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

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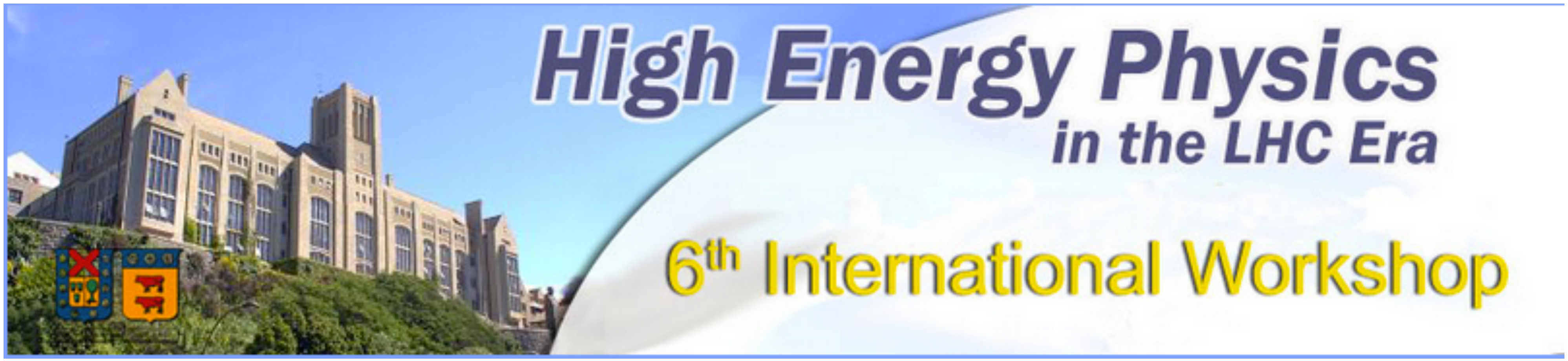
ALICE



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- Motivation
  - ✓ Why to study open heavy flavours?
  - ✓ Why to study pp, p-Pb and Pb-Pb collisions?
- Collision systems studied with ALICE
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- Selected open heavy-flavour studies with ALICE
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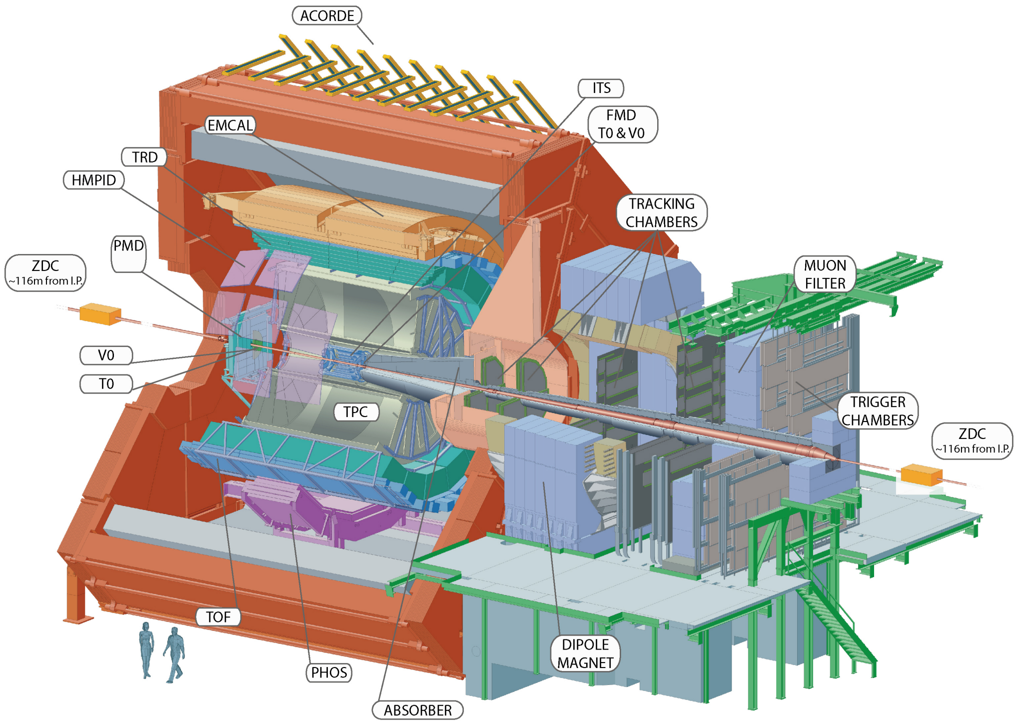
ALICE
A Large Ion Collider Experiment

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



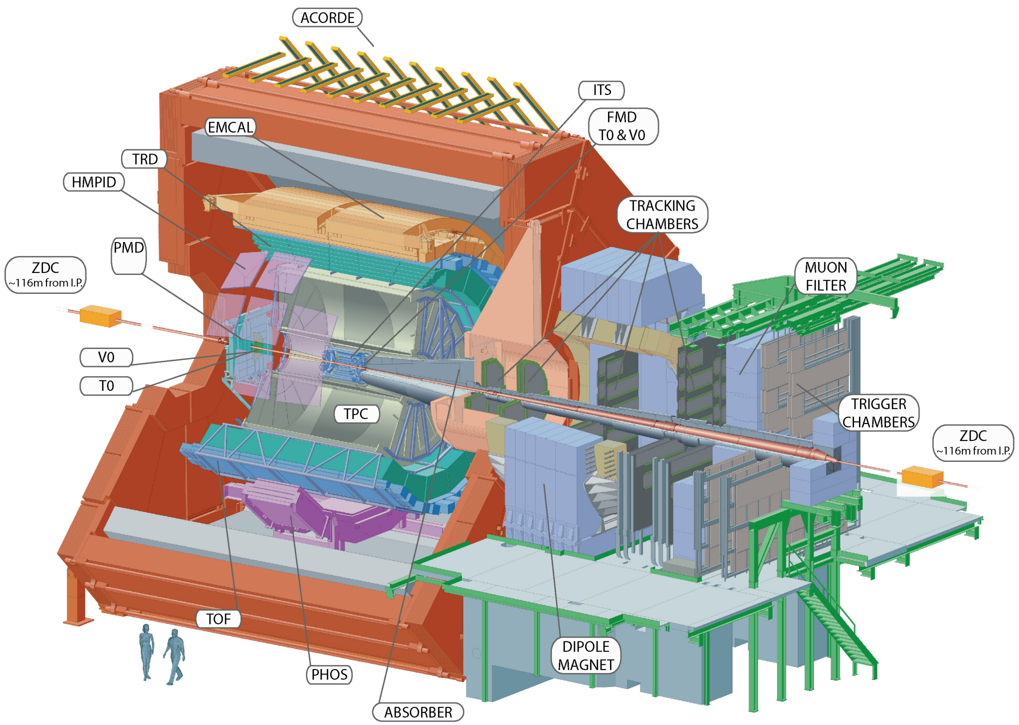
✓ **The Quark Gluon Plasma (QGP) is a high energy-density state of strongly-interacting matter in which partons are deconfined.**

✓ **This state of matter can be studied experimentally only via heavy-ion (A-A) collisions at high energy where the necessary energy density for the phase transition to the QGP can be attained.**

✓ **ALICE can perform various measurements to study the QGP: heavy flavours, light flavours, photons, jets, quarkonia, etc.**

ALICE
A Large Ion Collider Experiment

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



And more:
HMPID (High-Momentum Particle Identification Detector), PHOS (PHOton Spectrometer), ACORDE (Alice Cosmic Ray DEtector), ZDC (Zero Degree Calorimeter), PMD (Photon Multiplicity Detector), FMD (Forward Multiplicity Detector) and T0.

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

V0 detector:
- Centrality
- Trigger

Muon spectrometer:
- Muon ID
- Trigger
- Tracking

Motivation: why to study open heavy flavours?

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

- **They 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**

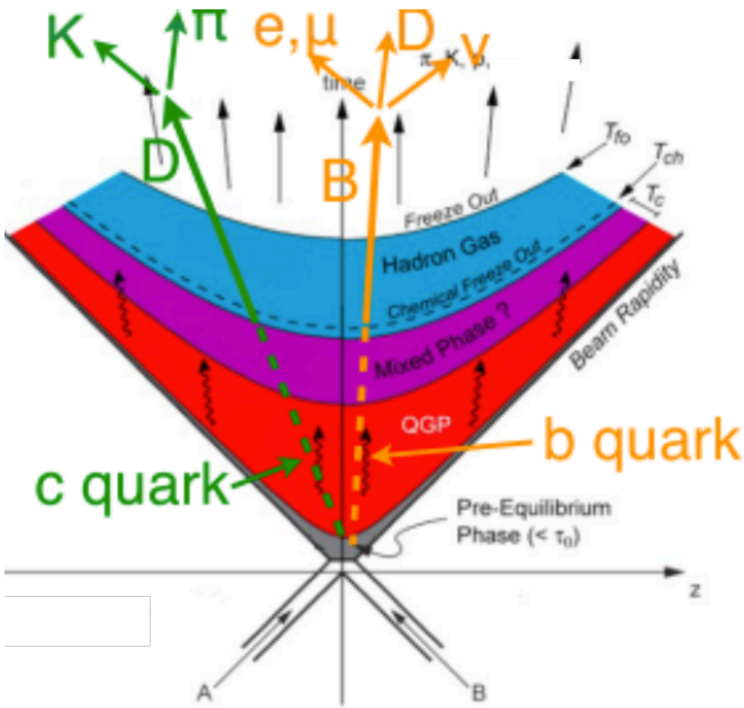
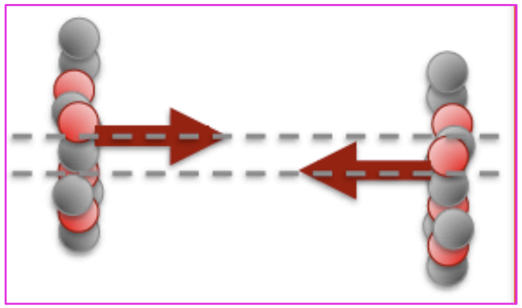


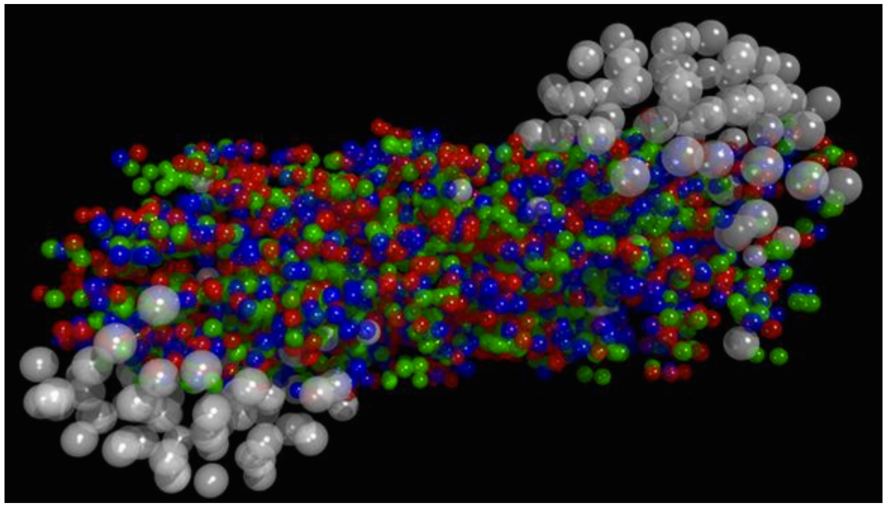
Figure from Ralf Averbeck presentation at Quark Matter 2015

- **They can experience the full evolution of the system:**
  - ✓ **They live much longer (around 10^{-11} sec) than the duration of the QGP (around 10^{-23} sec)** PRD 74(2006)054010

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

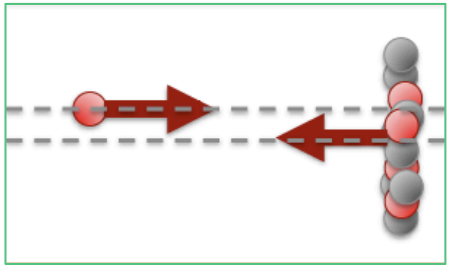
- **Pb-Pb collisions:**
  - ✓ Formation of a Quark-Gluon Plasma (QGP) is expected.
  - ✓ Study the properties of QGP.
  - ✓ Parton energy loss via radiative and elastic processes.
  - ✓ Use pp collisions as reference.





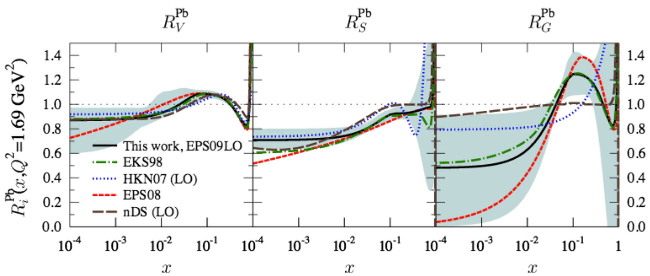
Motivation: why to study Pb-Pb, p-Pb and pp collisions?

- **p-Pb collisions:**

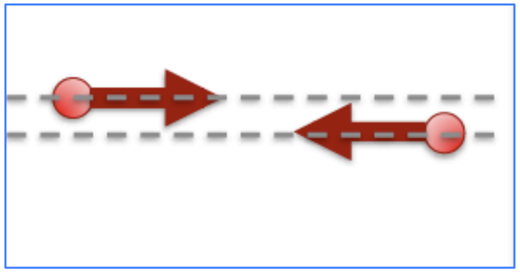


  - ✓ Intermediate state between pp collisions and Pb-Pb collisions.
  - ✓ Control experiment for Pb-Pb measurements.
  - ✓ Cold nuclear matter effects can be studied:
    - Nuclear modification of Parton Distribution Function (shadowing/saturation/CGC)
    - k_T broadening
    - Energy loss

Figure from **JHEP 0904 (2009) 065**



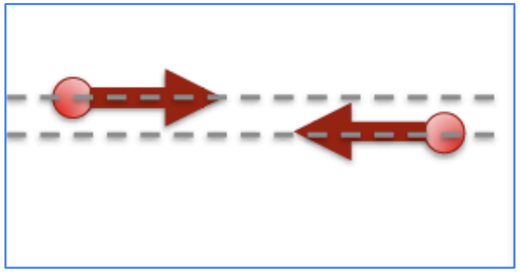
- **pp collisions:**



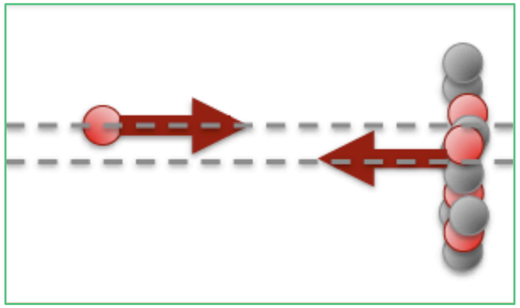
  - ✓ Reference for studies with p-Pb collisions and Pb-Pb collisions.
  - ✓ Test for perturbative QCD calculations.

