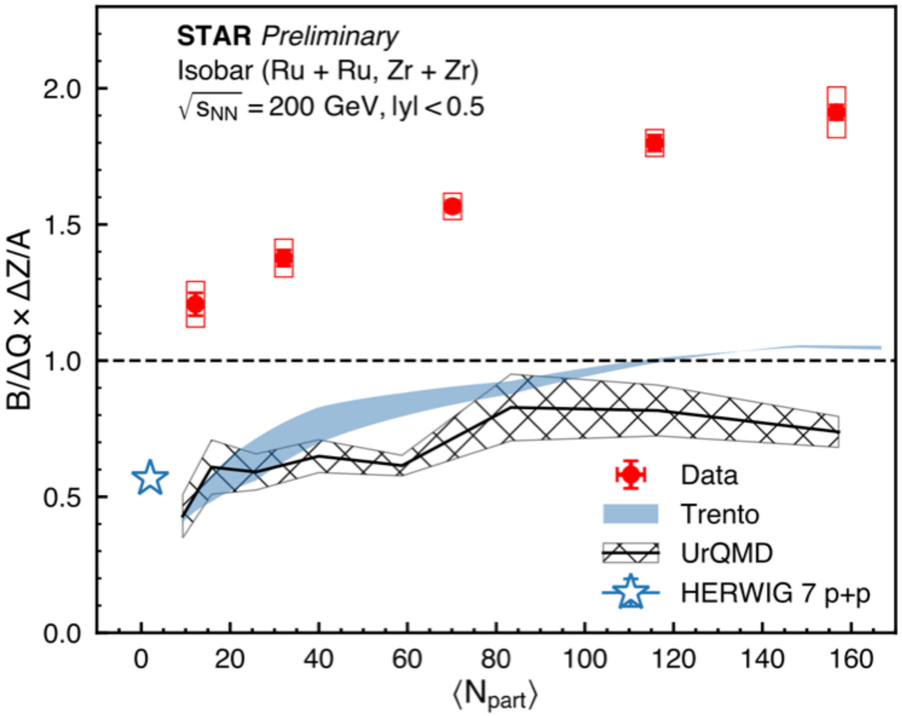
2) A baryon stopping puzzle

Rongrong Ma at the Baryon Dynamics workshop, Jan 2024.

For isobar collisions
^{96}Ru relative to ^{96}Zr
at mid-rapidity:

models give
$B/\Delta Q*\Delta Z/A < 1$.

Preliminary data > 1.



- The gluon junction, a Y-shaped gauge-invariant configuration connecting three quarks, has long been suggested to be the carrier of baryon number; in contrast to the usual picture (*where q carries 1/3 B*).

Rossi and Veneziano, NPB123 (1977); Kharzeev, PLB378 (1996).

- The gluon junction, as a new mechanism of baryon transport, should increase B stopping relative to Q stopping. Lewis et al., EPJC 84 (2024)

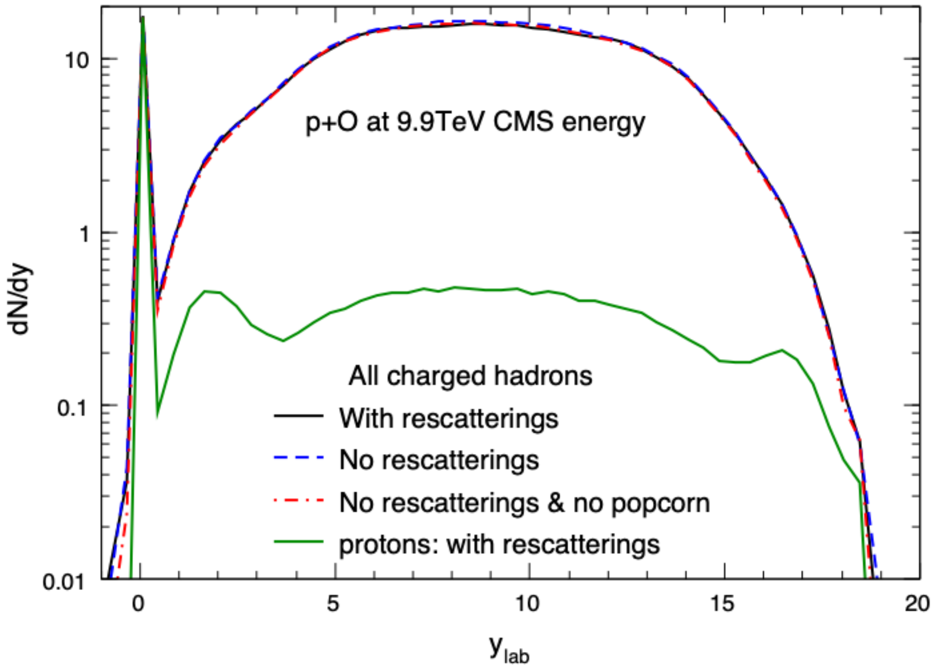
3) Some results of p+O collisions from AMPT

