Open heavy-flavour measurements with ALICE at the LHC

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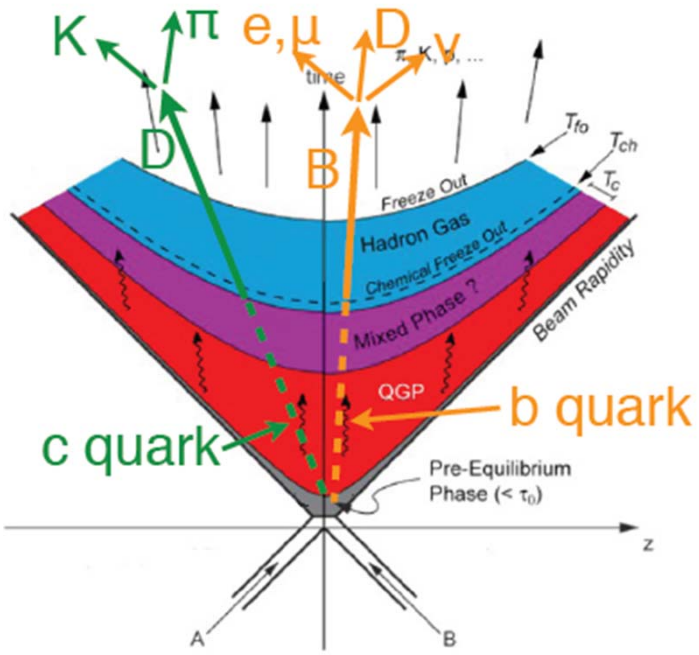
12th International Conference on Nucleus-Nucleus Collisions
Catania, Italy
21-26 June 2015

Outline

- Physics motivations
- Open heavy-flavour measurements with ALICE
- Selection of results in p-Pb and Pb-Pb collisions
  - Nuclear modification factor
  - Elliptic flow
  - Azimuthal correlations
  - Model comparisons
- Conclusion

Relevance of open heavy flavours in heavy-ion collisions at the LHC

- Charm and beauty quarks produced in initial hard scatterings with a short formation time $\tau_f \sim 1/2m_{c/b} \sim 0.02\text{-}0.1$ fm/c $< \tau_0 << \tau_{QGP} \sim 5\text{-}10$ fm/c
- Flavour conserved by the strong interaction
- Experience the full collision history
  - ➢ Sensitive probes of the medium properties



Open heavy flavours in Pb-Pb collisions probe

- In-medium parton energy loss
  - Color-charge and quark-mass dependence
    Dokshitzer & Kharzeev, PLB 519 (2001) 199
  - Expected: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
    ⟶ $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?
- Heavy quark participation in the collective expansion

Observables

- Nuclear modification factor: $$R_{AA}(p_T) = 1/< T_{AA} > \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$
- Elliptic flow, v_2: $$\frac{2\pi}{N}\frac{dN}{d\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_n)]$$ with $$v_2 = < \cos[2(\varphi - \Psi_n)] >$$

Relevance of open heavy flavours in pp and p-Pb collisions

A meaningful interpretation of Pb-Pb data needs data from:

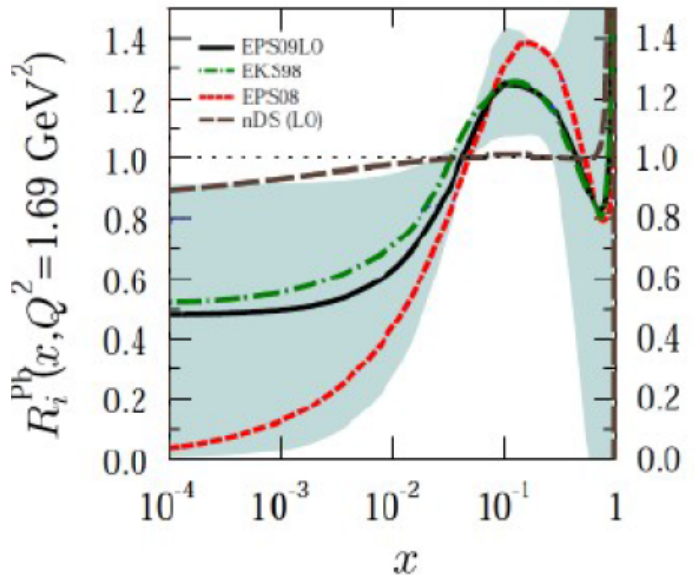
p-Pb collisions

- Control experiment for Pb-Pb collisions
- Cold nuclear matter effects
  - Nuclear modification of Parton Distribution Functions (PDF): shadowing or gluon saturation
  - Energy loss
  - k_T broadening, multiple-soft interactions
  - Possible final-state effects

pp collisions

- Reference for Pb-Pb and p-Pb collisions
- Test of perturbative QCD calculations
- Insights into production mechanisms

Ratio of PDF (gluons) in the nucleus and in the nucleon



K. J. Eskola et al., JHEP 0904 (2009) 65

D.E. Kharzeev et al., arXiv:1205.1554

F. Dominguez et al., arXiv:1109.1250

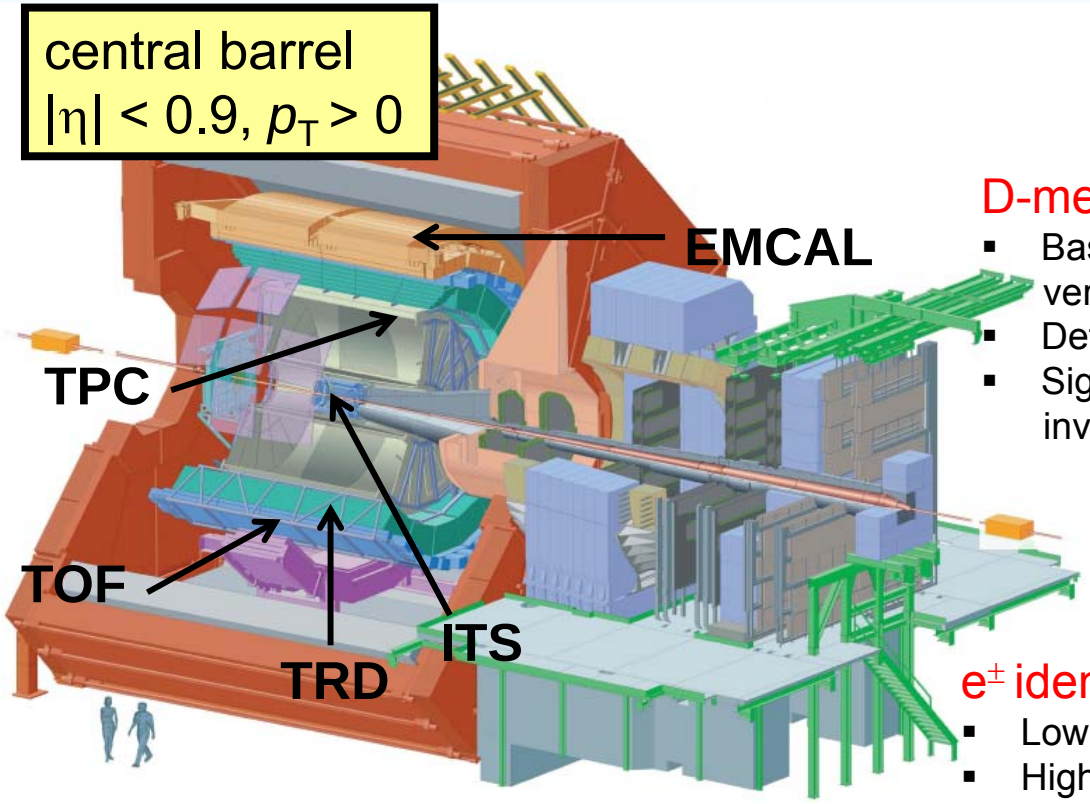
R. Vogt, Phys. Rev C81 (2010) 044903

F. Arleo et al., arXiv:1204.4609

C. Lourenco et al., JHEP 0902 (2009) 014

Open heavy flavours with the ALICE central barrel

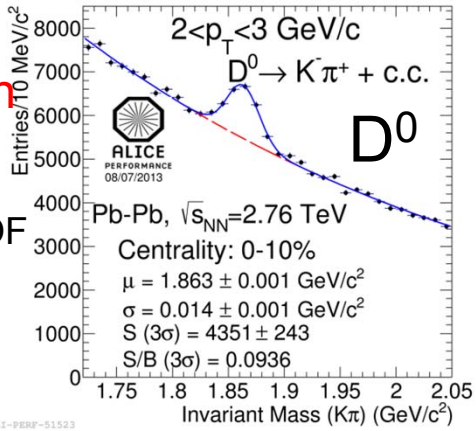
central barrel
$|\eta| < 0.9$, $p_T > 0$



Semi-electronic decays:
D, B, Λ_c, … → e + anything
Hadronic decays:
$D^0 \rightarrow K^-\pi^+$ $D^+_s \rightarrow \varphi\pi^+ \rightarrow K^+K^-\pi^+$
$D^+ \rightarrow K^-\pi^+\pi^+$ $D^{*+} \rightarrow D^0\pi^+$

D-meson identification

- Based on displaced vertices
- Detectors: ITS, TPC, TOF
- Signal extracted via invariant mass analysis



$e^{\pm}$ identification

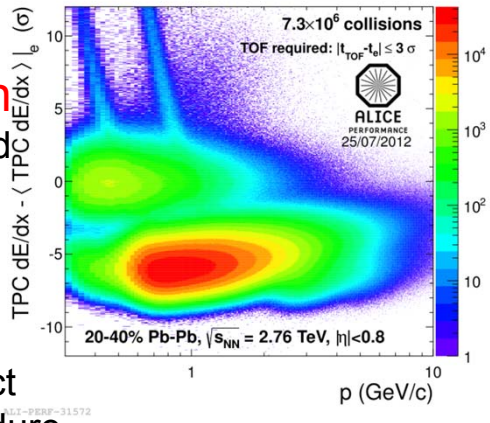
- Low p_T: ITS, TPC, TOF
- High p_T: TPC, EMCAL

$e^{\pm} \leftarrow$ b, c identification

- Background $e^{\pm}$ estimated via data-tuned cocktail, e^+e^- invariant mass analysis

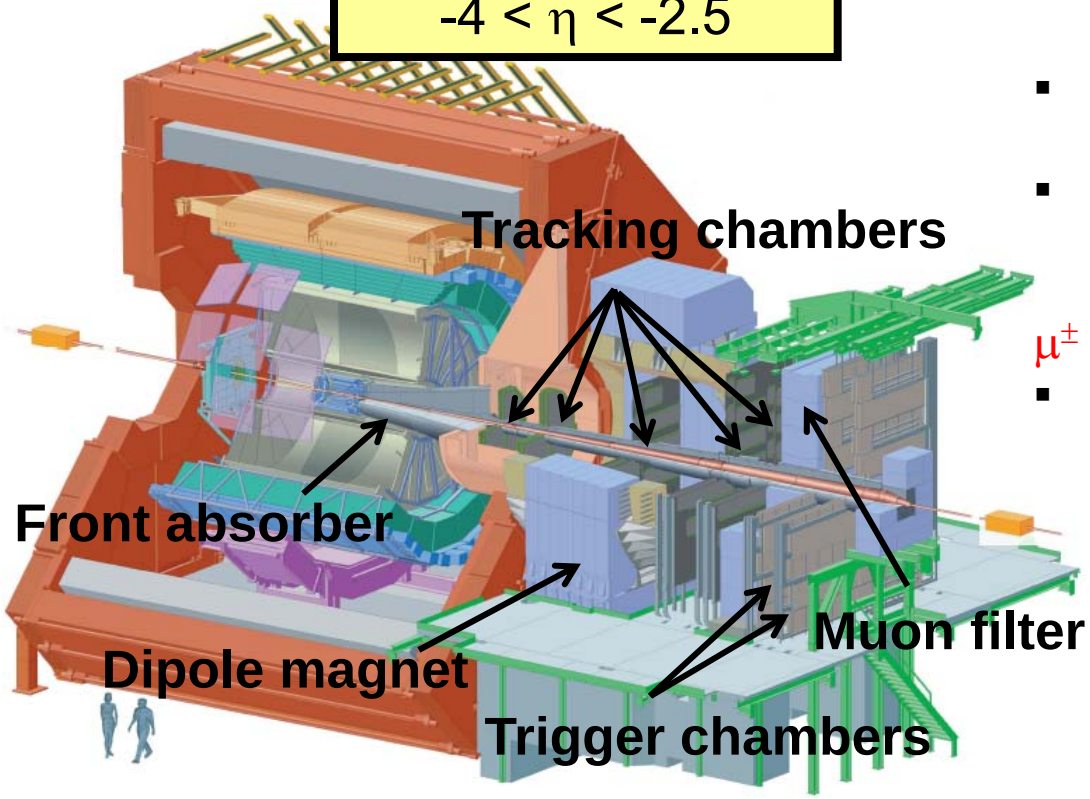
$e^{\pm} \leftarrow$ b identification

- Based on electron impact parameter with fit procedure



Open heavy flavours with the ALICE muon spectrometer

Muon spectrometer
$-4 < \eta < -2.5$



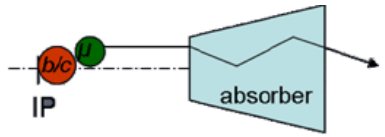
Semi-muonic decays:
D, B, Λ_c, … $\rightarrow \mu$ + anything

