Open heavy-flavour production in pp, p-Pb and Pb-Pb collisions with ALICE at the LHC

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ALICE

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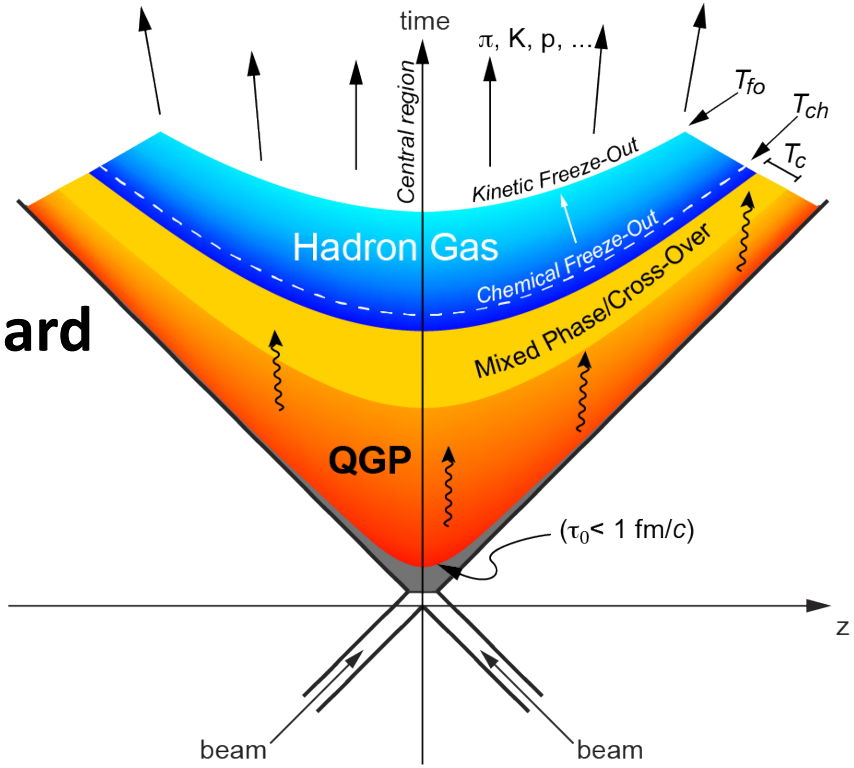
- Motivation
  - ✓ Why to study open heavy flavours?
  - ✓ Why to study pp, p-Pb and Pb-Pb collisions?
- How to study open heavy flavours?
- ALICE detector and particle identification
- Selected measurements of open heavy flavours
  - ✓ pp results
  - ✓ p-Pb results
  - ✓ Pb-Pb results
- Conclusions

Motivation: why to study open heavy flavours?

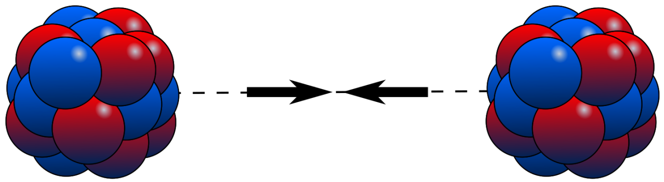
- Heavy-flavour (HF) particles contain charm or beauty quarks:
  - ✓ B meson, D meson, Λ_c and Λ_b



- Charm and beauty are produced (in hard scatterings) in the early stages of the collision:
  - ✓ Large mass ($m_{c,b} >> \Lambda_{QCD}$)
    - -> short formation time
    - -> hard probes, even at low p_T

- Charm and beauty can experience the full evolution of the system:
  - ✓ They live much longer than the duration of the QGP (around 10^{-23} s) PRD 74(2006)054010

Motivation: why to study Pb-Pb, p-Pb and pp collisions?



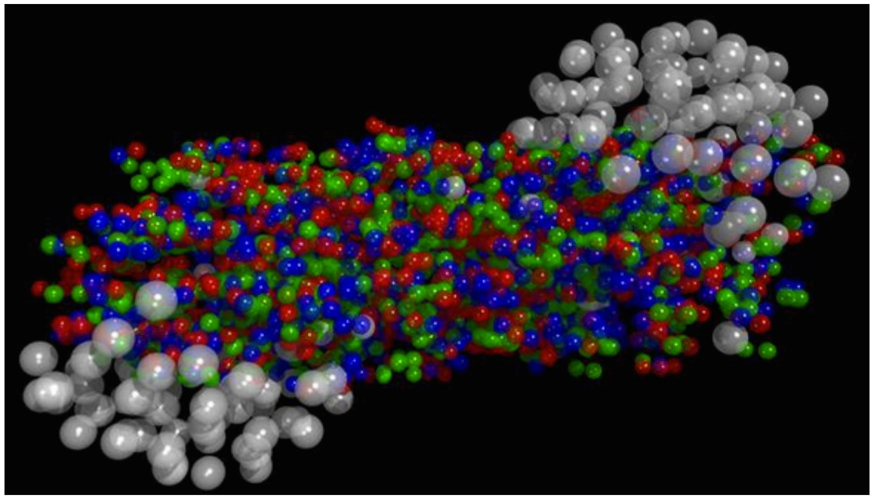
- **Pb-Pb collisions:**

✓ **Formation of a Quark-Gluon Plasma (QGP) is expected.**

✓ **Study parton energy loss mechanisms: radiative vs. elastic processes.**

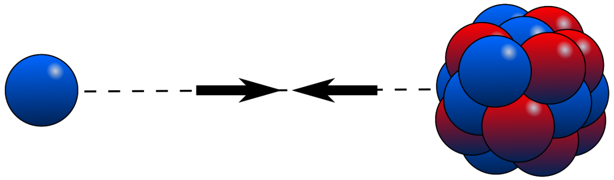
✓ **Possible thermalization of heavy-quarks in the medium.**

✓ **Evaluate the properties of the medium like density, temperature, transport properties, etc.**



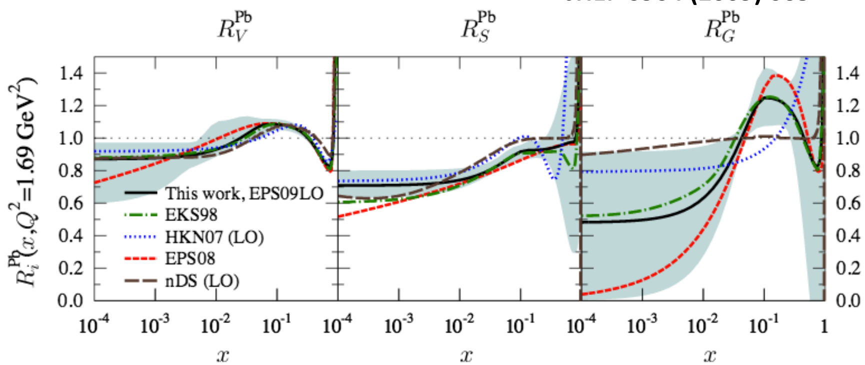
Motivation: why to study Pb-Pb, p-Pb and pp collisions?

- **p-Pb collisions:**

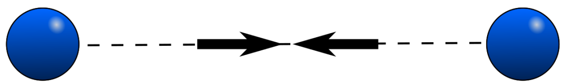


  - ✓ Intermediate state between pp collisions and Pb-Pb collisions.
  - ✓ Control experiment for Pb-Pb measurements.
  - ✓ Cold nuclear matter effects can be studied:
    - Nuclear modification of Parton Distribution Function (shadowing/saturation/CGC)
    - k_T broadening
    - Energy loss
  - ✓ Possible final-state effects.

JHEP 0904 (2009) 065



- **pp collisions:**



  - ✓ Reference for studies with p-Pb collisions and Pb-Pb collisions.
  - ✓ Test for perturbative QCD calculations.

How to study open heavy flavours?

Nuclear modification factor:

$$R_{AA} = \frac{1}{T_{AA}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

✓ **It is used to quantify medium effects and helps to understand the energy loss in the QGP:**

- **If $R_{AA} = 1$ (at high p_T) -> no hot medium effects and no cold nuclear matter effects.**
- **If $R_{AA} < 1$ (at high p_T) -> energy loss and/or cold nuclear matter effects.**

✓ **Expected mass dependence of energy loss:**

$$\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b) \quad \Rightarrow \quad R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)\ ?$$

PLB 519(2001)199

- **Energy loss is expected to depend on the parton colour-charge, parton mass and path length.**

How to study open heavy flavours?

Anisotropic flow:

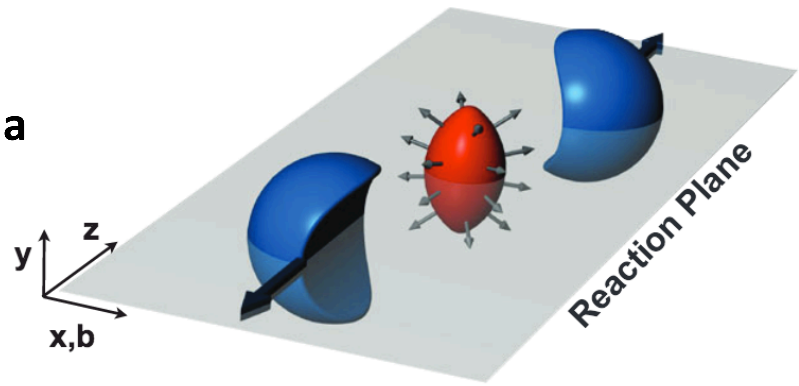
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+2\sum_{n=1}^{\infty} v_n \cos\left[n(\varphi-\Psi_{RP})\right]\right)$$

$$v_n(p_T, y) = \left\langle \cos\left[n(\varphi-\Psi_{RP})\right]\right\rangle$$

✓ **The second Fourier coefficient is called elliptic flow (v_2).**

✓ **Anisotropic flow is caused by the initial asymmetries in the geometry of the system produced in a non-central collision.**

✓ **Initial spatial anisotropy of the created particles is converted in momentum anisotropy due to the pressure gradients.**



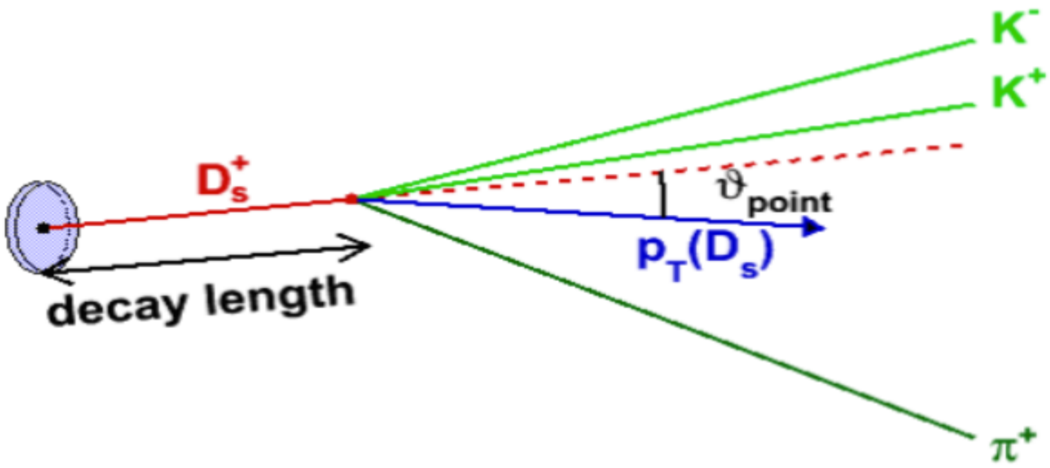
arXiv:1102.3010v2

✓ **Thermalized particles participate in the collective motion of the system.**

Open heavy flavours in ALICE

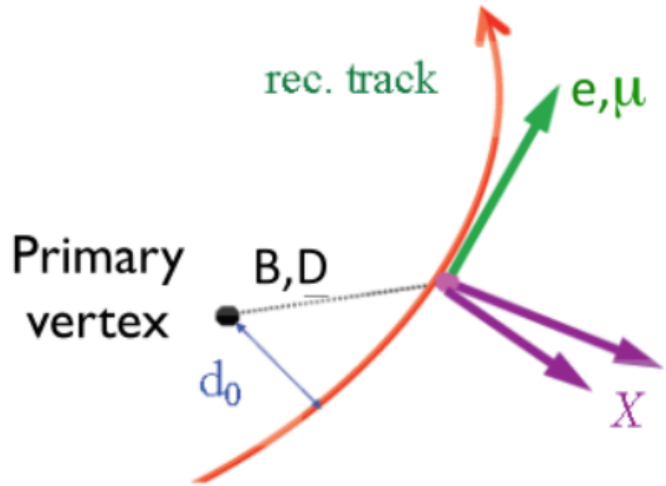
Open heavy-flavour studies with ALICE are done via the following channels:

✓ **Hadronic decays: reconstruction of D^+, D^0, D^{*+} and D_s^+ via their hadronic decays.**



✓ **Semileptonic decays (electrons and muons): branching ratio of the order of 10%:**

- **B, D -> l + X**
- **Separation of electrons from beauty-hadron decays using the impact parameter (long life time of beauty hadrons).**



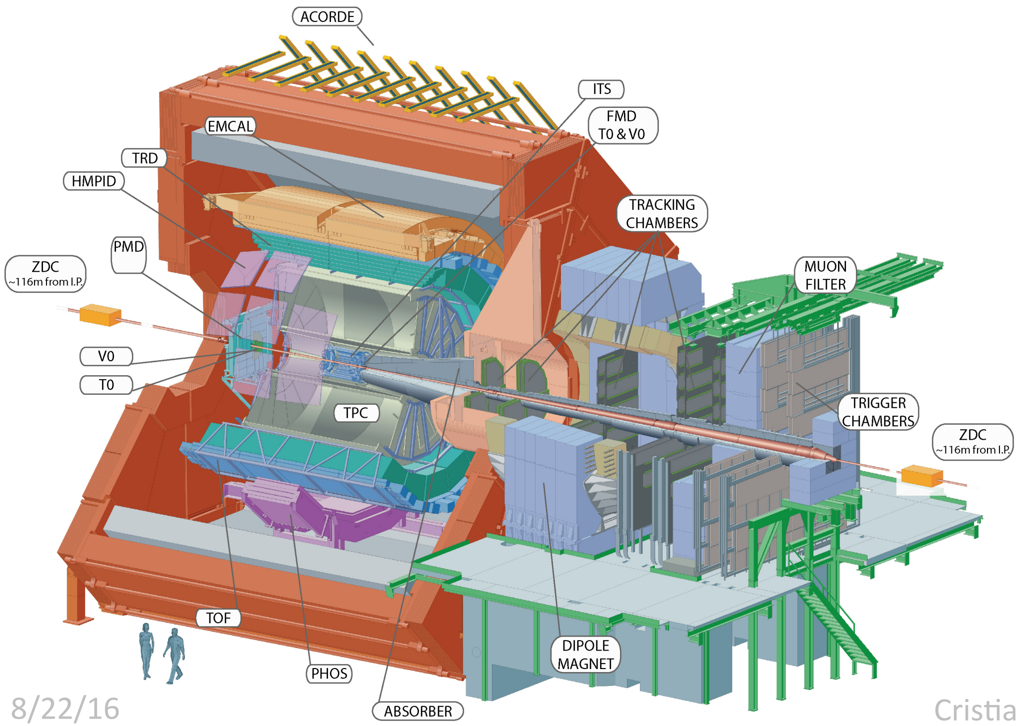
- **At high p_T, it is expected that most of the leptons are from beauty-hadron decays (B).**

ALICE
A Large Ion Collider Experiment

Dedicated experiment to study heavy-ion collisions and the QGP.

ITS (Inner Tracking System):
- Tracking
- Vertexing
- Particle identification (PID)

TPC (Time Projection Chamber):
- Tracking
- PID



TRD (Transition Radiation Detector):
- PID
- Trigger

TOF (Time Of Flight):
- PID

EMCal (Electromagnetic Calorimeter):
- PID
- Trigger

Muon spectrometer:
- Muon ID
- Trigger
- Tracking

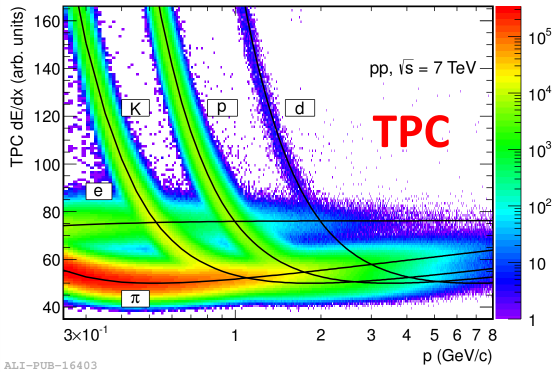
V0 detector:
- Centrality
- Trigger

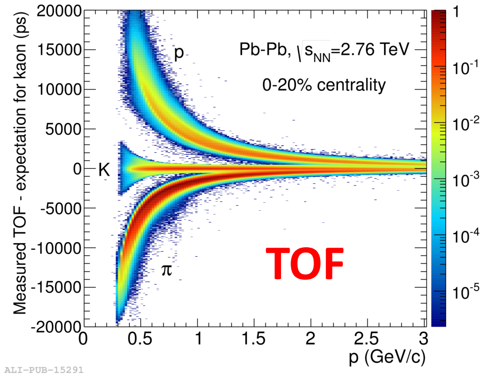
ZDC (Zero Degree Calorimeter):
- Centrality

Particle Identification with ALICE

Hadron and electron identification

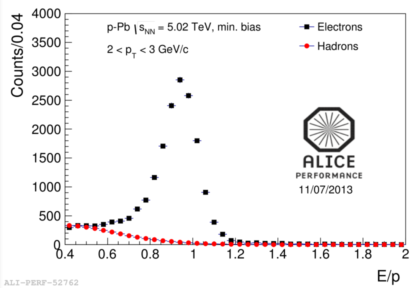
PRD 86(2012)112007





✓ TPC signal: specific energy deposit dE/dx in the TPC expressed in terms of the deviation from the expected particle dE/dx

✓ Time of flight signal is used to identify electrons and hadrons.

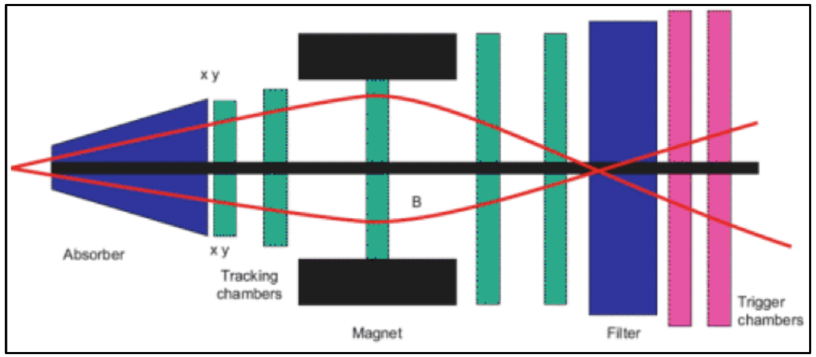


✓ EMCal: electron ID based on E/p, where p is the momentum of tracks and E the energy.

- Electrons and hadrons are measured at midrapidity
- Muons are measured at forward and backward rapidity (p-Pb collisions)

Muon identification

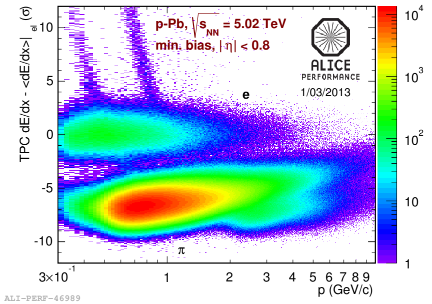
- **Absorber:** to absorb hadrons and photons;
- **Tracking chambers:** two-dimensional hit information;
- **Filter:** passive muon-filter wall;
- **Trigger chambers:** muon tracks required (above a p_T cut).



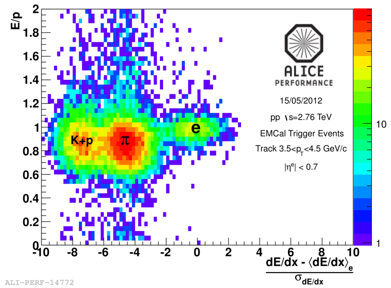
Particle Identification with ALICE: analysis strategy

✓ **Electrons:** TPC, TOF and EMCal detectors are used to select electrons and to remove hadron contamination.

TPC+TOF



TPC+EMCal

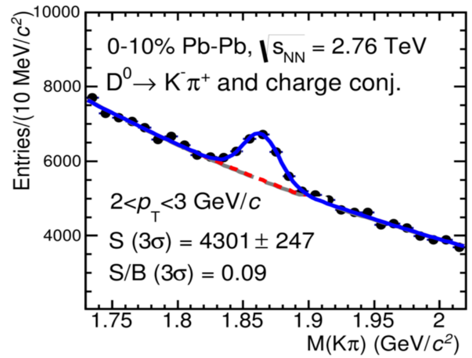


✓ Non-HFE background (photon conversions, η and π^0 Dalitz decays, mainly) removed using cocktail or invariant mass method.

✓ **Muons:**

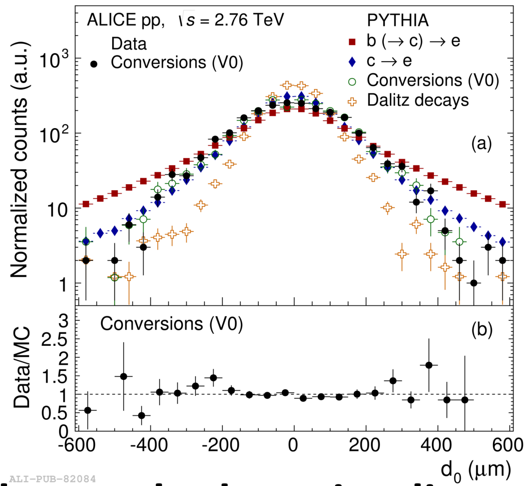
- Tracks are matched with trigger
- Pointing angle to the vertex
- Muons from π, K and W subtracted with MC or data-tuned MC cocktail

✓ **D-meson** ID via the reconstruction of their hadronic decays: invariant mass and secondary vertex.



JHEP 1209(2012)112

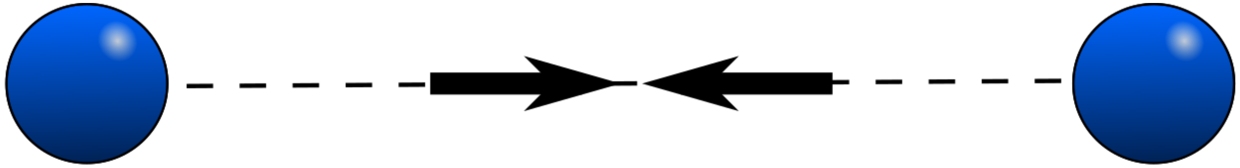
✓ Separation of **electrons from beauty-hadron decays** using the impact parameter.



