ALICE results on open-charm production and prospects for the upgrade

Cristina Terrevoli
University & INFN Padova
for the ALICE Collaboration

Outline

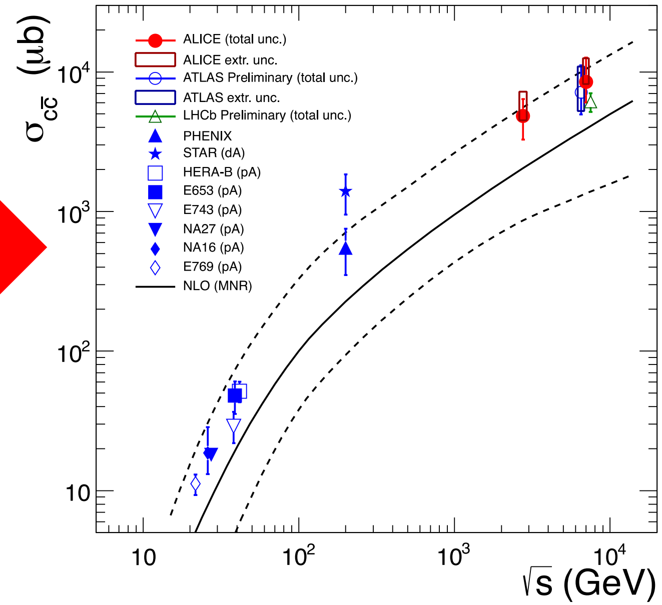
- Why heavy flavour?
  - heavy quarks (charm and beauty) probe the properties of the Quark Gluon Plasma (QGP)
- Heavy-flavour hadrons in ALICE
  - Reconstruction strategy
  - Results
- Why and how to upgrade the detector?
- Heavy-flavour prospects with upgraded detector

Why heavy flavour at the LHC ?

ALICE

LHC as a heavy-flavour factory

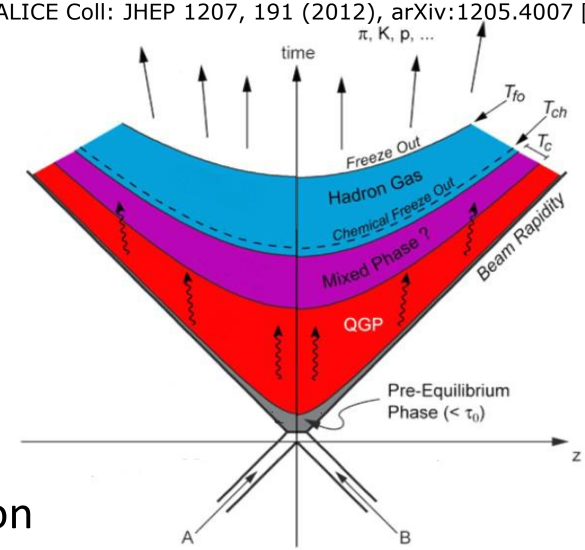
- Large cross section for $c\bar{c}$ and $b\bar{b}$ production
  - for example: $c\bar{c}$ cross section >5 times larger than at RHIC energy



ALICE Coll: JHEP 1207, 191 (2012), arXiv:1205.4007 [hep-ex].

m_c~1.5 GeV, m_b~5 GeV

- produced at the early stage of the collision
  $\Delta t < 1 / 2m_c \sim 0.1$ fm/c $<< \tau_0^{QGP} \sim 1$ fm/c
  - temporal and spatial scales sufficiently small for the production to be unaffected by the properties of the medium
- while propagating through the medium heavy quarks interact with its constituents
  - elastic and inelastic QCD processes depend on the medium properties: density, opacity and extension

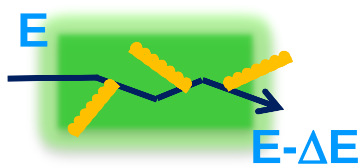


Heavy-quark interaction with the QGP

- **Energy loss via radiative and collisional processes:**

Theoretical prediction: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ color charge and mass dependence of energy loss

Key measurement: Nuclear modification factor: $R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$



Y.L.Dokshitzer, D. Kharzeev
Phys. Lett. B 519 (2001) 199

Prediction: R_{AA} (π) ~ R_{AA} (D) (or slightly smaller)

difficult to compare: different production kinematics and fragmentation between light partons and charm quark tend to compensate the color-charge dependence of ΔE

and R_{AA} (D) < R_{AA} (B)

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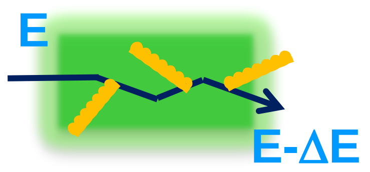

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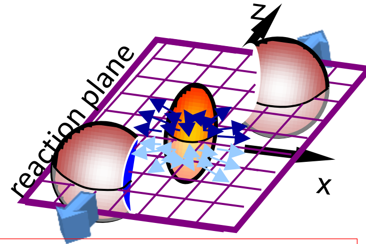
- sensitive to the thermalization of c and b quarks in QGP
- low-p_T c and b quarks participate in the collective expansion of the system?
- path-length dependence of energy loss?

Key measurement: elliptic flow v_2 and R_{AA} dependence on the azimuthal angle relative to the reaction plane



Initial spatial anisotropy → momentum anisotropy of particles

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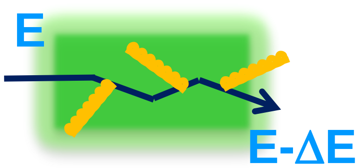

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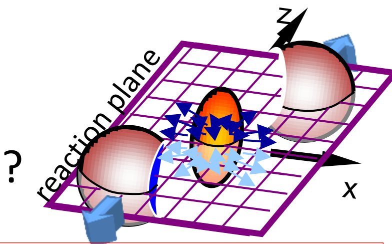


Initial spatial anisotropy → momentum anisotropy of particles

- **Hadronization mechanisms:**

  Recombination of quarks from the QGP might contribute to HF hadron production

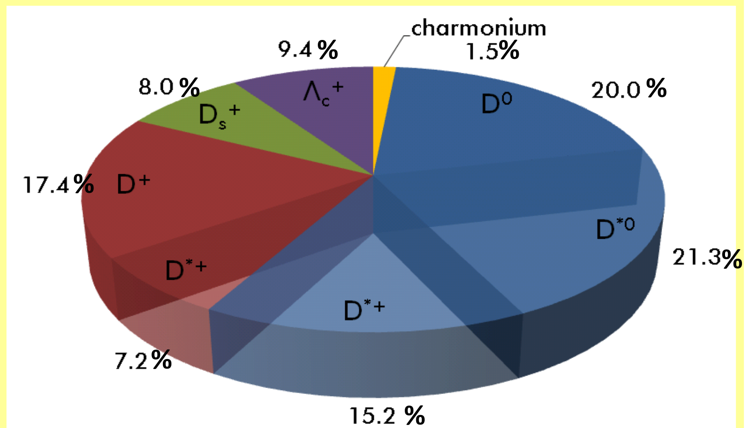
  Coalescence models predict an increase of baryon-to-meson ratio for light and heavy flavour

  (S.H.Lee Phys. Rev. Lett. 100, 222301 (2008); Y. Oh, C.M.Ko et al., Phys. Rev. C79, 044905 (2009))

  Prediction: enhancement of ratios strange/non-strange (D_s/D) and baryon/meson (Λ_c/D) **(M. He, R. J. Fries and R. Rapp, (2012) arXiv:1204.4442; Kuznetsova, Rafelski, Eur.Phys.J. C51 (2007) 113.)**

Reconstruction of heavy-flavour hadrons in ALICE

Where does charm go?



