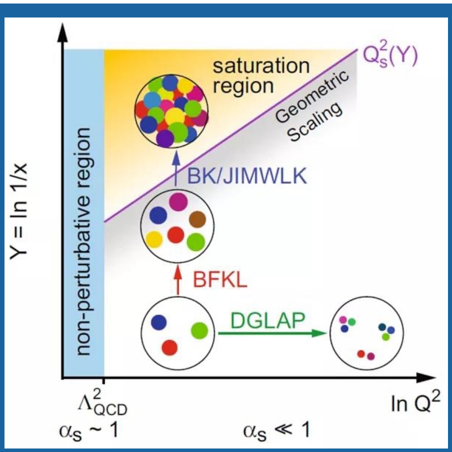
Connection Between the AMPT Model and Gluon Saturation

Zi-Wei Lin (林子威)
East Carolina University

LHCx

July 6 – 9, 2026
CCNU



The first workshop on the physics of small-x

Outline

1. Motivation and the AMPT model
2. $\sqrt{s}$- and A-dependent minijet cutoff p_0 for central $A+A$
3. Local nuclear scaling of p_0 and b_L for any collisions
4. Cronin effect of D-mesons in pPb collisions
5. Summary / Discussions

National
Science
Foundation

1. Motivation: for comprehensive simulations of heavy ion collisions

What we need:	***What options we have:***
Initial particle/energy production	*Soft+hard model (+string melting), CGC, Glauber model, pQCD, Lund strings, ...*
Pre-equilibrium interactions: *equilibration, thermalization, pre-flow*	*Parton cascade (ZPC, MPC, BAMPS), EKT/ free streaming, CGC, AdS/CFT, ...*
Space-time evolution of QGP	*Parton cascade (ZPC, MPC, BAMPS), (ideal or viscous) hydrodynamics, ...*
Hadronization /QCD phase transition	*Quark coalescence/parton recombination, fragmentation, Cooper-Frye, statistical hadronization, rate equations, ...*
Hadronic interactions	*Hadron cascade (ART, UrQMD, SMASH), ...*

1. Motivation: for comprehensive simulations of heavy ion collisions

What we need:	***What options we have:***
Initial particle/energy production	*Soft+hard model (+string melting), CGC, Glauber model, pQCD, Lund strings, ...*
Pre-equilibrium interactions: *equilibration, thermalization, pre-flow*	*Parton cascade (ZPC, MPC, BAMPS), EKT/free streaming, CGC, AdS/CFT, ...*
Space-time evolution of QGP	*Parton cascade (ZPC, MPC, BAMPS), (ideal or viscous) hydrodynamics, ...*
Hadronization /QCD phase transition	*Quark coalescence/parton recombination, fragmentation, Cooper-Frye, statistical hadronization, rate equations, ...*
Hadronic interactions	*Hadron cascade (ART, UrQMD, SMASH), ...*

Green choices: a multi-phase transport (AMPT) model
Red choices: a hybrid model (hydrodynamics+hadron cascade)

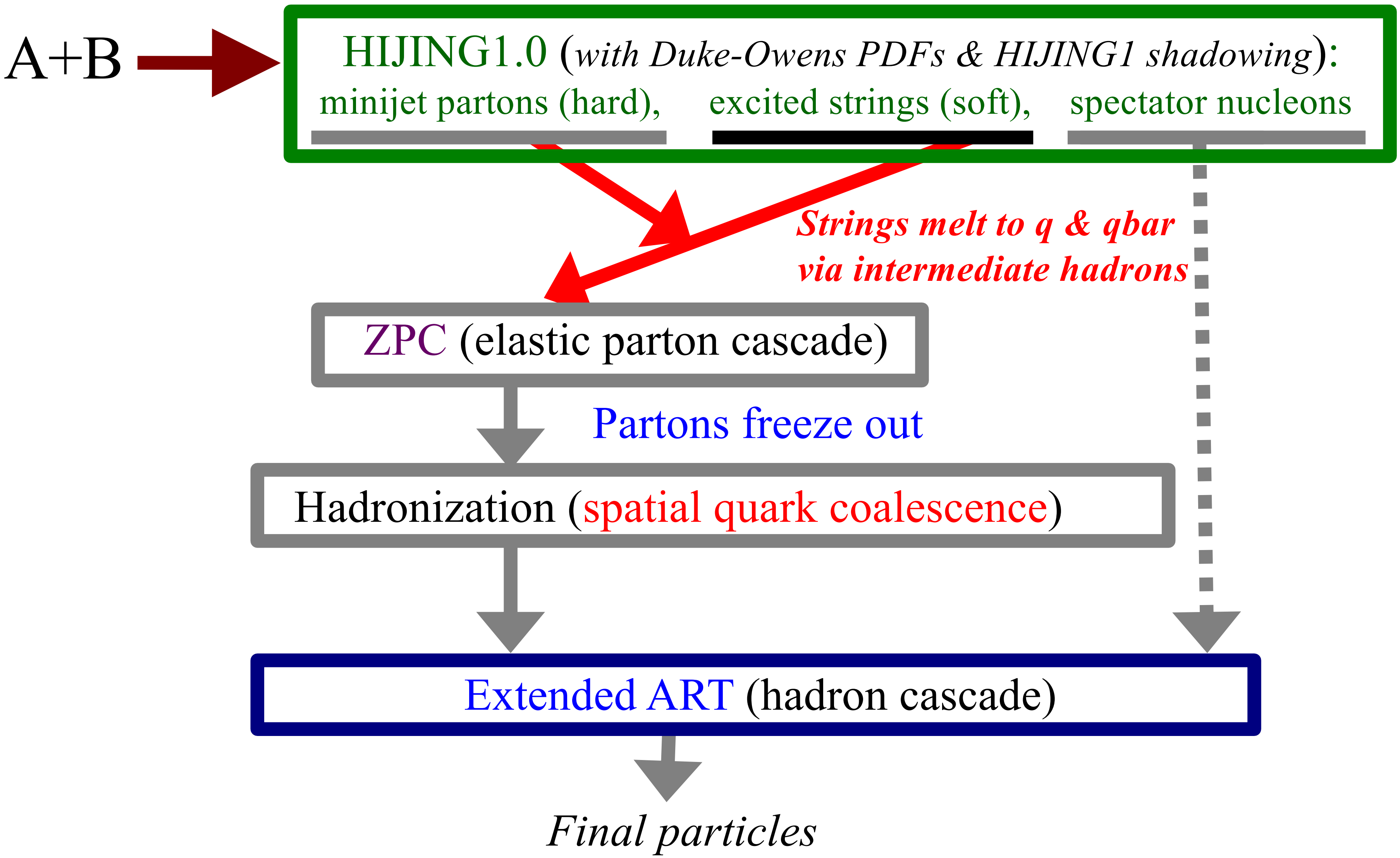
1. Motivation: for comprehensive simulations of heavy ion collisions

What we need:	***What options we have:***
Initial particle/energy production	*Soft+hard model (+string melting), **CGC**, Glauber model, pQCD, Lund strings, ...*
↓	↓
Pre-equilibrium interactions: *equilibration, thermalization, pre-flow*	*Parton cascade (ZPC, MPC, BAMPS), EKT/free streaming, **CGC**, AdS/CFT, ...*
↓	↓
Space-time evolution of QGP	*Parton cascade (ZPC, MPC, BAMPS), (ideal or viscous) hydrodynamics, ...*
↓	↓
Hadronization /QCD phase transition	*Quark coalescence/parton recombination, fragmentation, Cooper-Frye, statistical hadronization, rate equations, ...*
↓	↓
Hadronic interactions	*Hadron cascade (ART, UrQMD, SMASH), ...*

Green choices: a multi-phase transport (AMPT) model
Red choices: a hybrid model (hydrodynamics+hadron cascade)
***Purple**:* CGC-based theory including small-x gluon saturation

1. The public AMPT model: the string melting (SM) version

ZWL & Ko, PRC 65 (2002)
Source codes at the ECU website
https://myweb.ecu.edu/linz/ampt/

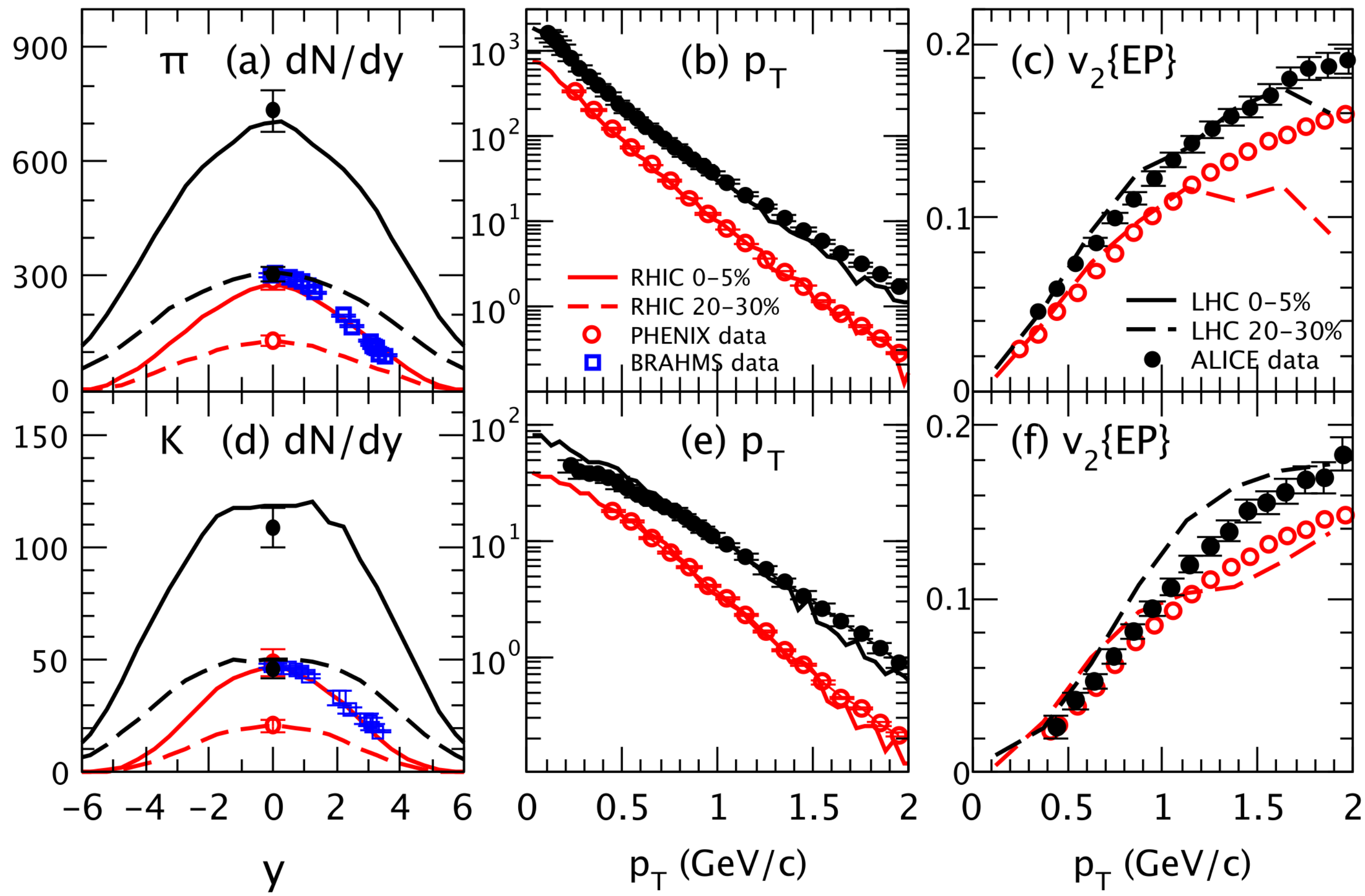


1. The public AMPT model: the string melting (SM) version

- String melting version is applicable when we expect formation of a parton matter.

