Open heavy-flavor measurements with ALICE at the LHC

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on behalf of the ALICE Collaboration

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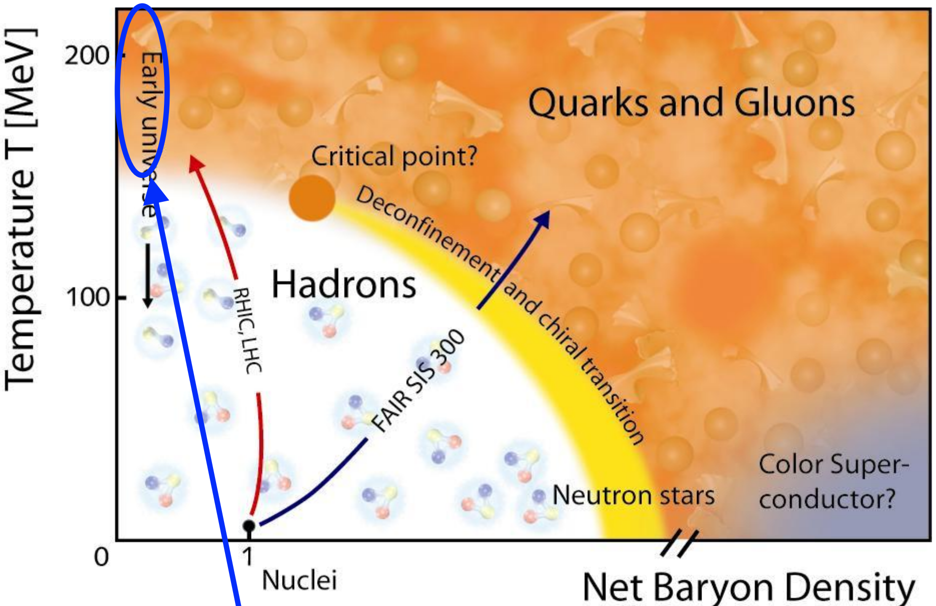
QCD matter

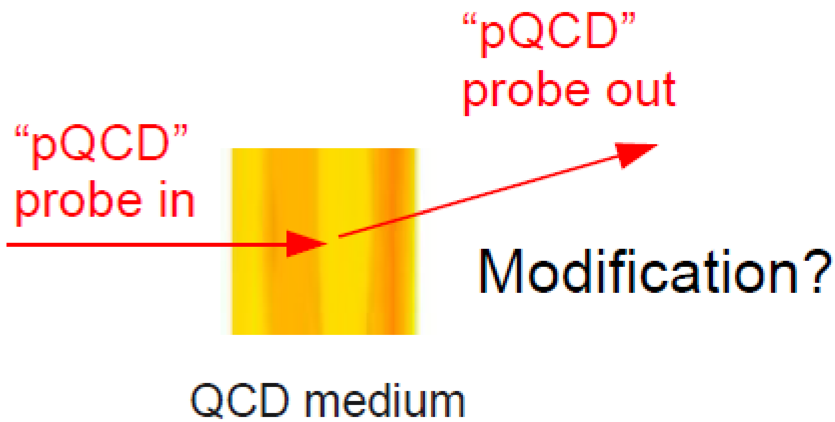


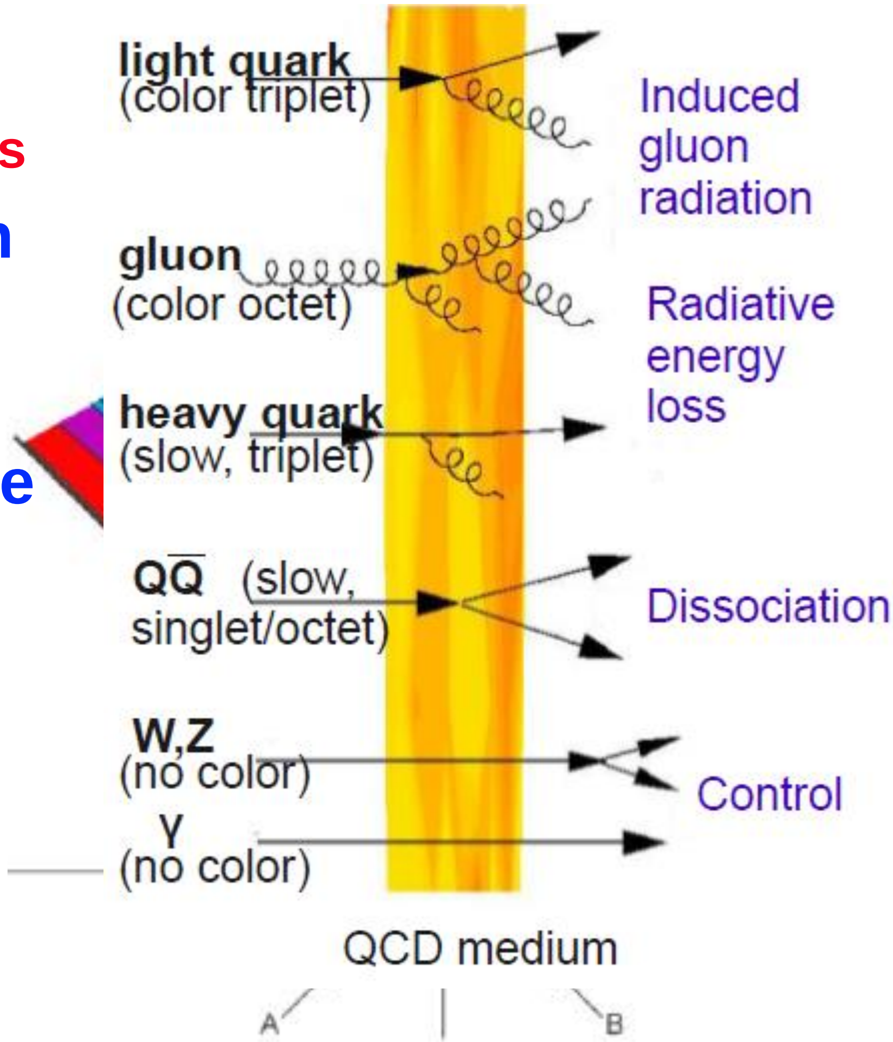
- phase diagram of strongly interacting matter
- deconfined QCD matter at high temperature T and/or baryochemical potential μ_B

- ALICE is the experiment dedicated to the study of the quark-gluon plasma produced with high T and low μ_B in Pb-Pb collisions at the Large Hadron Collider

Tomography of QCD matter

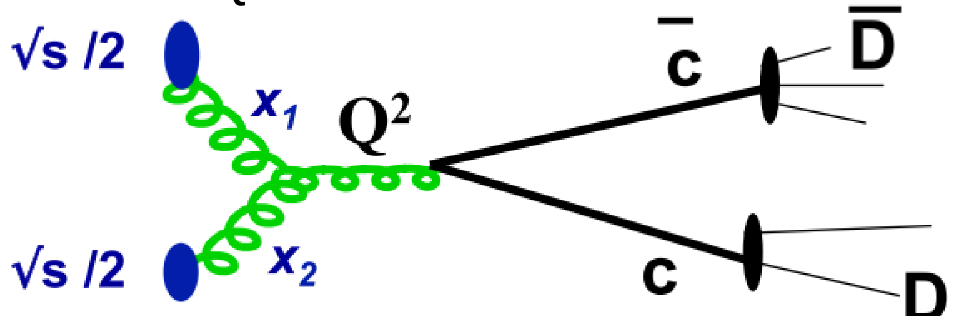
- hard (large Q^2) probes of QCD matter
  - jets, photons, W, Z, heavy quarks
- self generated in the collision at $t \sim 1/Q$ (or $t \sim 1/m$)
- "tomographic" probes of the hottest and densest phase of the collision





Role of heavy quarks

- **heavy quarks:** charm (m_c ~ 1.5 GeV), beauty (m_b ~ 5 GeV)
- $m_{c,b} \gg \Lambda_{QCD}$
  → heavy quarks = genuine hard probes, even at low p_T
  (in contrast to jets)
- large mass → short formation time:
  $\tau^{form} \sim 1/2m \sim 0.1$ fm $\ll \tau_{QGP} \sim 5\text{-}10$ fm



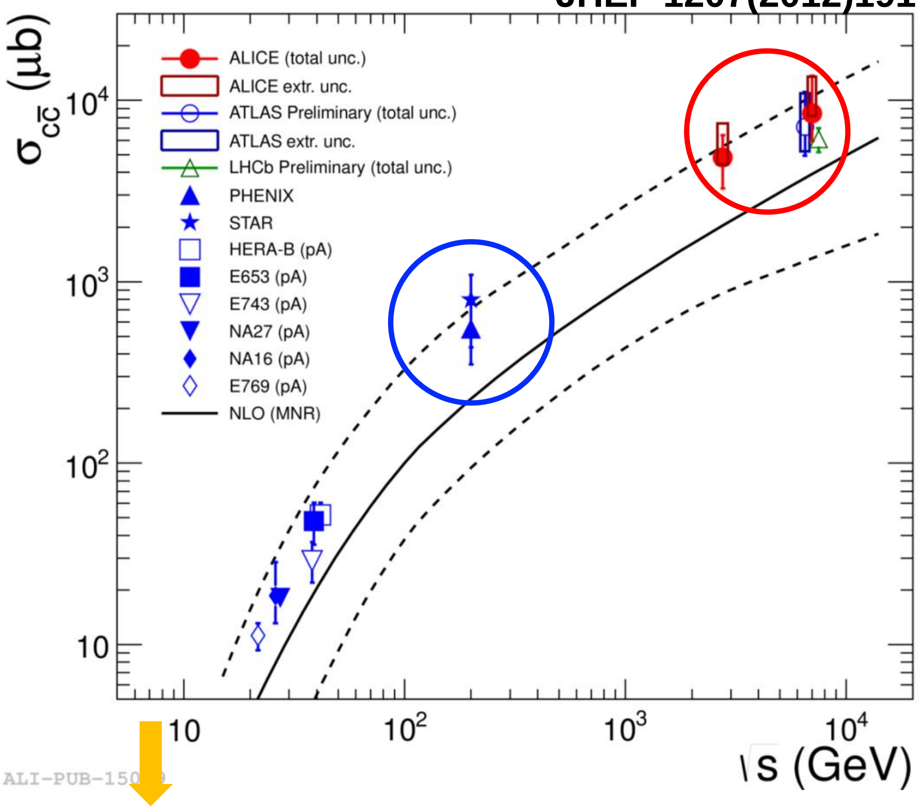
- heavy quarks are unique
  - interactions with produced QCD medium don‘t change the flavor but can modify the phase-space distribution of heavy quarks
  - thermal production rate in the QGP is „small“ (but maybe measurable → T)

  → destruction or creation in the medium is difficult
  → transported through the whole evolution of the system

The LHC: a heavy-quark factory

- charm quark-antiquark production cross section in pp collisions

JHEP 1207(2012)191



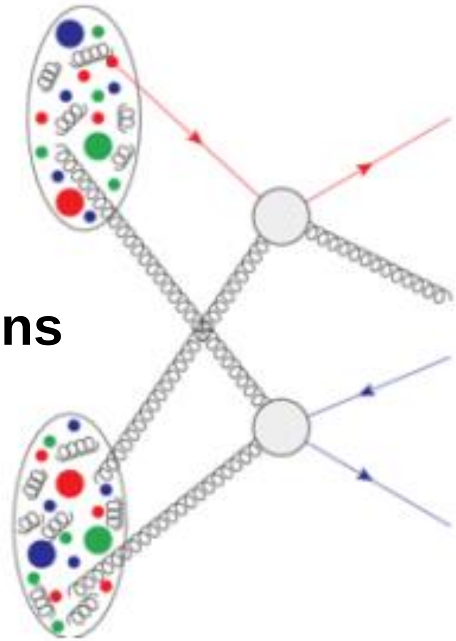
σ_{cc}(FAIR) ~ 10^{-1} μb

- measured charm cross sections compatible with Next-to-Leading-Order (NLO) perturbative QCD (pQCD) calculations
- from RHIC to the LHC
  - σ_{cc}(LHC) ~ 10 x σ_{cc}(RHIC)
  - σ_{bb}(LHC) ~ 50 x σ_{bb}(RHIC)
- central Pb-Pb collisions at the LHC
  - ~100 $c\bar{c}$ pairs
  - ~10 $b\bar{b}$ pairs

→ charm (and beauty) are NOT rare probes at the LHC and at RHIC, but they are at FAIR!