for minimum bias collisions at these two energies:

RHIC		LHC	
170 GeV	&	9.9 TeV	$\sqrt{s_{NN}}$ (GeV)
~15,400		~52,200,000	E_{LAB} (GeV)
~1.54 x10^{13}		~5.22 x10^{16}	E_{LAB} (eV)

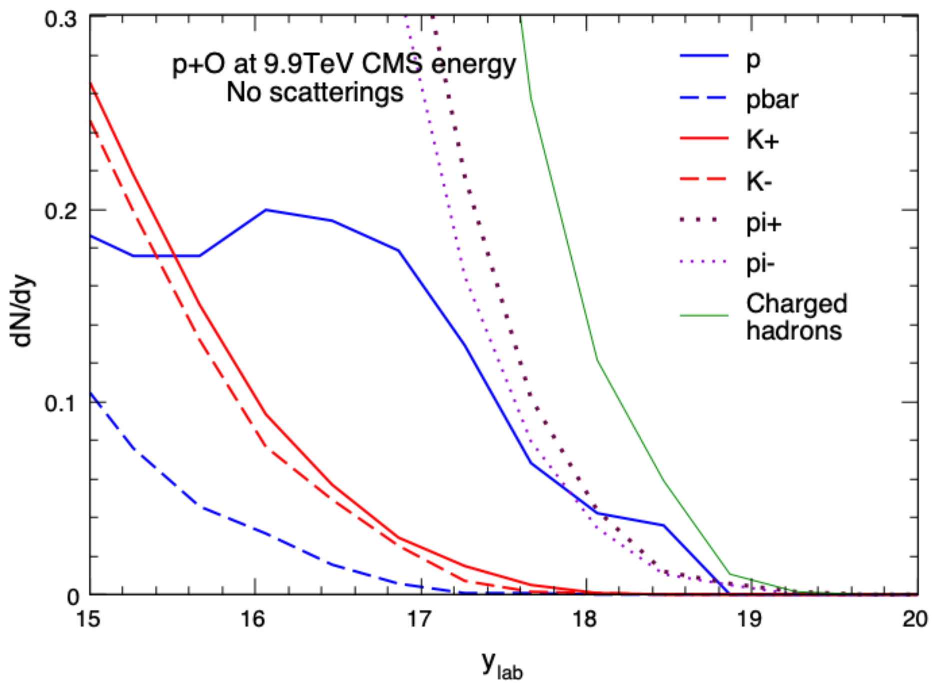
"The Large High Altitude Air Shower Observatory (LHAASO) can detect cosmic rays with energies ranging from around 10^{11} eV to 10^{17} eV (100 PeV)."