Phys Rev D 86 010001 (2012)   Courtesy of J. Mercado, 2013

Channels studied:

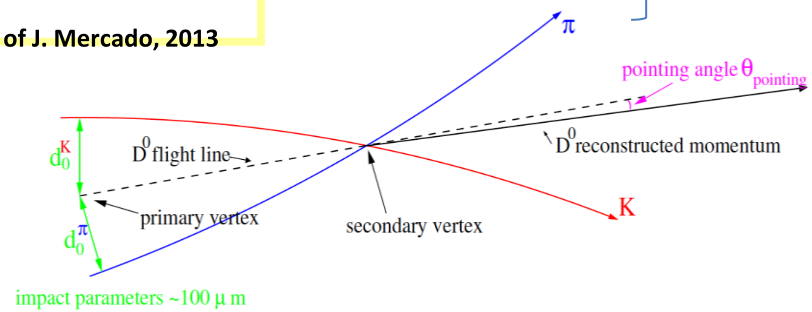
$D^0 \rightarrow K^-\pi^+$
$D^+ \rightarrow K^-\pi^+\pi^+$
$D^{*+} \rightarrow D^0\pi^+$
$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$

Ongoing studies:

$\Lambda_c^+ \rightarrow pK^-\pi^+$
$\Lambda_c^+ \rightarrow K^0_S p$

cτ = 100 - 300 μm:
displaced decay vertex is signature of heavy-quark decay

cτ = 60 μm ! challenge!

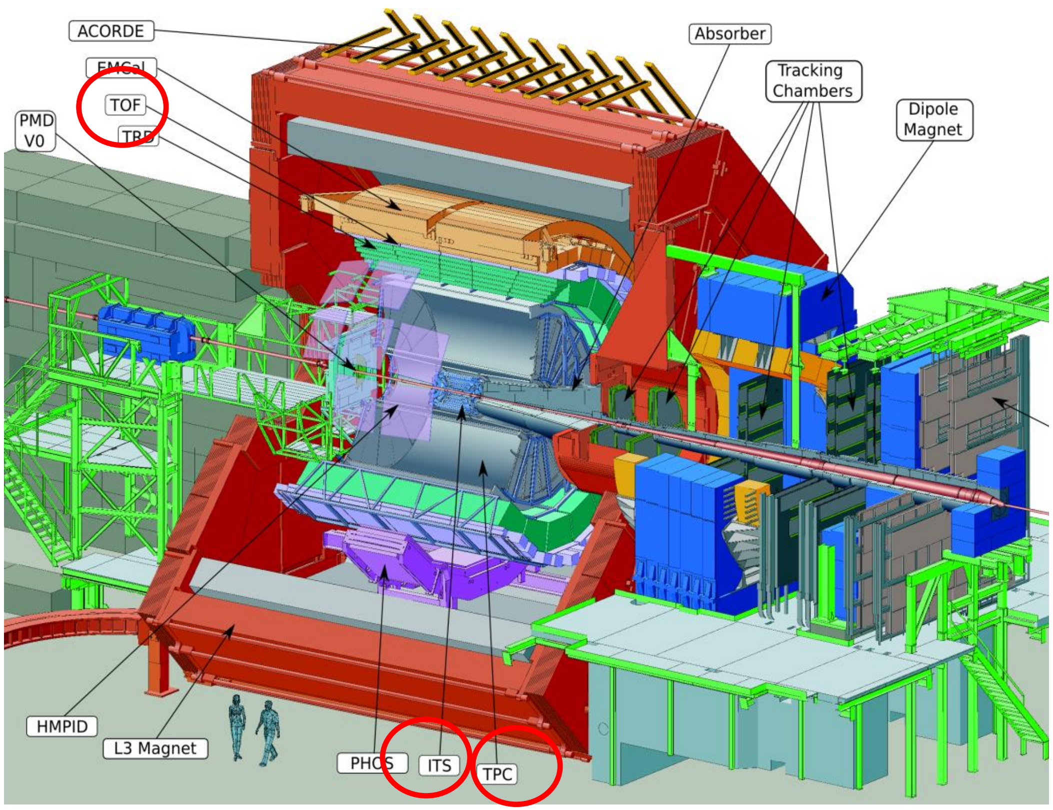


Open-charm reconstruction based on invariant mass analysis of the secondary vertex topology, displaced from the primary vertex, selected using geometrical cuts and particle identification

tracking and vertexing precision crucial for heavy-flavour analysis

D-meson reconstruction with the ALICE detector

- Excellent track and vertex reconstruction capabilities in a high multiplicity environment in a wide transverse momentum range
- Particle Identification in wide p_T range (ALICE Coll. CERN-PH-EP-2014-031)



- Inner Tracking System (ITS)
  - Vertex reconstruction
  - Tracking
- Time Projection Chamber (TPC)
  - Tracking
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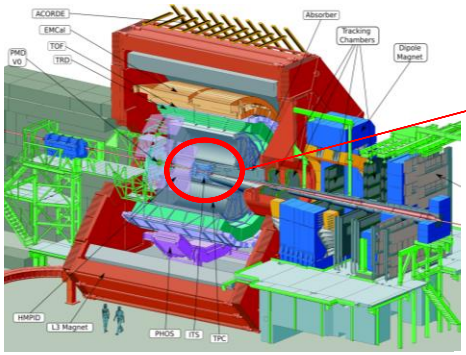

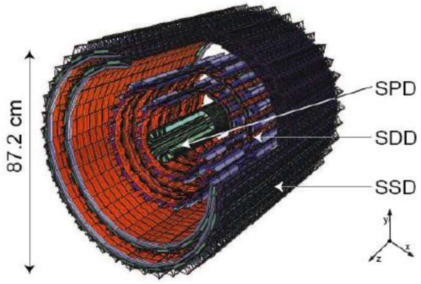

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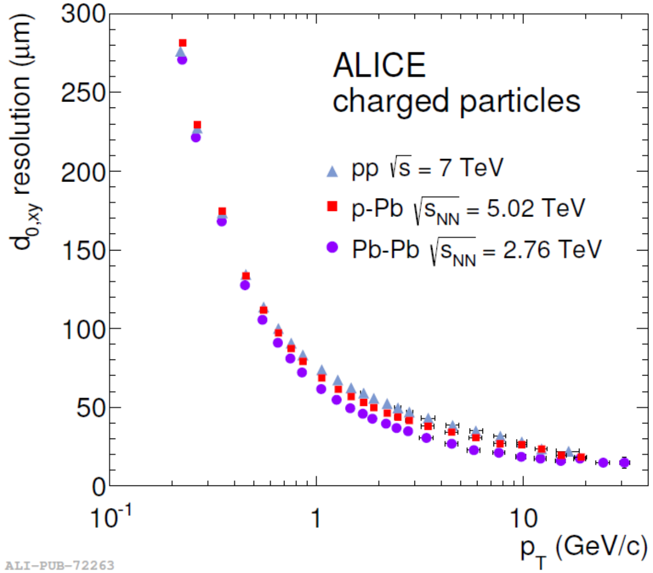

