Elliptic anisotropy of hard probes from parton scatterings in small collision systems

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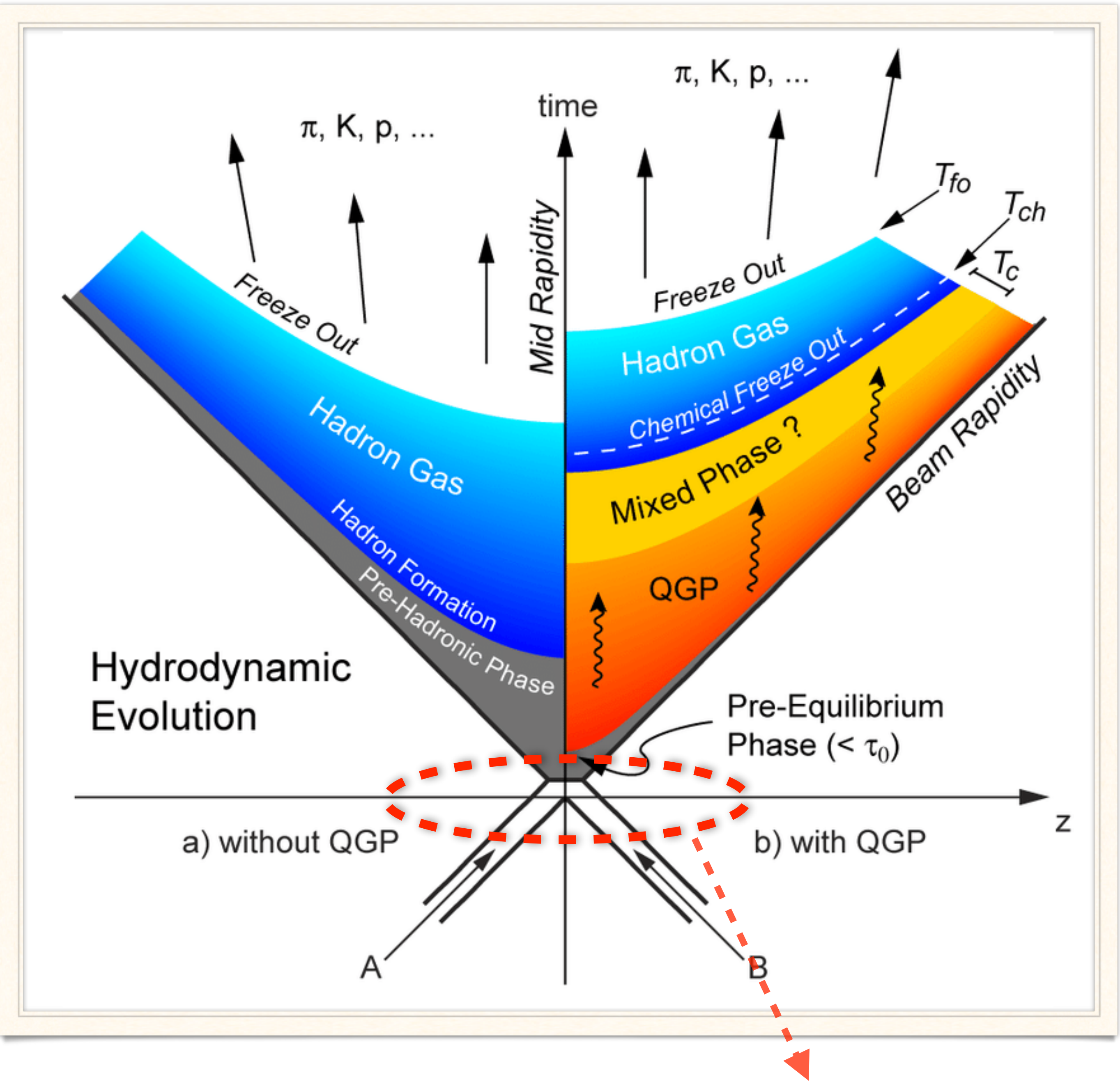
Based on: 2303.06577, 2210.07767 and ongoing work with:

Chao Zhang (张潮), Renzhuo Wan (万仁卓), Zi-wei Lin (林子威)

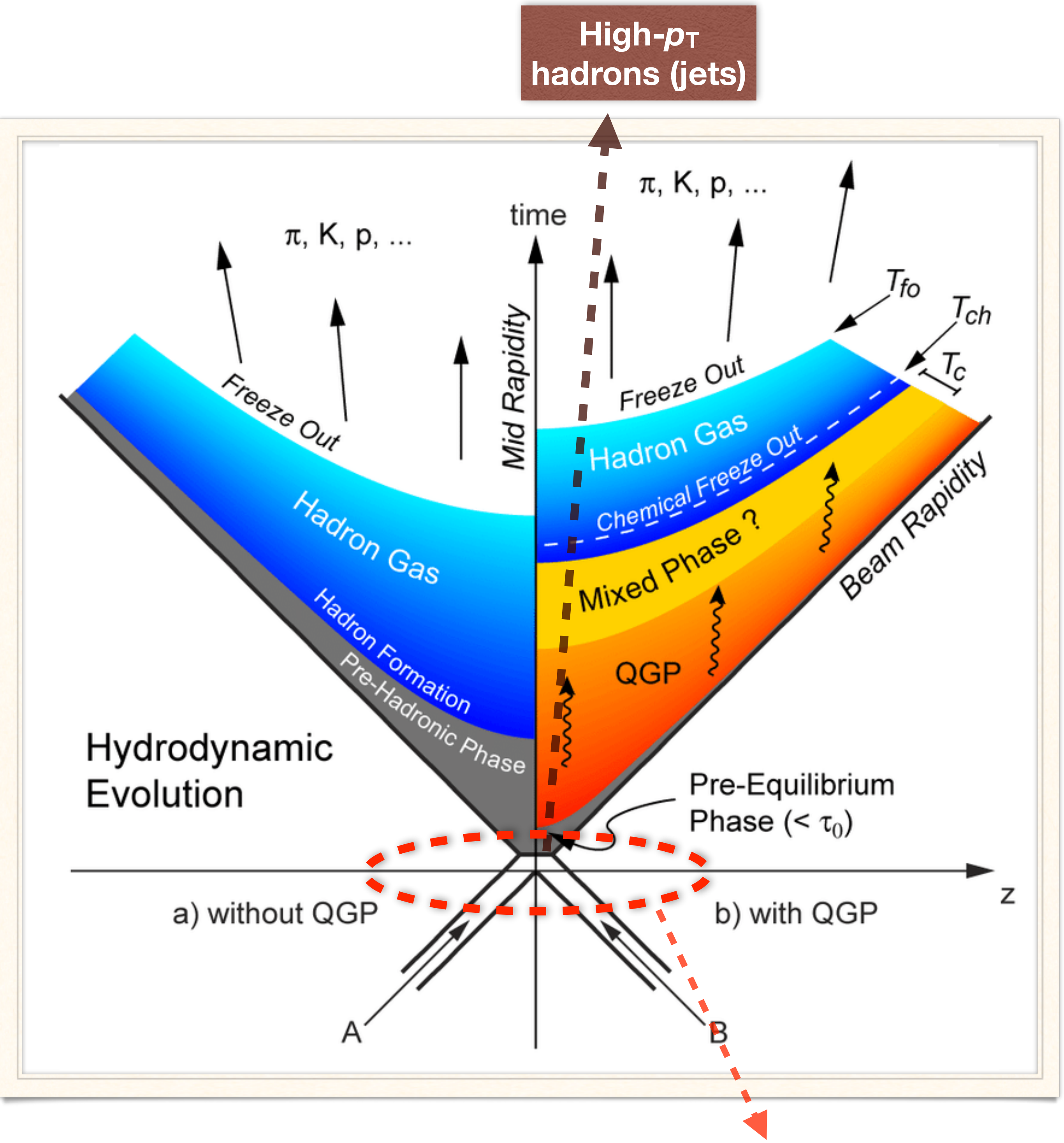
Hard probes in heavy-ion collisions



Hard scattering

- **Hard probes:** originate from hard scatterings with high Q^2
  - Penetrating probes created before the QGP is formed

Hard probes in heavy-ion collisions



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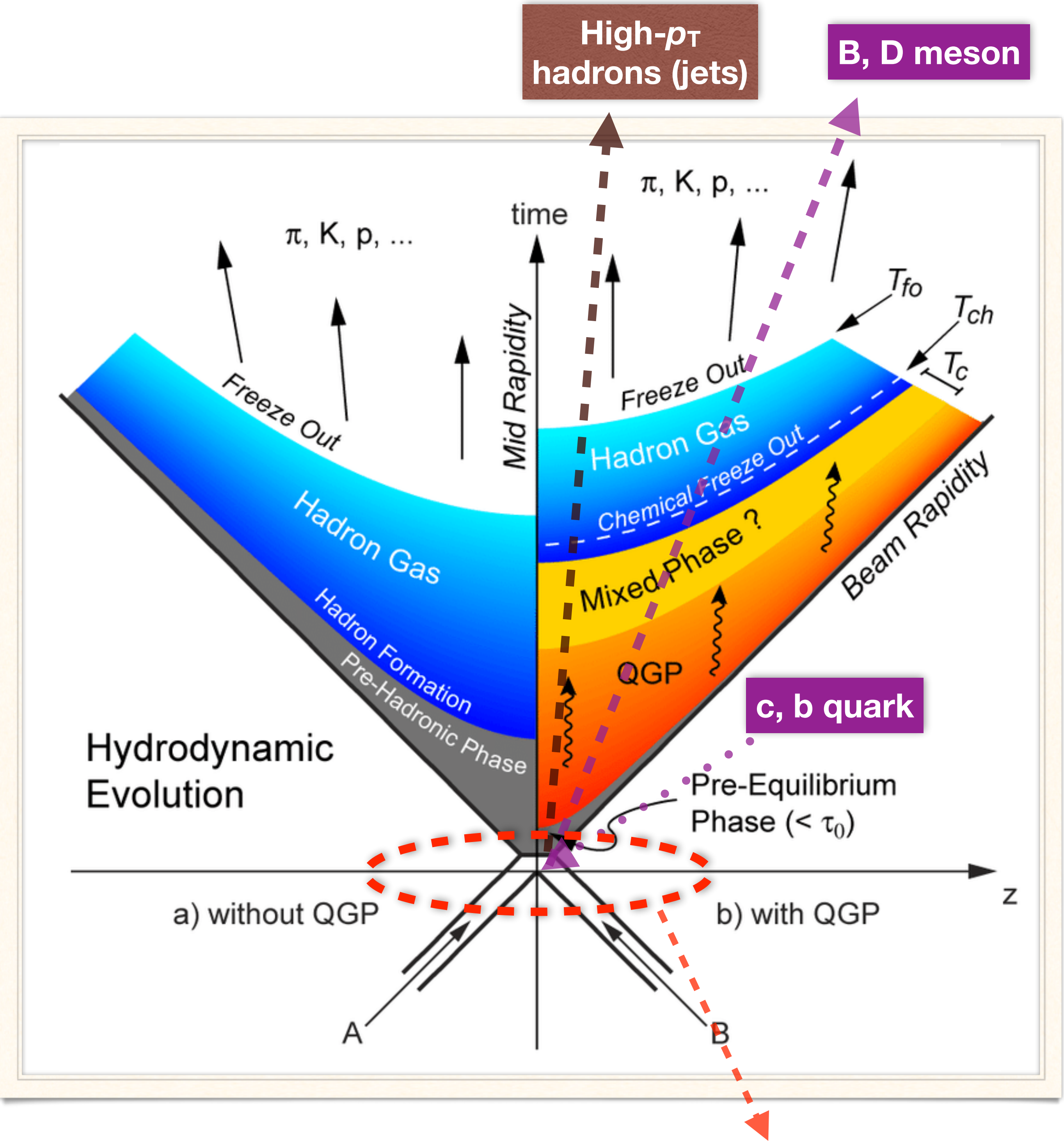

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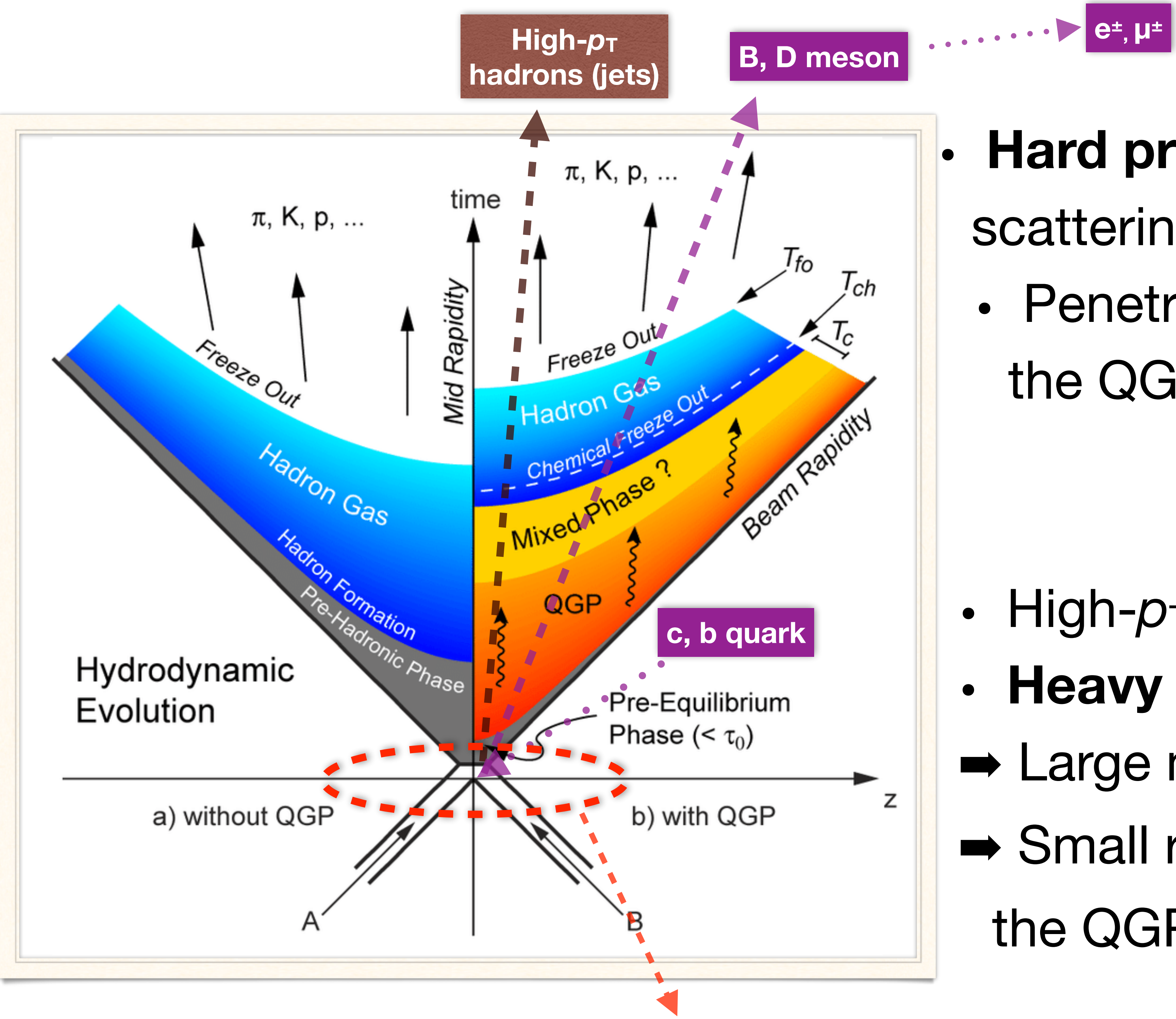
- **Heavy flavours: charm and beauty**

➡ Large mass, short formation time

➡ Small rate of thermal production in the QGP

Hard probes in heavy-ion collisions



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Azimuthal anisotropy

- The azimuthal anisotropy is studied by a Fourier expansion of azimuthal distribution of final-state particles:

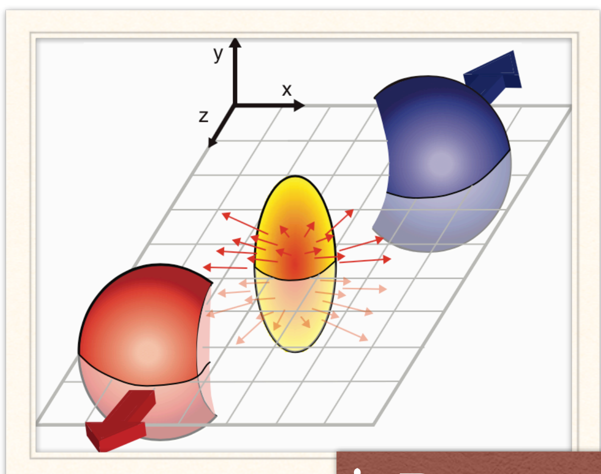
$$v_n = \langle \cos(n(\varphi - \Psi_n)) \rangle$$

