Open Heavy Flavour Production in pp and p-Pb Collisions with ALICE

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DIS 2018
April 18, 201

OUTLINE

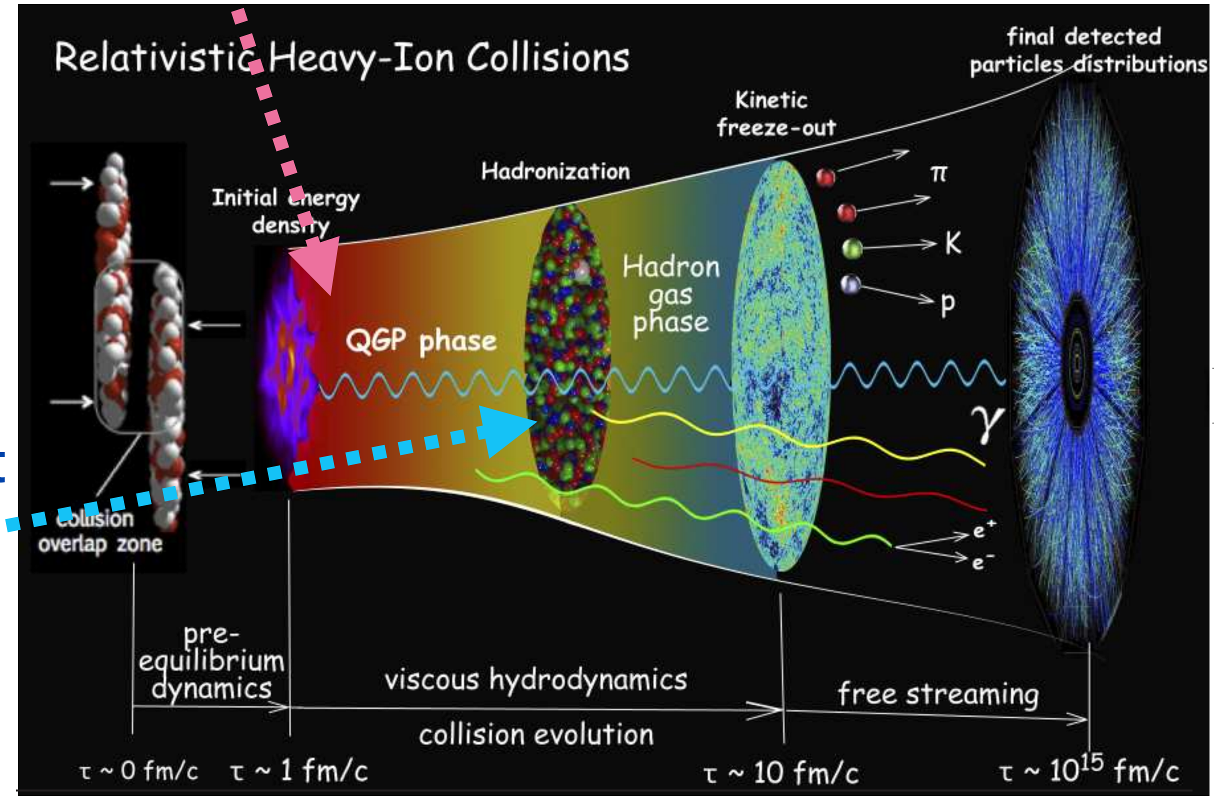
- **Why heavy flavours in heavy-ion collisions**
- **ALICE detector & heavy-flavour observables**
- **Main and recent heavy-flavour measurements in pp, p-Pb collisions**
- **Summary and outlook**

What's special about heavy quarks

- Heavy-ion (HI) collisions at LHC energies
  - QGP phase expected (lifetime ~ O(10 fm/c))
- QGP tomography with heavy quarks: efficient probes for understanding the transport properties of the medium
  - Early production in hard-scattering processes with high Q^2 , transported through the full system evolution

    at all p_T for charm and beauty (large masses >> Λ_{QCD})
  - Production cross sections calculable with perturbative QCD
  - Traversing the medium while interacting with its constituents
  - Hard fragmentation ➜ measured hadron properties closer to parton ones

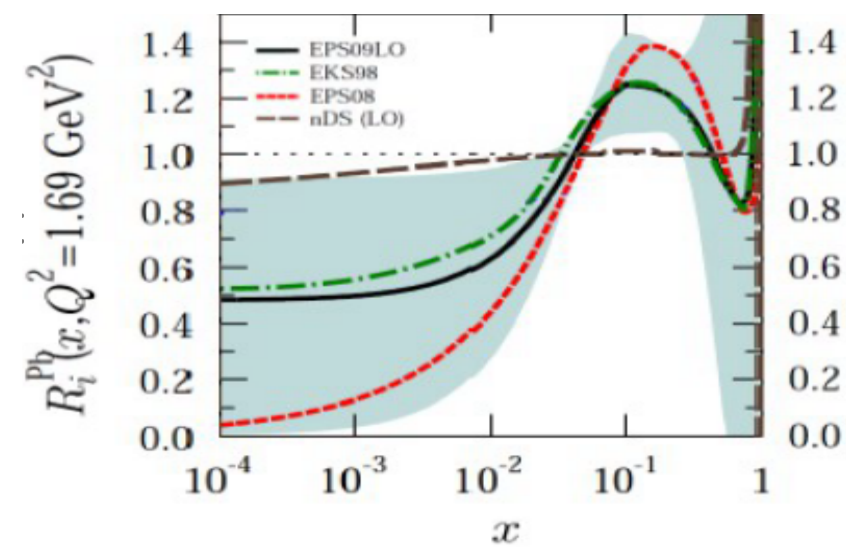
⇨ "Calibrated probes" of the medium



NOTE: Heavy flavours not only give information about the QGP phase, but also about the hadronization phase (i.e. to study hadronization mechanisms like fragmentation vs recombination -D_s,...)

What we learn from small systems: pp and p-Pb collisions

- **pp collisions**
  - Testing ground for perturbative QCD calculations
  - Relevant production mechanisms on the parton level
    - **LO: gluon fusion, quark-antiquark annihilation**
    - **NLO: gluon splitting, flavor excitation**
  - Multi Parton Interactions (MPI)
  - Reference for p-Pb and Pb-Pb collisions

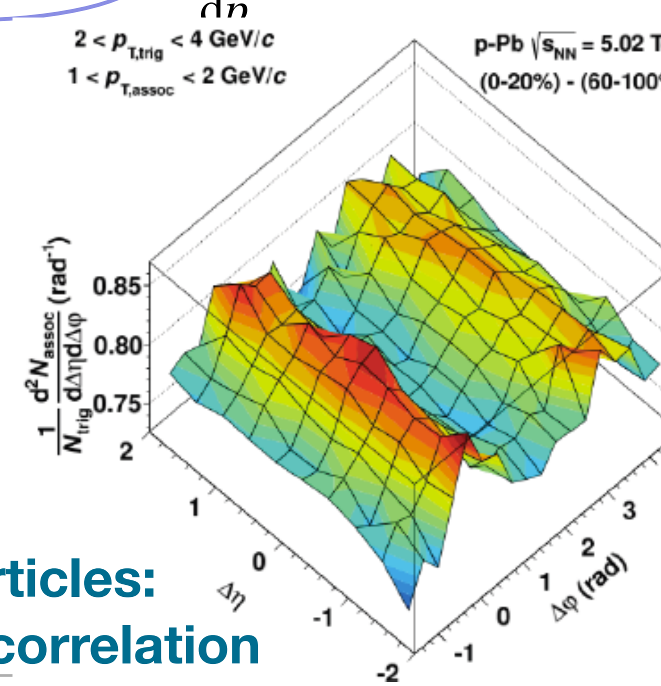


K. J. Eskola et al: JHEP04(2009)065

- **p-Pb collisions**
  - Quantify cold nuclear matter effects: measure effects, not due to QGP formation, that can modify the yield of hard probes in nuclear collisions

$$\frac{dN^D_{PbPb}}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T} \otimes P(\Delta E) \otimes D_{c\to D}(z)$$

    - **nuclear modification of Parton Distribution Functions (shadowing, gluon saturation)**
    - **k_T broadening via multiple of the parton before the hard scattering**
    - **energy loss in cold nuclear matter**
  - Final-state effects? (e.g. from system collectivitiy/hydro)
  - Reference for Pb-Pb collisions

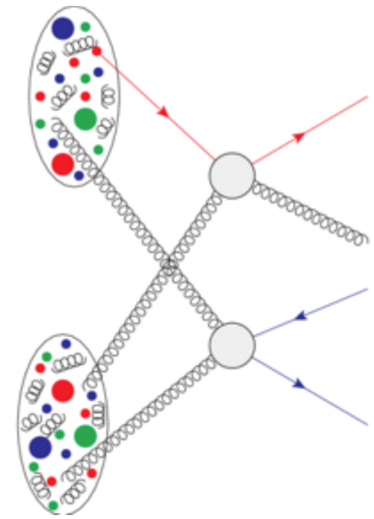


charged particles: long range correlation

Phys.Lett. B719 (2013) 29-41

Physics observables with different sensitivity

HF production vs. multiplicity in pp and p-Pb collisions



- Interplay between **hard and soft** processes in particle production
- Study the role of **multi-parton interactions (MPI)** in the **heavy-flavour** sector
- Investigate a **possible centrality dependence** of the modification of the the p_T spectra in p-Pb w.r.t. pp collisions

Nuclear modification factor

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \times dN_{pp}/dp_T} = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

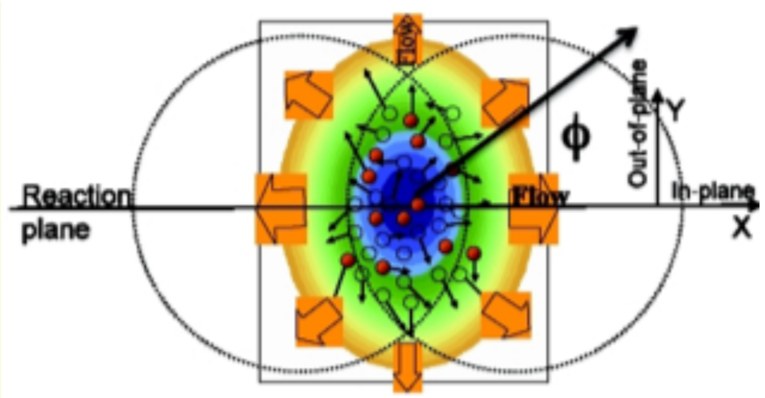
Binary scaling based on the Glauber Model

$R_{AA} = 1$: binary scaling

$R_{AA} \neq 1$: medium effect

Anisotropic flow: v_2

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

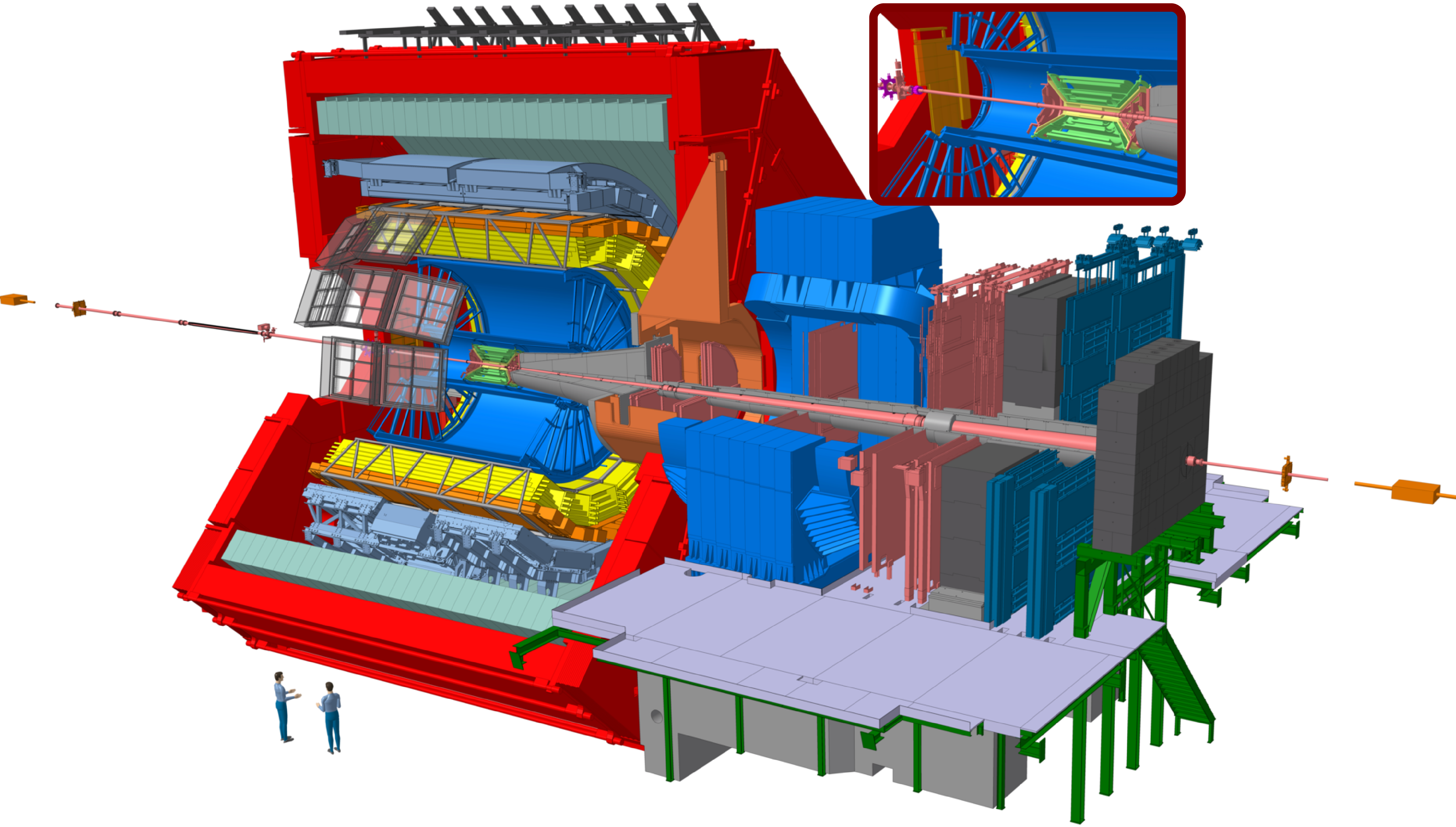


Initial spatial anisotropy $\xrightarrow{\text{via re-scatterings}}$ momentum anisotropy of particle emission

