Exploring the elliptic anisotropy of heavy flavors in small collision systems at LHC

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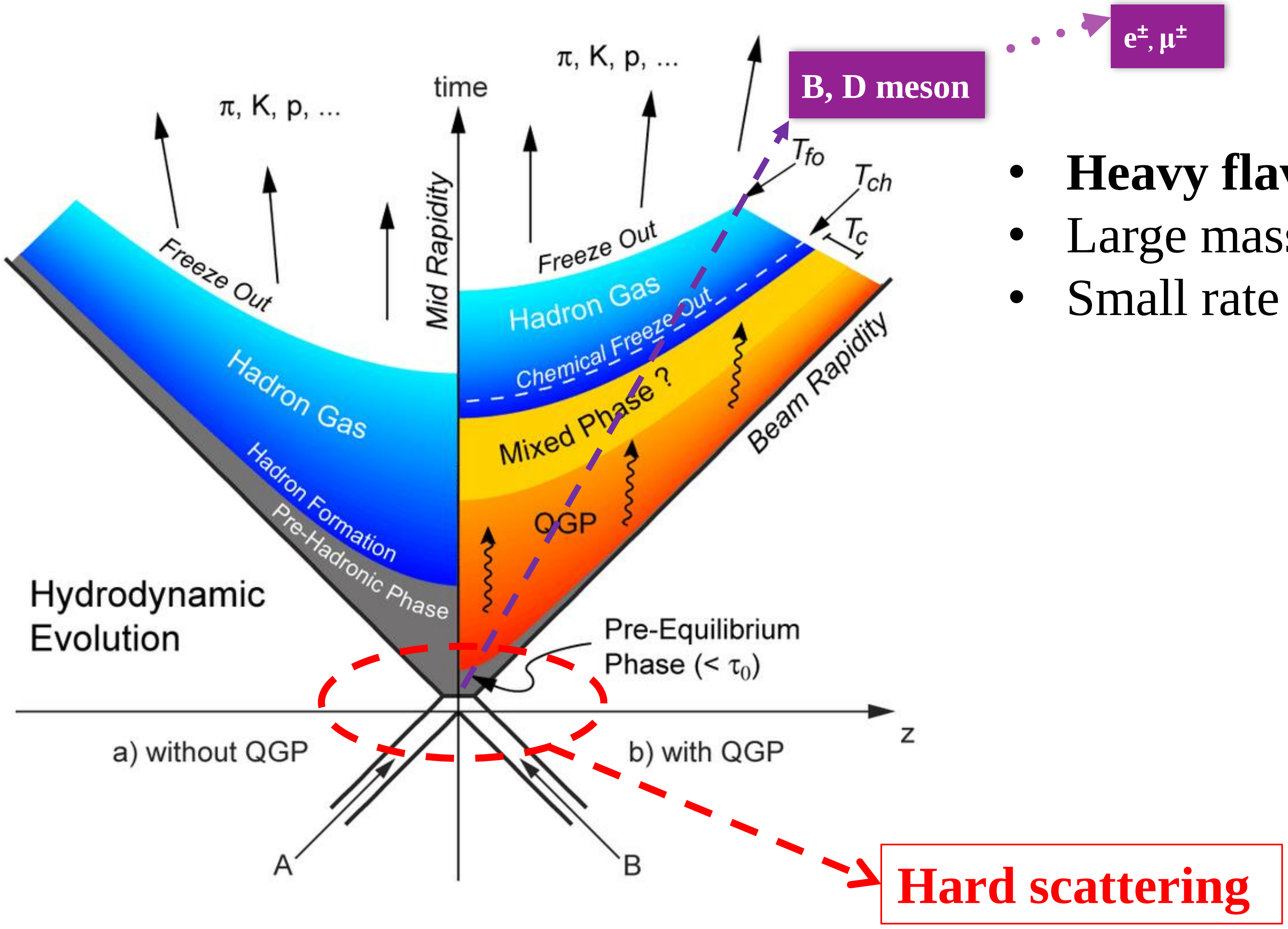
Based on: ***Phys.Lett.B 846 (2023) 138219***, ***Phys.Rev.C 109 (2024) 6, 064902, Nucl. Sci. Tech.*** **35 (2024) 2, 32** and ongoing works with:

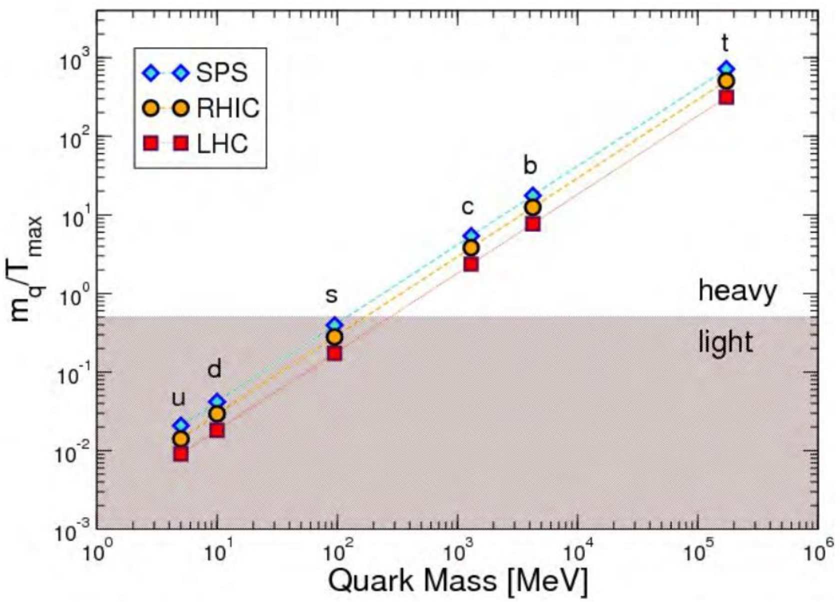
Chao Zhang (张潮)，Ren-zhuo Wan (万仁卓)，Guo-liang Ma (马国亮)，Zi-wei Lin (林子威)

Hard probes in heavy-ion collisions



- **Heavy flavours:** charm and beauty
- Large mass, short formation time
- Small rate of thermal production in the QGP

DOI:10.16943/ptinsa/2015/v81i1/48068

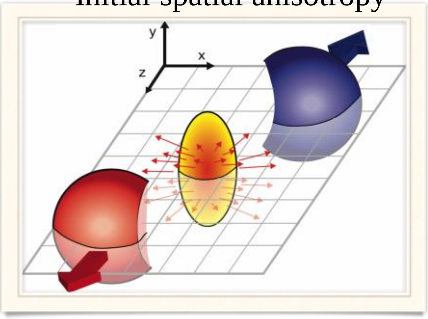


Azimuthal anisotropy

- The azimuthal anisotropy is studied by a Fourier expansion of azimuthal distribution of final-state particles: $E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}(1+\sum_{n=1}^{\infty}2v_n\cos(n(\varphi-\Psi_n)))$ **Flow coefficients** $v_n = \langle\cos(n(\varphi-\Psi_n))\rangle$ ***n*=2, elliptic flow *v*₂**

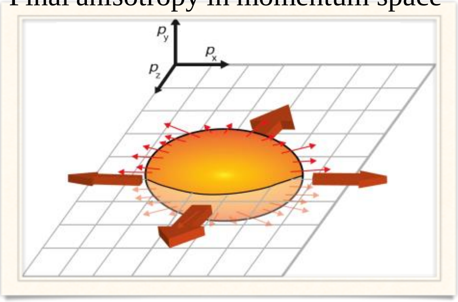
Initial spatial anisotropy

Heavy quarks



- **Pressure gradient**
- **Expansion of the QGP**

Final anisotropy in momentum space



Elliptic flow of heavy quark?

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***n*=2, elliptic flow v_2**

Initial spatial anisotropy

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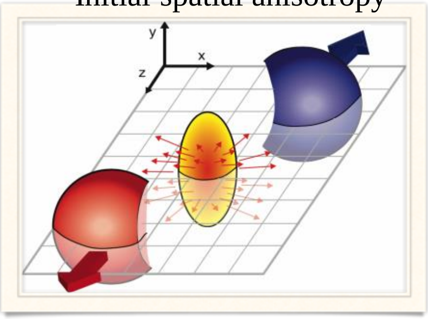

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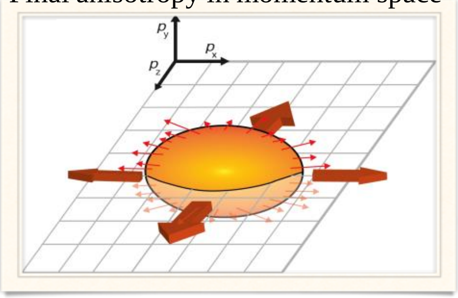
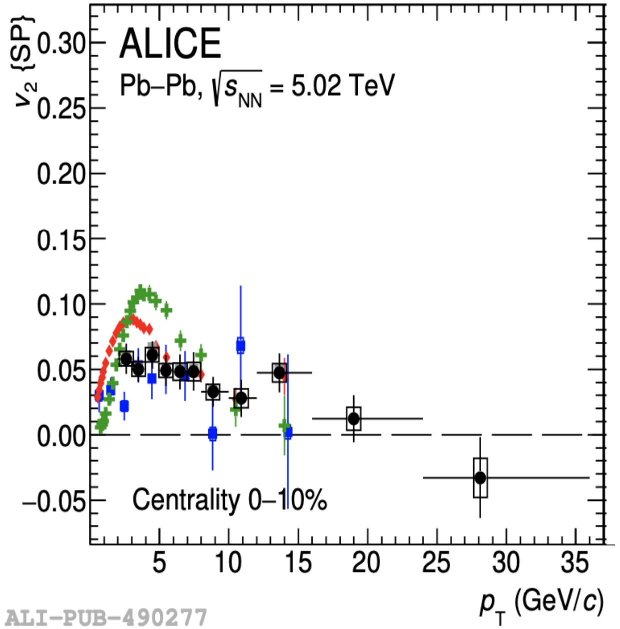
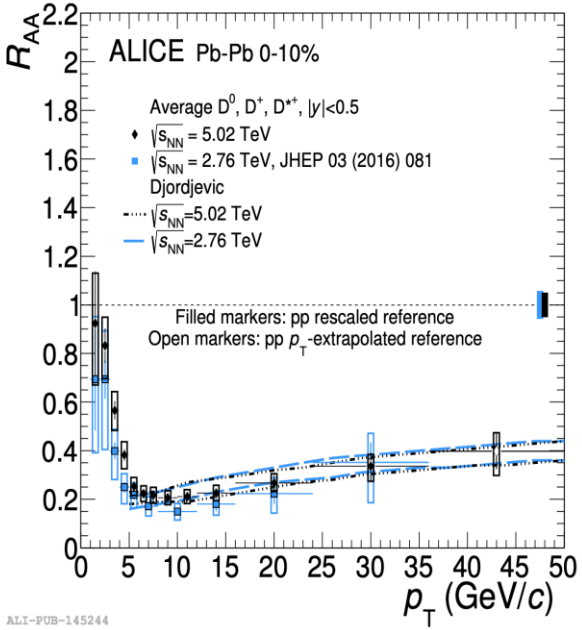


