The R_{pA} and v_2 puzzle of D^0 mesons in p−Pb collisions at the LHC

Zi-Wei Lin
East Carolina University (ECU)

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Outline

- The D^0 R_{pA} and v_2 puzzle
- An improved multi-phase transport model
- A solution of the R_{pA}/v_2 puzzle with the Cronin effect
- Effects from parton scatterings & Cronin effect
- Summary

Based on 2210.07767
with Chao Zhang, Liang Zheng, Shusu Shi,
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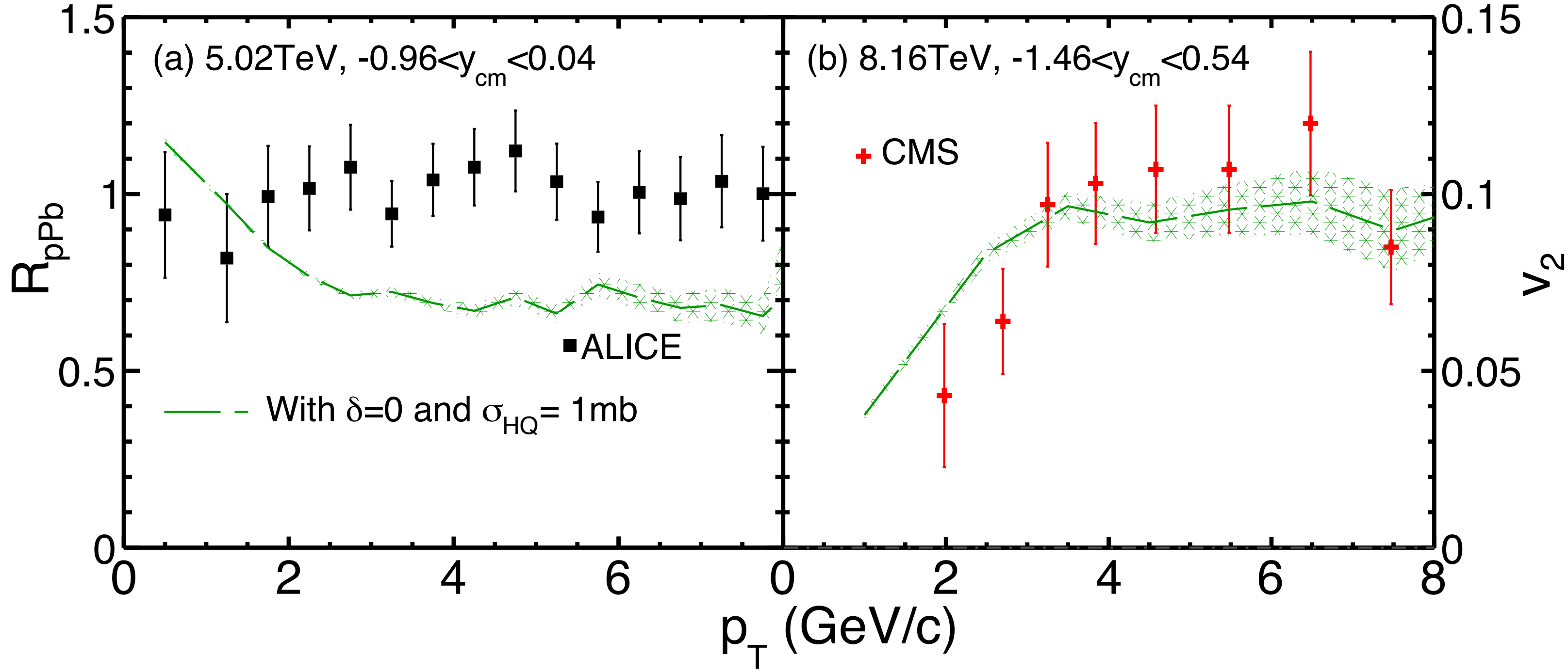
The D^0 R_{pA} and v_2 puzzle

LHC p-Pb data on D^0 mesons show

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



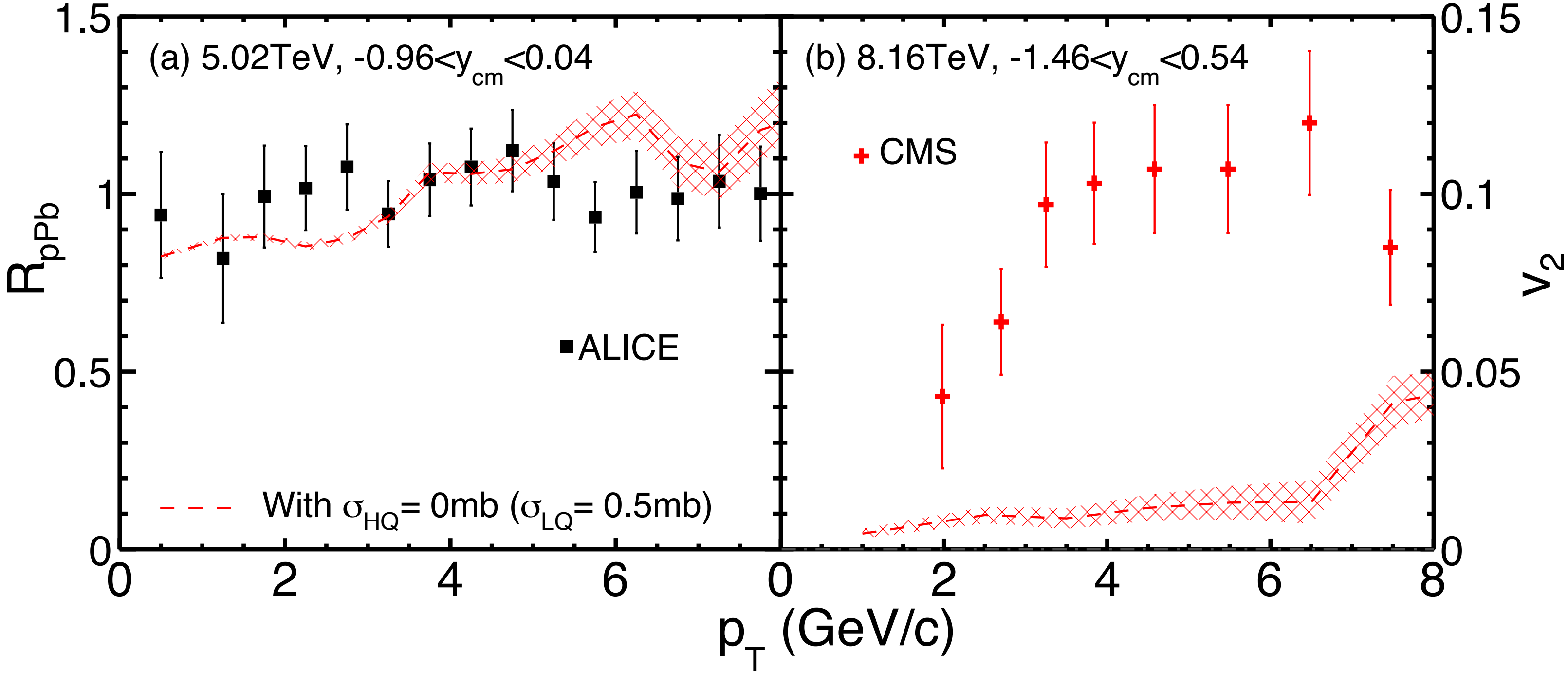
It has been a challenge to describe both data simultaneously:

- 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)

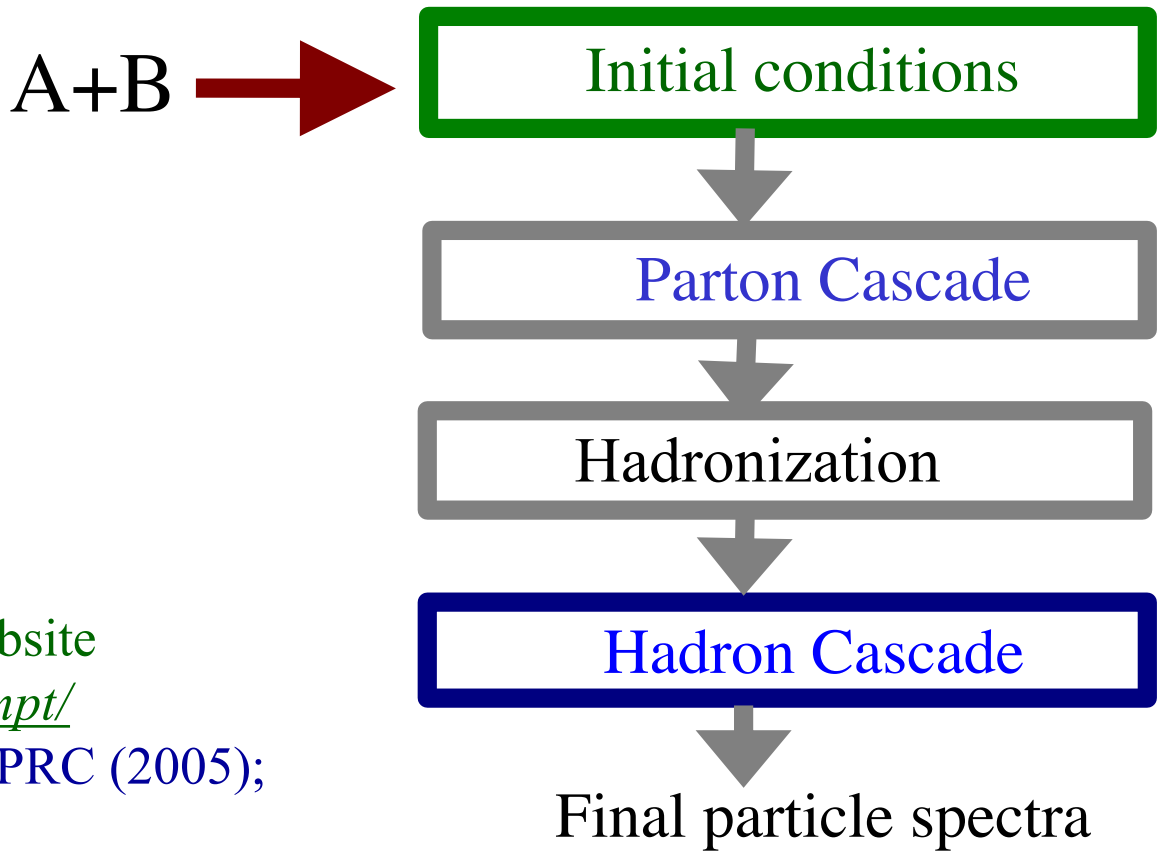
- A simultaneous description of the R_{pA} and v_2 data could disentangle different effects (*initial state correlations, cold nuclear, hot medium*) and help understand onset of collectivity & formation of parton matter or QGP

An improved multi-phase transport model

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;
- non-equilibrium initial condition & dynamics (*more important for small systems*).



