2015 KOBE JAPAN

ALICE

Measurements of heavy-flavour production in p-Pb collisions with ALICE

Jeremy Wilkinson *(Universität Heidelberg, Germany)*
on behalf of the **ALICE Collaboration**

Quark Matter 2015
Kobe, Japan
29/09/2015

BMBF Forschungsschwerpunkt
ALICE Experiment 201
ALICE

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

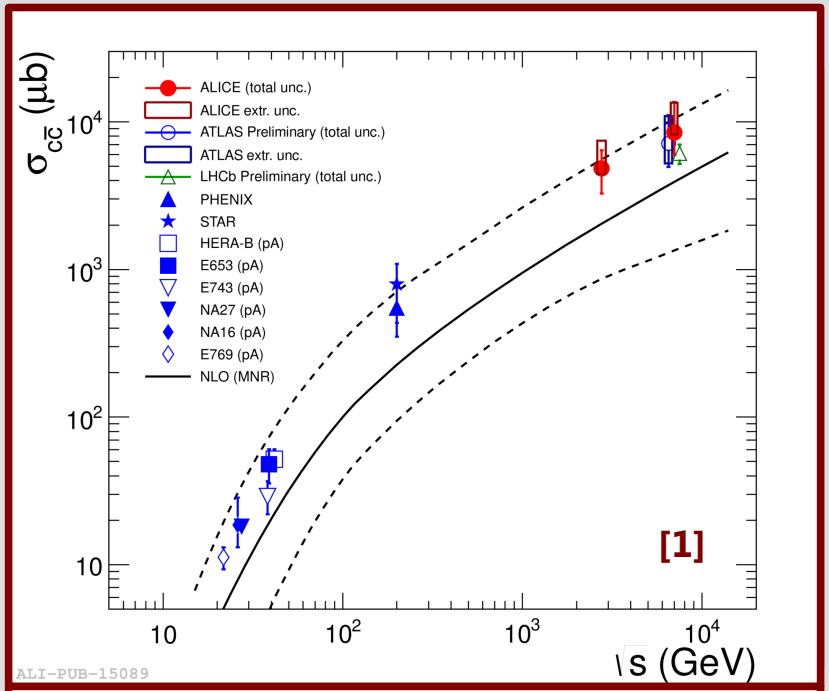
Motivation: Why open heavy flavour in p-Pb?

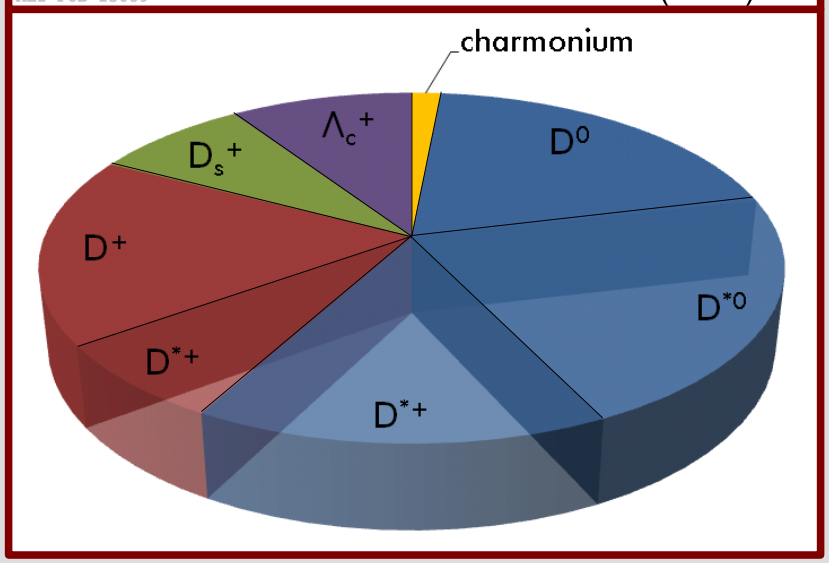
- Heavy-flavour (charm & beauty) production offers a unique probe into the properties of the **Quark-Gluon Plasma (QGP)** formed in heavy-ion collisions

- Due to their large masses, charm and beauty quarks are produced in the **early stages** of the collision.
  → Experience the **full evolution** of the system.
  → Described well by pQCD calculations in pp collisions

- p-Pb: moderate number of binary collisions ($\langle N_{coll} \rangle \approx 7$); **no medium formed**
  → Comparisons of results (such as nuclear modification factors) in p-Pb and Pb-Pb disentangle in-medium effects from cold nuclear matter effects (e.g. transverse momentum broadening, initial-state energy loss, nuclear shadowing)

- Production measured in ALICE in three ways:
  → Hadronic decays of D mesons at mid-rapidity
  → Semileptonic decays at mid-rapidity ($D \rightarrow e^{\pm} + X$, $B \rightarrow e^{\pm} + X$)
  → Semileptonic decays at forward/backward rapidity ($D/B \rightarrow \mu^{\pm} + X$) (to probe different Bjorken-*x* regions)

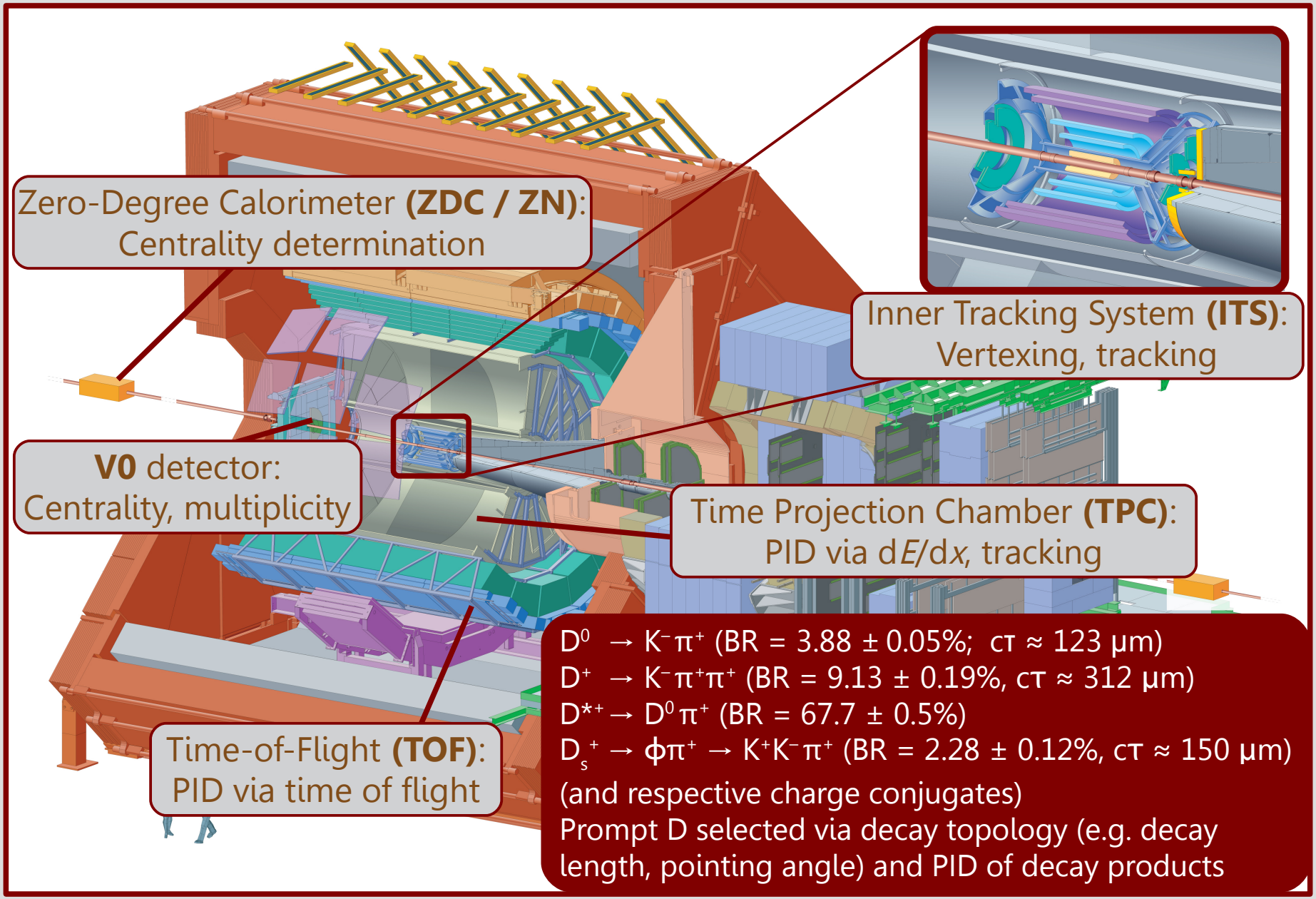




Blue: D^0, Red: D^+; Solid: Direct production, Hollow: feed-down from resonant state)

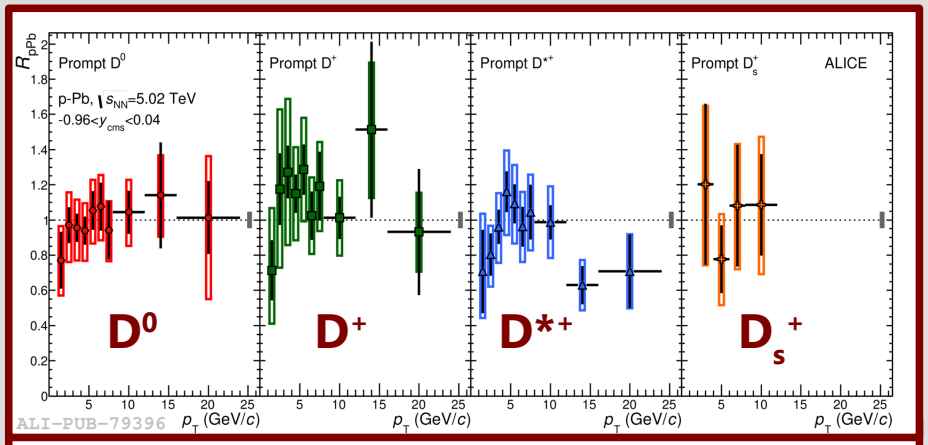
[1] ALICE Collaboration: *JHEP 07 (2012) 191*

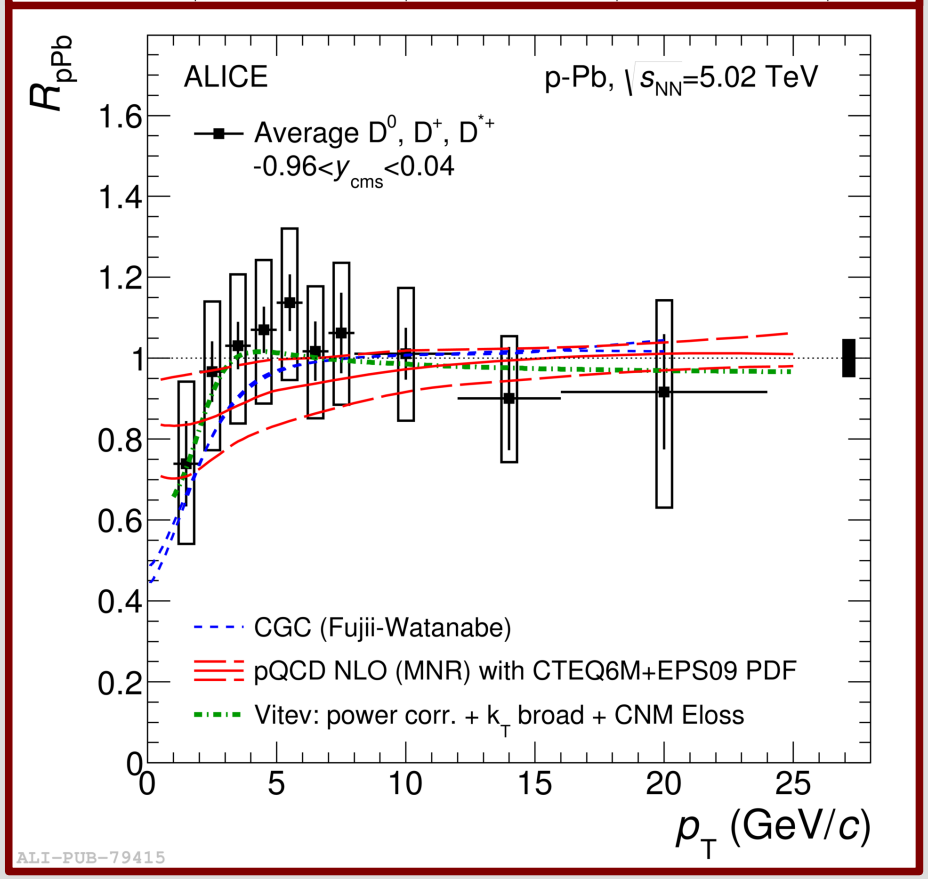
ALICE: A Large Ion Collider Experiment (D mesons)



$D^0 \rightarrow K^-\pi^+$ (BR = 3.88 ± 0.05%; $c\tau \approx 123$ μm)
$D^+ \rightarrow K^-\pi^+\pi^+$ (BR = 9.13 ± 0.19%, $c\tau \approx 312$ μm)
$D^{*+} \rightarrow D^0\pi^+$ (BR = 67.7 ± 0.5%)
$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$ (BR = 2.28 ± 0.12%, $c\tau \approx 150$ μm)
(and respective charge conjugates)
Prompt D selected via decay topology (e.g. decay length, pointing angle) and PID of decay products

