ALICE results on open heavy-flavour production in pp, p-Pb and Pb-Pb collisions at the LHC

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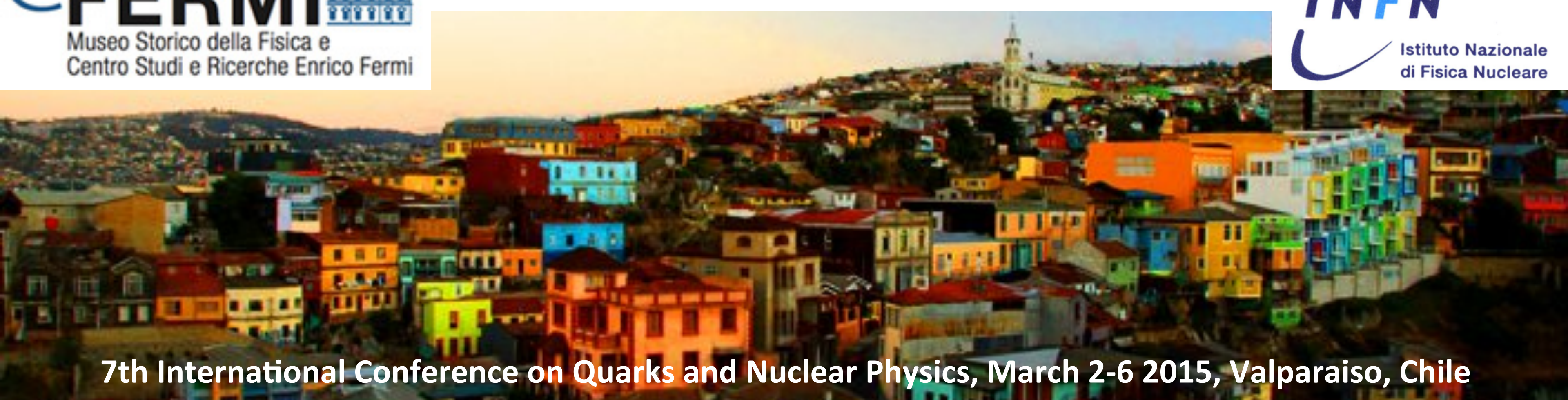
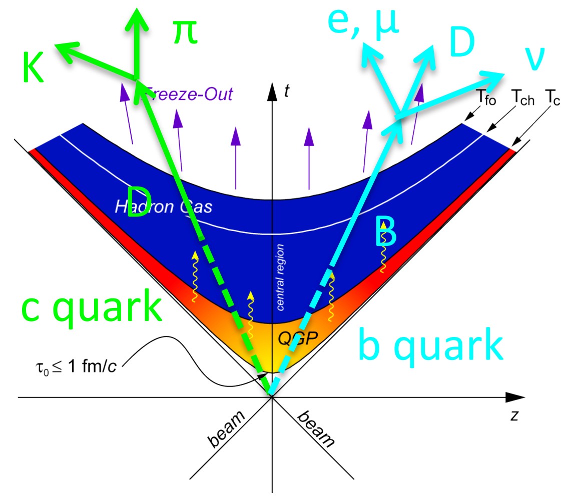
Centro Fermi – Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi

INFN – Istituto Nazionale di Fisica Nucleare

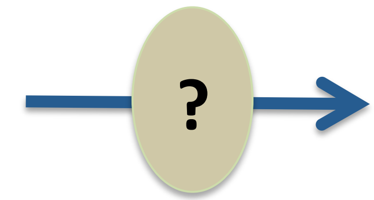


7th International Conference on Quarks and Nuclear Physics, March 2-6 2015, Valparaiso, Chile

Heavy flavour in heavy-ion collisions



- Because of their large masses, charm ($m_c \approx 1.5$ GeV) and beauty ($m_b \approx 5$ GeV) are produced at the early stages of the collisions
  - hard scattering with large Q^2 → **production cross section calculable with perturbative QCD**
- $m_{c,b} >> \Lambda_{QCD}$ → heavy quarks are genuine hard probes **even at low p_T** (in contrast to jets)
- $\tau_{prod} \approx 1/(2m_Q) \approx 0.1$ fm/c << $\tau_{QGP} \approx 5 - 10$ fm/c at LHC
- they interact with the QCD high-density medium, but those interactions don't change their flavour
  - **destruction or creation in the medium is difficult**
  - **transported through the whole evolution of the system**



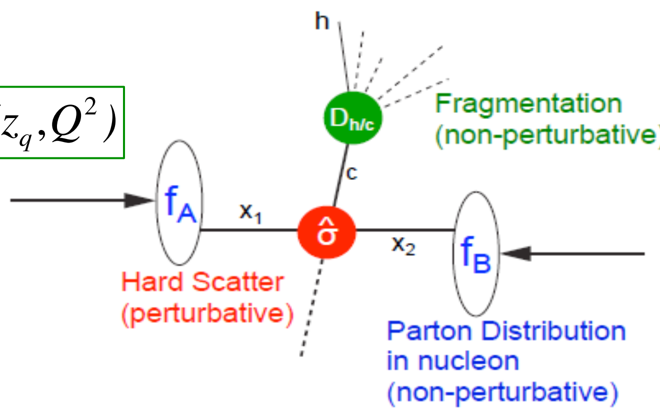
they behave as penetrating probes ("*direct*" info from the medium)

Main questions:
- **do heavy quarks lose energy in the QGP and if so, how?**
- **do heavy quarks participate in the medium collective motion?**

Heavy flavour in pp and p-Pb collisions

- **pp collisions**
  - precision test of pQCD-based predictions for production cross sections at the highest collision energies.

$$\sigma_{hh\to Hx} = PDF(x_a,Q^2)PDF(x_b,Q^2) \otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to H}(z_q,Q^2)$$



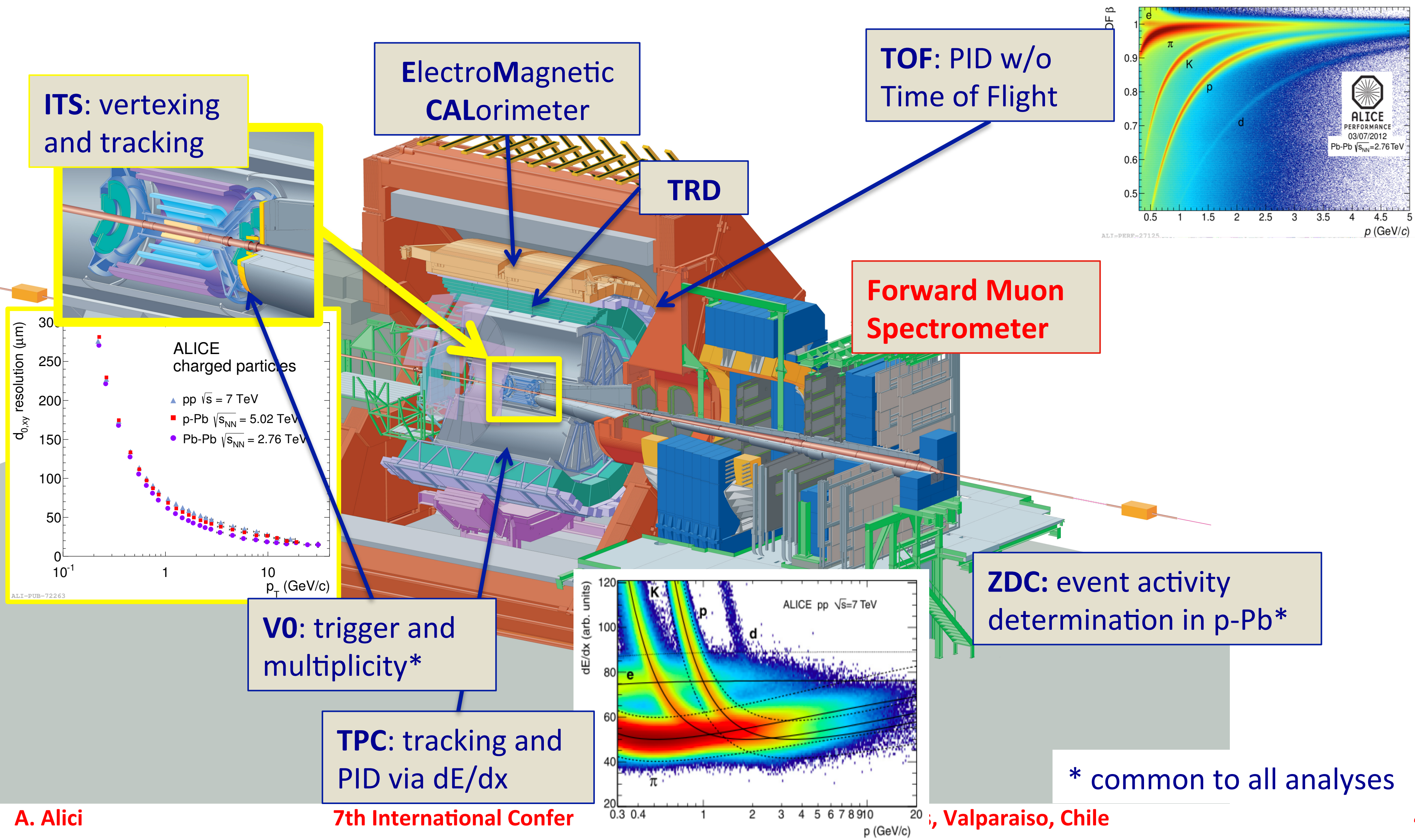
  - study the role of multi-parton interactions (MPI) in heavy-flavour production.
  - reference for p-Pb and Pb-Pb measurements.

- **p-Pb collisions**
  - address initial-state (or cold-nuclear-matter) effects, such as
    - shadowing and gluon saturation (CGC)
    - energy loss in cold nuclear matter
    - k_T-broadening
  - reference for Pb-Pb measurements.

