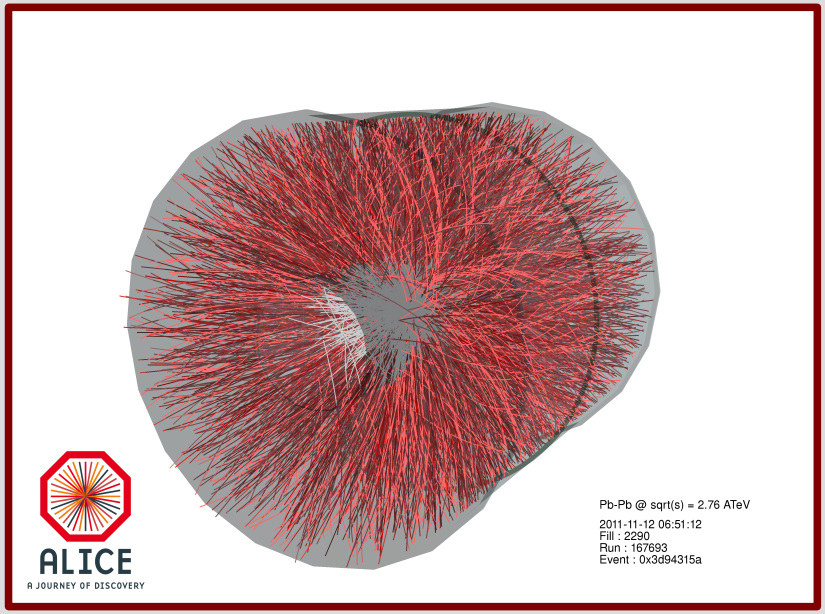
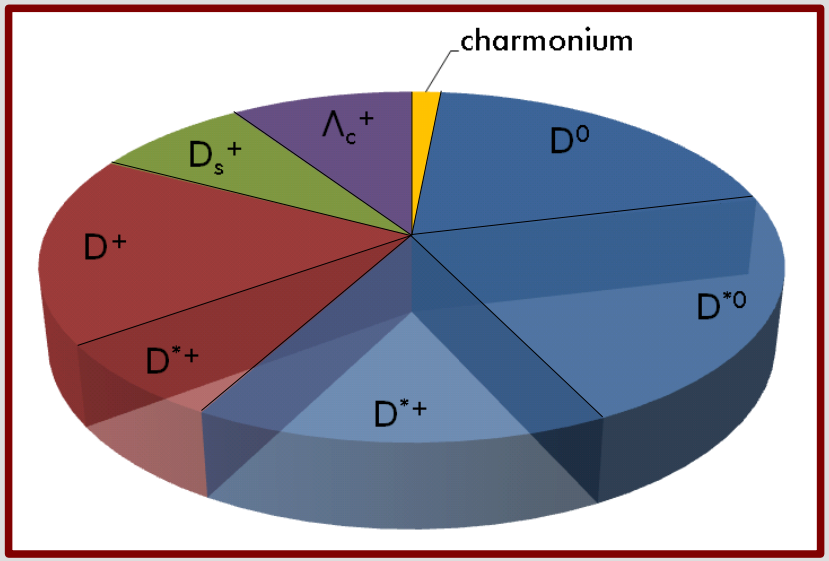
Recent open heavy-flavour results from ALICE at the LHC

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

Motivation: Why open heavy flavour?

- 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 large mass, charm and beauty quarks are produced in the **early stages** of the collision.
  → Experience the **full evolution** of the system.
- Expected hierarchy: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ due to colour charge & mass dependence of in-medium energy loss[1]
- Production measured in ALICE in three ways:
  → Hadronic decays of D mesons at mid-rapidity
  → Semileptonic decays at mid-rapidity ($D/B \rightarrow e^{\pm} + X$)
  → Semileptonic decays at forward/backward rapidity ($D/B \rightarrow \mu^{-} + X$); probes different Bjorken-*x* region

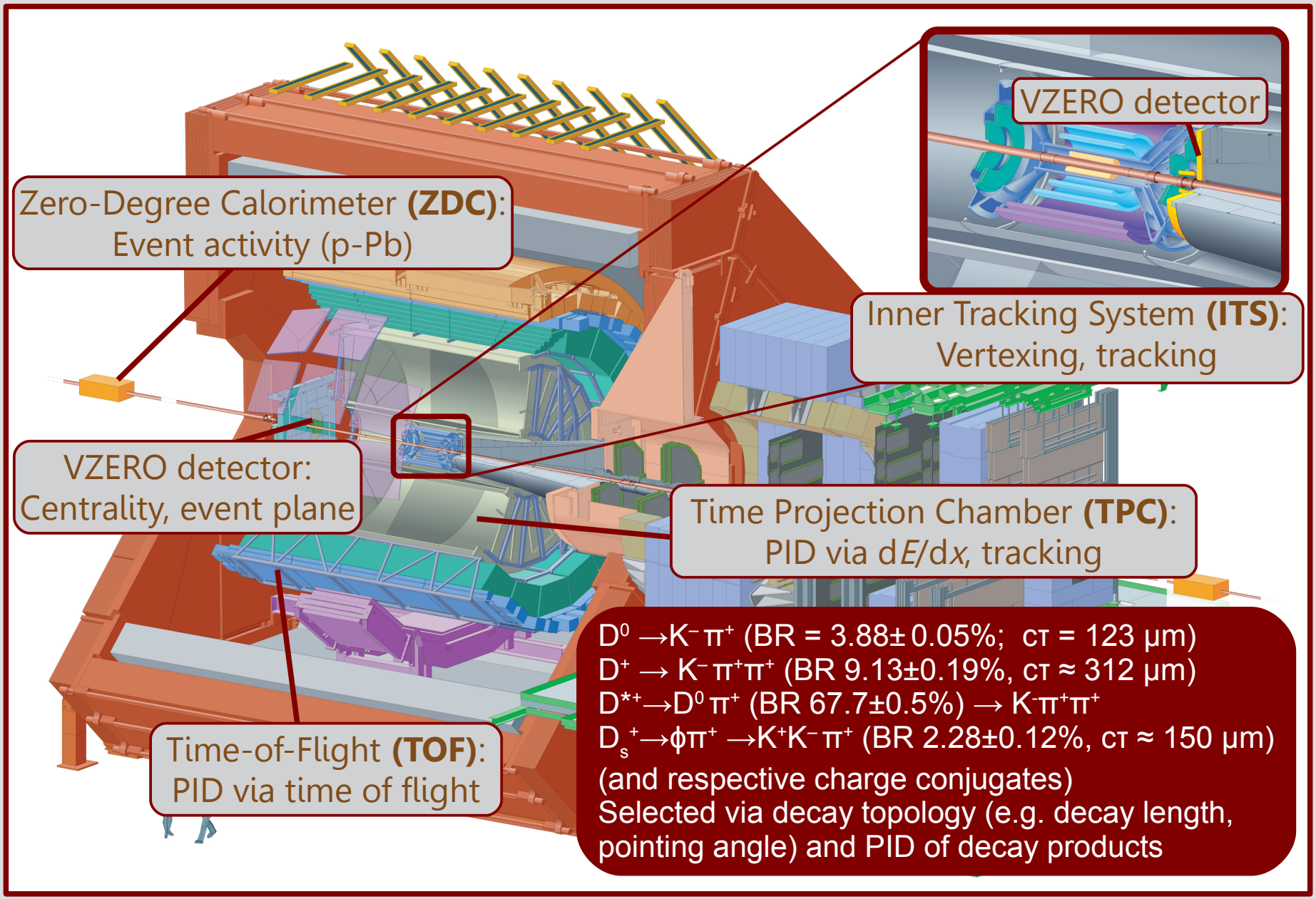




Blue: D^0, Red: D^+; Solid: Direct production, Hollow: feed-down from resonant state)

[1] Y. L. Dokshitzer, D. E. Kharzeev, Phys. Lett. B519 (2001)

ALICE: A Large Ion Collider Experiment (D mesons)



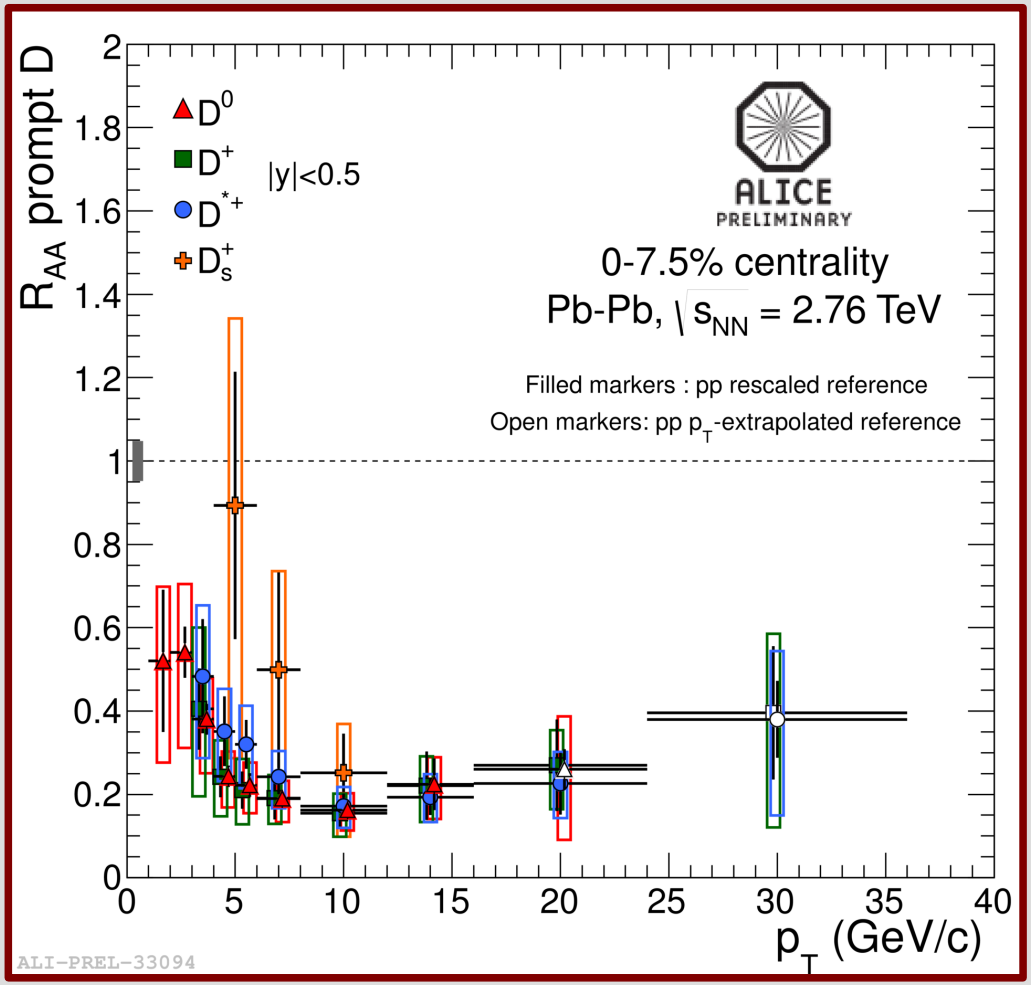
$D^0 \rightarrow K^- \pi^+$ (BR = 3.88± 0.05%; cτ = 123 μm)
$D^+ \rightarrow K^- \pi^+ \pi^+$ (BR 9.13±0.19%, cτ ≈ 312 μm)
$D^{*+} \rightarrow D^0 \pi^+$ (BR 67.7±0.5%) → $K^- \pi^+ \pi^+$
$D_s^+ \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$ (BR 2.28±0.12%, cτ ≈ 150 μm)
(and respective charge conjugates)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

Measured R_{AA} of D mesons

- Nuclear modification in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV measured for all four species using:

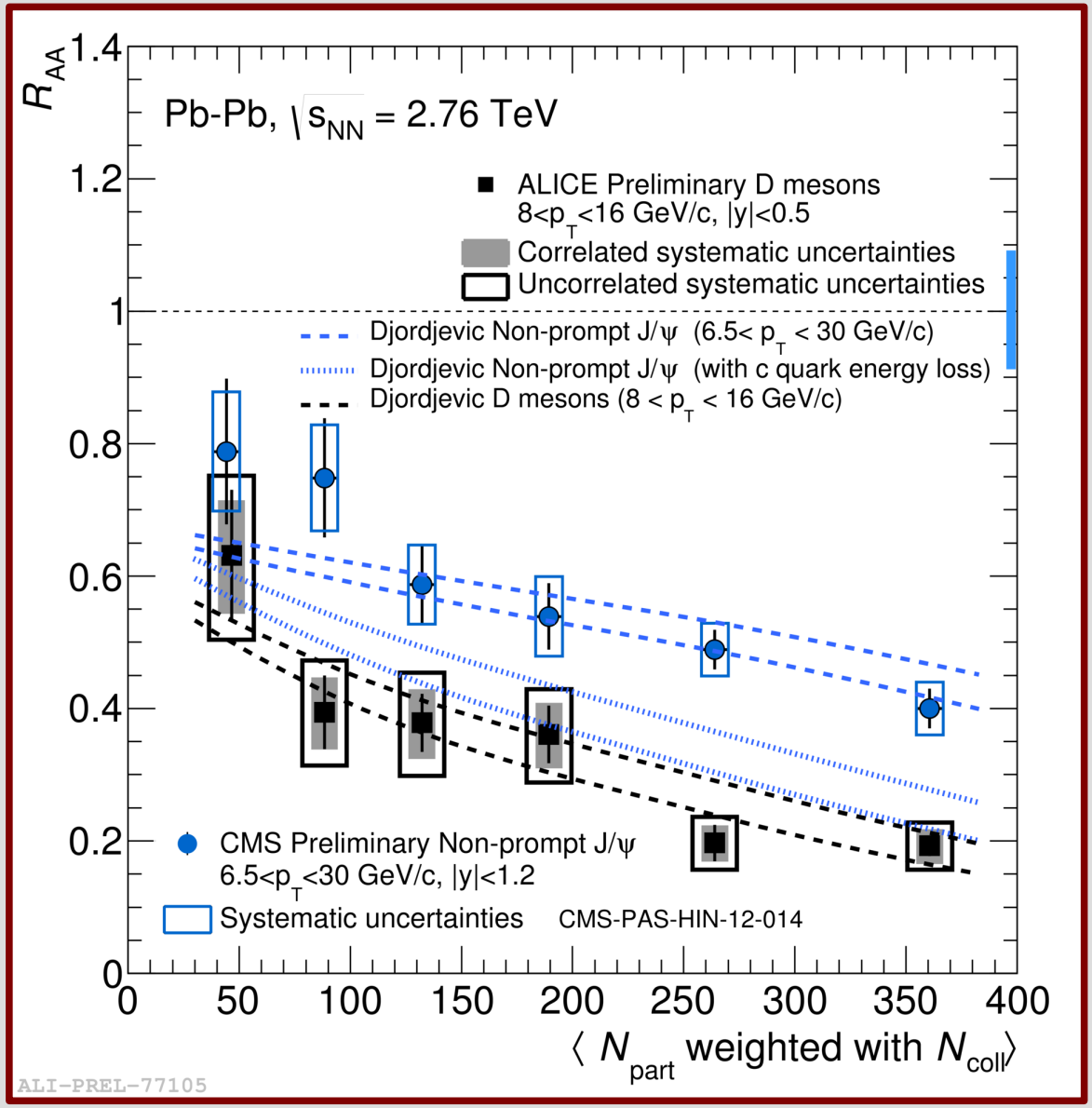
$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