R_{pPb} of D mesons





ALICE Collaboration: *Phys. Rev. Lett. 113 (2014) 232301*

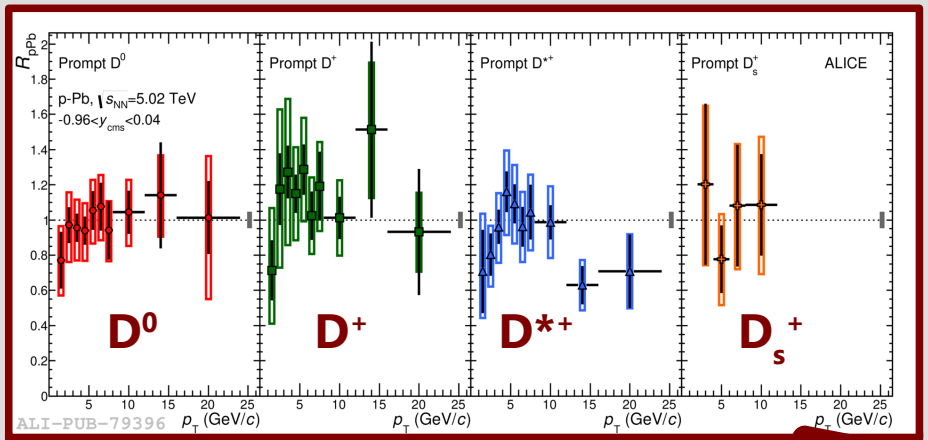
- **Nuclear modification factor R_{pPb}:** D^0, D^+, D^{*+}, D_s^+ (top-left), average of D^0, D^+, D^{*+} (bottom-left)

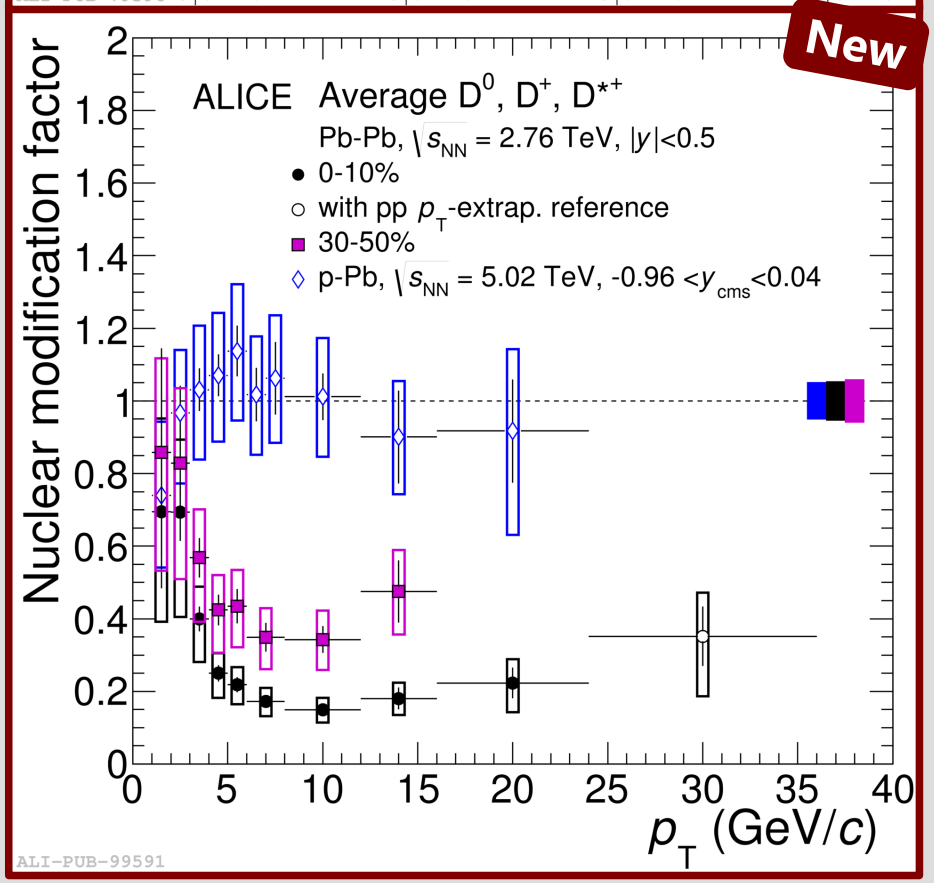
$$R_{pPb} = \frac{\frac{d\sigma_{pPb}}{dp_T}}{A \times \frac{d\sigma_{pp}}{dp_T}}$$

- R_{pPb} of all species **consistent with unity** & each other within uncertainties
- Described within uncertainties by models that include initial-state effects

CGC: *H. Fujii & K. Watanabe, arXiv:1308.1258;* ***pQCD NLO (MNR):*** *M. Mangano et al., Nucl. Phys. B 373 (1992) 295;* ***EPS09***: *K. J. Eskola et al., JHEP 04 (2009) 065;* ***Vitev***: *Phys. Rev. C75 (2007) 064906*

R_{pPb} of D mesons





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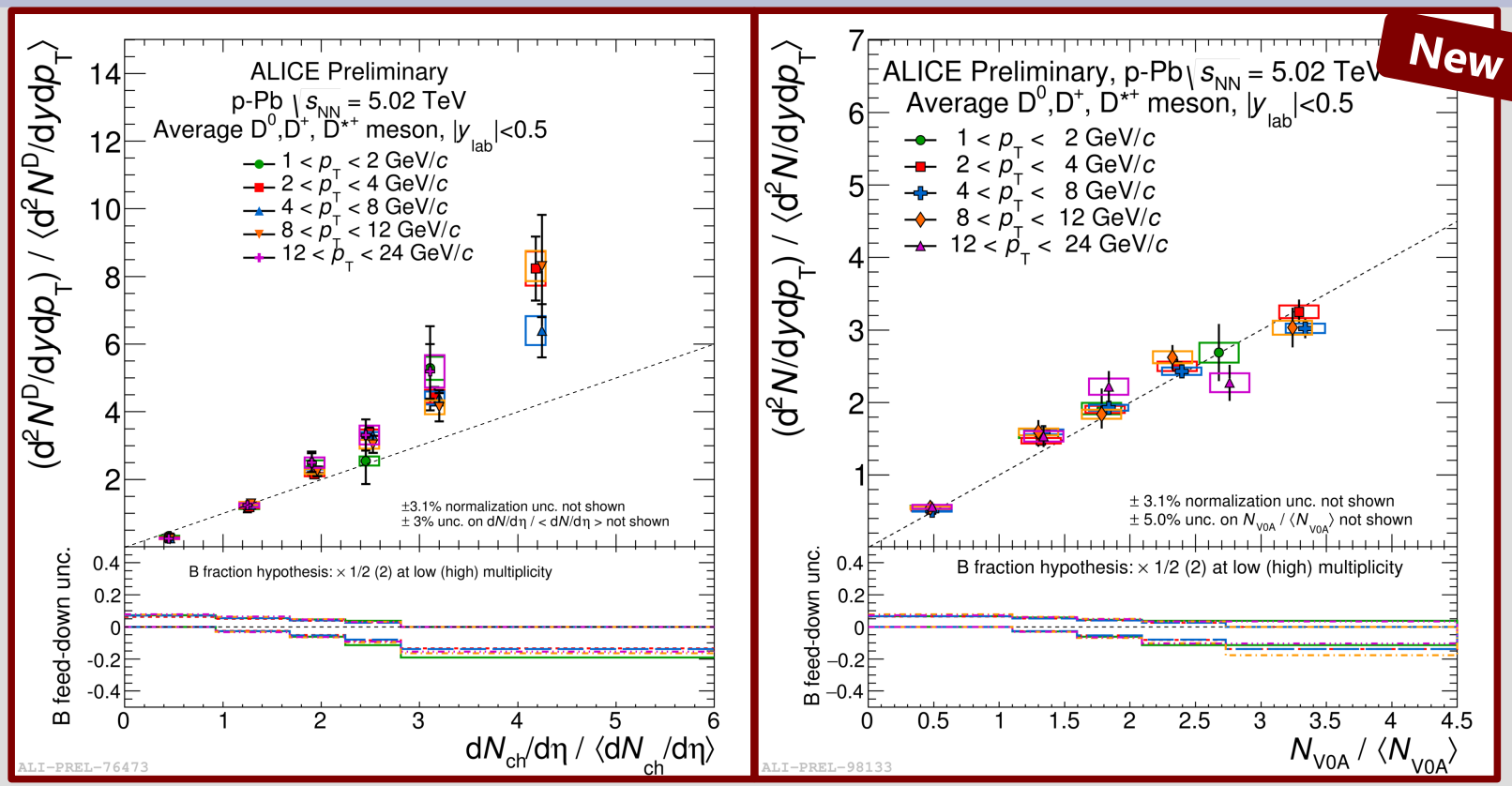
- R_{pPb} of all species **consistent with unity** & each other within uncertainties
- Described within uncertainties by models that include initial-state effects
- **R_{AA} significantly < 1** for p_T > 3 GeV/c; R_{pPb} consistent with unity
  - → No suppression at intermediate-high p_T in p-Pb collisions
  - → Suppression of yield in Pb-Pb collisions in this momentum region is **due to in-medium effects**
- **See poster by Jasper van der Maarel (p-Pb) and talk by Andrea Dubla (Pb-Pb) for more details**

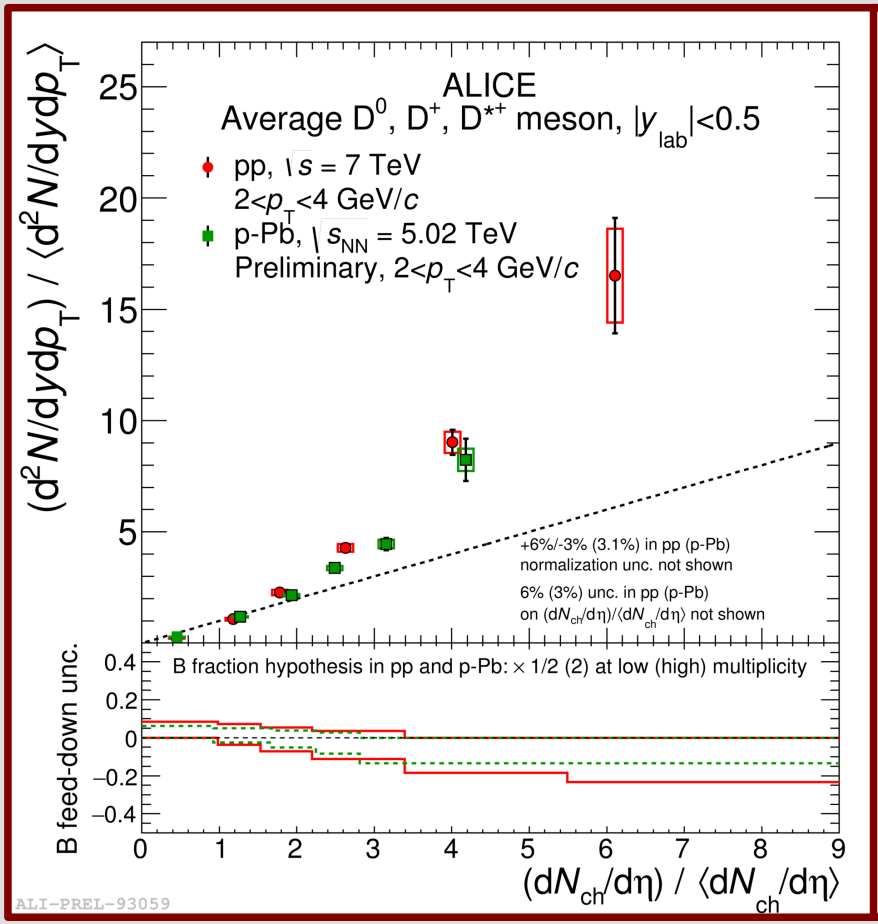
ALICE Collaboration: p-Pb: *Phys. Rev. Lett. 113 (2014) 232301;* ***Pb-Pb:*** *arXiv:1509.06888*

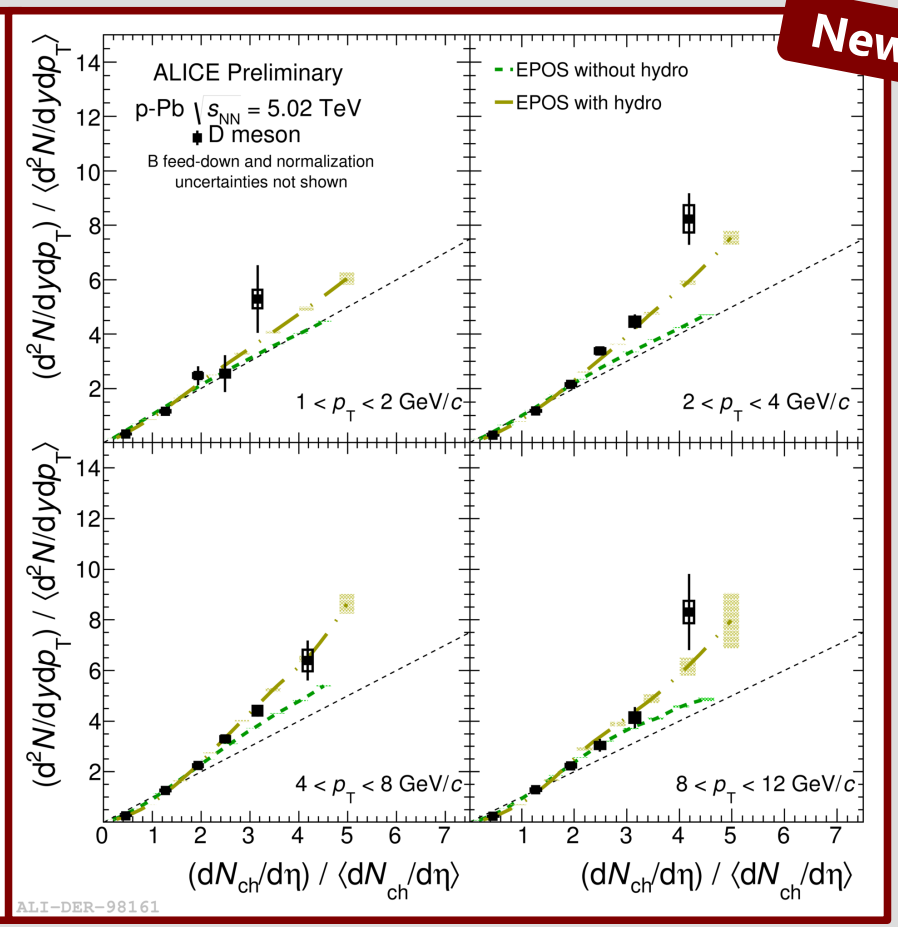
Multiplicity dependence of D-meson production