Collision systems studied with ALICE

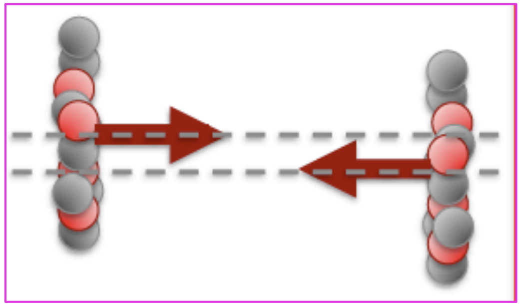
- **pp collisions:**
  - ✓ $\sqrt{s}$ = 0.9, 2.76, 7 and 8 TeV



- **p-Pb collisions:**
  - ✓ $\sqrt{s_{NN}}$ = 5.02 TeV



- **Pb-Pb collisions:**
  - ✓ $\sqrt{s_{NN}}$ = 2.76 TeV



How to study open heavy flavours?

Nuclear modification factor:

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

✓ **Defined as the ratio of the p_T-differential yield measured in A-A collisions and the corresponding yield in pp collisions multiplied by the number of binary collisions;**

✓ **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 medium effects and no nuclear effects.**
- **If $R_{AA} < 1$ (at high p_T) -> energy loss of the partons shifts the momentum spectra of the heavy-flavour particles.**

✓ **Expected mass dependence of energy loss due to colour-charge and dead cone effect:**

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

PLB 519(2001)199

✓ **The nuclear modification factor is also studied in a control experiment, in p-A collisions, to quantify cold nuclear matter effects.**

$$R_{pPb} = \frac{1}{N_{coll}} \frac{dN_{pPb}/dp_T}{dN_{pp}/dp_T} = \frac{1}{A} \frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T}$$

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.**

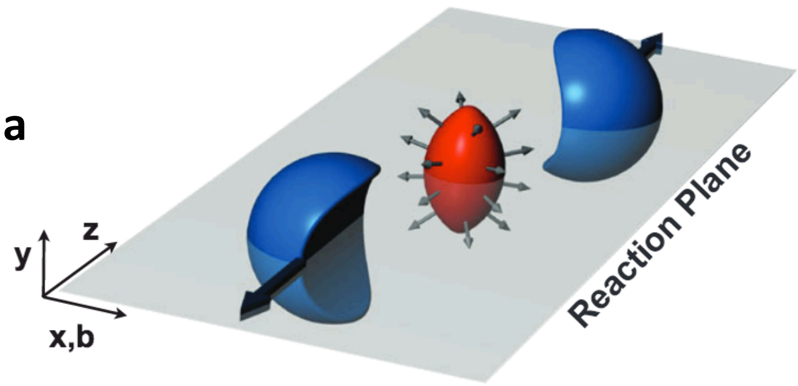


Fig. from arXiv:1102.3010v2

✓ **Thermalized particles participate in the collective motion;**

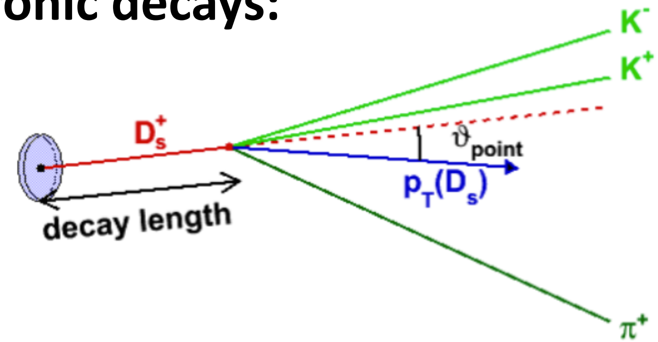
Open heavy flavours in ALICE

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:

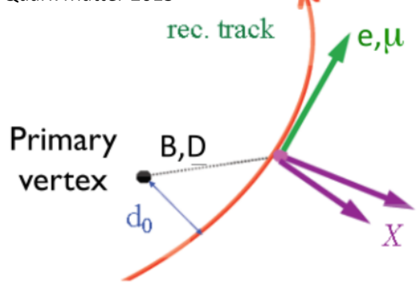
- **$D^+ \to K^-\pi^+\pi^+$ (BR=9.13%)**
- **$D^0 \to K^-\pi^+$ (BR=3.88%)**
- **$D^{*+} \to D^0\pi^+$ (BR=67.7%)**
- **$D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+$ (BR=2.28%)**



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

- **Semi-leptonic decay channels have a branching ratio of the order of 10%:**
- **B, D -> l + X**

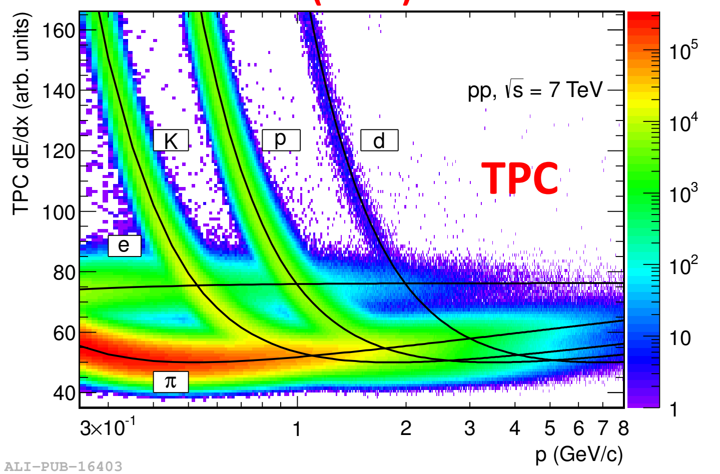
Figures from Ralf Averbeck presentation at Quark Matter 2015

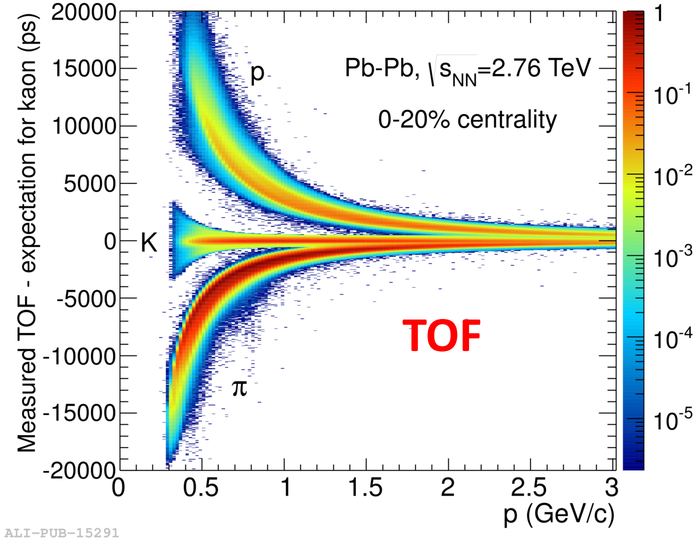


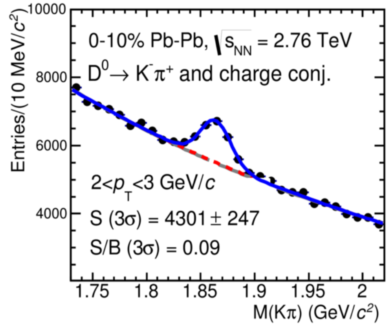
- **Separation of electrons from beauty-hadron decays using the impact parameter (long life time of beauty hadrons).**

Particle Identification with ALICE: D mesons

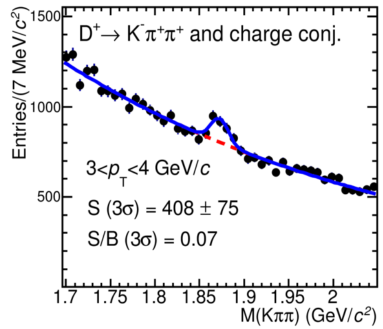
PRD 86(2012)112007

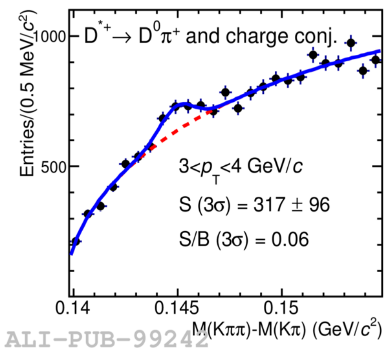






JHEP 1209(2012)112





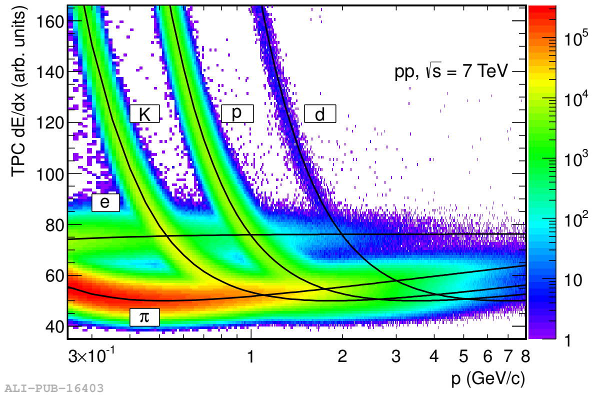
✓ **TPC signal: specific energy deposit d*E*/d*x* in the TPC expressed in terms of the deviation from the expected hadron d*E*/d*x* (measured in units of standard deviations σ);**

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

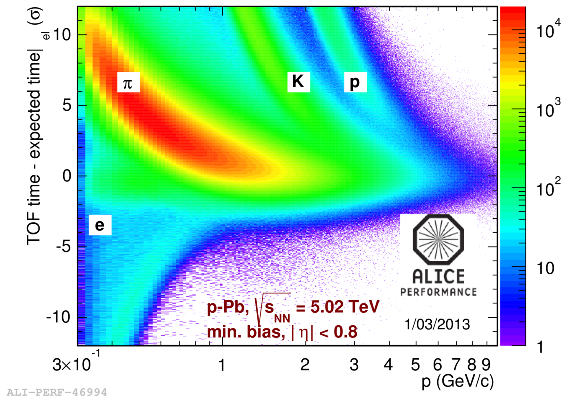
- $D^+ \to K^-\pi^+\pi^+$
- $D^0 \to K^-\pi^+$
- $D^{*+} \to D^0\pi^+$
- $D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+$

Particle Identification with ALICE: electrons

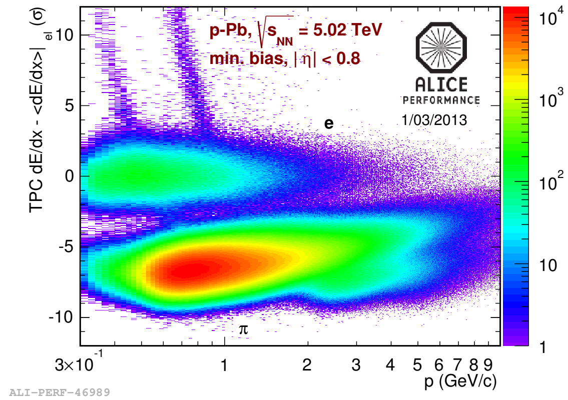
Ref: PRD 86(2012)112007



TPC signal



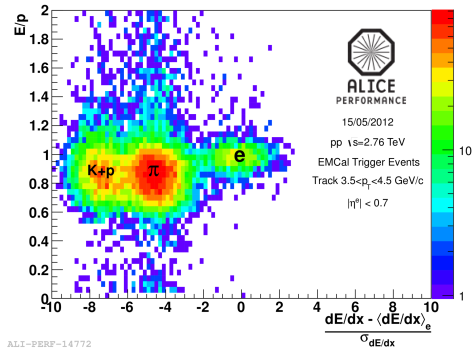
TOF signal

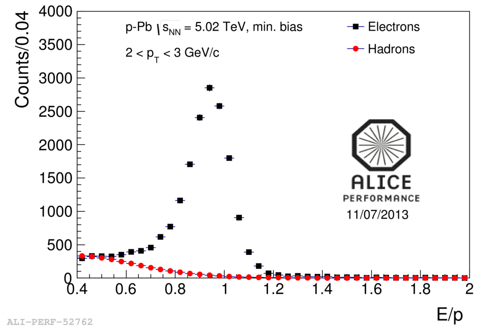


TPC signal after TOF cut

✓ TPC signal combined with TOF signal leads to more pure electron sample at low p_T than TPC-only or TOF-only.

✓ Electron ID based on *E*/*p*, where *p* is the momentum measured by TPC and *E* the energy measured by EMCal.

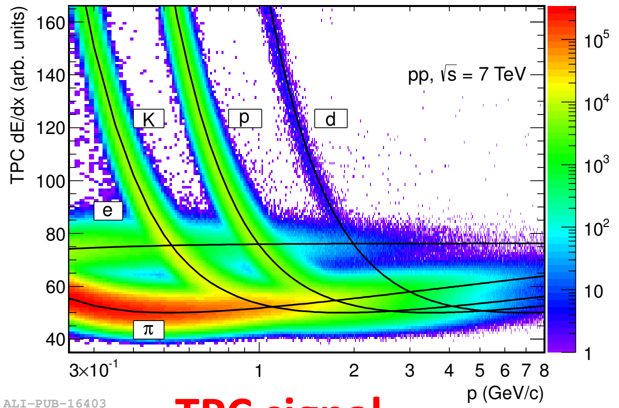




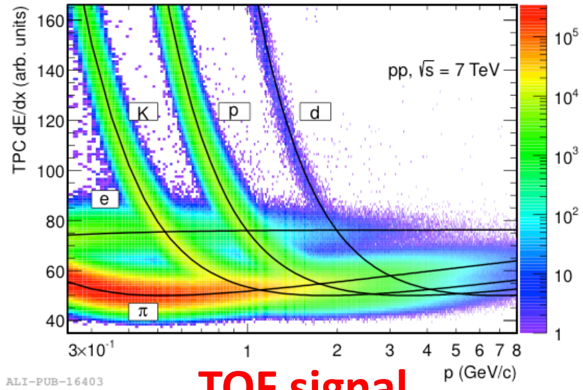
✓ Non-HFE background (photon conversions, η and π^0 Dalitz decays, mainly) removed using cocktail or invariant mass method.