K.J. Eskola et al, JHEP 0904 (2009) 65
H. Fuji, K. Watanabe, NPA 915 (2013) 1
I. Vitev et al, PRC 75 (2007) 064906
X.N. Wang, PRC 61 (2000) 064910

The ALICE experiment

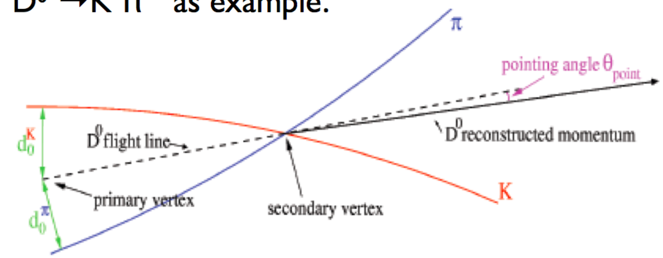
High precision tracking, good vertexing capabilities and excellent particle identification



* common to all analyses

HF in the central barrel – D mesons

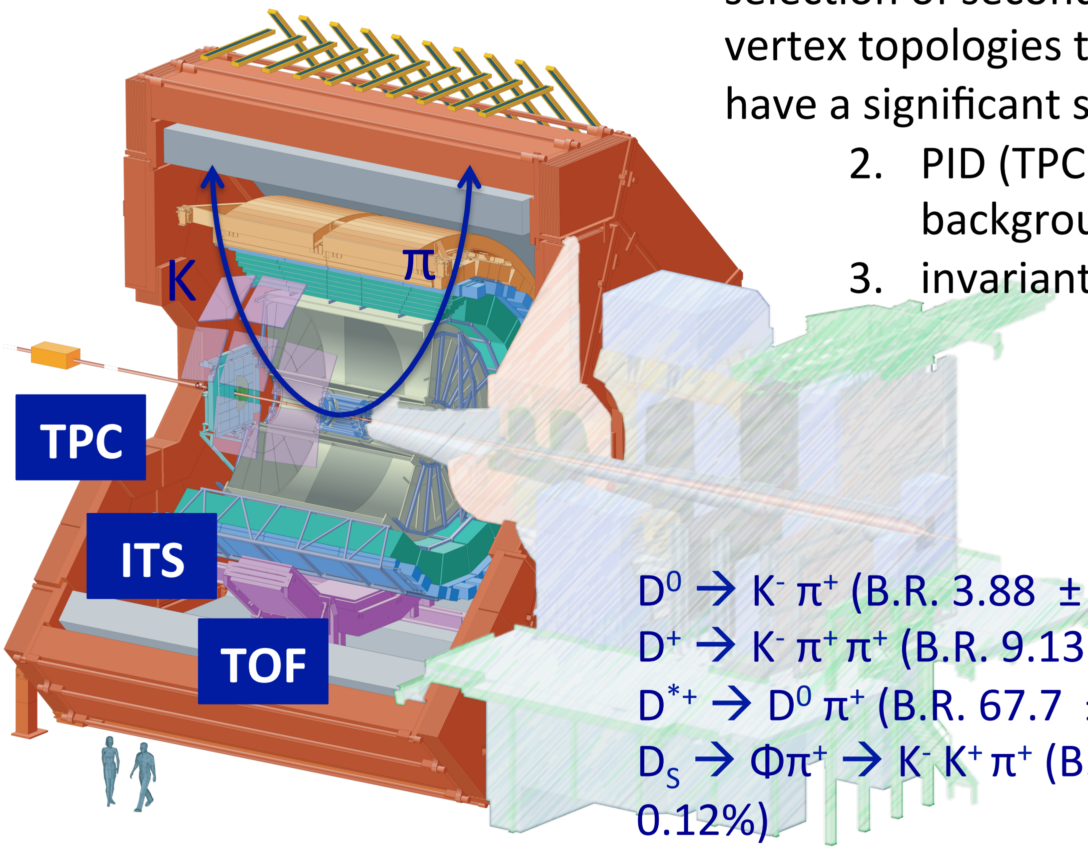
$D^0 \rightarrow K^- \pi^+$ as example.



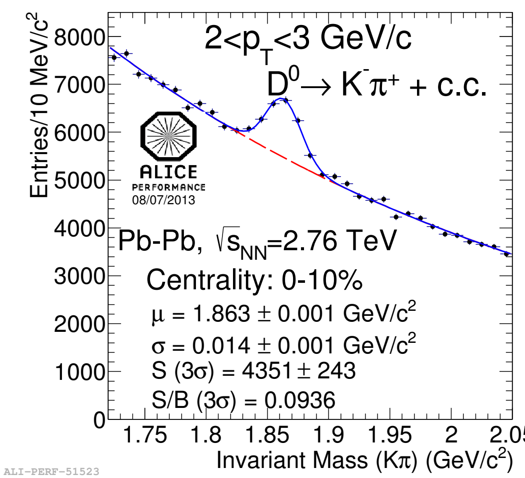
|y| < 0.5

Analysis strategy:

1. reconstruction and selection of secondary vertex topologies that have a significant separation from the primary vertex;
2. PID (TPC and TOF) to reduce combinatorial background, especially at low p_T;
3. invariant mass analysis to extract the signal.



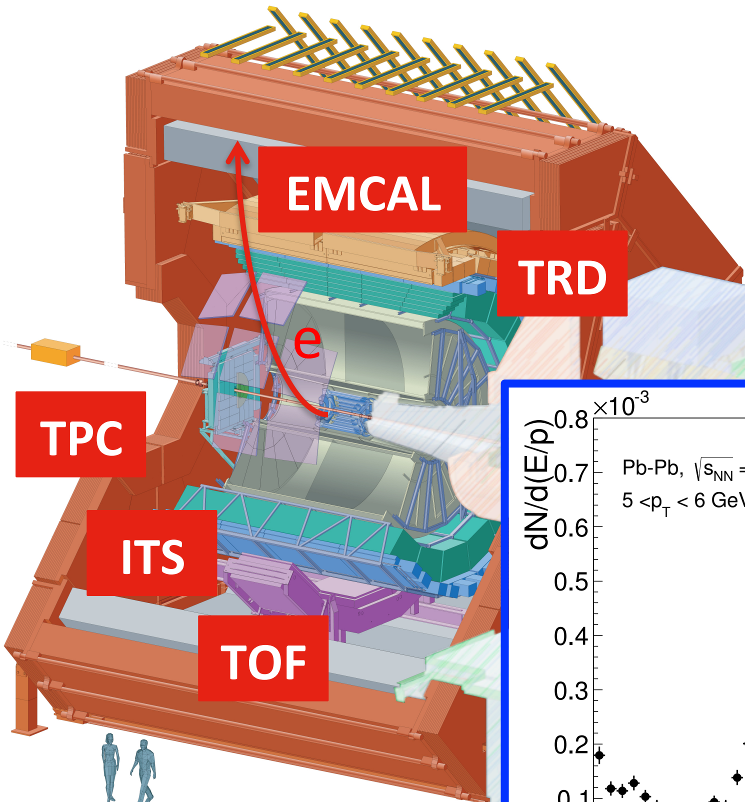
$D^0 \rightarrow K^- \pi^+$ (B.R. 3.88 ± 0.05%)
$D^+ \rightarrow K^- \pi^+ \pi^+$ (B.R. 9.13 ± 0.19%)
$D^{*+} \rightarrow D^0 \pi^+$ (B.R. 67.7 ± 0.5%)
$D_S \rightarrow \Phi\pi^+ \rightarrow K^- K^+ \pi^+$ (B.R. 2.28 ± 0.12%)



HF in the central barrel – electrons

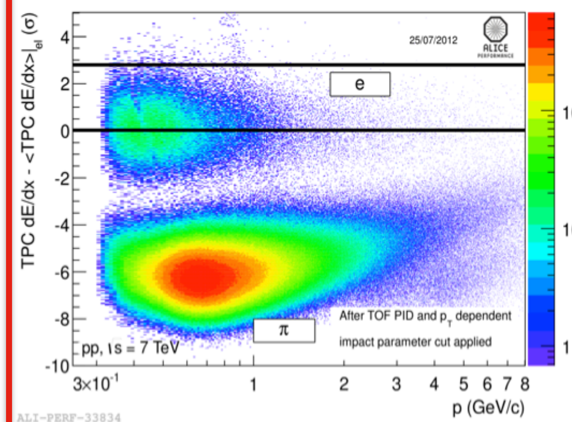
B → e + X (B.R. ~ 11%)
D → e + X (B.R. ~ 10%)
large S/B from other electron sources, especially at high p_T

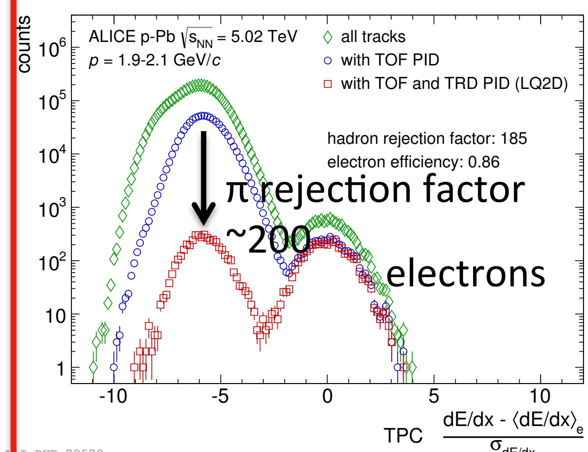
|y| < 0.5

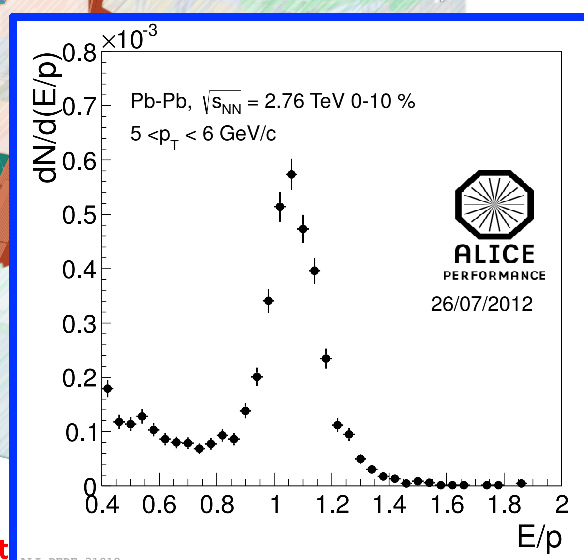


Analyses based on electron identification via two approaches:

- TPC, TOF and TRD
- TPC and EMCAL





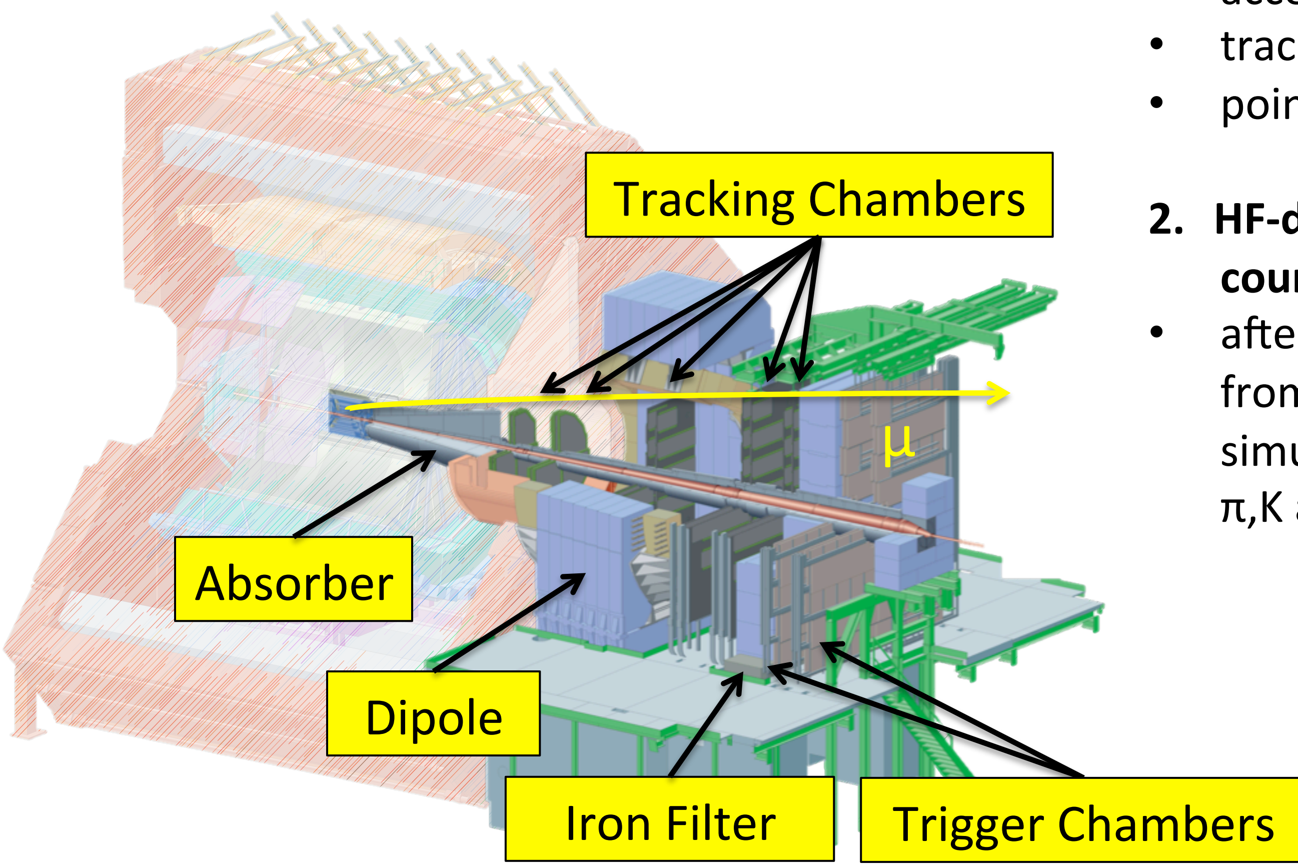


inclusive electron yield determination, background from other electron sources calculated using a cocktail approach and subtracted.

