Open heavy-flavour results from ALICE

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BIRMINGHAM SQM 2013

ALICE

Outline

Heavy flavours: why?

- Heavy quarks are produced in the initial hard scattering processes
- They are exposed to the evolution of the high energy-density medium formed in ultra-relativistic heavy-ion collisions

What can we test?

A–A collisions: probing the high density medium

- Energy loss
  - Color charge dependence ($\Delta E_g > \Delta E_q$) $\Rightarrow$ compare with light hadrons
  - Quark mass dependence ($\Delta E_c > \Delta E_b$) $\Rightarrow$ compare charm/beauty
- Thermalization in the QGP (low-p_{T})

Reference needed:

p–p collisions

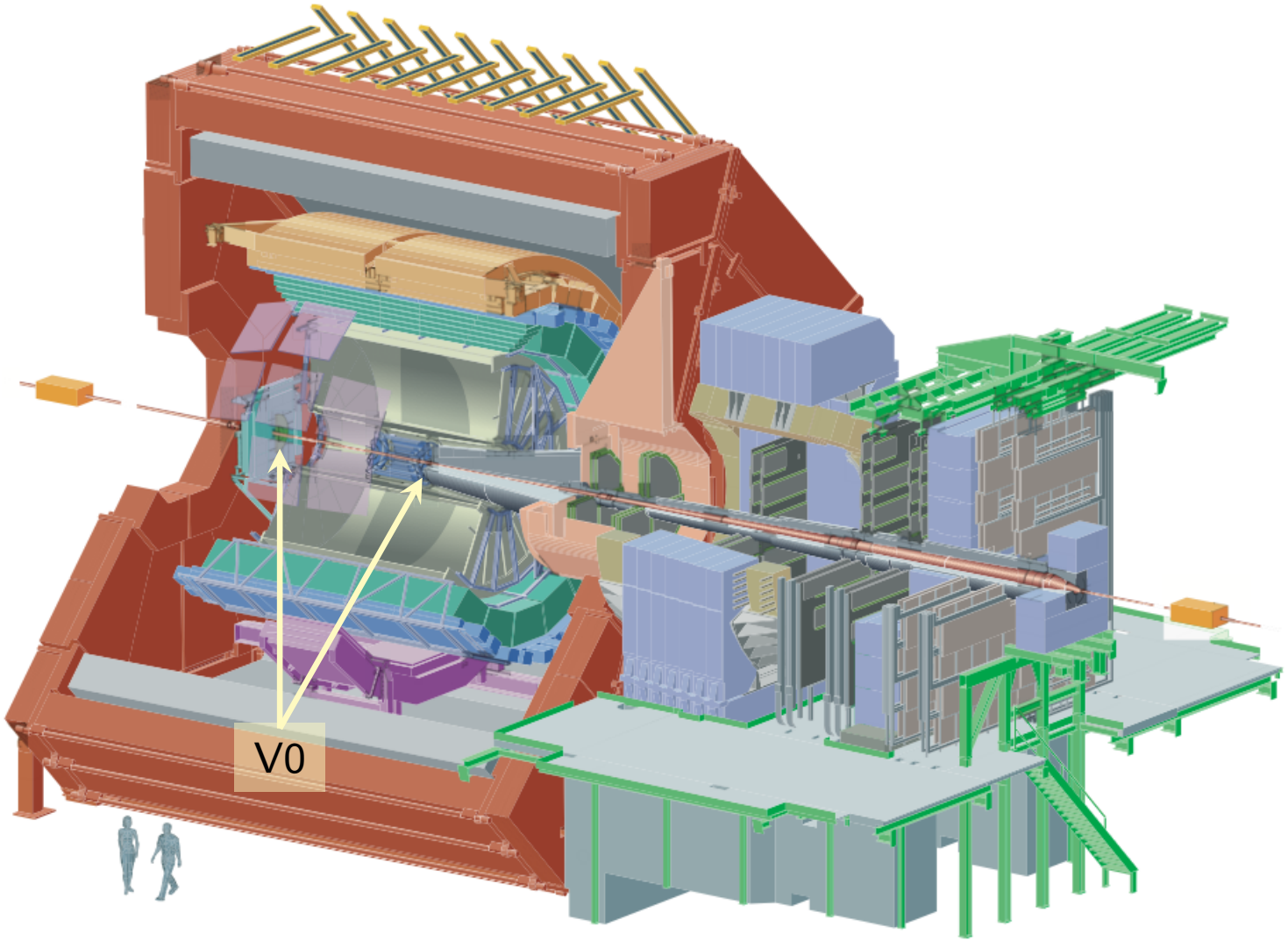
- Reference to study the effects in A–A collisions
- Test of perturbative QCD

Disentangle the "initial state" effects:

p–A collisions

- Modification of parton distributions in nuclei (shadowing)
- Gluon saturation

ALICE layout

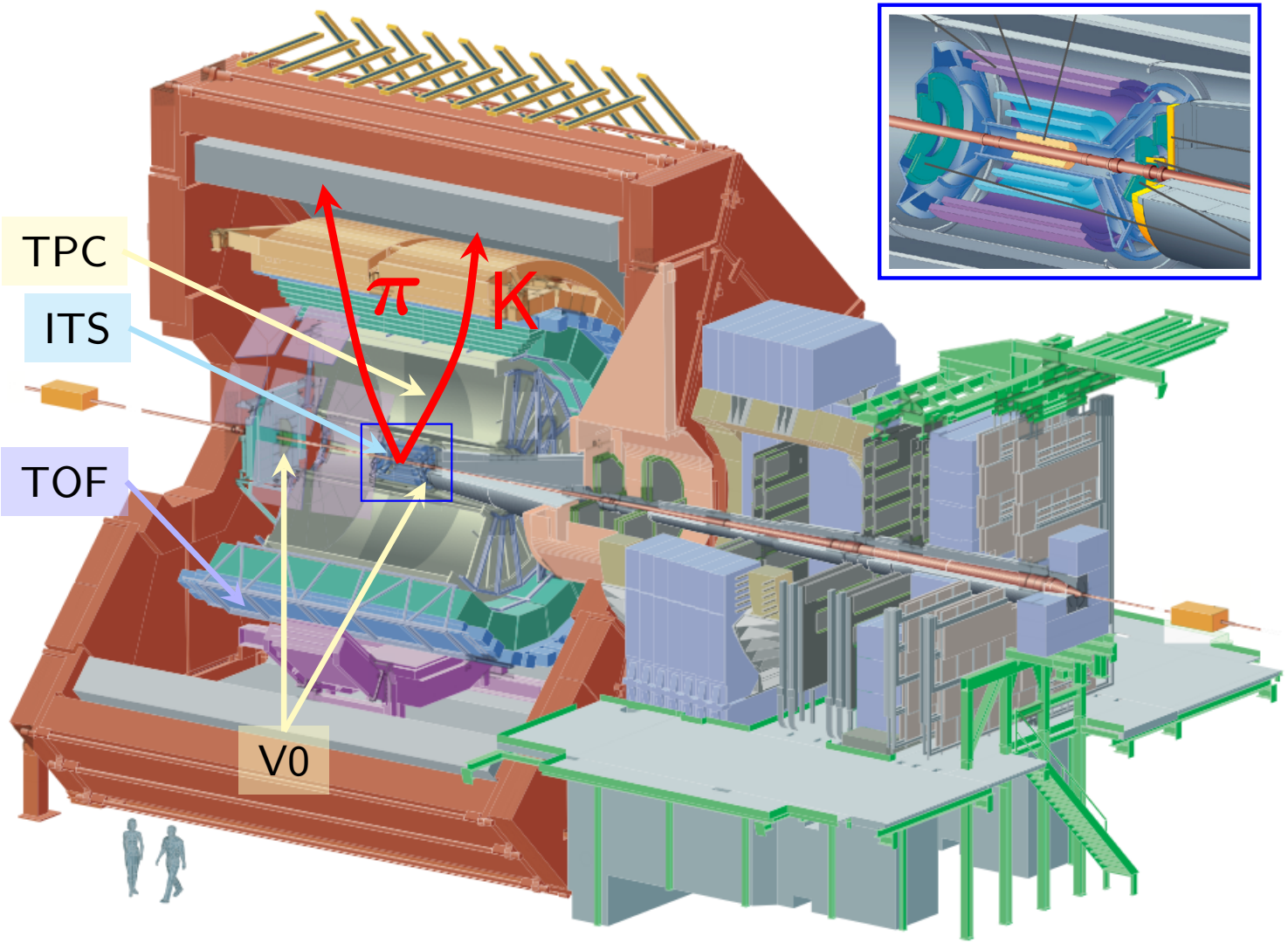


$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow K^- \pi^+ \pi^+$

$D^{*+} \rightarrow D^0 \pi^+$

$D_s^+ \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$



- $|\eta| < 0.9$
- ITS, TPC, TOF: vertex, tracking, PID

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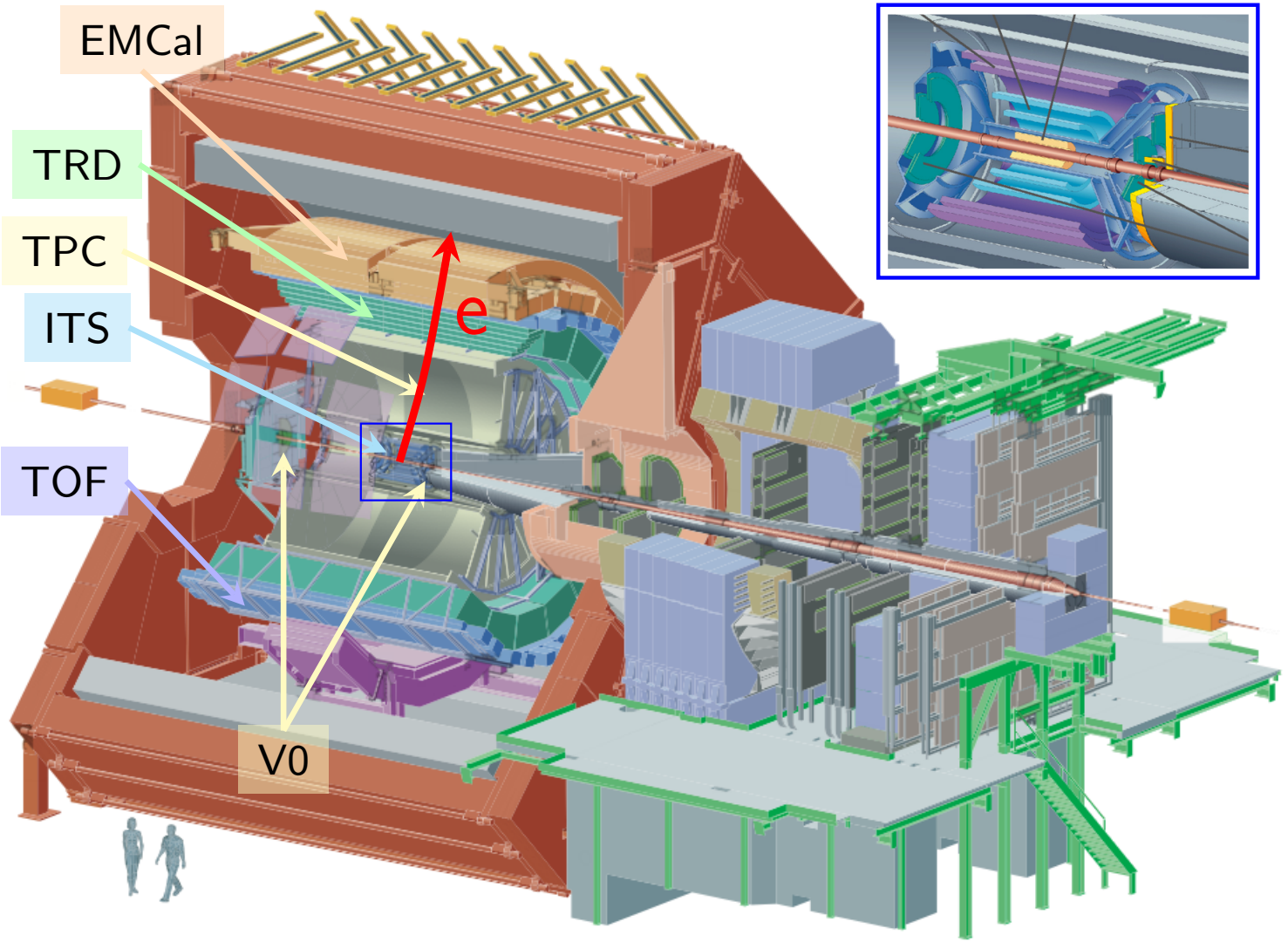
$c, b \rightarrow e + X$



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- ITS, TPC, TOF: vertex, tracking, PID
- TRD, EMCal: electron PID

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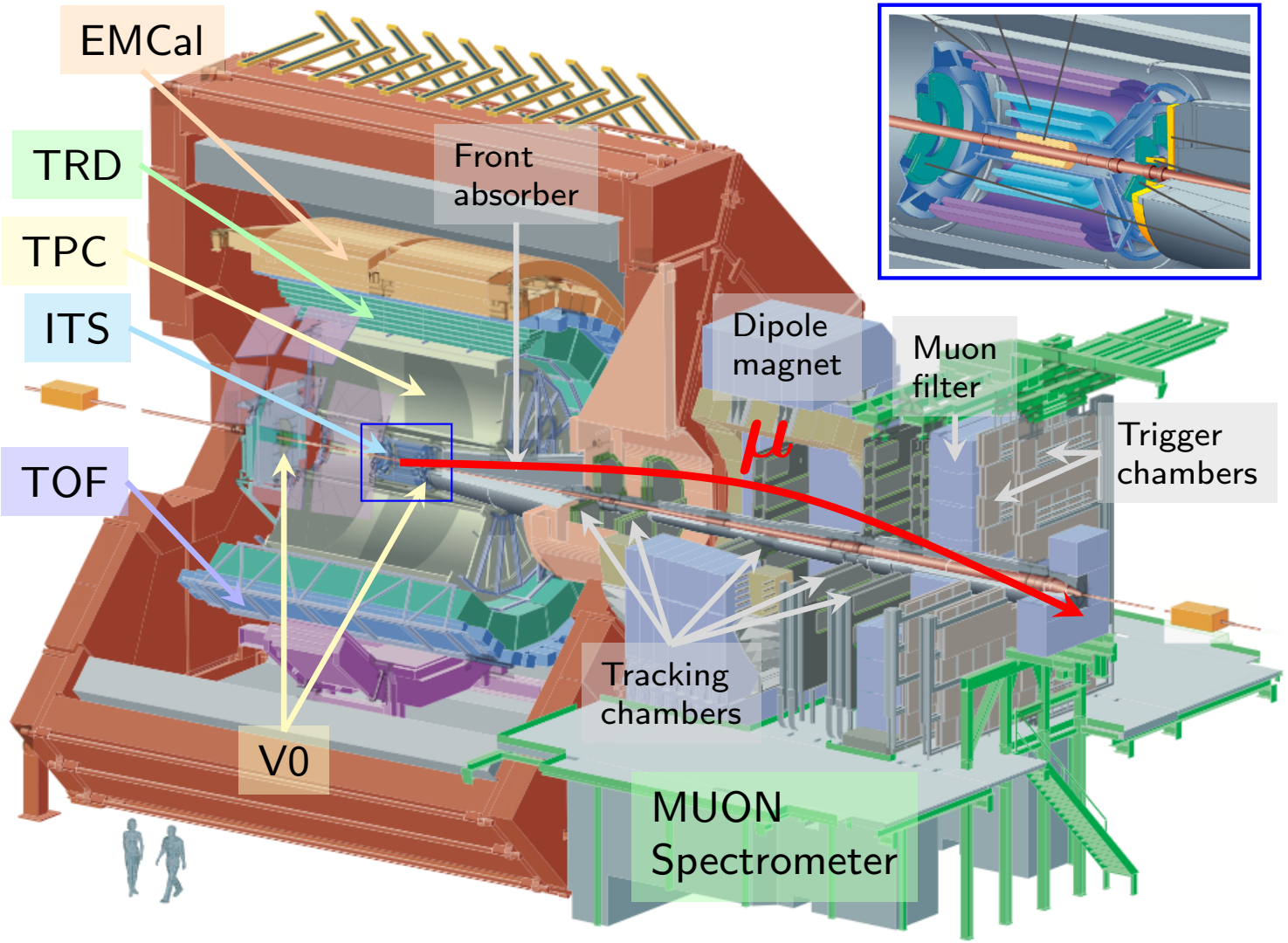
$c, b \to e + X$

$c, b \to \mu + X$



- $|\eta| < 0.9$
- ITS, TPC, TOF: vertex, tracking, PID
- TRD, EMCal: electron PID