Muon track selection

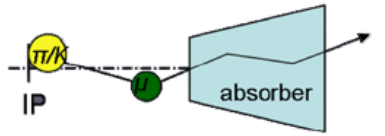
- Acceptance & geometrical cuts
  select tracks in the spectrometer acceptance
- Tracks matched with trigger
  reject hadrons crossing the absorber
- Pointing angle to the vertex
  reject beam-gas interactions & particles produced in the absorber

$\mu^{\pm} \leftarrow$ b, c identification

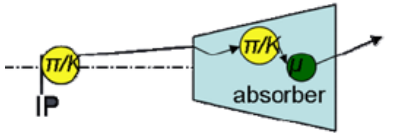
- Remaining background: $\mu \leftarrow$ primary π, K decays estimated via data-tuned MC cocktail



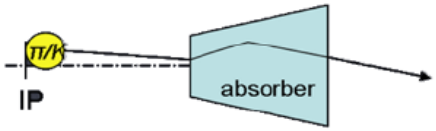
μ from heavy flavours



μ from primary π, K

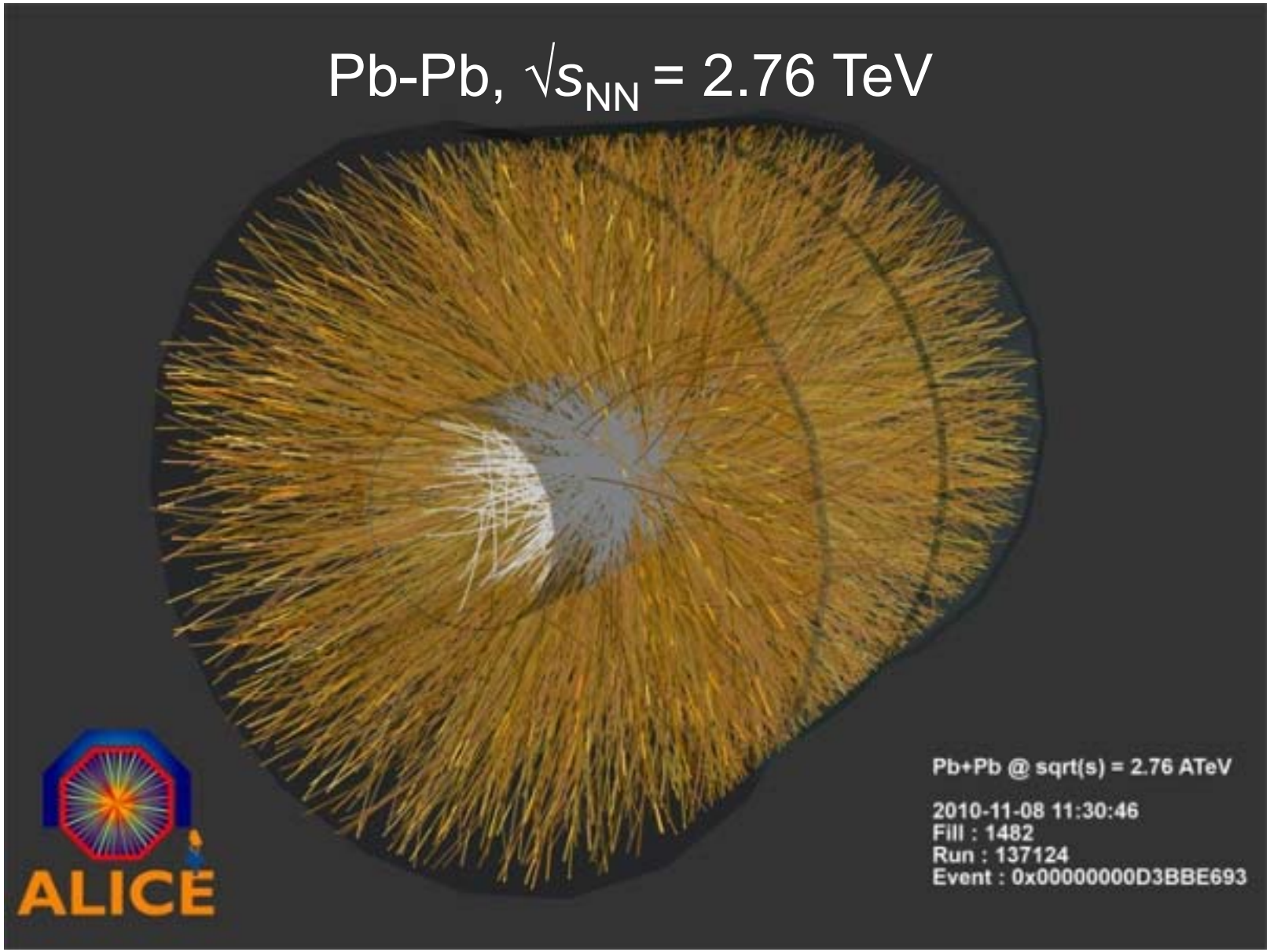


μ from secondary π, K

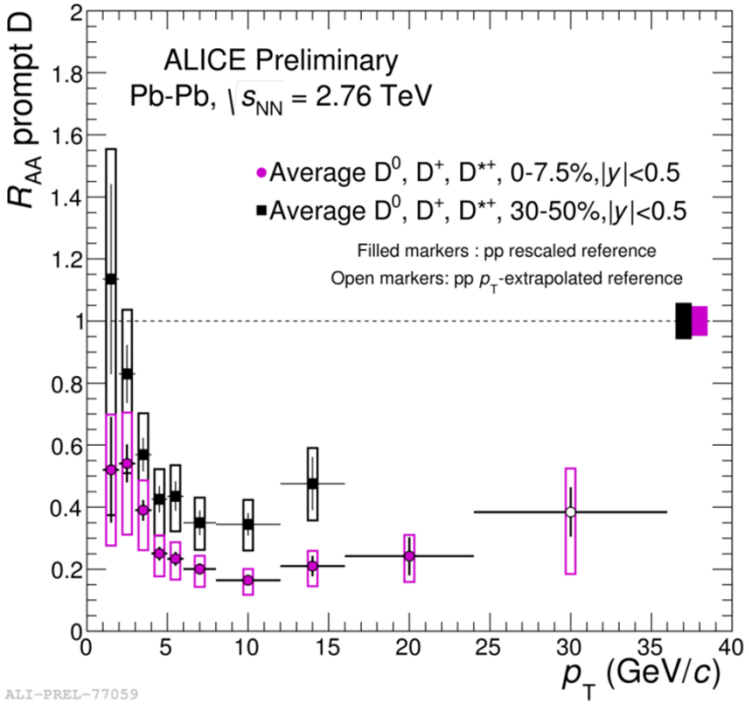


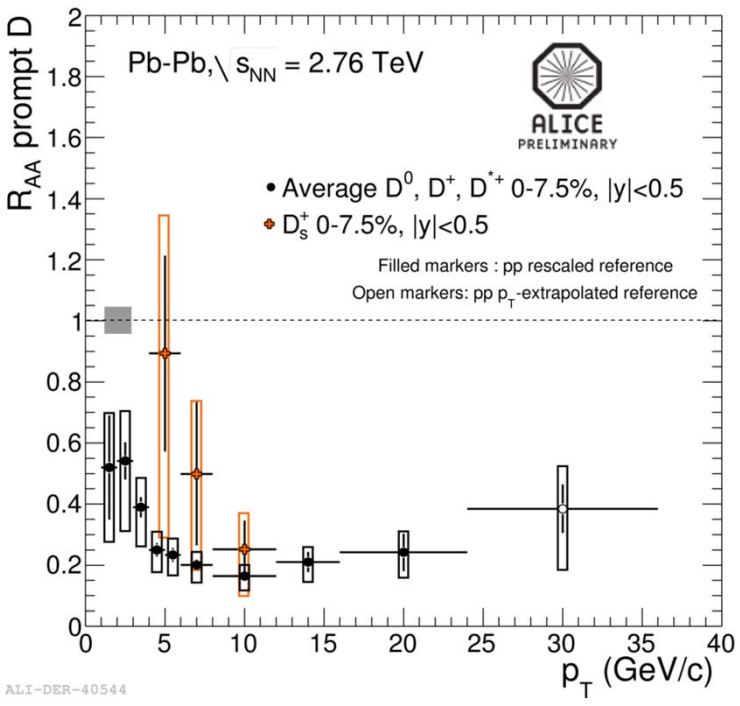
punch through hadrons

Open heavy-flavour results in Pb-Pb collisions



D mesons: R_{AA} vs p_T

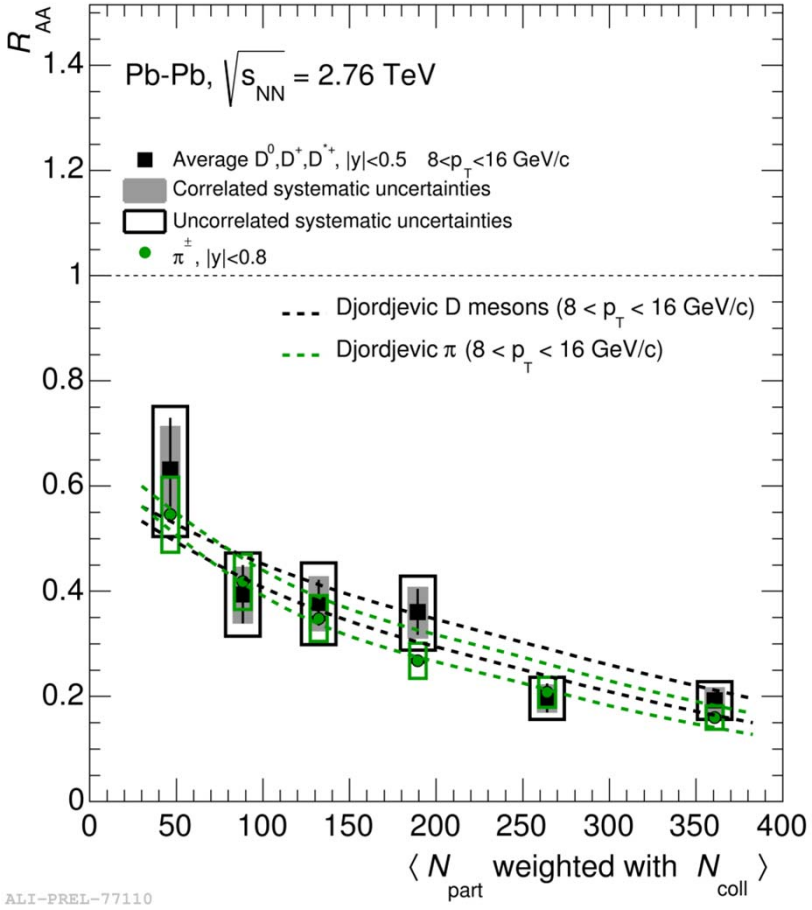




- Strong suppression of D-meson yield at high p_T in central Pb-Pb collisions relative to the binary scaled pp reference: a factor 3-5 for $p_T > 5$ GeV/c
- Similar suppression for D^+_s as for other D mesons in $8 < p_T < 12$ GeV/c
- More statistics needed at intermediate p_T to conclude about a possible D^+_s enhancement due to recombination or coalescence

Kuznetsova, Rafelski, EPJ C 51 (2007) 113; He et al., PRL 110 (2013) 112301; Andronic et al., PLB 659 (2008) 149

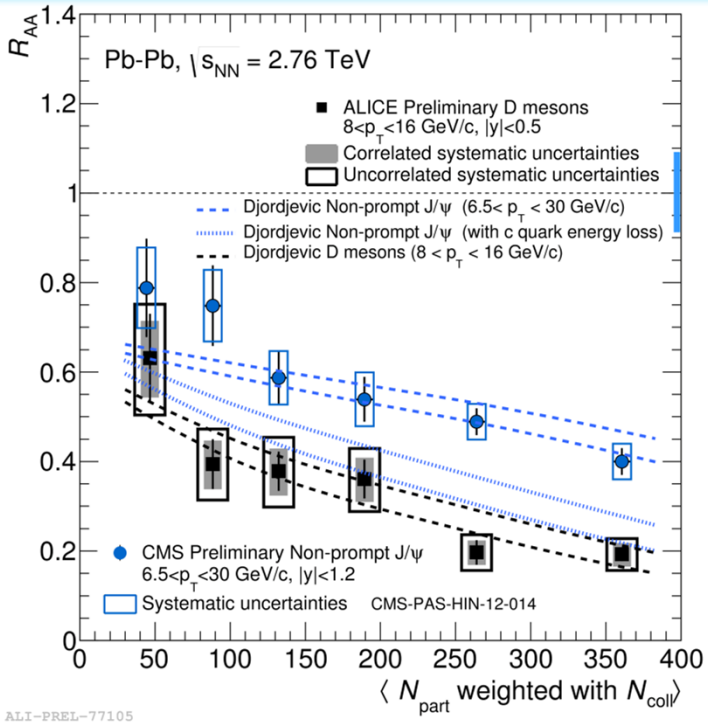
D-meson R_{AA} vs centrality: comparison with charged pions



