Measurement of open heavy-flavour production with ALICE at the LHC

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Outline

- Physics Motivation
- Observables
- Measurement of open heavy flavours with ALICE
- Results :

- pp collisions ($\sqrt{s}$ = 2.76 TeV and 7 TeV)
- p-Pb collisions ($\sqrt{s_{NN}}$ = 5.02 TeV)
- Pb-Pb collisions ($\sqrt{s_{NN}}$ = 2.76 TeV)

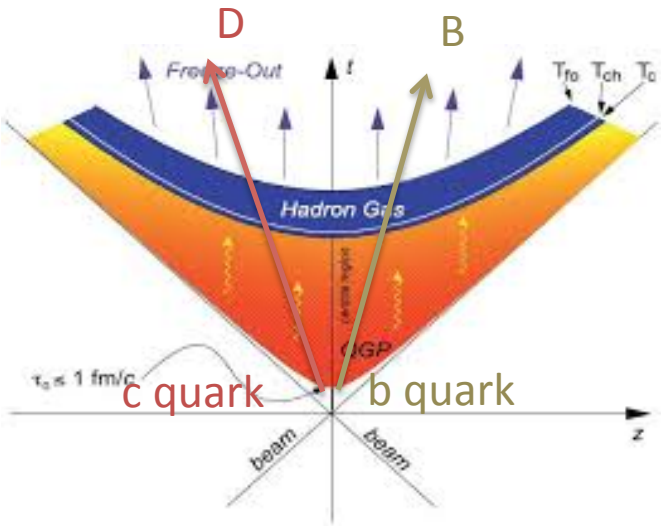
- Summary and outlook

Physics Motivation

➢ In Pb-Pb collisions :

Heavy quarks, i.e. charm and beauty quarks are excellent probes to study the properties of the strongly-interacting medium created in heavy-ion collisions :

- ✓ Produced in the early stages of the collisions
- ✓ Witness entire space-time evolution of the system
- ✓ Interact with the hot and dense QCD matter
- ✓ Parton energy loss by radiative and elastic processes



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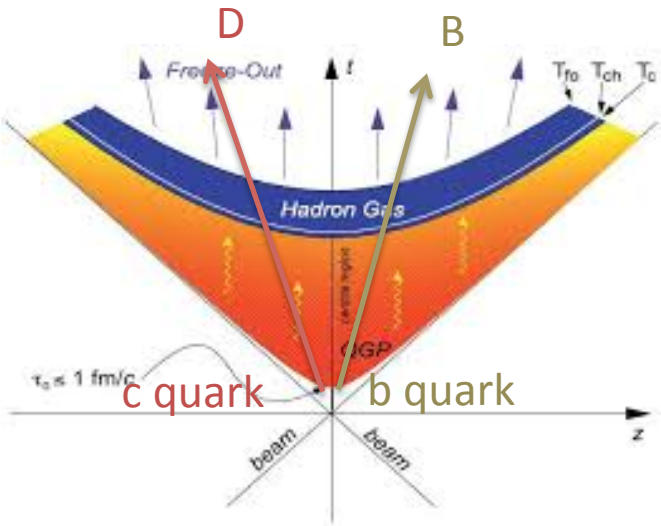

➢ In p-Pb collisions :

Cold nuclear matter effects :

- ✓ modifications of the parton distribution functions in nuclei (nPDF) **(see Jianhui Zhu's talk)**
- ✓ Gluon saturation at low x (color glass condensate)
- ✓ k_T-broadening
- ✓ Energy loss

Possibility of final-state effects *: Phys.Rev. D83 (2011) 114036, CMS PLB 718 (2013) 795*

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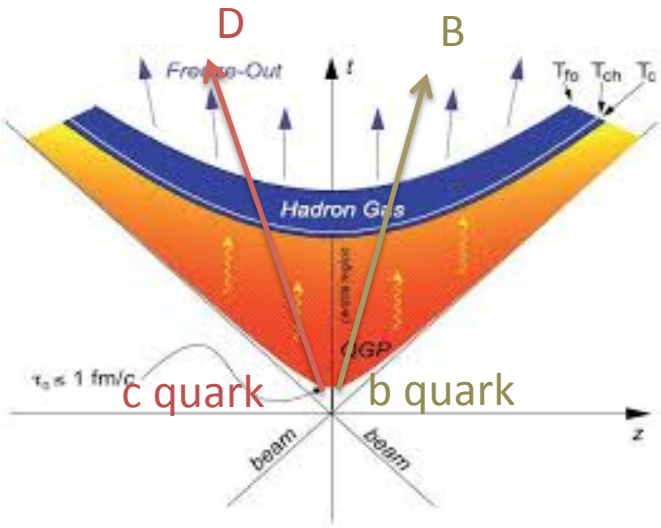

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Possibility of final-state effects *: Phys.Rev. D83 (2011) 114036, CMS PLB 718 (2013) 795*

➢ In pp collisions :

- ✓ Test of perturbative QCD (pQCD) calculation
- ✓ Study the Multi-Parton interactions (MPIs)
- ✓ Reference for p-Pb and Pb-Pb collisions

Observables : Nuclear modification factor

- Defined as :

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

- Quantify the energy loss in medium by collisional and radiative processes :
  - ✓ Colour-charge dependence :
  - ✓ Dead-cone effect -> expected mass-dependent energy loss :

$$\Delta E(g) > \Delta E(q)$$

$$\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b) \qquad \textit{PLB 519 (2001) 199}$$

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

- R_{AA} = 1 at high transverse momentum (p_T) indicates no medium effects
- R_{AA} < 1 at high p_T indicates a modification/softening of the spectra at high p_T which can be related to parton energy loss.

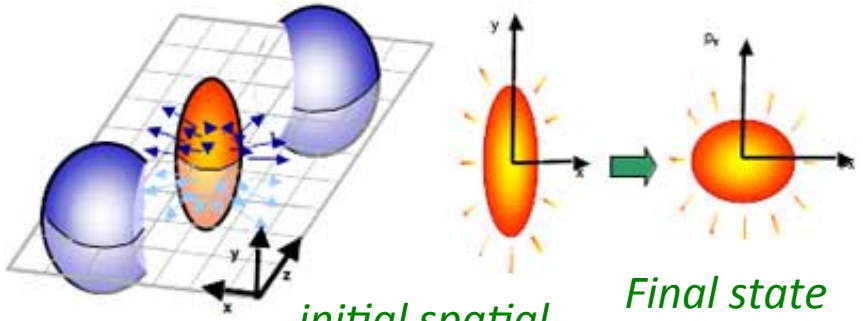
Observables : Anisotropic flow

- measures the momentum anisotropy of the final-state particles
- created due to the initial spatial anisotropy of the overlap region

$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_{RP})]$$

- quantified as the v_n, Ψ_{RP} is the reaction plane angle

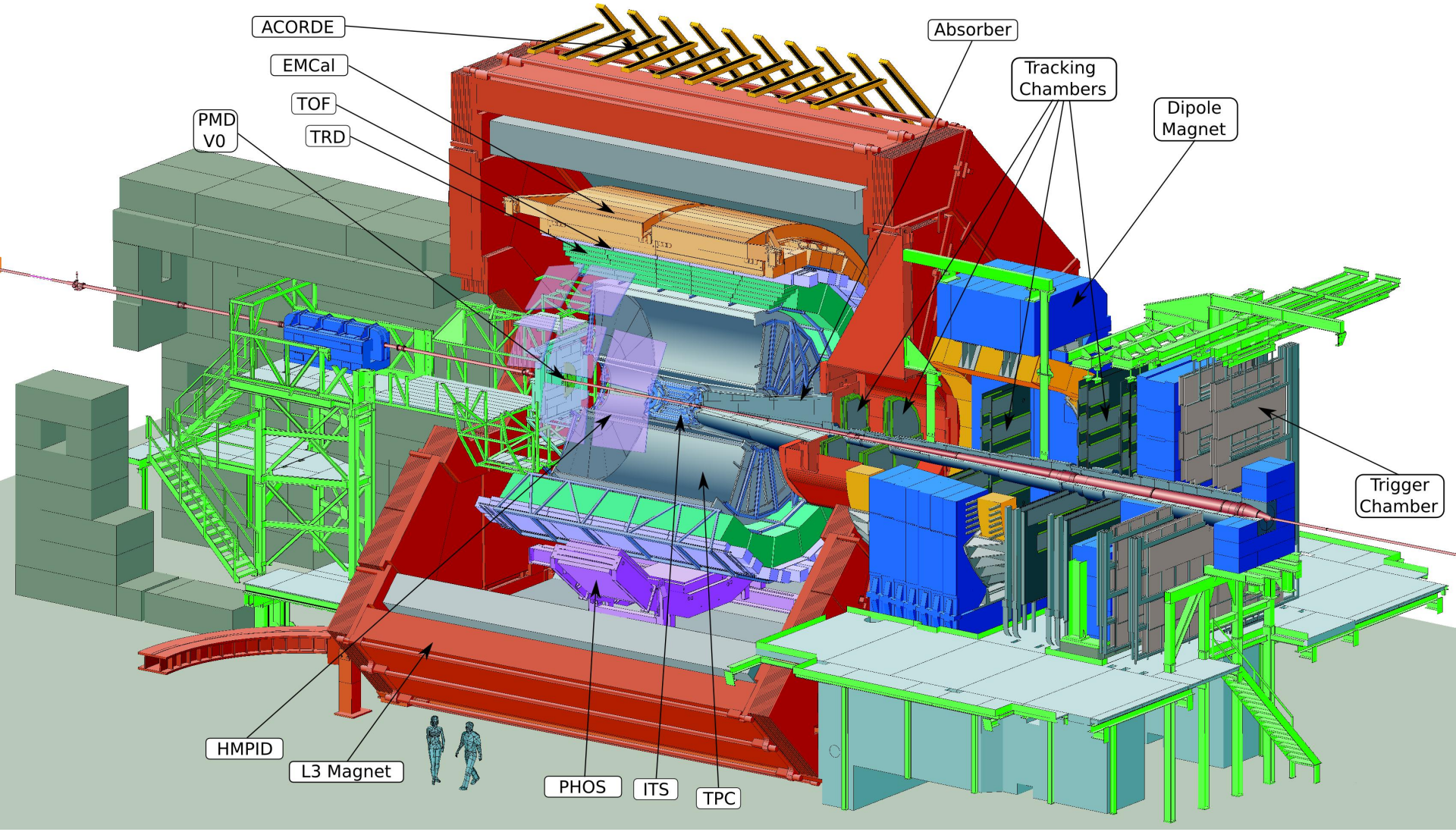
- The second Fourier coefficient of the distribution is called elliptic flow (v_2).



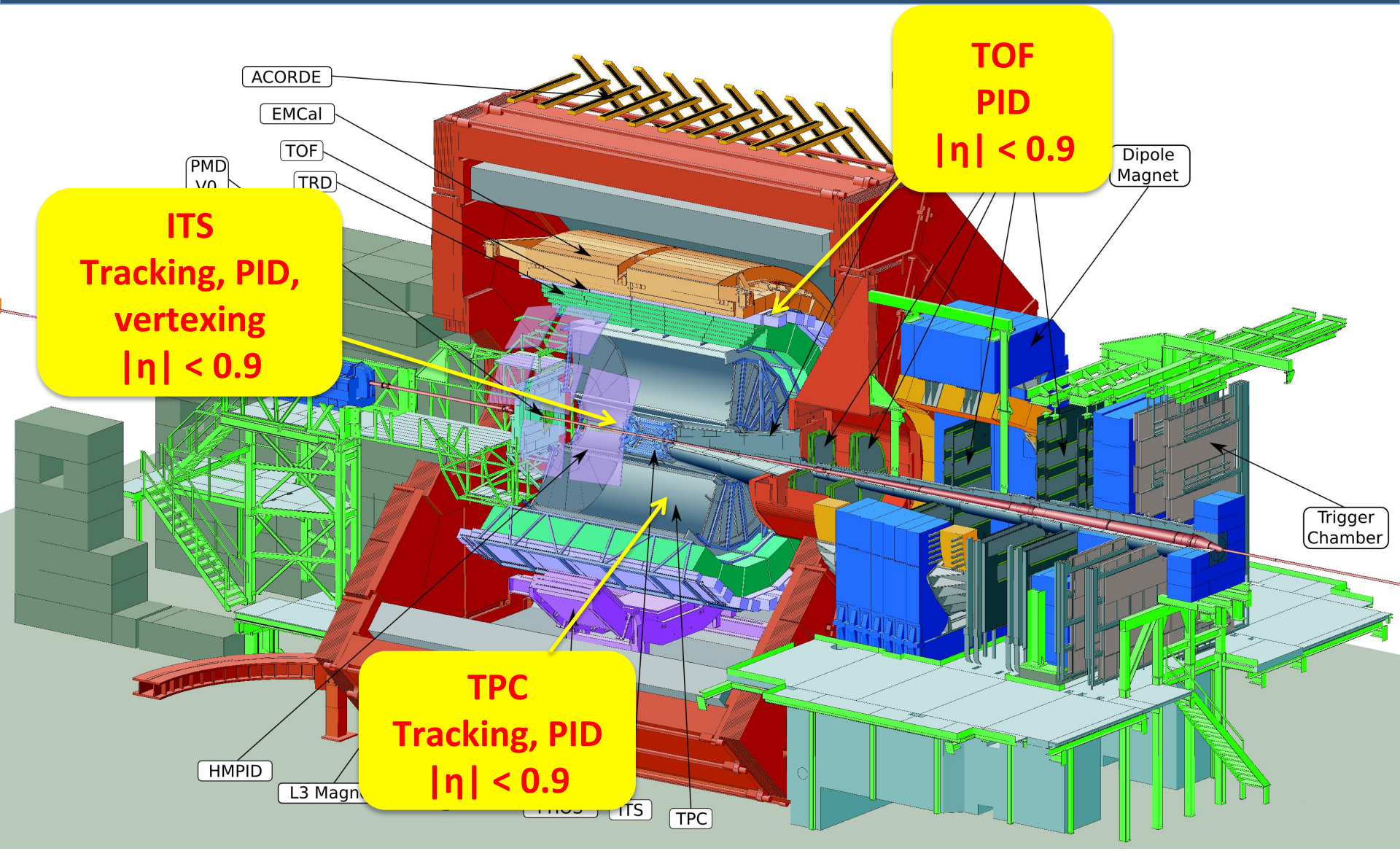
- Elliptic flow of heavy-flavour particles provides information on:

✓ Collective expansion dynamics and possible thermalization (low p_T)
✓ Path-length dependence of heavy-flavour energy loss (high p_T)

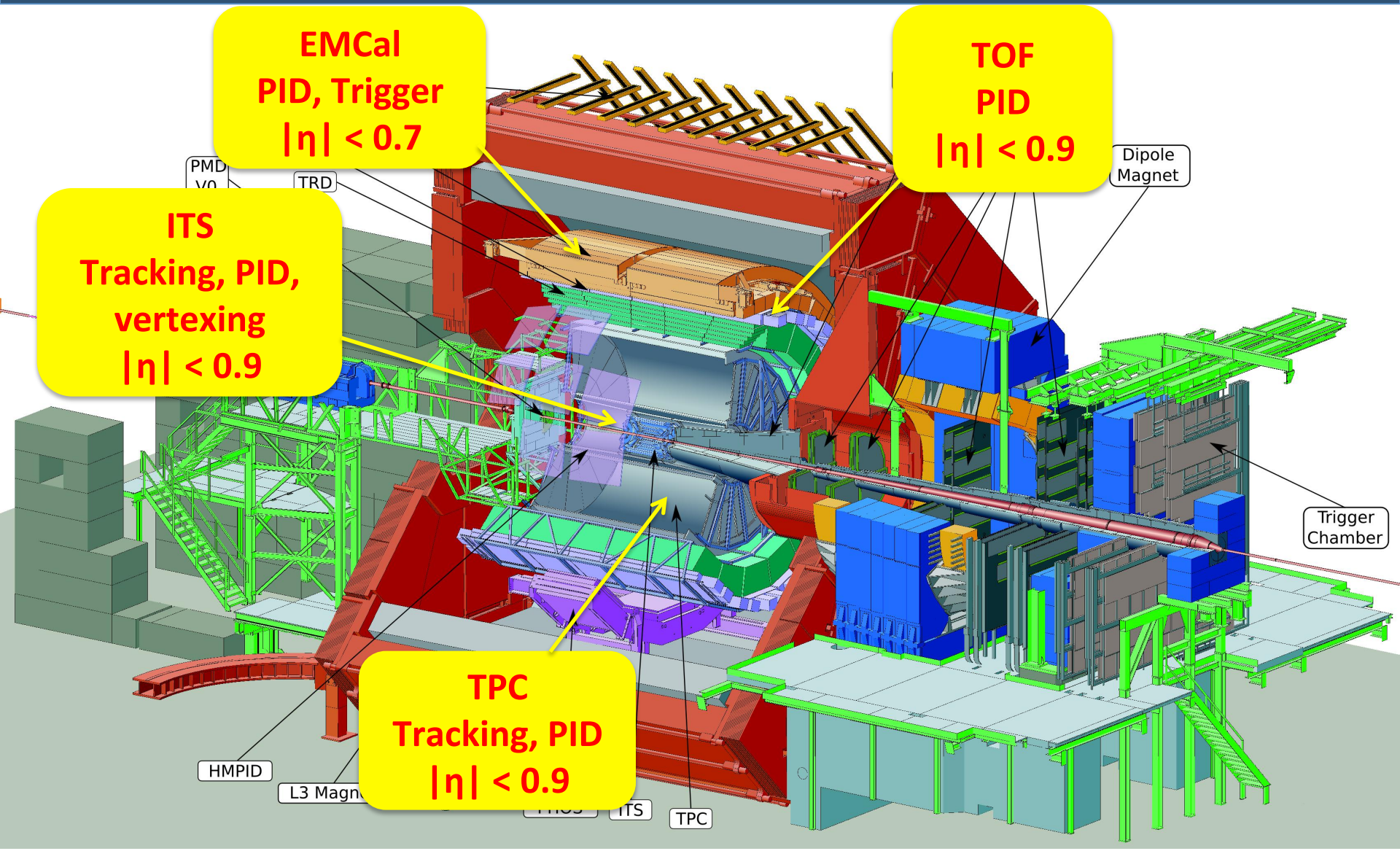
A Large Ion Collider Experiment (ALICE)



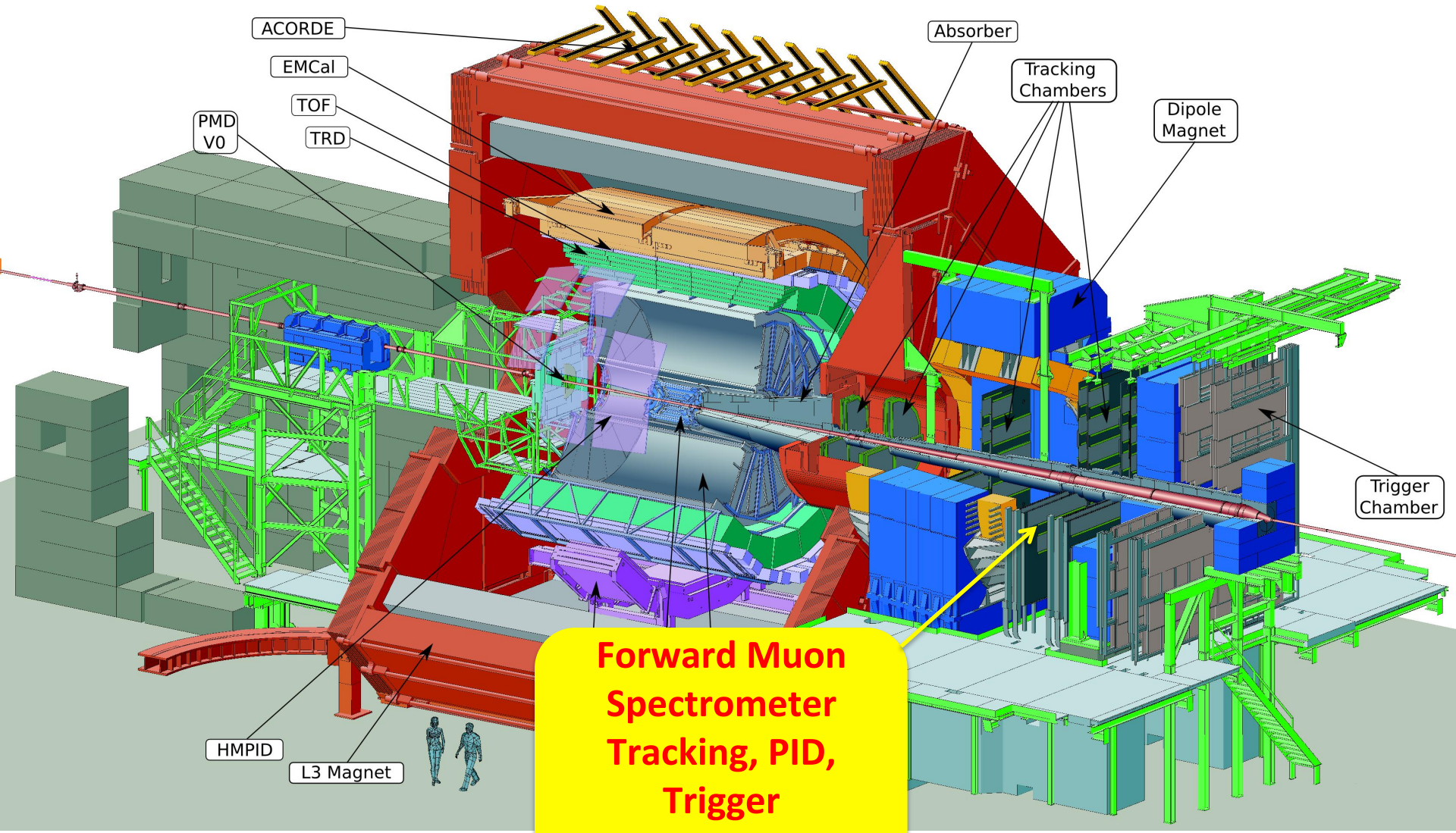
ALICE : D-meson reconstruction



ALICE : heavy-flavour hadron decay electrons



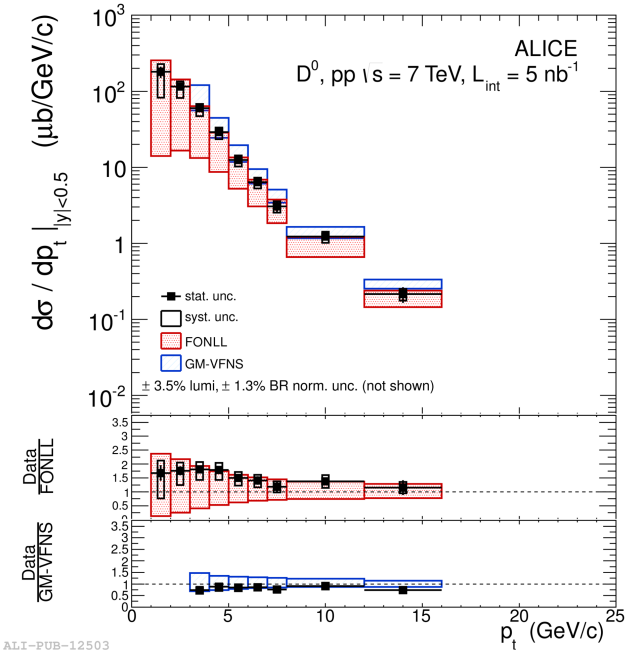
ALICE : heavy-flavour hadron decay muon



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

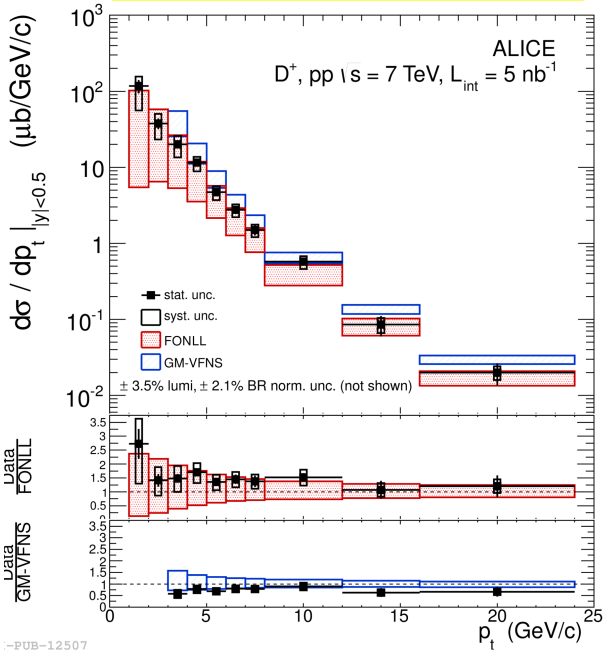
pp collisions: D mesons

D^0, $\sqrt{s}$ = 7 TeV



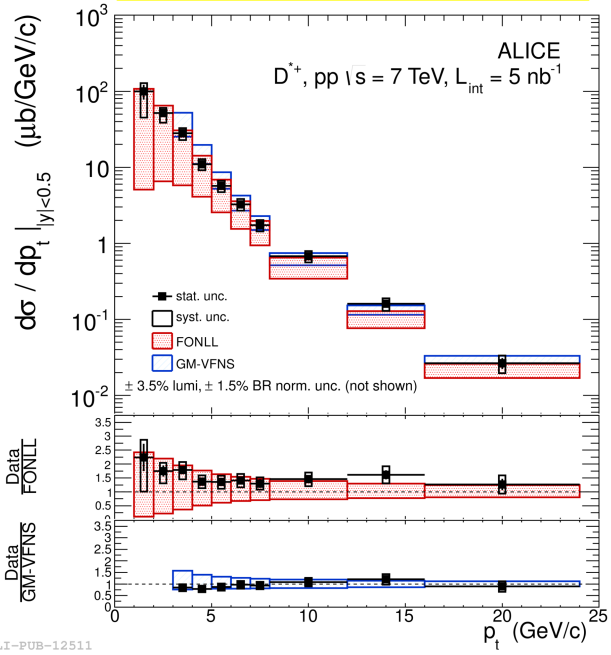
JHEP 1201(2012)128

D^+, $\sqrt{s}$ = 7 TeV



JHEP 1201(2012)128

D^{*+}, $\sqrt{s}$ = 7 TeV



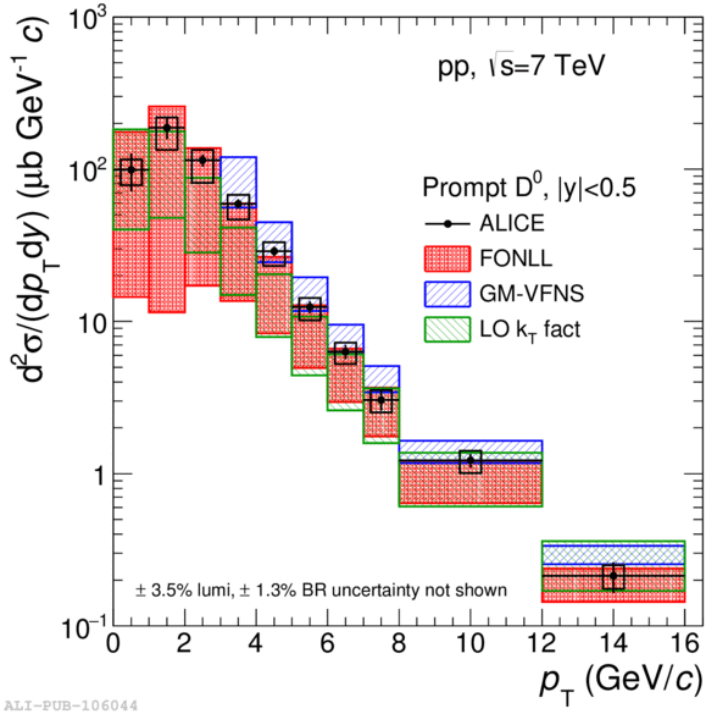
JHEP 1201(2012)128

- p_T-differential cross sections of D mesons (D^0, D^+, D^{*+}) are compatible with the pQCD calculations within uncertainties
- Similar agreement is also found at $\sqrt{s}$ = 2.76 TeV (*JHEP 1207(2012)191*)

