Summary of Recent AMPT Developments and Future Directions

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Outline

- Motivation
- Recent developments to improve AMPT
- Possible future directions

Outline

- **Motivation**
- Recent developments to improve AMPT
- Possible future directions

A Multi-Phase Transport (AMPT) serves as a comprehensive event generator for heavy ion collisions.

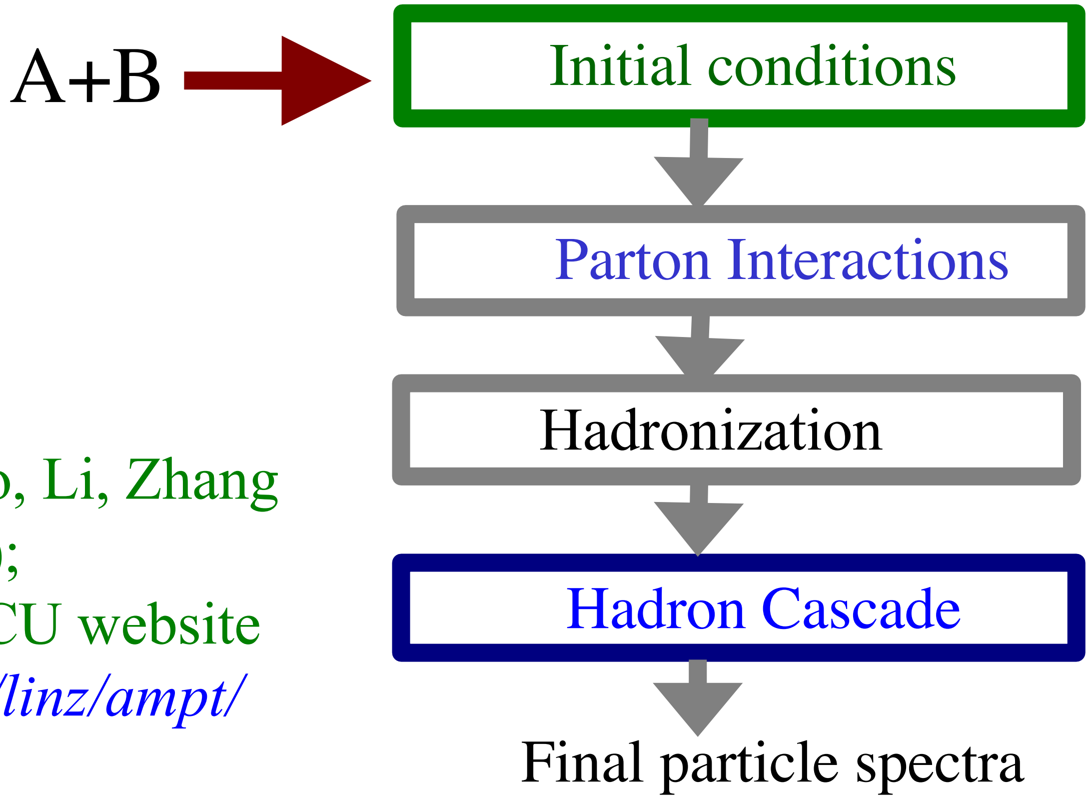
So it aims to

evolve the system from initial condition to final observables;

include particle productions of different flavours at different P_T & y;

keep non-equilibrium features and dynamics

(e.g. intrinsic fluctuations and correlations).



A+B

Initial conditions

Parton Interactions

Hadronization

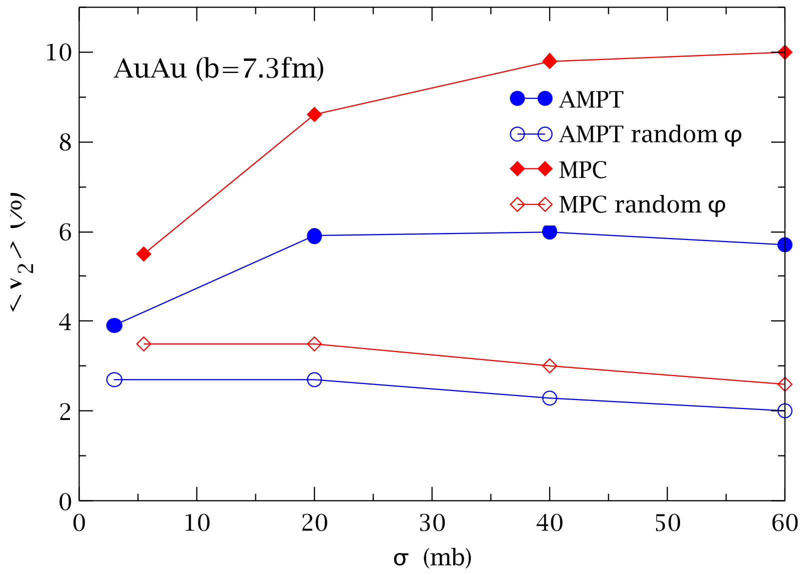
Hadron Cascade

Final particle spectra

Long paper: ZWL, Ko, Li, Zhang & Pal, PRC 72 (2005);
source codes at the ECU website
http://myweb.ecu.edu/linz/ampt/

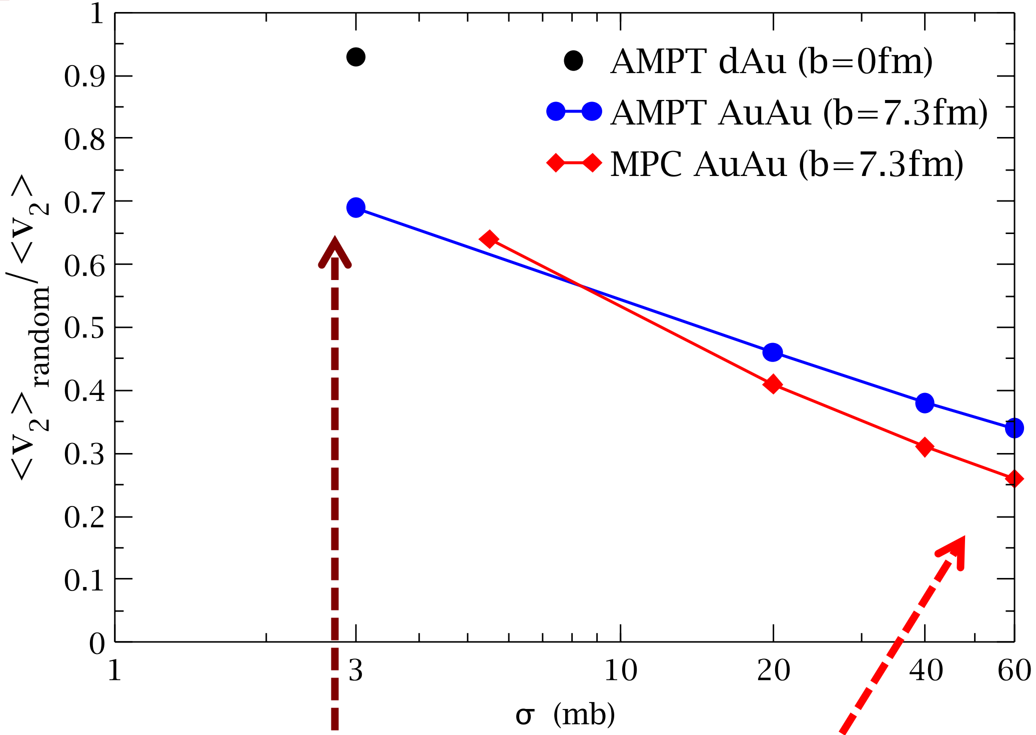
Difference between transport and hydro for finite systems

The escape mechanism:
anisotropic escape as
interaction-induced response
to anisotropic geometry



L He et al. PLB 753 (2016)
ZWL et al. NPA 956 (2016)

v_2 Ratio



Anisotropic particle escape
is dominant contribution of v_2 for small systems
& even for semi-central AuAu at RHIC

At very large σ or opacity,
hydrodynamic collective flow
will be the dominant contribution of v_2

v_2 from the escape mechanism has strong flavor dependence

ZWL at SQM2017
HL Li et al., PRC 99 (2019)

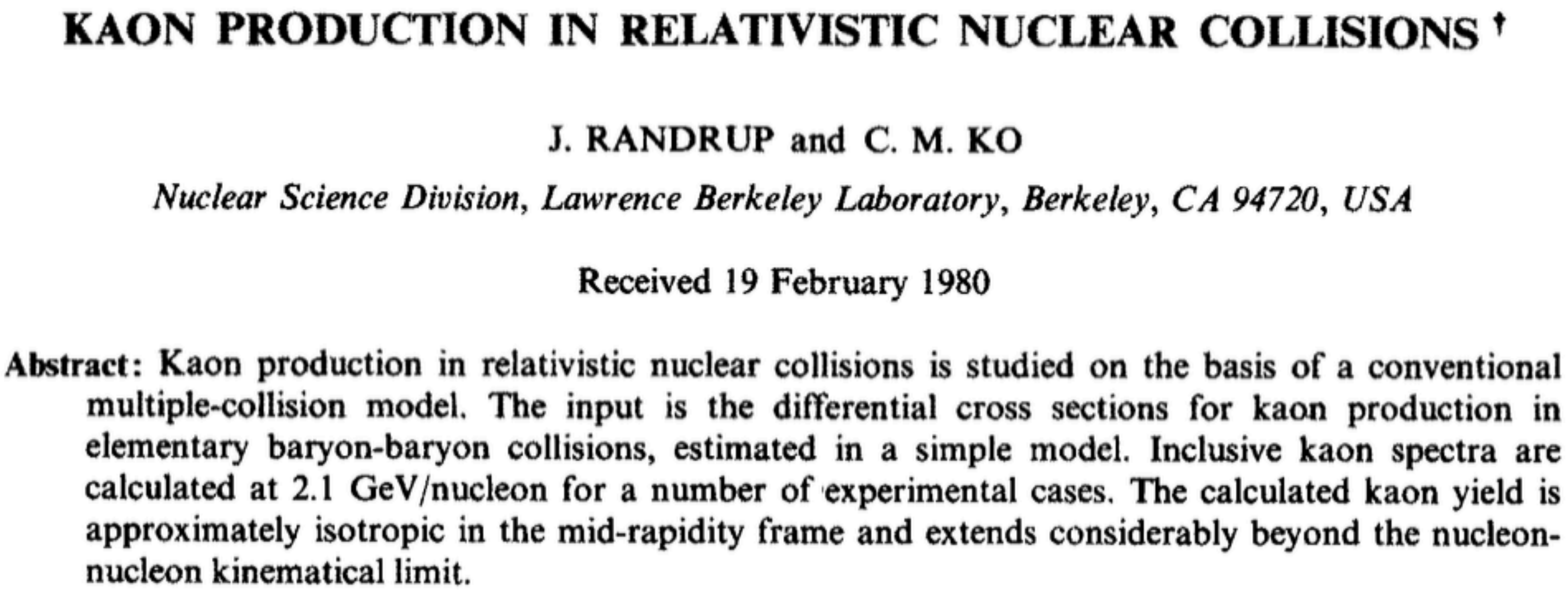
	pPb ($b = 0$ fm)			AuAu ($b = 6.6$-8.1 fm)			PbPb ($b = 8$ fm)		
Quark flavor	u,d	s	c	u,d	s	c	u,d	s	c
$\langle N_{\mathrm{coll}} \rangle$	2.02	2.54	4.23	4.58	5.45	8.68	9.82	11.14	15.48
$\sigma_{\Delta\phi}$	0.86	0.55	0.20	1.04	0.70	0.27	1.00	0.70	0.26
$\sigma_{\Delta\phi} \cdot \sqrt{\langle N_{\mathrm{coll}} \rangle}$	1.22	0.87	0.41	2.23	1.63	0.80	3.13	2.34	1.02
$\langle v_2 \rangle_{\mathrm{Random}}$	2.39%	1.89%	1.21%	2.93%	2.27%	0.85%	3.21%	2.23%	0.67%
$\langle v_2 \rangle_{\mathrm{Normal}}$	3.28%	3.20%	2.14%	4.47%	4.78%	3.89%	7.56%	8.42%	7.92%
$\langle v_2 \rangle_{\mathrm{Random}} / \langle v_2 \rangle_{\mathrm{Normal}}$	73%	59%	57%	66%	47%	22%	43%	27%	8.5%

Escape fraction ~

- This reflects the difference between kinetic theory/transport model & hydrodynamics for finite opacity/size
- It is important to develop transport model/kinetic theory & compare with hydro to understand the physics of different systems

Heiselberg and Levy 1999; Borghini and Gombeaud 2011;
Borghini et al. 2018; Kurkela et al. 2018

History: difference between transport model, thermal model, and kinetic equation for finite systems



KAON PRODUCTION IN RELATIVISTIC NUCLEAR COLLISIONS †

J. RANDRUP and C. M. KO

Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA

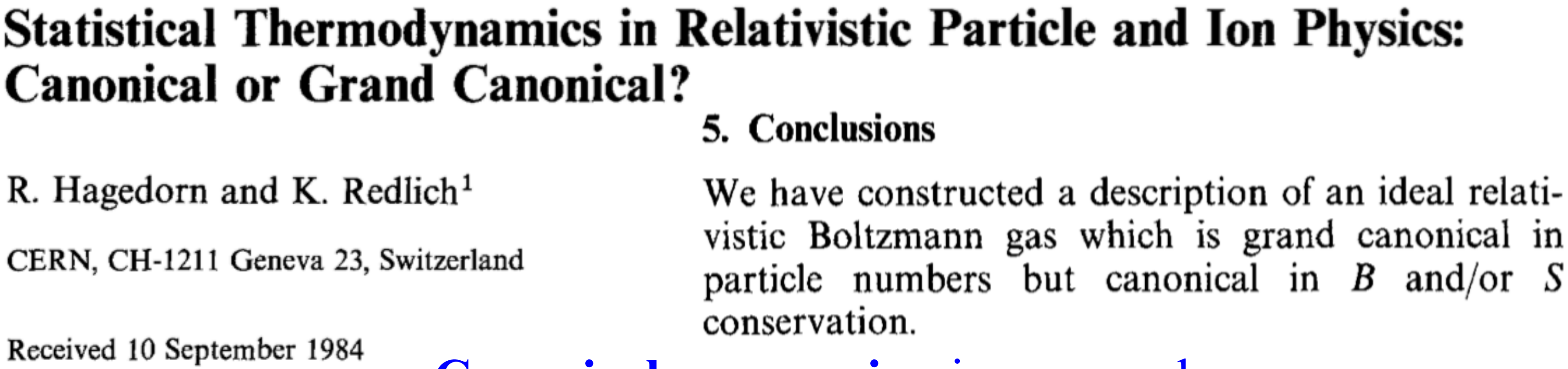
Received 19 February 1980

Abstract: Kaon production in relativistic nuclear collisions is studied on the basis of a conventional multiple-collision model. The input is the differential cross sections for kaon production in elementary baryon-baryon collisions, estimated in a simple model. Inclusive kaon spectra are calculated at 2.1 GeV/nucleon for a number of experimental cases. The calculated kaon yield is approximately isotropic in the mid-rapidity frame and extends considerably beyond the nucleon-nucleon kinematical limit.