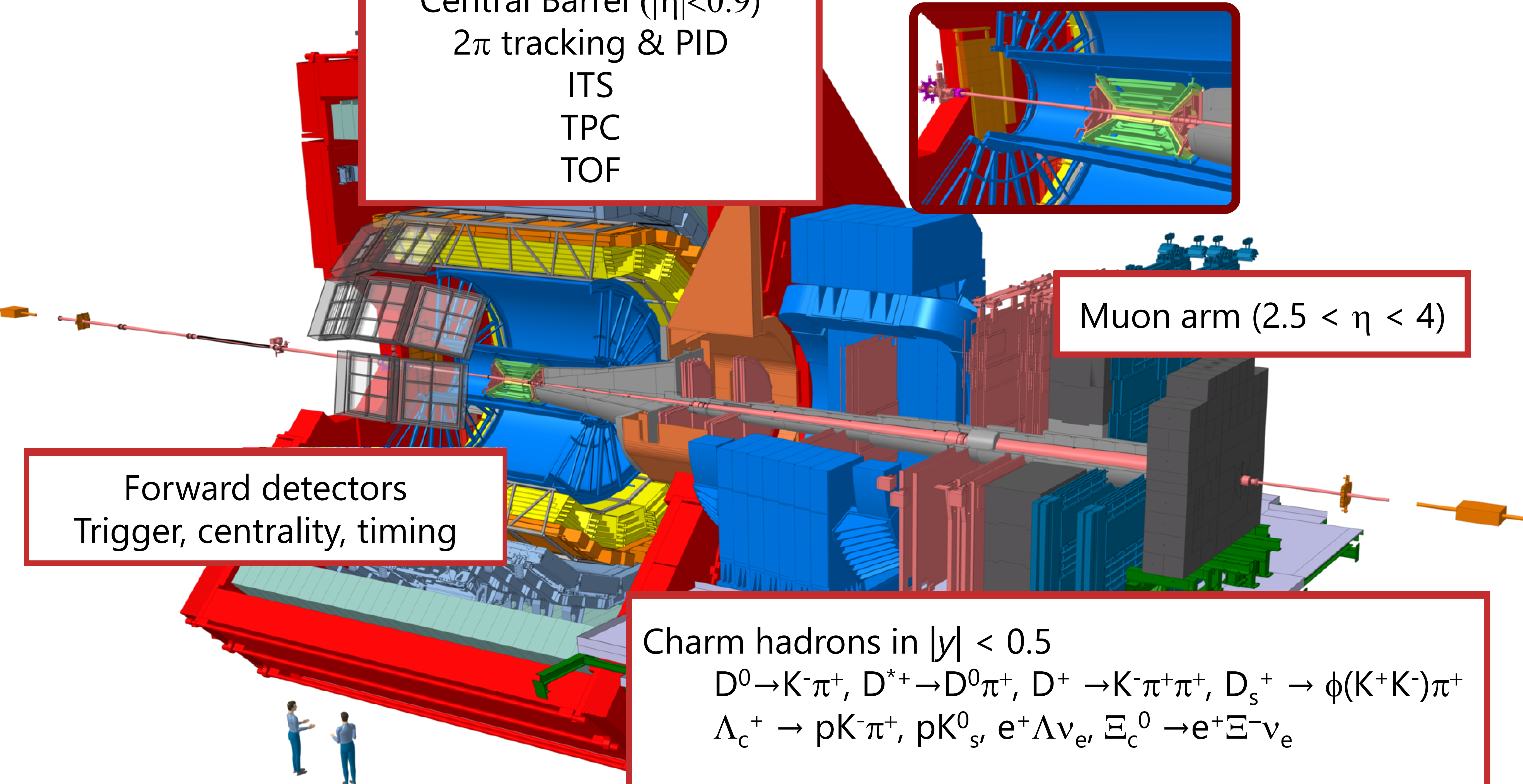
The anisotropy is quantified via a Fourier expansion in the reaction plane (ψ_{RP})

⇒ must measure observables with different sensitivity to the various ingredients

Heavy-flavour reconstruction in ALICE



Heavy-flavour reconstruction in ALICE



Central Barrel ($|\eta|<0.9$)
2π tracking & PID
ITS
TPC
TOF

Muon arm ($2.5 < \eta < 4$)

Forward detectors
Trigger, centrality, timing

Charm hadrons in $|y| < 0.5$

$D^0 \to K^-\pi^+$, $D^{*+} \to D^0\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to \phi(K^+K^-)\pi^+$

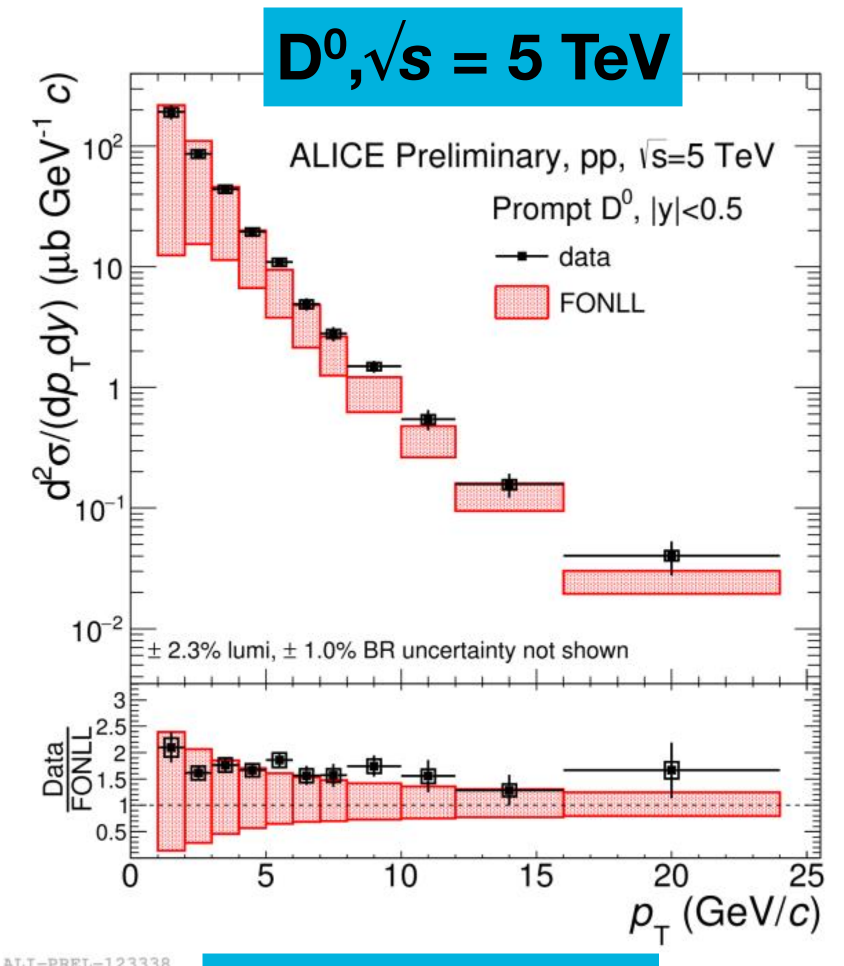
$\Lambda_c^+ \to pK^-\pi^+$, pK^0_s, $e^+\Lambda\nu_e$, $\Xi_c^0 \to e^+\Xi^-\nu_e$

