Overview of heavy-Flavor Physics - LHC

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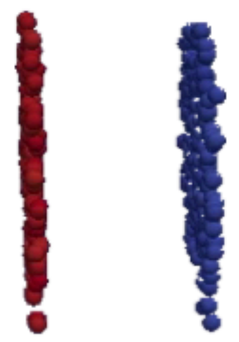
06/12/2024

Probing quark-gluon plasma (QGP) with heavy flavor

Initial state



Time

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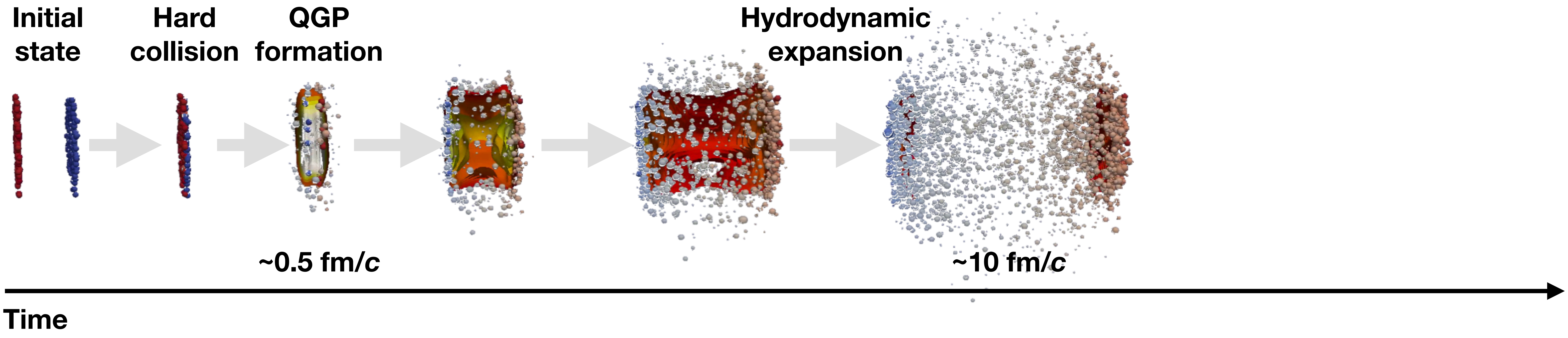

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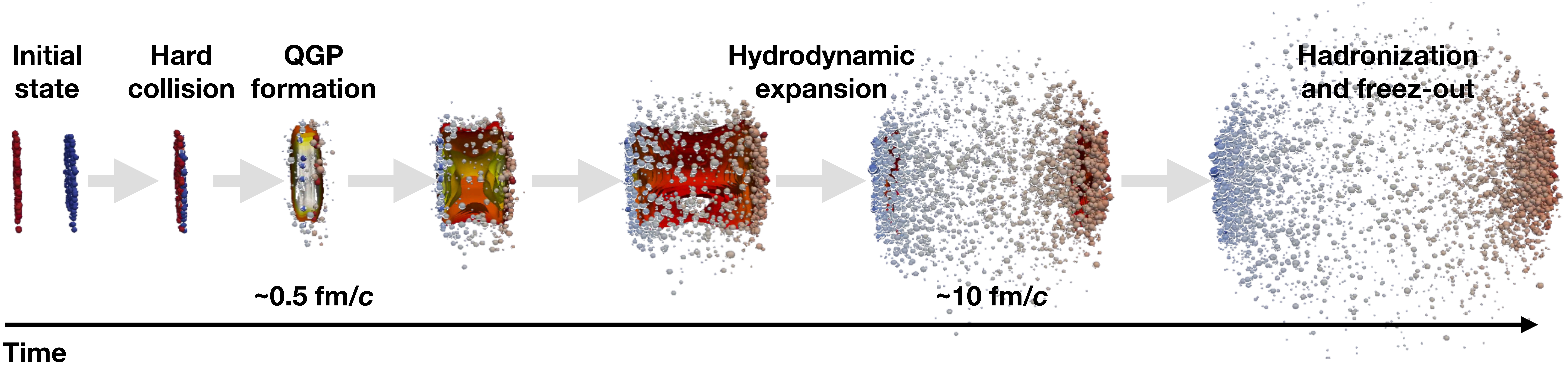

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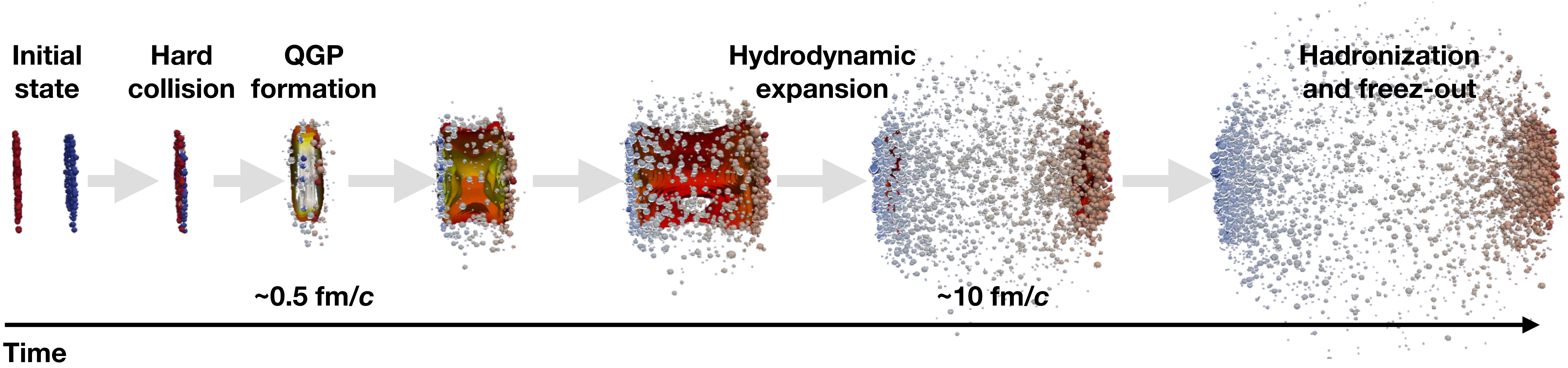
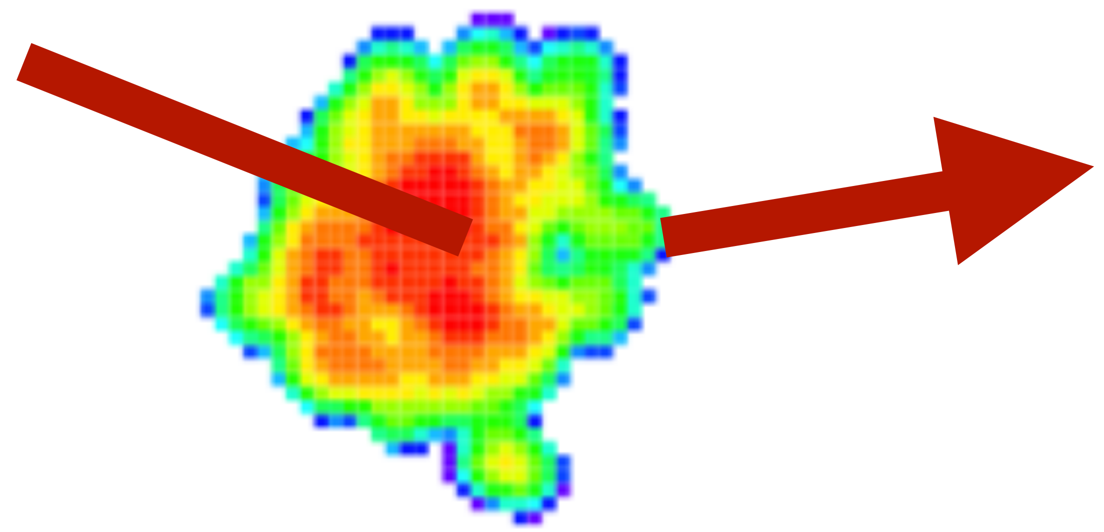


The QGP is too small and too short-lived to be probed in a traditional scattering experiment



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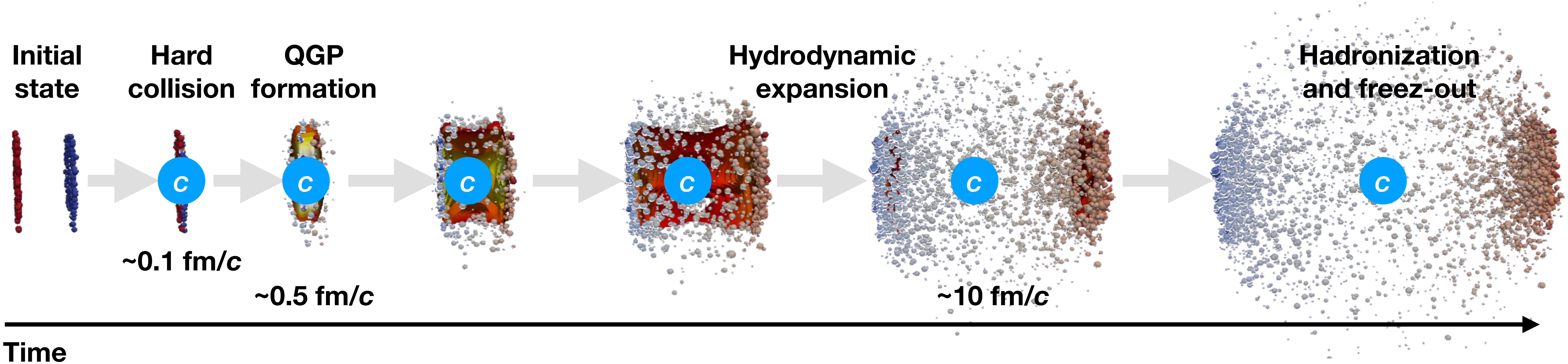


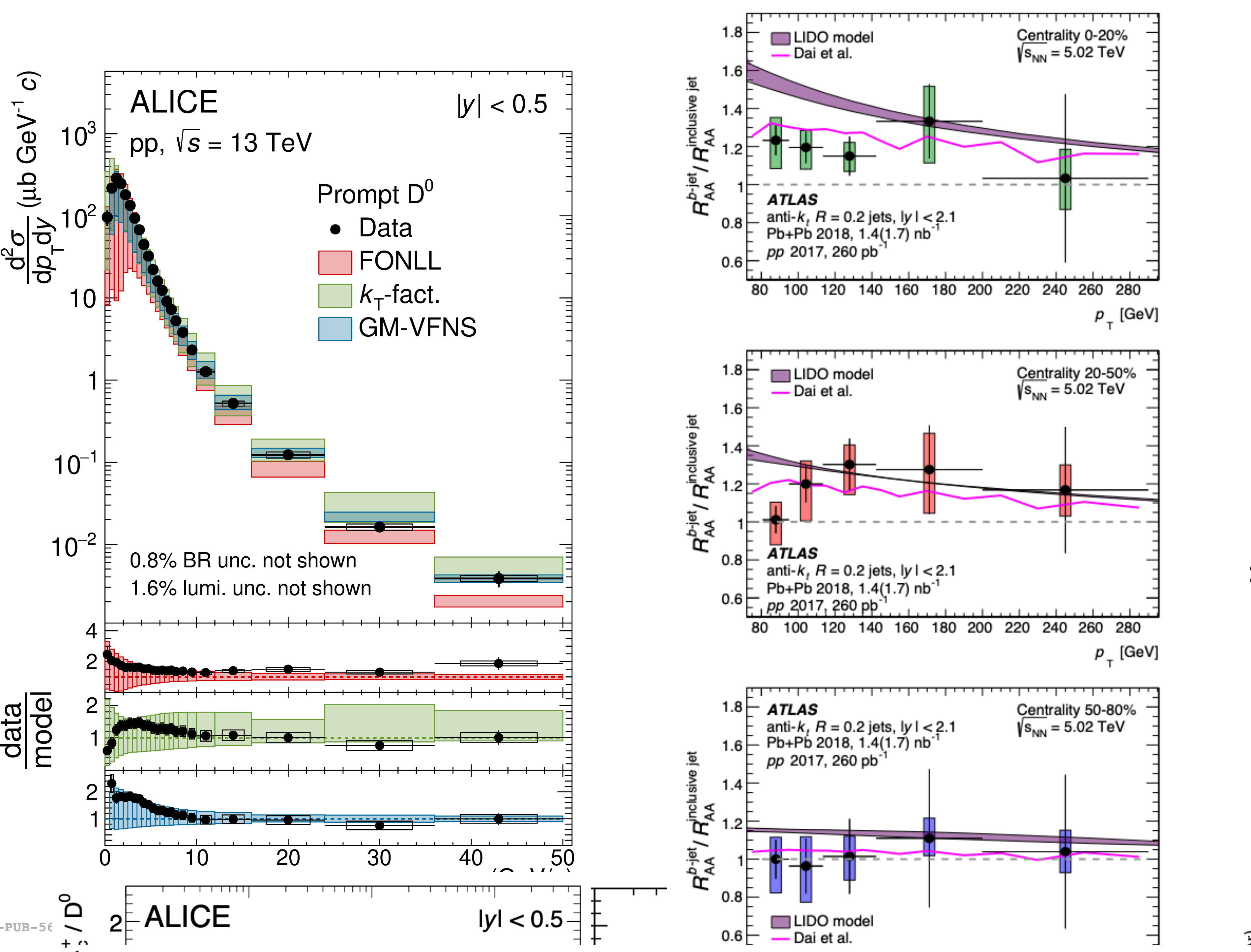
Visualization by J.E Bernhard arXiv:1804.06469

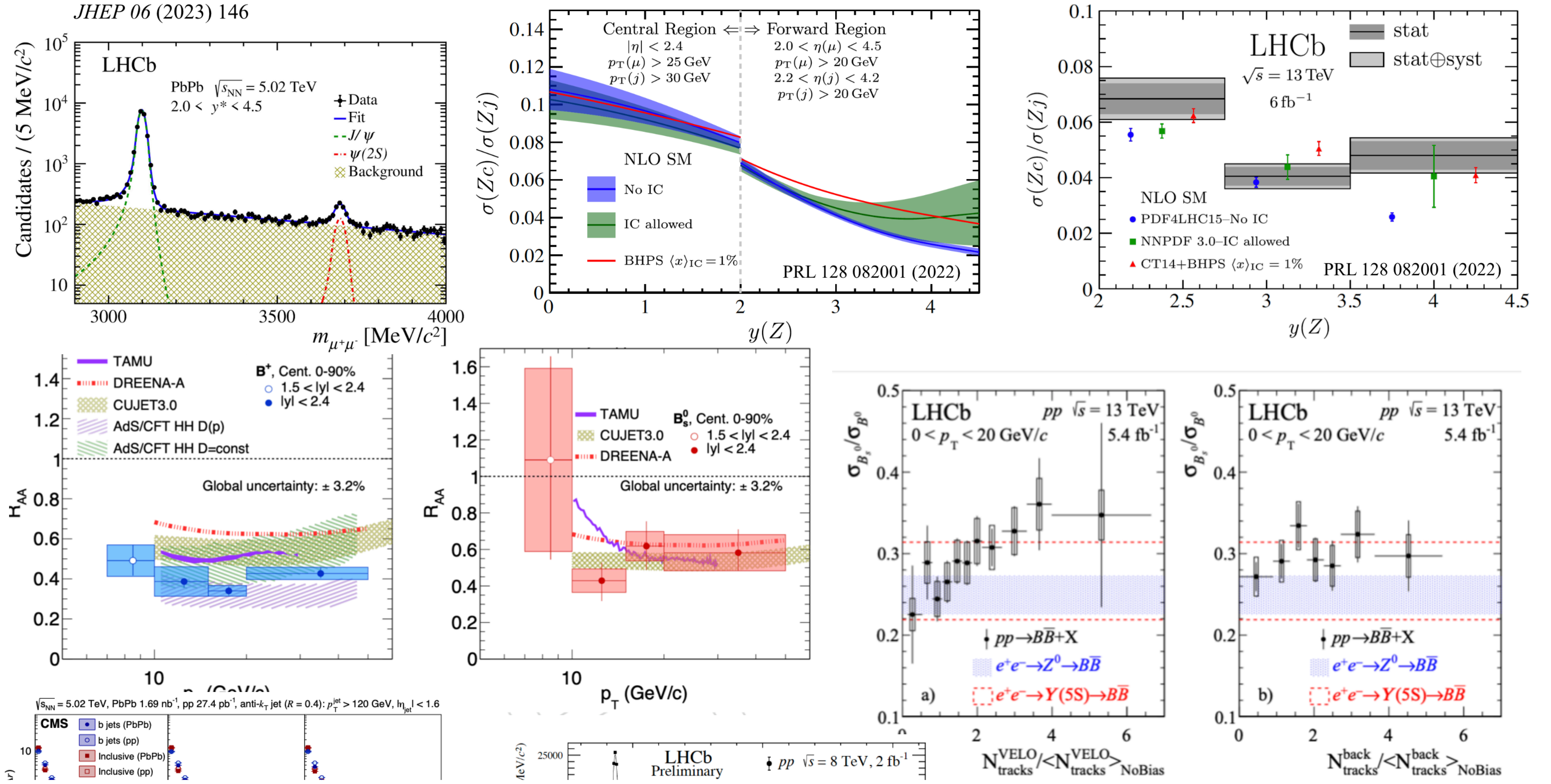
The QGP is too small and too short-lived to be probed in a traditional scattering experiment

Heavy-flavor excellent probe!

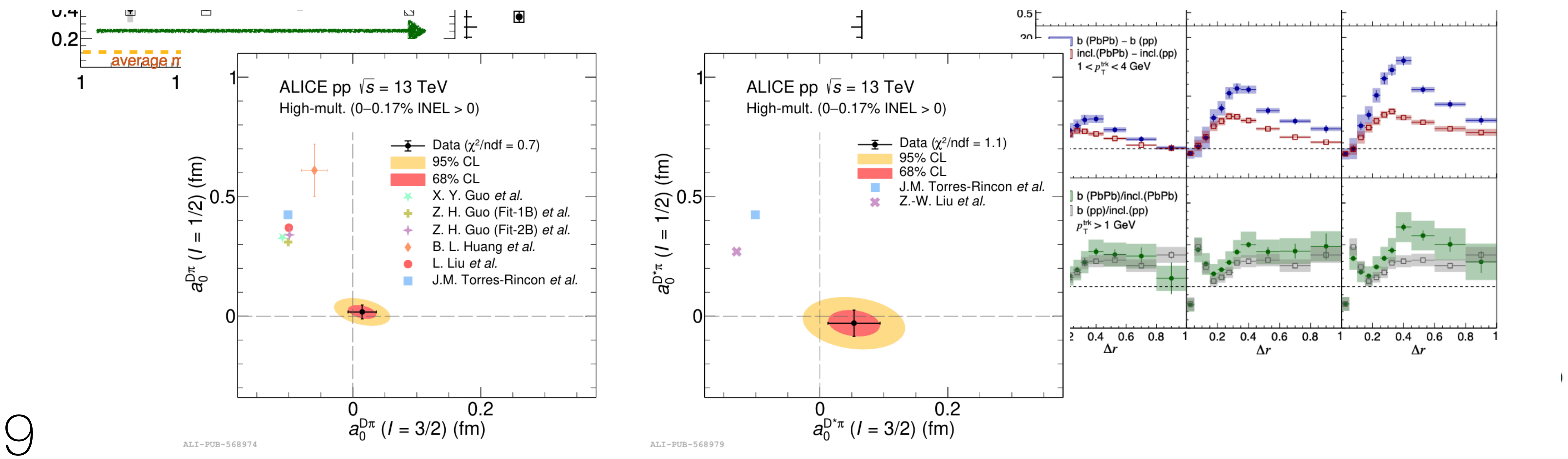
- $m_Q >> \Lambda_{QCD}$
  Their production cross section calculable with pQCD
- $m_Q >> T_{QCD}$
  production restricted to initial hard scatterings ($\tau_{HF} \leq \hbar/m \sim 0.05 - 0.1\ \mathrm{fm}/c$)

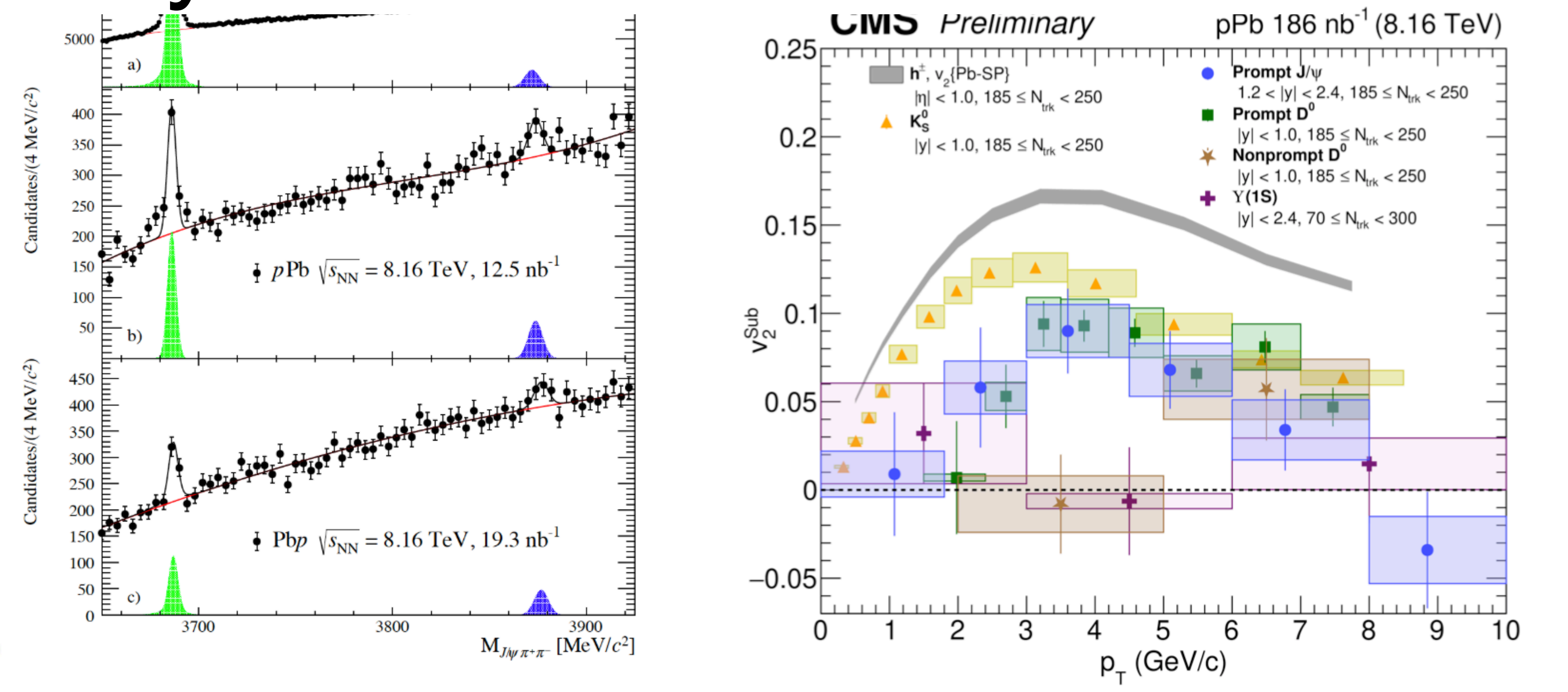
Heavy-flavor at LHC





Studies from their production to their “journey” into the medium until the formation of heavy-flavor hadrons!!!!





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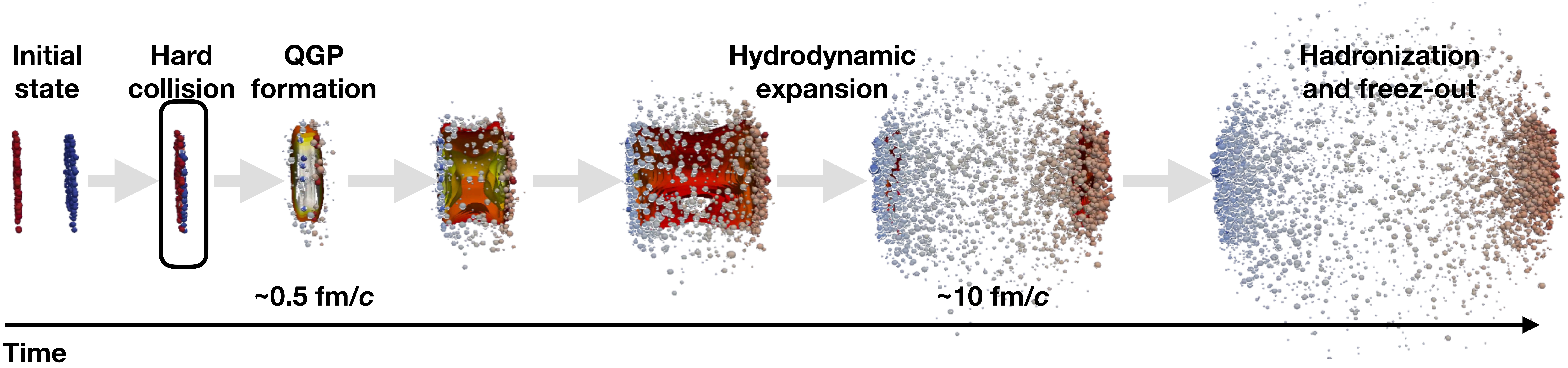
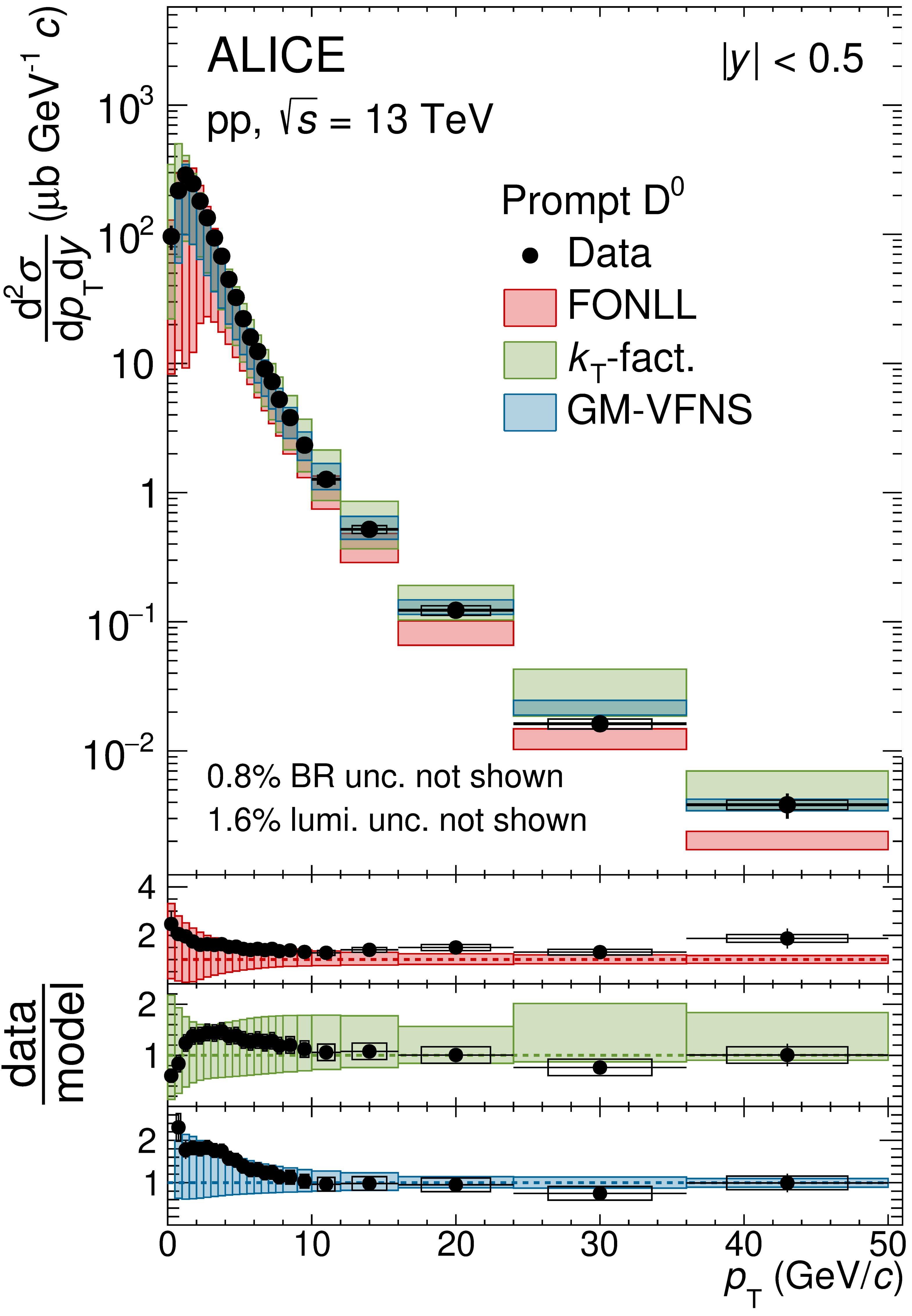
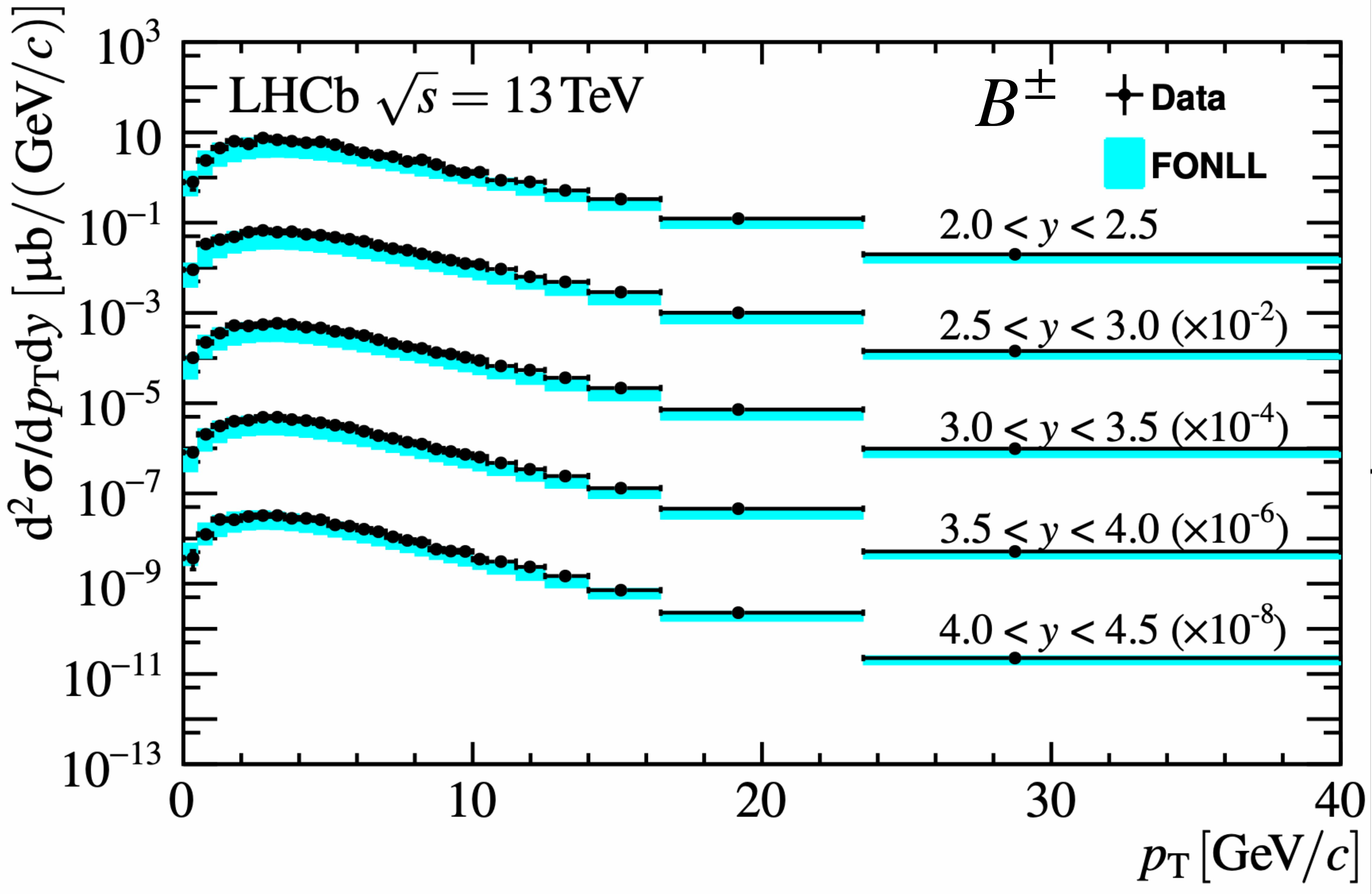
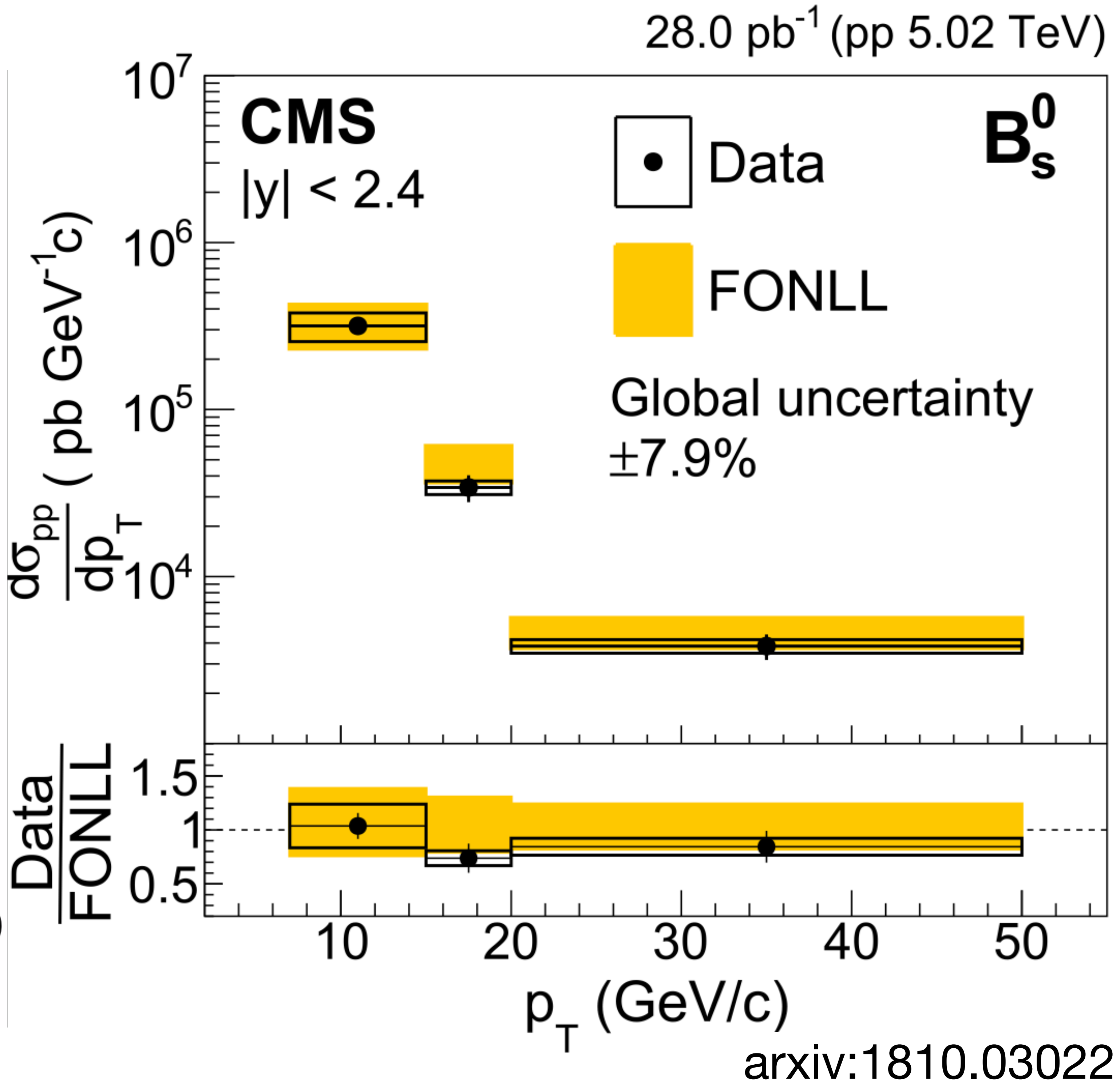


Heavy-flavor production in small system







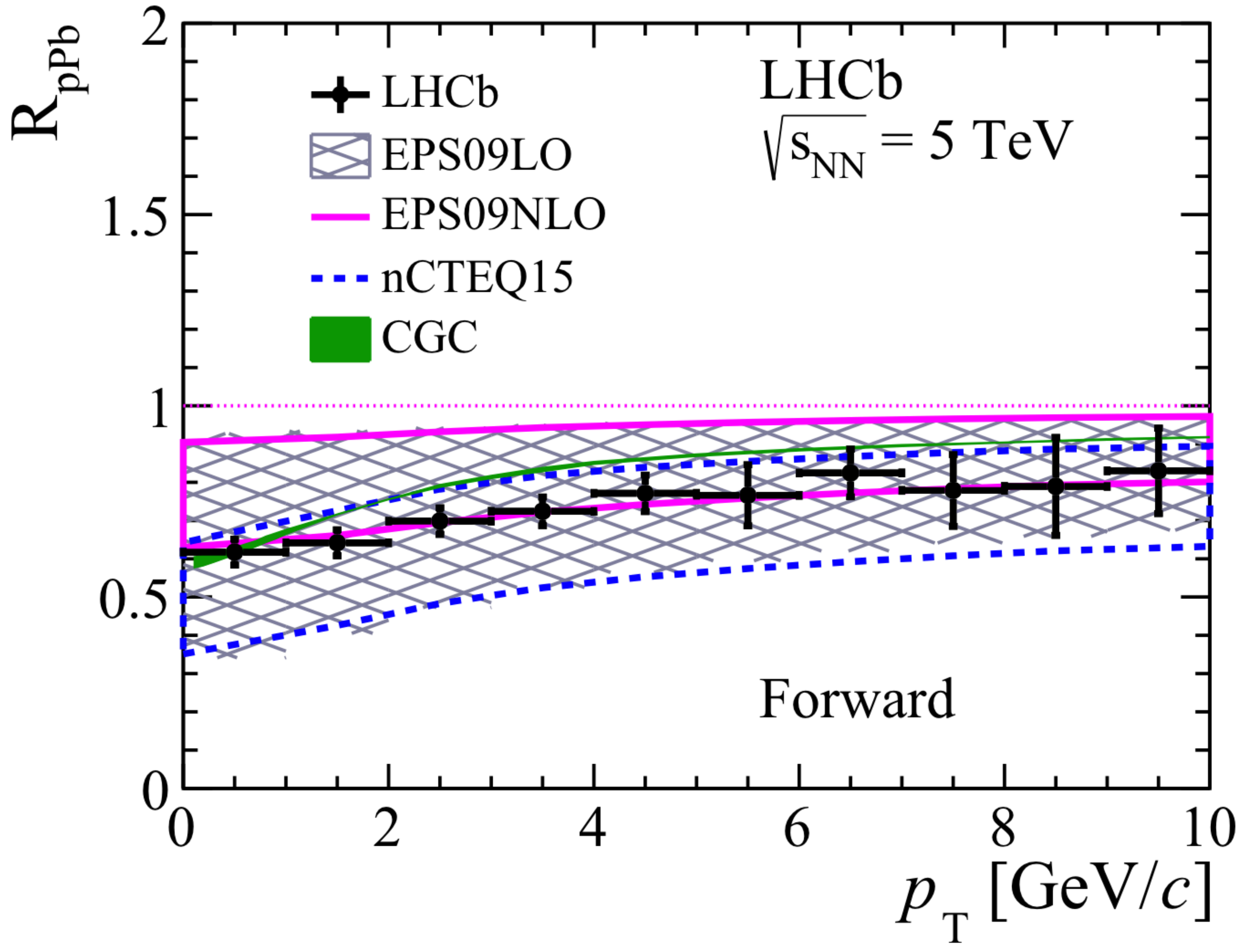
arxiv:1810.03022

- Precise production measurement in pp down to low p_T (~ 0 with D^0).

Comparison with models:

- Data **described by pQCD** calculations.
- Data is more precise than the model prediction. Need to constrain the model prediction.

