ALICE

Open heavy-flavour production with ALICE at the LHC

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NWO
Netherlands Organisation for Scientific Research

Open heavy-flavour production

ALICE

- **pp collisions:**
  - Test pQCD calculations
  - Study hadronization mechanism
  - Set a reference for p-Pb and Pb-Pb
- **p-Pb collisions**
  - Study cold nuclear matter (CNM) effects (nPDF, shadowing, gluon saturation, k_T-broadening, energy loss in CNM in the initial and final state)
  - Address possible collective effects and effects related to the (possible) formation of a QGP in p-Pb collisions.
- **Pb-Pb collisions**
  - Heavy-quarks effective probe for the properties of the hot and dense QCD matter produced in heavy-ion collisions
    - Heavy-quark energy loss
    - Quarkonium dissociation/regeneration

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See talk of Enrico Scomparin

Heavy-quarks in AA: General Picture

- Heavy quarks produced at the early stage of the collision ($\Delta t \sim 1/2m \sim 0.01\text{-}0.13$ fm)

- Traverse the hot and dense medium:
  - Thermal production in the medium expected to do not play a major role (depend from initial temperature)

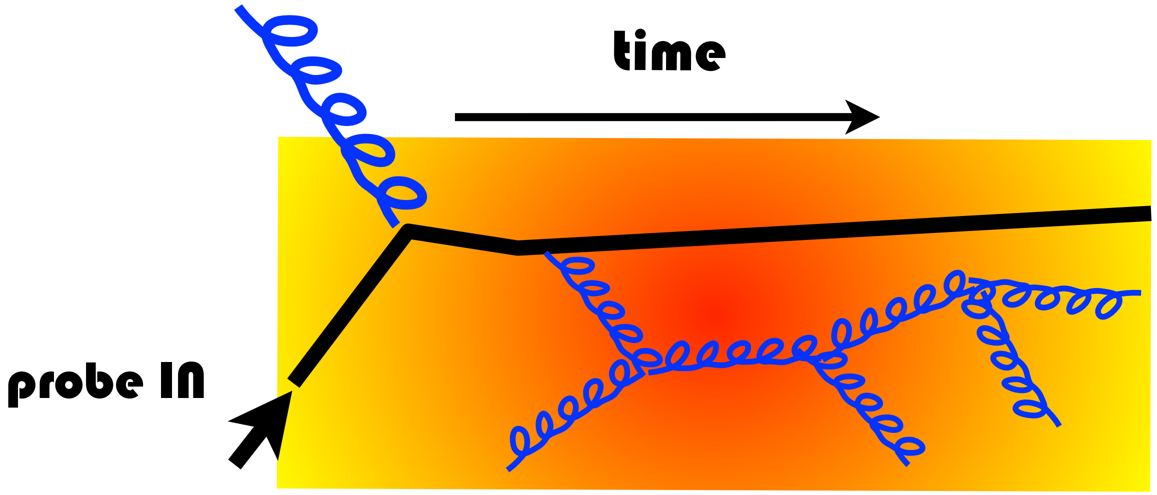
    Phys.Rev. C51 (1995) 3326–3335
  - Thermal production from hadronic matter (i.e $\pi N \rightarrow \Lambda_c D$) expected to play a minor effect

    Phys. Rev. C56, 2707 (1997)

- Expected to lose less energy than light quarks and gluons due to color-charge and dead cone effect → higher penetrating power into QCD medium.

Yu. Dokshitzer and D.E. Kharzeev, Phys.Lett. B 519 199-206 (2001). Armesto, Carlos A. Salgado and Urs A. Wiedemann. PRD 69 (2004) 114003

M. Djordjevic, M. Gyulassy, Nucl. Phys. A733 (2004) 265.



$E_{loss}(light) > E_{loss}(c) > E_{loss}(b)$

- What about charm strange hadrons (D_s)? If quark coalescence dominant mechanism of charm hadron formation at low $p_T \rightarrow$ strange charm hadrons strongly enhanced.

I. Kuznetsova and J. Rafelski, Eur.Phys.J. C51 (2007) 113-133.

M. He, R. J. Fries and R. Rapp, arXiv:1204.4442 [nucl-th].

One observable: *Nuclear Modification Factor*

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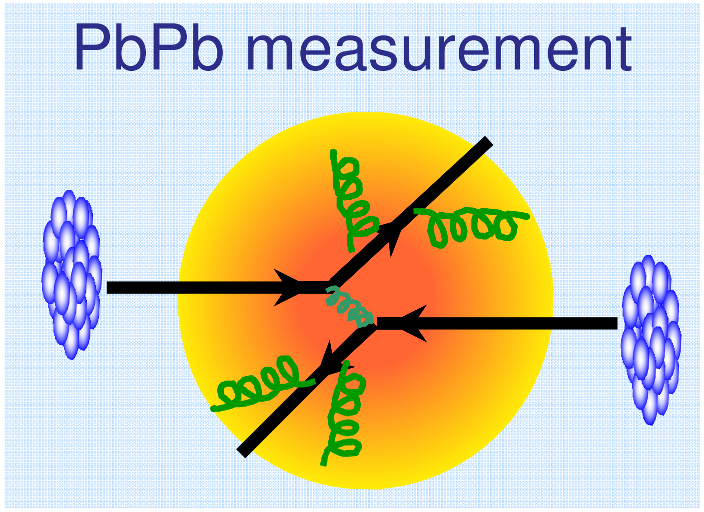
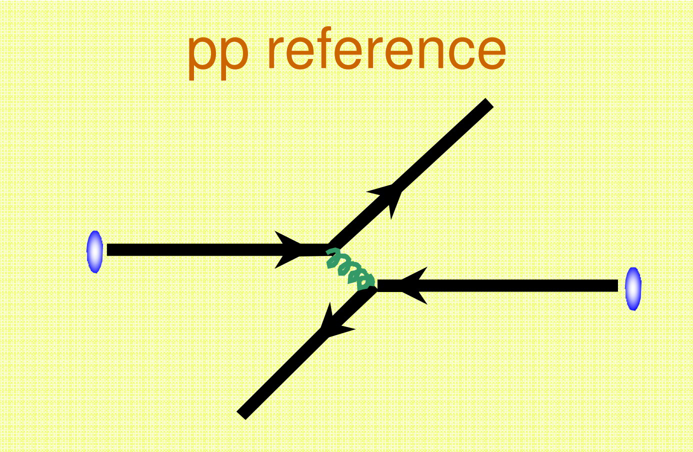
- Observable: Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} = \frac{\textit{QCD Medium}}{\textit{QCD vacuum}}$$





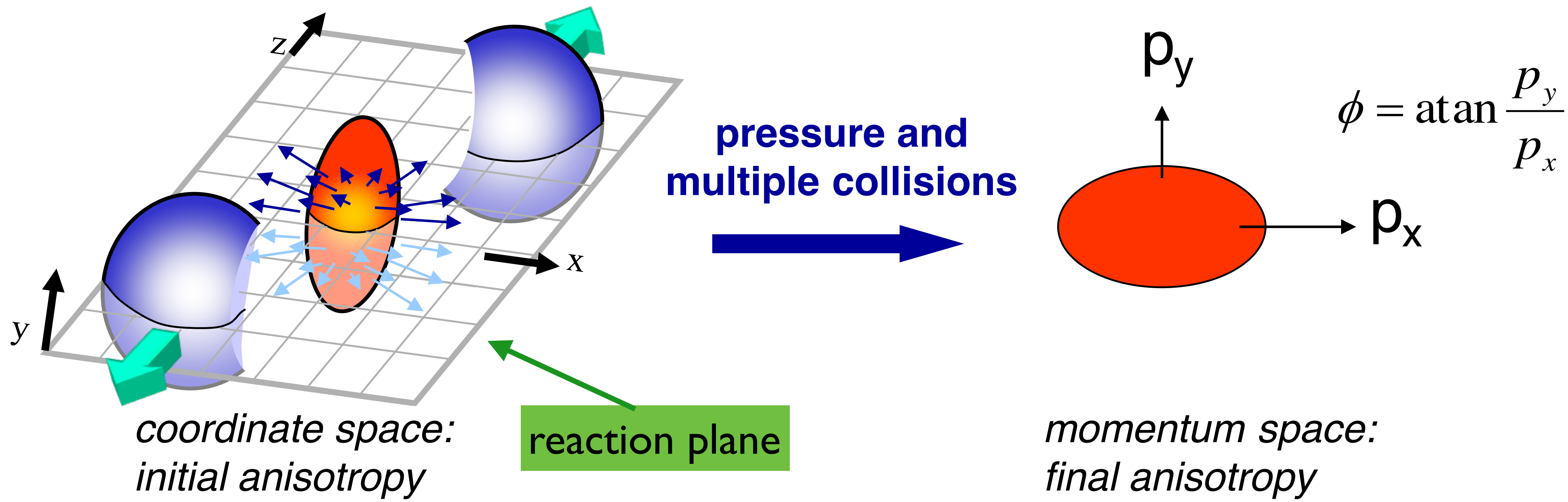
- What are the possibilities?
  - If no nuclear effects present: $R_{AA} = 1$
  - Effects of the hot and dense medium produced in the collision break binary scaling: $R_{AA} \neq 1$

$R_{AA}(\text{light}) < R_{AA}(D) < R_{AA}(B)$

several caveats to take into account!!

- But also cold nuclear matter effects may lead to $R_{AA} \neq 1$ (needs solid pA reference)

.. a more differential one: *elliptic flow*



- Quantified via the 2nd order Fourier coefficient **v_2 (elliptic flow)**

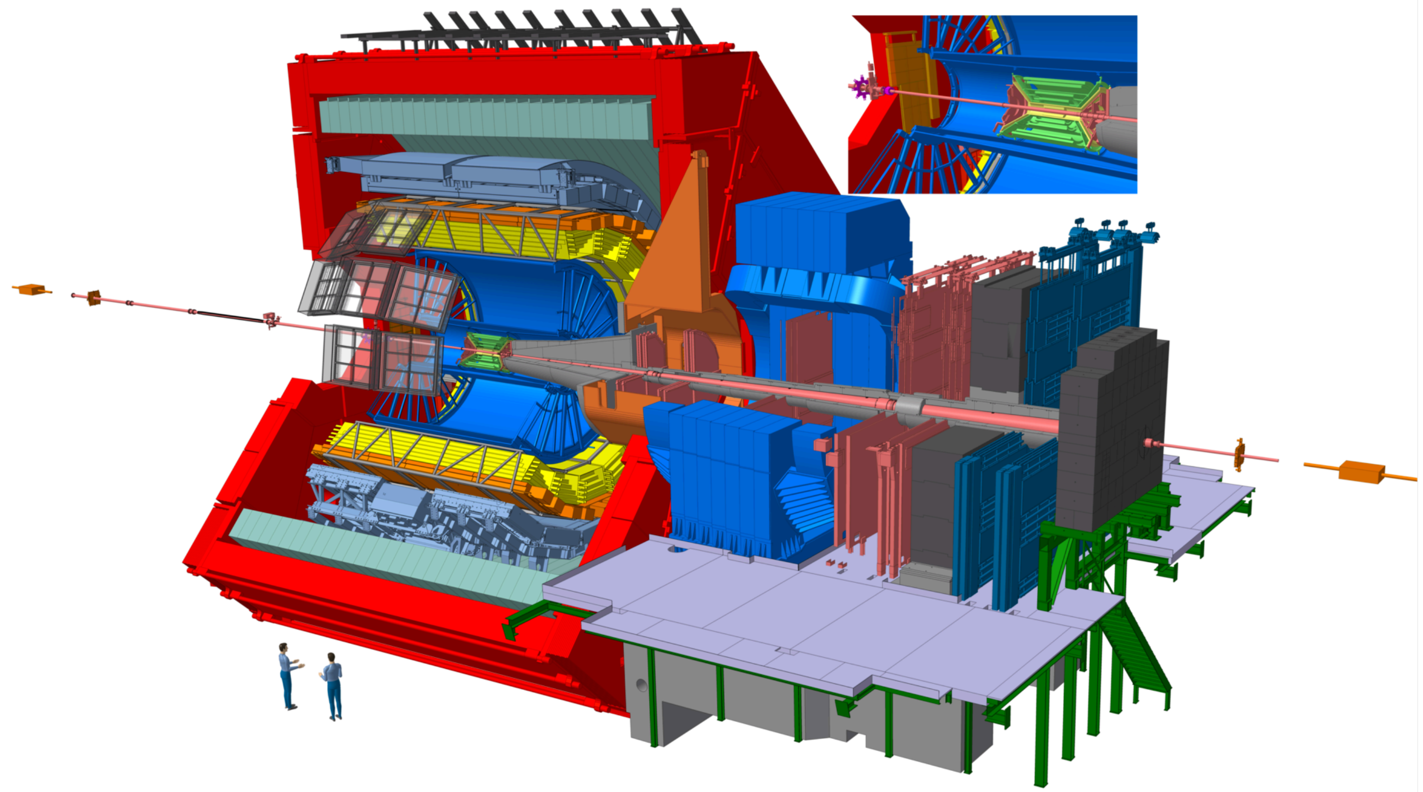
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}(1+2v_1\cos(\varphi-\Psi_{RP})+2v_2\cos 2(\varphi-\Psi_{RP})+.....)$$

- Carries information on medium transport properties:
  - **Low p_T: do *b* and *c* take part to the collective motion?**
  - **High p_T: path-length dependence of parton energy loss**

Open heavy-flavours in ALICE

- Charmed hadrons in |y|<0.5:

  $D^0 \rightarrow K^-\pi^+$
  $D^{*+} \rightarrow D^0\pi^+$
  $D^+ \rightarrow K^-\pi^+\pi^+$
  $D^+_s \rightarrow \Phi(K^-K^+)\pi^+$
  $\Lambda_c^+ \rightarrow pK^-\pi^+$ and pK^0_s
  $\Lambda_c^+ \rightarrow e+\Lambda(p\pi^-)\nu_e$
  $\Xi_c^0 \rightarrow e+\Xi^-(\pi^-\Lambda)\nu_e$



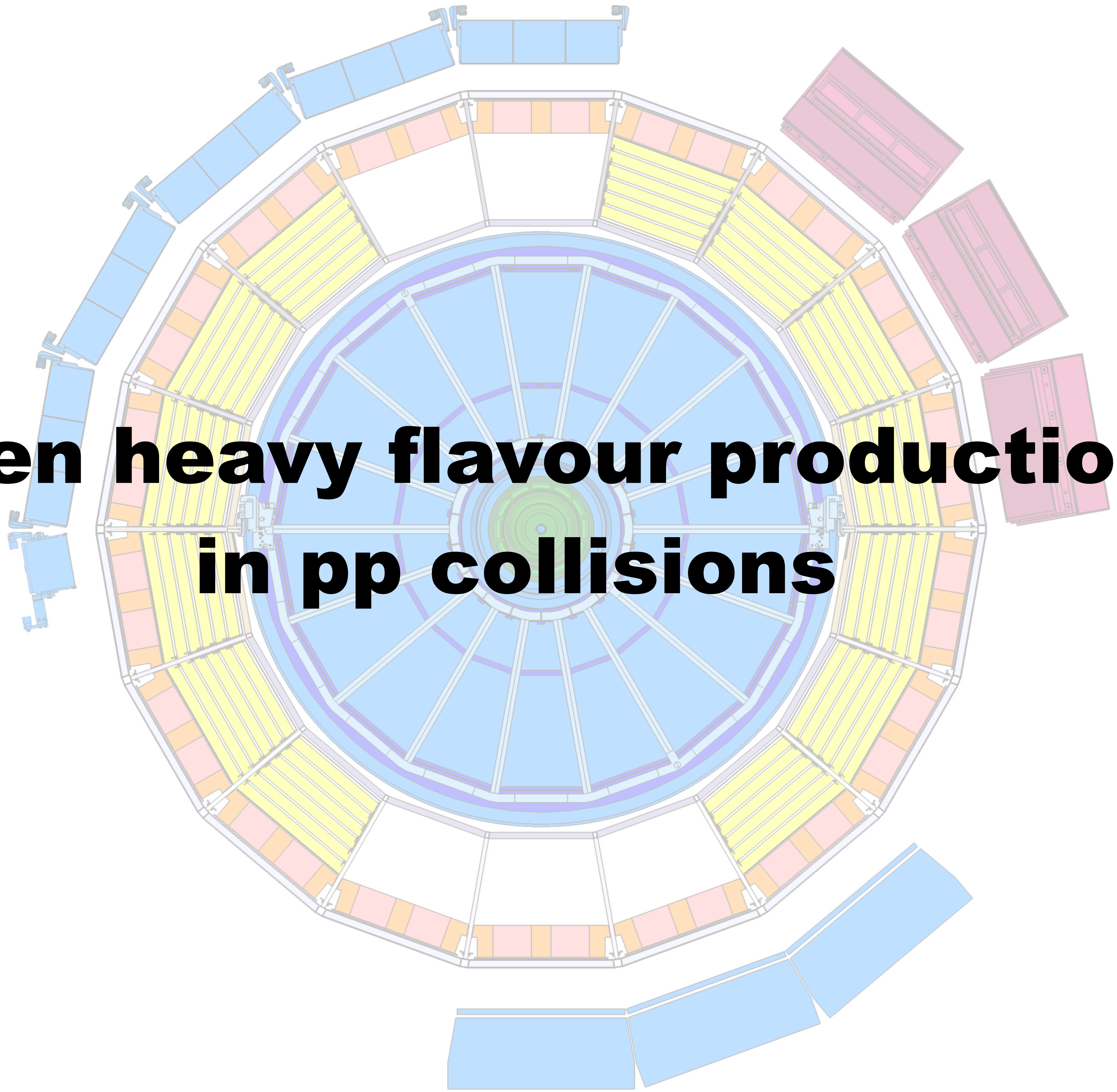
- HF-hadron decay electrons (c,b hadrons → eX) in |y|<0.9

- HF-hadron decay muons (c,b hadrons → μX) in 2.5<y<4

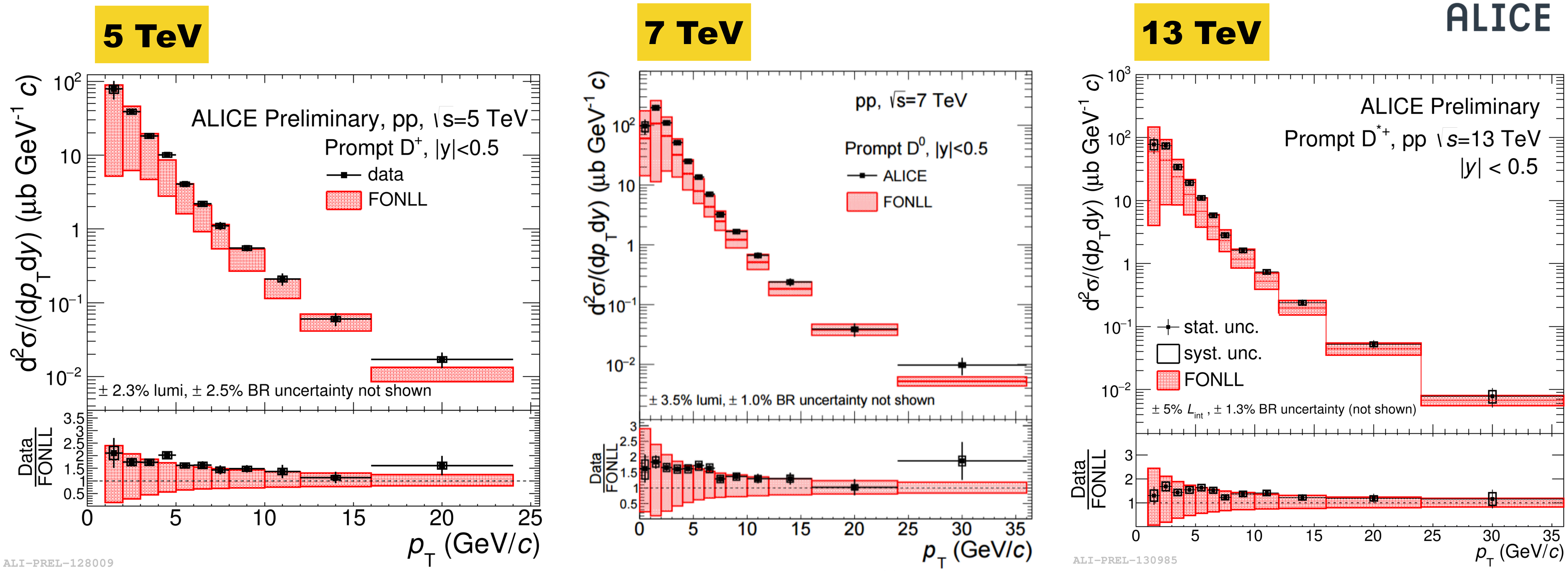
- B mesons via non-prompt J/Ψ (b hadron → J/ΨX with J/Ψ in e^+e^-) in |y|<0.9

- HF-jets production, correlations with charged particles, …

Open heavy flavour production in pp collisions



D-meson production cross section at 5 and 7 TeV

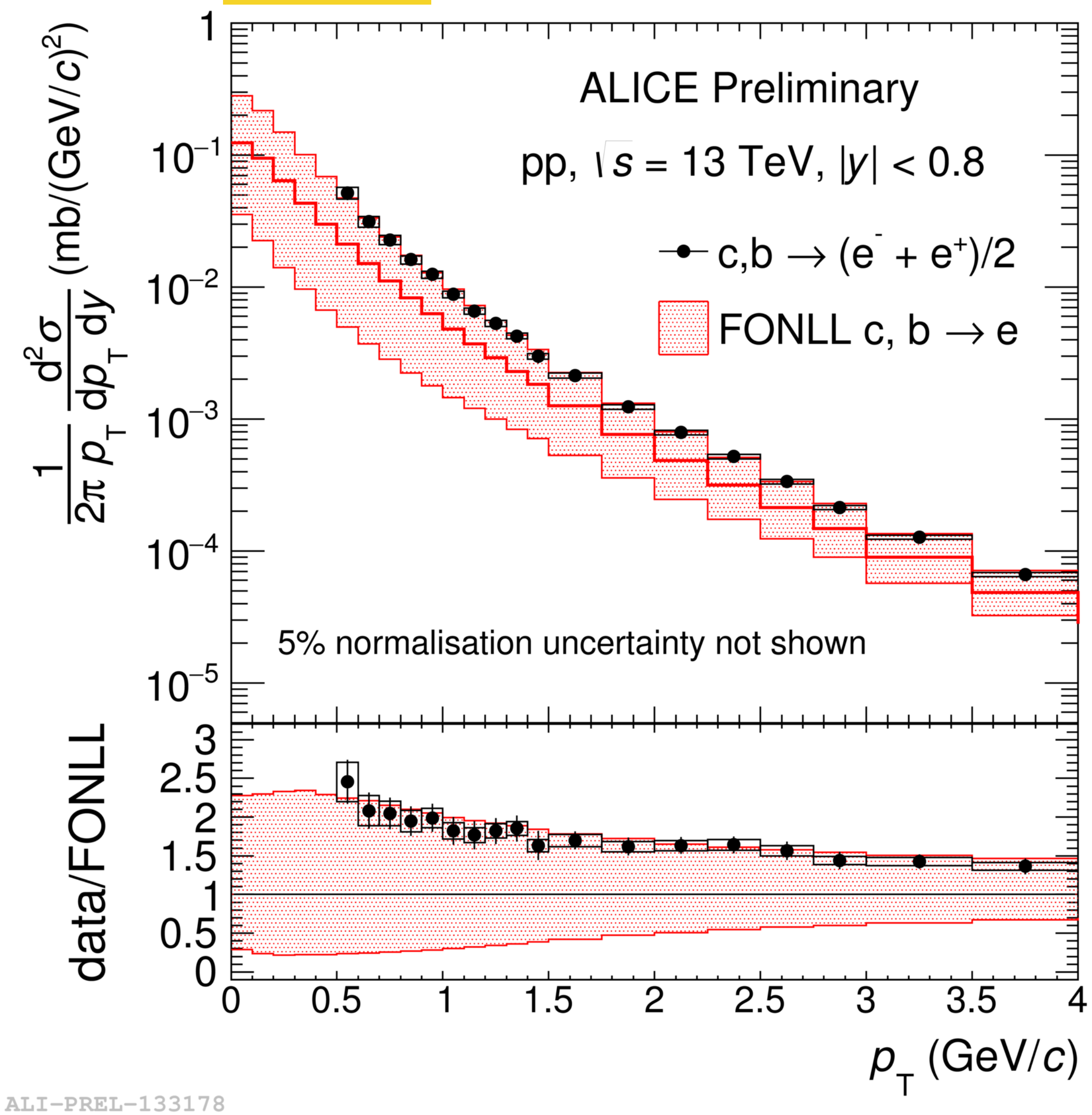


arXiv:1702.00766

- D-meson (D^0, D^+, D^{*+} and D_s^+) production cross section measured at several collision energies
  - Down to p_T=0 for D^0 at 7 TeV
  - pQCD calculations describe the data within uncertainties, data uncertainties much lower than theoretical ones

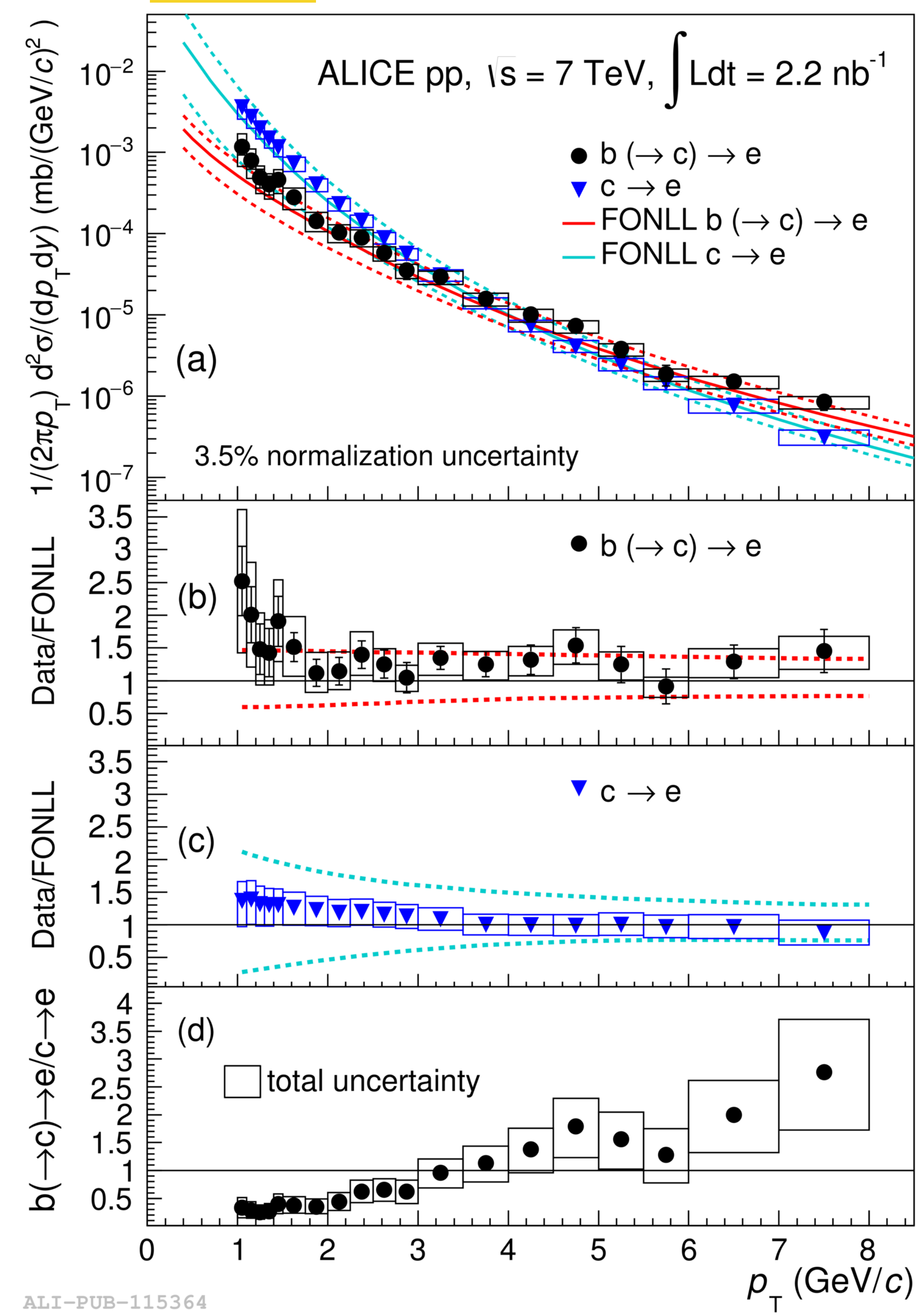
Electrons from heavy-flavour hadron decays