- Studies vs multiplicity **probe interplay of hard & soft processes** in charm production
- "Self-normalised yield" as a function of charged-particle multiplicity from two estimators:
  - → **Multiplicity at mid-rapidity** via tracklets (track segments) reconstructed in Silicon Pixel Detector within $|\eta| < 1.0$ (left)
  - → **Multiplicity at backward rapidity** (Pb-going direction) measured in **V0A detector** (right)
- Results **independent of p_T for both estimators**
- Slightly faster-than-linear increase at high multiplicity in the mid-rapidity region
- Linear increase in measured multiplicity interval for V0A estimator; **consistent with mid-rapidity result in measured interval** within uncertainties

Comparison of result vs. $dN_{ch}/d\eta$ with pp results & models

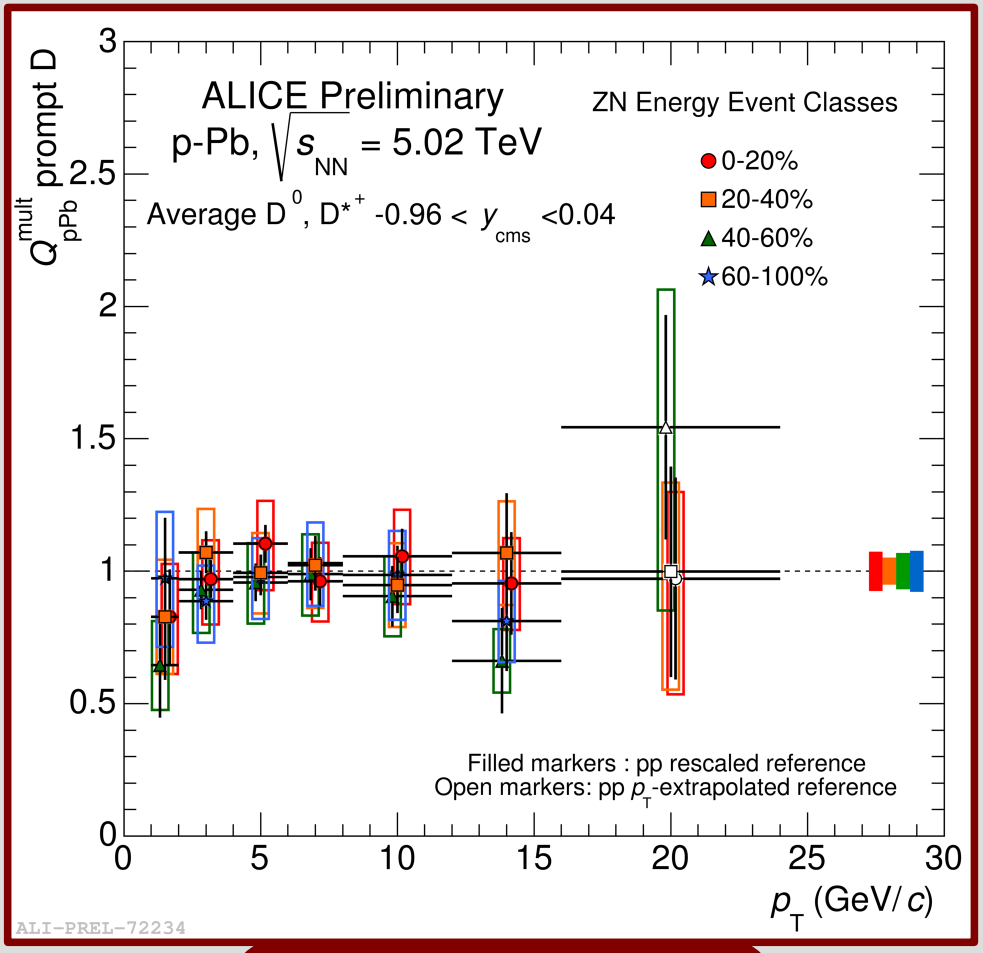




- Multiplicity at mid-rapidity: trend for average D-meson result is **similar in pp and p-Pb collisions**
  → Behaviour at high multiplicities consistent between collision systems at mid-rapidity
- Results compared with **EPOS 3 event generator** → slightly closer consistency with calculations that **include viscous hydro** at high multiplicity
- **See talk by Fabio Colamaria (next) for more on multiplicity dependence in pp and p-Pb**

EPOS: *Phys. Rept. 350 (2001) 93-289, Phys. Rev. C89 (2014) 064903*
ALICE Collaboration (pp results): *arXiv:1505.00664*

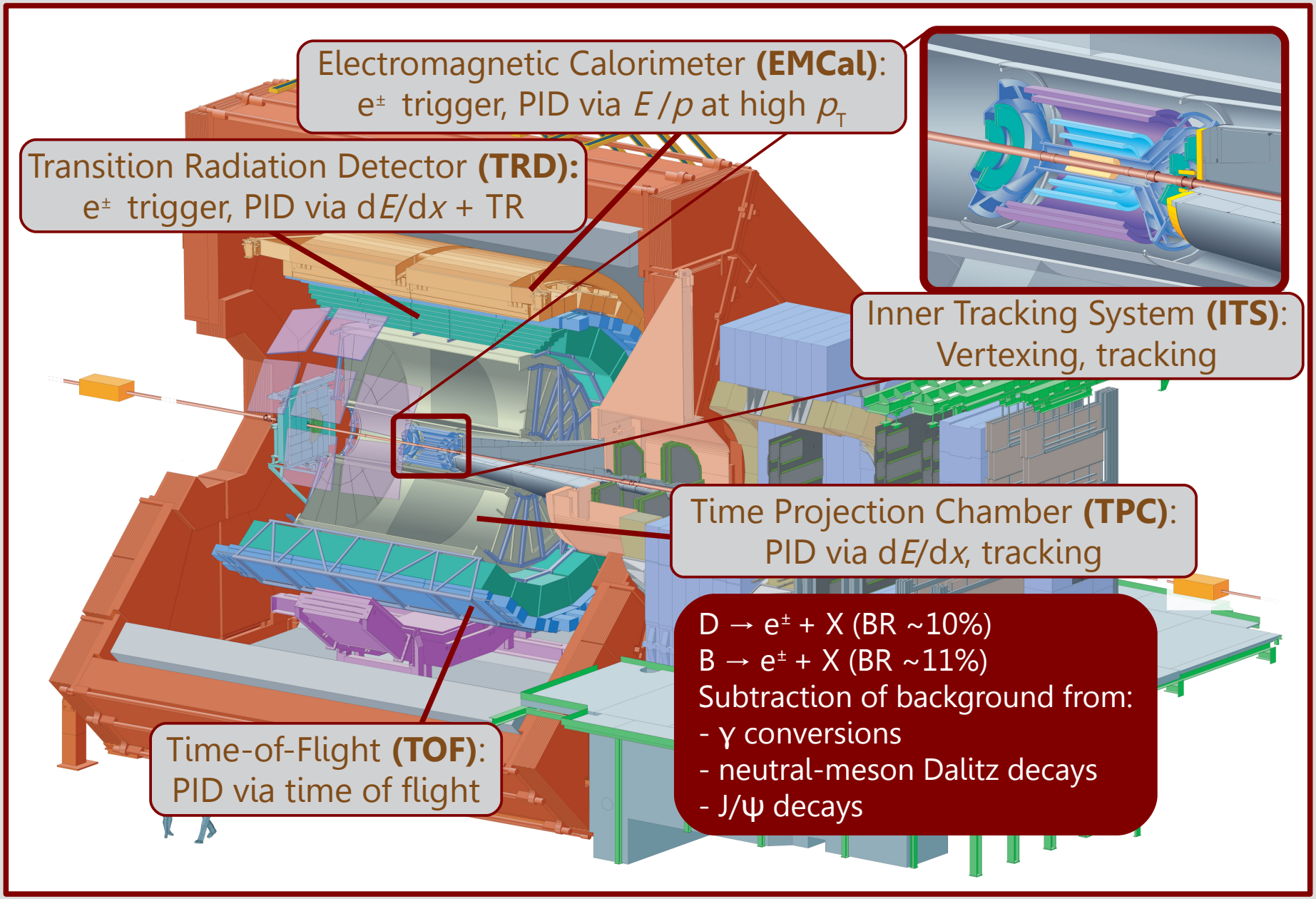
Multiplicity dependence of D-meson production (Q_{pPb})



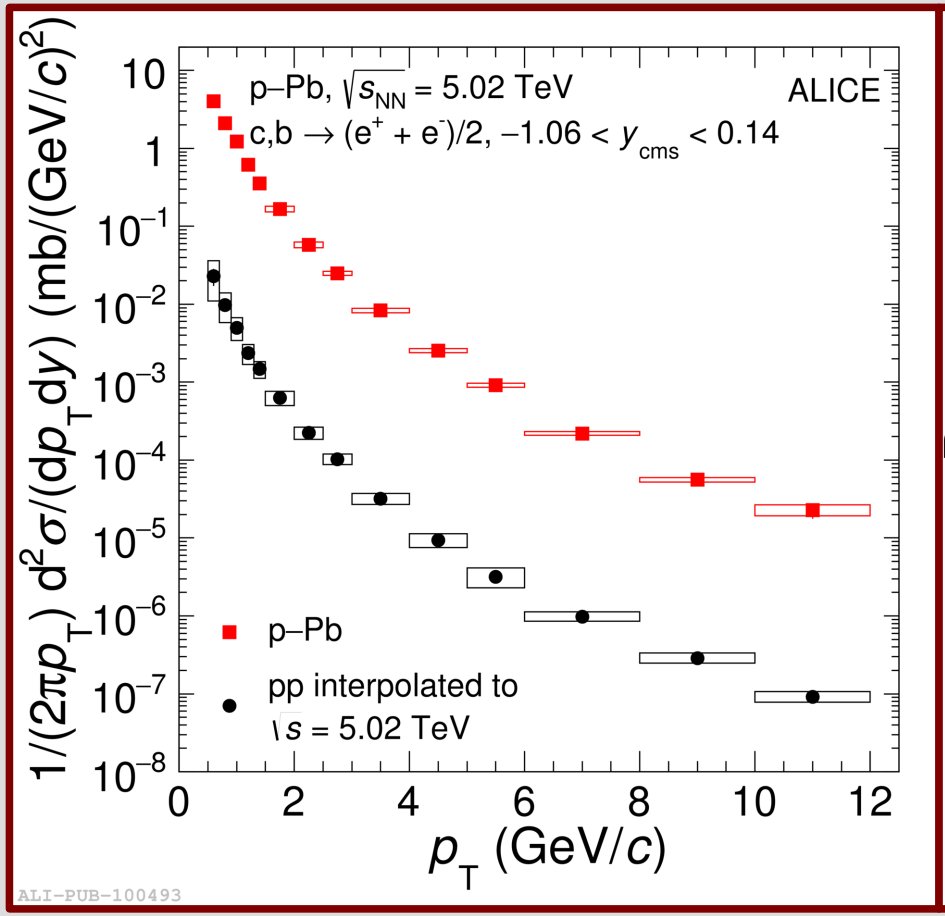
$$Q^{mult}_{pPb} = \frac{\dfrac{dN^{D}_{pPb}}{dp_T}}{\langle T^{mult}_{pPb} \rangle \dfrac{d\sigma^{D}_{pp}}{dp_T}}$$

