Resolving the R_{pA} and v_2 puzzle of D^0 mesons in p–Pb collisions

Zi-Wei Lin
East Carolina University (ECU)

National
Science
Foundation

Based on 2210.07767 & update by
Chao Zhang, Liang Zheng, Shusu Shi & ZWL

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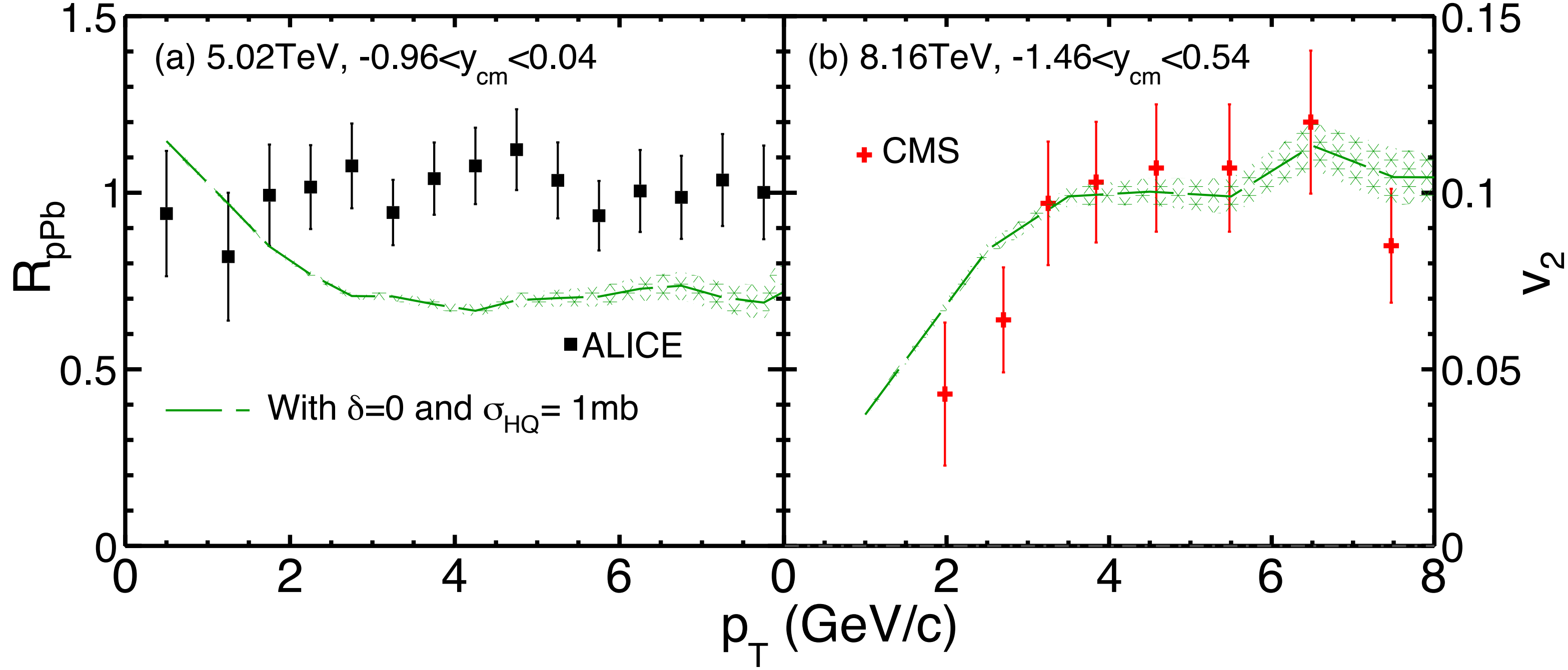
Outline

- The D^0 R_{pA} and v_2 puzzle
- Improved multi-phase transport model for heavy flavors
- Possible solution of the R_{pA}/v_2 puzzle with the Cronin effect
- Summary

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



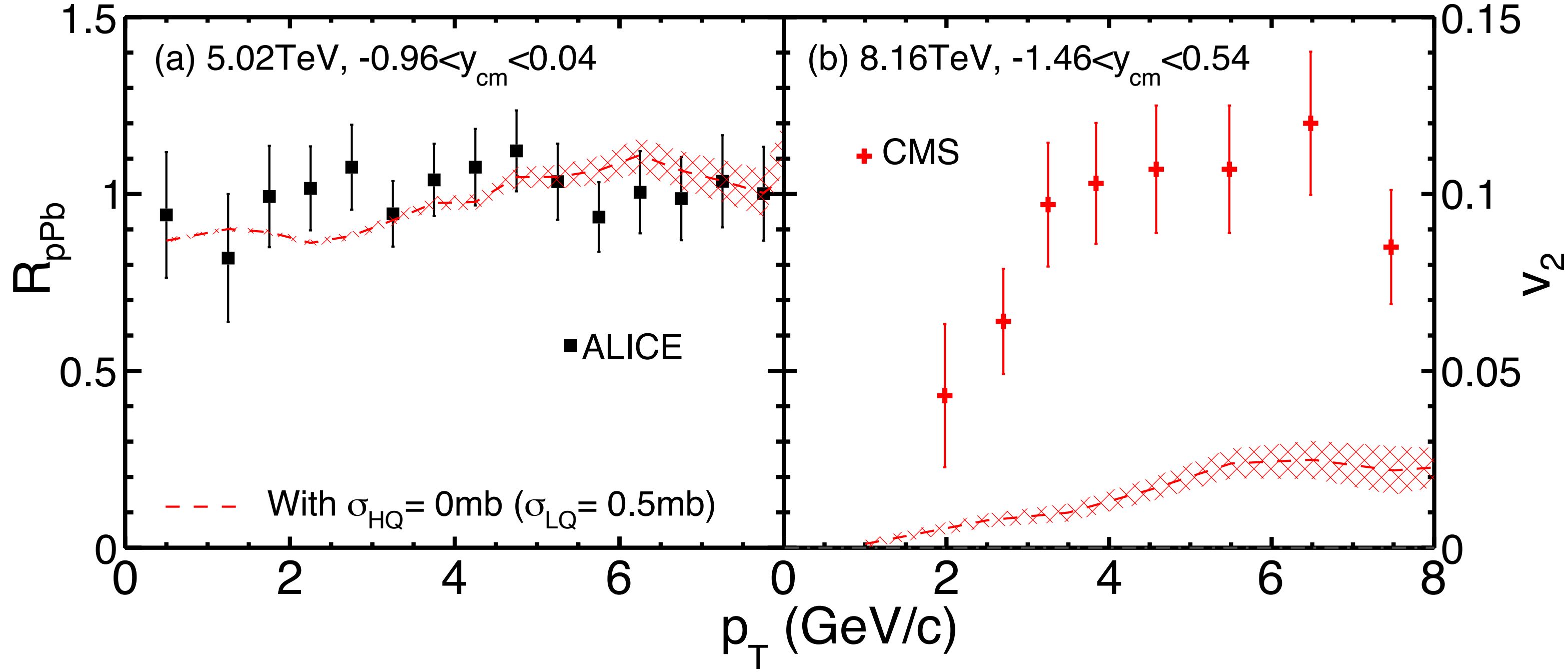
It has been a challenge to describe both data simultaneously:

- 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)

The D^0 R_{pA} and v_2 puzzle

- Without charm quark scatterings (below),
  R_{pA} result can be close to data, but v_2 is very small.



- This was seen in an earlier study:
  ~ no suppression in R_{pA}, then v_2 is too small.

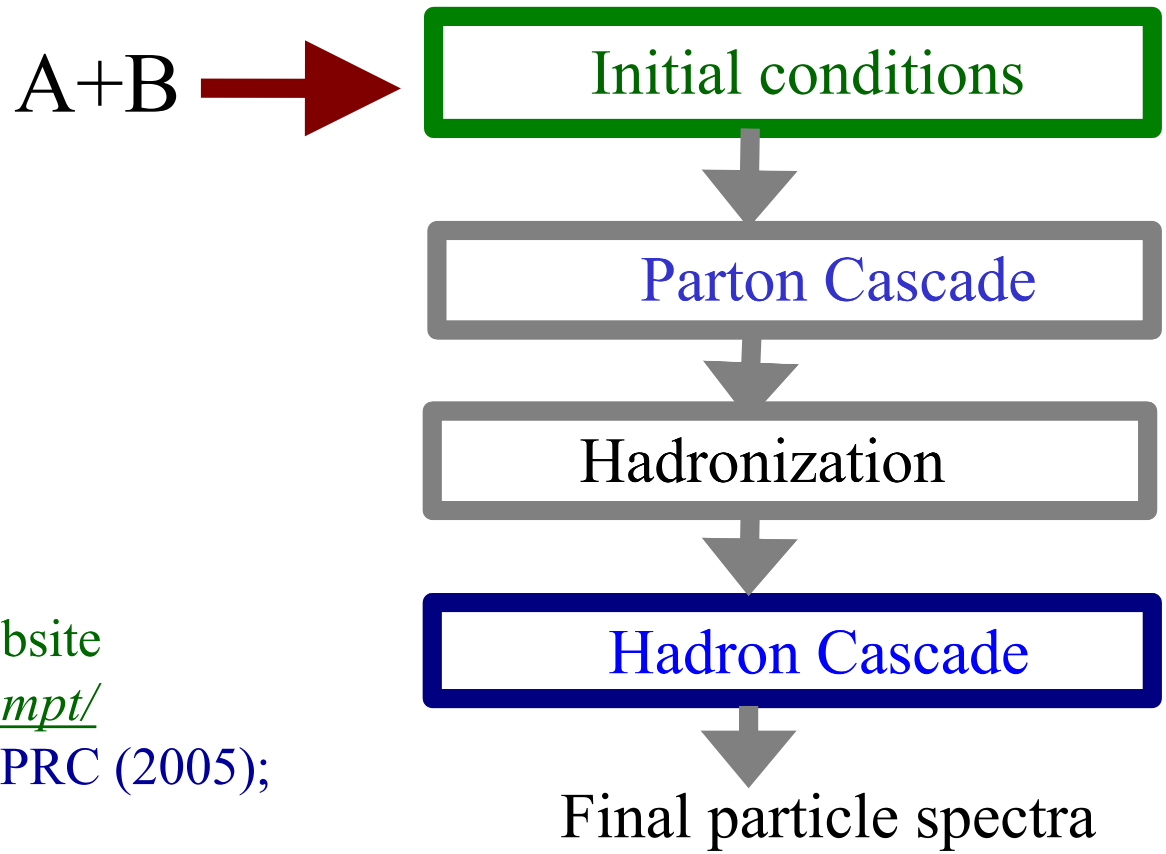
Beraudo et al. JHEP (2016)

- 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

Improved multi-phase transport model for heavy flavors

We use a multi-phase transport (AMPT) model for this study.
It was constructed as a self-contained kinetic description of heavy ion collisions:

- evolves the system from initial condition to final observables;
- particle productions of all flavors from low to high p_T;
- addresses non-equilibrium evolution/dynamics (*more important for smaller systems*).