- D-meson and $\pi^{\pm}$ suppression increases with increasing centrality
- Similar suppression for D mesons and charged pions: $R_{AA}(D) \approx R_{AA}(\pi^{\pm})$
- In agreement with models taking into account $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$
  but also:
  - Different shapes of parton p_T distributions
  - Different fragmentation functions

  Djordjevic, PLB 734 (2014) 286;
  Wicks, Horowitz, Djordjevic, NPA 872 (2011) 265

D-meson R_{AA} vs centrality: comparison with beauty



Data points:

- D mesons: ALICE
- Non-prompt J/ψ: CMS

Djordjevic: PLB 734 (2014) 286

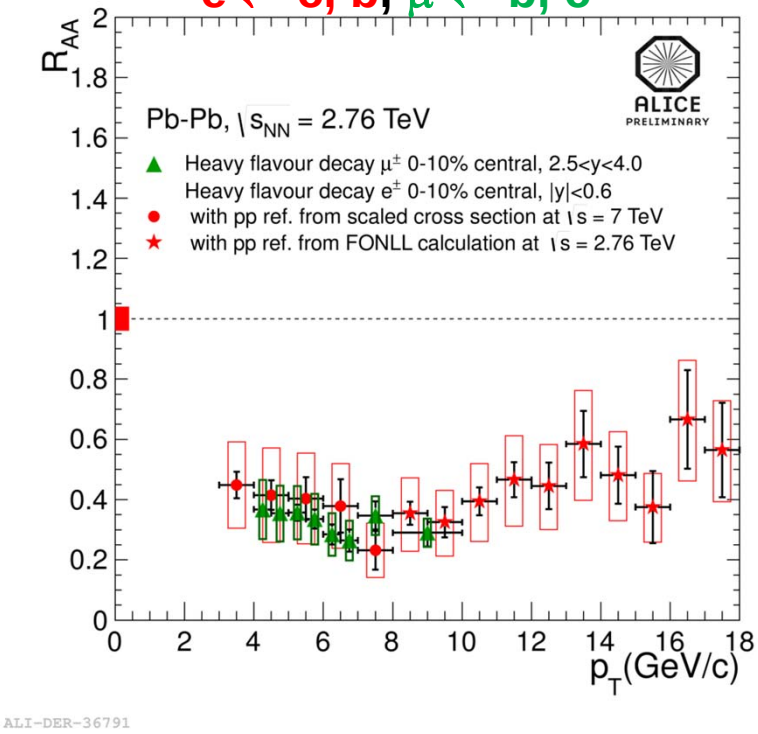
non-prompt J/ψ

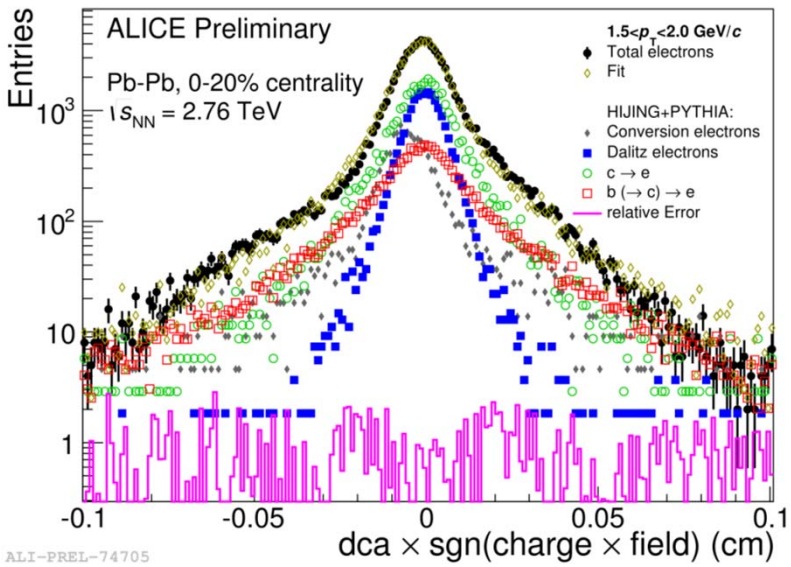
non-prompt J/ψ with c quark energy loss

- Non-prompt J/ψ (i.e. from B decays) measured by CMS less suppressed than D mesons in central collisions: consistent with the expectation $\Delta E_c > \Delta E_b$ (dead cone effect, *PLB 519 (2001) 199*)
  - Similar $\langle p_T \rangle$ ~ 10 GeV/*c* for D and B mesons and slightly different *y* range
- Measurements in agreement with pQCD calculations including mass-dependent radiative and collisional energy loss
- Similar trends for other calculations (TAMU, BAMPS, WHDG, MC@sHQ+EPOS2, Vitev et al.)

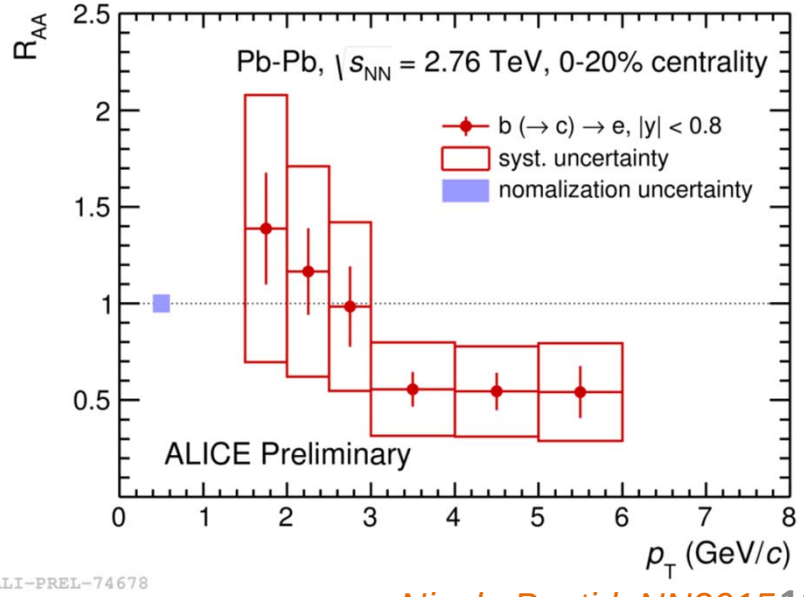
Heavy-flavour decay leptons: R_{AA} *vs* p_T

e ← c, b, μ ← b, c





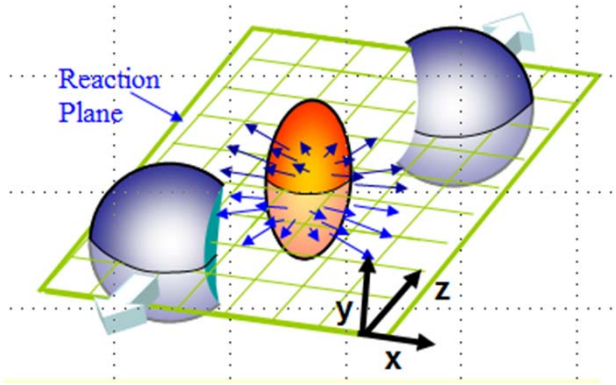
e ← b



- Similar suppression of μ ← c, b yields at forward rapidity and e ← c, b yields at mid-rapidity in the 0-10% centrality class: a factor 3-4 in $4 < p_T < 10$ GeV/*c*
- Hint for a suppression of e ← b yields: $R_{AA} < 1$ for $p_T > 3$ GeV/*c*

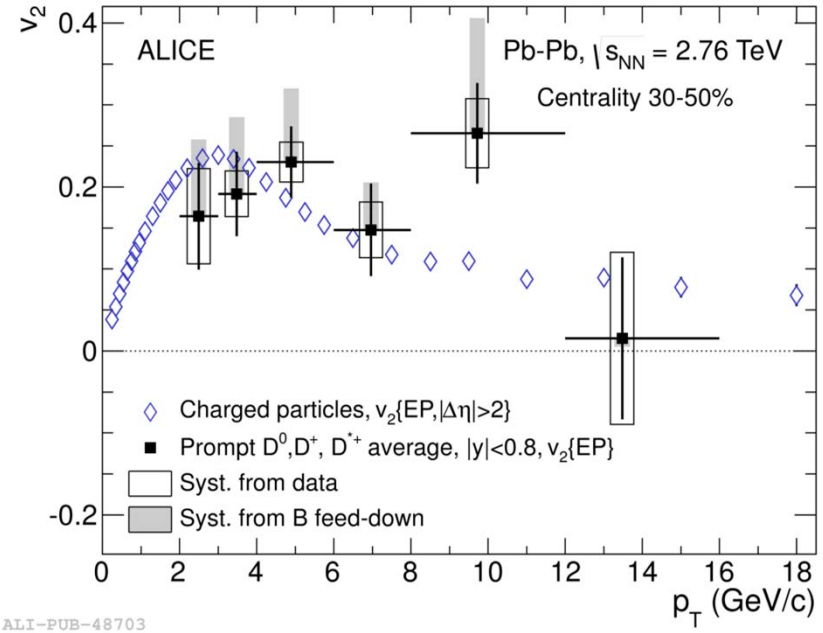
Azimuthal anisotropy: D-meson v_2 vs p_T

Initial spatial anisotropy → momentum anisotropy of heavy-flavour hadrons if enough scattering of heavy quarks in the medium



- v_2 sensitive to:
  - Low p_T: collective motion
  - High p_T: path-length dependence of parton energy loss

$$\frac{2\pi}{N}\frac{\mathrm{d}N}{\mathrm{d}\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_n)]$$



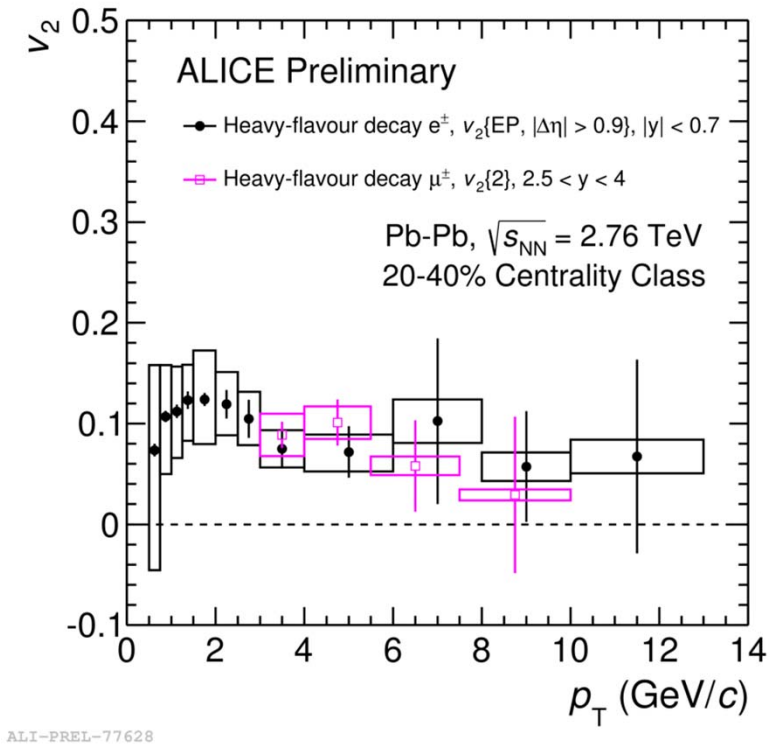
- Positive v_2 of D mesons observed: a 5.7σ effect for $2 < p_T < 6$ GeV/c
- Similar v_2 for charged particles and D mesons

- Confirmation of significant interaction of charm quarks with the medium → collective motion of low p_T charm quarks in the expanding fireball

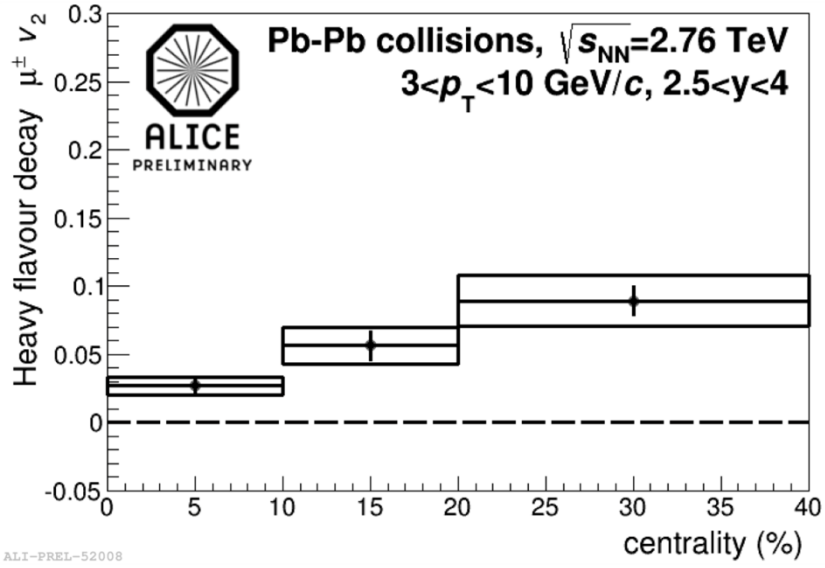
PRL 111 (2013) 102301; PRC 90 (2014) 034904