- Results in most-central collisions consistent between D^0, D^+ and D^{*+} at all p_T
- Significant suppression at high p_T, due to substantial energy loss of charm quarks in medium
- Not yet possible to draw firm conclusions on predicted enhancement of D_s^+ yield relative to non-strange D mesons at low p_T due to recombination[1,2]
  → More statistics needed to reduce uncertainties



[1] M. He, R. J. Fries and R. Rapp, arXiv:1204.4442 [nucl-th]
[2] I. Kuznetsova, J. Rafelski, Eur.Phys.J.C51:113-133,2007

R_{AA} compared with CMS non-prompt J/ψ

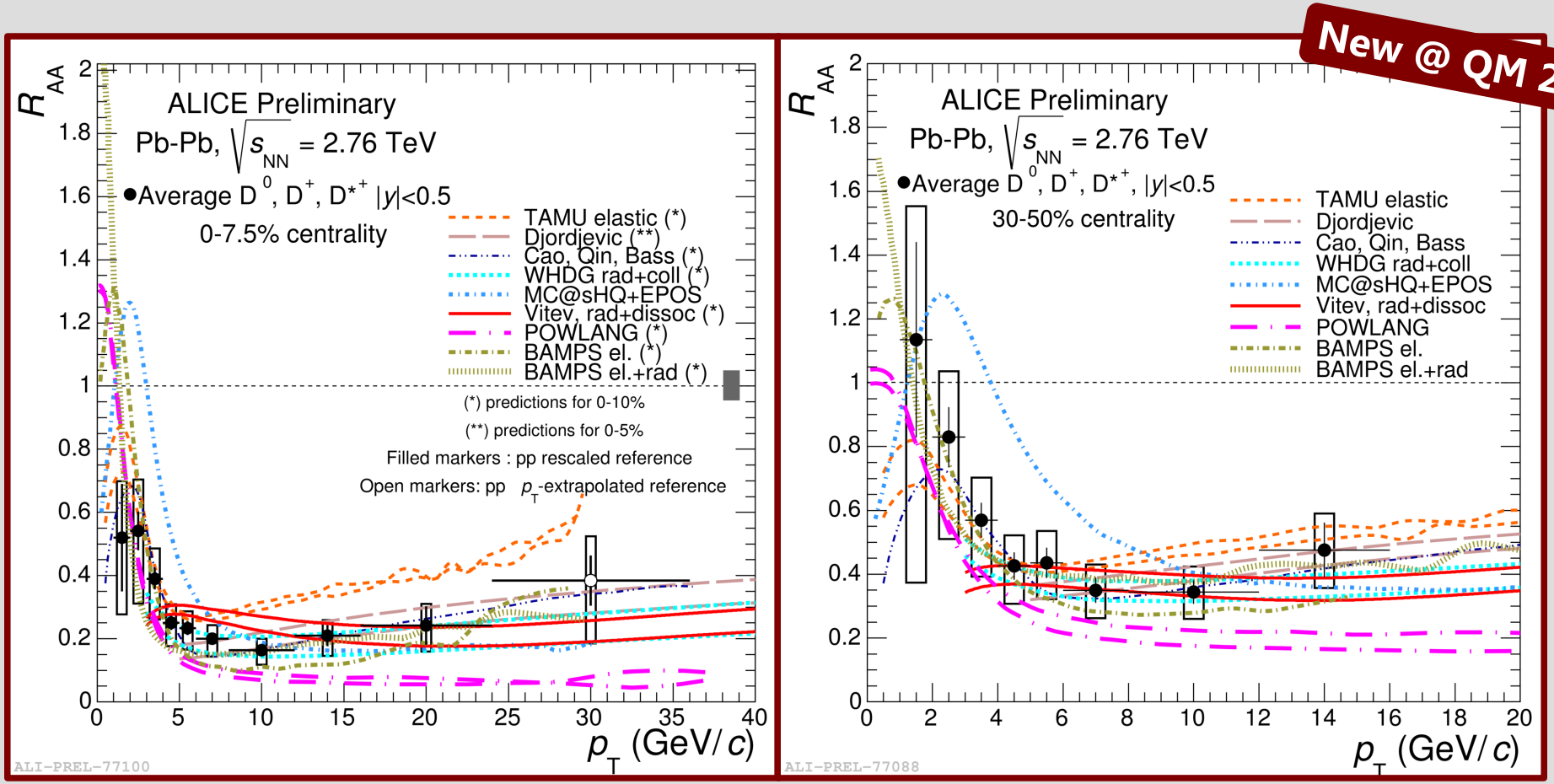


Peripheral → *Central*

- D-meson results compared with non-prompt J/ψ (i.e. from B decays) measured by CMS collaboration as function of centrality
  → Different rapidity & p_T ranges, but similar kinematic region
- Indicates R_{AA}(D) < R_{AA}(B) in central Pb-Pb collisions
  → Observed difference is described by models including mass-dependent energy loss

Djordjevic et al: *arXiv:1307.4098*

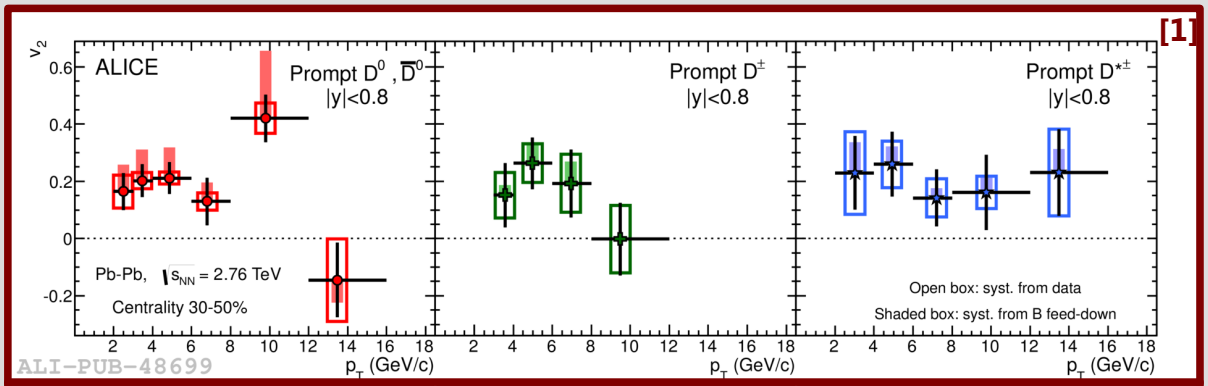
R_{AA} of D mesons in 30-50% centrality

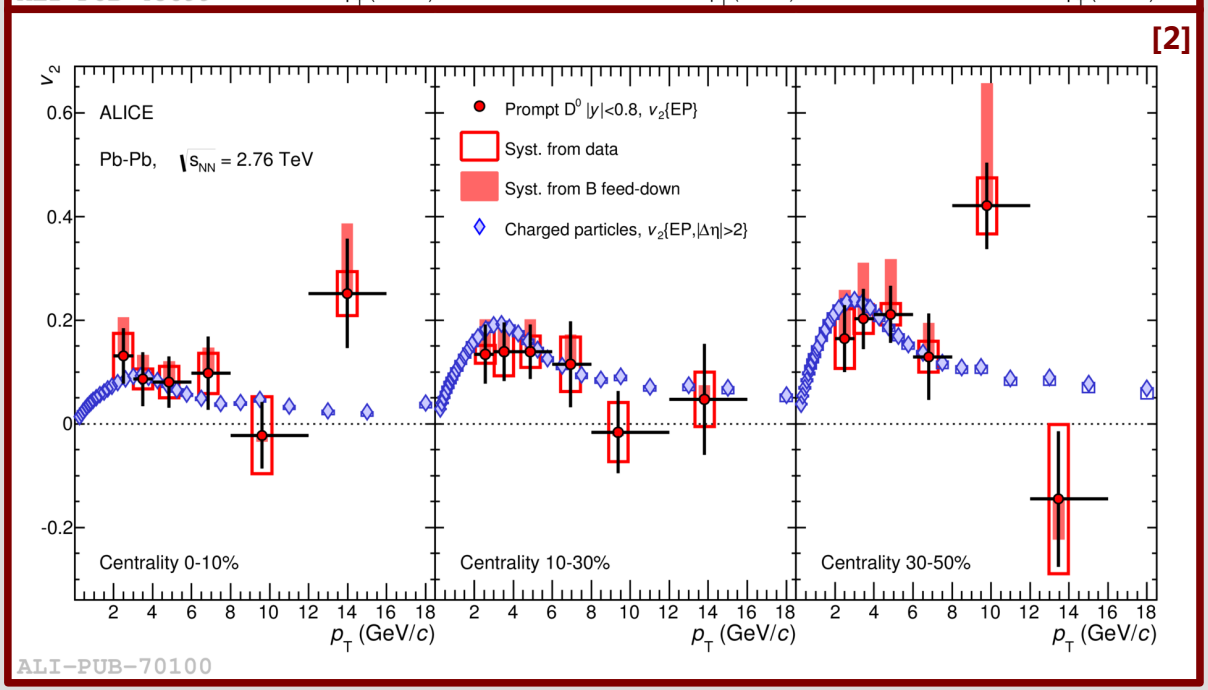


- New measurements in the 30-50% centrality interval in Pb-Pb
- Simultaneous comparison in two centrality classes → provides constraints on model predictions

BAMPS: *J. Uphoff et al., Phys. Lett. B 717 (2012) 430;* ***POWLANG***: *M. Monteno et al., J. Phys. G 38 (2011) 124144*
WHDG: *Horowitz et al., JPhys G38 (2011) 124114;* ***TAMU***: *M. He et al., arXiv:1401.3817;* ***Cao, Qin, Bass***: *Phys. Rev. C 88 (2013) 044907;*
Djordjevic et al: *arXiv:1307.4098;* ***Vitev et al***: *Phys. Rev. C80 (2009) 054902, Phys. Lett. B 713 (2012) 224*

Measured v_2 of D mesons





[1] B. Abelev et al. (ALICE collaboration), Phys. Rev. Lett. 111, 102301 (2013)
[2] B. Abelev et al. (ALICE collaboration), arXiv:1405.2001 (2014)

- Elliptic flow v_2 measured using event-plane method:

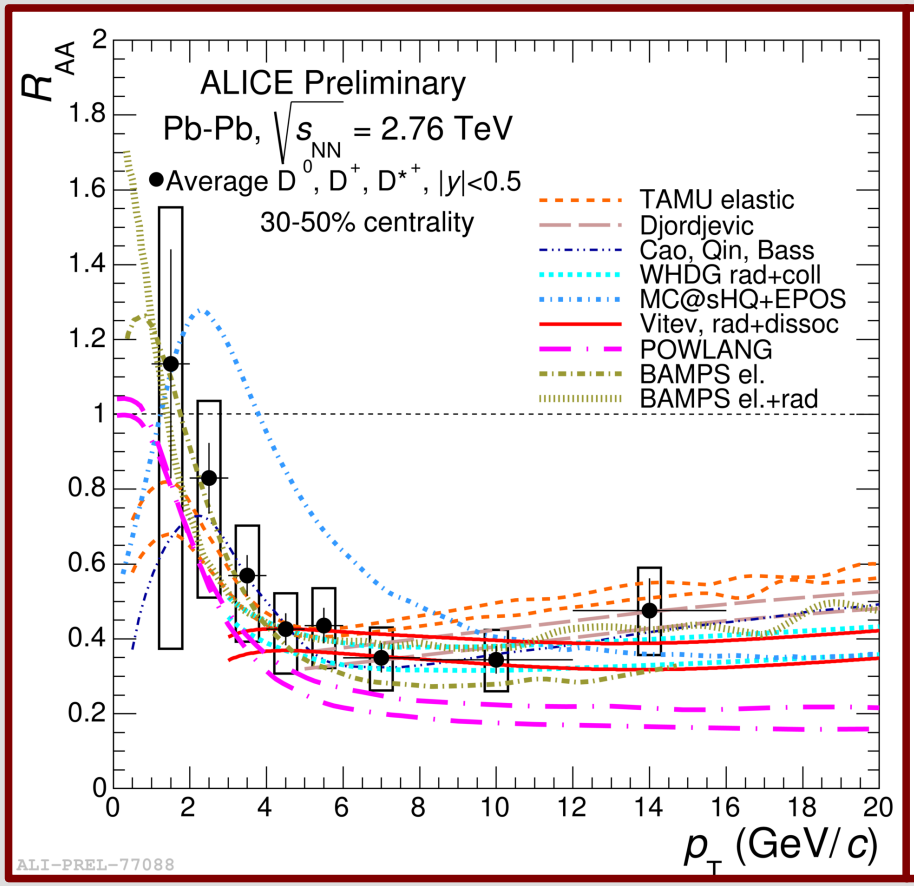
$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}$$

