ALICE

The University of Texas at Austin

Recent open Heavy Flavour results from ALICE

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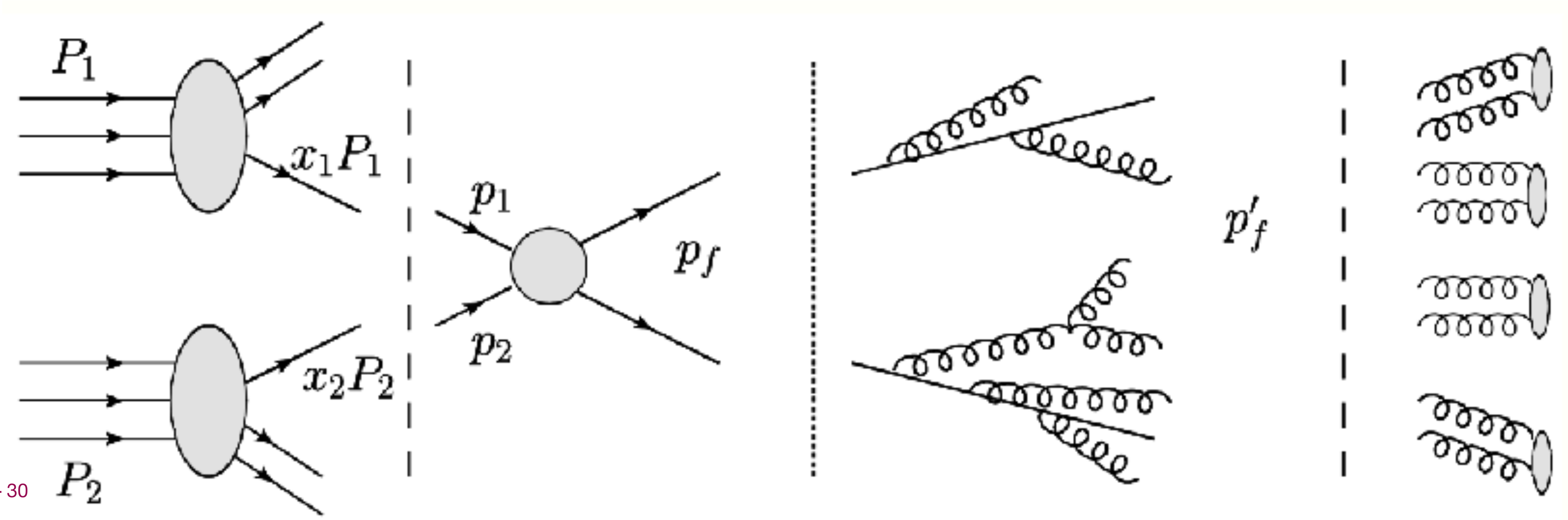
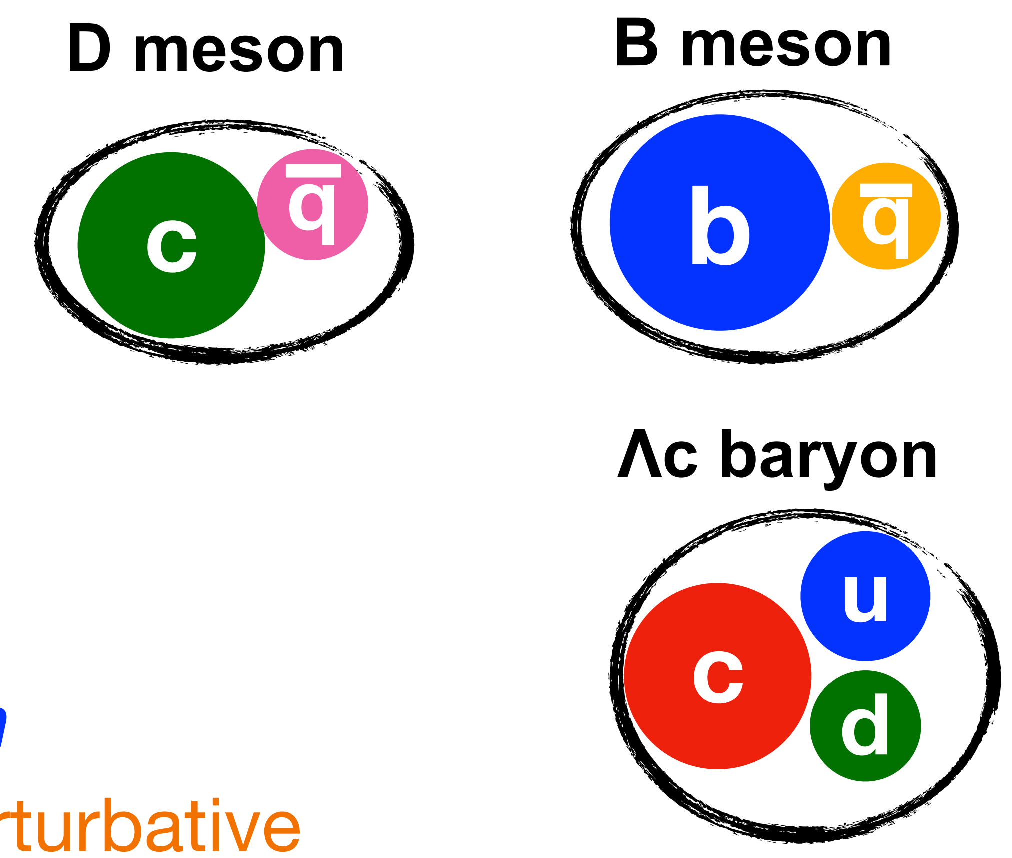
Introduction

- Heavy quarks (charm and beauty) are primarily produced in hard scattering processes with large momentum transfer
- Production cross-sections is calculated in pQCD by the convolution of 3 ingredients utilizing a factorization approach.



Physics Procedia 51 (2014) 25 – 30



Fractorization theorem

$f_i(x_i, \mu_F)$ *pdf* — non-perturbative, Initial condition from data

$d\sigma$ *hard x-section* — perturbative

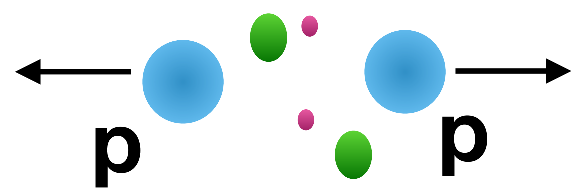
Parton shower — perturbative

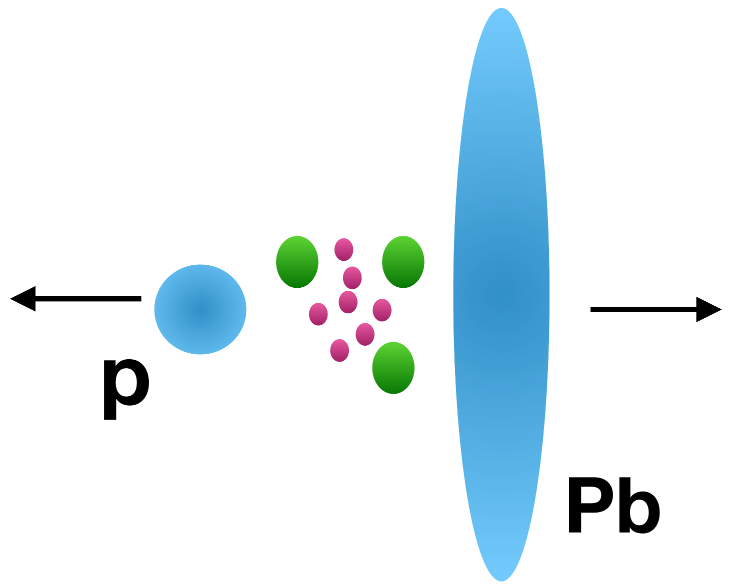
Hadronization — non-perturbative, phenomenology + fit to data (e+e-, e-p)

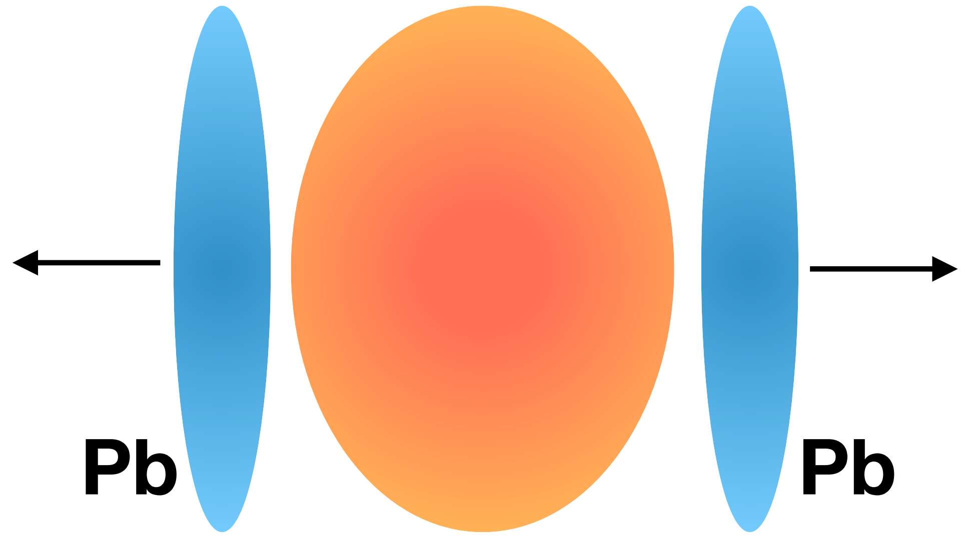
$$\frac{d\sigma^{\mathrm{D}}}{dp_T^{\mathrm{D}}}(\mu_F, \mu_R) = PDF(x_1)\ PDF(x_2)\ \times\ \frac{d\sigma^{\mathrm{c}}}{dp_T^{\mathrm{c}}}\ \times\ D_{\mathrm{c}\to\mathrm{D}}(z = p_{\mathrm{D}}/p_{\mathrm{c}})$$

Measurements of heavy flavor particles—> test the perturbative QCD (pQCD) calculations and provide input for the data driven non-perturbative QCD (npQCD) quantities.

System size dependence







pp

- Test and constraint pQCD calculations and phenomenological models.
- Jet fragmentation and hadronization

Talk by
Amanda Flores

p—Pb

- study effects of cold nuclear matter
  - nPDFs
  - Initial and final state radiation
  - Gluon saturation at low x
  - k_T broadening
- Jet fragmentation and hadronization
- Study collective effects

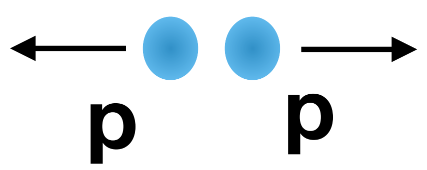
Pb—Pb

- Study transport properties of QGP using heavy quark interactions with medium constituents.
- Hadronization in the presence of QGP.

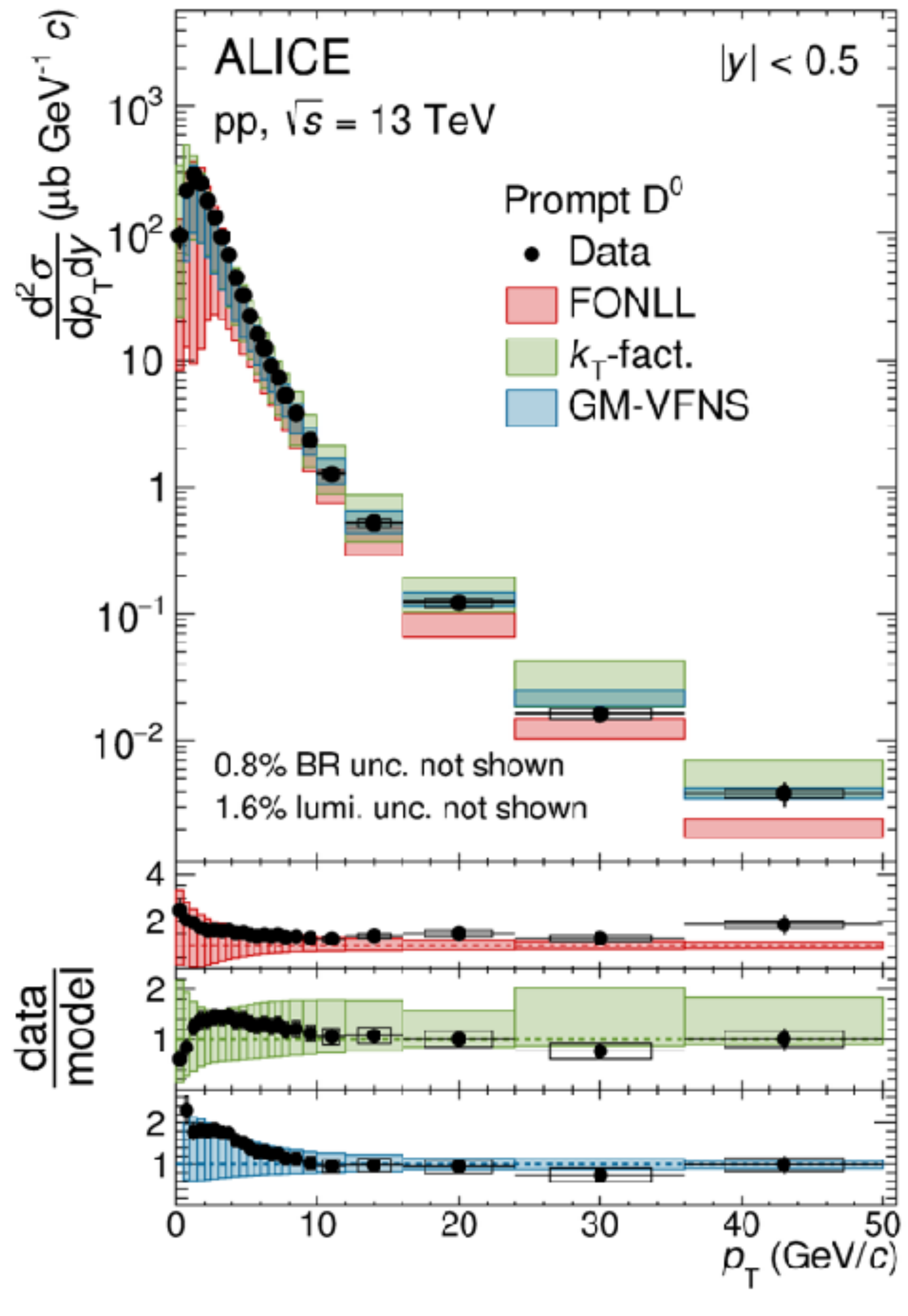
This talk:

- **Charm and beauty hadron measurements with the ALICE detector.**
- **What we can learn about pp, p—Pb, Pb—Pb from these measurements?**

Charm meson measurements



Charm hadron cross sections measurements in pp collisions



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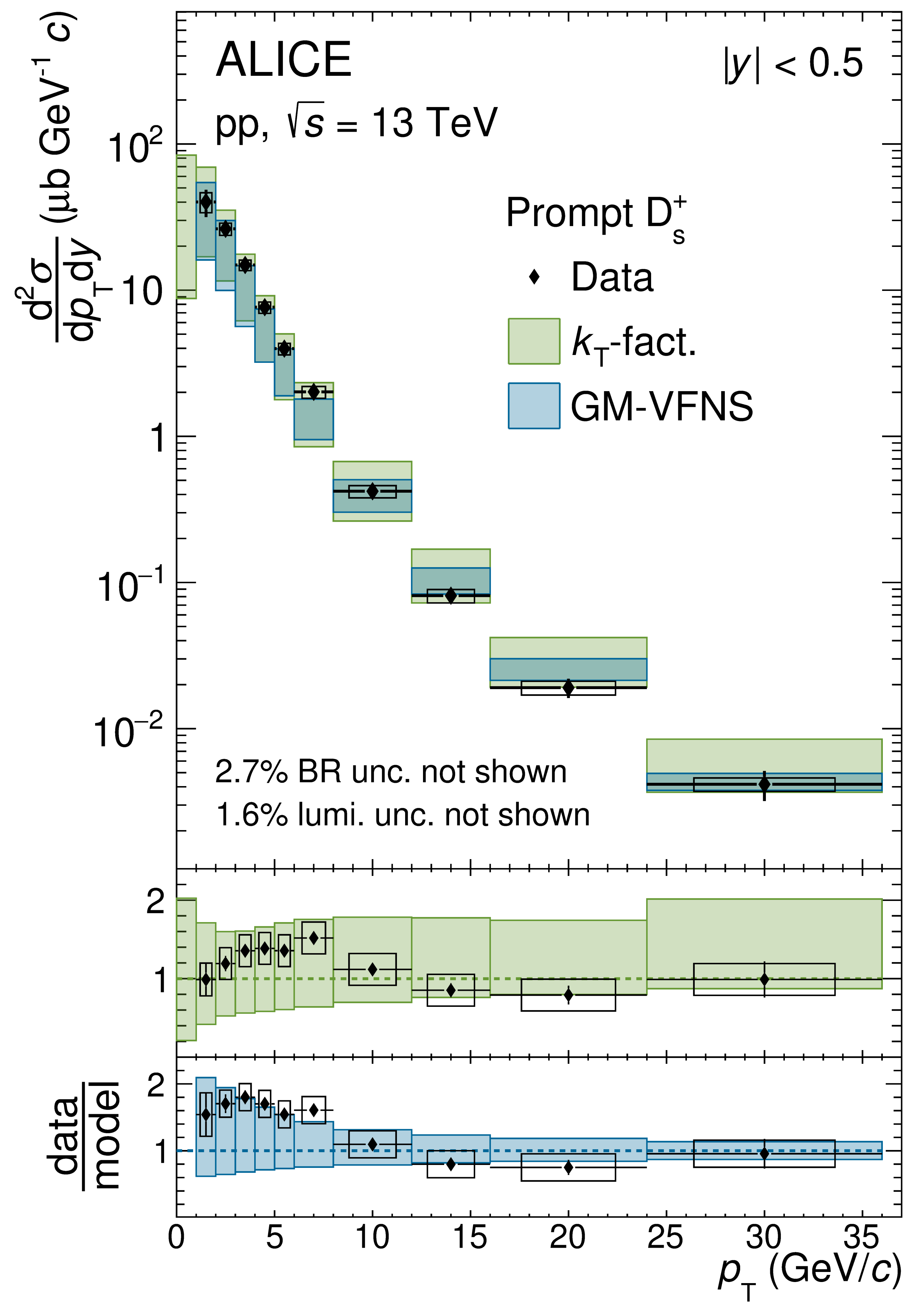

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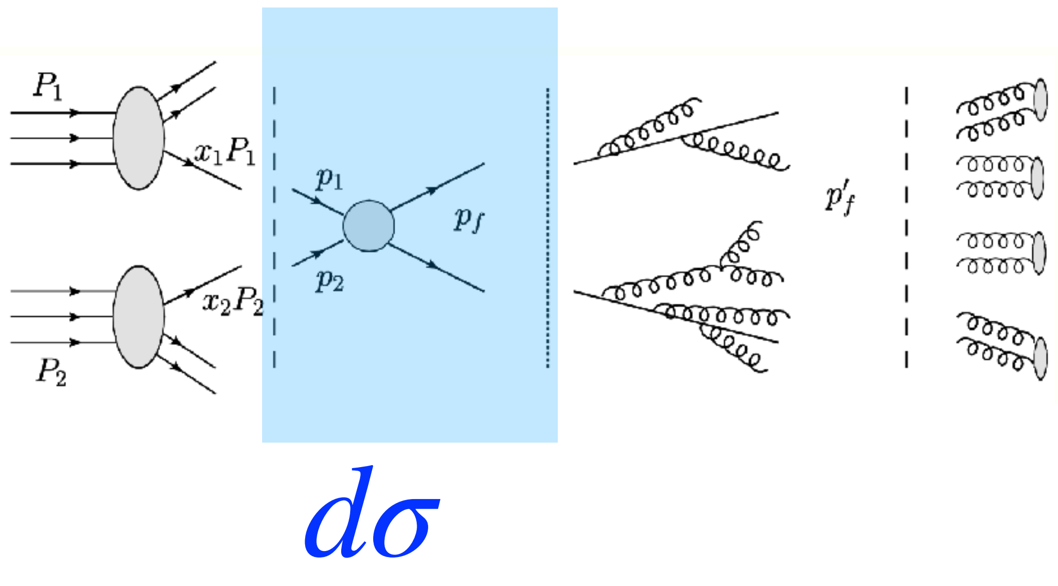
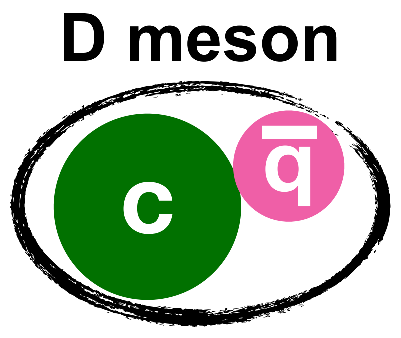
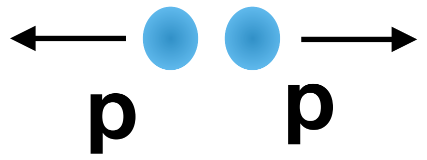




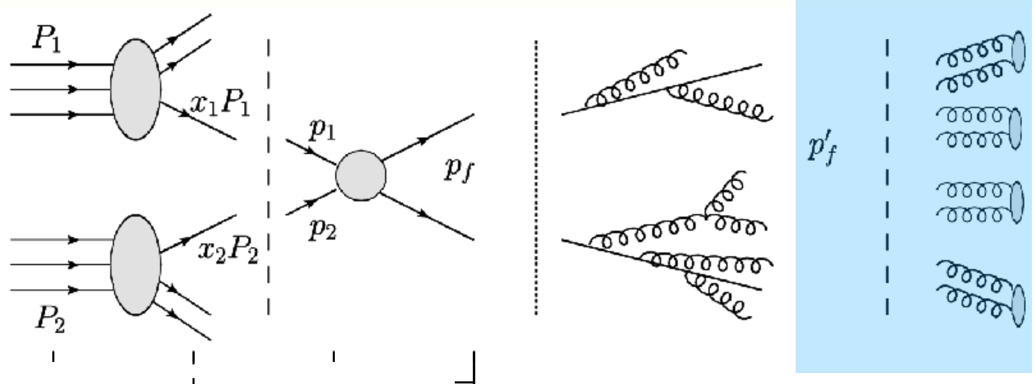
High precision measurements of p_T differential production cross sections of different prompt D meson compared to pQCD calculations (FONLL, GM-VFNS, k_T-factorisation)

