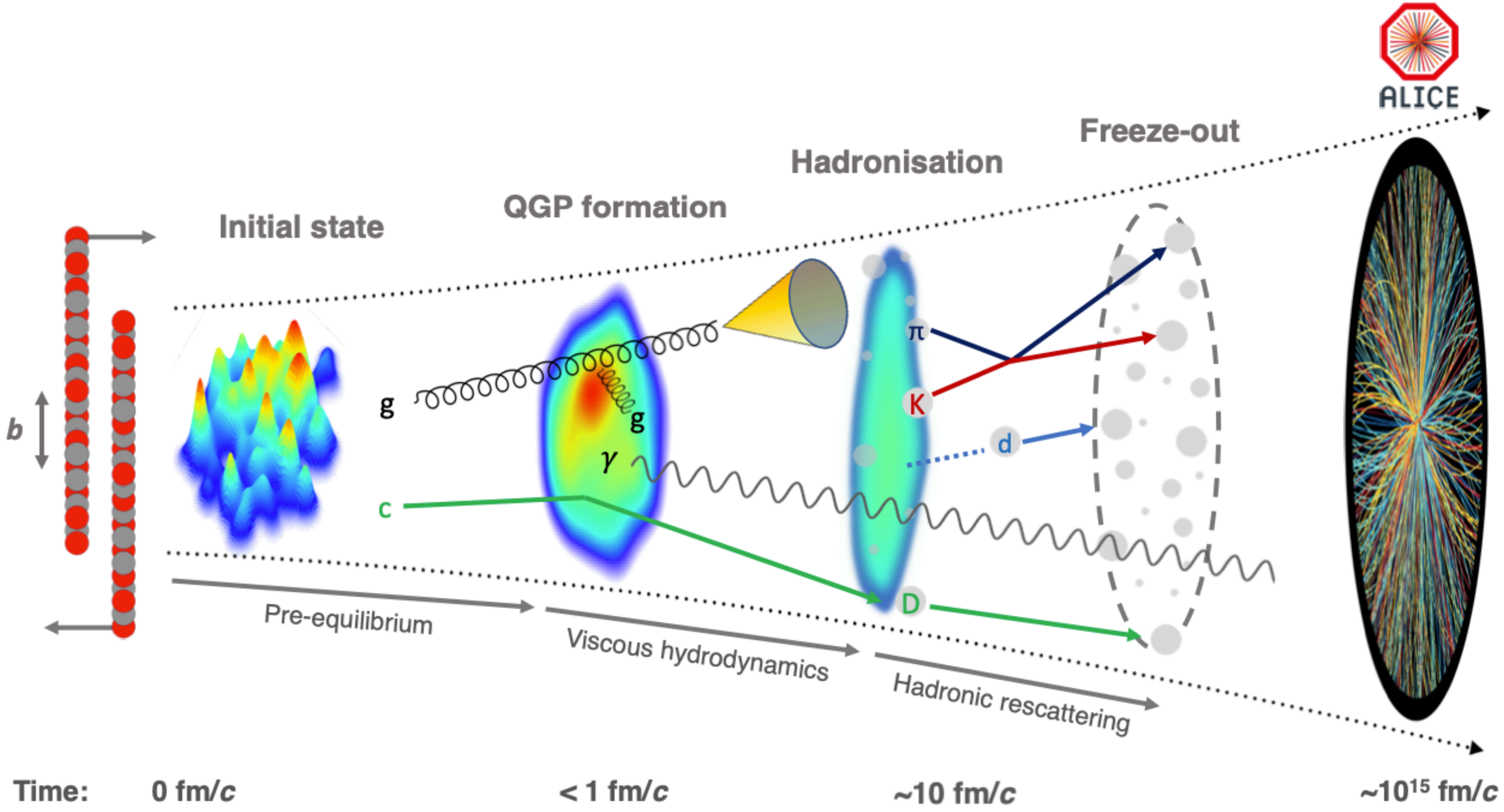
Characterising the QGP with heavy flavour hadrons with ALICE: state of the art and prospects

Marianna MAZZILLI on behalf of the ALICE Collaboration

BEAUTY 2023 - Clermont Ferrand
06/07/2023

Heavy quarks in heavy-ion collisions

Heavy quarks: ideal probes to characterise the QGP phase (and not only!)



Heavy quarks carry information of:

- Initial conditions
- QGP properties
- Hadronisation mechanisms
- Rescattering in hadronic phase

Heavy quarks in heavy-ion collisions

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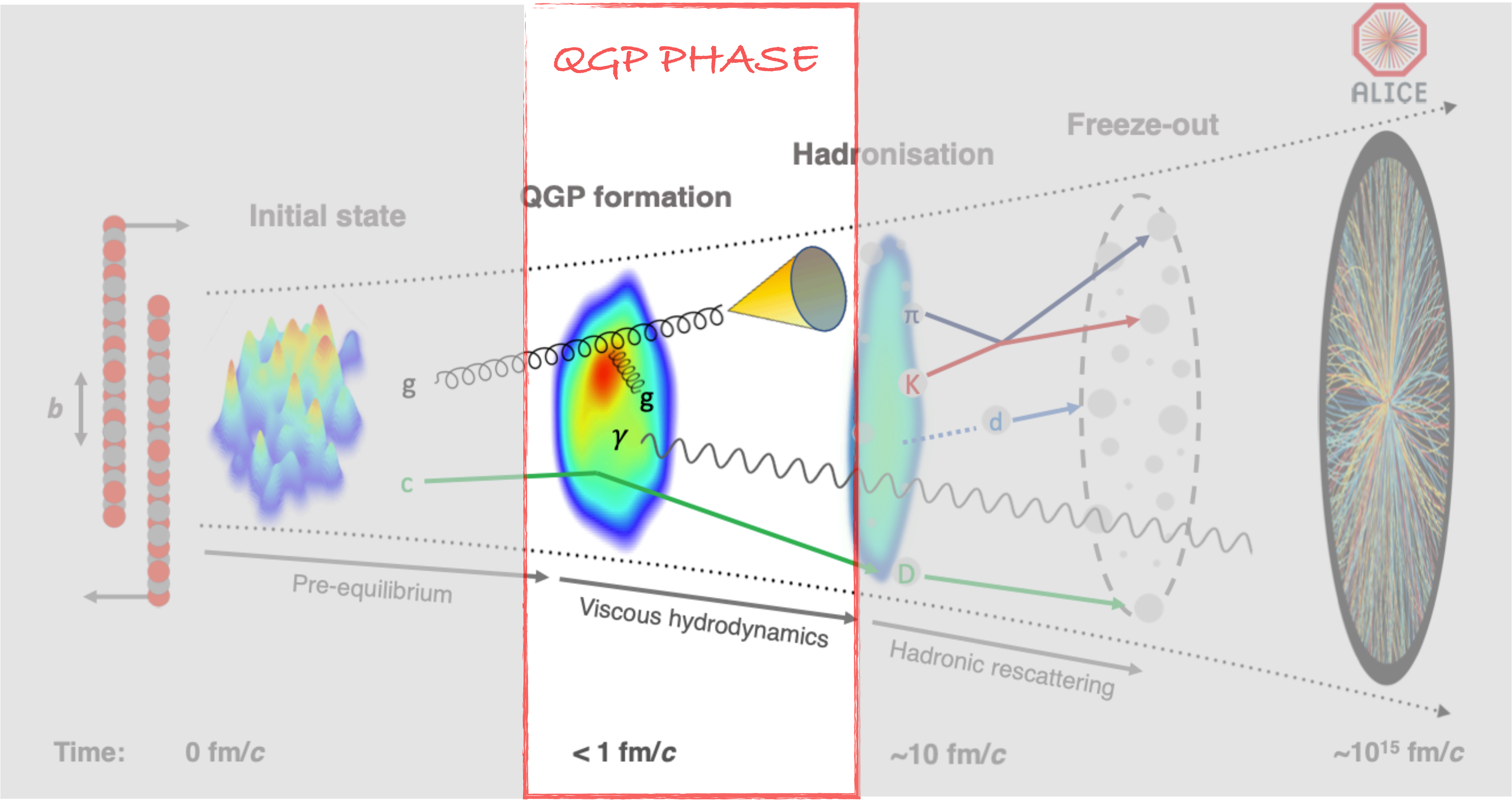

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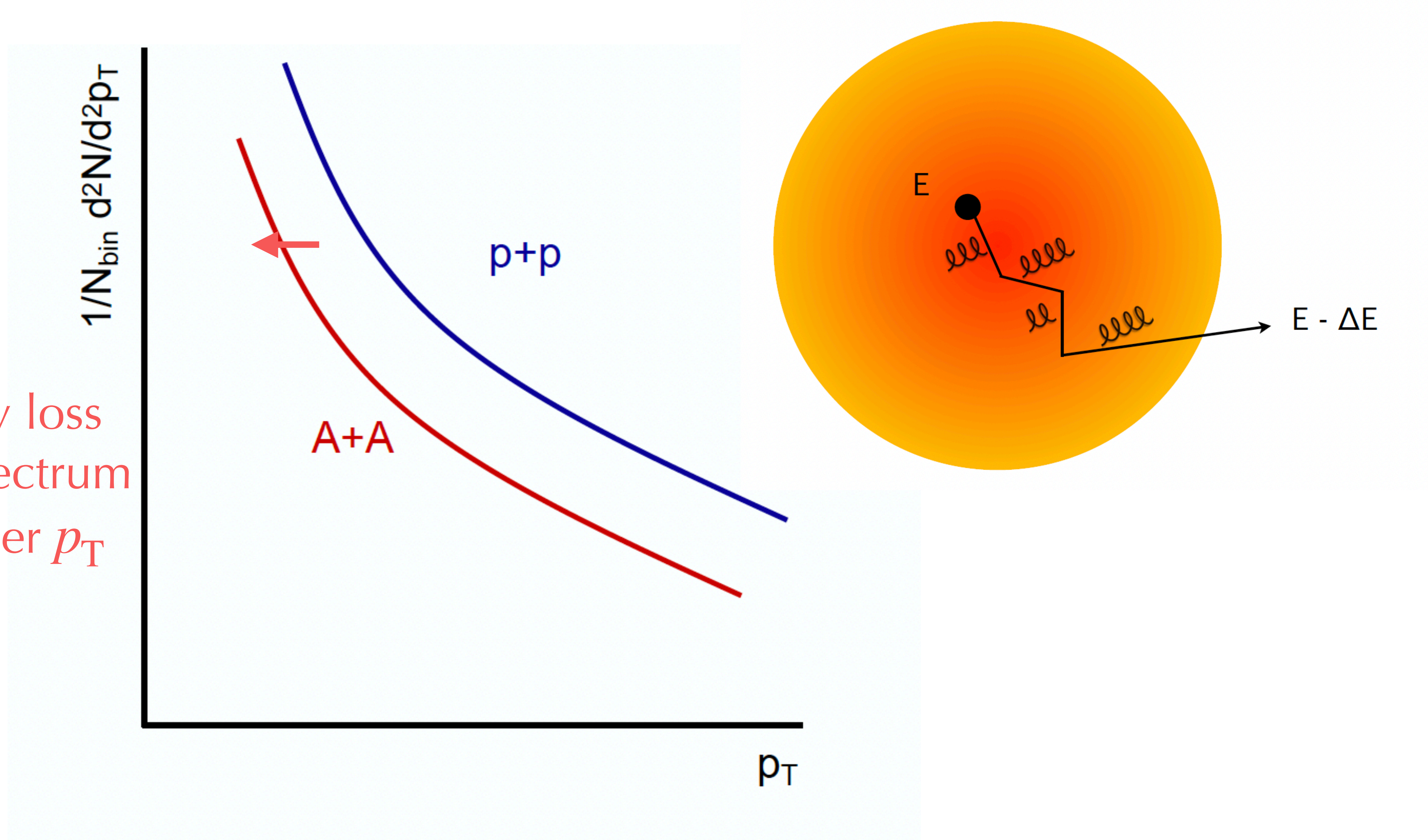
- Initial conditions
- **QGP properties**
- Hadronisation mechanisms
- Rescattering in hadronic phase

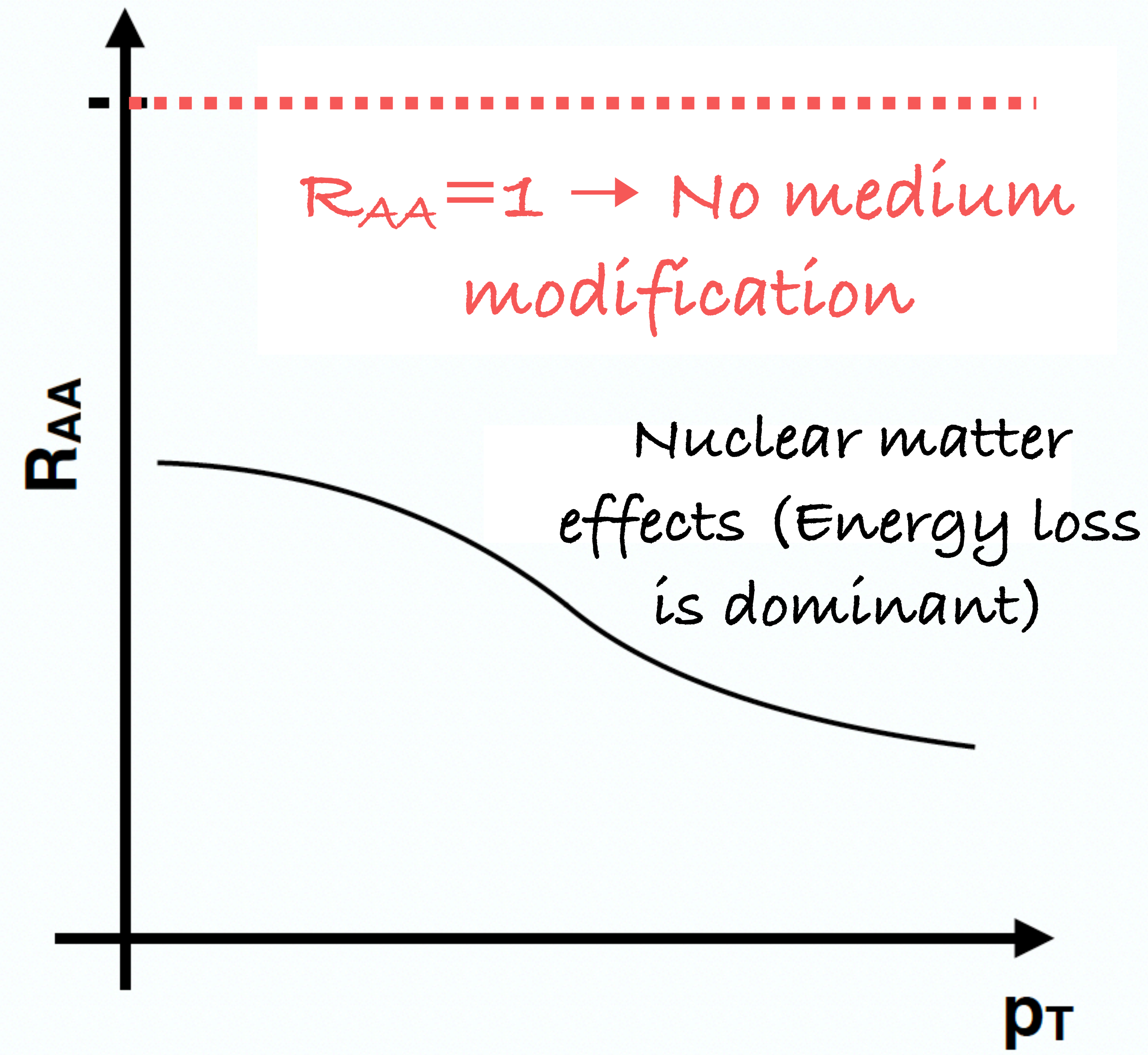
How do we access QGP properties?



Energy loss shift spectrum to lower p_T

Nuclear modification factor

$$R_{AA}(p_T) = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



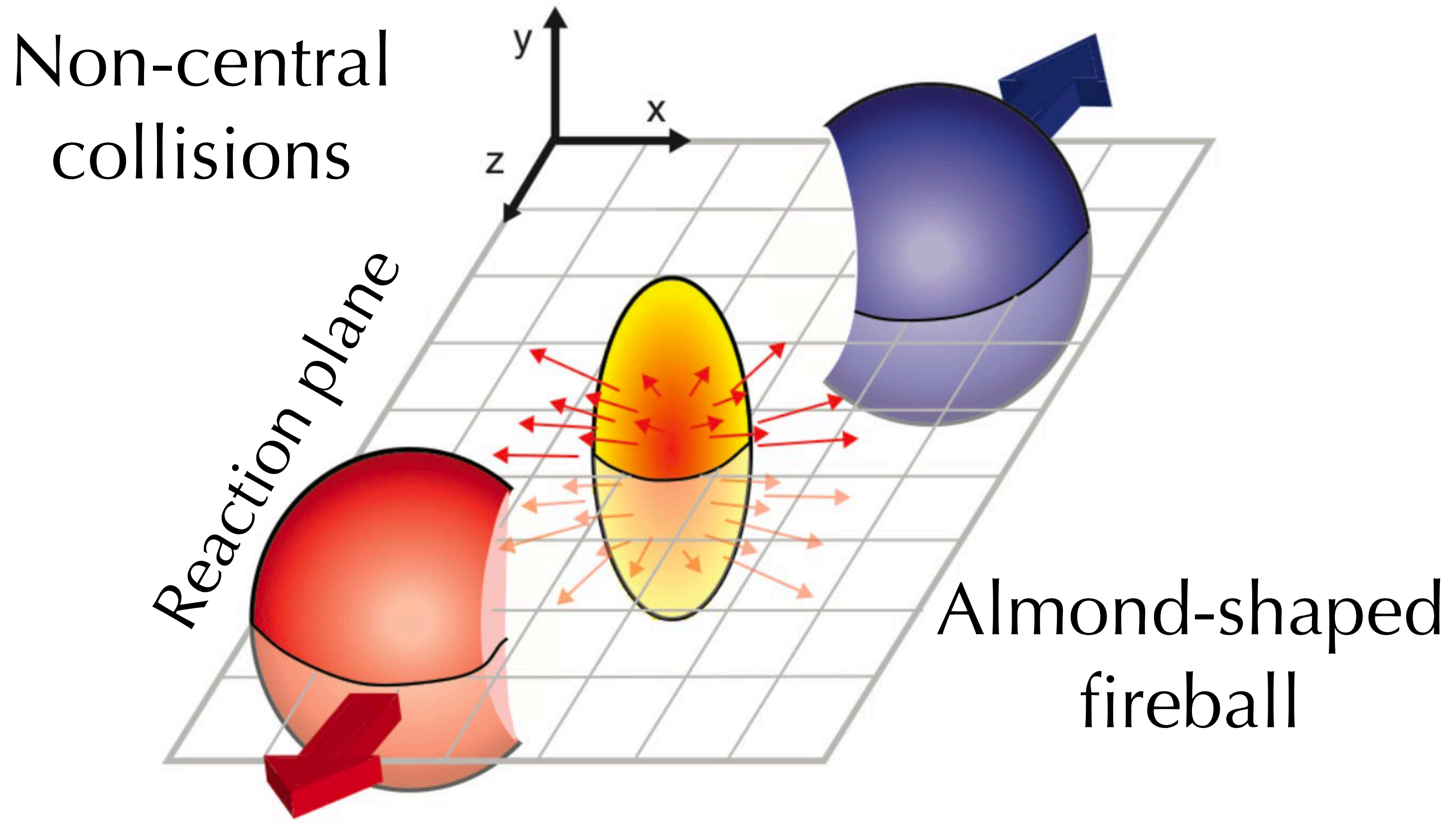
$R_{AA}=1 \rightarrow$ No medium modification

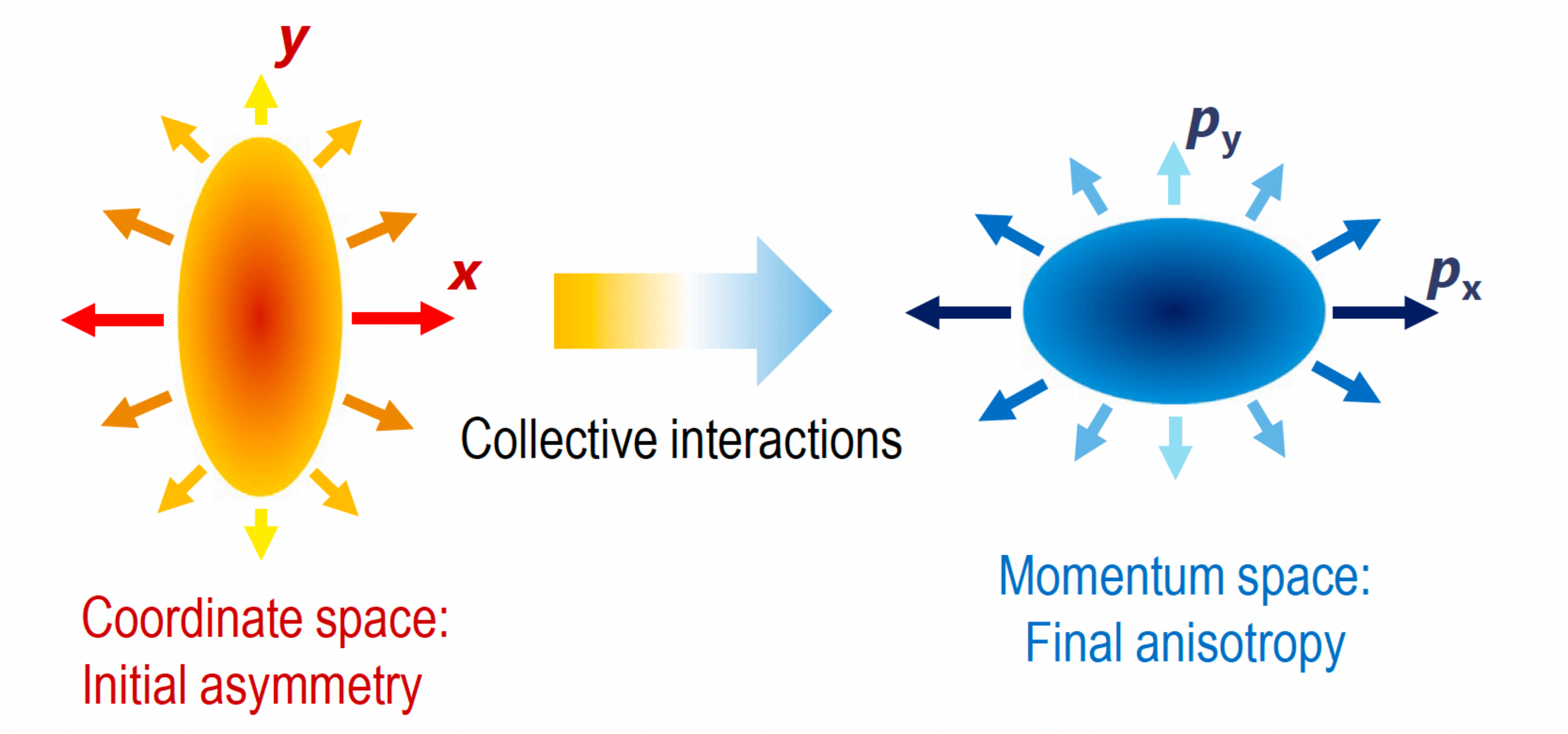
Nuclear matter effects (Energy loss is dominant)

Heavy quarks interact with QGP constituents

- **Low** p_T: Elastic collision with medium constituents (diffusion Brownian motion, possible thermalisation in the medium)
- **High** p_T: Radiative energy loss (gluon emission)

How do we access QGP properties?