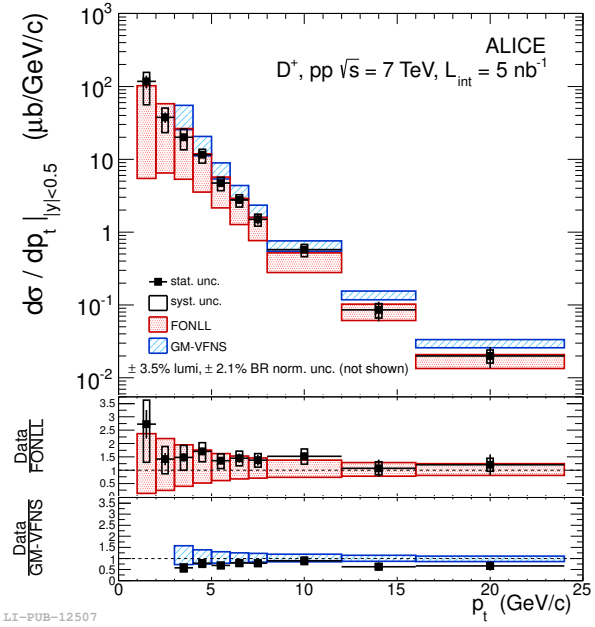
- Muon Spectrometer: tracking and PID in $-4 < \eta < -2.5$

pp collisions at $\sqrt{s} = 2.76$ and 7 TeV

D mesons

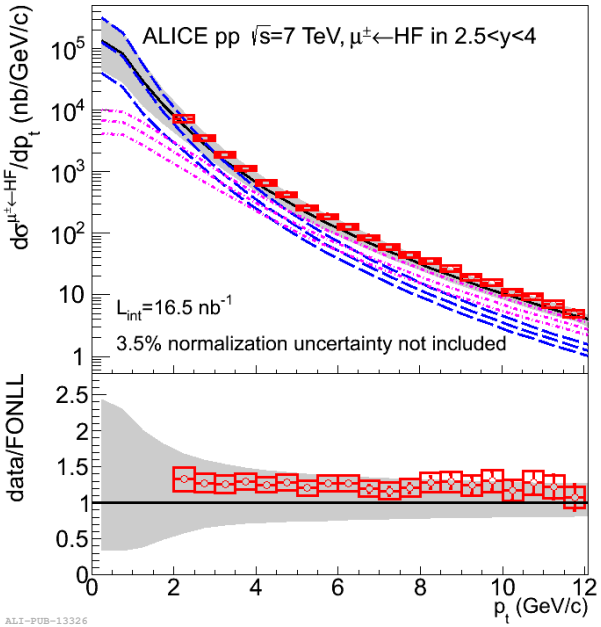
JHEP **1201** (2012) 128

see also: Phys. Lett. B **718** (2012) 279 for D_s^+

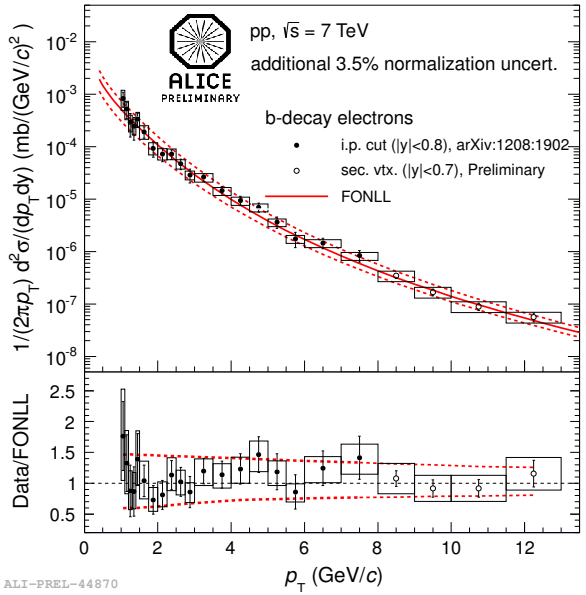


Heavy-flavour decay muons

Phys. Lett. B **708** (2012) 265



Heavy-flavour decay electrons



- Reminder: p_{T}-differential cross-sections measured in all channels

D mesons

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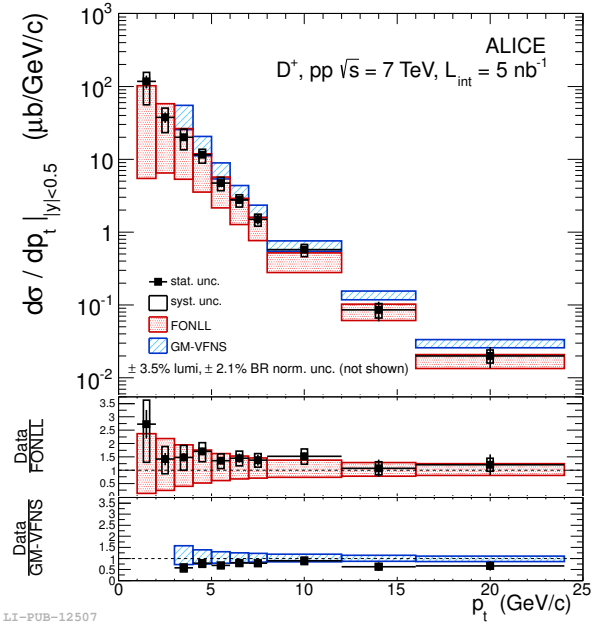

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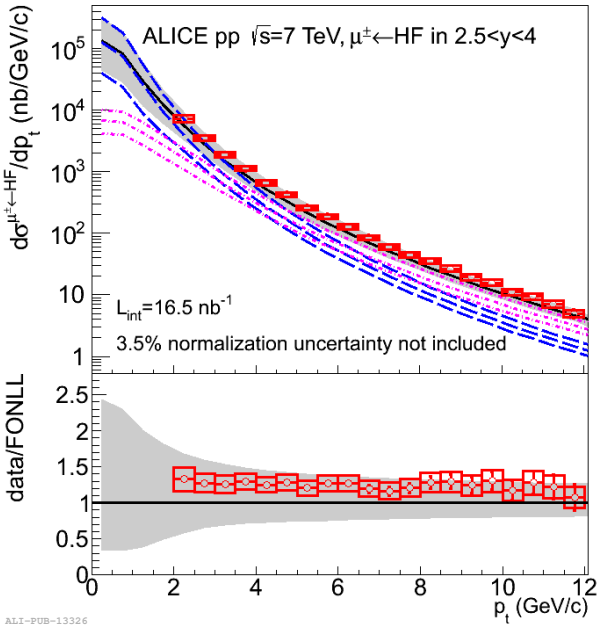
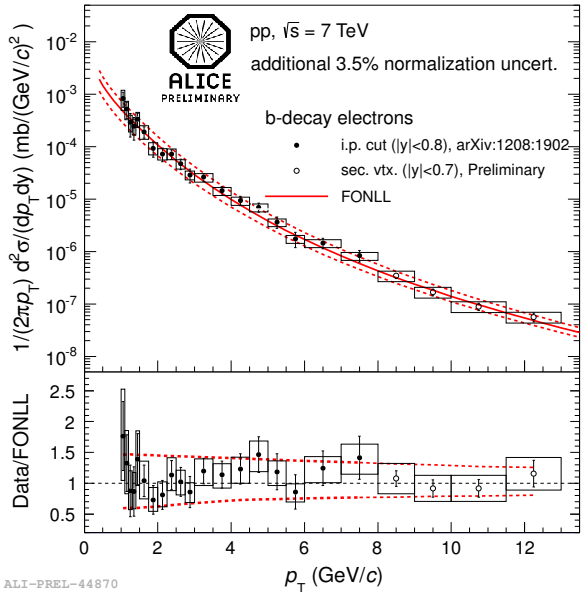


Heavy-flavour decay electrons

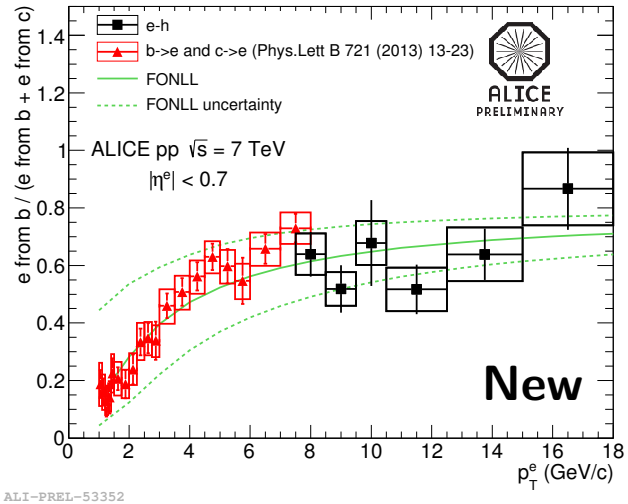


- Reminder: p_{T}-differential cross-sections measured in all channels
- News: extended p_{T} reach in electron measurements

M. Heide. p–A collisions, Fri. 14:20

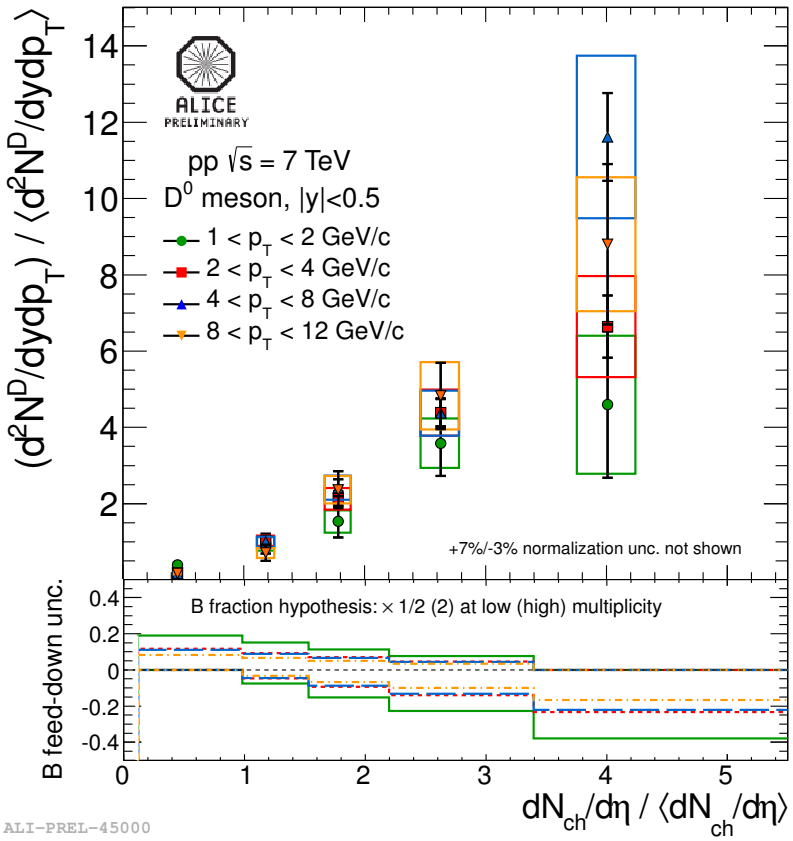
- All results well described by pQCD calculations

[FONLL: JHEP **1210** (2012) 137], [GM–VFNS: Eur. Phys. J. C **72** (2012) 2082], [k_t factorisation: arXiv:1301.3033]



An interesting pp study

- Measurement of D meson production vs. charged particle multiplicity in pp collisions at $\sqrt{s} = 7$ TeV
- Motivation:
  - understand the contribution of Multi-Parton Interaction
  - check for any collective behavior in high multiplicity pp collisions (higher mult. than in Cu–Cu collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC)
  - reference for analogous measurement with J/ψ [ALICE Collab., Phys. Lett. B **712** (2012) 165]

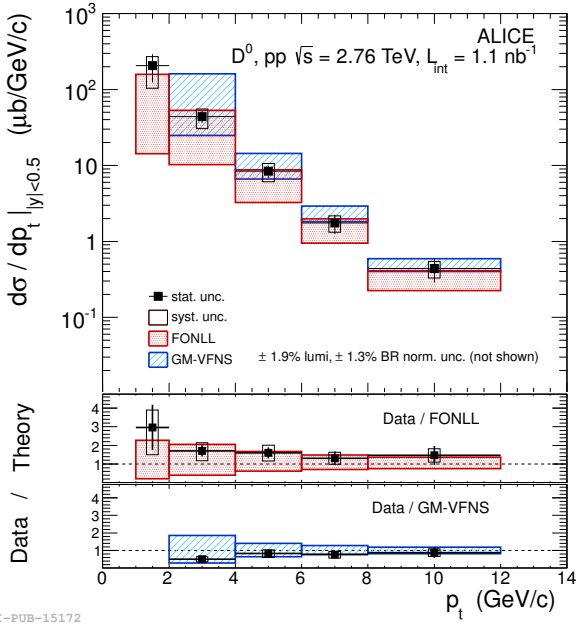


- Increase of yield with multiplicity
- No p_{T} dependence observed with current uncertainties
- **Won't go into details here.** Please see:

R. Bala. Heavy Flavour 2, Thu. 15:40

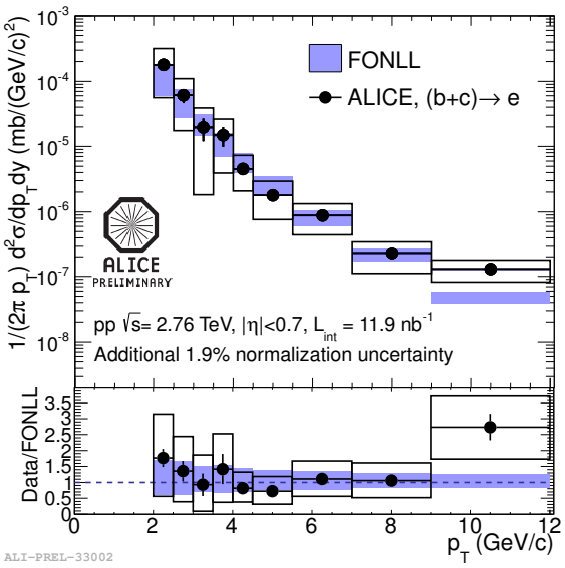
D mesons

JHEP **1207** (2012) 191



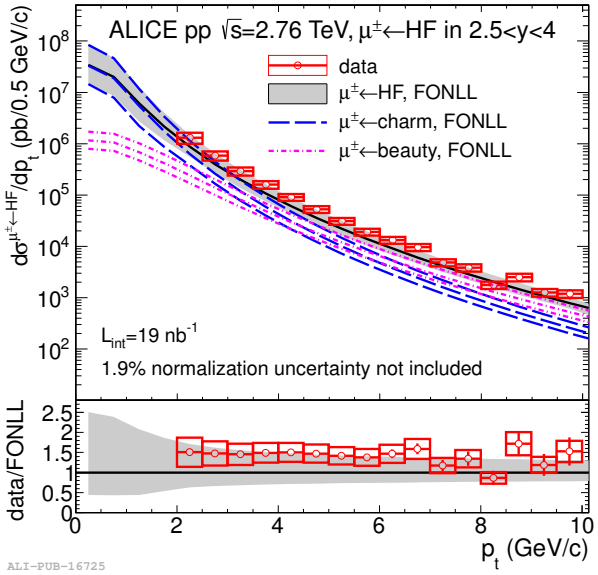
Heavy-flavour decay electrons

Phys. Lett. B **721** (2013) 13



Heavy-flavour decay muons

Phys. Rev. Lett. **109** (2012) 112301



- Data well described by pQCD calculations [FONLL: JHEP **1210** (2012) 137], [GM–VFNS: Eur. Phys. J. C **72** (2012) 2082]

- HF decay muon data used as reference for Pb–Pb collisions at the same energy
- For other channels (and for p–Pb at 5.02 TeV), due to the limited statistics in pp collisions at $\sqrt{s} = 2.76$ TeV, an extrapolation based on pQCD calculations is performed
  - data at $\sqrt{s} = 2.76$ TeV used to test the scaling

Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

Nuclear modification factor:

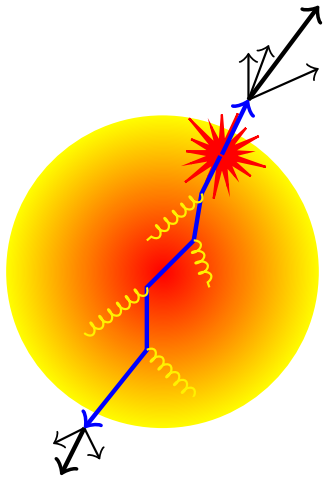
$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

- QCD-based models describing collisional and radiative energy loss in the medium predict: [Dokshitzer *et al.*, PLB **519** (2001) 199], [Armesto *et al.*, PRD **69** (2004) 114003], [Djordjevic *et al.*, NPA **783** (2007) 493], [...]

$$E_{loss}(g) > E_{loss}(u,d,s) > E_{loss}(c) > E_{loss}(b)^*$$

$$\Downarrow$$

$$R_{AA}(\text{light hadrons}) < R_{AA}(c) < R_{AA}(b)$$



I_{AA}: ratio of yields measured in AA and pp collisions.
Used in correlation studies

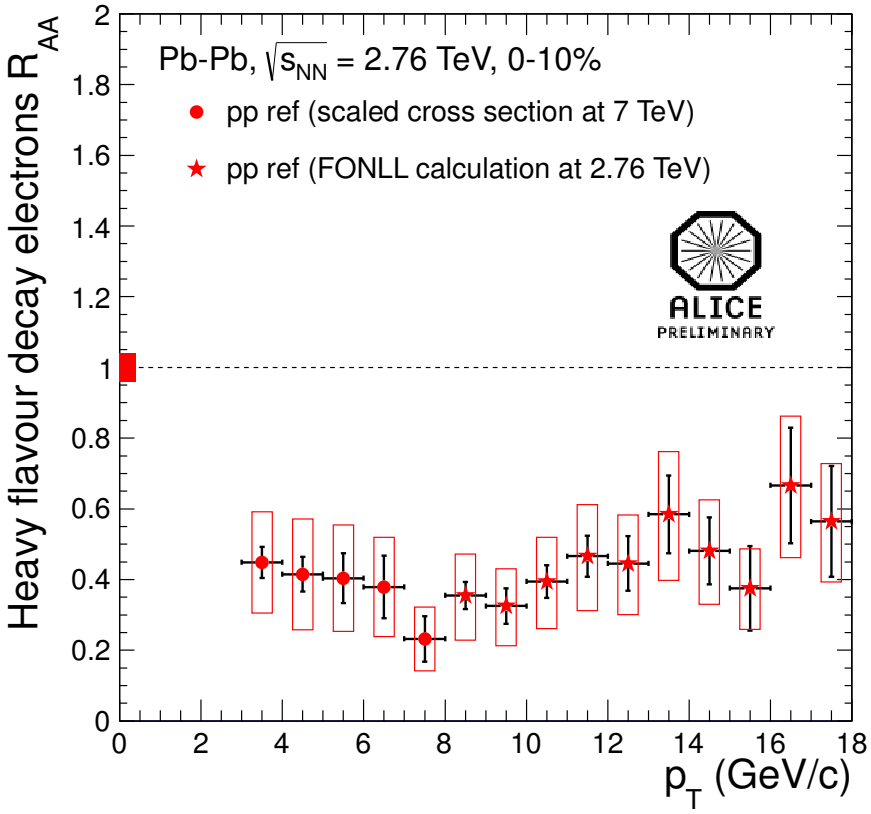
$$I_{AA} = \frac{\int_{\phi_1}^{\phi_2} d\Delta\phi \frac{dN_{AA}}{d\Delta\phi}}{\int_{\phi_1}^{\phi_2} d\Delta\phi \frac{dN_{pp}}{d\Delta\phi}}$$

- Near side (around $\Delta\phi = 0$): sensitive to fragmenting jet leaving the medium
- Away side (around $\Delta\phi = \pi$): sensitive to the probability that the recoiling particle survives the passage through the medium

