Investigating the D meson production and elliptic flow in p-Pb collisions at LHC

Chao Zhang
Wuhan University of Technology(WUT)

Collaborators: Liang Zheng, Shusu Shi, Zi-Wei Lin
Based on 2210.07767 & 2403.06099

Spicy Gluons(胶麻) May 16-19, 2024, Hefei, Anhui, China.

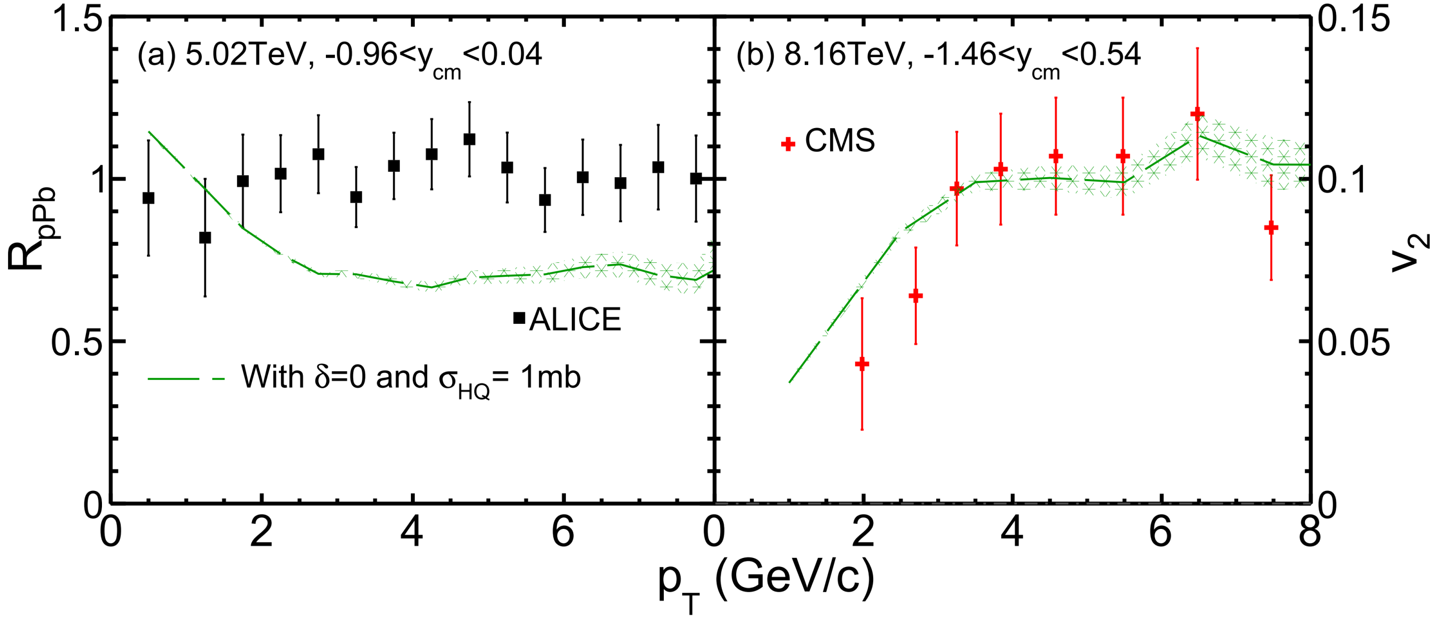
Outline

- The D^0 R_{pA} and v_2 puzzle
- Improvement on the multi-phase transport model
- Possible solution of the R_{pA}/v_2 puzzle with the Cronin effect
- D^0 and D_s^+ meson production at forward rapidities
- 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:

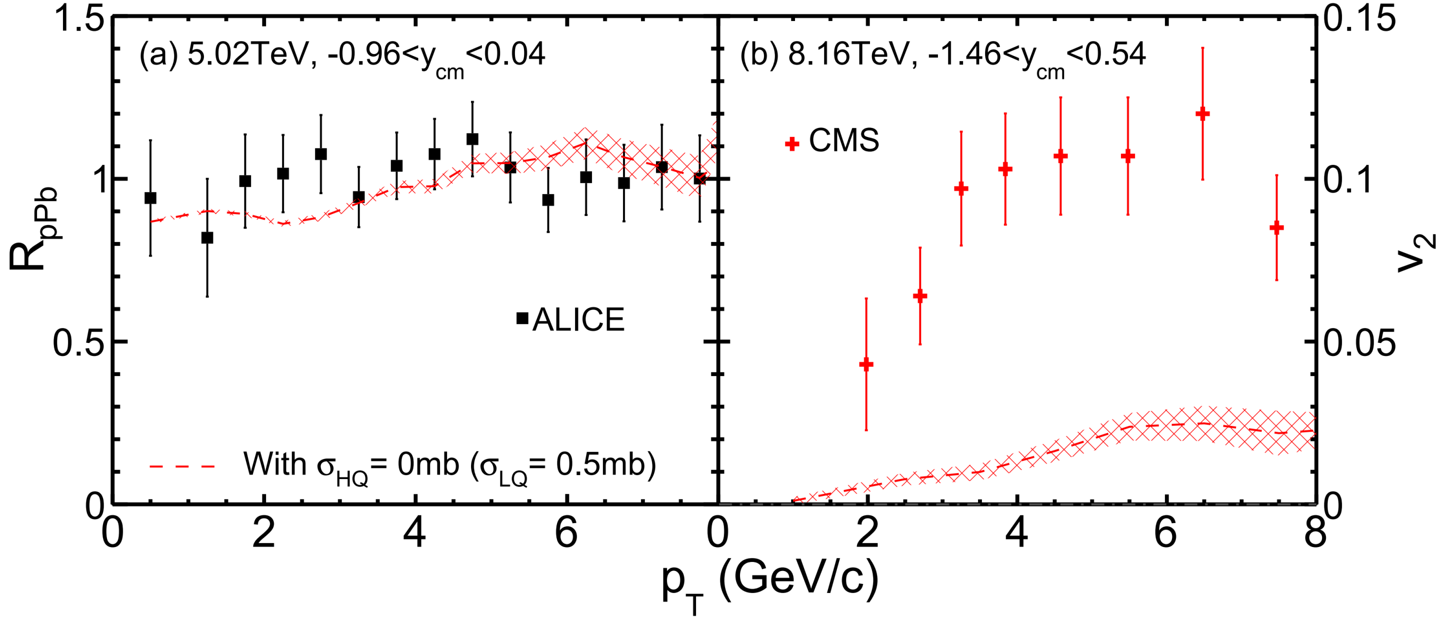
- sizable v_2 → significant charm quark interaction with medium
  → suppression of charm high p_T spectrum in pA and R_{pA} (above)

- 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: Beraudo et al. JHEP (2016)
  ~ no suppression in R_{pA}, then v_2 is too small.