Heavy quarks in pp collisions

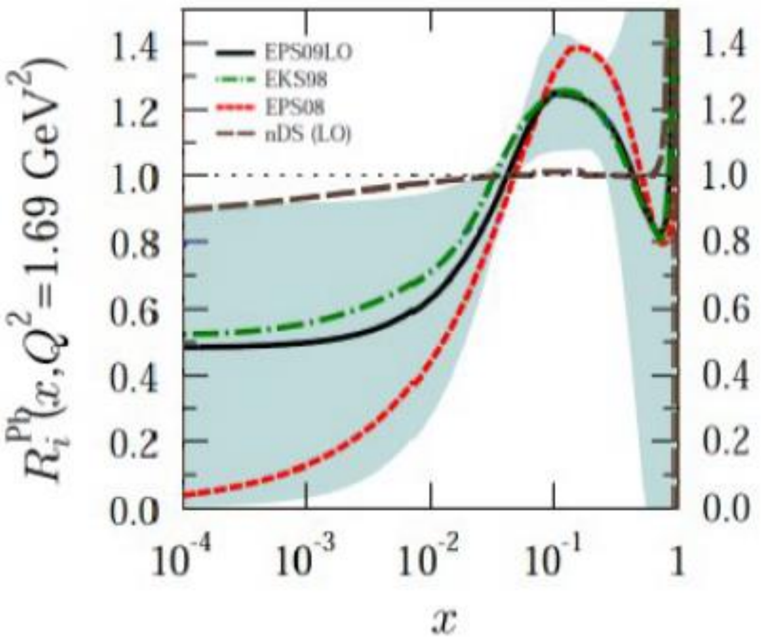
- **test understanding of heavy-quark production**
  - **what are the relevant production mechanisms on the parton level**
    - **LO contributions:**
      gluon fusion, quark-antiquark annihilation
    - **NLO contributions:**
      gluon splitting, flavor excitation
    - **or even more complex,**
      e.g. Multi Parton Interactions (MPI)
  - **testing ground for perturbative QCD calculations**
    - **theoretical uncertainties are driven by**
      - **renormalization and factorization scales**
      - **quark masses**
  - **investigate production mechanisms**
    via more differential measurements
    - **multiplicity dependence of heavy-flavor cross sections**
    - **D meson – hadron correlation measurements**
  - **reference for p-Pb and Pb-Pb collisions**



Heavy quarks in p-Pb collisions

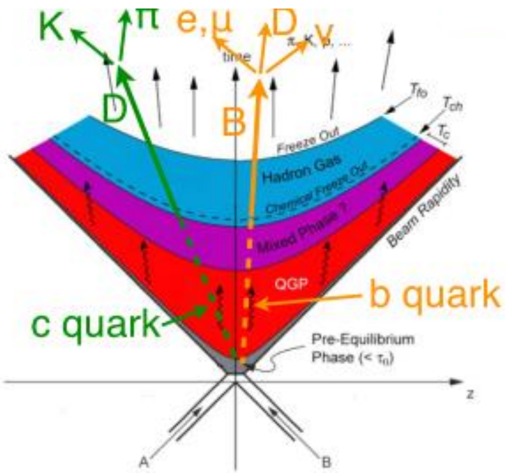
• quantify cold nuclear matter effects

- **nuclear modification of Parton Distribution Functions**
  - shadowing: K.J. Eskola et al., JHEP 0904(2009)65
  - gluon saturation, Color Glass Condensate: H. Fuji & K. Watanabe, NPA 915(2013)1
- **k_T broadening**
- **energy loss in cold nuclear matter: I. Vitev at al., PRC 75(2007)064906**
- **multiple binary collisions: A.M. Glenn et al., PLB 644(2007)119**
- **reference for Pb-Pb collisions**



Heavy quarks in Pb-Pb collisions

- **study the interaction of heavy quarks with the medium**
  - **parton energy loss via radiative and collisional processes**
    - **depends on**
      - **color charge**
      - **quark mass**
      - **path length in the medium**
      - **medium density**



→ **expect:** $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

- **might translate into a hierarchy of nuclear modification factors (see caveats later):**

$R_{AA}{}^{\pi}$, $R_{AA}{}^{D}$, $R_{AA}{}^{B}$

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \times dN_{pp}/dp_T} = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

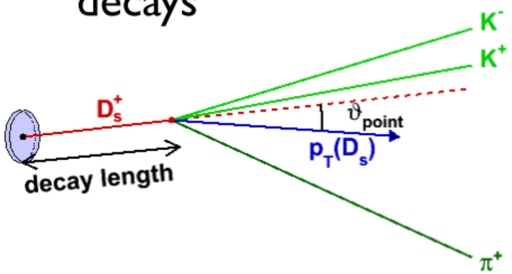
- **collectivity in the QGP**
  - **in general: initial spatial asymmetry → azimuthal asymmetry of particle emission in momentum space**
  - **heavy quarks participate in collectivity of the medium in case of sufficient re-scattering → approach to thermalization**
  - **high p_T: path length dependence of energy loss introduces azimuthal asymmetry as well**

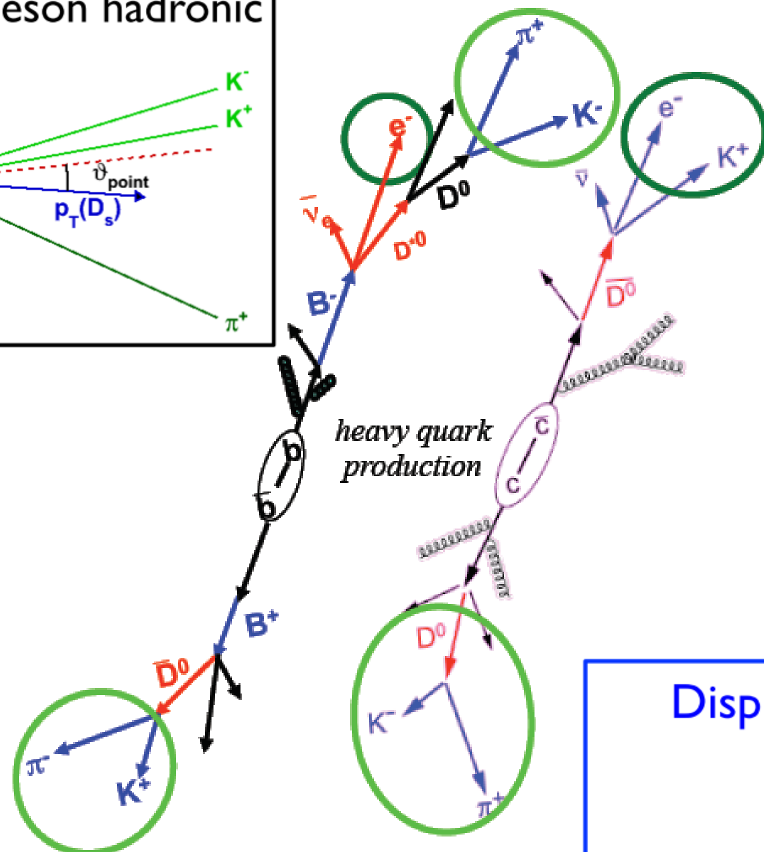
How to measure open heavy flavor?

- **heavy-flavor hadrons decay via weak interaction: lifetimes $c\tau$ ~ few 100 μm → measure decay products**

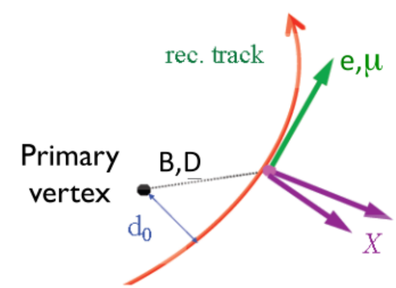
Full reconstruction of D meson hadronic decays

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

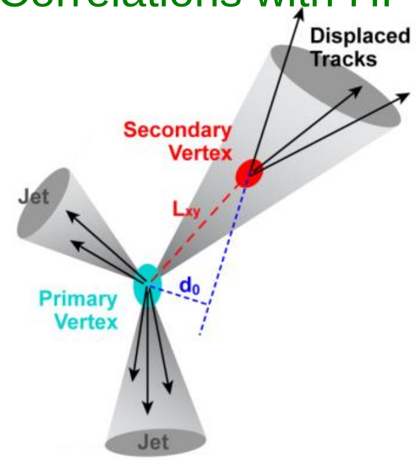




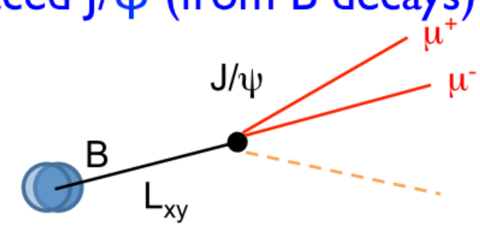
Semi-leptonic decays (c,b)



HF jets
Correlations with HF

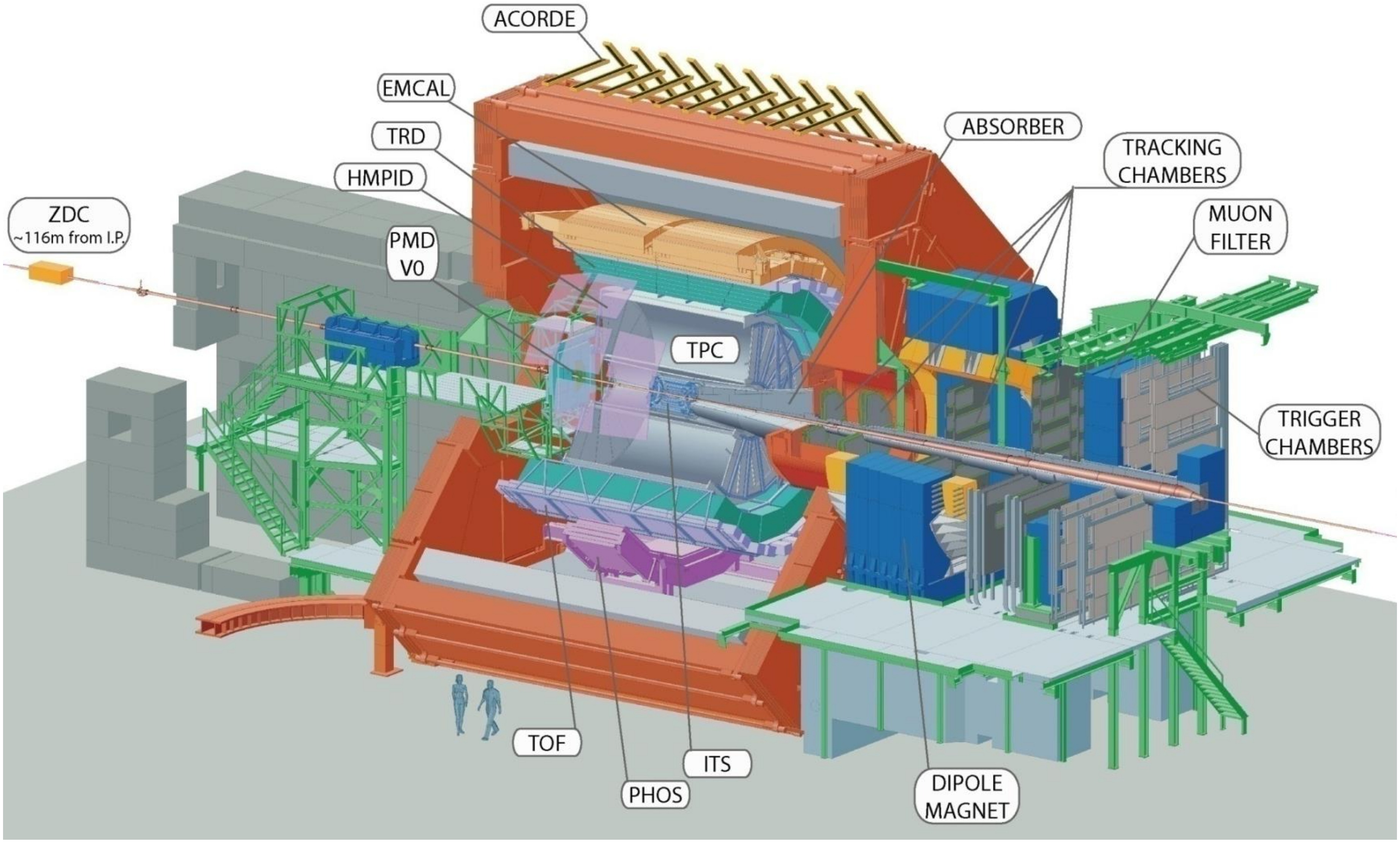


Displaced J/ψ (from B decays)