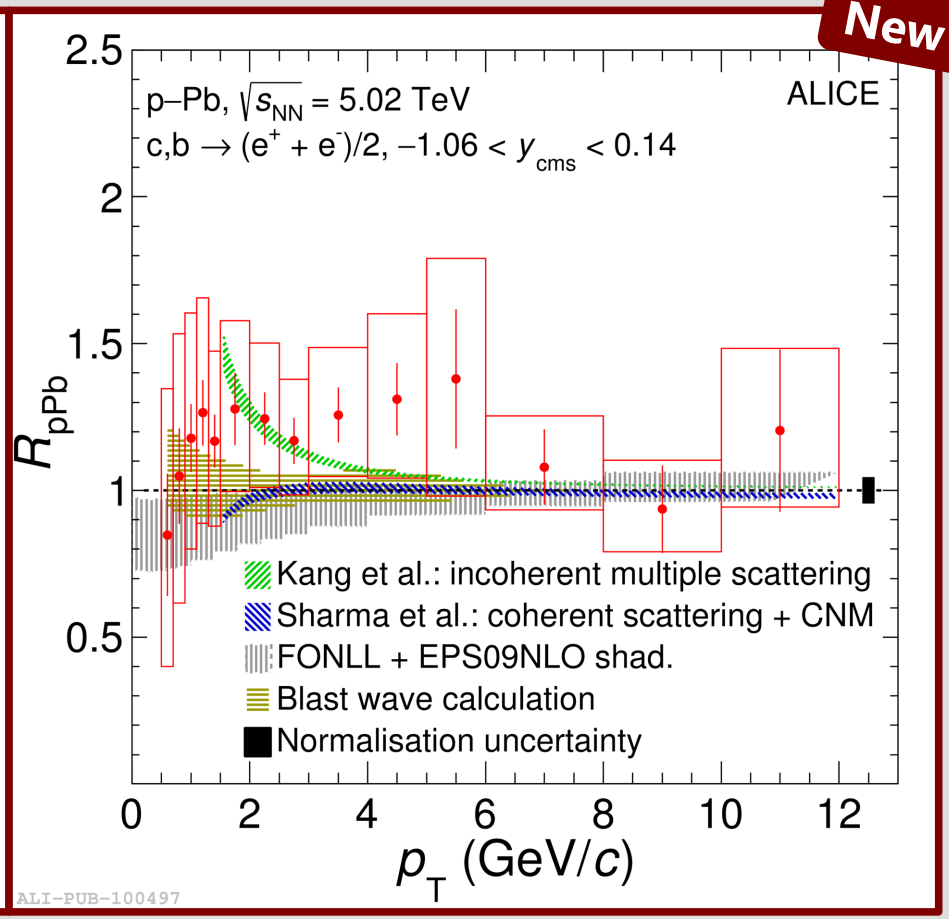
- **Centrality-dependent nuclear modification factor Q_{pPb}**: alternative approach to studying multiplicity dependence of D-meson production in p-Pb collisions
  - → Collision centrality expressed in terms of nuclear overlap function T_{pPb}
  - → Determined using Zero-Degree Neutron Calorimeter (ZN); based on energy deposited by neutrons at forward rapidity
  - → T_{pPb} & N_{coll} determination relies on the assumption that charged-particle multiplicity at mid-rapidity scales linearly with N_{part}
  - → **No centrality dependence** of nuclear modification seen, nor any significant p_T dependence in any centrality class.
  - → **See poster by Riccardo Russo for further details on multiplicity analysis & Q_{pPb} results**

ALICE: A Large Ion Collider Experiment (Electrons)



R_{pPb} of inclusive heavy-flavour decay electrons

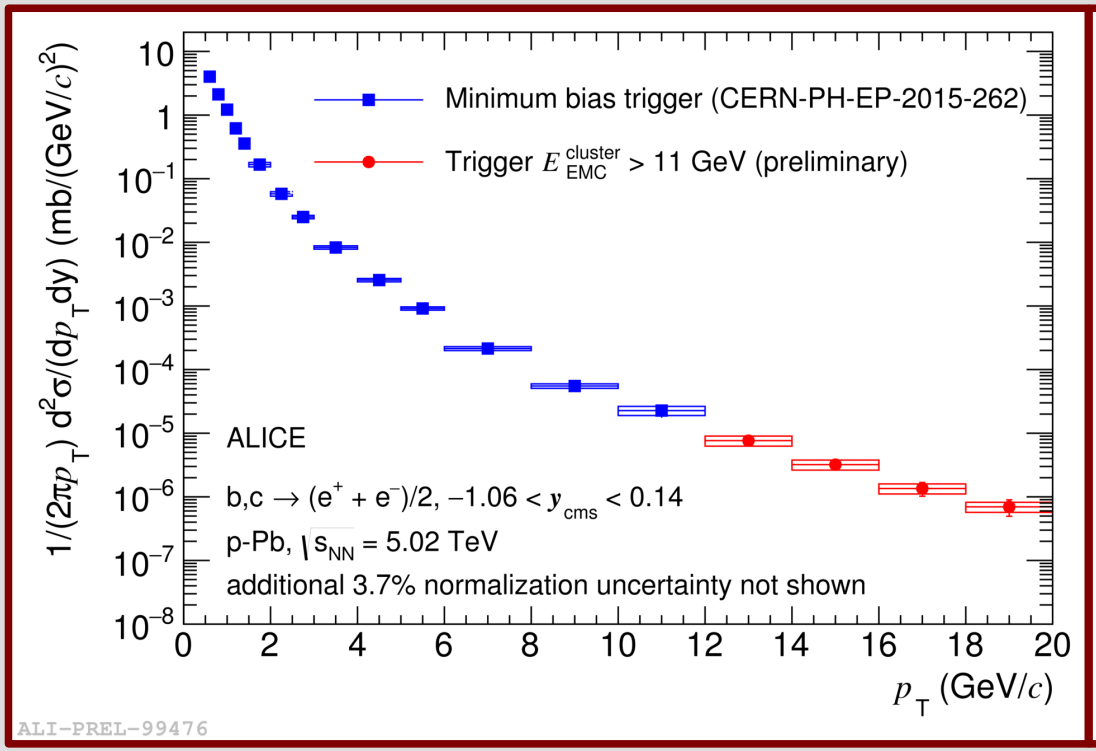


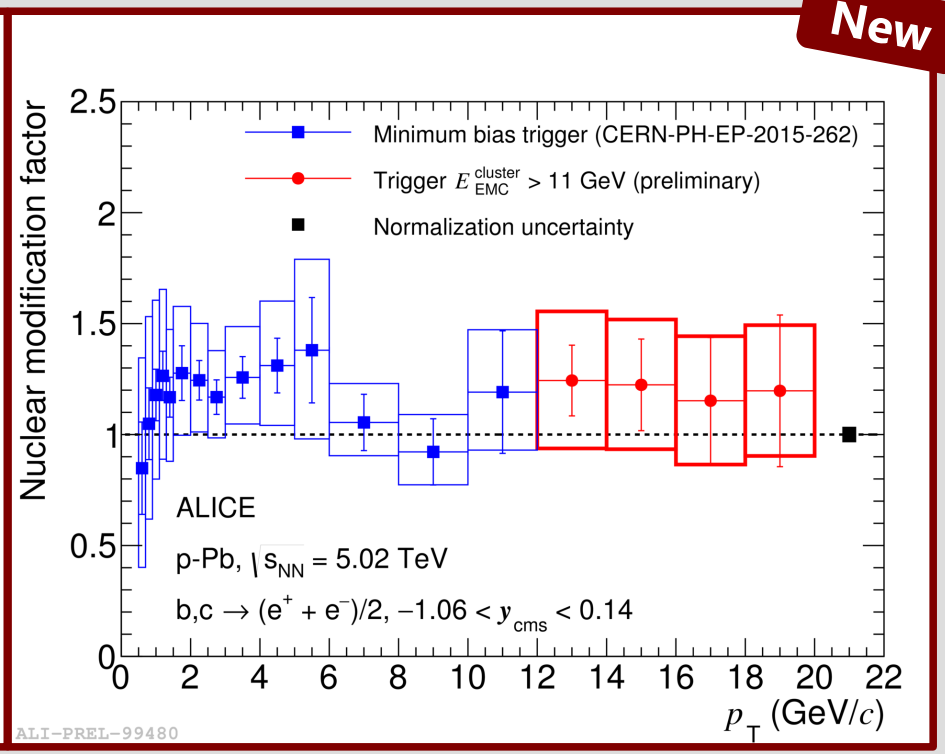


- Left: p_T-differential cross section measured in minimum-bias p-Pb collisions for inclusive electrons from heavy-flavour decays in $0.5 < p_T < 12$ GeV/c, compared with rescaled pp results. Right: R_{pPb} results compared with model calculations.
- **R_{pPb} is consistent with unity** & described by various models, as seen for D mesons

Kang et al.: *PLB 740 (2015) 23 ;* ***Sharma et al.:*** *Phys. Rev. C80 (2009) 054902;*
FONLL*: M. Cacciari et al., JHEP 9805 (1998) 007;* ***EPS09****: K. J. Eskola et al., JHEP 04 (2009) 065;*
ALICE Collaboration: *arXiv:1509:07491*

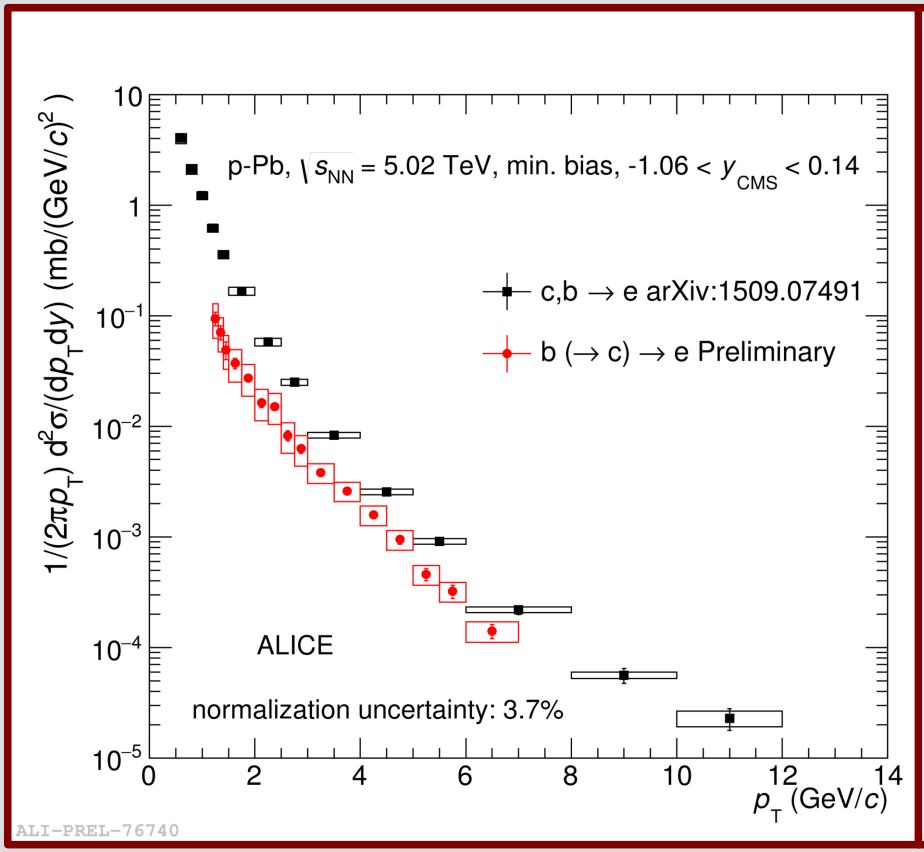
Heavy-flavour decay electrons at high p_T using EMCal

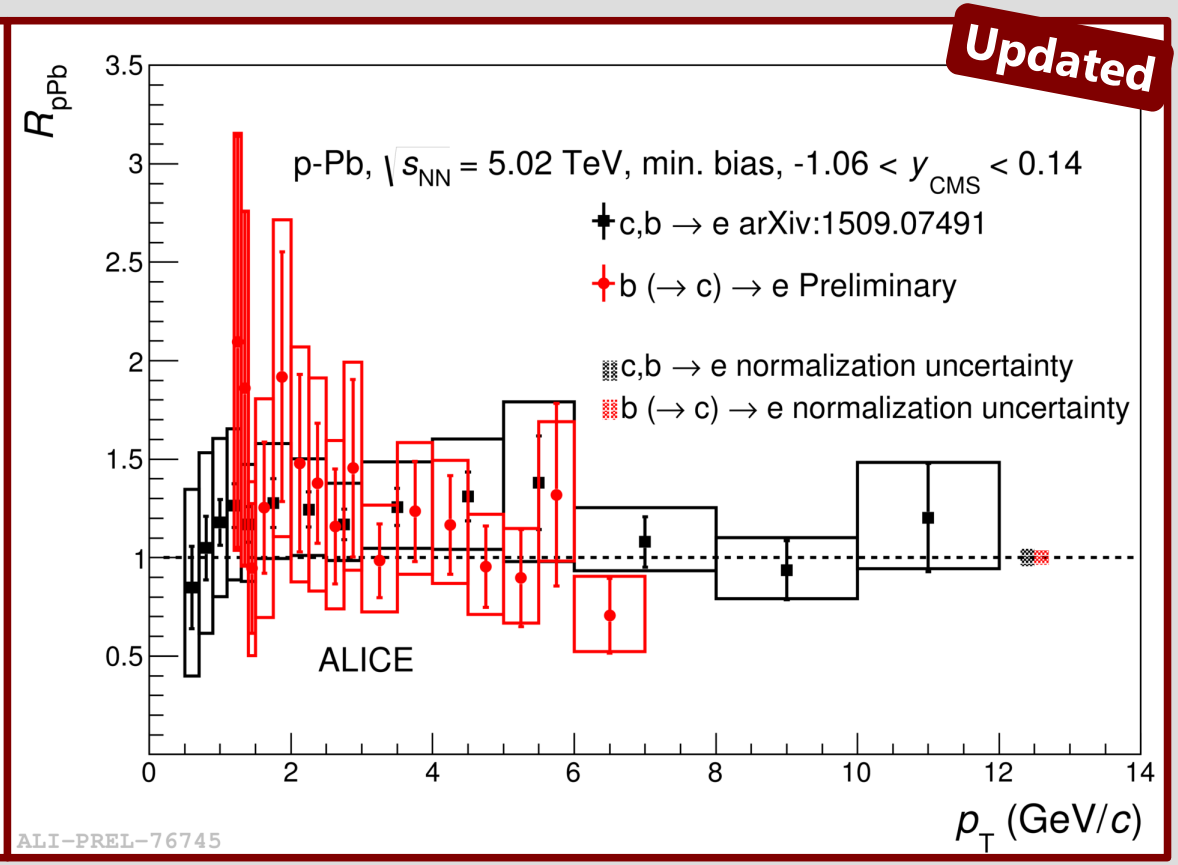




- Additional analysis of inclusive heavy-flavour decay electrons **using trigger from EMCal** (Electromagnetic Calorimeter), with trigger on deposited energy > 11 GeV
- **Results consistent with minimum-bias analysis**, extending R_{pPb} above p_T = 12 GeV/c, consistent with unity over entire momentum range
  → **See poster by Cristiane Jahnke for further details**