13 TeV



7 TeV

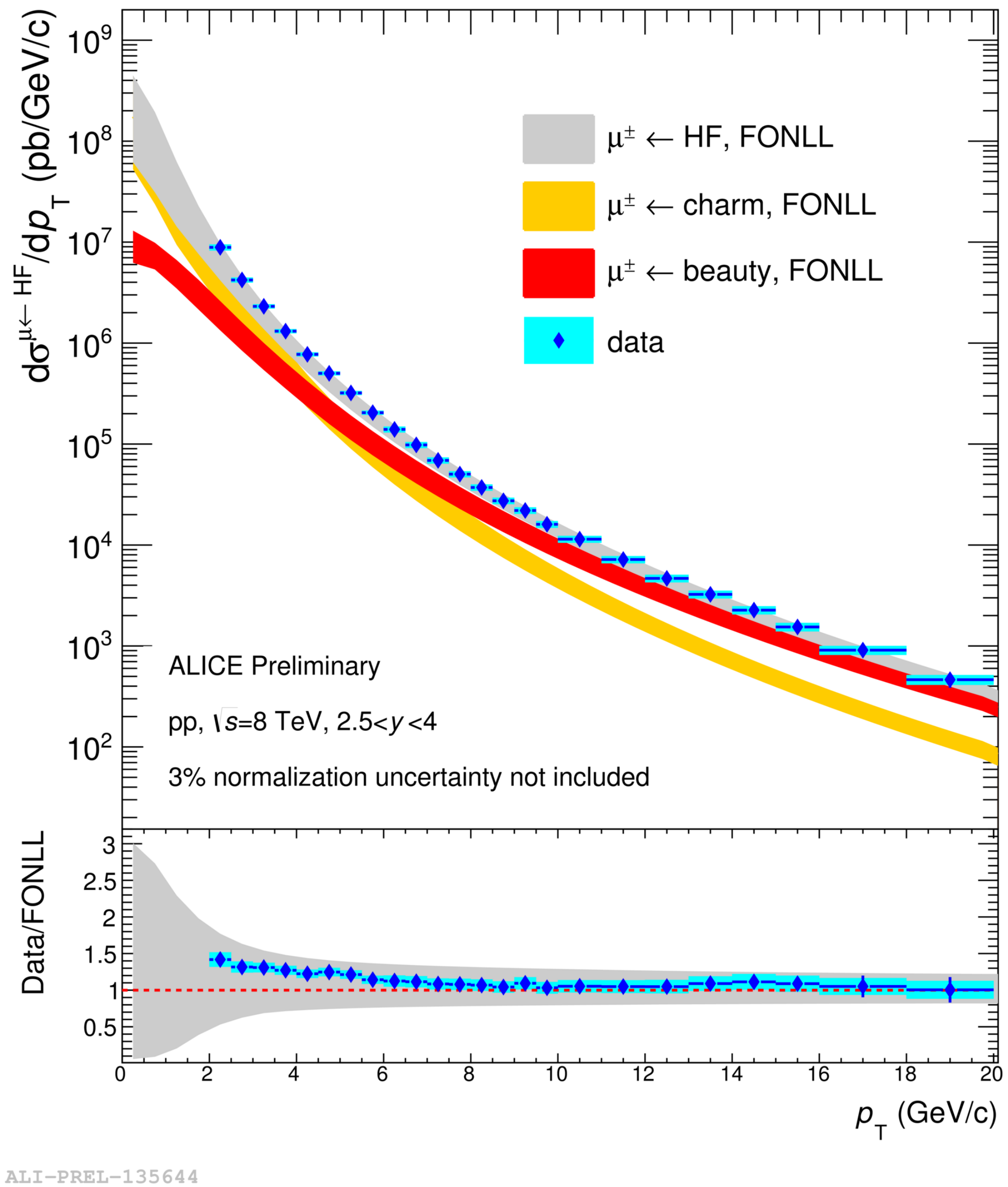
PLB, 721 (2013), 13-23

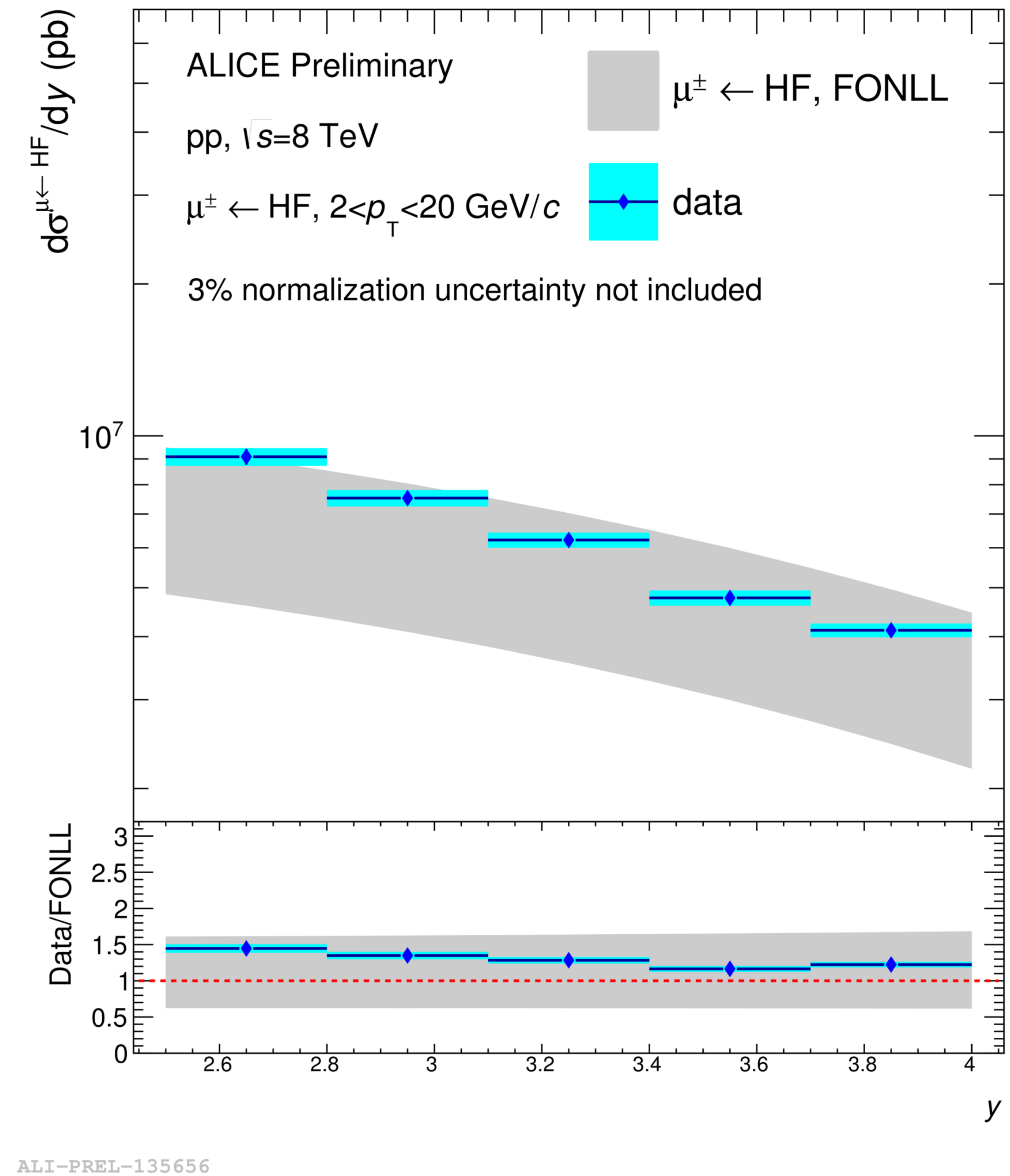


- Very precise data to constrain charm and beauty production → *down to 500 MeV/c!*

Muons from heavy-flavour hadron decays

8 TeV





- Cross section at 8 TeV in 2.5<y<4 rapidity integrated (left) and vs rapidity (right). Similar agreement with pQCD calculations (FONLL) as the one found at central rapidity

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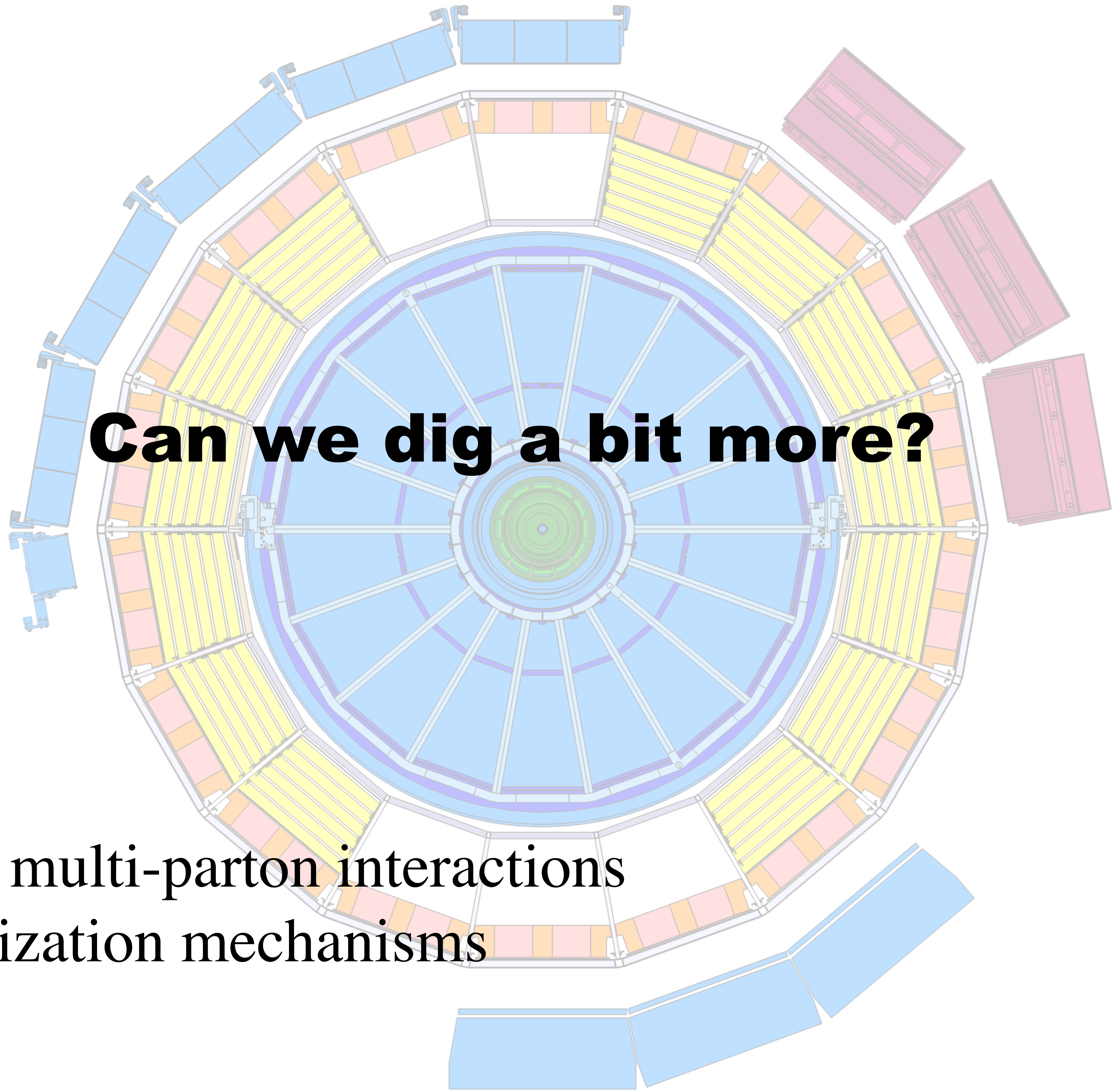
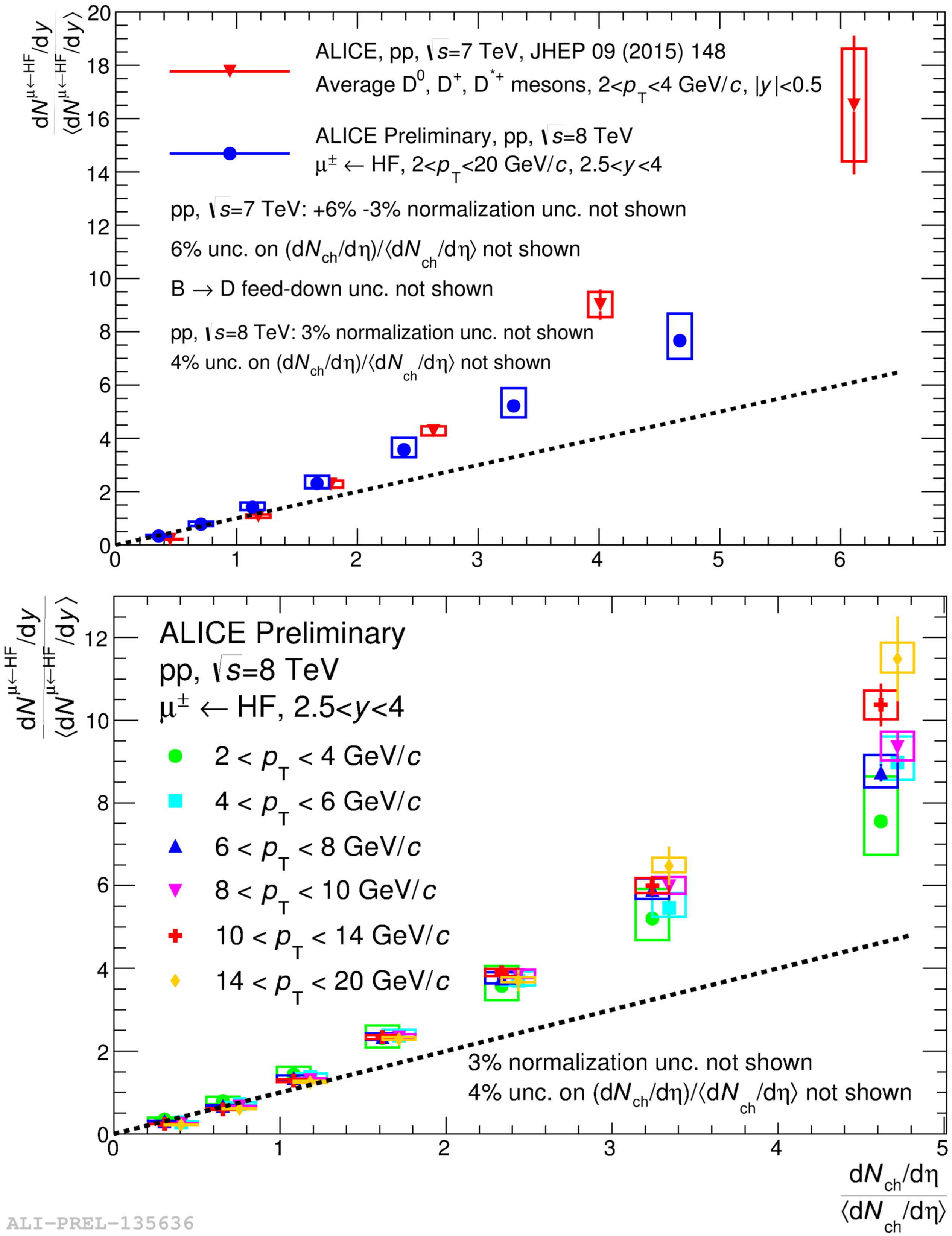


Can we dig a bit more?

- Role of multi-parton interactions
- Hadronization mechanisms
- ……

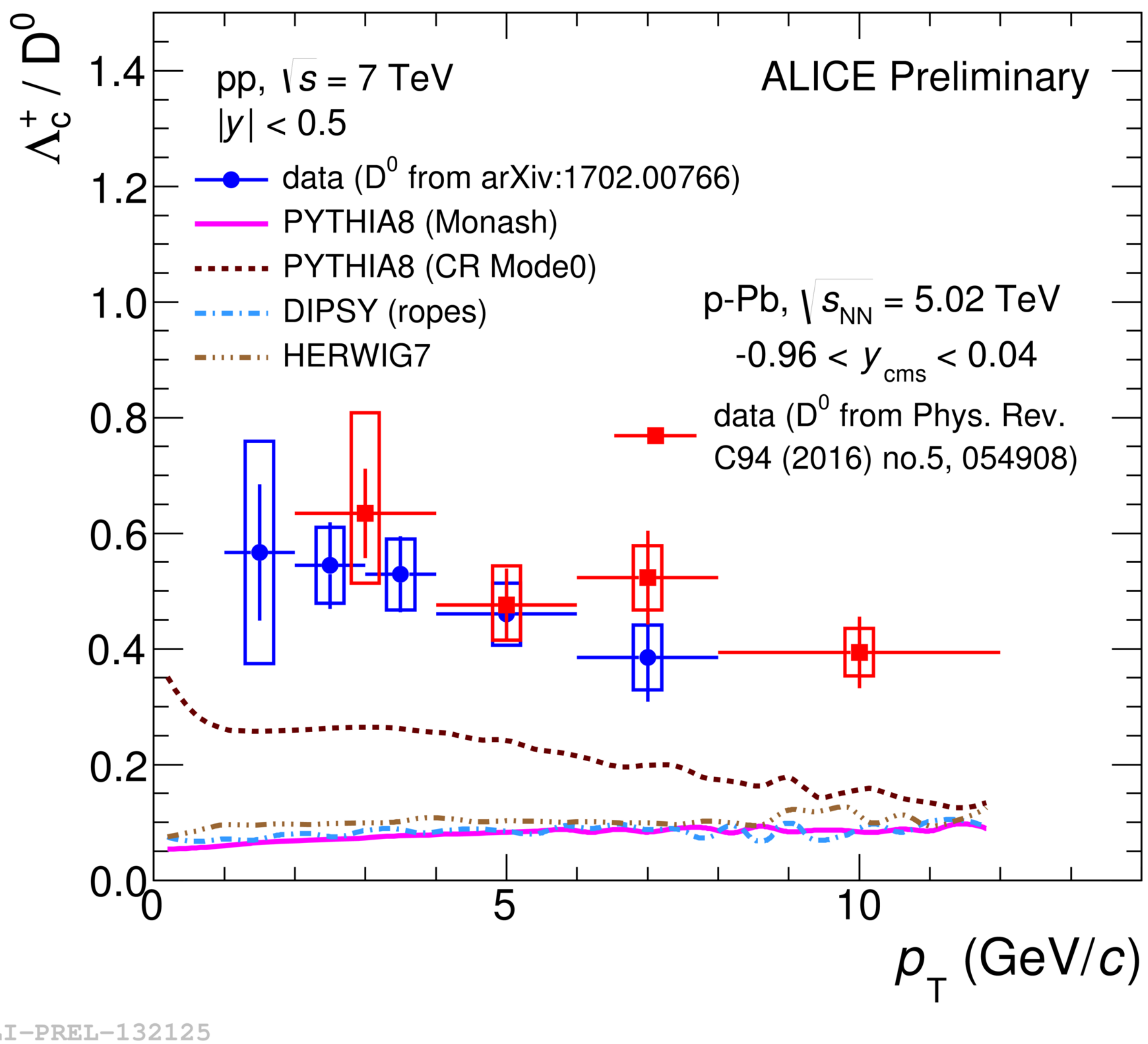
Production vs charged particle multiplicity

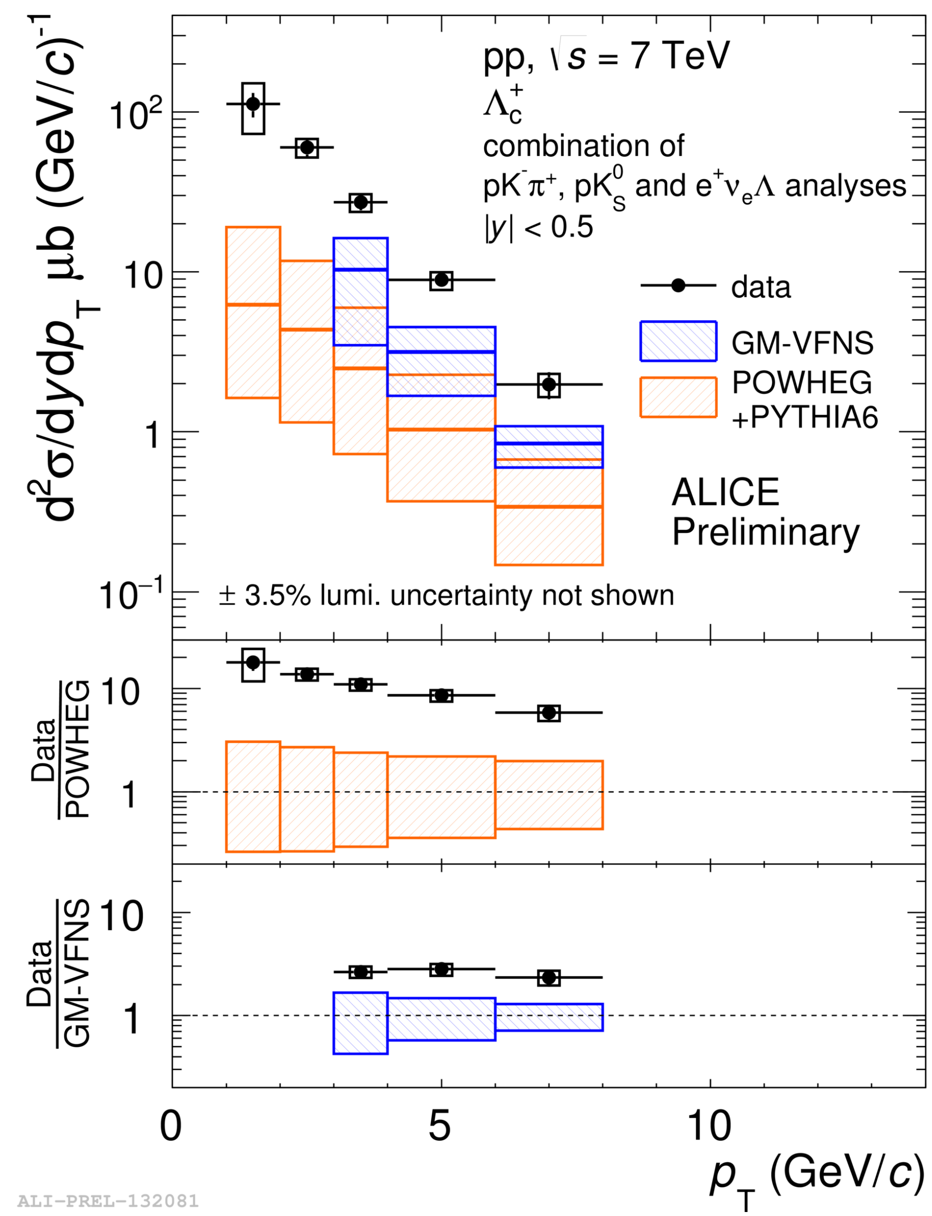


- Yield of forward HF-decay muons increases with charged particle multiplicity at central rapidity
  - Faster than linear increase at high mult.
  - Similar trend for HF-decay muons (2.5<y<4) and D mesons (|y|<0.5)
  - Model calculations need to include multiple parton interactions to qualitative describe the trend (*see D mesons in backup*)
  - p_T dependence?

Baryon to meson ratio in pp (and p-Pb): Λ_c

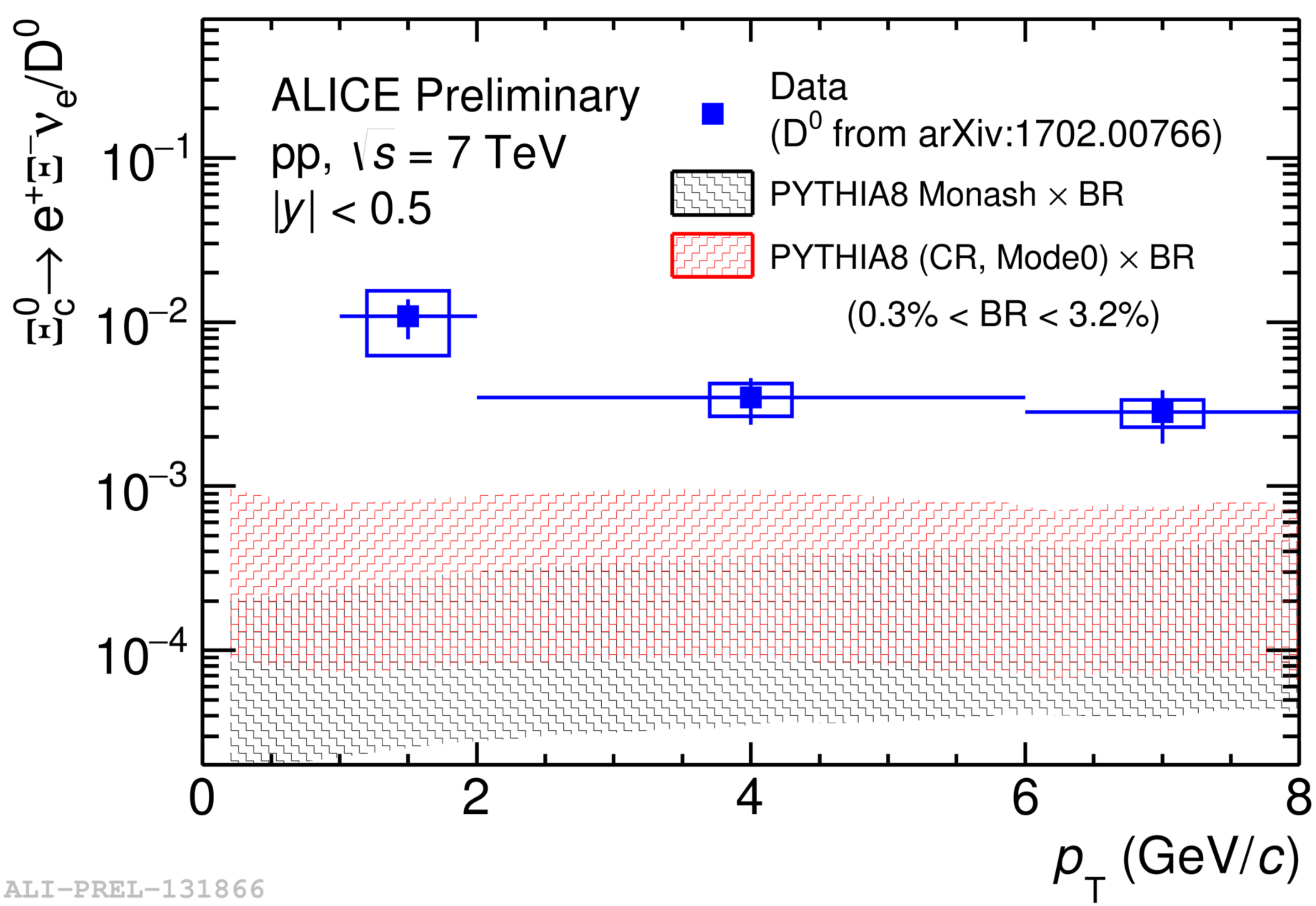
- Further understanding of charm hadronization models:
  - Do we know charm fragmentation in baryons?