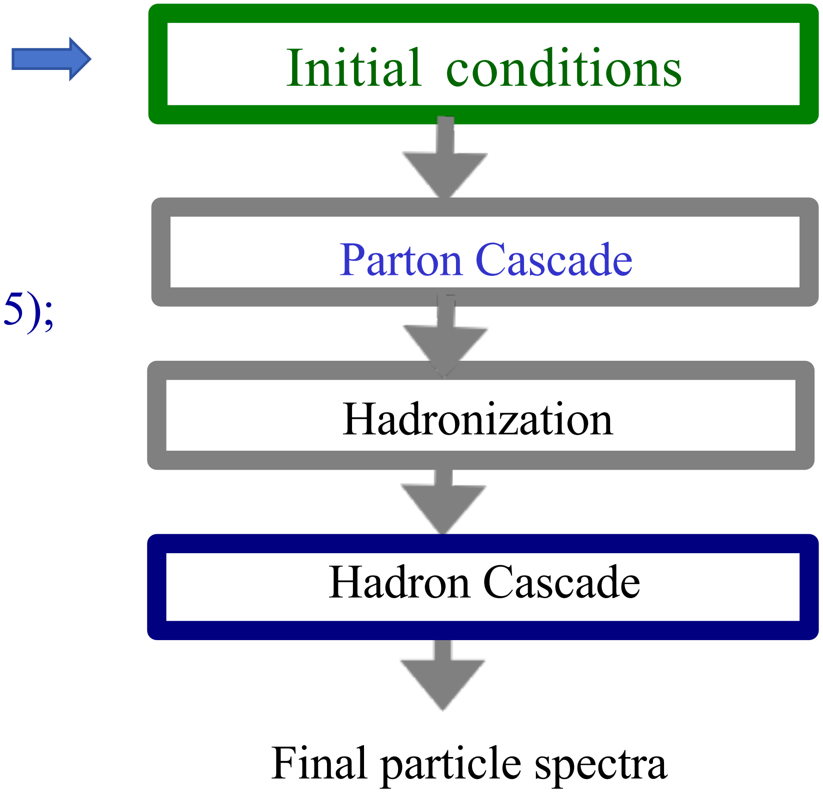
- A simultaneous description of the R_{pA} and v_2 data could disentangle different effects (*initial state correlations, cold nuclear, hot medium*) and help understand onset of collectivity & formation of parton matter or QGP

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*).

A+B



ZWL, Ko, Li, Zhang & Pal, PRC (2005);
ZWL & Zheng, NST (2021)

improvement on the heavy flavor of AMPT

We take the charm quark from HIJING initial conditions with the formation time given by $t_F = E/m_T^2$.

improvement on the heavy flavor of AMPT

We take the charm quark from HIJING initial conditions with the formation time given by $t_F = E/m_T^2$.

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).

improvement on the heavy flavor of AMPT

We take the charm quark from HIJING initial conditions with the formation time given by $t_F = E/m_T^2$.

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 coalescence plus fragmentation mechanism are frequently used in modeling the heavy quark hadronzation.

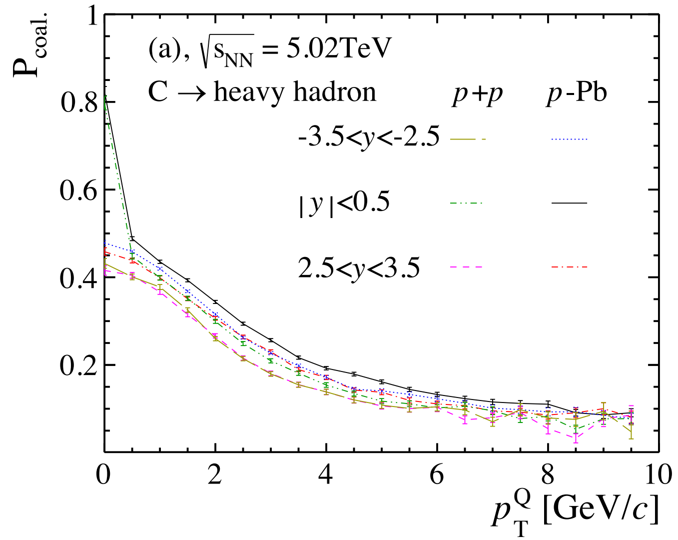
Hendrik van Hees et al. PRC(2006)
M He et al. PRC(2012)
Cao et al. PRC(2015)

We implement the fragmentation for heavy quark hadronization in the AMPT model by utilizing the PYTHIA independent fragmentation.

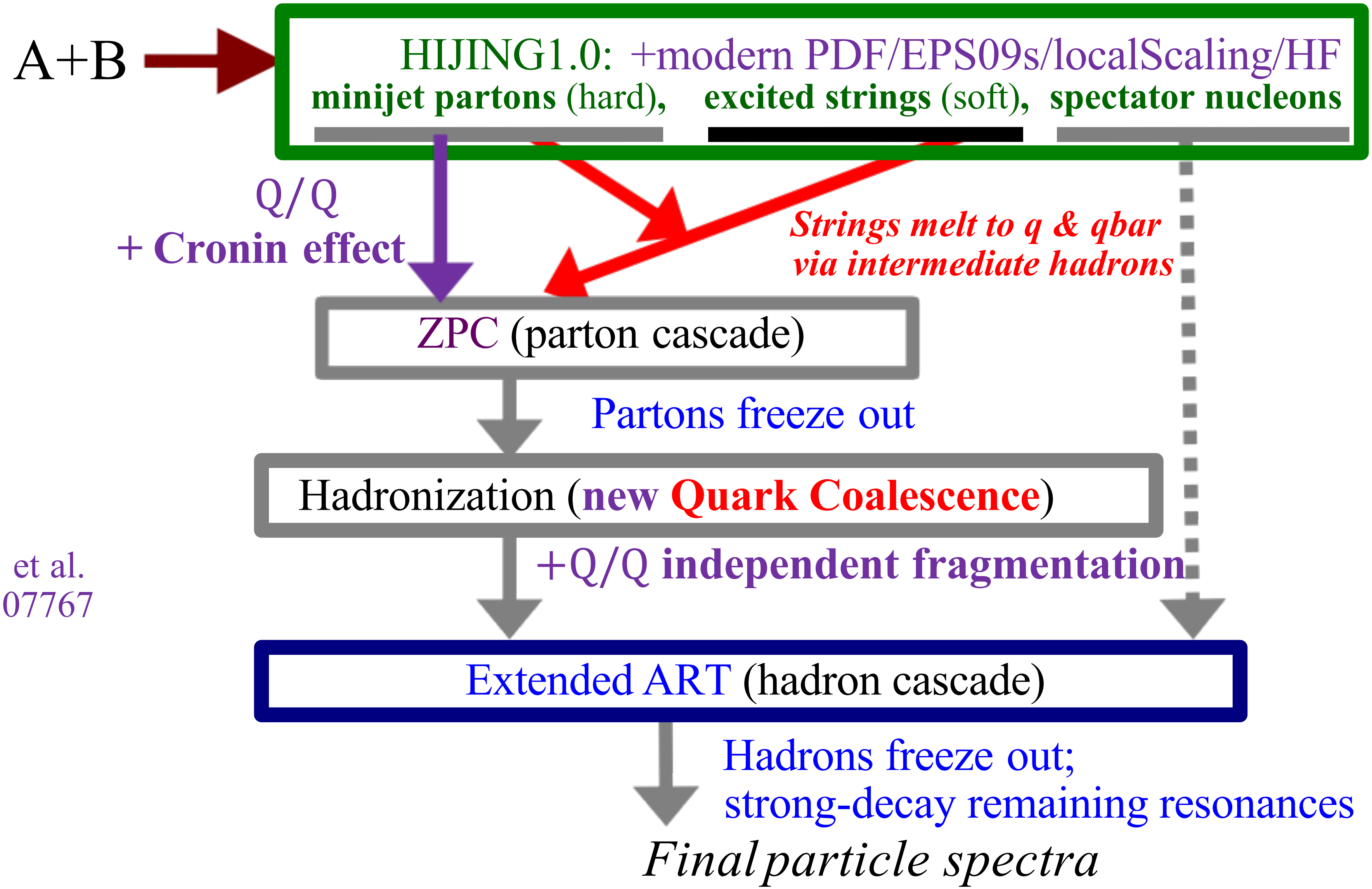
A simplified parameters controlled method is used to select the hadronization process.