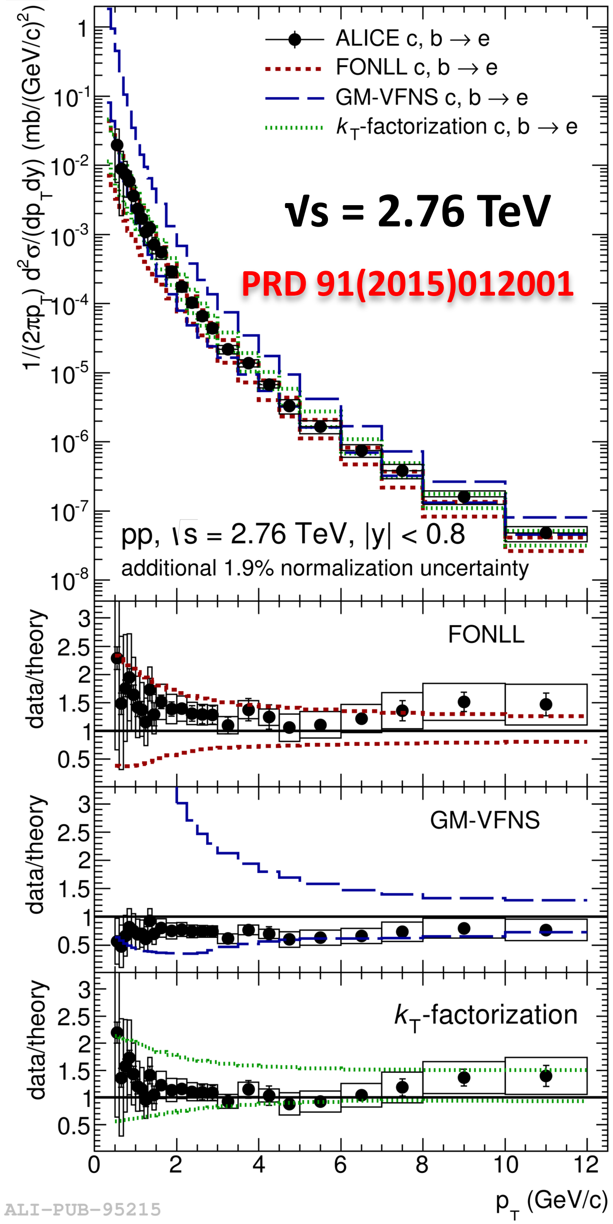
PLB 738 (2014) 97

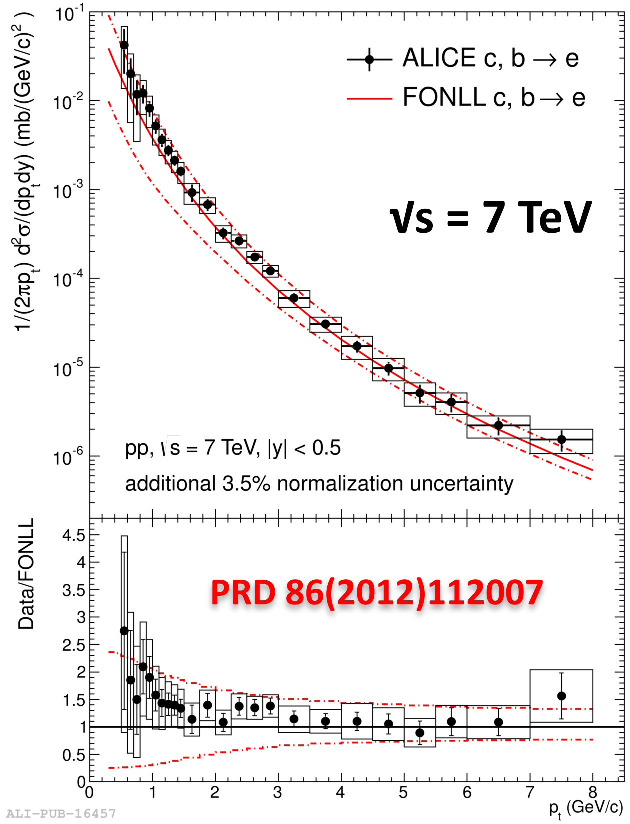
✓ Longer life time of beauty hadrons implies a broader distribution of impact parameter.

Results in pp collisions



pp results: semi-electronic decay channel

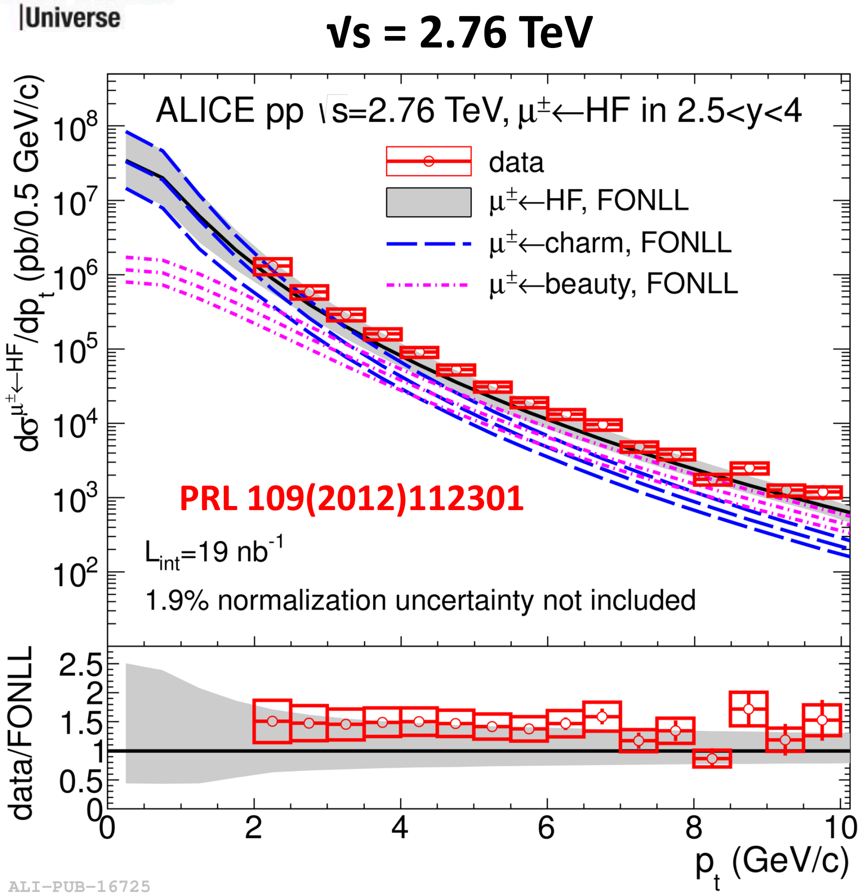


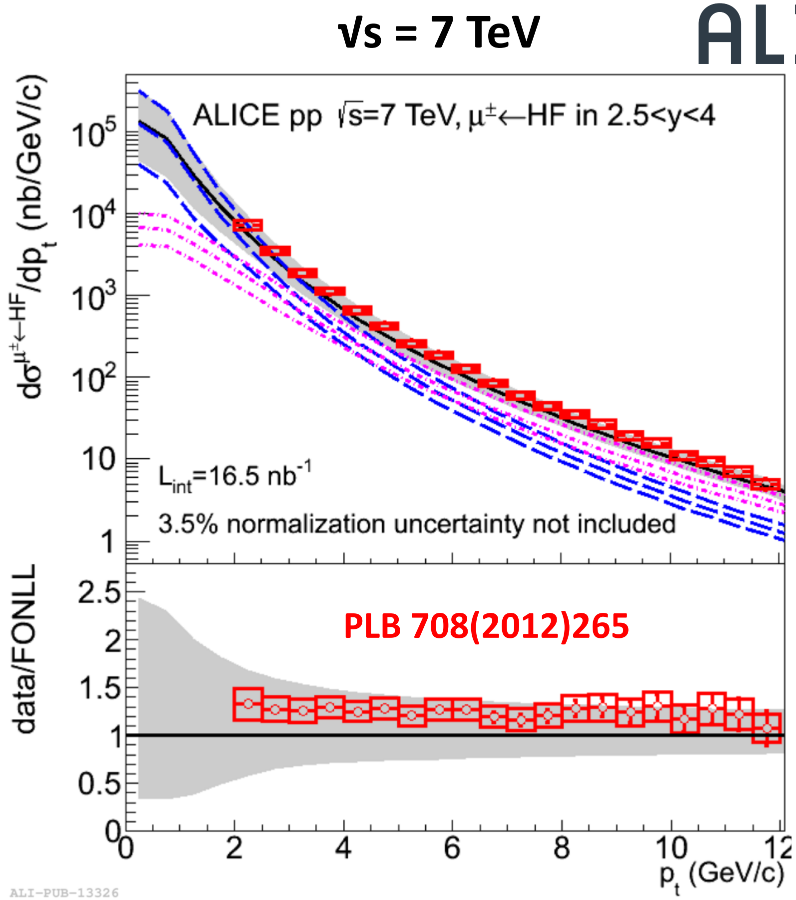


pQCD calculations:
- **FONLL: JHEP 1210(2012)37**
- **GM-VFNS: EPJ C72(2012)2082**
- **k_T factorization: PRD 87(2013)094022**

- **$e^{\pm}$ from HF decays at mid-rapidity**
- **pQCD calculations in reasonable agreement with data within uncertainties**

pp results: semi-muonic decay channel

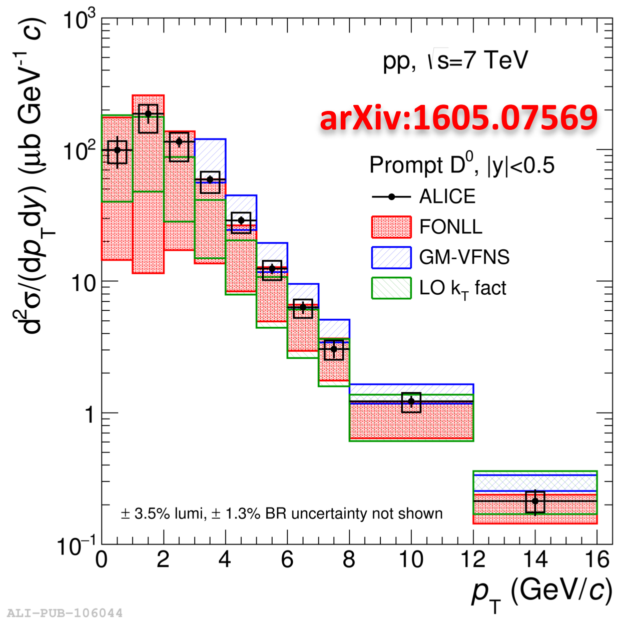




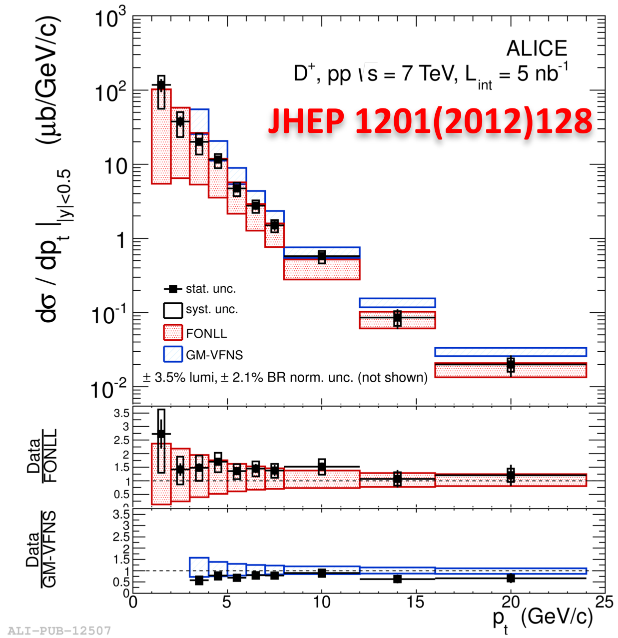
- $\mu^{\pm}$ from HF decays at forward rapidity
- pQCD calculations in reasonable agreement with data within uncertainties

pp results: hadronic decay channels

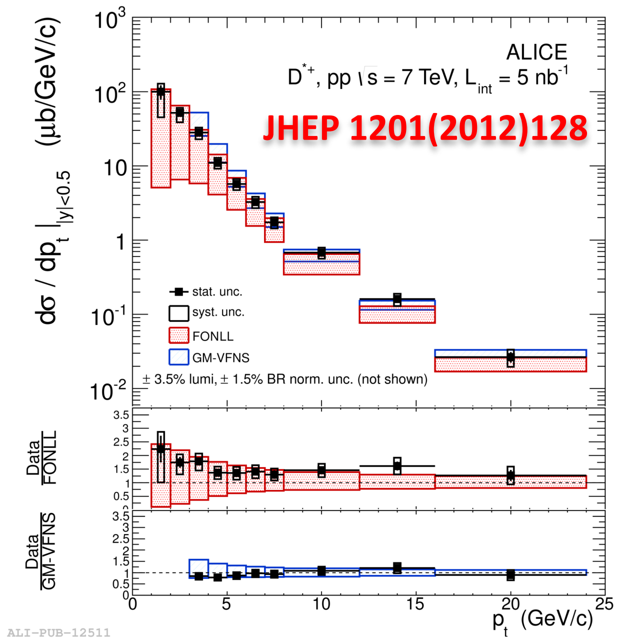
D0



D+



D*+

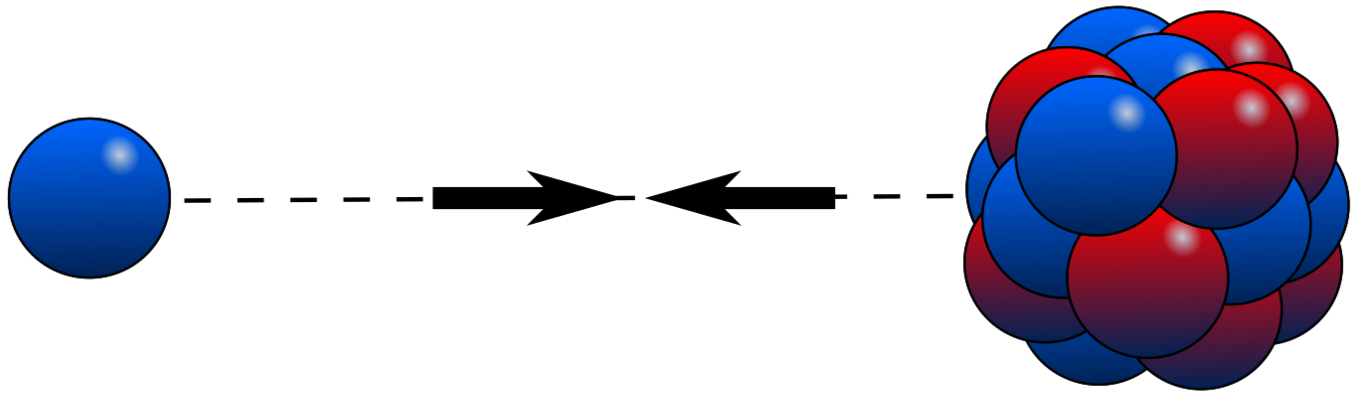


- **pQCD calculations in reasonable agreement with data within uncertainties for all D-meson species.**

pQCD calculations:

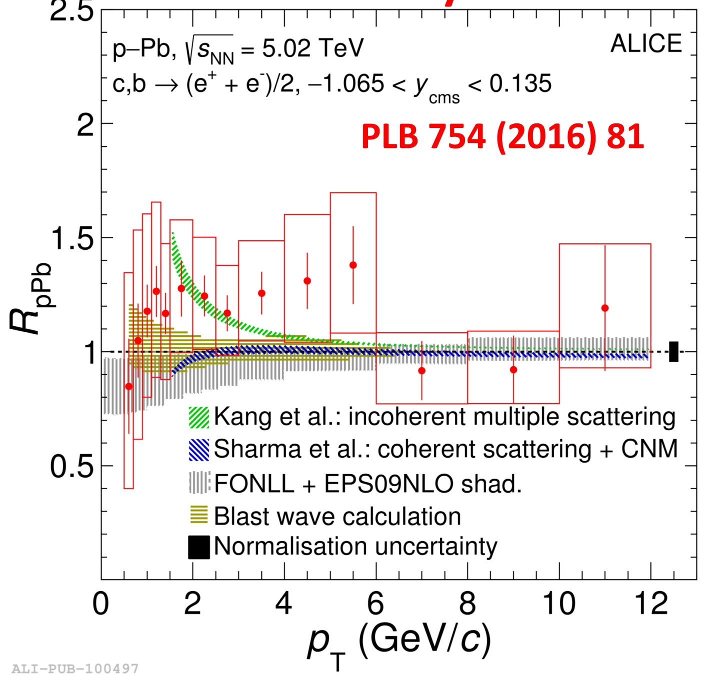
- **FONLL: JHEP 1210(2012)37**
- **GM-VFNS: EPJ C72(2012)2082**

Results in p-Pb collisions

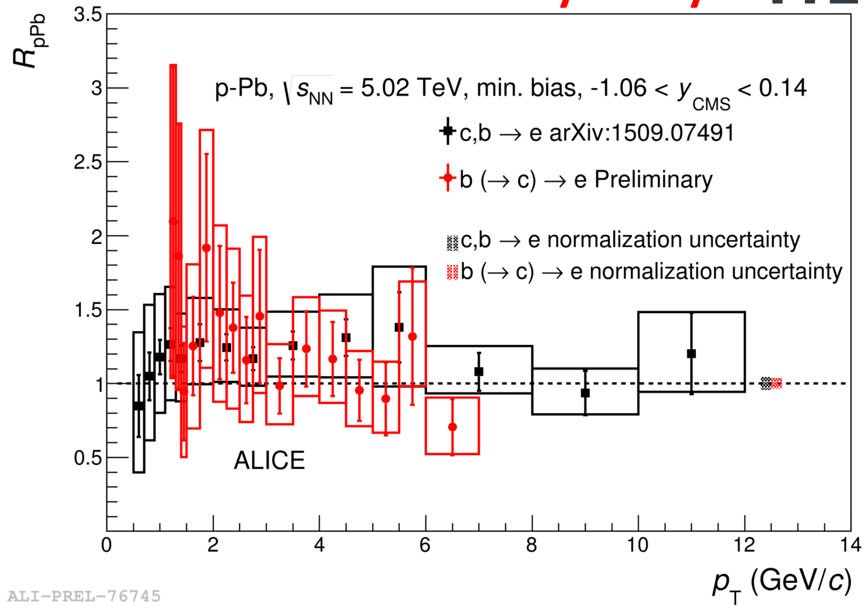


p-Pb results: semi-electronic decay channel

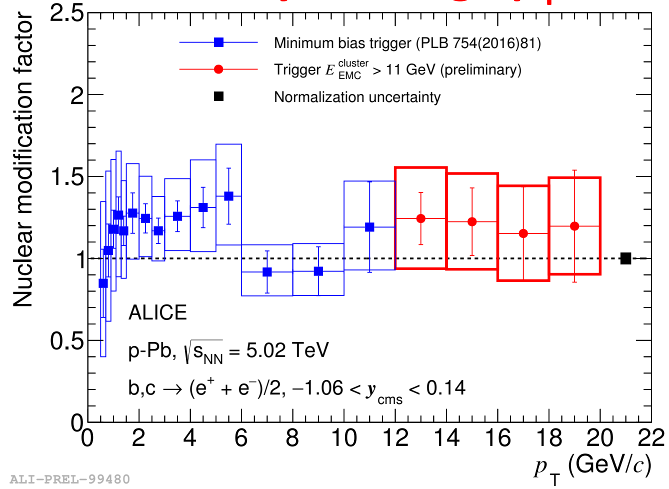
HF decay e±



e± from beauty decay

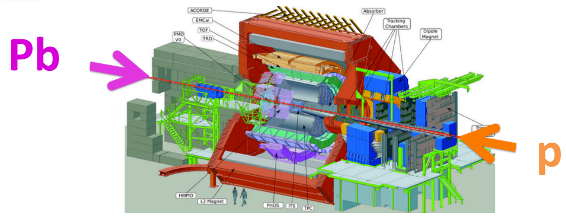


HF decay e± at high-p_T

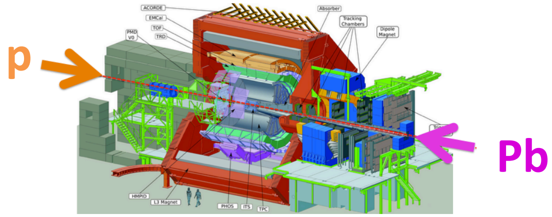


- R_{pPb} of c,b -> e and b -> e are both consistent with unity;
- R_{pPb} consistent with small deviations expected by CNM effects (~10%);
- Extension of HF-decay e± to high p_T using the EMCal trigger.

