Heavy Flavors in the AMPT Model

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Outline

- Introduction
- Recent improvements on heavy flavors in AMPT (after 2019)
- Recent studies of D mesons in p-Pb collisions with AMPT
- Summary and outlook

Mostly based on summary in ZWL & Liang Zheng, Nucl Sci Tech 32, 113 (2021)
& works with Chao Zhang, Liang Zheng and Shusu Shi

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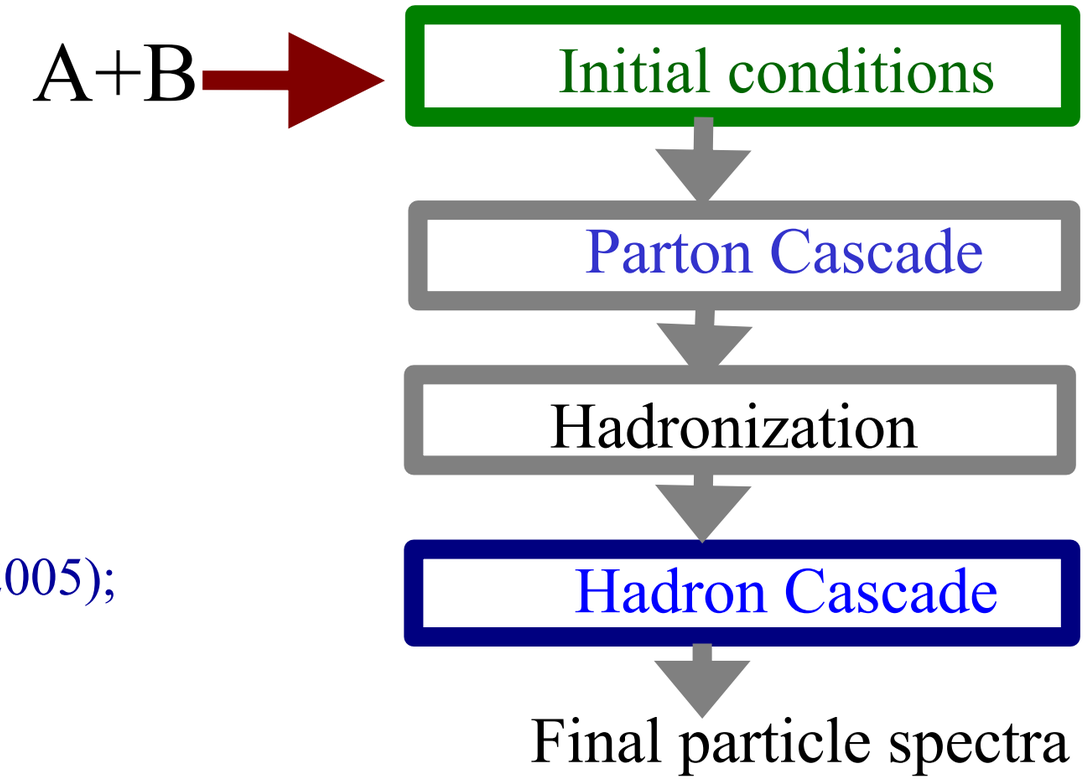
Introduction

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
- includes particle productions of all flavors from low to high p_T
- ideal for non-equilibrium dynamics (*more important for heavy flavors and small systems*).

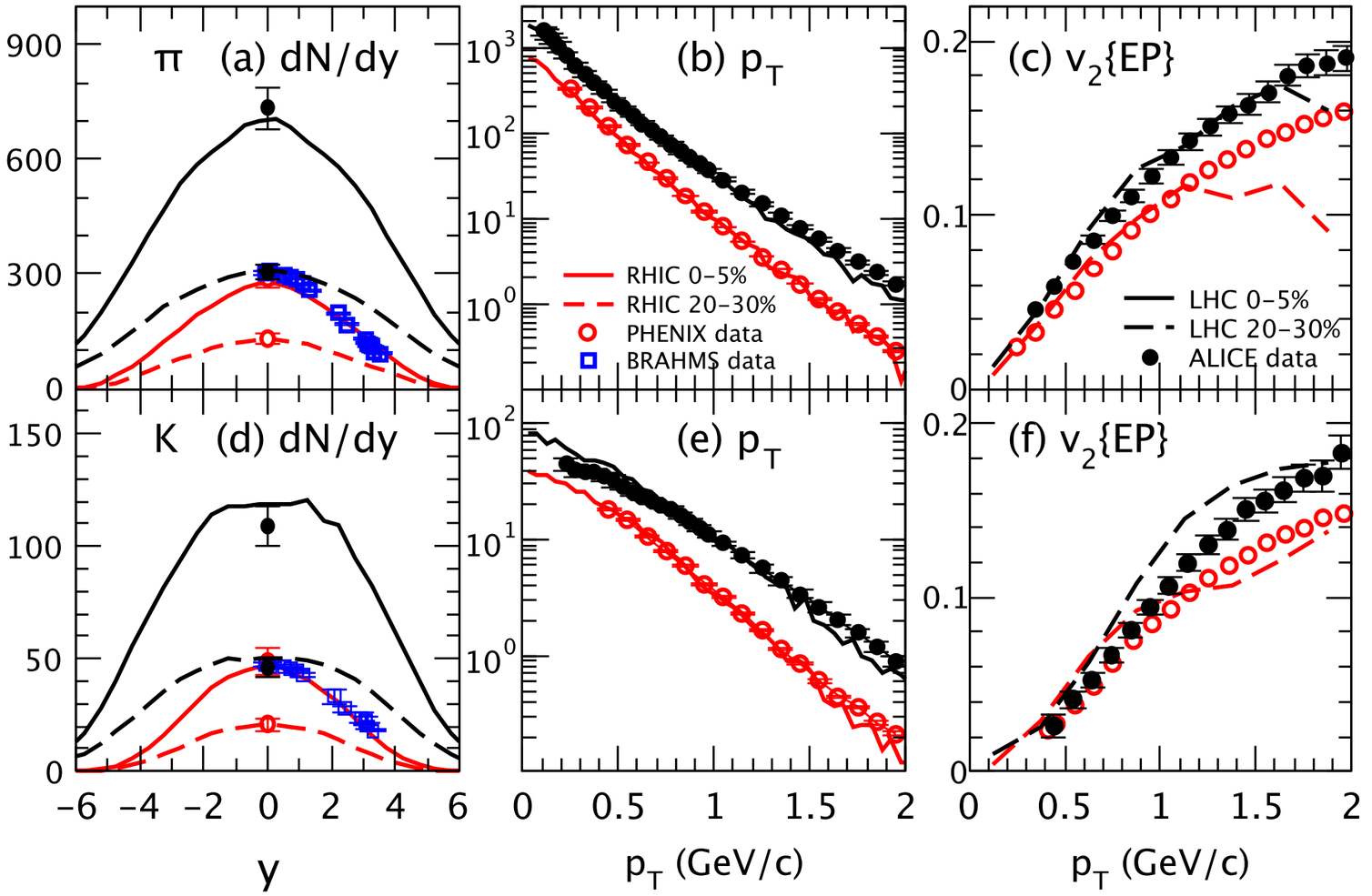


Source codes at the ECU website
https://myweb.ecu.edu/linz/ampt/
ZWL, Ko, Li, Zhang & Pal, PRC 72 (2005);
ZWL & Zheng, NST 32 (2021)