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

Improved heavy flavor (HF) productions in AMPT

$gg \to gg$ cross section in leading-order pQCD is divergent for massless g,

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

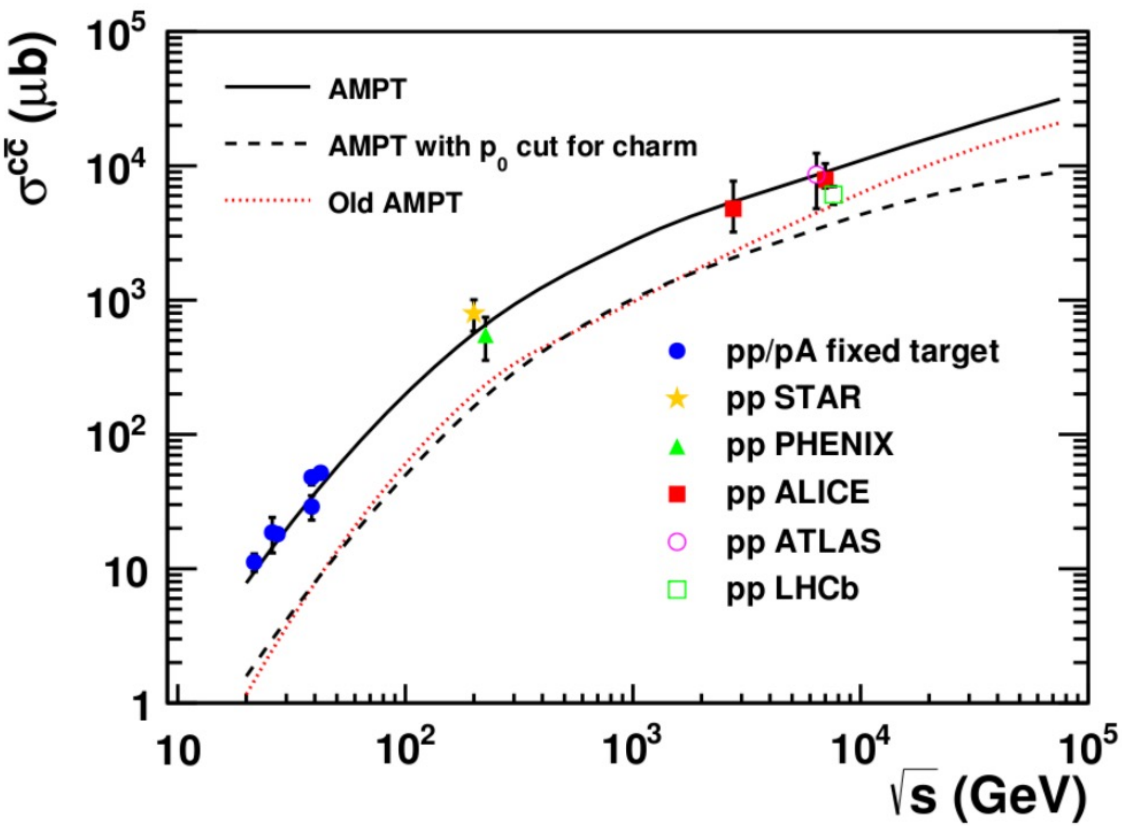
so HIJING uses a **minijet cutoff p_0** for minijets (of ALL flavors).

But heavy flavor production does not need a cutoff due to heavy quark mass >> Λ_{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 two-component model HIJING for AMPT. Zheng et al. PRC (2020)
- Unlike HIJING, we include HF in σ_{jet}: $\sigma_{jet} = \sigma_{jet}^{LF} + \sigma^{HF}$
- We also correct factor of ½ in certain σ_{jet} channels

Improved heavy flavor (HF) productions in AMPT



Zheng et al. PRC (2020)

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

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 ~ 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:

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

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

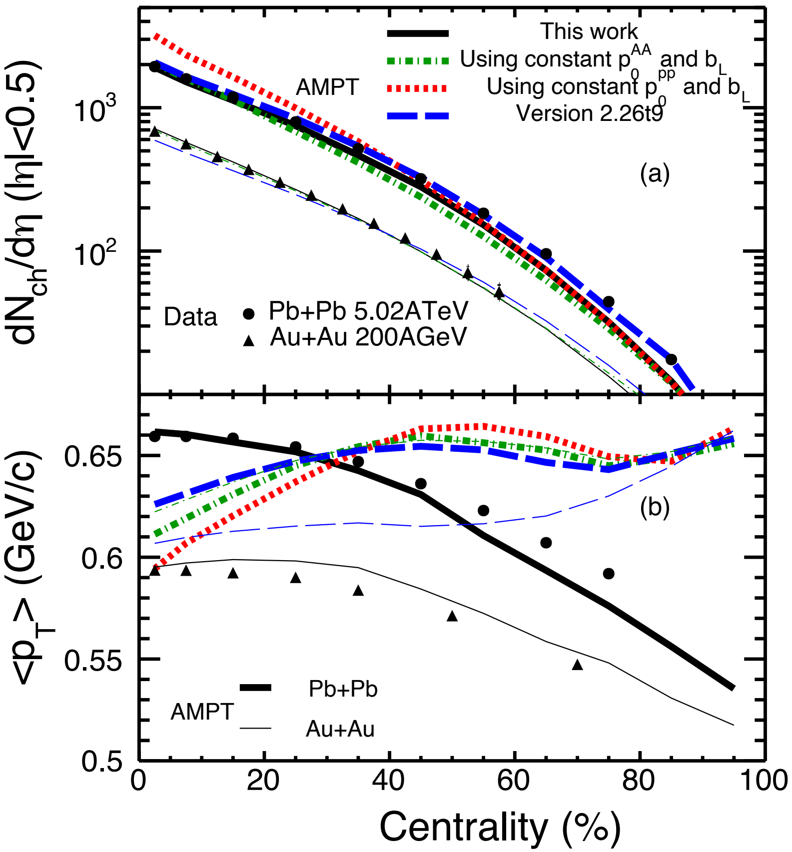
Chao Zhang et al. PRC (2021)