- Now it can reasonably describe the bulk matter observables at low p_T
  in high energy central & mid-central A+A collisions
  (*after using a very small Lund parameter b_L=0.15/GeV^2*):

ZWL, PRC 90 (2014)



1. Recent developments of the AMPT model

Modern PDFs & spatially-dependent nuclear shadowing — C Zhang, Zheng, Liu, Shi & ZWL, PRC 99 (2019)

Local nuclear scaling for self-consistent size dependence — C Zhang, Zheng, Shi & ZWL, PRC 104 (2021)

Improvements of heavy flavors — L Zheng, Zhang, Shi & ZWL, PRC 101 (2020); C Zhang, Zheng, Shi & ZWL, PLB 846 (2023)

Implementation of electric charge conservation — ZWL & Ma, unpublished (~2018); Q Chen, Wen, Yin, Fu, ZWL & Ma, 2402.12823

Benchmark and improve ZPC parton transport — XL Zhao, Ma, Ma & ZWL, PRC 102 (2020); Mendenhall & ZWL, NPB 1022 (2026); Ross & ZWL, 2606.21722

Include nonzero nuclear thickness — ZWL, PRC 98 (2018); HS Wang, Ma, ZWL & Fu, PRC 105 (2022)

New version AMPT-HC: pure hadron cascade with mean field potentials — GC Yong, Xiao, Gao & ZWL, PLB 820 (2021); GC Yong, Li, Xiao & ZWL, PRC 106 (2022)

Include subnucleon structure of the proton — L Zheng, Zhang, Liu, ZWL, Shou & Yin, EPJC 81 (2021)

O+O systems with modified hadronization criterion — XL Zhao, ZWL, Zhou, Zhang & Ma, PLB 874 (2026)

1. Recent developments of the AMPT model

Modern PDFs & spatially-dependent nuclear shadowing — C Zhang, Zheng, Liu, Shi & ZWL, PRC 99 (2019)

Local nuclear scaling for self-consistent size dependence — C Zhang, Zheng, Shi & ZWL, PRC 104 (2021)

Improvements of heavy flavors — C Zhang, Zheng, Shi & ZWL, PLB 846 (2023)

This talk will discuss the first 3 developments and their possible connections to CGC/small-x.

Outline

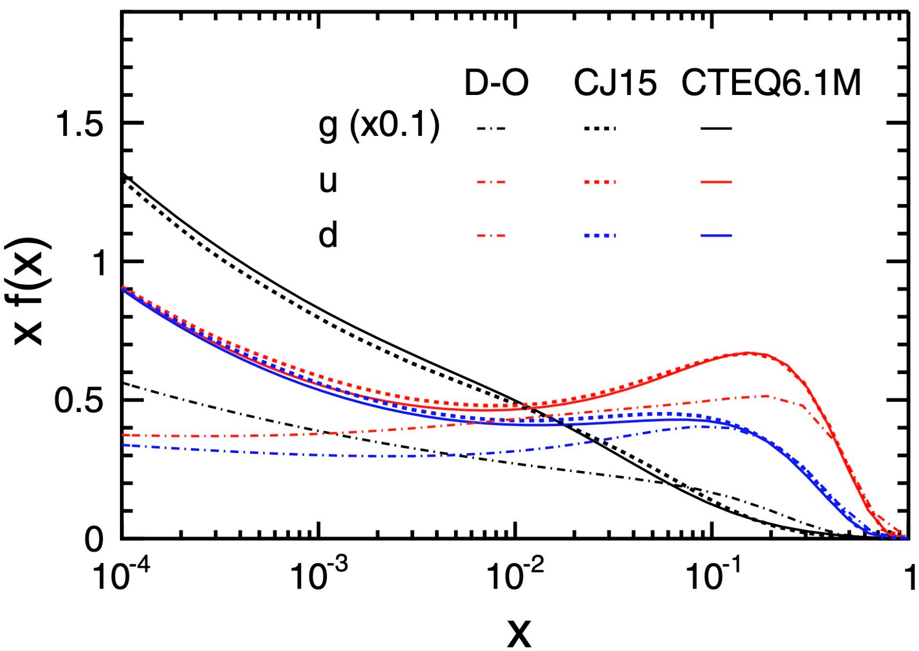
1. Motivation and the AMPT model
2. $\sqrt{s}$- and A-dependent minijet cutoff p_0 for central $A+A$
3. Local nuclear scaling of p_0 and b_L for any collisions
4. Cronin effect of D-mesons in pPb collisions
5. Summary / Discussions

Modern nPDFs are important for hard probes such as high p_T and heavy flavors:

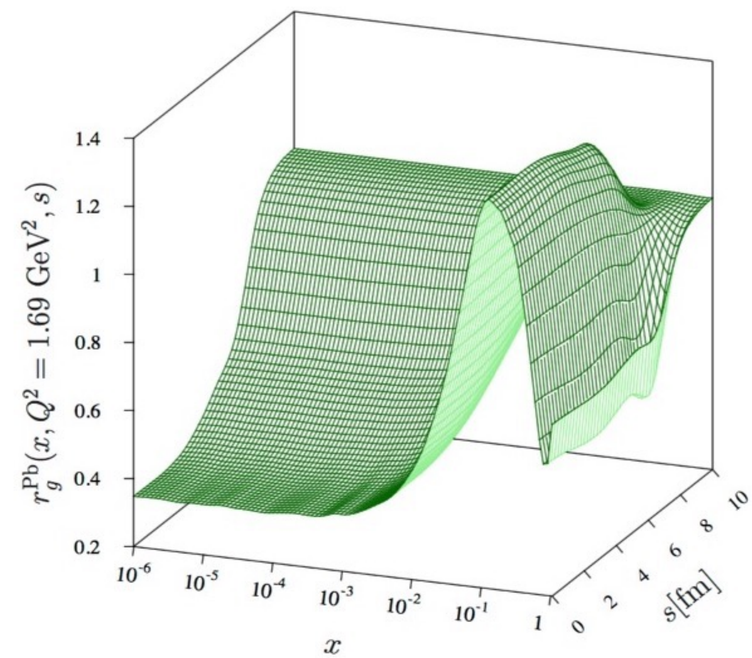
$$\frac{d\sigma^{Q\bar{Q}}}{dp_T^2 dy_1 dy_2} = K \sum_{a,b} x_1 f_a(x_1, \mu_F^2) x_2 f_b(x_2, \mu_F^2) \frac{d\sigma^{ab\to Q\bar{Q}}}{d\hat{t}}$$

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

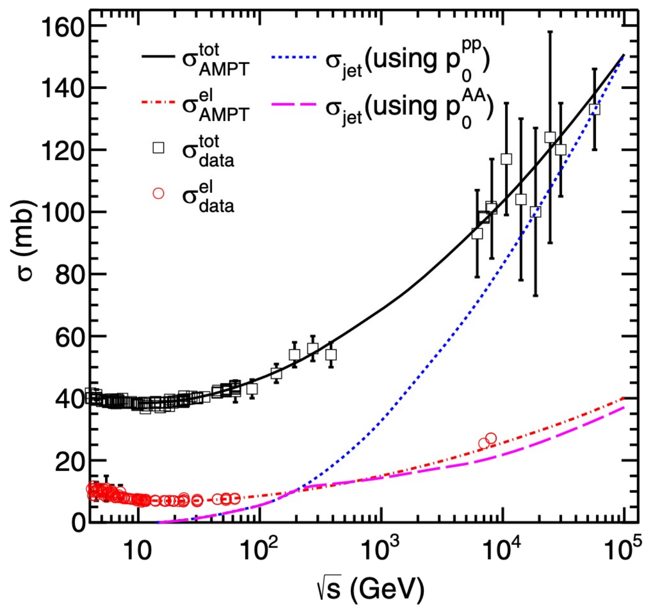
We incorporated the modern CTEQ6.1M PDFs for free nucleon & EPS09s nuclear shadowing:



Free proton PDFs vs x from CTEQ6.1M & the old Duke-Owens set in HIJING1



Shadowing function for Pb vs x and transverse position s

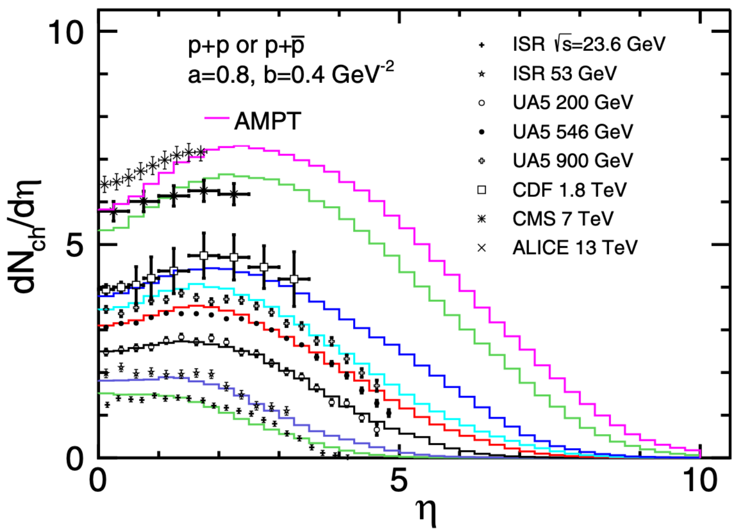


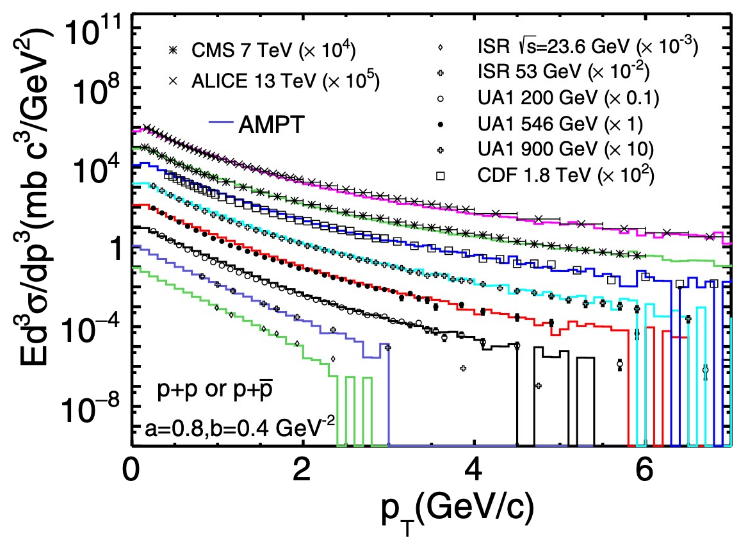
We fixed model parameters with p+p data:

1) fixed p_0 & σ_{soft} vs $\sqrt{s}$ with cross section data.