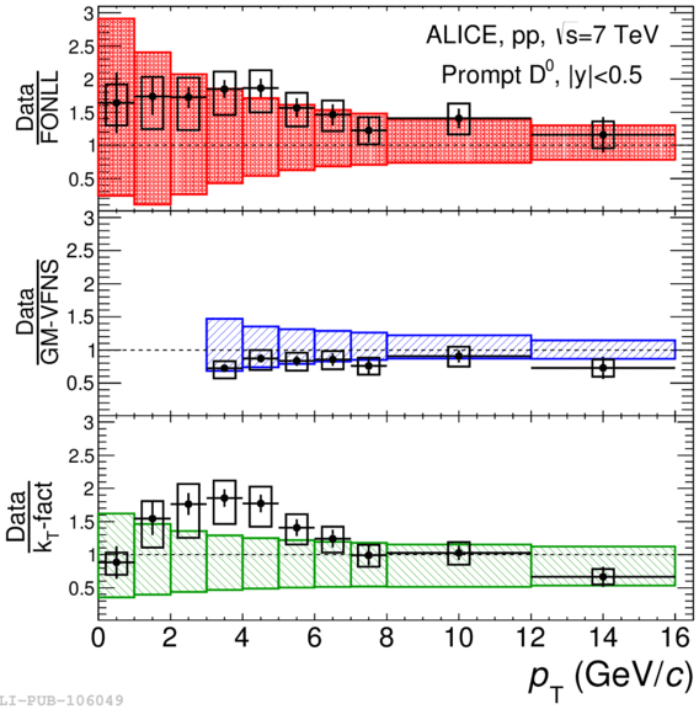
FONLL: *JHEP 1210(2012)37*
GM-VFNS: *EPJC C72(2012)2082*

pp collisions: D mesons down to p_T = 0

arXiv: 1605.07569v1



arXiv: 1605.07569v1

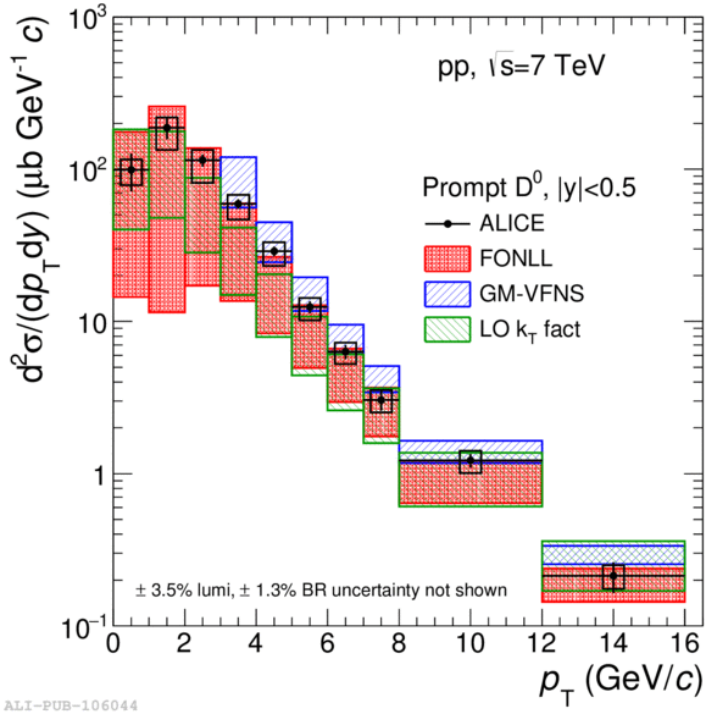


- p_T-differential cross section of D^0 mesons are measured down to p_T = 0 at $\sqrt{s}$ = 7 TeV
- Results are compatible with the pQCD calculations within uncertainties

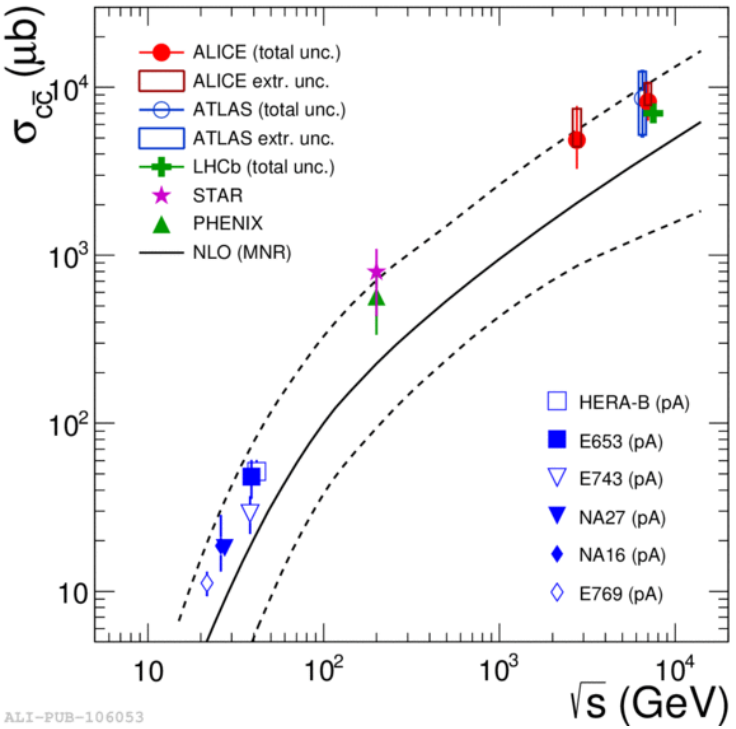
FONLL: *JHEP 10(2012)137*
GM-VFNS: *EPJ C72(2012)208*
LO K_T fact: *PRD 87 9(2013) 094022*

pp collisions: D mesons down to $p_T = 0$

arXiv: 1605.07569v1



arXiv: 1605.07569v1

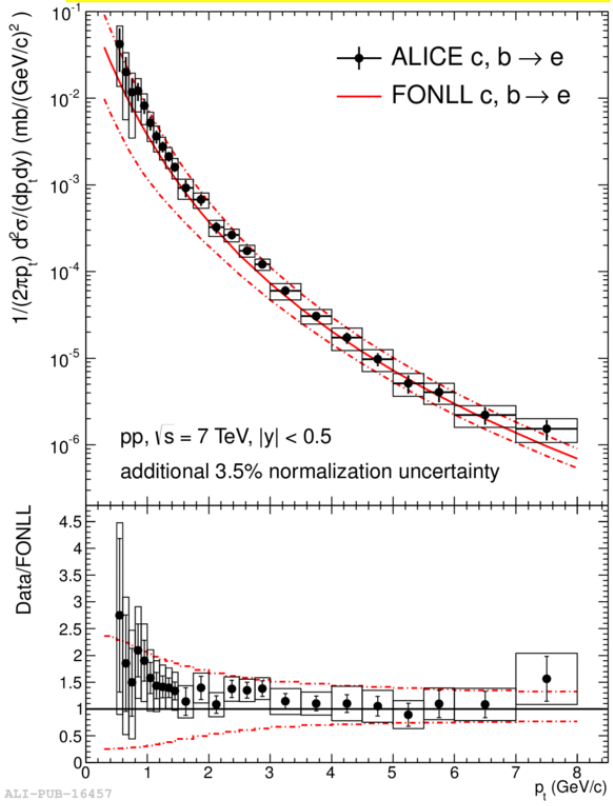


- p_T-differential cross section of D^0 mesons are measured down to $p_T = 0$ at $\sqrt{s}$ = 7 TeV
- Results are compatible with the pQCD calculations within uncertainties
- More precise measurement of the total charm cross section

FONLL: *JHEP 10(2012)137*
GM-VFNS: *EPJ C72(2012)208*
LO K_T fact: *PRD 87 9(2013) 094022*
NLO: *Nucl. Phys. B373(1992)295*

pp collisions: heavy-flavour hadron decay leptons

$e^{\pm}$,$\sqrt{s}$ = 7 TeV

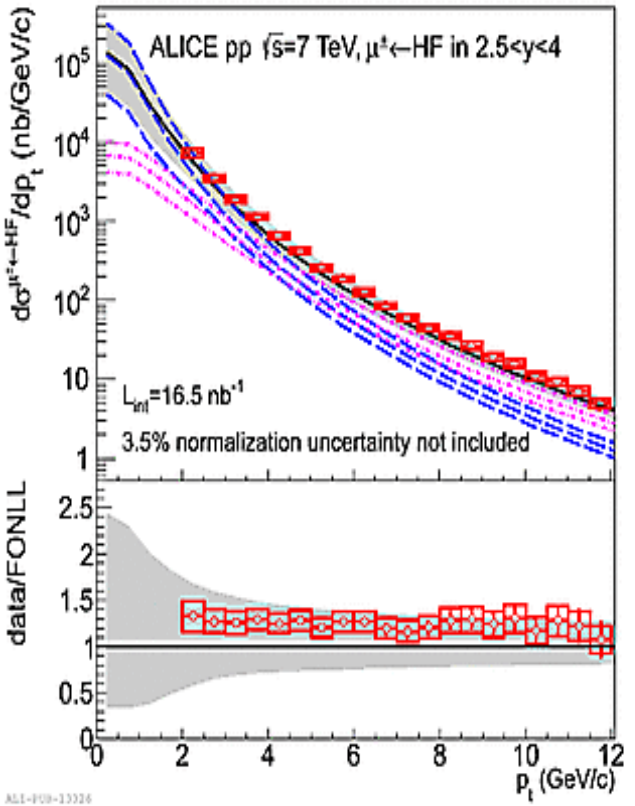


$e^{\pm}$: *PRD 86(2012)112007*

$\mu^{\pm}$: *PLB 708(2012)265*

FONLL: *JHEP 1210(2012)37*
GM-VFNS: *EPJ C72(2012)2082*
k_T factorization:
PRD 87(2013)094022

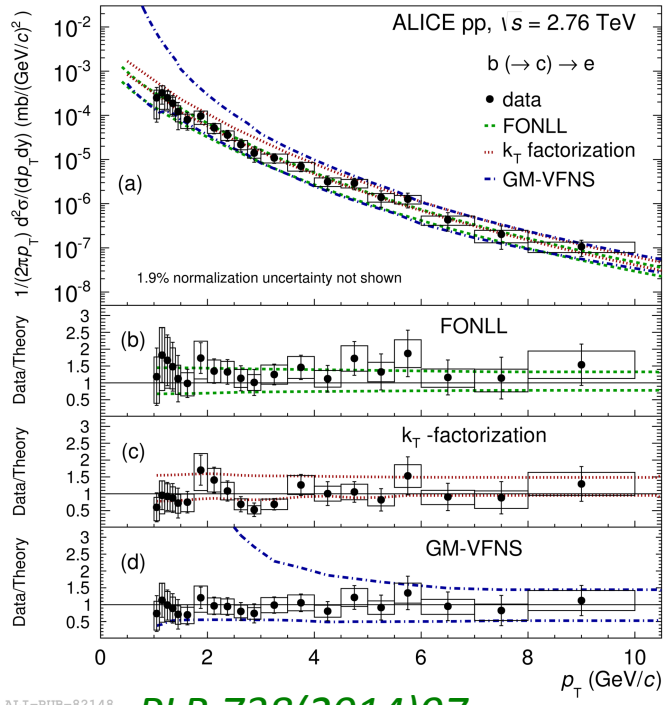
$\mu^{\pm}$, $\sqrt{s}$ = 7 TeV



- p_T-differential cross section of heavy-flavour decay electrons is measured at mid rapidity (|y| < 0.5) and heavy-flavour decay muons is measured at forward rapidity (2.5 < y < 4)
- pQCD calculations describe the heavy-flavour decay leptons spectra within uncertainties

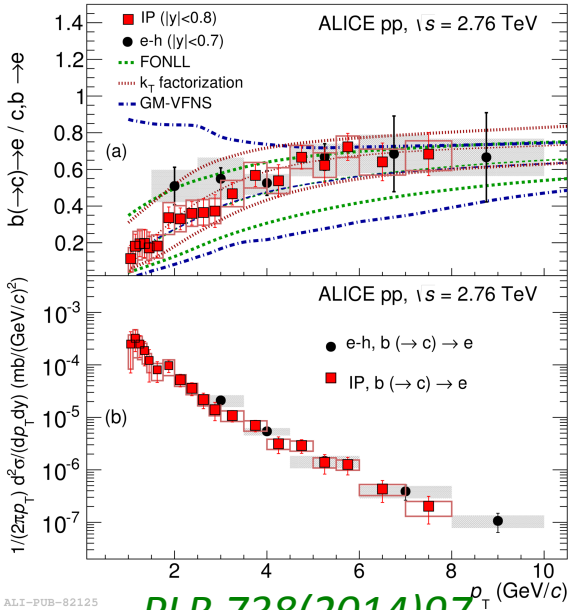
pp collisions: beauty-hadron decay electrons