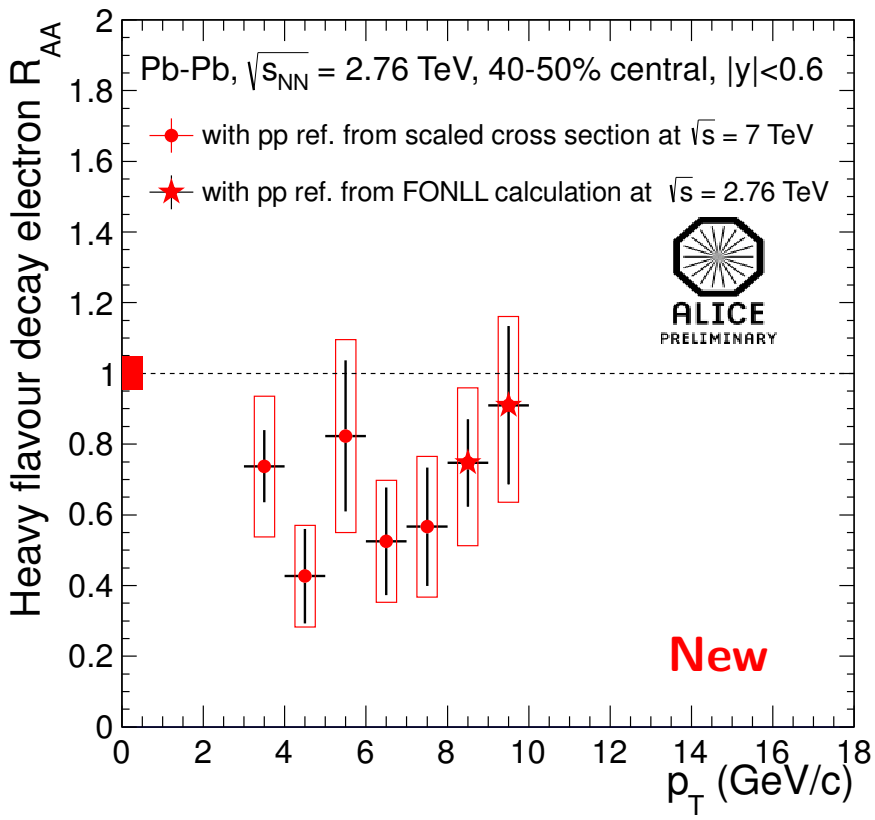
*The mass hiearchy holds in the p_T range where the quark mass is relevant

Heavy-flavour decay electrons R_{AA}

Central



Peripheral

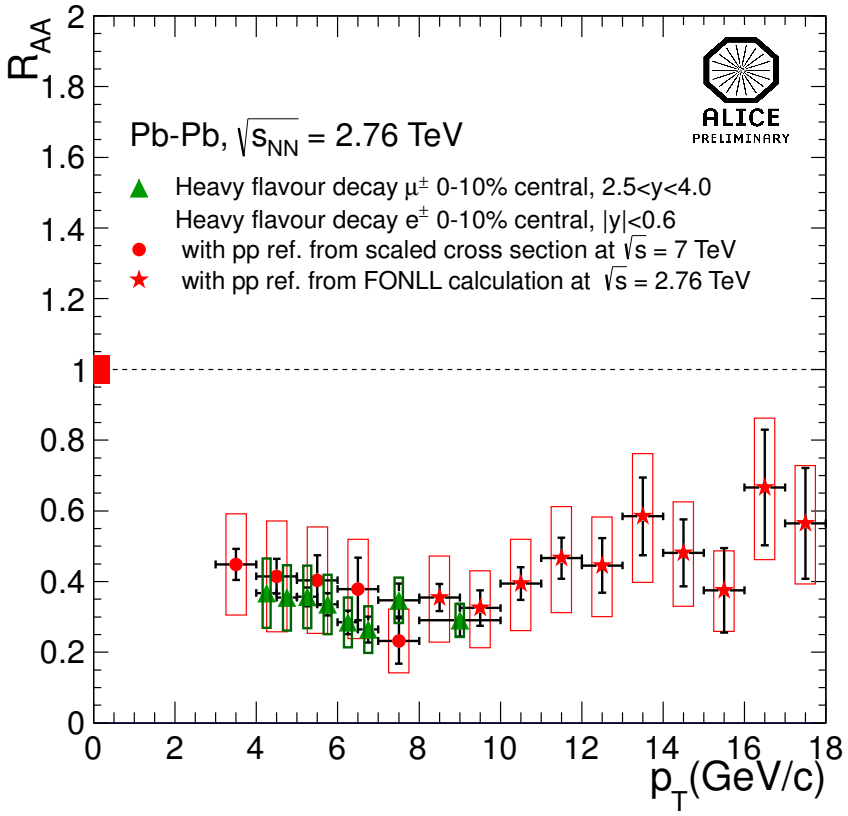


- R_{AA} measured in central (0–10%) and peripheral (40–50%) collisions
  - hint for larger reduction of yields in most central collisions

D. Thomas. Heavy Flavour 2, Thu. 15:00

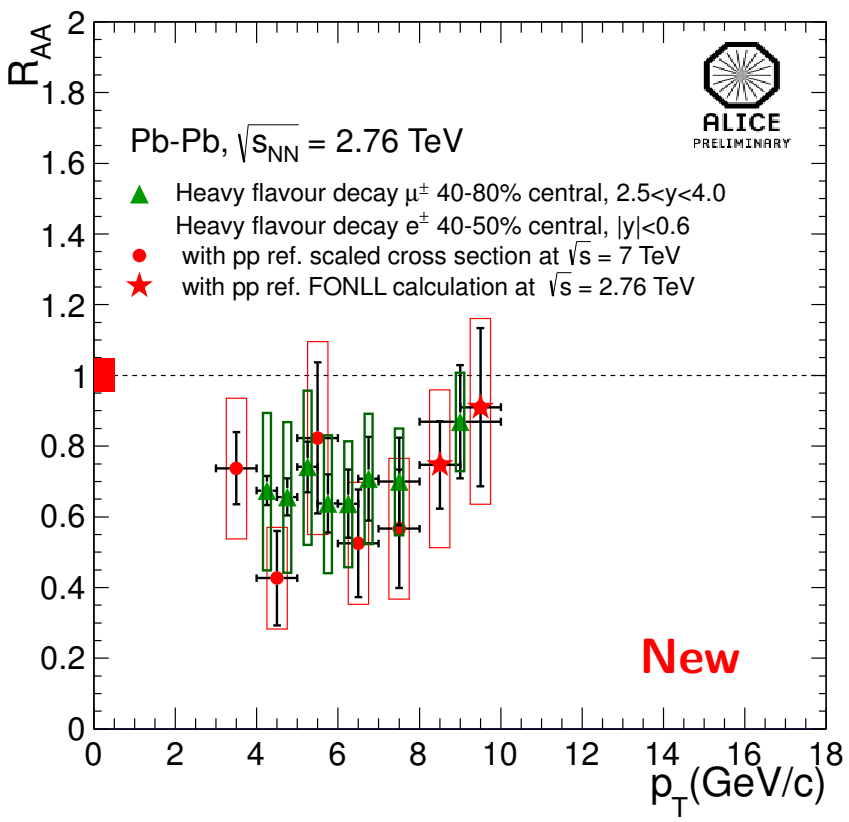
Heavy-flavour decay electrons R_{AA}

Central



ALI-DER-36791

Peripheral



ALI-DER-53851

- R_{AA} measured in central (0–10%) and peripheral (40–50%) collisions
  - hint for larger reduction of yields in most central collisions
- R_{AA} values comparable with muon results at forward rapidity (0–10% and 40–80% centralities)

D. Thomas. Heavy Flavour 2, Thu. 15:00

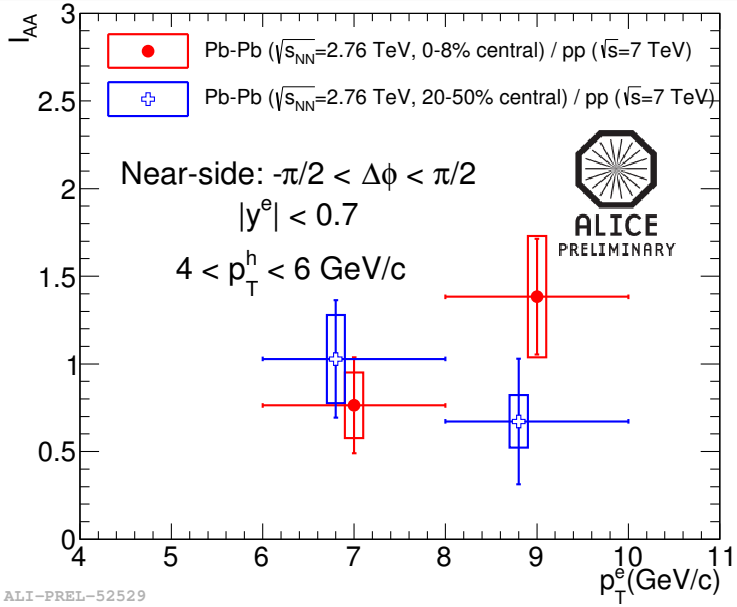
Heavy-flavour decay electrons I_{AA}

- Electron-hadron azimuthal correlation measured in pp and Pb–Pb collisions

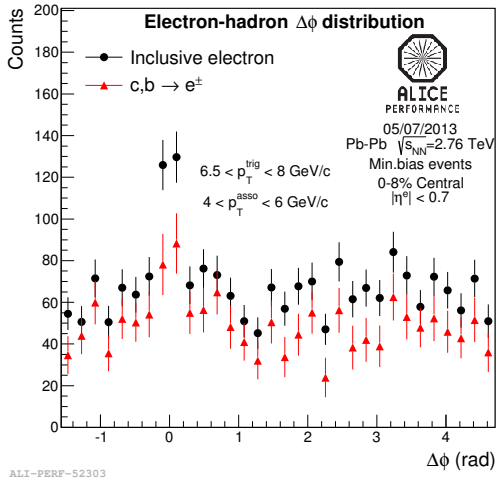
E. Pereira. Poster

- Near-side I_{AA} was built from:
  - 2011 Pb–Pb data at $\sqrt{s_{NN}} = 2.76$ TeV
  - 2011 pp data at $\sqrt{s} = 7$ TeV

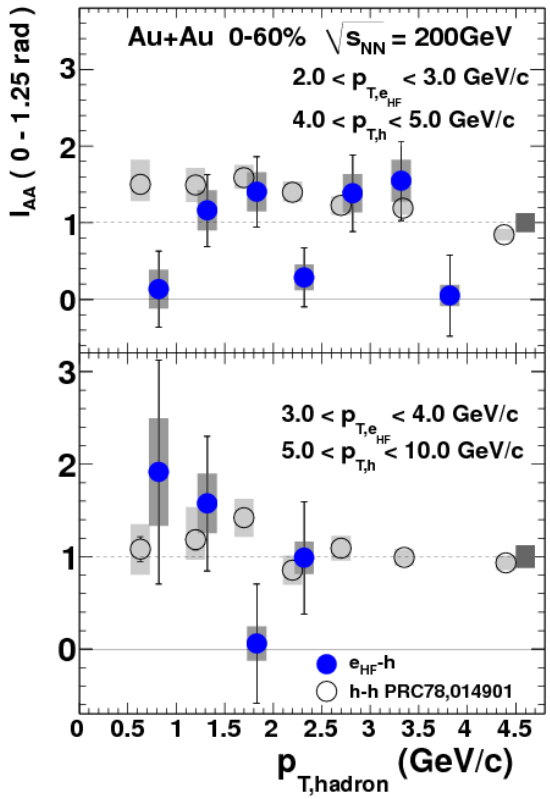
D. Thomas. Heavy Flavour 2, Thu. 15:00



- Results similar to PHENIX in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- Analysis is ready, but need further statistics for a more precise measurement



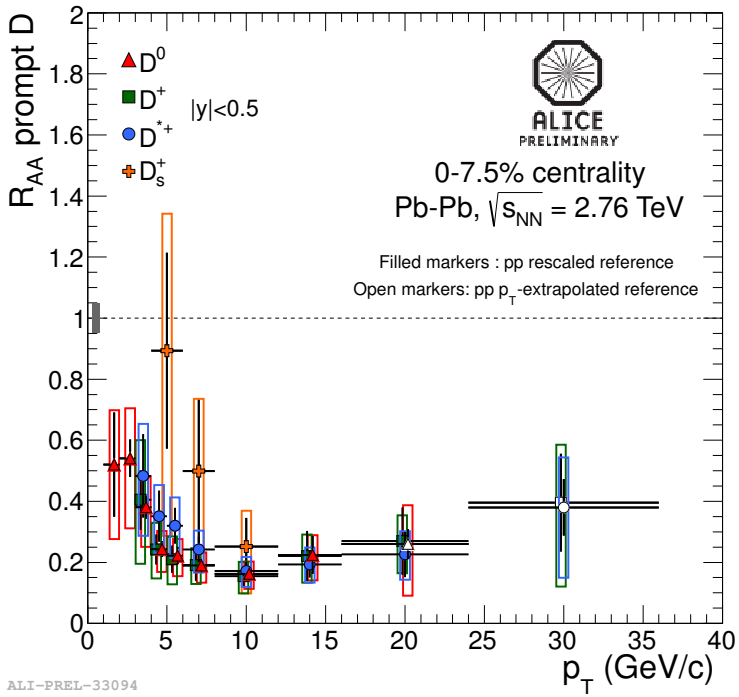
PHENIX, Phys. Rev. C **83** (2011) 044912



D mesons R_{AA}: status so far

- D meson R_{AA} was measured up to $p_T = 16$ GeV/c with 2010 Pb–Pb data
- pp reference: ALICE results at $\sqrt{s} = 7$ TeV [JHEP **1201** (2012) 128] scaled to $\sqrt{s} = 2.76$ TeV with FONLL [Cacciari *et al.*, JHEP **1210** (2012) 137]

- Larger p_T-reach with 2011 data (up to 36 GeV/c in 0–7.5% most central collisions)
- First measurement of D_s^+ was shown in QM2012



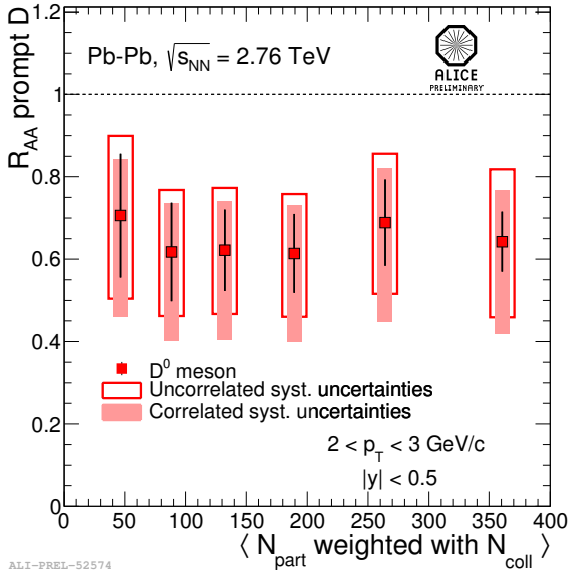
- Expectation: relative enhancement of the strange/non-strange D meson production at intermediate p_T due to recombination/coalescence [Kuznetsova and Rafelski, Eur. Phys. J. C **51** (2007) 113], [He *et al.*, Phys. Rev. Lett. **110** (2013) 112301], [Andronic, Phys. Lett. B **659** (2008) 149]

D mesons R_{AA}: updates

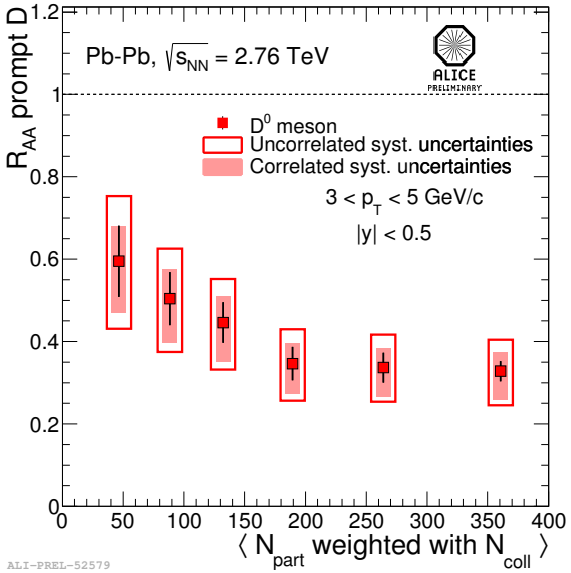
- Dataset:
  - 0–50%: 2011 data
  - 50–80%: 2010 data
- D meson production vs. centrality in several p_T bins

E. Bruna. Heavy Flavour 2, Thu. 15:20

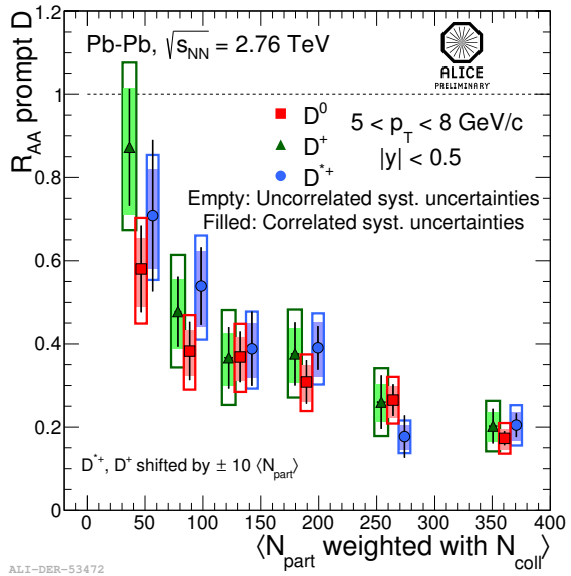
D^0, $2 < p_T < 3$ GeV/c



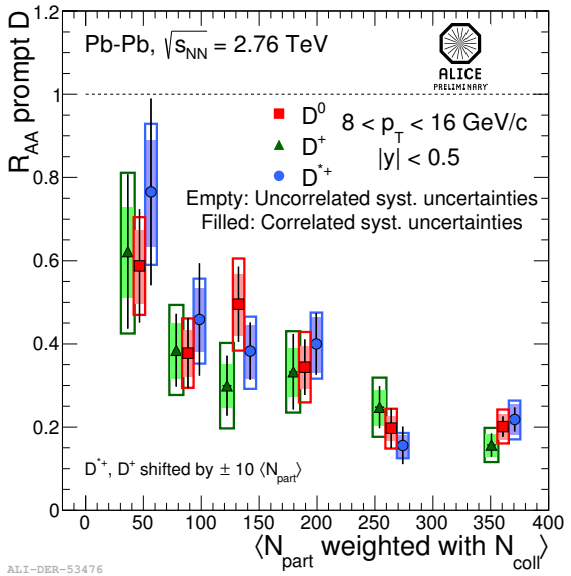
D^0, $3 < p_T < 5$ GeV/c



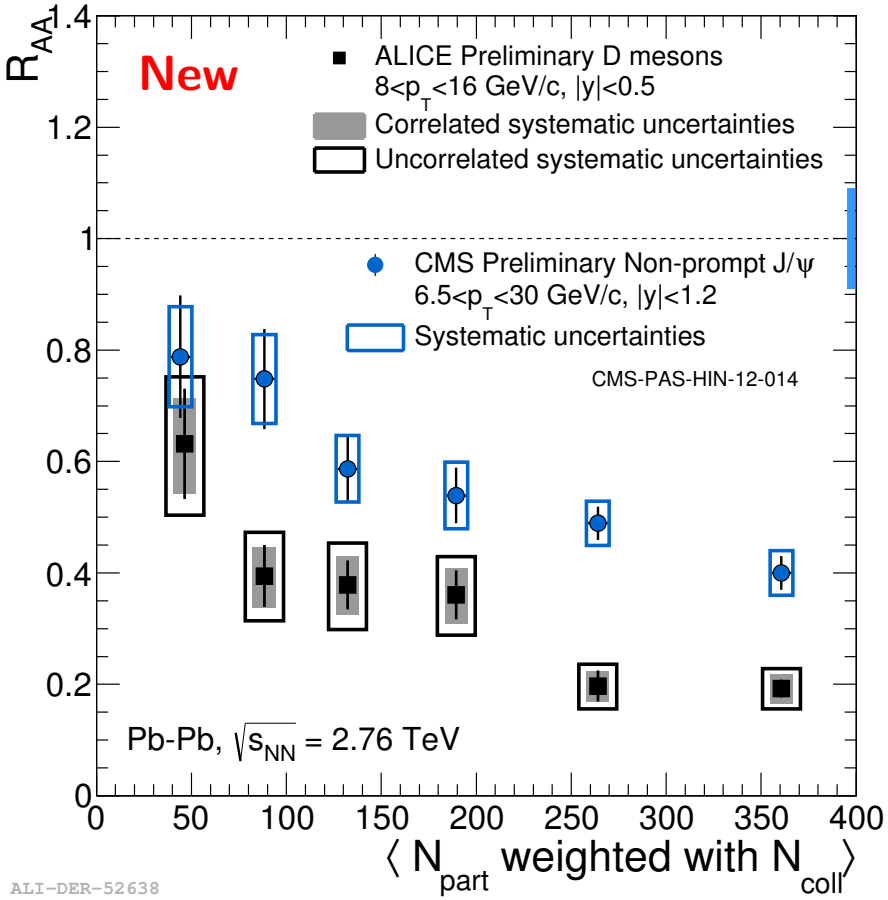
$5 < p_T < 8$ GeV/c



$8 < p_T < 16$ GeV/c



- Testing the mass hierarchy of energy loss. **Expected: $R_{AA}(c) < R_{AA}(b)$**
- First comparison performed in 2012, however: $\langle p_T^D \rangle \neq \langle p_T^{B(\to J/\psi)} \rangle$
- New data allow for a comparison in a compatible p_T range of D and of the parent B of non-prompt J/ψ