Heavy-flavor production in small system



LHCb D meson data: significantly more precise than calculations from older nPDF sets

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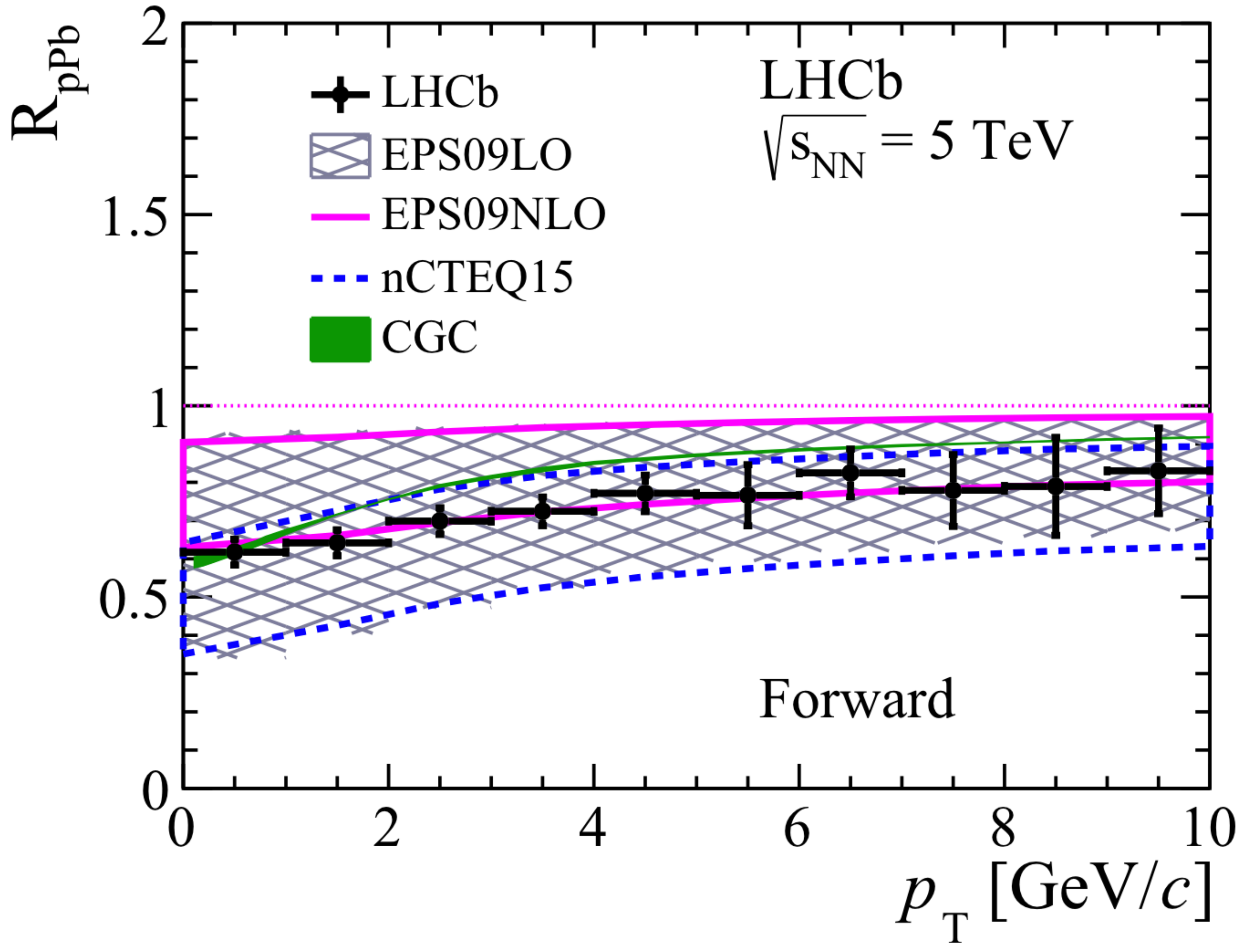

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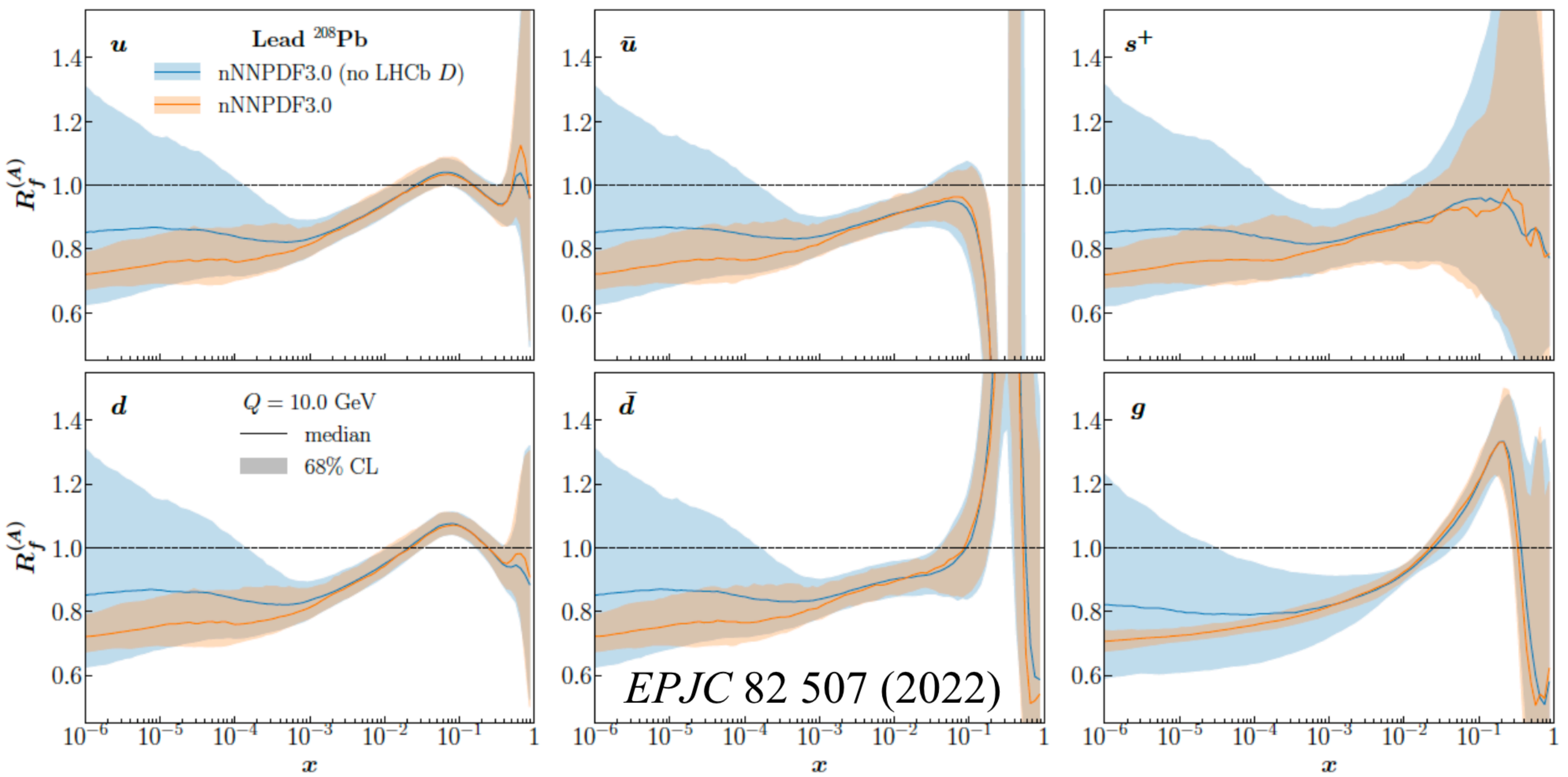
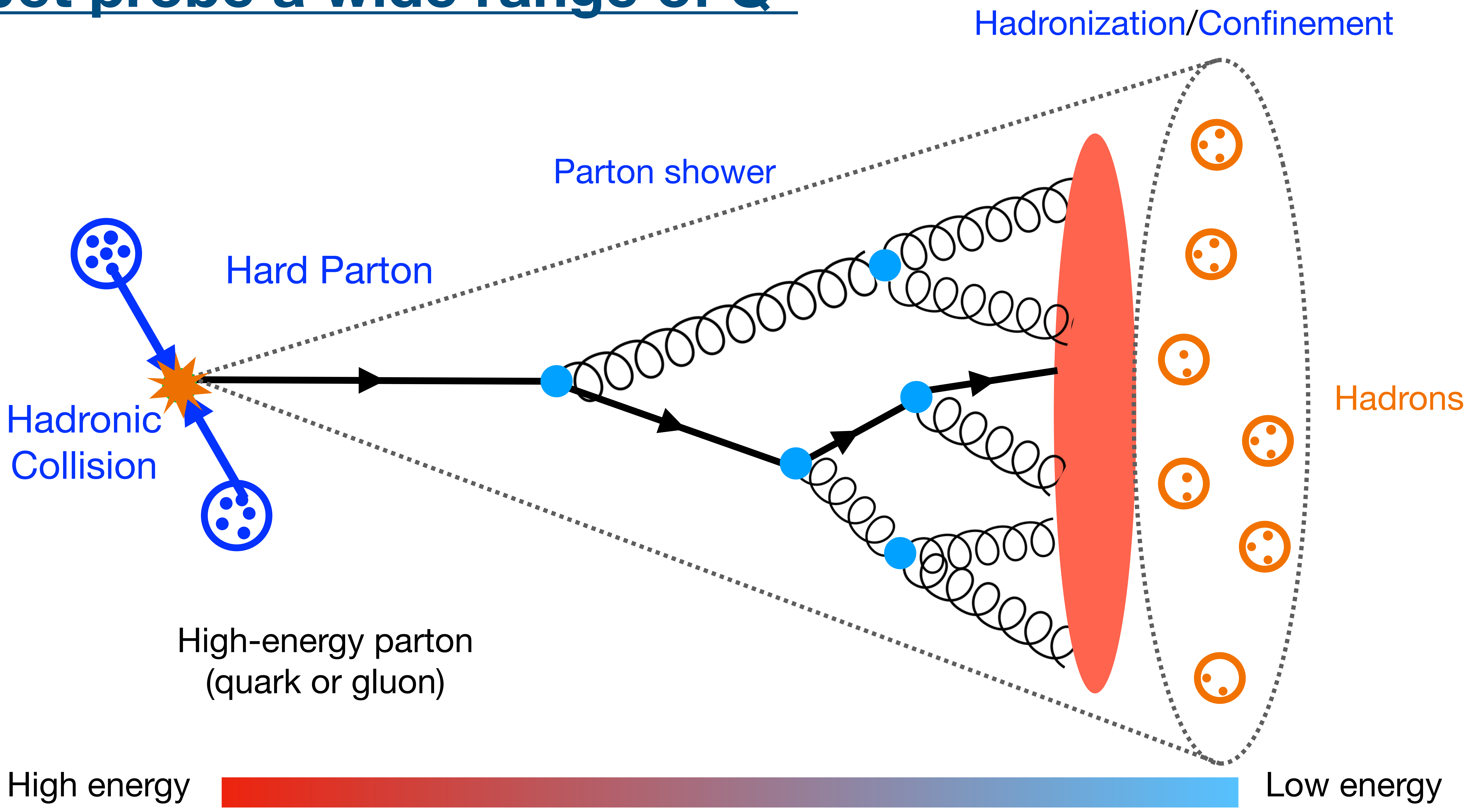


LHCb data currently constrains nPDFs down to $x \sim 10^{-6}$

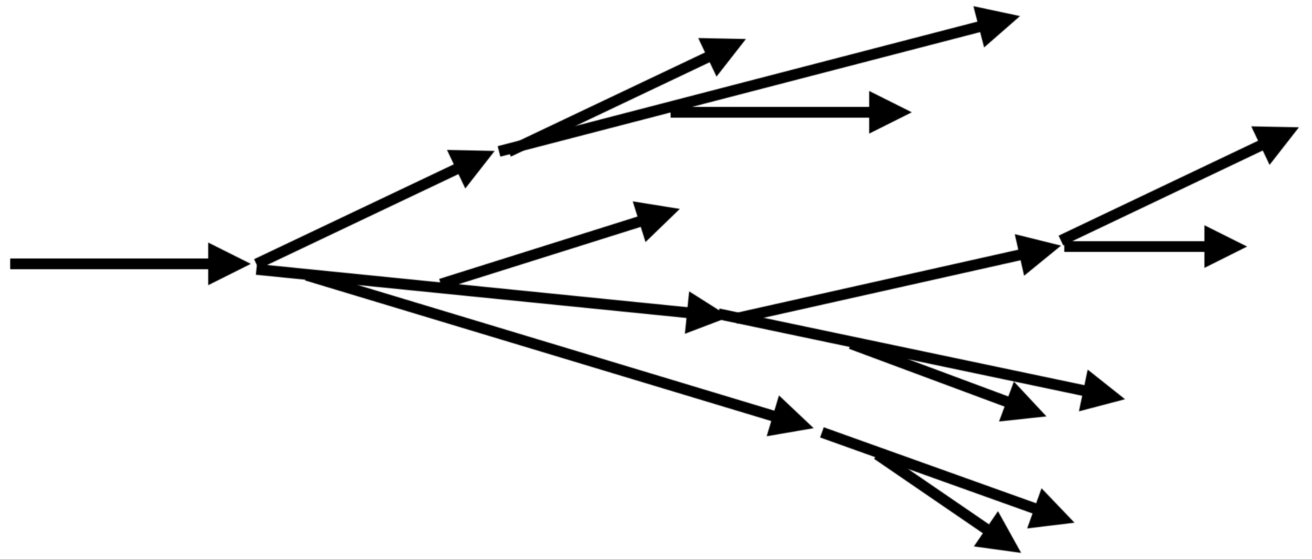
Places especially stringent bounds on gluon nPDF

Jet probe a wide range of Q^2



Probing flavor dependence in the QCD shower

Gluon-initiated shower



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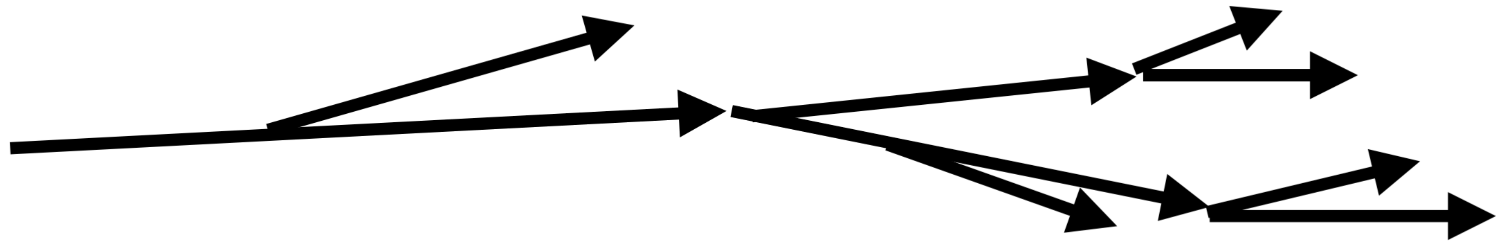

$$\frac{C_{\mathrm{A}}}{C_{\mathrm{F}}} = \frac{9}{4}$$

Casimir color factors

Gluon-initiated showers are expected to have a broader and softer fragmentation profile than quark-initiated showers

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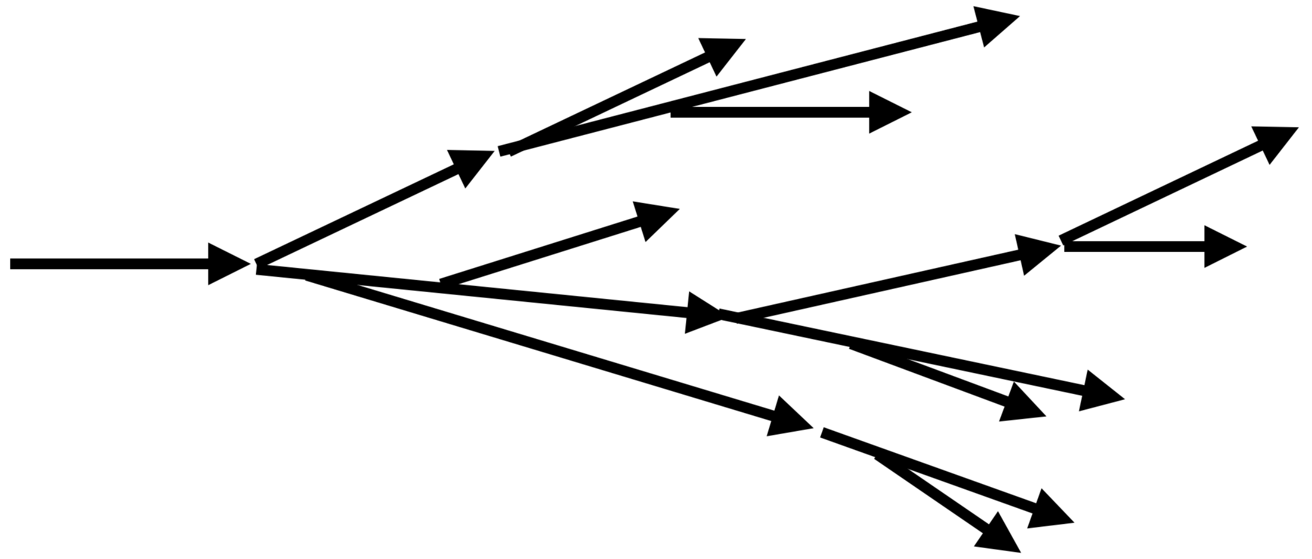

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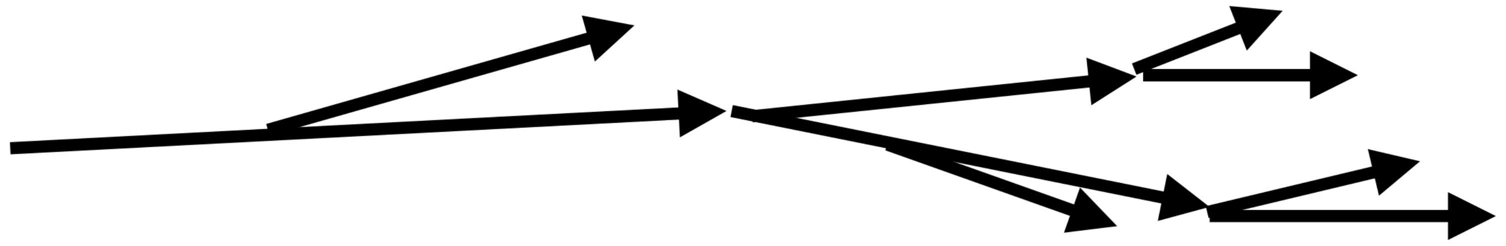
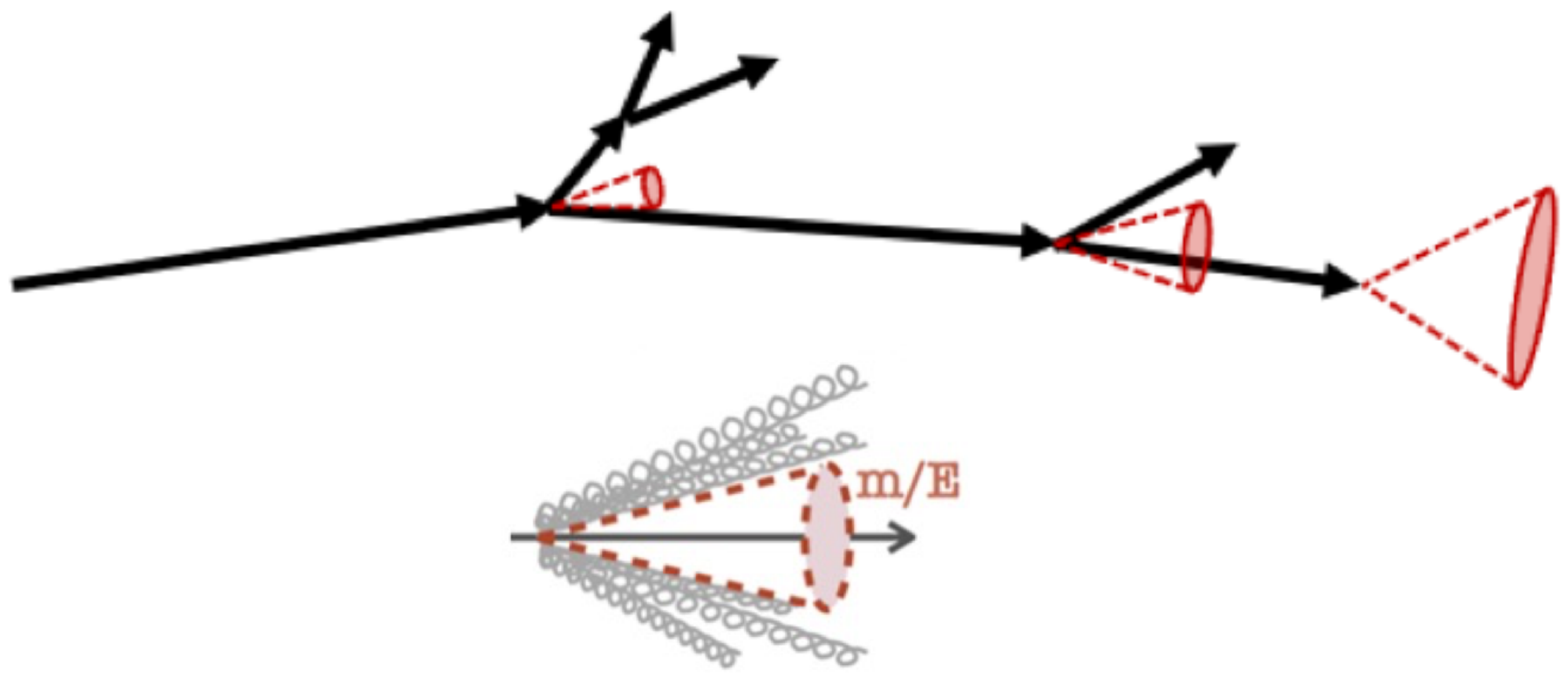


Heavy-quark-initiated shower



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Mass effects

A harder fragmentation is expected in low energy heavy-quark initiated showers due to the presence of the dead-cone effect

Probing flavor dependence in the QCD shower

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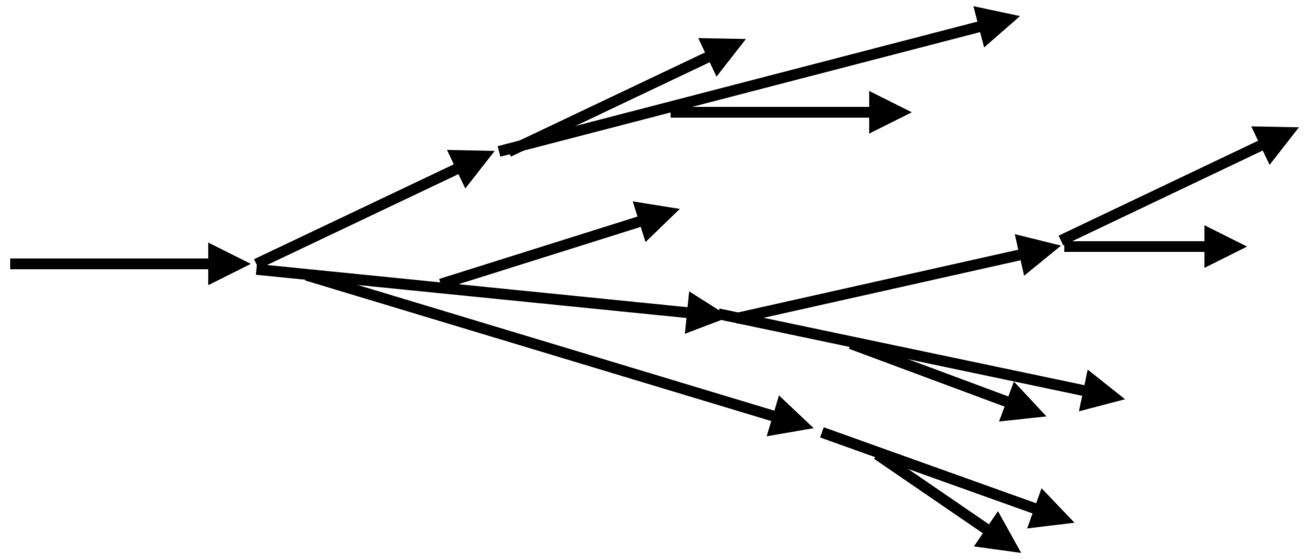

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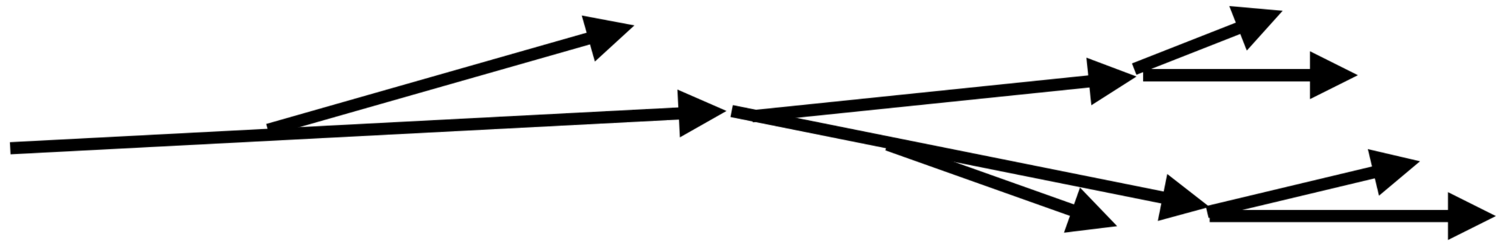

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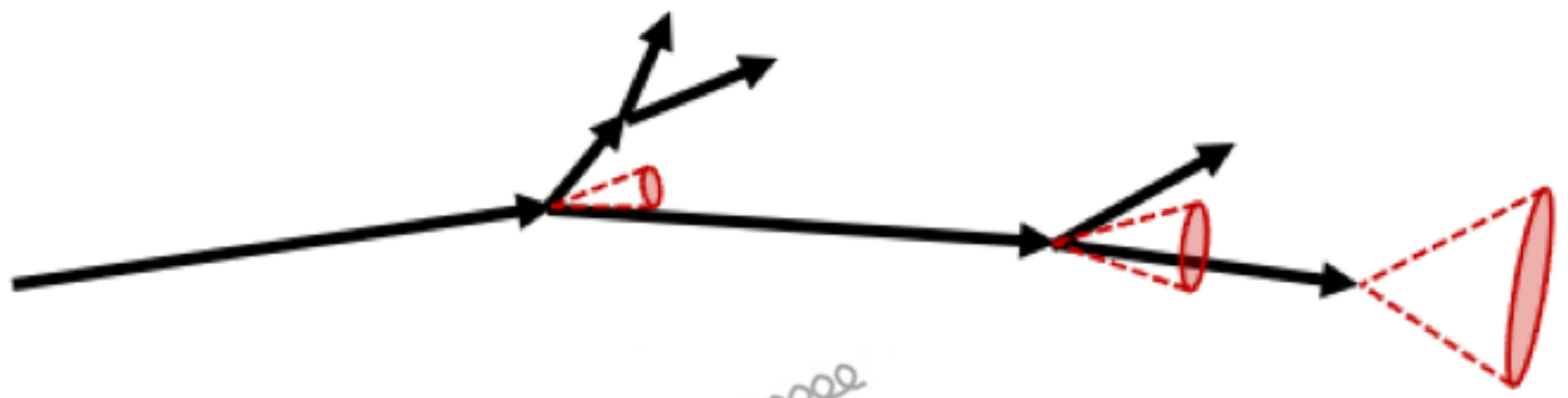

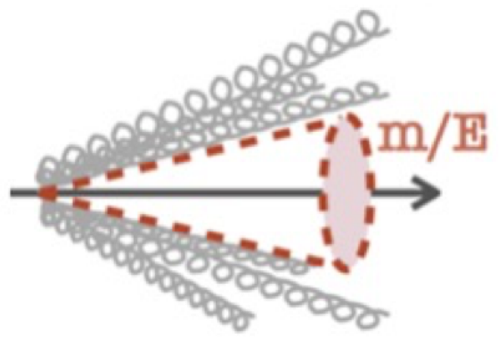

Casimir color factors

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Mass effects

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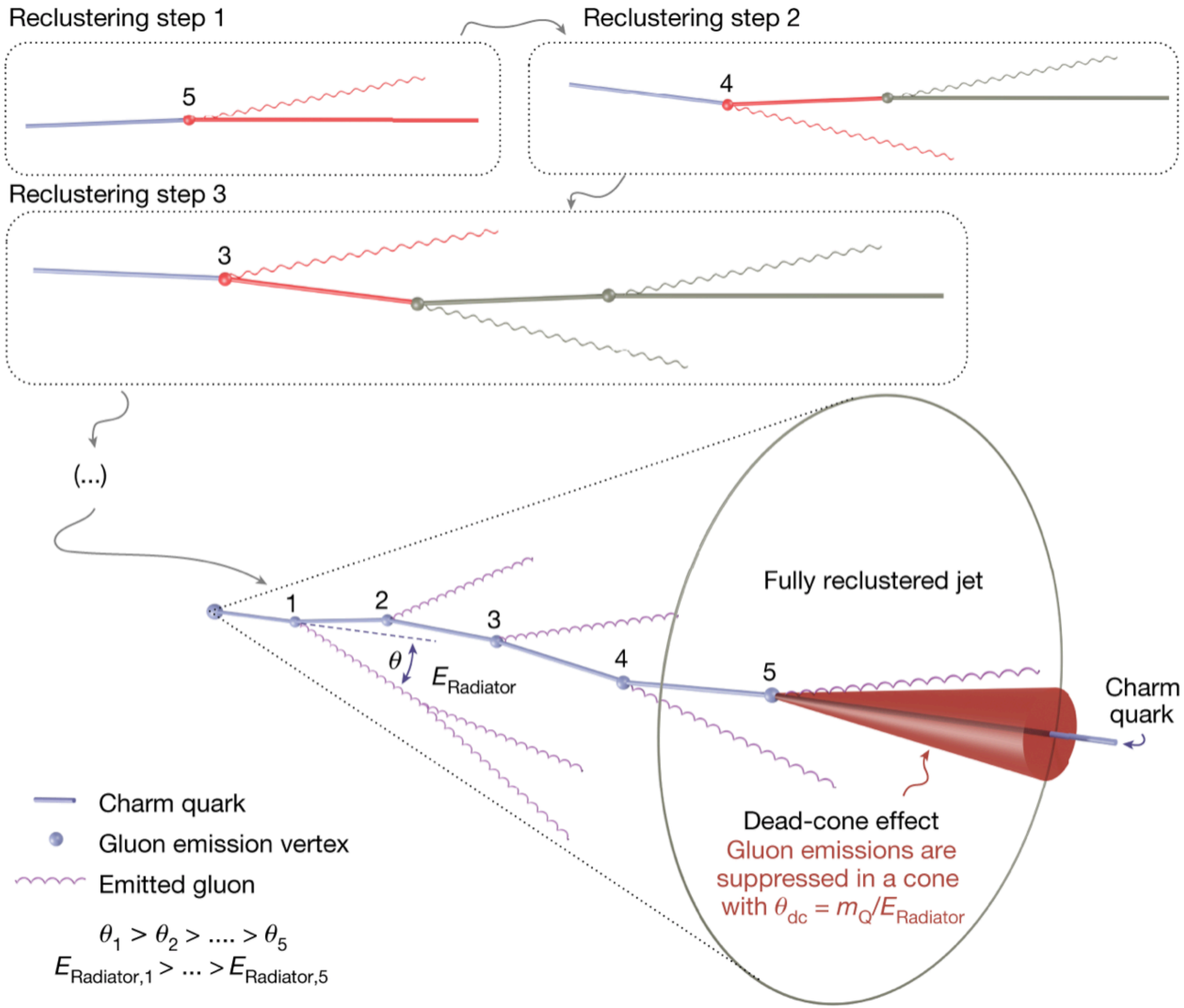
Mass effects are dominant at low p_T

$$\theta_c \sim \frac{m_Q}{E}$$

First direct observation of dead-cone effect

Challenges of Measurement:

- Determining the dynamic direction of heavy-quark throughout the shower



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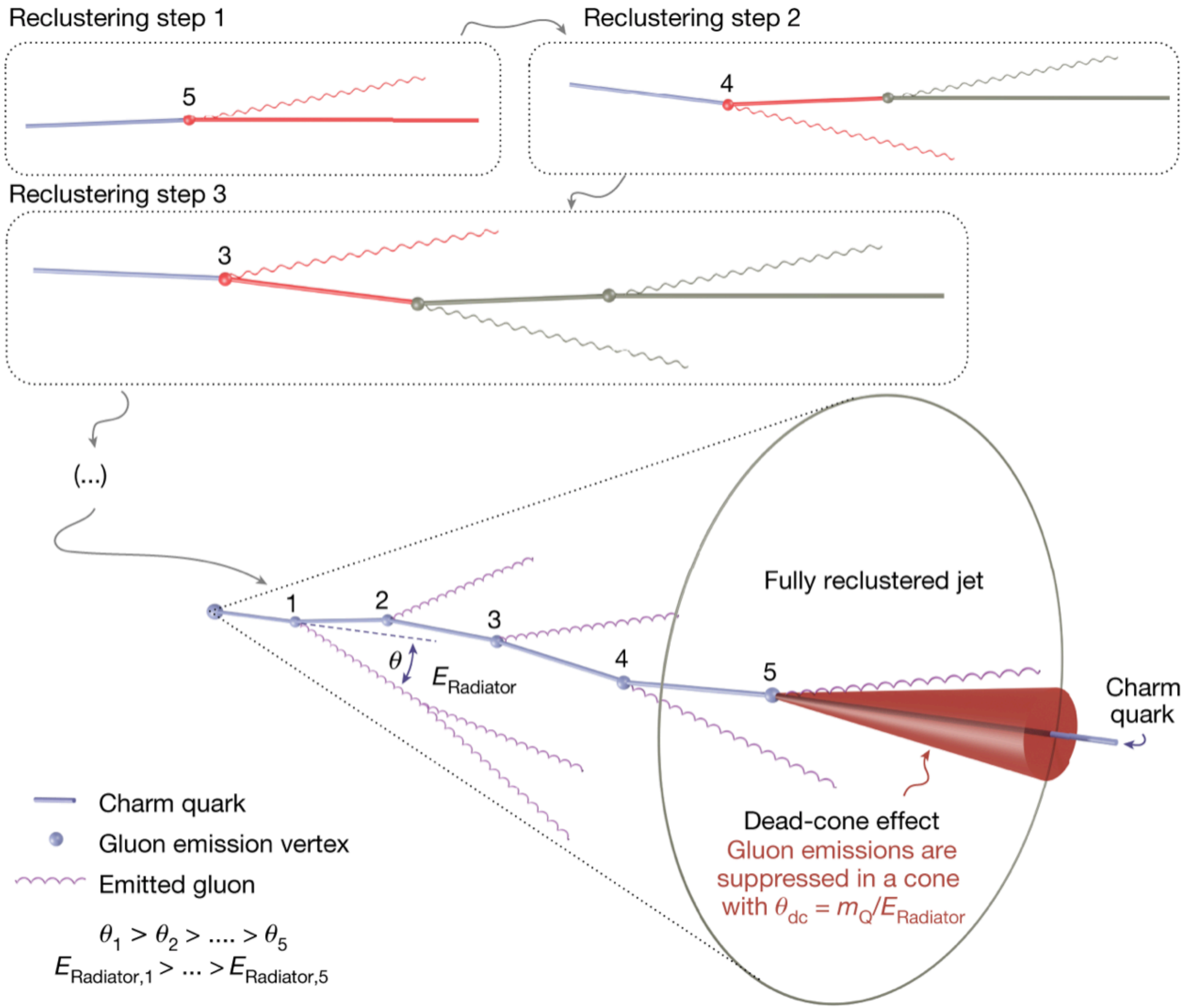

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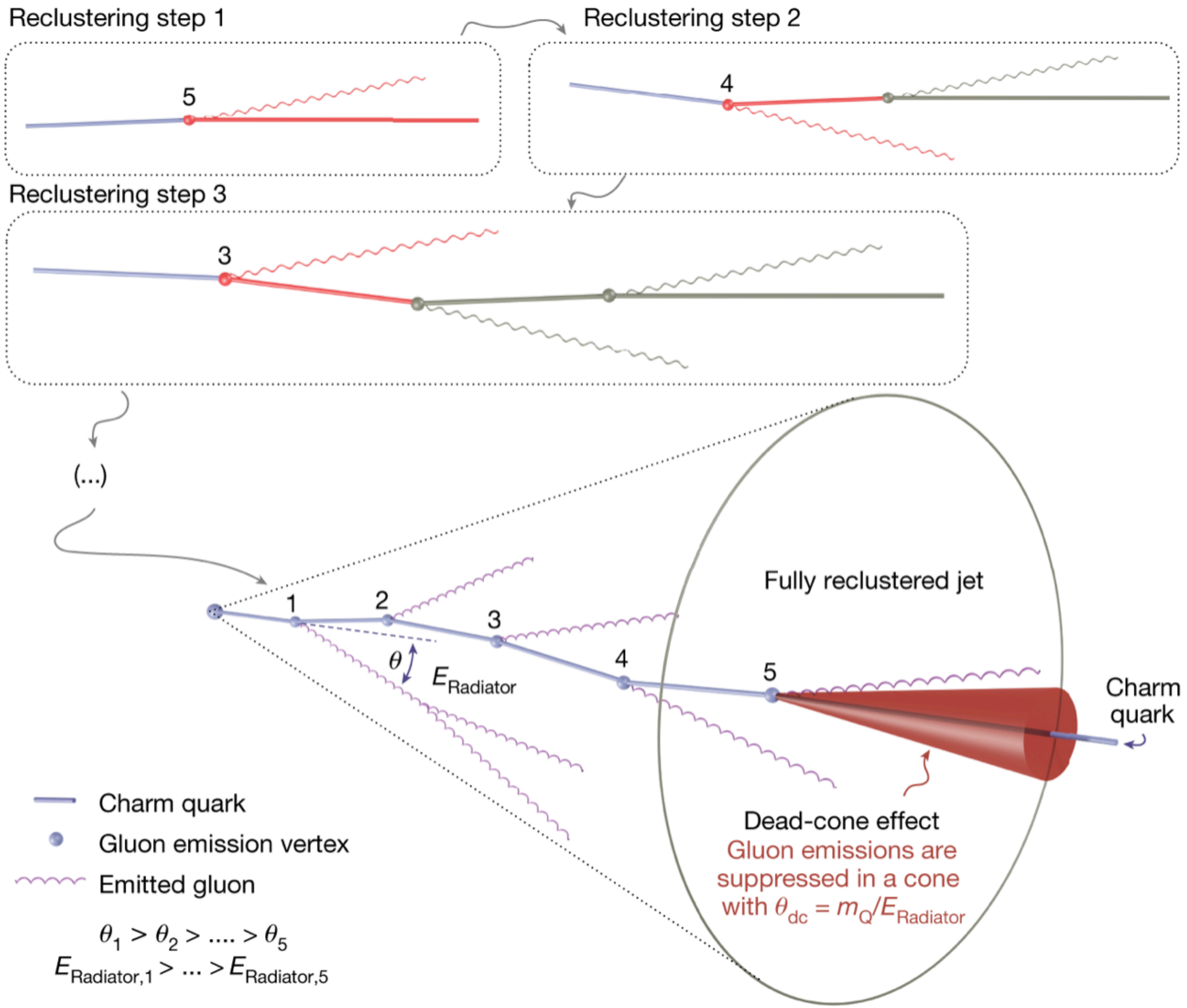
→ matches QCD



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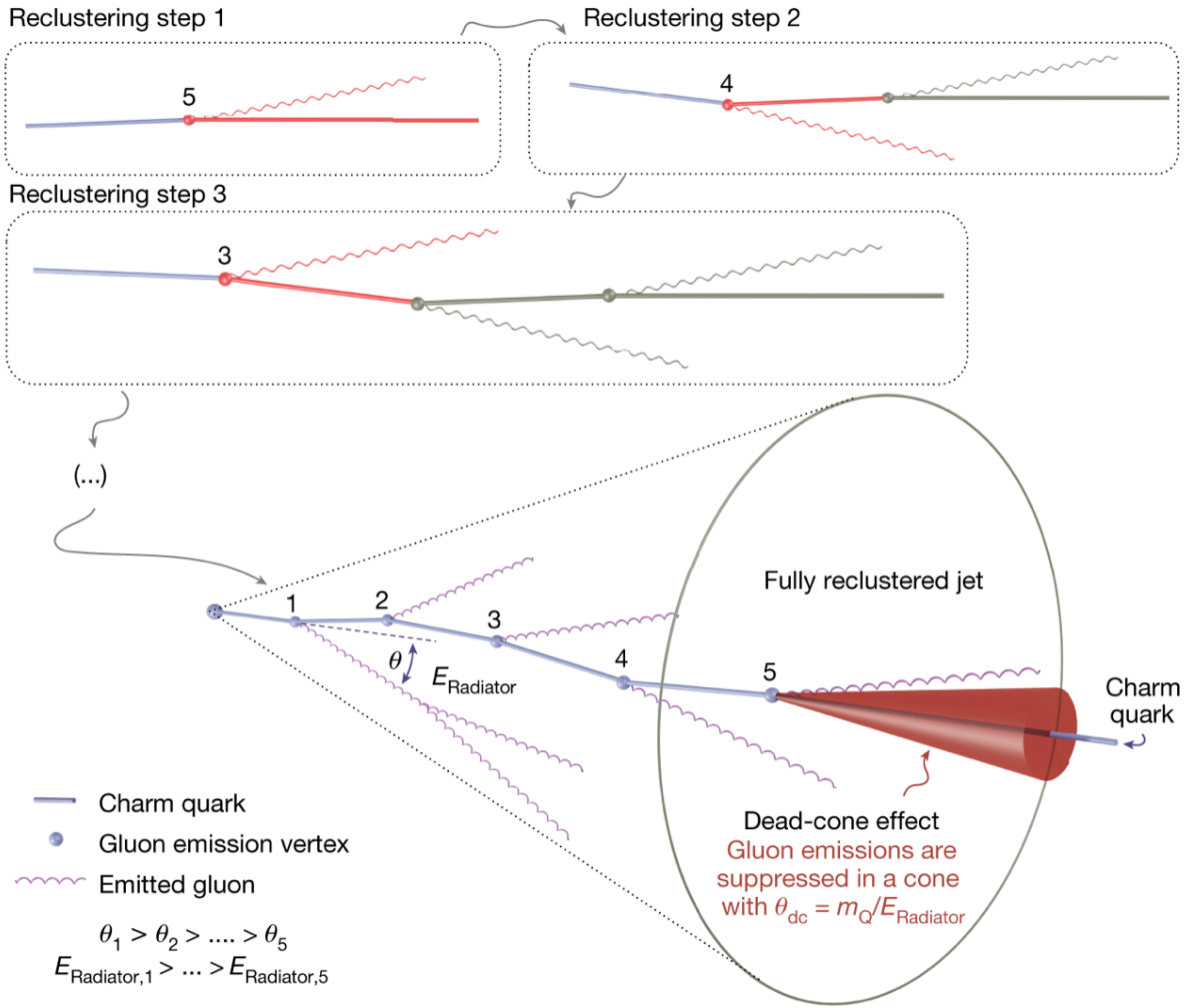