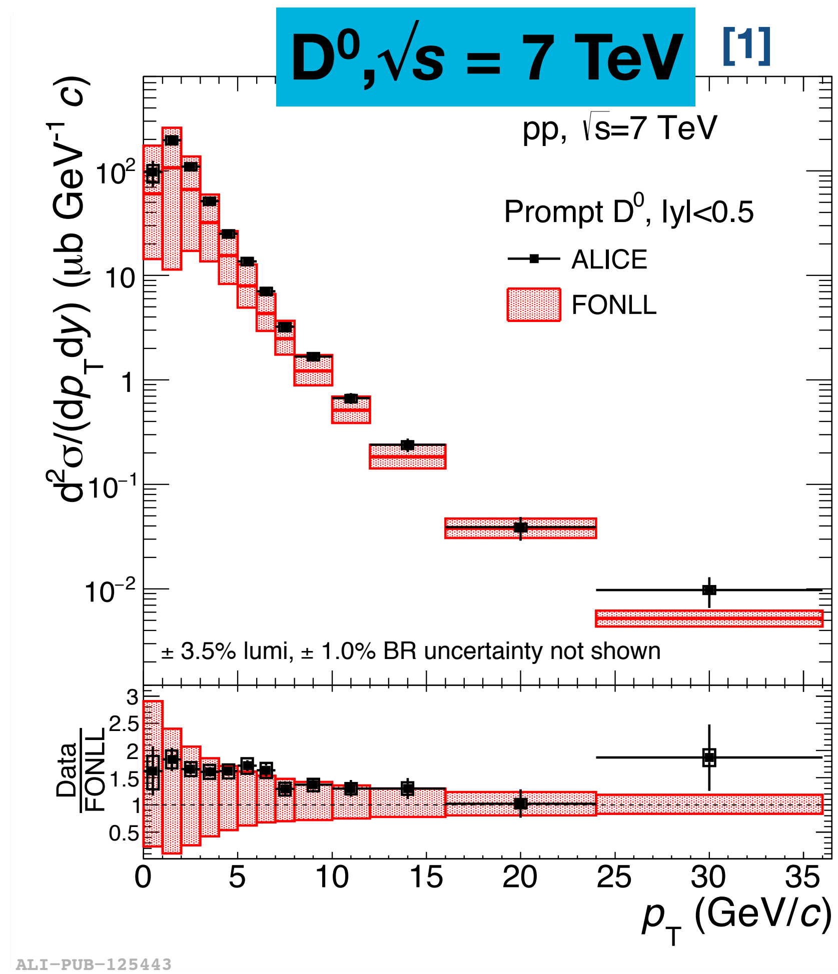
Leptons from heavy-flavor hadron decay

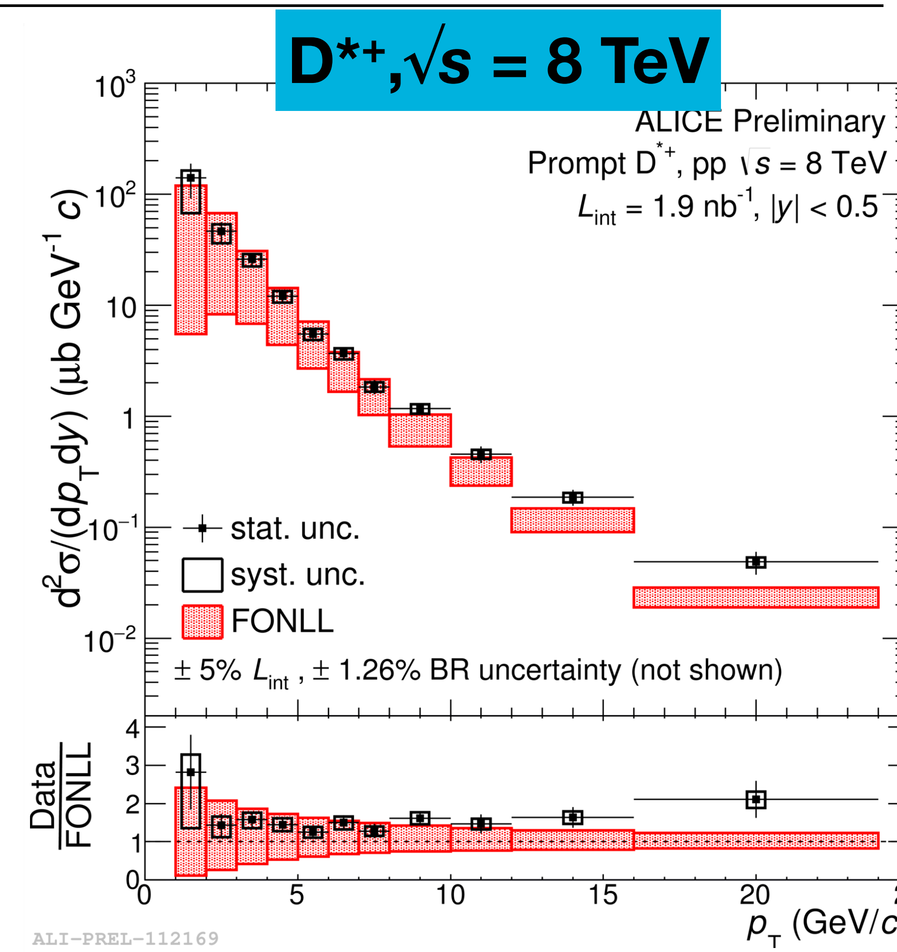
Electrons in $|y|<0.9$

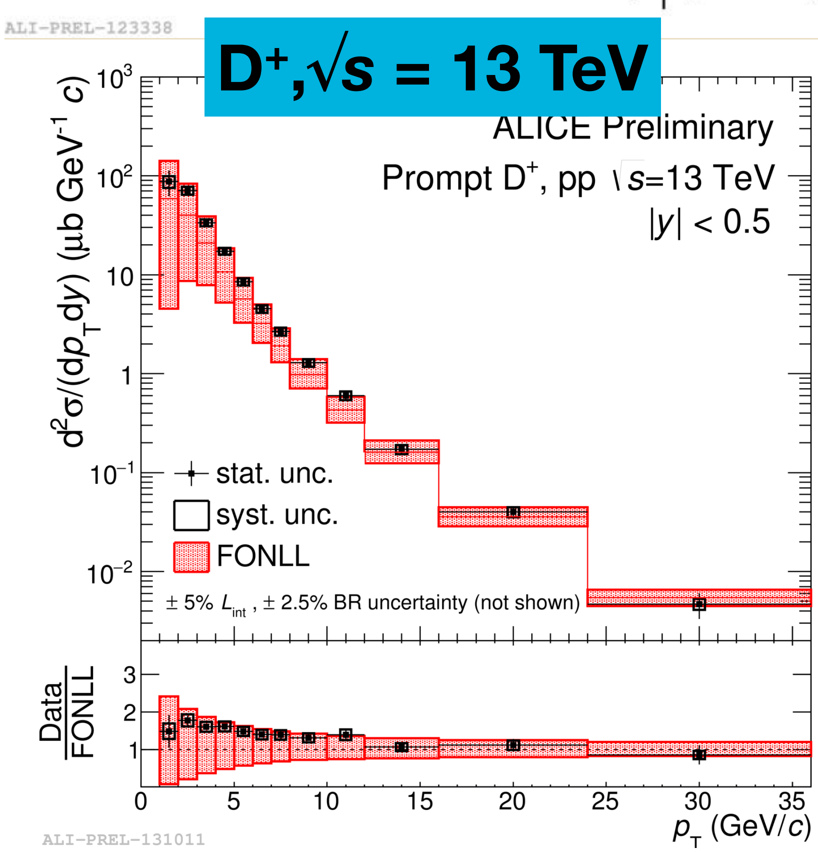
Muons in $2.5 < y < 4$

D mesons in pp collisions







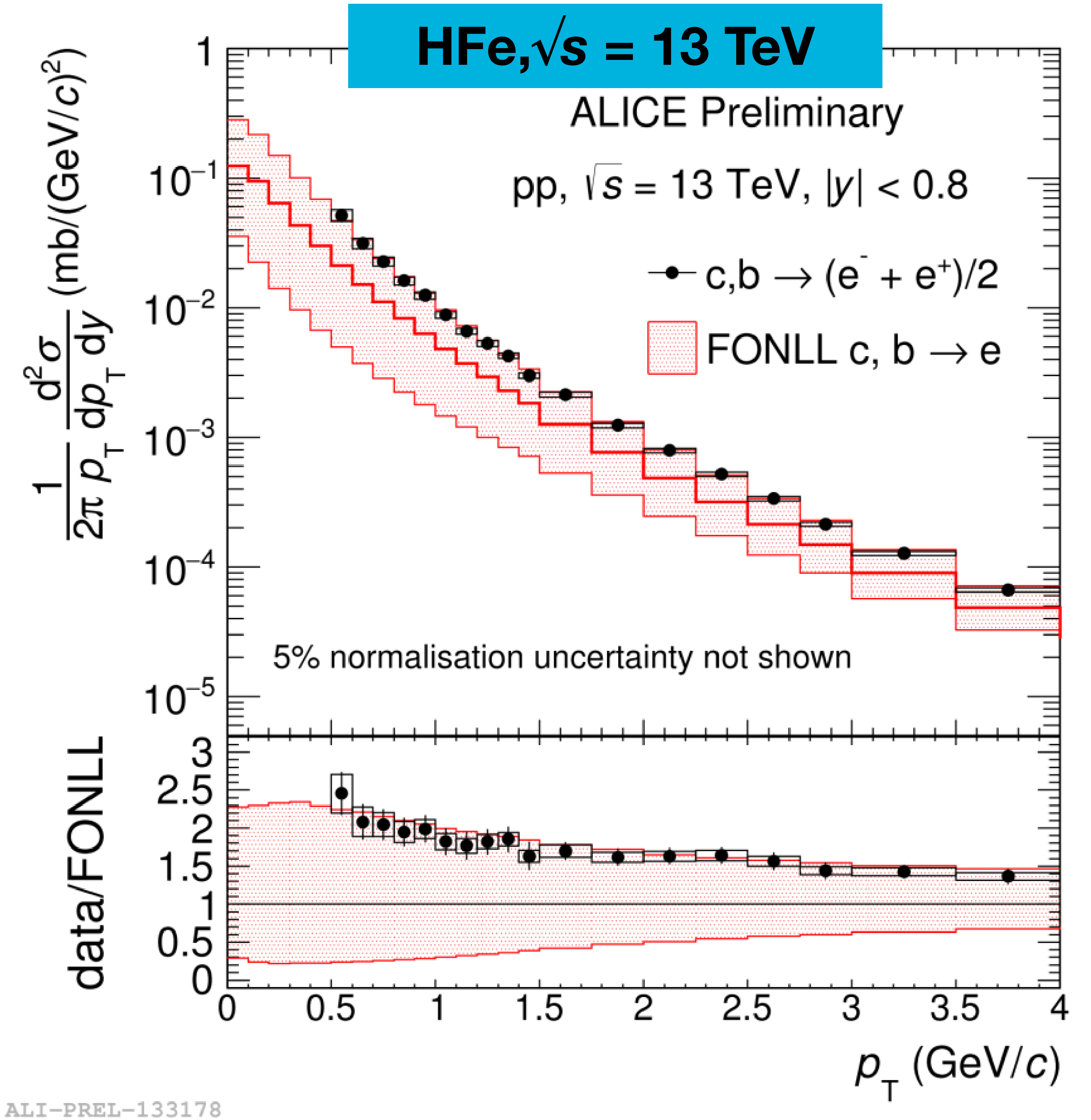


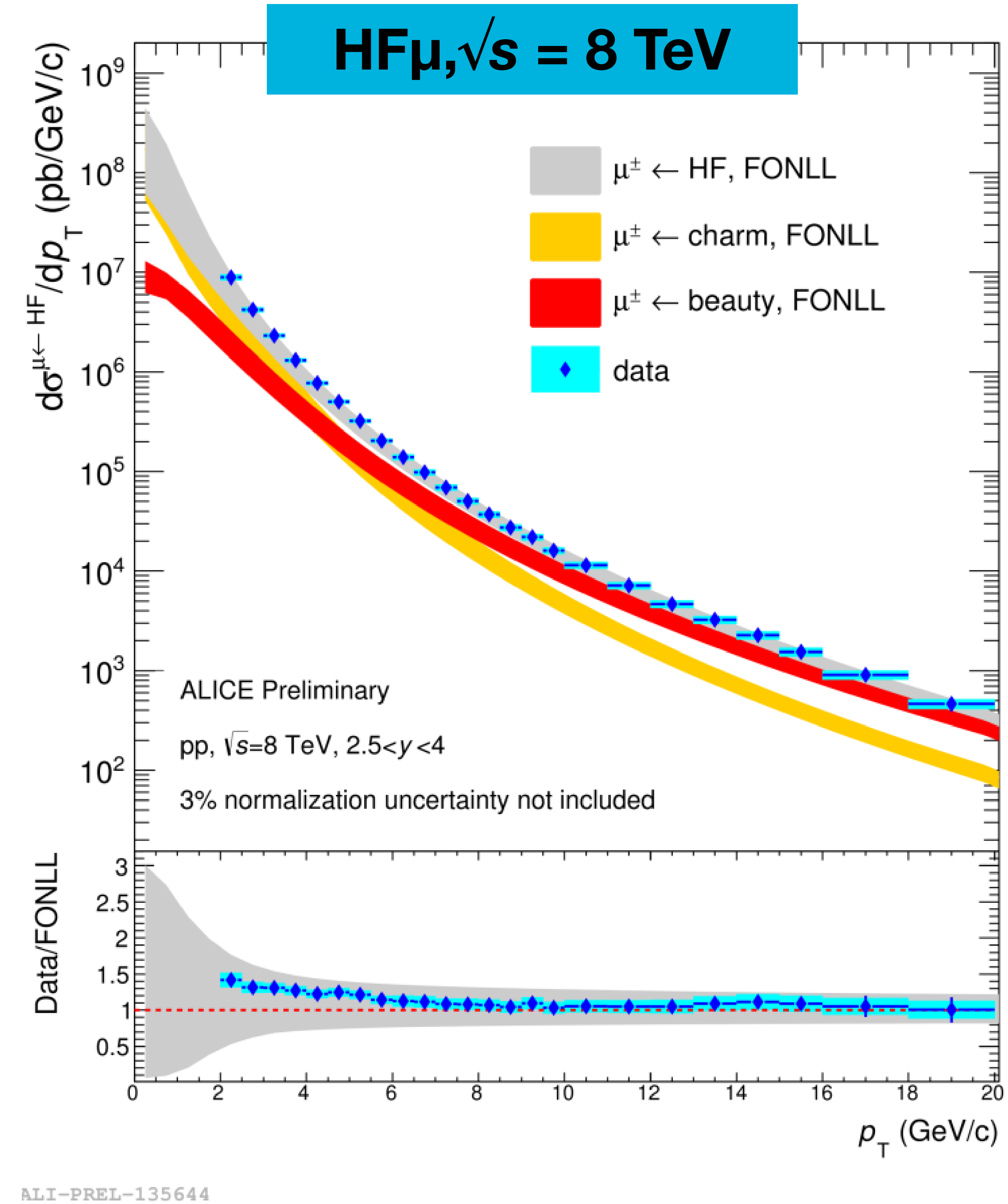
D meson production cross section measured at several collision energies (D^0,D^+,D^{*+},D^+_s)

- D^0 -mesons measured down to $p_T = 0$ using non-topological analysis; allows full mid-rapidity cross section to be measured without extrapolation
- pQCD-based theoretical calculations reproduce the data
- **Data much more precise** than theoretical calculations

[1] Eur.Phys.J. C77 (2017) 550

Heavy-flavour leptons in pp collisions

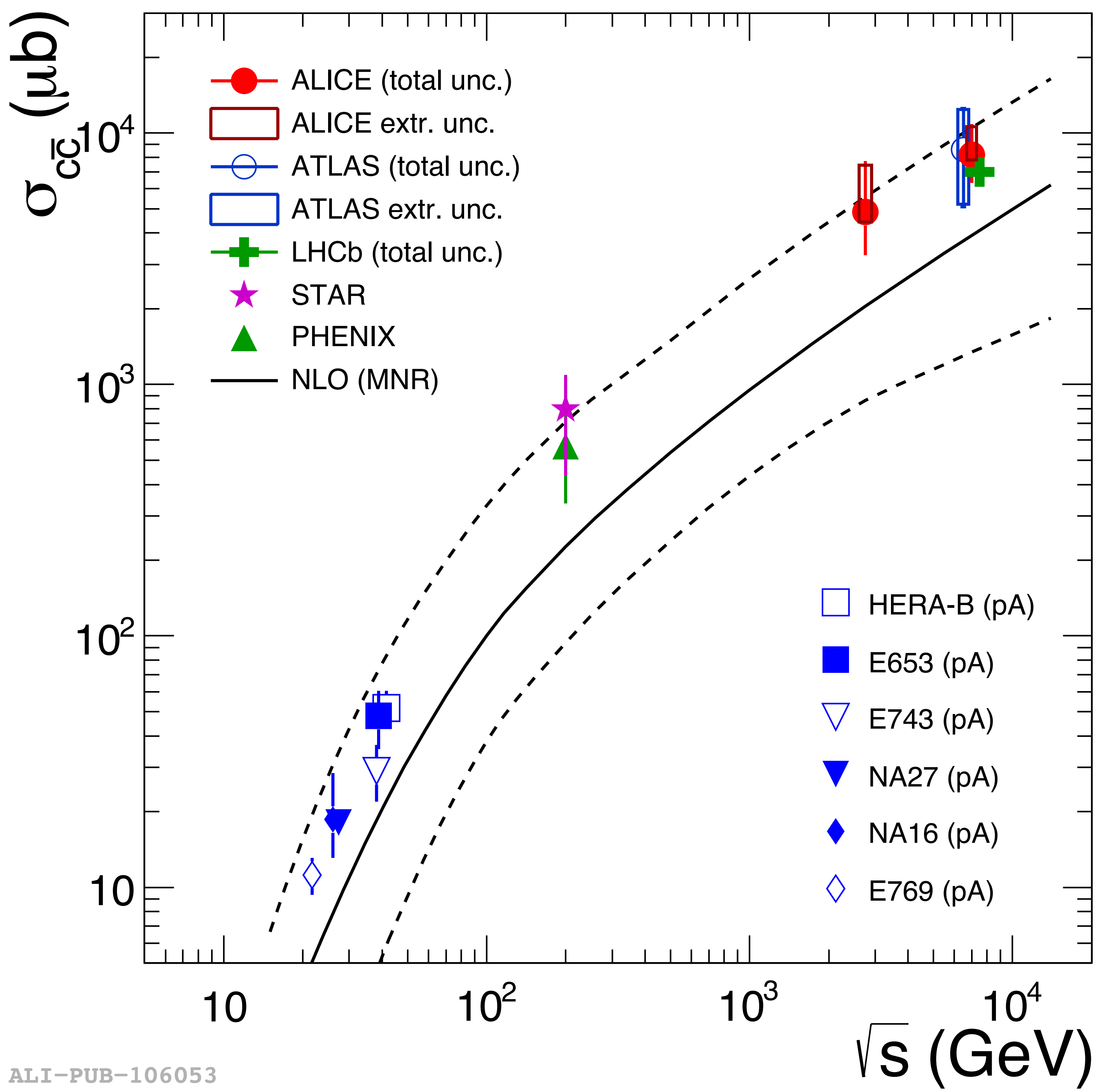


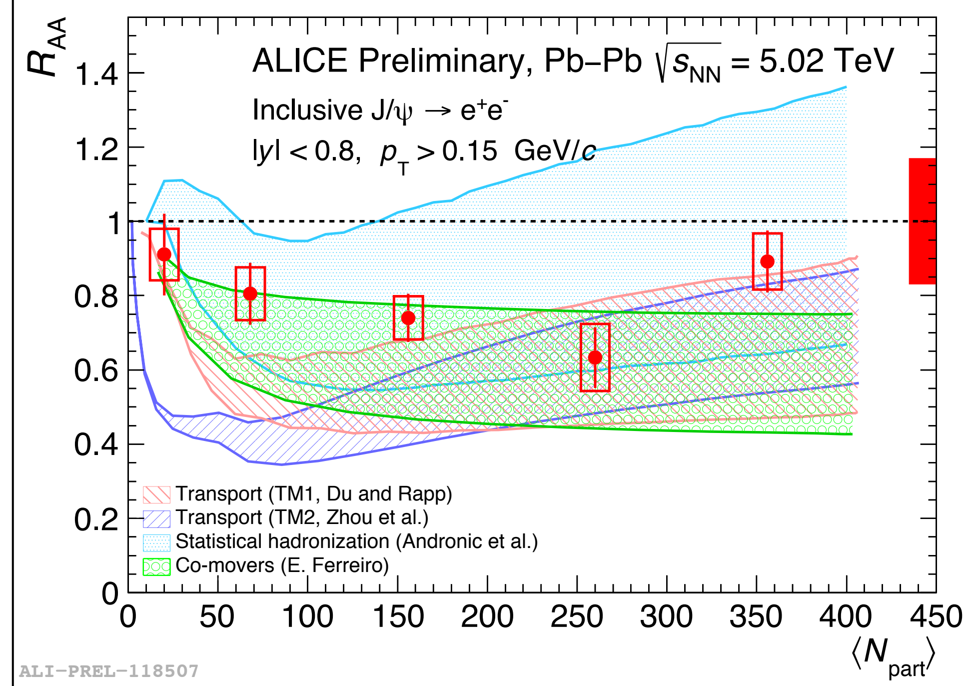


- Beauty is the main component from $p_T > \sim 5$ GeV/c
- Precise data to **constrain charm and beauty production** over a wide rapidity interval
- **Similar agreement** with FONLL is found in the **two rapidity** intervals

Total charm cross section

Phys. Rev. C 94, 054908 (2016)



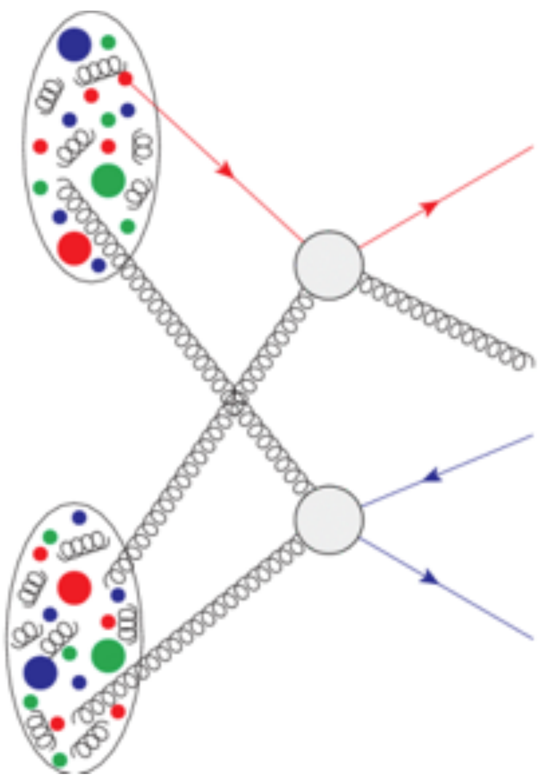


Transport and statistical models have large uncertainties
(shadowing+open charm cross section)

Factor ~2 reduction on systematic uncertainty

Important to constraint model!

