Open heavy-flavour measurements with ALICE

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for the ALICE Collaboration

Santa Fe
Jets and Heavy Flavor Workshop
January 11-13, 2016

Heavy quarks in various collisions systems

- Heavy quarks (charm and beauty): large mass, short formation time
  - $\tau_{c,b} \sim 1/2m_{c,b} < 0.1$ fm << $\tau_{QGP} \sim 5$-10 fm

- **pp** collisions:

  Test for pQCD, reference for p-A and A-A collisions

  Can we learn on Multi-Parton Interactions in the heavy-flavour sector?

- **p-A** collisions:

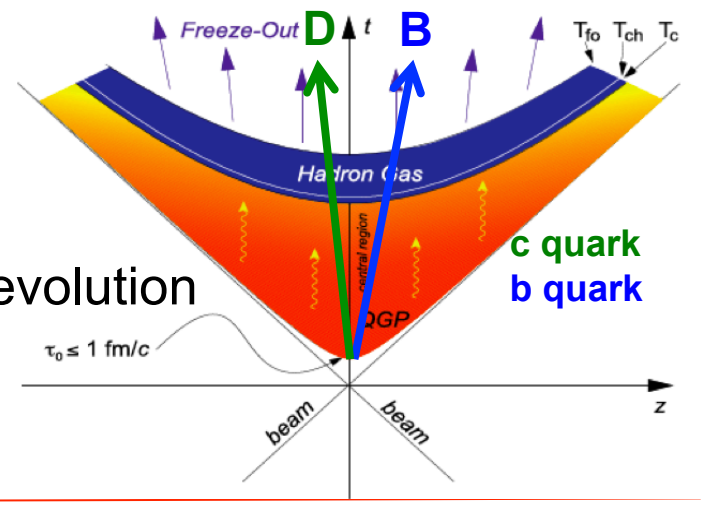
  Explore cold nuclear matter effects

- **A-A** collisions:

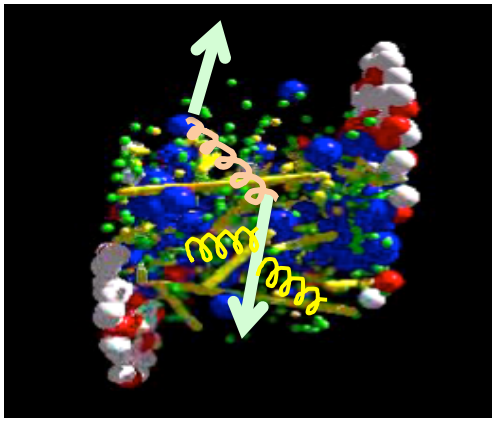
  "Self-generated" probes exposed to the medium evolution

  How do heavy quarks interact with the medium?

  Information on medium properties?



Heavy Flavours and Heavy-Ion Collisions



Heavy-Flavour (HF) energy loss mechanism via:

- radiative gluon emission and elastic collisions

Which **medium properties** can be extracted via energy loss?

- Medium **density**, transport parameter ($\hat{q}$) in the medium via path-length, colour charge, mass ("dead-cone") dependence of energy loss:

$$\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2 \quad \Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$$

Dokshitzer and Kharzeev, PLB 519 (2001) 199.

- Medium **temperature**

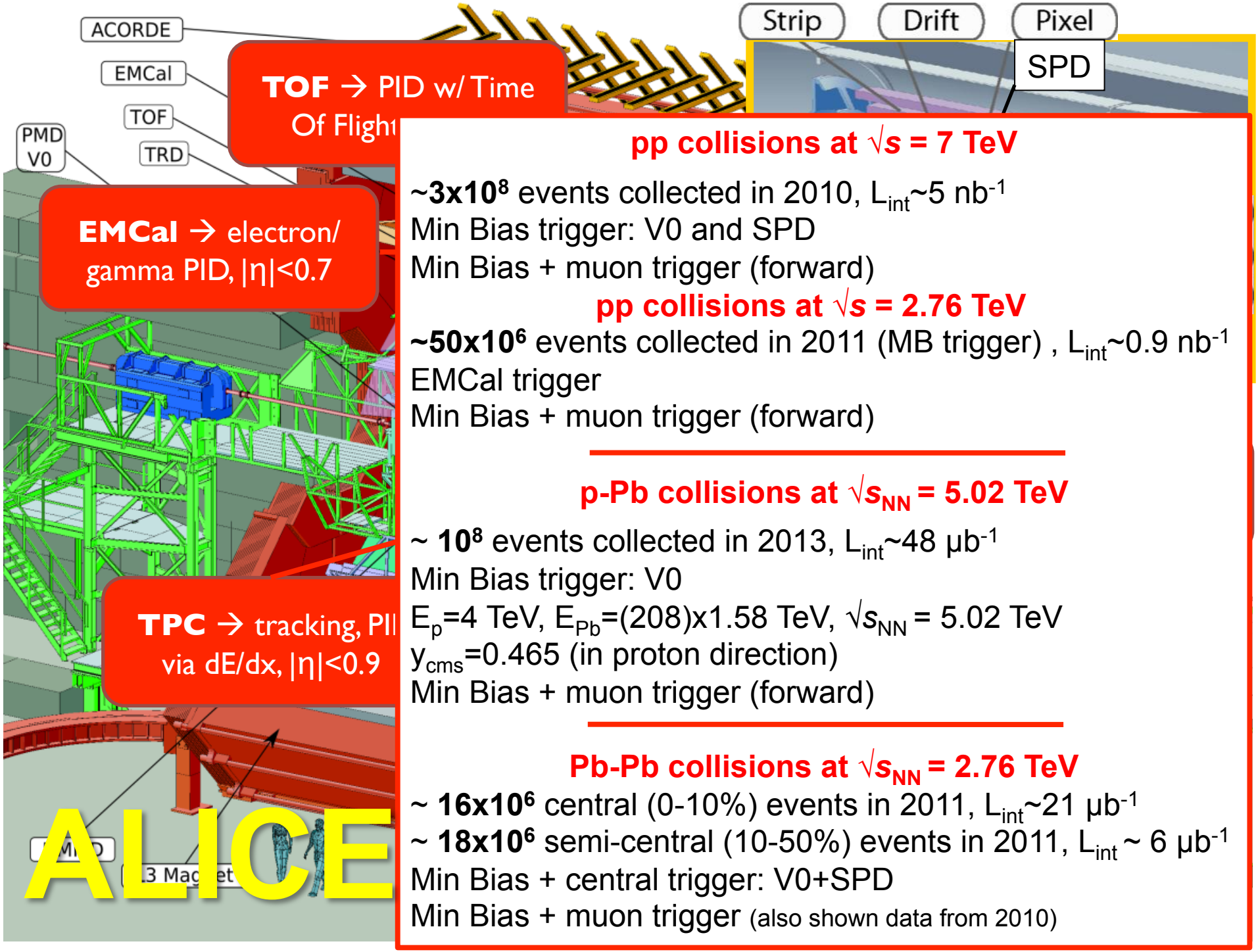
Do HF participate in **collective motion**?

- at low p_T → information on the medium transport properties

How to **disentangle cold and hot nuclear matter effects**?

- Pb-Pb collisions: nuclear matter under extreme conditions of temperature/energy density
- p-Pb collisions: control experiment used as reference (and test for "small-system QGP")


ACORDE
EMCal
TOF
TRD
PMD
V0
TOF → PID w/ Time Of Flight, |η|<0.9
EMCal → electron/ gamma PID, |η|<0.7
Strip
Drift
Pixel
SPD
V0
T0
FMD
ITS→ vertexing, tracking, |η|<0.9
VZERO → trigger and multiplicity
TPC → tracking, PID via dE/dx, |η|<0.9
Forward Muon Spectrometer
ALICE
PHOS
ITS
TPC
Elena Bruna (INFN-GSI)



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

~**3x10^8** events collected in 2010, L_{int}~5 nb^{-1}
Min Bias trigger: V0 and SPD
Min Bias + muon trigger (forward)

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

~50x10^6 events collected in 2011 (MB trigger) , L_{int}~0.9 nb^{-1}
EMCal trigger
Min Bias + muon trigger (forward)

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

~ **10^8** events collected in 2013, L_{int}~48 μb^{-1}
Min Bias trigger: V0
E_p=4 TeV, E_{Pb}=(208)x1.58 TeV, $\sqrt{s_{NN}}$ = 5.02 TeV
y_{cms}=0.465 (in proton direction)
Min Bias + muon trigger (forward)

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

~ **16x10^6** central (0-10%) events in 2011, L_{int}~21 μb^{-1}
~ **18x10^6** semi-central (10-50%) events in 2011, L_{int} ~ 6 μb^{-1}
Min Bias + central trigger: V0+SPD
Min Bias + muon trigger (also shown data from 2010)

Heavy flavours with ALICE

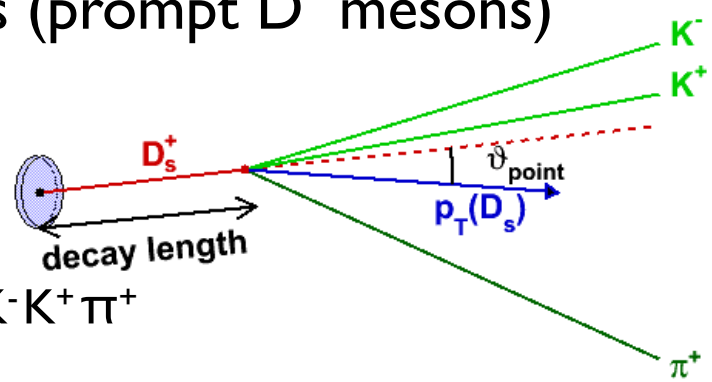
Full reconstruction of D meson hadronic decays (prompt D mesons)

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

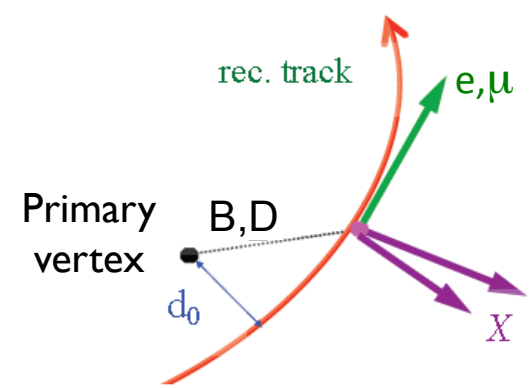
$D^+ \rightarrow K^-\pi^+\pi^+$

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

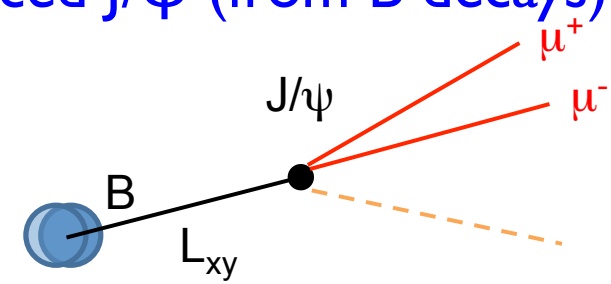
$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$



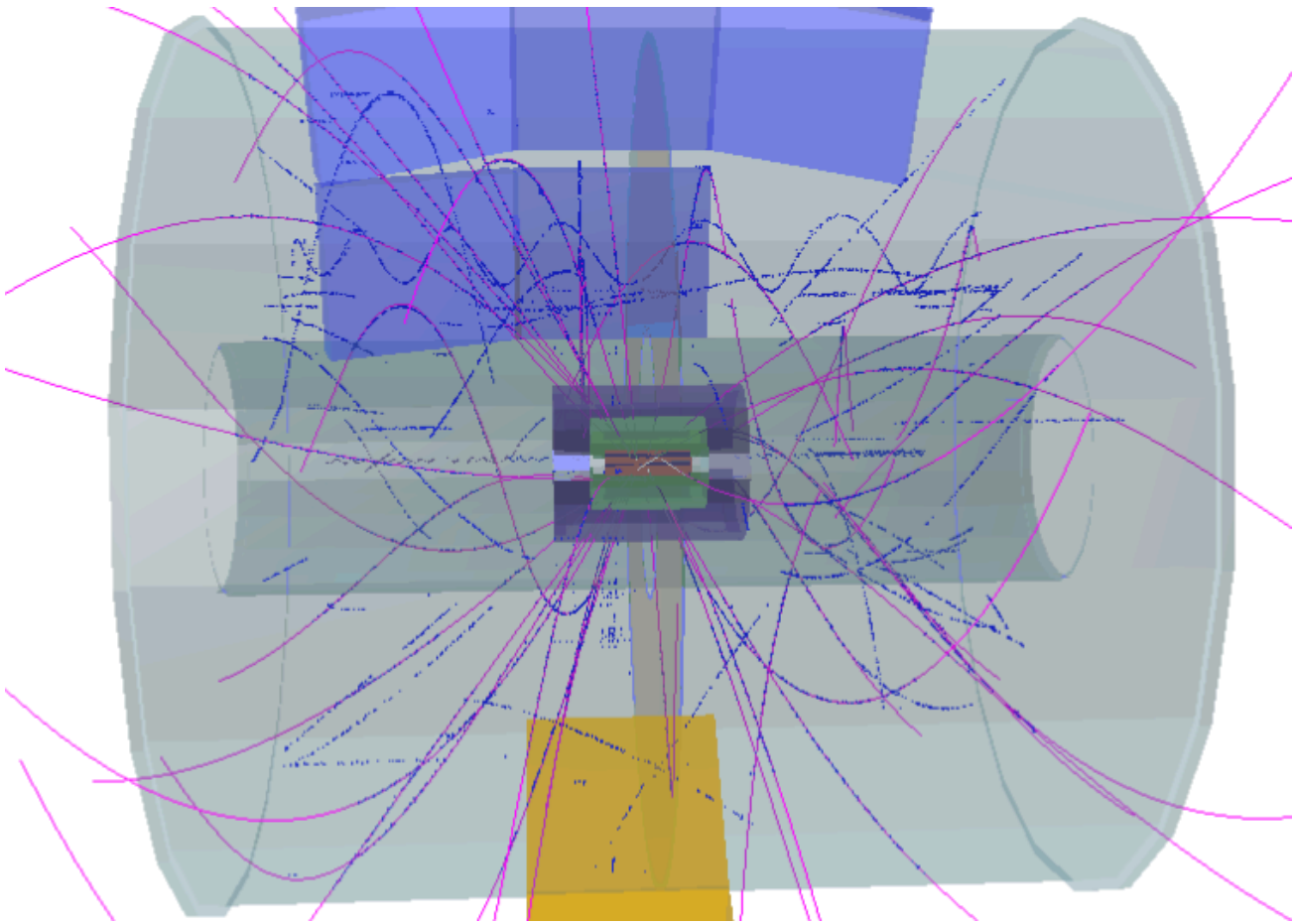
Semi-leptonic decays (charm, beauty)



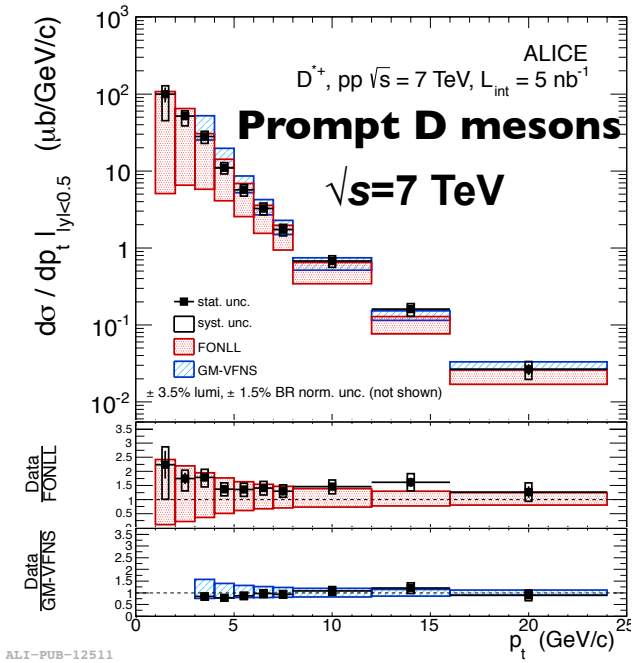
Displaced J/ψ (from B decays)