Anisotropic flow

Sensitivity to initial geometry (elliptic flow coefficient v_2) and event-by-event fluctuations (triangular flow)

Quantified via Fourier expansion of $\mathrm{d}N/\mathrm{d}\phi$ distribution:

$$\mathrm{d}N/\mathrm{d}\phi \approx 1 + 2\sum_{\mathrm{n}} v_{\mathrm{n}} \cos[\mathrm{n}(\phi - \Psi_{\mathrm{n}})]$$

Non-central collisions:

Initial **spatial anisotropy** → different pressure gradients → final **momentum anisotropy**

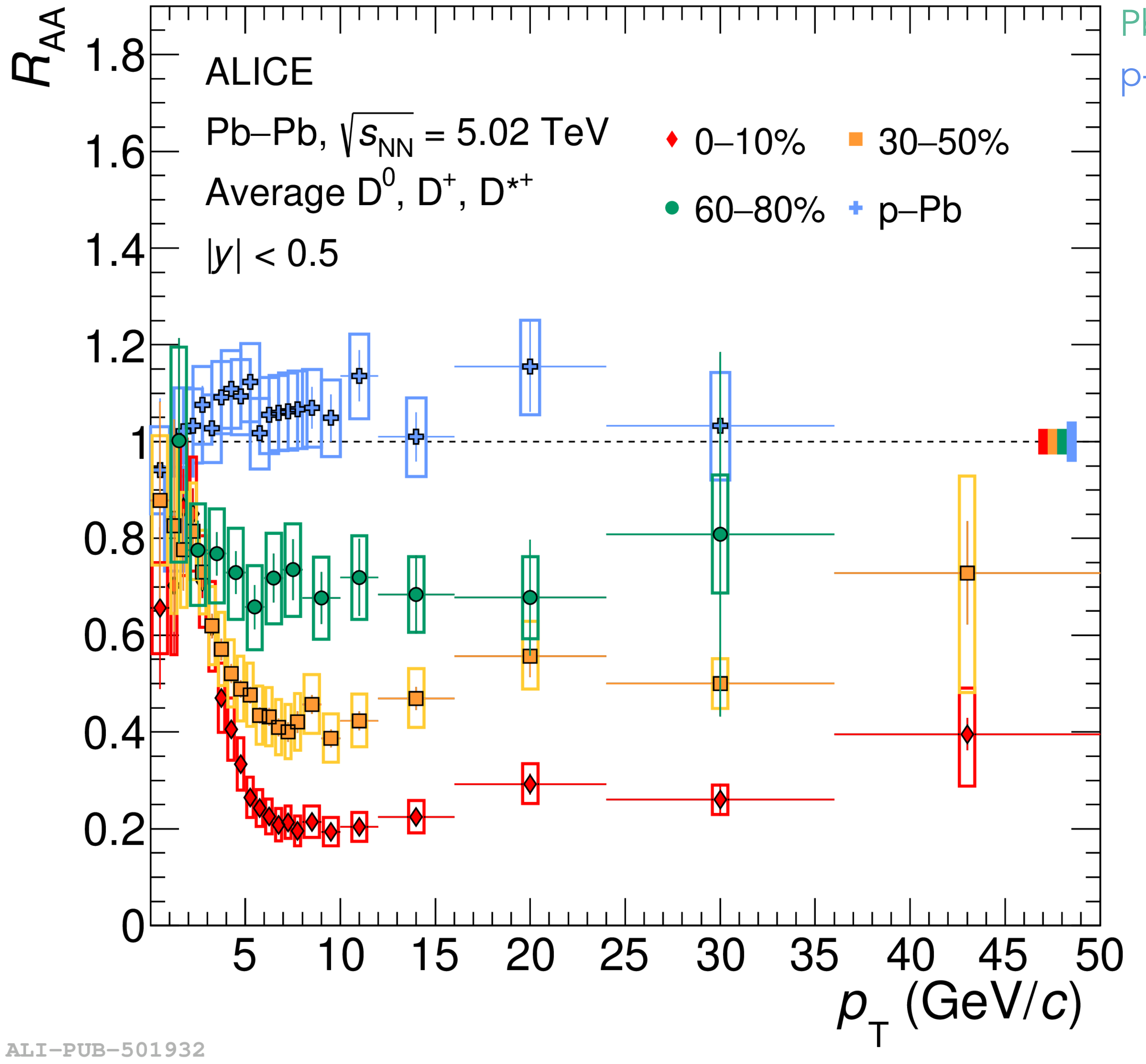
Elliptic flow (v_2)

- **Low p_{T}:** participation in collective motion and thermalisation of heavy quarks
- **High p_{T}:** path-length dependence of energy loss

Sensitive to the ratio of the **shear viscosity** to the **entropy density, *η/s***

QGP with the nuclear modification factor

JHEP 01 (2022) 174

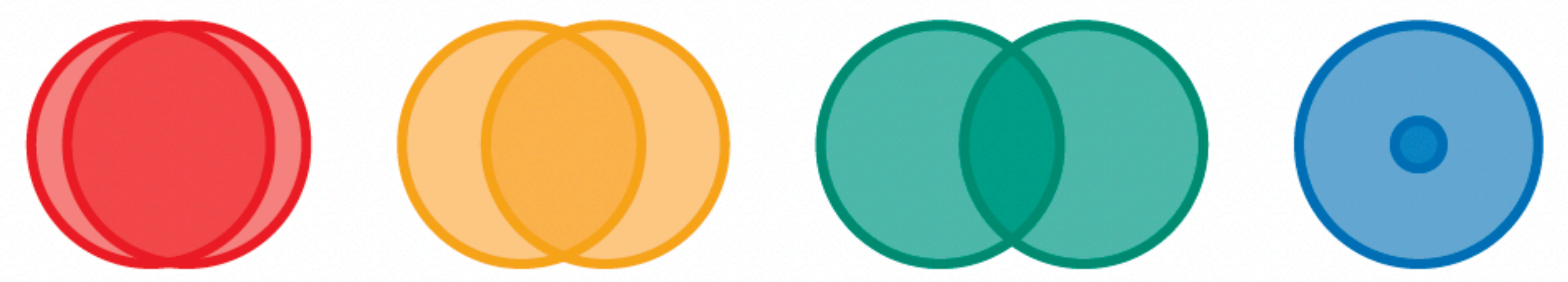


Pb-Pb 60-80%: JHEP 10 (2018) 174

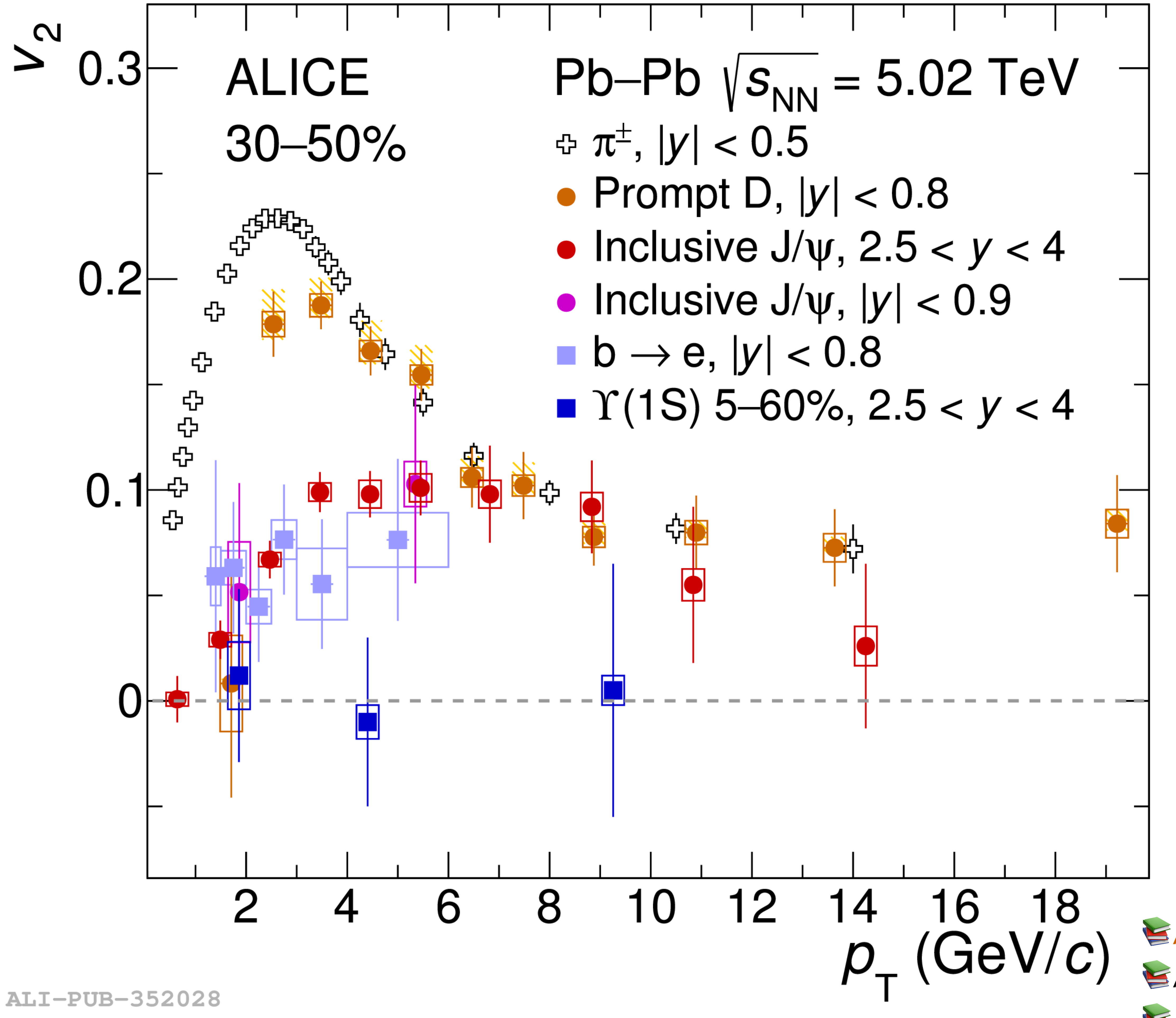
p-Pb: JHEP 12 (2019) 092

Nuclear modification factor in different centrality classes in Pb-Pb collisions (0-10%, 30-50%, 60-80%) + p-Pb collisions

Suppression increasing with collision centrality
due to increasing density, size, and lifetime of the medium



Azimuthal anisotropies to access HQ thermalisation (and not only!)



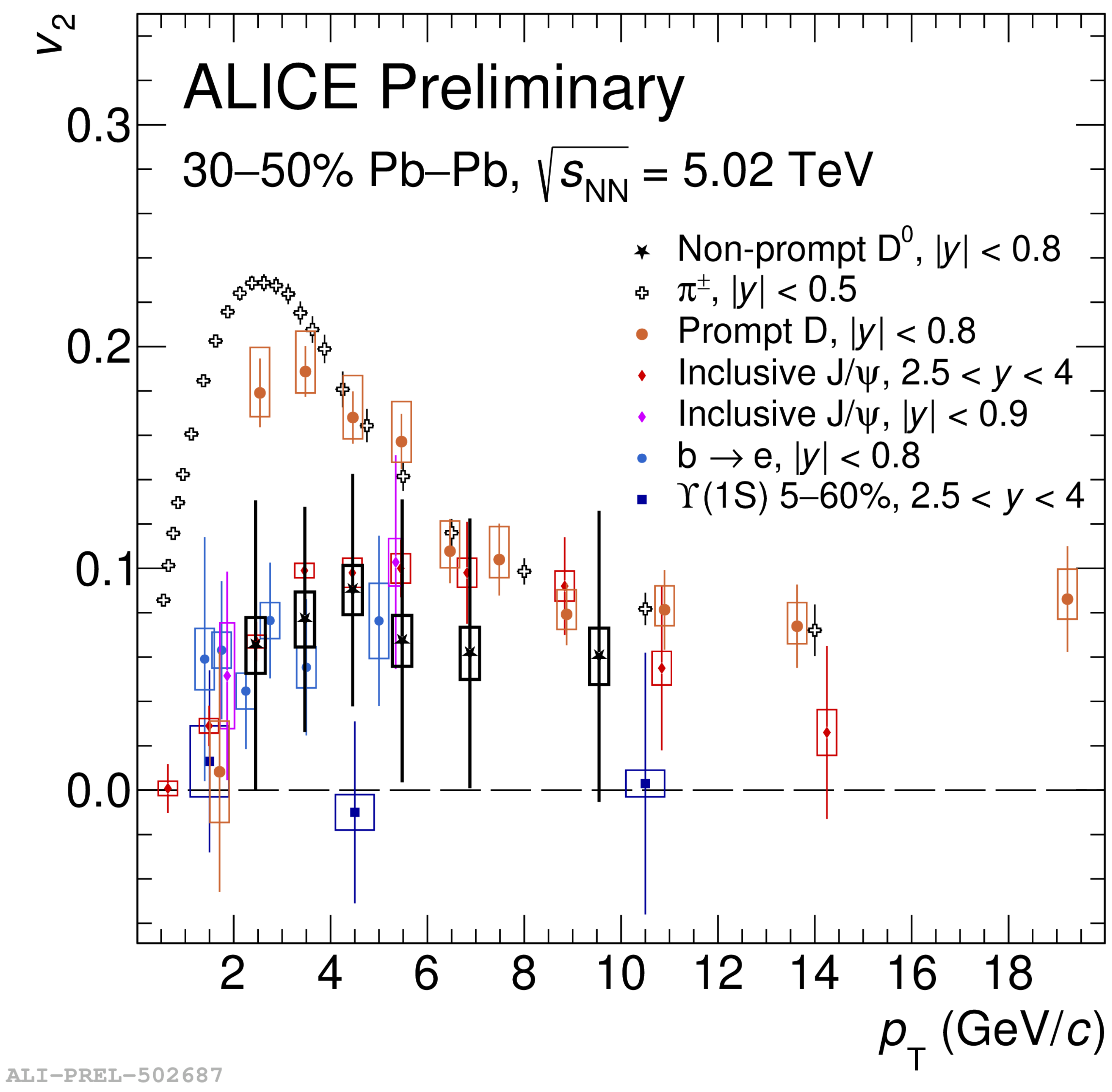
Positive v_2 for open/hidden charm and e←b

- p_T **< 3 GeV/c** : thermalisation of charm quarks
  - ➡ $v_2(\Upsilon) \lesssim v_2(\text{e}\leftarrow\text{b}) \approx v_2(J/\psi) < v_2(\text{D}) < v_2(\pi)$
- **3 <** p_T **< 6 GeV/c** : contribution from hadronisation via coalescence with flowing light quarks
  - ➡ $v_2(J/\psi) < v_2(\text{D}) \approx v_2(\pi)$
  - ➡ $v_2(\Upsilon) < v_2(\text{e}\leftarrow\text{b})$
- p_T **> 6 GeV/c** : path-length dependence of in-medium energy loss
  - ➡ $v_2(J/\psi) \approx v_2(\text{D}) \approx v_2(\pi)$

Bottomonium v_2 compatible with zero

ALICE Prompt D: PLB 813 (2021) 136054
ALICE π: JHEP 1809 (2018) 006
ALICE b→e: PRL 126 (2021) 16200
ALICE ϒ(1S): PRL 123 (2019) 192301
ALICE J/Psi: JHEP 10 (2020) 141

Extending to beauty sector



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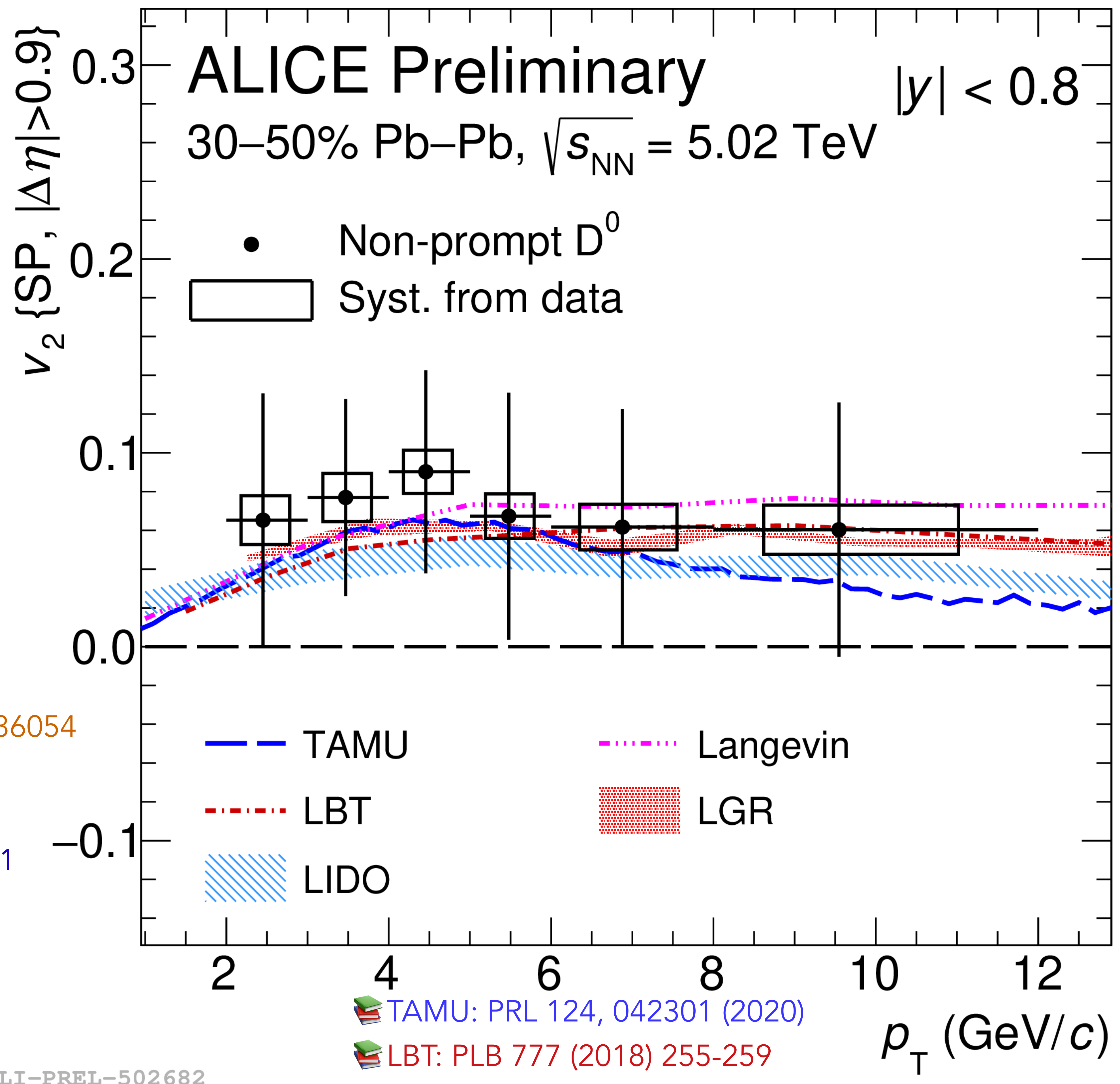


TAMU: PRL 124, 042301 (2020)
LBT: PLB 777 (2018) 255-259
LIDO: PRC 98 064901 (2018)
LGR: EPJC, 80 7 (2020) 671

Positive non-prompt $\mathbf{D^0}$ v_2 observed in $2 < p_T < 12$ GeV/c in semicentral collisions

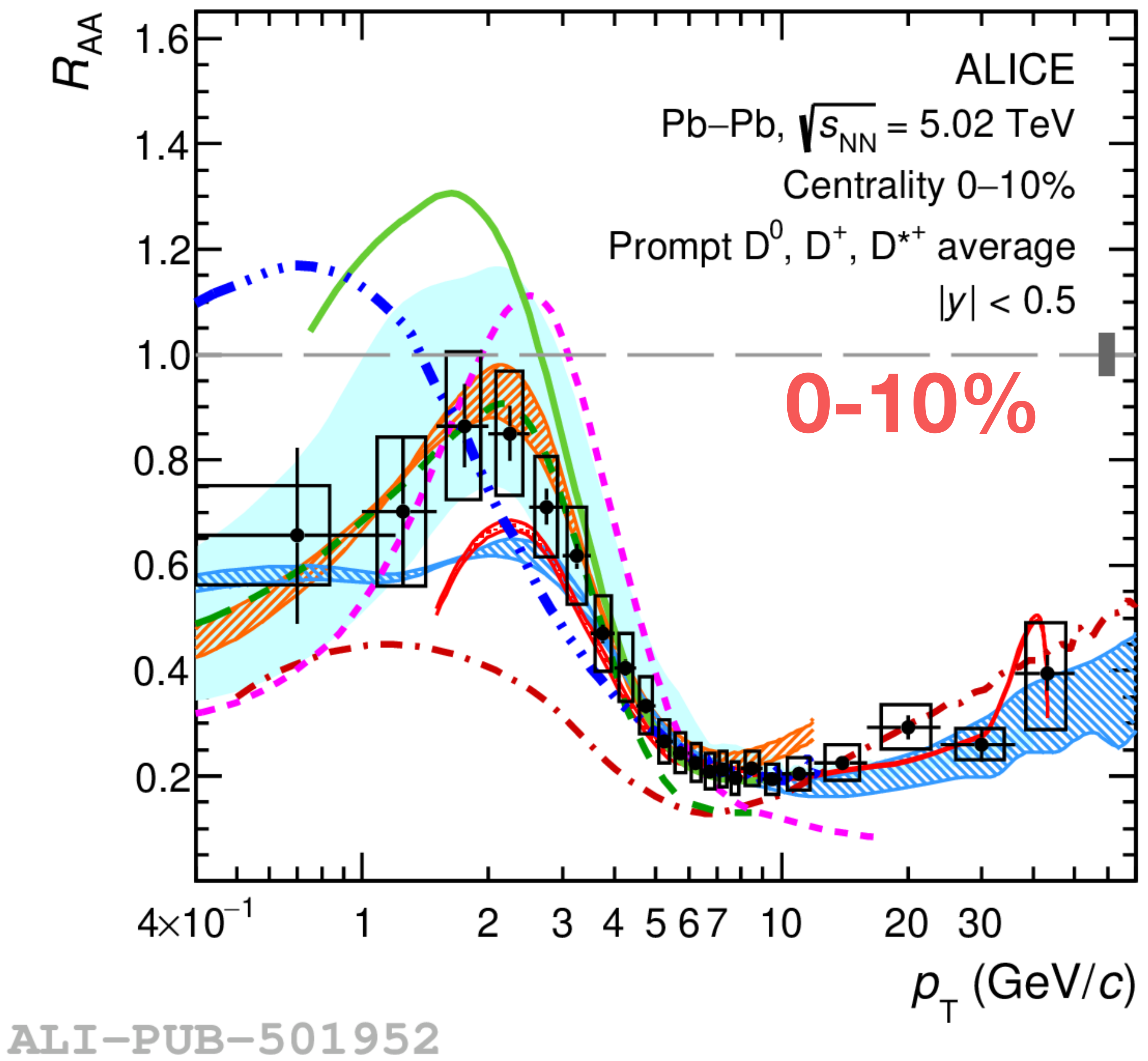
- Lower than prompt D^0 and compatible with e←b elliptic flow results indicates lower degree of thermalisation for beauty quarks

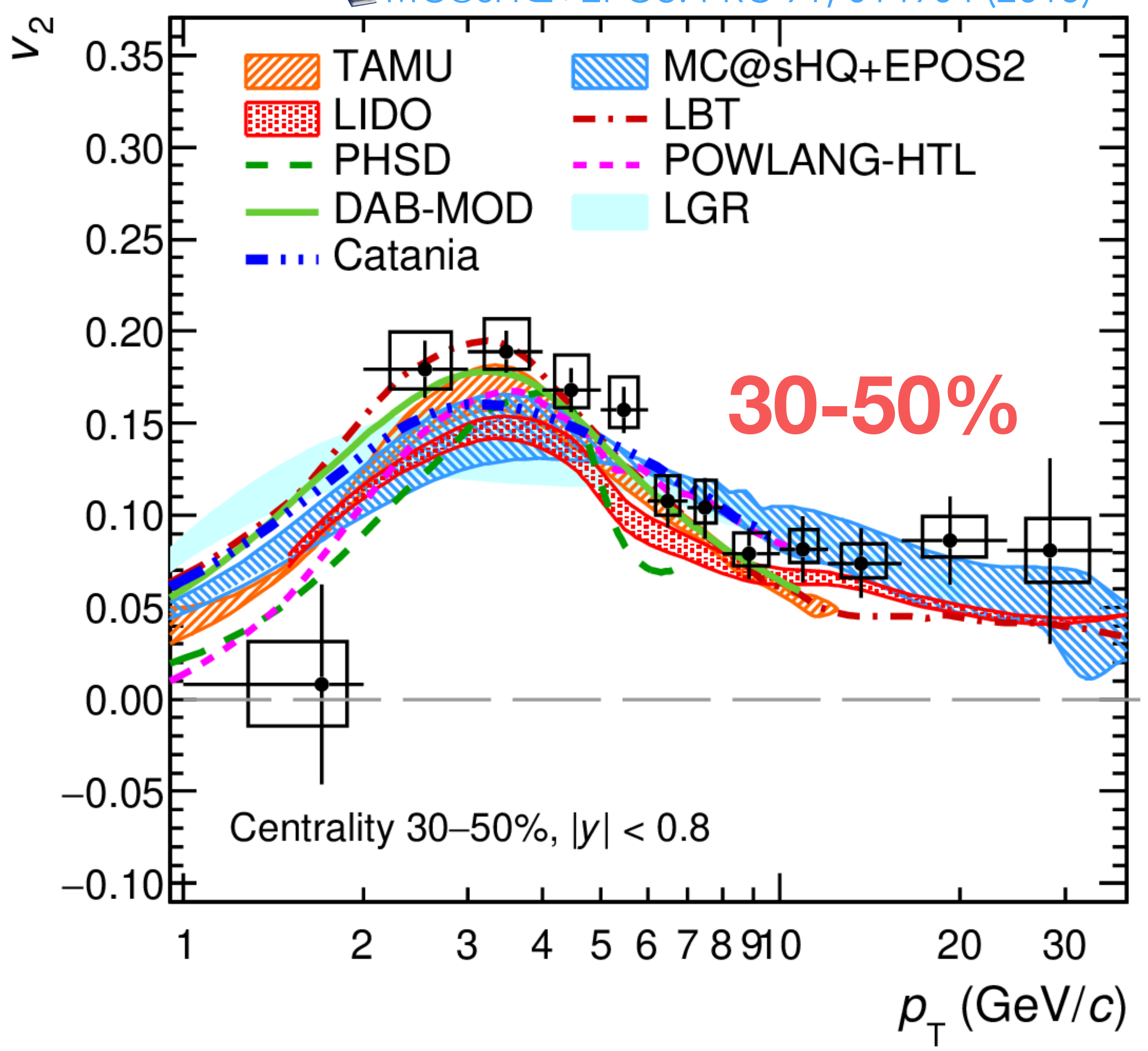
Results described by predictions from models including hadronization via coalescence in addition to fragmentation

QGP transport properties

- TAMU: PRL 124, 042301 (2020)
- PHSD: PRC 93, 034906 (2016)
- POWLANG: EPJC 75, 121 (2015)
- CATANIA: PRC 96, 044905 (2017)
- MC@sHQ+EPOS: PRC 91, 014904 (2015)
- LIDO: PRC 98 064901 (2018)
- LBT: PLB 777 (2018) 255-259
- LGR: EPJC, 80 7 (2020) 671
- DAB-MOD M&T: PRC 96 064903 (2017)

ALICE, JHEP 01 (2022) 174





The low-p_T region provides insight into the heavy quark interactions with the medium

For p_T < 5 GeV/c sensitivity not only to charm-quark interaction with the medium
- shadowing
- bulk evolution of the medium

Simultaneous description of R_{AA} and v_2 challenging for charm-quark transport models

Model-to-data comparison to understand relevant physics effects and estimate the charm-quark spatial diffusion coefficient D_s