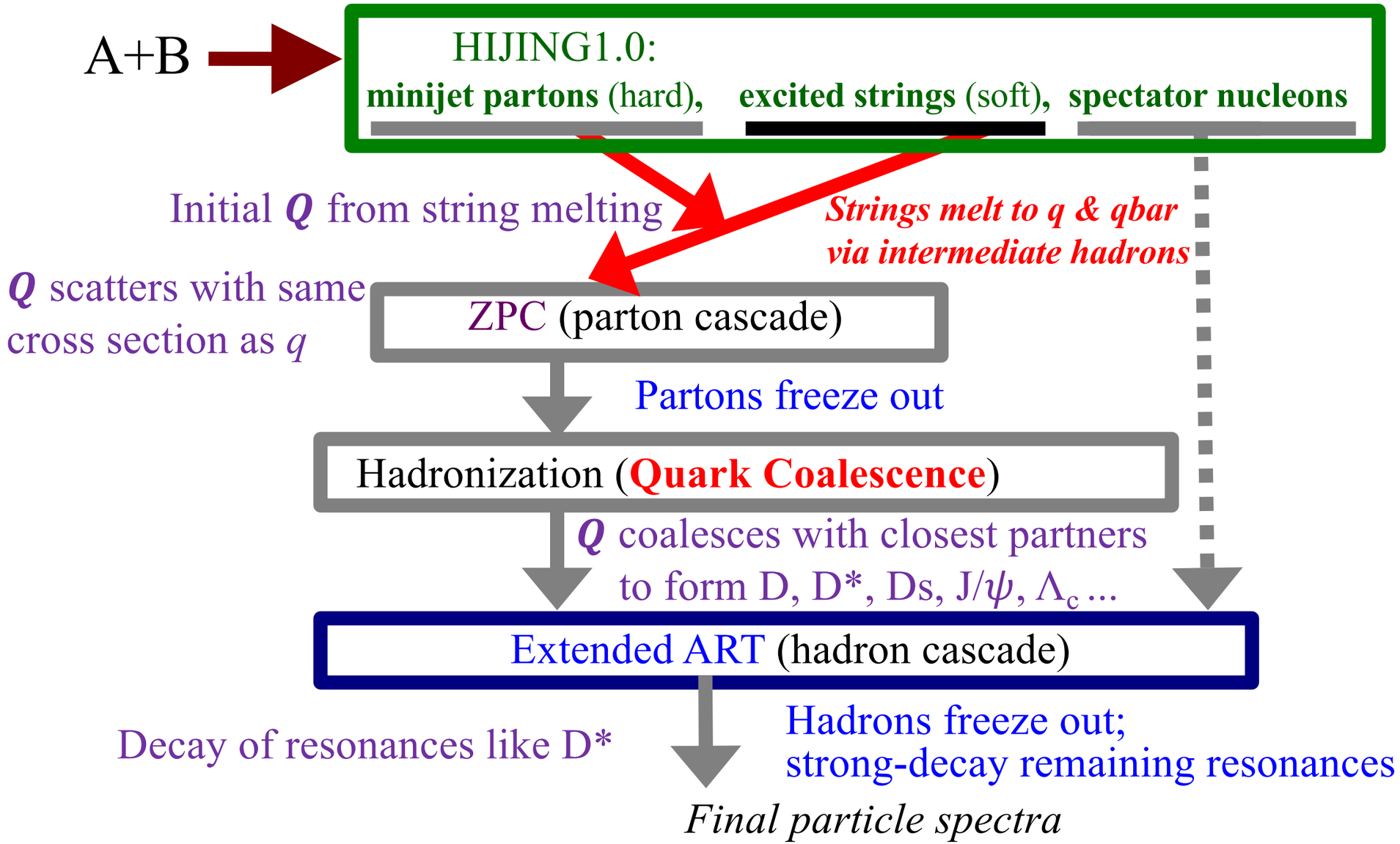
String melting version of AMPT

- The string melting AMPT model is applicable when we expect the formation of a parton matter
- It can reasonably describe the bulk matter observables at low p_T in high energy A+A collisions *(after using a very small Lund string parameter b_L=0.15/GeV^2)*

ZWL, PRC 90 (2014)



Structure of AMPT (String Melting version) before ~2019 for heavy quark *Q*



Recent improvement of HF productions in AMPT

$gg \to gg$ cross section in leading-order pQCD $\frac{d\sigma}{dt} \sim \frac{9\pi\alpha_s^2}{2t^2}$
is divergent for massless g,
so HIJING uses a **minijet cutoff $\boldsymbol{p_0}$** for minijets of ALL flavors.

But heavy flavor (HF) production does not need a cutoff
due to heavy quark mass $m_Q >> \Lambda_{QCD}$ (e.g. in FONLL)

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

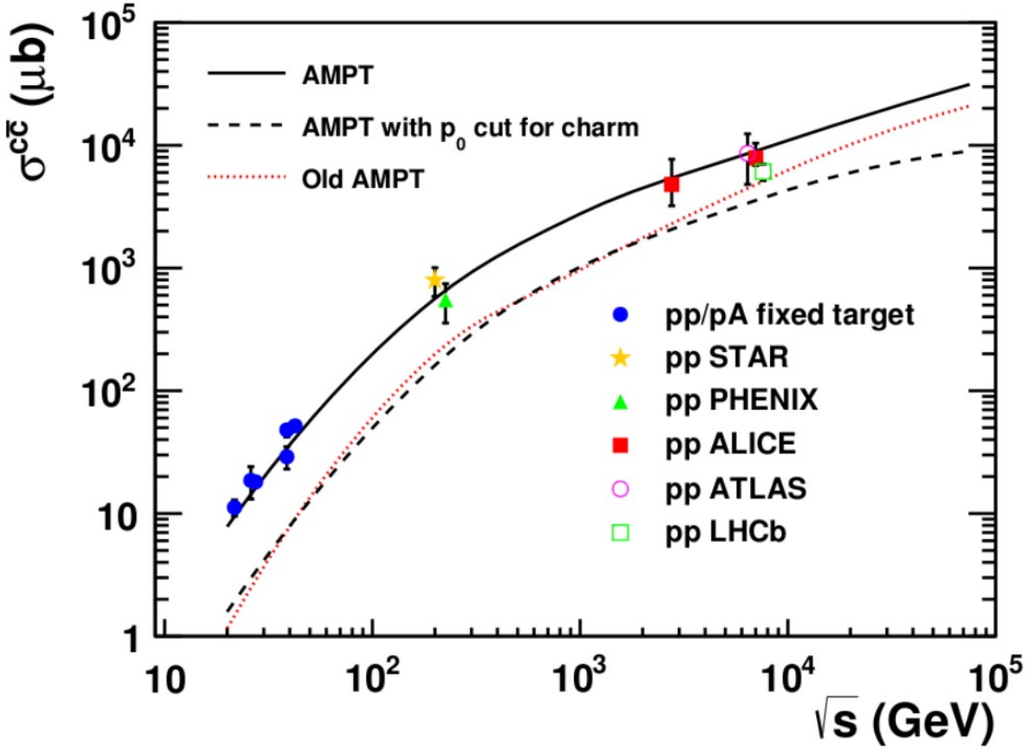
- So we remove the p_0 cut on HF productions in the HIJING model initial condition for AMPT

