Heavy-flavour hadrons as probes of strongly-interacting matter: highlights from ALICE

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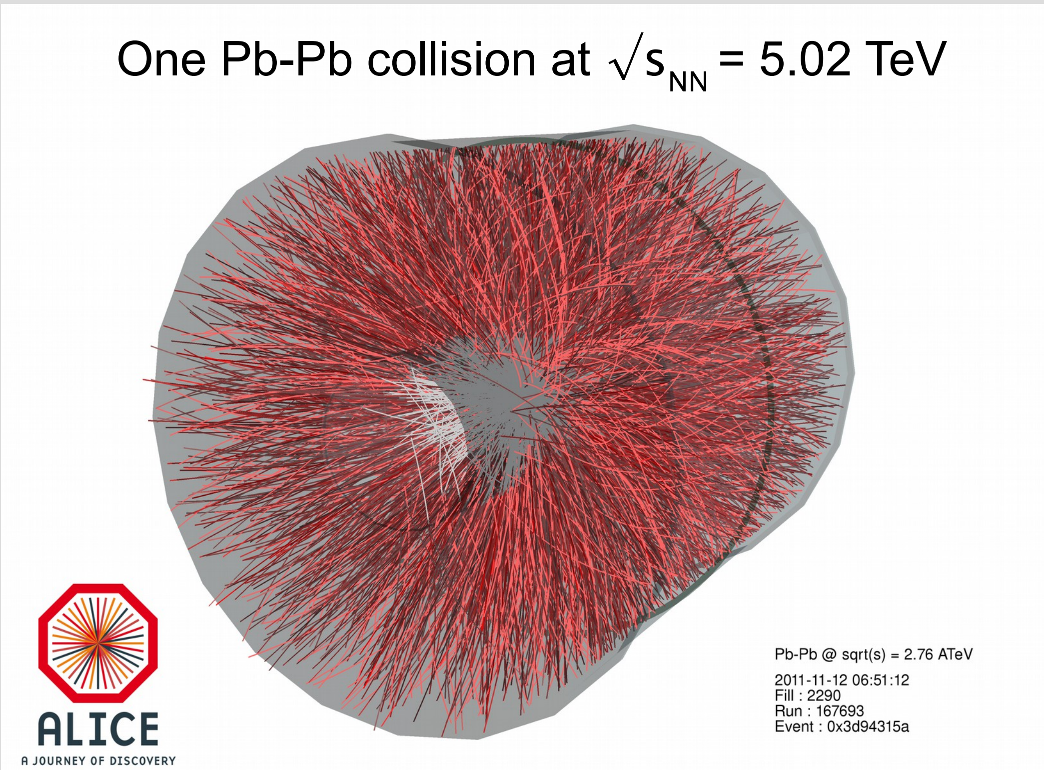
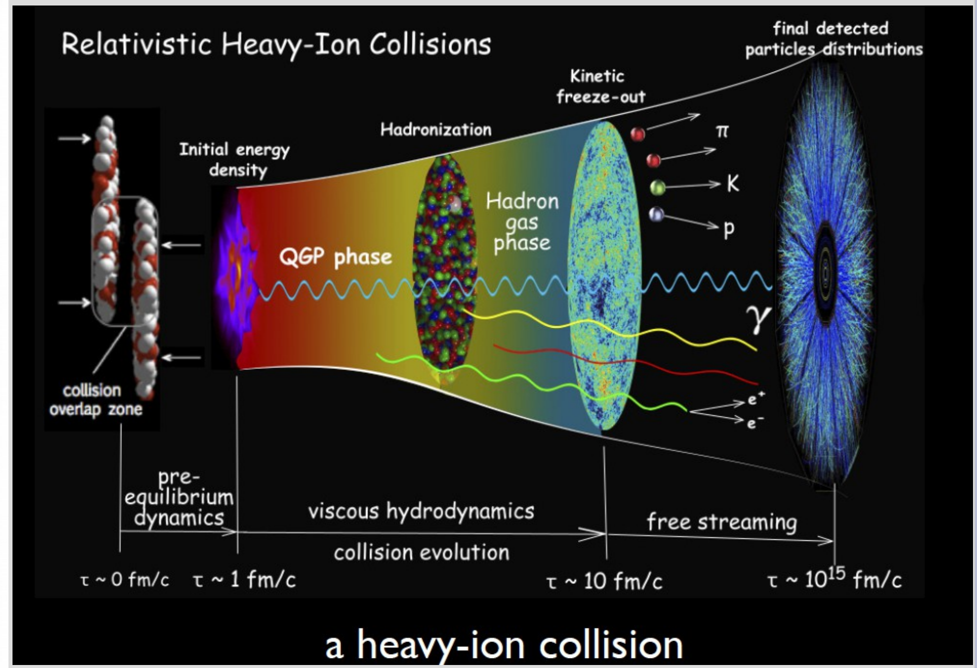
PH seminar at CERN
11.03.2014

Outline

- Introduction
- Heavy-flavour measurements in ALICE
  - Muons from heavy-flavour hadron decays
  - Electrons from heavy-flavour hadron decays
  - D mesons
- Results
  - pp at $\sqrt{s}$ = 7, 2.76 TeV
  - p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
  - Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

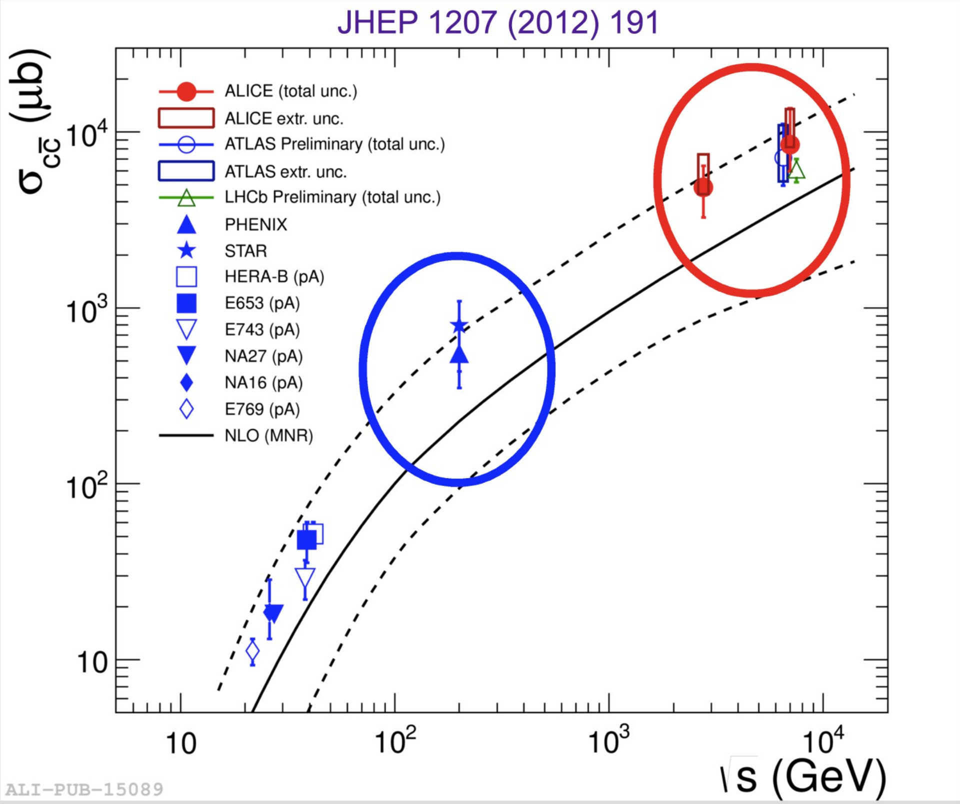
Pb-Pb collision in ALICE





Main purpose of ALICE:
Study the Quark Gluon Plasma (QGP), the deconfined state of strongly-interacting matter produced in high-energy collisions of heavy ions

LHC as heavy-quark factory



$\sigma_{c\bar{c}}^{LHC} \sim 10\ \sigma_{c\bar{c}}^{RICH}$

$\sigma_{b\bar{b}}^{LHC} \sim 50\ \sigma_{b\bar{b}}^{RICH}$

Factor 2 uncertainty on the total cross section calculated from theory in pp collisions

Heavy quarks, i.e. charm and beauty, are produced abundantly at LHC energies

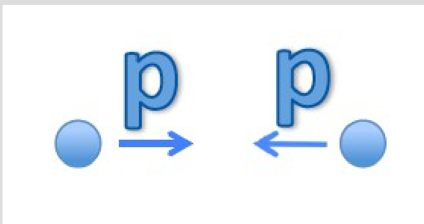
About 100 $c\bar{c}$ pairs and 10 $b\bar{b}$ pairs in central Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

Why heavy quarks ?
In pp collisions

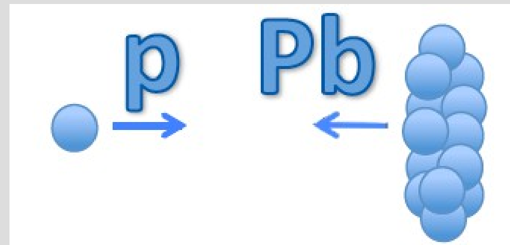
- In Quantum-ChromoDynamics theory
  - Heavy-quark production calculated perturbatively (large quark mass)
  - Theoretical uncertainties mostly driven by the scales and quark masses still large

- Measurements allow to
  - Test perturbative Quantum-ChromoDynamics predictions
    Total and p_T-differential production cross section
  - Investigate charm production mechanisms via more differential studies
    - Multiplicity dependence
    - D meson-hadron correlation studies
  - Provide a reference for p-Pb and Pb-Pb measurements

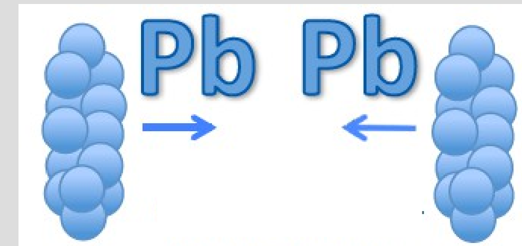
Why heavy quarks ? In p-Pb collisions



Elementary collision
No nuclear matter effects



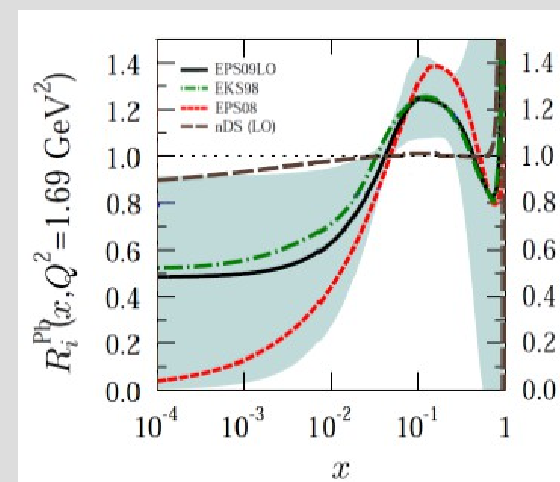
Cold nuclear matter (CNM) effects
Without QGP



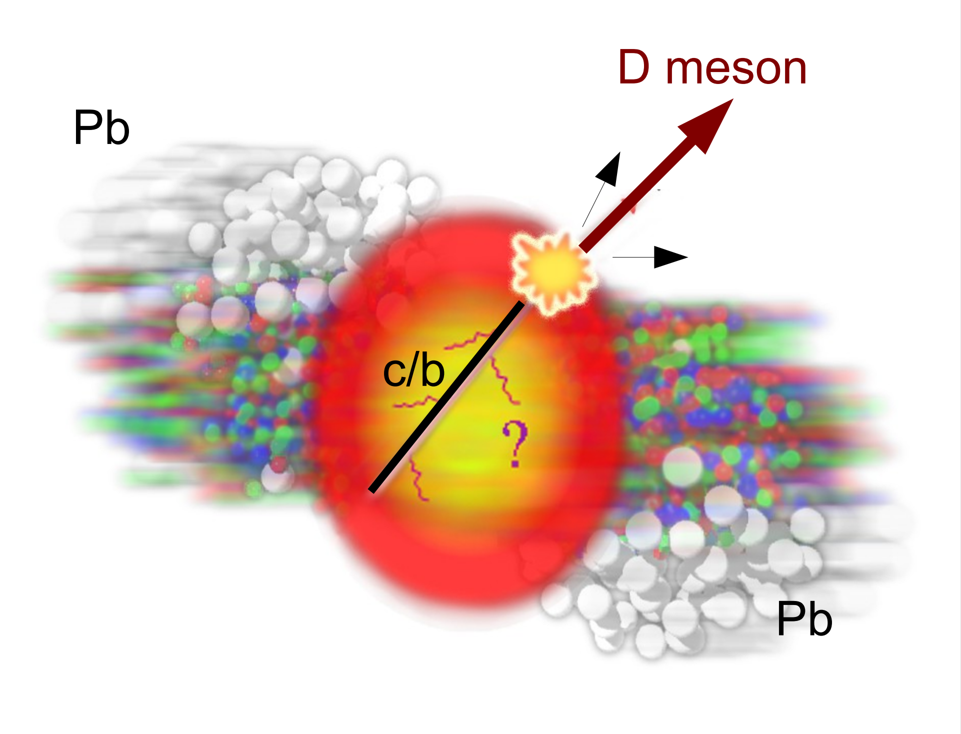
CNM effects
+ hot matter effects
(related to the QGP)

- Study cold nuclear matter effects
  - Modification of the parton distribution function inside the nucleus
    K.Eskola et al., JHEP 0904:065 (2009)
  - Initial state parton saturation in nucleus at low x (gg→ g)
    Color Glass Condensate (CGC) Fujii-Watanabe, arXiv:1308.1258
  - k_T broadening, Energy loss in the CNM
    Vitev, PRC 75 (2007) 064906
- Control experiment for Pb-Pb measurements

Ratio of PDF in nucleus and in nucleon



Why heavy quarks ?
In Pb-Pb collisions



Study the interaction of heavy quarks with the medium

Why heavy quarks ?
In Pb-Pb collisions

Parton energy loss

- Colour-charge dependence

$$\langle \Delta E \rangle \propto C_R$$

$C_R = 3$ for gluons
$C_R = 4/3$ for quarks

- Quark-mass dependence: dead cone effect

$$\Delta E(\text{light}) > \Delta E(c) > \Delta E(b)$$

Y.L Dokshitzer, et al., J. Phys. G 17, 1602 (1991)
Y.L. Dokshitzer and D.E. Kharzeev, Phys. Lett. B 519, 199 (2011)

Are these effects visible in the suppression of different hadrons ?

$$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B) \quad ?$$

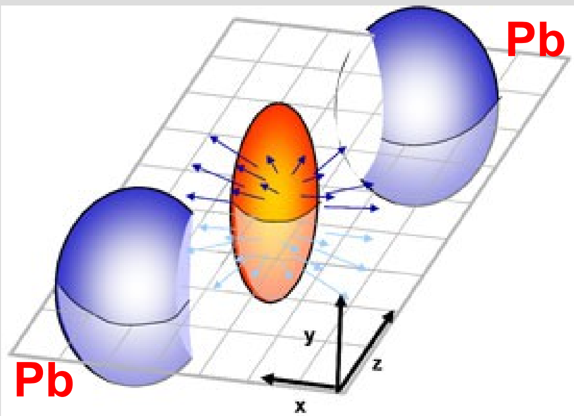
Not trivial: different spectral shape of the quarks,
different fragmentation function,
role of radial flow for soft π production

Nuclear modification factor

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle \times dN_{pp}/dp_T}$$

Why heavy quarks ? In Pb-Pb collisions

Elliptic flow v_2



Initial spatial anisotropy
→ momentum anisotropy of heavy-flavour hadrons
If sufficient re-scattering of heavy quarks in the medium

Study azimuthal distribution of heavy-flavour hadrons w.r.t the reaction plane

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \ldots\right)$$

Heavy-flavour hadron v_2 measurements allow to probe:

- At low p_T the heavy-quark participation in the collective expansion of the QGP
  Thermalization of heavy quarks: longer relaxation time expected for heavy quarks than for light quarks (Moore and Teaney, PRC 71 (2005) 064904)
- At high p_T the path-length dependence of the heavy-quark energy loss

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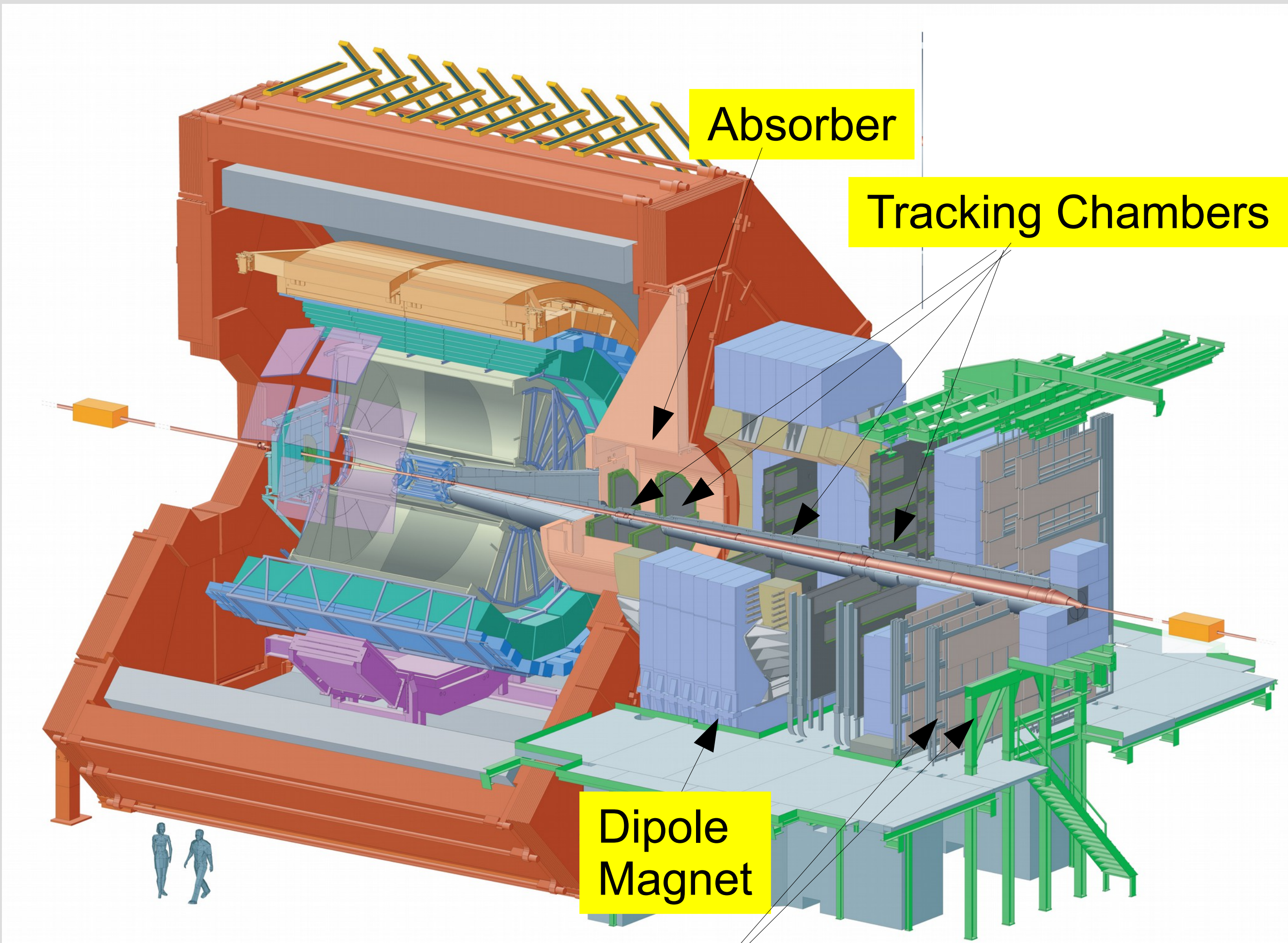
Heavy-flavour decay muons in ALICE