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\varphi - \Psi_n)))$$

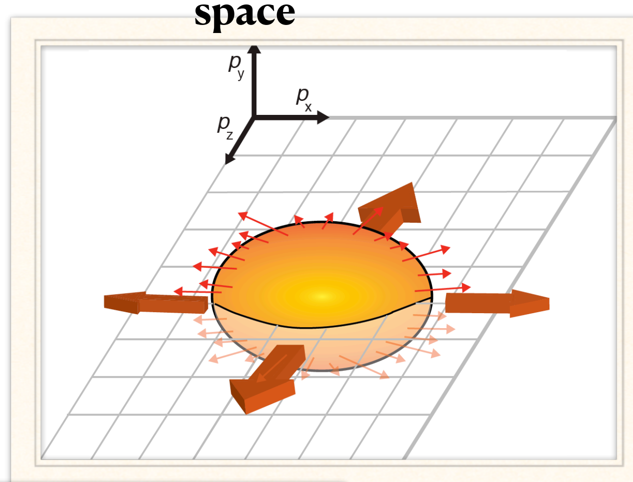
Flow coefficients

n=2, elliptic flow v_2

Initial spatial anisotropy



Final anisotropy in momentum space



* Pressure gradient
* Expansion of the QGP

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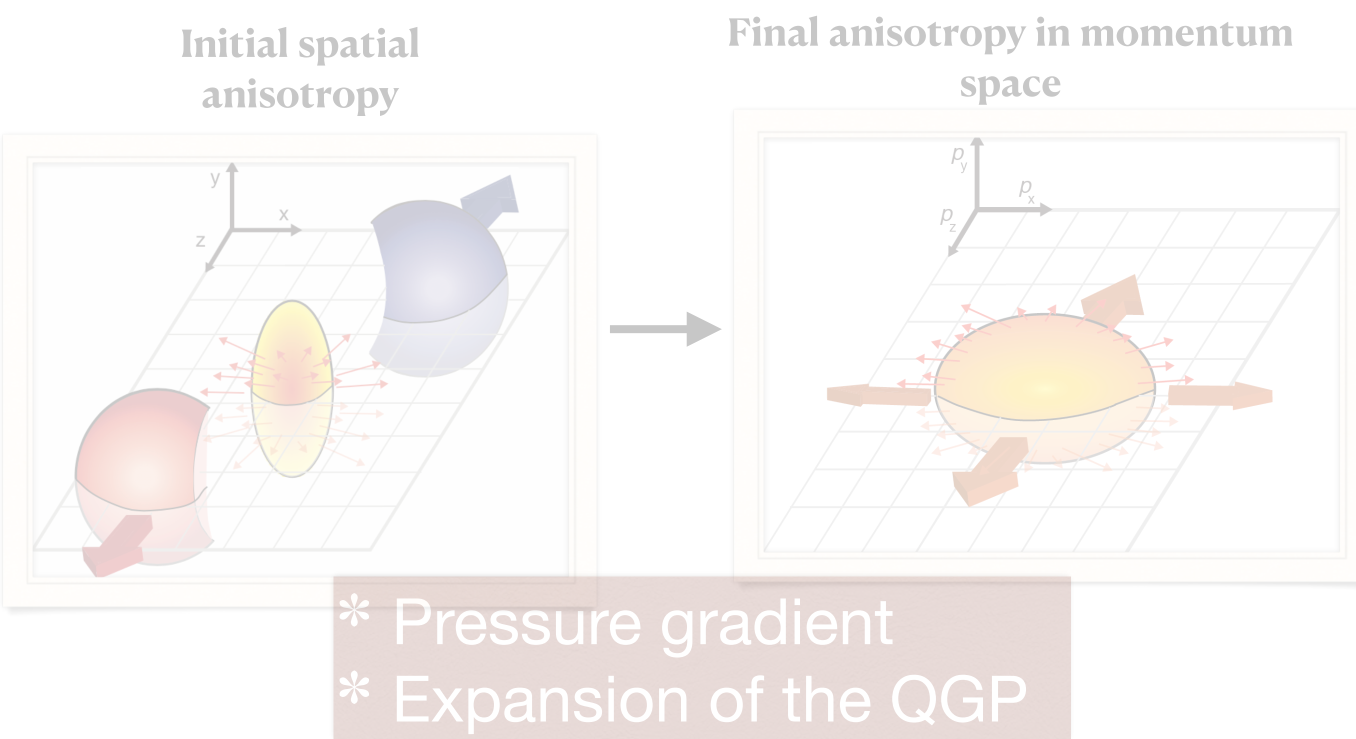
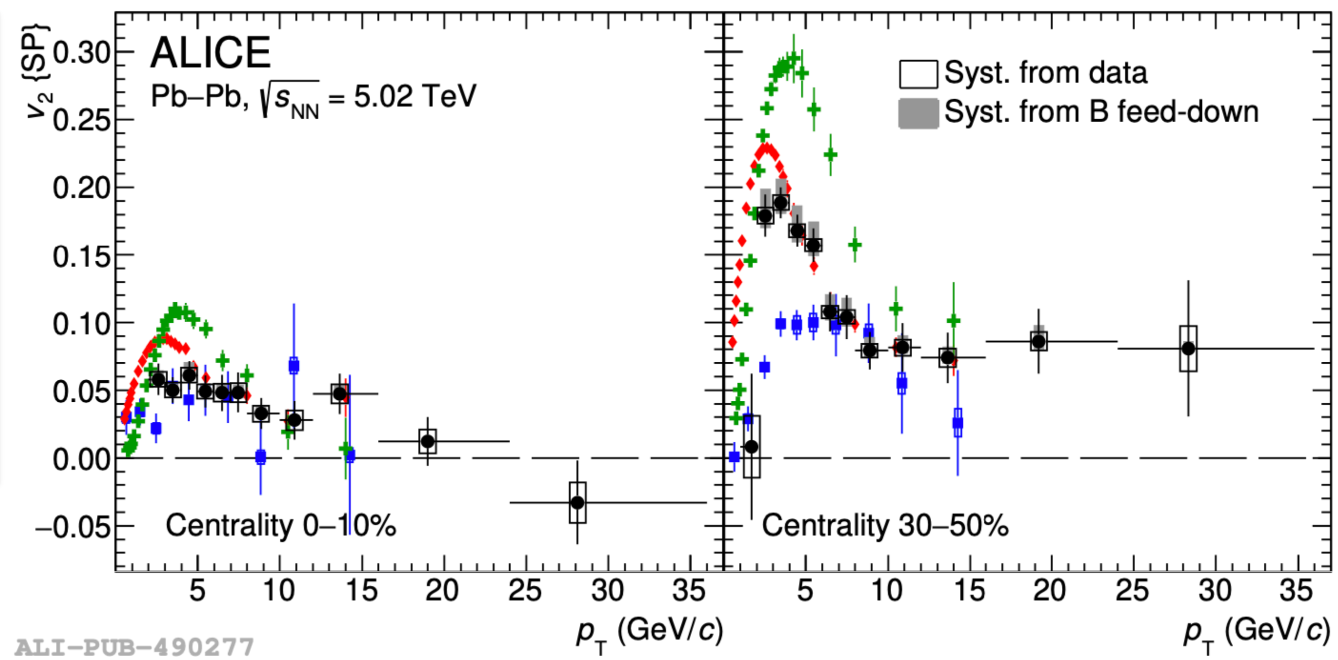


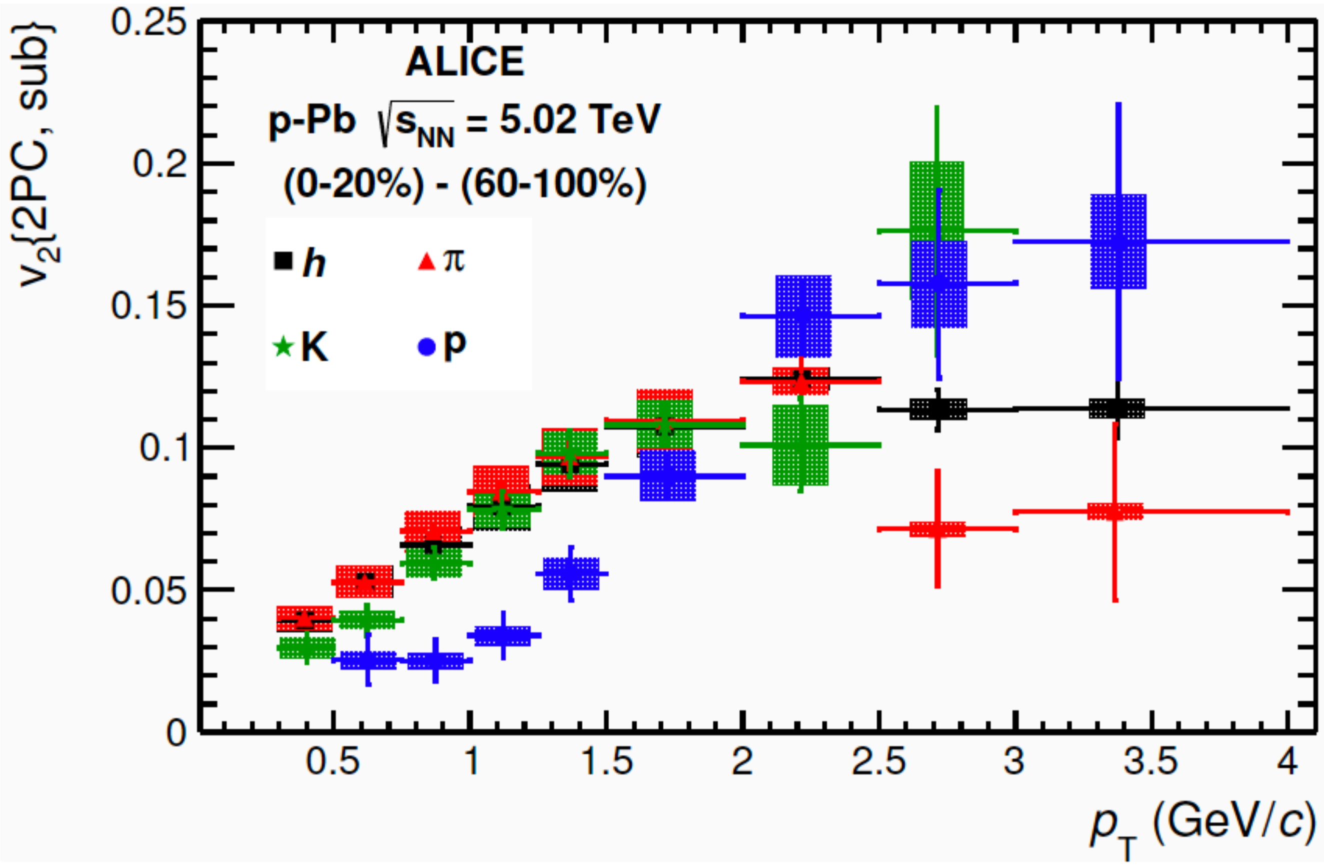
ALICE, PLB 813 (2021) 136054



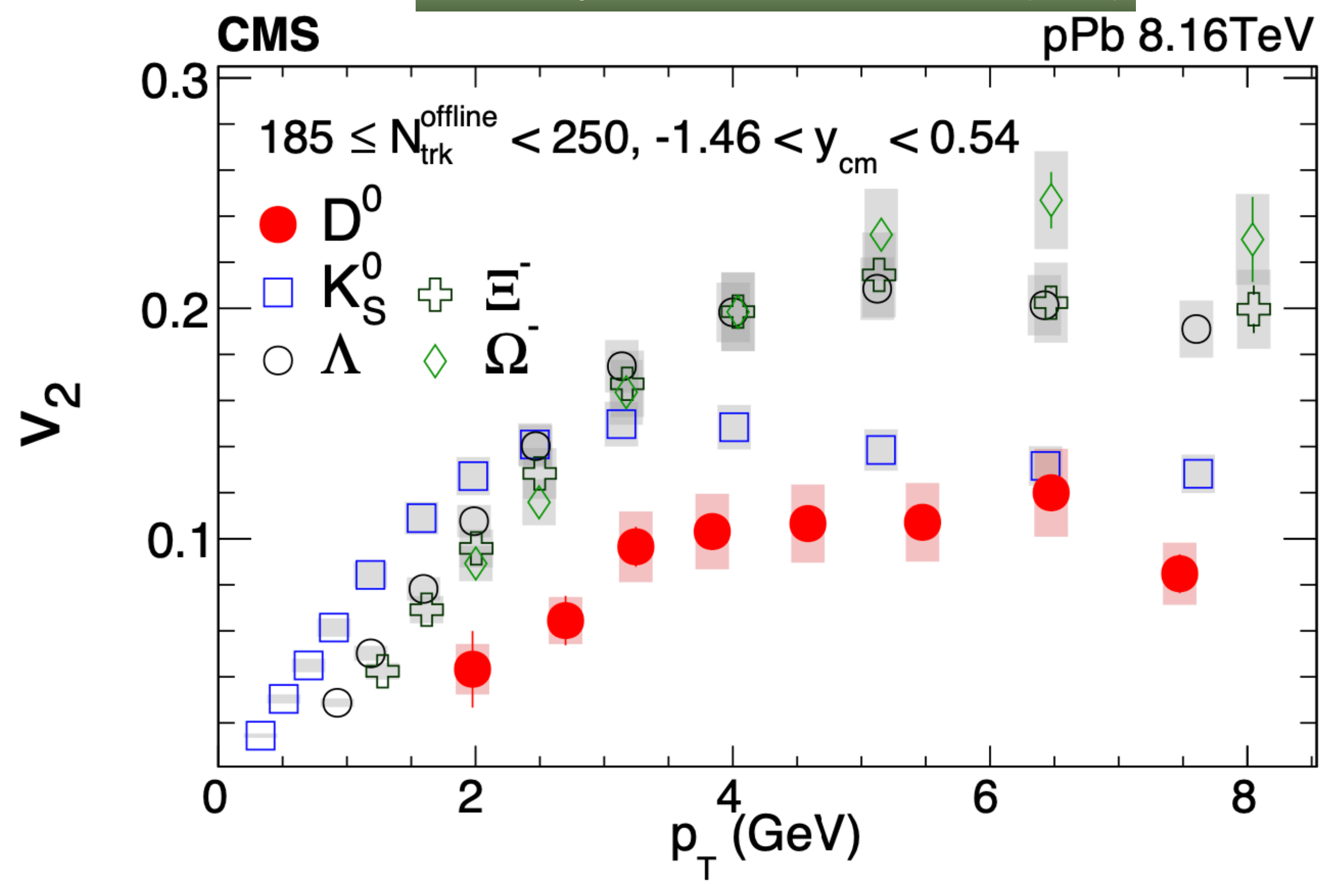
- **Open heavy flavours:**
  - Low and intermediate p_T: collective motion and properties of thermalization
  - High p_T: path-length dependence of the heavy-quark energy loss

Small collision systems

ALICE, Phys. Lett. B 726 (2013) 164–177



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



- Long-range flow-like angular correlations are observed in high-multiplicity small collision systems
  - A clear **mass ordering effect** at low p_T and **baryon-meson splitting** at intermediate p_T is observed in p–Pb even pp collisions

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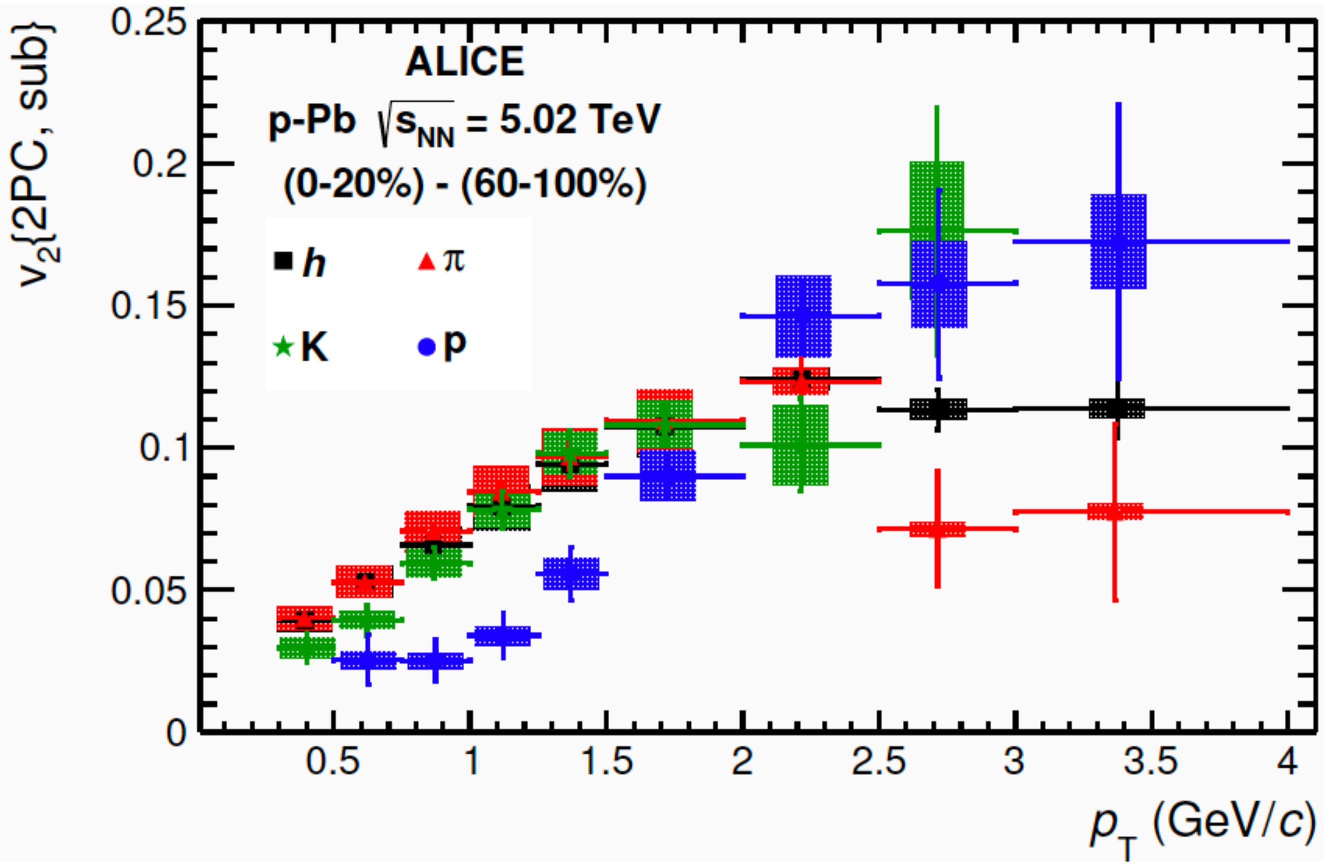