Elliptic flow of heavy quark?

v_2 vs R_{AA}

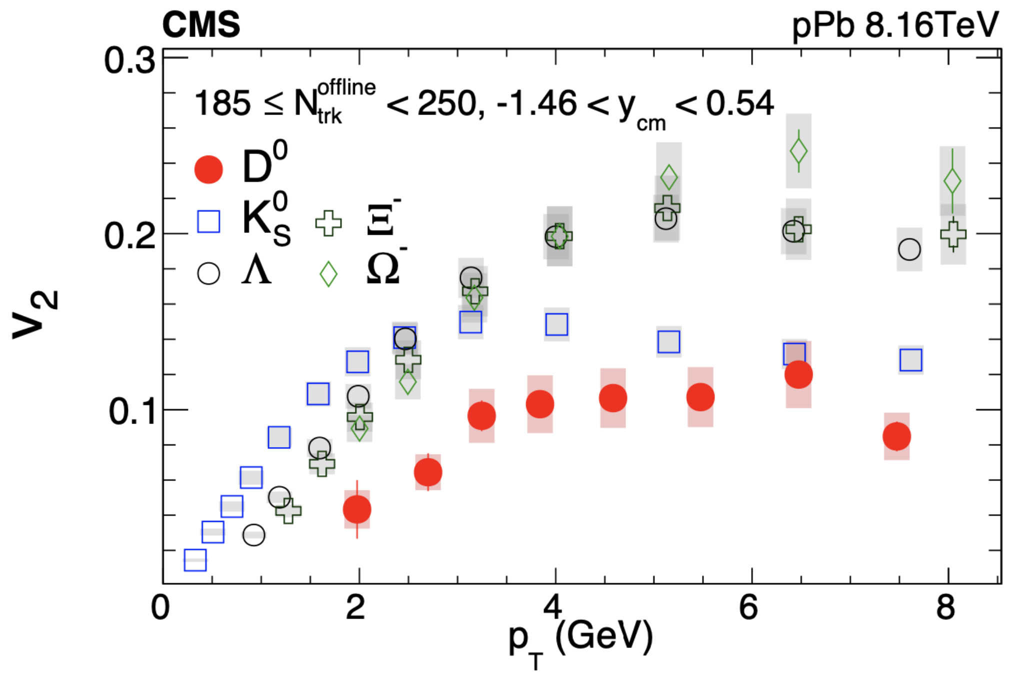




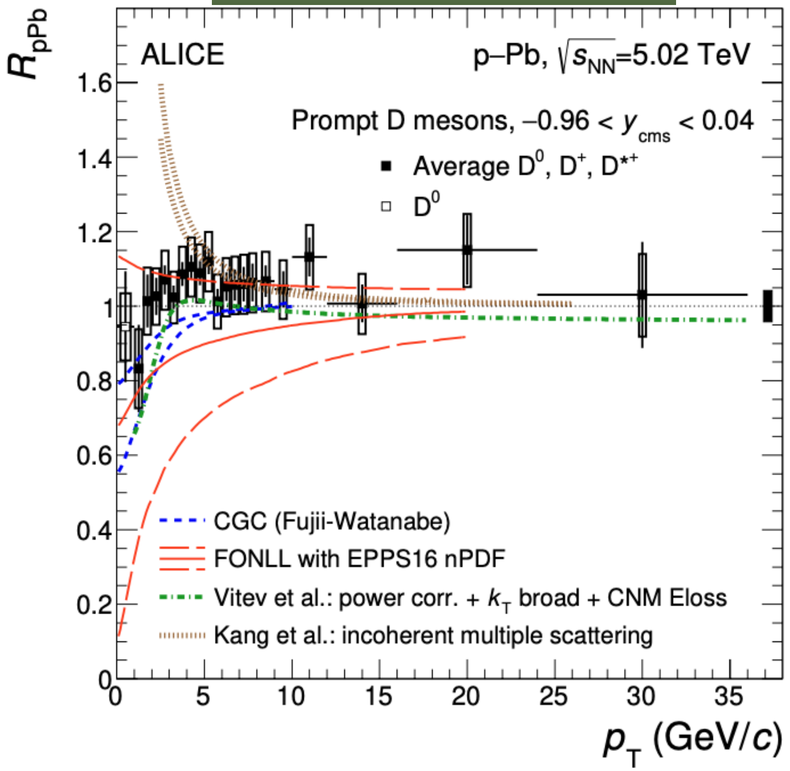
- **Open heavy flavours:**
  - Low and intermediate p_T: collective motion and properties of thermalization
  - High p_T: path-length dependence of the heavy-quark energy loss

Puzzles in small collision systems

CMS, Phys. Rev. Lett. 121, 082301 (2018)



ALICE, *JHEP* 12 (2019) 092



- Little to no nuclear suppression R_{pA} but a sizable v_2 have been observed for D mesons in p−Pb collisions at the LHC energies

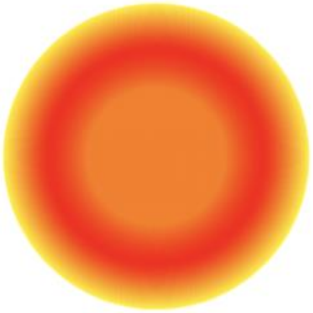
Can the R_{pA} and v_2 be simultaneously described in the small collision systems?

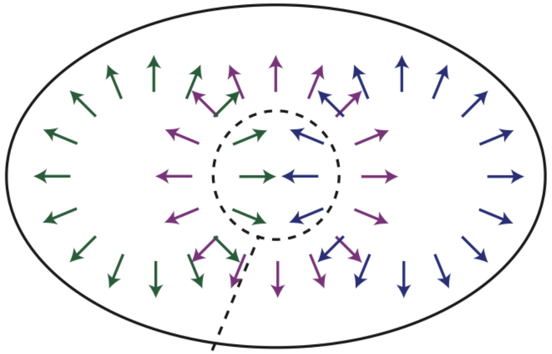
Possible theoretical explanations

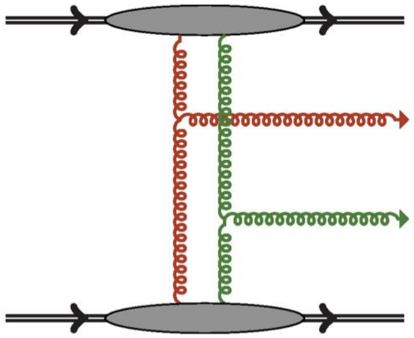
Many scatterings

Few scatterings

Initial conditions







hydrodynamics

Parton escaping

Initial-momentum correlations

(Perfect) fluid dynamics

AMPT

Free streaming limit (CGC)

+ Coalescence/Fragmentation …

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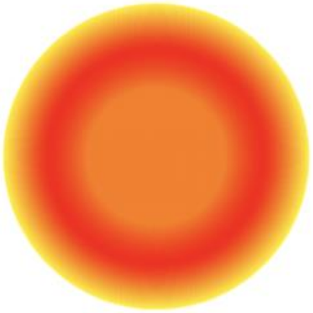