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

Improved multi-phase transport model for heavy flavors

$gg \rightarrow gg$ cross section in leading-order pQCD
is divergent for massless g,
so HIJING uses a **minijet cutoff $\boldsymbol{p_0}$** for minijets (of ALL flavors).

$$\frac{d\sigma}{dt} \sim \frac{9\pi\alpha_s^2}{2t^2}$$

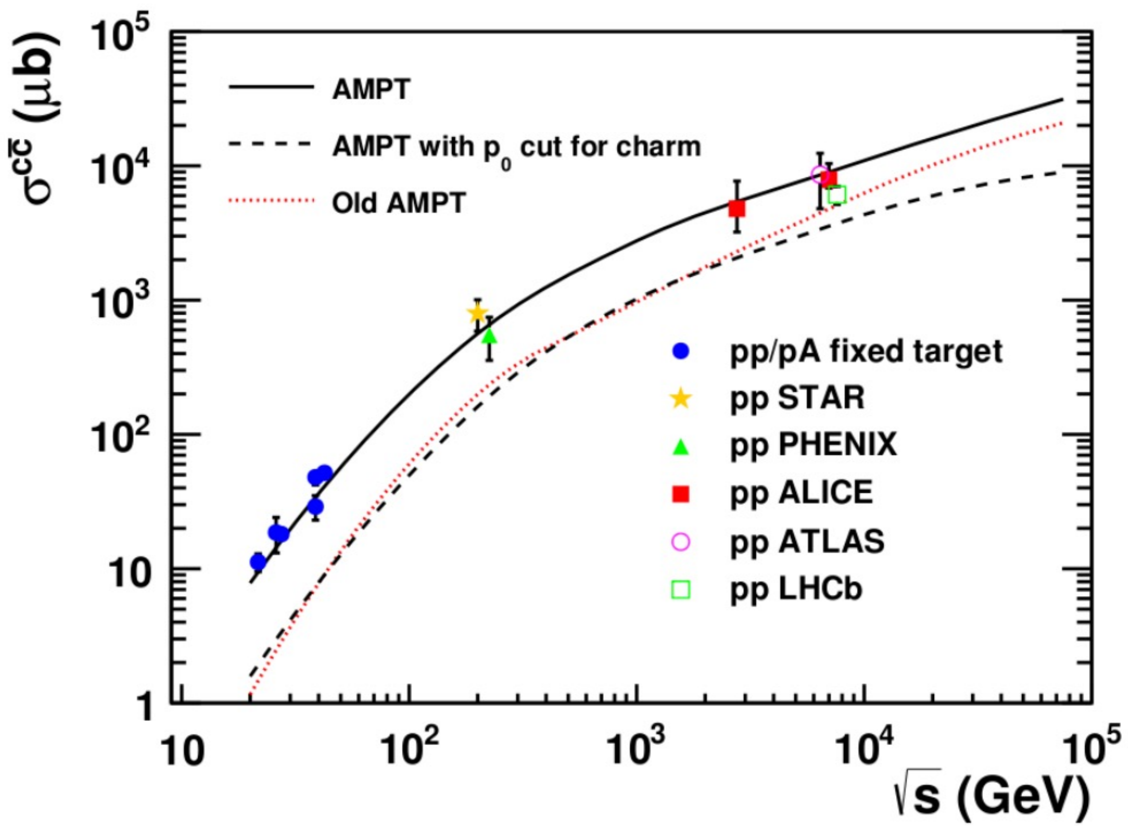
But heavy flavor (HF) production does not need a cutoff
due to heavy quark mass >> Λ_{QCD} (e.g. in FONLL)

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

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

  Zheng et al. PRC (2020)
- Unlike HIJING, we include HF in σ_{jet}: $\sigma_{jet} = \sigma_{jet}^{LF} + \boldsymbol{\sigma^{HF}}$
- We also correct factor of ½ in certain σ_{jet} channels

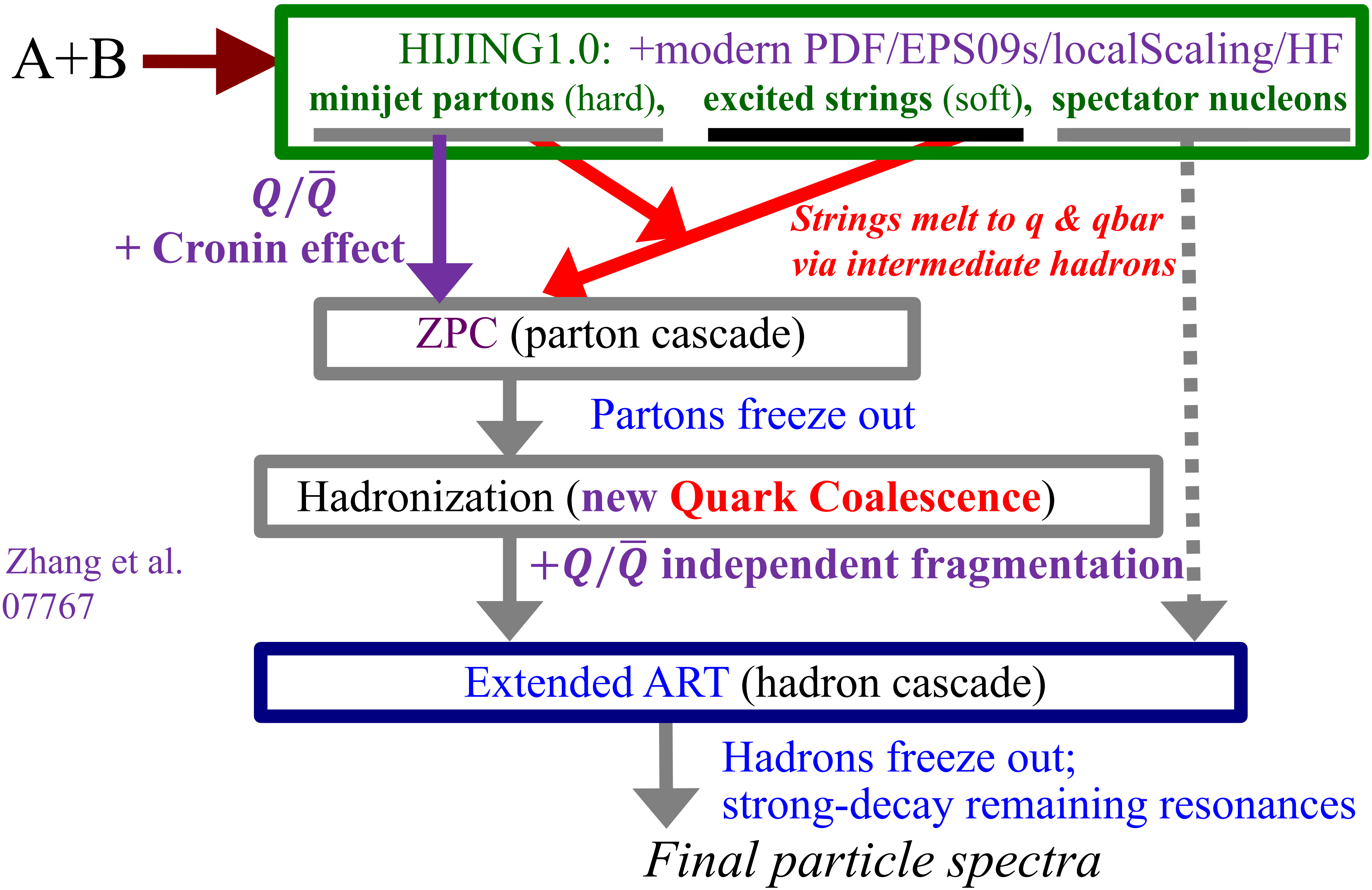
Improved multi-phase transport model for heavy flavors