- Indication of smaller energy loss for beauty than charm

D mesons R_{AA}: comparison with non-prompt J/ψ

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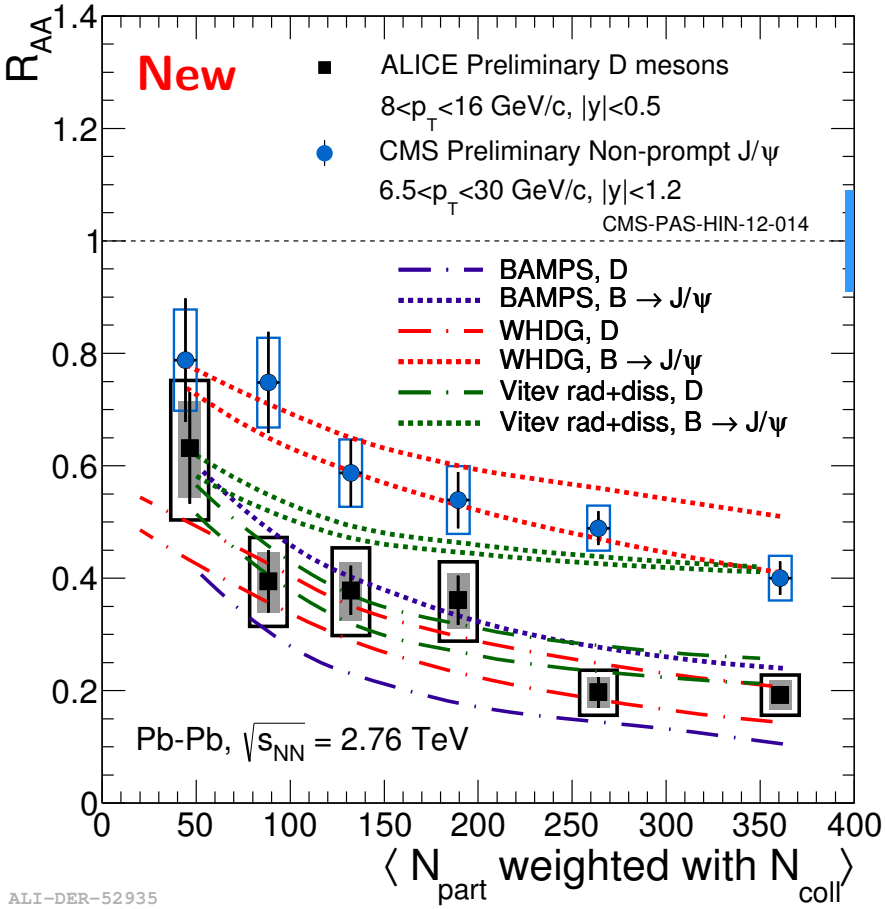
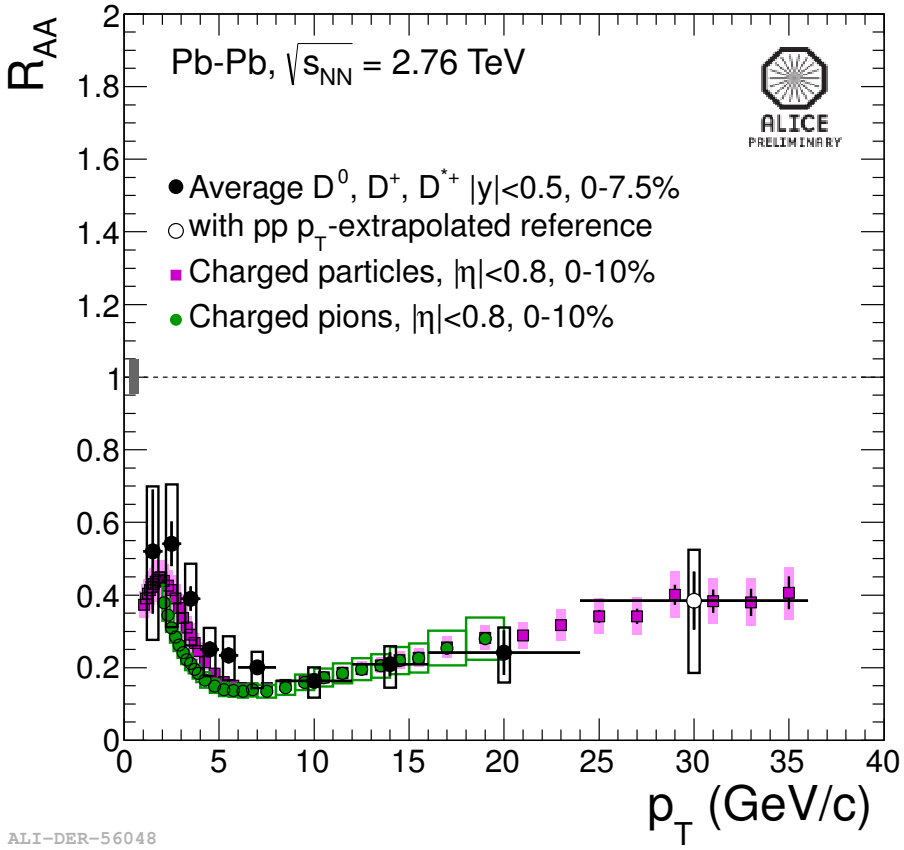


- Indication of smaller energy loss for beauty than charm
- A challenge for models [BAMPS: J. Phys. G **38** (2011) 124152], [WHDG: J. Phys. G **38** (2011) 124114], [Vitev *et al.*, Phys. Rev. C **80** (2009) 054902]

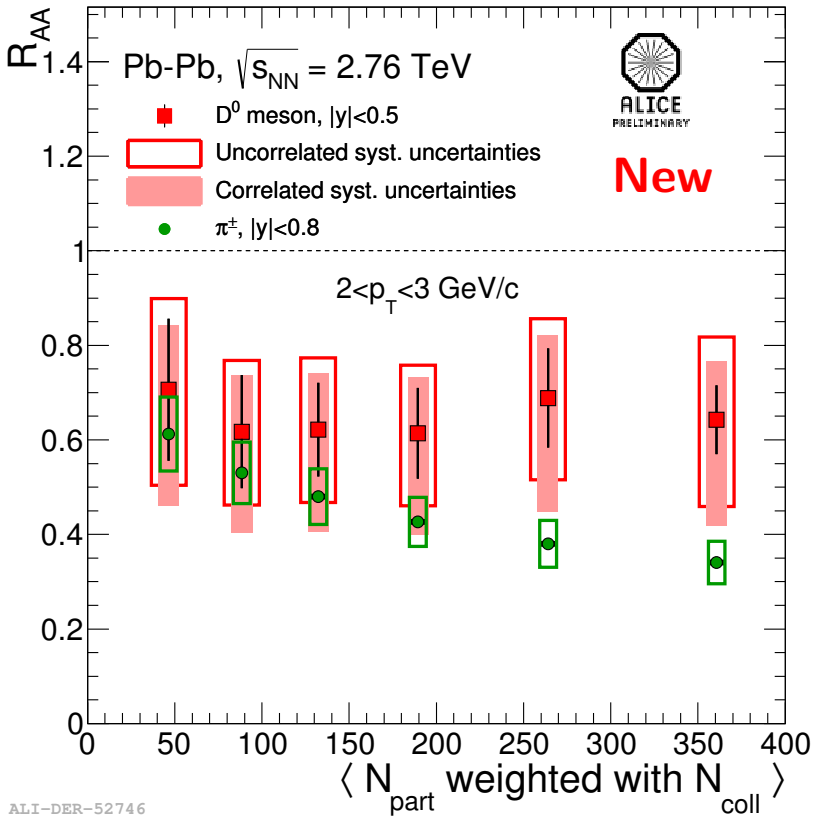
D mesons R_{AA}: comparison with pions

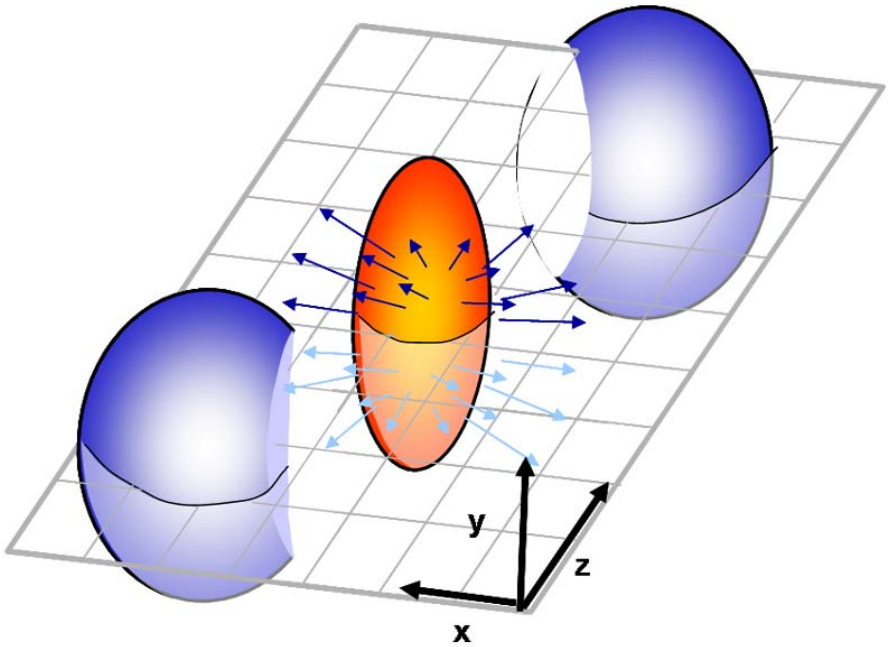
- Testing the color charge dependence of energy loss. Expected: $R_{AA}(\text{light hadrons}) < R_{AA}(c)$

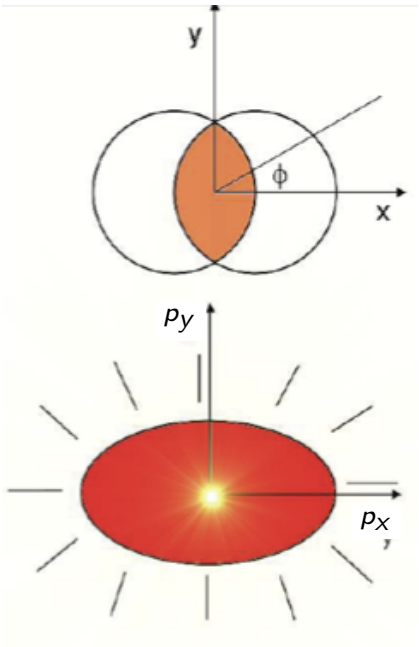
- Comparison with pions in most central collisions performed in 2012: similar R_{AA} at high-p_T; hint for difference for $p_T < 5$ GeV/c



- New: comparison of R_{AA} of D^0 and pion vs. centrality at low-p_T







- Spatial anisotropy is converted via multiple collisions into an anisotropic momentum distribution
- Reaction plane (Ψ_{RP}): defined by the beam axis and the impact parameter vector of the two colliding nuclei
- Azimuthal distributions of particles measured with respect to the reaction plane can be expanded in a Fourier series:

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\mathrm{T}\mathrm{d}p_\mathrm{T}\mathrm{d}y}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n(\phi-\Psi_{RP})\right)\right)$$

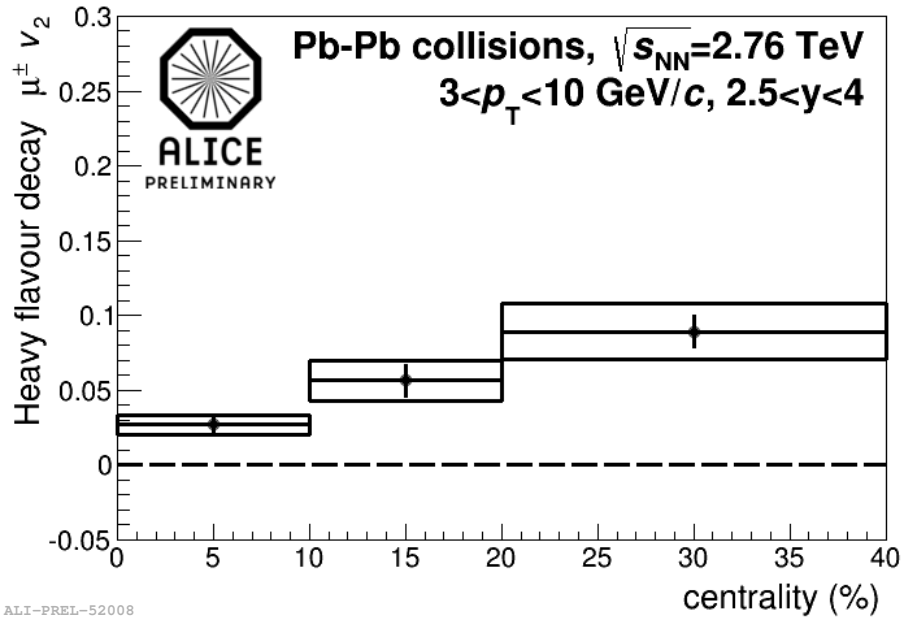
- The elliptic flow is defined as:

$$v_2 = \langle\cos(2(\phi-\Psi_{RP}))\rangle$$

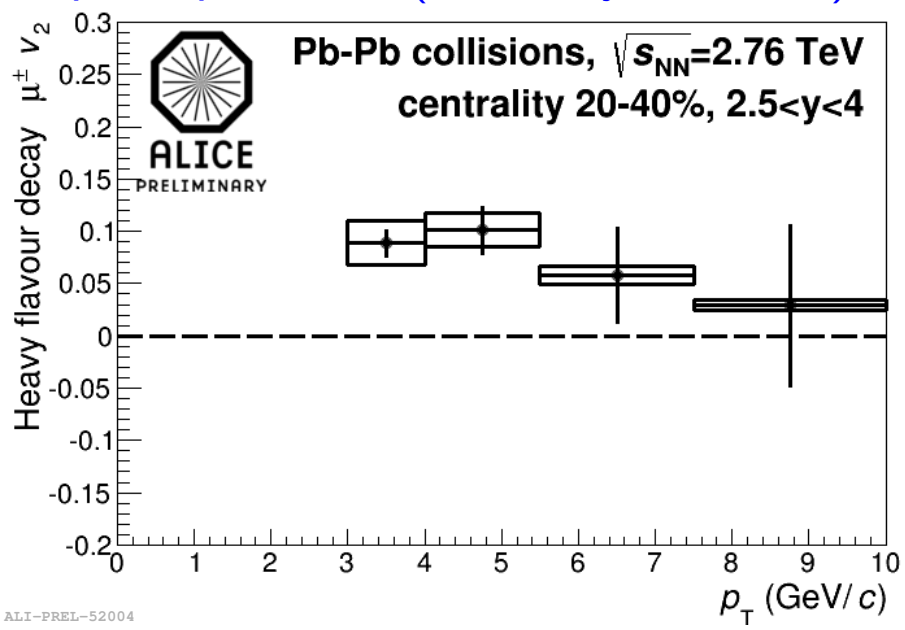
- Elliptic flow of muons from heavy-flavour decays measured in $2.5 < y < 4$
- Dataset: 2011 Pb–Pb run

X. Zhang. Heavy Flavour 1, Tue. 16:20

Centrality dependence



p_T dependence (centrality: 20–40%)



- v_2 increases from central to peripheral collisions in the measured range (0–40%)
- Non-zero v_2 (3σ) observed in the centrality class 20–40%

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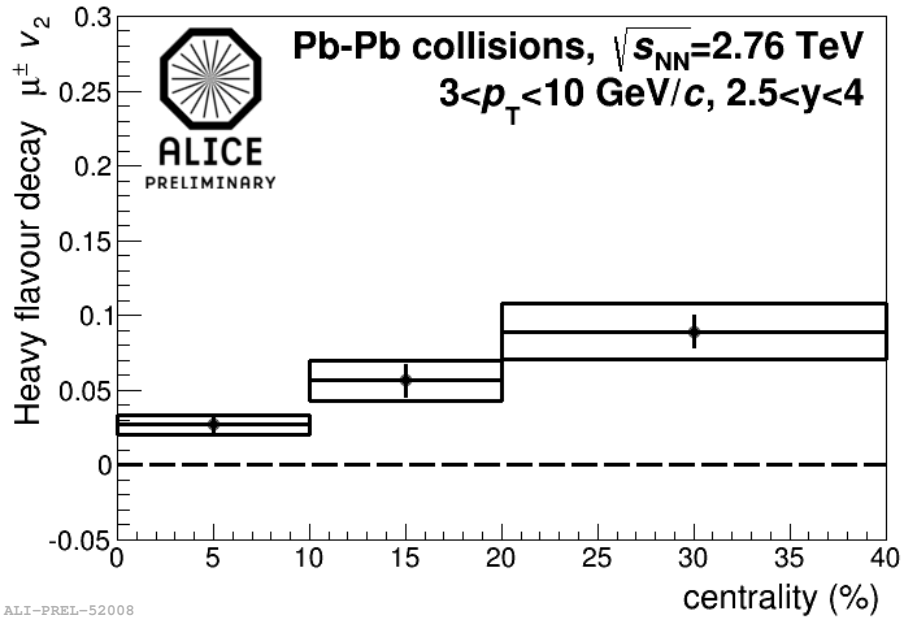