PYTHIA8: Comput. Phys. Commun. 178 (2008) 852-867, CR, ropes: Phys. Rev. D92 no. 9, (2015) 094010, DIPSY:JHEP 08 (2011) 103 , HERWIG: Eur. Phys. J. C58 (2008) 639-707

Baryon to meson ratio in pp: Ξ_c^0



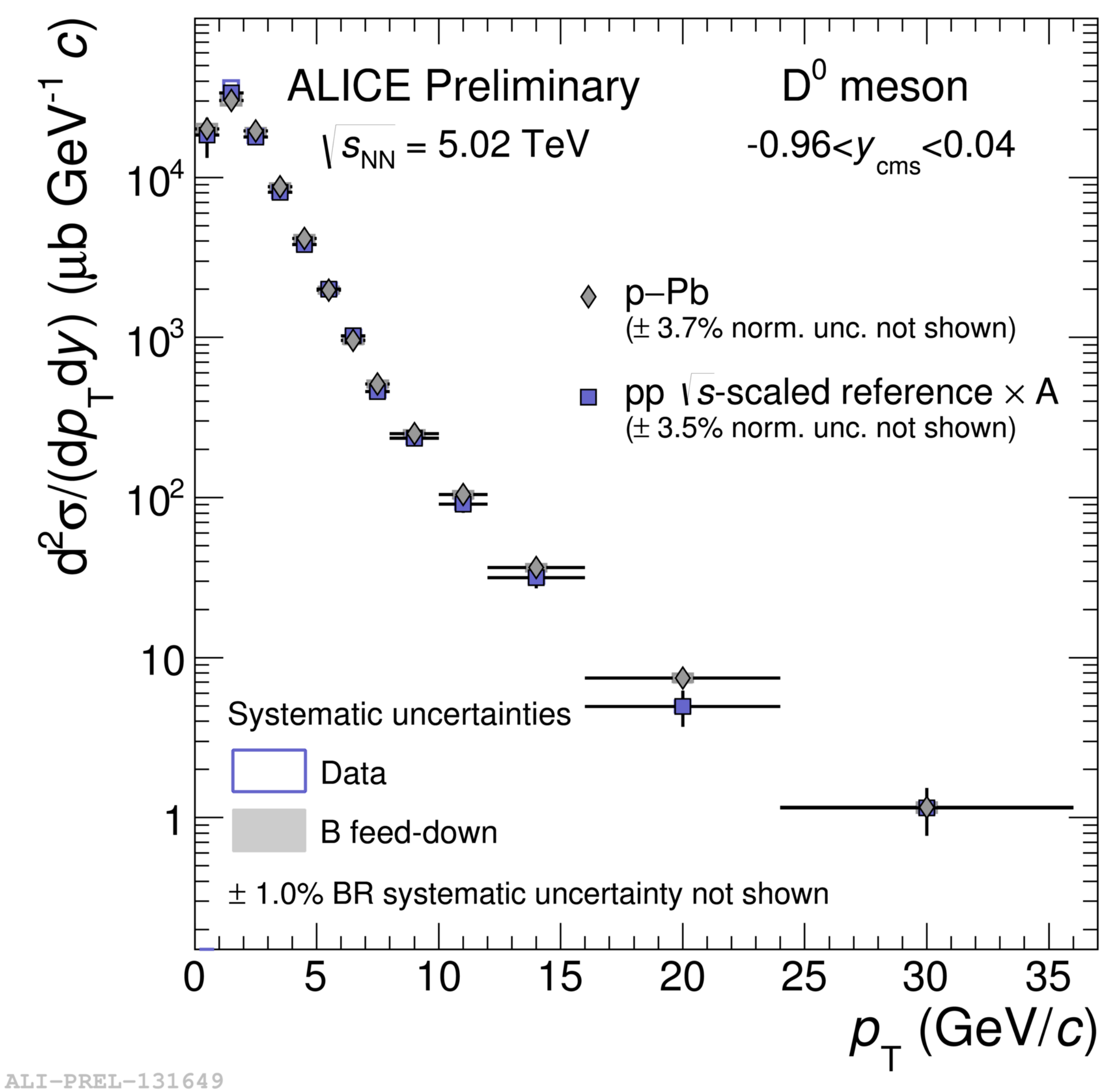
- Ratio not reproduced by Pythia tunes. Note: bands on Pythia due to unknown BR.

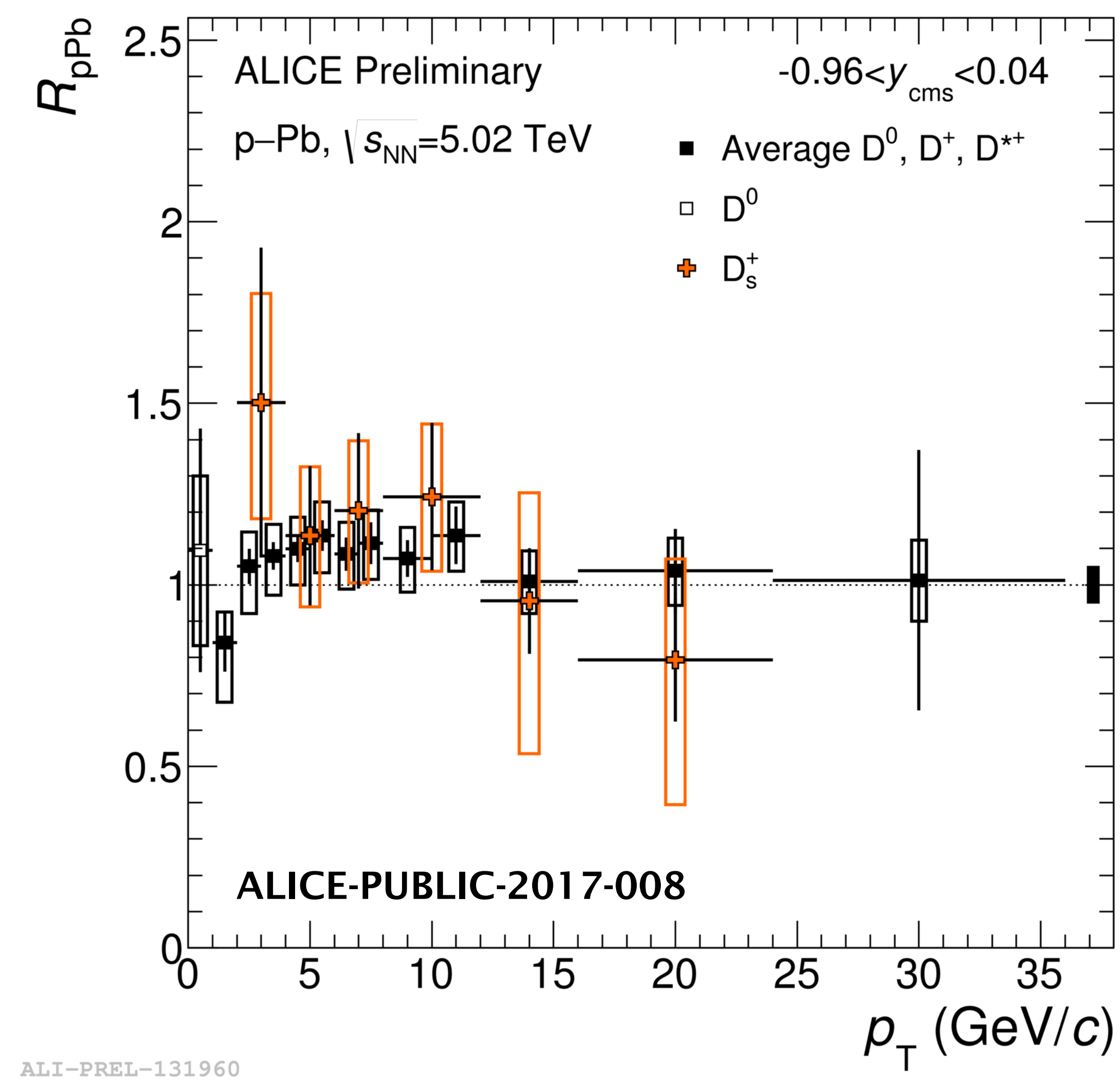
Open heavy flavour production in p-Pb collisions

- Reference for cold nuclear matter (CNM) effects.
- Initial/final-state effects (nPDF, saturation, k_T broadening, energy loss)
- Role of collision geometry/multiplicity density
- Collective effects in small systems?

D-meson production

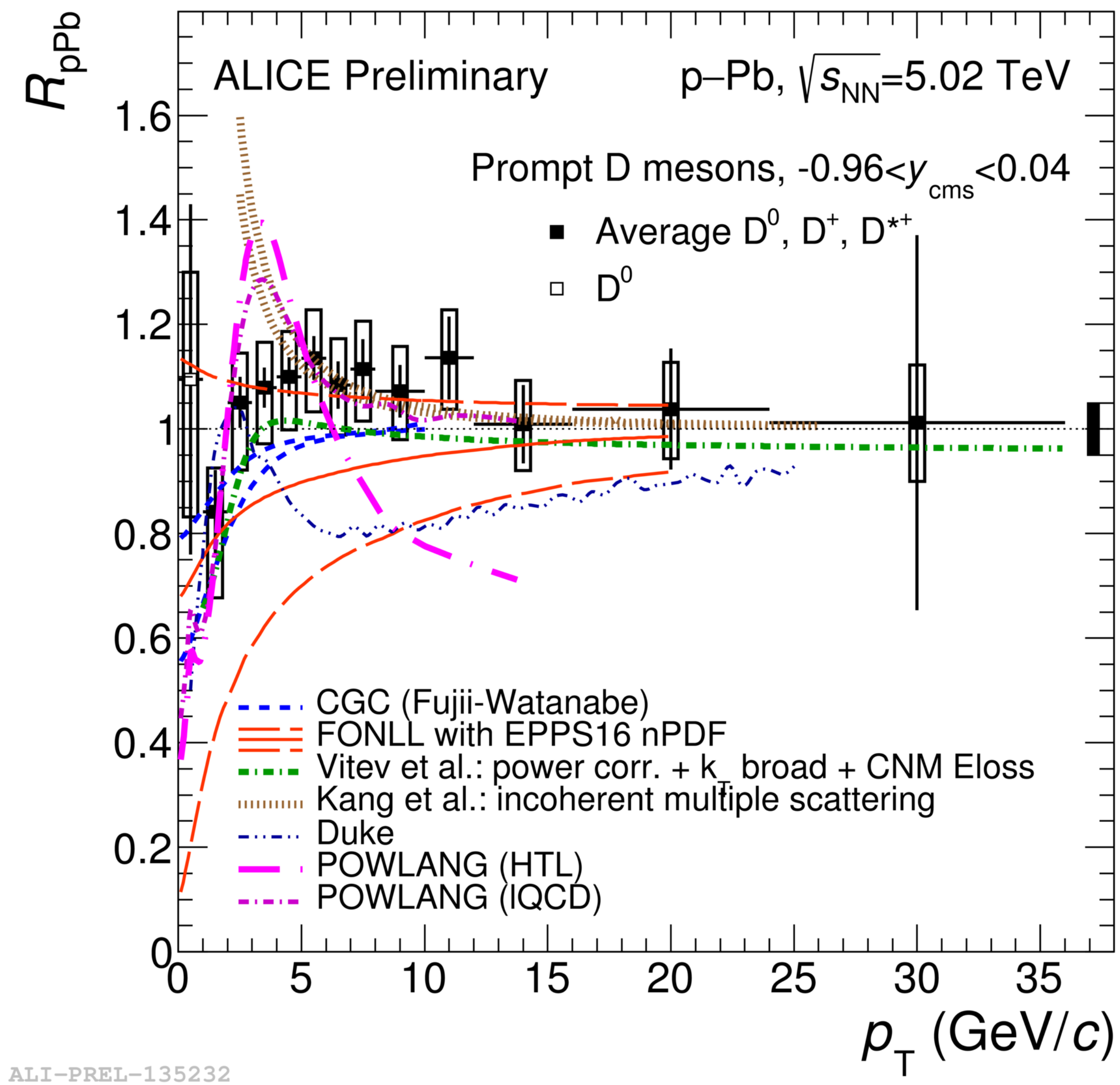
$$R_{\rm pPb} = \frac{({\rm d}\sigma/{\rm d}p_{\rm T})_{\rm pPb}}{A \times ({\rm d}\sigma/{\rm d}p_{\rm T})_{\rm pp}}$$





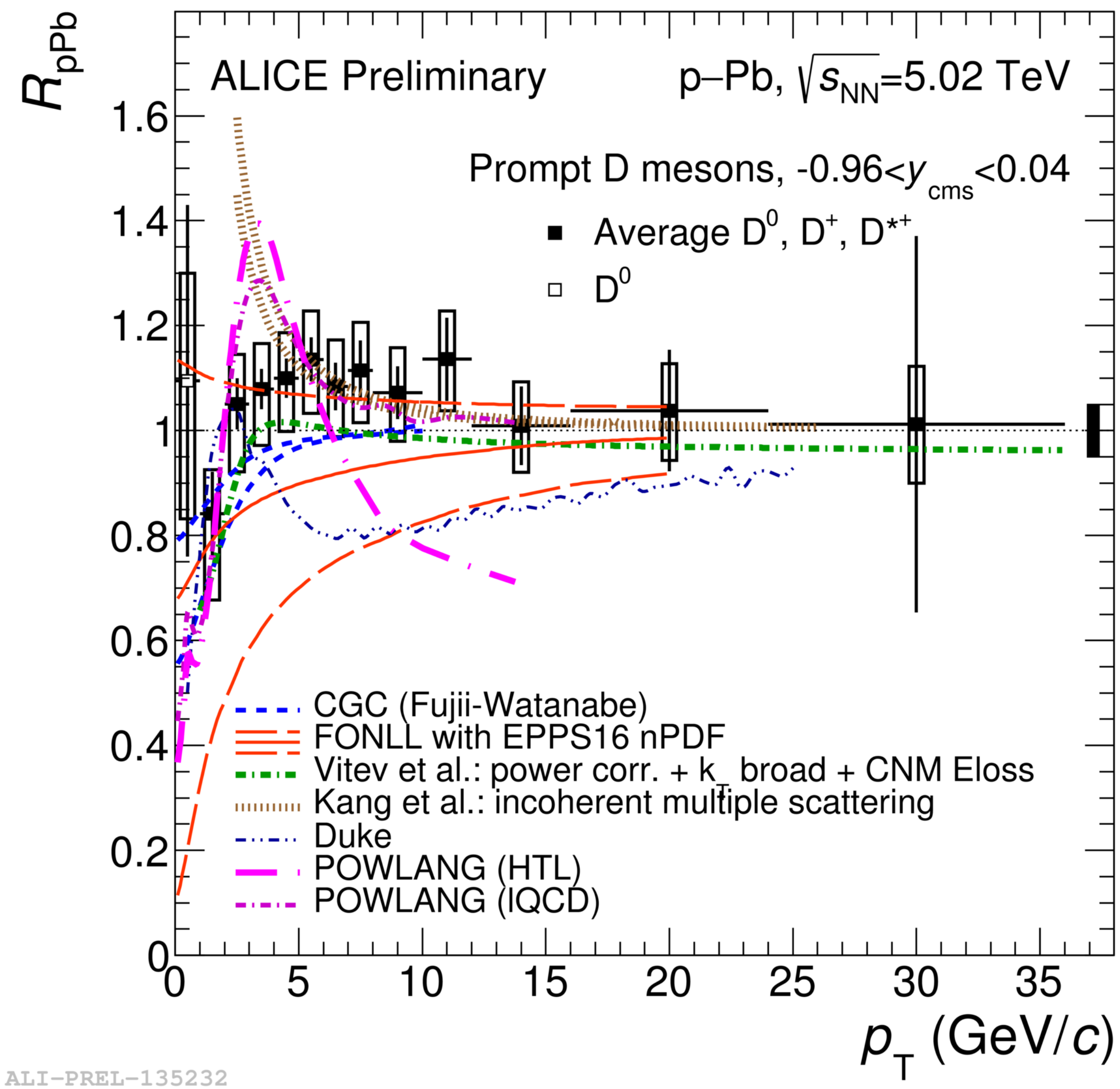
☑ R_{AA} of strange and non-strange D mesons compatible with unity. Consistent with small initial state effects at LHC.

D-meson production



- Described by models including cold nuclear-matter effects
- Described my models including the formation of QGP in p-Pb:
  - ➡ data disfavour suppression >~15% at high-p_T
  - ➡ need to improve the precision of the measurement for a more conclusive statement

D-meson production



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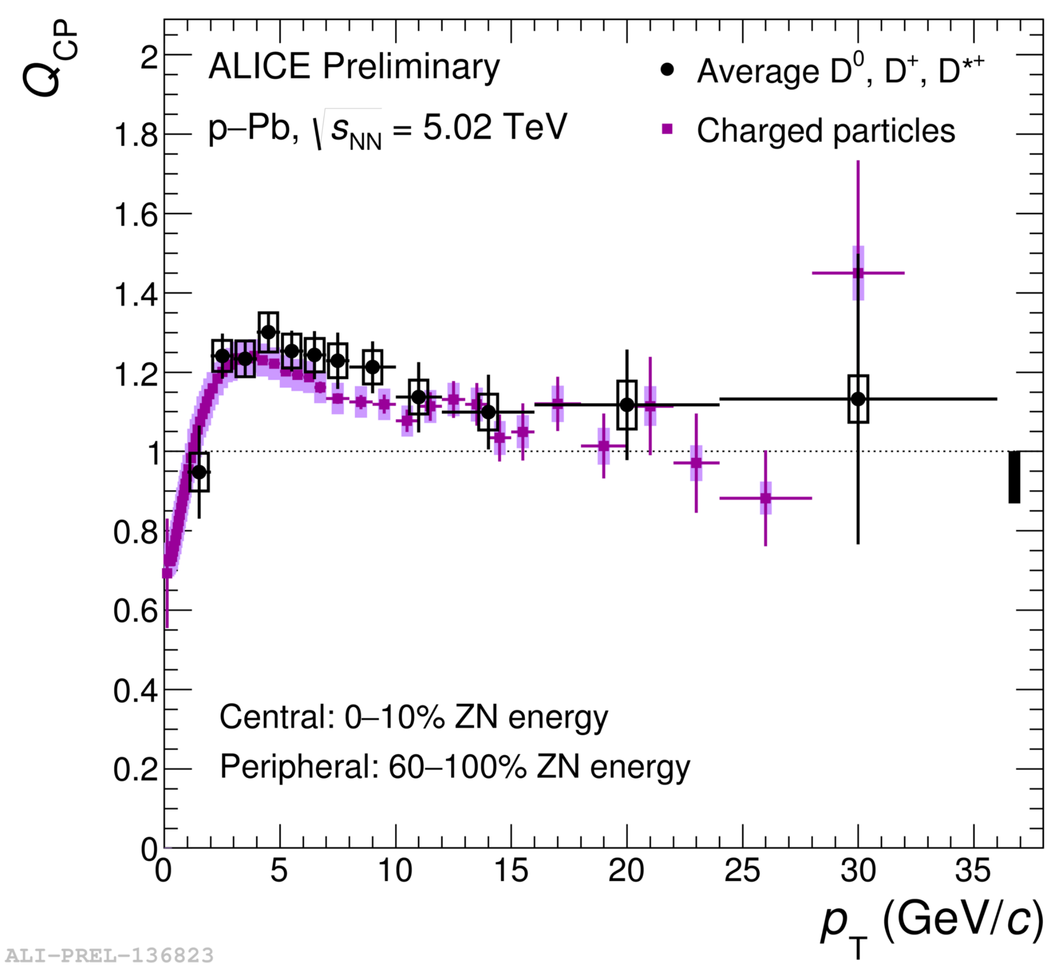
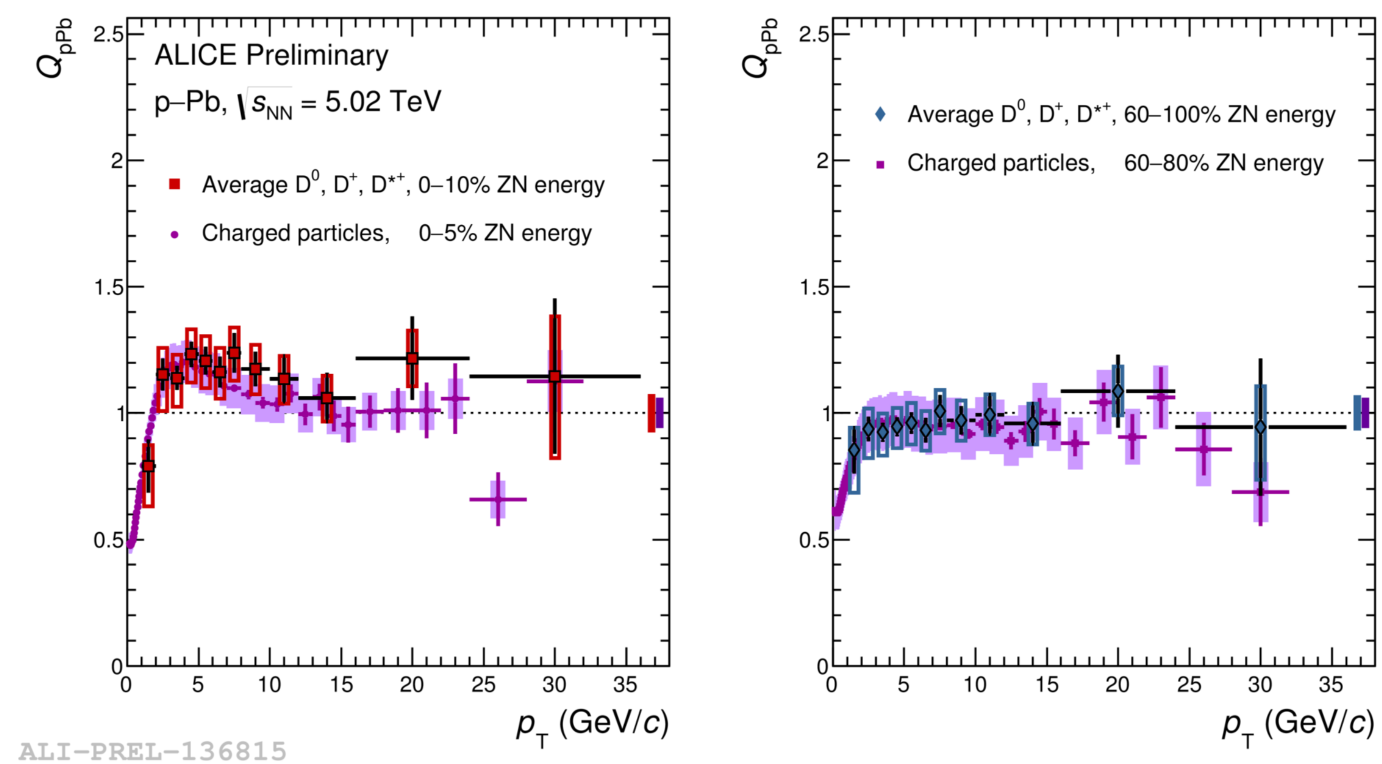
New pp@ 5 TeV reference will improve significantly the measurement

D-meson production vs centrality

ALICE-PUBLIC-2017-008

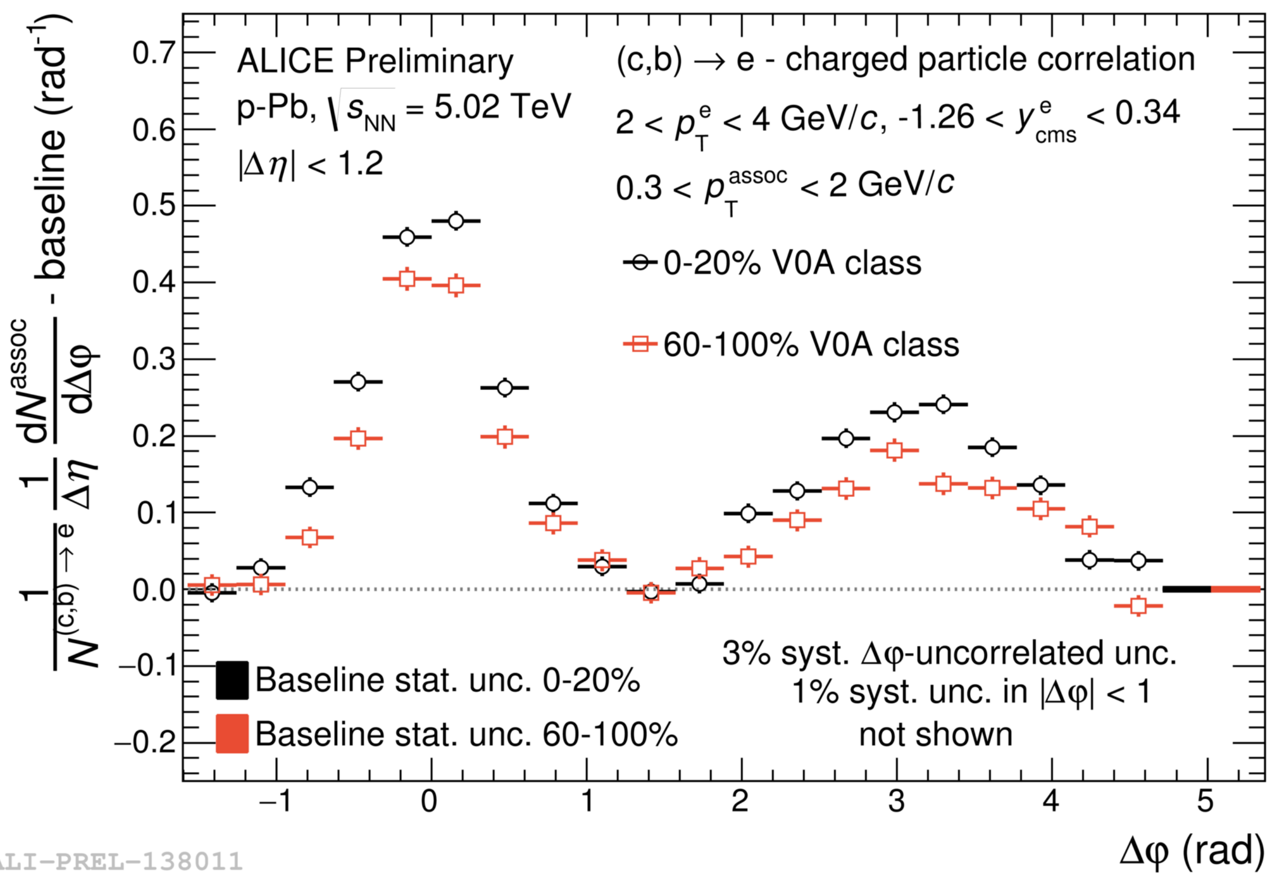


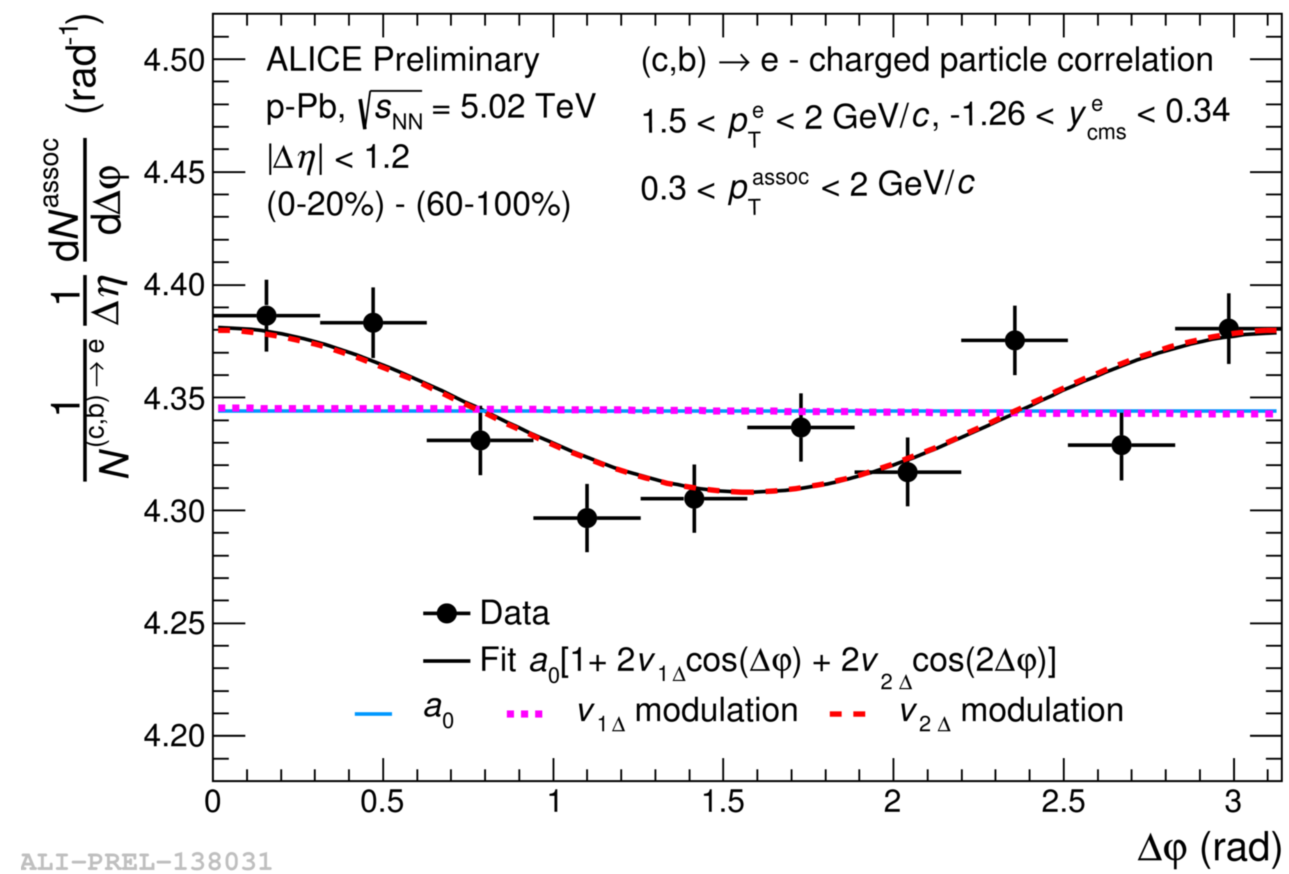
$$Q_{pPb}^{0-10\%}(p_T) = \frac{dN_{pPb}^{0-10\%} / dp_T}{\langle T_{AA} \rangle_{0-10\%} \times d\sigma_{pp} / dp_T}$$



