# Measurement of open heavy-flavour production in pp and p-Pb collisions with ALICE at the LHC

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The 21st Particles & Nuclei International Conference

1-5 September 2017, IHEP, Beijing, China

# ROADMAP

Introduction: Why heavy flavours?

ALICE detector and heavy-flavour reconstruction

Latest results in pp and p-Pb collisions

- ➡ $p_T$-differential cross section
- ➡ Open heavy-flavour production as a function of charged-particle multiplicity
- ➡ Nuclear modification factor
- ➡ Centrality dependent nuclear modification factor
- ➡ Angular correlation of D mesons with charged particles

Summary

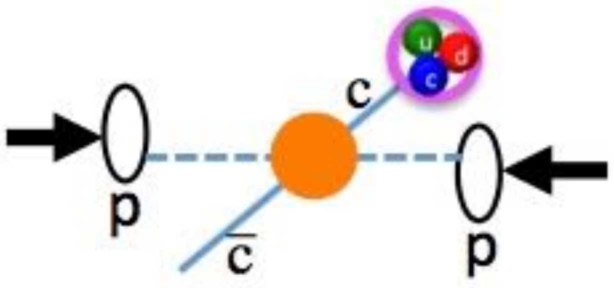
# Why heavy flavours?

➡ Heavy quarks (c and b quarks) are produced at the early stages of the collision (large $Q^2$) **PLB 519 (2001) 199**

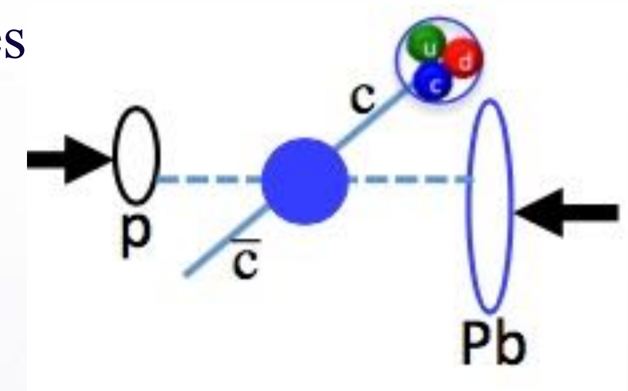
$\tau_p \sim 1/2m_c$ (~0.07 fm/$c$) < QGP formation time (~0.1-1fm/$c$) << QGP life time (10 fm/$c$)

➡ Experience the full collision history ➡ Sensitive probes of the hot and dense QCD matter (QGP)

Heavy flavours in pp collisions




- ➡ test pQCD predictions at the highest colliding energies
- ➡ insight into the production mechanisms
- ➡ shed light on c-quark hadronisation: different charmed meson/baryon species
- ➡ reference for p-A and A-A collisions



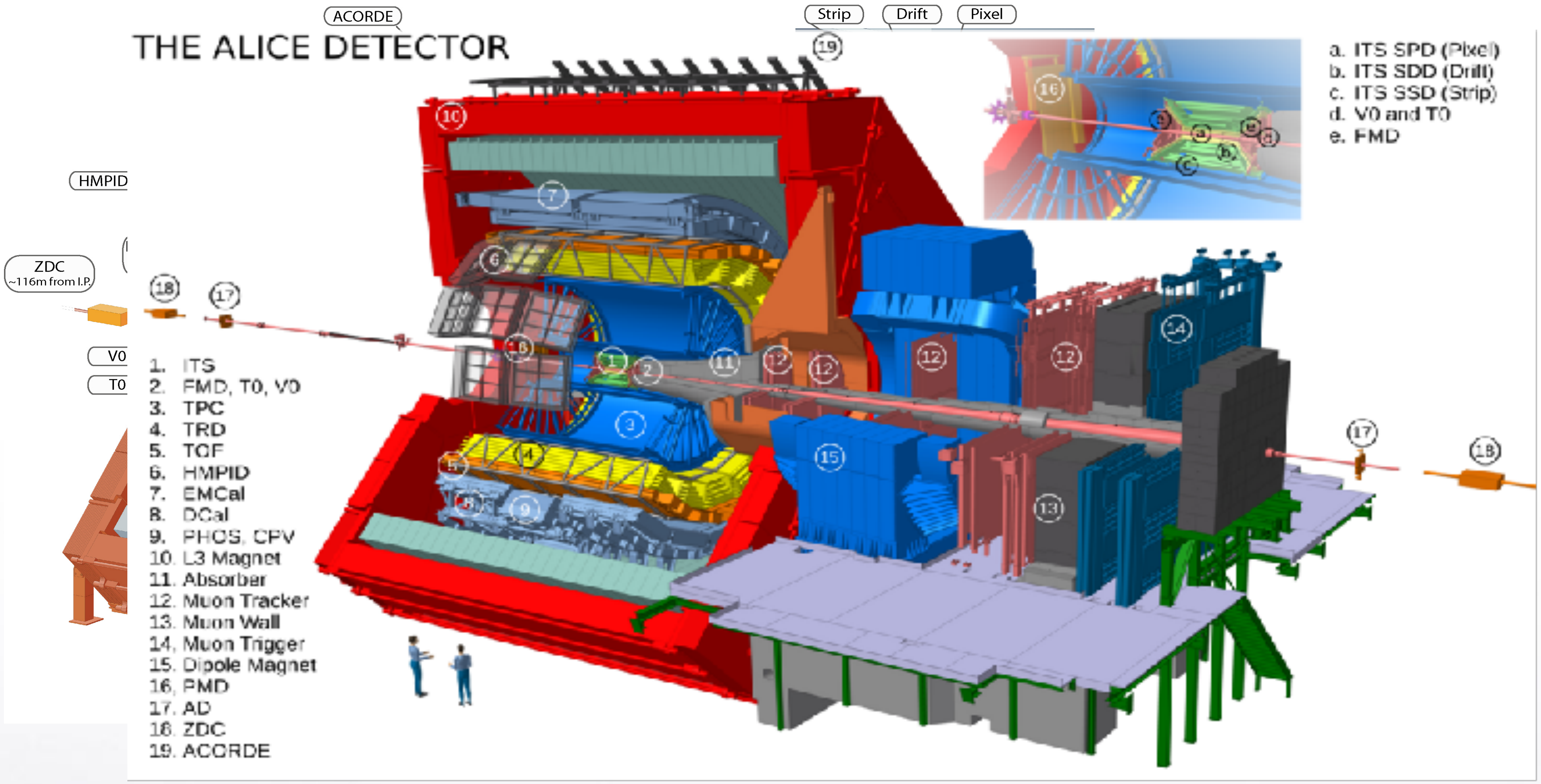

Heavy flavours in p-A collisions

- ➡ control experiment for the Pb-Pb measurements
- ➡ address cold nuclear matter effects (Cronin enhancement, nuclear PDFs, energy loss….)

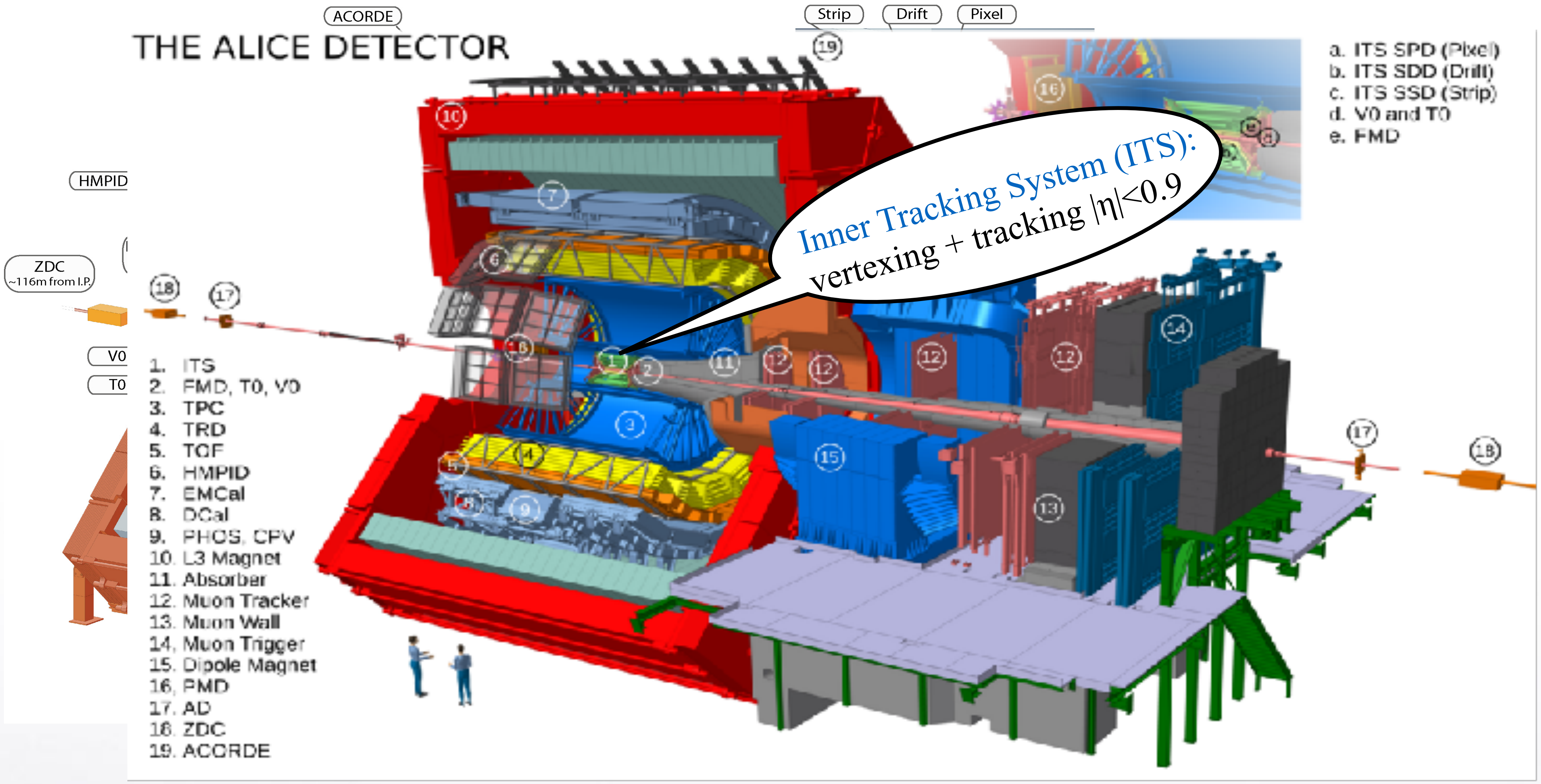
Heavy flavours in AA collisions

- ➡ parton in-medium energy loss
- ➡ possible thermalisation of heavy quarks in the medium

Talk by
Syaefudin Jaelani


ACORDE
THE ALICE DETECTOR
Strip
Drift
Pixel
HMPID
ZDC
~116m from I.P.
V0
T0
a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD
1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE

# The ALICE detector



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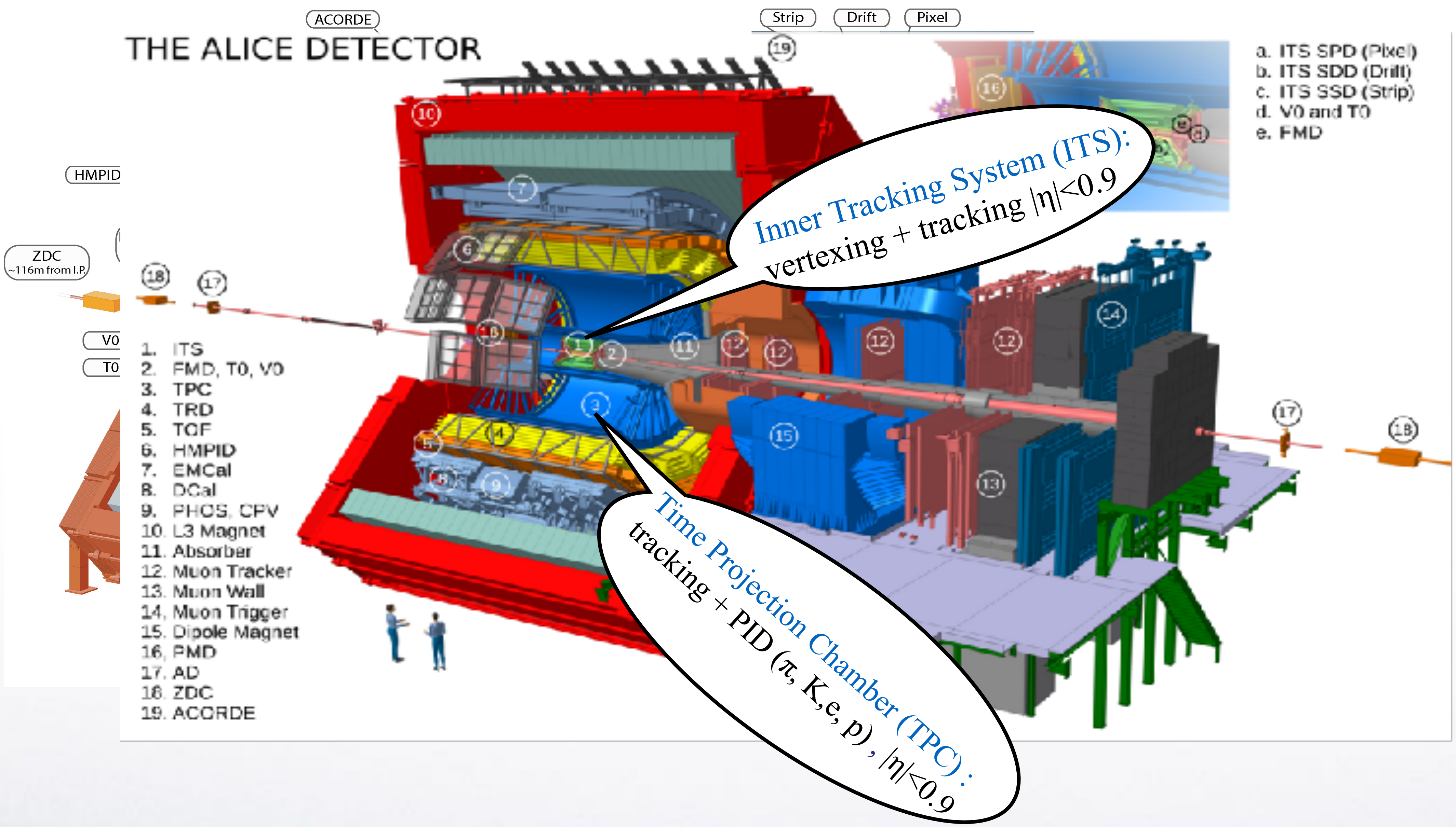

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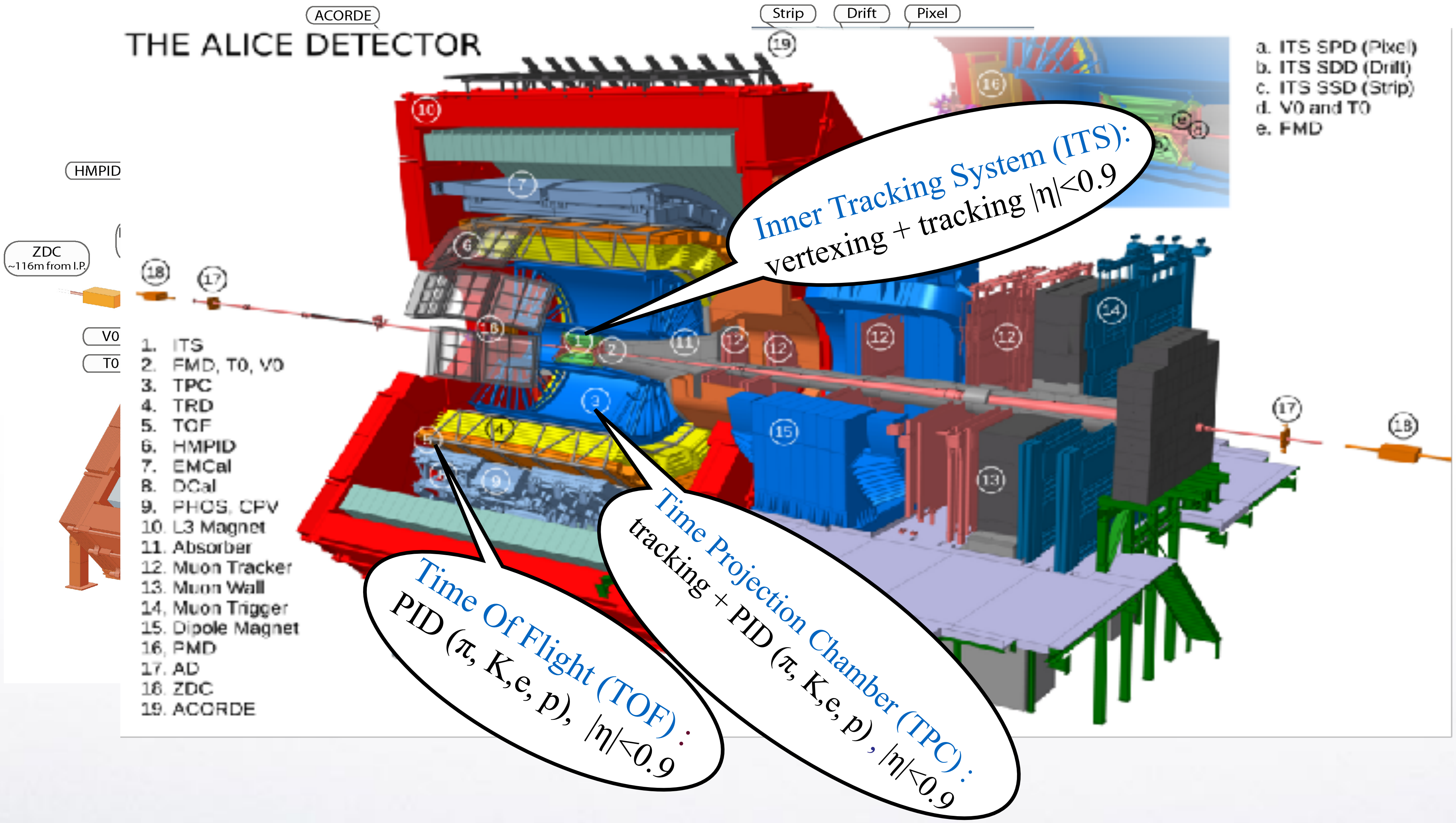