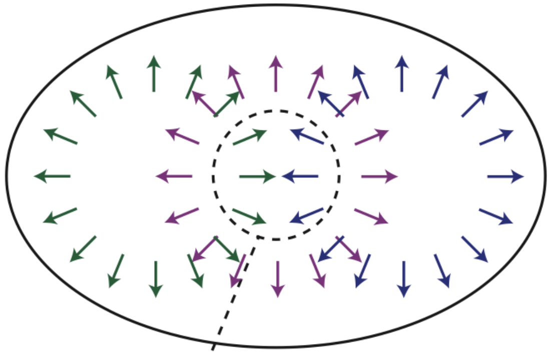

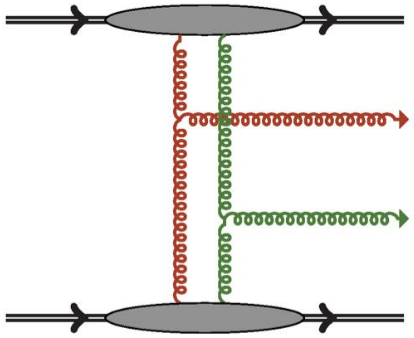

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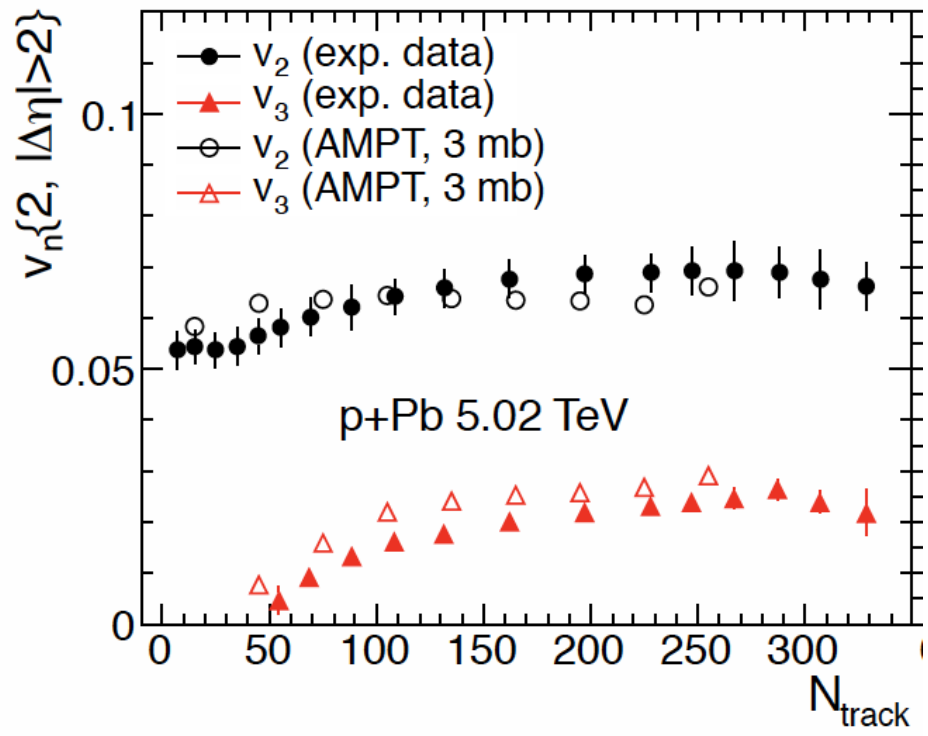
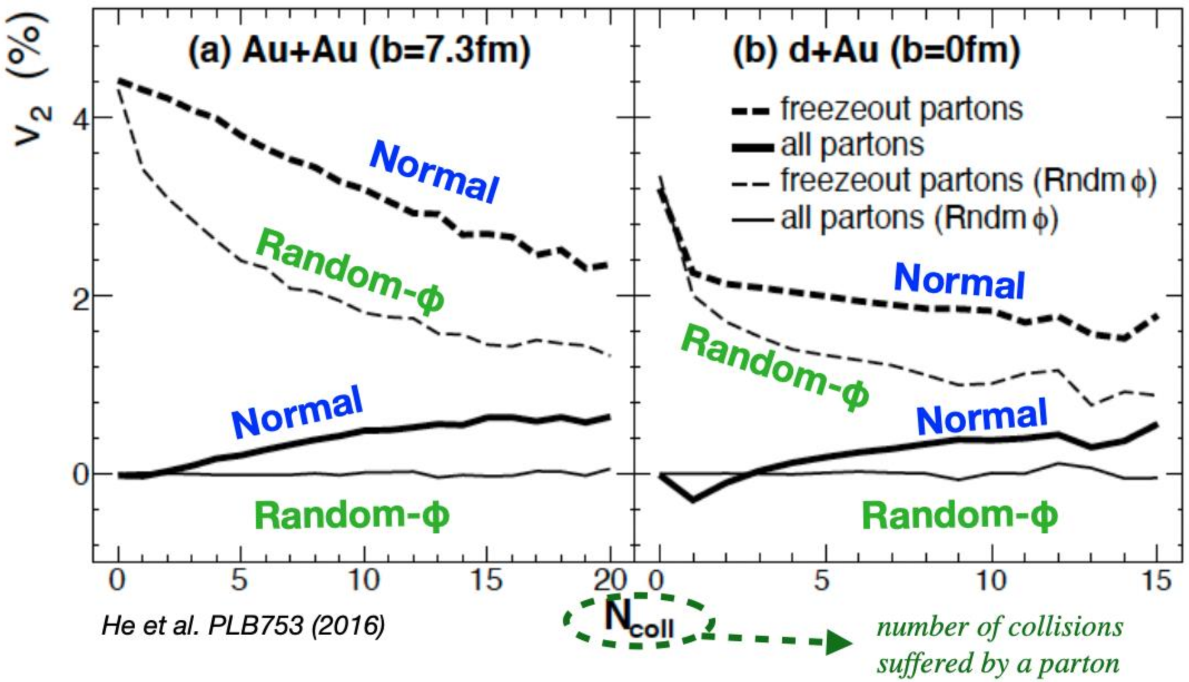
A.Bzdak et al, Phys. Rev. Lett. 113, 252301 (2014)



Zi-Wei Lin, IHEP2016

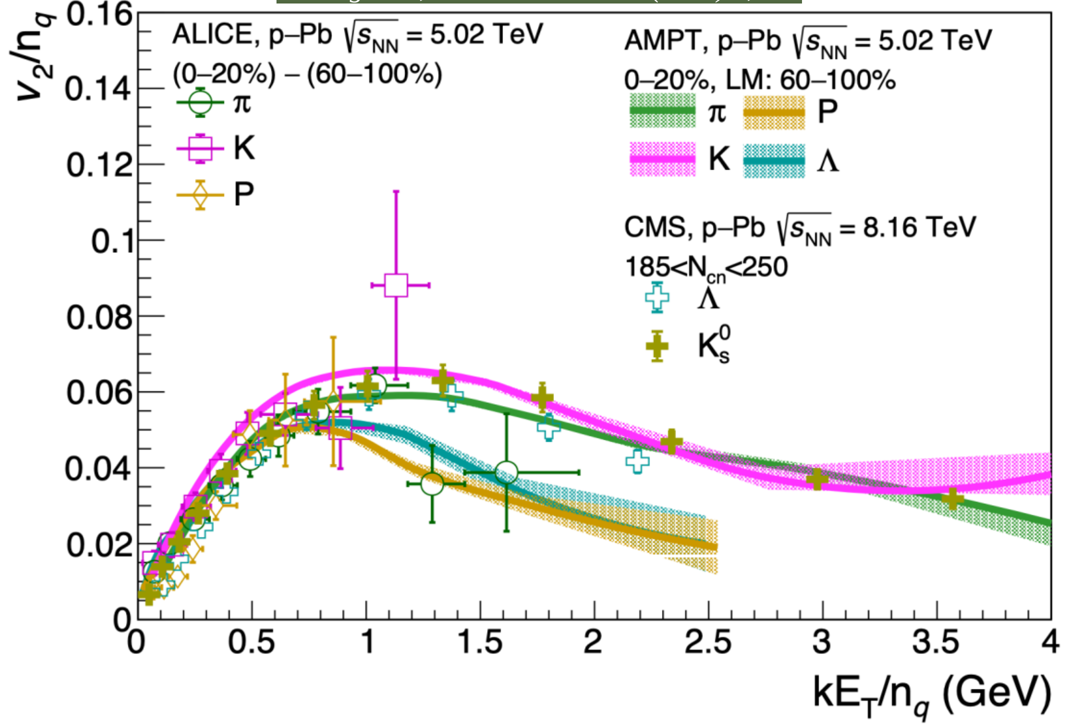


- The AMPT calculations with string melting can nicely describe the v_2 and v_3 in p-Pb collisions with a modest elastic cross section (σ = 1.5 – 3 mb)

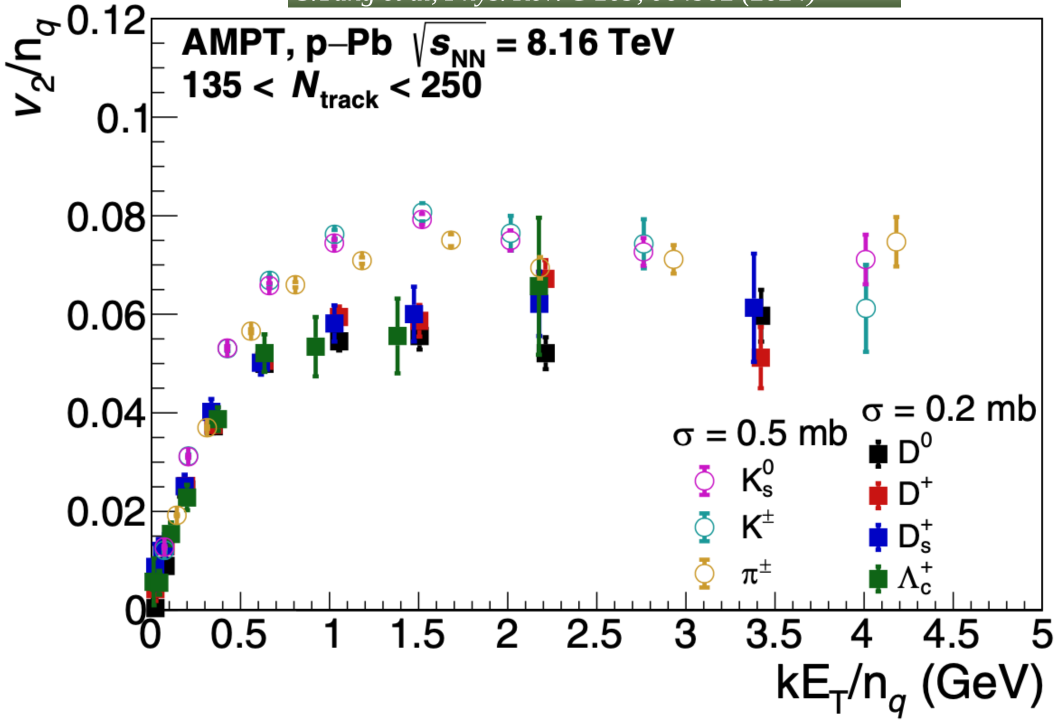
➡ Parton escape mechanism is responsible for the anisotropy build up in AMPT

Parton escaping

S.Tang et al, Nucl. Sci. Tech. 35 (2024) 2, 32



S.Tang et al, Phys. Rev. C **109**, 064902 (2024)



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➞ Parton escape mechanism is responsible for the anisotropy build up in AMPT

Even for heavy quarks!

➞ Parton cascade + coalescence approximately reproduce the NCQ scaling of v_2 at intermediate kE_T