R_{pPb} of beauty-decay electrons

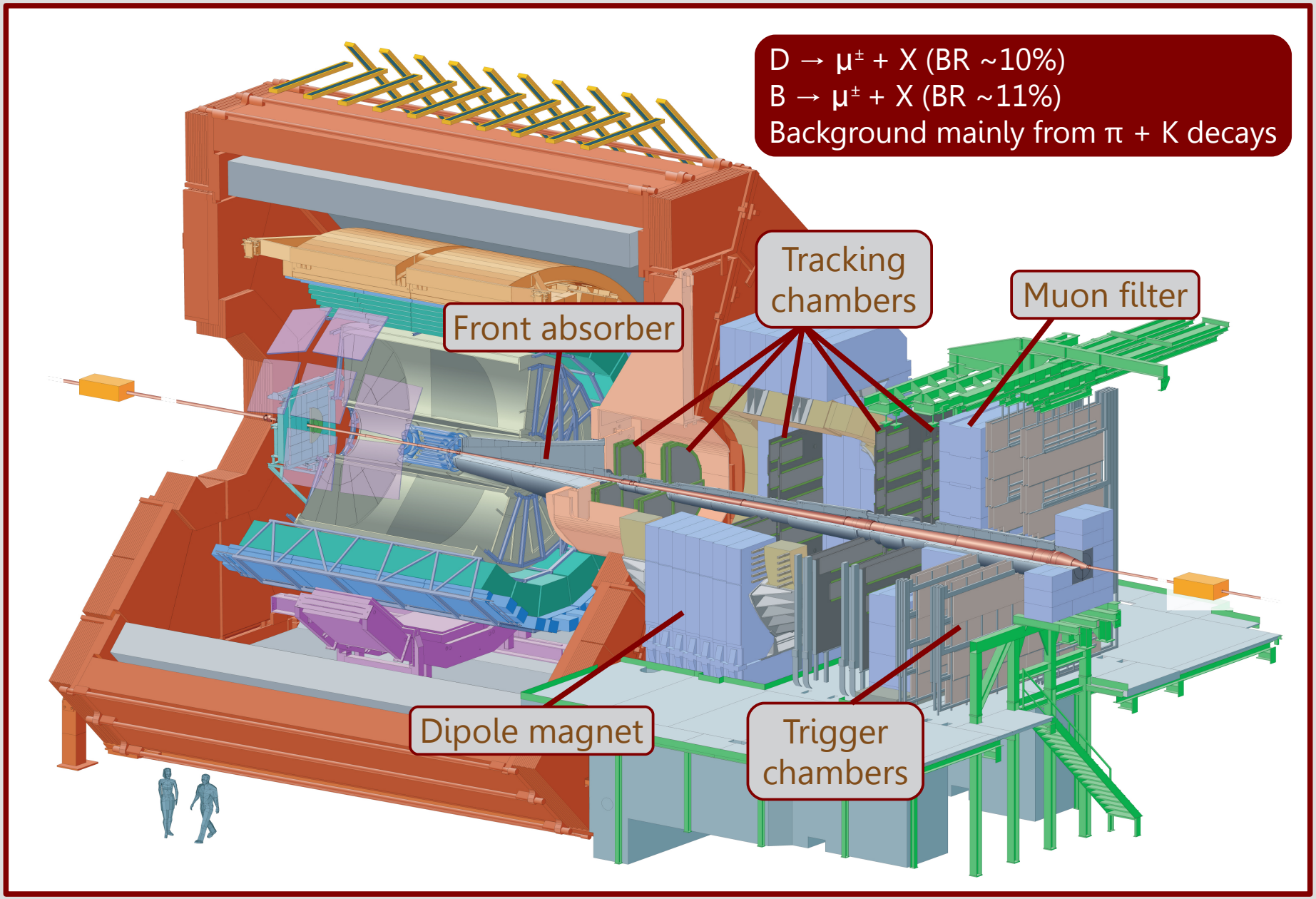




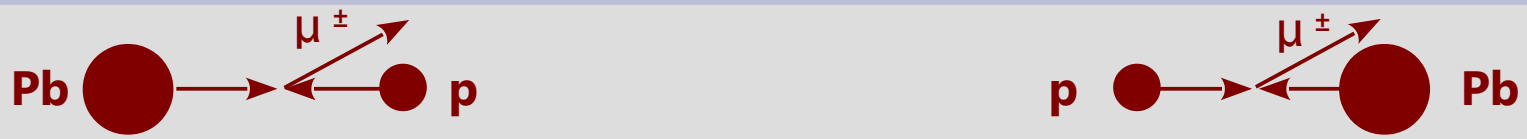
- Nuclear modification factor of **beauty-decay electrons** measured in p-Pb collisions
- Beauty-decay electrons are separated from inclusive heavy-flavour decay electrons via their impact parameter distributions
- R_{pPb} of beauty-decay electrons is **consistent with that of inclusive heavy-flavour decay electrons & with unity**

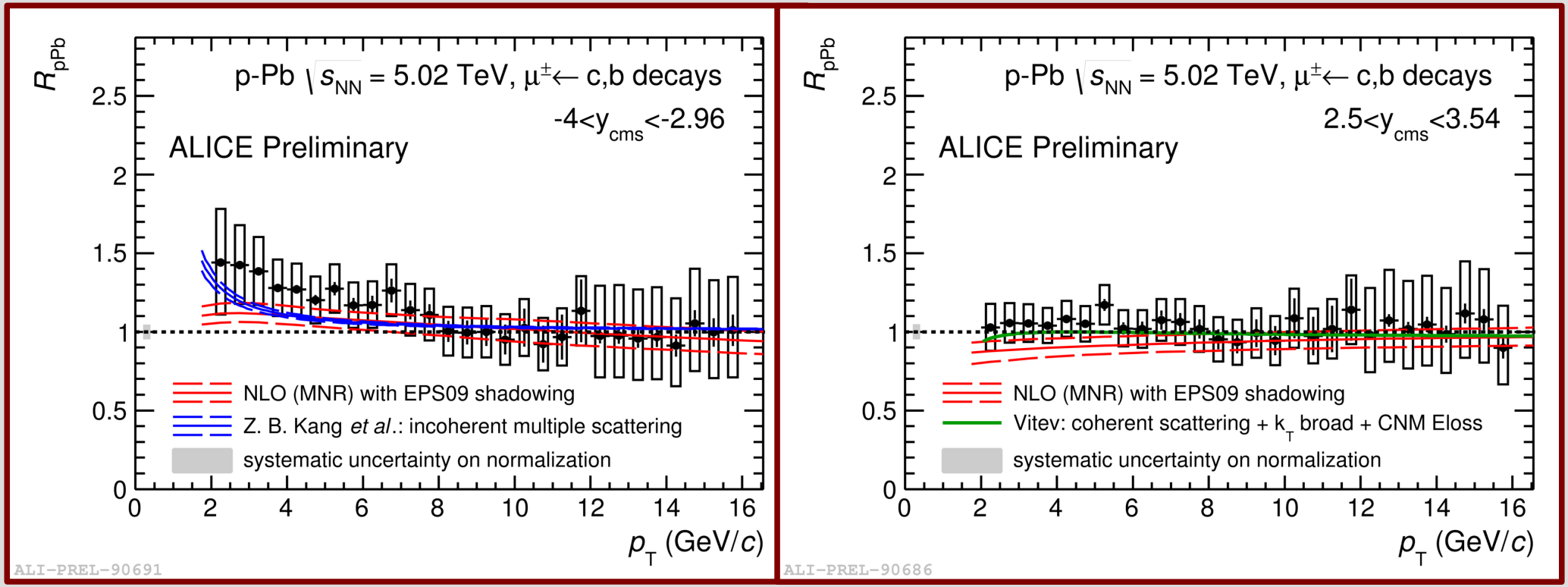
ALICE Collaboration (b,c → e): *arXiv:1509.07491*

ALICE: A Large Ion Collider Experiment (Muons)



R_{pPb} of heavy-flavour decay muons





- **Consistent with unity** at backward (Pb-going, left) and forward (p-going, right) rapidity at high p_T
  → Backward rapidity: slightly larger than unity in $2 < p_T < 4$ GeV/c
- Data described within uncertainties by model calculations that include cold nuclear matter effects

***pQCD NLO (MNR)**: M. Mangano et al., Nucl. Phys. B 373 (1992) 295; **EPS09**: K. J. Eskola et al., JHEP 04 (2009) 065 ;*
***Z. B. Kang et al.:** PLB 740 (2015) 23 ; **I. Vitev:** PRC 75 (2007) 064906*

Summary

- **Nuclear modification factor R_{pPb}** measured for prompt D mesons & semileptonic heavy-flavour decays at mid-, forward and backward rapidity
  → All channels (D mesons, electrons, muons) show **charm R_{pPb} consistent with unity**; yield suppression seen at high p_T in Pb-Pb collisions is due to in-medium effects
  → **Beauty R_{pPb}** measured via electron decays; consistent with R_{pPb} of heavy-flavour decay electrons and with unity

- **Centrality-dependent Q_{pPb}** measured for D mesons
  → Results consistent with unity for all p_T and centrality
    → **Consistent with binary scaling**

- Measurement of relative **D-meson yields as a function of multiplicity**:
  → Slightly faster-than-linear increase seen for D mesons with respect to charged particles at high multiplicity at mid-rapidity; roughly linear for V0A multiplicity over measured interval. **Estimators consistent within uncertainties**.
  → Multiplicity dependence **comparable with that measured in pp for charged-particle multiplicity at mid-rapidity**
  → Results in this region described more closely by EPOS 3 calculations that **include viscous hydrodynamics**

Future prospects – what's next?

- **Run I**
  - → **D^0** under study **at ultra-low p_T** (< 1 GeV/c) in pp & p-Pb collisions
    - → Greatly reduced uncertainties on open-charm cross section; R_{pPb} down to p_T = 0 GeV/c
  - → Centrality-dependent **Q_{pPb} of heavy-flavour decay muons** also being studied

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- **Run II (2015-2017)**
  - → **Higher $\sqrt{s}$ + increased luminosity** in all systems
  - → **Transition Radiation Detector (TRD) completed, with full azimuthal coverage**
    - → Enhanced electron triggering + identification at intermediate & high p_T
  - → Further p-Pb run planned at higher $\sqrt{s_{NN}}$ towards end of Run II

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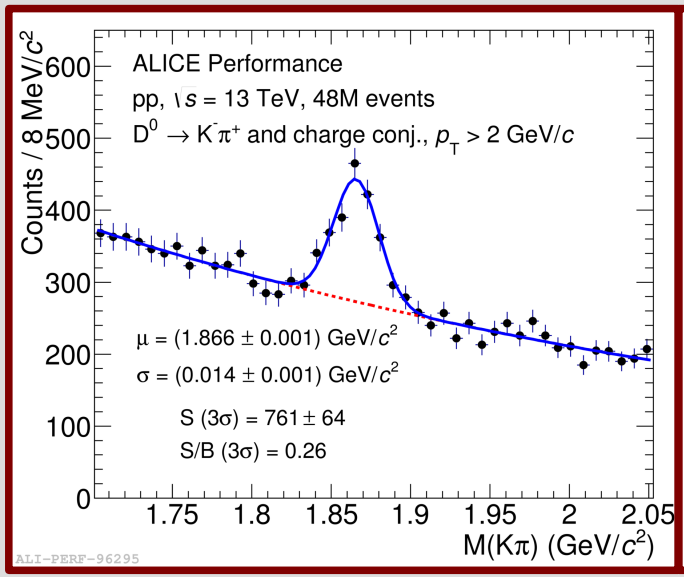
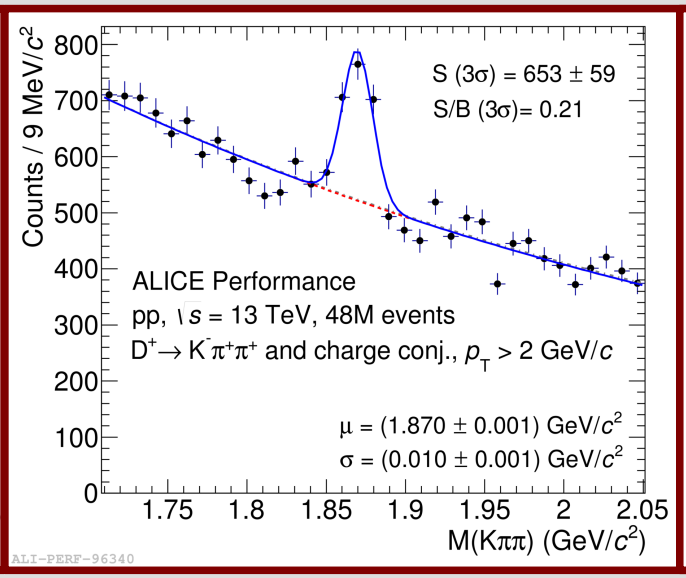
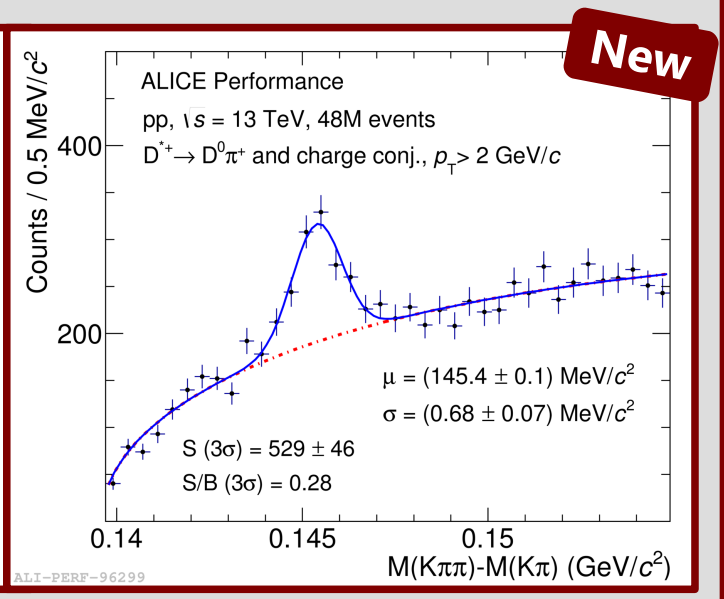
  - → Further p-Pb run planned at higher $\sqrt{s_{NN}}$ towards end of Run II
  - → **First look at Run II data in pp collisions at $\sqrt{s}$ = 13 TeV**: already high statistical significance for D^0, D^+ and D^{*+} for p_T > 2 GeV/c in first 48M events







