Using heavy quarks and jets to probe the Quark Gluon Plasma: Highlights from ALICE

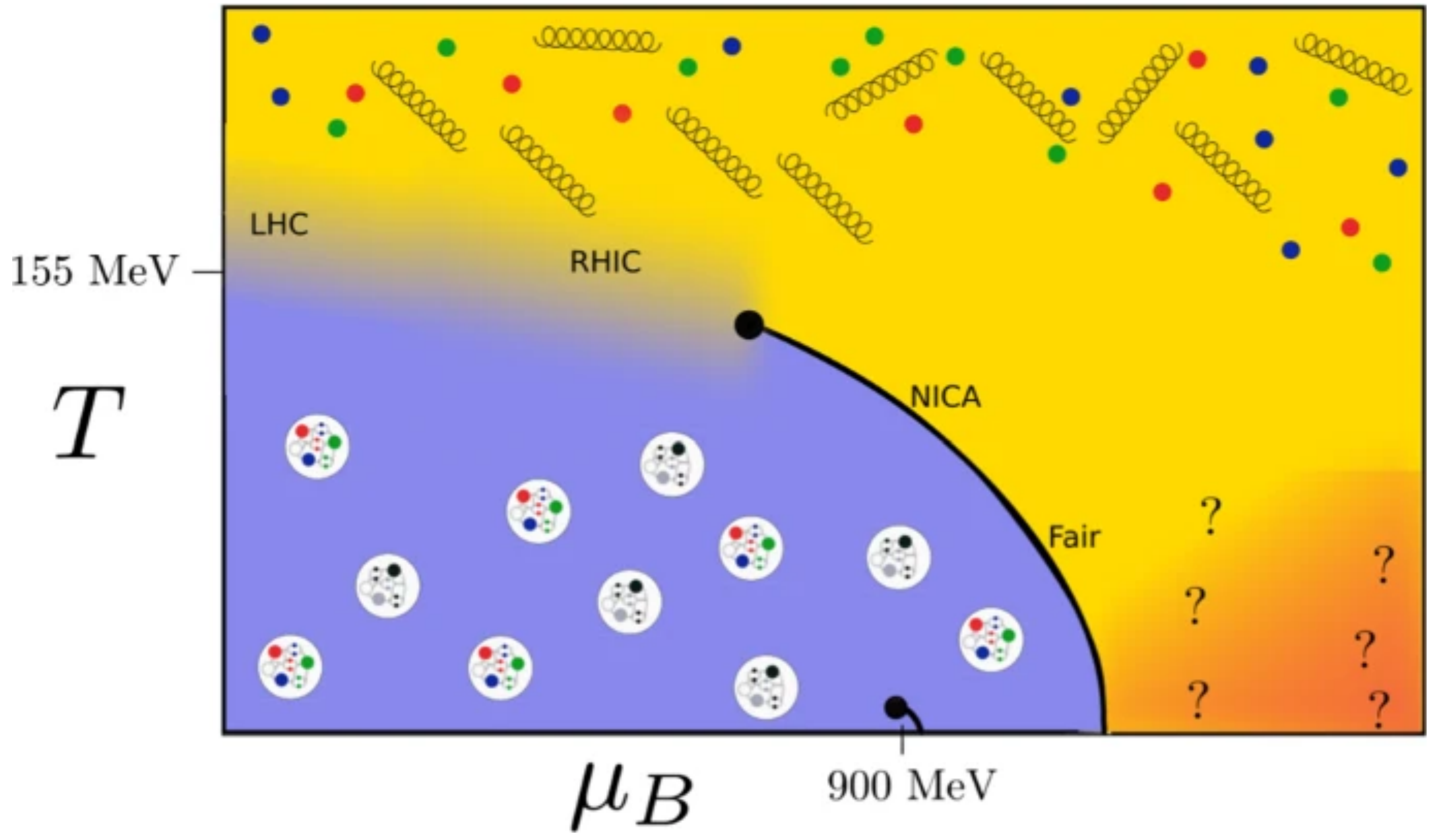
Jaime Norman (University of Liverpool) - on behalf of ALICE

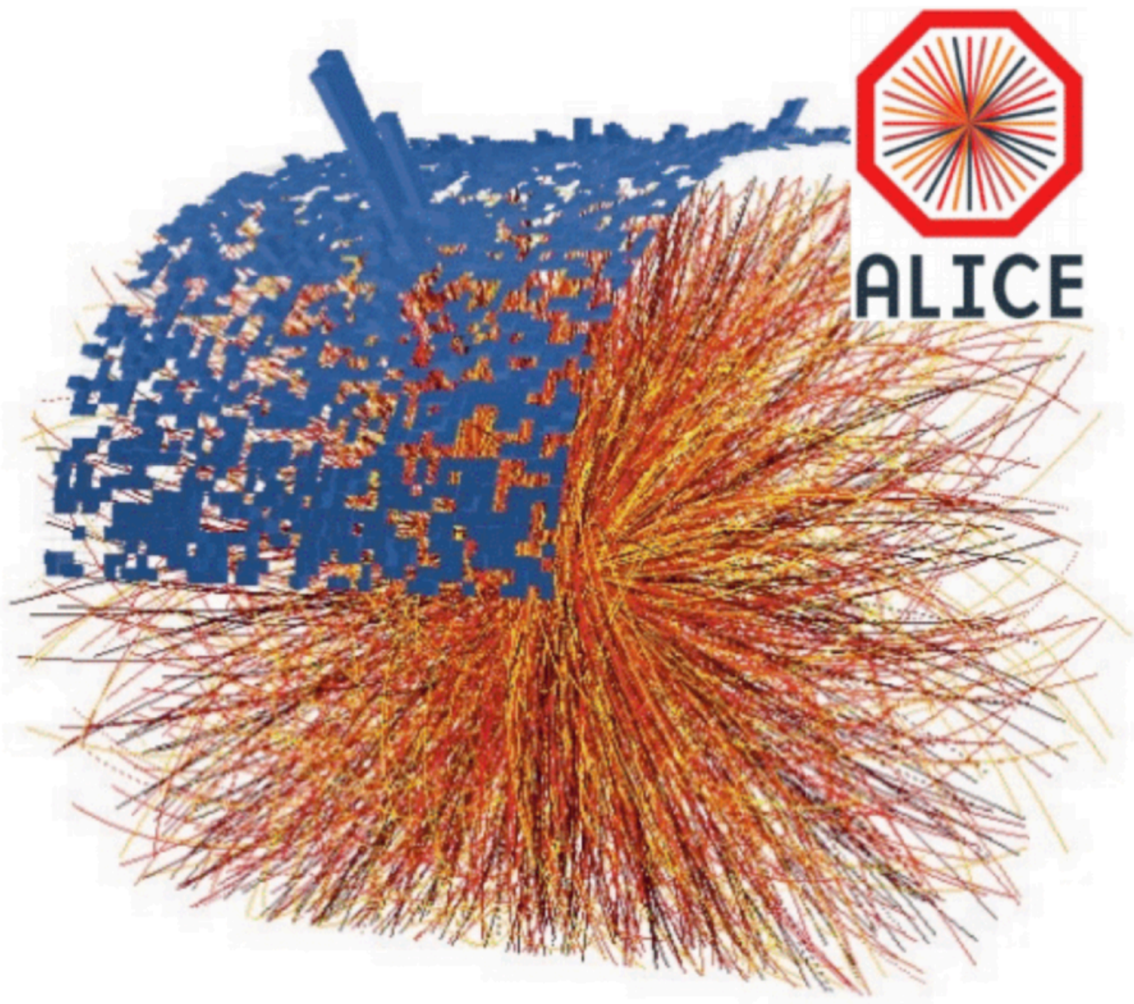
Excited QCD 2022

Deconfinement and the QGP

J. Guenther, EPJA 57 136 (2021)

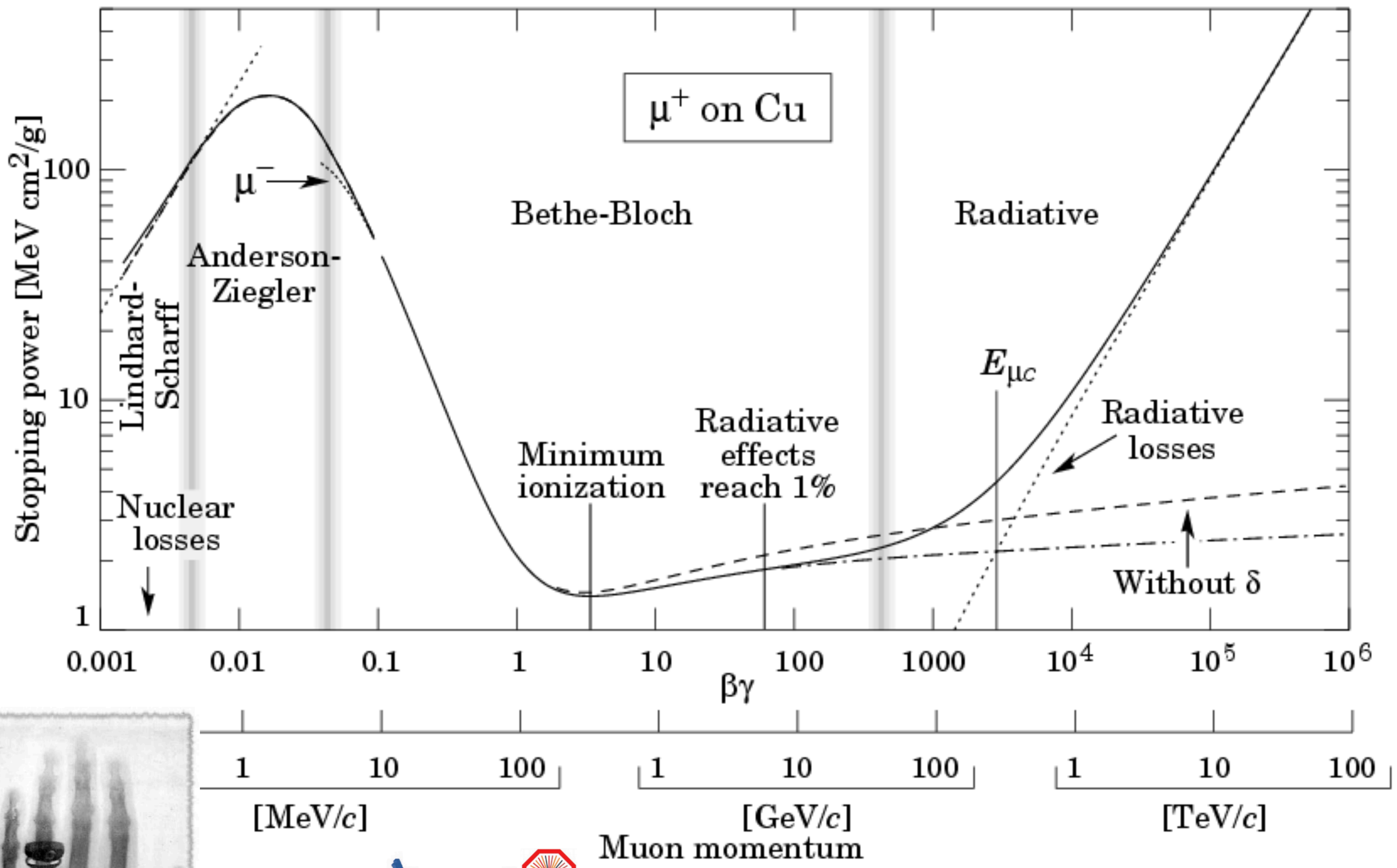
- QCD under high temperatures or densities undergoes a phase transition to a deconfined state of quarks and gluons, the Quark-Gluon Plasma (QGP)
- Its study addresses fundamental questions related to the bulk properties and dynamics of hot QCD matter and confinement
- This state of matter is achieved and studied using lead-lead (Pb-Pb) collisions at the LHC

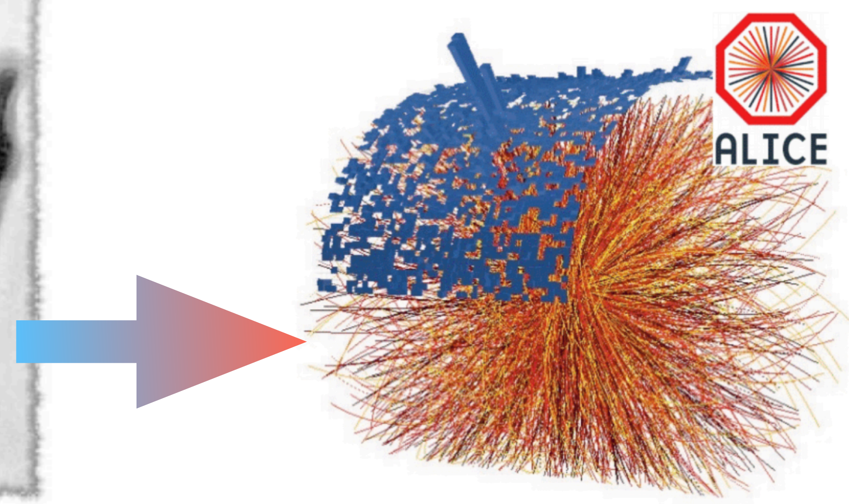




Mapping the Bethe-Bloch of QCD matter

PDG

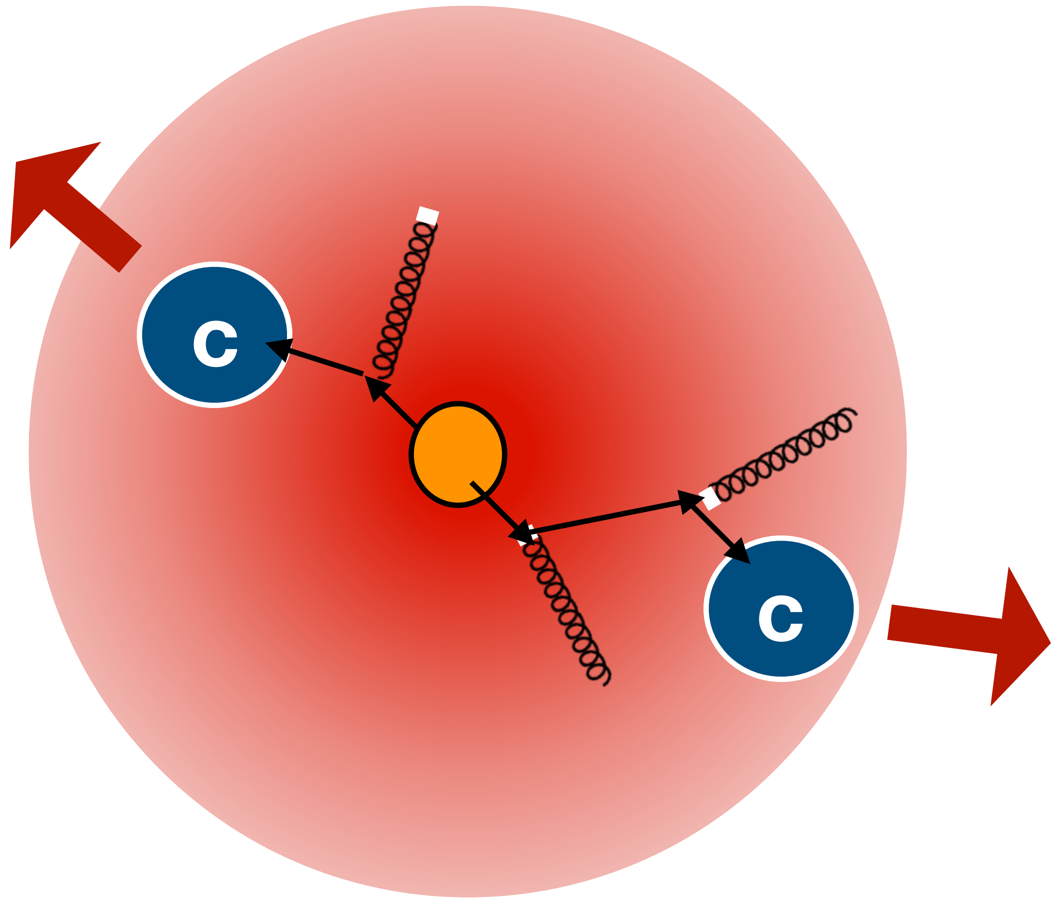




- Tomographic 'probes' can be used to study matter
  - Bethe-Bloch curve → connection of 'local' interactions with global medium properties
- Study the properties of ordinary matter using **QED probes** (x-rays, MRI, PET,…)
- Likewise, QGP studied using **QCD probes**

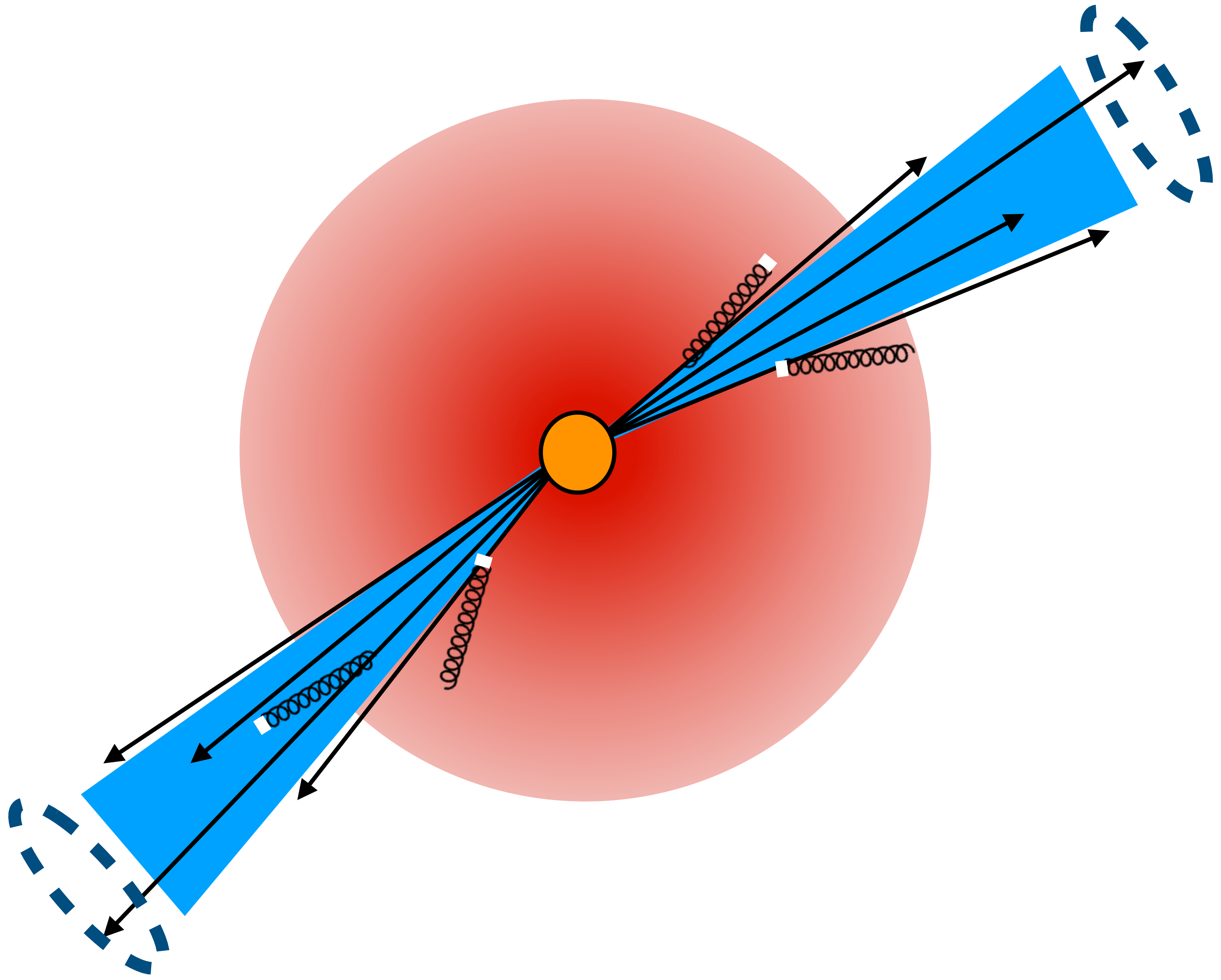
Probes of the QGP: Heavy Quarks

- I will talk about 2 different types of probes:
  - **Heavy quarks (c, b)** produced in early stages of the collision, with negligible thermal production ($m_{c,b} > T_{QGP}$) - can be tracked through all stages of collision
    - *collisional* and *radiative* interactions with medium results in heavy-quark energy loss
  - Heavy quarks can be measured by studying the production of heavy-flavour hadrons (D/B mesons, Λ_c^+, Λ_b^0 baryons...)