Transport model described the kaon yield in low energy collisions.

But thermal model yield is much higher / wrong.

Why?



Statistical Thermodynamics in Relativistic Particle and Ion Physics: Canonical or Grand Canonical?

R. Hagedorn and K. Redlich[1]

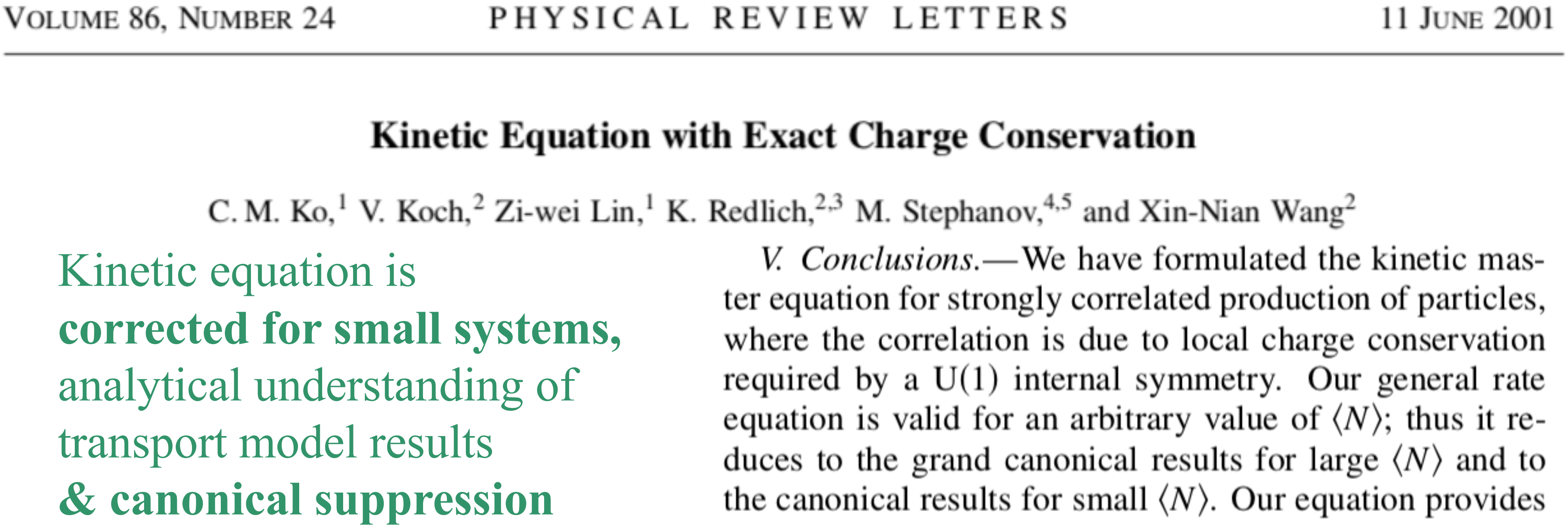
CERN, CH-1211 Geneva 23, Switzerland

Received 10 September 1984

5. Conclusions

We have constructed a description of an ideal relativistic Boltzmann gas which is grand canonical in particle numbers but canonical in B and/or S conservation.

Canonical suppression is proposed
& thermal model yield is corrected **when Nk is small**.



VOLUME 86, NUMBER 24 PHYSICAL REVIEW LETTERS 11 JUNE 2001

Kinetic Equation with Exact Charge Conservation

C. M. Ko,[1] V. Koch,[2] Zi-wei Lin,[1] K. Redlich,[2,3] M. Stephanov,[4,5] and Xin-Nian Wang[2]

V. Conclusions.—We have formulated the kinetic master equation for strongly correlated production of particles, where the correlation is due to local charge conservation required by a U(1) internal symmetry. Our general rate equation is valid for an arbitrary value of $\langle N\rangle$; thus it reduces to the grand canonical results for large $\langle N\rangle$ and to the canonical results for small $\langle N\rangle$. Our equation provides

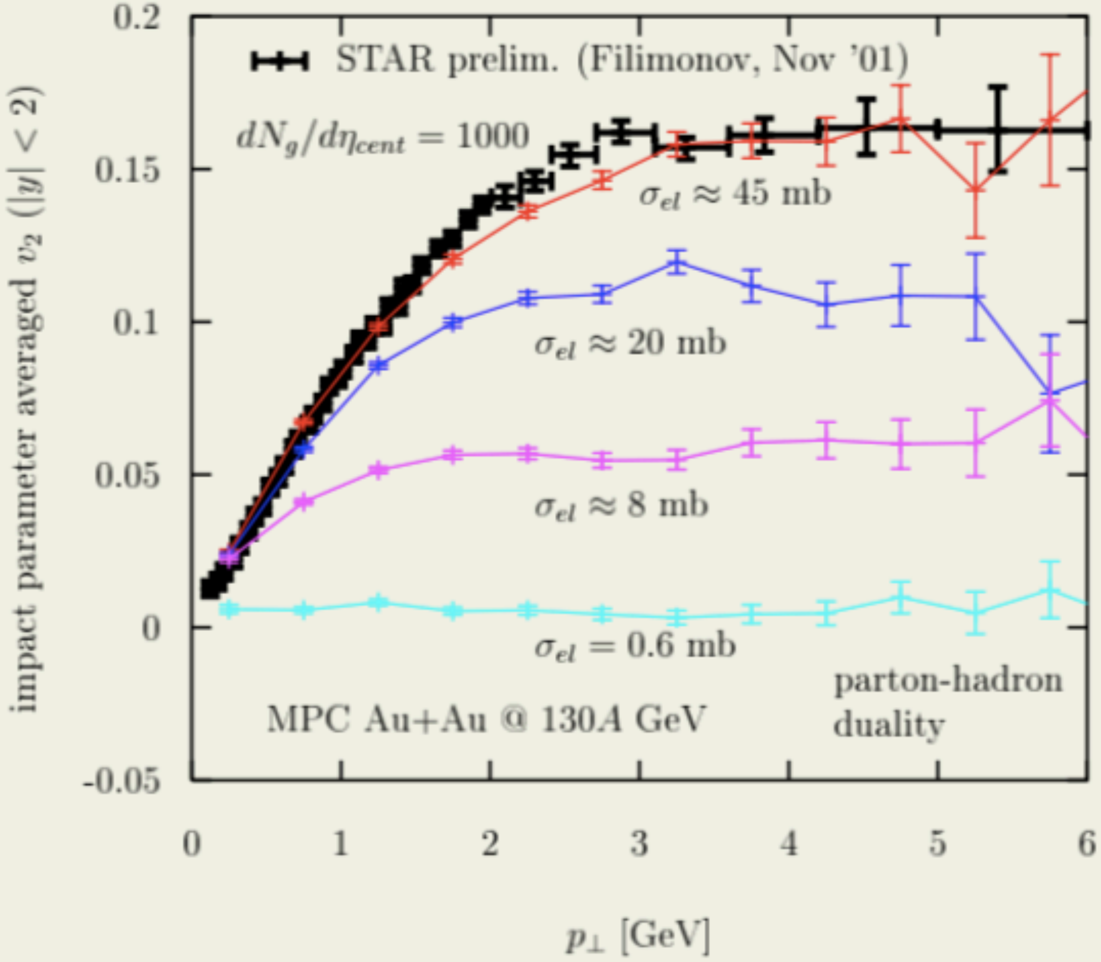
Kinetic equation is
corrected for small systems,
analytical understanding of
transport model results
& canonical suppression

Parton opacity puzzle

Only resolved recently

DM & Gyulassy, NPA 697 ('02): $v_2(p_T, \chi)$ in Au+Au at RHIC

From Denes Molnar



parton transport model MPC

$2 \to 2$ **only, forward-peaked**

$\sigma_{tr} \approx 0.3\sigma_{tot}$

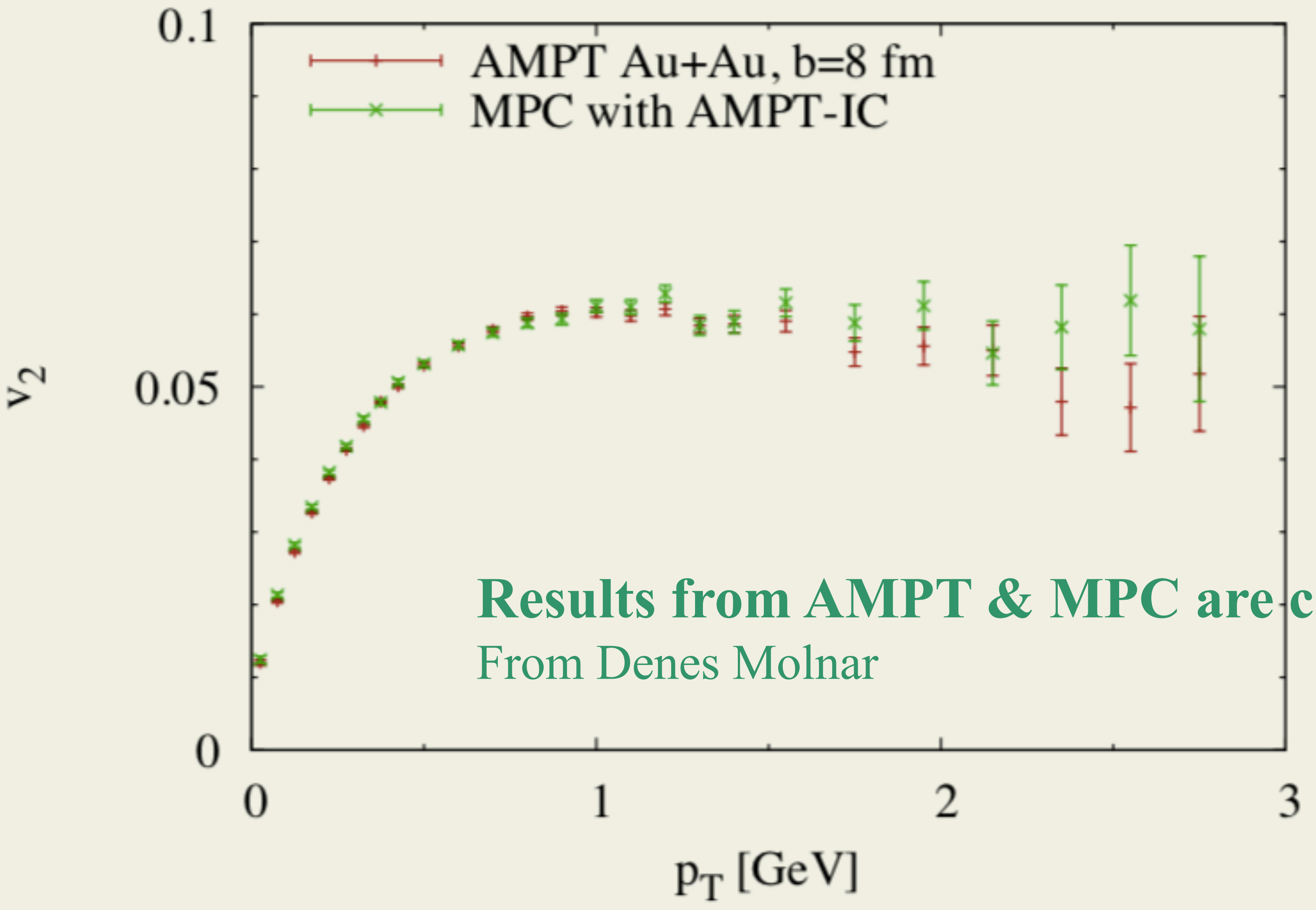
Au+Au @ 130 GeV, $b = 8$ fm

- minijet initconds
- 1 parton → 1 π hadronization

perturbative $\sigma_{gg\to gg} \approx 3$ **mb gives** $v_2 \approx 2\%$ → **need 15× higher opacity**

radiative $gg \leftrightarrow ggg$ **helps (e.g., BAMPS)... but AMPT has pure elastic** $2 \to 2$

4) MPC with full AMPT initial conditions (same $\vec{p}$, $\vec{x}$, t for each parton)