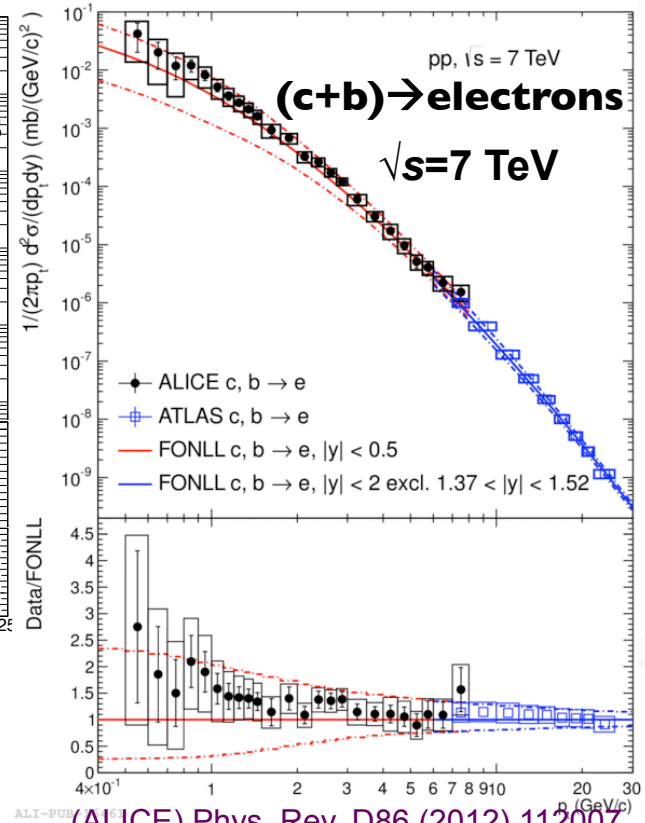
pp



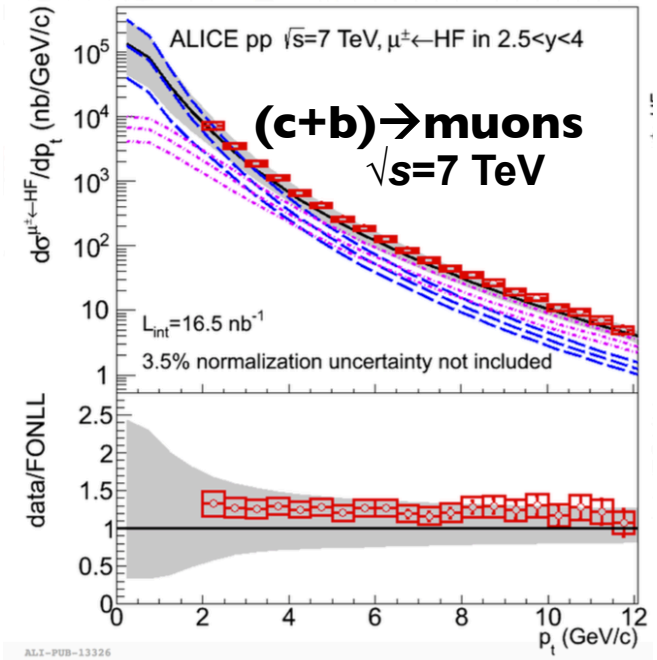
Test for pQCD and reference for p-A and A-A collisions



JHEP 1201 (2012) 128



(ALICE) Phys. Rev. D86 (2012) 112007
(ATLAS) PLB 707 (2012) 438



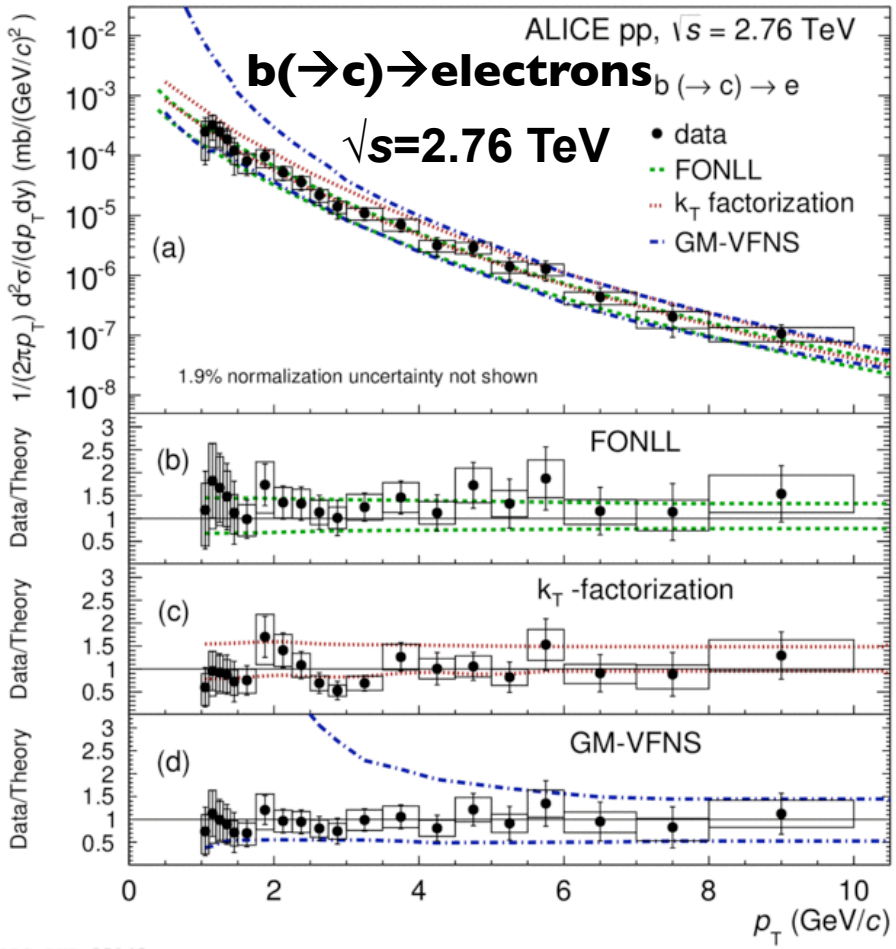
PLB 708 (2012) 265

FONLL: JHEP0407 (2004) 033,
JHEP, 1210 (2012) 137.
GM-VFNS:Eur.Phys.J., C72 (2012) 2082.
LO k_T fact: Phys.Rev., D87 (2013) 094022.

Cross sections described by FONLL, GM-VFNS, k_T factorization pQCD calculations

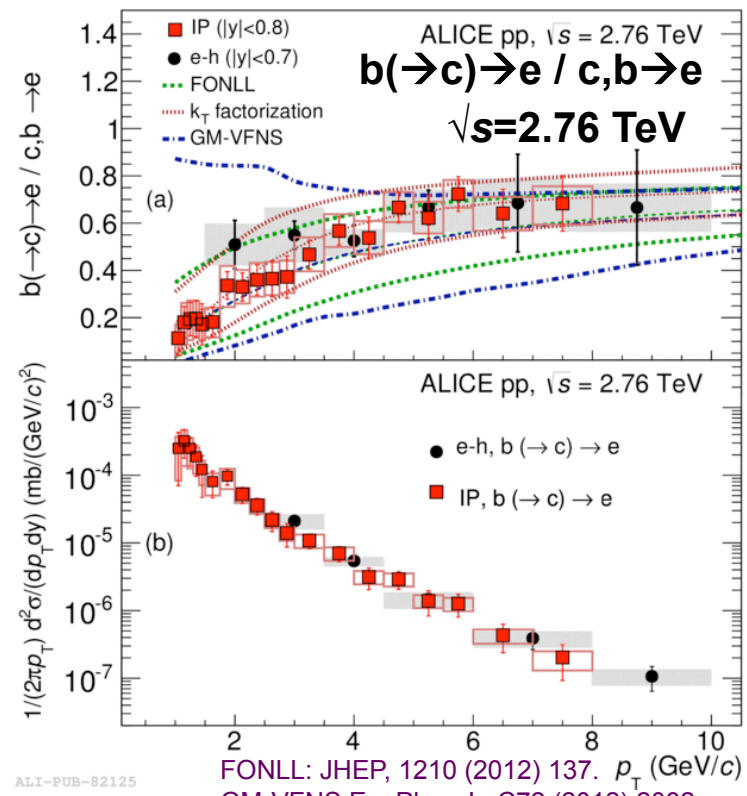
Low p_T semi-leptonic cross section in good agreement with ATLAS at high p_T

Leptons from heavy-flavour decay: beauty



Phys. Rev. D 91, 012001 (2015), PLB 738 (2014) 97-108

Separation between charm and beauty via displaced decay electrons

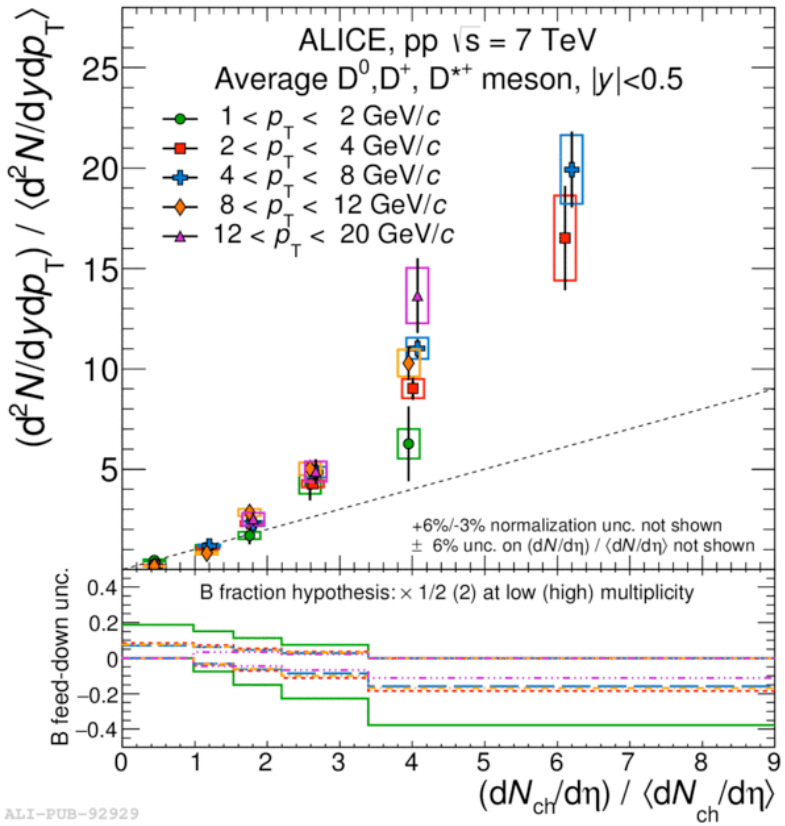


FONLL: JHEP, 1210 (2012) 137.
GM-VFNS:Eur.Phys.J., C72 (2012) 2082.
LO k_T fact: Phys.Rev., D87 (2013) 094022.

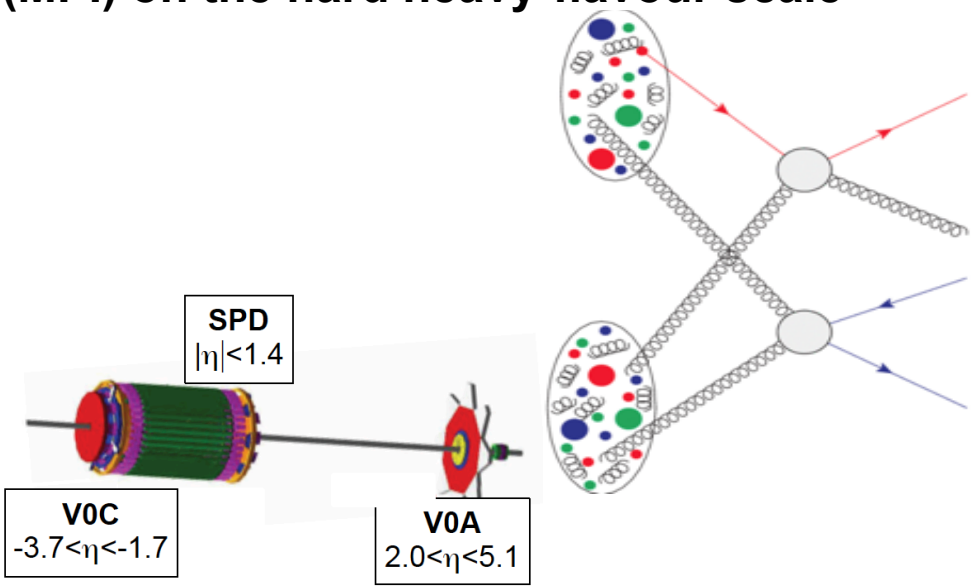
Same agreement with FONLL calculations as at 7 TeV

More differential measurements: D mesons vs multiplicity

ALICE, JHEP 09 (2015) 148.



Study the effect of multi-parton interactions (MPI) on the hard heavy-flavour scale



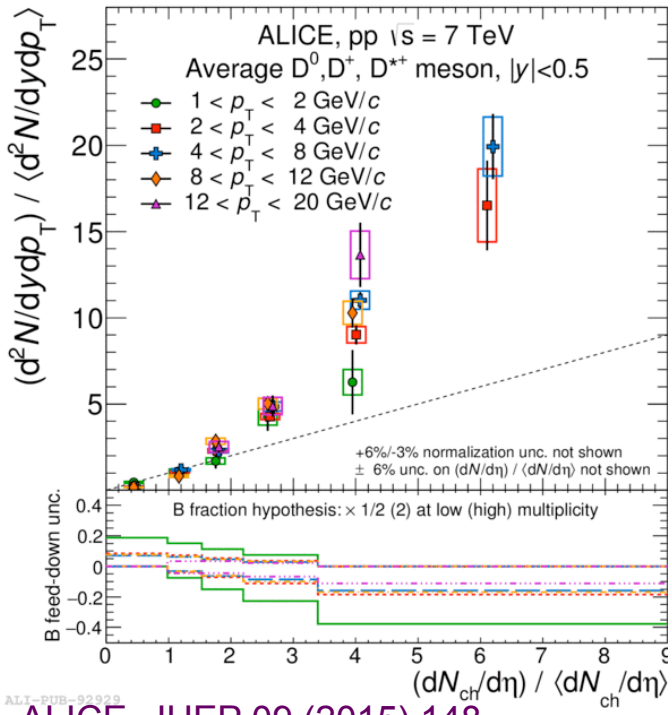
Multiplicity measured at mid-rapidity (SPD tracklets)

Results from different p_T ranges in agreement within the uncertainties

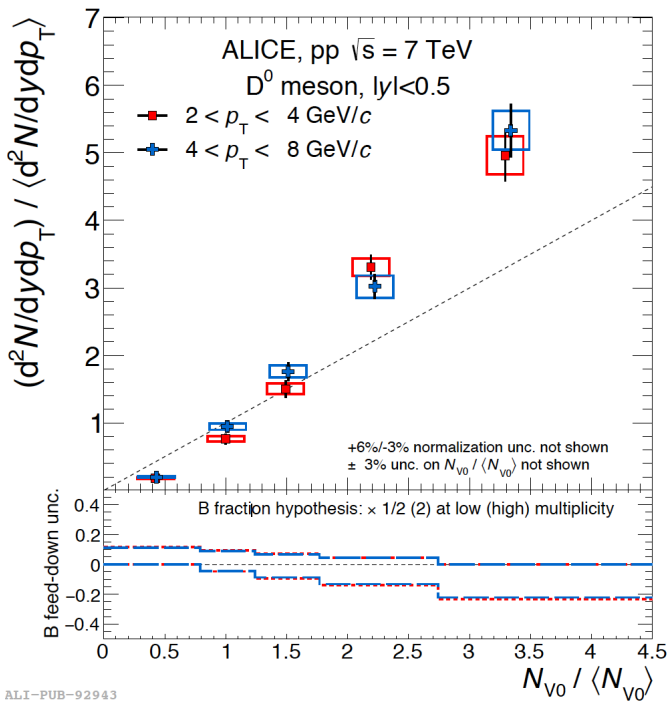
Increasing trend of D-meson yield vs charged multiplicity in pp collisions → models including an MPI contribution seem to describe the data

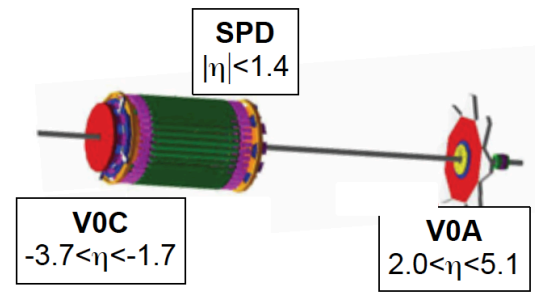
More differential measurements: D mesons vs multiplicity

Multiplicity at mid-rapidity



Multiplicity at large rapidity (V0A,V0C)





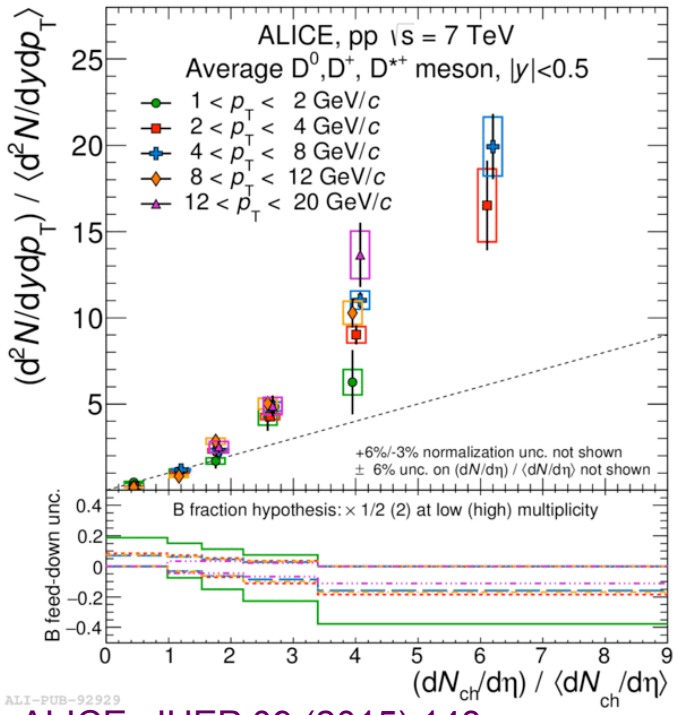
ALICE, JHEP 09 (2015) 148.