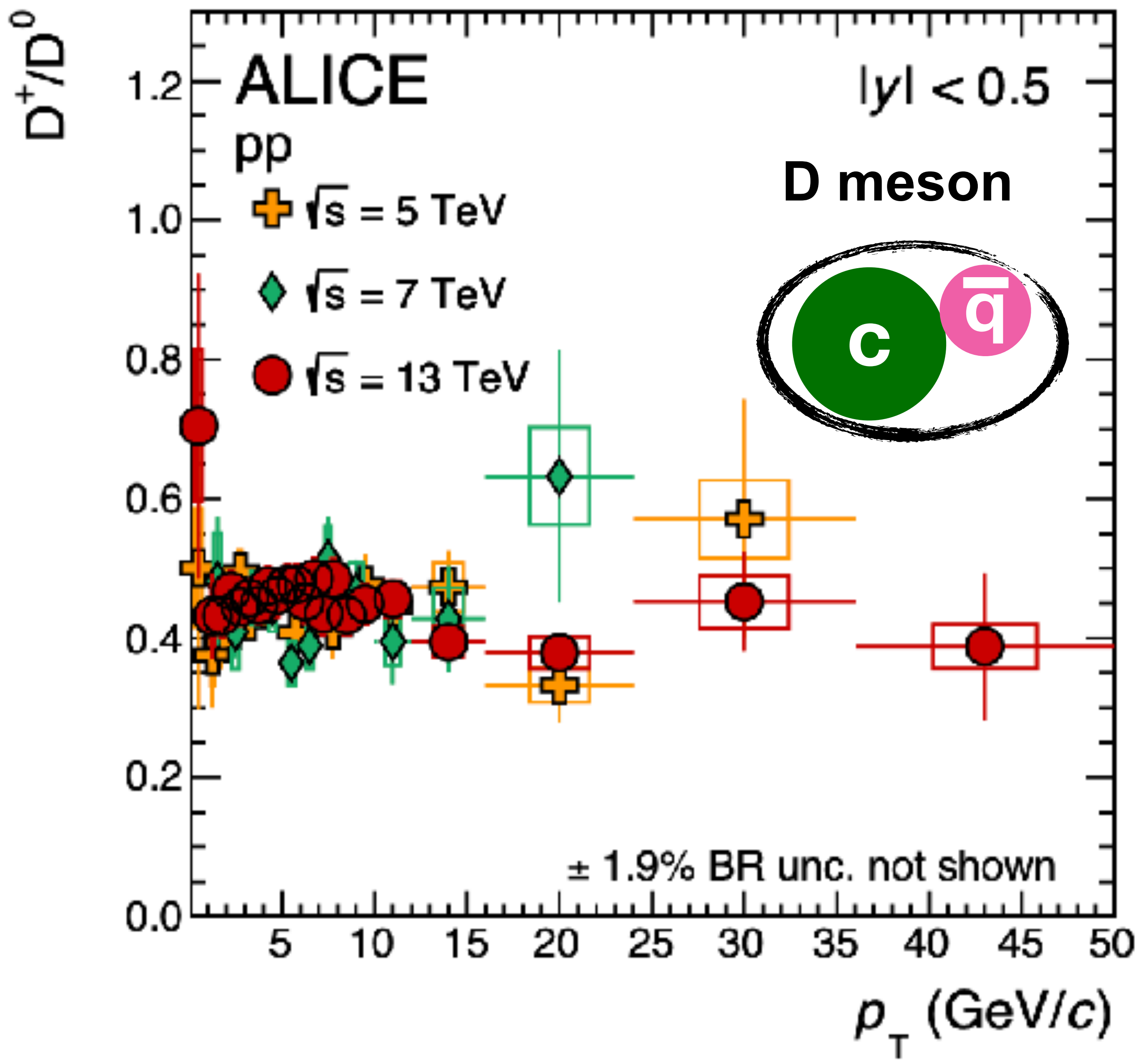
JHEP 12 (2023) 086

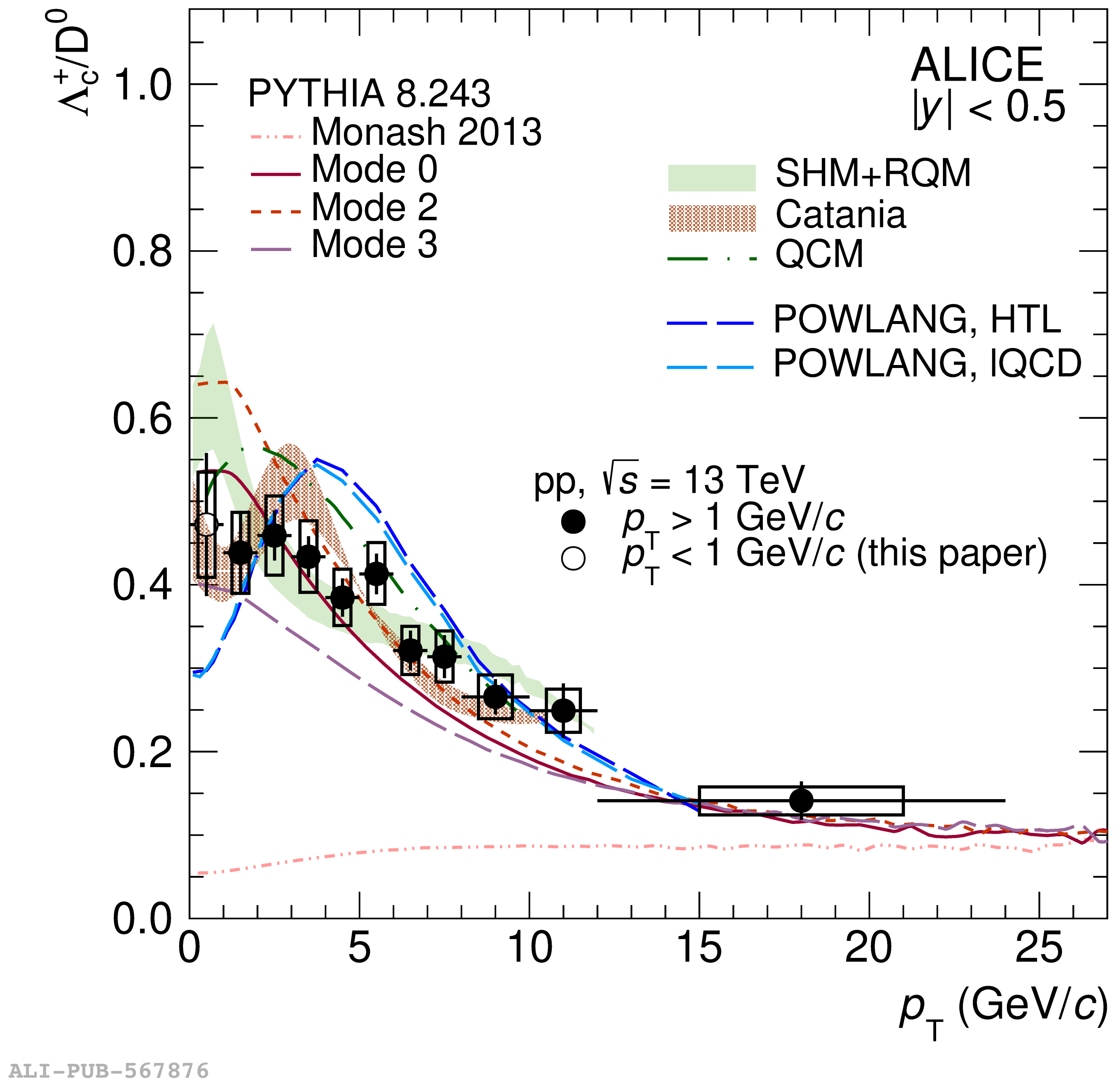
Charm baryon measurements

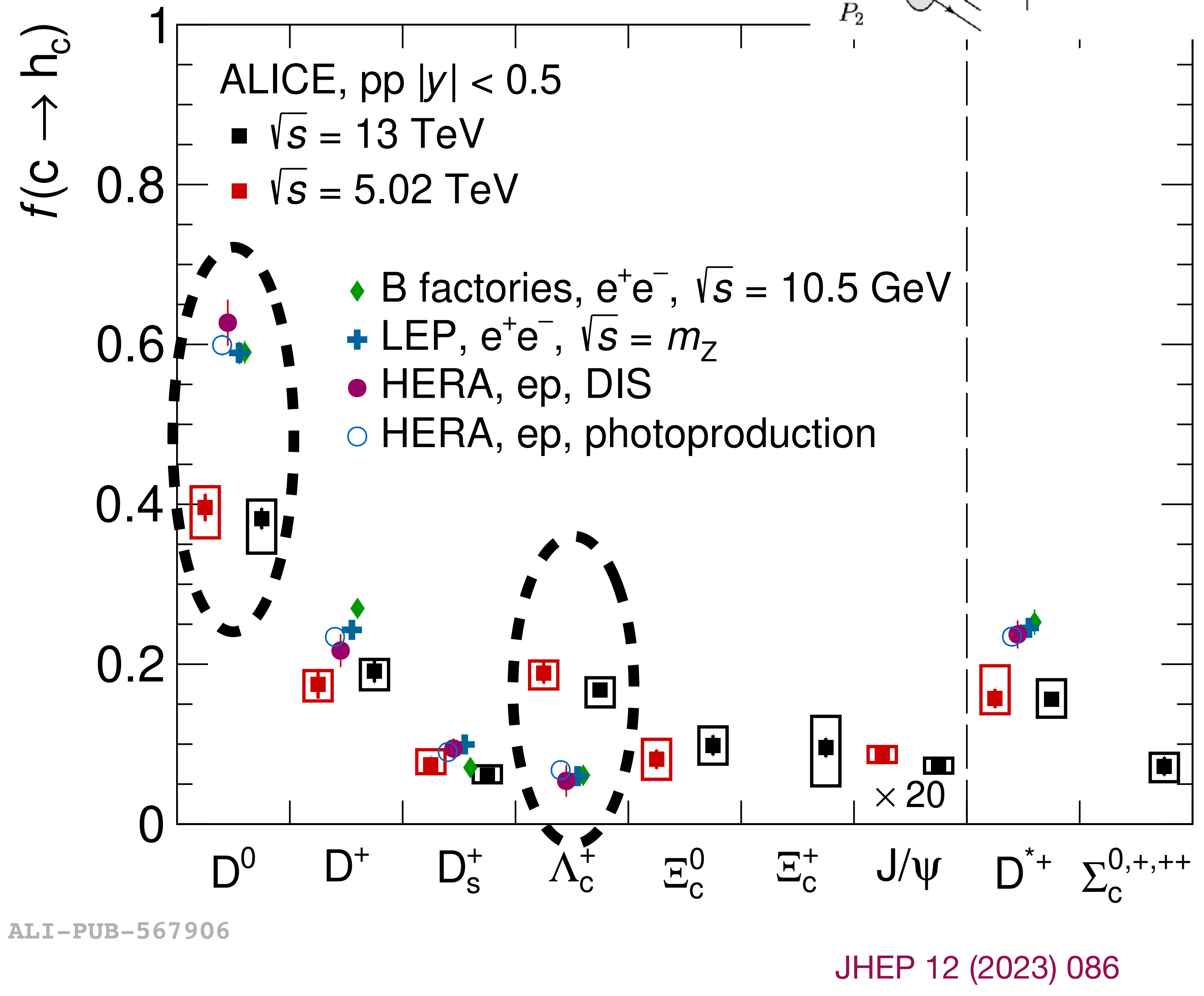


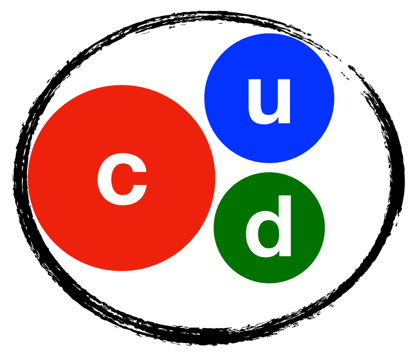
Study charm quark hadronisation to mesons and baryons











Ratios of p_T-differential cross sections of D^+ and other mesons to D^0 mesons.

- No significant dependence on the p_T of D mesons
- Common fragmentation functions of charm quark to mesons.

Ratios of p_T-differential cross sections of Λ_c baryons to D^0 mesons.

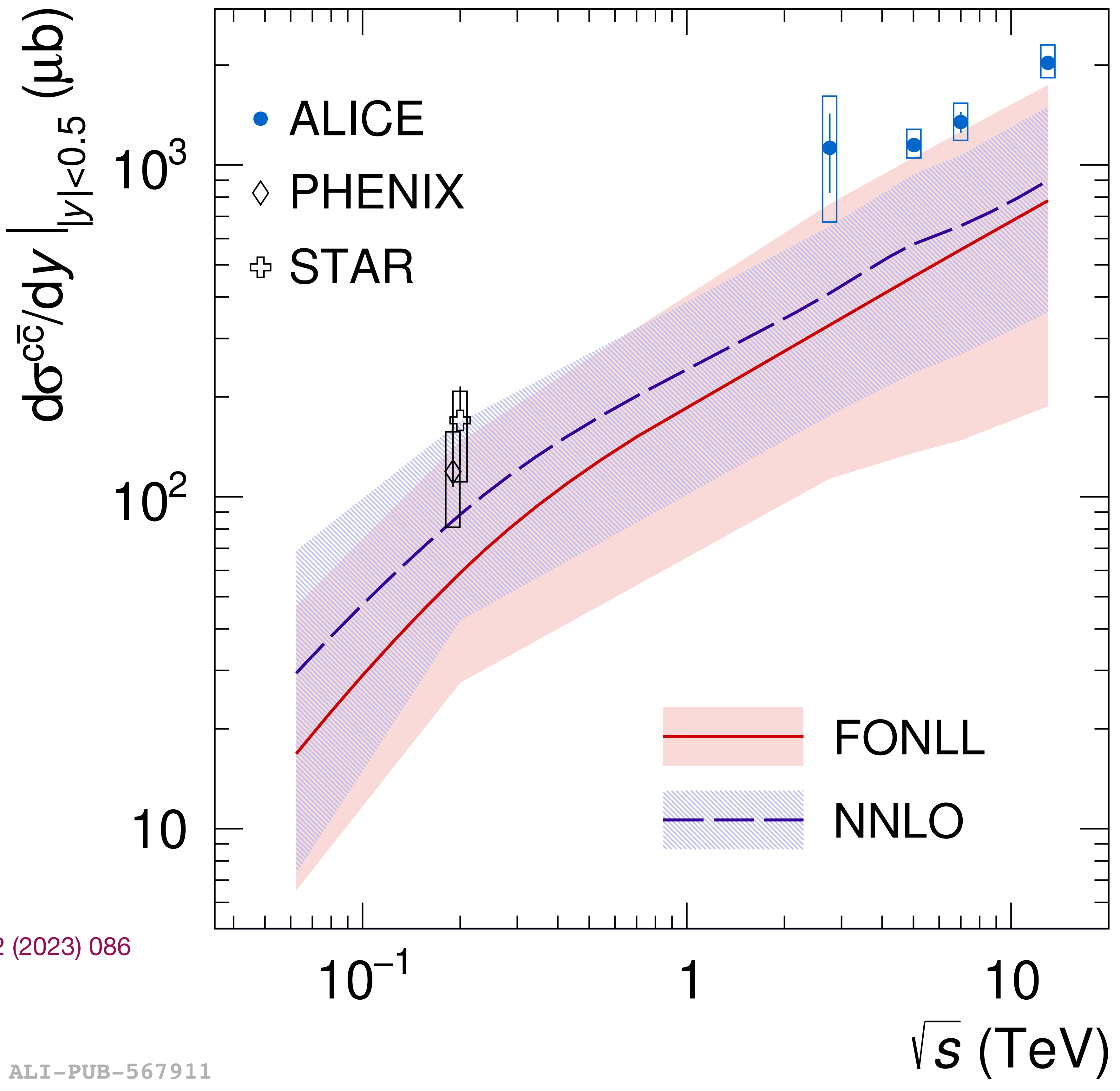
- Compared with PYTHIA 8, Catania & QCM models (recombination), SHM+RQM (statistical hadronisation), POWLANG (recombination in QGP)
- **PYTHIA with CR, SHM+RQM, Catania models describe the data.**

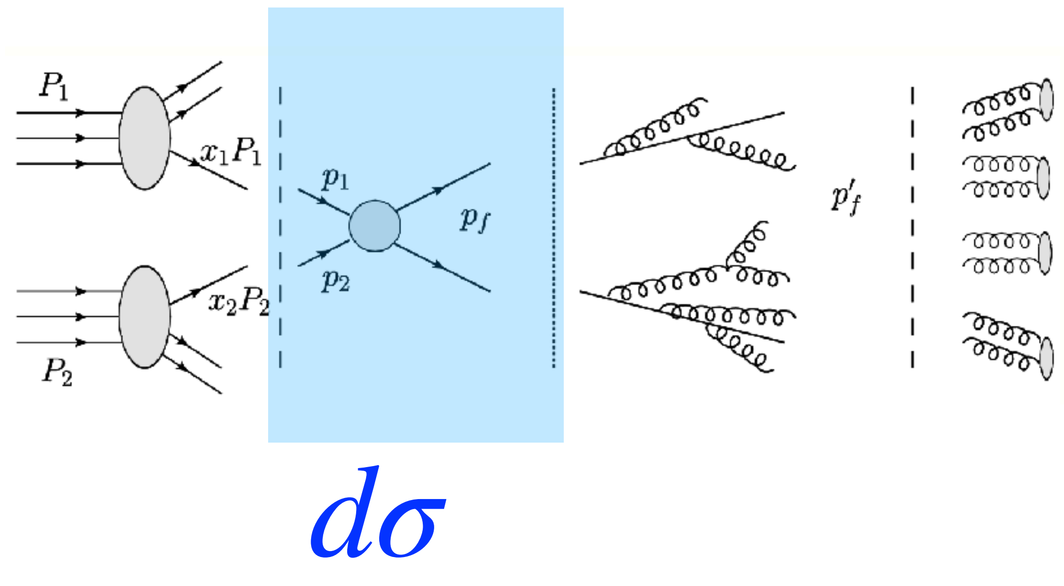
Charm-quark fragmentation fractions to different hadrons f(c —> h_c) at the LHC compared with LEP and HERA results.

- No significant energy dependence at the LHC.
- Enhancement of baryon —> overall reduction of relative D-meson abundance by a factor of 1.5 w.r.t e^+e^- and ep collisions.

Charm cross section

Total charm cross sections measurements in pp collisions





Total $c\bar{c}$ cross-section is calculated from sum of production cross-sections of D^0, D^-, D^+_s, J/ψ, Λ_c, Ξ^0_c, Ξ^+_c hadrons in mid-rapidity.

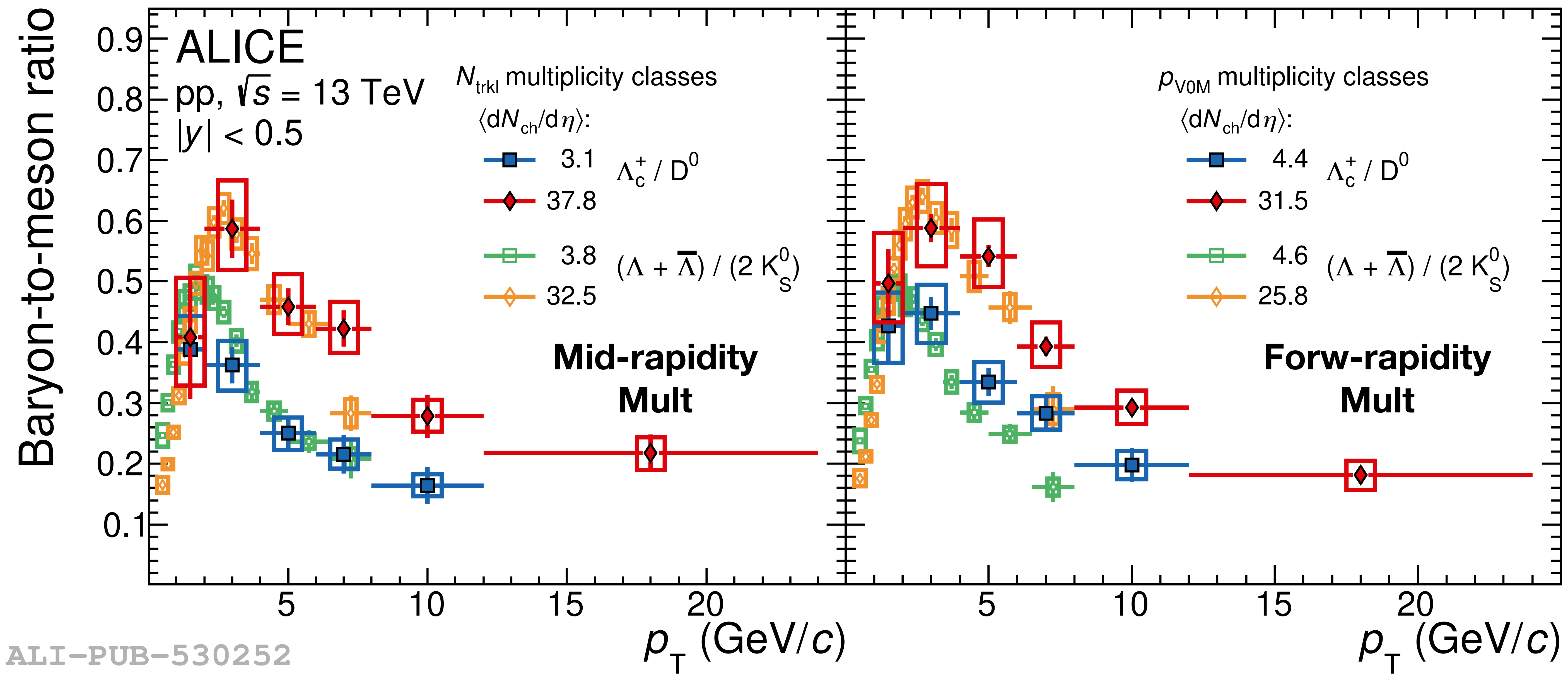
Cross-section compared with FONLL and NNLO predictions and RHIC energies.

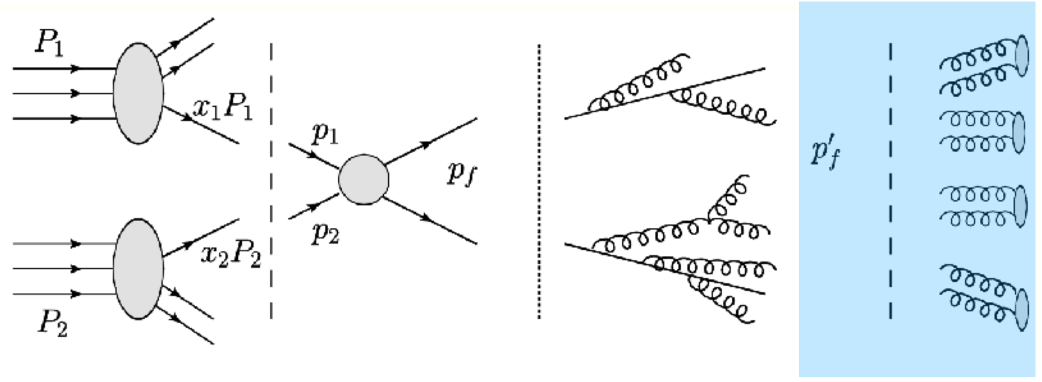
- LHC results higher than RHIC due to baryon enhancement at mid-rapidity.
- LHC results compatible with the upper edge of FONLL and NNLO calculations.

Charm Hadronisation

p p

Study charm quark hadronisation to mesons and baryons vs multiplicity





High Mult

Λ_c/D⁰

Λ/K_s^0

Low Mult

Λ_c/D⁰

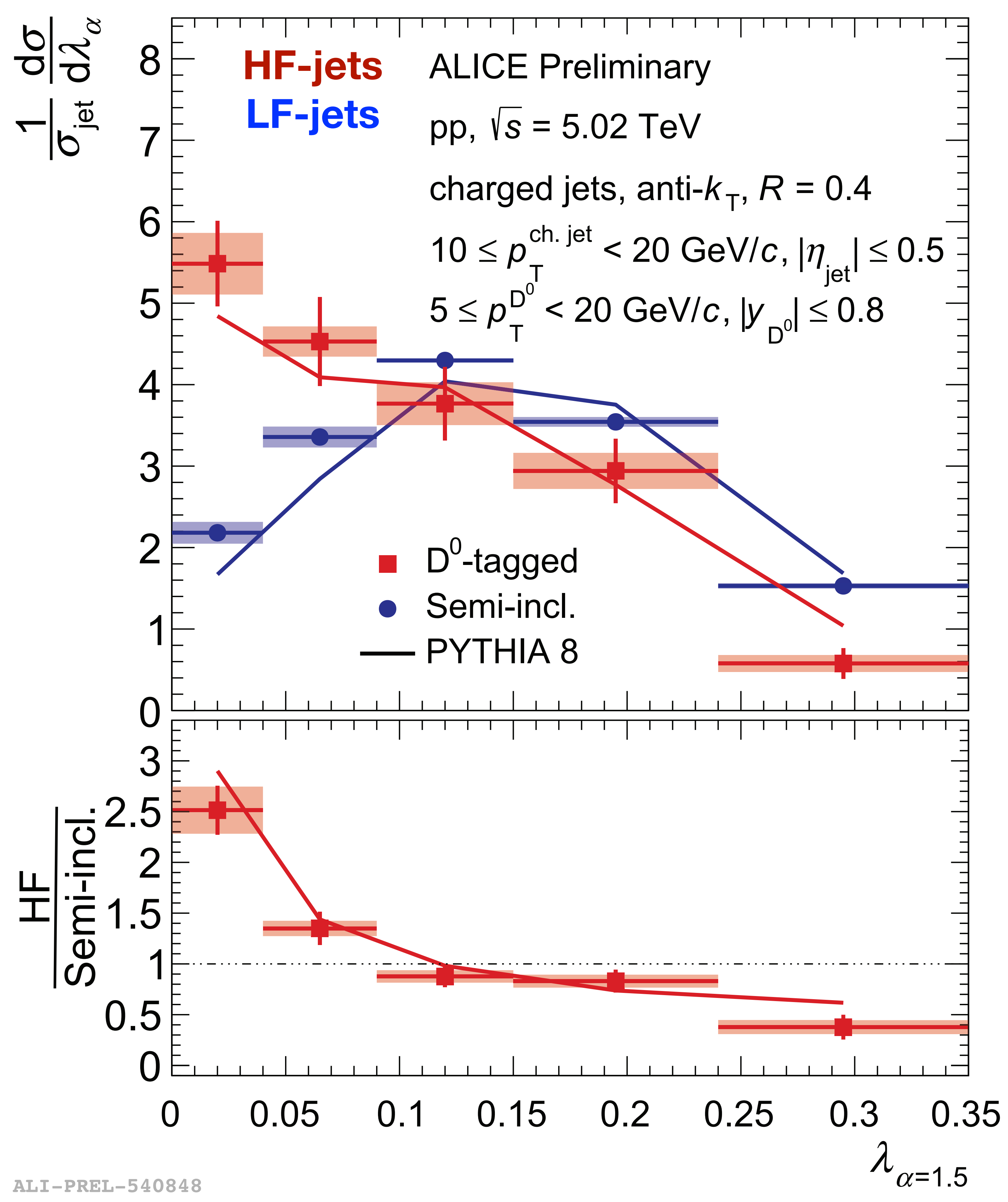
Λ/K_s^0

PLB 829 (2022) 1237065

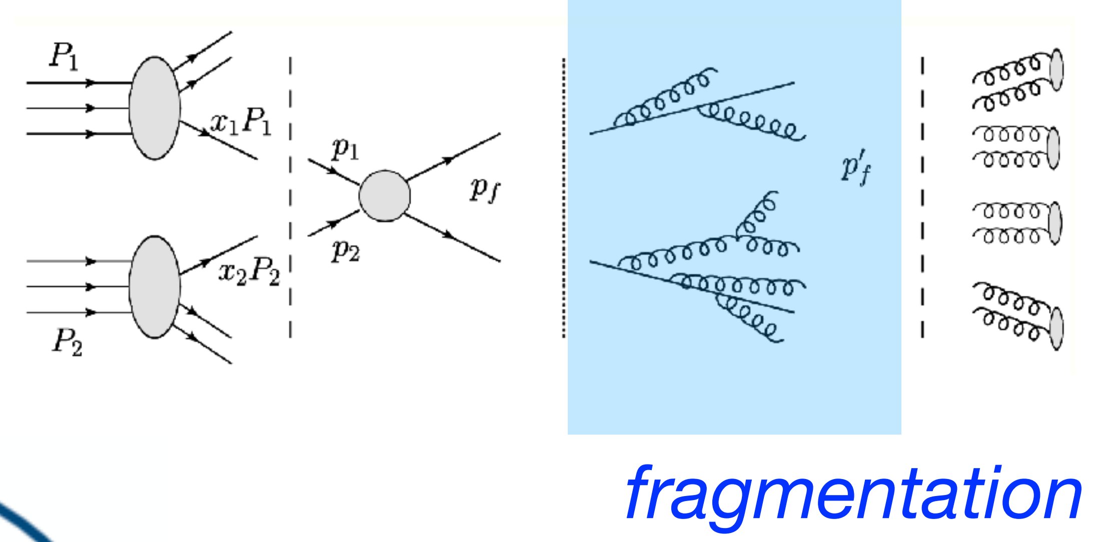
- Λ_c/D⁰ vs multiplicity from both forward mid rapidity multiplicity estimators.
  - Multiplicity dependent —> hierarchy from low to high multiplicity intervals for both multiplicity estimators.
- Λ_c/D⁰ compared with Λ/K^0_s in similar multiplicity classes.
  - Despite different production mechanism for light and heavy-favor quarks, both shows similar trend vs multiplicity.
  - Similar shift in peaks towards higher p_T with increasing multiplicity.
- Common mechanism for light- and charm-baryon formation in hadronic collisions at LHC energies.