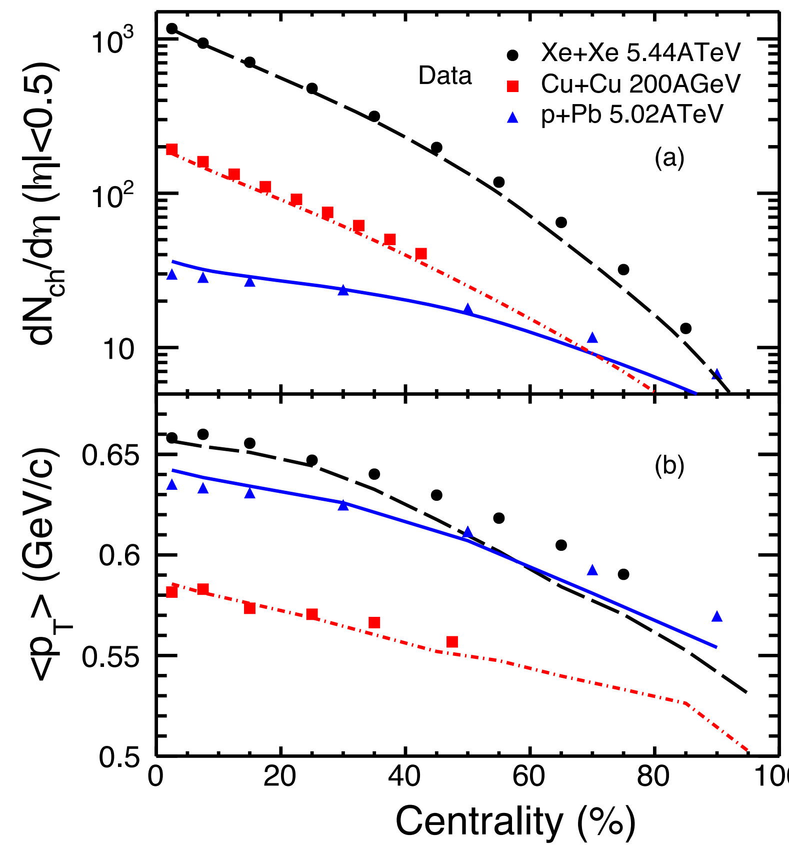
We fit charged hadron $\langle p_T \rangle$ in *pp* to determine b_L^{pp} =0.7,
then used central AuAu/PbPb $\langle p_T \rangle$ data to determine α(s), $\beta(s)$ versus energy $\sqrt{s}$

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 and smaller systems.

Chao Zhang et al. PRC (2021)

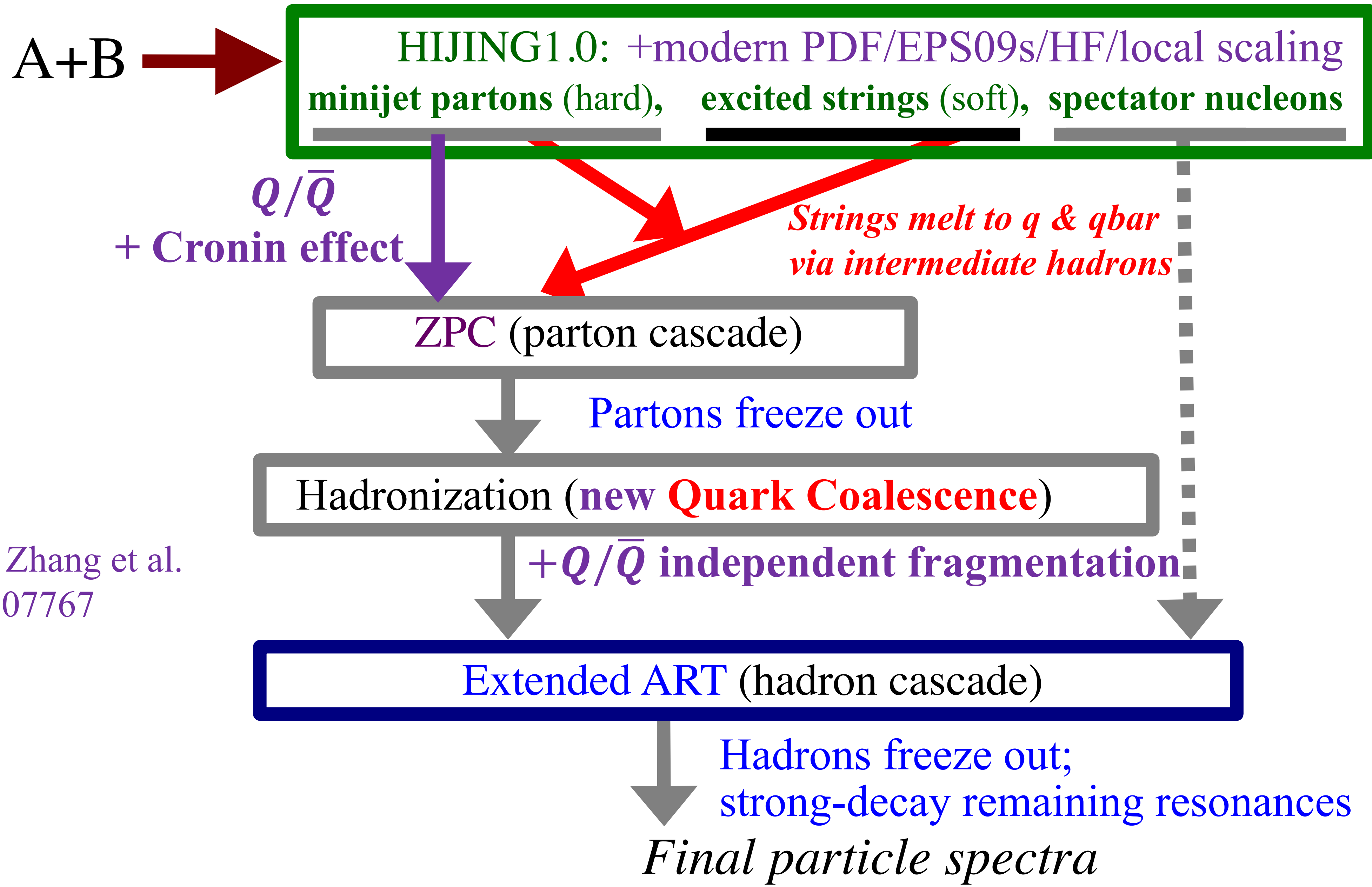




Centrality dependence of <p_T> is now reasonable, much better than public AMPT (v2.26t9)

Also works for smaller systems

Structure of improved AMPT (String Melting version)