√s = 2.76 TeV



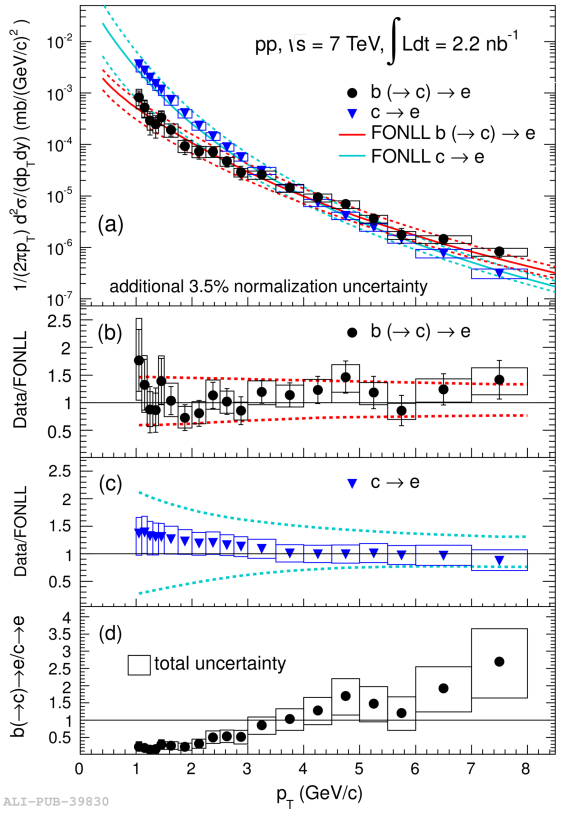
PLB 738(2014)97

√s =2.76 TeV



PLB 738(2014)97

√s = 7 TeV



PLB 721(2013)13

FONLL: *JHEP 1210(2012)37*

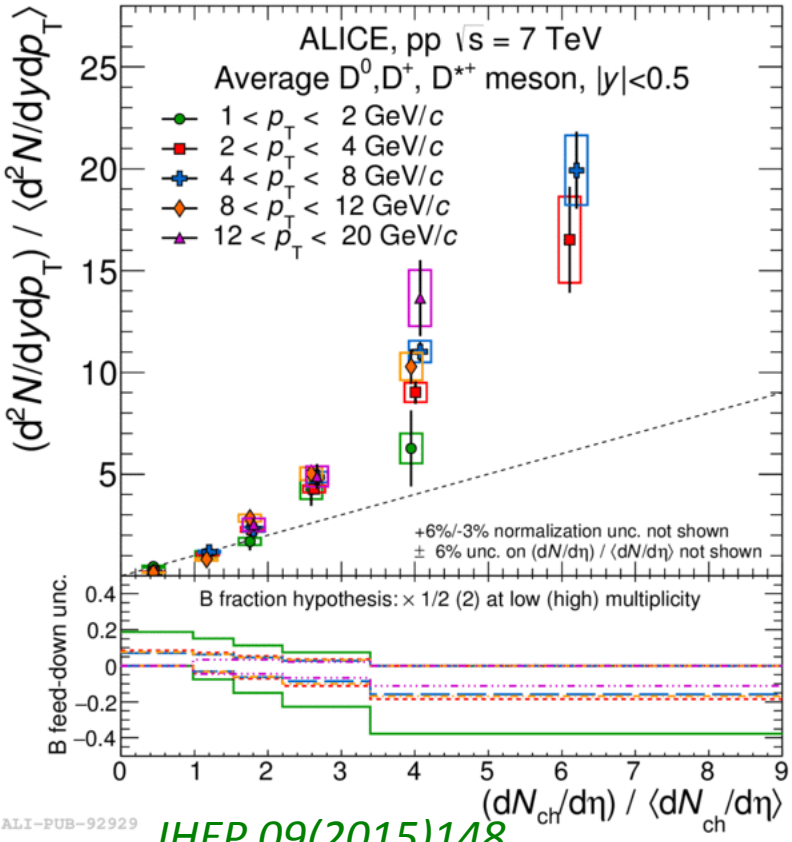
GM-VFNS: *EPJ C72(2012)2082*

kT factorization:
PRD 87(2013)094022

- Electrons from beauty-hadron decays are in agreement with pQCD calculations within uncertainties at both energies
- Beauty is then main source of heavy-flavour decay electrons for $p_T > 4$ GeV/c

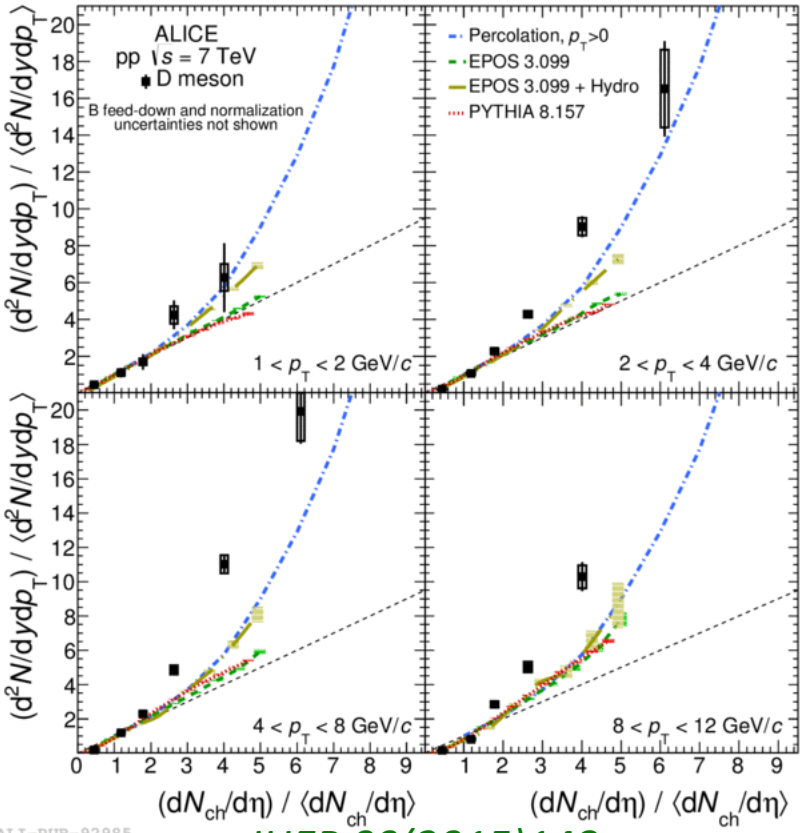
pp collisions: D-meson yields vs multiplicity

$\sqrt{s}$ = 7 TeV



JHEP 09(2015)148

$\sqrt{s}$ = 7 TeV



JHEP 09(2015)148

EPOS:
PRC 89(2014) 064903

PYTHIA:
Comput.Phy. Commun.178 (2008)852-867

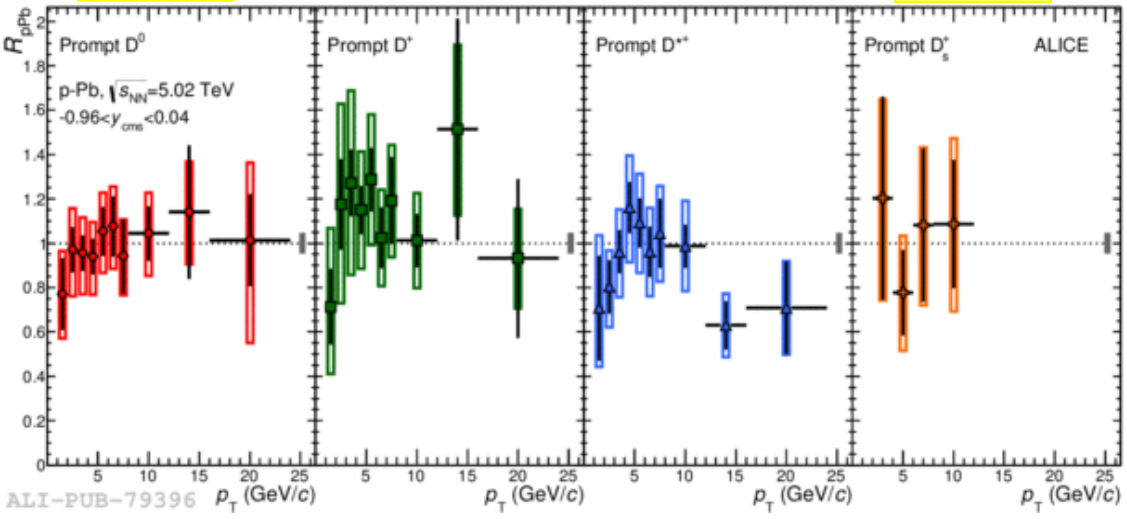
Percolation:
PRC 86(2012) 034903

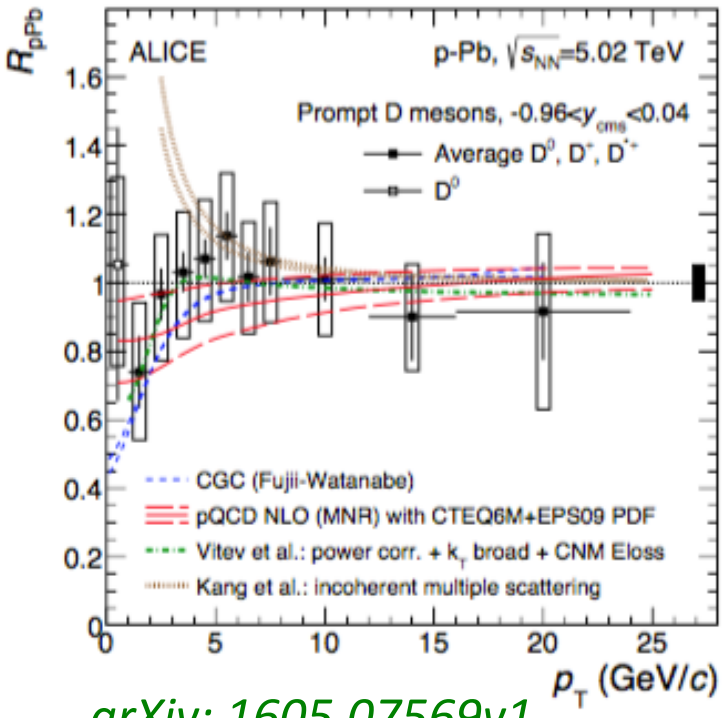
- Stronger than linear increase of self-normalized yield of D mesons (D^0, D^+, D^{*+}) as a function of charged-particle multiplicity ($dN_{ch}/d\eta$)
- Qualitative agreement with models containing MPI and hydrodynamic effects

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

p-Pb collisions: D-meson R_{pPb}

D^0 D^+ D^{*+} D_s^+ R_{pPb}





PRL 113(2014)232301

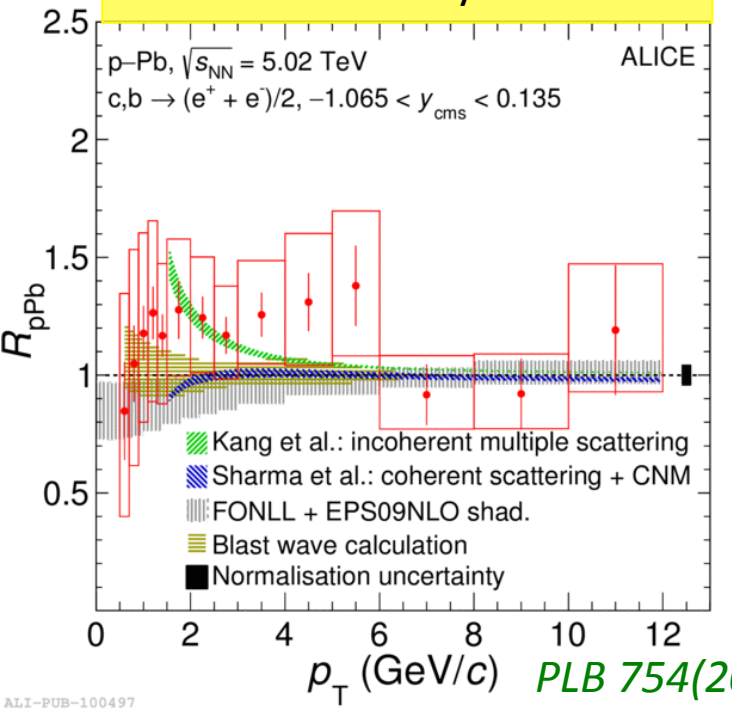
$$R_{pPb}(p_T) = \frac{1}{A}\frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T}$$

arXiv: 1605.07569v1

- R_{pPb} is consistent with unity for all the D-meson species at high p_T
- Models including initial-state effects describe the data within uncertainties
- No modification of the yields observed at high p_T, within uncertainties

p-Pb collisions: heavy-flavour hadron decay electrons R_{pPb}

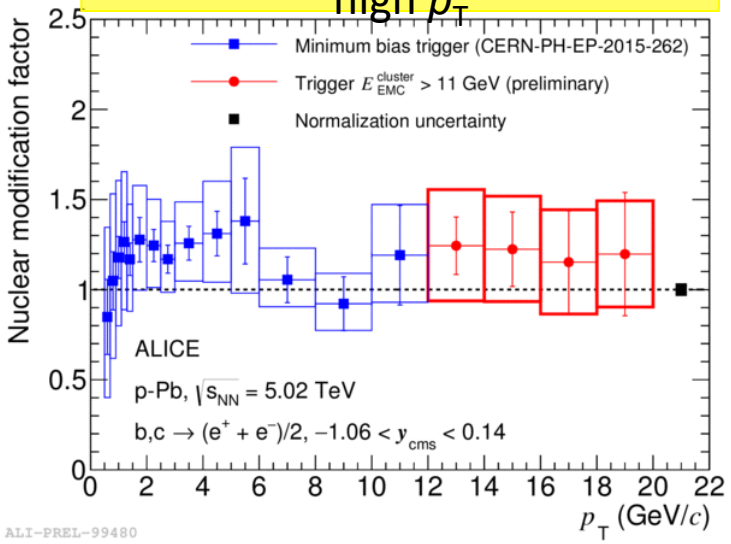
HF hadron decay electrons



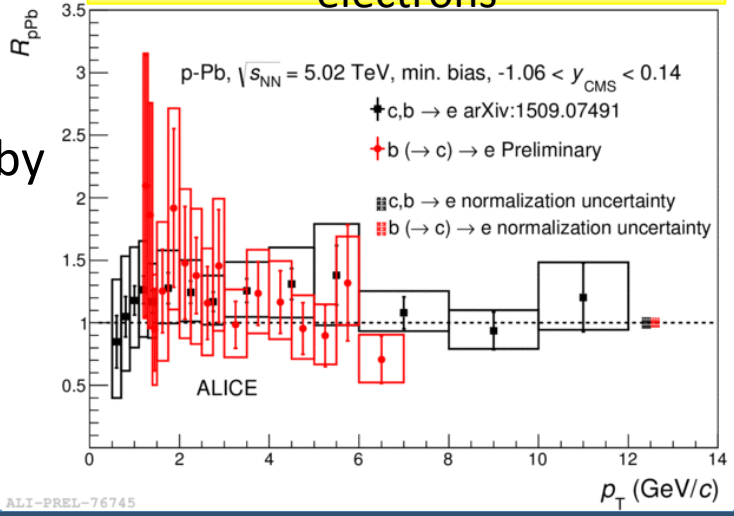
Kang et al: *PLB 740(2015)23*
Sharma et al: *PRC 80(2009) 054902*
FONLL: *JHEP 9805 (1998)007*
EPOS09: *JHEP 04 (2009)065*