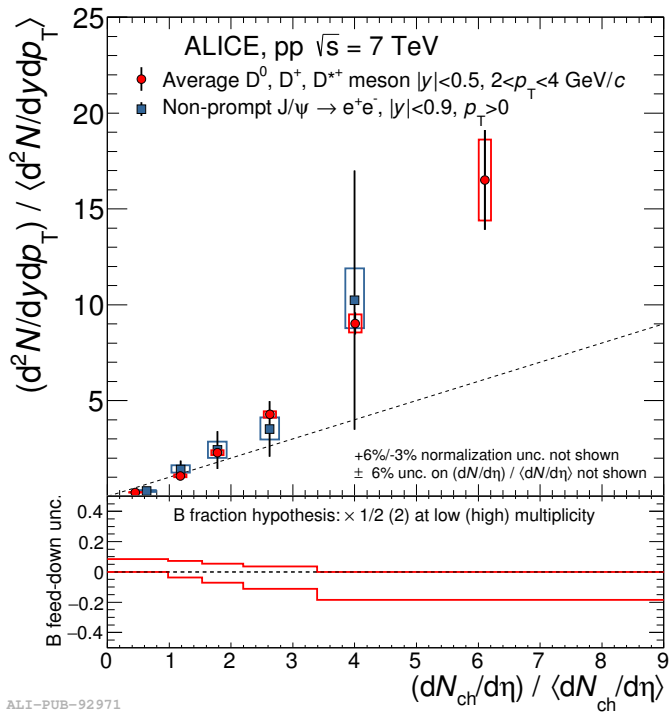
Investigate effect of auto-correlations using multiplicity measured in a different rapidity range than heavy-flavour yields.

Qualitatively similar increasing trend of D-meson yields when a η gap is introduced

More differential measurements: D mesons vs multiplicity

non-prompt J/Ψ → e⁺e⁻



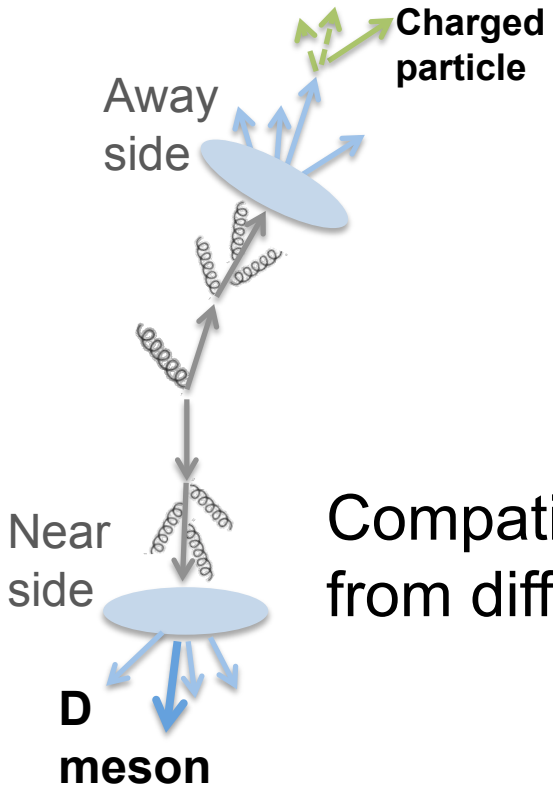


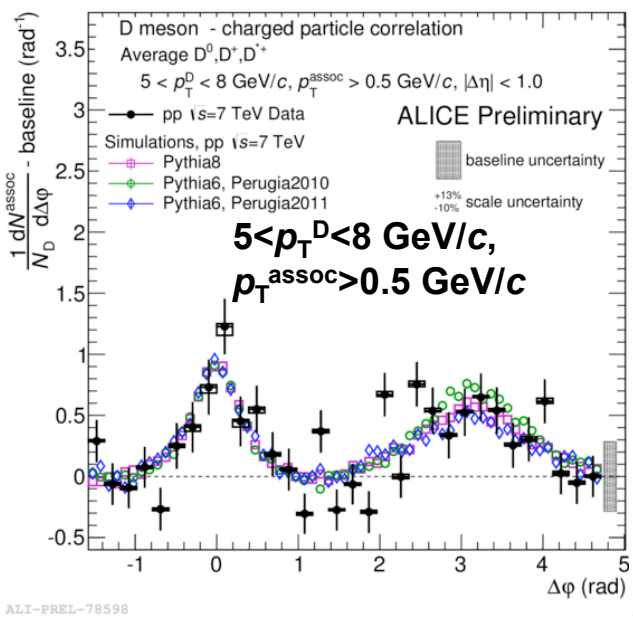
ALICE, JHEP 09 (2015) 148.

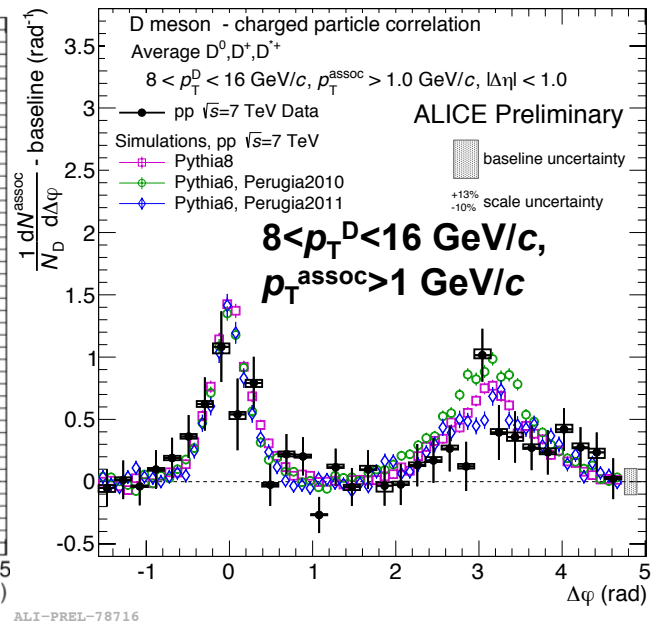
Similar increase of open charm and open beauty as a function of multiplicity at mid-rapidity

More differential measurements: D meson – charged particles correlations

Sensitive to **charm production and fragmentation**
→charm jet properties
→constrain models

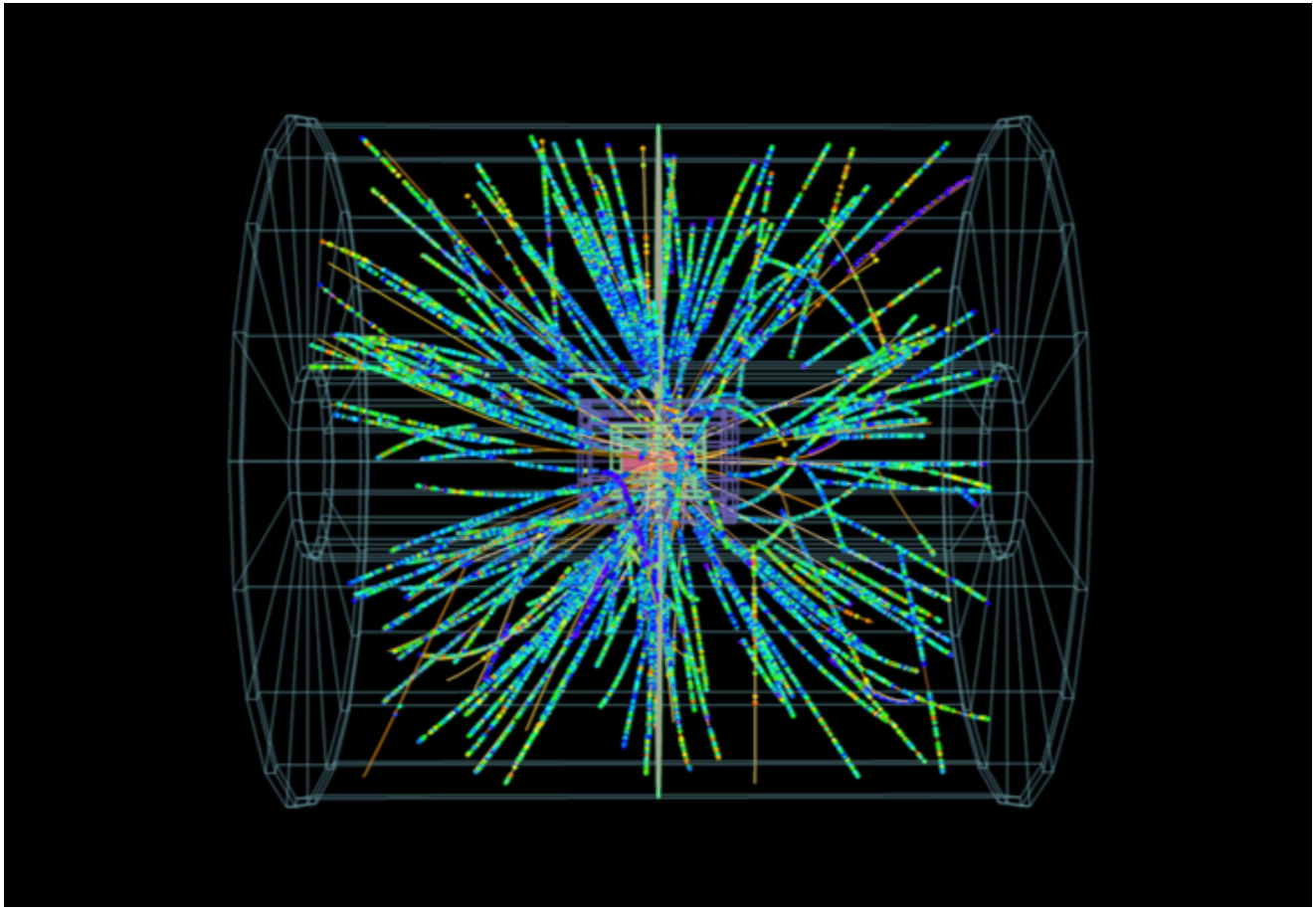






Compatible within uncertainties with expectations from different Pythia tunes after baseline subtraction

p-Pb



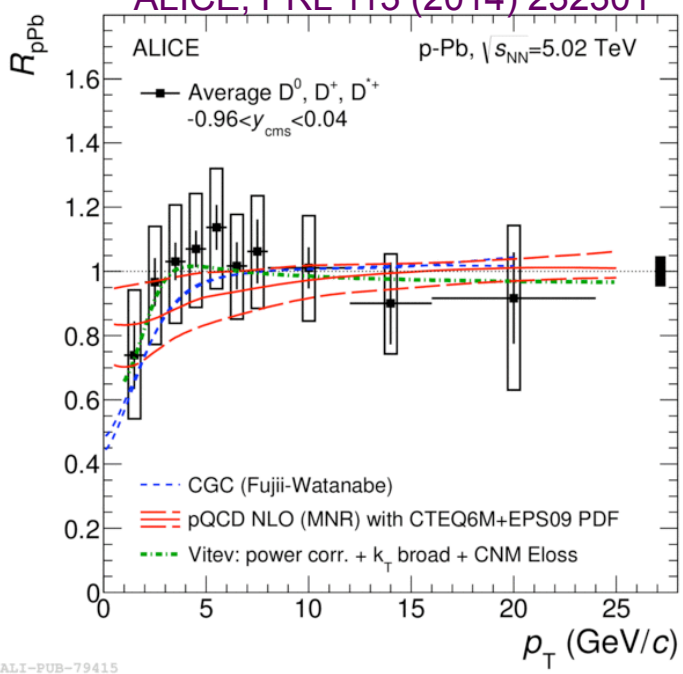
p-A: control experiment

$$R_{pPb} = \frac{(d\sigma/dp_T)_{pPb}}{A \times (d\sigma/dp_T)_{pp}}$$

Mid-rapidity

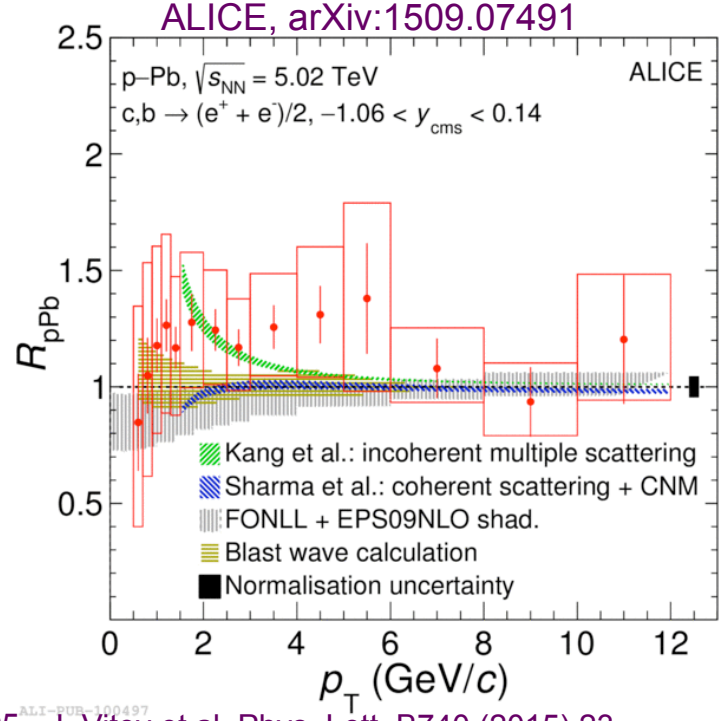
D mesons

ALICE, PRL 113 (2014) 232301



HF decay electrons

ALICE, arXiv:1509.07491

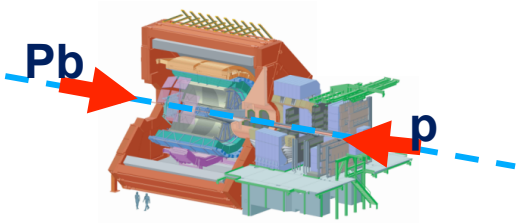


M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B373 (1992) 295
K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP 04 (2009) 065
R. Sharma, I. Vitev, B. Zhang, Phys. Rev. C 80 (2009) 054902
Fujii - Watanabe, private communication