Probes of the QGP: Jets

- I will talk about 2 different types of probes:
  - Heavy quarks (c, b)
  - **Jets:** In-medium evolution and parton shower modified at all stages of the system's lifetime
    - Jet loses energy in-medium (jet quenching)
    - Jets axis is modified (jet deflection)
    - Jet substructure is modified



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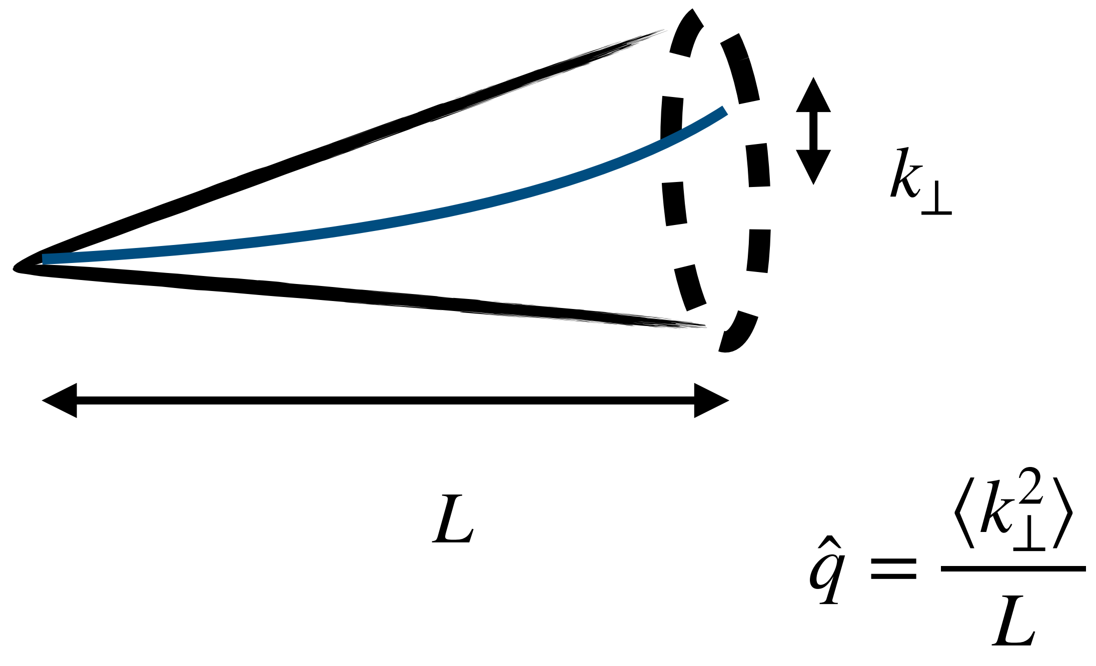
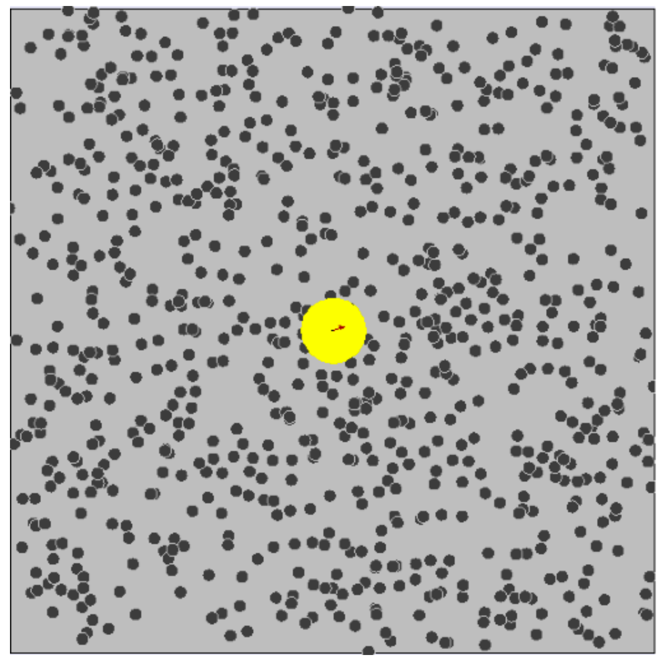
  - **Heavy quarks (c, b)**
  - **Jets**



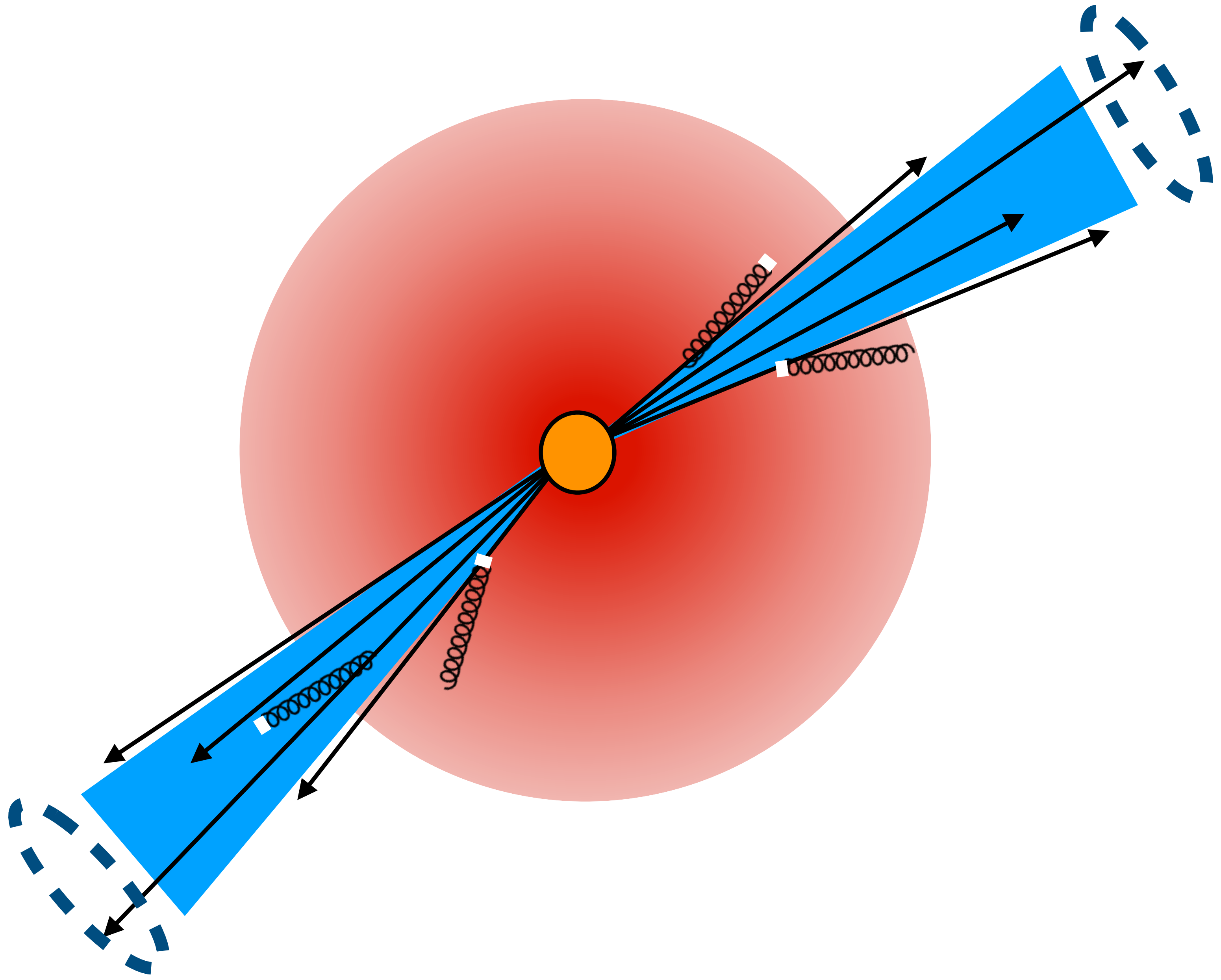
jet transport coefficient $\hat{q}$:

- Describes average momentum transfer transverse to the jets direction per unit length



Heavy quark spacial diffusion coefficient D_s:

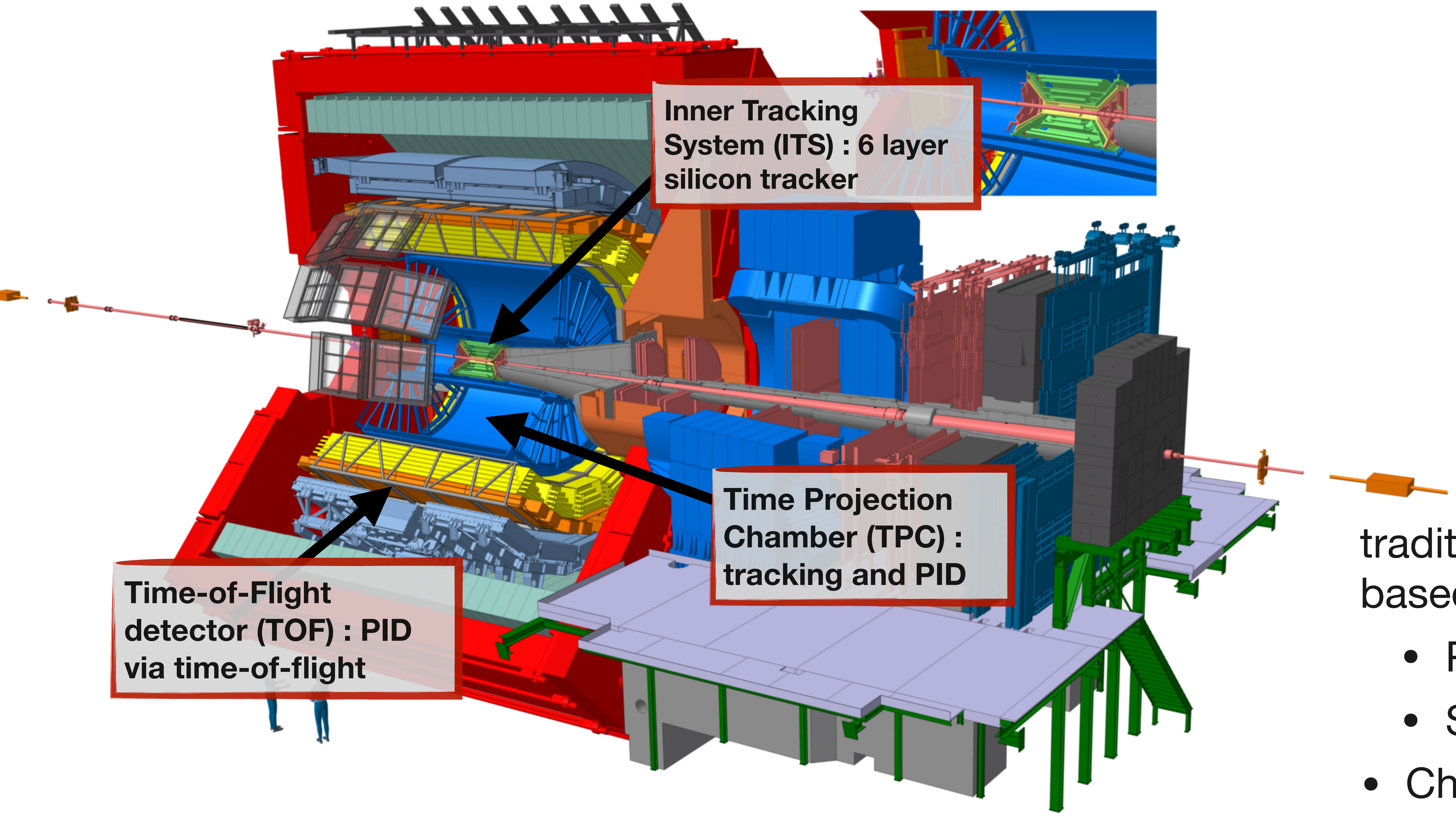
- Characterises low-momentum interaction strength of heavy-quarks with the medium

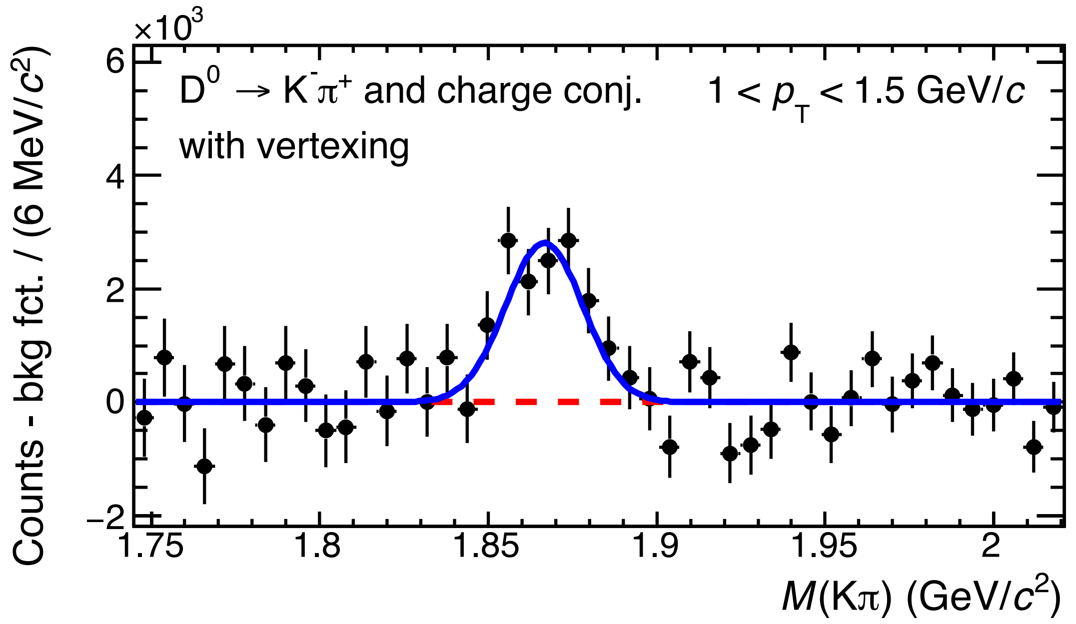


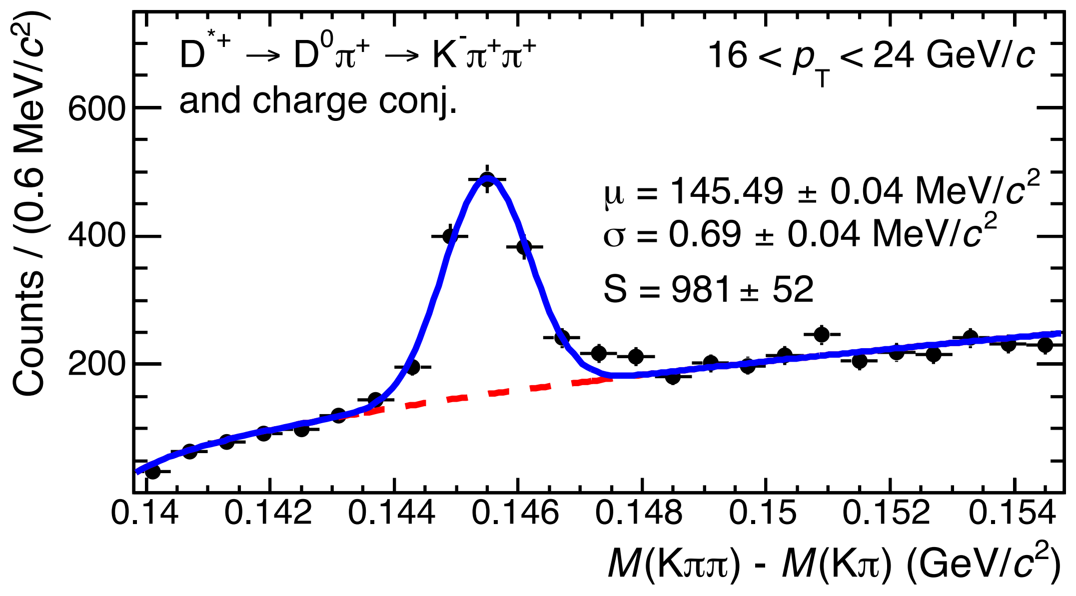
→ **Inner structure of the QGP can be probed with jet and heavy-flavour measurements**

The ALICE experiment

Heavy-flavour hadrons reconstructed in central barrel ($|\eta| < 0.9$)







traditional cut-based or machine-learning-based selection of HF decays via

- PID of decay products
- Selection on topology of decay

- Charm hadrons from beauty decays separated via fit data-driven techniques

The ALICE experiment

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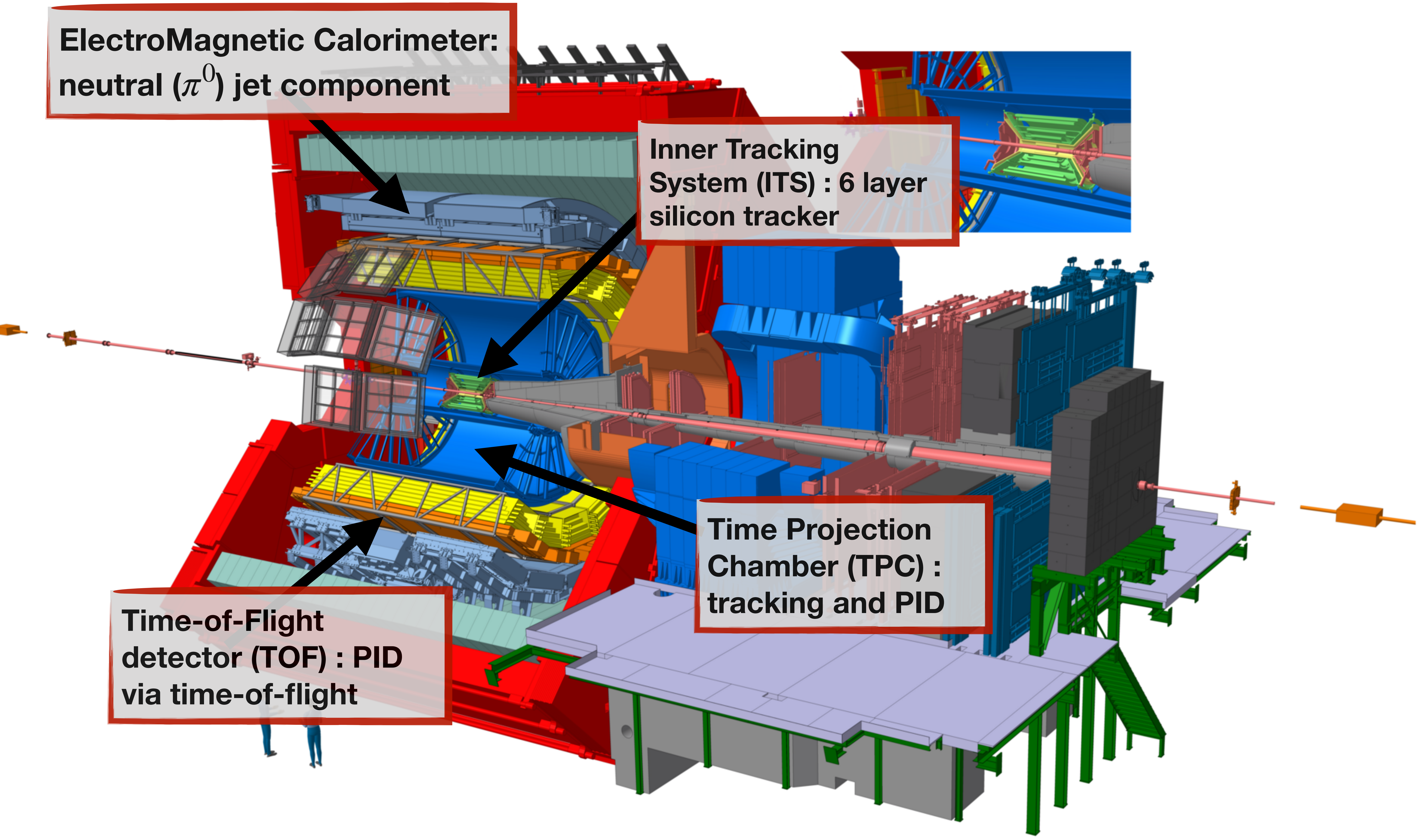


Reconstructed as:

- 'track-based' (charged) jets using charged tracks
- 'Full' jets reconstructing neutral component with EMCal

- Flavour of jet can be tagged by reconstructing specific flavoured hadron within jet

→ ALICE optimal for low p_T probes!

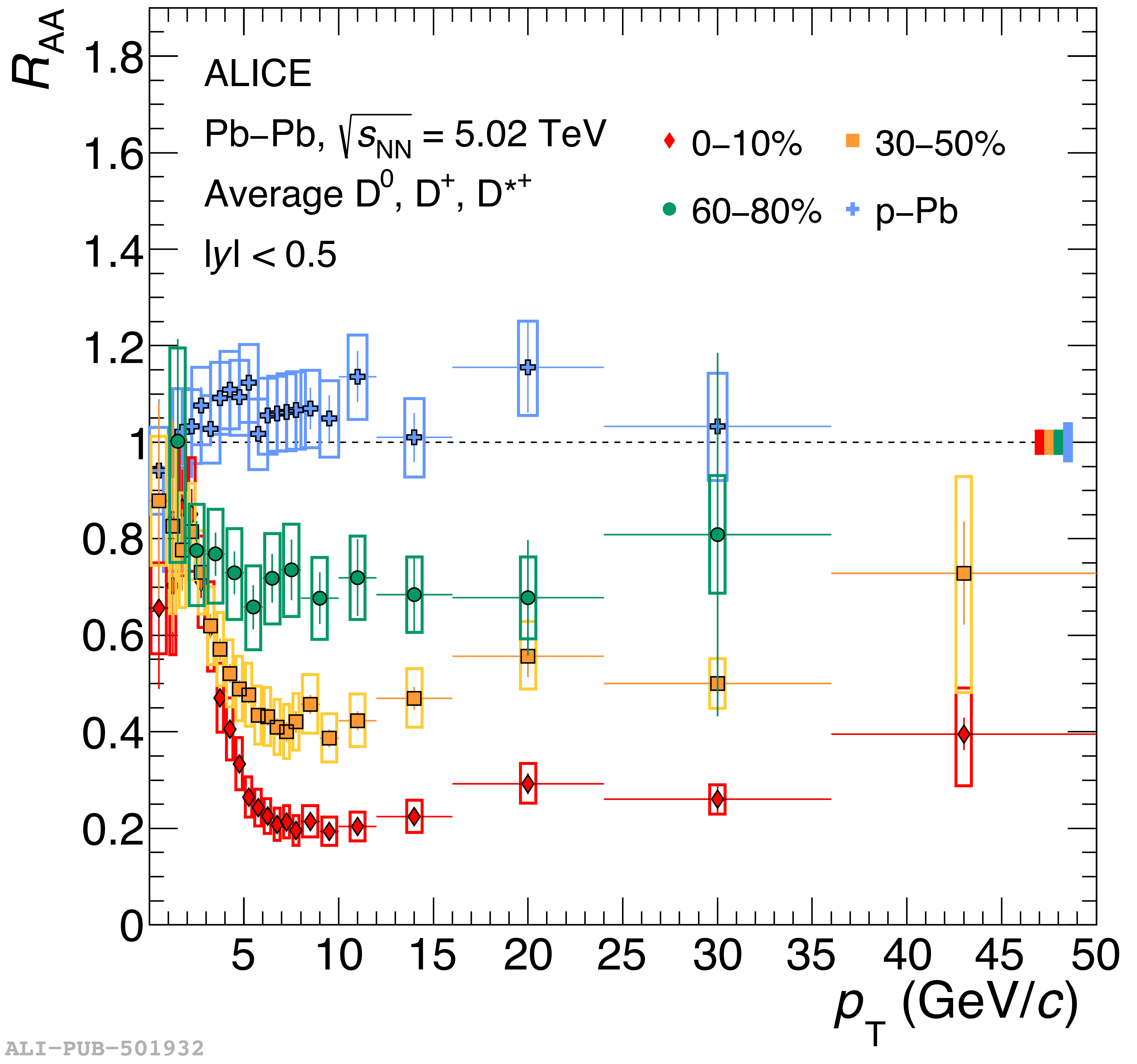
Charm hadron production: D mesons

ALICE: JHEP 01 (2022) 174

Nuclear modification factor
R_{AA}**<1 - suppression**
R_{AA}**=1 - no suppression**

$$R_{AA} = \frac{1}{< T_{AA} >} \frac{dN_{AA}/dp_{T}}{d\sigma_{pp}/dp_{T}}$$

- Precise D-meson measurements using Run 2 data:
  - **Significant suppression of D mesons in Pb-Pb collisions** —> in-medium energy loss
  - **No suppression in p-Pb collisions** —> suppression in Pb-Pb collisions primarily due to final-state effects