Chao Zhang, Zheng, Liu,
Shi & ZWL, PRC 99 (2019)

2) fixed Lund a_L & b_L constants with yield and p_T spectra data.

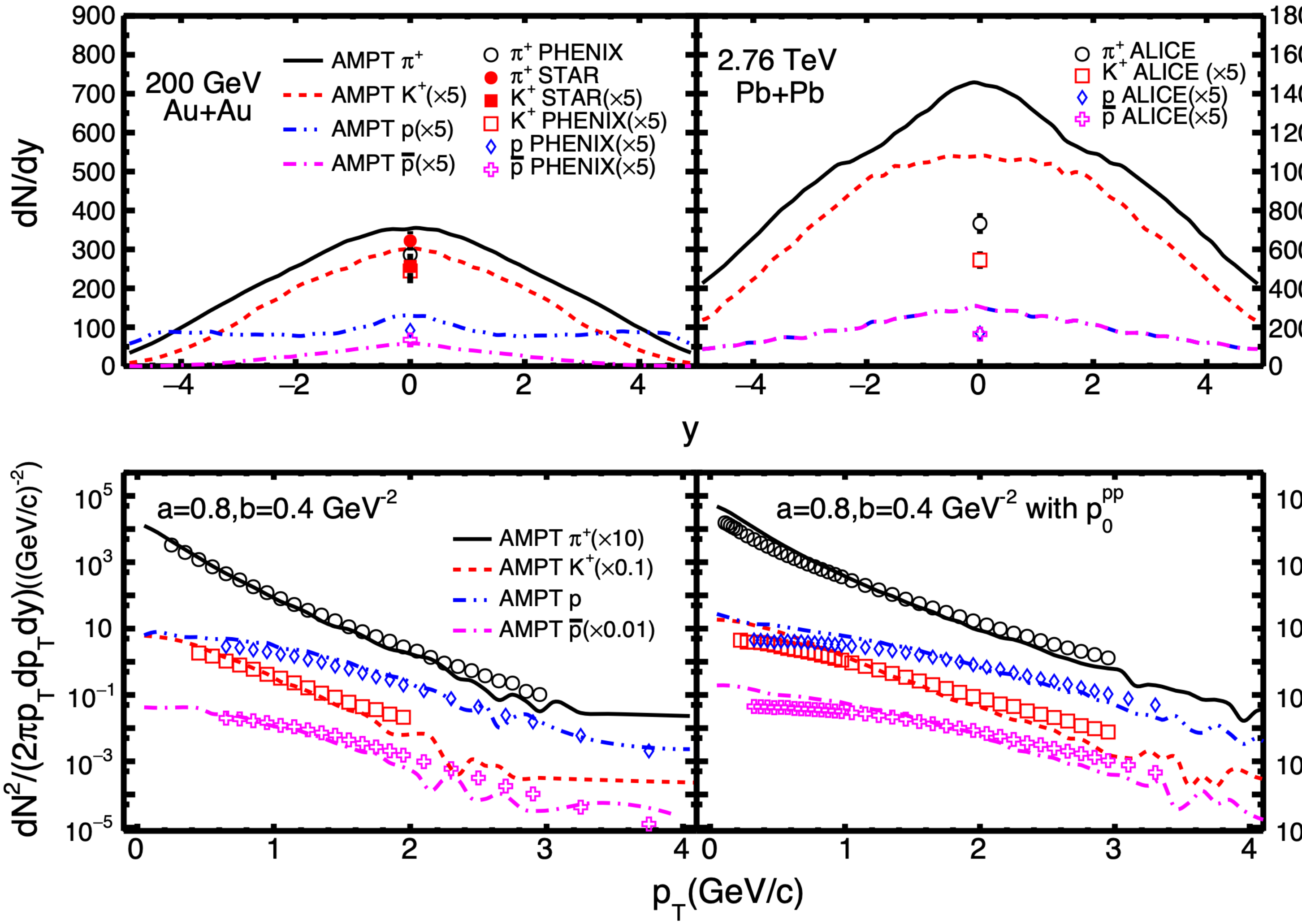




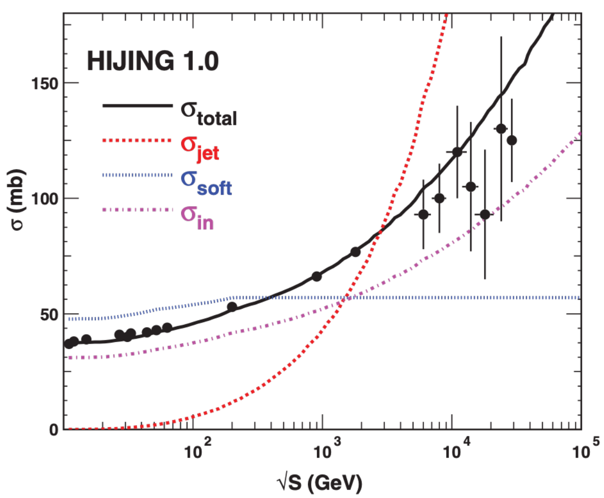
3) The model then reasonably describes the p+p data from ~20 GeV to 13 TeV.

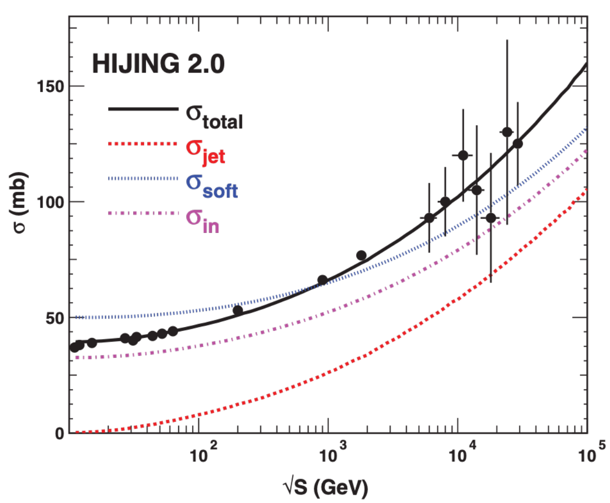
However, the model fails to describe central AA data at LHC energies: it overestimates most particle yields and gives too-soft p_T spectra.

This issue was known & can be solved with a smaller b_L value, but that will NOT solve the yield problem. ZWL, PRC 90 (2014)



Deng, Wang & Xu, PRC 83 (2011)





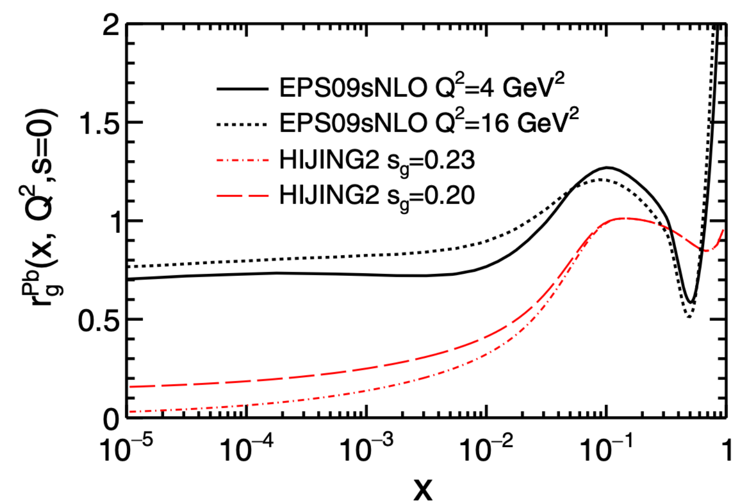
Earlier, HIJING2.0 model also replaced the old Duke-Owens set in HIJING1: it also fixed key model parameters (including p_0) with *p+p* data & reasonably describes the *p+p* data.

It also overpredicts particle yields in AA; then it uses a parameterized nuclear shadowing:

$$R_q^A(x,b) = 1.0 + 1.19 \log^{1/6} A(x^3 - 1.2x^2 + 0.21x) - s_q(b)(A^{1/3}-1)^{0.6}(1-3.5\sqrt{x}) \times \exp(-x^2/0.01), \quad (13)$$

$$R_g^A(x,b) = 1.0 + 1.19 \log^{1/6} A(x^3 - 1.2x^2 + 0.21x) - s_g(b)(A^{1/3}-1)^{0.6}(1-1.5x^{0.35}) \times \exp(-x^2/0.004), \quad (14)$$

But it needs very strong shadowing to describe particle yields in AA:



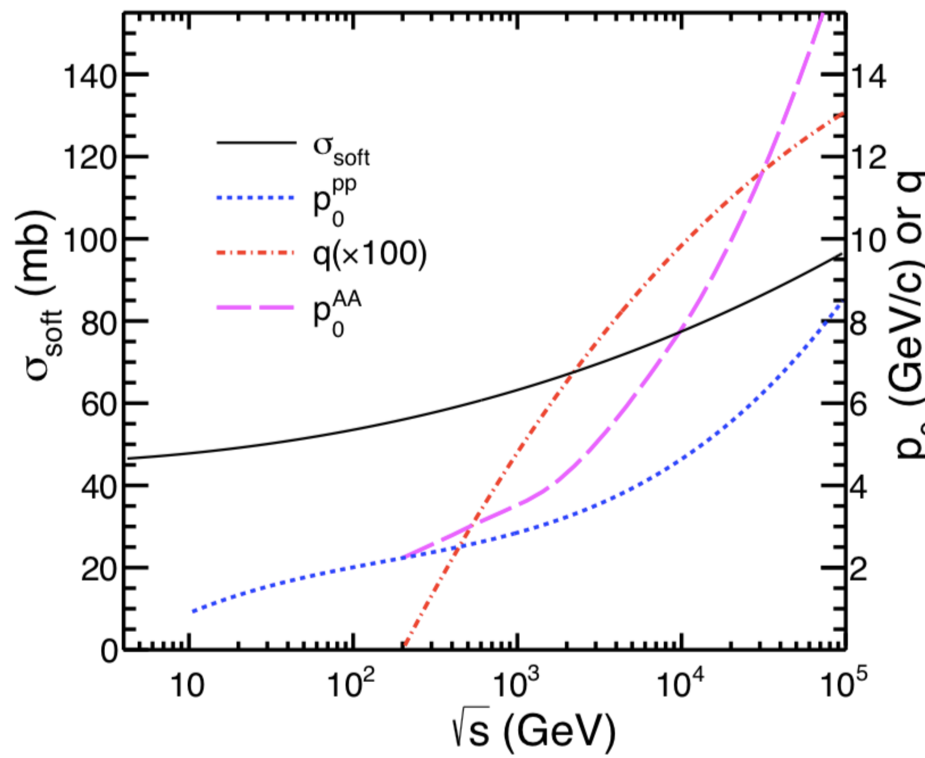
For AA at high energies, we already included state-of-art nuclear shadowing,
so we chose to increase the minijet cutoff p_0
to suppress σ_{jet} and the pQCD/hard contribution to particle yields:

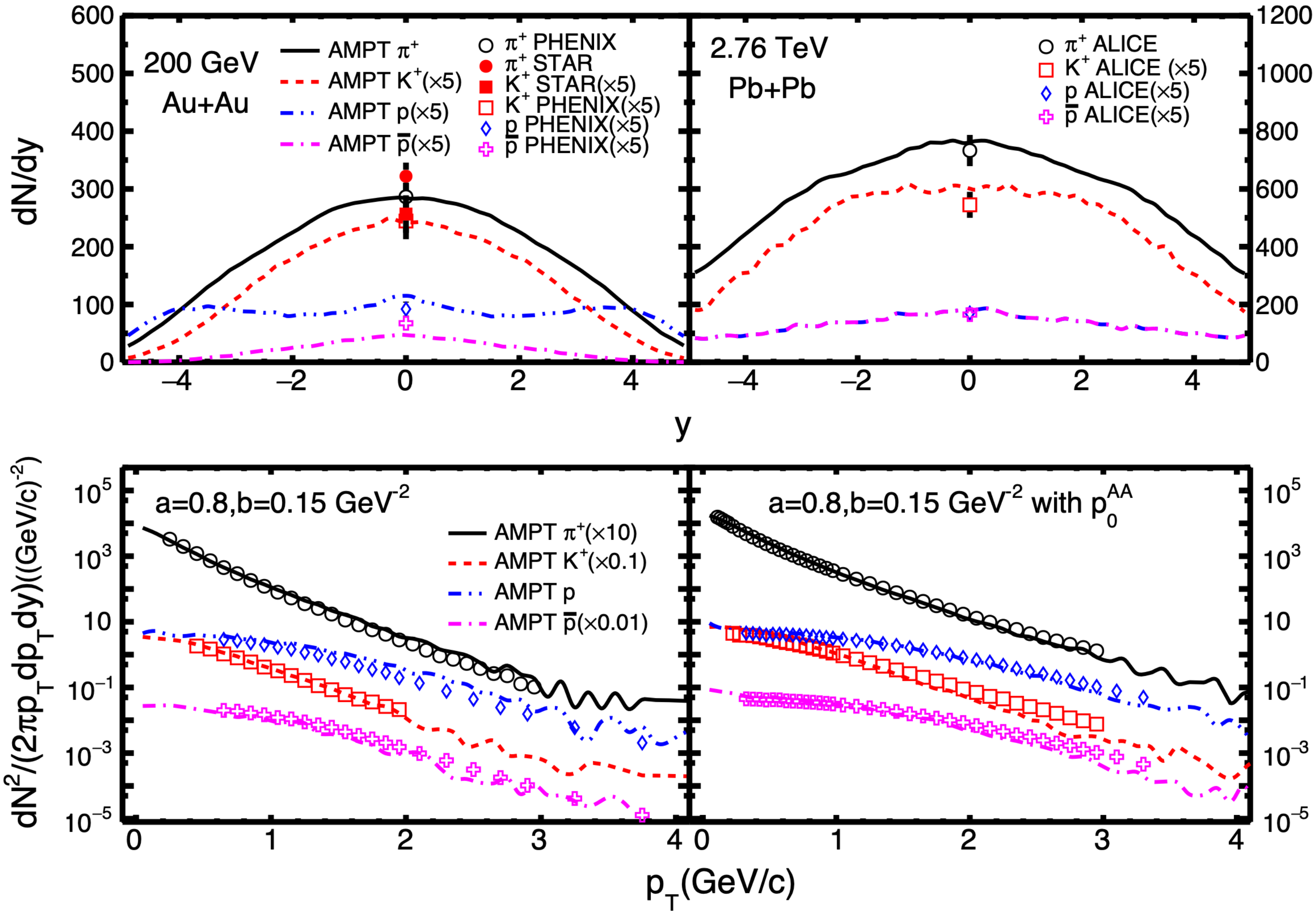
$$\sigma_{\text{jet}} = \sum_{c,d} \frac{1}{1+\delta_{cd}} \int_{p_0^2}^{s/4} dp_{\mathrm{T}}^2 dy_1 dy_2 \frac{d\sigma^{cd}}{dp_{\mathrm{T}}^2 dy_1 dy_2}$$

→ We introduce the A-scaling of p_0
for central AA collisions:

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

- This scaling is motivated by CGC/saturation, where $Q_s \propto A^{1/6}$ in the saturation region.
- *q(s): fitted,* $=0$ if $\sqrt{s} \leq 200$A GeV, $\sim 1/6$ at $>>10^5$A GeV.

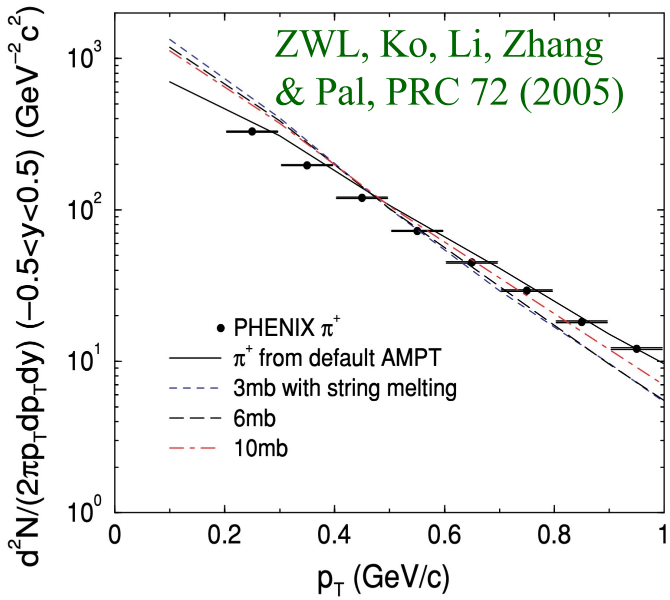




After the A-scaling of p_0 (*and decreasing Lund b_L to 0.15/GeV^2*), the string melting AMPT model can reasonably describe central AA data.

Outline

1. Motivation and the AMPT model
2. $\sqrt{s}$- and A-dependent minijet cutoff p_0 for central A+A
3. Local nuclear scaling of p_0 and b_L for any collisions
4. Cronin effect of D-mesons in pPb collisions
5. Summary / Discussions

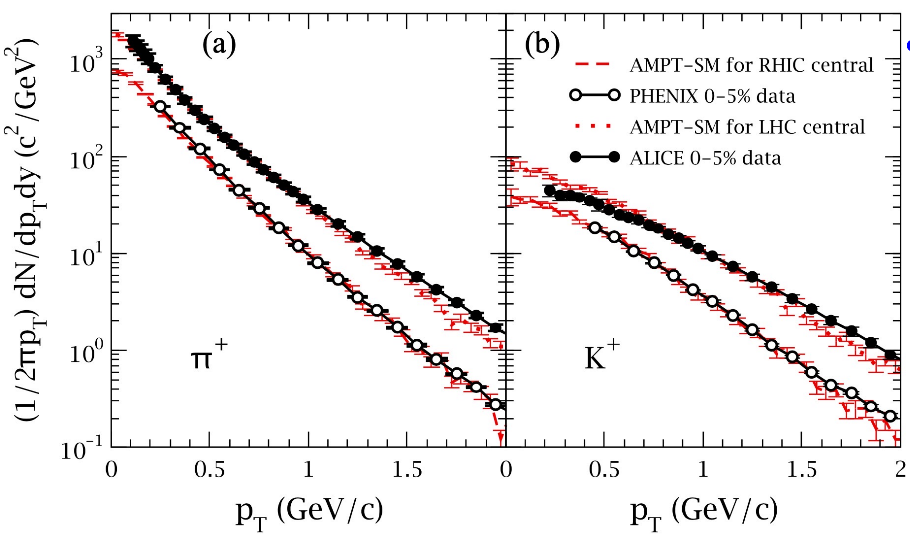


- String Melting AMPT describes flows and HBT but before 2014 it failed badly in hadron p_T spectra.

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 GeV^{-2}):
0.5 (AMPT), ~0.58 (PYTHIA6.2), 0.9 (HIJING1)



ZWL, PRC 90 (2014)

- We later realized that the model can simultaneously describe dN/dy, p_T–spectra & v_2 at low p_T in high energy central AA collisions *if we use a very small Lund parameter b_L~0.15.*

Smaller $b_L \rightarrow$ higher string tension κ:

$$\kappa \propto \frac{1}{b_L(2+a_L)} \sim \langle p_T^2 \rangle$$

So different values of b_L are needed for p+p and central AA;
this is also true for the minijet cutoff scale p_0 (*after using modern nPDFs*).

How about AA collision at any impact parameter (or centrality)?

We have used A-scaling of p_0 for central AA as motivated by CGC.

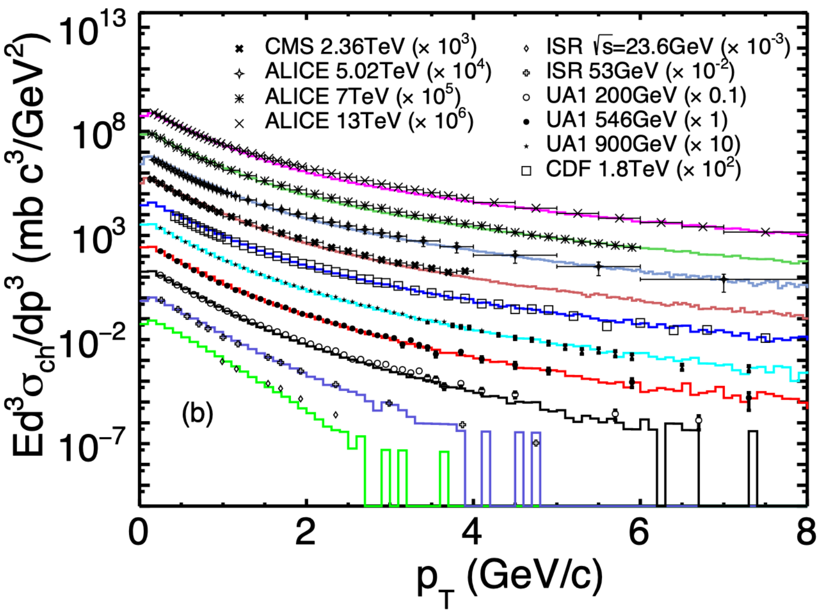
→ So we propose a more general scaling by using local nuclear densities T_A & T_B right after the primary AA collision:

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

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

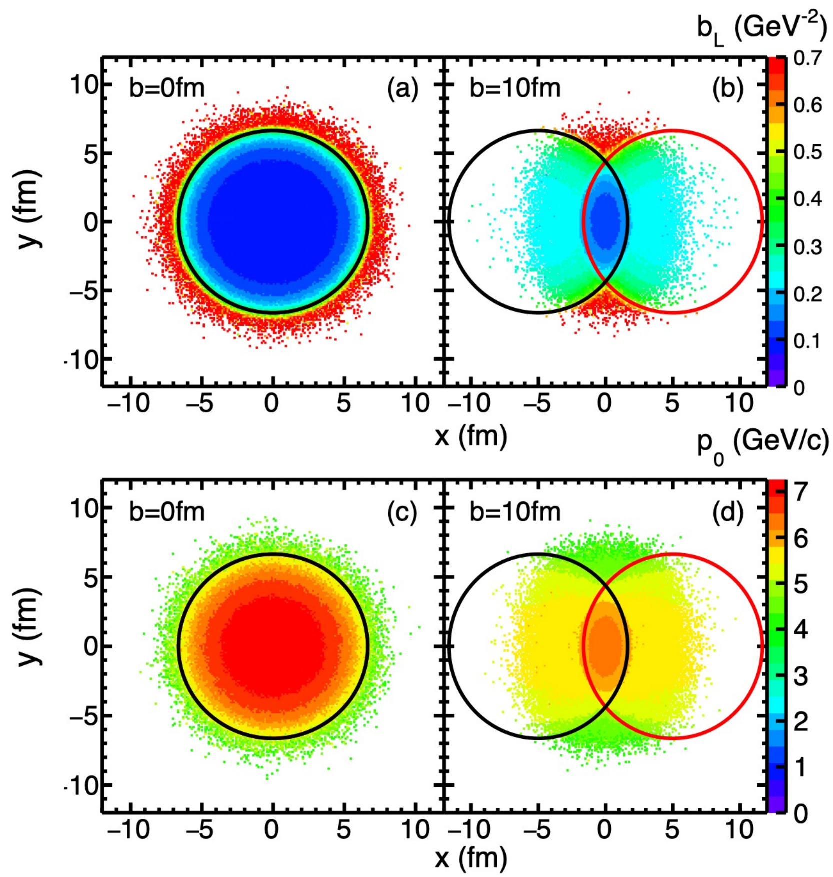
Chao Zhang, Zheng, Shi
& ZWL, PRC 104 (2021)

1) We fit charged hadrons in *pp* to determine b_L^{pp} =0.7/GeV^2, then used central Au+Au/Pb+Pb data to fit $\alpha(s)$ & $\beta(s)$.



$p + p$ or $p + \bar{p}$ collisions

2)⟶ Pb+Pb @ $\sqrt{s}$= 5.02A TeV:

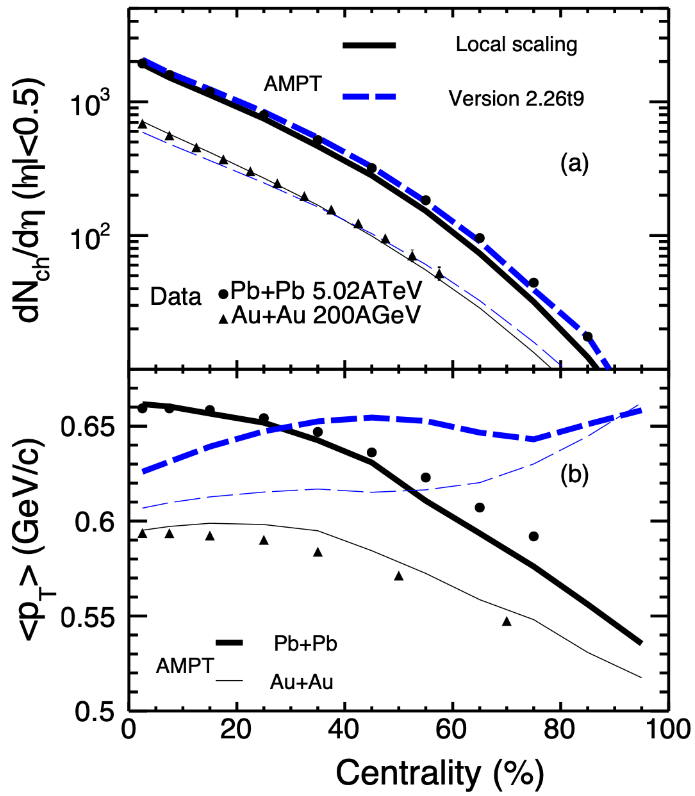


b_L

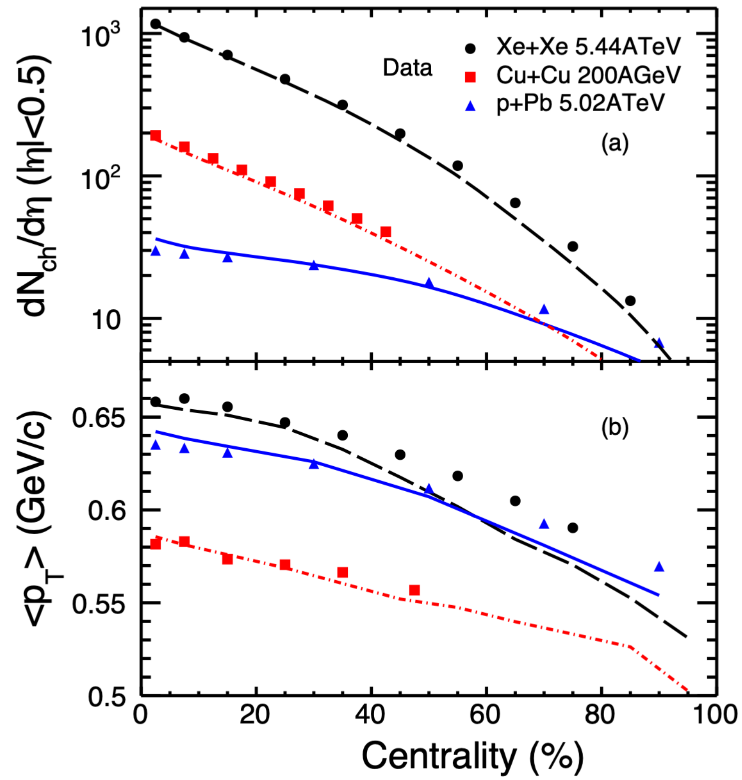
p_0

This allows AMPT-SM to self-consistently describe system size dependence, including centrality dependences and smaller systems.

Centrality dependences of $\langle p_T \rangle$ are reasonable, much better than public AMPT (v2.26t9):



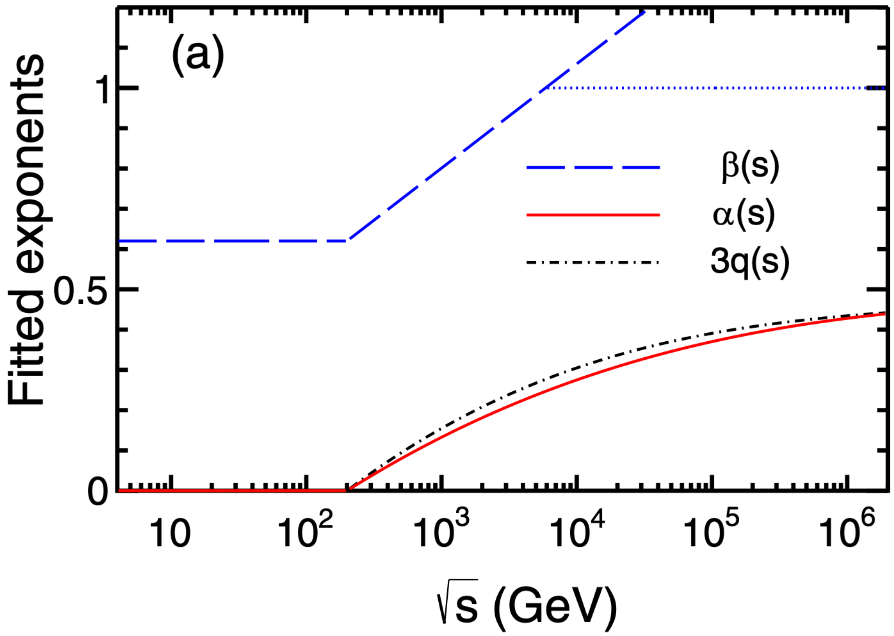
Scaling also works for smaller systems:



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

No longer free parameters → can focus on QGP properties σ, η, ...

We have used central Au+Au/Pb+Pb data to fit $\alpha(s)$ & $\beta(s)$:



Motivated by CGC/saturation, where $Q_s \propto A^{1/6}$ in the saturation region:

- *q(s): fitted,* =0 if $\sqrt{s} \leq 200$A GeV, ~1/6 at >>10^5A GeV.
- $\alpha(s)$: *fitted,* ~*3q(s).*
- $\beta(s)$: *fitted,* ~constant ≤ 200A GeV, ? beyond LHC.

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

Chao Zhang, Zheng, Shi & ZWL, PRC 104 (2021)

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

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

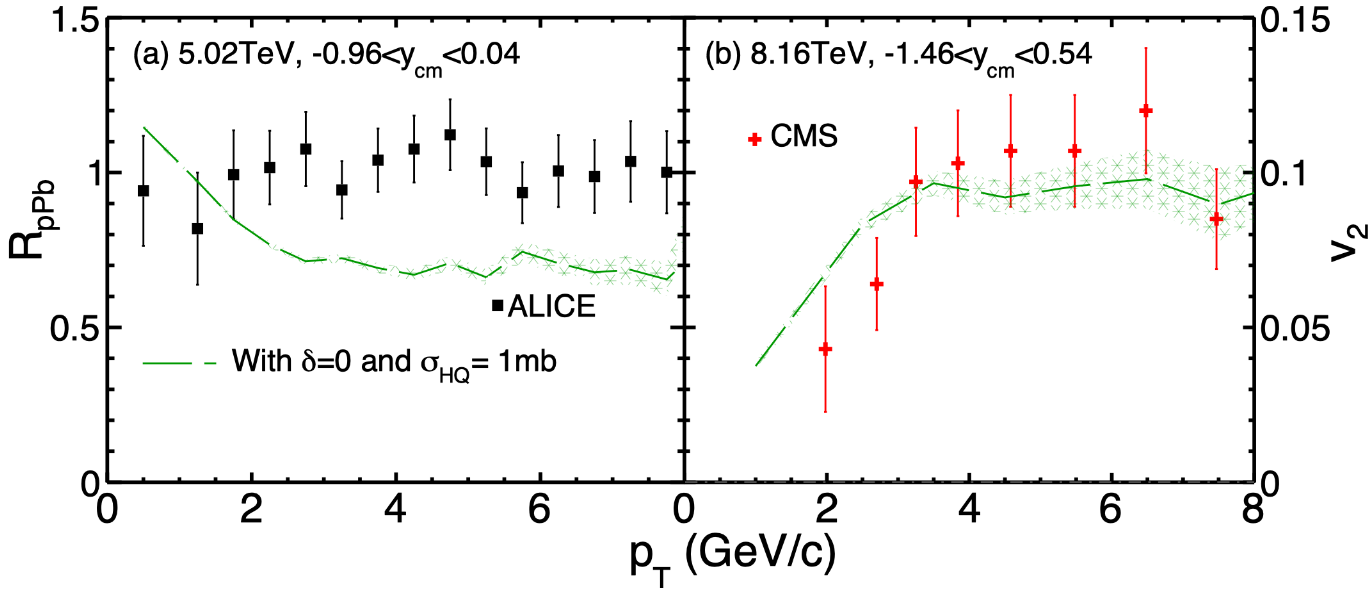
Outline

1. Motivation and the AMPT model
2. $\sqrt{s}$- and A-dependent minijet cutoff p_0 for central A+A
3. Local nuclear scaling of p_0 and b_L for any collisions
4. Cronin effect of D-mesons in pPb collisions
5. Summary / Discussions