Chao Zhang et al.
2210.07767

The AMPT model used in this R_{pA}/v_2 study contains all these improvements

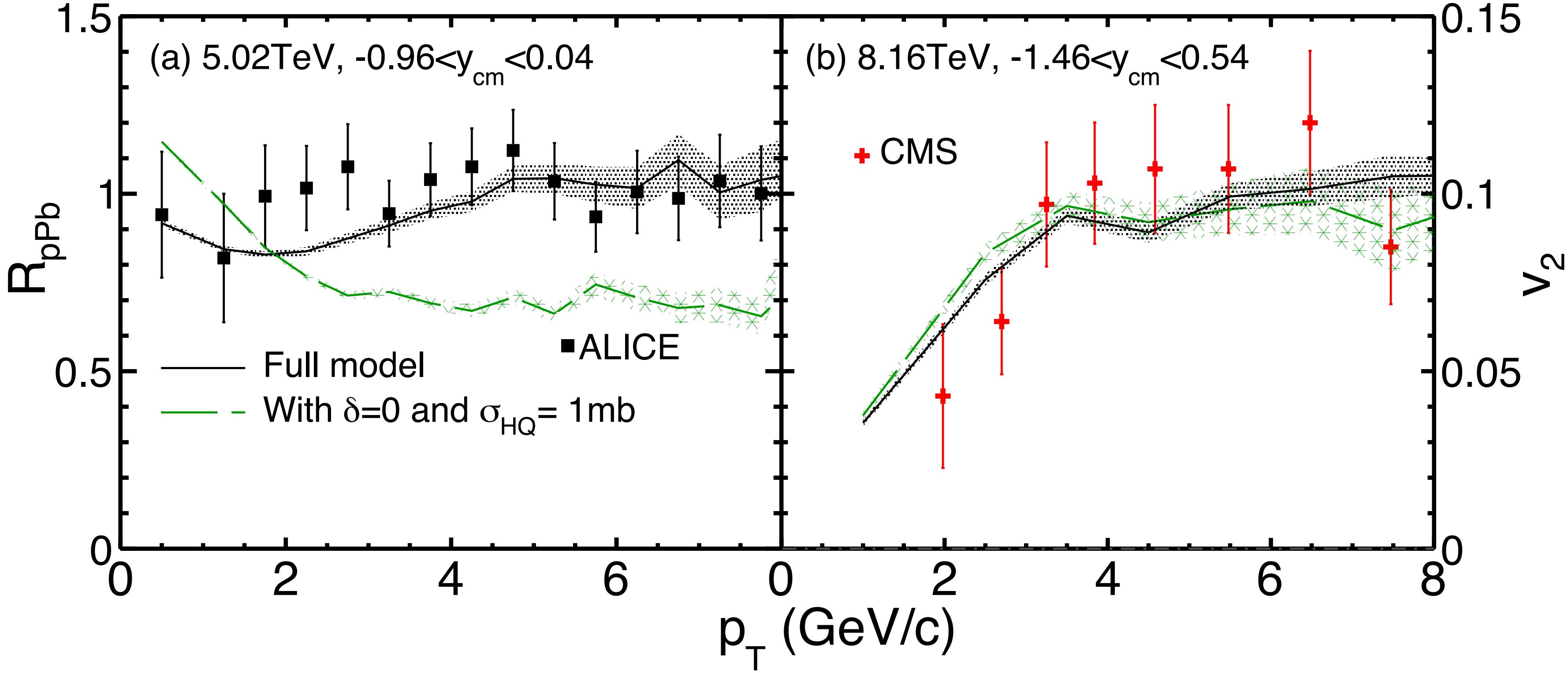
A solution of the R_{pA}/v_2 puzzle with the Cronin effect

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

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

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

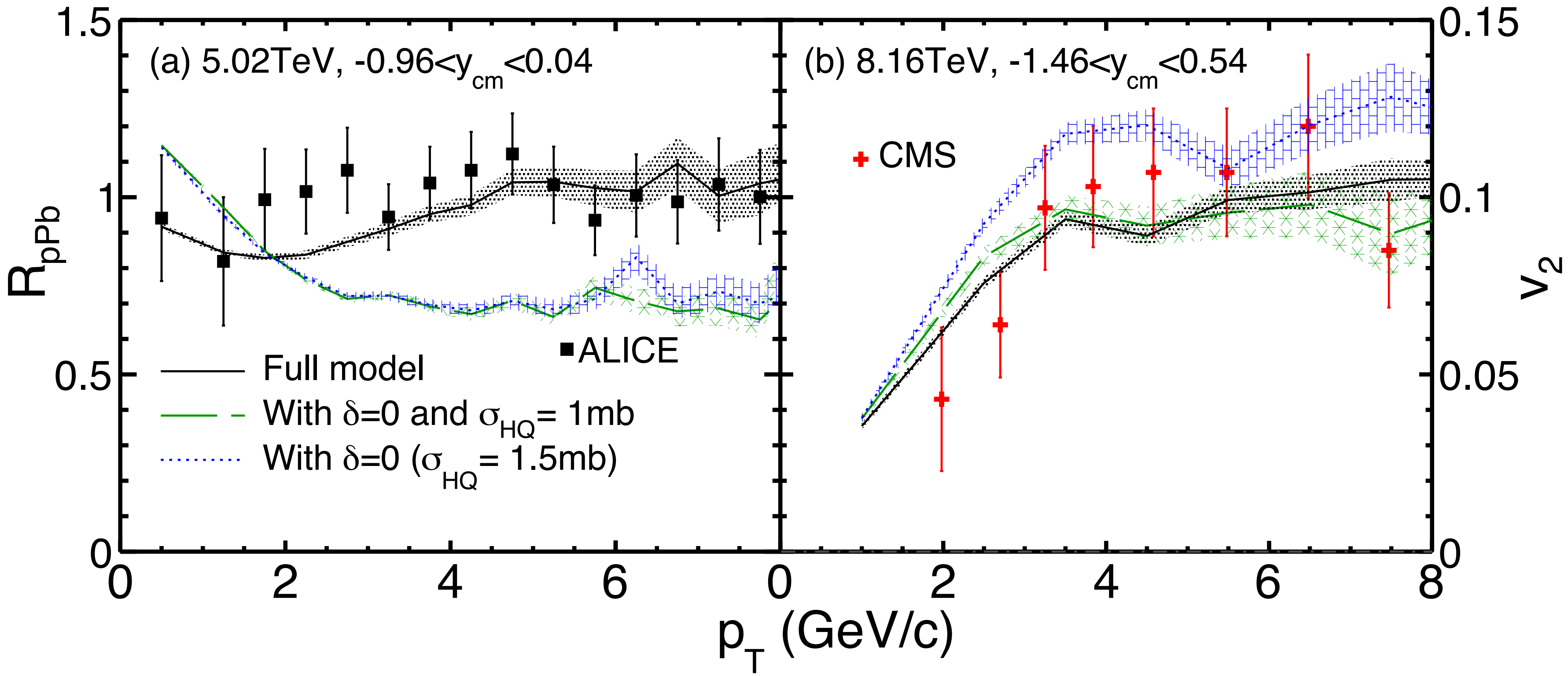
$w = w_0\sqrt{1 + (n_{coll} - i)\delta}$ grows with # of NN collisions of the wounded nucleon(s).