Results from AMPT & MPC are consistent

From Denes Molnar

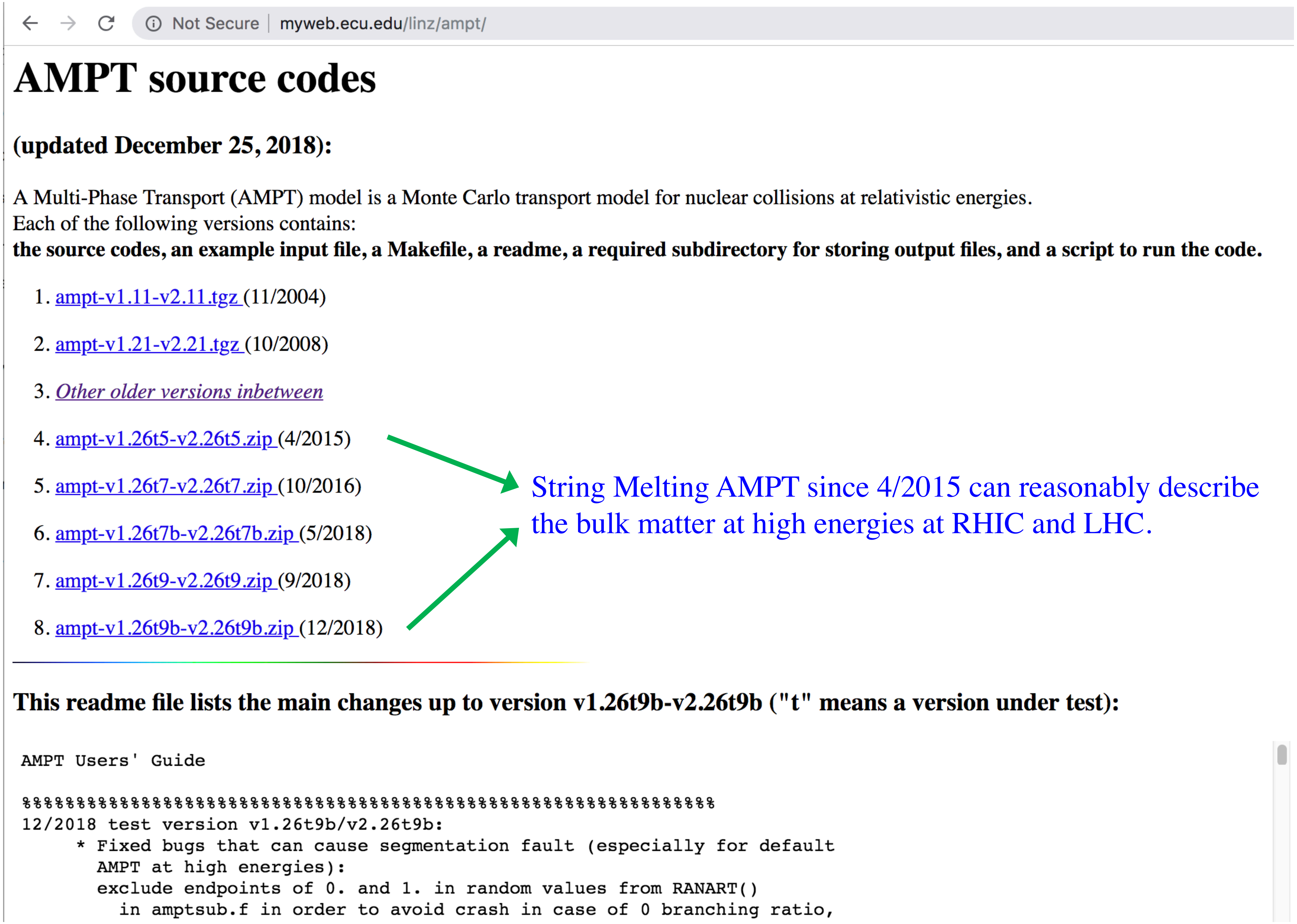
MPC with $\sigma = 3$ mb ($\ell = 1$) **reproduces the elliptic flow from AMPT!**

We need to further develop AMPT model with better & new physics
in order to more accurately describe the dense matter evolution
(including non-equilibrium effects) and extract its properties

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

- Discovery of the triangular flow v_3 — Alver & Roland, PRC 81 (2010)
- Longitudinal (de)correlations of flows — Pang et al. PRC 91 (2015) & EPJA52 (2016)
- v_2 may be dominated by anisotropic escape but has strong flavor dependence — L He et al. PLB 753 (2016); ZWL et al. NPA 956 (2016); ZWL at SQM2017; HL Li et al. PRC 99 (2019)
- CME signal and background — Shou, Ma & Ma, PRC 90 (2014); Huang, Ma & Ma, PRC 97 (2018); HJ Xu et al. PRL 121 (2018), CPC 42 (2018); Zhao, Ma & Ma, PRC 97 (2018), PRC 99 (2019) & PLB 792 (2019)
- Vorticity & polarization observables — Jiang et al. PRC 94 (2016); H Li et al. PRC 96 (2017); Lan et al. PLB 780 (2018)