Liang Zheng et al.
PRC 101 (2020)

- Unlike HIJING, we include HF in total jet cross section: $\sigma_{jet} = \sigma_{jet}^{LF} + \boldsymbol{\sigma^{HF}}$

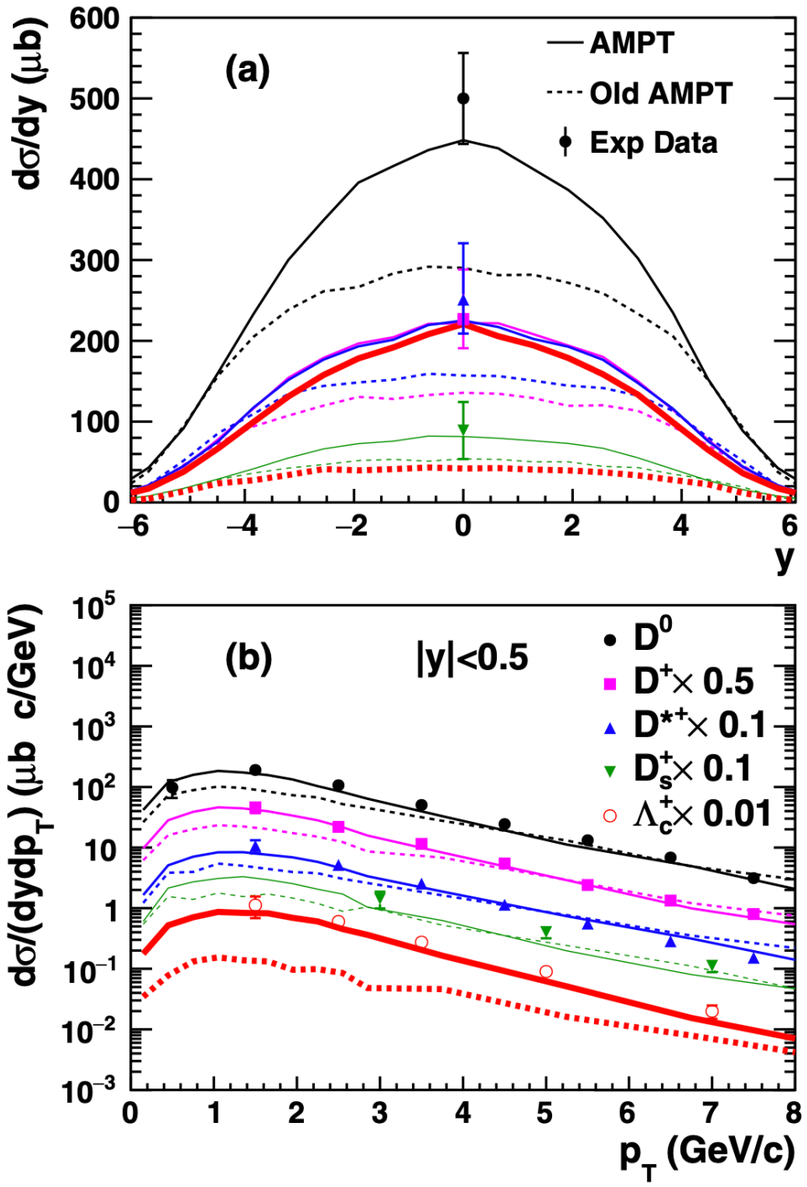
- We also correct the factor of ½ in certain σ_{jet} channels

Recent improvement of HF productions in AMPT



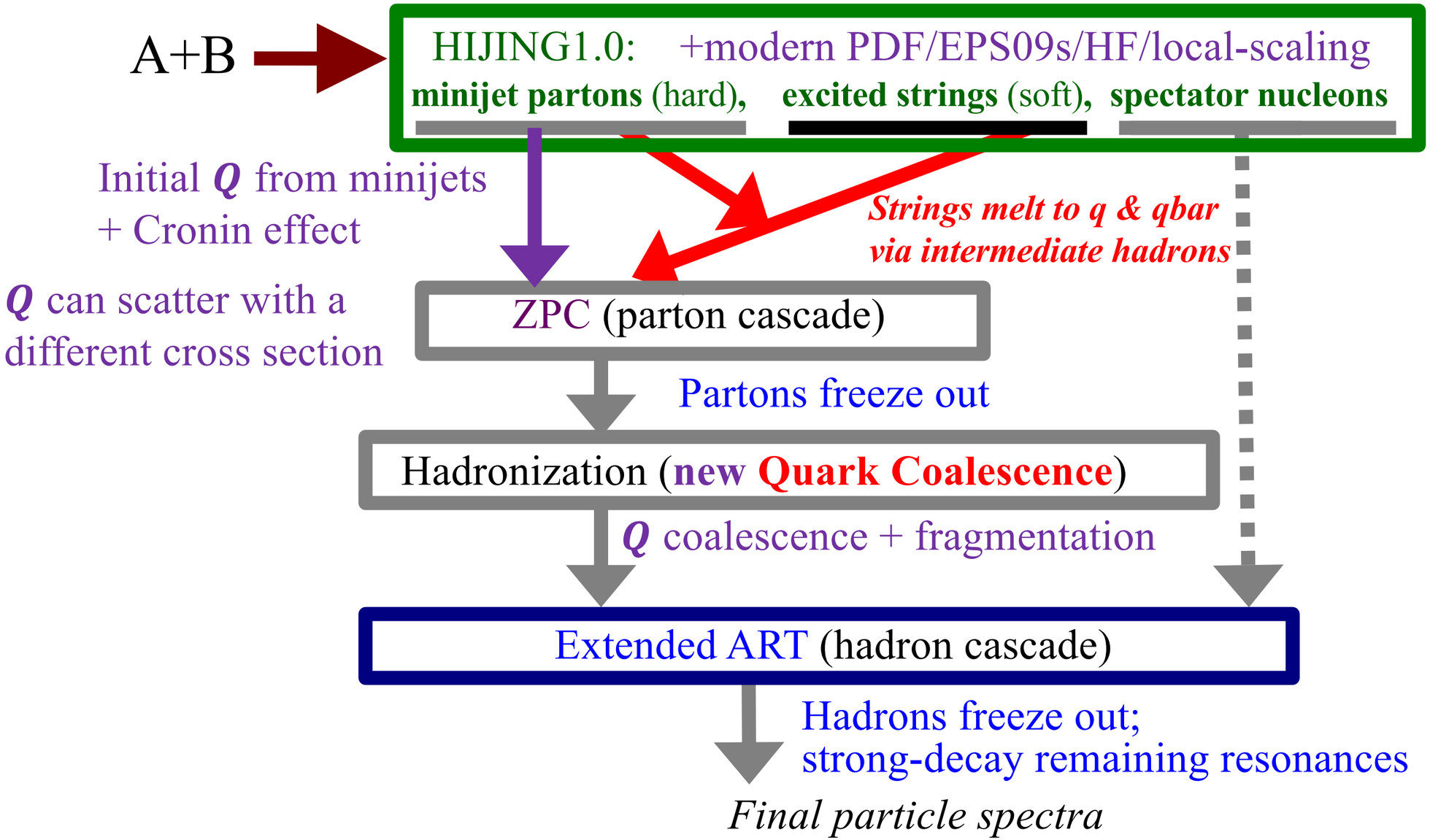
- Old/public AMPT charm yield << data
- Removing p_0 in HF greatly enhances charm yield
- AMPT now well describes the total $c\bar{c}$ cross section
- Reasonable description of charm hadron spectra in *pp*