Charm hadron production: D mesons to $p_T = 0$

ALICE: JHEP 01 (2022) 174

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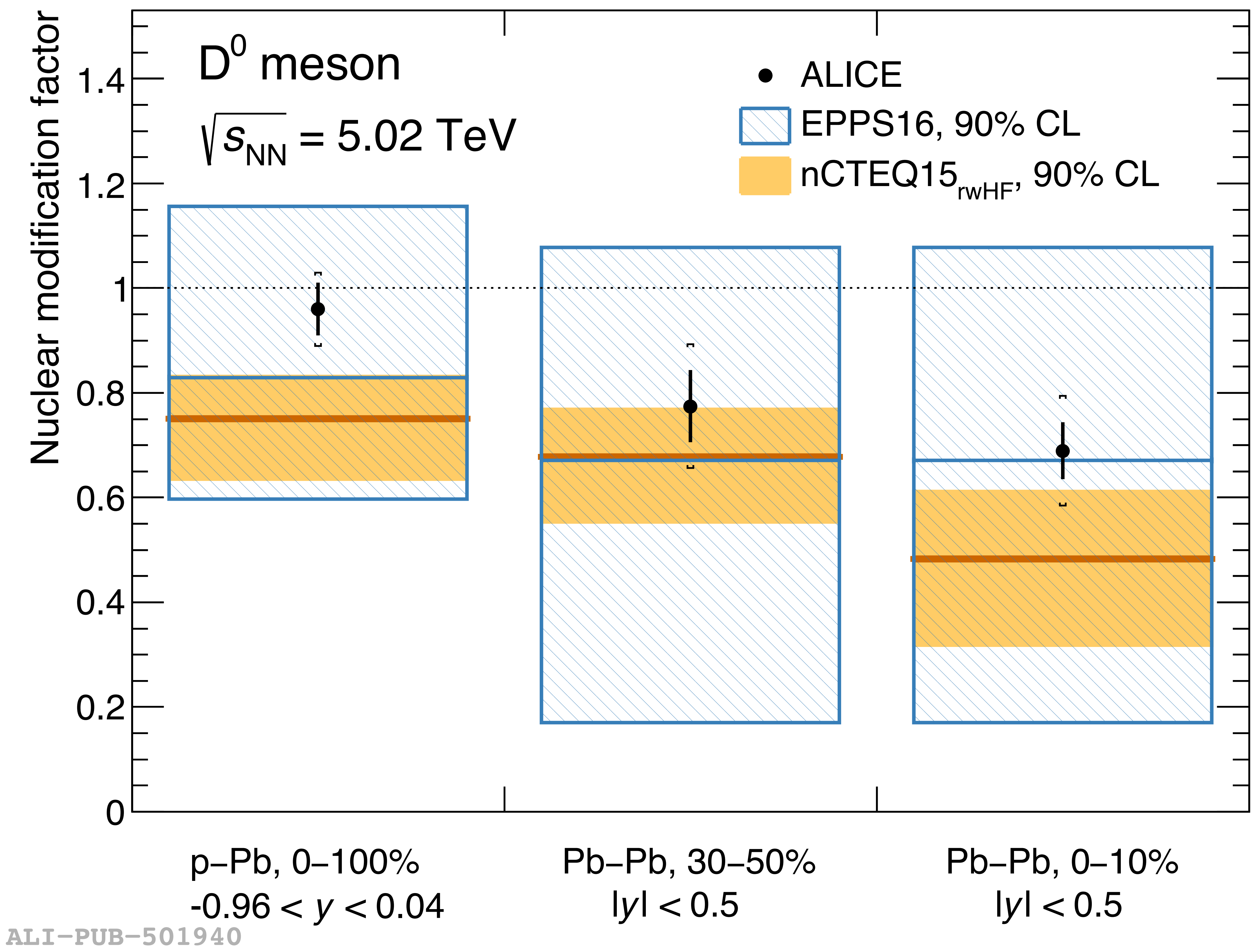
$$R_{AA} = \frac{1}{< T_{AA} >} \frac{dN_{AA}/dp_{\mathrm{T}}}{d\sigma_{pp}/dp_{\mathrm{T}}}$$

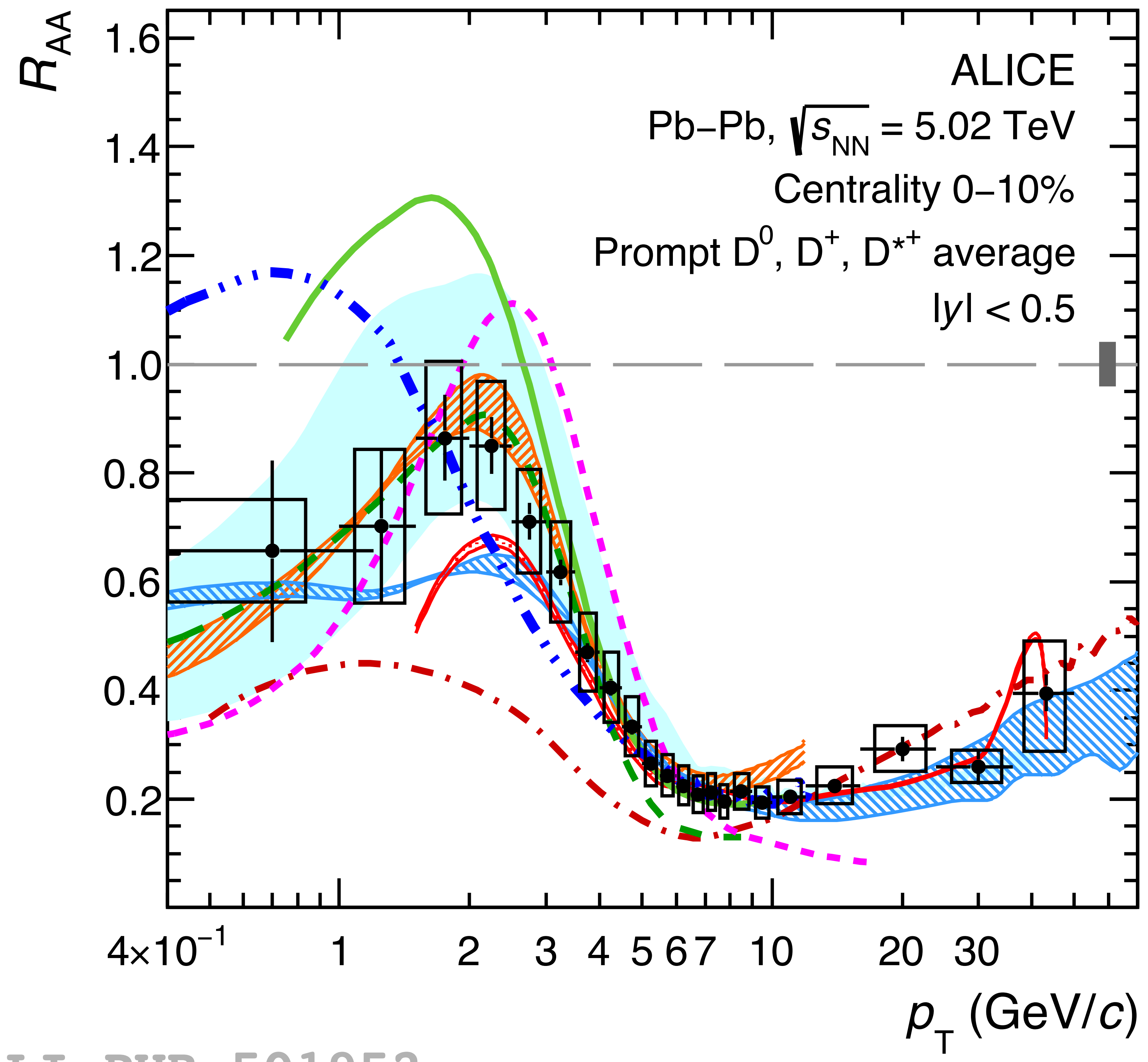


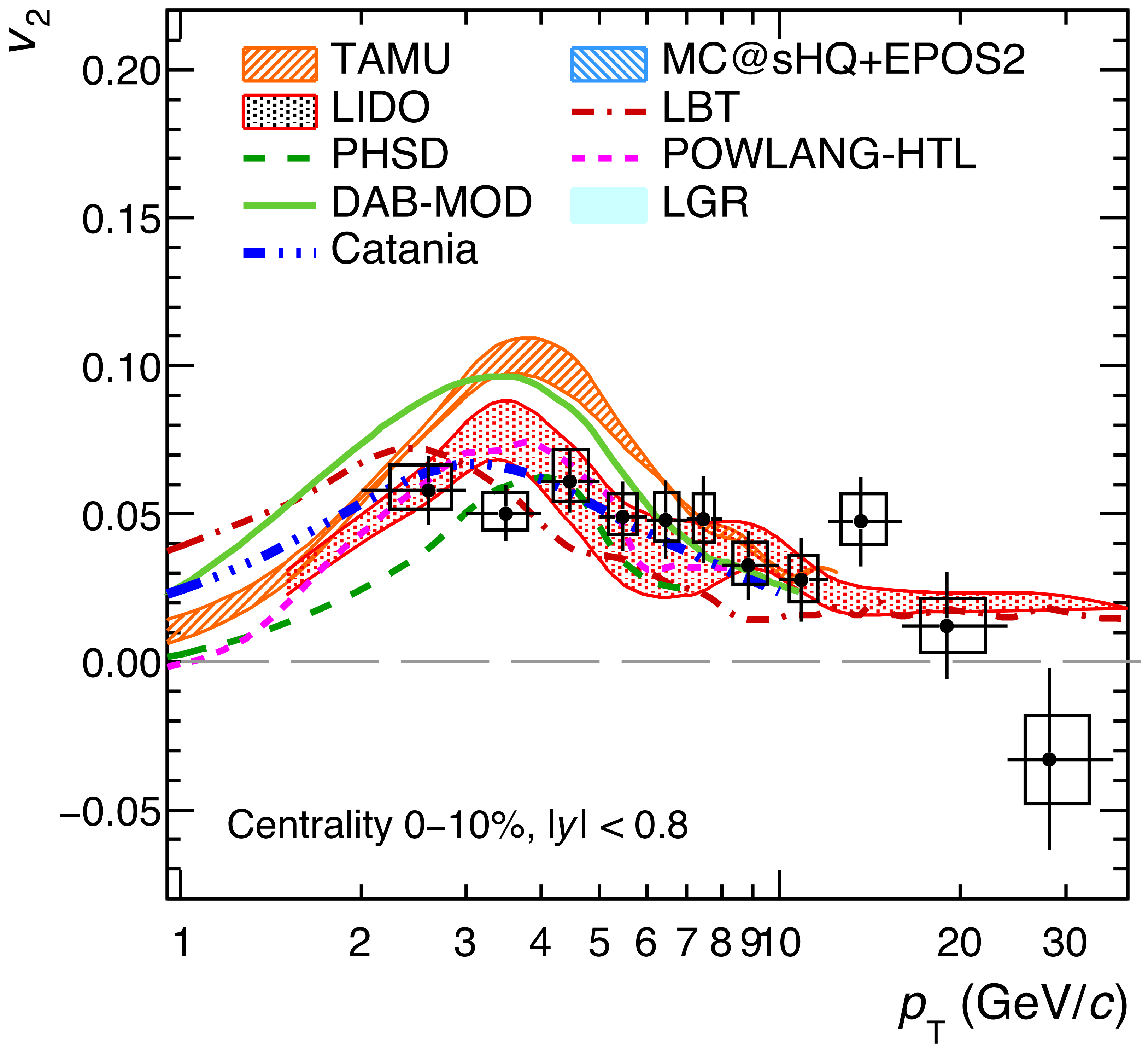
- Total D⁰ meson nuclear modification factor < 1 for central Pb-Pb collisions - **total yield is suppressed**
- **Consistent with expectation from the modification of parton distributions** within the nucleus

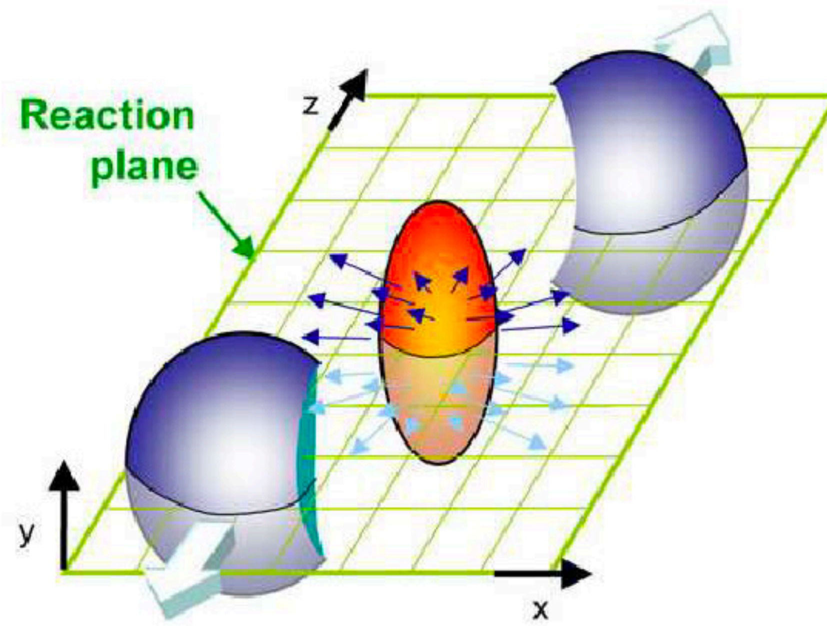
Charm hadron production: Constraining QGP properties

ALICE: JHEP 01 (2022) 174

$$R_{AA} = \frac{1}{< T_{AA} >} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$







ALI-PUB-501952

- **Precise R_{AA} and elliptic flow (v_2, v_3) measurements of non-strange D mesons provide significant constraints on to charm quark energy loss models**

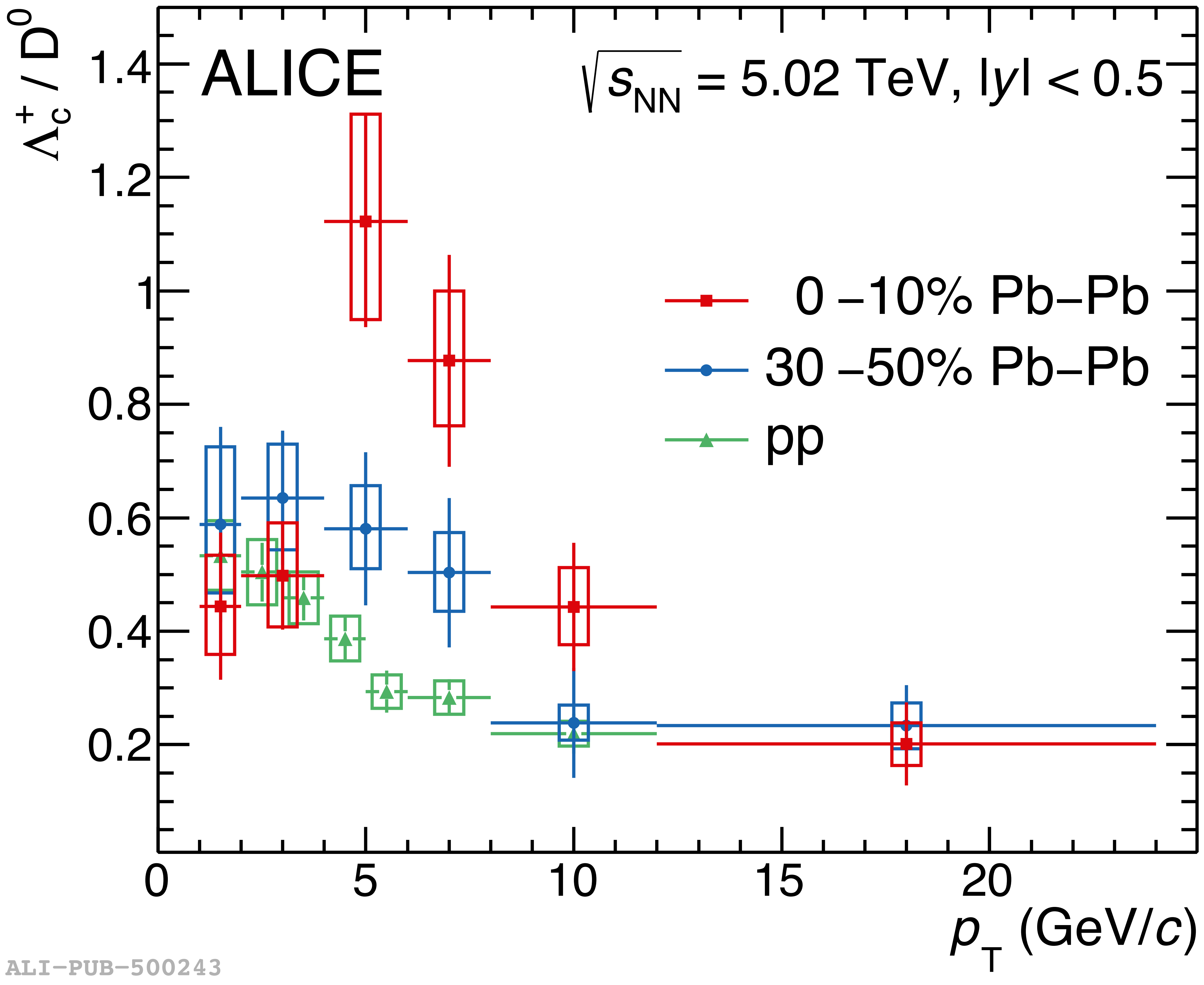
- χ^2 analysis gives $1.5 < 2\pi D_s T_c < 4.5$ for $T_c = 155$ MeV

Charm hadron production: Λ_c^+ baryon

- Evidence of **enhanced charmed-baryon production** in the measured p_T range going from pp —> Pb-Pb
  → **modification of hadronisation**

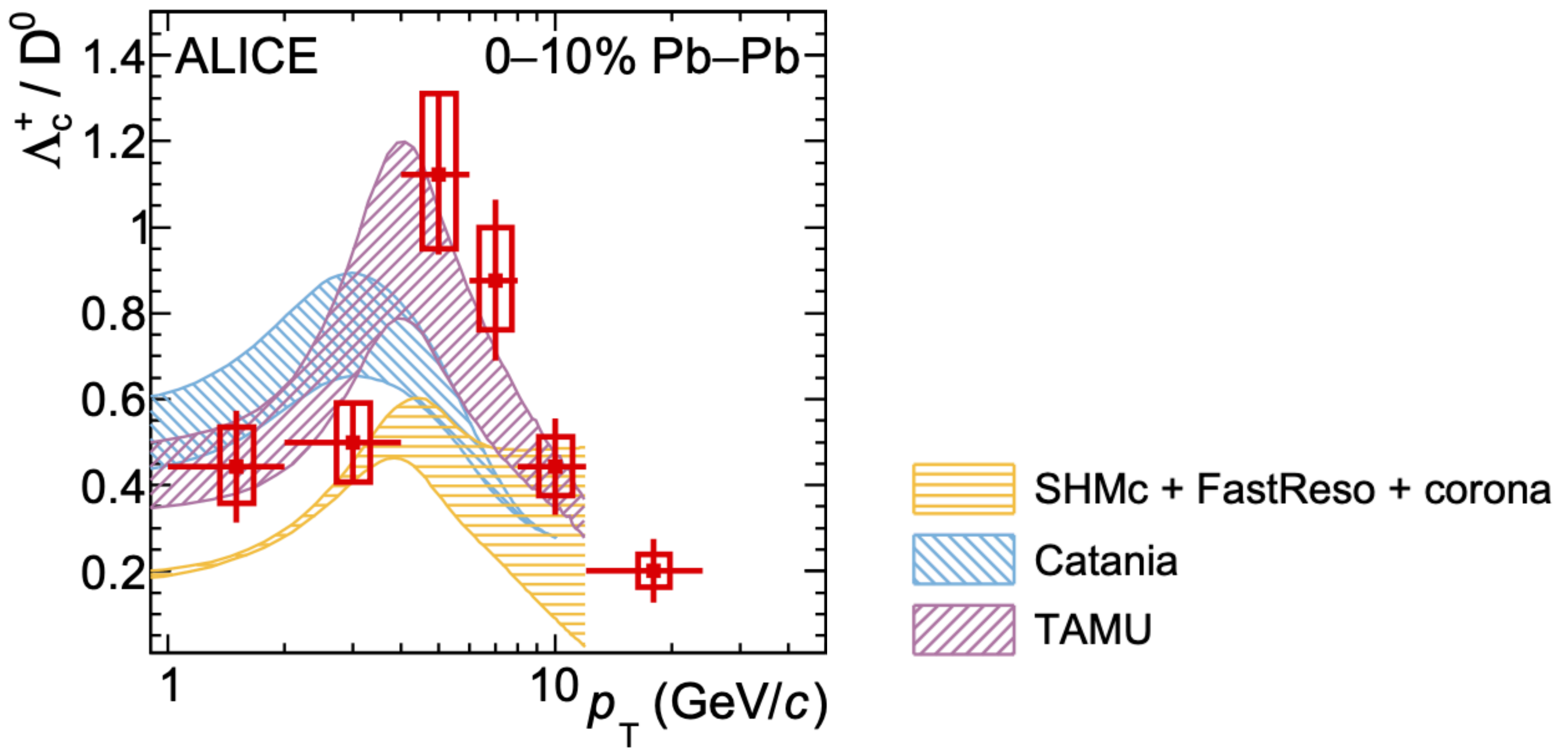
‘Baryon-to-meson’ production ratio

ALICE: arxiv:2112.08156



Charm hadron production: Λ_c^+ baryon

- Evidence of **enhanced charmed-baryon production** in the measured p_T range going from pp —> Pb-Pb → **modification of hadronisation**
  - Models which include hadronisation via coalescence capture features of the data
- Constraining hadronisation processes in QGP improve energy loss modelling