3) Some results of p+O collisions from AMPT



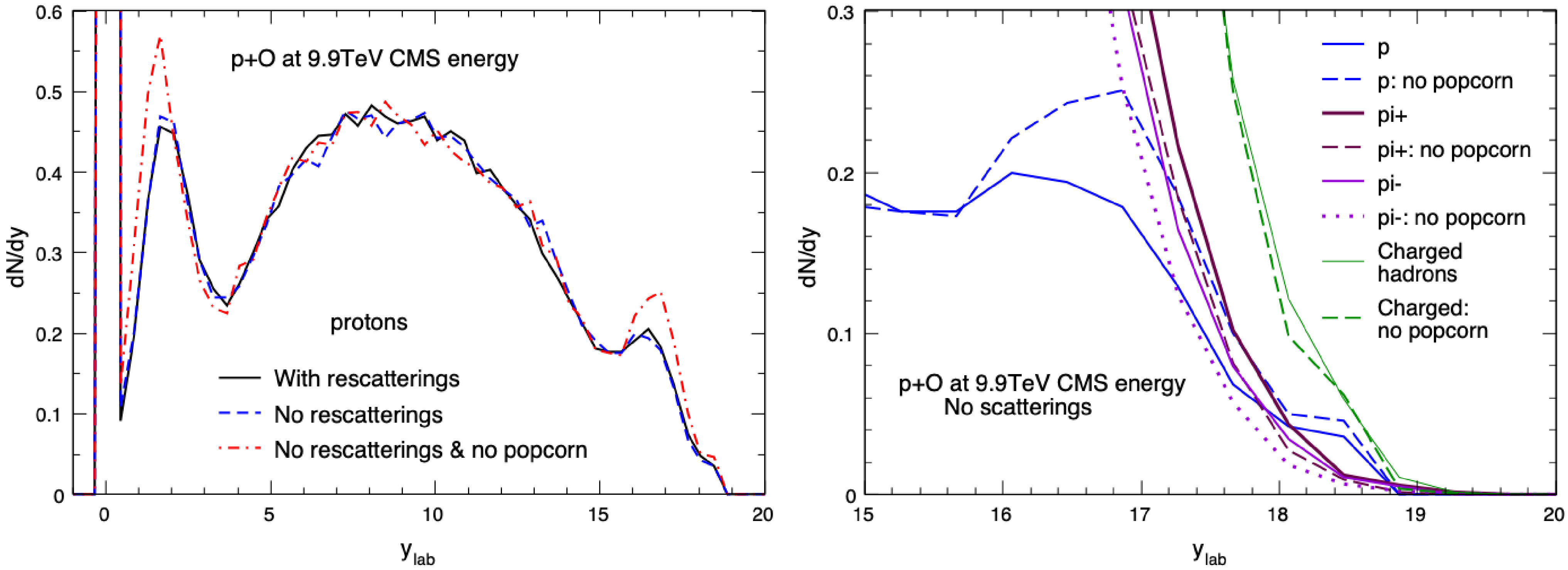
At $\sqrt{s_{NN}} = 9.9$ TeV or $E_{LAB} = 5.22$ x1016 eV:

- rescattering effect seems small on charged hadrons



- protons dominate at large y around *yBeam* (18.5 here), pions also contribute
- there are even some pions with *y* > *yBeam*

3) Some results of p+O collisions from AMPT



At $\sqrt{s_{NN}} = 9.9$ TeV:

- rescattering effect is small on protons
- popcorn mechanism suppresses protons a few units away from *yBeam*.
- popcorn mechanism enhances pions at forward rapidities
  as it increase baryon stopping

3) Some results of p+O collisions from AMPT

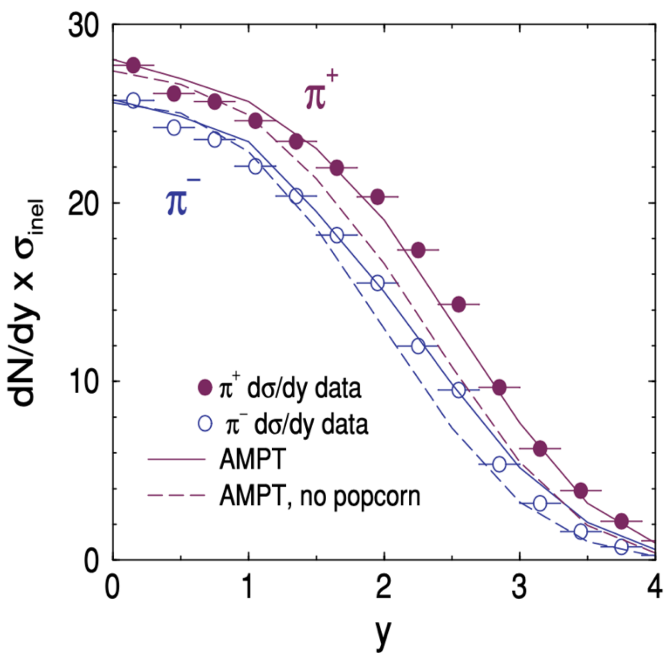


FIG. 7. (Color online) Rapidity distributions of pions for *pp* collisions at $P_{\rm lab} = 400$ GeV/c. Circles are data from the LEBC-EHS Collaboration [100].