Liang Zheng et al. PRC 101 (2020)



AMPT vs ALICE data for *pp* at 7TeV

Structure of AMPT (String Melting version) improved for heavy quark *Q*



Improvement with modern PDF/EPS09s

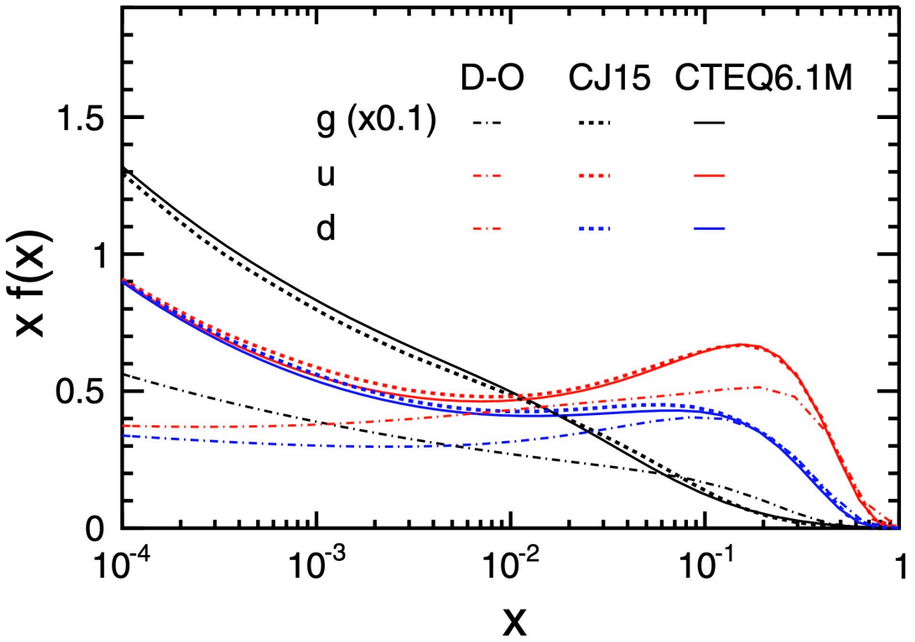
Modern nPDFs should improve AMPT on pQCD observables such as HF & high p_T:

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

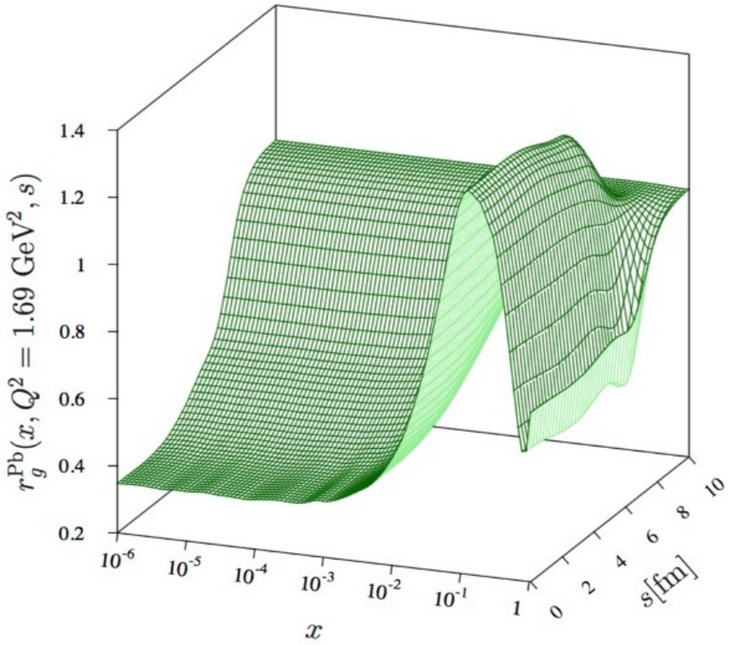
$$f_i^{p/A}(x,Q^2) \equiv R_i^A(x,Q^2) f_i^p(x,Q^2) \qquad R_i^A(x,Q^2) \equiv \frac{1}{A}\int d^2\mathbf{s}\, T_A(\mathbf{s})\, r_i^A(x,Q^2,\mathbf{s})$$

We have incorporated
CTEQ6.1M PDFs for the free nucleon & EPS09s b-dependent nuclear shadowing:

Chao Zhang et al.
PRC 99 (2019)



Free proton PDFs vs x from
the old Duke-Owens set and newer sets



Shadowing function for Pb vs x
and s (transverse radius)

Improvement with local scaling

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

We systematically scale them with local nuclear densities $T_A(s)$: Chao Zhang et al. PRC 104 (2021)

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

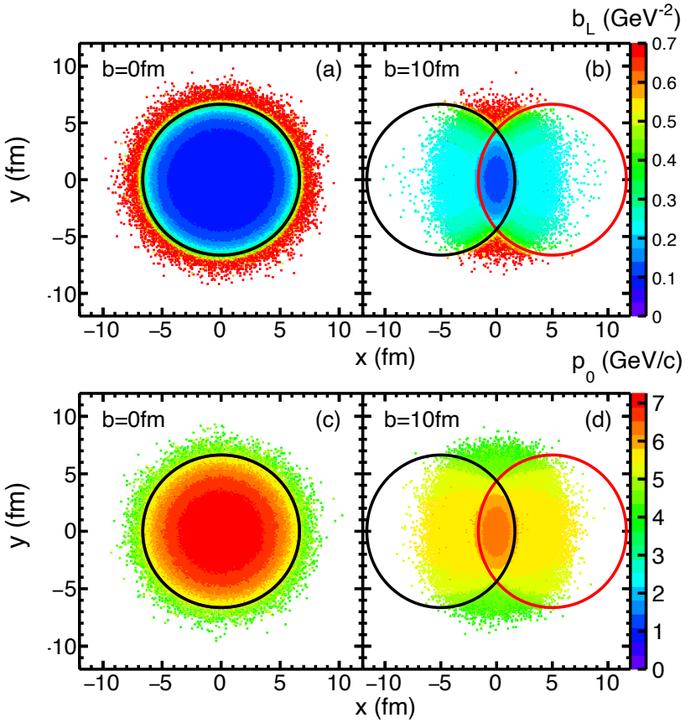
$$p_0(s_A, s_B, s) = p_0^{pp}(s)[\sqrt{T_A(s_A)T_B(s_B)}/T_p]^{\alpha(s)}$$