PLB 754(2016)81-93

HF hadron decay electrons at high p_T

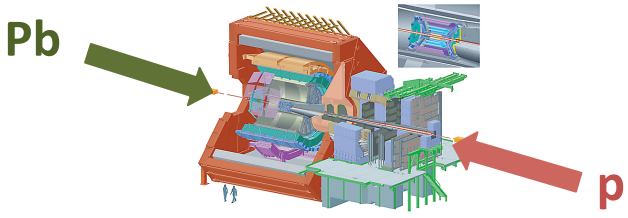


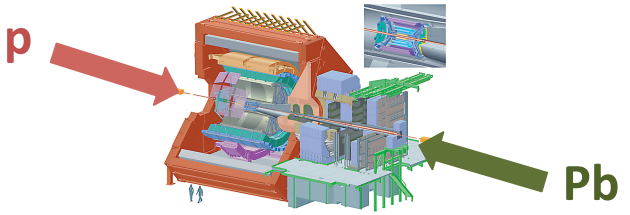
Beauty-hadron decay electrons



- R_{pPb} of heavy-flavour decay electrons is consistent with unity at high p_T and described by models including initial-state effects
- EMCal detector is used to obtain high-p_T data points
- R_{pPb} of beauty-decay electrons is consistent with HF-decay electrons and with unity

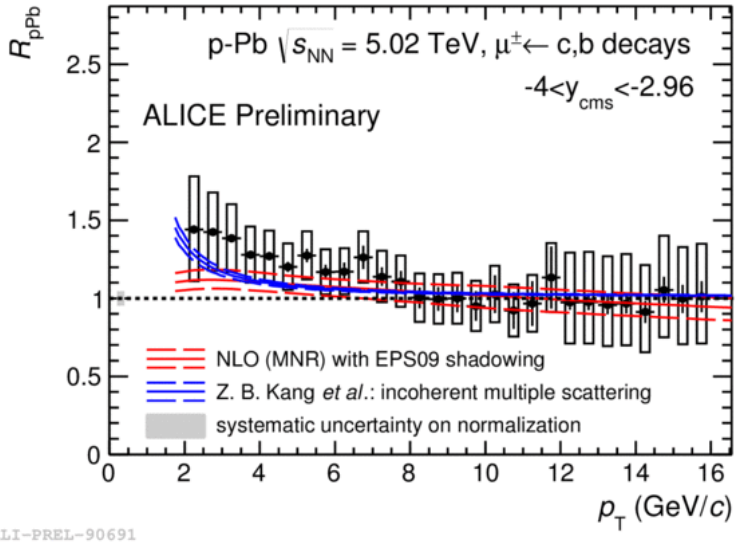
p-Pb collisions: heavy-flavour hadron decay muons



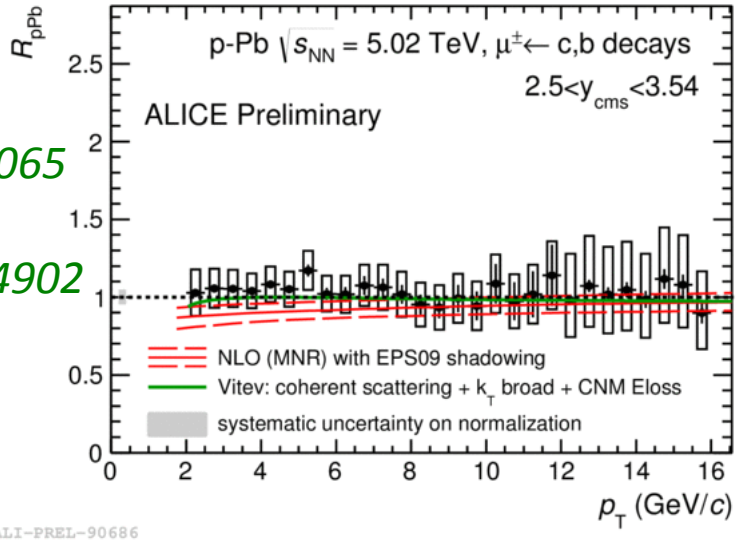


Pb-going (backward)

p-going (forward)



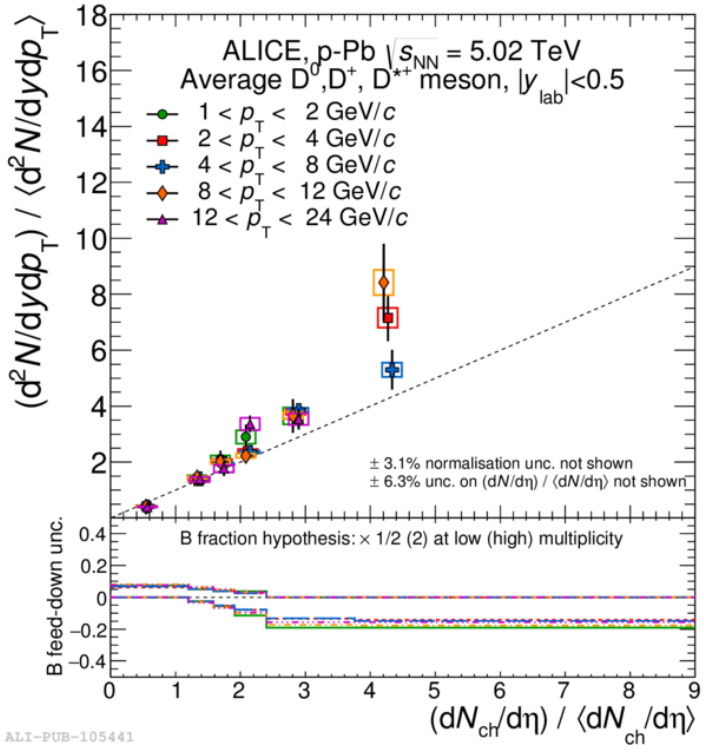
EPOS09:
JHEP 0904(2009)065
Vitev et al.:
PRC 80(2009)054902
Z.B.Kang et al.:
PLB 740(2015)23



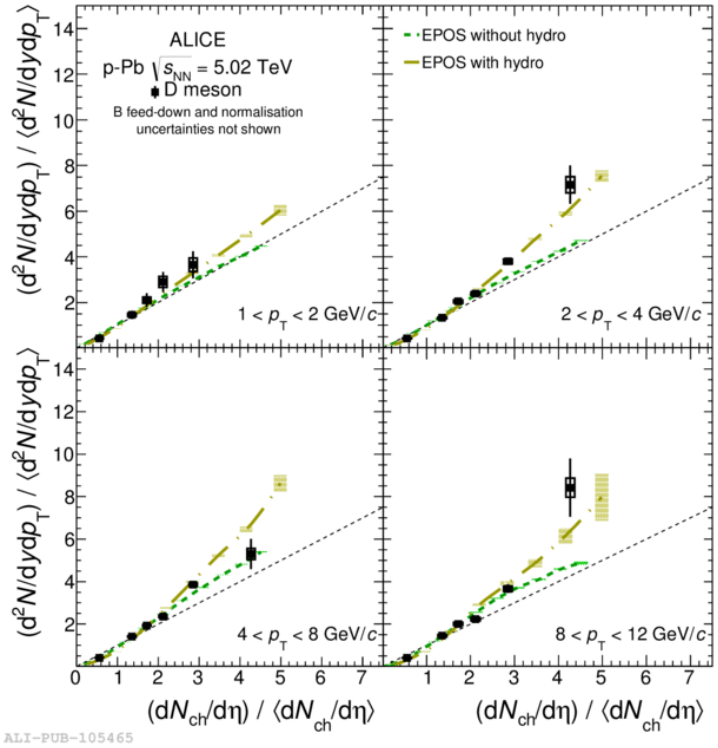
- Study in different rapidity ranges allows us to explore different *x* regimes
- R_{pPb} of heavy-flavour decay muons is consistent with unity at forward rapidity and slightly above the unity at backward rapidity in $2 < p_T < 4$ GeV/c
- Models including cold nuclear matter effects describe the data within uncertainties

p-Pb collisions: D-meson yields vs multiplicity

arXiv:1602.07240v1



arXiv:1602.07240v1



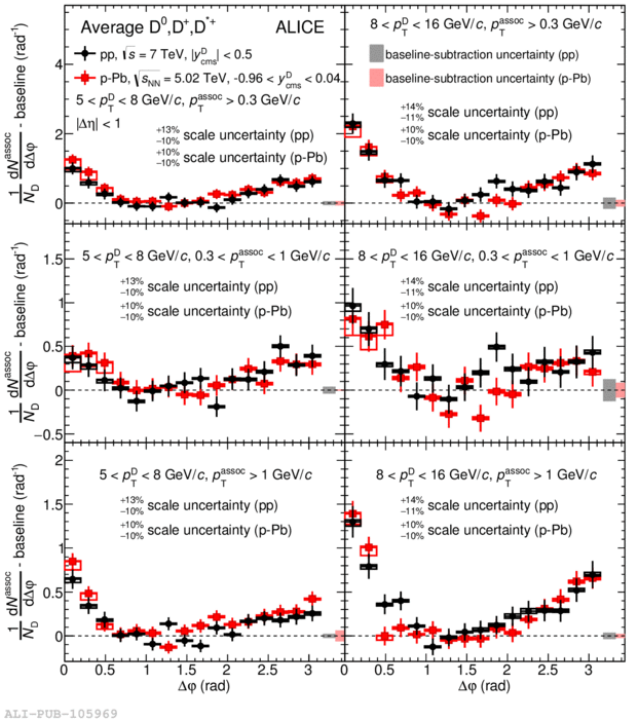
EPOS: *PRC 89(2014) 064903*

- D-meson yield exhibits a faster-than-linear increase as a function of charged-particle multiplicity (dN_{ch}/dη)
- Similar behaviour was found in pp collisions
- Data are reproduced well by the model including hydrodynamic flow

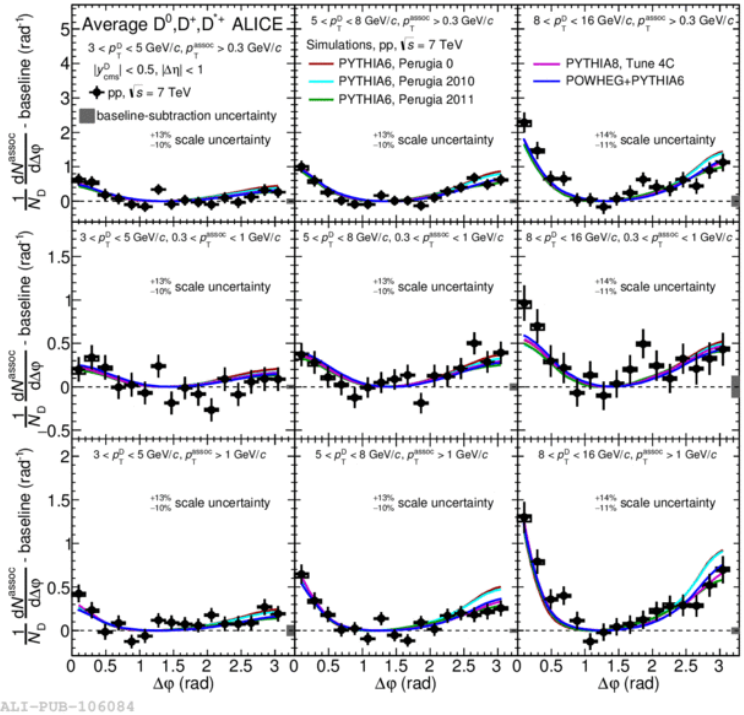
p-Pb collisions: correlations between D mesons and charged particles

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

pp $\sqrt{s}$ = 7 TeV



arXiv:1605.06963



Trigger particle: D mesons

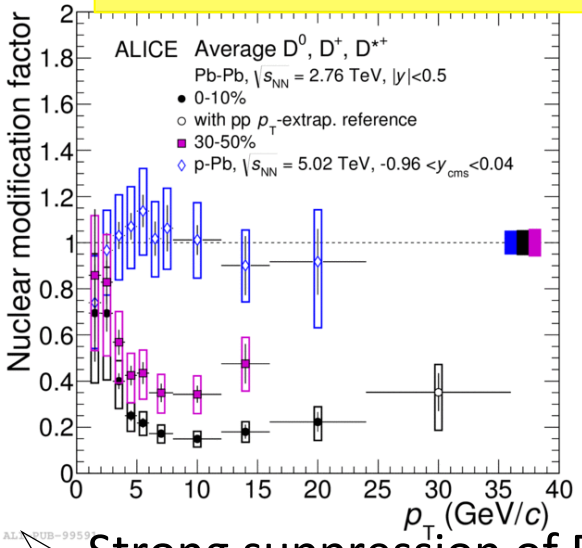
Associated particle: charged particles

- Azimuthal angular correlations between D mesons and charged particles are compatible both in pp and p-Pb collisions after baseline subtraction
- Results are described by the different tunes of PYTHIA and POWHEG event generator at $\sqrt{s}$ = 7 TeV after baseline subtraction