Declustring: Follow the branch with the D meson to identify the c-branch

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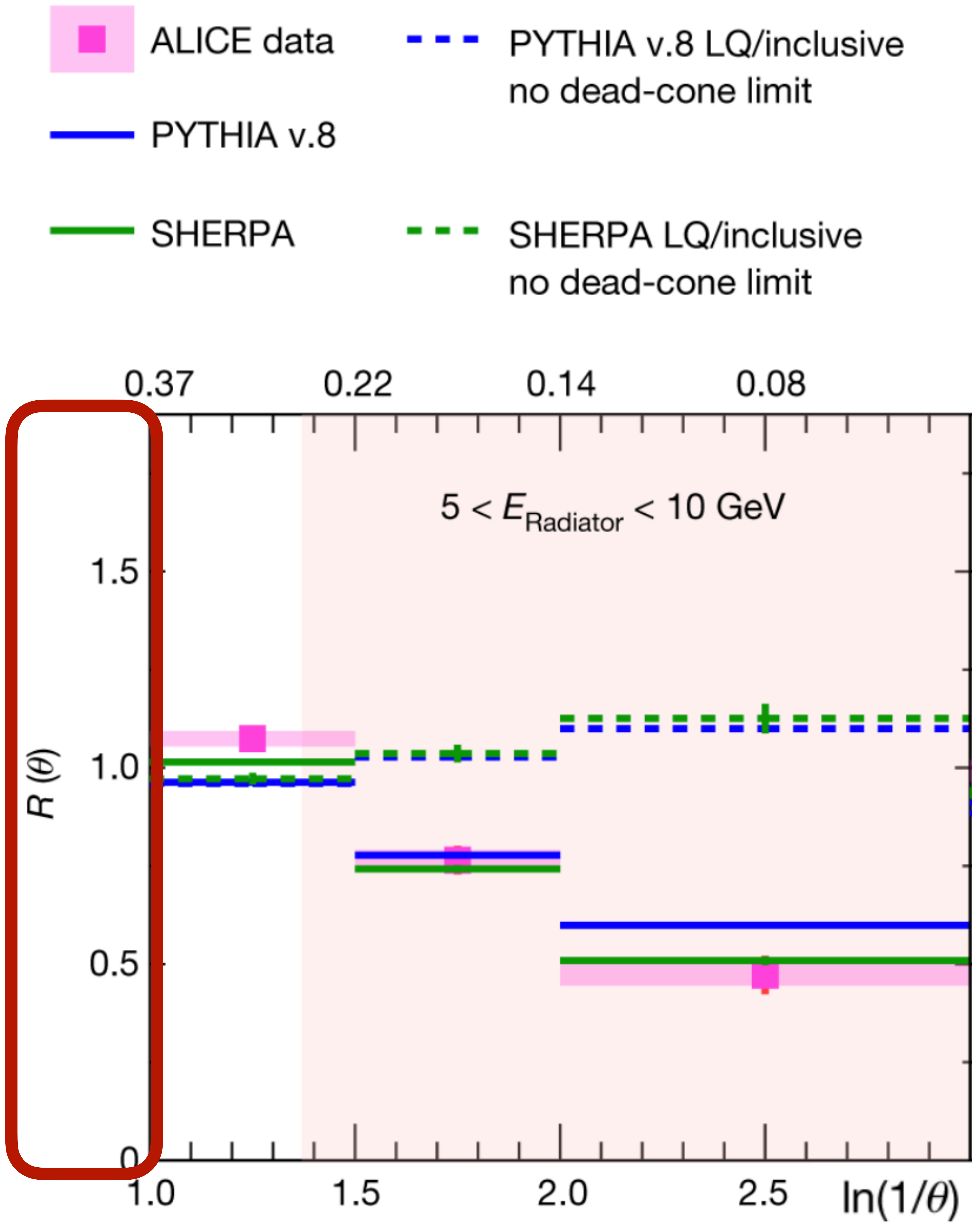

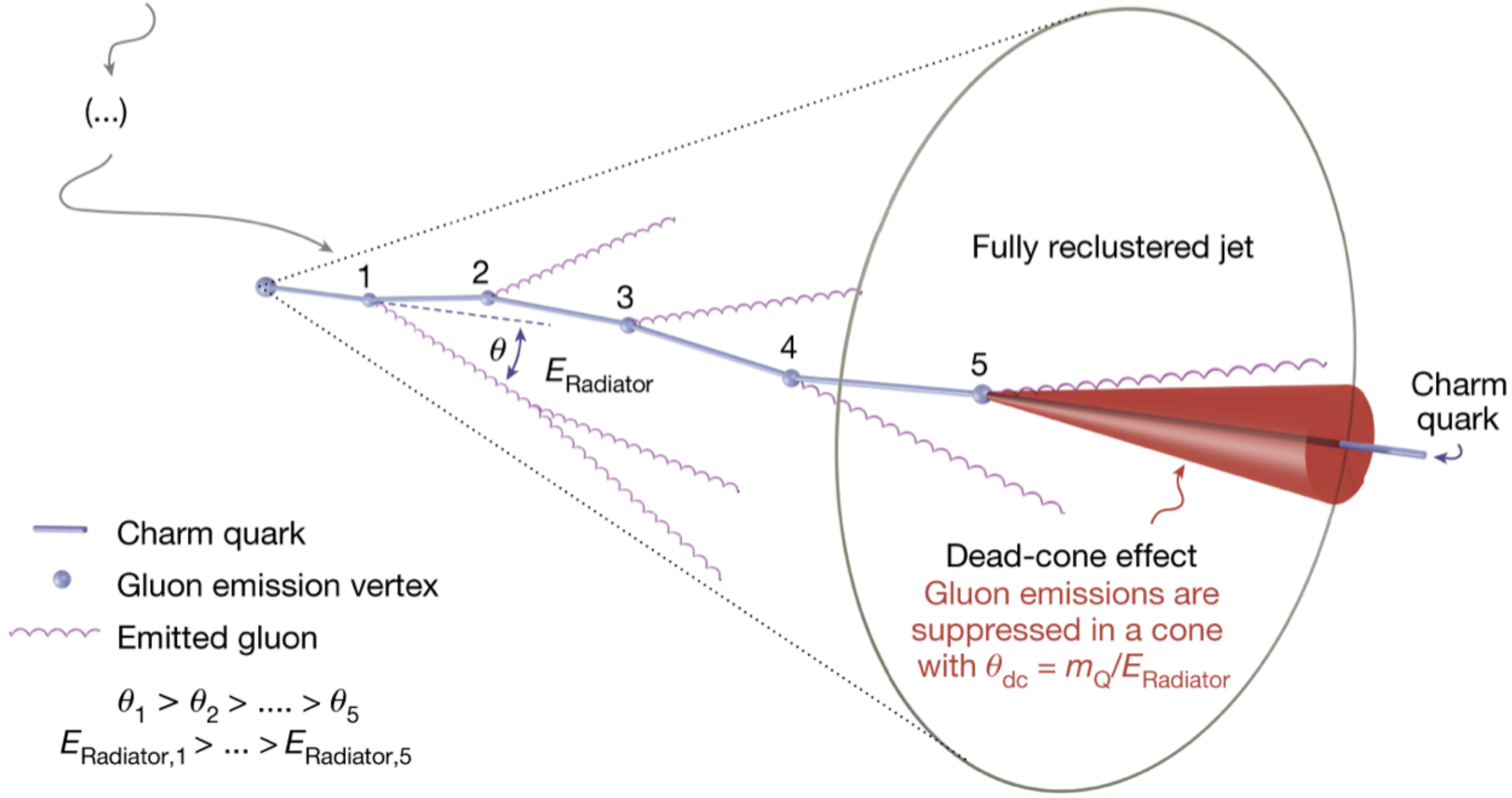

ratio of the splitting angle (θ) distribution for D^0-tagged vs. inclusive jets, vs. E_{Radiator}

$$R(\theta) = \frac{1}{N^{\mathrm{D^0 jets}}}\frac{\mathrm{d}n^{\mathrm{D^0 jets}}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{N^{\text{inclusive jets}}}\frac{\mathrm{d}n^{\text{inclusive jets}}}{\mathrm{d}\ln(1/\theta)}\Big|_{k_{\mathrm{T}},E_{\text{Radiator}}}$$

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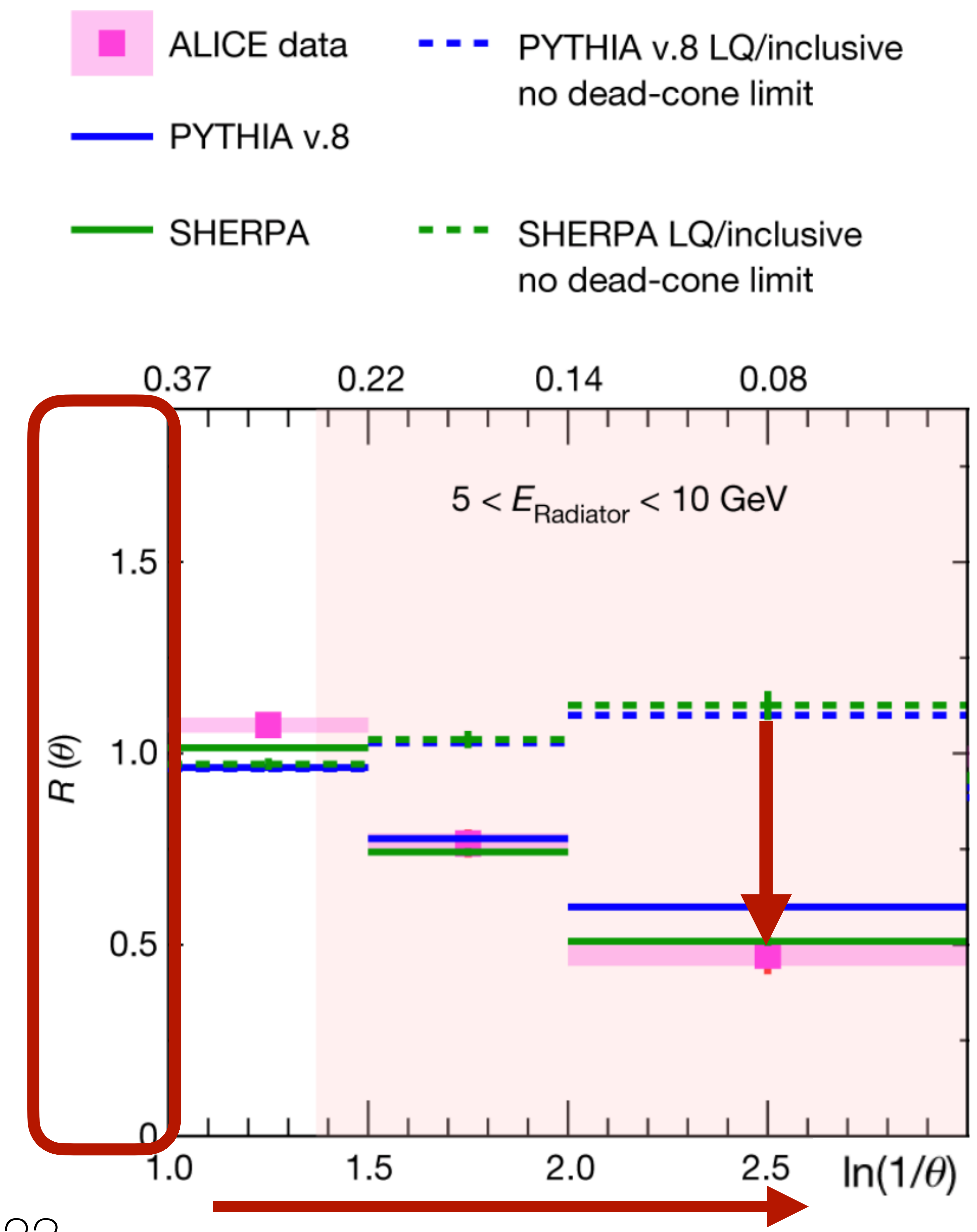
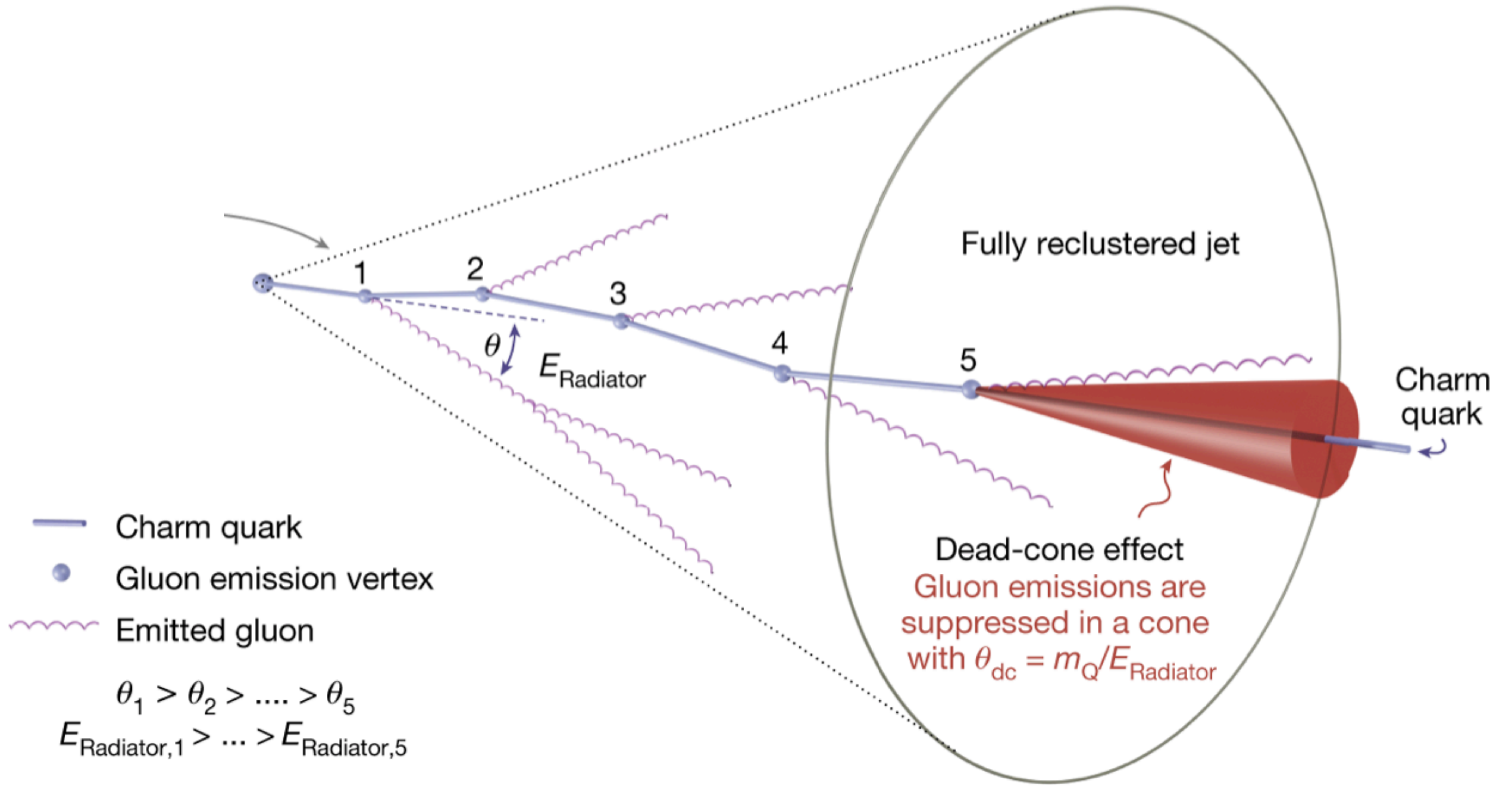


Smaller angles



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significant suppression of small-angle emissions

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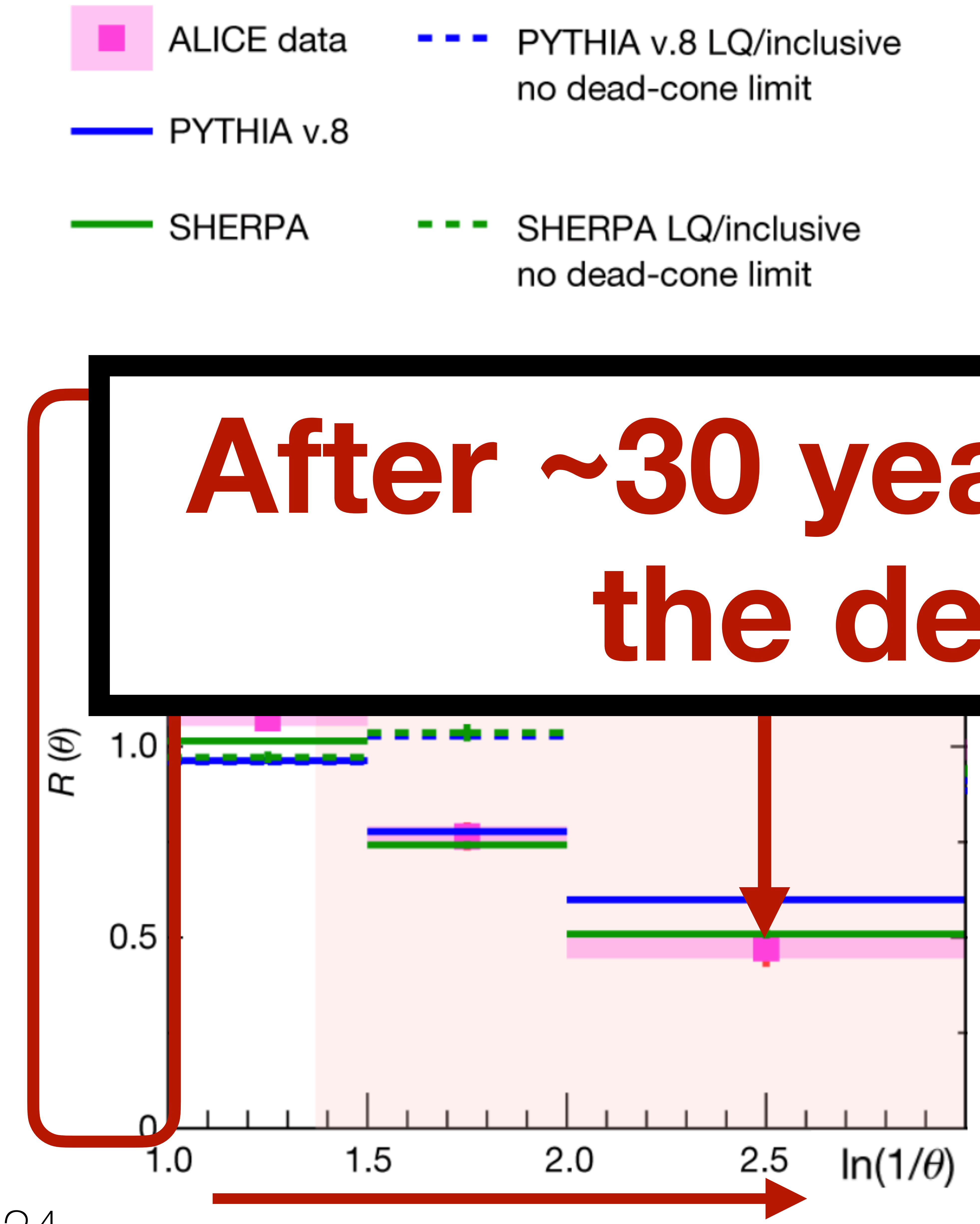

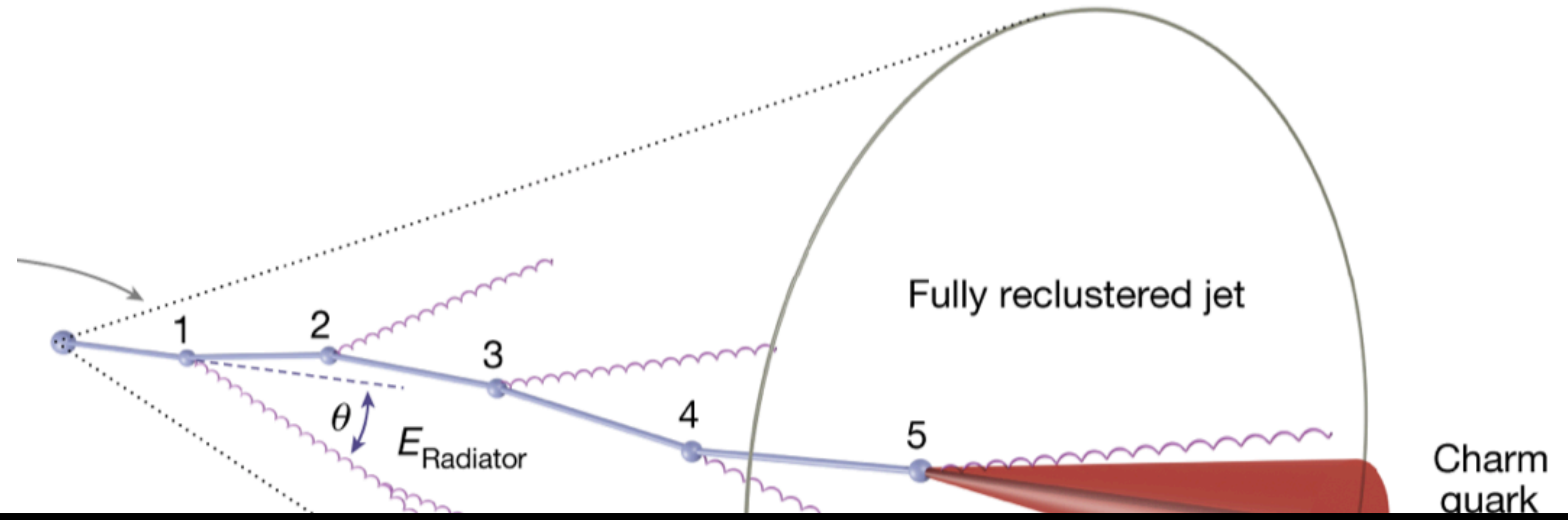

After ~30 years, directly measured the dead-cone effect!

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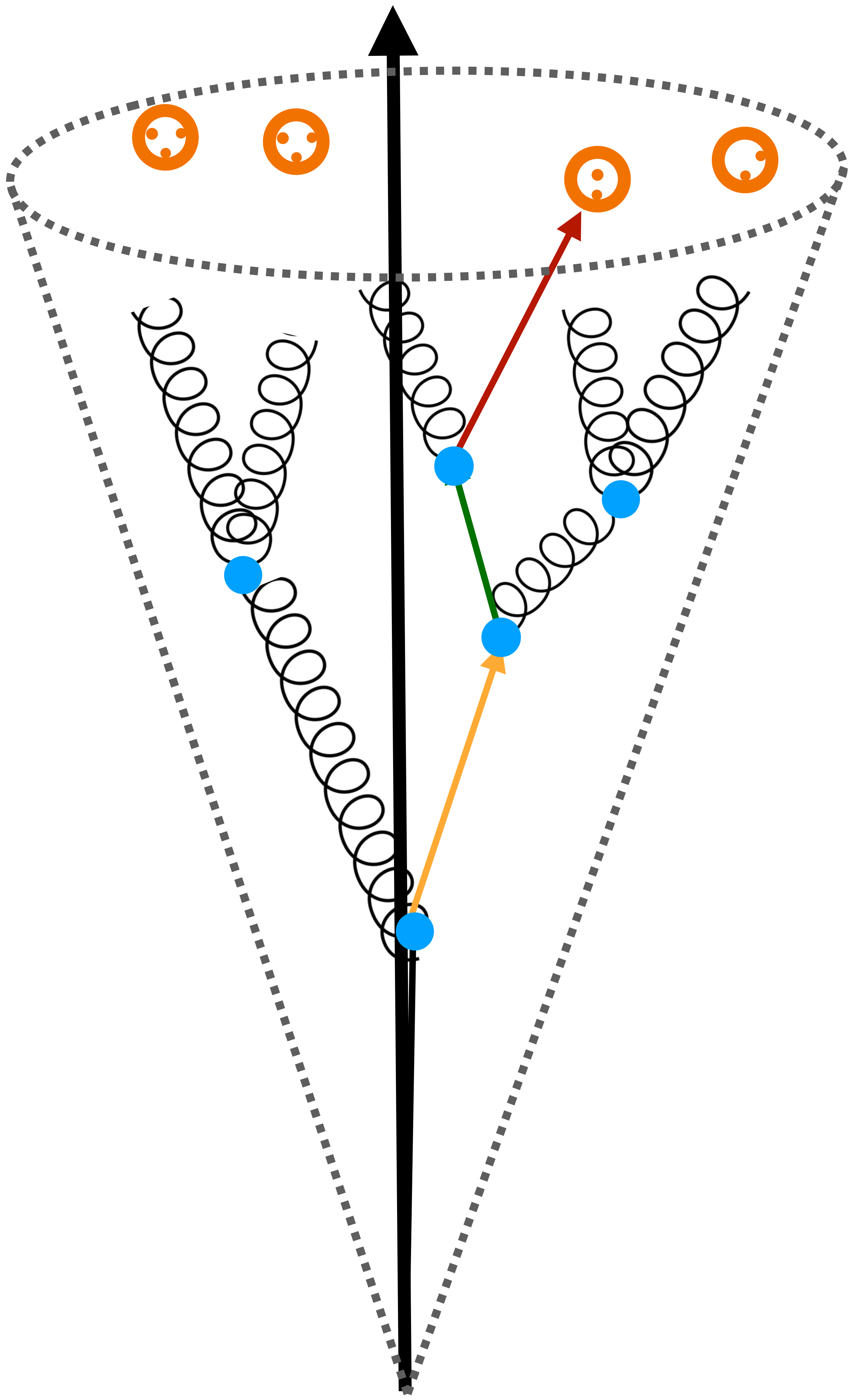
Smaller angles

Where is the p_T in the jet?

Jet Angularities :

$$\lambda_{\alpha} = \sum_{i \in jet} \dots$$



Where is the p_T in the jet?

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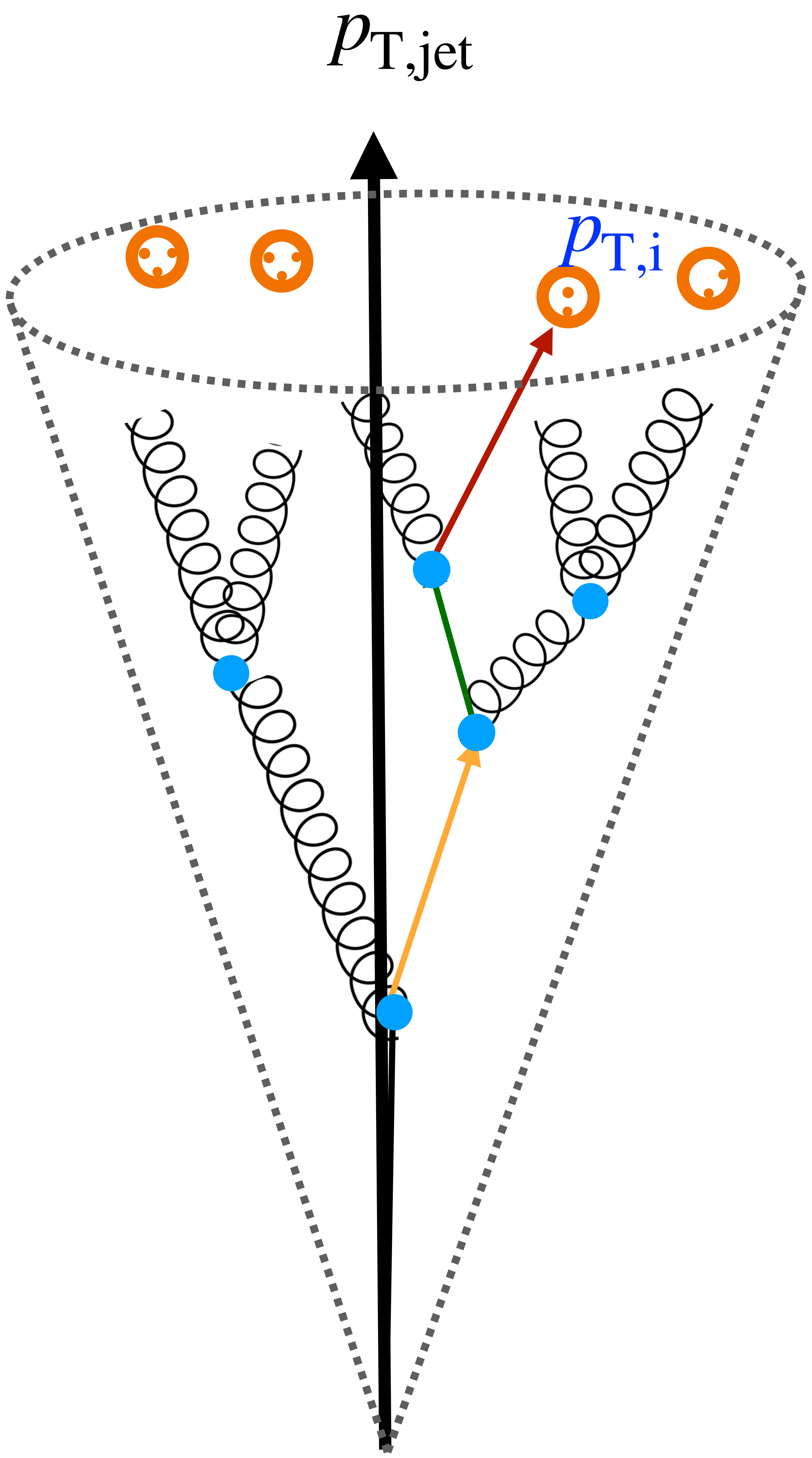

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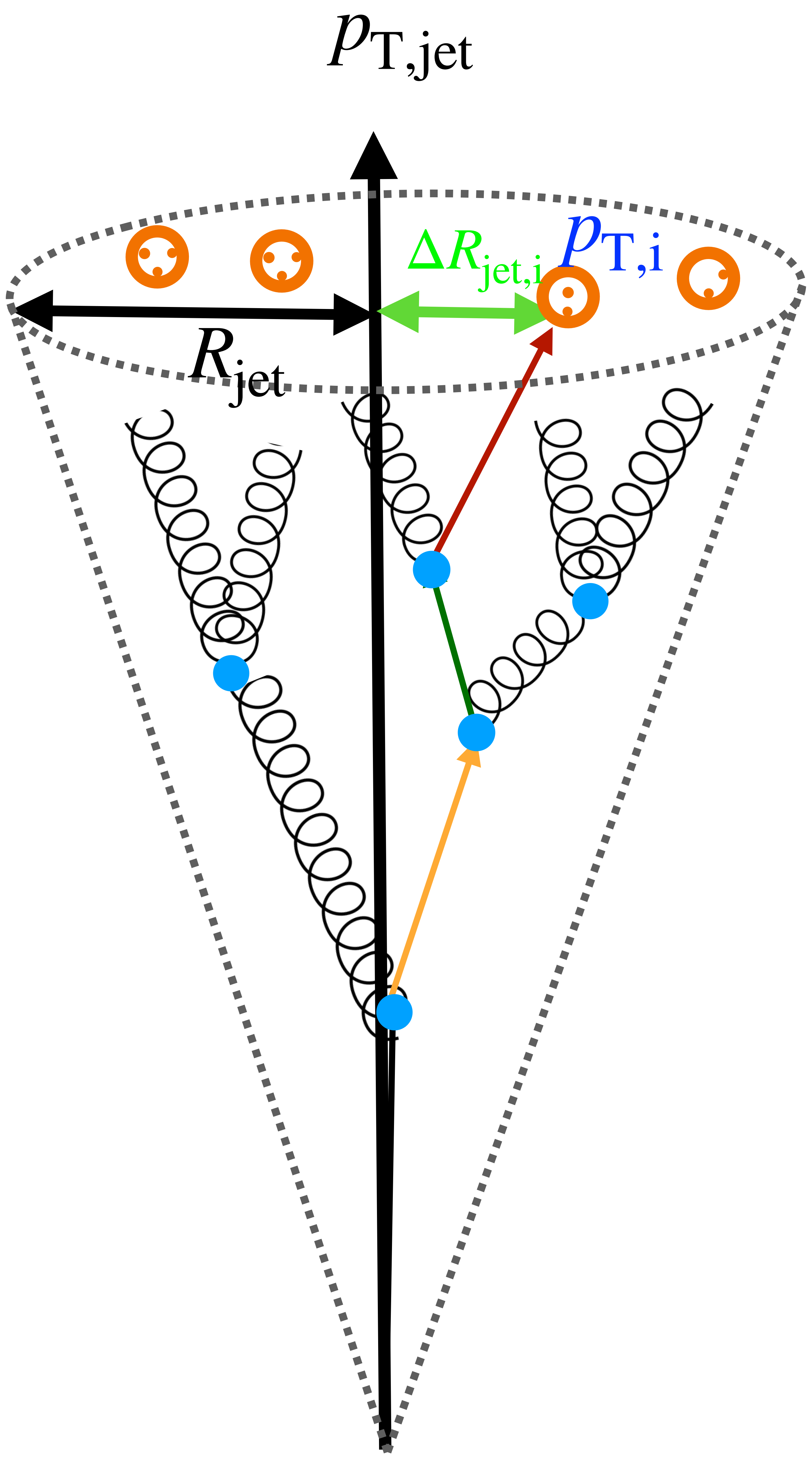

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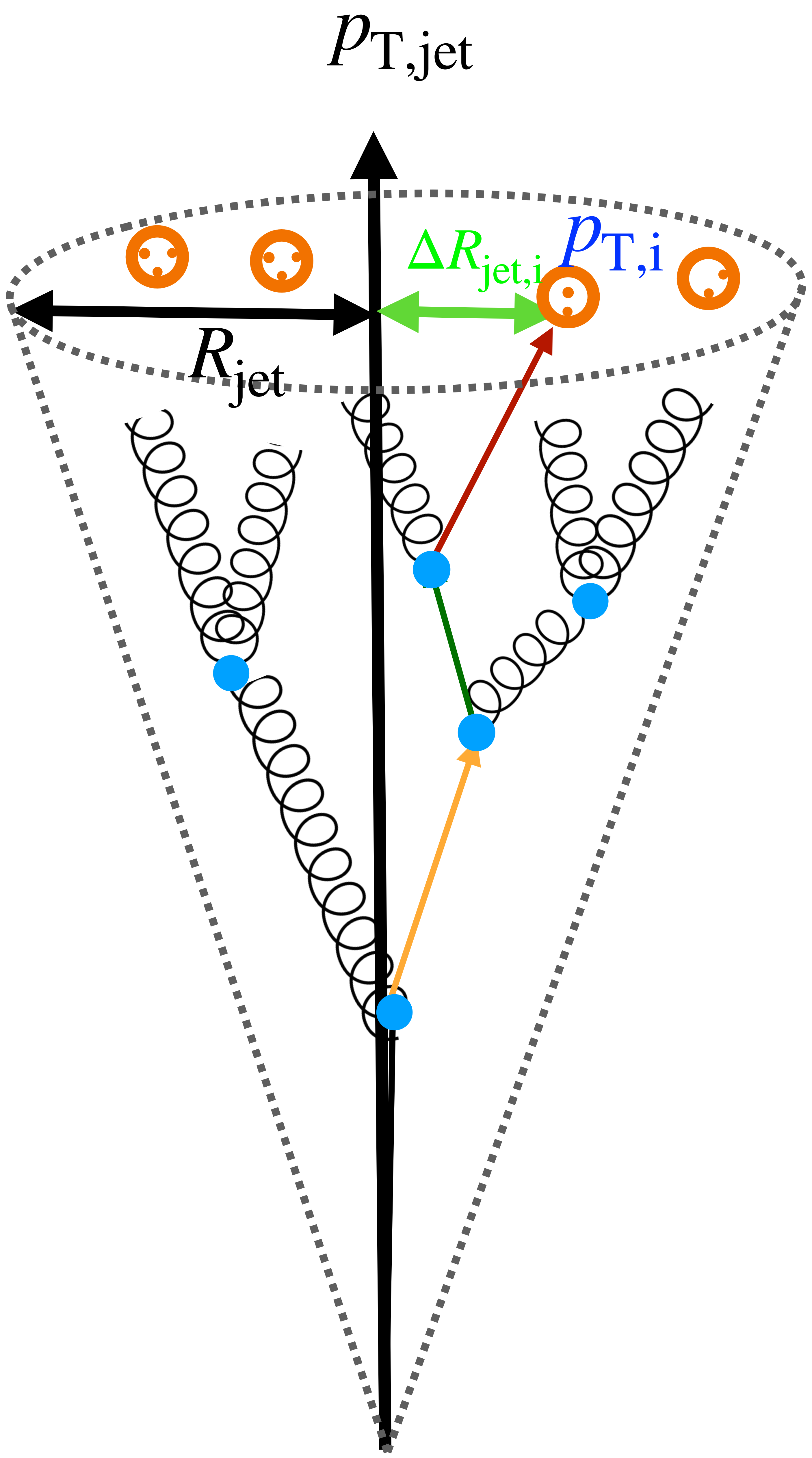

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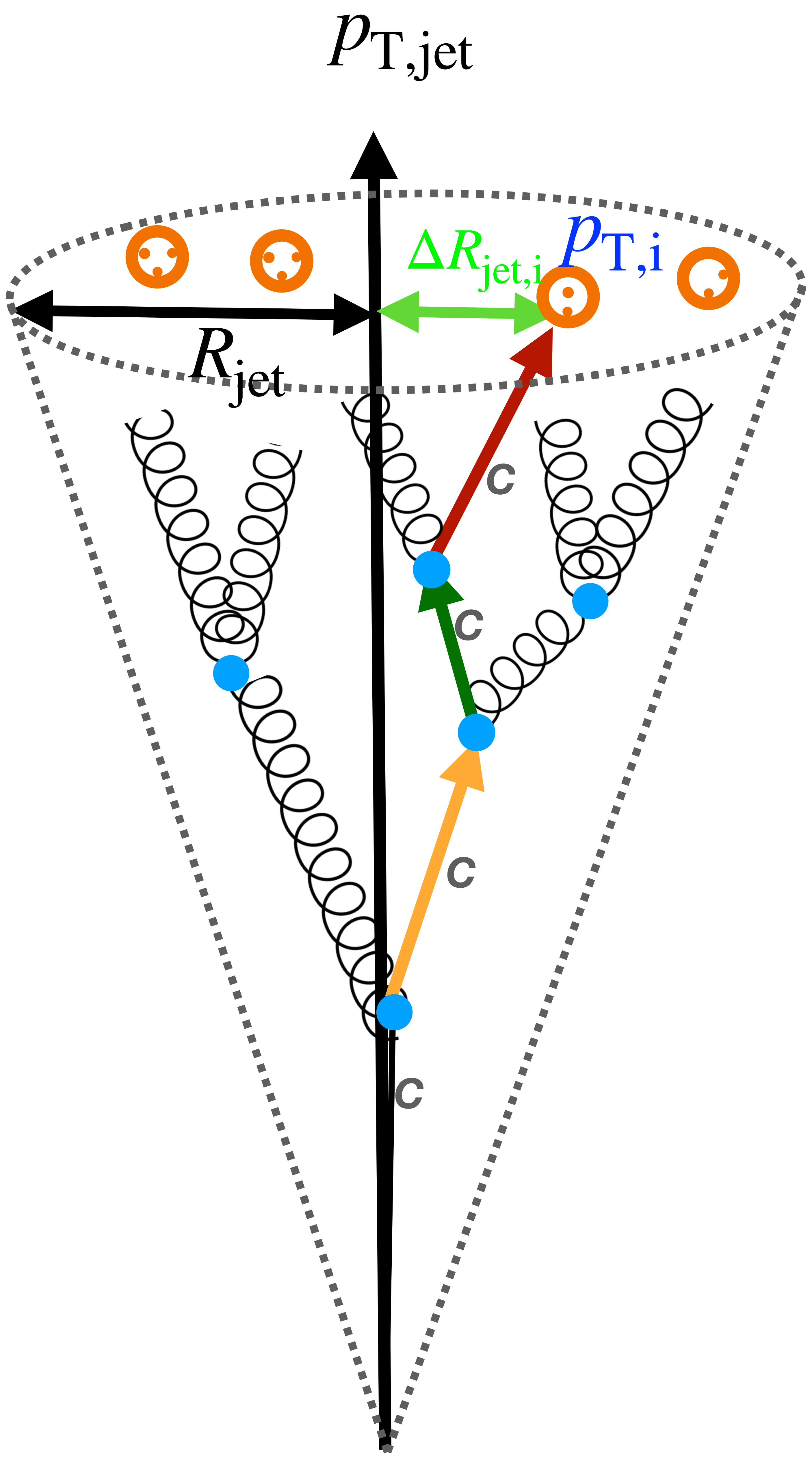