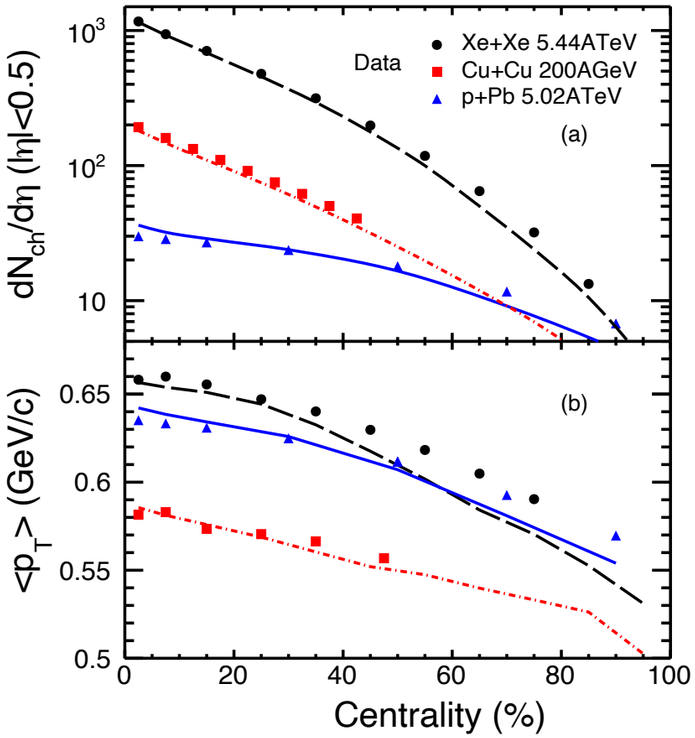
$\mathbf{b_L}$

&

$\mathbf{p_0}$

for 5.02ATeV Pb+Pb





Local scaling finally allows AMPT to self-consistently describe the system size dependence,
including the centrality dependence of $<p_T>$ in large and smaller systems.

Recent improvement of HF productions in AMPT

Merzlaya for NA61/SHINE,
SQM 2024 proceedings
arXiv:2410.24014

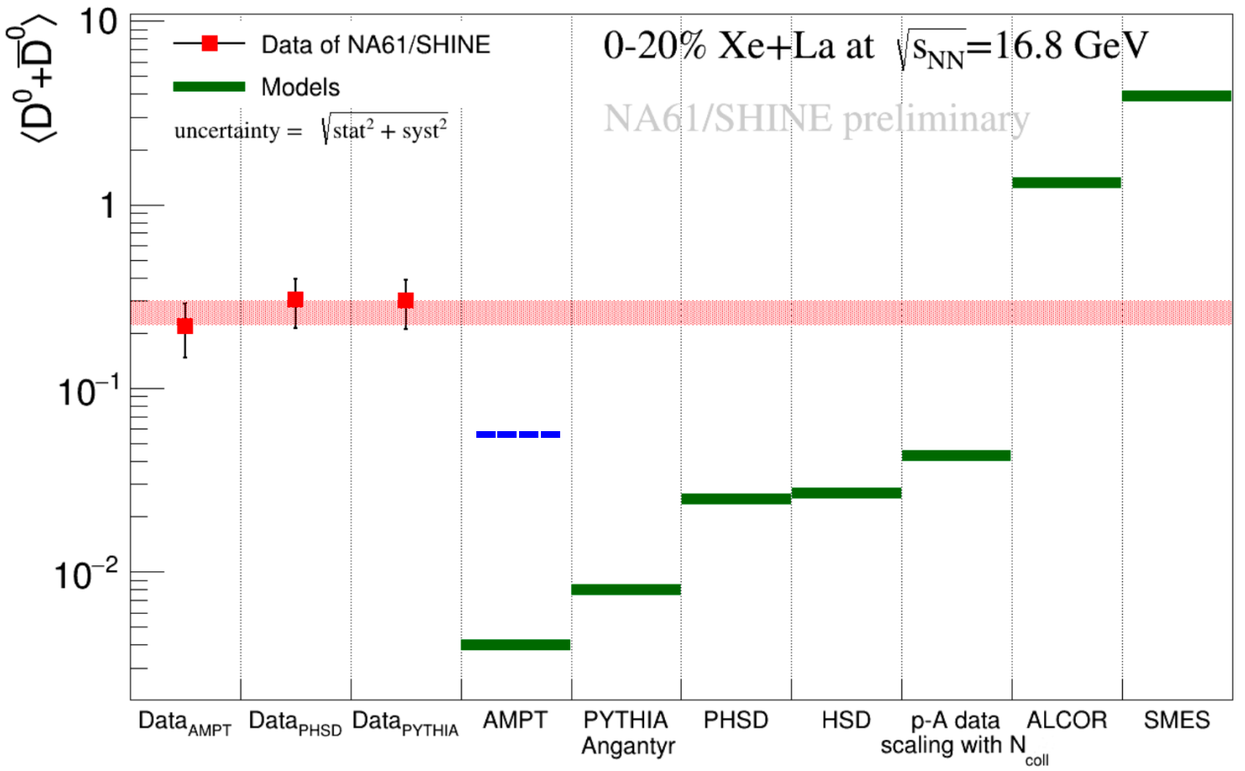


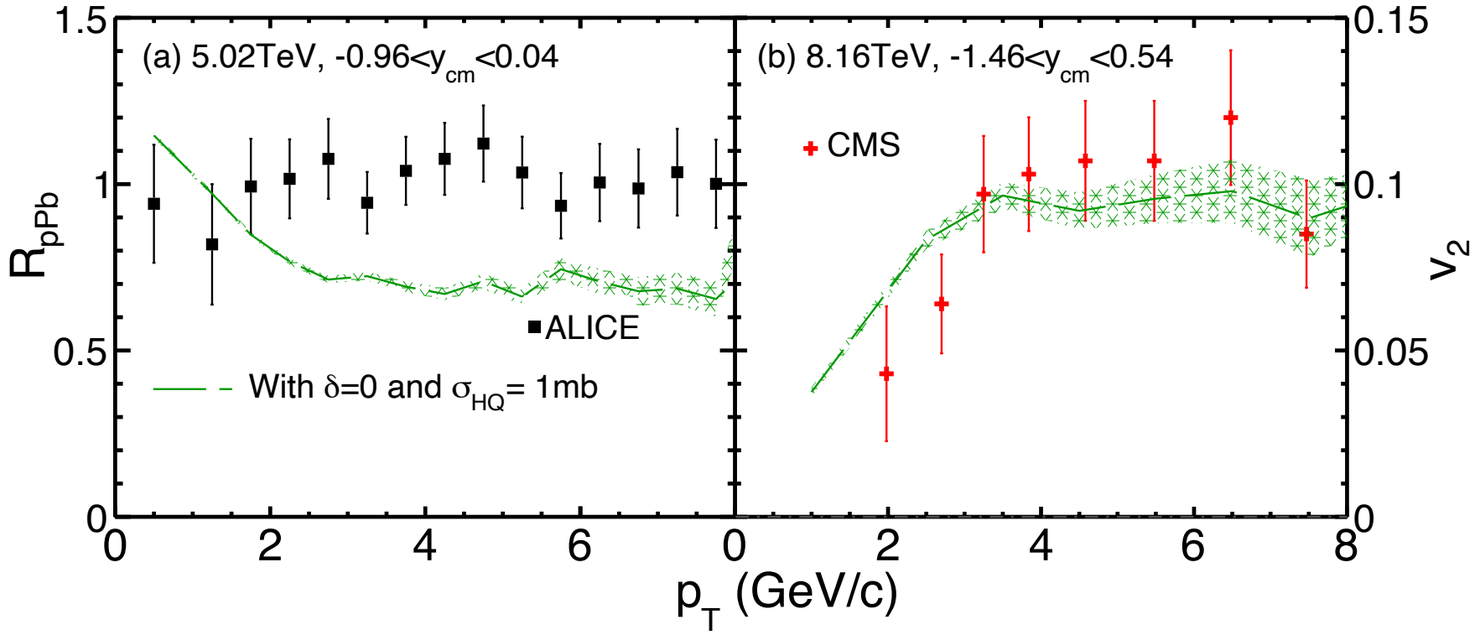
Figure 2. Comparison of the obtained result to theoretical model predictions. The red band indicates the theoretical uncertainty of the result due to the unknown phase space distribution of D^0, $\overline{D}^0$.