Particle Identification with ALICE: electrons from beauty-hadron decays

PRD 86(2012)112007

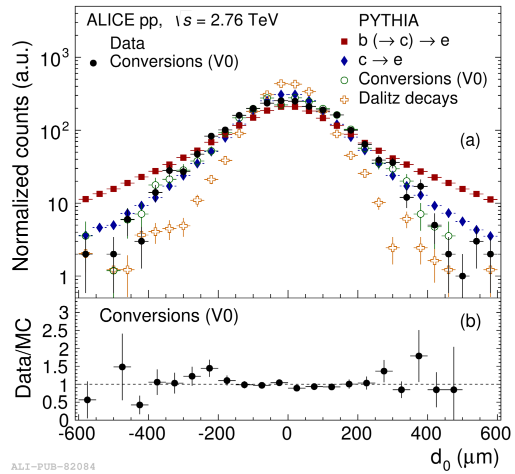


TPC signal



TOF signal

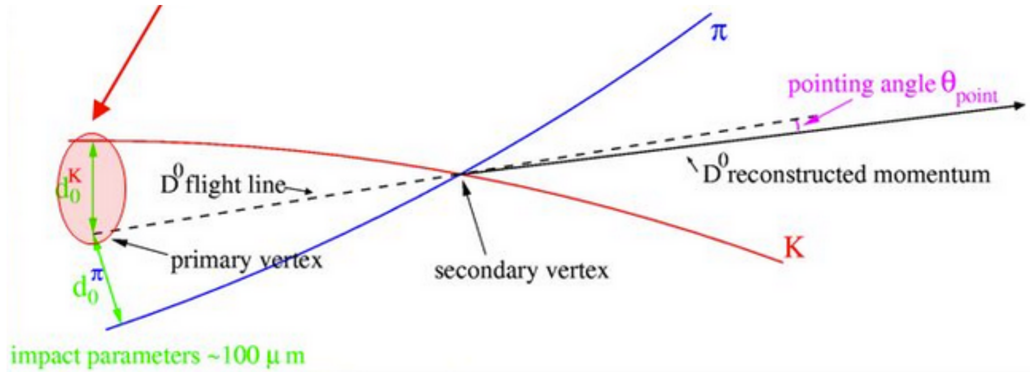
PLB 738 (2014) 97



Impact parameter distribution

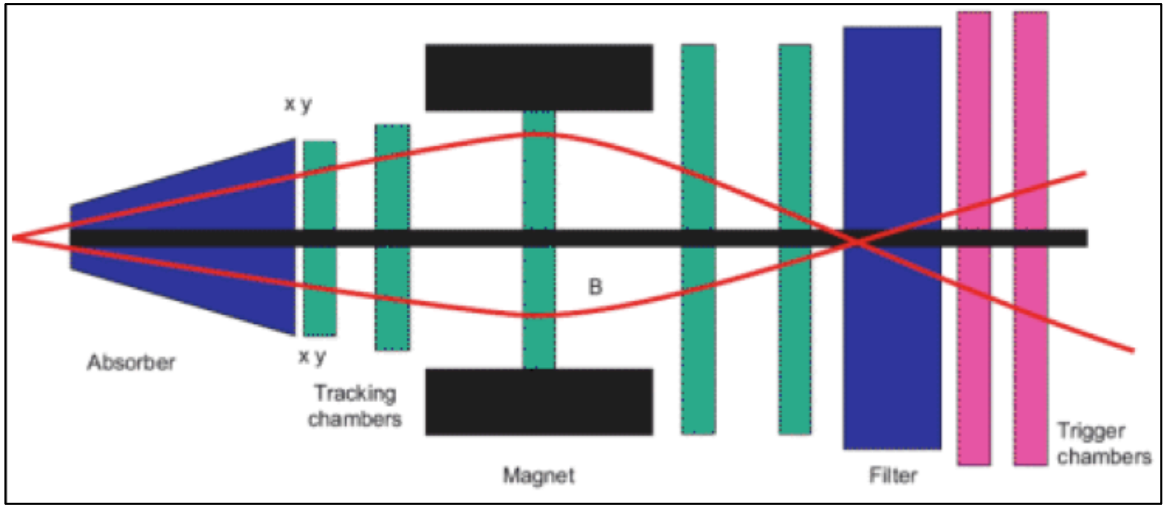
- ✓ **Separation of electrons from beauty-hadron decays using the impact parameter (the distance of closest approach of the track to the interaction vertex);**

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



Particle Identification with ALICE: muons

Muons reconstructed in the forward muon spectrometer



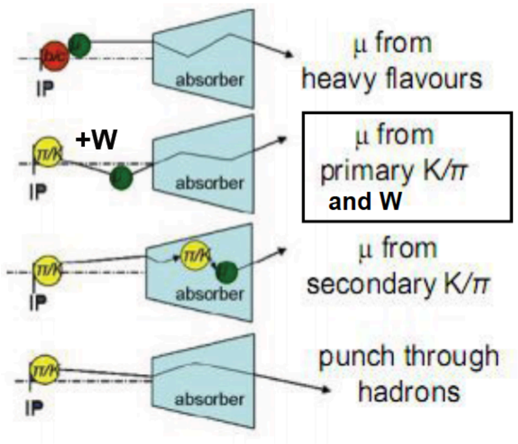
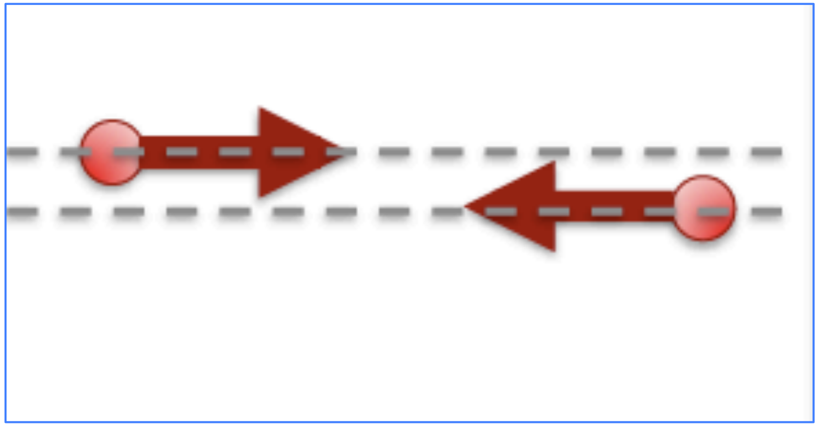


Figure from Zuman Zhang poster presented in QM2016

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

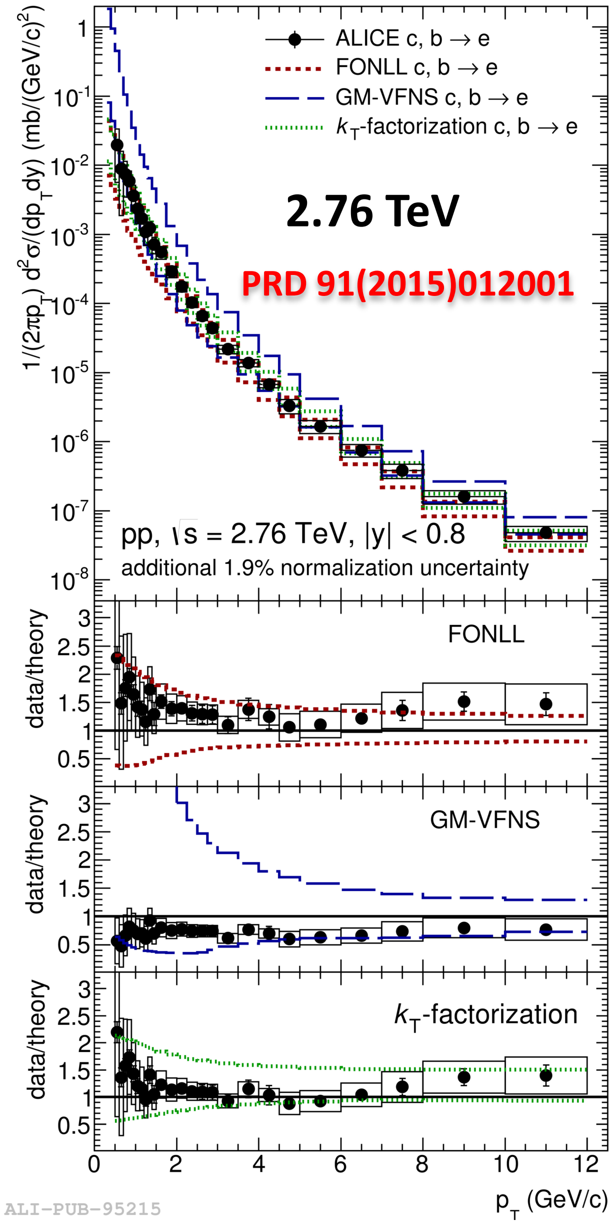
- ✓ **Absorber: to absorb hadrons and photons from the interaction vertex;**
- ✓ **Tracking chambers: 10 detection planes, which gives two-dimensional hit information;**
- ✓ **Filter: passive muon-filter wall to protect the trigger chambers;**
- ✓ **Trigger chambers: requires at least one single muon 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.**

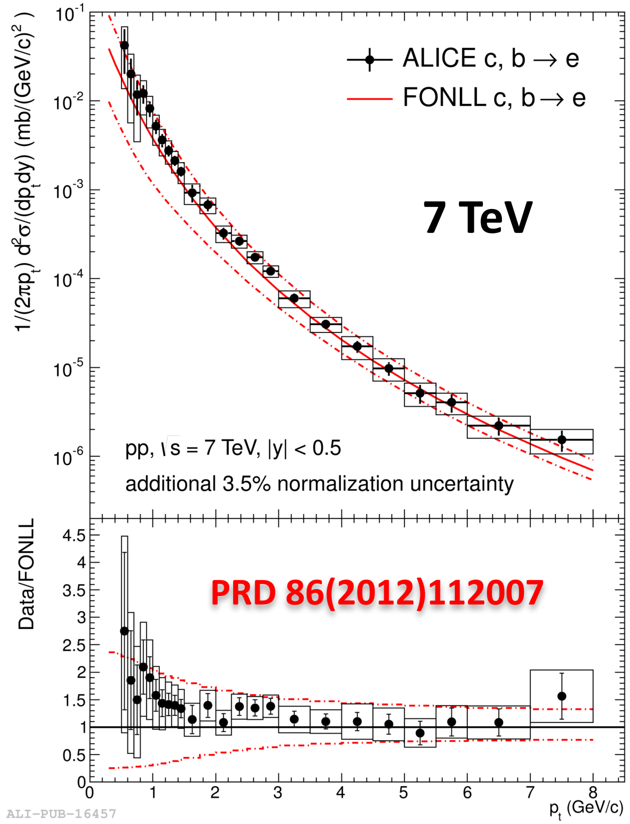
Results in pp collisions



pp

pp results: semi-electronic decay channel



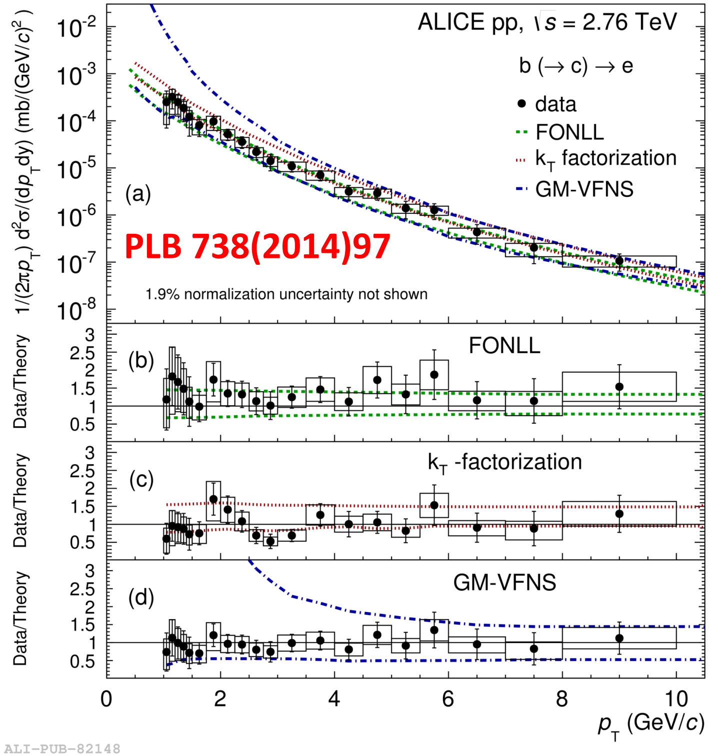


pQCD calculations:
- **FONLL: JHEP 1210(2012)37**
- **GM-VFNS: EPJ C72(2012)2082**
- **k_T factorization: PRD 87(2013)094022**