Relative distance: $d < p_r$,

Invariant mass: $m_{inv} < \sum m_Q + p_m(m_H - \sum m_Q)$.



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



The AMPT model used in this study contains all these improvements

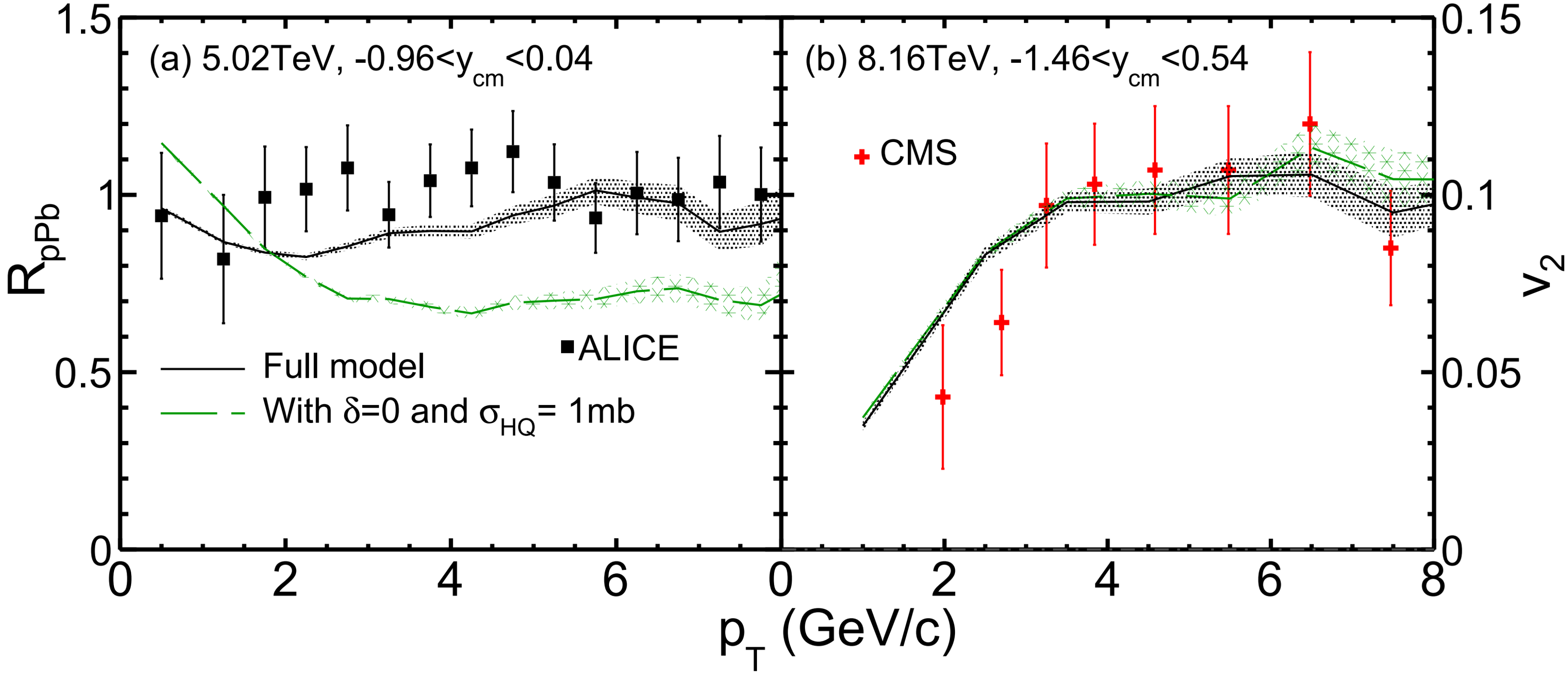
Possible solution of the R_{pA}/v_2 puzzle with the Cronin effect

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).



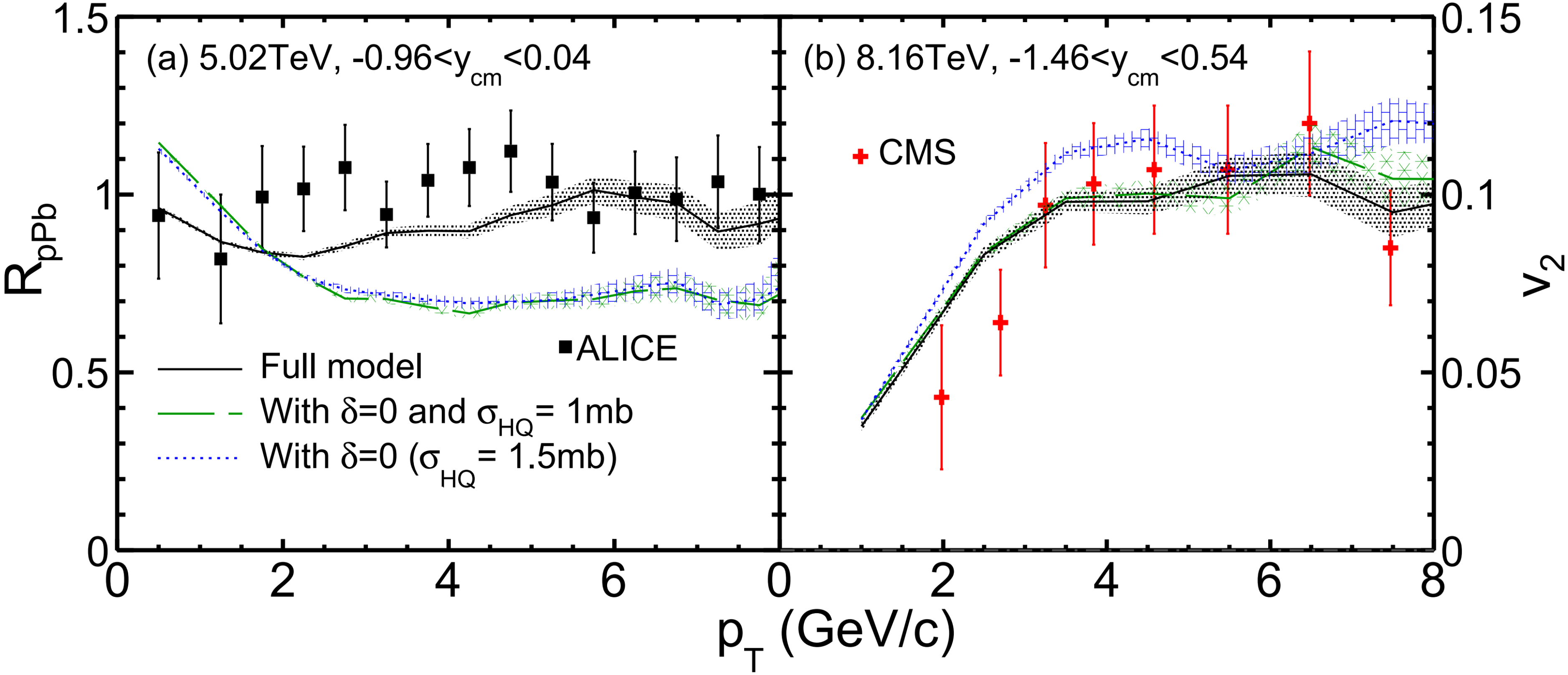
Full model, with Cronin effect at δ=5, σ_{LQ}=0.5mb (for scatterings among u/d/s quarks), σ_{HQ}=1.5mb (for scatterings of charm quarks with other partons), can describe both R_{pA} and v_2 data of D^0 mesons