AMPT codes are available online since 2004



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 the bulk matter at high energies at RHIC and 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,
```

Outline

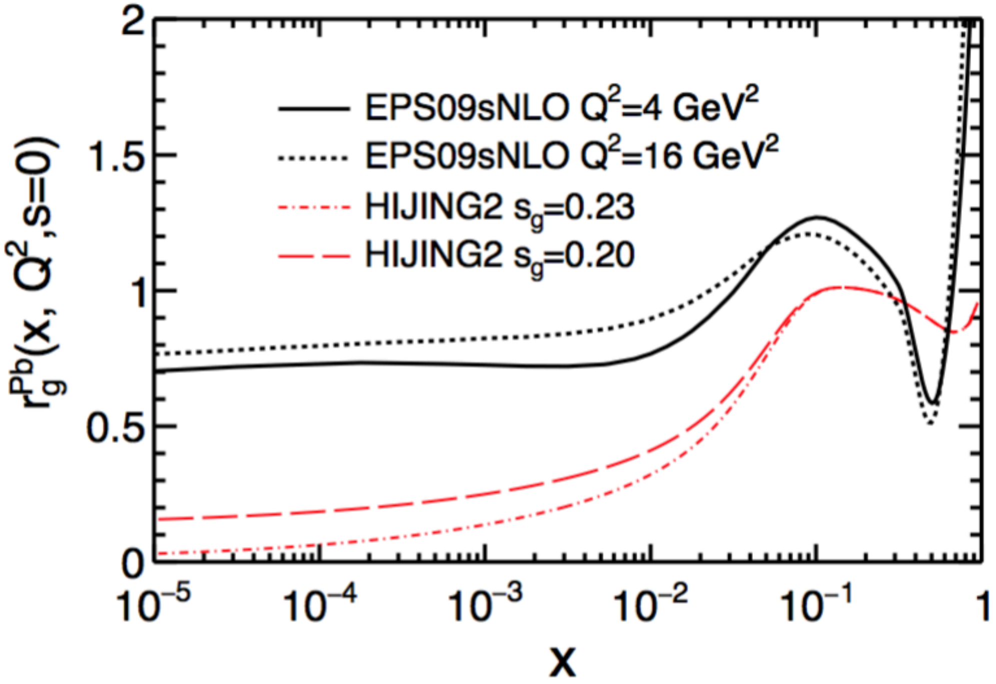
- Motivation
- **Recent developments to improve AMPT**
- Possible future directions

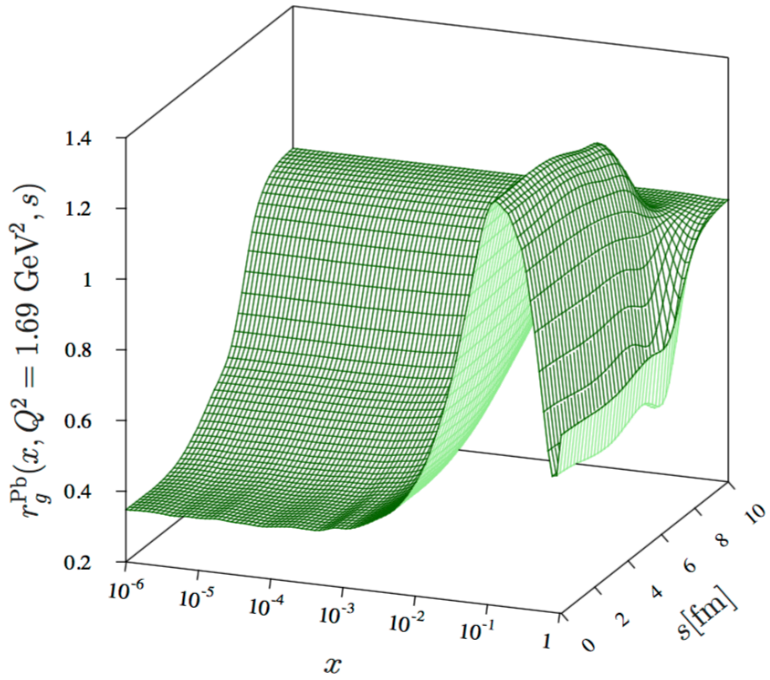
Recent efforts to improve the AMPT model include

- Improvement of quark coalescence — He & ZWL, PRC 96 (2017)
- Correction of hadron cascade for charge conservation — ZWL & GL Ma
- Include finite nuclear thickness in string-melting AMPT — ZWL, PRC 98 (2018)
  ZWL & Mendenhall
- Implement modern PDF and nuclear shadowing & improvements of heavy flavor productions — ZWL & CCNU/Liu, Shi, Zhang & Zheng
- Benchmark and improve ZPC parton cascade — X Zhao & ZWL
- Extension with chiral dynamics & potentials — J Xu et al.

Improve AMPT with Modern PDFs of Nuclei

$$f_i^A(x,Q^2) \equiv R_i^A(x,Q^2) f_i^{\mathrm{CTEQ6.1M}}(x,Q^2)$$





Incorporation of modern nPDFs should improve AMPT on heavy flavor & high p_T observables:

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

We now use

CTEQ6.1M PDFs for free nucleon

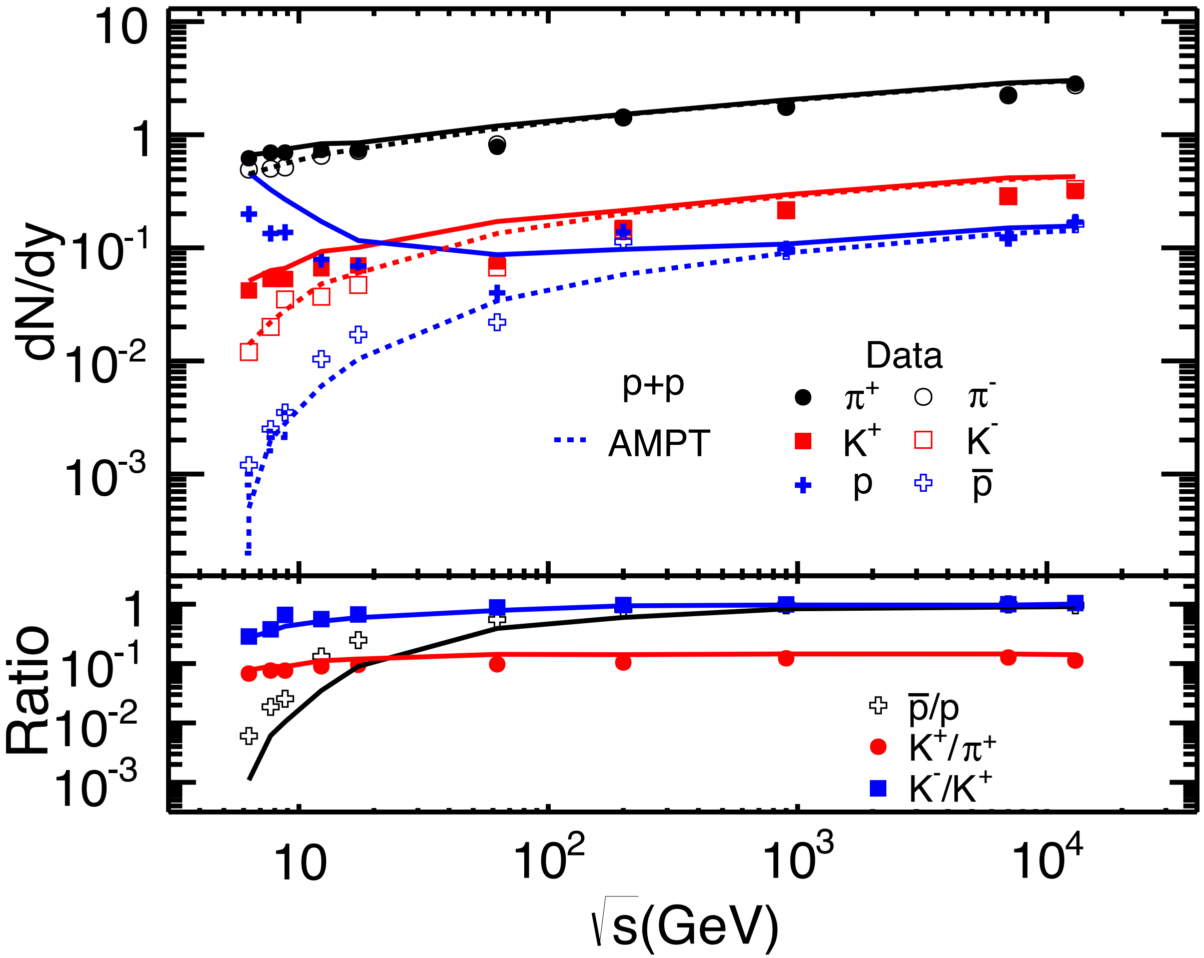
EPS09s: Spatial-dependent nuclear shadowing, has Q^2 evolution

arXiv:1903.03292

Based on Chao Zhang's talk

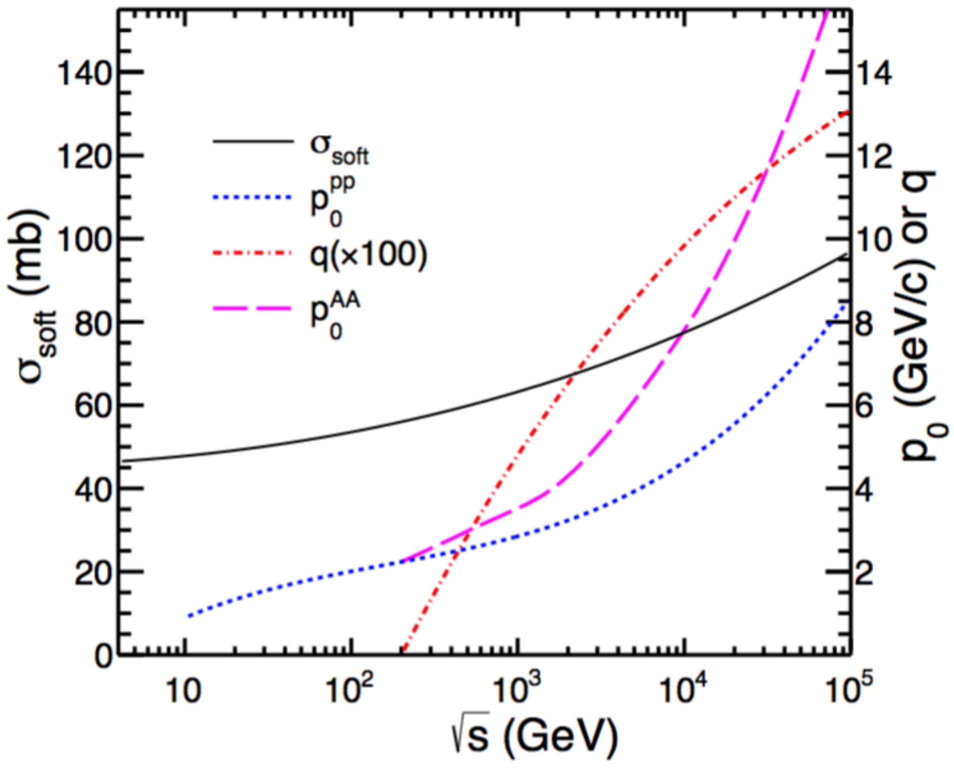
π/K/p productions in pp

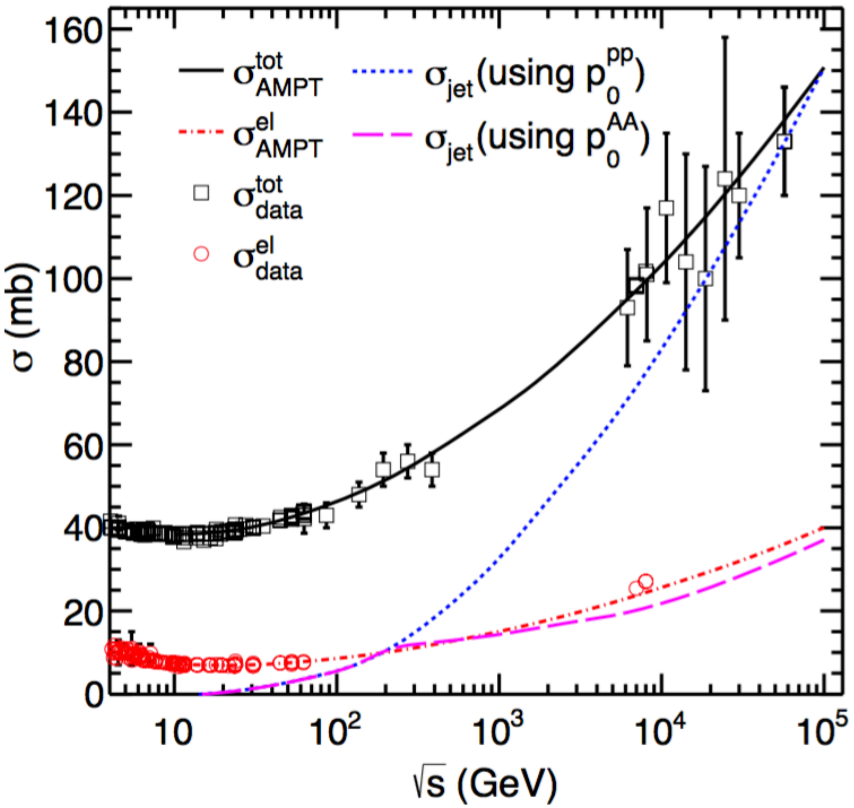
- ➢ π and K productions from the new AMPT model are consistent with data.
- ➢ AMPT underestimates anti-proton yields and overestimates the proton yields at low colliding energies.



Based on Chao Zhang's talk

Nuclear scaling of minijet cutoff p_0





$$p_0^{AA} = p_0^{pp} A^{q(s)}$$

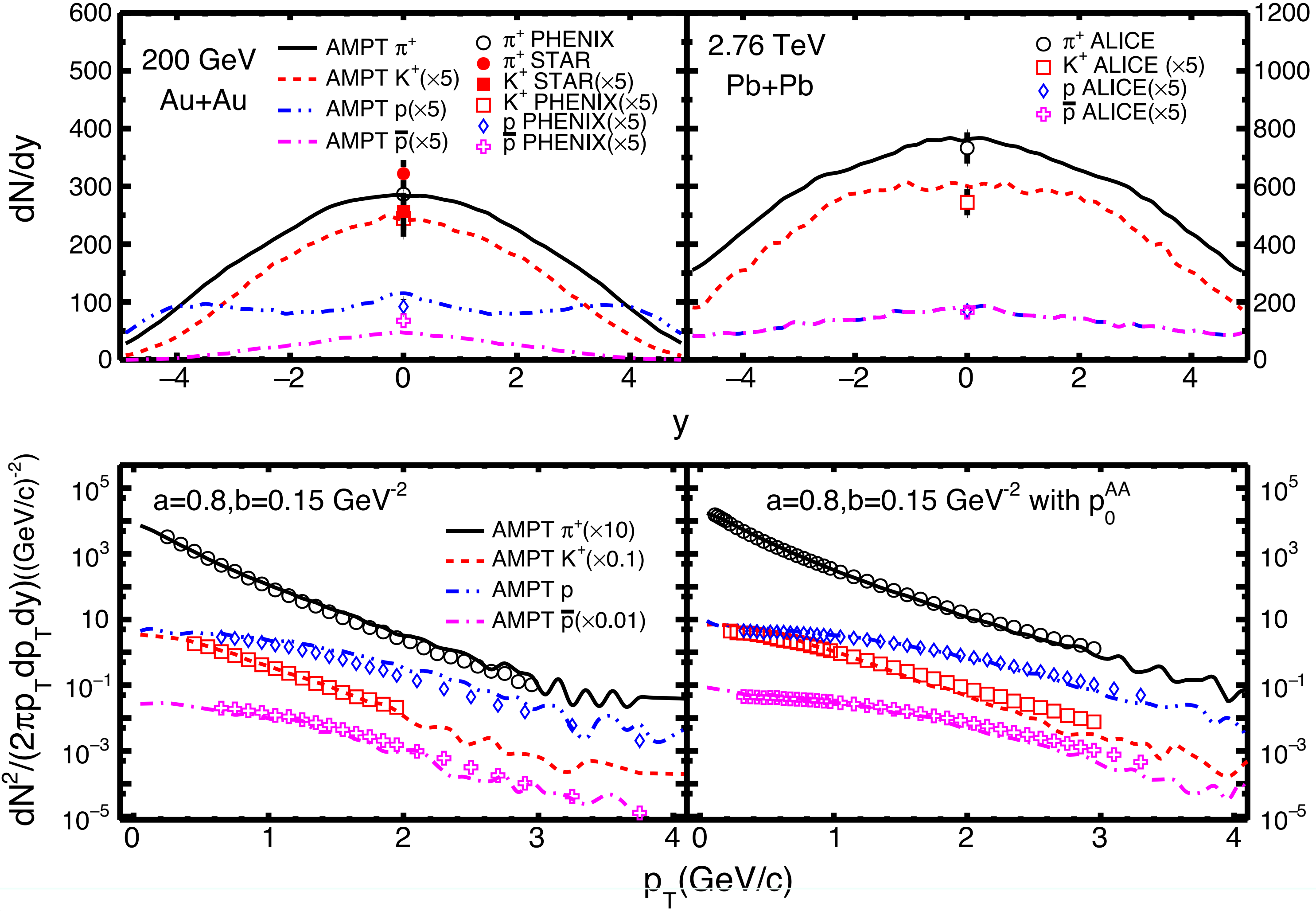
Motivated by *Qs* of saturation models.

q(s): starts from 0 at 200AGeV,
~0.16 at ~10^7AGeV

- **A significant increase of p_0^{pp} leads to big suppression of σ_{jet}**

Based on Chao Zhang's talk

π/K/p productions in AA



- **String melting AMPT reasonably reproduce bulk data for central AA collisions at RHIC and LHC energies**

Based on Chao Zhang’s talk

Improve Heavy Flavor (HF) Productions

$gg \rightarrow gg$ cross section
in leading-order pQCD:

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

$$\simeq \frac{9\pi\alpha_s^2}{2}\left(\frac{1}{t^2} + \frac{1}{u^2}\right) \simeq \frac{9\pi\alpha_s^2}{2t^2}$$

is divergent for massless g,
so HIJING uses a
minijet cutoff p_0