HF in the forward region – muons

$-4 < \eta < -2.5$

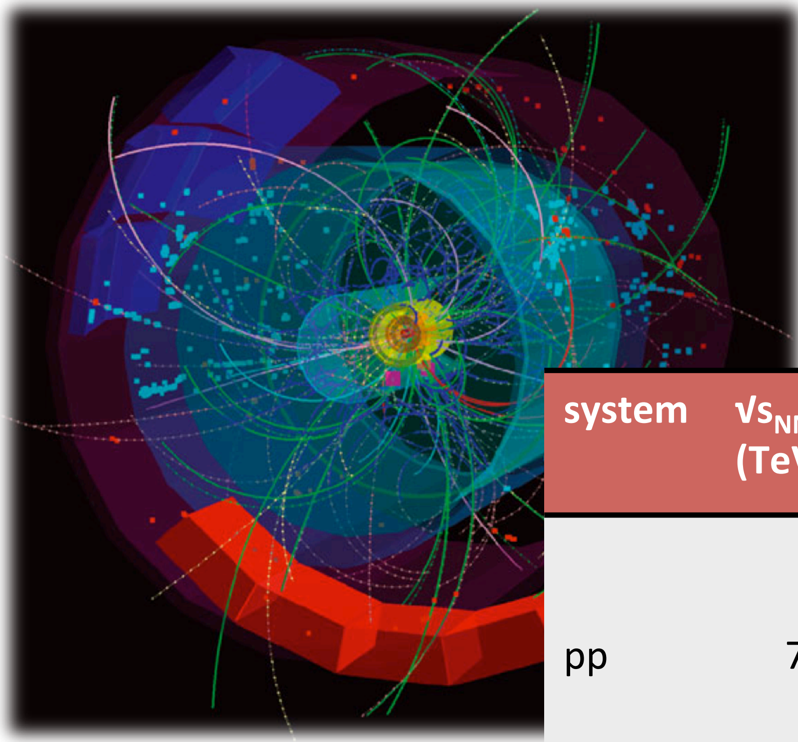
$B \rightarrow \mu + X$ (B.R. ~ 11%)
$D \rightarrow \mu + X$ (B.R. ~ 10%)



Analysis strategy:

1. **muon track selection**
   - acceptance/geometrical cuts
   - tracks matched with trigger
   - pointing to the IP

2. **HF-decay muon signal counting**
   - after subtraction of muons from primary π,K decays via simulations with data tuned π,K abundances

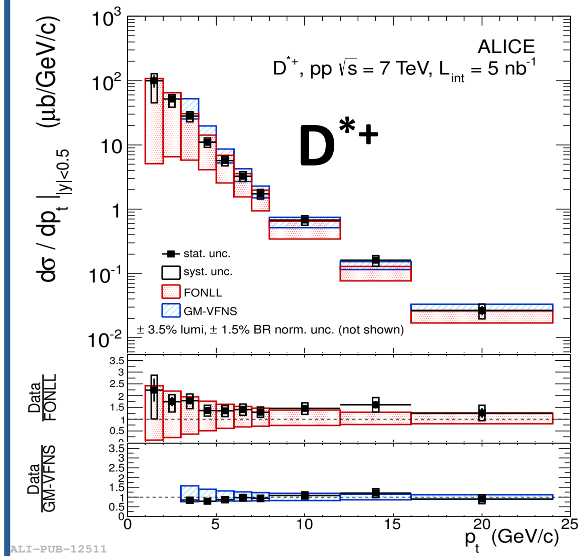


pp collisions

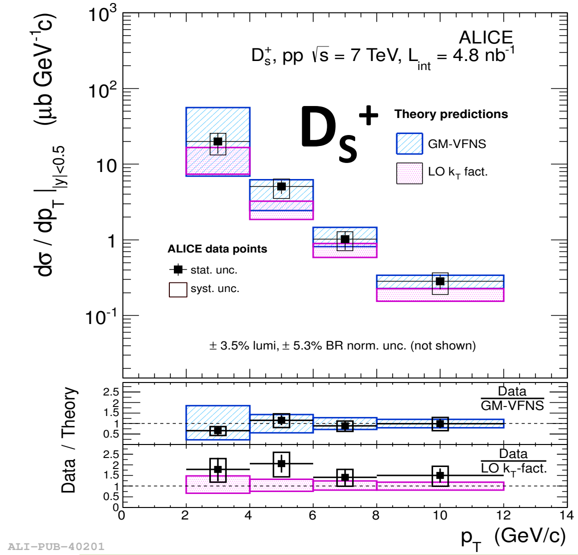
system	$\sqrt{s_{NN}}$ (TeV)	year	Luminosity	Analyses
pp	7	2010	2.6 nb^{-1}	HF-decay electrons
			2.2 nb^{-1}	Beauty-decay electrons
			16.5 nb^{-1}	HF-decay muons
			5 nb^{-1}	D mesons
pp	2.76	2011	0.5 (11.9) nb^{-1}	HF-decay electron and beauty-decay electrons Min. Bias (EmCAL)
			19 nb^{-1}	HF-decay muons
			1.1 nb^{-1}	D mesons

D-meson production cross sections

pp, √s = 7 TeV

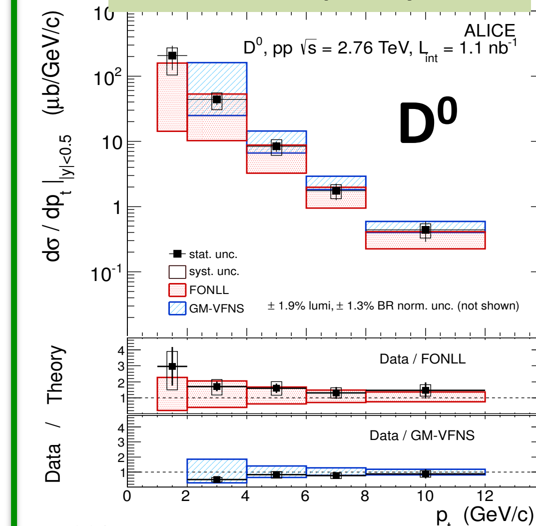


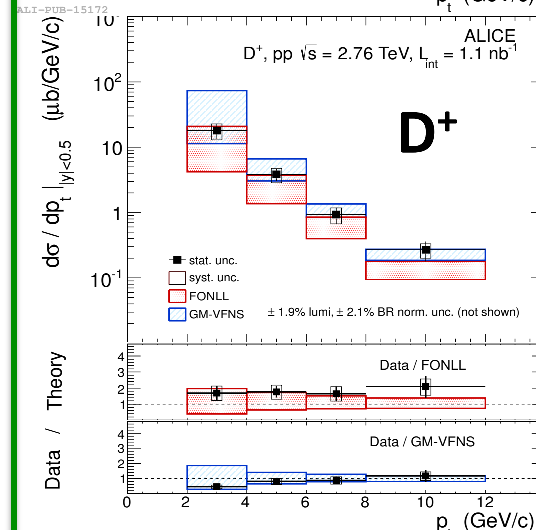
JHEP 1201 (2012) 128



Phys. Lett. B718 (2012) 279-294

JHEP 1207 (2012) 191





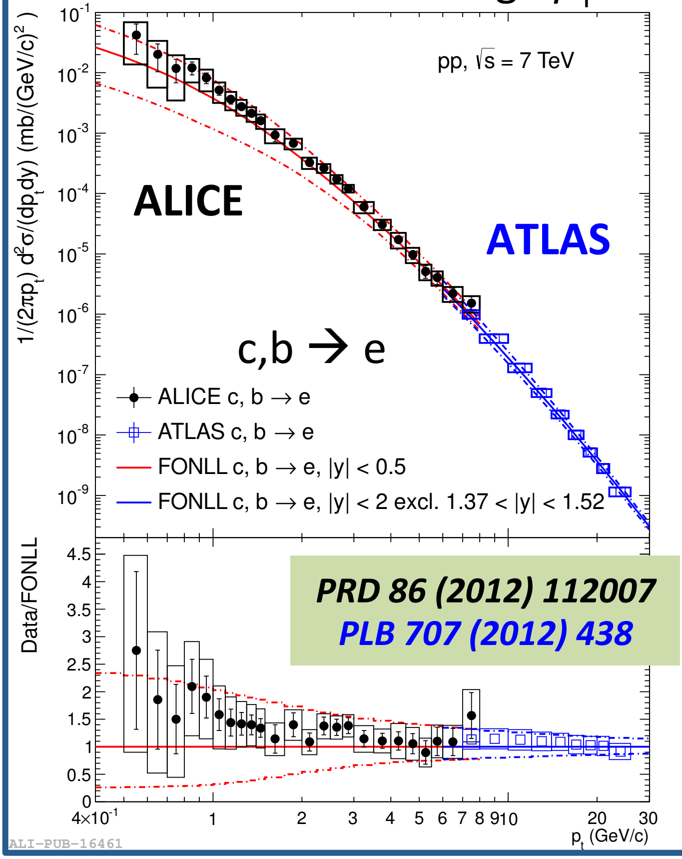
pp, √s = 2.76 TeV

- The p_T-differential production cross sections are reproduced within uncertainties by theoretical predictions based on pQCD
  - *FONLL: JHEP 1210 (2012) 37*
  - *GM-VFNS: EPJ C72 (2012) 2082*
  - *LO k_T factorization: Phys. Rev. D87 (2013) 094022*