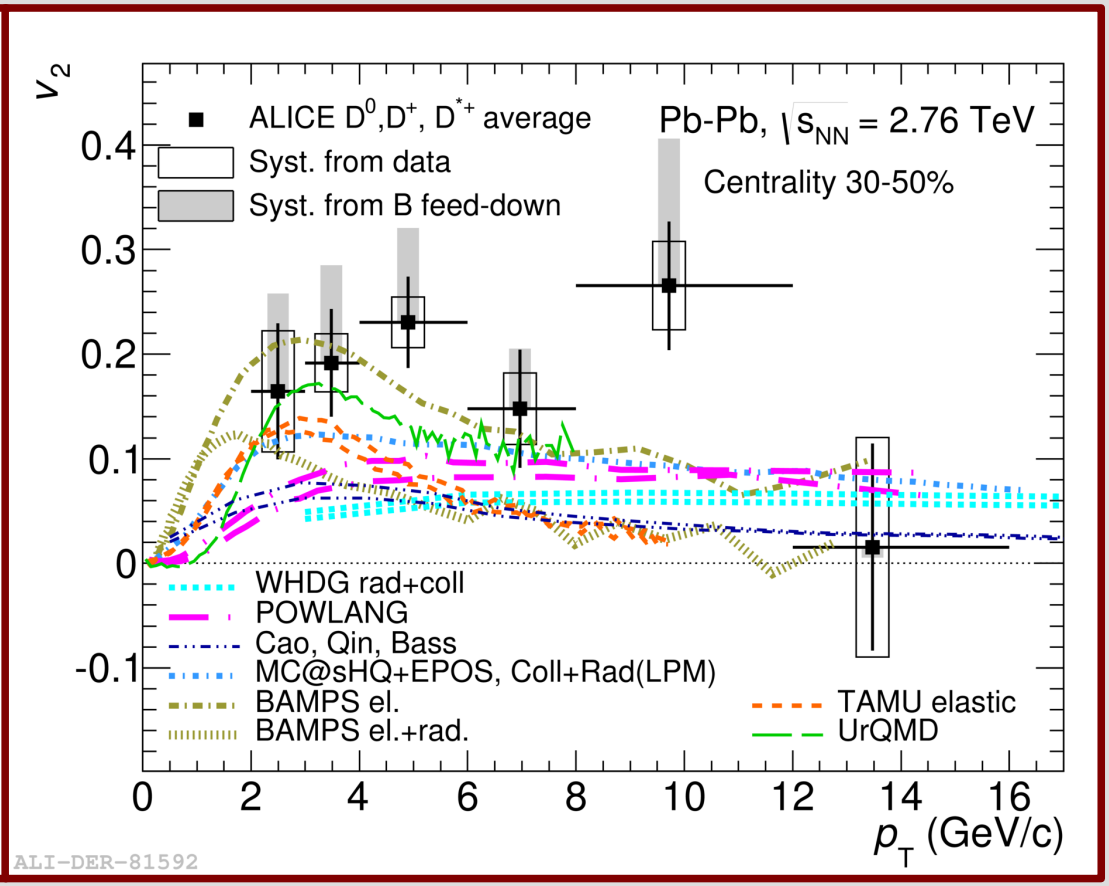
- Definition: $N_{\text{in-plane}}$ = particles within $\Delta\phi$ =]-π/4, π/4] &]3π/4, 5π/4] relative to reaction plane; $N_{\text{out-of-plane}}$ = particles within $\Delta\phi$ =]π/4, 3π/4] &]5π/4, 7π/4].
- Above: results for D^0, D^+, D^{*+}; below: D^0 compared with charged-particle measurement (dominated by pions)

→ Results for species consistent with one another

→ Significantly > 0 at low p_T; compatible with light-flavour measurements → suggests collective motion of charm quarks in medium

Comparison of R_{AA} and v_2 with models





- Simultaneous description of R_{AA} and v_2 by models remains challenging → considering both observables together provides useful constraint for theory

BAMPS: *J. Uphoff et al., Phys. Lett. B 717 (2012) 430;* ***POWLANG***: *M. Monteno et al., J. Phys. G 38 (2011) 124144*
UrQMD: *T. Lang et al, arXiv:1211.6912 [hep-ph], T. Lang et al., arXiv:1212.0696 [hep-ph];* ***WHDG***: *Horowitz et al., JPhys G38 (2011) 124114;*
TAMU: *M. He et al., arXiv:1401.3817* ***Cao, Qin, Bass***: *Phys. Rev. C 88 (2013) 044907;* ***Djordjevic et al***: *arXiv:1307.4098;*
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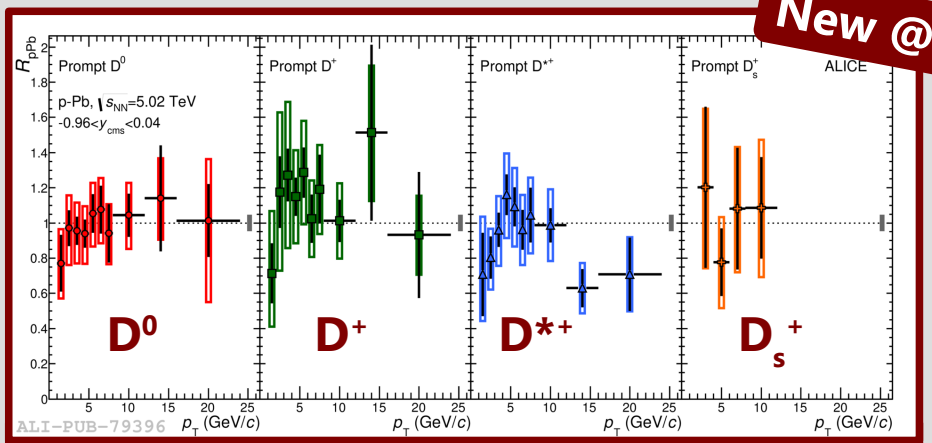
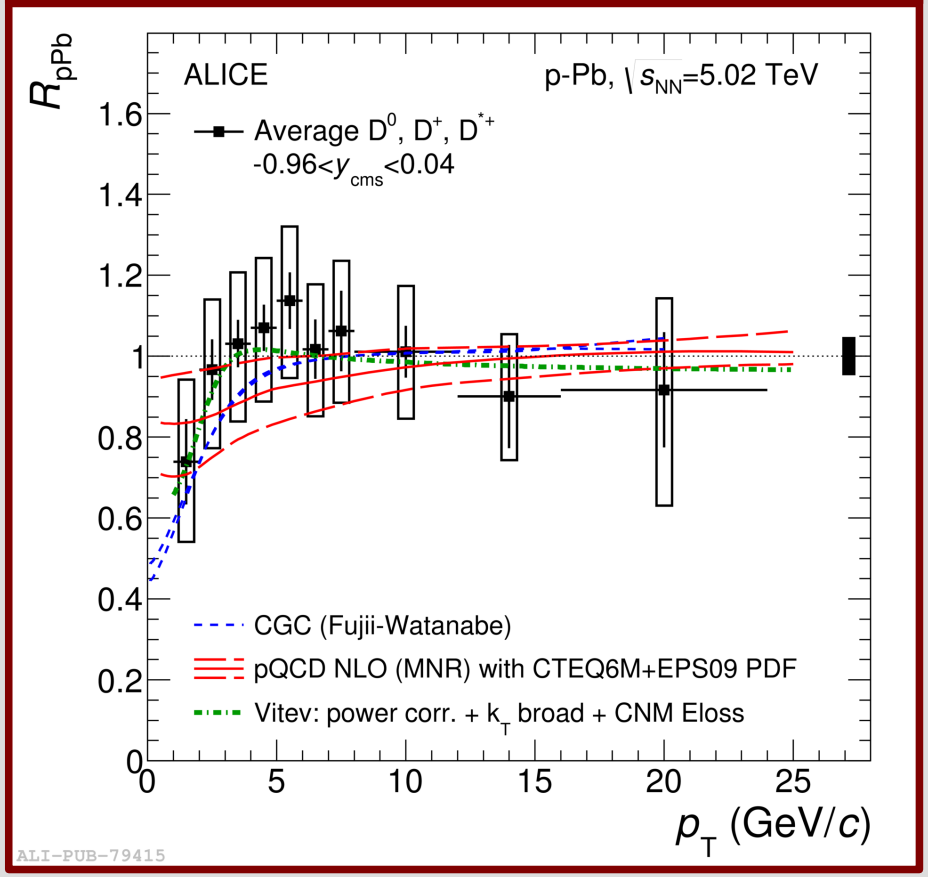
B. Abelev et al. (ALICE collaboration), arXiv:1405.2001 (2014)

R_{pPb} of D mesons

New @ QM 2014



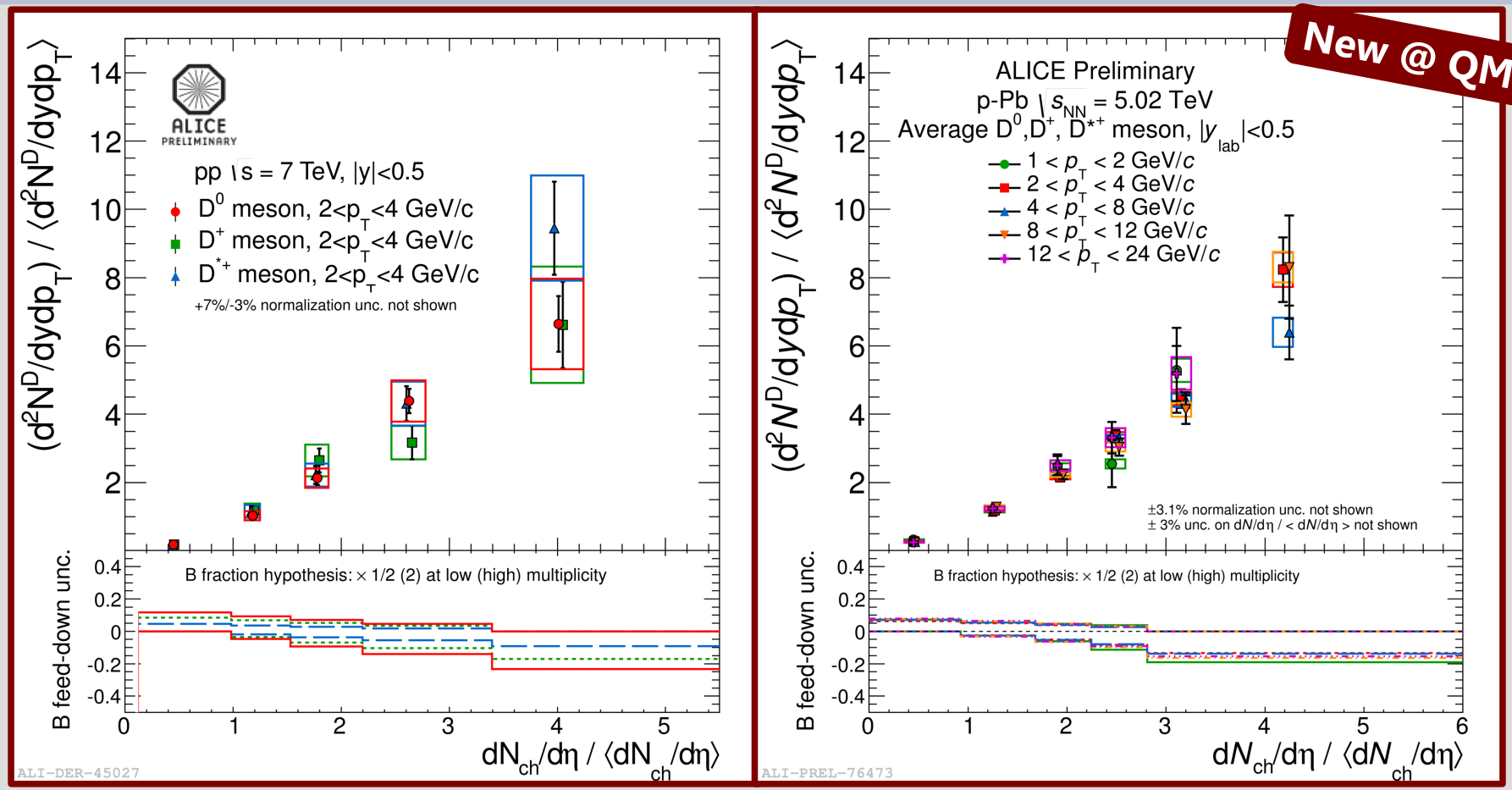


- Measured similarly to R_{AA}; D^0, D^+, D^{*+} & D_s^+ (above), average of D^0, D^+, D^{*+} (below)
- All meson species in agreement within uncertainties
- R_{pPb} consistent with unity
  - → No significant suppression of D mesons in p-Pb at higher p_T
  - → Suppression in Pb-Pb is hot medium effect rather than initial-state effect
- Described by models including initial-state effects within uncertainties