- Hint for D-meson "Central-to-peripheral" ratio (Q_{CP}) larger than unity
  - ✓ 1.5σ in $2<p_T<8$ GeV/c
- Very similar to charged pion Q_{CP}
  - Initial-state effect? Mass effect? Radial flow?
  - … need comparison with theoretical calculations

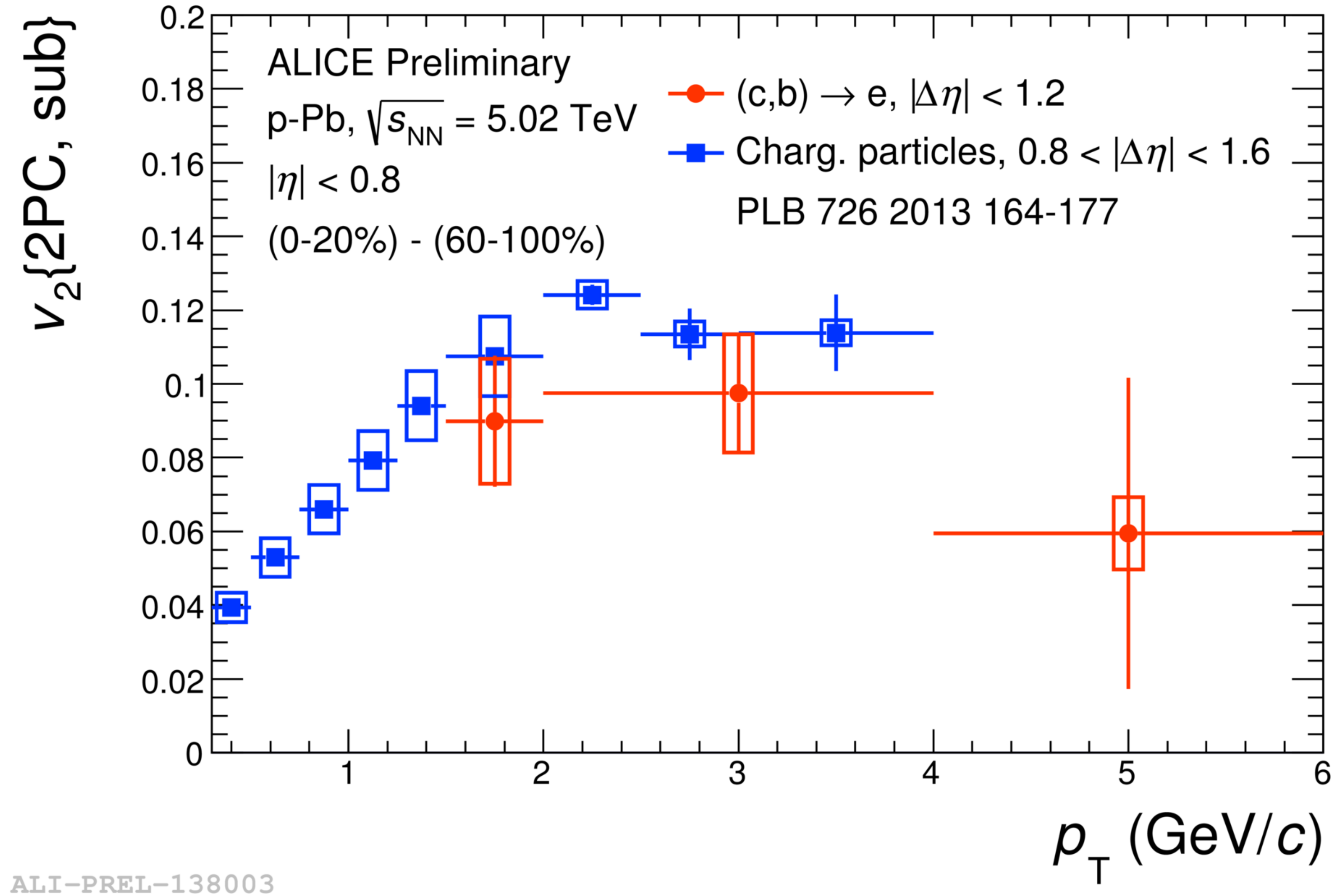
Heavy-flavour decay electron v_2





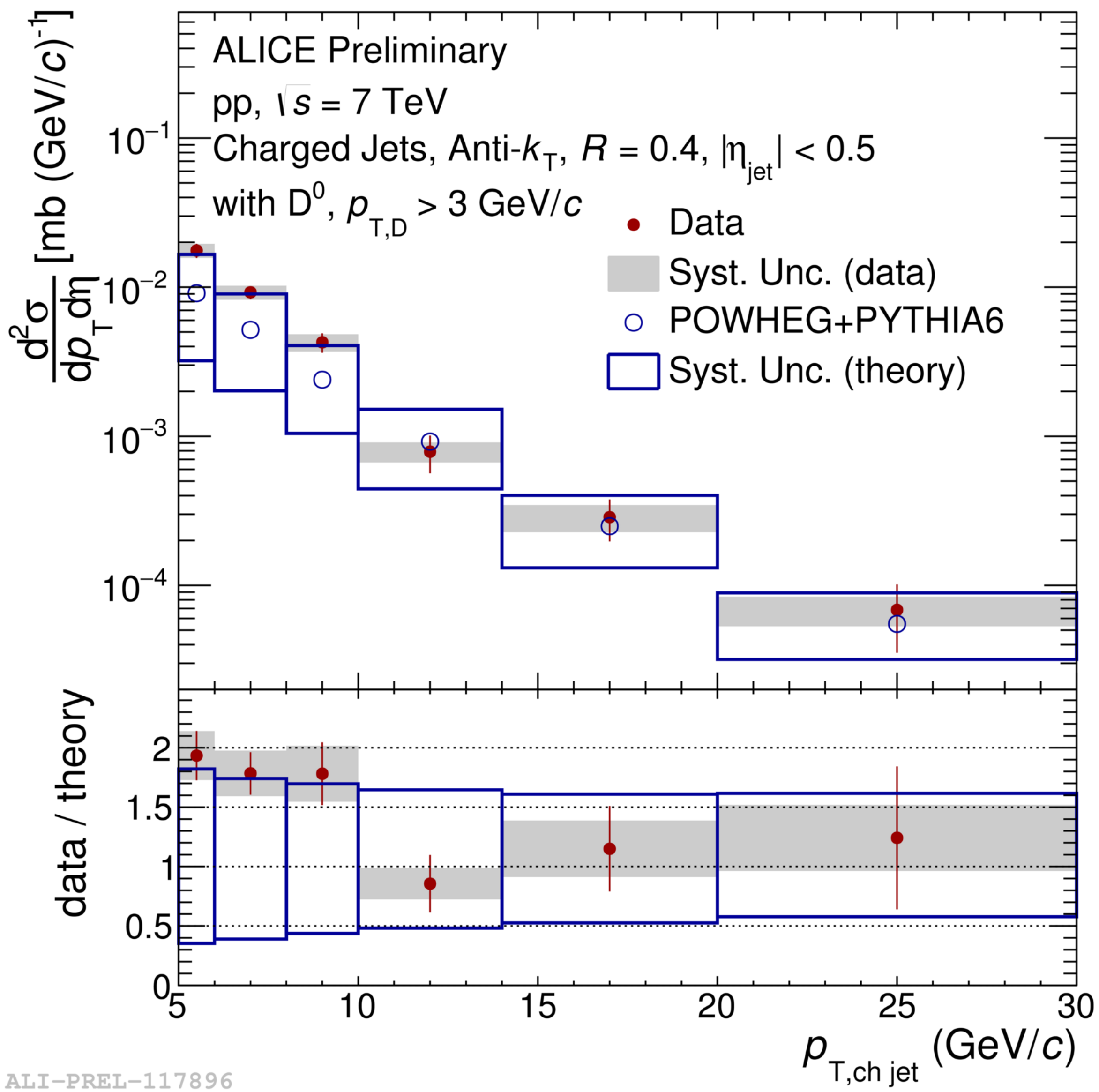
- ☑ Analysis of electron-hadron azimuthal correlations in 20% collisions with higher multiplicity
- ☑ 60-100% multiplicity class used to subtract the jet contribution

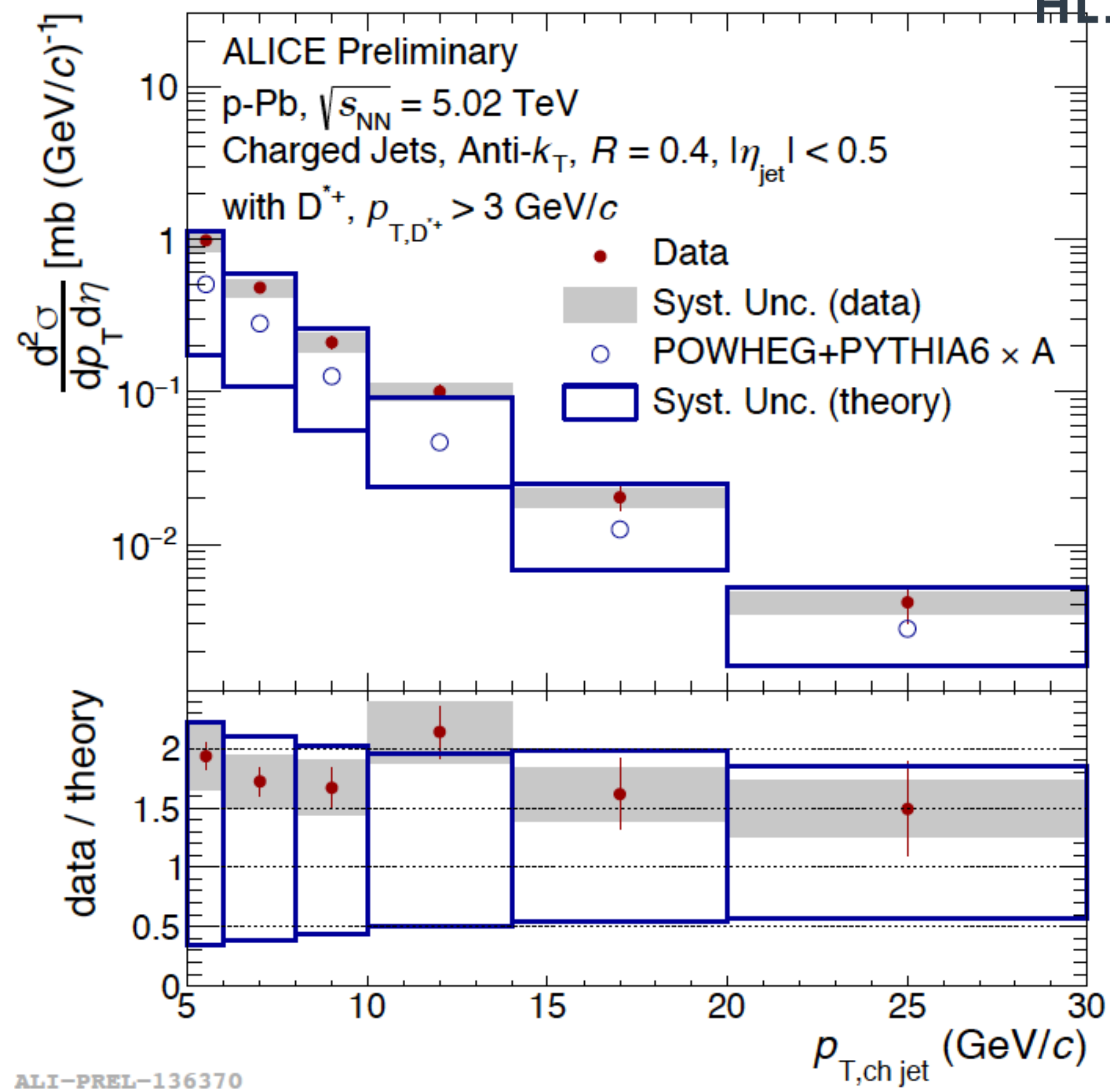
Heavy-flavour decay electron v_2



- Positive v_2 measured for heavy-flavour decay electrons at ~4.4σ:
  - ☑ Initial-state effects, collective effects?
  - ☑ Data suggest a v_2 comparable with the one of charged particles

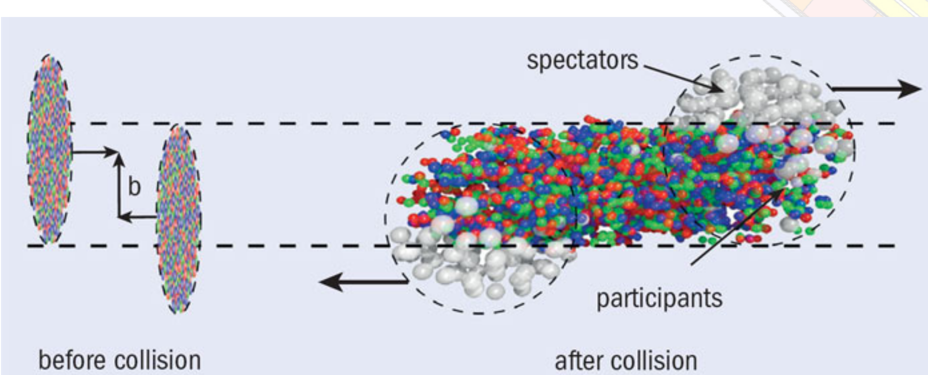
Study of HF jet production in p-Pb (and pp)





- ☑ D-jet spectrum measured down to p_T = 5 GeV/c → *strong constraint for theory*
- ☑ Described by POWHEG+PYTHIA6 (Perugia 2011 tune) simulation within uncertainty
- ☑ Unique opportunity to study charm jet properties and structure (… in Pb-Pb)

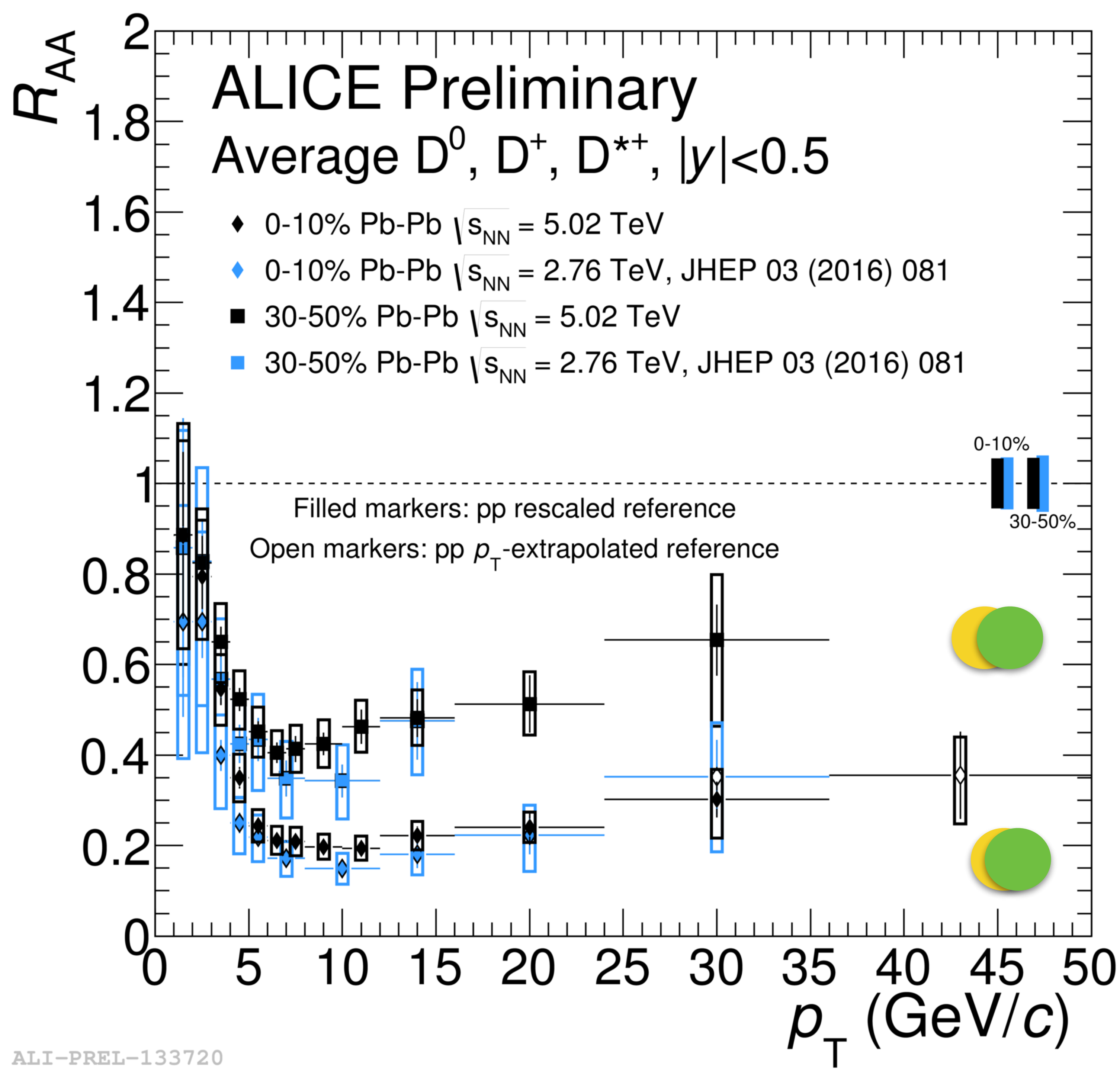
Open heavy flavour production in Pb-Pb collisions



Note: lead ions are extended objects therefore collisions can be classified based on "centrality". In central collisions, i.e 0-10%, we have larger overlap than in peripheral.

D-mesons R_{AA}

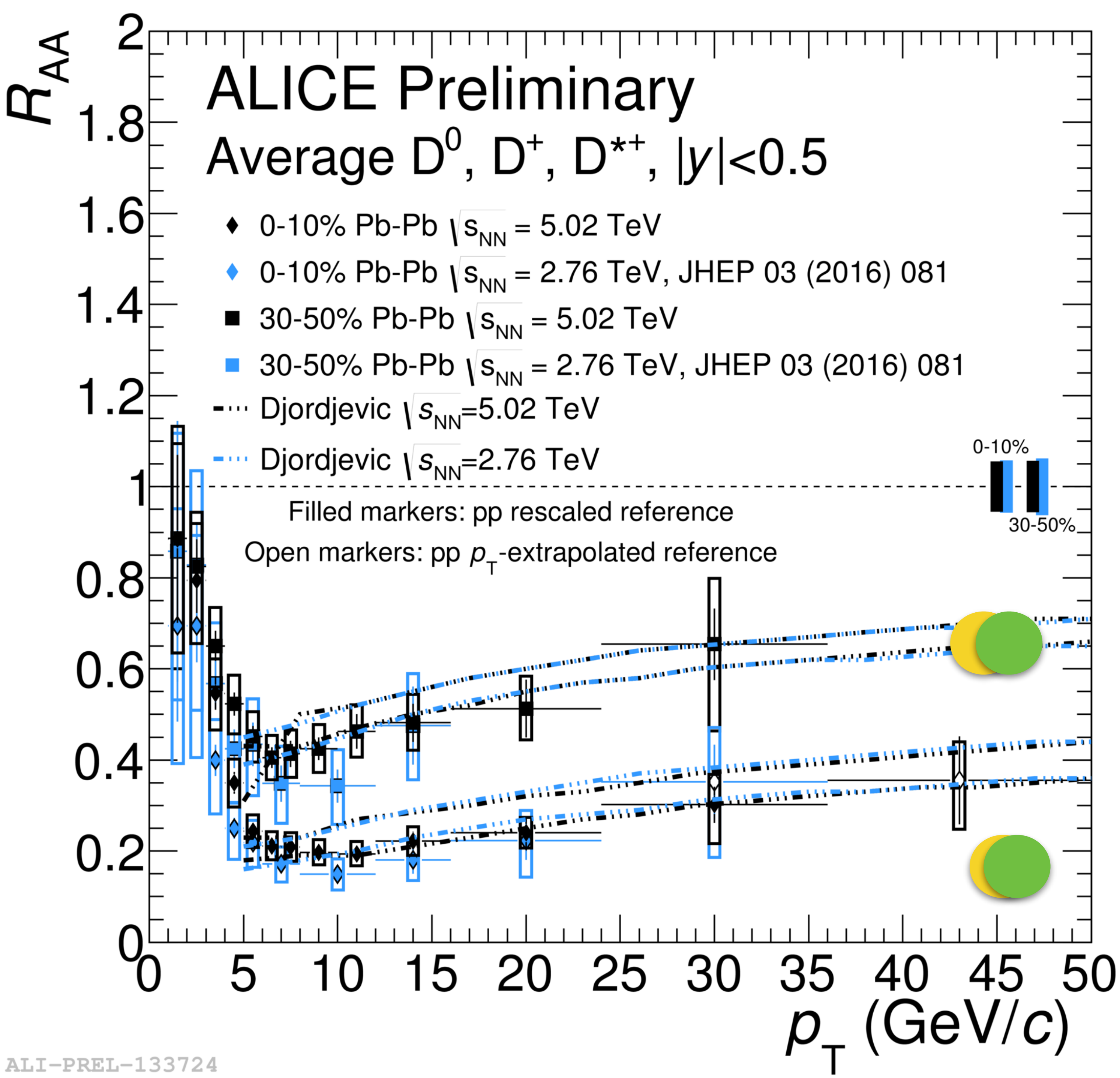
JHEP 03 (2016) 081 ALICE-PUBLIC-2017-003



- ALICE measured non-strange D mesons R_{AA} in LHC run I and II in several centrality regions
- Run II data: extended p_T reach and increased statistical precision
- Similar suppression at 2.76 and 5.02 TeV .. that cannot be explained with initial state effects

D-mesons R_{AA}

JHEP 03 (2016) 081 ALICE-PUBLIC-2017-003



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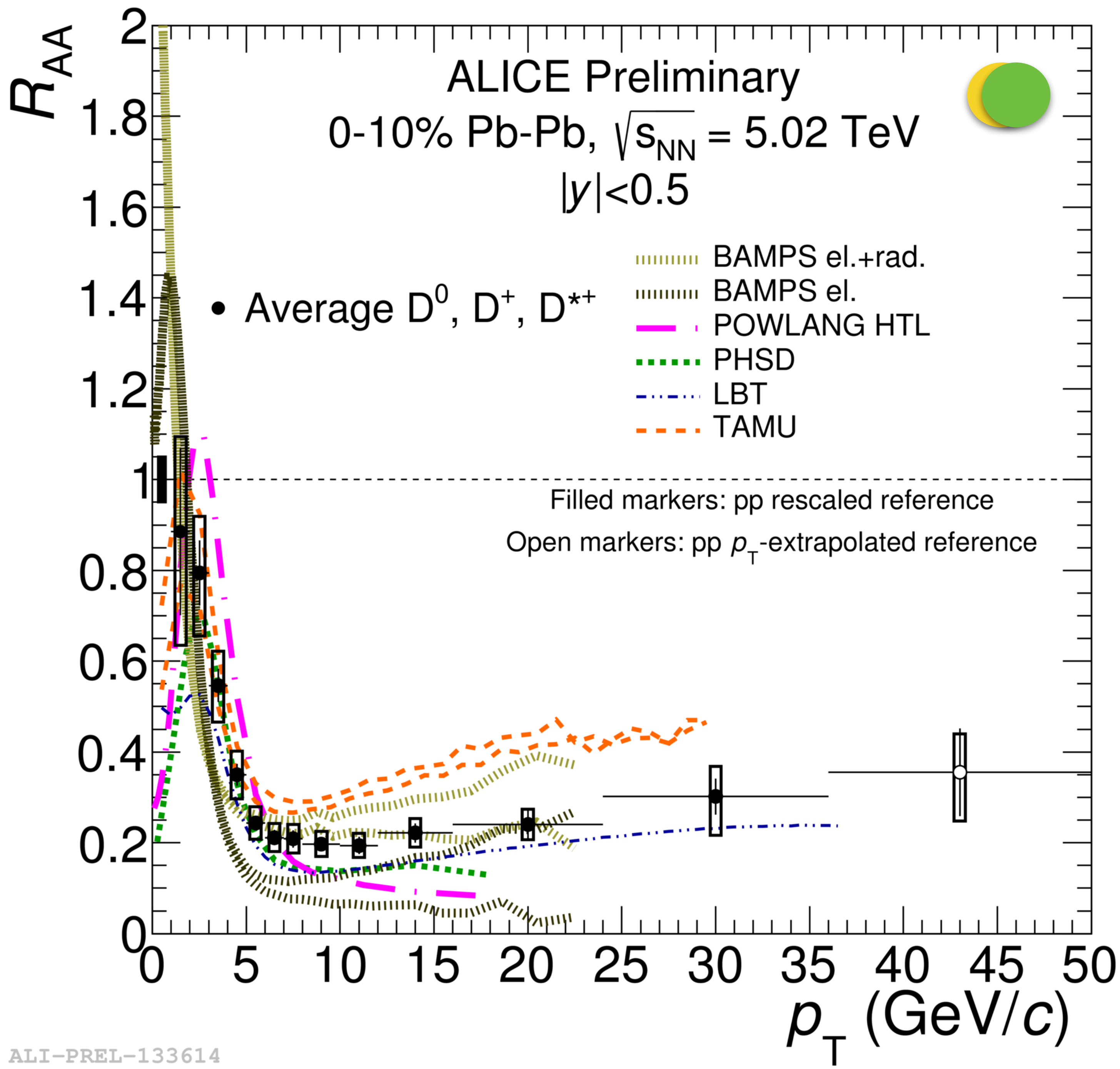
- Run II data: extended p_T reach and increased statistical precision
- Similar suppression at 2.76 and 5.02 TeV .. that cannot be explained with initial state effects

Expected from theory calculations as a consequence between the balance between harder spectrum and denser medium

Djordjevic, Phys. Rev. C92 (2015) 024918

D-mesons R_{AA}: comparison with models



Transport models

PHSD PRC 93 (2016) 034906 (collisional + radiative energy loss, recombination, hydro and nPDF)

LBT arXiv:1703.00822 (collisional + radiative energy loss, recombination, hydro and nPDF)