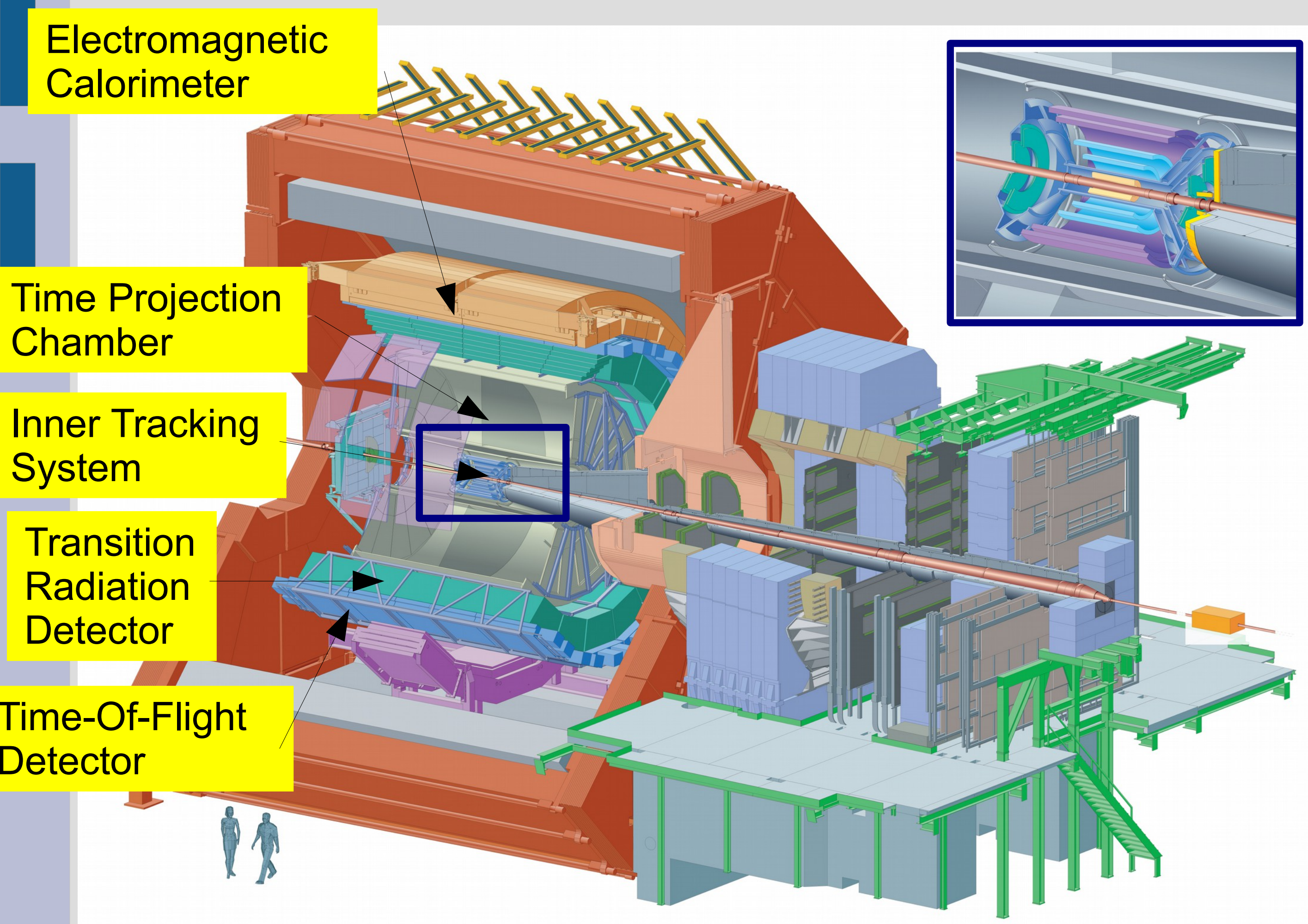


$D, B, \Lambda_c, \Lambda_b \ldots \rightarrow \mu + X$
Br=10%

$-4 < \eta < -2.5$

Muon spectrometer:
μ identification via tracks matched with trigger system

Heavy-flavour decay electrons in ALICE



D, B, Λ_c, Λ_b… → e + X Br=10%

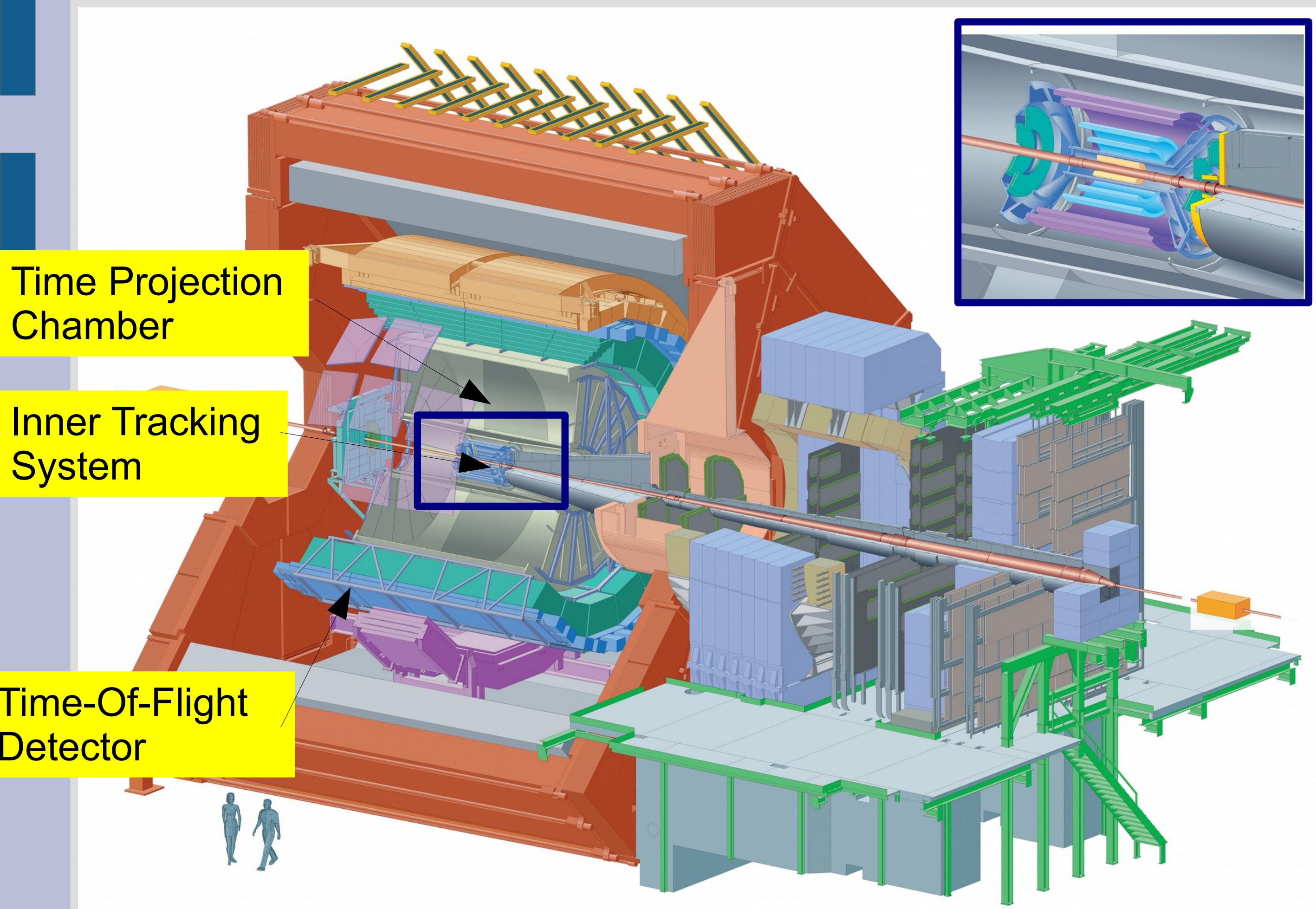
B, Λ_b...→ e + X Br=10%
cτ(B) ~ 500 μm

- 0.9 < η < 0.9

Identify e with:
TOF,TPC,TRD,EMCal

Use large lifetime of B hadrons to separate the beauty contribution using the ITS

D mesons in ALICE



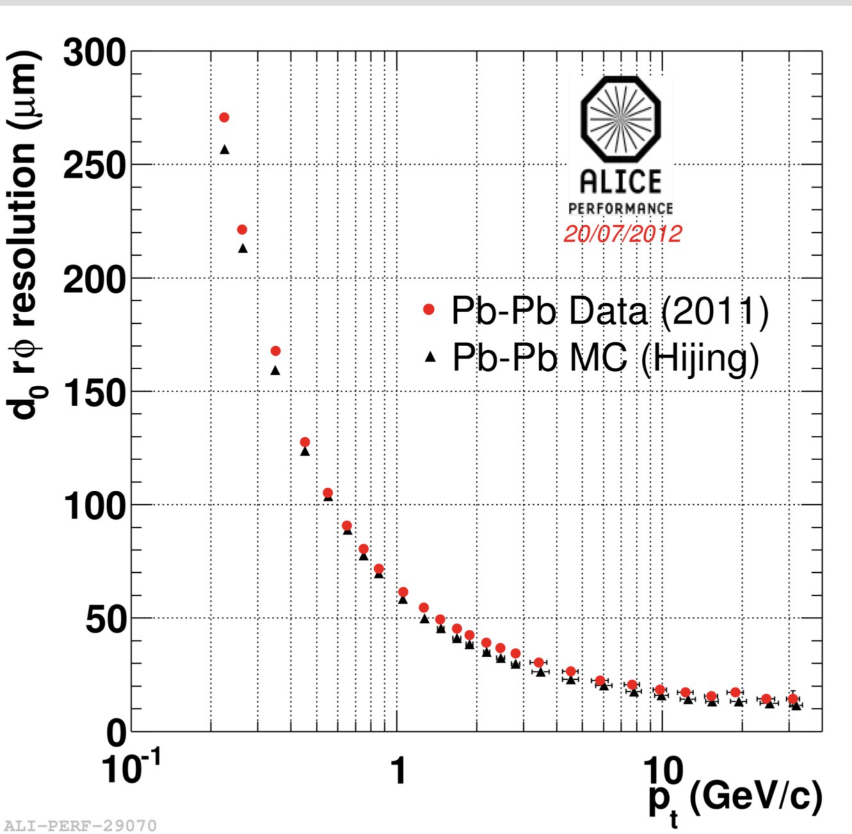
$D^0 \rightarrow K^-\pi^+$	Br=3.87%
$D^+ \rightarrow K^-\pi^+\pi^+$	Br=9.13%
$D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^-$	Br=2,59%
$D_s^+ \rightarrow \Phi\pi^+ \rightarrow K^-K^+\pi^+$	Br=2,28%

$-0.9 < \eta < 0.9$

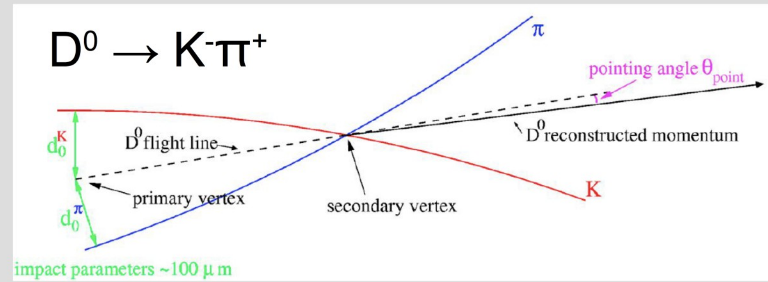
Reconstruct secondary vertices from tracks reconstructed in ITS and TPC

Identify decay products (TPC, TOF)

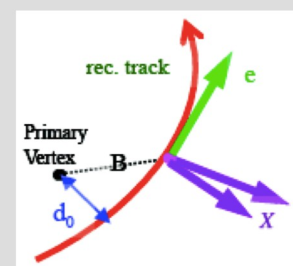
Impact parameter resolution in ALICE



Impact parameter resolution ~ 60 μm for p_T=1 GeV/c

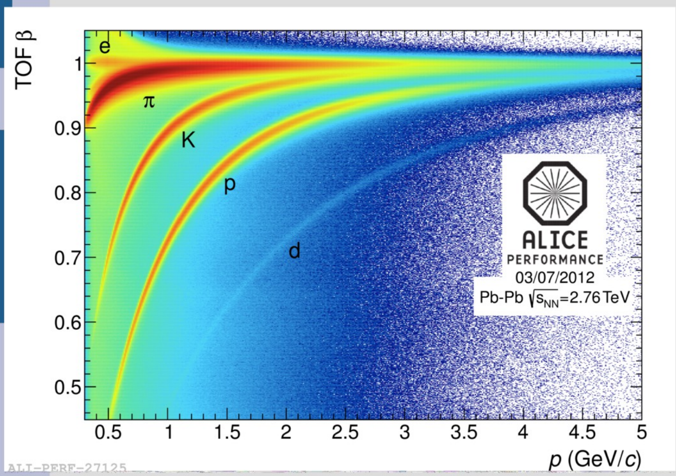


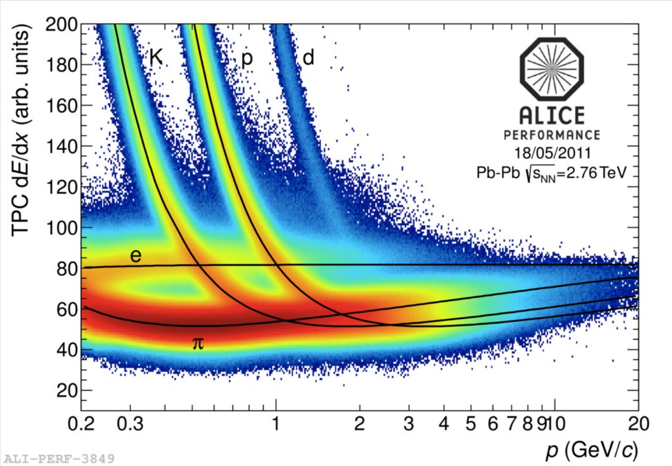
- D mesons reconstructed via topological selections
  → Reconstruct decay vertices displaced by few hundreds of μm from the primary vertex (expect D^{*+})

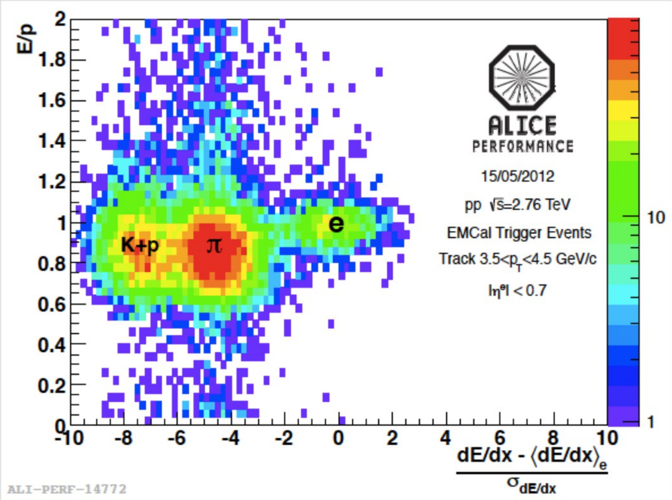


- Electrons from B hadron decays do not point to the primary vertex (cτ(B)=500μm)
  → Select electron tracks displaced by few hundreds of μm from the primary vertex

Particle Identification in ALICE







Velocity measurement in TOF

Energy loss in TPC

Deposited energy in EMCal

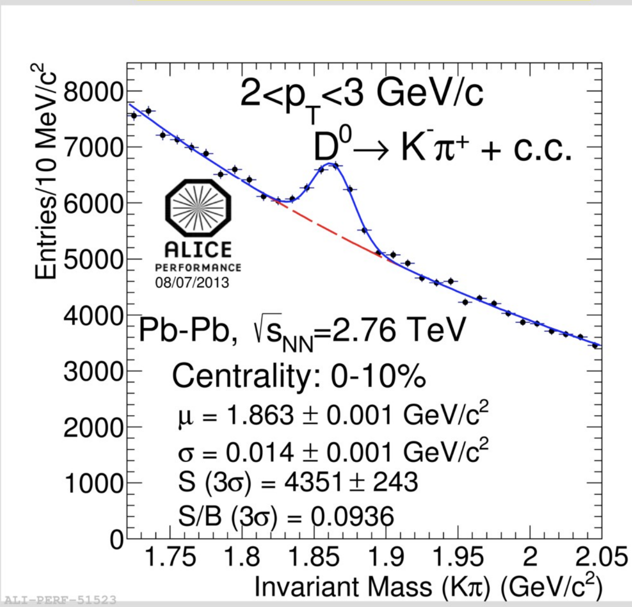
Both used to identify K for D meson analyses and e at low p

Reduce the combinatorial background by a factor 3 for D mesons

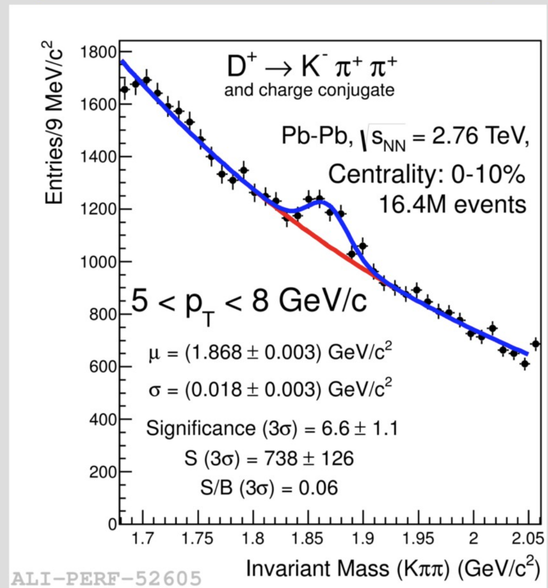
Electron Identification at high p

D mesons reconstructed in ALICE

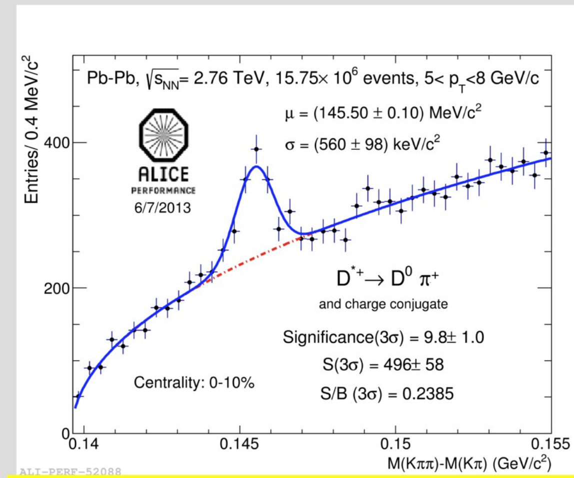
$D^0 \rightarrow K^- \pi^+$ + c.c.



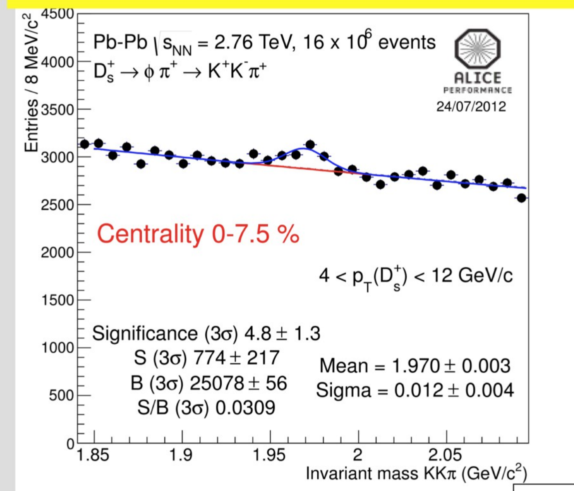
$D^+ \rightarrow K^- \pi^+ \pi^+$ + c.c.



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



$D_s^+ \rightarrow \Phi \pi^+ \rightarrow K^- K^+ \pi^+$ + c.c.

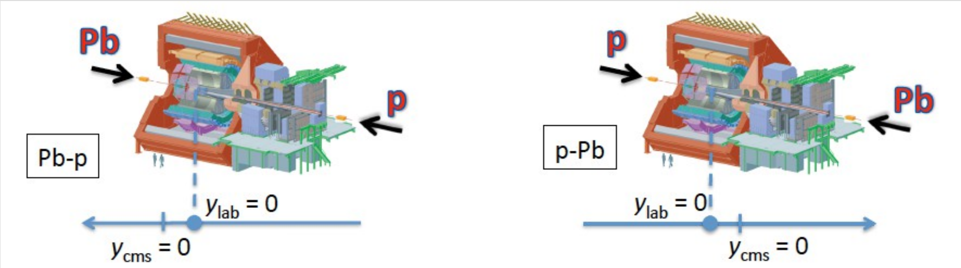


Central Pb-Pb collisions (2011 Data)

Data samples

LHC Run	Data Sample	D mesons	HF muons	HF electrons
2010	pp, 7 TeV	5 nb^{-1} (MB trigger) JHEP 01 (2012) 128	16.5 nb^{-1} (μ trigger) PLB 708 (2012) 265	2.6 nb^{-1} (MB trigger) PRD 87 052016 (2013)
2010	Pb-Pb, 2.76 TeV	2.12 μb^{-1} (0-80%) JHEP 09 (2012) 112	2.7 μb^{-1} (μ trigger) PRL 109 112301 (2012)	2.0 μb^{-1} (0-80%)
2011	pp, 2.76 TeV	1.1 nb^{-1} (MB trigger) JHEP 07 (2012) 191	19 μb^{-1} (μ trigger) PRL 109 112301 (2012)	0.5 (11.9) nb^{-1} MB (EMCAL) triggers
2011	Pb-Pb, 2.76 TeV	23 μb^{-1} (0-10%) 6.2 μb^{-1} (10-50%) PRL 111 102301 (2013)	11.3 μb^{-1} (0-10%) 3.5 μb^{-1} (10-40%)	22 (37) μb^{-1} in 0-10% 6 (34) μb^{-1} in 20-40% MB (EMCAL) trig.
2013	p-Pb 5.02 TeV	48.6 μb (MB trigger)	work in progress	48.6 μb (MB trigger)

Shift in rapidity |Δy|= 0.465



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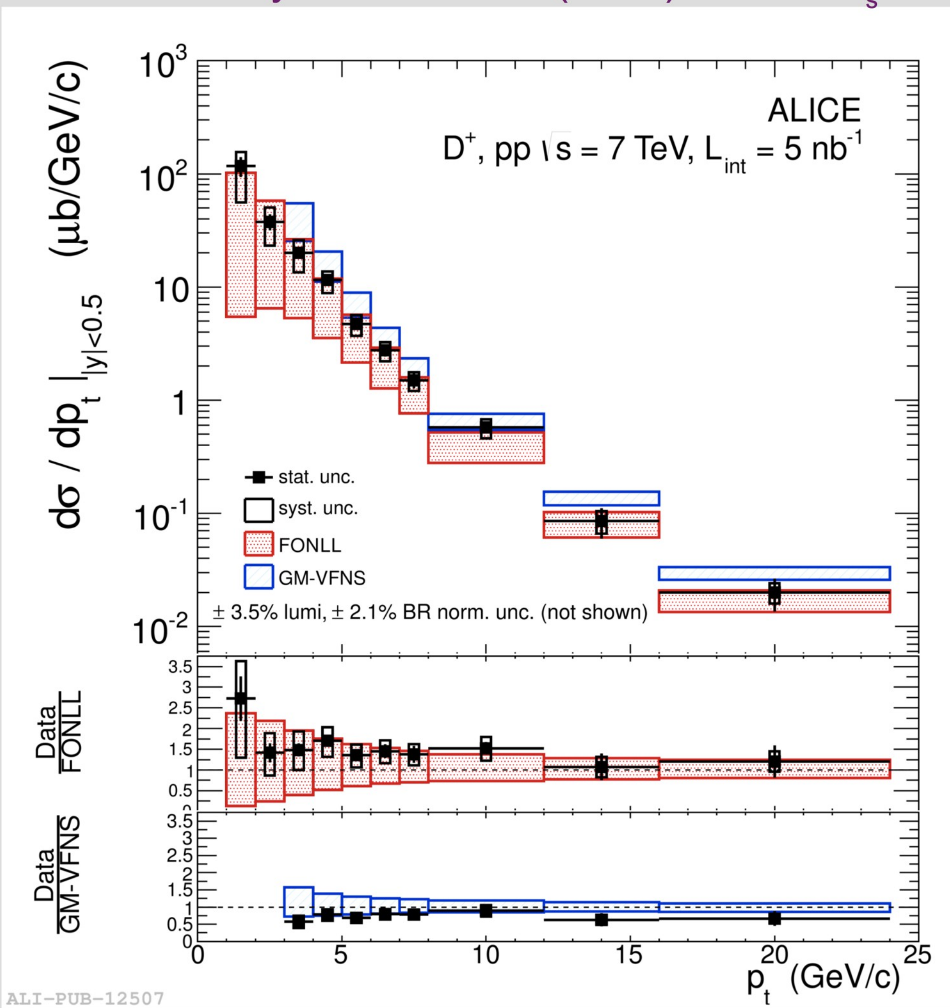
D mesons in pp collisions at $\sqrt{s}$=7 TeV