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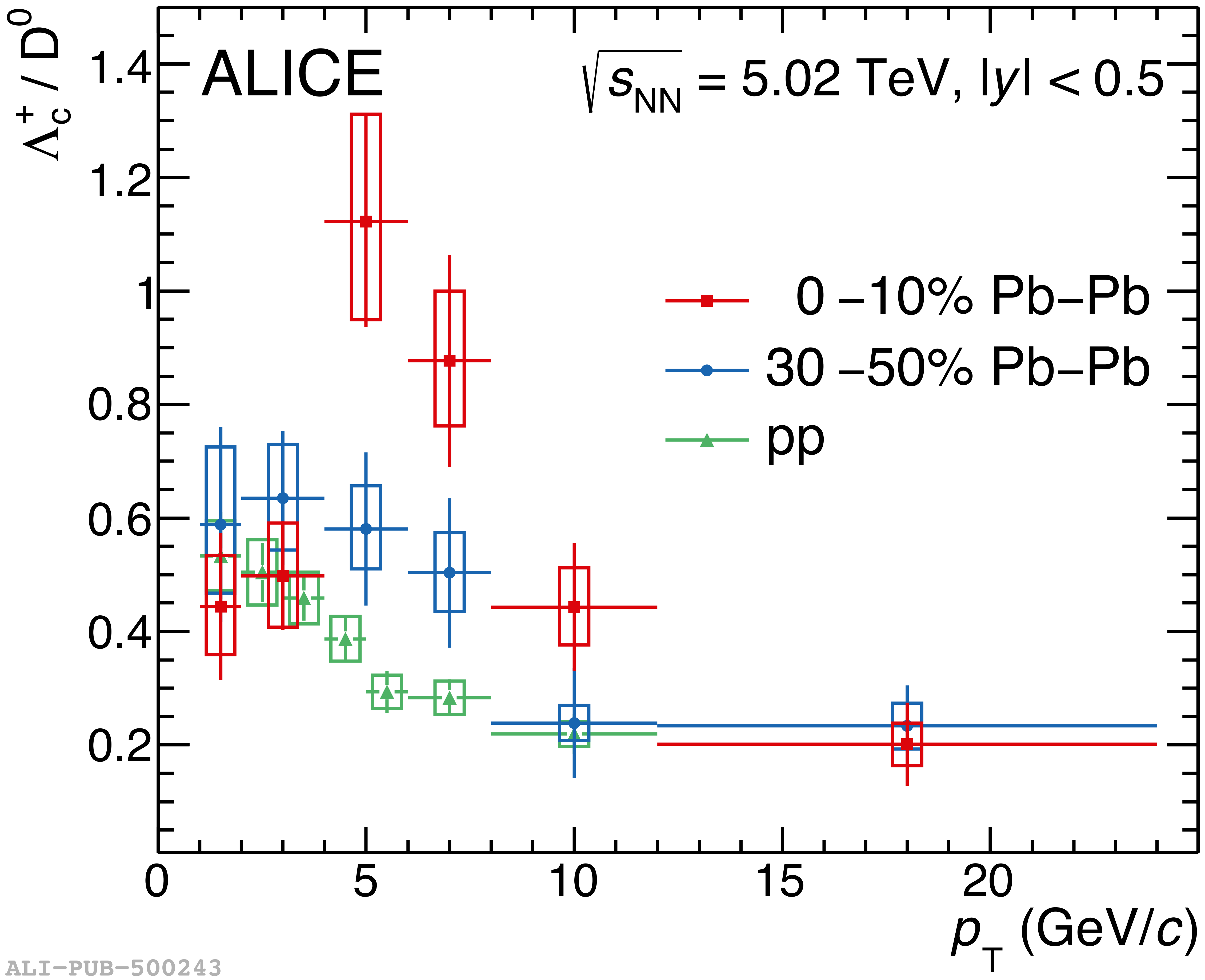


Beauty hadron production: Non-prompt D^0

ALICE: arxiv:2202.00815

- **Beauty: less equilibrated, better theoretical control on in-medium transport calculations**

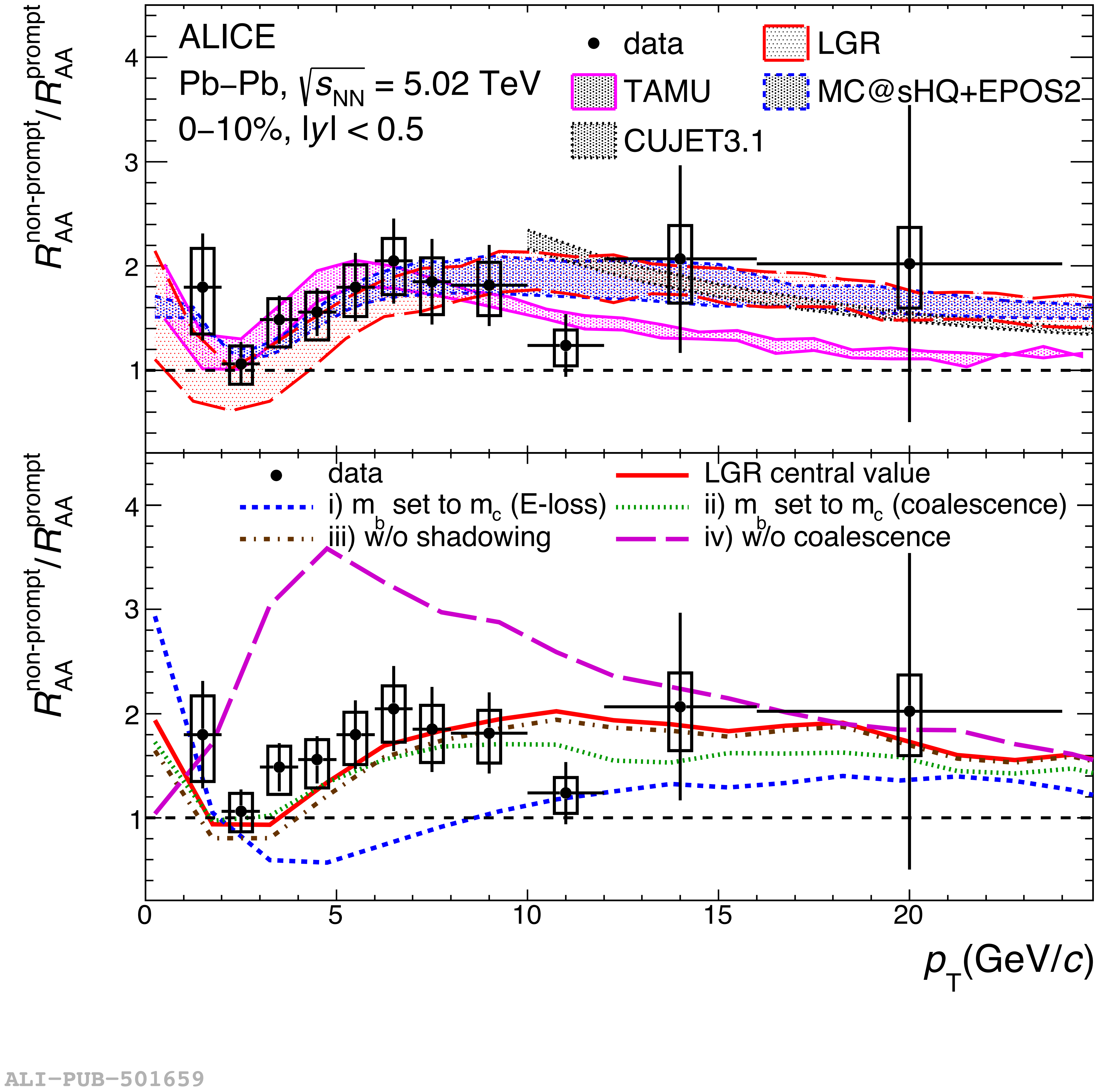
- **Enhancement of the non-prompt D^0 R_{AA} w.r.t prompt D^0** - beauty quarks lose less energy than charm quarks!

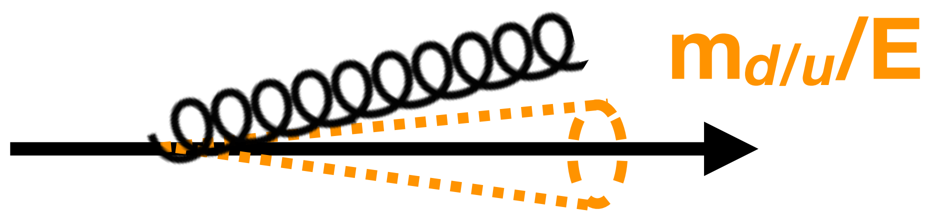
- Described by models which include mass-dependent effects

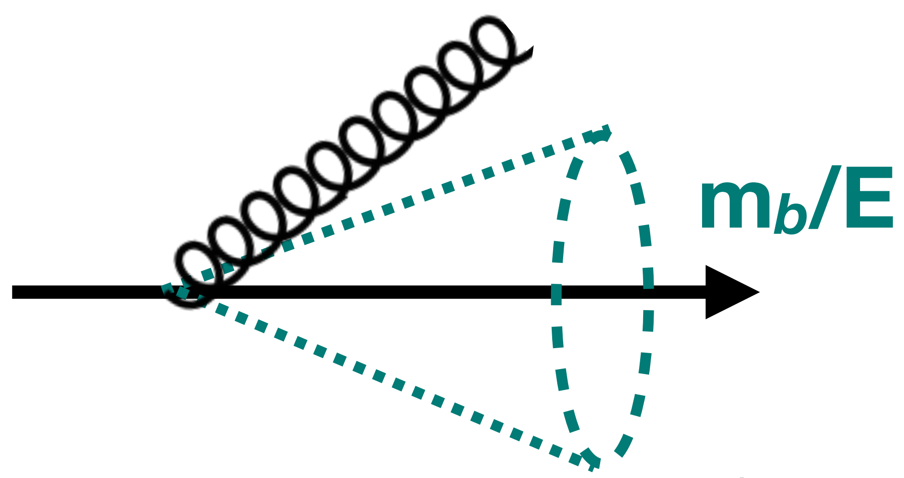
    - dead-cone effect (first direct observation by ALICE in pp collisions)

ALICE: Nature 605 (2022) 440-446

- Varying parameters of models give insight into how each physical process contributes to the R_{AA}



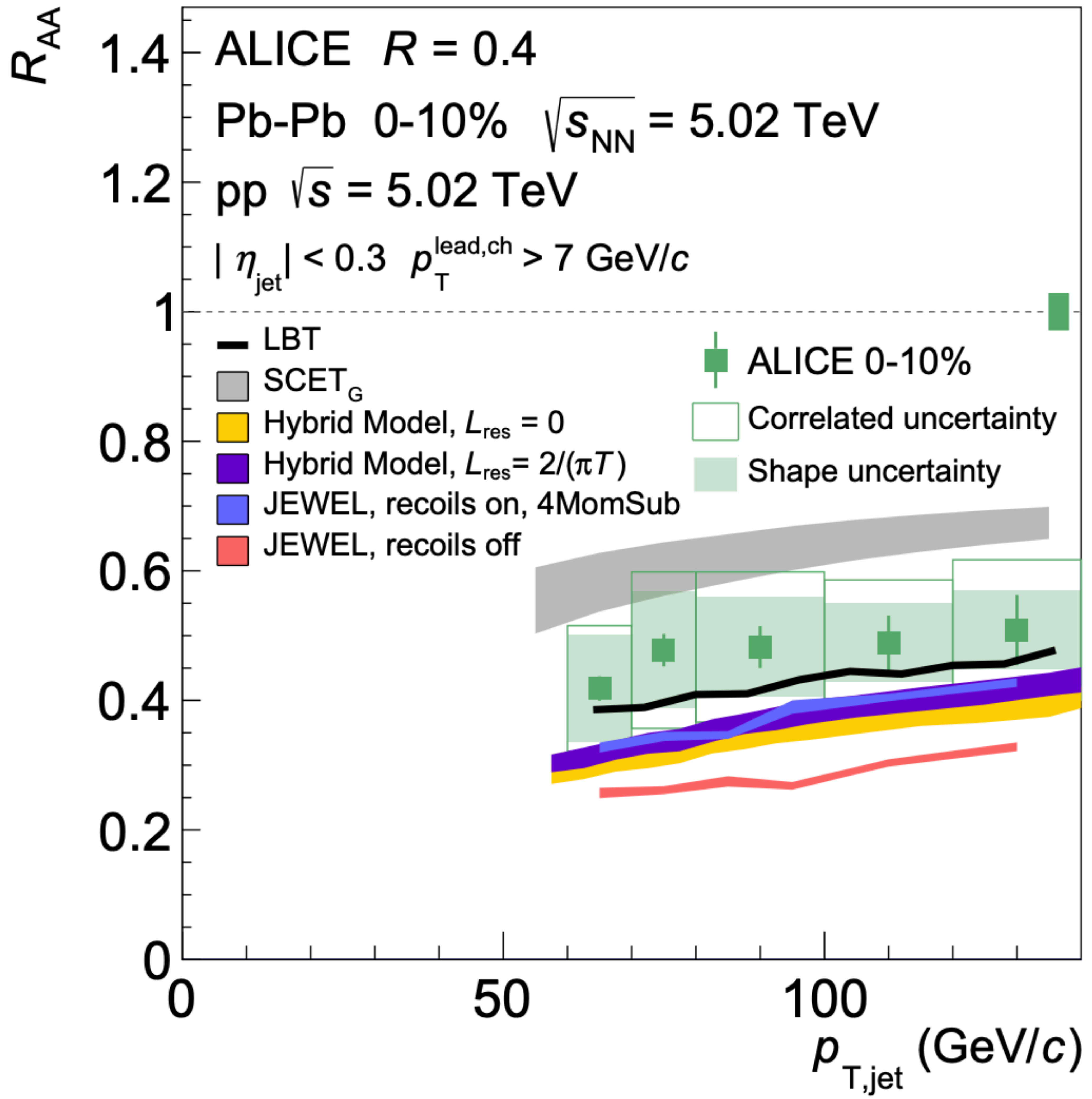




Jet suppression in Pb-Pb collisions

- **Jets are suppressed in heavy-ion collisions** due to in-medium interactions (energy loss)
  - Different models predict different levels of quenching → R_{AA} **offers significant constraining power**
  - Most models have slight tension with data
- Lower p_T reach than ATLAS/CMS

ALICE: Phys. Rev. C 101 (2020) 034911



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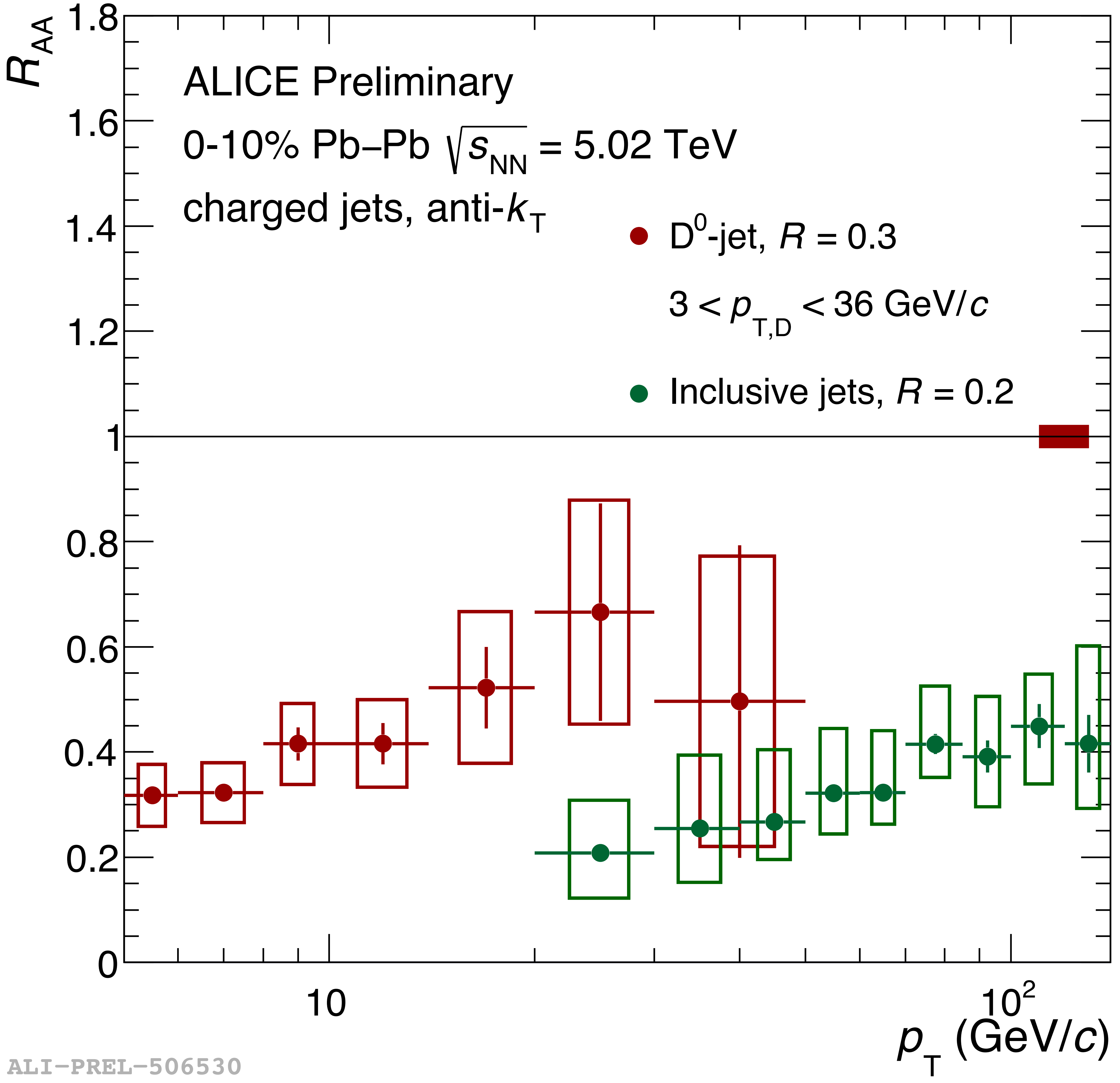
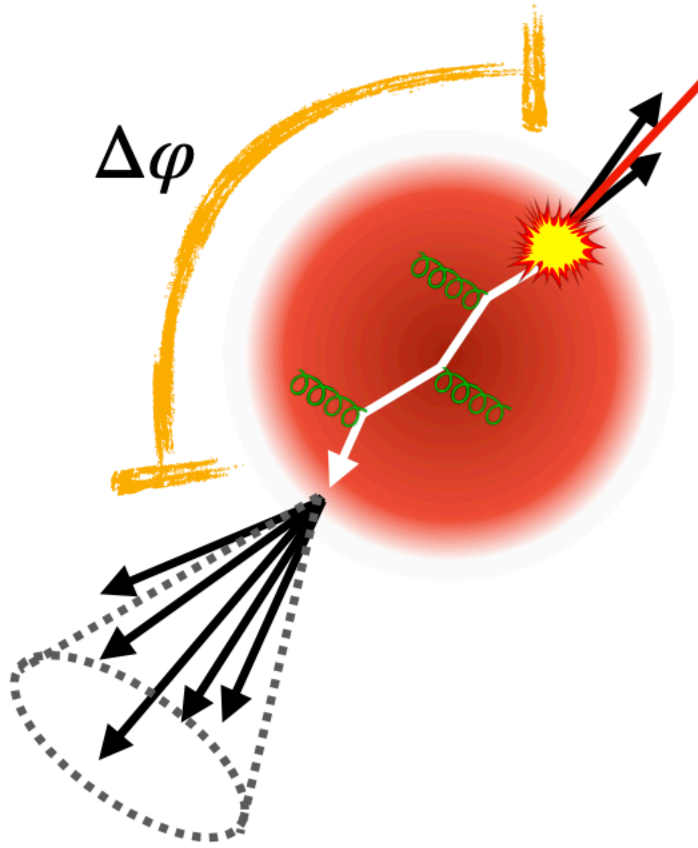
- Lower p_T reach than ATLAS/CMS
- **First measurement of charm-tagged jet R_{AA} in heavy-ion collisions**
- Comparison with (charged) inclusive jet measurement hints at **less suppression for charm** → further evidence for mass-dependent energy loss



Dijet acoplanarity via hadron+jet measurement



Subtract combinatorial background through difference between two 'triggered' distributions - access low-p_T jets

$$\Delta_{\mathrm{recoil}} \sim \frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}} \frac{\mathrm{d}^3 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\Delta\varphi \mathrm{d}\eta_{\mathrm{jet}}}\bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT}_{\mathrm{Sig}}} - \frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}} \frac{\mathrm{d}^3 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\Delta\varphi \mathrm{d}\eta_{\mathrm{jet}}}\bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT}_{\mathrm{Ref}}}$$

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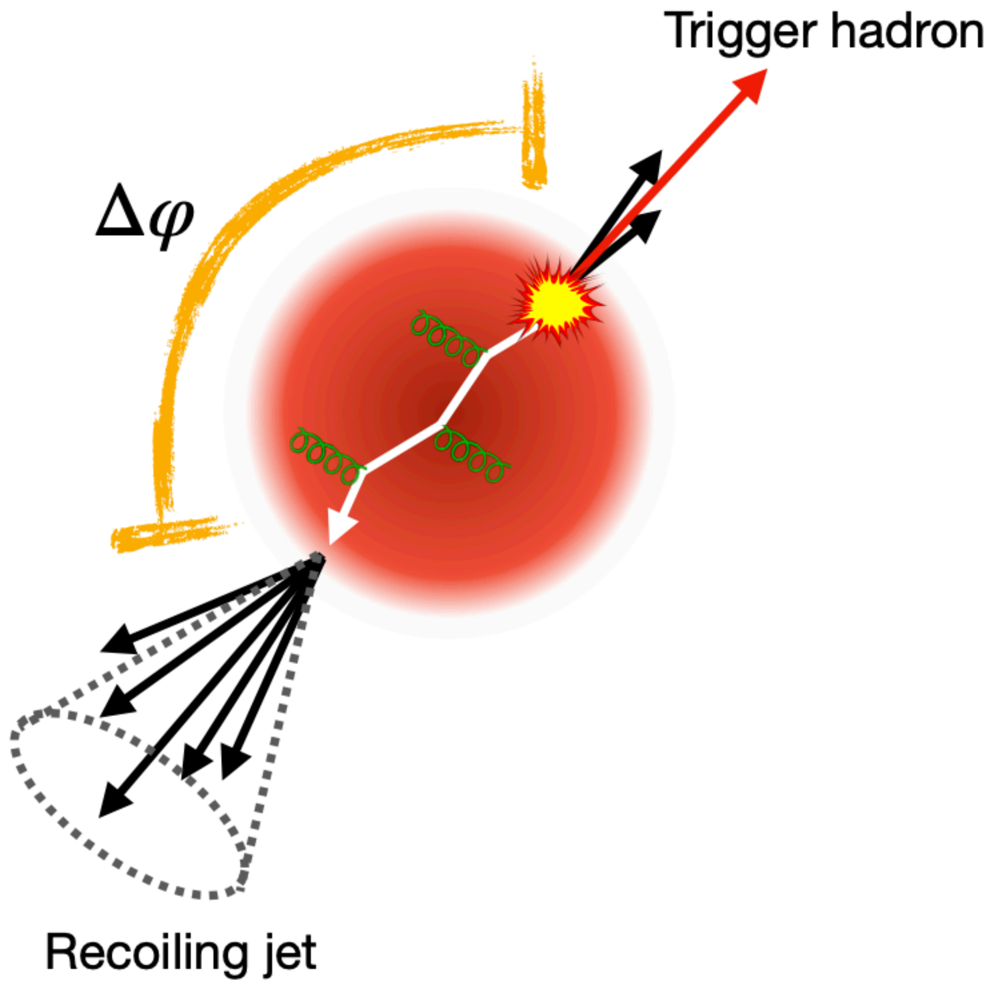