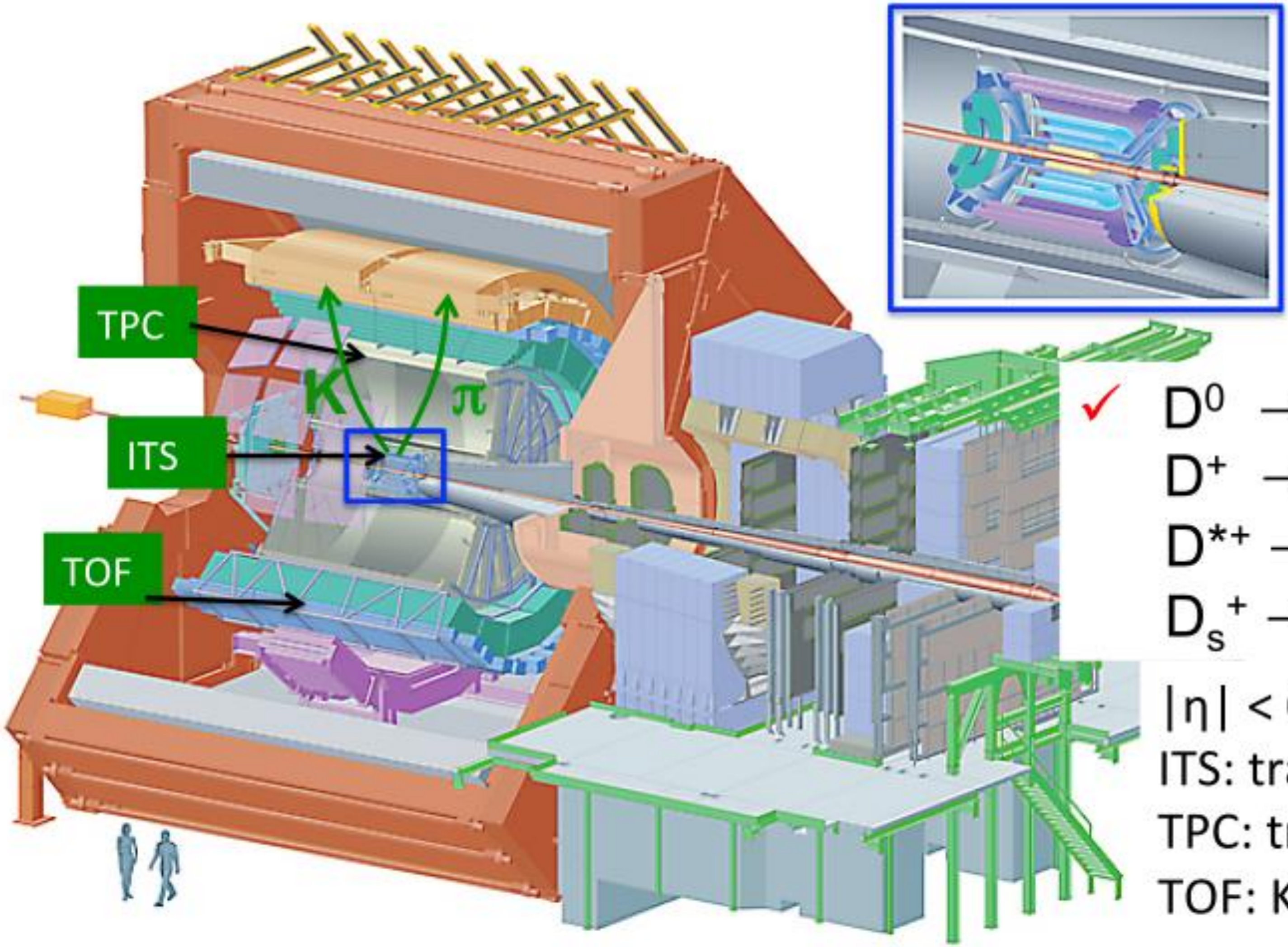


A Large Ion Collider Experiment

ALICE



ALICE: D-meson measurement



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

$|\eta| < 0.9$

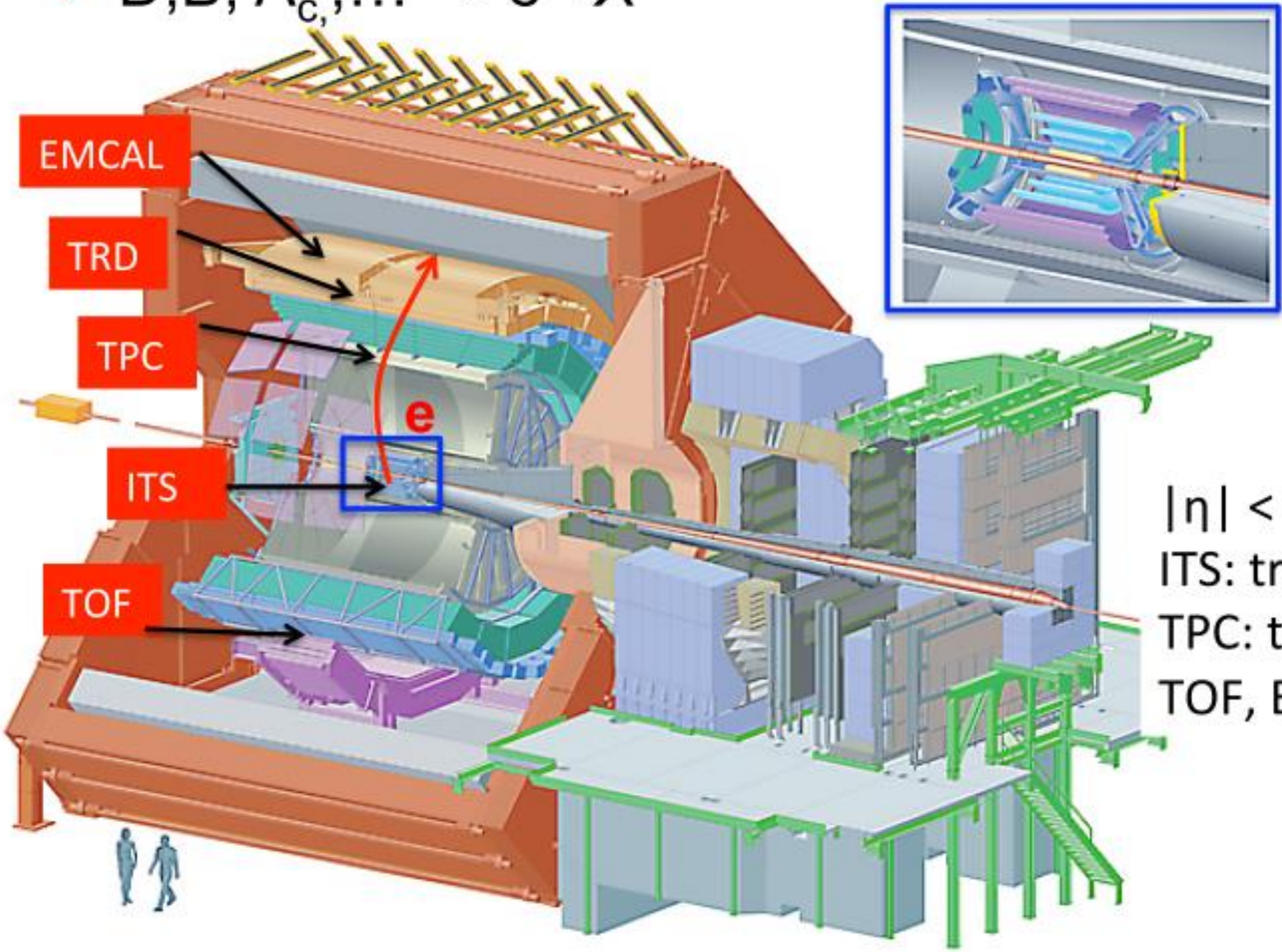
ITS: tracking, vertexing

TPC: tracking, PID

TOF: K-ID

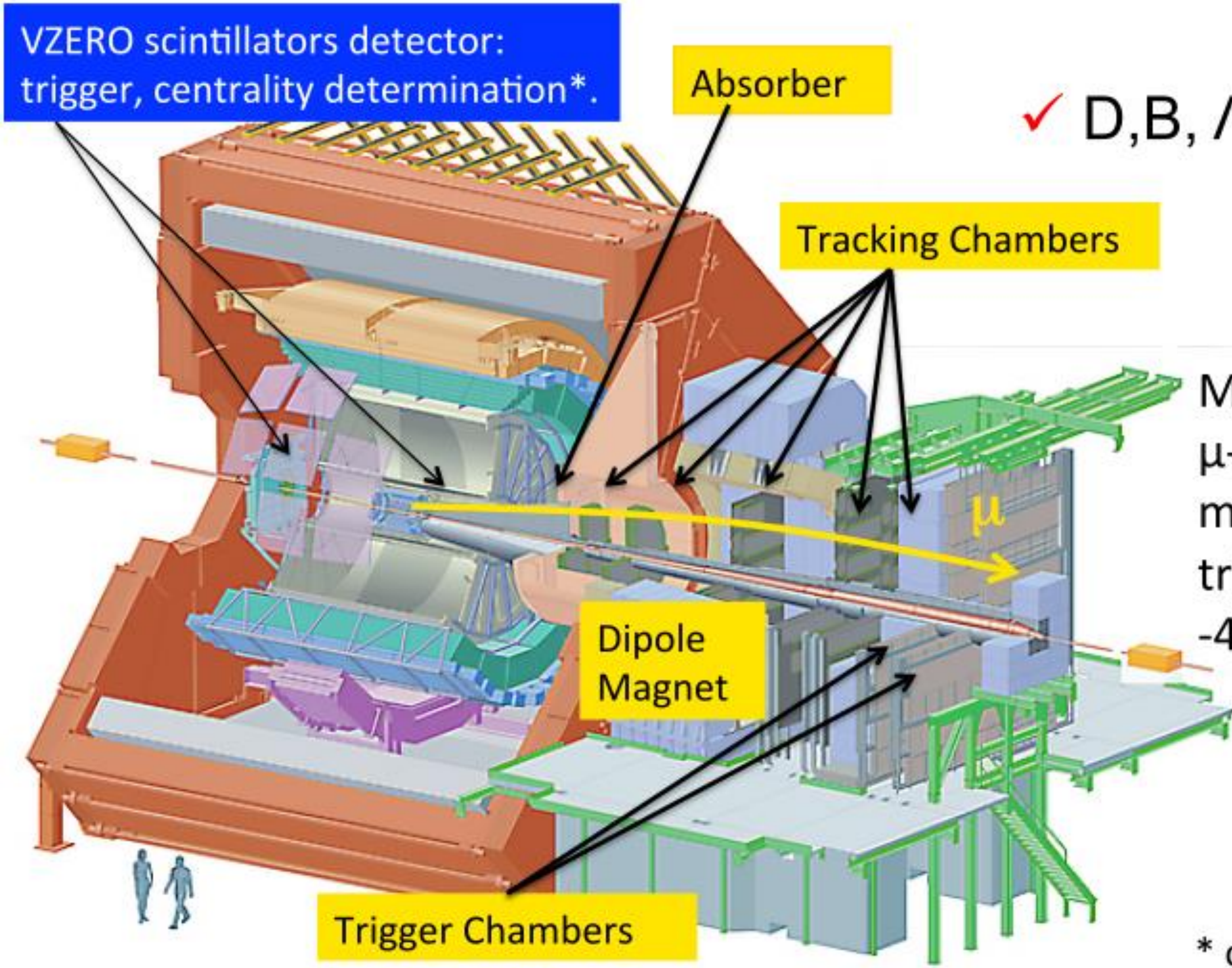
ALICE: electron measurement

✓ D,B, Λ_{c},... → e +X



$|\eta| < 0.9$
ITS: tracking, vertexing
TPC: tracking, PID
TOF, EMCAL, TRD: e-ID

ALICE: muon measurement



✓ D,B, Λ_{c},… → μ+X

Muon spectrometer:
μ-ID via tracks matched with and trigger system
$-4 < \eta < -2.5$

