# Heavy-flavour observables at ALICE

MinJung Kweon for the ALICE Collaboration
Inha University

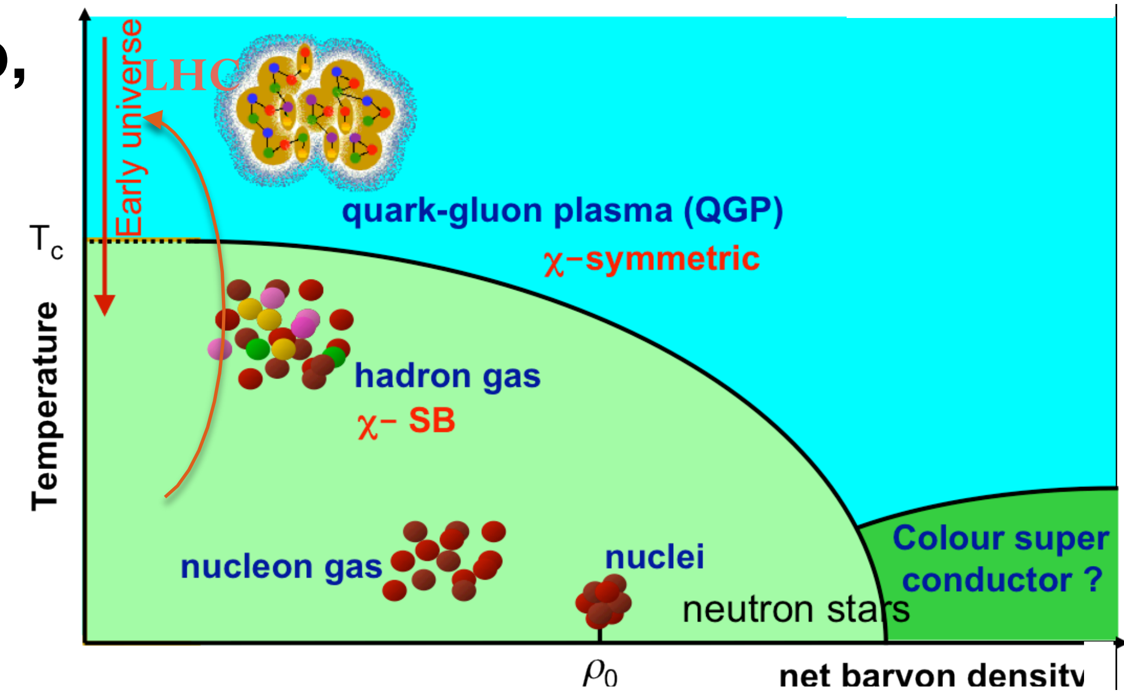
HIM
Pusan University, May 16, 201

# Outline

- Why Heavy-flavours in heavy-ion physics
- ALICE experiment
- Experimental results
  - Open heavy flavour results in pp, p-Pb, Pb-Pb collisions
- Summary & Outlook

# Heavy-ion physics

First phase diagram for nuclear matter: Cabibbo, Parisi PL B59 (1975): "We suggest ... a different phase of the vacuum in which quarks are not confined"