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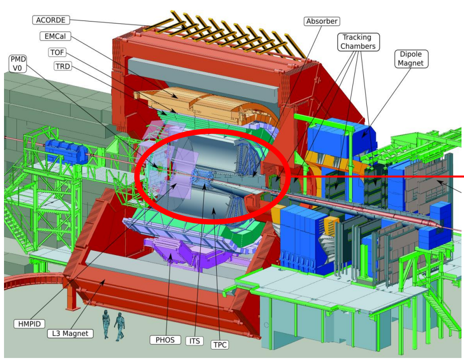

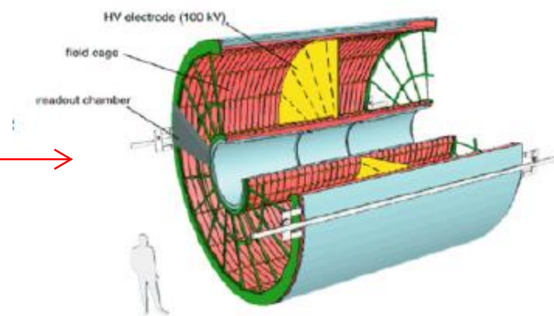

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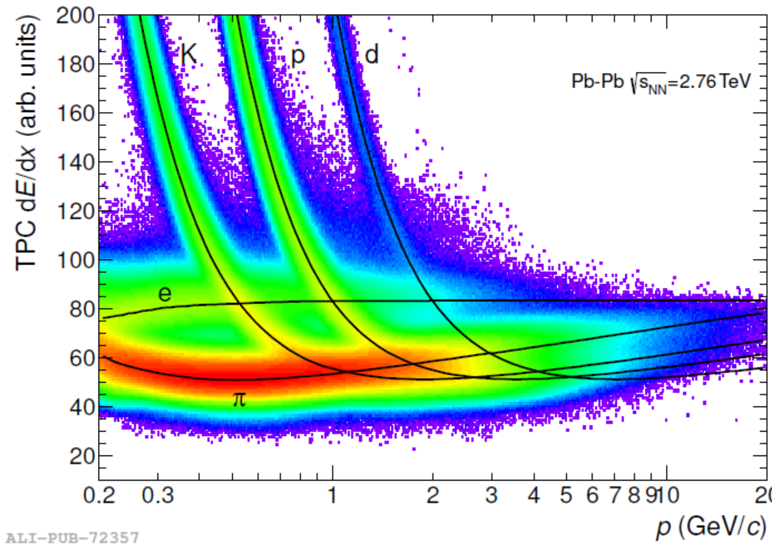

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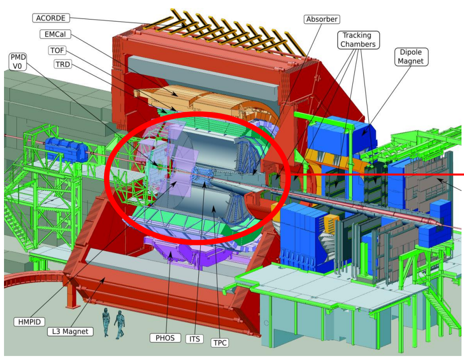

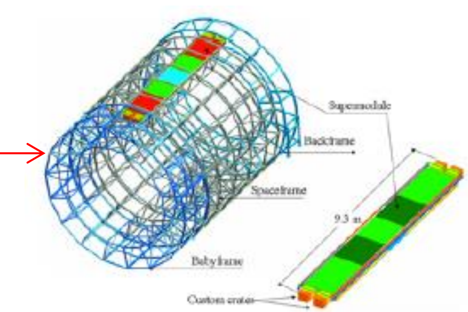

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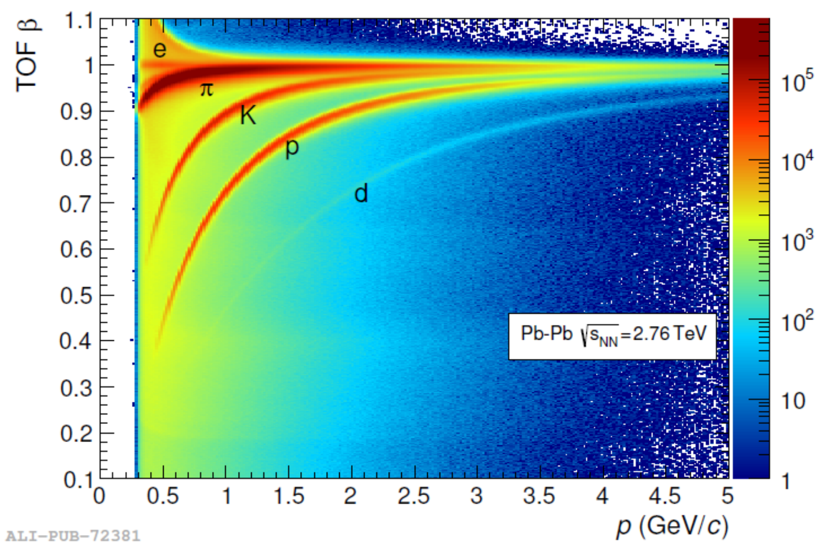
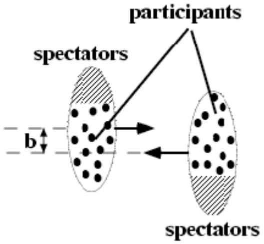


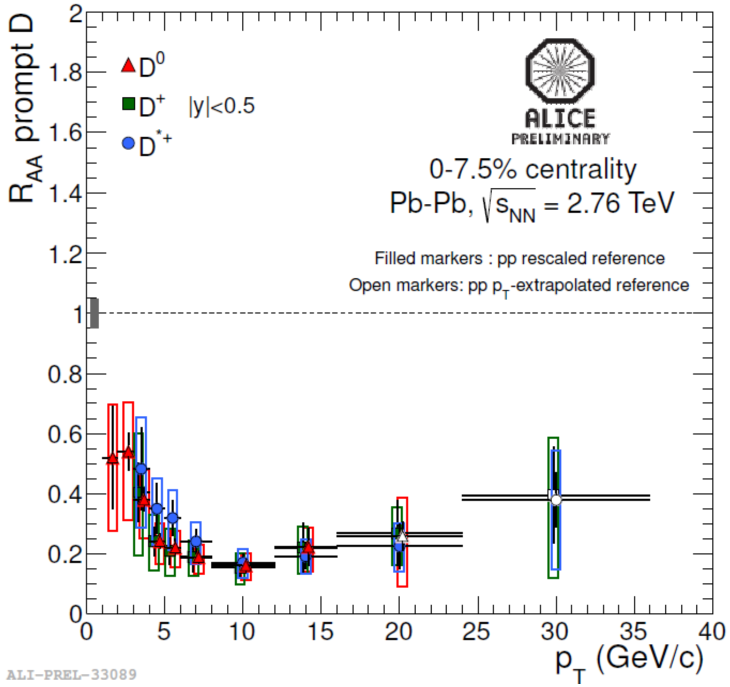
D-meson R_{AA}

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



Central collision:

- Small impact parameter b
- Large number of nucleon-nucleon collisions $<N_{coll}>$



D meson R_{AA} vs p_T 0-7.5% centrality class

- Strong suppression observed w.r.t the binary scaled pp reference in the p_T range 2-24 GeV/c
- Factor 3-5 for p_T>5 GeV/c
- Same suppression for different non-strange D-meson species

D-meson R_{AA}

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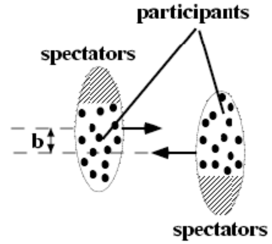

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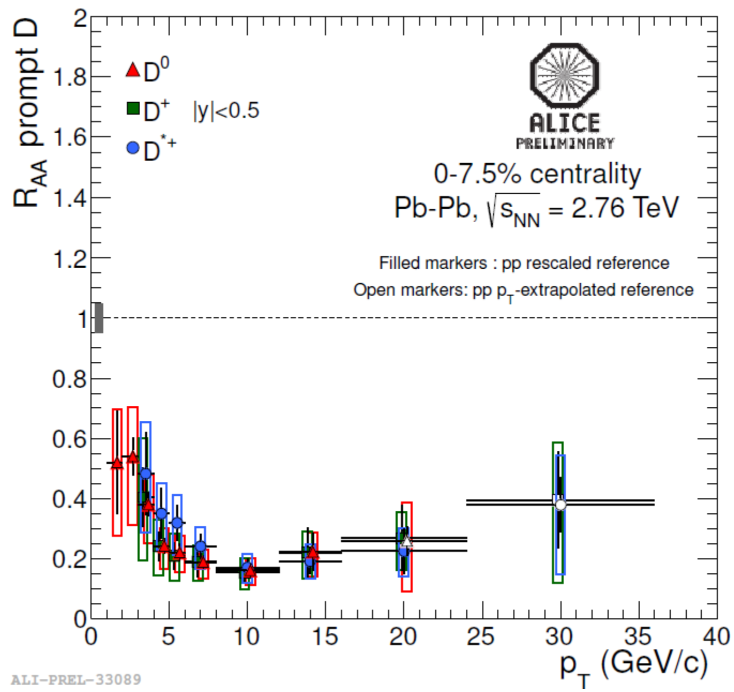
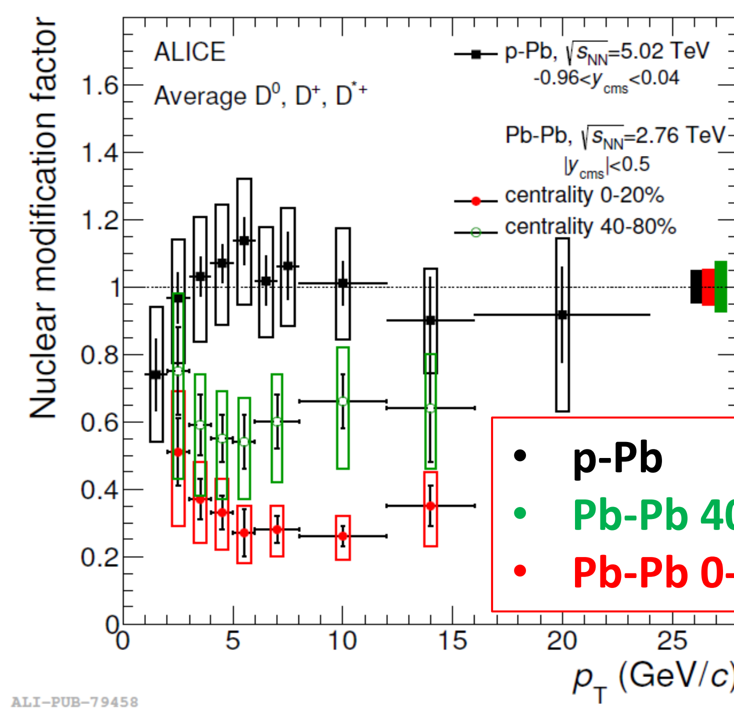




- **p-Pb**
- **Pb-Pb 40-80%**
- **Pb-Pb 0-20%**

Comparison with p-Pb results indicates that the suppression observed in Pb-Pb is due to final state effects induced by partonic medium

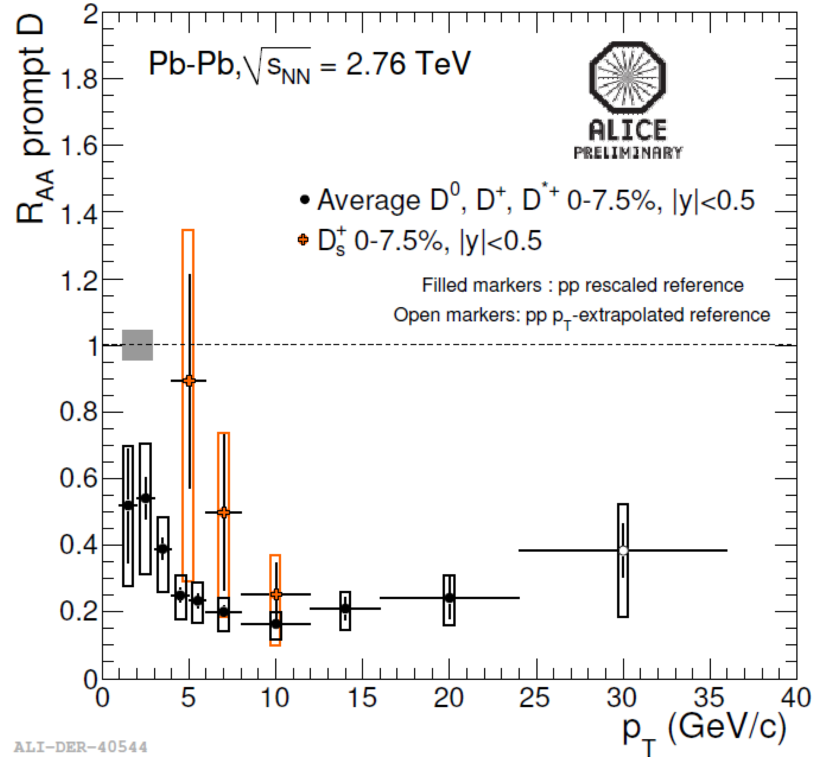
ALICE Coll. CERN-PH-EP-2014-90 arXiv: 1405.3452

D_s-meson R_{AA}

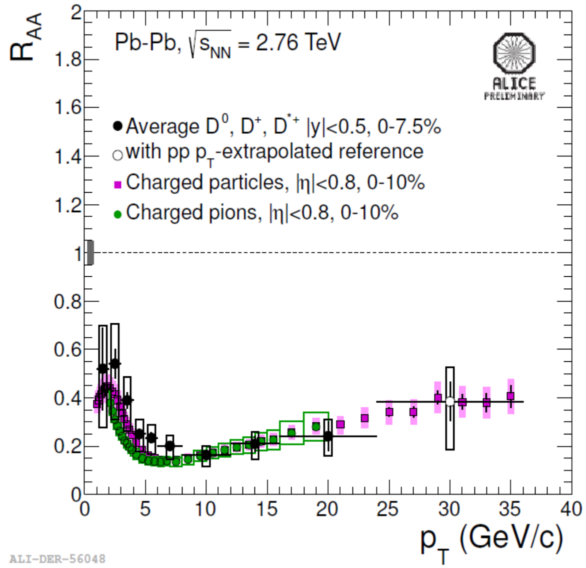
D_s R_{AA} in Pb-Pb

- Similar suppression as for non-strange D mesons in 8-12 GeV/c

- *Low-p_T measurements have large uncertainty and are not conclusive with respect to possible enhancement of D_s/D → Higher precision needed!*