JHEP 1201 (2012) 128
Phys. Lett. B 718 (2012) 279 for D_s



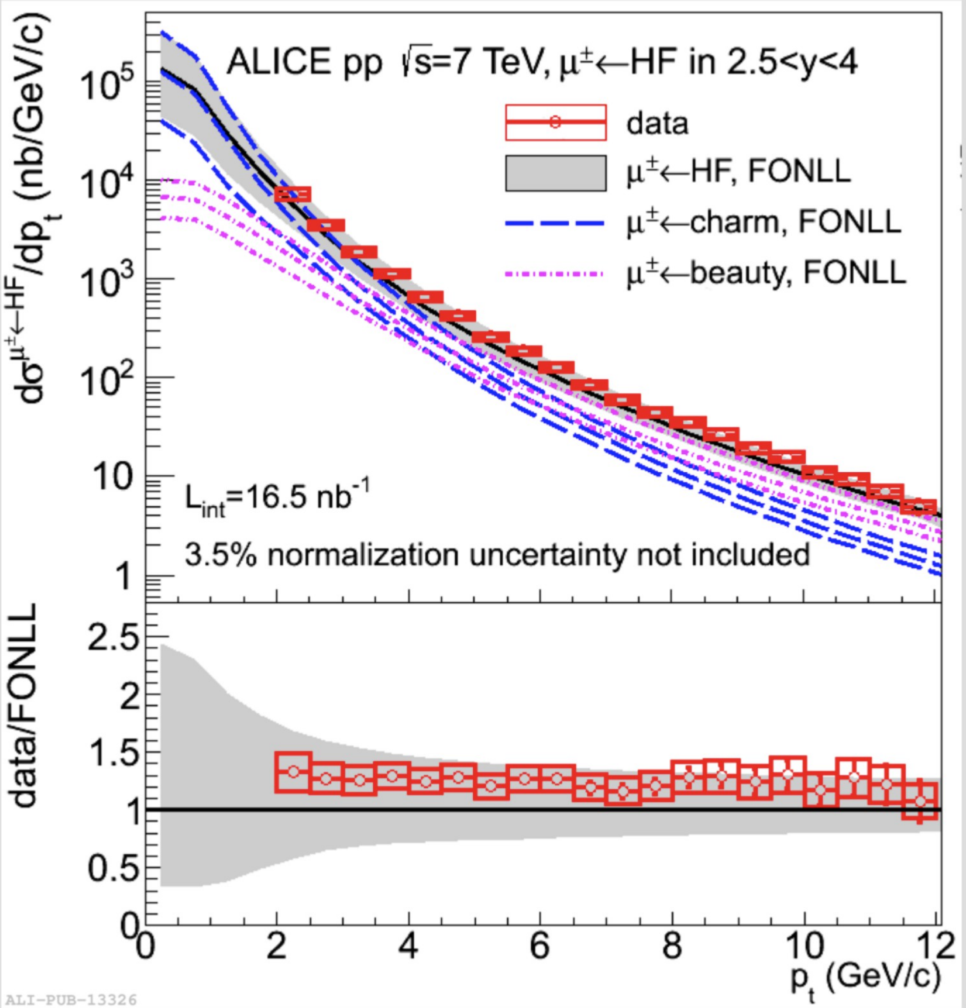
- Heavy-flavour measured in all channels
  - D mesons:
    - D^0 — 1 GeV/c < p_T < 16 GeV/c
    - **D^+**, D^{*+} — 1 GeV/c < p_T < 24 GeV/c
    - D_s — 2 GeV/c < p_T < 12 GeV/c
  - D,B → μ + X
  - D,B → e + X
  - B → e + X

- pQCD-based calculations (FONLL, GM-VFNS) compatible with data

FONLL, Cacciari et al., arXiv:1205.6344
GM-VFNS Kniehl at al., arXiv:1202.0439

Heavy-Flavour decay muons in pp collisions at $\sqrt{s}$=7 TeV

Phys. Lett. B 708 (2012) 265



- Heavy-flavour measured in all channels
  - D^0, D^+, D^{*+}, D_s
  - D,B → μ + X   2 GeV/c < p_T < 12 GeV/c
  - D,B → e + X
  - B → e + X

- pQCD-based calculations (FONLL, GM-VFNS) compatible with data

FONLL, Cacciari et al., arXiv:1205.6344
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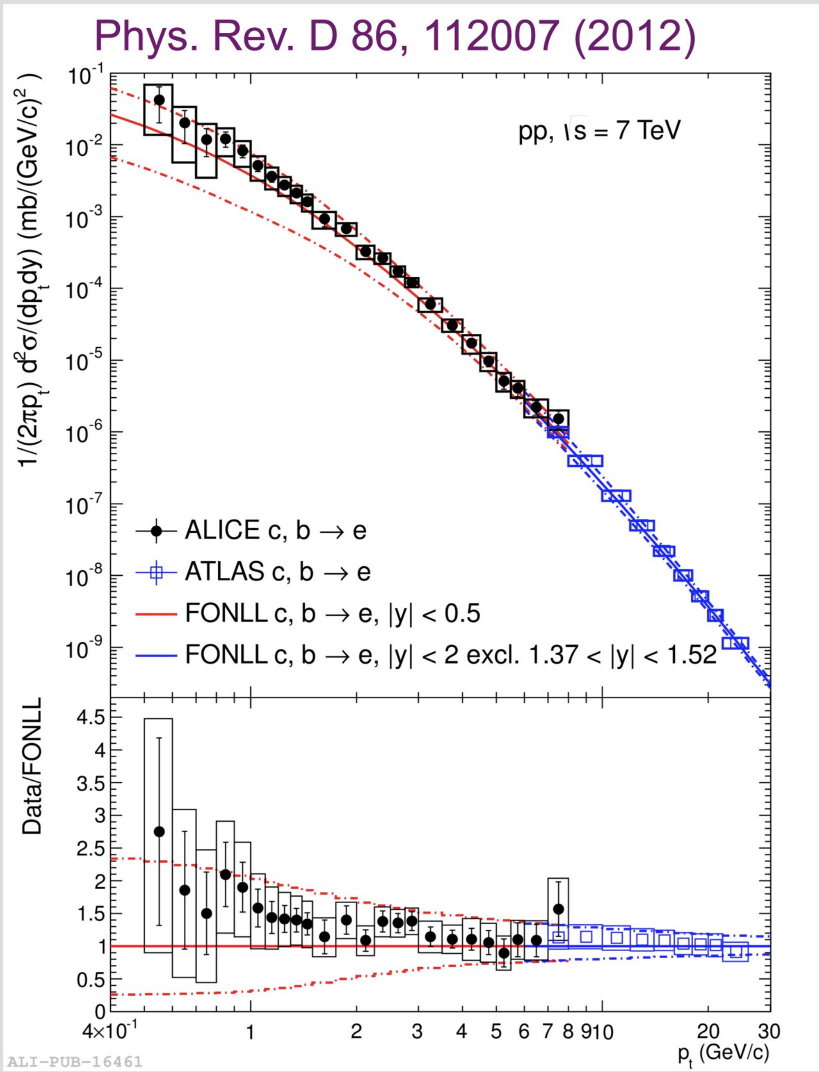
Heavy-Flavour decay electrons in pp collisions at $\sqrt{s}$=7 TeV



- Heavy-flavour measured in all channels
  - D^0, D^+, D^{*+}, D_s
  - D,B → μ + X
  - D,B → e + X   0.5 GeV/c < p_T < 8 GeV/c
  - B → e + X

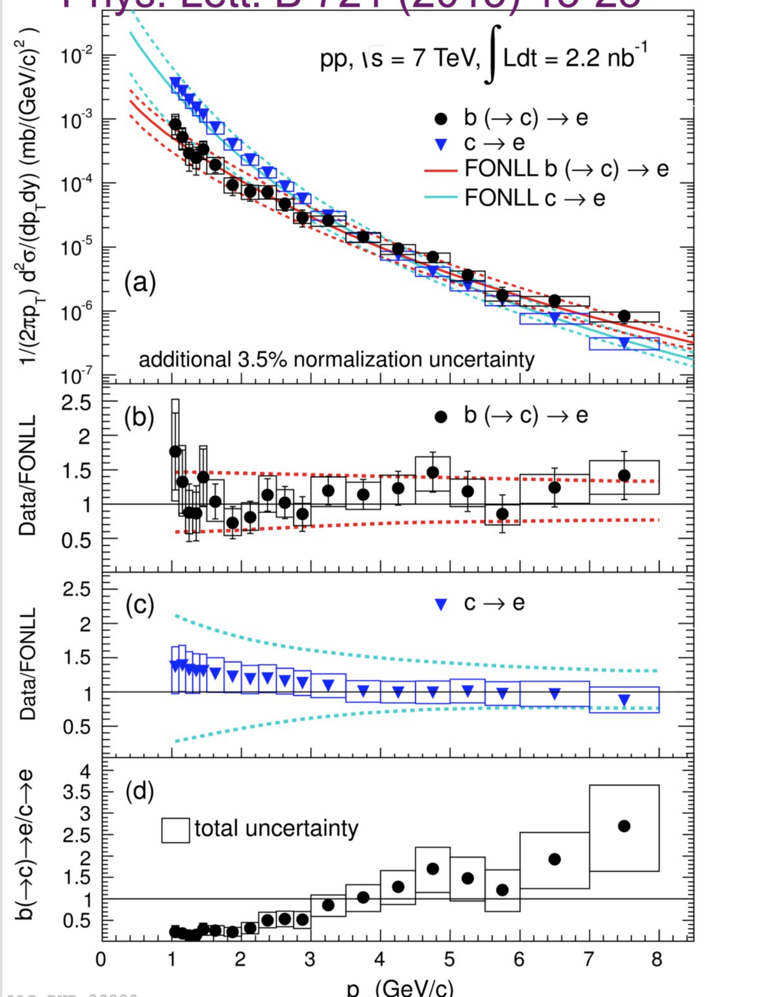
- ALICE results at low p_T complementary to the ATLAS measurements at higher p_T

- pQCD-based calculations (FONLL, GM-VFNS) compatible with data

FONLL, Cacciari et al., arXiv:1205.6344
GM-VFNS Kniehl at al., arXiv:1202.0439

Beauty decay electrons in pp collisions at √s=7 TeV

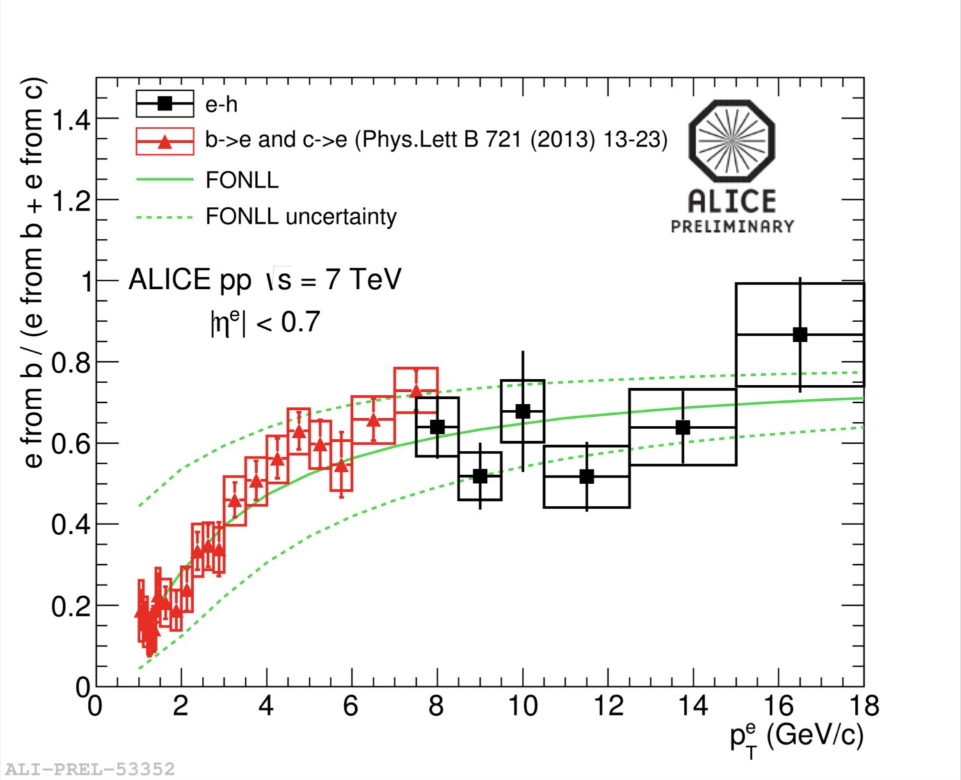
Phys. Lett. B 721 (2013) 13-23



- Heavy-flavour measured in all channels
  - D^0, D^+, D^{*+}, D_s
  - D,B → μ + X
  - D,B → e + X
  - B → e + X   1 GeV/c < p_T < 8 GeV/c
- Electrons from beauty hadron decays selected with a minimum impact parameter cut
- pQCD-based calculations (FONLL, GM-VFNS) compatible with data

FONLL, Cacciari et al., arXiv:1205.6344
GM-VFNS Kniehl at al., arXiv:1202.0439

Beauty decay electrons in pp collisions at √s=7 TeV



- Heavy-flavour measured in all channels
  - D^0, D^+, D^{*+}, D_s
  - D,B → μ + X
  - D,B → e + X
  - B → e + X   b/(b+c) ratio up to 18 GeV/c

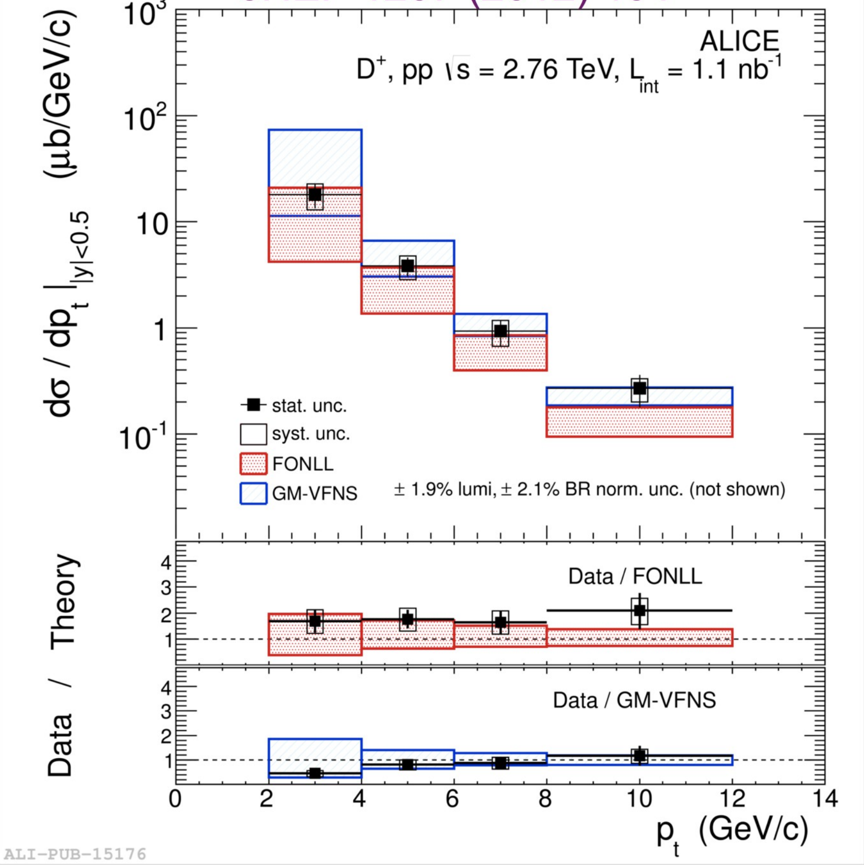
- Heavy-flavour decay e-h correlation used to extract the relative fraction of beauty decay electrons

- pQCD-based calculations (FONLL, GM-VFNS) compatible with data

FONLL, Cacciari et al., arXiv:1205.6344
GM-VFNS Kniehl at al., arXiv:1202.0439

Heavy-Flavour cross sections in pp collisions at $\sqrt{s}$=2.76 TeV

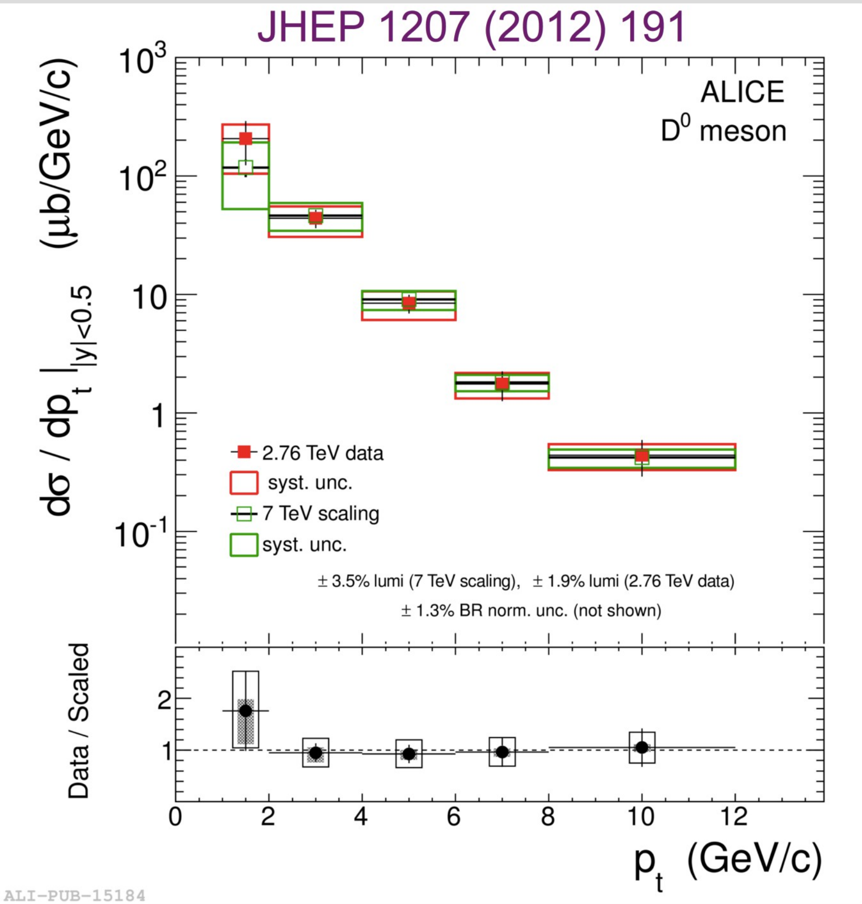
JHEP 1207 (2012) 191



- Smaller integrated luminosity than in pp at 7 TeV
  Heavy-flavour measured in all channels
  - D^0, **D^+**, D^{*+}
  - D,B → μ + X
  - D,B → e + X
  - B → e + X
- pQCD-based calculations compatible with data (FONLL, GM-VFNS)

FONLL, Cacciari et al., arXiv:1205.6344
GM-VFNS Kniehl at al., arXiv:1202.0439

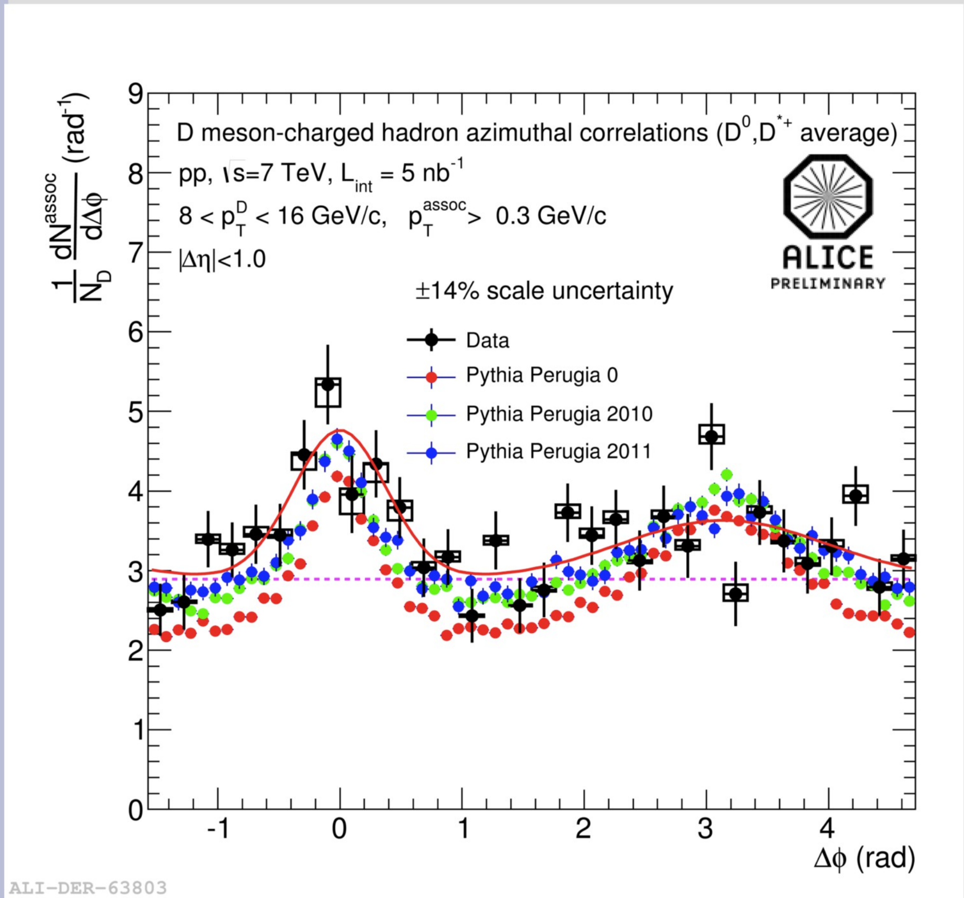
Heavy-Flavour cross sections in pp collisions at $\sqrt{s}$=2.76 TeV



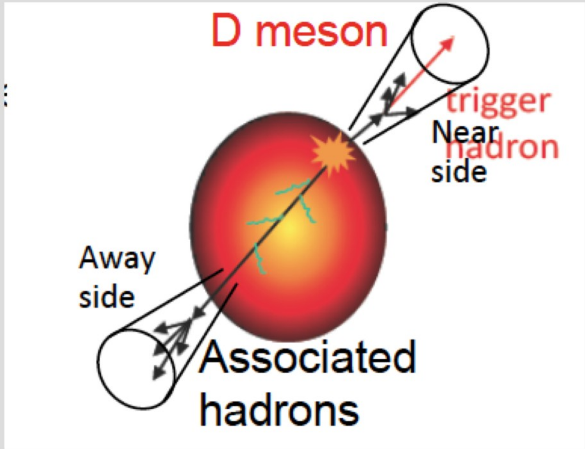
Reference for Pb-Pb at 2.76 TeV

- Heavy-flavour decay μ:
  Use directly measurement in pp at 2.76 TeV
- D mesons for p_T < 24 GeV/c
  and Heavy-flavour decay e for p_T < 8 GeV/c:
  Use the measurements in pp at 7 TeV scaled to 2.76 TeV with a $\sqrt{s}$ extrapolation based on pQCD calculations
  R.Averbeck et al., arXiv:1107.3243

D-h correlations in pp collisions at √s=7 TeV



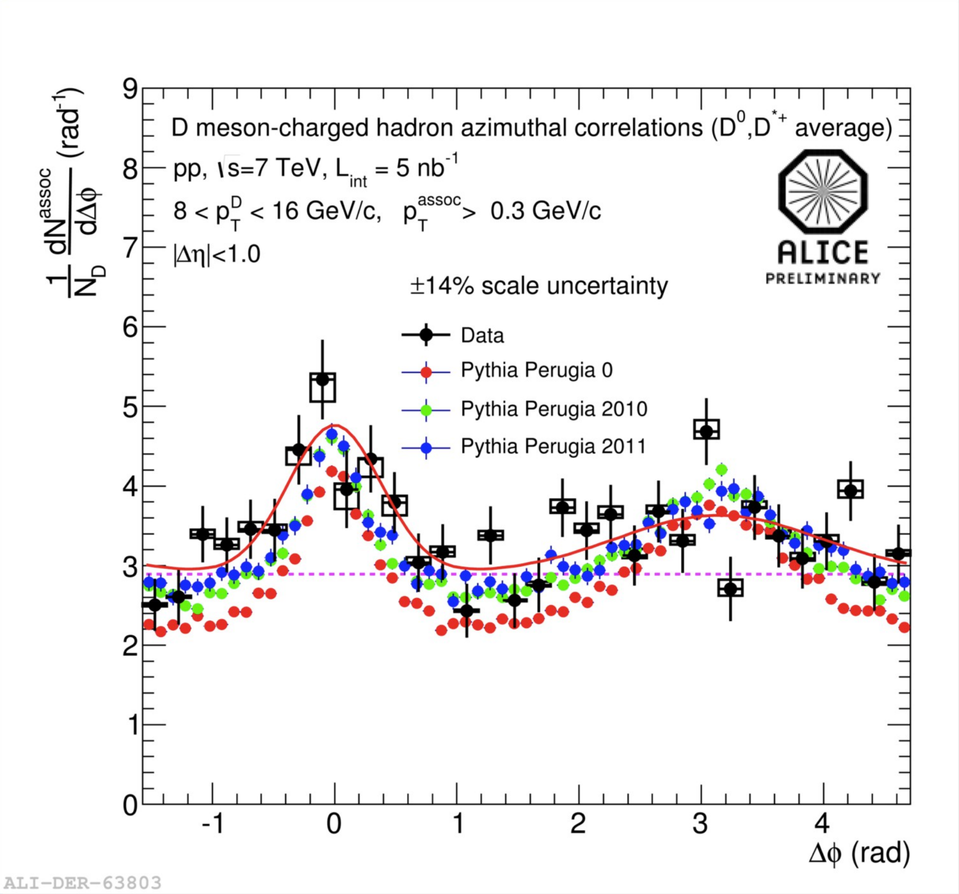
Measure the associated hadron yields in the near and away side regions