*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*

B. Abelev et al. (ALICE Collaboration); arXiv:1405.3452

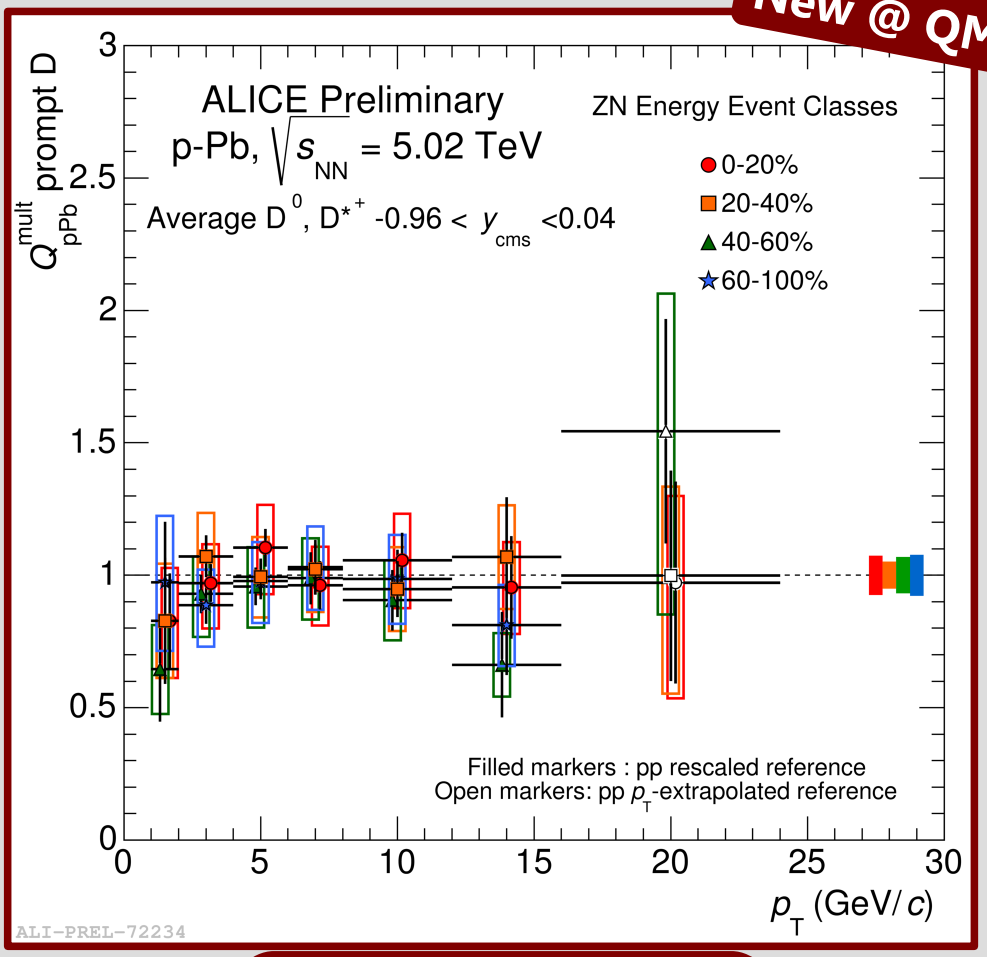
Multiplicity dependence of D-meson production (vs. N_{ch})



- Measured in pp & p-Pb to probe role of multi-parton interactions in charm production
- "Self-normalised yield" as function of charged-particle multiplicity N_{ch} (left: D^0, D^+, D^{*+} in pp; right: average of species in p-Pb)
  - → Multiplicity estimator: tracklets (track segments) reconstructed in Silicon Pixel Detector within $|\eta| < 1.0$
- Increase of D-meson yield as function of multiplicity consistent between pp and p-Pb
- Self-normalised yield independent of p_T.

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

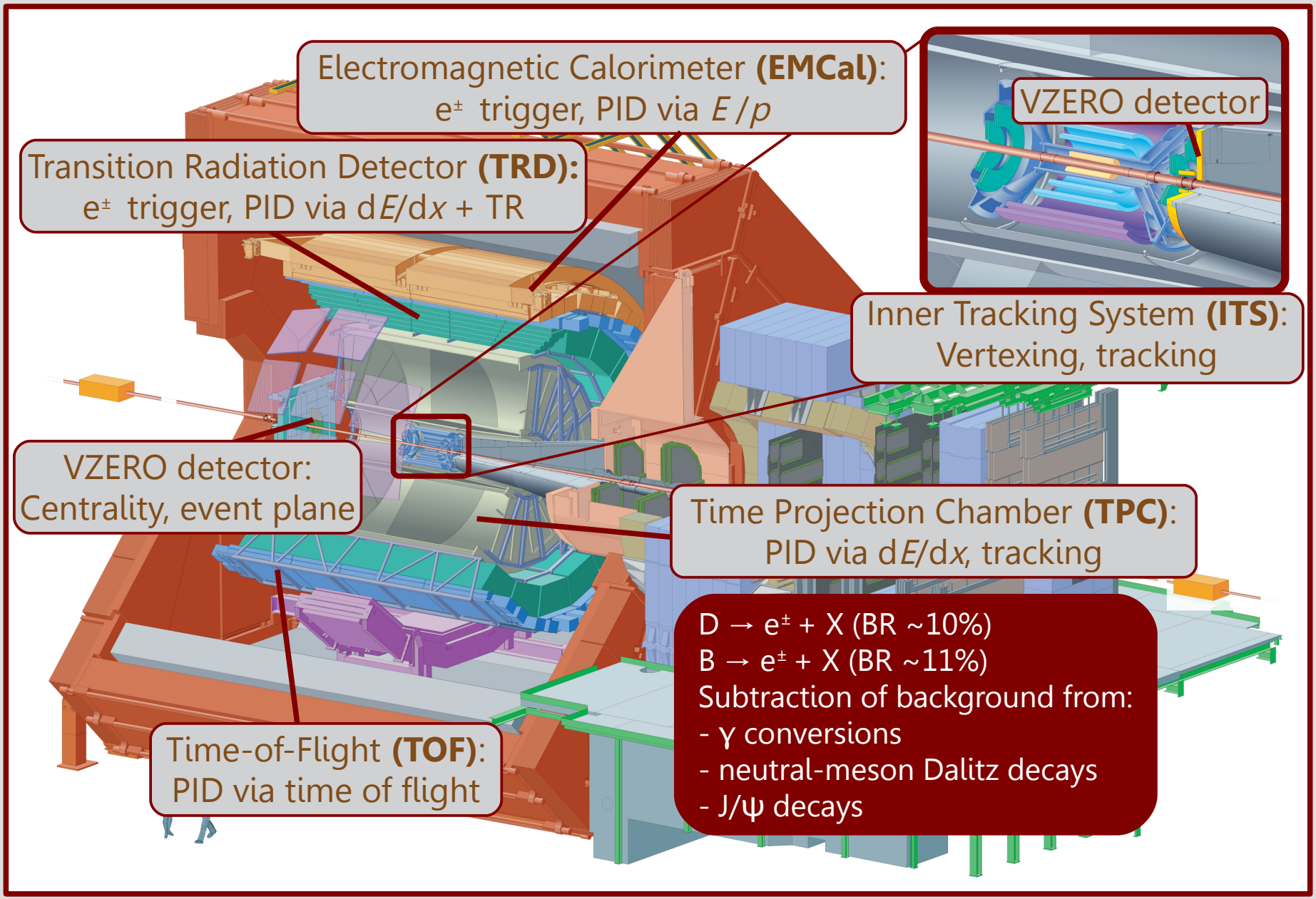
New @ QM 2014



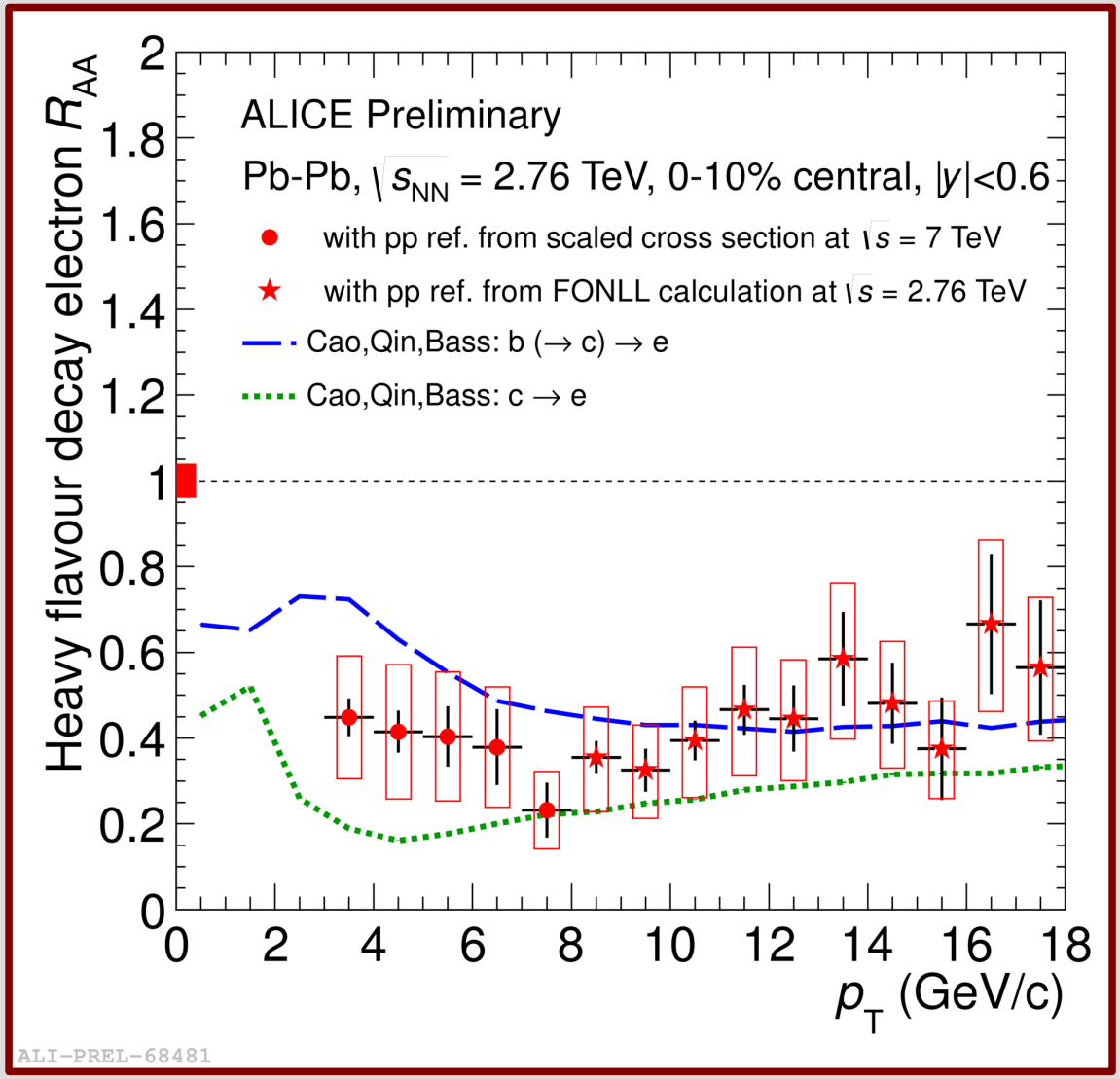
$$Q_{pPb}^{mult} = \frac{\frac{dN_{pPb}^{ZN}}{dp_T}}{\langle N_{coll}^{mult} \rangle \frac{dN_{pp}}{dp_T}}$$

- Multiplicity-dependent nuclear modification Q_{pPb} (D^0, D^{*+} in p-Pb) to study p_T dependence in multiplicity classes
  - → Second approach to studying multiplicity dependence of D-meson production in p-Pb: Event activity determined using Zero-Degree Calorimeter
  - → N_{coll}^{mult} determined assuming that charged-particle multiplicity at mid-rapidity is proportional to number of participants (N_{part}).
  - → No multiplicity dependence of nuclear modification seen.

ALICE: A Large Ion Collider Experiment (Electrons)



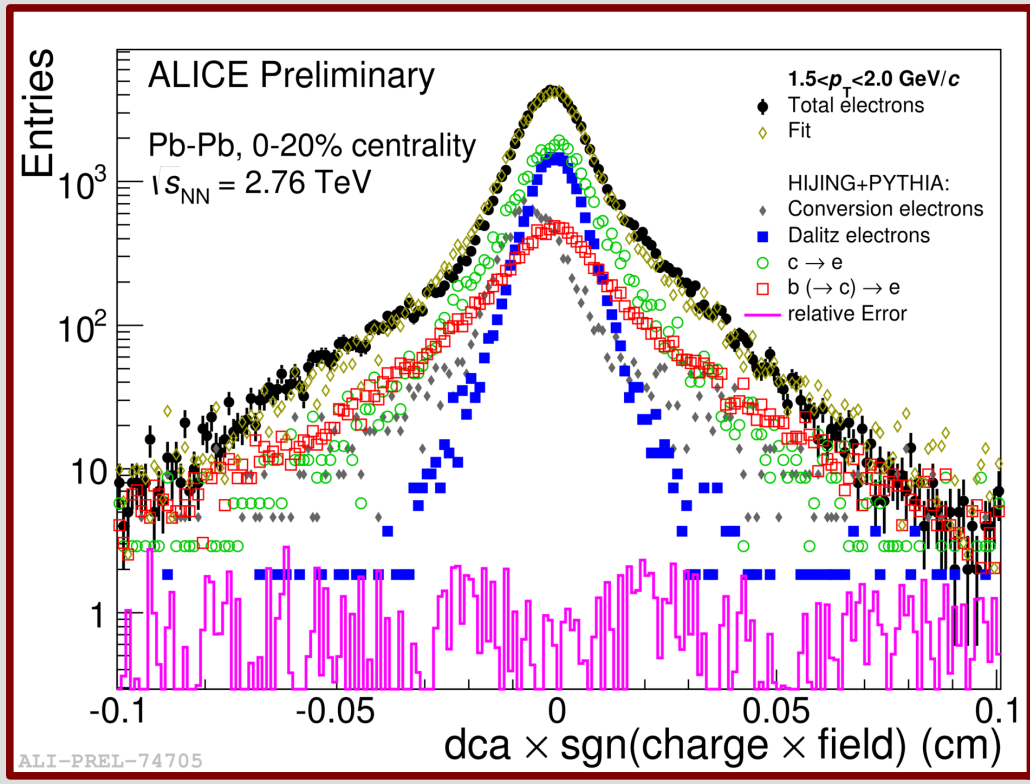
R_{AA} of heavy-flavour decay electrons

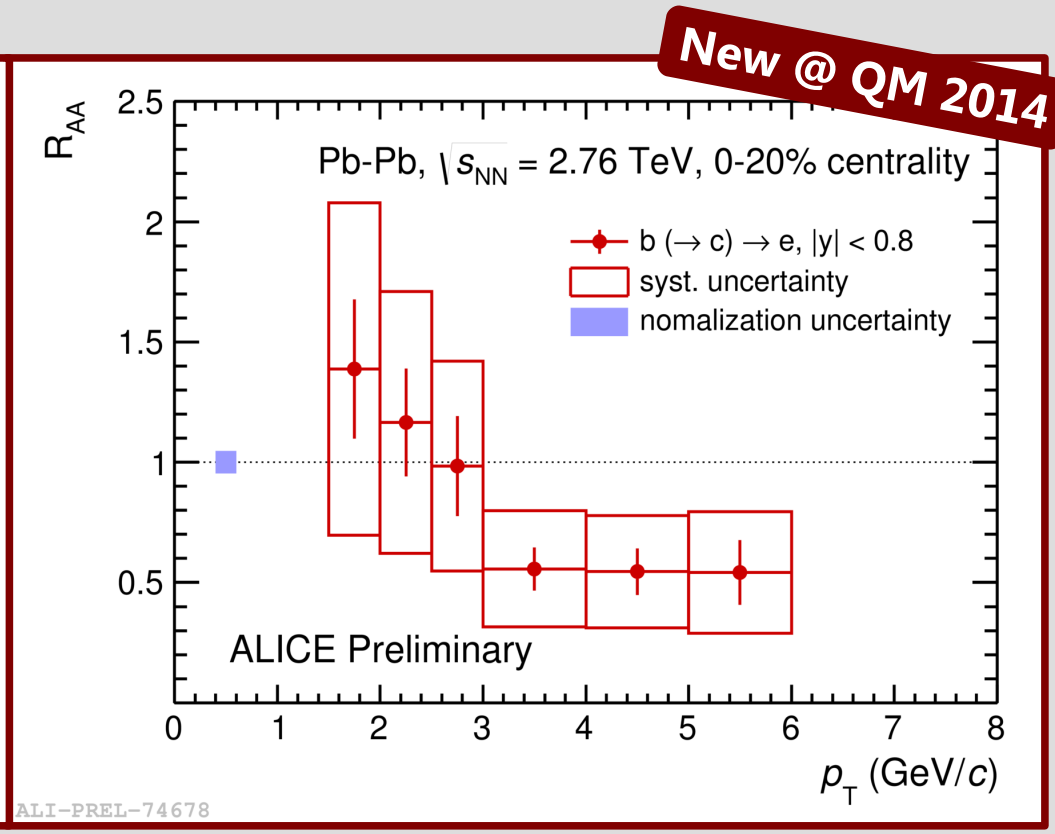


- Significant suppression of heavy-flavour decay electrons observed in $3 < p_T < 18$ GeV/c
- Theoretical models give different predictions for R_{AA} of electrons from b and c decays
- Electrons dominated by b → e at high pT