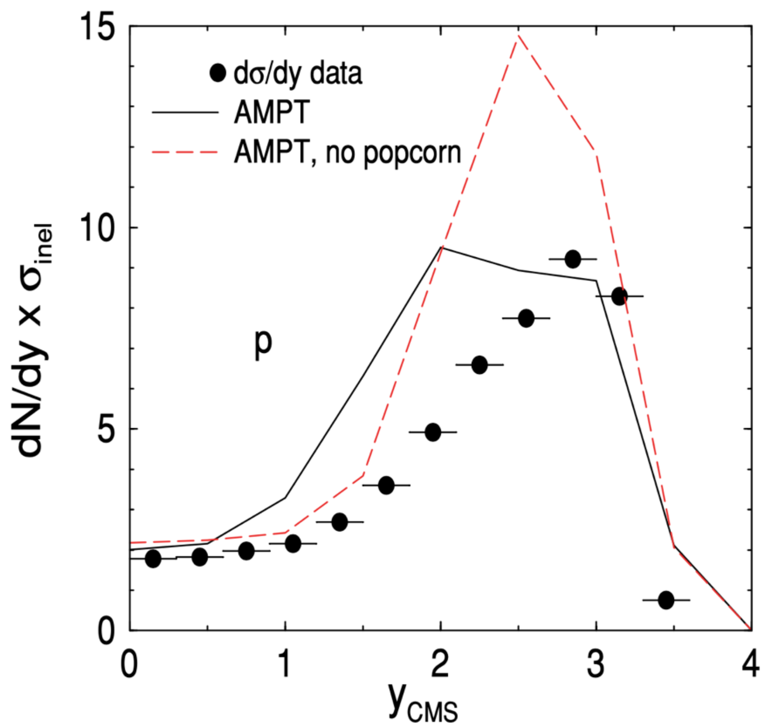


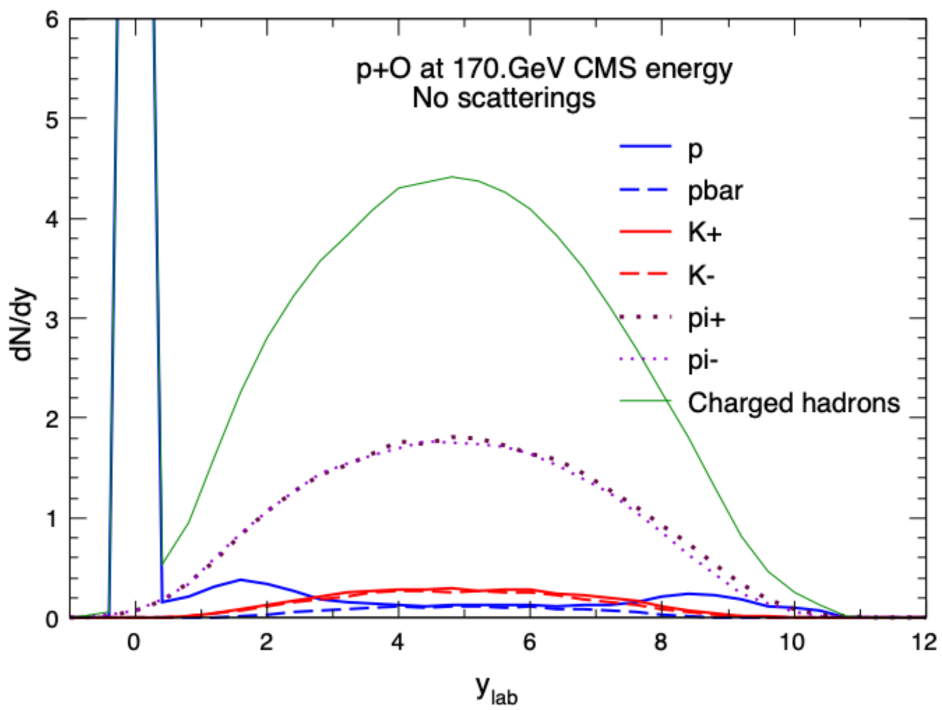
FIG. 9. (Color online) Same as Fig. 7 for protons.