Goals:

- In pp, p-Pb:
  Study charm production and fragmentation mechanism
- In Pb-Pb:
  Study modification of charm jet properties and path-length dependence of energy loss

D-h correlations in pp collisions at √s=7 TeV



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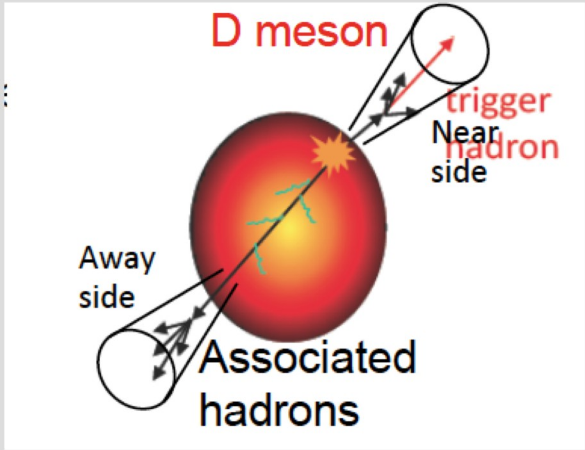
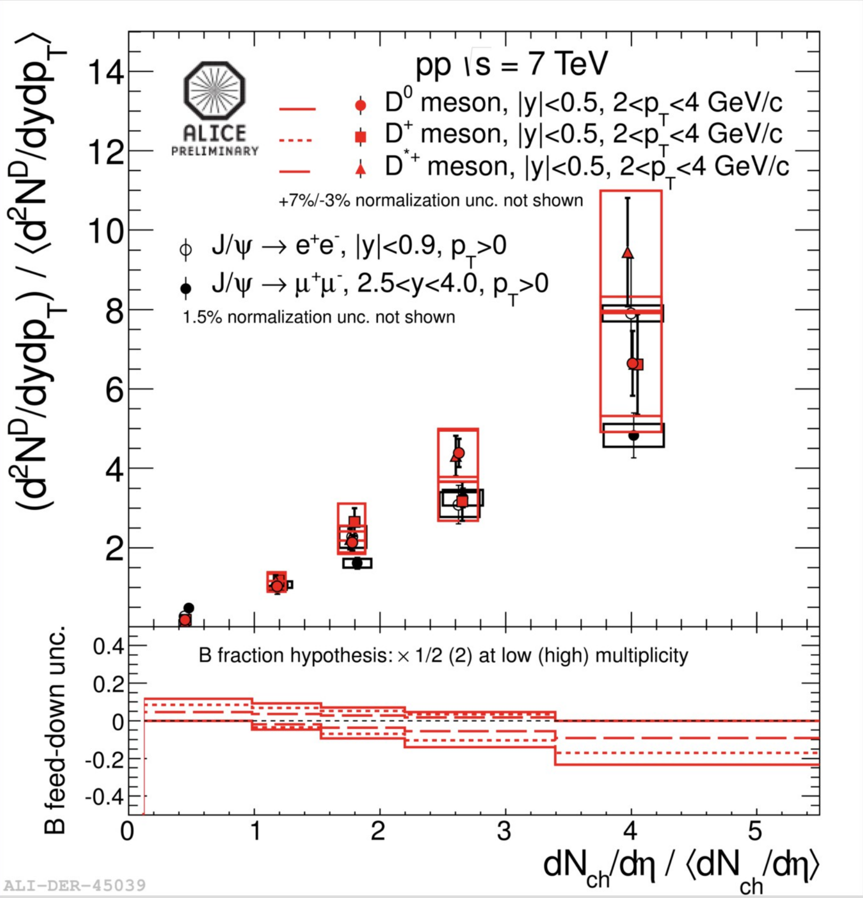


- In pp 7 TeV:
  Correlation measurements in agreement with Pythia within large statistical and systematic uncertainties

- Quantitative measurements expected from Run2

Multiplicity dependence in pp collisions at $\sqrt{s}$=7 TeV



Prompt D and inclusive J/ψ yields versus multiplicity

- Study the role of Multi Parton Interaction and possible contributions from hadronic activity associated with heavy-flavour production.
- **Observed an approximately linear increase of the yields with charged particle multiplicity**
- **Similar trend for prompt D mesons and inclusive J/ψ (B) within stat. and sys. uncertainties**
- **Similar results obtained for the D meson in different p_T ranges**

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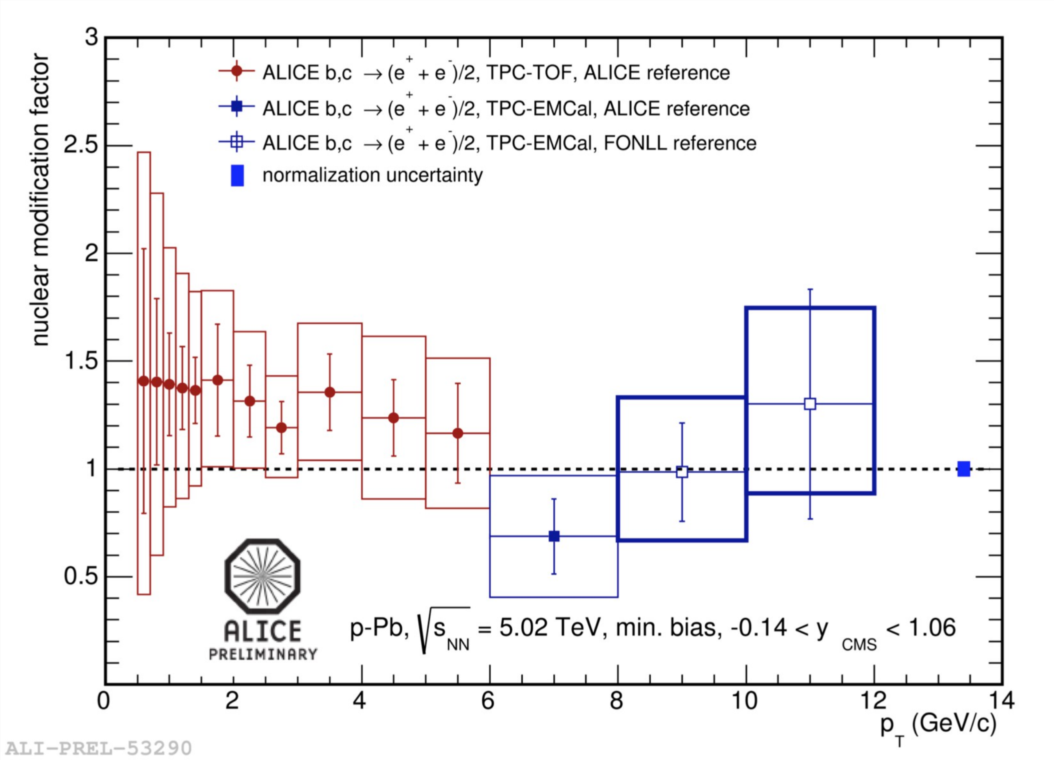
Heavy-Flavour decay electrons in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV



- Minimum bias p-Pb collisions
- Two different electron identification strategies:
  - TPC-TOF (more suited for low p_T e)
  - TPC-EMCal (more suited for high p_T e)
- HFe $R_{p\text{-}Pb}$ compatible with unity within uncertainties

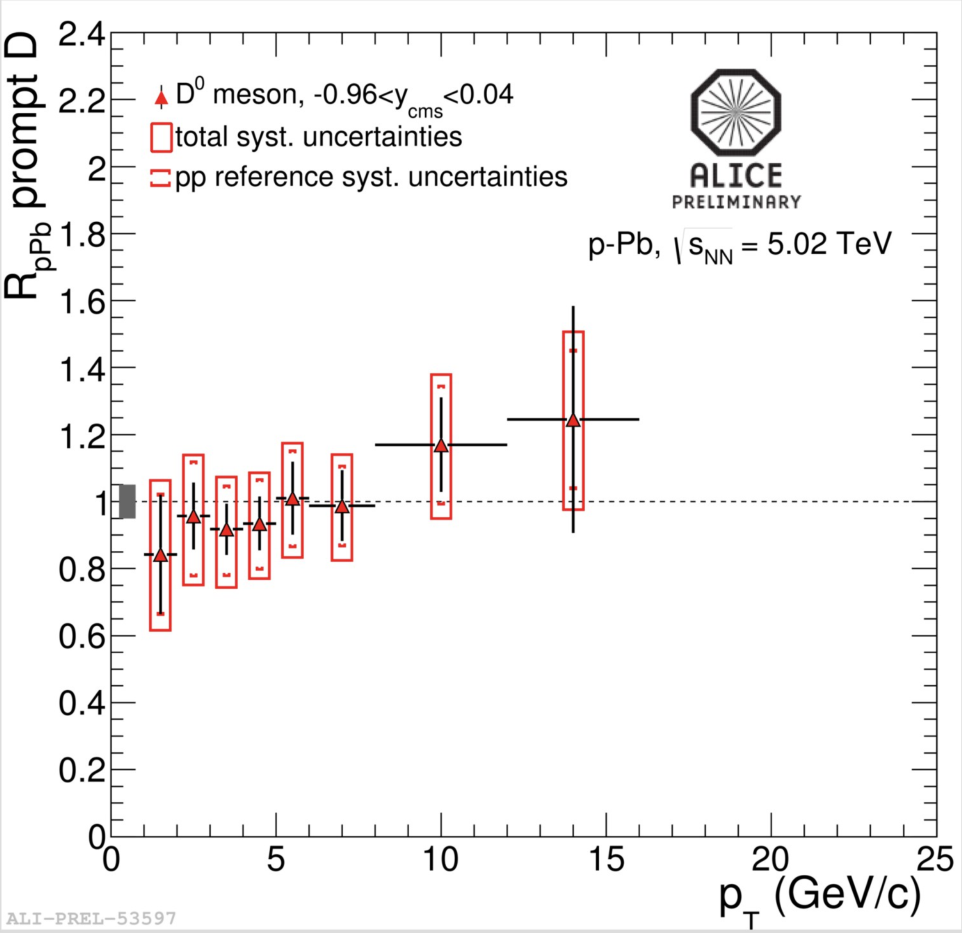
$$R_{pPb} = \frac{dN_{pPb}/dp_T}{\langle N_{coll}\rangle \times dN_{pp}/dp_T}$$

N_{coll} number of binary nucleon-nucleon collisions

R_{pPb} = 1 binary scaling, small CNM effects

CNM effects are small

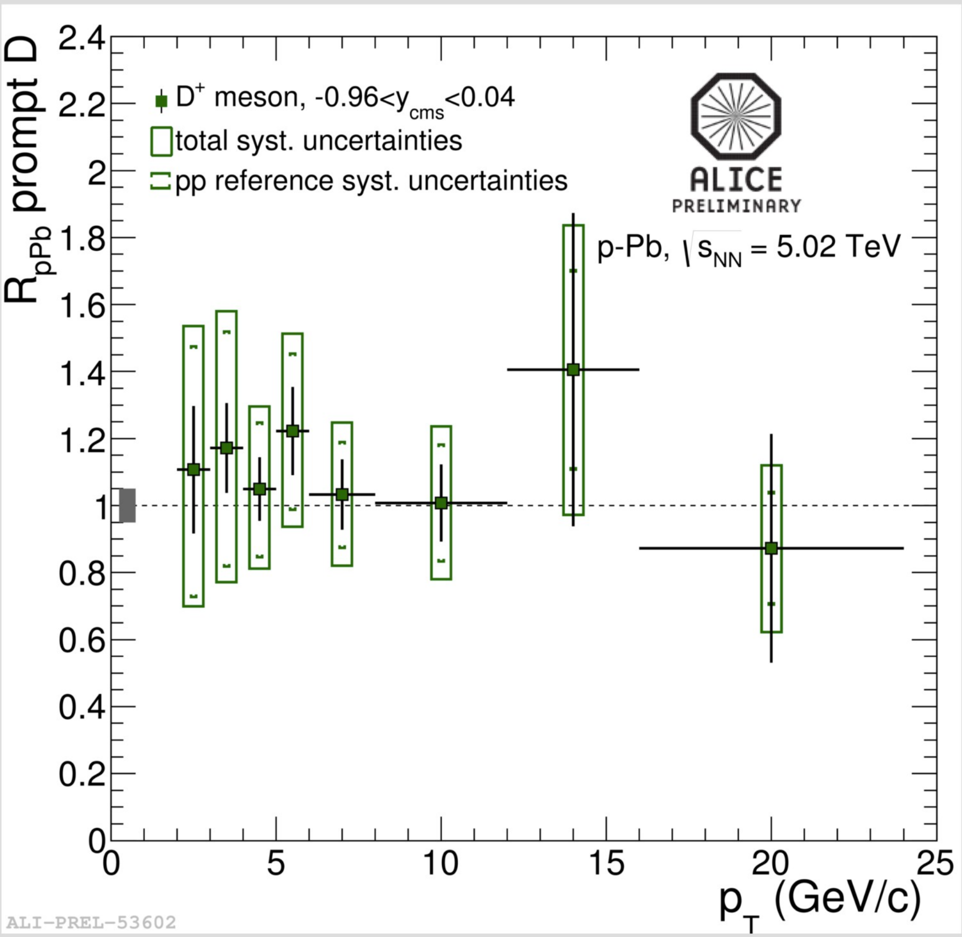
D mesons in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV



- D^0, D^+, D^{*+}, D_s measured in minimum bias p-Pb collisions
- D meson $R_{p\text{-}Pb}$ compatible with unity within uncertainties
- Similar $R_{p\text{-}Pb}$ for the four D-meson species (including D_s)

CNM effects are small

D mesons in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV



- D^0, D^+, D^{*+}, D_s measured in minimum bias p-Pb collisions
- D meson $R_{p\text{-}Pb}$ compatible with unity within uncertainties
- Similar $R_{p\text{-}Pb}$ for the four D-meson species (including D_s)

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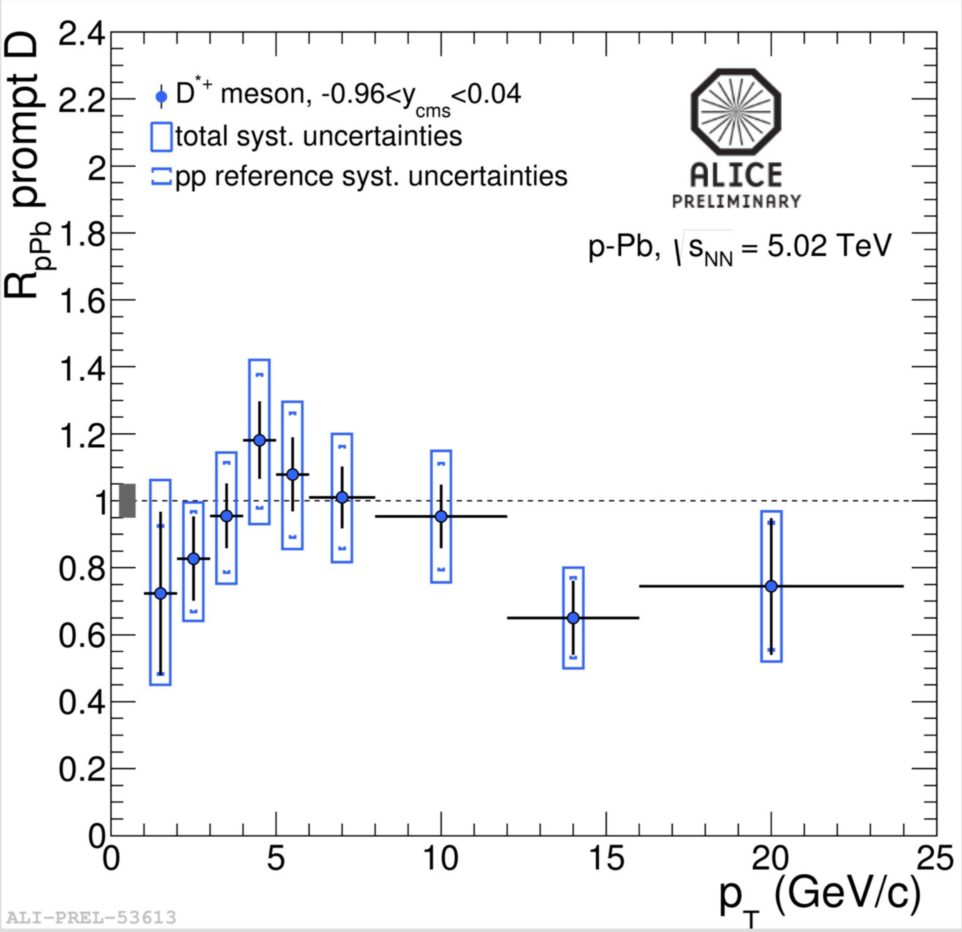

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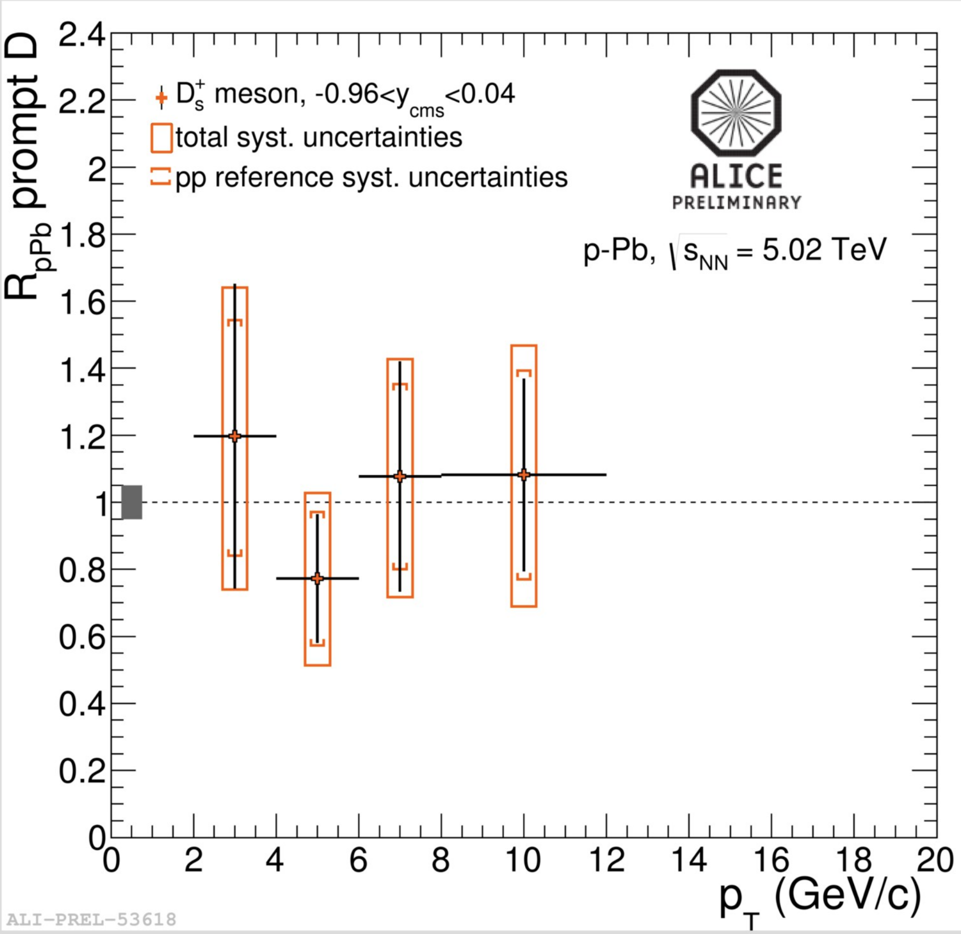

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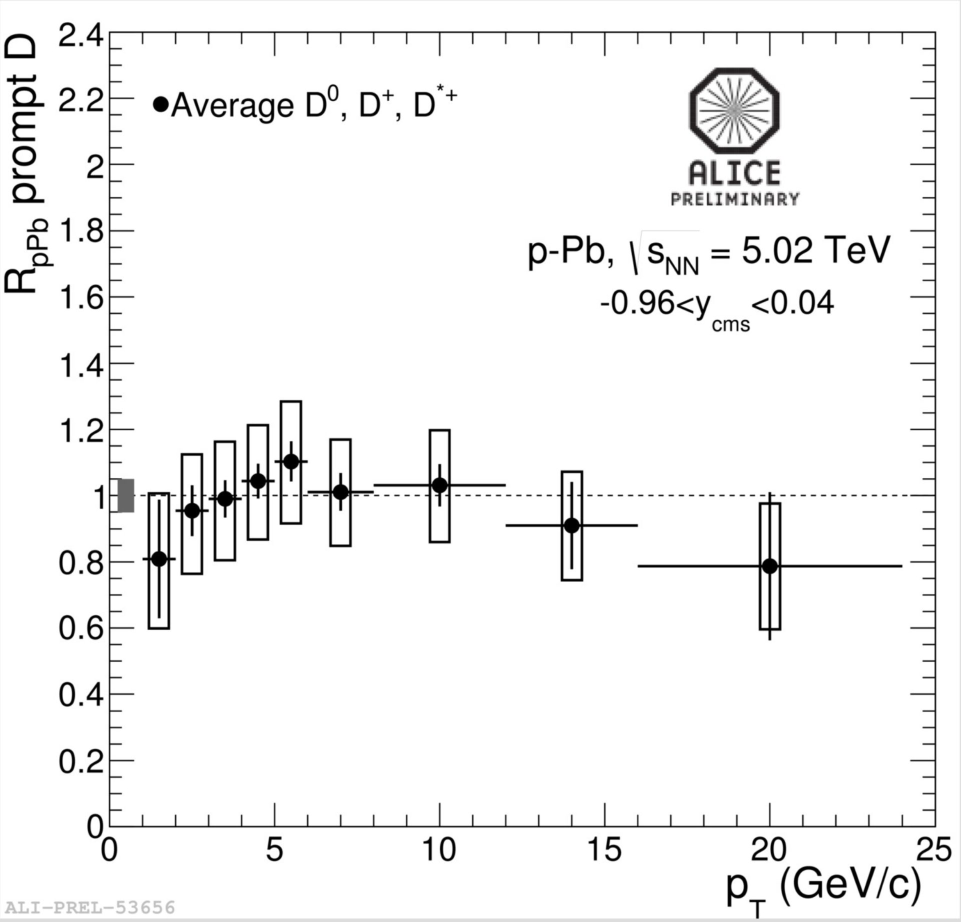