Multiplicity dependence of heavy-flavour production



Particle production in pp collisions at the LHC shows a better agreement with models including Multi-Parton Interactions (MPIs)

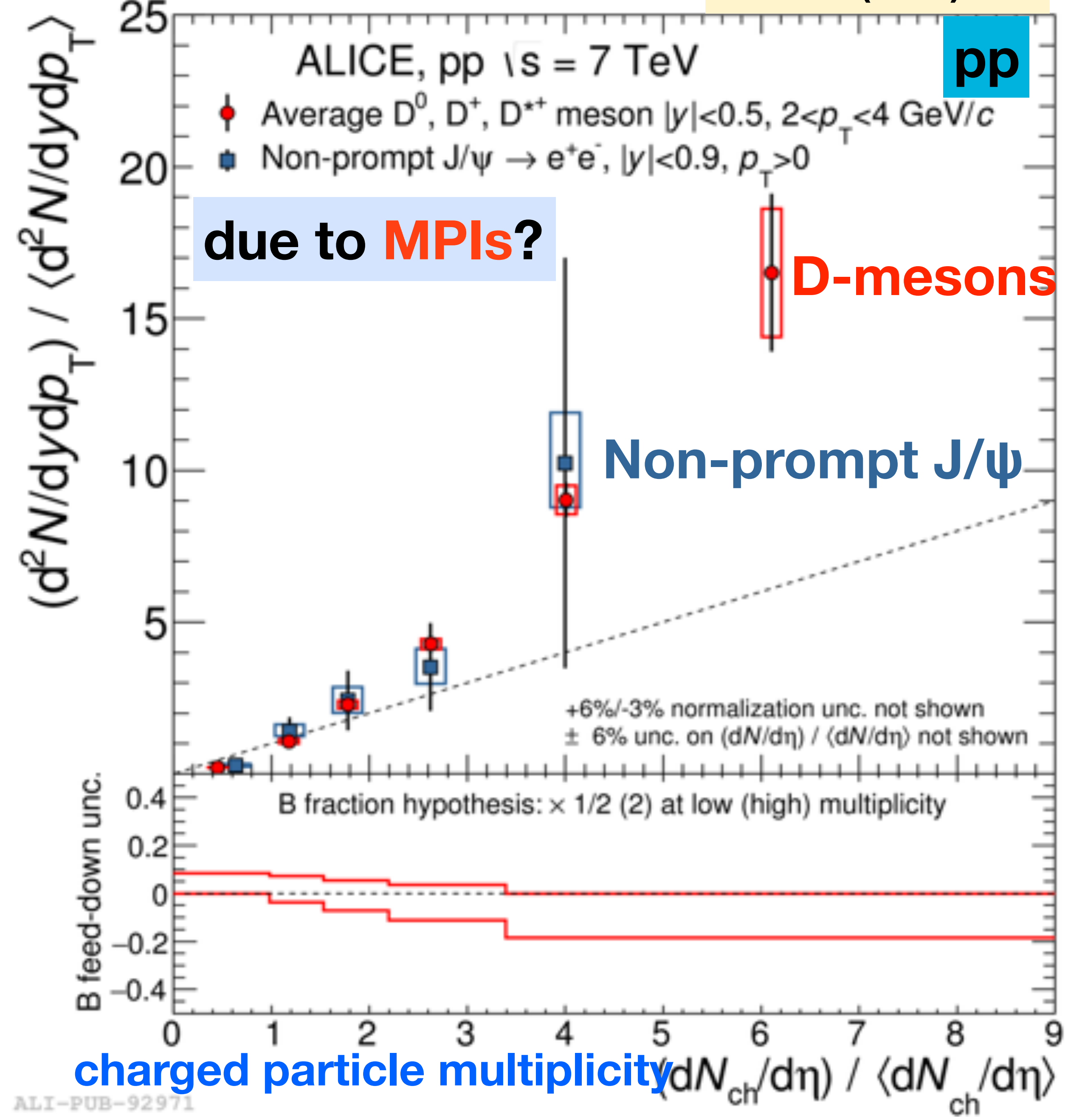
Eur. Phys. J. C 73 (2013) 2674

For heavy flavours:

- LHCb: double charm production agrees better with models including double parton scattering

J. High Energy Phys., 06 (2012) 141

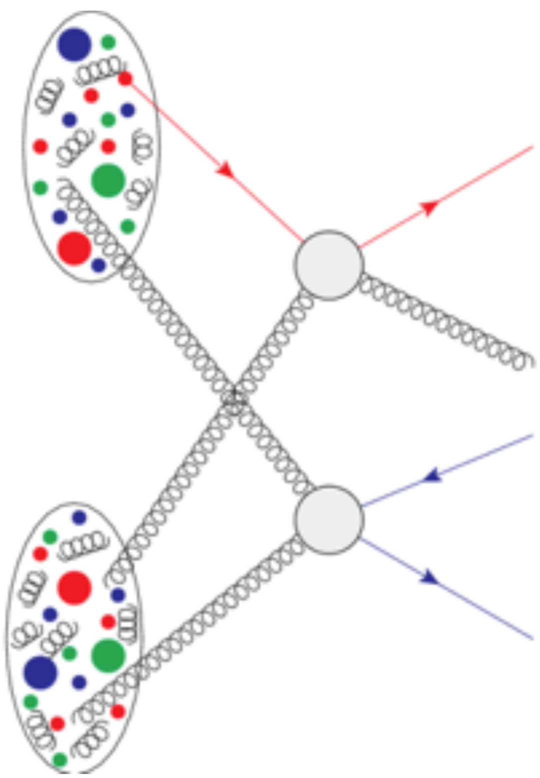
JHEP09 (2015) 148



MPIs involving only light quarks and gluons, or for heavy-flavour production?

- D-meson, non-prompt J/ψ yields increase with charged-particle multiplicity → presence of MPIs and contribution on the harder scale?

Multiplicity dependence of heavy-flavour production



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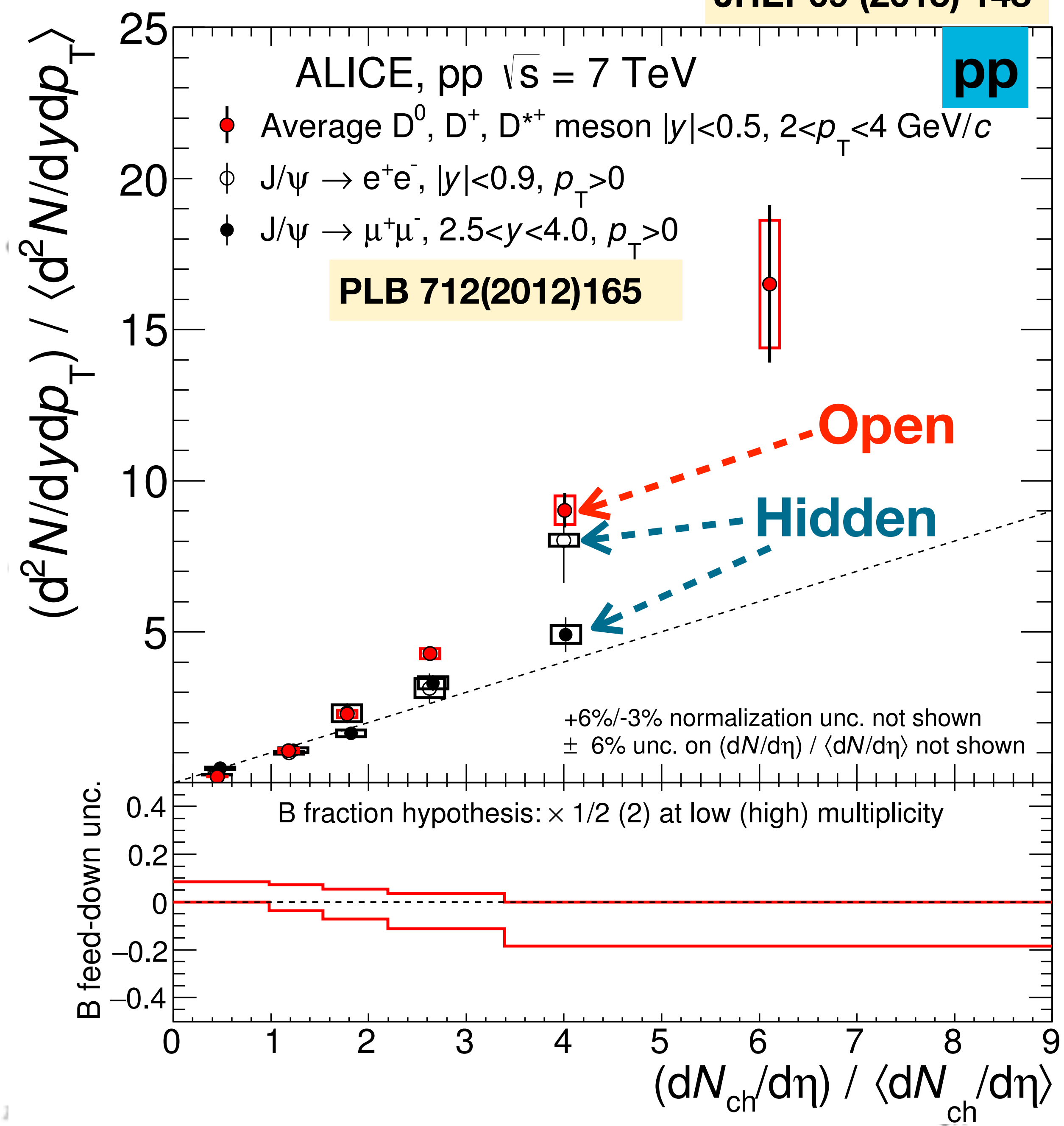
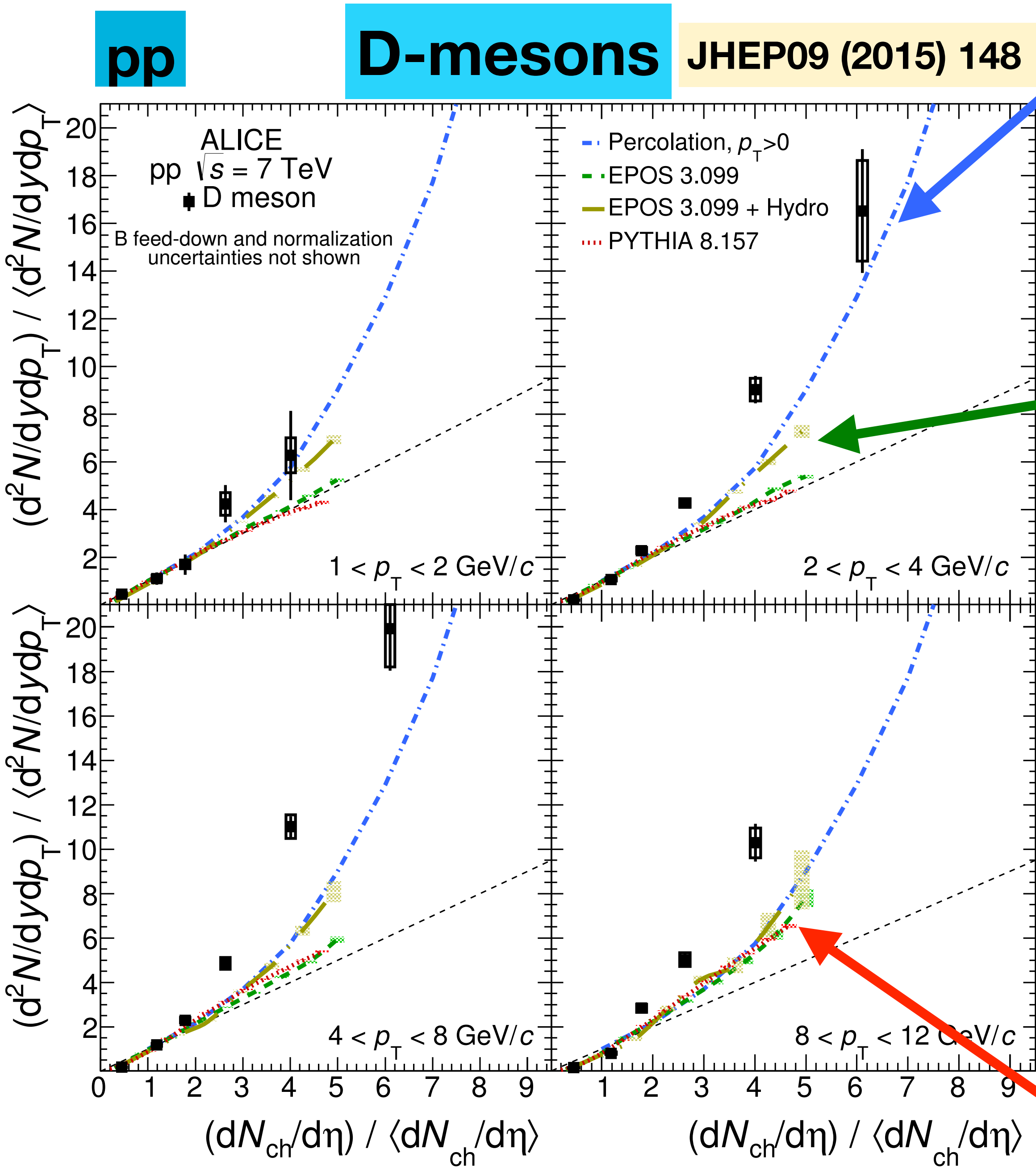


MPIs involving only light quarks and gluons, or for heavy-flavour production?

Same behavior for open and hidden charm production
→ this behaviour is most likely related to the $c\bar{c}$ and $b\bar{b}$ production processes, but not significantly influenced by hadronisation!

D-meson yields vs. multipicity: comparison with models (pp)



charged particle multiplicity

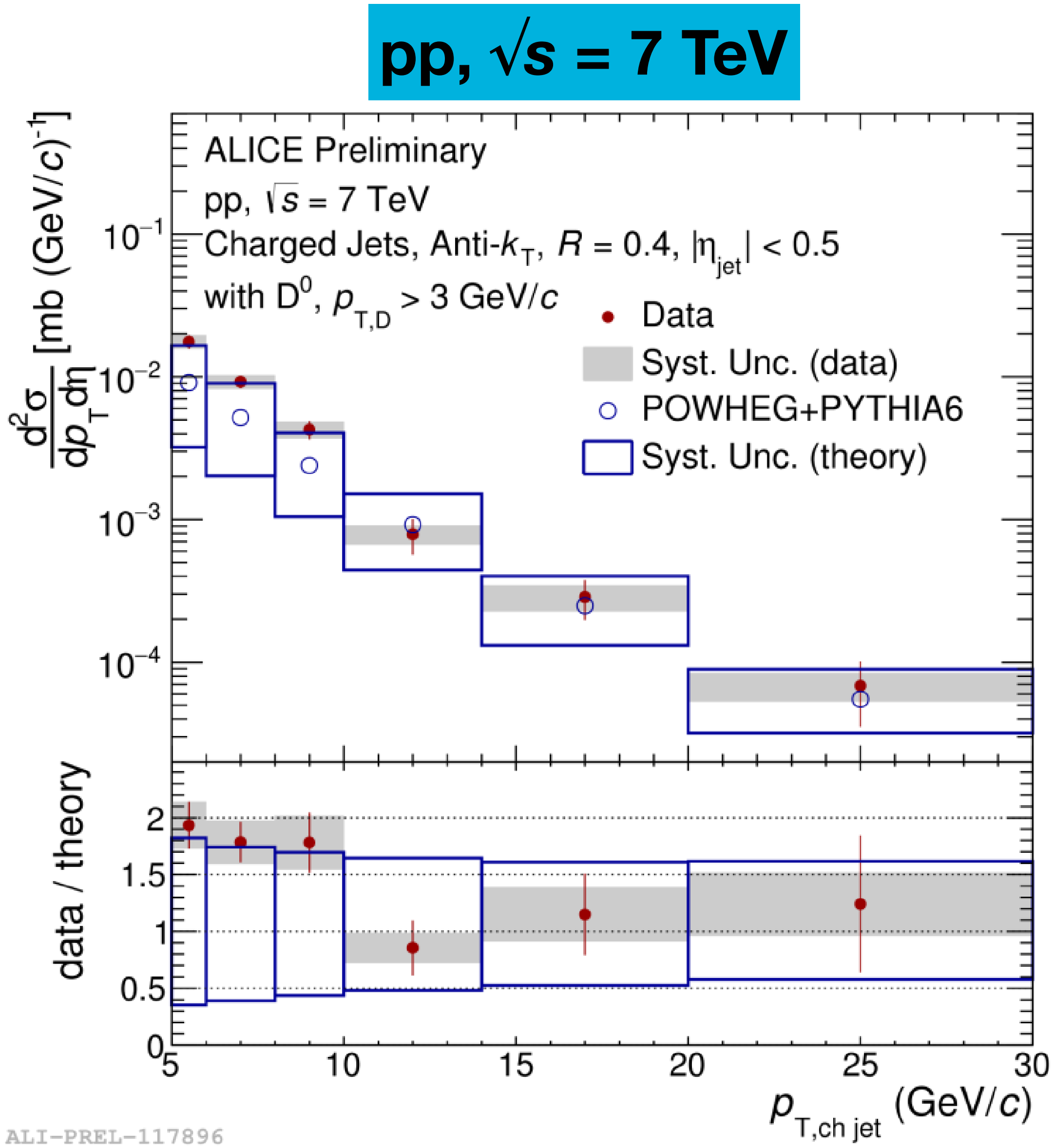
- **Percolation (Ferreiro, Pajares, PRC 86 (2012) 034903)**