I. Vitev et al. Phys. Lett. B740 (2015) 23
A. Sickles, Phys. Lett. B731 (2014) 51
M. Cacciari et al. JHEP 05 (1998) 007

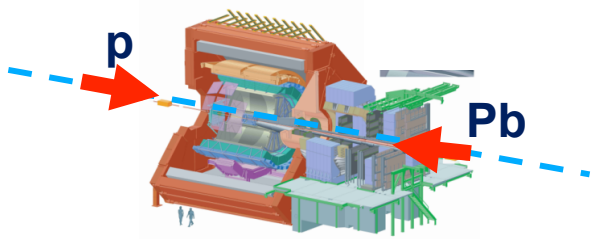
R_{pPb}~1 for D mesons (p_T>2 GeV/c) and HF decay electrons in p-Pb collisions
Models with CNM describe the data within the uncertainties

p-A: control experiment



$-4.46<y_{CMS}<-2.96$

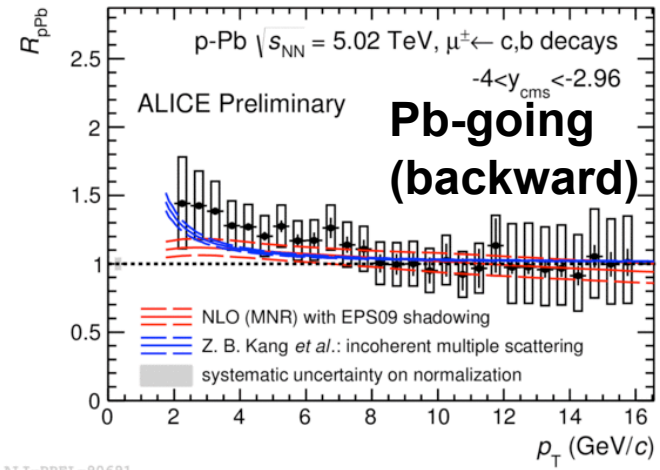
$10^{-2}<x<5\cdot10^{-2}$

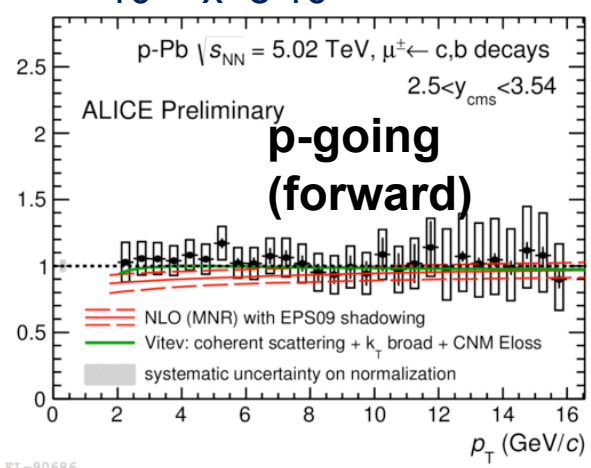


$2.03<y_{CMS}<3.53$

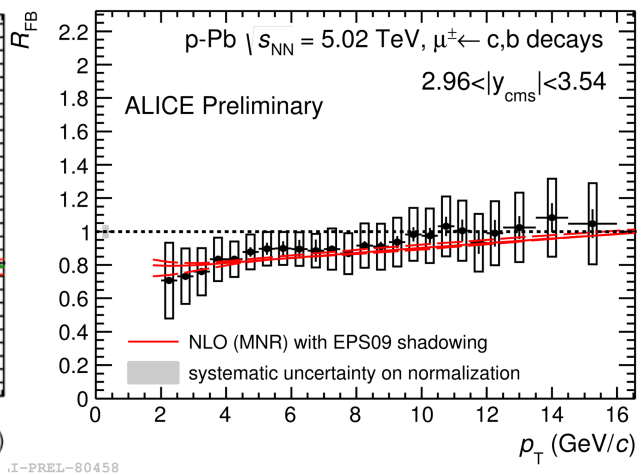
$10^{-5}<x<8\cdot10^{-5}$

Forward and backward rapidity





Forward/backward



M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B373 (1992) 295
K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP 0904 (2009) 065
R. Sharma, I. Vitev et al., PRC 80 (2009) 054902
Z.B. Kang et al., PLB 740 (2015) 23

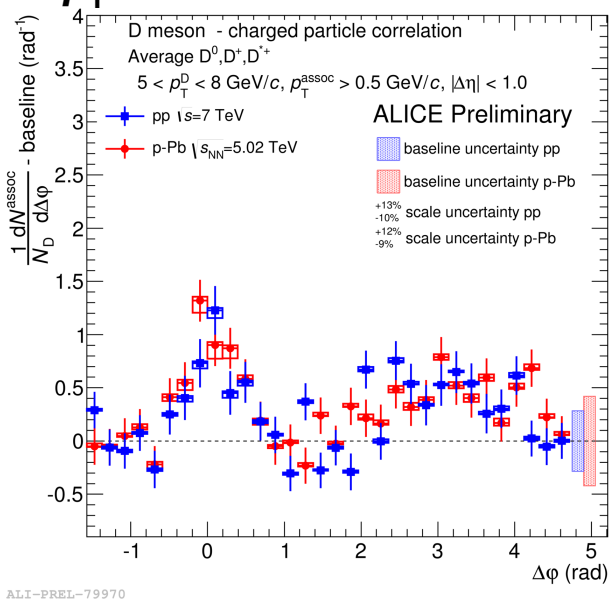
Different *x* regimes explored in different rapidity ranges with HF probes

→shadowing/saturation relevant at low p_T at the LHC

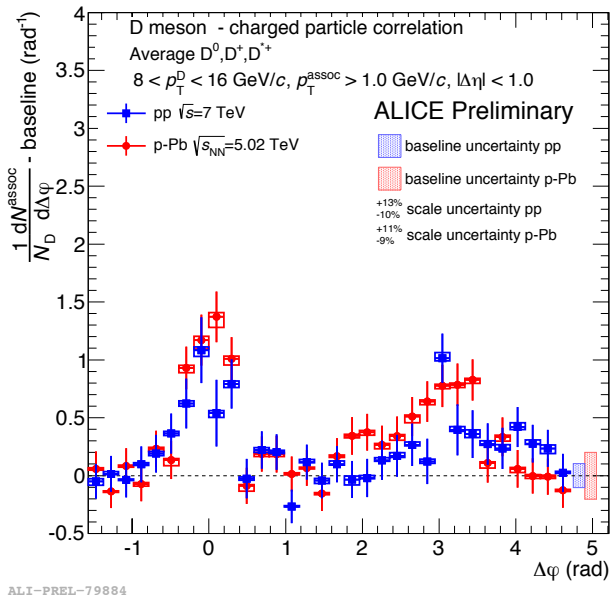
Data described within uncertainties by the models with initial-state effects

p-A: D-h correlations

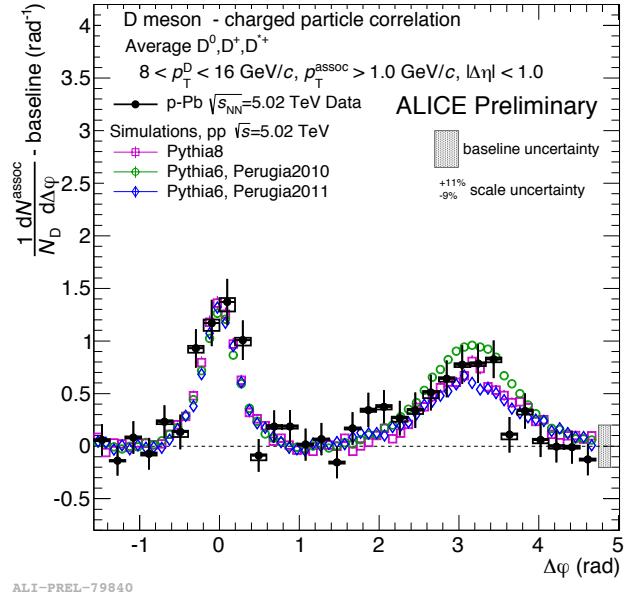
pp&p-Pb: $5<p_T^D<8$ GeV/c
$p_T^{assoc}>0.5$ GeV/c



pp&p-Pb: $8<p_T^D<16$ GeV/c
$p_T^{assoc}>1$ GeV/c



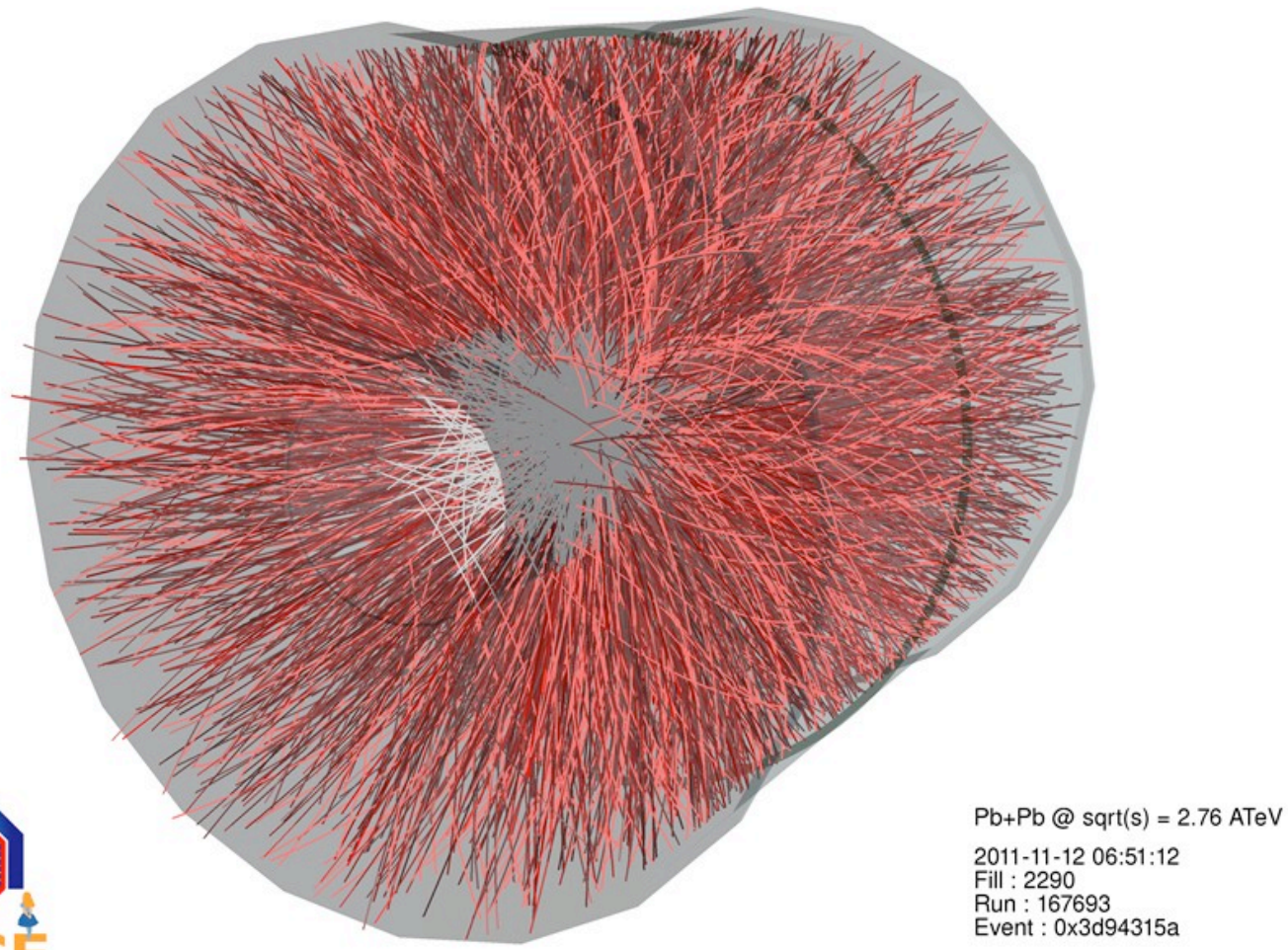
p-Pb&PYTHIA: $8<p_T^D<16$ GeV/c
$p_T^{assoc}>1$ GeV/c



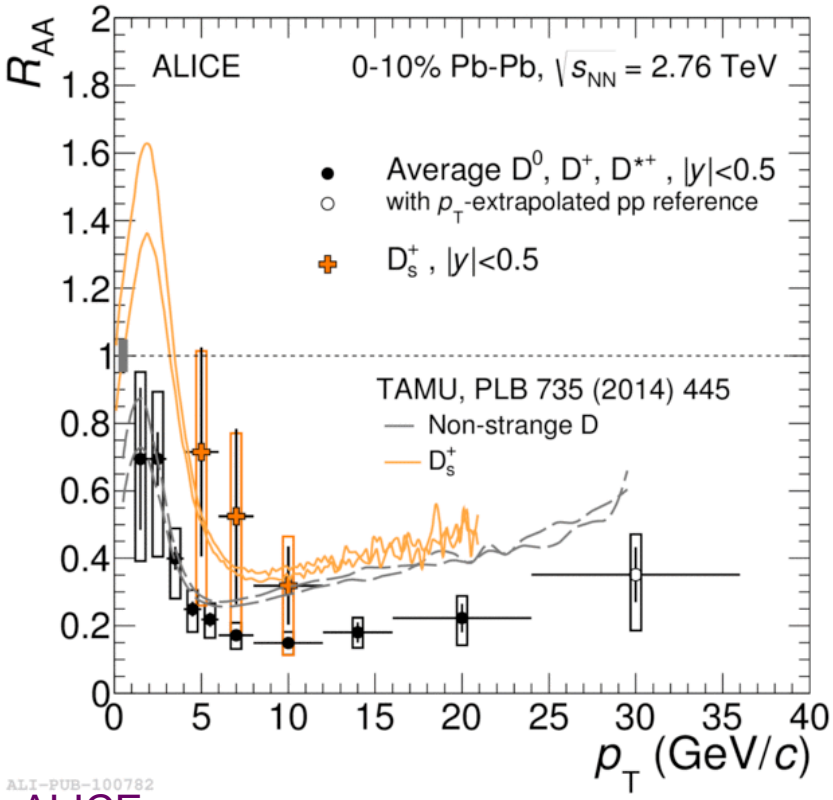
Compatibility within uncertainties between pp collisions at $\sqrt{s}$ = 7 TeV and p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV after baseline subtraction

p-Pb data described well by Pythia

Pb-Pb


Pb+Pb @ sqrt(s) = 2.76 ATeV
2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a

D-meson R_{AA}



ALICE:
arXiv:1509.06888
arXiv:1509.07287

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

Large suppression in a wide p_T range:

- factor of 4-5 in $5<p_T<15$ GeV/c

D_s in Pb-Pb collisions:

- suppression by a factor 3-5 in 8-12 GeV/c
- low-p_T R_{AA} described by TAMU model based on on heavy-quark diffusion and hadronization via recombination

TAMU, Phys. Lett. B 735 (2014) 445

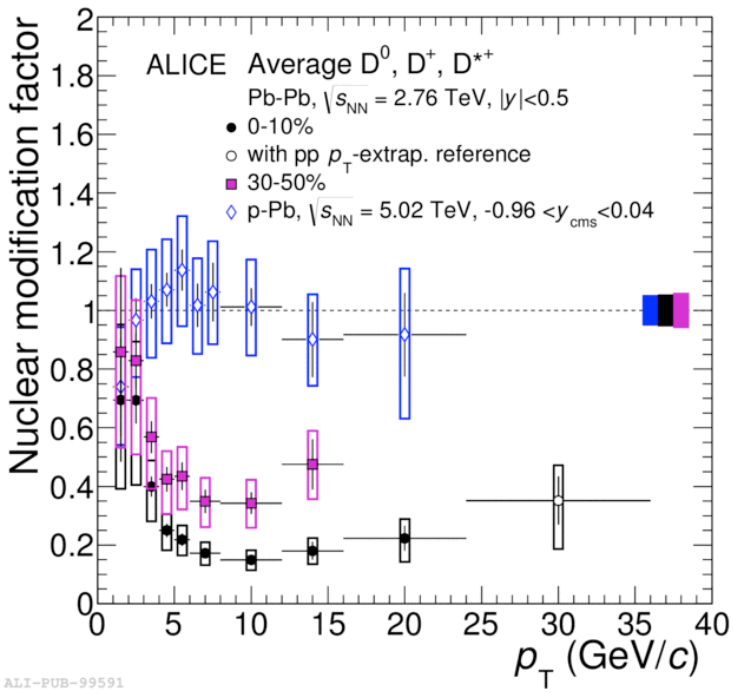
- more statistics needed to conclude on possible enhancement at low p_T due to c-quark recombination with strange quarks

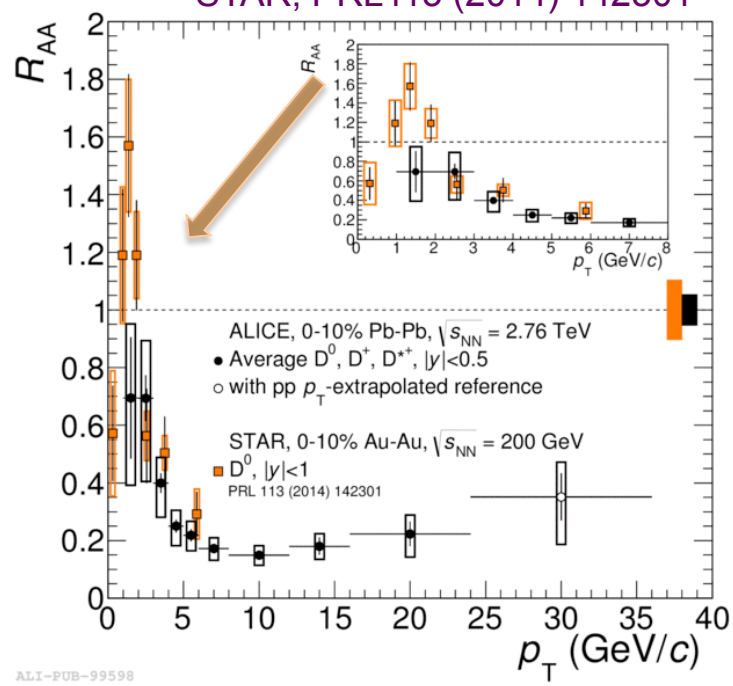
Kuznetsova, Rafelski, EPJ C51(2007)113
He et al., arXiv:1204.4442;
Andronic et al., arXiv:0708.1488