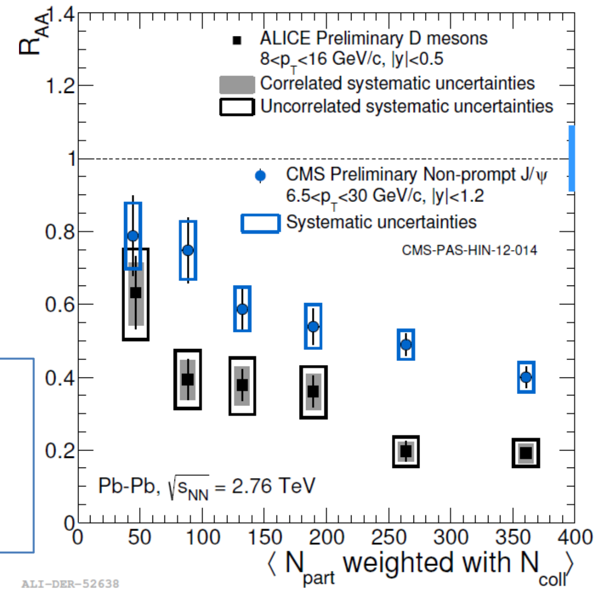


Study of flavour dependence of R_{AA}



- R_{AA} (π) ~R_{AA} (D) compatible within uncertainties

Hint of R_{AA} (D) >R_{AA} (π) at p_T ~ 4-5 GeV/c ?
→ Higher precision needed!



- Comparison with beauty **(CMS)**:
  - p_T interval for D mesons chosen in order to have similar kinematics w.r.t. B mesons decaying in J/ψ
    → <p_T> of about 10 -11 GeV/c for both D and B mesons

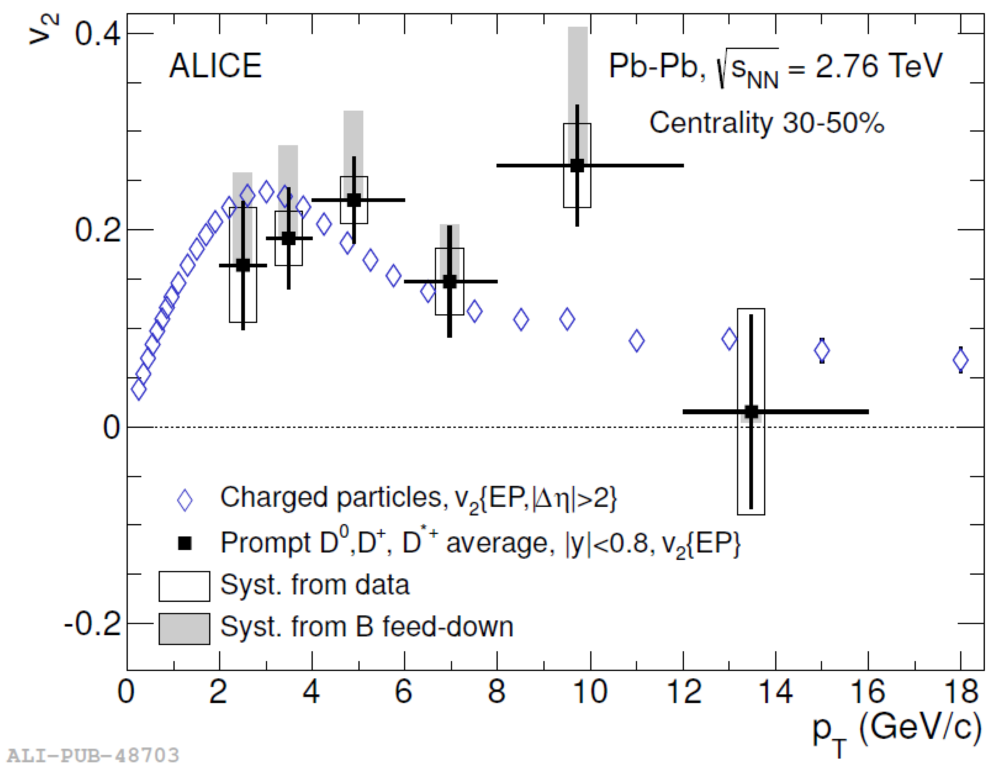
Smaller R_{AA} for charm than beauty hadrons in central Pb-Pb collisions, described by models including the mass dependence of in-medium parton energy loss

Elliptic flow: v_2

The anisotropy is quantified via a Fourier expansion in azimuthal angle (ψ) w.r.t. the reaction plane (Ψ_{RP})

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}(1 + 2v_1\cos(\varphi - \Psi_{RP}) + 2v_2\cos[2(\varphi - \Psi_{RP})] + \ldots)$$

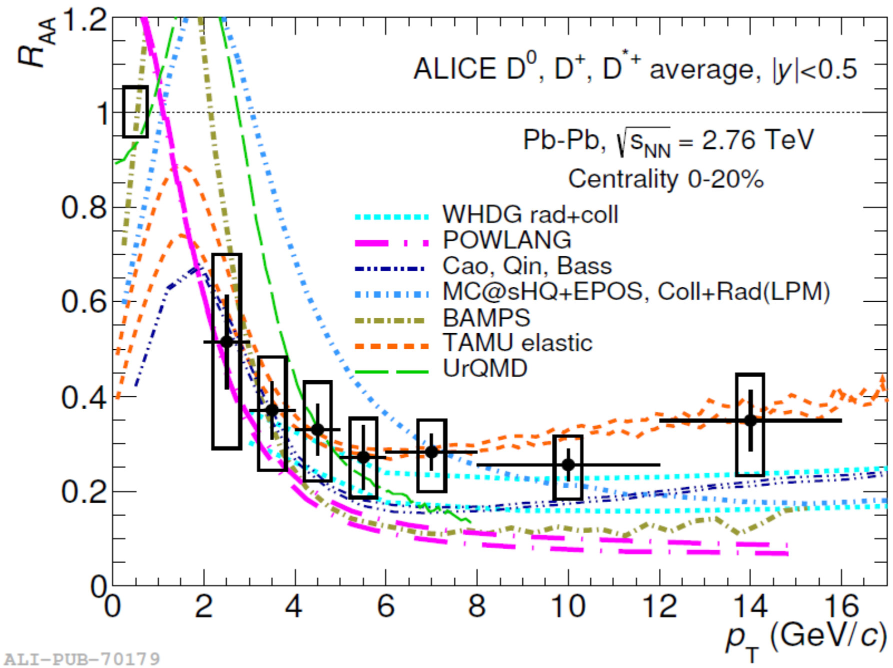
Do heavy quarks take part in the collective expansion of the medium?
D-meson v_2 >0 in 2-6 GeV/c and comparable with charged-particle v_2