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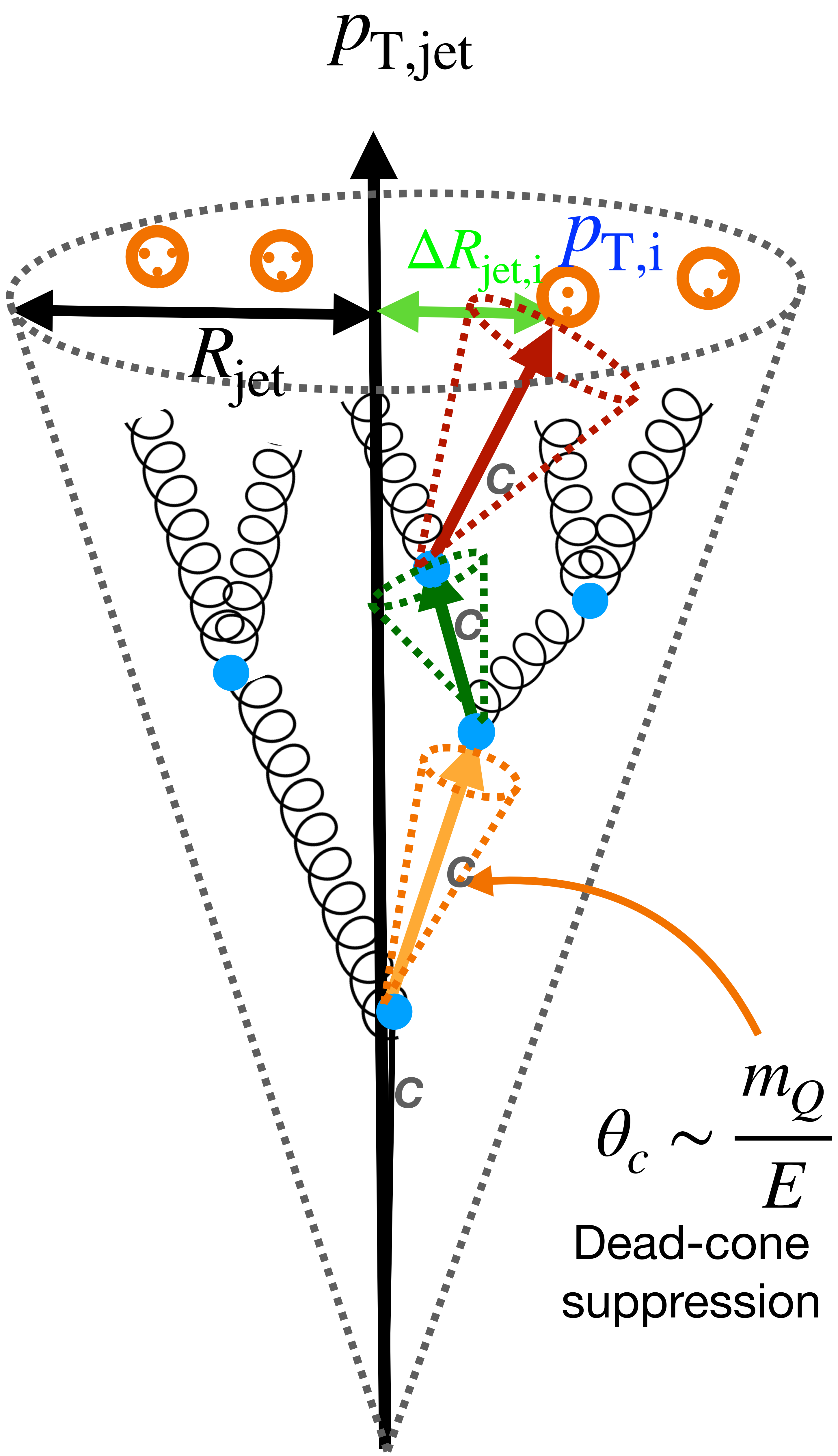

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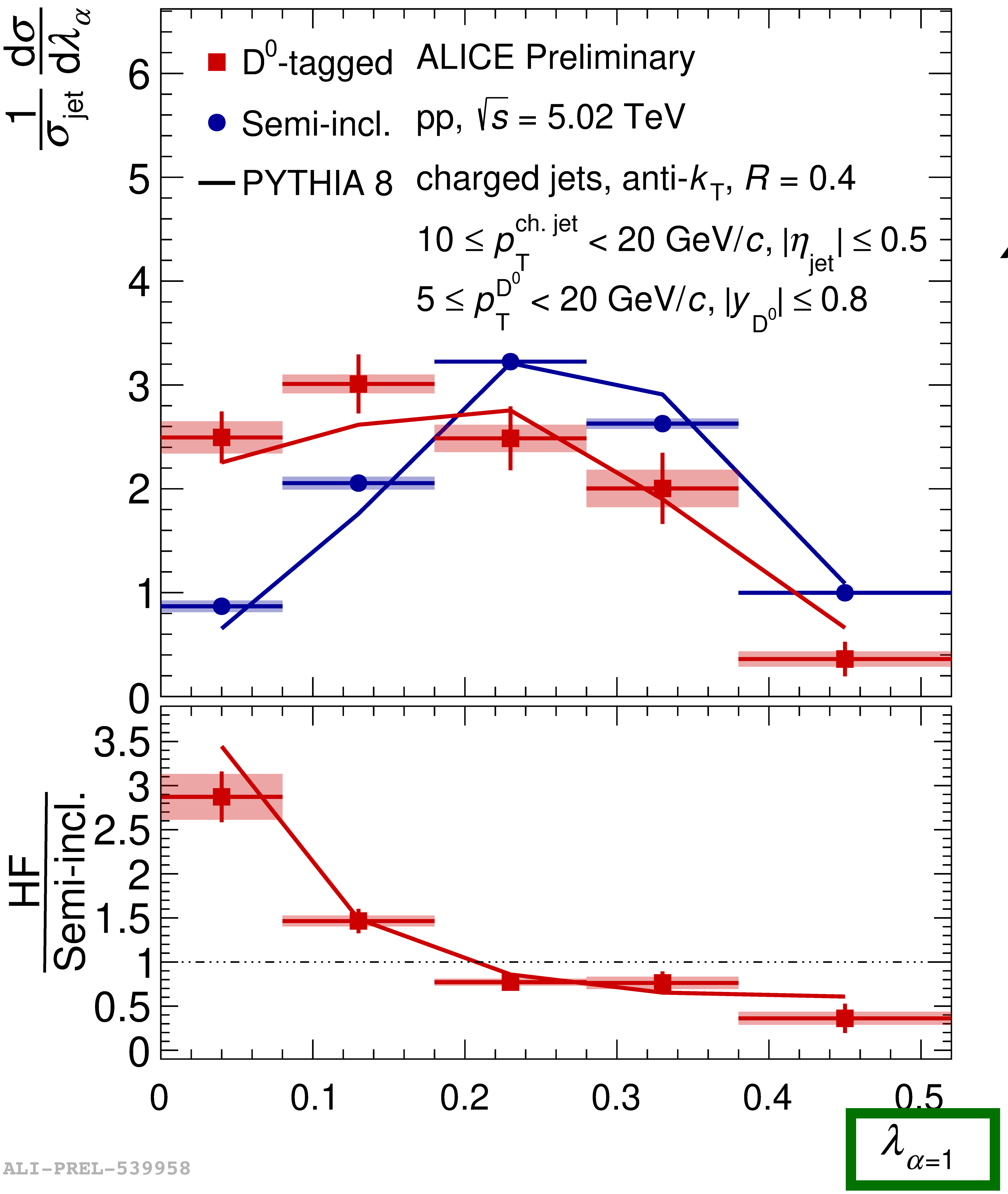

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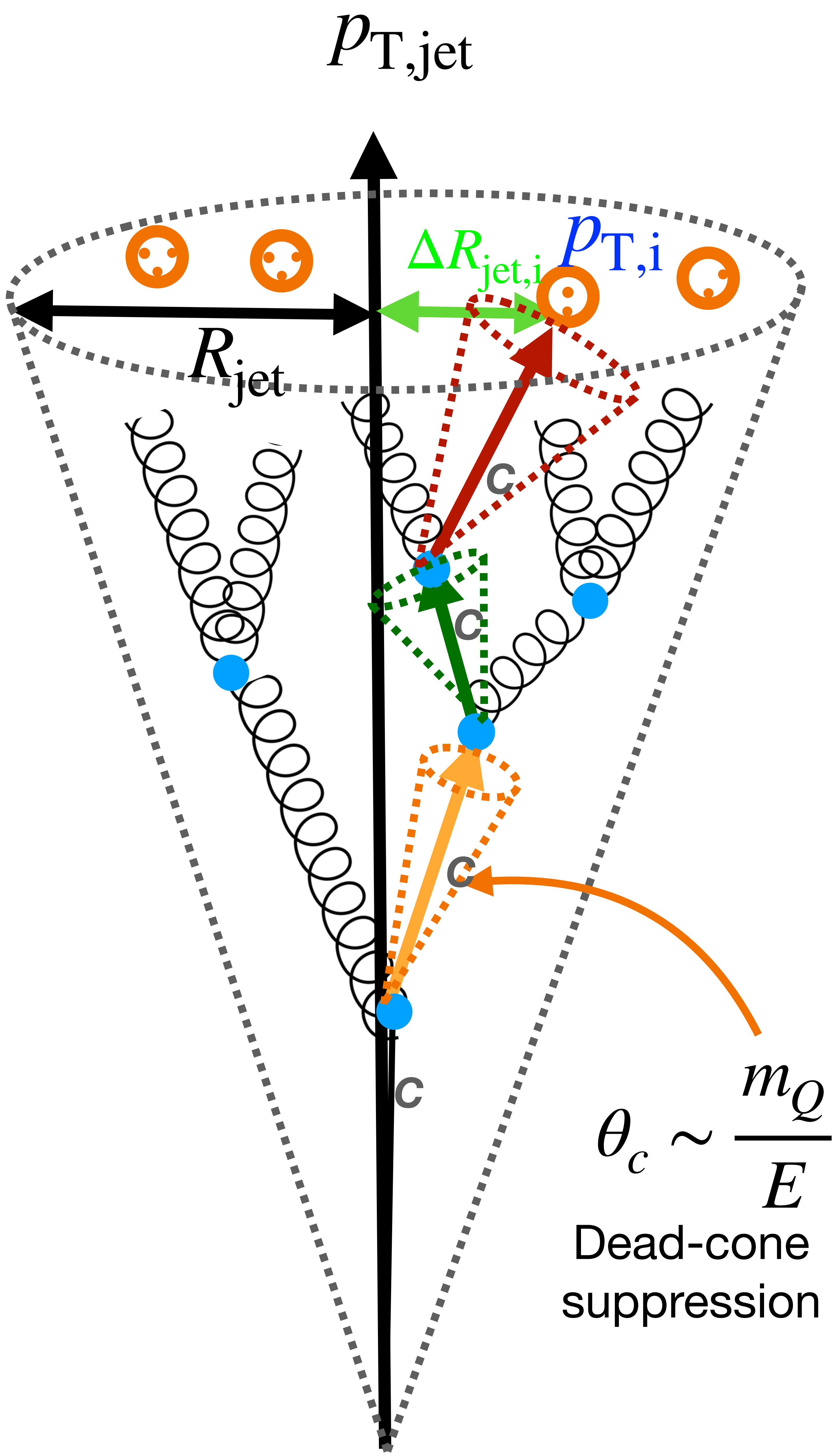

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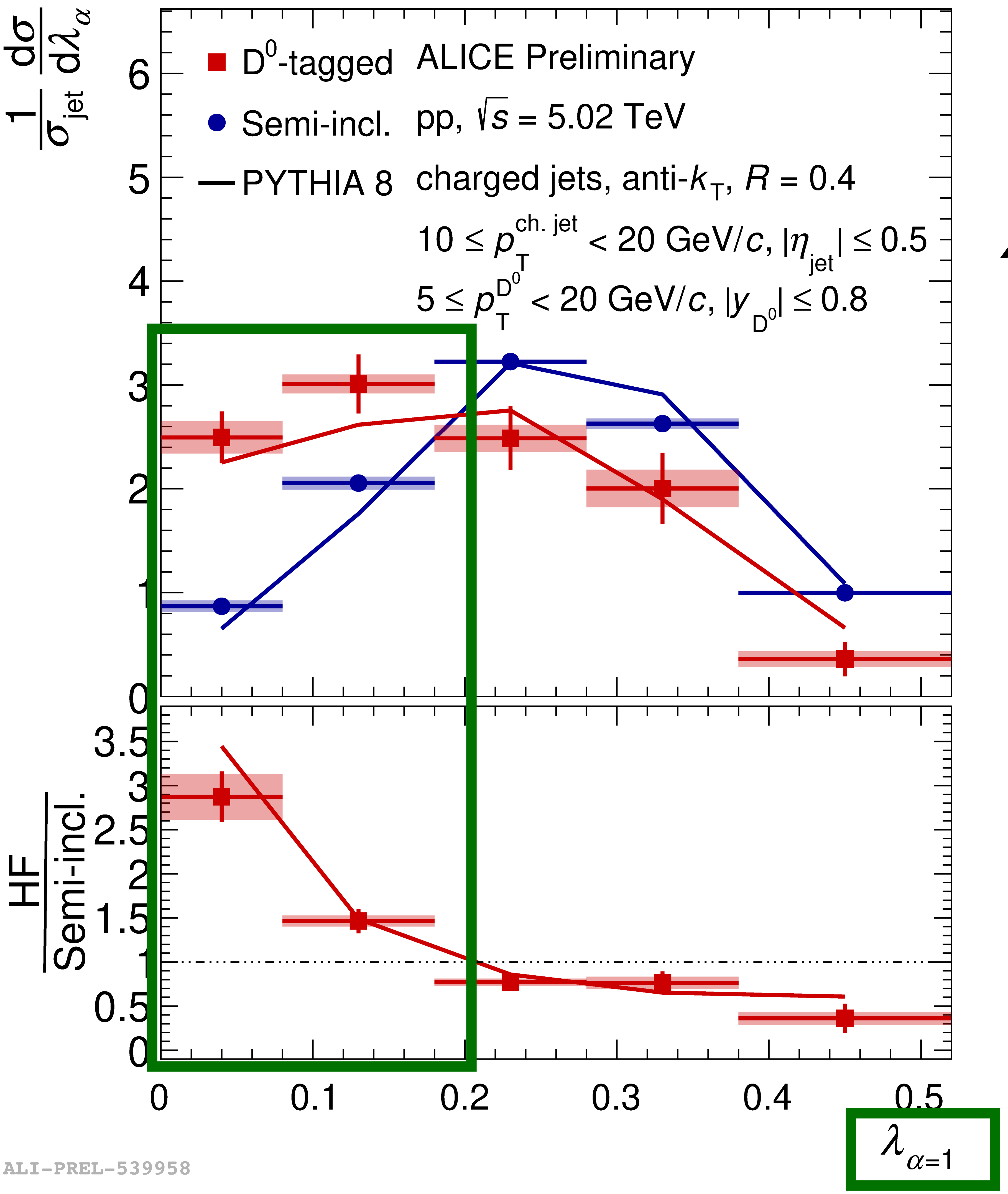

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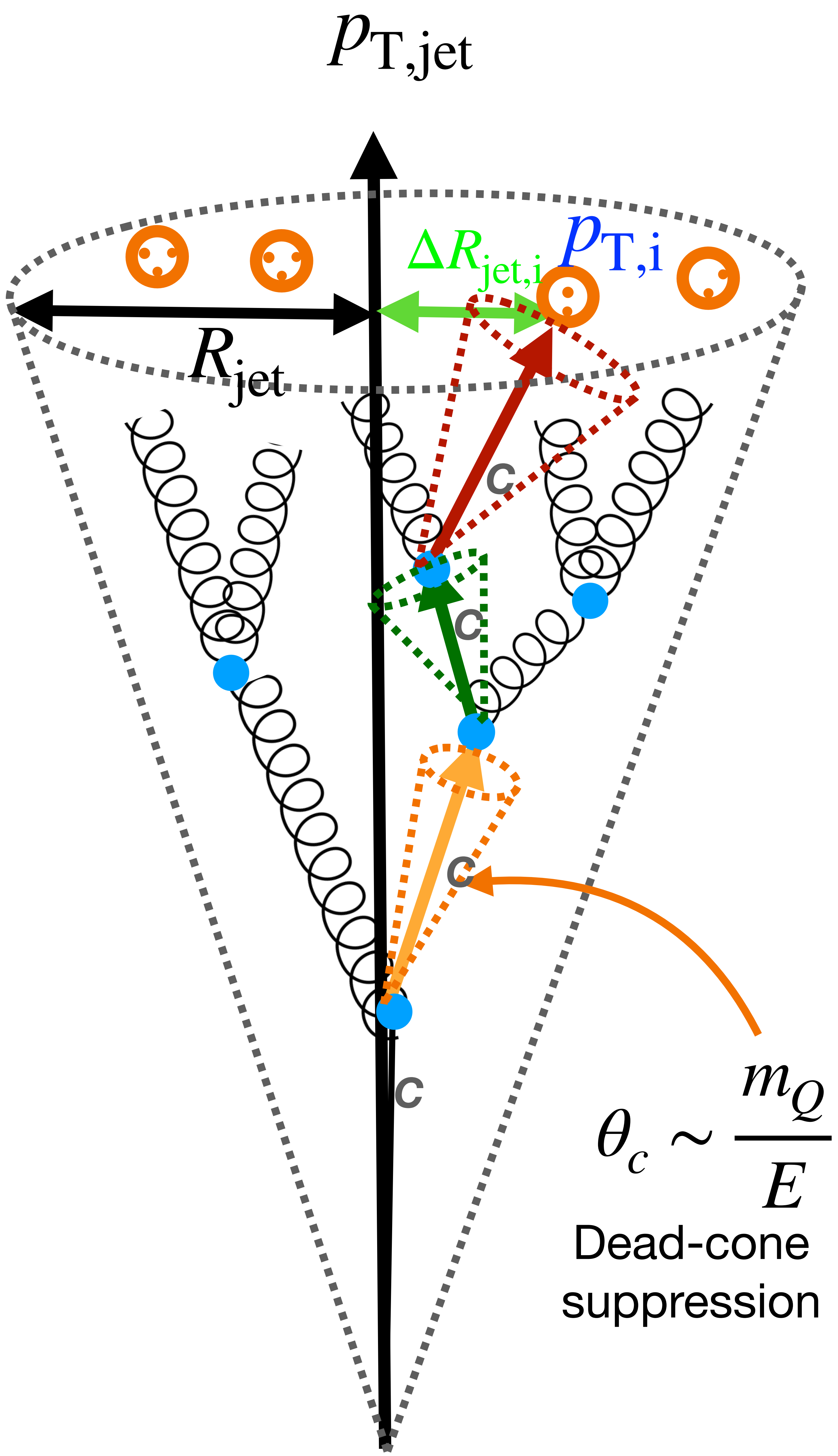
charm distribution shifted to lower values of $\lambda_{\alpha=1}$
→Dead-cone/mass effects



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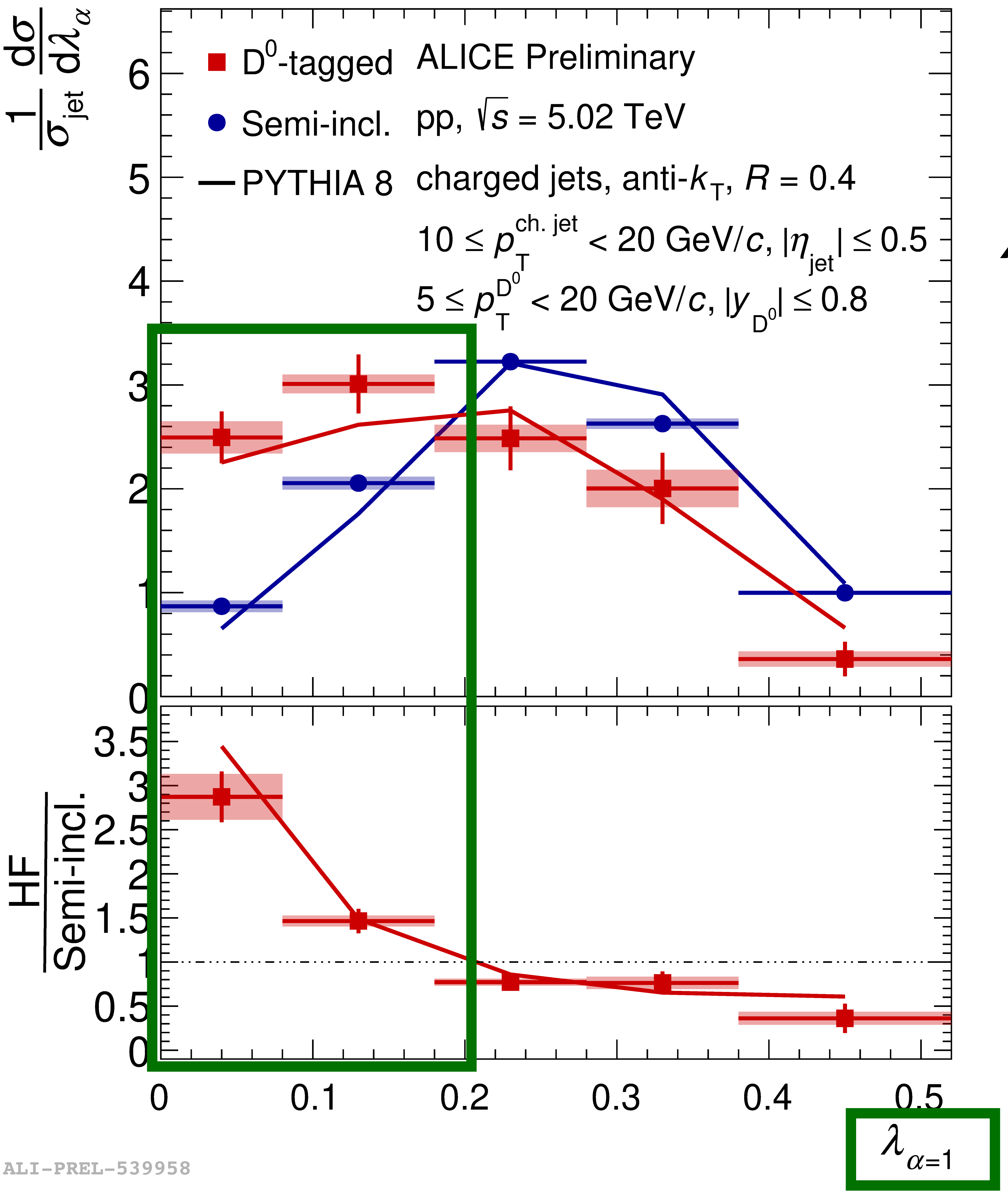

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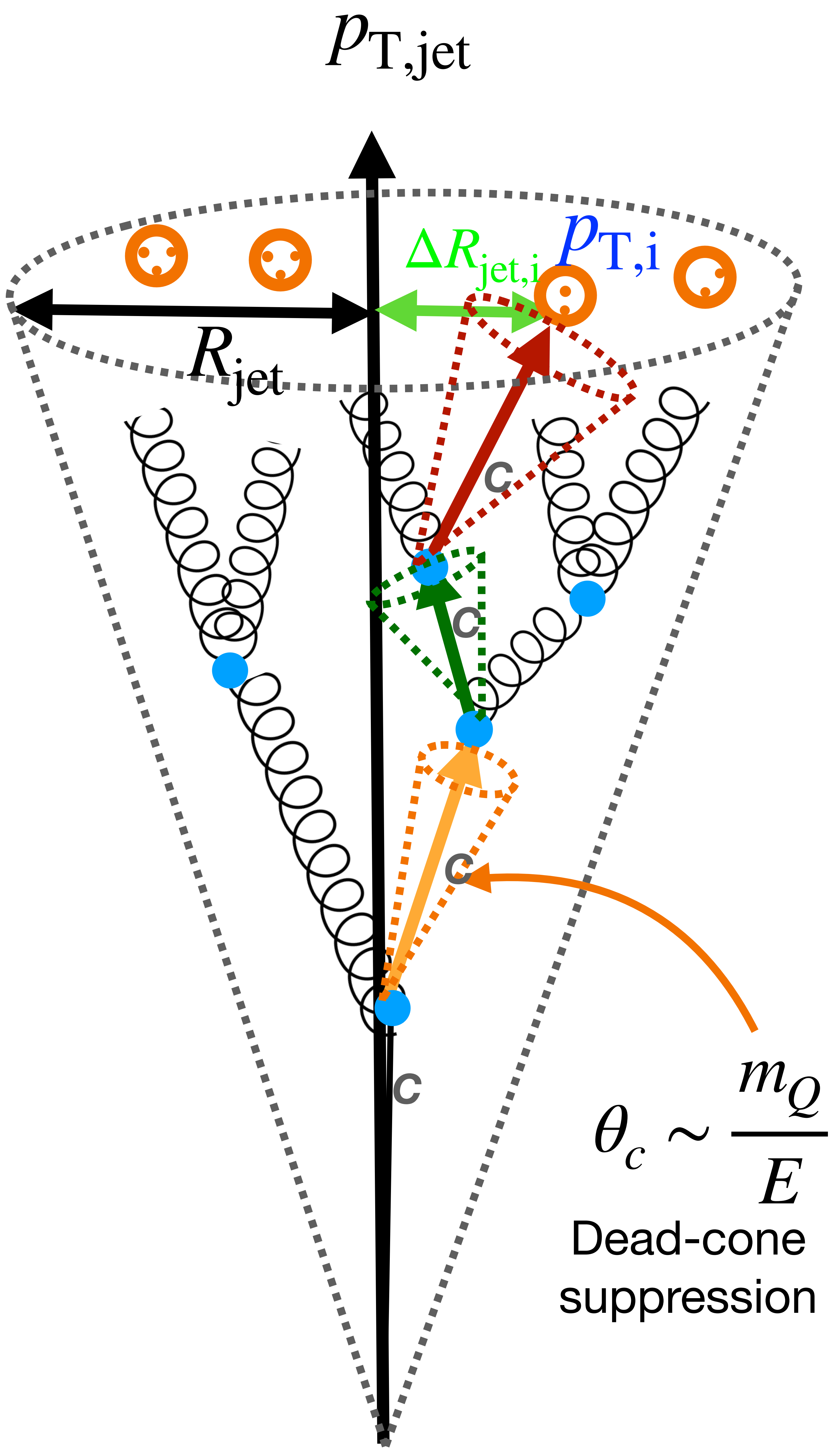

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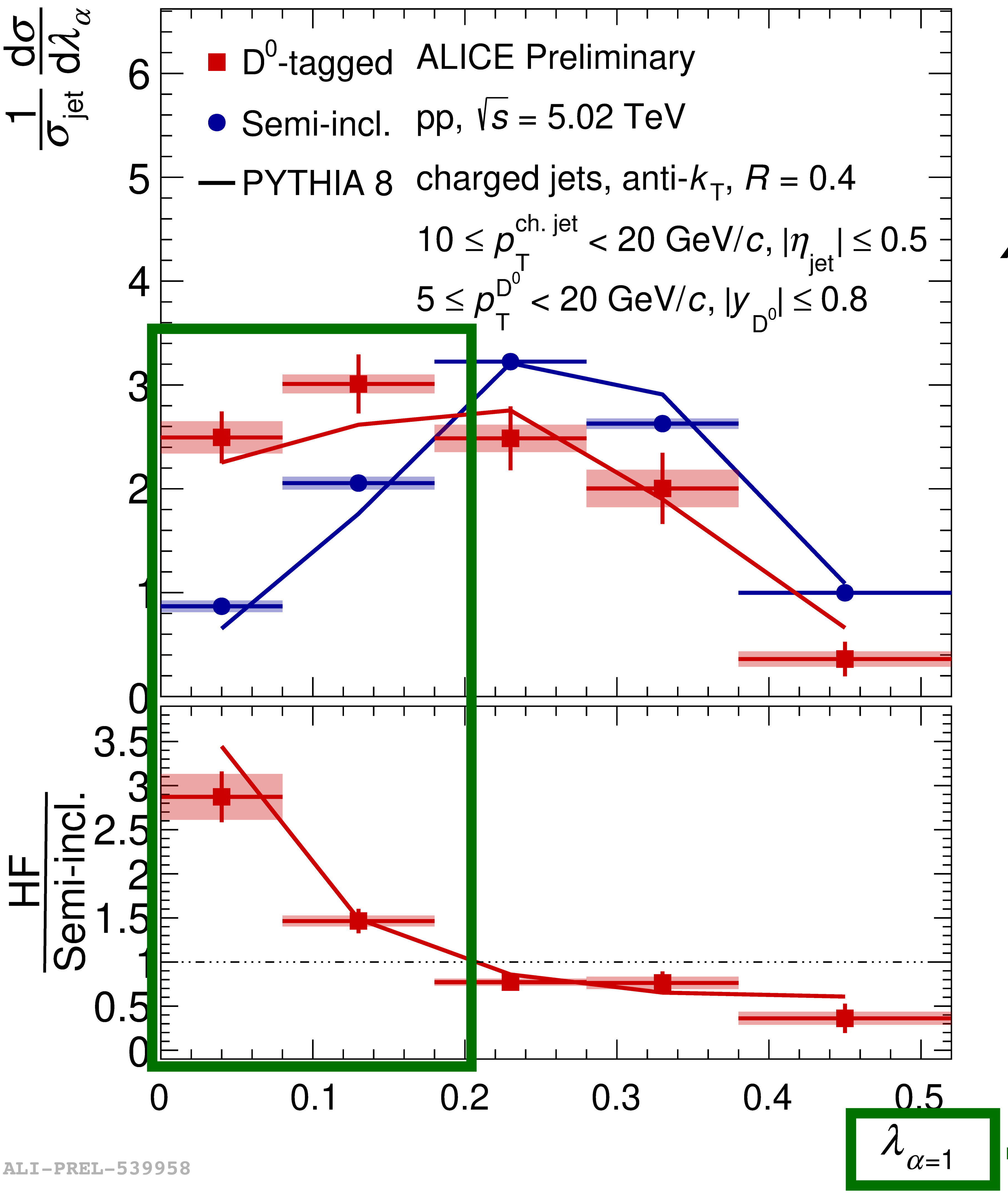

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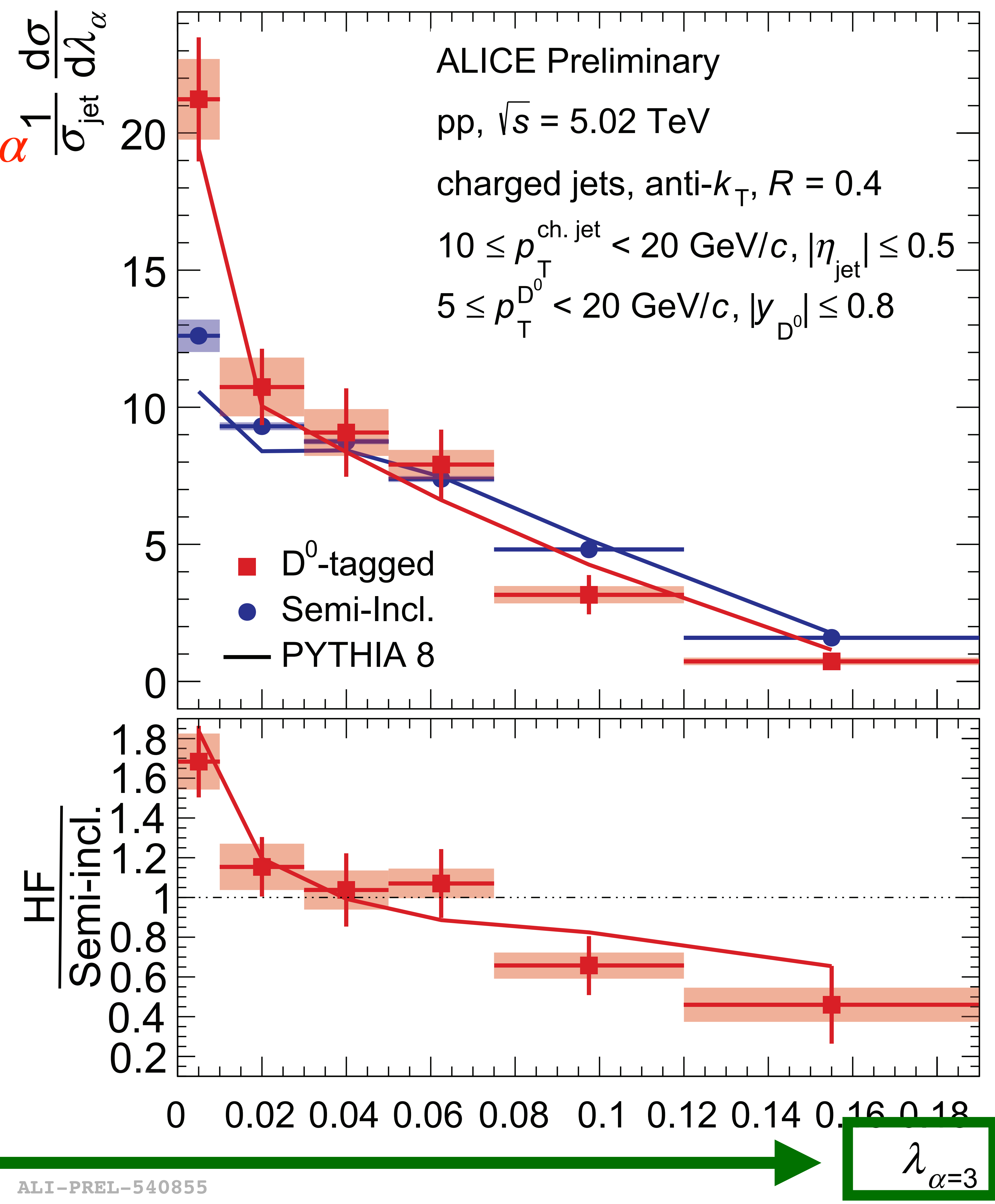
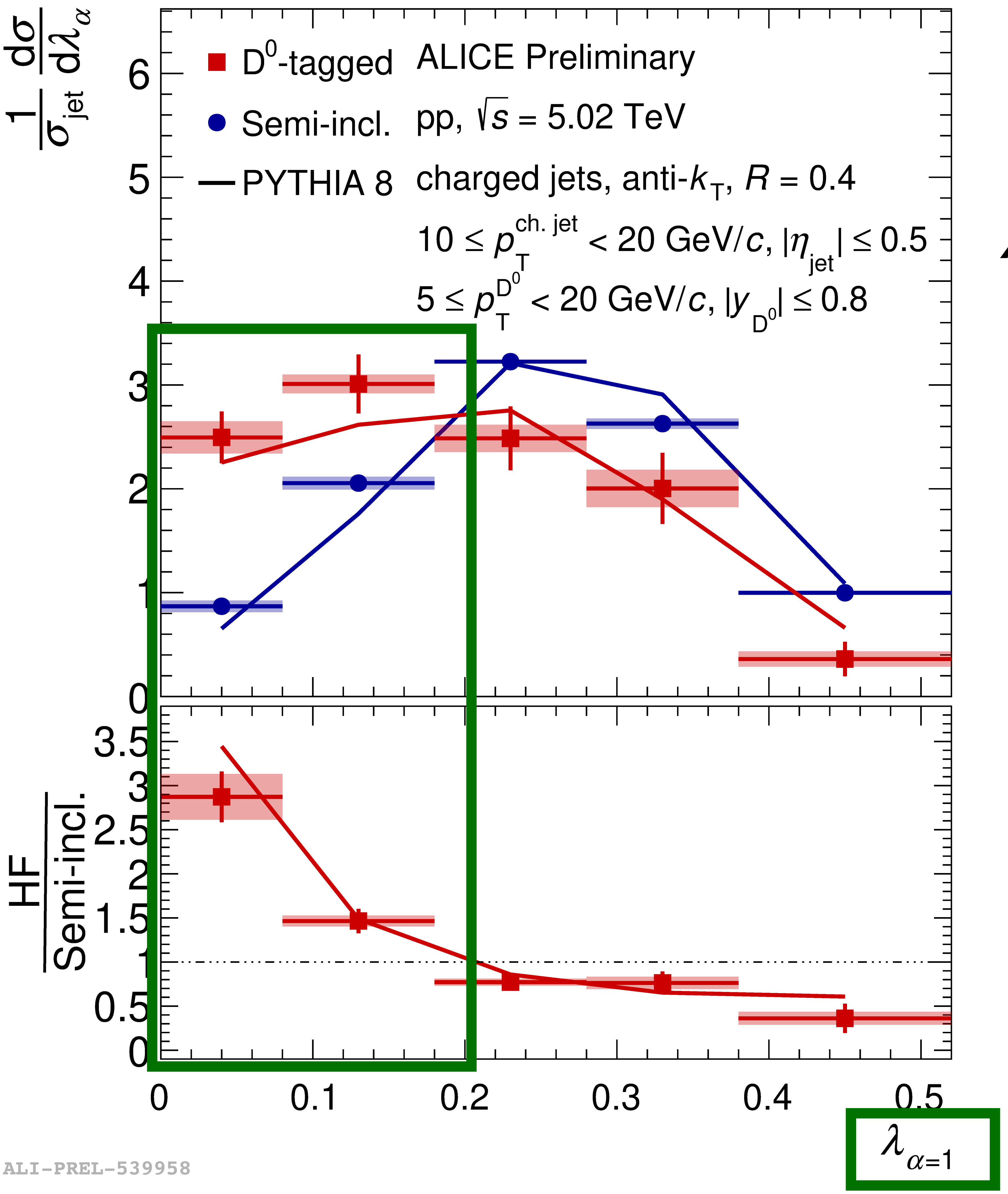
Higher α → more weight on wide angle emissions