Zheng et al. PRC (2020)

- Older/public AMPT charm yield << data
- Removing p_0 in HF production greatly enhances charm yield
- This AMPT model well describes world data on total $c\bar{c}$ cross section

Structure of **improved** AMPT (String Melting version)



Chao Zhang et al.
2210.07767

The AMPT model used in this study contains all these improvements

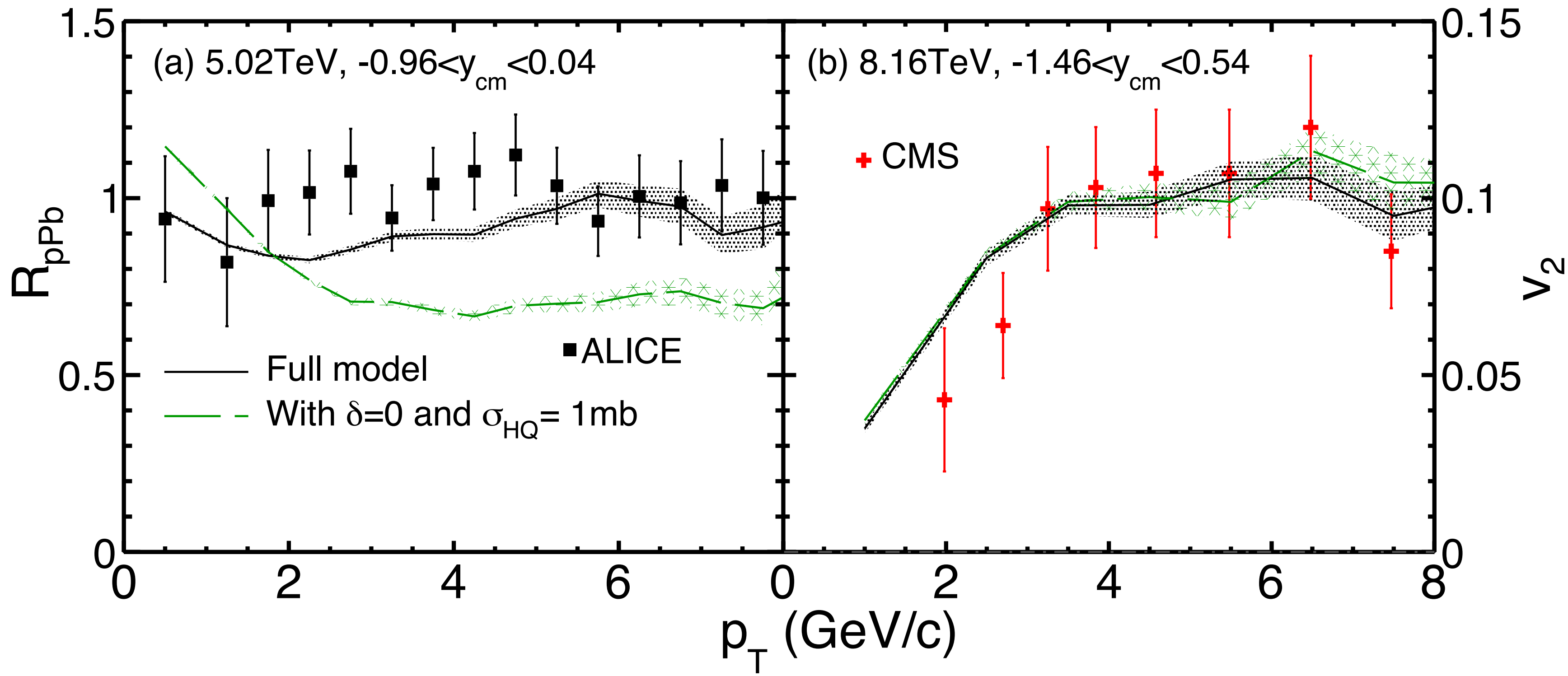
Possible solution of the R_{pA}/v_2 puzzle with the Cronin effect

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)