for minijets of all flavors.

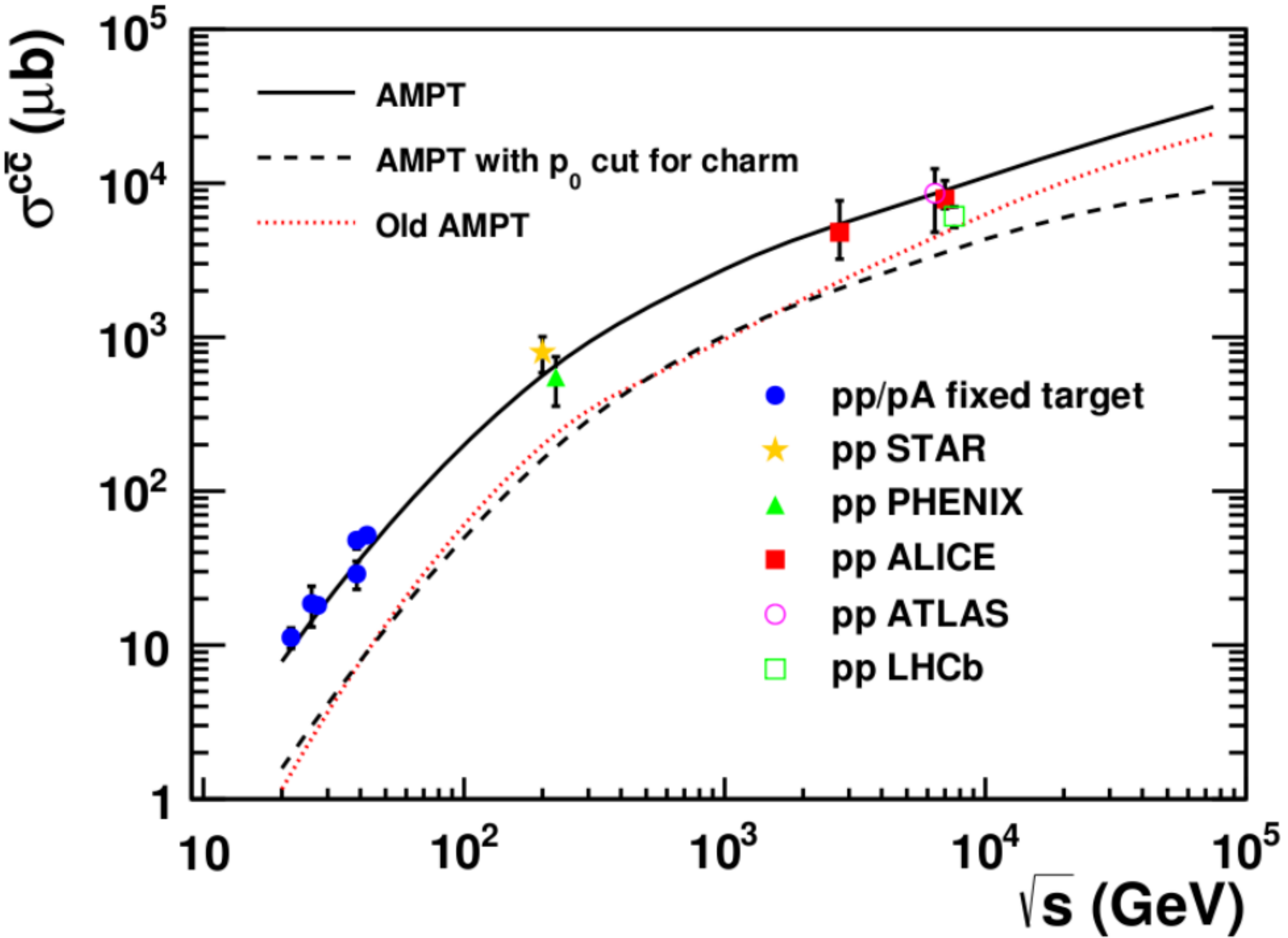
But heavy flavor production should not be subject to this cutoff due to the heavy quark mass >> Λ_{QCD} , e.g. in FONLL

$$q + \bar{q} \rightarrow Q + \bar{Q}, \quad g + g \rightarrow Q + \bar{Q}$$

So we now remove the p_0 cut on HF productions

Based on Liang Zheng's talk

Charm quark productions in pp

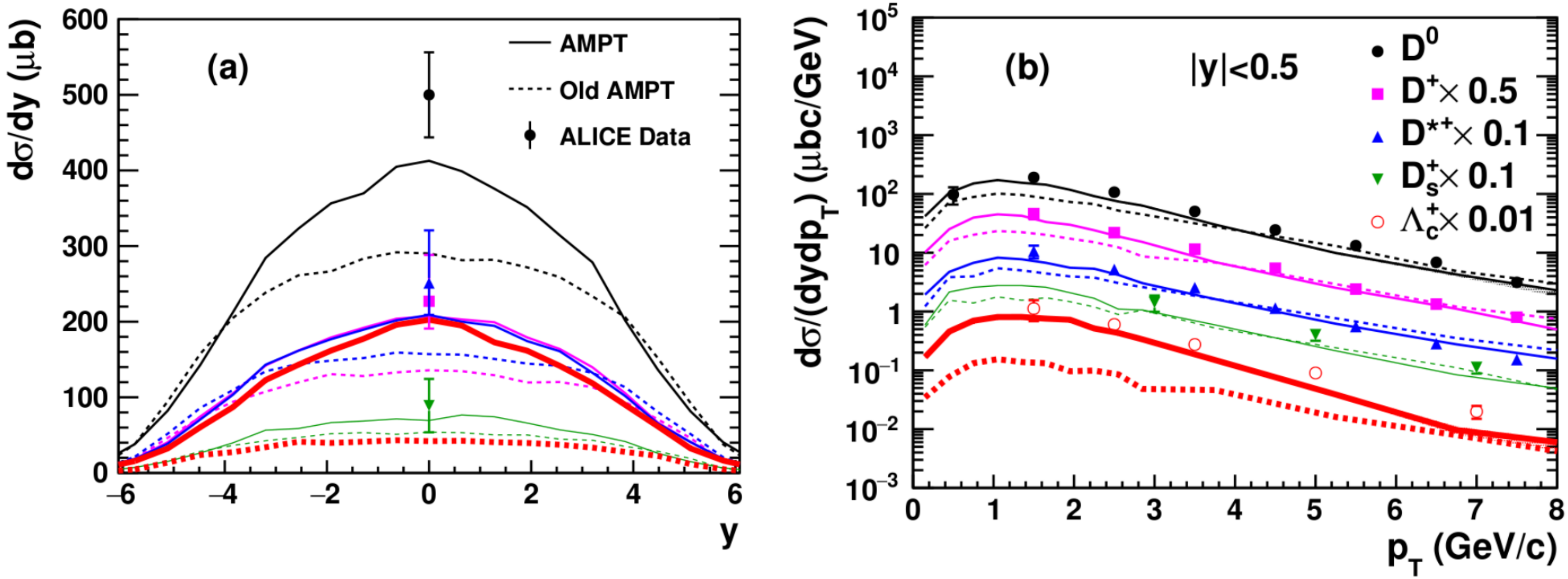


- **Old AMPT charm yield << data**
- **Removing p_0 greatly enhances charm yield**
- **Updated AMPT model well describes world data**

Based on Liang Zheng's talk

Charm hadron productions in pp

pp at 7 TeV

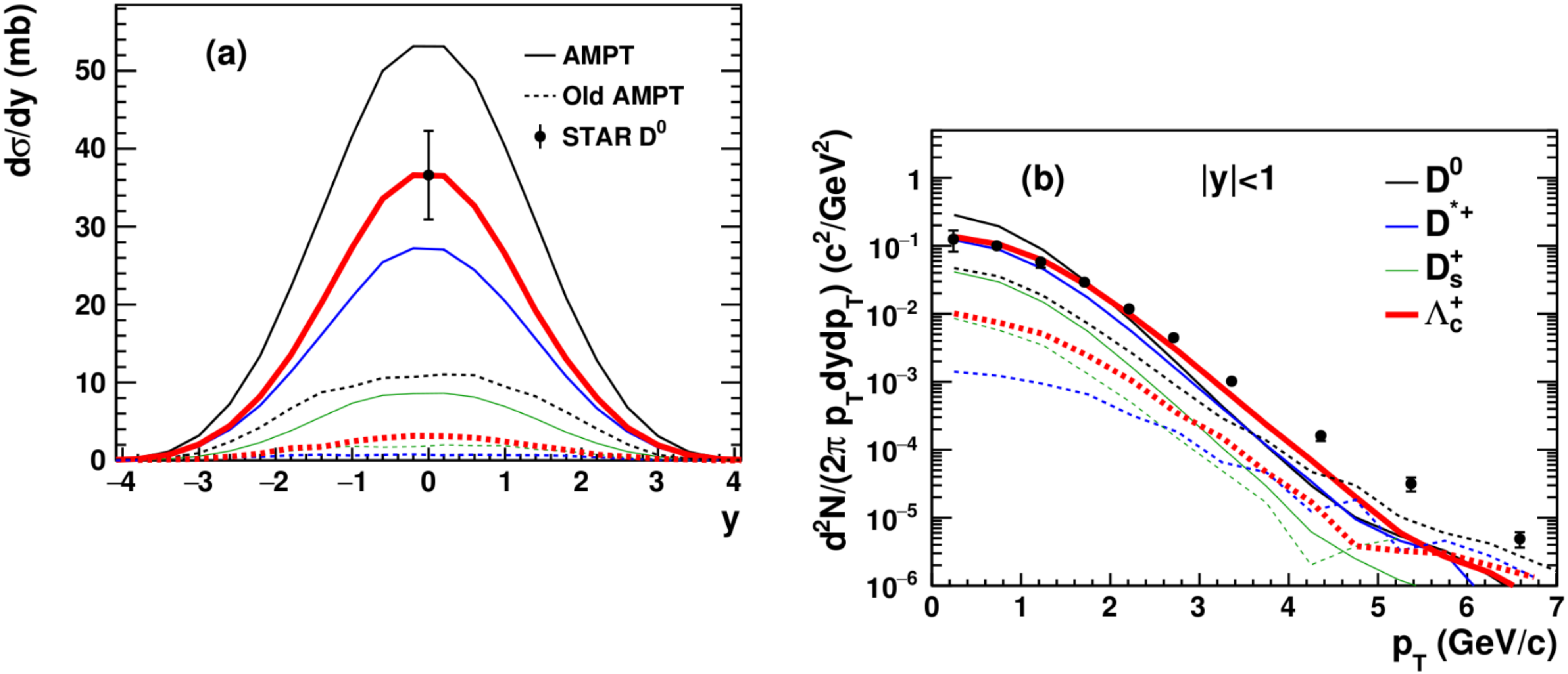


- **Reasonable agreement with data for various open charm particles**

Based on Liang Zheng’s talk

Charm hadron productions in AA

AuAu 200 GeV

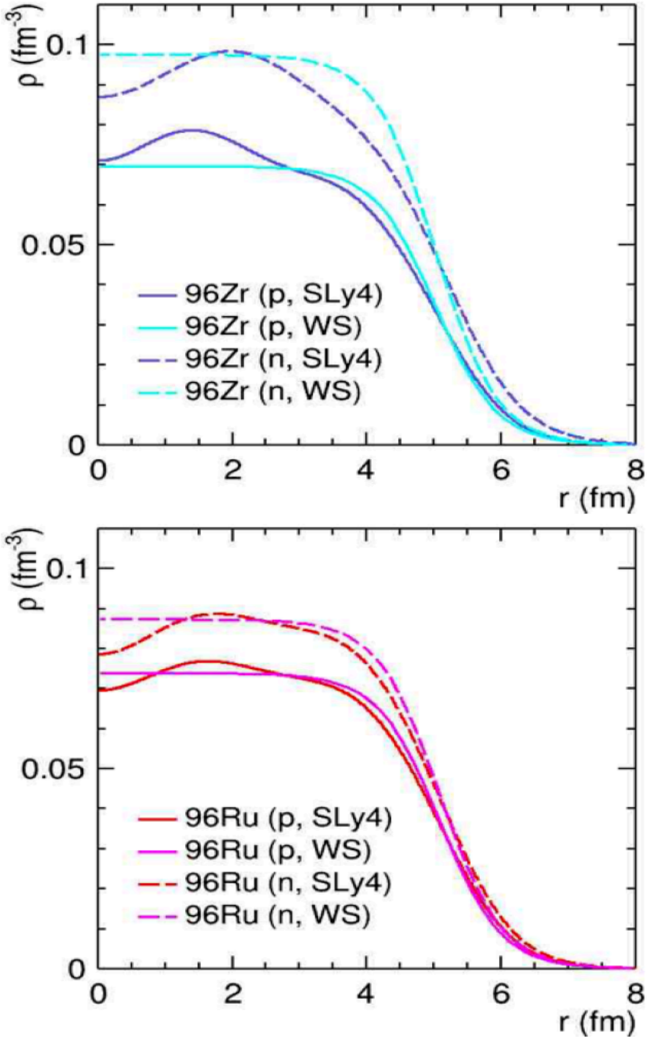


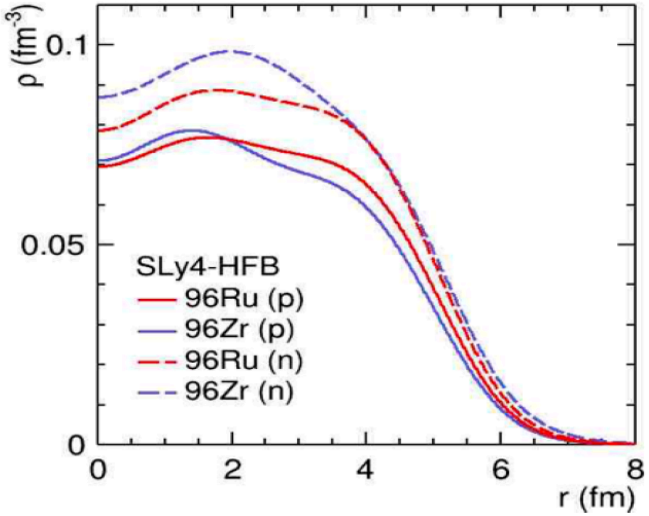
- **D^0 yield roughly consistent with STAR data**
- **D^0 spectrum is softer than data,** but depends on parton cross section and flavor excitation process (*not explored yet*)

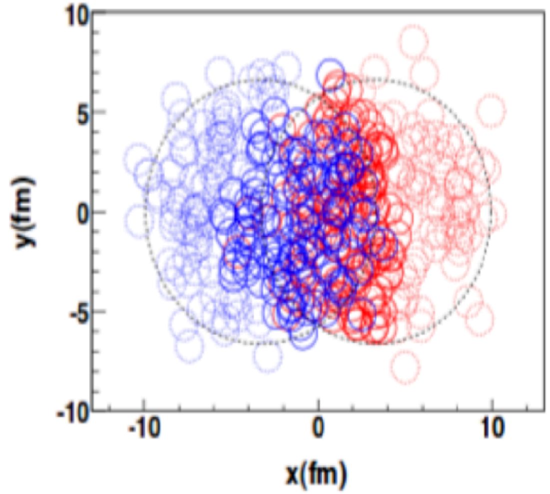
Based on Liang Zheng's talk

Density profiles

AMPT is modified to take in arbitrary p & n density profiles:
HJ Xu et al. PRL 121 (2018), CPC 42 (2018)





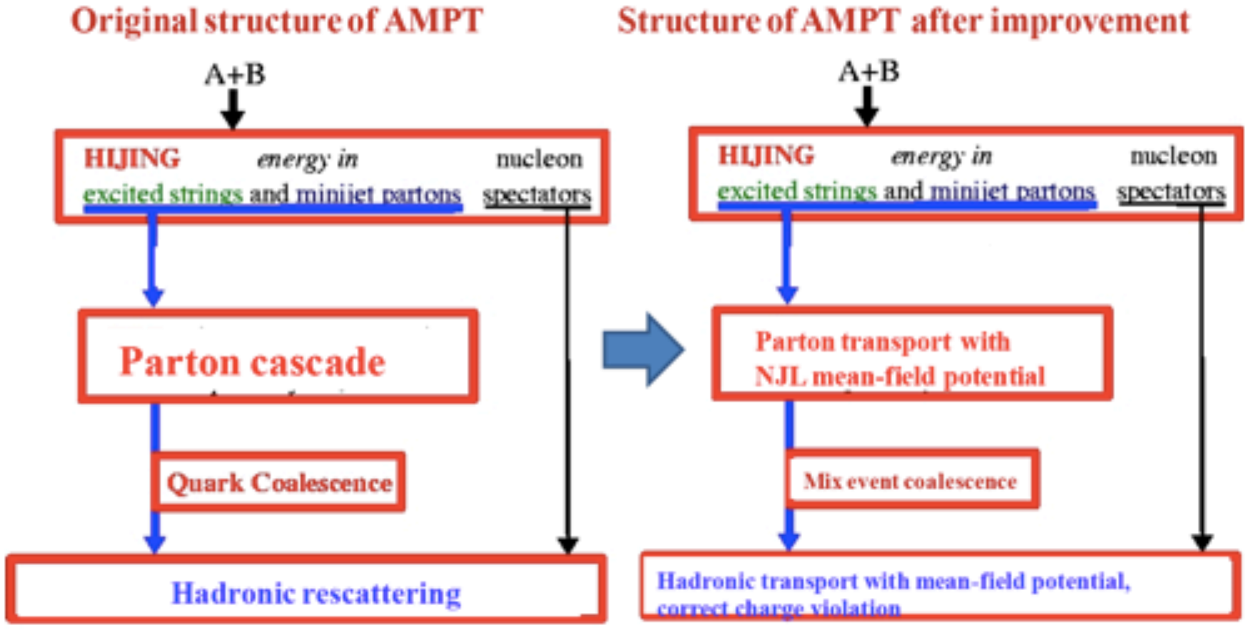


DFT VS WS

Event by event fluctuations

From Hanlin Li

An extended AMPT with mean-field potentials



Original structure of AMPT

A+B

HIJING *energy in* excited strings and minijet partons | nucleon spectators

Parton cascade

Quark Coalescence

Hadronic rescattering

Structure of AMPT after improvement

A+B

HIJING *energy in* excited strings and minijet partons | nucleon spectators

Parton transport with NJL mean-field potential

Mix event coalescence

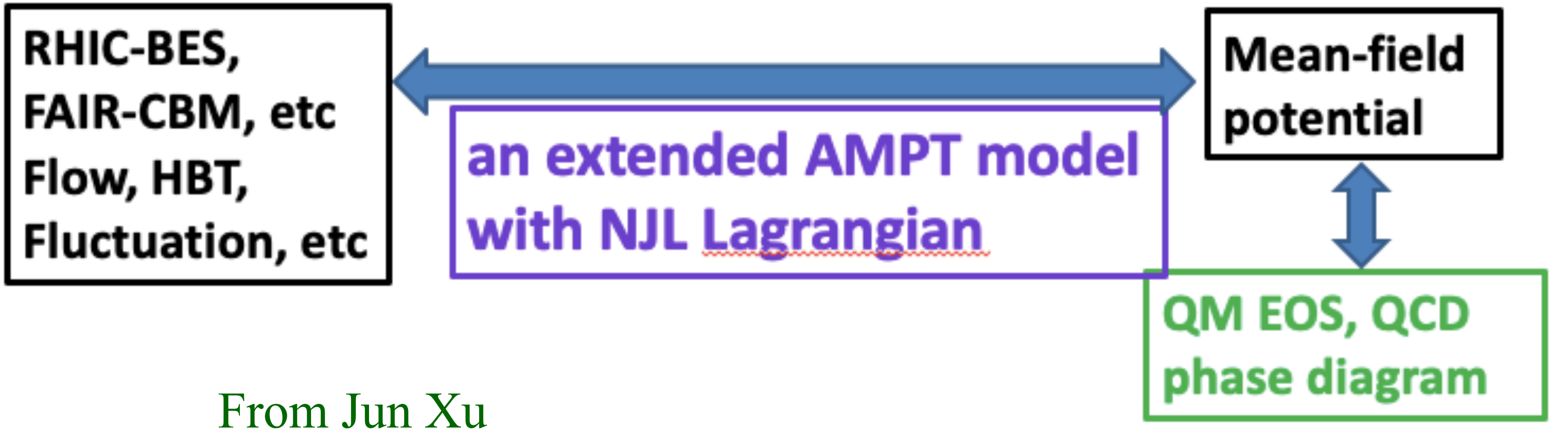
Hadronic transport with mean-field potential, correct charge violation

Suitable for top RHIC and LHC

Suitable for RHIC-BES and FAIR-CBM

In progress:
pNJL transport
He Liu and
Che Ming Ko

In progress:
Coalescence in
both r and p space
Feng-Tao Wang and
Jun Xu



RHIC-BES,
FAIR-CBM, etc
Flow, HBT,
Fluctuation, etc

an extended AMPT model
with NJL Lagrangian

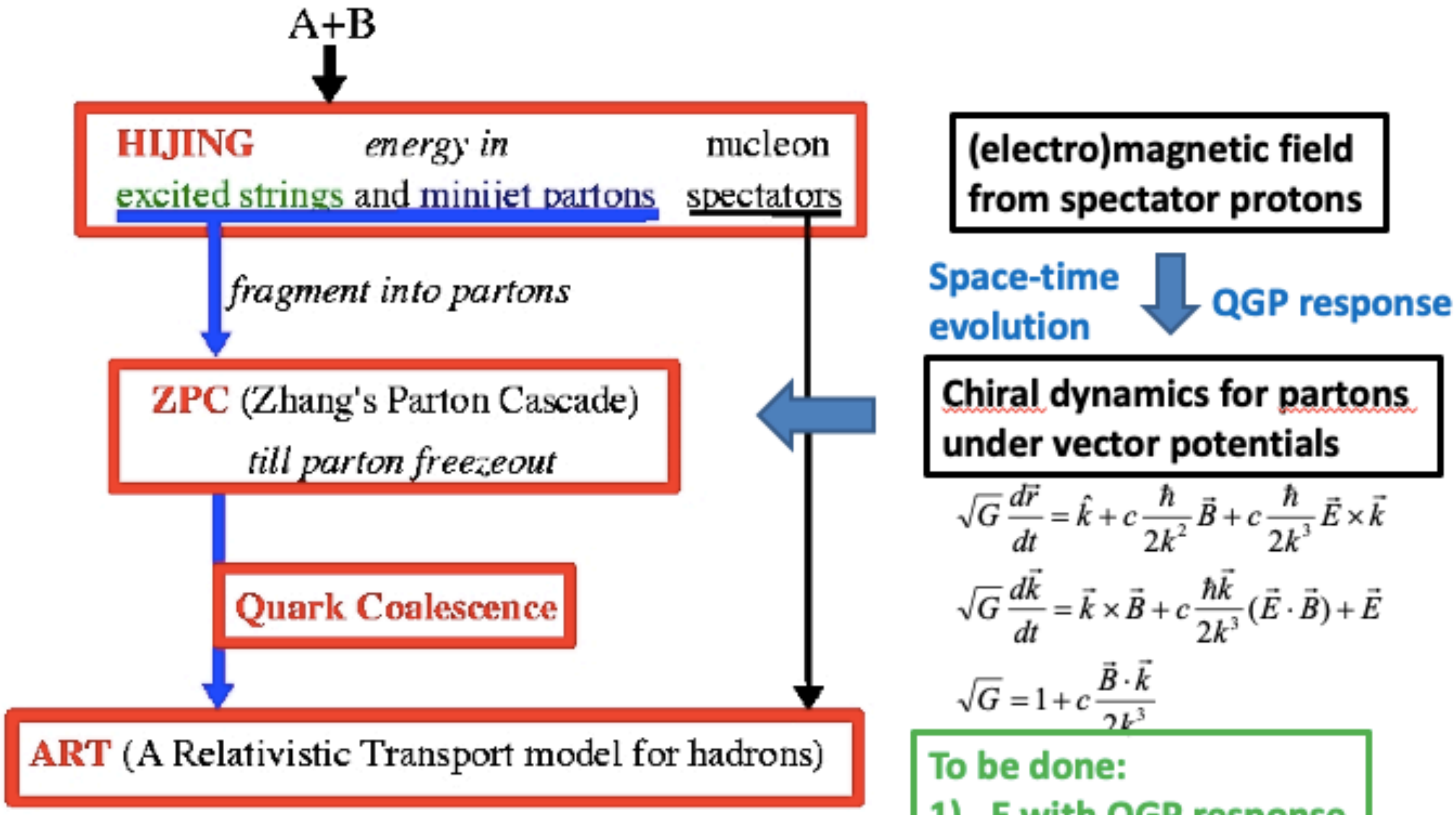
Mean-field
potential

QM EOS, QCD
phase diagram

From Jun Xu

An extended AMPT with chiral dynamics

Structure of AMPT model with string melting



A+B

HIJING *energy in* excited strings and minijet partons

nucleon spectators

fragment into partons