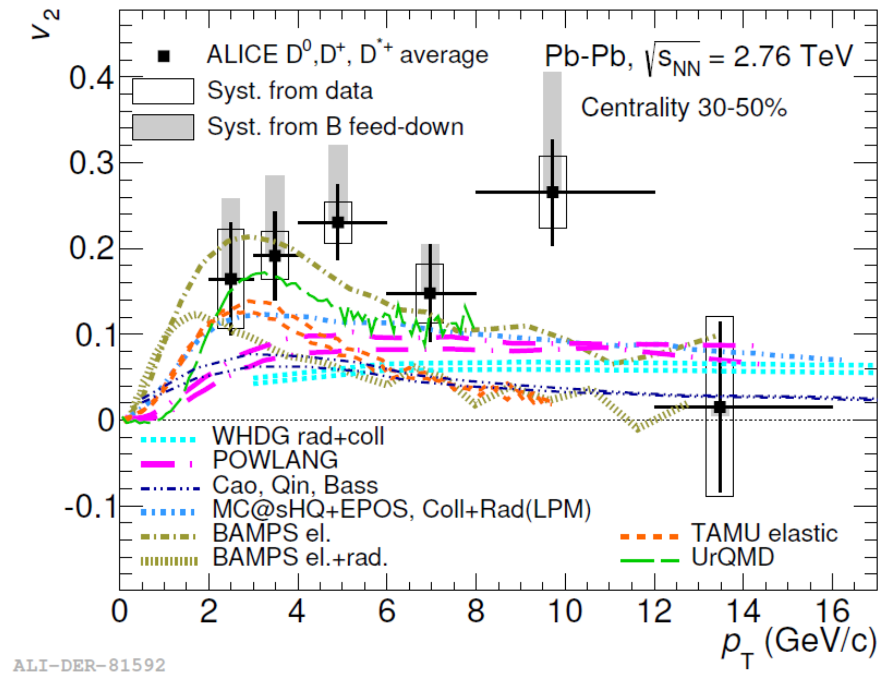


- Information on the initial azimuthal anisotropy of the medium transferred to charm quarks
- Consistent with strong coupling of c quarks with the medium

(ALICE Collaboration, Phys. Rev. Lett. 111, 102301 (2013))

R_{AA} and v_2 compared with models





(ALICE Collaboration, Phys. Rev. C 90 034904 (2014))

Challenging for models to describe simultaneously R_{AA} and v_2

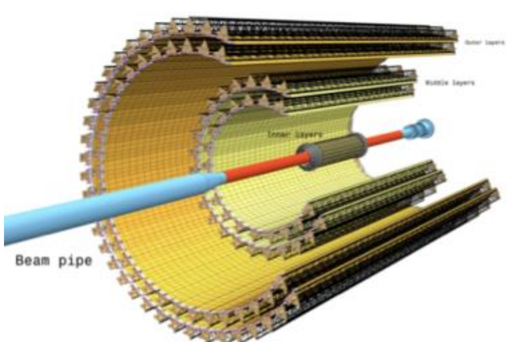
- large suppression of D mesons in central collisions
- azimuthal anisotropy in non-central collisions.

→ R_{AA} and v_2 measurements together start to provide constraints for the in-medium energy loss models

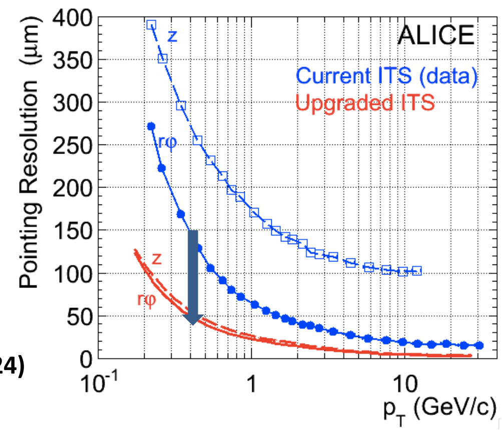
ALICE Upgrade: Why and How?

Improve precision of heavy-flavour measurements to get further insight in the properties of the QGP

- Higher integrated luminosities
- Improved resolution of the primary and decay vertex
  - → higher statistical precision to put more stringent constraints to models
  - → possibility of measuring rare probes (Λ_c,Λ_b …) which are not accessible with current setup



(CERN-LHCC-2013-024)



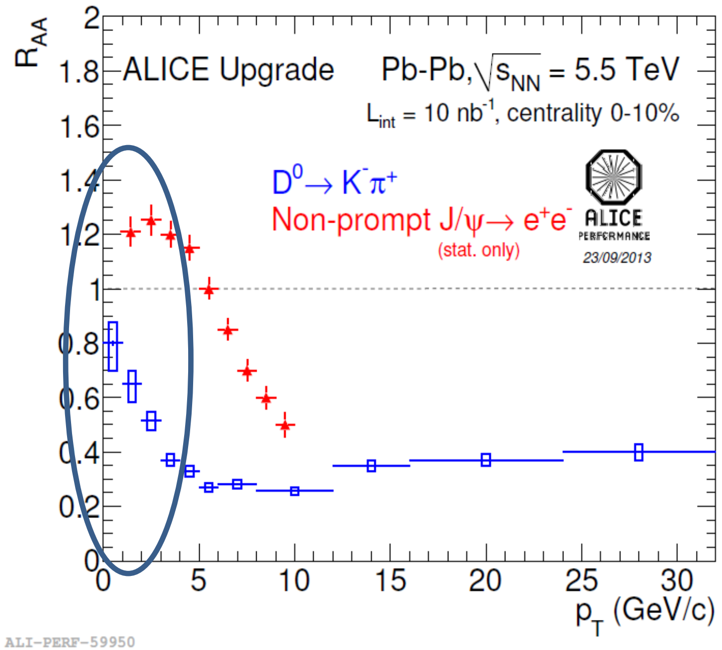
ALICE Upgrade:

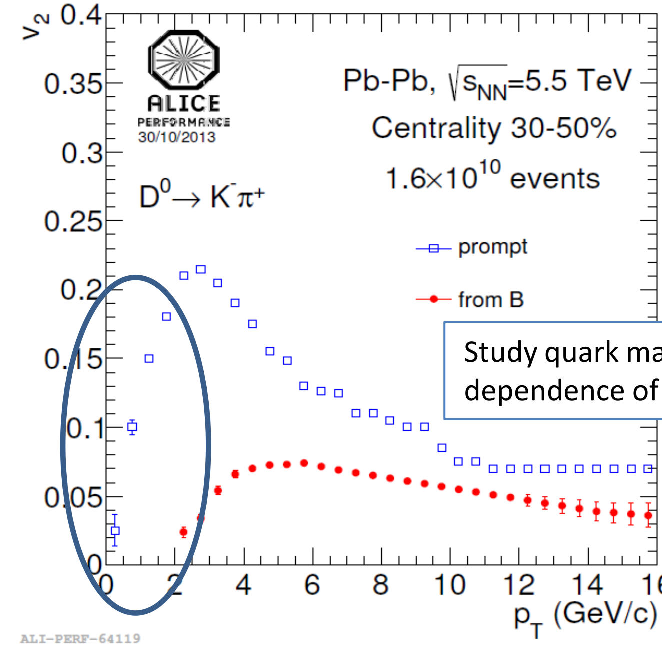
Full ALICE Upgrade strategy:
M. Masera's talk (Tuesday, 9:00)