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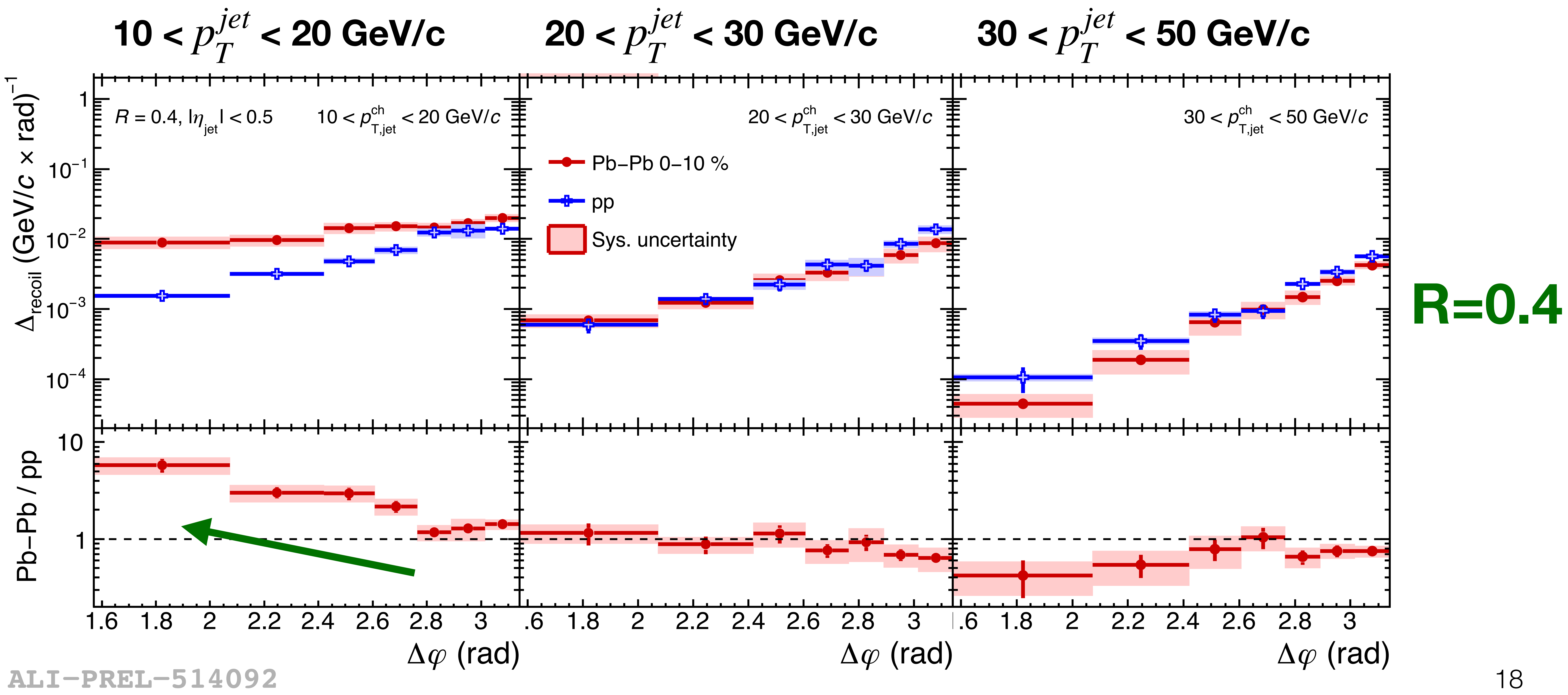
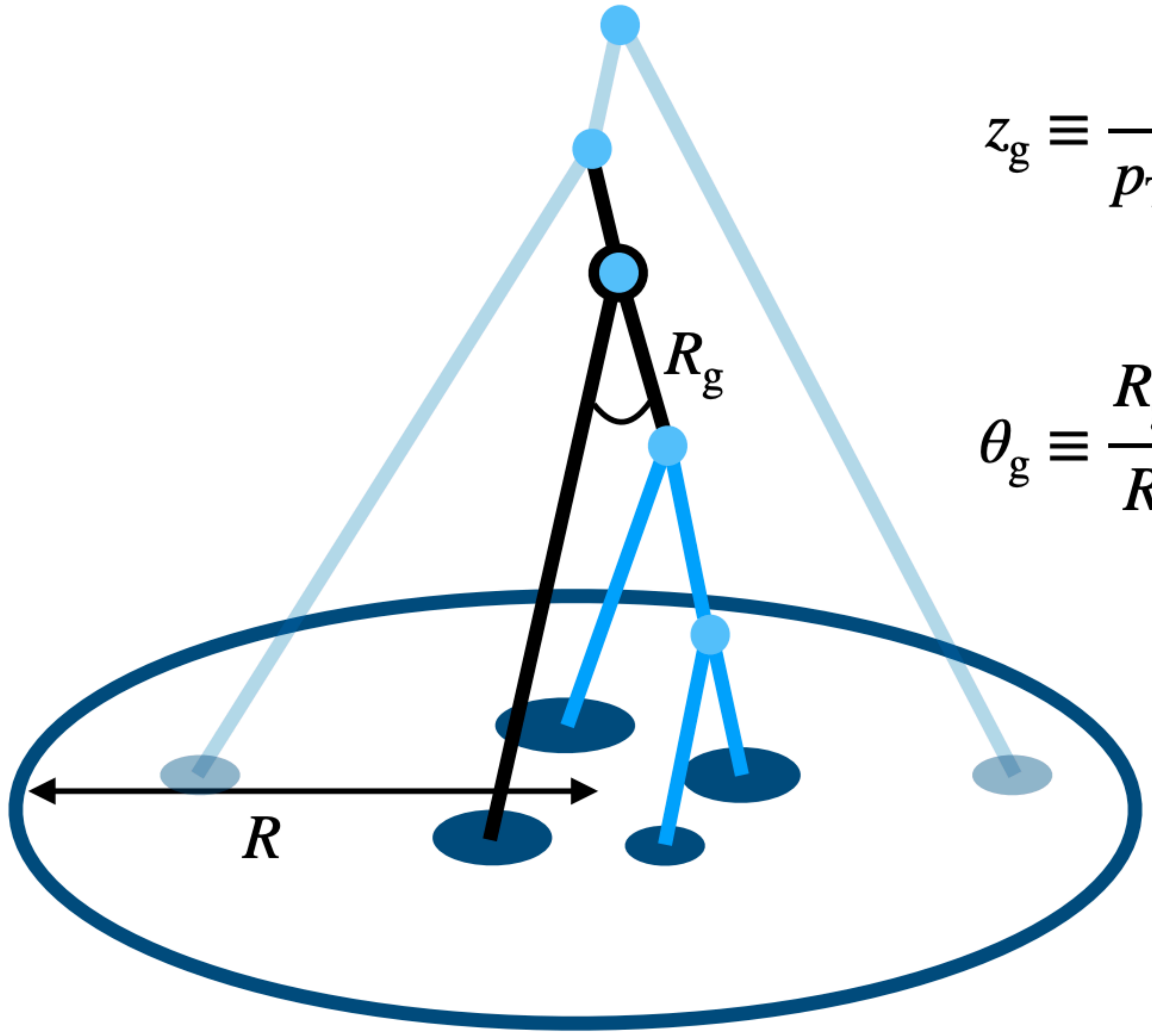
- **Azimuthal decorrelation of jets**
- Modification occurs for R=0.4, soft jets
- Azimuthal deflection? Jet fragments?



Groomed jets and jet substructure

- Recluster jet, ordering constituents in the jets to isolate the subjets (splittings) within the jet
  - Grooming techniques used to separate out hard jet core and hard parton splittings from softened constituents and medium response
- Study of jet splittings and their modification is a relatively new field sensitive to many important jet quenching mechanisms

From ALICE: Phys. Rev. Lett. 128 (2022) 102001



$$z_g \equiv \frac{p_{T,\mathrm{subleading}}}{p_{T,\mathrm{leading}} + p_{T,\mathrm{subleading}}}$$

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

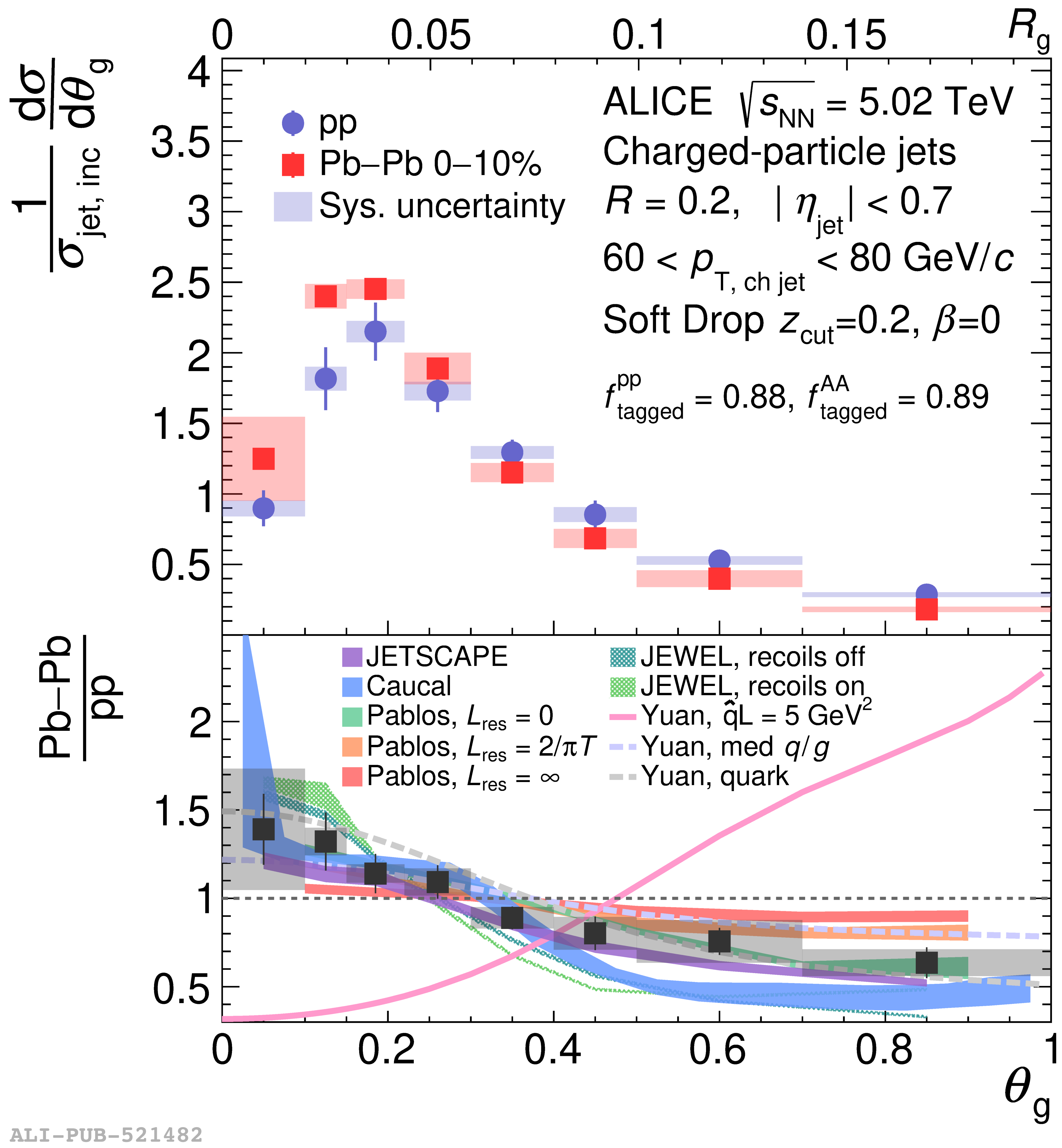
Groomed jet radius and momentum splitting fractions

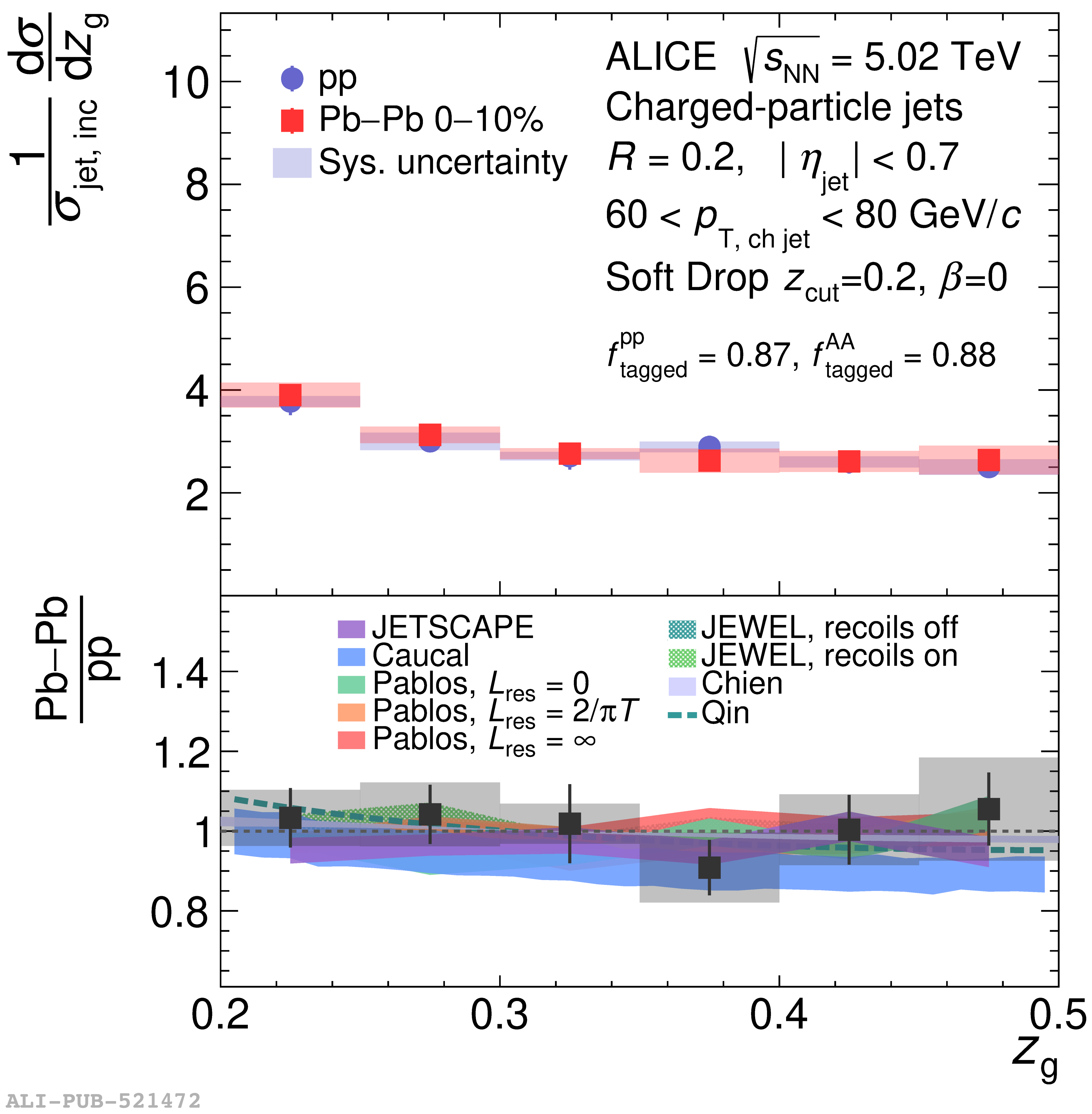
ALICE: Phys. Rev. Lett. 128 (2022) 102001

$$\theta_g = \frac{r_g}{R}$$

$$z_g = \frac{p_{\mathrm{T,subleading}}}{p_{\mathrm{T,leading}} + p_{\mathrm{T,subleading}}}$$

- **Narrowing of jet core** due to QGP (i.e. wider jets are more suppressed)
- **Minimal modification** to relative p_T scale of leading and subleading subjets





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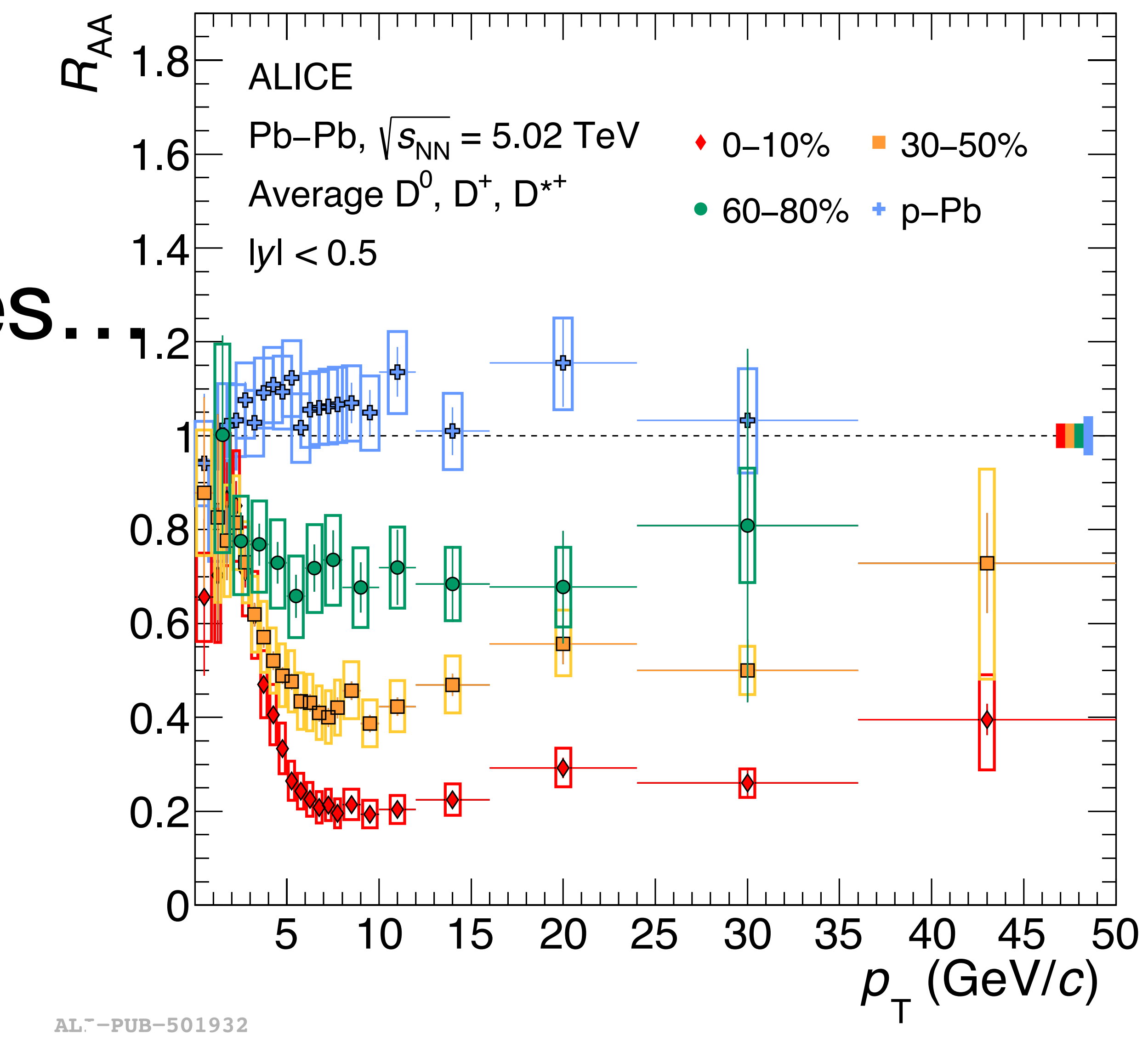