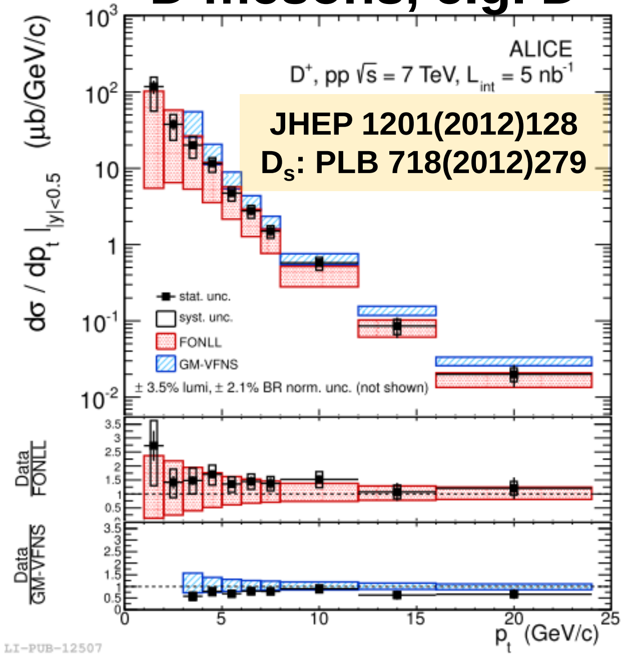
* common for all analyses

The pp reference

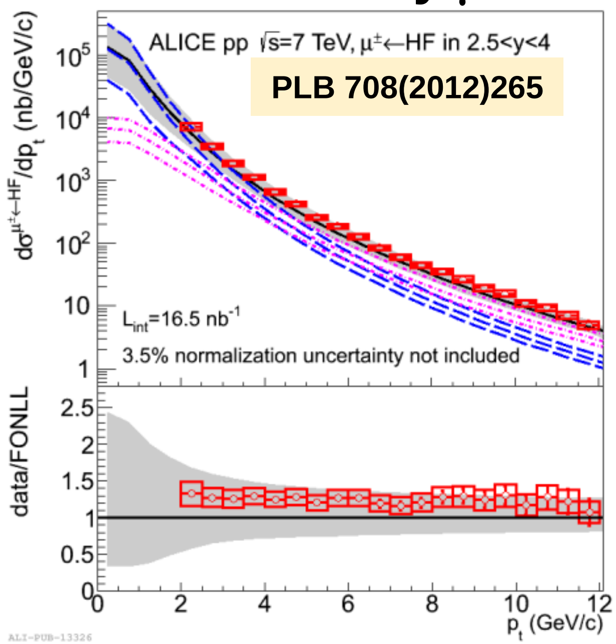
pp collisions at $\sqrt{s}$ = 7 TeV

- p_T-differential cross sections in all channels

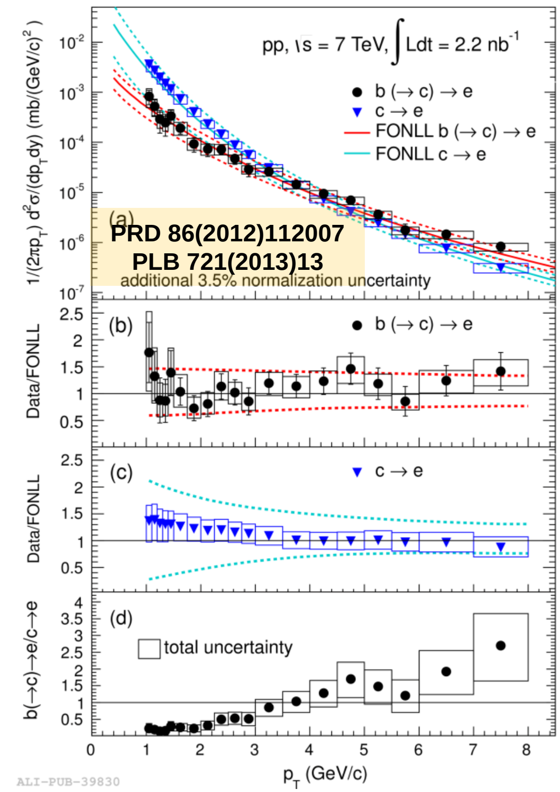
D mesons, e.g. D^+



HF decay $\mu^{\pm}$



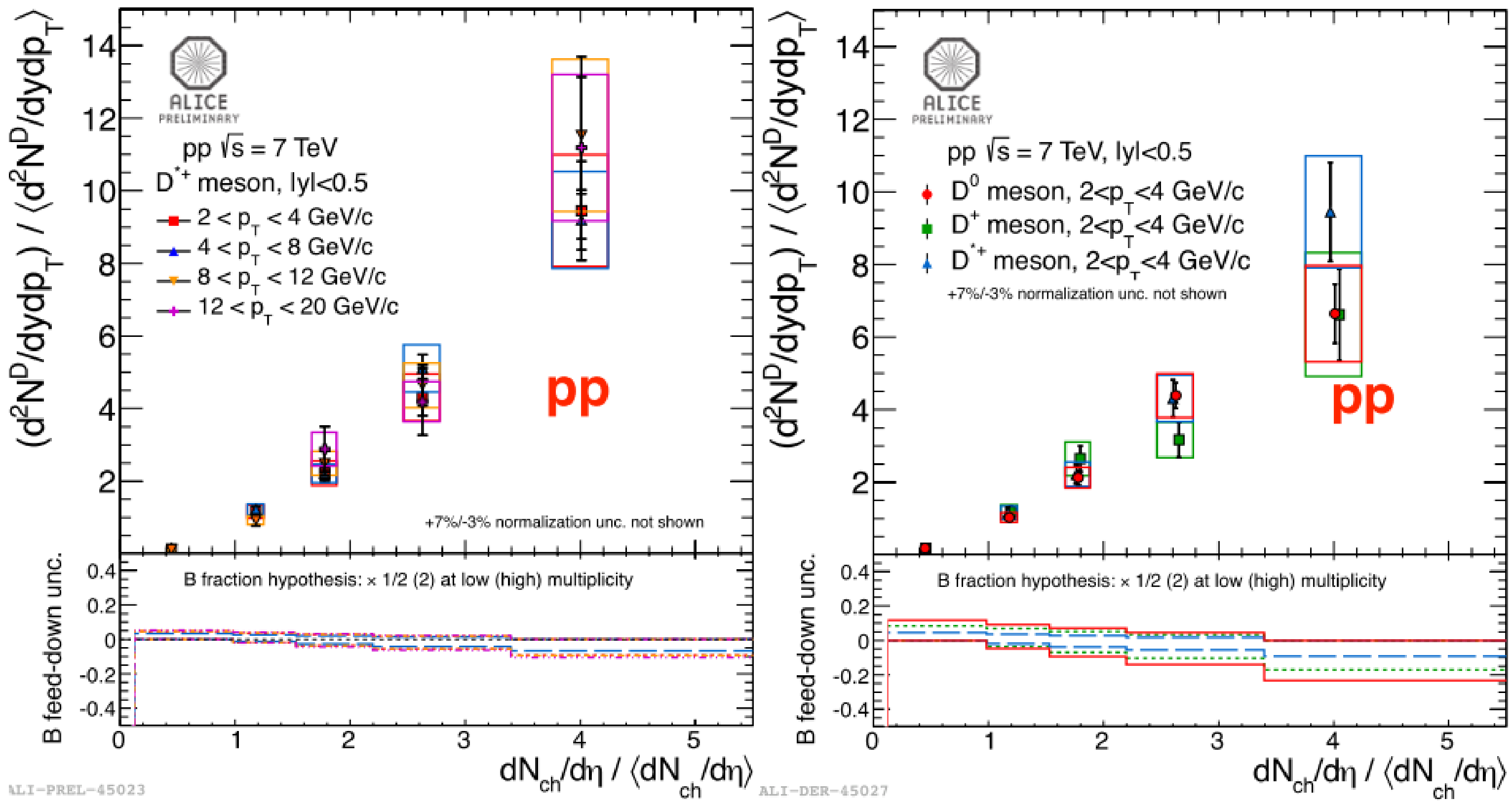
HF decay $e^{\pm}$



- pQCD calculations in reasonable agreement with all cross sections
  - FONLL: JHEP 1210(2012)37
  - GM-VFNS: EPJ C72(2012)2082
  - k_T factorization: arXiv:1301.3033
- similar situation at $\sqrt{s}$ = 2.76 TeV
- extended to higher p_T via measurement of secondary vertex and via e-h correlations

Multiplicity dependence

- self-normalized D-meson yields vs. charged particle multiplicity in pp collisions at $\sqrt{s}$ = 7 TeV

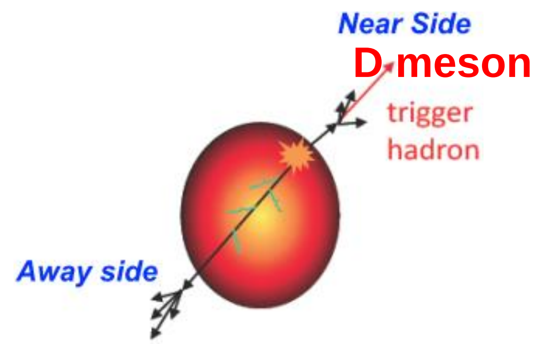


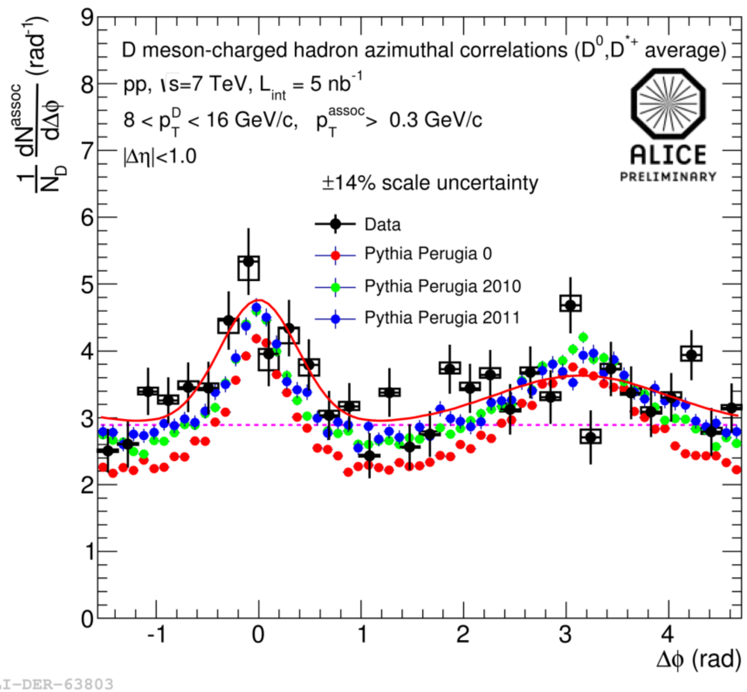
→ **yields of all D-meson species increase with multiplicity without a significant p_T dependence**

- indication for MPI on a hard scale?

D – hadron correlations

- **goals**
  - **study charm production mechanisms (pp, p-Pb)**
  - **study possible modification of charm-jet properties and path-length dependence of energy loss (Pb-Pb)**
- **approach**
  - **measurement of the associated hadron yields on the near and away sides in azimuth and pseudorapidity**





$$\frac{1}{N_{trig}}\frac{d^2 N_{assoc}}{d\Delta\varphi\Delta\eta} = \frac{S(\Delta\varphi,\Delta\eta)}{B(\Delta\varphi,\Delta\eta)}$$

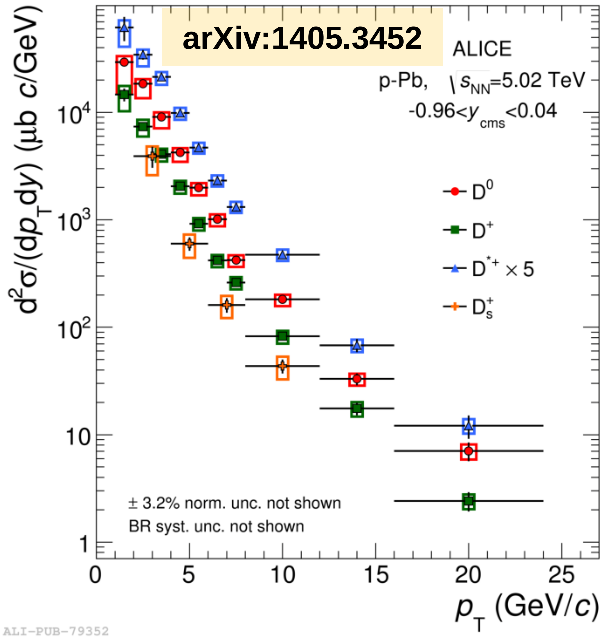
- **PYTHIA calculations agree with correlation measurement within large statistical and systematic uncertainties**
- **precision measurement expected from Run-II at the LHC**