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

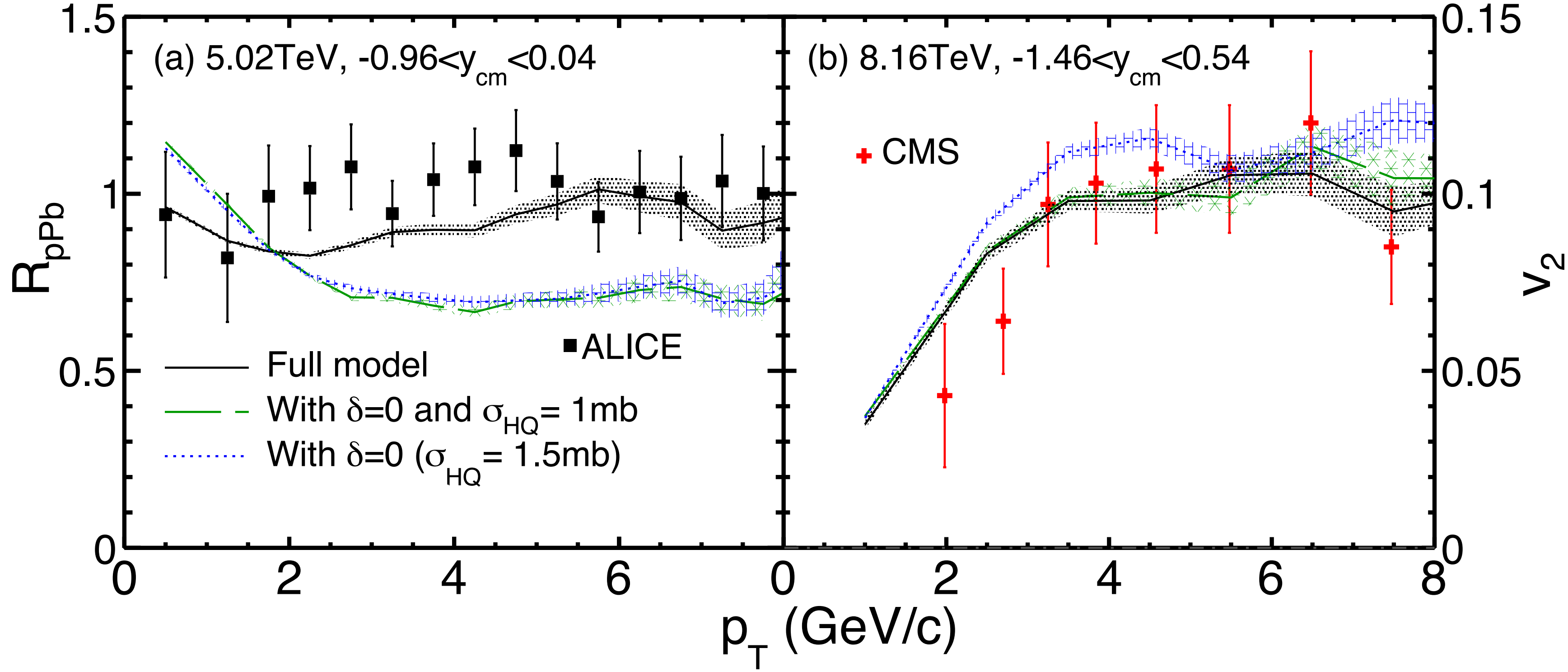
$w = w_0\sqrt{1+(n_{coll}-i)\delta}$ grows with # of NN collisions of the wounded nucleon(s).



Full model, with Cronin effect at δ=5, σ_{LQ}=0.5mb (for scatterings among 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

Possible solution of the R_{pA}/v_2 puzzle with the Cronin effect

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

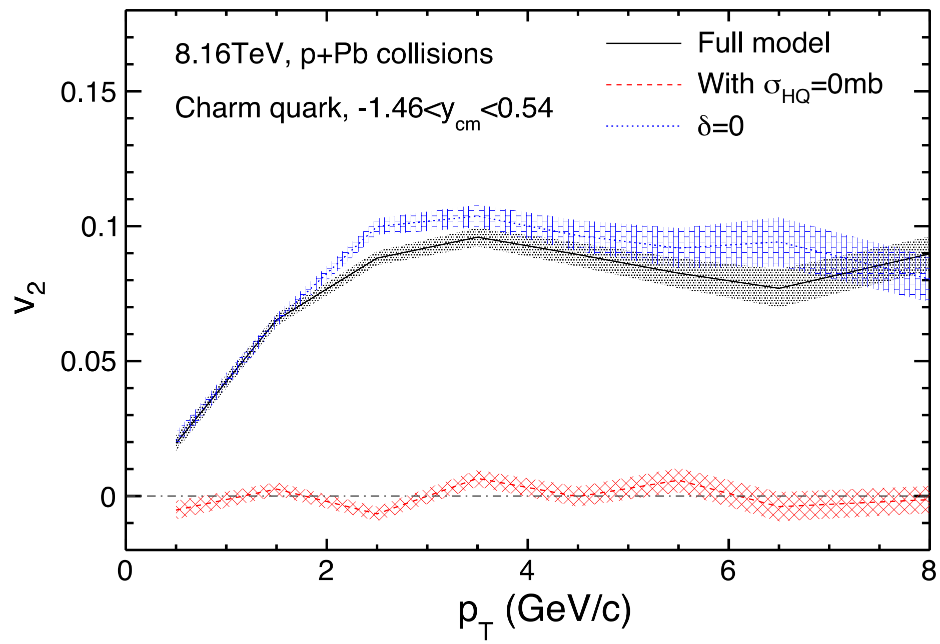


Black curve vs blue curve (*both at* σ_{HQ}*=1.5mb*):
the Cronin effect significantly increases charm R_{pA} at moderate/high p_T
but modestly decreases charm v_2