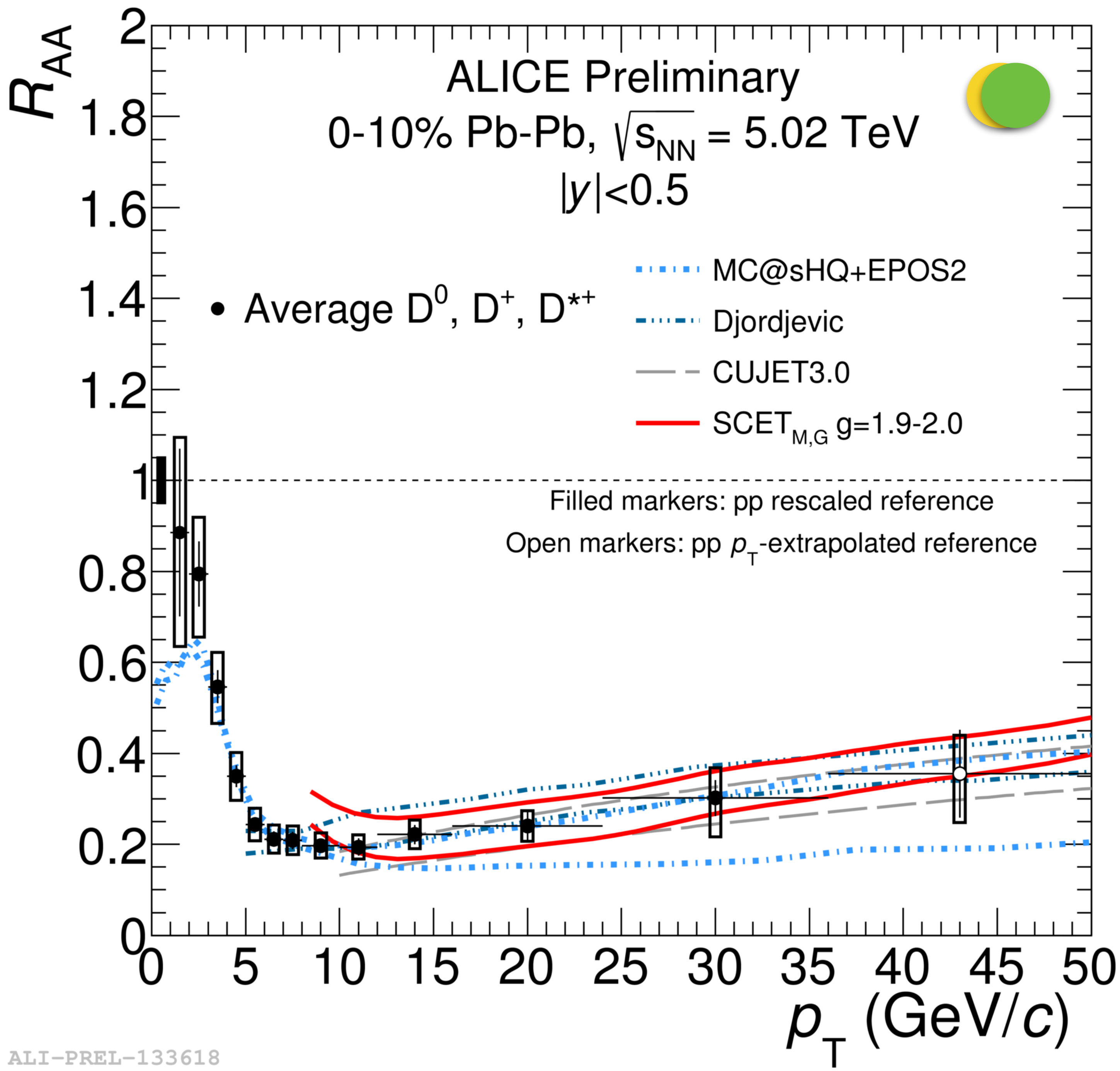
BAMPS J. Phys. G42 (2015) 115106 (collisional + radiative energy loss, hydro)

POWLANG EPJC 75 (2015) 121 (collisional energy loss, recombination, hydro + nPDF)

TAMU Phys. Lett. B735 (2014) 445 (collisional energy loss, recombination, hydro + nPDF)

☑ Radiative energy loss needed to describe the data at high p_T while at low p_T collisional + shadowing improve the data description

D-mesons R_{AA}: comparison with models



QCD based E_{loss} models

CUJET3.0 JHEP 02 (2016) 169 (collisional + radiative energy loss)

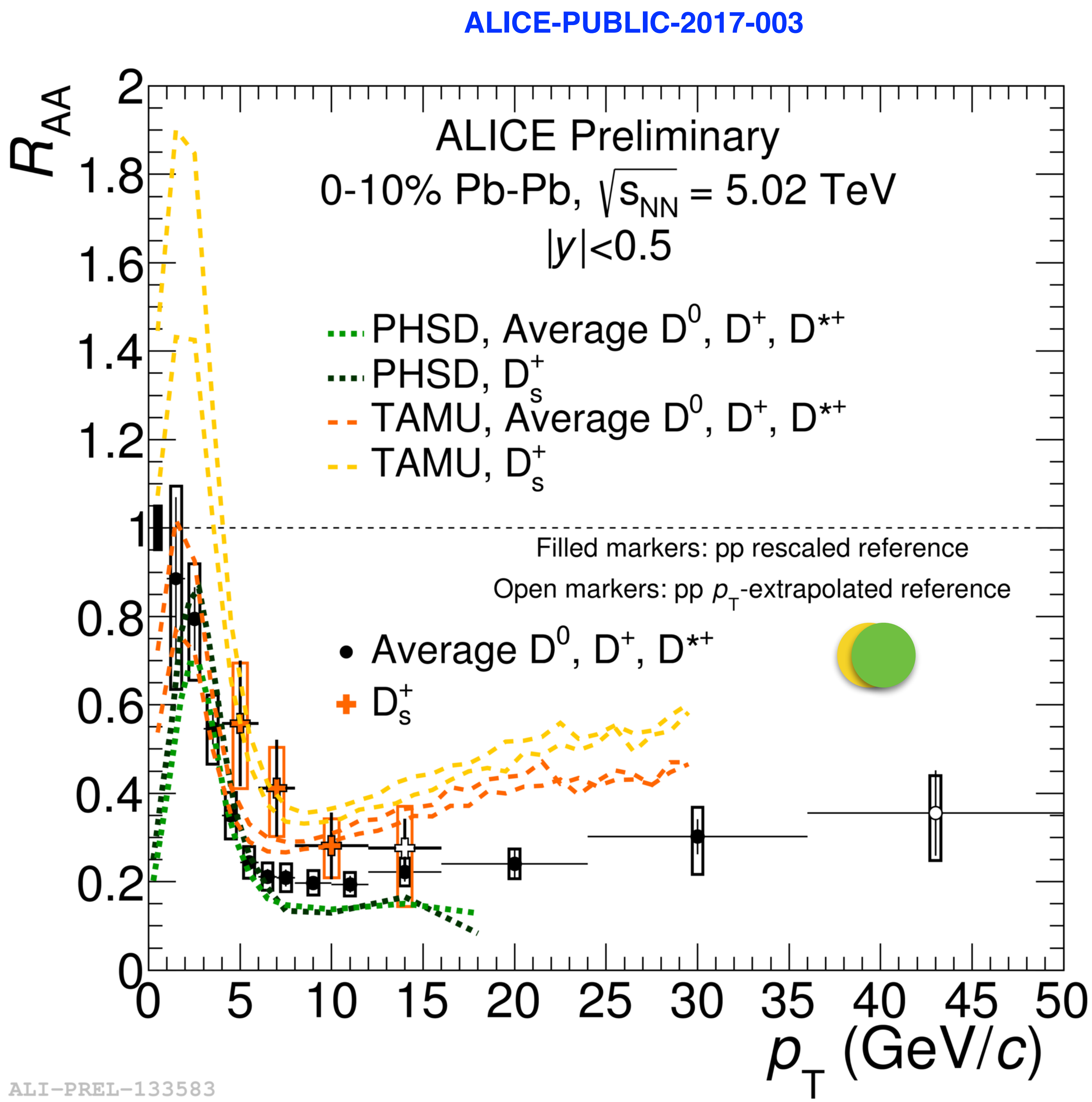
Djordjevic PRC 92 (2015) 024918 (collisional + radiative energy loss, nPDF)

MC@sHQ+EPOS PRC 89 (2014) 014905 (collisional + radiative energy loss, recombination, hydro and nPDF)

SCET JHEP 03 (2017) 146 (collisional + radiative energy loss, nPDF)

☑ Radiative energy loss needed to describe the data at high p_T while at low p_T collisional + shadowing improve the data description

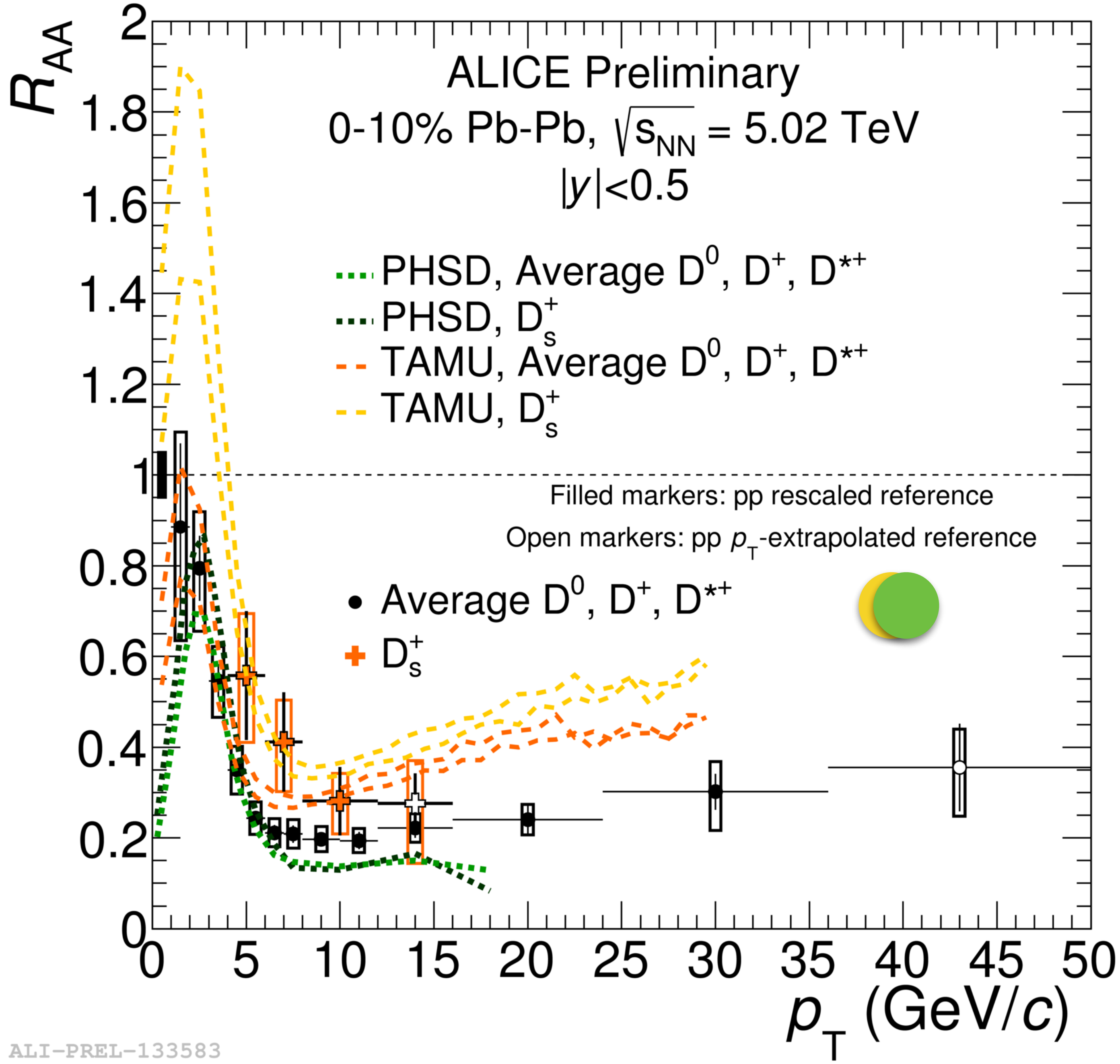
D_s meson R_{AA}



- If coalescence processes play a major role in charm hadronization, the R_{AA} of D_s is expected to be largely enhanced with respect the other D R_{AA}
- D_s in ALICE data show an hint of enhancement wrt the non-strange D mesons.

D_s meson R_{AA}

ALICE-PUBLIC-2017-003



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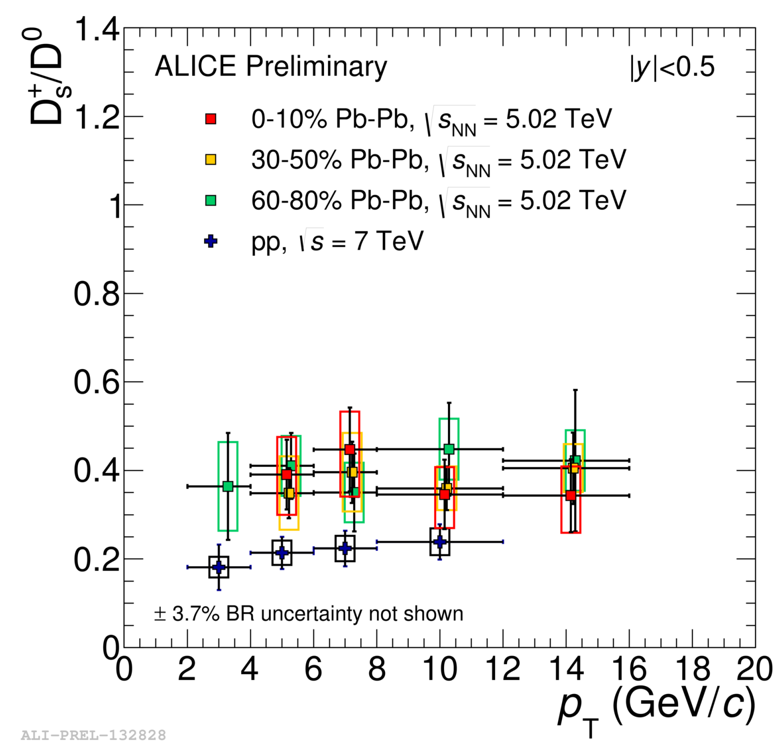
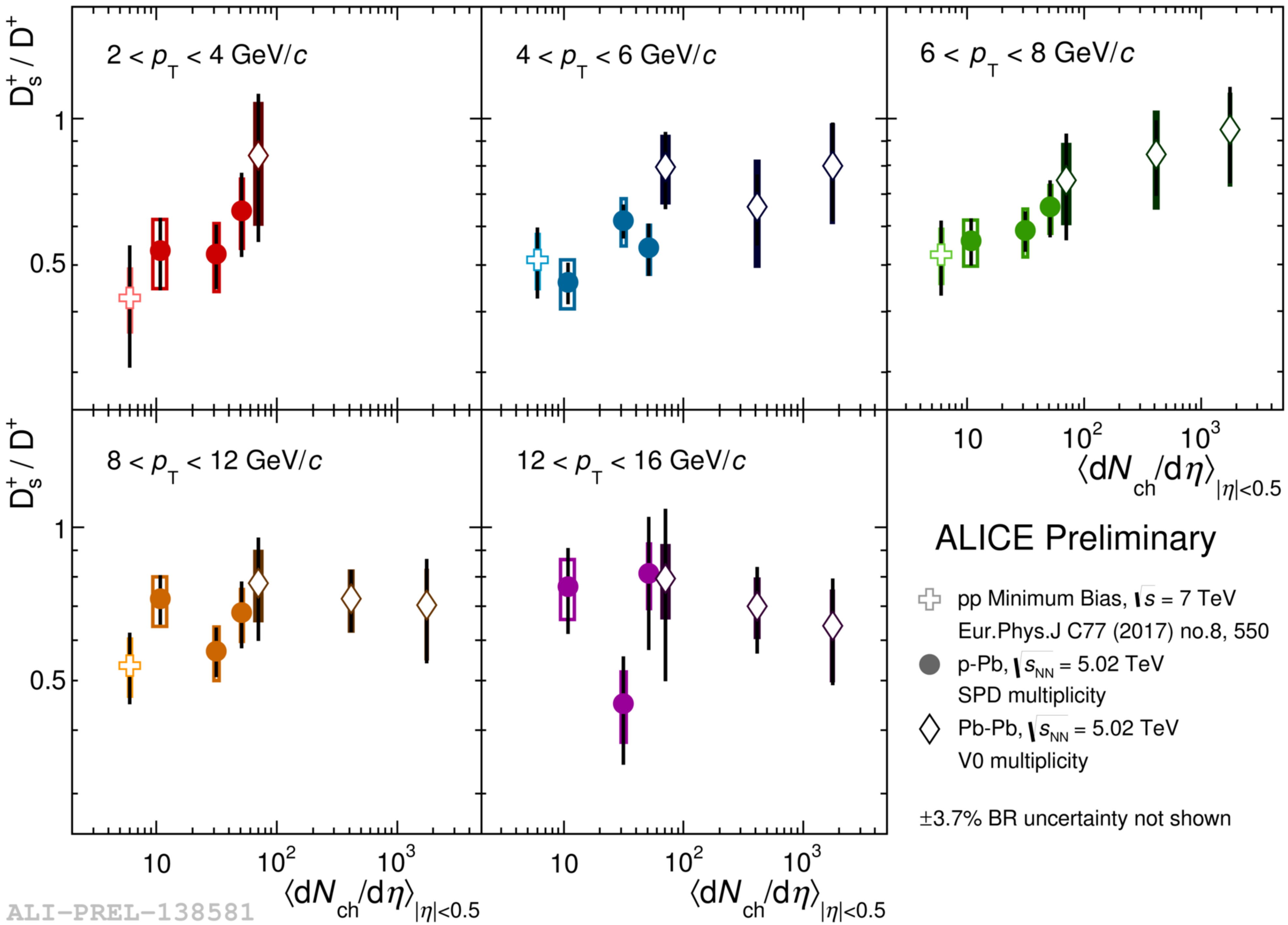


➡ Not conclusive, additional data needed

D_s/D^0 ratios in pp, p-Pb and Pb-Pb



Mass dependence: D vs B

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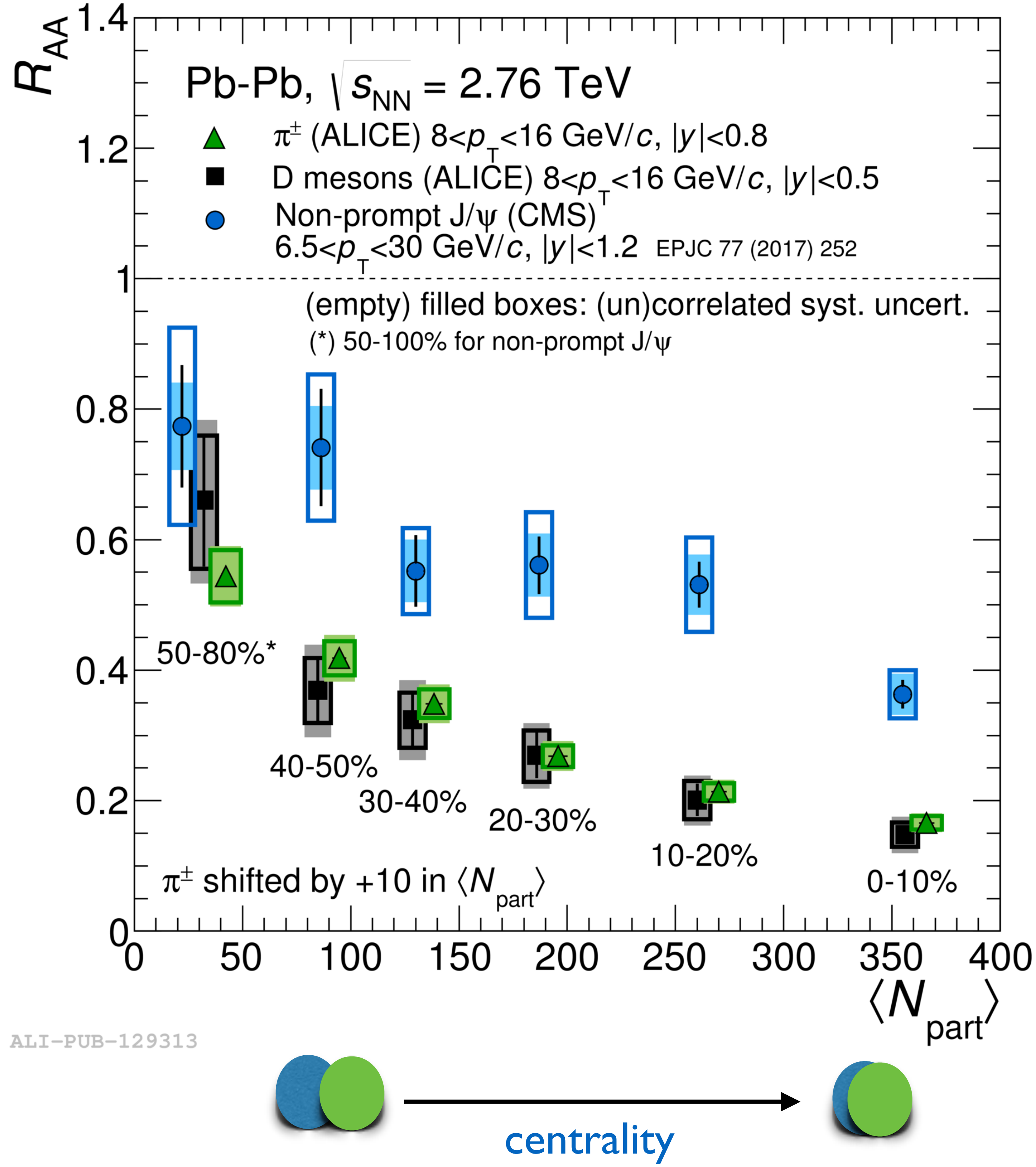
D meson from ALICE and non-prompt J/ψ from CMS



JHEP 1511 (2015) 205, JHEP 1706 (2017) 032

EPJ C 77 (2017) 252

JHEP 1706 (2017) 032

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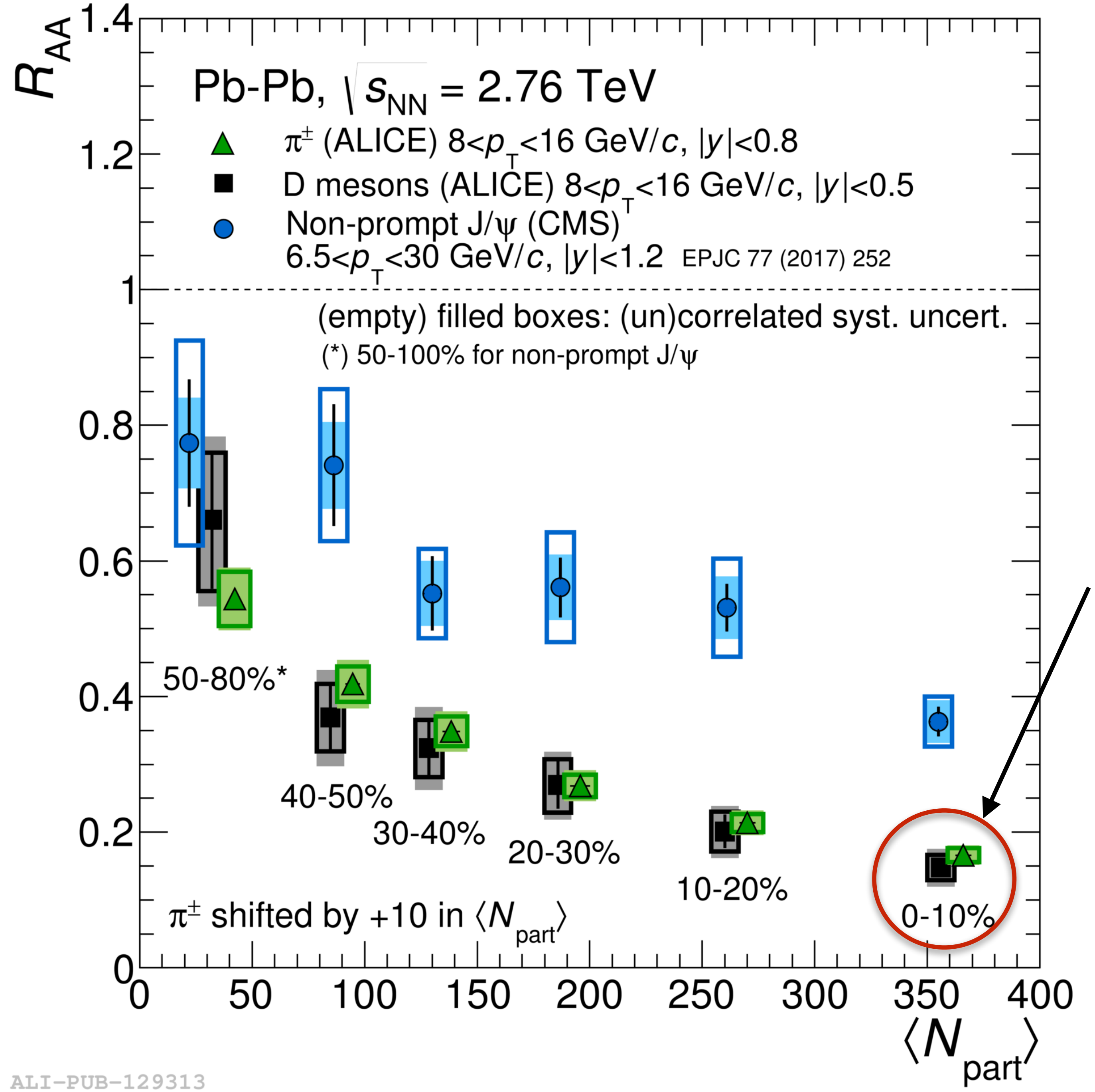
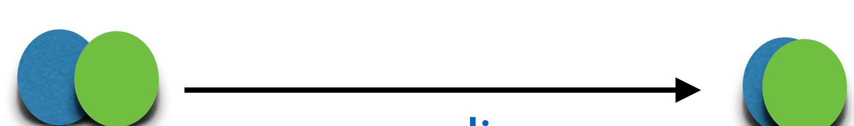
D meson from ALICE and non-prompt J/ψ from CMS





JHEP 1511 (2015) 205, JHEP 1706 (2017) 032

EPJ C 77 (2017) 252

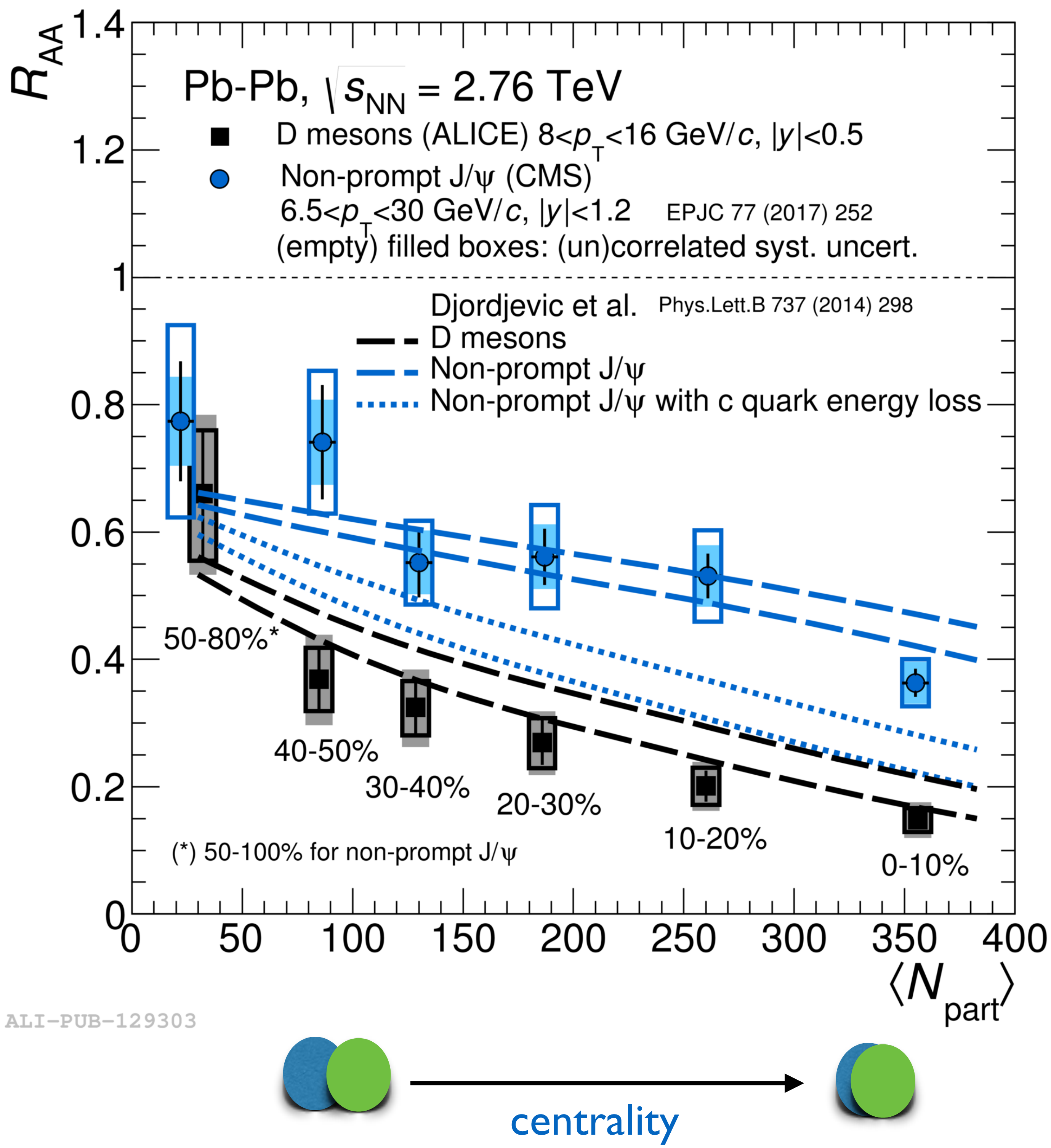
- Similar D meson and pion R_{AA} Expected from charm-quark mass effects + different charm and gluon/light-quark spectrum slope and fragmentation