Heavy-flavour decay leptons

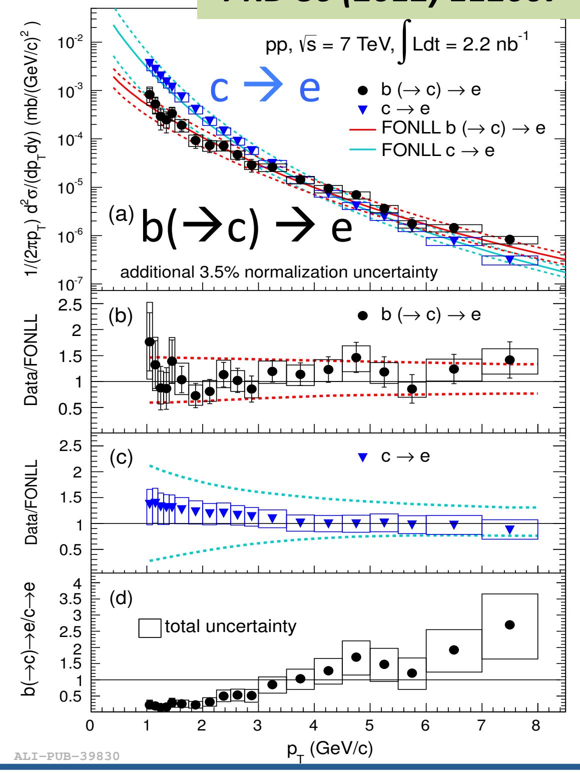
complementary with ATLAS measurements at high p_T

pp, √s = 7 TeV



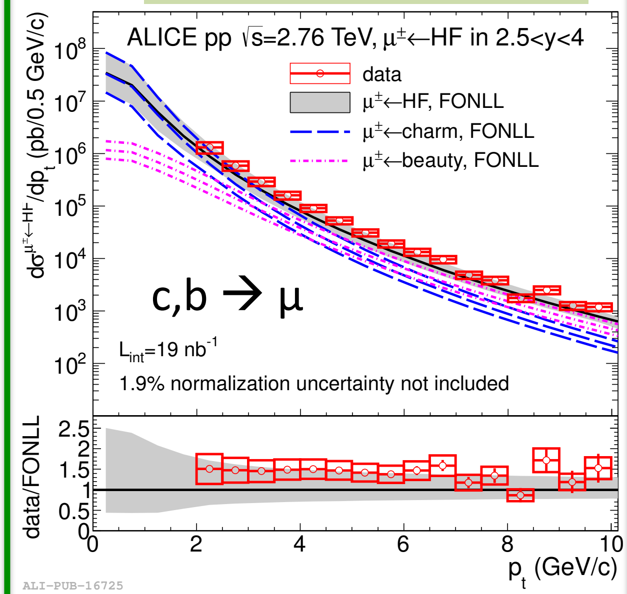
PRD 86 (2012) 112007
PLB 707 (2012) 438

PRD 86 (2012) 112007



pp, √s = 2.76 TeV

PRL 109 (2012) 112301



- HF-decay lepton p_T-differential production cross sections are reproduced within uncertainties by theoretical predictions based on pQCD (from p_T = 0.5 to 25 GeV/c)

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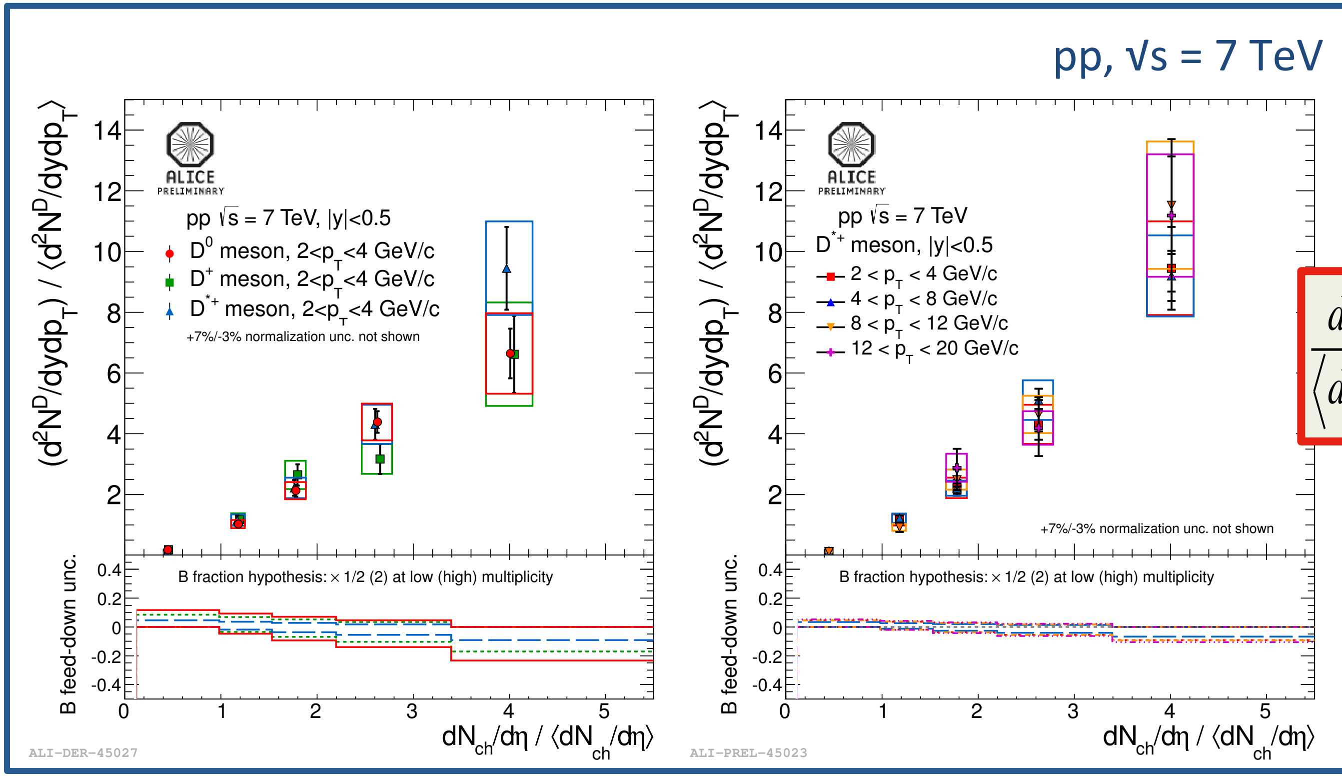
Multiplicity dependence

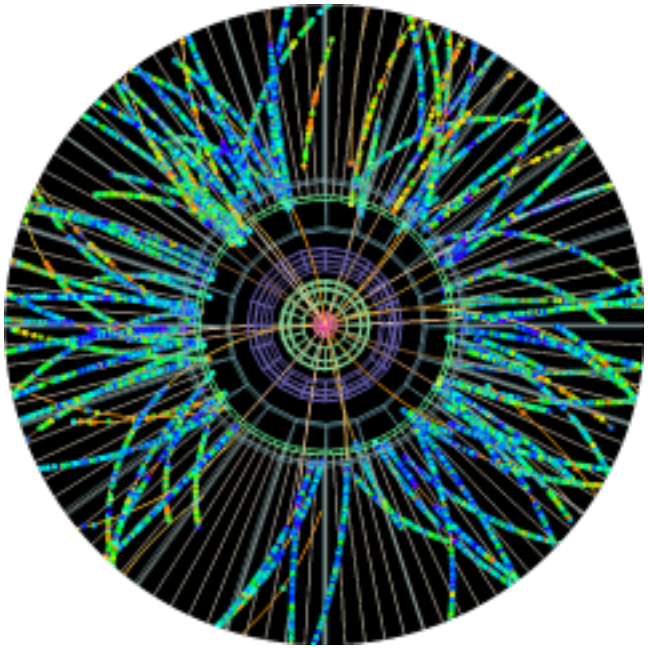


Self-normalized D-meson yields vs. charged-particle multiplicity in pp collisions at √s = 7 TeV.

$$\frac{d^2N/dydp_T}{\langle d^2N/dydp_T\rangle} = \frac{Y^{mult}/(\varepsilon^{mult}\times N^{mult}_{event})}{Y^{tot}/(\varepsilon^{tot}\times N^{tot}_{event}/\varepsilon^{trigger})}$$

- Yields of all D-meson species increase with multiplicity w/o a significant p_T dependence
  - Indication of Multi-Parton Interaction on a hard scale?

Similar trend observed also in p-Pb and Pb-Pb collisions.



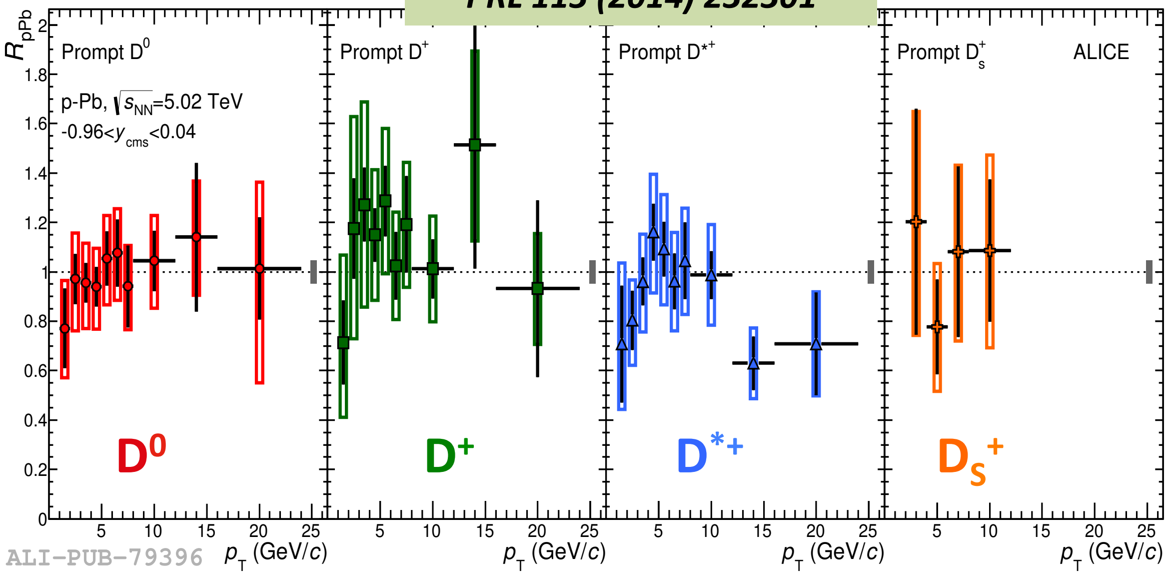
p-Pb collisions

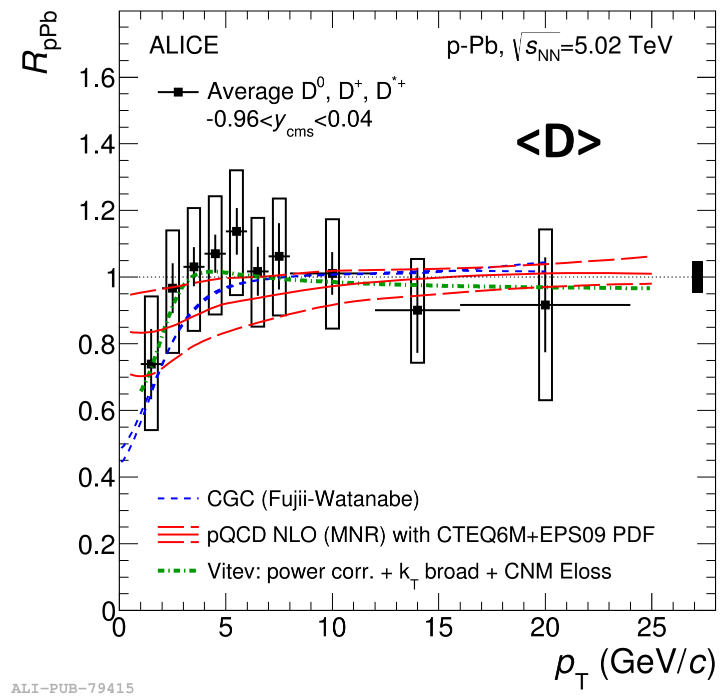
system	$\sqrt{s_{NN}}$ (TeV)	year	Luminosity (Min. Bias)	Analyses
p-Pb	5.02	2013	48.6 μb^{-1}	D mesons, HF-decay electrons and muons, beauty-decay electrons, HF-decay electrons – charged-hadron correlation