Full model, with Cronin effect at δ=7, 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

A 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

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.

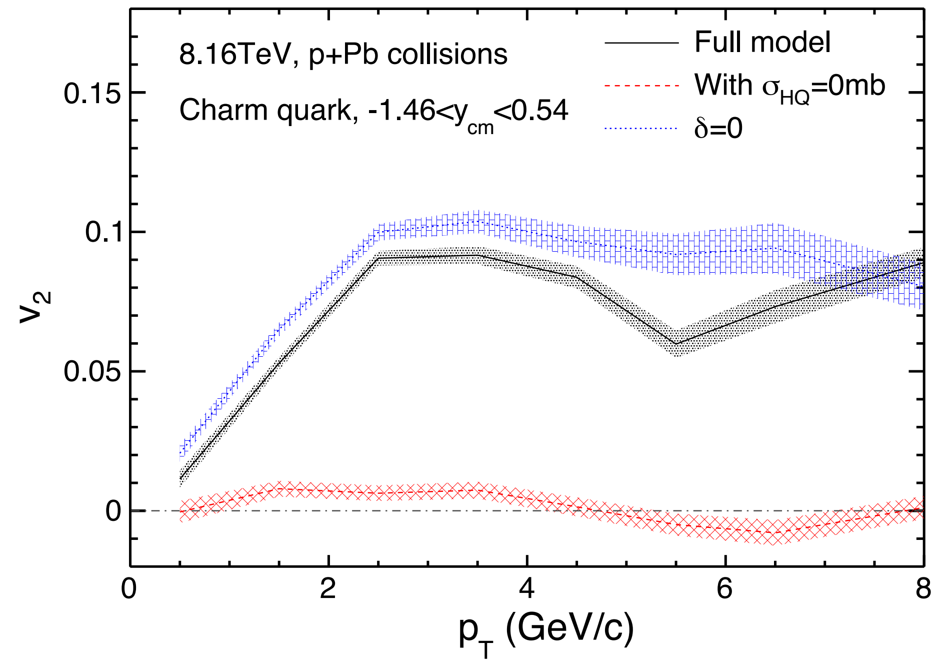
$$w_0 = (0.35\ {\rm GeV}/c)\ \sqrt{b_{\rm L}^0(2 + a_{\rm L}^0)/b_{\rm L}/(2 + a_{\rm L})}\ \propto \sqrt{\kappa}$$

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

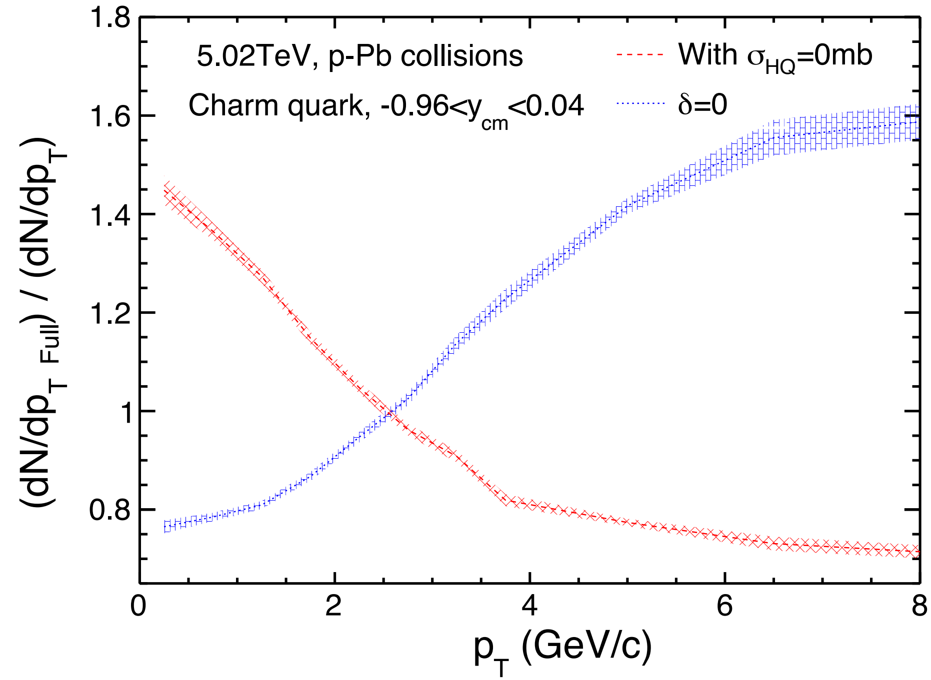
Effects from parton scatterings & Cronin effect

Test results for charm quarks:

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

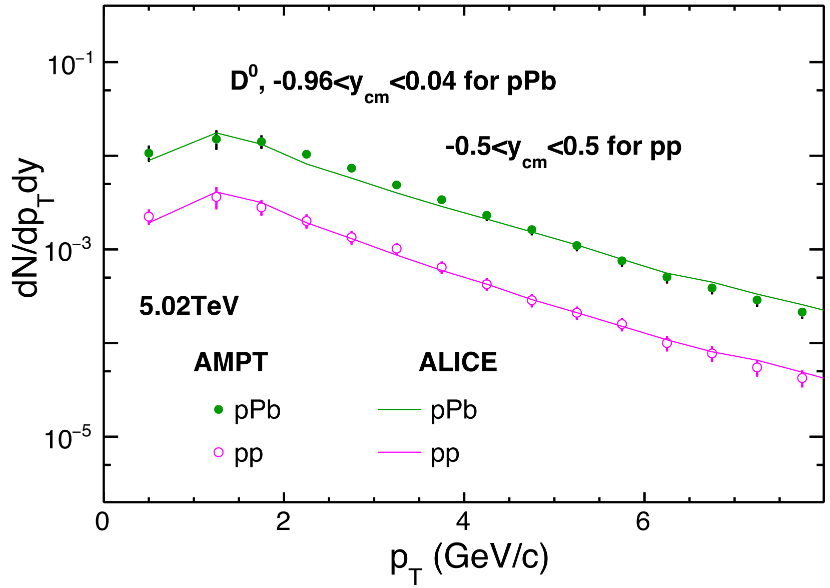


- parton scatterings significantly suppress charm spectra at moderate/high p_T
- the Cronin effect significantly increases charm spectra at moderate/high p_T