M. Djordjevic, PRL112 (2014) 042302

JHEP 1706 (2017) 032

Mass dependence: D vs B

- D meson from ALICE and non-prompt J/ψ from CMS



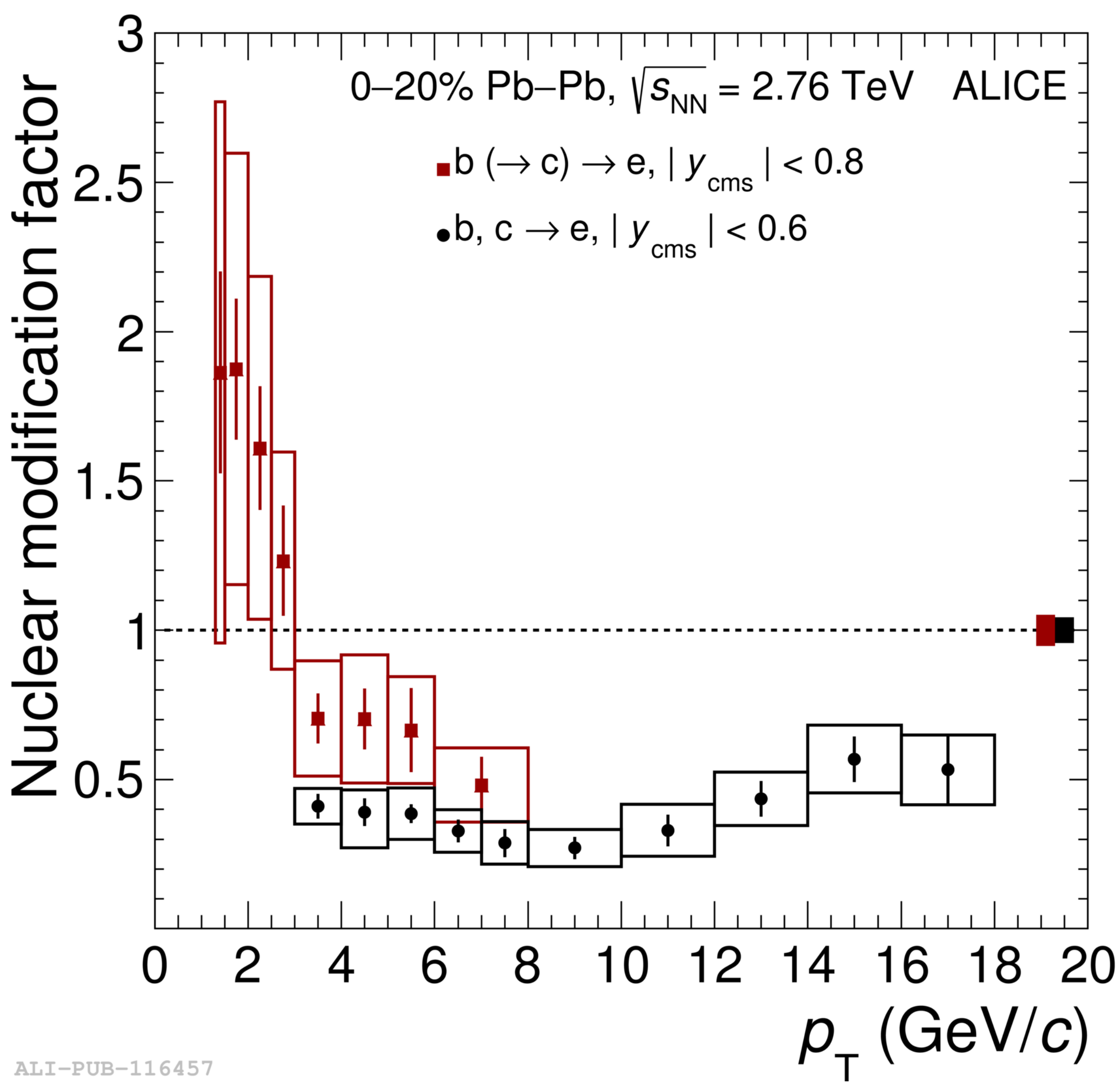
JHEP 1511 (2015) 205, JHEP 1706 (2017) 032
EPJ C 77 (2017) 252

} consequence of mass difference in pQCD based model calculation

JHEP 1706 (2017) 032
Djordjevic: Phys.Lett. B734 (2014)

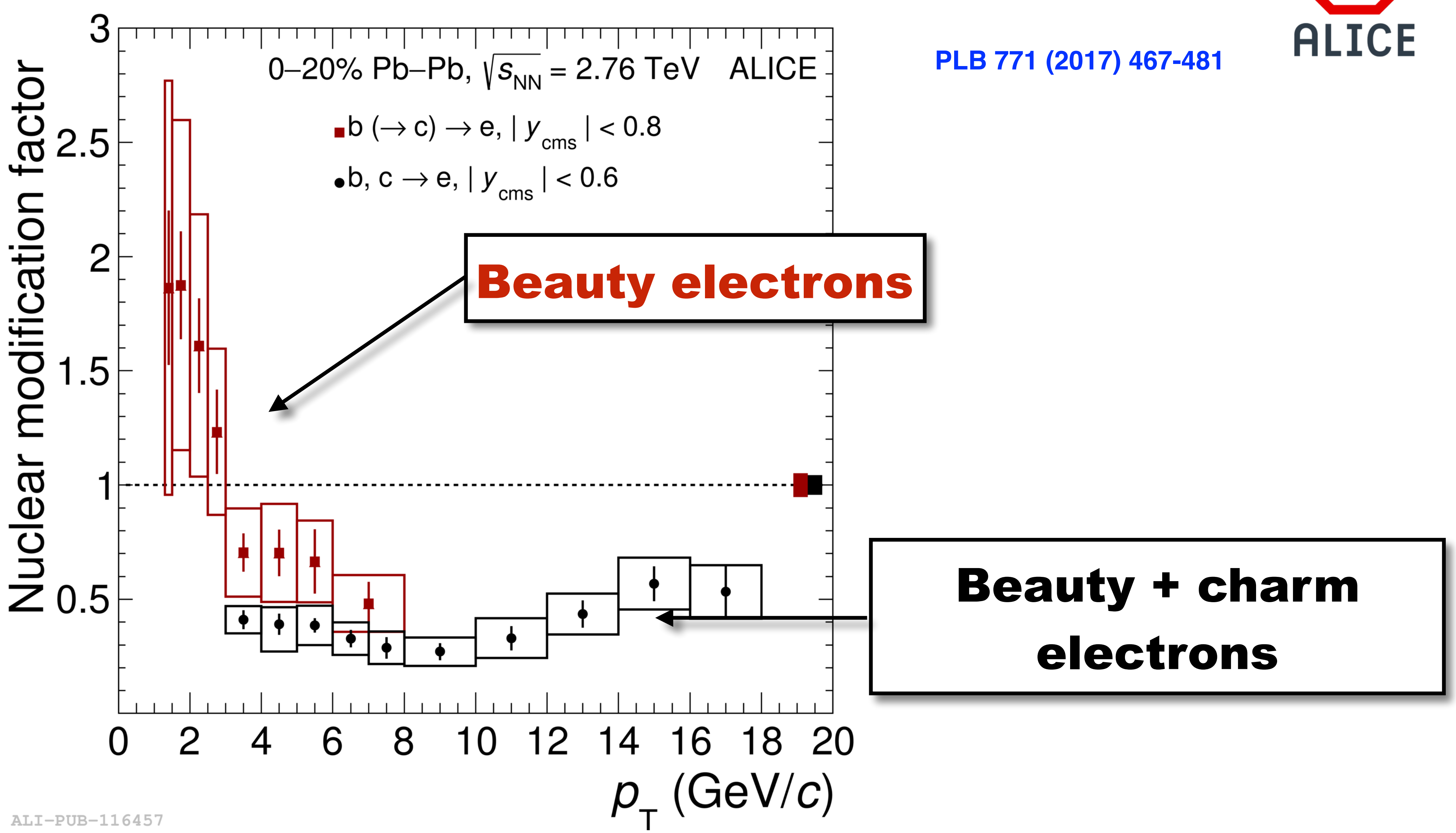
Heavy-flavour decay leptons

PLB 771 (2017) 467-481



- Beauty main component from p_T > 5 GeV/c → indication of beauty suppression at high p_T
- Beauty-electron R_{AA} measured directly with impact parameter fit → indication of suppression for p_T>3 GeV/c

Heavy-flavour decay leptons



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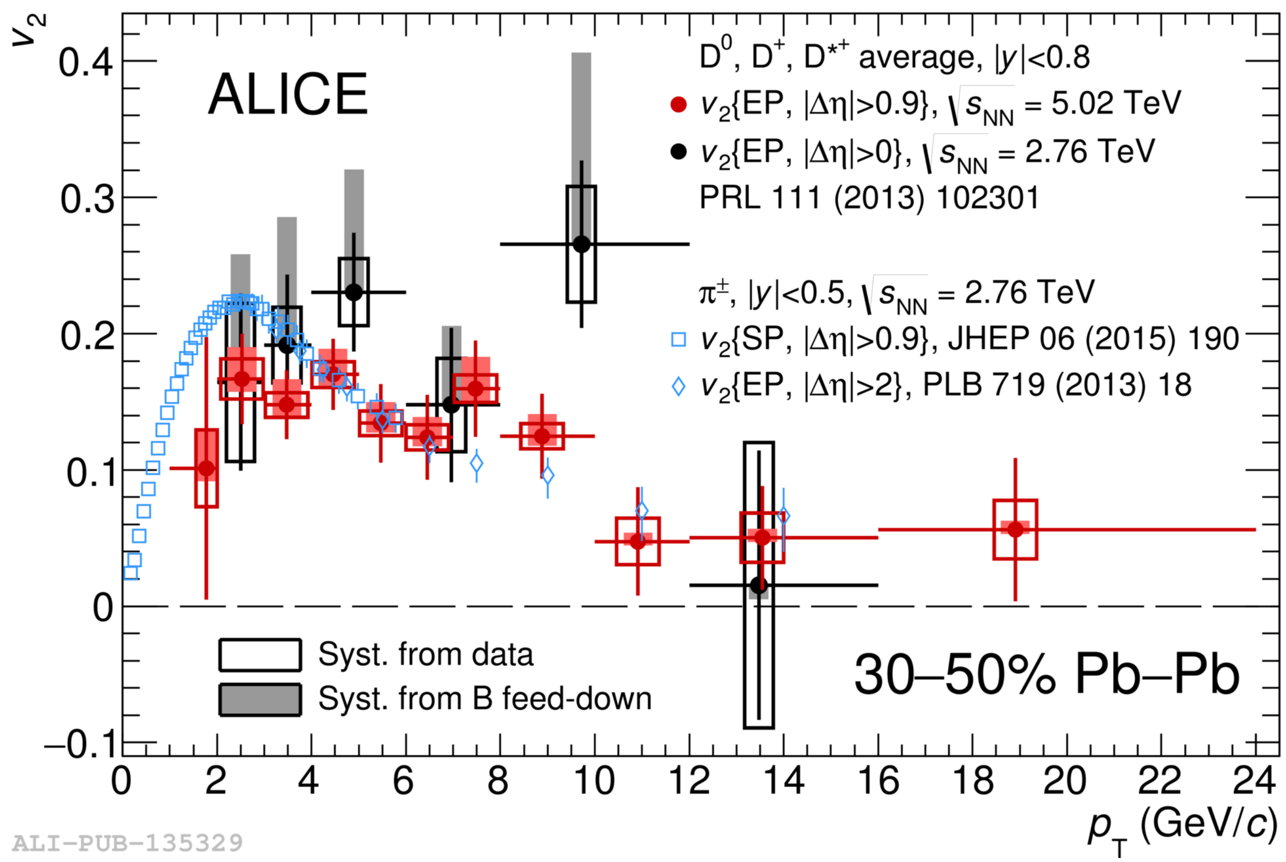
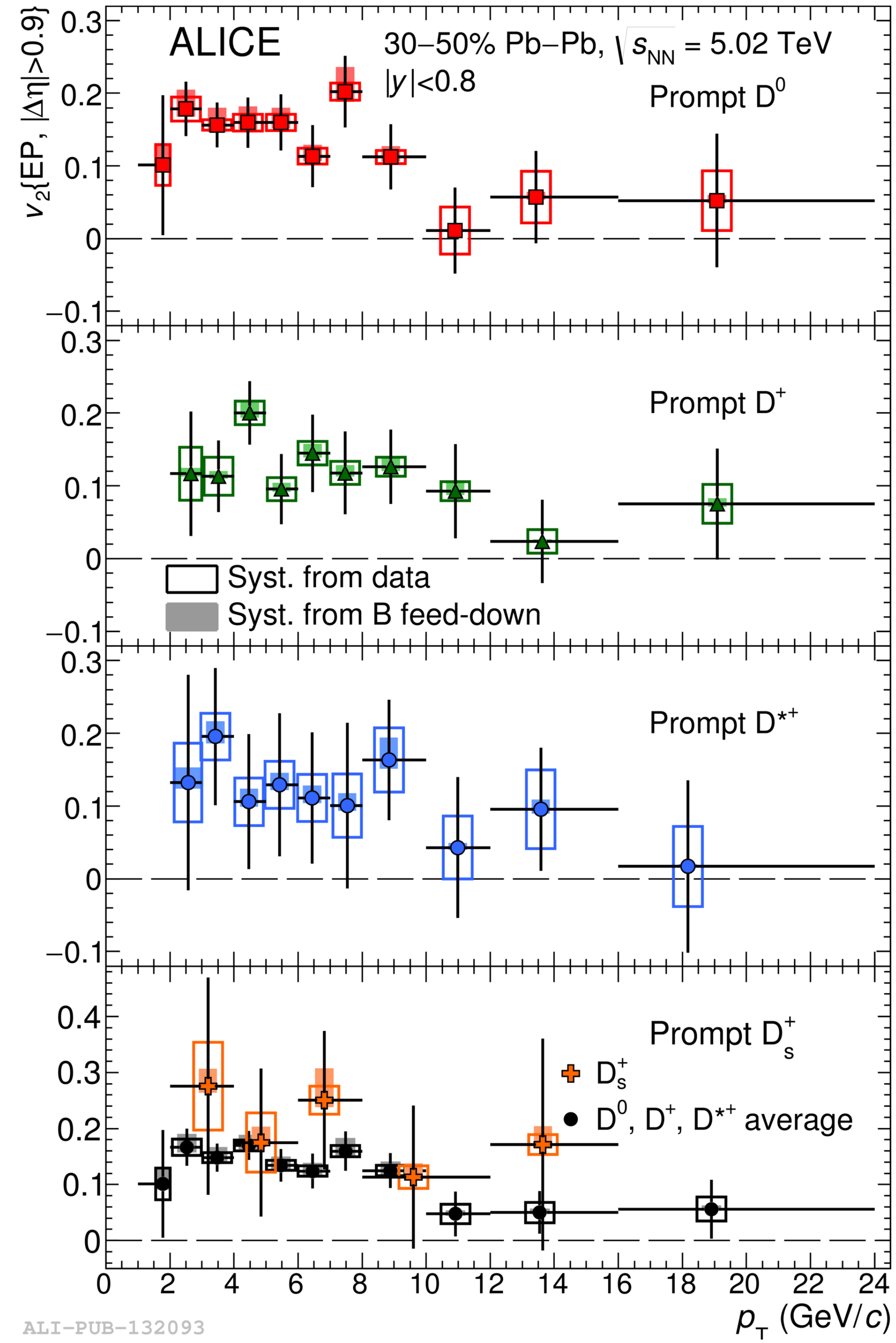
Collectivity

Elliptic flow

arXiv:1707.01005





- Compatible v_2 of D^+, D^{*+} and D^0
- Average D $v_2 > 0$. Charm flows
- Hint of a difference between charm and pions below 4 GeV/c
- First measurement of D_s v_2!

Elliptic flow

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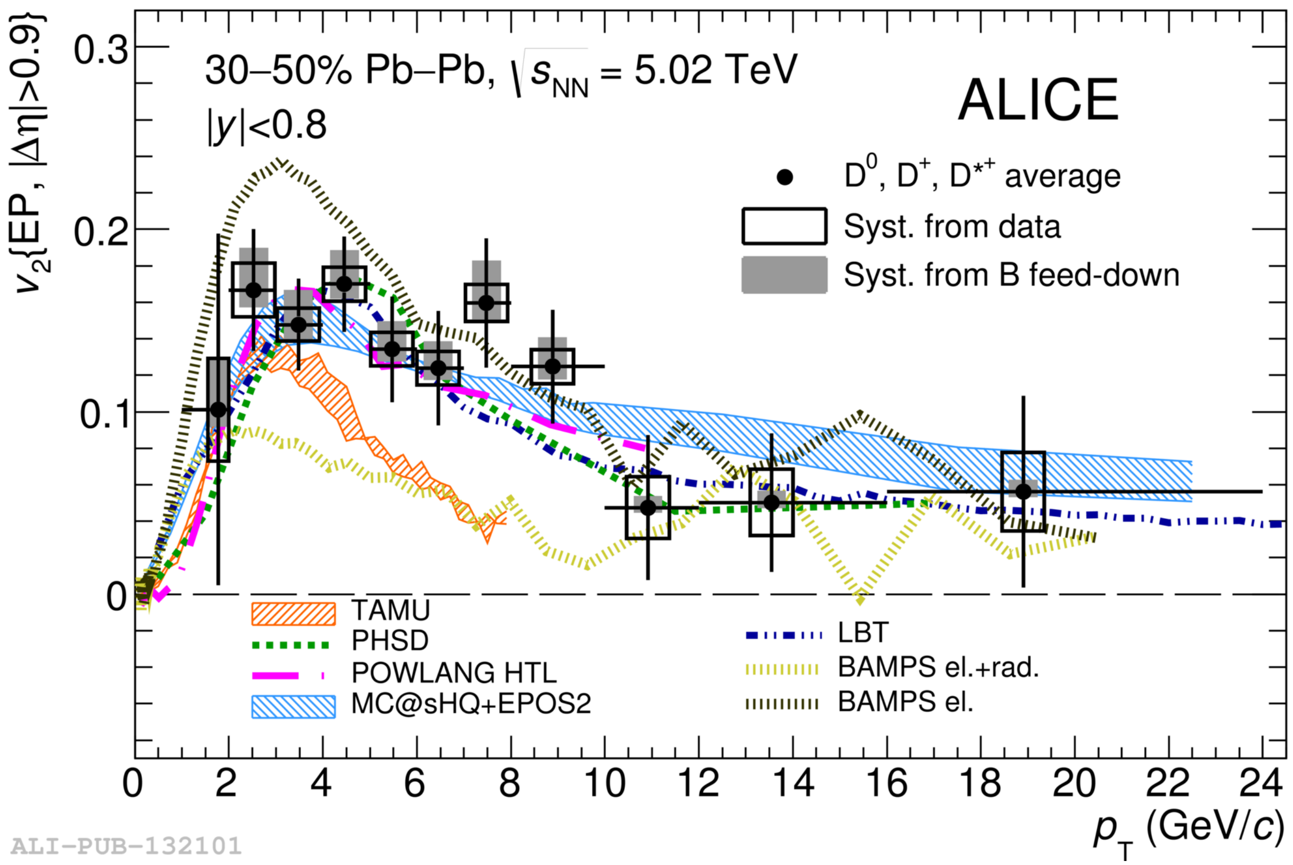

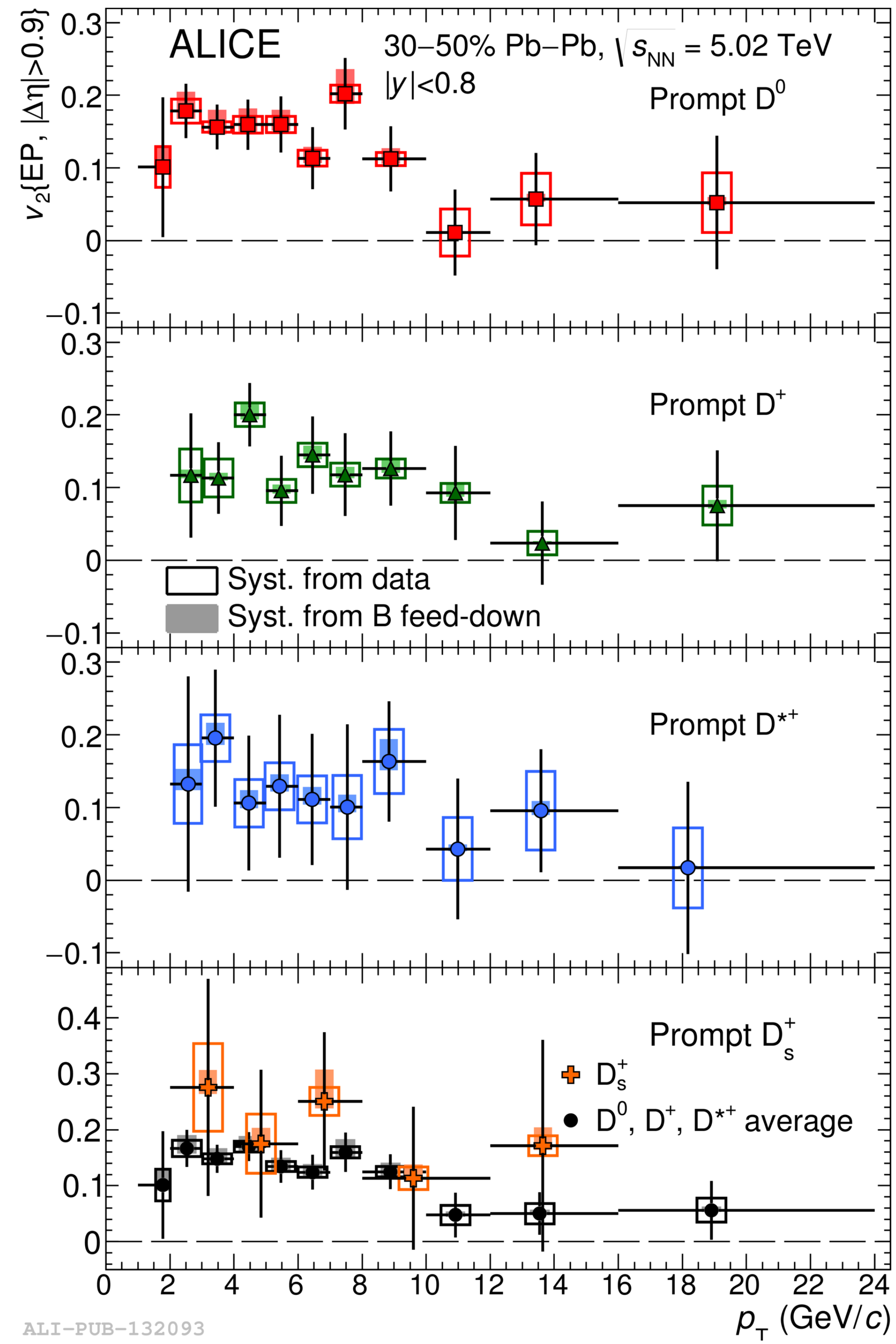

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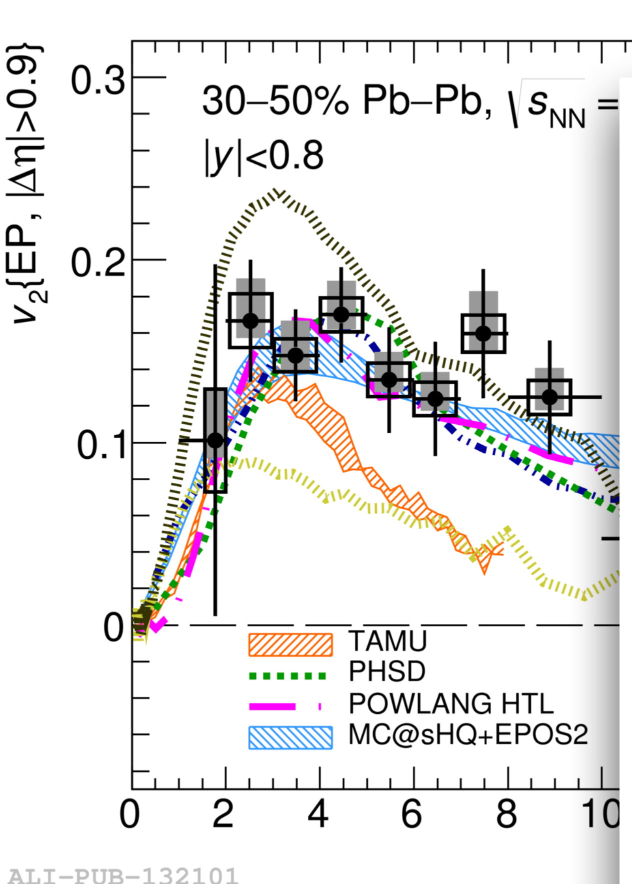