- The Green AMPT value comes from the old/public AMPT
- The AMPT model with improved HF physics gives a much higher yield ----
  similar to the binary/Ncoll scaling estimate as expected.

Study of the D^0 R_{pA} and v_2 puzzle

LHC p-Pb data on D^0 mesons show

~ no suppression in D^0 R_{pA} but significant v_2



It has been a challenge to describe both data simultaneously:

- sizable v_2 → significant charm quark interaction with medium
  → suppression of charm high p_T spectrum in pA and R_{pA} (above)

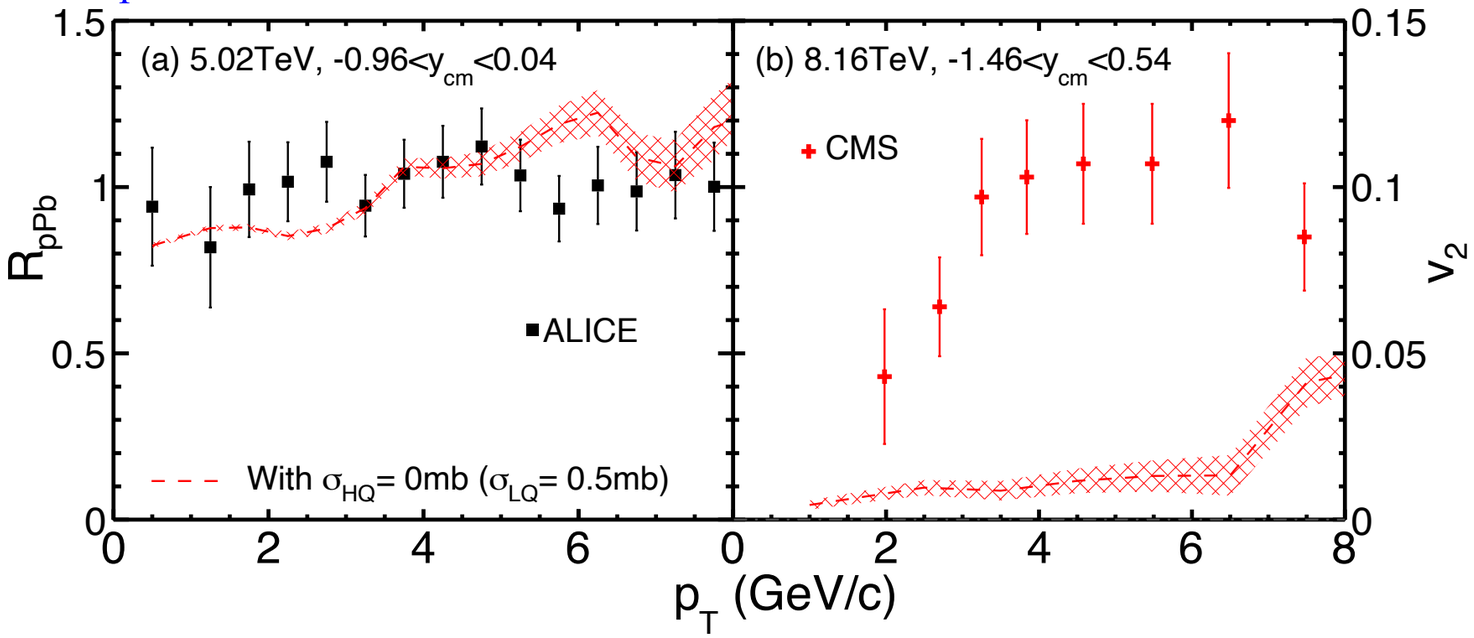
- Studies based on color glass condensate can describe D and J/ψ v_2, no R_{pA} results yet.

Cheng Zhang et al. PRL (2019), PRD (2020)

Study of the D^0 R_{pA} and v_2 puzzle

- Without charm quark scatterings,

  R_{pA} result can be close to data, but v_2 is very small.



- This was seen in an earlier study: Beraudo et al. JHEP (2016)

  ~ no suppression in R_{pA}, then v_2 is too small.

- A simultaneous description of the R_{pA} and v_2 data could disentangle different effects (*initial state correlations, cold nuclear, hot medium*) and help understand onset of collectivity & formation of parton matter or QGP

Study of the D^0 R_{pA} and v_2 puzzle

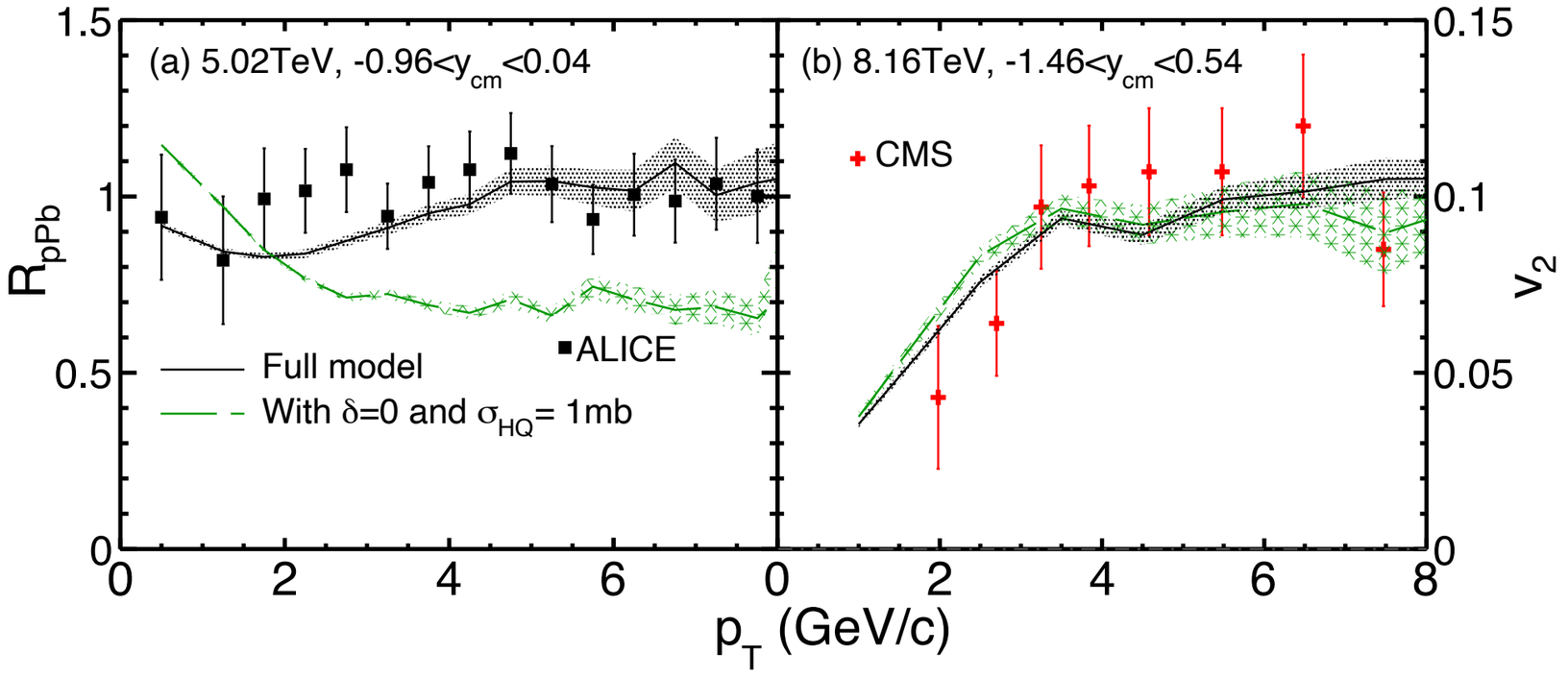
We implement the Cronin effect on initial charm by broadening $c\bar{c}$ p_T with a random k_T :