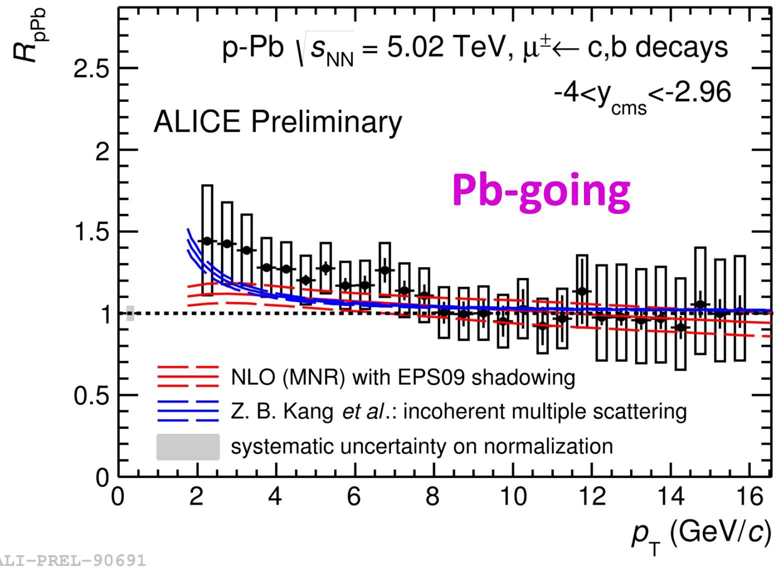
p-Pb results: semi-muonic decay channel

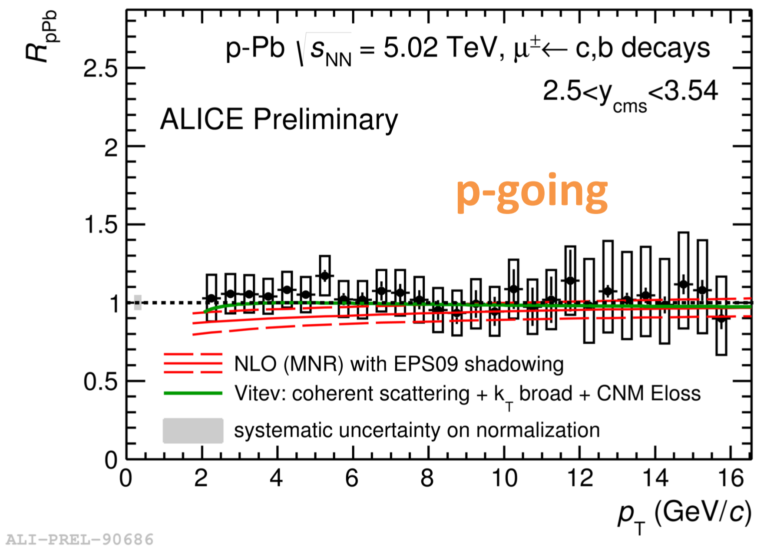


HF decay $\mu^{\pm}$ backward



HF decay $\mu^{\pm}$ forward

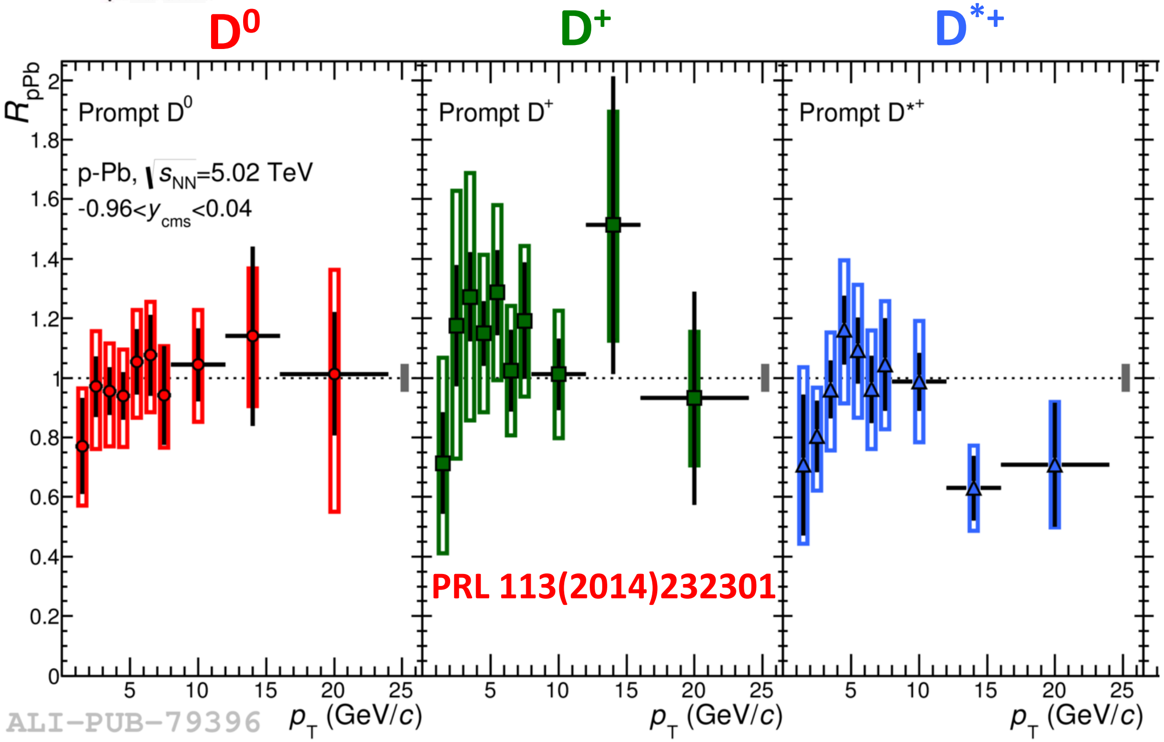


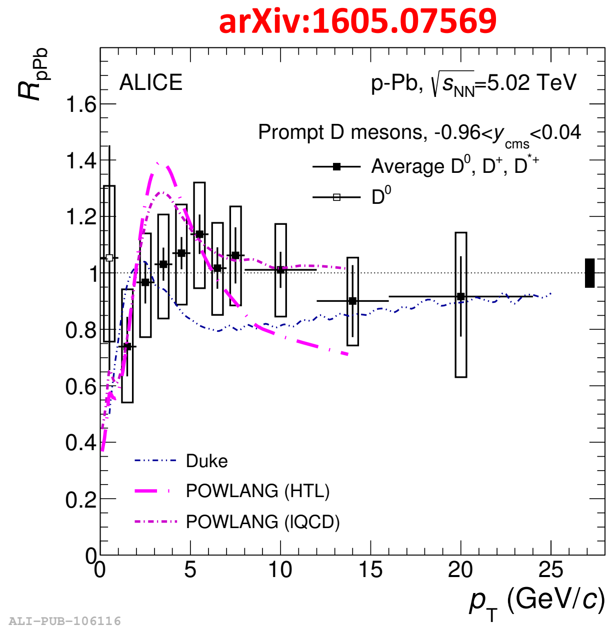


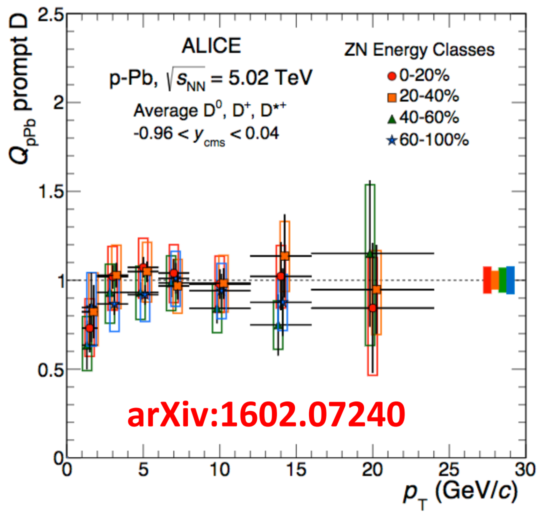
Muons:

- Different rapidity ranges allows the study of different *x* regimes of heavy-flavour production.
- R_{pPb} of HF decay muons is consistent with unity at forward rapidity and slightly larger than unity at backward rapidity for $2 < p_T < 4$ GeV/c.
- Described within uncertainties by models including cold nuclear matter effects.

p-Pb results: hadronic decay channels

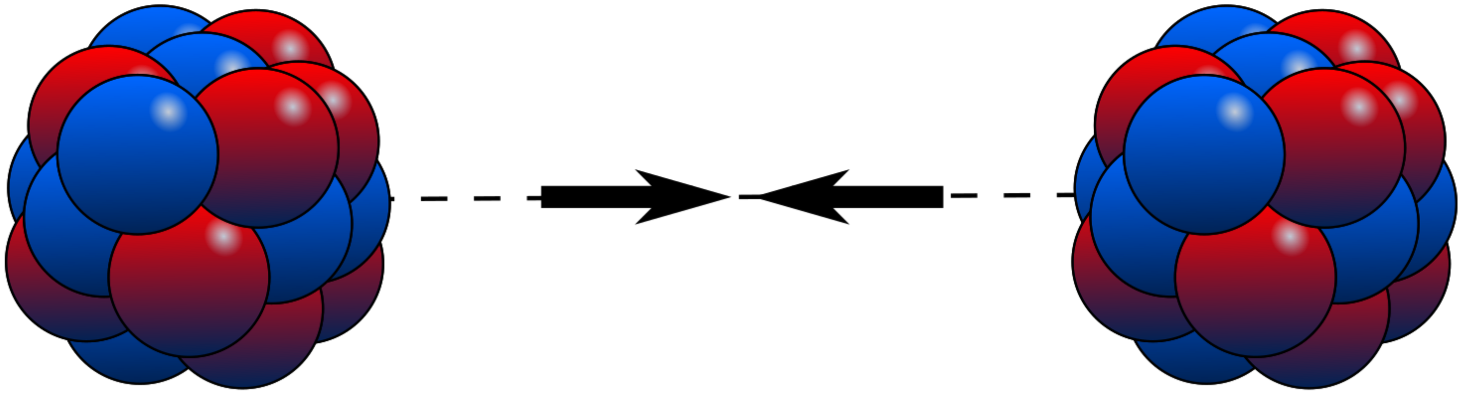






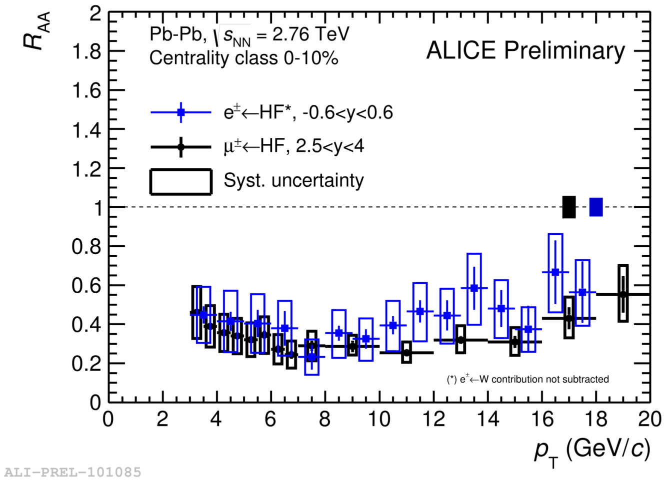
- R_{pPb} consistent with unity for all D-meson species;
- Described within uncertainties by models including initial-state effects;
- No indication for suppression at intermediate/high p_T;
- No multiplicity dependence.

Results in Pb-Pb collisions

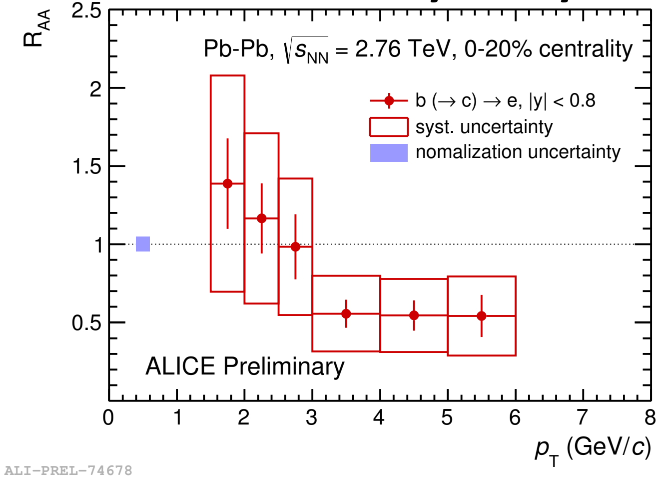


Pb-Pb results: semi-leptonic decay channels

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



$e^{\pm}$ from beauty decay



✓ Similar suppression for HF-decay electrons ($|y|$ < 0.6) and muons (2.5 < y < 4) at intermediate/high p_T;

✓ Electrons from beauty decays suppressed above 3 GeV/c;

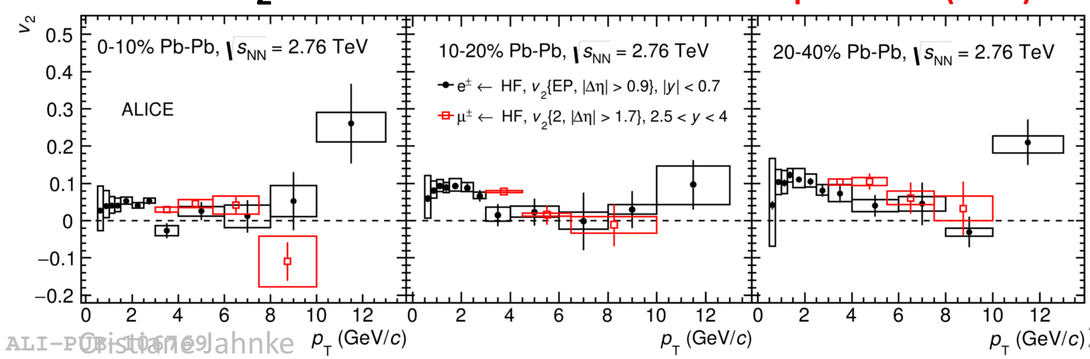
▪ Strong suppression of the yields of HF-decay $e^{\pm}$ and $\mu^{\pm}$ is due to the energy loss in the QGP (R_{pPb} is compatible with unity);

v_2

e: arXiv:1606.00321 μ: PLB 753 (2016) 41

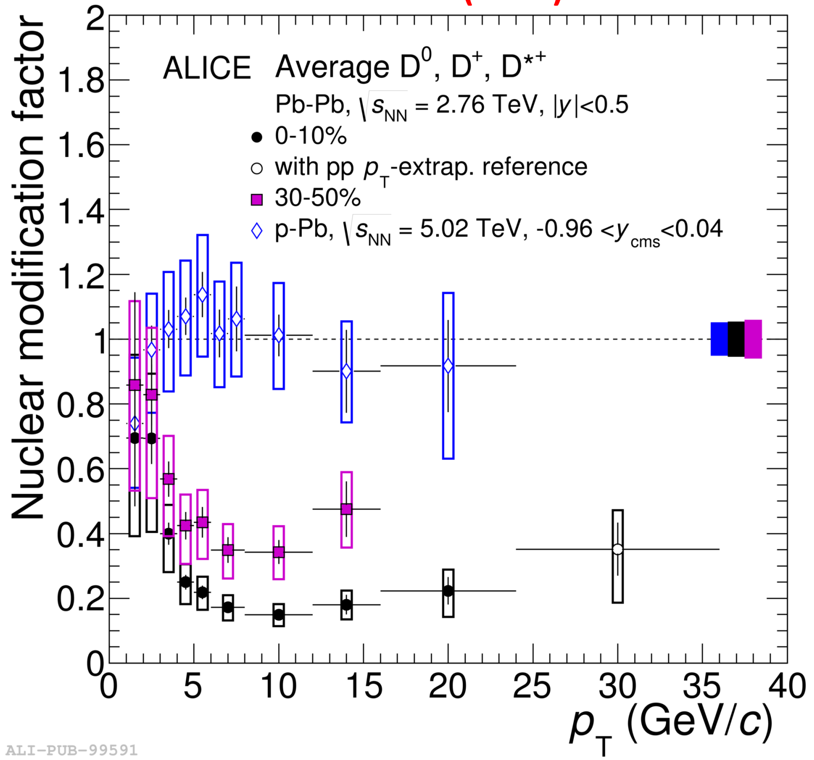
✓ v_2 > 0 confirms the strong interaction of heavy quarks with the medium;

▪ Indication that heavy quarks participate in the collective expansion of the QGP.