A Multi-Phase Transport (AMPT) model

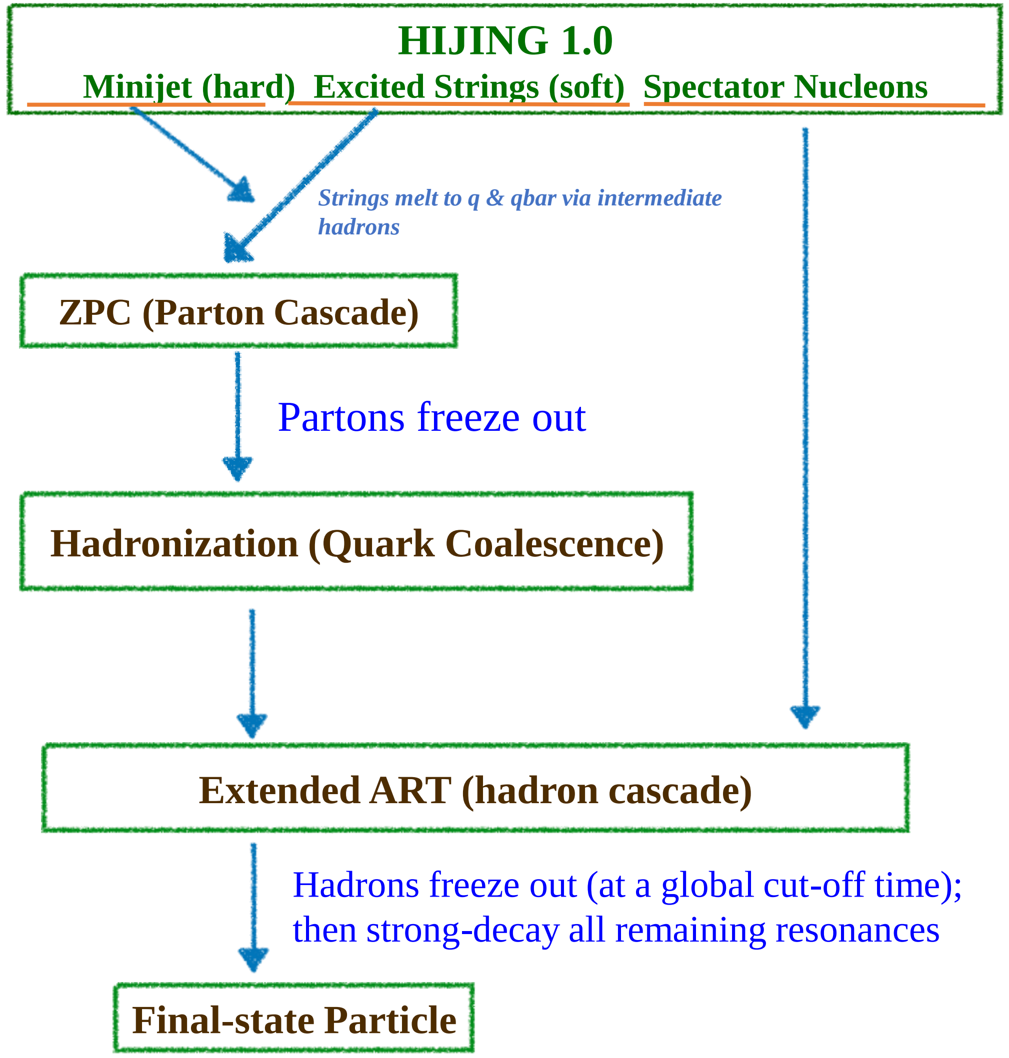
- **Initial conditions:** HIJING
- **String melting:** hadrons from string fragmentation are melted into primordial quarks and antiquarks
- **Parton cascade:** two-body elastic scattering described by ZPC model

Debye screening mass

$$\frac{d\sigma}{dt} = \frac{9\pi\alpha_s^2}{2}\left(1+\frac{\mu^2}{s}\right)\frac{1}{(t-\mu^2)^2}$$

- **Coalescence:** combine nearest quarks to meson/baryon
- **A Relativistic Transport (ART)** to describe hadron scatterings

Structure of public AMPT v2.xx (String Melting Version)



Improvements for heavy flavors

- **Remove the p0 cut for the HF production**
- because the large heavy quark mass naturally control the heavy quark total cross section
- **Replace the PDF and nPDF**
- modern PDF (CTEQ6.1M) and a spatial dependence of nuclear shadowing functions (eps09s NLO) are incorporated
- **Local scaling for self-consistent size dependence**
- collision system dependence is introduced in Lund symmetric string fragmentation function (b_L) and minijet cutoff (p_0)
- **Add Cronin effect**
- implement the p_T broadening by adding a p_T kick (k_T) in the initial state where k_T is sampled from a two-dimensional Gaussian
- **Add independent fragmentation**
- according to the relative distance and invariant mass of the heavy hadron system

Improved AMPT structure

HIJING 1.0+modernPDF/EPS09s/localscaling/HF

Heavy quark **Light quark** **Spectator Nucleons**

Cronin effects

Strings melt to q & qbar via intermediate hadrons

ZPC (Parton Cascade)

Partons freeze out

Hadronization (Quark Coalescence+Fragmentation)

Extended ART (hadron cascade)

Hadrons freeze out (at a global cut-off time); then strong-decay all remaining resonances

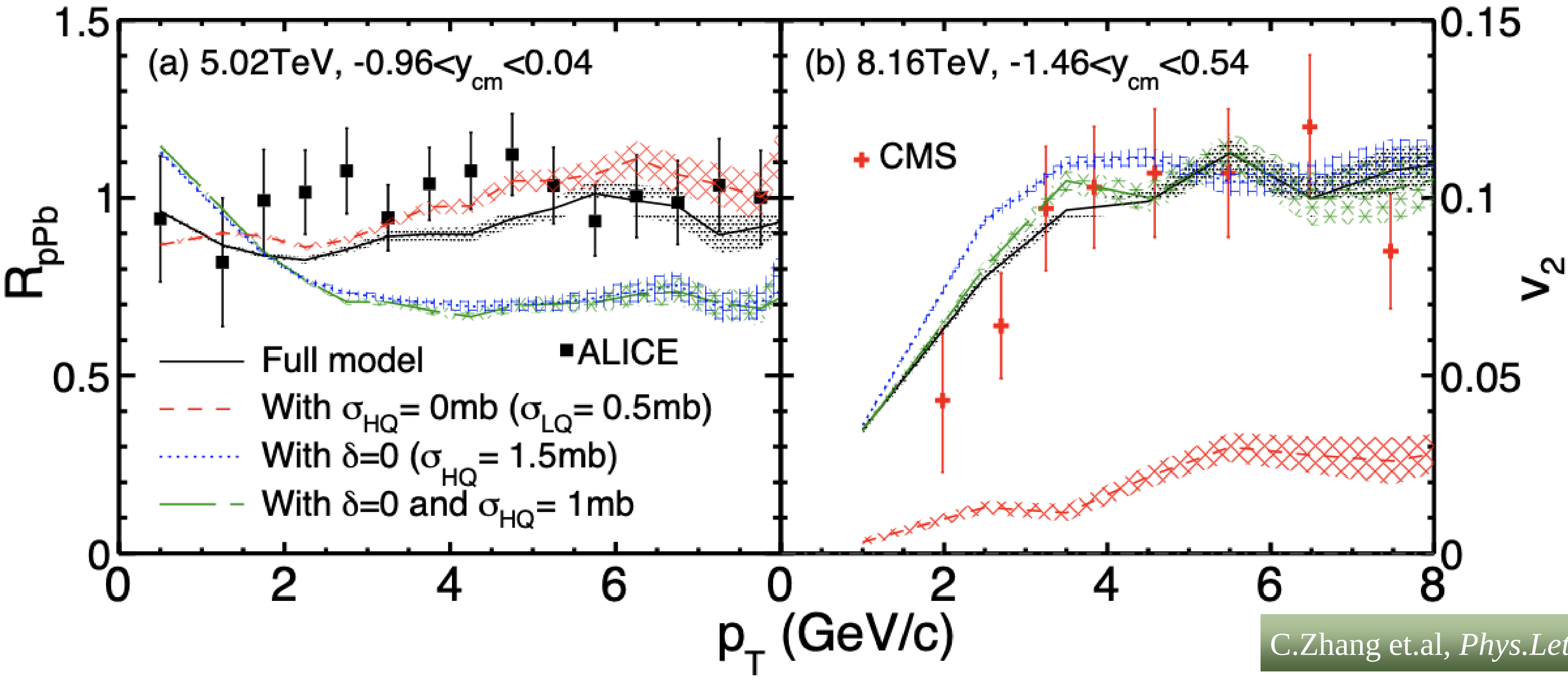
Final-state Particle

C. Zhang, *Phys.Rev.C* 99 (2019) 6, 064906

L. Zhang, *Phys.Rev.C* 101 (2020) 3, 034905

C.Zhang, *Phys.Rev.C* 104 (2021) 1, 014908

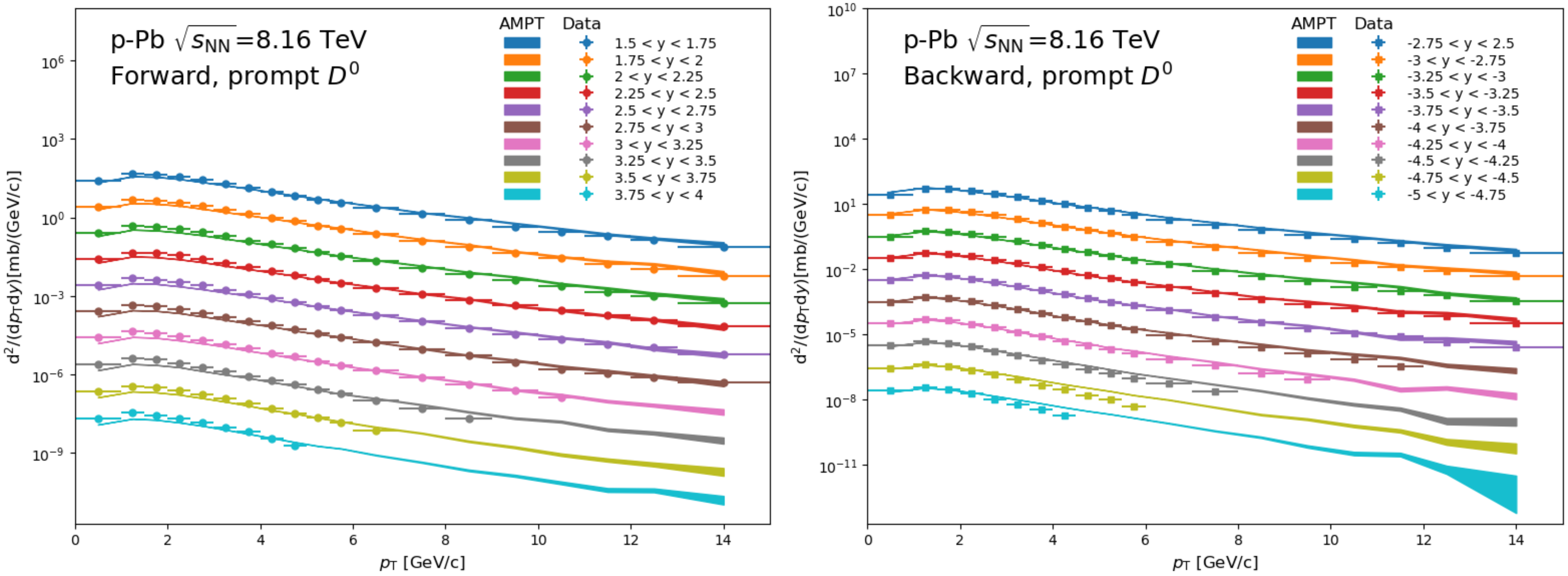
Heavy flavor v_2/R_{pA} at mid-rapidity



C.Zhang et.al, *Phys.Lett.B 846 (2023) 138219*

- A simultaneous description of the R_{pA} and v_2 is provided by the improved AMPT model
- The **Cronin effect** significantly enhances D^0 production at intermediate/high p_T, while modestly decrease the D^0 meson v_2
- Parton scatterings are mostly responsible for generating the D^0 meson v_2