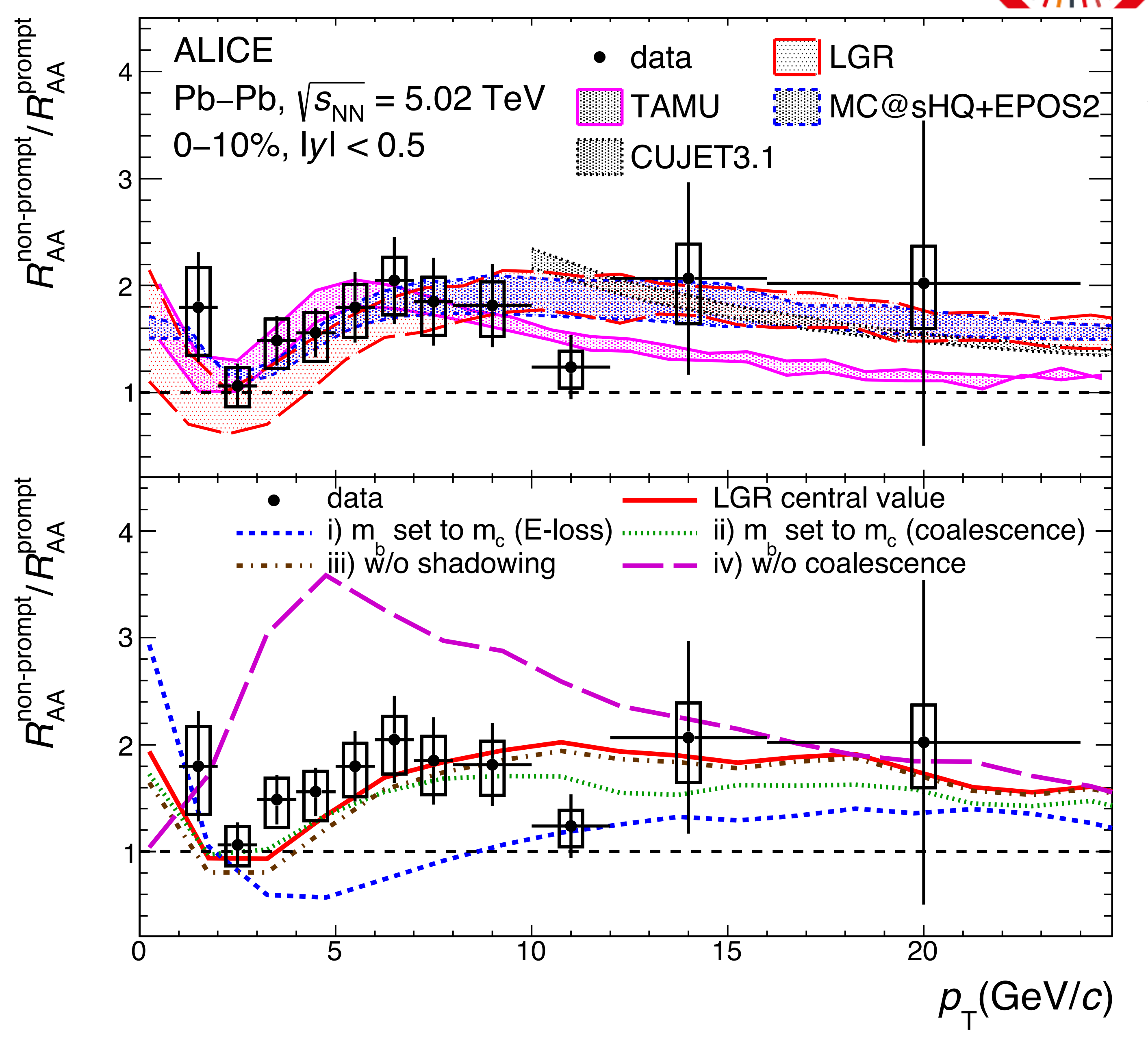

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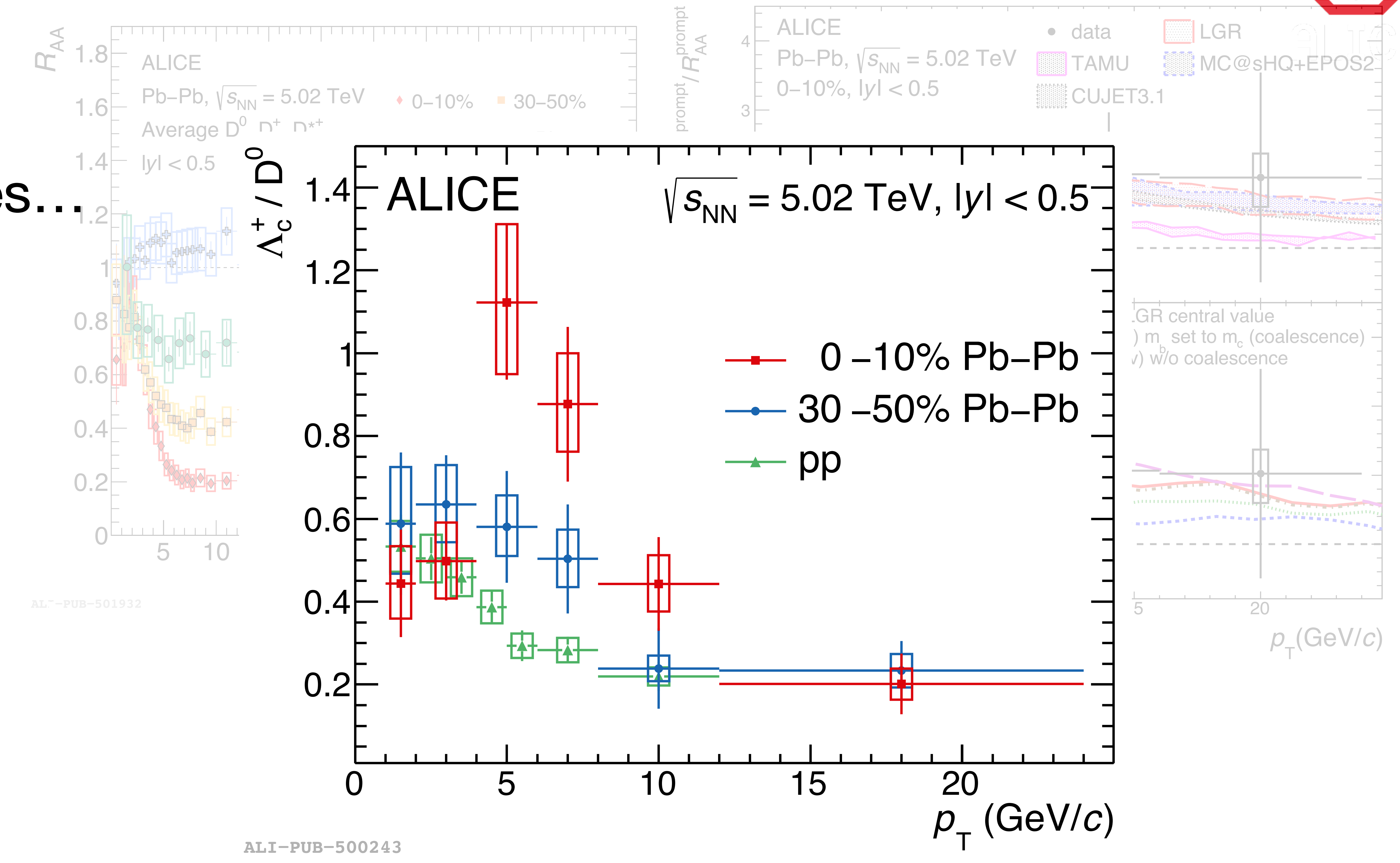

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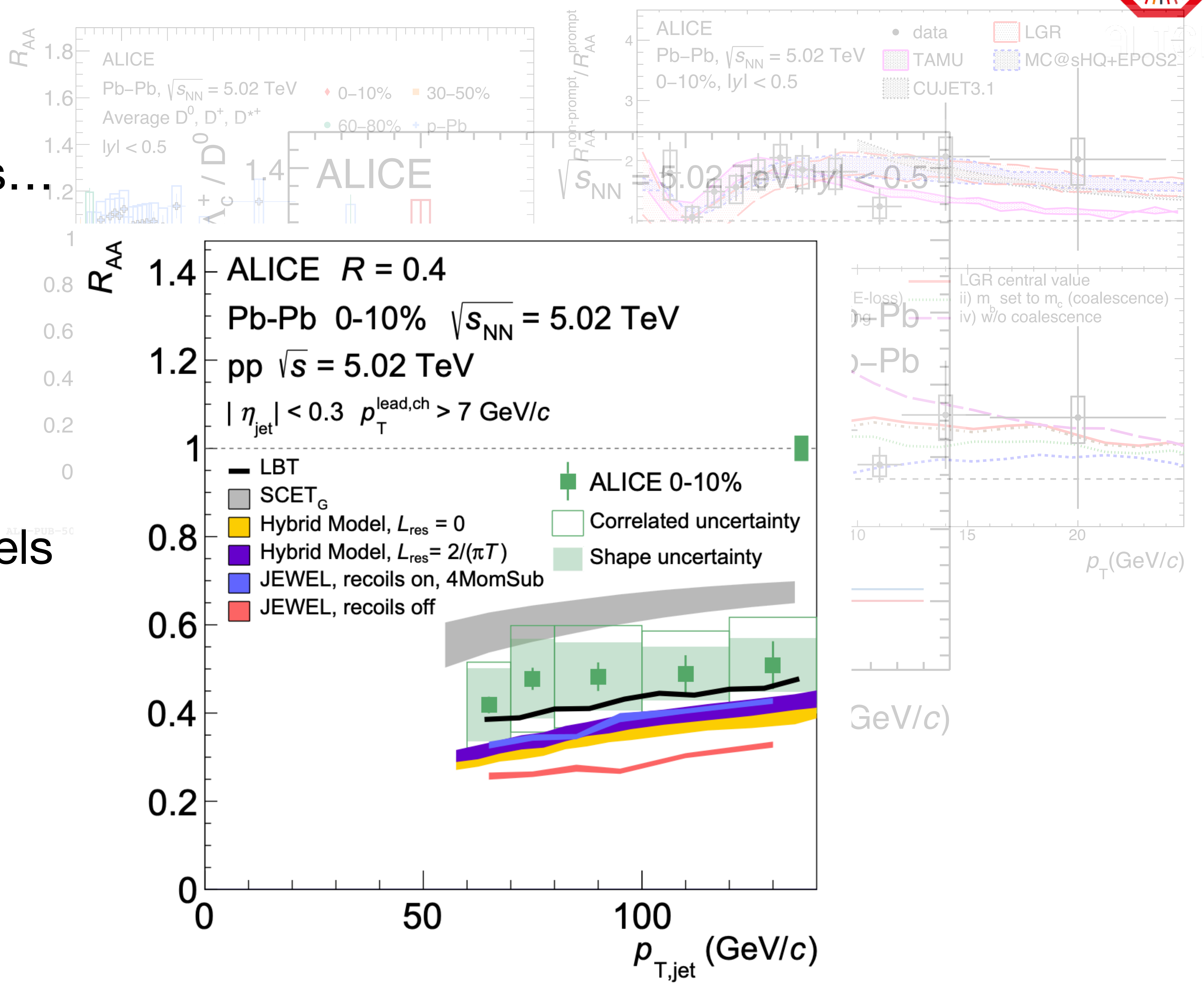

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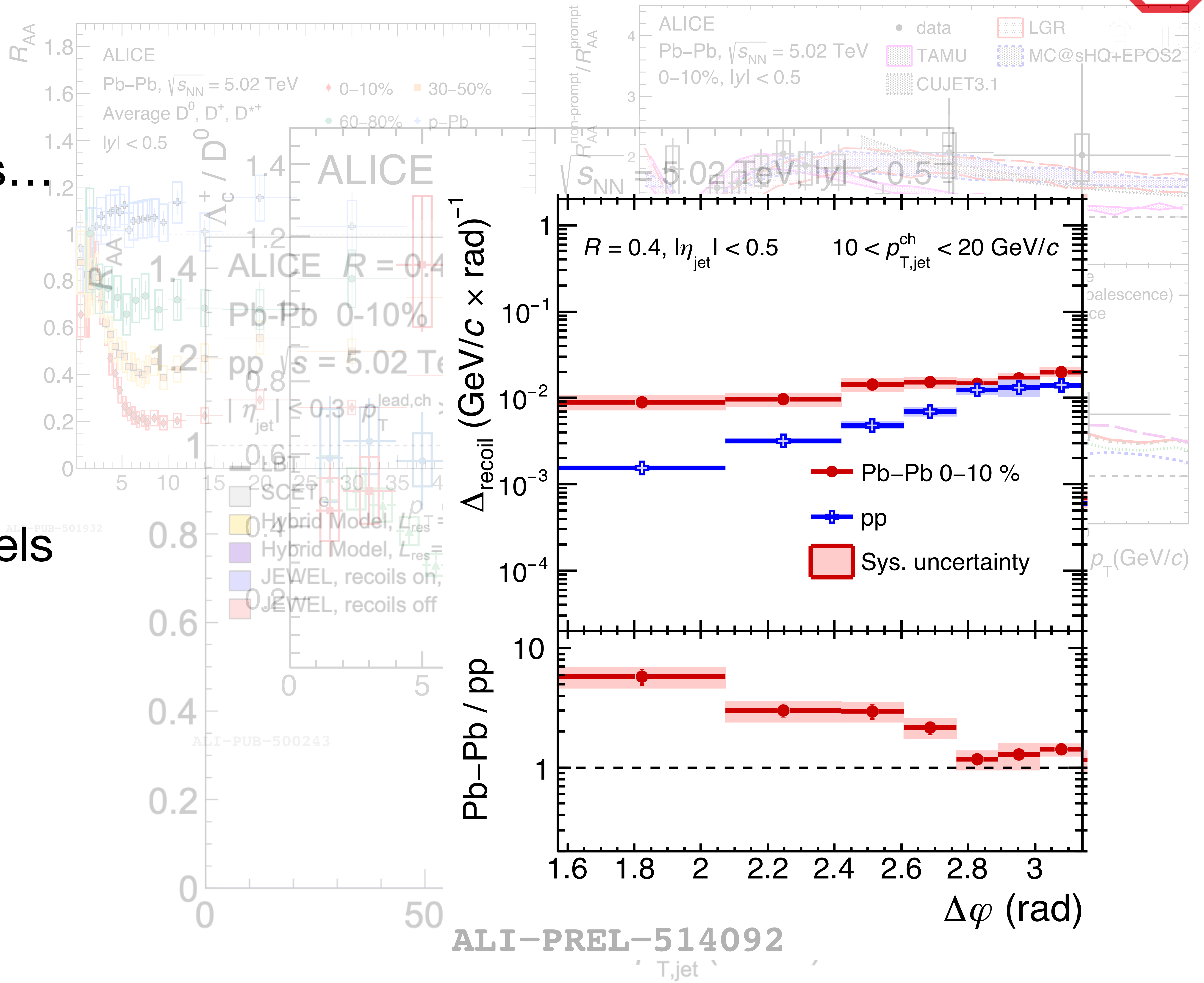

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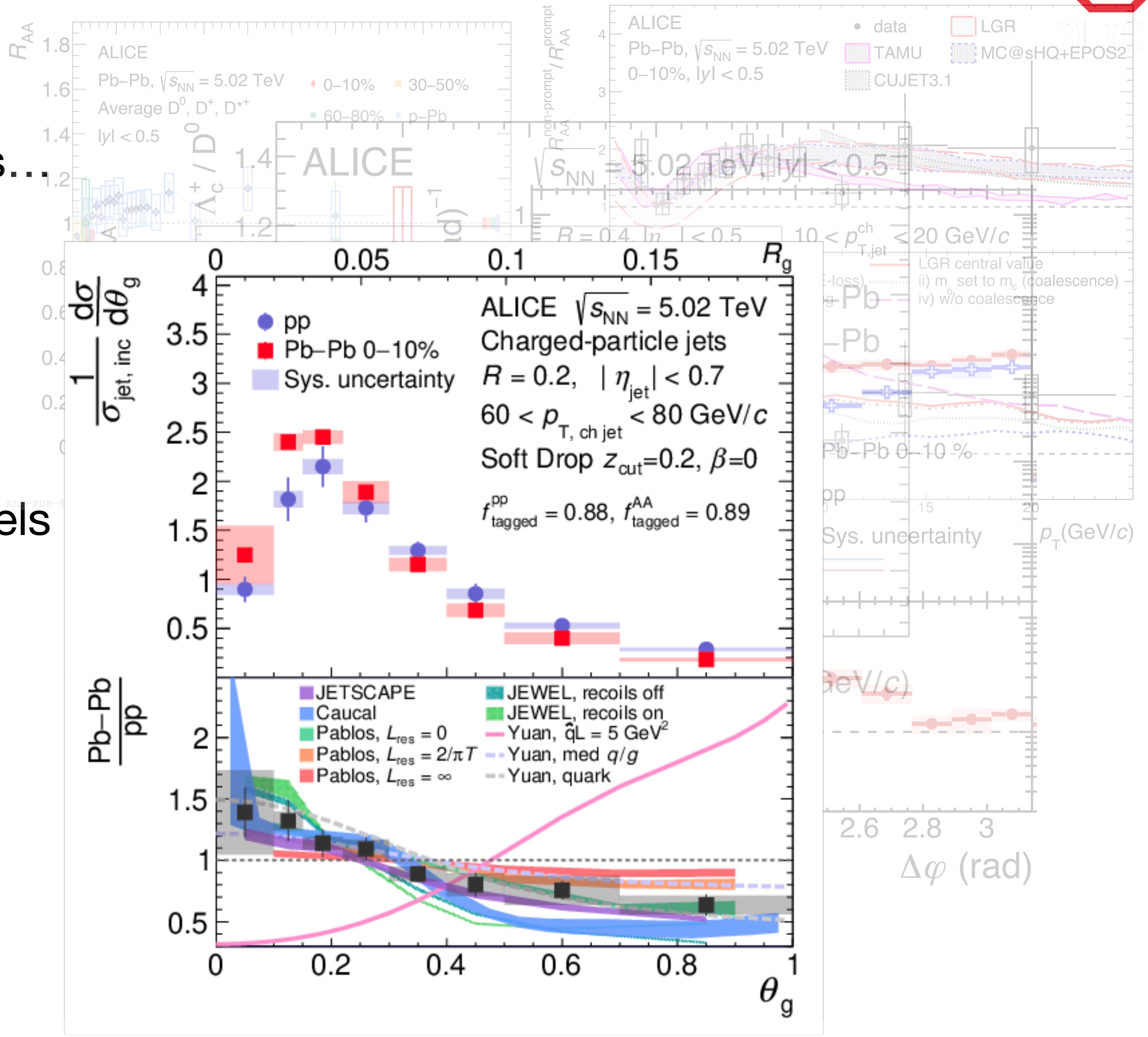

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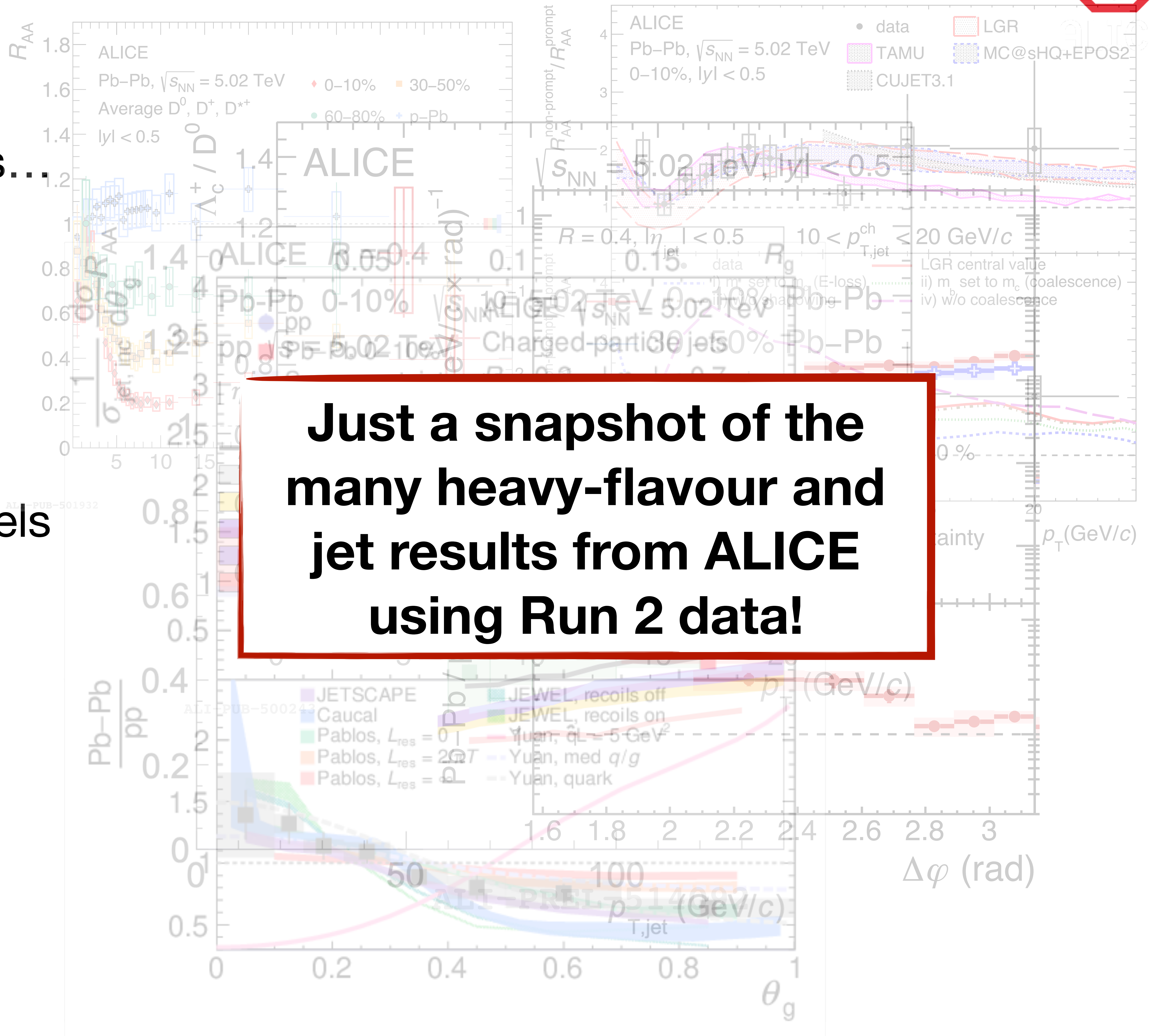
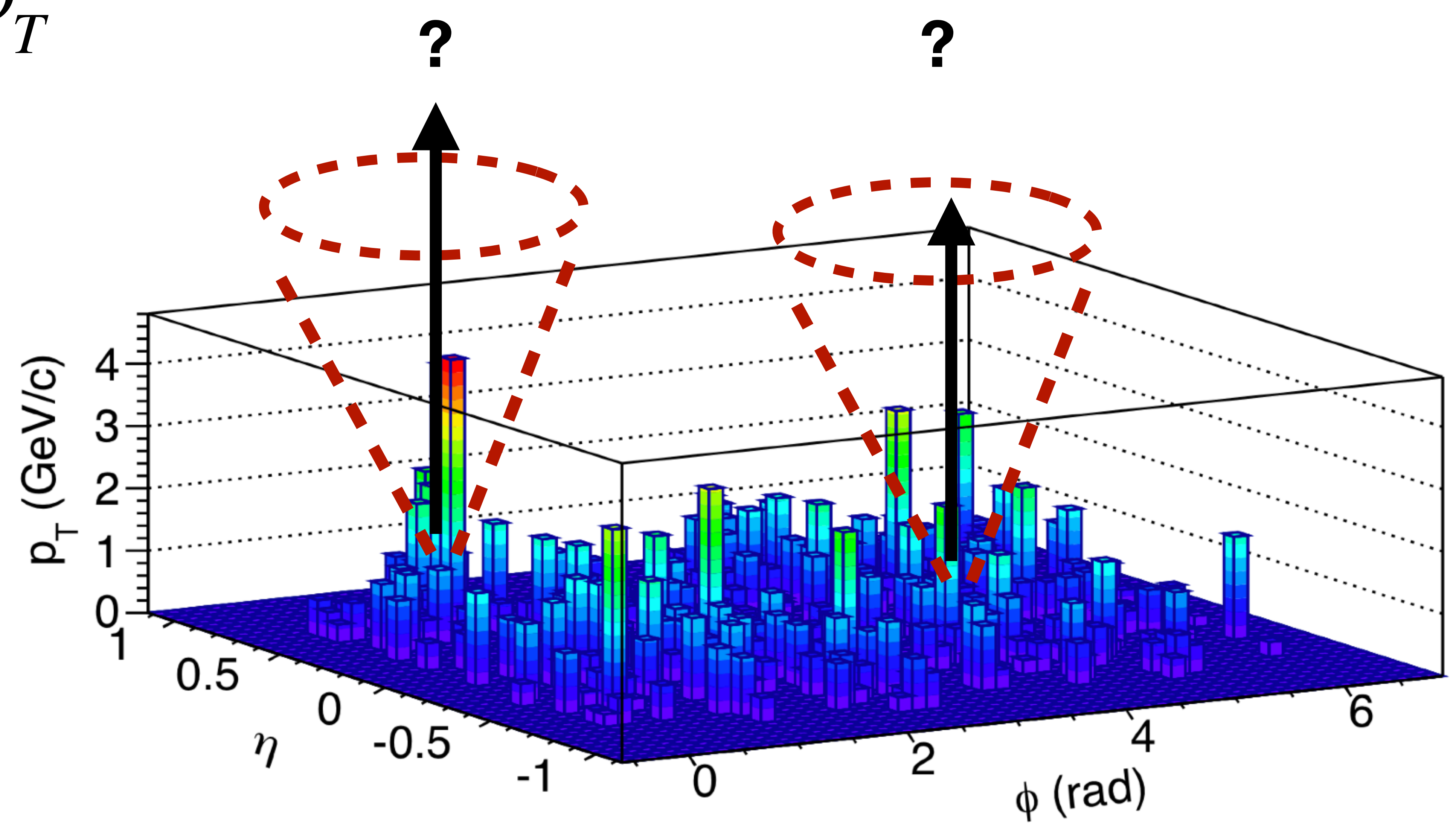


Just a snapshot of the many heavy-flavour and jet results from ALICE using Run 2 data!