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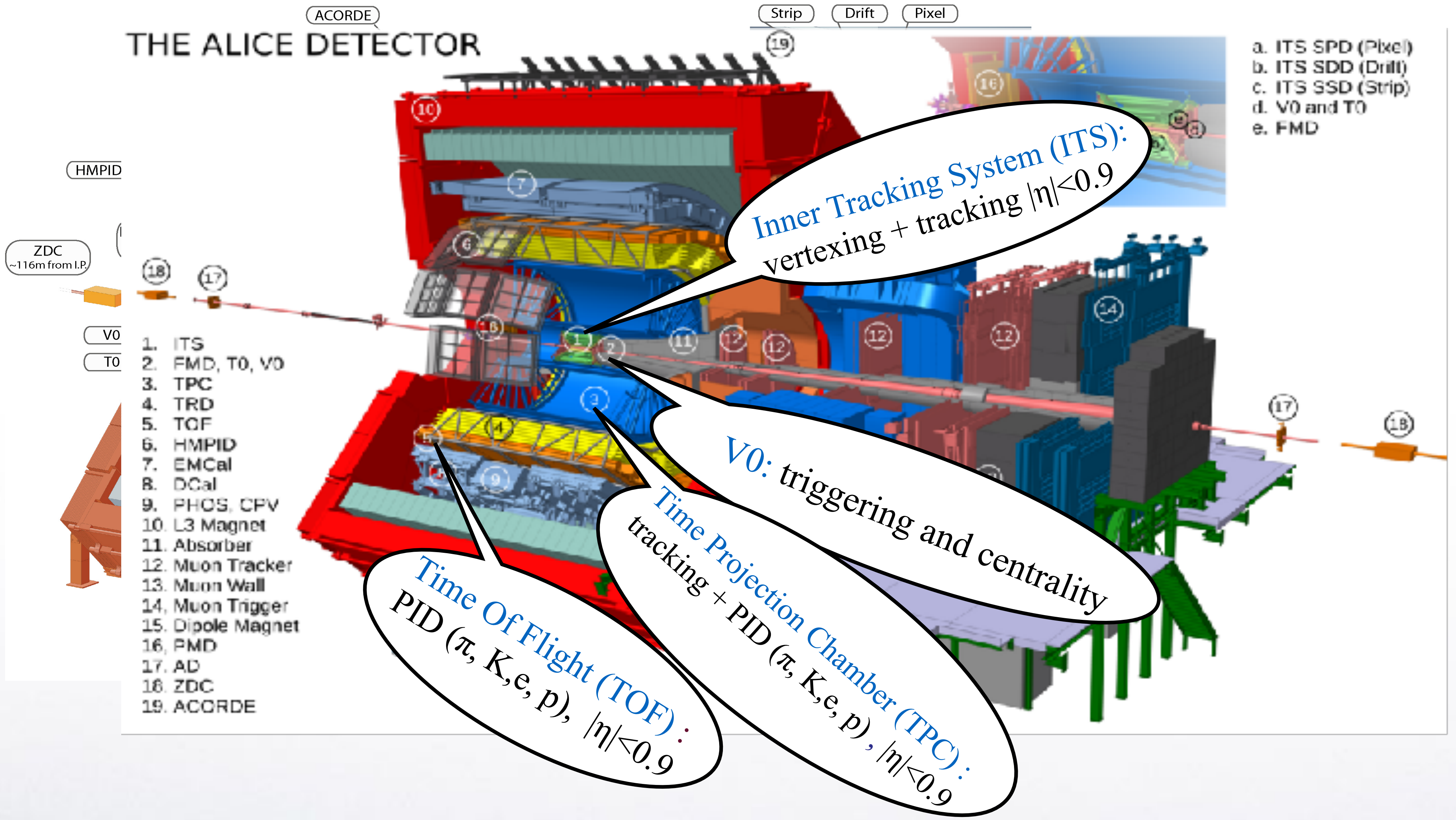

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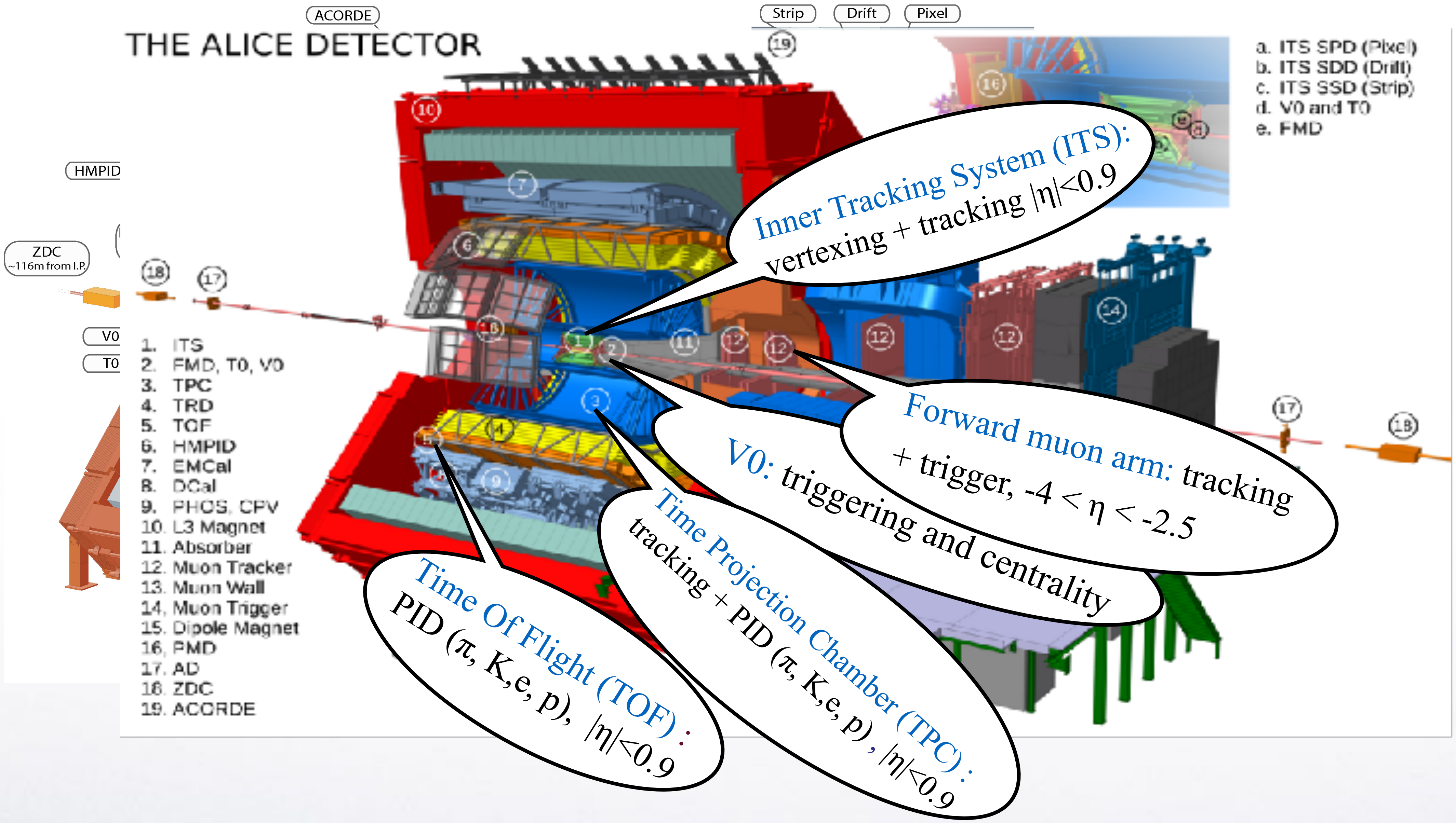
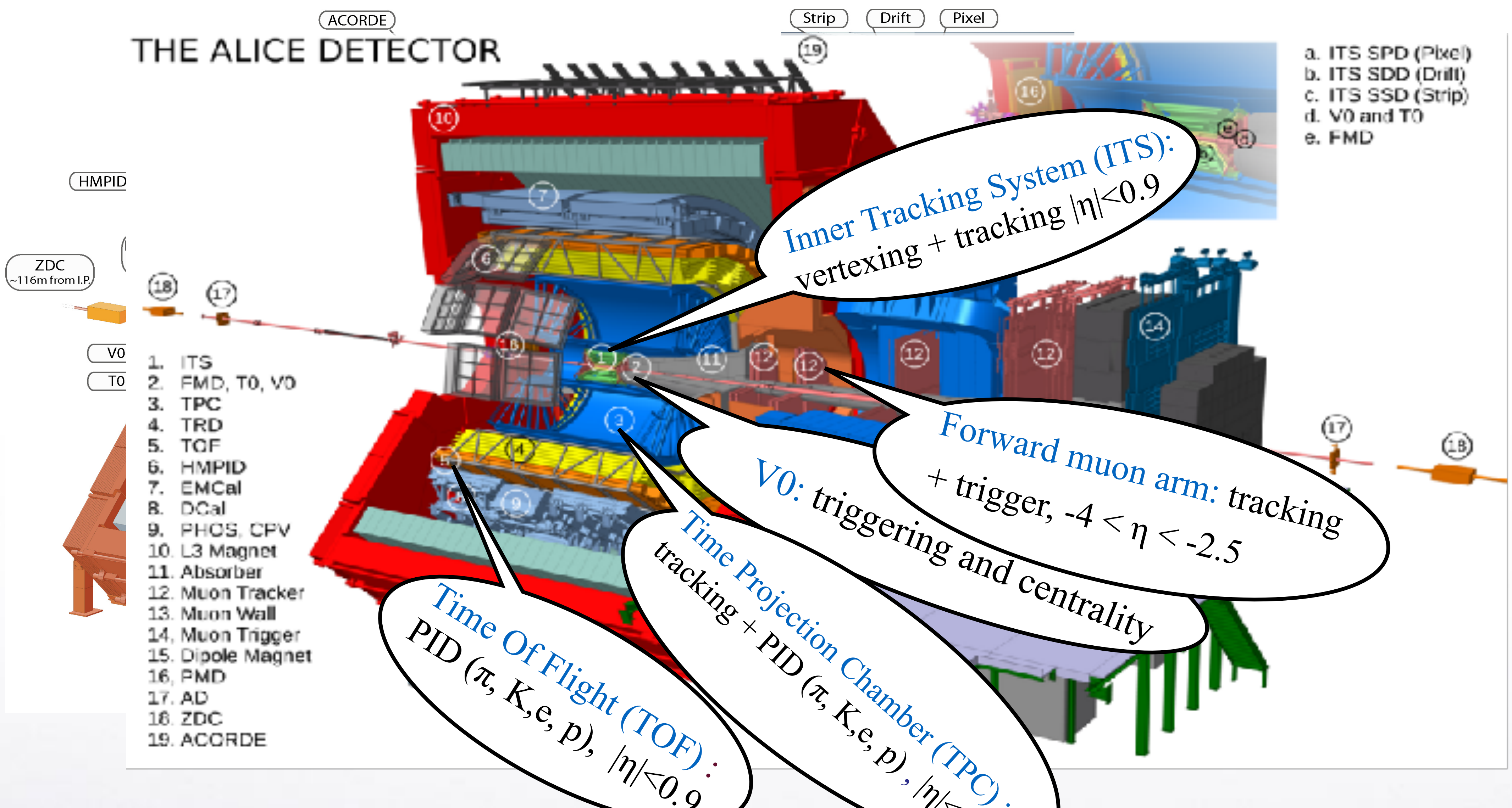


# The ALICE detector




**Min. bias data samples used for the analysis**

**pp collisions**

Run-1: $\sqrt{s}$ = 7 TeV: ~370 M min. bias events, $L_{int} \approx 6$ $nb^{-1}$
$\sqrt{s}$ = 8 TeV: ~100 M min. bias events, $L_{int} \approx 1.8$ $nb^{-1}$

Run-2: $\sqrt{s}$ = 5 TeV: ~120 M min. bias events, $L_{int} \approx 2.3$ $nb^{-1}$
$\sqrt{s}$ = 13 TeV: ~190 M min. bias events, $L_{int} \approx 3.3$ $nb^{-1}$

**p-Pb collisions**

Run-1: $\sqrt{s_{NN}}$ = 5.023 TeV: ~100 M min. bias events, $L_{int} \approx 48.6$ $\mu b^{-1}$

Run-2: $\sqrt{s_{NN}}$ = 5.023 TeV: ~600 M min. bias events, $L_{int} \approx 292$ $\mu b^{-1}$

$D^0 \to K^-\pi^+$ BR ~ 3.93 %; $c\tau \approx 123$ μm, $D^+ \to K^-\pi^+\pi^+$ BR ~ 9.46 %; $c\tau \approx 312$ μm, $D^{*+} \to D^0 \pi^+$ BR ~ 67.7 % $\to K^-\pi^+\pi^+$

$D_s^+ \to \varphi\pi^+ \to K^+K^-\pi^+$ BR ~ 2.28 %; $c\tau \approx 150$ μm, $\Lambda_c^+ \to pK^-\pi^+$ BR ~ 6.35 % ; $c\tau \approx 60$ μm, $\Lambda_c^+ \to pK^0_s$ BR ~1.58 % ; $c\tau \approx 60$ μm

**D-meson reconstruction:**

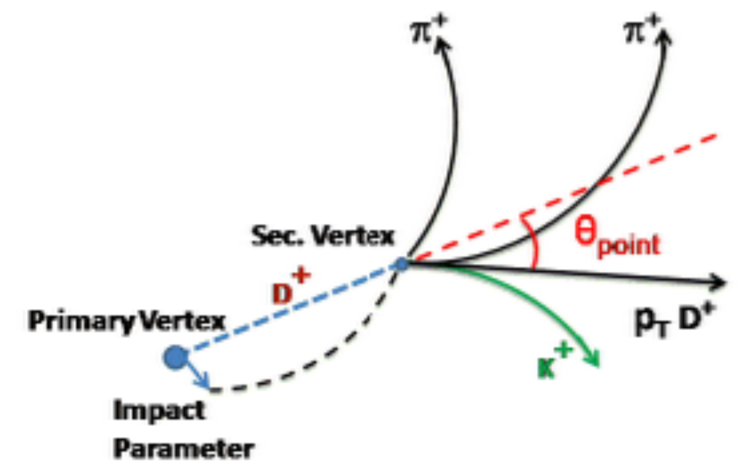
Invariant mass analysis of pairs/triplets

background reduction via

particle identification, (K/π) separation

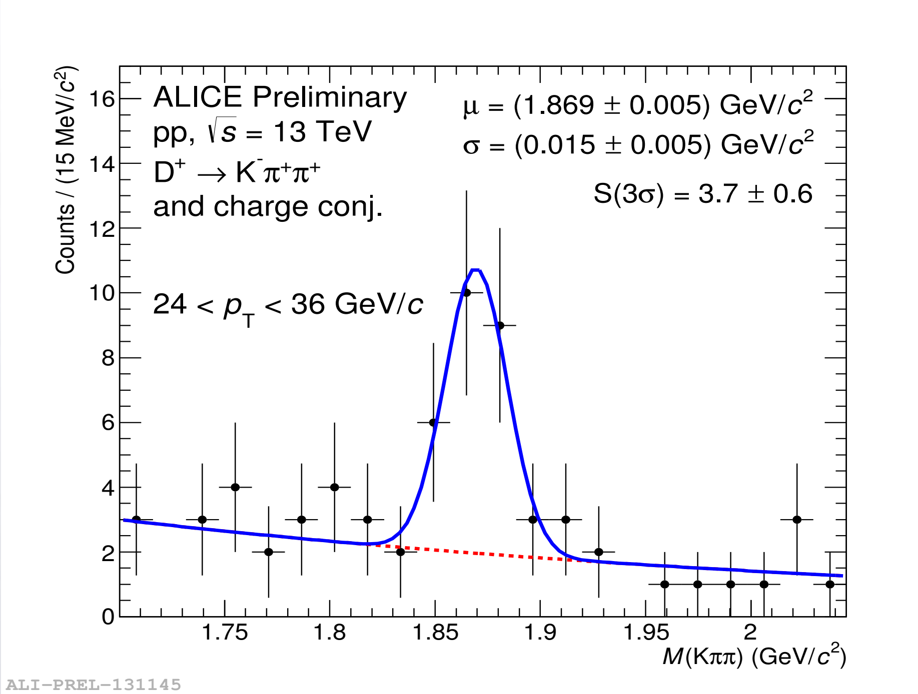
topological selection and/or background subtraction techniques

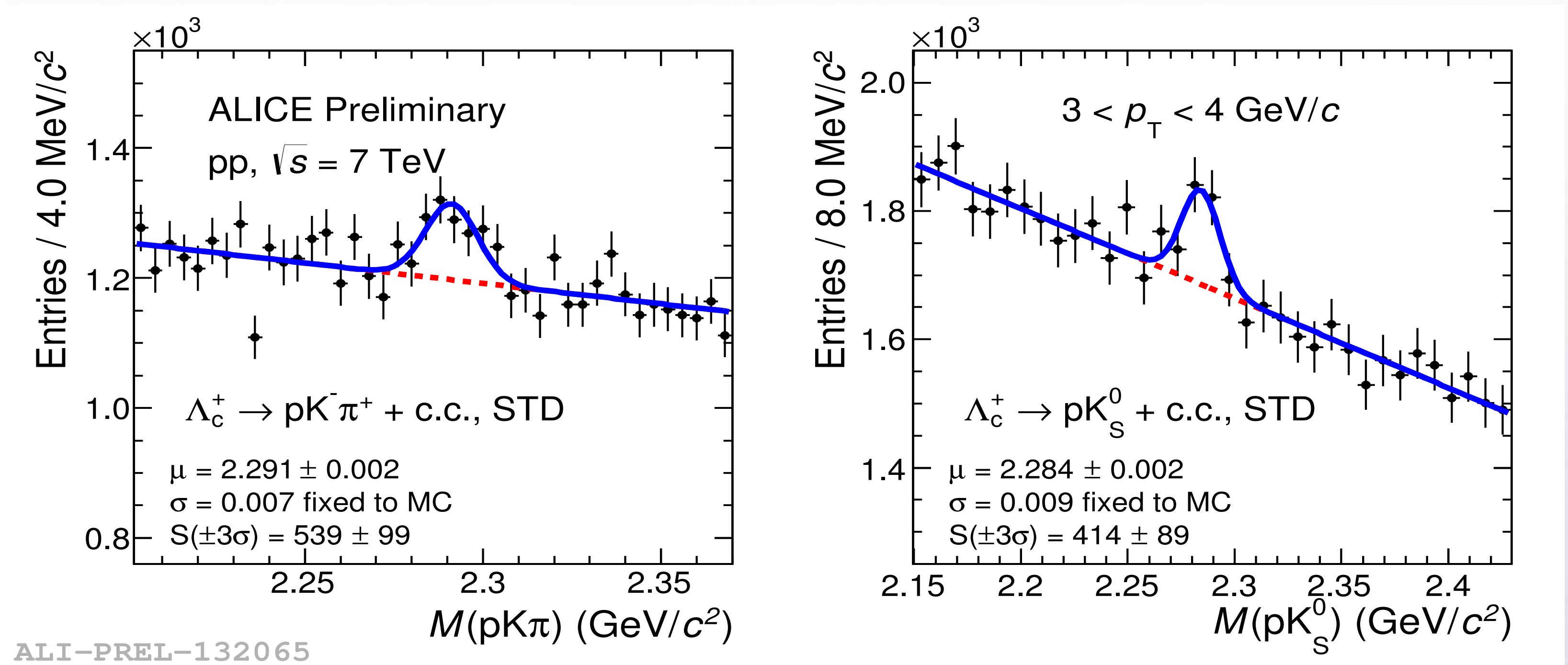
correction for beauty feed down based on pQCD (FONLL) calculation