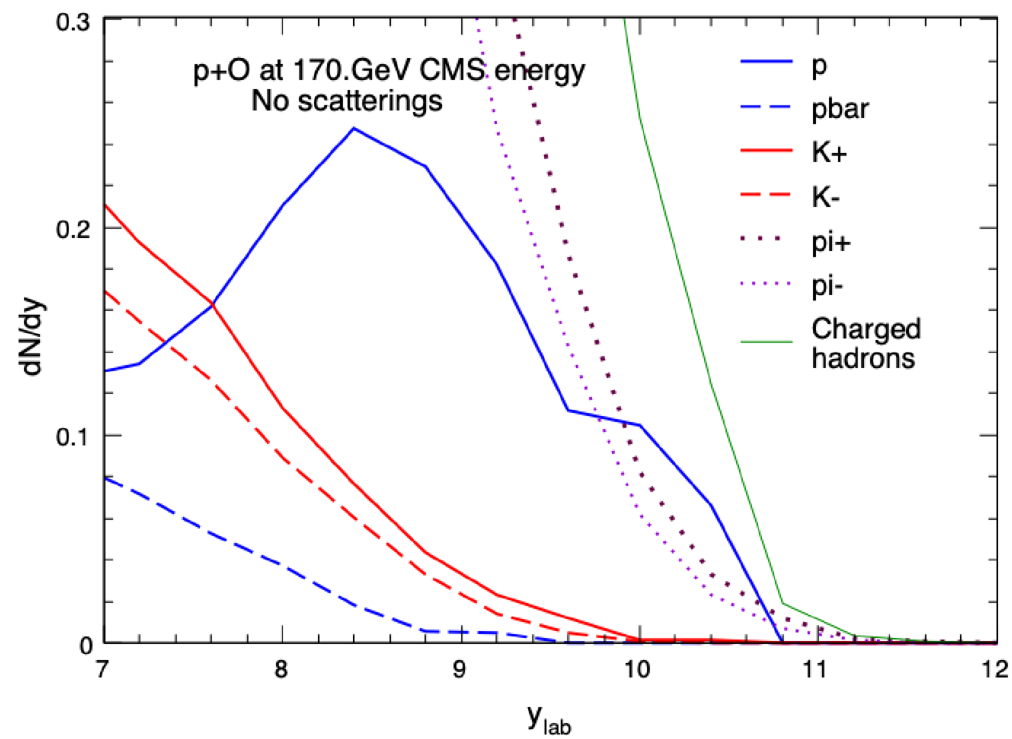
ZWL et al, PRC 72 (2005)

These features were observed before for p+p collisions at lower energies:

- popcorn mechanism suppresses protons a few units below *yBeam*.
- popcorn mechanism enhances pions at forward rapidities
  as it increase baryon stopping

3) Some results of p+O collisions from AMPT





At $\sqrt{s_{NN}} = 170$ GeV or $E_{LAB} = 1.54$ x1013 eV:

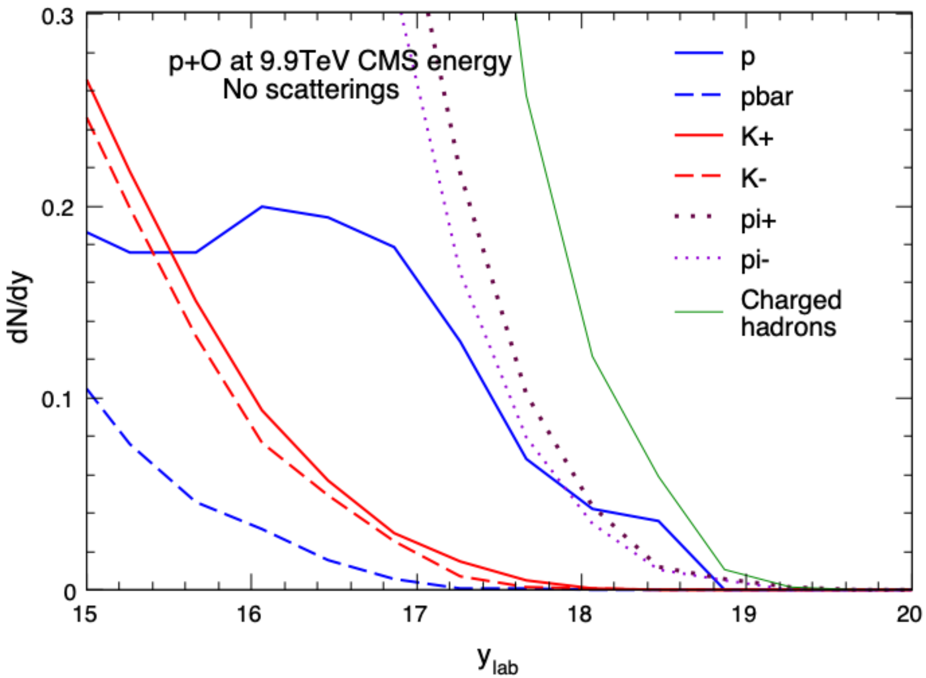
Anti-protons

- ~ protons at mid-rapidity (*yBeam/2)*
- much lower at forward rapidities

At forward rapidities:

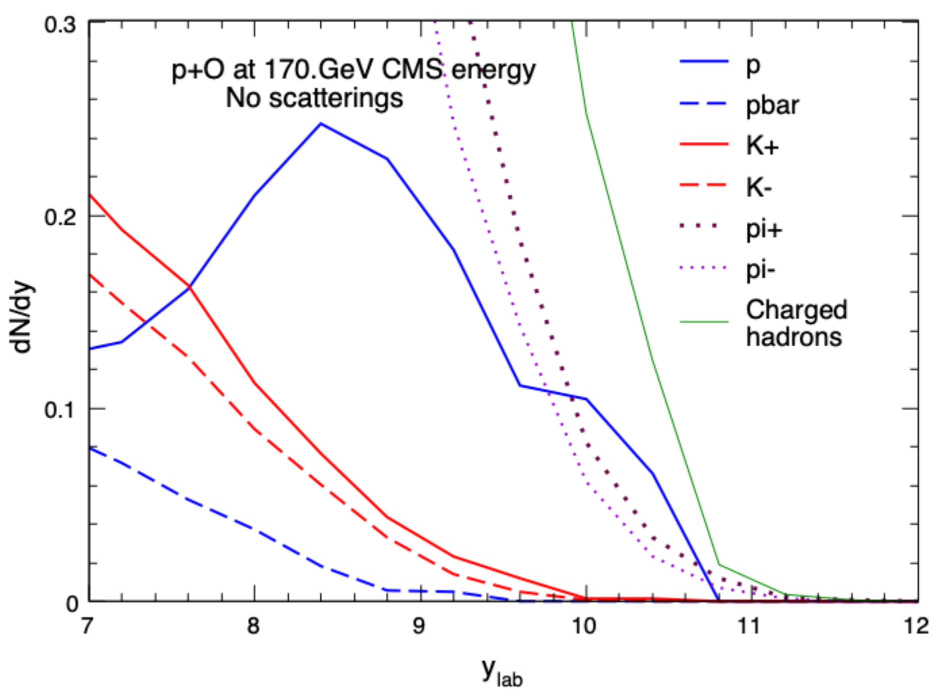
- protons dominate at large y around *yBeam* (10.4 here), pions also contribute
- even some pions with *y>yBeam*