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}).



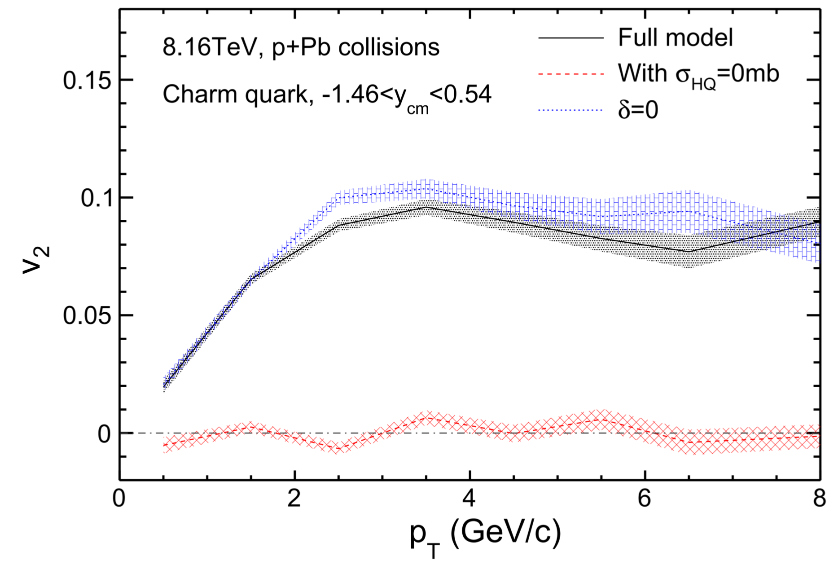
Black curve vs blue curve (*both at σ_{HQ}=1.5mb*):

the Cronin effect significantly increases charm R_{pA} at moderate/high p_T but modestly decreases charm v_2

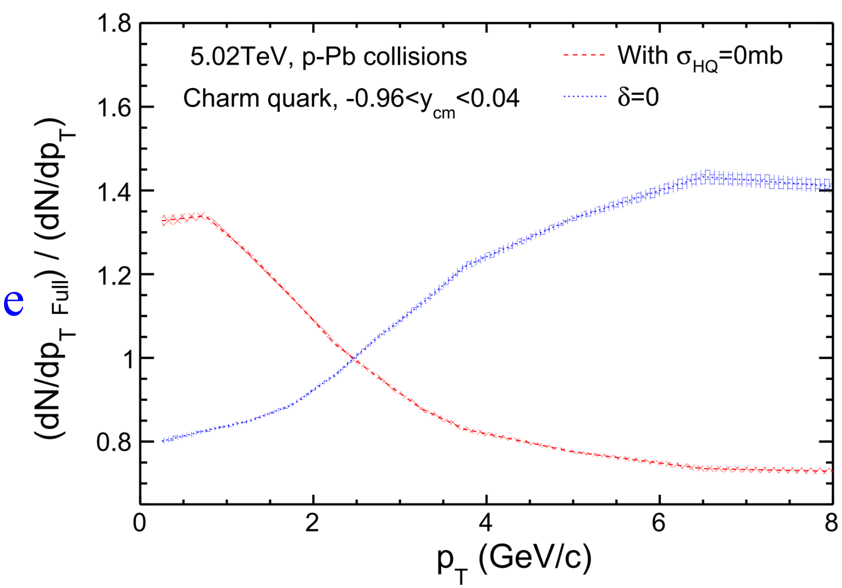
Effects from parton scatterings & Cronin effect

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 increase charm spectra at moderate/high p_T



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.

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

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

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.

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

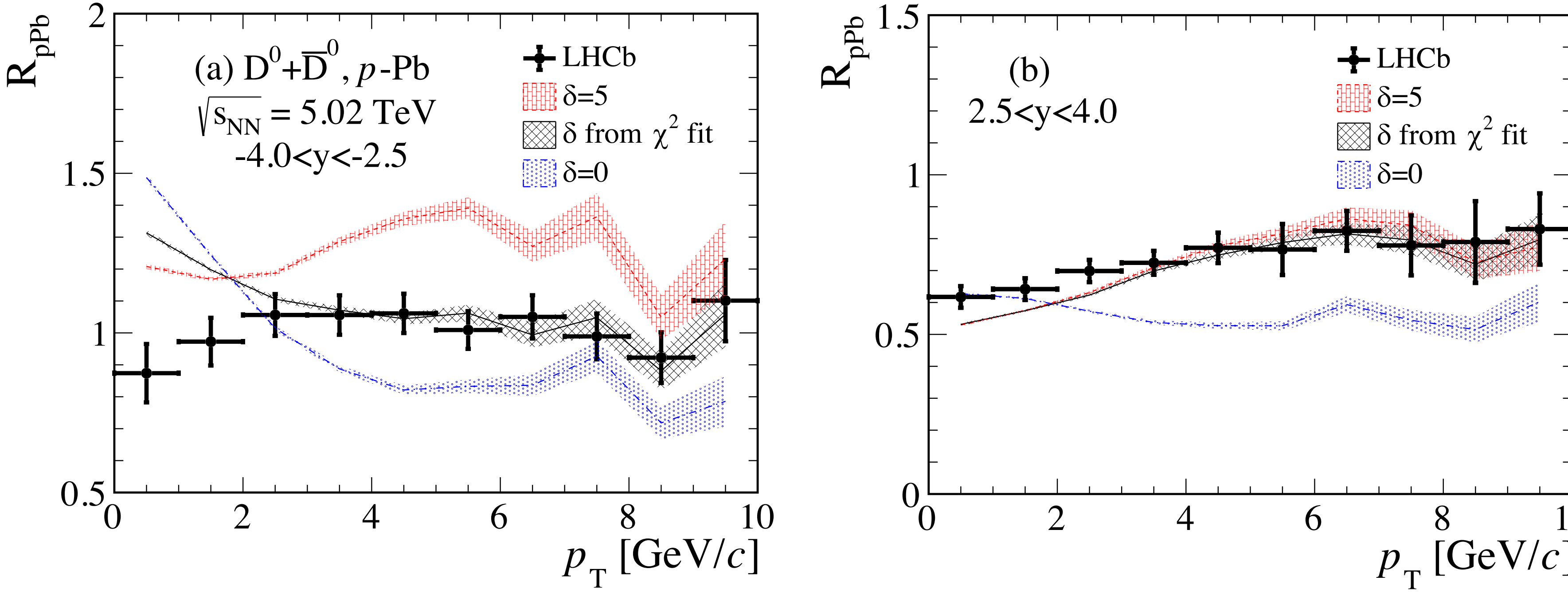
motivated by $\kappa \propto \dfrac{1}{b_{\rm L}(2+a_{\rm L})}$ for Lund string fragmentation.