- Faster readout of ALICE sub-detectors in minimum-bias mode
- New Inner Tracking System with improved tracking precision and efficiency

- Allow for the measurement of D mesons with higher precision and extend to low p_T region
- Open the way to the measurement of B-meson R_{AA} , Λ_c and Λ_b

Upgrade: D-meson R_{AA} and v_2





Study quark mass dependence of v_2

D-meson reconstruction with the upgraded ALICE detector:

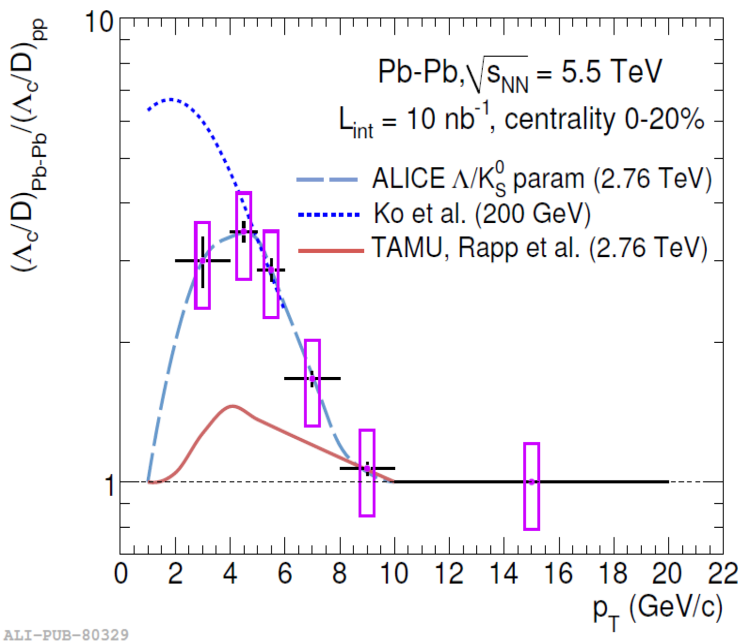
- D^0 R_{AA} : down to p_T = 0 and higher precision
- D^0 from B meson :
  B-meson measurement via displaced D^0 and J/ψ
- D-meson v_2 :
  - precise measurement of prompt D and D from B meson
  - down to p_T = 0

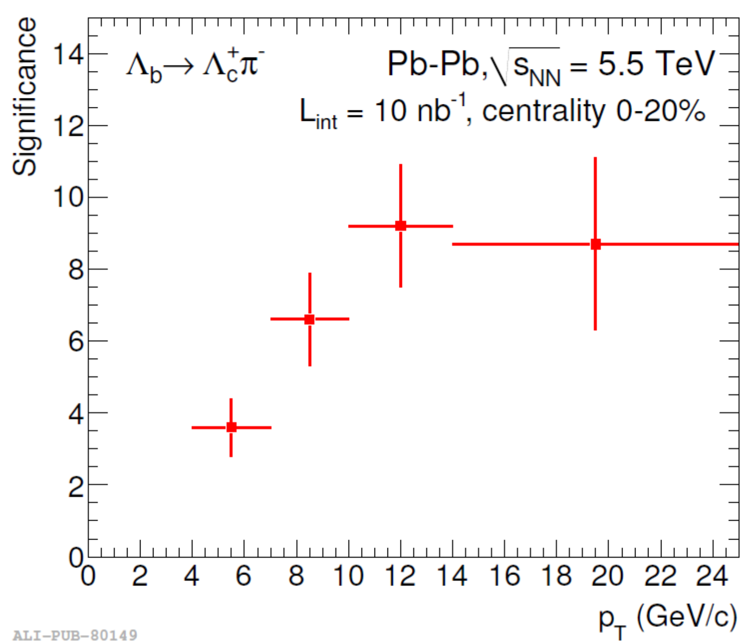
Upgrade: heavy-flavour hadronization? Λ_c and Λ_b

Baryon/meson enhancement: measured in ALICE in p/π and Λ/K
Extend measurement to HF sector? Λ_c/D , Λ_b/B

Λ_c (cτ = 60 μm) not accessible with the current ITS in Pb-Pb collisions

- **Upgrade:**
  - Improvement in resolution allows for cleaner vertex separation
  - → Λ_c production measurable down to 2 GeV/c with good precision
  - → $\Lambda_b \rightarrow \Lambda_c \pi$ accessible for the first time in ALICE **(CERN-LHCC-2013-024)**

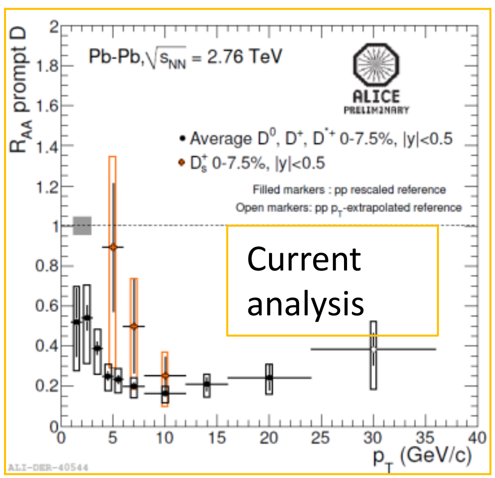




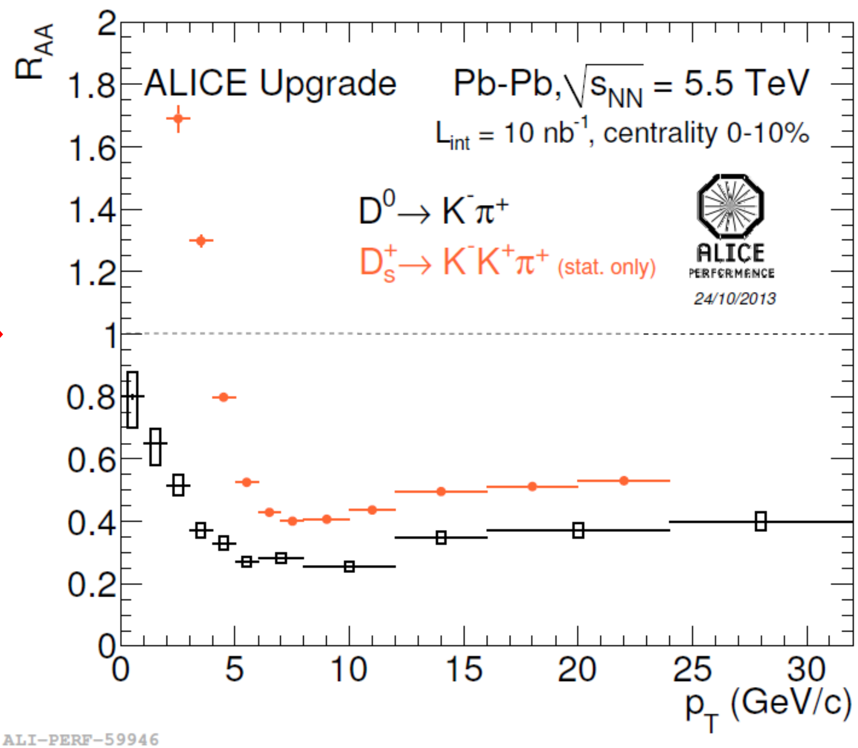
Upgrade: heavy-flavour hadronization? D_s