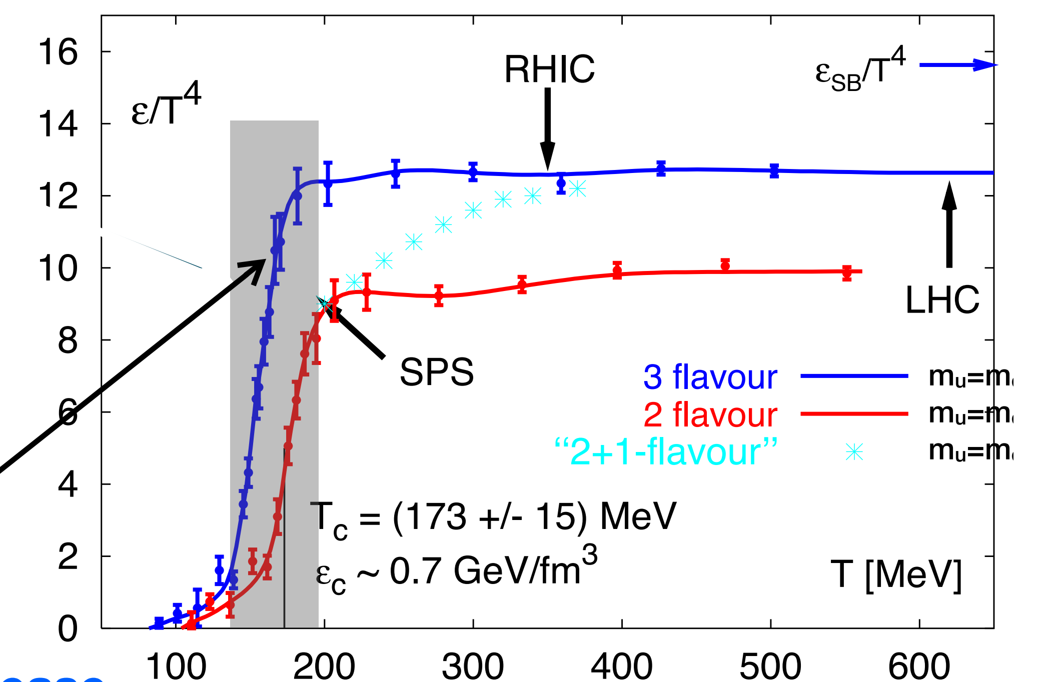

T.D. Lee (1975) suggested to distribute a high amount of energy over a relatively large volume

Collisions of nuclei at very high energy

- Temperature of the produced "fireball" $O(10^{12}$ K)
  - $10^5 \times$ T of the centre of the Sun
  - ≈T of the Universe $10^{-5}$s after Big Bang

Study nuclear matter at extreme conditions of temperature and density

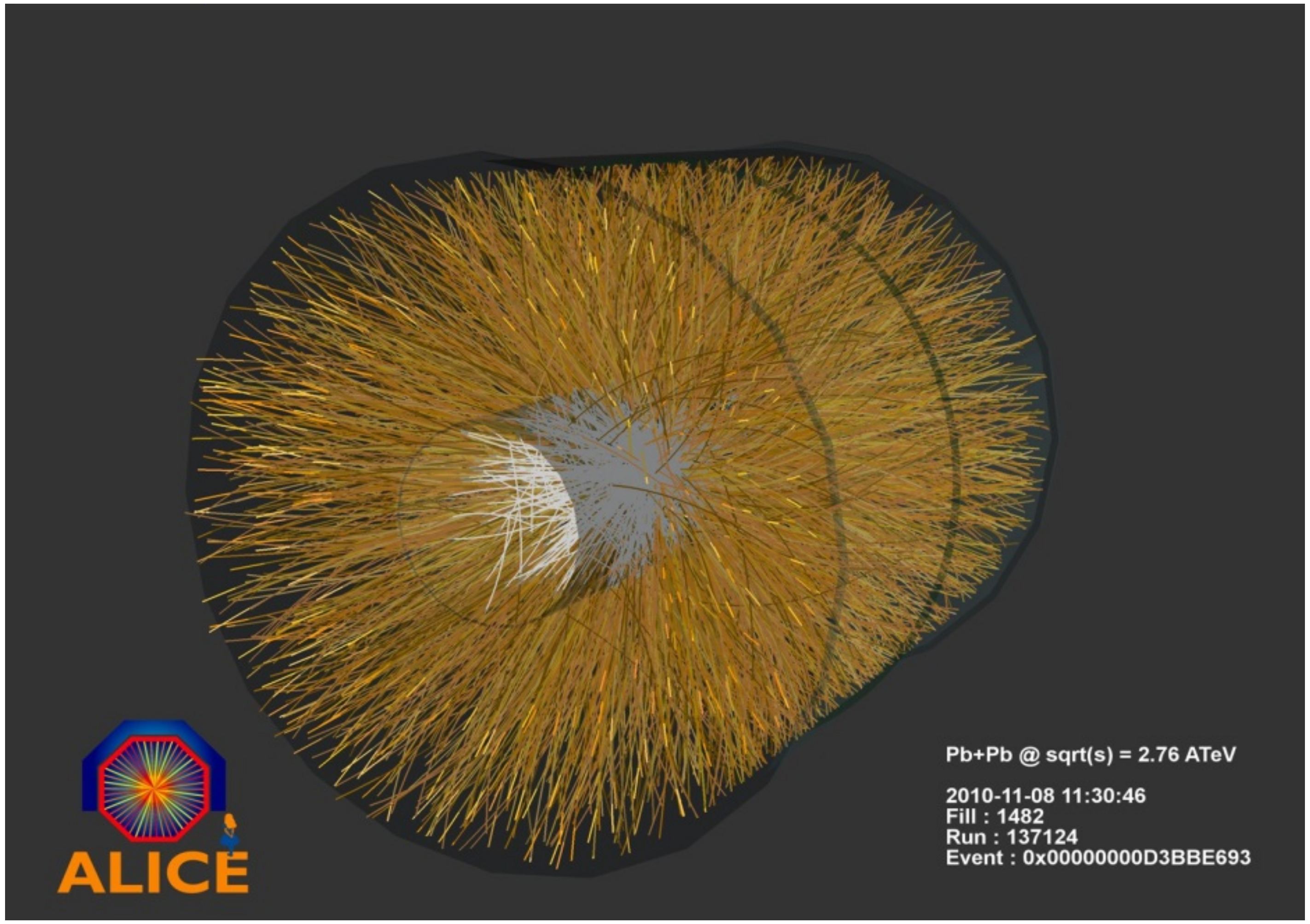
- Collect evidence for a state where quarks and gluons are deconfined (Quark Gluon Plasma) and study its properties
- Phase transition predicted by Lattice QCD calculations
  - $T_C \approx 170$ MeV → $\varepsilon_C \approx 0.6$ GeV/fm$^3$