Heavy flavor spectrum at forward/backward rapidity



- The D^0 meson spectrum at forward and backward can be well reproduced by the improved AMPT model
- The Cronin strength is quantified in different rapidity

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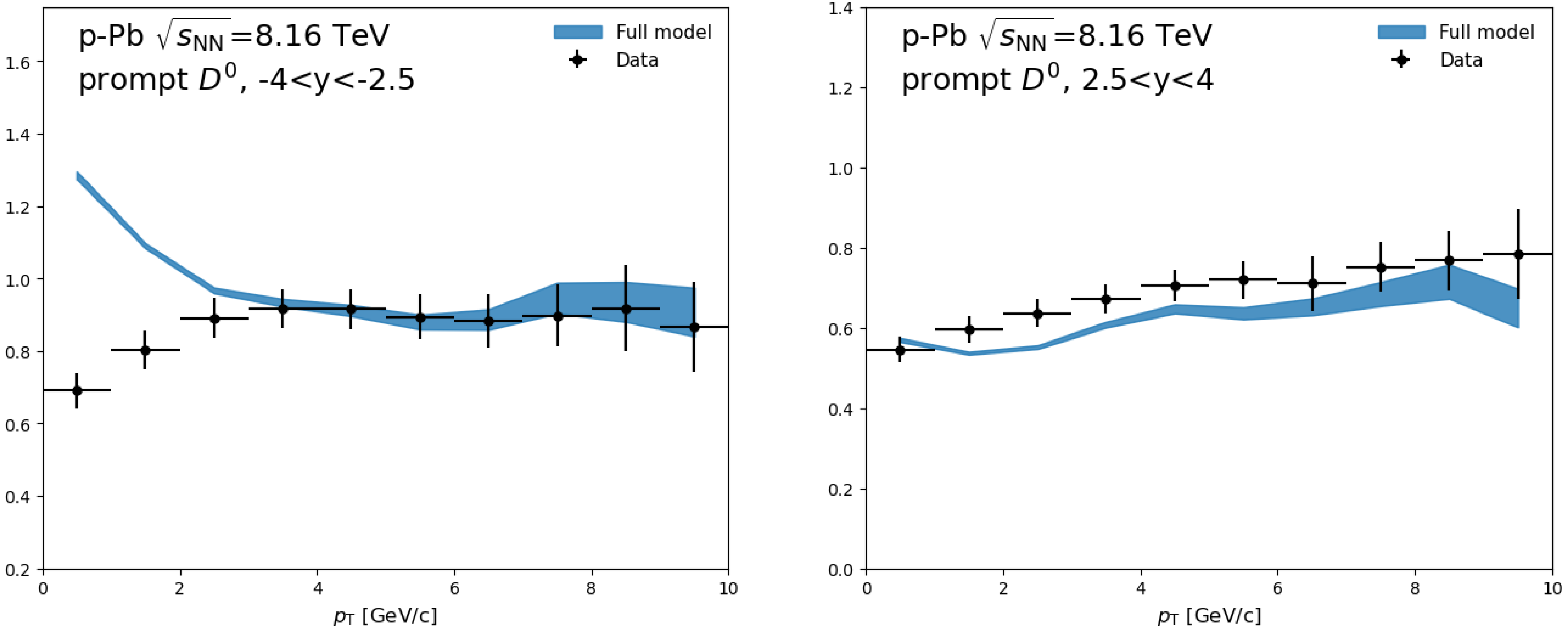

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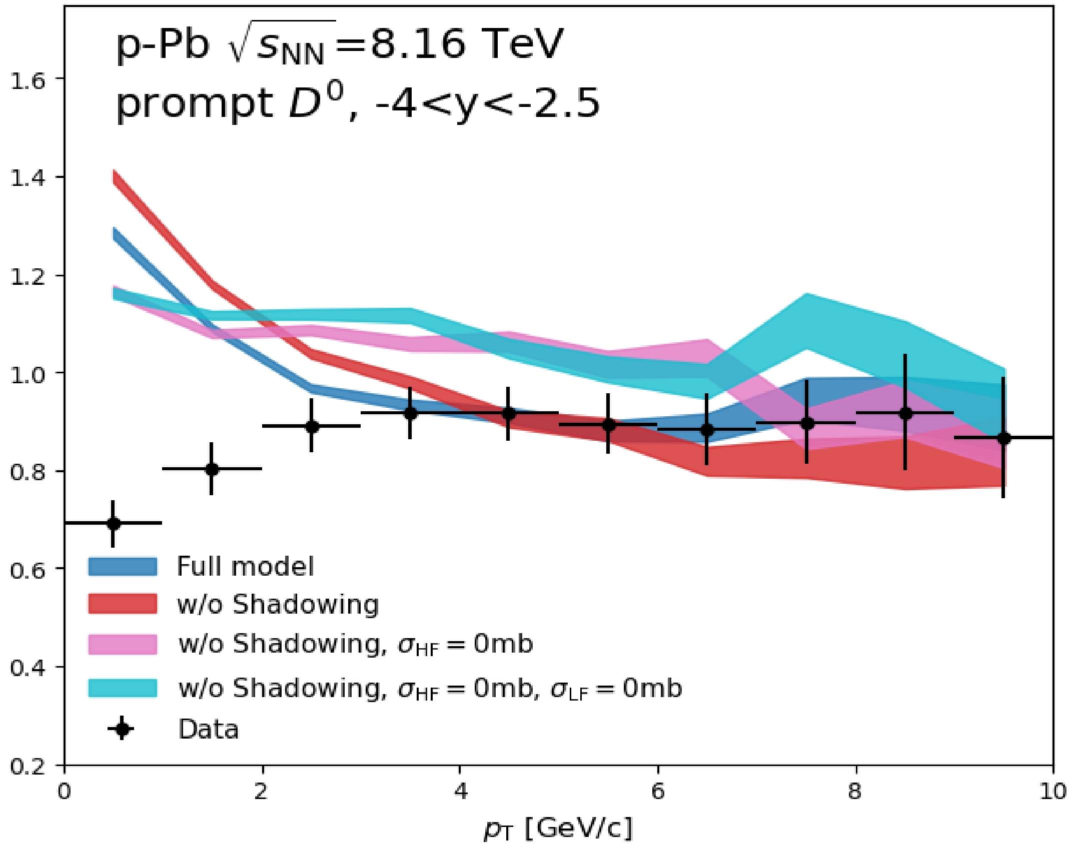
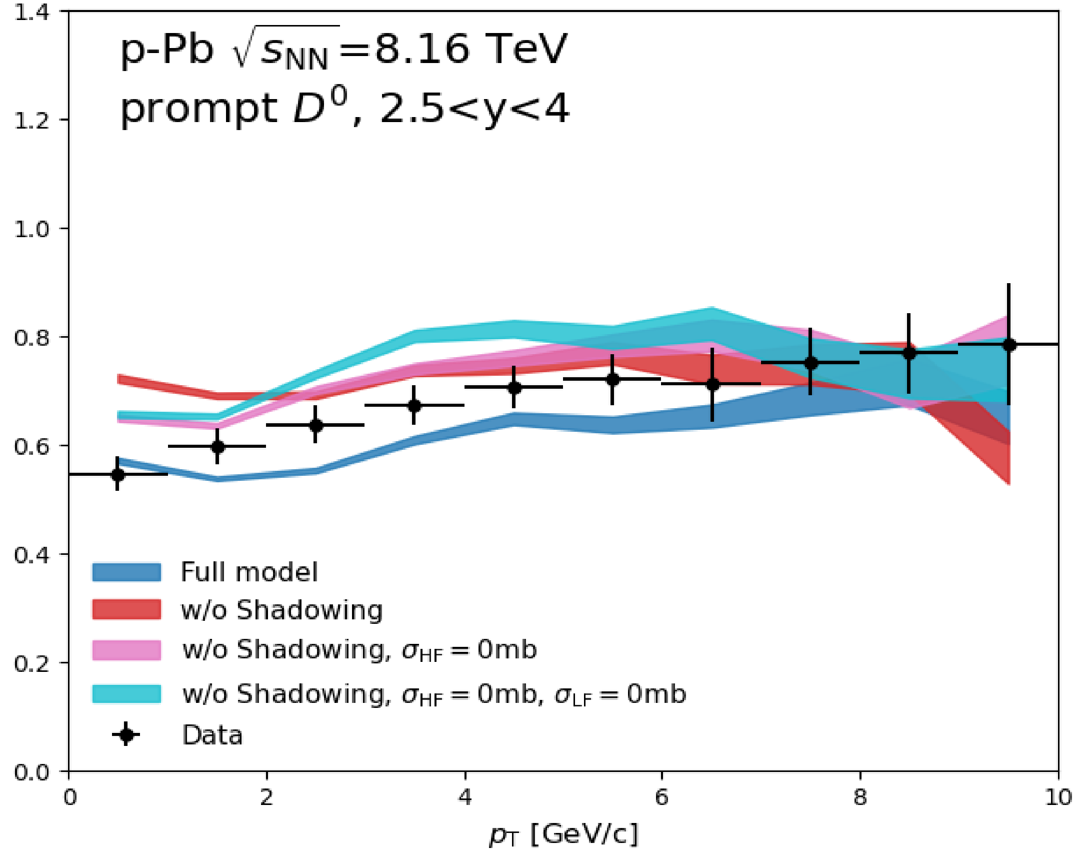
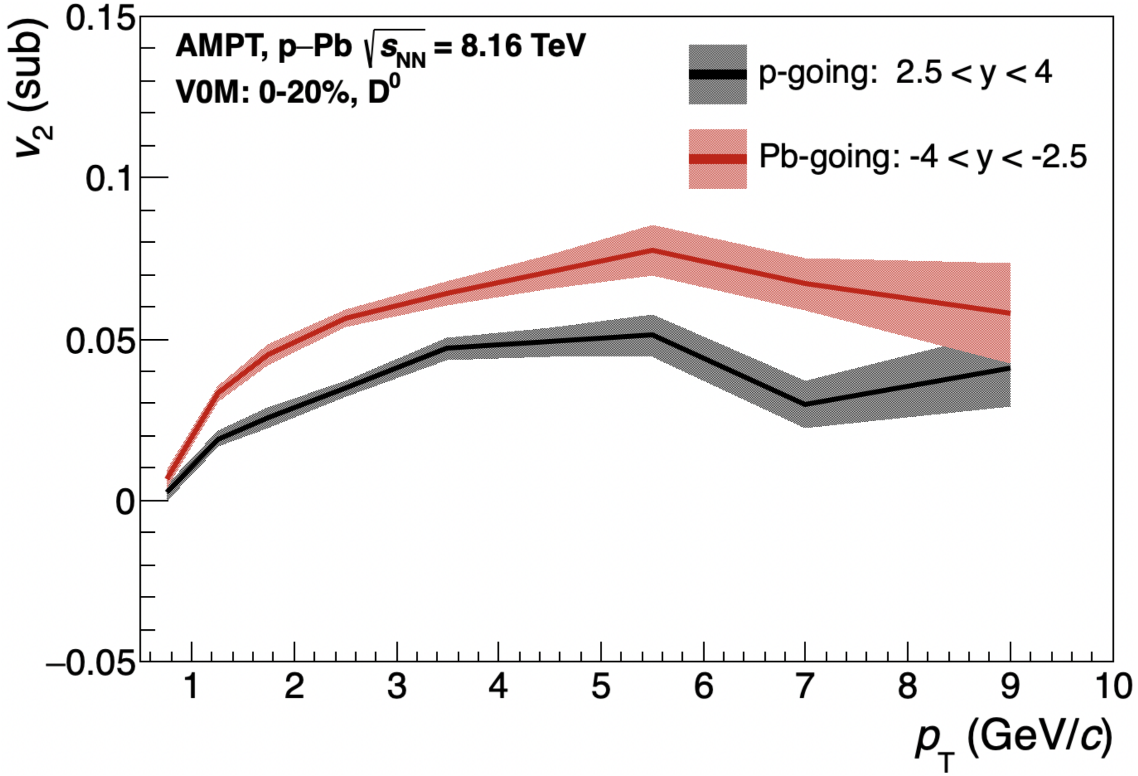
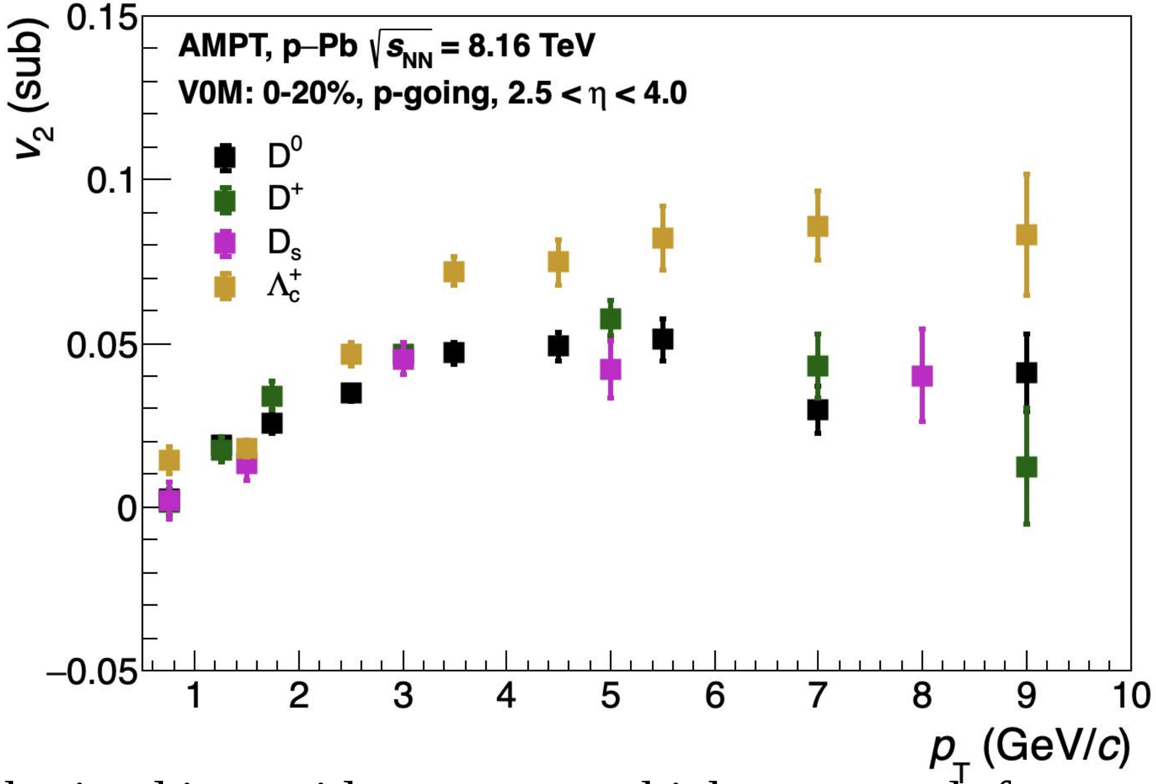