ZPC (Zhang's Parton Cascade) *till parton freezeout*

Quark Coalescence

ART (A Relativistic Transport model for hadrons)

(electro)magnetic field from spectator protons

Space-time evolution

QGP response

Chiral dynamics for partons under vector potentials

$$\sqrt{G}\frac{d\vec{r}}{dt} = \hat{k} + c\frac{\hbar}{2k^2}\vec{B} + c\frac{\hbar}{2k^3}\vec{E}\times\vec{k}$$

$$\sqrt{G}\frac{d\vec{k}}{dt} = \vec{k}\times\vec{B} + c\frac{\hbar\vec{k}}{2k^3}(\vec{E}\cdot\vec{B}) + \vec{E}$$

$$\sqrt{G} = 1 + c\frac{\vec{B}\cdot\vec{k}}{2k^3}$$

To be done:

1) E with QGP response
2) EOM with vorticity

From Jun Xu

Improve String Melting AMPT by Including Finite Nuclear Thickness

The Bjorken formula $\epsilon(\tau) = \frac{1}{\tau_F A_T} \frac{dE_T(\tau)}{dy}$

neglects

the finite thickness of (boosted) nuclei

→ it is only valid at high energies

where crossing time $d_t << \tau_F$

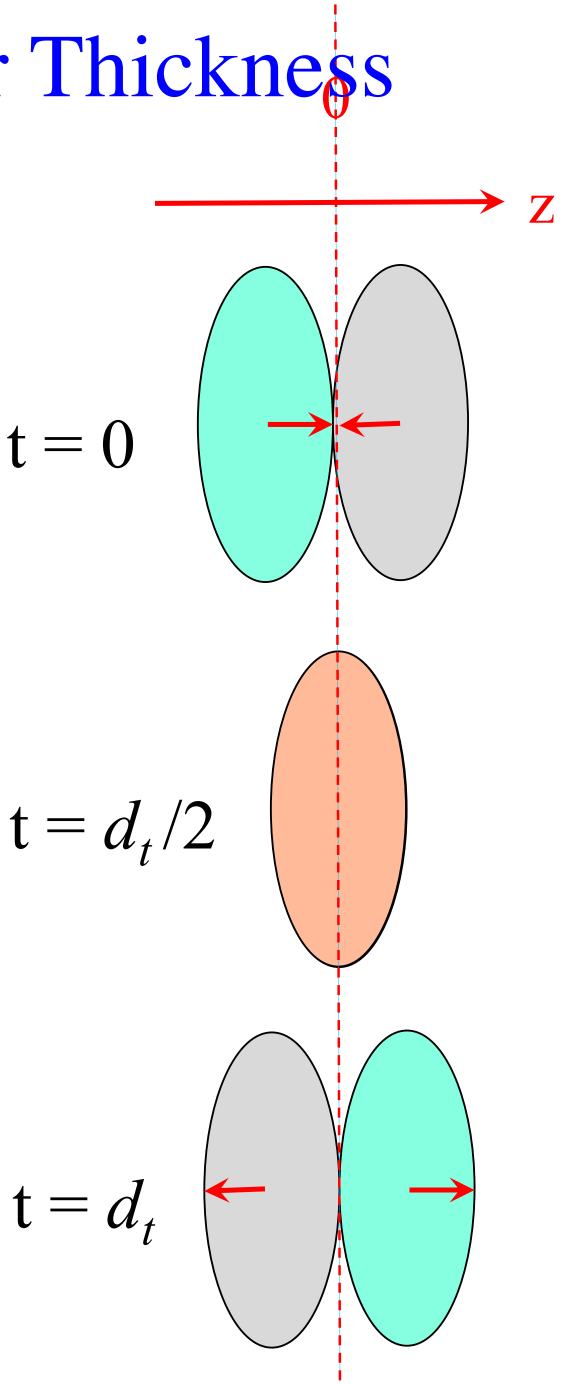
Crossing time $$d_t = \frac{2R_A}{\sinh y_{CM}} = \frac{2R_A}{\gamma \beta}$$

For central Au+Au collisions:

$\sqrt{s_{NN}}\ (GeV)$	5	11.5	27	50	200
$d_t\ (fm/c)$	5.3	2.2	0.91	0.49	0.12

→ the Bjorken formula is only valid for

$\sqrt{s_{NN}} \gg 50GeV$ for $\tau_F = 0.5\ fm/c$

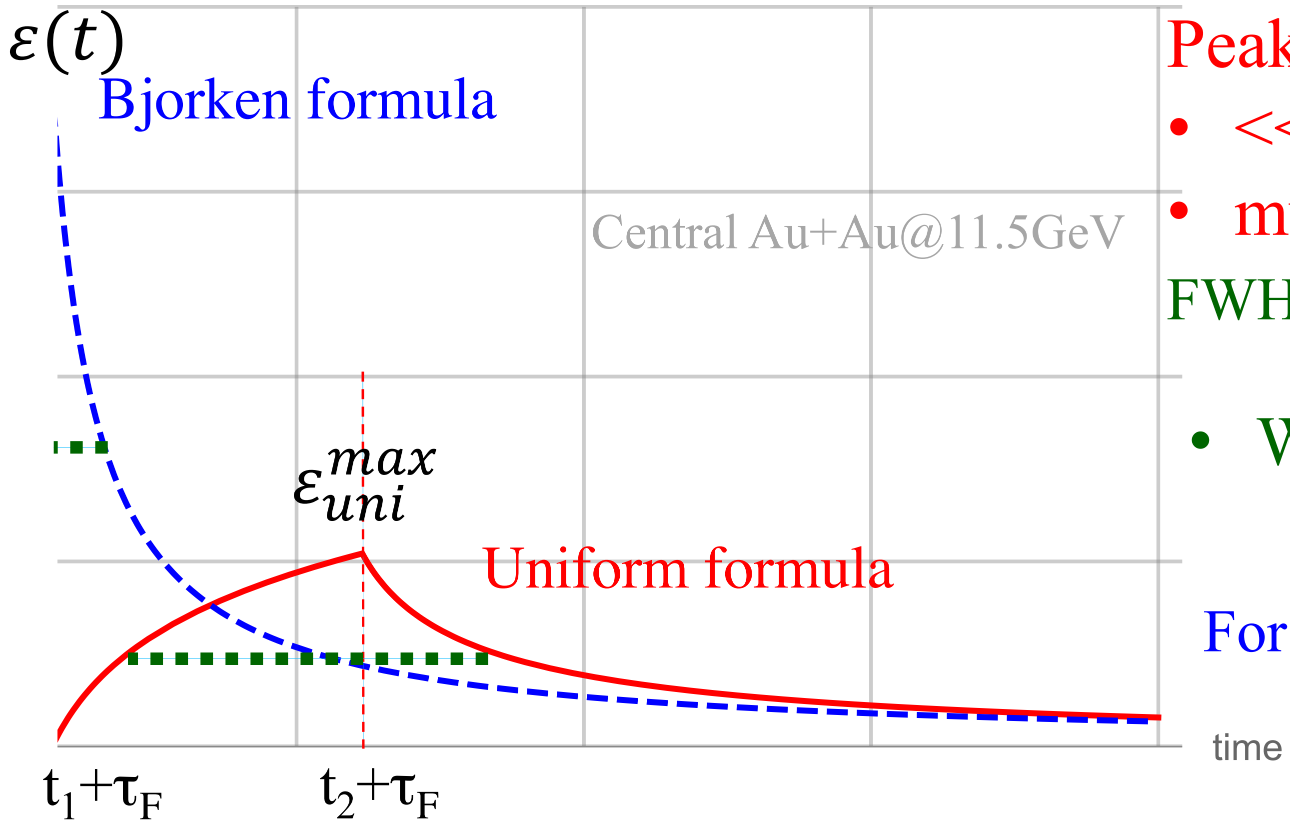


Extension of the Bjorken formula: the uniform profile:

initial energy (at y~0) is produced uniformly from time ***t_1*** to ***t_2***

$$\begin{aligned}\epsilon_{\rm uni}(t) &= \frac{1}{A_{\rm T} t_{21}} \frac{dE_{\rm T}}{dy} \ln\left(\frac{t-t_1}{\tau_{\rm F}}\right), \text{if } t \in [t_1+\tau_{\rm F}, t_2+\tau_{\rm F}]; \\ &= \frac{1}{A_{\rm T} t_{21}} \frac{dE_{\rm T}}{dy} \ln\left(\frac{t-t_1}{t-t_2}\right), \text{if } t \geq t_2+\tau_{\rm F}.\end{aligned}$$

$$t_{21} \equiv t_2 - t_1$$



At low energy: $t_{21}/\tau_F >> 1$:

Peak energy density:

- << Bjorken value
- much less sensitive to τ_F

FWHM width in t >> Bjorken

- When $t >> (t_2+\tau_F)$:
  $\varepsilon_{uni}(t) \to \varepsilon_{Bj}(t)$

For $t_{21}/\tau_F \to 0$ (high energy):
our result → *Bjorken*

ZWL, PRC 98 (2018)

ZWL, PRC 98 (2018)

- AMPT with F.T.

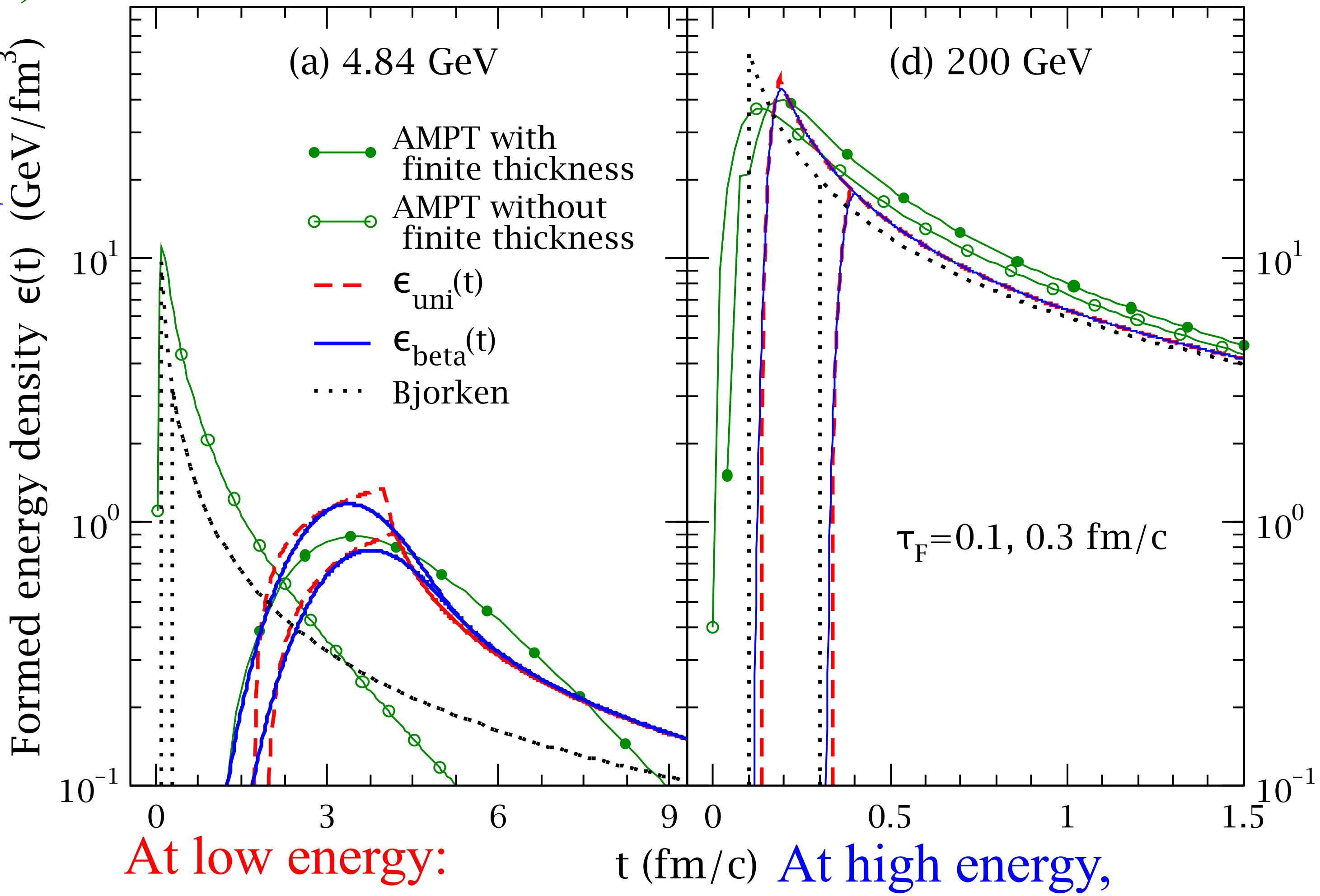
~analytical extension of Bjorken formiula

- AMPT w/o F.T.

~ Bjorken formula.

- *Small F.T. effect at high energy.*

F.T.=finite thickness



At low energy:

ε^{max} << Bjorken value,

is much less sensitive to τ_F :

factor of 2.1 or 2.5 change (not factor of 9) when τ_F changes from 0.1 to 0.9 fm/c.

At high energy, solution ~ Bjorken.