Strong charm energy loss in the medium

D-meson R_{AA}

ALICE:
arXiv:1509.06888
arXiv:1509.07287
STAR, PRL113 (2014) 142301





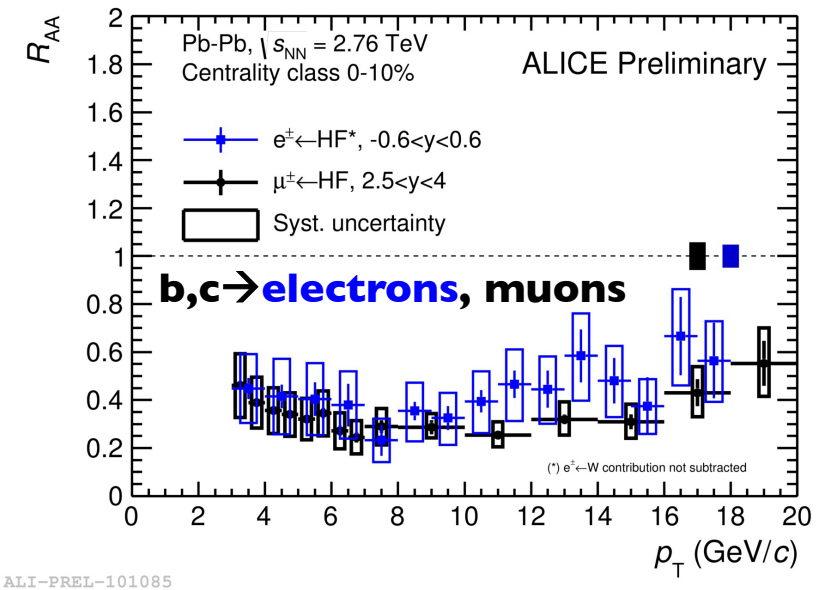
Strong suppression in central and semi-central Pb-Pb collisions at intermediate-high p_T **due to final-state effects** (R_{pPb}~1)

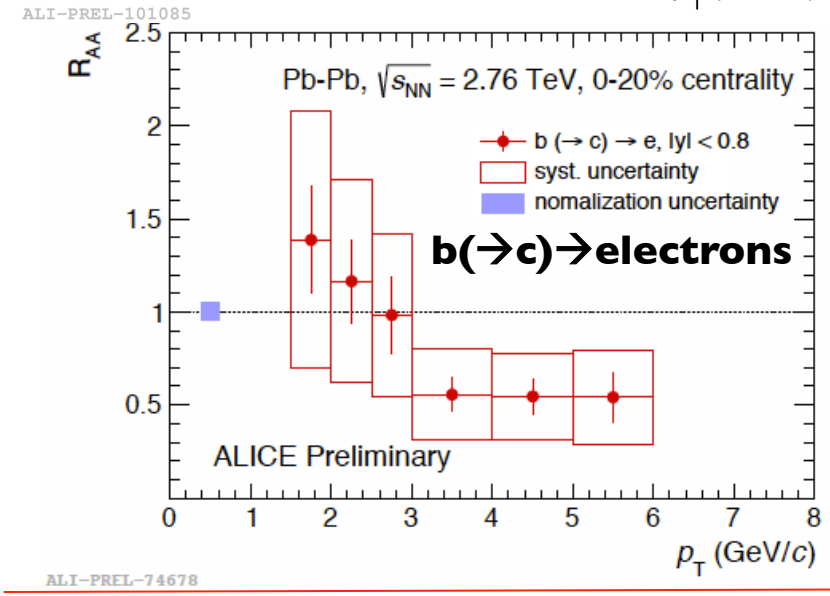
D mesons at RHIC vs LHC: different R_{AA} trend for p_T<2 GeV/c?

Stronger shadowing, less steep pp spectrum at LHC, different effect of radial flow and coalescence. Some models (TAMU, Phys. Lett. B 735 (2014) 445) can describe both results.

Low-p_T measurements crucial to test binary scaling in charm production

R_{AA} of heavy-flavour decay leptons





Similar suppression of **electrons and muons from heavy-flavour** hadron decays at the LHC.

Different rapidity ranges:

electrons: |y|<0.6

muons: 2.5<y<4

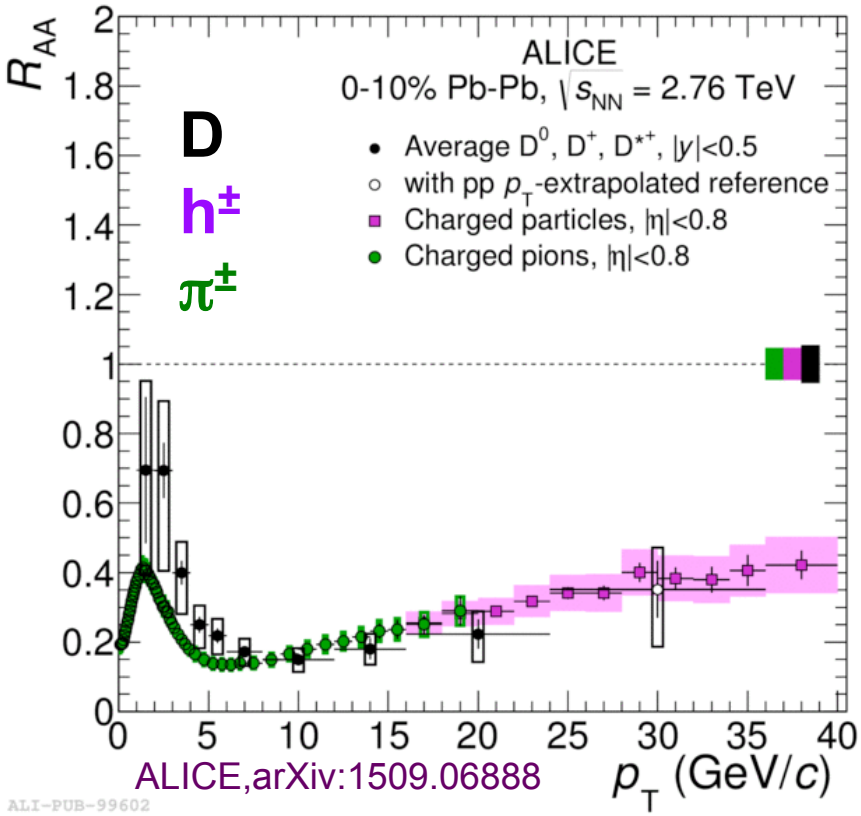
ALICE, PRL 109 (2012) 112301 (HF decay muons)

Electrons from beauty-hadron decays in Pb-Pb collisions.

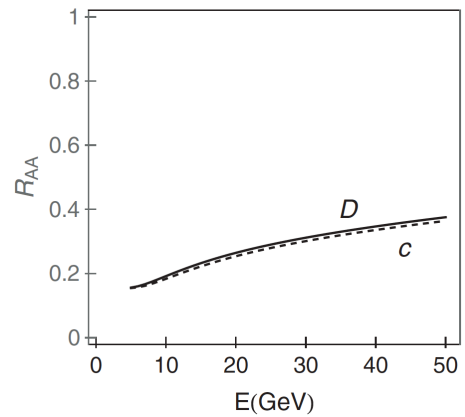
Hint for suppression for p_T>3 GeV/c

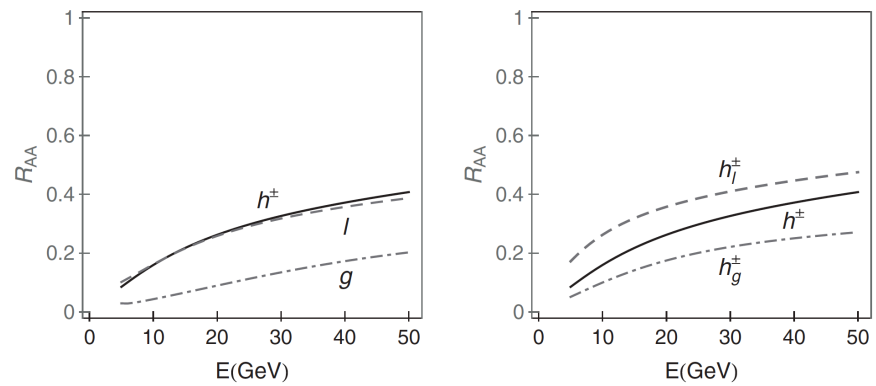
R_{AA}: D mesons and charged hadrons

Mass/colour dependence of energy loss?



ALICE,arXiv:1509.06888





M.Djordjevic, PRL 112, 042302 (2014)

R_{AA}(D)~R_{AA}(π,h±) ΔE(udsg)>ΔE(c) ? R_{AA}(D)>R_{AA}(π,h±)

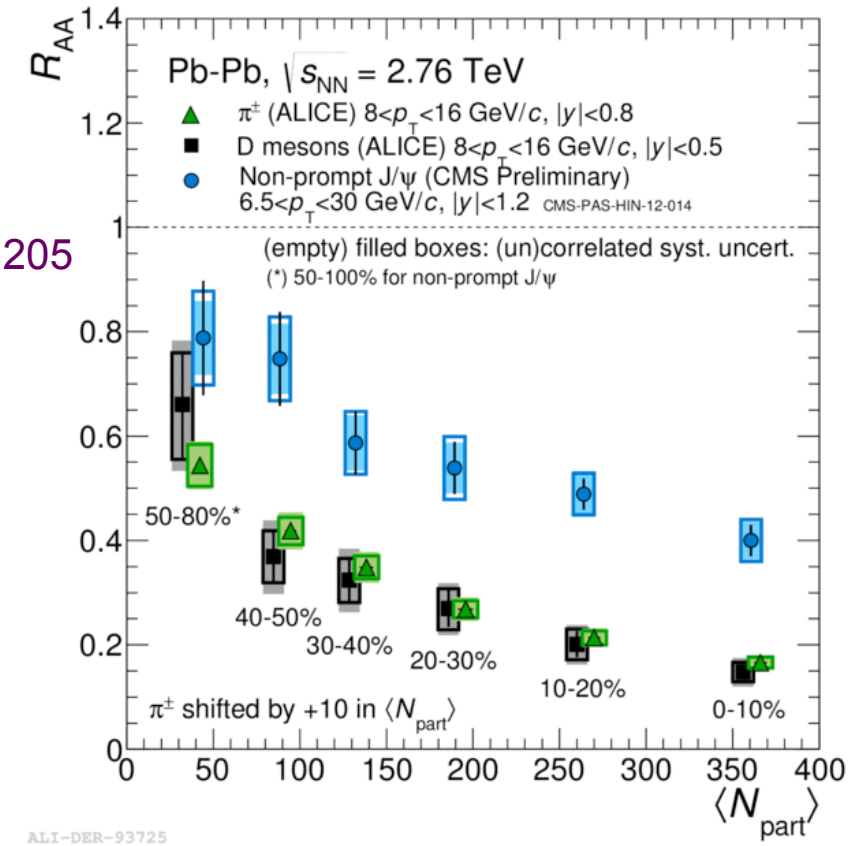
Described by models with:

- Mass and colour charge dependent energy loss
- Different quark p_T spectra
- Different fragmentation functions for light quarks, heavy quarks and gluons

R_{AA}: D mesons and non-prompt J/ψ

Mass dependence of energy loss?

ALICE, JHEP 1511 (2015) 205
CMS, PAS-HIN-12-014



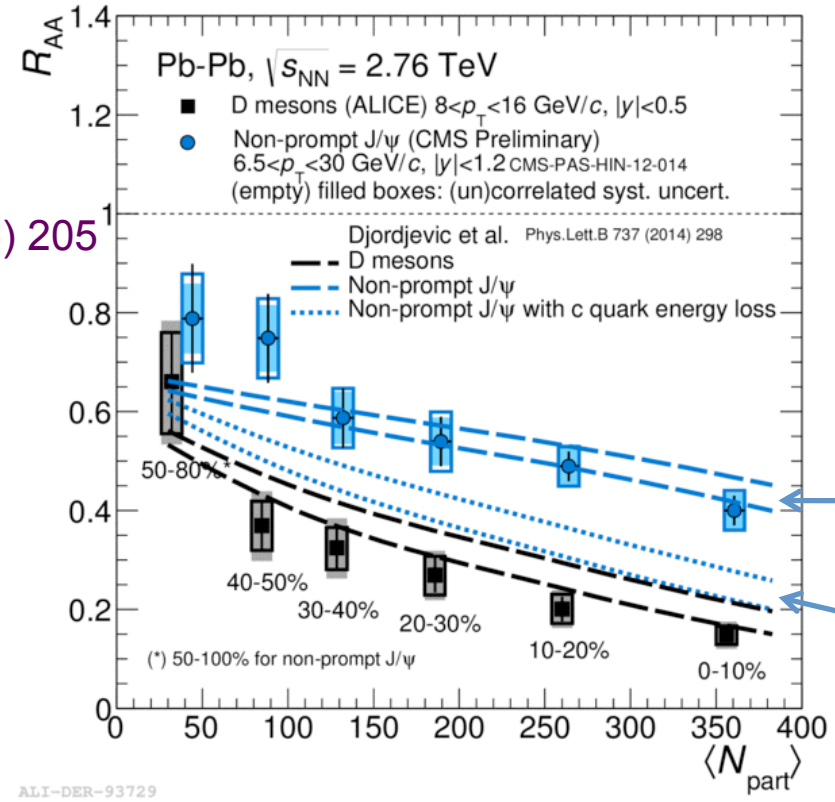
similar kinematics for D and B mesons (**<p_T>~10 GeV/c**)
different y ranges for D and non-prompt J/ψ

Indication of a difference between charm and beauty suppression in central collisions

R_{AA}: D mesons and non-prompt J/ψ

Mass dependence of energy loss?