- 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

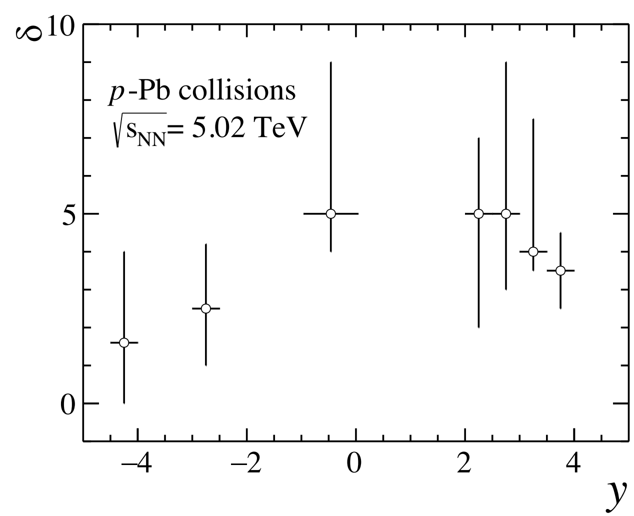
Our extra broadening (p-Pb relative topp) is stronger than HVQMNR; further checks are needed (e.g.from J/ψ or Λ spectra).

The D^0 production at forward/backward rapidities

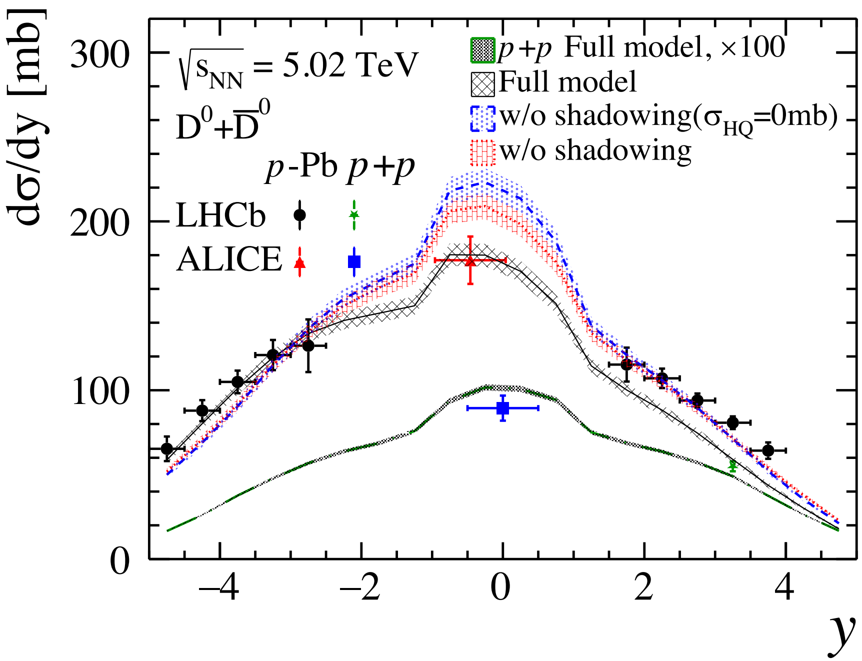


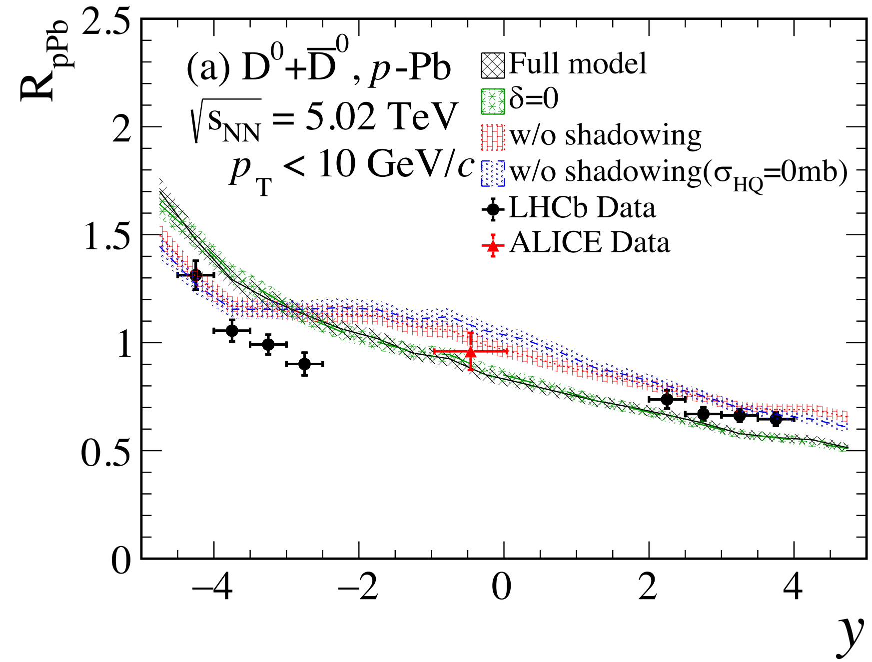
Considerable over-estimation of the R_{pA} in backward rapidity indicating a rapidity dependent of cronin width.

A χ^2 fitting is used to extract the rapidity dependence.



The D^0 production at different rapidity





Slightly overestimates production at mid-rapidity

underpredicts it in the forward region

Shadowing: suppress the production at mid and forward rapidity.

Scattering: suppress the production at mid while enhance at far forward rapidity

no significant effect resulting from the Cronin

The variation of momentum fraction x across different rapidity leads to the intersection.