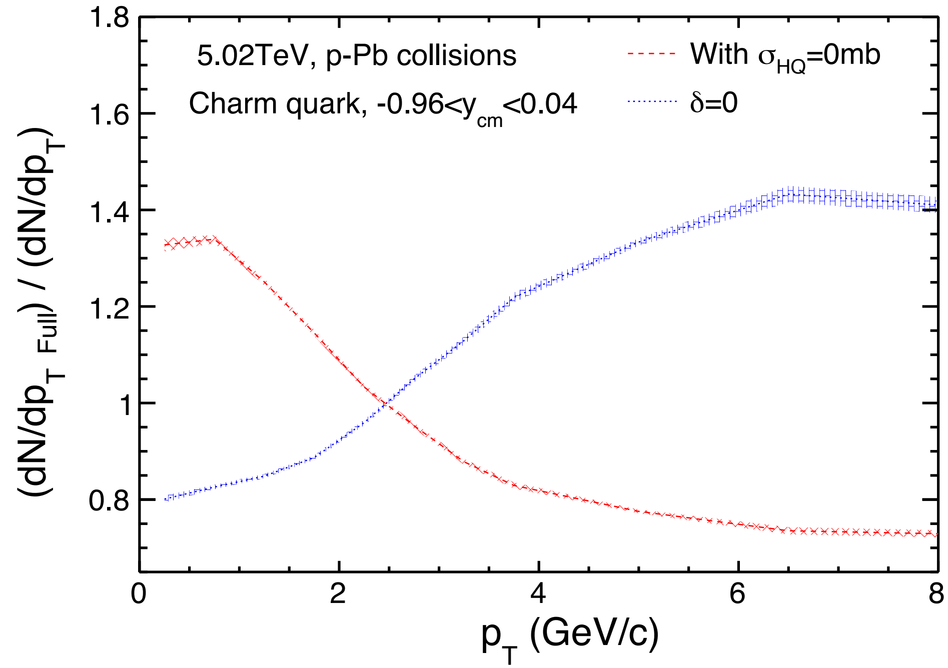
Effects from parton scatterings & Cronin effect

Test results for charm quarks:

- parton scatterings are mostly responsible for generating charm v_2
- the Cronin effect modestly decreases charm v_2

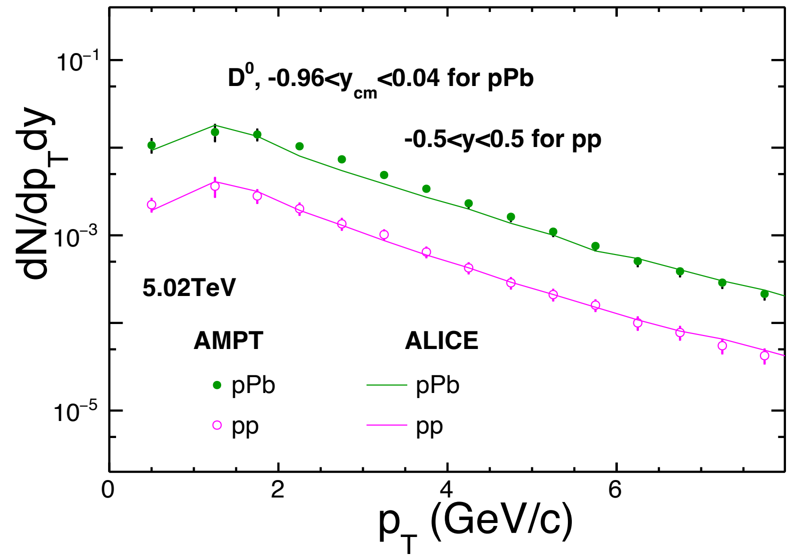


- parton scatterings significantly suppress charm spectra at moderate/high p_T
- the Cronin effect significantly increases charm spectra at moderate/high p_T

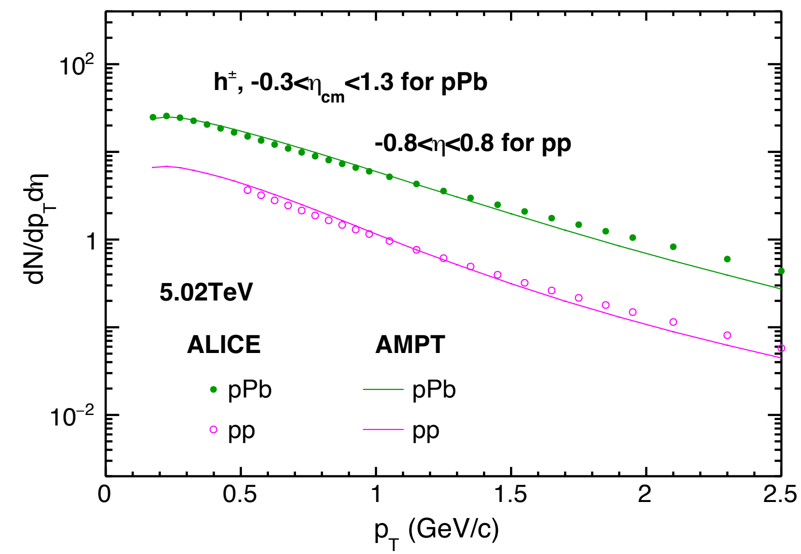


At 5.02 TeV, the full model also reasonably describes

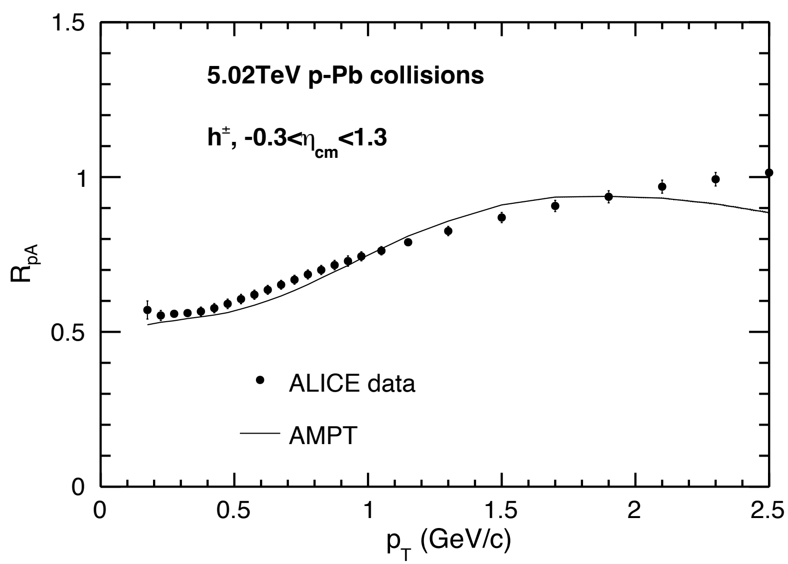
D^0 p_T spectra (to ~8GeV/c)