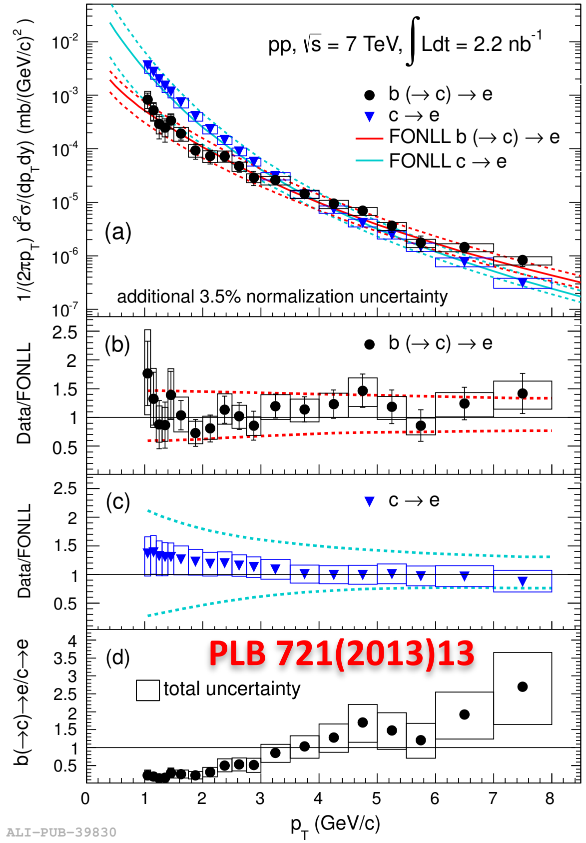
- **$e^{\pm}$ from HF decays at mid-rapidity**
- **pQCD calculations in reasonable agreement with data within uncertainties**

pp results: electrons from beauty-hadron decays

2.76 TeV



7 TeV



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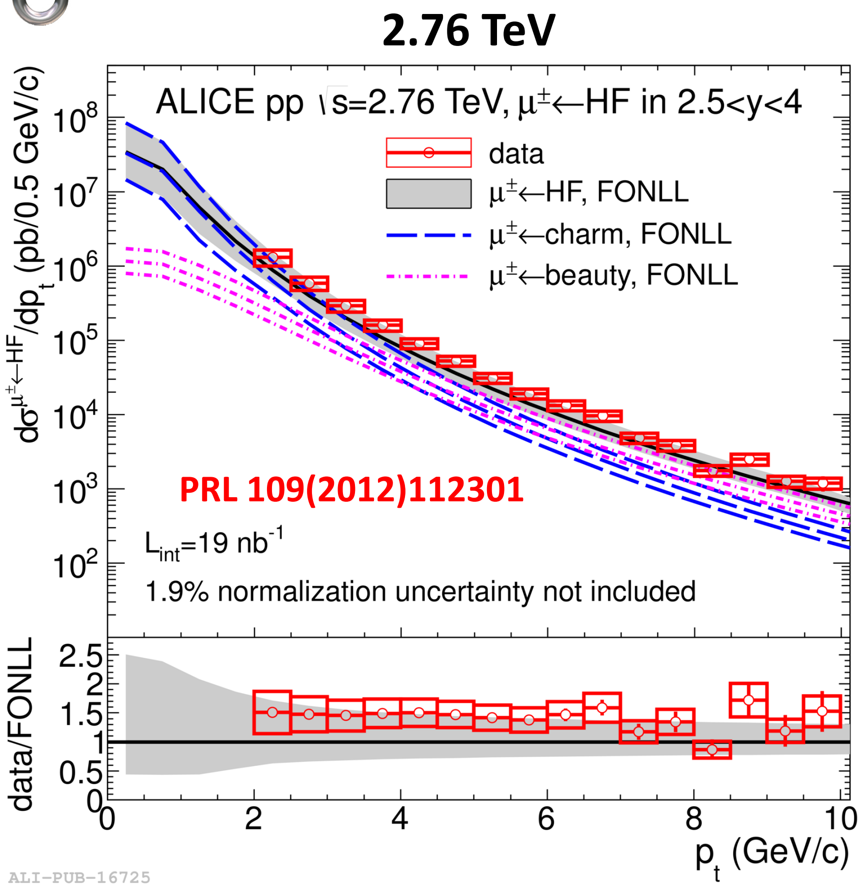
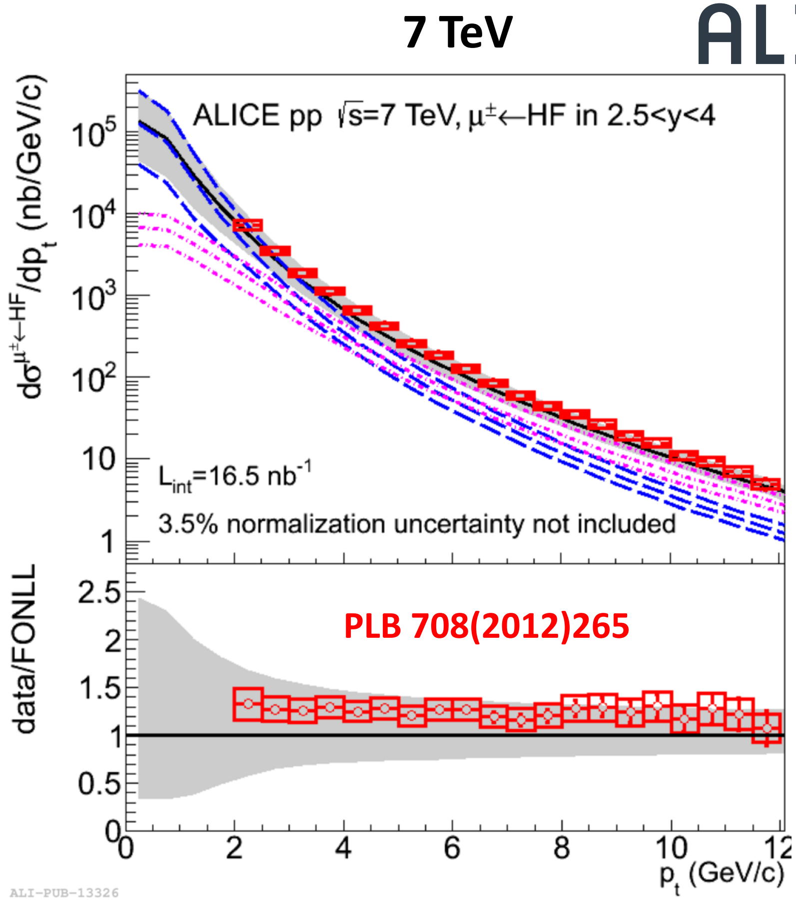
- **e$^{\pm}$ from beauty decays at mid-rapidity**
- **pQCD calculations in reasonable agreement with data within uncertainties**

pp results: semi-muonic decay channel



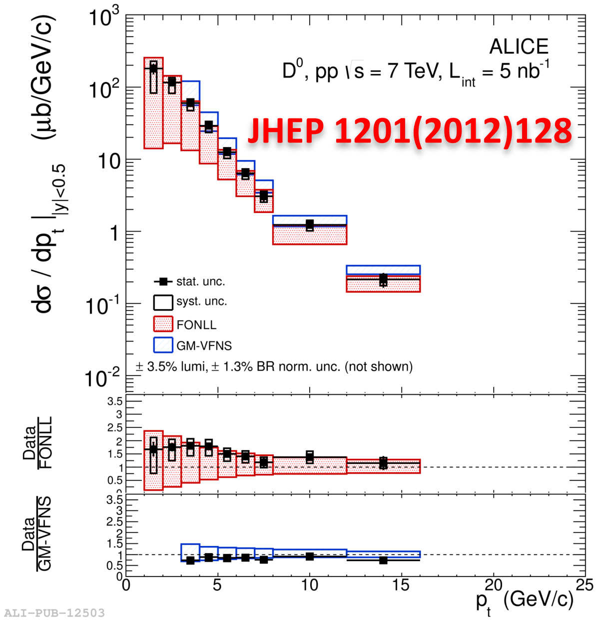


- $\mu^{\pm}$ from HF decays at forward rapidity
- pQCD calculations in reasonable agreement with data within uncertainties

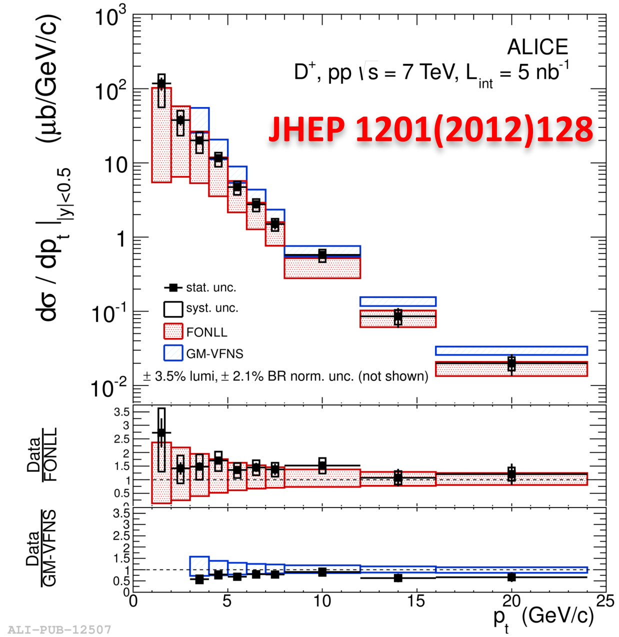
pp results: hadronic decay channels

ALICE

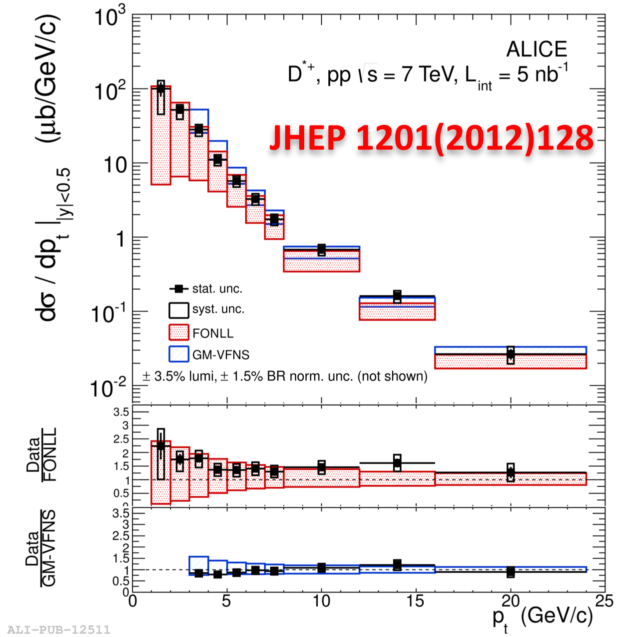
D^0



D^+



D^{*+}

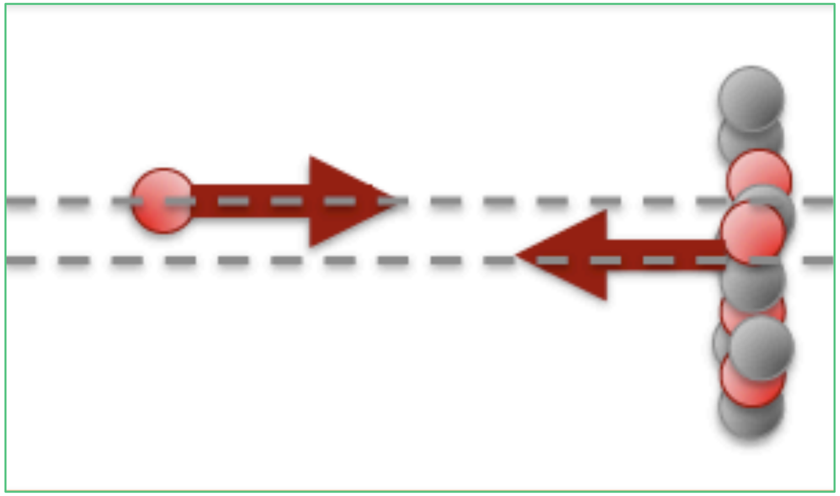


- **pQCD calculations in reasonable agreement with data within uncertainties for all D-meson species.**

pQCD calculations:

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

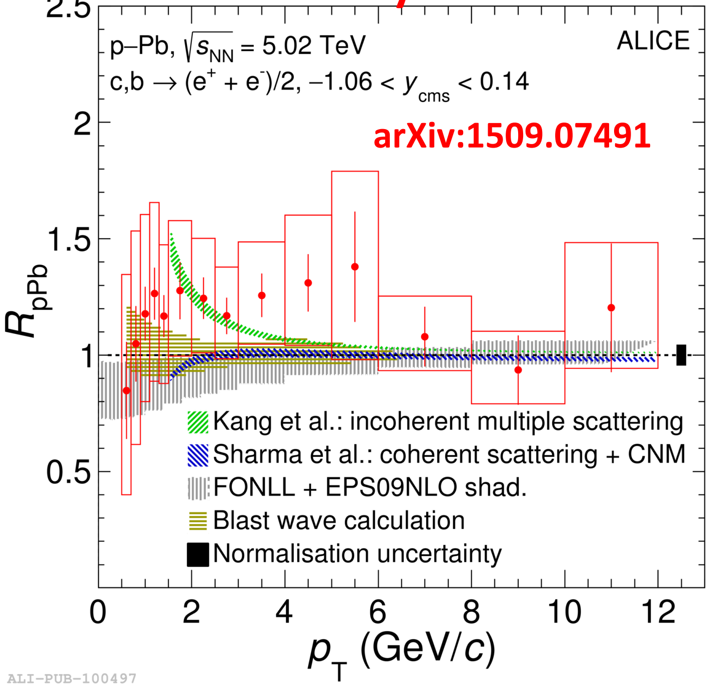
Results in p-Pb collisions



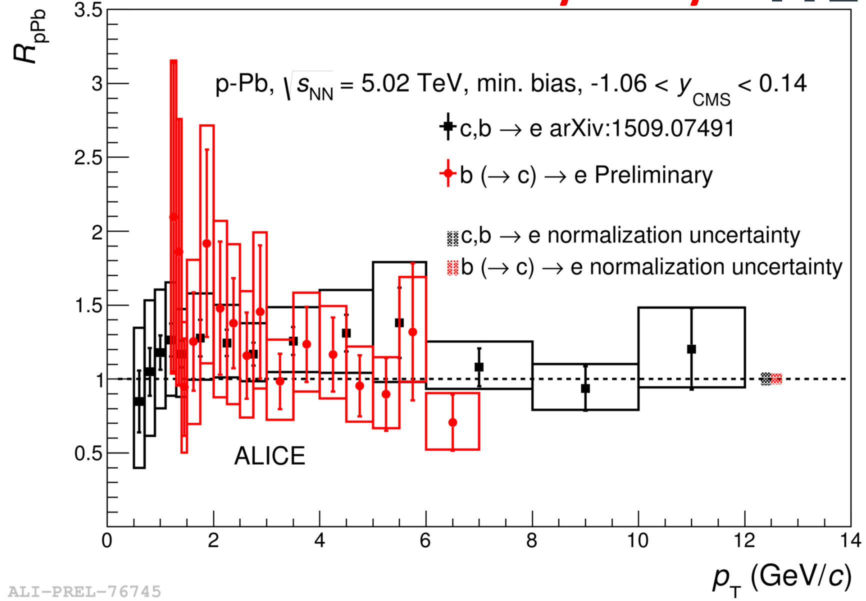
p-Pb

p-Pb results: semi-electronic decay channel

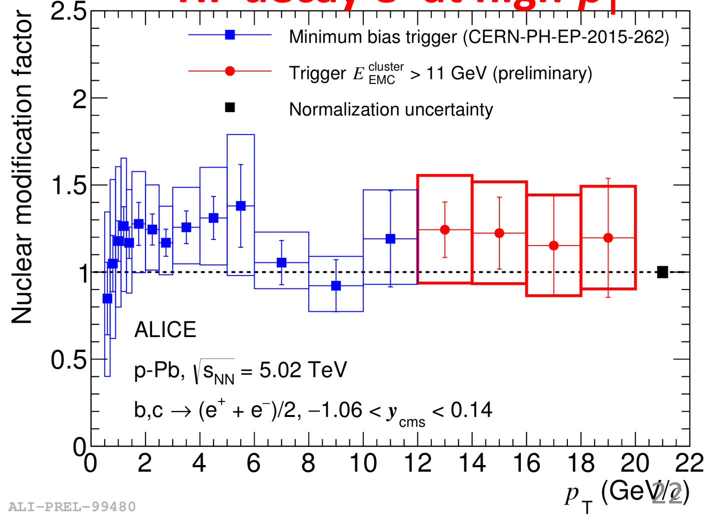
HF decay e±



e± from beauty decay



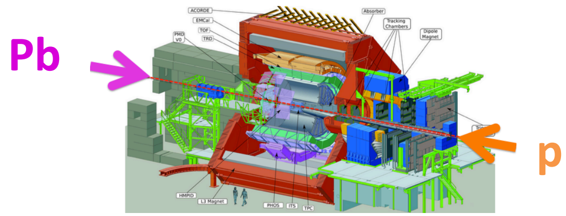
HF decay e± at high-p_T



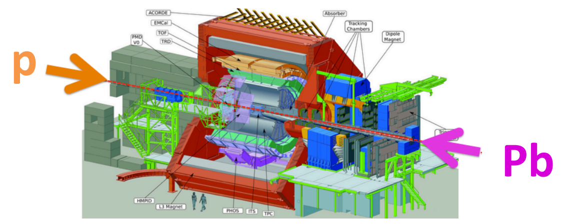
Electrons:

- R_{pPb} of HF-decay e± consistent with unity and described by models including initial-state effects or radial flow within uncertainties;
- R_{pPb} of beauty-hadron decay electrons consistent with HF-decay electron R_{pPb} and with unity;
- Extension of HF-decay e± in high-p_T using the EMCal trigger;
- No indication for suppression at intermediate/high p_T

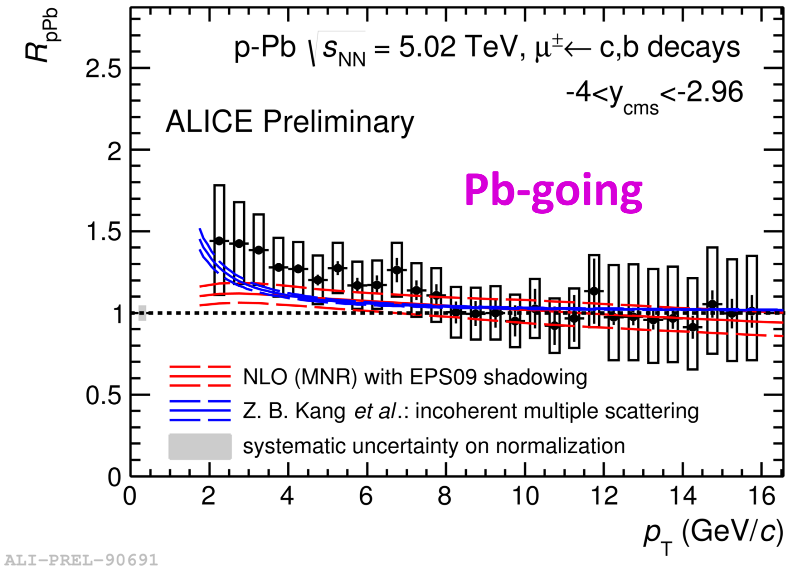
p-Pb results: semi-muonic decay channel

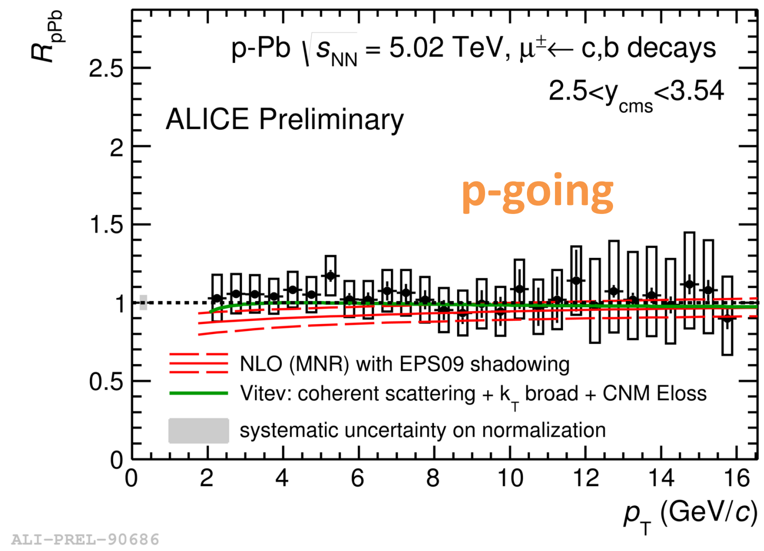


HF decay μ± backward



HF decay μ± forward

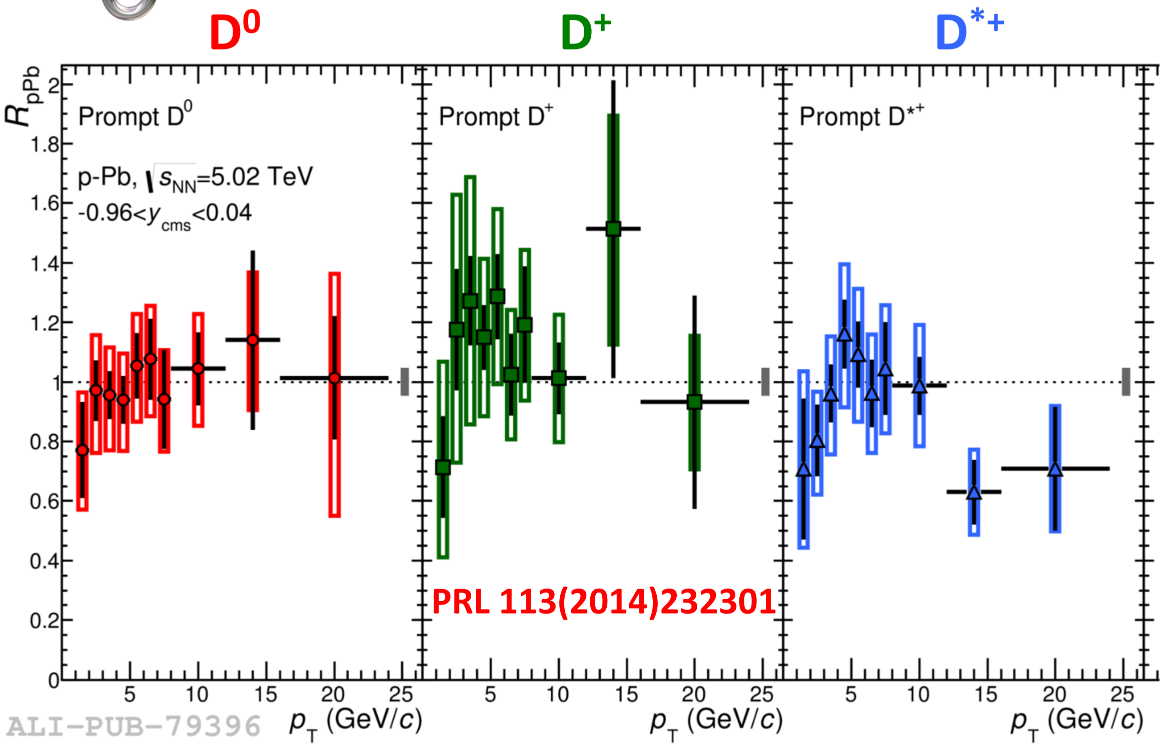


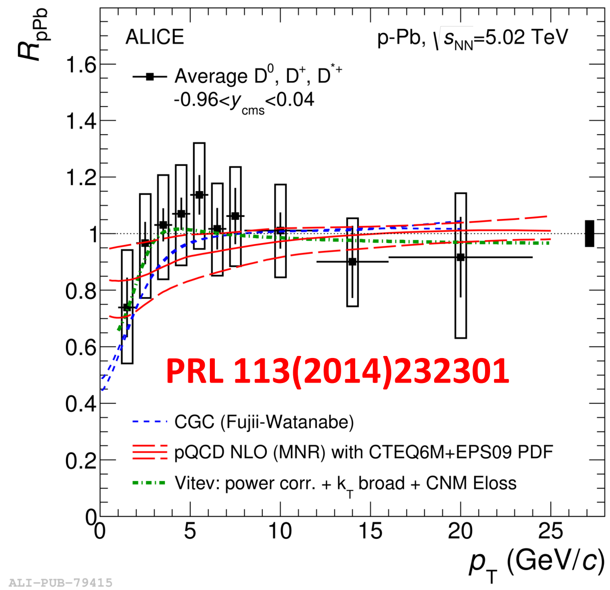


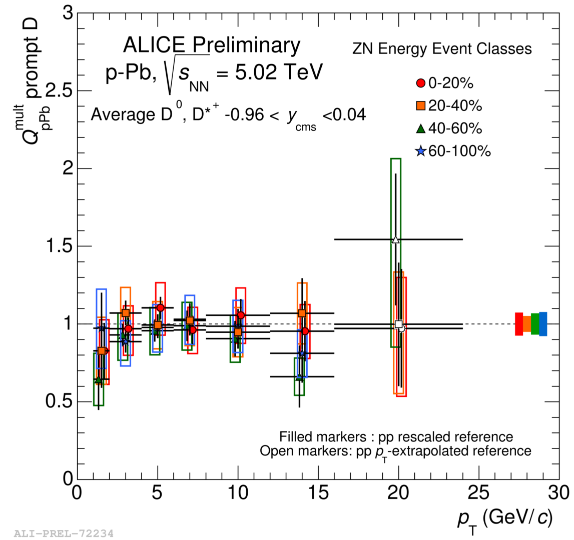
Muons:

- 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

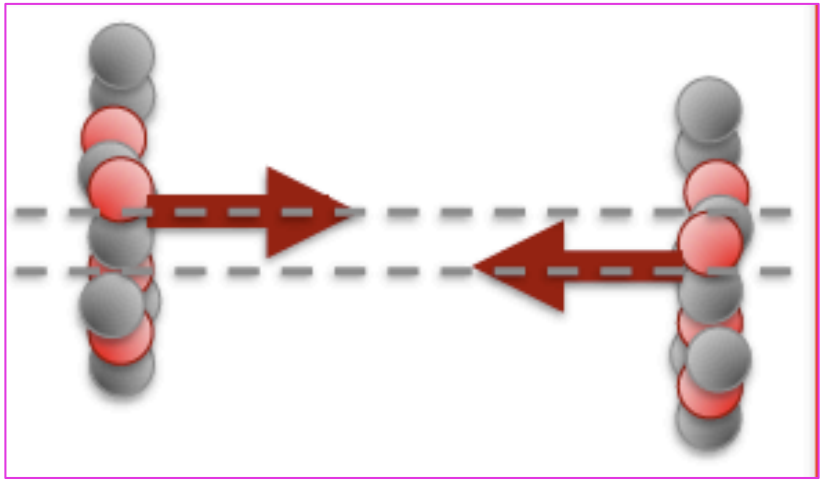






- R_{pPb} consistent with unity for all D-meson species
- Described within uncertainties by models including initial-state effects
- No indication for suppression at intermediate/high p_T
- No multiplicity dependence