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 $1/\mathrm{GeV}^2$):

~ 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:

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

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* $Q_s \propto A^{1/6}$)

C. Z. et al. PRC (2019)
Zheng et al. PRC (2020)

→ We scale them with local nuclear thickness functions:

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

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

C. Z. et al. PRC (2021)

We fit charged hadron $\langle p_T \rangle$ in *pp* to determine b_L^{pp} =0.7,

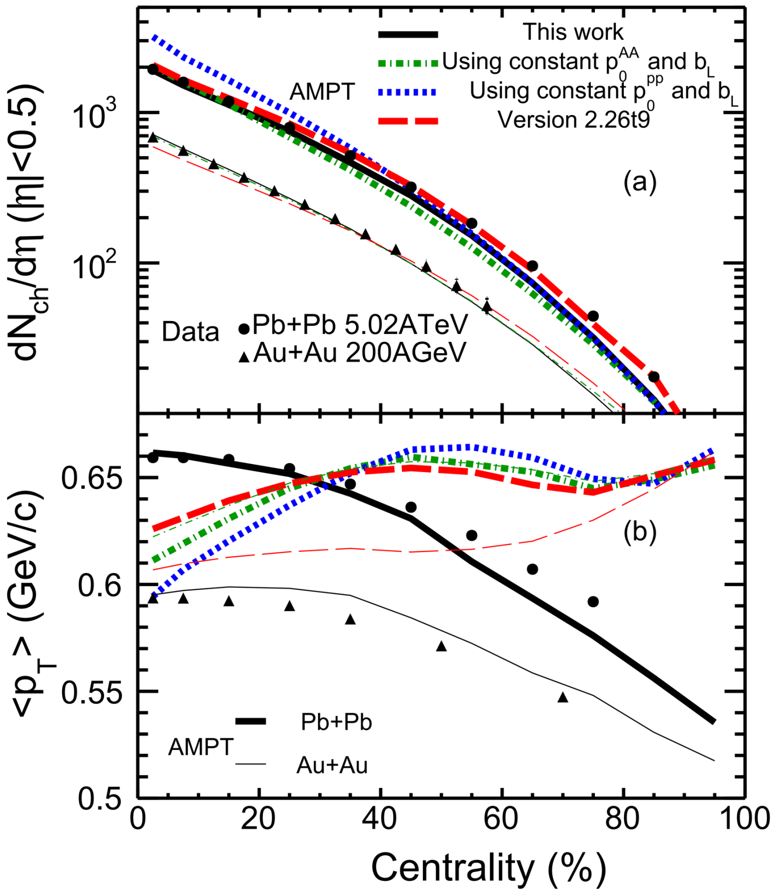
then used central AuAu/PbPb $\langle p_T \rangle$ data to determine $\alpha(s)$, $\beta(s)$ versus energy

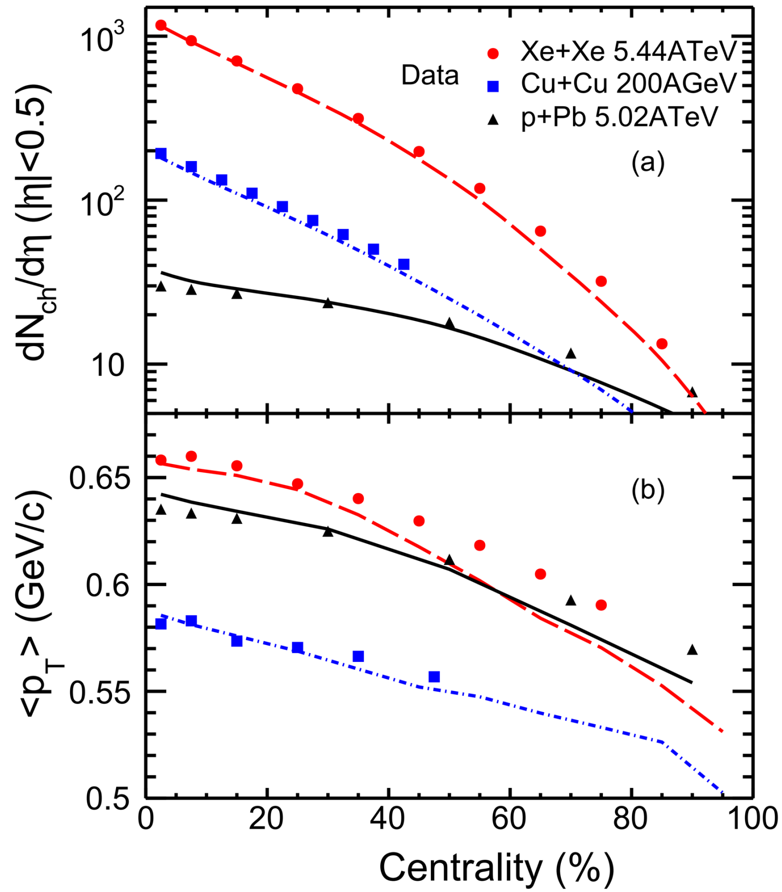
Local scaling for self-consistent size dependence in AMPT

The scaling allows AMPT to self-consistently describe the system size dependence,

including centrality dependences of AuAu & PbPb:

C. Z. et al. PRC (2021)



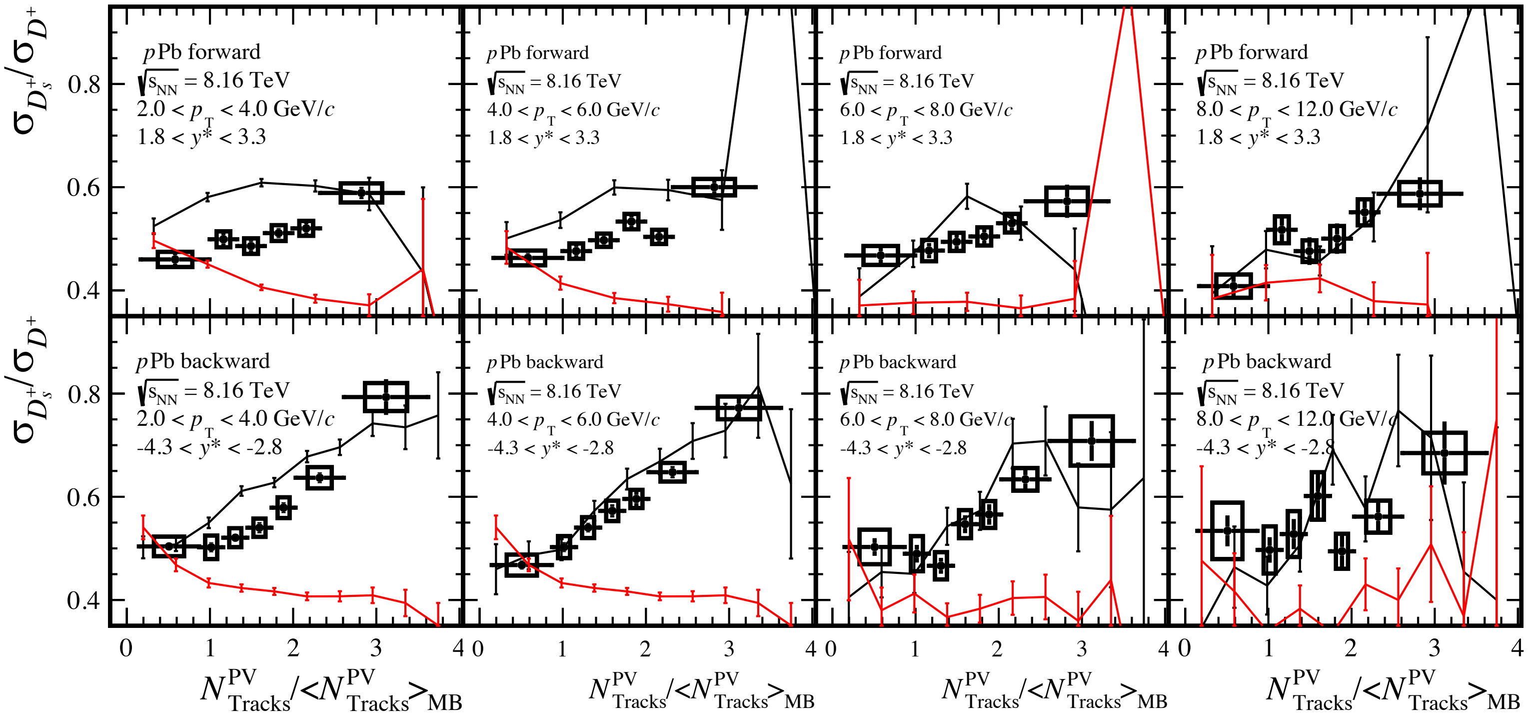


Centrality dependence of $<p_T>$ is now reasonable, while previous/public AMPT (v2.26t9) fails