Heavy-flavour decay leptons: v_2 vs p_T and centrality

e ← c, b; μ ← c, b

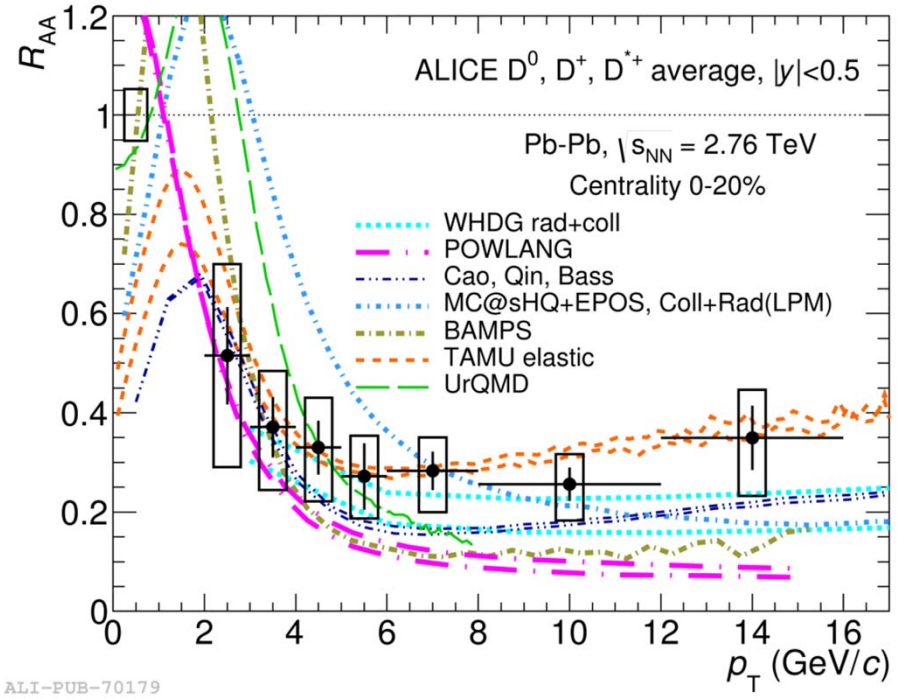


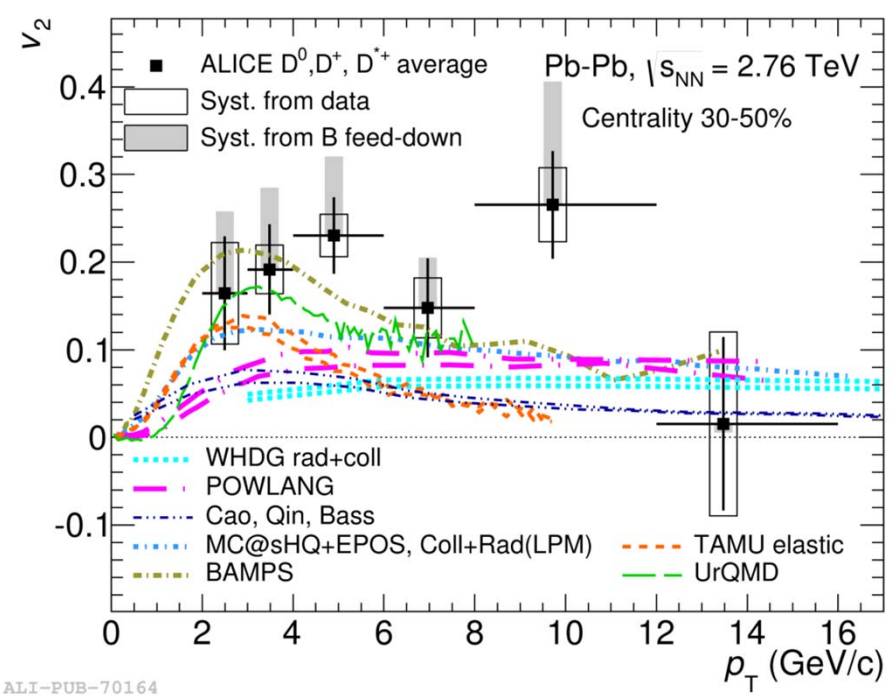
μ ← c, b



- μ ← c, b measured at forward rapidity in 2.5 < y < 4 exhibit a positive v_2: a 3σ effect for 3 < p_T < 5 GeV/c in 20-40% centrality class
- Increasing v_2 of μ ← c, b from central to semi-central collisions
- Consistent results with e ← c, b measured at mid-rapidity in |y| < 0.7
- Confirmation of significant interaction of heavy quarks with the medium

Model comparisons: D-meson R_{AA} and v_2





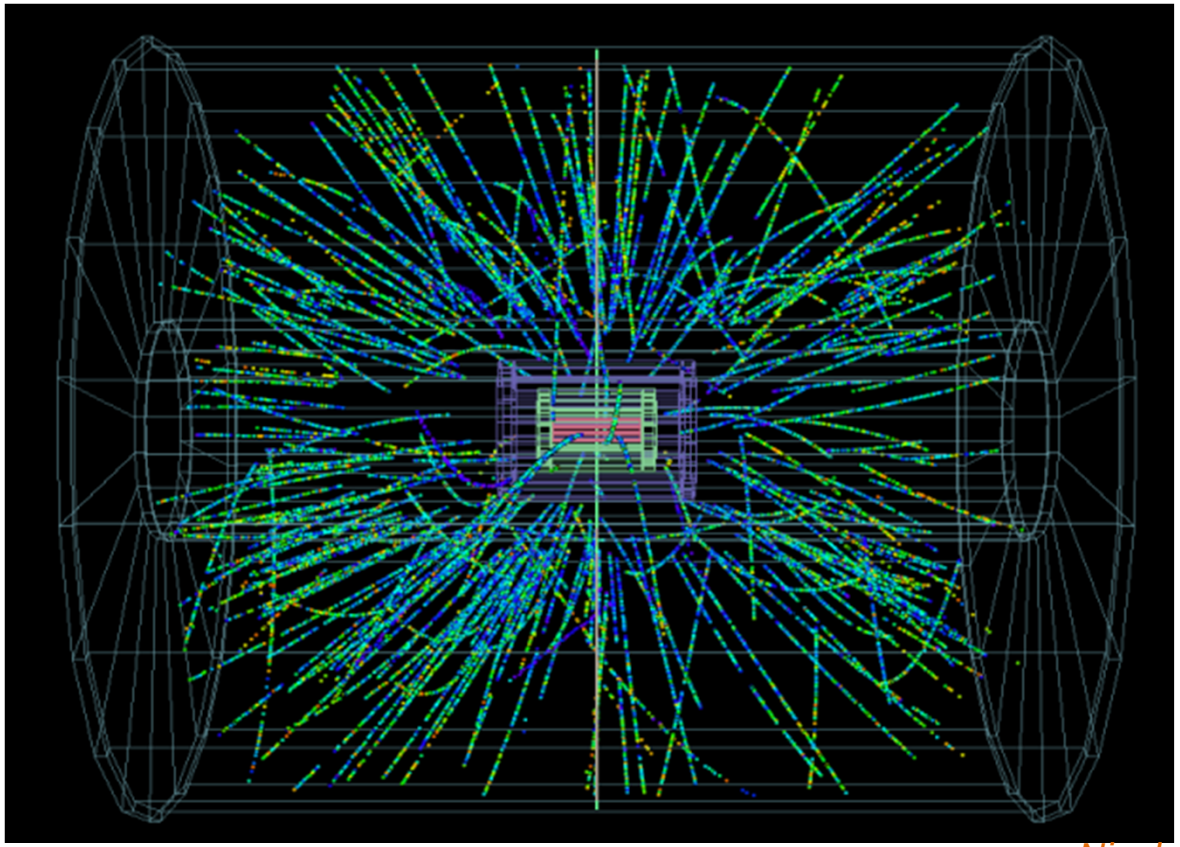
PRC 90 (2014) 034904

WHDG: Nucl. Phys. A 872 (2011) 265; Cao, Qin, Bass: Phys. ReV. C 88 (2013) 044907;
POWLANG: Eur. Phys. J. C 71 (2011) 1666, J. Phys. G 38 (2011) 124144;
BAMPS: Phys. Lett. B 717 (2012) 430; TAMU elastic: arXiv: 1401.3817;
MC@ sHQ+EPOS, Coll + Rad (LPM): Phys. Rev. C 89 (2014) 014905; UrQMD: arXiv:1211.6912

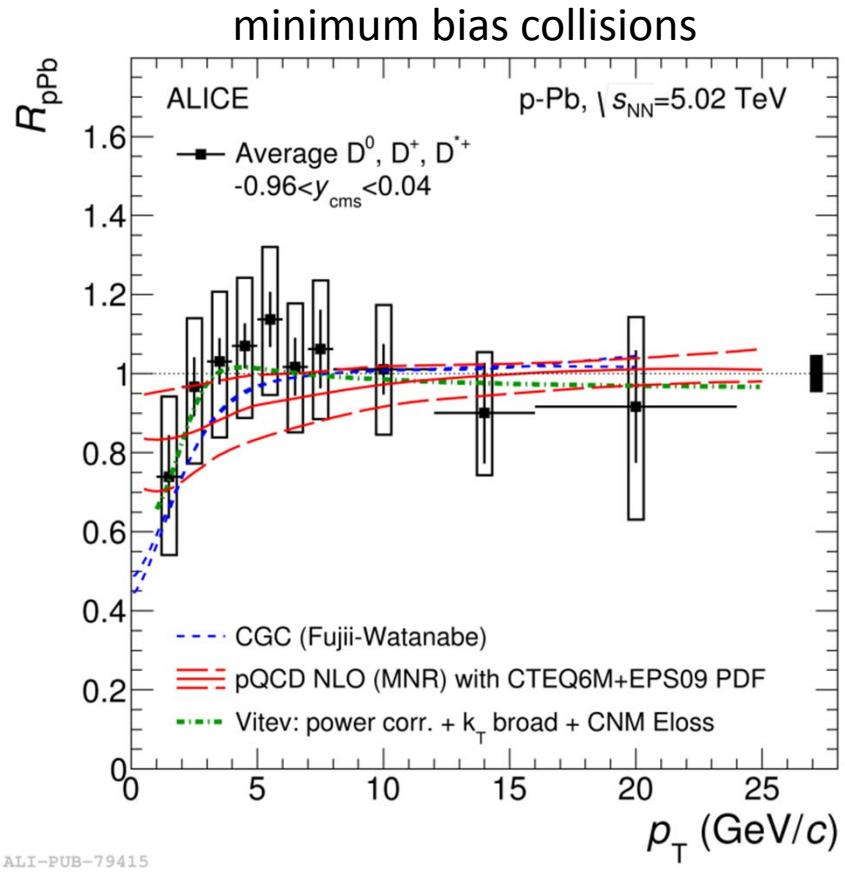
- Simultaneous description of D-meson R_{AA} and v_2 is challenging and provides constraints on energy loss models
- Similar picture for heavy-flavour decay leptons

Open heavy-flavour results in p-Pb collisions

- p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
  - ✓ Rapidity shift: $|\Delta y|$ = 0.465 in the p-beam direction (positive *y*)
  - ✓ Two configurations:
    - ➢ p-Pb , muon spectrometer in p-going direction
    - ➢ Pb-p, muon spectrometer in Pb-going direction



D mesons: R_{pPb} *vs* p_T



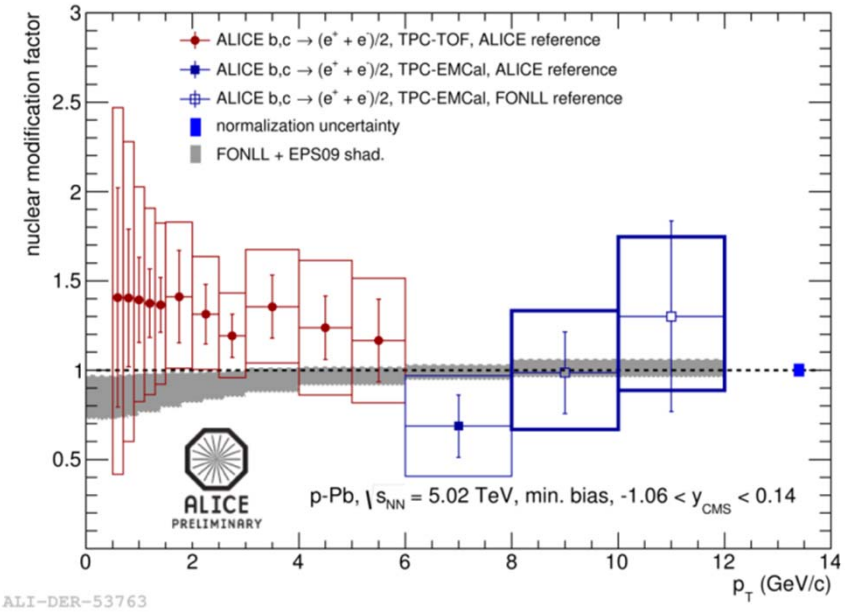
$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) = 1/A \times \frac{\mathrm{d}N_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