Coalescence mechanism and strangeness enhancement: D_s vs D

- **Upgrade:**
  - Reduce strongly the uncertainties and extend the measurement in the low p_T region
  - Possibility to measure v_2 of D_s



R_{AA}: uncertainties reduced; extended p_T coverage



Conclusions

HF results in Pb-Pb collisions:

- **Strong suppression** for p_T>5 GeV/c in central Pb-Pb collisions w.r.t. the binary scaled pp reference in the same range
  - due to the charm quark energy loss in the QGP, confirmed by R_{pPb}~1
- **R_{AA} (D) < R_{AA} (B)** larger suppression for charm than beauty
  - described by models with mass-dependent energy loss
- Comparison between R_{AA} (π) and R_{AA} (D) not conclusive with current statistics
- **D-meson v_2 >0** in 2<p_T<6 GeV/c
  - compatible with light-hadron v_2
    →charm quarks participate in the collective expansion of the medium

ALICE has a **strong upgrade programme** for precision QGP studies through HF measurements

- better tracking precision
- enhanced readout capabilities

→ R_{AA} and v_2 measurement possible down to zero p_T , higher precision, open the possibility to study other interesting channels

The ALICE upgrade will mark the transition from the exploratory phase to the era of precision measurements with heavy quarks

BACKUP

Semi Leptonic decays: R_{AA}

R_{AA}: electrons and muons from charm and beauty hadron decays

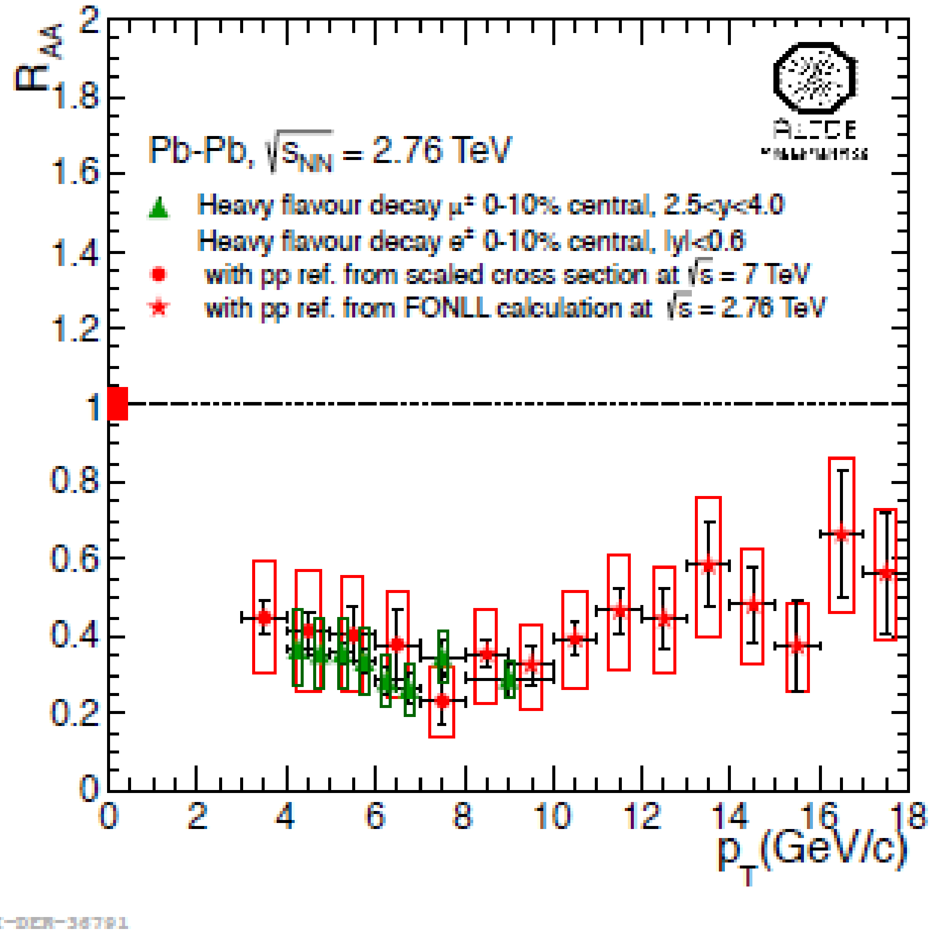
Clear suppression in 3<pt<18 GeV/c for electrons

and in 4<pT<10 GeV/c for muons in the 10% most central Pb-Pb collisions

Different rapidity range:

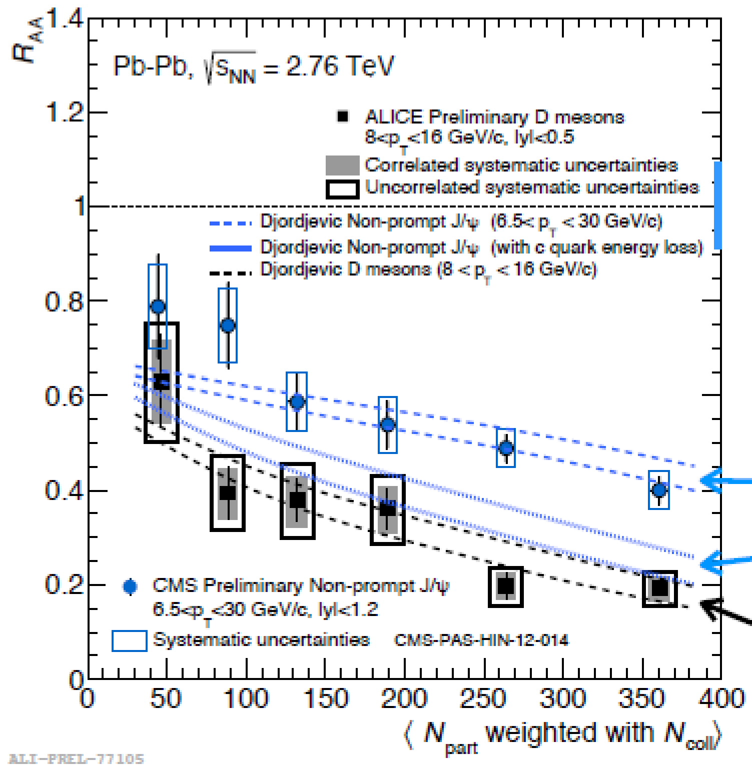
μ : 2.5 < y < 4

e : |y|<0.6



Heavy-flavour decay muon R_{AA} at forward rapidity compatible with that of heavy-flavour decay electrons at mid-rapidity

Study of flavour dependence of R_{AA}



- Similar <p_T> ~ 10 GeV/c for D and B mesons (B →J/ψ)
- Rapidity range slightly different

✓ Djordjevic: non-prompt J/ψ R_{AA} considering for energy loss
- b quark mass
- c quark mass

} to test the mass dependence

✓ Djordjevic: D meson R_{AA}

Djordjevic: arXiv:1307.4098

- **pQCD model including mass-dependent radiative and collisional energy loss predicts a difference between the D-meson and non-prompt J/ψ similar to that observed.**
- Similar pattern from other calculations (e.g. BAMPS, WHDG, Vitev et al.).