- D^0, D^+, D^{*+}, D_s measured in minimum bias p-Pb collisions
- D meson $R_{p\text{-}Pb}$ compatible with unity within uncertainties
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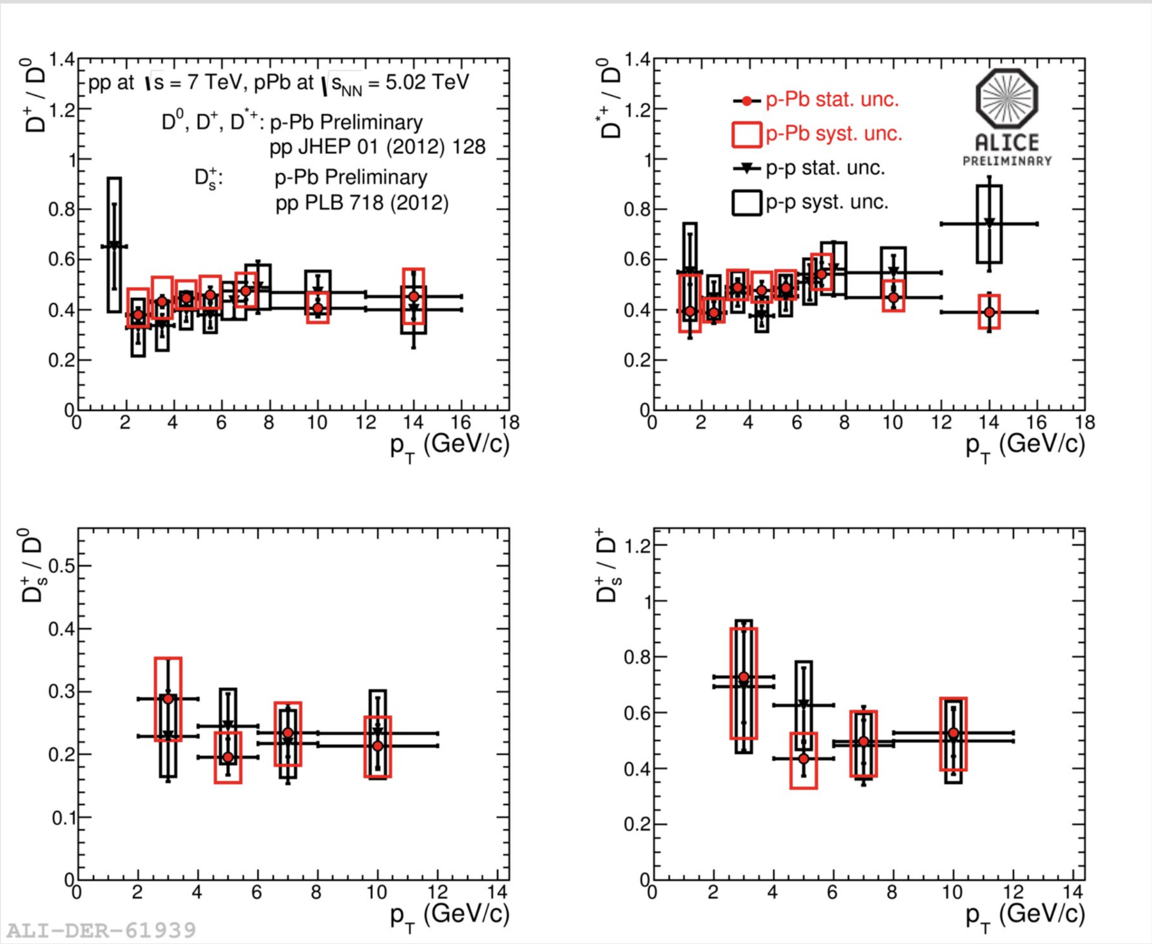
D mesons in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV



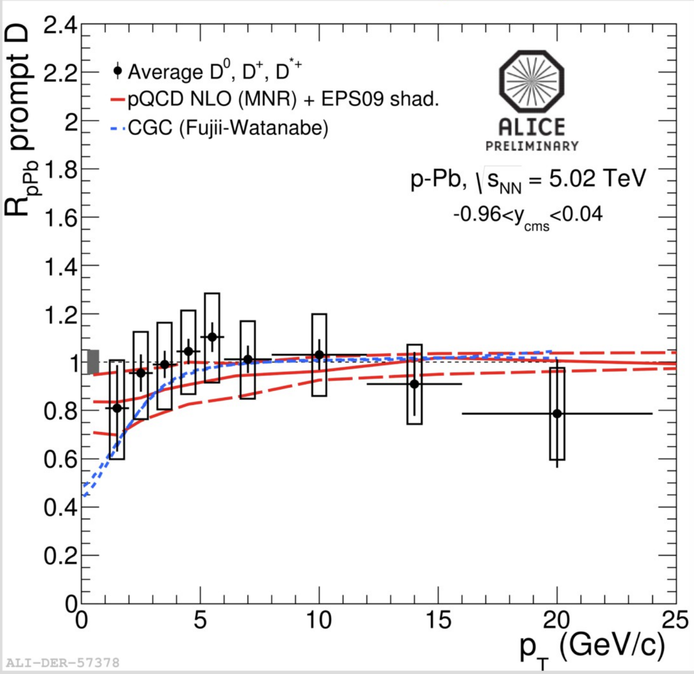
Compatible D meson production ratios between;

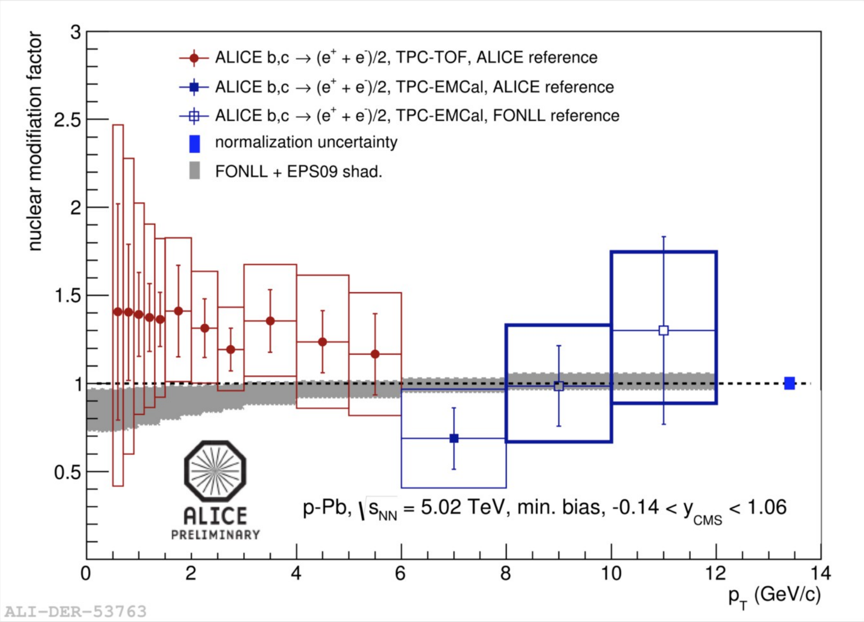
- pp collisions at $\sqrt{s}$ = 7 TeV
- Minimum bias p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

D mesons and HFe
in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

- Comparison of the measured R_{pPb} with models considering:
  - Shadowing: MNR calculation with EPS09 parametrizations of nuclear Parton Distribution Function
    Mangano et al., Nucl. Phys. B 373 (1992) 295. Eskola et al., JHEP 0904 (2009) 065
  - Saturation regime: Color Glass Condensate predictions Fujii-Watanabe, arXiv:1308.1258

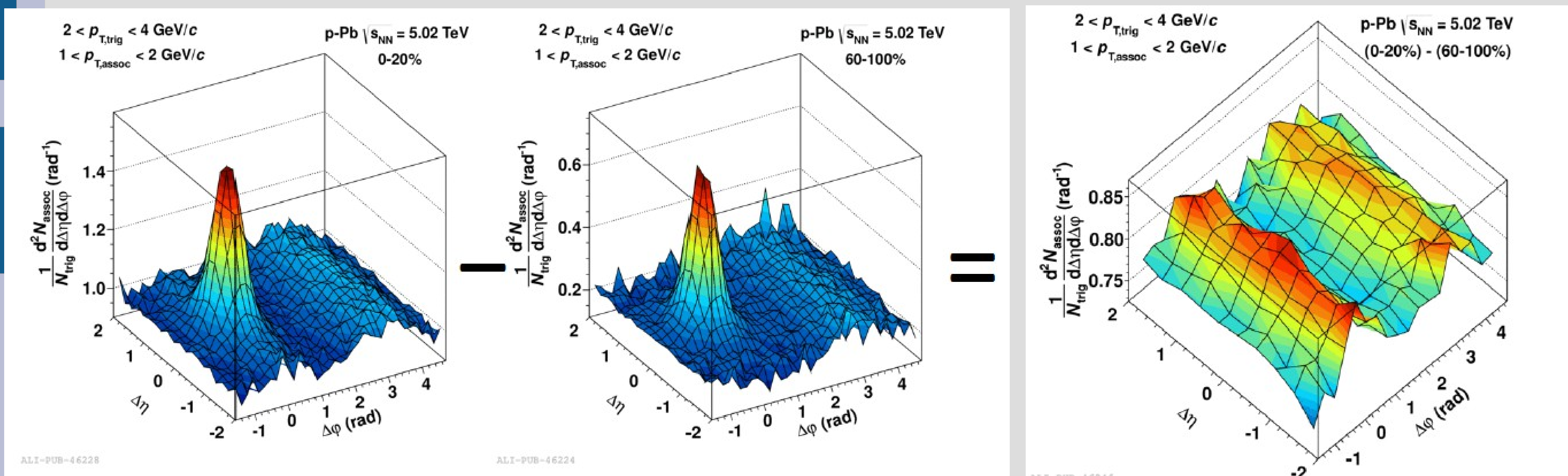
CNM effects expected at low p_T





Models including Cold Nuclear Matter effects describe the data

h-h correlations in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV



0-20% Highest multiplicity

60-100% lowest multiplicity

(0-20%) - (60-100%)

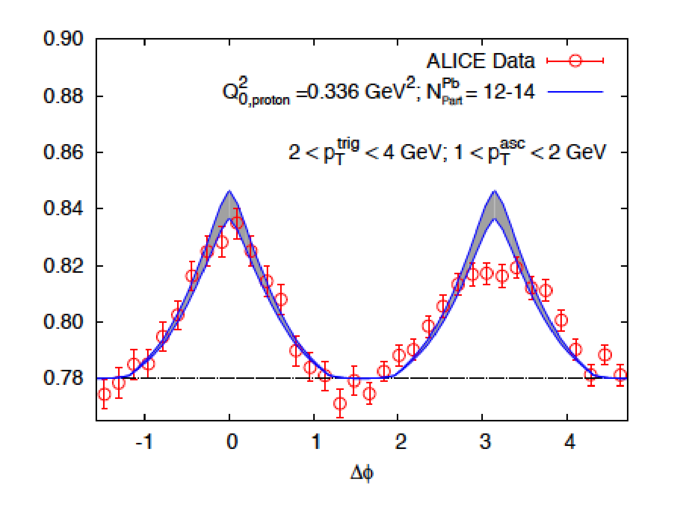
Multiplicity classes defined with V0A detector
(Multiplicity in the region $2.8 < \eta < 5.1$ in the Pb hemisphere)

PLB 719 (2013) 29-41
PLB 726 (2013) 164

Two-ridge struture observed in ALICE di-hadron correlation analysis in p-Pb as well as h-π, h-K and h-p correlation analyses

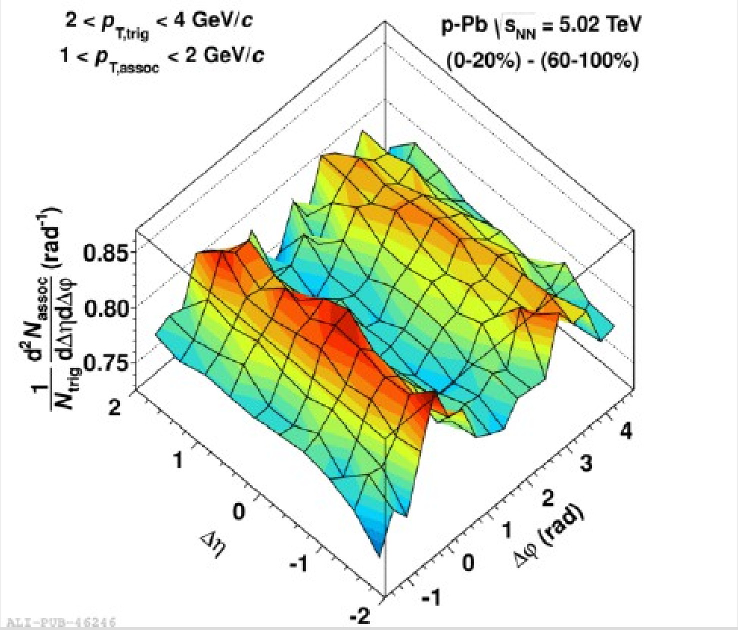
h-h correlations in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

- Yield comparison, extraction of v2, v3 from $\Delta\phi$ projection
- The origin of collective features might be
  - Initial state parton saturation in nucleus (CGC)
  - Hydrodynamic expansion of high-density medium



CGC
ALICE data

K.Dusling,
R.Venugopalan
arXiv:1302.7018



(0-20%) - (60-100%)

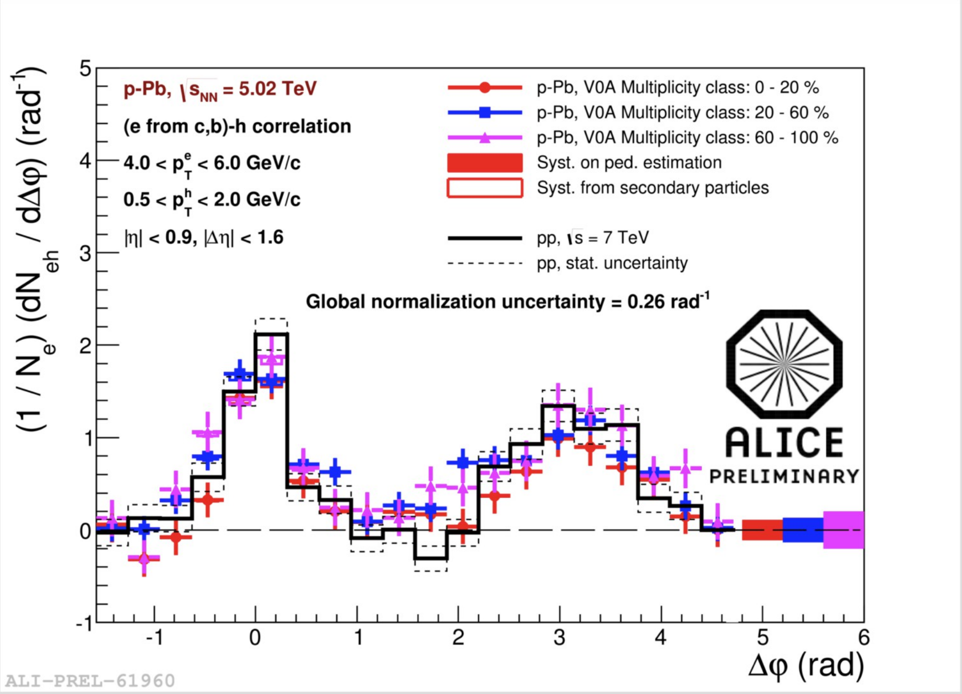
PLB 719 (2013) 29-41
PLB 726 (2013) 164

What about the heavy-flavour sector ?
Do we observe a similar structure ?

HFe-h correlations in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

$4 < p_T^e < 6$ GeV/c

$0.5 < p_T^h < 2$ GeV/c



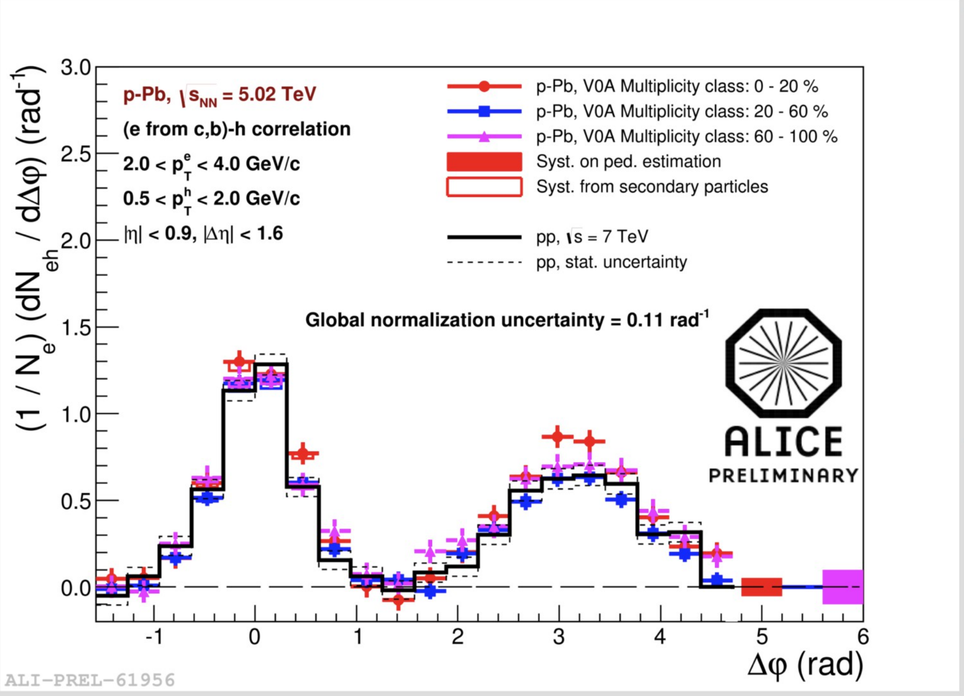
- Study the angular correlation between:
  - Trigger particles: heavy-flavour decay electron
  - Associated particles: charged hadrons

- Analysis performed for three multiplicity classes defined with V0A detector
  - 0-20% V0A multiplicity class
  - 20-60% V0A multiplicity class
  - 60-100% V0A multiplicity class

HFe-h correlations in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

$2 < p_T^e < 4$ GeV/c

$0.5 < p_T^h < 2$ GeV/c



- Study the angular correlation between:
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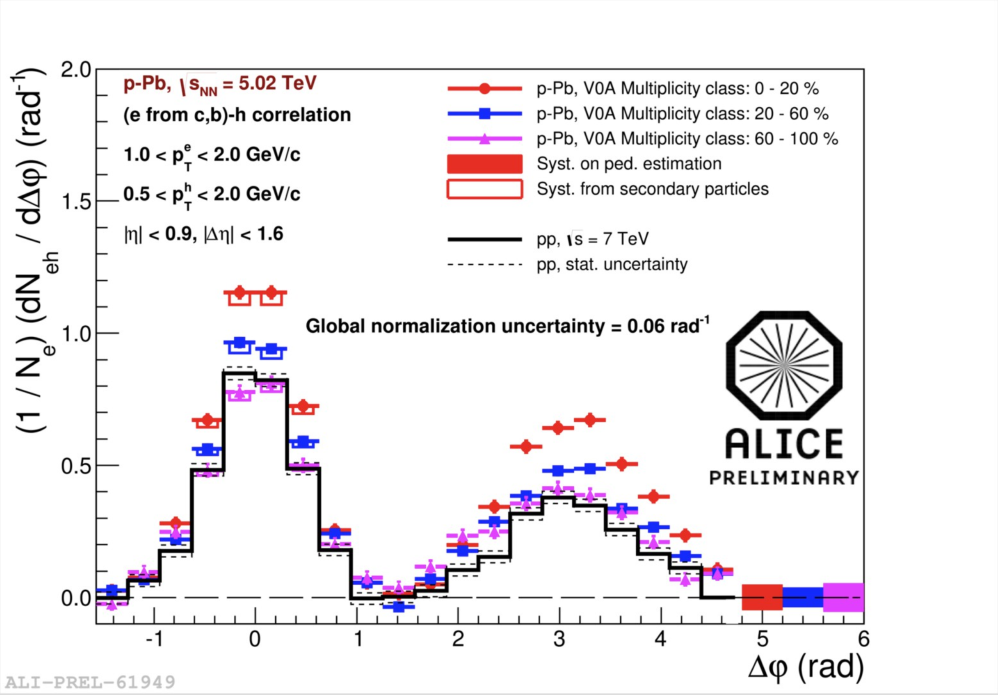
  - 0-20% V0A multiplicity class
  - 20-60% V0A multiplicity class
  - 60-100% V0A multiplicity class

HFe-h correlations in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

$1 < p_T^e < 2$ GeV/c

$0.5 < p_T^h < 2$ GeV/c



- Study the angular correlation between:
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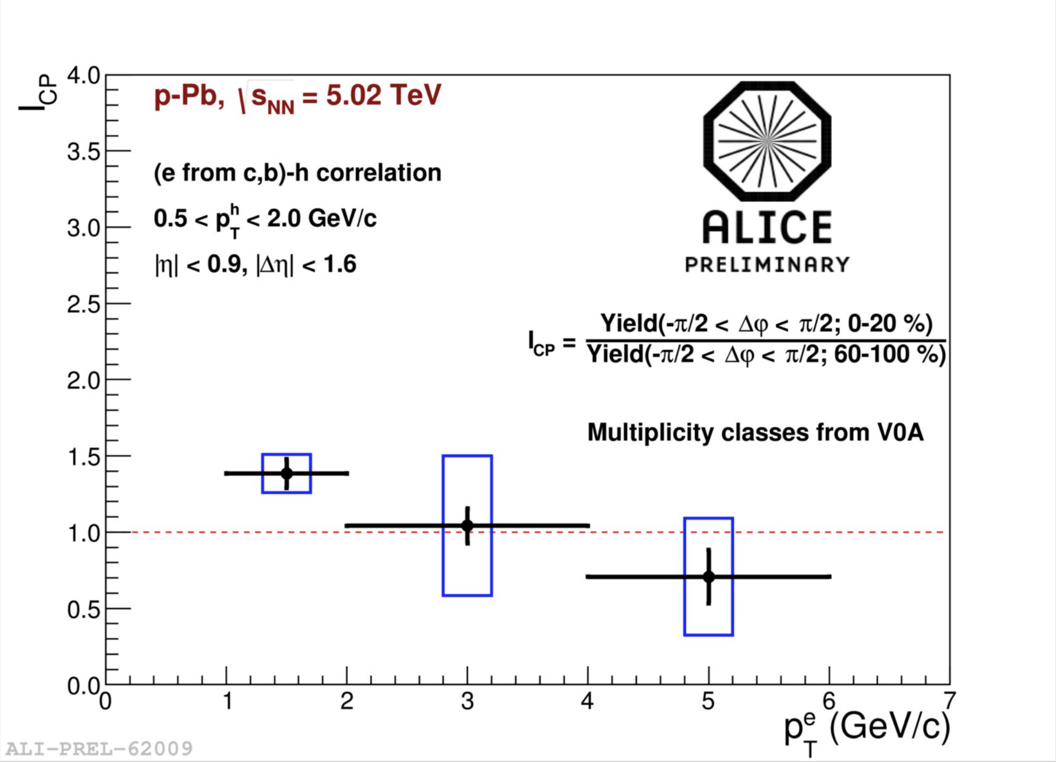
  - 60-100% V0A multiplicity class