***Cao, Qin, Bass**: Phys. Rev. C 88 (2013) 044907*

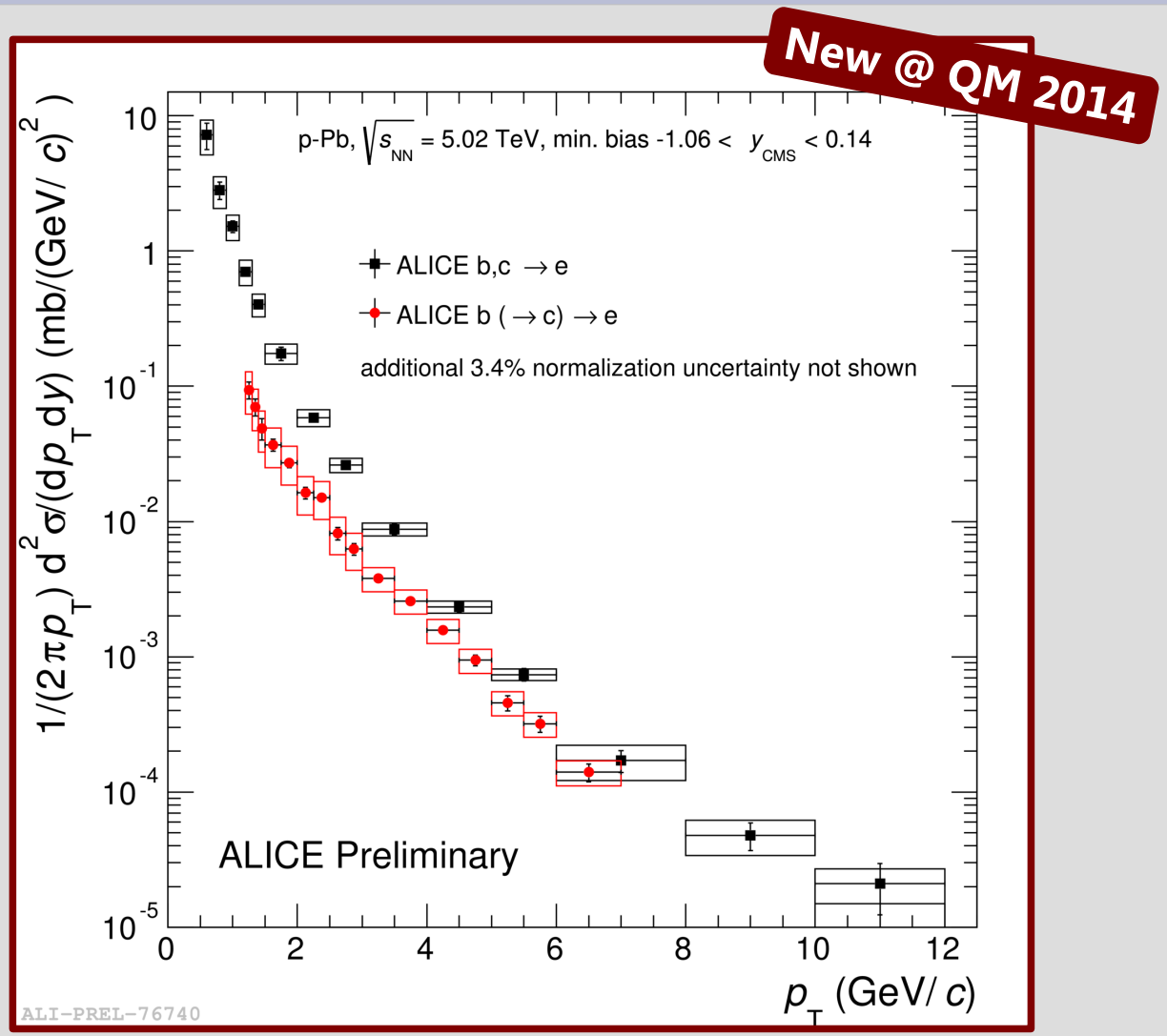
Electrons from beauty decays in Pb-Pb





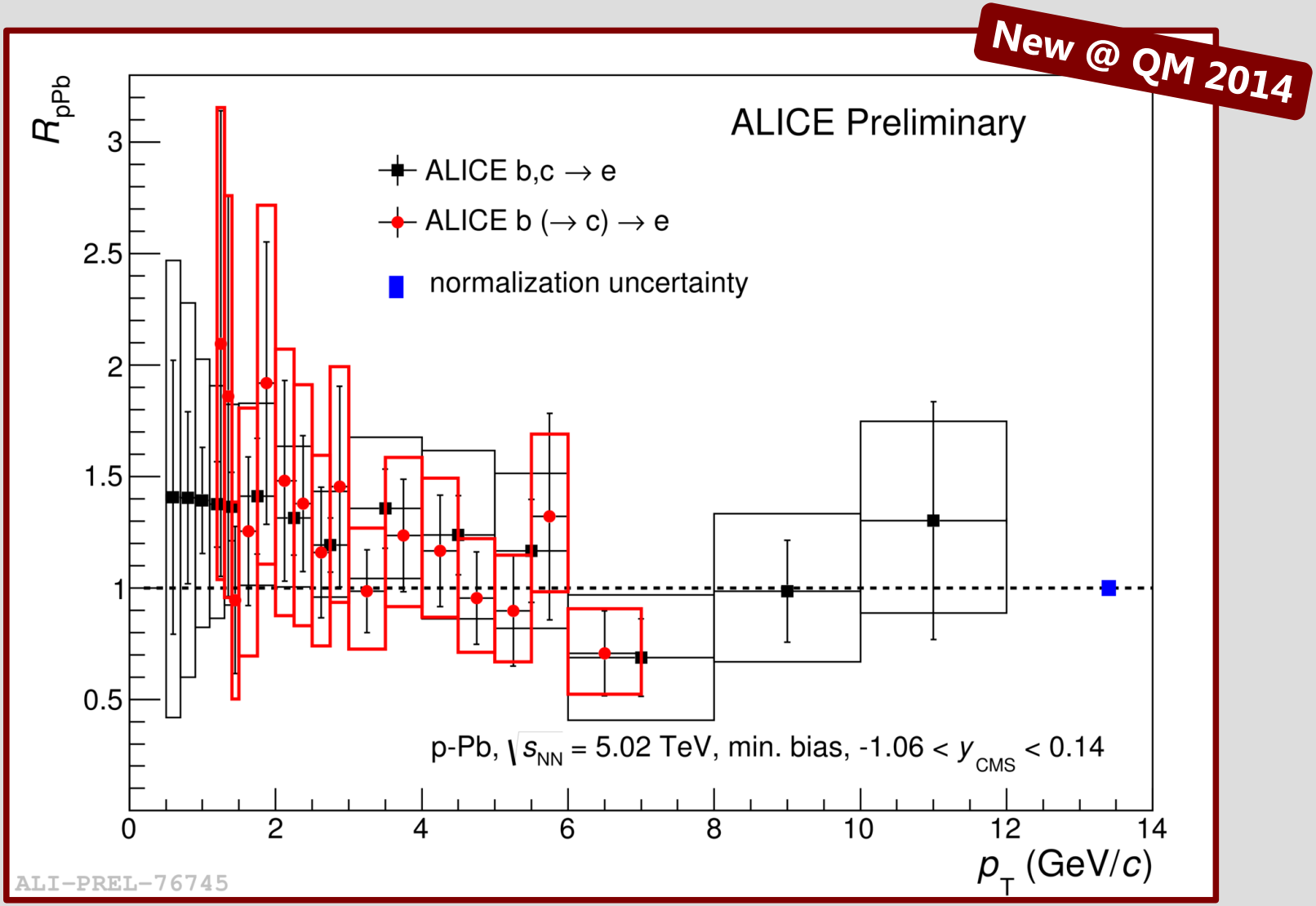
- Analysis based on impact parameter distribution of electrons
- Preliminary measurements in 0-20% most-central events suggest $R_{AA}(e \leftarrow b) < 1$ for $p_T > 3$ GeV/c

p_T-differential cross section of e± in p-Pb collisions



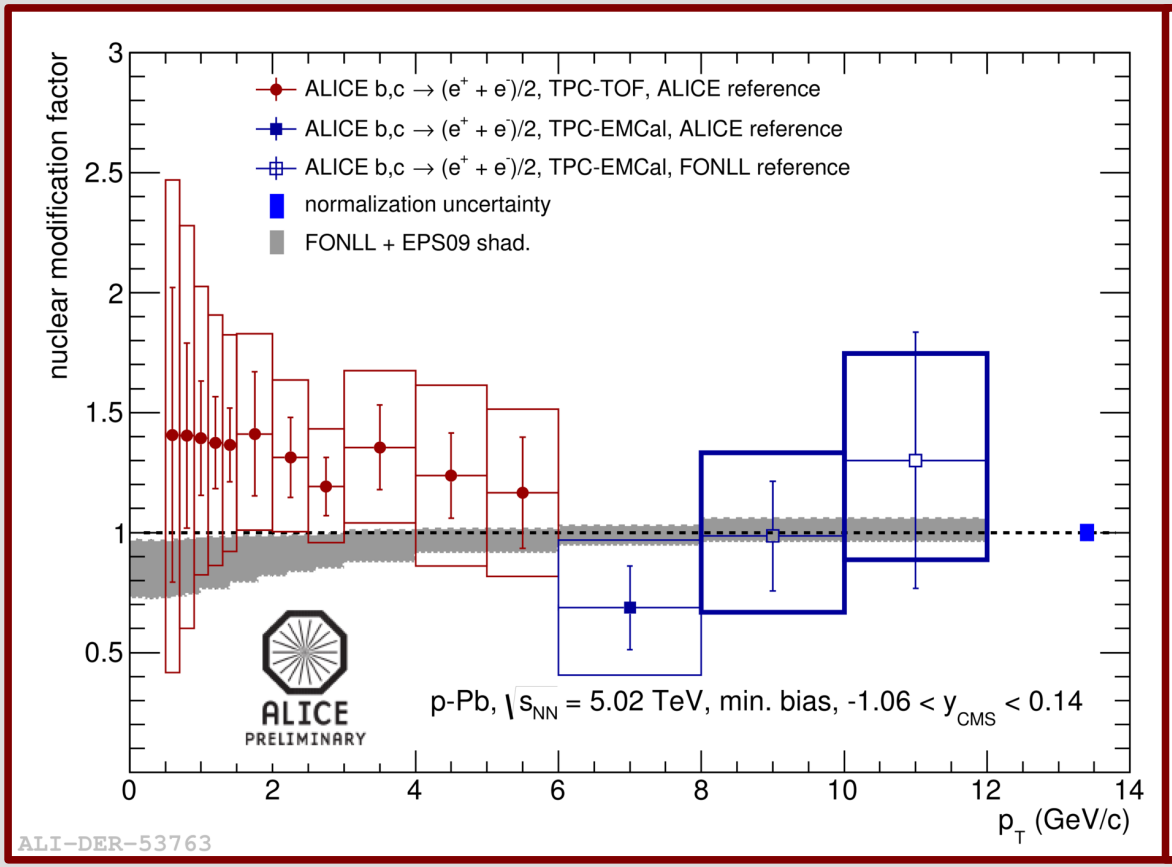
- p_T-differential cross sections measured in minimum-bias p-Pb collisions for:
  → inclusive electrons from heavy-flavour decays in $0.5 < p_T < 12$ GeV/c
  → electrons from beauty-hadron decays in $1.2 < p_T < 7$ GeV/c