Flavor dependencies in QCD shower



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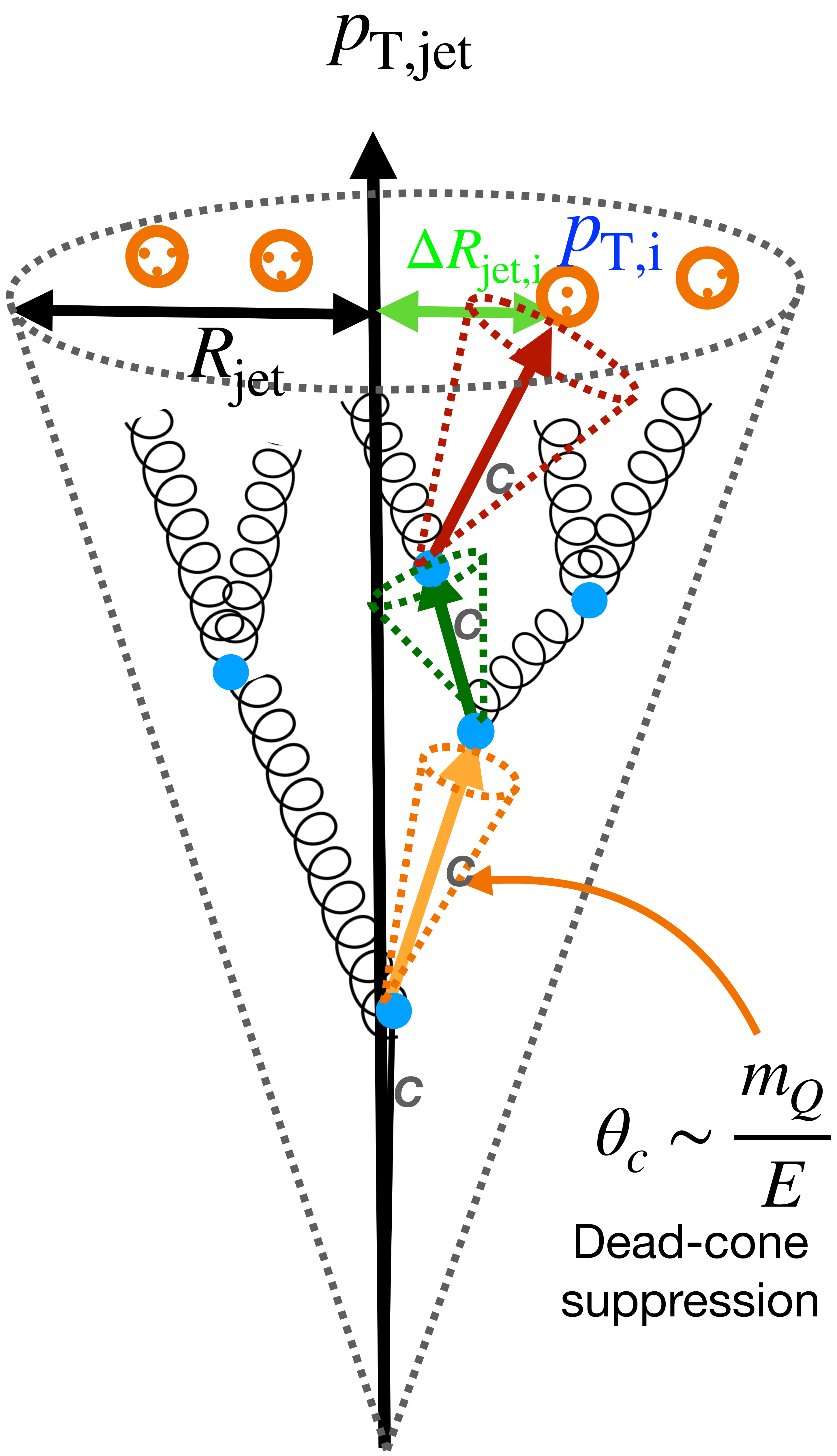
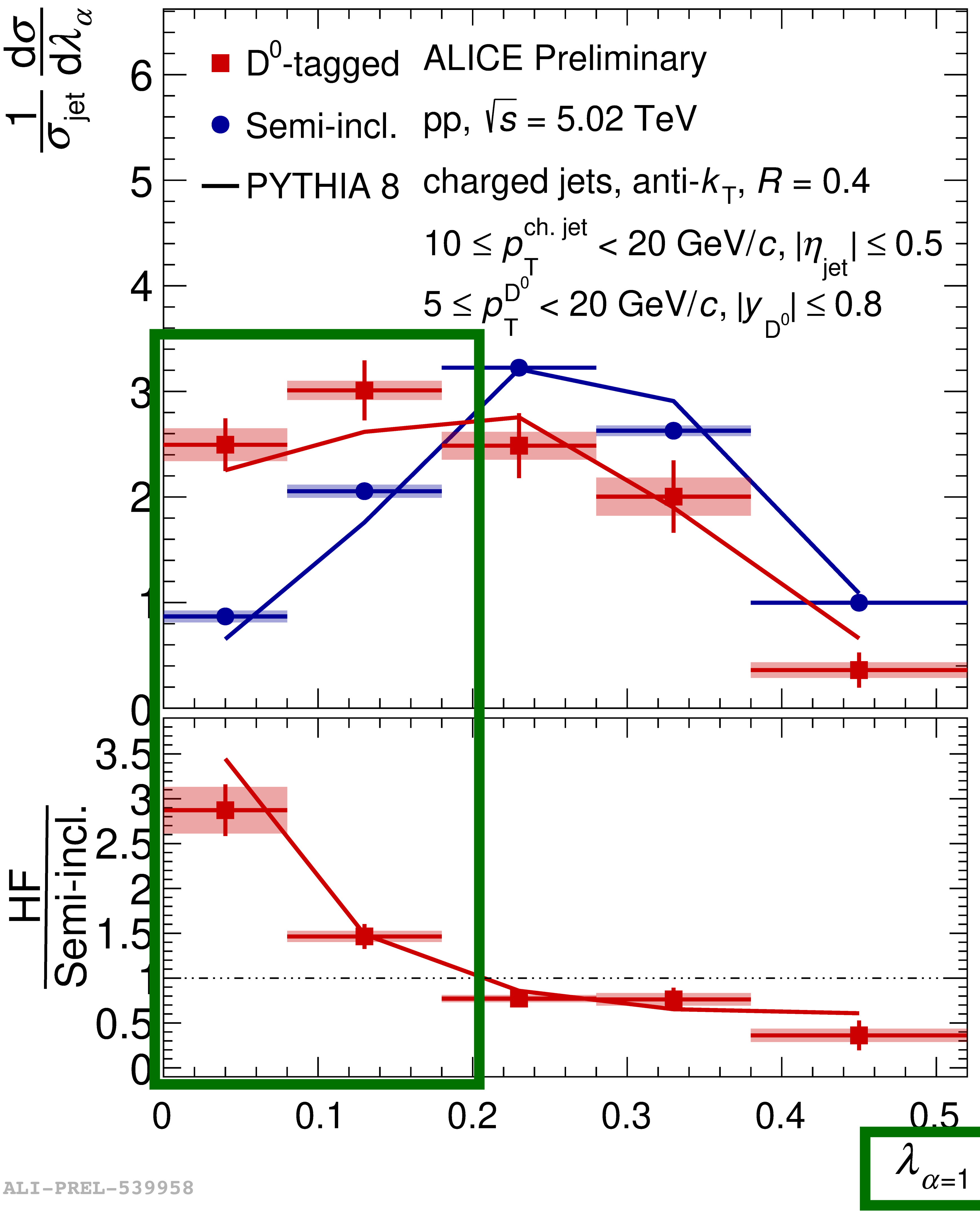


Flavor dependencies in QCD shower

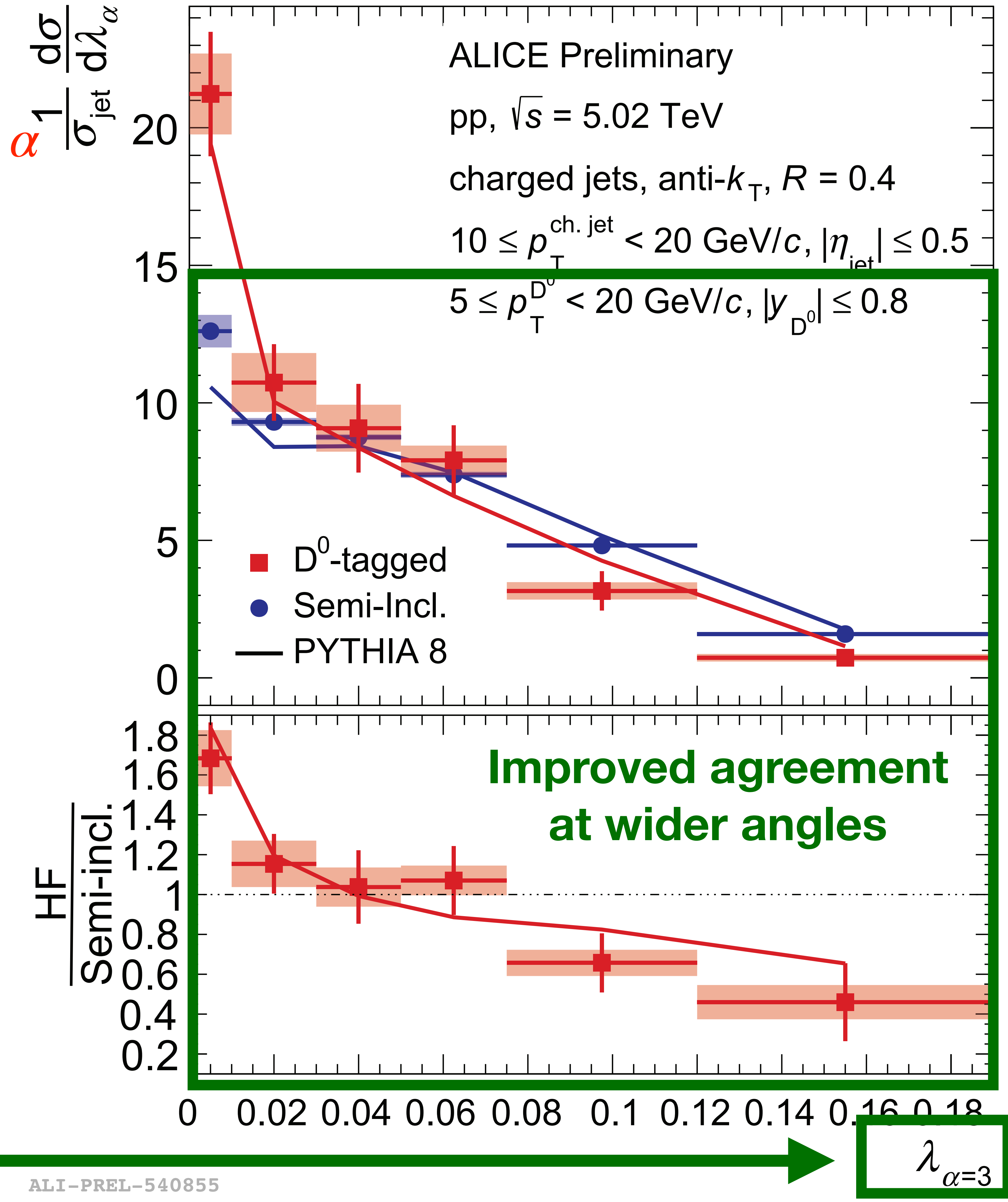


Jet Angularities :

$$\lambda_\alpha = \sum_{i \in jet} \left(\frac{p_{T,i}}{p_{T,jet}}\right)\left(\frac{\Delta R_{jet,i}}{R_{jet}}\right)^\alpha$$

$$= \sum_{i \in jet} z_i \theta_i^\alpha$$

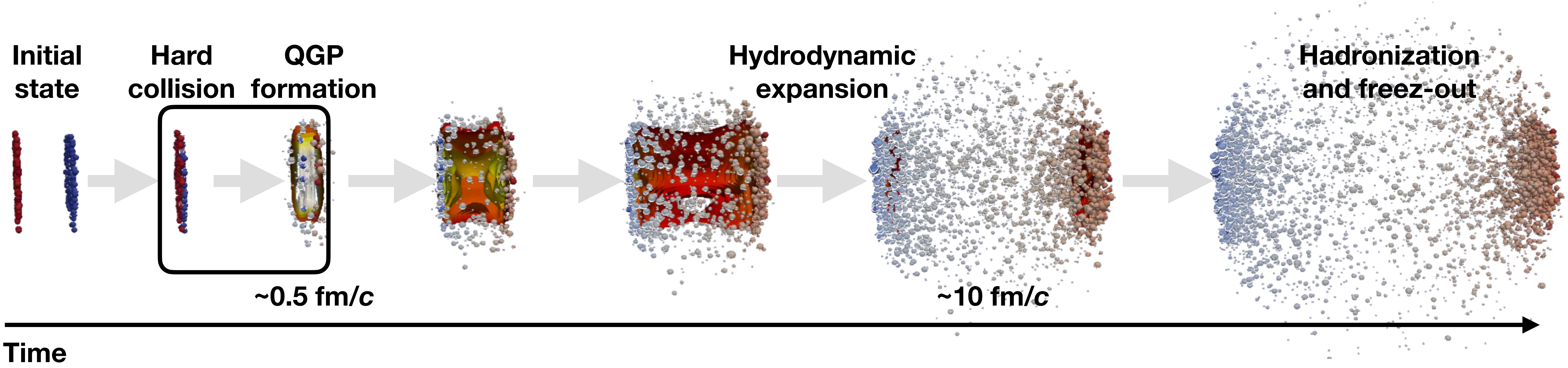
Higher α → more weight on wide angle emissions



$\lambda_{\alpha=1}$ → $\lambda_{\alpha=3}$

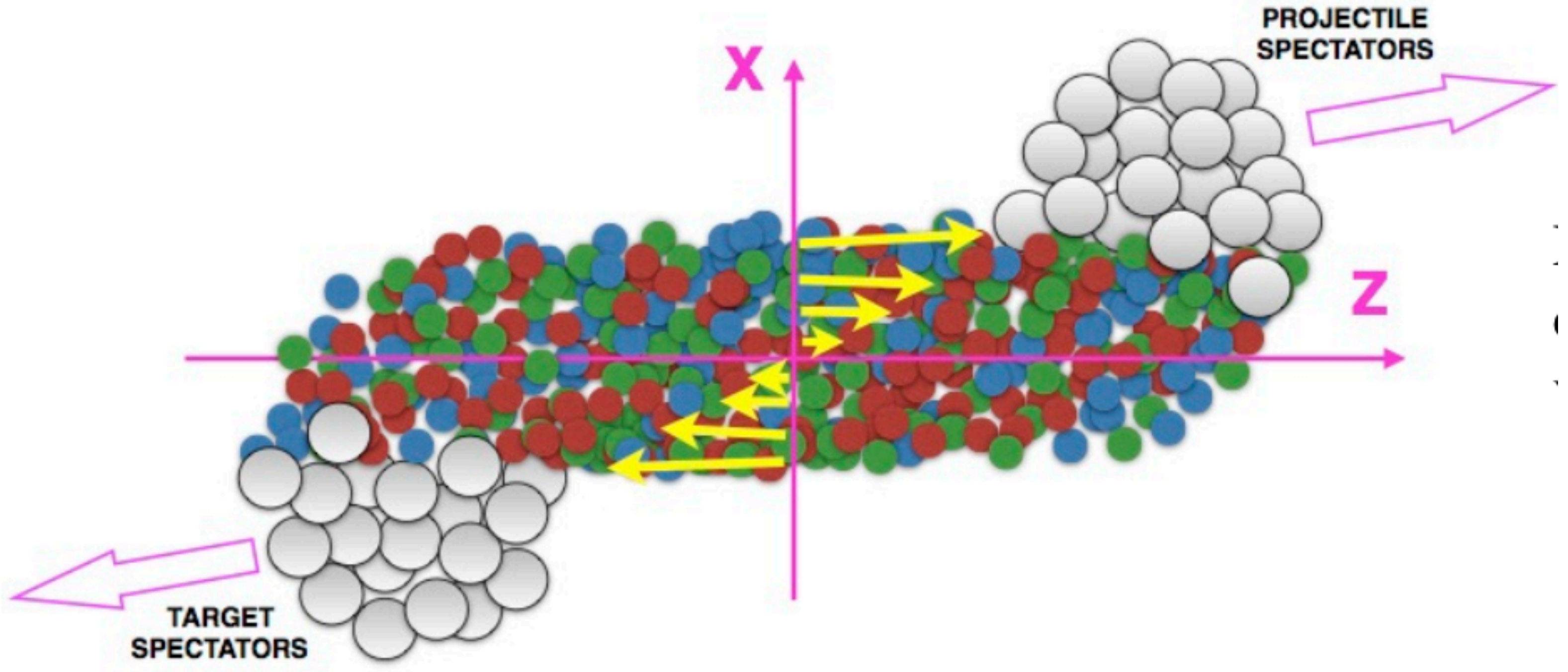
Mass effects → **Casimir color effects**

Probing quark-gluon plasma (QGP) with heavy flavor



Spin alignment of D*+ and J/ψ mesons

Non-central collisions



- Large angular momentum due to the medium rotation
- Huge initial magnetic field (B ~ 10^{16} T) generated in the early state of the collision

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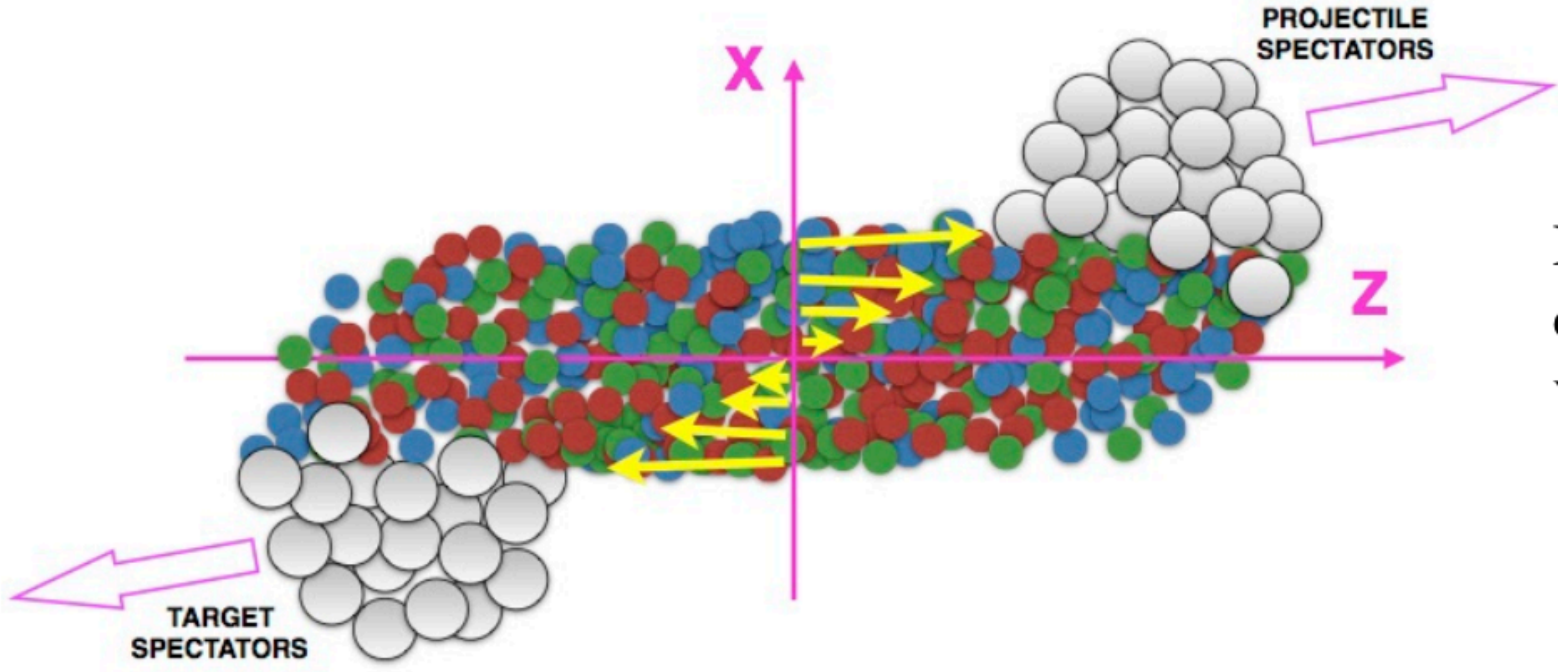

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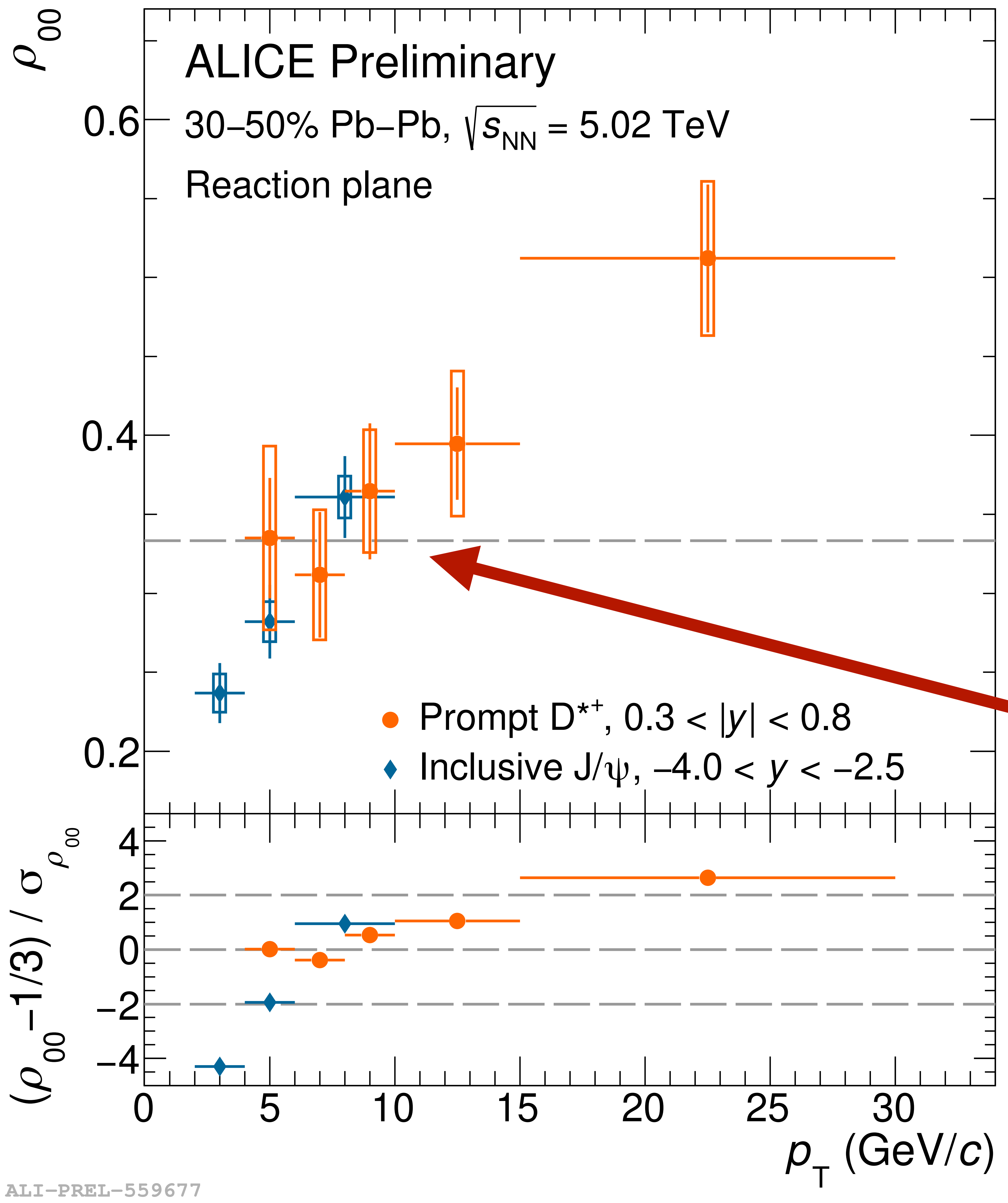
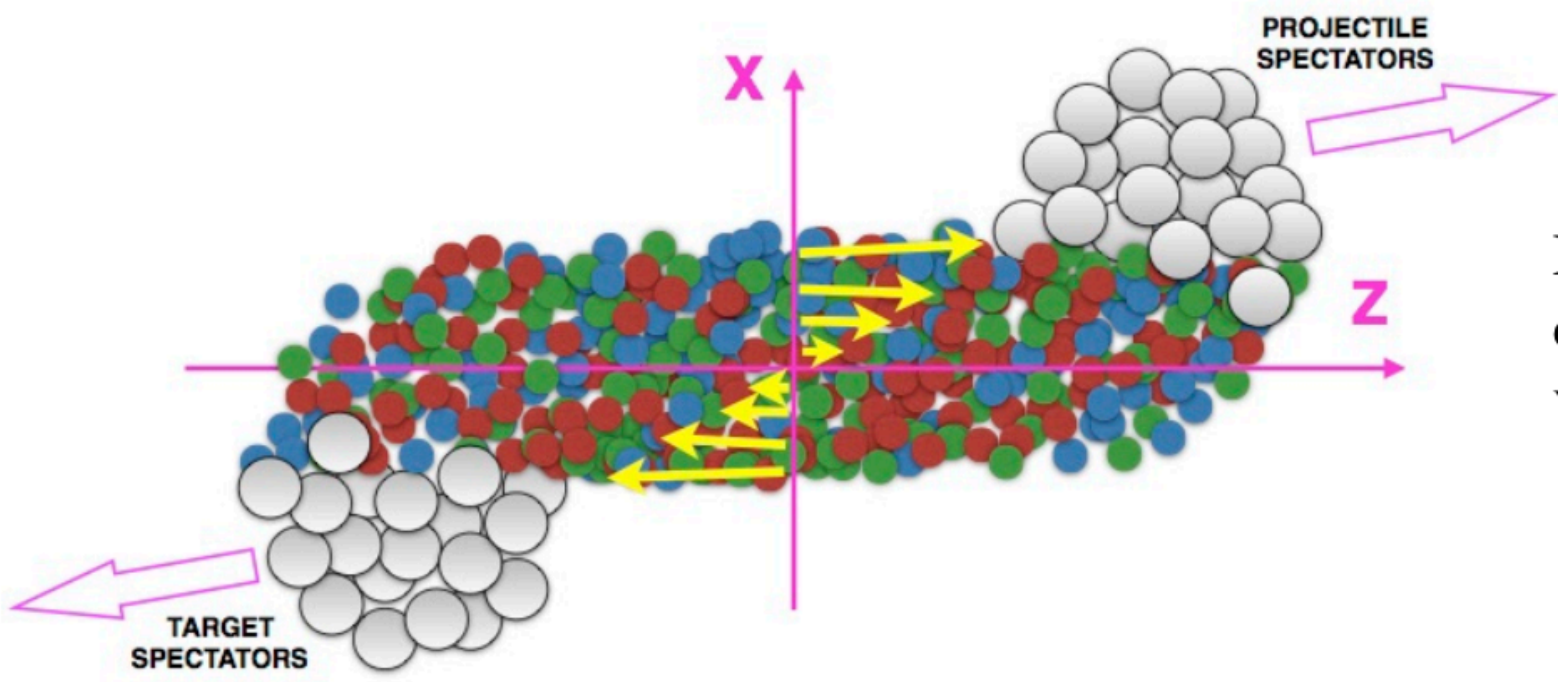
Charm **formation time ~ 0.1 fm/c** comparable to the time scale when B is maximum
Expected to be more sensitive to the magnetic field
→ excellent probes to study induced B field!

Spin alignment of D^{*+} and J/ψ mesons



Non-central collisions



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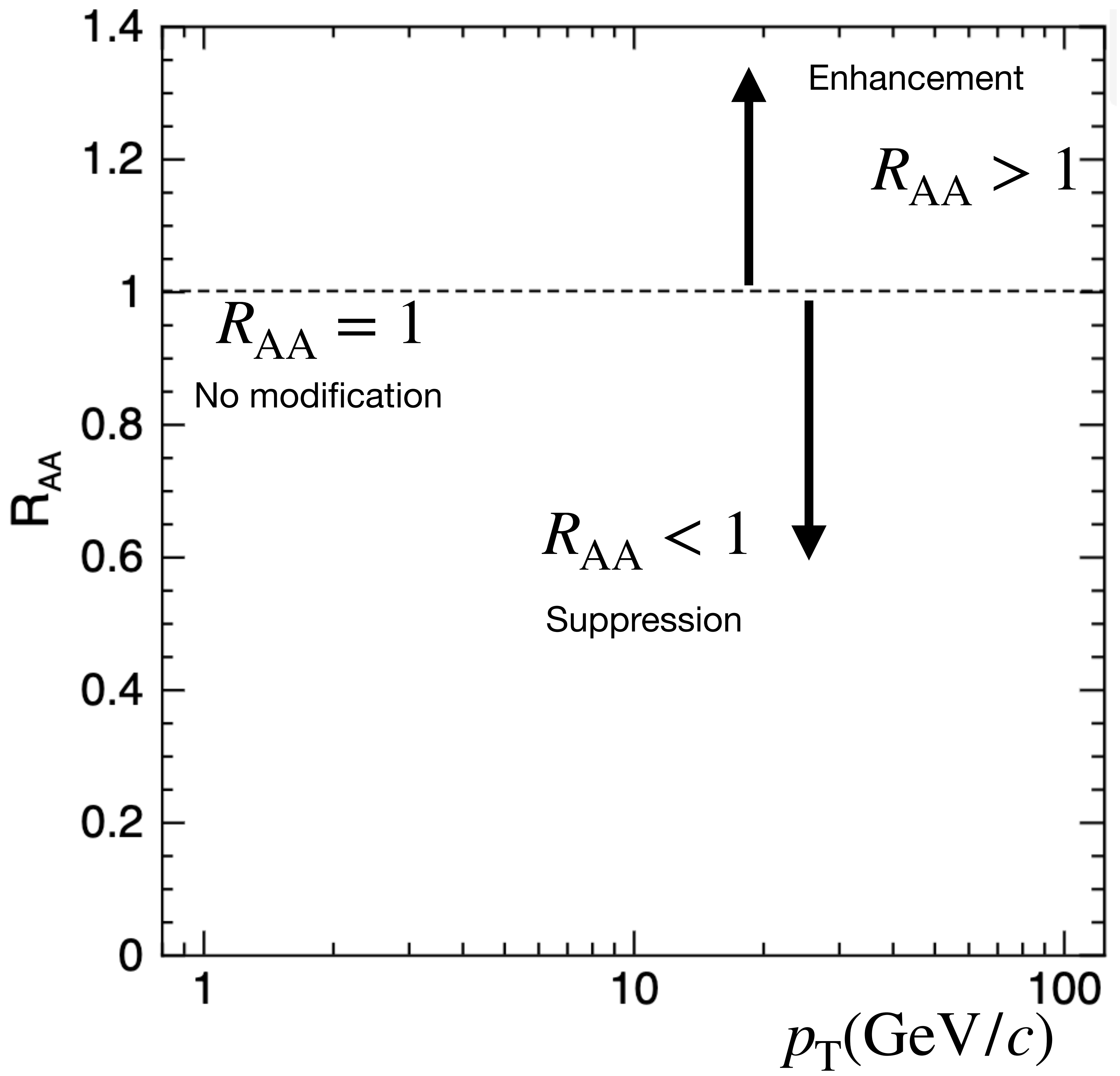
Expected to be more sensitive to the magnetic field
→ excellent probes to study induced B field!

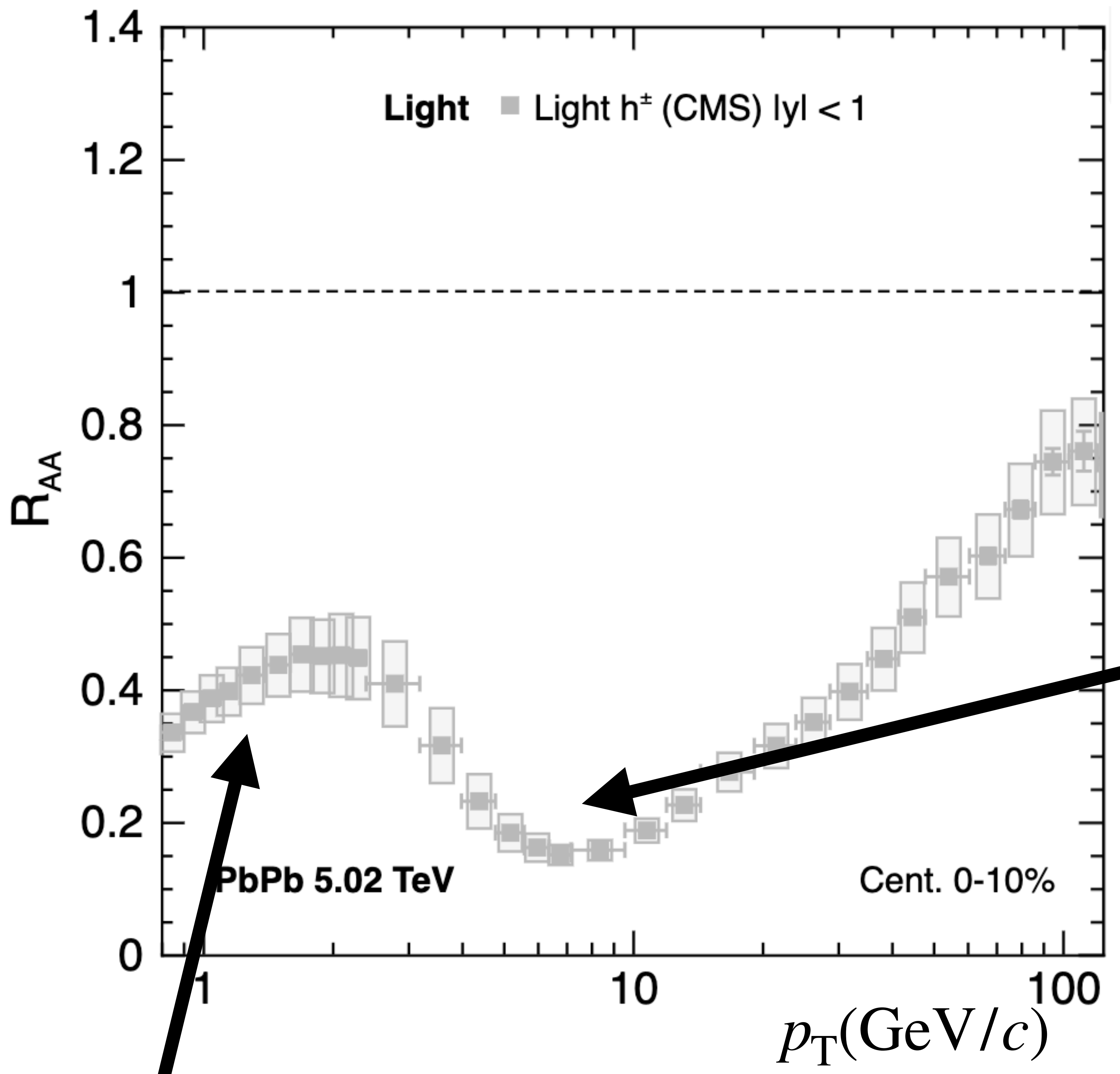
Polarization of charm quark transferred to hadrons through hadronization process

Interaction of heavy quarks with the QGP



$$R_{AA} = \frac{dN_{AA}/dp_T}{< T_{AA} > d\sigma_{pp}/dp_T}$$

Interaction of heavy quarks with the QGP



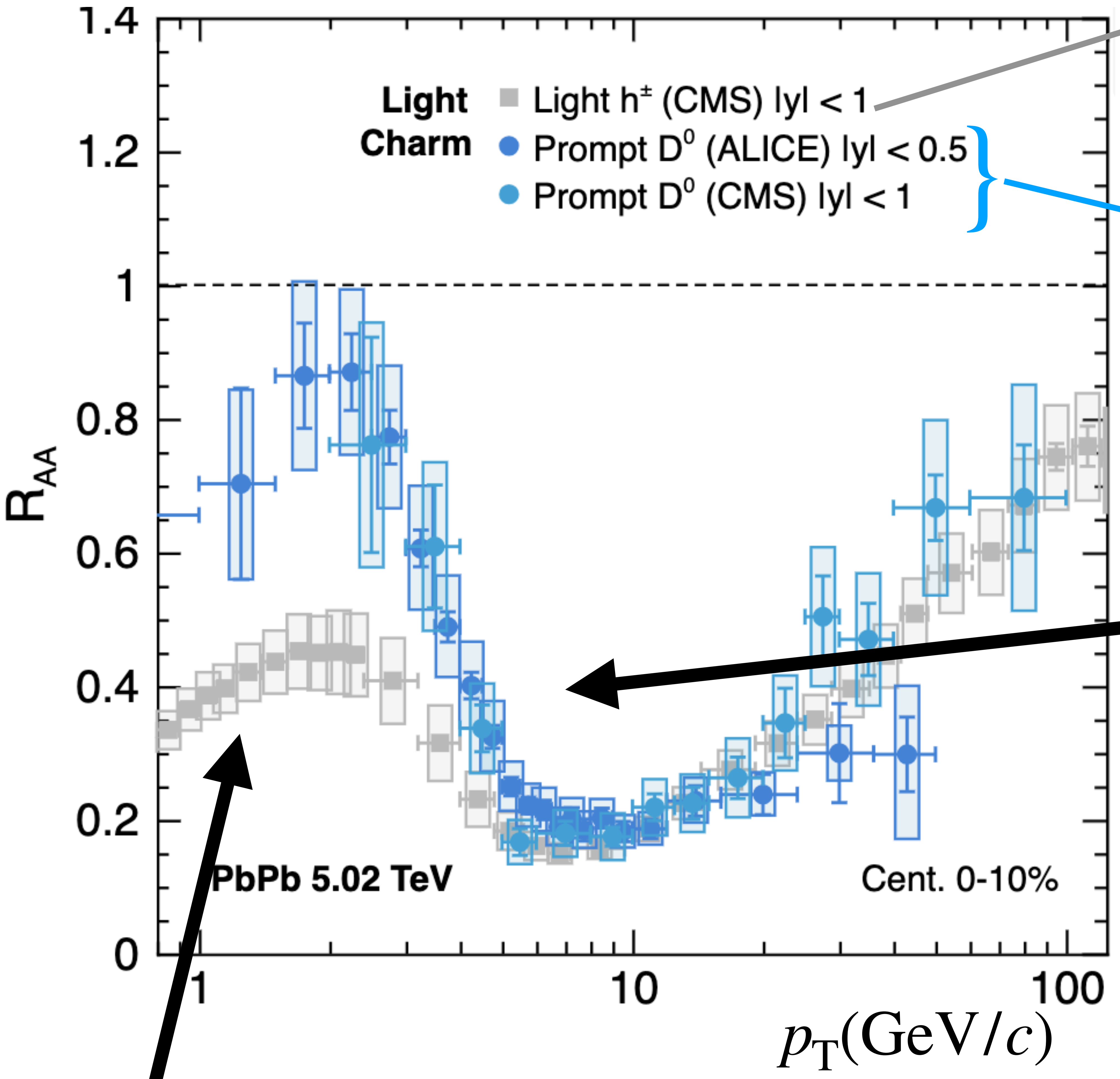
Significant suppression observed for light hadrons

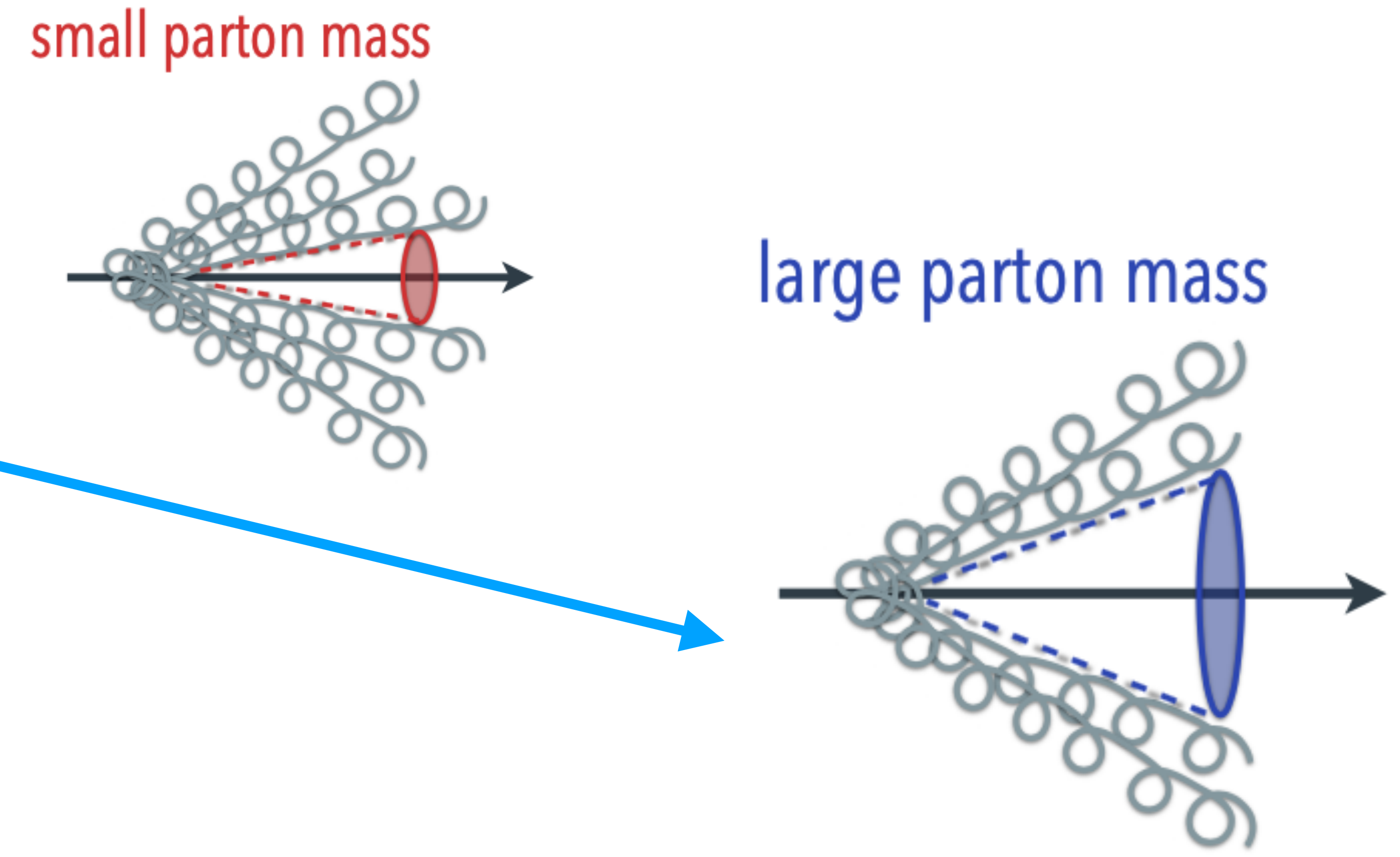
Probe modified by the medium!!

$$R_{AA} = \frac{dN_{AA}/dp_T}{< T_{AA} > d\sigma_{pp}/dp_T}$$

"Flow bump" due to (radial) flow of medium and coupling at small p_T

Interaction of heavy quarks with the QGP





Dead cone effect: gluon radiation suppressed at angles smaller than $\theta < m/E$