$$f(\vec{k_T}) = \frac{1}{\pi w^2} e^{-k_T^2/w^2}$$

Mangano et al. NPB (1993)
Vogt, PRC (2018, 2021)

$w = w_0\sqrt{1+(n_{\rm coll}-i)\delta}$ grows with # of NN collisions of the wounded nucleon(s).

Chao Zhang et al.
PLB 846 (2023)



The full model, with Cronin effect at δ=7, can describe both R_{pA} and v_2 data of D^0 mesons

Study of the D^0 R_{pA} and v_2 puzzle

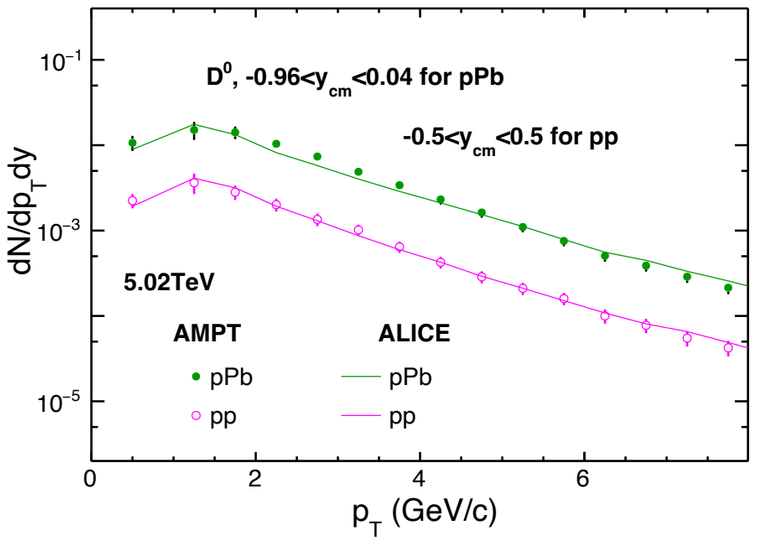
Chao Zhang et al.
PLB 846 (2023)

At 5.02 TeV, the full model also reasonably describes other relevant observables.

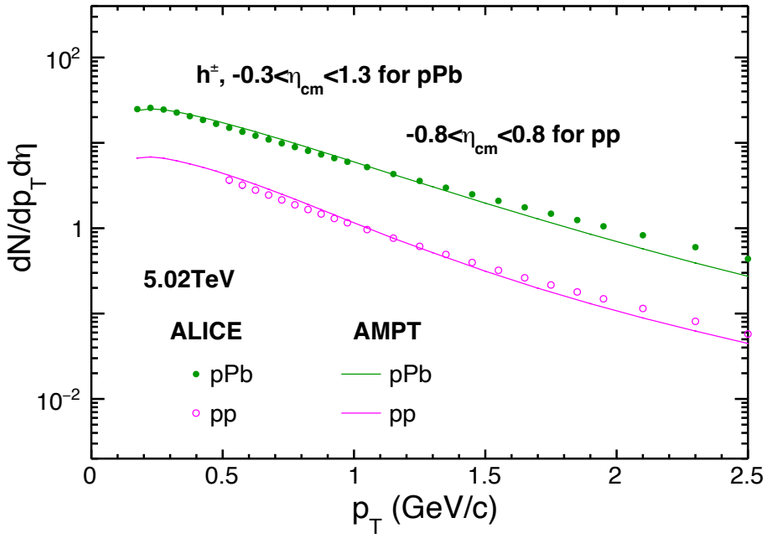
- A strong Cronin effect provides a solution to the puzzle in pPb.

- Magnitude of k_T broadening is expected to be higher for central AA; how about the Cronin effect for heavy flavors there?

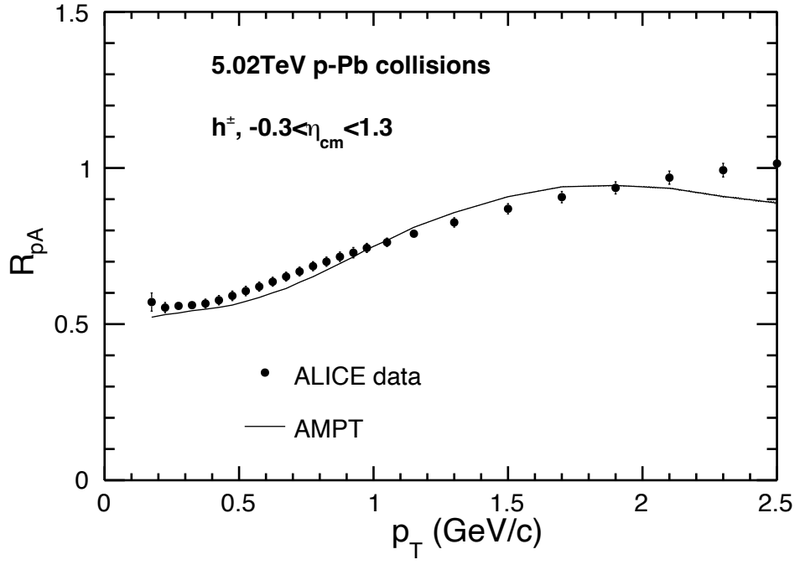
D^0 p_T spectra (to ~8GeV/c)



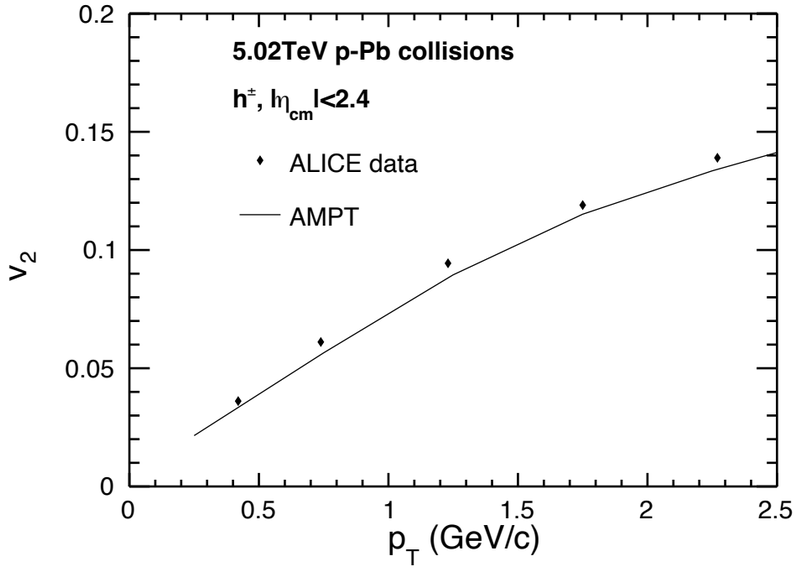
Charged hadron p_T spectra (to ~1.5 GeV/c)