ALICE: arXiv:1405.3452
CGC: H.Fujii and K. Watanable, arXiv: 1308.1258
pQCD NLO (MNR): Nucl. Phys. B 373 (1992) 295,
EPS09: K. J. Eskola et al., JHEP 04 (2009) 065
Vitev: Phys. Rev. C 80461 (2009) 054901

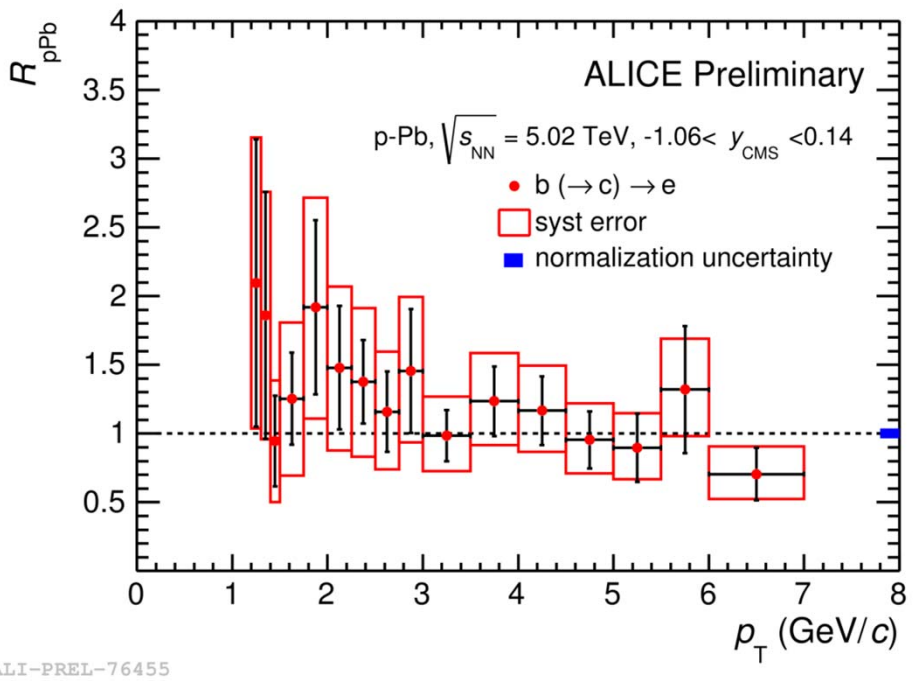
- Nuclear modification factor (R_{pPb}) consistent with unity in the region p_T > 2 GeV/c
- D-meson R_{pPb} in agreement with:
  - Perturbative QCD calculations including EPS09 parameterization of shadowing
  - Color Glass Condensate (CDG) predictions
  - Model including energy loss, shadowing and k_T broadening
- Cold nuclear matter effects are small at high p_T

Heavy-flavour decay electrons: R_{pPb} *vs* p_T

e ← c, b



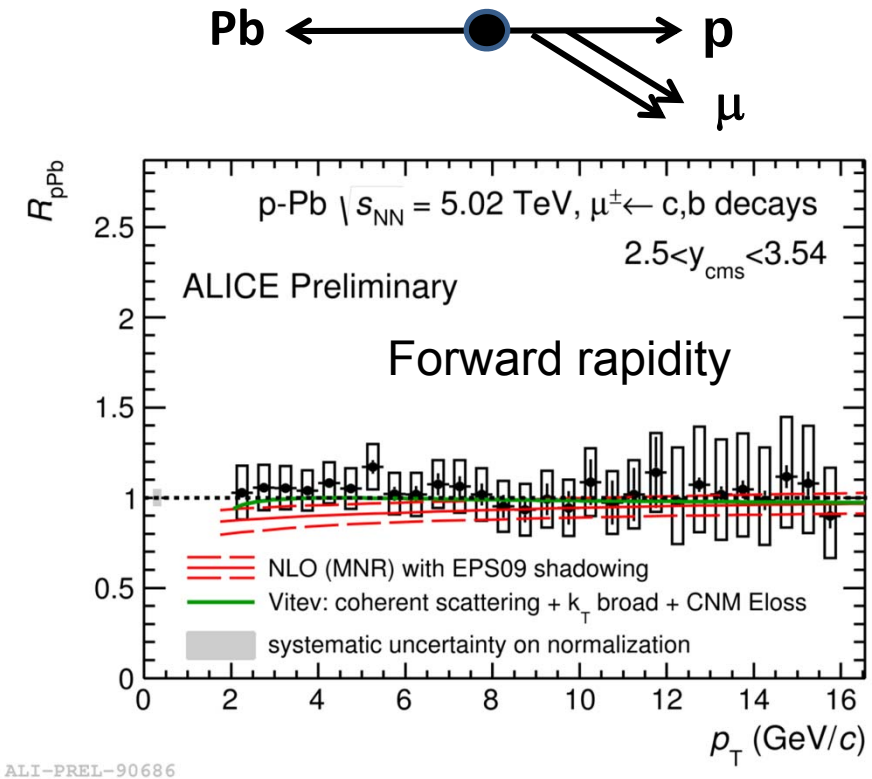
e ← b

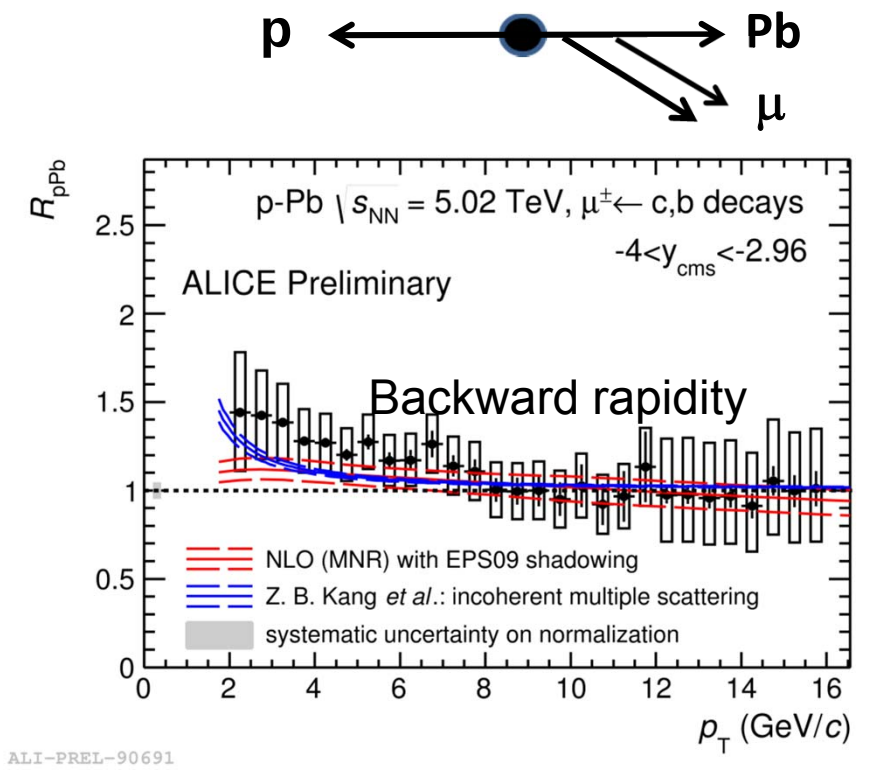


- R_{pPb} consistent with unity within uncertainties for electrons from heavy-flavour hadron decays and beauty-hadron decays
- R_{pPb} in agreement with perturbative QCD calculations including EPS09 parameterization of shadowing

FONLL: M. Cacciari et al., JHEP 007 (1998) 9805, JHEP 006 (2001) 0103
pQCD NLO (MNR): Nucl. Phys. B 373 (1992) 295, EPS09: K. J. Eskola et al., JHEP 04 (2009) 065

Heavy-flavour decay muons: R_{pPb} *vs* p_T



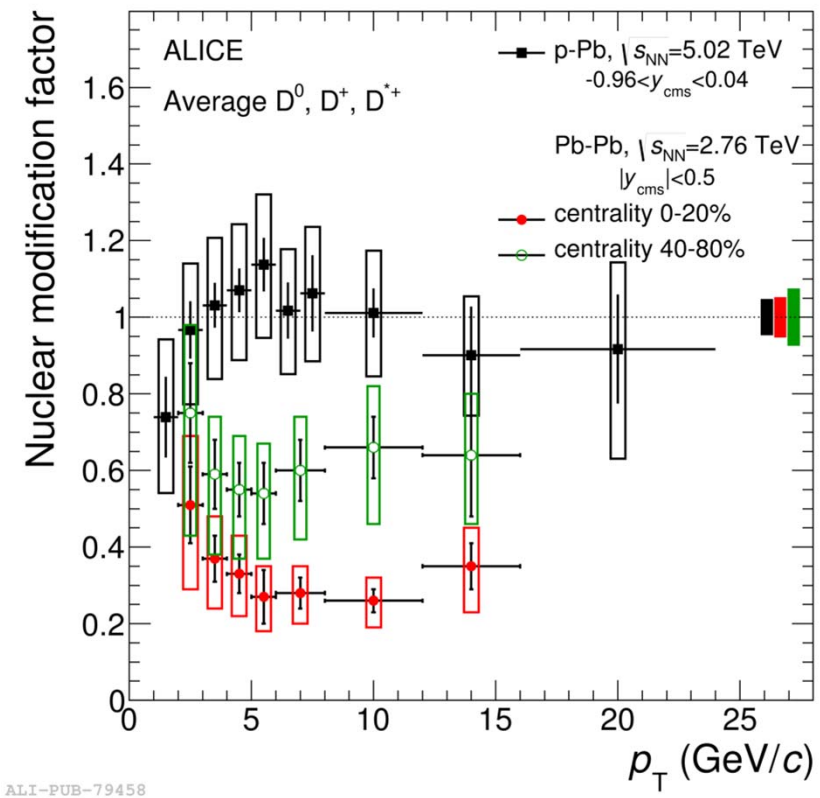


- R_{pPb} at forward rapidity is consistent with unity and, at backward rapidity is slightly larger than unity in $2 < p_T < 4$ GeV/c and close to unity at higher p_T
- Cold nuclear matter effects are small
- R_{pPb} described by perturbative QCD calculations implementing cold nuclear matter effects

pQCD NLO (MNR): Nucl. Phys. B 373 (1992) 295, EPS09: K. J. Eskola et al., JHEP 04 (2009) 065
R. Sharma et al., Phys. Rev. C 80 (2009) 054902; Z.B. Kang et al., Phys. Lett. B 740 (2015) 23