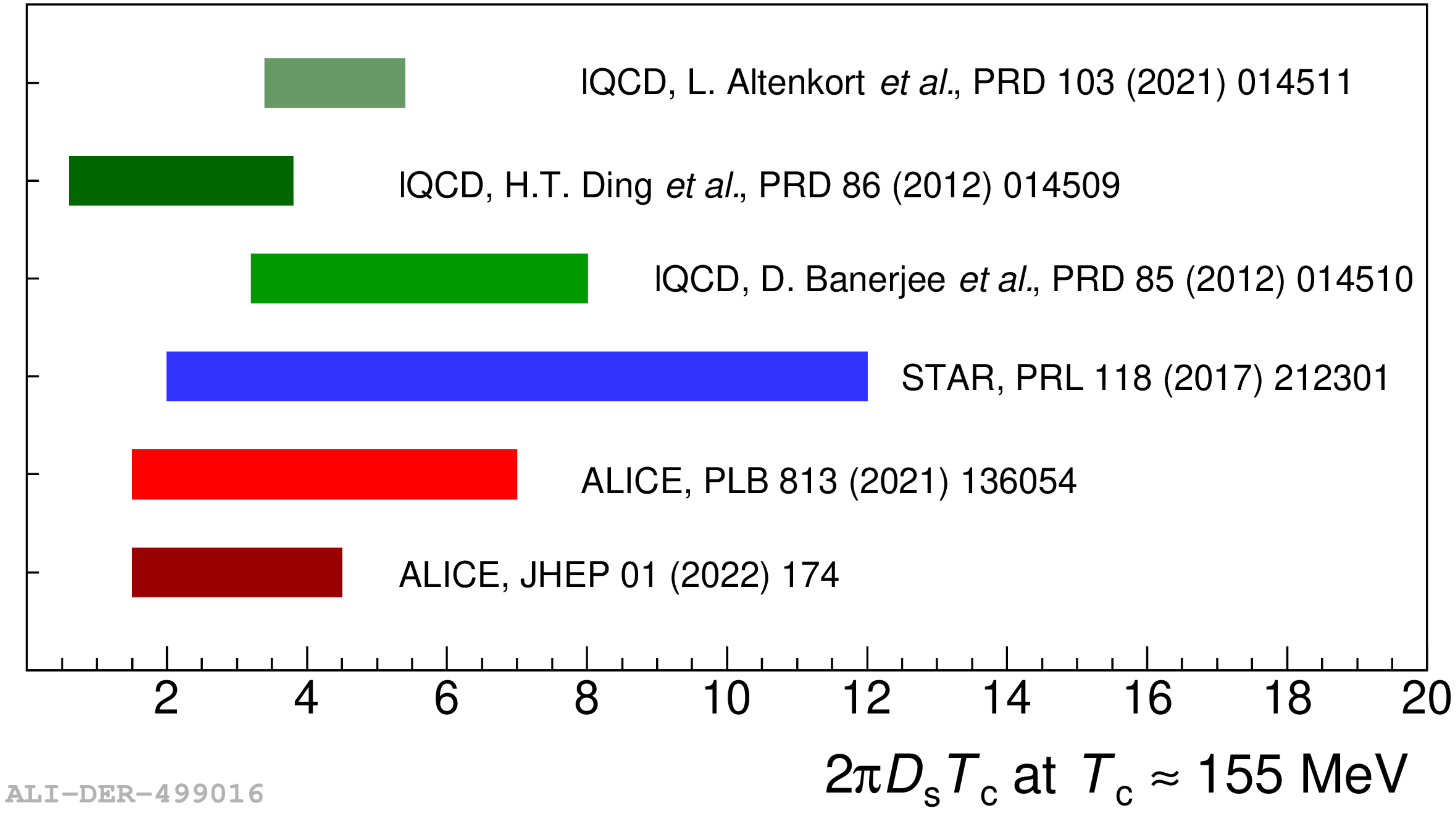
- Radiative energy loss important to describe intermediate and high p_T — small impact on low-p_T region
- Charm-quark hadronisation via recombination crucial to describe low and intermediate p_T: D mesons acquire additional flow from charm-quark recombination with light quarks

QGP transport properties

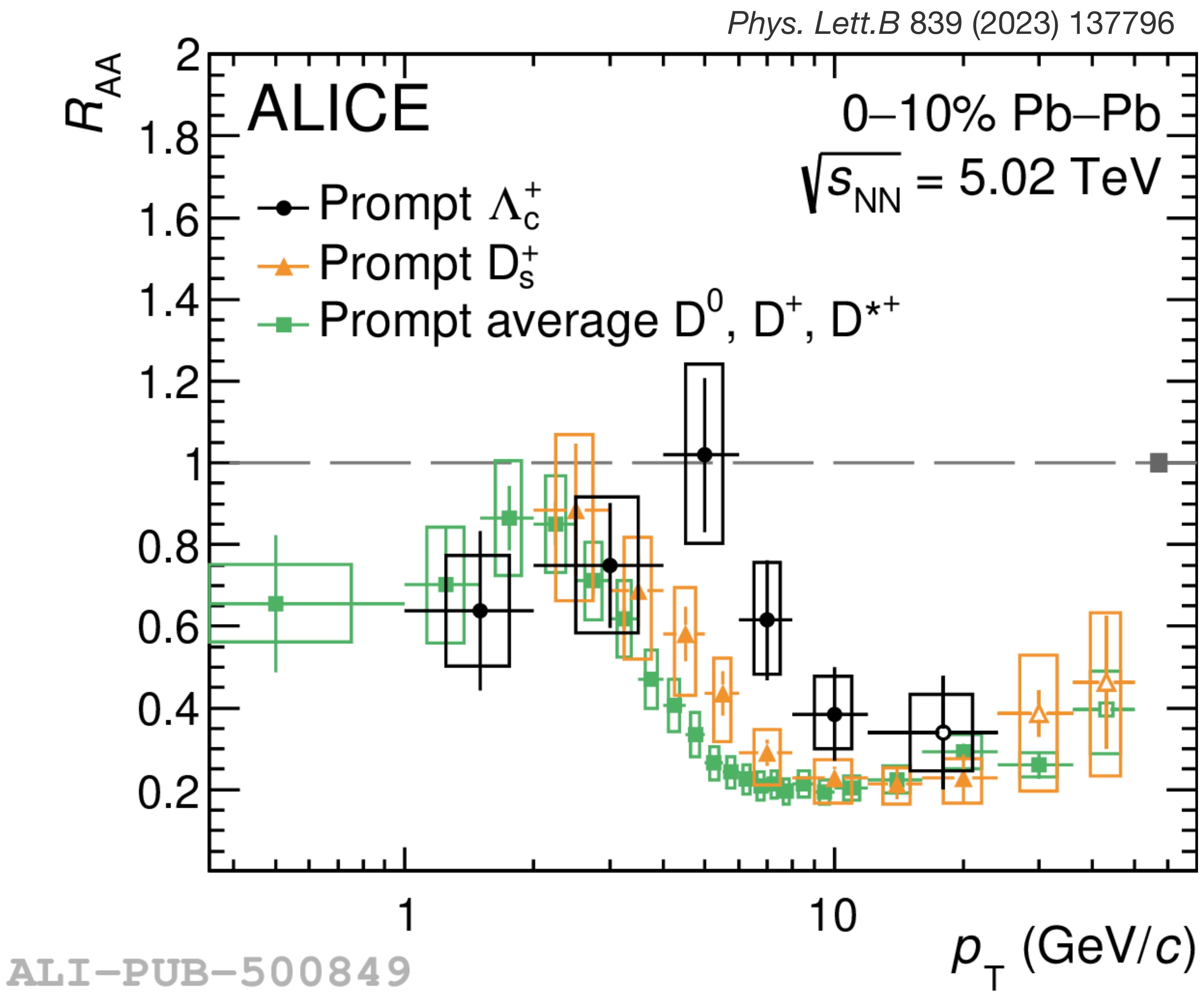
Estimate of spatial diffusion coefficient (related to the thermalisation time of charm quark) obtained considering the values used in transport models that reproduce the data:

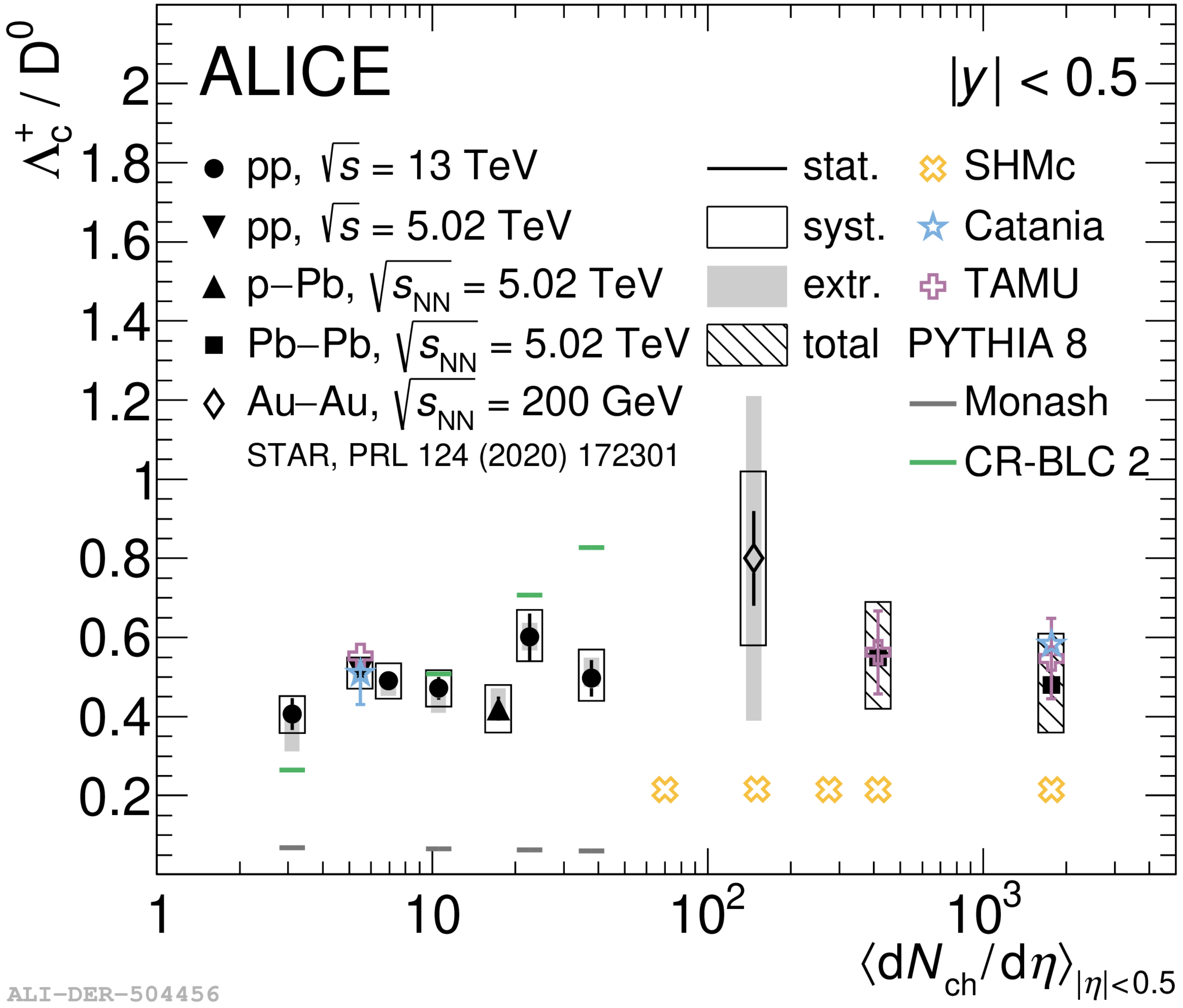
- **$1.5 < 2\pi D_s T_c < 4.5$** which correspond to a **$3 < \tau_{charm} < 9$ fm/c**

The thermalisation of charm quark happens within the QGP lifetime



Looking at open charm hadrochemestry





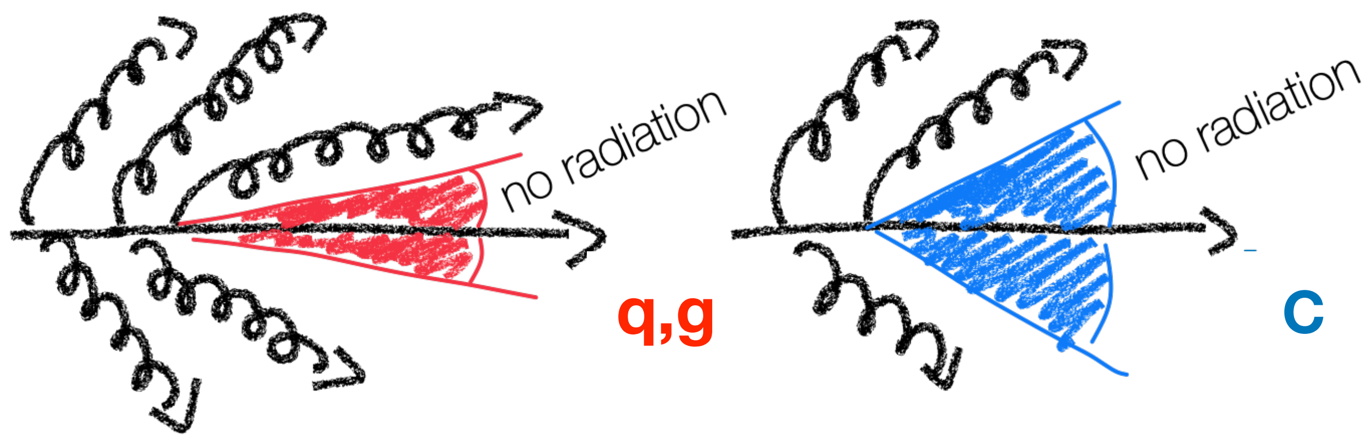
- Hint of **hadron-mass ordering** $R_{AA}(\Lambda_c^+) > R_{AA}(D_s^+) > R_{AA}(D)$ for 4 GeV/c < p_T < 10 GeV/c (recombination region)
- Indication of **flat p_T integrated Λ_c^+/D^0 ratio with event multiplicity**, from pp to Pb–Pb collisions

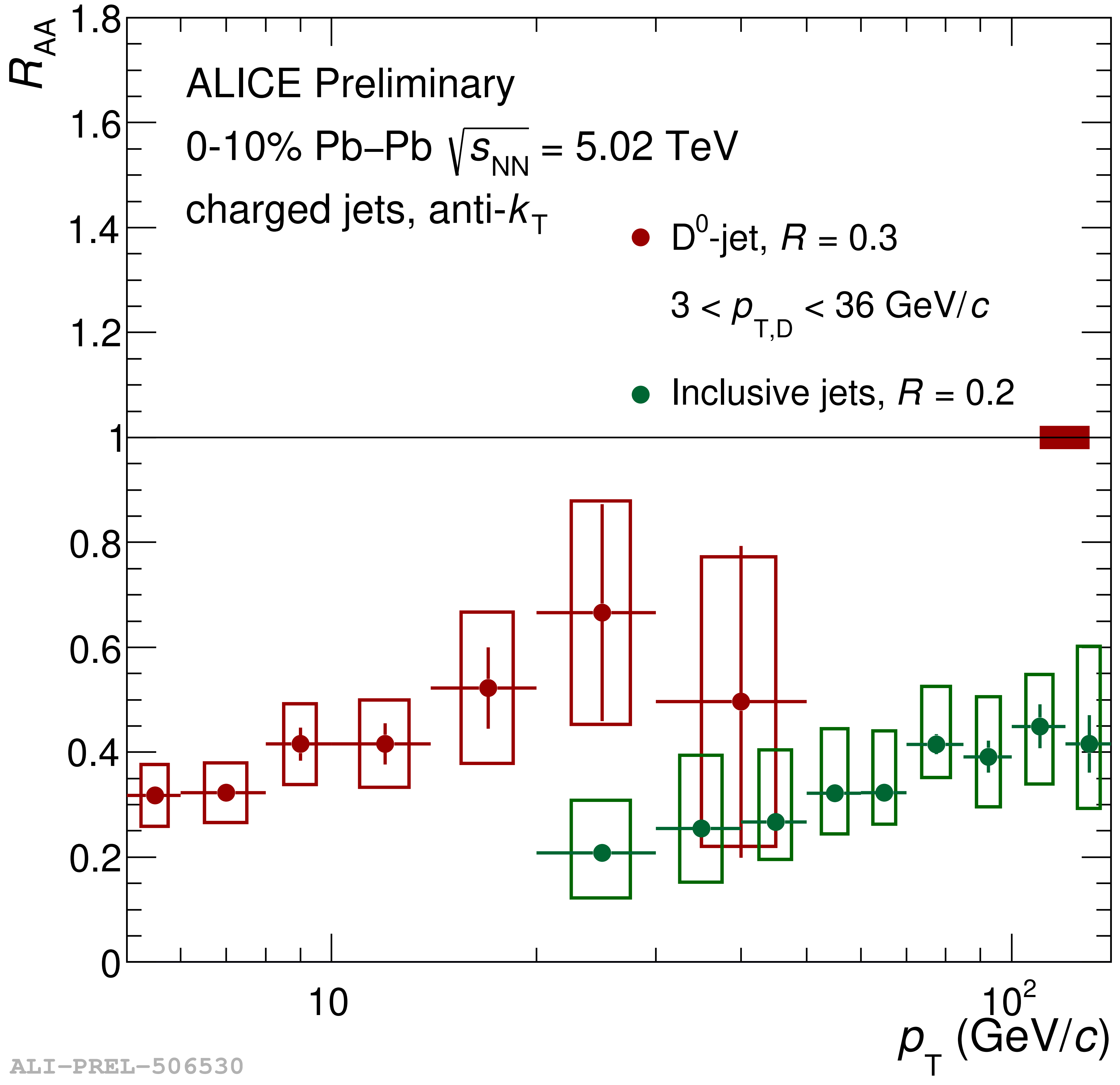
  $R_{AA}(\Lambda_c^+) > R_{AA}(D)$ at intermediate p_T from interplay between recombination and radial flow? —> different p_T redistribution between baryons and mesons?

Flavour dependence of energy loss

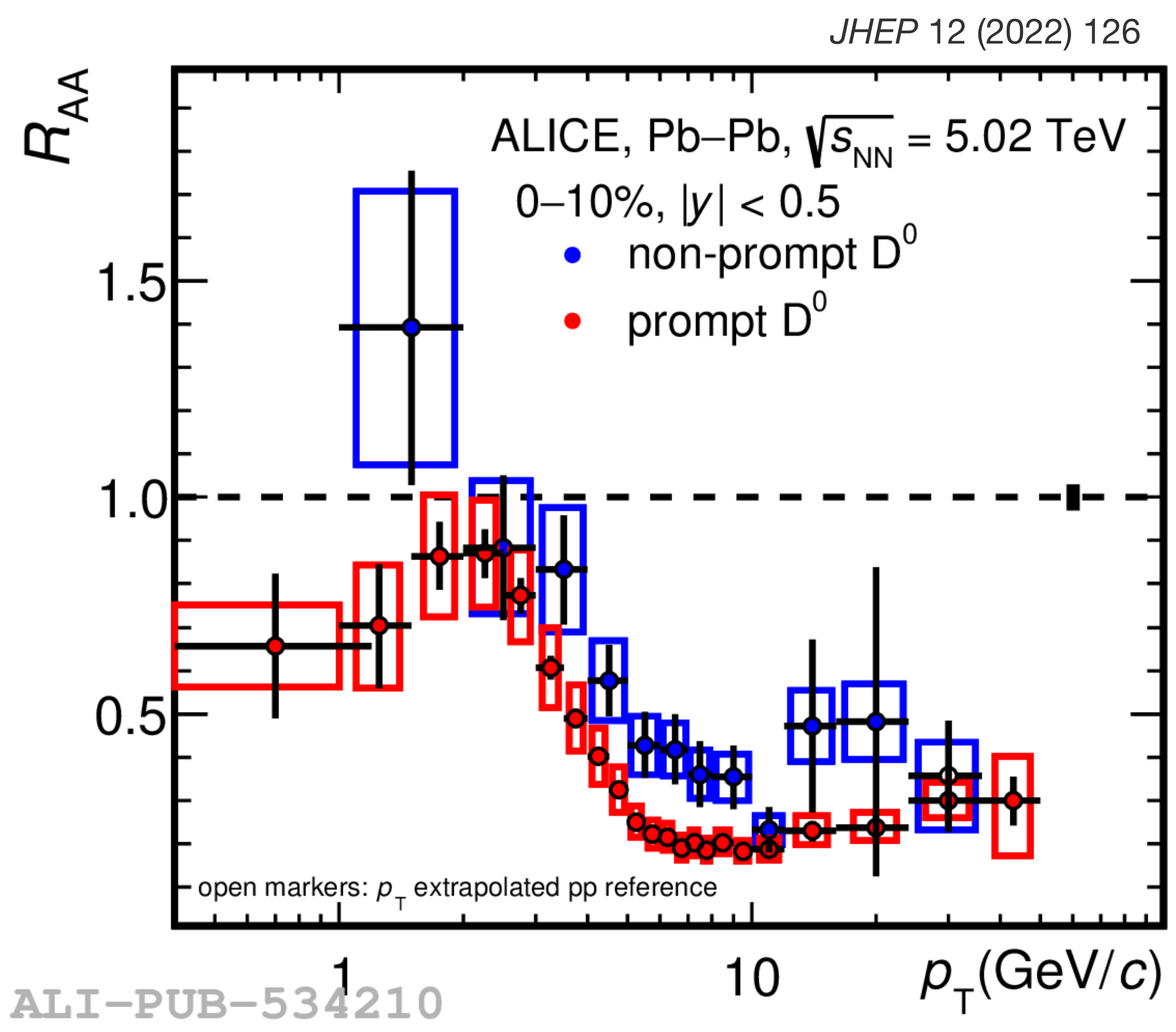
- **Heavy-flavour jets (tagged with D^0 mesons)**: more direct access to the initial parton kinematics
  - The 4-momentum of the jet is a **proxy** for the 4-momentum of the charm quark initiating the parton shower

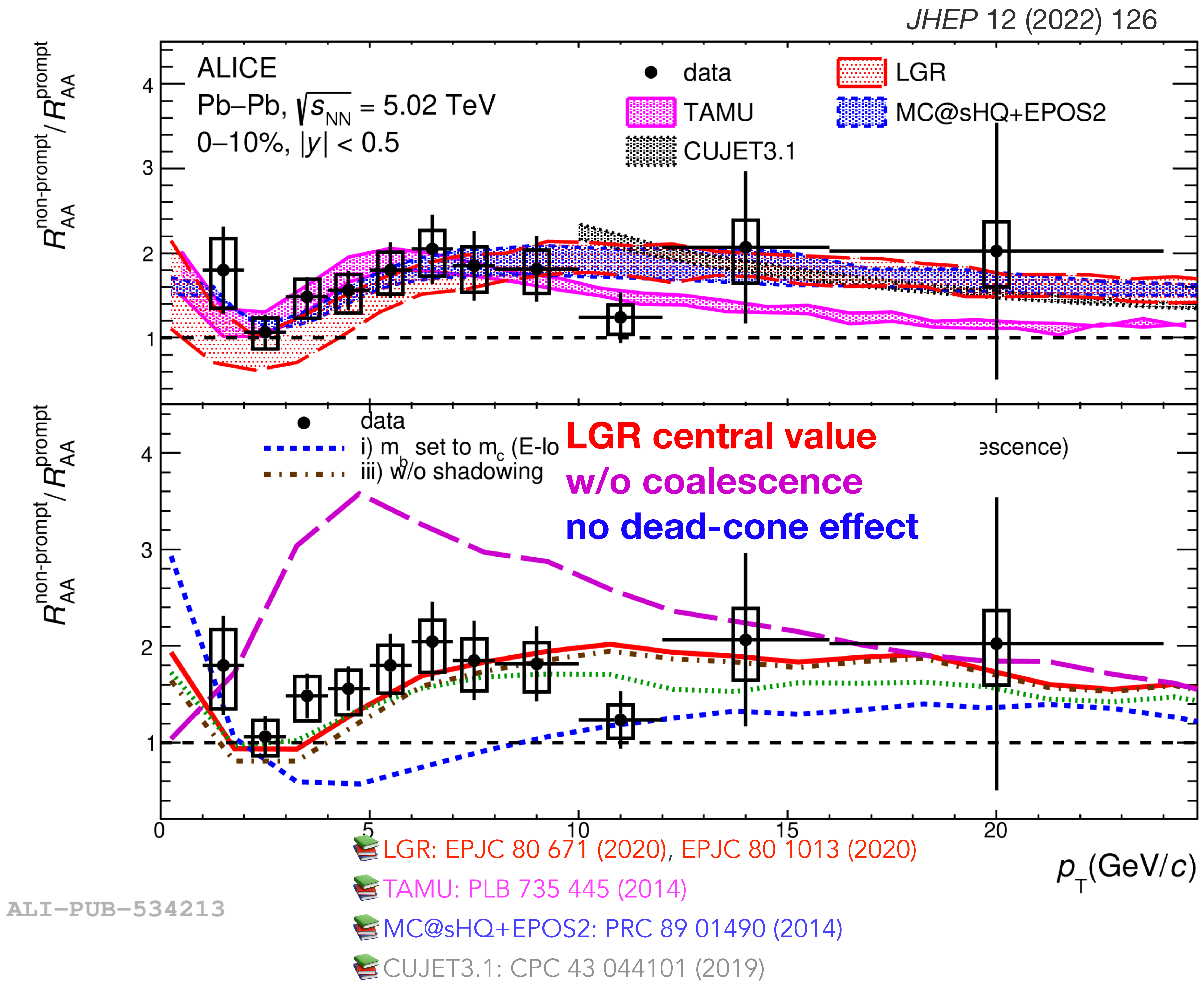
- **Higher R_{AA} of D^0-jet compared to inclusive jets in PbPb?**
  - Comparison is sensitive to:
    - difference between quarks and gluon energy loss (**Casimir colour effect**)
    - mass effects (**dead-cone effect**)





Flavour dependence of energy loss





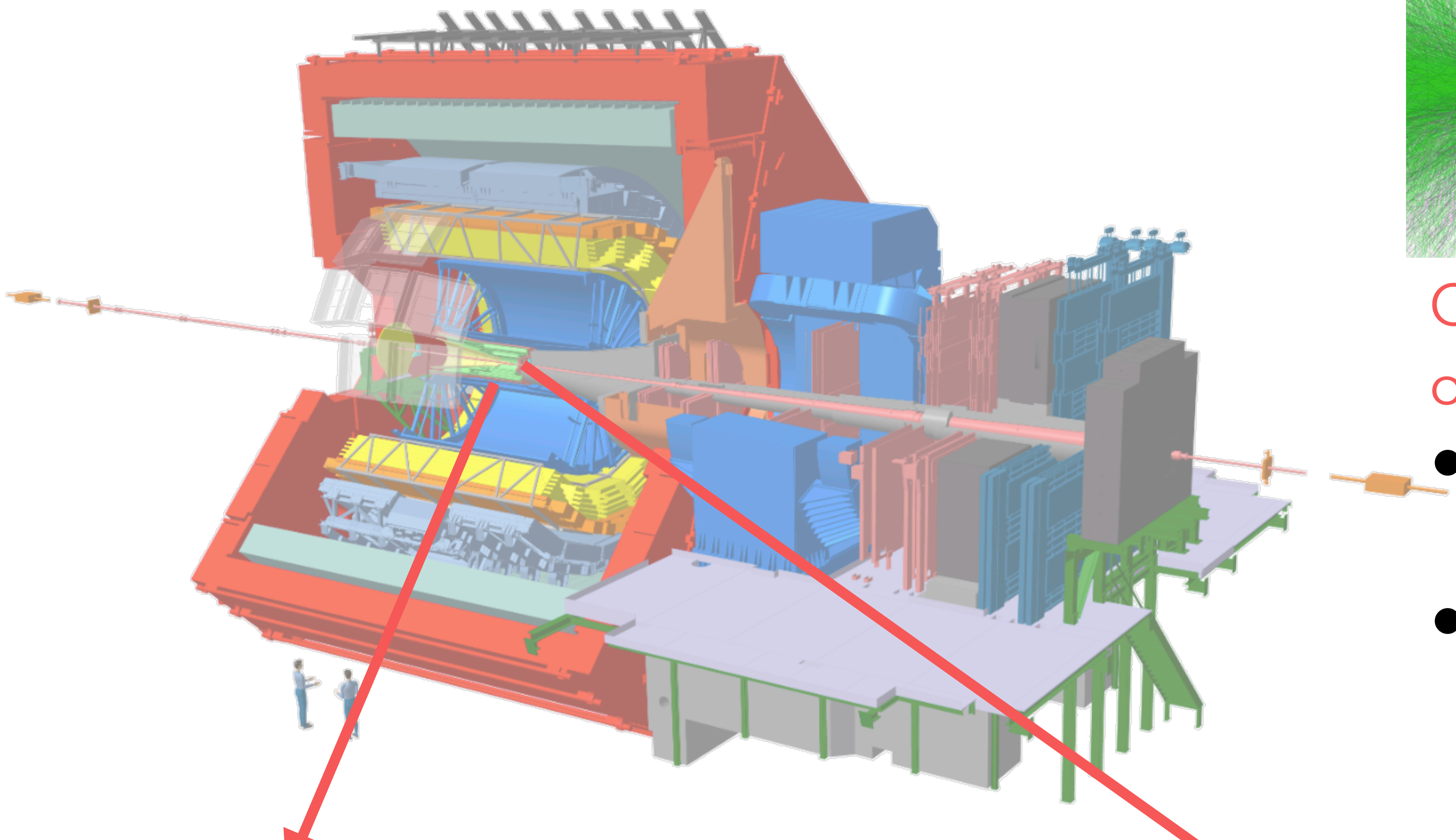
Hint of **R_{AA}(beauty hadron) > R_{AA}(charm hadron)** at low and intermediate p_T