**$\Lambda_c$ reconstruction :**

similar technique as for D mesons (Standard) + Multivariate approach (MVA)(p-Pb)



**B, D$\rightarrow e^{\pm}$ + X   B, D$\rightarrow \mu^{\pm}$ + X   $\Lambda_c^+ \rightarrow e^+\Lambda\nu_e$   $\Xi_c^0 \rightarrow e^+ \Xi^- \nu e$**

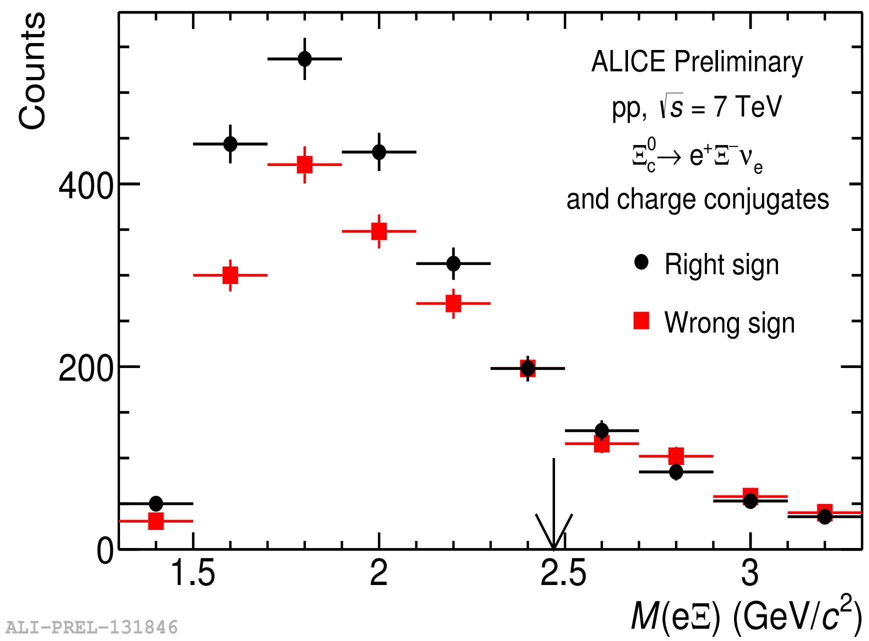
## Electron and muon reconstruction:

**Electrons** identified with TPC, TOF, EMCAL and/or TRD

**Non-heavy-flavour electrons** (from $\pi^0$, η Dalitz decays, photon conversions) removed with invariant mass method ($e^+e^-$) and/or cocktail

**Beauty-hadron decay electrons** are measured using the impact parameter distribution

**Muons**: background (π, K decays) subtracted with data-tuned MC cocktail (p-Pb, Pb-Pb)




## $\Lambda_c^+$ and $\Xi_c^0$ reconstruction

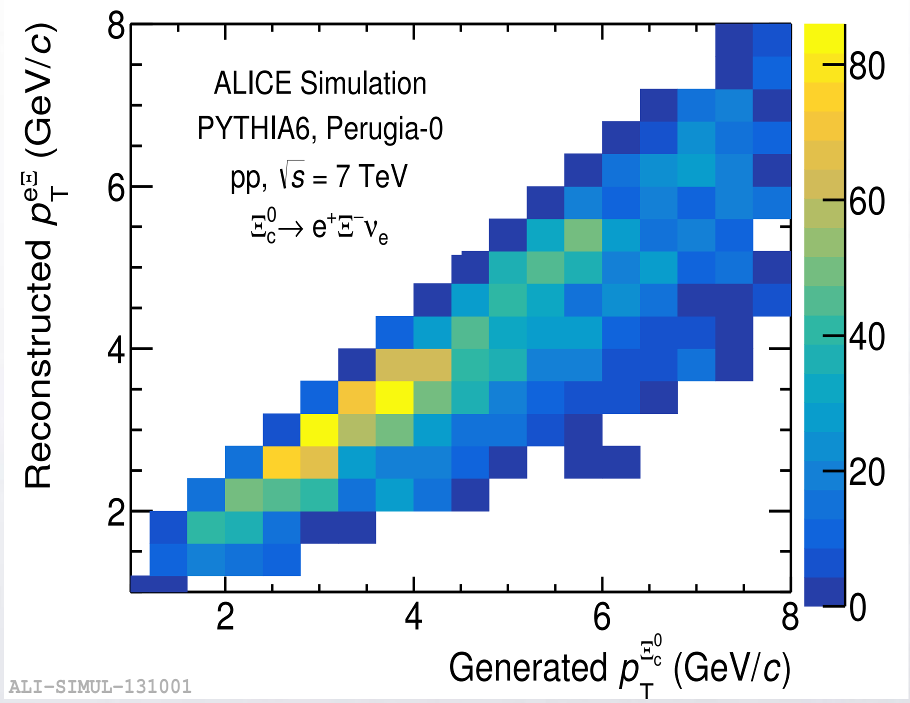
➡ Wrong-sign $e^-\Lambda$ ($e^-\Xi^-$) pairs subtracted from right-sign spectra $e^+\Lambda$ ($e^+\Xi^-$)

➡ correct for $\Lambda_b^0$ ($\Xi_b^0$) contribution in wrong-sign spectra and $\Xi_c^{0,+}$ contribution in right-sign spectra for $\Lambda_c^+$ measurement

➡ Unfold reconstructed $e^-\Lambda$ ($e^-\Xi^-$) $p_T$ spectra to obtain $\Lambda_c^+$ ($\Xi_c^0$)

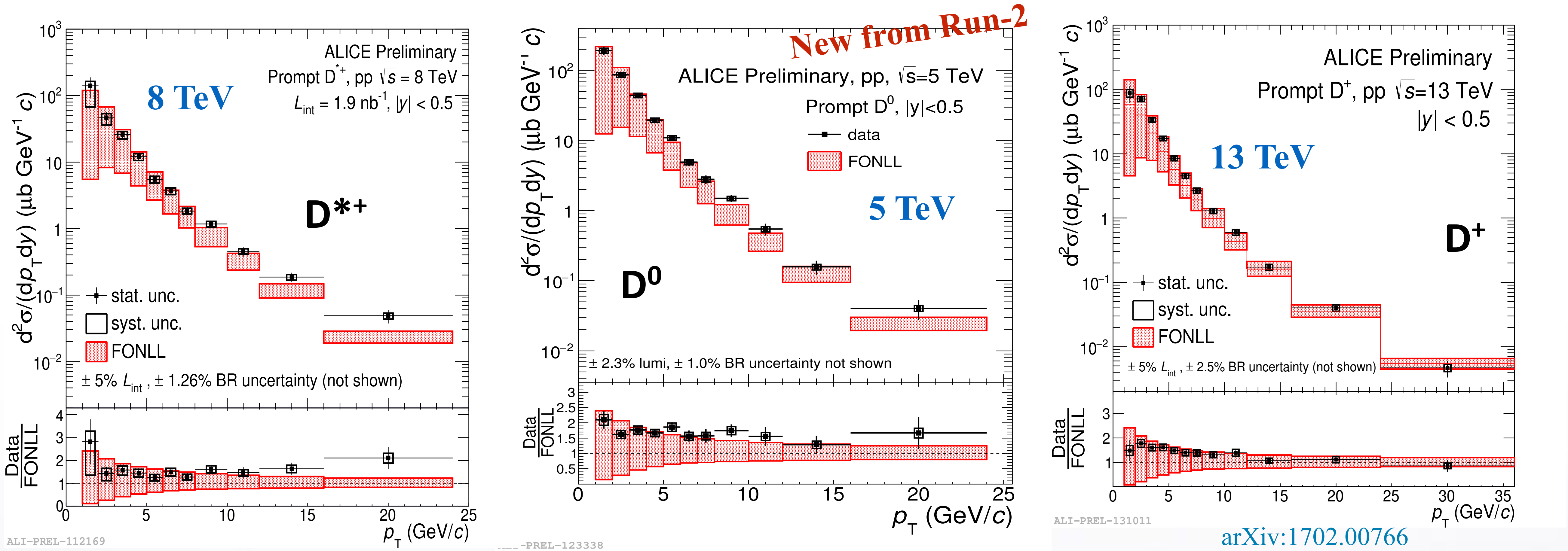
➡ No feed down subtraction from $\Xi_b$

➡ lack of knowledge of the absolute BR of $\Xi_b \rightarrow \Xi_c^0 + X$



# Proton-proton results

$\sqrt{s}$= 5, 7, 8 and 13 TeV

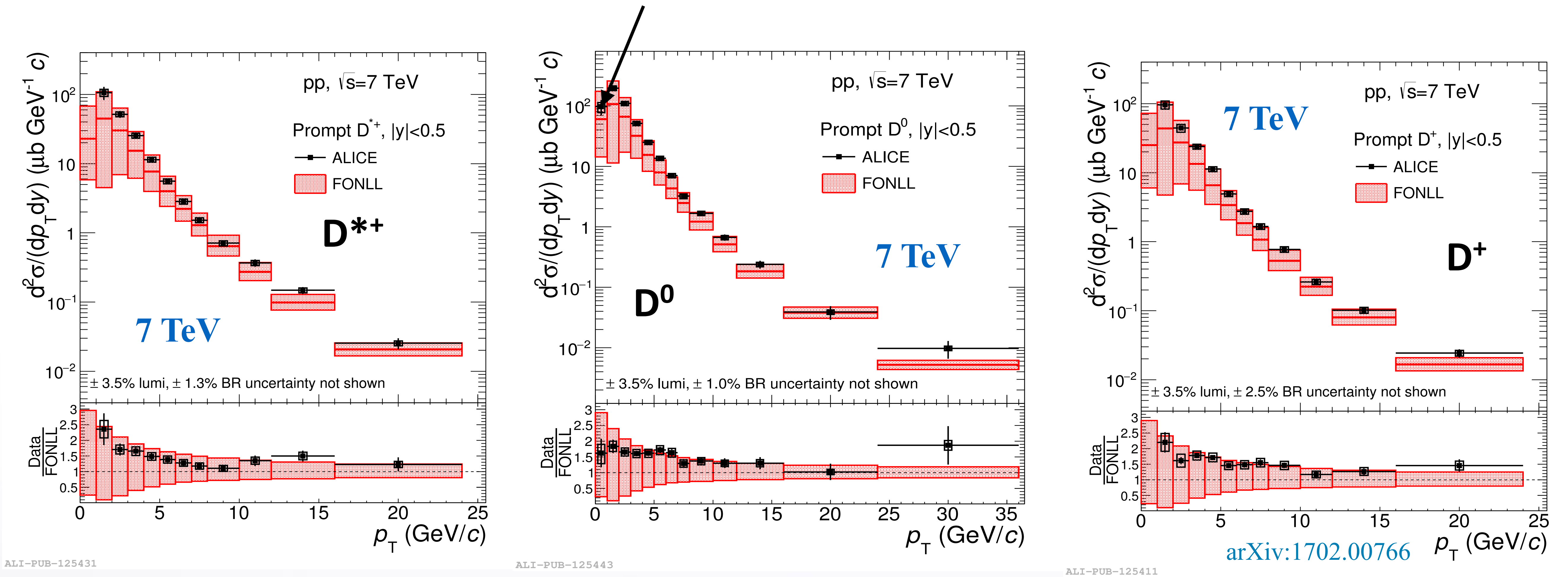



arXiv:1702.00766

$p_T$-differential production cross sections for $D^0$, $D^+$ and $D^{*+}$ in pp collisions at 5, 7, 8 and 13 TeV

Described by pQCD-based calculations within uncertainties

FONLL (JHEP, 1210 (2012) 137), GM-VFNS (Eur. Phys. J. C72 (2012) 2082) $k_T$ factorization (Phys.Rev., D87 (2013) 094022).




$p_T$-differential production cross sections for $D^0$, $D^+$ and $D^{*+}$ in pp collisions at 5, 7, 8 and 13 TeV

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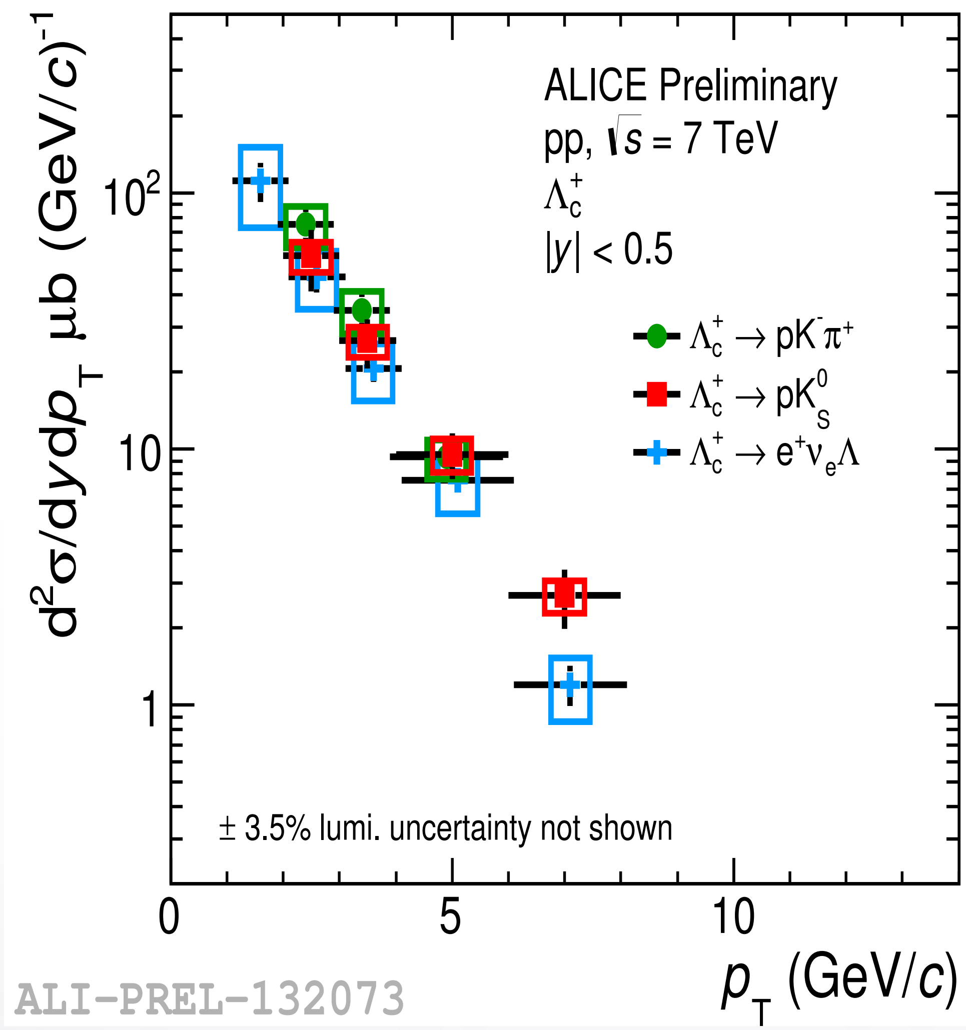
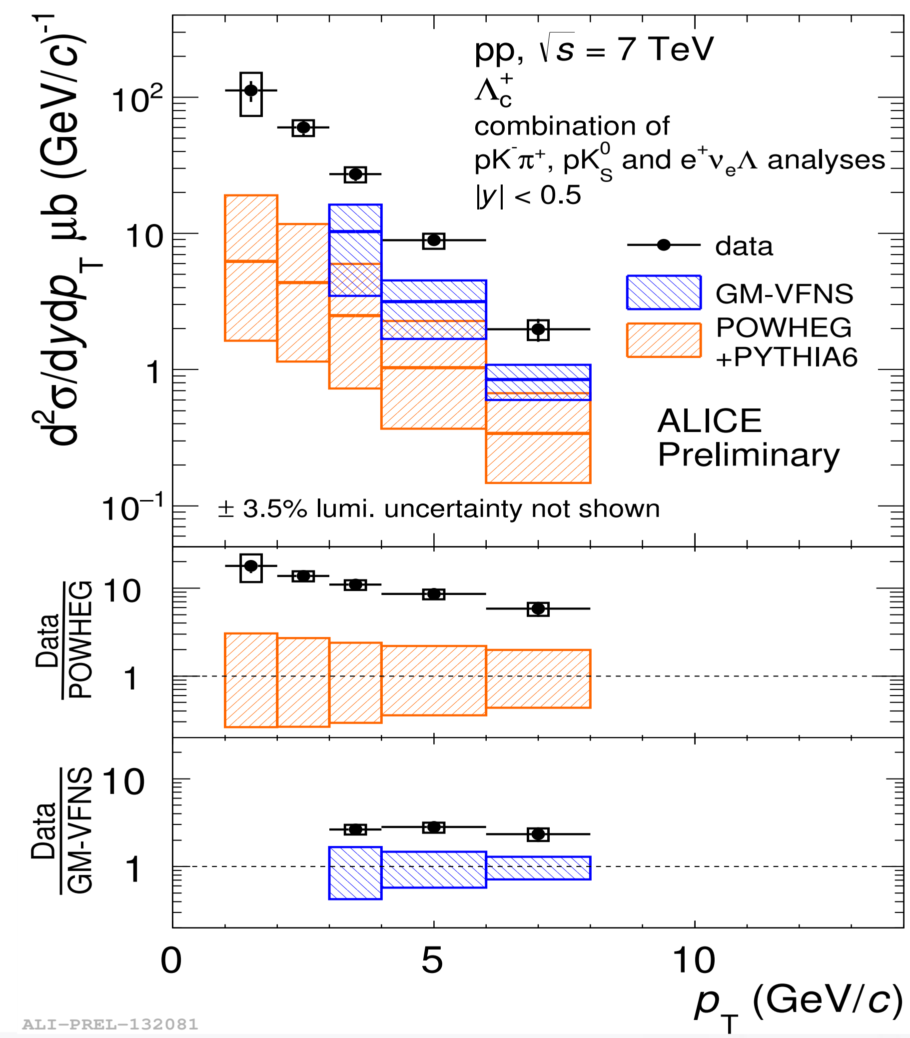
$D^0$ meson cross section down to $p_T$=0 [Phys. Rev. C 94 (2016) 054908]