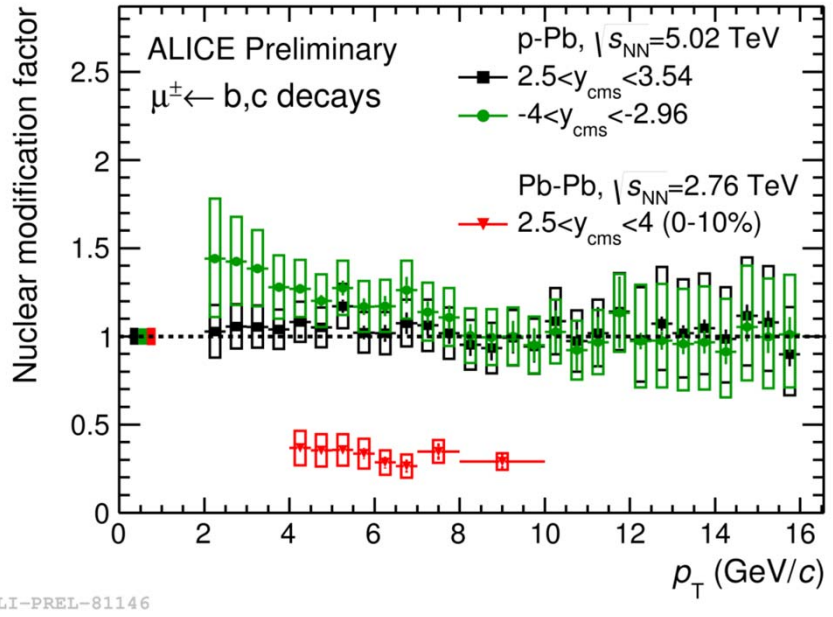
Comparison to R_{AA} vs p_T

D mesons



Phys. Rev. Lett. 113 (2014) 232301

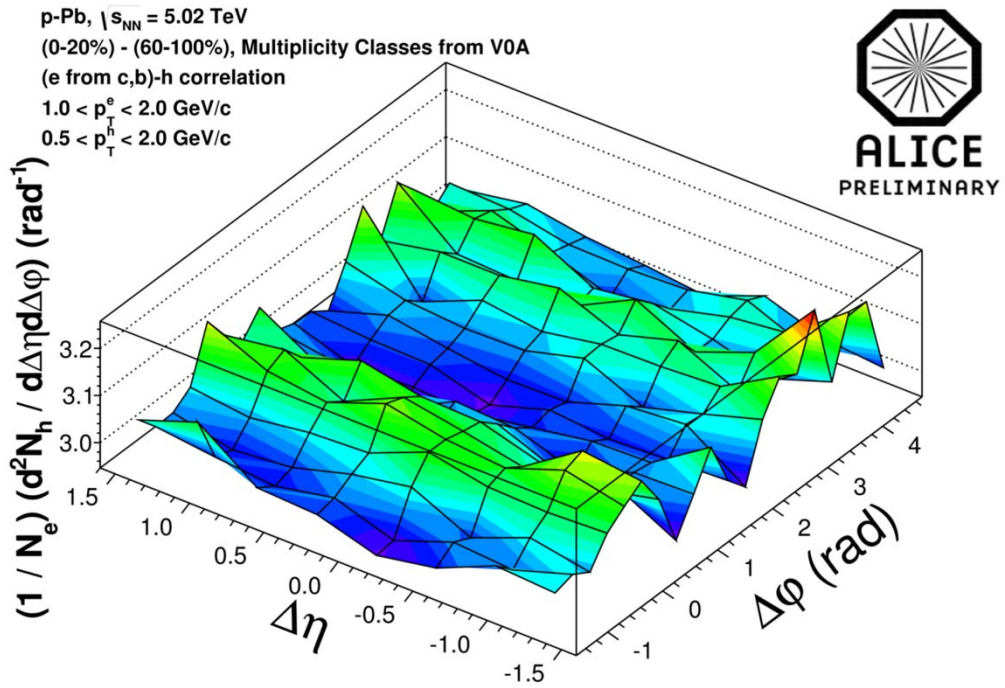
μ ← c, b



Pb-Pb: Phys. Rev. Lett. 109 (2012) 112

- The strong suppression measured at high p_T in central Pb-Pb collisions is due to final-state effects
- Same conclusion also for e ← c, b and e ← b

Heavy-flavour decay electron-hadron azimuthal correlations



ALI-PREL-62026

- Trigger particle: electron from heavy-flavour hadron decay
- Associated particle: charged hadron
- Jet contribution removed by subtracting angular correlations in highest multiplicity (0-20%) and lowest multiplicity (60-100%) p-Pb event class

- Double-ridge structure observed in high-multiplicity p-Pb collisions after subtraction of the baseline, as in the light-flavour sector
  Phys. Lett. B 719 (2013) 29, Phys. Lett. B 726 (2013) 164
- Initial-state effects (CGC) or collective flow?
  CGC: Dusling, Venugopalan, Phys. Rev. D 87 (2013) 094034
  Hydrodynamics in final state: Bozek, Broniowski, Phys. Lett. B 718 (2013) 1557

Conclusion

Pb-Pb collisions:

- Strong interaction of heavy quarks with the medium
  - Suppression of open heavy-flavour yields at high p_T in central collisions
  - Participation of heavy quarks (charm, mainly) in the collective expansion of the system

- Larger suppression for D mesons than for B mesons at p_T ~ 10 GeV/c

- Simultaneous description of different observables (R_{AA}, v_2) provides constraints on energy loss models

p-Pb collisions:

- Cold nuclear matter effects are small
  - The measured suppression of open heavy-flavour yields at high p_T in central Pb-Pb collisions is a medium effect related to in-medium parton energy loss

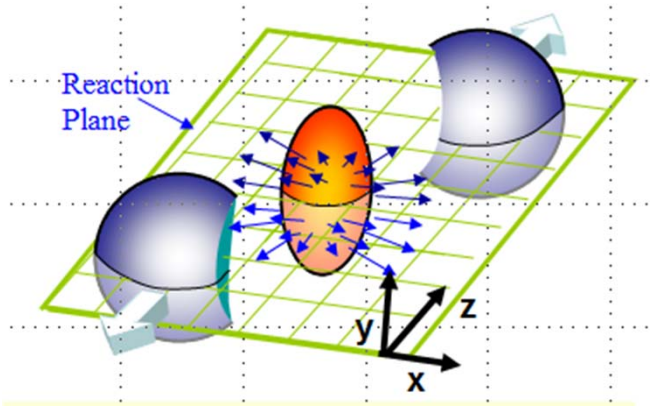
More precise measurements to come soon with the LHC run 2


Thank you for
your attention

Backup

Heavy quarks in Pb-Pb: azimuthal anisotropy

Initial spatial anisotropy → momentum anisotropy of heavy-flavour hadrons if enough scattering of heavy quarks in the medium



- Study azimuthal distributions w.r.t. the reaction plane

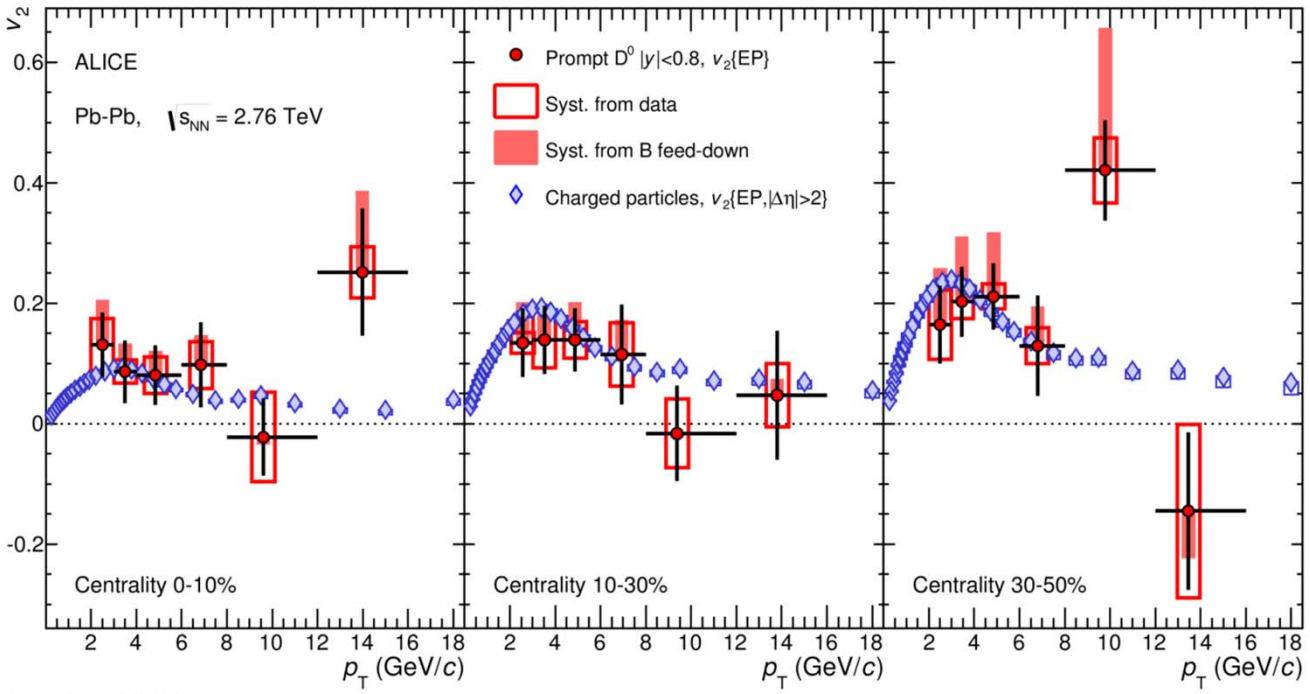
$$\frac{2\pi}{N}\frac{\mathrm{d}N}{\mathrm{d}\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_n)]$$

elliptic flow: $v_2 = < \cos[2(\varphi - \Psi_n)] >$

Heavy-flavour v_2 measurements probe:

- Low/intermediate p_T: collective motion, thermalization of heavy quarks and hadronization mechanism (recombination)
  - due to their large mass, heavy quarks should feel less the collective expansion
- High p_T: path-length dependence of heavy quark energy loss
  - linear for collisional processes
  - close to quadratic for radiative processes

D mesons: v_2 vs p_T



PRL 111 (2013) 102301; PRC 90 (2014) 034904

Event plane method

$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\mathrm{IN}} - N_{\mathrm{OUT}}}{N_{\mathrm{IN}} + N_{\mathrm{OUT}}}$$

R_2: event plane resolution correction factor

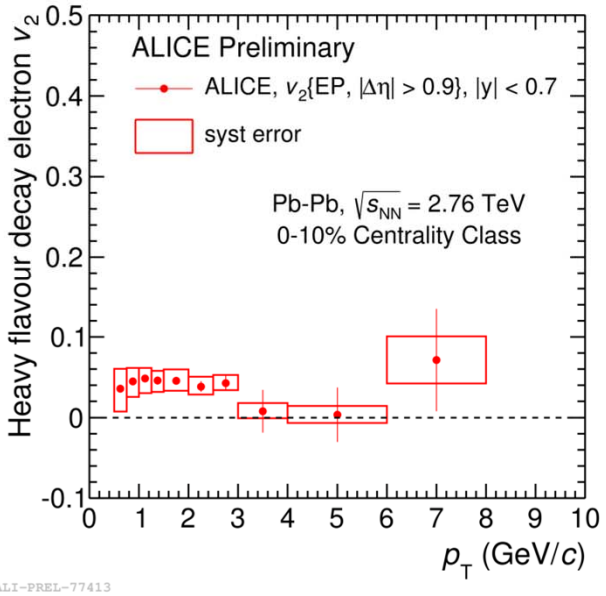
- Positive v_2 observed: a 5.7σ effect for $2 < p_T < 6$ GeV/c in 30-50% centrality
- Hint for an increase of v_2 from central to semi-central collisions
- D-meson v_2 similar to charged-particle v_2

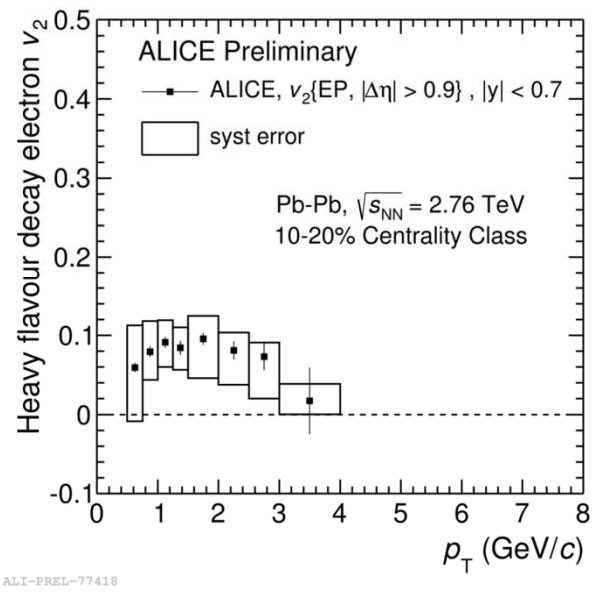
- Confirmation of significant interaction of charm quarks with the medium
  → collective motion of low p_T charm quarks in the expanding fireball

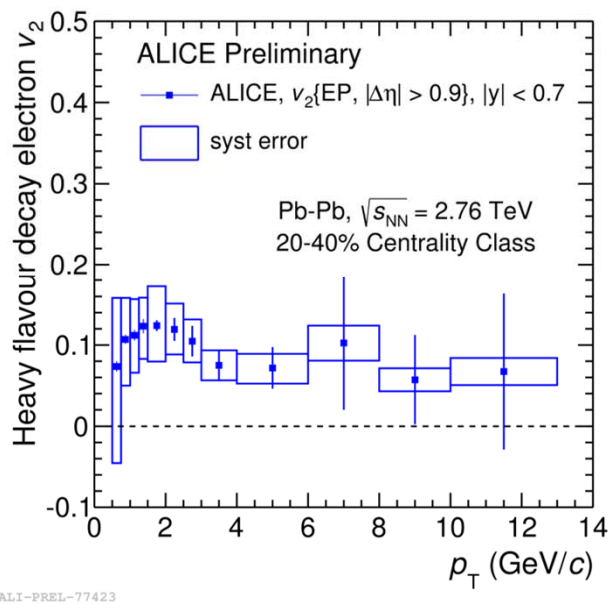
Electrons from heavy-flavour decays: v_2 vs p_T

$$v_2 = \frac{(1 + R_{SB}) v_2^{\text{incl e}} - v_2^{\text{bkg e}}}{R_{SB}}$$

$v_2^{\text{incl e}}$: event-plane method
$V_2^{\text{bkg e}}$: invariant mass, cocktail based on data
R_{SB}: signal to background ratio