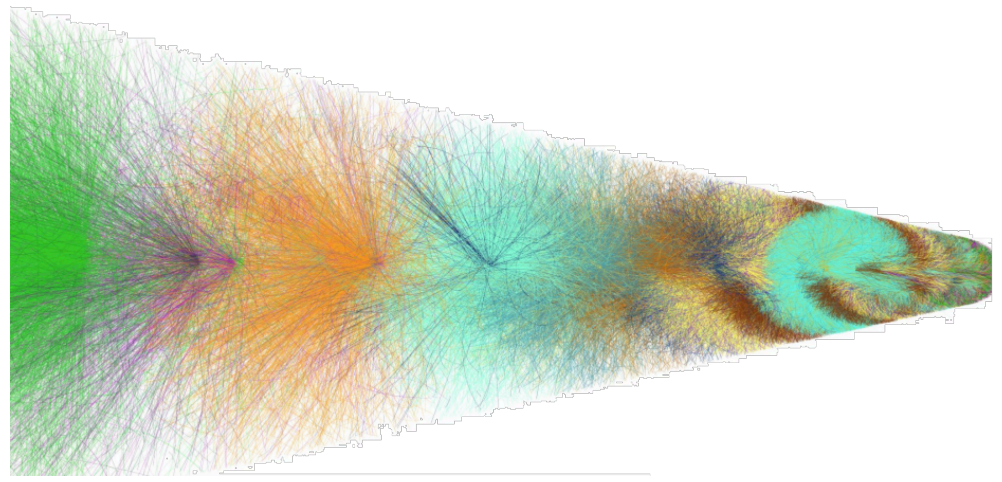
- Different shadowing or hadronisation via recombination
- Mass dependence of in-medium energy loss —> $\Delta E_b < \Delta E_c$

Further insights testing different **LGR model** configuration (**radiative+collisional** energy loss, hadronisation via **fragmentation+coalescence**)

- **Prompt-D⁰ formation via coalescence** explains the minimum (2-3 GeV/c)
- Ratio closer to unity if using charm mass for *b* quarks for *E*-loss calculation
  —> **Relevant role of dead-cone effect**

ALICE detector in Run 3

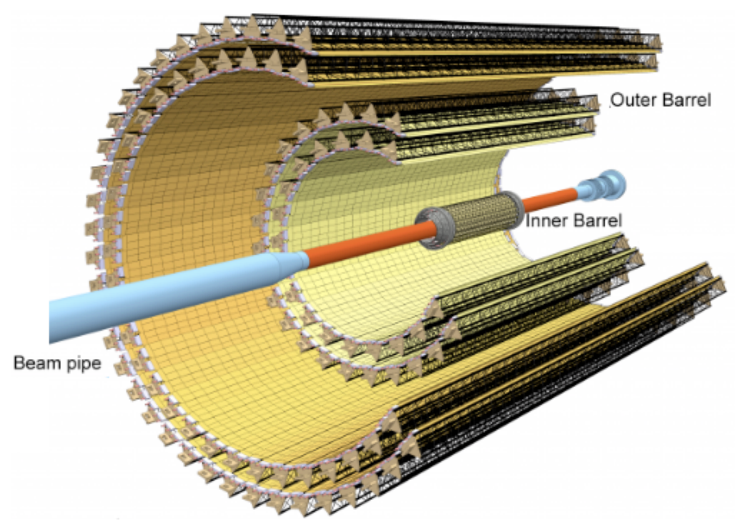




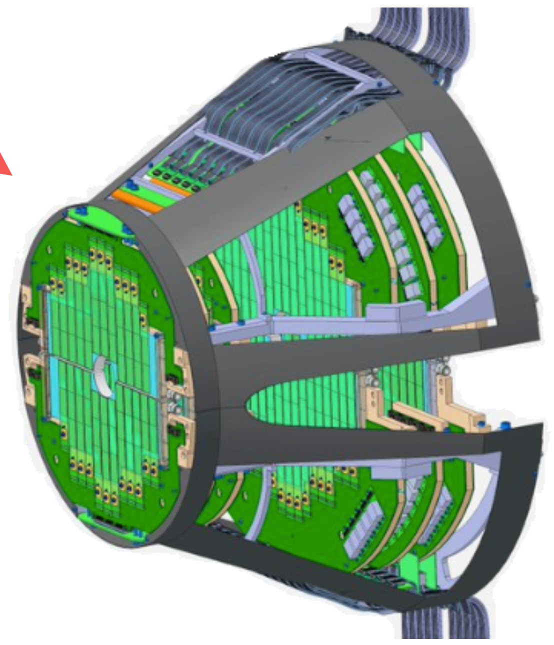
Continuous readout (instead of triggered events)

- ~500 kHz interactions at pp data taking
- will operate at 50 kHz during Pb-Pb run

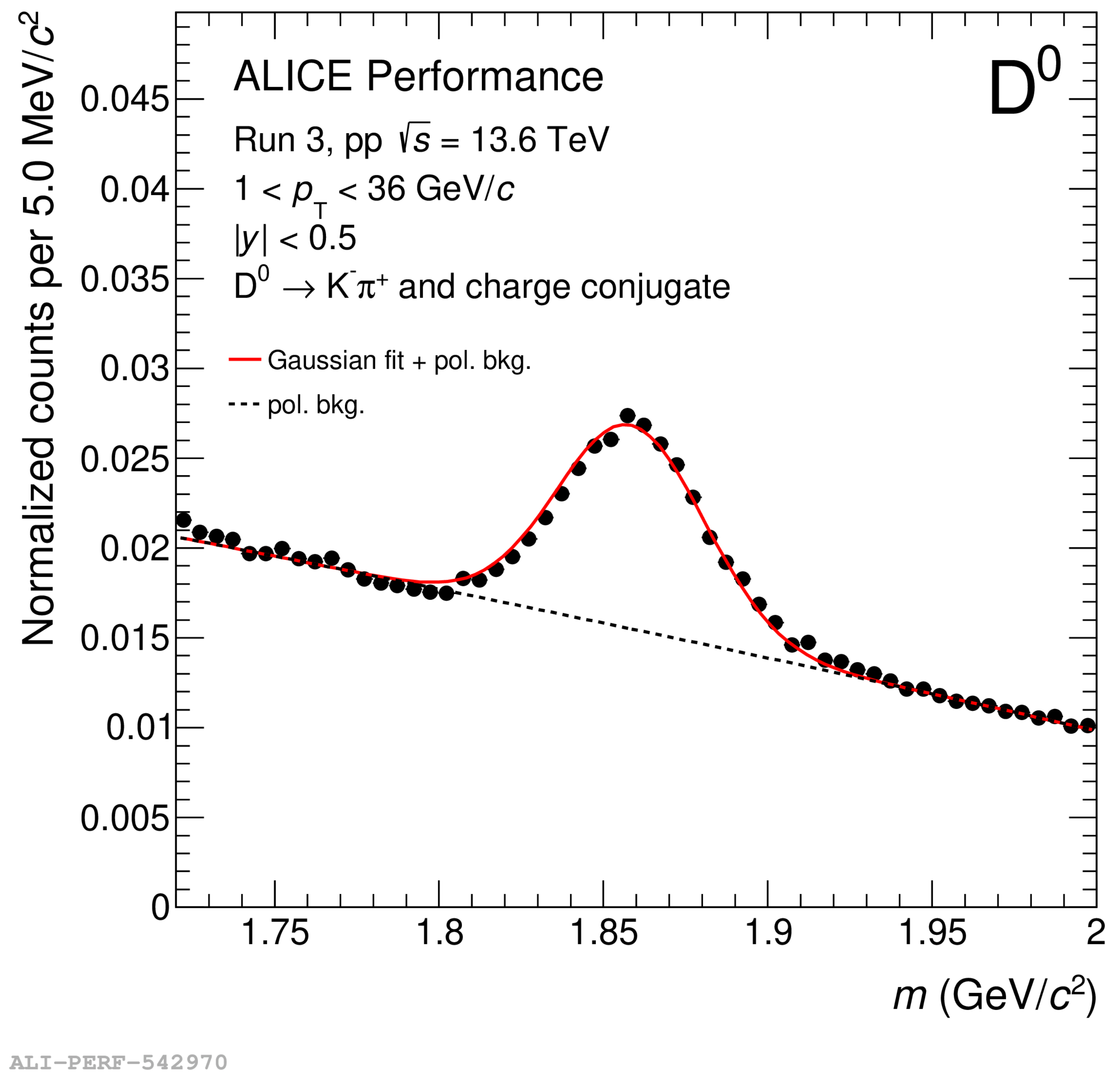
- Operation at much higher interaction rate
- Improved vertexing (central and forward) and tracking resolution at low p_T



New Inner Tracking System (ITS2)
7 layers, 10 m² silicon tracker based on MAPS (12 G pixels)



New Muon Forward Tracker (MFT)
5 planes of MAPS forward vertexing for muons



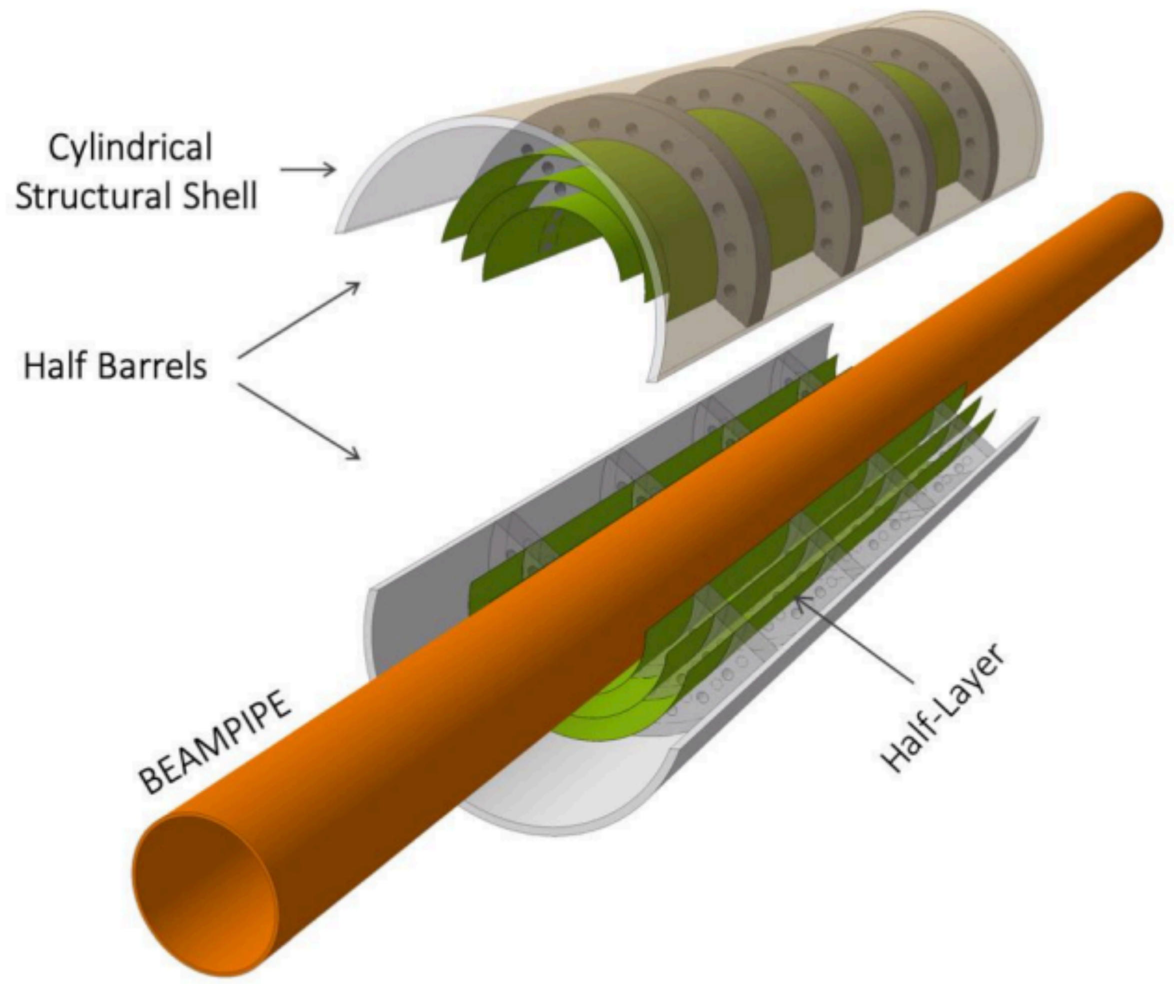
Good reconstruction performance with the latest calibrations

ALICE 2.1 (Run 4): ITS 3

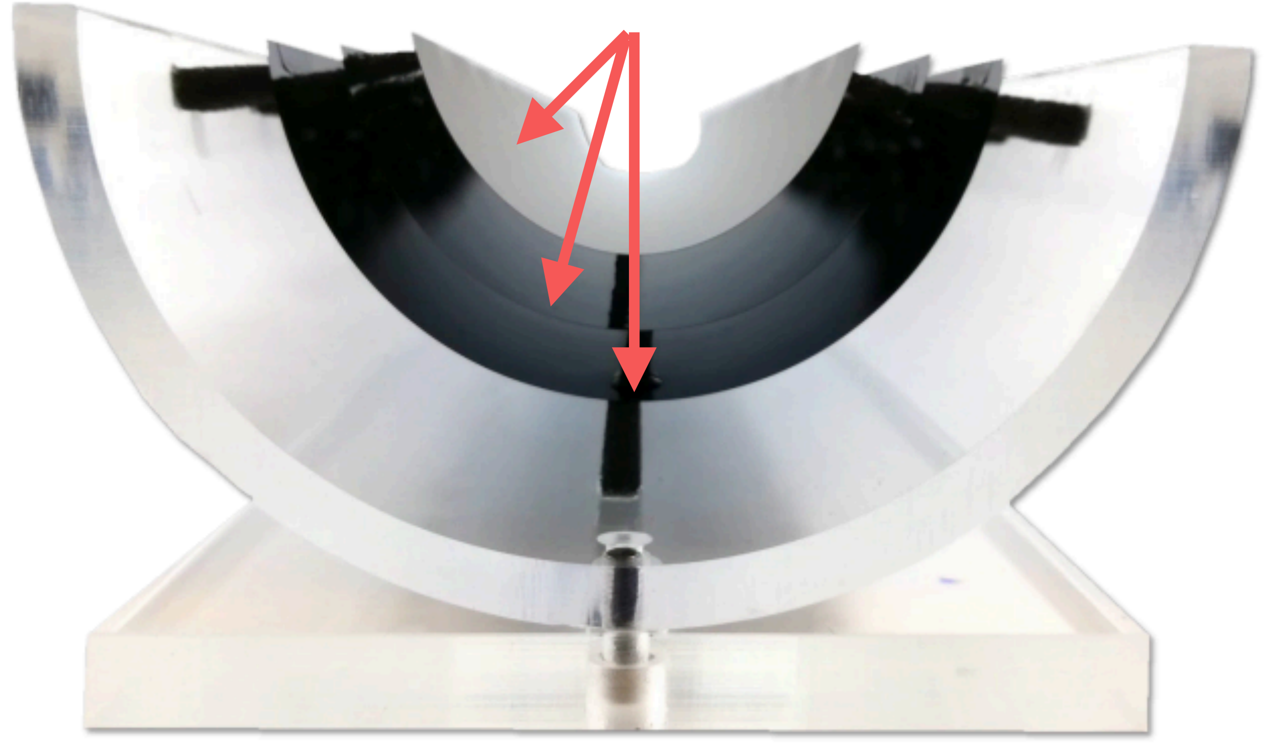
A next-generation vertex detector will replace the inner barrel of ITS 2:

ultra-light, truly cylindrical layers made of wafer scale 65 nm MAPS

- Improved DCA resolution ($\propto r_0 \cdot \sqrt{x/X_0}$)
    - reduced material budget: X/X_0 from 0.35% to 0.15%
    - innermost layer from 22 mm to 18 mm (closer radial distance to beam pipe)
    - thinner and smaller beam pipe (from 700 µm to 500 µm and from 18 mm to 16 mm)

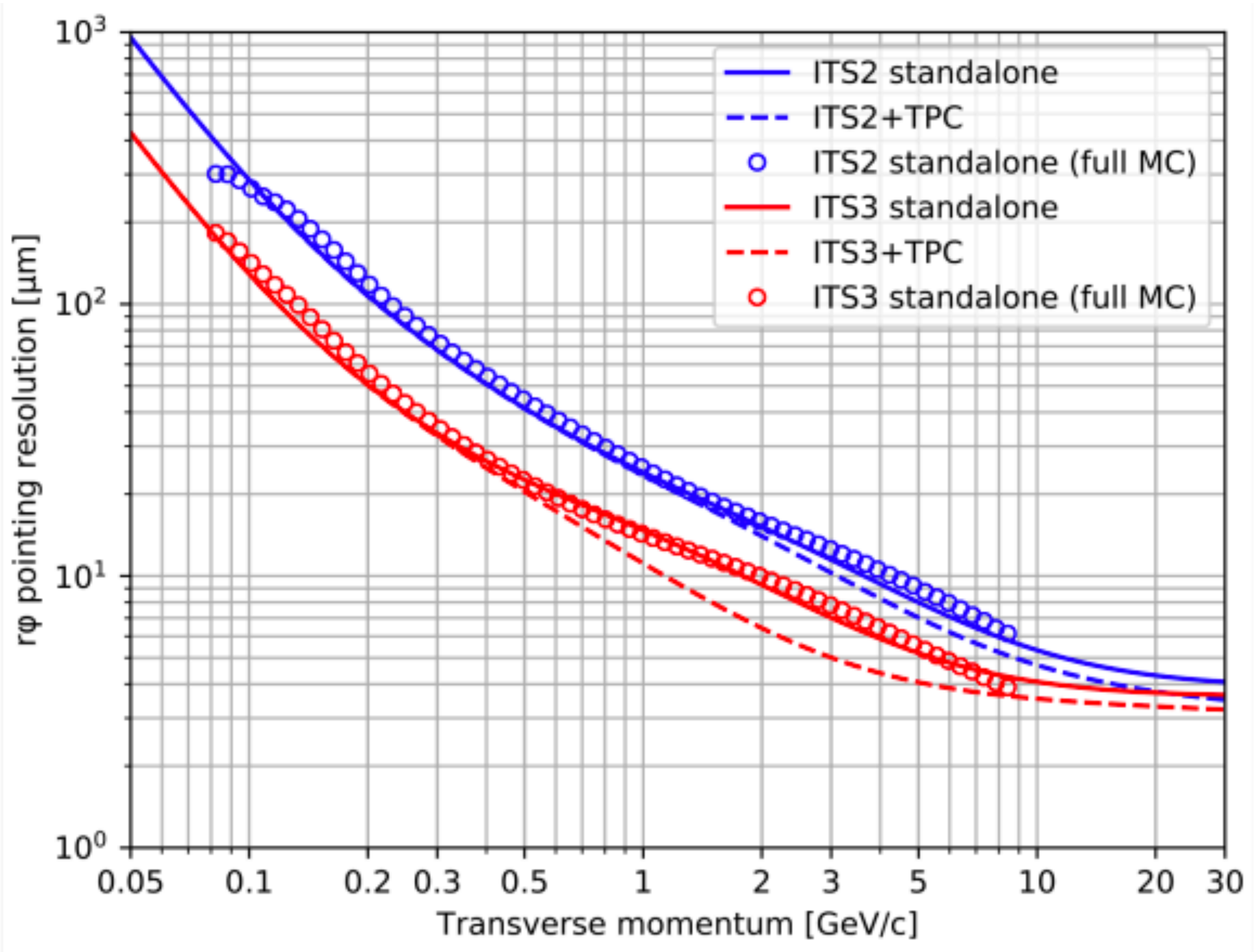


R=18, 24, 30 mm
(beam pipe: 16 mm)



From 432 to 6 bent sensors

Letter of Intent: CERN-LHCC-2019-018



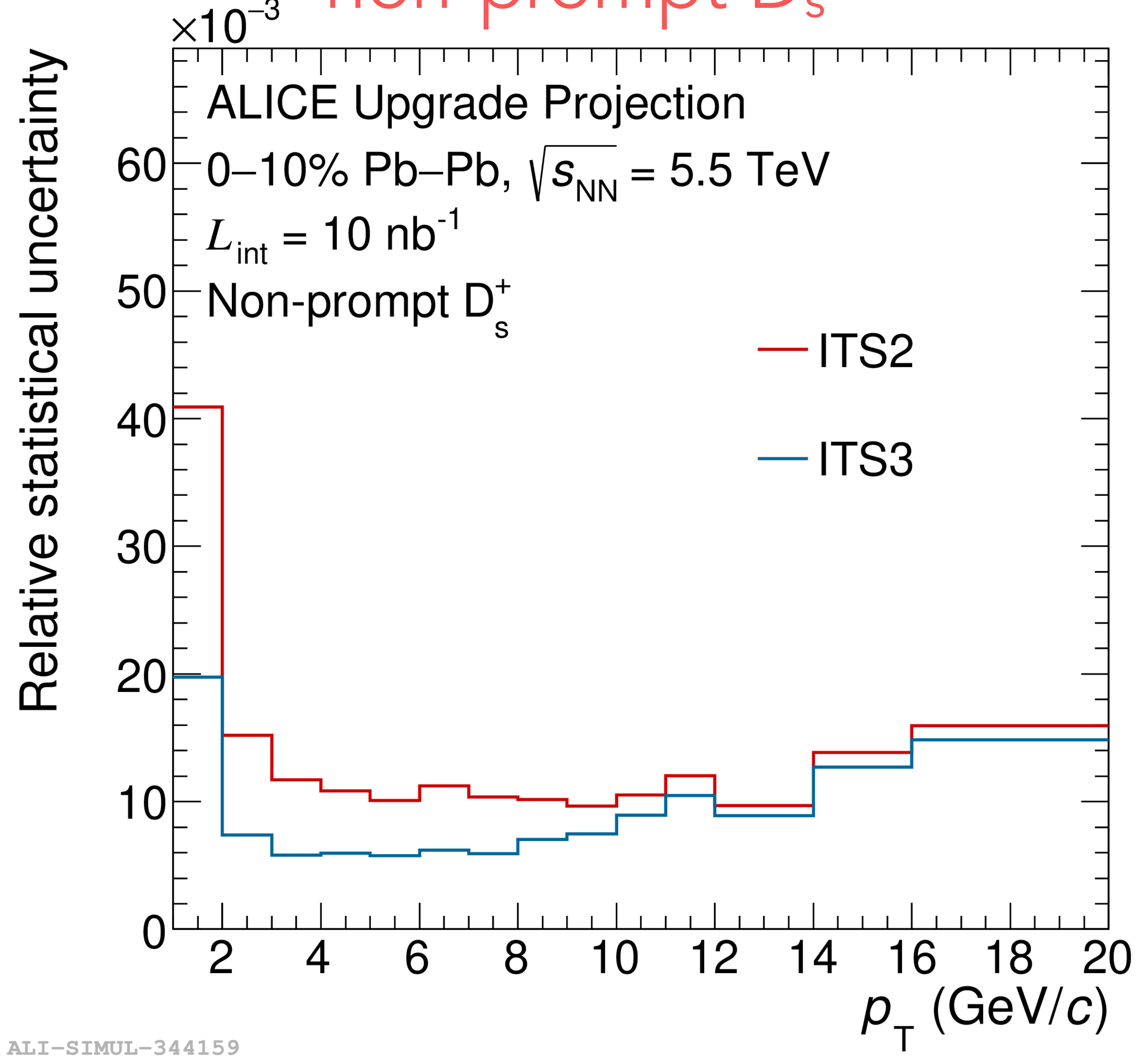
DCA resolution improves of a factor 2 w.r.t. ITS 2