Charm jet properties

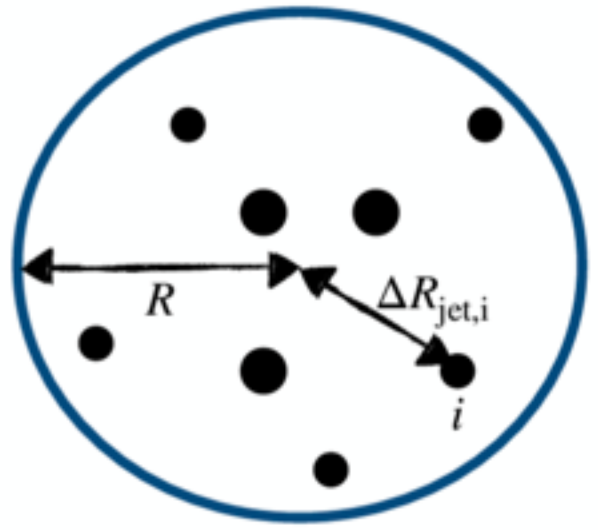
Charm jet substructure measurements



Jet Angularities: substructure observable dependent on p_T and angular distribution of tracks within jets.



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



More studies on fragmentation by Amanda Flores

Jet p_T fraction carried by constituent i

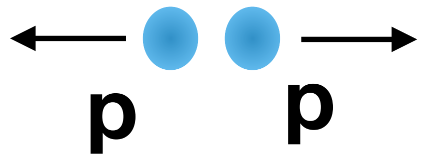
$\Delta R_{jet,i}$ distance of constituent i to the jet axis.

Infra red safe observable for $k = 1, \alpha > 0$ —> calculable in pQCD

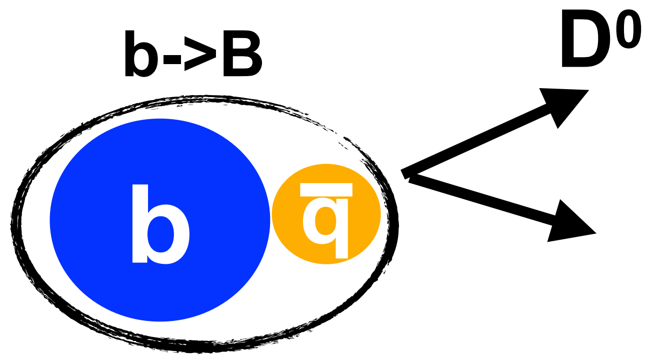
D⁰-tagged jets have lower angularities than semi-inclusive jets.

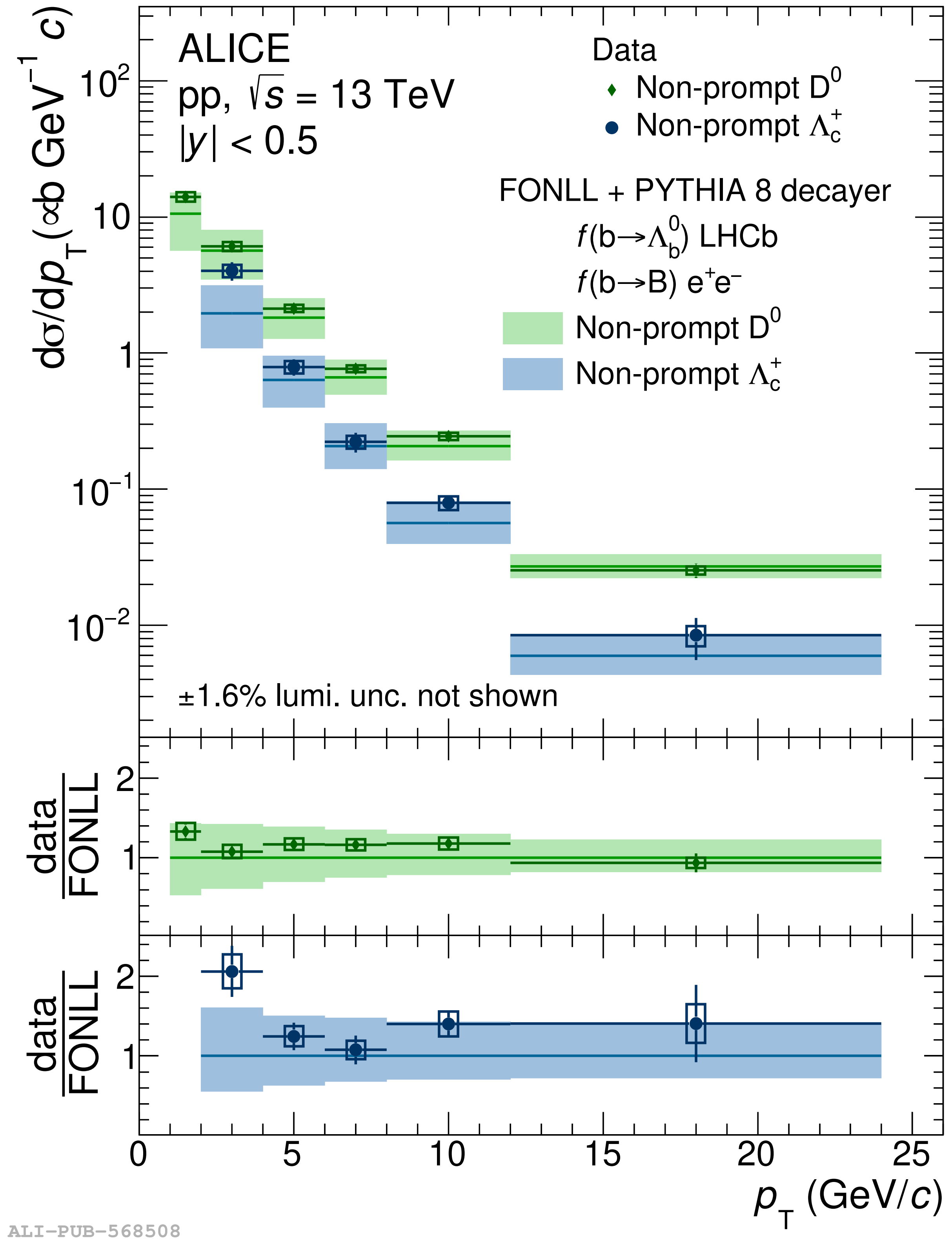
- HF jets more collimated than semi-inclusive jets
- PYTHIA describes angularities of charm-tagged jets better than semi-inclusive jets.

Beauty cross section

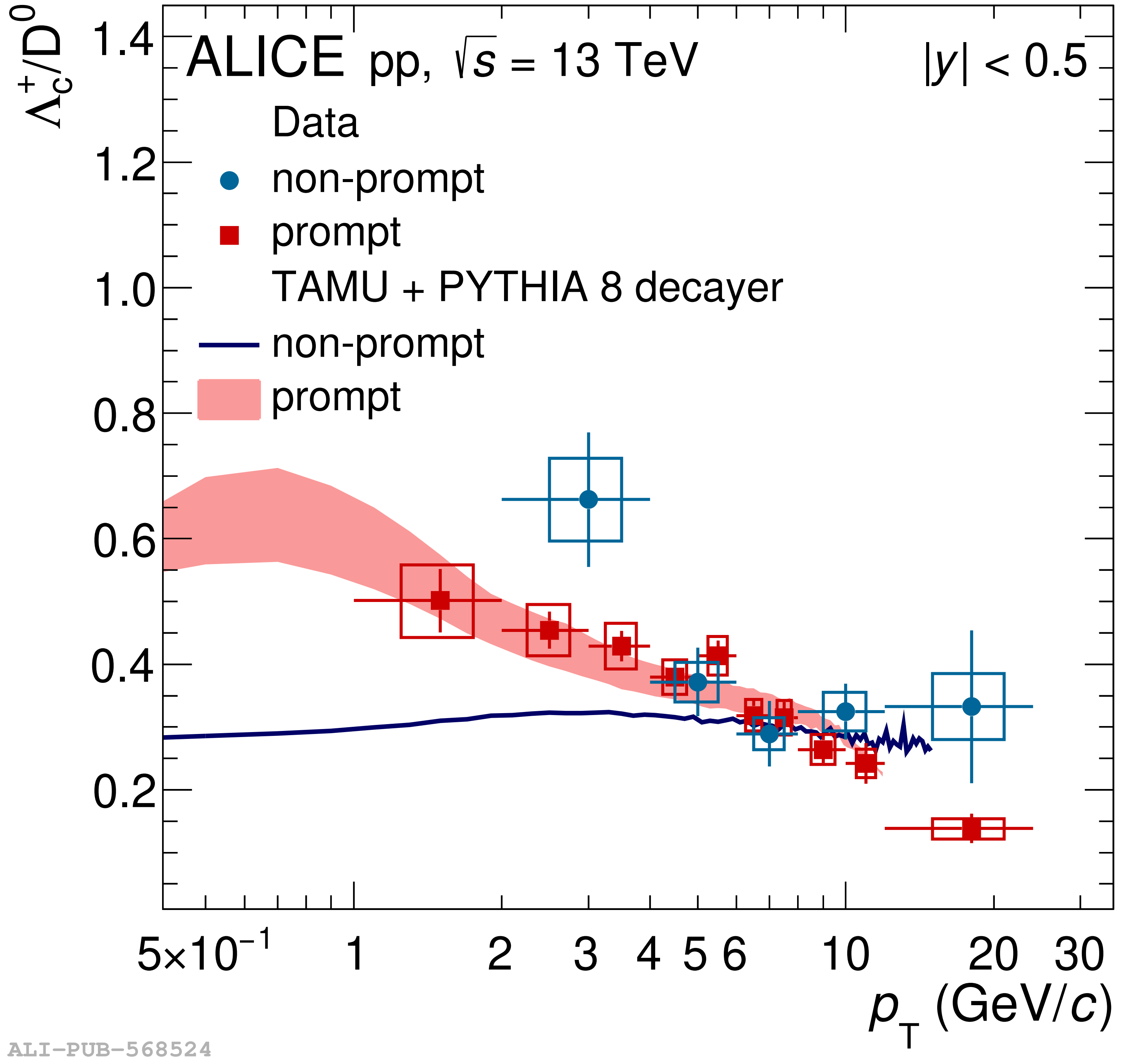


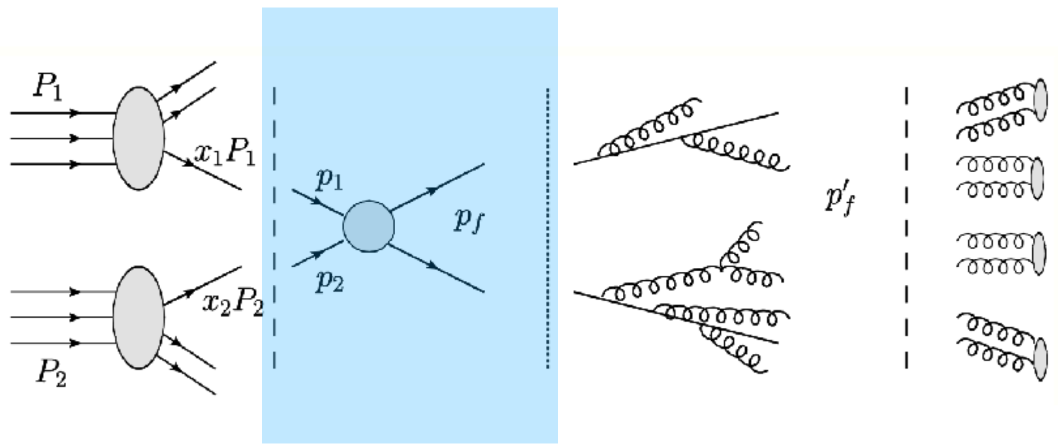
Beauty hadron measurements in pp collisions

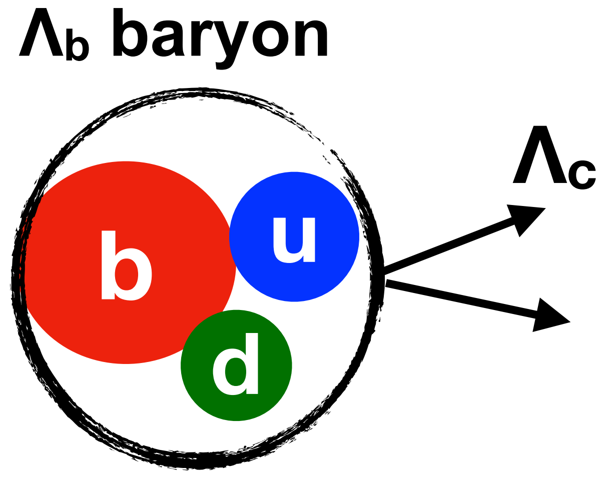




PRD 108, 112003 (2023)



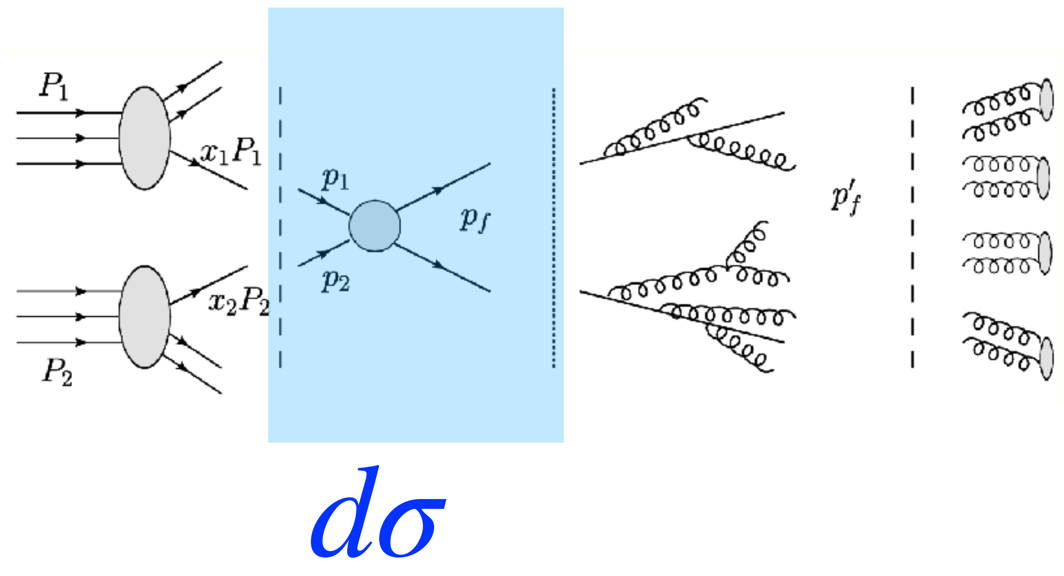




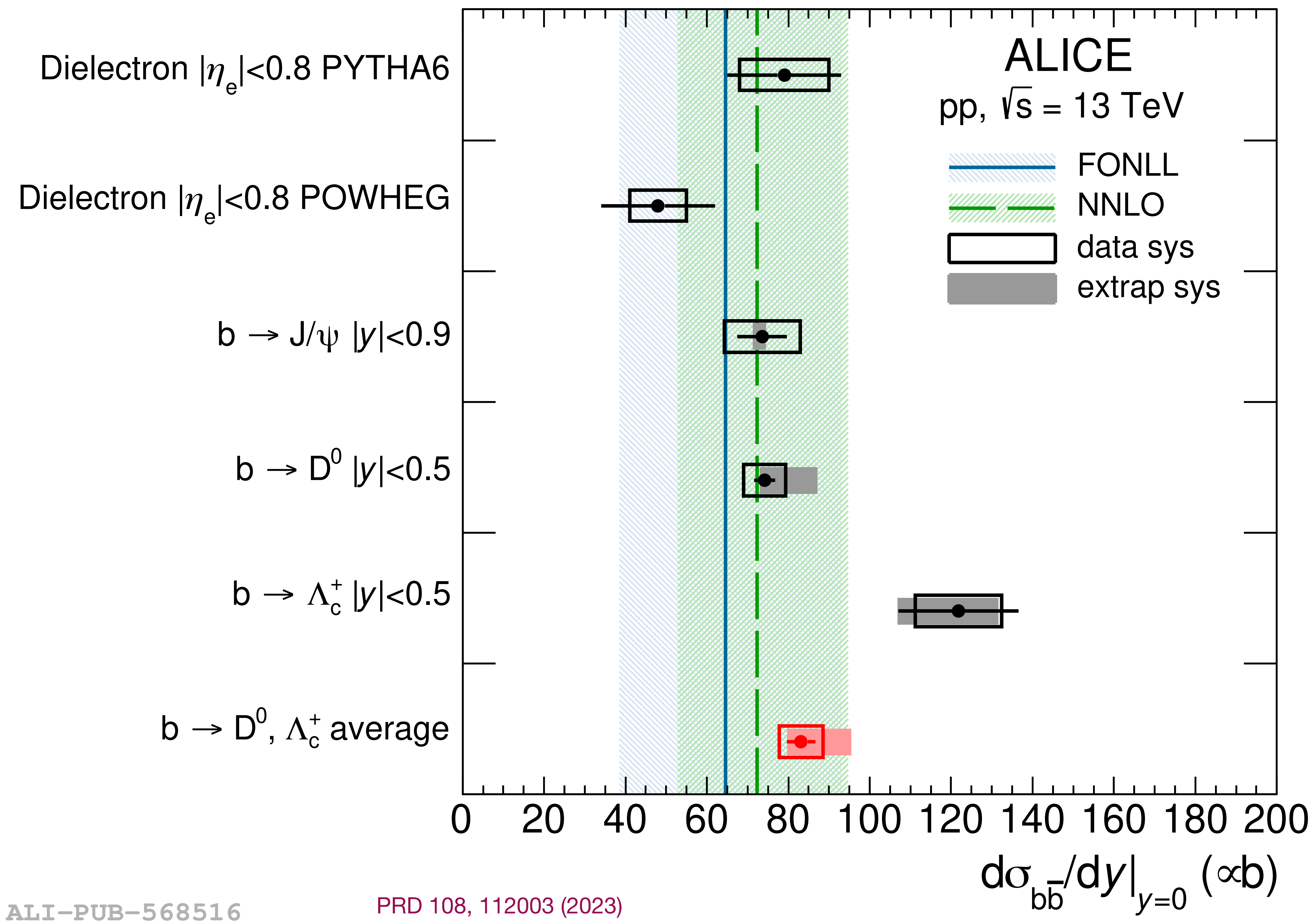
- p_T-differential cross sections of non-prompt D^0 (b—>D^0) and non-prompt Λ_c (b—>Λ_c) compared with FONLL and TAMU.
  - Theory predictions describe b—>D^0 in the full p_T range; Under predicts b—>Λ_c at low p_T.
- Most of non-prompt Λ_c originate from Λ_b^0-baryons; Non-prompt Λ_c/D^0 used to study beauty hadronization.
  - Prompt and non-prompt Λ_c/D^0 vs p_T similar, except at low p_T.
  - **TAMU prediction for non-prompt Λ_c/D^0 describes data for p_T > 4 GeV/c.**

Beauty cross section

p p



Total beauty cross sections measurements in pp collisions



PRD 108, 112003 (2023)

- Measured cross-section extrapolated to full p_T range using an extrapolation factor from FONLL+PYTHIA8 prediction.
  —> assuming accurate description of p_T shape outside the measured range.

Total $b\bar{b}$ cross-section compatible with dielectron and b—> J/ψ measurements and FONLL and NNLO calculations.

Charm hadron measurements in p—Pb

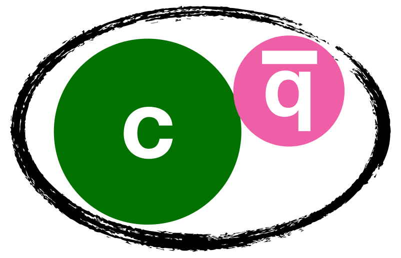
p Pb

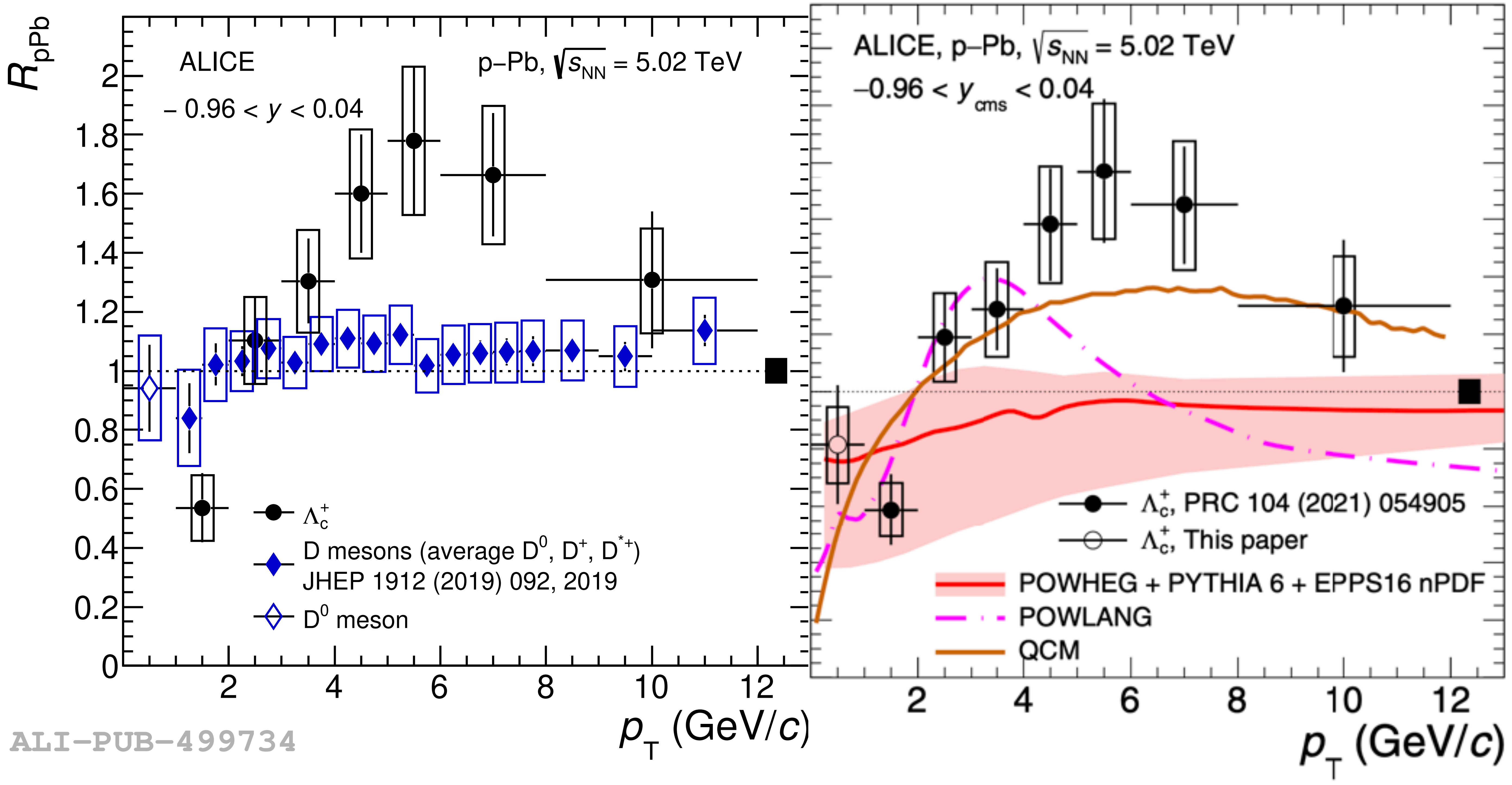
R_{pPb} of charm hadrons in p—Pb collisions

PRC 107 (2023) 064901
PRL 127 (2021) 202301
PRC 104 (2021) 054905
JHEP 12 (2019) 012

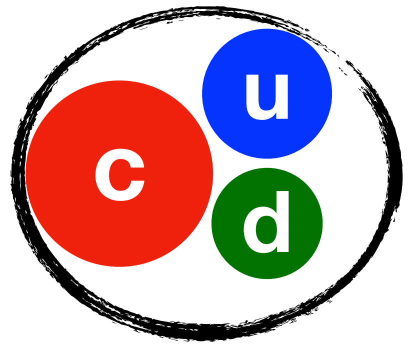
$$R_{pPb} = \frac{1}{A}\frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T}$$

D meson





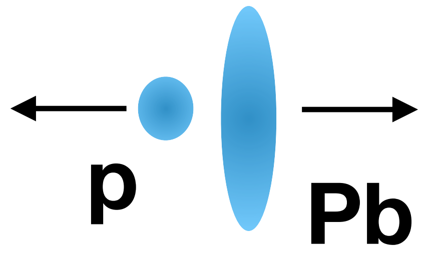
Λc baryon



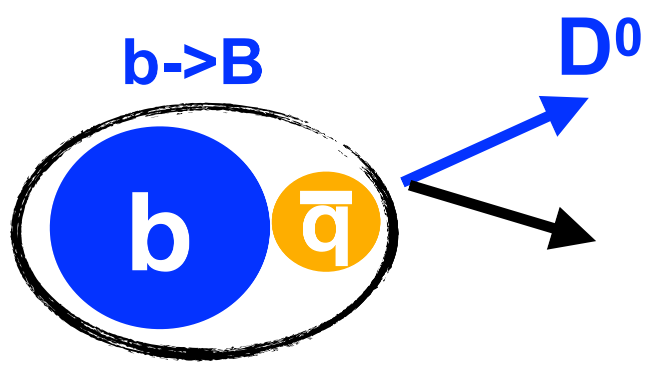
- R_{pPb}(D) ~ unity.
- R_{pPb} of D mesons and Λ_c similar for p_T < 4 GeV/c; At higher p_T, R_{pPb} of Λ_c > 1 and greater than D mesons for 4 < p_T < 8 GeV/c.
  - Possible suppression of Λ_c at low p_T and enhancement at mid-p_T w.r.t pp collisions.