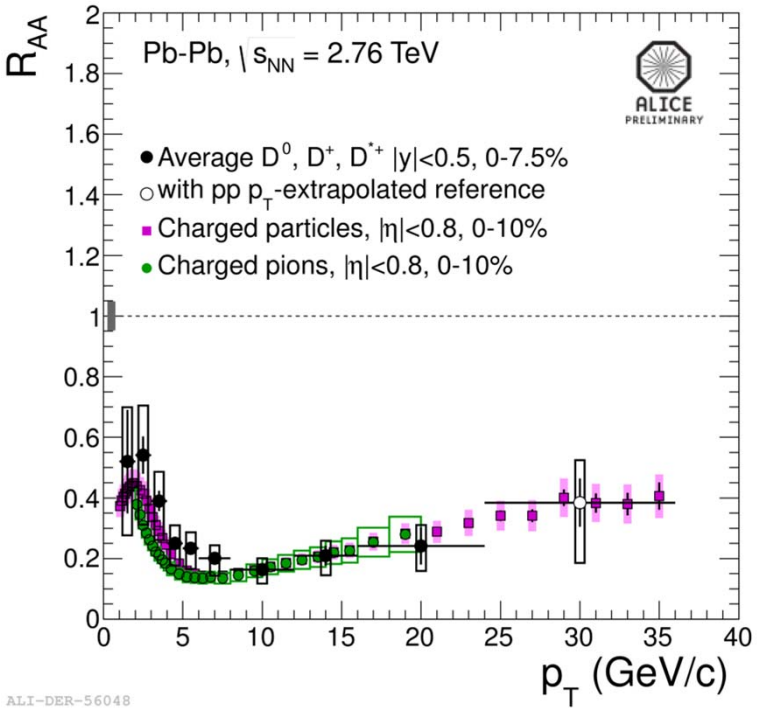




- Positive v_2 observed: a 3σ effect for $2 < p_T < 3$ GeV/c in 20-40% centrality class with similar centrality dependence as observed for D mesons

- Confirmation of significant interaction of heavy quarks with the medium
  → collective motion of low p_T heavy quarks (mainly charm) in the expanding fireball

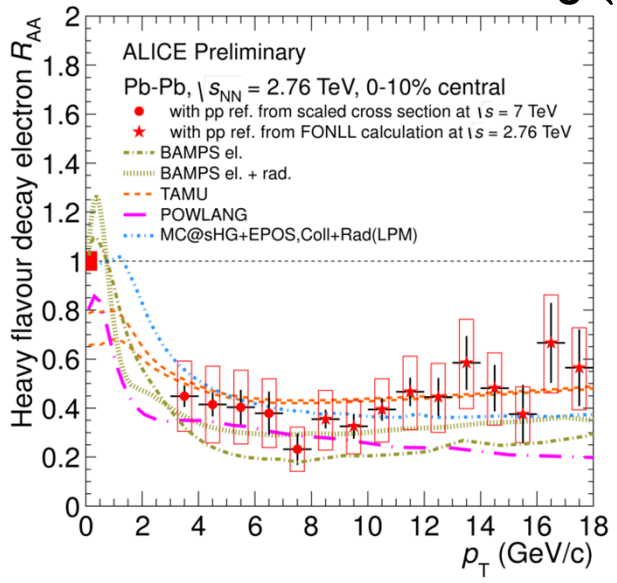
D-meson R_{AA} vs p_T: comparison with pions

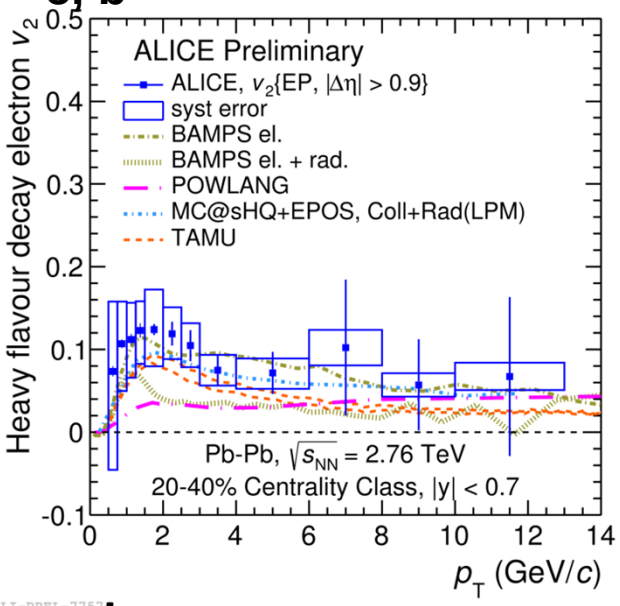


- D-meson and $\pi^{\pm}$ R_{AA} as a function of p_T compatible within uncertainties
- In agreement with models taking into account $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ but also:
  - different shapes of the parton p_T distributions
  - different fragmentation functions
    Djordjevic, PLB 734 (2014) 286; Wicks, Horowitz, Djordjevic, Nucl. Phys. A 872 (2011) 265
  - soft production mechanism for low p_T charged pions

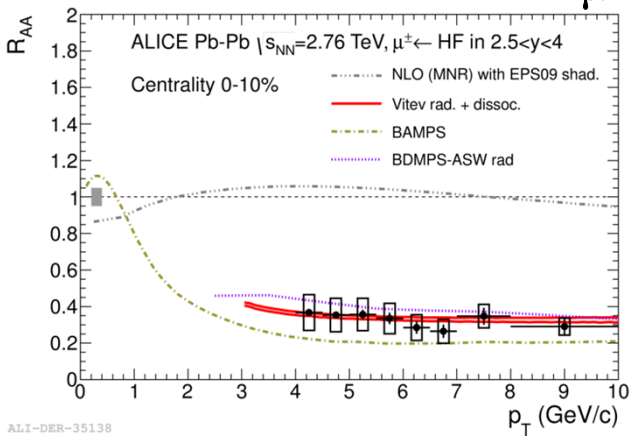
Model comparisons: heavy-flavour lepton R_{AA} & v_2

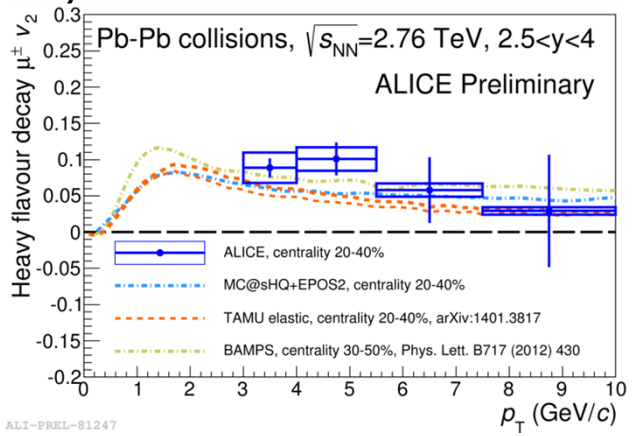
e ← c, b





μ ← c, b





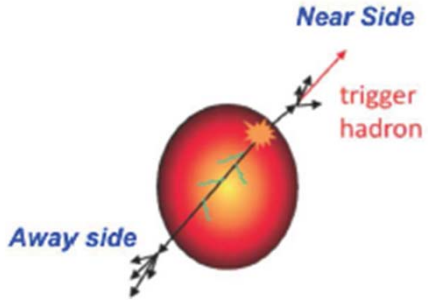
- Similar picture from the comparison of R_{AA} and v_2 to models as for D mesons
- Simultaneous measurement of R_{AA} and v_2 allows one to constrain models

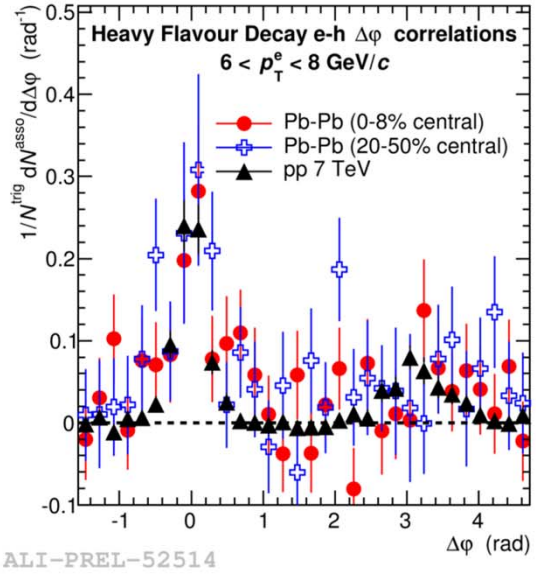
BAMPS: PLB 717 (2012) 430, arXiv:1401.3817; POWLANG: Eur. Phys. J. C 71 (2011) 1666, J. Phys. G 38 (2011) 124144; TAMU elastic: arXiv:1401.3817; MC@ sHQ+EPOS, Coll + Rad(LPM): PRC 89 (2014) 014905

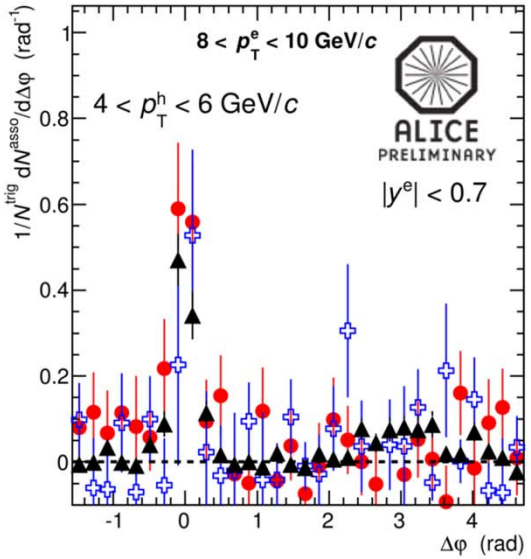
Heavy-flavour decay electron-hadron azimuthal correlations in Pb-Pb

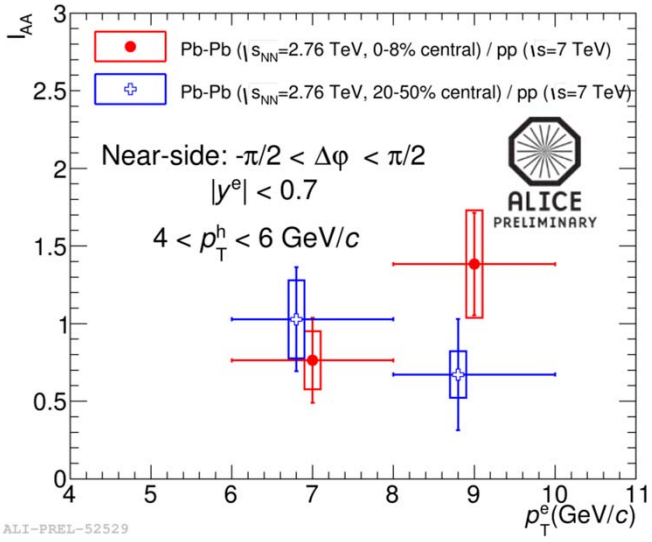
- Near side: modifications of the properties of jets containing heavy flavours
- Away side: path-length dependence of in-medium energy loss
- Observable: I_{AA}

$$I_{AA} = \frac{Y_{AA}}{Y_{pp}}, \qquad Y = \frac{1}{N_{trig}} \int_{NS} \frac{dN^{assoc}(\Delta\varphi)}{d\Delta\varphi} d\Delta\varphi$$







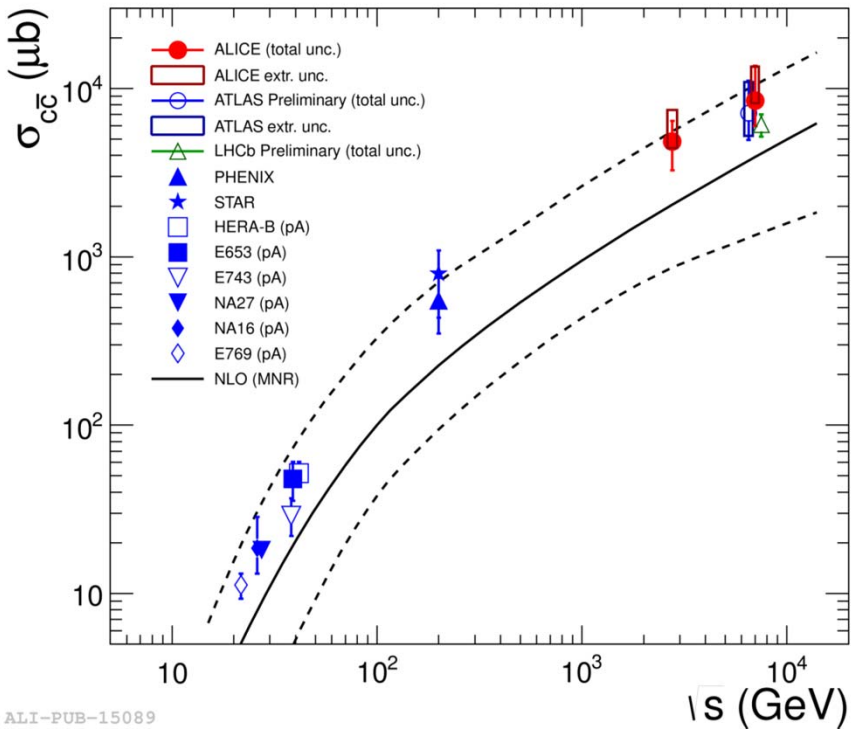


- Measured I_{AA} compatible with unity: difficult to conclude on possible medium-induced modification of fragmentation due to limited statistics