ALICE 2.1 (Run 4): ITS 3

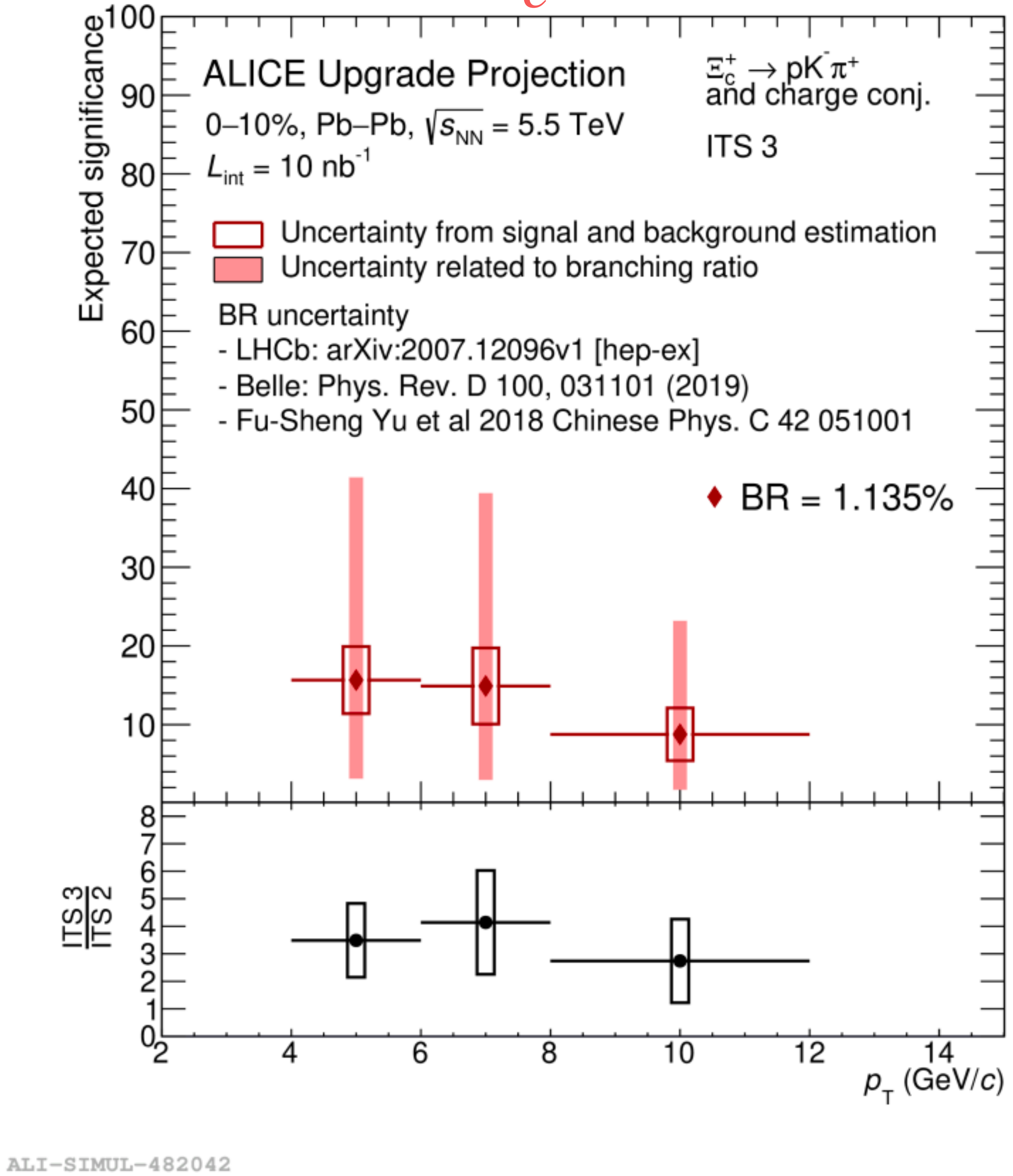
Heavy flavour measurements will strongly benefit from ITS 3 upgrade

- better significance for heavy flavour hadrons w.r.t ITS 2 (factor ~4 for Ξ_c^+ and larger than factor ~2 for Λ_b)
- relative statistical uncertainties improve by ~2 at low p_T for non prompt Ds

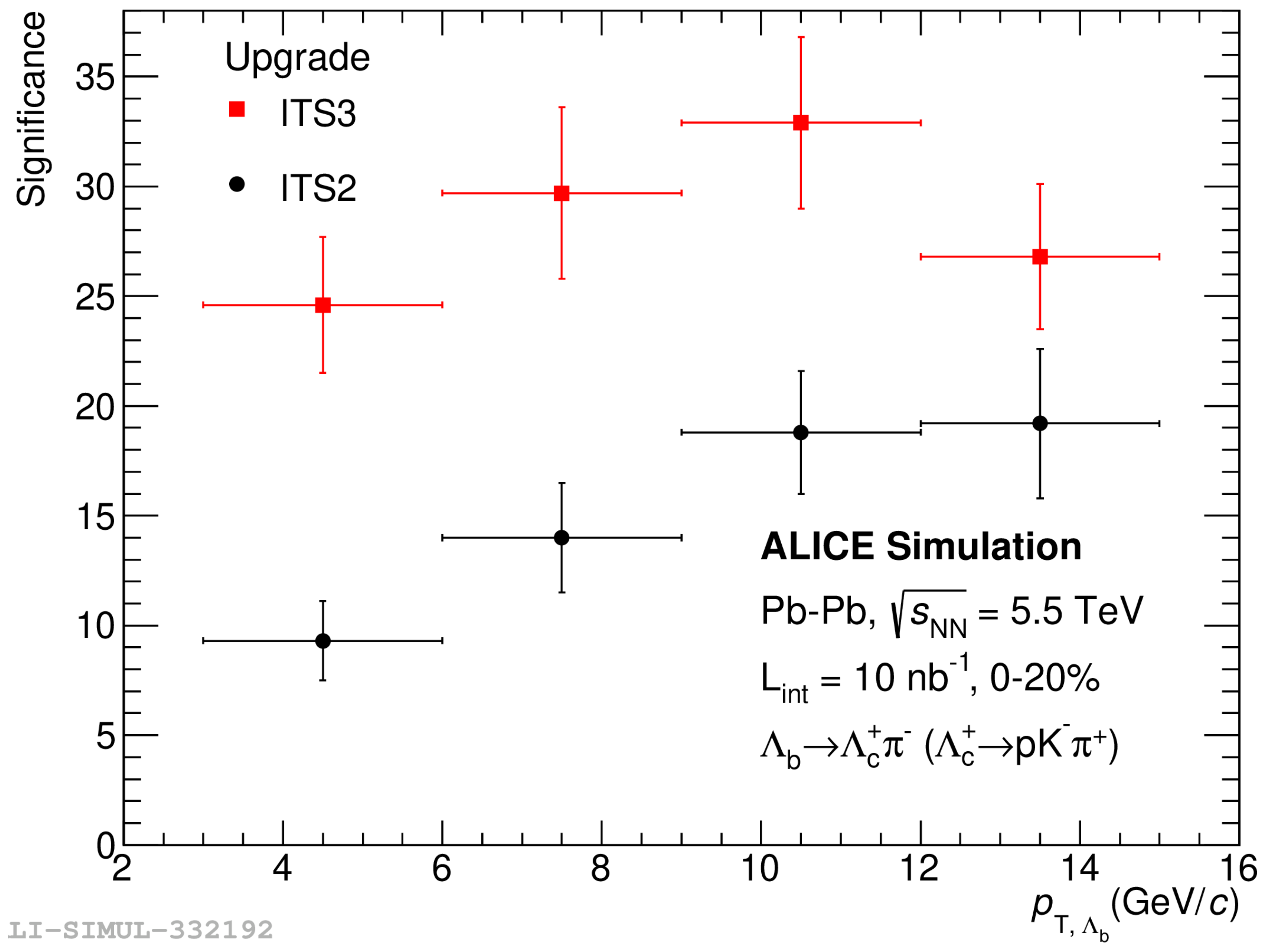
non-prompt D_s



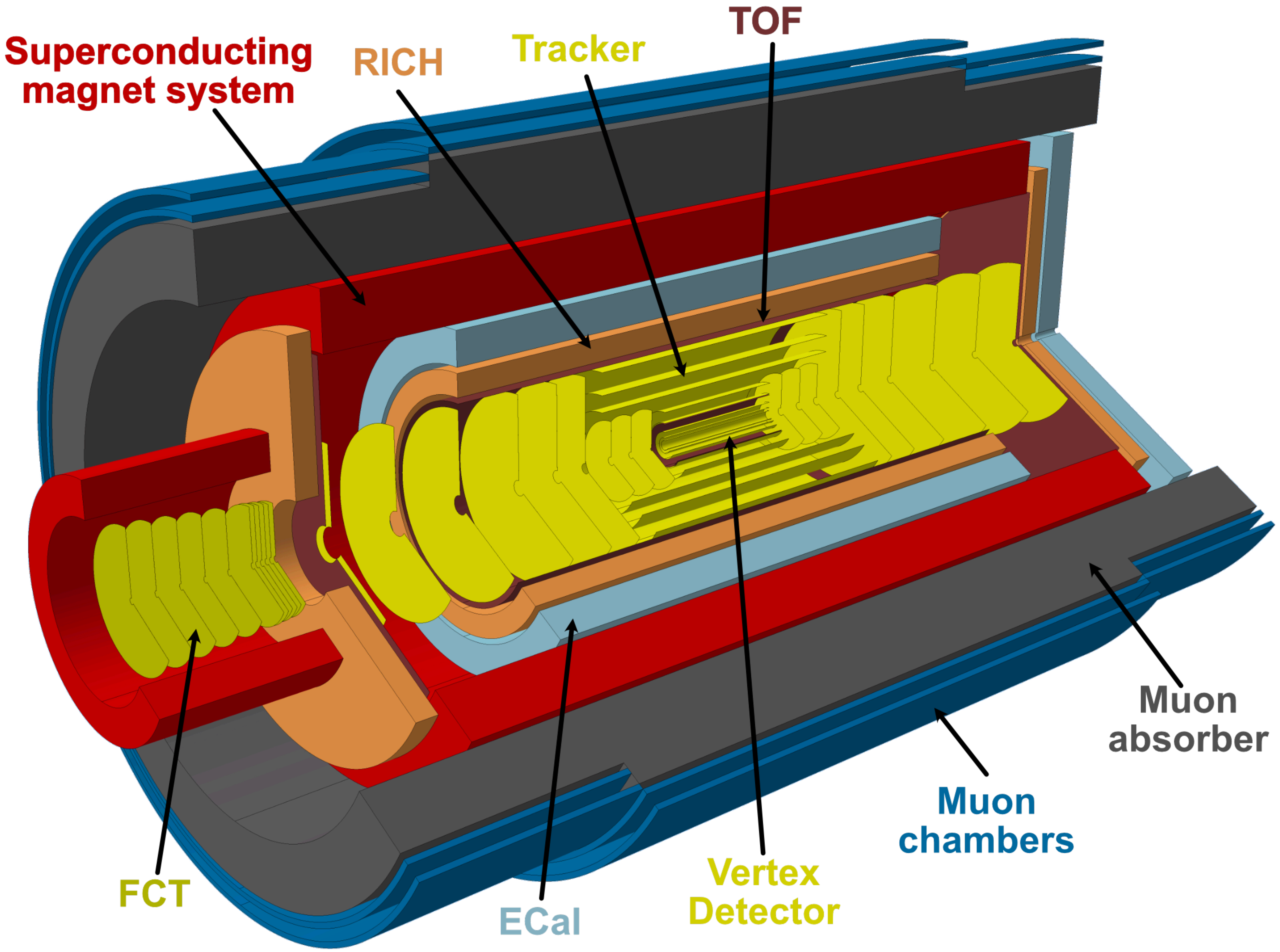
Ξ_c^+



Λ_b



ALICE 3: a next generation detector for the 2030s



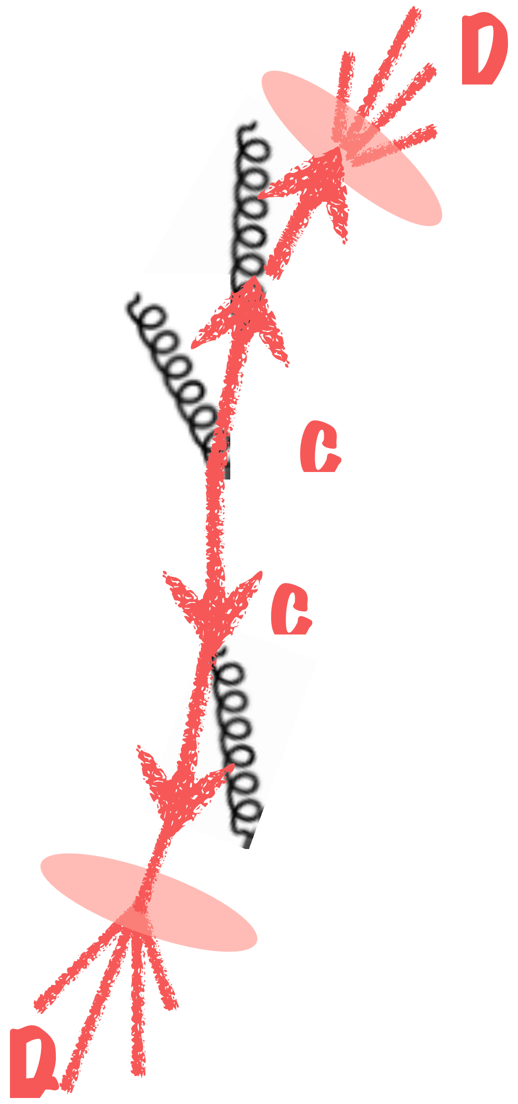
- **Fully silicon, large acceptance, low p_T tracker**
  - High rate: 5x bigger luminosity, exploit LHC
  - Momentum resolution of σ_{p_T}/p_T ~ 1-2%
  - 10% X_0 overall material budget
- **State-of-the-art particle identification**
  - Silicon based TOF and RICH
  - Muon identification
- **Very high vertexing precision**
  - First layer at 5 mm from the interaction point
  - Impact parameter resolution
    - ~10 μm at p_T~ 200 MeV/c
    - ~3 μm at p_T > 1 GeV/c

Enables a rich physics programme —> Few highlights

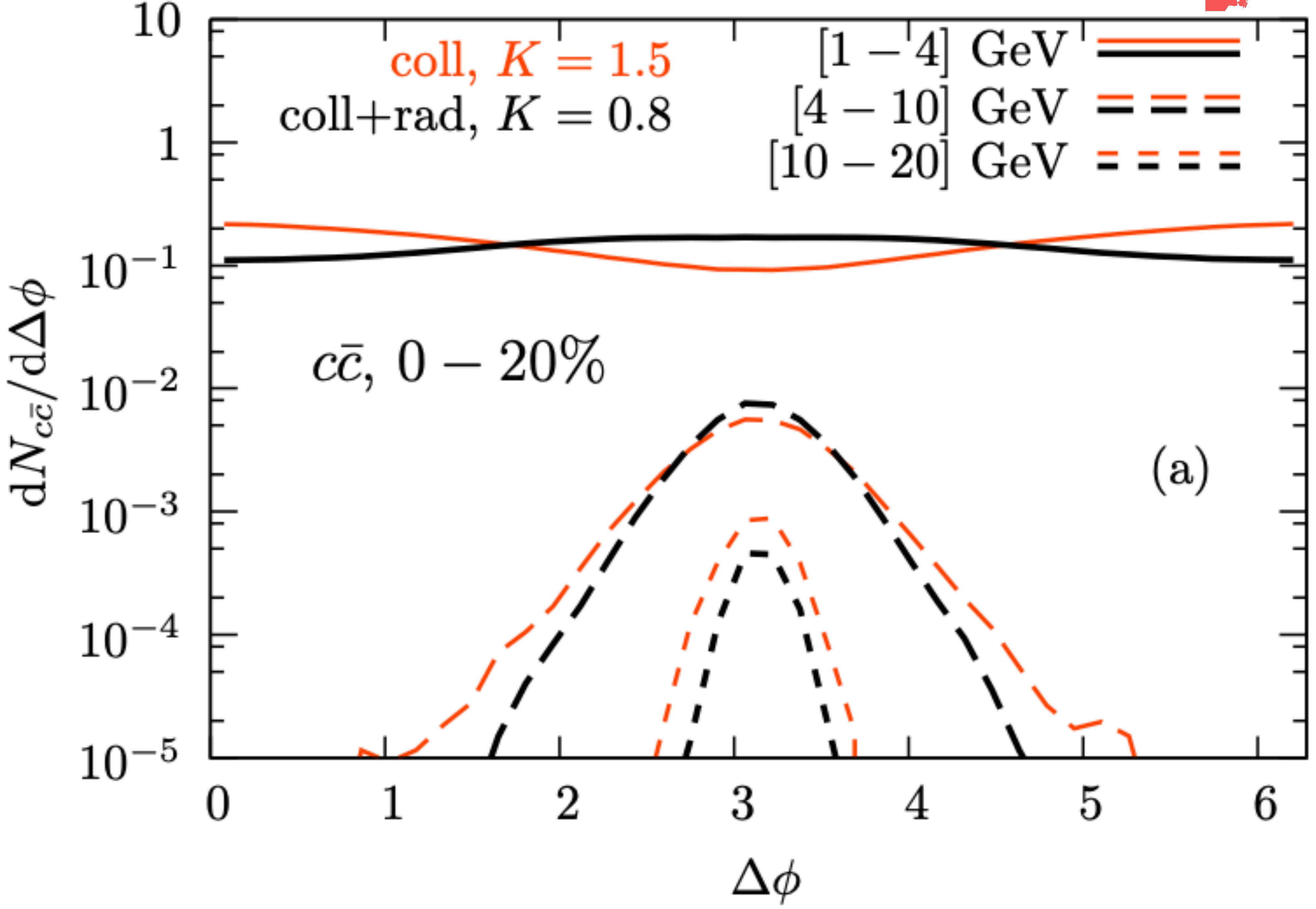
Direct measurement of cc (de-)correlation in the medium

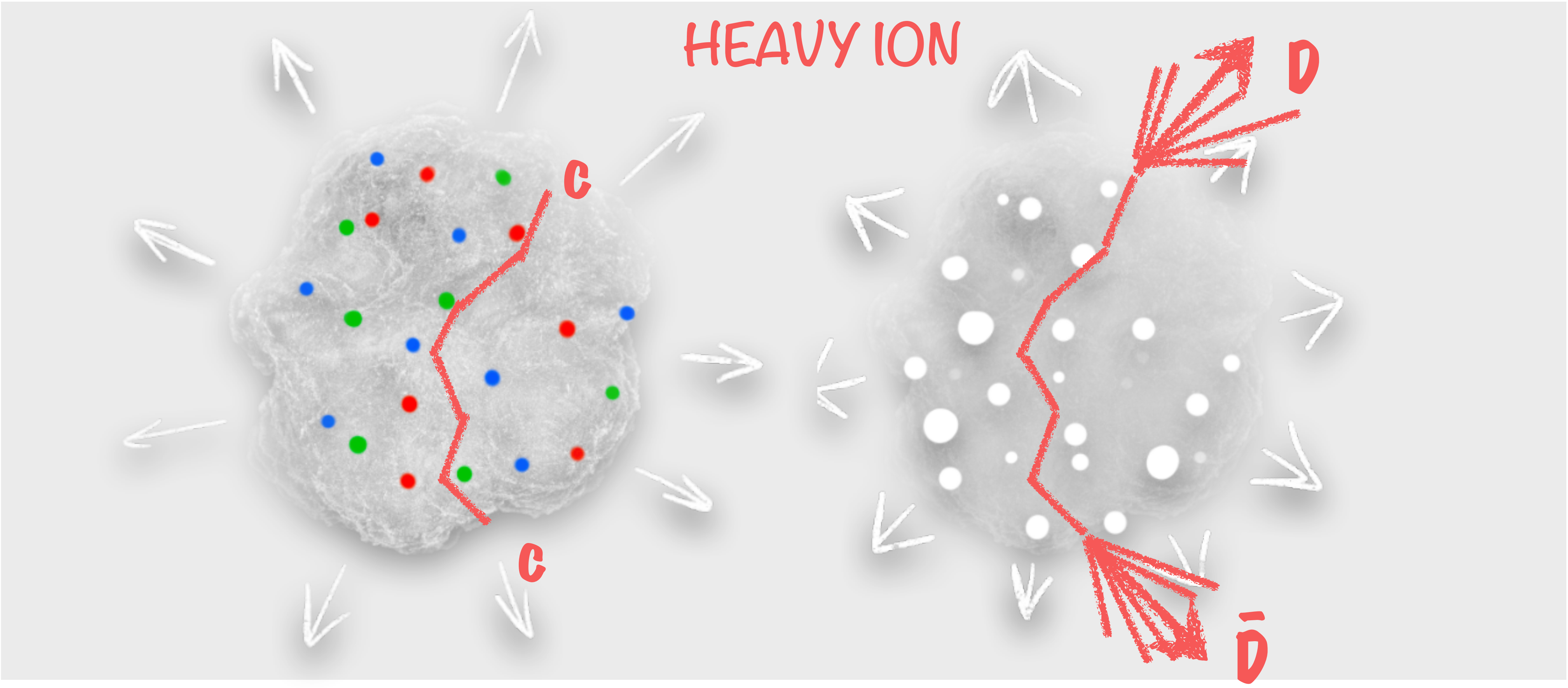
Angular correlations of $D\bar{D}$ directly probe $c\bar{c}$ pair decorrelation (degree of thermalisation) and energy loss

- Brownian motion of charm in the QGP
- Collisional vs radiative energy losses
- Signal strongest at low p_{T}



Phys. Rev. C 90, (2014) 024907





In Pb-Pb: scatterings in the deconfined medium can decorrelate the pairs

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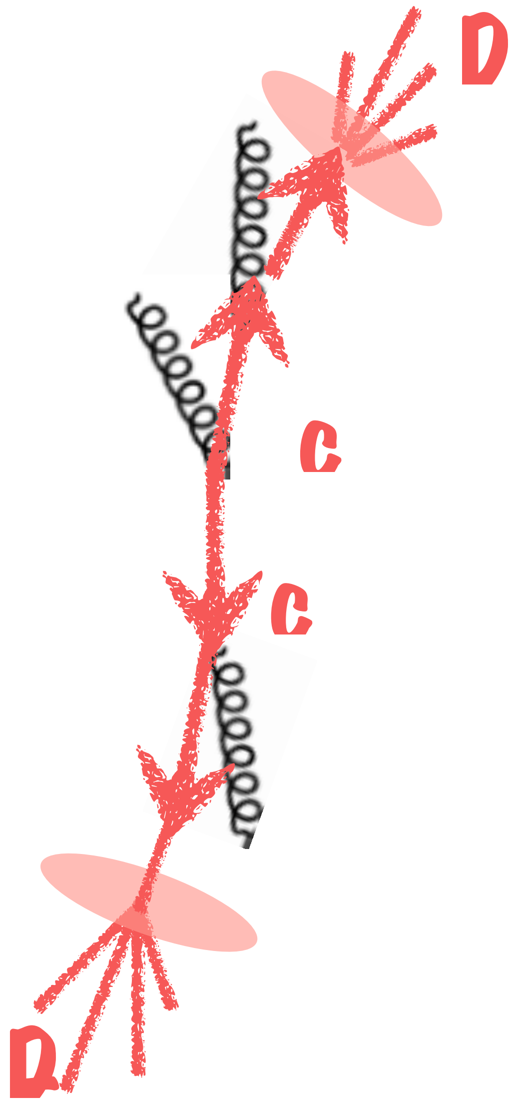
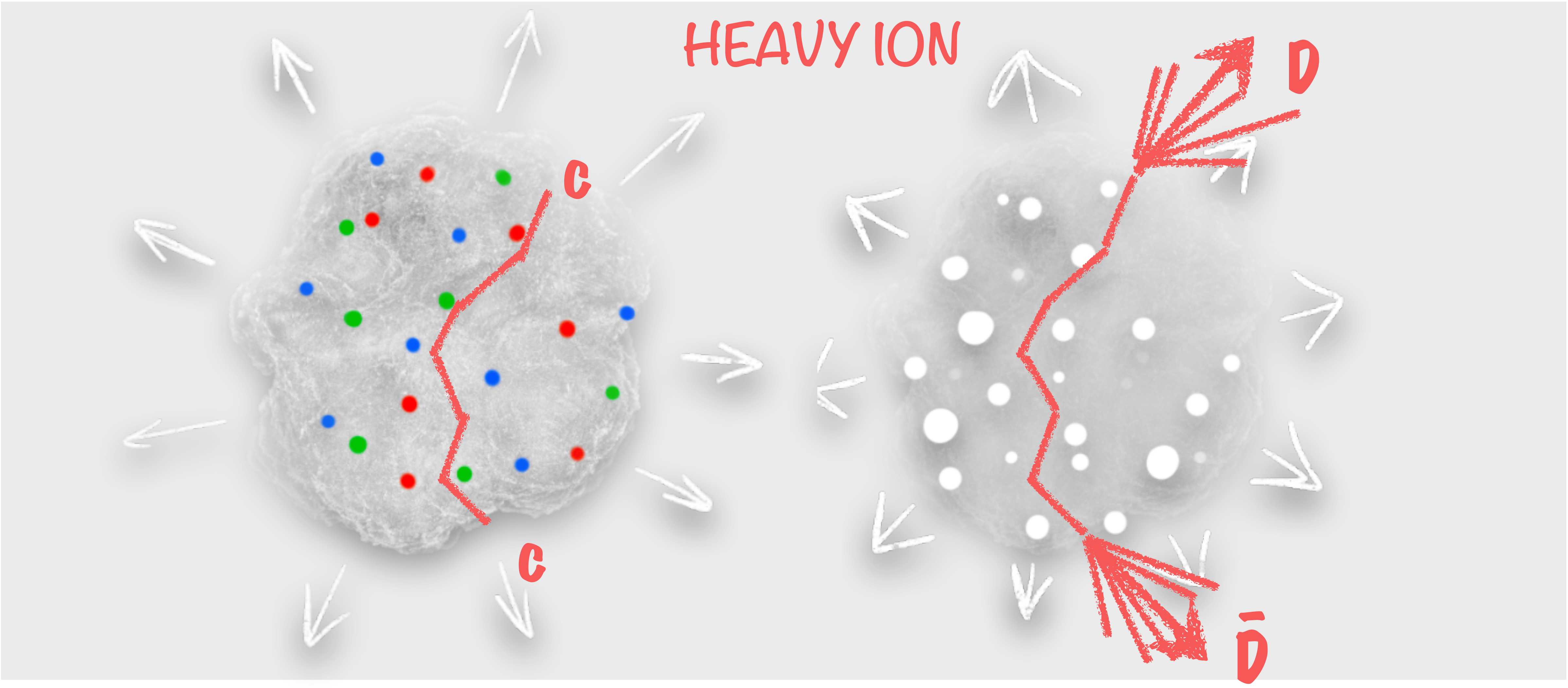
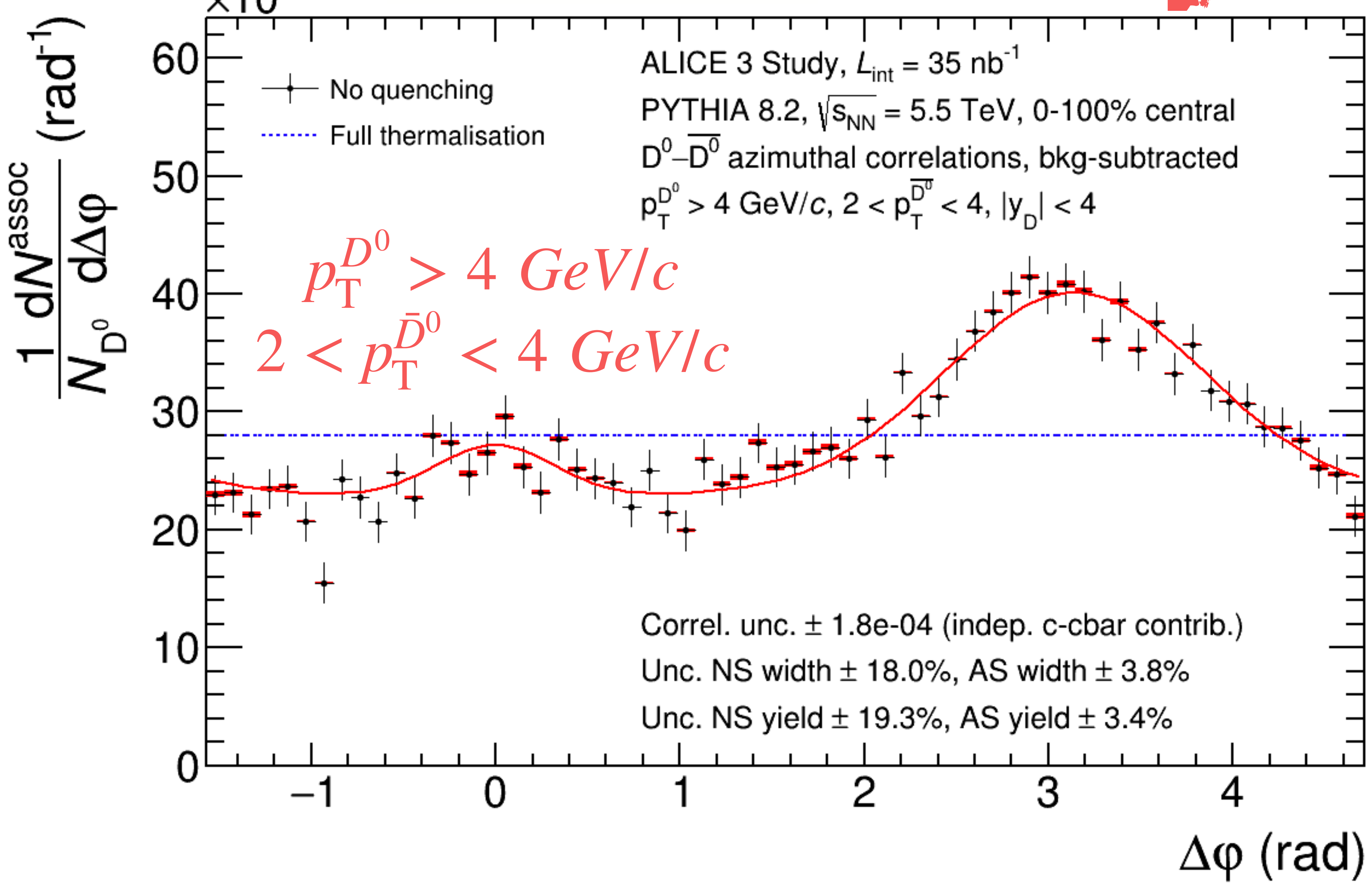