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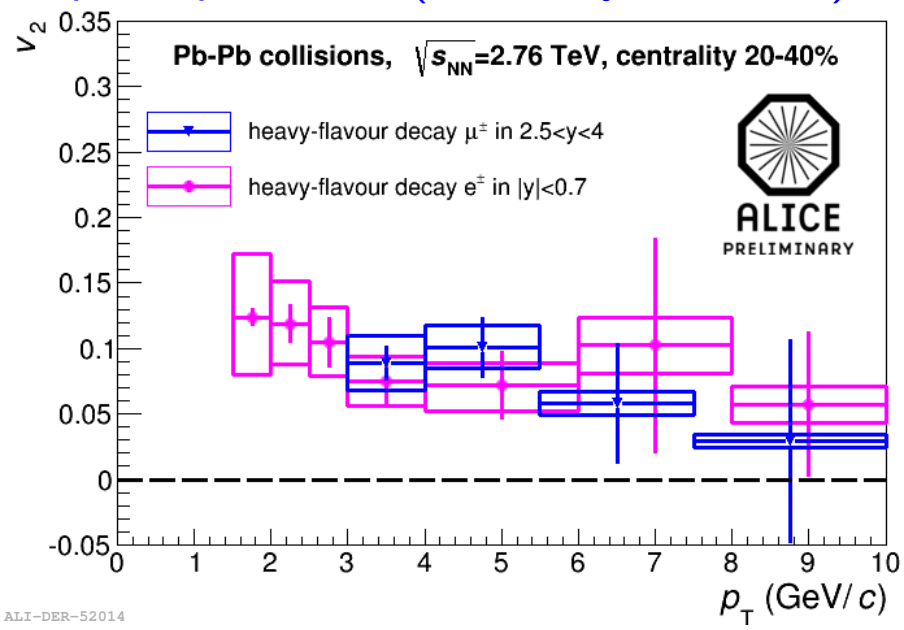
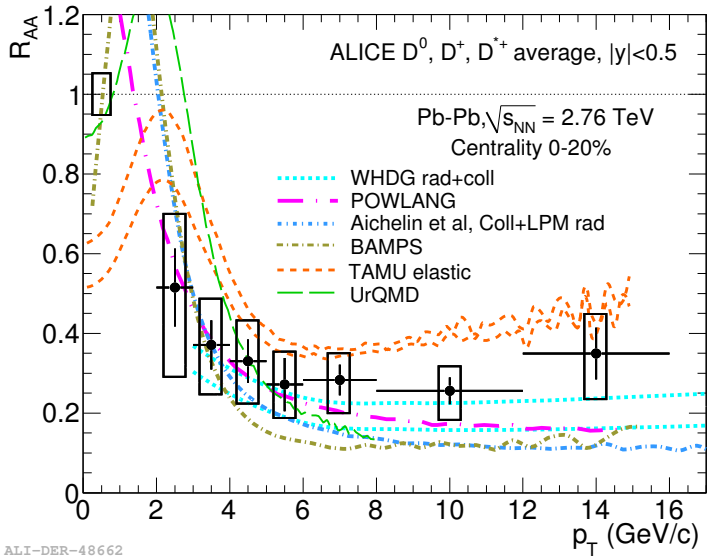


- v_2 increases from central to peripheral collisions in the measured range (0–40%)
- Non-zero v_2 (3σ) observed in the centrality class 20–40%
- Similar v_2 values for heavy-flavour decay muons at forward rapidity and heavy-flavour decay electrons at mid-rapidity

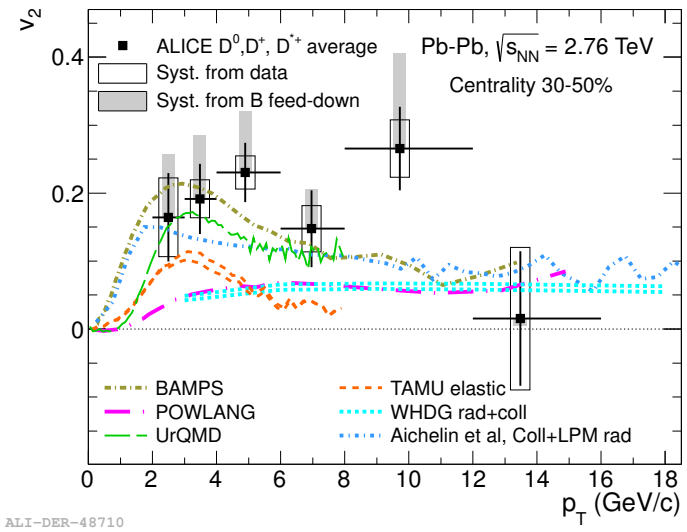
A. Dubla. Poster

Comparison with models

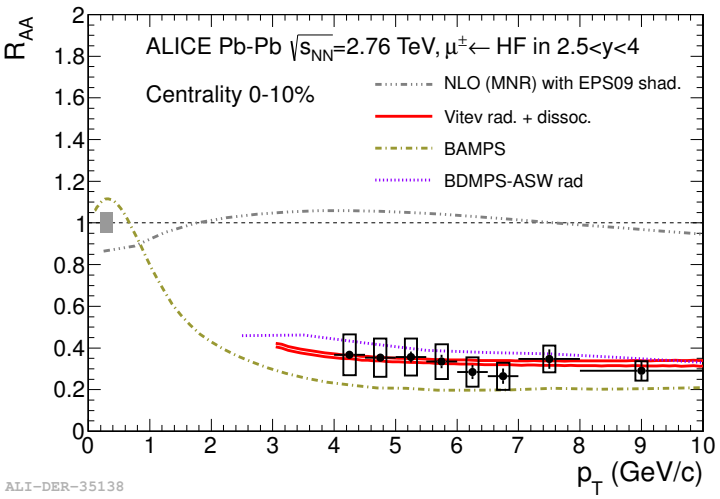
JHEP **1209** (2012) 112

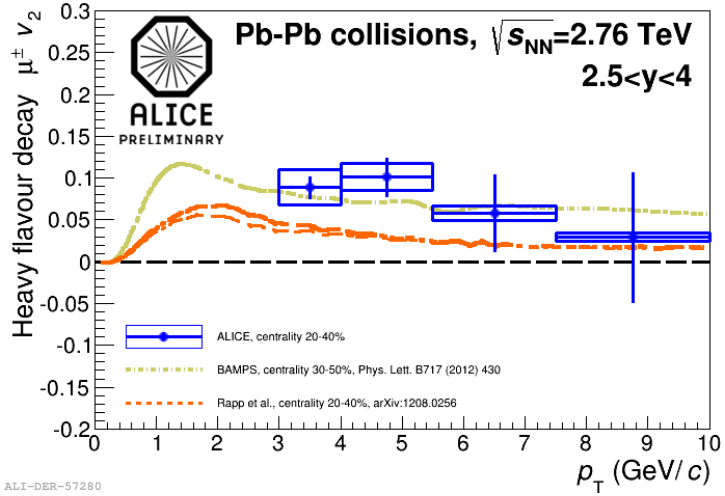


arXiv:1305.2707



Phys. Rev. Lett. **109** (2012) 112301





D mesons

[BAMPS: J. Phys. G **38** (2011) 124152; Phys. Lett. B **717** (2012) 430]

[POWLANG: Eur. Phys. J C **71** (2011) 1666]

[UrQMD: arXiv:1211.6912, J. Phys. Conf. Ser. **426**, 012032 (2013)]

[TAMU: Phys. Rev. C **86** (2012) 014903]

[WHDG: J. Phys. G **38** (2011) 124114]

[Aichelin *et al.*, Phys. Rev. C **79** (2009) 044906, J. Phys. G **37** (2010) 094019]

Heavy-flavour decay muons

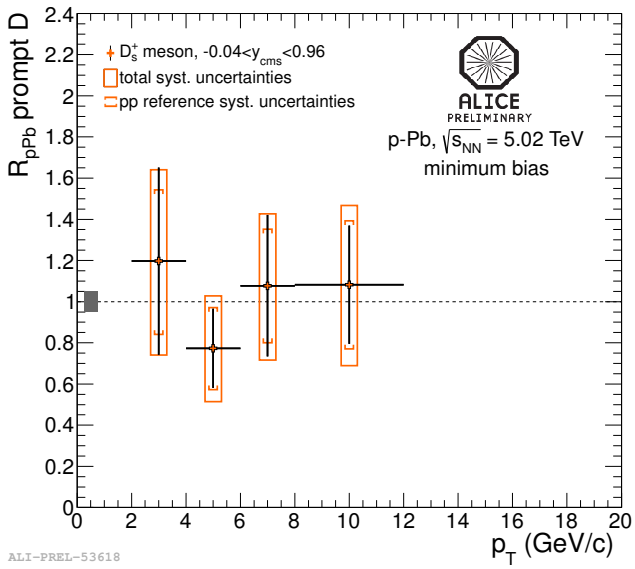
- Simultaneous reproduction of R_{AA} and v_2 is challenging for models
- Reduction of statistical and systematic uncertainties needed for data

p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV: first results

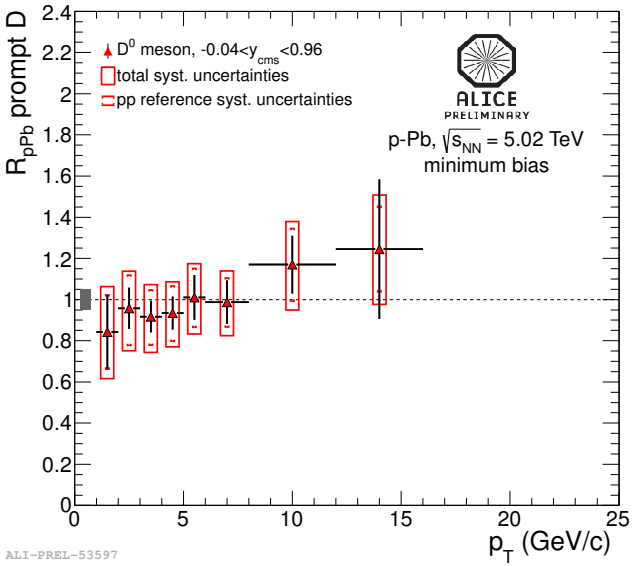
- Dataset: 2013 p–Pb data
- pp reference: ALICE results at $\sqrt{s} = 7$ TeV [JHEP **1201** (2012) 128] scaled to $\sqrt{s_{NN}} = 5.02$ TeV with FONLL [Cacciari *et al.*, JHEP **1210** (2012) 137]
- Compatible results for D^0,D^+,D^{*+} and D_s^+
- All measurements compatible with 1 within uncertainties

G. Luparello. p–A collisions, Fri. 14:00

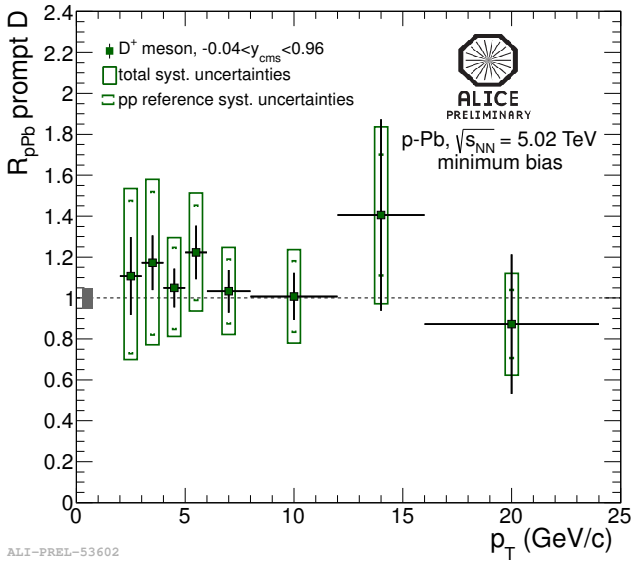
D_s^+



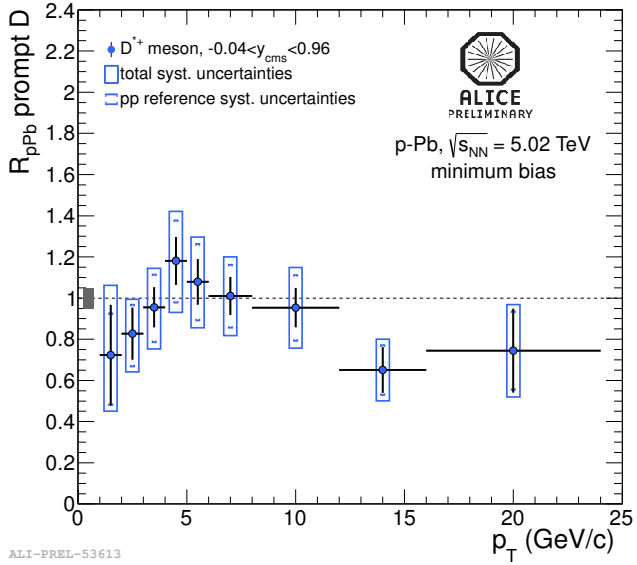
D^0



D^+



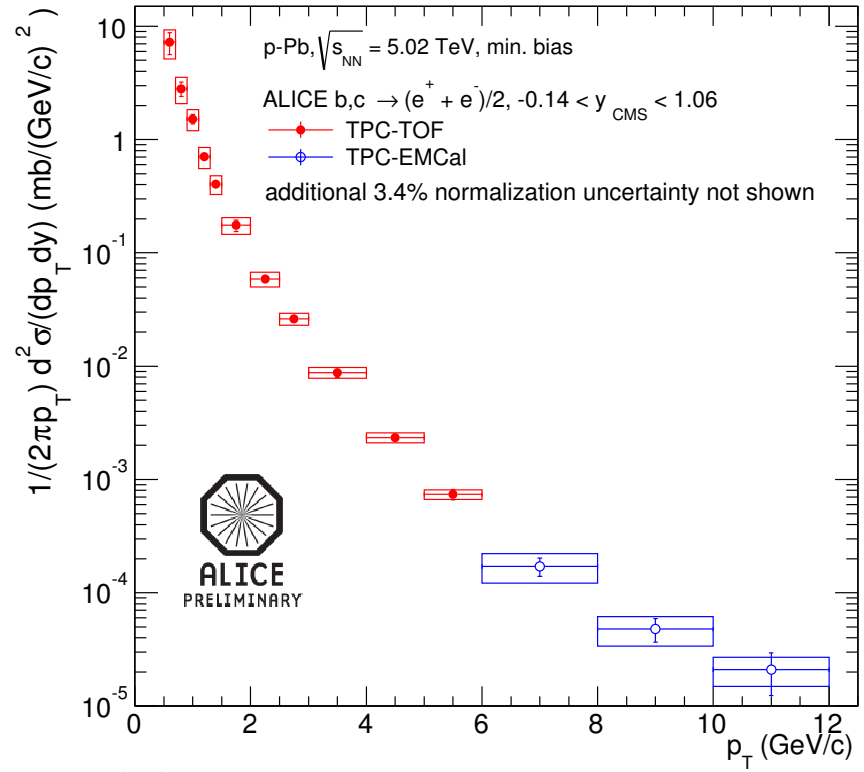
D^{*+}

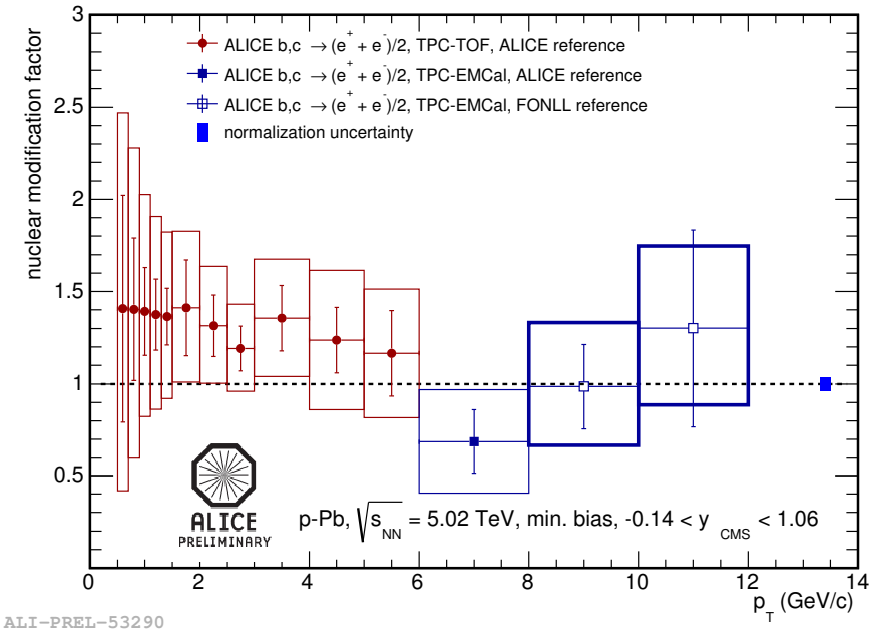


Heavy-flavour decay electrons R_{pPb}

- Dataset: 2013 p–Pb data
- pp reference:
  - $p_T < 8$ GeV/c: ALICE results at $\sqrt{s} = 7$ TeV [Phys. Rev. D **86** (2012) 112007] scaled to $\sqrt{s_{NN}} = 5.02$ TeV with FONLL [Cacciari *et al.*, JHEP **1210** (2012) 137]
  - $p_T > 8$ GeV/c: FONLL extrapolation