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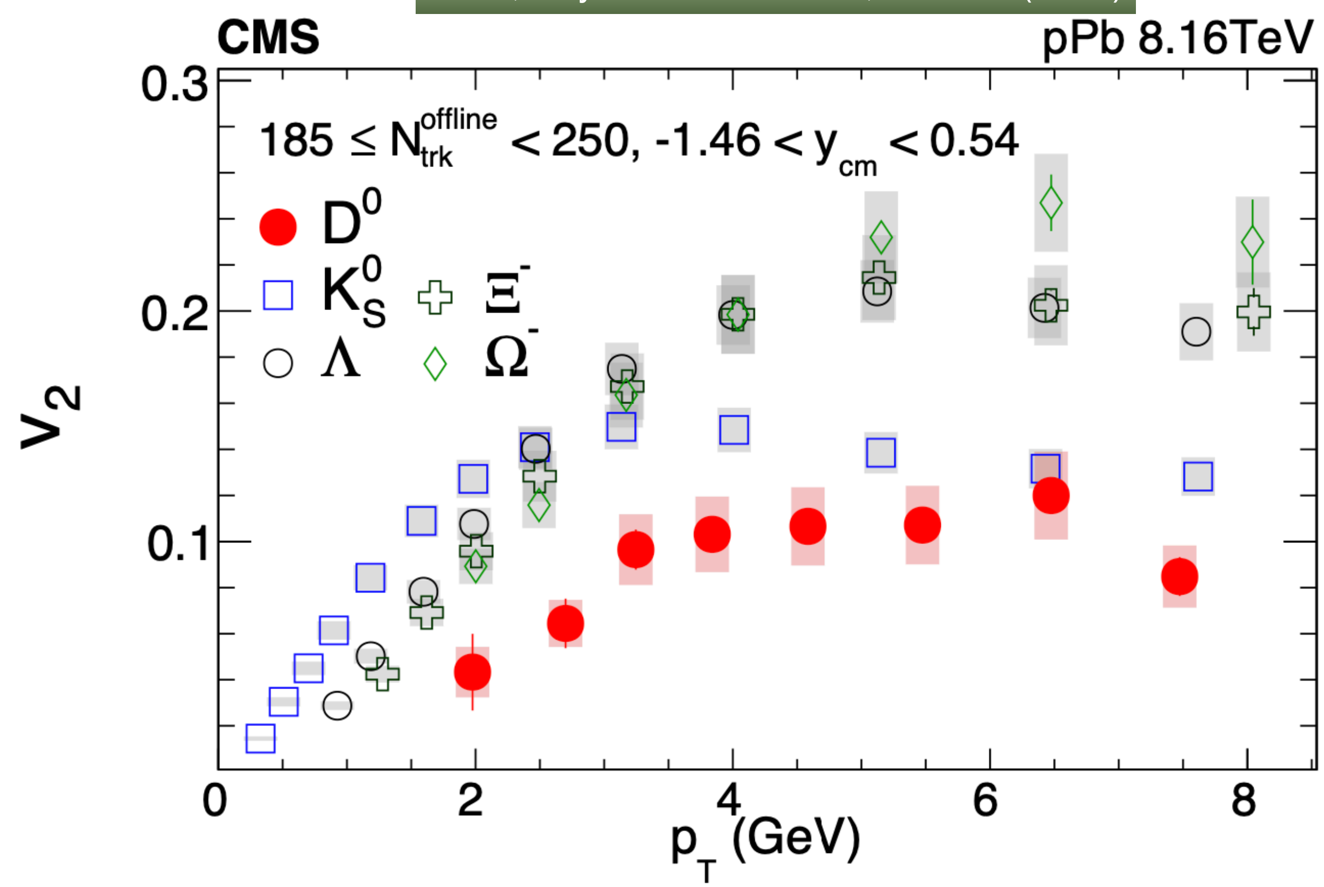

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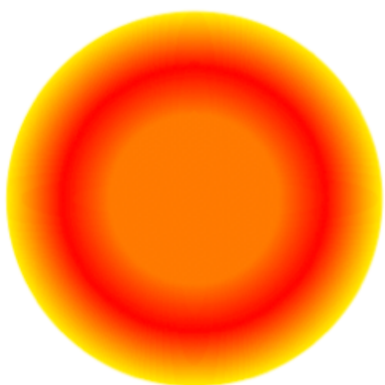
➡ hydrodynamics? initial-state effects? or other finals-state effects?

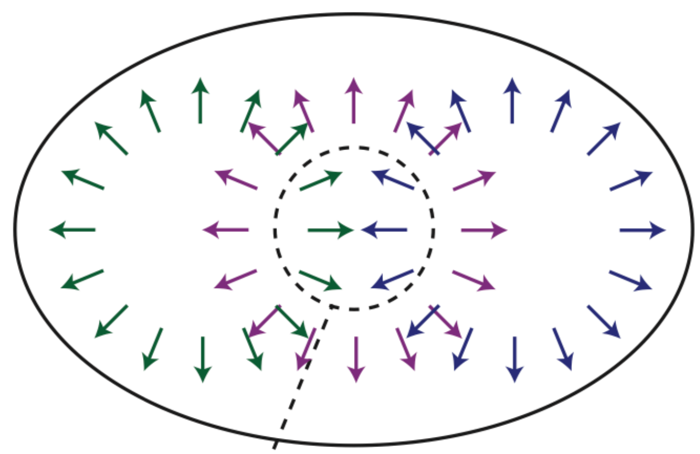
Possible Explanations

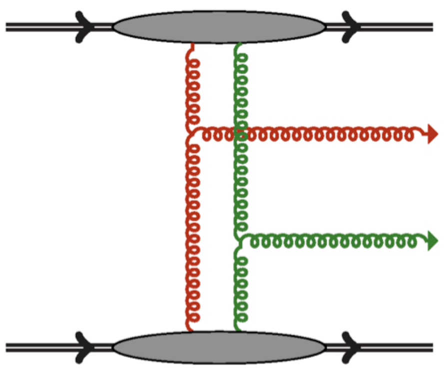
Many scatterings

Few scatterings

Initial conditions







hydrodynamics

parton escaping

Initial-momentum correlations

(Perfect) fluid dynamics

AMPT

Free streaming limit (CGC)

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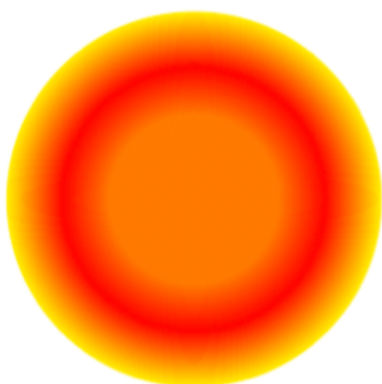

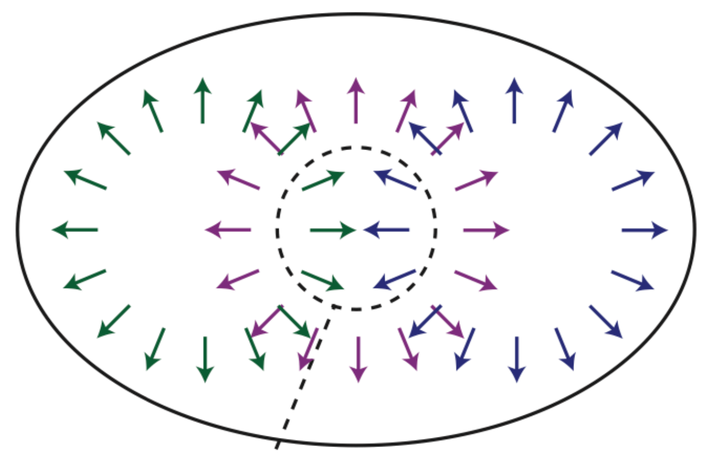

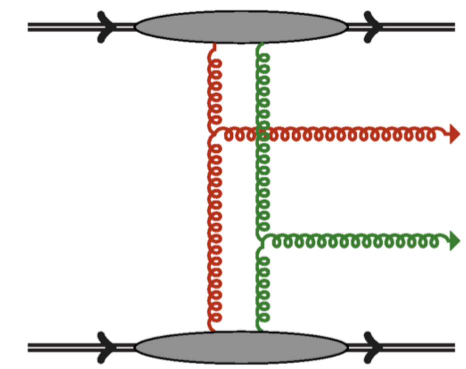

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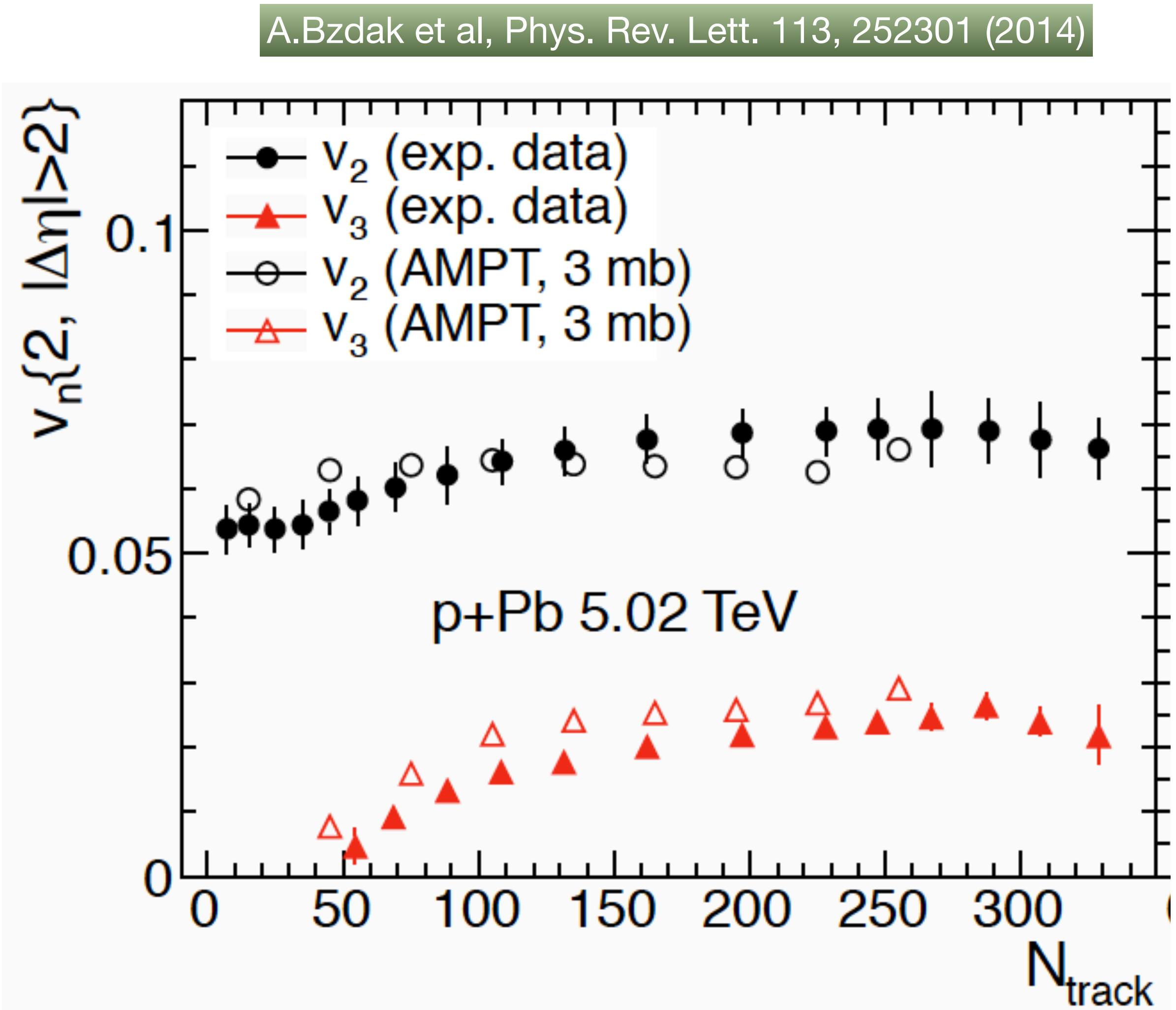
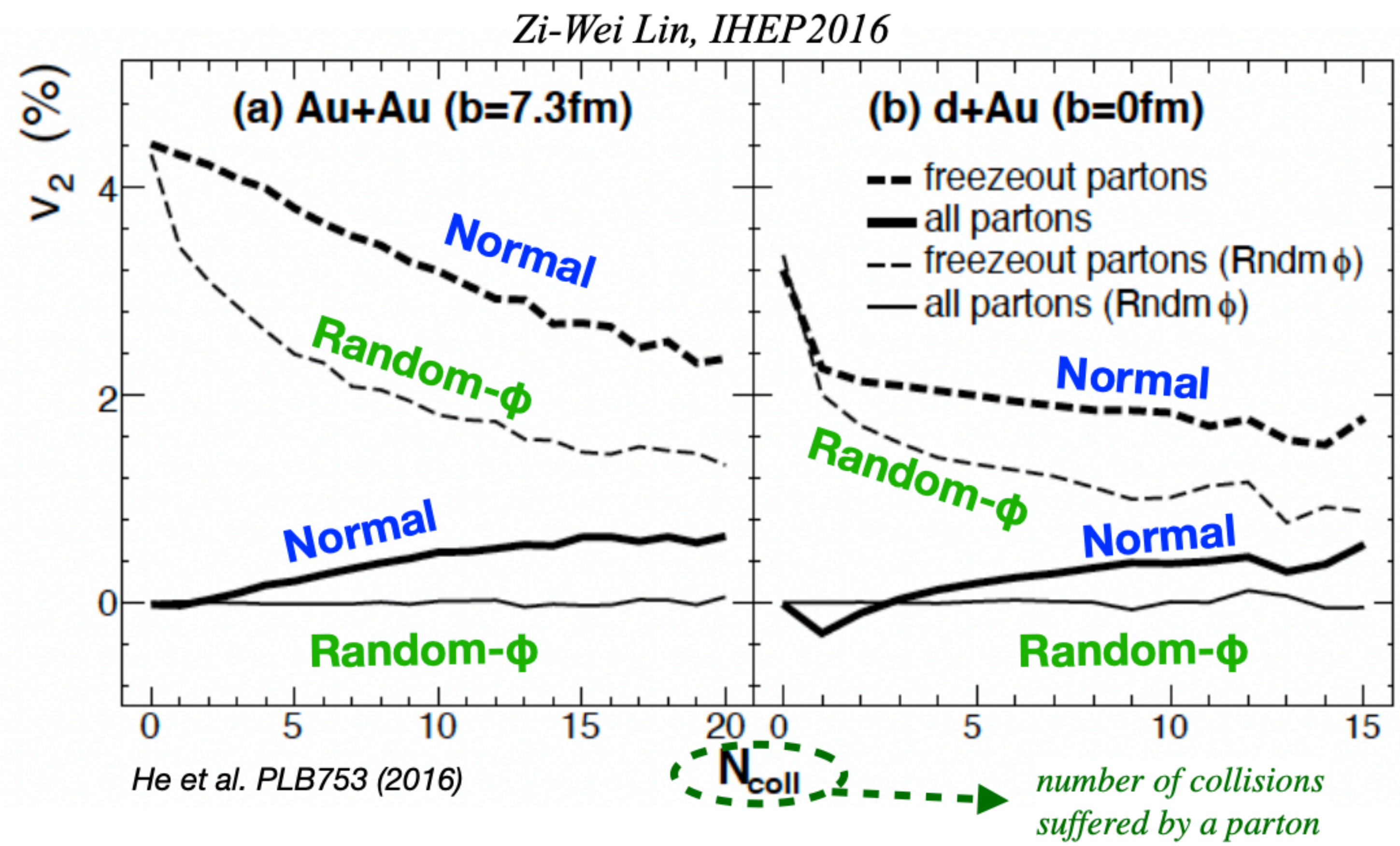
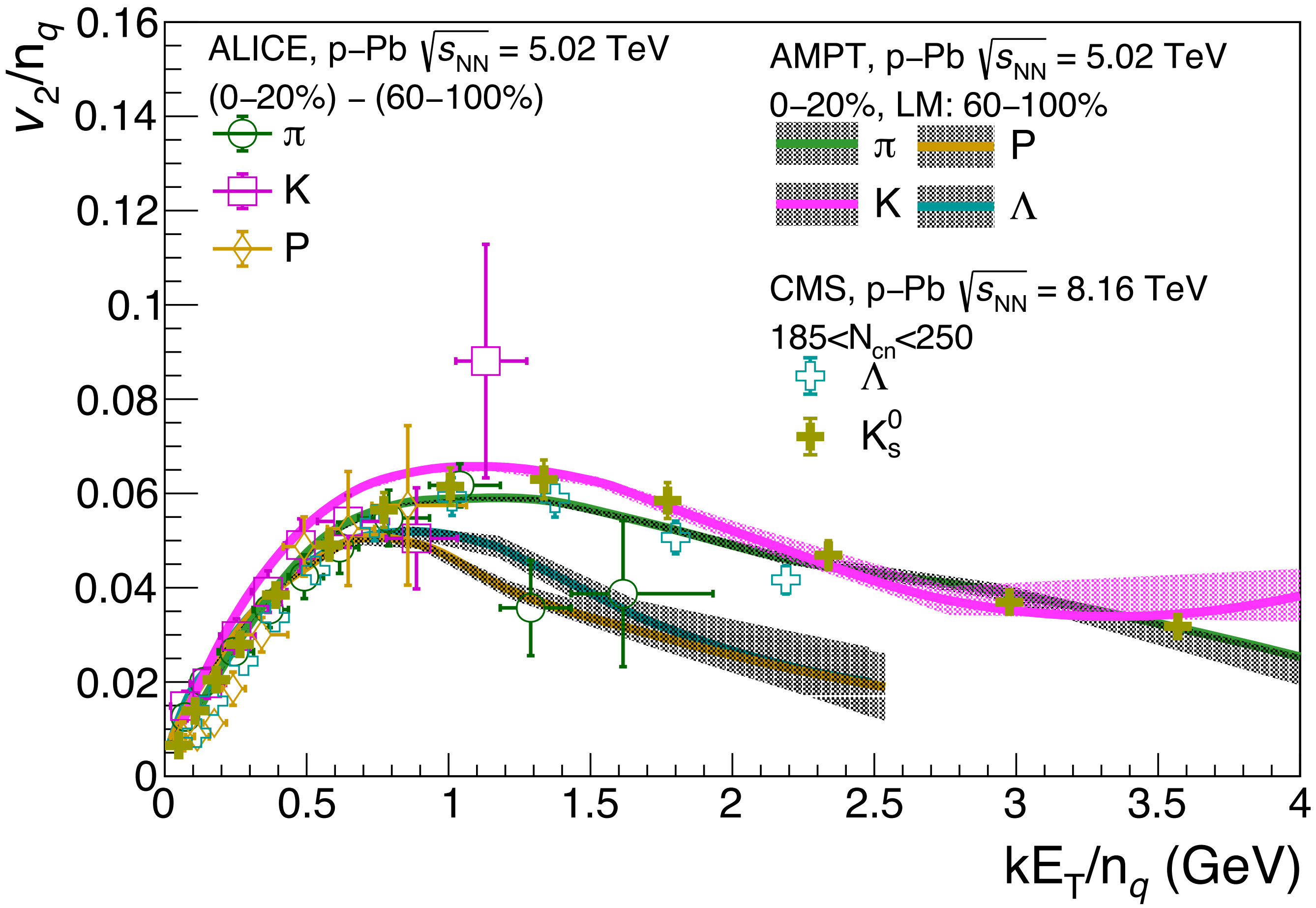