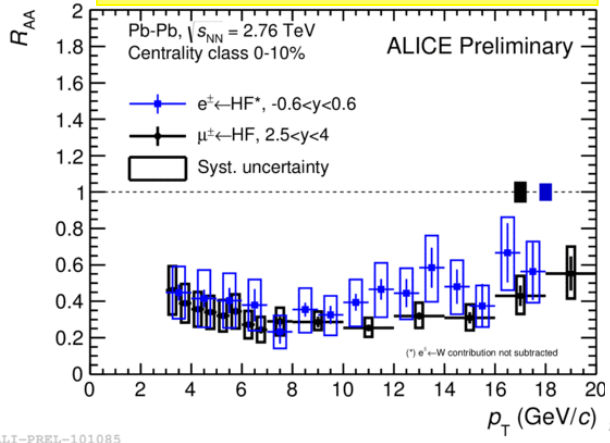
Results in Pb-Pb collisions
$\sqrt{s_{NN}}$ = 2.76 TeV

Pb-Pb collisions: R_{AA} of D mesons and heavy-flavour hadron decay leptons

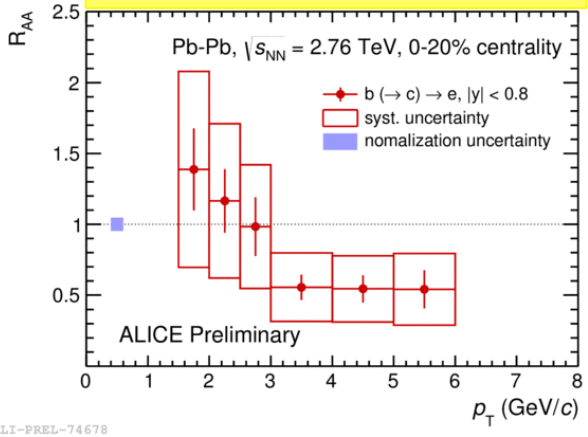
D mesons



HF $e^{\pm}$ $\mu^{\pm}$



Beauty-decay $e^{\pm}$

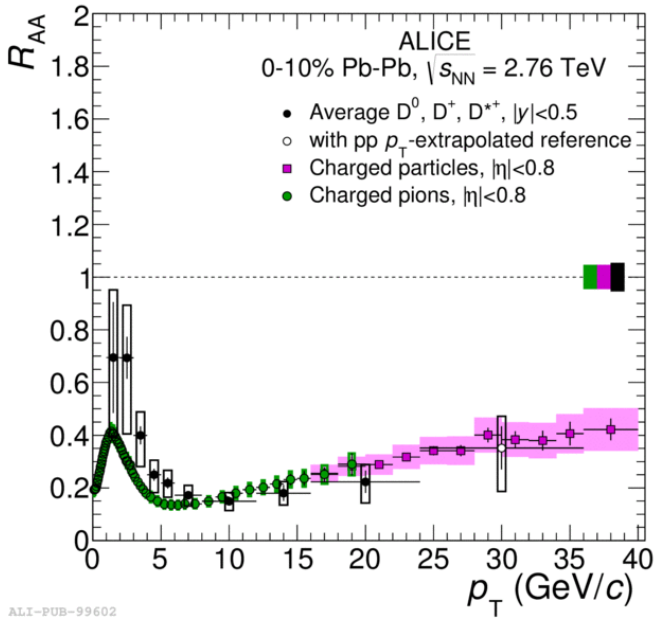


JHEP 03 (2016) 081

- Strong suppression of D mesons is observed for central and semi-central Pb-Pb collisions at intermediate and high p_T
- Similar suppression for heavy-flavour decay electrons (|y|<0.6) and muons (2.5 < y < 4) is observed
- A hint of suppression for beauty-decay electrons is observed at p_T > 3 GeV/c
- R_{pPb} consistent with unity indicates that the suppression in Pb-Pb collisions is not due to initial-state effects
- Significant energy loss of heavy quarks in the medium

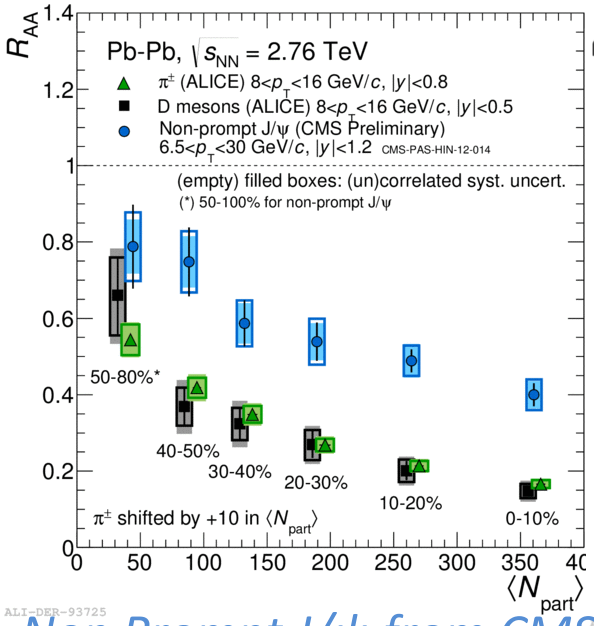
Pb-Pb collisions: R_{AA} of D mesons vs charged hadrons and non-prompt J/Ψ

JHEP: 03 (2016) 081



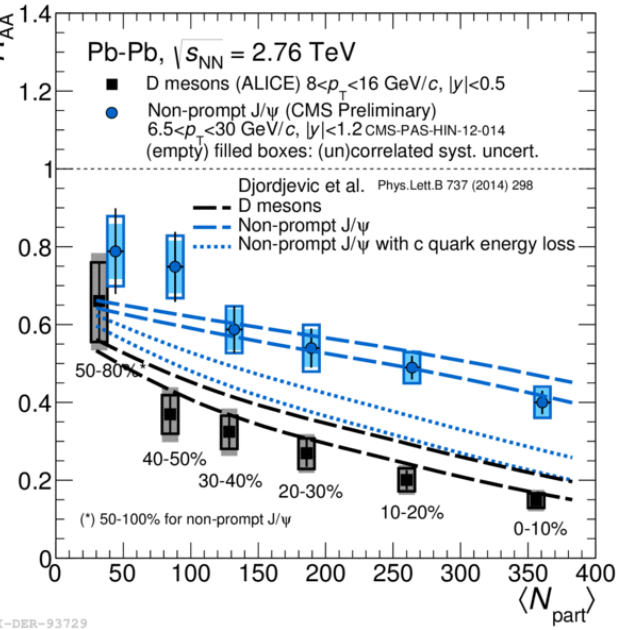
$R_{AA}(\pi) \sim R_{AA}(D)$

JHEP: 1511(2015)205



Non Prompt J/ψ from CMS: CMS-PAS-HIN-12-014

JHEP: 1511(2015)205

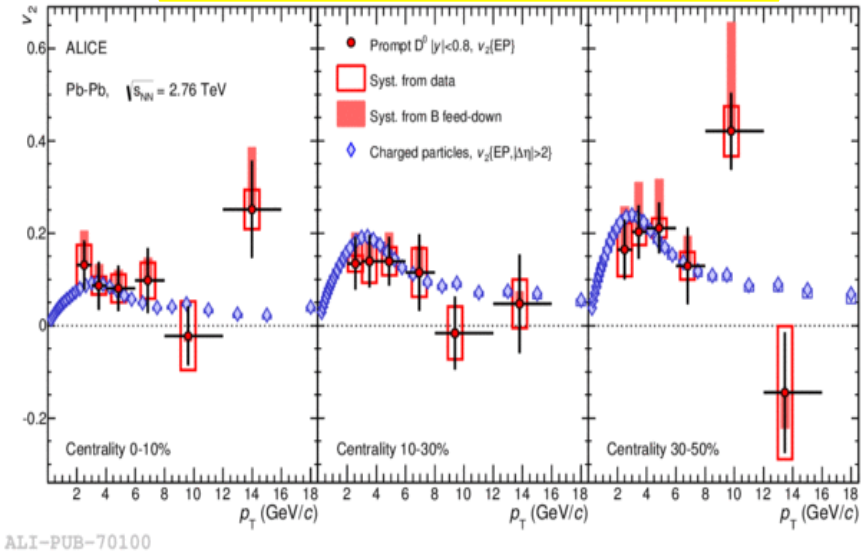


$R_{AA}(D) < R_{AA}(B)$

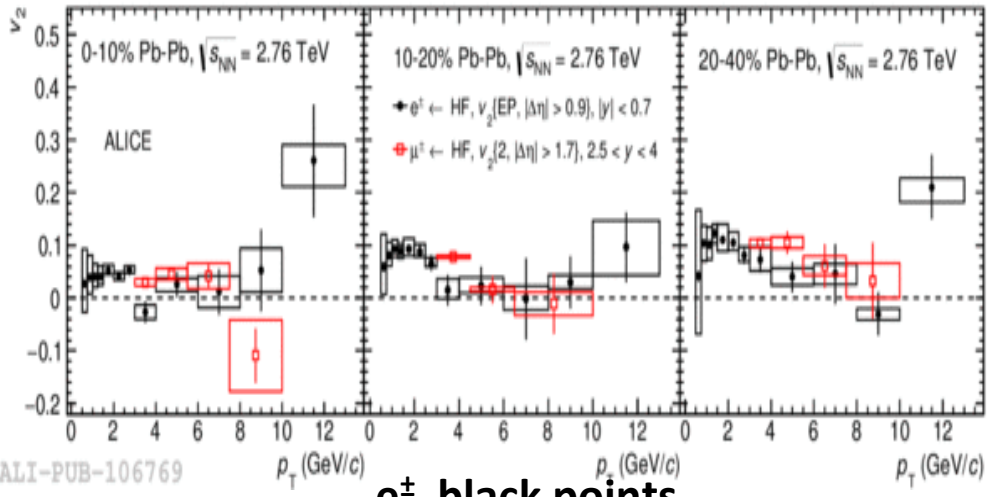
- R_{AA} of pions are compatible with the R_{AA} of D mesons within uncertainties
- R_{AA} of non-prompt J/ψ (from b quarks) > R_{AA} of D mesons (c quarks): explained by models including mass-dependent energy loss *(PRL 112(2014)042302)*

Pb-Pb collisions: heavy-flavour anisotropic flow (v_2)

v_2 of D mesons



HF decay $e^{\pm}$ $\mu^{\pm}$ v_2



PRL: 111(2013)102301

$e^{\pm}$ black points

$\mu^{\pm}$ Red points

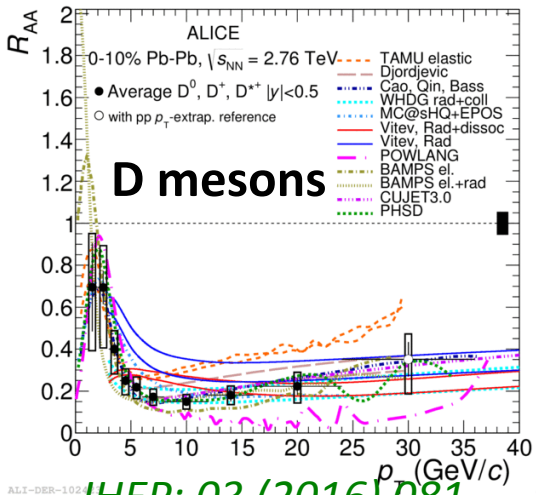
HF-> $\mu^{\pm}$: *PLB: 753(2016)41*

HF-> $e^{\pm}$: *arXiv:1606.00321*

- Positive v_2 of D mesons and heavy-flavour decay leptons is measured
- D-meson v_2 is compatible with the charged-particles v_2 within uncertainties
- Positive v_2 indicates that the heavy-quarks participate in the collective motion of the medium

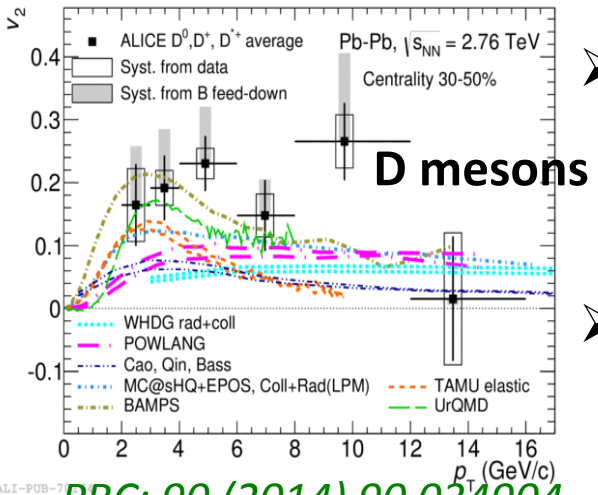
Pb-Pb collisions: Comparison with models