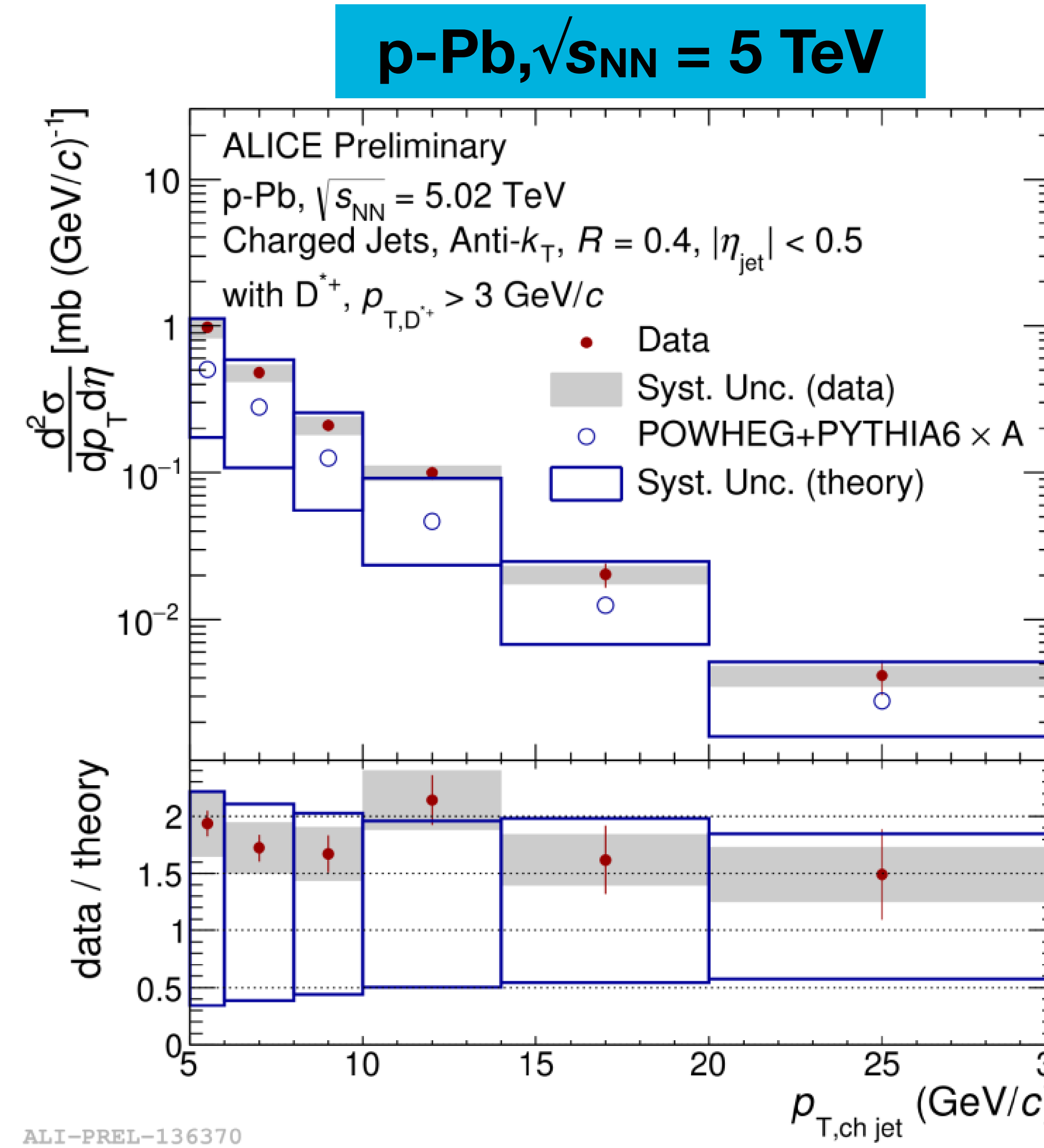
  Particle production via exchange of colour sources between projectile and target (close to MPI scenario) → Faster than linear increase

- **EPOS 3.099 (Werner et al., PRC 89 (2014) 064903)**
  - Gribov-Regge multiple-scattering formalism
  - Saturation scale to model non-linear effects
  - Number of MPI directly related to multiplicity → slightly faster than linear
  - With hydrodynamical evolution applied to the core of the collision→faster than linear increase

- **PYTHIA 8 (Sjostrand et al., Comput. Phys. Commun. 178 (2008) 852)**
  - Sok-QCD tune
  - Colour reconnection
  - MPI

Charm jet in pp and p-Pb collisions

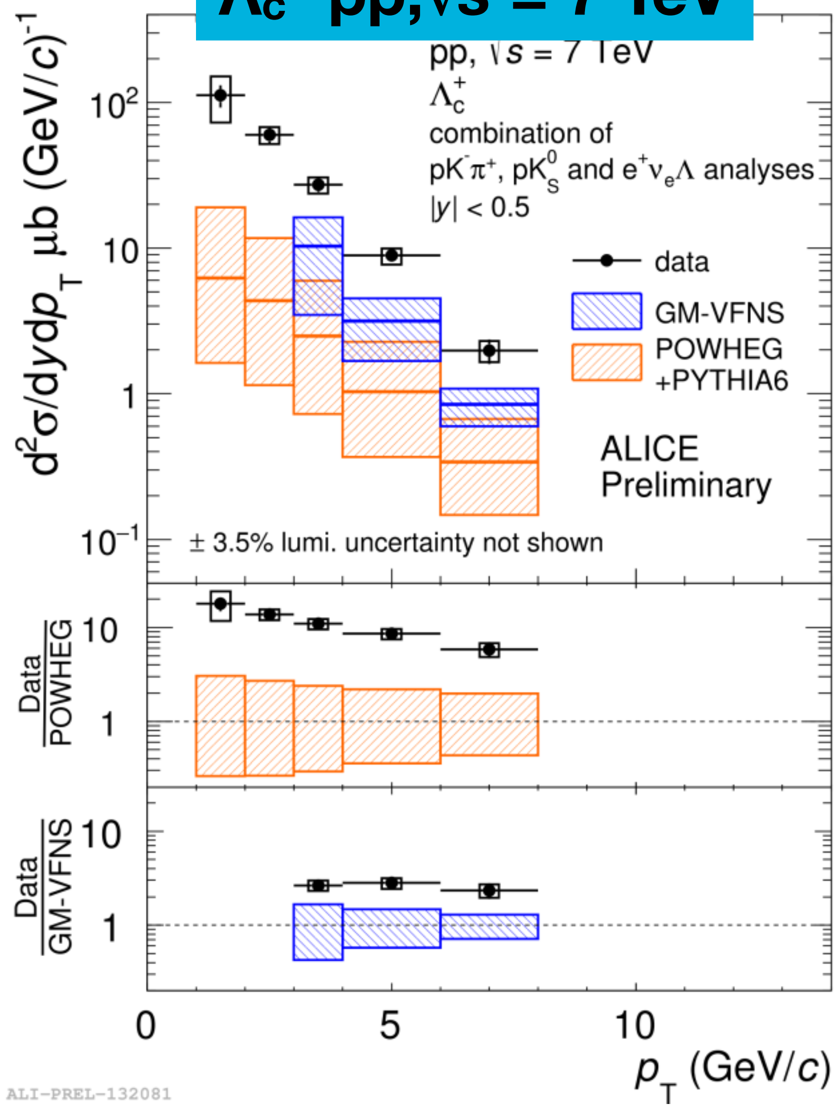




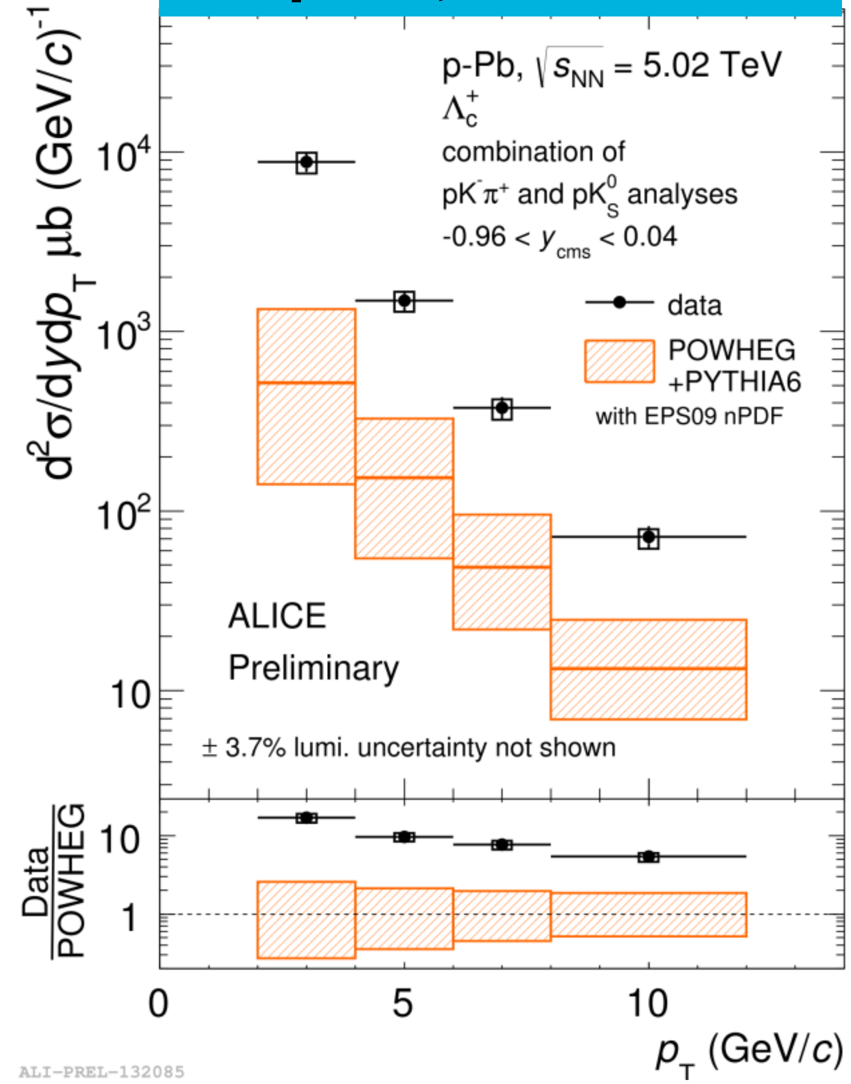
- Charm jets tagged by the presence of a fully reconstructed D meson
- D-jet spectrum measured from p_T = 5 GeV/*c* to 30 GeV/*c*
- **Described by POWHEG+PYTHIA6** (Perugia 2011 tune) simulation within uncertainty
  - Data uncertainty smaller than theoretical ones

Λ_c^+ & Ξ_c^0 in pp and p-Pb collisions

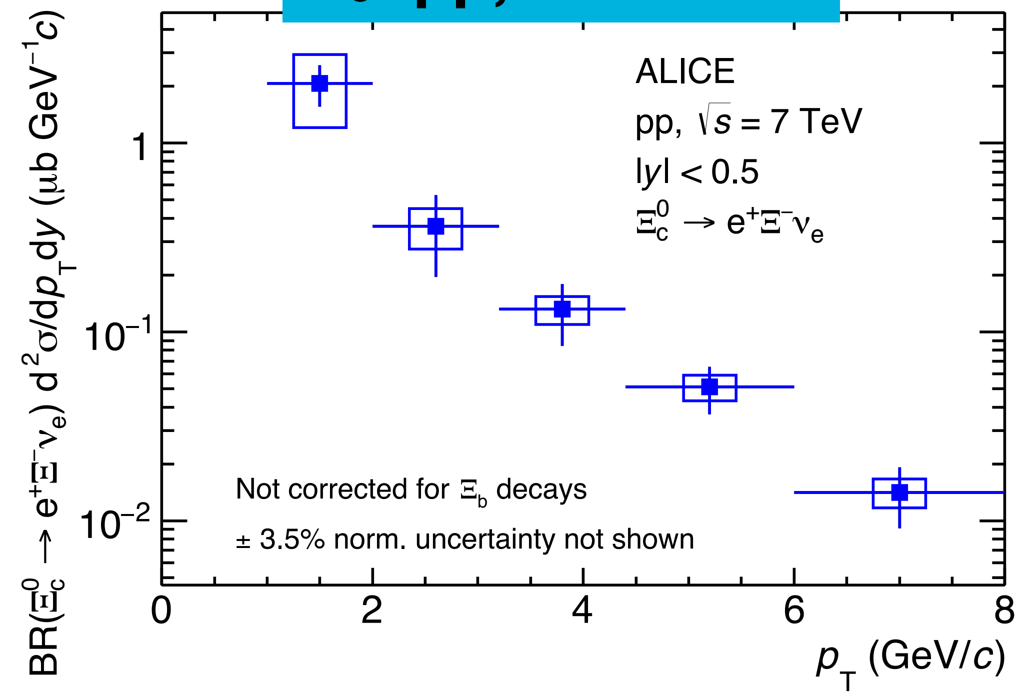
Λ_c^+ pp, $\sqrt{s}$ = 7 TeV



Λ_c^+ p-Pb, $\sqrt{s_{NN}}$ = 5 TeV



Ξ_c^0 pp, $\sqrt{s}$ = 7 TeV

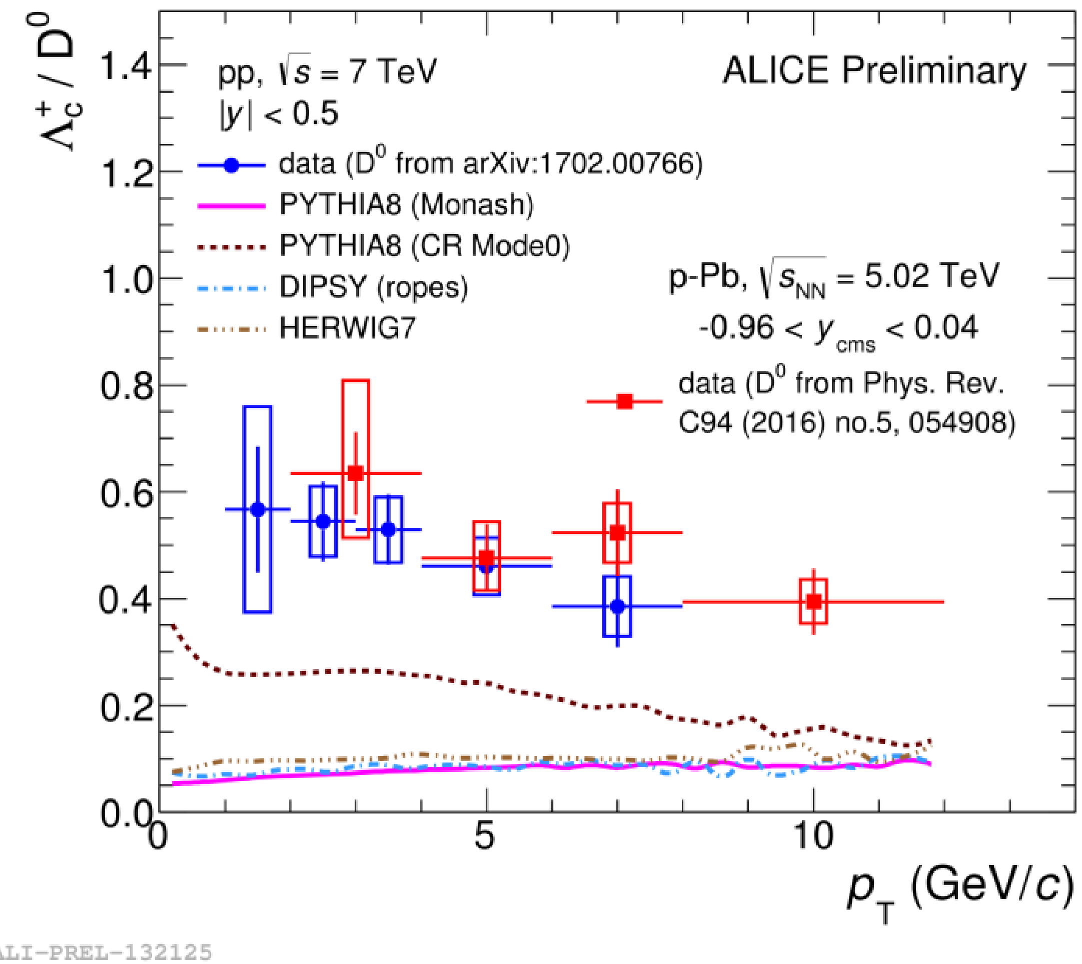


- Measured using 3 decay channels (hadronic + semileptonic) in pp
- Measured using 2 decay channels (hadronic) in p-Pb