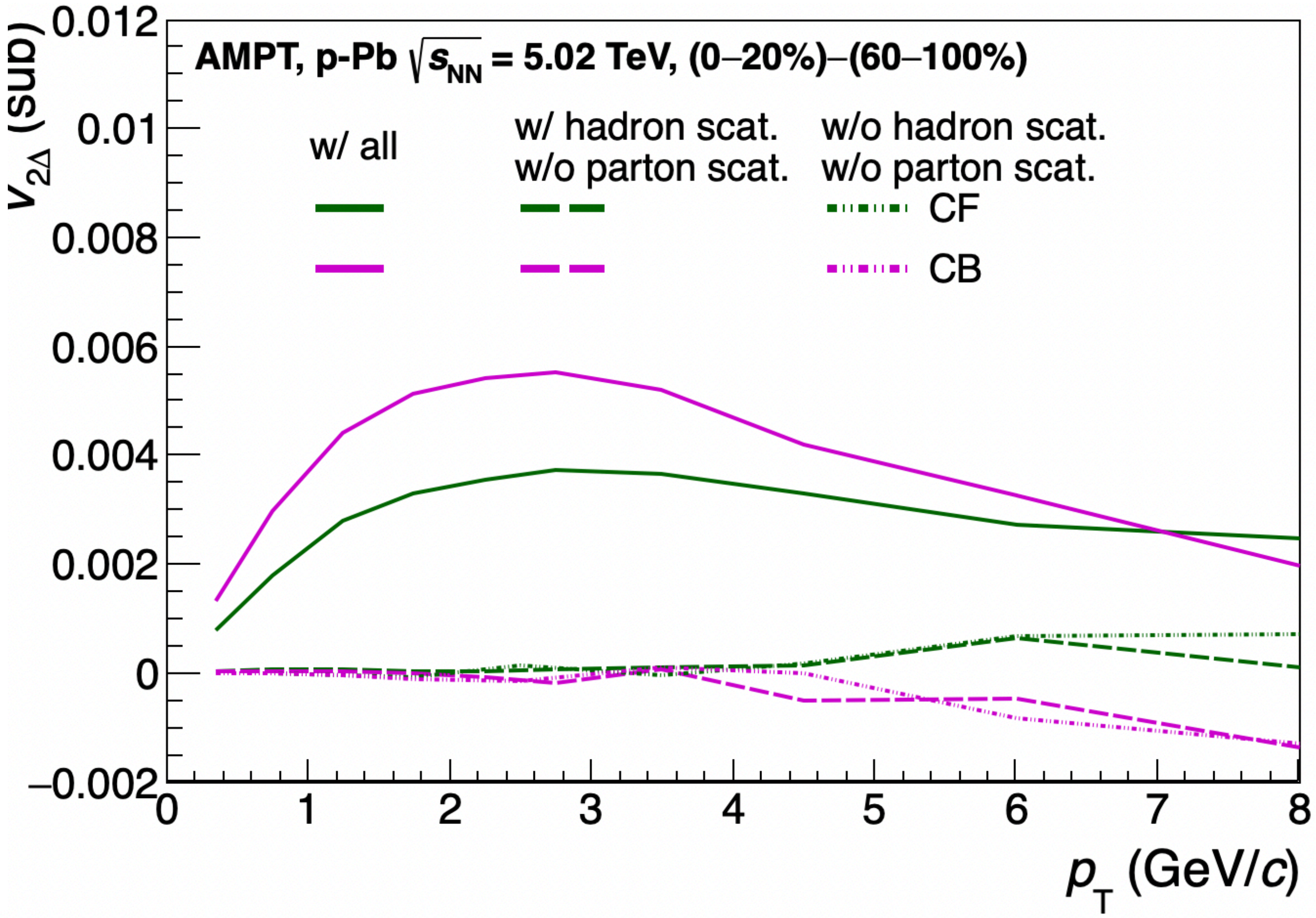


- The AMPT calculations with string melting can nicely describe the v_2 and v_3 in p-Pb collisions with a modest elastic cross section (σ = 1.5 – 3 mb)

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

Parton escaping





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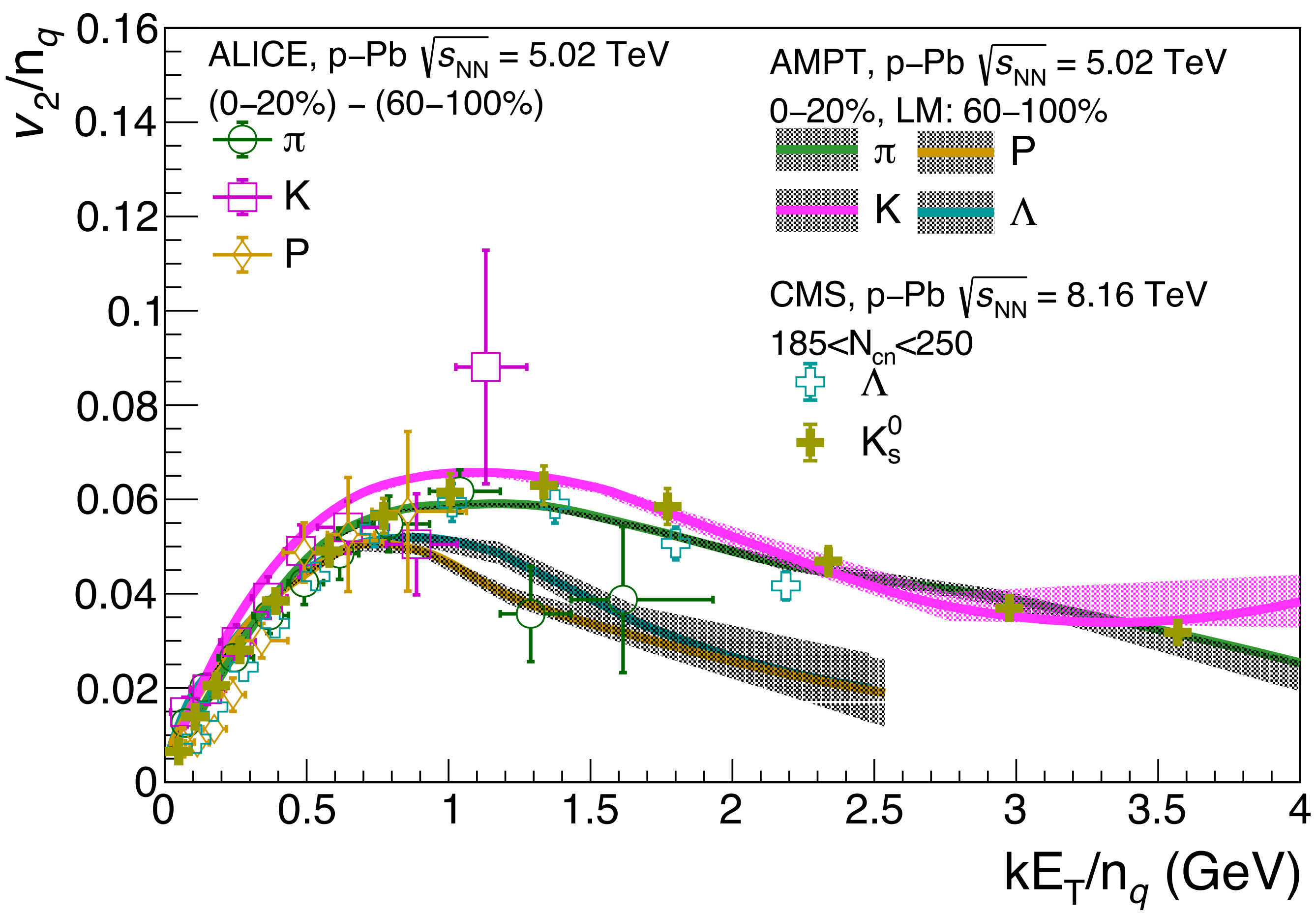

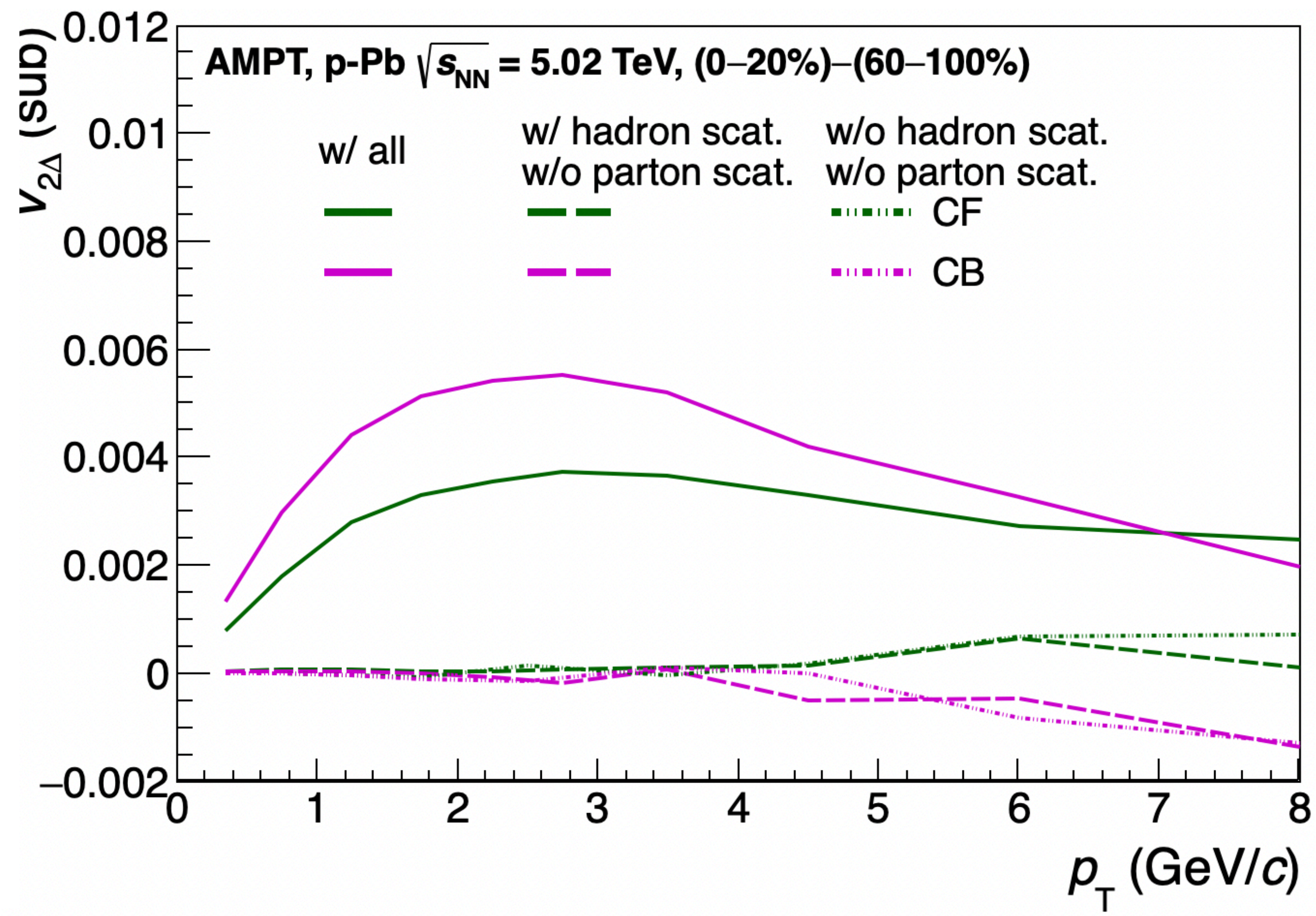

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How about the heavy flavors?

A Multi-Phase Transport (AMPT) model

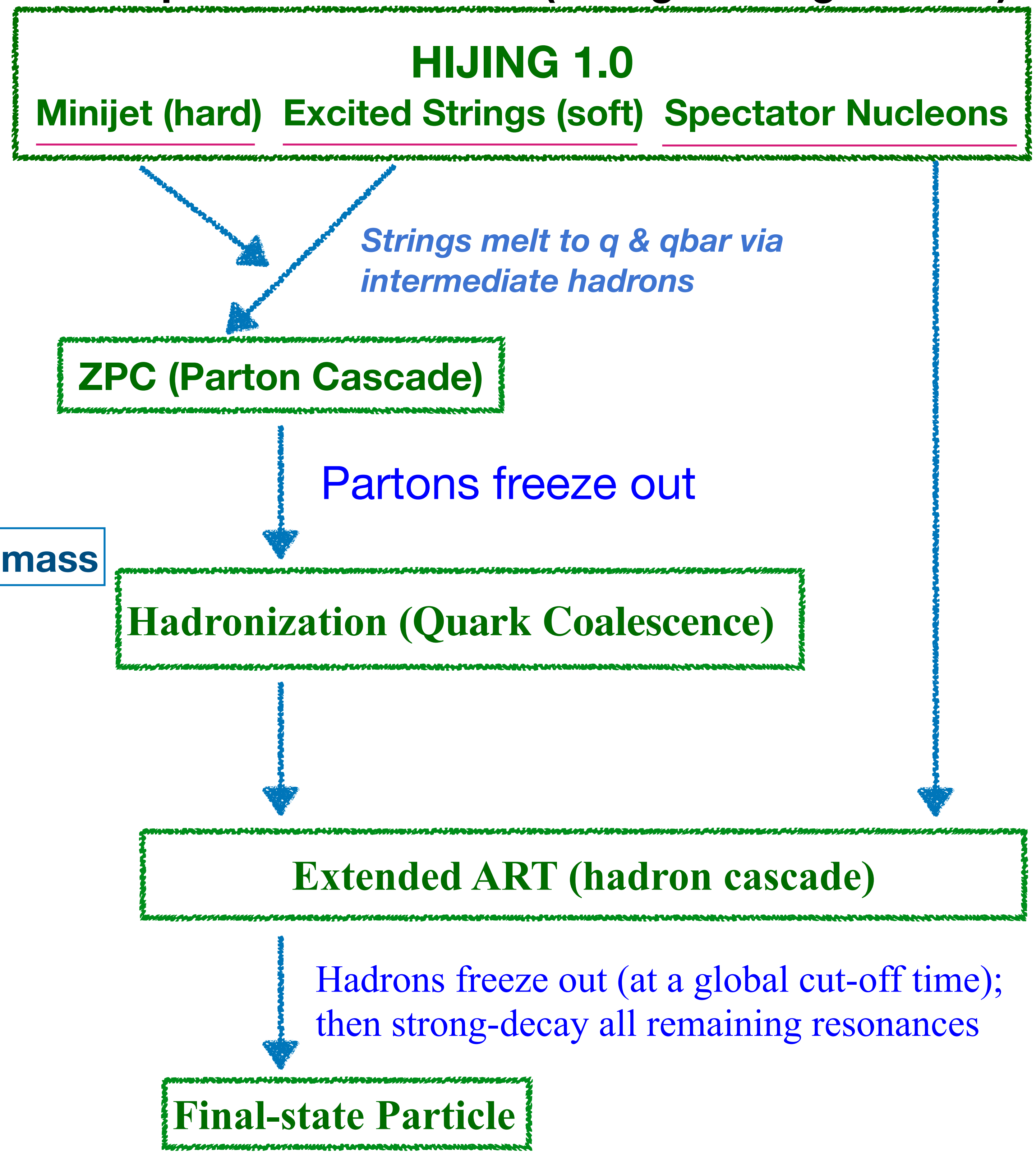
- **Initial conditions:** HIJING
- **String melting:** hadrons from string fragmentation are melted into primordial quarks and antiquarks
- **Parton cascade:** two-body elastic scattering described by ZPC model