ALICE, JHEP 1511 (2015) 205
CMS, PAS-HIN-12-014



Theory model (Djordjevic):
two assumptions on the quark mass in the energy loss to calculate non-prompt J/ψ R_{AA}:

-b quark mass

-c quark mass

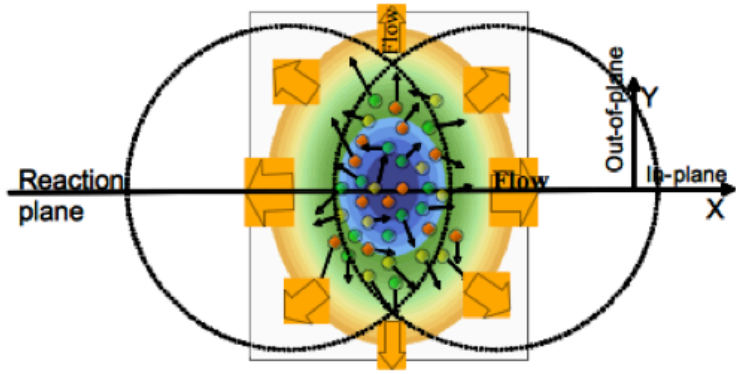
Difference comes from the different masses

M.Djordjevic, PRL 112, 042302 (2014)

similar kinematics for D and B mesons (**<p_T>~10 GeV/c**)
different y ranges for D and non-prompt J/ψ

pQCD in-medium energy loss model based on mass dependent energy loss in agreement with data

Heavy-flavour azimuthal anisotropy



In non-central Pb-Pb collisions:

initial spatial asymmetry → azimuthal anisotropy of final hadrons

→non-isotropic azimuthal emission can be parametrized by:

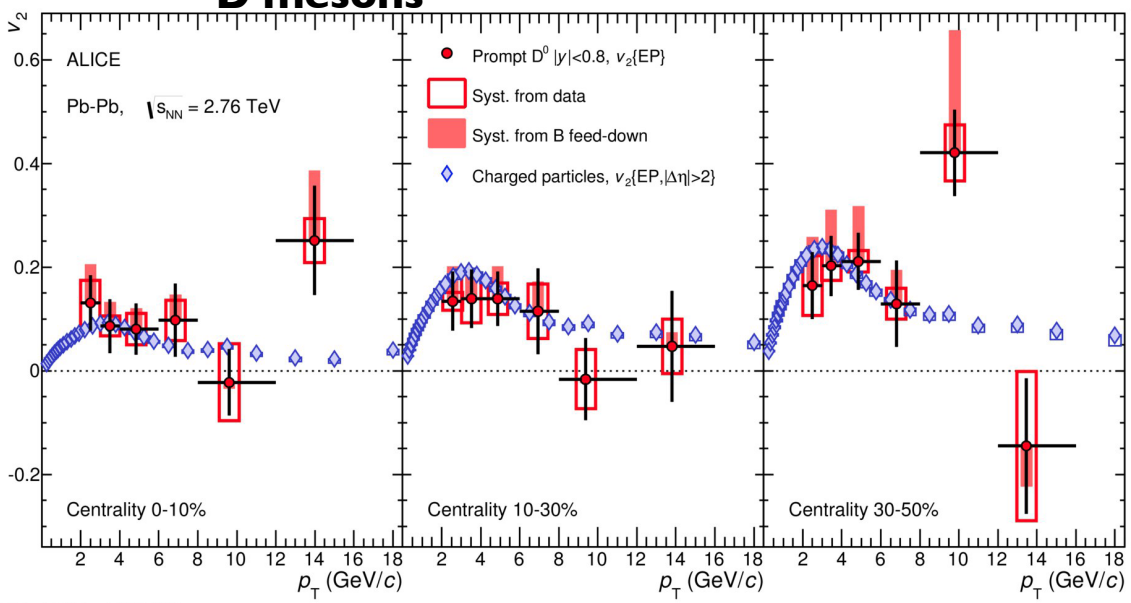
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \dots\right)$$

Can originate from:

- thermalization/collective motion (low p_T)
- path-length dependence of energy loss (high p_T)

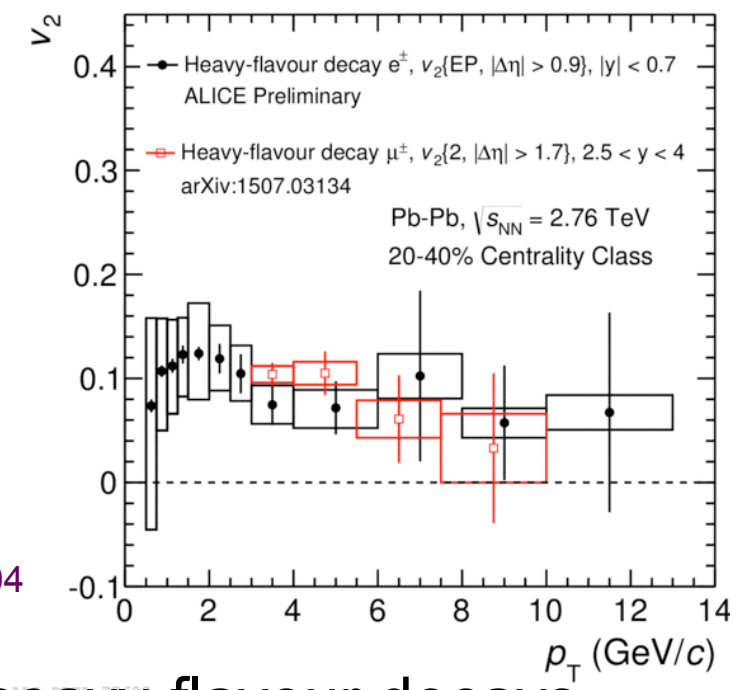
Heavy-flavour azimuthal anisotropy

D mesons



ALICE, PRL 111, 102301 (2013)
ALICE, Phys.Rev. C90 (2014) 3, 034904
ALICE, Phys.Lett. B753 (2016) 41

(c,b)→electrons, muons



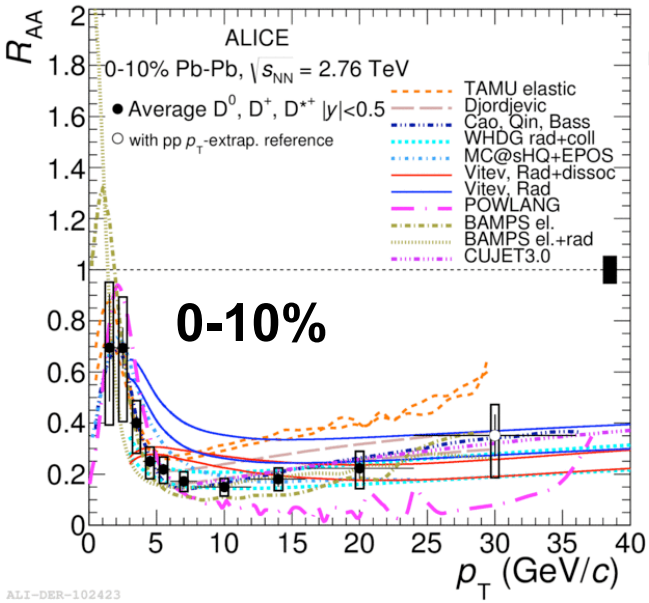
Positive v_2 for D mesons and e/μ from heavy-flavour decays

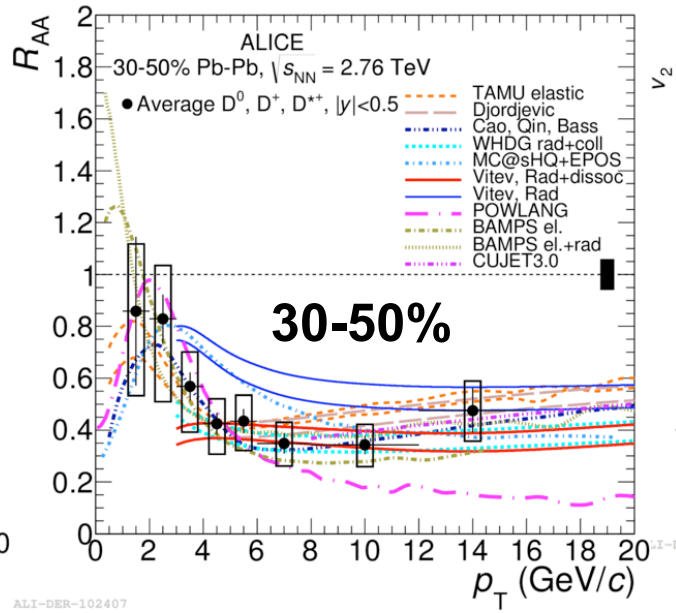
D-meson $v_2>0$ in $2<p_T<6$ GeV/c (with 5.7σ), compatible with v_2 of charged particles

Hint for collective motion of charm quarks at low p_T

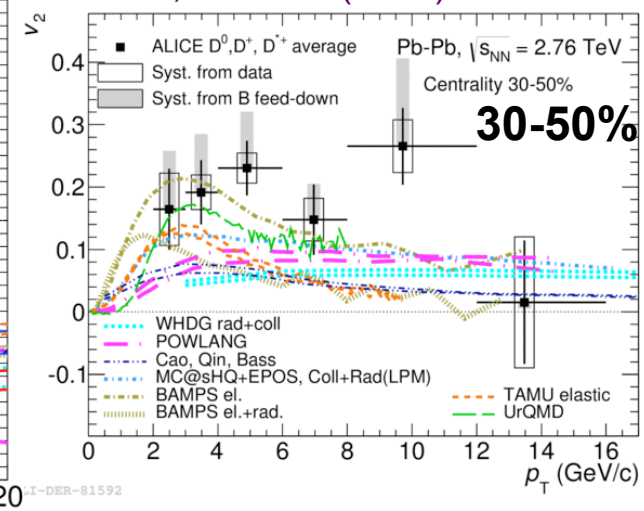
R_{AA} and v_2: constraints to models

ALICE,arXiv:1509.06888





ALICE, PRL 111 (2013) 102301



R_{AA} and v_2 results start to provide constraints to models.

Simultaneous description of heavy-flavour R_{AA} and v_2 still challenging.

More precise measurements needed to further constrain models

BAMPS: Fochler et al., J. Phys. G38 (2011) 124152
POWLANG: Alberico et al., Eur.Phys.J C71 (2011) 1666
UrQMD: T. Lang et al, arXiv:1211.6912 [hep-ph];
T. Lang et al., arXiv:1212.0696 [hep-ph].
TAMU: Rapp, He et al., Phys. Rev. C 86 (2012) 014903
WHDG: Horowitz et al., JPhys G38 (2011) 124114
Aichelin et al.:Phys. Rev. C79 (2009) 044906
J. Phys. G37 (2010) 094019

Summarizing ALICE HF from Run I

Large array of heavy-flavour measurements from ALICE !

HF in pp collisions:

- Reference system, test for pQCD at LHC energies
- HF fragmentation properties via correlations
- Access interplay of soft and hard processes in the charm sector

HF in p-Pb collisions:

- Investigate Cold Nuclear Matter Effects in different x ranges

Summarizing ALICE HF from Run I

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- HF fragmentation properties via correlations
- Access interplay of soft and hard processes in the charm sector

HF in p-Pb collisions:

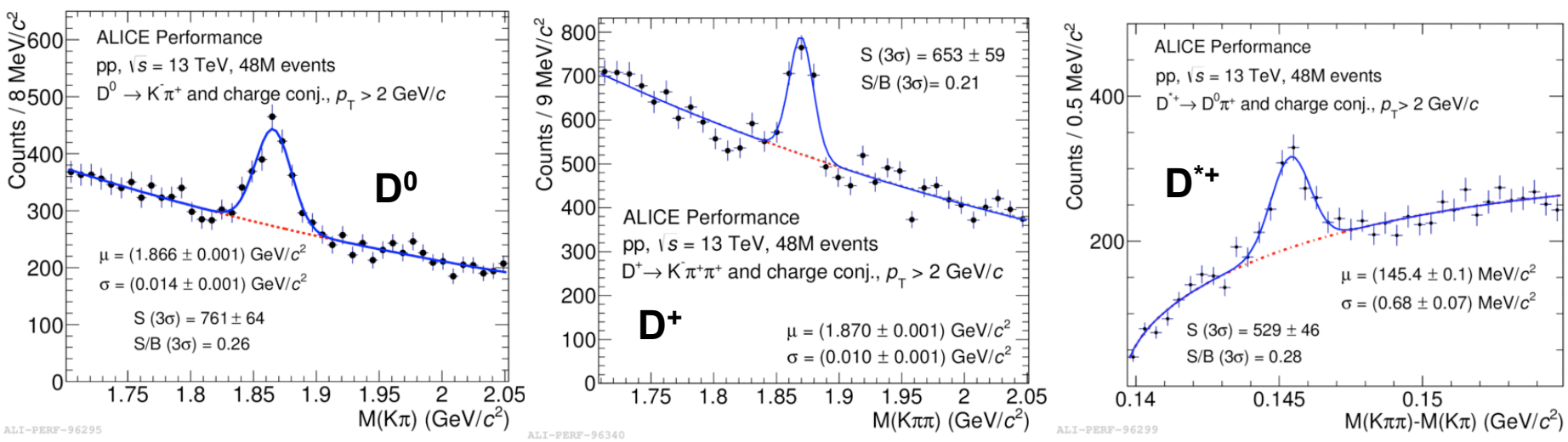
- Investigate Cold Nuclear Matter Effects in different x ranges

HF in Pb-Pb collisions:

- Open heavy flavours strongly affected by the medium
- Mass dependence of suppression trends in agreement with models
- Positive v_2 suggests collective motion for charm at low p_T

HF era in Run 2

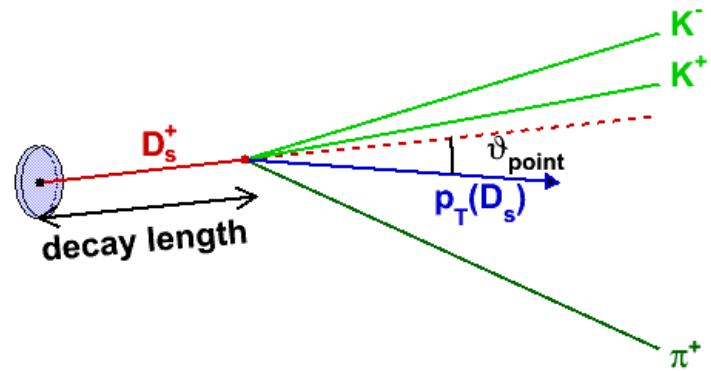
- pp collisions at $\sqrt{s}$ = 5 and 13 TeV, p-Pb,Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5 TeV
- Significant increase of statistics (L~1 nb^{-1} for Pb-Pb collisions)
  - Strangeness enhancement affects D_s production?
  - Extend p_T range, to ~0 (D^0) and to high p_T
  - Beauty at low p_T to study collectivity in the beauty sector
  - Smaller uncertainties and new differential measurements will help to further constrain theory (and add information on path-length dependence of energy loss, energy loss mechanisms, thermalization of HF, coalescence for HF,…)



Extra slides

Measurements of Heavy Flavours in ALICE: D mesons

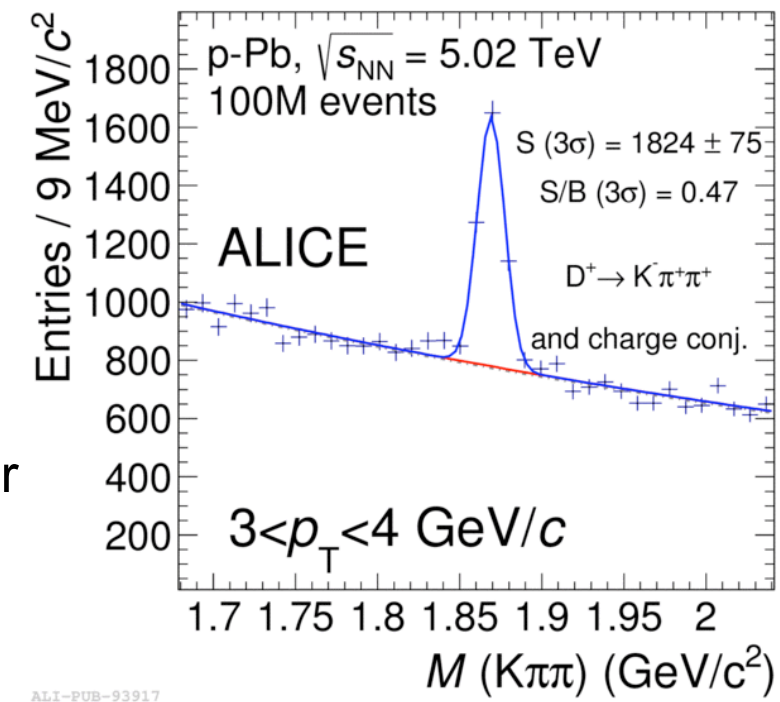
$D^0 \rightarrow K^-\pi^+$	BR: 3.88%
$D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$	BR: 2.63%
$D^+ \rightarrow K^-\pi^+\pi^+$	BR: 9.13%
$D_s^+ \rightarrow \phi(\rightarrow K^+K^-)\pi^+$	BR: 2.24%



Invariant mass analysis based on displaced secondary vertices, selected with topological cuts and PID

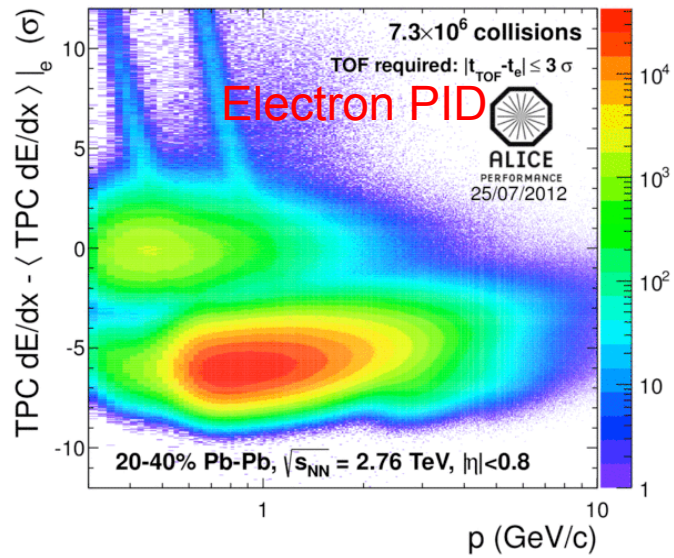
Correction for beauty feed-down (based on FONLL pQCD calculation) to extract results for prompt D mesons