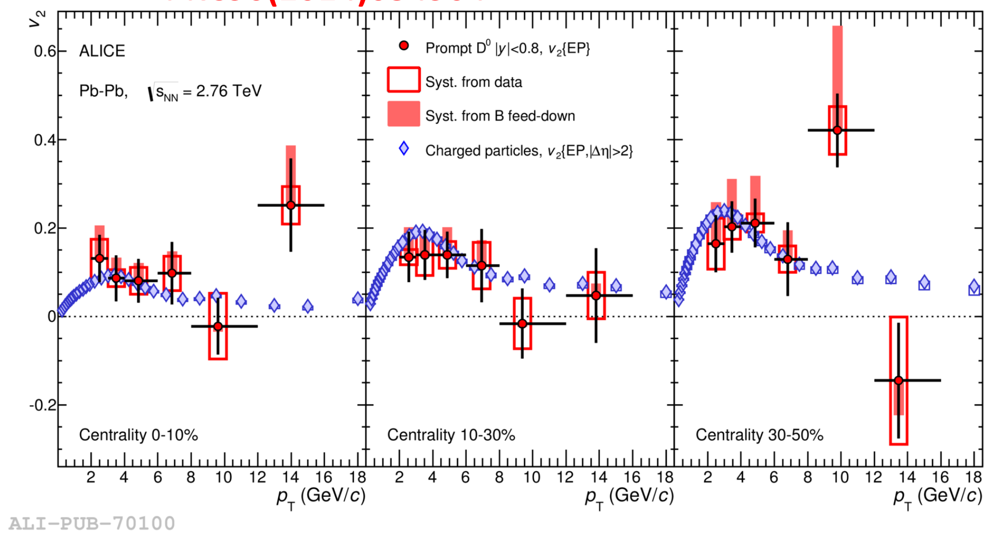


Pb-Pb results: hadronic decay channels

JHEP 1603 (2016) 081



PRC90(2014)034904

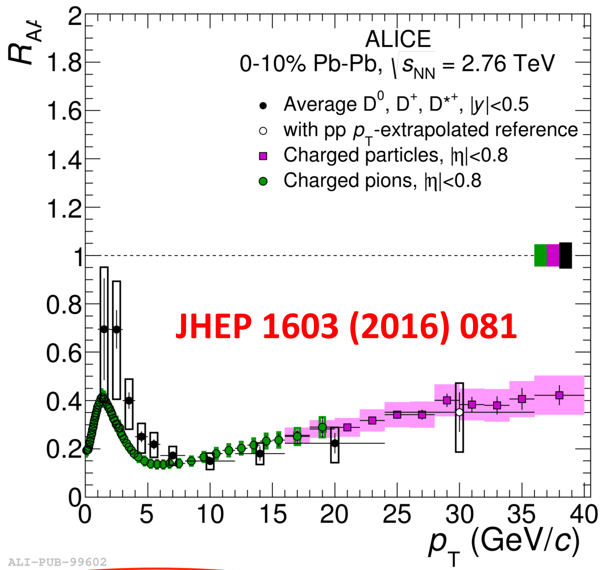


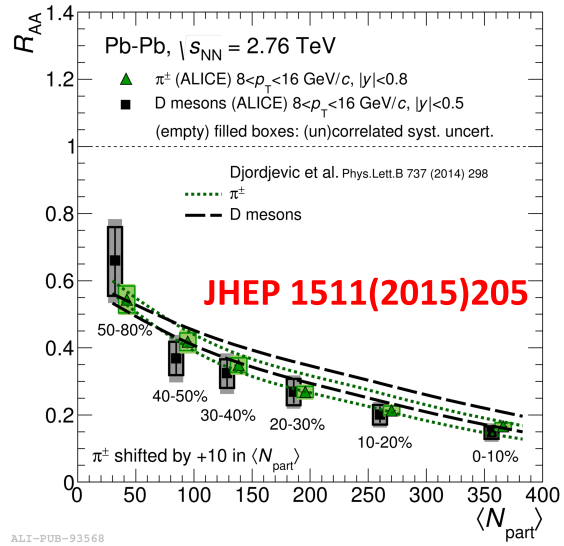
- D-meson v_2 > 0 and similar to charged-particle v_2;
- Increasing v_2 with decreasing centrality;
- Indication of collective motion of low-p_T charm quarks in the medium.

- No suppression in p-Pb collisions;

- Observed suppression at p_T > 2 GeV/c in central Pb-Pb collisions is due to the interaction of charm quarks with the QGP.

Pb-Pb results: D mesons vs. light particles





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

- **D-meson R_{AA} is compatible with pion R_{AA} within the uncertainties:**
  - **Effects could counterbalance the energy loss for light hadrons:**

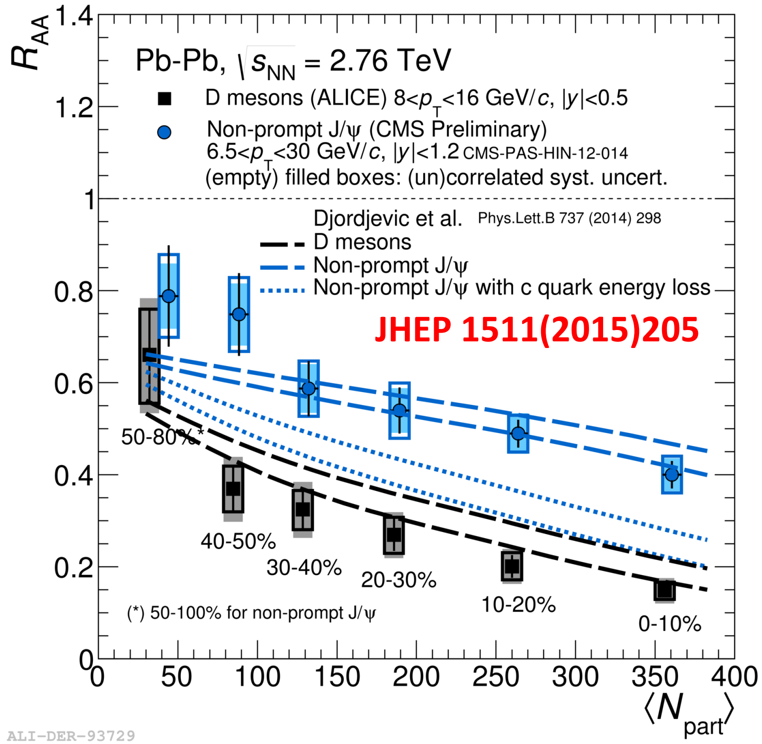
✓ **Colour-charge energy loss dependence;**

✓ **Softer fragmentation of gluons (light-flavour originates mainly from gluon fragmentation at LHC energy) ;**

✓ **Different shapes of the parton-p_T distributions.**

▪ **Models including mass dependence of energy loss, different shape of parton-p_T distributions and different fragmentation functions can explain:** $R_{AA}(\pi) \approx R_{AA}(D)$ **PRL 1124(2014)042302**

Pb-Pb results: D mesons vs. non-prompt J/ψ



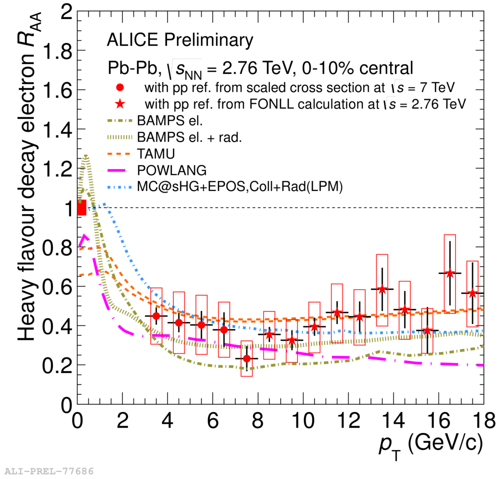
$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?

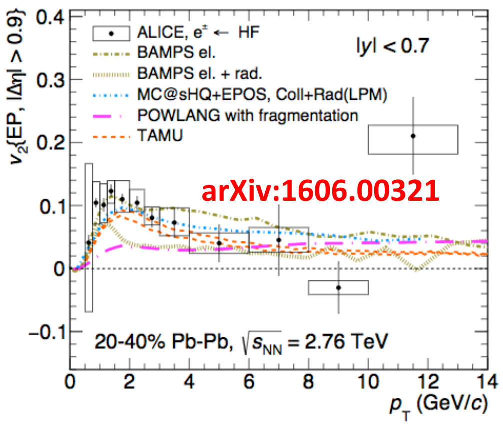
Non-prompt J/ψ: B -> J/ψ
Measured by CMS: CMS-PAS-HIN-12-014

- Different suppression observed for D mesons and non-prompt J/ψ:
  - ✓ Radiative energy loss mass dependence;
  - ✓ Collisional energy loss expected to be reduced for heavier quarks;
- Difference predicted by models including mass dependence of the energy loss.

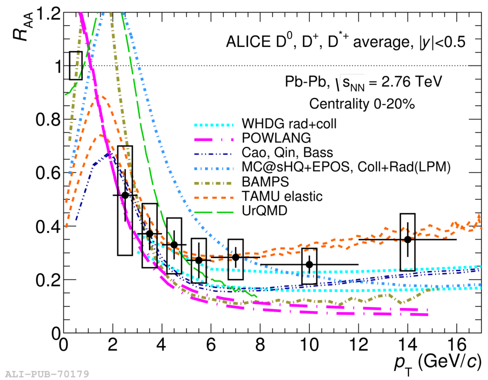
PRL 112(2014)042302

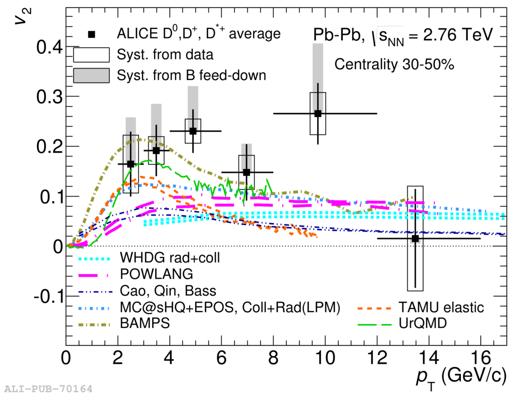
Pb-Pb results: comparison with models





PRC 90(2014)034904





- R_{AA} and v_2 provide constraints to models;
- Collisional energy loss describes v_2 but fails to describe R_{AA};
- Adding radiative energy loss the models can describe R_{AA} but do not produce enough v_2;
- Simultaneous description of R_{AA} and v_2 is challenging.

BAMPS JPG38 (2011) 124152
BAMPS el. + rad. JPG(2015)11,115106
TAMU PRC 86 (2012) 014903
POWLANG EJC71 (2011) 1666

MC@HQ+EPOS Coll+Rad(LPM) PRC79(2009)044906
WHDG JG38 (2011) 124114
Cao,Quin,Bass PRC 92(2015)2,024907
UrQMD arXiv:1211.6912

Conclusions

pp collisions

- **Heavy-flavour cross sections are described by pQCD calculations within uncertainties.**

p-Pb collisions

- **Cold nuclear matter effects are small.**
- **Some models including collectivity in small systems can describe the data.**

Pb-Pb collisions

- **Strong interaction of heavy quarks with the QGP.**
- **Suppression of yields at high p_T consistent with partonic energy loss models.**
- **The strong suppression at high p_T is due to the hot and dense medium, since R_{pPb} is consistent with unity.**
- **Indication for charm participating in the collective expansion of the QGP.**

More ALICE results:

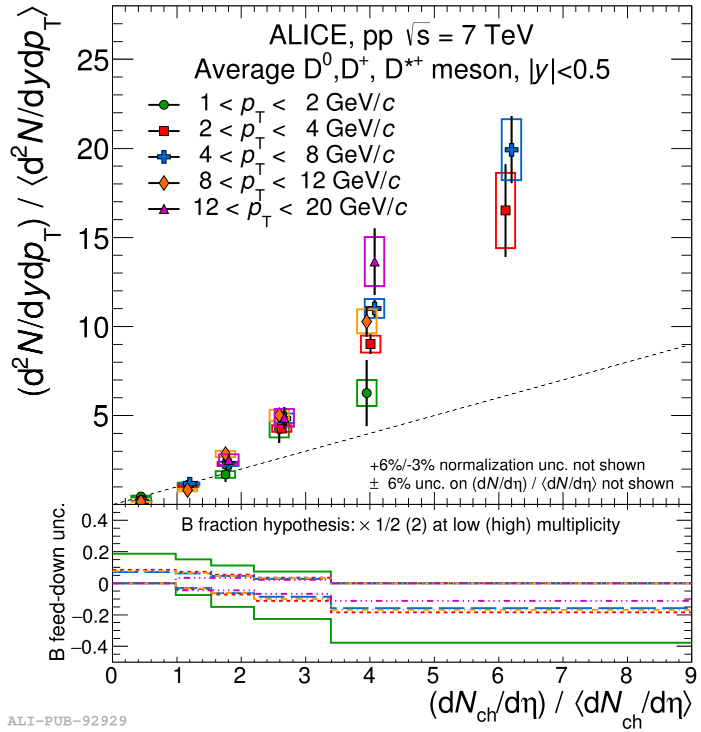
- **Yields versus multiplicity:** JHEP 09 (2015) 148 JHEP 8 (2016) 1-44
  - **Interplay between hard and soft mechanisms in particle production;**
  - **Studies of Multiple-Parton Interactions (MPI);**
  - **Investigations of CNM effects;**
- **Correlations between D mesons and charged hadrons in pp and p-Pb collisions:** arXiv: 1605.06963
  - **Investigations of heavy-flavour quark fragmentation (pp collisions) and CNM (p-Pb collisions).**

Thank you for your attention!