HFe-h correlations in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

Near side peak

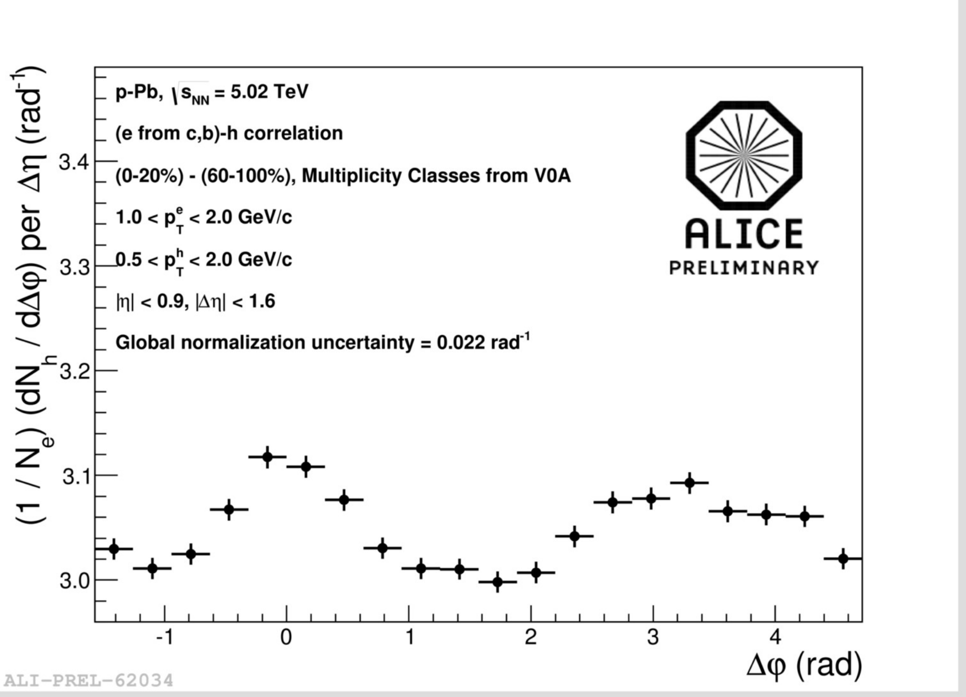


- I_{CP} = Yield(0-20%) / Yield(60-100%)
- Low p_T trigger particle:
  Enhancement in the away and near side peak for highest multiplicity event
- Intermediate p_T trigger particle:
  Compatible yields in the two multiplicity classes

HFe-h correlations in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

(0-20%) - (60-100%) Multiplicity classes

$1 < p_T^e < 2$ GeV/c
$0.5 < p_T^h < 2$ GeV/c



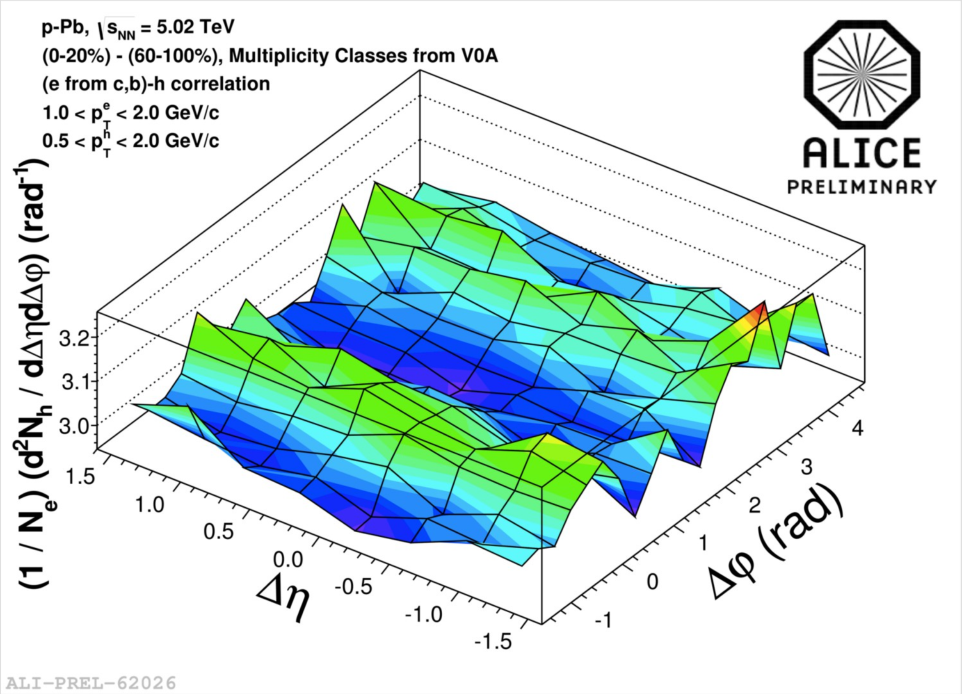
Double ridge structure observed as in h-h correlations
Mechanism behind the double ridge affects also HF

HFe-h correlations in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV

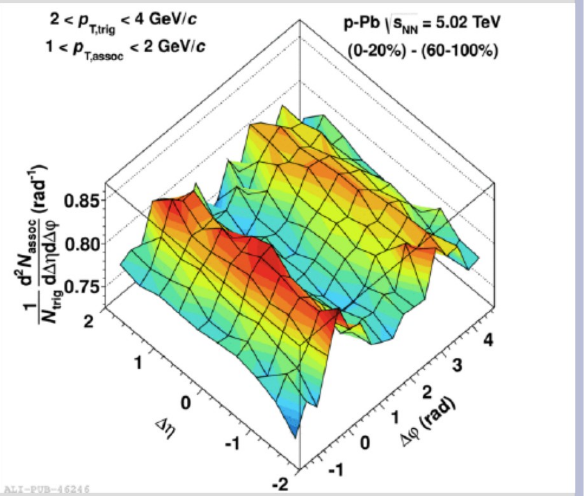
(0-20%) - (60-100%) Multiplicity classes

$1 < p_T^e < 2$ GeV/c

$0.5 < p_T^h < 2$ GeV/c



h-h correlation



Double ridge structure observed as in h-h correlations

Mechanism behind the double ridge affects also HF

Outline

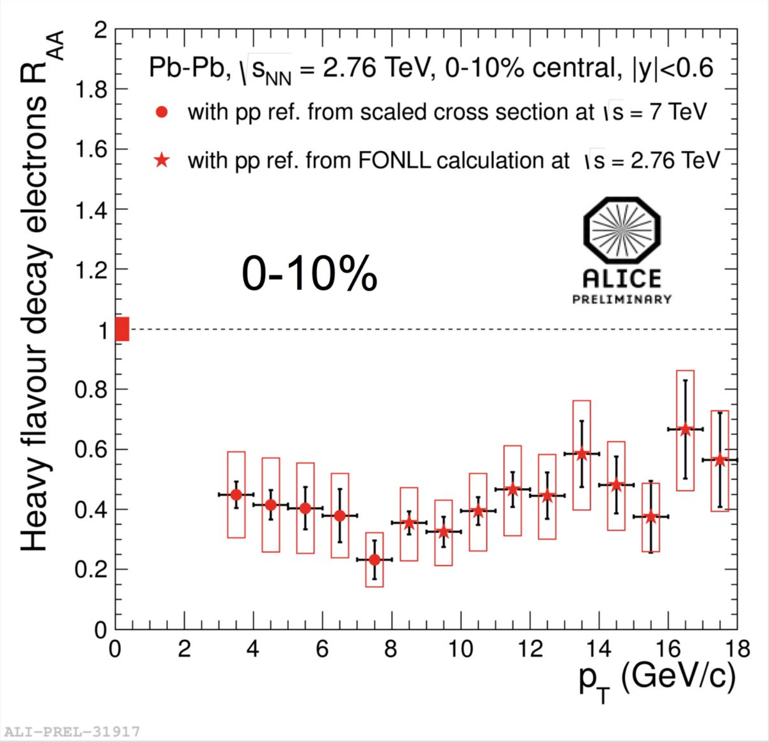
- Introduction

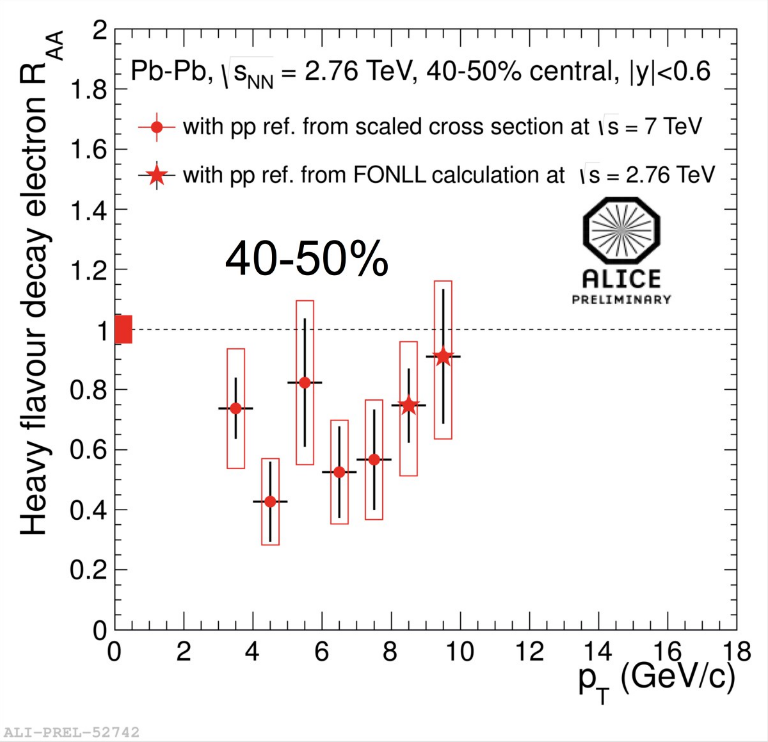
- Heavy-Flavour measurements in ALICE
  - Muons from heavy-flavour hadron decays
  - Electrons from heavy-flavour hadron decays
  - D mesons

- Results
  - pp at $\sqrt{s}$ = 7, 2.76 TeV
  - p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
  - Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

Heavy-Flavour decay electrons in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

- Clear suppression of heavy-flavour decay electrons for $3 < p_T < 18$ GeV/c for central Pb-Pb collisions
- Hint for a smaller suppression in semi-central Pb-Pb collisions

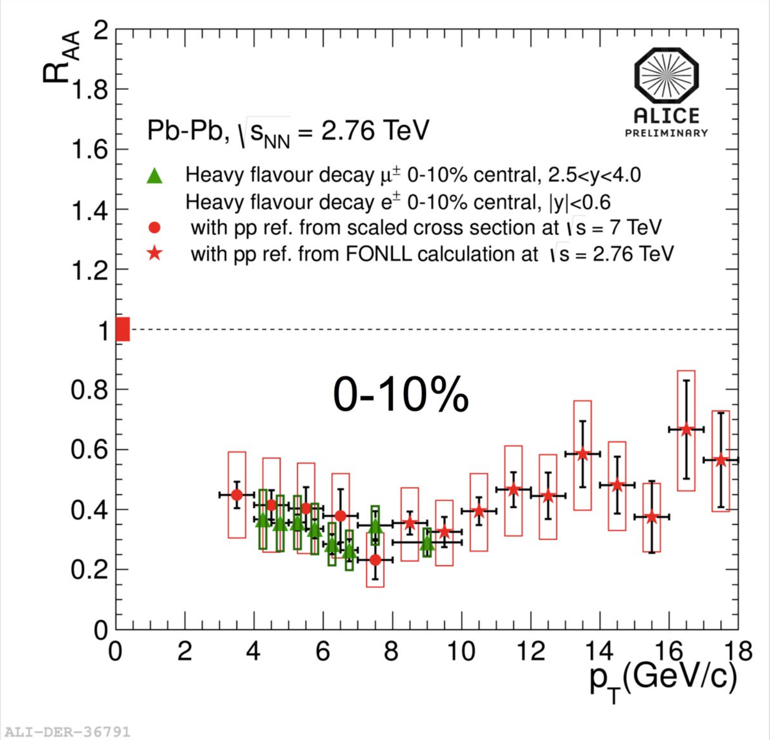


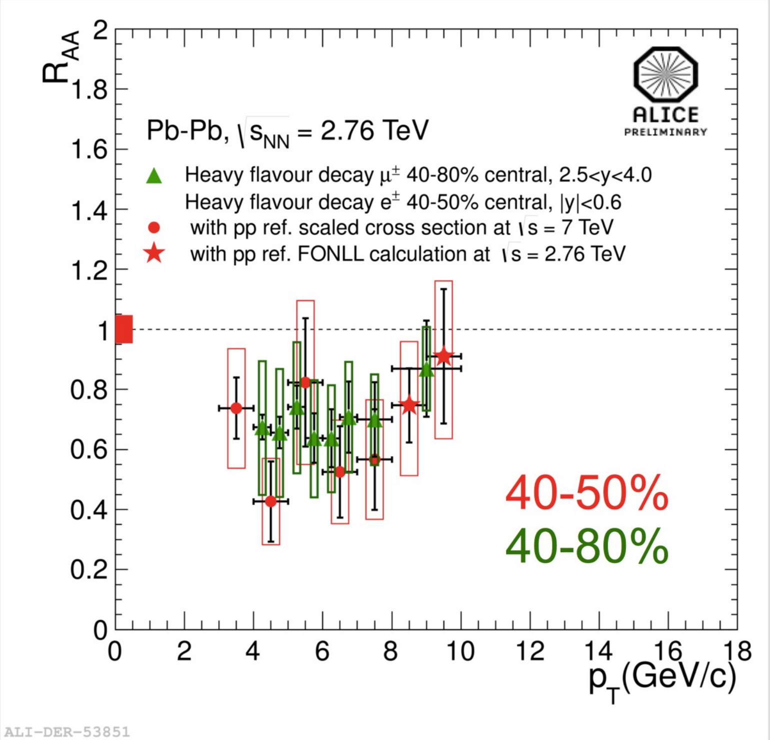


For $p_T > 8$ GeV/c take FONLL calculations for pp at $\sqrt{s}$ = 2.76 TeV as reference

Heavy-Flavour decay leptons in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

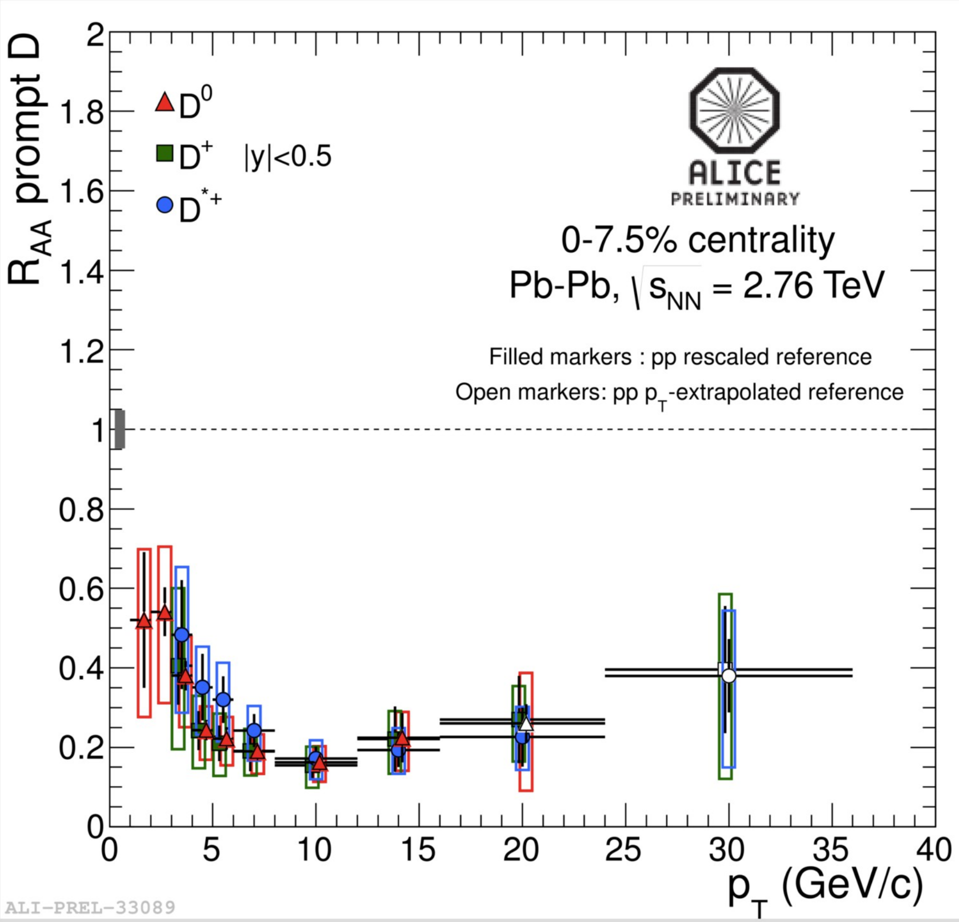
Similar suppression at central (electrons) and forward (muons) rapidity





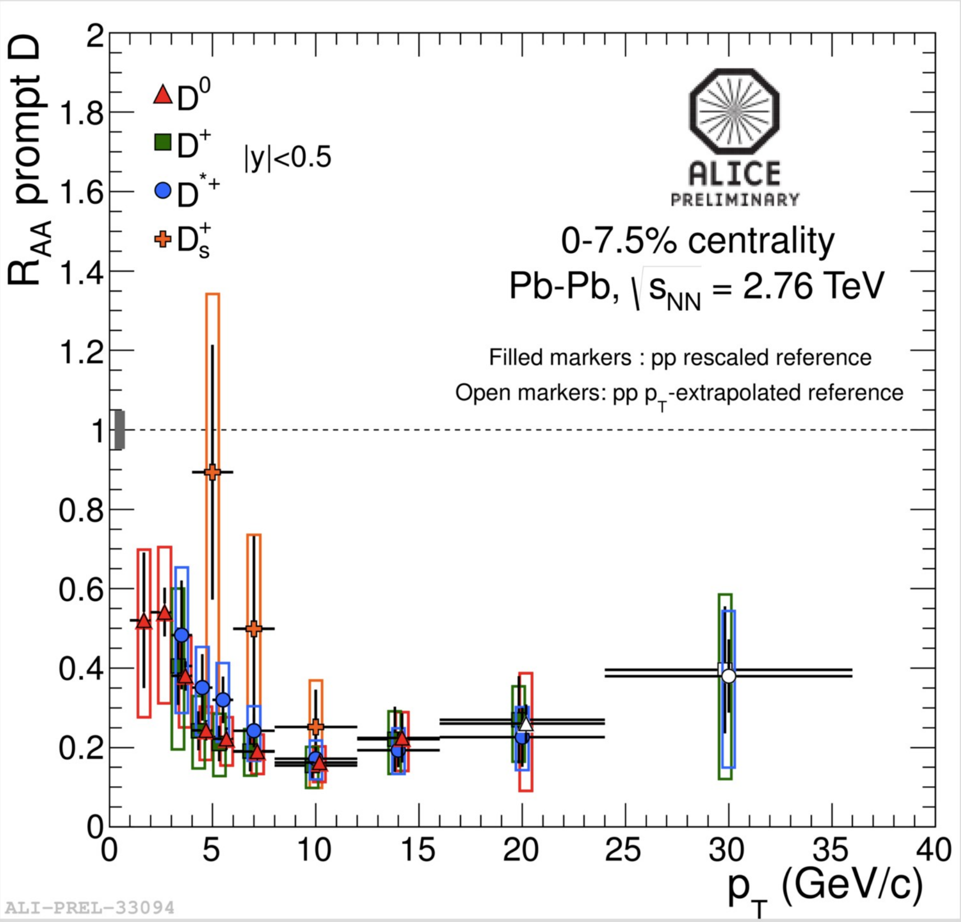
Phys. Rev. Lett. 109 (2012) 112301 for muons

D mesons in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV



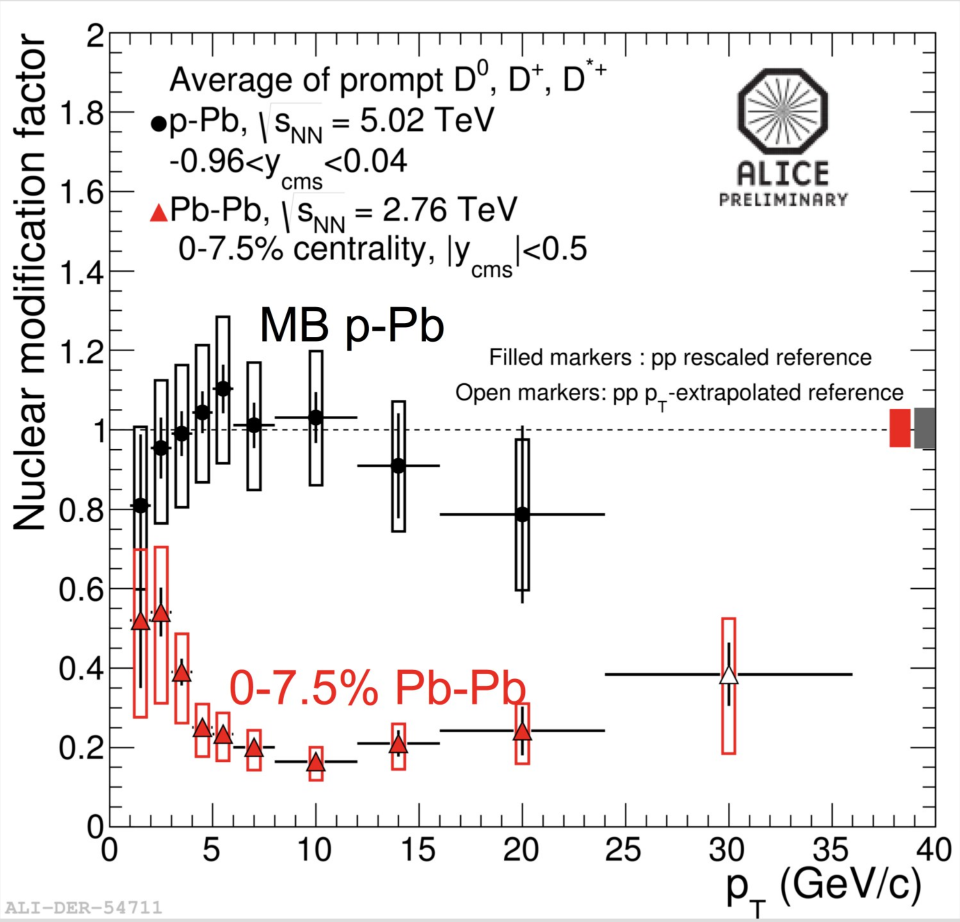
- D meson R_{AA} first measured with 2010 data JHEP 09 (2012) 112
- Extended p_T range and reduced uncertainties with data from 2011
- D^0, D^+, D^{+*} suppressed by up to a factor 5 at p_T ~ 10 GeV/c in central collisions
- Similar suppression for the three D meson species

D_s mesons in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV



- Similar suppression of strange D meson (D_s^+) as other D mesons at high p_T ($8<p_T<12$ GeV/c)
- Predicted enhancement at low/intermediate p_T for strange charmed meson due to quark coalescence/recombination + strangeness enhancement
  Kuznetsova and Rafelski, Eur. Phys. J. C51 (2007) 113
  He et al., Phys. Rev. Lett. 110 (2013) 112301
  Andronic, Phys. Lett. B 659 (2008) 149
- Better accuracy of the measurements needed to make a statement