The D^0 R_{pA} and v_2 puzzle:

LHC *pPb* data show

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



It has been a challenge to describe both data simultaneously:

- sizable v_2 → significant charm quark interaction with medium
  → suppression of high p_T charm in pA and expect R_{pA}<1 (green curves)

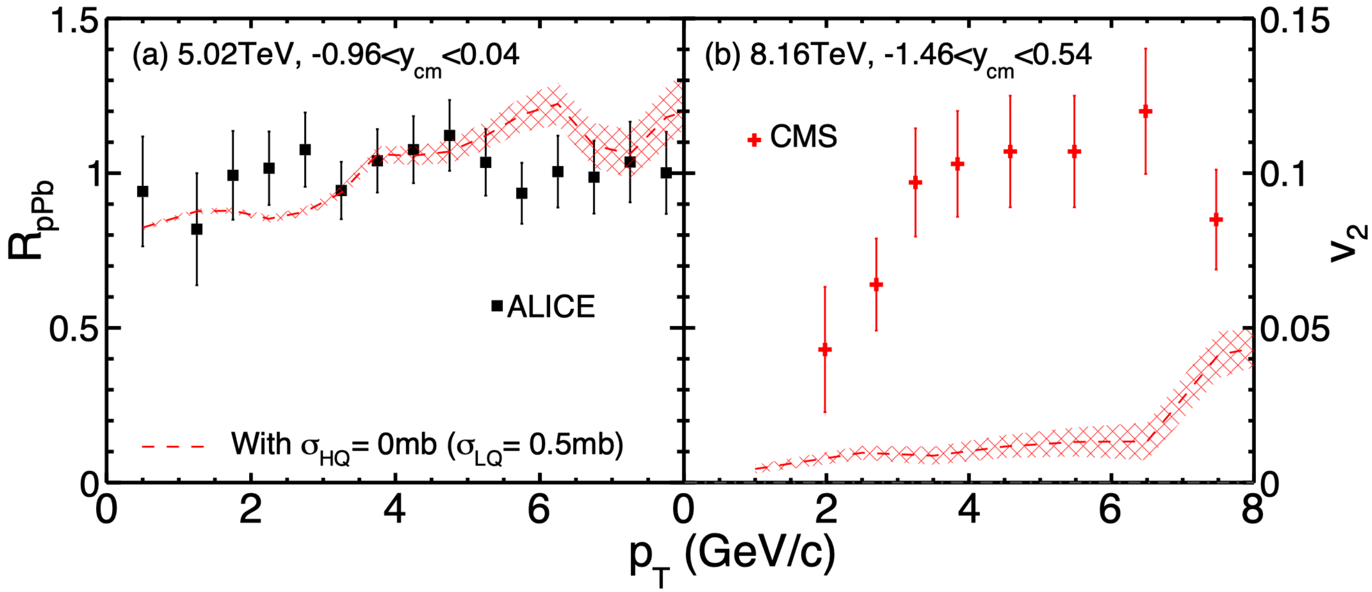
- Studies based on CGC can describe D and J/ψ v_2 ; no R_{pA} results yet.

Cheng Zhang, Marquet, Qin, Wei & Xiao, PRL 122 (2019);
Cheng Zhang, Marquet, Qin, Shi, Wang, Wei & Xiao, PRD 102 (2020)

The D^0 R_{pA} and v_2 puzzle:

without charm quark scatterings (red curves),

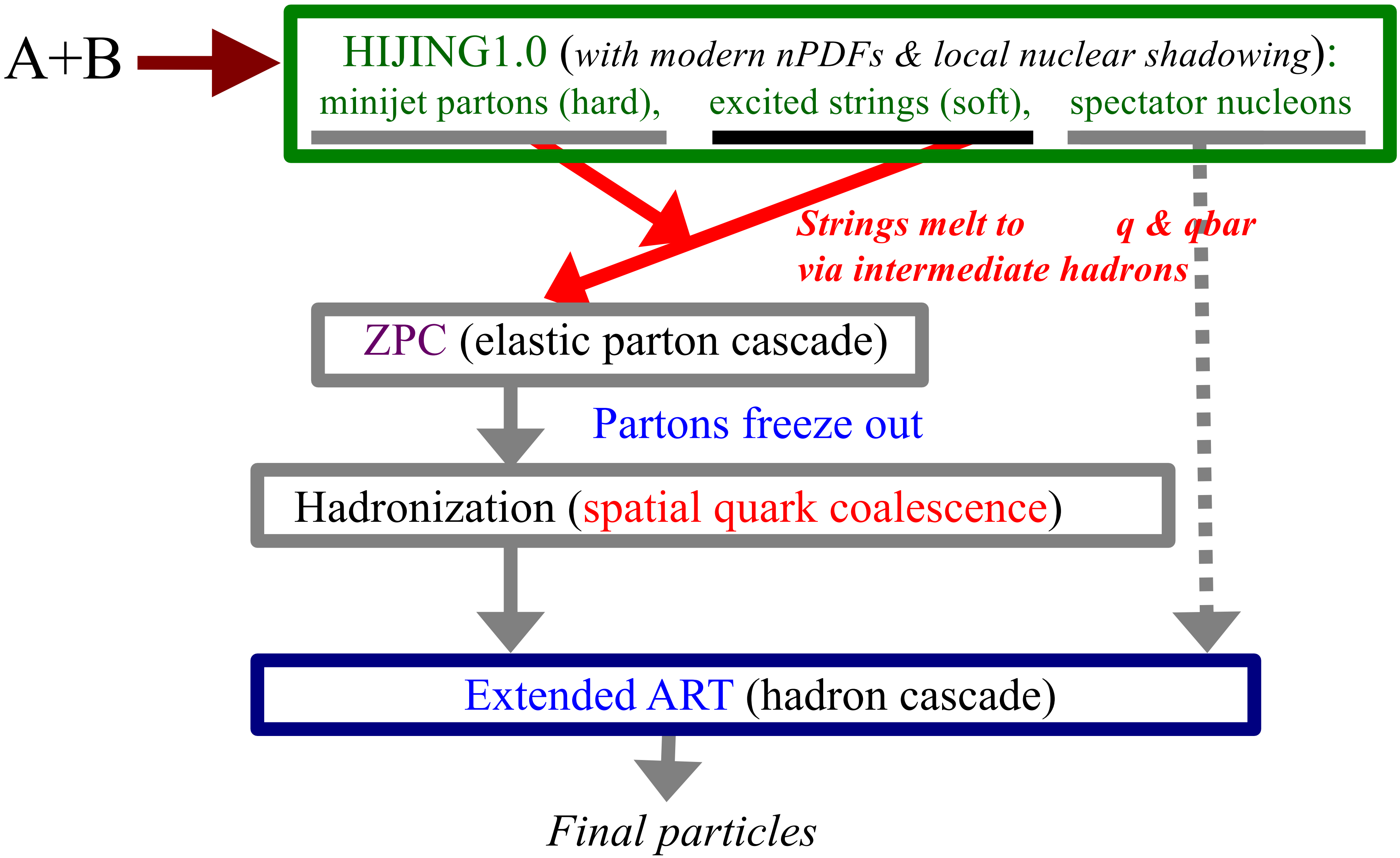
R_{pA} result can be close to data, but v_2 is very small.



- This has been seen in an earlier study: Beraudo et al. JHEP 03 (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*)

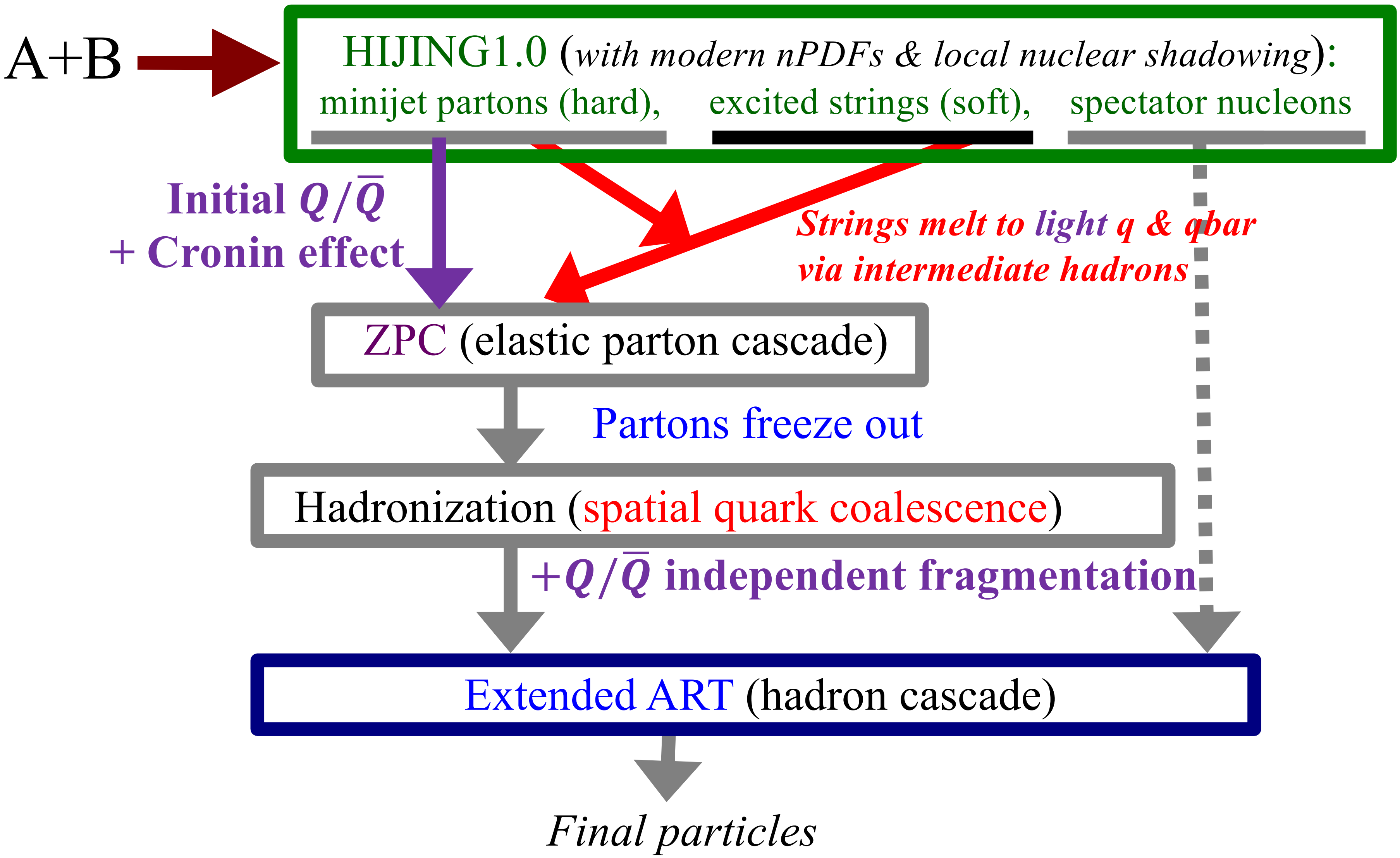
We started with the AMPT-SM version with the first 3 recent developments:



We then further improved heavy flavors in AMPT:

Chao Zhang, Zheng, Shi & ZWL, PLB 846 (2023)

Improved AMPT-SM:

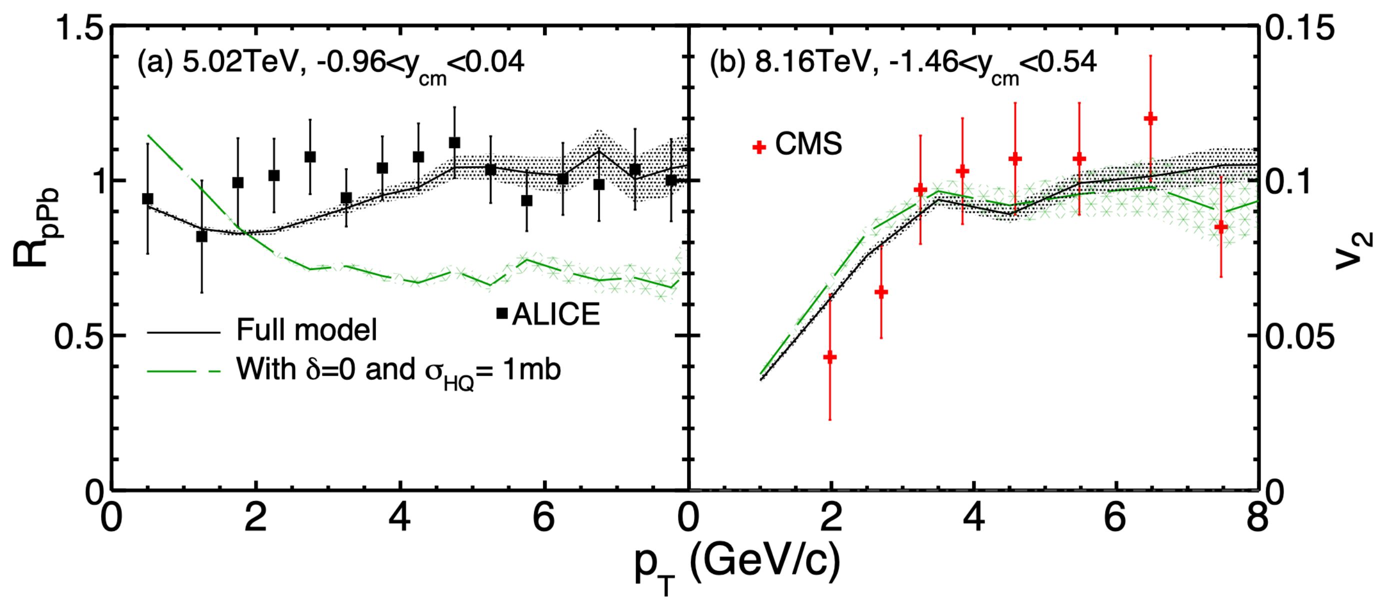


We implement the Cronin effect on initial charm quarks by broadening $c\bar{c}$ p_T with a random k_T sampled from

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

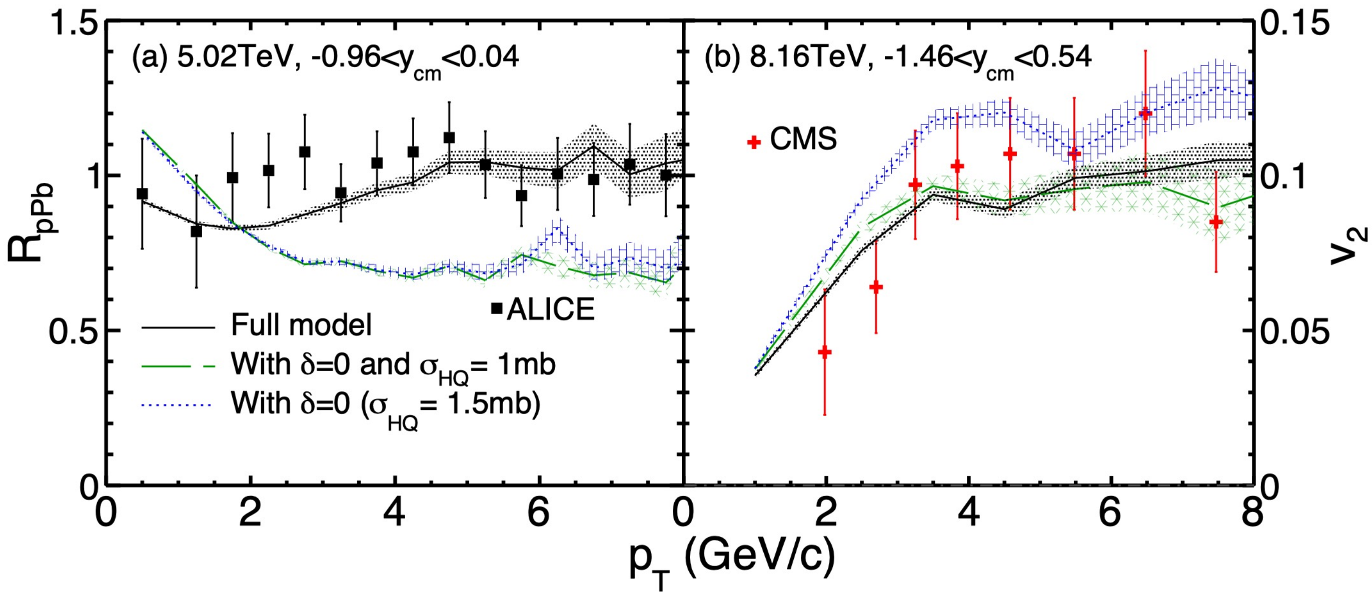
$$f(\vec{k_T}) = \frac{1}{\pi w^2} e^{-k_T^2/w^2}$$

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



The full model, with Cronin effect at δ=7, σ_{LQ}=0.5mb (for u/d/s quarks), σ_{HQ}=1.5mb (for scatterings of charm quarks with other partons), can describe both R_{pA} and v_2 data of D^0 mesons.

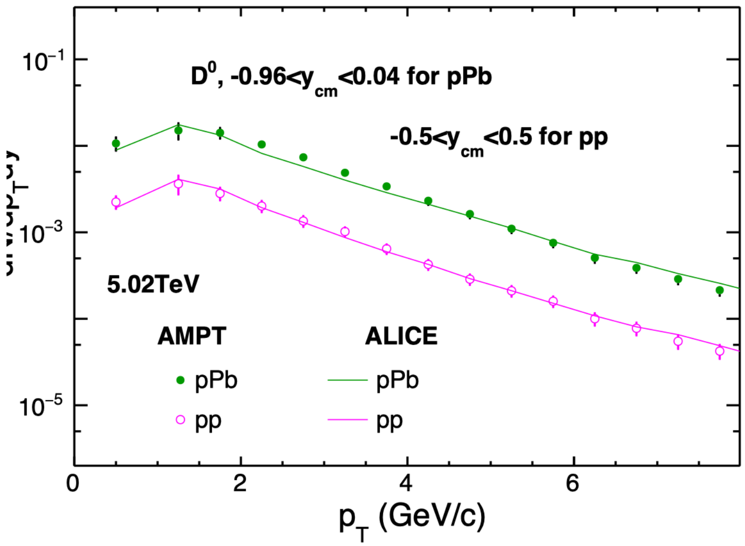
Without the Cronin effect (or δ=0):
we can get sizable v_2,
but D^0 R_{pA} is underestimated due to charm scatterings with the medium (via σ_{HQ}).



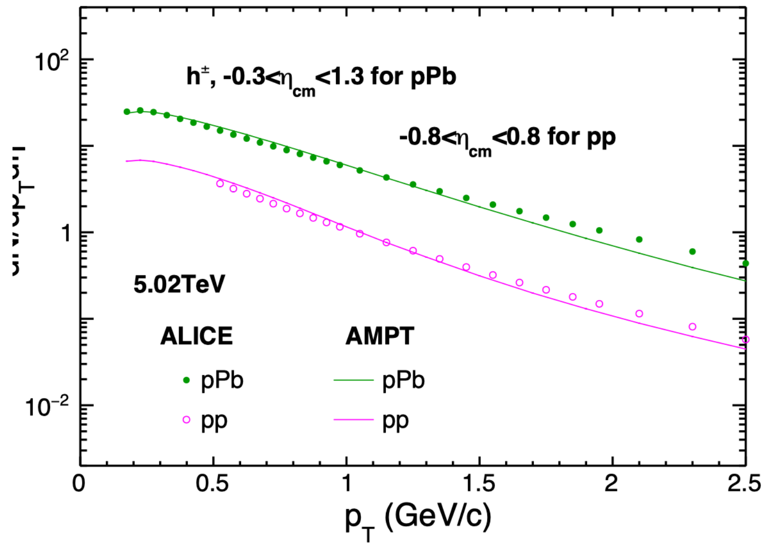
Black curve vs blue curve (*both at σ_{HQ}=1.5mb*):
the Cronin effect significantly increases charm R_{pA} at moderate/high p_T
but modestly decreases charm v_2

The full model also reasonably describes various observables at 5.02 TeV:

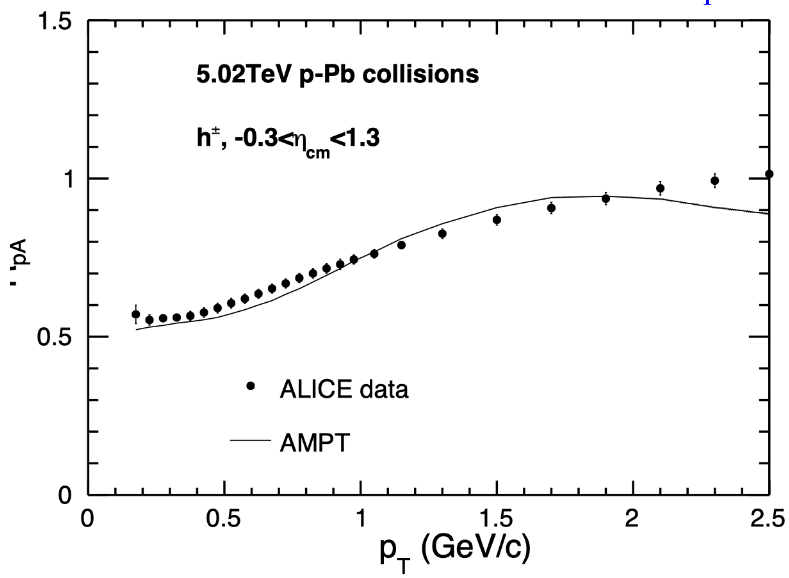
D^0 p_T spectra (to ~8GeV/c)