Cold nuclear matter effects in p-Pb collisions

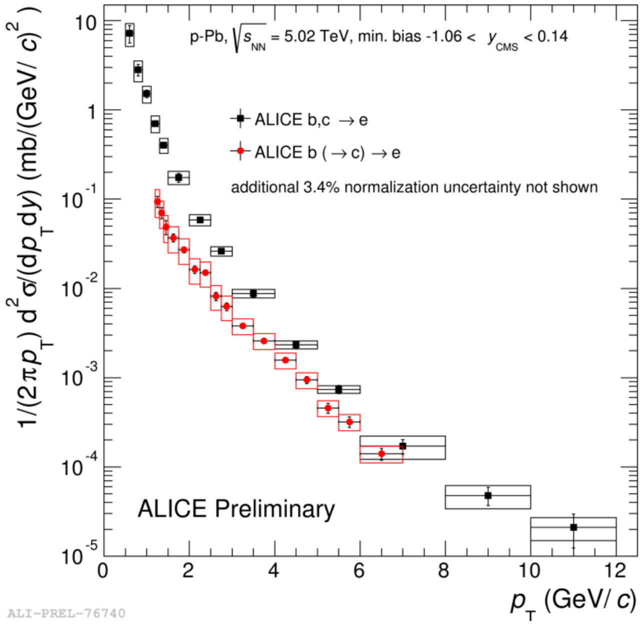
p_T-differential cross sections

ALICE

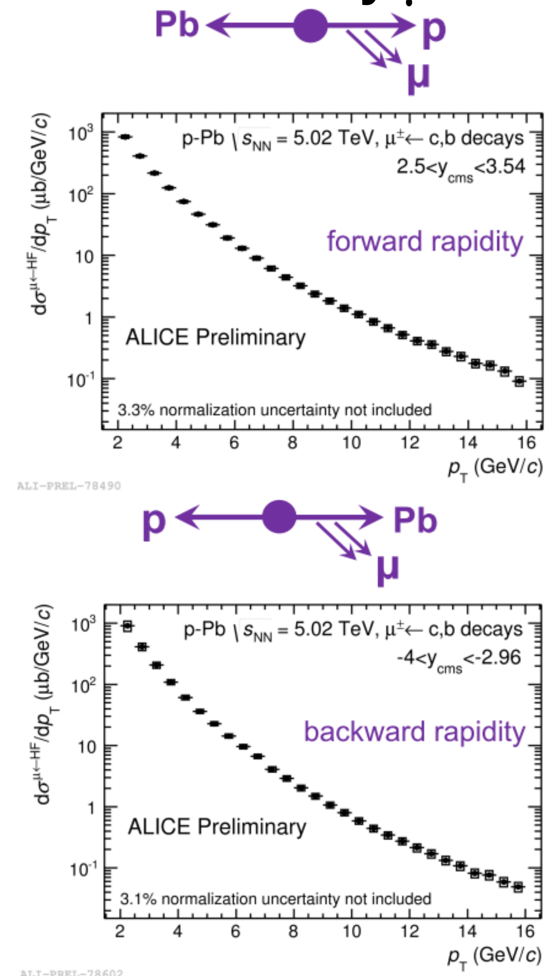
D mesons



HF decay e±



HF decay μ±

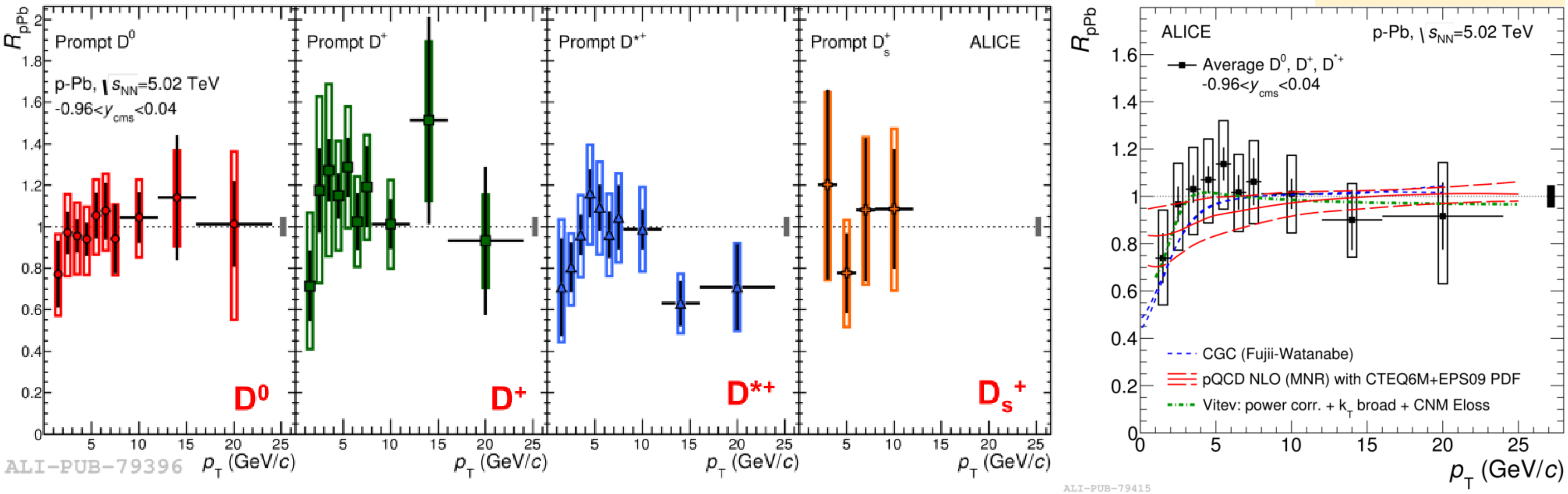


- **heavy-flavor production in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV: all channels are measured!**

D mesons: p_T-differential R_{pPb}

$$R_{pA} = \frac{1}{<T_{pA}>} \frac{dN_{pA}/dp_T}{d\sigma_{pp}/dp_T} = \frac{1}{A} \frac{d\sigma_{pA}/dp_T}{d\sigma_{pp}/dp_T}$$

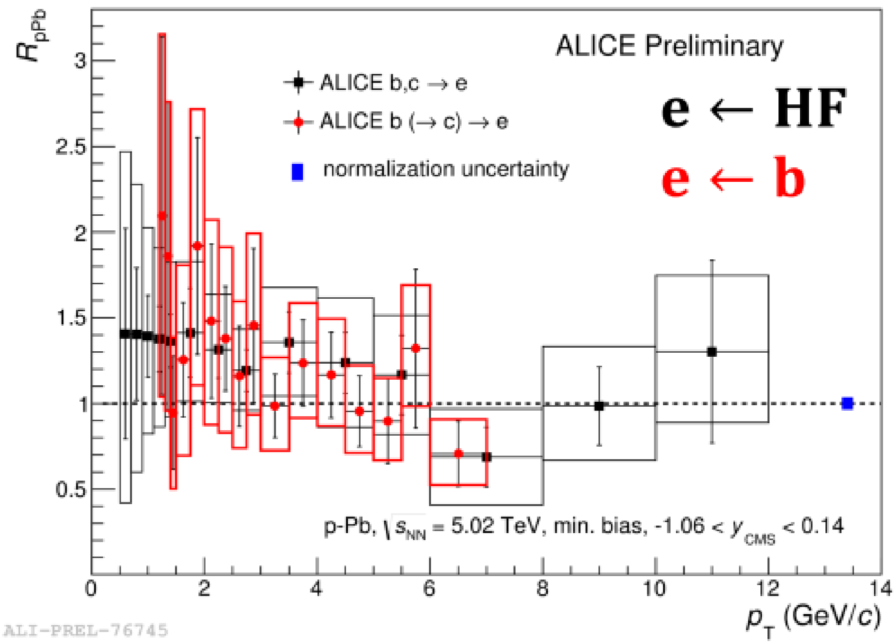
arXiv:1405.3452

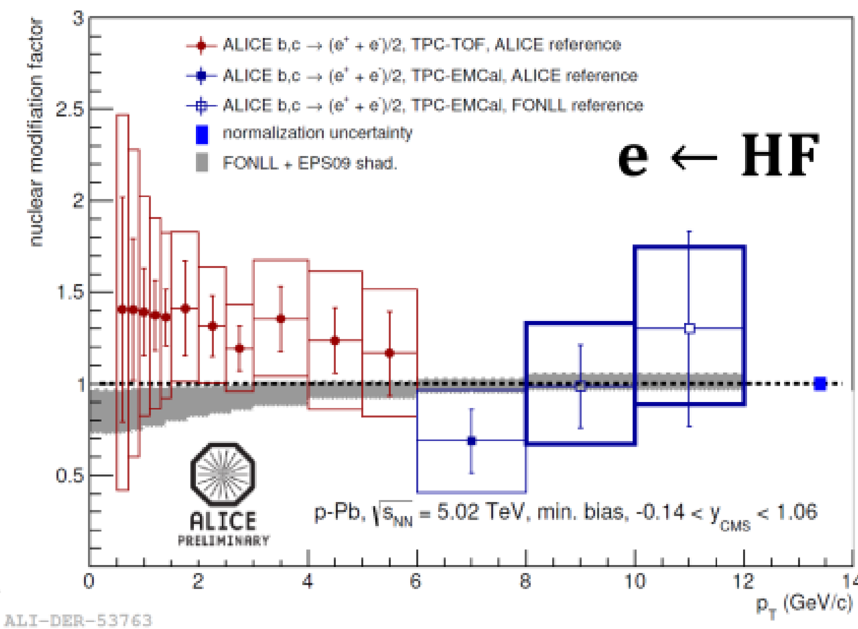


- R_{pPb} consistent with unity for all D-meson species
- D-meson R_{pPb} can be described by
  - Color Glass Condensate (CGC) calculations (arXiv:1308.1258)
  - MNR pQCD calculations (NPB 373(1992)295) with EPS09 nuclear PDF (JHEP 04(2009)065)
  - model inclusdng energy loss in cold nuclear matter, nucler shadowing, and k_T broadening (PRC 75(2007)064906)

→ cold nuclear matter effects are small!

Electrons from heavy-flavor decays

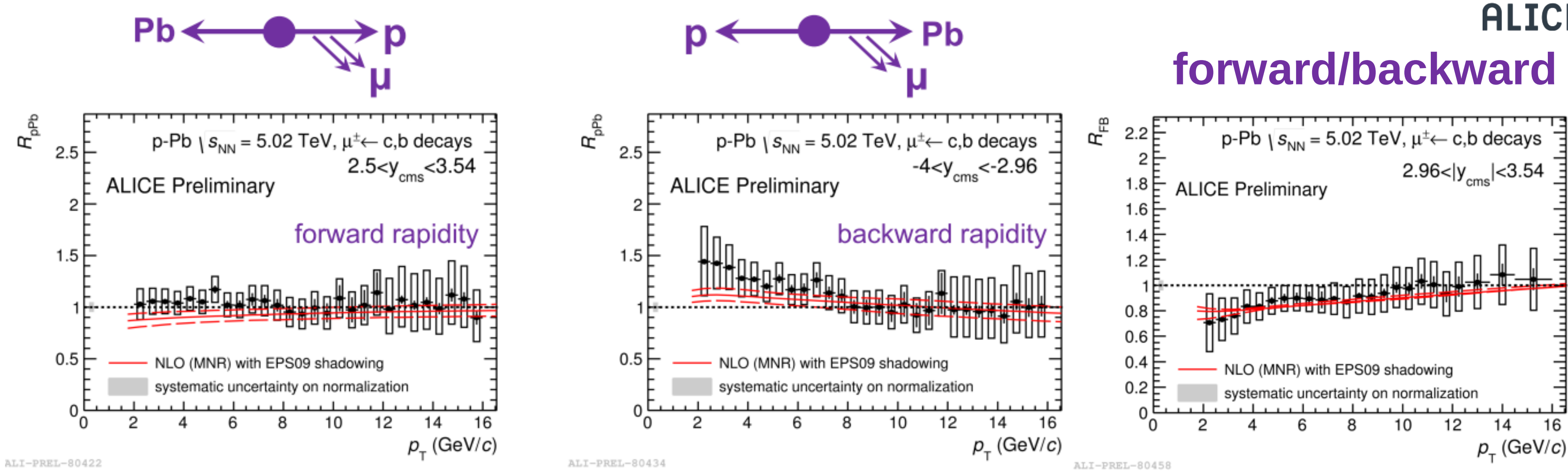




- R_{pPb} consistent with unity for electron from **heavy-flavor hadron** decays and from beauty-hadron decays
- electron R_{pPb} can be described by
  - FONLL pQCD calculations (JHEP 006(2001)0103) with EPS09 nuclear PDF (JHEP 04(2009)065)

→ cold nuclear matter effects are small!