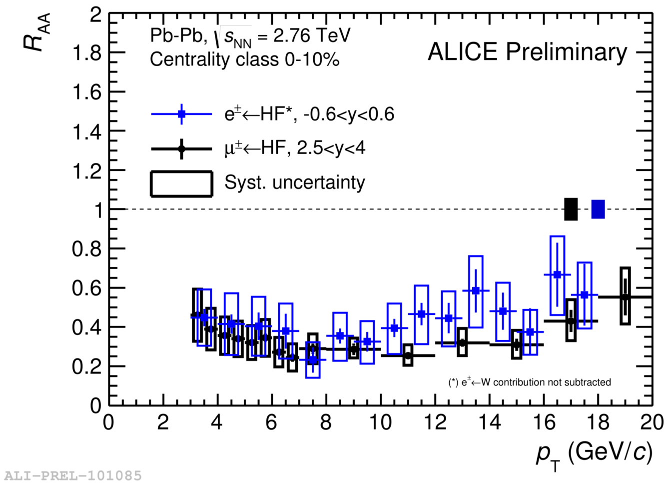
Results in Pb-Pb collisions



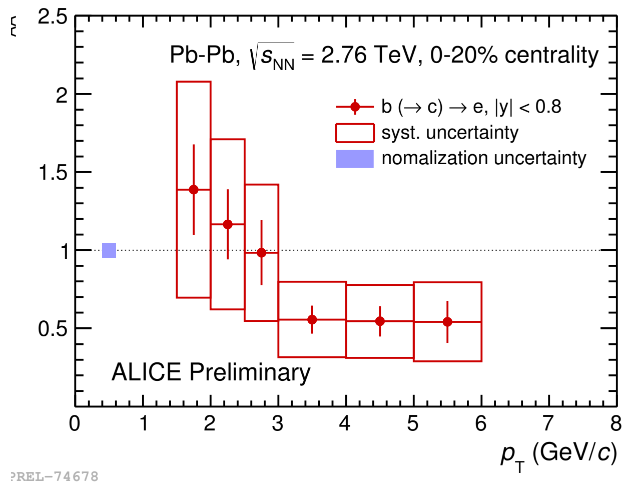
Pb-Pb

Pb-Pb results: semi-leptonic decay channels

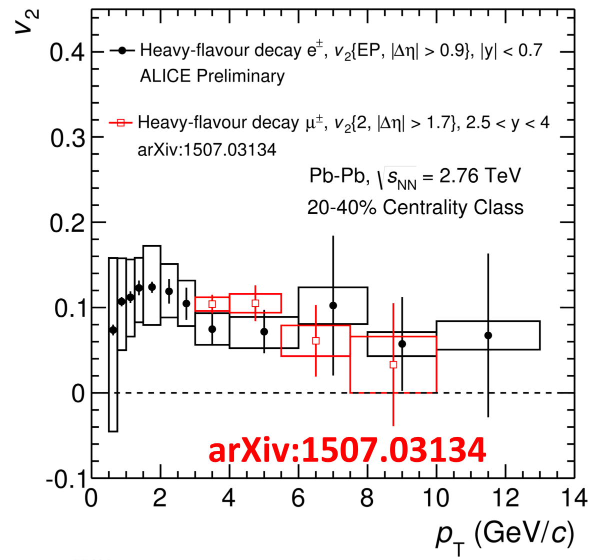
HF decay e± and μ±



e± from beauty decay



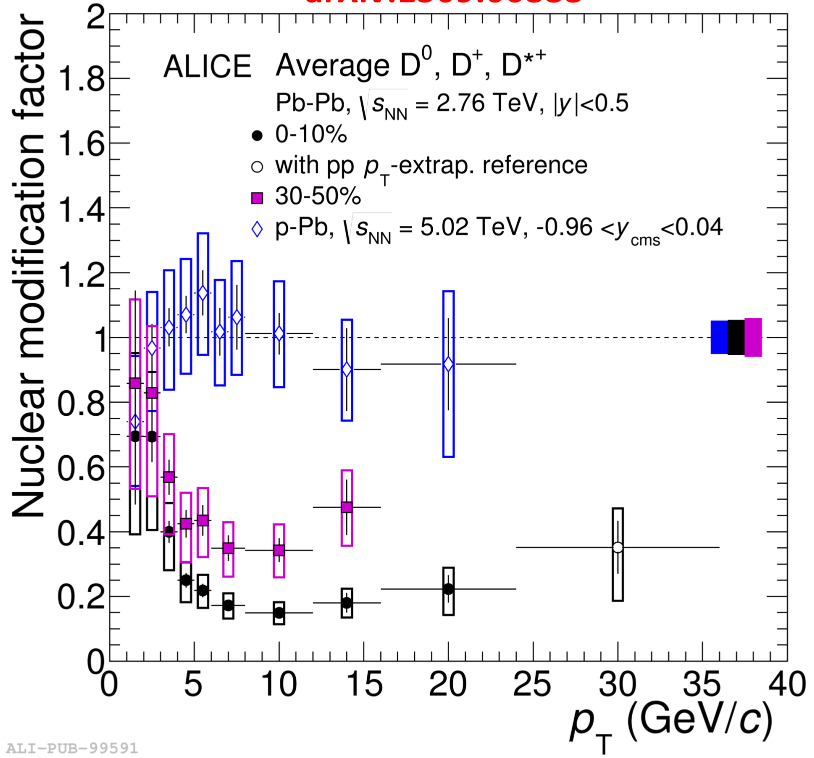
v_2



- Similar suppression for HF decay electrons ($|y|$ < 0.6) and muons (2.5 < y < 4) in high p_T
- Electrons from beauty decays suppressed above 3 GeV/c
- Strong suppression of the yields of HF decay electrons and muons in intermediate/high p_T indicates a strong modification of the spectra in central Pb-Pb collisions due to the energy loss in the parton level.
- Similar elliptic flow for HF decay electrons and muons in high p_T
- 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

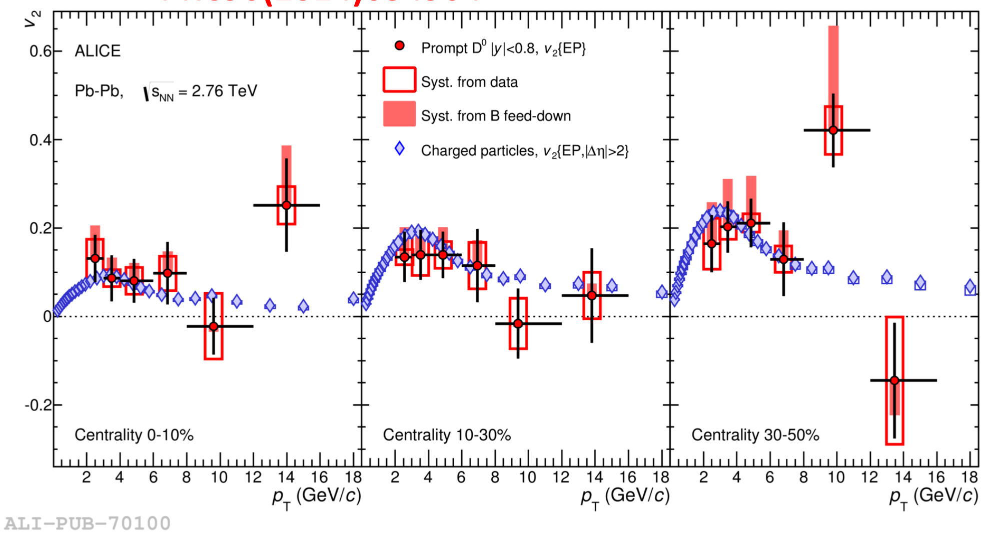
Pb-Pb results: hadronic decay channels

arXiv:1509.06888



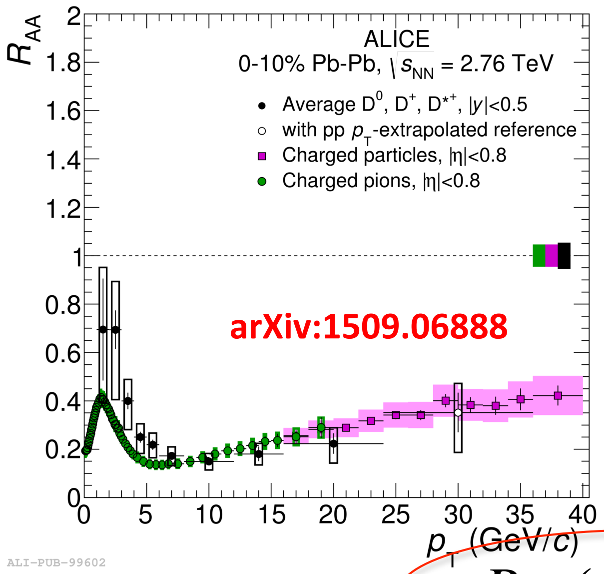
- No suppression in p-Pb
- Observed suppression at intermediate/high p_T (p_T > 2 GeV/c) in central Pb-Pb collisions at the LHC is due to the strong interaction of charm quarks with the QGP

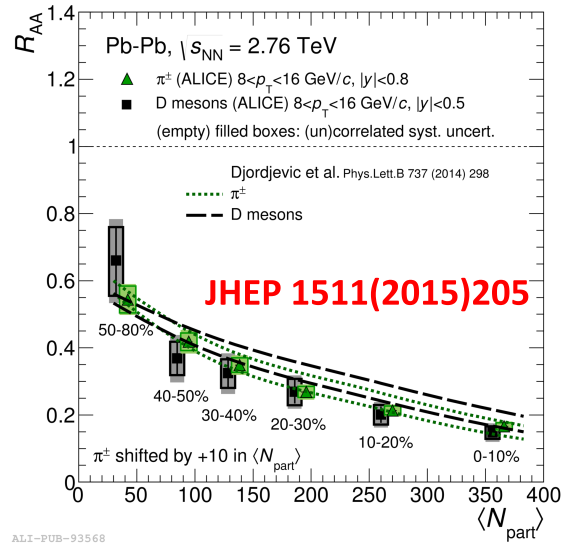
PRC90(2014)034904



- 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

Pb-Pb results: D mesons vs. light particles

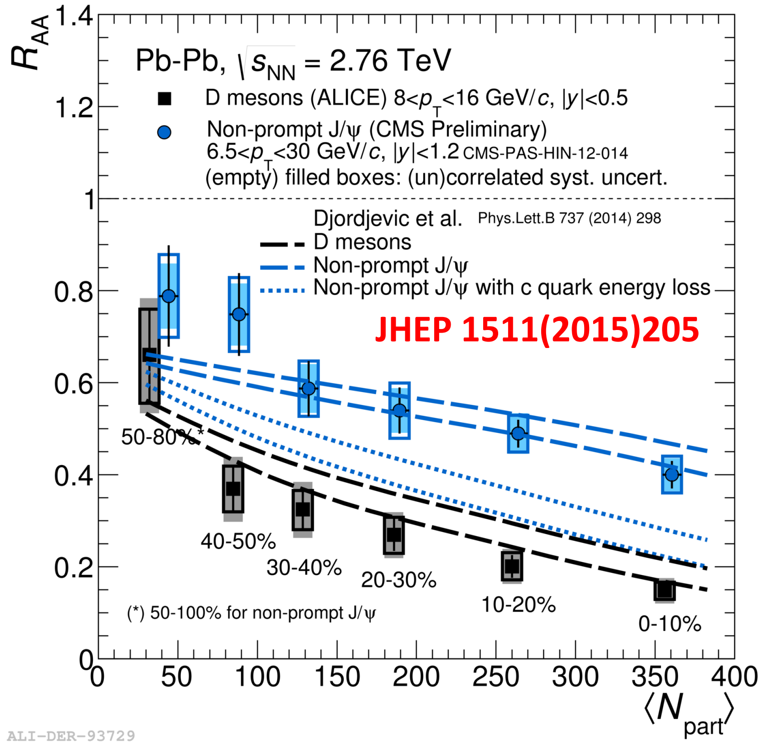




$$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$$

- **D-meson R_{AA} is compatible with pion R_{AA} within the uncertainties:**
  - ✓ **Colour-charge energy loss dependence;**
  - ✓ **Softer fragmentation of gluons (light-flavour originates mainly from gluon fragmentation at LHC energy) ;**
  - ✓ **Different shapes of the partons p_T distributions;**
  - **Effects counterbalance the energy loss for light hadrons.**
- **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



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

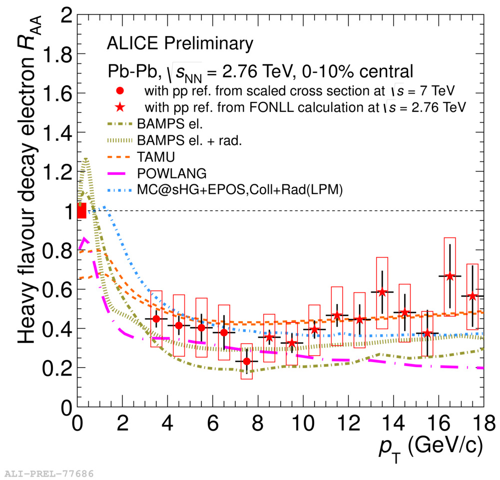
Non-prompt J/ψ: B -> J/ψ

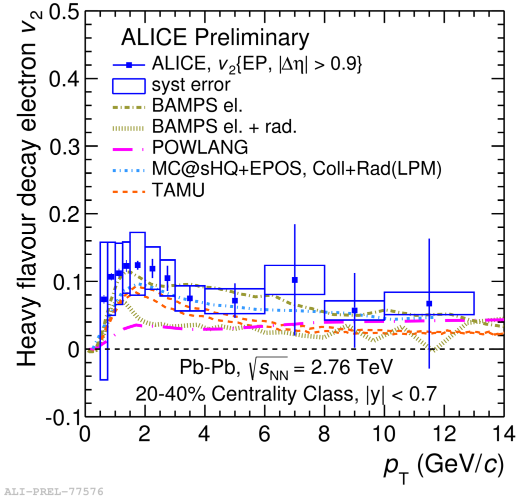
Measured by CMS: CMS-PAS-HIN-12-014

- **Different suppression observed for D mesons and non-prompt J/ψ:**
  - ✓ **Dead-cone effect reduces radiative energy loss (*E*/*m*);**
  - ✓ **Collisional energy loss expected to be reduced for heavier quarks;**
- **Difference predicted by models including mass dependence of the energy loss**

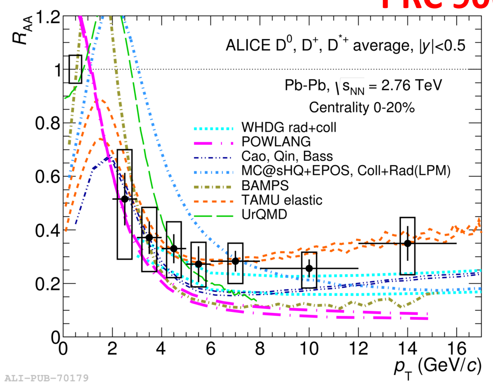
PRL 112(2014)042302

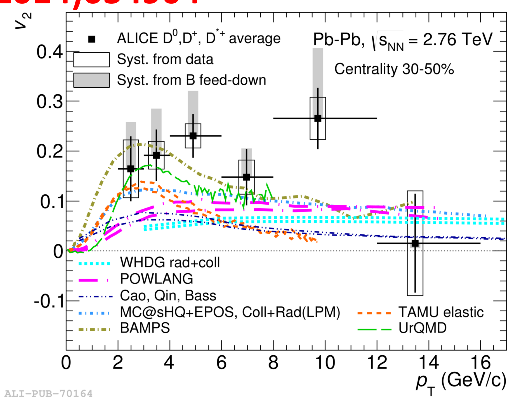
Pb-Pb results: comparison with models





PRC 90(2014)034904





- R_{AA} and v_2 provides constraints to model;
- 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