Further talks & posters on HF in p-Pb in ALICE

- **Fabio Colamaria**, Heavy-flavour correlations and multiplicity dependence in pp and p-Pb collisions with ALICE *(Next talk in this session)*

Posters:

- **Yasser Corrales Morales**, MC performance studies of beauty-jet tagging in p-Pb collisions
- **Cristiane Jahnke**, High-p_T heavy-flavour decay electron measurements in p-Pb collisions with the ALICE EMCal
- **Jasper van der Maarel**, D^{*+}-meson production in p-Pb collisions in ALICE
- **Riccardo Russo**, D^+-meson production as a function of charged-particle multiplicity in p-Pb collisions
- **Sonia Rajput**, Measurement of D meson-charged particle azimuthal angular correlations in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE

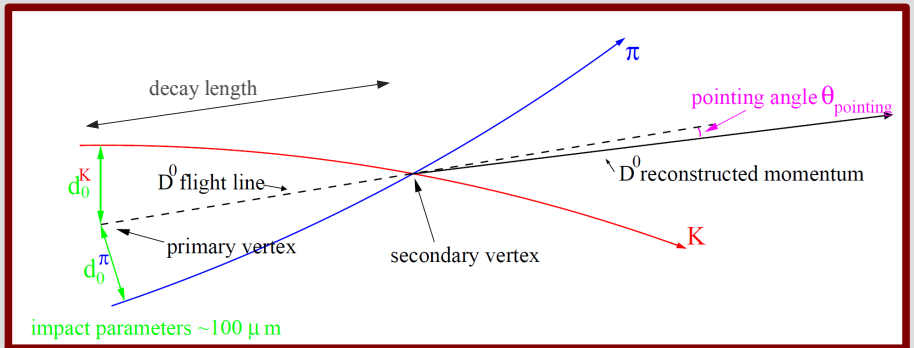
– Backup slides –

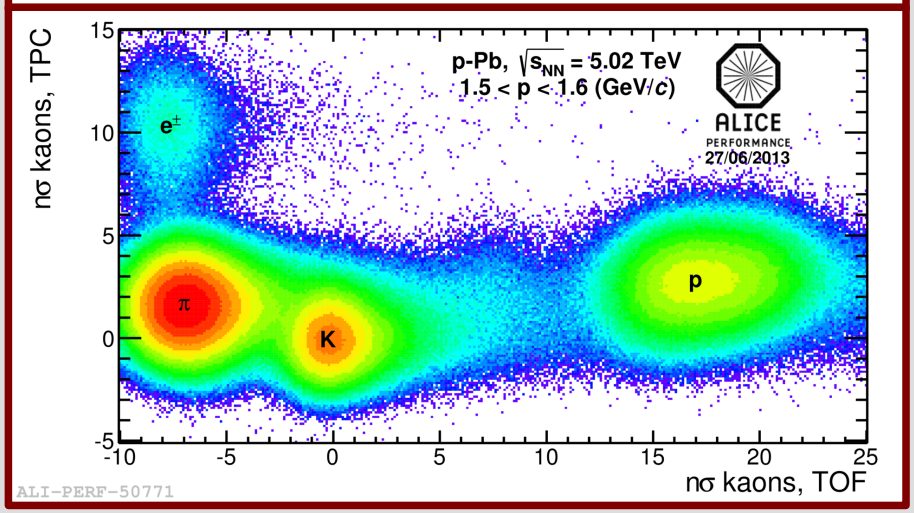
Reconstruction of D mesons

- Strategy: full reconstruction of hadronic decays of D mesons
  → Retains full kinematic information of original particle

$D^0 \rightarrow K^-\pi^+$ (BR = 3.88 ± 0.05%; $c\tau \approx 123$ μm) $D^{*+} \rightarrow D^0\pi^+$ (BR = 67.7 ± 0.5%)
$D^+ \rightarrow K^-\pi^+\pi^+$ (BR = 9.13 ± 0.19%, $c\tau \approx 312$ μm) $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$ (BR = 2.28 ± 0.12%, $c\tau \approx 150$ μm)
(and respective charge conjugates)

- Standard reconstruction relies on topological + PID selections to reduce combinatorial background



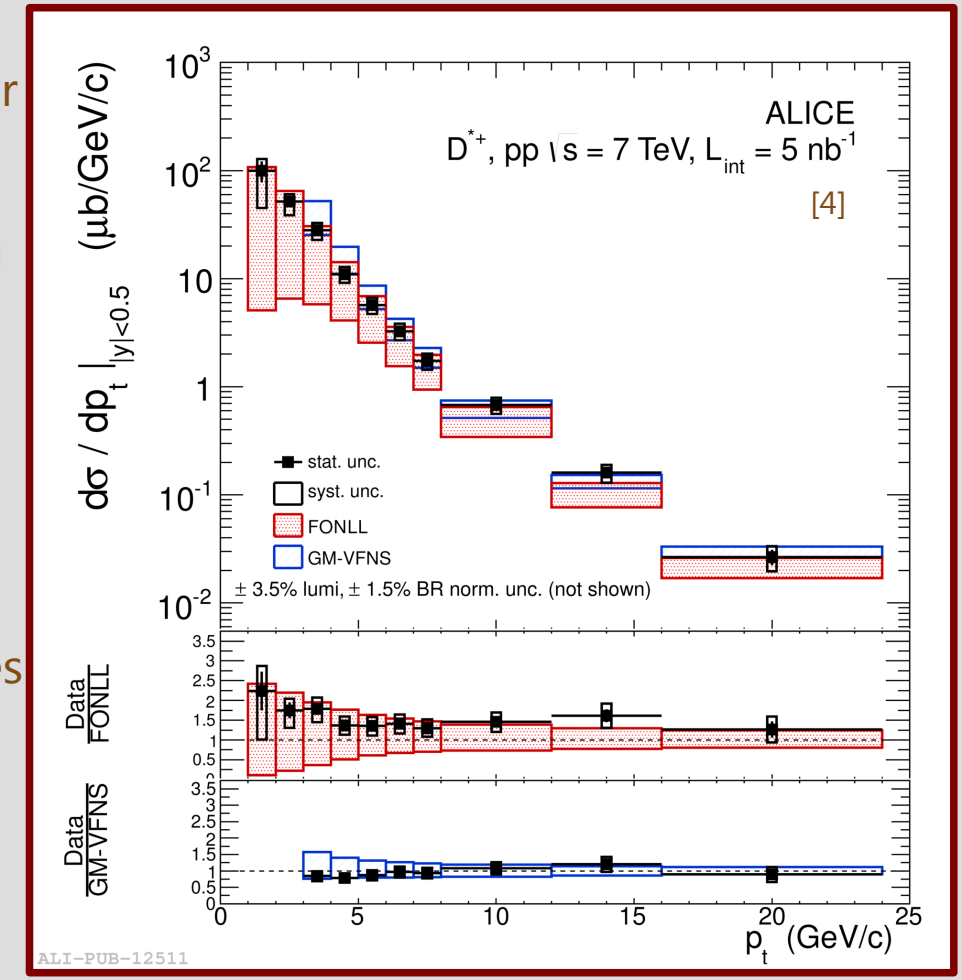


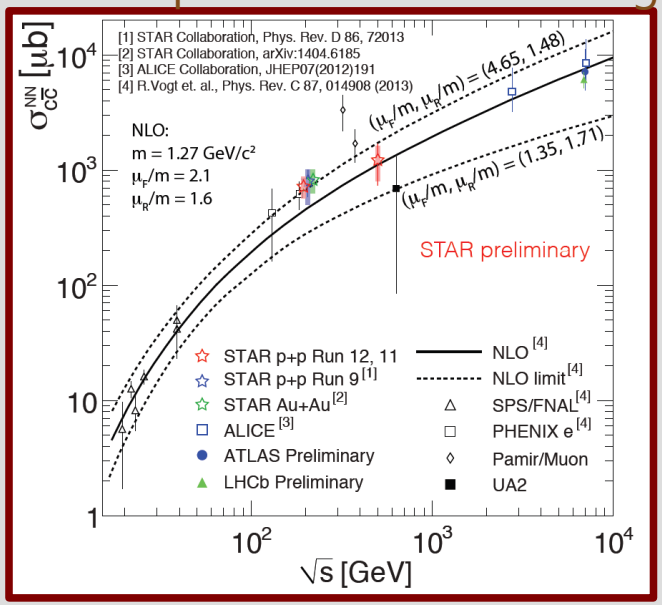
- Example (left): D^0 meson: non-zero lifetime; decay vertex of mesons displaced from interaction point (primary vertex)
  → Decay length, impact parameter, pointing angle (for example) can be used to select candidates
- For D^{*+}, D^0 candidate paired with soft π^+ at primary vertex
- Standard PID at mid-rapidity uses TOF (where available) + TPC, with 'nσ' PID
  → Strong separation of pions, kaons and protons at wide range of momenta

[1] Particle Data Group, Chin. Phys. C, 38, 090001 (2014)

D-meson measurements in pp

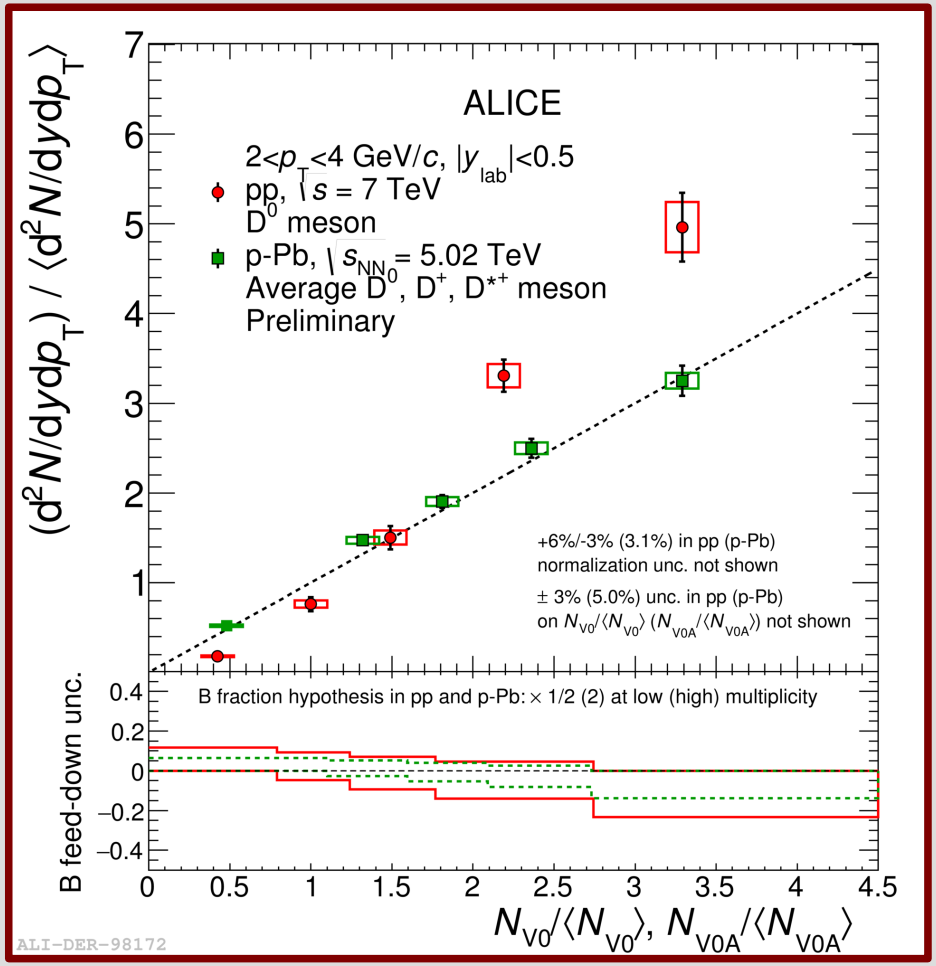
- Results at √s = 7 TeV used as reference for p-Pb and Pb-Pb collisions
  → Energy scaled using **FONLL**[1] where necessary for other systems
- Provides constraint on model calculations
  → Results well described by FONLL and GM-VFNS[2] pQCD frameworks (right: results for D^{*+})
- Results for all D-meson species at √s = 2.76 and 7 TeV extrapolated to full phase space using FONLL to extract total $c\bar{c}$ cross section (below, latest STAR result)
  → Good agreement with NLO[3] predictions & trend from other experiments at wide range of energies





[1] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007
[2] B. A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, arXiv:1202.0439 [hep-ph]
[3] M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B373 (1992) 295
[4] B. Abelev et al. (ALICE collaboration), JHEP 1201 (2012) 128