R_{AA}



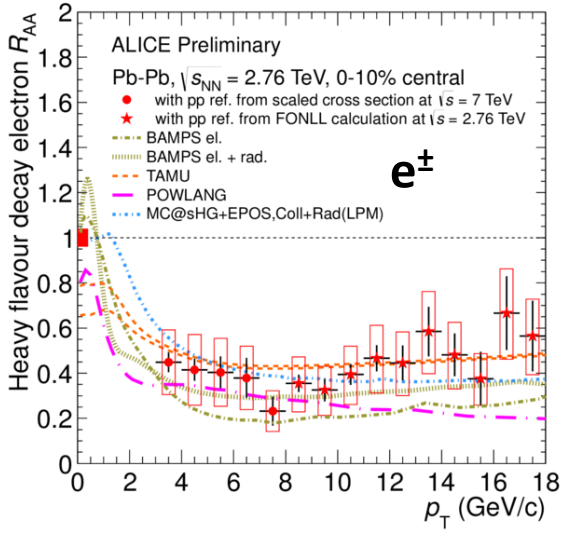
JHEP: 03 (2016) 081

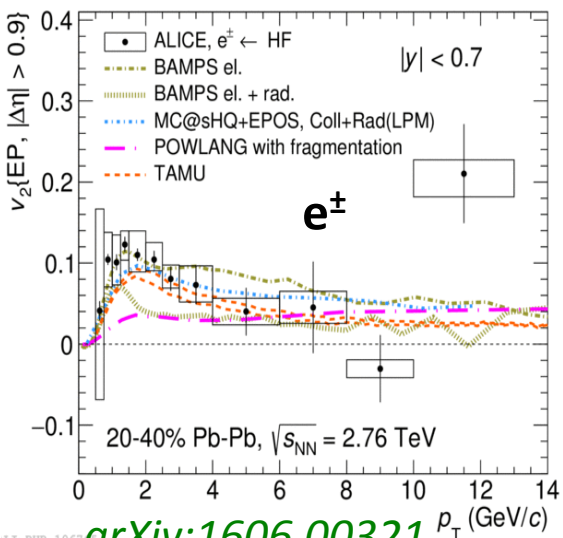
v_2



PRC: 90 (2014) 90 034904

- R_{AA} and v_2 results provide constraints to the existing models
- Simultaneous model description of heavy-flavour R_{AA} and v_2 is still challenging.





arXiv:1606.00321

TAMU: *PRC 86(2012)014903*
BAMPS: *JPG 38(2011)124152*
BAMPS+rad.: *JPG 11(2011)115106*
WHDG: *JPG 38(2011)124114*
POWLANG: *EPJ C71(2011)1666*
Cao,Qin,Bass: *PRC 92(2015)024907*
UrQMD: *Prog.Part. Nucl. Phys. 41, 225 (1998)*

Summary and outlook

Significant amount of interesting results on open heavy-flavour production in ALICE from LHC Run I data :

- Results from pp collisions are well described by the pQCD calculations within the uncertainties
- D-meson self-normalized yield as a function of multiplicity is consistent with calculations including a contribution from MPI
- R_{pPb} is consistent with unity, indicates that the initial-state effects are negligible at high p_T
- D-hadron correlations in p-Pb collisions are found compatible with pp collisions and with different PYTHIA tunes and POWHEG event generator
- Large suppression of the yield of heavy-flavour particles in central Pb-Pb collisions indicates the strong medium effects
  - ✓ Suppressions are consistent with collisional and radiative energy loss models
  - ✓ Measurements described by models considering a dependence of the energy loss with the parton mass and color charge
- Positive v_2 indicates the collective motion of charm quarks in the medium

- **Results from Run II data will allow for more precise measurements of all HF observables, in particular for rare probes: beauty-hadron decay electrons, HF correlations and HF jet study**

Back up slides

Reconstruction of D mesons

- D-meson reconstruction via their hadronic channels with invariant mass method

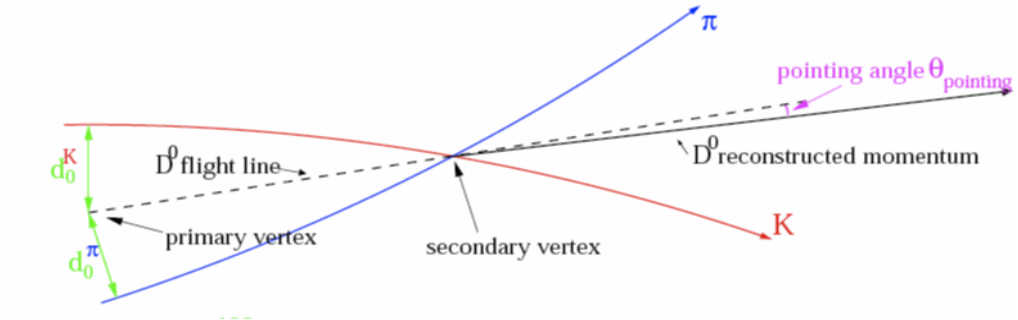
chanel :

D^0 -> $K^-\pi^+$ BR -> 3.88%

D^+ -> $K^-\pi^+\pi^+$ BR -> 9.13%

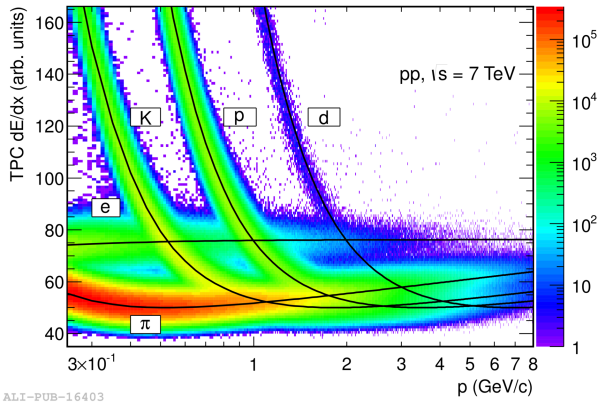
D^{*+} -> $D^0\,\pi^+$ BR -> 67.7%

D_s^+ -> $\phi\pi^+$->$K^-K^+\pi^+$ BR -> 2.28%

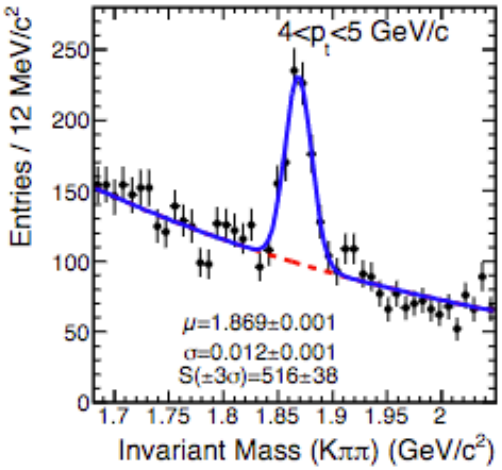


- PID using TPC and TOF
- Analysis performed via reconstruction of decay vertex topologies displaced from the primary vertex
- Feed-down subtracted using pQCD prediction

PRD 86 (2012) 112007



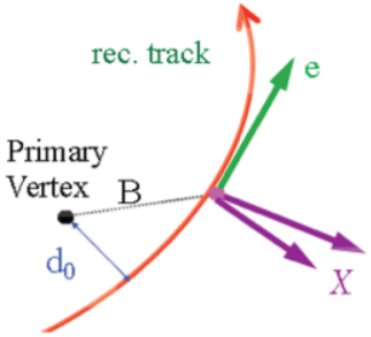
JHEP 01 (2012) 128



Invariant mass distributions of D^+

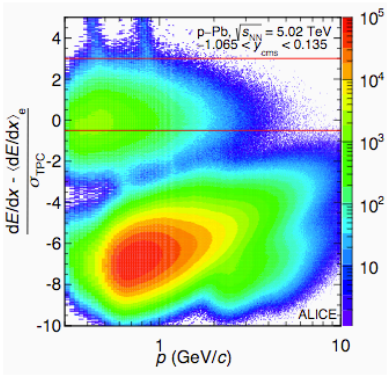
Reconstruction of heavy-flavour hadron decay electrons

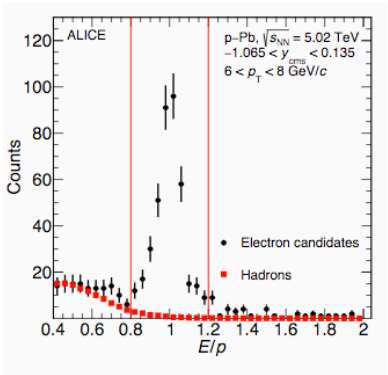
- Heavy flavour hadron decay electrons are identified using TPC and TOF for low p_T and TPC and EMCal For high p_T
- Non heavy-flavour background (Dalitz decay from neutral mesons and photon conversion) removed using invariant mass method i.e. reconstruction of e^+e^- pairs or cocktail method

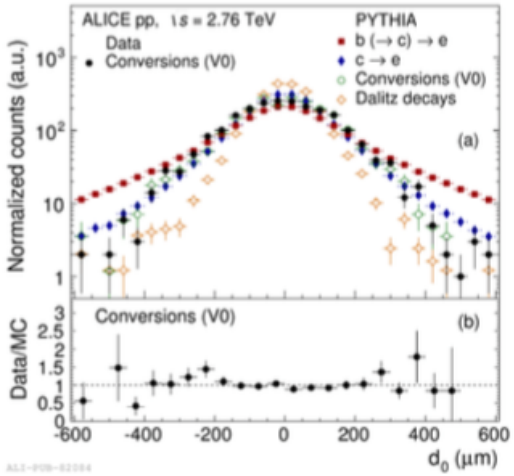


- Beauty-hadron decay electrons are separated using the impact parameter distribution
- ✓ Beauty-hadron decay electrons have broader track impact parameter distribution due to the longer life time of the beauty hadrons

PLB 754 (2016) 81-93



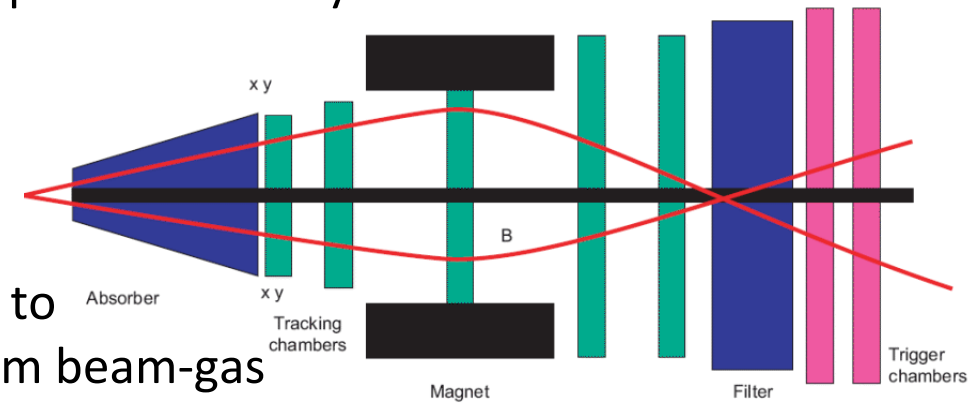




PLB 738 (2014) 97

Reconstruction of heavy-flavour hadron decay muon

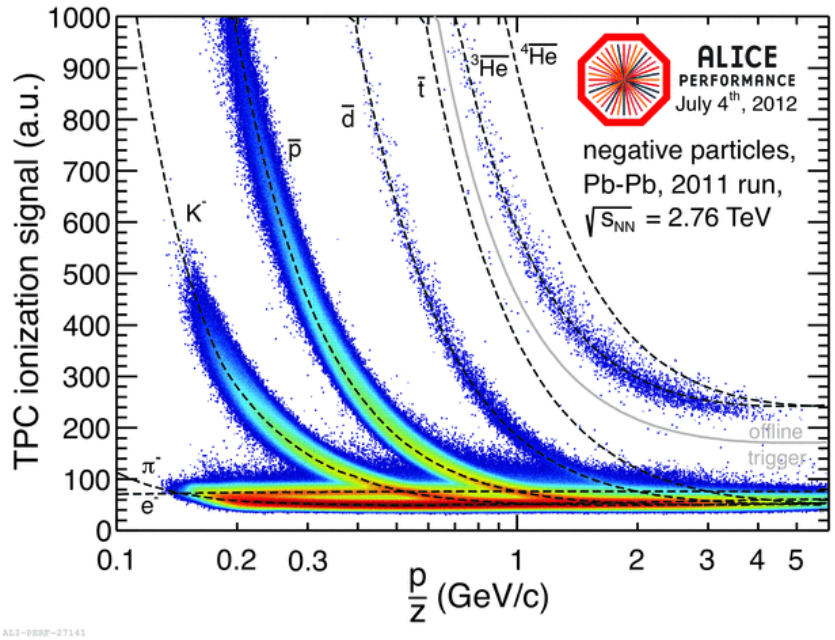
- Heavy-flavour hadron decay muons are reconstructed using forward muon spectrometer
- Acceptance and geometrical cuts are applied to identify the muons
- Track matching with trigger chambers is applied to reject hadrons
- Cut on the distance of closest approach to the primary vertex to remove tracks from beam-gas interactions



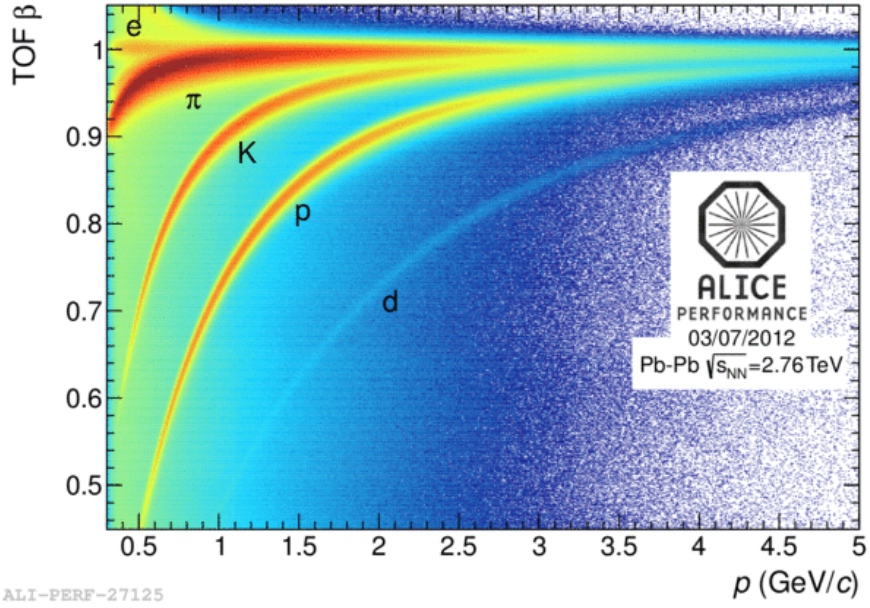
- Background (mainly coming from primary k and π decays) is estimated via Monte Carlo (MC) simulations in pp collisions or via data-tuned MC cocktail in p-Pb and Pb-Pb collisions
- High p_T background from W decays are estimated using MC simulation