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** **R**elativistic **T**ransport (ART) to describe hadron scatterings

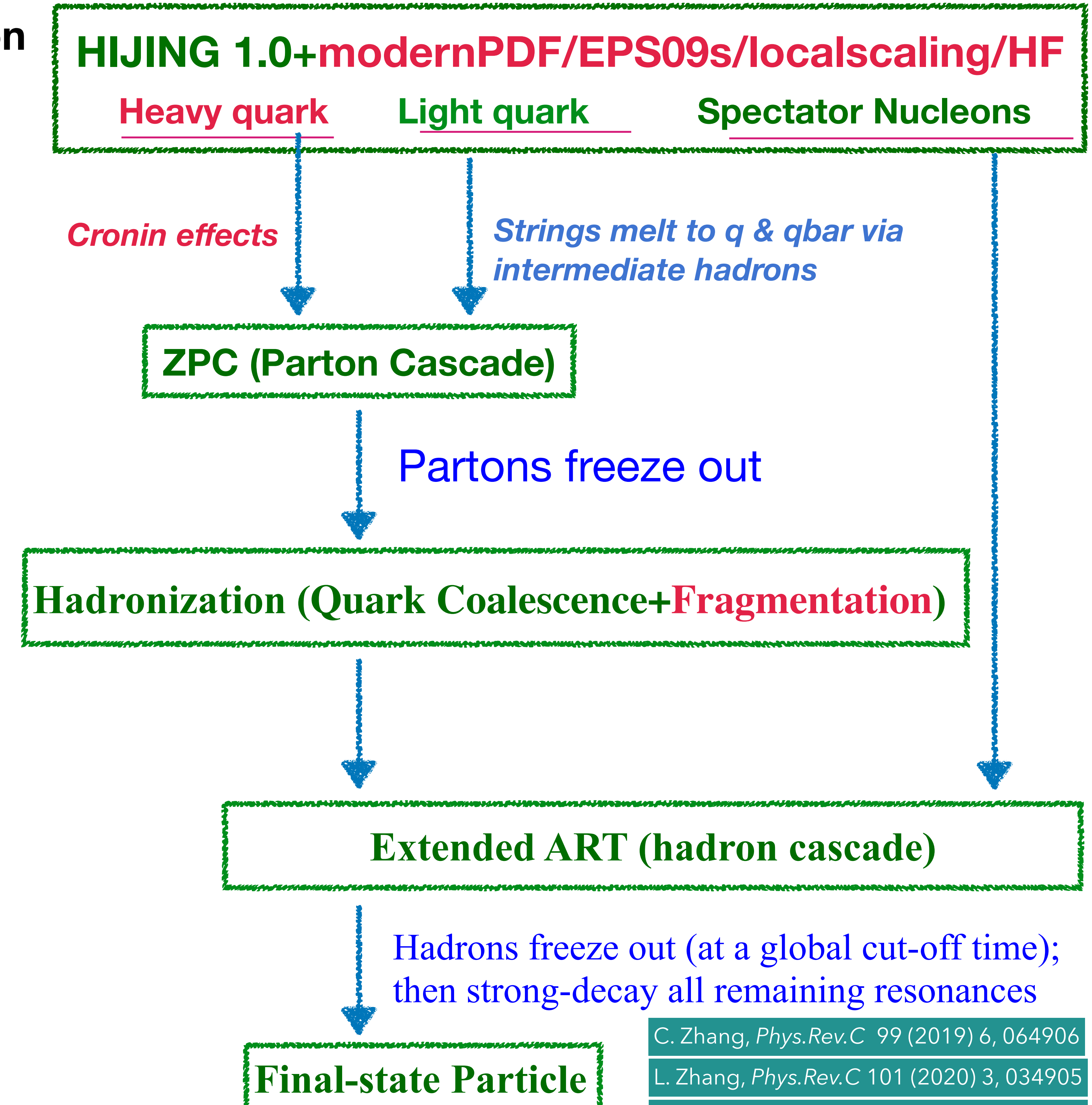
Structure of public AMPT v2.xx (String Melting Version)



Improvements for heavy flavors

- **Remove the p0 cut for the HF production**

Improved AMPT structure



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

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

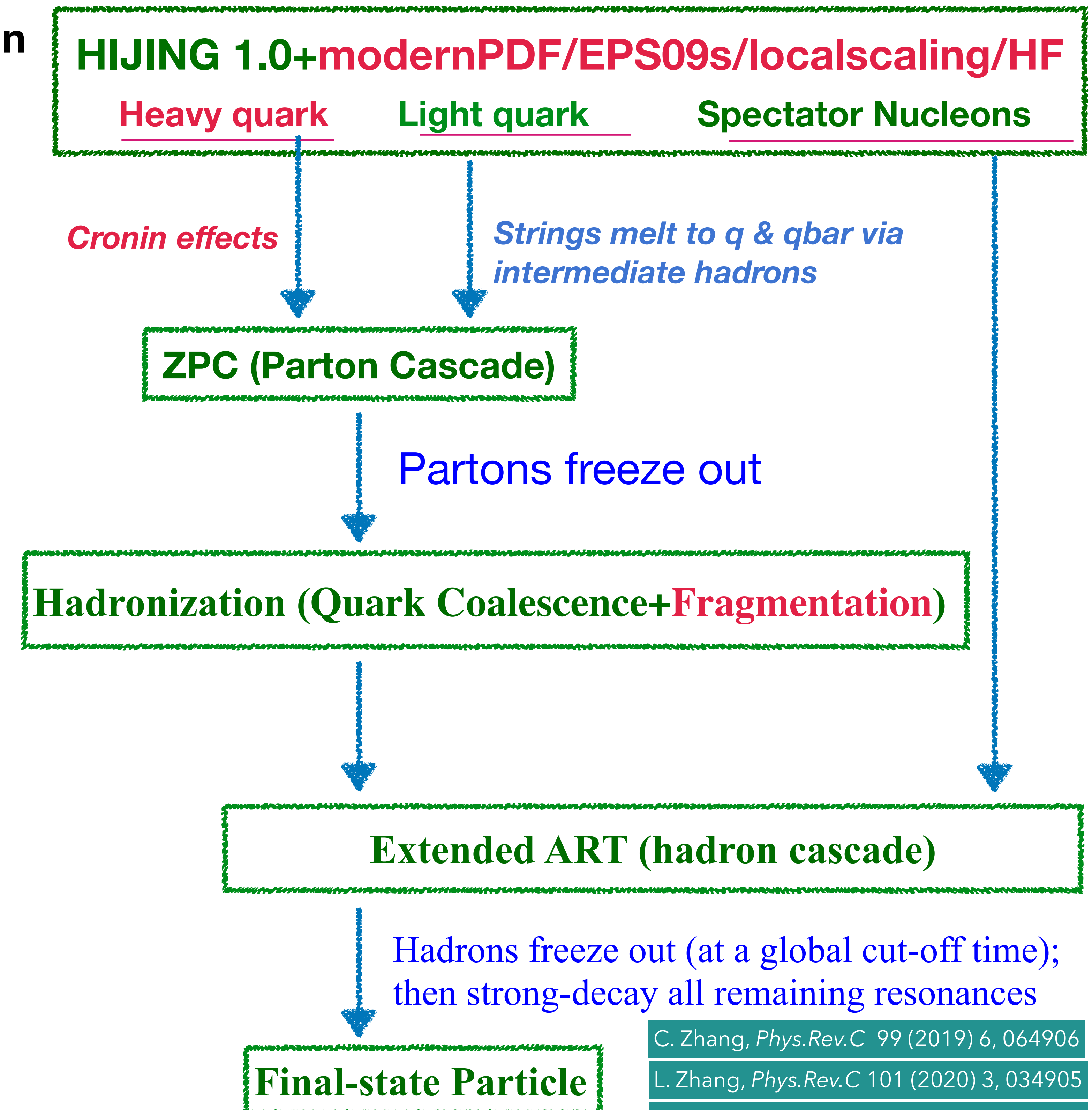
C.Zhang, *Phys.Rev.C* 104 (2021) 1, 014908

More details in Chao's poster

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.

Improved AMPT structure



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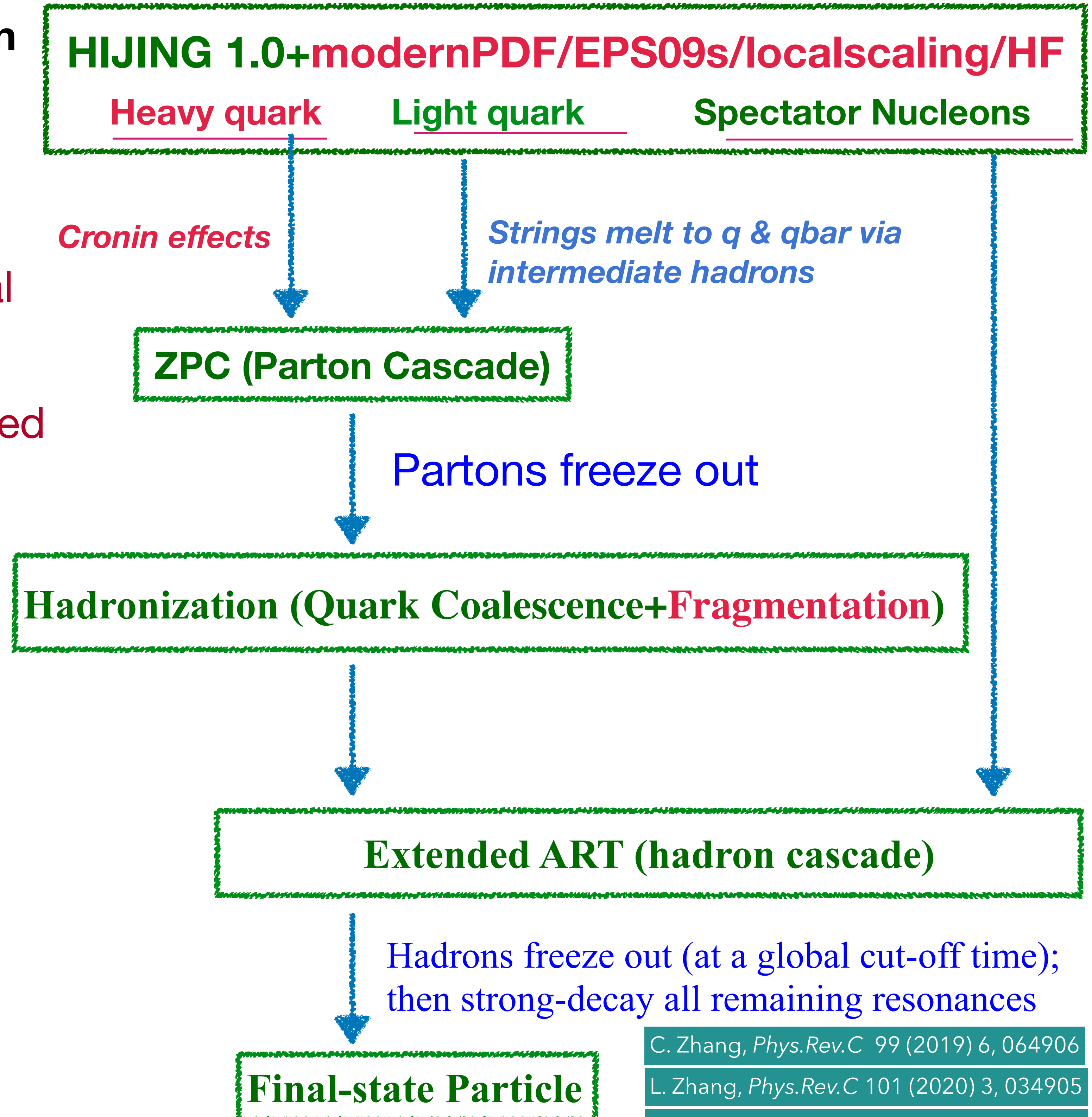
Improvements for heavy flavors

- **Remove the p0 cut for the HF production**
- **Replace the PDF and nPDF**
  - modern PDF (CTEQ6.1M) and a spatial dependence of nuclear shadowing functions (eps09s NLO) are incorporated

Improved AMPT structure



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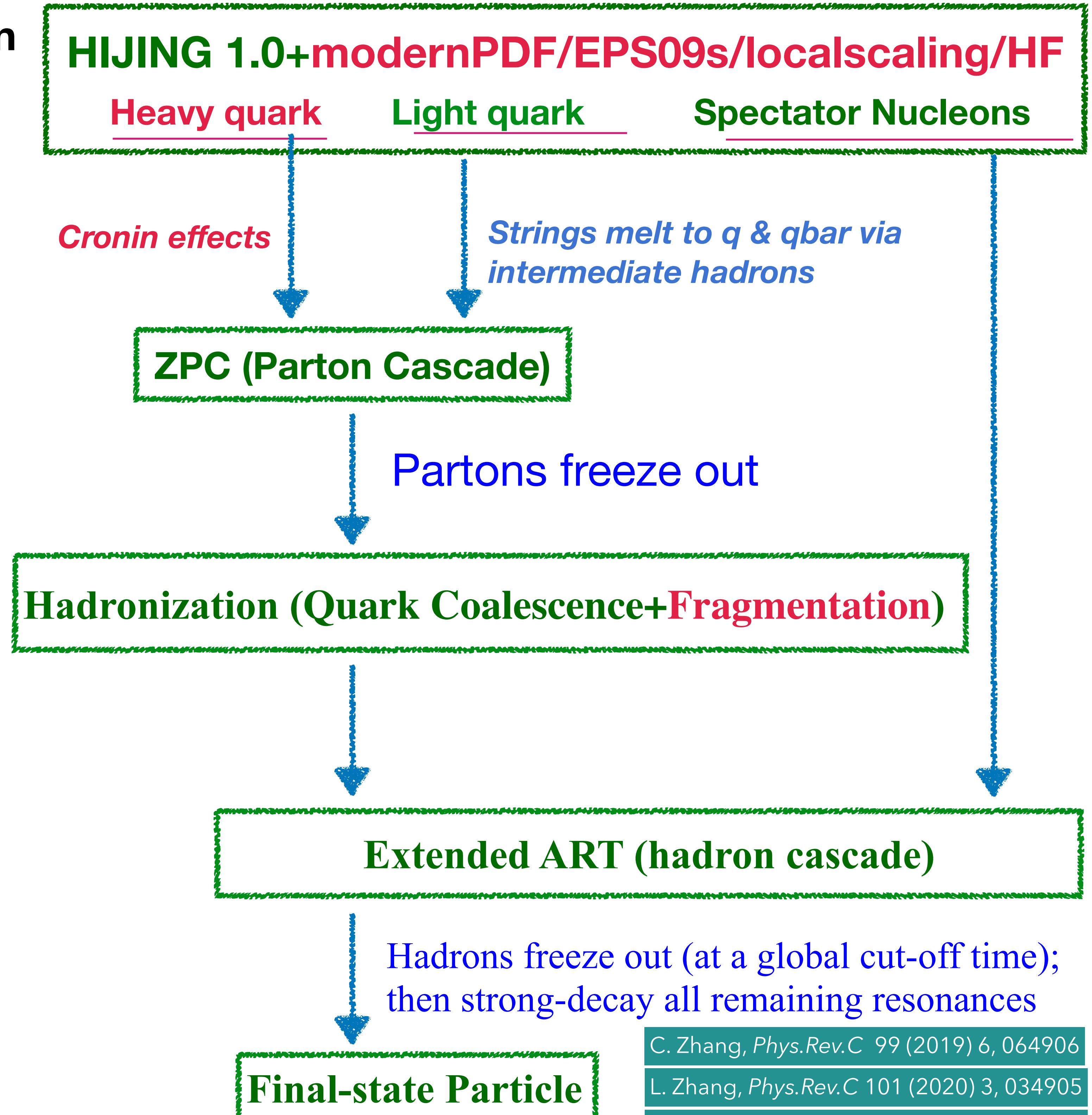
Improvements for heavy flavors

- **Remove the p0 cut for the HF production**
- **Replace the PDF and nPDF**
- **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)