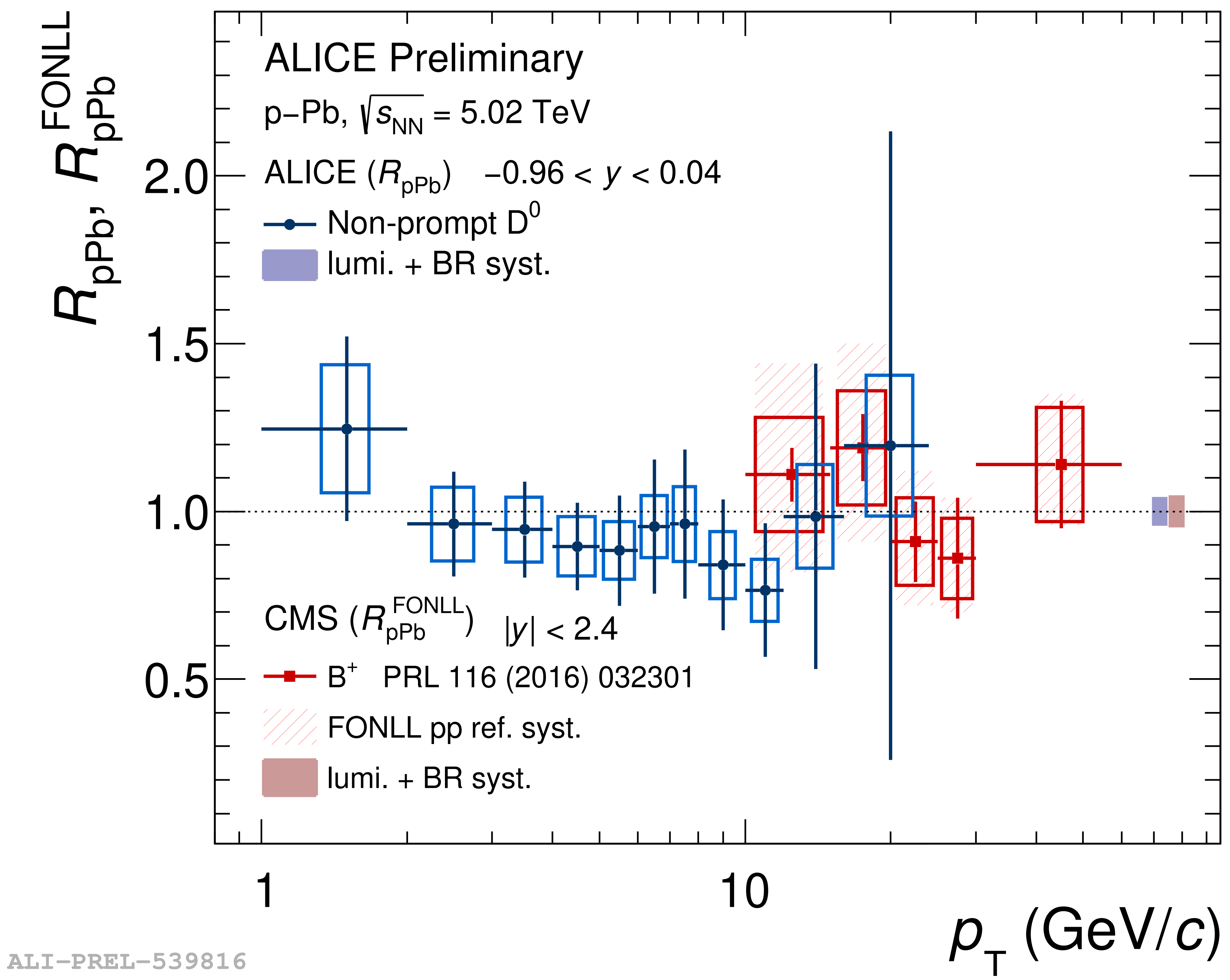
- R_{pPb} of Λ_c compared with POWHEG+PYTHIA (CNM effects), POWLANG (QGP) and QCM (coalescence) models.
  - QCM model gives closest description of the data in full p_T range.

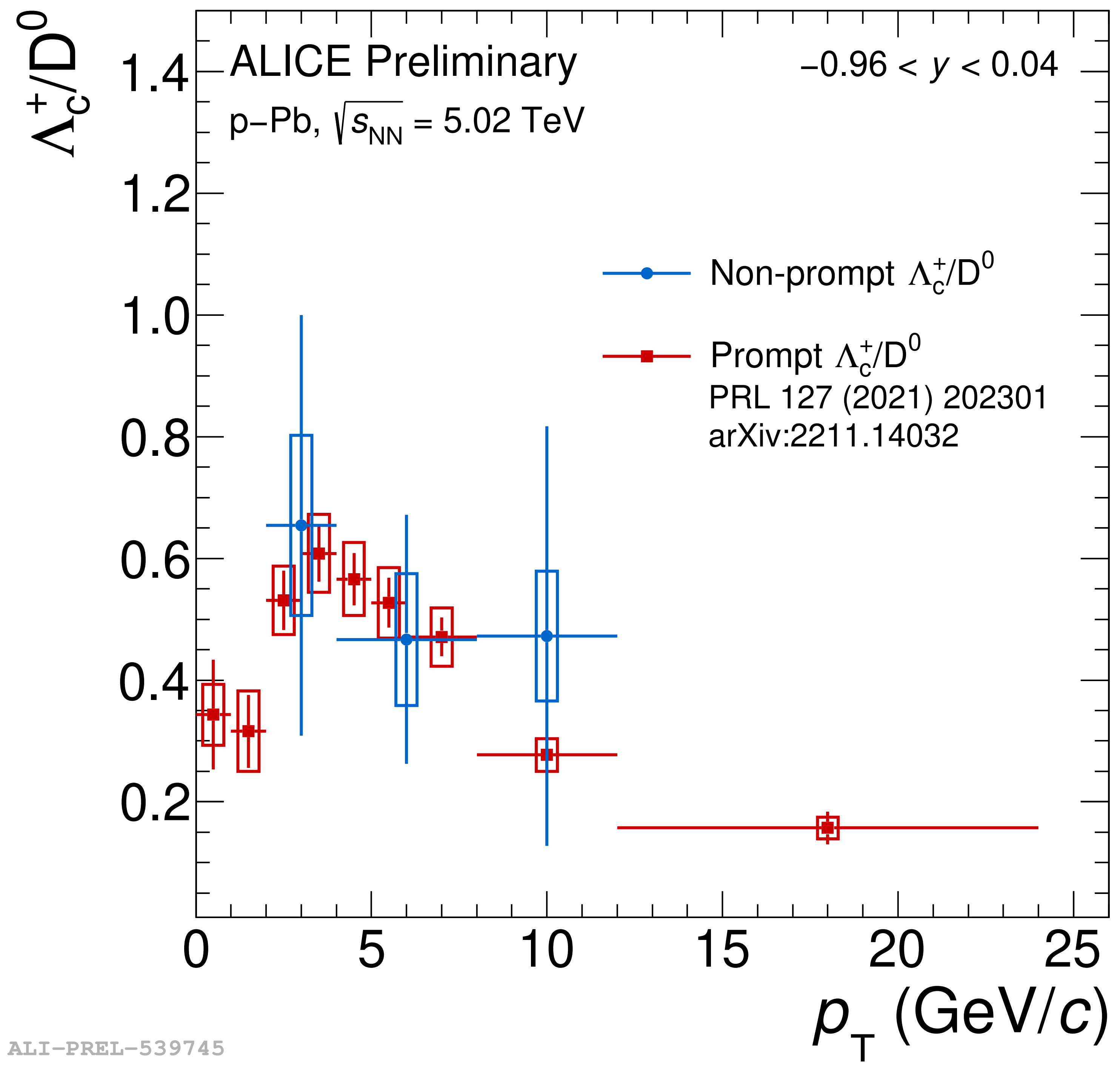
Beauty hadron measurements in p—Pb

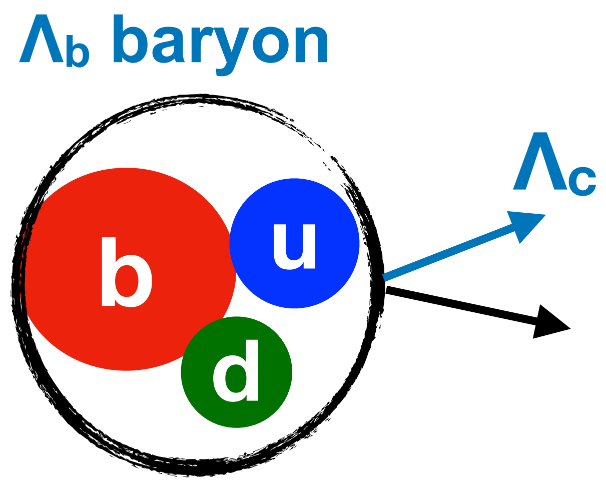


R_{pPb} of beauty hadrons in p—Pb collisions







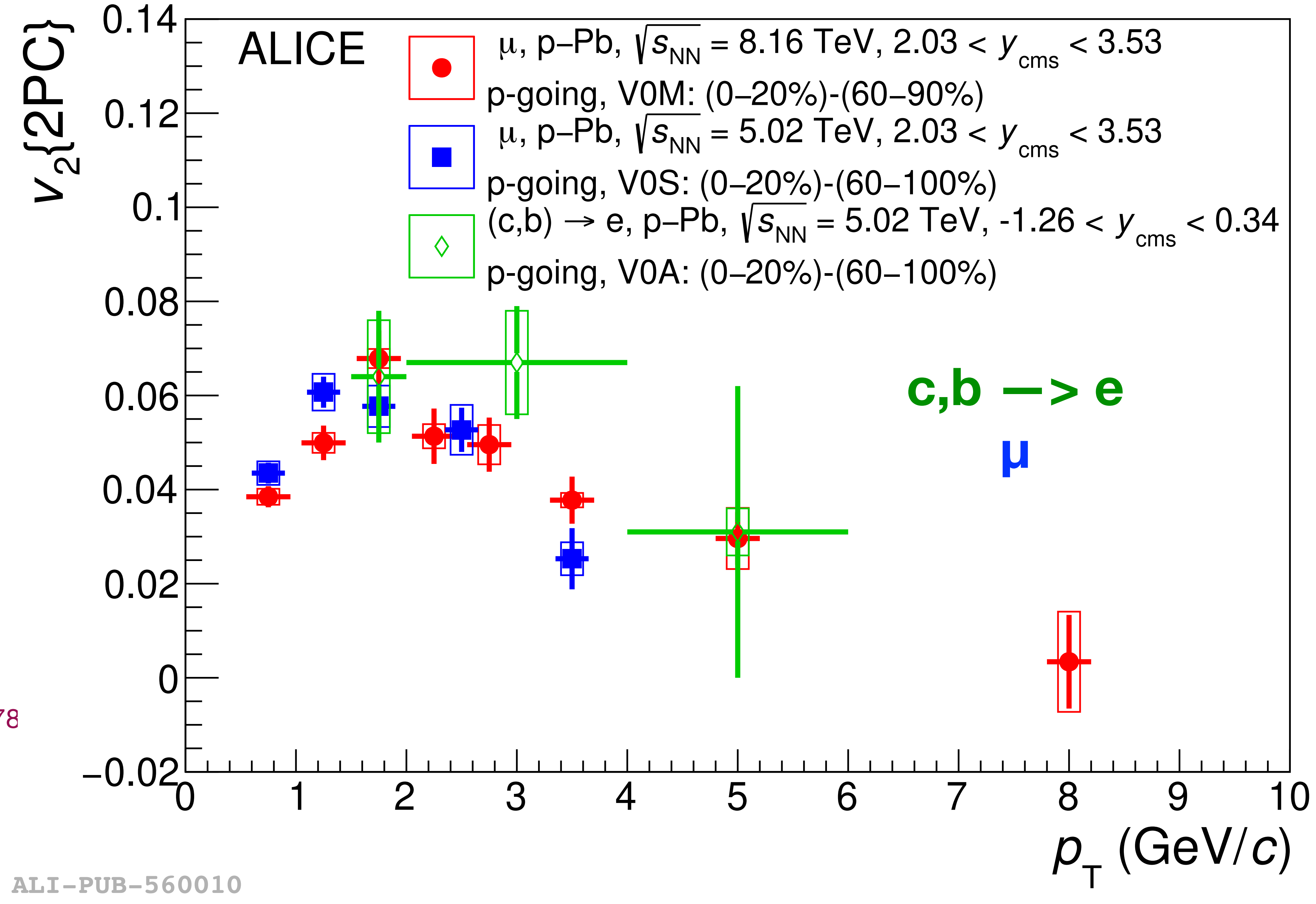


- R_{pPb}(b—>D⁰) ~ unity.
- R_{pPb}(b—>D⁰) consistent with R_{pPb}(B) from CMS at high p_T.
- Not significantly affected by cold-nuclear effects.

- Most of non-prompt Λ_c originate from Λ_b^0-baryons; Non-prompt Λ_c/D⁰ used to study beauty hadronization.
  - Similar p_T trends for prompt and non-prompt Λ_c/D⁰.

Azimuthal anisotropy in small systems

v_2 of HF particles in high multiplicity p—Pb collisions.



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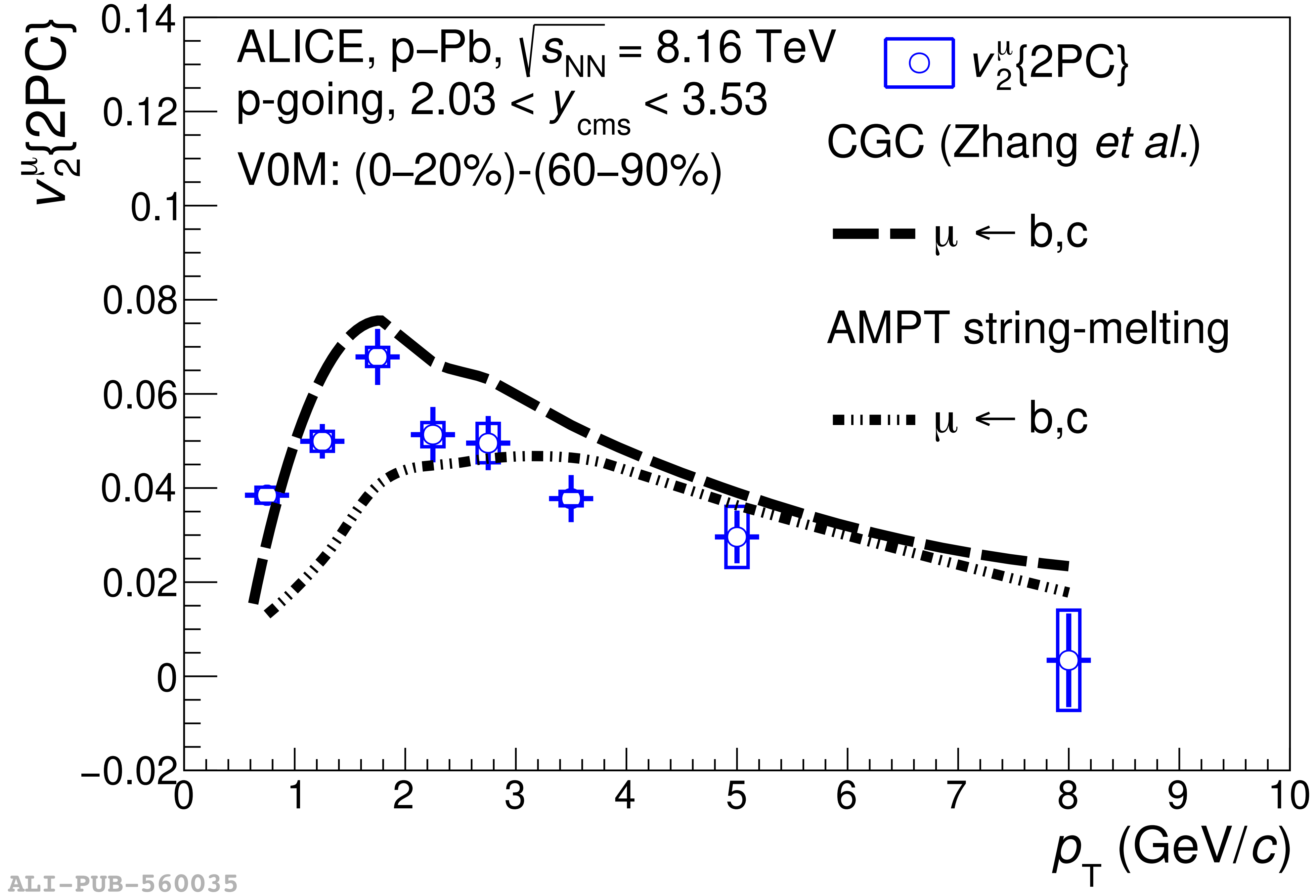


- v_2 of inclusive muons (dominated by HF decays at high p_T) at forward rapidity compared with c,b —> e at mid-rapidity.
  - Good agreement within uncertainties.

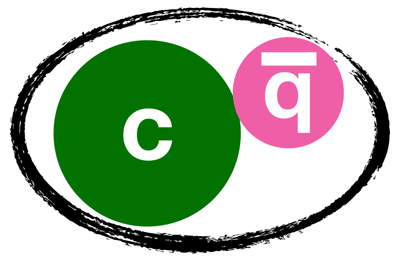
- Data compared with predictions from CGC and AMPT models for c,b —> μ
  - AMPT: v_2 driven by the anisotropic parton escape mechanism
  - CGC: correlations between partons in the initial stages generate a v_2
- **Both models describe data at high p_T**

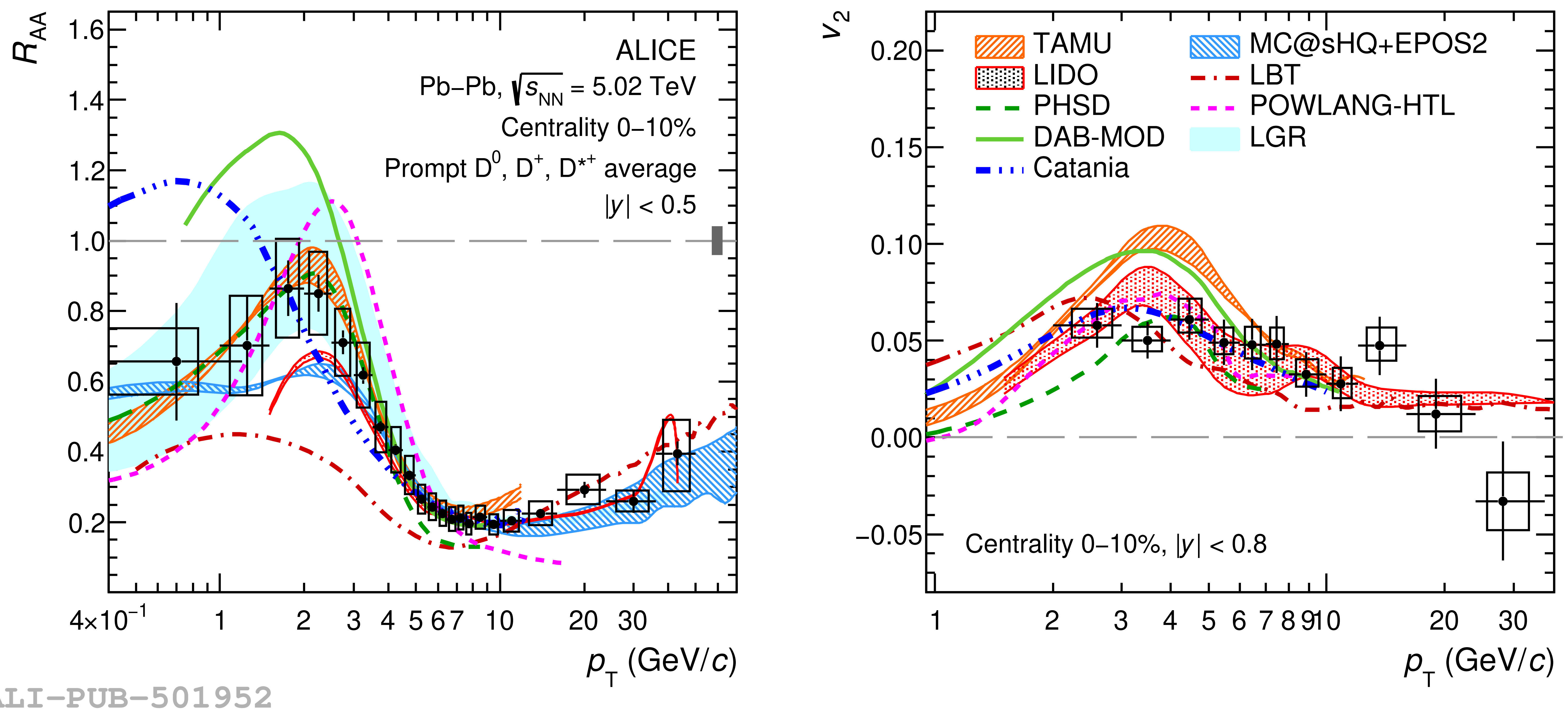
Charm quark in Pb-Pb collisions

Charm quark interaction and energy loss in the QGP

$$R_{AA} = \frac{1}{< N_{coll} >} \frac{Y_{AA}}{Y_{pp}}$$

D meson





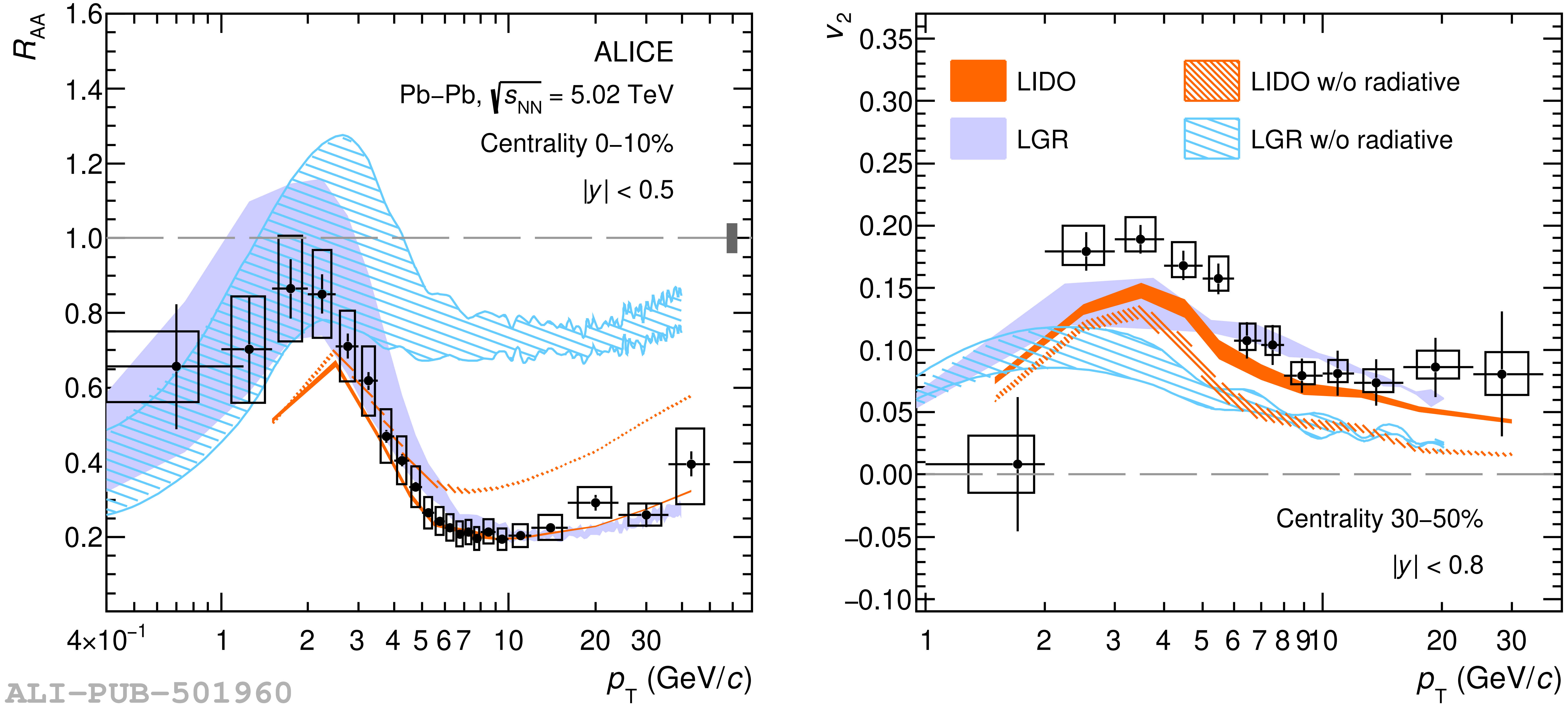
$$v_2 = < \cos[2(\phi - \Psi_2)] >$$

JHEP 01 (2022) 174 ALI-PUB-501952

- Understanding interaction and energy loss of heavy quarks in the QGP over time —> Simultaneous comparison of D-meson R_{AA} and v_2
- Interplay of CNM effects, realistic evolution of the QGP, heavy-quark interaction (radiative and/or collisional) and hadronization via coalescence and/or fragmentation required to describe data.
- Models provide fair description of data —> still challenging for models to describe R_{AA} and v_2 simultaneously in the full p_T range.