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

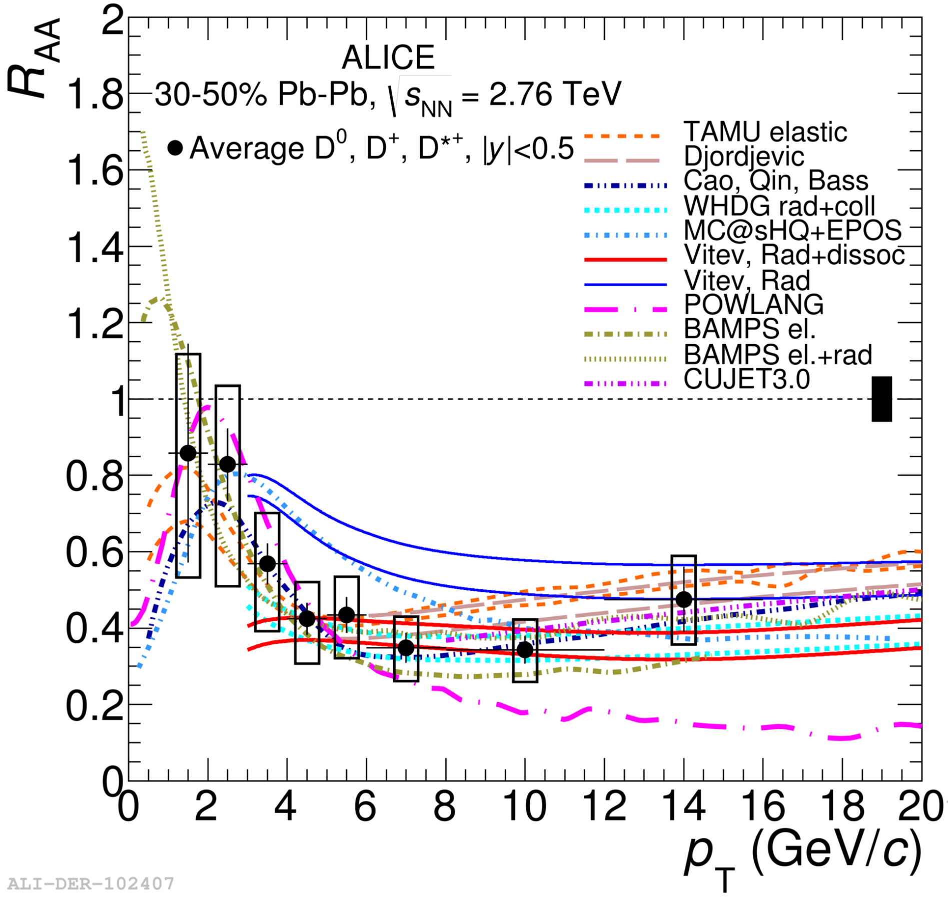
- **Strong interaction of heavy quarks with the QGP.**
- **Suppression of yields at high p_T consistent with partonic energy loss models.**
- **The strong suppression at high p_T is due to the hot and dense medium, since R_{pPb} is consistent with unity.**
- **Indication for charm participating in the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

Thank you for your attention!

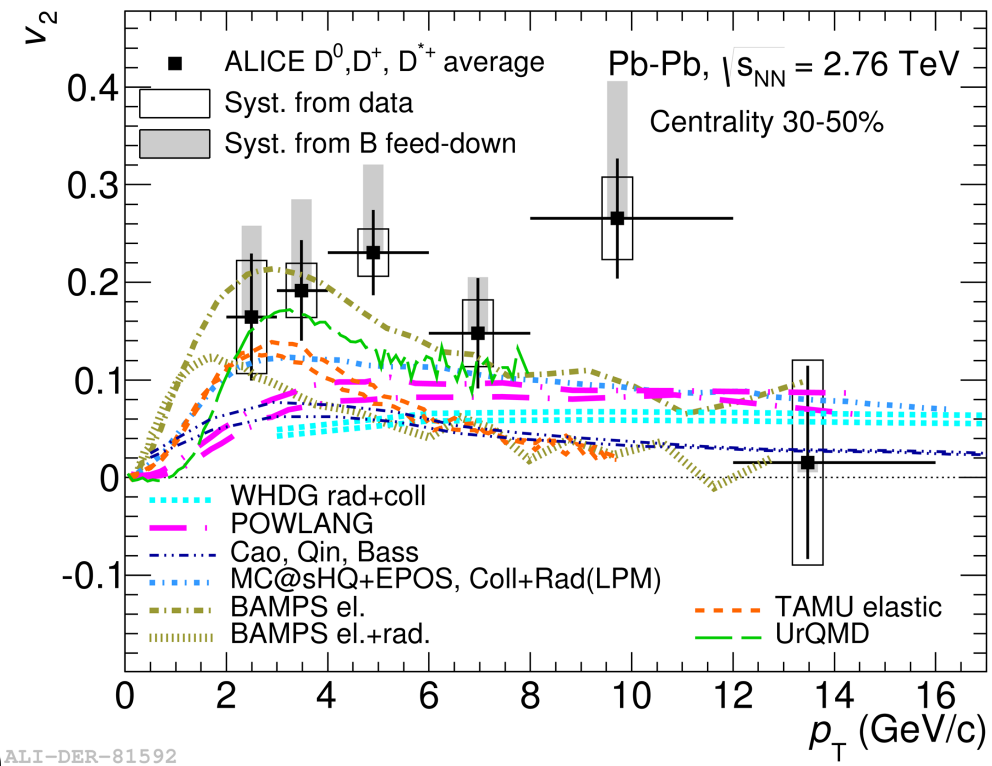
Extra slides

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

arXiv:1509.06888



PRL 111 (2013)102301



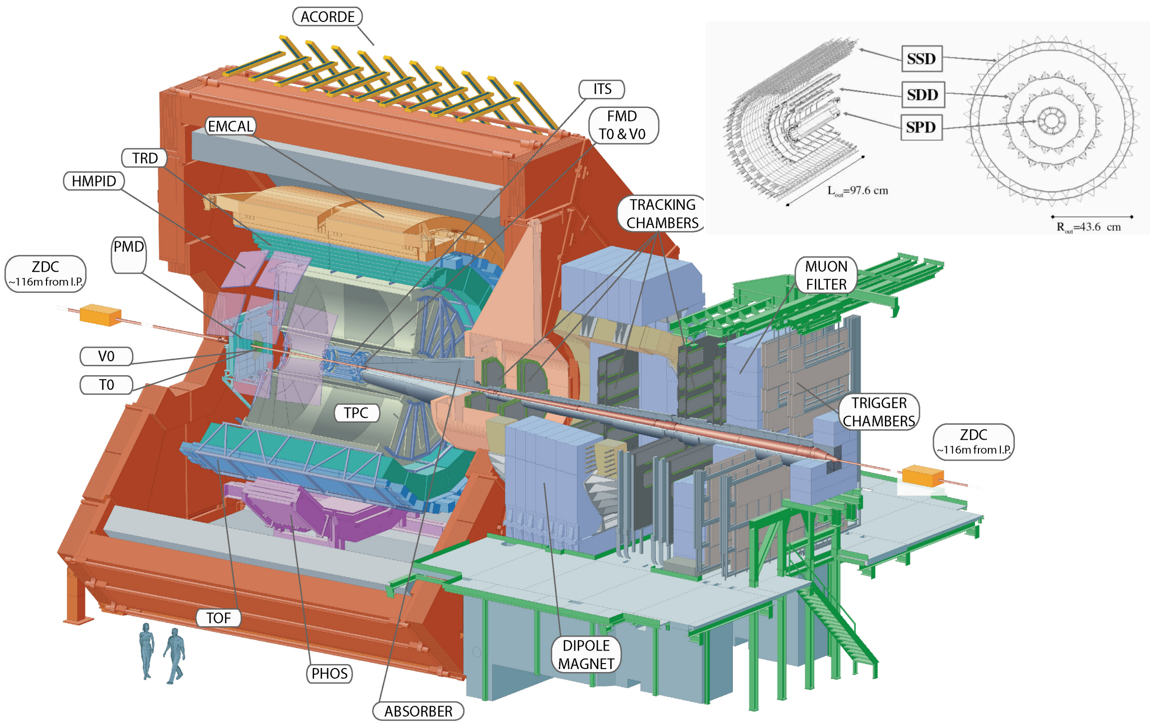
ALICE

✓ **Main observables measured by ALICE:**

- **Heavy flavour production and jet fragmentation: to probe energy loss in the plasma phase and parton kinematics;**
- **Elliptic flow: sensitive to QGP properties (shear viscosity/ equation of state);**
- **Prompt photons: to study the thermal radiation from the early phase;**
- **Quarkonia production: probes deconfinement and parton recombination;**
- **Particles ratios and p_T distributions: can reveal thermodynamical properties and hydrodynamical evolution of the medium.**

ALICE
A Large Ion Collider Experiment

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



ITS (Inner Tracking System):

✓ The ITS is a silicon detector.

✓ It is used to identify trajectories and determine the primary and secondary vertices.

✓ It is used for particle identification through the measurement of specific energy loss.

✓ It consists of six layers with three different technologies:

- SPD - Silicon Pixel Detector
- SDD - Silicon Drift Detector
- SSD - Silicon Strip Detector

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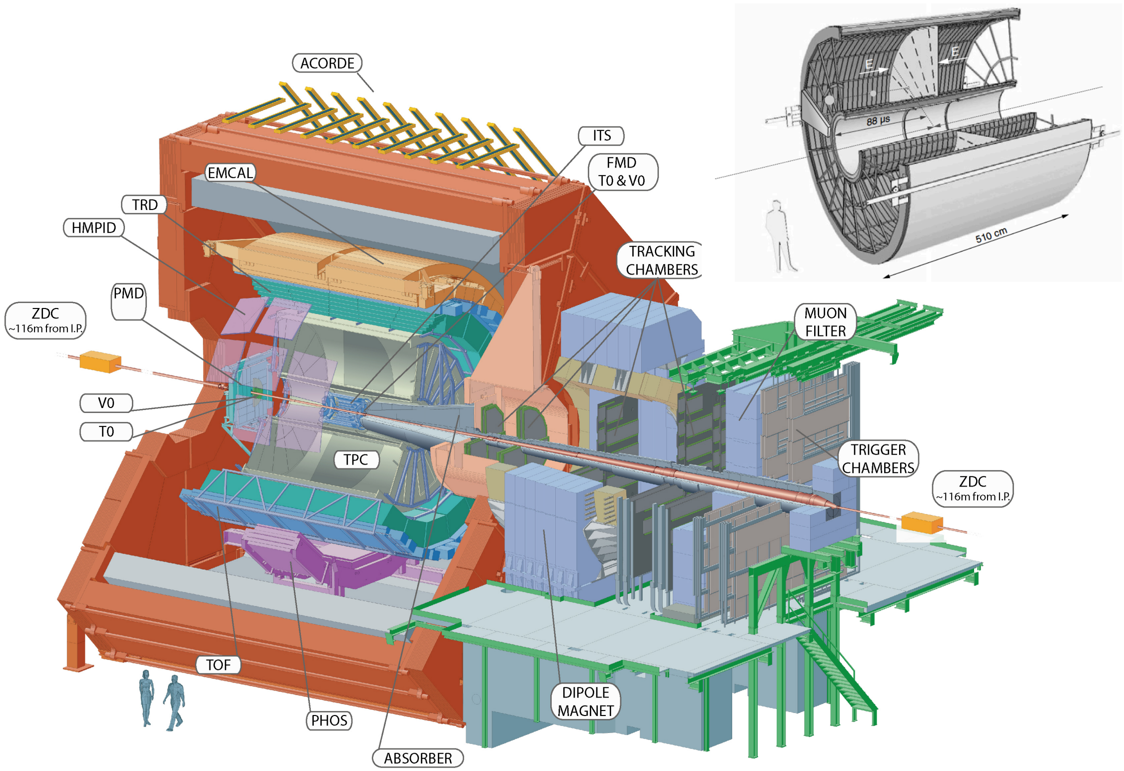

TPC (Time Projection Chamber):

✓ The TPC is a gaseous detector.

✓ It is the main tracking detector of the ALICE.

✓ It is used for particle identification through the measurements of specific energy loss in the gas.

✓ The detector consists of a big cylinder with internal radius of 85 cm and external radius of 250 cm. Its length in the beam direction is 500 cm.

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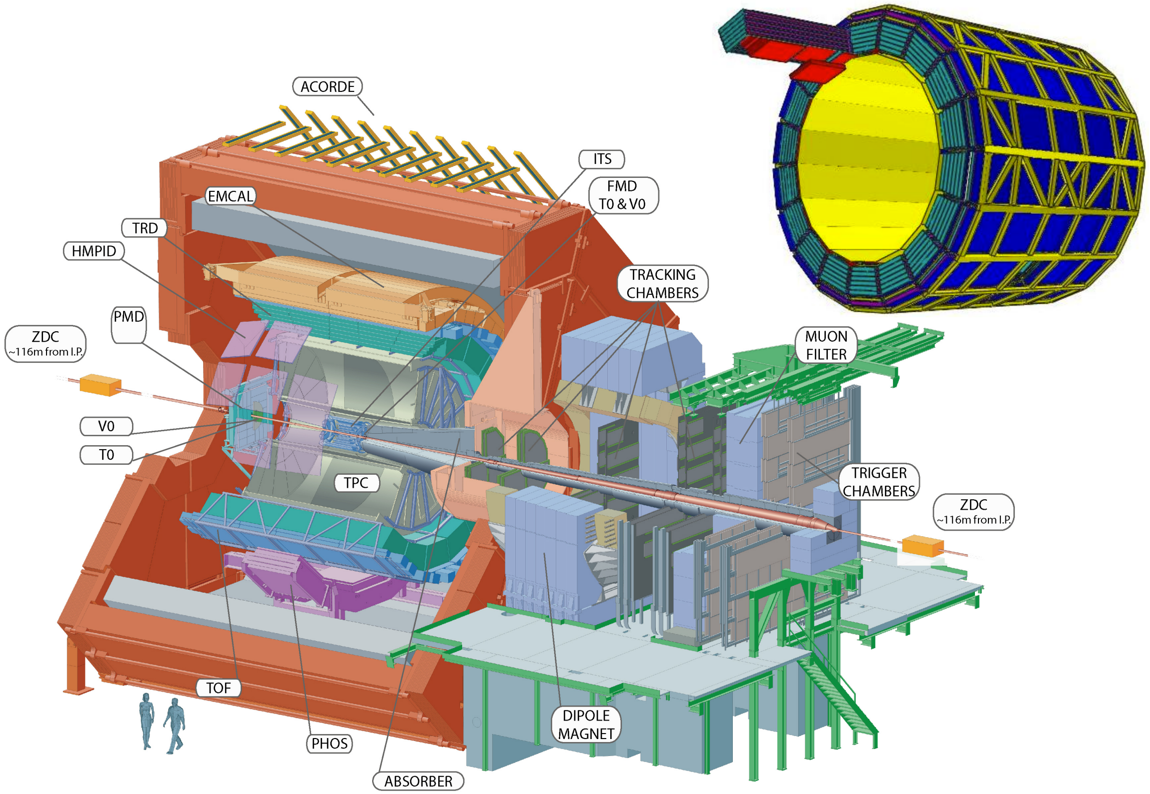

TRD (Transition Radiation Detector):

✓ It consists of a radiator, followed by a drif section and a multi-wire proportional chamber;

✓ The main purpose of the TRD is to provide electron identification;

✓ Specific energy loss in the gas (X_e/ CO_2) is used to separate electrons and hadrons;

✓ It covers 360^o in the azimuthal direction and in pseudo-rapidity the acceptance is $-0.84 \leq \eta \leq 0.84$.