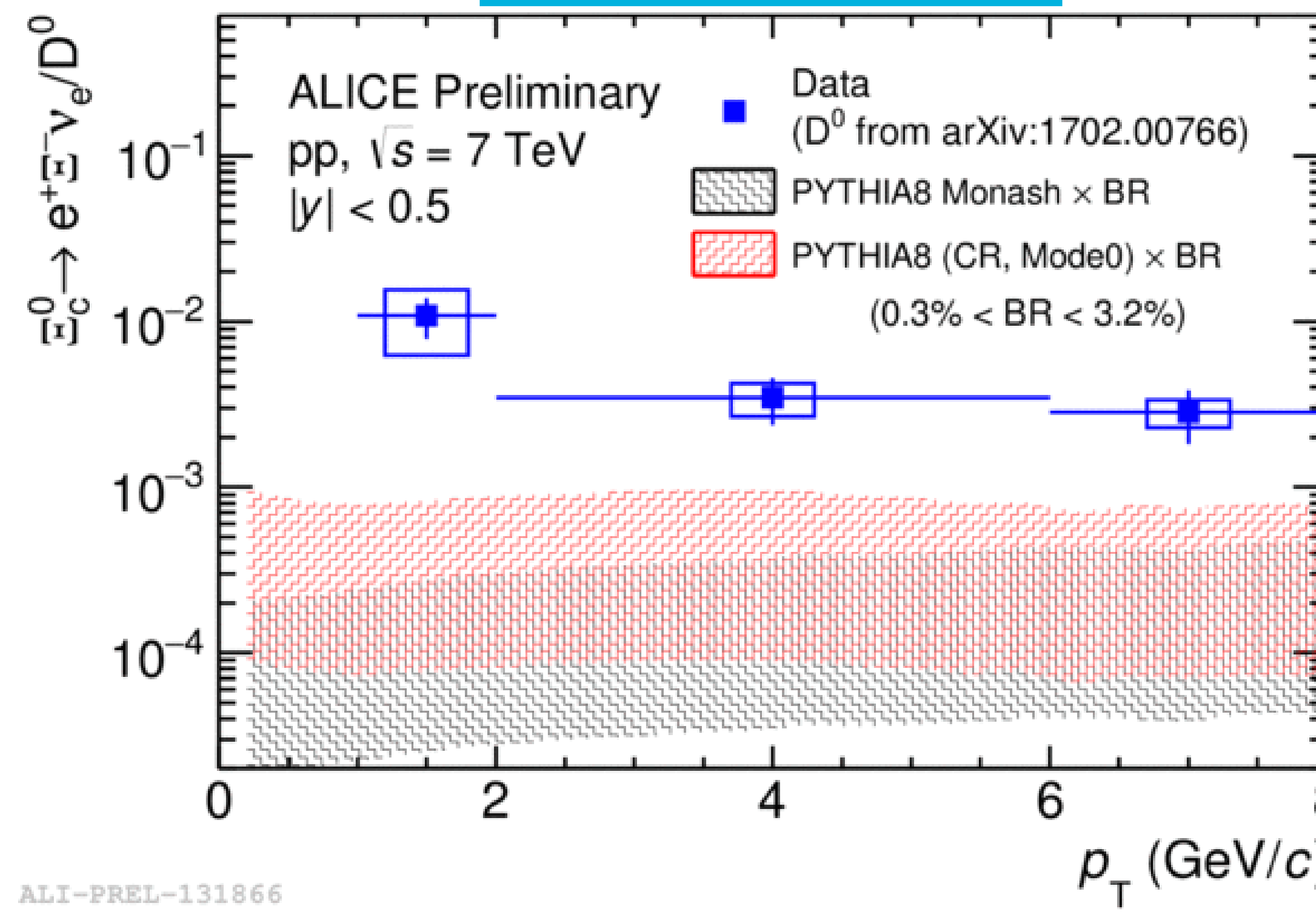
- Study **charm hadronization mechanisms** using baryons
- Λ_c^+ cross section **underestimated** by theory in pp and p-Pb collisions
  - x 2-3 higher than GM-VFNS
  - Up to x 20 higher than POWHEG+PYTHIA6
- Ξ_c^0 baryon in pp collisions at $\sqrt{s}$ = 7 TeV, using semileptonic decay channel ($\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$)
  - **First measurement of Ξ_c^0 baryon production at the LHC**

Baryon-to-meson ratio

pp, √s = 7 TeV, p-Pb,√sNN = 7 TeV



pp, √s = 7 TeV

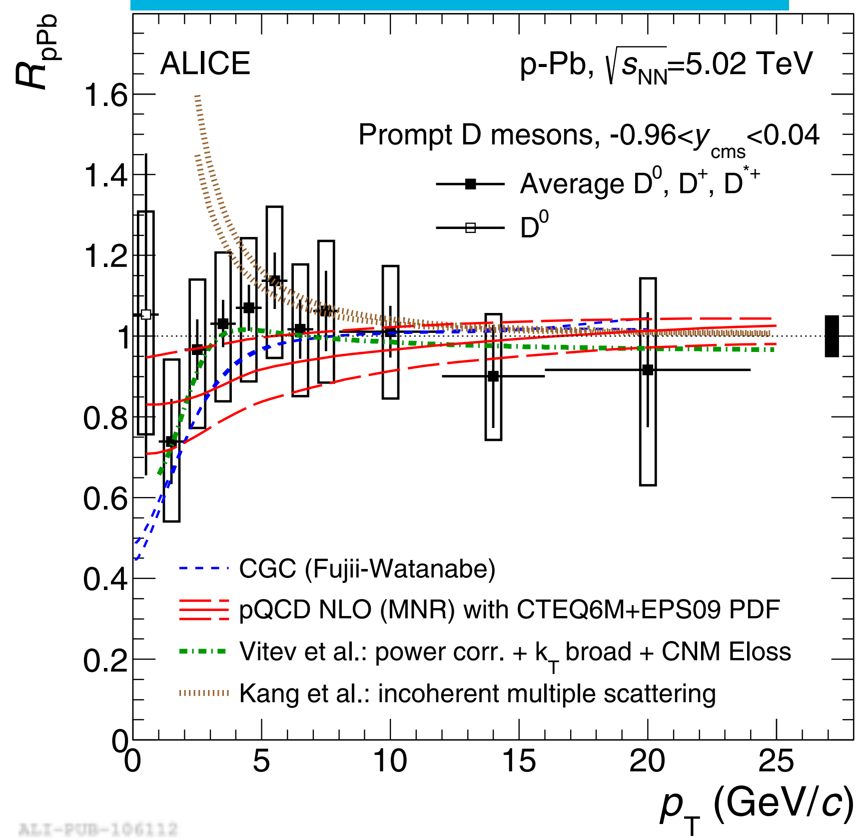


- Λ_c^+/D^0 in pp and p-Pb collisions compatible within uncertainties
- Λ_c^+/D^0 ratio higher than expectation from MC
  - Enhanced color reconnection mode [1] in PYTHIA 8 closer to data
- Ξ_c^0/D^0 in pp collisions
  - Bands represent the range of the currently available theoretical predictions of the branching ratio → Experimental values are awaited!

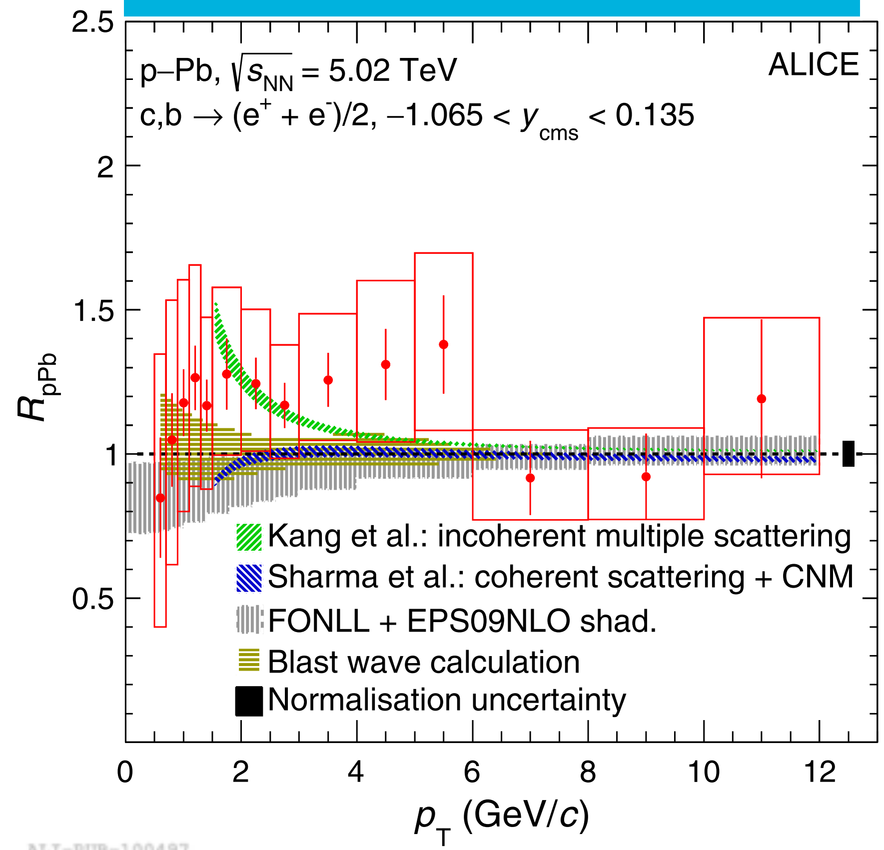
[1] J. Christiansen, P. Skands JHEP 08 (2015) 003

D-meson, Λ_c^+, charm and beauty electron R_{pPb}

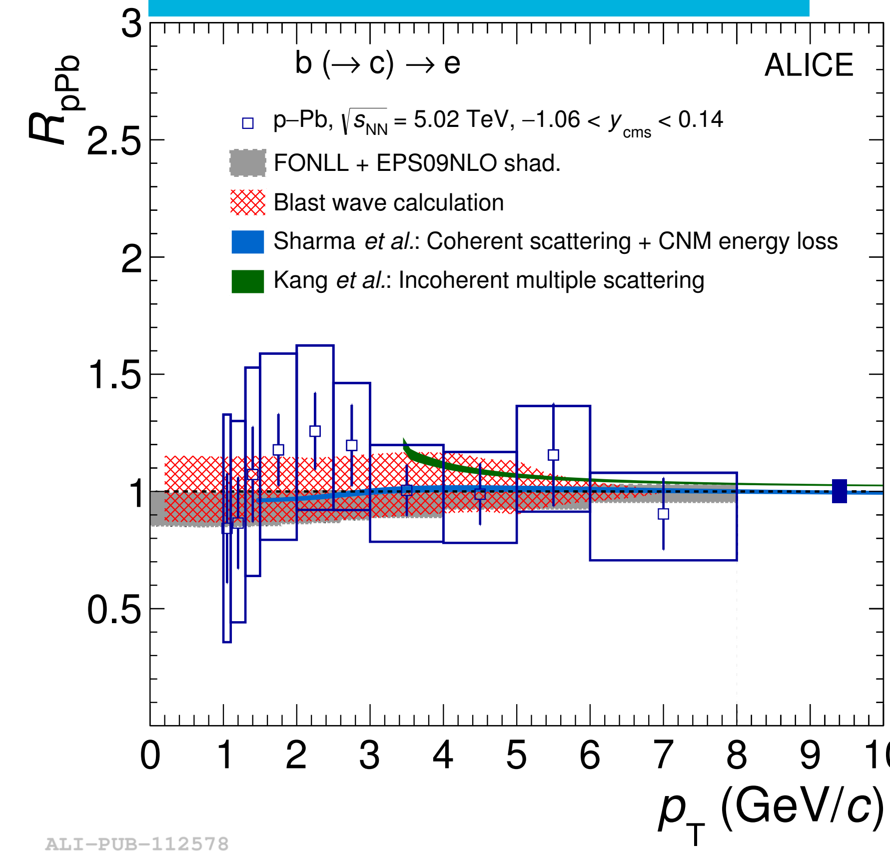
D, $\sqrt{s_{NN}}$ = 5 TeV [1]



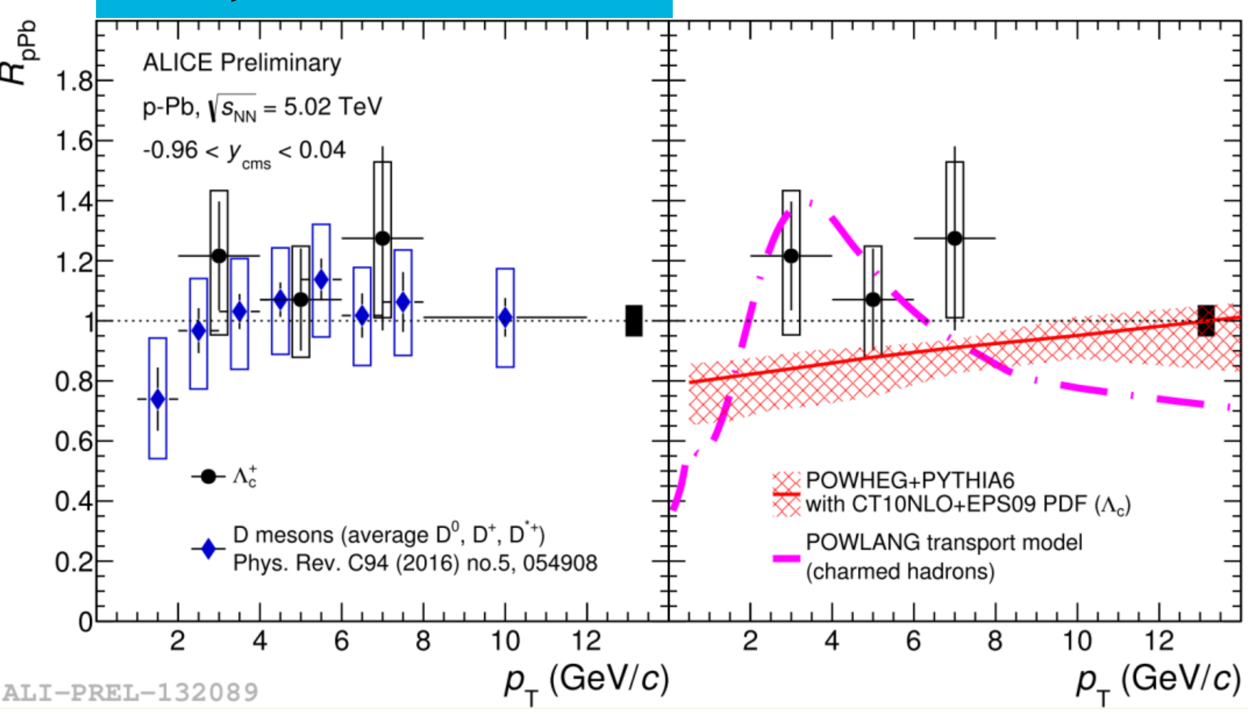
c,b→e, $\sqrt{s_{NN}}$ = 5 TeV [2]



b→e, $\sqrt{s_{NN}}$ = 5 TeV [3]