D meson: p_T-differential R_{pPb}

PRL 113 (2014) 232301

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

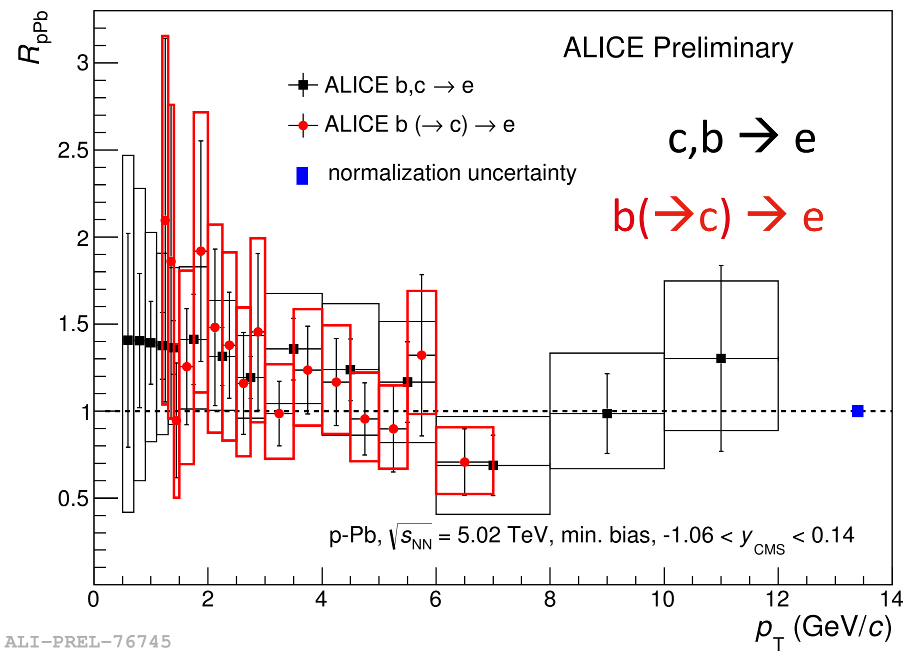


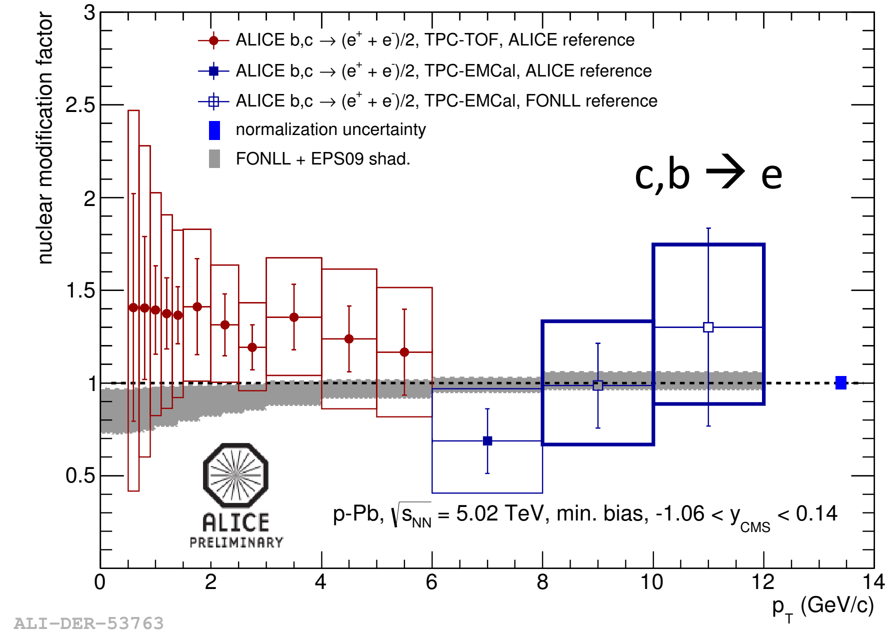


- R_{pPb} consistent with unity for all D-meson species
- Good agreement with theoretical calculations:
  - CGC calculations (*NPA 915 (2013)*).
  - MNR pQCD calculations with EPS09 nuclear PDF (*JHEP 04 (2009) 065*)
  - model including energy loss in cold nuclear matter, nuclear shadowing and k_T broadening (*PRC 75 (2007) 064906*)

- **Small cold nuclear matter effects for p_T > 2 GeV/c**

HF-decay electron R_{pPb}





- R_{pPb} consistent with unity for heavy-flavour decay electrons at mid-rapidity
- FONLL pQCD calculations with EPS09 shadowing parameterization in agreement with the data (*JHEP 006 (2001) 0103, JHEP 04 (2009) 065*)

- **Small cold nuclear matter effects for p_T > 2 GeV/c**

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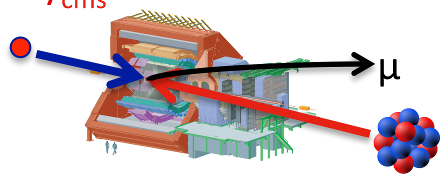
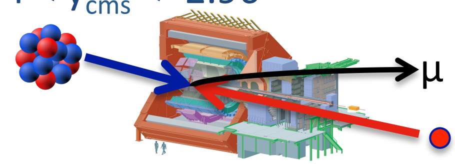
HF-decay muon R_{pPb}

$2.5 < y_{cms} < 3.54$

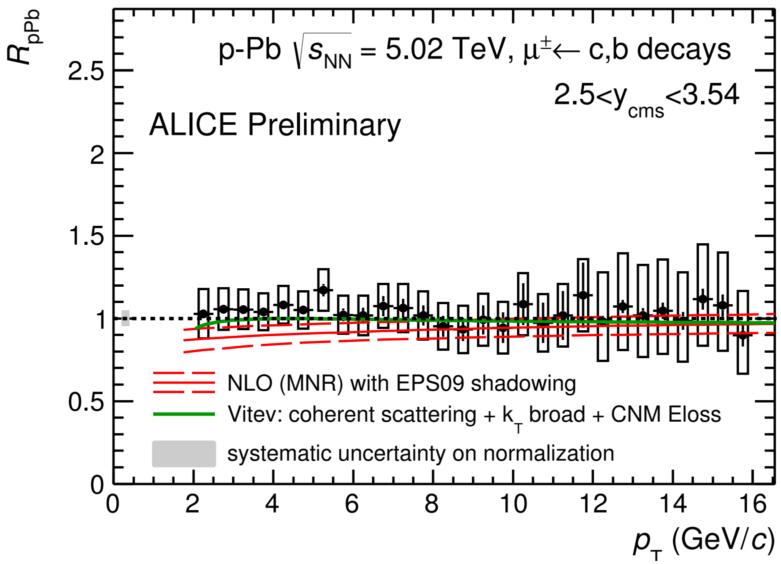


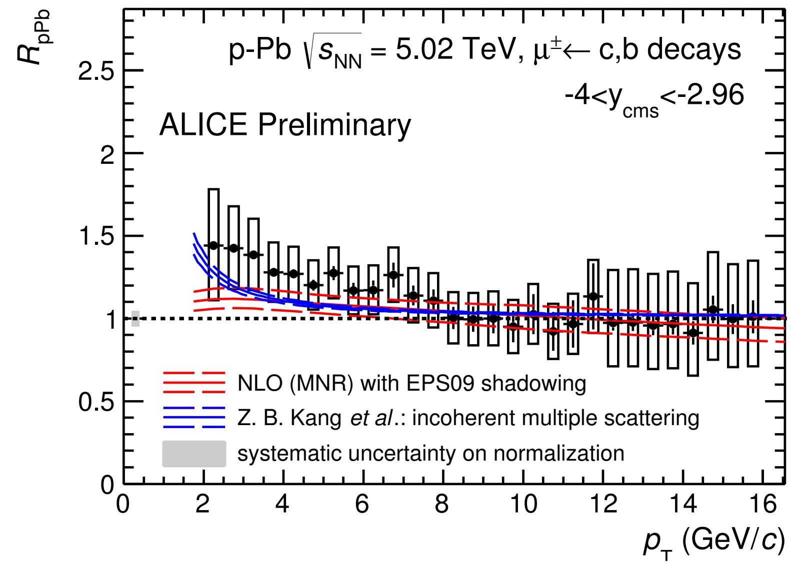
Forward
(probing low x in Pb nucleus)

$-4 < y_{cms} < -2.96$



Backward
(probing high x in Pb nucleus)



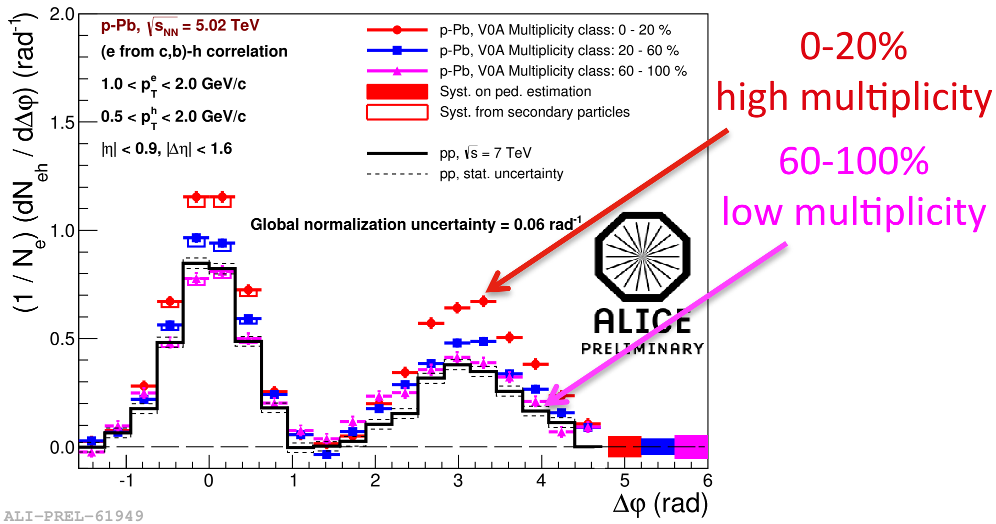


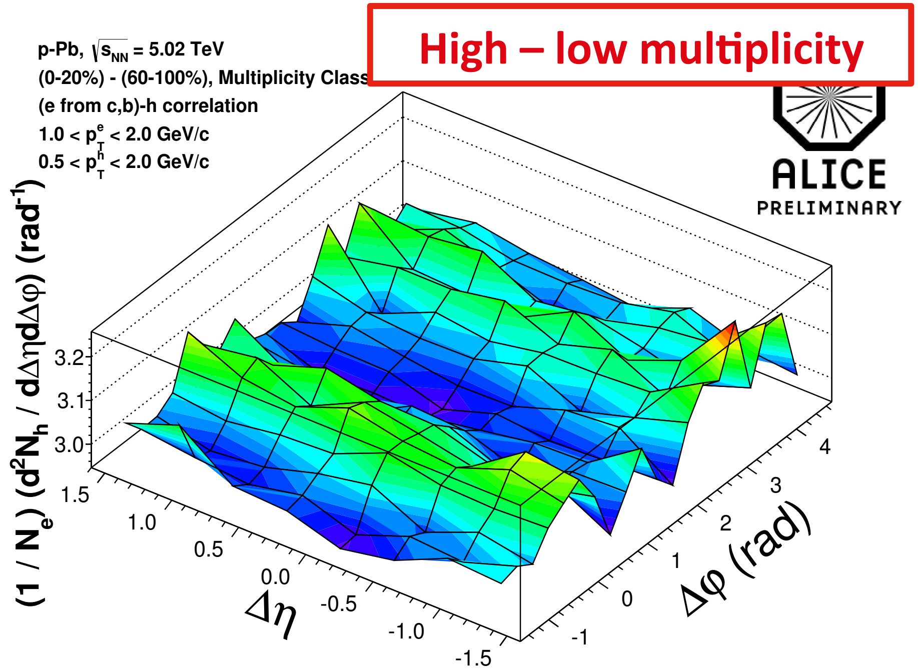
- R_{pPb} consistent with unity at forward rapidity
- R_{pPb} slightly larger than unity at backward rapidity (in the range $2 < p_T < 4$ GeV/c)
- Data are well described by pQCD models including cold nuclear matter effects (*NPB 373 (1992) 295, JHEP 04467 (2009) 065, PRC 75 (2007) 064906, arXiv:1409.2494*)