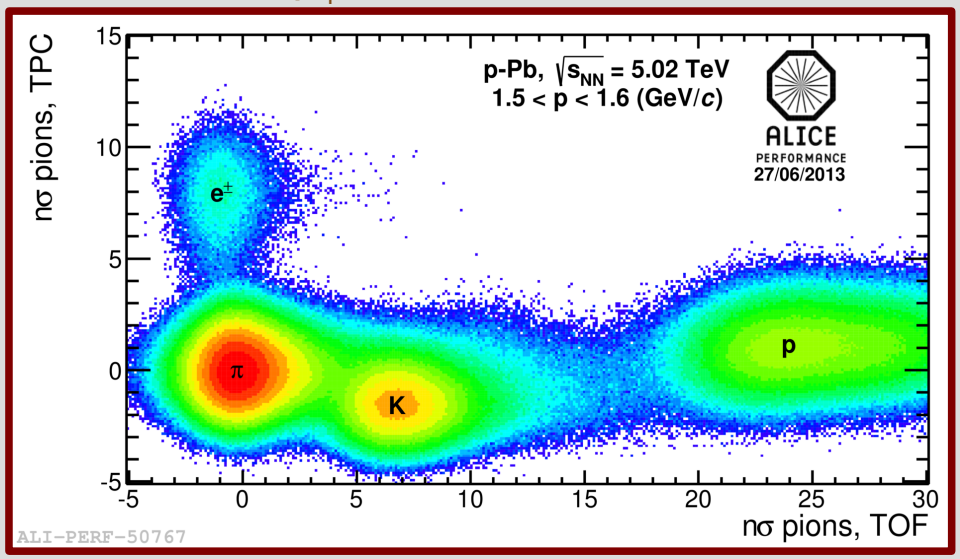
D mesons vs V0A multiplicity: comparison with pp



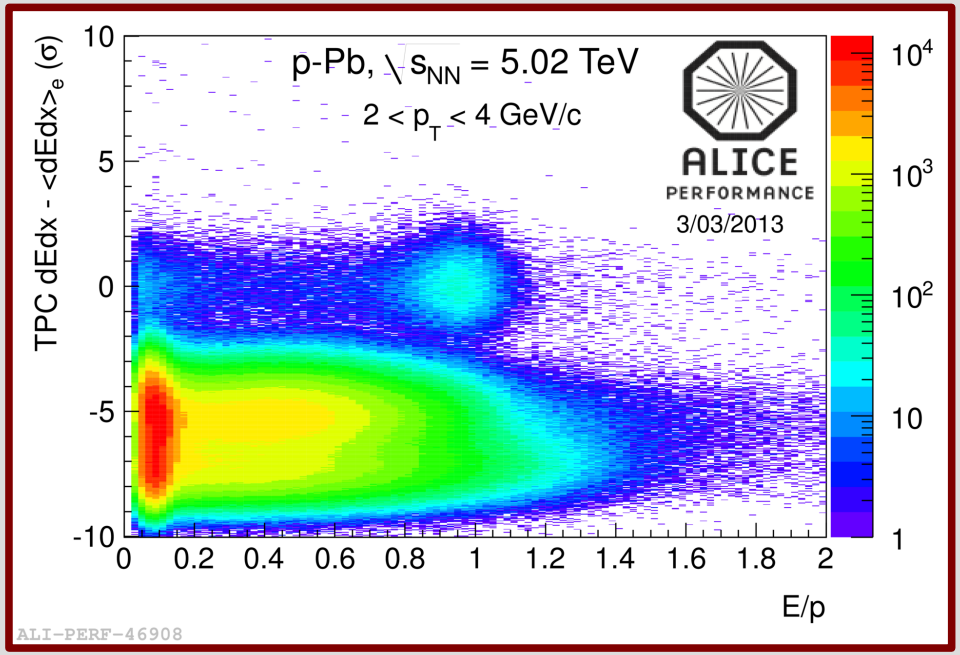
- **pp results show faster-than-linear increase** at high multiplicity
- **p-Pb: consistent with linear increase** with respect to backward multiplicity
- Caveat: multiplicity in different rapidity intervals in two measurements (due to coverage of detector & rapidity of p-Pb centre-of-mass system with respect to lab frame)
  - → **Requires model calculations with multiplicity at backward rapidity** to fully understand difference between collision systems

Heavy-flavour decay electron identification

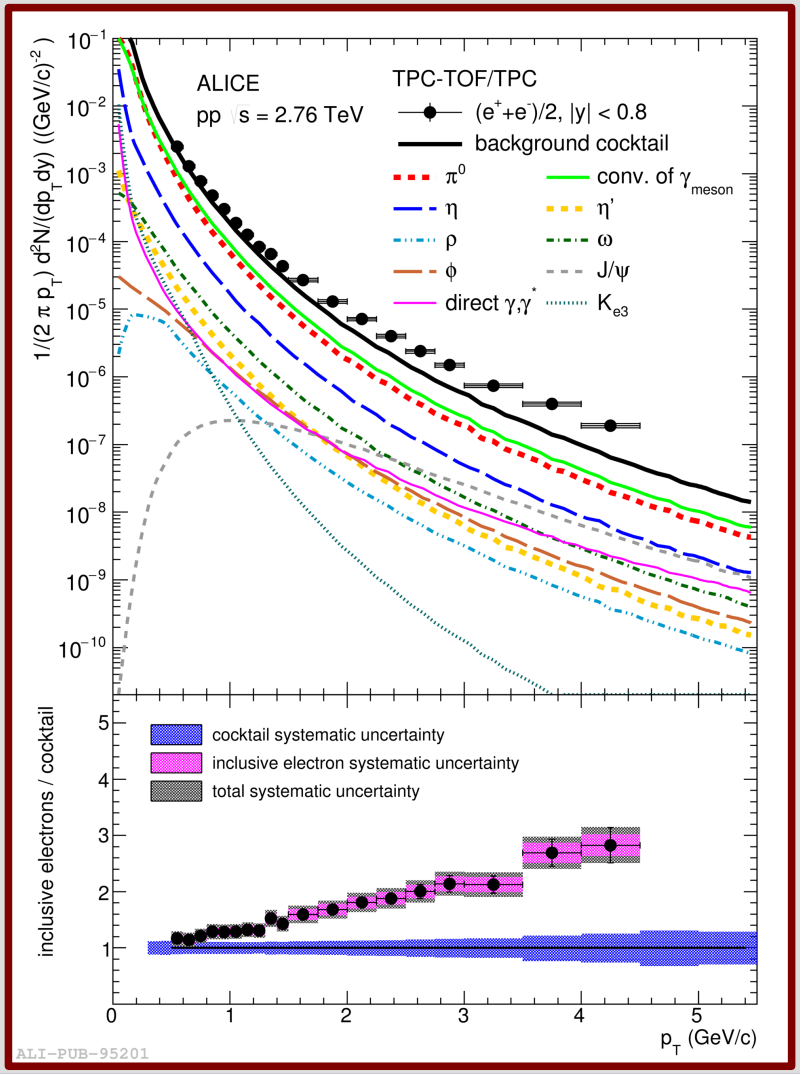
- PID at low p_T: TPC, TOF, TRD



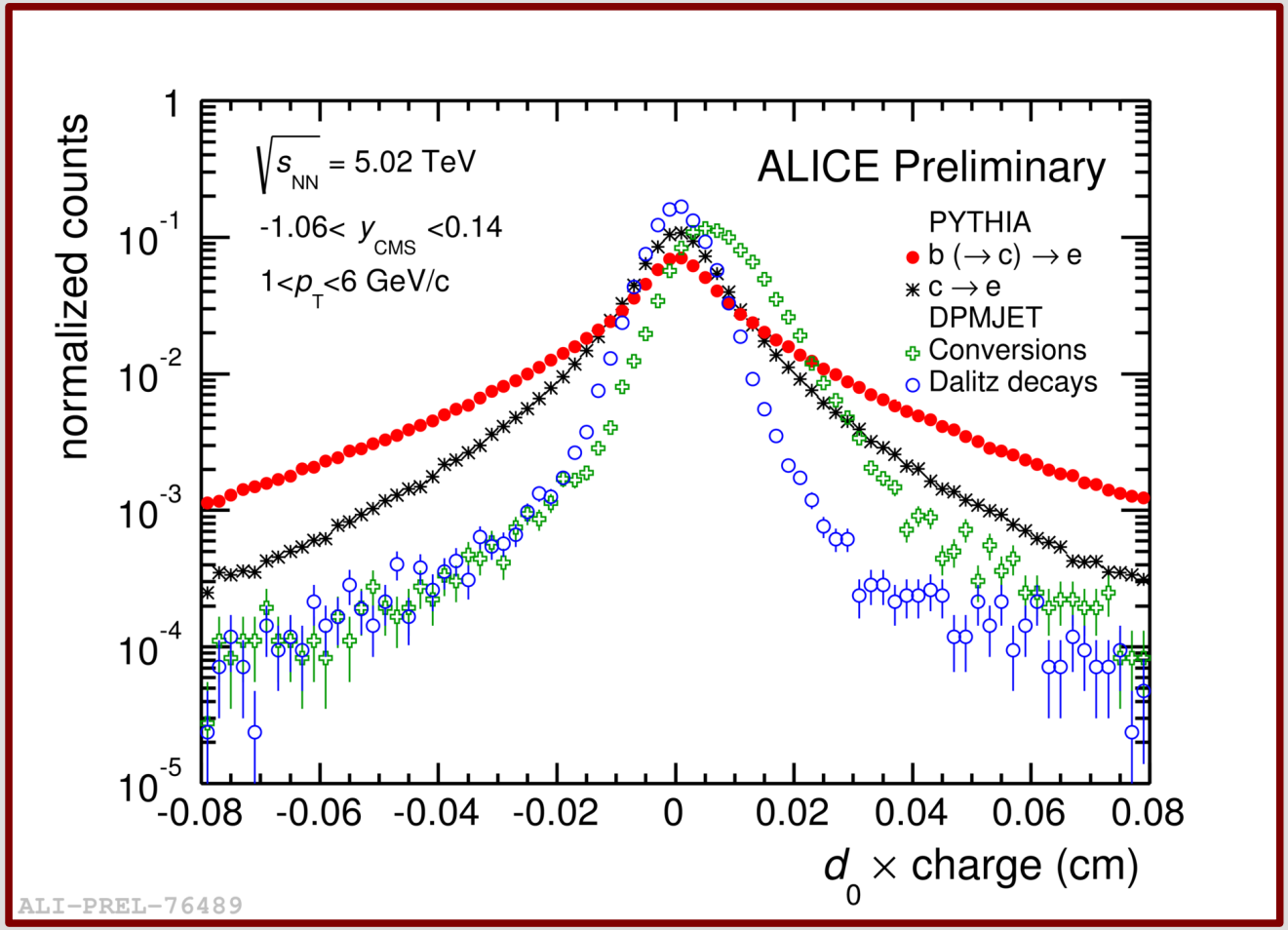
- PID at high p_T: TPC + EMCal



- Background subtraction:
  - → Cocktail method: MC generator for variety of hadronic sources
  - → Invariant mass method for e^+e^- to remove photon conversions and Dalitz decays