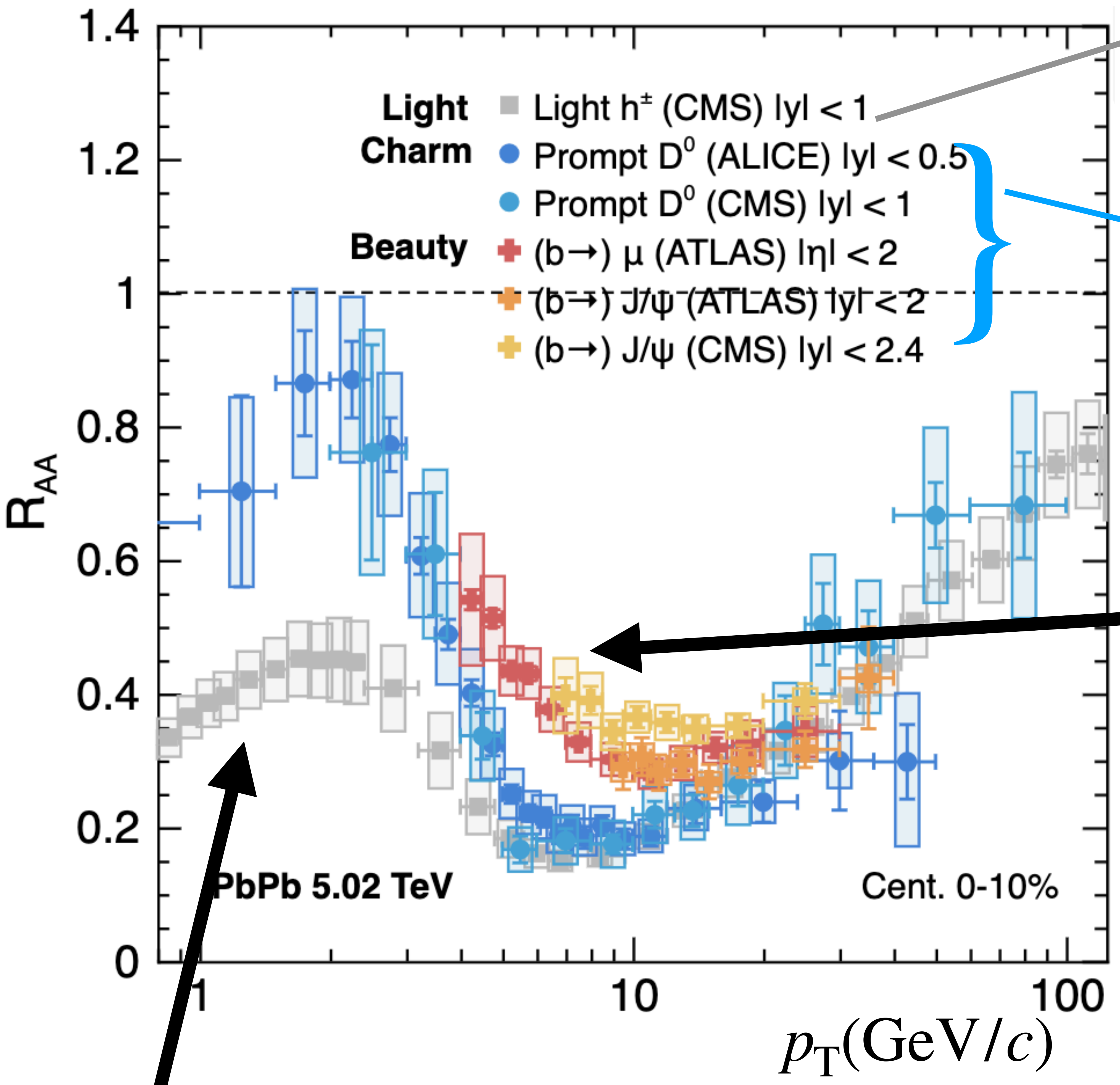
Reduced suppression for HF hadrons

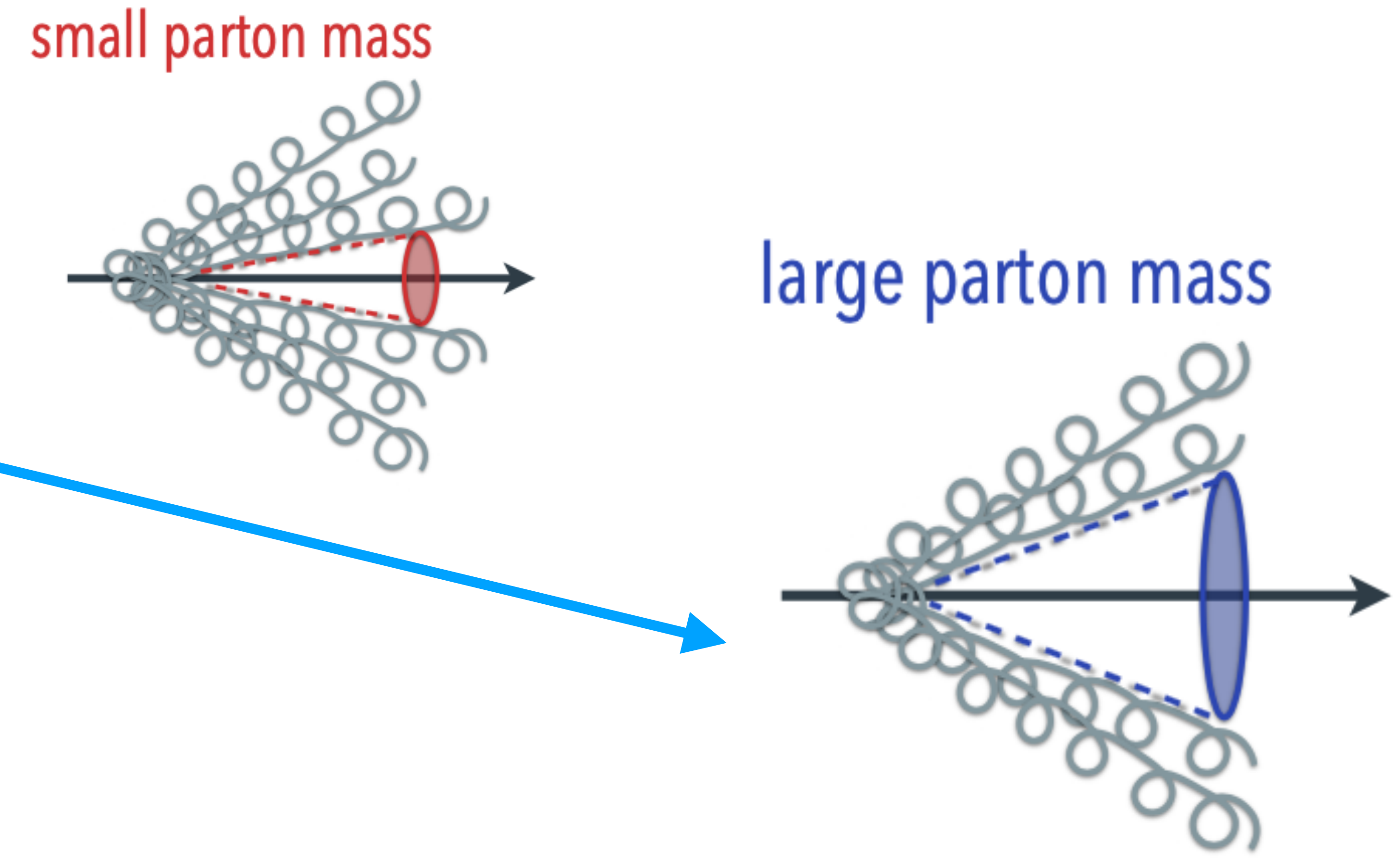
Probe modified by the medium!!

$$R_{AA} = \frac{dN_{AA}/dp_T}{< T_{AA} > d\sigma_{pp}/dp_T}$$

“Flow bump” due to (radial) flow of medium and coupling at small p_T

Interaction of heavy quarks with the QGP





Dead cone effect: gluon radiation suppressed at angles smaller than $\theta < m/E$

Consistent with mass dependent hierarchy!!!

RAA(q/g) < RAA(c) < RAA(b)

Probe modified by the medium!!

$$R_{AA} = \frac{dN_{AA}/dp_T}{< T_{AA} > d\sigma_{pp}/dp_T}$$

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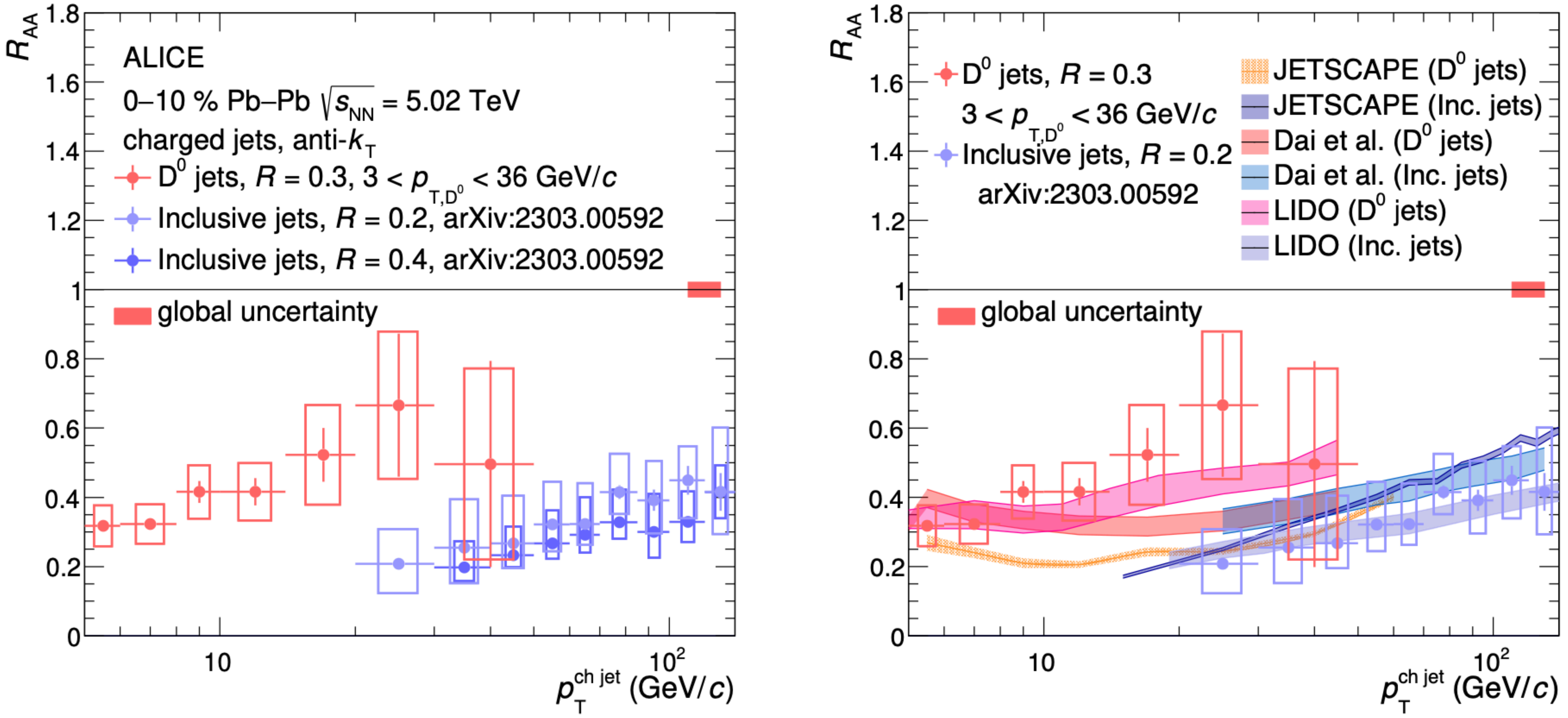
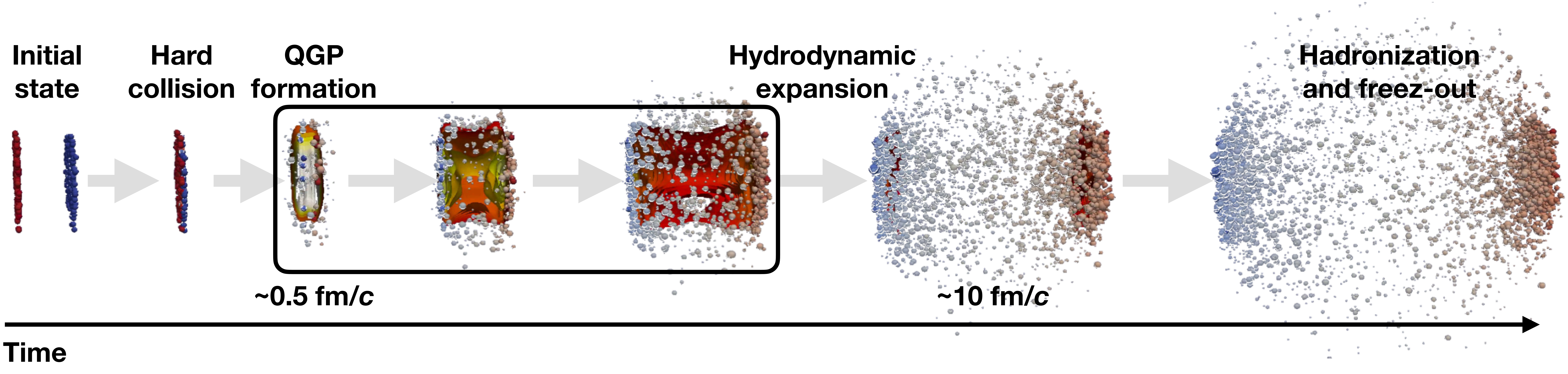
Interaction of heavy quarks with the QGP

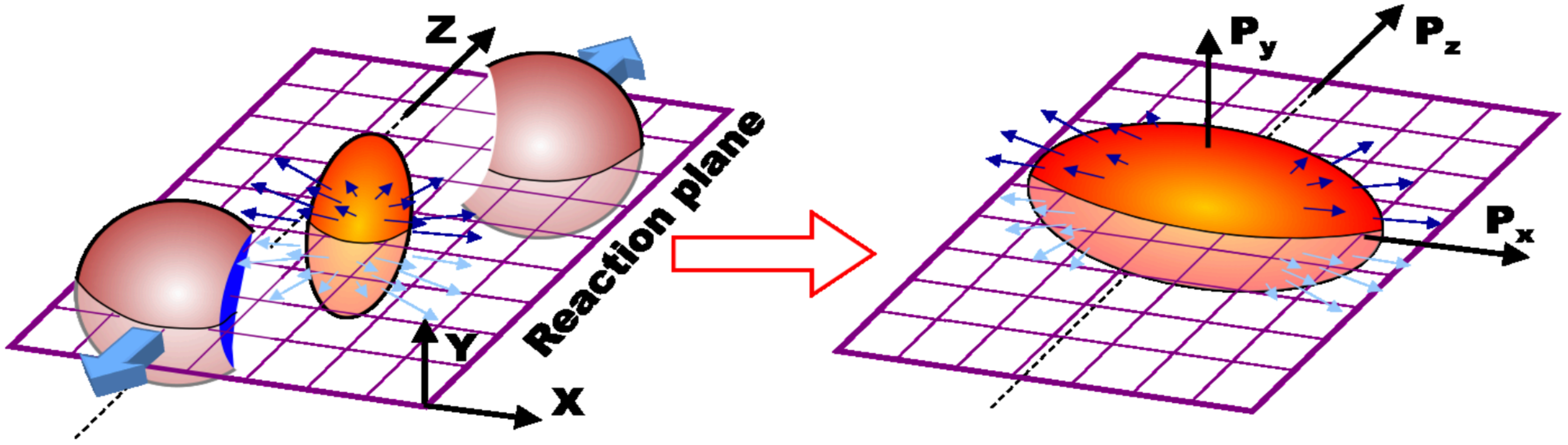


Extended to D0-tagged jet measurement and compared with inclusive jet to probe flavor dependencies!!

Probing quark-gluon plasma (QGP) with heavy flavor



Collective flow



Distribution of emitted particles can be written as Fourier formula:

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

$$v_2 = \langle cos[2(\varphi - \Psi_2)]\rangle$$

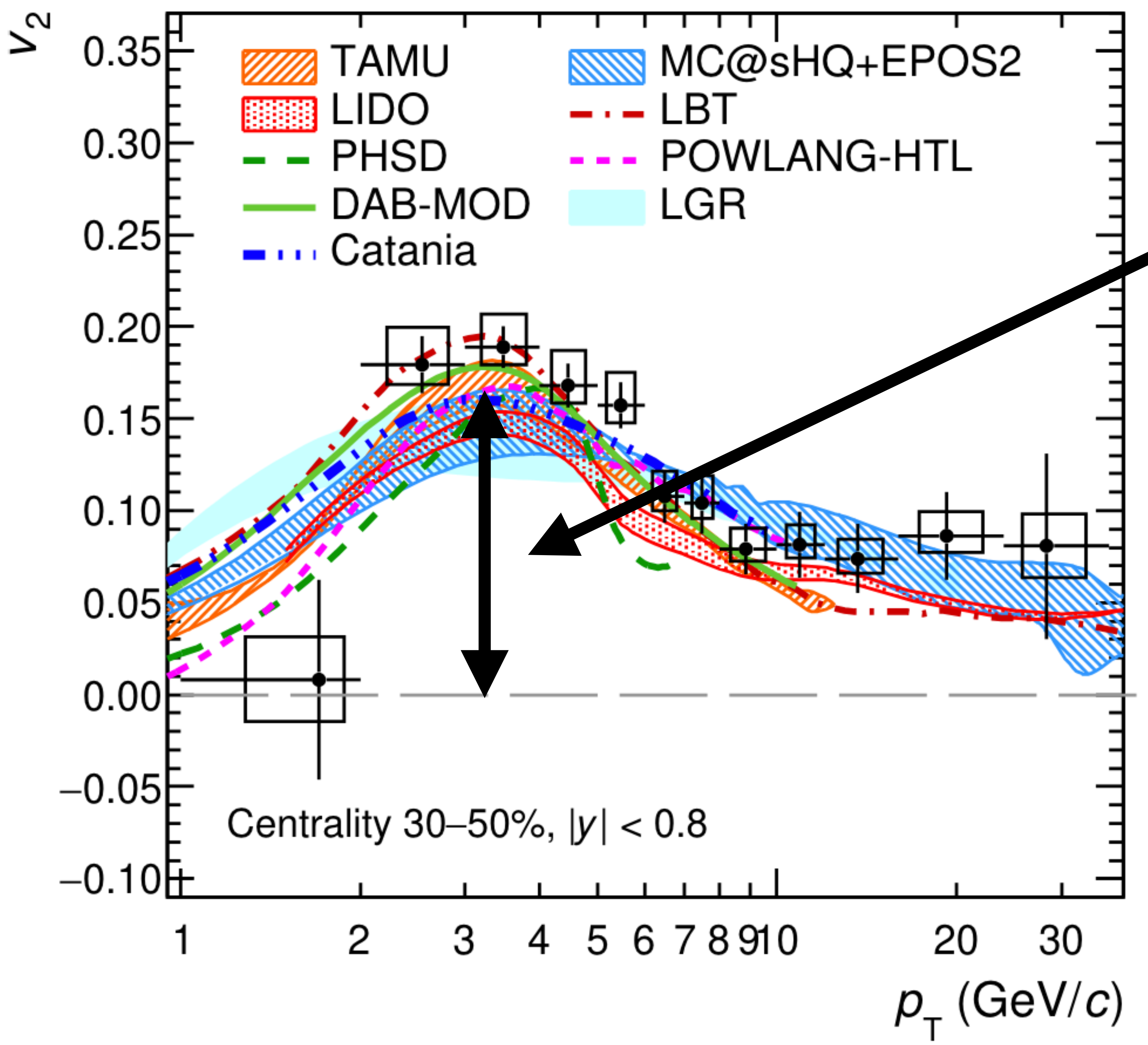
Ψ_n: Azimuthal angle of Event Plane

φ: Azimuthal angle of emitted particles

v_n: Different flow harmonics

v_2: Elliptic flow

Collective flow: do heavy-quark flow?



- Significantly positive v_2 observed for charm hadron

→ charm flows collectively with the medium

→Diffusing charm quark moves with expanding medium

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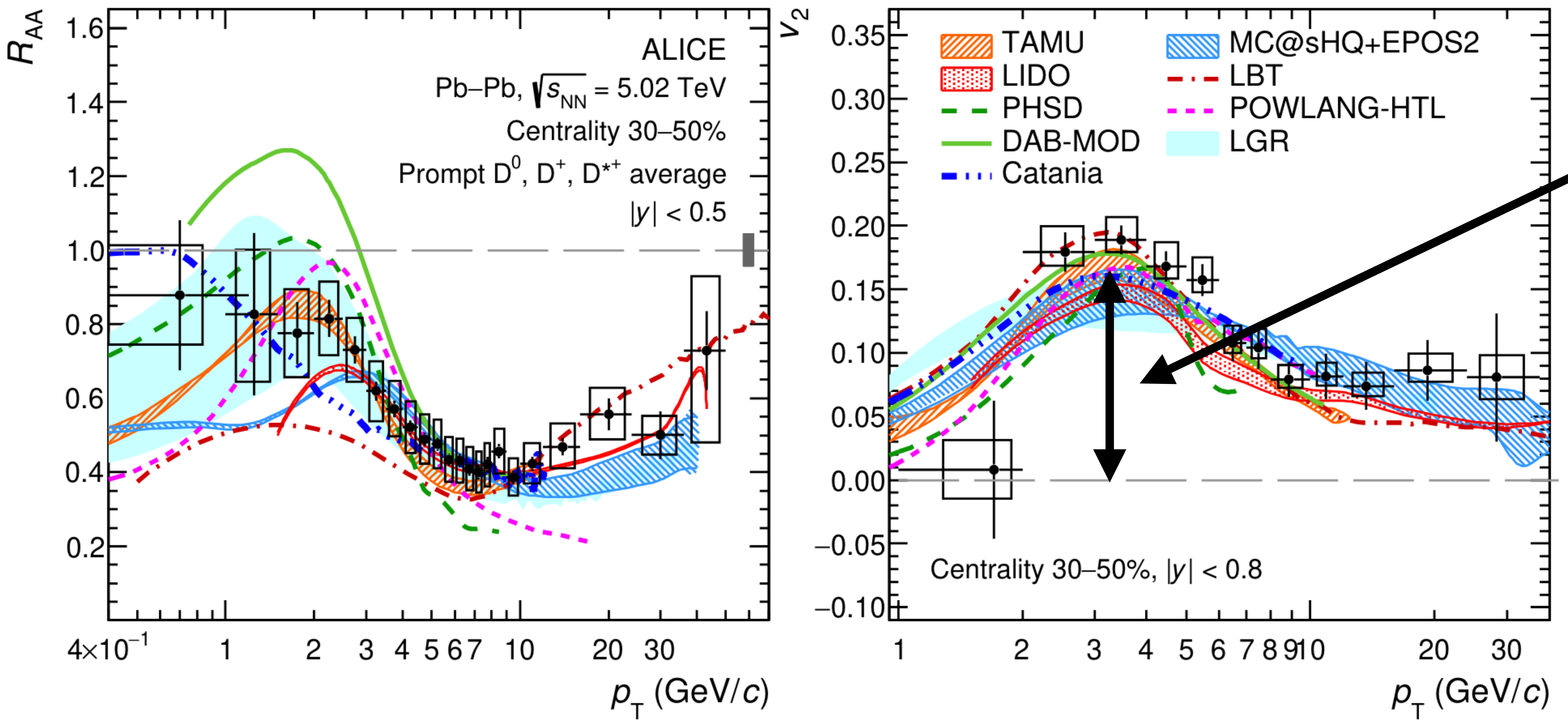

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Constraining spatial diffusion coefficient D_s via D-meson

- Simultaneous fitting the models to describe R_{AA} and v_2.

→Used to extract the diffusion coefficient D_s

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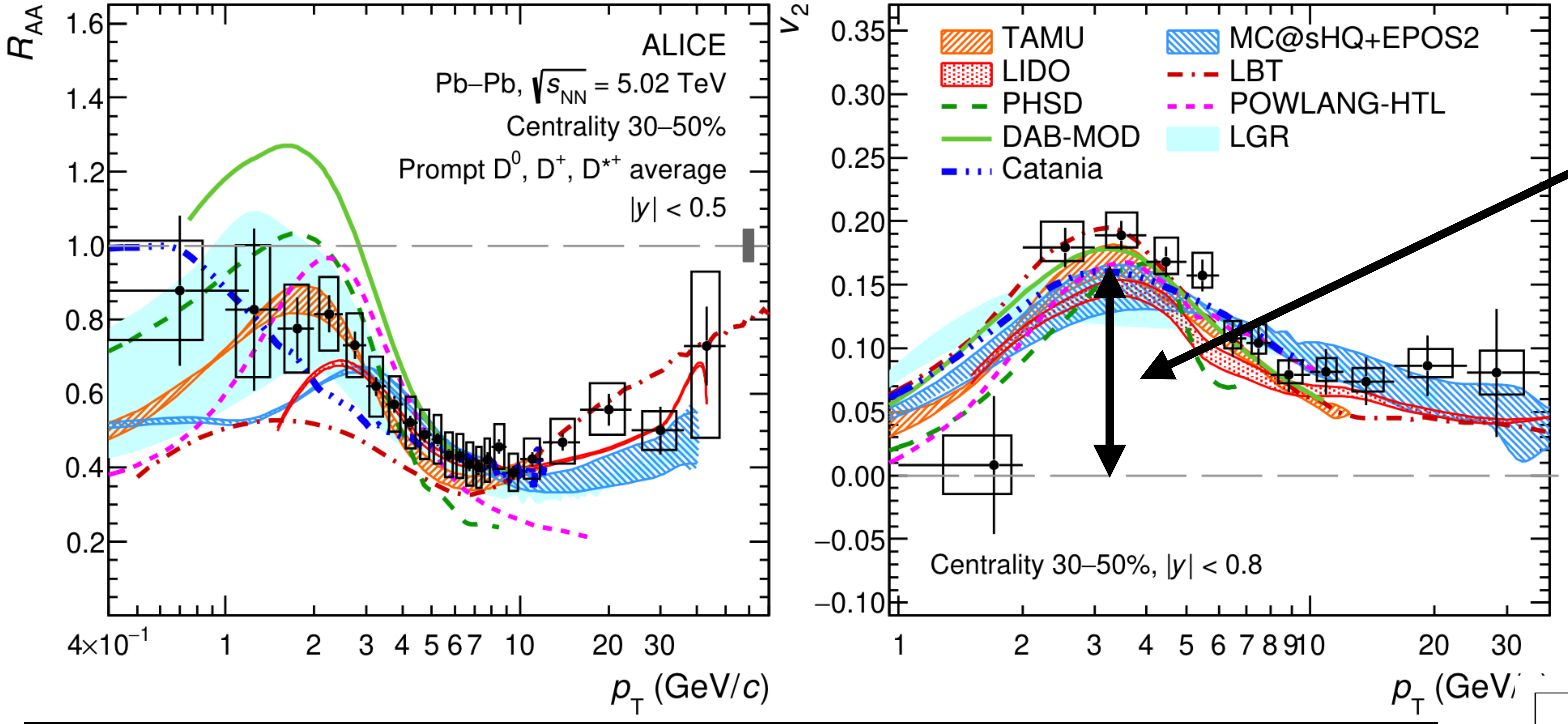

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Constraining spatial diffusion coefficient D_s via D-meson

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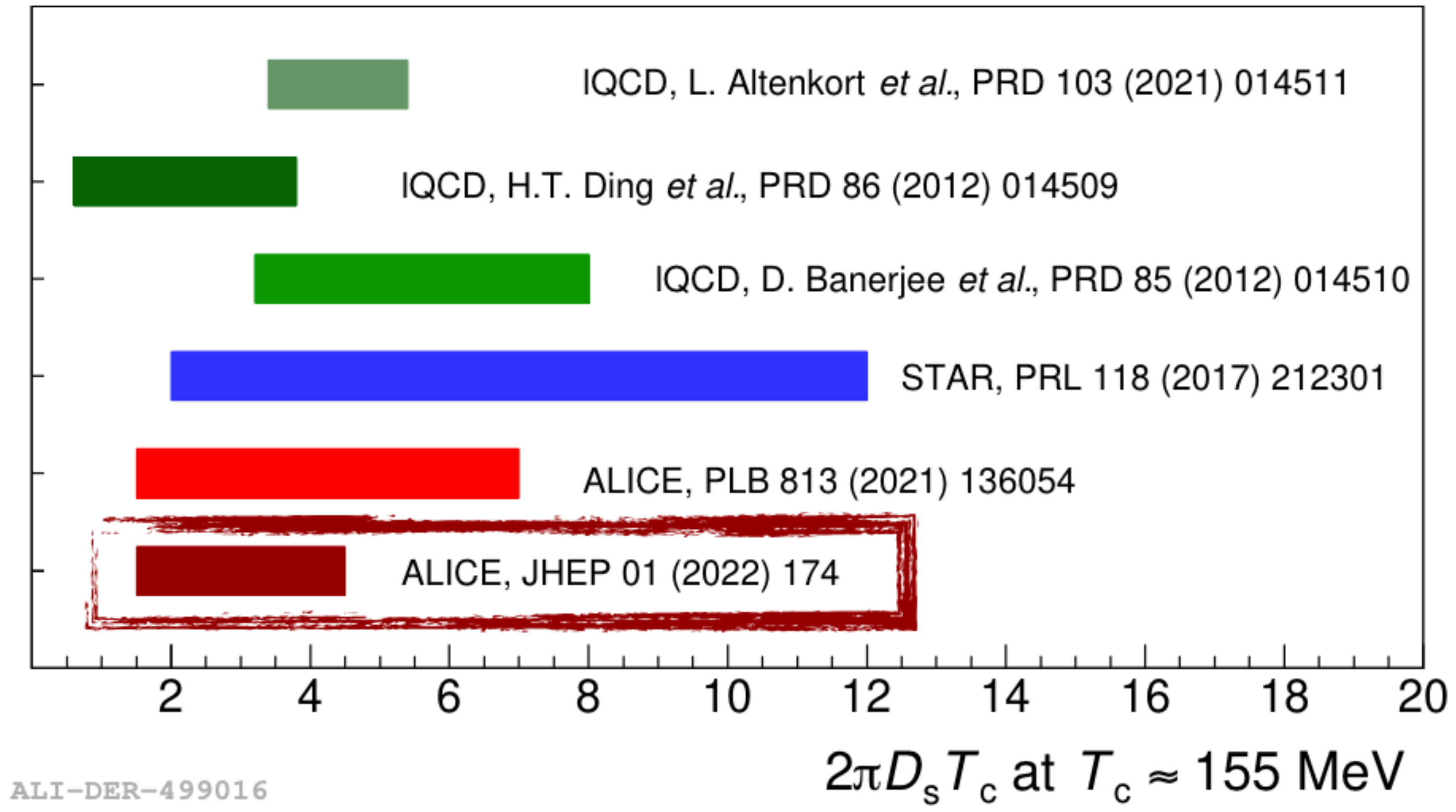
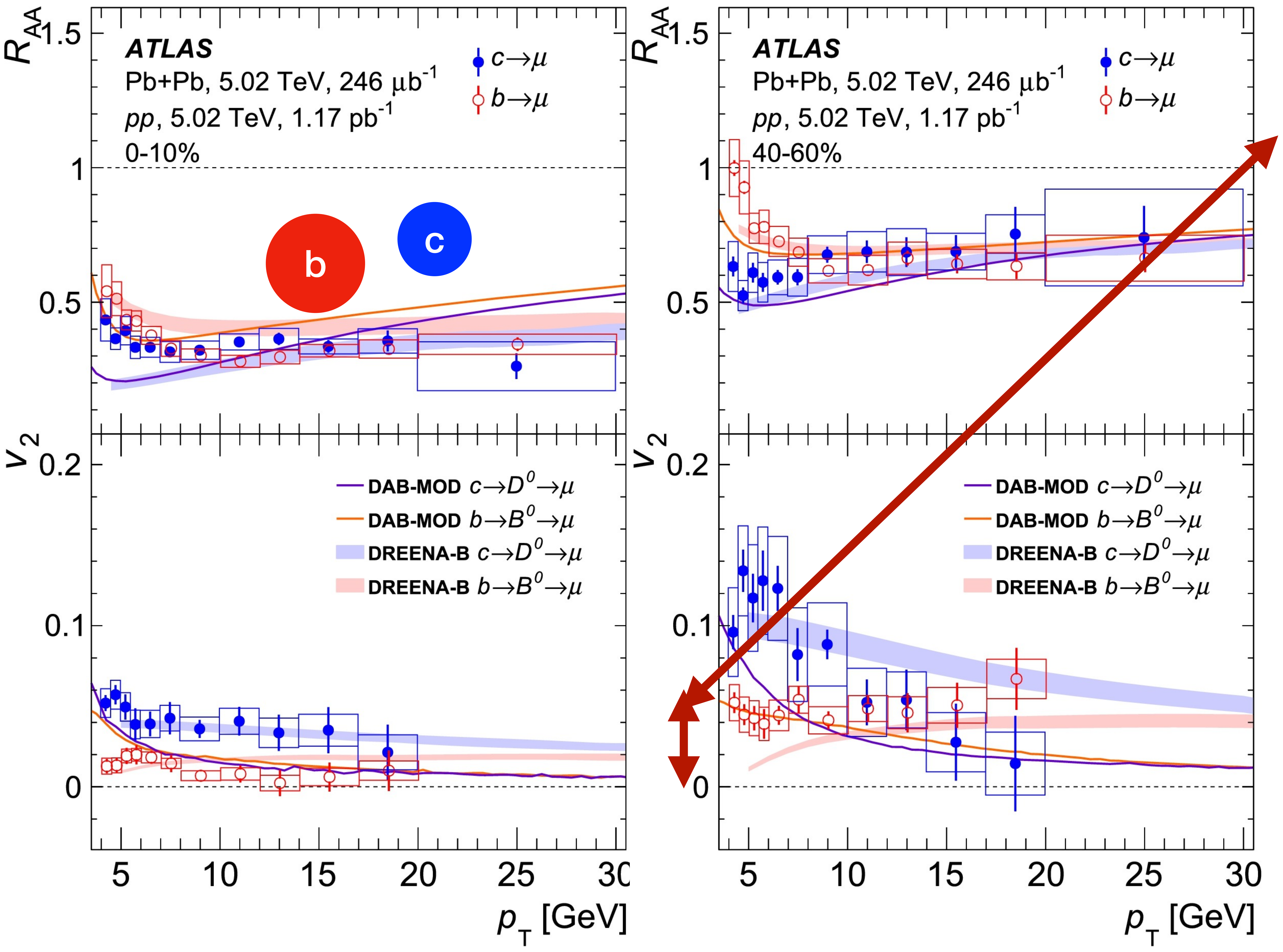
→Used to extract the diffusion coefficient D_s

$$1.5 < 2\pi D_s T_c < 4.5 \rightarrow \tau_{charm} = 3-8\ \mathrm{fm}/c$$



Collective flow: do heavy-quark flow?

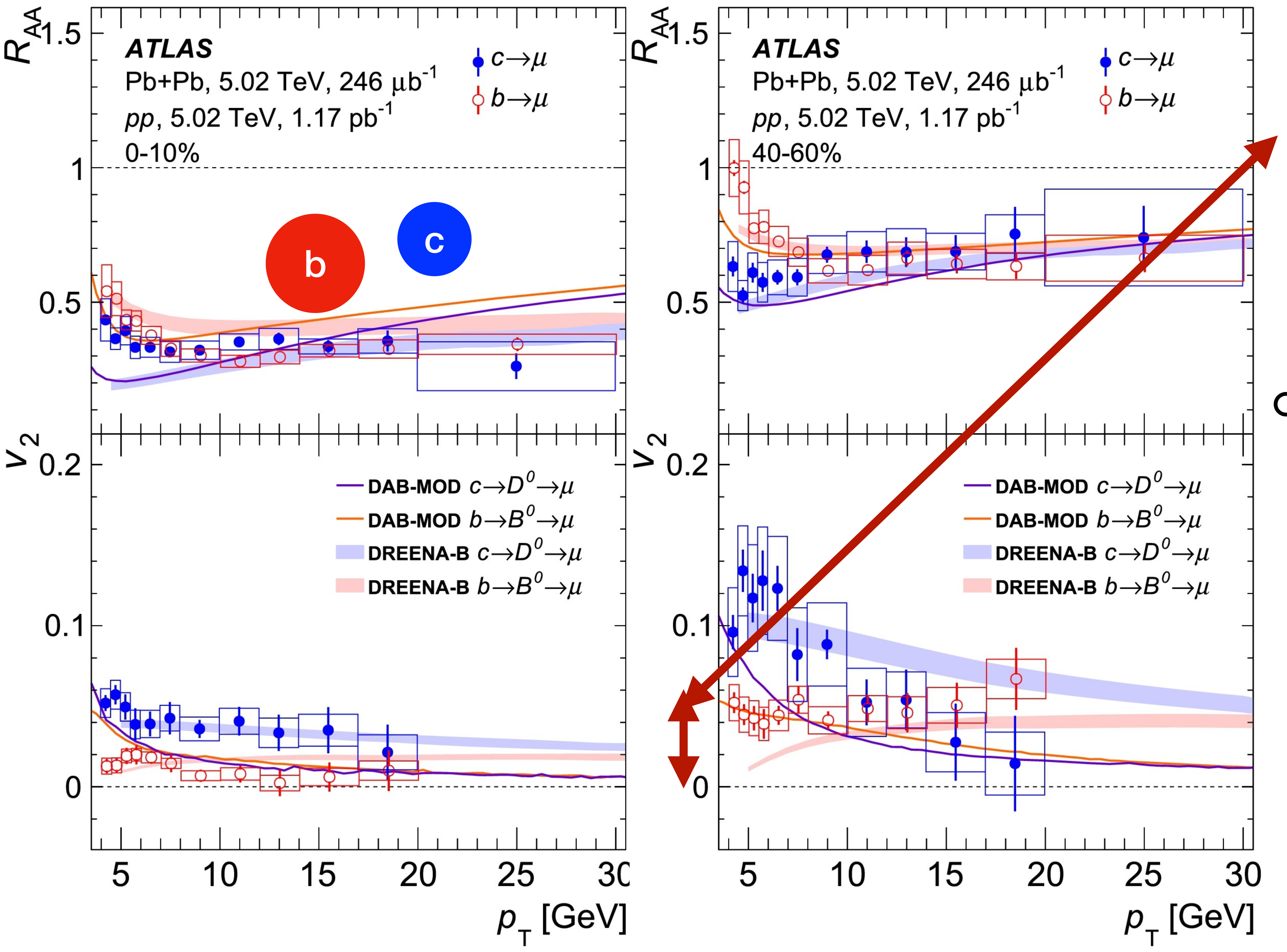


- positive v_2 observed for μ from charm and beauty.
- beauty v_2 < charm v_2

→consistent with mass hypothesis.

ATLAS, PLB 829 (2022) 137077

Collective flow: do heavy-quark flow?



- positive v_2 observed for μ from charm and beauty.
- beauty v_2 < charm v_2

  →consistent with mass hypothesis.