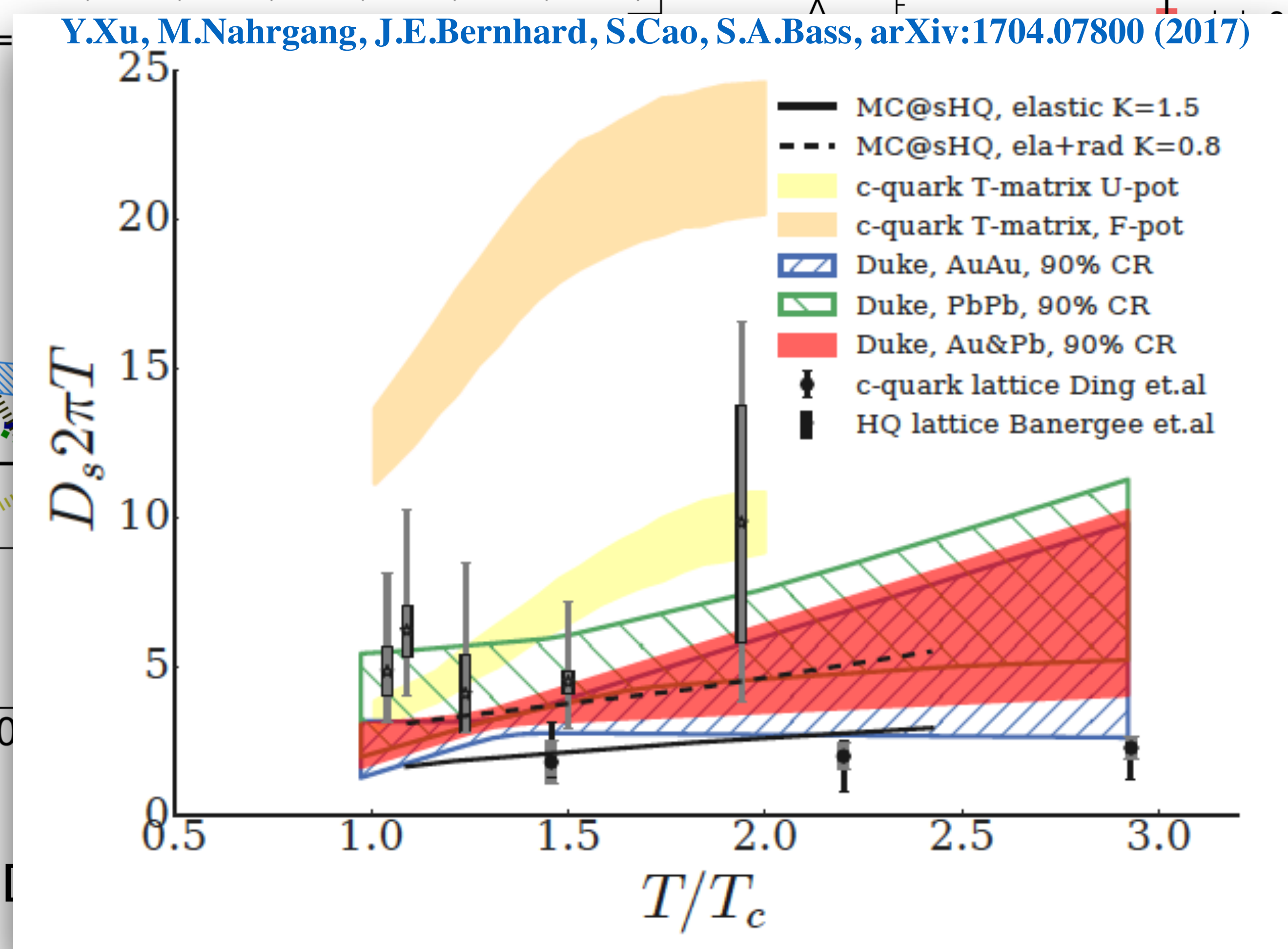

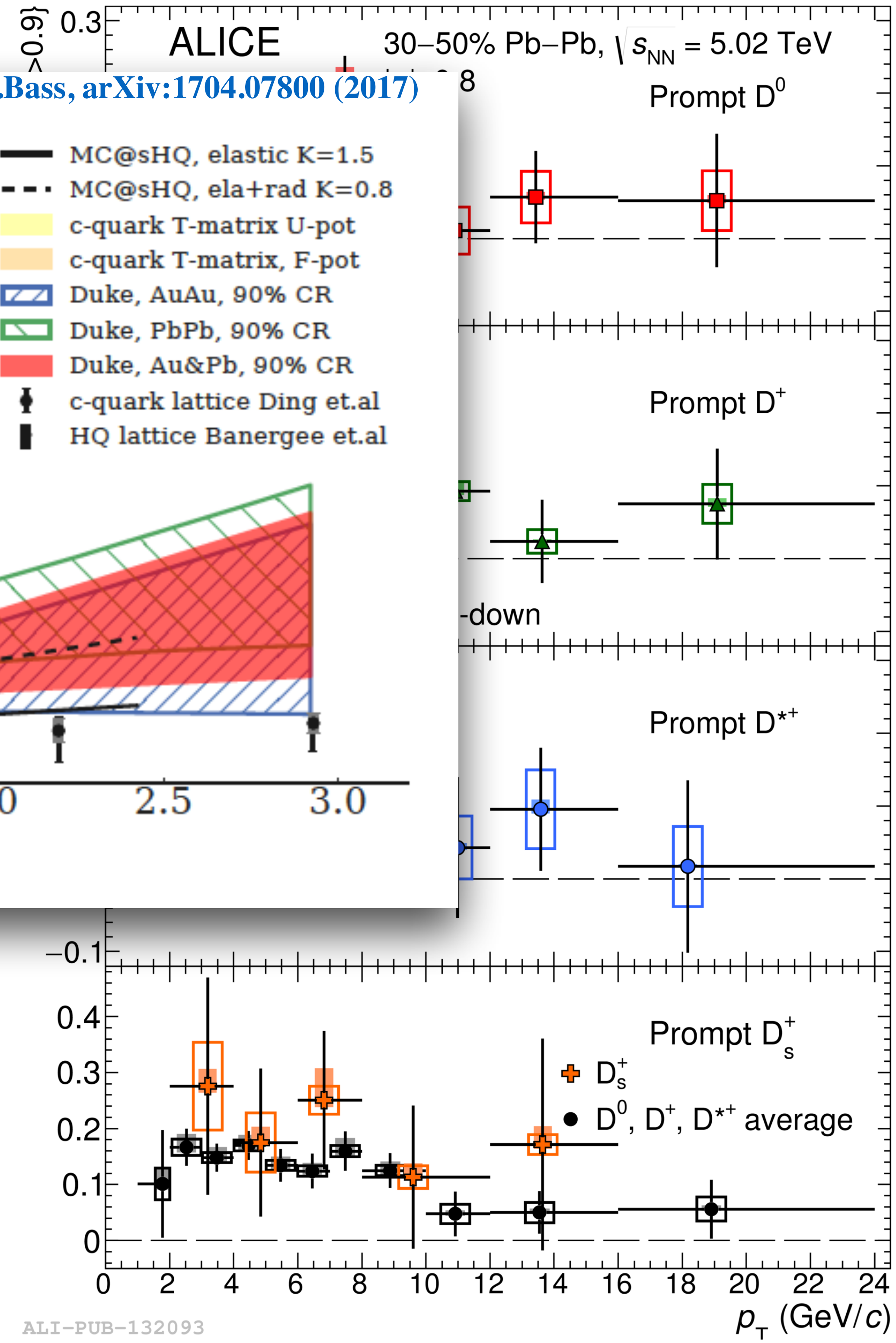

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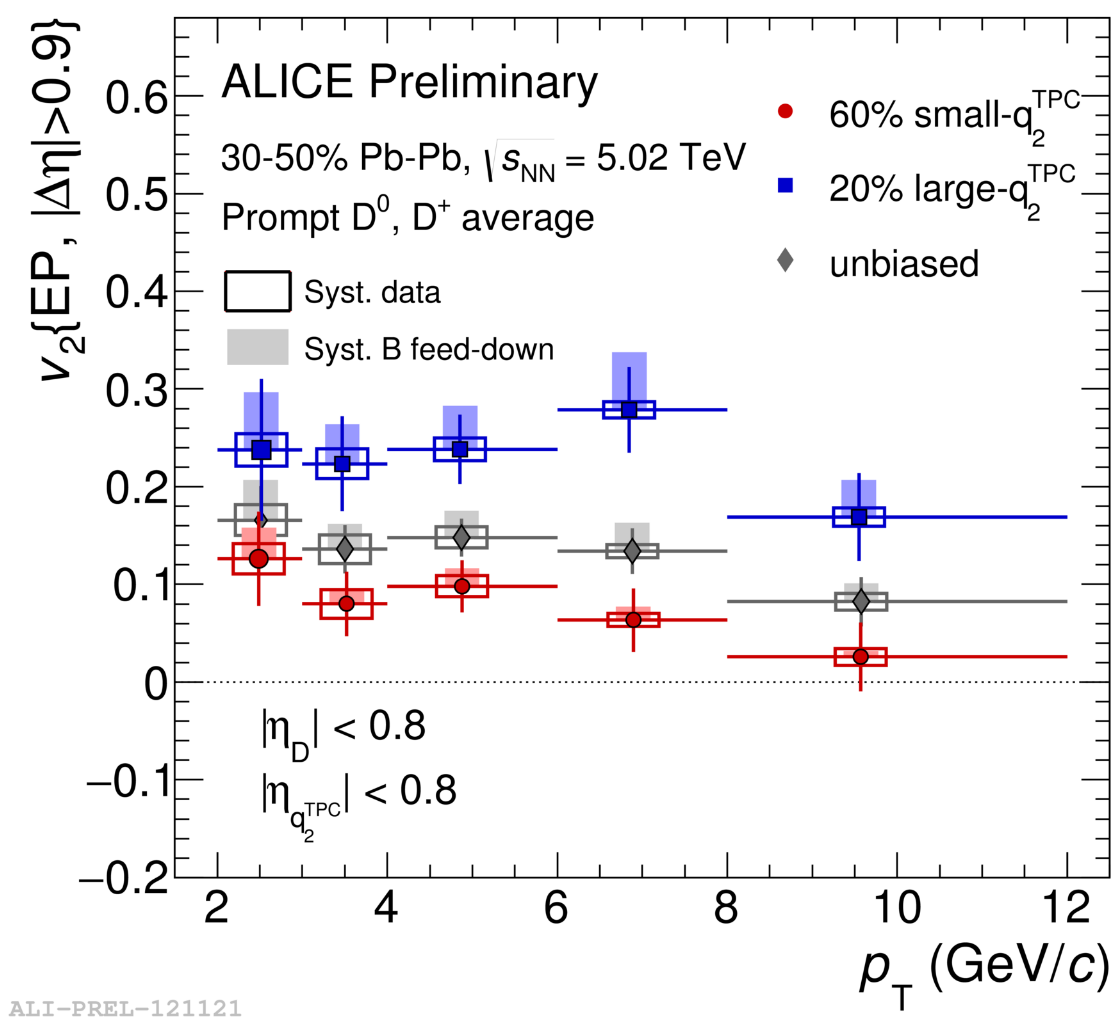
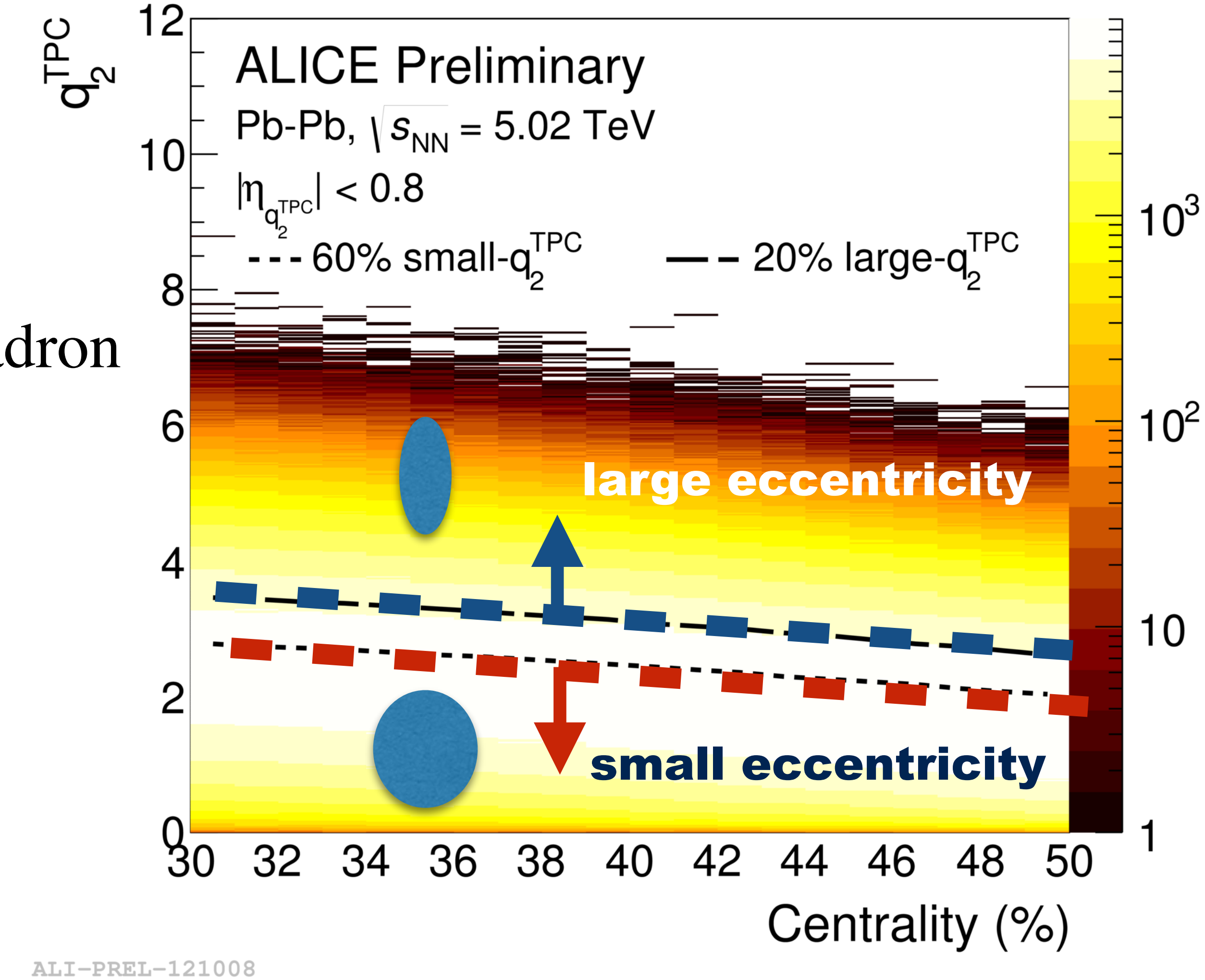
Elliptic flow with Event-Shape Engineering

- Event eccentricity quantified by q_2:

$$\langle q_2^2 \rangle \approx 1 + \langle M - 1 \rangle \langle v_2^2 - \delta_2 \rangle$$

Study the charm-quark coupling to the light-hadron bulk by measuring v_2 at different q_2 values

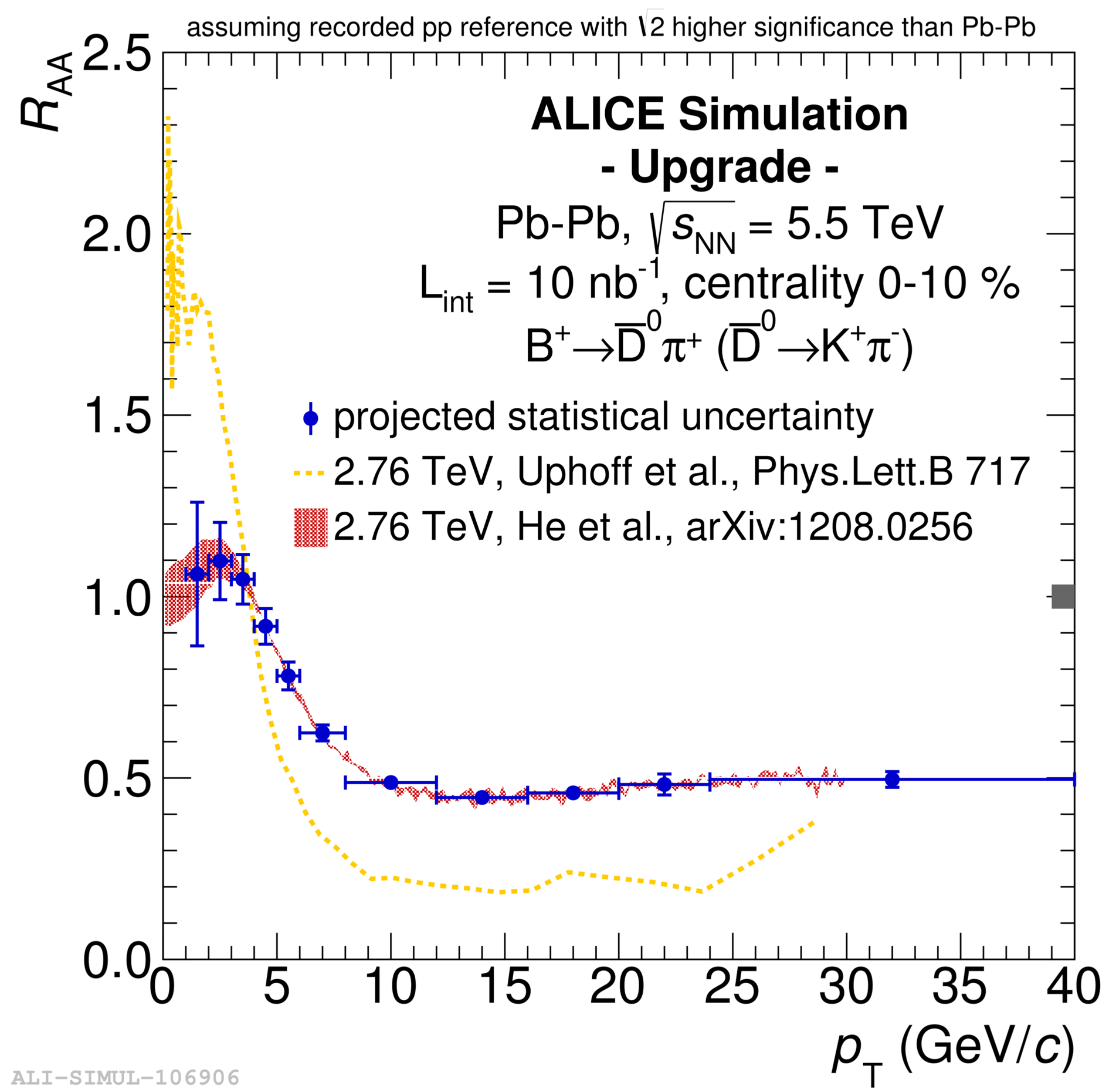


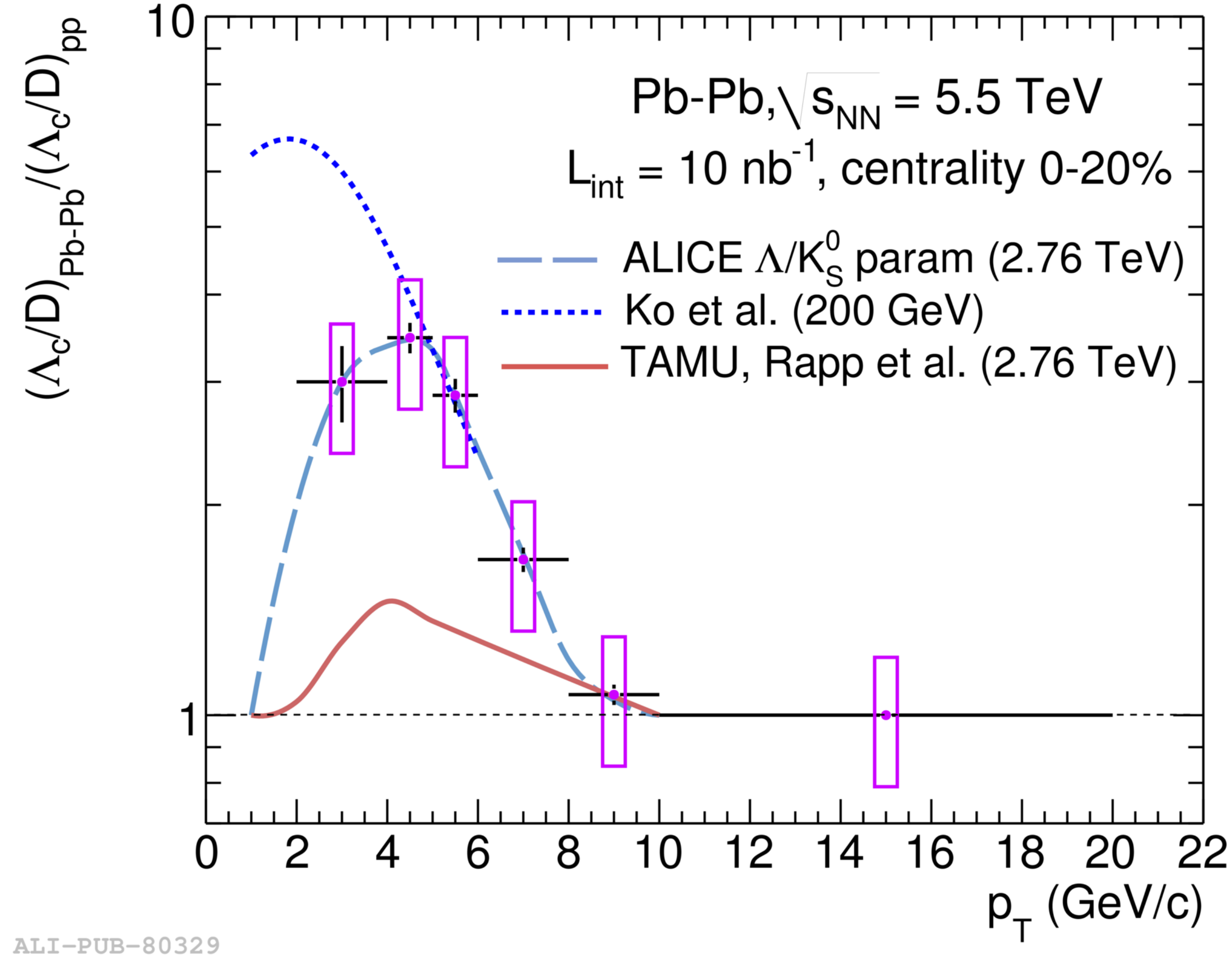


Significant separation of D-meson v_2 in events with large and small q_2:

➡ Charm quarks sensitive to the light hadron bulk collectivity and event-by-event initial condition fluctuations

ALICE upgrade: toward LHC run III





- The upgrade of the ALICE detector in long shutdown II will improve its heavy-flavour measurement capabilities
  - Precise D and B measurements will be possible down to low-p_T (0 for D mesons)
  - Precise charmed baryon/meson ratios in Pb-Pb down to low-p_T
  - Heavy-flavour leptons, correlations ……..

J. Phys. G **41 (2014) 087002**

Summary

- Precision cross-section measurements in pp. Differential production (vs charged particle multiplicity) investigated
- pPb measurements to investigate initial state effects
- Energy loss via D and B measurements
- Test of charm hadronization in QGP via coalescence
- Charm takes part to the collective expansion of the medium

Some open question:

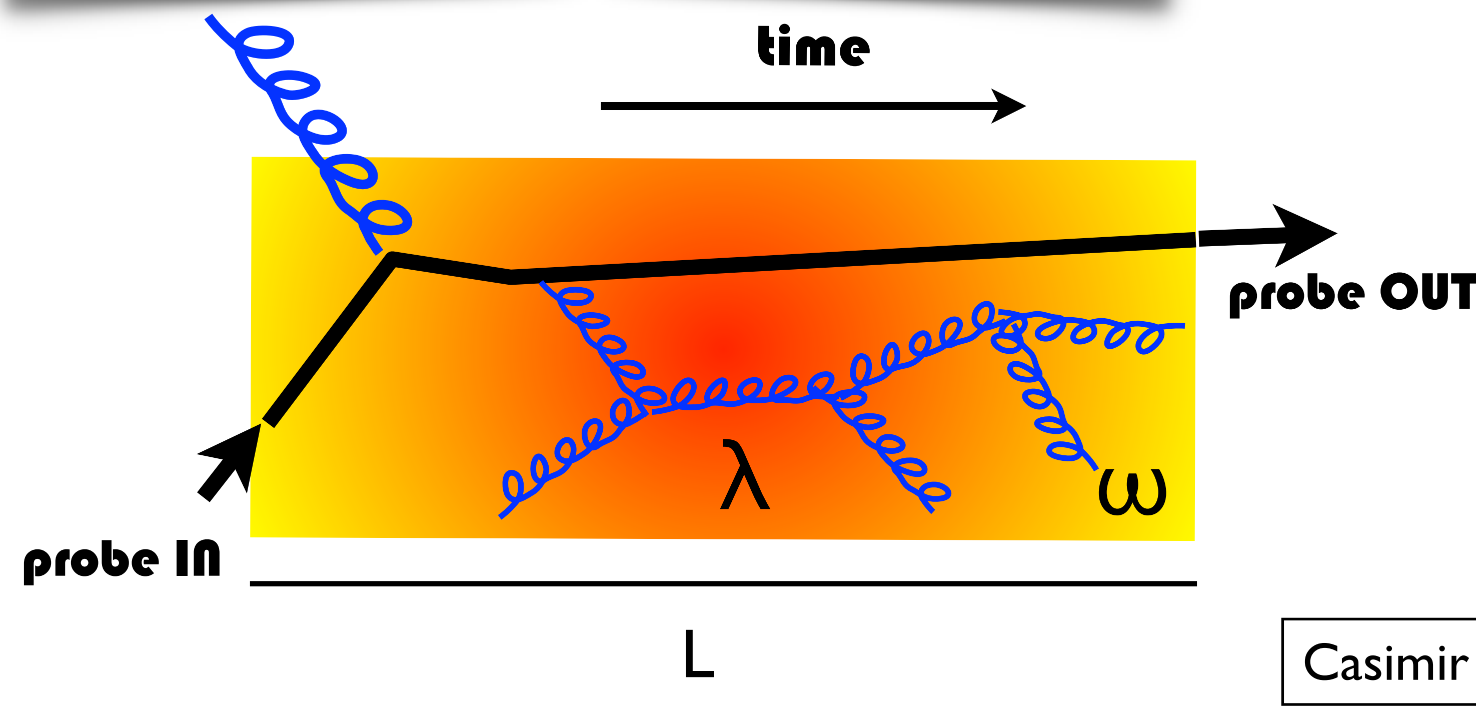
- What is the role of collisional energy loss?
- Have we observed charm coalescence?
- Do we see collectivity also in pPb?
- Is charm thermalised?
- Does beauty takes part in the collective expansion of the medium?

Extra Slides

a.grelli@uu.nl

.. a bit more in detail

Color charge dependence of radiative E_{loss}



$$\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$$

transport coeff.