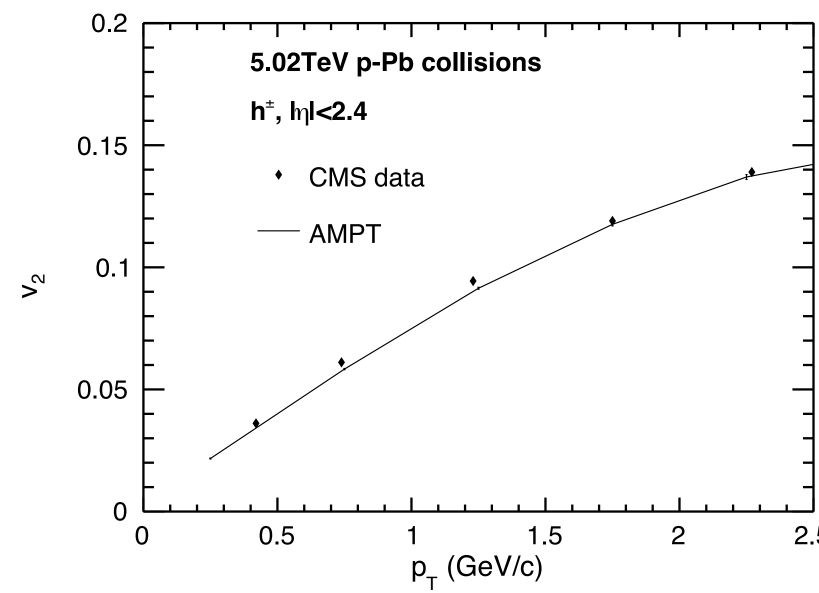
Charged hadron p_T spectra (to ~1.5 GeV/c)



Charged hadron R_{pA}



Charged hadron v_2 in pPb



More on the Cronin effect

Often considered as transverse momentum broadening of a produced parton from a hard process due to multiple scatterings of initial parton(s) in the nucleus

Kopeliovich et al. PRL (2002)
Kharzeev et al. PRD (2003)
Vitev et al. PRD (2006)
Accardi, hep-ph/0212148

- We take the k_T width as $w = w_0 \sqrt{1 + (n_{\rm coll} - i)\delta}$

grows with n_{coll} : # of NN collisions of the wounded nucleon(s),
i=1 for $c\bar{c}$ produced from the radiation of 1 wounded nucleon,
=2 for $c\bar{c}$ produced from the collision of 2 wounded nucleons,
This way, $w=w_0$ for pp collisions.

$$w_0 = (0.35\ {\rm GeV}/c)\ \sqrt{b_{\rm L}^0(2+a_{\rm L}^0)/b_{\rm L}/(2+a_{\rm L})}\ \propto \sqrt{\kappa}$$

motivated by $\kappa \propto \dfrac{1}{b_{\rm L}(2+a_{\rm L})}$ for Lund string fragmentation.

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- For comparison, $\langle k_T^2 \rangle$ (in GeV^2) at 5.02TeV for minimum-bias collisions:

	Our value	HVQMNR Vogt, PRC (2021)
pp	0.04	1.46
p-Pb	3.27	2.50

Our extra broadening (p-Pb relative to pp) is stronger than HVQMNR; further checks are needed (e.g. from J/ψ or Λ_c spectra).

Summary

We have studied p-Pb collisions at LHC energies with
an improved multi-phase transport model.

Including a strong Cronin effect allows a simultaneous description
of the D^0 meson R_{pA} and v_2 data (at $p_T \leq 8$ GeV/c);
further checks with other methods/observables are needed.

Parton scatterings significantly suppress charm spectra at moderate/ high p_T,
Cronin effect significantly increases charm spectra at moderate/high p_T
and thus compensates for the effect from parton scatterings

Charm v_2 is found to be mostly generated by charm quark scatterings,
Cronin effect slightly decreases the charm quark or meson v_2

The Cronin effect is expected to grow with the system size,
so this may imply the importance of including the Cronin effect
in heavy flavor studies (e.g. R_{AA}) in large systems

Backup Slides

Local scaling for self-consistent size dependence in AMPT

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 1/GeV^2):
~ 0.58 (PYTHIA6.2), 0.9 (HIJING1.0), 0.7-0.9 (AMPT for pp)

$b_L \sim 0.15$ is needed for string melting AMPT to describe the bulk matter at high energy AA collisions. ZWL, PRC (2014)

This corresponds to a much higher string tension κ:

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

ZWL et al. PRC (2005)

pp and AA collisions need different values of $\mathbf{b_L}$; same for minijet cutoff $\mathbf{p_0}$ (*for modern PDFs, is related to* $Q_s \propto A^{1/6}$)

Chao Zhang et al. PRC (2019)
Zheng et al. PRC (2020)

→ We scale them with local nuclear thickness functions:

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

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

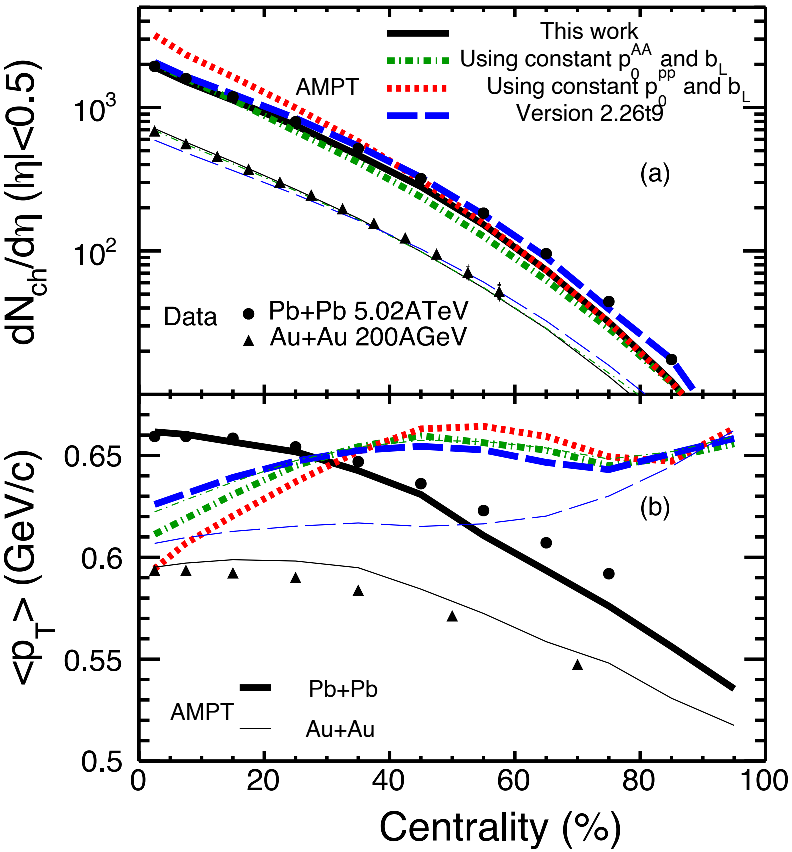
Chao Zhang et al. PRC (2021)