Muons from heavy-flavor decays



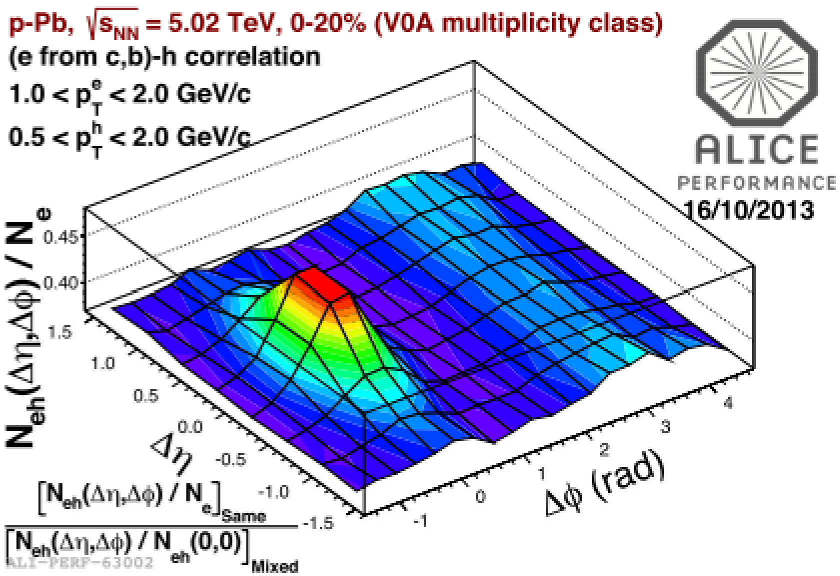
- muon R_{pPb} consistent with unity at forward rapidity (p going direction)
- muon R_{pPb} slightly larger than unity in the range $2 < p_T < 4$ GeV/c at backward rapidity (Pb going direction)
- muon R_{pPb} and forward/backward ratio R_{FB} can be described by
  - MNR pQCD calculations (NPB 373(1992)295) with EPS09 nuclear PDF (JHEP 04(2009)065)

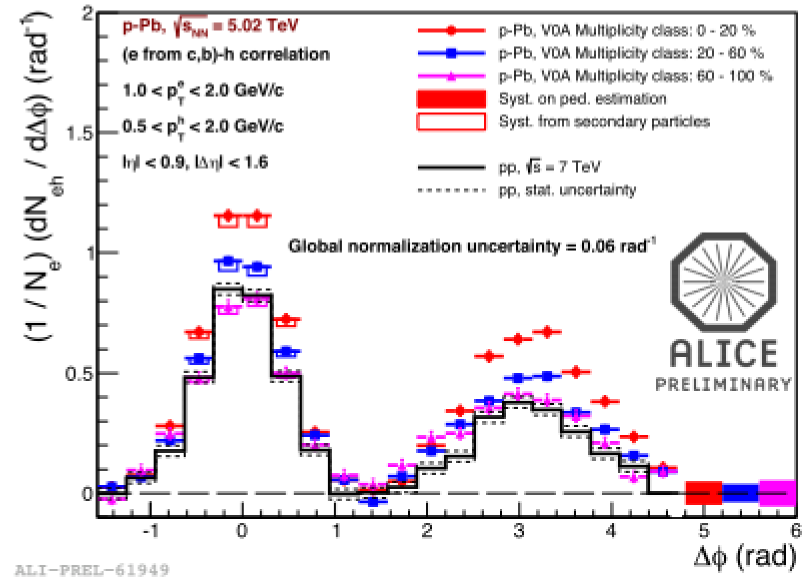
→ cold nuclear matter effects are small!

HF e-h correlations in p-Pb collisions

ALICE

- **study of the correlation function between**
  - **trigger particles (electrons from heavy-flavor hadron decays)**
  - **associated particles (charged hadrons)**
- **analysis performed in 3 p-Pb multiplicity classes**

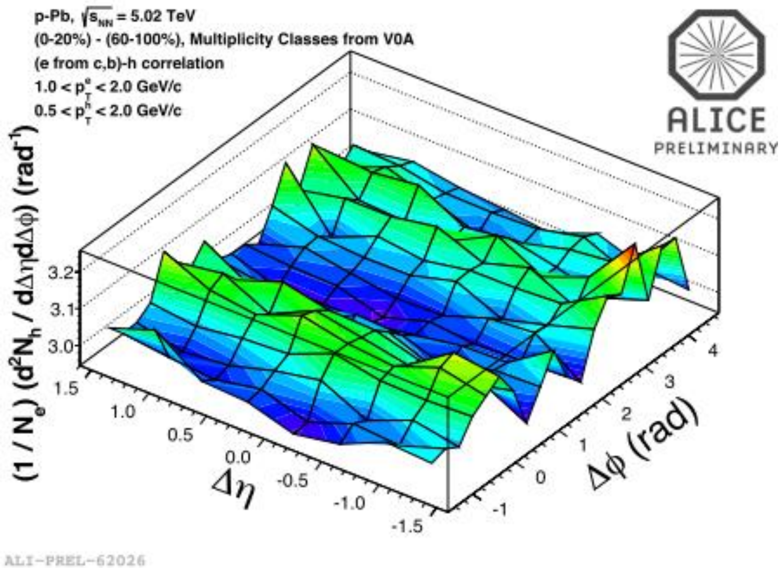


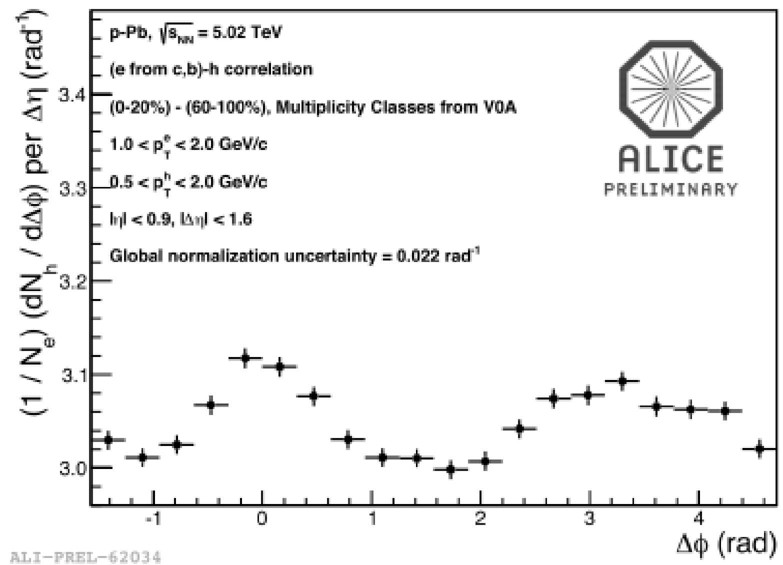


- **low-p_T trigger particle: enhancement of the associated yields in the near- and away side peaks for the highest multiplicity collisions (no enhancement observed for intermediate-p_T trigger particles)**

HF e-h correlations in p-Pb collisions

- **difference of correlation functions in high- and low-multiplicity p-Pb collisions to remove correlations due to jets**





- **double-ridge structure emerges**
- **also observed in hadron-hadron correlations in the light-quark sector**
- **description possible with models based on**
  - **CGC → related to initial conditions?**
  - **hydrodynamics → indication for collectivity in p-Pb collisions?**

Hot QCD matter effects in Pb-Pb collisions

Nuclear modification factor R_{AA}

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

R_{AA} = 1: binary scaling
R_{AA} ≠ 1: medium effect

- in-medium energy loss leads to $R_{AA} < 1$
- QCD-based models with in-medium radiative or collisional energy loss (Dokshitzer, Kharzeev, PLB 519(2001)199; Armesto et al., PRD 69(2004)114003; Djordjevic et al., NPA 783(2007)493)

→ ΔE(g) > ΔE(u,d,s) > ΔE(c) > ΔE(b)

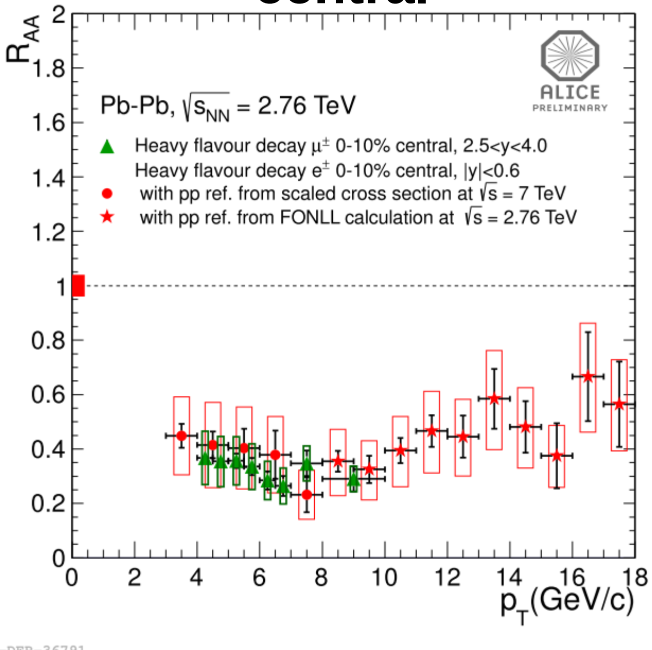
→ R_{AA}(light hadrons) < R_{AA}(c) < R_{AA}(b), but with caveats:

- different shapes of the p_T distributions in pp collisions
- different fragmentation functions
- role of soft particle production at low p_T

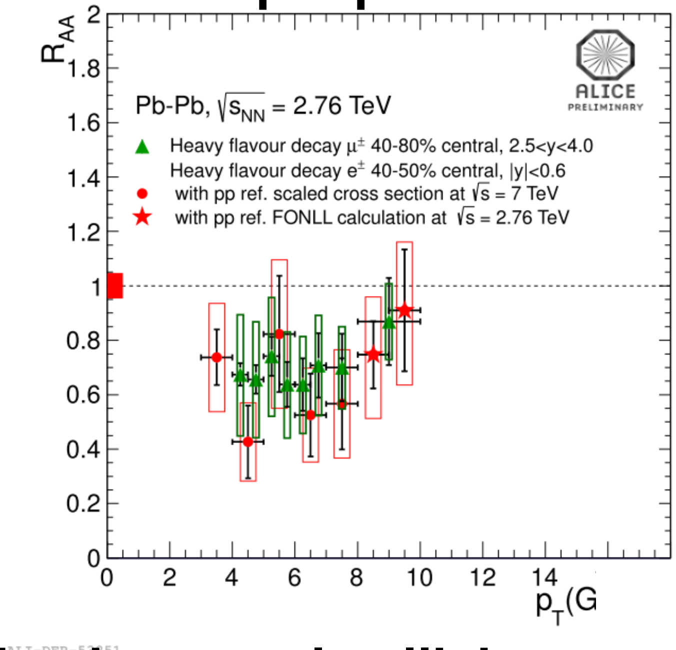
R_{AA}: leptons from HF decays

- R_{AA} in central and peripheral Pb-Pb collisions
  - electrons at mid-rapidity
  - muons at forward rapidity

central



peripheral



→ indication for larger suppression in central collisions

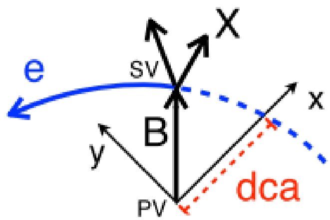
→ R_{AA} for electrons and muons comparable