- Simultaneous fitting the models to describe R_{AA} and v_2 of muons from HF hadron decays

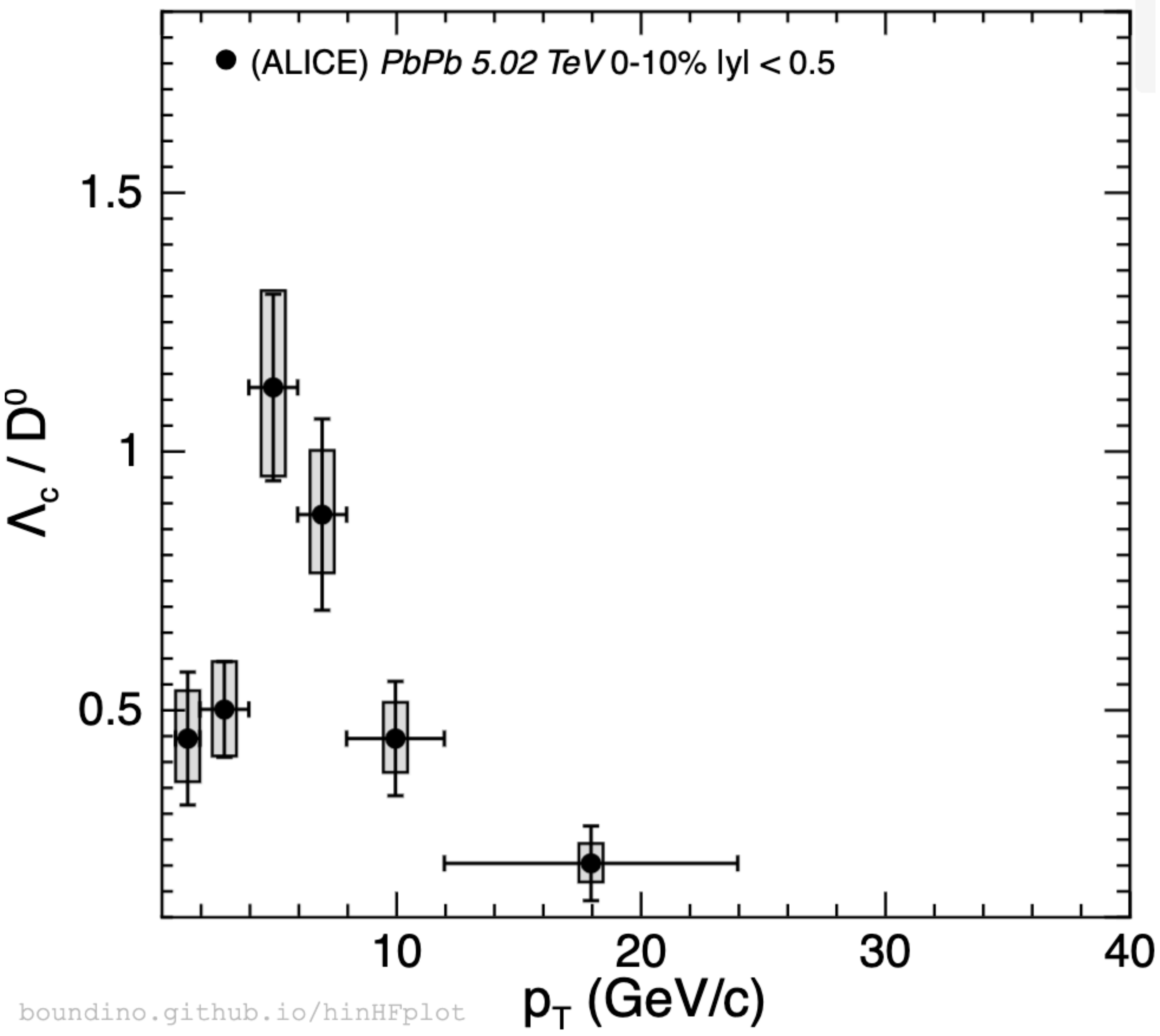
  → Charm: $2\pi D_s T_c$ = 2.23,

  Bottom: $2\pi D_s T_c$= 2.79

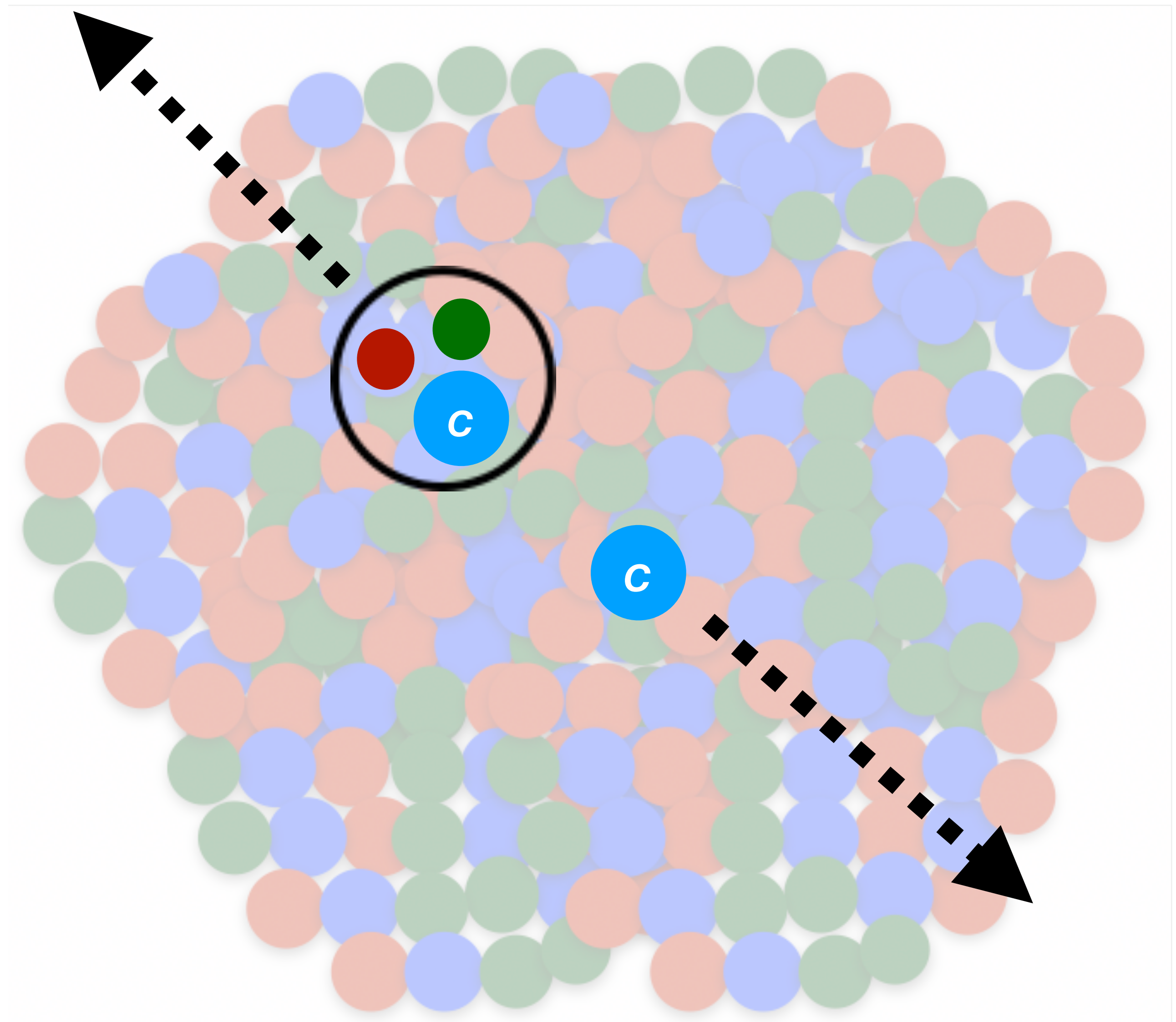
  →Compatible results between ALICE and ATLAS

ATLAS, PLB 829 (2022) 137077

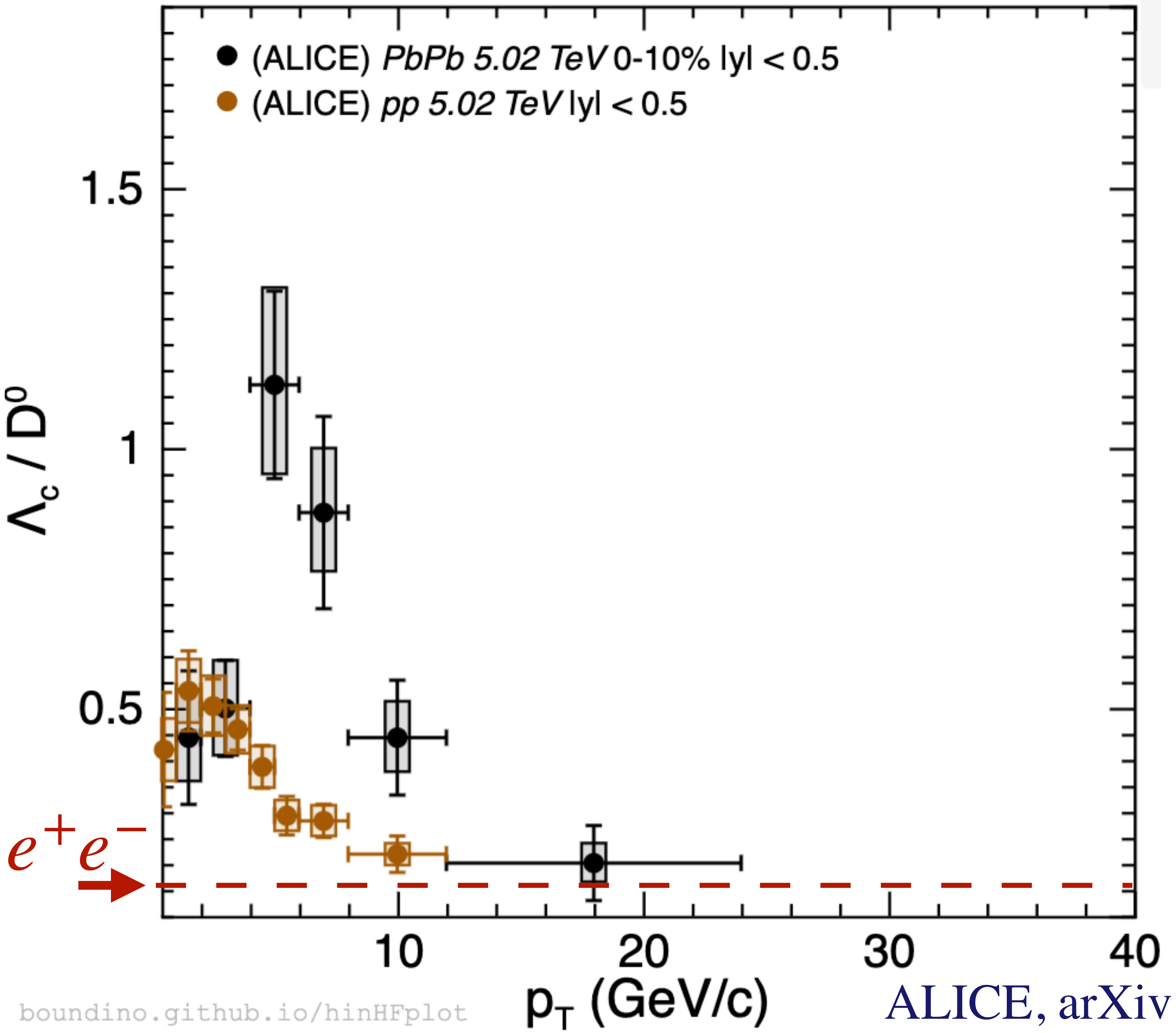
Hadronization of charmed hadrons



- Λ_c^+/D^0 ratio is expected to increase in the presence of charm recombination in the QGP.



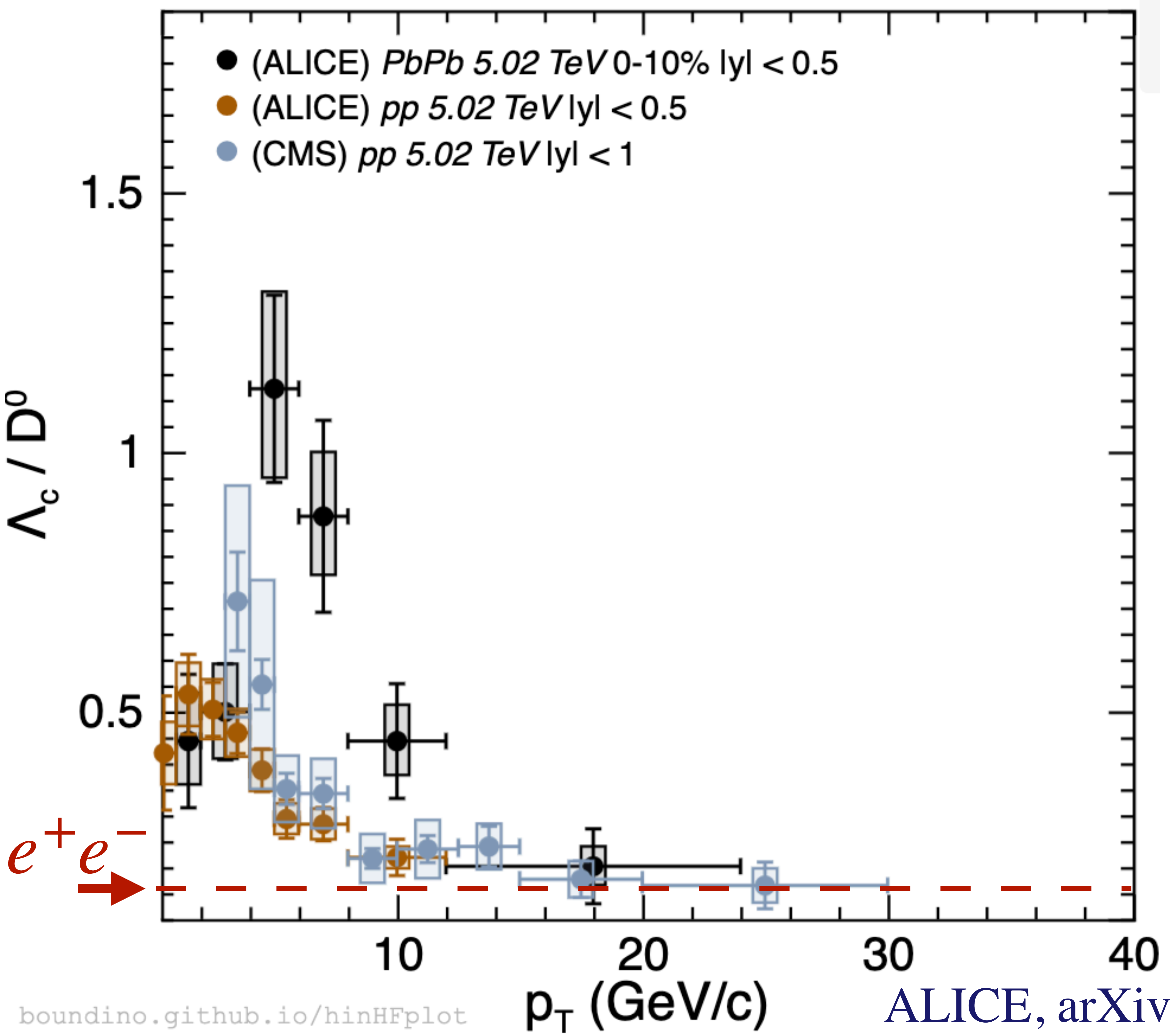
Hadronization of charmed hadrons



ALICE, arXiv:2211.14032

- Λ_c^+/D^0 ratio is expected to increase in the presence of charm recombination in the QGP.
- Λ_c^+/D^0 ratio in PbPb shows moderate enhancement from pp at intermediate p_T within uncertainties.
  - →Hadronization is modified already in pp collisions
  - →Very different than e^+e^-

Hadronization of charmed hadrons



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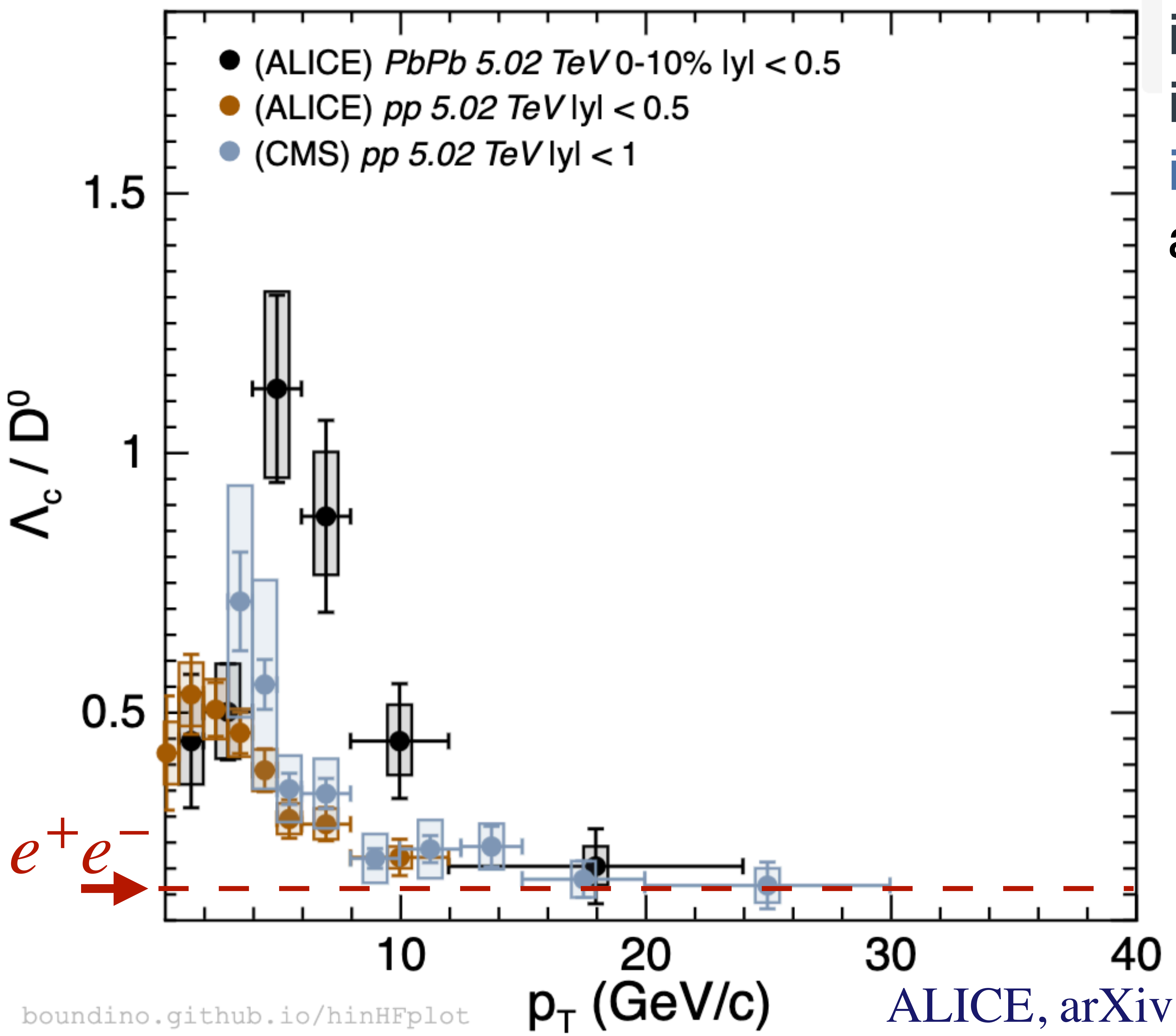
ALICE, arXiv:2211.14032
CMS, arXiv:2307.11186

Good agreement between ALICE and CMS data!

Hadronization of charmed hadrons

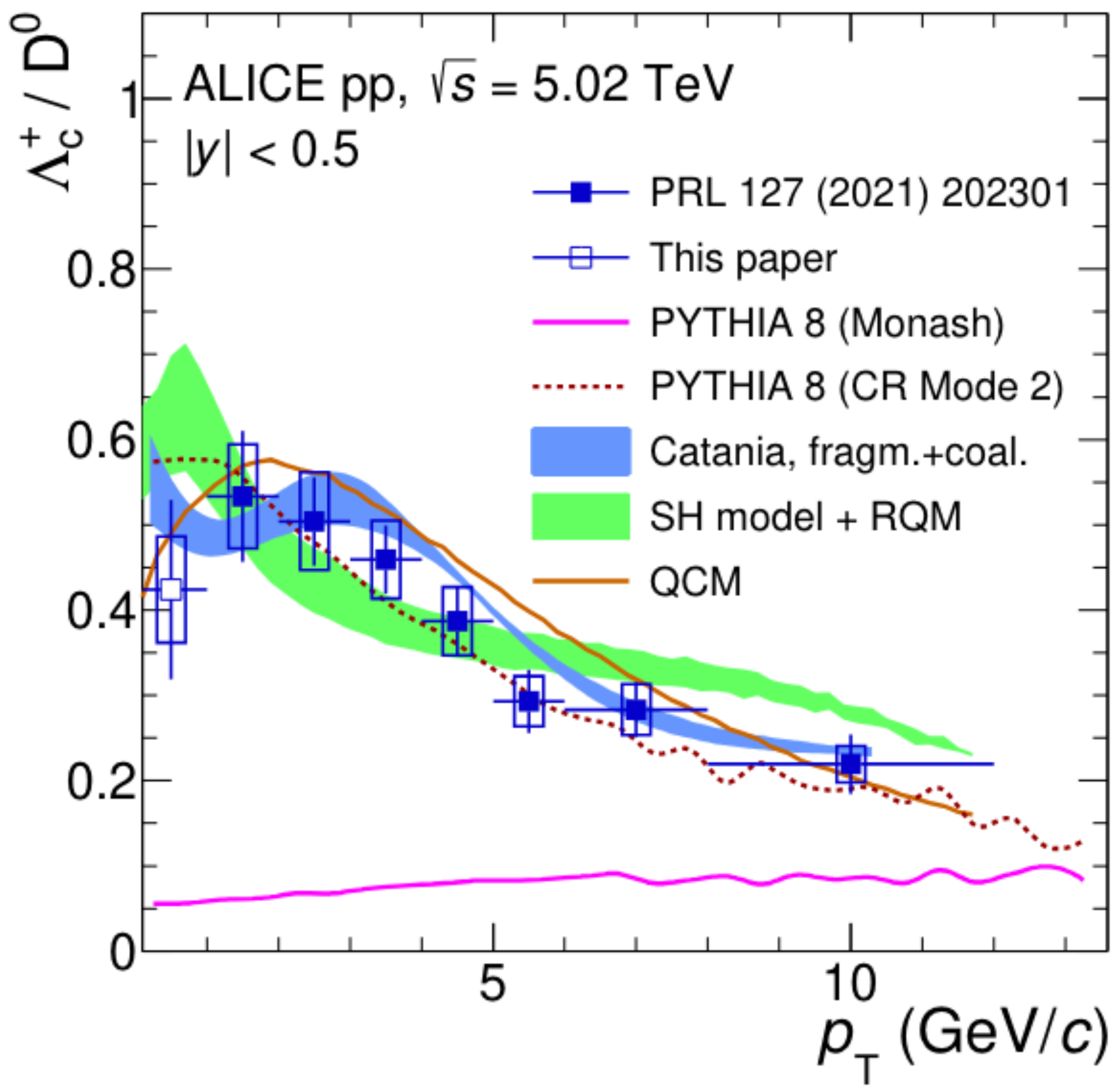


ALICE, arXiv:2211.14032
CMS, arXiv:2307.11186

Good agreement between ALICE and CMS data!

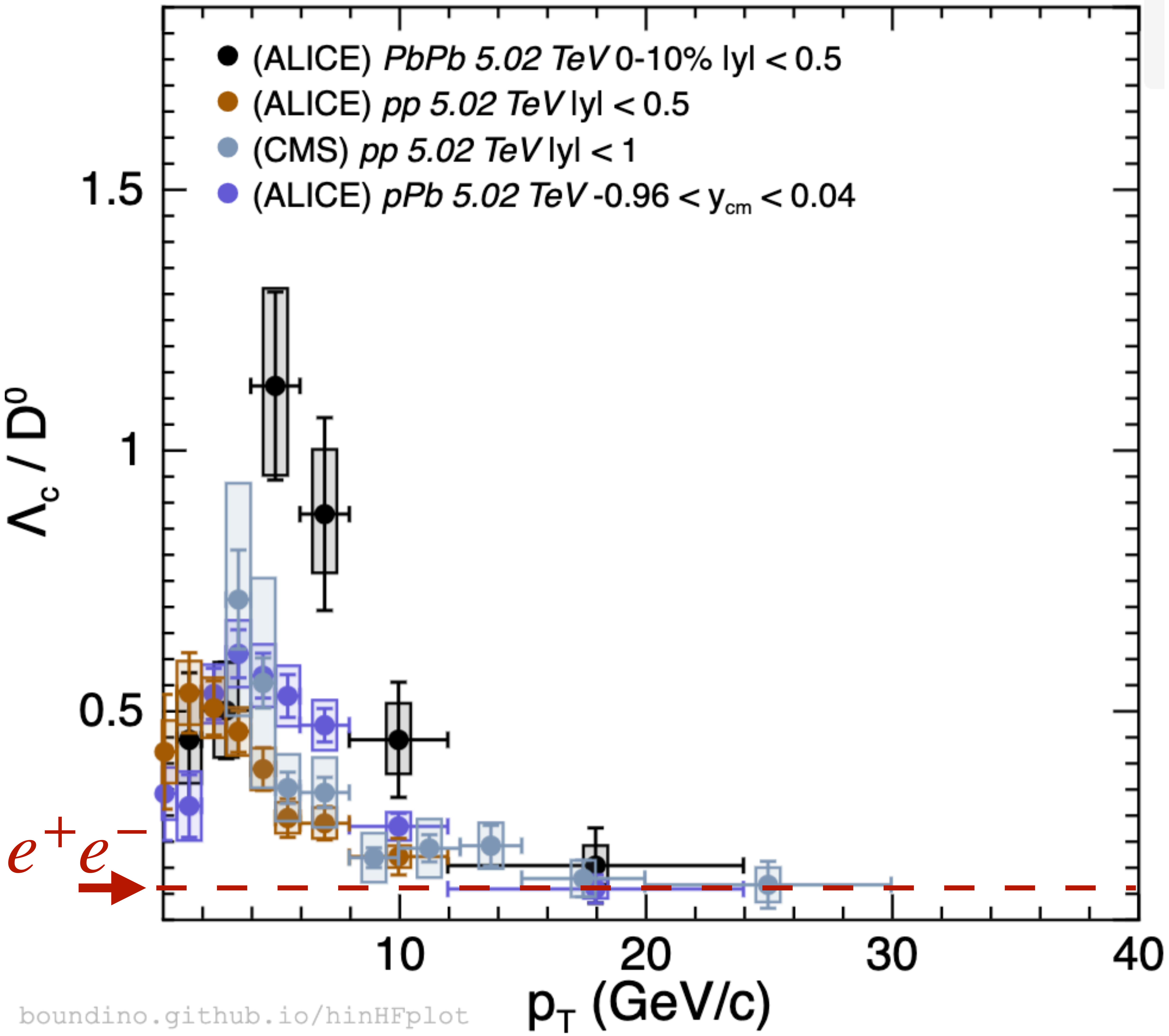
Described by models based on

i) Colour reconnection beyond the leading color
ii) Quark-coalescence
iii) Statistical hadronisation model (SHM) with augmented set of charm-baryon excited states



ALICE, arXiv:2211.14032

Hadronization of charmed hadrons



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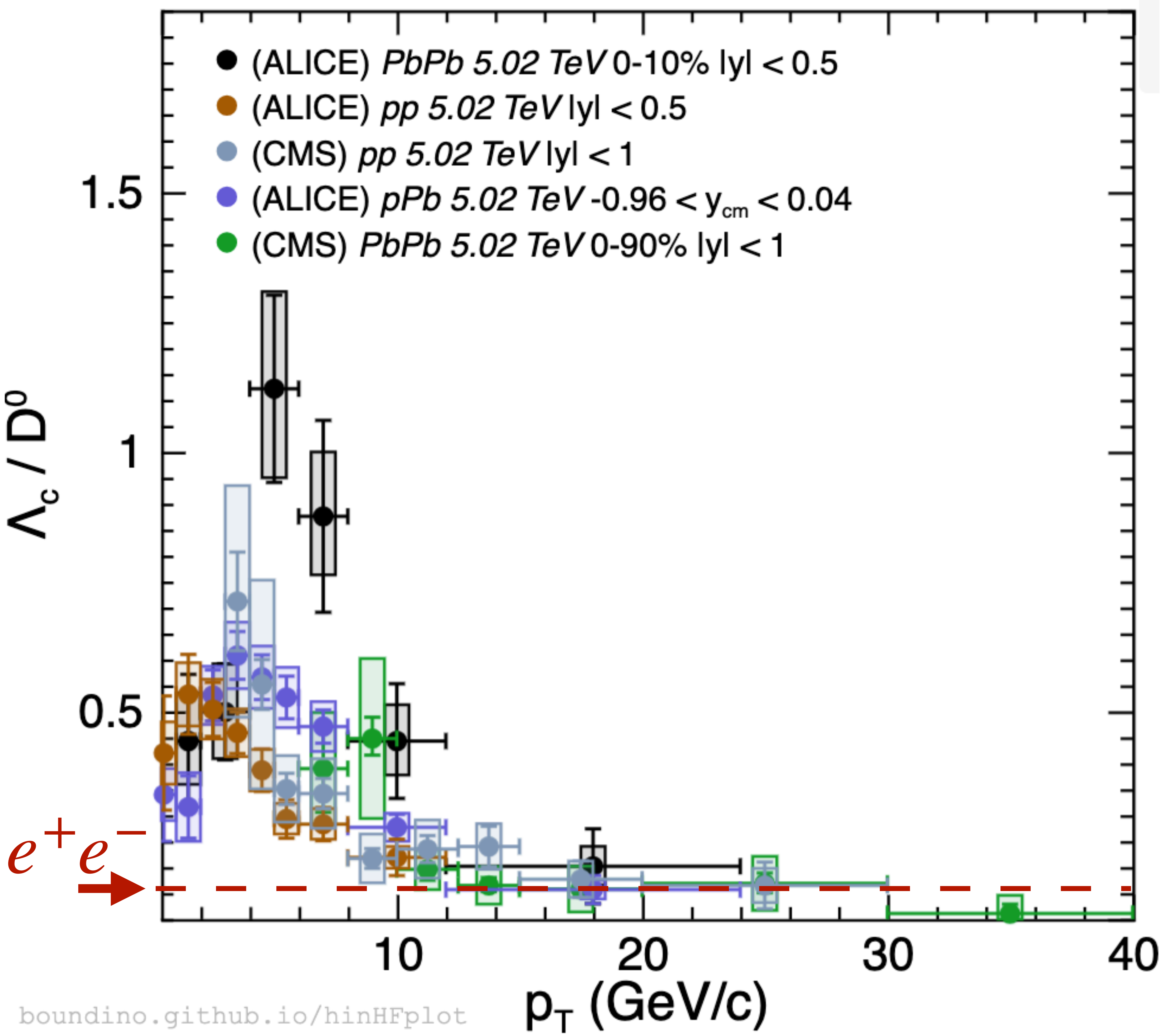
- Modification of the Λ_c^+/D^0 ratio in p—Pb collisions

  →Radial-flow like effect or q recombination

Good agreement between ALICE and CMS data!

Hadronization of charmed hadrons



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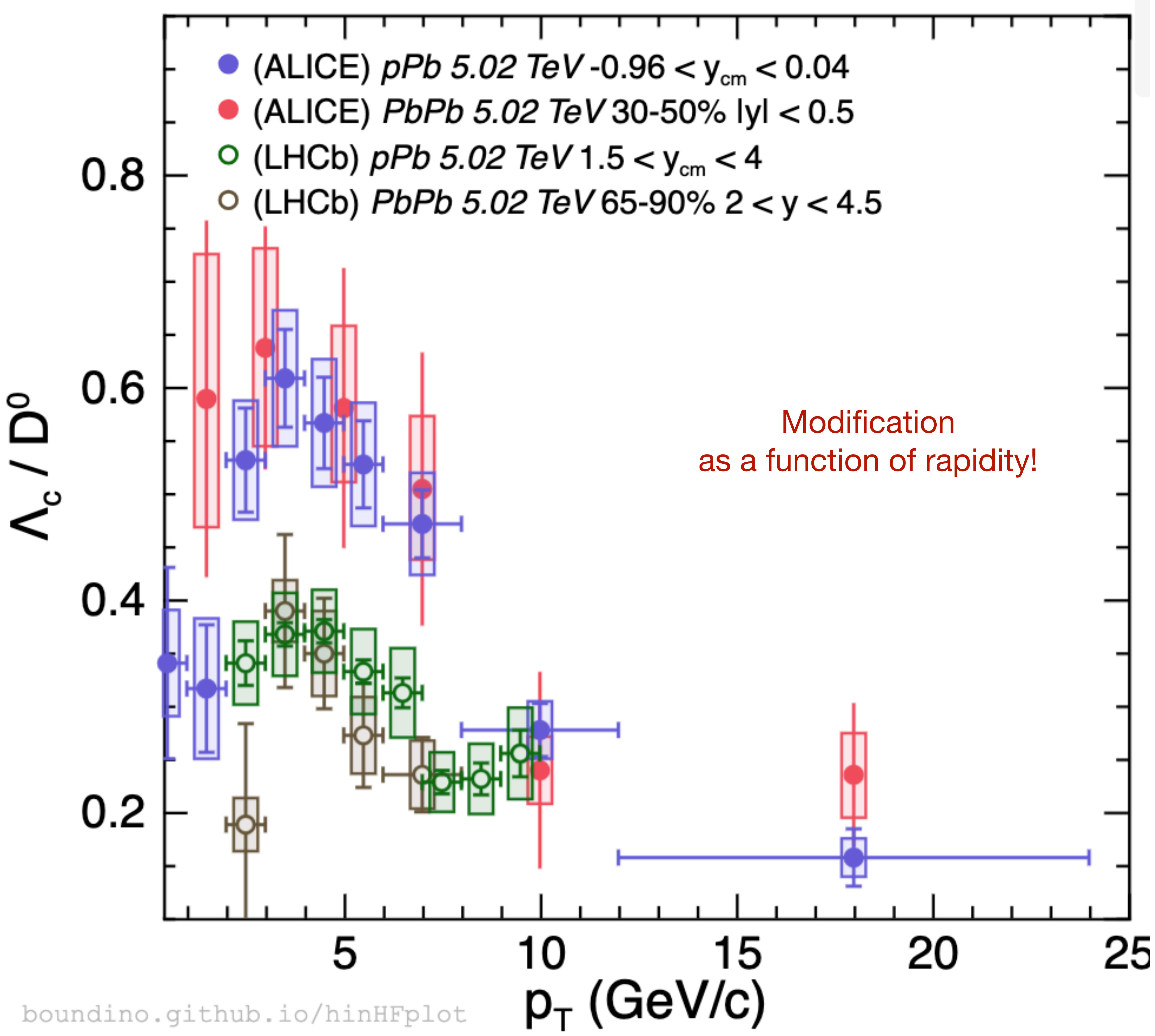
  → Very different than e^+e^-
- Modification of the Λ_c^+/D^0 ratio in p—Pb collisions

  → Radial-flow like effect or q recombination
- CMS: Similar modification in Pb—Pb collisions, increasing with centrality

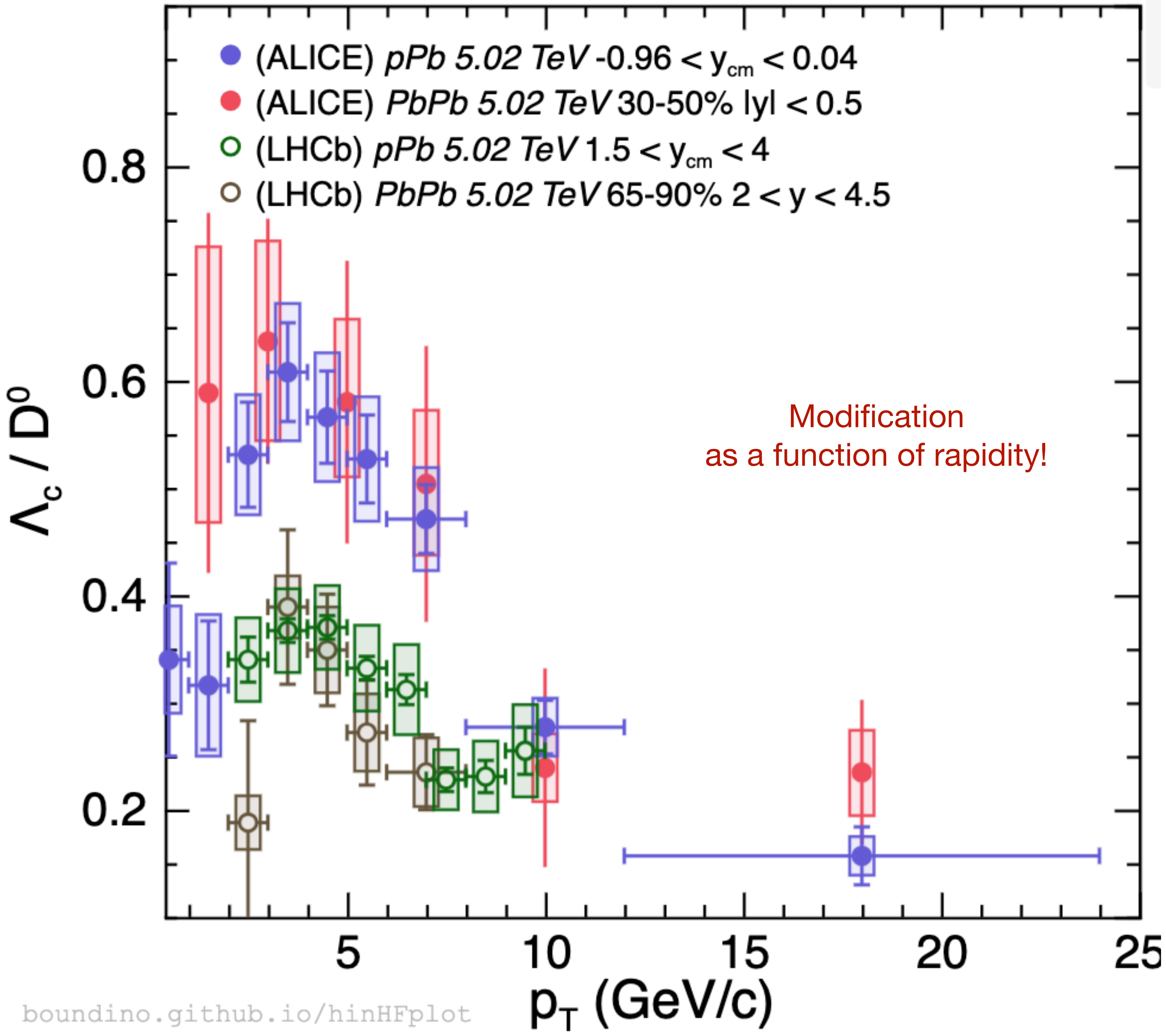
Good agreement between ALICE and CMS data!

Hadronization of charmed hadrons

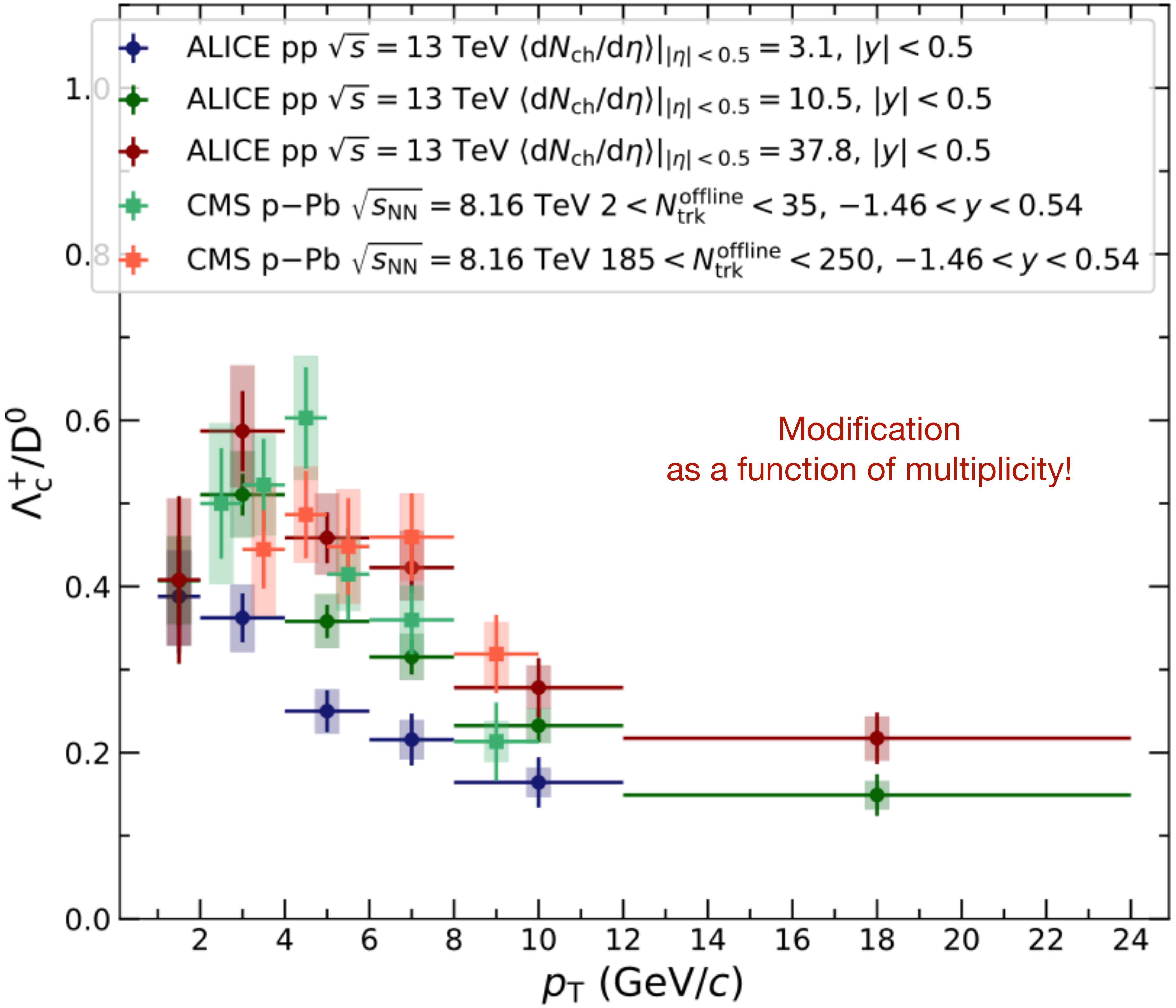


Similar behaviour at forward rapidity, but lower in absolute value than mid-rapidity

Hadronization of charmed hadrons



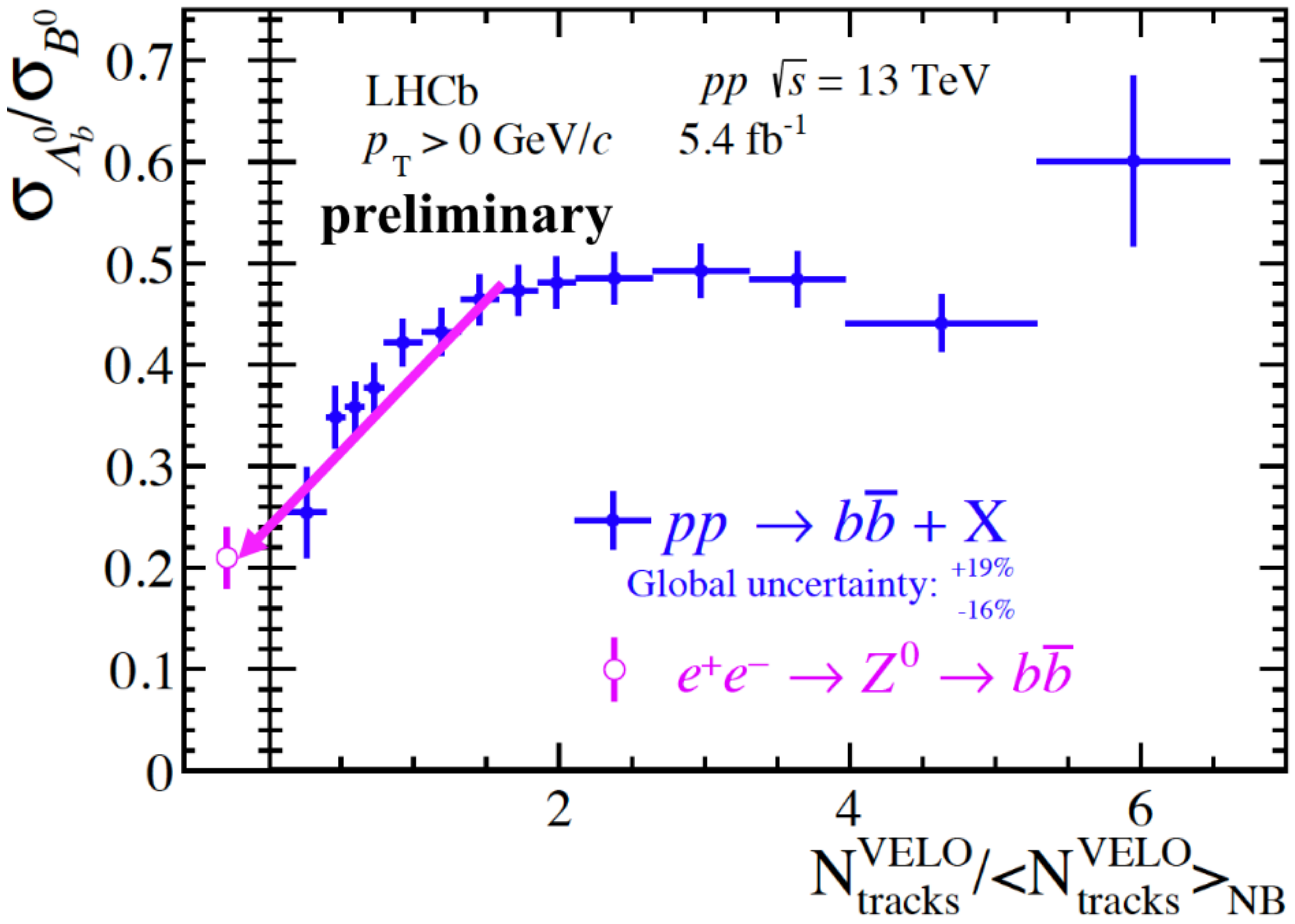
boundino.github.io/hinHFplot



Similar behaviour at forward rapidity, but lower in absolute value than mid-rapidity

Modification of ratio mostly in low multiplicity collisions
No evidence of modification in p—Pb collisions by CMS, but compatible with ALICE results

Hadronization of beauty hadrons

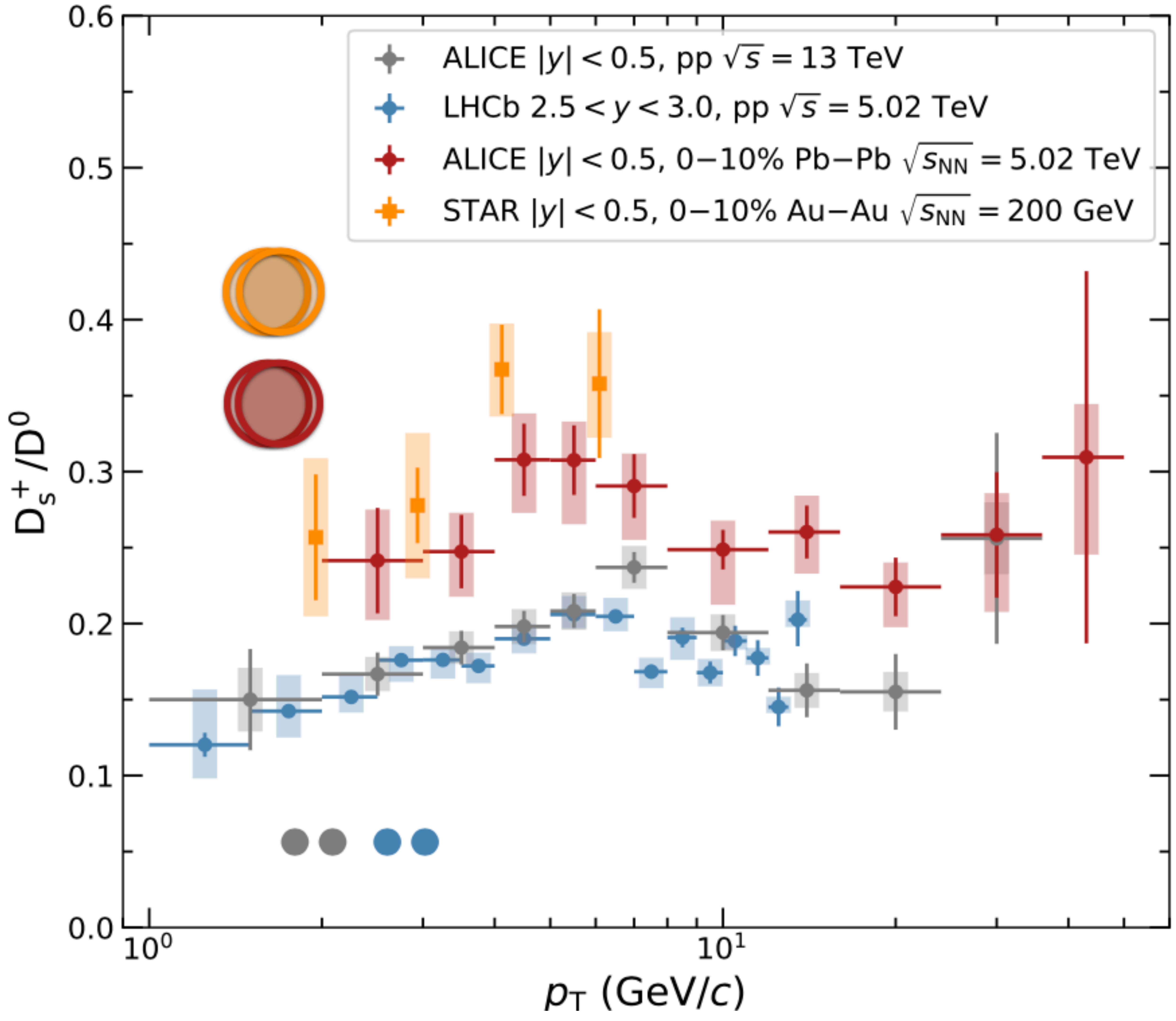


- Λ_b^0/B^0 shows modification as a function of multiplicity!!