FONLL: JHEP, 1210 (2012) 137



Measurements of Heavy Flavours in ALICE: electrons

Electrons: mid-rapidity



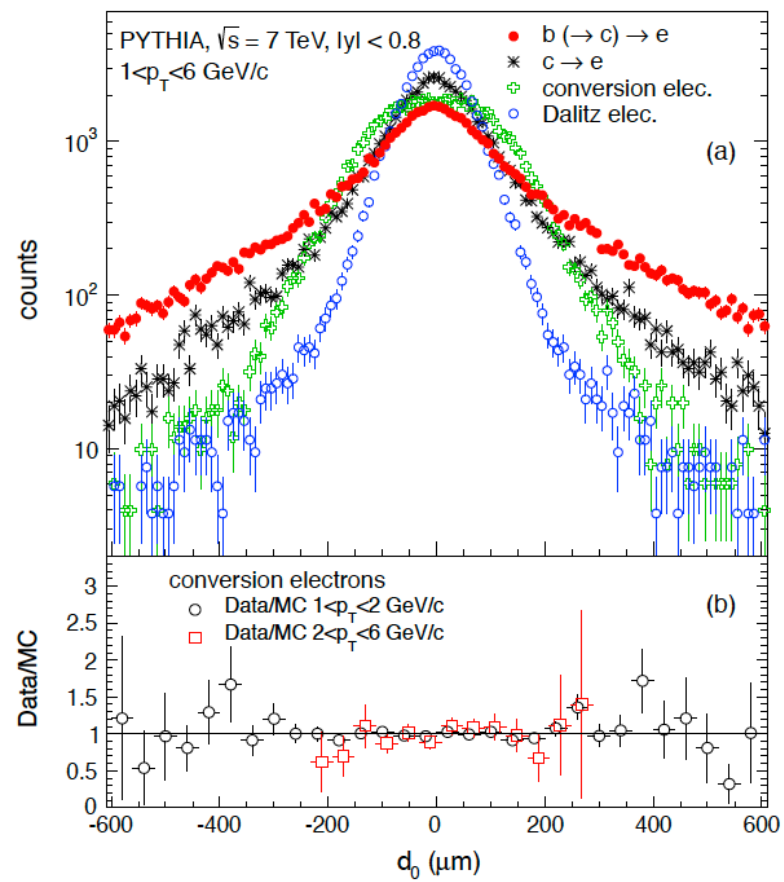
Background (mainly π^0/η Dalitz decays, photon conversions) subtracted with:

→ Invariant mass of low-mass e^+e^- pairs

→ Cocktail of different background sources with MC hadron-decay generator

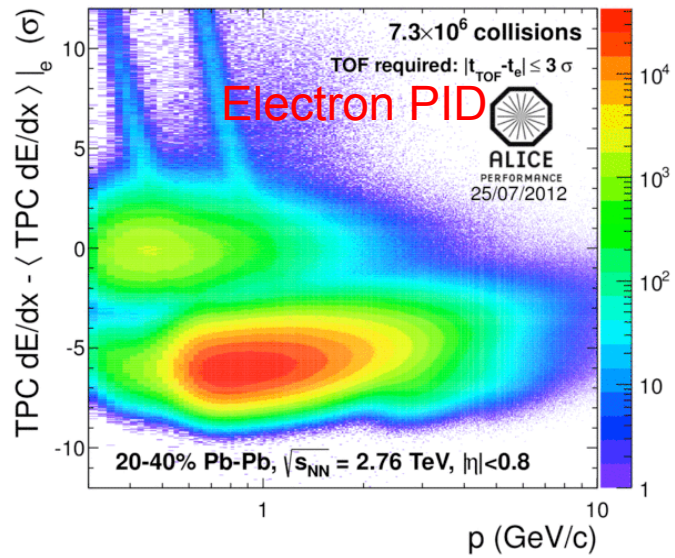
Beauty-decay electrons: extra cut on impact parameter, separation via e-h correlations

Phys.Lett. B721 (2013) 13-23



Measurements of Heavy Flavours in ALICE: electrons/muons from c and b

Electrons: mid-rapidity



Background (mainly π^0/η Dalitz decays, photon conversions) subtracted with:

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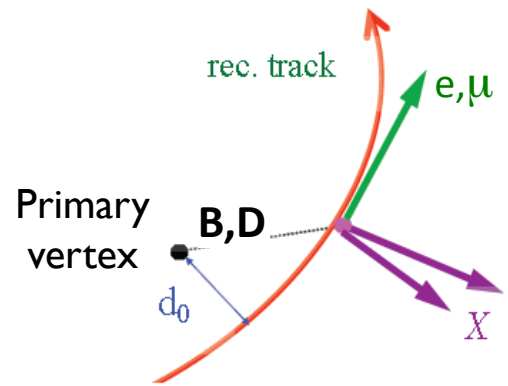
→ Cocktail of different background sources with MC hadron-decay generator

Beauty-decay electrons: extra cut on impact parameter, separation via e-h correlations

Muons: forward rapidity



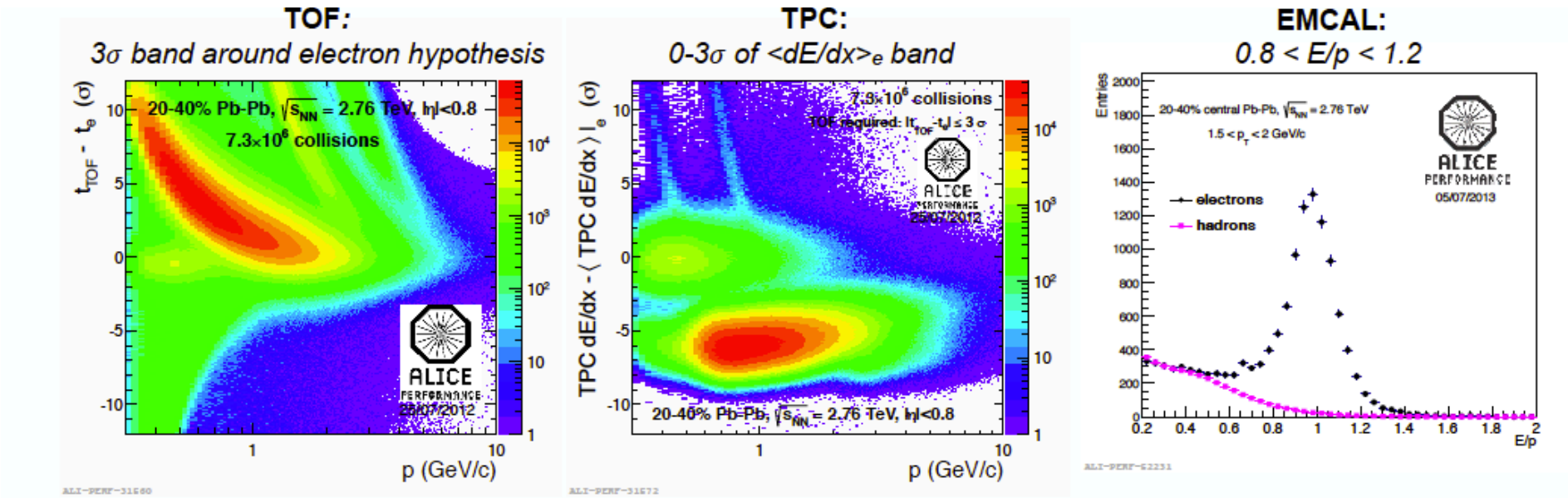
Geometrical cuts, track matching with trigger (from muon chambers)

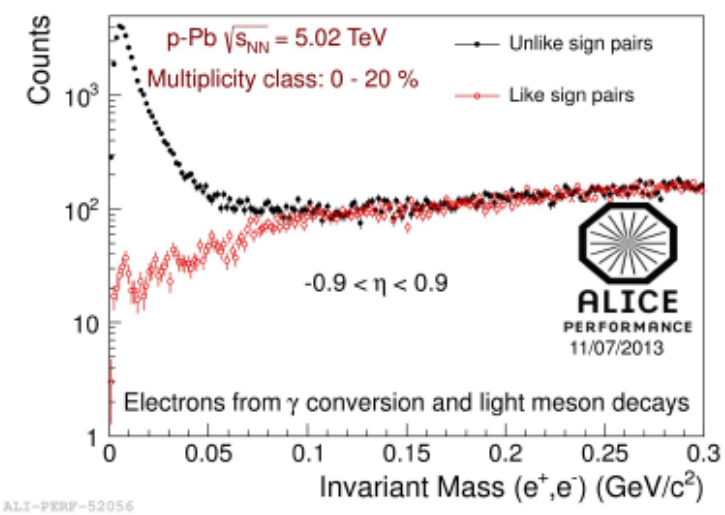
Impact parameter cut to reject part of beam-gas interactions and decays

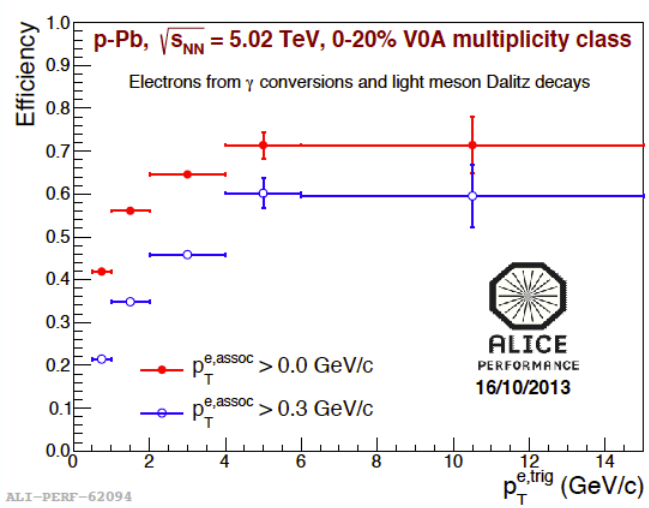
Remaining background (π,K→μ) subtracted with MC (pp) and data-tuned MC cocktail (p-Pb, Pb-Pb)

Low p_T cut to reject π, K decays > 2 (4) GeV/*c* in pp, p-Pb (Pb-Pb)

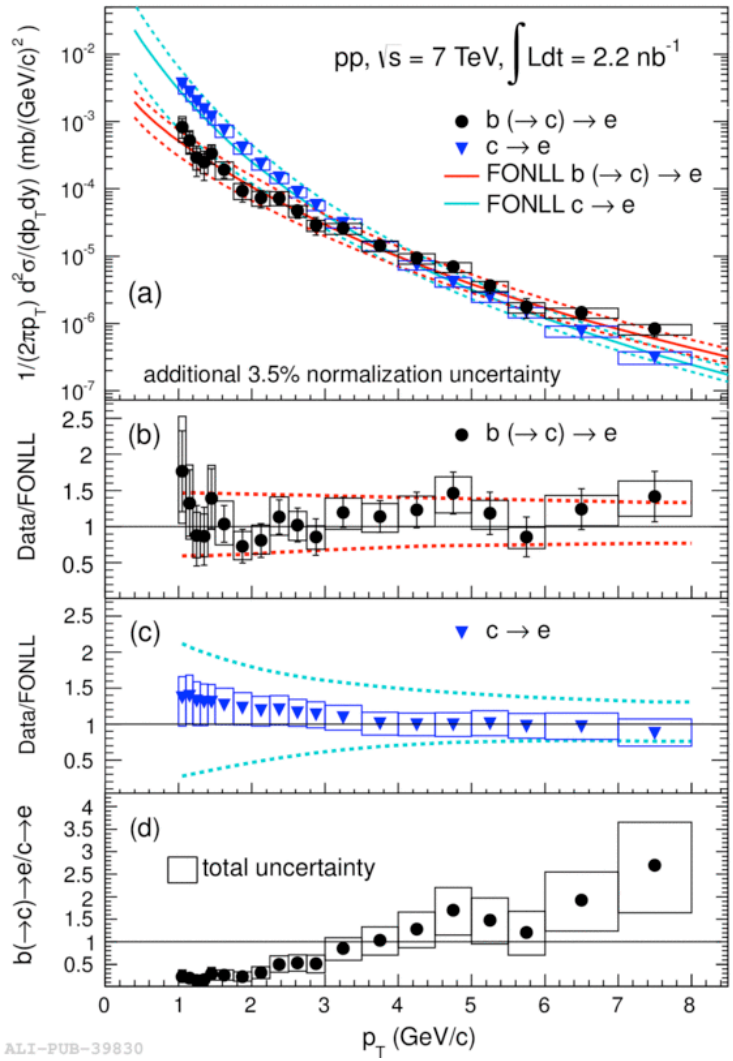
Electron identification







Beauty decay electrons in pp at 7 TeV



Physics Letters B 721 (2013) 13

Measurements of Heavy Flavours in ALICE: Beauty decay electrons

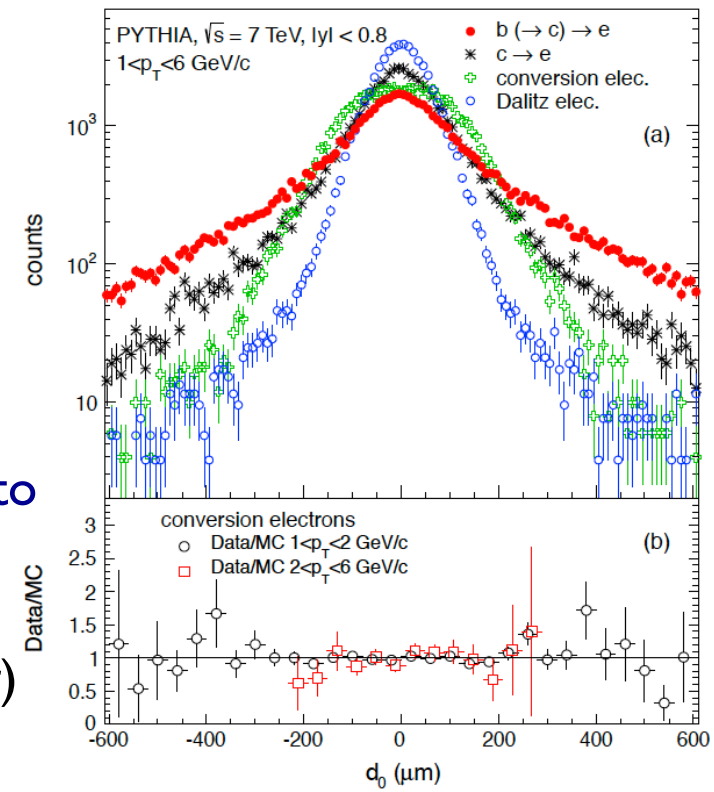
(1) electron PID: *dE/dx* (TPC) + TOF

(2) Cut on d_0 to enhance the S/B

(3) Background sources from light hadrons/quarkonia subtracted with a cocktail approach

(4) Here: residual electrons from charm decays need to be subtracted
Estimated $e^{\pm}$ yield from measured D-meson cross sections (FONLL-extrapolated to 50 GeV/*c*)

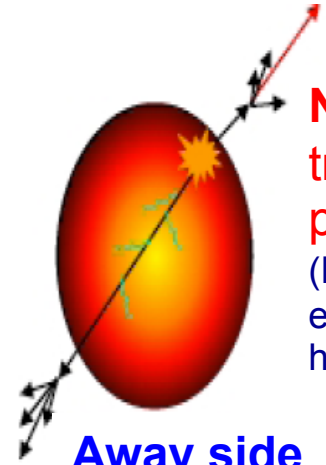
Phys.Lett. B721 (2013) 13-23



Heavy-flavour azimuthal correlations

In pp collisions:

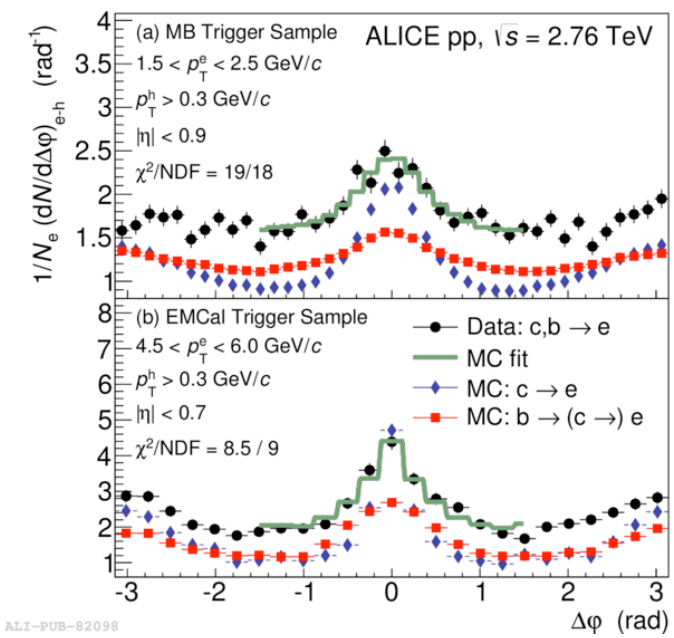
- Extract relative contributions of electrons from charm and beauty decays