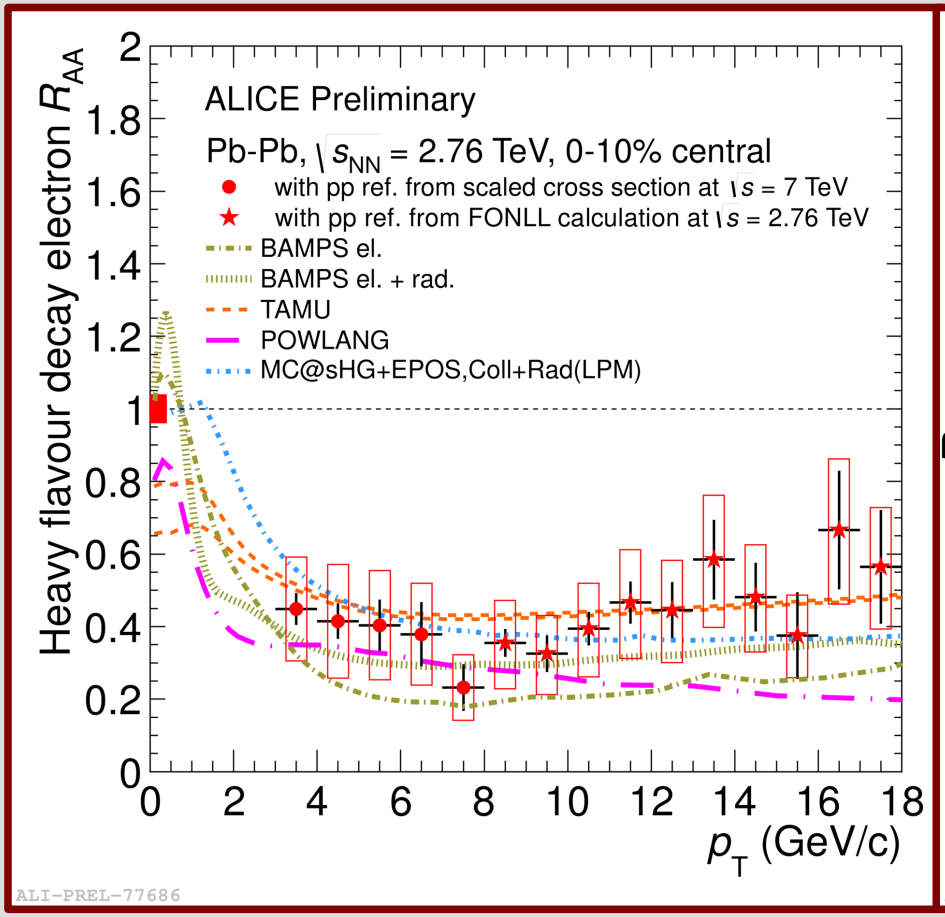


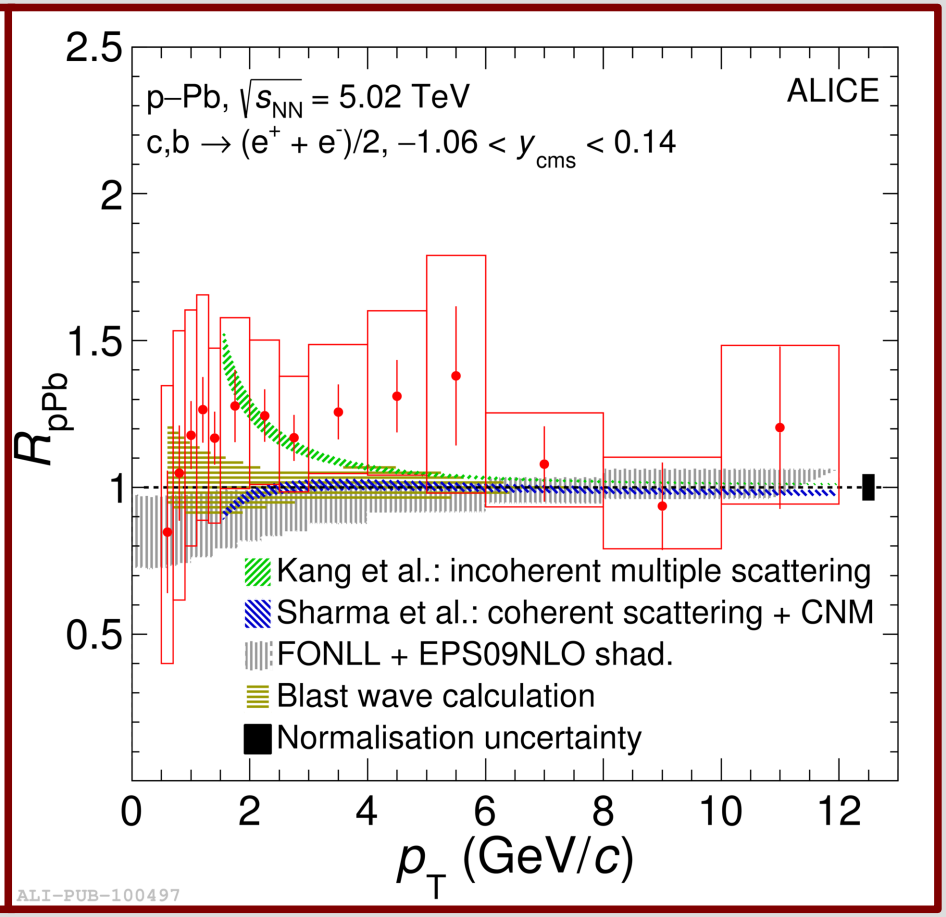
Impact parameter distributions for electrons from b, c



- Maximum-likelihood fit to impact parameter distribution used to extract fraction of electrons from beauty-hadron decays
- Template impact parameter distributions for electrons from beauty, charm, conversions, Dalitz decays via PYTHIA generator & DPMJET
- Impact parameter distribution from beauty-decay electrons broad due to large decay length ($c\tau \approx 490$ μm)

R_{AA} & R_{pPb} of heavy-flavour decay electrons

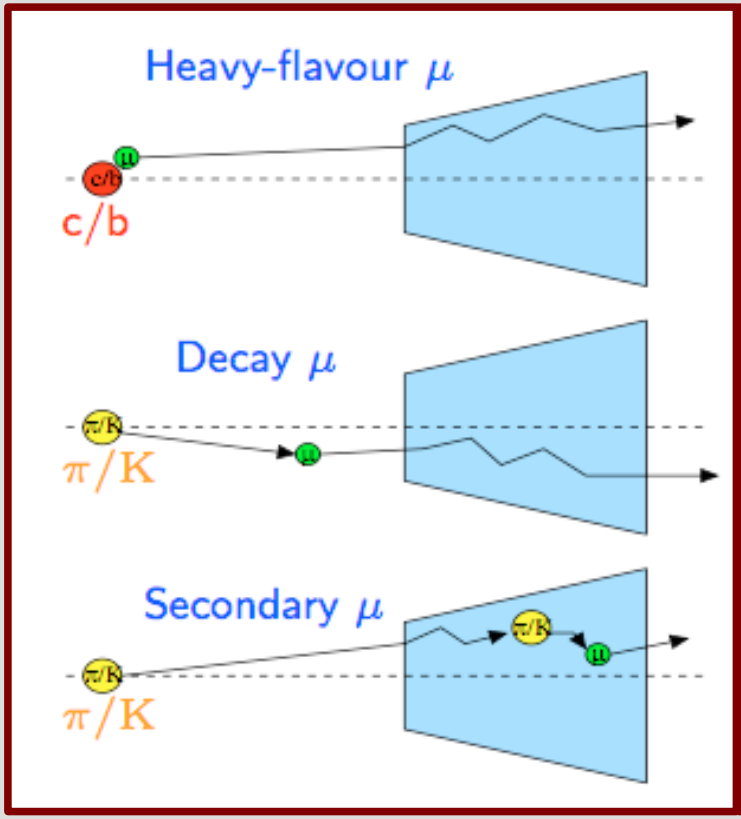


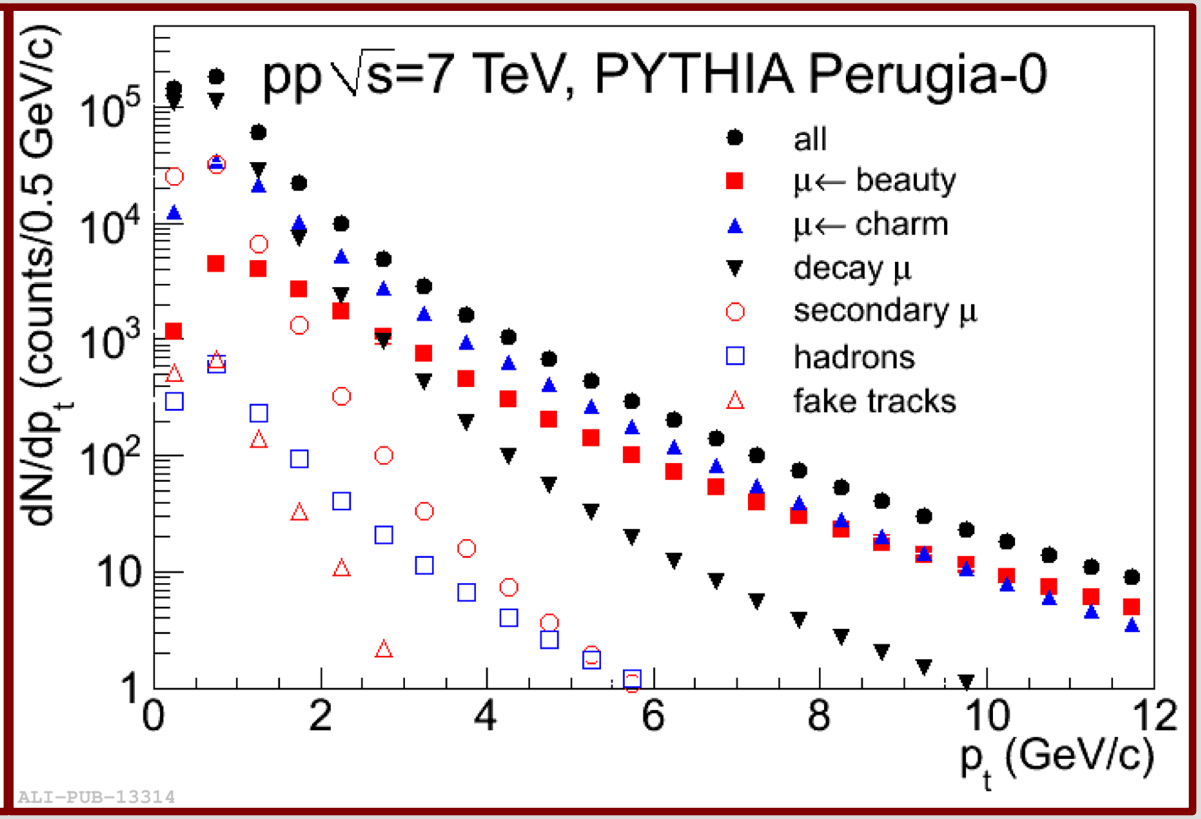


- R_{pPb}: consistent with unity & models that include initial-state effects
- R_{AA}: significantly less than unity above p_T = 3 GeV/c, consistent with models that include final-state effects
  - → Yield suppression at high p_T in Pb-Pb collisions is due to in-medium effects

__BAMPS__: Fochler et al., J. Phys. G38 (2011) 124152; __POWLANG__: Alberico et al., Eur.Phys.J C71 (2011) 1666;
__TAMU__: Rapp, He et al., Phys. Rev. C 86 (2012) 014903; __Kang et al.:__ PLB 740 (2015) 23 ; __Sharma et al.:__ Phys. Rev. C80 (2009) 054902;
__FONLL__: M. Cacciari et al., JHEP 9805 (1998) 007; __EPS09__: K. J. Eskola et al., JHEP 04 (2009) 065
__ALICE Collaboration (p-Pb):__ arXiv:1509.07491

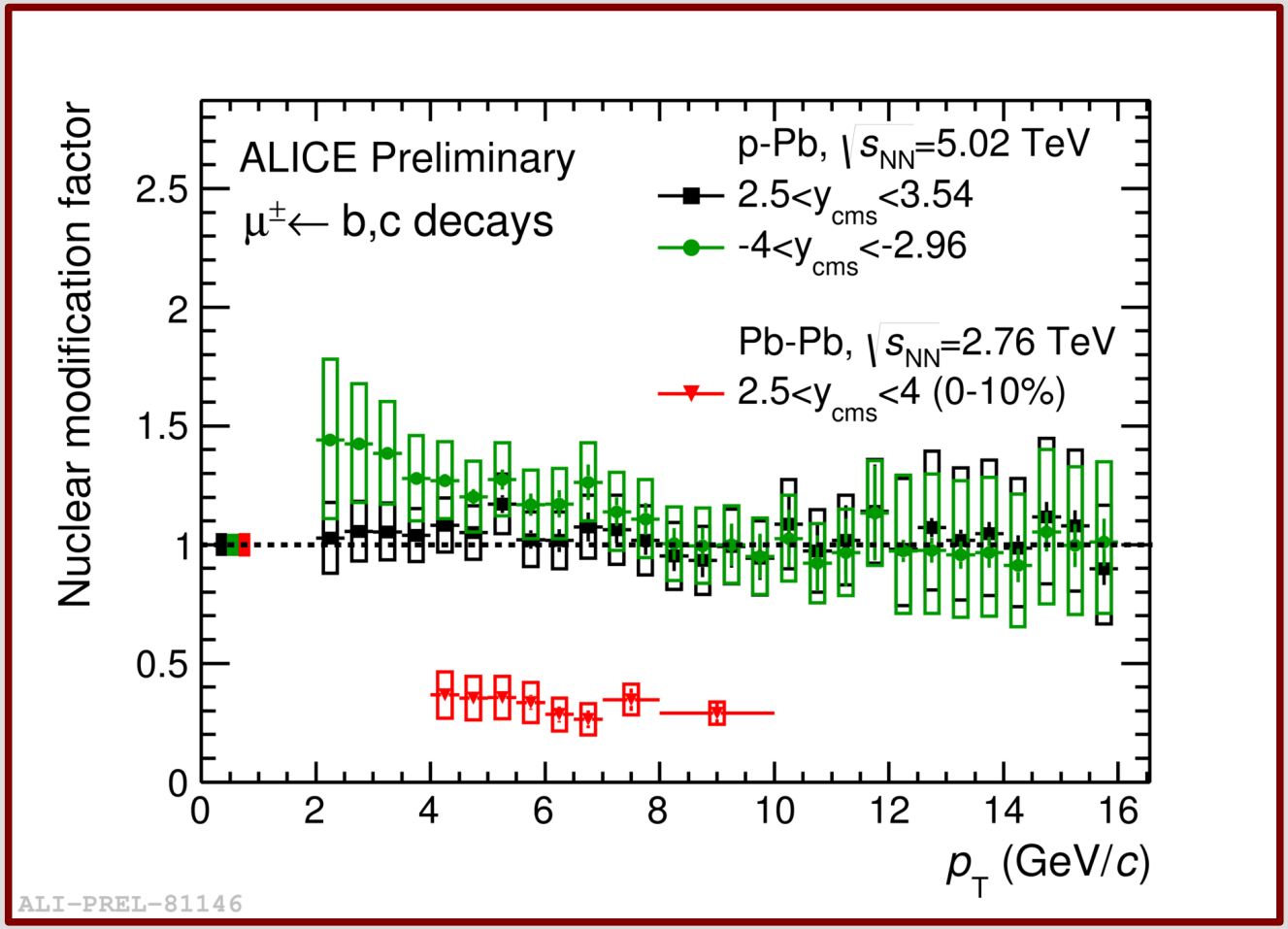
Identification of heavy-flavour decay muons





- Track selection:
  - → Acceptance: $-4 < \eta_{lab} < -2.5$
  - → Punch-through hadrons removed by muon trigger matching
  - → Beam-gas & secondary muons removed using muon trigger signal & cut on p x DCA
- Background subtraction:
  - → Main source: muons from decays of pions and kaons; subtracted using MC dN/dp_T normalised to data at low p_T
  - → Background decreases with increasing p_T

R_{pPb} & R_{AA} of heavy-flavour decay muons



- R_{pPb}: consistent with unity at both forward and backward rapidity
- R_{AA}: significantly smaller than unity for $4 < p_T < 10$ GeV/c
  → Suppression is due to in-medium effects