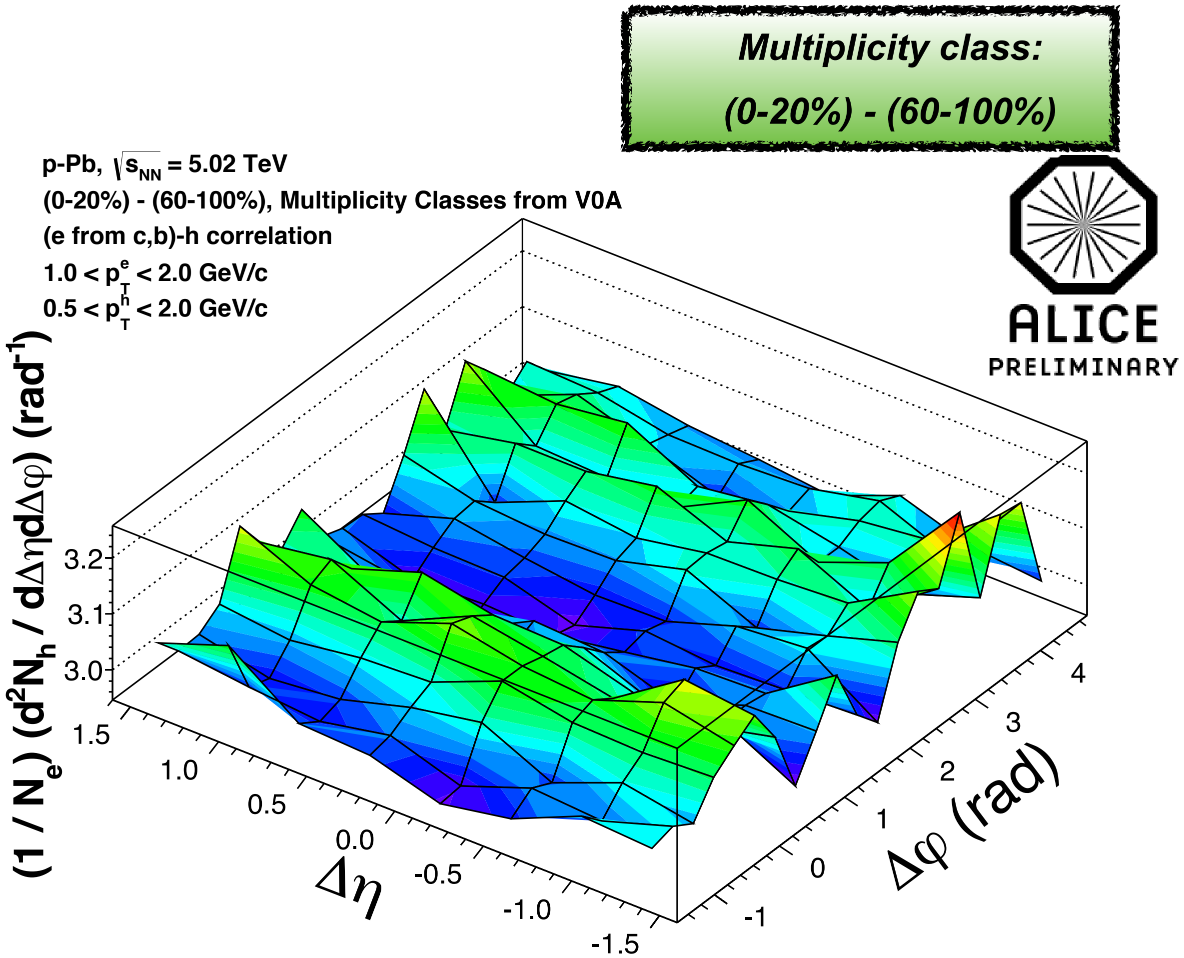
Λ_c^+, $\sqrt{s_{NN}}$ = 5 TeV

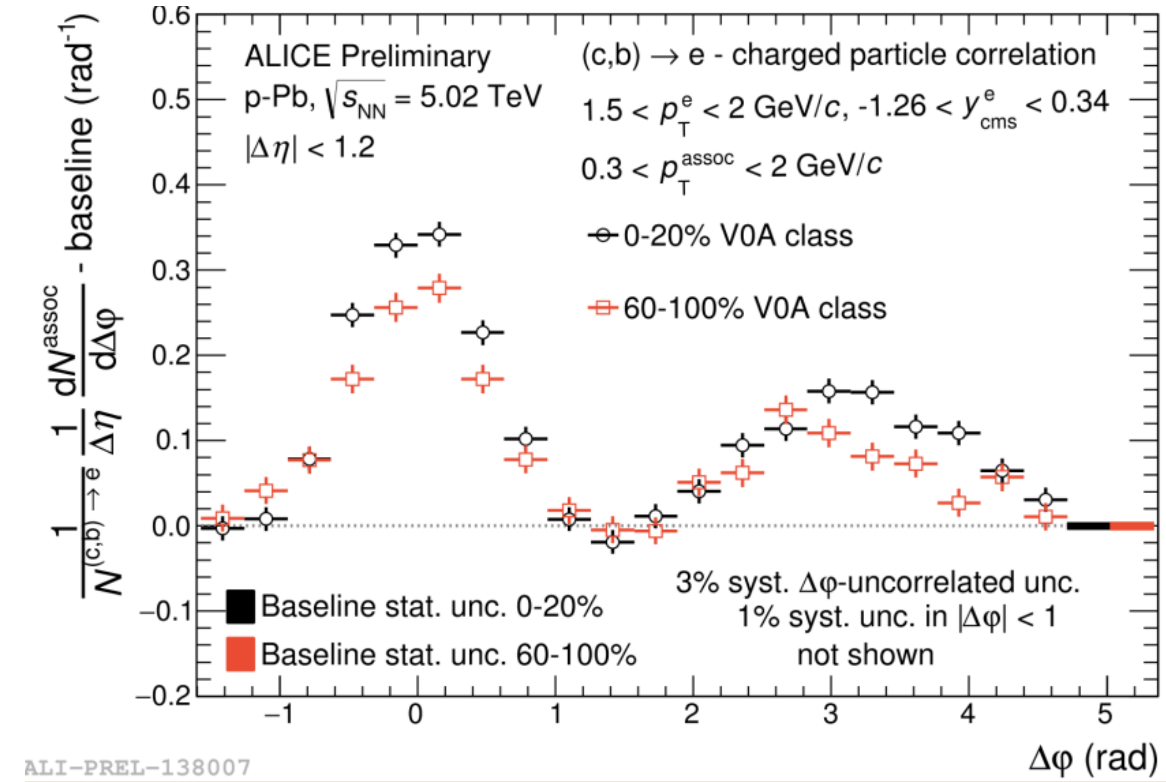


- D meson, Λ_c^+, charm and beauty electron R_{pPb} **compatible with unity within uncertainties**
- Data are described by models including **initial-state and cold nuclear matter effects**
- **Need larger samples** of both p-Pb and pp collisions at 5 TeV for constraining models at low p_T where predictions differentiate.

[1] PHYSICAL REVIEW C 94, 054908 (2016)
[2] Physics Letters B 754 (2016) 81–93
[3] JHEP07 (2017) 052

Heavy-flavour electron-hadron correlations





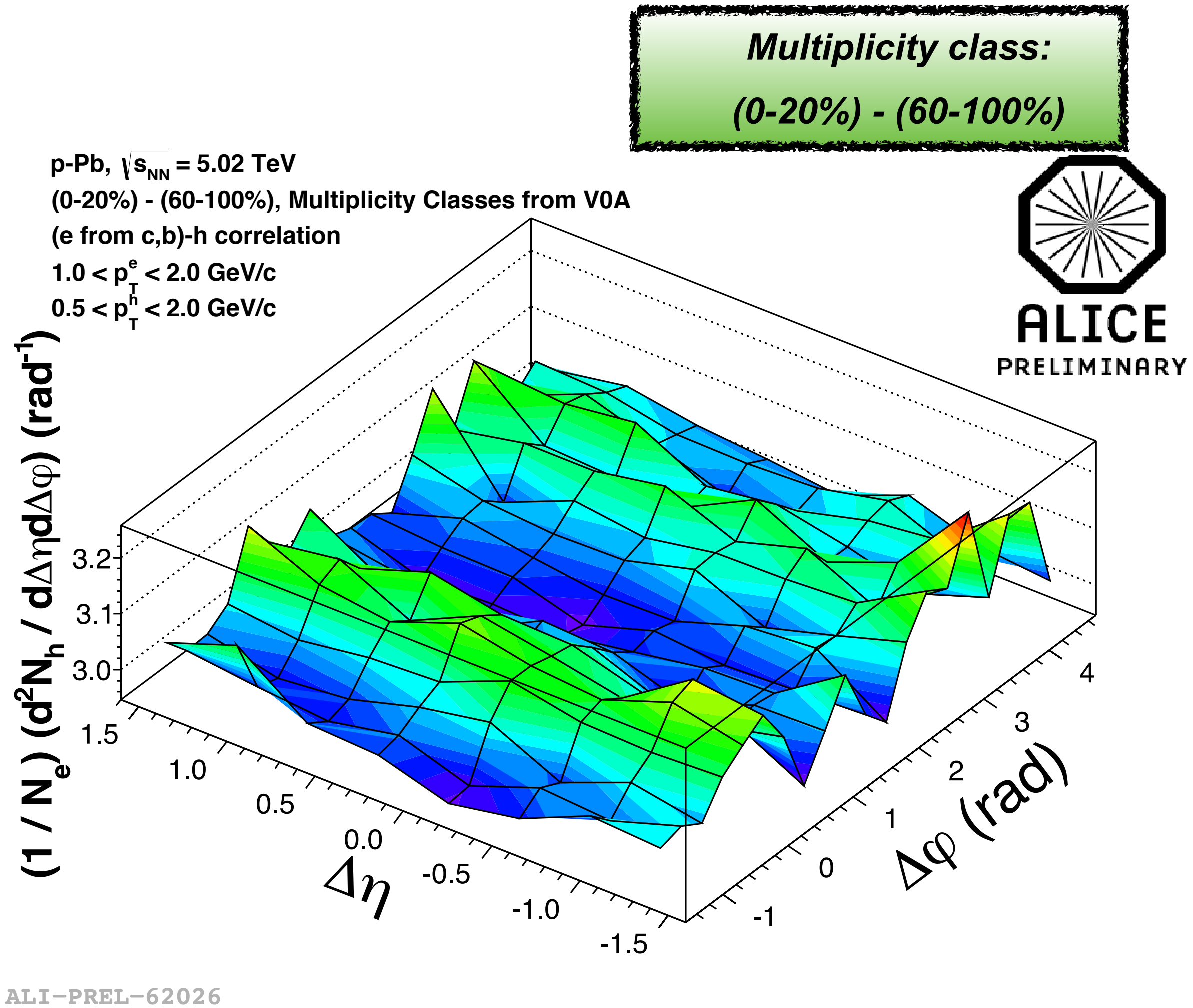
Resembles the structure observed in Pb-Pb collisions that is interpreted in terms of collective flow

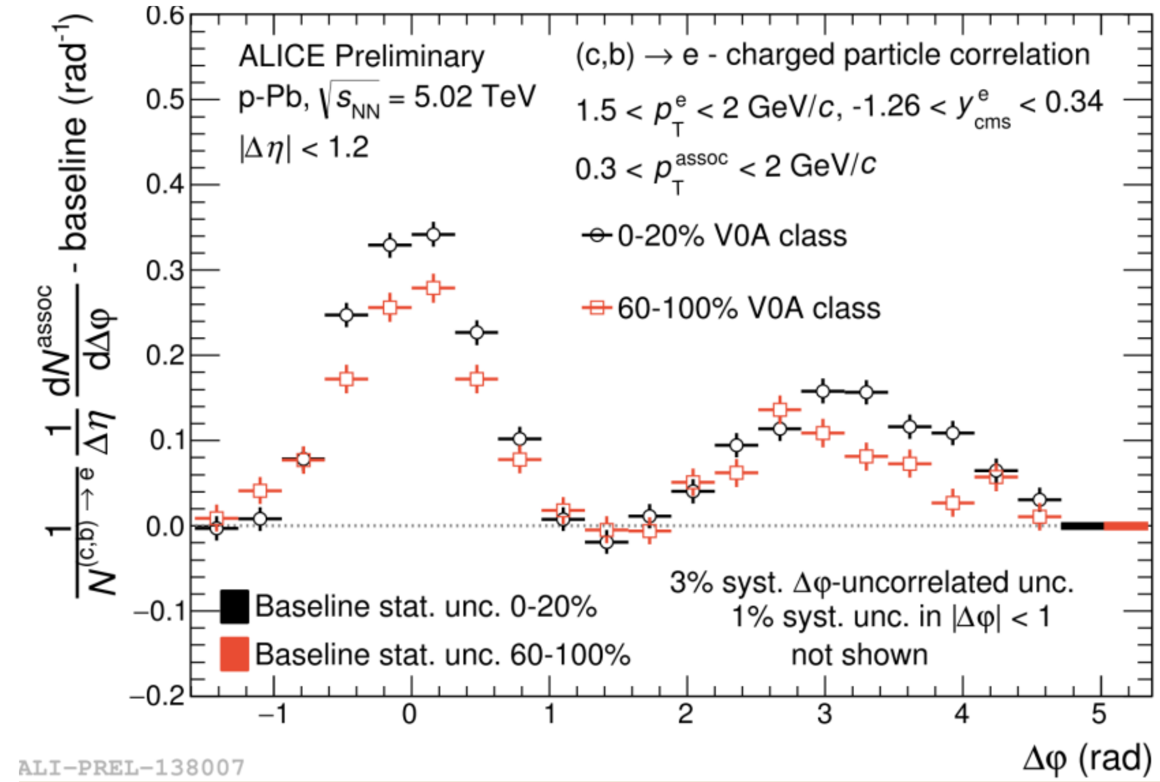
- Analysis of electron-hadron azimuthal correlation in 0-20% events with highest multiplicity
  - Jet contribution estimated and subtracted with peripheral events

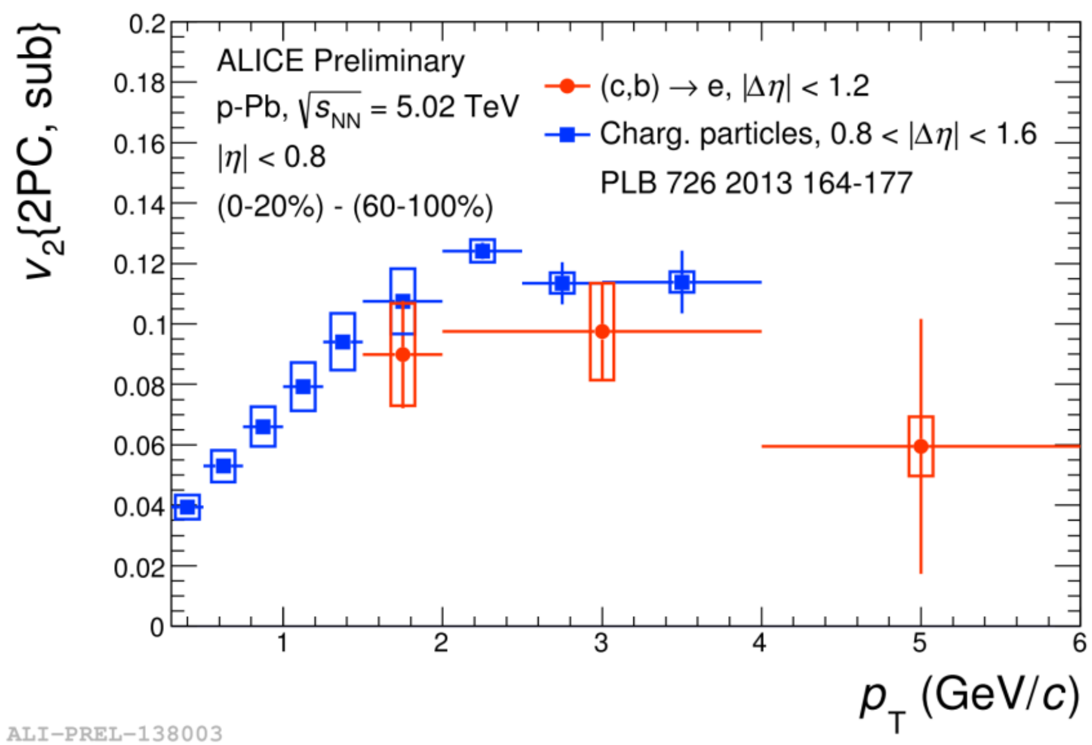
The double ridge also observed in heavy-flavour sector!