Understanding HQ interaction with QGP

Model calculations with and without radiative energy loss

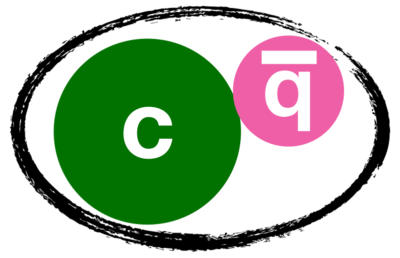


JHEP 01 (2022) 174

D mesons

Model (LIDO & LGR)
Model w/o radiative E. loss

D meson

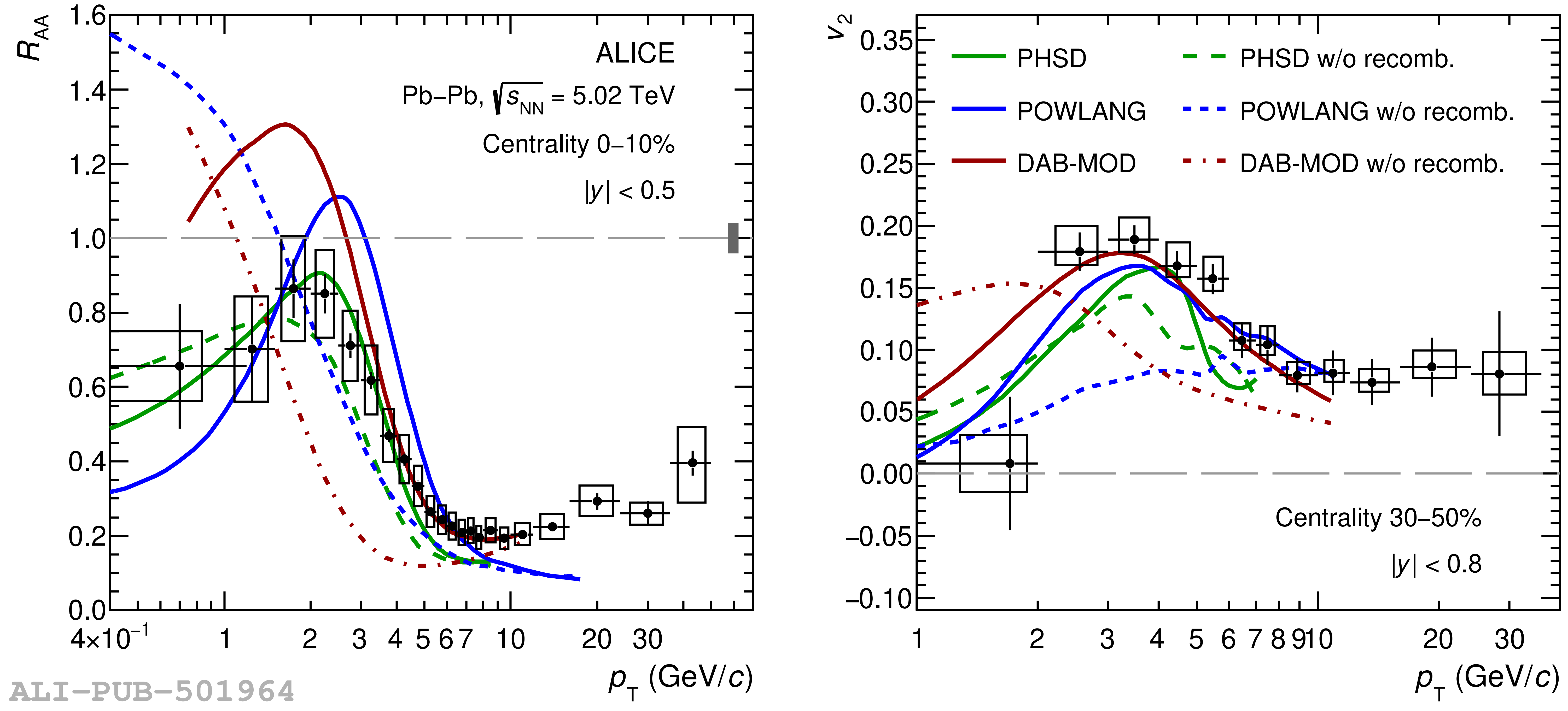


- Radiative energy loss important to describe intermediate and high p_T.

Understanding HQ interaction with QGP

Model calculations with different hadronization process

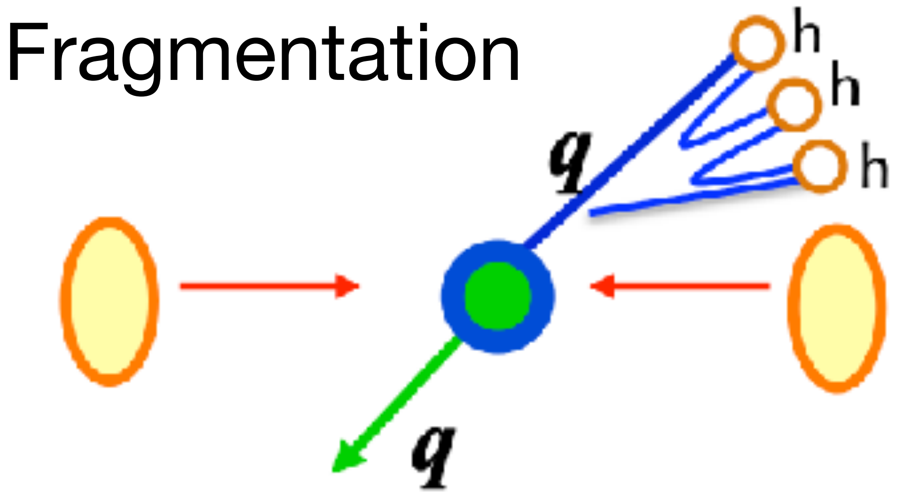
D mesons



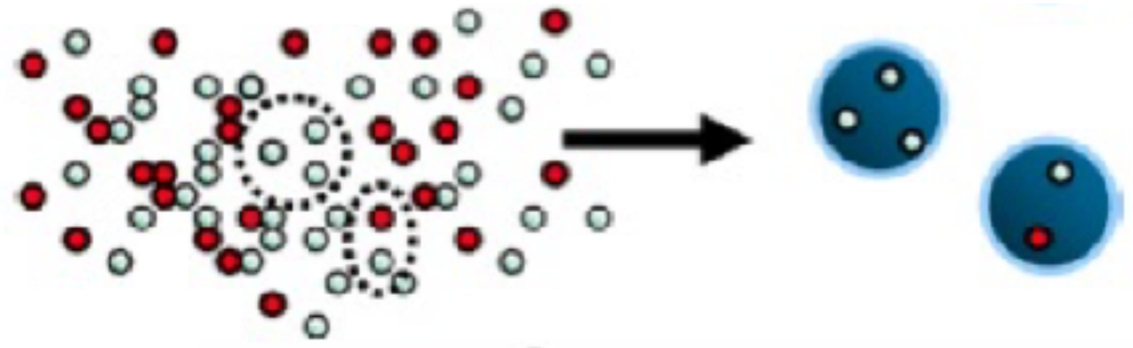
JHEP 01 (2022) 174

Model (PHSD, POWLANG, DAB-MOD)
Model w/o coalescence

Fragmentation



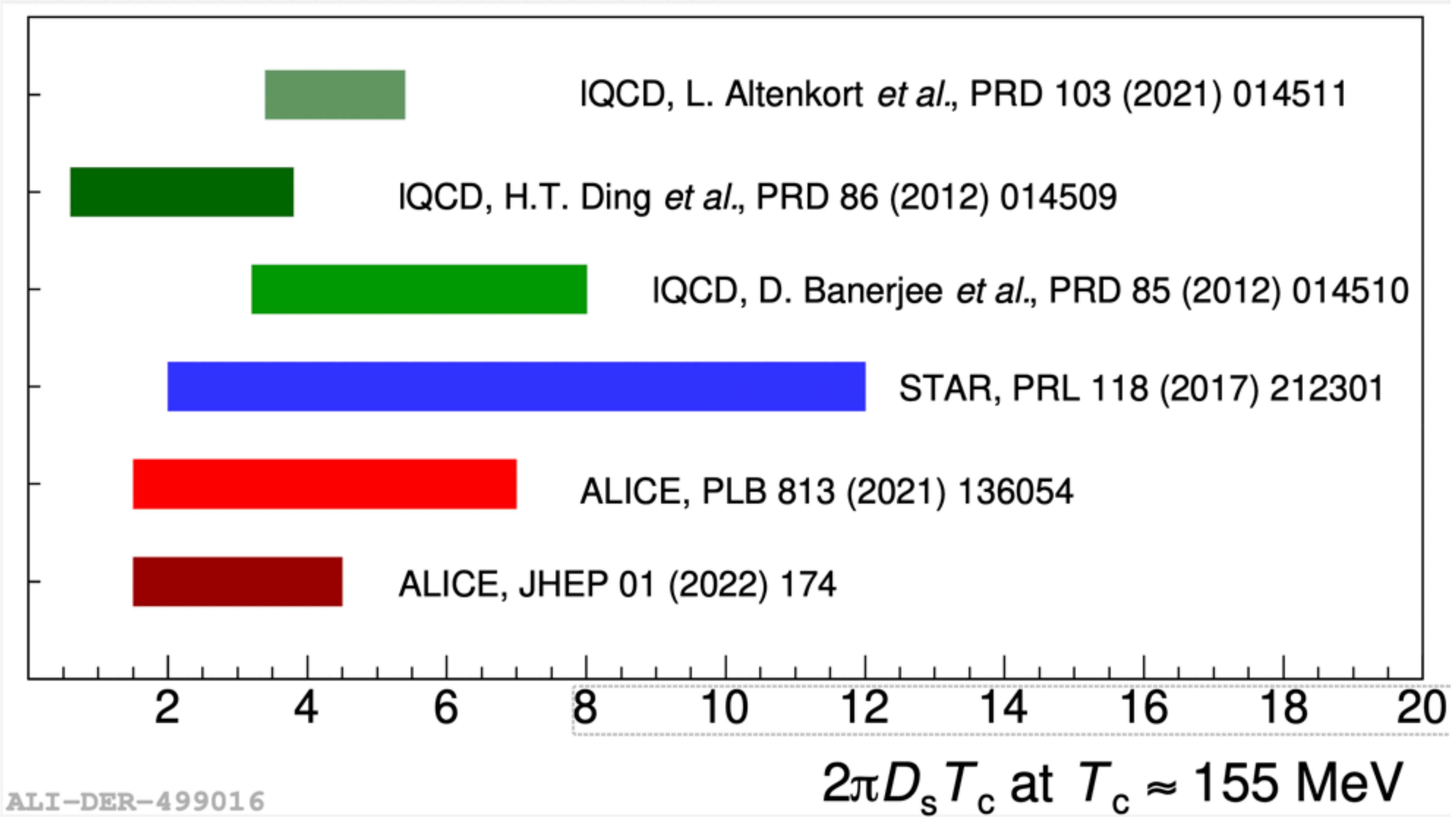
Coalescence



- Hadronization via coalescence important to describe low and intermediate p_T.

Heavy-flavor transport coefficients

Using data to constraint model parameters : compute χ^2/ndf between measurements and model predictions



χ^2/ndf < 5

JHEP 01 (2022) 174

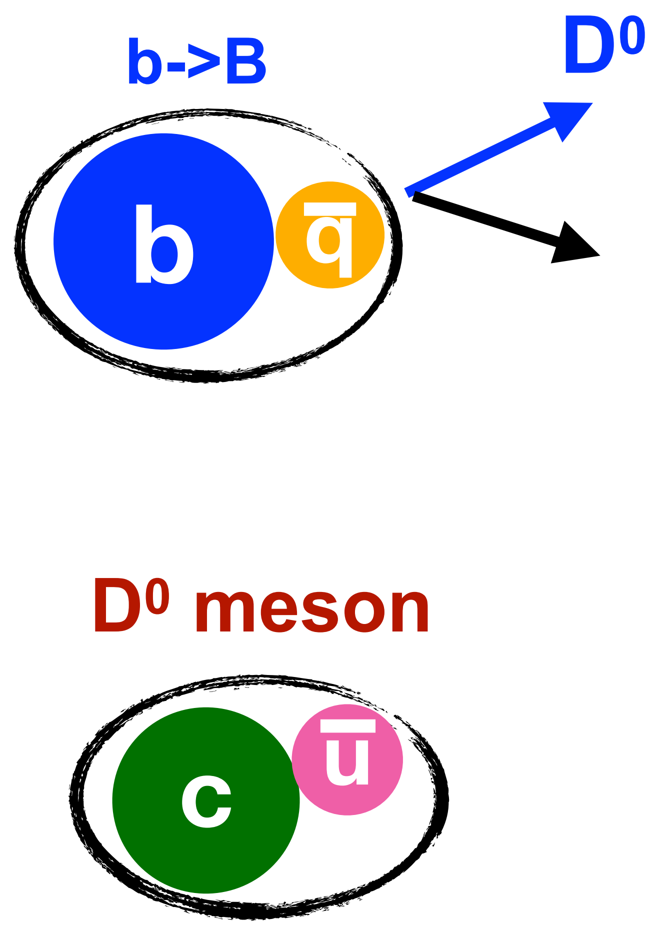
Models use spacial diffusion coefficient at T_c: 1.5-4.5

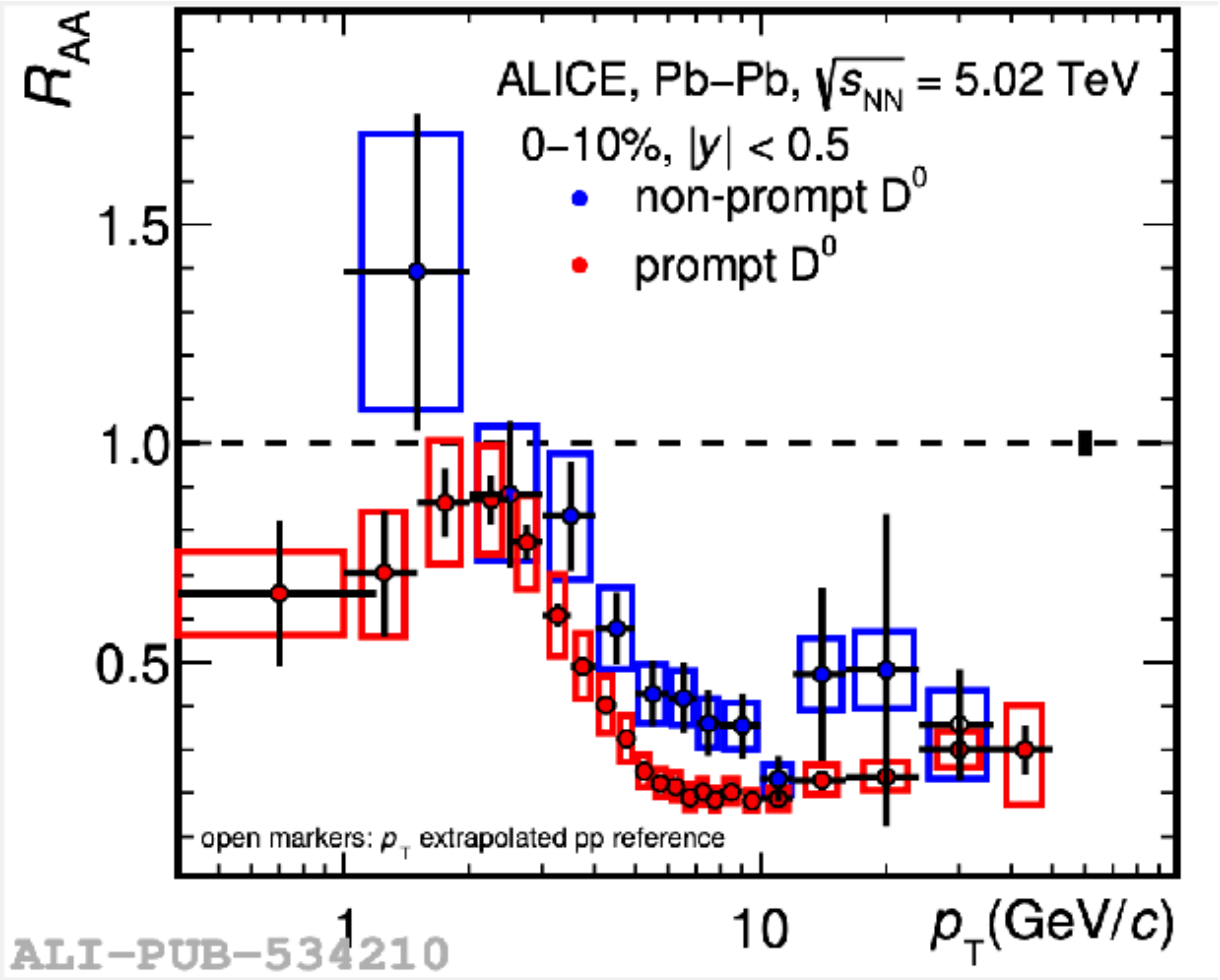
—> Thermalization time for charm quark: 3 - 9 fm/*c*

Beauty Quark Energy Loss

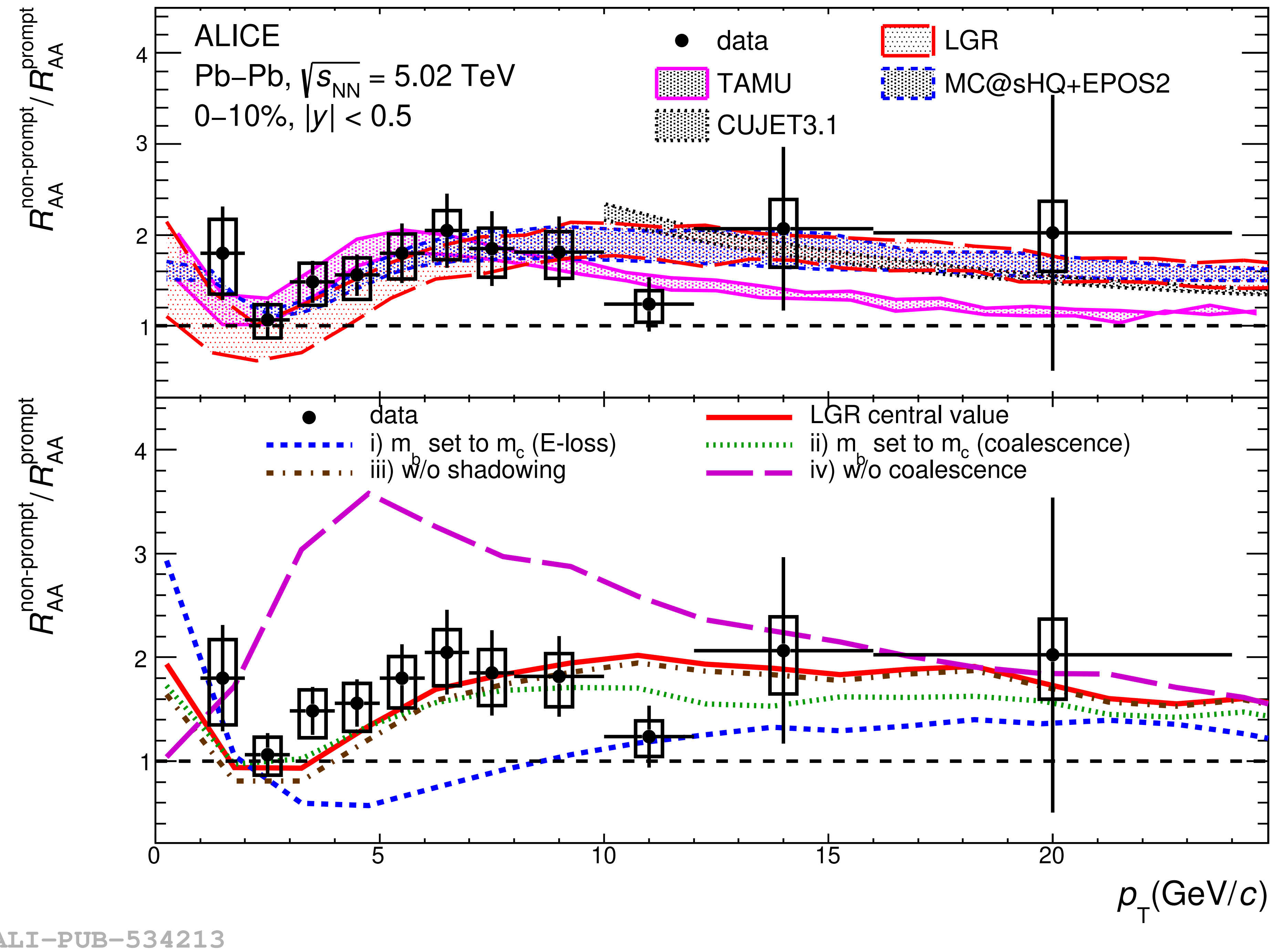
Beauty quark interaction and energy loss in the QGP —> less diffusion and longer relaxation time than charm

$$\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b) => R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$$





JHEP 12 (2022) 126



R_{AA}(b->D⁰) / R_{AA}(D⁰)

LGR

LGR w/o coalescence

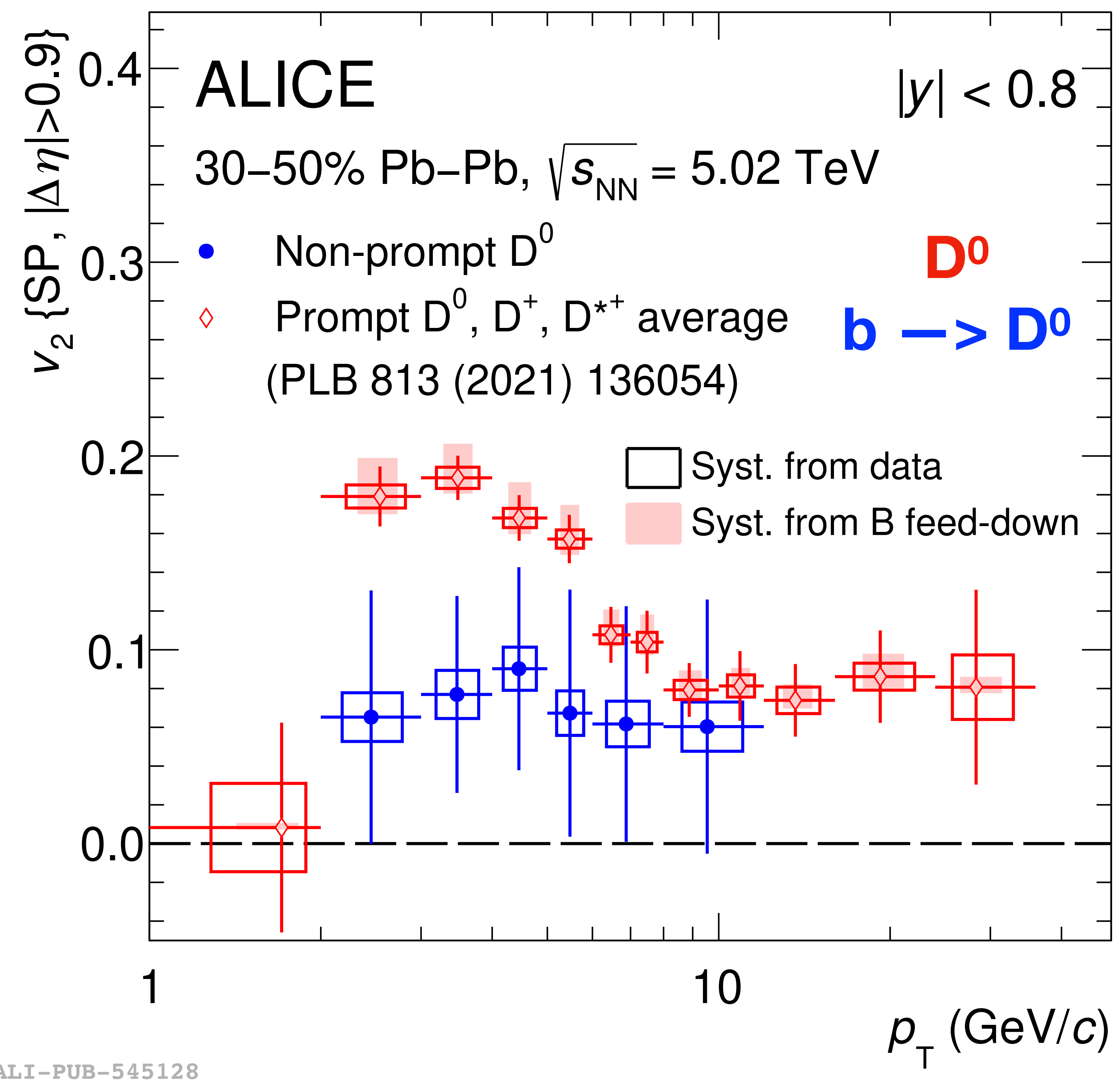
Intermediate p_T (5-20 GeV/c): R_{AA}(b) > R_{AA}(c)

High p_T: R_{AA}(b) ~ R_{AA}(c)

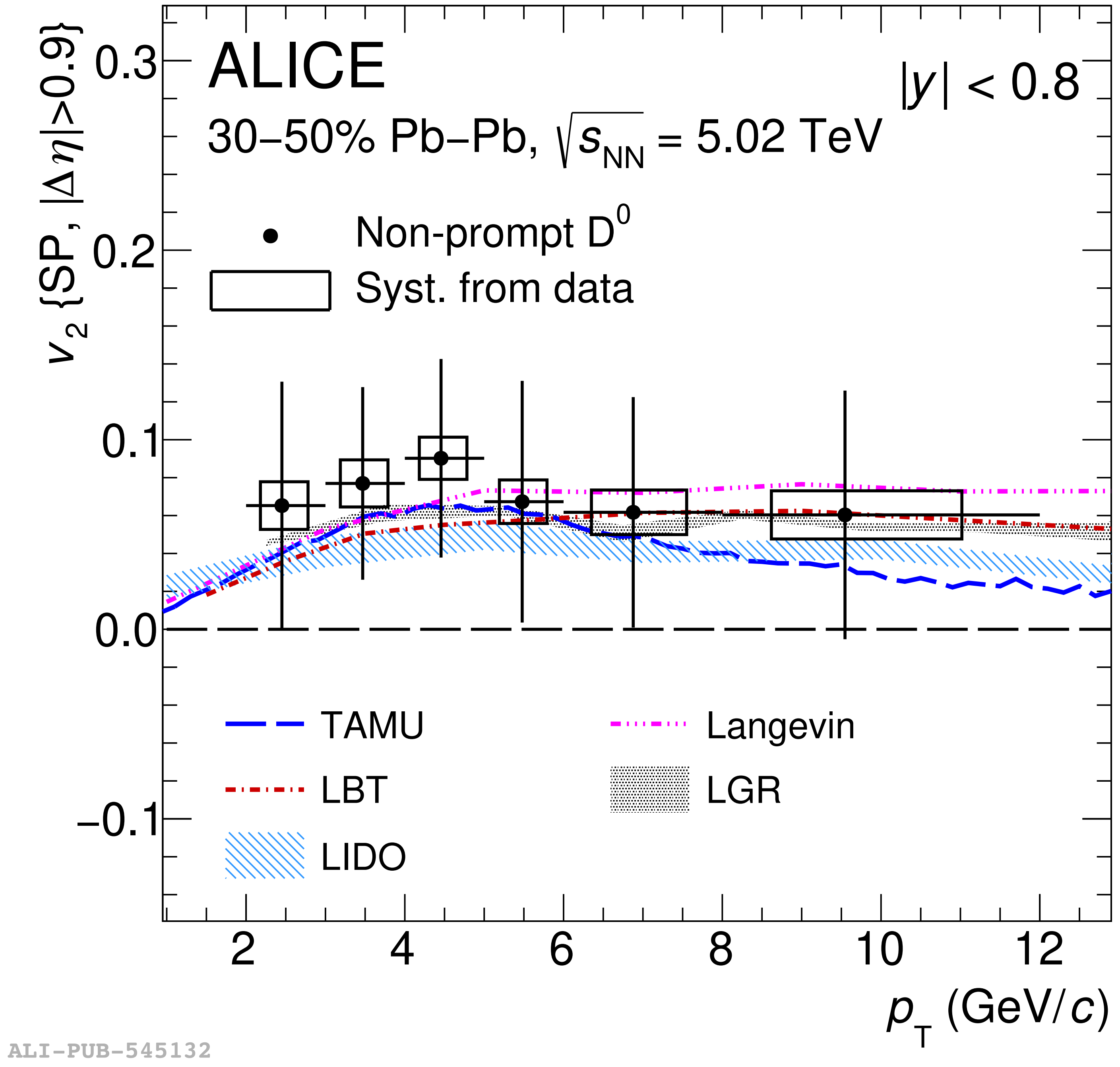
- Qualitatively described by models: smaller b quark energy loss + dead cone for gluon radiation
- Dip due to formation of D and B mesons via coalescence harding the D p_T spectra

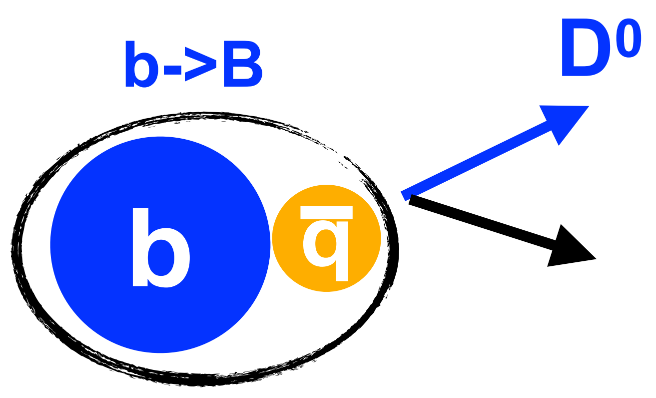
v_2 of Beauty Quarks

Probe beauty quark interaction with QGP and hadronizarion via recombination with light quark at low-intermediate p_T, path length dependent energy loss at high p_T.