M. Heide. p–A collisions, Fri. 14:20



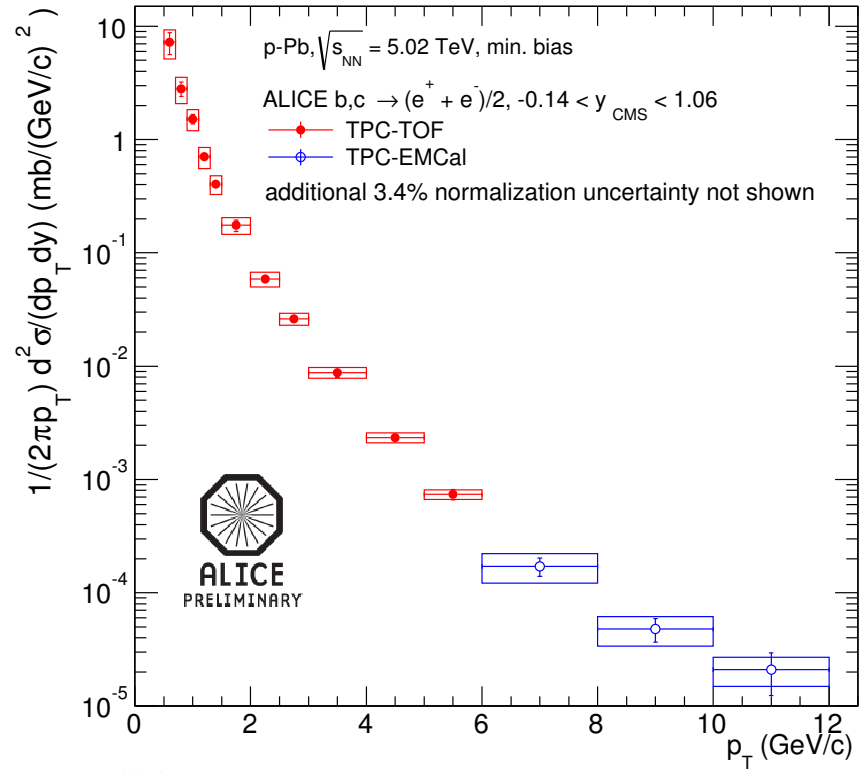


- Consistent results with two analyses based on different PID strategies

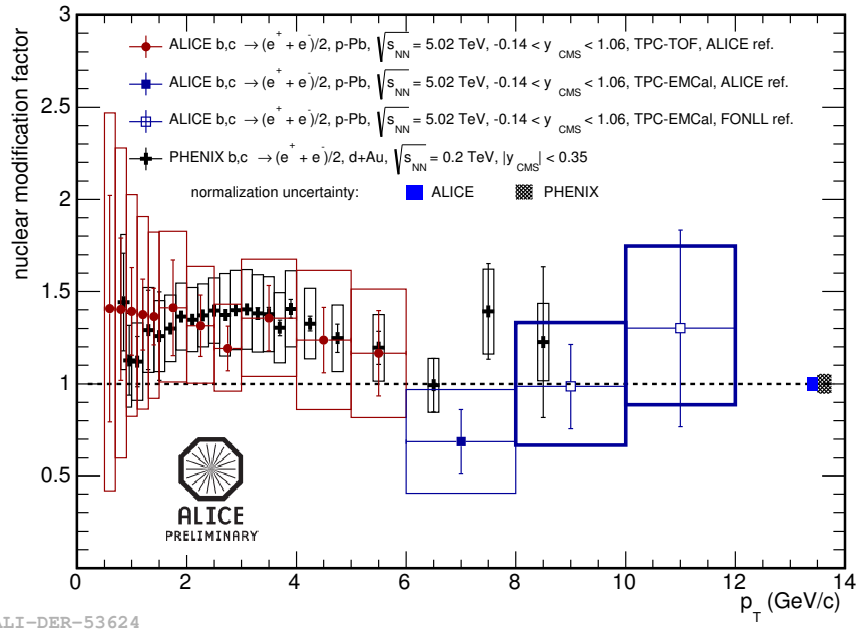
Heavy-flavour decay electrons R_{pPb}

- Dataset: 2013 p–Pb data
- pp reference:
  - $p_T < 8$ GeV/c: ALICE results at $\sqrt{s} = 7$ TeV [Phys. Rev. D **86** (2012) 112007] scaled to $\sqrt{s_{NN}} = 5.02$ TeV with FONLL [Cacciari *et al.*, JHEP **1210** (2012) 137]
  - $p_T > 8$ GeV/c: FONLL extrapolation

M. Heide. p–A collisions, Fri. 14:20



ALI-PREL-53256



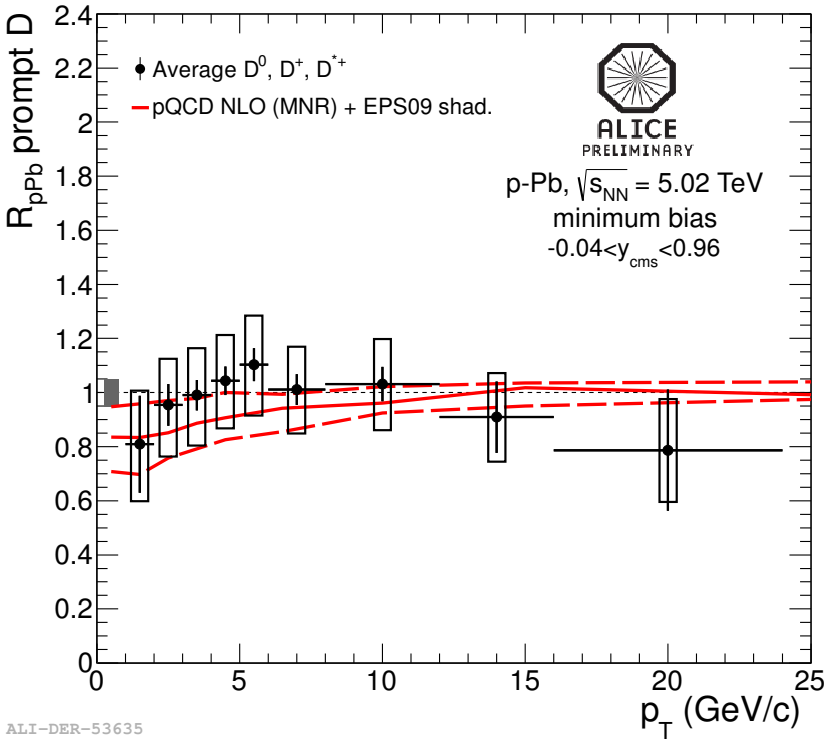
ALI-DER-53624

- Consistent results with two analyses based on different PID strategies
- Results comparable with PHENIX [Phys. Rev. Lett. **109** (2012) 242301]

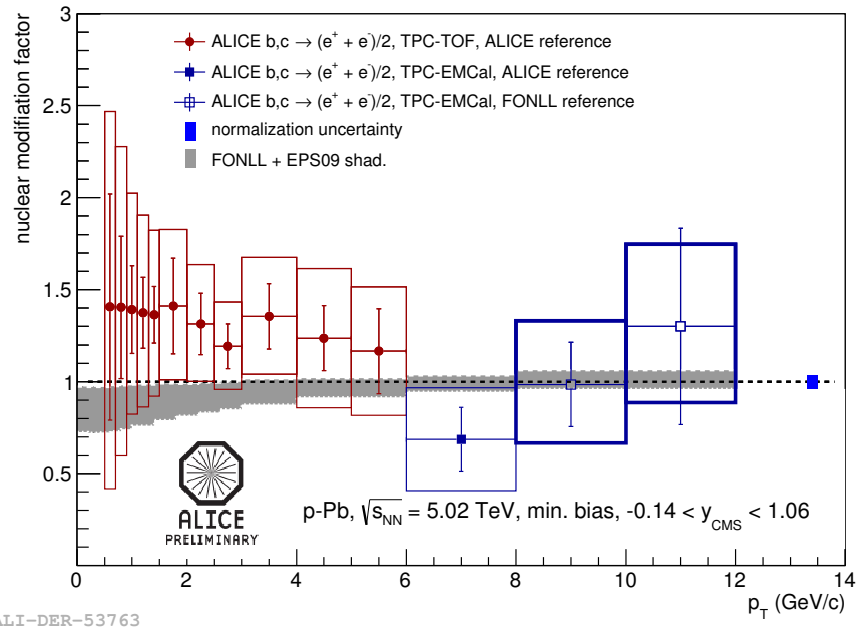
Heavy-flavour R_{pPb}: comparison with shadowing

- Results compared to MNR [Mangano *et al.*, Nucl. Phys. B **373** (1992) 295] calculations for heavy-flavour production with EPS09 [Eskola *et al.*, JHEP **0904** (2009) 065] parameterization of shadowing

Average of D^0, D^+, D^{*+}



Heavy-flavour decay electrons

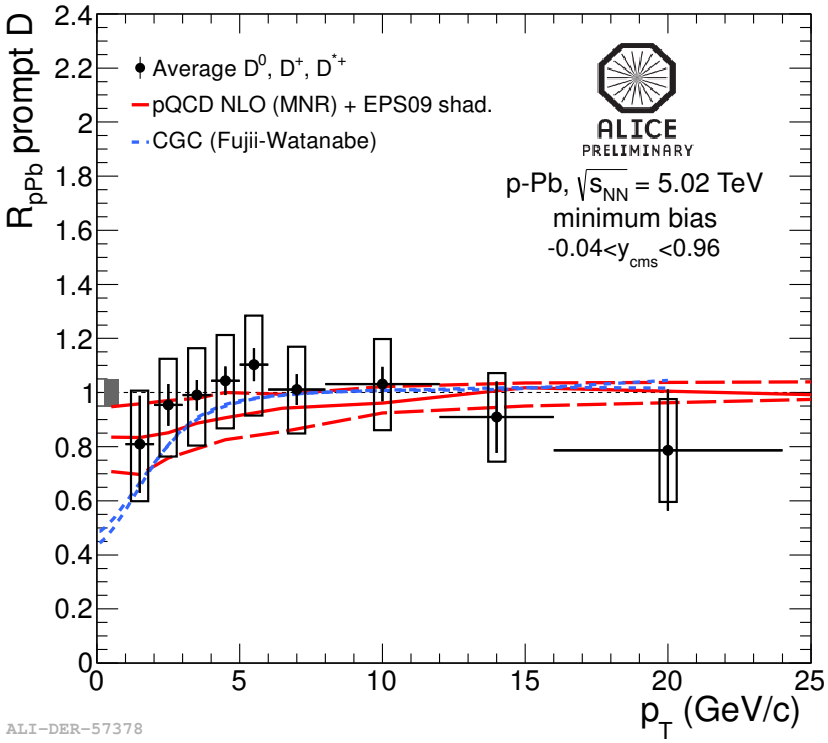


- Calculations in agreement with data within uncertainties

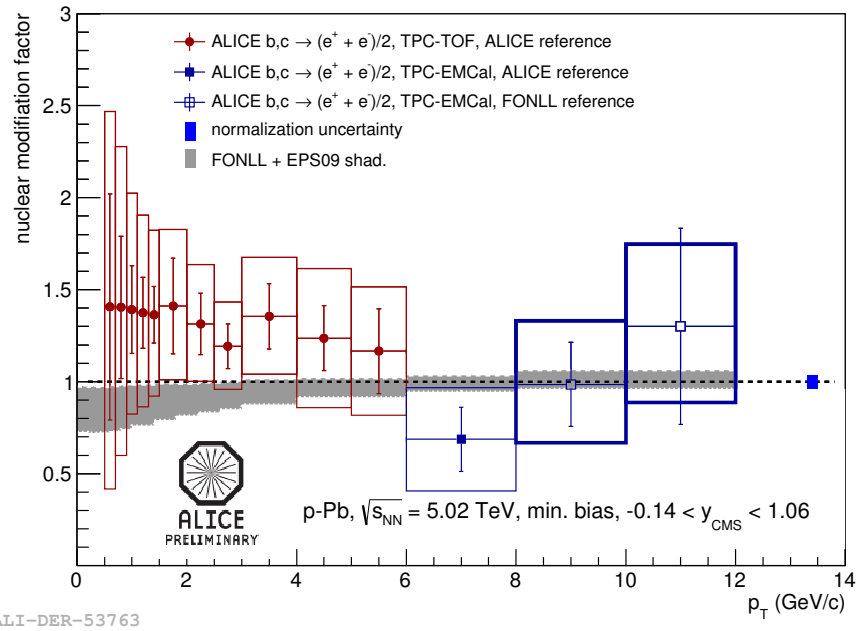
Heavy-flavour R_{pPb}: comparison with shadowing

- Results compared to MNR [Mangano *et al.*, Nucl. Phys. B **373** (1992) 295] calculations for heavy-flavour production with EPS09 [Eskola *et al.*, JHEP **0904** (2009) 065] parameterization of shadowing

Average of D^0, D^+, D^{*+}



Heavy-flavour decay electrons

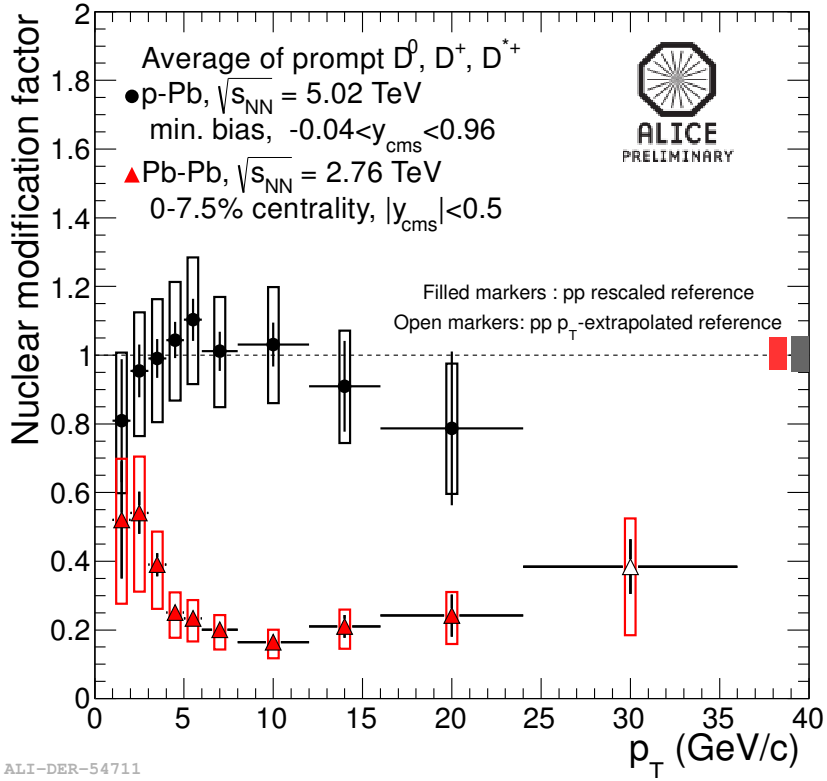


- Calculations in agreement with data within uncertainties
- Data in agreement with CGC predictions as well [Fujii-Watanabe, priv. comm.]

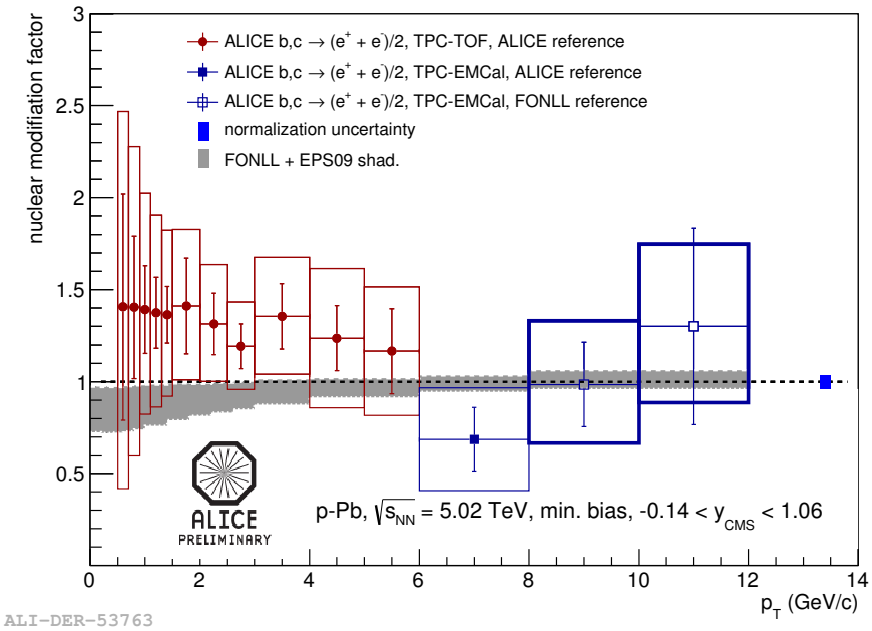
Heavy-flavour R_{pPb}: comparison with shadowing

- Results compared to MNR [Mangano *et al.*, Nucl. Phys. B **373** (1992) 295] calculations for heavy-flavour production with EPS09 [Eskola *et al.*, JHEP **0904** (2009) 065] parameterization of shadowing

Average of D^0, D^+, D^{*+}



Heavy-flavour decay electrons



- Calculations in agreement with data within uncertainties
- Data in agreement with CGC predictions as well [Fujii-Watanabe, priv. comm.]
- Small "initial state" effects $\Rightarrow$ the strong suppression at high-p_{T} observed in Pb–Pb collision is a Quark Gluon Plasma effect

Conclusions

Conclusions (I)

- The heavy-flavour measurements of ALICE in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV, Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and the first results in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV have been presented

pp collisions

- Perturbative QCD calculations **well describe all data** $\Rightarrow$ used to extrapolate the results at different energies for Pb–Pb and p–Pb studies
- **D meson** yields measured as a function of **charged particle multiplicity**

Pb–Pb collisions

- Measurement of heavy-flavour decay electron R_{AA} **extended to peripheral centralities**
- D mesons R_{AA} measured as a function of $\langle N_{part} \rangle$ in several p_T bins
  - updated comparison with non-prompt J/ψ $\Rightarrow$ **indication of larger suppression for charm than for beauty**
  - updated comparison with pion R_{AA} at low p_T $\Rightarrow$ no strong conclusion can be drawn with present uncertainties
- Analysis of D meson elliptic flow finalized: paper [arXiv:1305.2707] submitted to PRL
- Measurement of elliptic flow of muons from heavy-flavour decays at forward rapidity: **non-zero** v_2 **observed** in the centrality class 20–40% at 3σ

p–Pb collisions

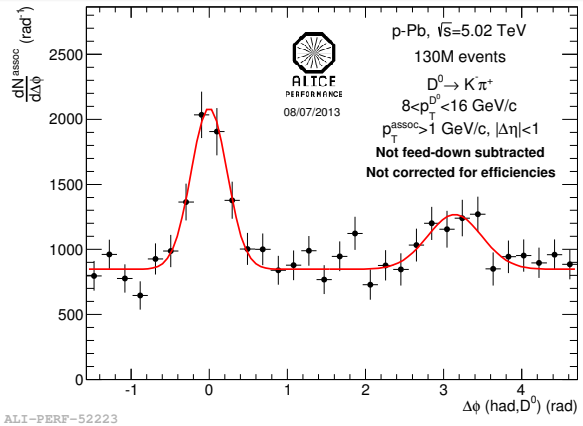
- First heavy-flavour measurements in p–A collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE
  - $R_{pPb}(p_T)$ of D mesons and electrons from heavy-flavour decays
- Results consistent with perturbative QCD calculations including shadowing
- **Small effect observed** in the transverse momentum range measured in Pb–Pb collisions $\Rightarrow$ the observed suppression at high momenta in Pb–Pb collisions is a Quark-Gluon Plasma effect