- **"w/o shadowing effect":** enhancement is observed, more significantly at forward rapidity
- **"σ_{HF} = 0 mb / σ_{LF} = 0 mb":** push more particles to higher p_T (> 2 GeV/c), but more significantly at backward rapidity

Heavy flavor v_2 at forward/backward rapidity

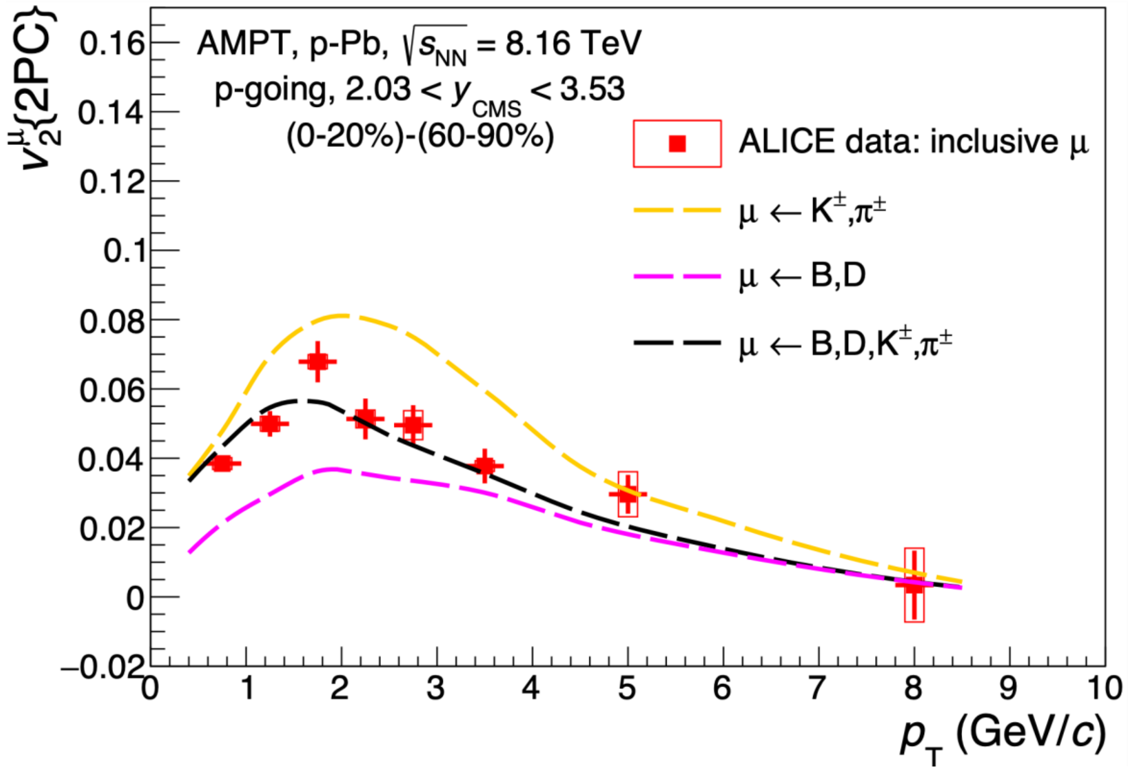


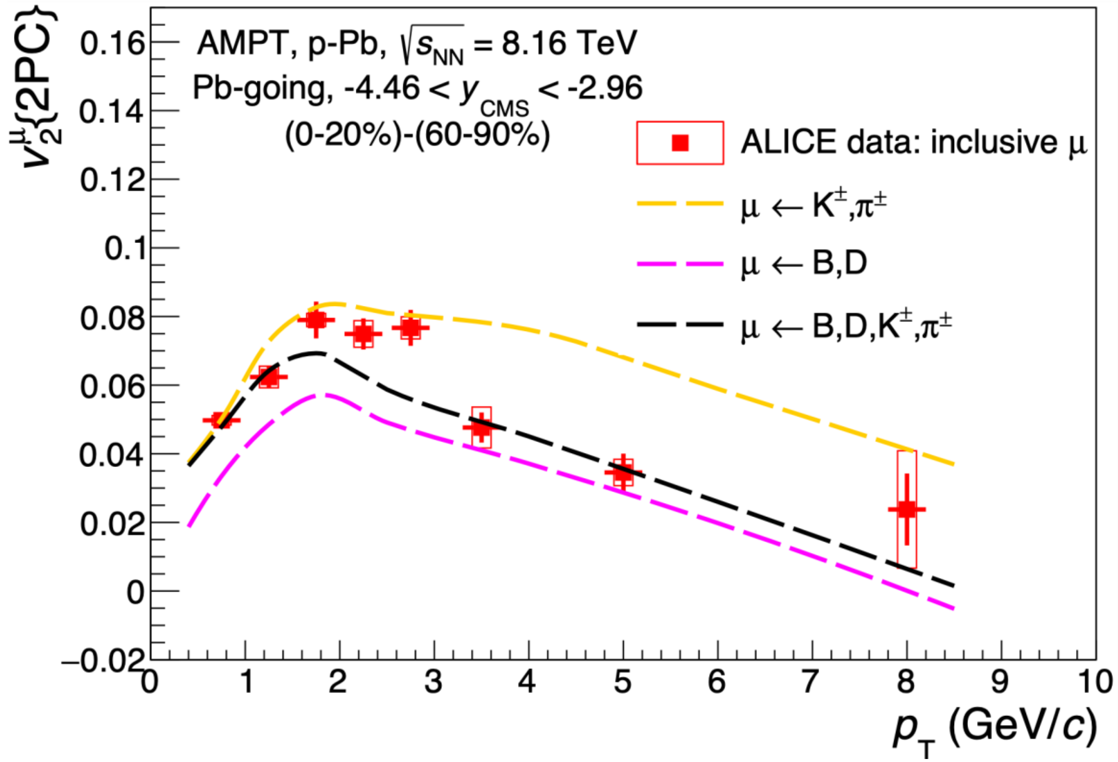


- Higher v_2 of D^0 for Pb-going side than p-going side is obtained in a wide p_T range, which may result from decorrelations of event planes at different rapidity
- Consistent v_2 of charm mesons (D^0, D^+, D_s) is obtained and baryon-meson grouping for charm hadrons is observed for p_T > 3 GeV/c

Need to be further constrained by data!