Also works for smaller systems

The D_s^+ enhancement in high multiplicity p-Pb collisions

Adopting the scaling strategy to the strange quark production in the excited strings,



- Black: applying local scaling
- Red: not applying

We provide the first description of the D_s^+ enhancement in high multiplicity p-Pb collsions.

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);

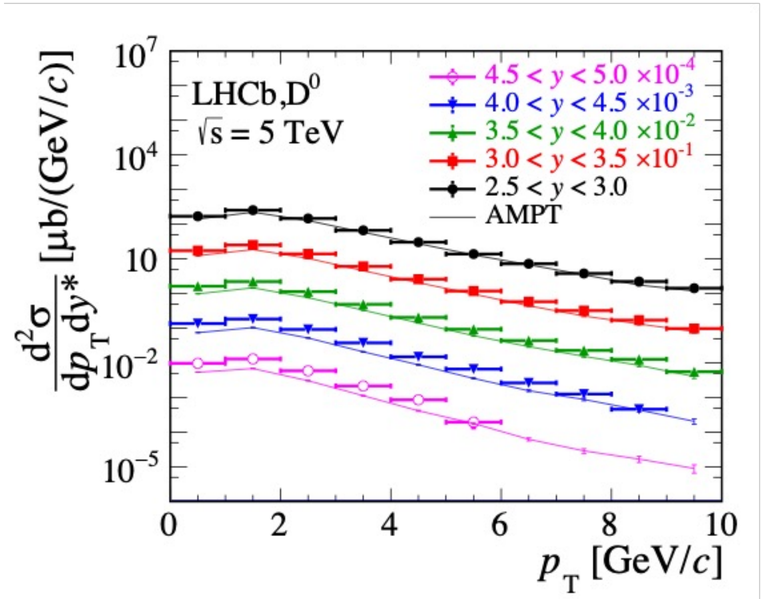
Parton scatterings significantly suppress charm spectra at moderate/ high p_T,
Cronin effect significantly increases charm spectra at moderate/high p_T and thus compensates for the effect from parton scatterings

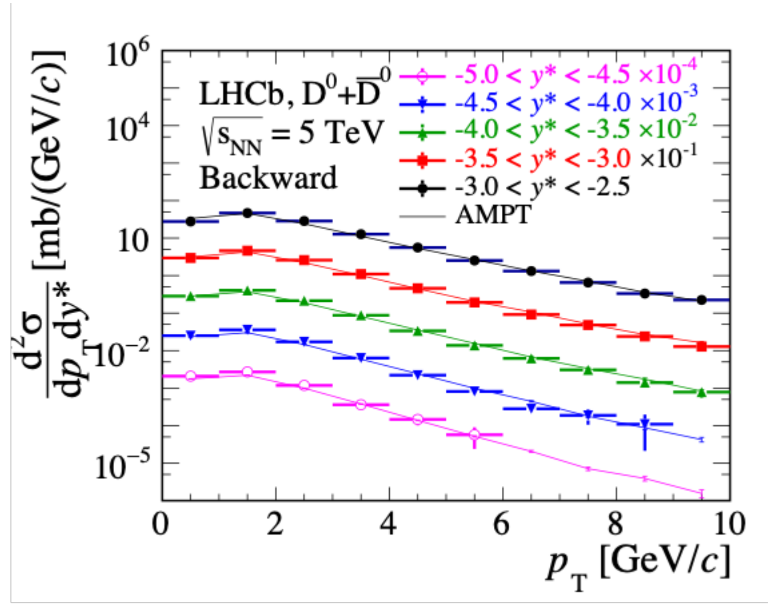
Charm v_2 is found to be mostly generated by charm quark scatterings,
Cronin effect slightly decreases the charm quark or meson v_2

The improved AMPT model can adequately describe the D^0 meson at larger rapidity and the D_s^+ enhancement at high multiplicity p-Pb collisions.

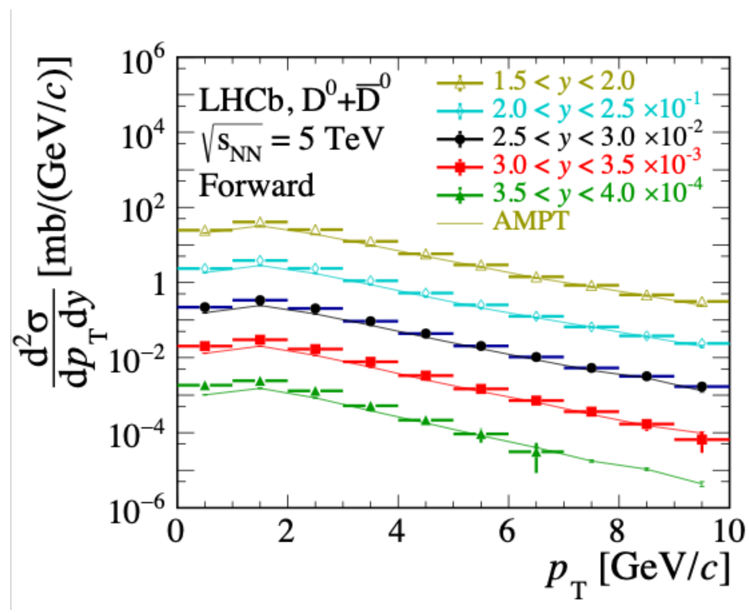
Backup Slides

More results on the D^0 spectra



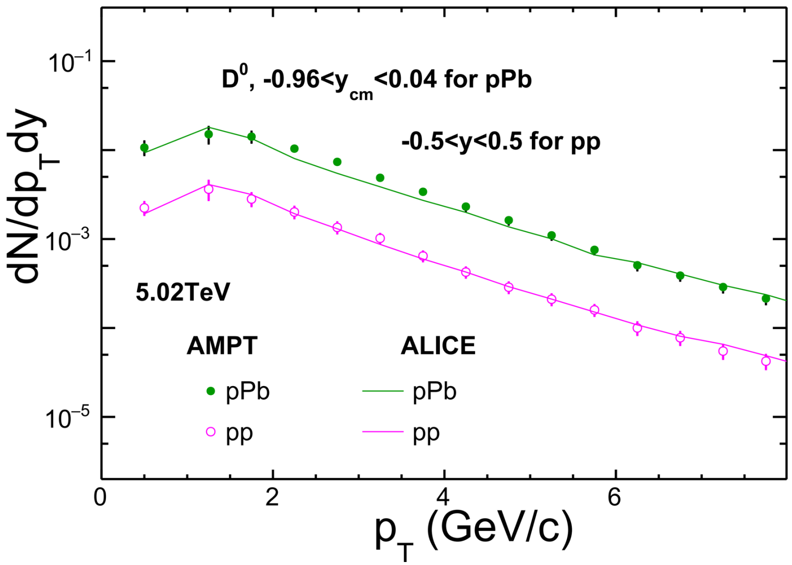


- The improved AMPT model can reasonably describe the D^0 meson spectra at forward and backward rapidity at LHC.
- The Cronin strength need to be quantified in different rapidity