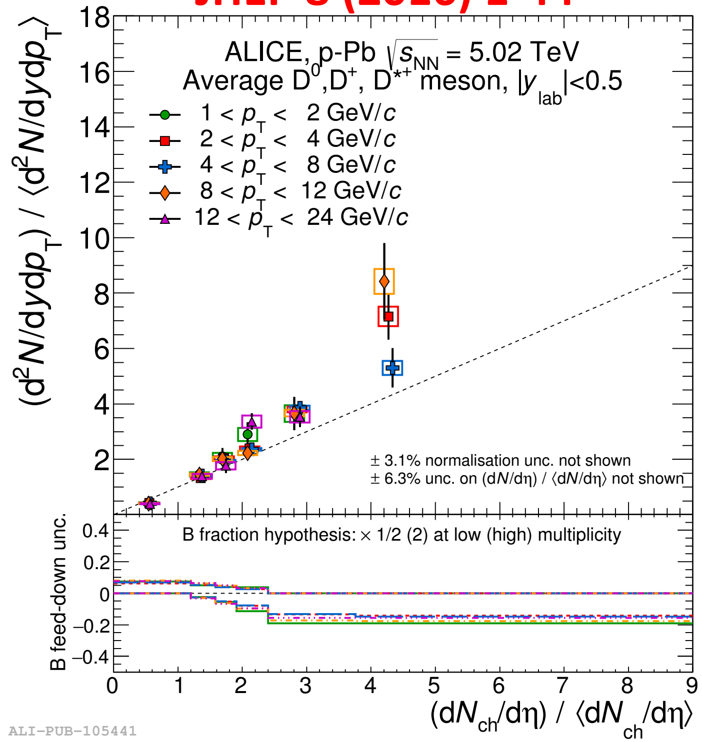
Extra slides

pp and p-Pb yields versus multiplicity

JHEP 09 (2015) 148



JHEP 8 (2016) 1-44



- **Some aspects are expected to be dependent on the energy and on the impact parameter of the collisions:**

✓ **Interplay between the hard and soft mechanisms in particle production.**

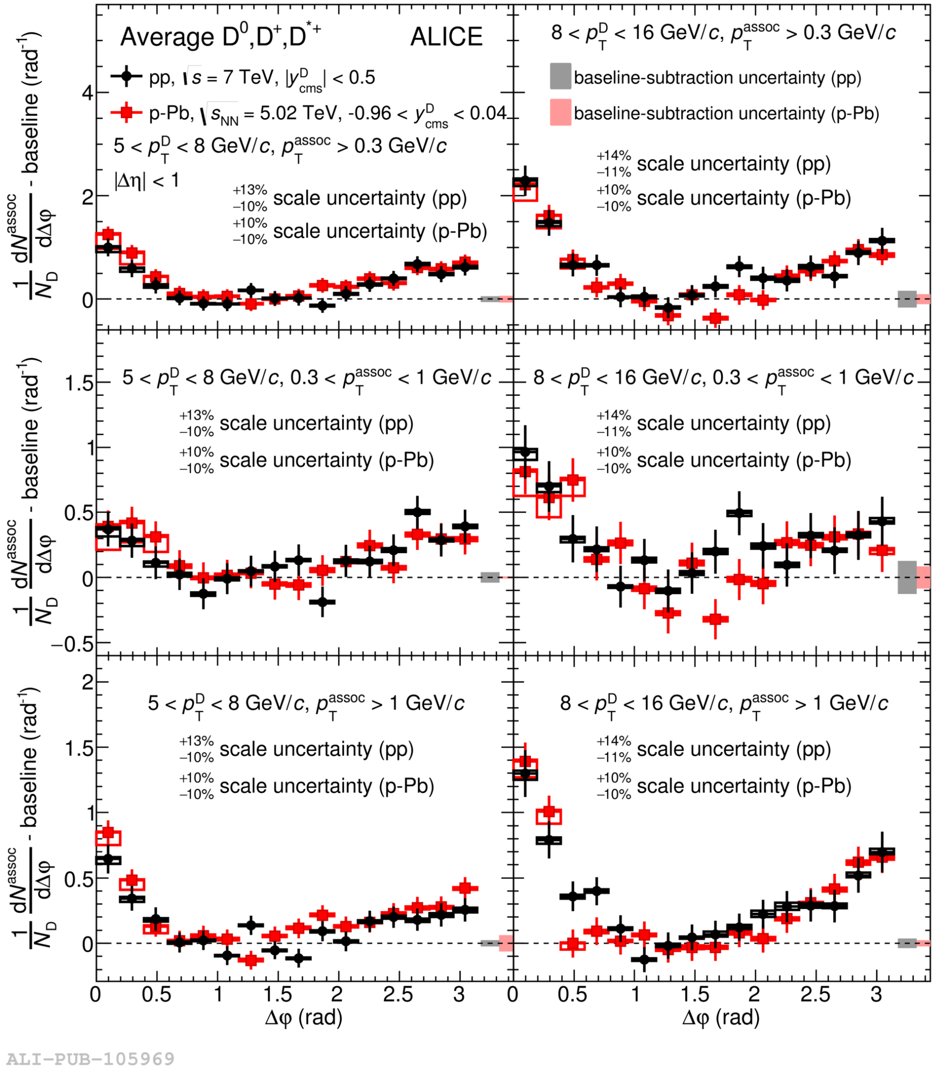
✓ **Multiple-Parton Interactions (MPI)**

✓ **Assess CNM effects in p-Pb collisions.**

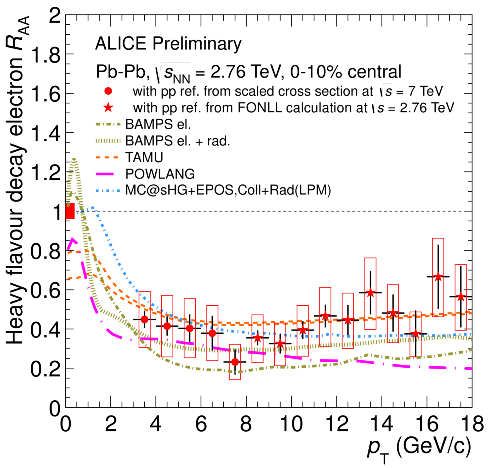
D-meson correlation to charged hadrons in pp and p-Pb collisions

arXiv: 1605.06963

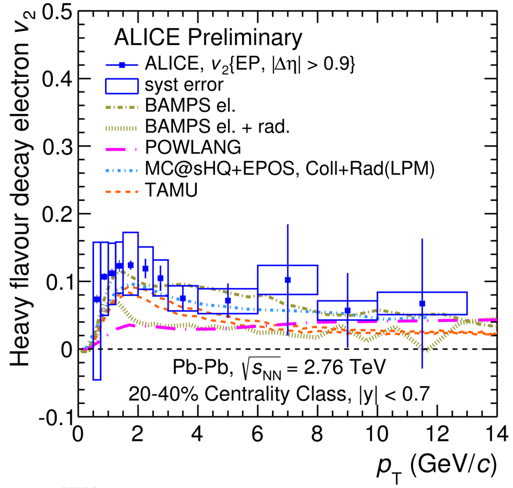
- pp collisions: characterization of charm production and fragmentation processes.
- p-Pb collisions: modifications of fragmentation functions due to CNM effects or hydrodynamics.
- Results for pp and p-Pb collisions are compatible.



Pb-Pb results: comparison with models

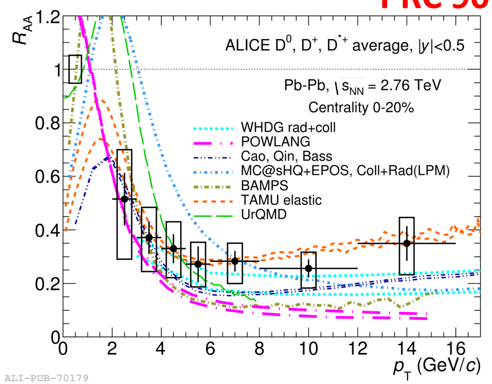


ALI-PREL-77686

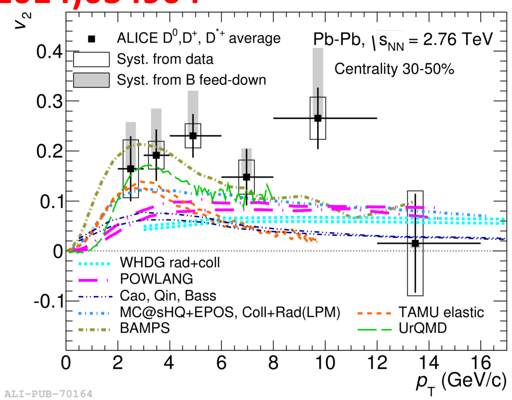


ALI-PREL-77576

PRC 90(2014)034904



ALI-PUB-70179



ALI-PUB-70164

- R_{AA} and v_2 provides constraints to models;
- Simultaneous description of R_{AA} and v_2 still challenging;

BAMPS: heavy-quark transport using Boltzmann equation with collisional energy loss in an expanding QGP. JPG38 (2011) 124152

BAMPS el. + rad.: uses LPM (Landau-Pomeranchuk-Migdal) to include radiative energy loss. JPG(2015)11,115106

TAMU: heavy-quark transport using resonant scatterings and recombination for the hadronization. PRC 86 (2012) 014903

POWLANG: heavy-quark transport using Langevin equation with collisional energy loss. EJC71 (2011) 1666

MC@HQ+EPOS Coll+Rad(LPM): includes collisional and radiative energy loss in an expanding medium, based on EPOS model. PRC79(2009)044906

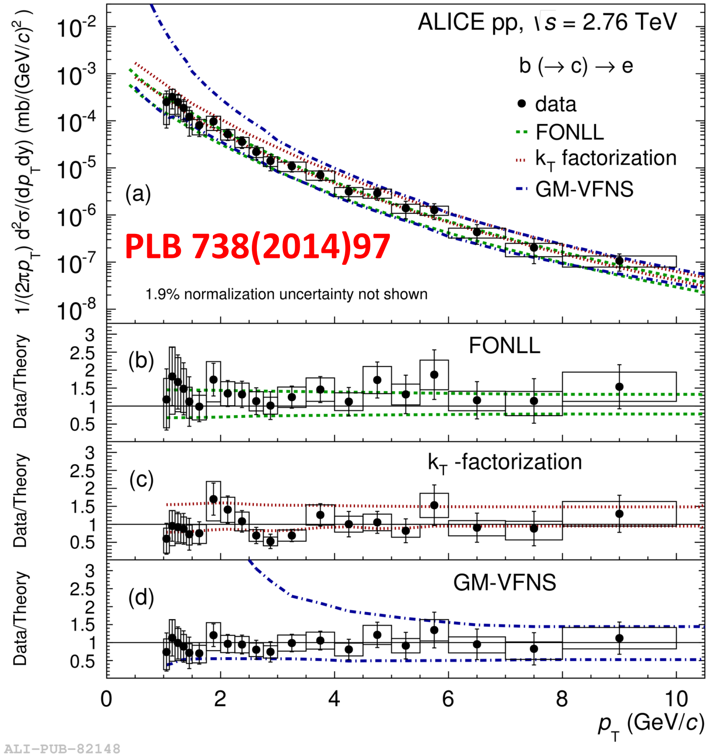
WHDG: pQCD calculations including radiative and collisional energy loss. JG38 (2011) 124114

Cao,Quin,Bass: uses Langevin with a radiative term and includes recombination. PRC 92(2015)2,024907