In Pb-Pb: scatterings in the deconfined medium can decorrelate the pairs

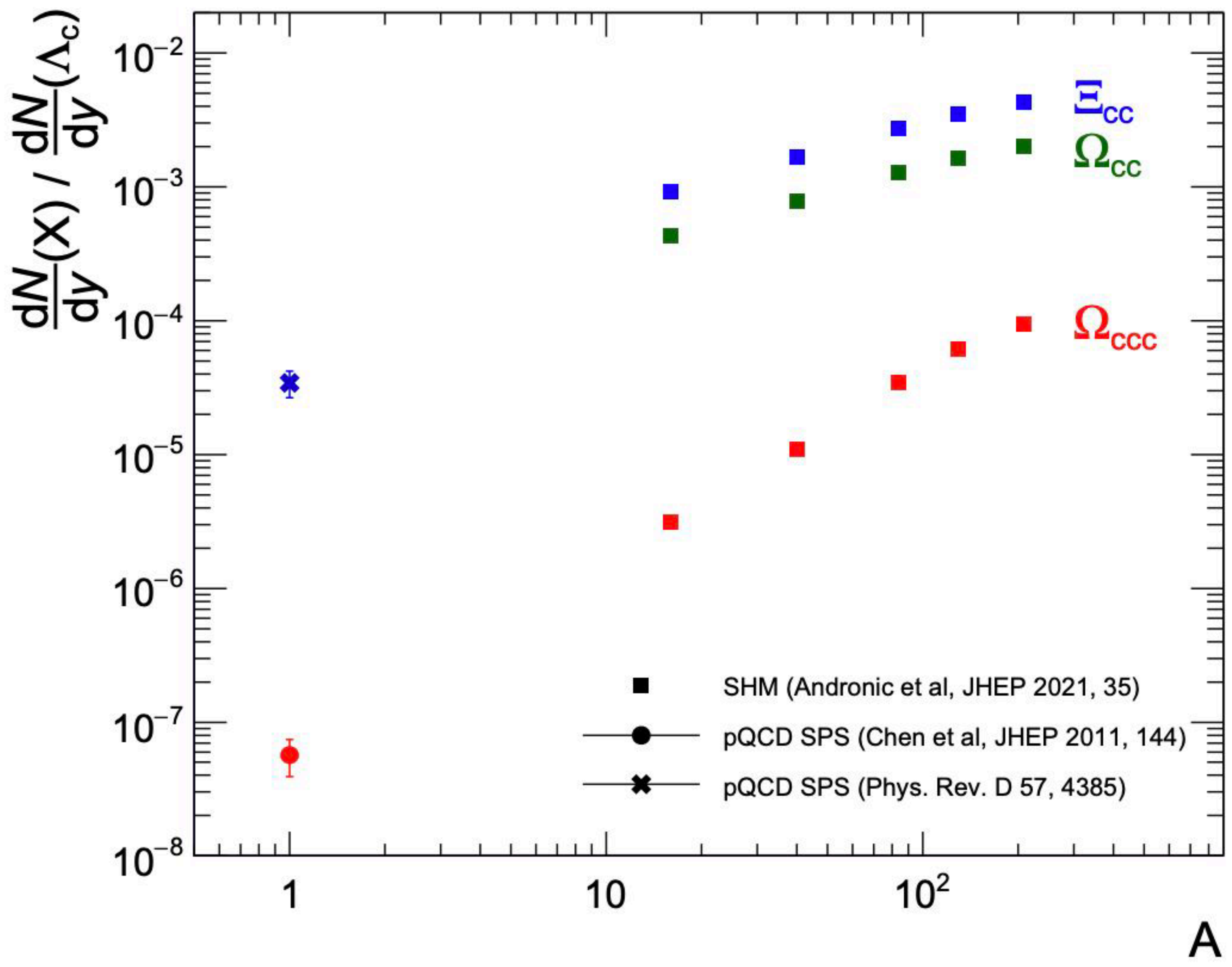
📚 CERN-LHCC-2022-009



Very challenging measurement:

- Need good purity, efficiency and η coverage
- Heavy-ion measurement only possible with ALICE 3

Multi-charm thermalisation



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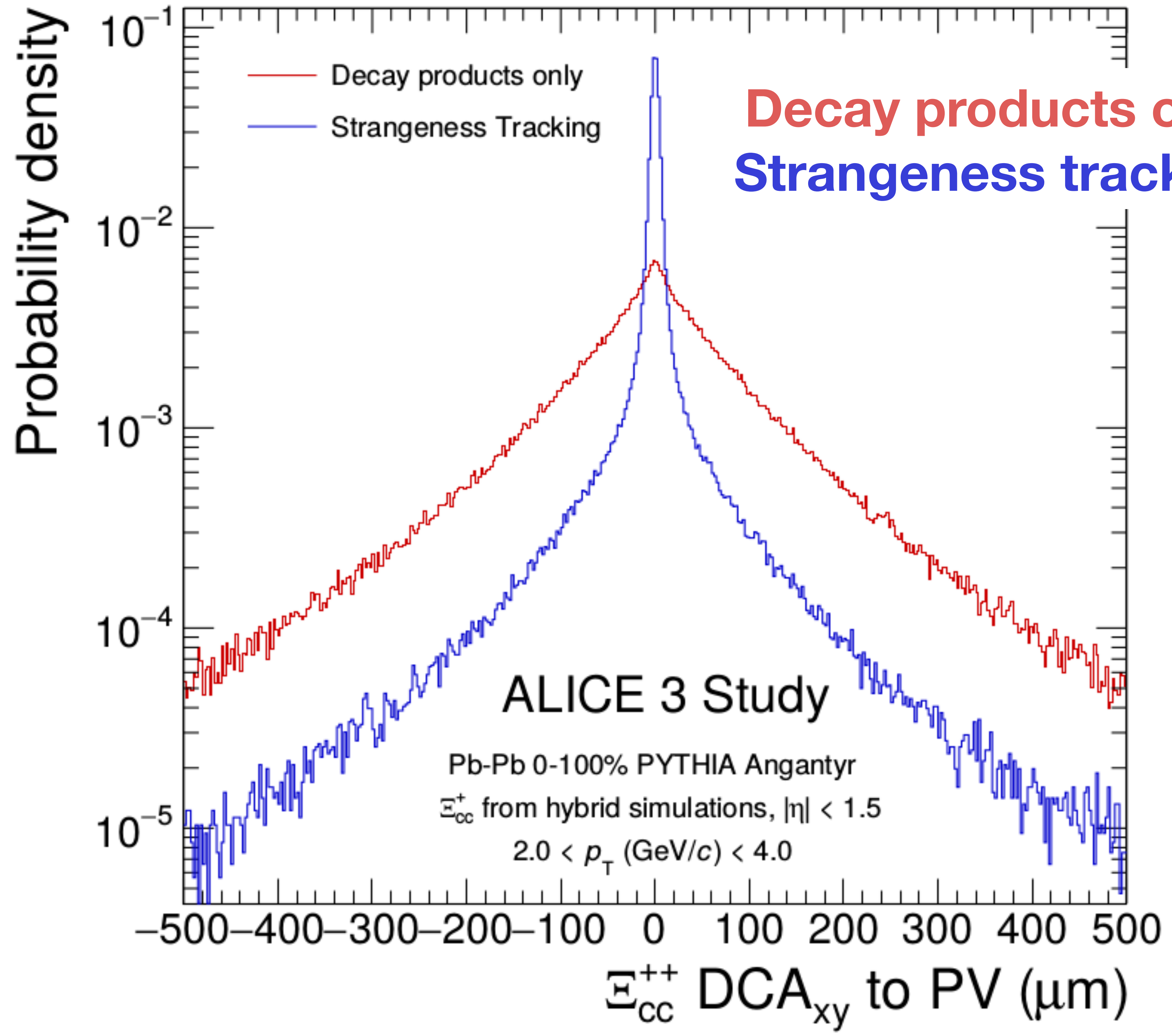
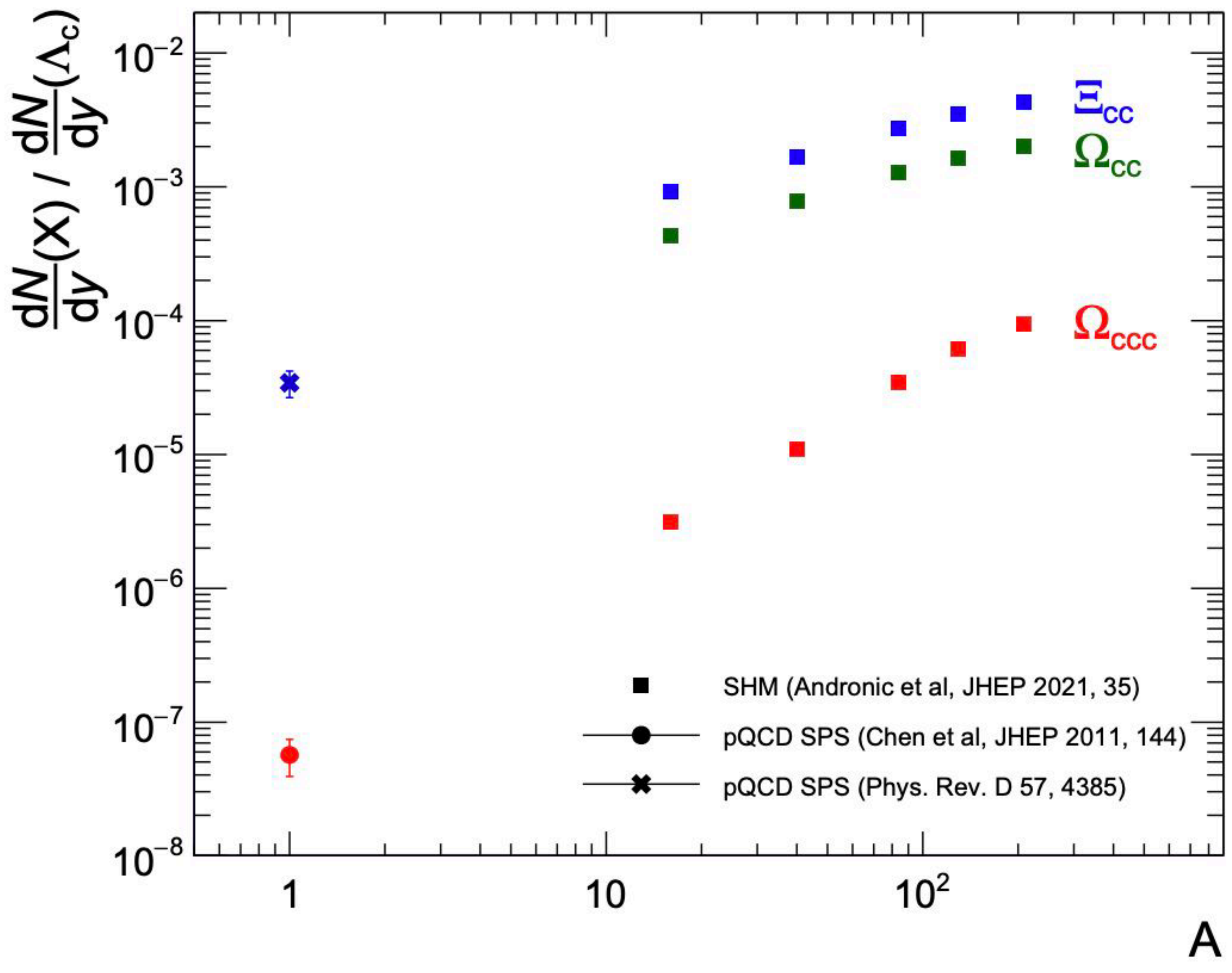


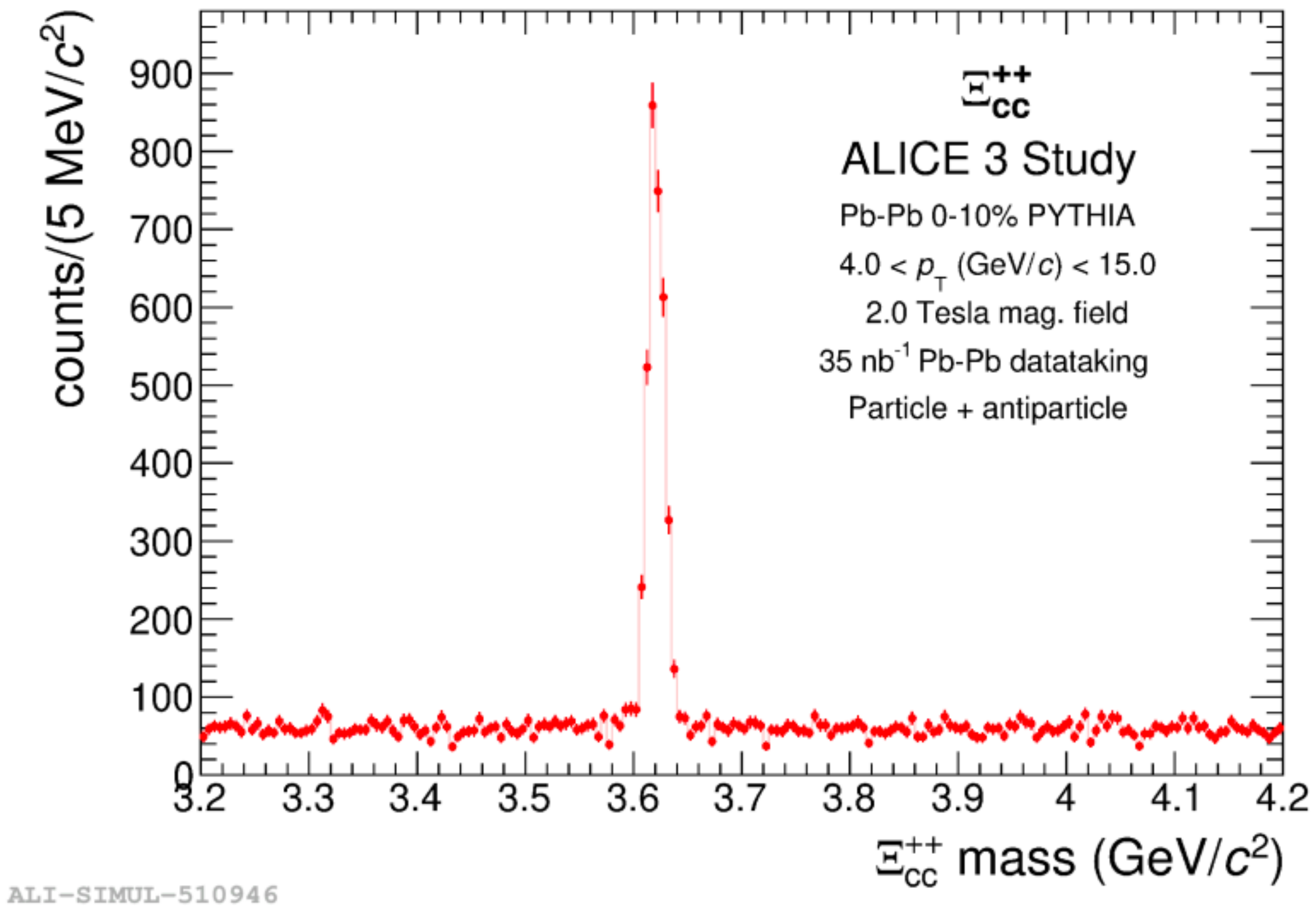
- Yields of multi-charm/single-charm hadrons predicted to be largely enhanced in A-A compared to pp collisions in SHM and coalescence models
  - Production in single hard scattering disfavoured

- **ALICE 3 suited for strangeness tracking —> multi-charm baryons**
  - Layers very close to the interaction vertex significantly increase the efficiency to track weakly decaying hadrons prior to their decay compared to ALICE

Multi-charm thermalisation



CERN-LHCC-2022-009



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Di-leptons as a QGP thermometer in Run 5+6

ALICE 3 uniqueness:

High-precision tracking

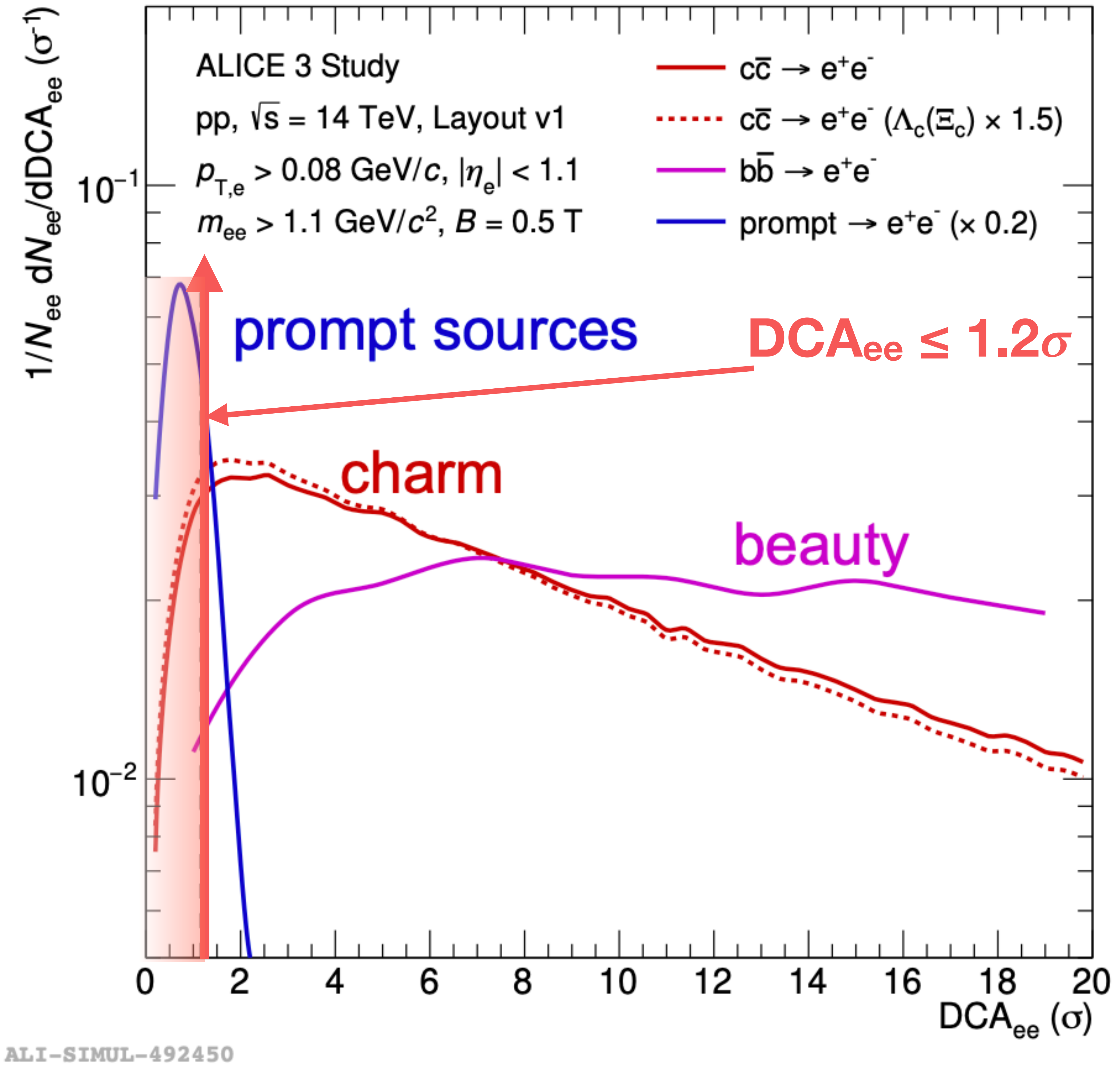
- 1^{st} layer at R = 5mm

Electron Identification

- Time-of-flight (TOF) via silicon
- Ring-imaging Cherenkov (RICH)
- Electromagnetic Calorimeter

Unprecedented HF rejection and low-p_T electron ID

- DCA_{ee}: separation of e^+e^- pairs and HF daughters
    - **Significant reduction of charm contribution and associated uncertainties**
    - Sets the stage: the ultimate dielectron experiment