EPJC 83 (2023) 1123

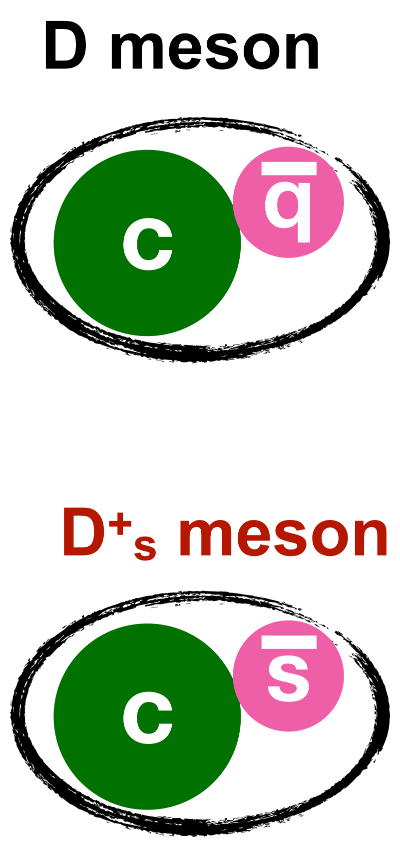


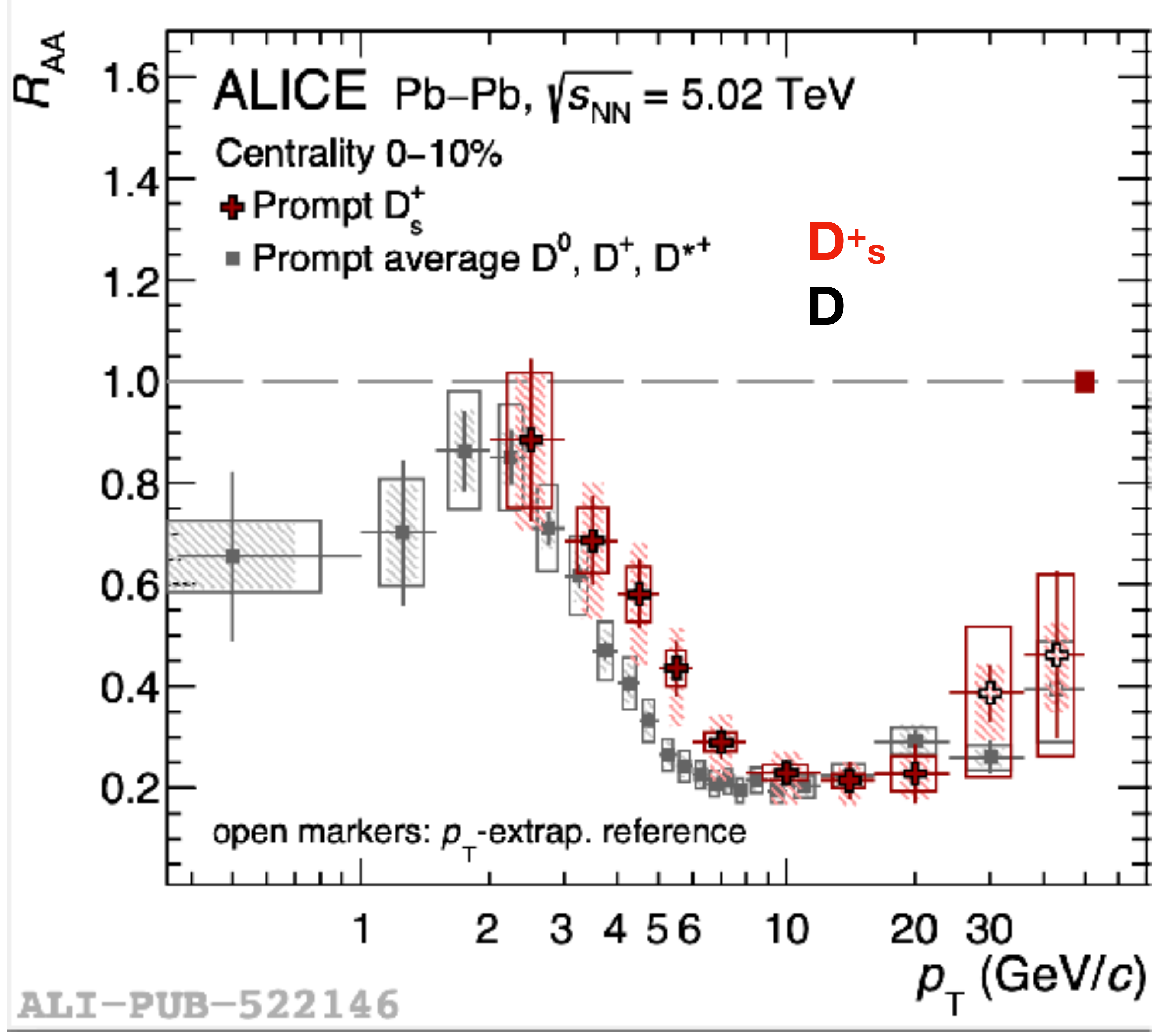


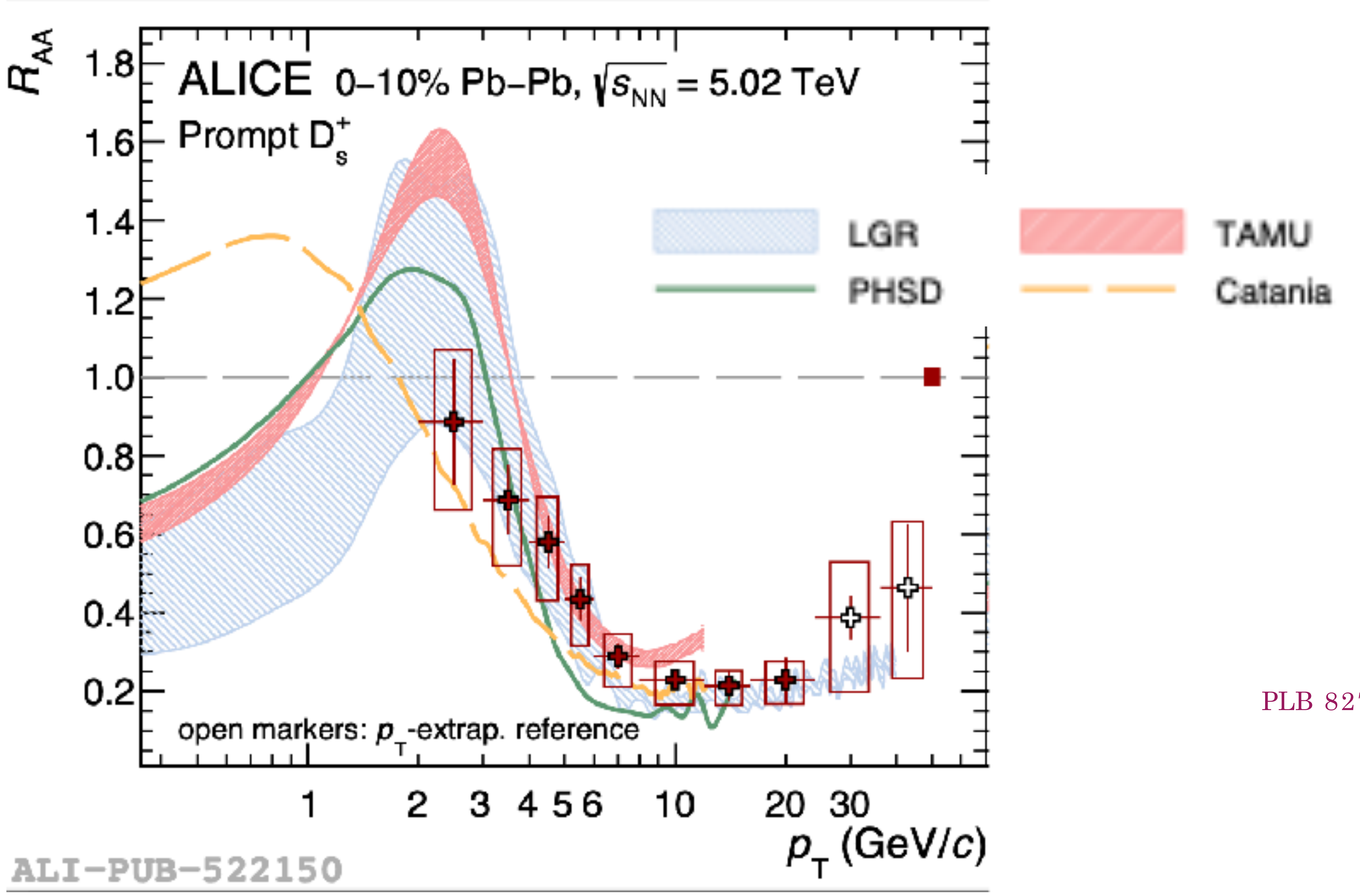
- v_2(b->D0) > 0; no strong p_T dependence;
- v_2(b->D0) < v_2(D) with 3.6σ significance.
- Theory models beauty quark transport in QGP —> give reasonable description of data.
  - All models, except TAMU (collisional only) include collisional interactions and radiative processes
  - Hadronisation via coalescence and fragmentation.

Prompt D_s^+ production

Probe hardronization via recombination in the strangeness rich environment using D_s^+







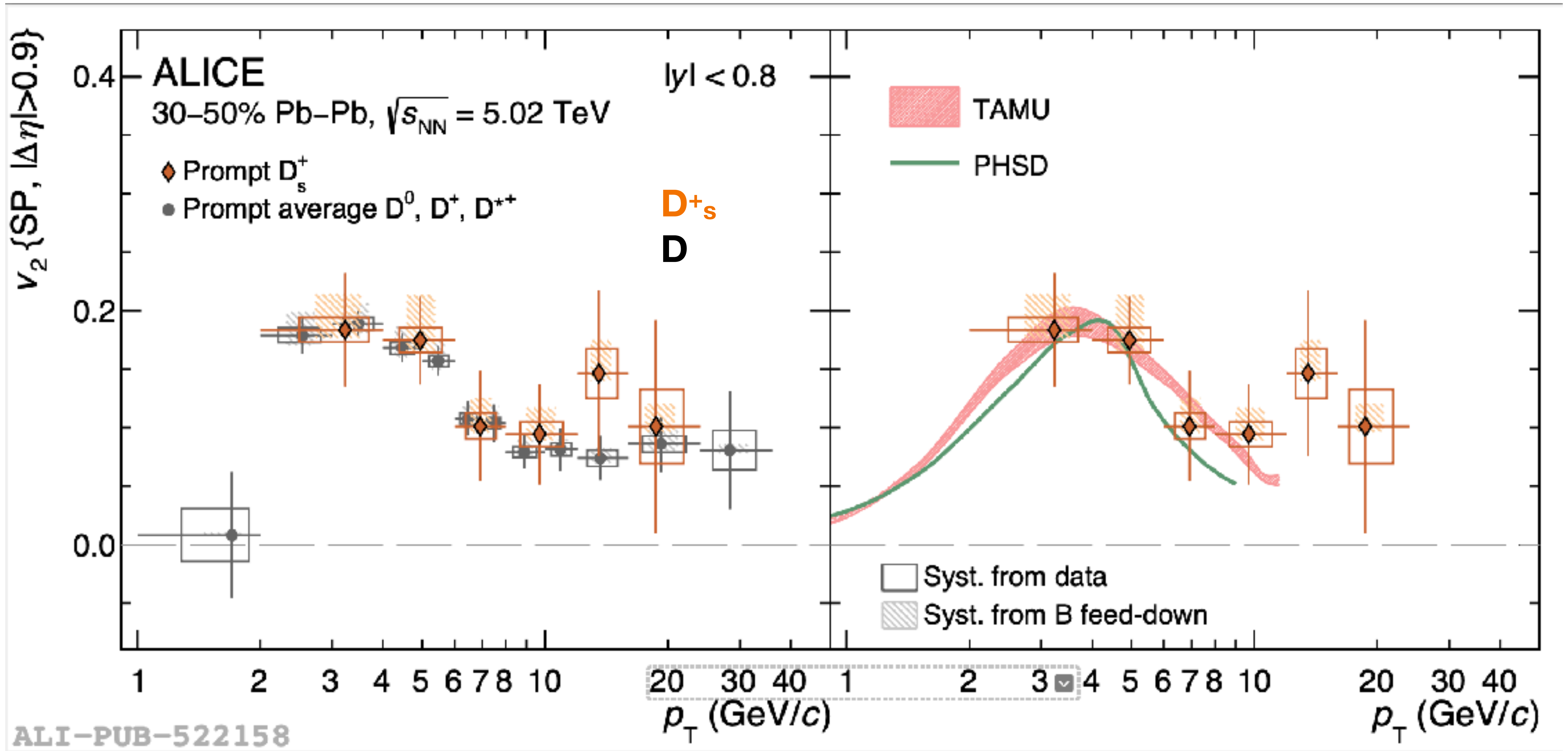
PLB 827 (2022) 136986

- ***R_{AA}*(D_s^+) > *R_{AA}*(D) for p_T < 10 GeV/*c*** —> recombination with abundantly produced strange quarks in the QGP.
- $R_{AA}(D_s^+)$ ~ R_{AA}(D) for p_T > 10 GeV/*c* —> hadronization via fragmentation.

- Comparison with models:
  - All models include enhancement of strangeness content of the QGP, hadronisation via recombination/coalescence at low p_T and fragmentation at high p_T.
  - **All models reproduce the p_T trend qualitatively.**
  - LGR model, which includes collisional and gluon-radiation processes for charm quark E.loss, best describes in the full p_T range.

v_2 of D^+_s

Probe hardronization via recombination in the strangeness rich environment using D^+_s



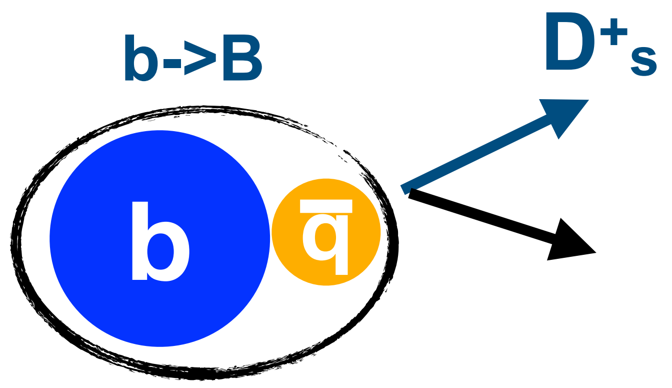
PLB 827 (2022) 136986

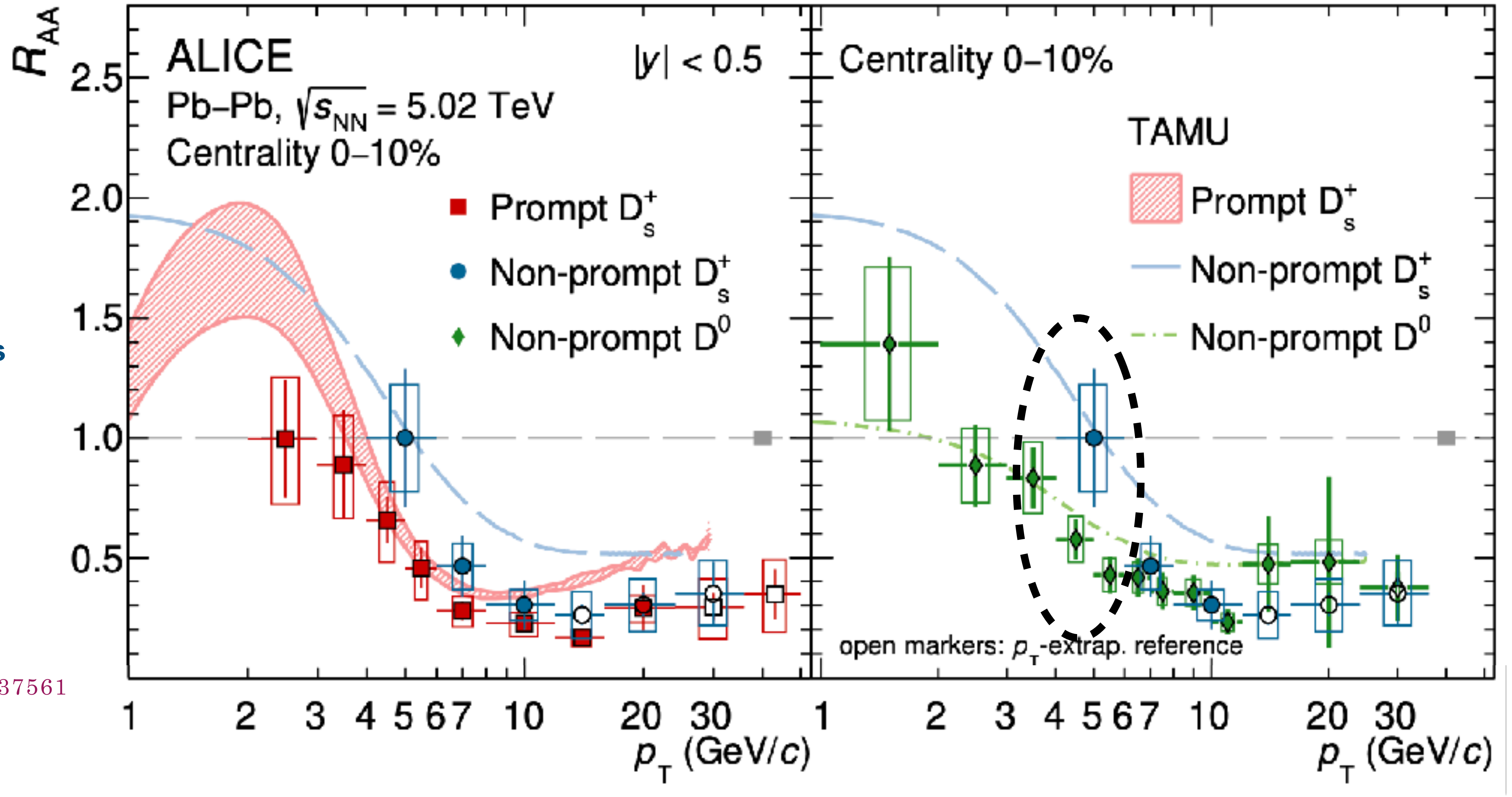
- $v_2(D^+_s)$ vs $v_2(D)$
  - Different mass
  - Recombination with strange vs light quarks
  - Different freeze out times in the hadronic phase
- **$v_2(D^+_s)$ ~ $v_2(D)$** in the full p_T range within uncertainties.
- TAMU and PHSD models describes the data.
  - Charm quark coalescence with flowing strange quarks in the QGP.

b—>D$^{+}_{s}$ quark

Pb Pb

Probe hardronization via recombination using non-prompt D$^{+}_{s}$ (b—>D$^{+}_{s}$)





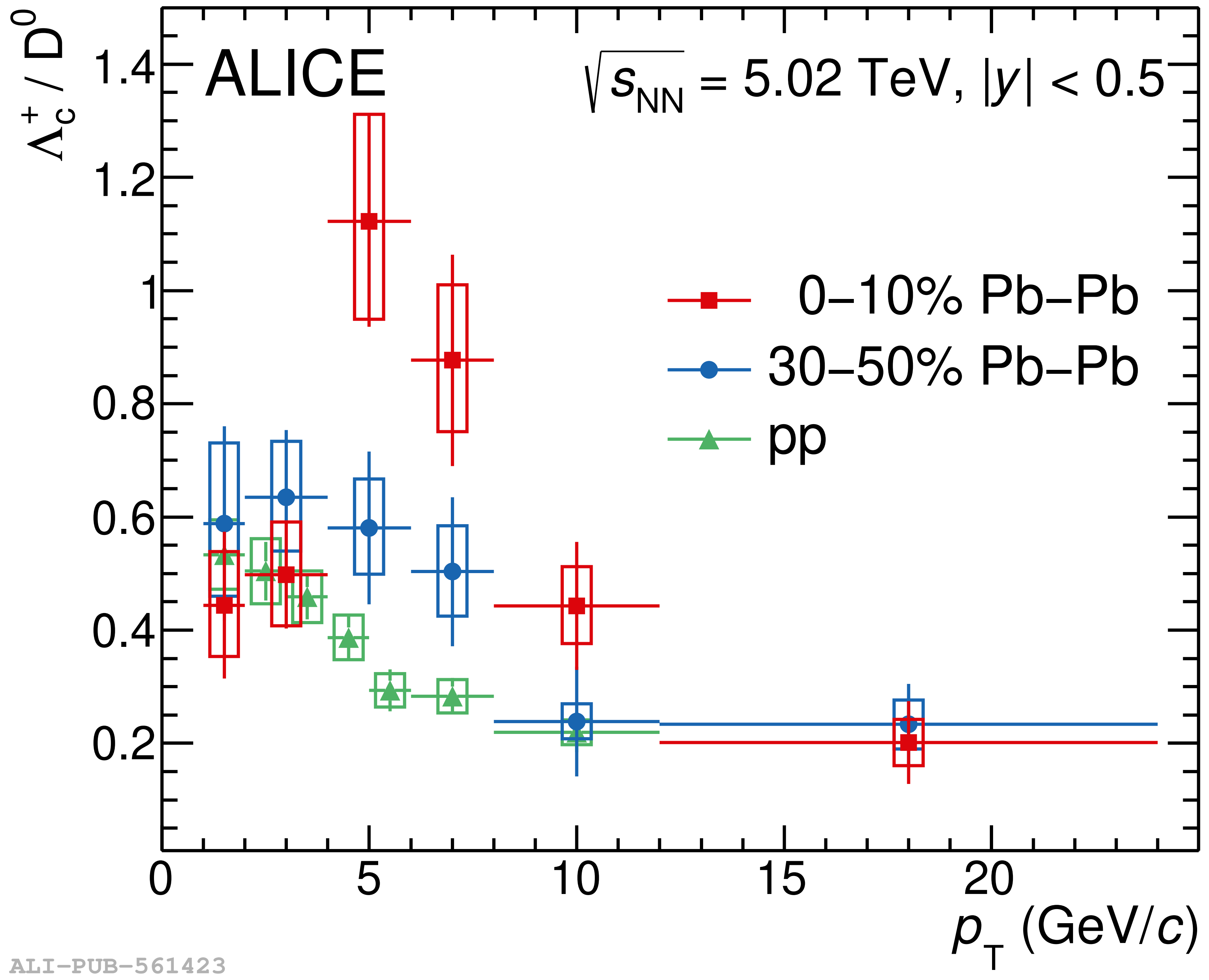
PLB 846 (2023) 137561

D$^{+}_{s}$
b—>D$^{+}_{s}$
b—>D^{0}

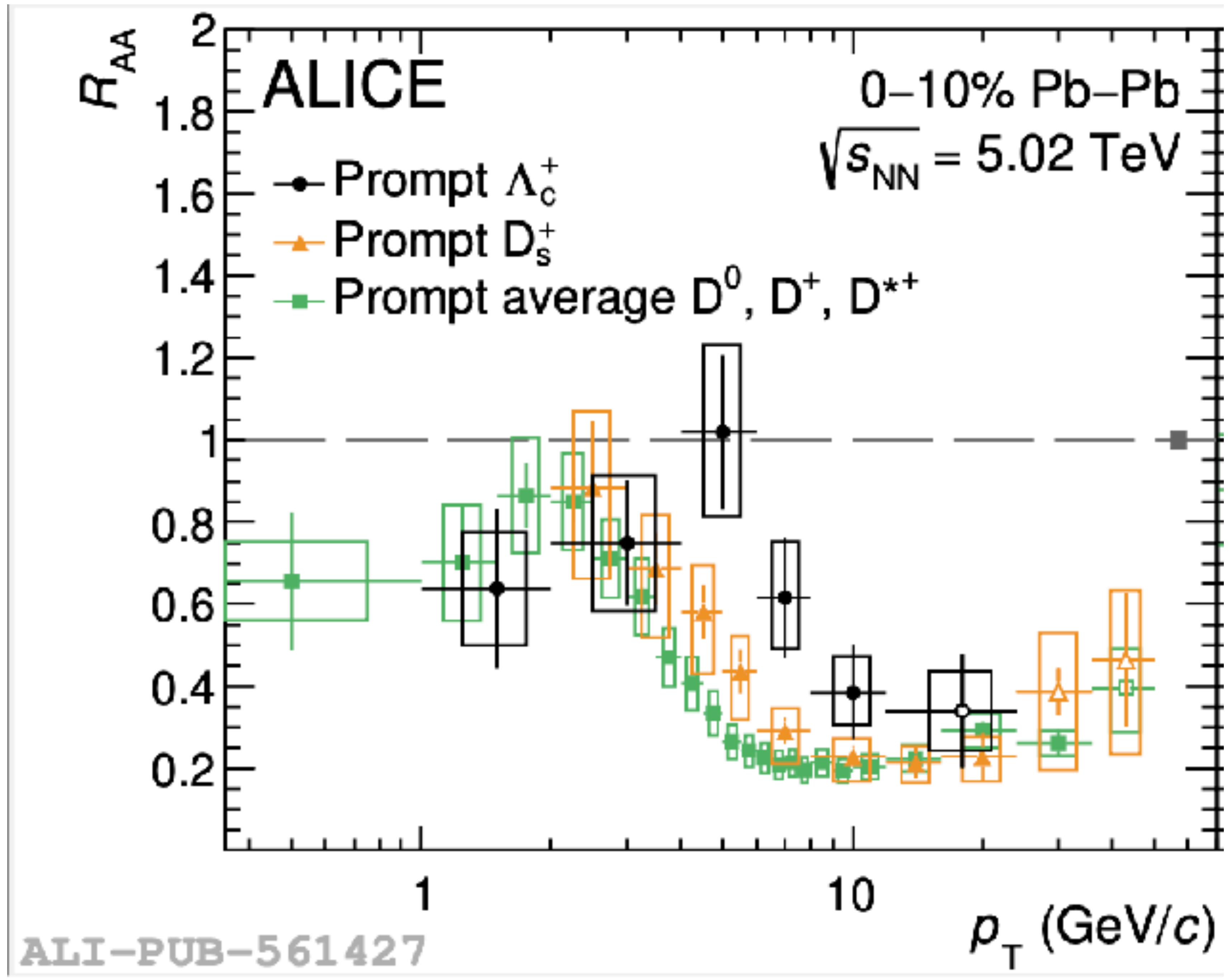
- p_{T} < 6 GeV/*c*: R_{AA}(b—>D$^{+}_{s}$) > R_{AA}(D$^{+}_{s}$) —> effect of mass dependent energy-loss mechanism.
- **p_{T} < 6 GeV/*c*: R_{AA}(b—>D$^{+}_{s}$) > R_{AA}(b—>D^{0})** —> effect of recombination with strange quarks in a strangeness-rich environment
- Comparison with TAMU:
  - Energy loss via collisional processes, and hadronisation via recombination or via fragmentation.
  - Qualitatively describes the p_{T} trend but overestimates the R_{AA}.