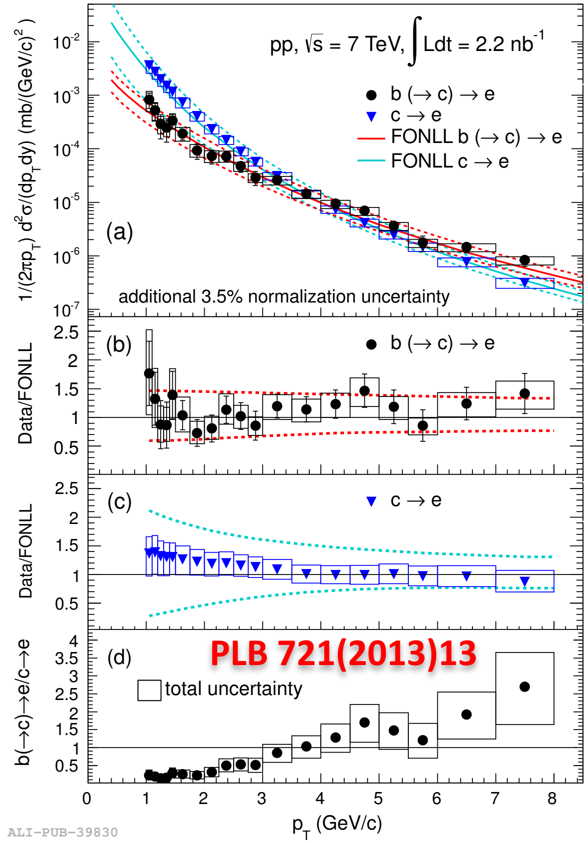
UrQMD: uses Langevin approach implemented within the UrQMD model. arXiv:1211.6912

pp results: electrons from beauty-hadron decays

2.76 TeV



7 TeV

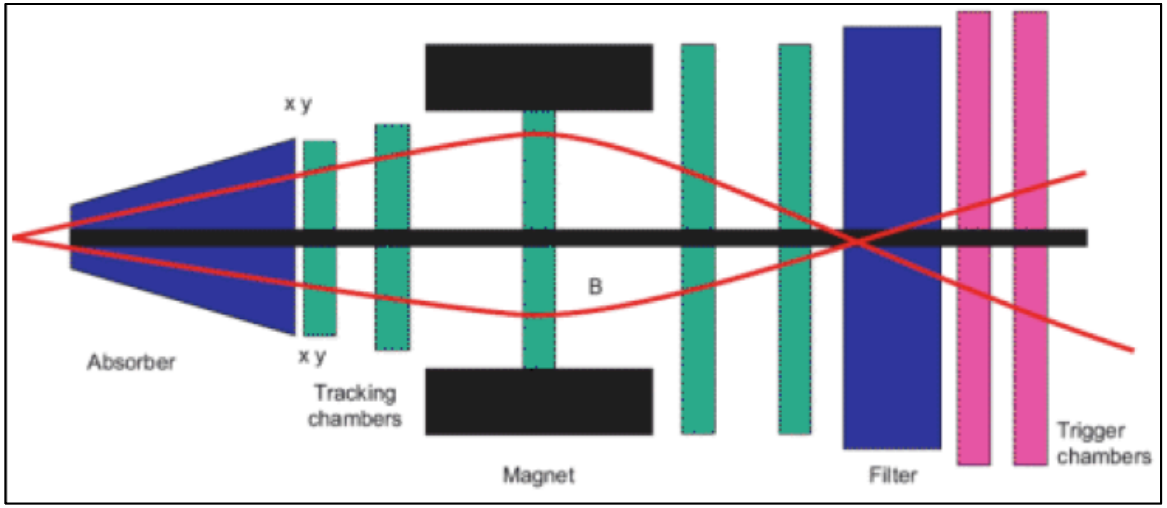


pQCD calculations:
- **FONLL: JHEP 1210(2012)37**
- **GM-VFNS: EPJ C72(2012)2082**
- **kT factorization: PRD 87(2013)094022**

- **$e^{\pm}$ from beauty decays at mid-rapidity**
- **pQCD calculations in reasonable agreement with data within uncertainties**

Particle Identification with ALICE: muons

Muons reconstructed in the forward muon spectrometer



Figures from http://aliceinfo.cern.ch/Public/en/Chapter2/Chap2_dim_spec.html

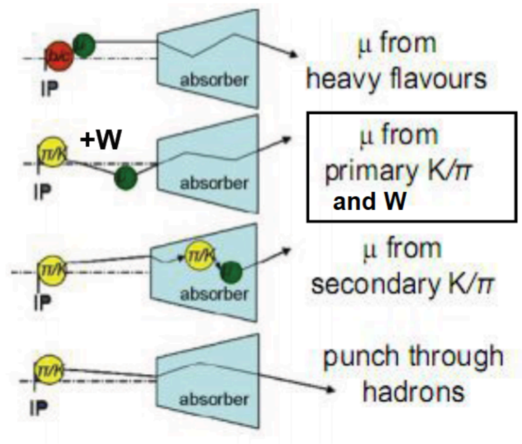
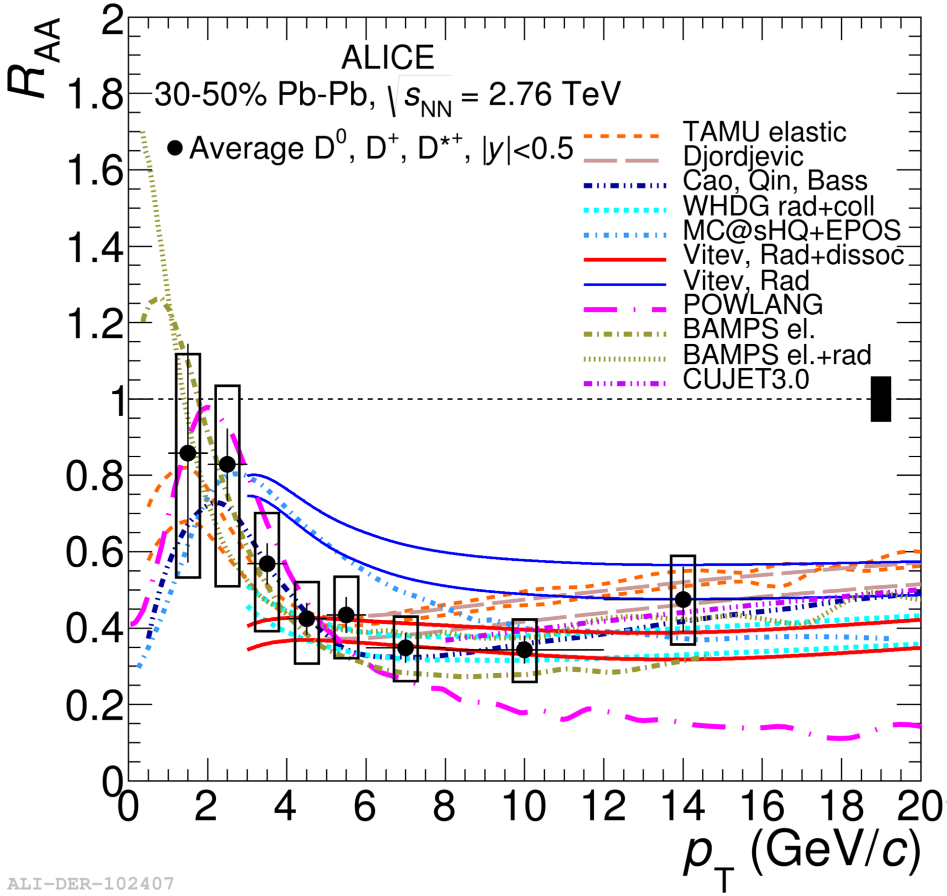


Figure from Zuman Zhang poster presented in QM2015

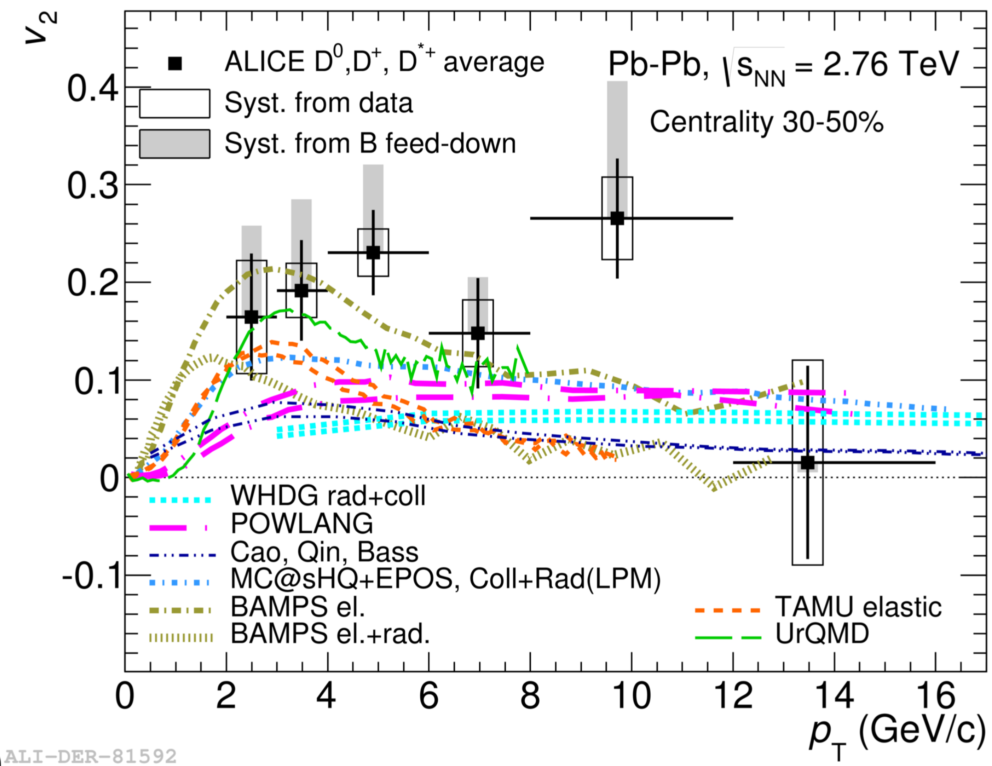
- ✓ **Absorber:** to absorb hadrons and photons from the interaction vertex;
- ✓ **Tracking chambers:** 10 detection planes, which gives two-dimensional hit information;
- ✓ **Filter:** passive muon-filter wall to protect the trigger chambers;
- ✓ **Trigger chambers:** requires at least one single muon tracks, or at least two unlike-sign muon tracks, or at least two like-sign muon tracks (above a p_T cut).
- ✓ Geometrical cuts, tracking-trigger matching and pointing angle to vertex are used;
- ✓ Impact parameter cut to reject part of beam-gas interactions and decays;
- ✓ Remaining background subtracted with MC (pp) and data-tuned MC cocktail (p-Pb, Pb-Pb).
- ✓ Low p_T cut to reject muons from secondary pions and kaons decays.

D-meson R_{AA}: 30-50%

arXiv:1509.06888



PRL 111 (2013)102301



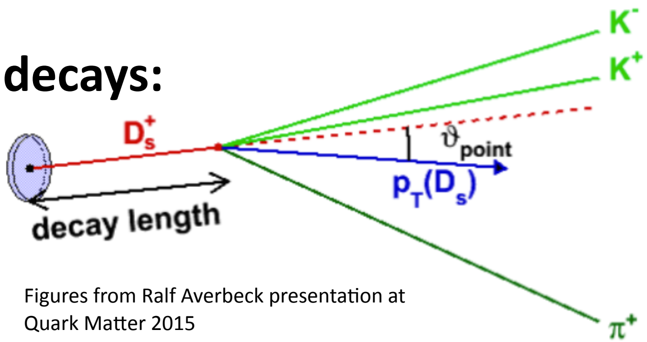
Open heavy flavours in ALICE

Open heavy-flavour studies with ALICE are done via the following channels:

✓ **Hadronic decays:**

Reconstruction of D^+, D^0, D^{*+} and D_s^+ via their hadronic decays:

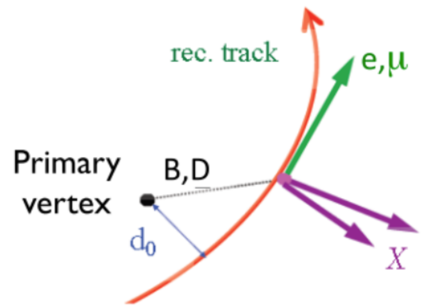
- **$D^+ \to K^-\pi^+\pi^+$ (BR=9.13%)**
- **$D^0 \to K^-\pi^+$ (BR=3.88%)**
- **$D^{*+} \to D^0\pi^+$ (BR=67.7%)**
- **$D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+$ (BR=2.28%)**



Figures from Ralf Averbeck presentation at Quark Matter 2015

✓ **Semileptonic decays (electrons and muons)**

- **Semi-leptonic decay channels have a branching ratio of the order of 10%:**
- **B, D -> l + X**
- **Separation of electrons from beauty-hadron decays using the impact parameter (long life time of beauty hadrons).**



▪ **At high p_T, it is expected that most of the leptons are from beauty-hadron decays (B).**