Backup

Pushing to low energy - Dealing with combinatorial background

- Combinatorial background a major challenge for jet measurements in heavy ion collisions - what is a 'true' jet from a hard scattering and what is from uncorrelated sources?
  - **Especially important for low p_T measurements** where $p_T^{jet} \sim p_T^{bkg}$
- Techniques developed to deal with combinatorial background



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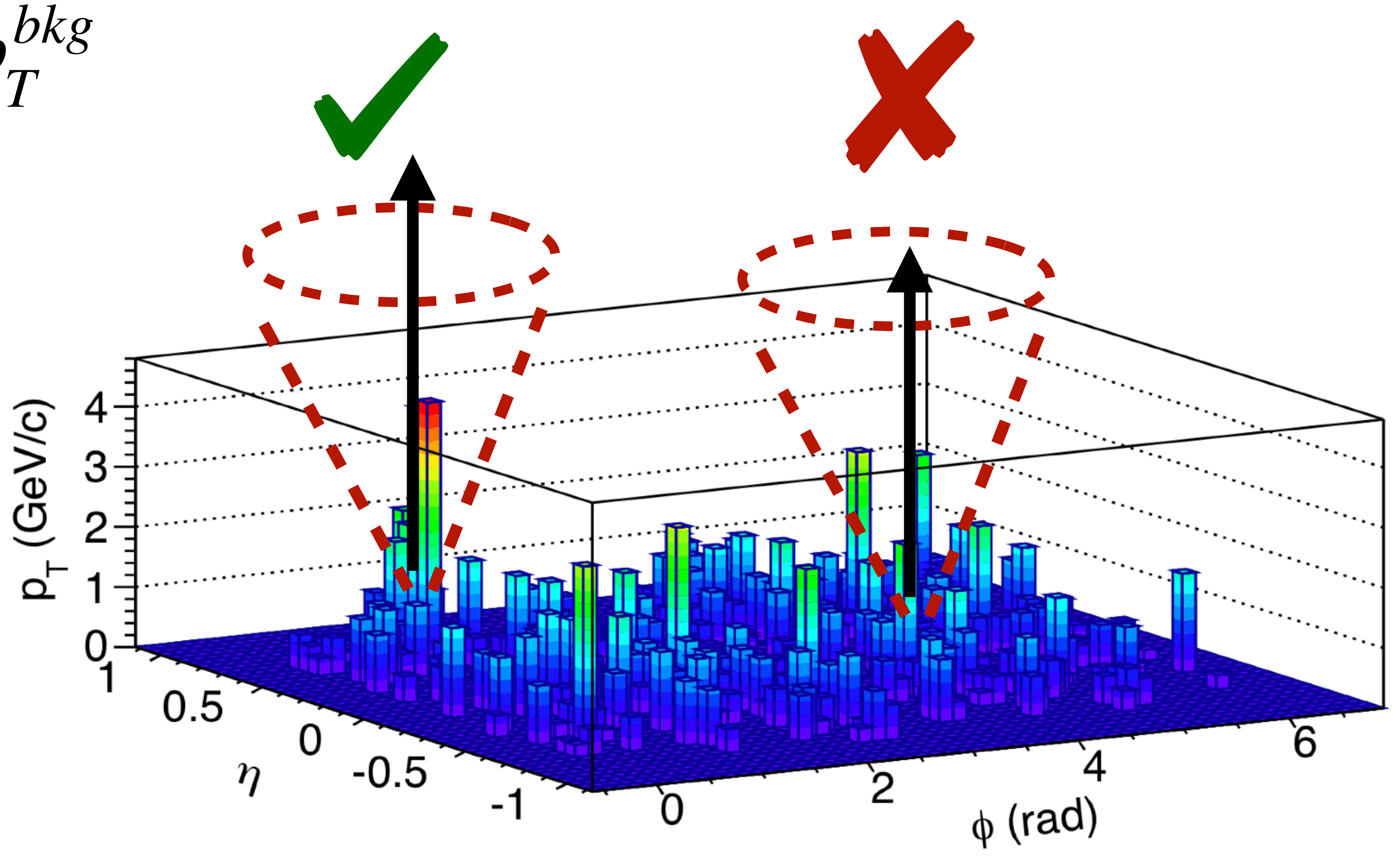
→ **Leading track/cluster p_T cut**

  - Requiring $p_T^{tr./cl.} > X$ ensures jet from hard scattering
  - Biases fragmentation pattern in 'selected' jet population



e.g. $p_T^{track} > 3$ GeV/c ?

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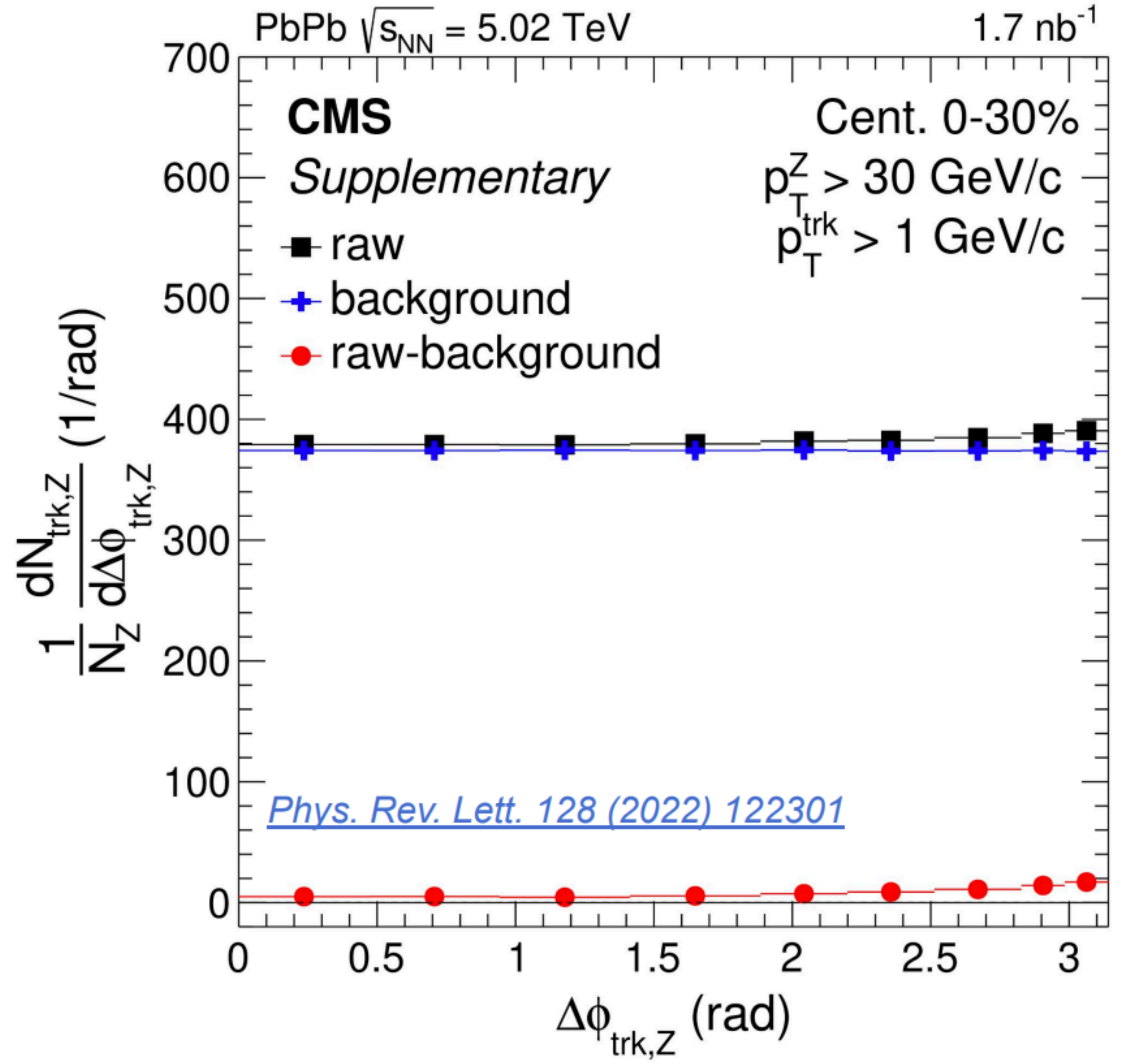
→ **Leading track/cluster p_T cut**

Statistical correction:

→ **Mixed event subtraction**

- Generate mixed events by randomly selecting tracks from many events

- Subtract mixed event background from raw spectra



CMS: Phys. Rev. Lett. 128 (2022) 122301

See also e.g. STAR: Phys. Rev. C 96, 024905 (2017

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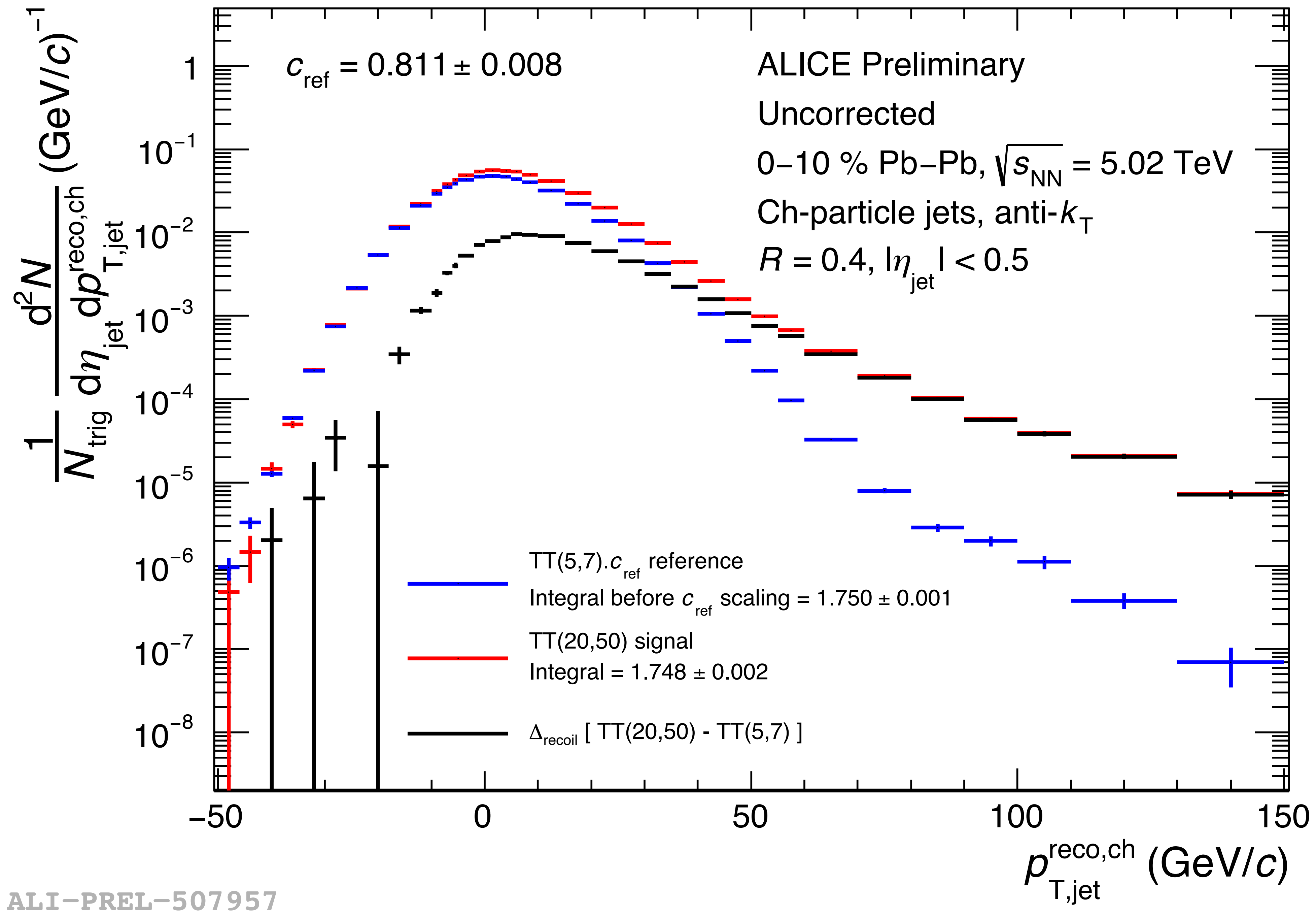
→ **Leading track/cluster p_T cut**

Statistical correction:

→ **Mixed event subtraction**

→ **Difference between two ‘triggered’ distributions**

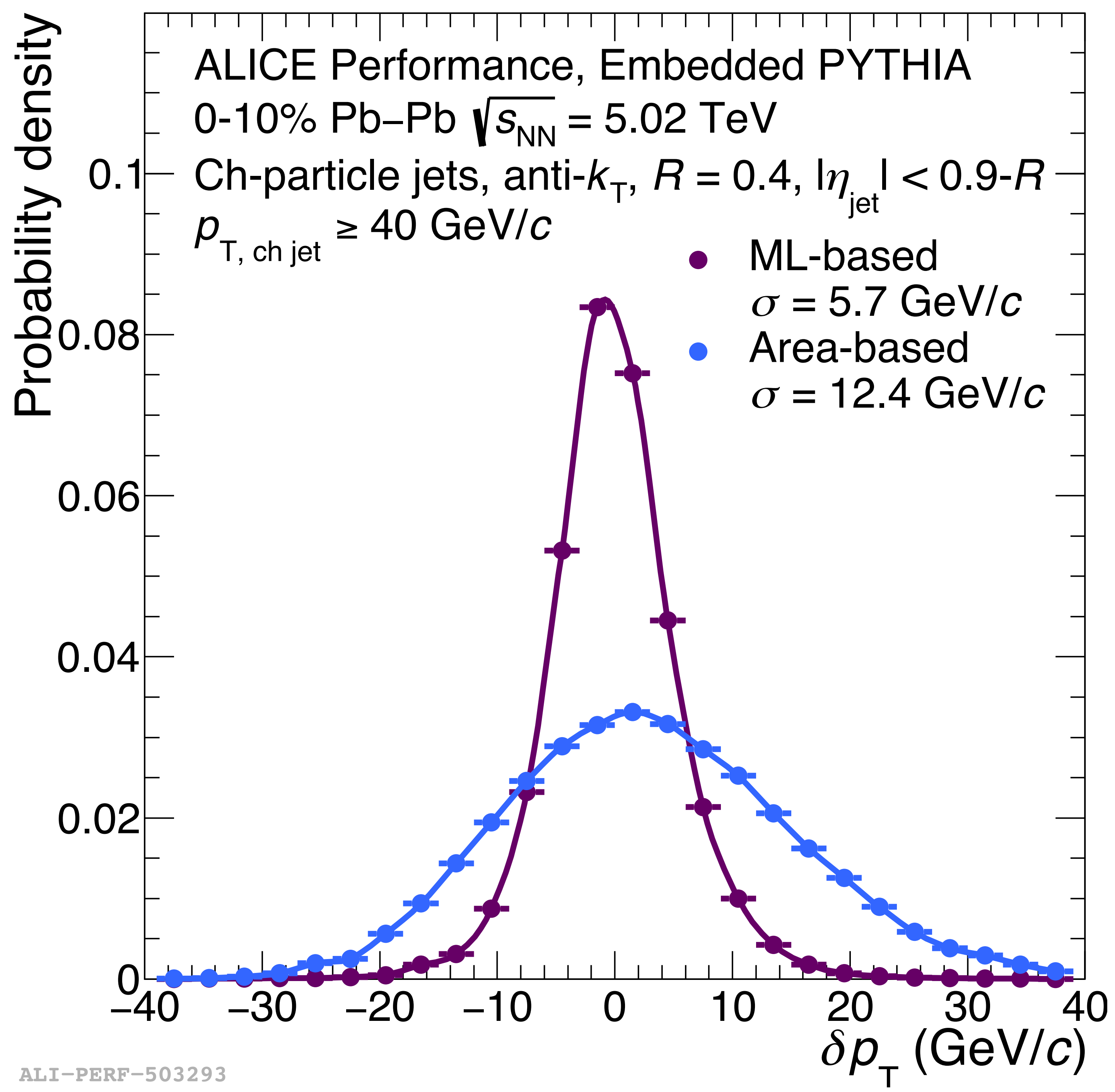
ALICE: JHEP 09 (2015) 170

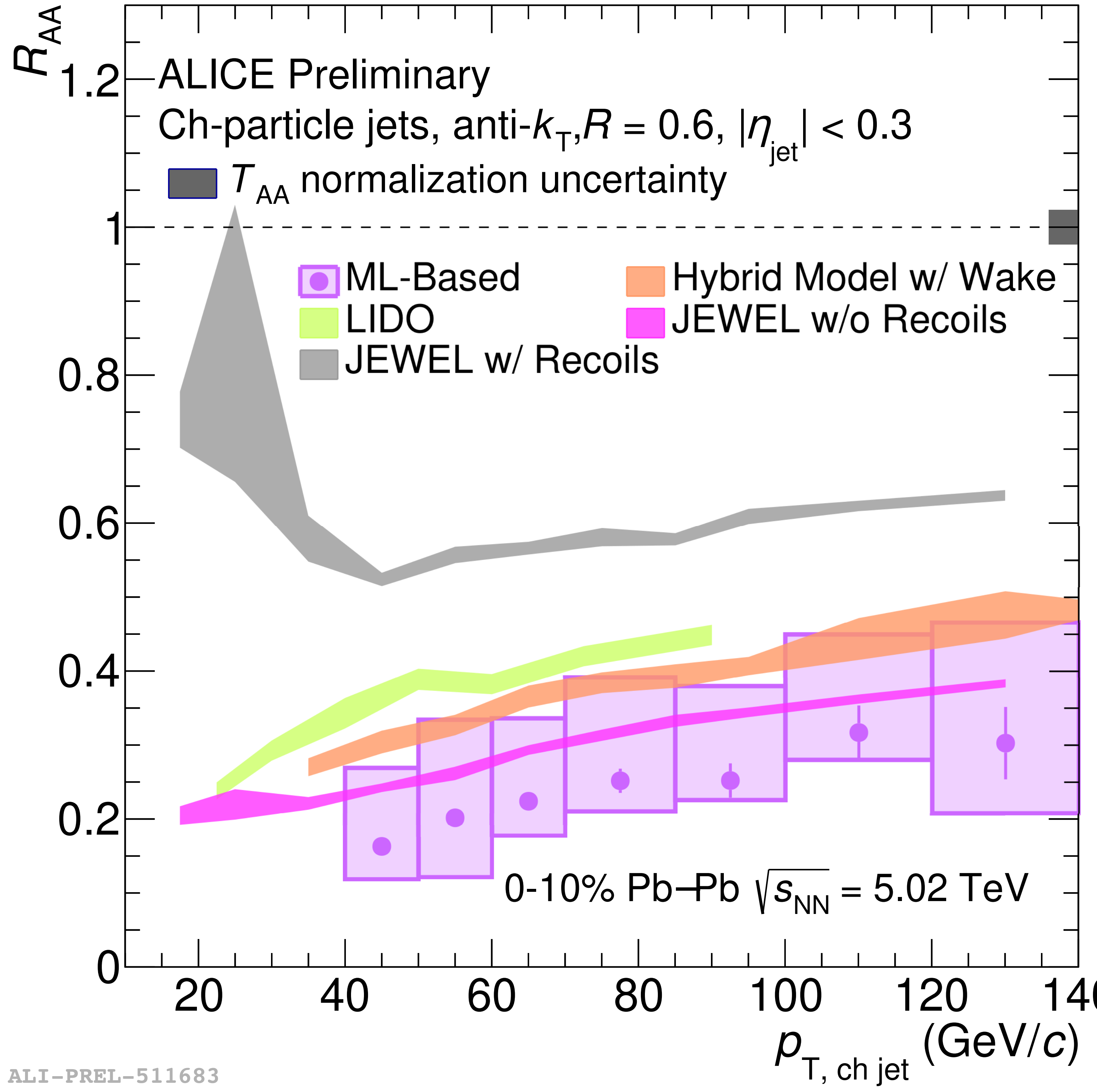


$$\Delta_{recoil} \sim \frac{1}{N_{trig}^{AA}} \frac{d^3N_{jet}^{AA}}{dp_{T,jet}^{ch} d\Delta\varphi d\eta_{jet}}\bigg|_{p_{T,trig}\in TT_{Sig}} - \frac{1}{N_{trig}^{AA}} \frac{d^3N_{jet}^{AA}}{dp_{T,jet}^{ch} d\Delta\varphi d\eta_{jet}}\bigg|_{p_{T,trig}\in TT_{Ref}}$$