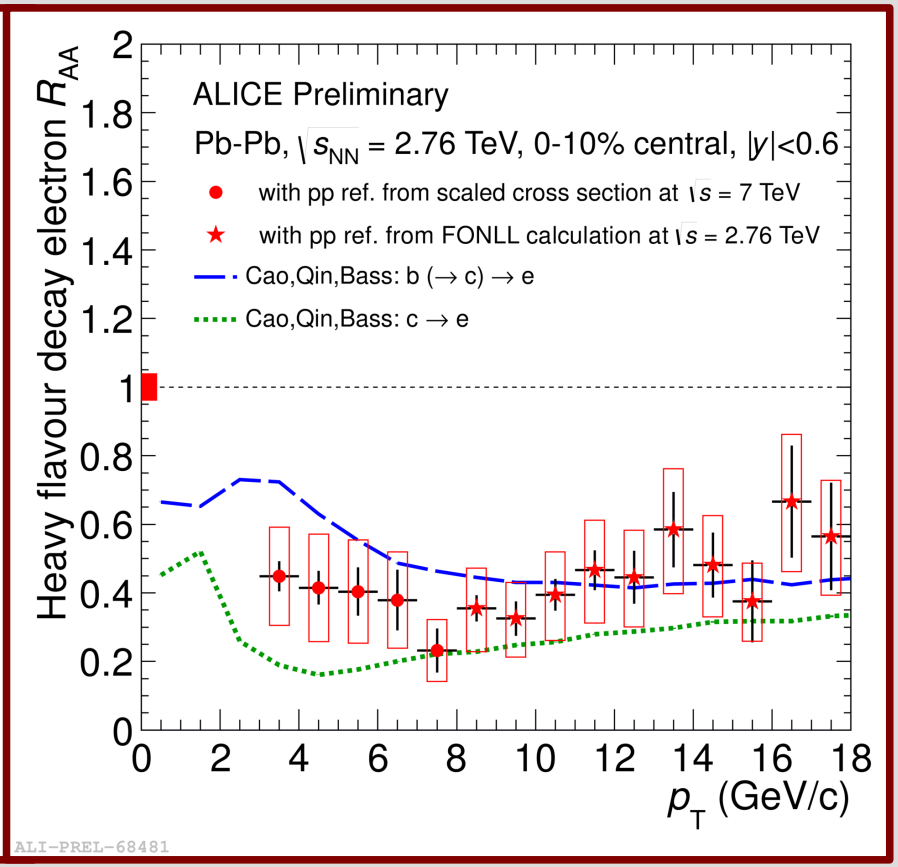
R_{pPb} of heavy-flavour decay electrons



- R_{pPb} of both heavy-flavour-decay and beauty-decay electrons consistent with unity within uncertainties

Comparison of R_{pPb} with R_{AA}, models





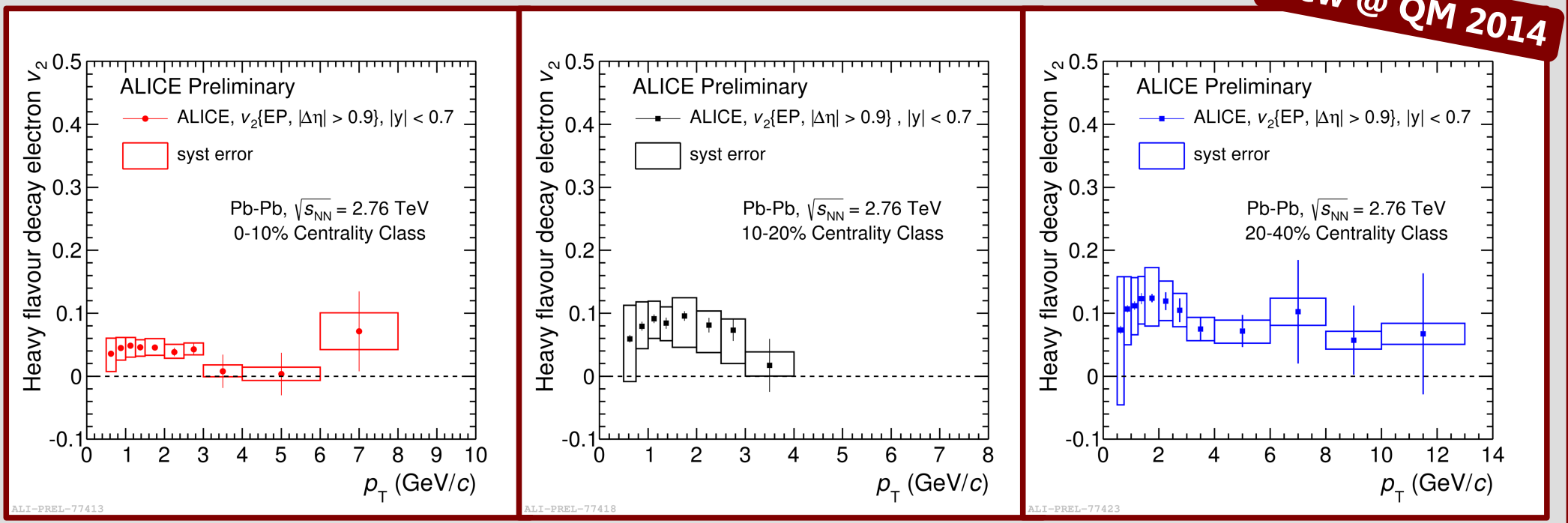
- R_{pPb} described within uncertainties by pQCD using EPS09 shadowing
- R_{pPb} compatible with unity (similar to result for D mesons)

  → Suppression in Pb-Pb due to hot medium effects rather than cold nuclear matter effects

__FONLL__: M. Cacciari et al, JHEP 007 (1998) 9805, JHEP 006 (2001) 0103; __Cao, Qin, Bass__: Phys. Rev. C 88 (2013) 044907
__pQCD NLO (MNR)__: M. Mangano et al., Nucl. Phys. B 373 (1992) 295; __EPS09__: K. J. Eskola et al., JHEP 04 (2009) 065

Elliptic flow of heavy-flavour decay electrons

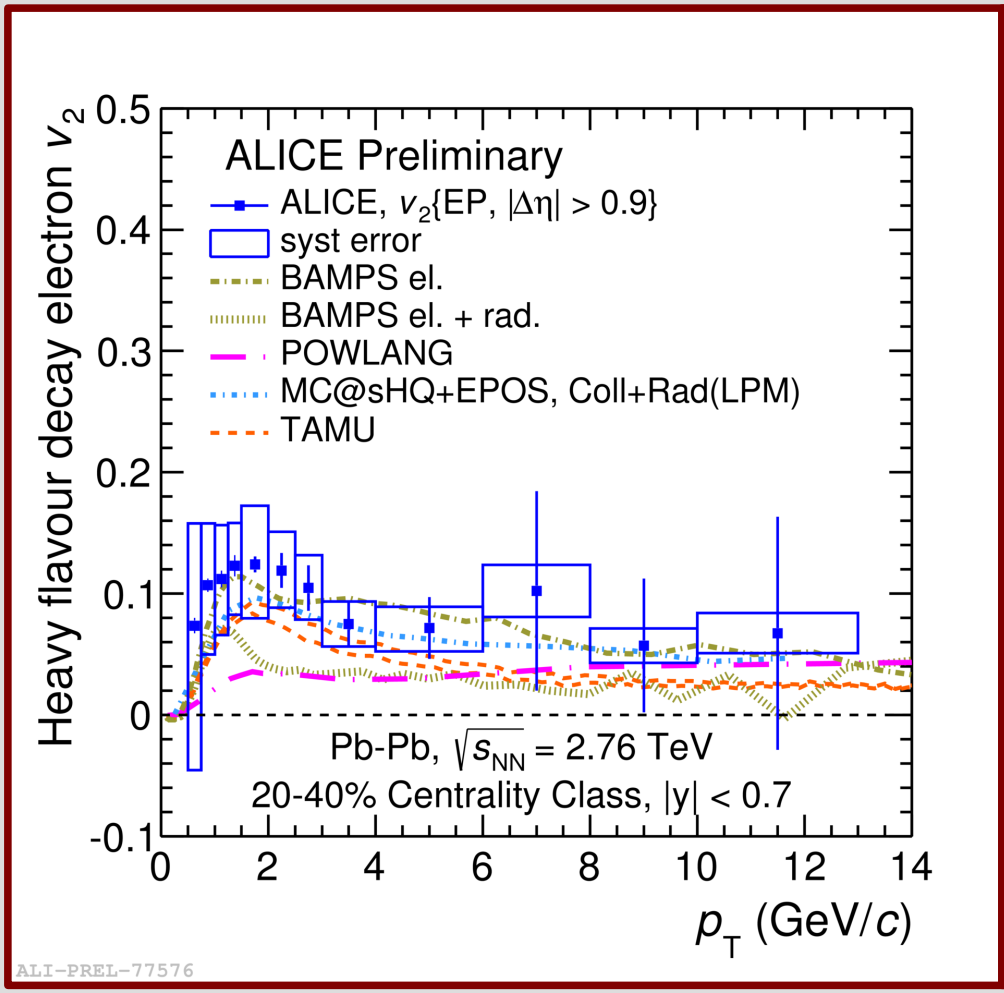
New @ QM 2014

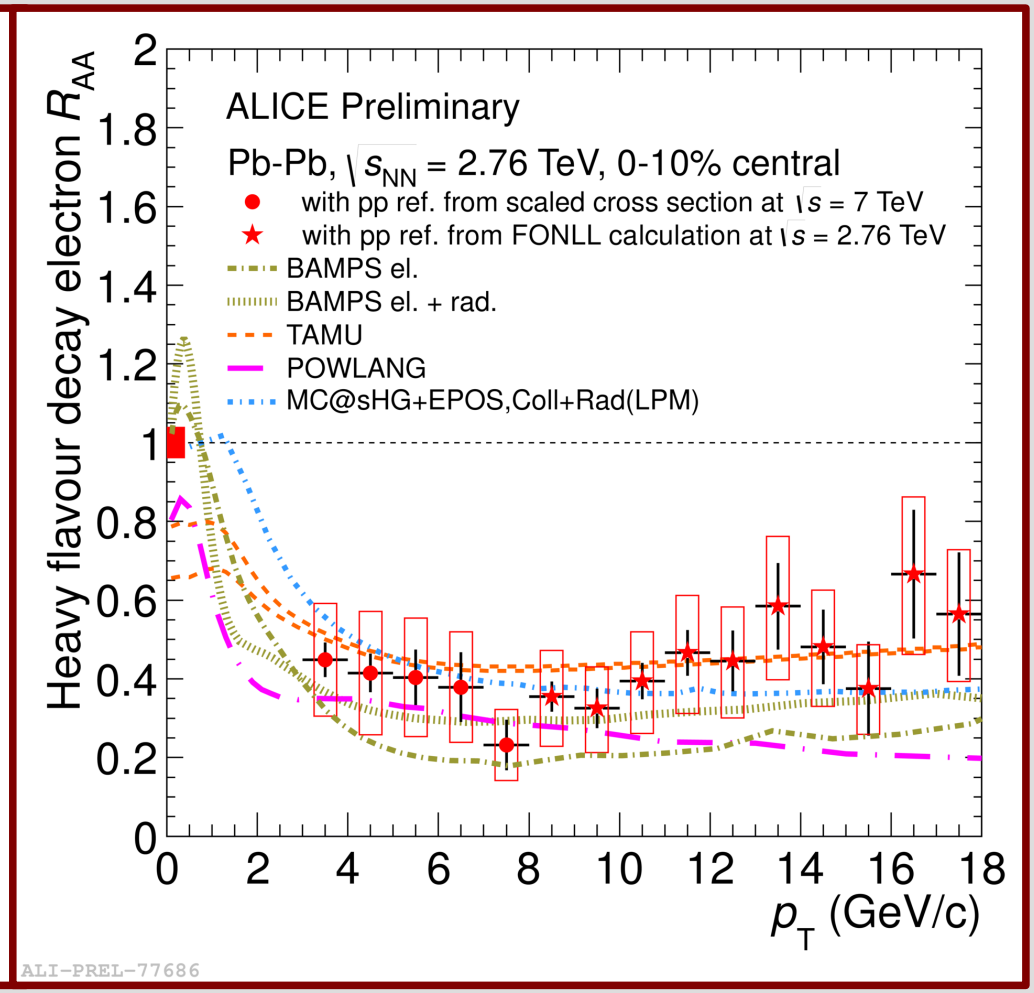


0-10% **10-20%** **20-40%**

- Measured via event-plane method using VZERO detector
- Confirms significant interaction of heavy quarks with medium
  → Hints at collective motion of low-p_T heavy quarks in expanding fireball
- Increase of elliptic flow of electrons when going from central to semi-central events