Baryon production

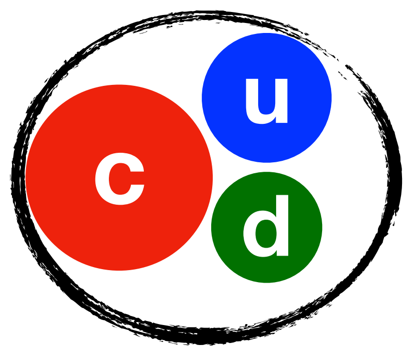
Study of baryon production with Λ_c



PLB 839 (2023) 137796



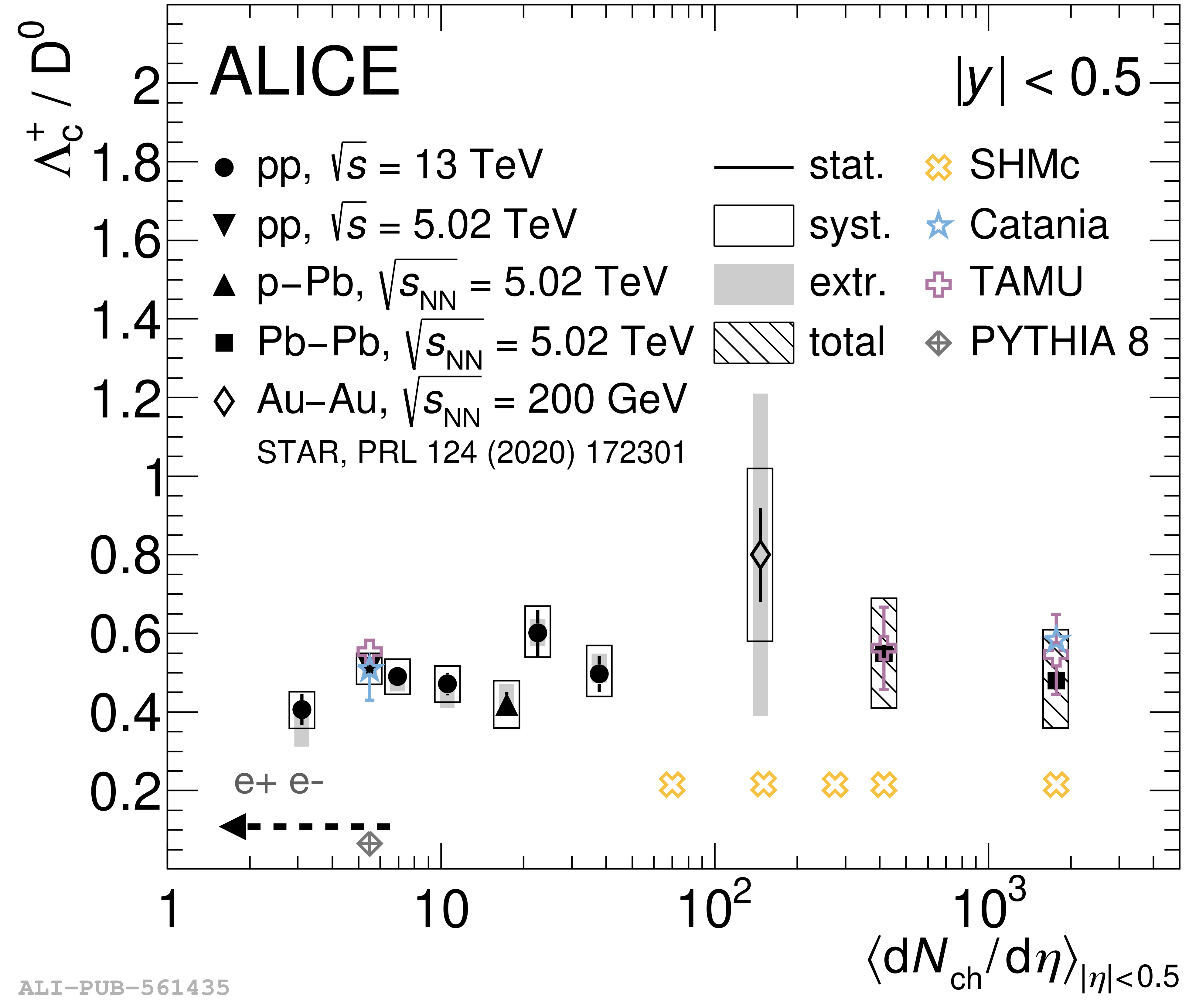
Λc baryon



- Λ_c/D⁰ ratio vs p_T in pp and 0—10% and 30—50% central Pb-Pb collisions
  - Ratio increases from pp to central Pb—Pb collisions in the mid-p_T region.
  - Similar behavior to p/π and Λ/K_s^0 ratios.
- **In the range 4 < p_T < 8 GeV/c, hint of hierarchy R_{AA}(D) < R_{AA}(D_s^+) < R_{AA}(Λ_c)**
  - Similar R_{AA} at high p_T where hadronization is via by fragmentation.

Baryon production

Baryon production vs multiplicity

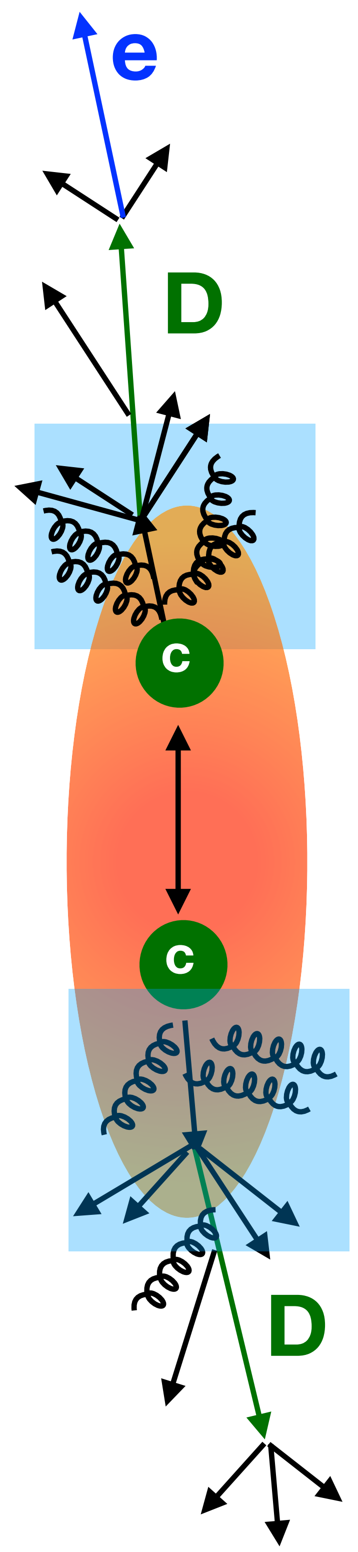


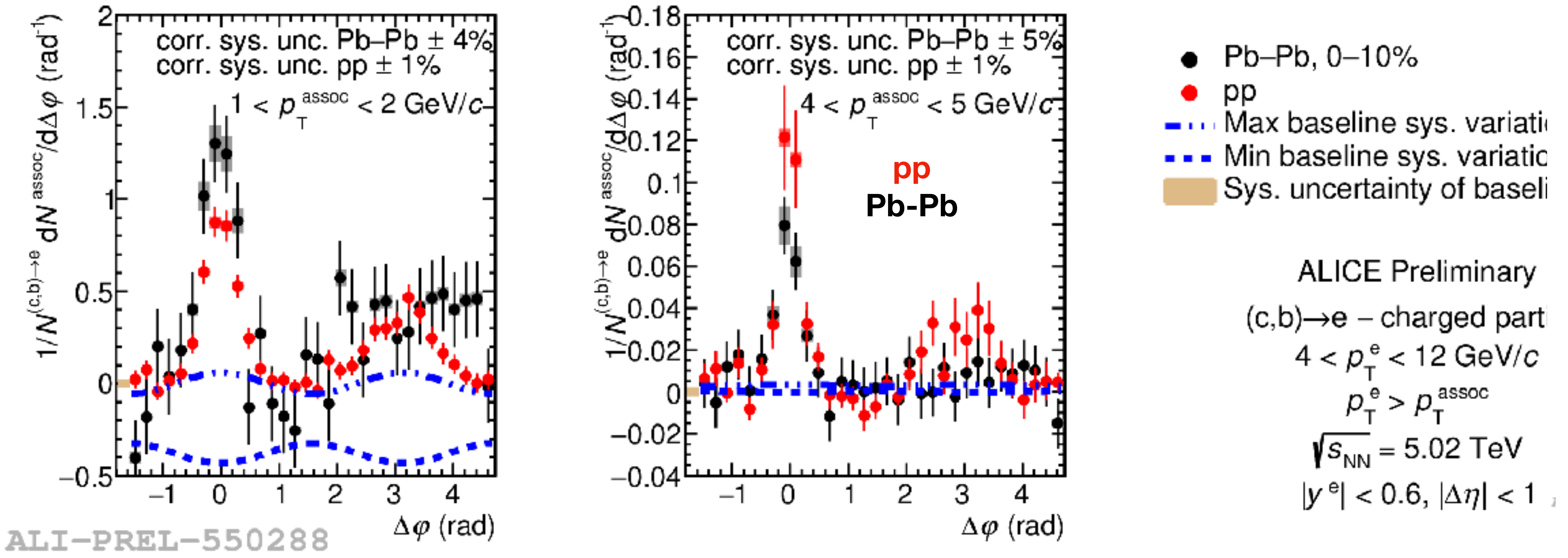
PLB 839 (2023) 137796

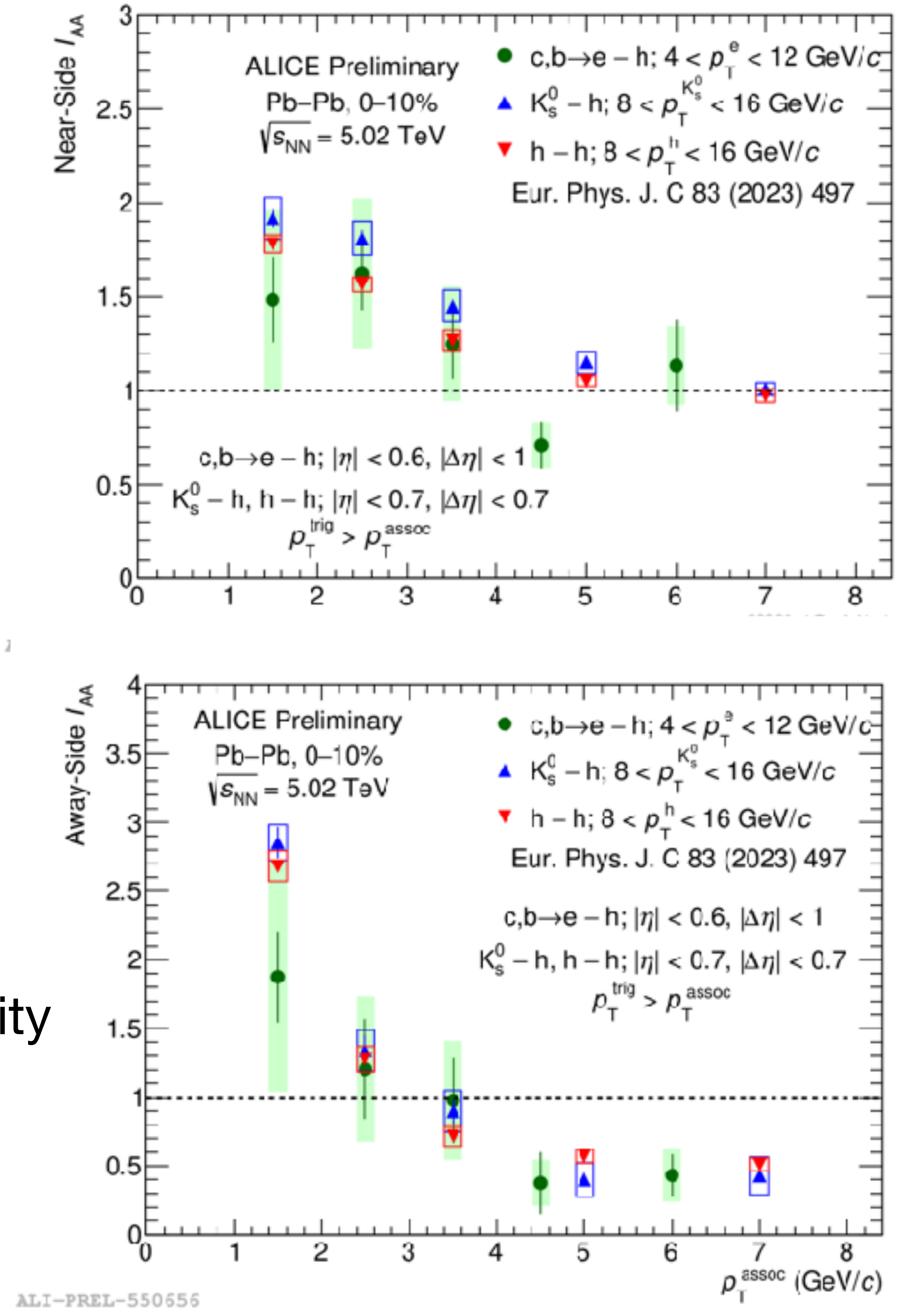
- p_T integrated Λ_c/D ratio vs multiplicity from pp to Pb-Pb collisions.
    - No multiplicity dependence observed.
- **Redistribution of p_T in the hadronic phase rather than an enhancement in the overall baryon yield**
    - Significantly higher values than e^+e^-
- PYTHIA 8 expects multiplicity dependence.
- SHMc : flat trend below data (unobserved charm-baryon states not included in normalization)
- TAMU, Catania: similar values in pp and Pb-Pb collisions

Jet-medium interaction

The hard scattered partons propagates through the QGP —> jet shower itself evolves; jet constituents interact with the medium modifying the shower.







- Near-side and away-side peaks qualitatively different in 0-10% central Pb-Pb collisions compared to pp
- Near-side yield slightly higher at low p_T with ~1.5σ significance, consistent with unity at high p_T.
- Suppression of away-side yield at high p_T.
- **Similar I_{AA} vs associated p_T for heavy-flavor and light-flavor particles**

Summary

- **Several charm and beauty hadron measurements performed in pp, p—Pb and Pb—Pb collisions with the ALICE detector.**

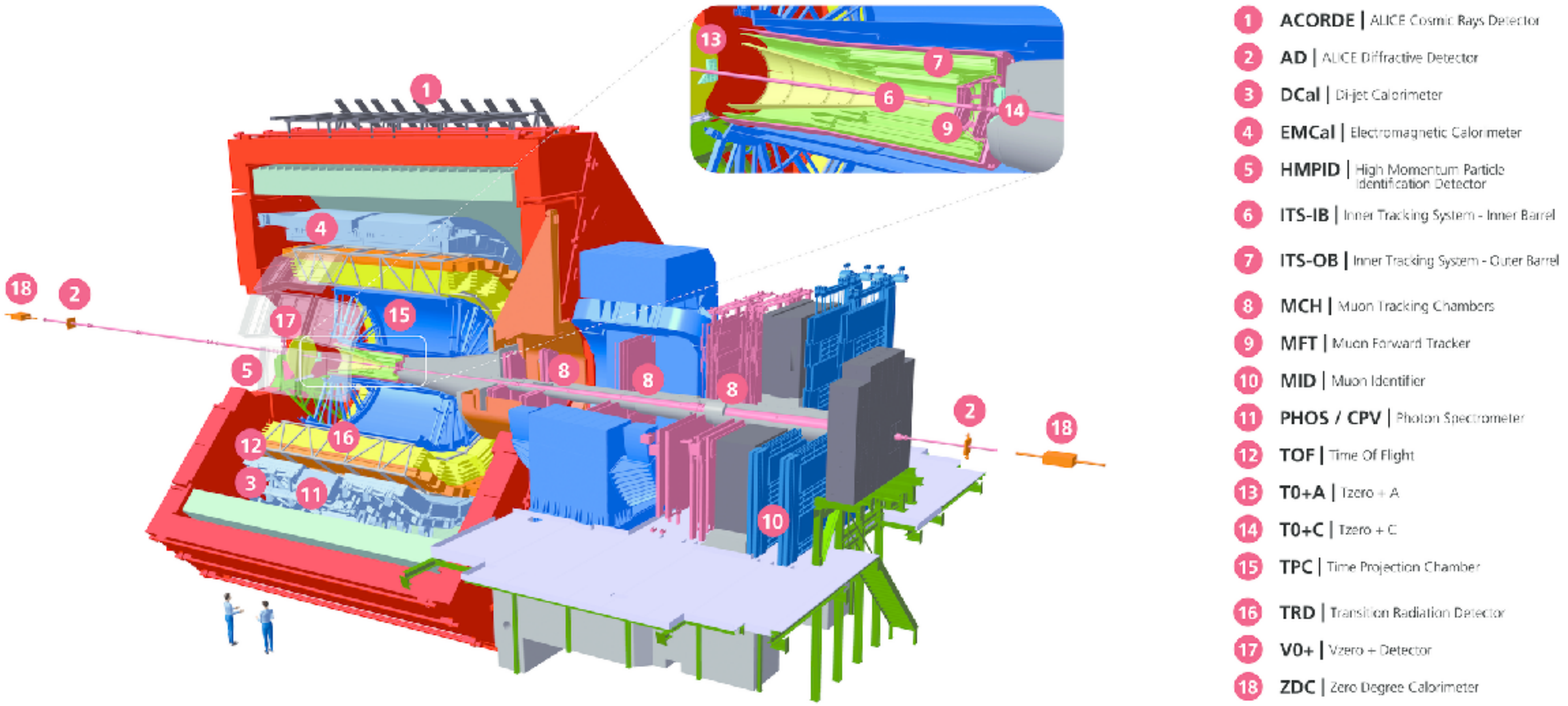
- **pp collisions:**
  - Cross-section of charm and beauty quarks described by pQCD calculations.
  - Fragmentation function universality violated in pp collisions —> hadronization via recombination dominant at low p_T.
    - Common mechanism for light- and HQ-baryon formation.
  - New observables to study heavy-quark jets and jet-substructures.

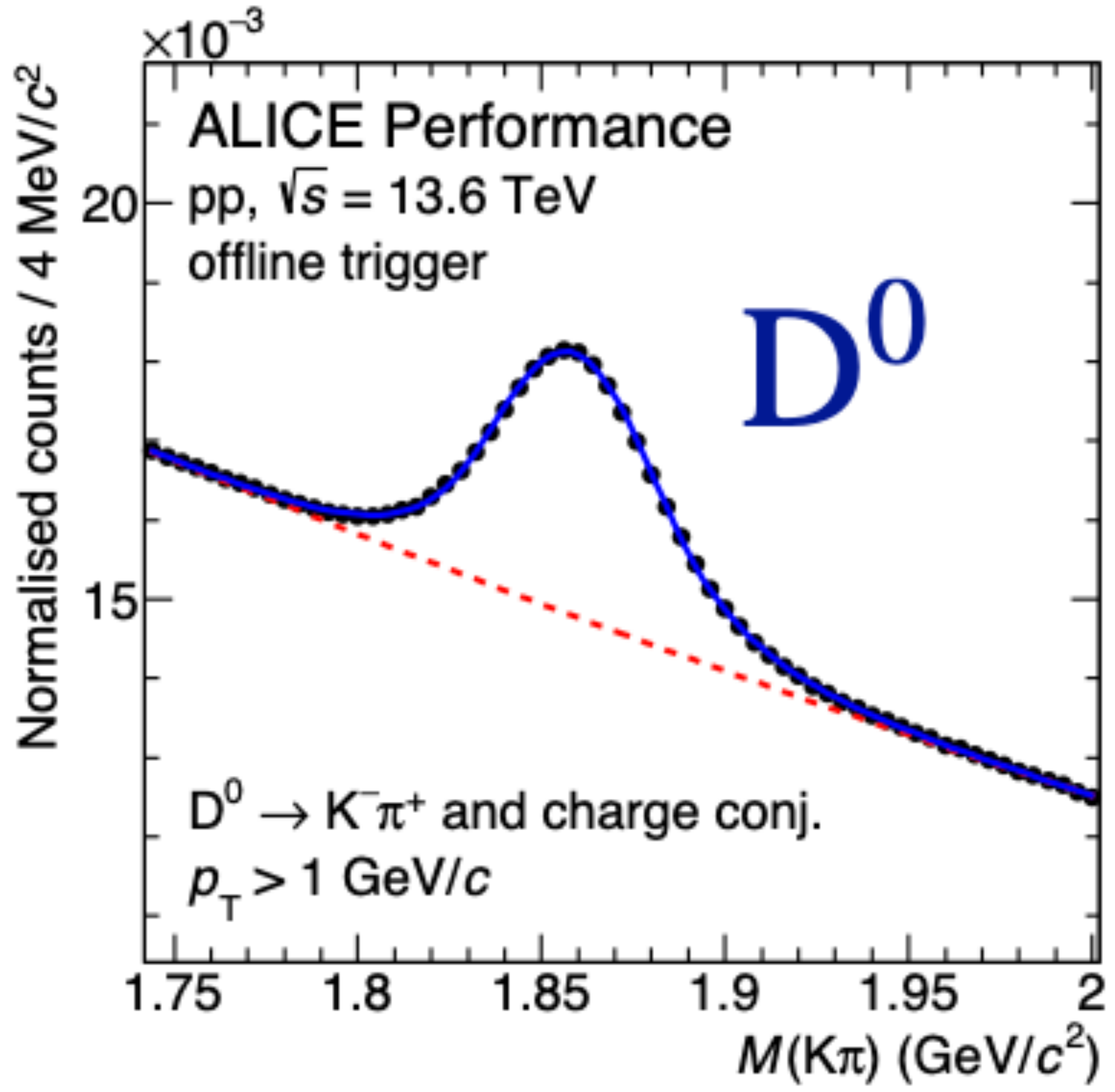
- **p—Pb collisions:**
  - Heavy quark production not significantly affected by CNM effects.
  - Enhanced production of baryons in p—Pb collisions compared to pp in the intermediate p_T range.

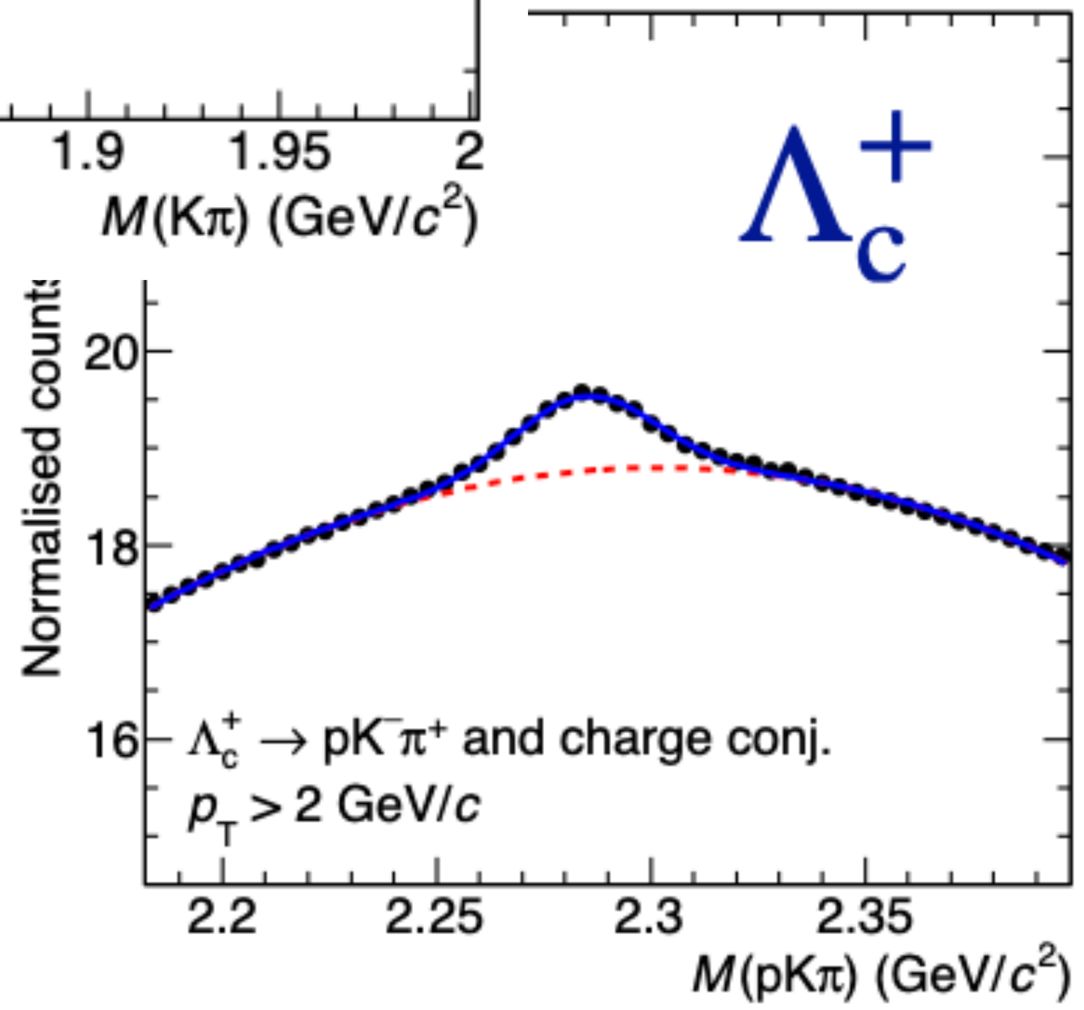
- **Pb—Pb collisions:**
  - Thermalization time for charm quark: 3-9 fm/*c*
  - Beauty quarks loose less energy than charm at low-intermediate p_T.
  - v_2(b) > 0 but lower than charm hadrons.
  - While a p_T-differential enhancement of baryons dependent on the event multiplicity is observed, p_T-integrated baryon/meson ratios consistent across systems from pp to Pb—Pb collisions —> but significantly higher values than e^+e^-.
  - HF-jet medium interactions being studied using azimuthal correlation measurements.