- **Small cold nuclear matter effects for $p_T > 4$ GeV/c**

HF-decay electron – hadron correlations

- study of the angular correlation between HF-decay electrons (*trigger particle*) and charged hadrons (*associated particle*) in 3 multiplicity classes





- Low-p_T trigger particle (1 <p_T^e < 2 GeV/*c*): enhancement in the near and away-side peaks for the highest multiplicity events (0-20%).
- double-ridge structure emerges (similar to what was observed in h-h correlations in the light quark sector).
- Same mechanism (CGC/hydro) for light and heavy flavour?

Phys. Lett. B719 (2013) 29-41
Phys. Lett. B726 (2013) 164-177

Phys. Rev. C88 (2013) 014903

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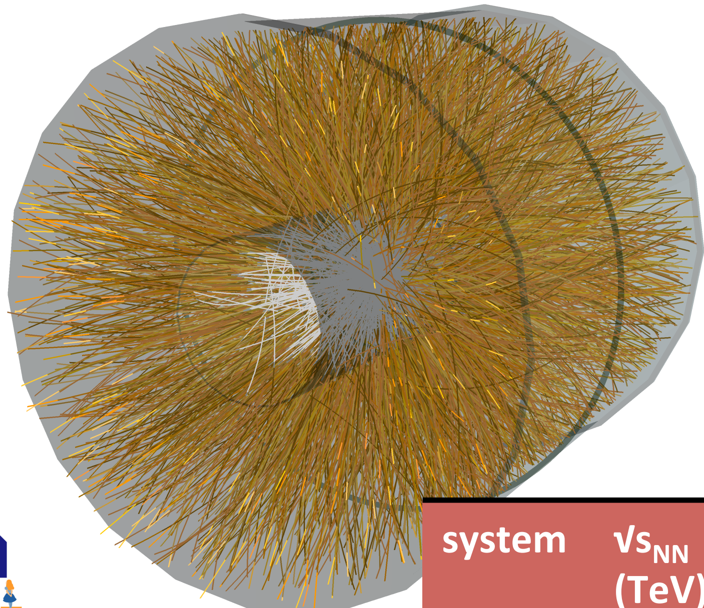
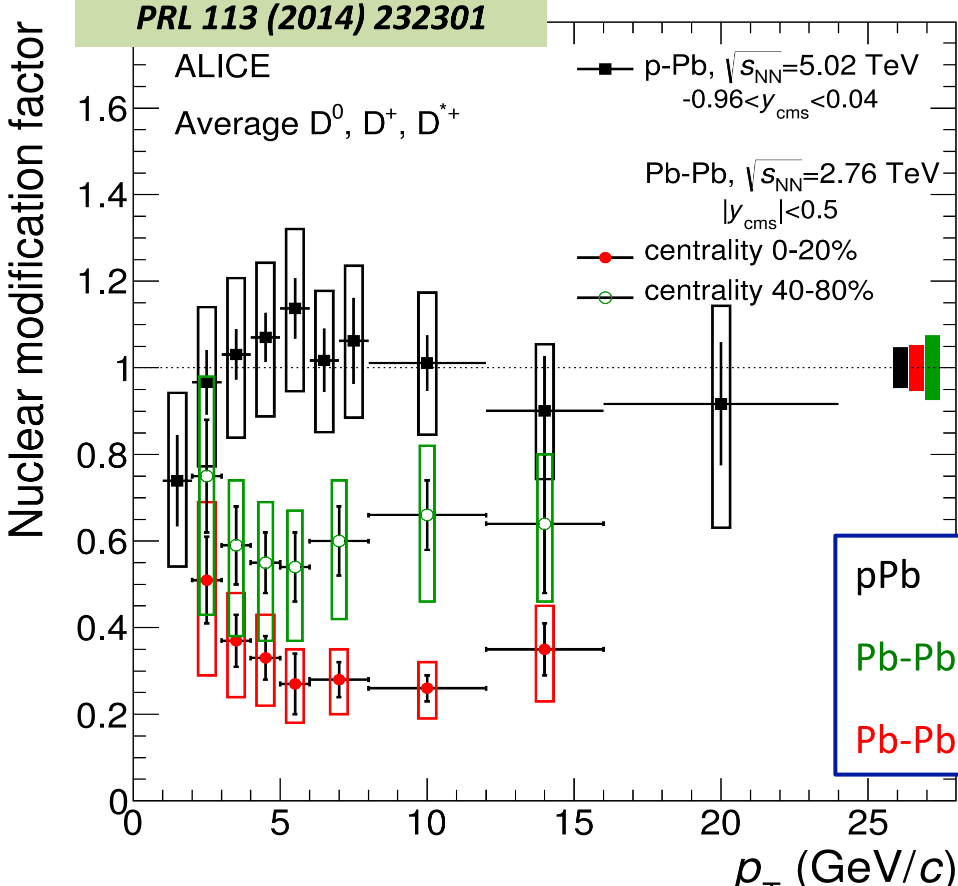


Pb-Pb collisions

system	$\sqrt{s_{NN}}$ (TeV)	year	Luminosity	Analyses
Pb-Pb	2.76	2010	2 μb^{-1}	HF-decay electrons
			2.7 μb^{-1}	HF-decay muons
			2.12 μb^{-1}	D mesons
Pb-Pb	2.76	2011	28 (37) μb^{-1}	central trigger (EmCAL)
			6 (34) μb^{-1}	semi-peripheral trigger (EmCAL)

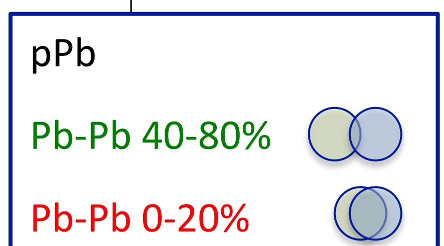
D-meson R_{AA} and R_{pPb} vs. p_T

PRL 113 (2014) 232301



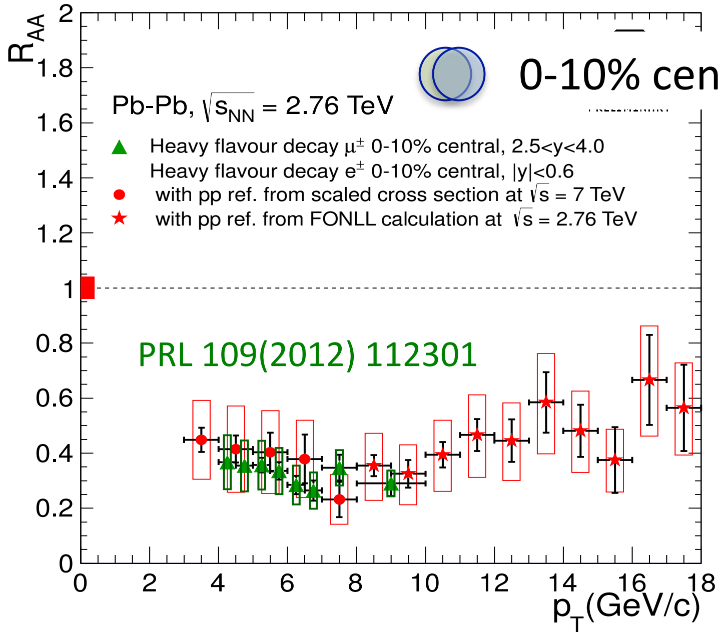
ALI-PUB-79458

$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle N_{COLL}\rangle_{AA}\,\text{Yield}_{pp}(p_T)}$$



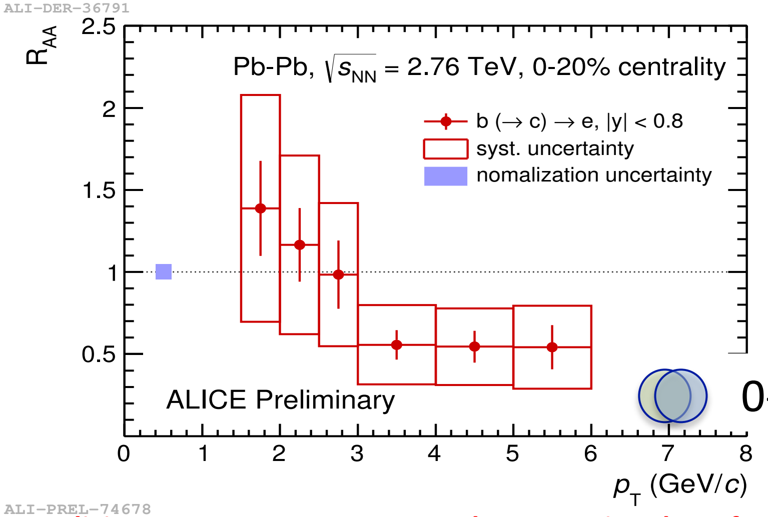
- Strong suppression observed (factor 3-5) for $p_T > 5$ GeV/c in central collisions
- Suppression increasing with centrality
- No suppression in p-Pb collisions, the suppression observed in Pb-Pb collisions is a final-state effect due to hot and dense QCD matter.