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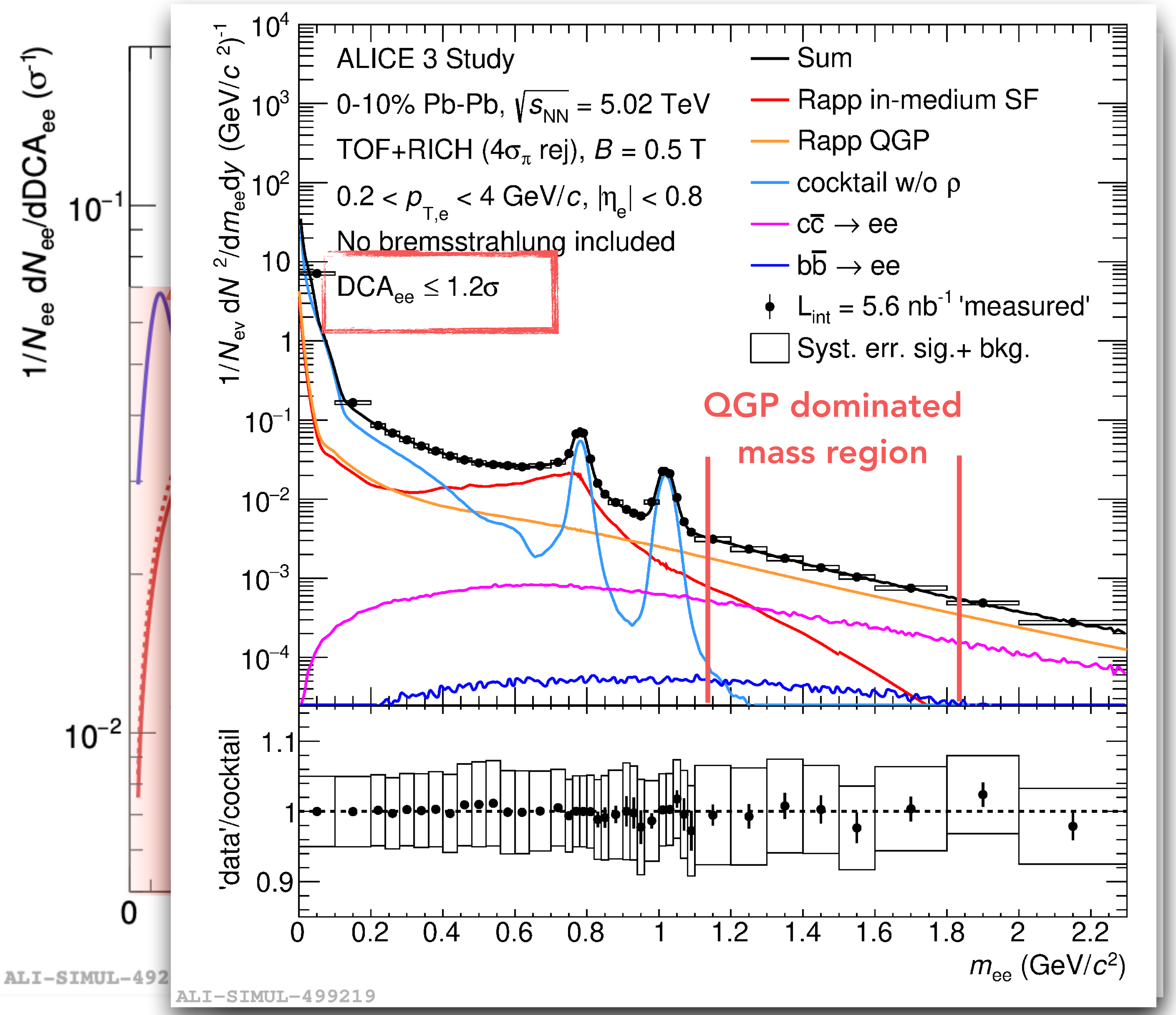
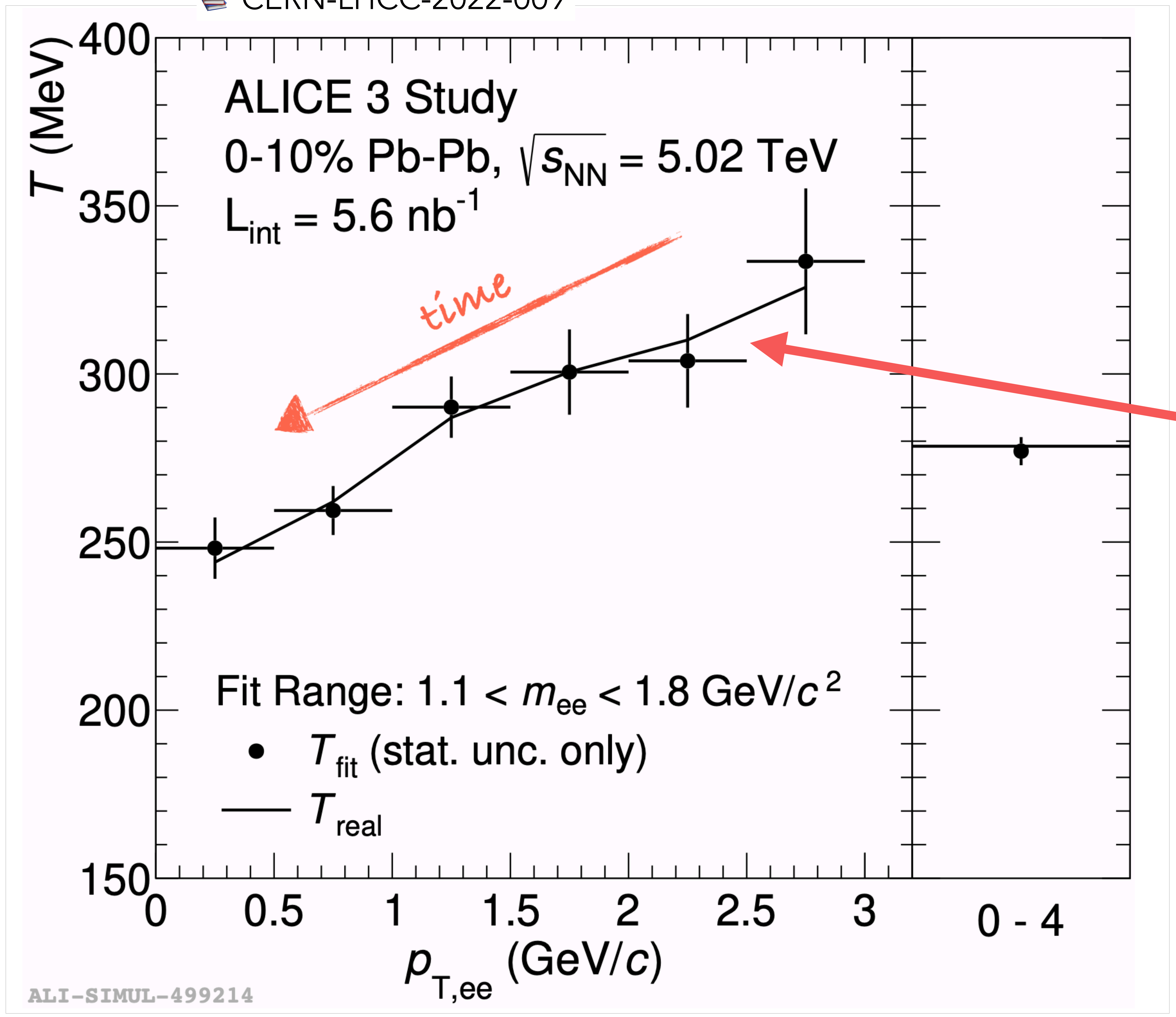
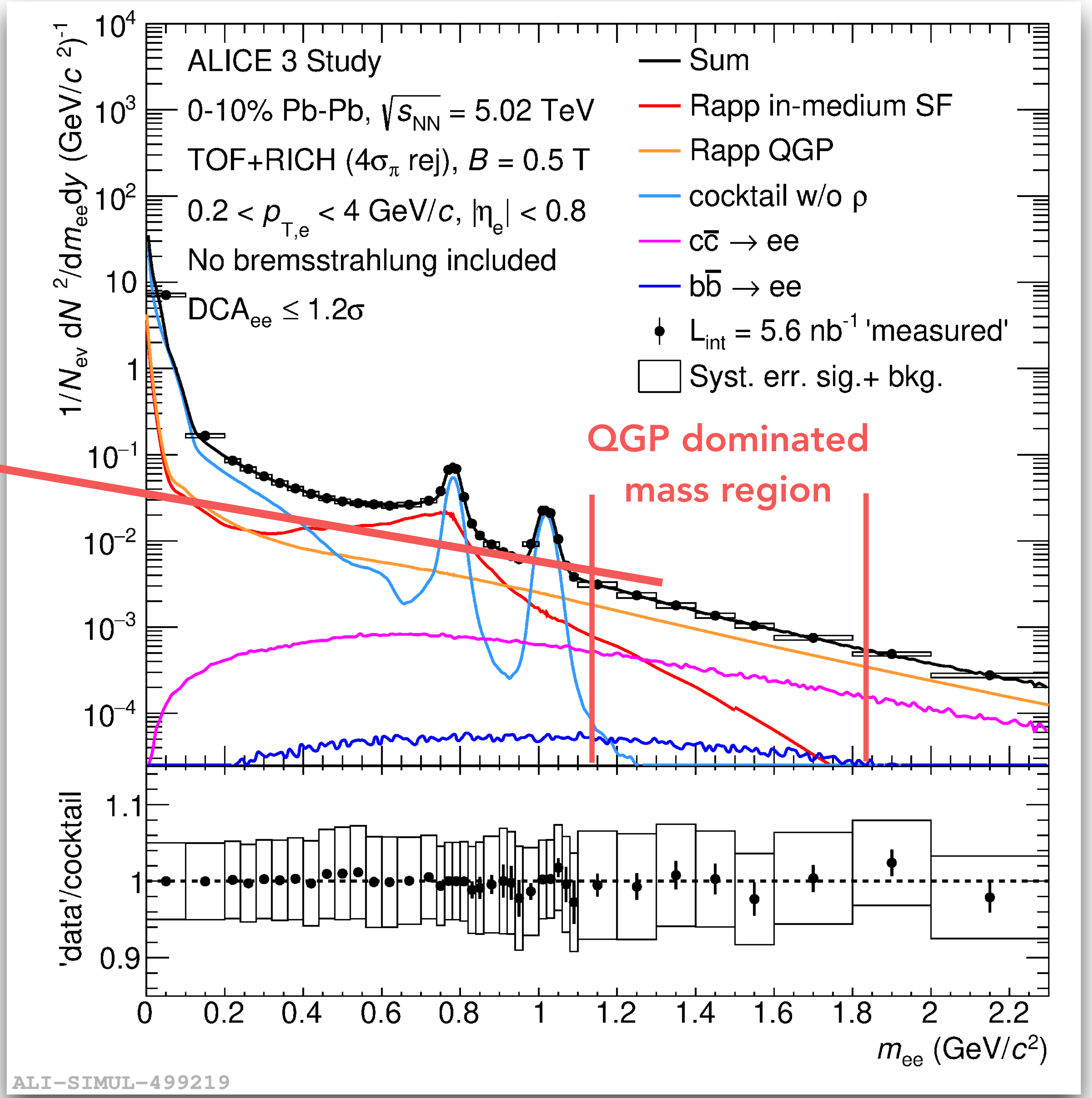


Di-leptons as a QGP thermometer in Run 5+6

CERN-LHCC-2022-009





- $p_{T,ee}$ -differential mass slope in QGP dominated region

Unique opportunity to probe the system evolution

Summary

State of the art…

- Low-momentum heavy quarks participate in the collective motion of the QGP (positive v_2)
- Comparisons of open-charm hadron measurements with transport models —> estimation of the charm spatial-diffusion coefficient D_s
  - Strong coupling of charm quark with QGP constituents at low momentum
- Mass-dependent energy loss: reduced for beauty with respect to charm quarks (dead-cone effect) and both radiative and collisional processes are necessary for the models to describe the data
- The assumption of coalescence from the QGP captures the main features of the data for charm and beauty hadrons

ALICE upgrades for **Run 3 (ongoing) and Run 4** will boost the core of HF physics program:

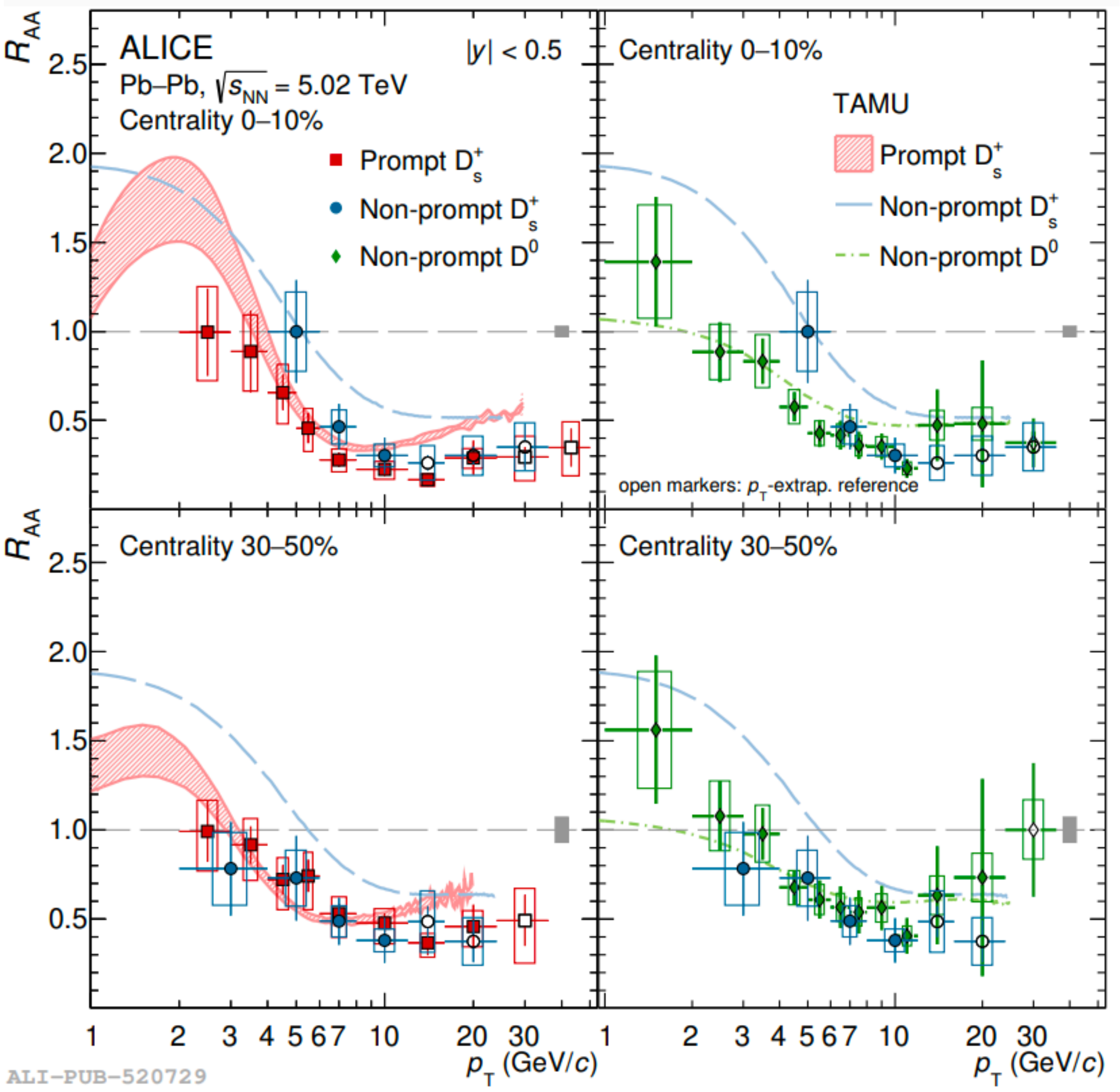
- Fully reconstructed beauty hadrons and more precise low momenta charm measurements

A bright heavy-ion programme with **ALICE 3** is under development for **Run 5 + 6**:

- Heavy flavour thermalisation and collectivity
- Heavy flavour correlations and diffusion
- (Multi-)charm and beauty yields down to zero p_T
- Differential QGP temperature measurements (HF subtraction is critical!)

Flavour dependence of energy loss

- Hint of larger R_{AA} for non-prompt D_s^+ *vs* prompt D_s^+ in $4 < p_T < 12$ GeV/*c*, for 0-10% collisions:
  - **Dead-cone effect suppresses the beauty energy loss**
- Similar hint for non-prompt D_s^+ *vs* non-prompt D^0 below 6 GeV/c in central collisions:
  - **Beauty-strange meson formation via quark coalescence in strangeness-rich environment**
- TAMU qualitatively describes the p_T trends, though slightly over predicts non-prompt D_s^+ R_{AA} values



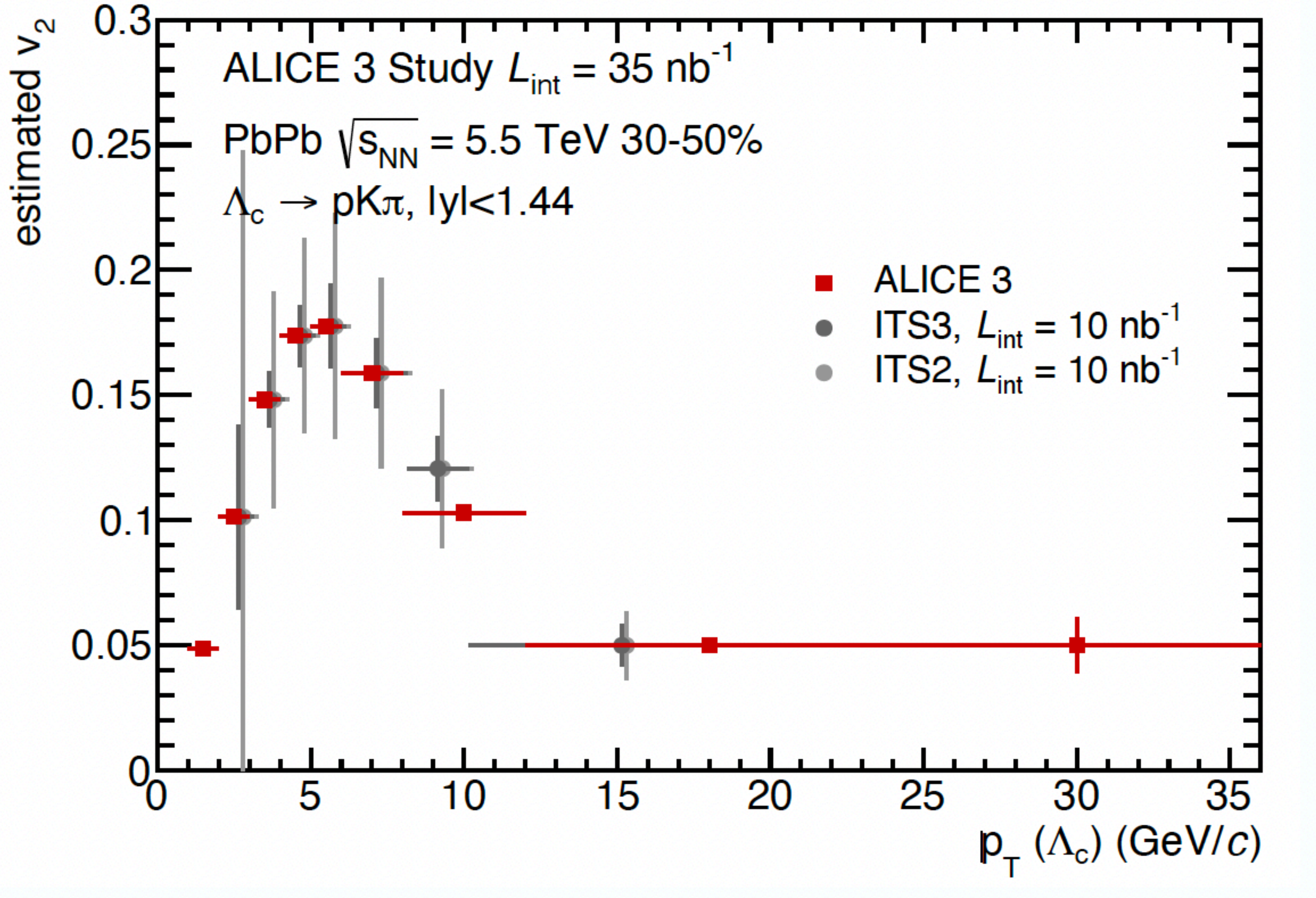
Heavy flavour transport

Heavy quarks: access to quark transport at baryon level

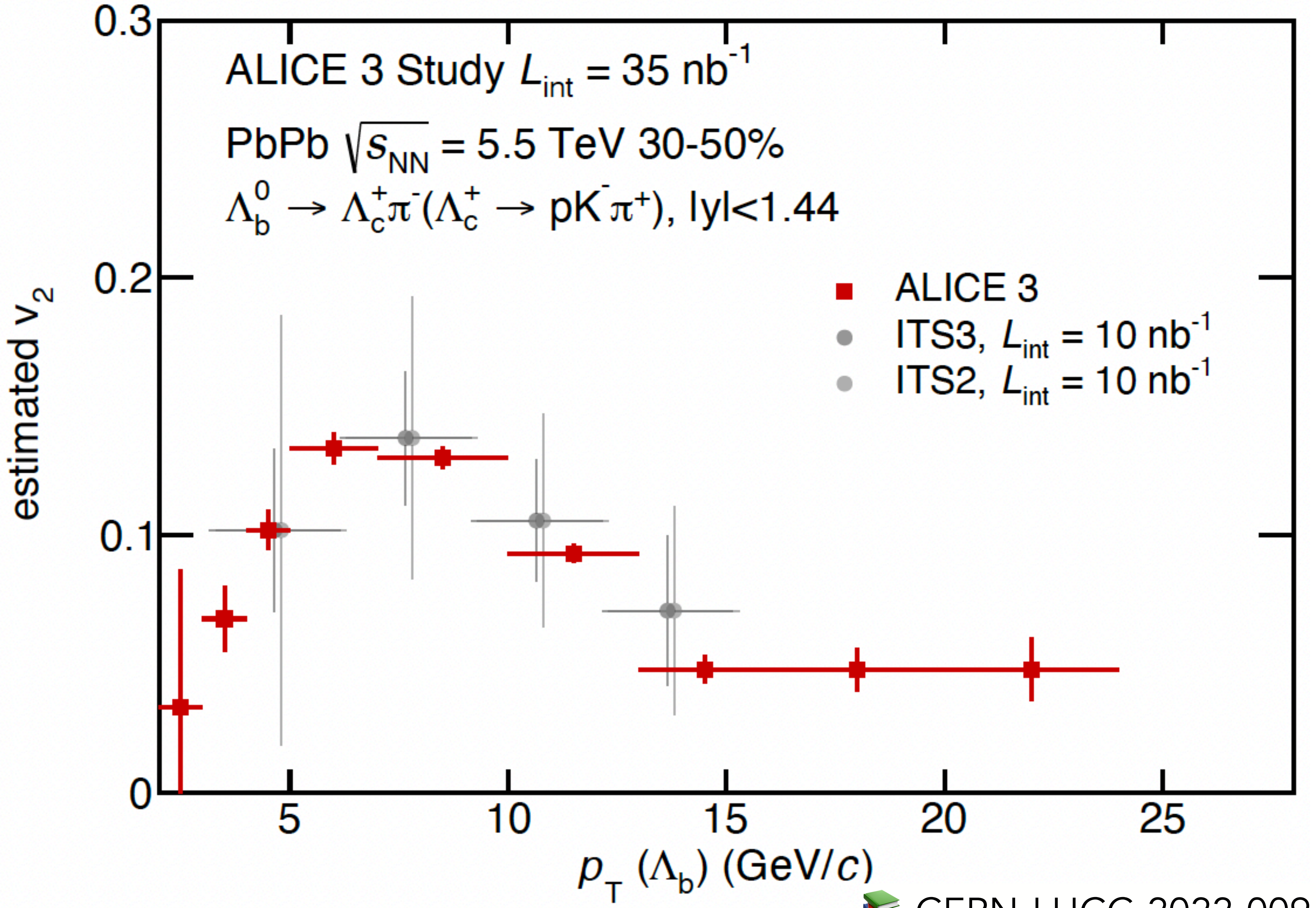
Expect beauty thermalisation slower than charm — smaller v_2

Need ALICE 3 performance (pointing resolution, acceptance) for precision measurement of e.g. Λ_c and Λ_b v_2

Λ_c v_2 performance



Λ_b v_2 performance



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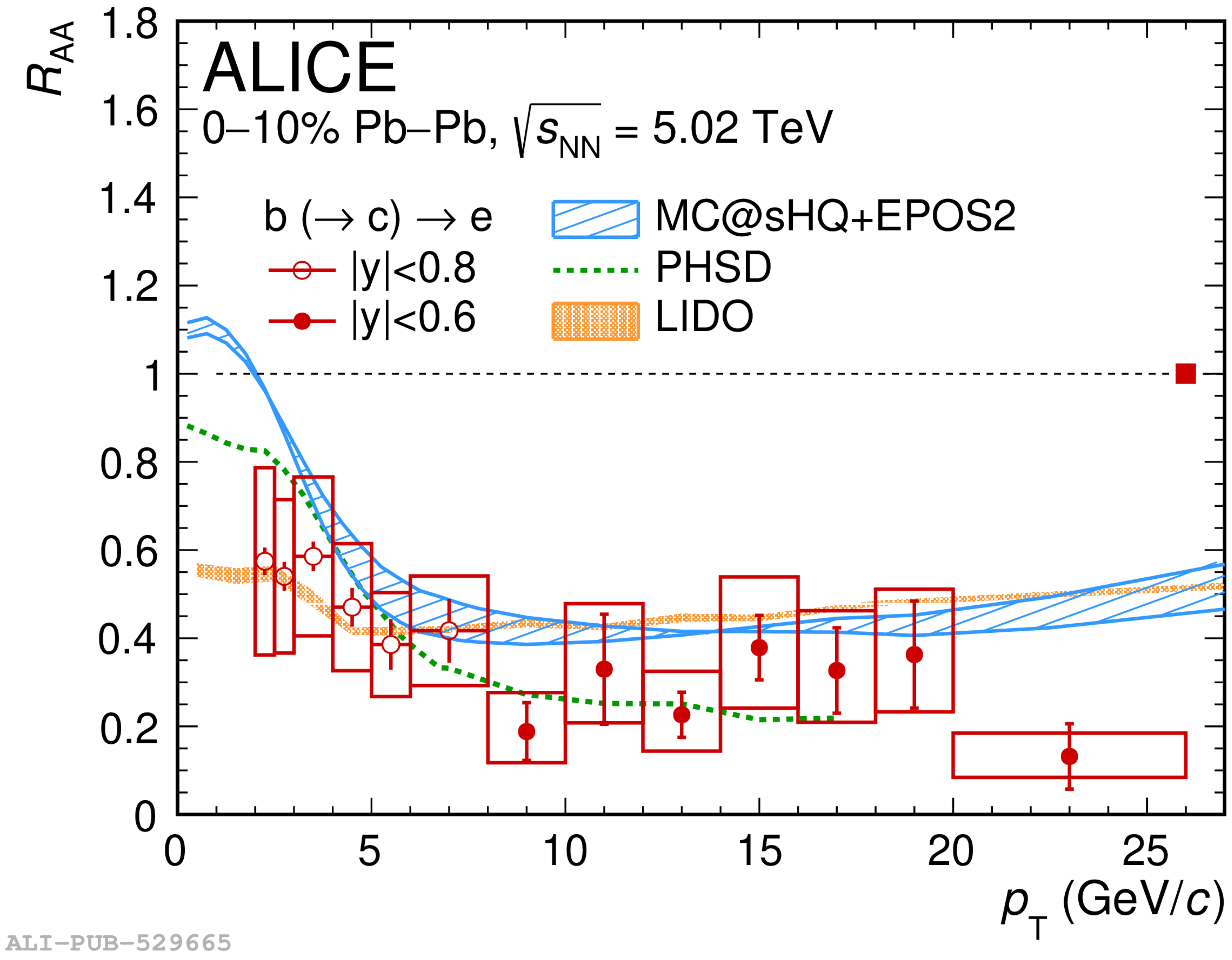
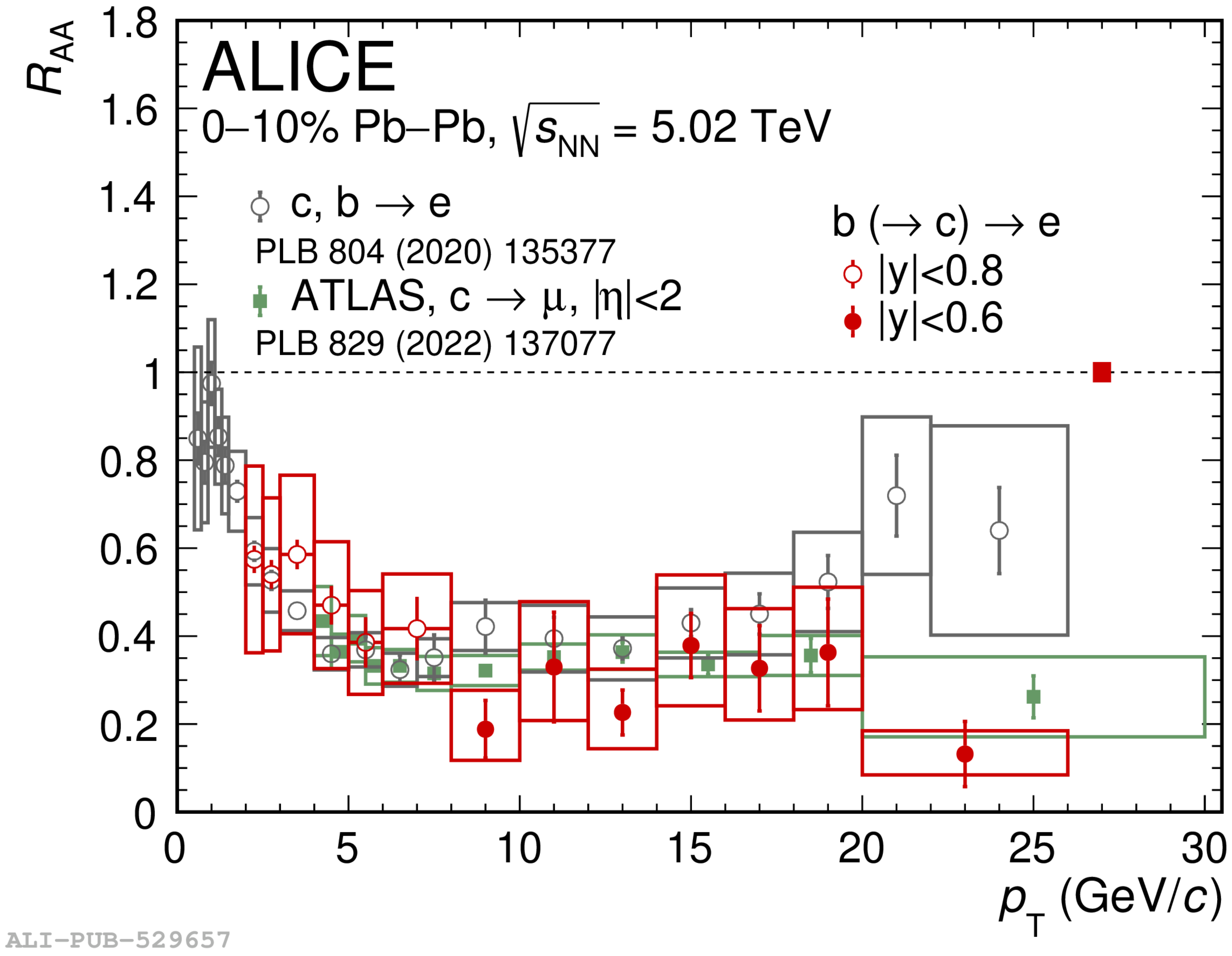
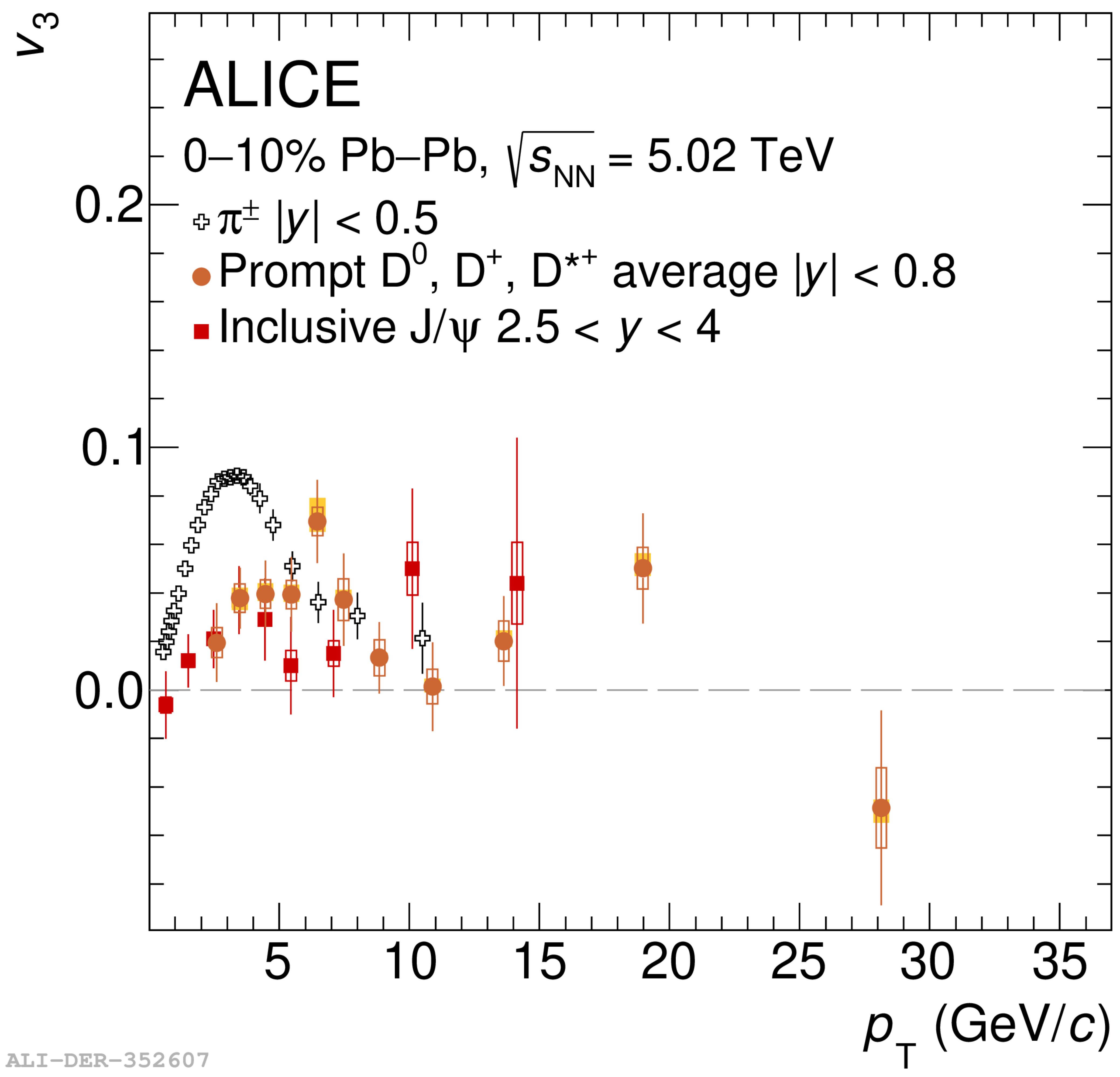
Flavour dependence of energy loss