Data samples: Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV

Observable	Integrated luminosity
D mesons	2010: 2.12 μb^{-1} (0-80%) 2011: 23 μb^{-1} (0-10%), 6.2 μb^{-1} (10-30%), 6.2 μb^{-1} (30-50%)
$e^{\pm} \leftarrow$ c, b	2010: 2.0 μb^{-1} (0-80%) 2011: 22 (37) μb^{-1} in 0-10% and 6 (34) μb^{-1} in 20-40% with MB (EMCAL) triggers
$\mu^{\pm} \leftarrow$ c, b	2010: 2.7 μb^{-1} (0-80%) 2011: 11.3 μb^{-1} (0-10%) and 3.5 μb^{-1} in 10-40%

The LHC: a heavy-flavour factory



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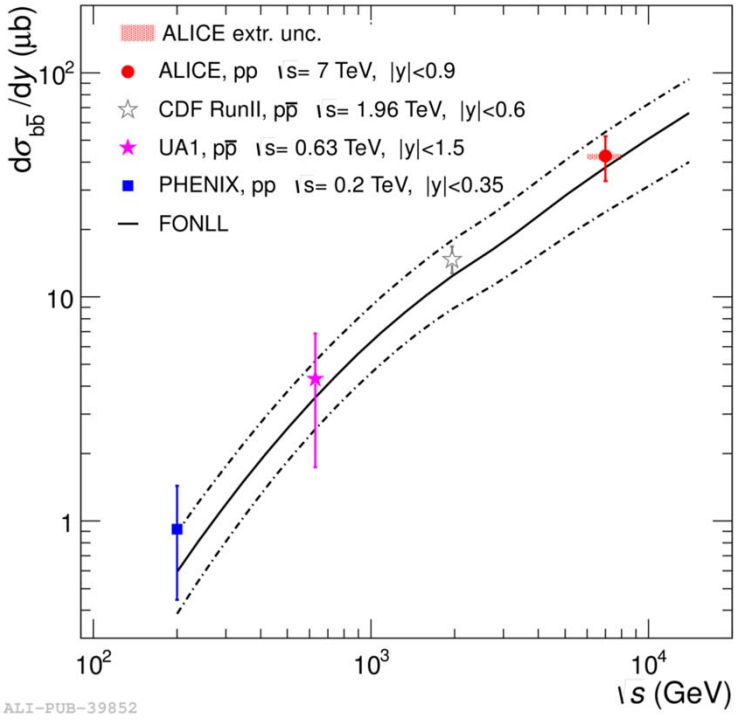


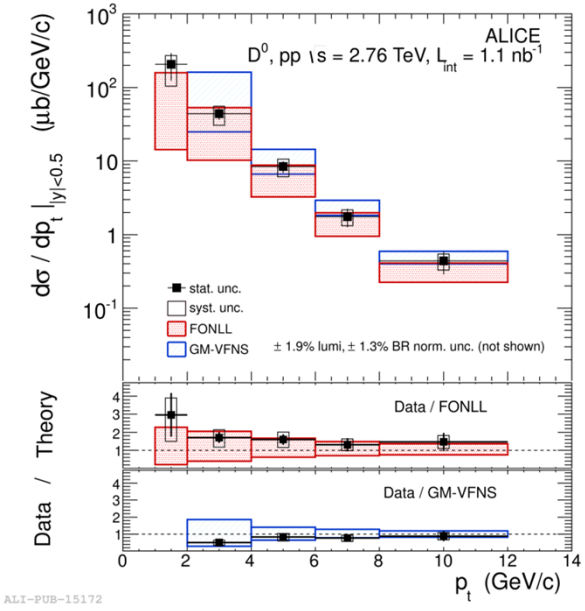
PLB 721 (2013) 13 & arXiv:1405.4144

- Abundant heavy-flavour production rates at the LHC, have been measured in pp collisions
  - σ_c(LHC) = σ_c(RHIC) x 10
  - σ_b(LHC) = σ_b(RHIC) x 50
- Central (5%) Pb-Pb (LHC, 2.76TeV) : ~60 $c\bar{c}$ & ~2 $b\bar{b}$

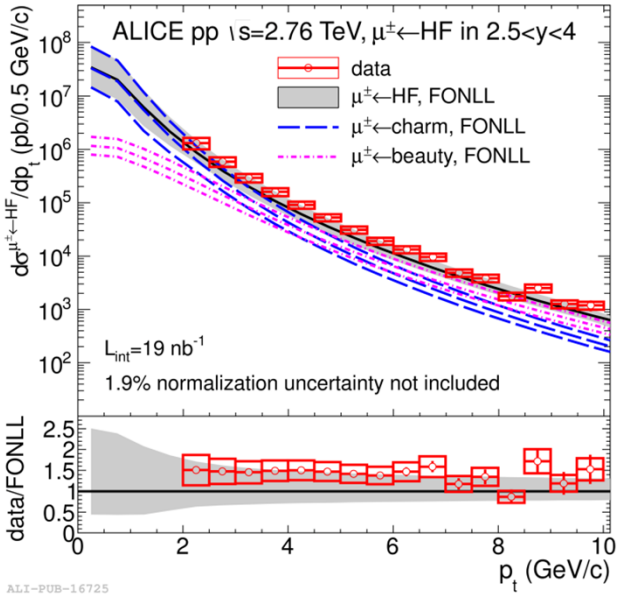
(MNR code: Nucl. Phys. B 373 (1992) 295; EKS98, EPS08: EPJ C9 (1999) 61, JHEP07 (2008) 102)

Differential cross sections in pp, √s = 2.76 TeV

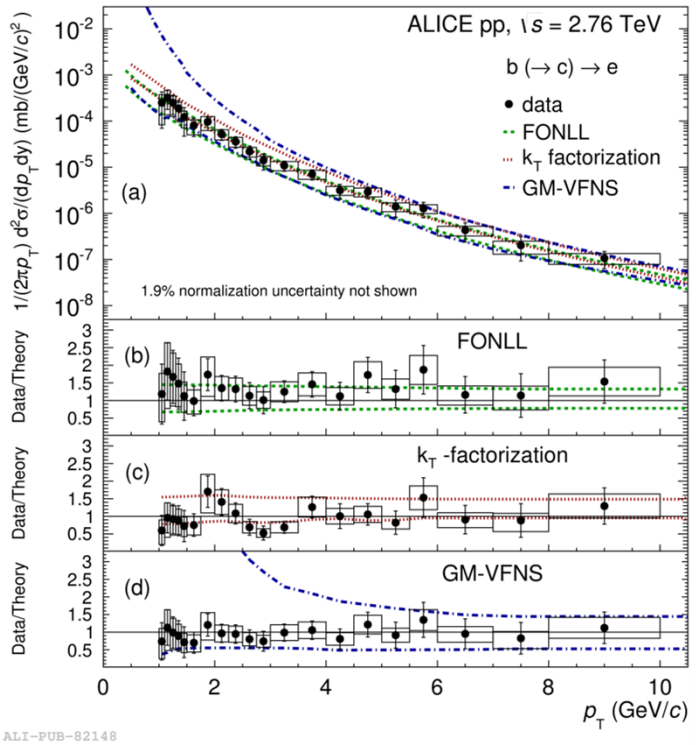
D mesons



$\mu^{\pm} \leftarrow$ b, c

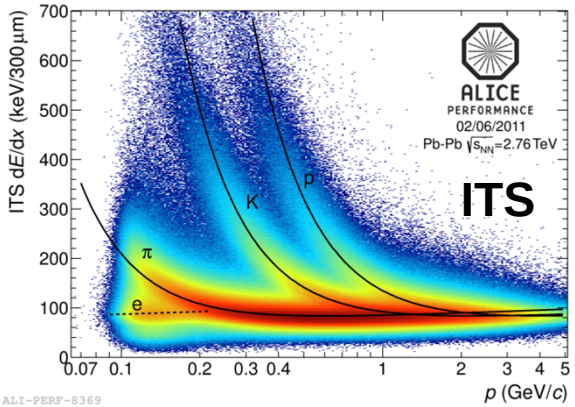


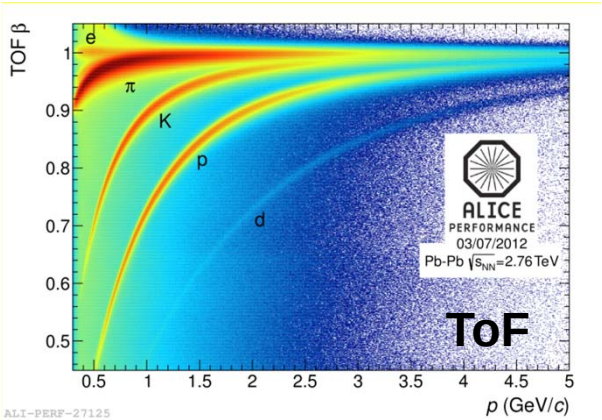
$e^{\pm} \leftarrow$ b

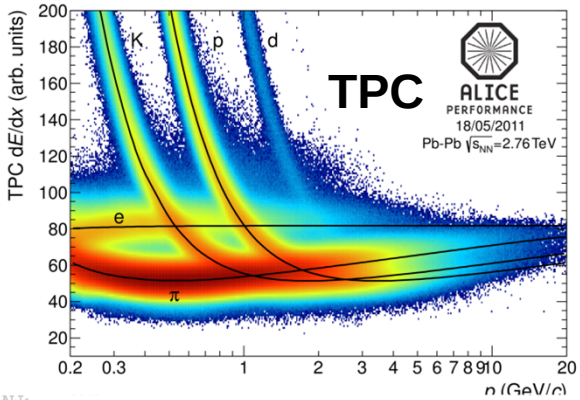


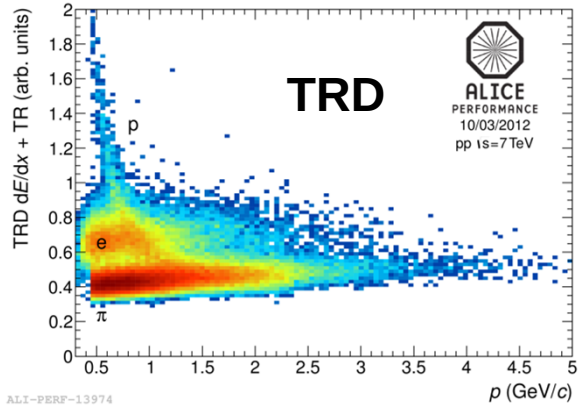
- Good agreement within uncertainties with pQCD calculations

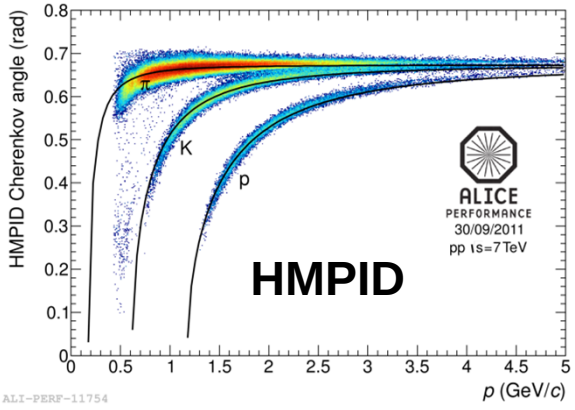
Particle IDentification (PID) in ALICE

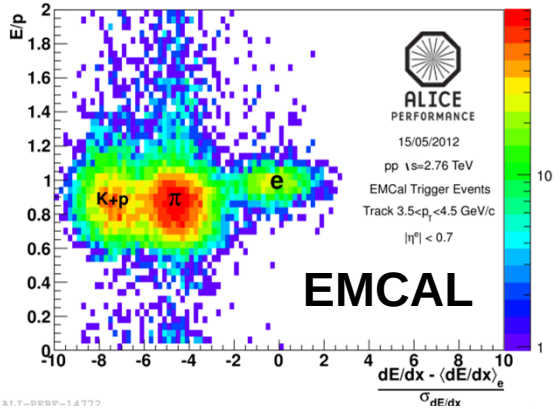


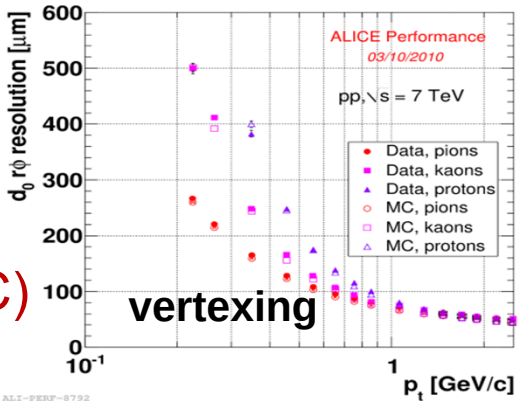












- particle identification over a large rapidity range (almost all known techniques)
- excellent tracking down to ~ 100 MeV/c & vertexing
- quarkonium detection down to $p_T = 0$ (unique at LHC)