HF-decay lepton R_{AA} vs. p_T



0-10% centrality

- **Strong suppression of electrons and muons from heavy-flavour decays in the most central Pb-Pb collisions**
- R_{AA} values similar at central and forward rapidity
  - **electrons**: $|\eta| < 0.6$
  - **muons**: $2.5 < y < 4$



0-20% centrality

- First measurement of electrons from beauty decays in Pb-Pb collisions
- hint for suppression for $p_T > 3$ GeV/c

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Hierarchy of parton energy loss

- Radiative parton energy loss is colour-charge sensitive (e.g. *BDMPS* approach, *Nucl. Phys. B483 (1997) 291*):

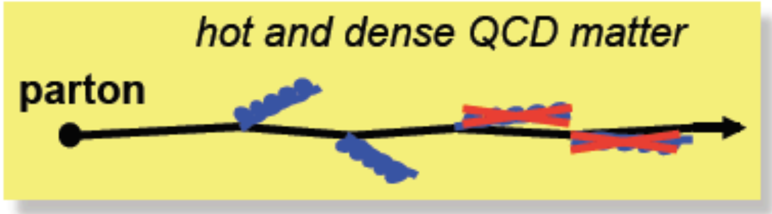
$$\langle \Delta E \rangle \propto \alpha_s \, C_R \, \hat{q} \, L^2$$

where C_R (Casimir coupling factor) is 4/3 for quarks and 3 for gluons.

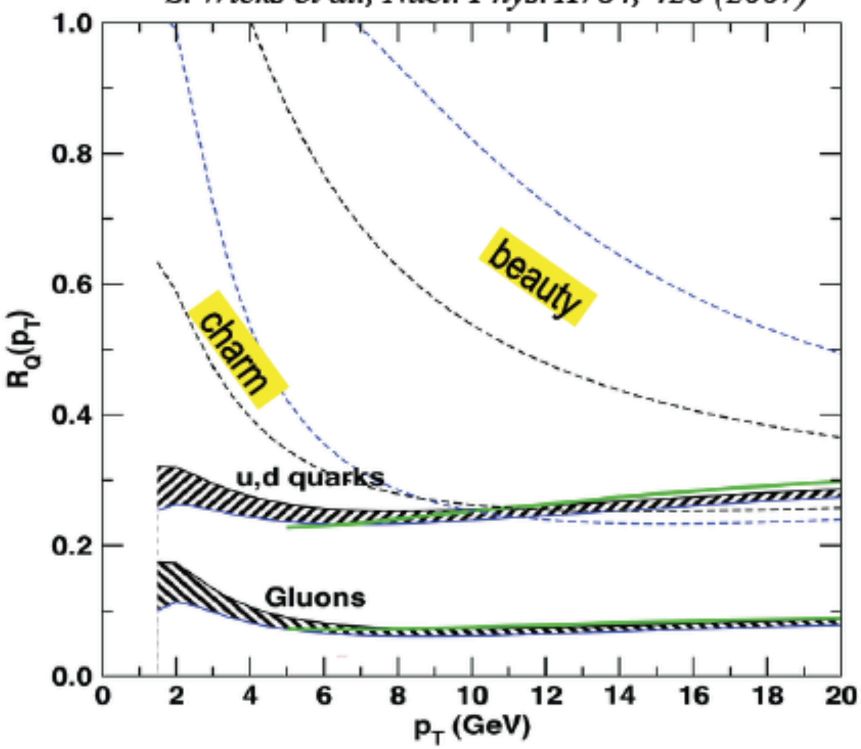
- Dead-cone effect (*JPLB 519 (2001) 199*): gluon radiation suppressed at angles $\theta < m_Q/E_Q$.

$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

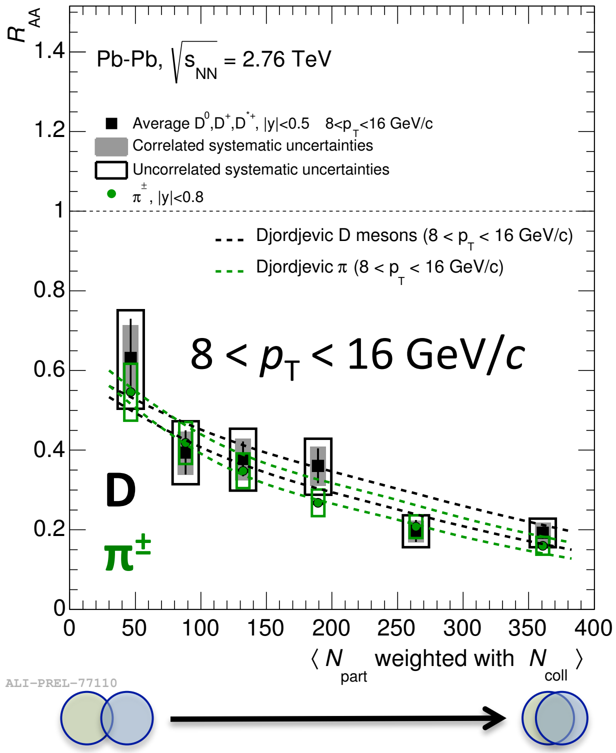
$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?

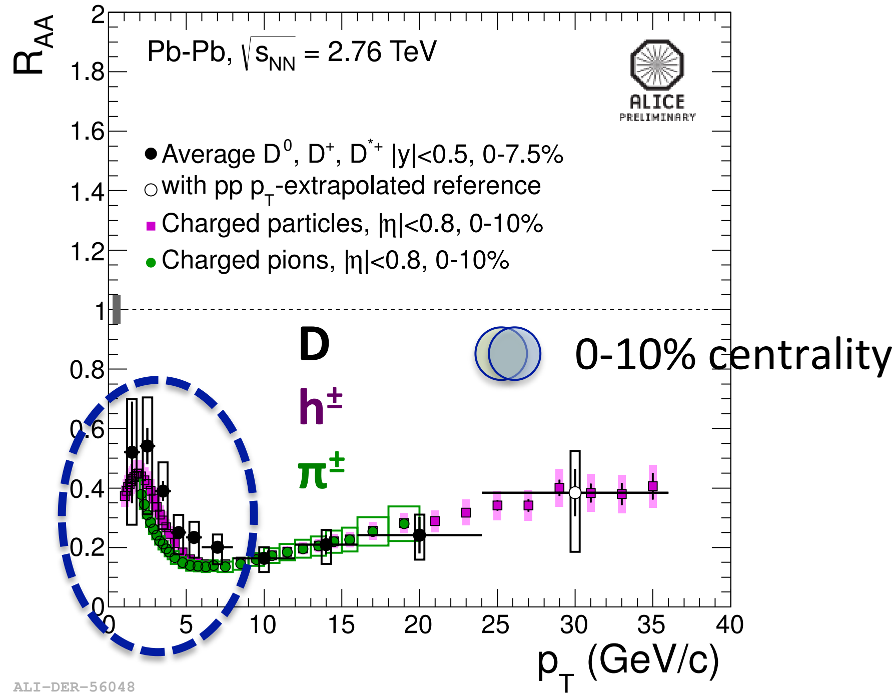


S. Wicks et al., Nucl. Phys. A784, 426 (2007)



R_{AA} mass hierarchy (charm vs. light quarks)

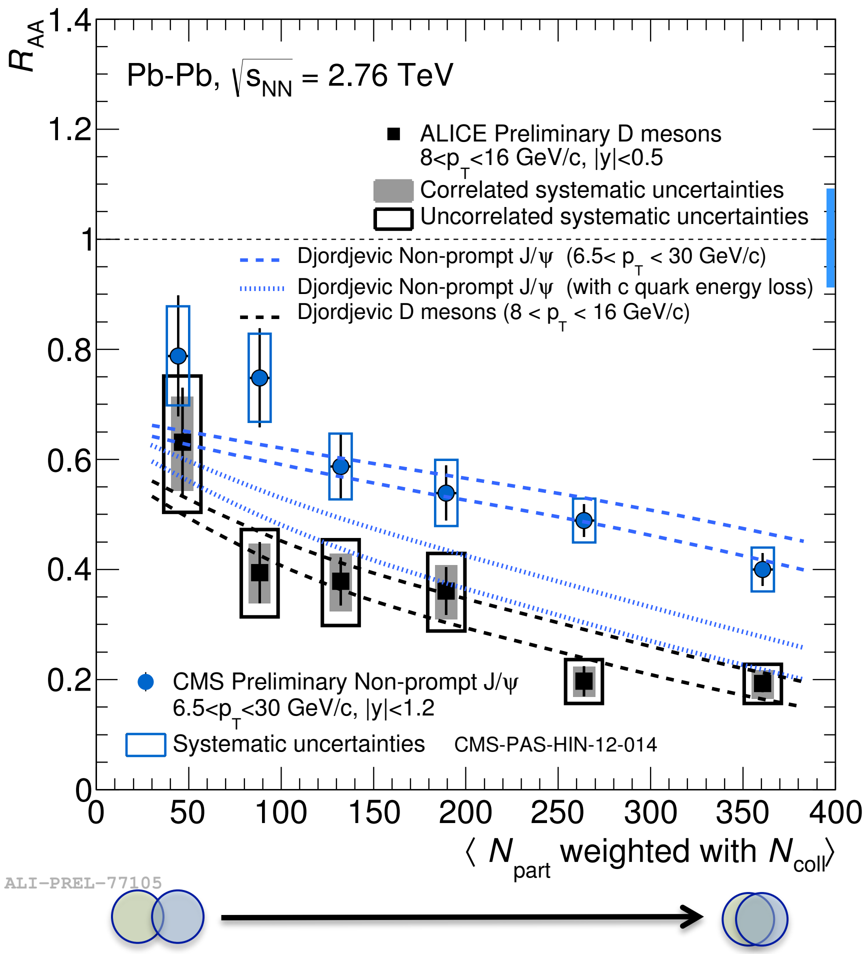




- R_{AA} for D mesons and π are compatible within uncertainties, measurements at low p_T not yet conclusive
- In agreement with models considering:
  - mass and colour-charge dependent energy loss
  - different p_T spectra of charm, light quarks and gluons
  - different fragmentation functions
  - soft production mechanism for low-p_T π

Djordjevic, PRL 112 (2014) 042302
Wicks et al, NPA 872 (2011) 265

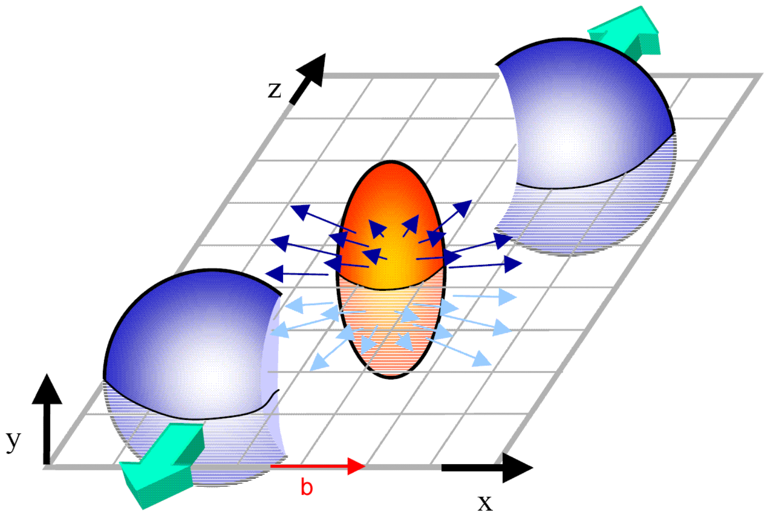
R_{AA} mass hierarchy (charm vs. beauty)



- ALICE prompt D-meson R_{AA} compared with non-prompt J/Ψ from CMS in a similar kinematic range (<p_T> ~ 10 GeV/*c*, slightly different rapidity)
- Indication of R_{AA}(B) > R_{AA}(D) in central Pb-Pb collisions
- The different suppression and the centrality dependence are described by pQCD models including quark-mass dependent energy loss (e.g. BAMPS, WHDG, TAMU, MC@sHQ+EPOS2, Vitev et al).