Elliptic flow and R_{AA} of heavy-flavour decay electrons

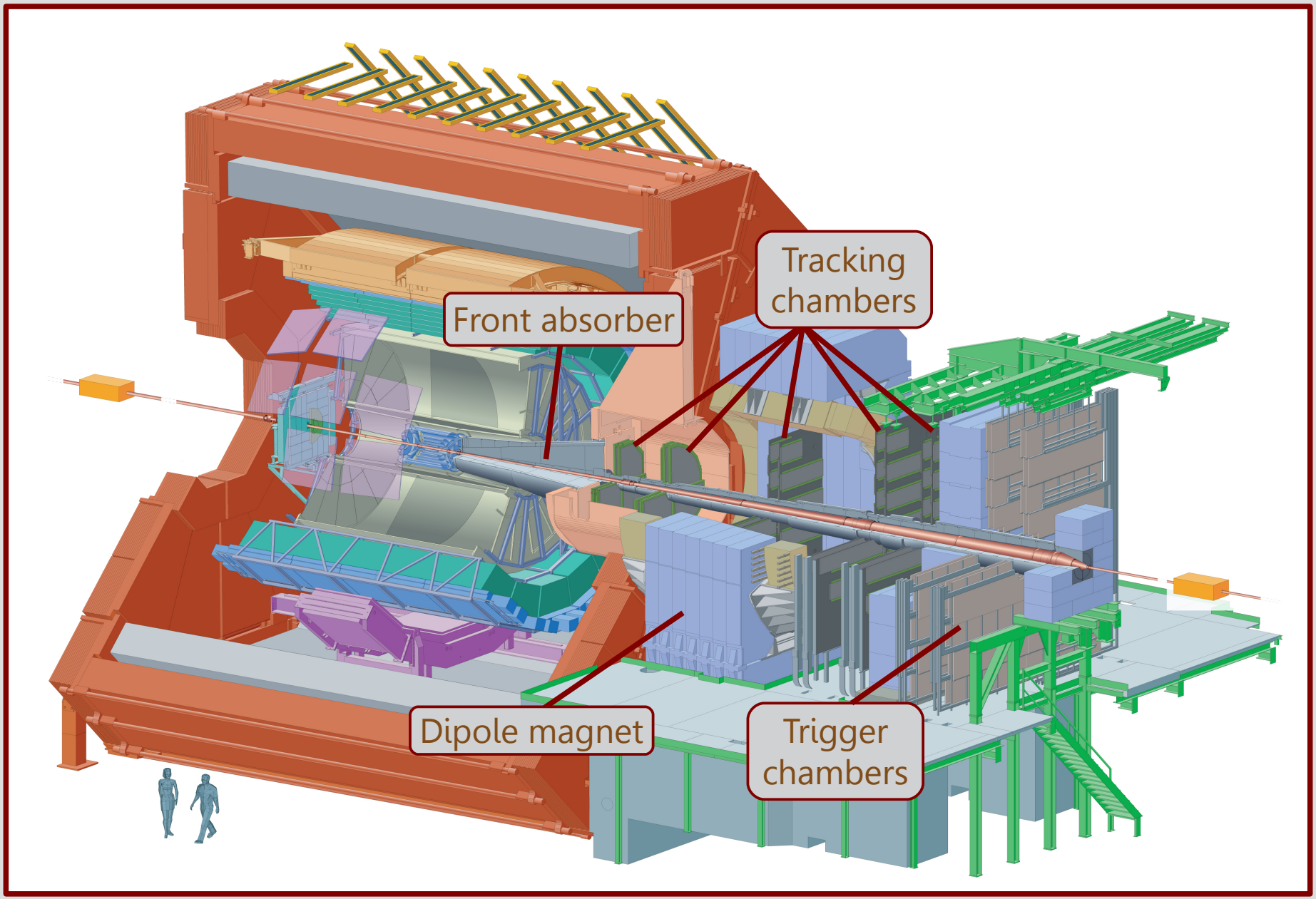




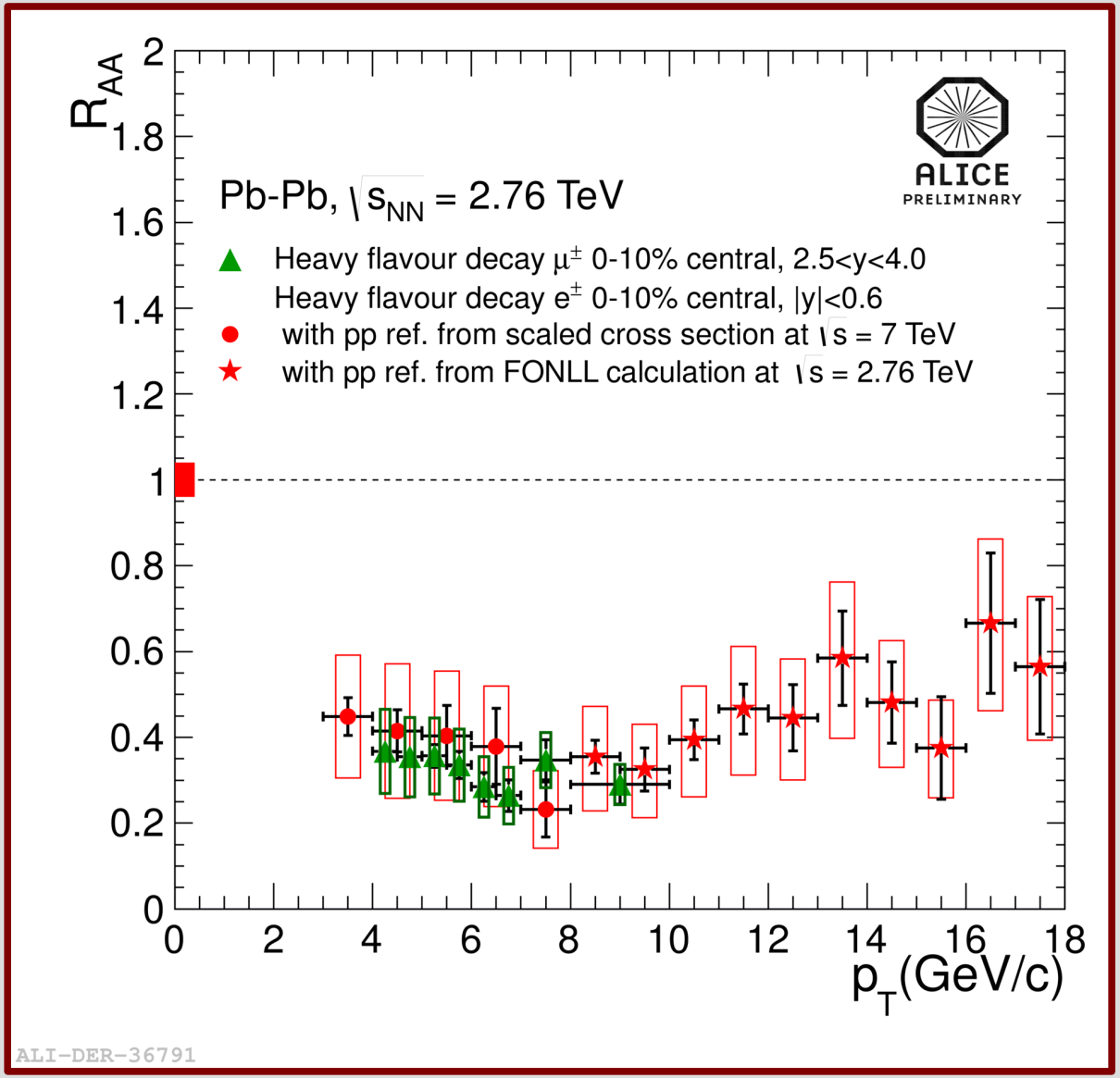
- R_{AA} and v_2 results consistent with picture from D mesons (significant suppression); help to provide further constraints to model calculations when compared side-by-side

***BAMPS**: Fochler et al., J. Phys. G38 (2011) 124152; **POWLANG**: Alberico et al., Eur.Phys.J C71 (2011) 1666*
*T**AMU**: Rapp, He et al., Phys. Rev. C 86 (2012) 014903*

ALICE: A Large Ion Collider Experiment (Muons)



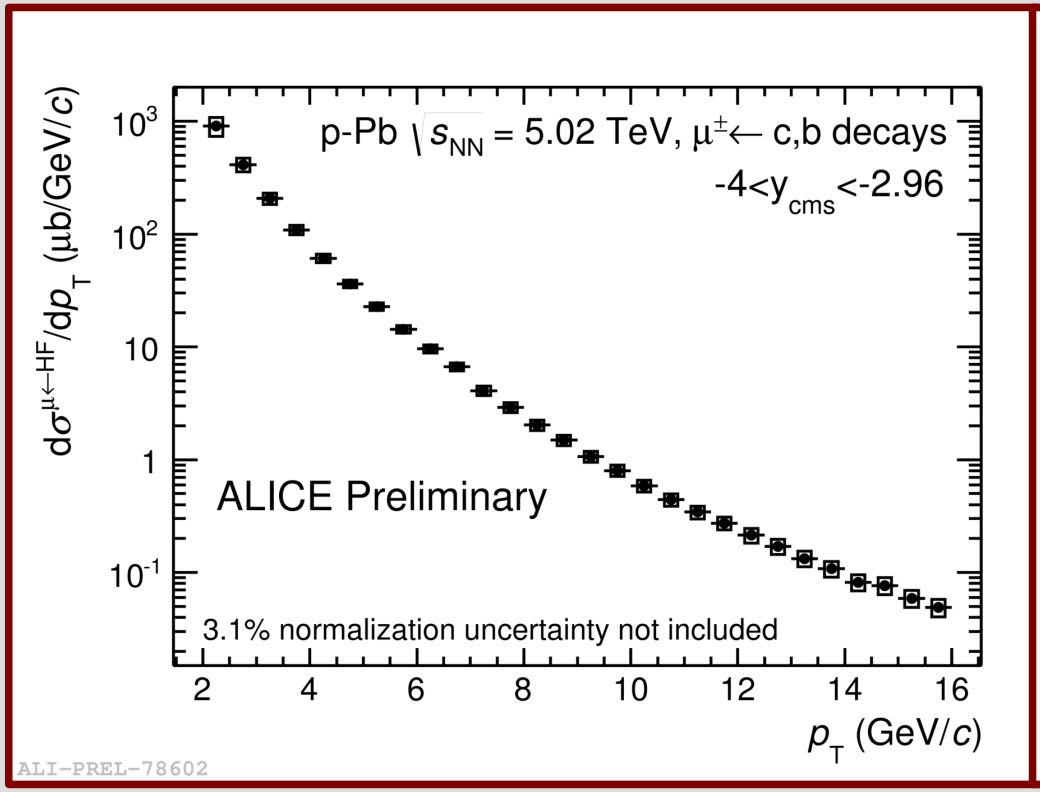
Heavy-flavour decay muon R_{AA}

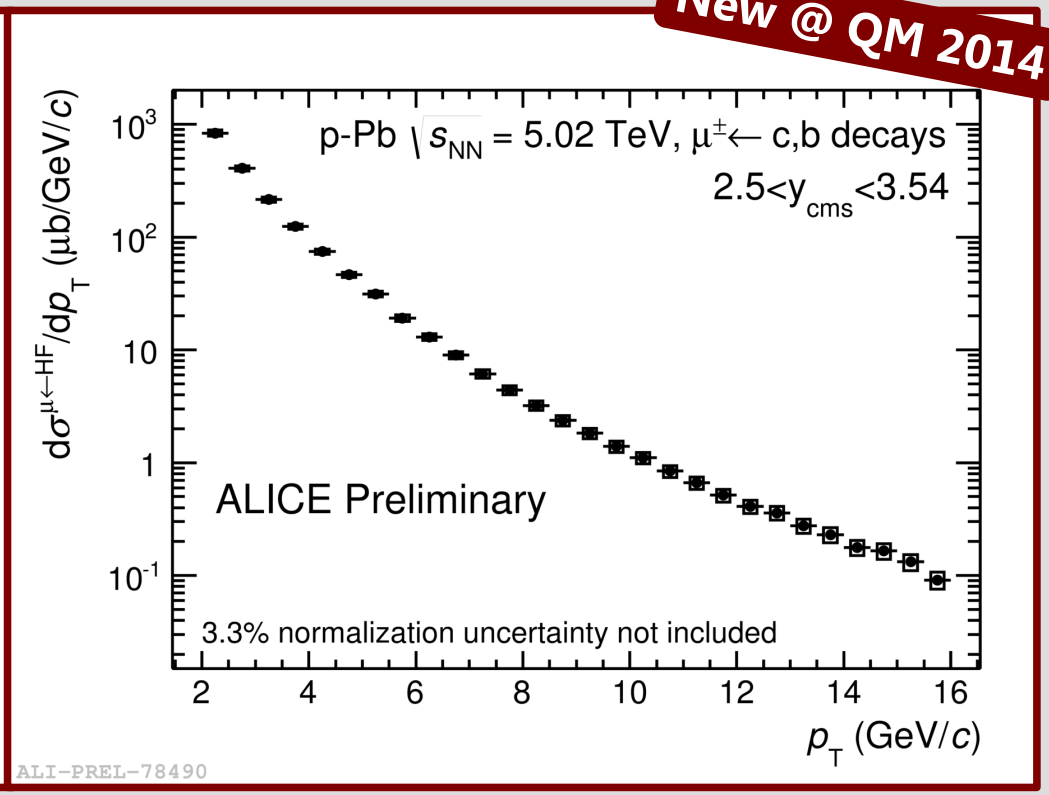


- Suppression of muons at forward rapidity (green, $2.5 < y < 4.0$) compatible with that of electrons at mid-rapidity (red, $|y| < 0.6$)

Cross section of heavy-flavour decay muons in p-Pb

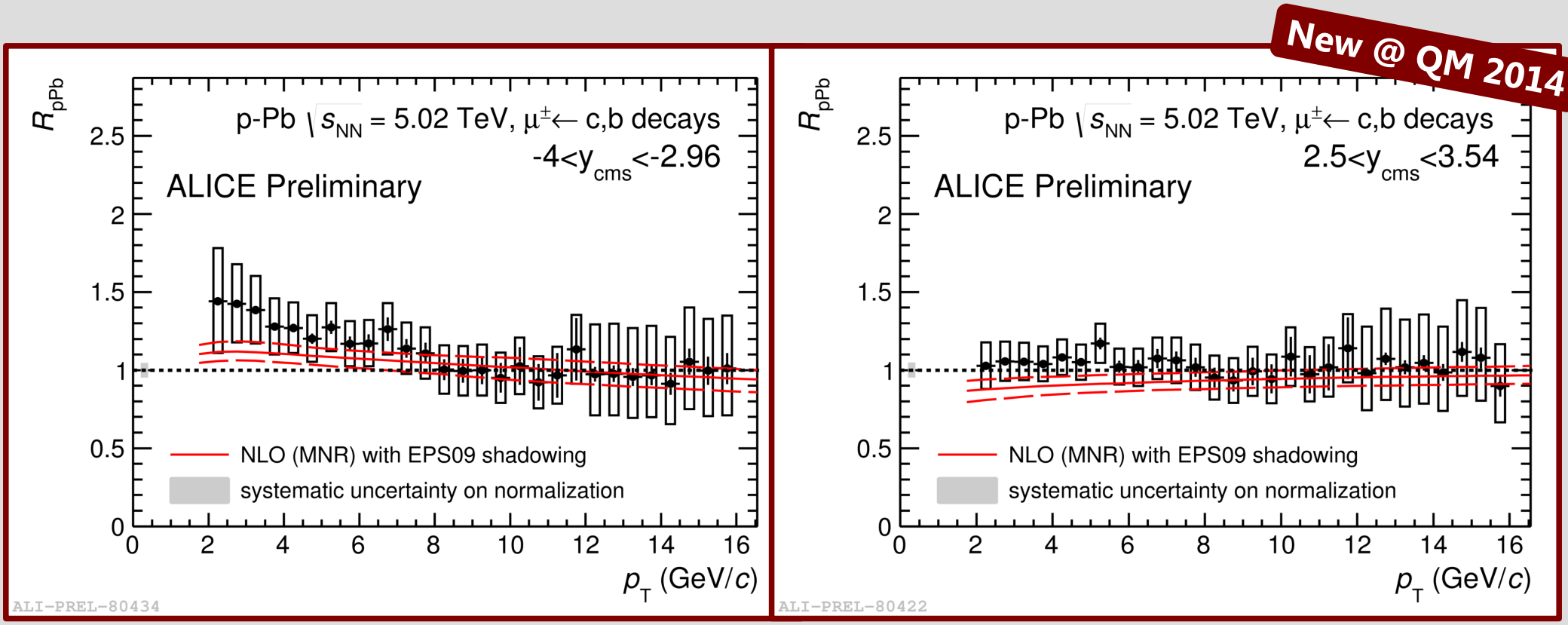
New @ QM 2014





- Measured in backward (Pb-going, left) and forward (p-going, right) rapidity in $2 < p_T < 16$ GeV/c