Run 3 outlook

ALICE upgraded for LHC Run 3 operations







- New Inner Tracker System
- New readout for most sub detectors
  - Allows triggerless data collection at higher interaction rates
  - Higher statistics and performance

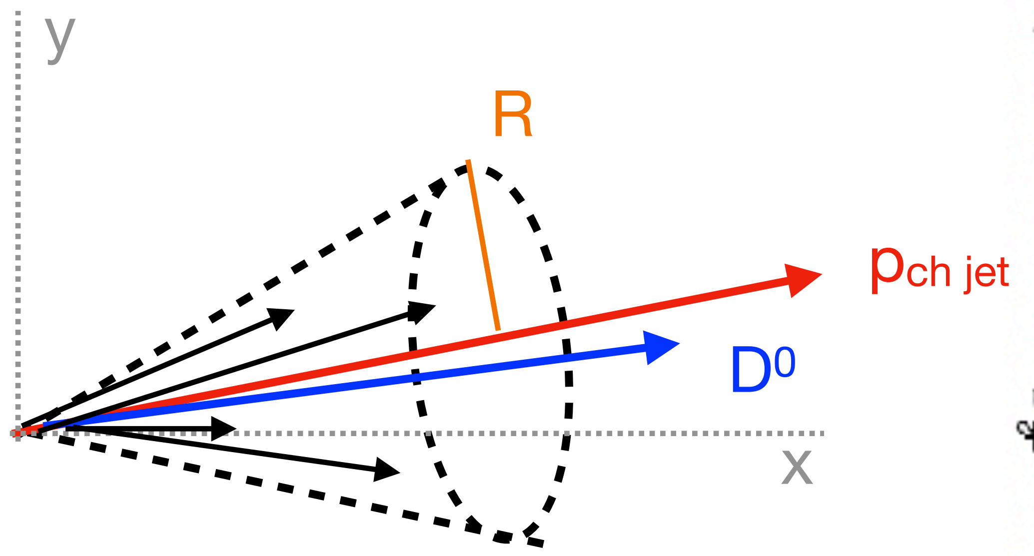
- More HF differential studies and new observables
  - correlations, jets, jet substructure measurements

BACK UP

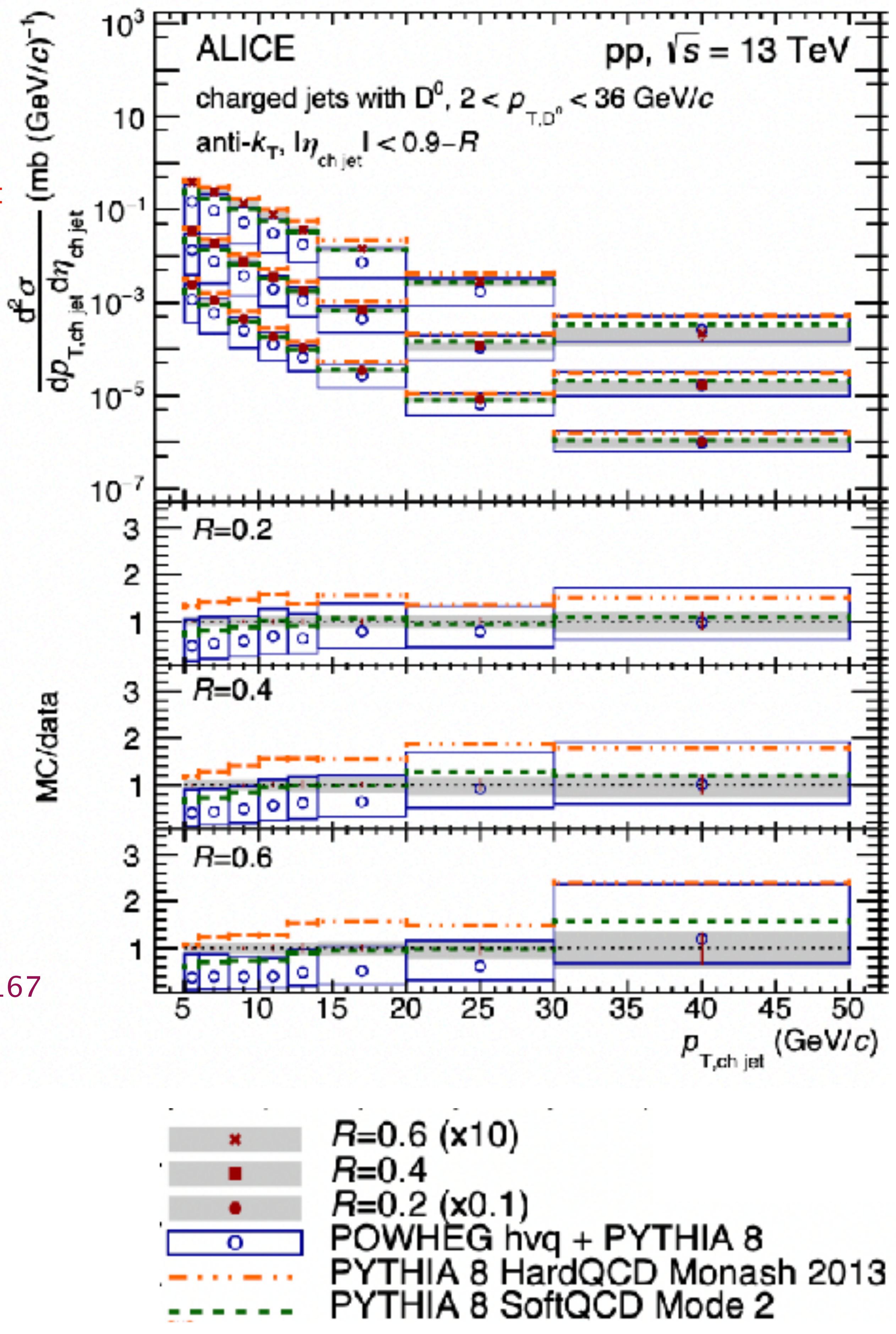
Fragmentation Function, D mesons

Study charm jets and fraction of jet momentum carried by D mesons

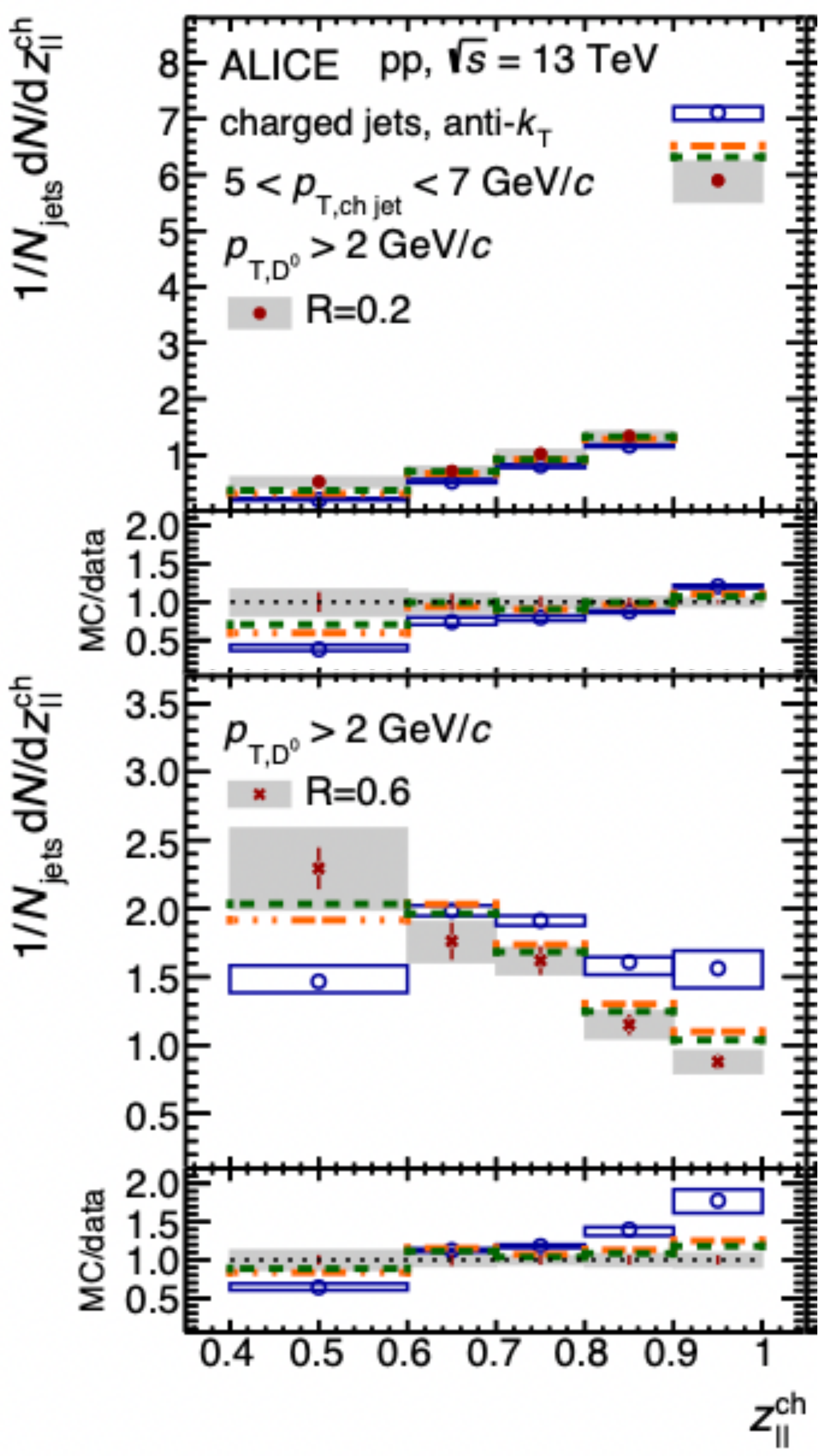
- provide insight into charm fragmentation

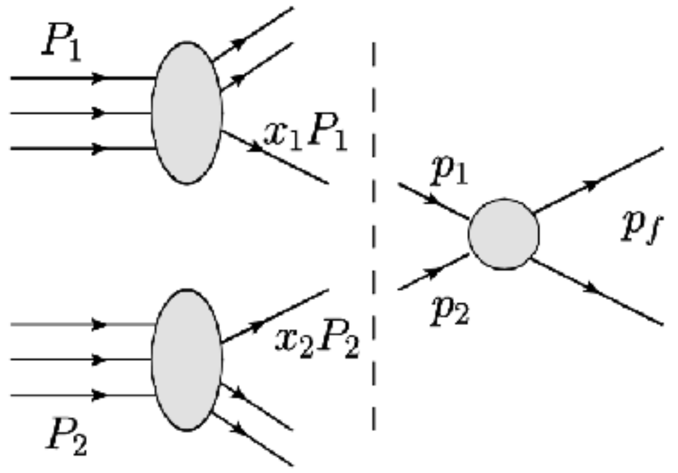


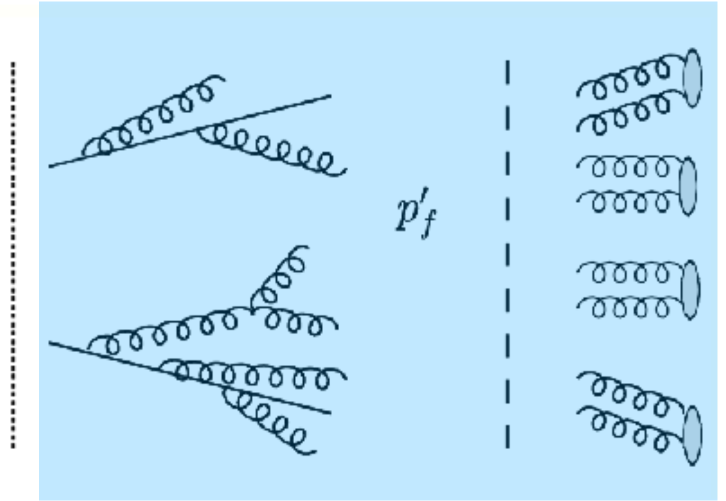
$$z_{||}^{ch} = \frac{p_{jet} \cdot p_{HF}}{p_{jet} \cdot p_{jet}}$$



arXiv:2204.10167





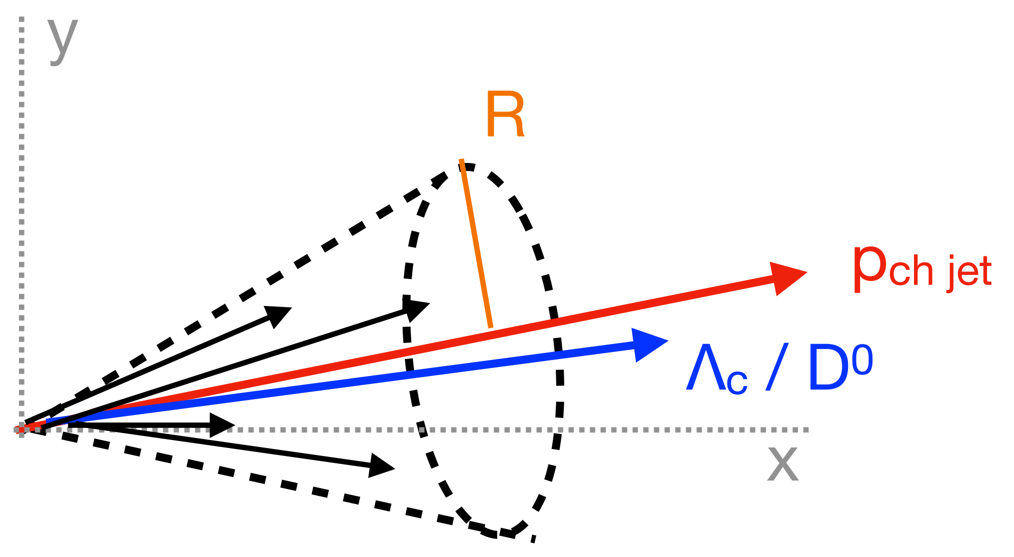


Parton shower and hadronization

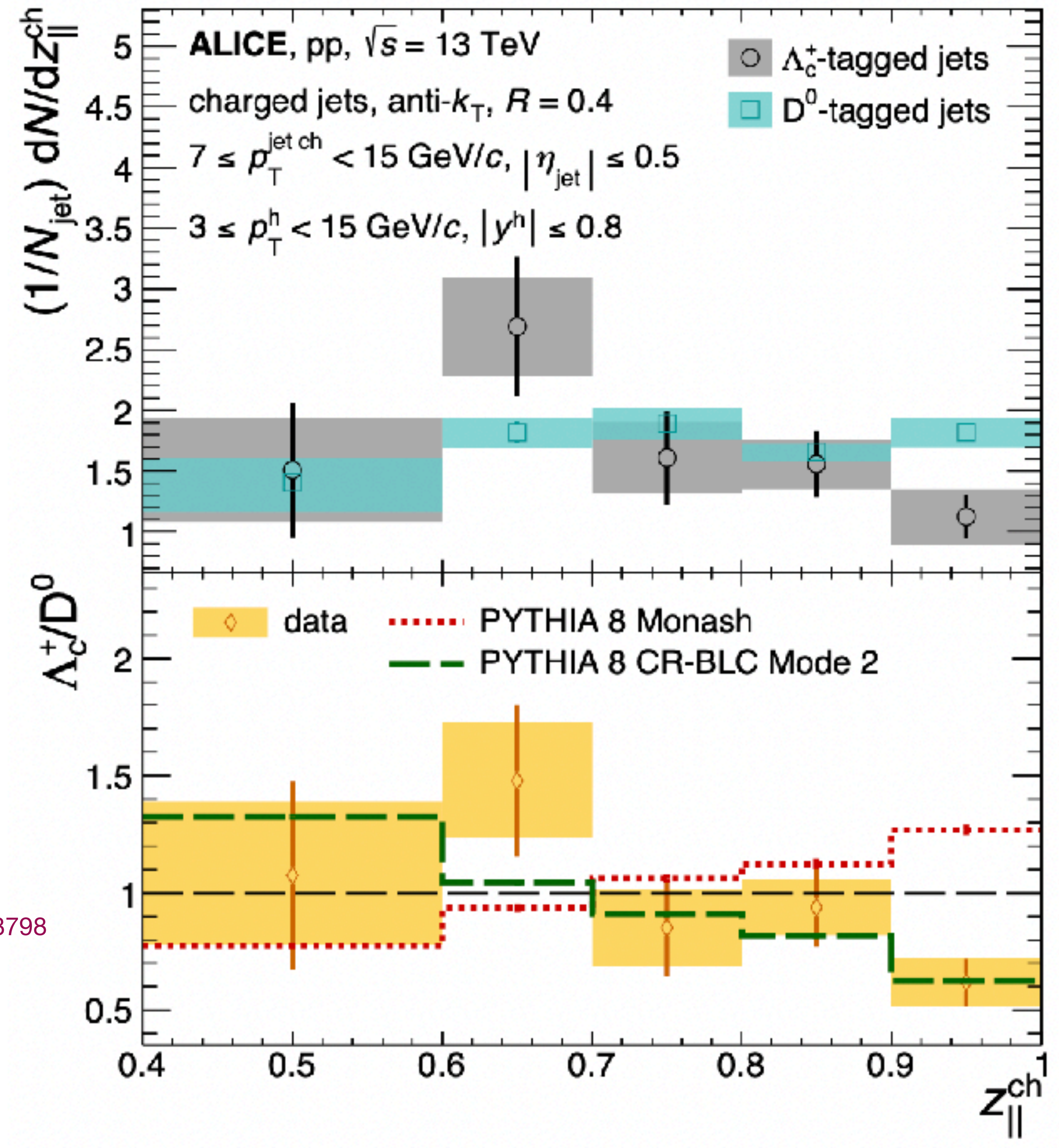
- D^0-jets measured for different R
  - described by PYTHIA and POWHEG MC simulations.
- z^{ch} ~ 1 for low p_T^{Jet} and R =0.2
  - D^0 is the only constituent
- z^{ch} distribution much softer for larger R
  - more activity inside the jet.
- z^{ch} well described by PYTHIA and POWHEG at high p_T^{Jet}
  - small deviations observed at low p_T^{Jet} especially for POWHEG

Fragmentation Function, charm baryon

Study charm jet fragmentation function to baryons



$$z_{||}^{ch} = \frac{p_{jet} \cdot p_{HF}}{p_{jet} \cdot p_{jet}}$$



arXiv:2301.13798

Softer fragmentation of charm quarks to Λ_c compared to D^0 mesons.

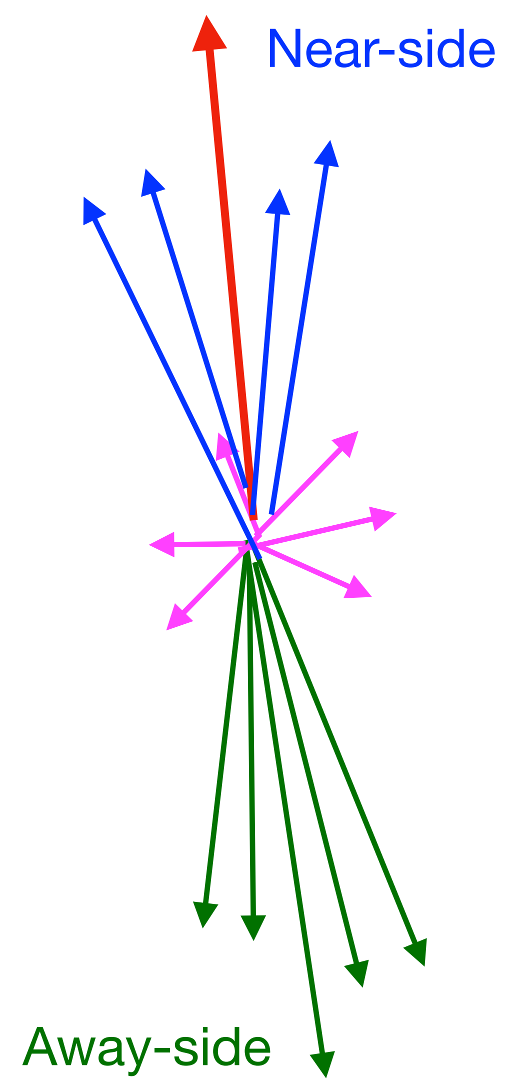
—> charm-baryon production is favored in the presence of higher particle multiplicity originating from jet fragmentation and underlying event

MC models:

- PYTHIA 8 Monash employs lund string fragmentation, tuned on e+e- data, predicts harder fragmentation than data
- PYTHIA 8 with CR mechanism gives a better description

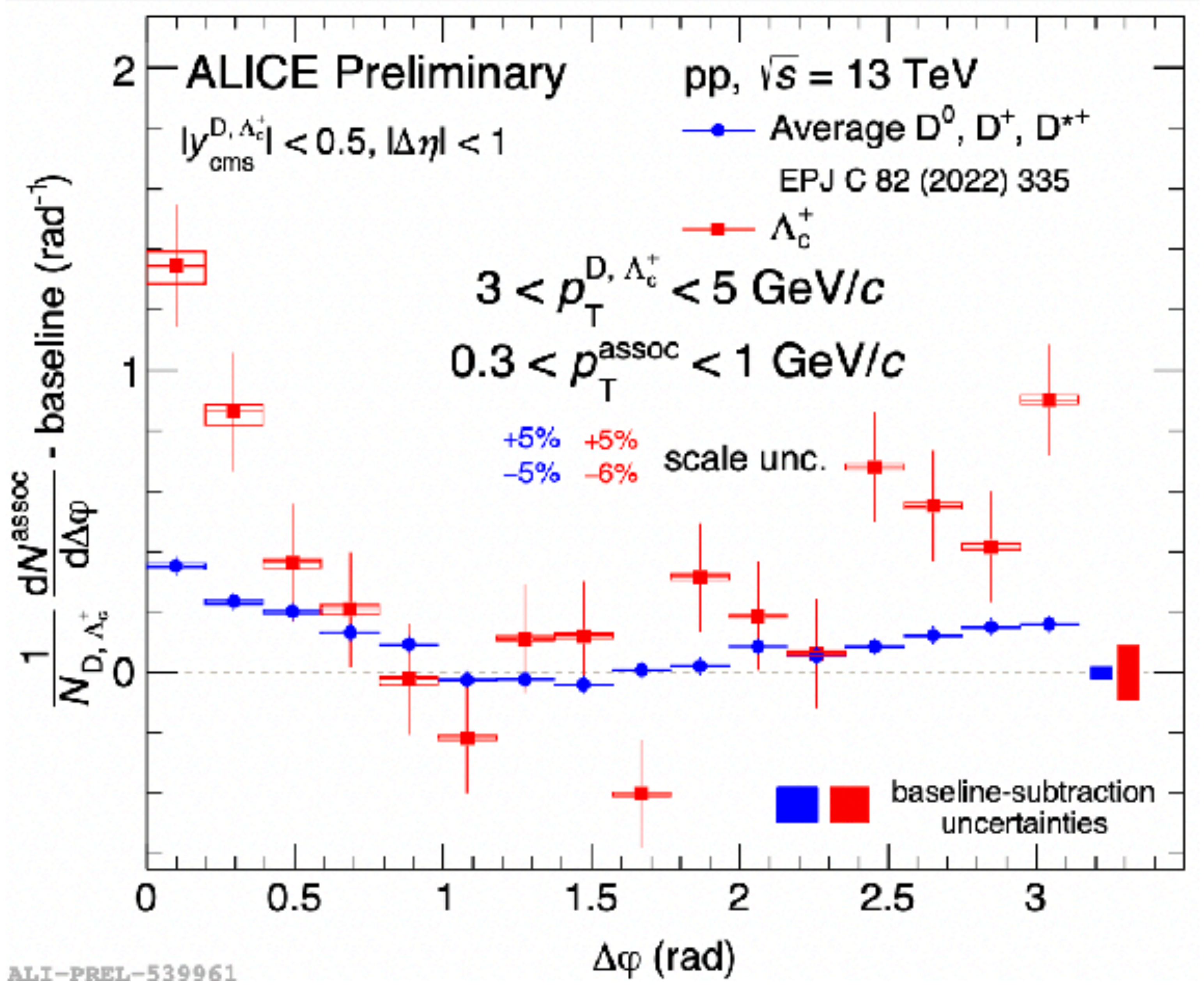
Jet shape and composition

Study HF jet radial profile and composition using HF-charged particle azimuthal distribution



HF-h Δφ distribution at LO:

- Near Side (NS): fragmentation of the tagged HF quark
- Away Side (AS): fragmentation of the other quark
- Transverse Region : Underlying event



Significant deviation between Λ_c-h and D-h low p_T

- probably as a consequence of softer fragmentation to Λ_c giving larger particle multiplicity inside the jet.