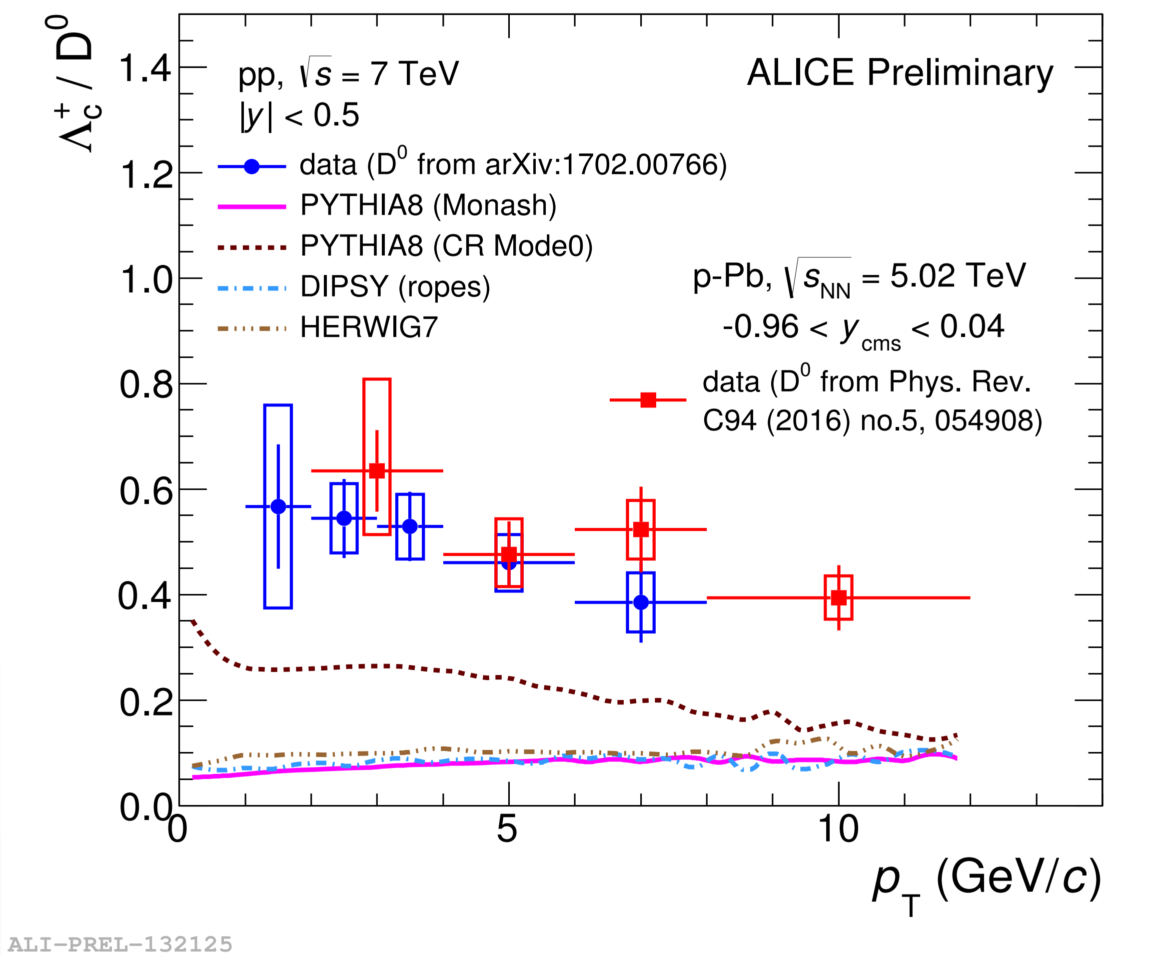
- ➡ No secondary vertex reconstruction, no topological selection
- ➡ Background subtraction by event mixing, like-sign distribution, track rotation or fit of sidebands

# $\Lambda_c^+$ $p_T$-differential cross section



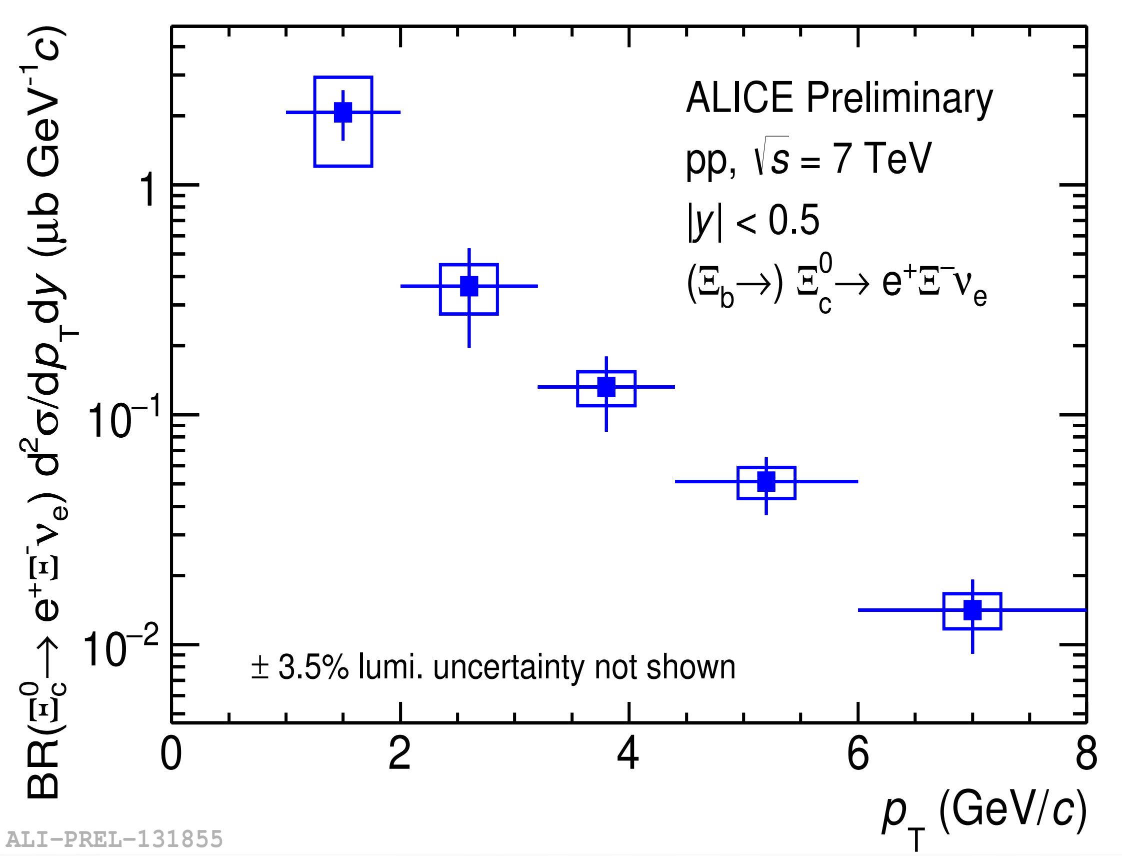



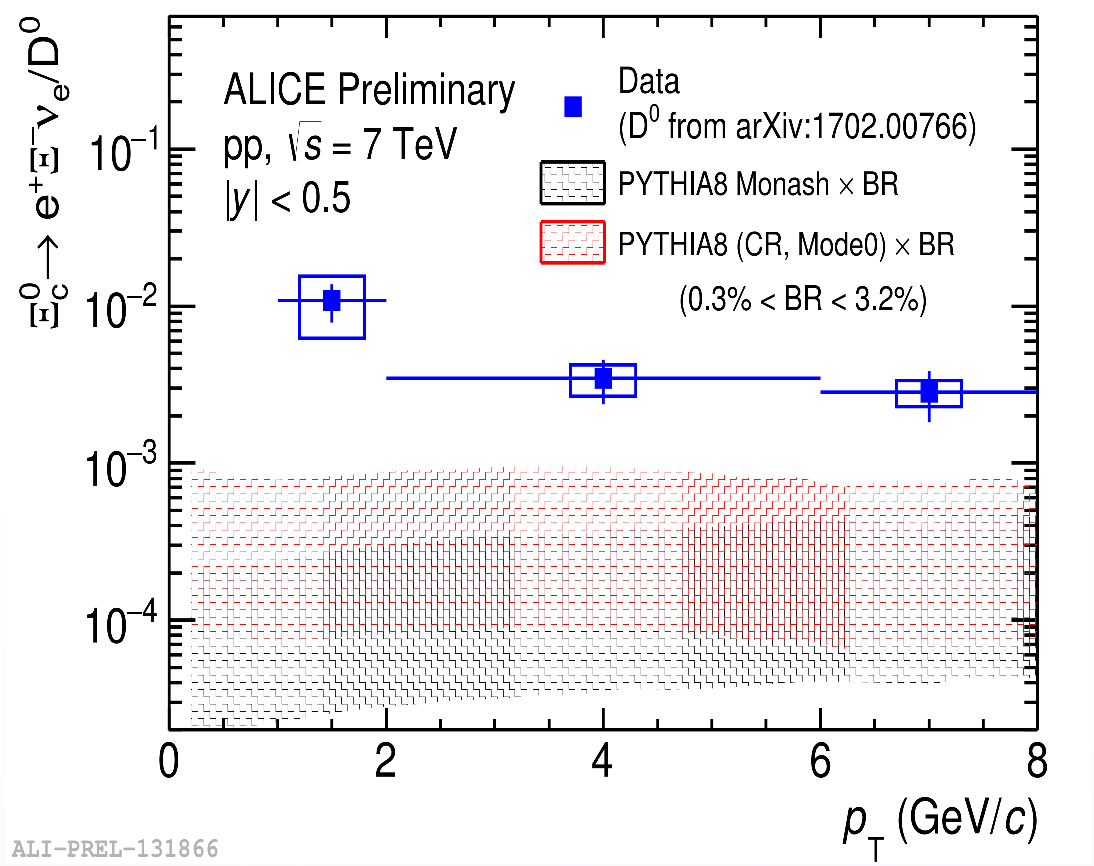

- ➡ The $p_T$ differential cross section of three measured decay channels (hadronic and semi leptonic) are compatible within statistical and systematical uncertainties
- ➡ The average $\Lambda_c^+$ $p_T$-differential cross section underestimated by the theory
  - GM-VFNS underestimates by a factor 2.5
  - POWHEG+PYTHIA6 significantly underpredicts (up to a factor ~20) the data



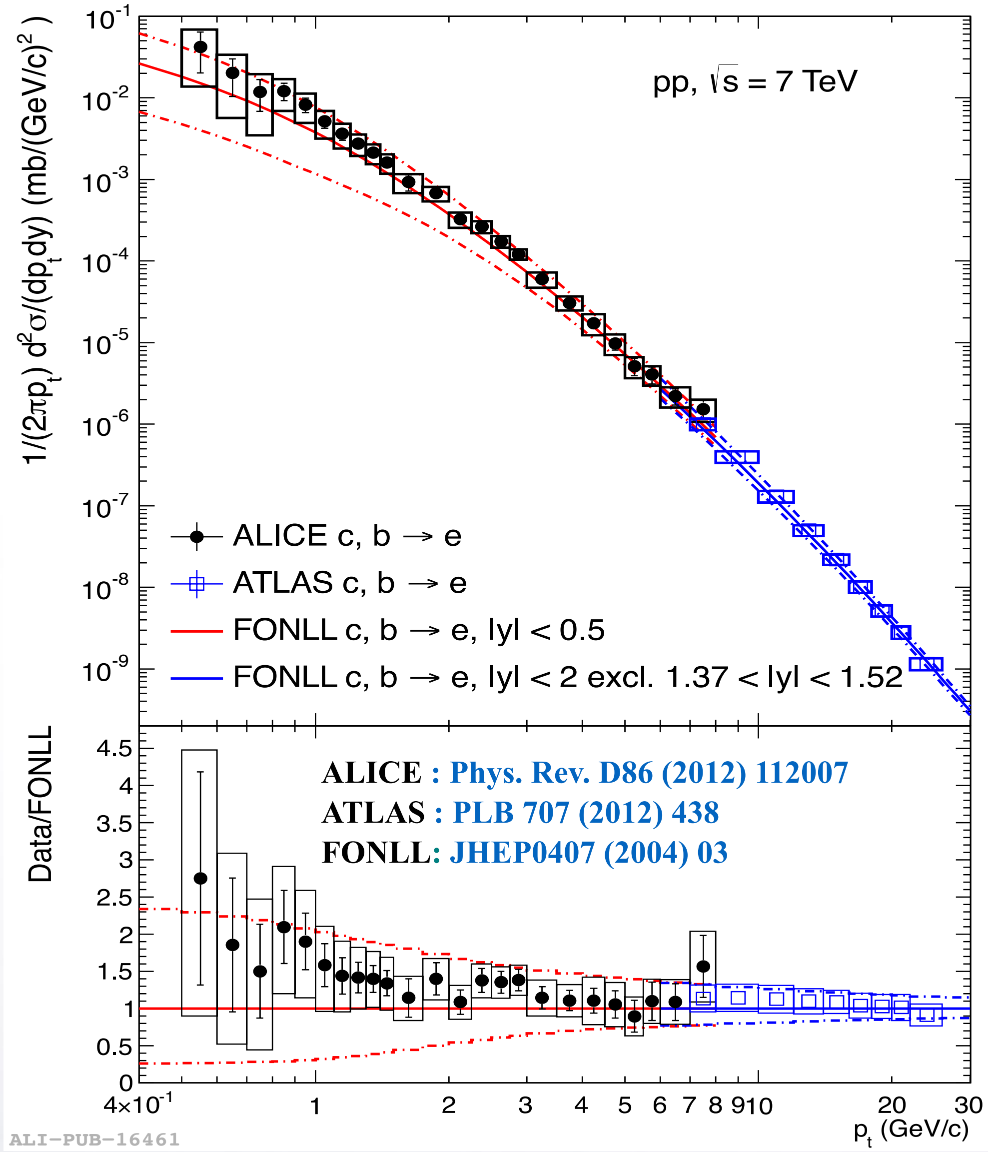

- ➡$\Lambda_c^+/D^0$ in pp and p-Pb collisions compatible within uncertainties
- ➡All theoretical predictions underestimate our measurements
  - ➡PYTHIA8 with enhanced colour-reconnection tune Mode0 (hadronisation of multi-parton system) is closer to the measurements

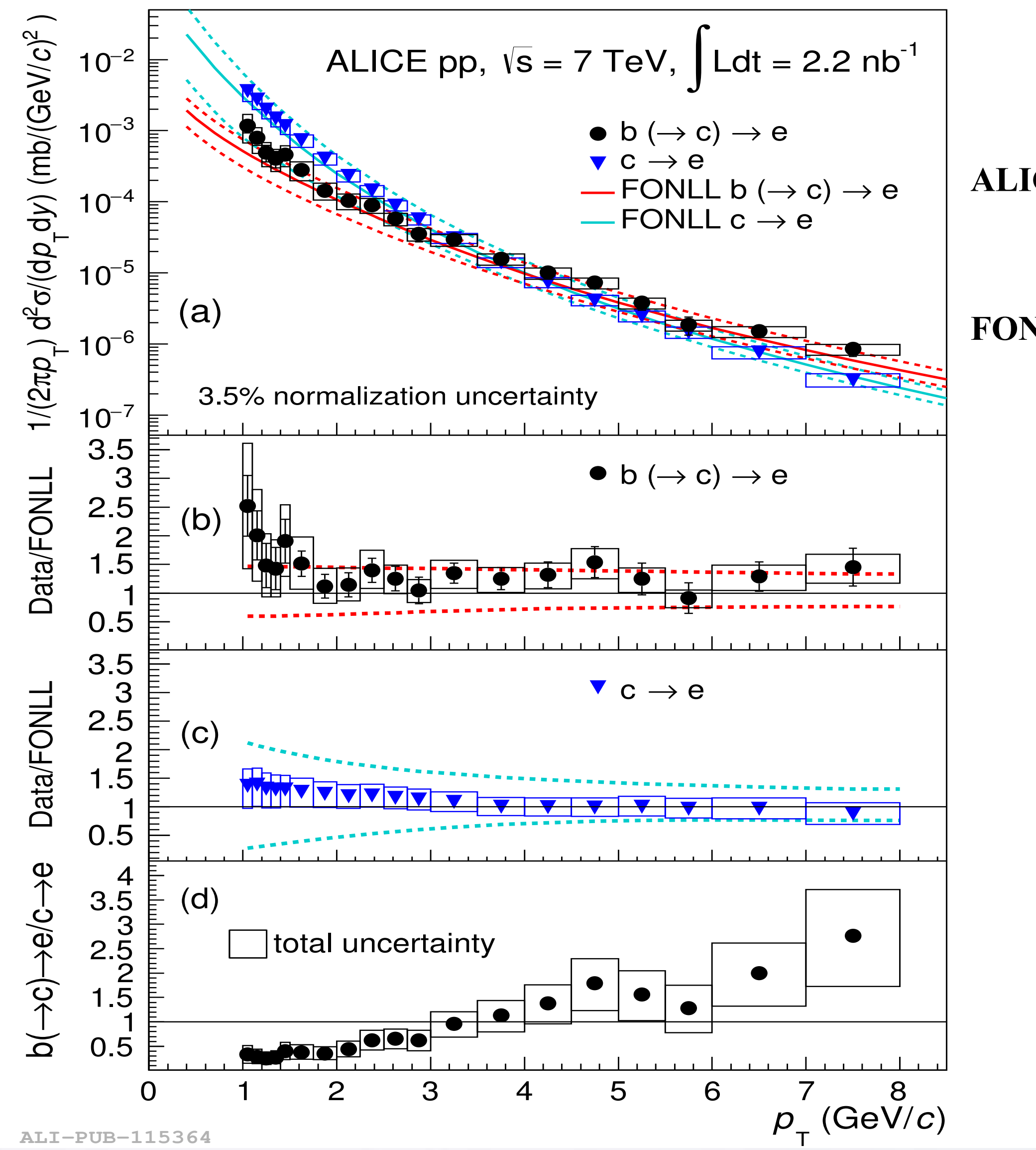
*PYTHIA8: Comput. Phys. Commun.* 178 (2008) 852–867, CR, ropes: Phys. Rev. D92 no. 9, (2015) 094010, DIPSY:*JHEP* 08 (2011) 103 , HERWIG: Eur. Phys. J. C58 (2008) 639–707