R_{pPb} of heavy-flavour decay muons



- Compatible with unity at forward and backward rapidity at high p_T
  → Backward rapidity: slightly larger than unity in $2 < p_T < 4$ GeV/c
- Data described by pQCD calculations with EPS09 shadowing within uncertainties

***pQCD NLO (MNR)**: M. Mangano et al., Nucl. Phys. B 373 (1992) 295; **EPS09**: K. J. Eskola et al., JHEP 04 (2009) 065*

Summary

- **Pb-Pb results:**
  - → Significant **suppression** of D mesons, electrons, muons **at high p_T** when compared with pp **at both forward and mid-rapidity**
  - → D-meson R_{AA} compared with CMS non-prompt J/ψ
    - → **R_{AA}(D) < R_{AA}(J/ψ ← B)**, as expected from energy-loss hierarchy
  - → Elliptic flow v_2 measured for D mesons, electrons and muons; compatible with measurement for charged particles
    - → Suggests **collective motion of charm quarks in medium**

- **p-Pb results:**
  - → Mid-rapidity: D-meson & electron R_{pPb} compatible with unity; **suppression in Pb-Pb is due to hot medium effects**
  - → R_{pPb} of **electrons from beauty decays** compatible with that from heavy flavour decays
  - → Muons: R_{pPb} also compatible with unity; slight enhancement over pp result at low p_T in backward rapidity region
  - → Multiplicity dependence of D-meson production compatible with that in pp

Future prospects

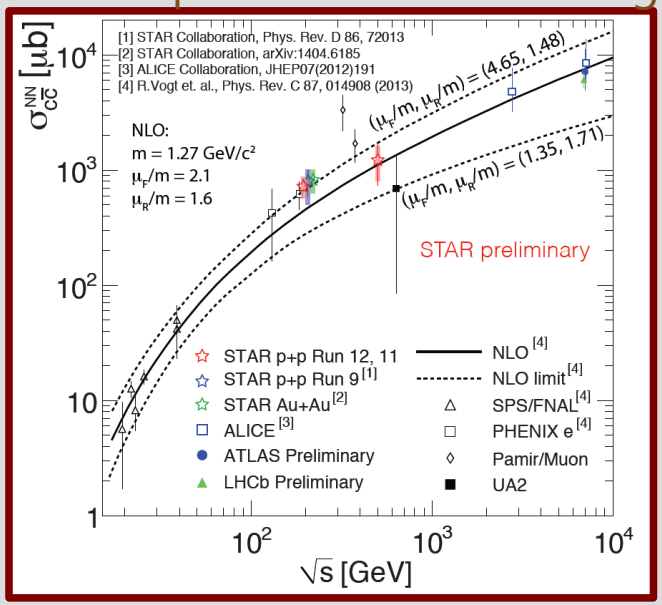
- Λ_c **being measured** in two channels ($\Lambda_c \rightarrow pK_S^0$ & $\Lambda_c \rightarrow pK\pi$)
- **D^0 at low p_T** (< 1 GeV/c) also under study
  → Resolution limits effectiveness of topological selections
  → Controlling background using track rotation, reflections
- **Run II (2015-2017)**
  → Higher $\sqrt{s}$ + increased luminosity in all systems
  → Transition Radiation Detector (TRD) at full coverage
    → Enhanced electron triggering + identification at high p_T
- **LS2 in 2017, Run III:** Further upgrade in luminosity, + upgrades to ITS and other detectors will allow for many refinements
  → Full reconstruction of B mesons via hadronic decays
  → Precision measurements of Λ_c and D_s R_{AA}; higher precision on D-meson v_2...
    → Will allow (among other things) measurement of baryon-to-meson ratio in charm sector

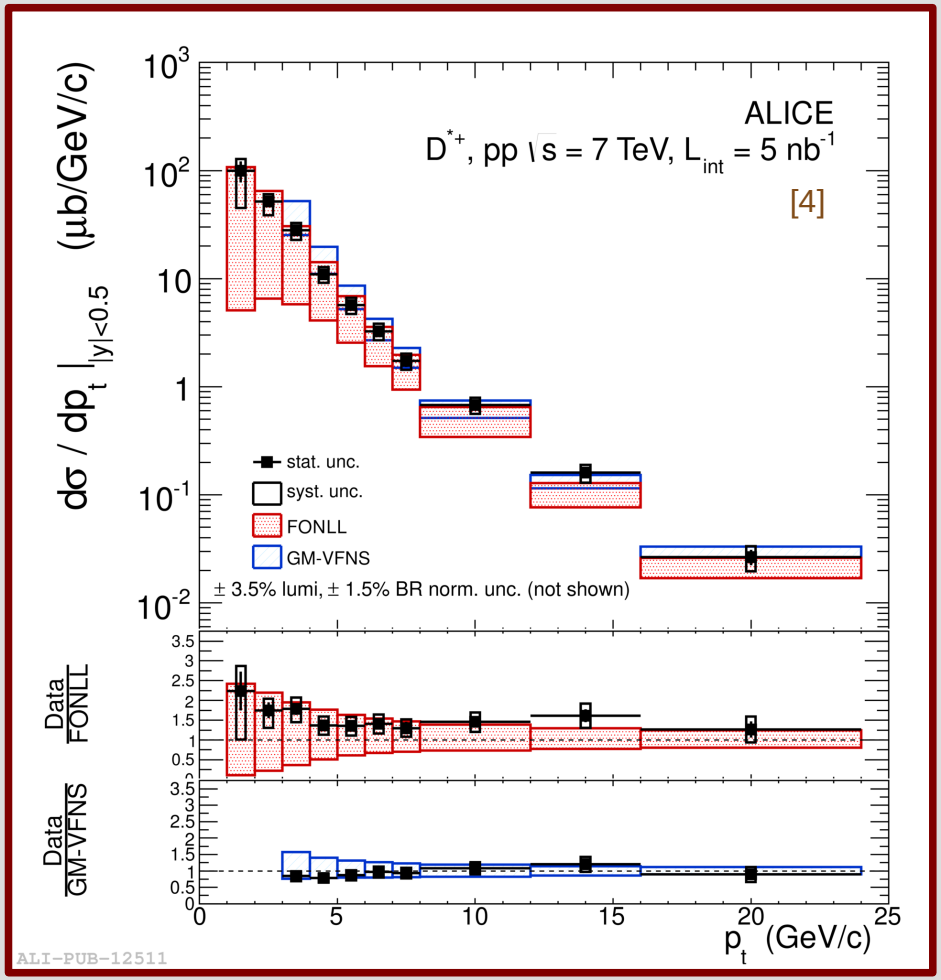
Many interesting results so far, but **still plenty more on the way!**

– Backup slides –

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

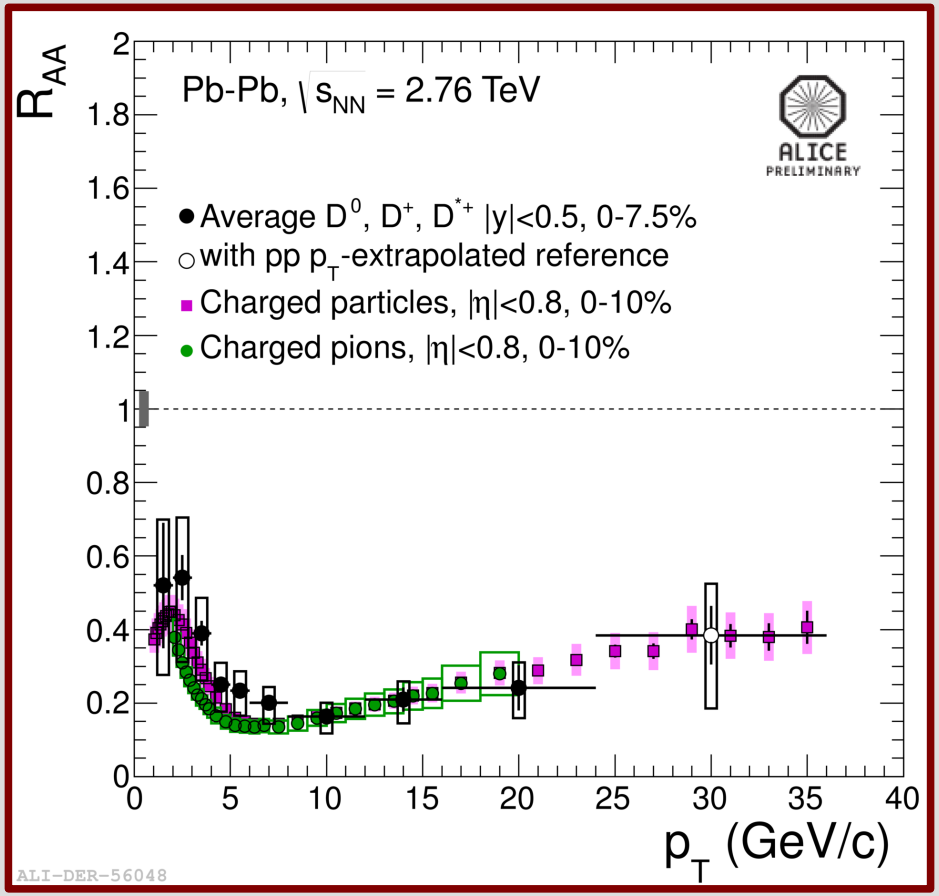




[1] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007
[2] B. A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, arXiv:1202.0439 [hep-ph]
[3] M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B373 (1992) 295
[4] B. Abelev et al. (ALICE collaboration), Phys.Rev. D86 (2012) 112007

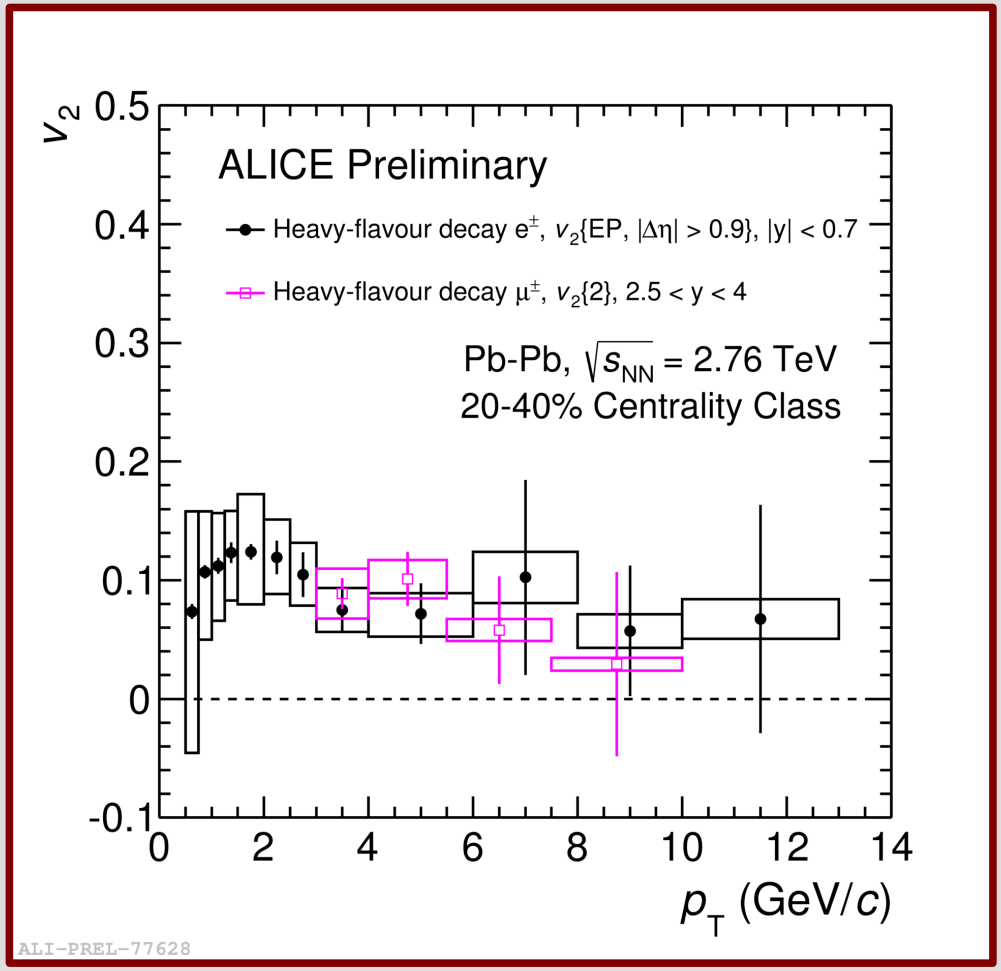
D-meson R_{AA} vs. charged particles

- D-meson R_{AA} compatible with pion R_{AA} within uncertainties
- Consistency described by models that take into account:
  → $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$
  → Different shapes of p_T distributions
  → Differing fragmentation functions



Heavy-flavour decay muon v_2

- Measured using $Q\{2\}$ cumulant method

$$v_2^{\mu \leftarrow HF} = \frac{v_2^{incl\,\mu} - f_{decay\,\mu}\, v_2^{decay\,\mu}}{1 - f_{decay\,\mu}}$$

- f_{decay} ~ 15 (5)% at p_T = 3 (10) GeV/c, based on extrapolation of π/K spectra at mid-rapidity
- v_2^{decay} determined using cocktail method based on data
- v_2 significantly greater than 0 (3σ effect for 3 < p_T < 5 GeV/c)
- Comparison with e±: $v_2^{\mu \leftarrow c,b}|_{forward} \sim v_2^{e \leftarrow c,b}|_{mid\text{-}rapidity}$