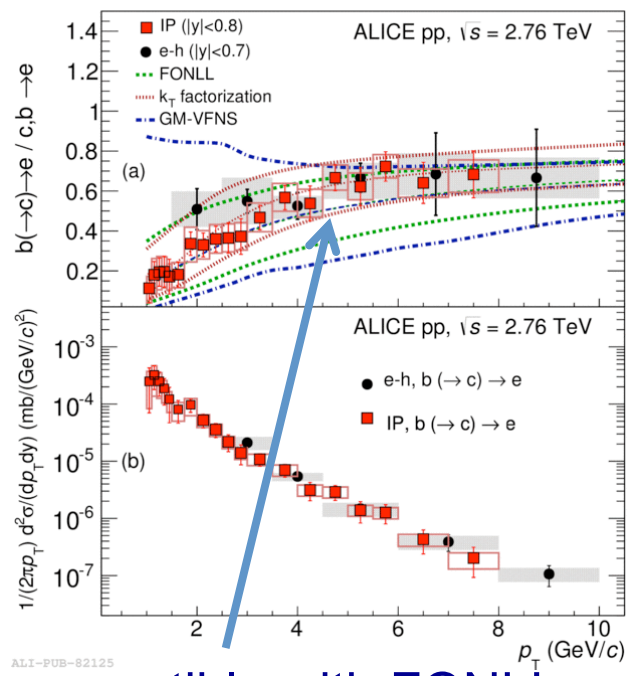


Near side trigger particle (D meson or electron from heavy-flavour)

Away side associate hadron

Heavy-flavour (HF) electron – hadron azimuthal correlations

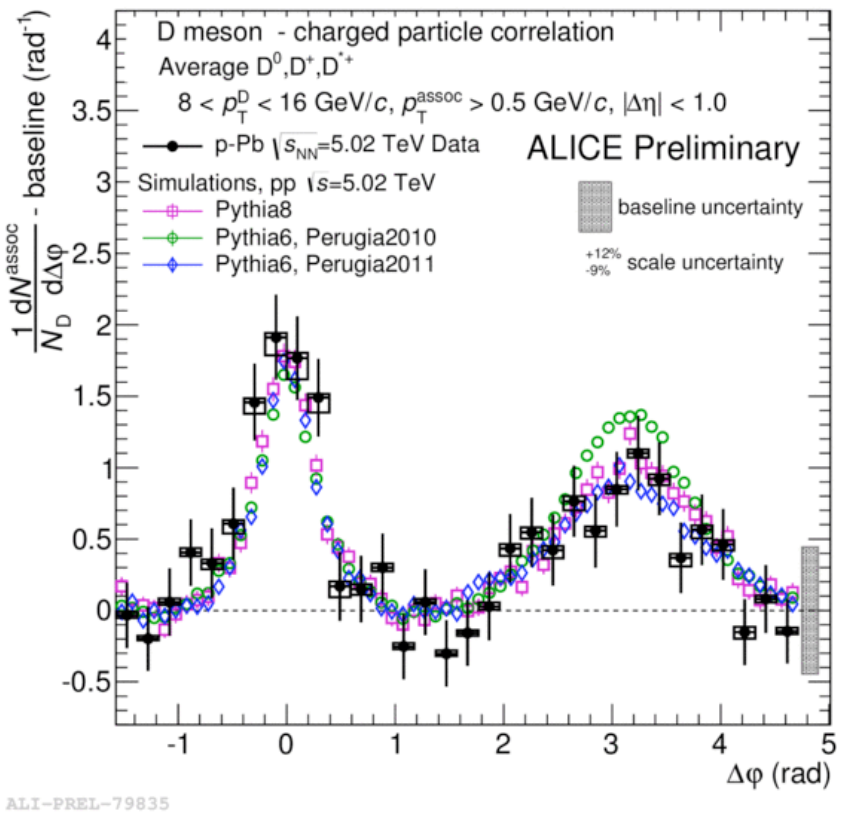




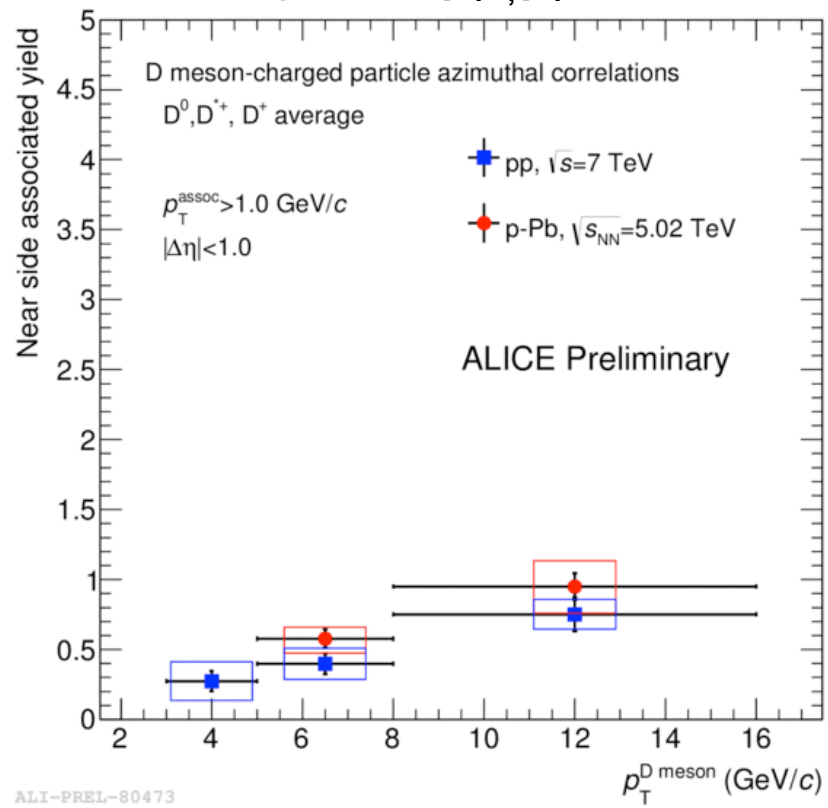
PLB 738 (2014) 97-108

b/c ratio compatible with FONLL prediction

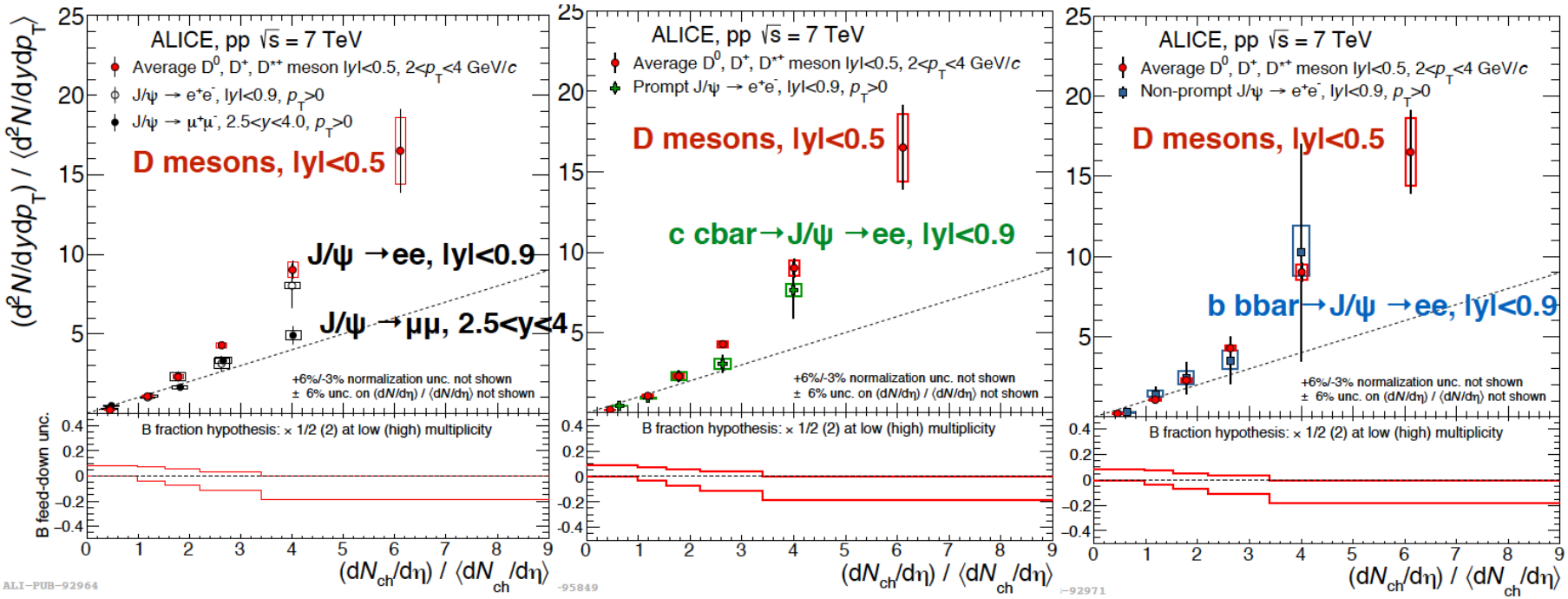
D-h azimuthal correlations in p-Pb



Near side yield vs p_T^D, p_T^{assoc}>1 GeV/*c*

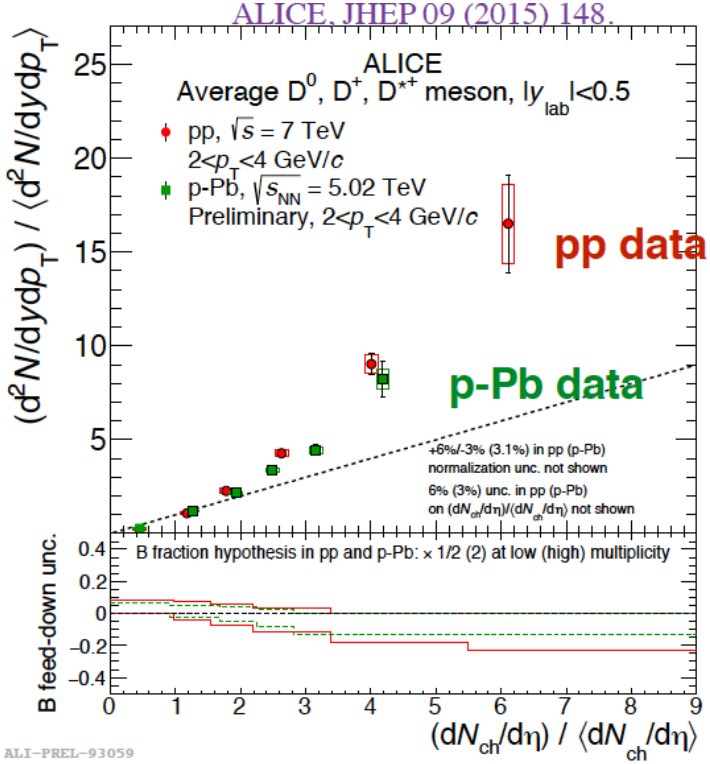


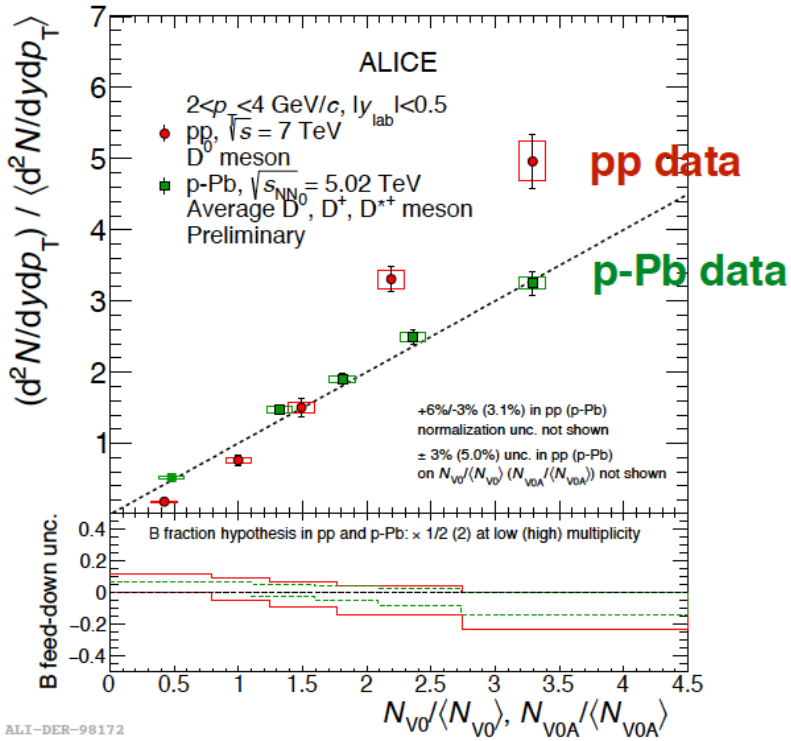
Open and hidden flavours

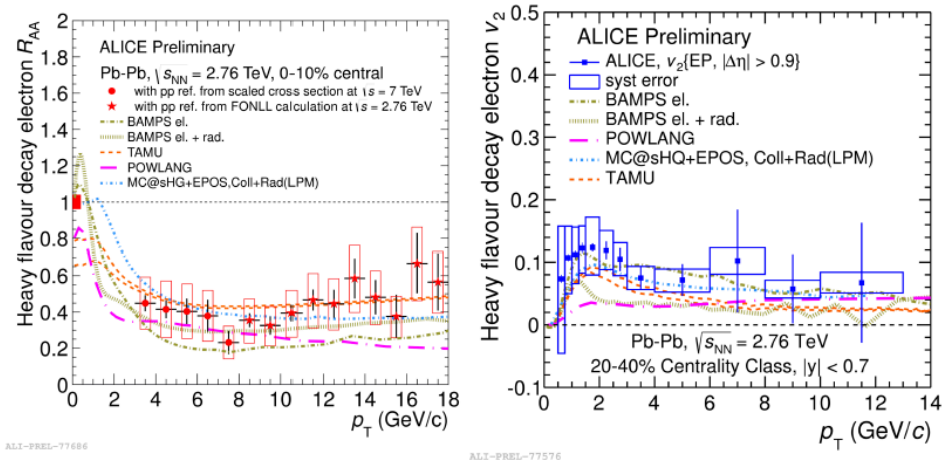


D mesons vs multiplicity in p-Pb

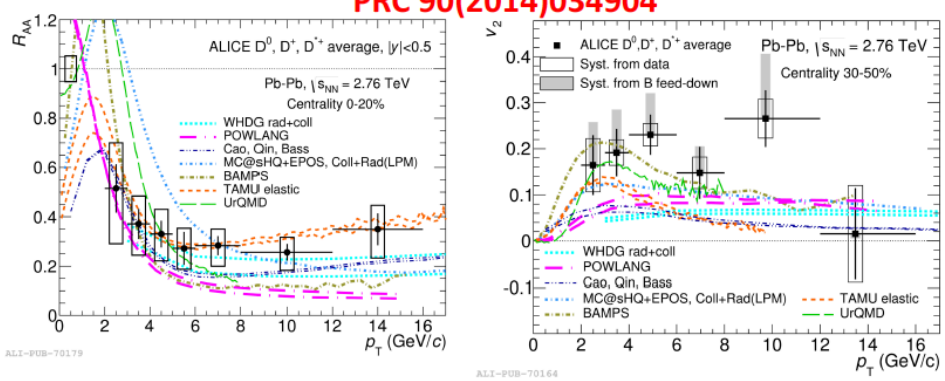
ALICE, JHEP 09 (2015) 148.







PRC 90(2014)034904



Simultaneous description of HFE and D mesons are still challenging.

BAMPS: heavy quark transport using Boltzmann equation with collisional energy loss in an expanding QGP .

BAMPS el. + rad.: uses LPM (Landau-Pomeranchuk-Migdal) to include radiative energy loss.

TAMU: heavy quark transport using ressonant scatterings and recombination for the hadronization.

POWLANG: heavy quark transport using Langevin equation with collisional energy loss.

MC@HG+EPOS Coll+Rad(LPM): includes collisional and radiative energy loss in an expanding medium, based on EPOS model.

WHDG: pQCD calculations including radiative and collisional energy loss.

Cao,Quin,Bass: uses Langevin with a radiative term and includes recombination.

UrQMD: uses Langevin approach implemented within the UrQMD model.