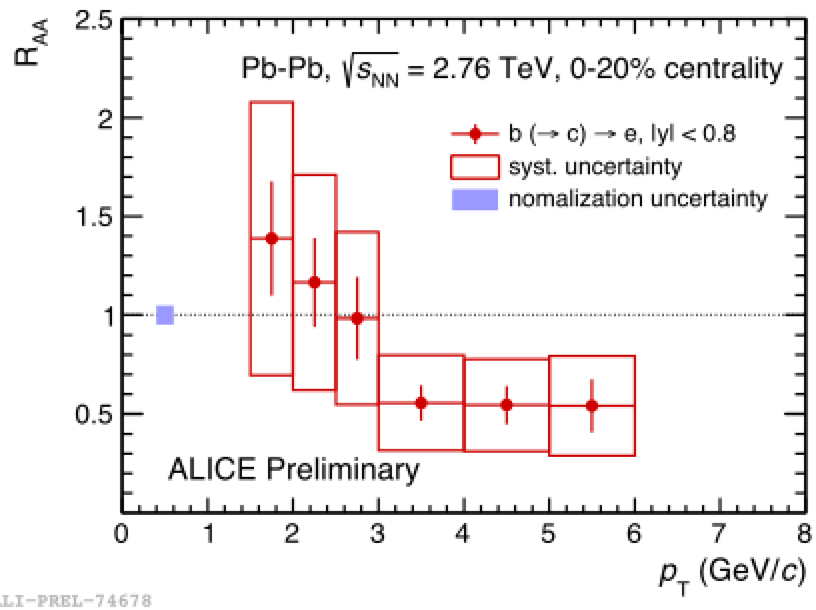
- R_{pPb} ~ 1

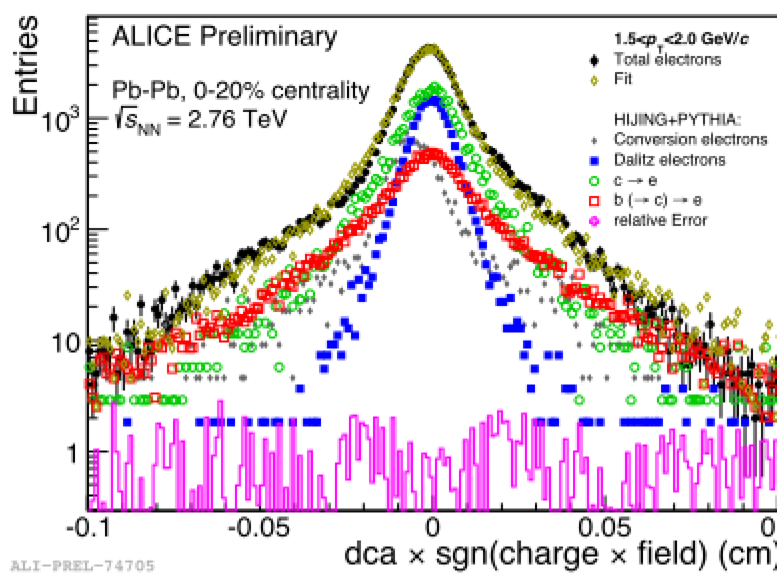
→ suppression in Pb-Pb due to hot medium effects!

R_{AA}: electrons from beauty decays

- **R_{AA} of electrons from beauty decays in 0-20% central Pb-Pb collisions**
  - **analysis based on the measured electron impact parameter distribution**
  - **first measurement indicates R_{AA} < 1 for p_T > 3 GeV/c**

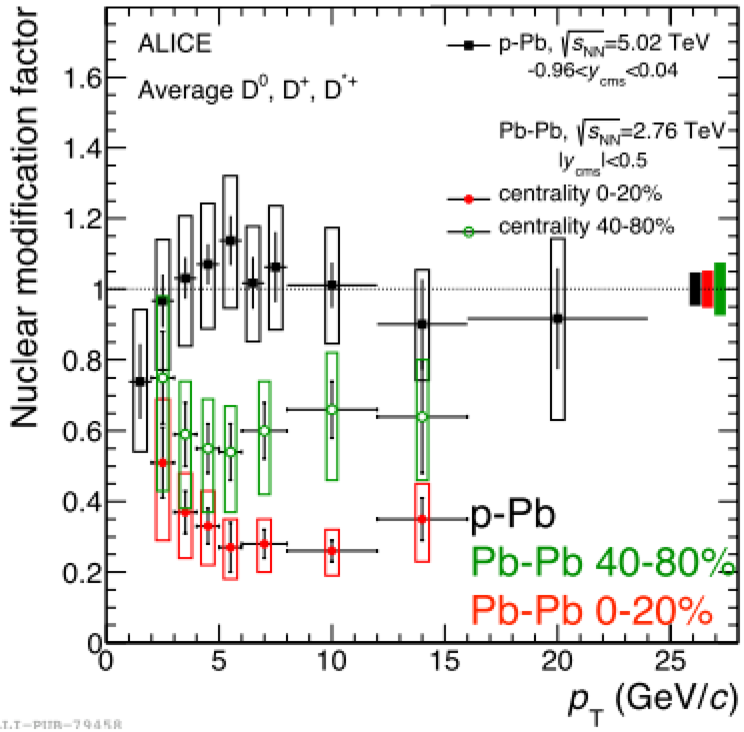


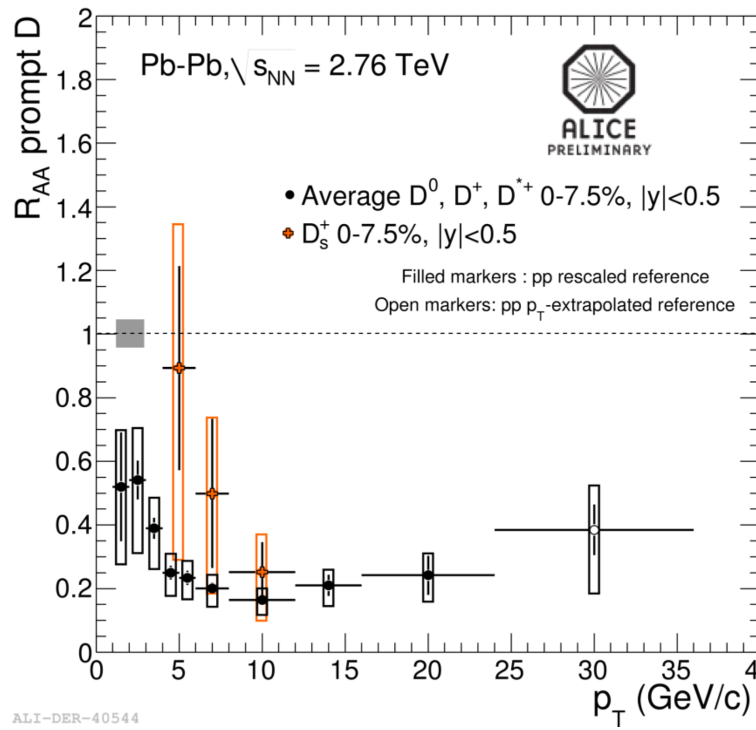




- **R_{pPb} ~ 1**
  → suppression in Pb-Pb due to hot medium effects!

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



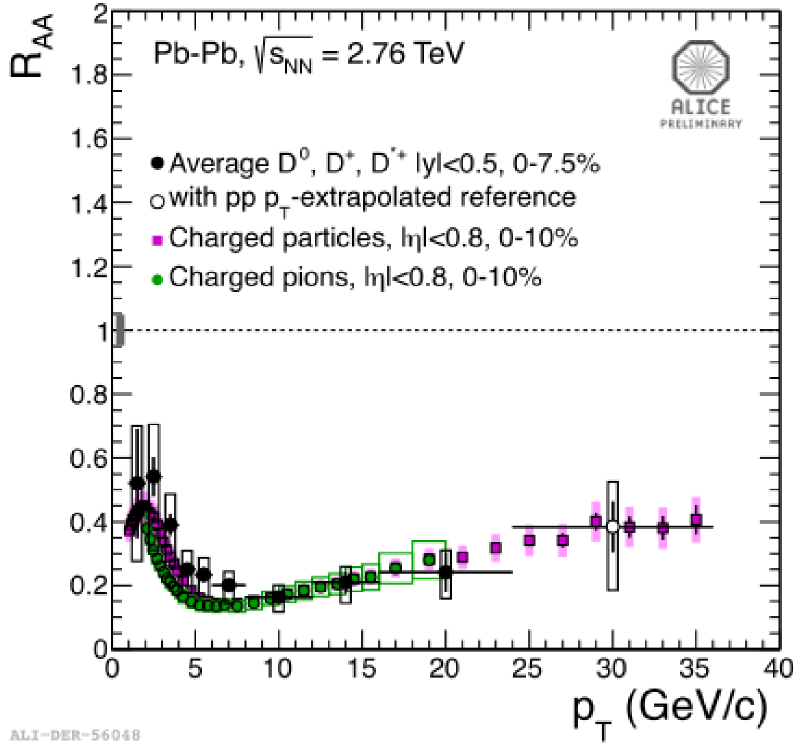


- observed suppression in central Pb-Pb collisions is due to the strong interaction of charm quarks with the hot partonic medium

- D_s^+ is suppressed as other D mesons for $8<p_T<12$ GeV/c
  - more statistics needed at low p_T where enhancement of D_s^+/D due to recombination is predicted:

Kuznetsova, Rafelski EPJ C 51 (2007) 113
He et al. PRL 110 (2013) 112301
Andronic et al. PLB 659 (2008) 149

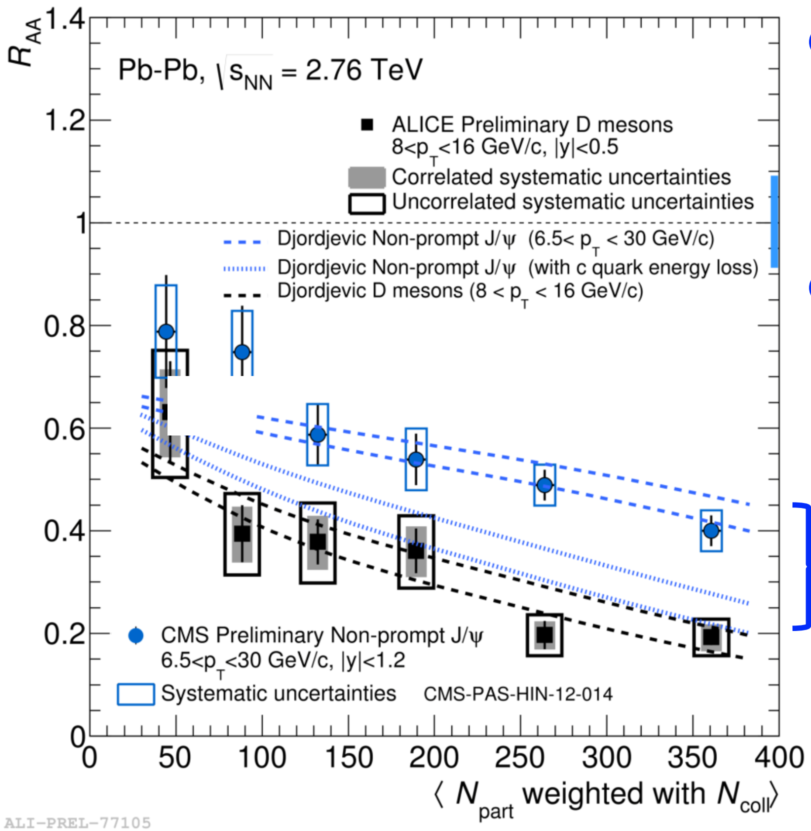
Comparison with pion R_{AA}



- D-meson and pion R_{AA} as a function of p_T are compatible with each other in agreement with models considering
  - energy loss hierarchy: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
  - different shapes of the p_T distributions
  - different fragmentation functions

Djordjevic, arXiv:1307.4098
Wicks, Horowitz, Djordjevic Nucl. Phys. A 872 (2011) 265

Comparison with beauty R_{AA}



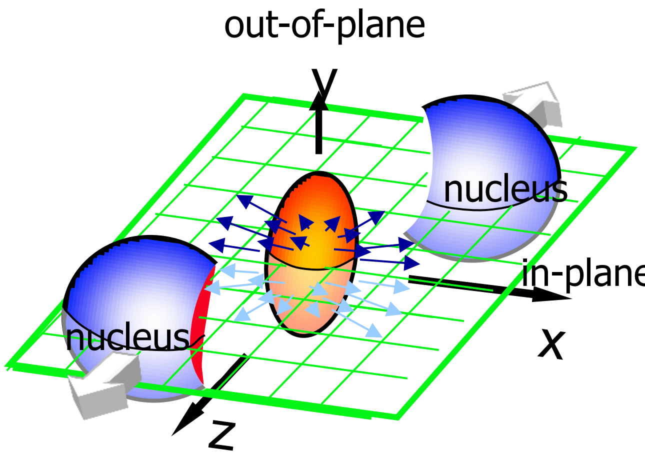
- similar $\langle p_T \rangle$ for D and B mesons (~10 GeV/c) but slightly different rapidity range
- indication for $R_{AA}(D) < R_{AA}(B)$ in central Pb-Pb collisions

consequence of mass difference in pQCD based model calculation (Djordjevic, arXiv:1307.4098)

- pQCD model including mass-dependent energy loss predicts a differences between the R_{AA} of D mesons and non-prompt J/ψ similar to the observation
- similar for other calculations (BAMPS, WHDG, Vitev et al.)