F. Colamaria. p–A collisions, Fri. 14:40

Further ongoing analyses:

- D meson–hadron correlations
- Heavy-flavour decay muons R_{pPb}
- b-jet tagging in pp

L. Feldkamp. Poster



In addition:

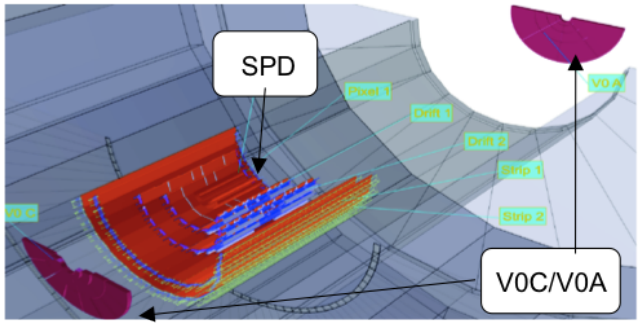
- better precision / new measurements (lower-p_T, c/b separation, charmed baryons, etc.) possible thanks to the future upgrades

C. Terrevoli. Future, Thu. 16:30

Backup slides

pp collisions

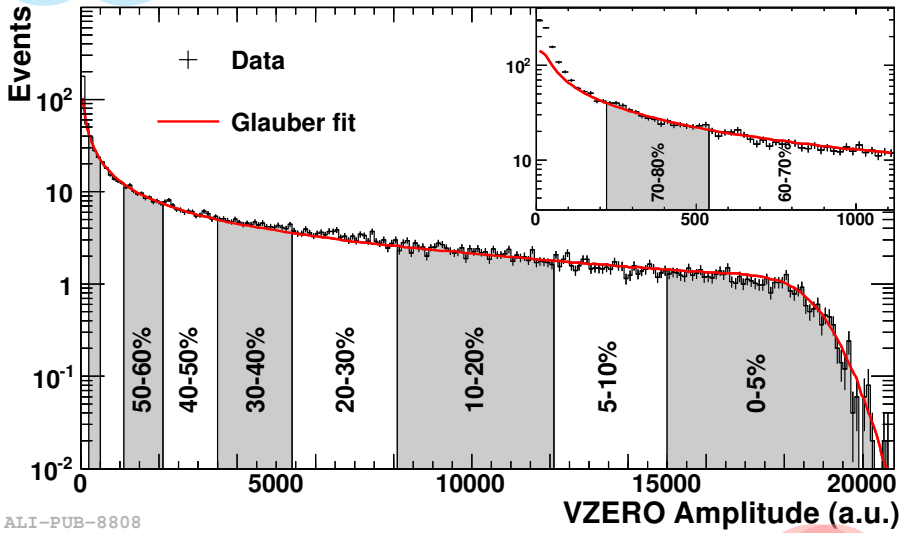
- Minimum Bias (MB): V0A or V0C or SPD
- MUON: MB + single muon trigger



Pb–Pb collisions

- MB: V0A and V0C
- MUON: MB + single muon trigger

Phys. Rev. Lett. **106** (2011) 032301

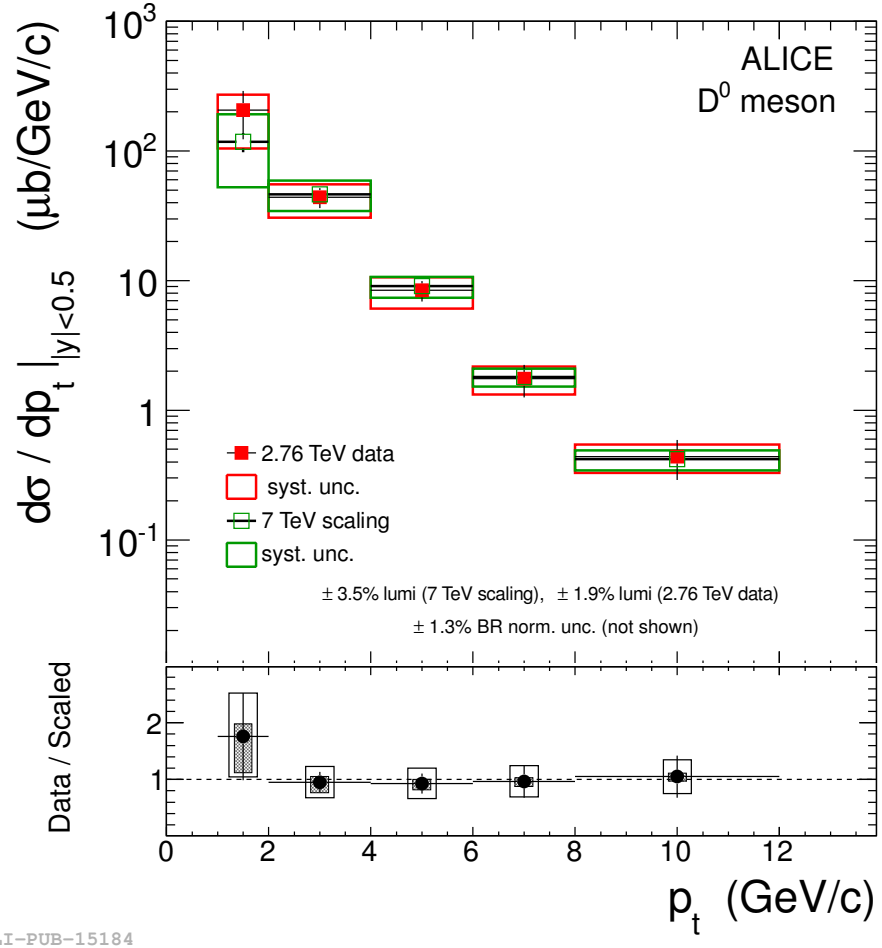


- Centrality selection based on a geometrical Glauber model fit of the V0 amplitude

- Data scaled with the ratio of FONLL [JHEP **1210** (2012) 137] cross sections at the two energies
- Scaling procedure checked by comparing with existing data

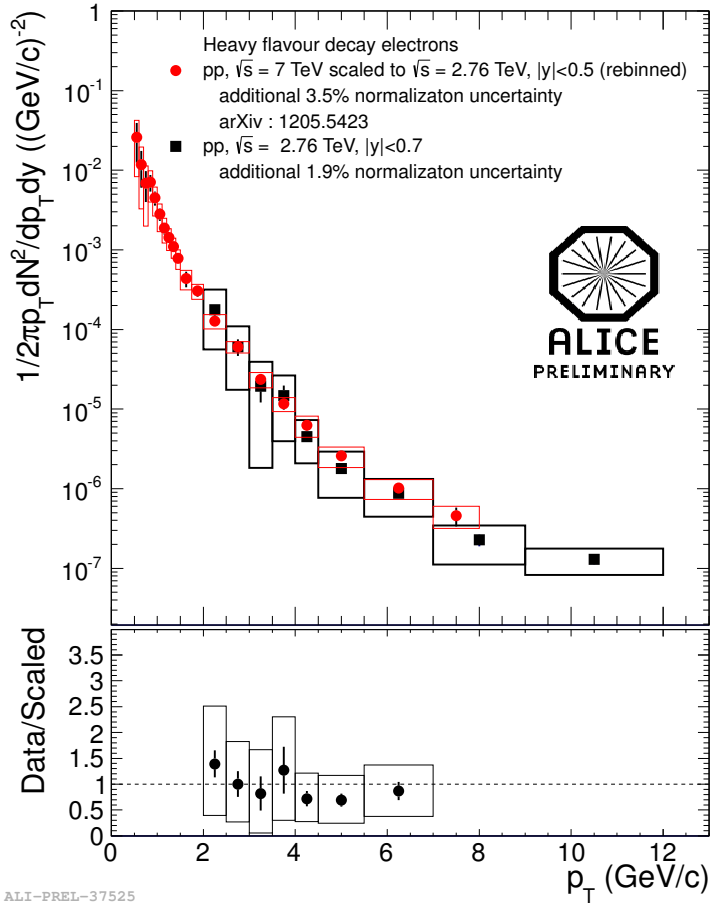
D^0

JHEP **1207** (2012) 191



ALI-PUB-15184

Heavy-flavour decay electrons

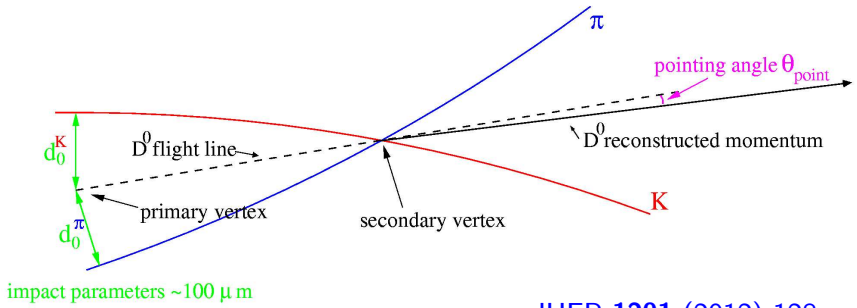


ALI-PREL-37525

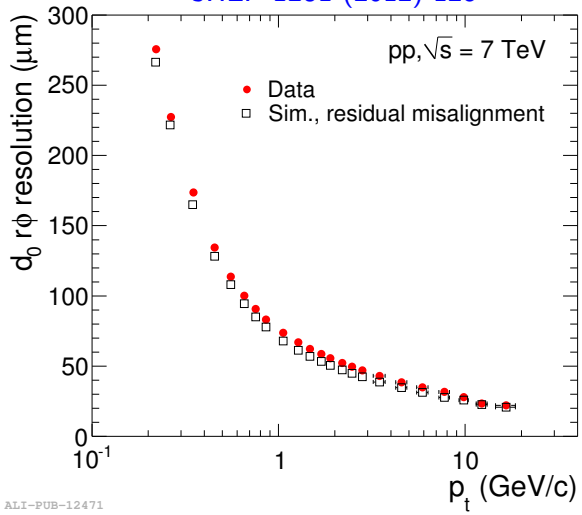
Charmed mesons in the hadronic decay channels

- Search for secondary vertices displaced of few hundreds μm

D_0	$\rightarrow K^-\pi^+$	$c\tau \sim 123\ \mu m$
D_+	$\rightarrow K^-\pi^+\pi^+$	$c\tau \sim 312\ \mu m$
D_{*+}	$\rightarrow D_0^{\pi^+}$	
D_s^+	$\rightarrow K^+K^-\pi^+$	$c\tau \sim 150\ \mu m$



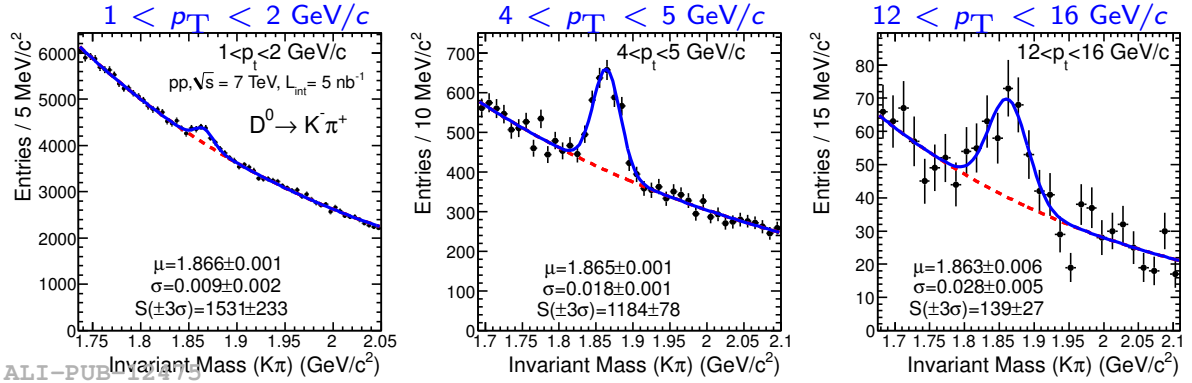
JHEP **1201** (2012) 128



- Selection criteria:
  - p_T and impact parameters of tracks
  - pointing angle
  - distance between primary and secondary vertices
  - kaon ID to reduce background at low p_T

- Signal extraction through fit of the invariant mass of the decay products

$1 < p_T < 2$ GeV/c | $4 < p_T < 5$ GeV/c | $12 < p_T < 16$ GeV/c

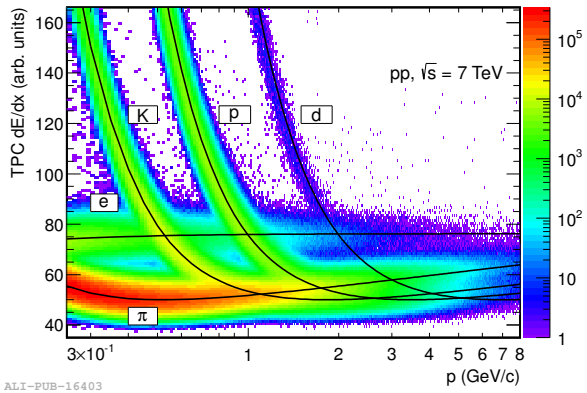


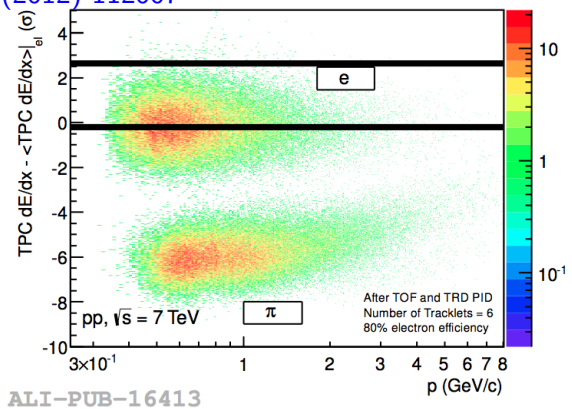
JHEP **1201** (2012) 128

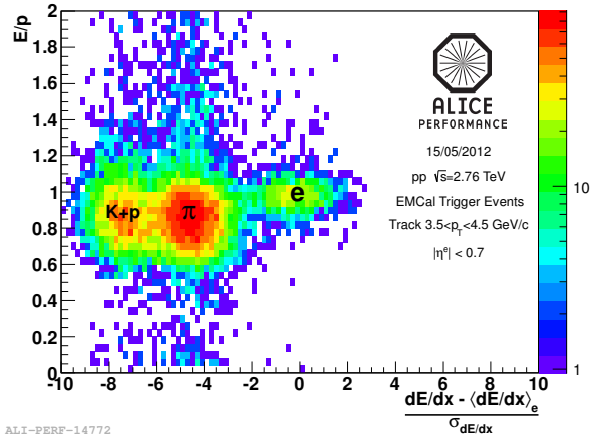
Heavy flavours in the semi-electronic decay channel

- Electron ID with:
  - TPC (dE/dx) + TOF + TRD
  - TPC (dE/dx) + EMCAL

Phys. Rev. D **86** (2012) 112007





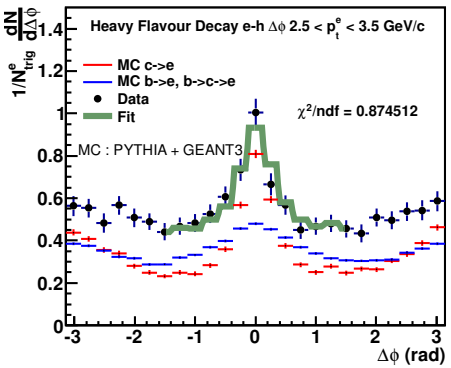


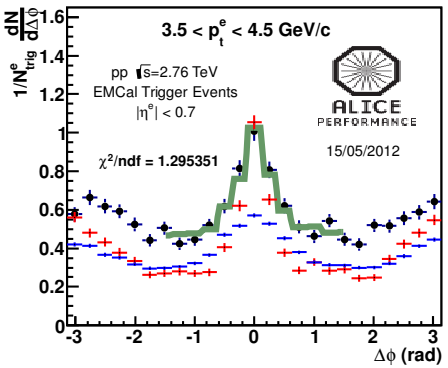
- Background subtraction:
  - e^+e^- invariant mass method: removes Dalitz decay and photon conversion
  - cocktail: MC hadron generator for different background sources

Beauty measurement:

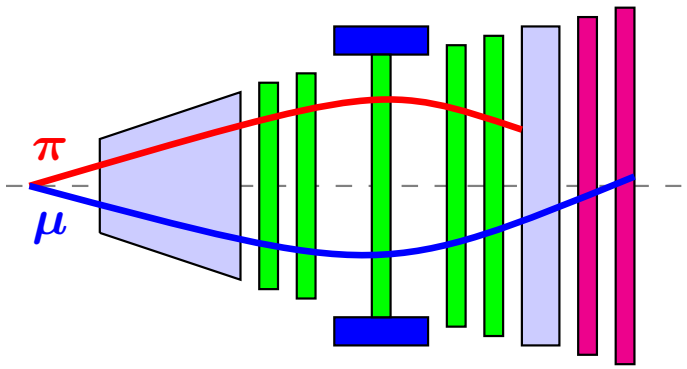
- B decay $c\tau = 500\ \mu\mathrm{m}$
- cut on impact parameter to enhance S/B
- subtract residual e from D decay: input from measured D mesons

- complementary method based on fit to MC templates of e-hadron correlation shapes for D and B (exploit the larger width of the near-side peak for B-hadron decays)

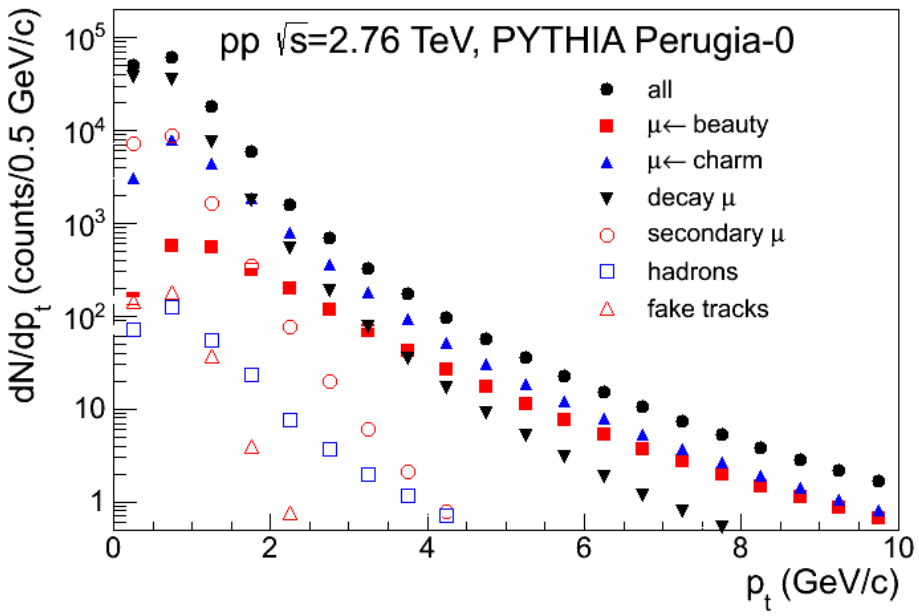




- Track selection:
  - Match track with tracklet in the trigger chambers ⇒ reject punch-through hadrons
  - $p \times$ DCA cut ⇒ reject tracks from beam-gas interaction