Excellent particle identification in ALICE

TPC PID

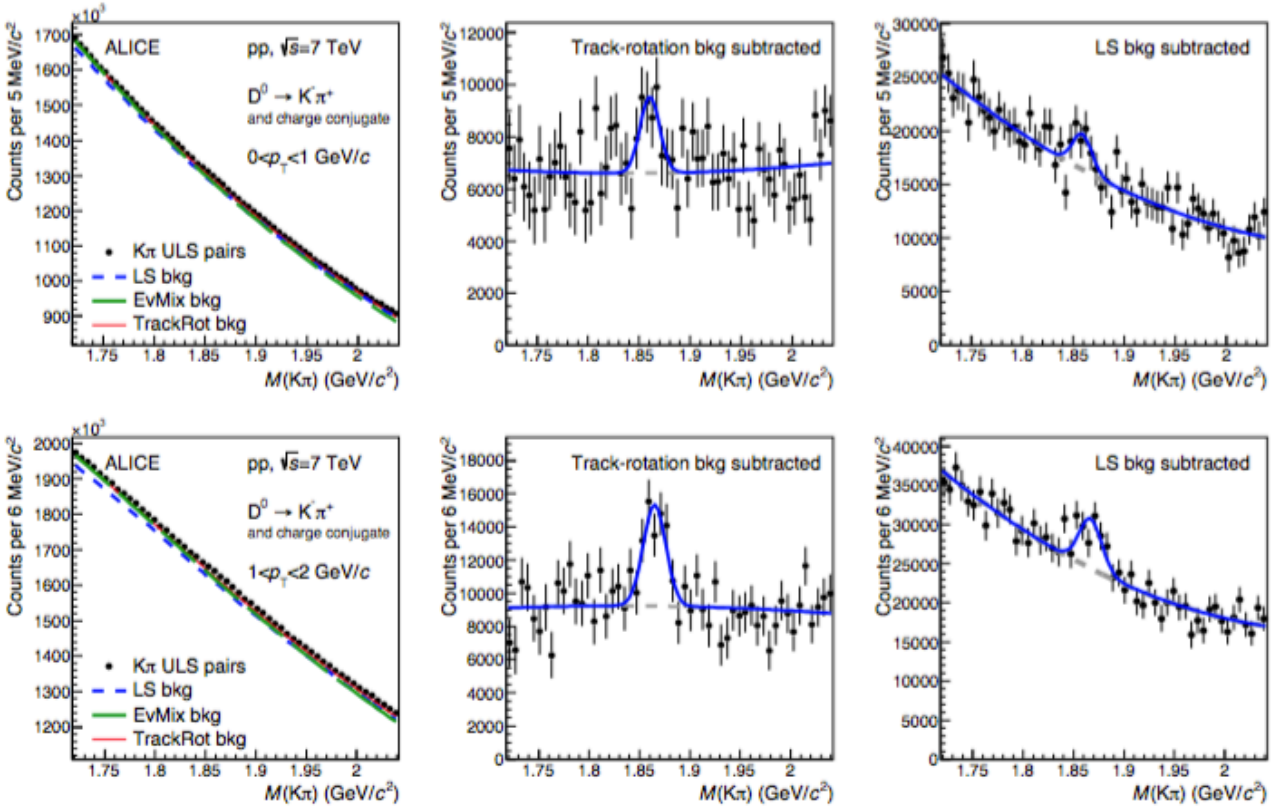


TOF PID



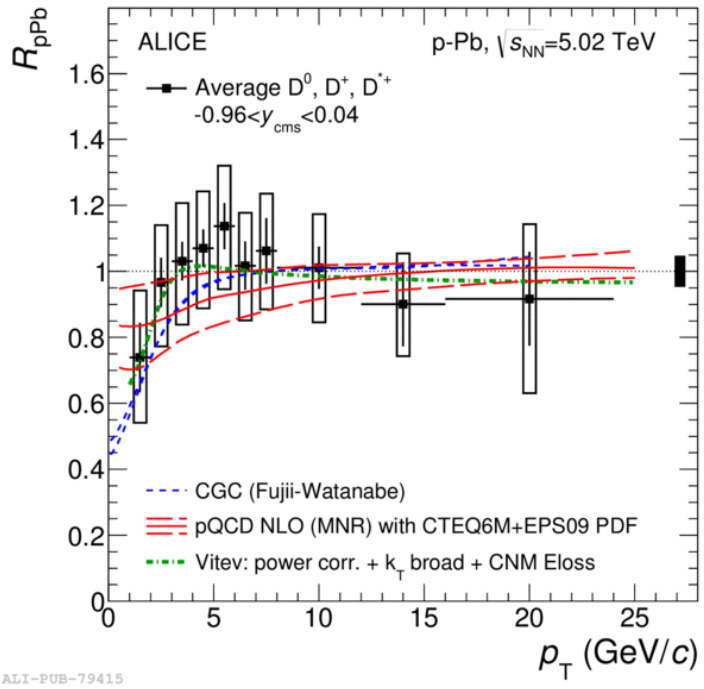
D mesons measurements at p_T = 0

arXiv: 1605.07569v1



- combinatorial background subtraction method is used to extract the signal

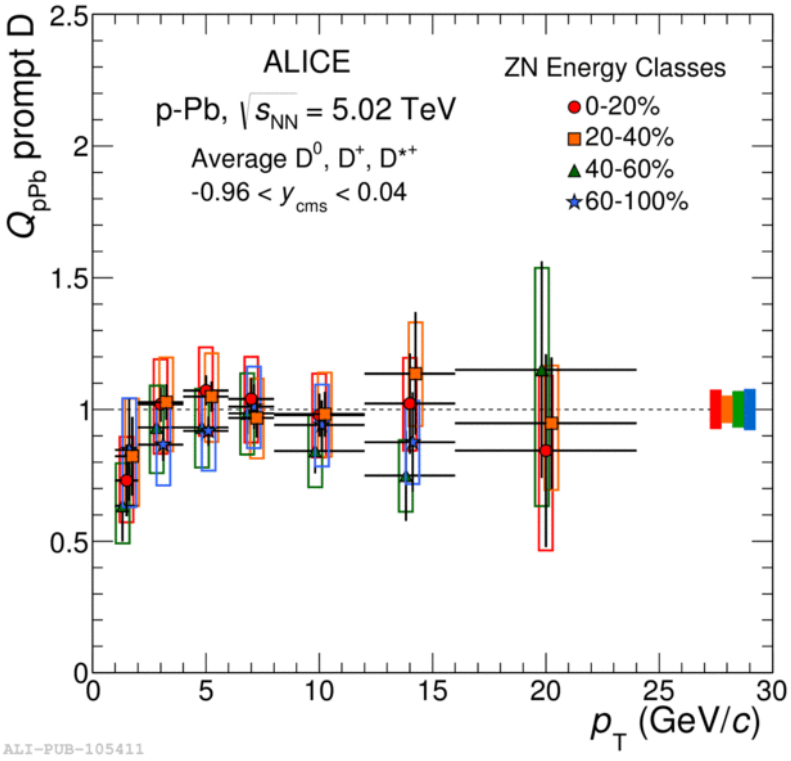
D mesons measurements



- Models including initial state effects describe the data within uncertainties

Q_{pPb} pf D mesons

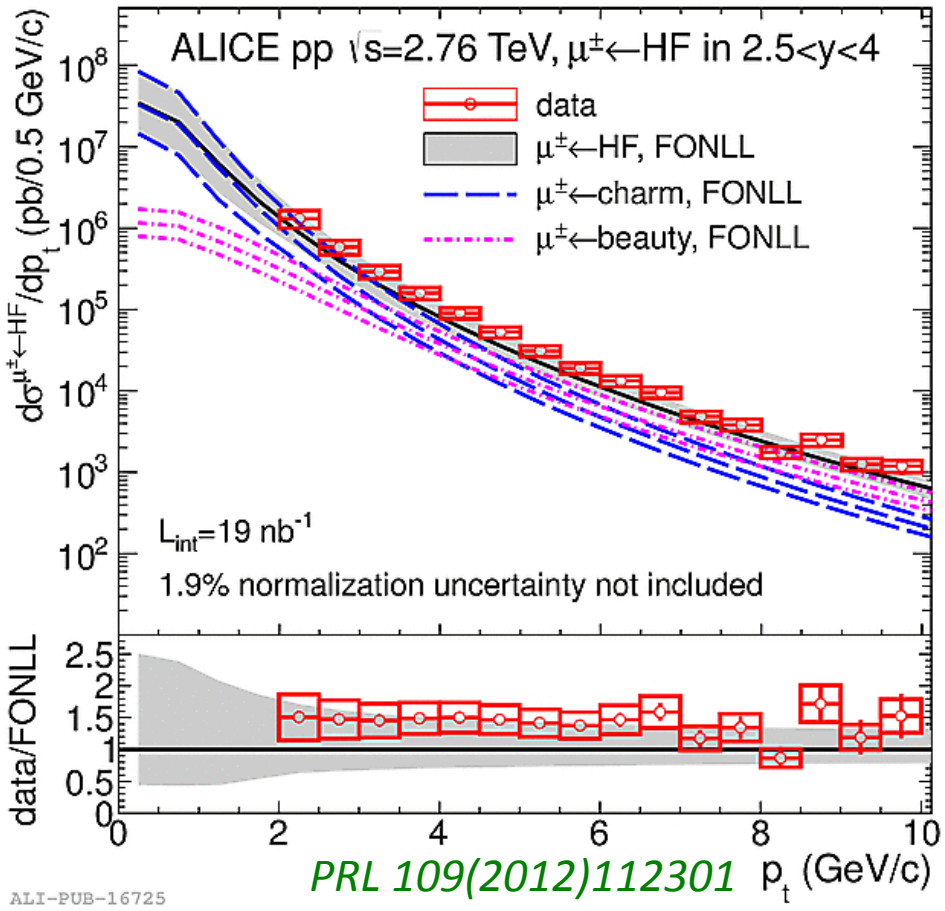
arXive:1602.07240v1



- Models including initial state effects describe the data within uncertainties

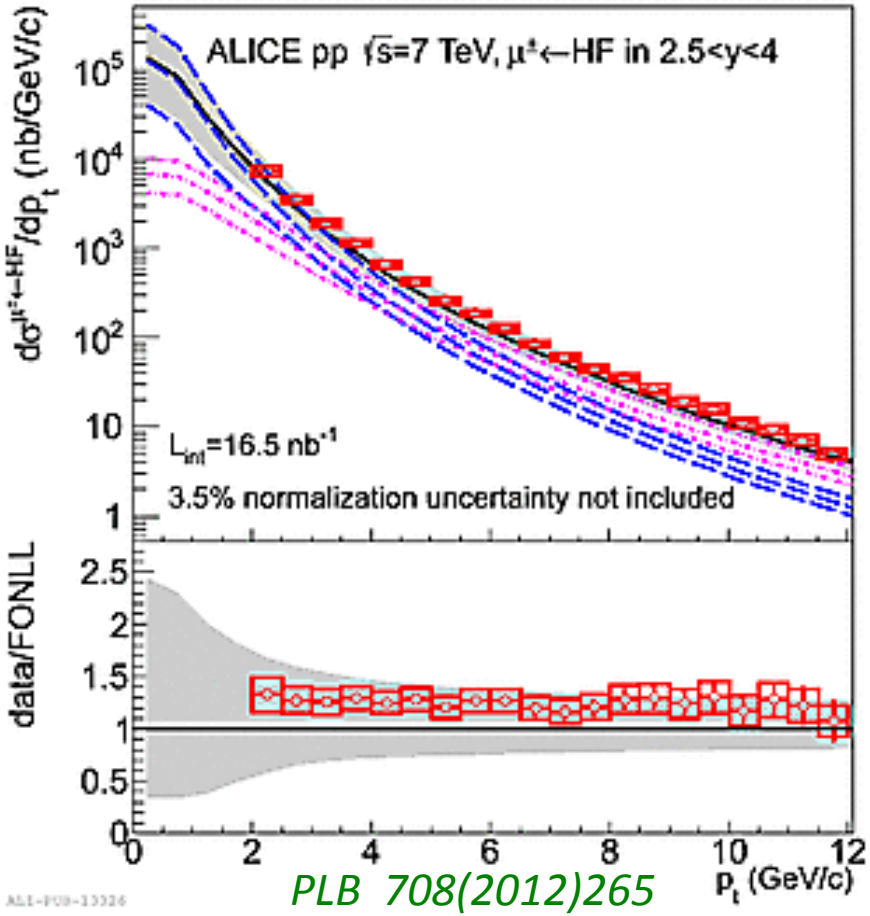
pp: heavy-flavour hadron decay muons

$\sqrt{s}$ = 2.76 TeV



PRL 109(2012)112301

$\sqrt{s}$ = 7 TeV



PLB 708(2012)265

- p_T-differential cross section of heavy-flavour decay muons are measured in forward rapidity (2.5 < y < 4)
- Results are described by pQCD calculations within uncertainties

Summary and outlook

Expectation from the LHC Run II data :

- Large data sample in pp at $\sqrt{s}$ = 5 TeV and 13 TeV and in p-Pb and Pb-Pb at $\sqrt{s_{NN}}$ = 5 TeV will help more precise measurements of all HF observables, in particular for rare probes: beauty-hadron decay electrons, HF correlations and HF jet study

- Probe very low p_T region (p_T ~ 0) and more precise D-meson measurement down to p_T = 0

- Large statistics will help us to reduce the uncertainties in the measurement and help to provide more precise constraints to the model calculations

Promising D-meson invariant mass distributions in pp collisions at $\sqrt{s}$ = 13 TeV