- First $\Xi_c^0$ production measurement at LHC
- Branching ratio not measured- range (0.3%-3.2%) estimated from theory
- Baryon to meson ratio $\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$ / $D^0$ higher than predictions
  - PYTHIA8 Monash (Eur. Phys. J. C74 (2014) 3024)
  - PYTHIA8 + enhanced colour reconnection Mode0 (JHEP 08 (2015) 003)




ALICE: PLB 738 (2014) 97;

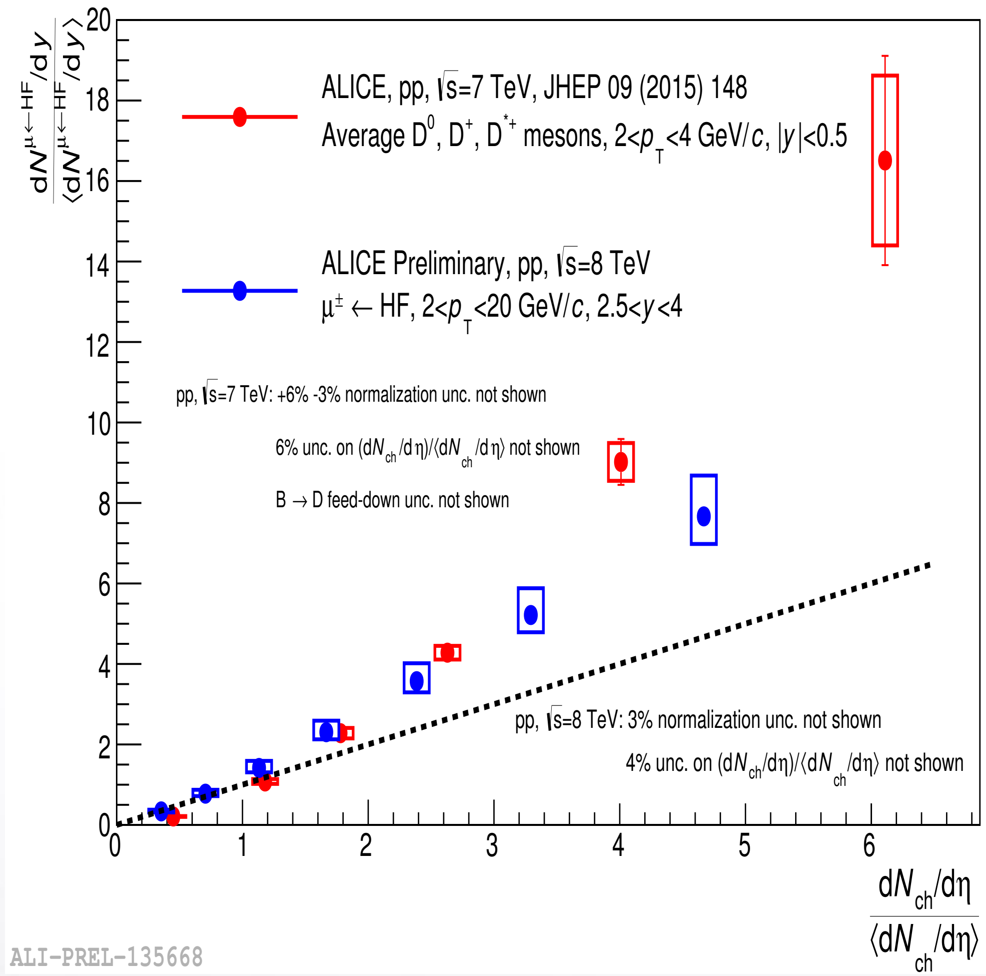
PLB 763 (2016) 507

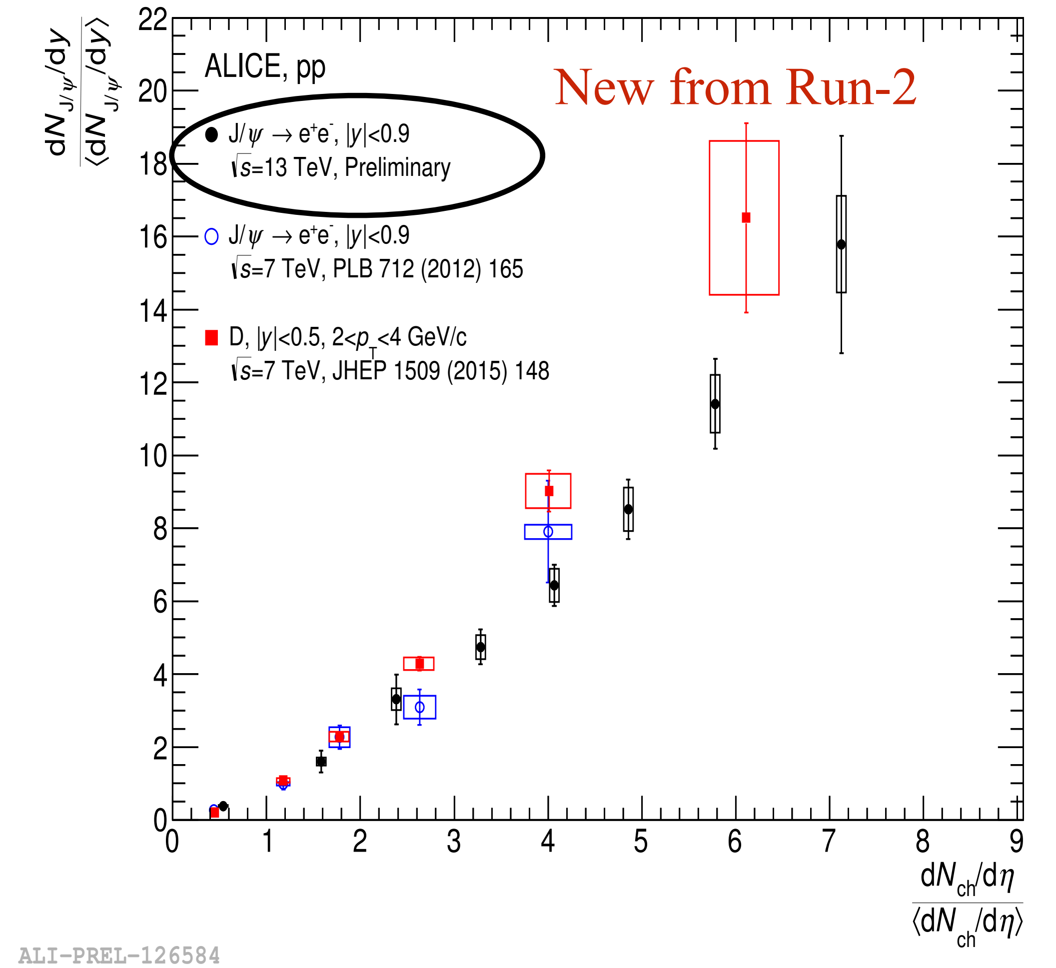
FONLL: JHEP 1210 (2012) 137

- ➡ FONLL pQCD provides good description over a wide $p_T$ range, both for charm and beauty
- ➡ Low $p_T$ semi-leptonic cross section in good agreement with ATLAS at high $p_T$ *(*complementary measurement*)*

# Open heavy flavour yields vs multiplicity

Study the effect of multi-parton interactions (MPI) on the hard heavy-flavour scale




- ➡ Increasing trend with multiplicity for muons from HF in pp at 8 TeV
- ➡ Same trend for D-mesons, non-prompt (B⟶)J/Ψ as well as prompt J/Ψ yields JHEP 1509 (2015) 148
- ➡ Similar increase in pp √s = 7, 8 and 13 TeV, multiplicity range extended by a factor ~2 for J/Ψ at 13 TeV.
  - ➡ suggests that MPI are influencing heavy-quark production in high-multiplicity events

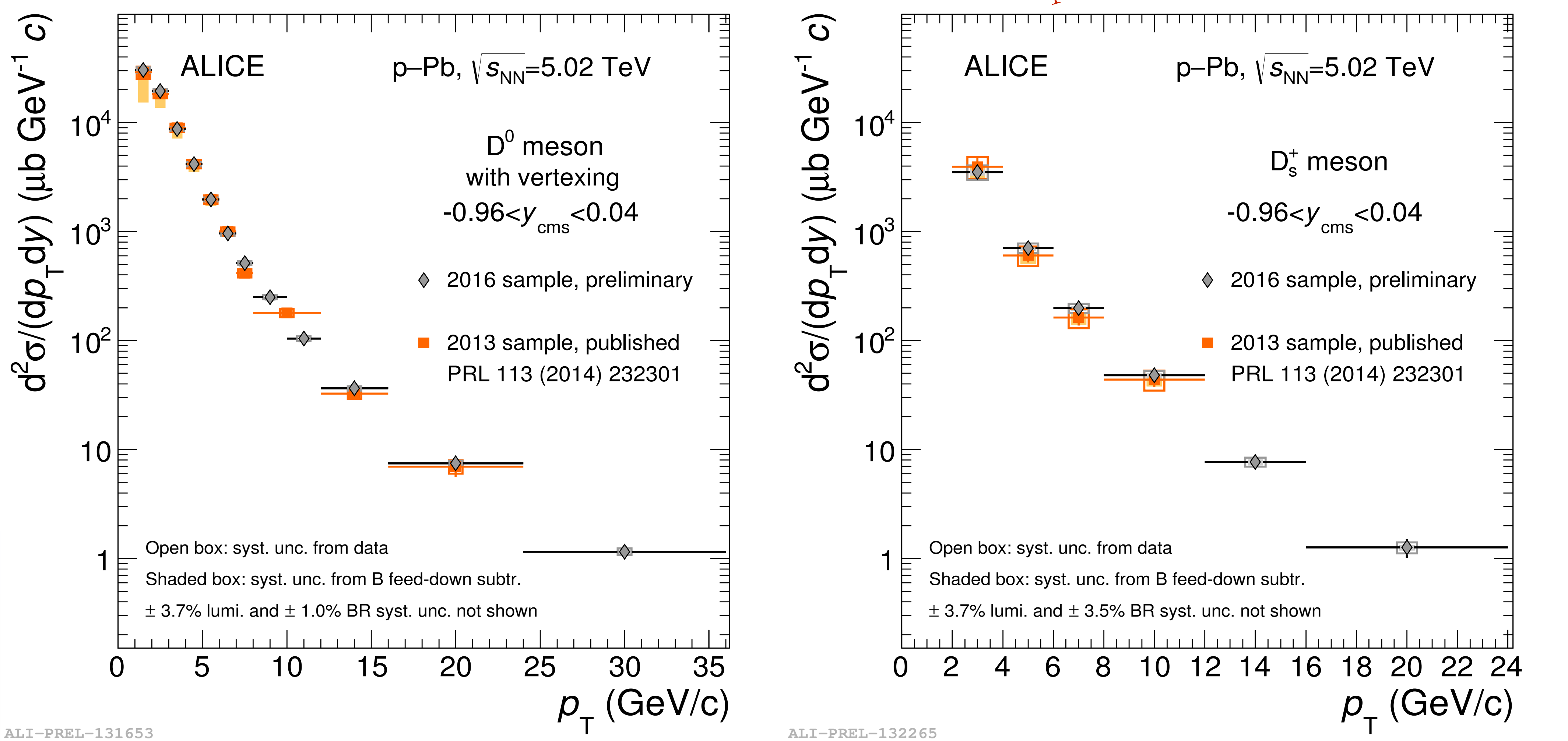
# proton-Pb results

$\sqrt{s_{NN}}$= 5.02 TeV [Run-1 and Run-2]

# D-meson $p_T$-differential cross section

ALICE-PUBLIC-2017-008

New from Run-2



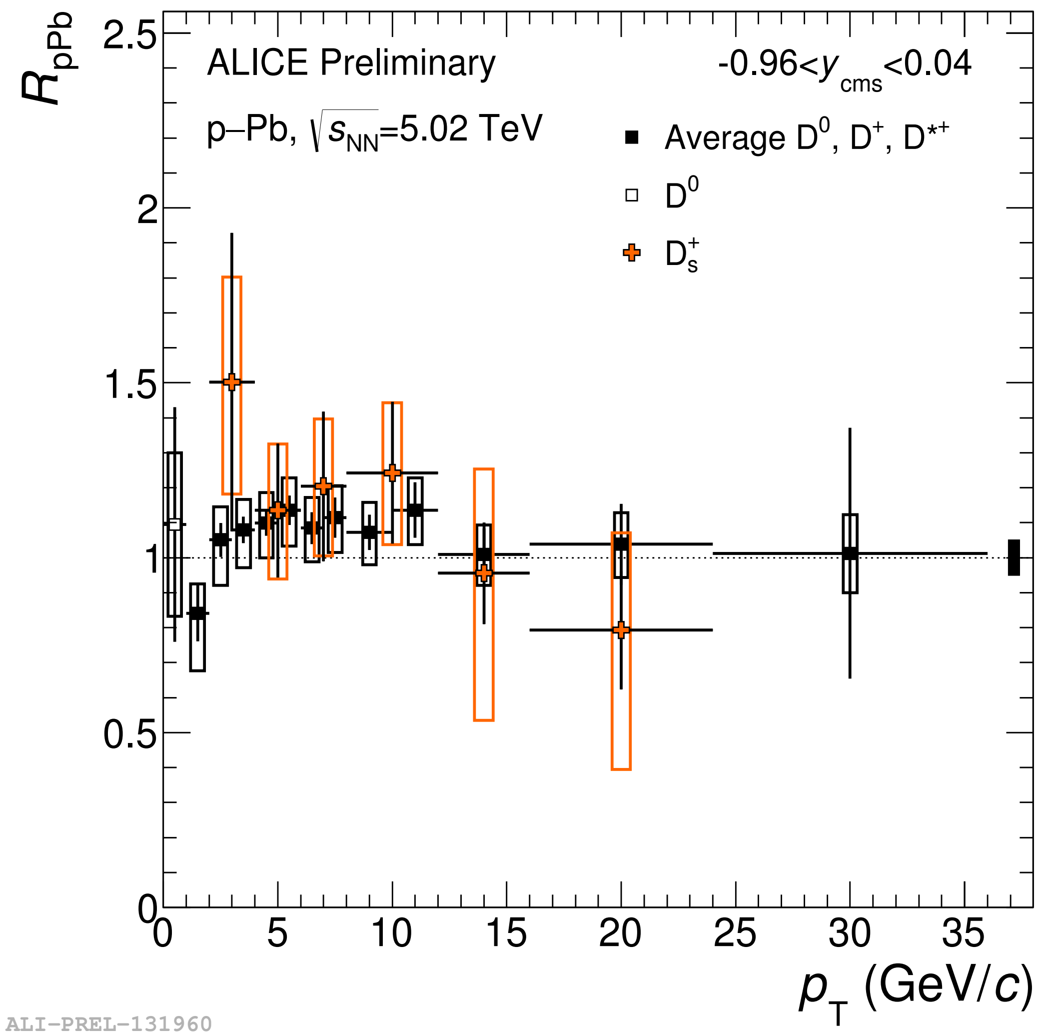

- ➡ Factor ~2 statistical improvement and extended $p_T$ reach w.r.t Run-1
- ➡ $p_T$-differential cross section for strange as well as non-strange D mesons from Run-1 (published) are compatible with Run-2 measurements