3) Some results of p+O collisions from AMPT



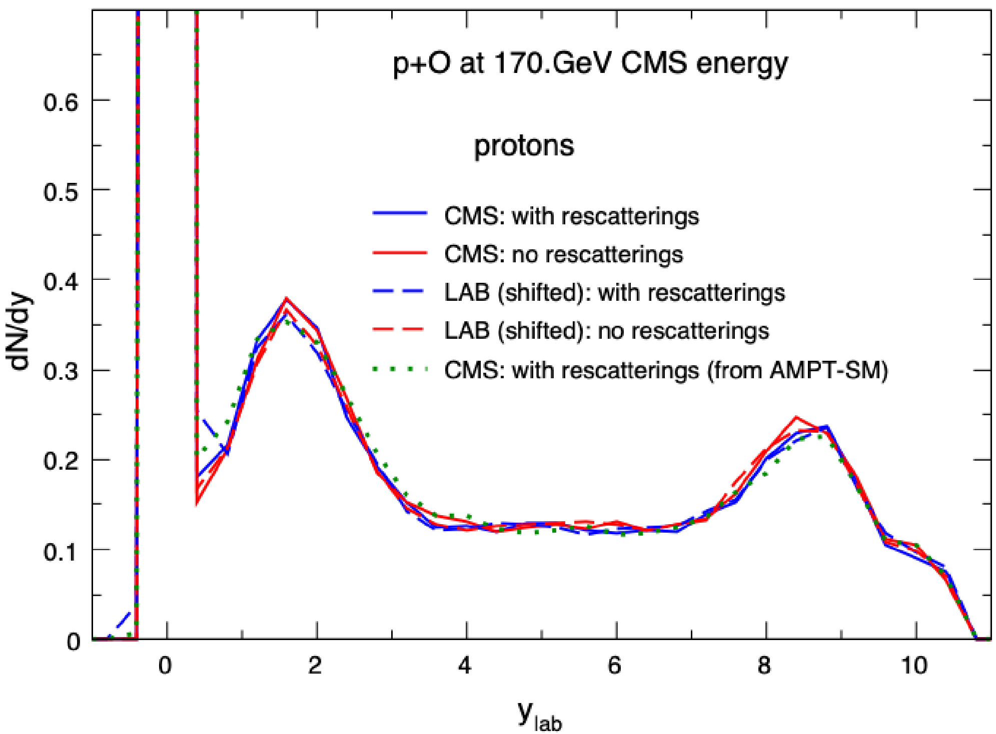
at $\sqrt{s_{NN}} = 9.9$ TeV

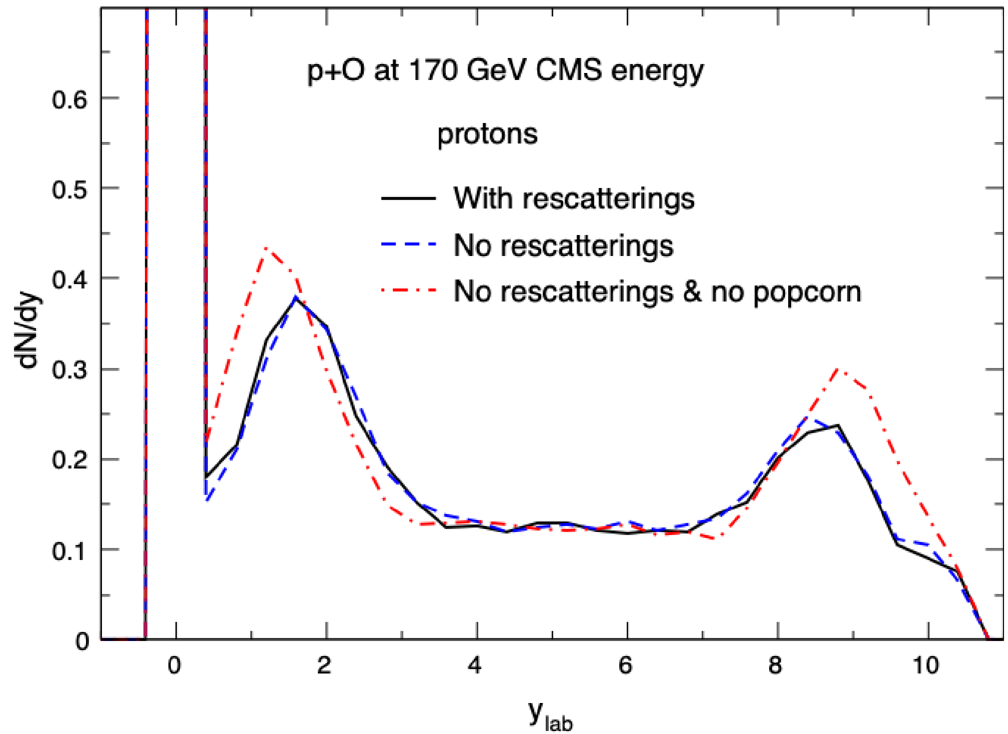
At forward rapidities:
results are qualitatively similar
at the two energies;
consistent with limiting fragmentation
or scaling with (*y-yBeam*)



at $\sqrt{s_{NN}} = 170$ GeV

3) Some results of p+O collisions from AMPT





At $\sqrt{s_{NN}} = 170$ GeV:

Similar proton results from:

- calculations in CMS or LAB frame
- AMPT-default & String Melting, showing little effect from parton or hadron rescatterings

Popcorn suppresses protons a few units away from *yBeam*, similar to $\sqrt{s_{NN}} = 9.9$ TeV

4) Summary

- The AMPT model provides a kinetic description of nuclear collisions including p+p, p+A, and A+A collisions
- Rescattering effect seems small for particle yields in p+O collisions
- Baryon stopping due to the popcorn mechanism (or gluon junction) typically suppresses protons but enhances pions are forward rapidities
- Understanding baryon stopping remains a challenge.
  With recent focus on high baryon density nuclear physics,
  we expect better understanding of baryon stopping/transport
  and better description of forward productions.