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 planes



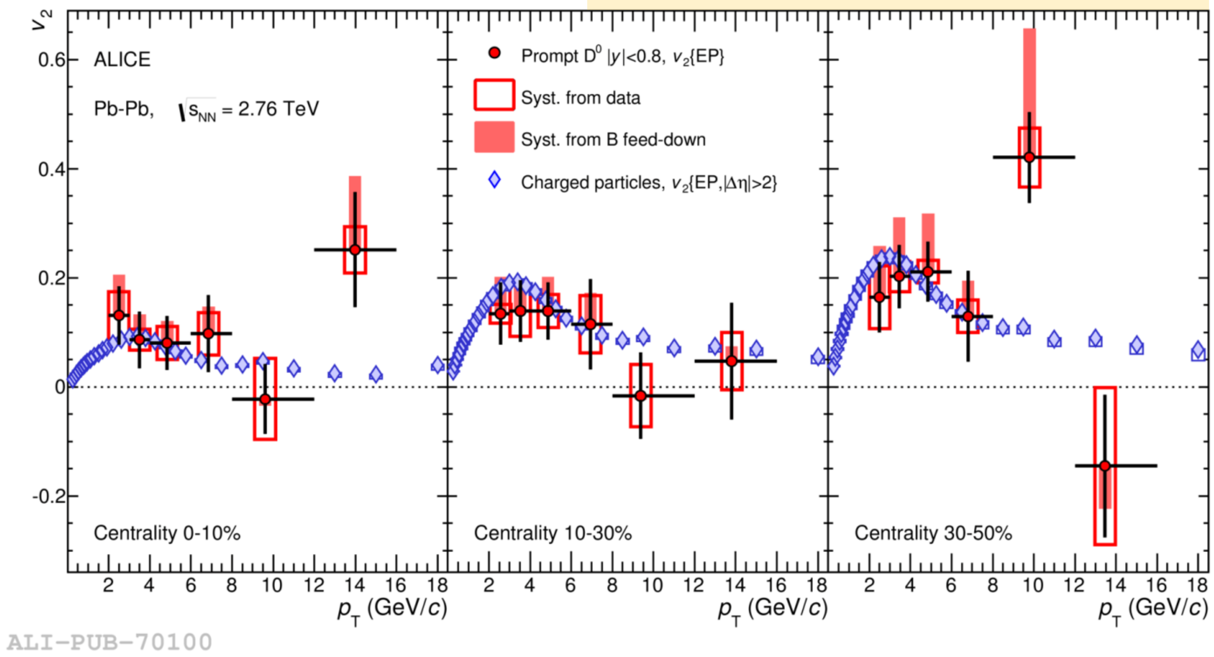
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}(1 + 2v_1 \cos(\varphi - \Psi_1) + 2v_2 \cos(\varphi - \Psi_2) + \ ...)$$

- various methods are available to evaluate v_2
  - event plane
  - 2-particle cumulants (QC, SP methods)
  - 4-particle cumulants (applied to muon measurement only)

  … not discussed in any detail

D-meson elliptic flow

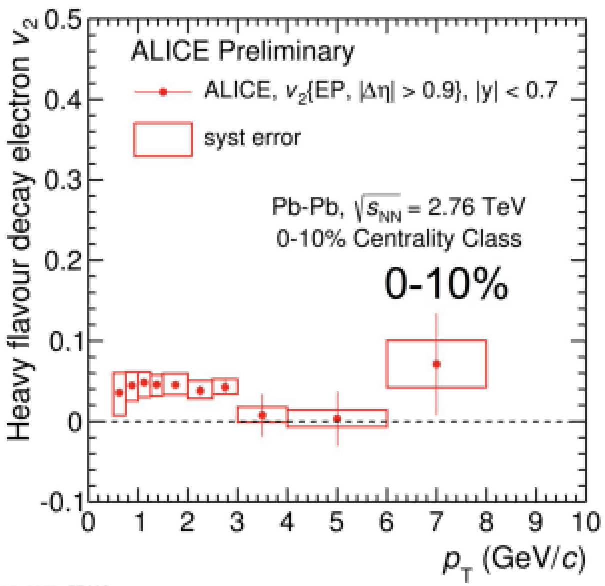
PRL 111(2013)102301, arXiv:1405.2001

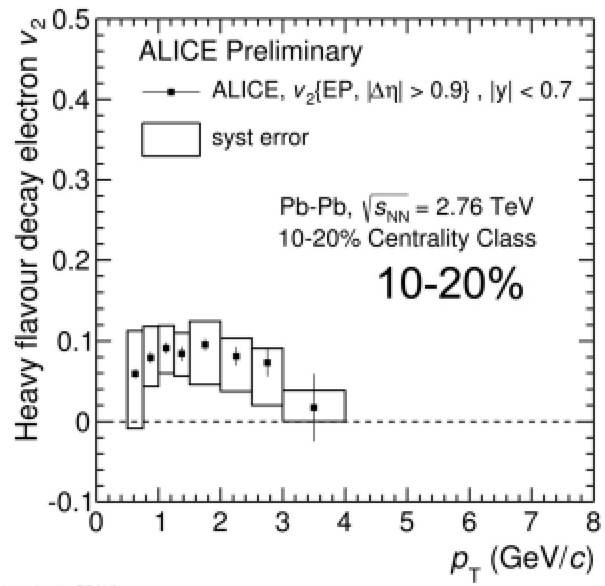


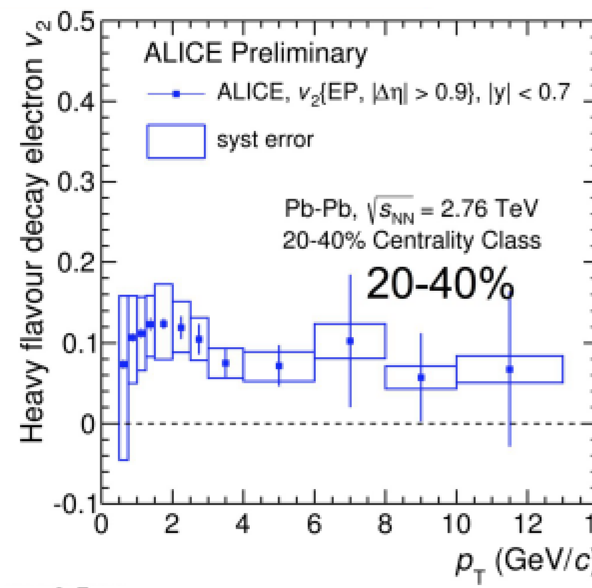
- positive D-meson v_2 similar to charged-particle v_2
- hint for increasing flow with decreasing centrality
- confirmation of significant interaction of charm quarks with the medium

→ collective motion of low-p_T charm quarks with the medium

Elliptic flow of leptons from HF decays

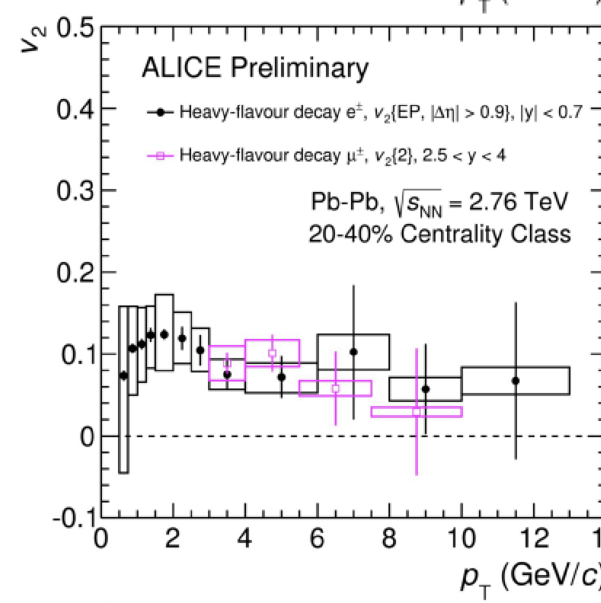




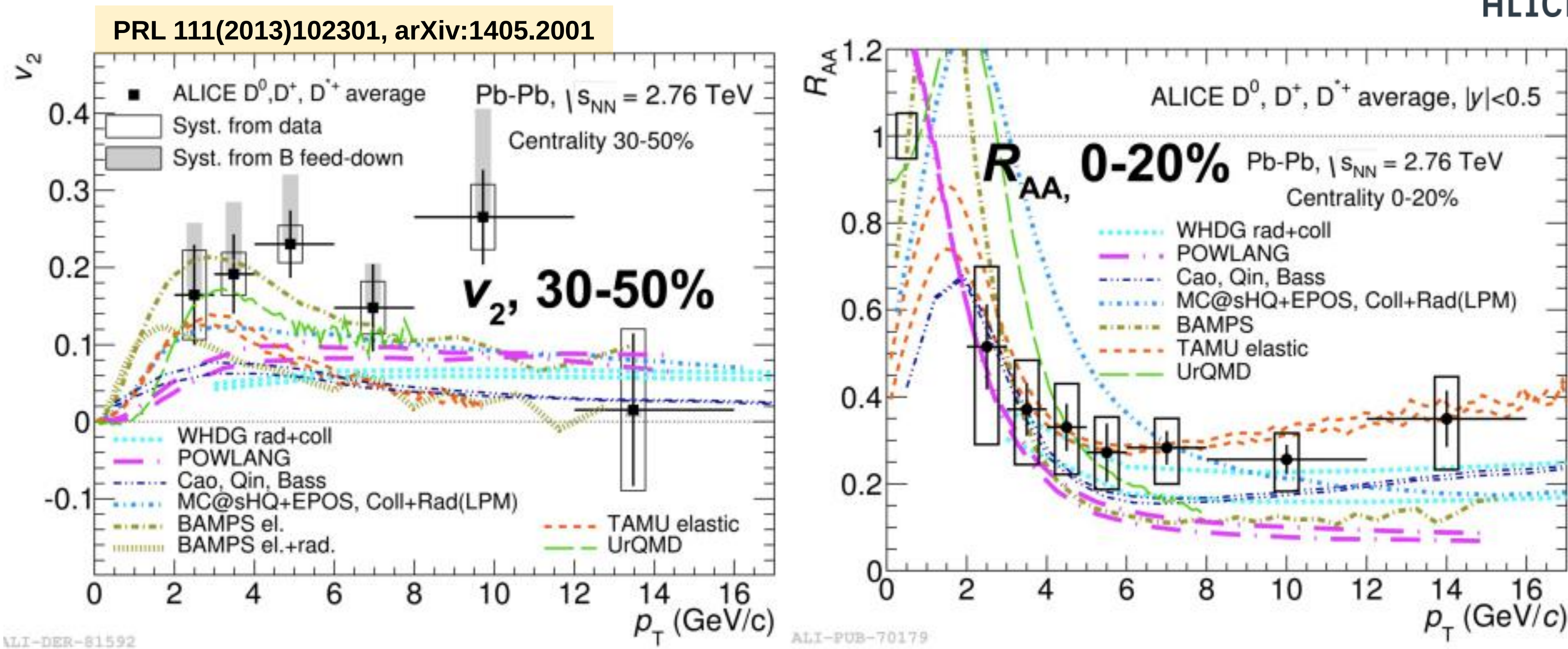


- **electrons and muons from heavy-flavor hadron decays exhibit positive v_2 with similar centrality dependence as observed for D mesons**

→ collective motion of low-p_T charm quarks with the medium



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



→ **simultaneous reproduction of R_{AA} and v_2 challenging for models**

→ **task for us: reduction of stat. and sys. uncertainties of data**

- **$e^{\pm}$ and $\mu^{\pm}$ from heavy-flavor decays: similar situation**

WHDG: Nucl. Phys. A 872 (2011) 265; MC@sHQ+EPOS, Coll+Rad(LPM): Phys. Rec. C89 (2004) 014905; TAMU elastic: arXiv:1401.3817 [nucl-th]; POWLANG: Eur. Phys. J. C71 (201) 1666, J.Phys. G 38 (2011) 124144; BAMPS: Phys. Rev. C 84 (2011) 024908; J. Phys. G38 (2011) 124152 Phys. Lett. B 717 (2012) 430;arXiv:1310.3597v1[hep-ph] ; UrQMD: arXiv:1211.6912[hep-ph]; J. Phys.Conf. Ser. 426 (2013) 012032; Cao, Qin, Bass: Phys. Rev. C 88 (2013) 044907

Summary

- **ALICE at the LHC: new quality of heavy-flavor measurements in heavy-ion collisions**
- **pp collisions**
  - **pQCD calculations describe the data well**
- **p-Pb collisions**
  - **results consistent with pQCD plus shadowing/saturation**
- **Pb-Pb collisions**
  - **strong interaction of heavy quarks with the medium**
    → suppression of yields at high p_T
    → indication for charm participating in the collective expansion of the medium

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further progress requires much more statistics
→ Run-II will be a crucial step forward at the LHC