Heavy flavor v_2 at forward/backward rapidity





- The muons from meson decay are obtained using PYTHIA decayer
- **A reasonable agreement with the data** at forward and backward rapidities is provided by the improved AMPT model

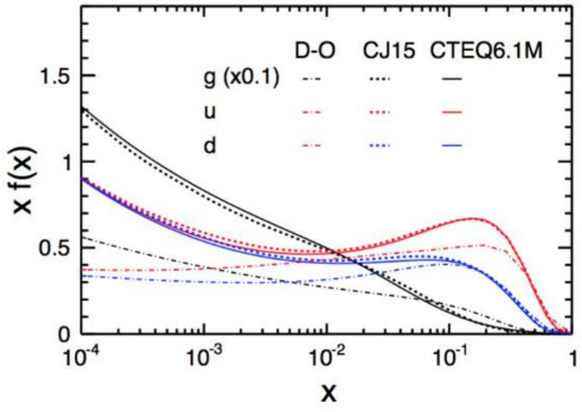
Summary & Outlook

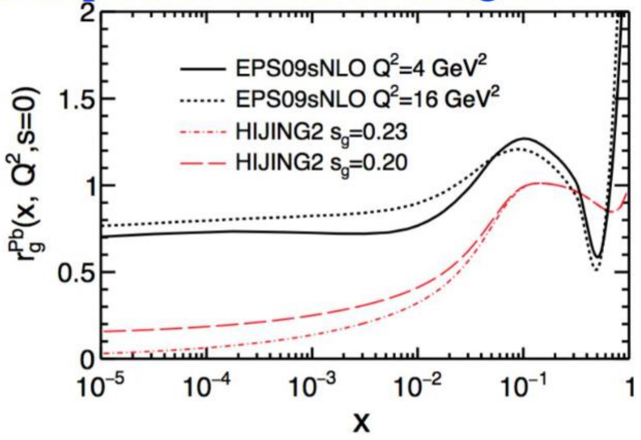
- Systematic calculations of the charm hadron v_2 are perform in p–Pb collisions with **an improved multi-phase transport model**
  - Including a strong **Cronin effect** allows a simultaneous description of the D^0 spectrum and v_2
  - The **parton scatterings** generate a significant v_2 for charm mesons, and well reproduce the rapidity dependence observed in data
  - *Future studies for bottom hadron/heavy quarkonium in the AMPT?*

Back up

Modern PDF and nPDFs

- *Duke-Owens*: used in the published AMPT model. *Outdated;*
- Modern PDF(CTEQ6.1M): gluon and quark distribution are much higher than Duke-Owens parameterization. important for LHC energies





- A spatial dependence of nuclear shadowing functions(eps09s NLO) is incorporated in the AMPT model.
- Energy dependence of the momentum cutoff p0 and soft cross-section σ_{soft} are needed for the pp collisions.
- A larger value of p_0 is needed for the AA collisions than pp collsions. *related to* $Q_s \propto A^{1/6}$

Chao Zhang et al. PRC (2019)

Back up

Improved multi-phase transport model for heavy flavors

$gg \rightarrow gg$ 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).

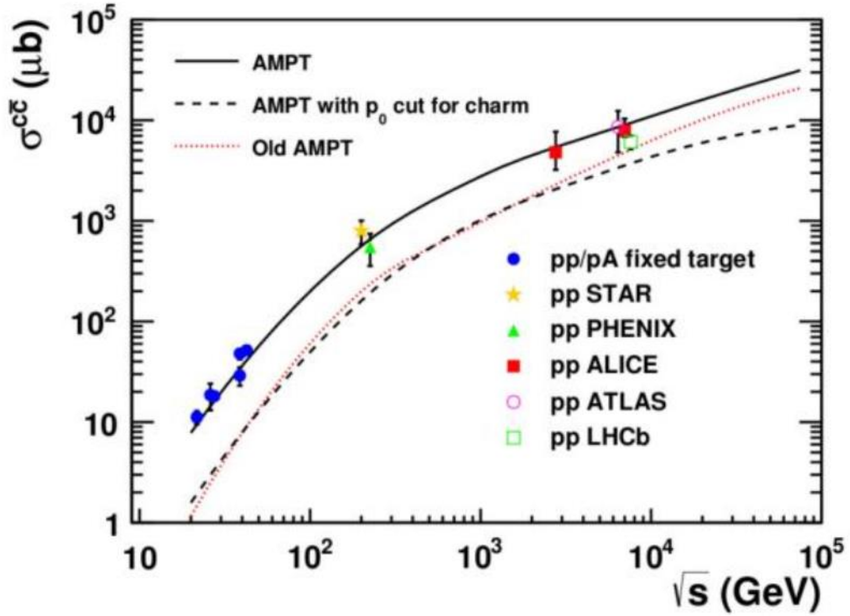
But heavy flavor (HF) production does not need a cutoff
due to heavy quark mass >> Λ_{QCD} (e.g. in FONLL)

$$g + g \rightarrow Q + \bar{Q} \qquad q + \bar{q} \rightarrow Q + \bar{Q}$$

- So we remove the p_0 cut on HF productions Zheng et al. PRC (2020) in the two-component model HIJING (initial condition for AMPT)
- 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

Back up

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

Back up

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:

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

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 $\alpha(s)$, $\beta(s)$ versus energy

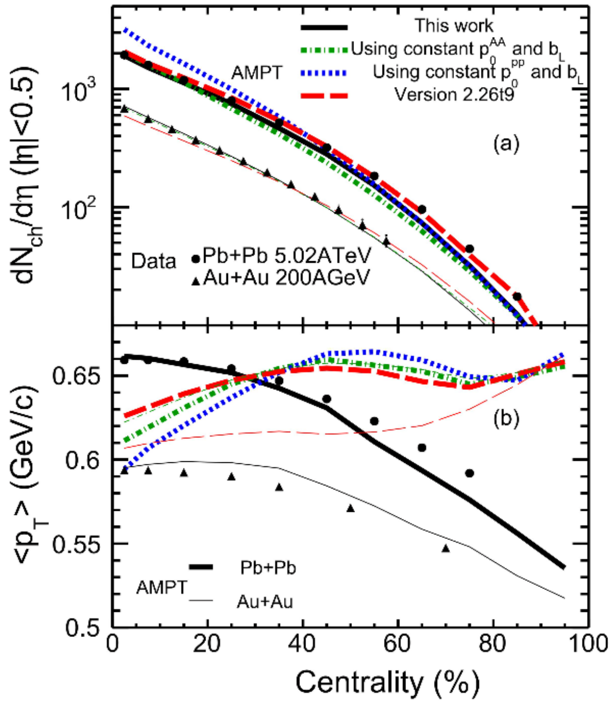
Back up

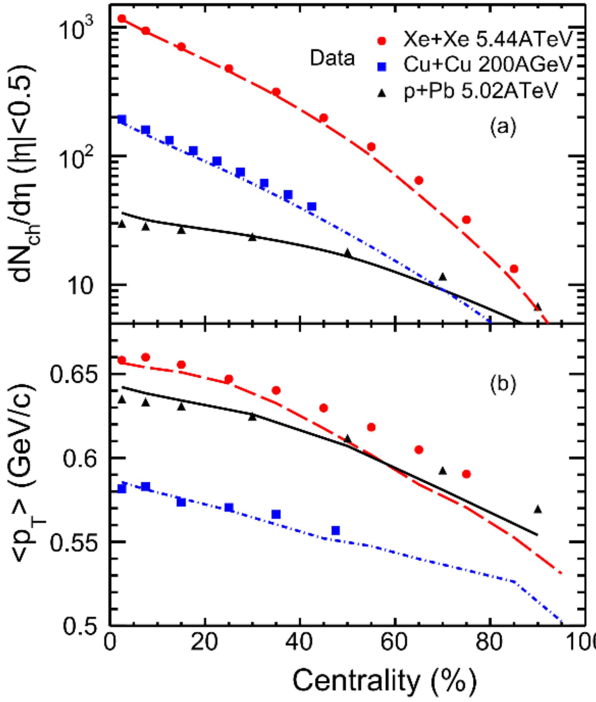
Local scaling for self-consistent size dependence in AMPT

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

Back up

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.

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

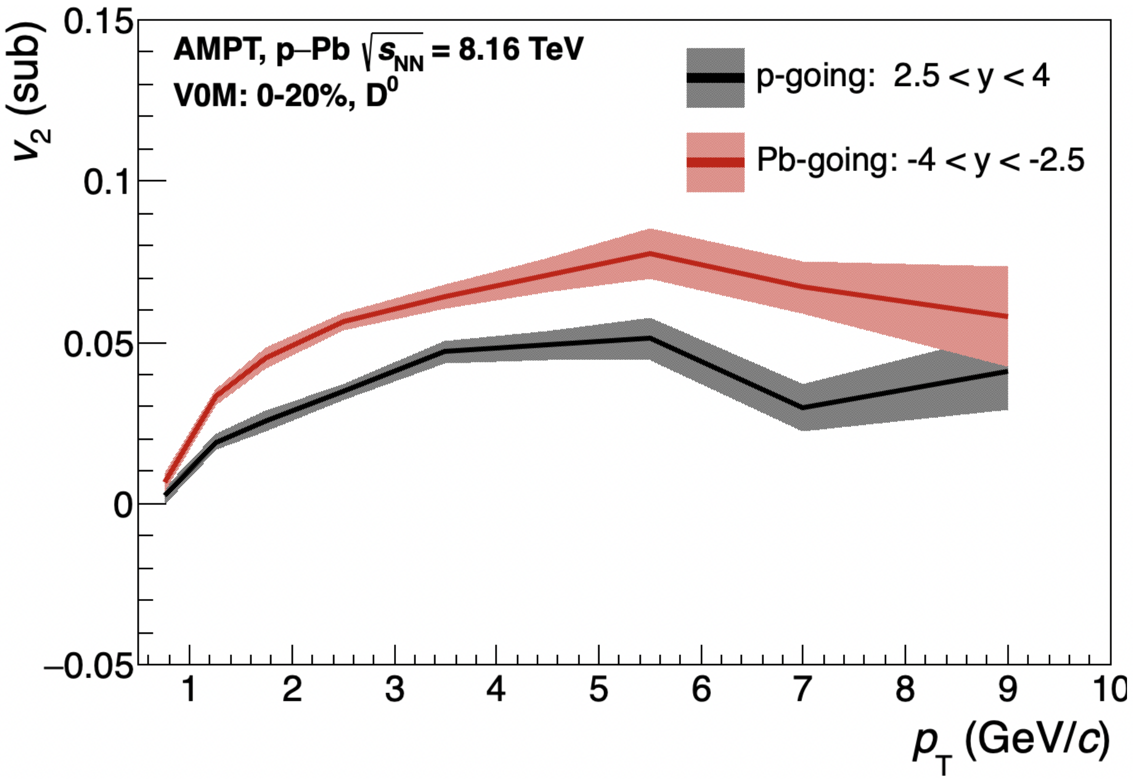
  motivated by $\kappa \propto \dfrac{1}{b_{\rm L}(2+a_{\rm L})}$ for Lund string fragmentation.