Charged hadron R_{pA}

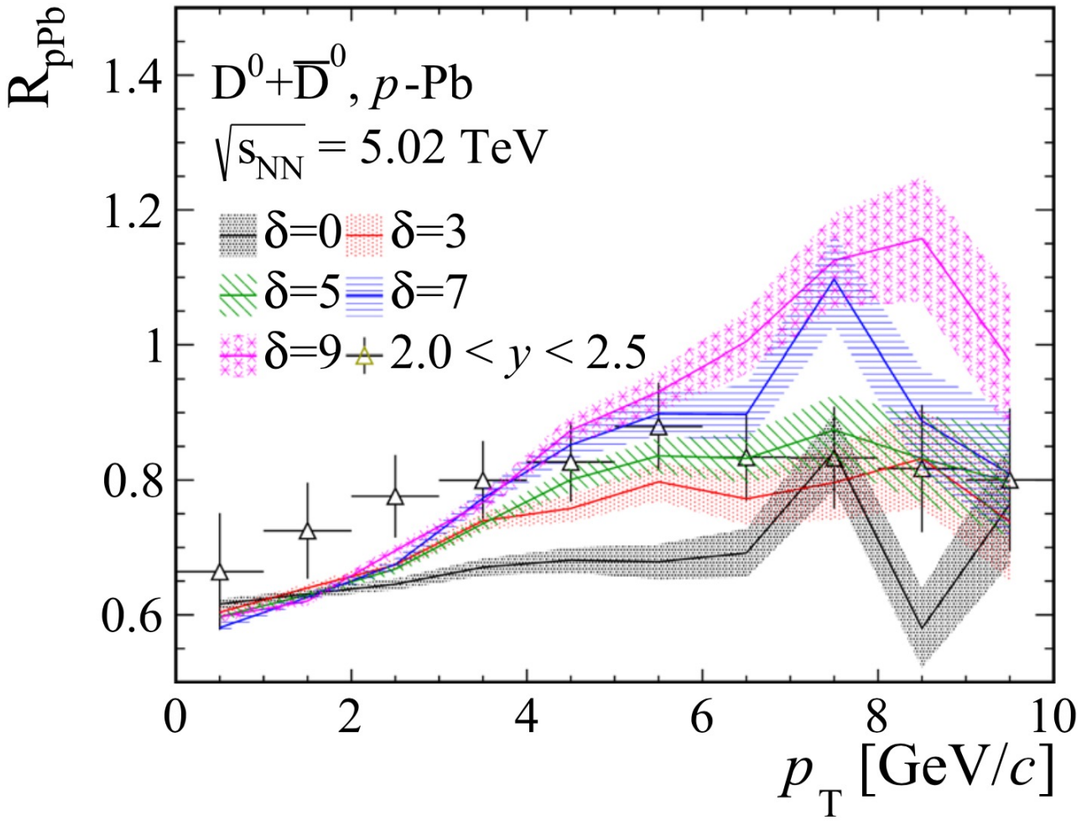


Charged hadron v_2 in pPb



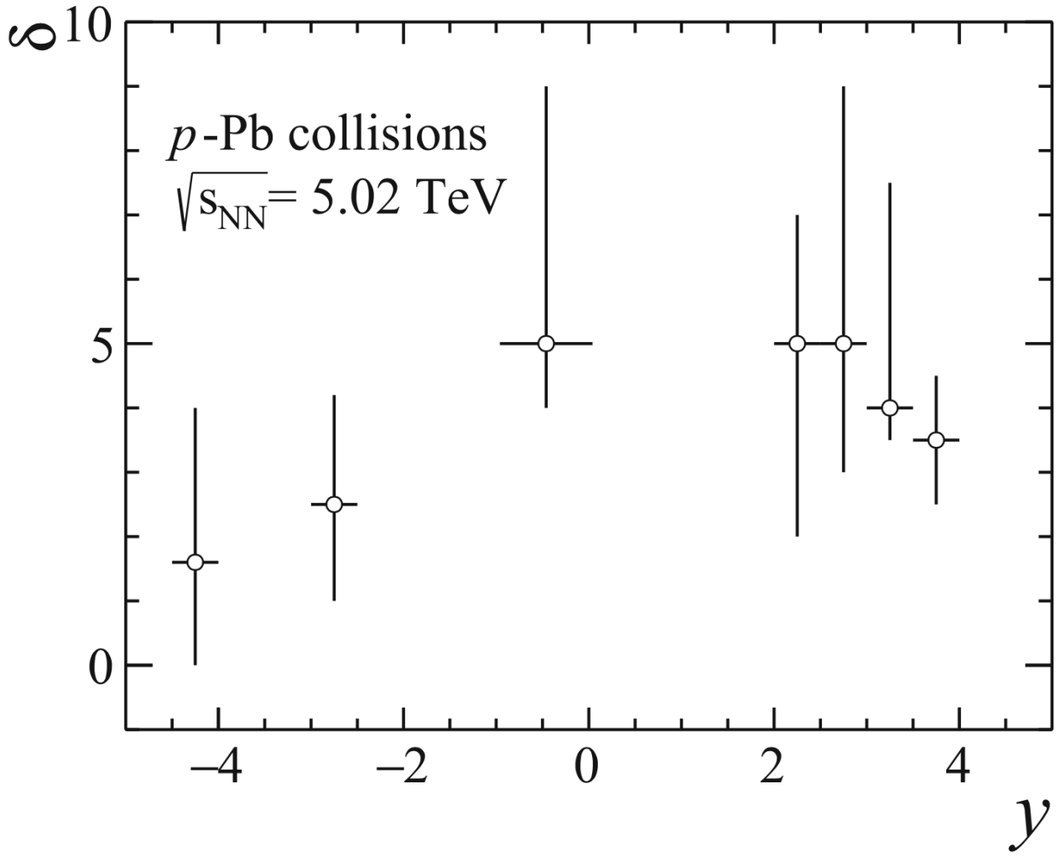
y-dependence of the Cronin effect

This full model has been compared with LHCb data on RpA at different y-intervals such as this:



Chao Zhang et al. EPJC 84 (2024)

The Cronin size parameter δ is extracted as a function of rapidity:



It will be desirable to have calculations of the Cronin effect from theory such as CGC

Summary:

The AMPT model provides a kinetic description of heavy ion collisions;
this is especially relevant for heavy flavors due to their non-equilibrium dynamics

- The model now well reproduces the world data on total $c\bar{c}$ cross section in *pp* and also reasonably describes charm hadron spectra in *pp*

- A strong Cronin effect provides a possible solution to the D^0 meson R_{pA} and v_2 puzzle in pPb collisions at the LHC

Outlook:

- Improve parton transport by including Qq or Qg scattering cross sections with finite-temperature screening
- Include HF inelastic energy loss to enable studies of AA collisions or high p_T