M. Djordjevic et al (*Phys. Lett. B 737(2014) 298*)
pQCD in-medium energy loss model based on mass dependent energy loss in agreement with data

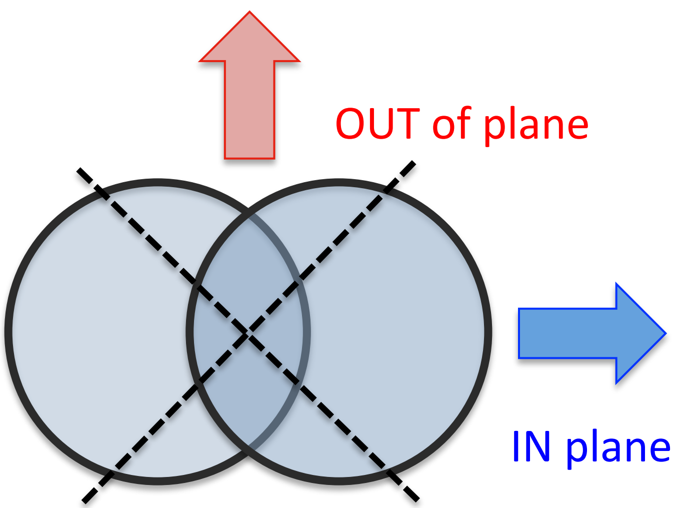
Azimuthal anisotropy



- Initial spatial anisotropy → anisotropy of particle emission in momentum space
- quantified via a Fourier expansion in azimuthal angle with respect to the reaction/symmetry plane

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

- **low p_T**: sensitive to collective hydrodynamical expansion of the medium
- **high p_T**: sensitive to path-length dependent in-medium parton energy loss



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

R_2: event plane resolution

Elliptic flow

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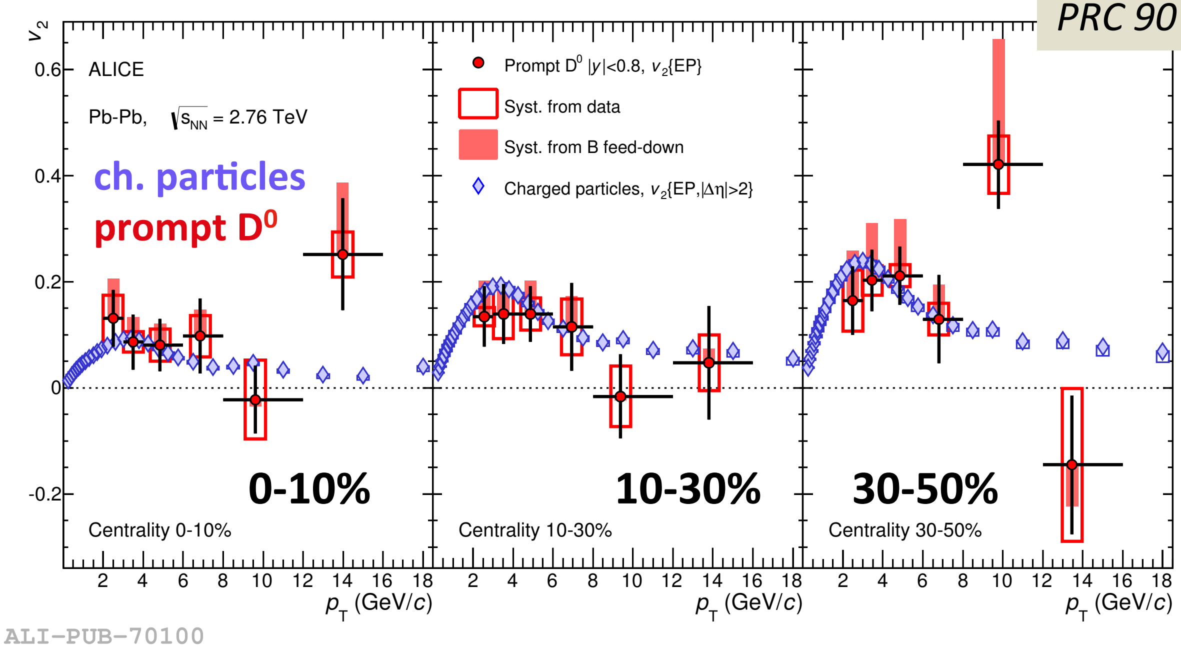

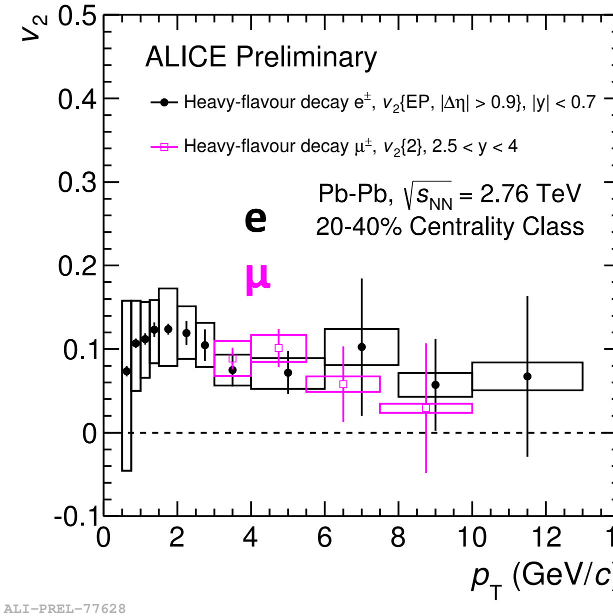

- Positive D-meson v_2 observed: 5.7σ effect for 2 < p_T < 6 GeV/*c* in 30-50% centrality
- Positive v_2 and similar centrality dependence as observed for D mesons also for HF-decay leptons. Positive v_2 suggests that low-p_T charm quaks participate in the collective expansion if the system.
- hint for an increase of v_2 from central to semi-central collisions.
- D-meson v_2 similar to charged-particle v_2.
- more statistics needed to quantify v_2 at high p_T

D-meson R_{AA} and v_2 vs. models

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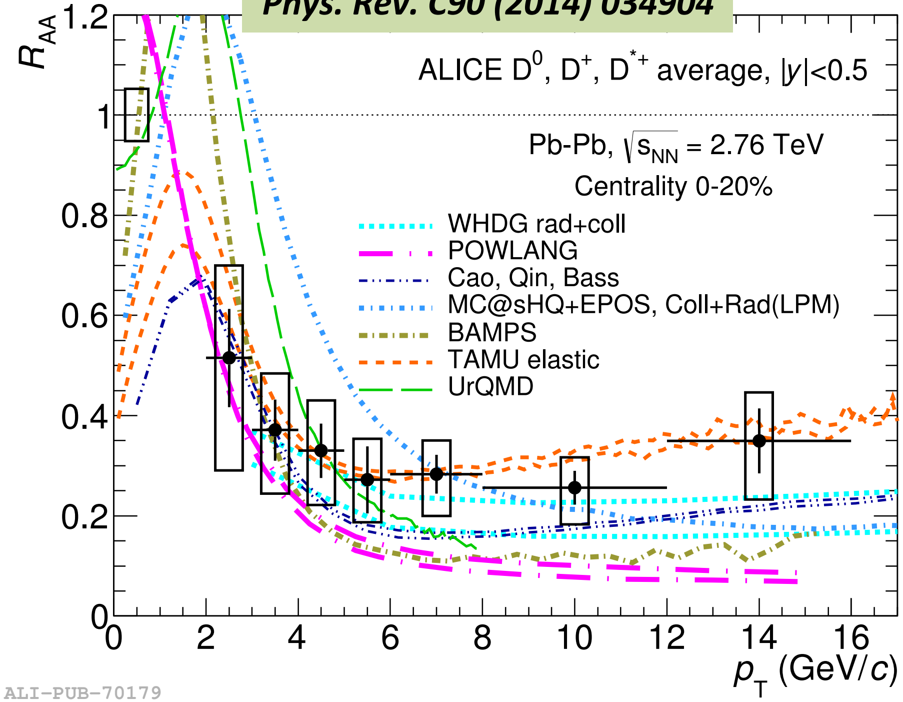

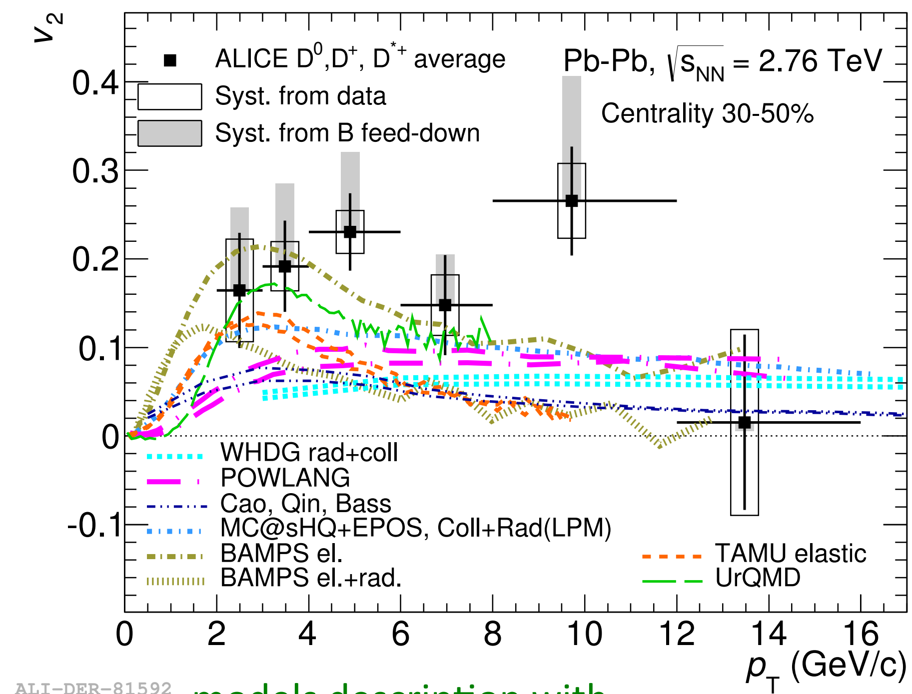

models description with references in extra sides

- Simultaneous description of open charm R_{AA} and v_2 is challenging.
- With current precision, measurements can start constraining models.

Conclusions

- **pp collisions**
  - Open heavy-flavour production is well described by pQCD calculations.
  - The increase of D-meson yields with charged-particle multiplicity can be interpreted in terms of MPIs.

- **p-Pb collisions**
  - Indication of small cold nuclear matter effect (R_{pPb} ~ 1 for p_T > 2 GeV/c at mid and forward rapidity and for p_T > 4 GeV/c at backward rapidity).
  - Data described within uncertainties by different models including initial-state effects.
  - Double-ridge structure appears in the study of HF-decay electron – hadron correlation (similar to what was observed in h –h correlation).

- **Pb-Pb collisions**
  - Heavy-flavour production is suppressed at high p_T in the most central Pb-Pb collisions with respect to the binary scaled pp collisions.
  - The suppression is due to final-state effects due to parton energy loss in the medium and consistent with expected mass ordering.
  - $v_2 > 0$ suggests that charm quarks participate in the system collective motion.
  - Simultaneous measurements of v_2 and R_{AA} are a tool to constrain models.