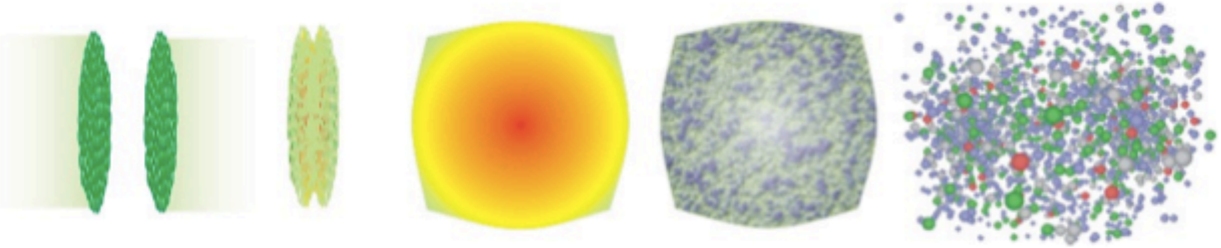
We are incorporating finite thickness into string melting AMPT that has the improved quark coalescence. Ongoing with Yuncun He

Outline

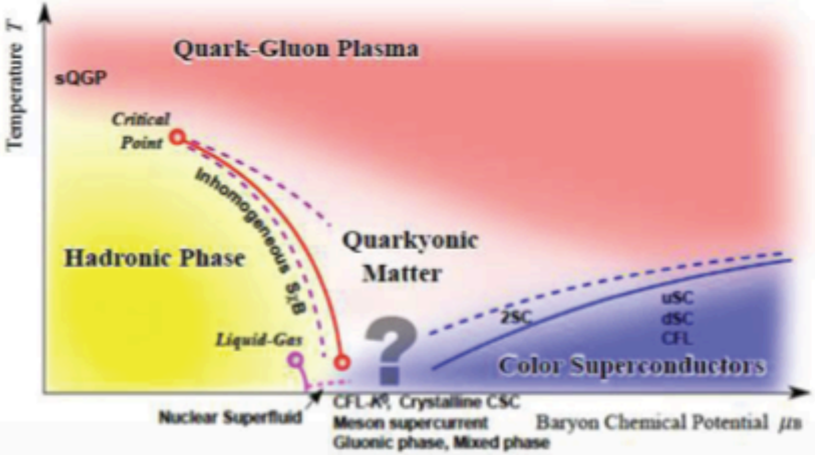
- Motivation
- Recent developments to improve AMPT
- **Possible future directions**
    - Couple AMPT with FRG to explore effects of QCD critical point
    - Further studies of heavy flavour observables
    - Validation and improvement of parton cascade

AMPT and FRG complement each other

- **AMPT**: a good **dynamical** model including important evolution stages of heavy-ion collisions, can directly compare with experimental observables.



- **FRG**: a non-perturbative **static** QCD approach, well describes QCD phase transitions, and consistent with lattice QCD.



From Wei-Jie Fu

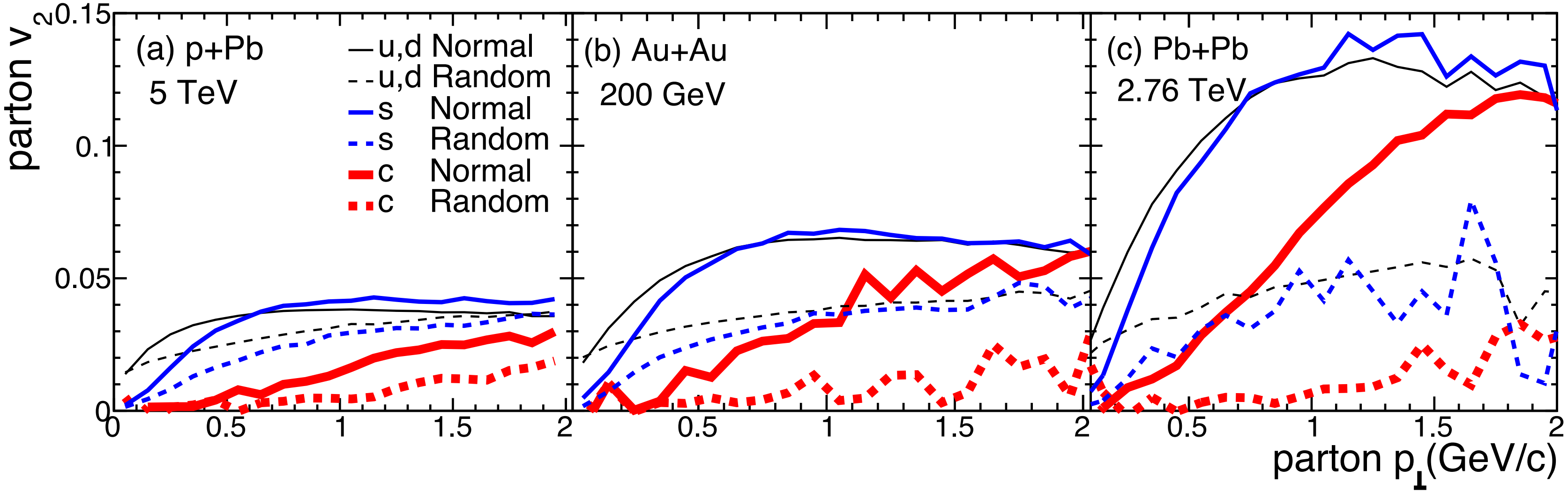
Plan of combining AMPT with FRG

- Model parton collisions with FRG at finite temperature and chemical potential.
- Relate chiral and deconfinement order parameters to parton potential in AMPT.
- Relate sigma mode near CEP to interaction potential.
- Improve the hadronization in AMPT with FRG phase transition.
- Study hadronic modification of CEP signals.

From Wei-Jie Fu

Further Studies of Heavy Flavor Observables

with CCNU/Shusu Shi et al.



HL Li, ZWL, F Wang, PRC 99 (2019)

Updated AMPT with modern nPDFs and removal of p0 cutoff provides a good transport model foundation for open heavy flavour.

We can study

- HF hadrons together with light hadrons
- ratios like Λc/D to study quark coalescence picture
- both HF flows and R_{AA} to extract HF transport property

(below the p_T scale where elastic dE/dx dominates)

Validation and Improvement of Parton Cascade

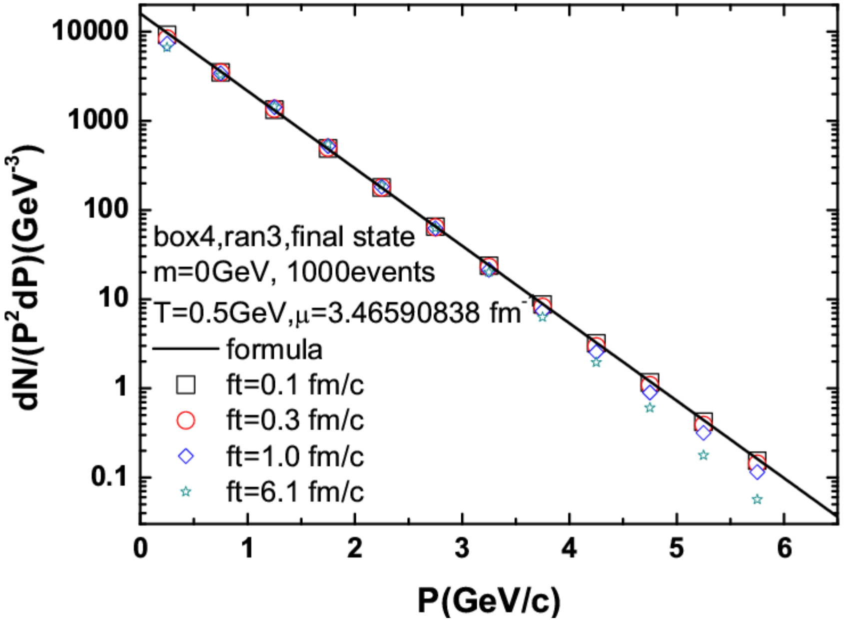
Zhao Xinli & ZWL

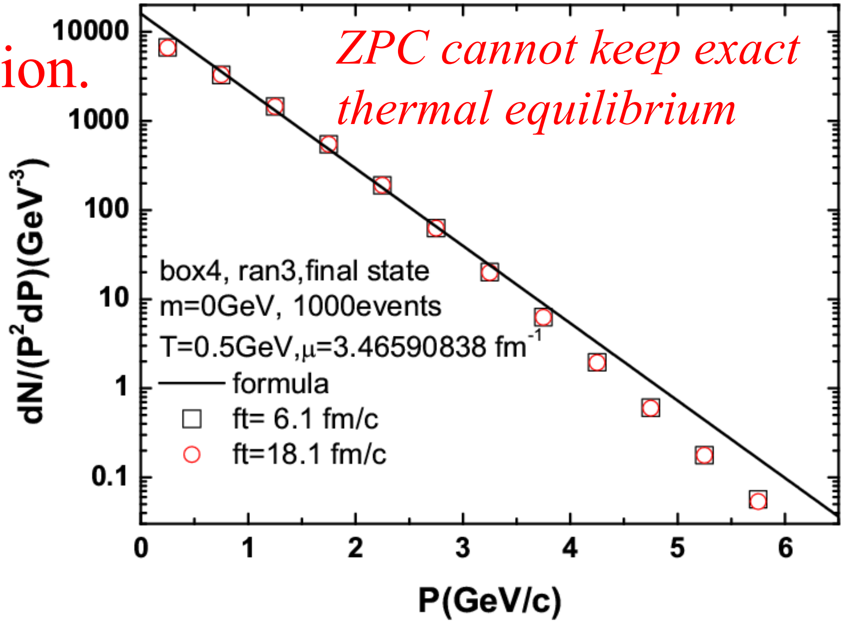
Flows like v_2 & v_3 at high energies
mostly comes from
the parton cascade in AMPT.

But ZPC/MPC cascade solution
of the Boltzmann equation is
well known to have causality violation.

Parton subdivision can resolve this problem:
but is very CPU-consuming
& affects/removes e-by-e fluctuation/correlation.

We can
→ study how accurate ZPC is
under expected densities from AMPT
→ explore better ways to
numerically solve Boltzmann equation
→ Then incorporate into AMPT





ZPC cannot keep exact thermal equilibrium

Challenges and Opportunities for AMPT

Outstanding physics problems for AMPT:

1) equation of state of the dense/partonic matter