Pb-Pb and p-Pb collisions



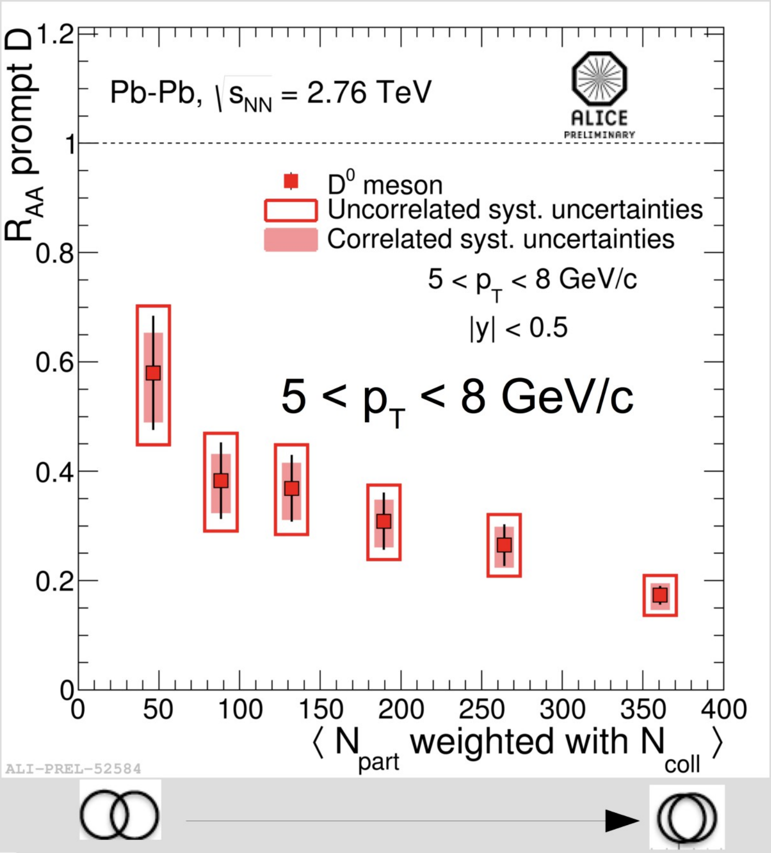
p-Pb results prove:

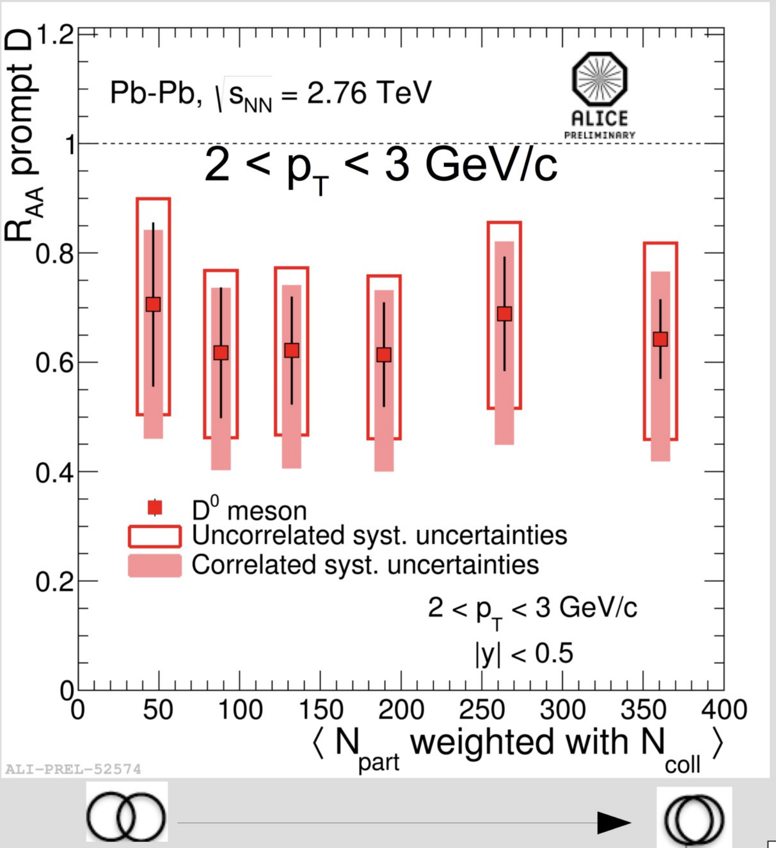
Suppression observed in central Pb-Pb collisions comes from a final state effect

for D mesons as well as for heavy-flavour decay electrons and muons

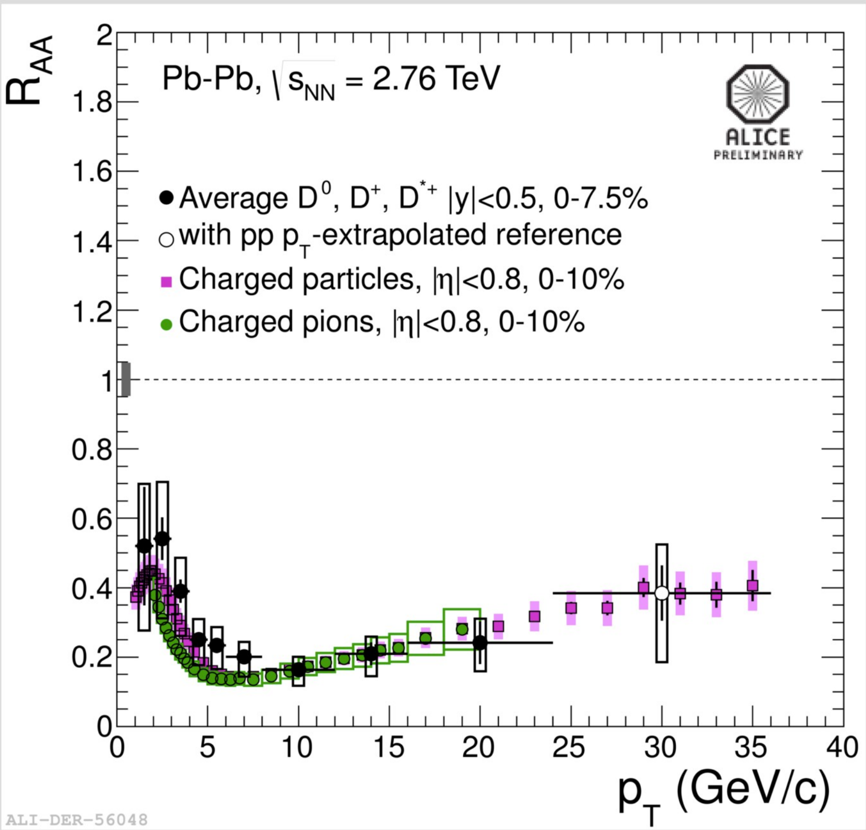
D meson R_{AA} vs centrality

- Suppression increases from peripheral to central collisions at high p_T (p_T > 3 GeV/c)
- Different trend at low p_T (2<p_T<3 GeV/c) for D^0 mesons





D mesons and π in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV



Test the parton energy loss models

- Color-charge dependence
- Quark-mass dependence

→ ΔE(g) > ΔE(q) > ΔE(c) ?

Is ΔE directly reflected in the R_{AA} ?

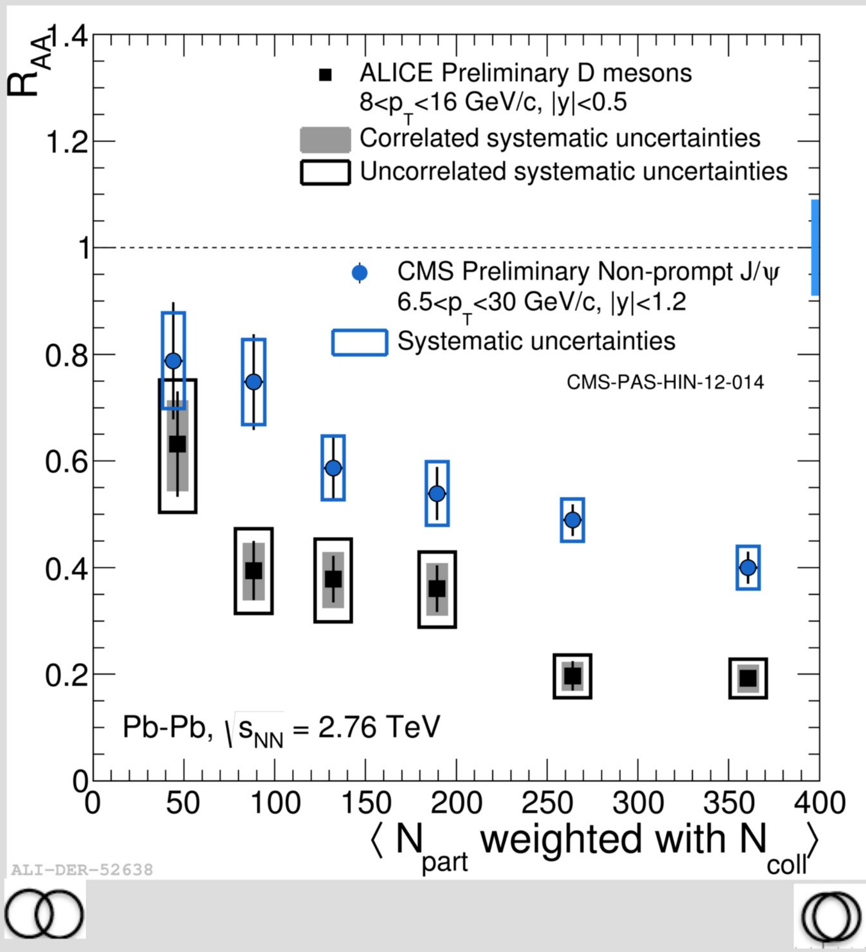
$R_{AA}(\pi) < R_{AA}(D)$??

not trivial: different fragmentation, spectral shape, bulk particles

Comparable results for π and D-meson R_{AA} within large uncertainties

Not yet conclusive

Charm and beauty in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV



Test the parton energy loss models

- Color-charge dependence
- Quark-mass dependence

→ ΔE(c) > ΔE(b) ?

Is ΔE directly reflected in the R_{AA} ?

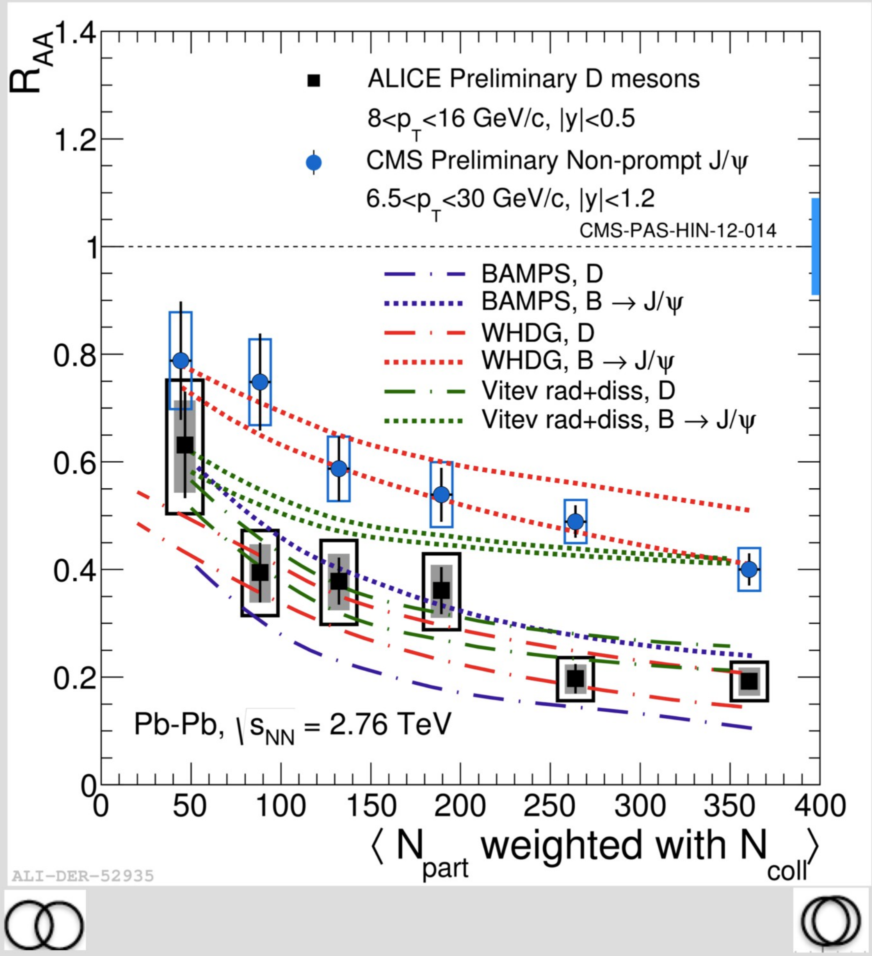
$R_{AA}(D) < R_{AA}(B)$??

ALICE D-meson R_{AA} compared with the R_{AA} of non-prompt J/ψ from B-meson decays measured with CMS in a similar kinematic range:

- **Central rapidity region**
- **B and D mesons $<p_T>$ ~10 GeV/c**

Indication for a larger suppression for charm than for beauty

Charm and beauty in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV



Test the parton energy loss models

- Color-charge dependence
- Quark-mass dependence

→ ΔE(c) > ΔE(b) ?

Is ΔE directly reflected in the R_{AA} ?

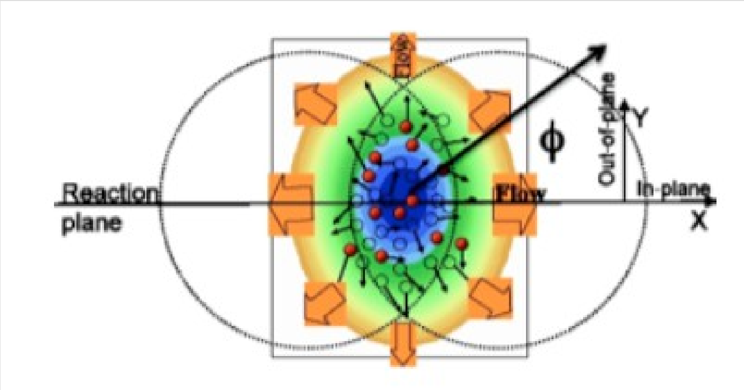
R_{AA}(D) < R_{AA}(B) ??

Difference in the R_{AA} for D mesons and non-prompt J/ψ expected from models inclusing mass dependent energy loss

BAMPS: J.Phys.G 38 (2011) 124152
WHDG: J.Phys.G38 (2011) 124114
Vitev et al.: Phys.Rev.C80(2009) 054902

Indication for a larger suppression for charm than for beauty

Elliptic flow v_2 measurements



Study azimuthal distribution of heavy-flavour hadrons w.r.t the reaction plane

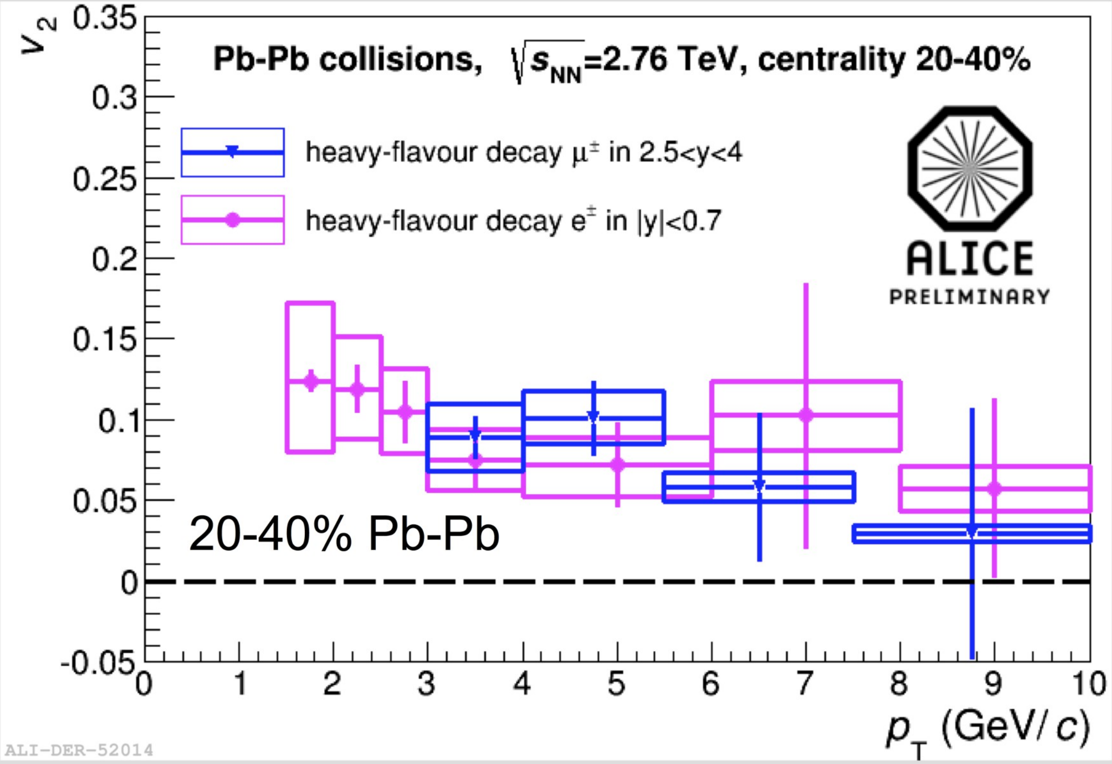
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \ldots\right)$$

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

Non zero v_2

- **Thermalization/ collective motion of heavy quarks at low p_T**
- **Path length dependence of heavy quark energy loss at high p_T**

Heavy-Flavour decay lepton v_2 in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV



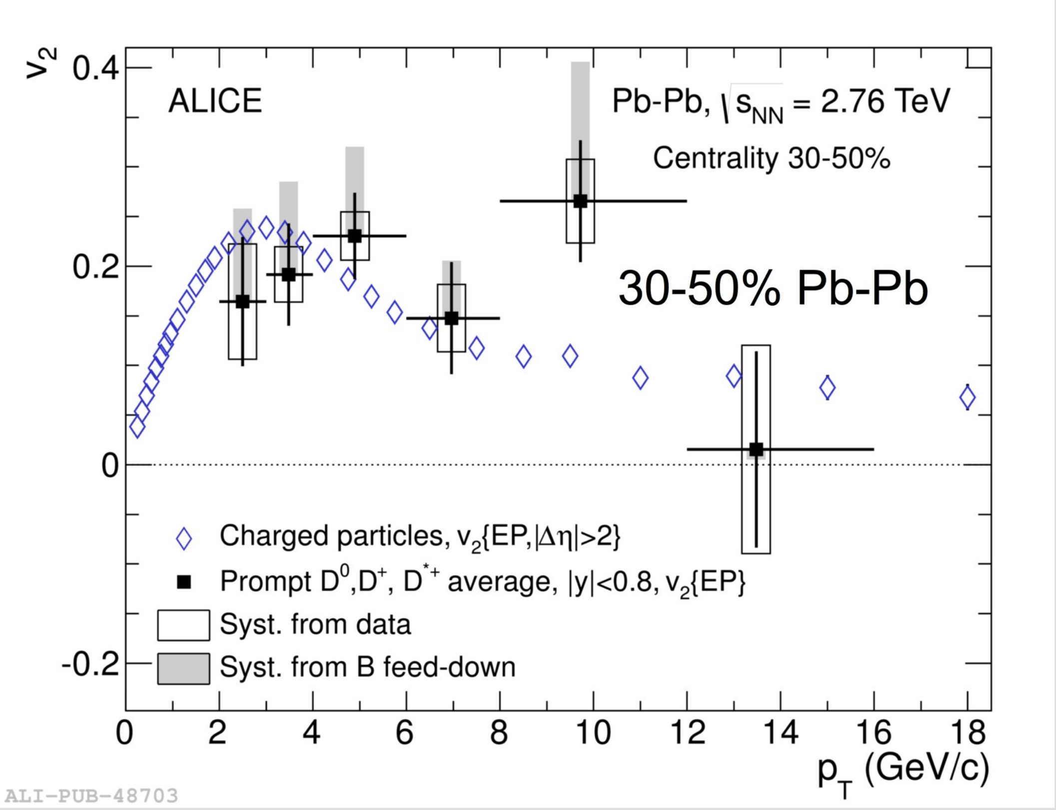
- Similar amount of v_2 for:
  - heavy-flavour decay muons
  - heavy-flavour decay electrons

  in different rapidity regions

- Positive v_2 measured

D meson v_2 in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

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



- Similar v_2 for D mesons and charged particles in semi-central collisions
- Positive D meson v_2 for 2 < p_T < 6 GeV/c (> 3σ effect)

Information on the initial azimuthal anisotropy transferred to charm quarks

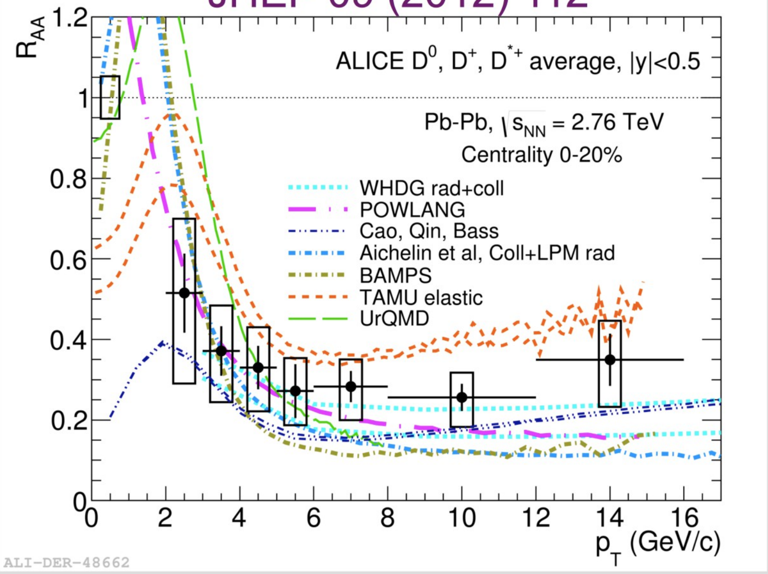
Simultaneous description R_{AA} and v_2 in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

Simultaneous description of D meson R_{AA} and v_2 by models

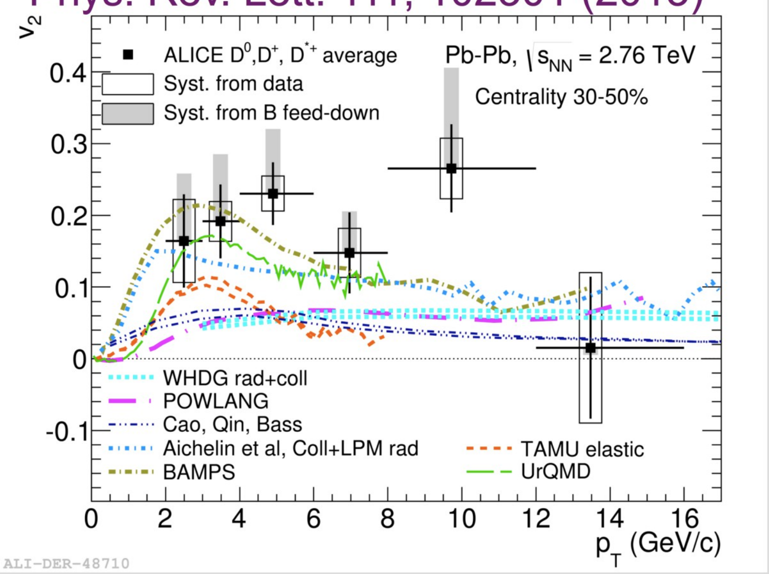
Same picture seen for heavy-flavour decay electrons

→ Understanding of heavy quark transport properties in the medium

JHEP 09 (2012) 112



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



BAMPS Uphoff et al. ArXiv:1112.1559, Aichelin et al. Phys. Rev.C 79 (2009) 044906, WHDG W.A.Horowitz et al. J. Phys. G38, 124064 (2011), POWLANG W.M.Alberico et al. Eur. Phys J.C 71, 1666 (2011),TAMU M. He, R. J. Fries and R. Rapp, arXiv:1204.4442[nucl - th], UrQMD arXiv:1211.6912, J. Phys. Conf. Ser. 426, 012032 (2013), Cao, Quin, Bass arXiv:1308.0617

Conclusion

- Two ridge structure observed in Heavy-flavour decay electron-hadron correlation in high multiplicity p-Pb collisions
  → Initial state parton saturation in nucleus (CGC)
  Or hydrodynamic expansion of high-density medium effects ?