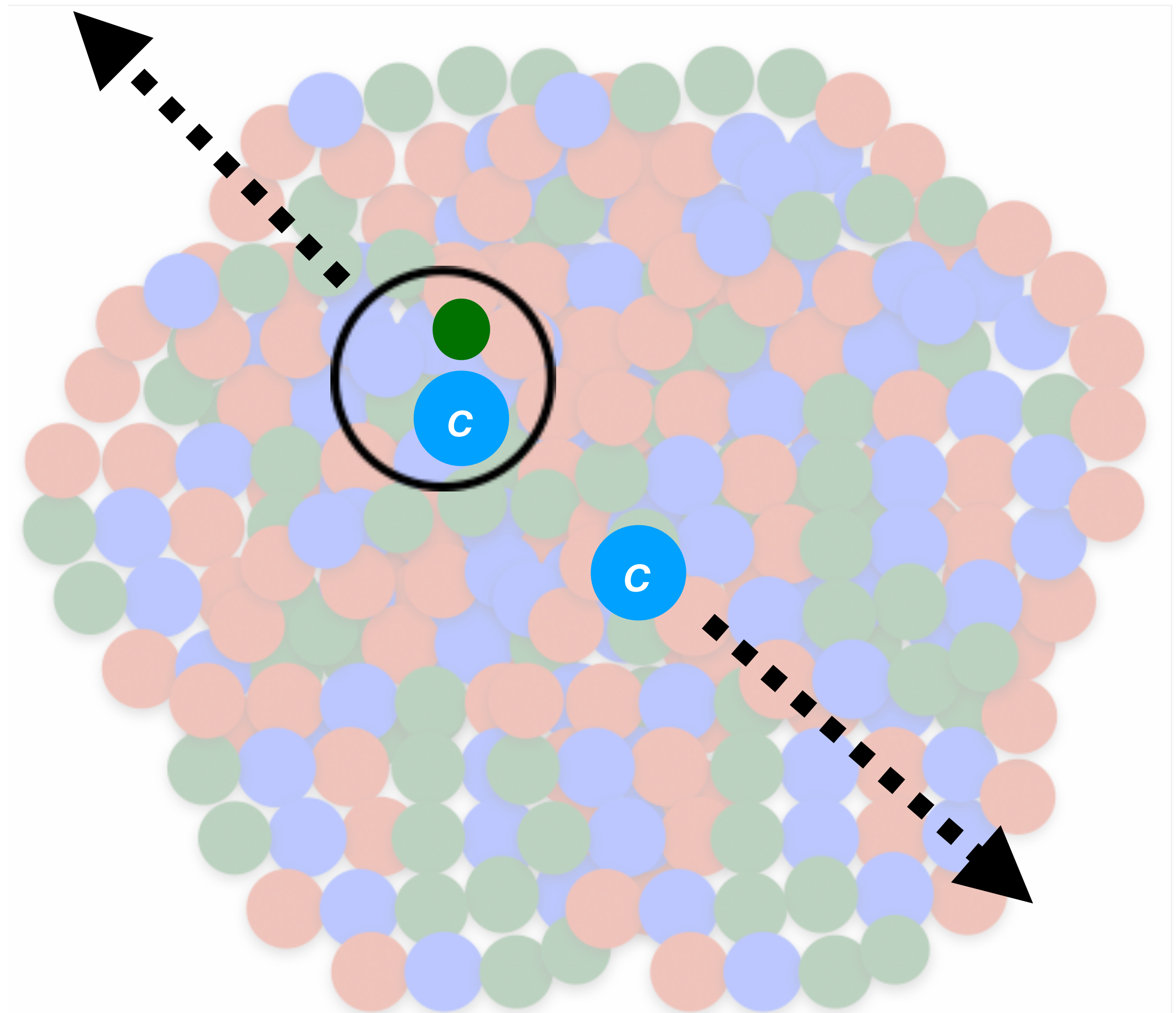
→Approaches e^+e^- value at very low multiplicity

→Saturates at high multiplicity

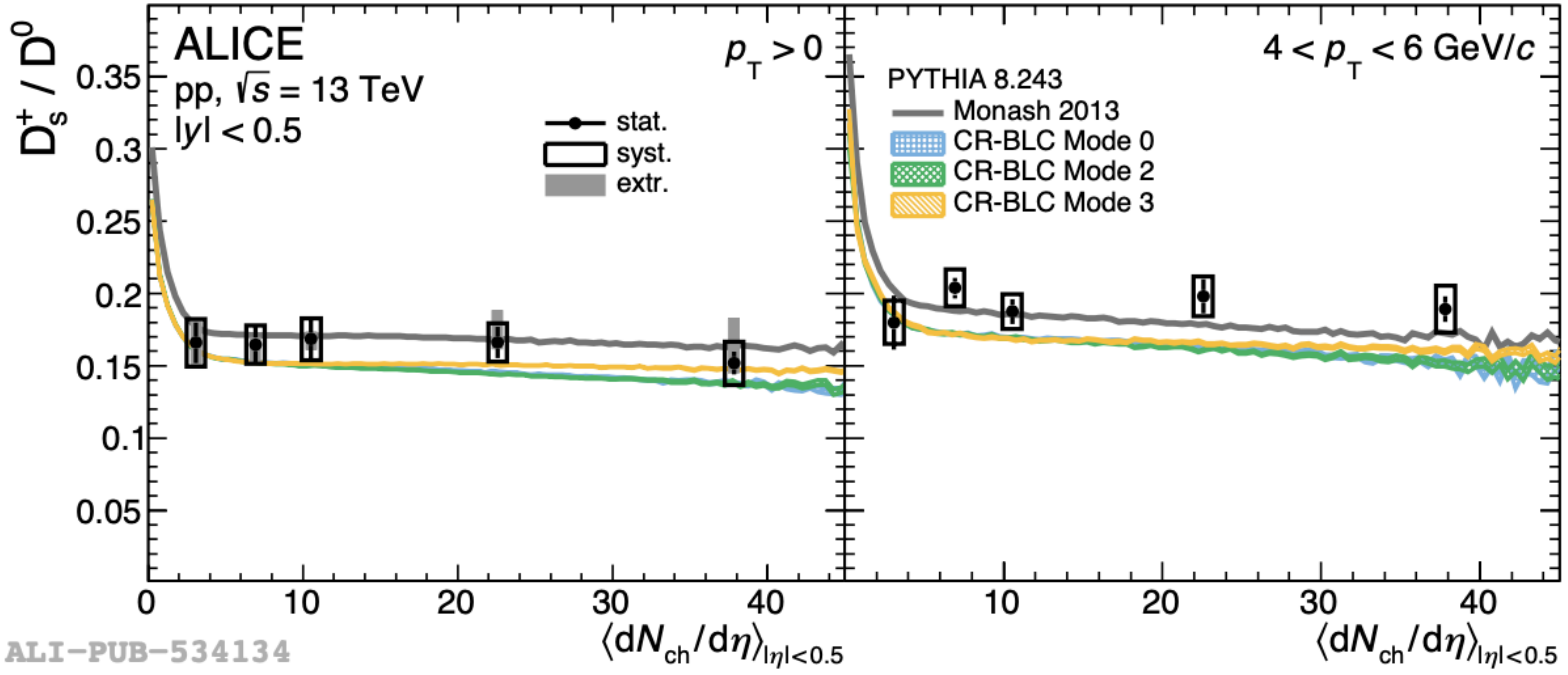
Hadronization of charm and strangeness enhancement



- Abundant production of strange quarks in the QGP.
- Recombination → strange hadrons expected to be enhanced
- Strange-to-nonstrange ratio higher in Pb—Pb than pp in charm sector



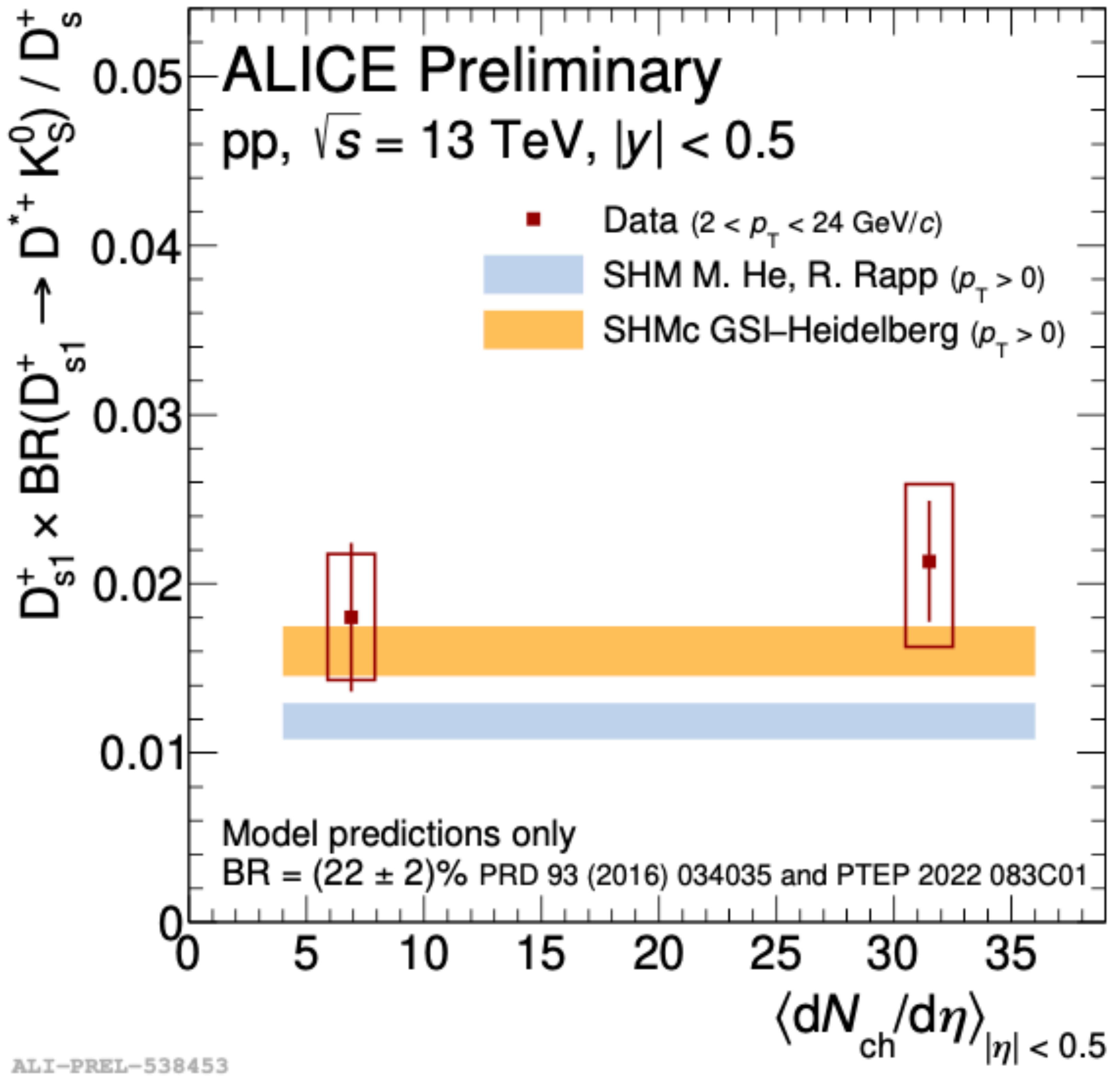
Hadronization of charm and strangeness enhancement



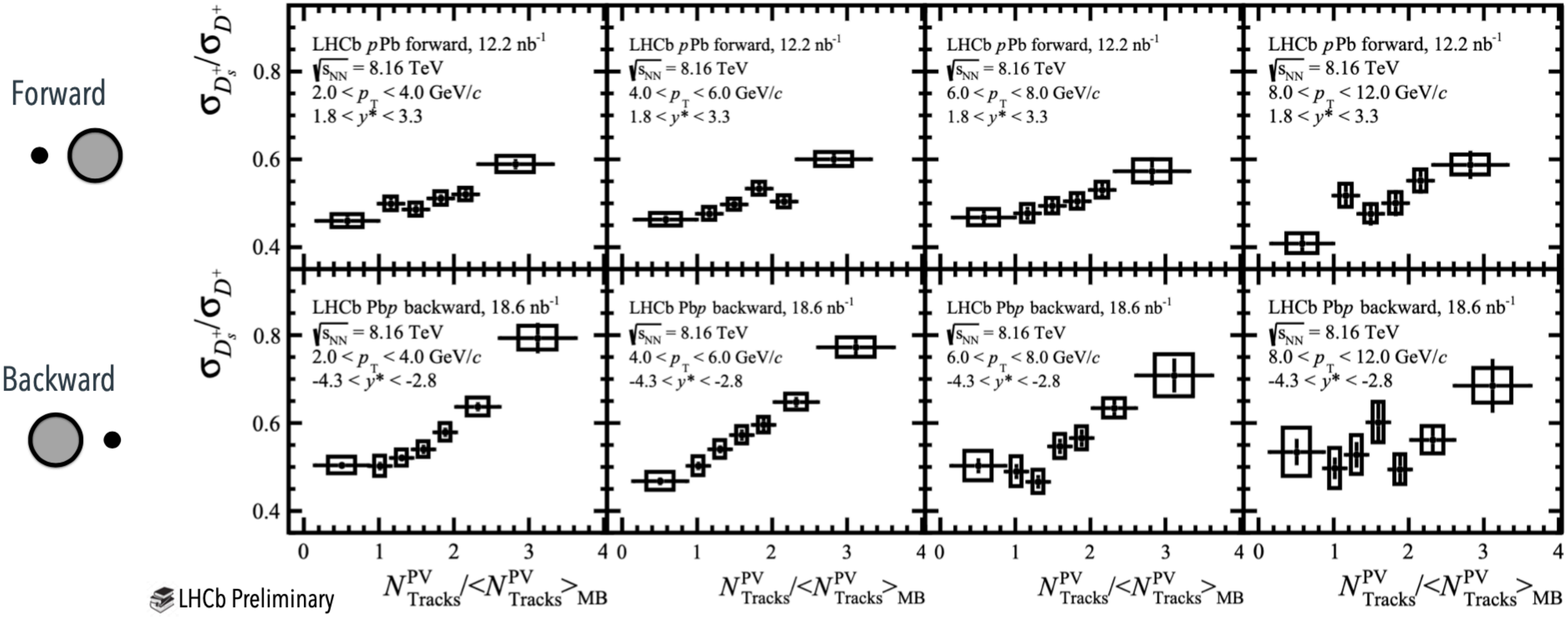
- No evidence of multiplicity dependence of D_s^+/D^0 in pp collisions

First measurement of excited D_S production as a function of multiplicity

- Ratio to the ground state does not show multiplicity dependence
- Larger data samples needed



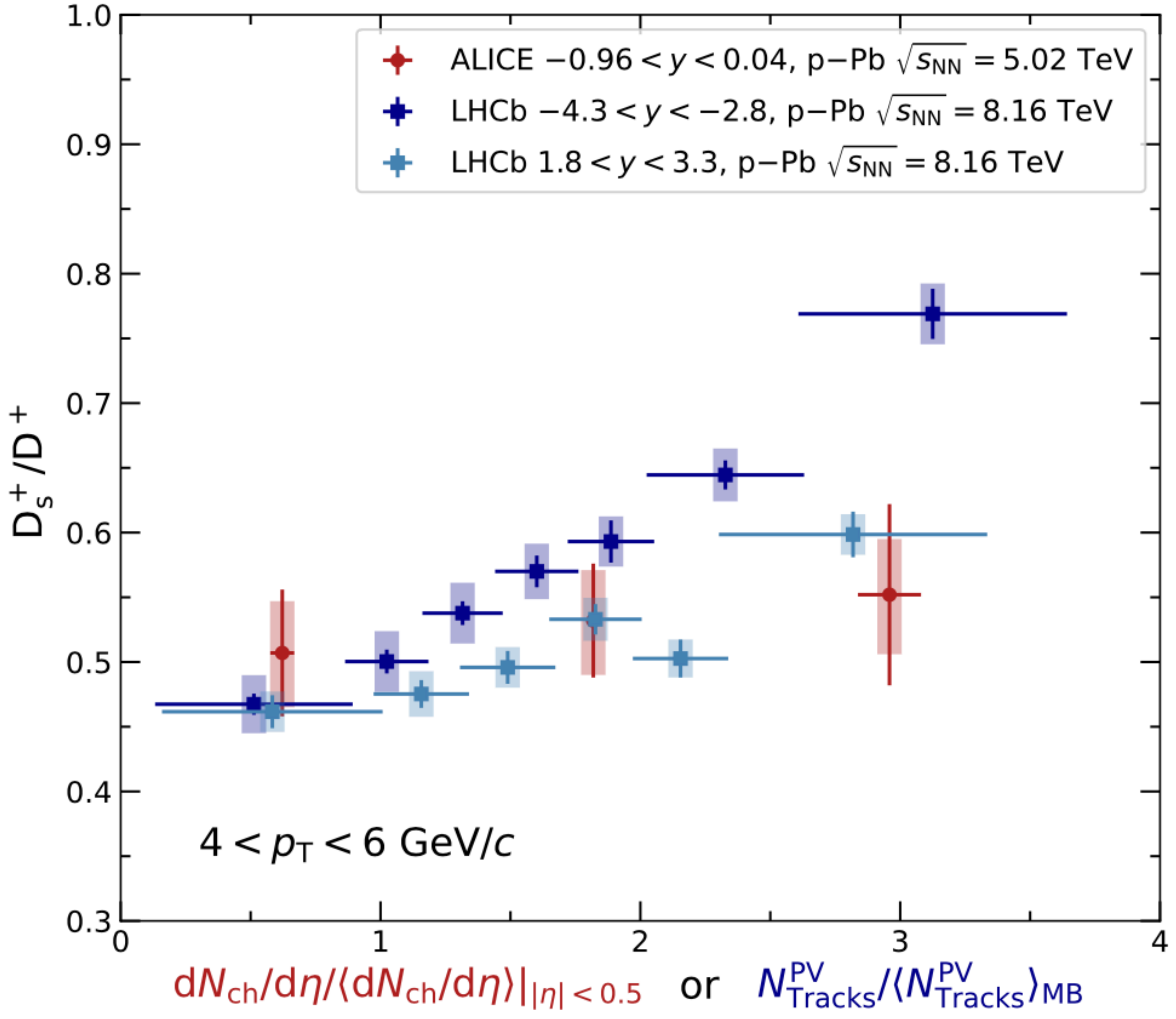
Hadronization of charm and strangeness enhancement



- First observation of D_S^+/D^+ increase as a function of multiplicity in p—Pb collisions at forward and backward rapidities

➡ Steeper increase at backward compared to forward rapidity → because of higher average multiplicity?

Hadronization of charm and strangeness enhancement



- No evidence of multiplicity dependence at midrapidity
- Compatible with forward rapidity measurement, tension with backward rapidity
- Steeper slope for backward rapidity probably due to different absolute multiplicity in different rapidity regions not considered in self normalized multiplicity
- Crucial to plot the D_s^+/D ratio as a function of the charged-particle density $dN_{ch}/d\eta$

Summary

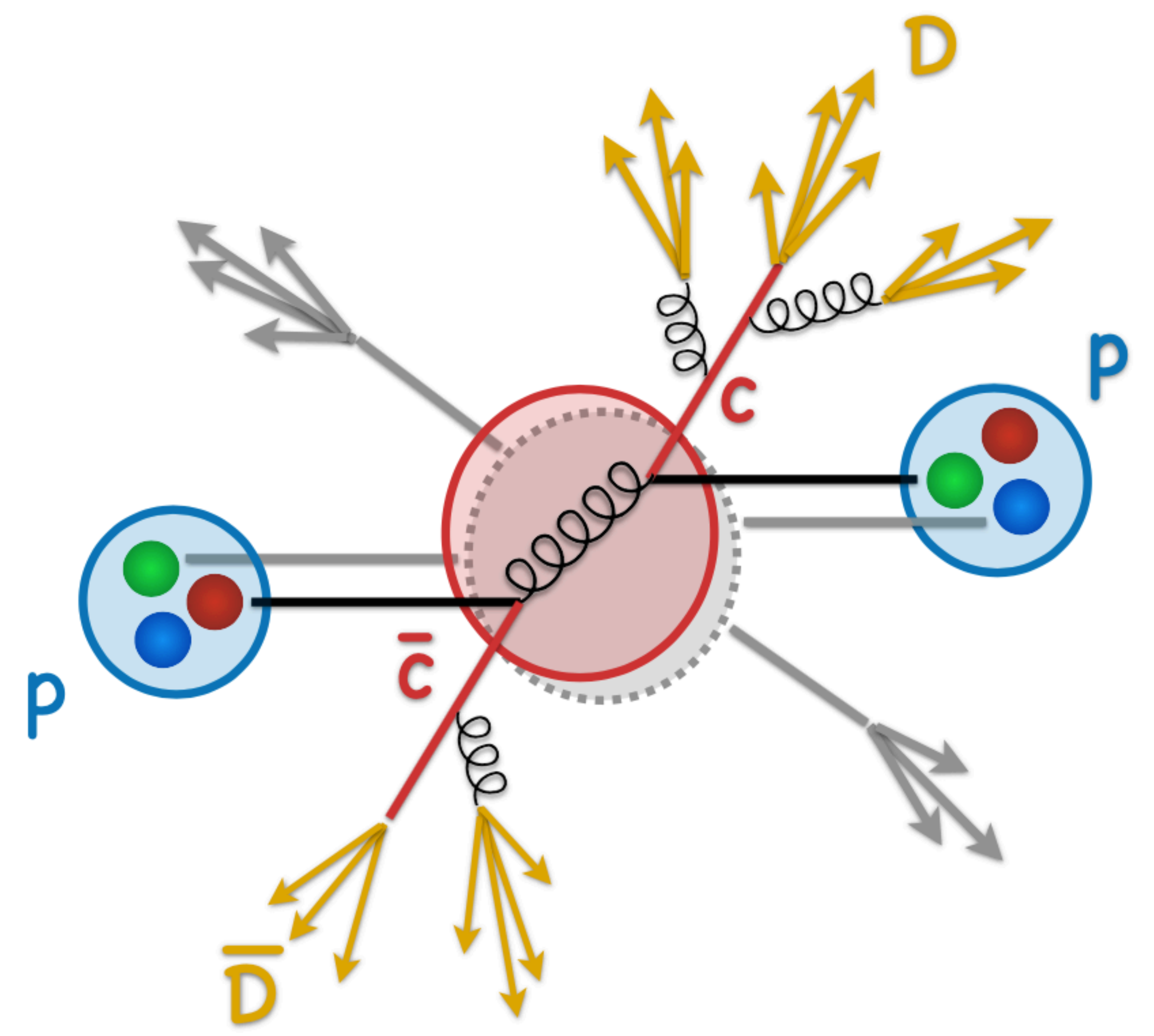
- Detailed insight on the QGP in heavy ion system using heavy quark from their production to their “journey” into the medium until the formation of heavy-flavour hadrons.
  - Heavy quark production
  - Heavy quark interaction
  - Energy loss measurement
  - Flow measurement
  - modification of hadronization mechanisms.

Many open question still need to be addressed with Run 3 data.

- Push experimental tests of pQCD with higher precision HF/HF-jet studies.
- Extend the studies to Beauty and to higher p_{T}
- Systematically probe non-perturbative effects such as hadronization
- Extension of program to heavy-ion collisions to characterize in-medium interactions in the quark-gluon plasma formed in heavy-ion collisions and distinguish the QGP behavior from the in-vacuum QCD dynamics

Backup slides

Heavy quark production in pp collisions



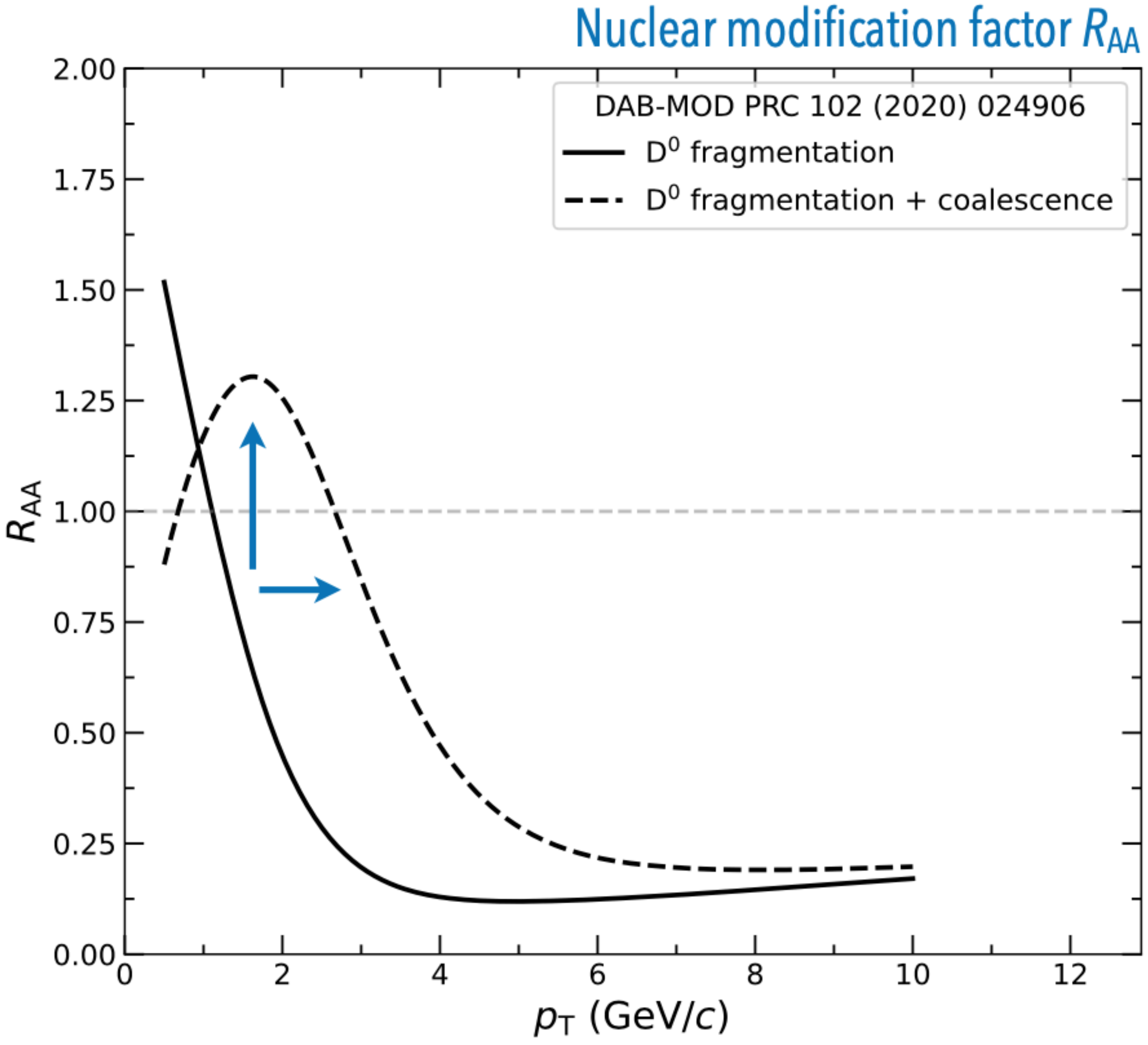
$$\sigma_{hh \to Hh} = \mathrm{PDF}(x_a, Q^2)\ \mathrm{PDF}(x_b, Q^2) \otimes \sigma_{ab \to q\bar{q}} \otimes D_{q \to h}(z_q, Q^2)$$

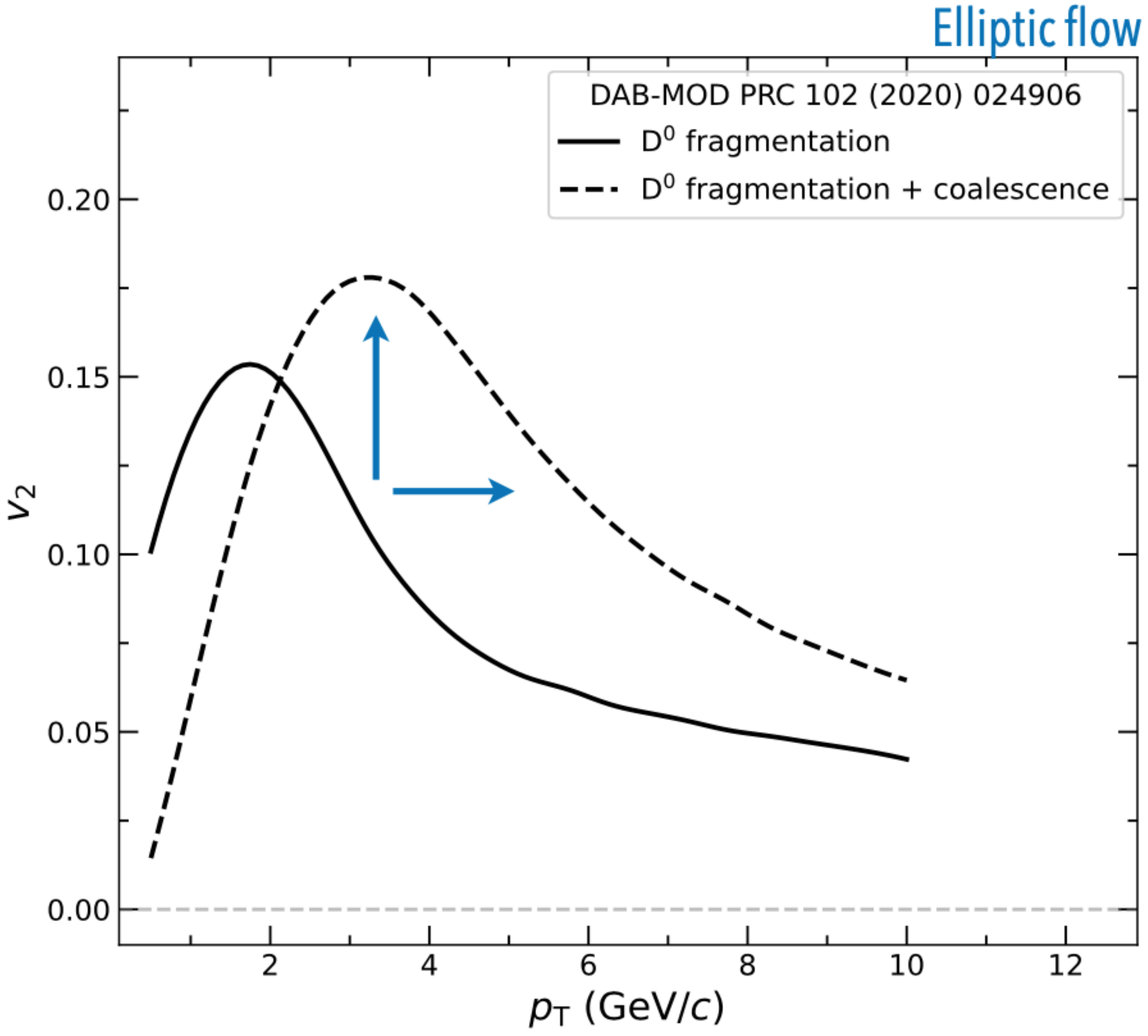
Parton distribution functions (non perturbative)

Partonic cross section (perturbative)

Fragmentation functions (non perturbative)

Charm quark hadronization from the medium





R. Katz et al, PRC 102 (2020) 024906

- Formation of a peak structure at intermediate p_T

Tuning the flavor dependence by varying alpha

$$\lambda_{\alpha}^{\kappa=1} = \sum_{i \in jet} z_i \theta_i^{\alpha}$$

- How much of this modification is due to the D0 jet being a **quark jet** versus being a **HF jet**?

- With increasing α the impact of mass effects is reduced : D0-tagged and quark-initiated distributions become more similar → cleaner sensitivity to Casimir colour effects
- At lower α where the core of the jet has a higher weight → large angle radiation has a lower weight, mass effects are more prominent

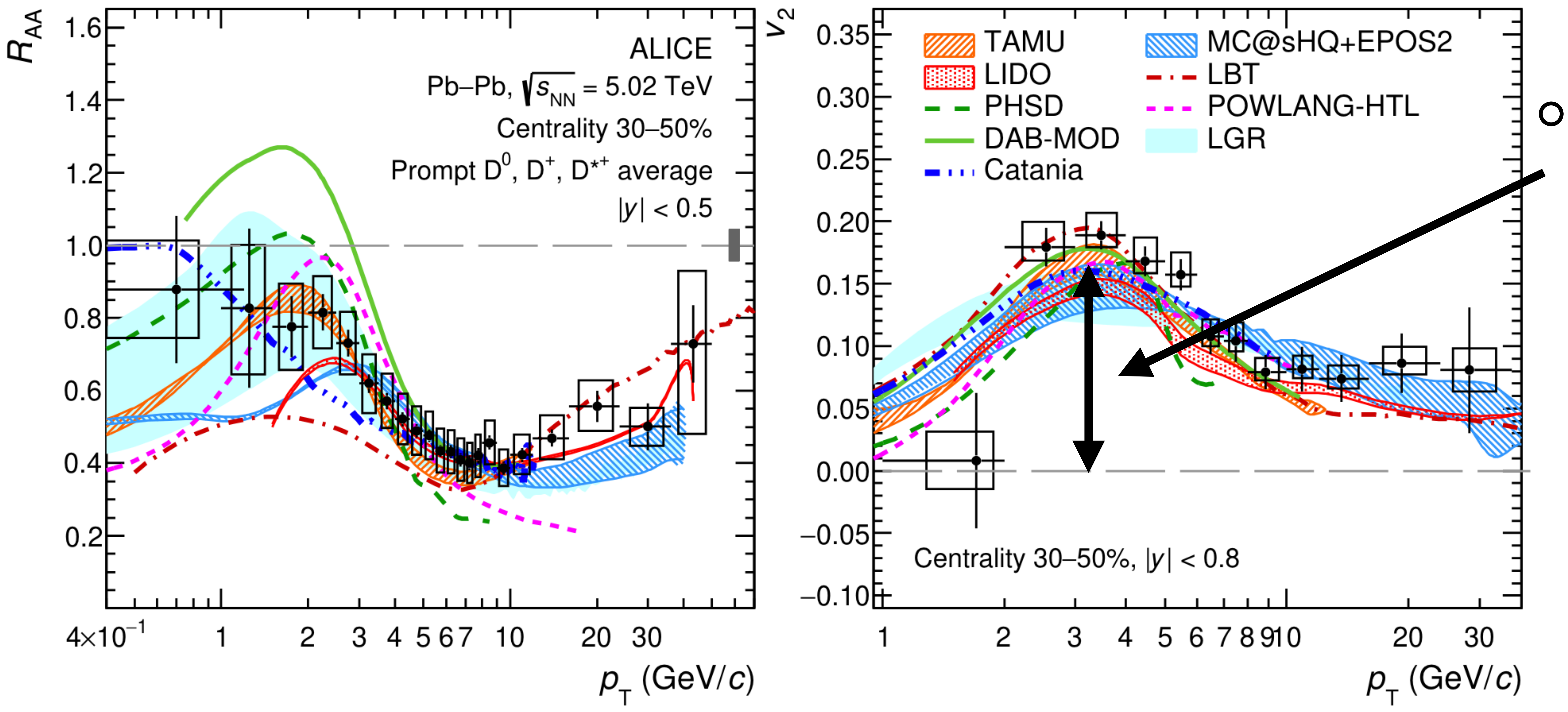
Scanning the angular profile of jets

$$\lambda_{\alpha}^{\kappa=1} = \sum_{i \in jet} z_i \theta_i^{\alpha}$$

Higher α →more weight on wide angle emissions

- With increasing α the shape of the charm-tagged and semi-inclusive angularities begin to converge

Collective flow: do heavy-quark flow?



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→ charm flows collectively with the medium

→Diffusing charm quark moves with expanding medium

POWLANG, BAMPS el, TAMU: do not include radiative energy loss

➡determination of onset of radiative contributions by deviations from experimental data at a certain p_T

• PHSD, MC@sHQ+EPOS2, BAMPS el.rad, LBT: both elastic and radiative contributions are included

• Quark recombination: in TAMU, POWLANG, PHSD, MC@sHQ, LBT, Catania