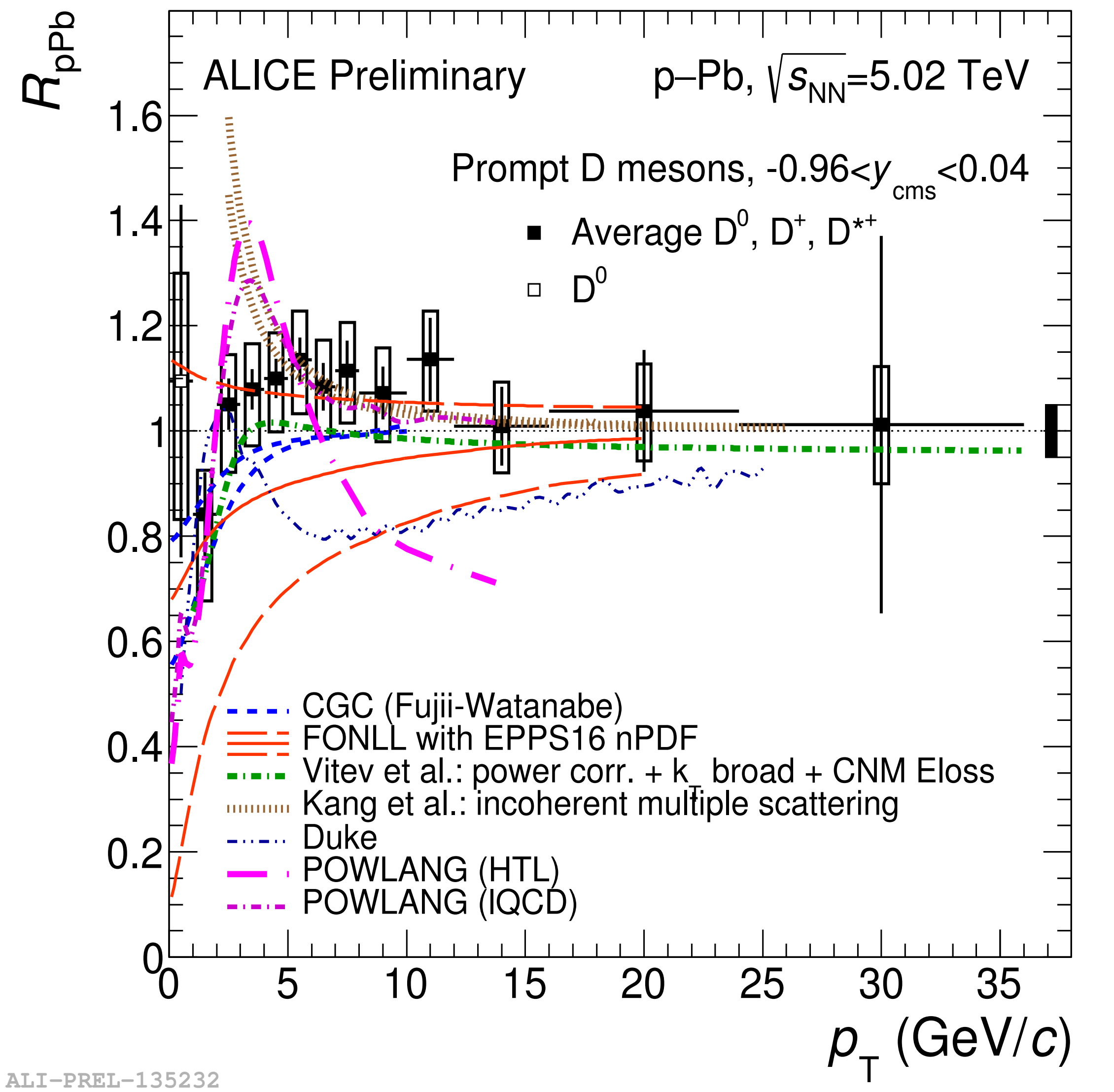
# D-meson $R_{pPb}$

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

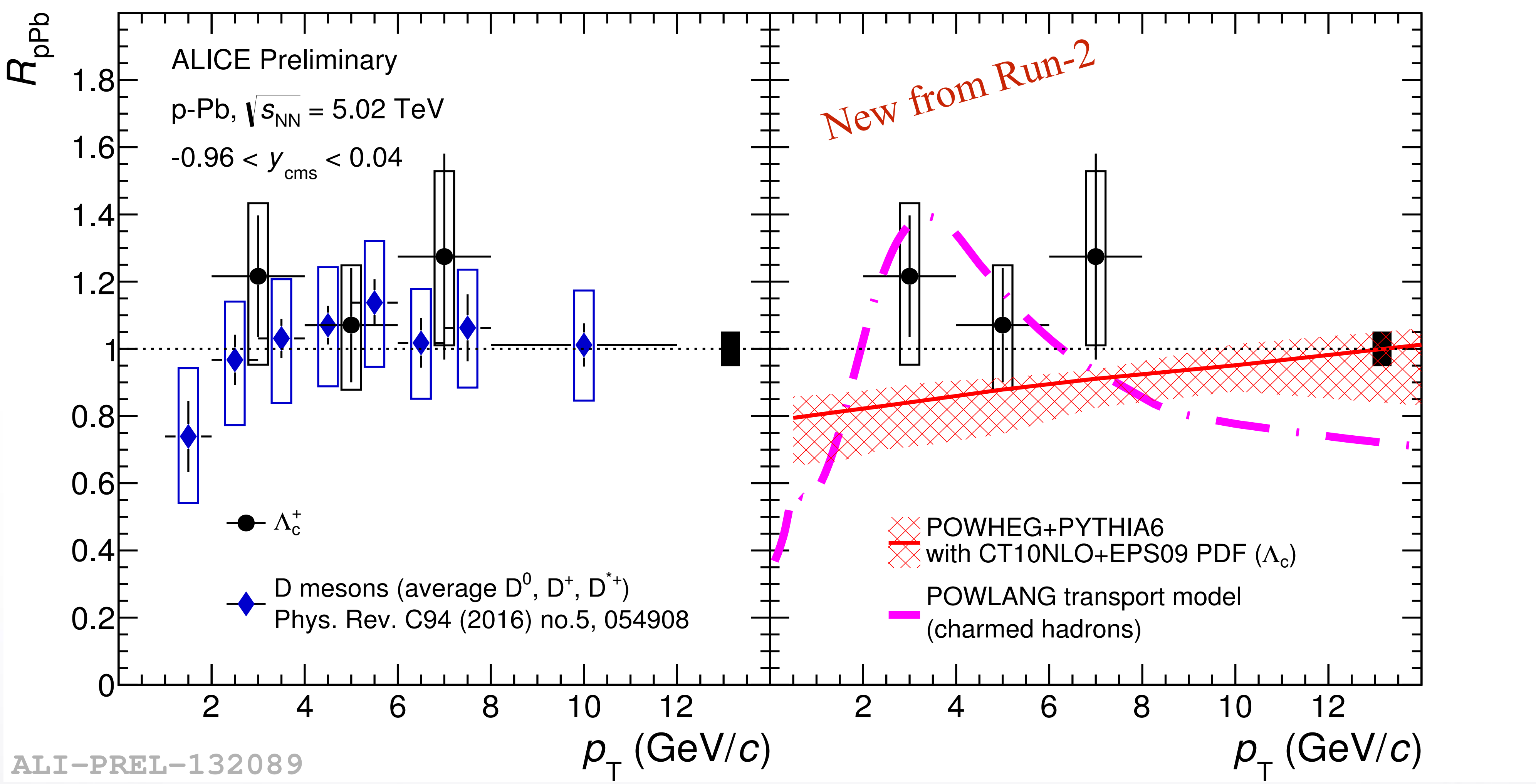
New from Run-2

ALICE-PUBLIC-2017-008



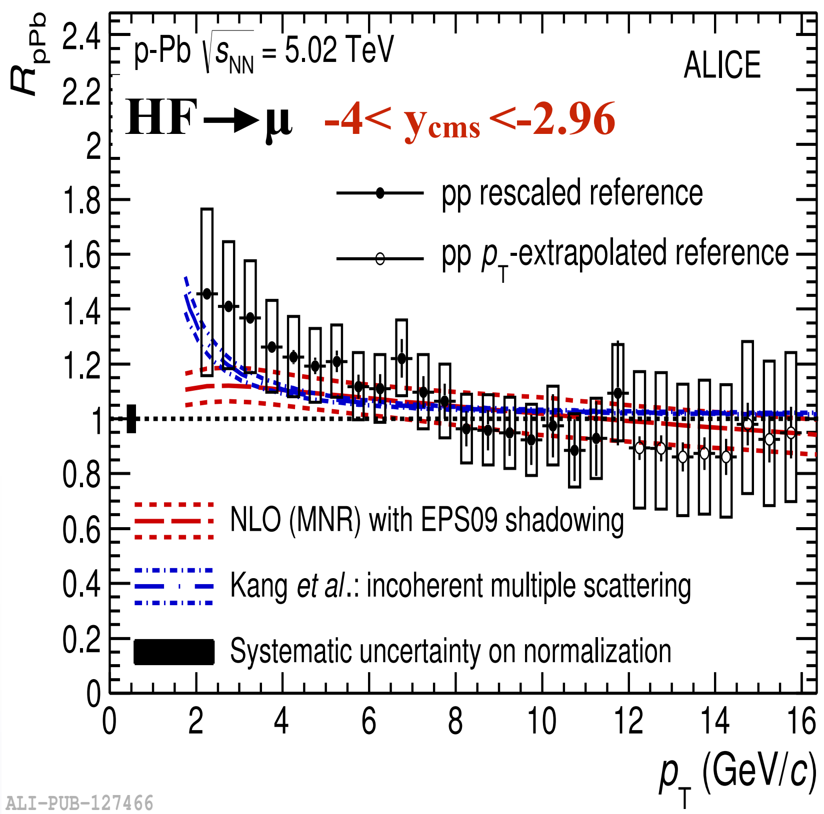

- ➡ Factor ~2 statistical improvement and extended $p_T$ reach w.r.t Run-1
- ➡ $R_{pPb}$ consistent with unity for strange as well as non-strange D-meson
- ➡ No indication for suppression at intermediate/high $p_T$
- ➡ $R_{pPb}$ described within uncertainties by models including initial- or final-state effects




➡ $\Lambda_c^+$ $R_{pPb}$ compatible with D mesons and with unity within uncertainties

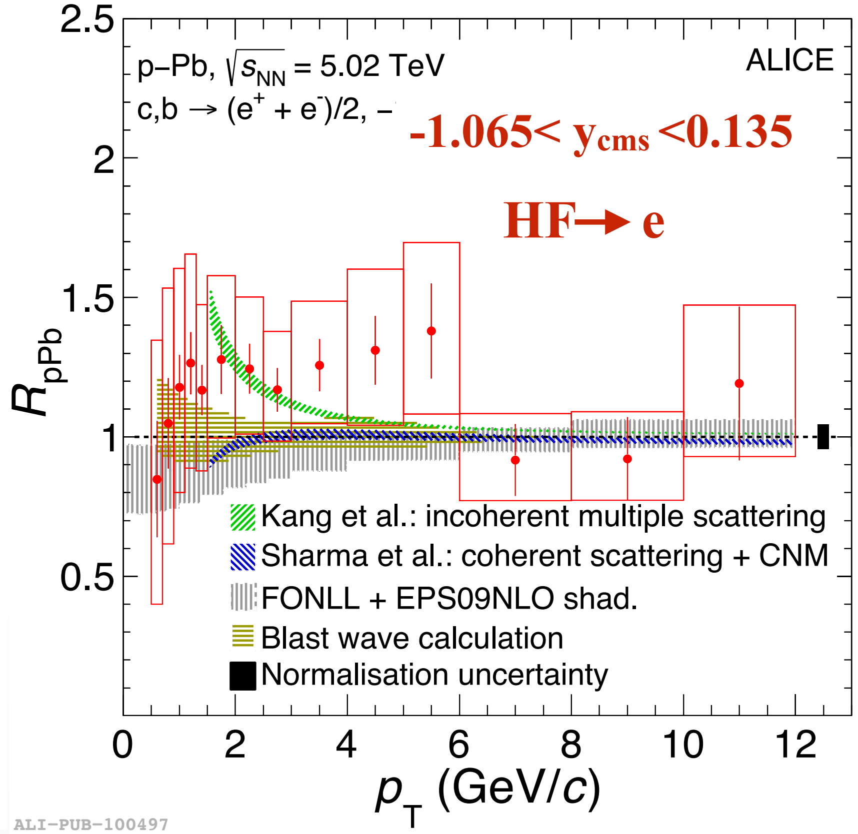
➡ Models including cold nuclear matter effects or small size QGP formation describe the data within uncertainties

Pb → ← p

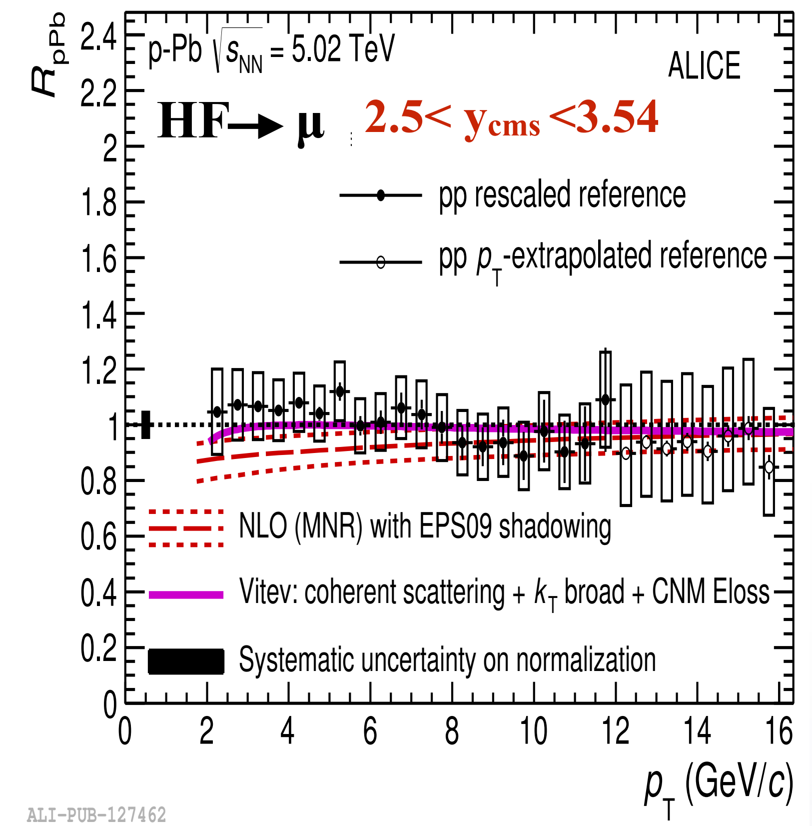



**Phys. Lett. B 770 (2017) 459**

**Phys. Lett. B 754 (2016) 81-93**



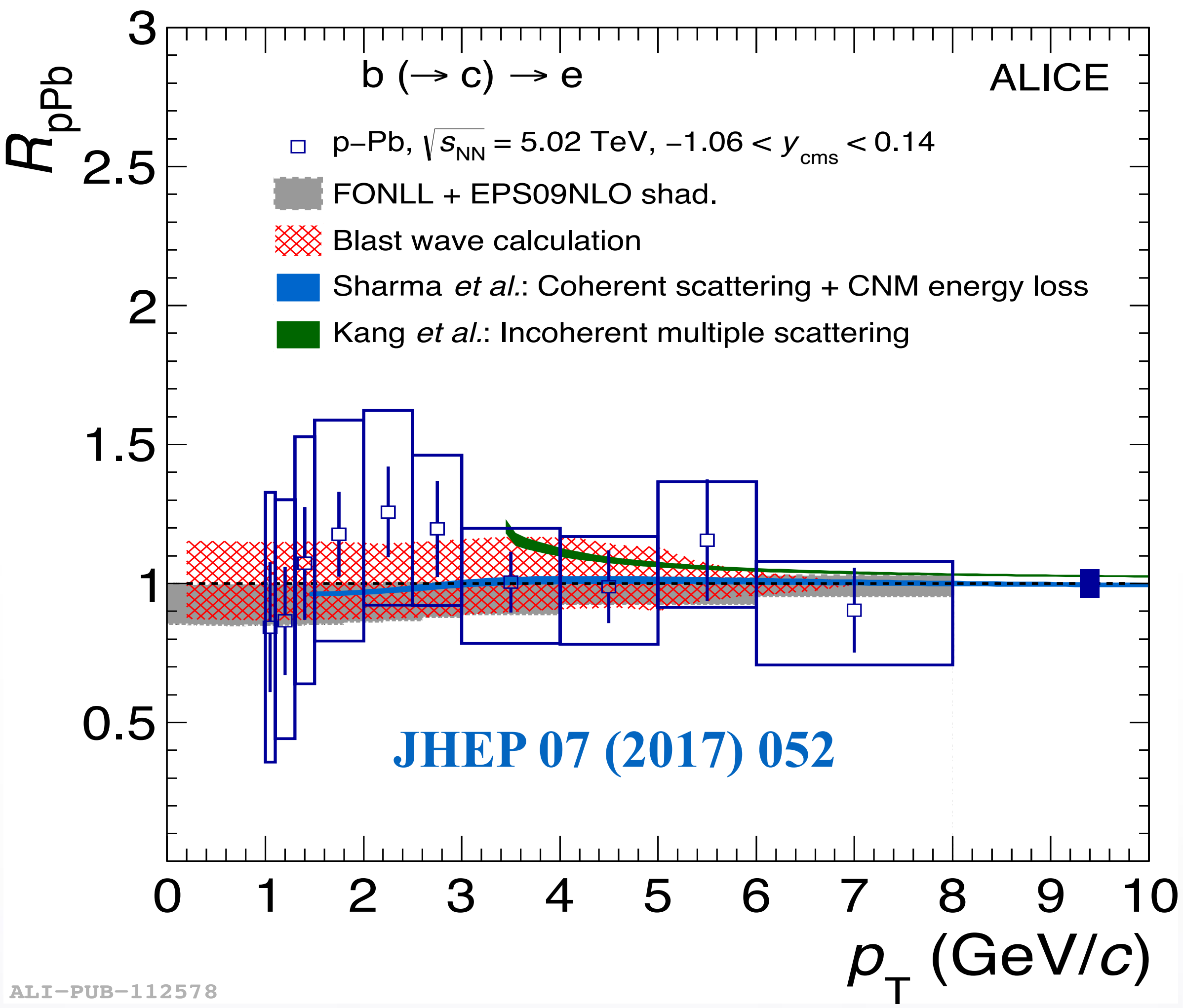

p → ← Pb




**Phys. Lett. B 770 (2017) 459**

- ➡ $\boldsymbol{R_{pPb}}$ measurements compatible with unity within uncertainties for backward, central and forward rapidity at high $\boldsymbol{p_T}$
  - ➡ different rapidity ranges allow us to access different $\boldsymbol{x}$ regimes
  - ➡ hint of $\boldsymbol{R_{pPb}} > 1$ at backward rapidity in $2 < \boldsymbol{p_T} < 4$ GeV/$\boldsymbol{c}$
- ➡ Described by the models including initial- or final-state effects

Kang et al: PLB 740(2015)23 Sharma et al: PRC 80(2009) 054902 FONLL: JHEP 9805 (1998)007 EPOS: JHEP 0904(2009)065 Vitev et al: PRC 80 (2009)054902 *Z.B.Kang et al.: PLB 740(2015)23*




➡ $R_{pPb}$ measurements compatible with unity within uncertainties

➡ Described by the models including initial-state effects and energy loss in CNM

FONLL: JHEP 1210, 137 (2012), EPS09: JHEP 0904, 065 (2009)
Incoherent scattering: Phys. Lett. B 740, 23 (2015), CNM energy loss: Phys. Rev. C 80, 054902 (2009)