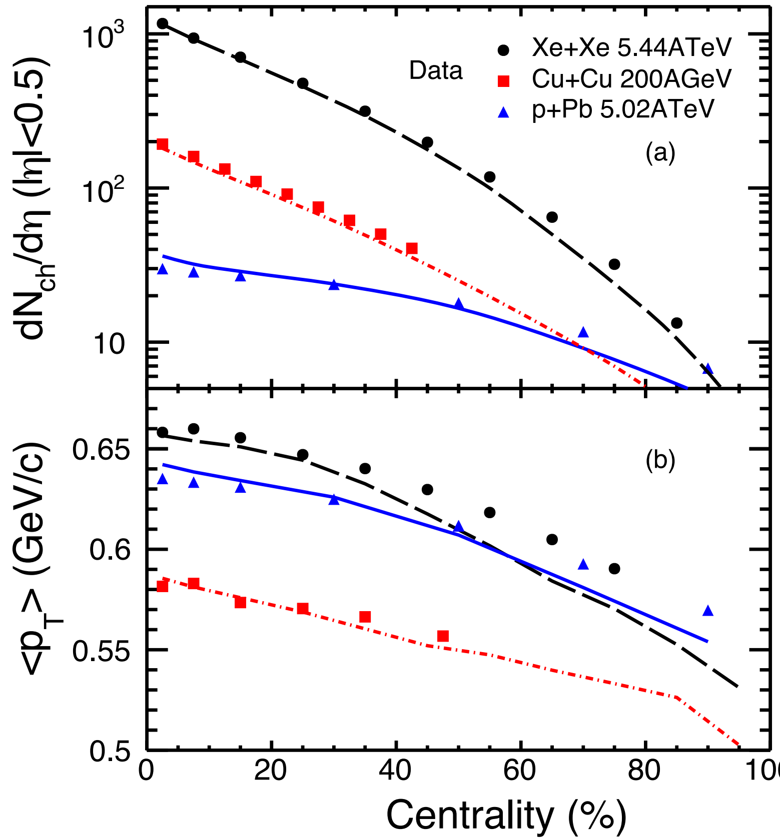
We fit charged hadron <p_T> in *pp* to determine $b_L^{pp} = 0.7$,
then used central AuAu/PbPb <p_T> data to determine $\alpha(s)$, $\beta(s)$ versus energy $\sqrt{s}$

Local scaling for self-consistent size dependence in AMPT

The scaling allows AMPT to self-consistently describe the system size dependence, including centrality dependences of AuAu & PbPb:

Chao Zhang et al. PRC (2021)



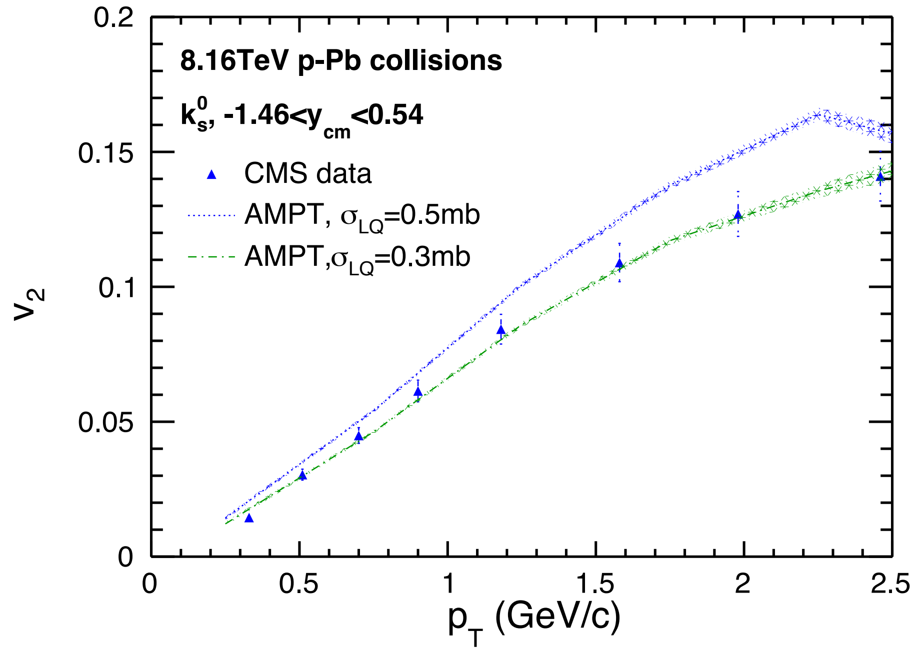


Centrality dependence of $<p_T>$ is now reasonable, while previous/public AMPT (v2.26t9) fails

Also works for smaller systems

The full model at 8.16 TeV

at the same σ_{LQ}=0.5mb
or a smaller σ_{LQ}=0.3mb
(better reproduces Ks v_2):



This change of σ_{LQ} has little effect on D^0 R_{pA} or v_2 :