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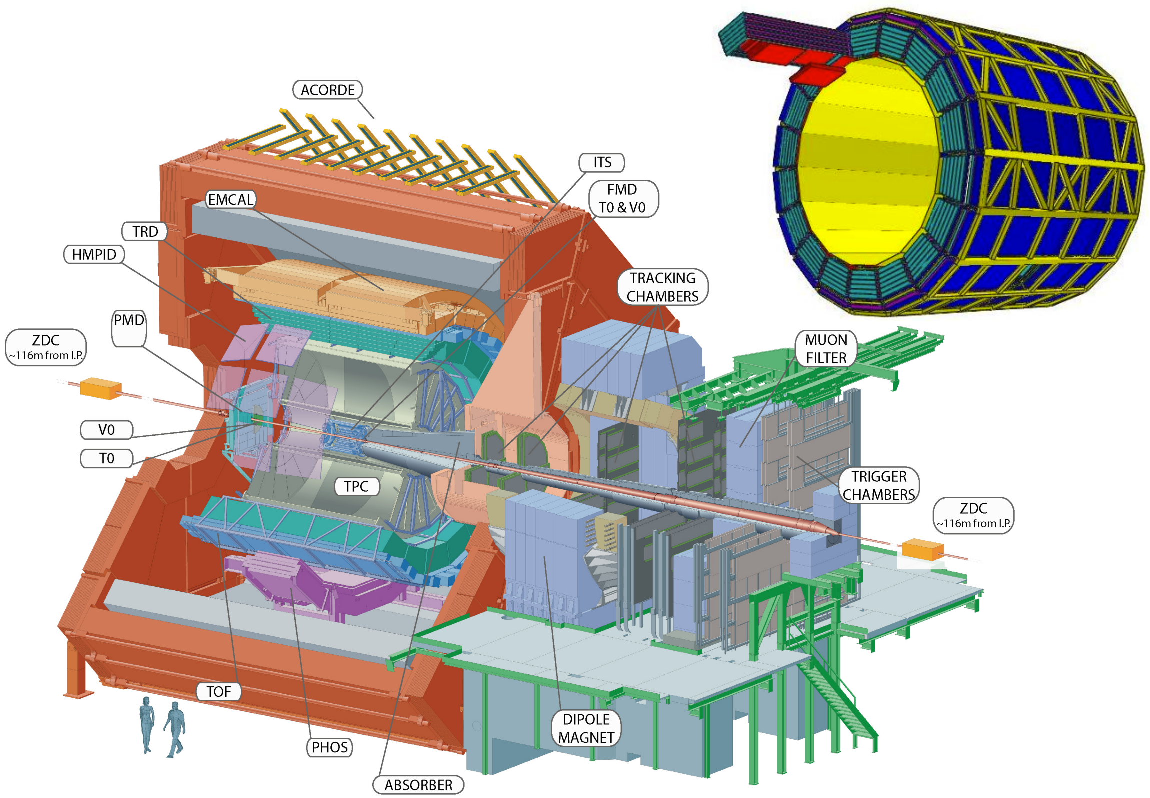

TOF (Time-Of-Flight):

✓ TOF is a detector used to identify particles in the range 0.2 to 2.5 GeV/c.

✓ The particle identification is based on the time-of-flight of the particles.

✓ The detector consists of a Multi-gap Resistive-Plate Chamber (MRPC), filled with gas.

✓ It consists of a large area array in the pseudo-rapidity region of $-0.9 \leq \eta \leq 0.9$. The azimuthal coverage is 360 degrees.

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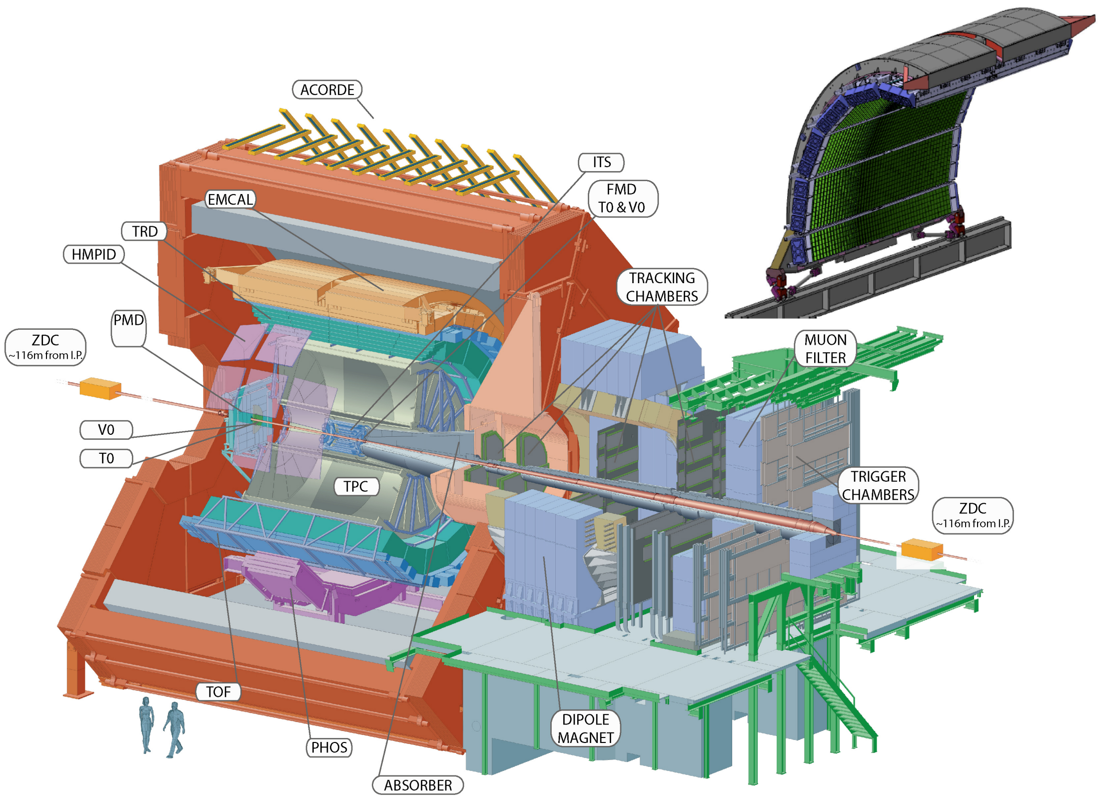

EMCal (ElectroMagnetic Calorimeter):

✓It measures energy of electrons and photons: the signal produced by the particle is proportional to the energy deposited.

✓ It is composed of alternating layers of Pb and scintillator (polystirene).

✓ It covers 107 degrees in the azimuthal direction and in pseudo-rapidity the acceptance is $-0.7 \leq \eta \leq 0.7$.

✓It is used as trigger;

✓Run 2: DCAl with 60 degrees in the azimuthal.

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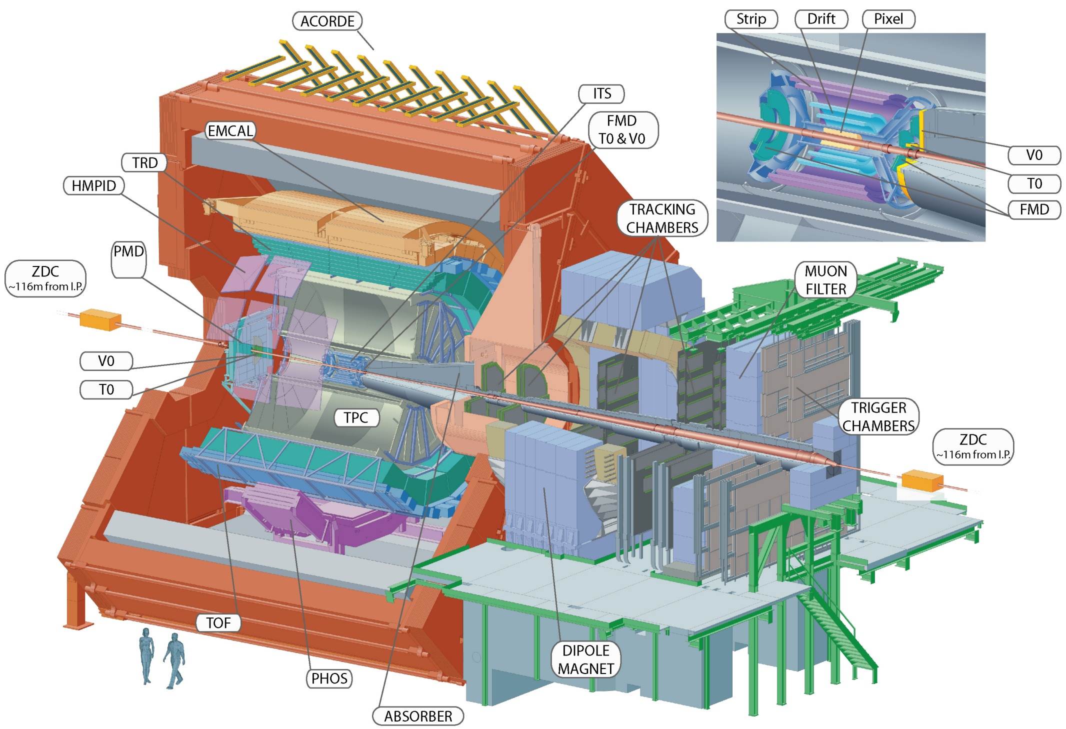

V0:

✓ The V0 is a scintillator detector used as trigger for minimum bias events.

✓ It is also used to measure the centrality of the collisions.

✓ The V0 is composed of two sections: V0A and V0C, located in each side of the interaction point.

✓ The V0A is located 340 cm from the vertex and the V0C is located 90 cm from the vertex.

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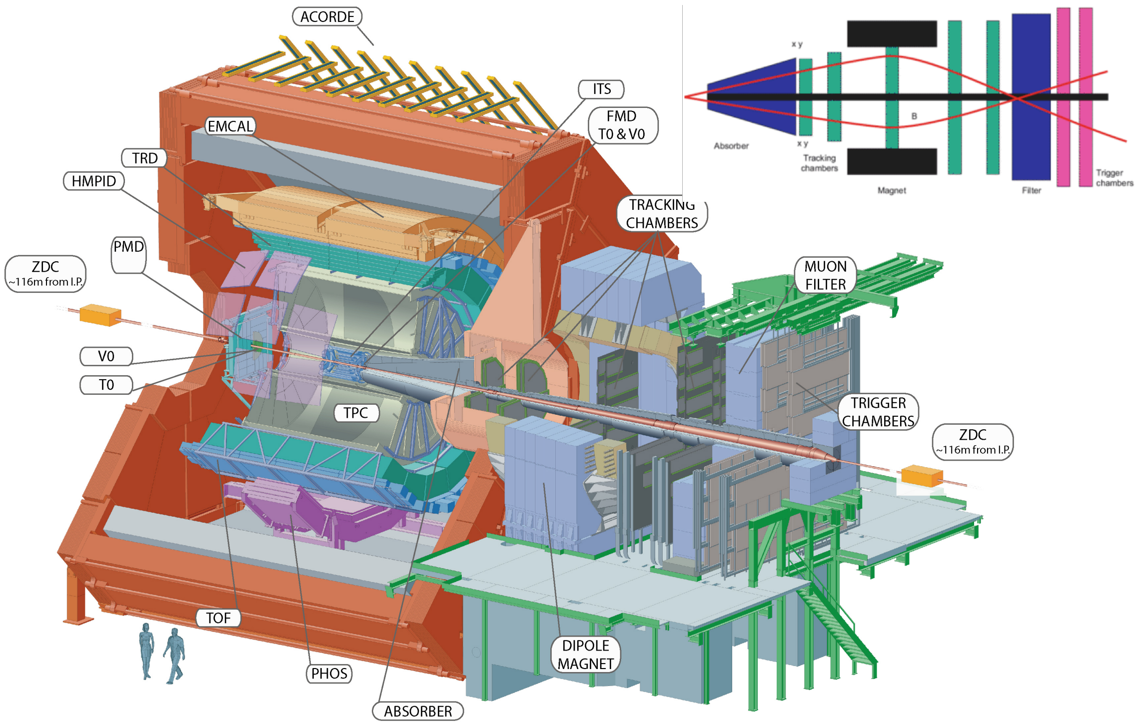
A Large Ion Collider Experiment

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



Muon spectrometer:

✓ Designed to detect muons at forward rapidity $-4.0 \leq \eta \leq -2.5$.

✓ The spectrometer consists of:

- A passive front absorber to absorb hadrons and photons;
- A high-granularity tracking system planes;
- A large dipole magnet;
- A passive muon filter wall;
- Four planes of trigger chambers;

✓ Optimized to study heavy quark resonances.