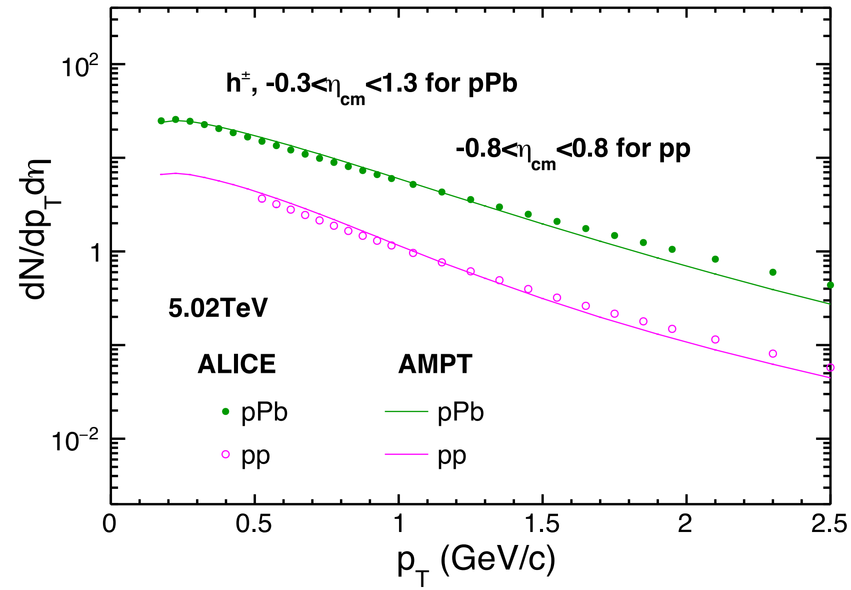


At 5.02 TeV, the full model also reasonably describes

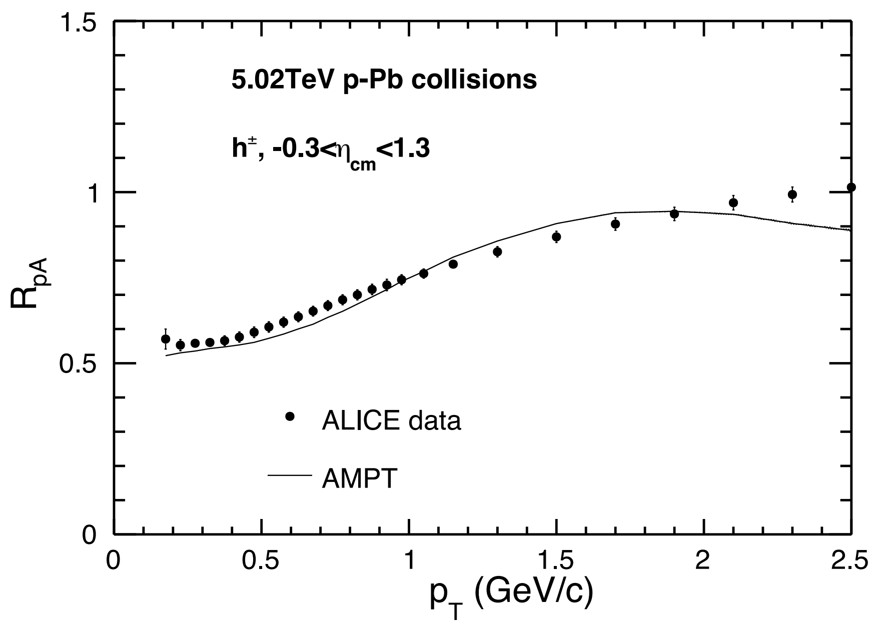
D^0 p_T spectra (to ~8GeV/c)



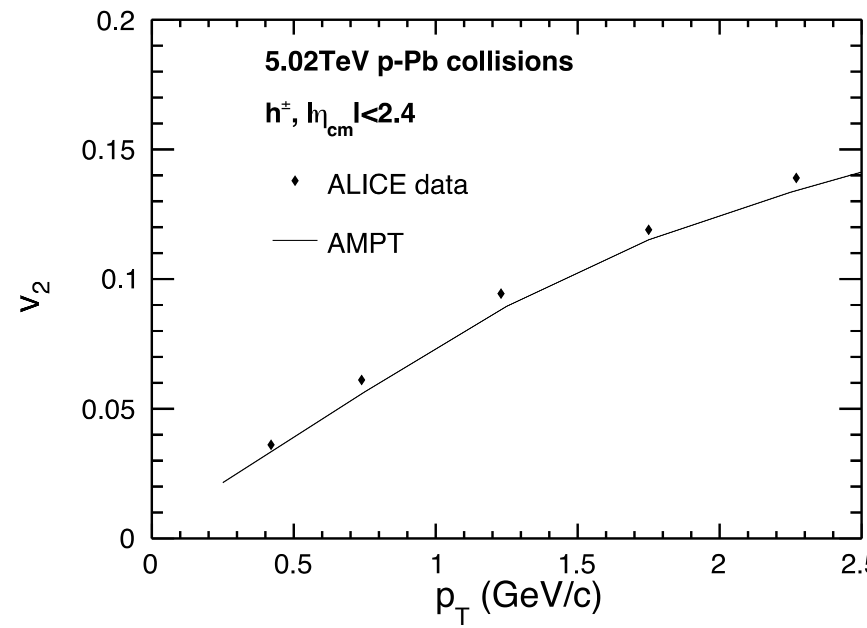
Charged hadron p_T spectra (to ~1.5 GeV/c)