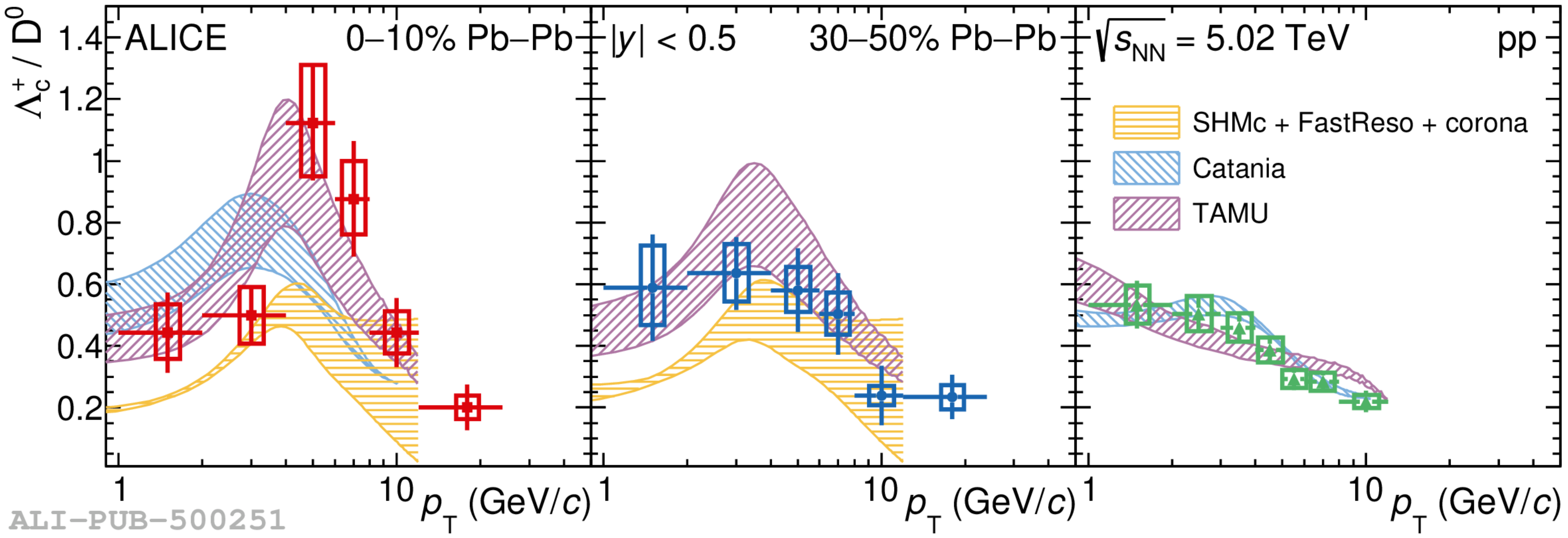
- Similar R_{AA} for electrons from beauty and charm —> Points to strong interaction with medium
- Models with QGP phase generally describe measurements
- Different beauty hadron species have similar branching ratios to electrons

Triangular flow of heavy-flavour hadrons



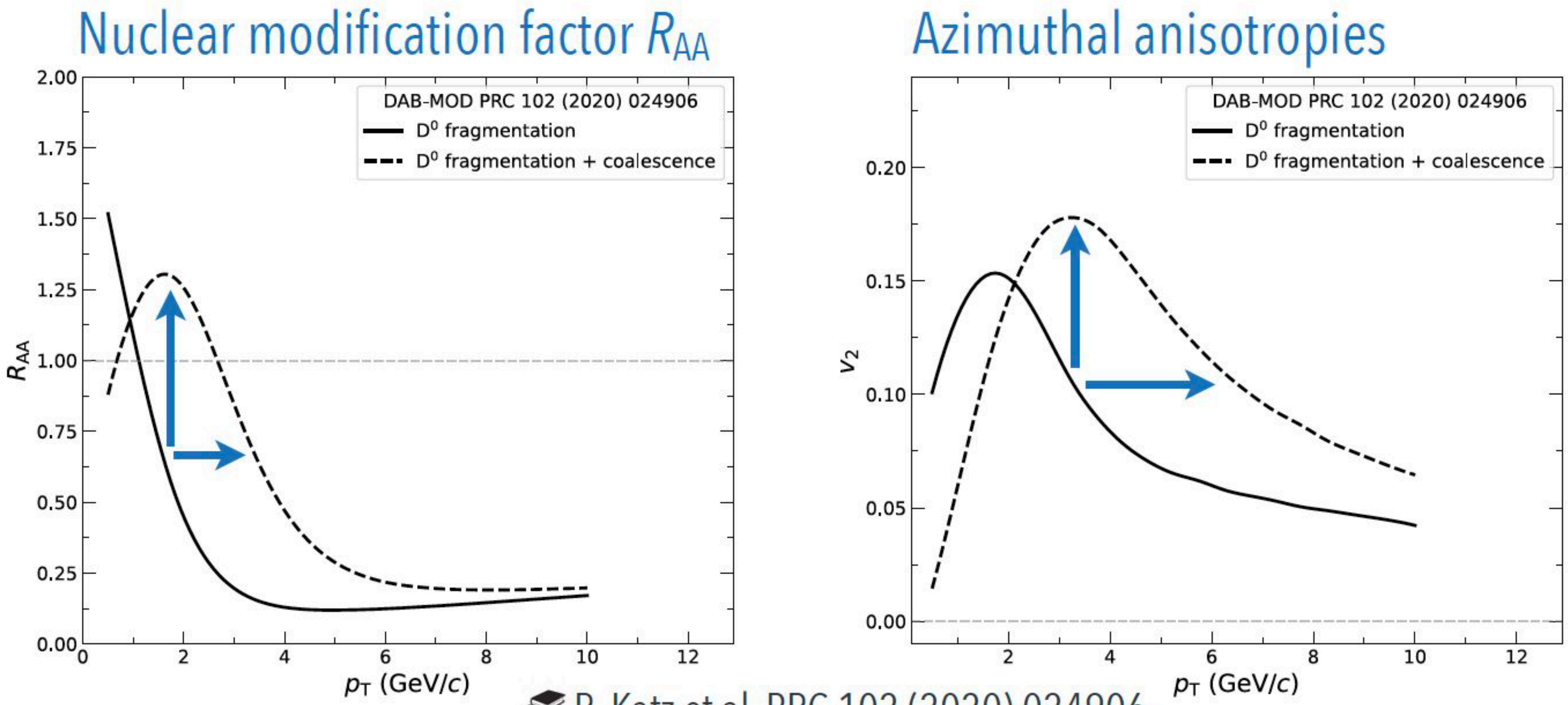
Positive v_3 for open/hidden charm

- p_T < 4 GeV/c: thermalisation of heavy quarks
  ➡ mass ordering observed
  ➡ $v_3(J/\psi) \approx v_3$(D) → interplay of anisotropic and radial flow
- 4 < p_T < 8 GeV/c: heavy-quark hadronisation via coalescence with flowing light quarks
- p_T > 8 GeV/c: path-length dependence of in-medium energy loss

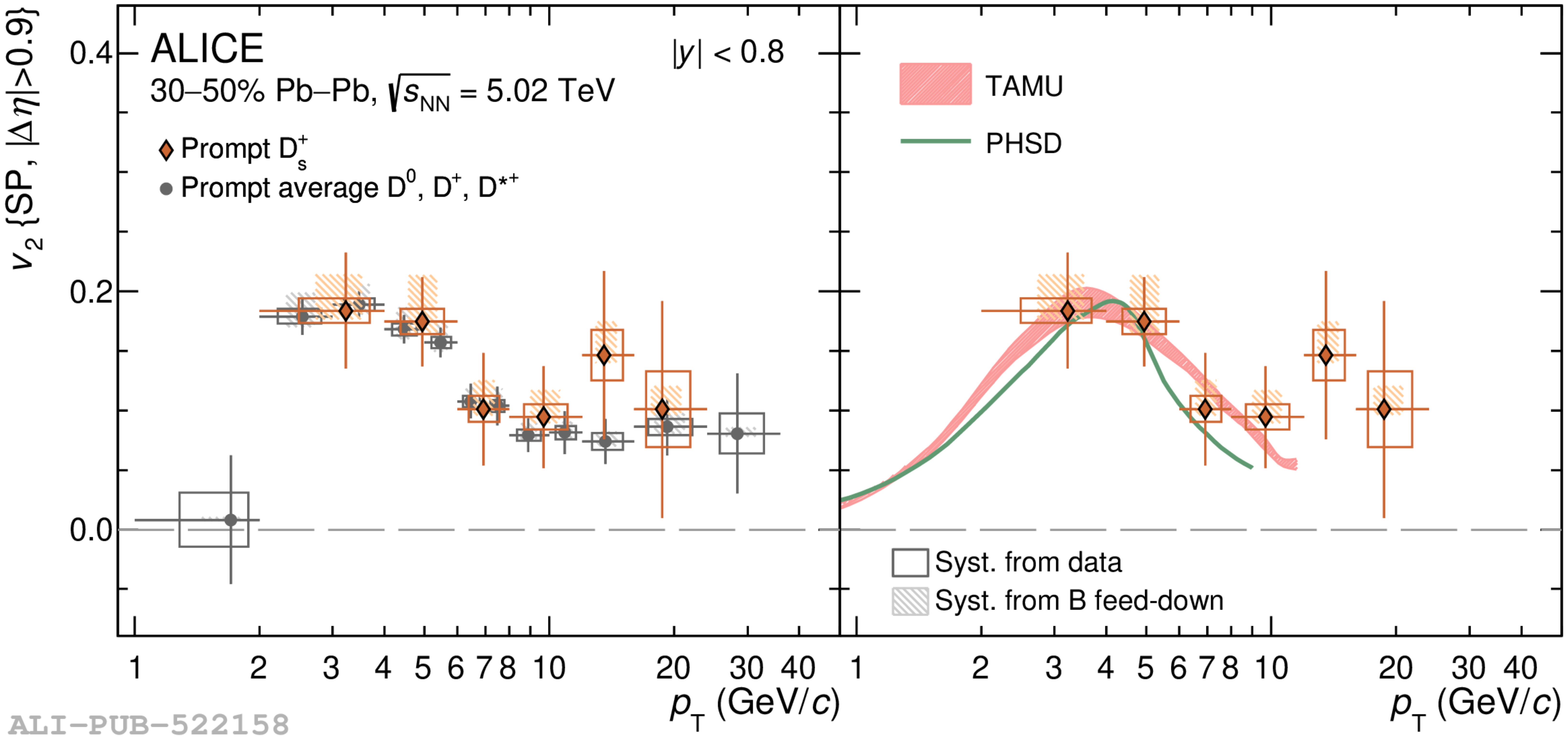


- Λ_c^+/D^0 ratio in central Pb-Pb and in pp:
  - For 4 < p_T < 8 GeV/c, 3.7σ significance for Λ_c^+ enhancement in 0-10% collisions
  - Proper description by TAMU, qualitative agreement for Catania and SHMc
  - Explained by different effects of radial flow and coalescence on baryons and meson

Coalescence role on R_{AA} and v_2



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



Positive D-meson v_3 charm-quark participation in QGP collective expansion

Positive D_s elliptic flow observed in $2 < p_T < 8$ GeV/c with a significance of 6.4σ

- in agreement with non-strange D-meson v_2 given current uncertainties
- Compatible with predictions from models including charm-quark coalescence with flowing strange quarks

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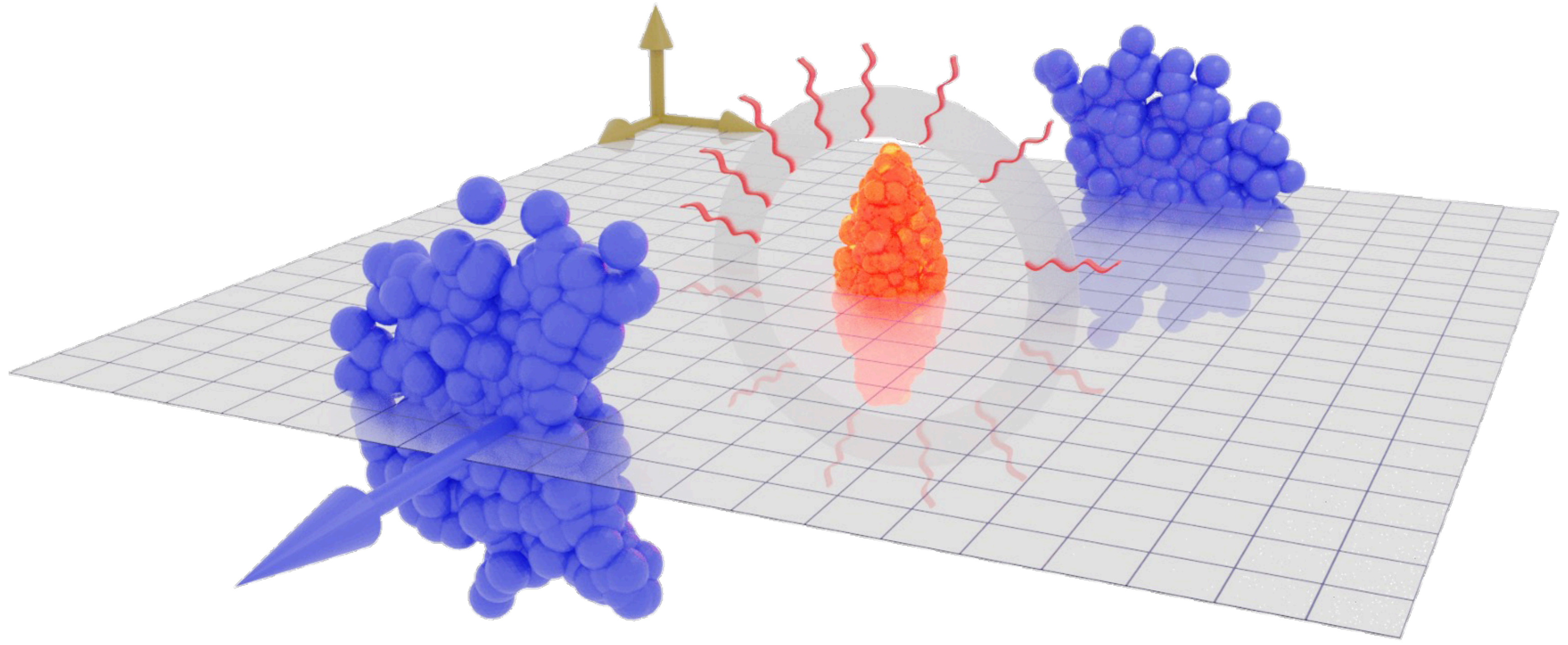

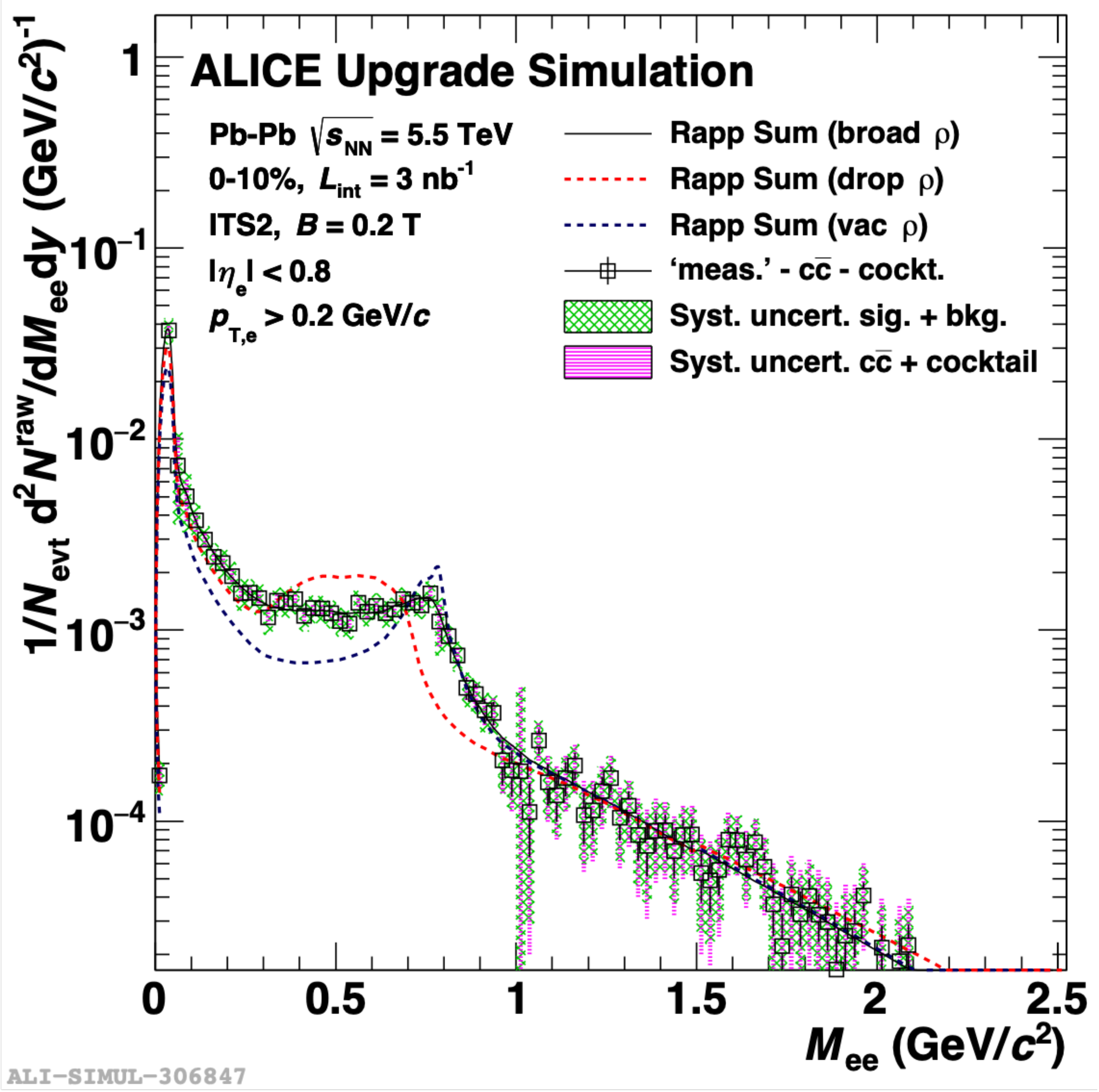

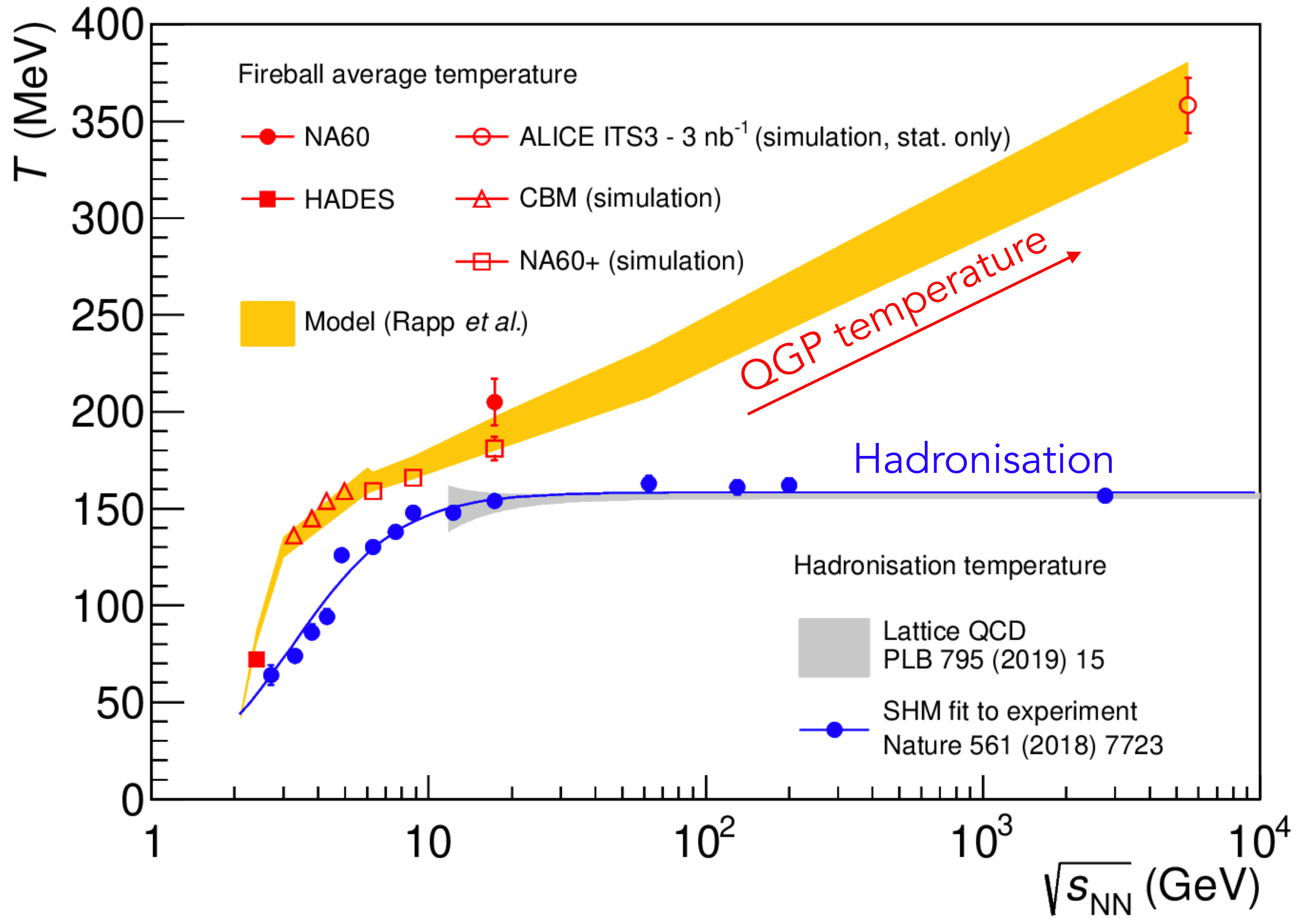

M. Mazzilli - BEAUTY 2023