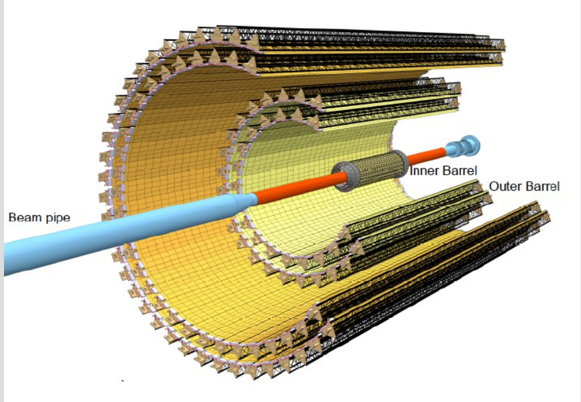
- Large suppression of heavy-flavour hadrons in central Pb-Pb collisions at high p_T
  → Strong modification of the momentum spectra of heavy-flavour hadrons

- R_{pPb} of heavy-flavour hadrons compatible with unity within uncertainties
  → Suppression observed in Pb-Pb mainly due to final state effects (QGP)

- R_{AA}(D) > R_{AA}(J/ψ from B) for central Pb-Pb collisions
  → Charm more suppressed than beauty at intermediate, high p_T

- $v_2 > 0$ all heavy-flavour channels at low p_T
  → Charm takes part in the anisotropic evolution of the system

ALICE upgrade



Expected integrated luminosity
In Pb-Pb at $\sqrt{s_{NN}}$=5.5 TeV: 10 nb^{-1}
Maximum collision rate 50 kHz

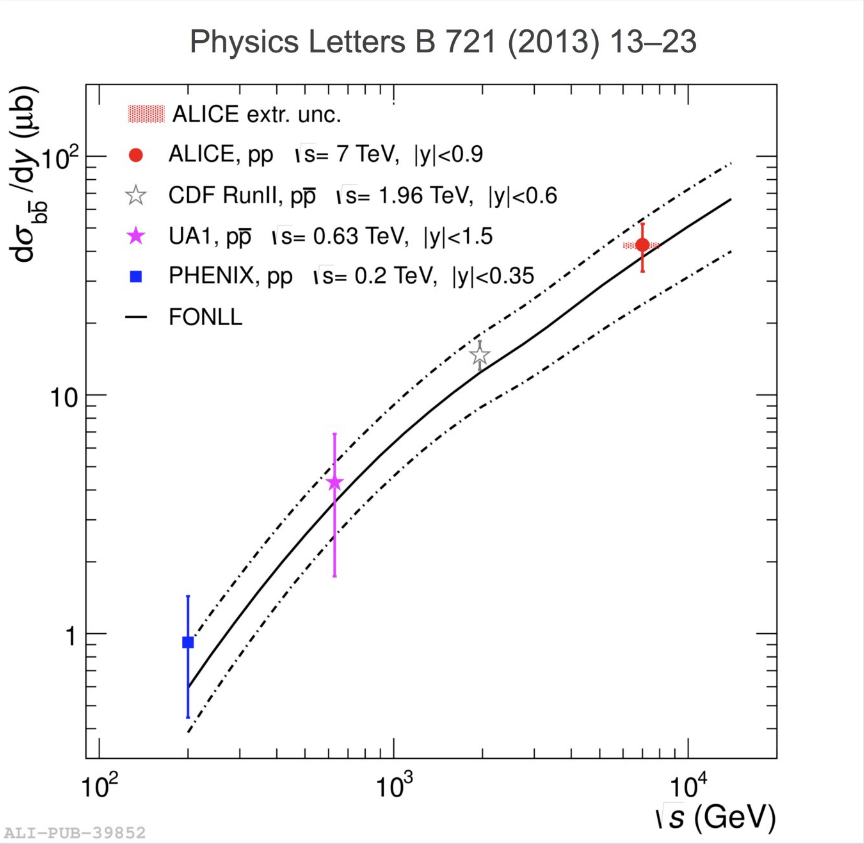
- New Inner Tracking System
  - Closer to beam axis
  - Increase granularity
- Time Projection Chamber upgrade
  - Continuous readout at 50 kHz
- Upgrade online systems
  - Online reconstruction and calibration

- **Beauty measurement strategies**
  - Non-prompt J/ψ
  - Direct beauty measurement B+ $\rightarrow D^0 \pi^+$
  - Leptons from beauty hadron decays

- **Heavy-flavour Baryons**
  - $\Lambda_c^+ \rightarrow pK^-\pi^+$ BR=5% down to p_T = 2 GeV/c
    Small cτ = 59,9 μm
  - $\Lambda_b \rightarrow \Lambda_c^+\pi^-$ BR=3 x 10^{-4} down to p_T = 4 GeV/c
    Large cτ = 417 μm, but very rare
  - Compare Baryon/meson yield in pp and Pb-Pb to access the hadronization mechanism

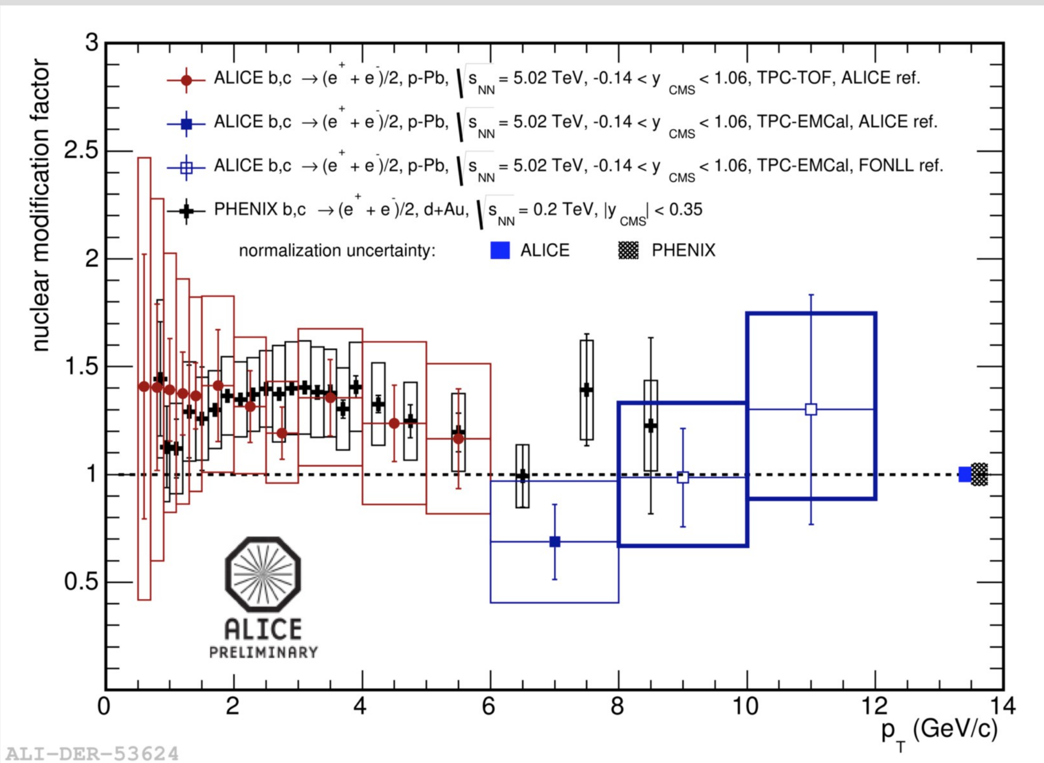
- **Reduce D_s error at low p_T**
  Enhanced in Pb-Pb ? Contribution from regeneration

LHC as heavy quarks factory



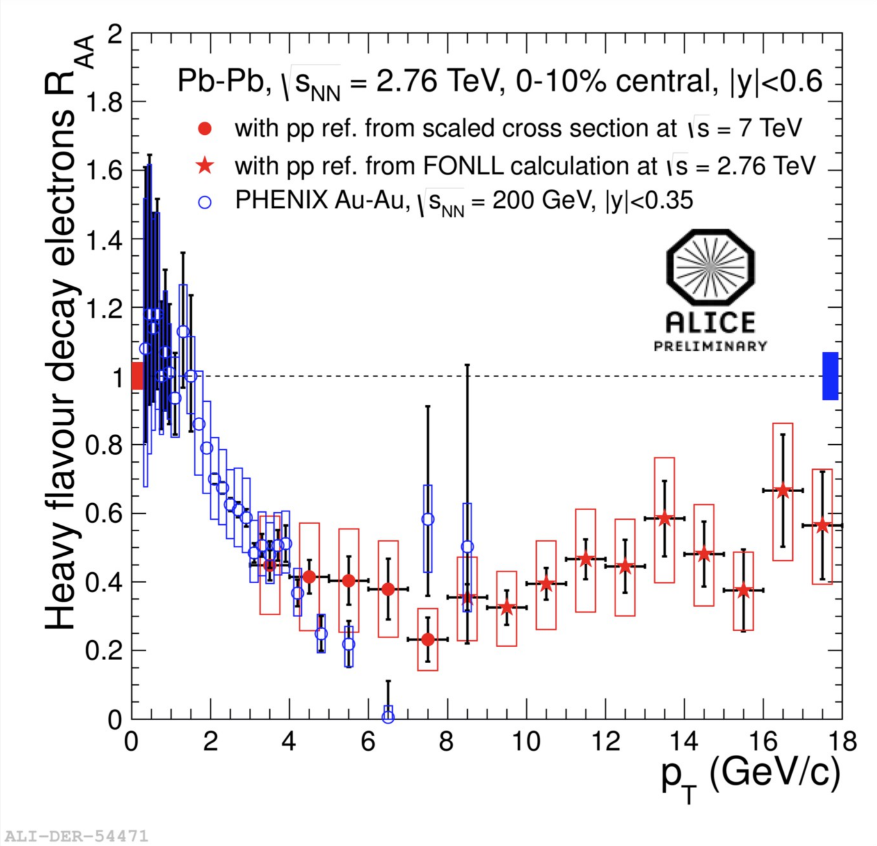
Heavy quarks, i.e. charm and beauty, are produced abundantly at LHC energies

Heavy-Flavour decay electrons in p-Pb



- Two different electron identification strategies:
  - TPC-TOF (more suited for low p_T e)
  - TPC-EMCal (more suited for high p_T e)
- Minimum bias p-Pb collisions
- Results similar to PHENIX at lower energy in Au-Au $\sqrt{s_{NN}}$ = 0.2 TeV

Open heavy-flavours at the LHC

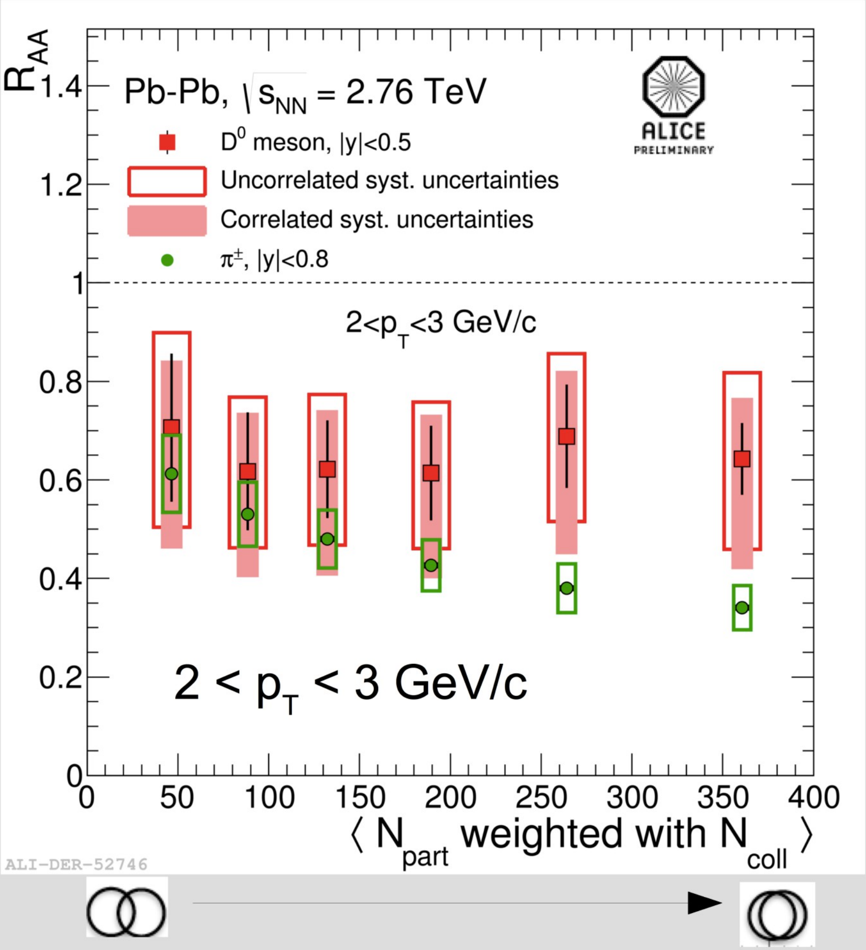


D/B → e + X

Au-Au $\sqrt{s_{NN}}$ = 200 GeV
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV

Similar suppression of heavy-flavour decay electrons for p_T > 3 GeV/c at the LHC and at RICH

D mesons and π in Pb-Pb



Test the parton energy loss models

- Color-charge dependence
- Quark-mass dependence

→ $\Delta E(g) > \Delta E(q) > \Delta E(c)$?

Is ΔE directly reflected in the R_{AA} ?

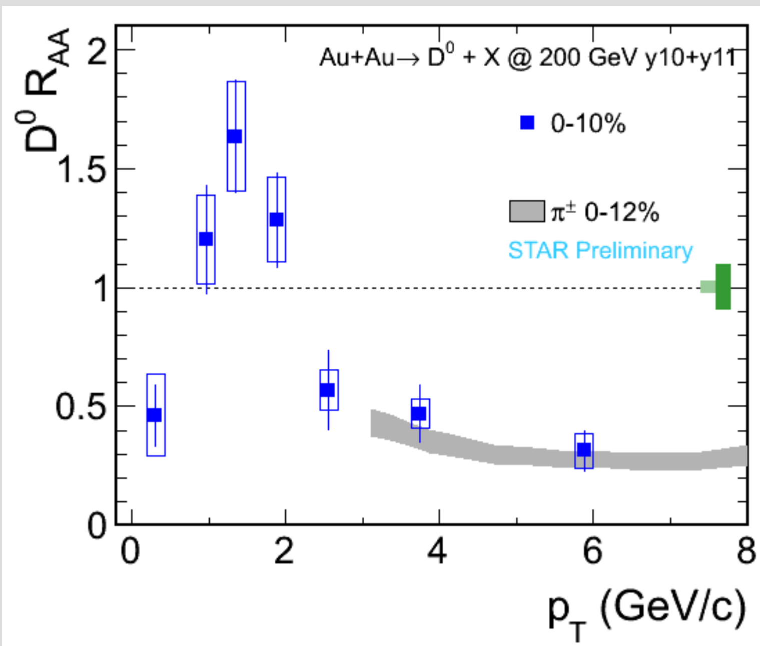
$R_{AA}(\pi) < R_{AA}(D)$??

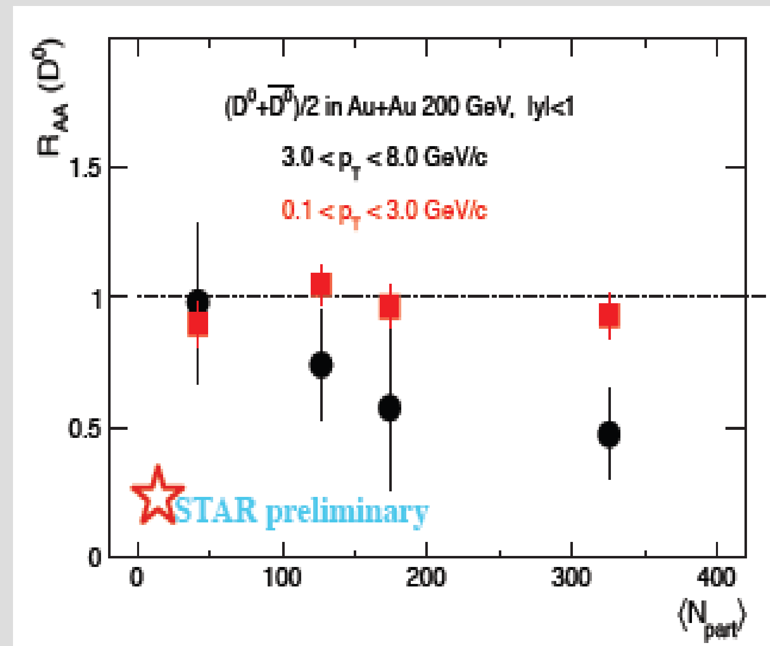
not trivial: different fragmentation, spectral shape, bulk particles

Comparable results for π and D mesons suppressions within large uncertainties
Not yet conclusive

D mesons measured with STAR

- STAR: direct charm measurement vs p_T, in bins of centrality
- pp reference consistent with FONLL upper limit

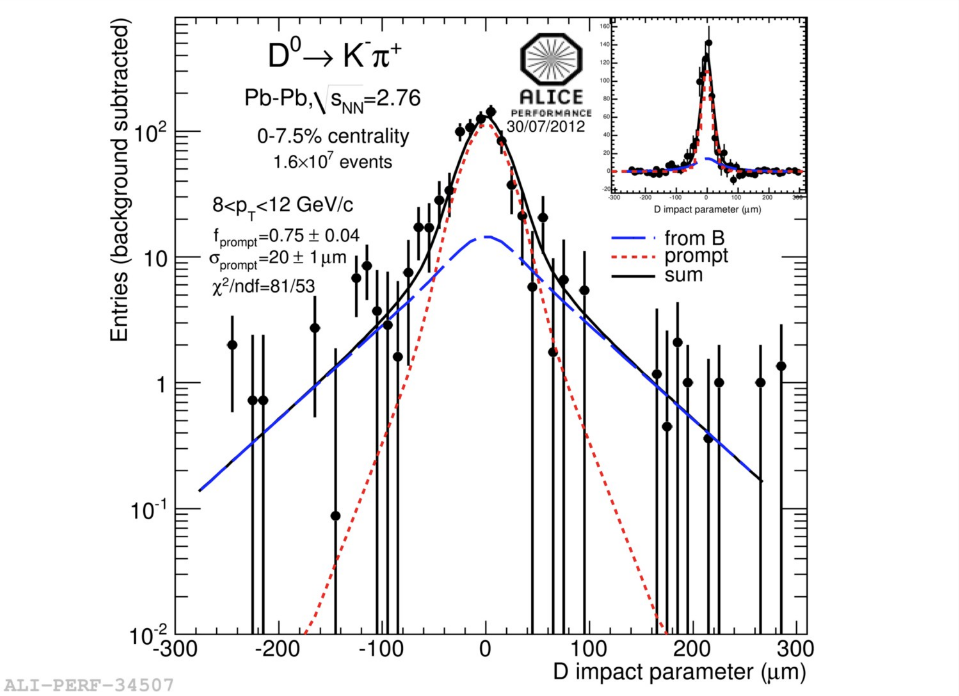




Suppression at high-p_T in central and mid-central collisions
Enhancement at "intermediate" p_T

(consistent with resonance re-combination model)

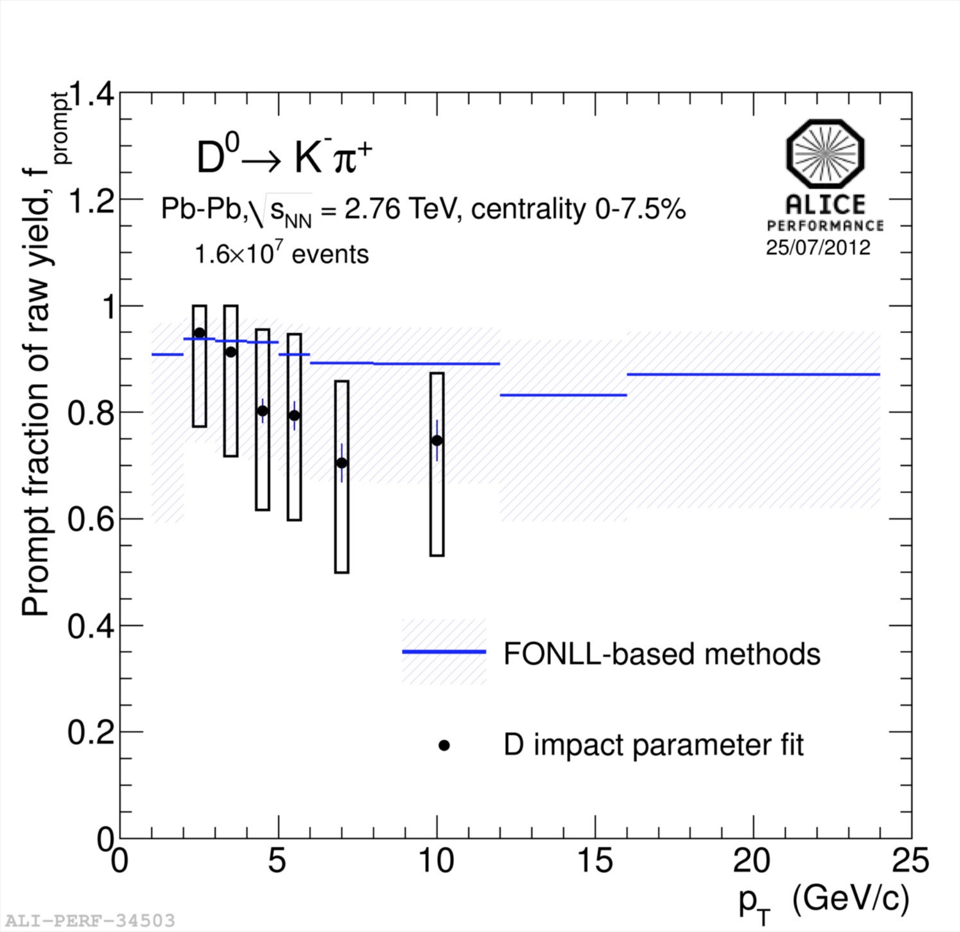
B feed down subtraction in Pb-Pb



- Subtraction of secondary D from B needed to compute prompt D-meson RAA
  - Rely on FONLL predictions as done in pp at √s=7 TeV and 2.76 TeV
  - Hypothesis on R_{AA} of D from B mesons

    $R_{AA}^{DfromB}/R_{AA}^{promptD}$ ranges from 0.3 to 3.0
- Data driven method in development:
  - Fit the impact parameter of D to measure the prompt charm fraction

B feed down subtraction in Pb-Pb



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