2) initial gluons & inelastic parton reactions (*QGP chemical composition*), including jet radiative energy loss
3) hadronization (*parton recombination/quark coalescence/fragmentation*)
4) potentials (*partonic and hadronic*)
5) coupling with vorticity
6) coupling with the QCD critical end point

*) other

➔ Outstanding problems for AMPT applications/data comparisons:

- ○ extraction of QGP properties like η/s and transport coefficients
- ○ R_{AA} & flow at high p_T, heavy flavor observables
- ○ modern programming for better maintenance & integration to experiments
- ○ how to distinguish escape mechanism/kinetic theory from hydro?
- ○ v_2 splitting at low energies, v_1
- ○ prediction of polarization observables
- ○ fluctuations from the QCD critical point such as net-baryon cumulants

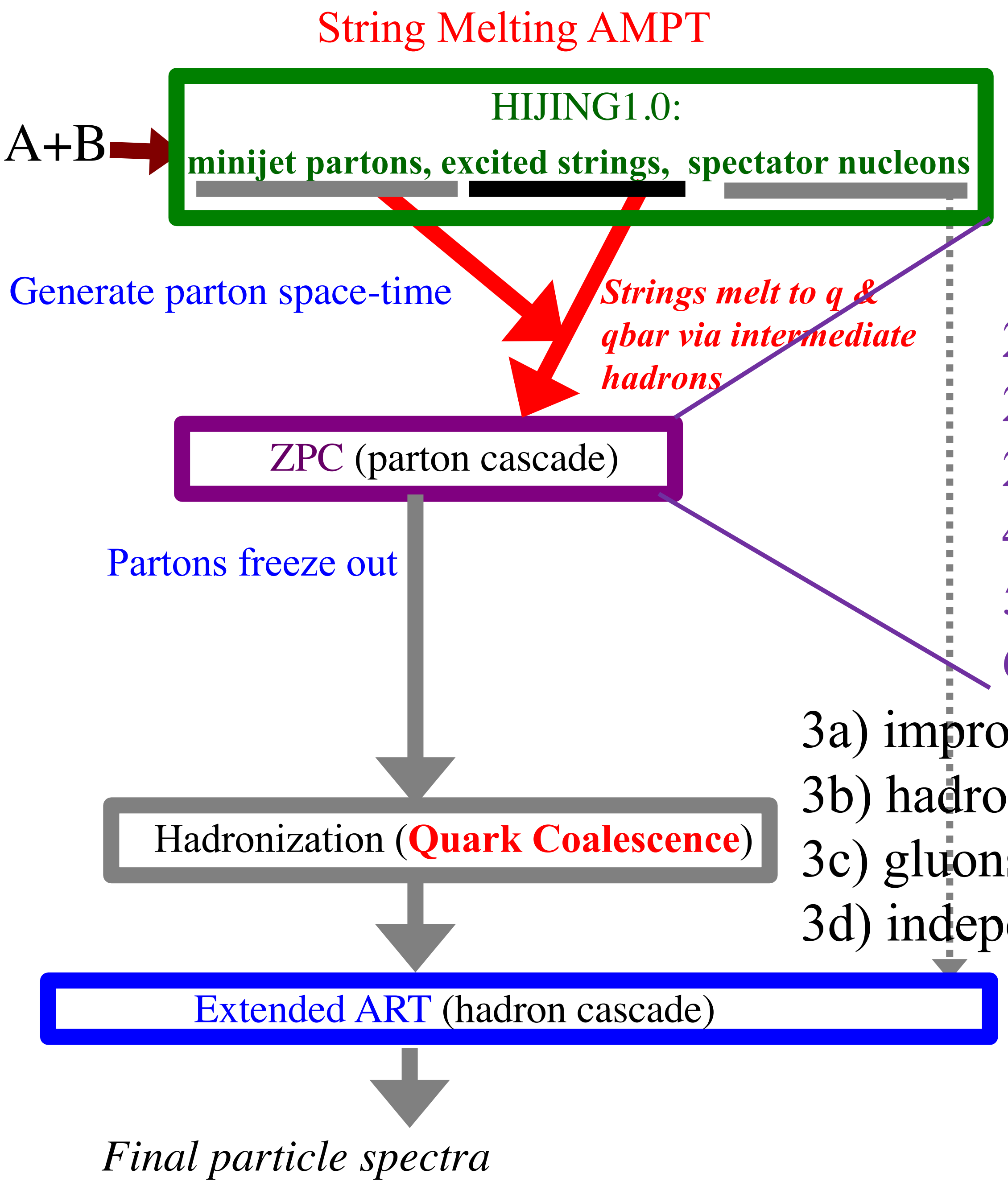
…

Challenges and Opportunities for the AMPT Model

- Some are more relevant for
  lower energies / **BES** energies
- Some are more relevant for
  higher energies / **top RHIC & LHC** energies

- *It will be beneficial to have coordinated efforts to improve AMPT in one or multiple major areas*

Challenges and possible future directions



String Melting AMPT

A+B

HIJING1.0:

minijet partons, excited strings, spectator nucleons

Generate parton space-time

Strings melt to q & qbar via intermediate hadrons

ZPC (parton cascade)

Partons freeze out

Hadronization (**Quark Coalescence**)

Extended ART (hadron cascade)

Final particle spectra

*) *new PDF & shadowing*

2a) gluons in initial condition

1) QCD equation of state

(dynamical parton mass / NJL / FRG?)

2b) 2←→2 inelastic parton reactions

2c) 2 ←→ 3 parton reactions

2d) high-P_T energy loss & HF

4a) parton potentials *(NJL/FRG?)*

5) coupling with vorticity

6) coupling with CEP

3a) improved coalescence/hadronization

3b) hadronization at PT boundary

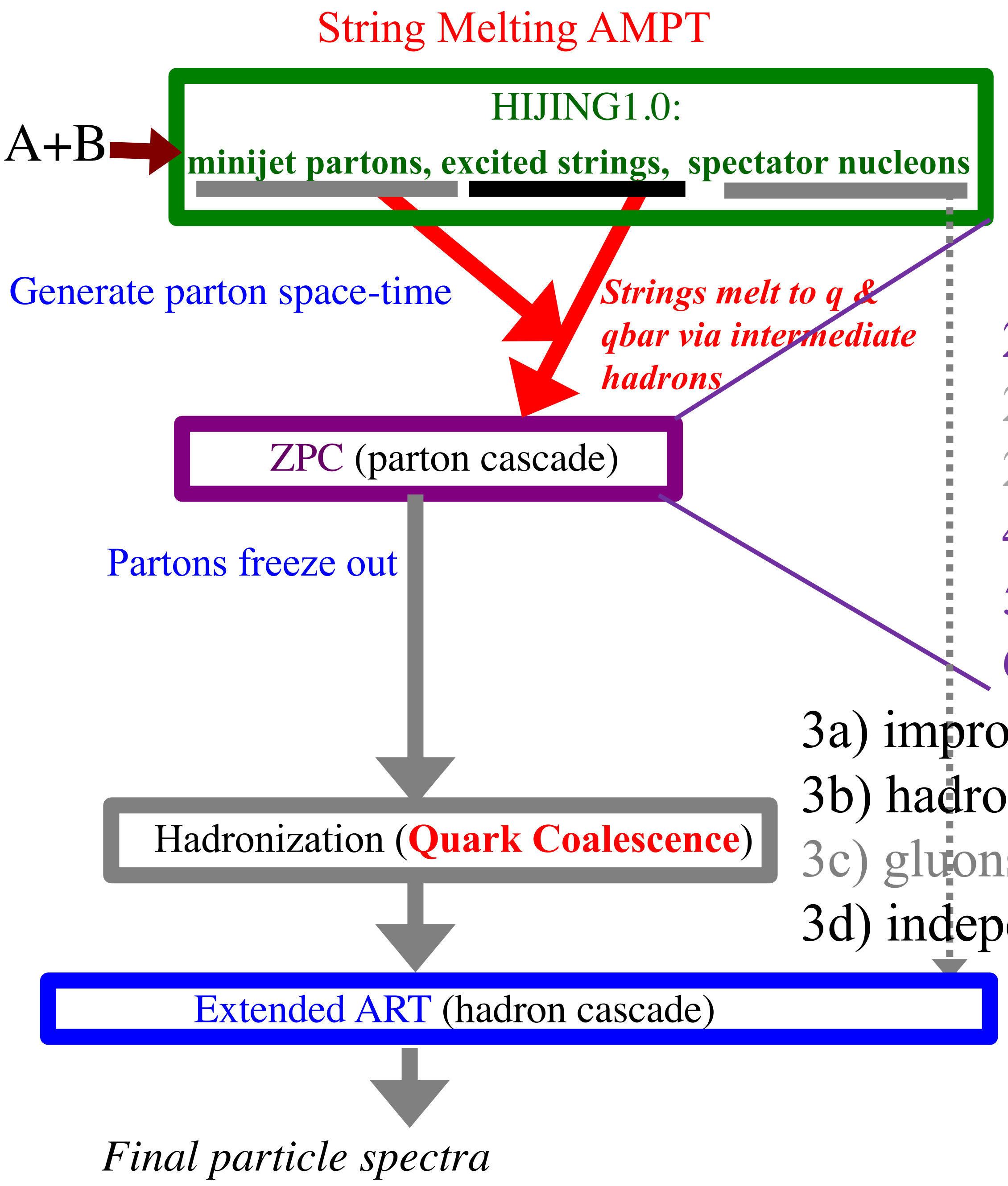
3c) gluons in hadronization

3d) independent fragmentation

4b) hadron potentials

*) *need more resonances*

Challenges and future directions 1: BES



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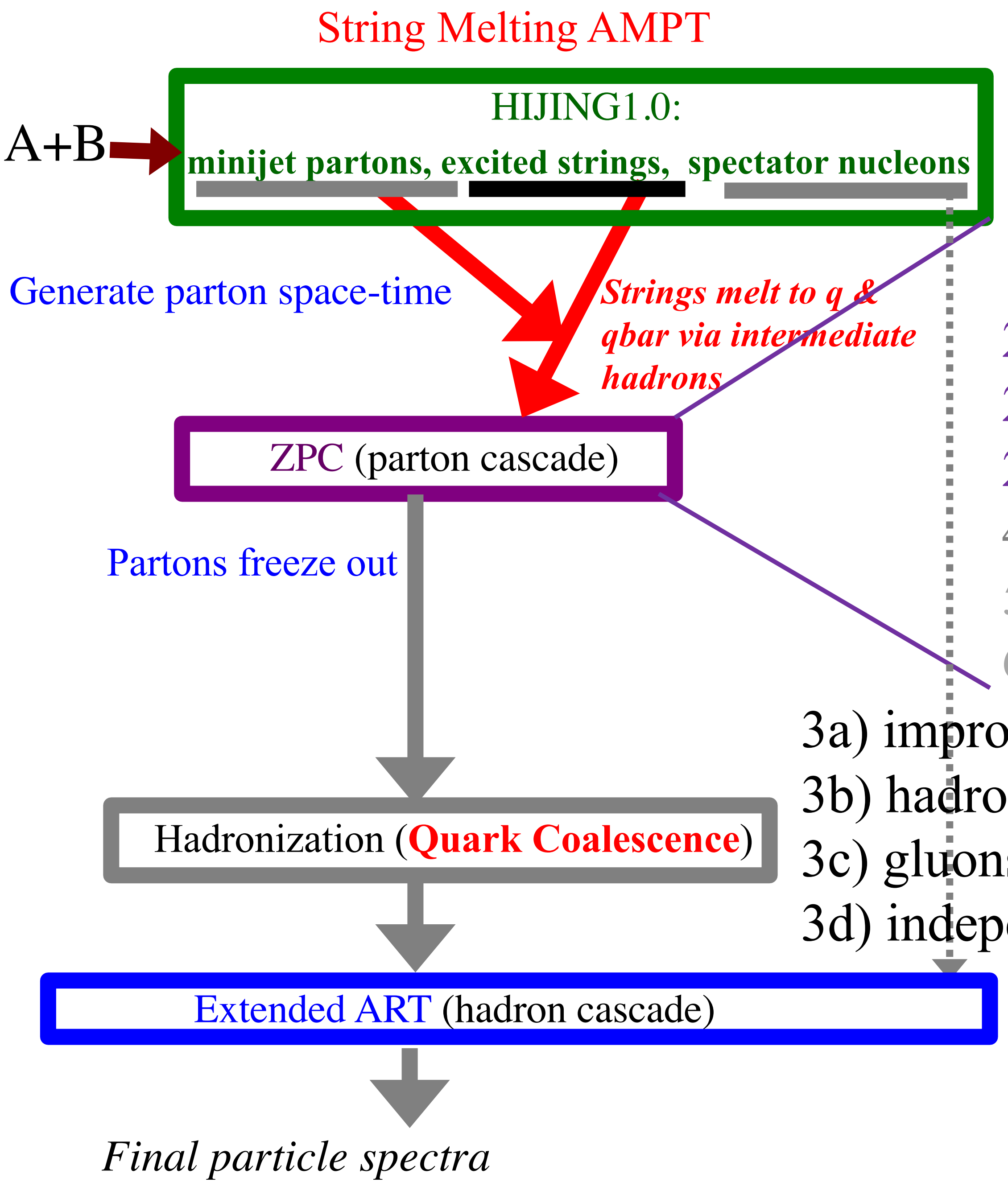
Challenges and future directions 2: top RHIC & LHC



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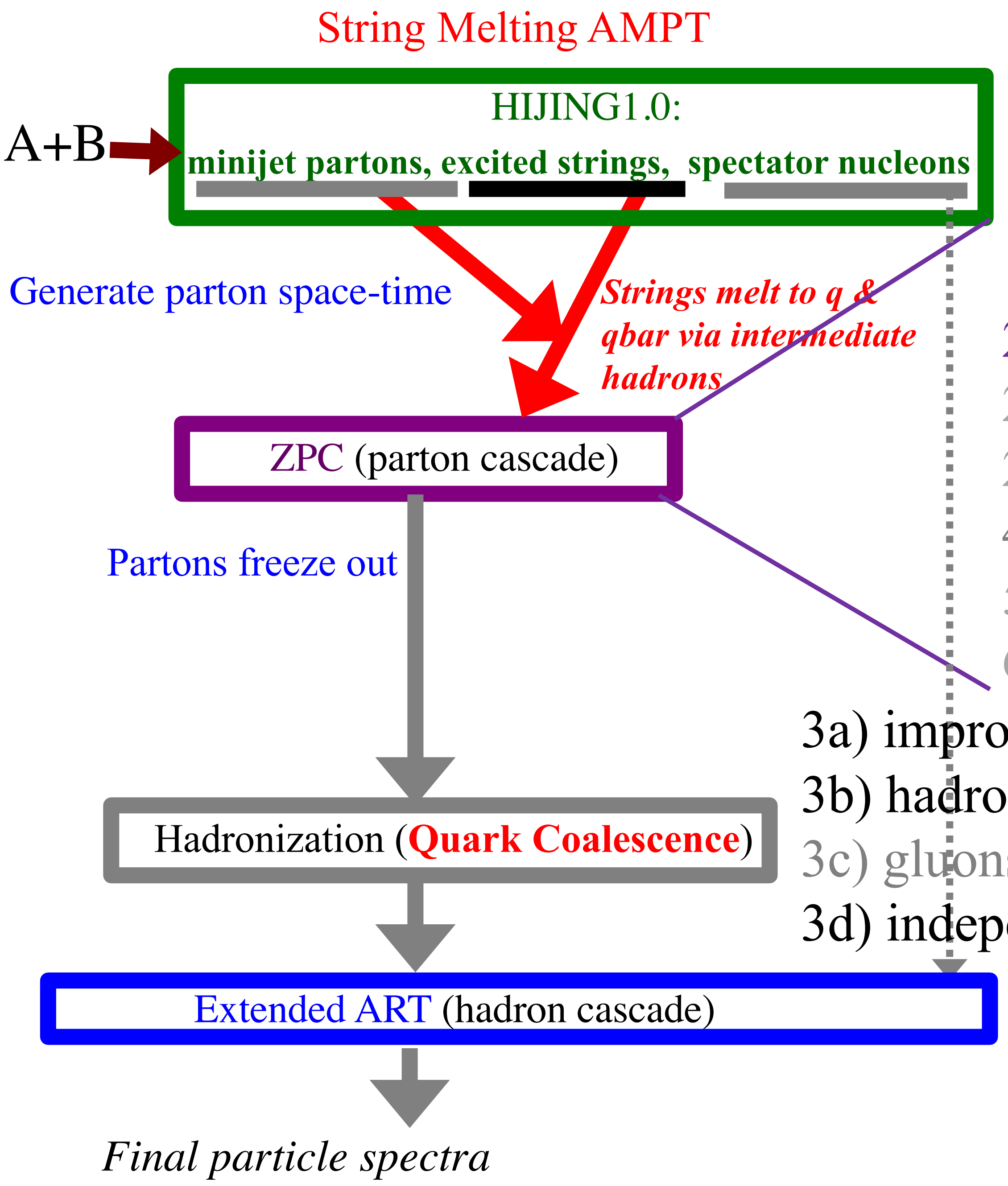
Challenges and future directions: common areas of 1)&2)



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Discussions:

Your insights and suggestions will be greatly appreciated