Improved AMPT structure



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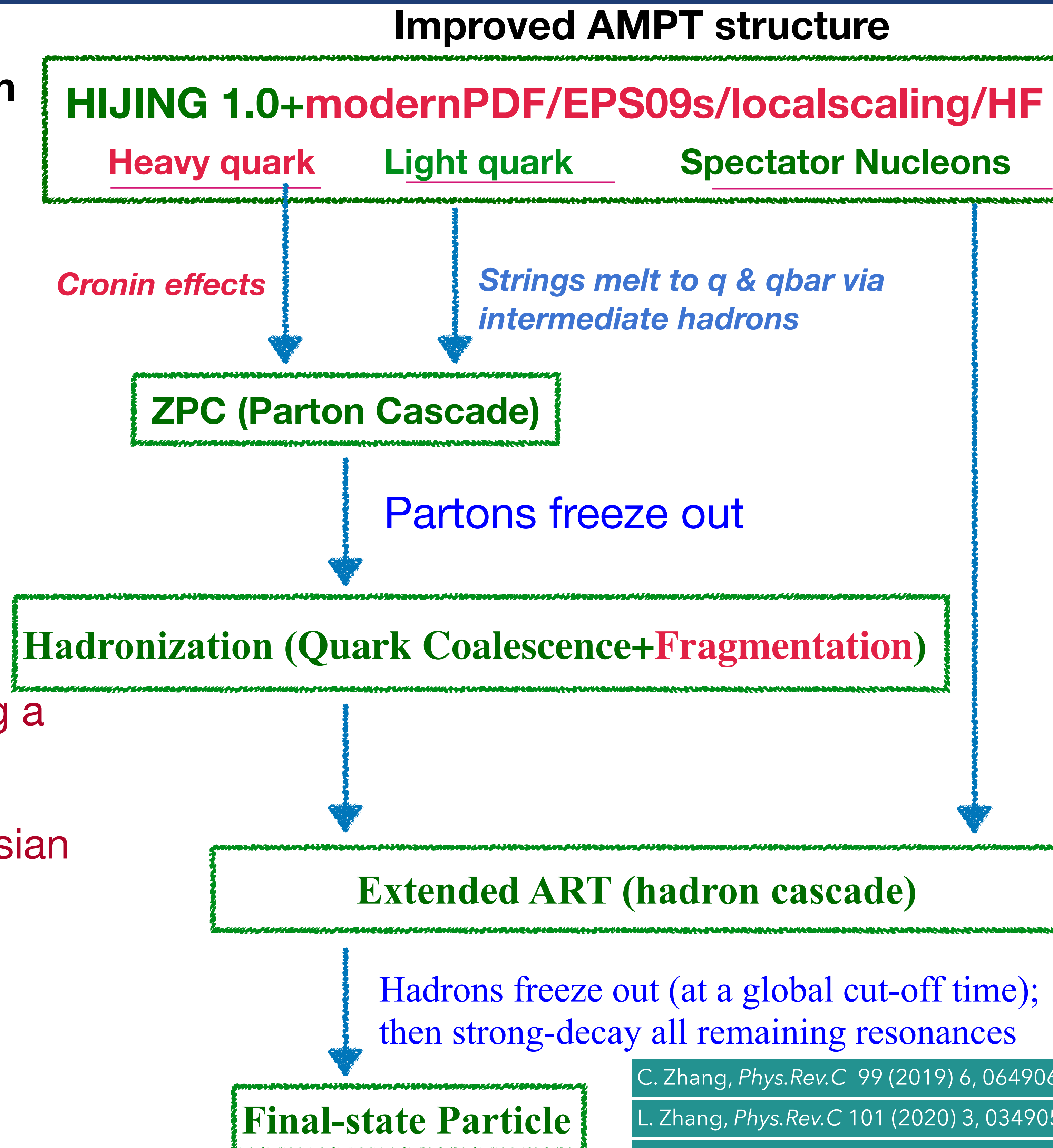
More details in Chao's poster

Improvements for heavy flavors

- **Remove the p0 cut for the HF production**
- **Replace the PDF and nPDF**
- **Local scaling for self-consistent size dependence**
- **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



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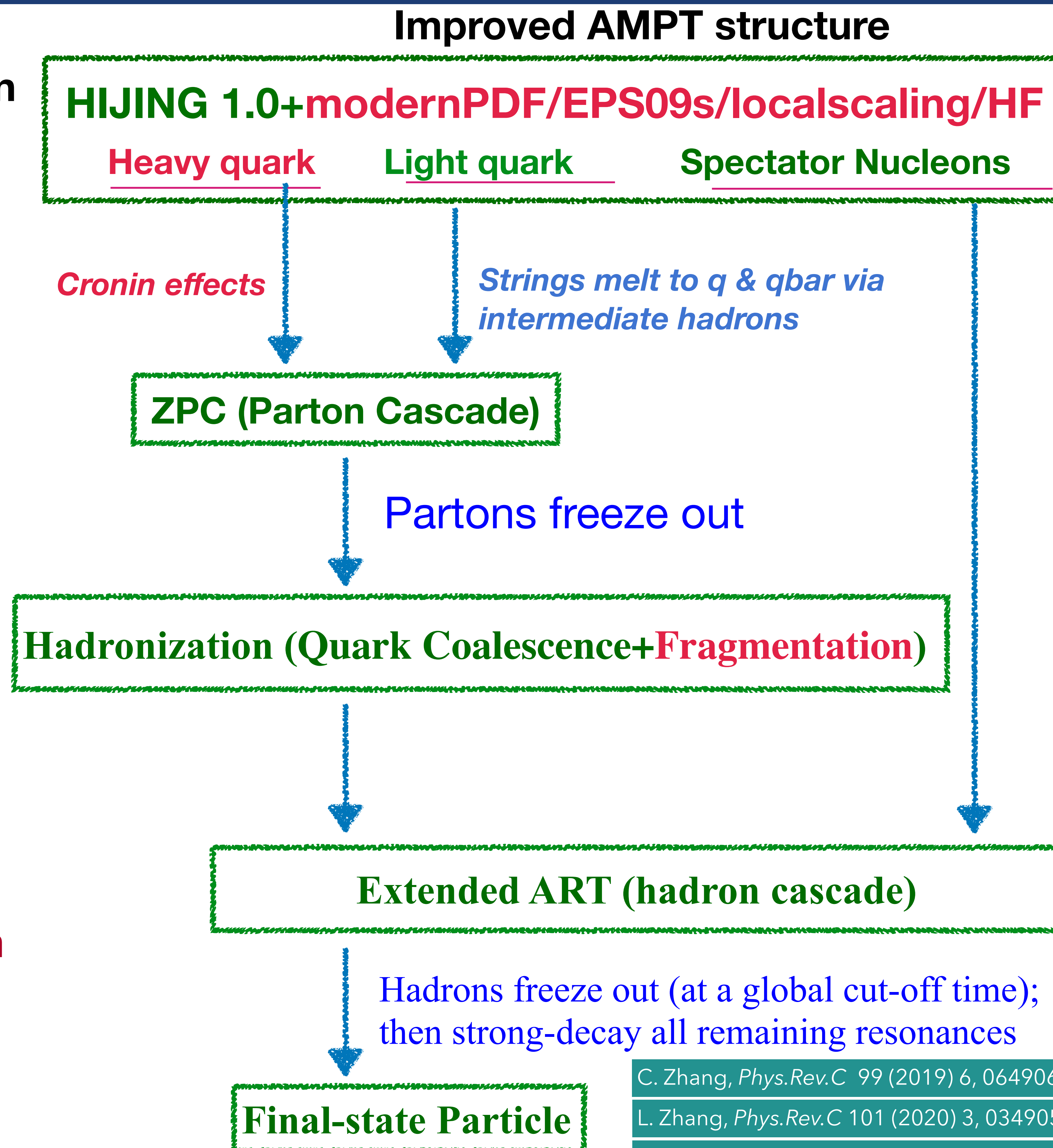
Improvements for heavy flavors

- Remove the p0 cut for the HF production
- Replace the PDF and nPDF
- Local scaling for self-consistent size dependence
- Add Cronin effect
- Add independent fragmentation
  - according to the relative distance and invariant mass of the heavy hadron system



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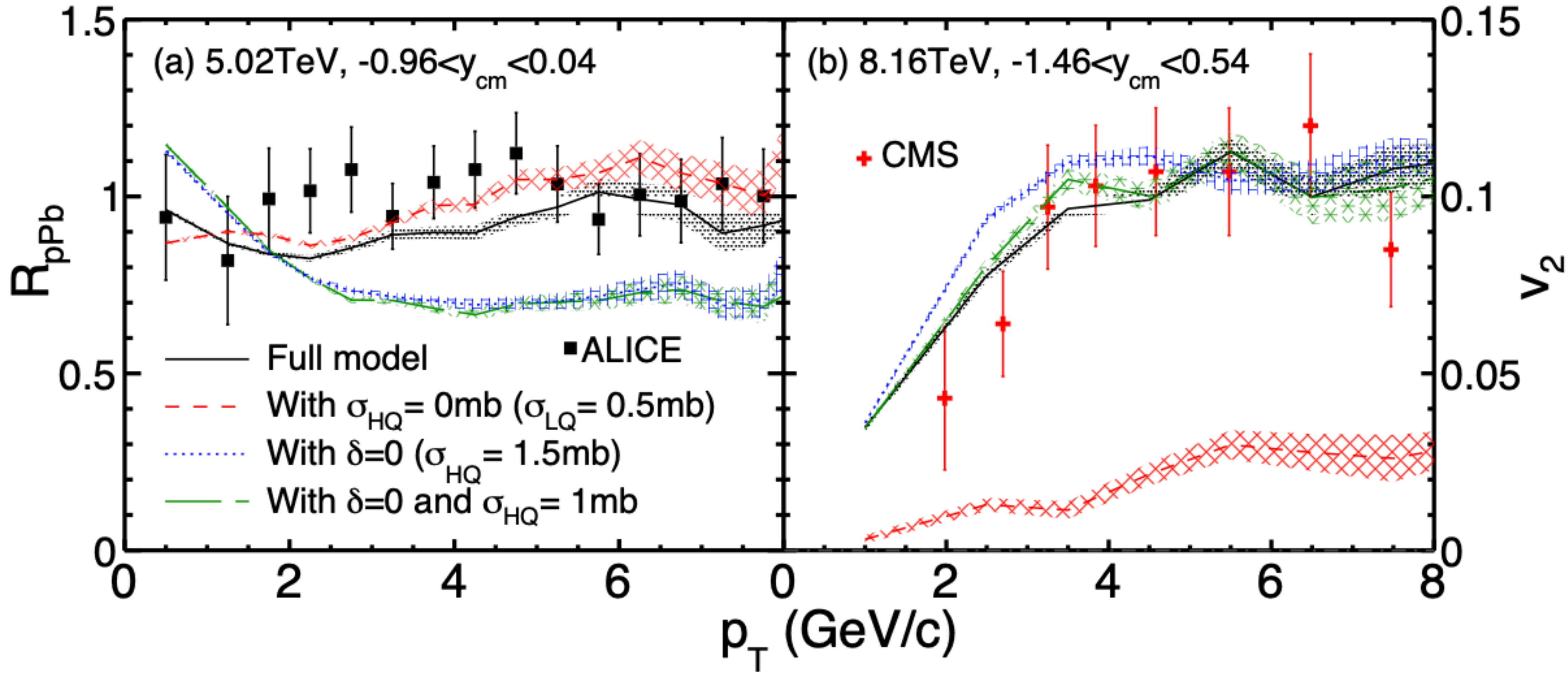
More details in Chao's poster

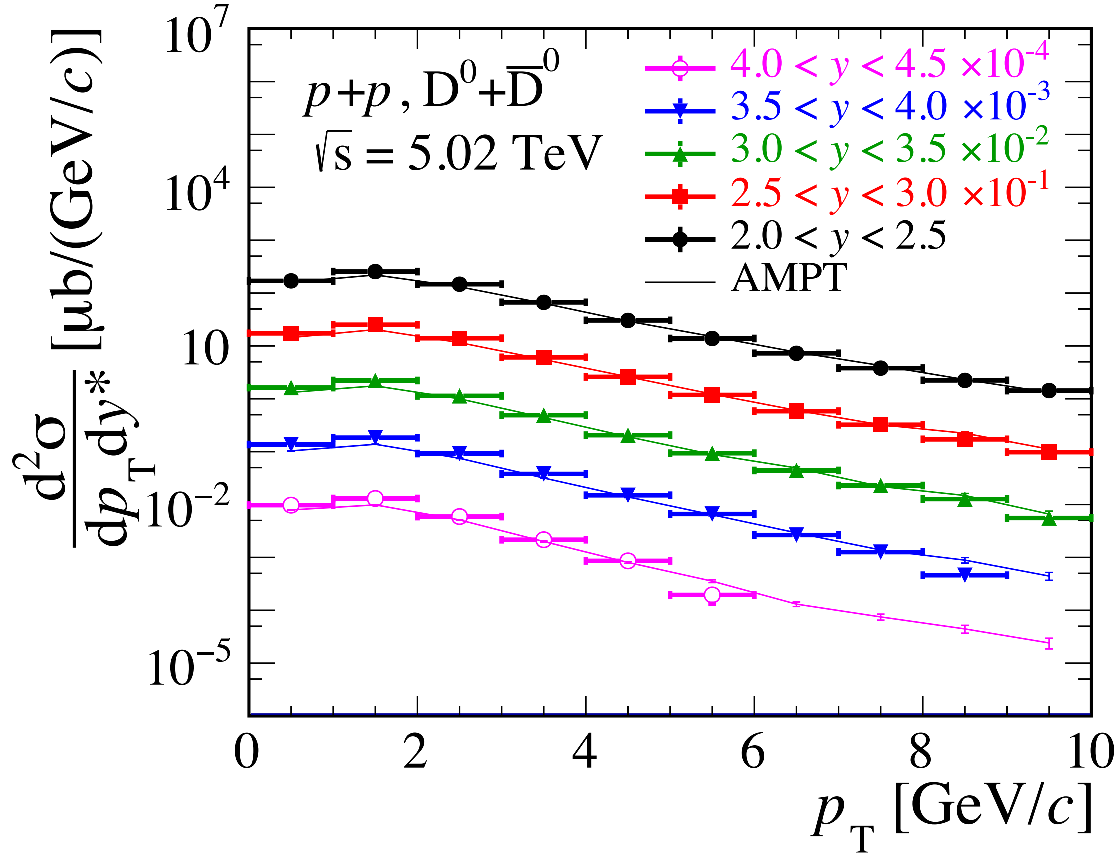
Heavy flavor R_{pA} and v_2 at mid-rapidity

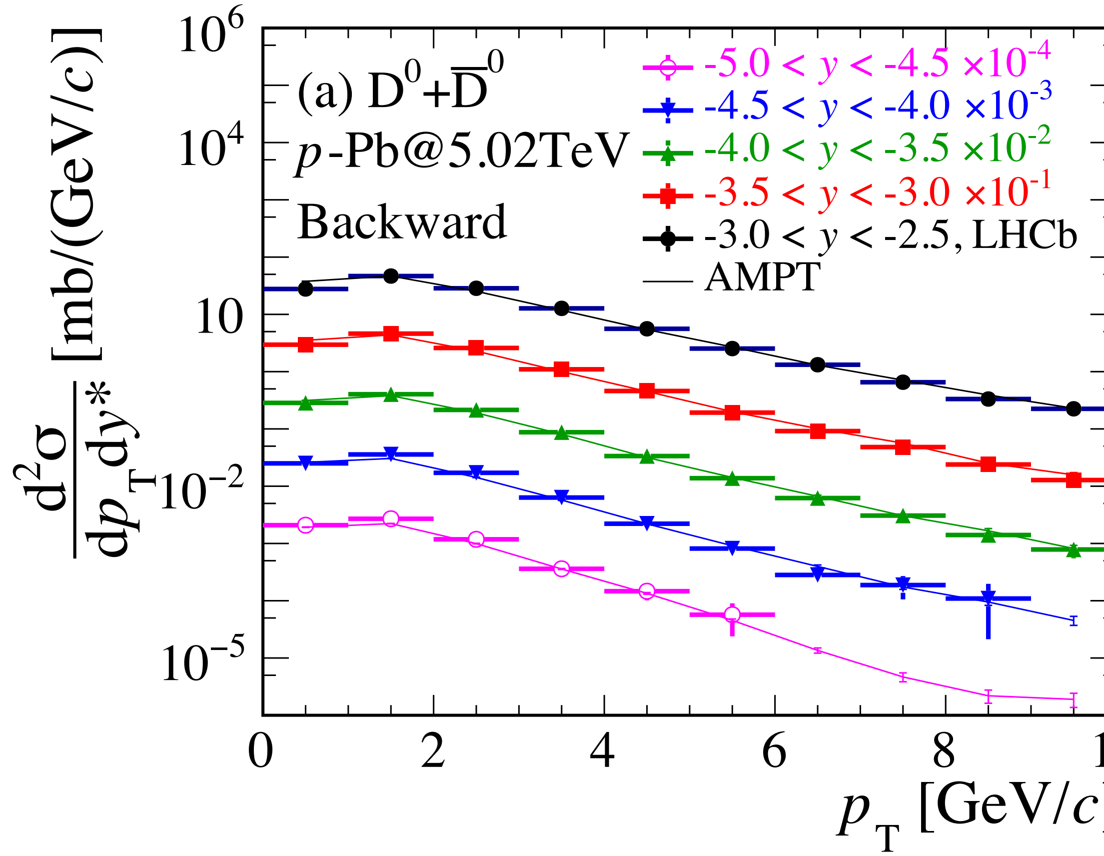


- A simultaneous description of the R_{pA} and v_2 is provided by the improved AMPT model
- The **Cronin effect** significantly enhances D^0 production at intermediate/high p_T, while modestly decrease the D^0 meson v_2
- Parton scatterings are mostly responsible for generating the D^0 meson v_2