The mechanism (CGC? Hydro?) that generates it affects also heavy flavor?

Heavy-flavour electron-hadron correlations and v_2







- Analysis of electron-hadron azimuthal correlation in 0-20% events with highest multiplicity
  - Jet contribution estimated and subtracted with peripheral events
- **Positive v_2**, almost comparable with the charged-particles (decay particles vs hadrons: not same p_T)
  - **Initial-state effects, collective effects?**

Summary and plans for Run2 and beyond

Summary

- Open heavy-flavour production in pp collisions described by perturbative QCD
- First measurement of Λ_c^+ (at mid-rapidity) and Ξ_c^0 at the LHC: baryon-to-meson ratio underpredicted by models
- In p-Pb collisions, nuclear modification factor consistent with unity
- In p-Pb collisions, positive v_2 of heavy-flavour decay electrons

Outlook

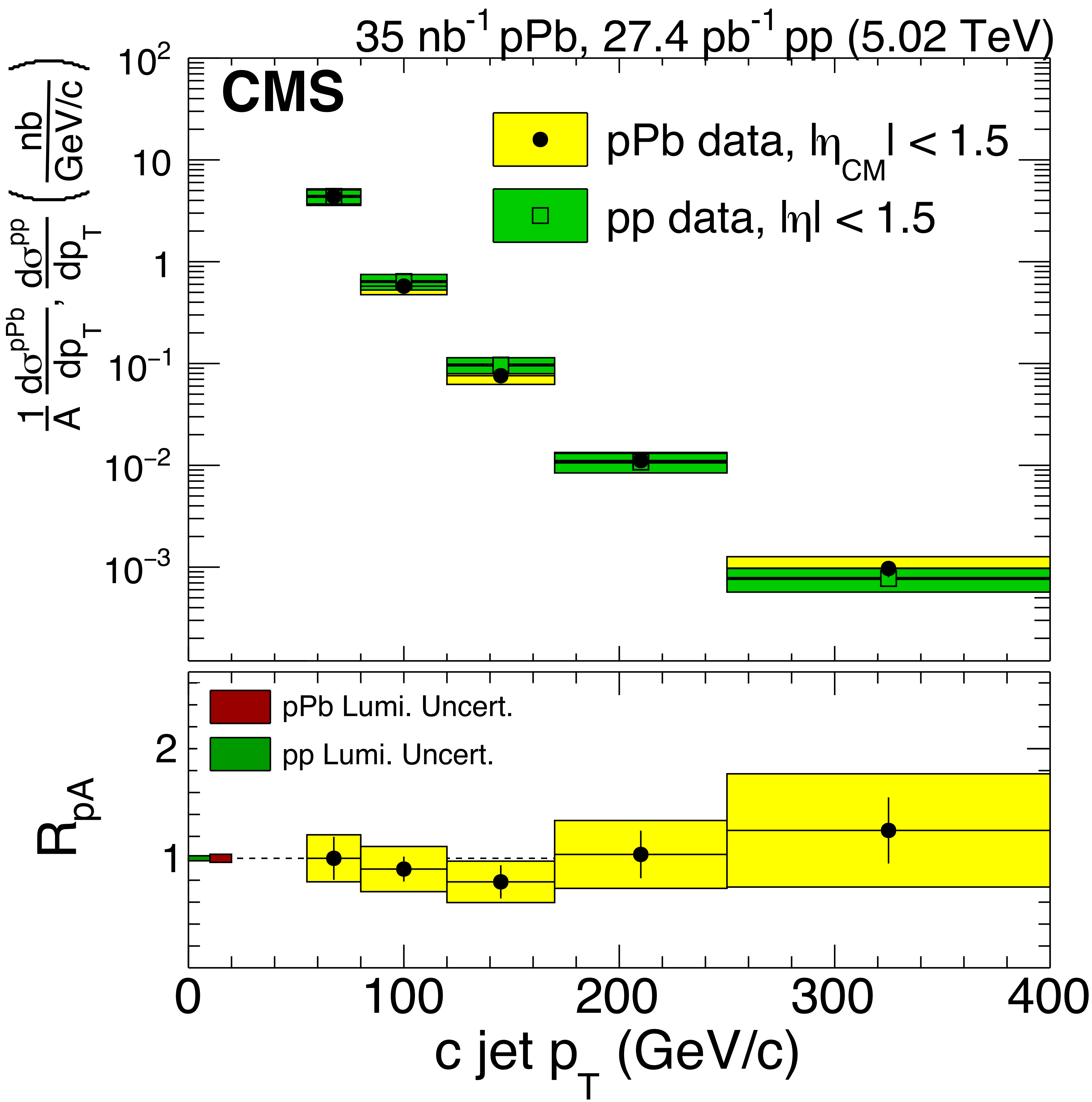
- Improve precision of multiplicity-differential studies in pp and p-Pb collisions
- Improved pp reference at 5.02 TeV will allow refinements to R_{pPb}
- New measurements of Λ_c, Ξ_c^0 production in pp collisions at 5 and 13 TeV, in p-Pb collisions (run 2, x6 more statistics)
- Measurements of charm- and beauty-jet properties in pp and p-Pb collisions (ongoing)

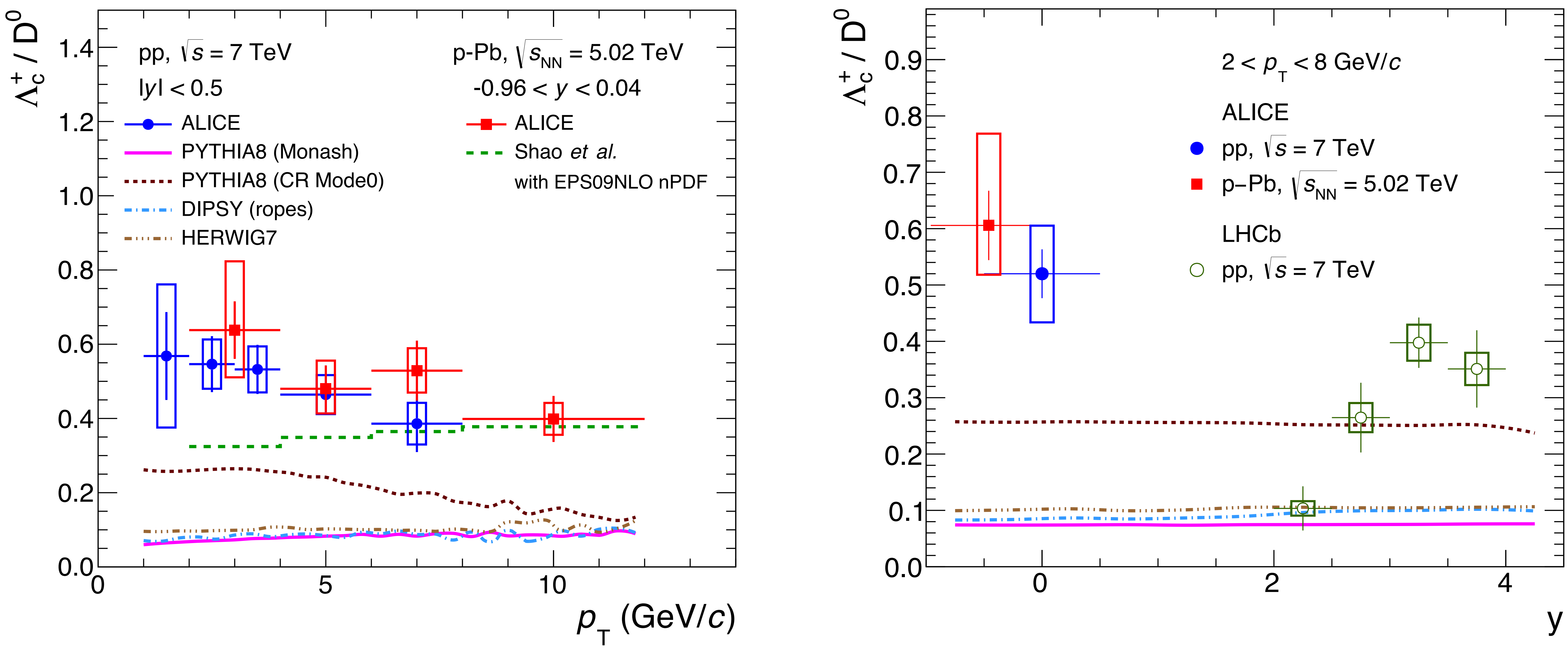
Run3: Long-shutdown 2 → Detector upgrade

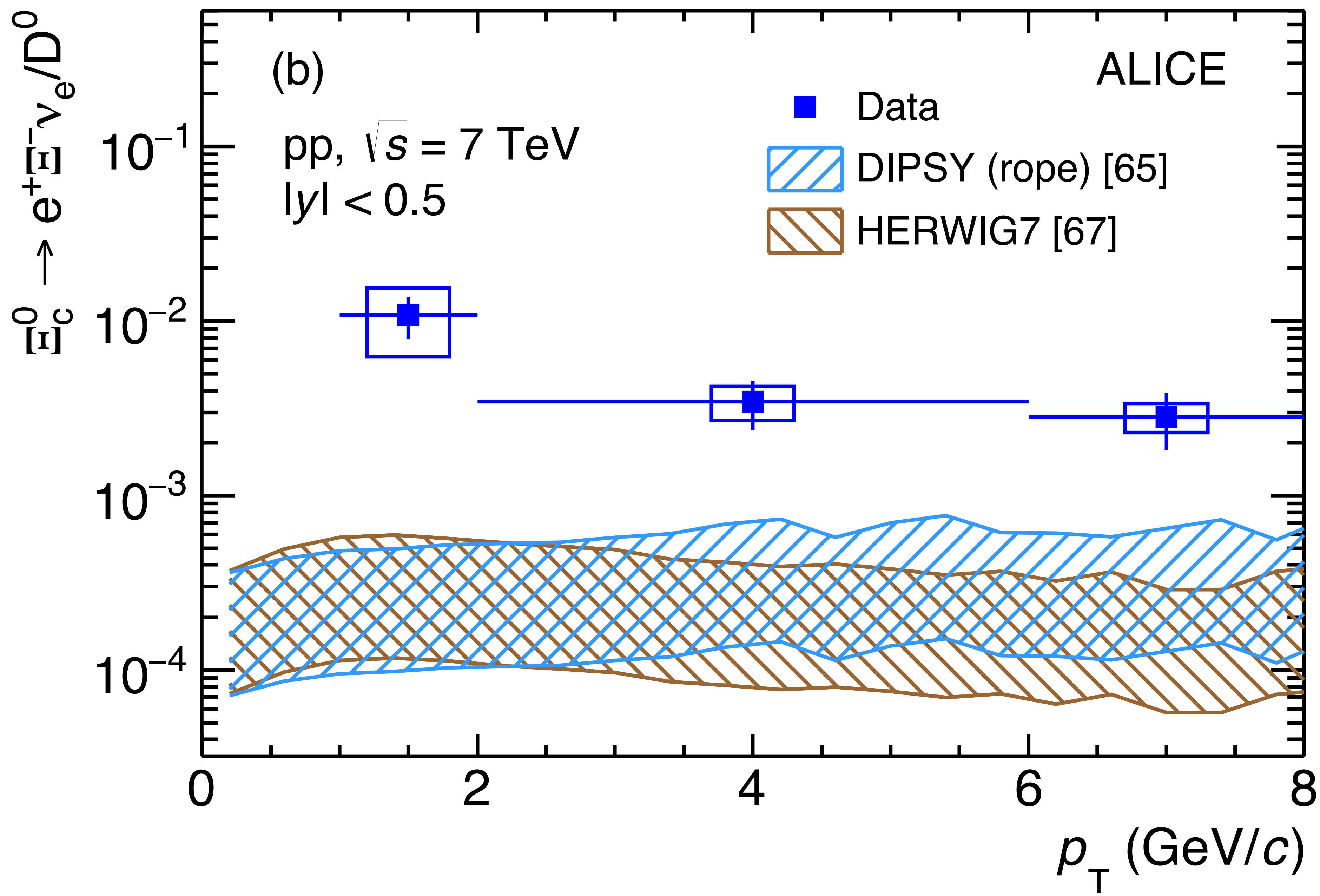
- New ITS, addition of MFT → **improve spatial resolution** at impact point at mid- and forward rapidity
- New readout for several subdetectors

→ **tremendous improvement** for reconstructing charm and beauty signals (including D_s, Λ_c, non- prompt J/ψ at mid and forward rapidity, B meson, Λ_b) **down to very low p_T**

Thank you for your attention!


35 nb-1 pPb, 27.4 pb-1 pp (5.02 TeV)
CMS
pPb data, |ηCM| < 1.5
pp data, |η| < 1.5
1/A dσpPb/dpT, dσpp/dpT (nb/GeV/c)
pPb Lumi. Uncert.
pp Lumi. Uncert.
RpA
c jet pT (GeV/c)


pp, $\sqrt{s}$ = 7 TeV
|y| < 0.5
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
-0.96 < y < 0.04
ALICE
PYTHIA8 (Monash)
PYTHIA8 (CR Mode0)
DIPSY (ropes)
HERWIG7
ALICE
Shao et al.
with EPS09NLO nPDF
Λ_c^+ / D^0
p_T (GeV/c)
2 < p_T < 8 GeV/c
ALICE
pp, $\sqrt{s}$ = 7 TeV
p–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
LHCb
pp, $\sqrt{s}$ = 7 TeV
y


(b)
ALICE
pp, $\sqrt{s}$ = 7 TeV
|y| < 0.5
Data
DIPSY (rope) [65]
HERWIG7 [67]
$\Xi_c^0 \rightarrow e^+\Xi^-\nu_e/D^0$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
p_T (GeV/c)