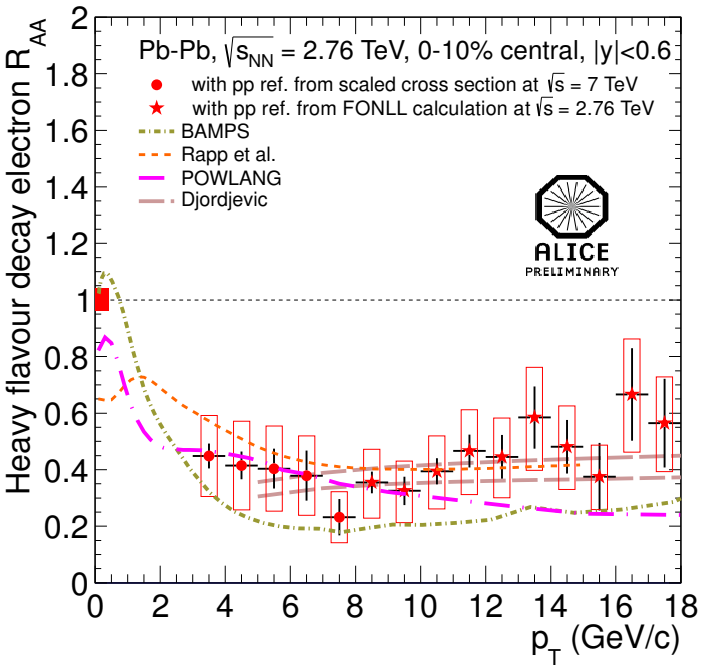


- Background subtraction:
  - bkg. contribution decreases with p_{T} ⇒ focus on $p_{\mathrm{T}} \geq 2$ GeV/c
  - main background source: muons from pion and kaon decays
  - subtraction using MC simulations as input (Pythia, Phojet)



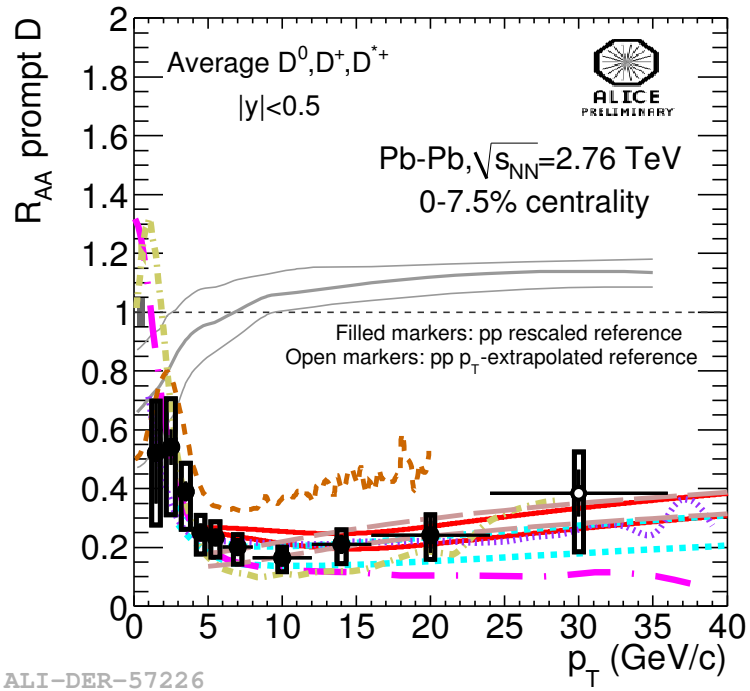
Heavy-flavour R_{AA}: further comparisons with models

Heavy-flavour decay electrons



ALI-DER-57138

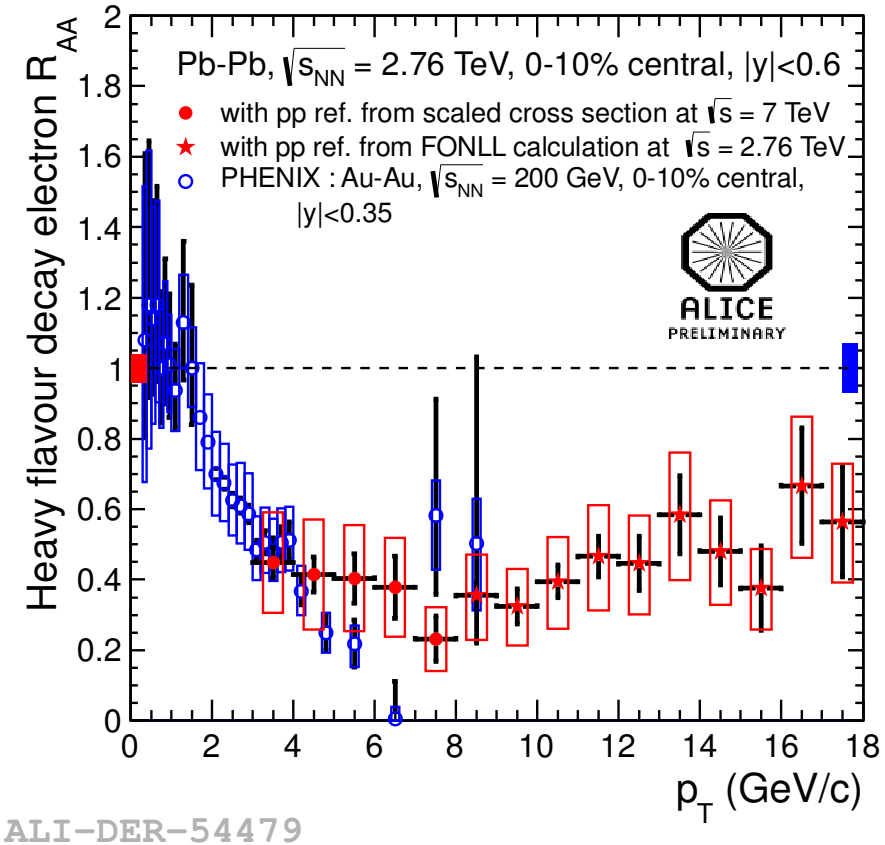
D mesons

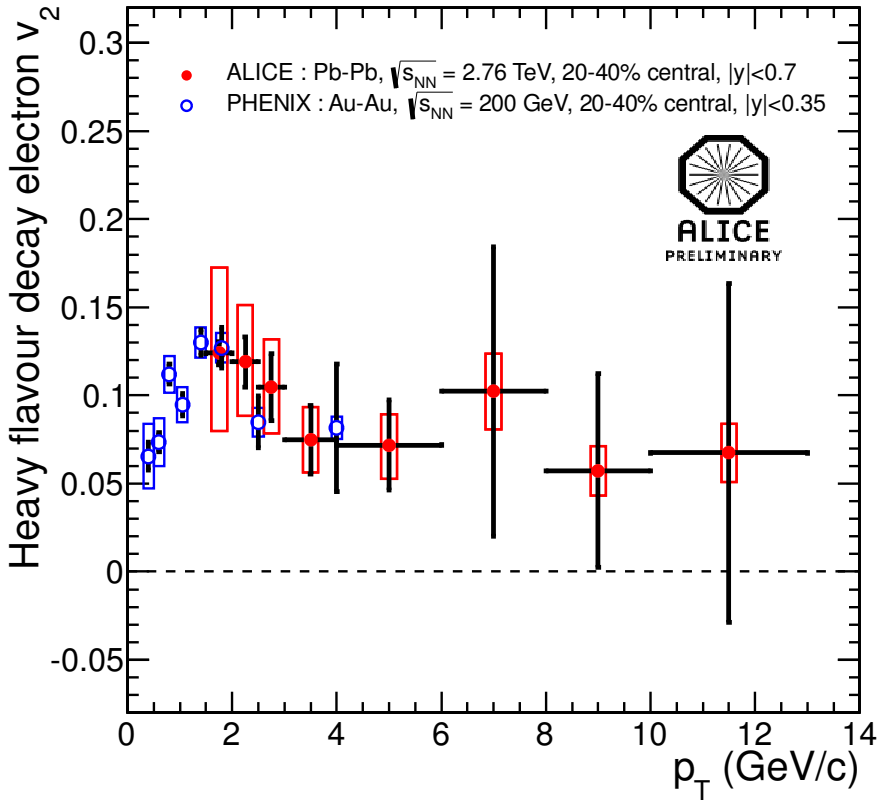


ALI-DER-57226

- Comparison with models [BAMPS: Phys. Lett. B **717** (2012) 430], [Rapp *et al.*: arXiv:1208.0256], [POWLANG: J. Phys. G **38** (2011) 124144], [Djordjevic, arXiv:1307.4098], [BDMPS-ASW, Phys. Rev. D **71** (2005) 054027], [WHDG: J. Phys. G **38** (2011) 124114], [Rad+dissoc: Vitev *et al.*, Phys. Rev. C **80** (2009) 054902]

Heavy-flavour decay electrons R_{AA} and v_2: comparisons

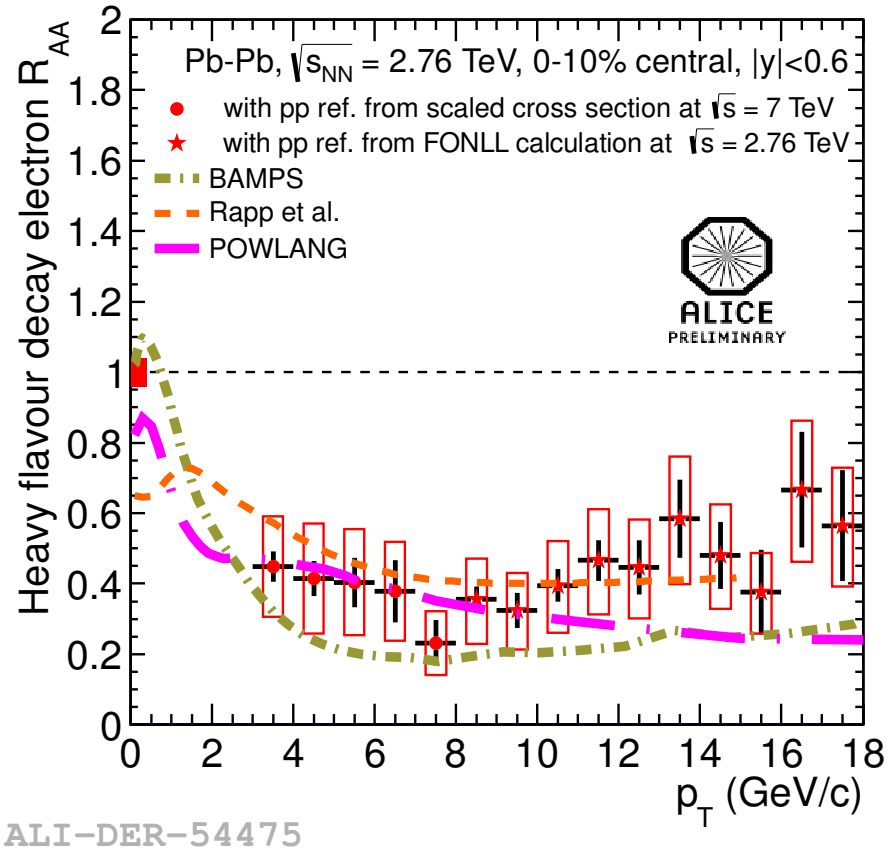


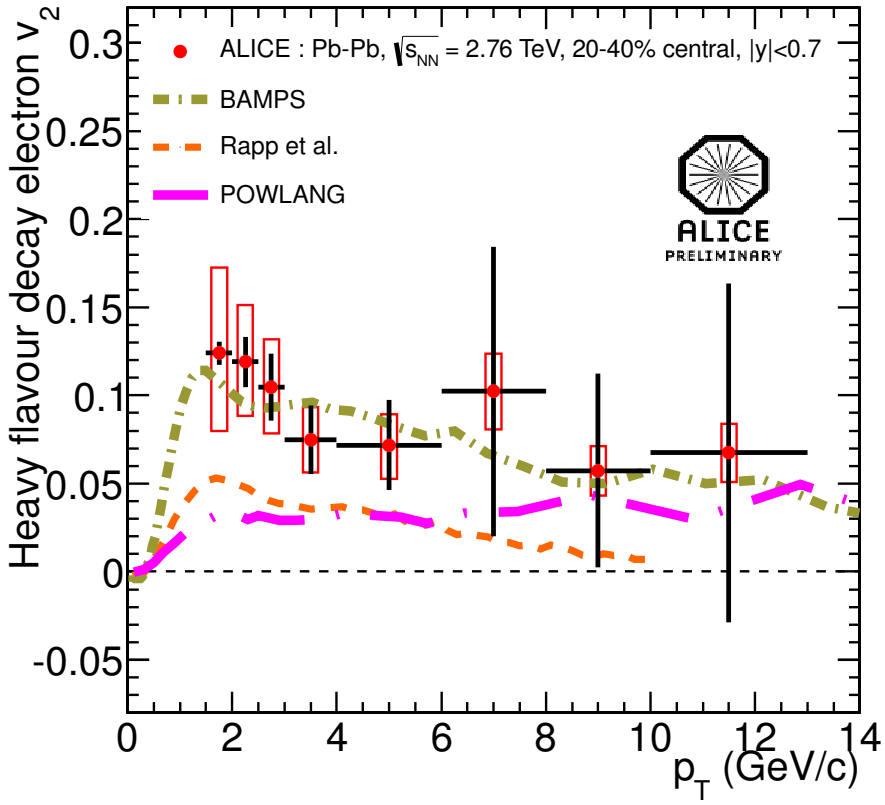


ALI-DER-54479

- Results compatible with PHENIX data in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [PHENIX: Phys. Rev. C **84** (2011) 044905]

Heavy-flavour decay electrons R_{AA} and v_2: comparisons



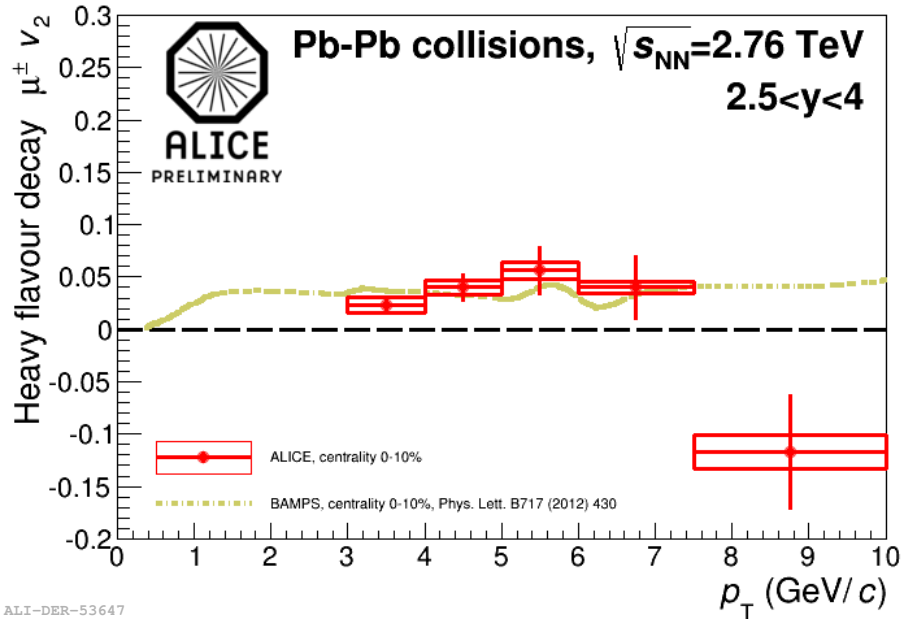


ALI-DER-54475

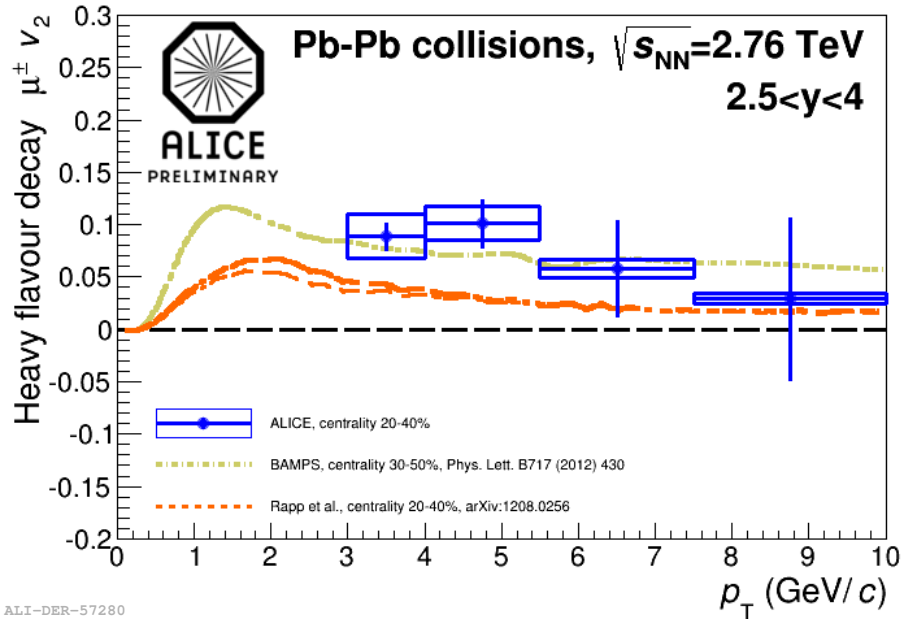
- Results compatible with PHENIX data in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [PHENIX: Phys. Rev. C **84** (2011) 044905]
- Simultaneous reproduction of R_{AA} and v_2 is challenging for models [BAMPS: Phys. Lett. B **717** (2012) 430], [Rapp *et al.*: arXiv:1208.0256], [POWLANG: J. Phys. G **38** (2011) 124144]

Heavy-flavour decay muons v_2

0–10%



20–40%



- Results in agreement with BAMPS predictions [BAMPS: Phys. Lett. B **717** (2012) 430] within errors
- Rapp's model (collisional elastic processes with strong coupling) [Rapp *et al.*: arXiv:1208.0256] tend to underestimate data points.

D meson cross sections in p–Pb collisions