Charged hadron R_{pA}

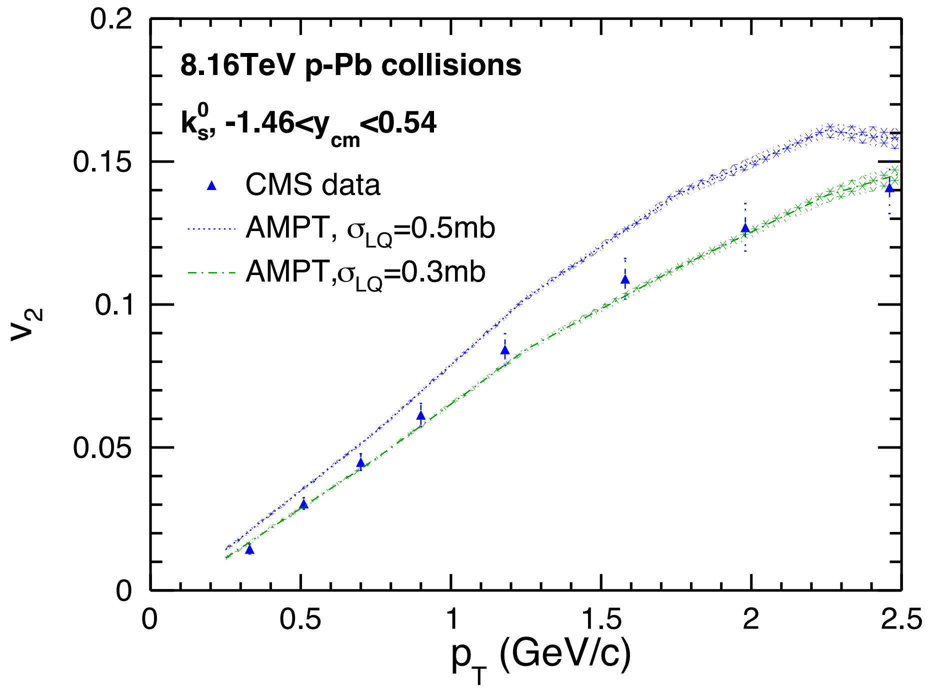


Charged hadron v_2 in pPb

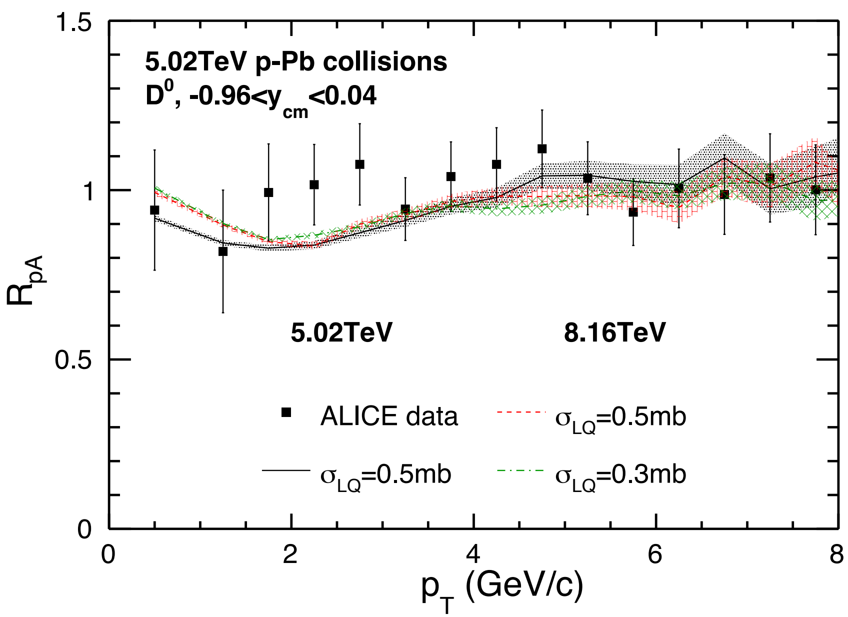


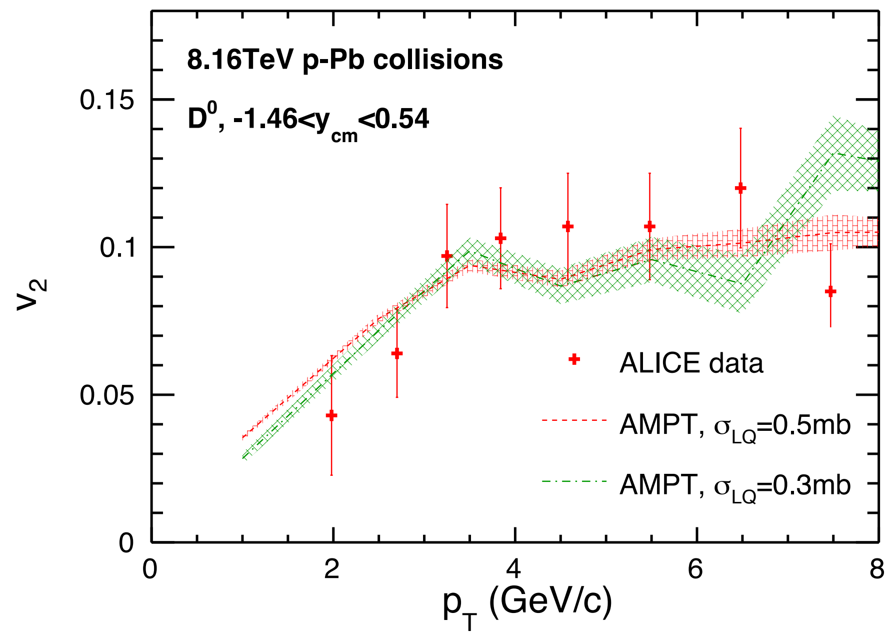
The full model at 8.16 TeV

at the same σ_{LQ}=0.5mb
or a smaller σ_{LQ}=0.3mb :



This change of σ_{LQ} has ~no effect on D^0 R_{pA} or v_2 :





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)

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 modestly decreases the charm quark or meson v_2

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