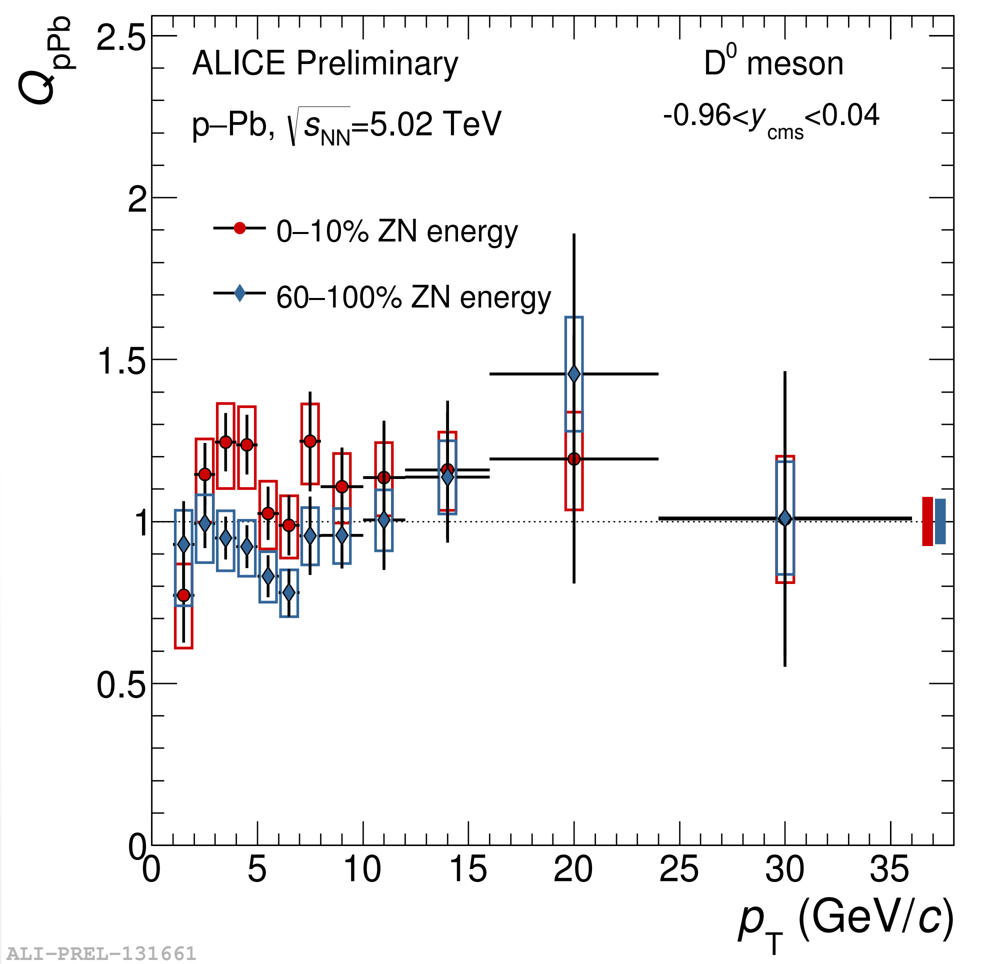
# D-meson production vs multiplicity

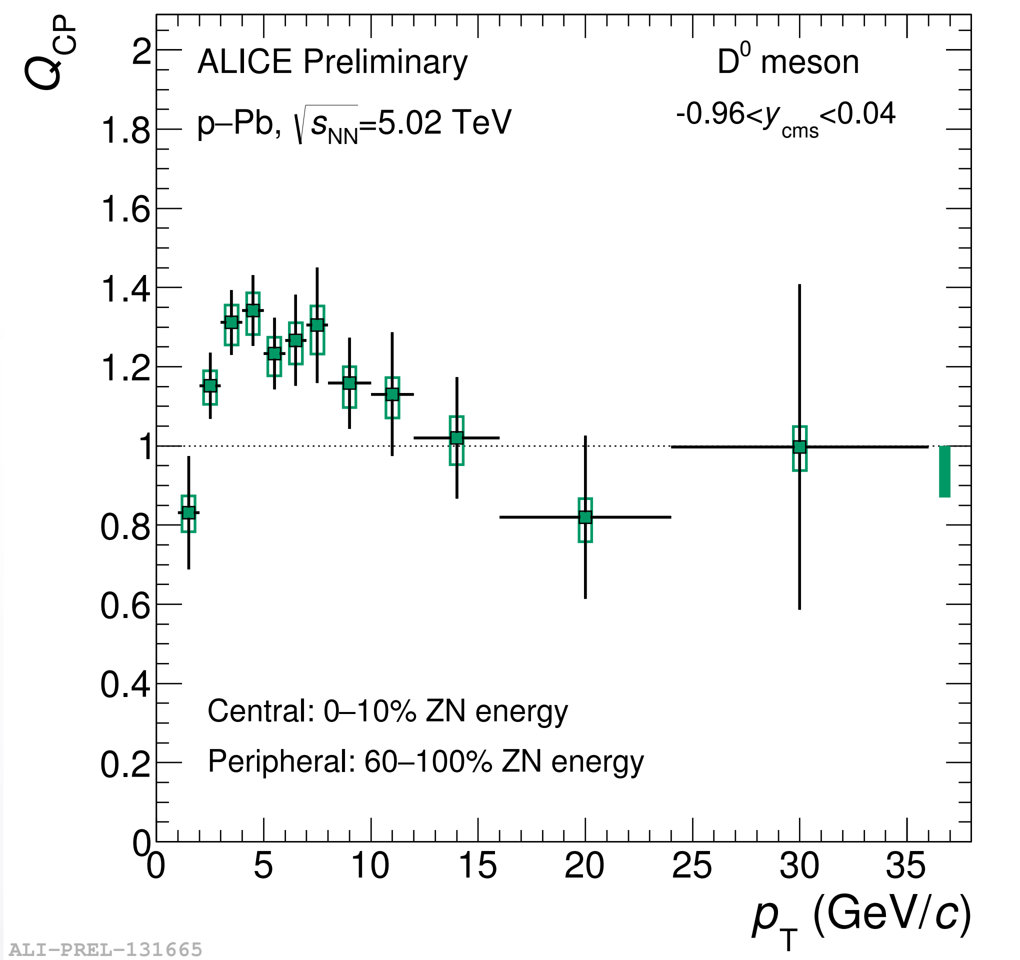
$$Q^{mult}_{\mathrm{pPb}}(p_{\mathrm{T}}) = \frac{1}{\langle T^{mult}_{\mathrm{pPb}} \rangle} \frac{\mathrm{d}N_{\mathrm{pPb}} / \mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}} / \mathrm{d}p_{\mathrm{T}}}$$

New from Run-2

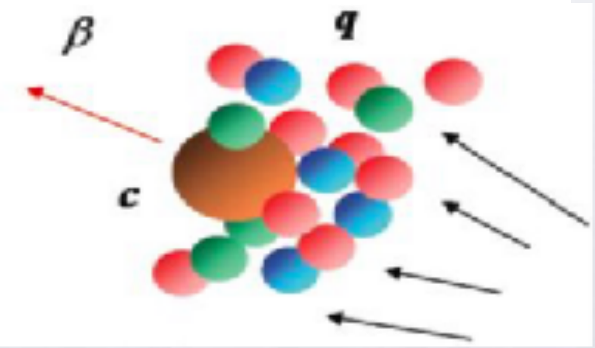
ALICE-PUBLIC-2017-008

$$Q_{\mathrm{CP}}(p_{\mathrm{T}}) = \frac{\langle T^{60-100}_{\mathrm{pPb}} \rangle}{\langle T^{0-10}_{\mathrm{pPb}} \rangle} \frac{(\mathrm{d}N_{\mathrm{pPb}} / \mathrm{d}p_{\mathrm{T}})^{0-10}_{\mathrm{pPb}}}{(\mathrm{d}N_{\mathrm{pPb}} / \mathrm{d}p_{\mathrm{T}})^{60-100}_{\mathrm{pPb}}}$$

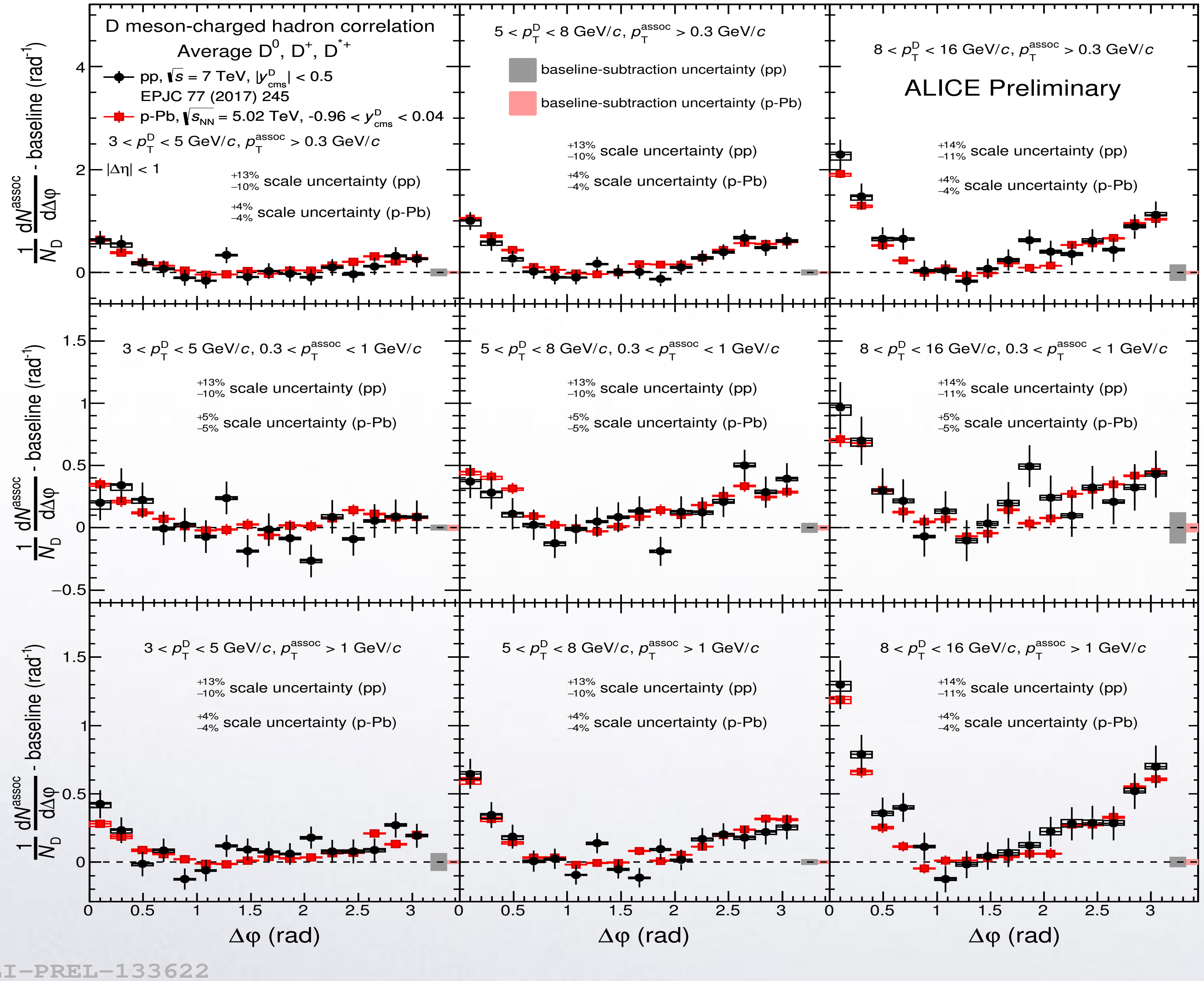



- ➡ $Q_{\mathrm{pPb}}$ in most central (0-10%) and peripheral collisions (60-100 %) are compatible and consistent with unity within uncertainties
- ➡ Ratio central to peripheral ($Q_{\mathrm{cp}}$) > 1 in $3 < p_{\mathrm{T}} < 8$ GeV/$c$ with 1.7 σ
- ➡ Possible influence of radial flow on HF particles in p-Pb collisions



Access the charm fragmentation and jet properties in presence of nucleus



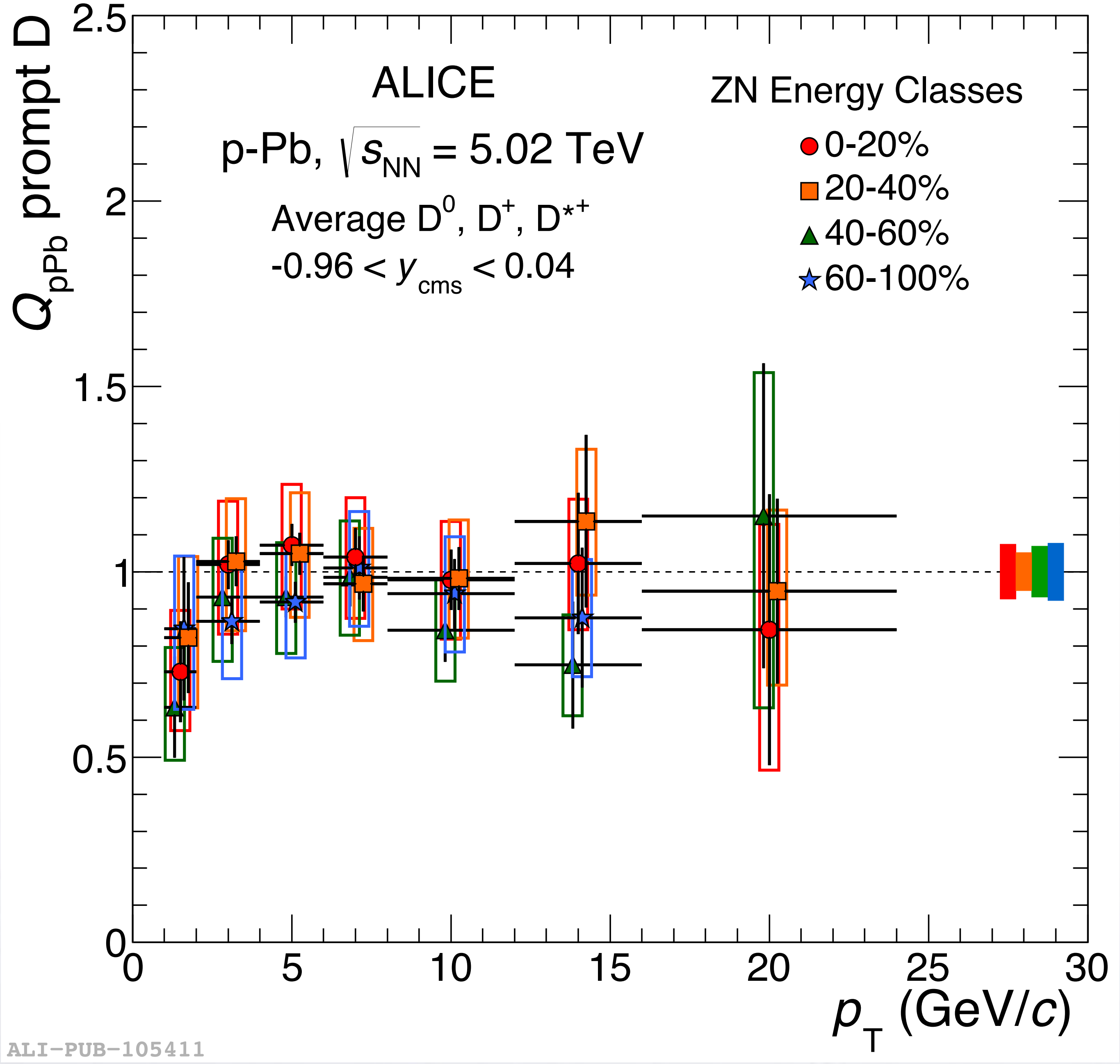

New from Run-2

- A significant increase of precision and access new $p_T$ interval w.r.t run-1
- Angular correlations are consistent within uncertainties in pp and p-Pb collisions after baseline subtraction
- No sign of modification in p-Pb collisions due to cold nuclear effects within uncertainties

# Summary

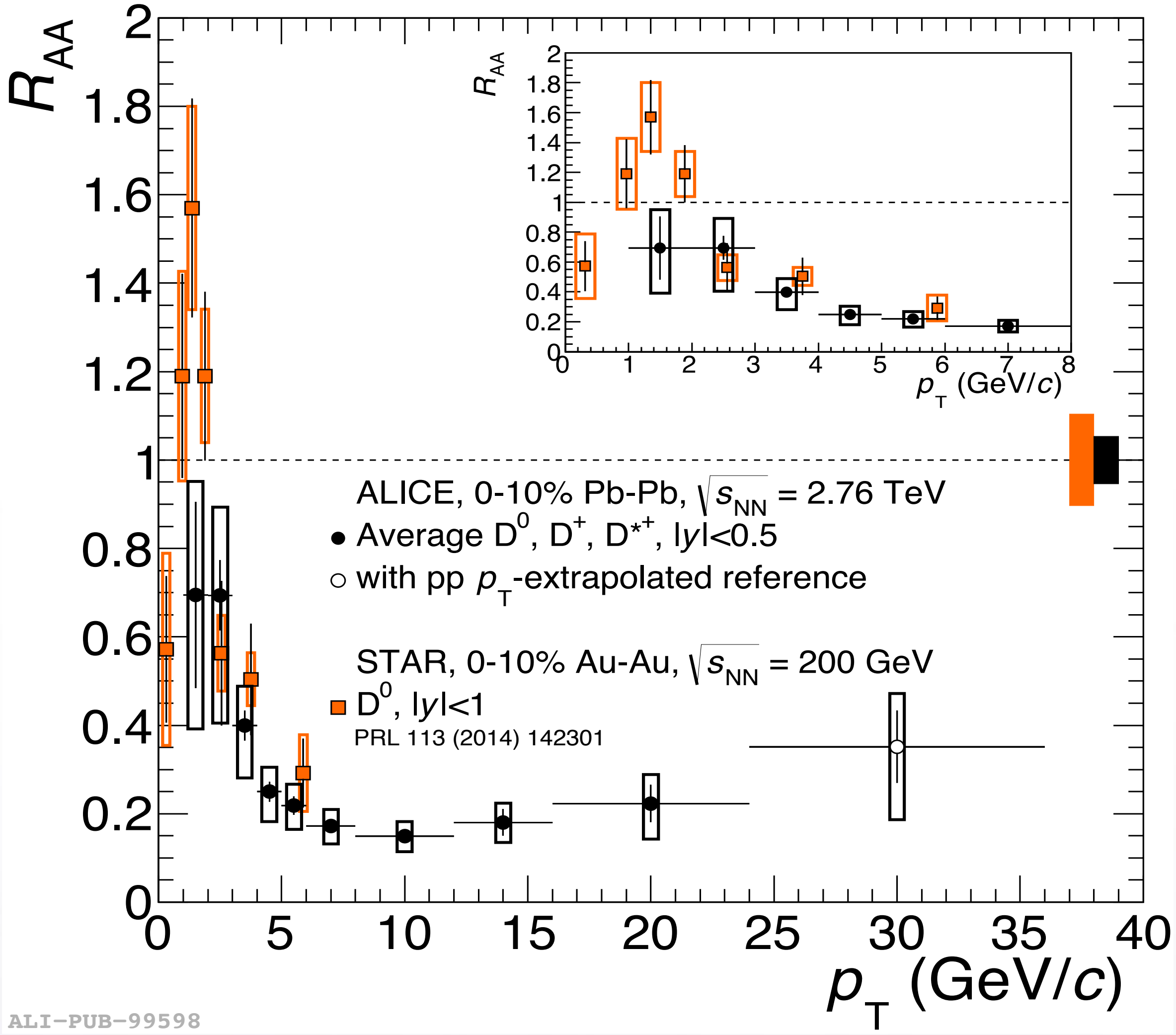
- D-meson production measurement at several collision energies reproduced by **pQCD** calculations
- **First charmed-baryon measurement at mid-rapidity at LHC energies**
  - measured cross section and baryon to charm ratios higher than all available theoretical predictions
- D-meson $R_{\mathrm{pPb}}$ : compatible results with run-1 analysis, **better precision, extended $p_{\mathrm{T}}$ reach**
- $R_{\mathrm{pPb}}$ of charm mesons, baryons and leptons consistent with unity and models including CNM effect
- Ratio central to peripheral ($Q_{\mathrm{cp}}$) >1:  initial- or final-state effect? radial flow in p-Pb?
- **No modification of azimuthal correlation** between D mesons and charged particles in p-Pb collisions. Consistent with pQCD-based model calculations within uncertainties.