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R \sqrt{\frac{\hat{q} L^2}{\omega}}$$

Casimir coupling factor: 4/3 for quarks and 3 for gluons

Phys.Rev.D71:054027, 2005   Nucl.Phys. A690 (2001) 731-751

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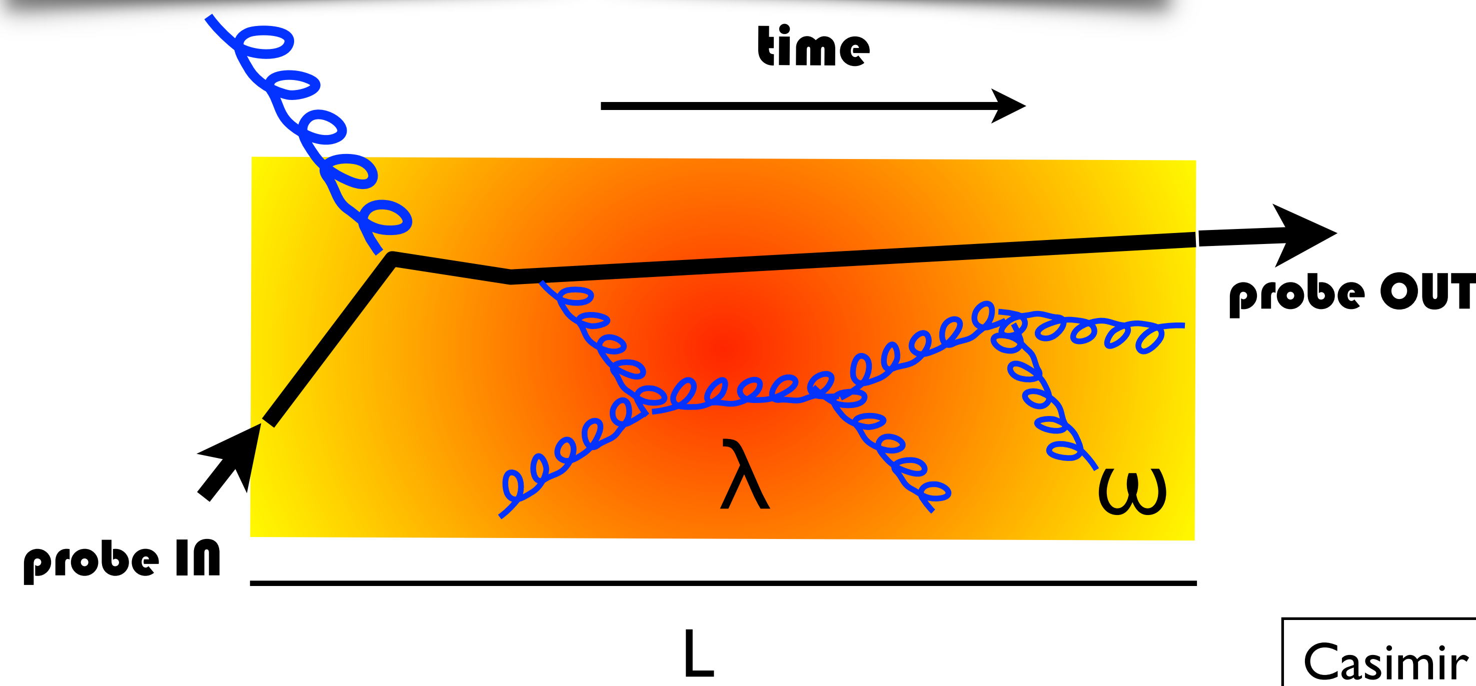

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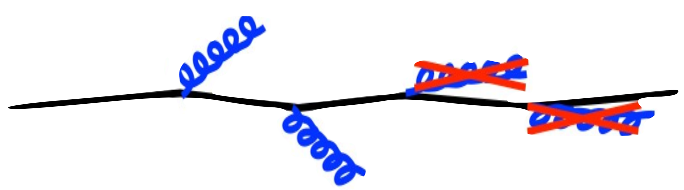
Mass dependence:

Radiative: Dead cone effect



Gluonsstrahlung probability

$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

Collisional (assuming Langevin formalism):

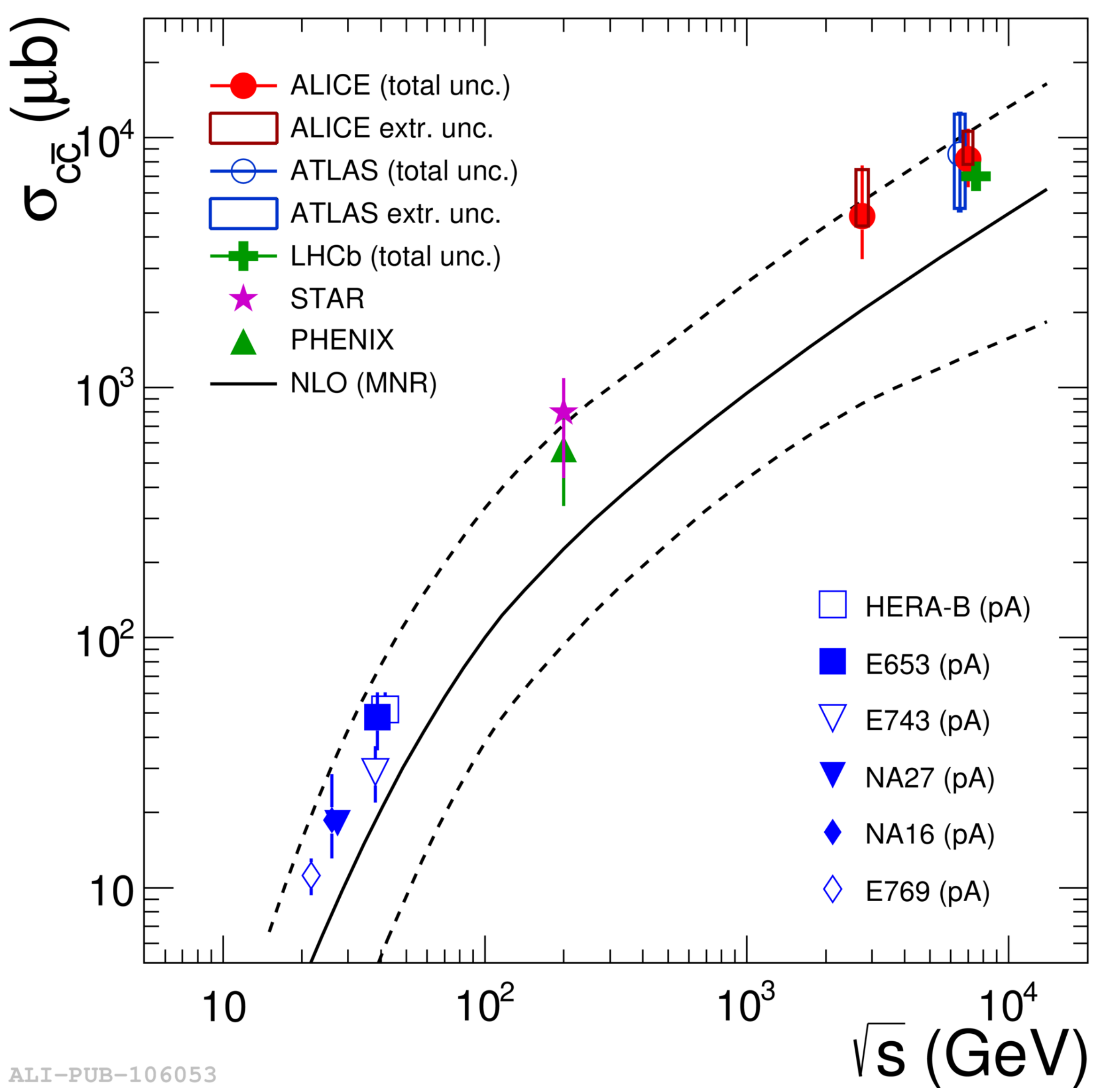
$$dx = \frac{p}{E} dt,$$

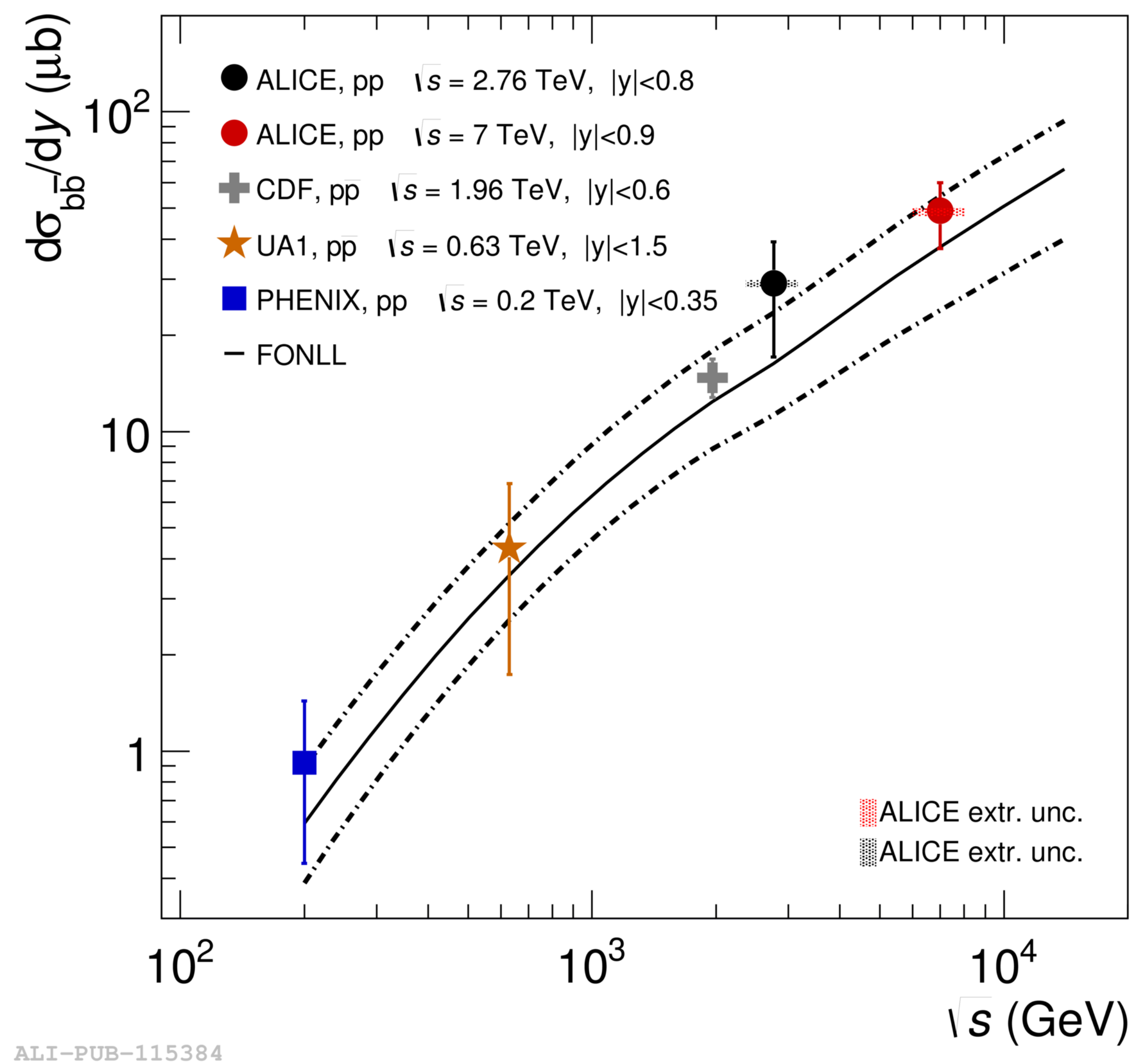
$$dp = -\Gamma(p)\, p\, dt + \sqrt{2D(p + dp)\, dt}\, \rho$$

Both the terms: $\Gamma(p)$ e D are proportional to $1/m_Q$

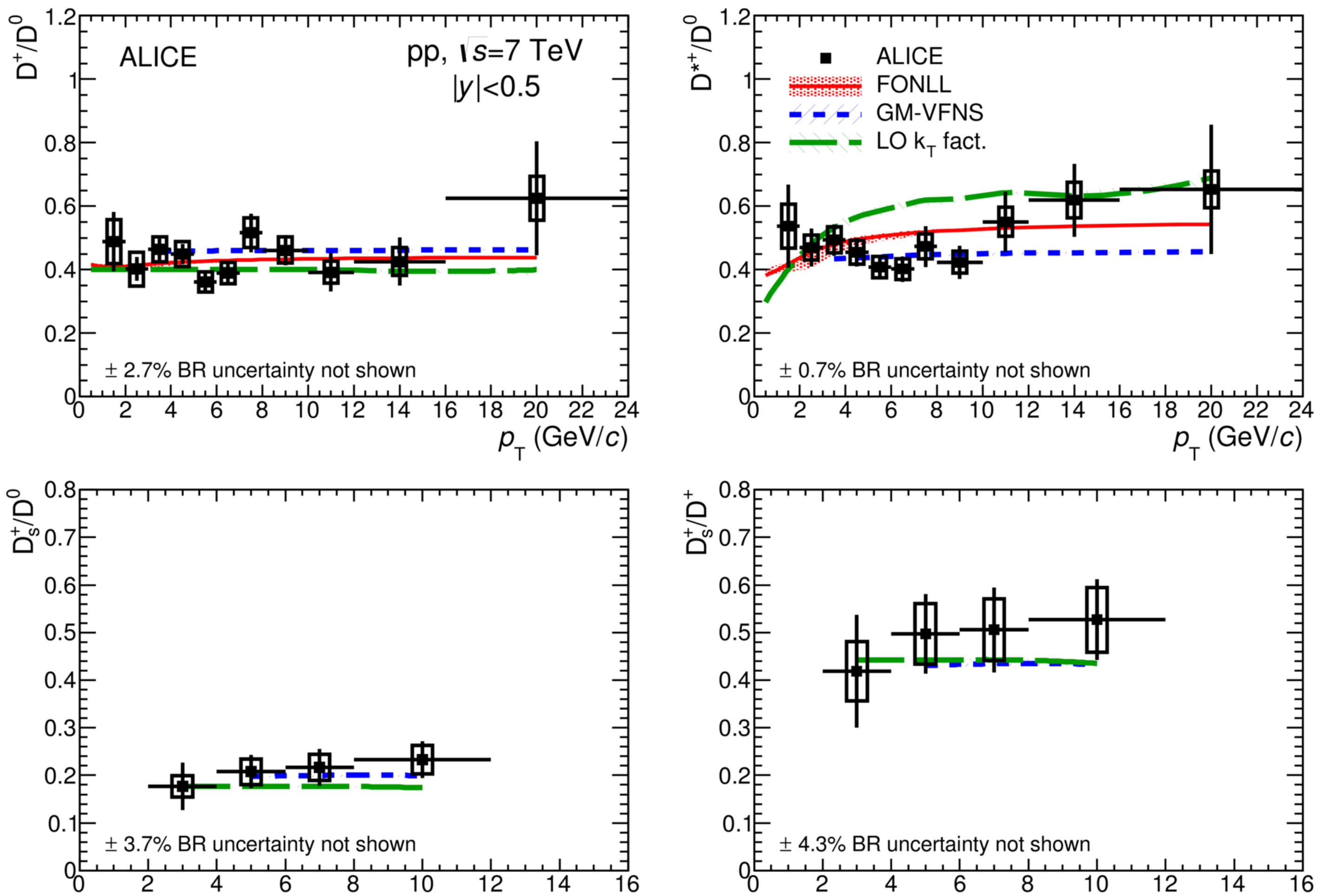
E_{loss}(light) > E_{loss}(charm) > E_{loss}(beauty)

Total cross-section

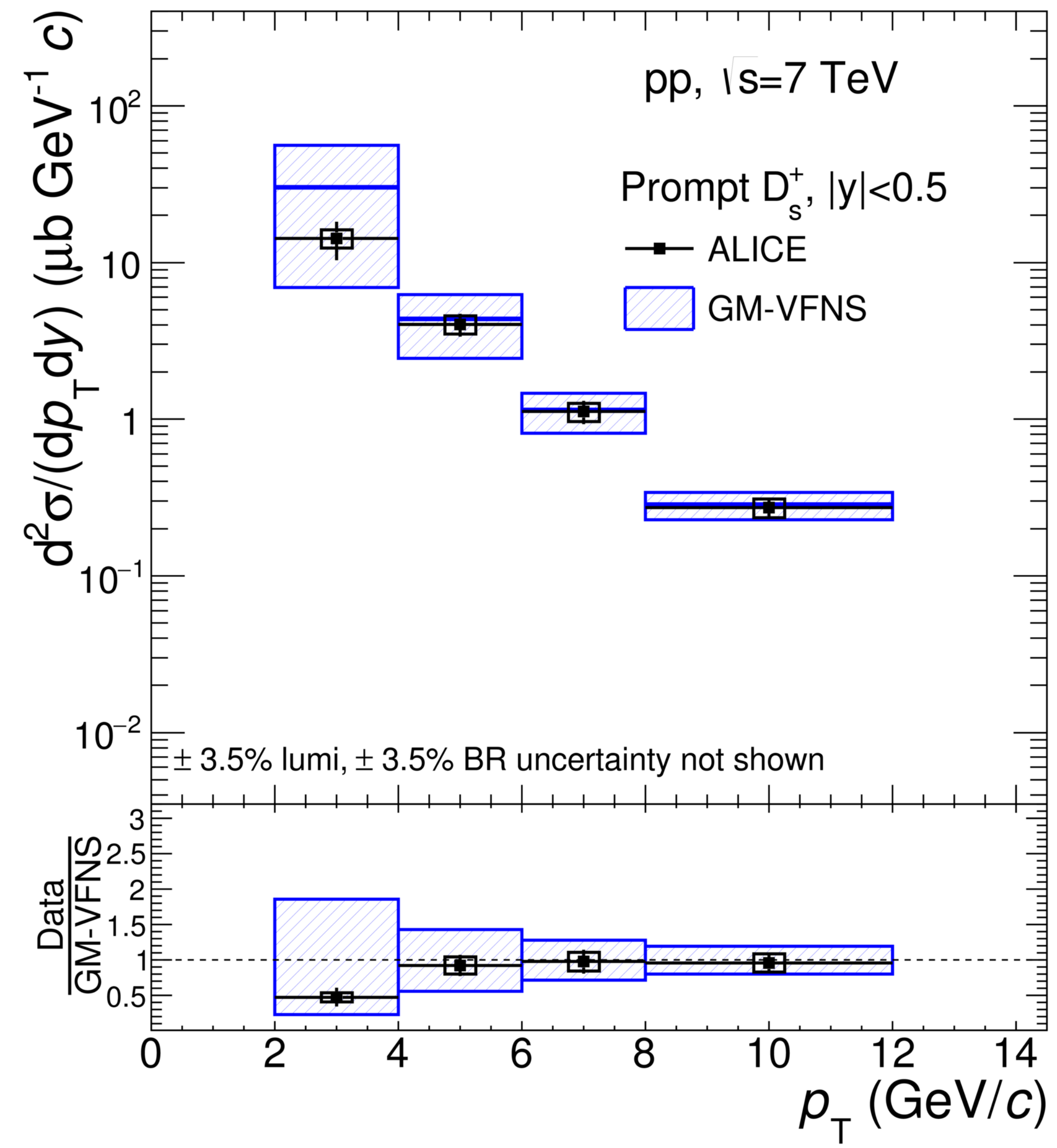




D ratios in pp and D_s cross-section

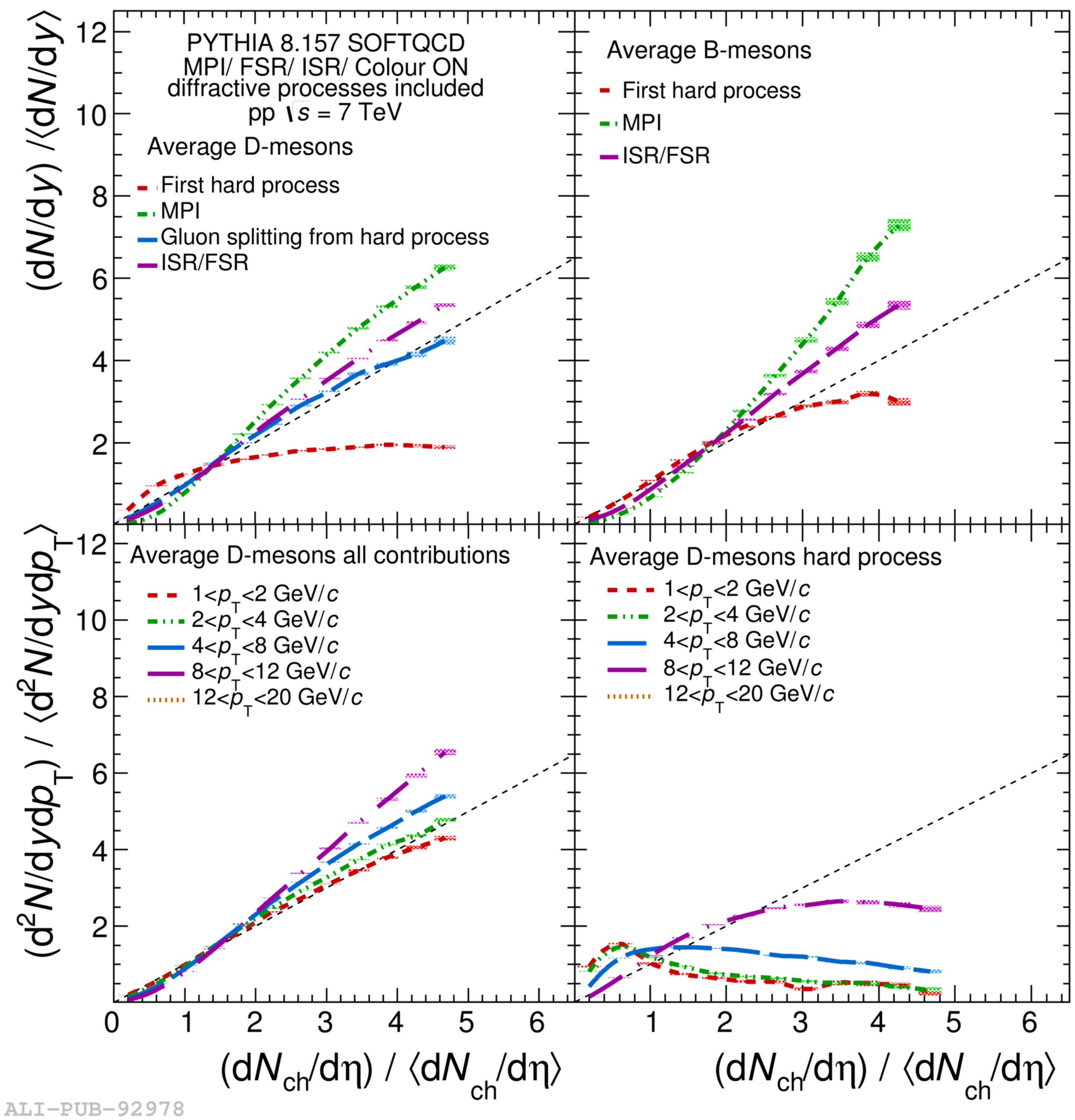


ALI-PUB-125407

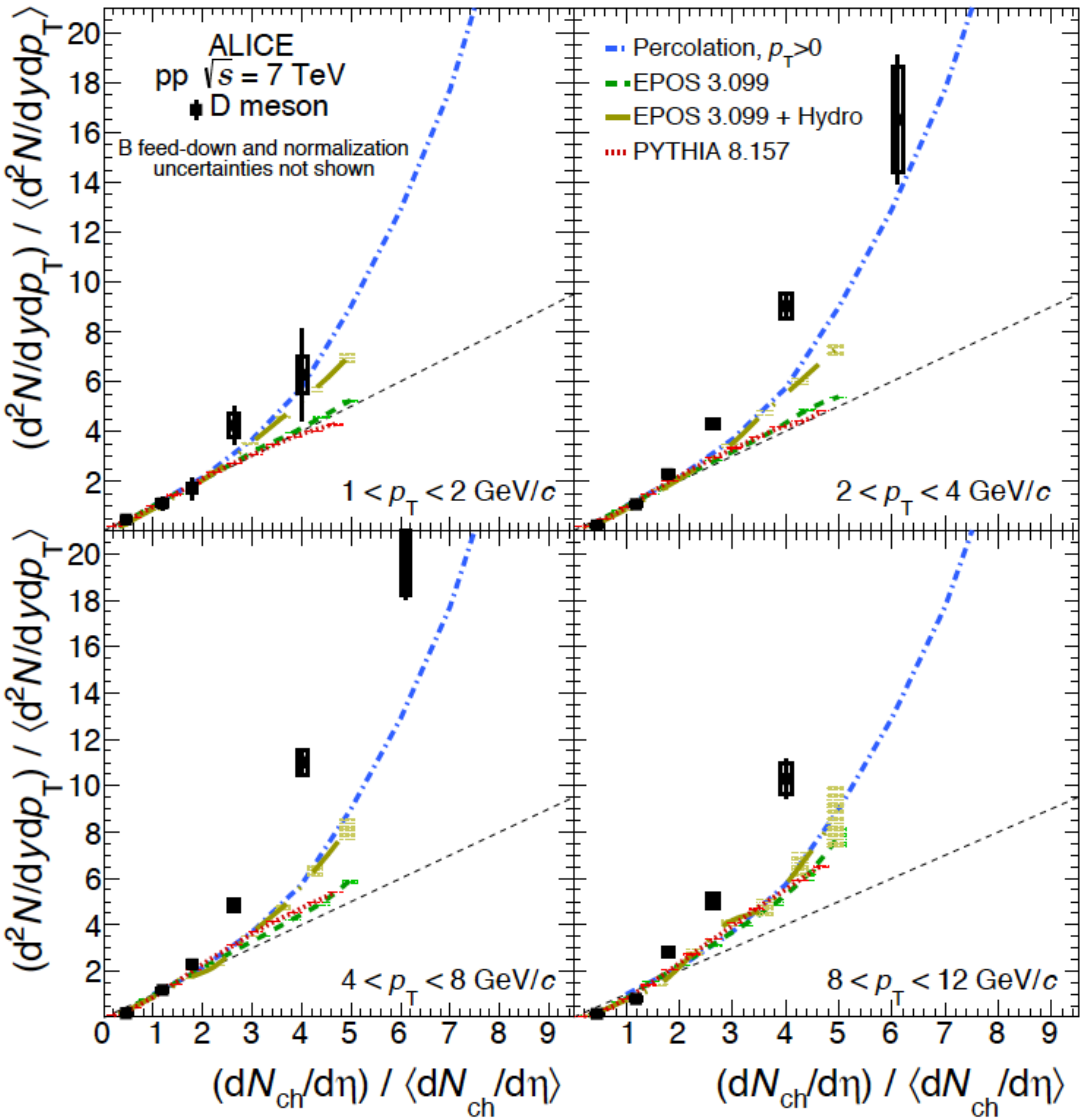


ALI-PUB-125423

Pythia8.157 - D, B vs multiplicity



D vs mult.: comparison with models



- Charm production at charged particle densities above 2-3 times the average not reproduced by models (expecially at high p_T)
- Interplay between MPI and additional hadronic interactions?
- Something else?

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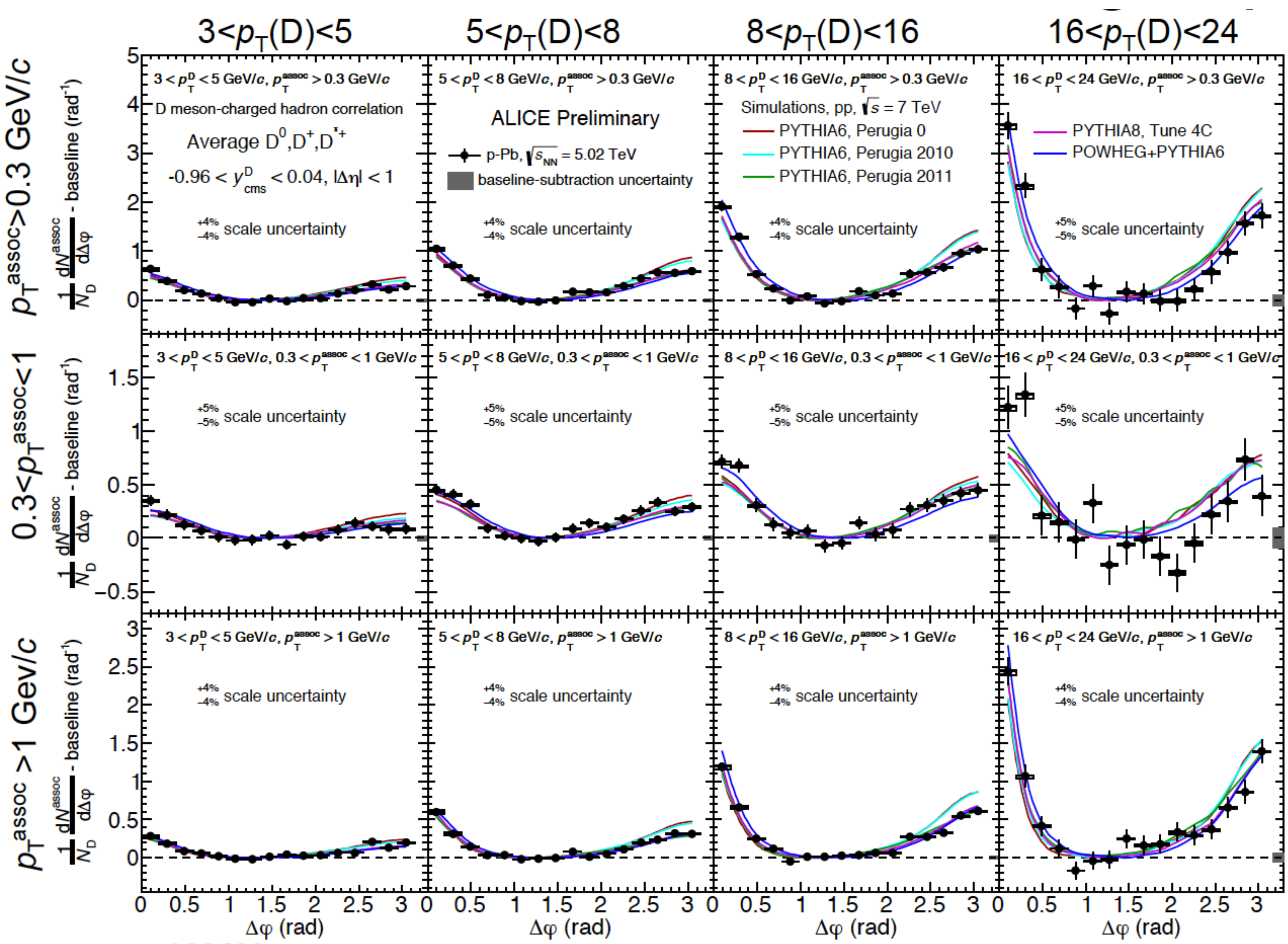
D-h correlations in pPb



HF-decay e-h correlations in Pb-Pb