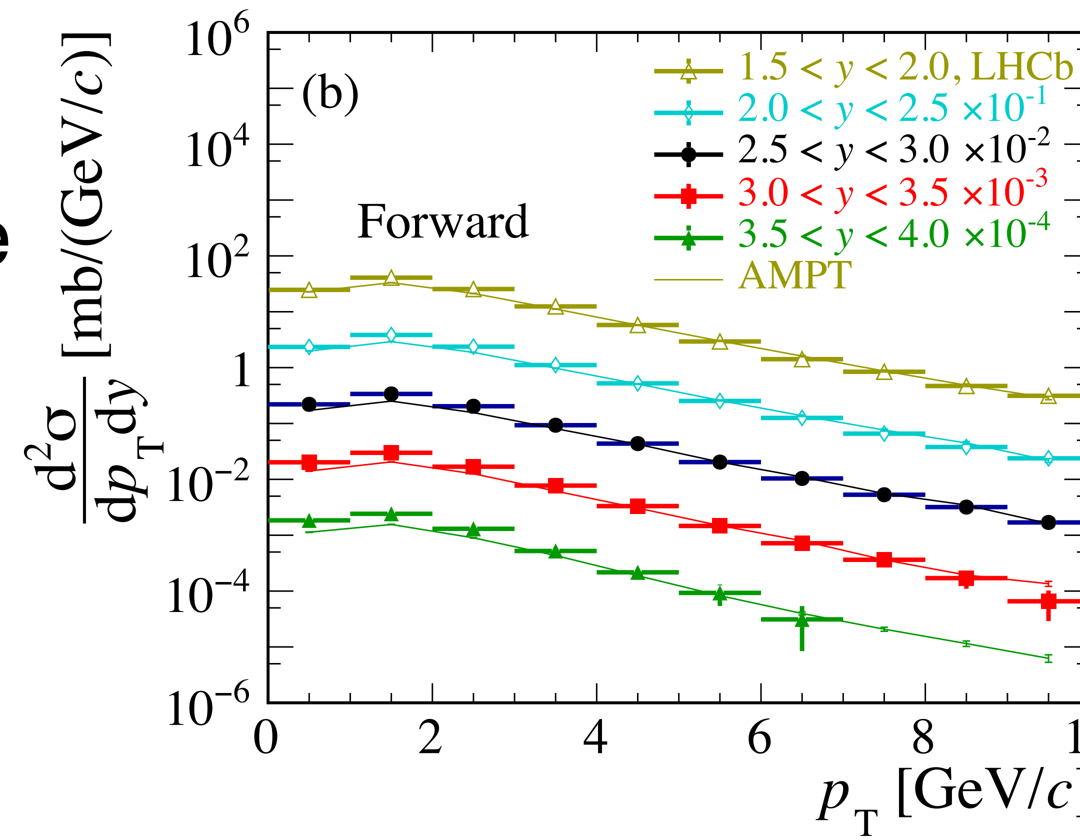
More details in Chao's poster

Heavy flavors spectrum at forward rapidity



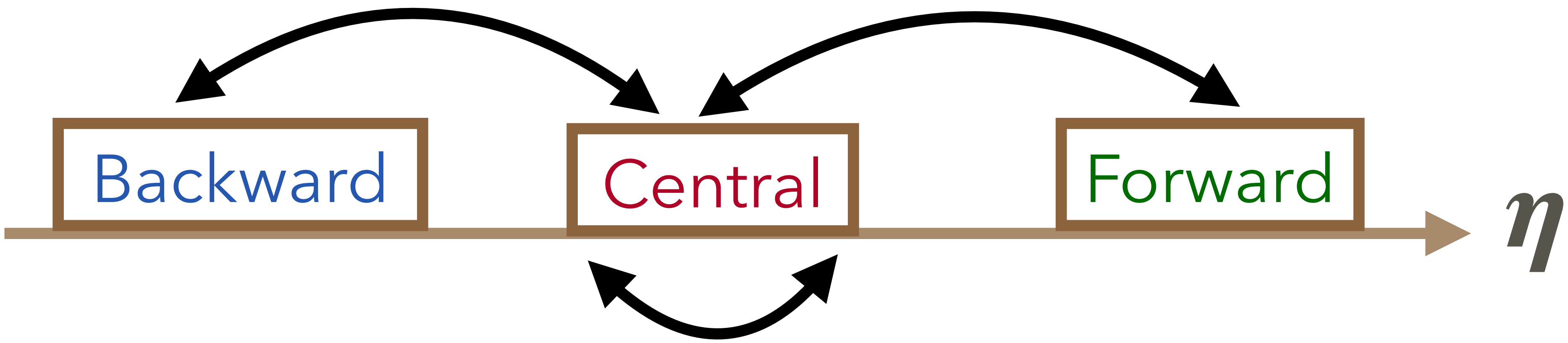


- The D^0 meson spectrum at forward and backward can be well reproduced by the improved AMPT model
- The Cronin strength needs to be quantified in different rapidity



Heavy flavors v_2 at forward rapidity

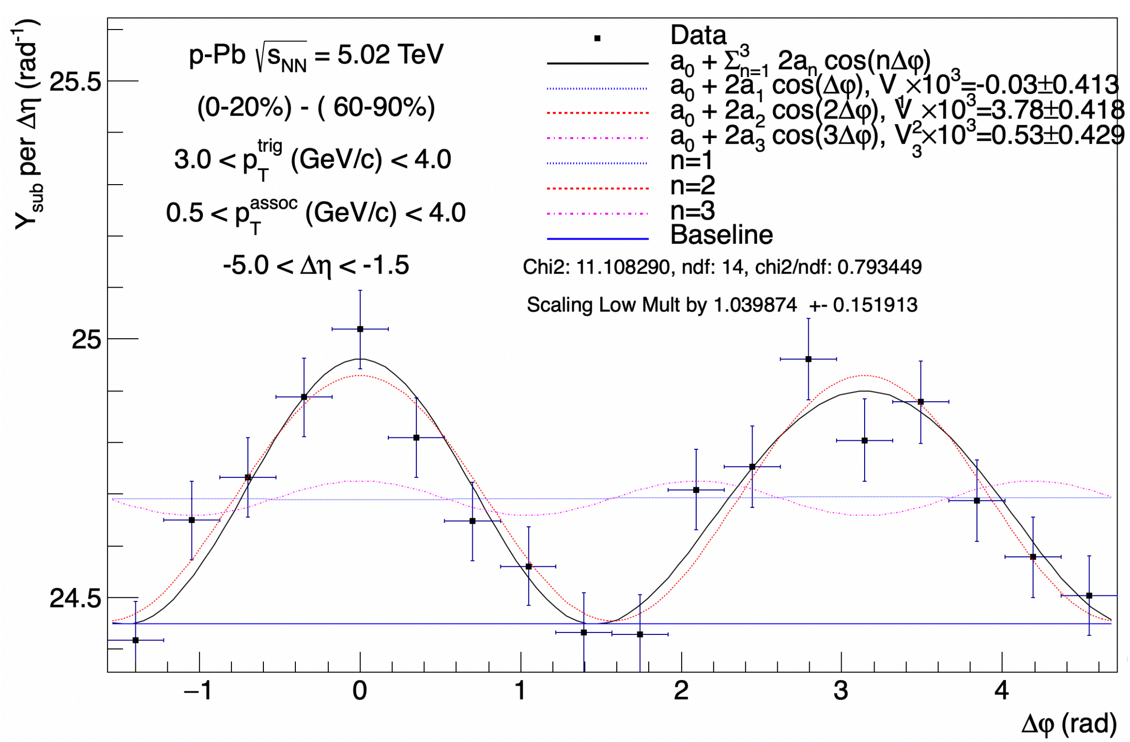
- **Calculation method:** long-range two-particle correlation



- **Factorization:** $v_2(\text{Forward}) = \frac{V_{2\Delta}(\text{FC})}{\sqrt{V_{2\Delta}(\text{CC})}}$ $v_2(\text{Backward}) = \frac{V_{2\Delta}(\text{BC})}{\sqrt{V_{2\Delta}(\text{CC})}}$
- The nonflow contribution is estimated in low-multiplicity collisions

$$Y(\Delta\varphi, 0-10\%) - \mathrm{F}\cdot \mathrm{Y}(\Delta\varphi, 60-100\%) = \mathrm{a}_0 + 2\sum_{n=1} \mathrm{v_n cos}(\mathrm{n}\Delta\varphi)$$

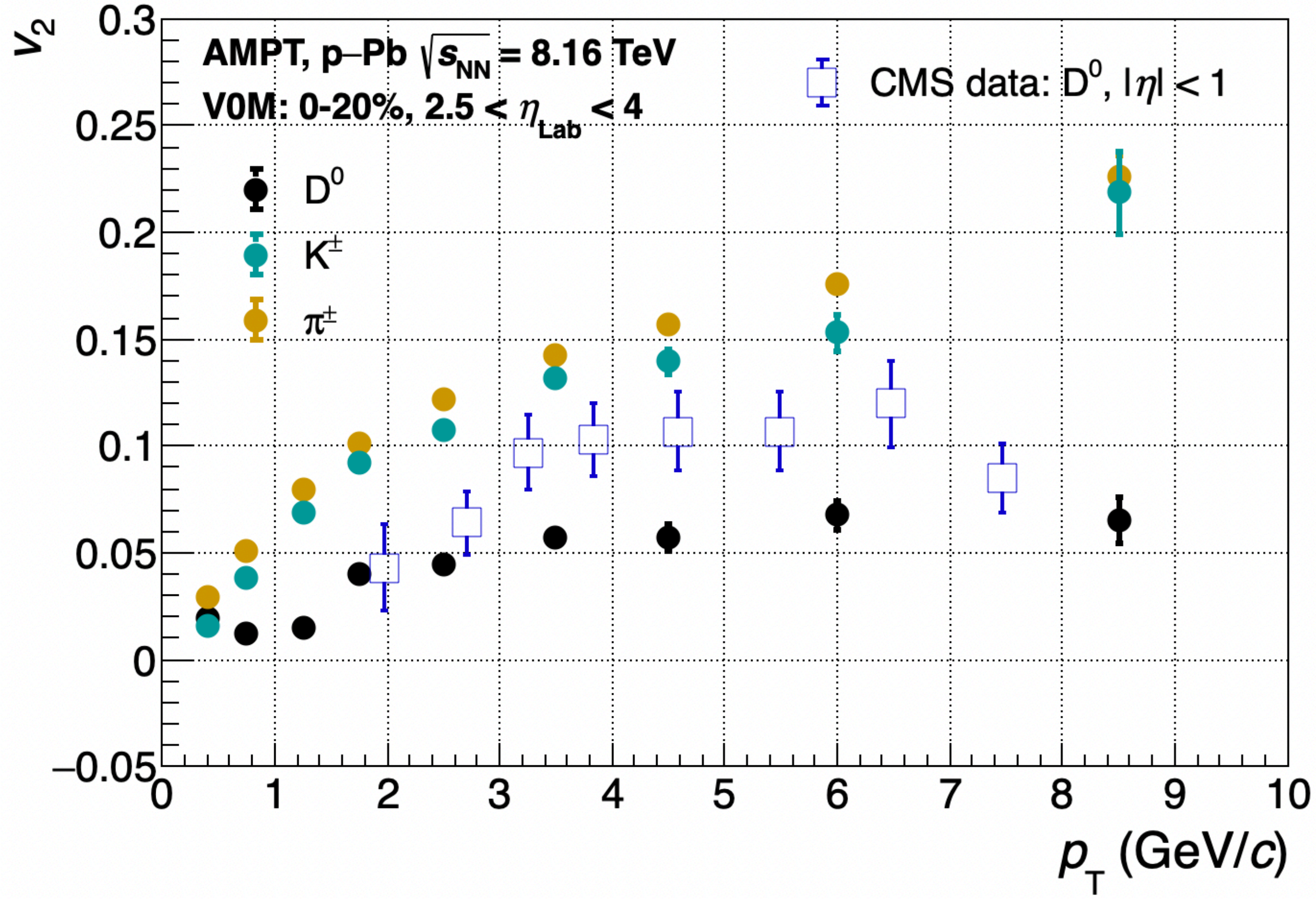
- the contribution in the low-multiplicity events is scaled by the ratio between the "away-side jet" yield in low- and high-multiplicity events



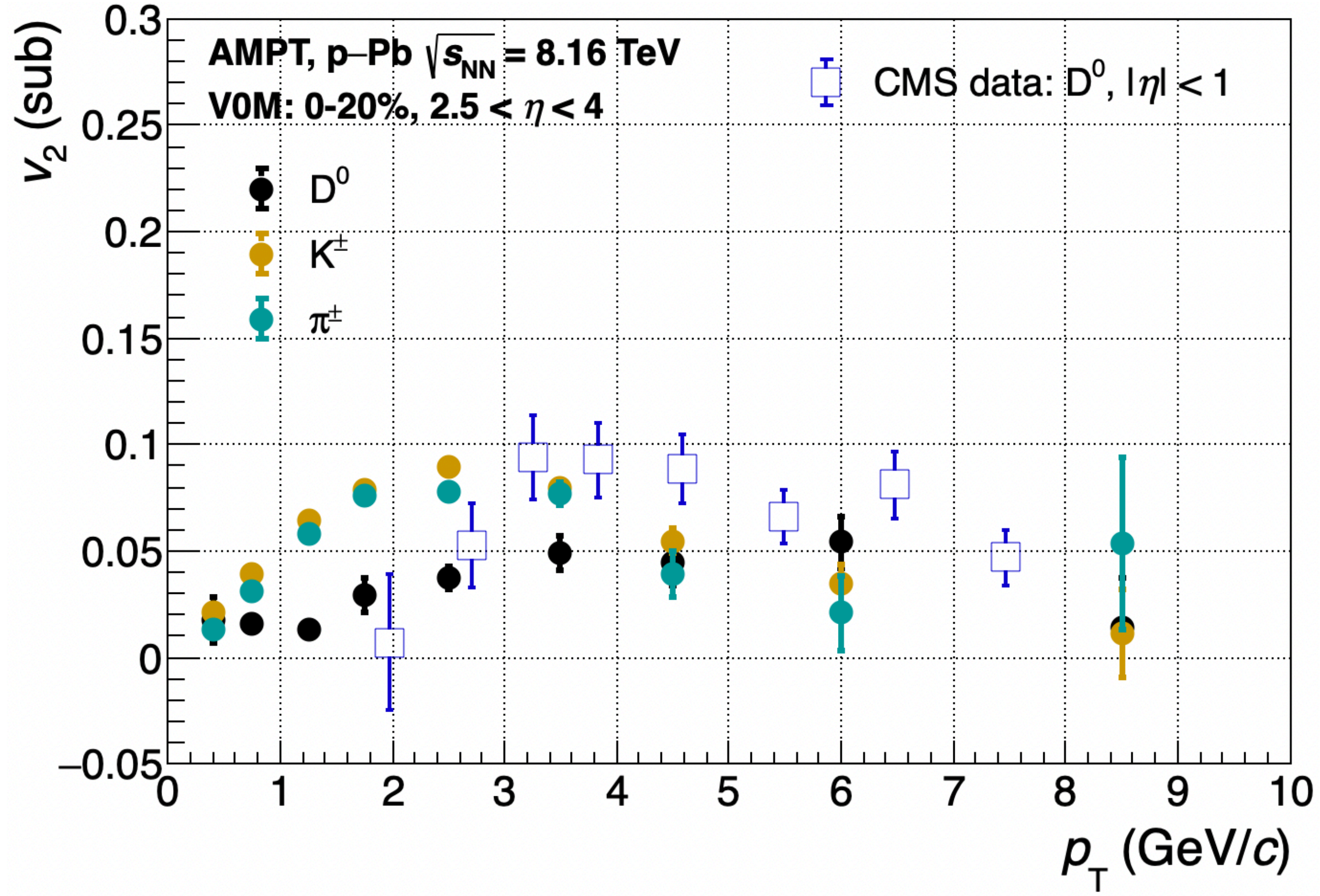
Physics Letters B 846 (2023) 137782

Heavy flavors v_2 at forward rapidity

Before nonflow subtraction

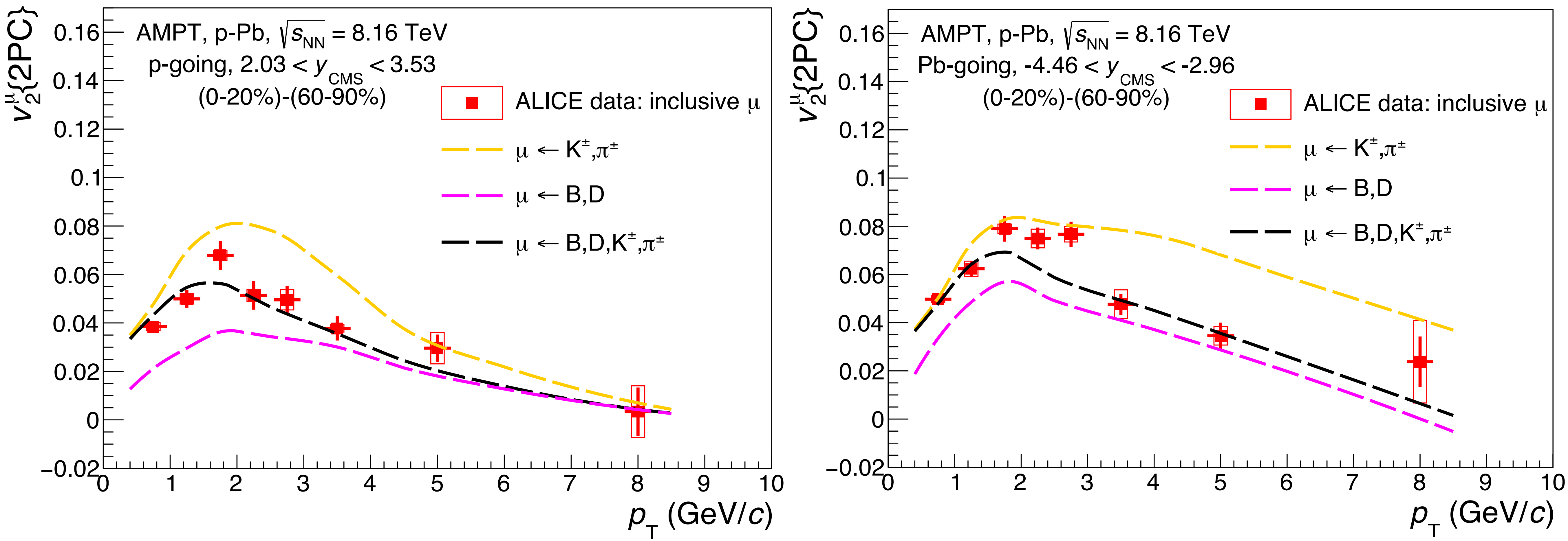


After nonflow subtraction



- A significant suppression is shown after the nonflow subtraction for light flavors, but not for heavy flavors
- The mass ordering of v_2 between light and heavy flavors is also obtained at forward rapidity with the AMPT model