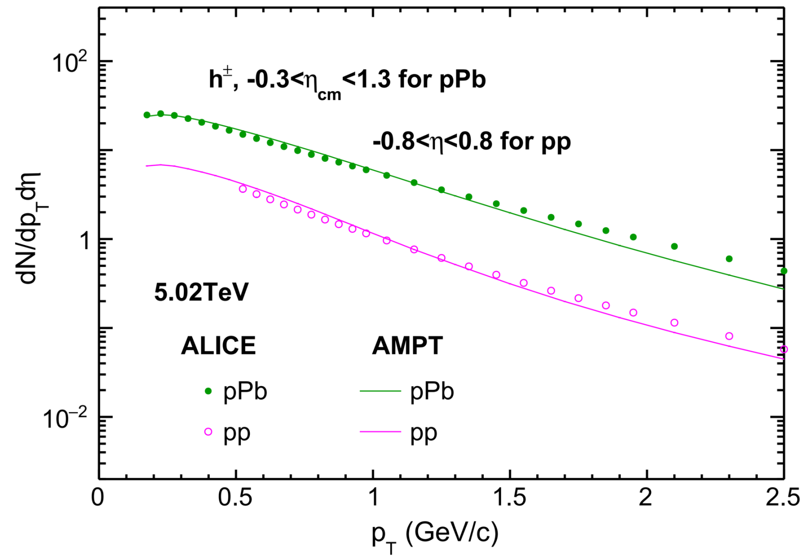


At 5.02 TeV, the full model also reasonably describes

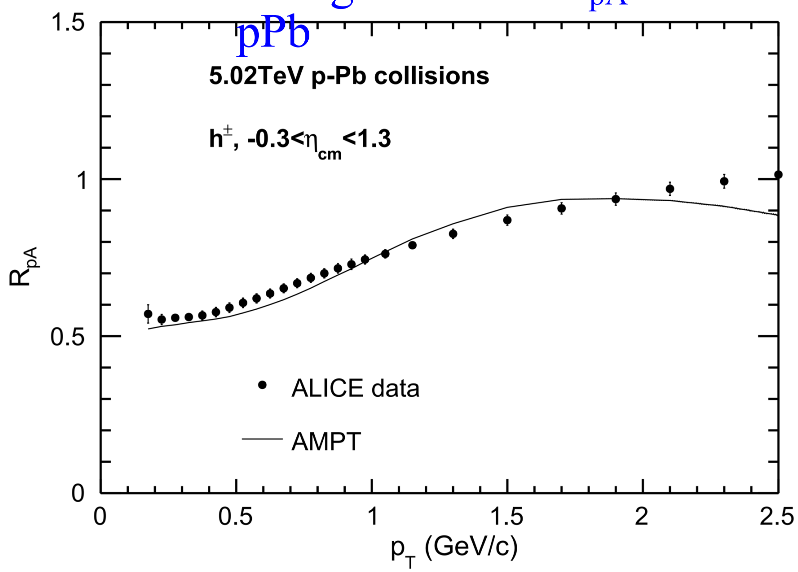
D^0 p_T spectra (to ~8GeV/c)



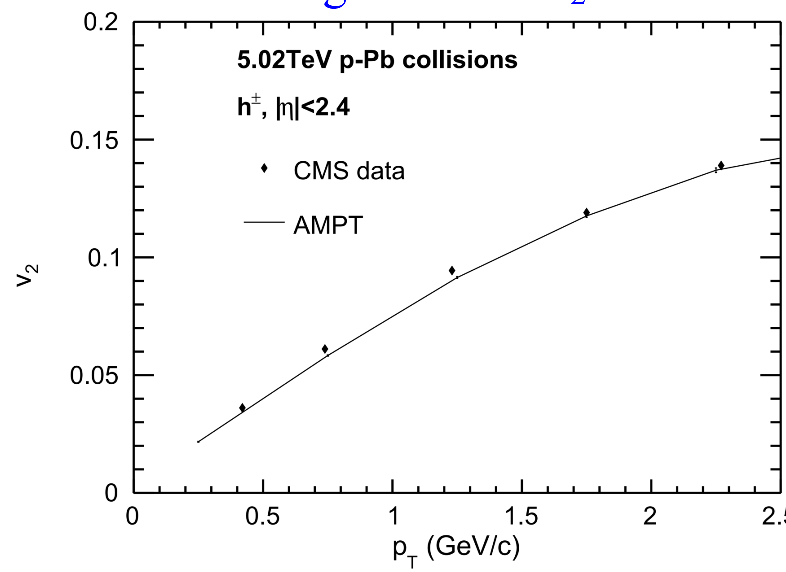
Charged hadron p_T spectra (to ~1.5 GeV/c)



Charged hadron R_{pA} pPb

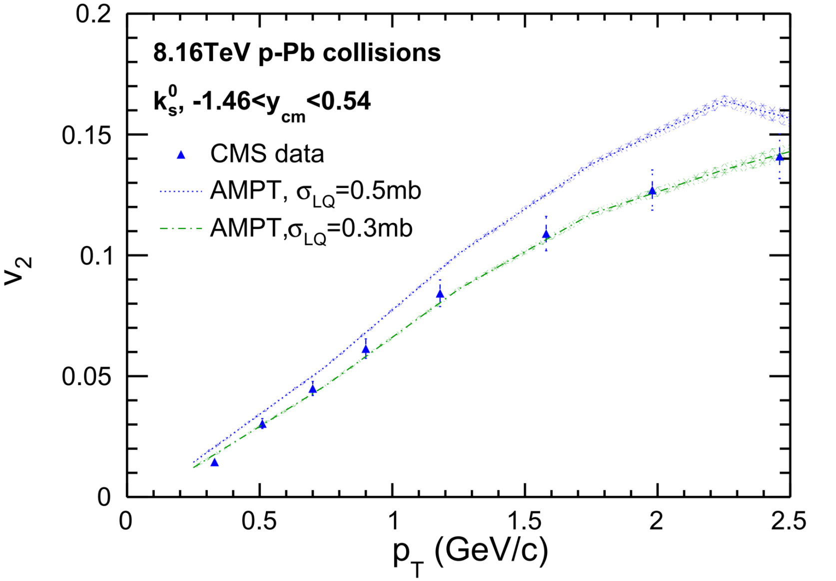


Charged hadron v_2 in



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 :