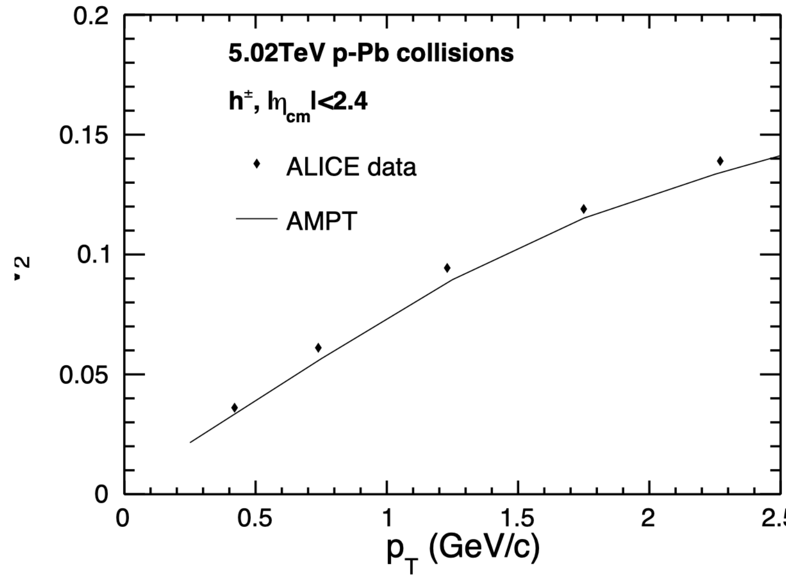
Charged hadron p_T spectra (to ~1.5 GeV/c)



Charged hadron R_{pA}

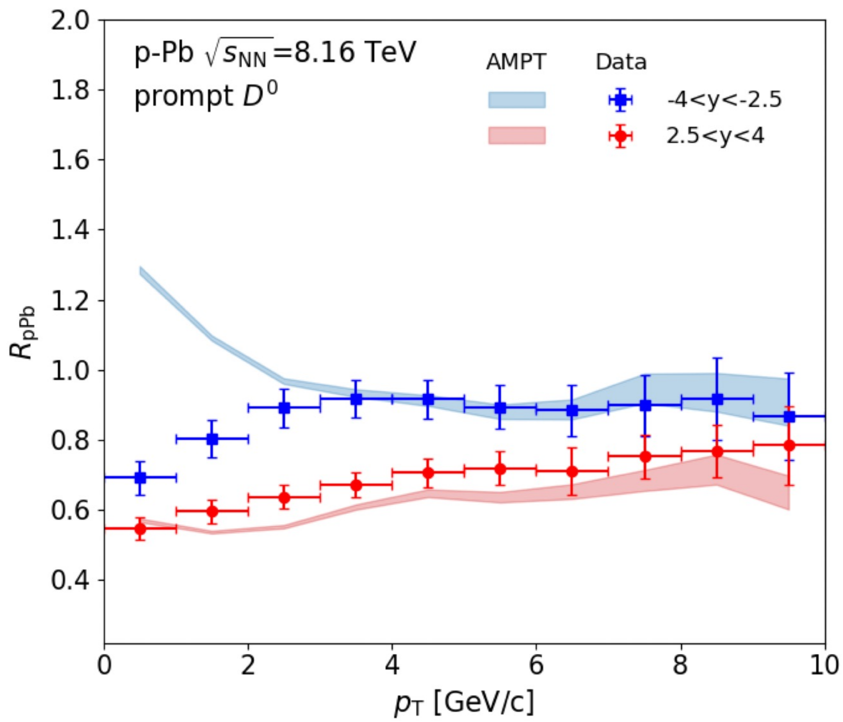


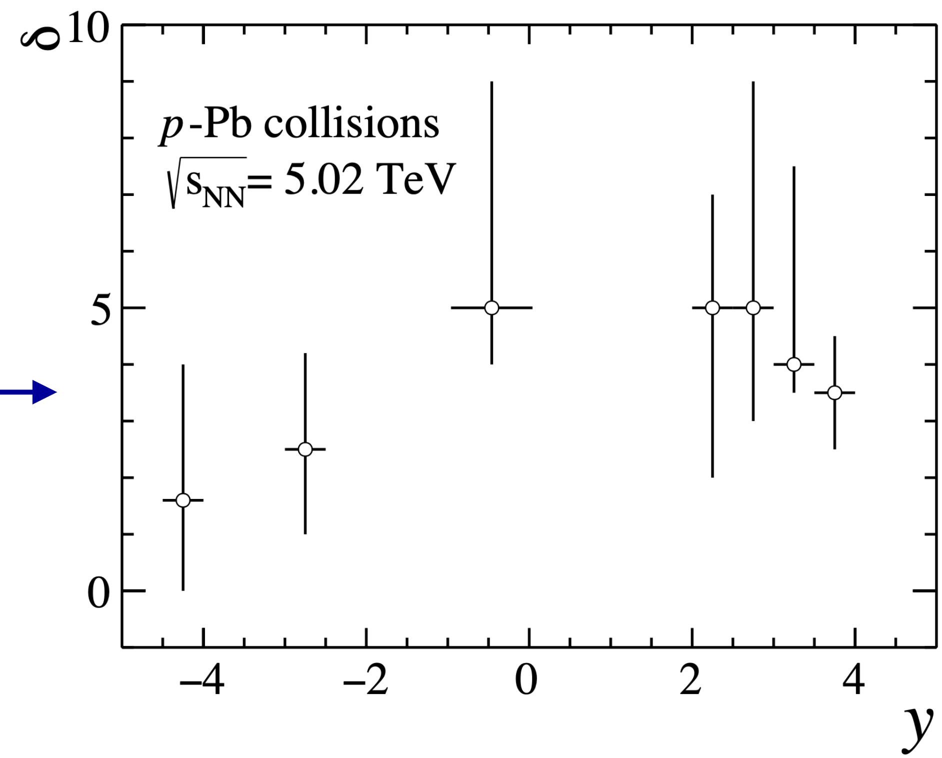
Charged hadron v_2 in pPb



Next we studied D^0 R_{pA} in forward/backward rapidities & extracted y-dependence of Cronin strength δ:

Chao Zhang, Zheng, Shi & ZWL, EPJC 84 (2024)

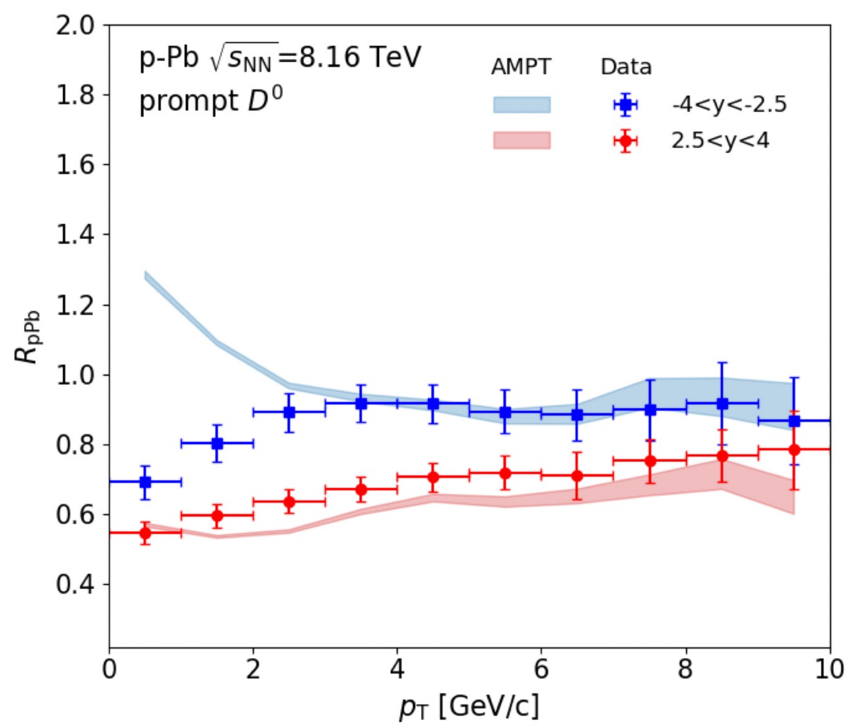


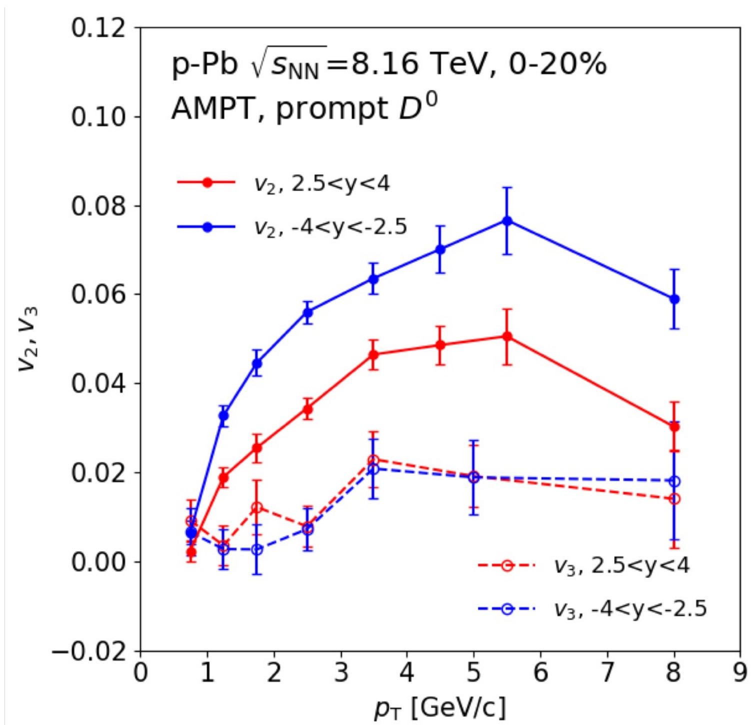


Tang, Zhang, Zheng, Wan, ZWL & Ma, 2606.28928

Recently we also studied forward/backward asymmetry of D^0 R_{pA} together with D^0 flows v_2 & v_3:

Tang, Zhang, Zheng, Wan, ZWL & Ma, 2606.28928





Questions:

- Is the strong Cronin effect & y-dep. supported by QCD/CGC calculations?
- Effect of Cronin broadening for hard observables in large systems?

Summary / Discussions*

A multi-phase transport (AMPT) model

provides a comprehensive kinetic description of heavy ion collisions

Recent developments of the AMPT model require

nuclear scaling of initial condition parameters p_0 and b_L,

motivated by the CGC-based theory & small-x saturation.

* Other and more quantitative connections remain unexplored, for example:

$\sqrt{s}$-, A-, position-dependence of jet production & parton $\langle p_T \rangle$ from CGC?

Could CGC/small-x approach produce an initial parton condition

that conserves energy-momentum and net-baryon number of an event?

Recent model study of D^0 R_{pPb} and v_2 indicate essential role of Cronin effect:

* Can CGC/small-x approach be used to study Cronin effect quantitatively?

Thank you!