backup




Average D-meson nuclear modification factor for different centrality classes selected with ZNA estimator

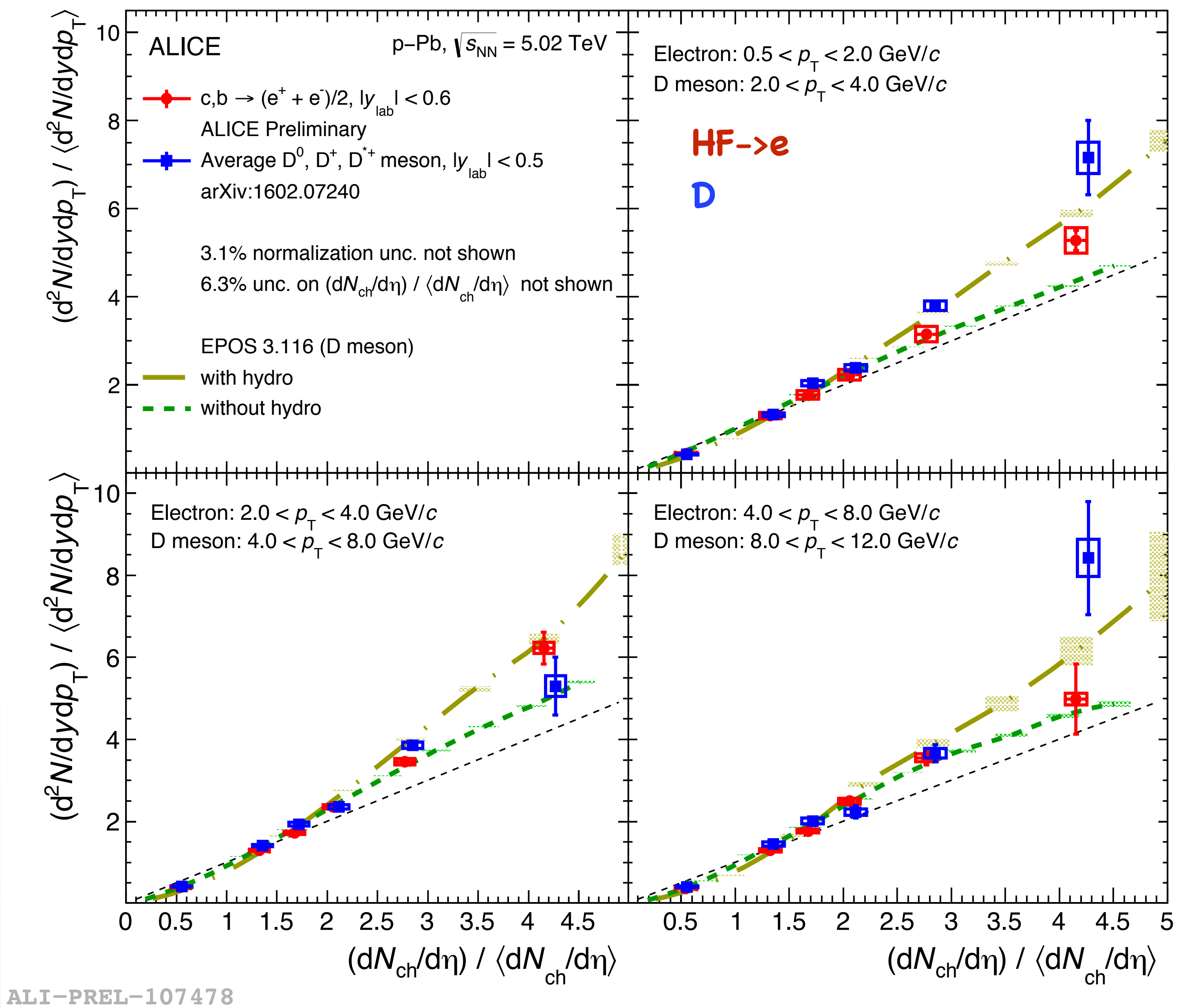
No centrality dependence was found pPb




- ✓ D mesons at RHIC vs LHC: different $R_{AA}$ trend observed for $p_T$ < 2 GeV/c?

  Caveats: Stronger shadowing, less steep pp spectrum at LHC, different effect of radial flow and coalescence.

- ✓ Some models (TAMU, Phys. Lett. B 735 (2014) 445) can describe both results.




Self normalised yields increase with charged-particle multiplicity at mid rapidity as observed in pp collisions

- ✓ faster than linear increase
- ✓ similar trend for heavy-flavour decay electrons and D mesons
- ✓ different $p_T$ ranges for better kinematic comparability
- ✓ at high $p_T$ electrons are dominated by beauty

Measurements are reproduced well by EPOS with hydro

EPOS: PRC 89(2014) 064903

The differential cross section is computed for eg: D+

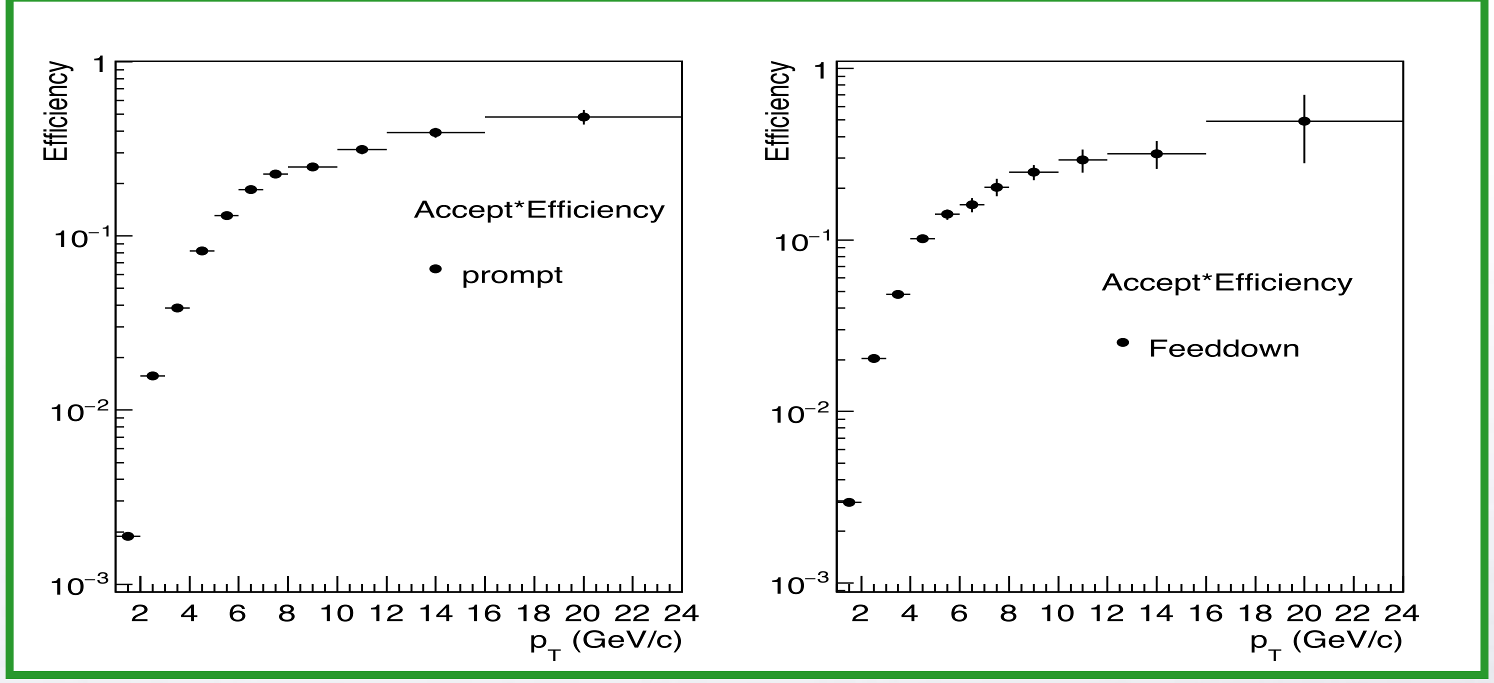
$$\left.\frac{d\sigma^{D^+}}{dp_t}\right|_{|y|<0.5} = \frac{1}{2}\frac{1}{\Delta y \Delta p_t}\frac{f_{prompt}(p_t) \cdot \left. N^{D^\pm\ raw}(p_t)\right|_{|y|<y_{fid}}}{(Acc \times \varepsilon)_{prompt}(p_t) \cdot BR \cdot L_{int}}.$$

From fits to invariant mass spectra

Correction for reconstruction and selection efficiency:

from MC simulation: Efficiencies x acceptance corrections increasing trending with $p_T$.

Secondary D mesons show higher efficiencies due to their large displacement.




Integrated luminosity Lint = No. of events analyzed/sigma INT7(56*10⁶nb)

https://indico.cern.ch/event/486605/contributions/1996610/attachments/1216371/1776468/PWG-PP_250116.pdf

The differential cross section is computed for eg: $D^+$

$$\left.\frac{d\sigma^{D^+}}{dp_t}\right|_{|y|<0.5} = \frac{1}{2}\frac{1}{\Delta y \Delta p_t}\frac{f_{prompt}(p_t)\cdot \left.N^{D^\pm\ raw}(p_t)\right|_{|y|<y_{fid}}}{(Acc\times\varepsilon)_{prompt}(p_t)\cdot BR\cdot L_{int}}.$$

Feed Down Correction:

Two ways of calculating the feed down correction. $N_b$ and $f_c$

$N_b$ method:

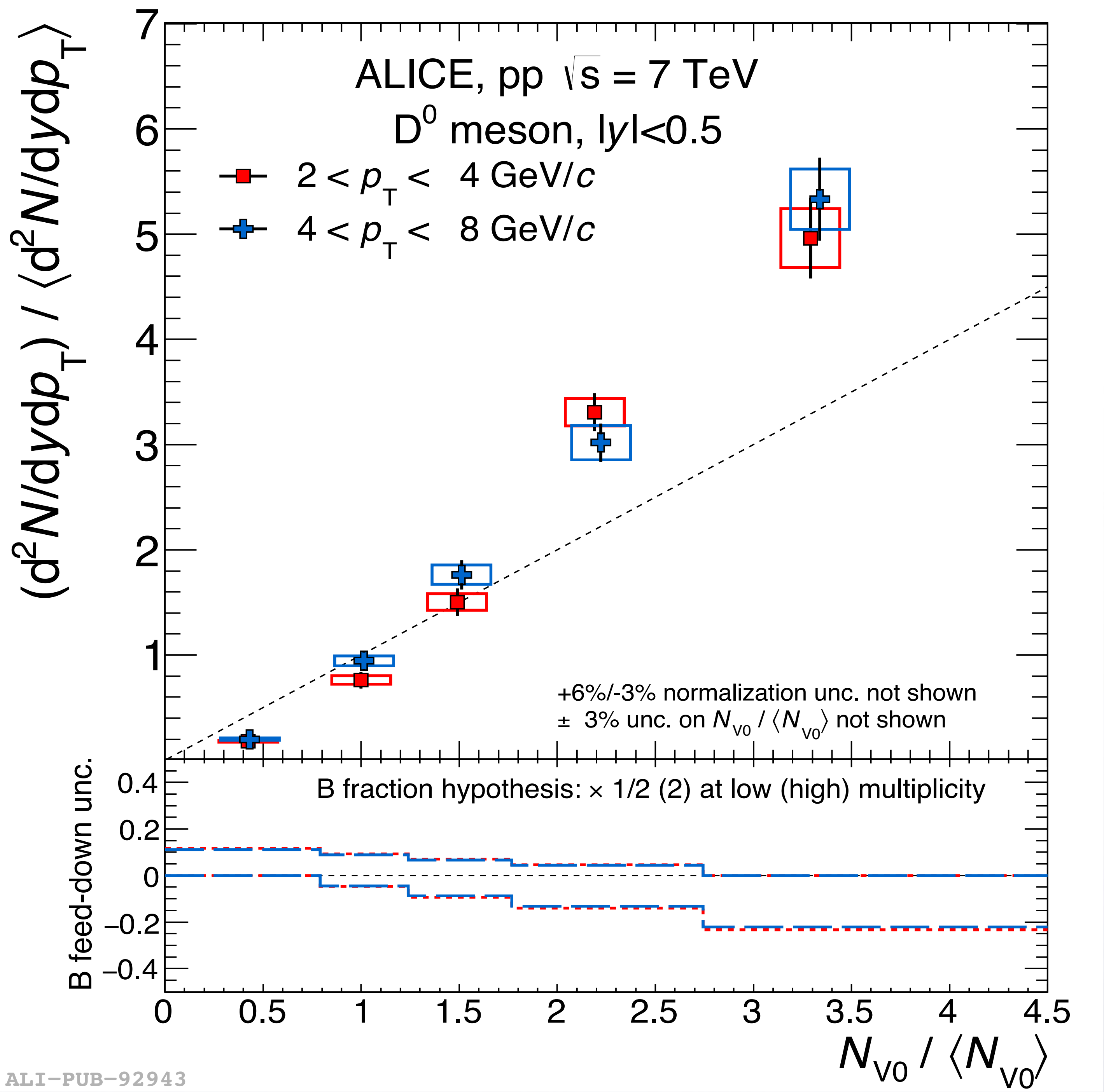
$$f_{prompt} = 1 - (N^{D\ feed-down\ raw}/N^{D\ raw}) = \\ = 1 - \left(\frac{d^2\sigma}{dy\,dp_T}\right)^{FONLL}_{feed-down}\cdot\frac{(Acc\times\varepsilon)_{feed-down}\cdot\Delta y\Delta p_T\cdot BR\cdot L_{int}}{N^{D\ raw}/2}$$

$F_c$ method:

$$f_{prompt} = \left(1 + \frac{(Acc\times\varepsilon)_{feed\text{-}down}}{(Acc\times\varepsilon)_{prompt}}\frac{\left.\frac{d\sigma^{D^+\ from\ B}_{FONLL}}{dp_T}\right|_{|y|<0.5}}{\left.\frac{d\sigma^{D^+}_{FONLL}}{dp_T}\right|_{|y|<0.5}}\right)^{-1}.$$

For this analysis $N_b$ is used to compute the central value since FONLL describes beauty better than charm at the LHC.

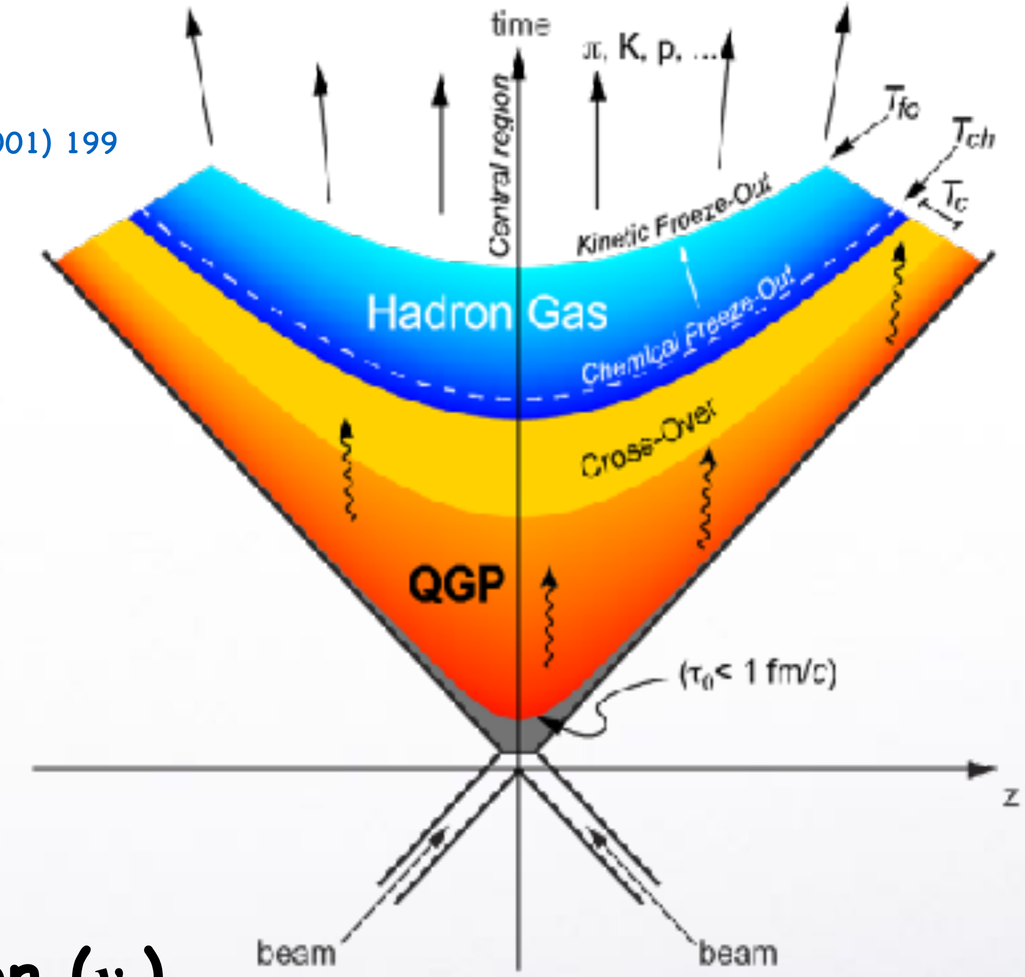
A convolution of fc and $N_b$ is taken as a systematic on $f_{prompt}$ .




V0A and V0C estimator

✓ Heavy quarks lose less energy than light quarks and gluons due to the color-charge and the dead-cone effects

$\Delta E(\mathrm{g}) > \Delta E(\mathrm{u,d,s}) > \Delta E\mathrm{c} > \Delta E\mathrm{b}$ Dokshitzer and Kharzeev, PLB 519 (2001) 199




**Observable: Nuclear modification factor ($R_{AA}$)**

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

**Expected Hierarchy: $R_{AA}(\mathrm{B}) > R_{AA}(\mathrm{D}) > R_{AA}(\pi)$ ?**

**Another observable: azimuthal anisotropy**

✓ Provides information on the **degree of thermalisation ($v_2$)** of heavy quarks in the medium at low / intermediate $p_T$ and is sensitive to the path-length dependence of heavy-quark **energy loss** at high $p_T$