Heavy flavors v_2 at forward 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 heavy flavor v_2 are perform in p–Pb collisions with **an improved multi-phase transport model**

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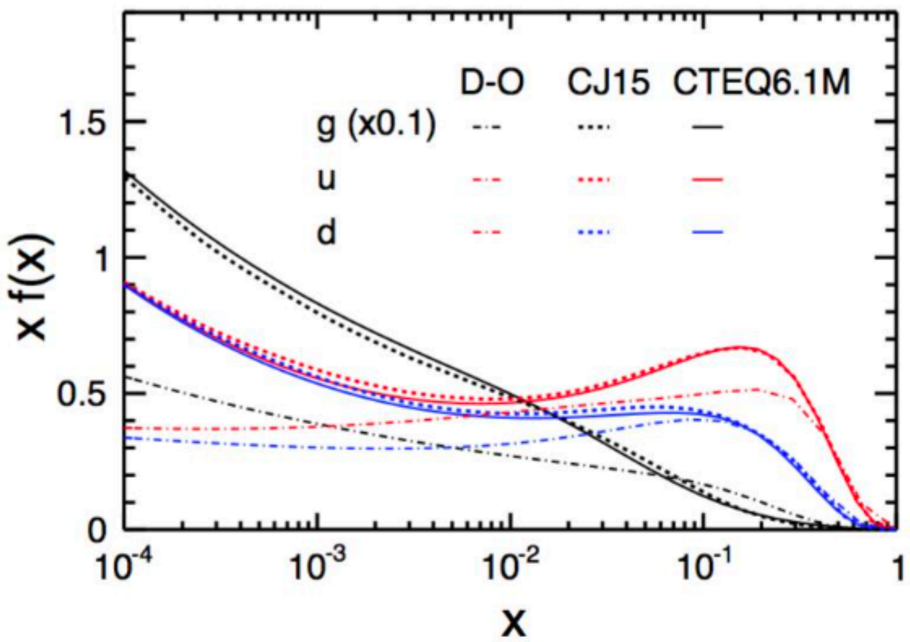
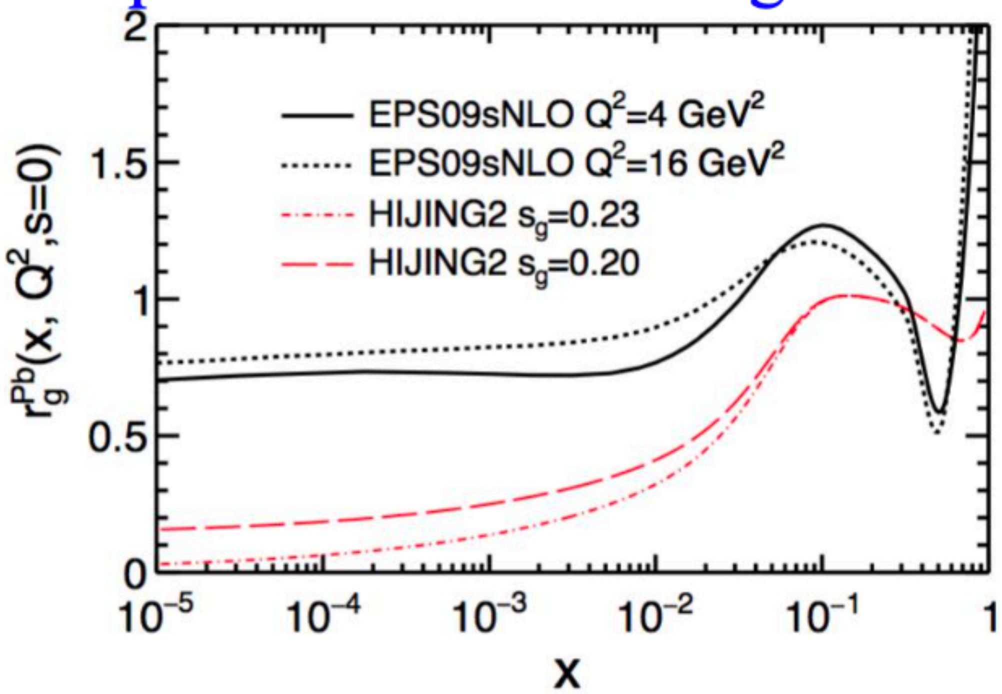
Thank you !

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)

Improved multi-phase transport model for heavy flavors

$gg \rightarrow gg$ cross section in leading-order pQCD is divergent for massless g, $\frac{d\sigma}{dt} \sim \frac{9\pi\alpha_s^2}{2t^2}$

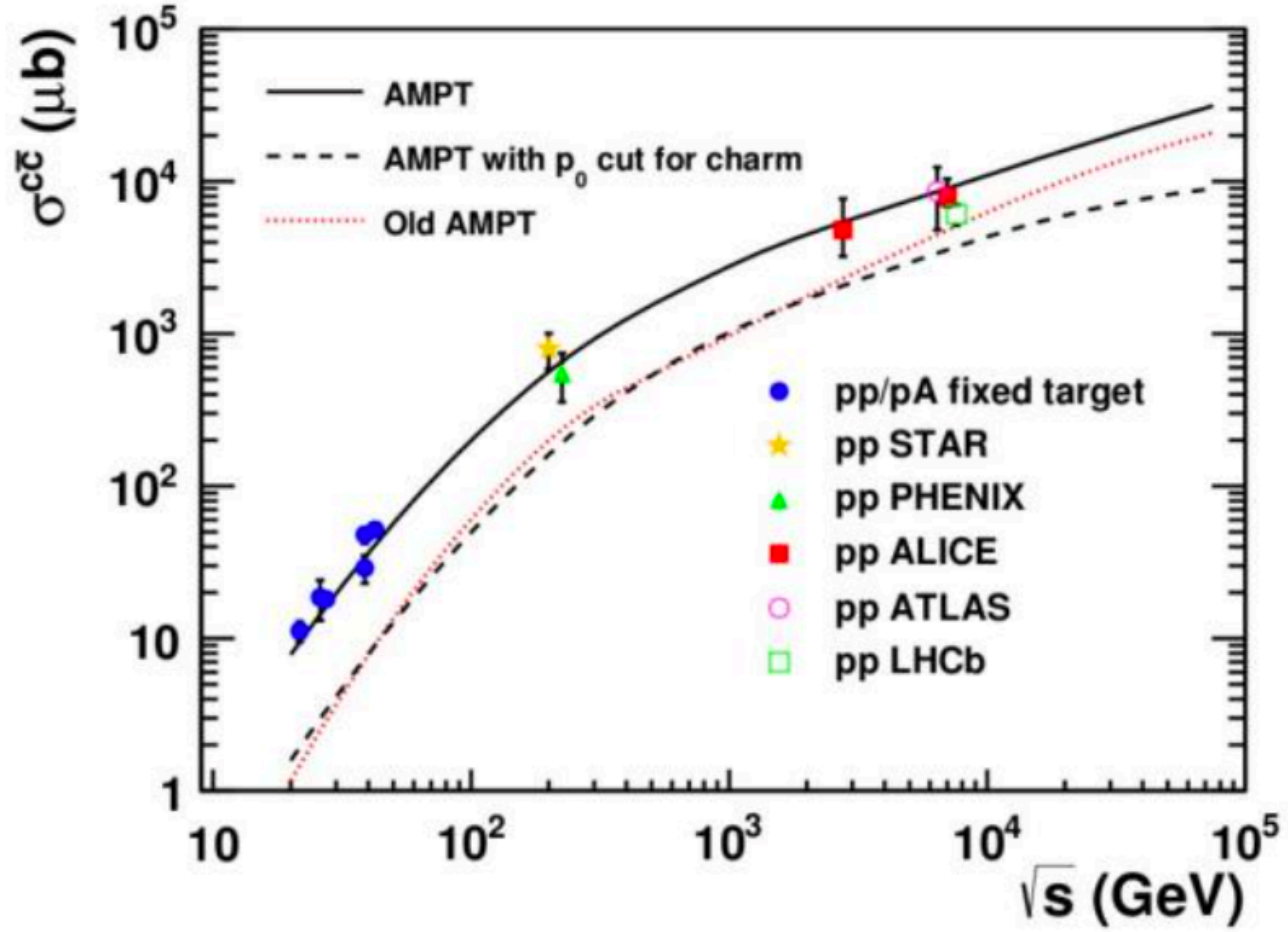
so HIJING uses a minijet cutoff p_0 for minijets (of ALL flavors).

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 in the two-component model HIJING (initial condition for AMPT) Zheng et al. PRC (2020)
- Unlike HIJING, we include HF in σ_{jet}: $\sigma_{jet} = \sigma_{jet}^{LF} + \sigma^{HF}$
- 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

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/GeV²):

~ 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,

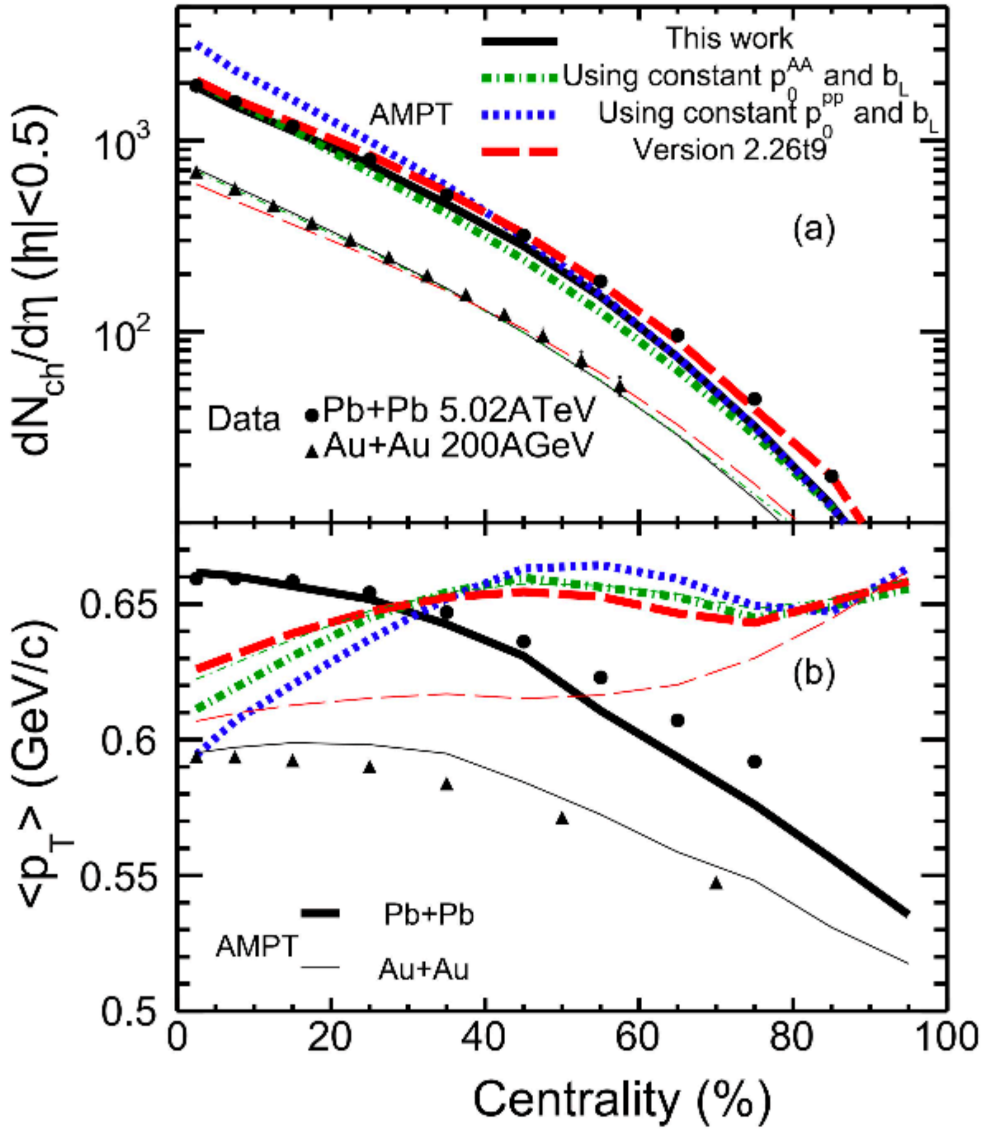
then used central AuAu/PbPb $\langle p_T \rangle$ data to determine $\alpha(s)$, $\beta(s)$ versus energy

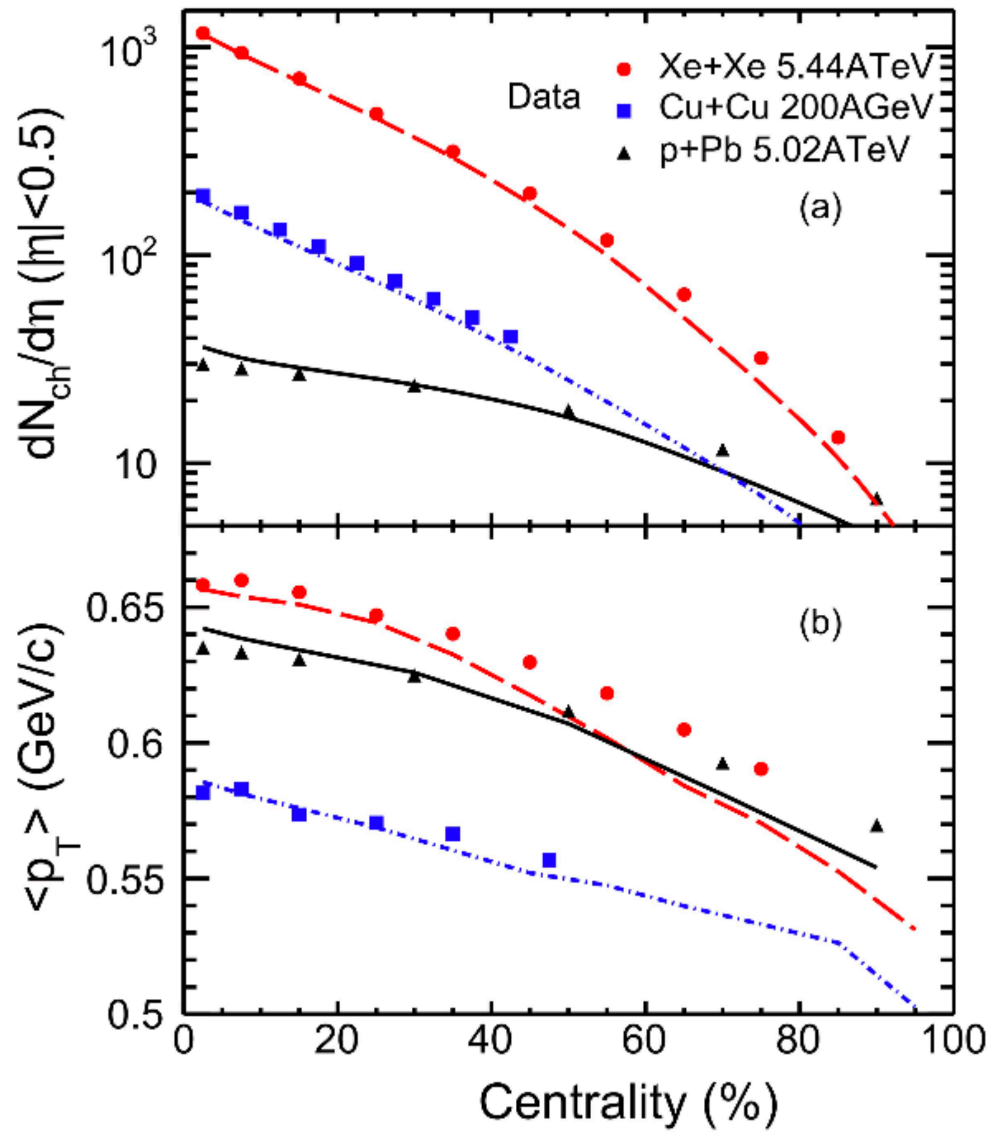
Local scaling for self-consistent size dependence in AMPT

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

including centrality dependences ofAuAu & 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

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.

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

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

- For comparison, <k_{T}^2> (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).