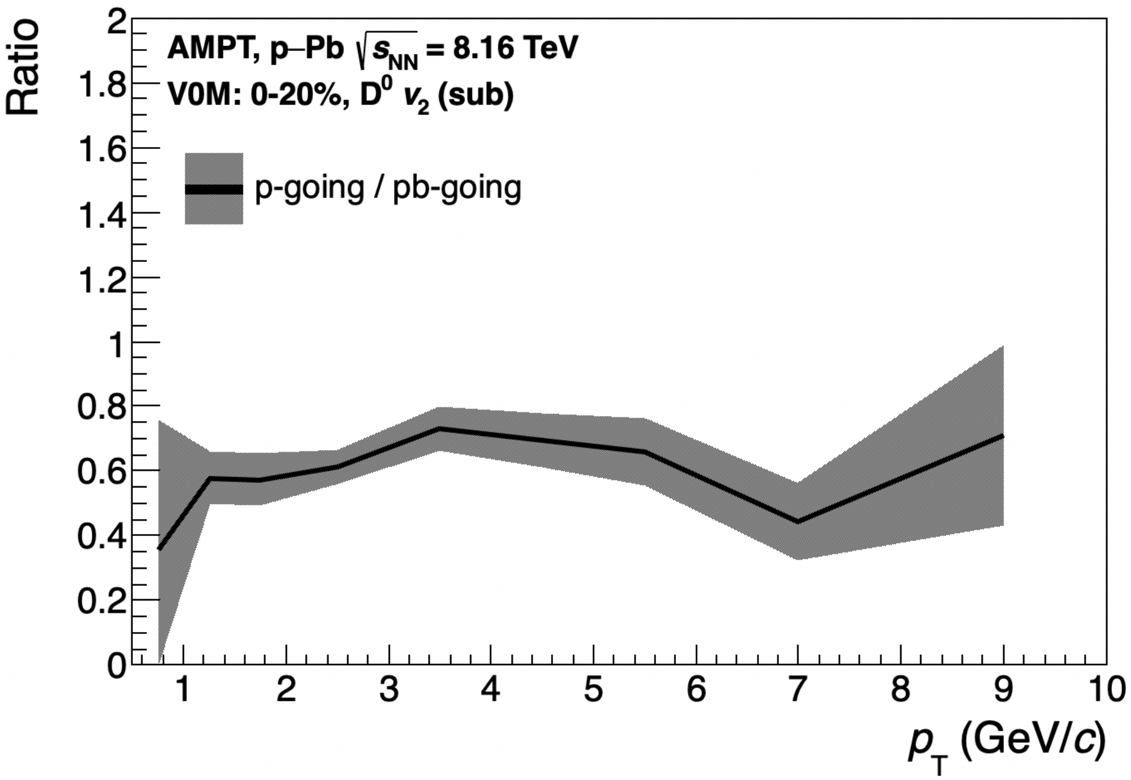
- For comparison, $\langle k_T^2\rangle$ (in GeV^2) at 5.02TeV for minimum-bias collisions:

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

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

Back up





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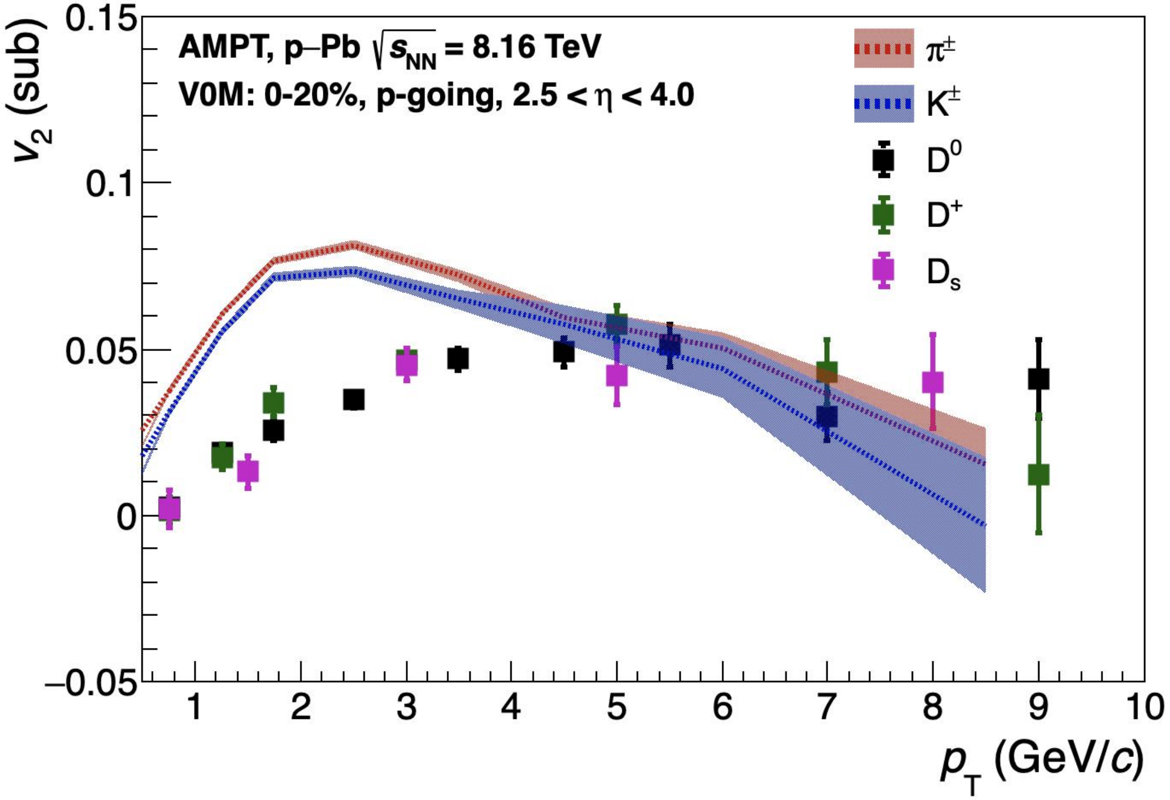
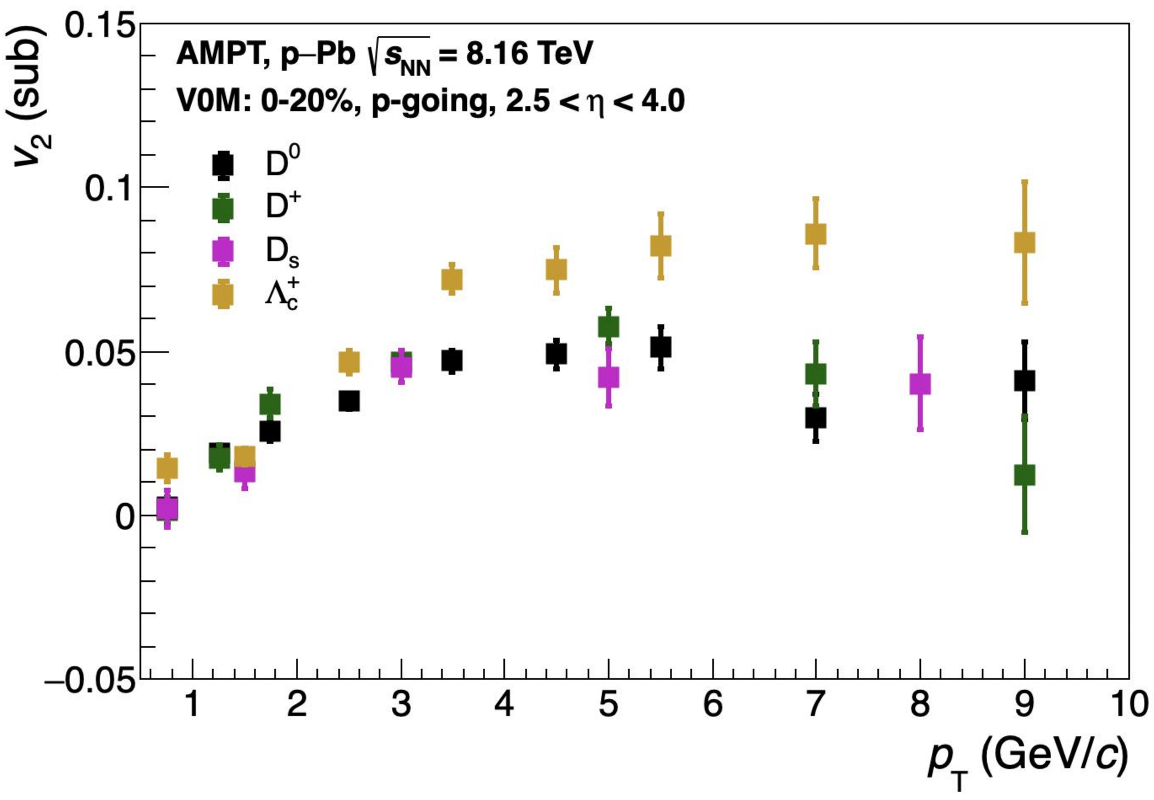
Back up





- Predictions for v_2 of charm mesons and baryons are provided
  - Consistent v_2 of charm mesons (D^0, D^+, D_s) is obtained, which are lower than the light meson v_2 ⟷ similar findings at the mid-rapidity
  - Baryon-meson grouping for charm hadrons is observed for $p_T > 3$ GeV/c

Need to be constrained by data!