Pushing to high jet R

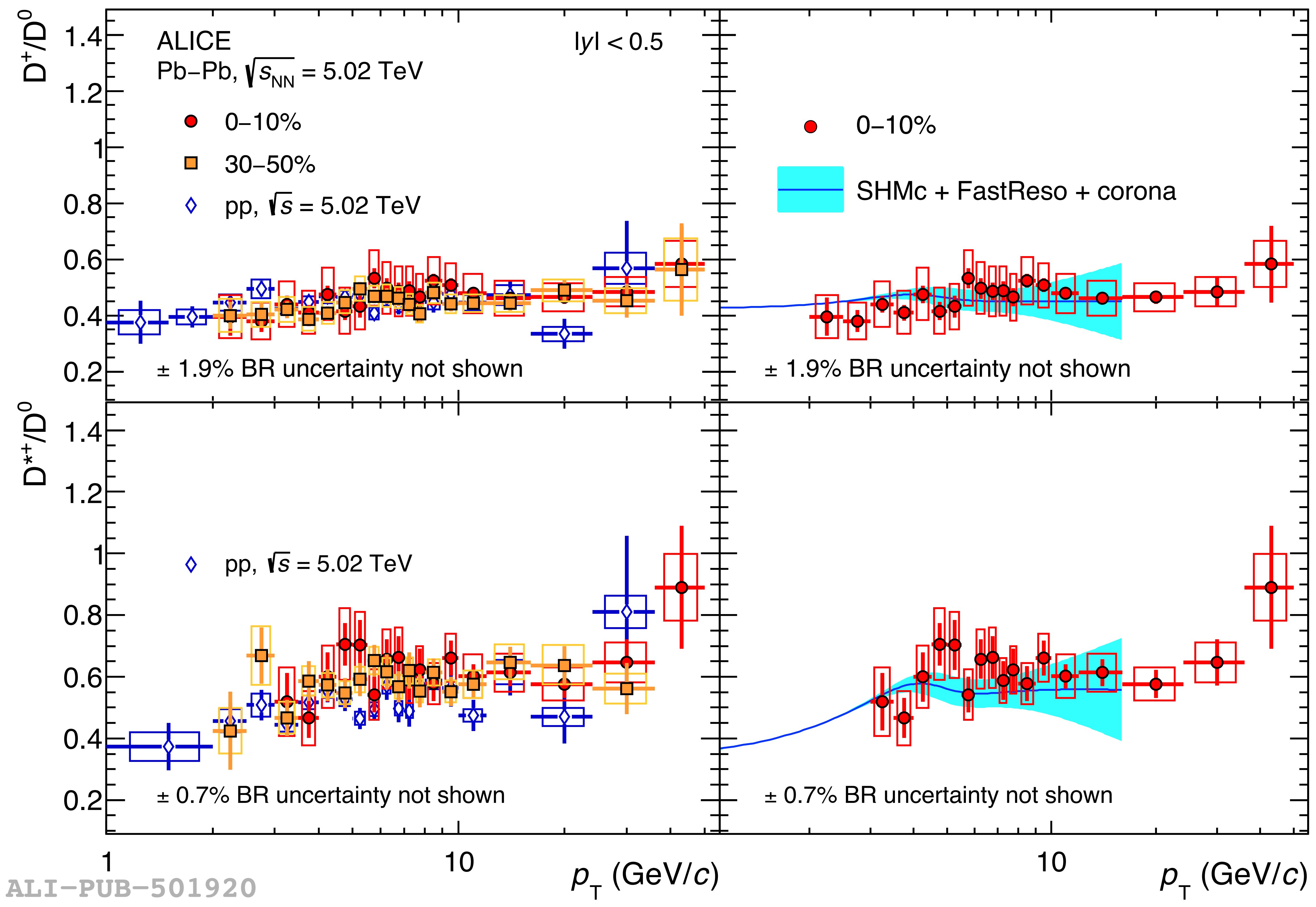
R. Haake, C. Loizides, Phys. Rev. C 99, 064904 (2019)





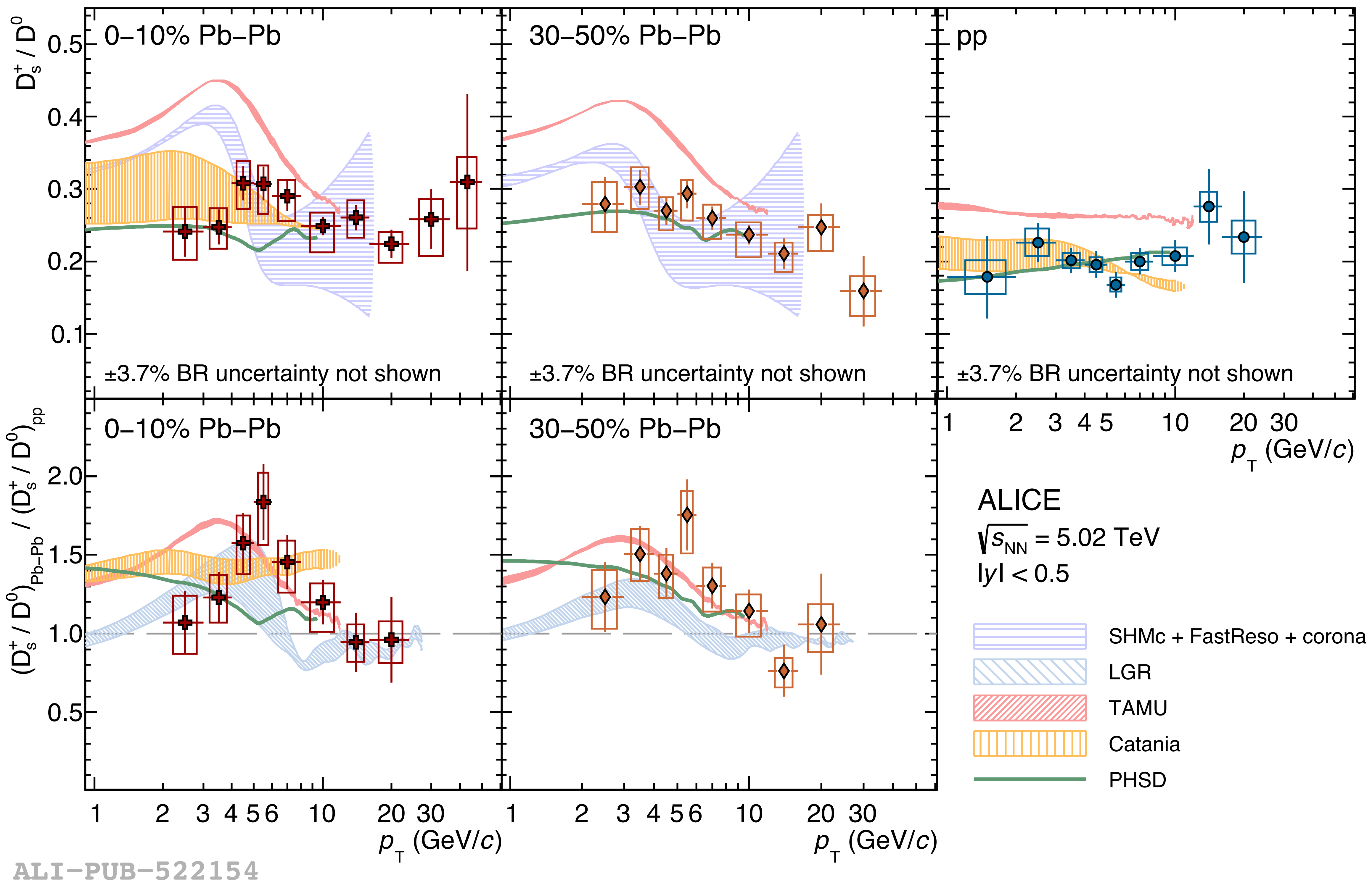
- **Correcting for detector effects and background resolution crucial** to make quantitative comparisons to theory
- Background resolution (calculated event-by-event) worsens as jet R increases - corrections become more difficult
  - Limit measurements to high jet p_T (where relative correction is smaller)
  - Machine learning for jet-by-jet estimation of underlying event density significantly improves resolution

D meson ratios



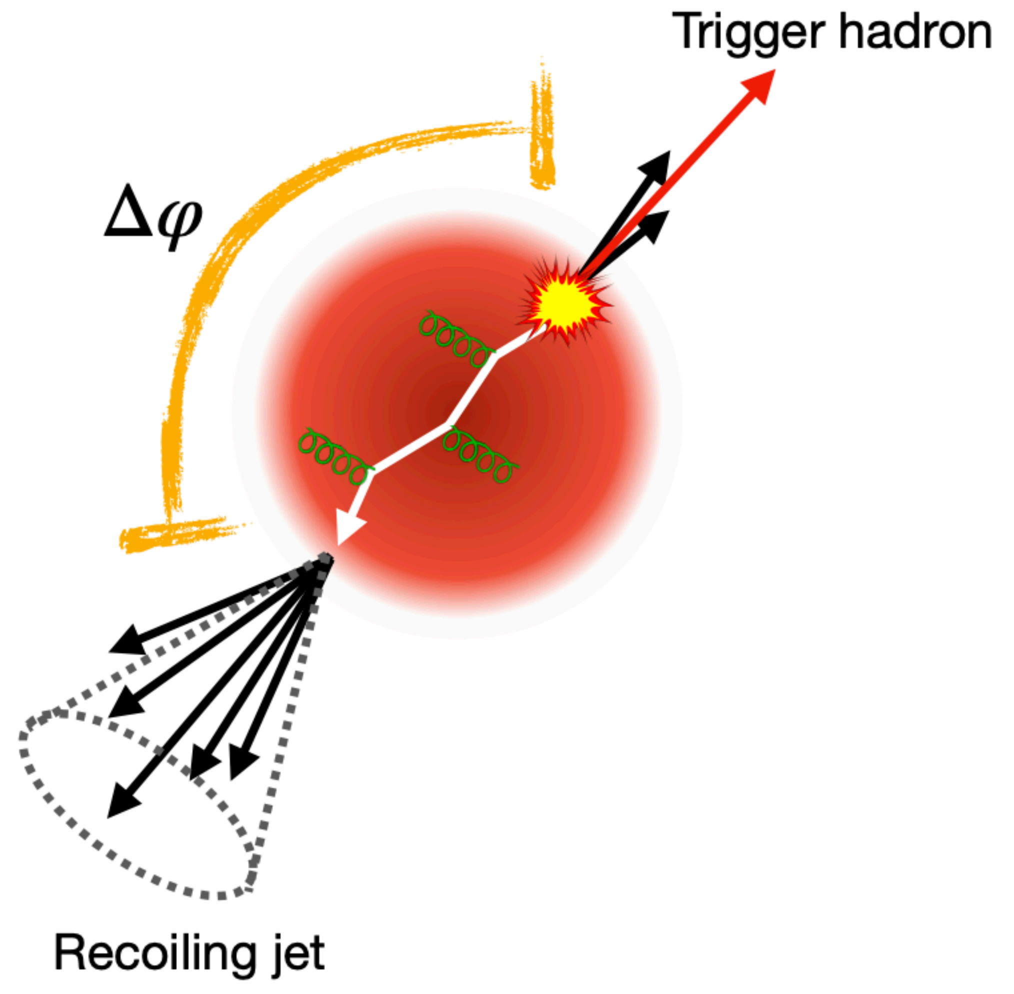
- Charm hadron ratios probe hadronisation within the QGP once quarks form
- (non-strange) D-meson ratios consistent going from pp —> central Pb—Pb..

D meson ratios

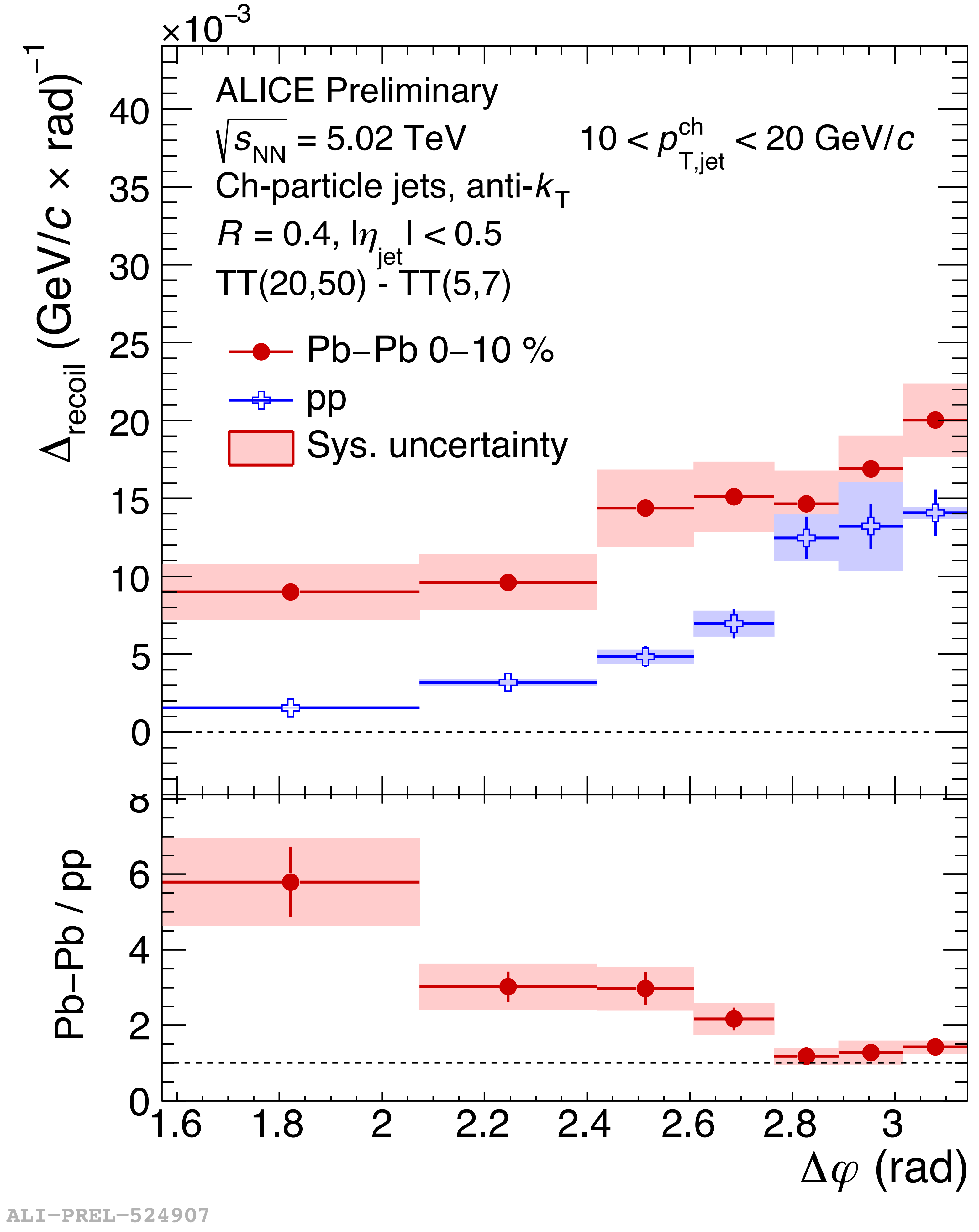


- Charm hadron ratios probe hadronisation within the QGP once quarks form
- (non-strange) D-meson ratios consistent going from pp —> central Pb—Pb..
- Hint of strange D-meson/non-strange D-meson ratios enhanced, indicating coalescence of quarks in-medium

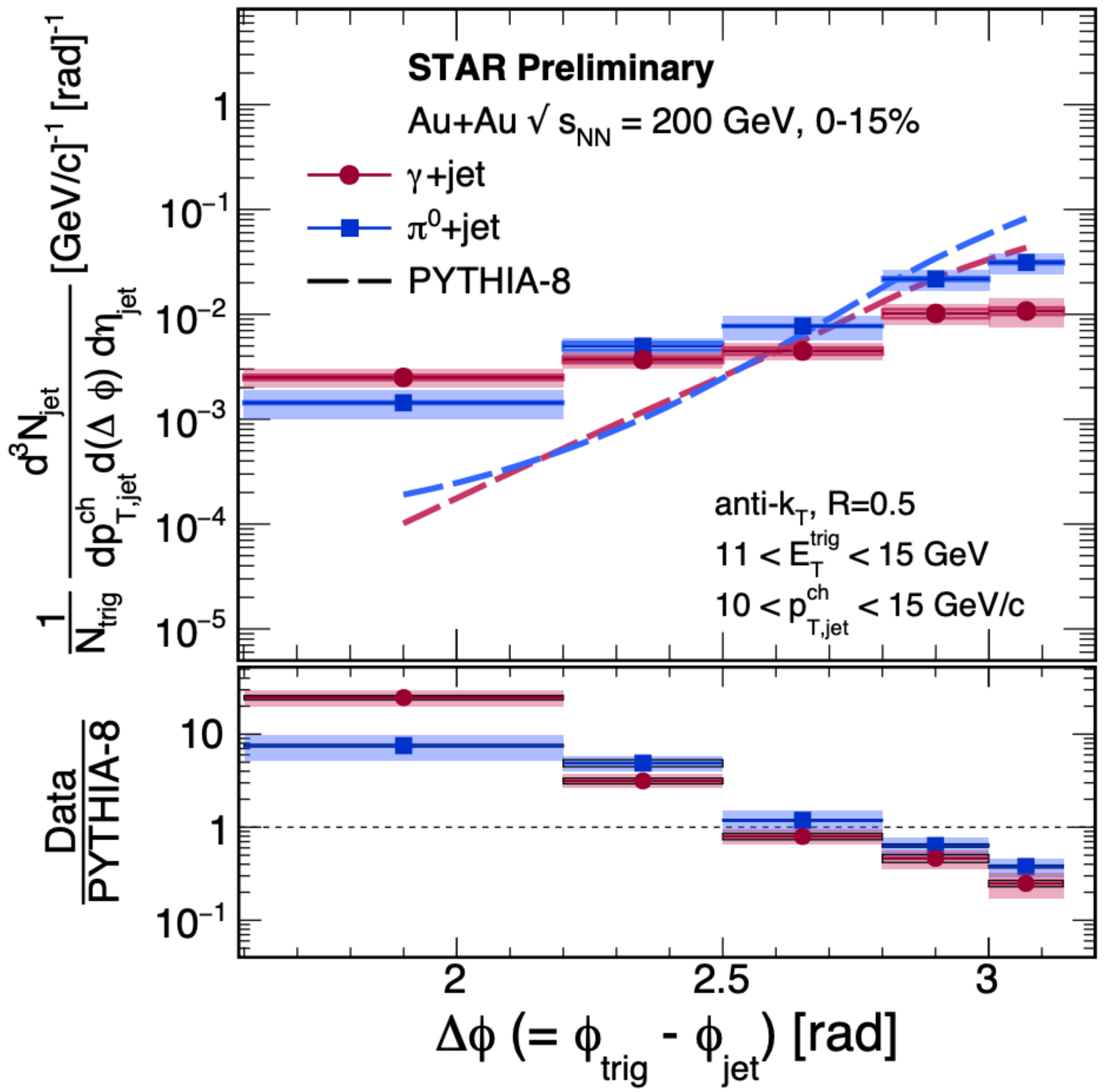
hadron+jet acoplanarity



$h^{\pm}$-jet



γ-jet and π^0-jet

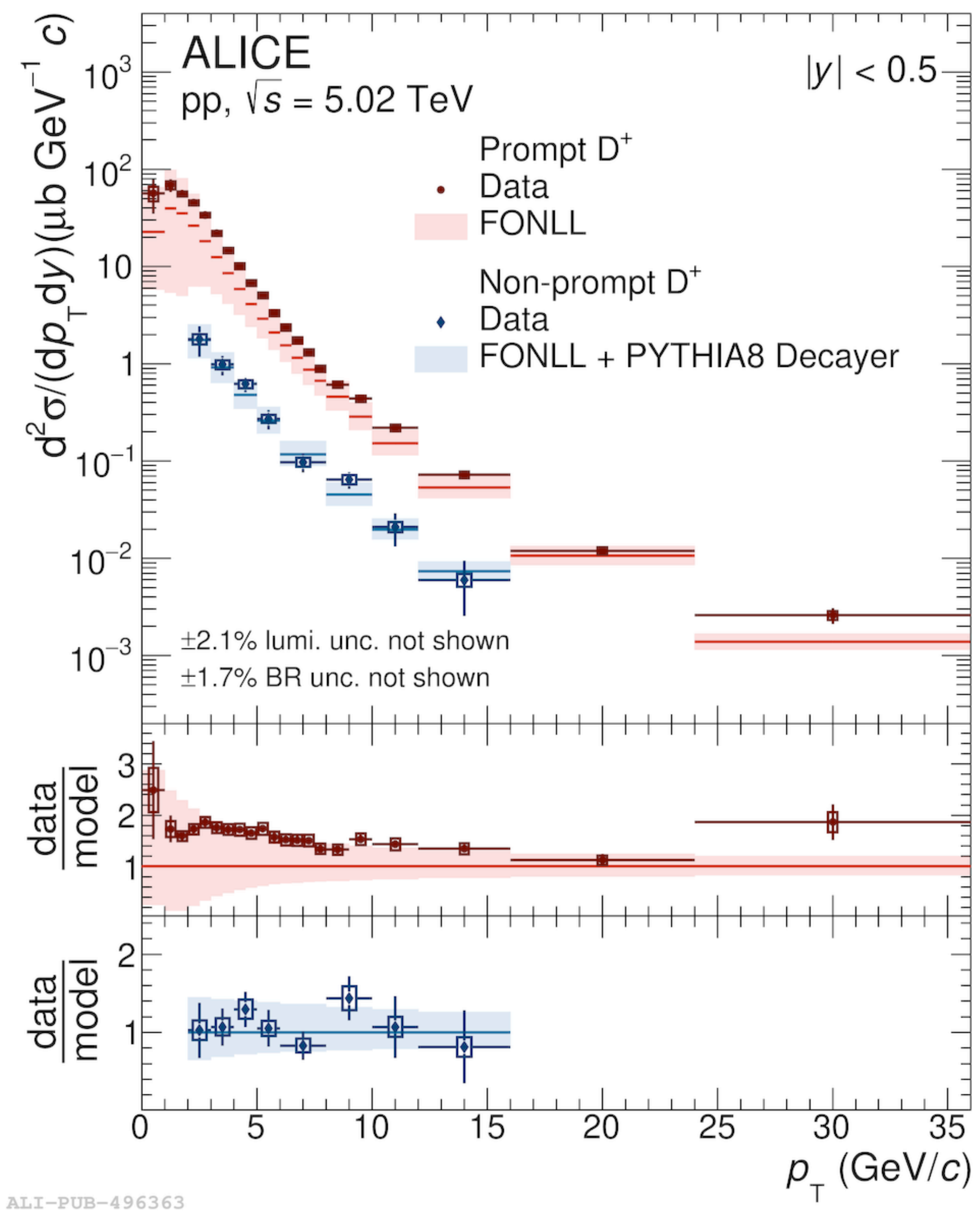


- **Azimuthal decorrelation of jets**
- Modification occurs for larger R, soft jets
- Azimuthal deflection? Jet fragments?

- **Same observation by STAR for γ-jet and π^0-jet $\Delta\phi$ distribution**

Heavy flavour and jet production in pp collisions

ALICE: JHEP 05 (2021) 220



- Calibrated reference measurements crucial for interpretation in heavy-ion collisions
- Heavy flavour and jet production **in general well understood in pp collisions**