sharp increase

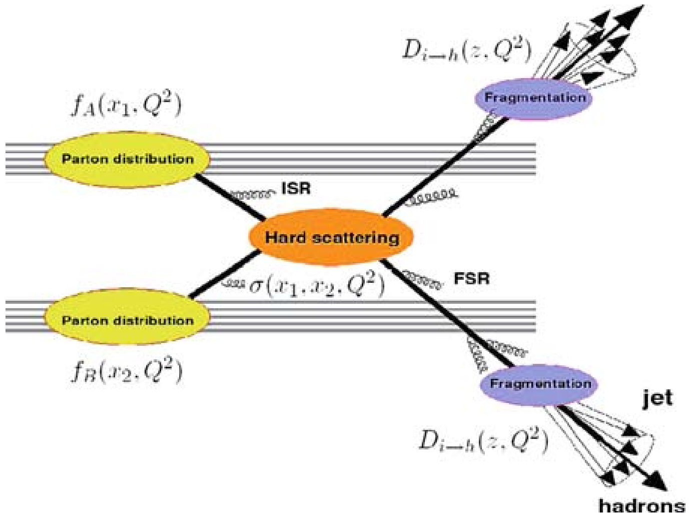
# Heavy-ion program at the LHC

- Heavy-ion program at the LHC started on Nov. 7th 2010 with Pb-Pb collisions at $\sqrt{S_{NN}}$=2.76 TeV
- Big jump in energy w.r.t. RHIC: 13.8×$\sqrt{S_{NN}}$
- 3 experiments: ALICE, ATLAS and CMS




ALICE is the experiment dedicated to the study of the quark-gluon plasma produced with high T and low $\mu_B$ in Pb-Pb collisions at the LHC

# Hard Tomographic Probes of QCD Matter I




What is Hard Probes?

- Some processes involve an energy scale Q that is much larger than the typical energy scale (≈ T≈200-400 MeV) of the created medium:
  - creation of heavy quark-antiquark pairs ($Q = 2m_Q$)
  - interactions at high momentum transfer, in particular the production of high-$p_T$ particles ($Q \approx p_T$)

- The corresponding length scale ≃ 1 /Q of such processes is thus much smaller ($\tau$<1/Q~0.1 fm/c) than the length scale of typical medium excitations, so that they are sufficiently point-like to be unaffected by the medium.
- Additionally, such processes are to a large extent calculable from first principles, i.e., using perturbative QCD.

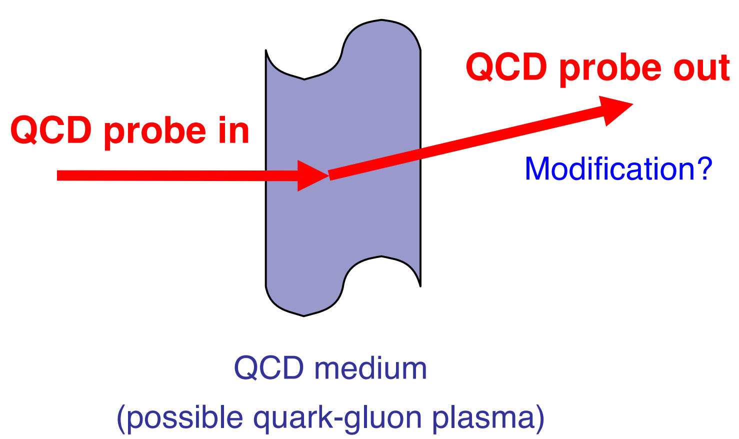
ex) jets, $\gamma$, $Q\bar{Q}$

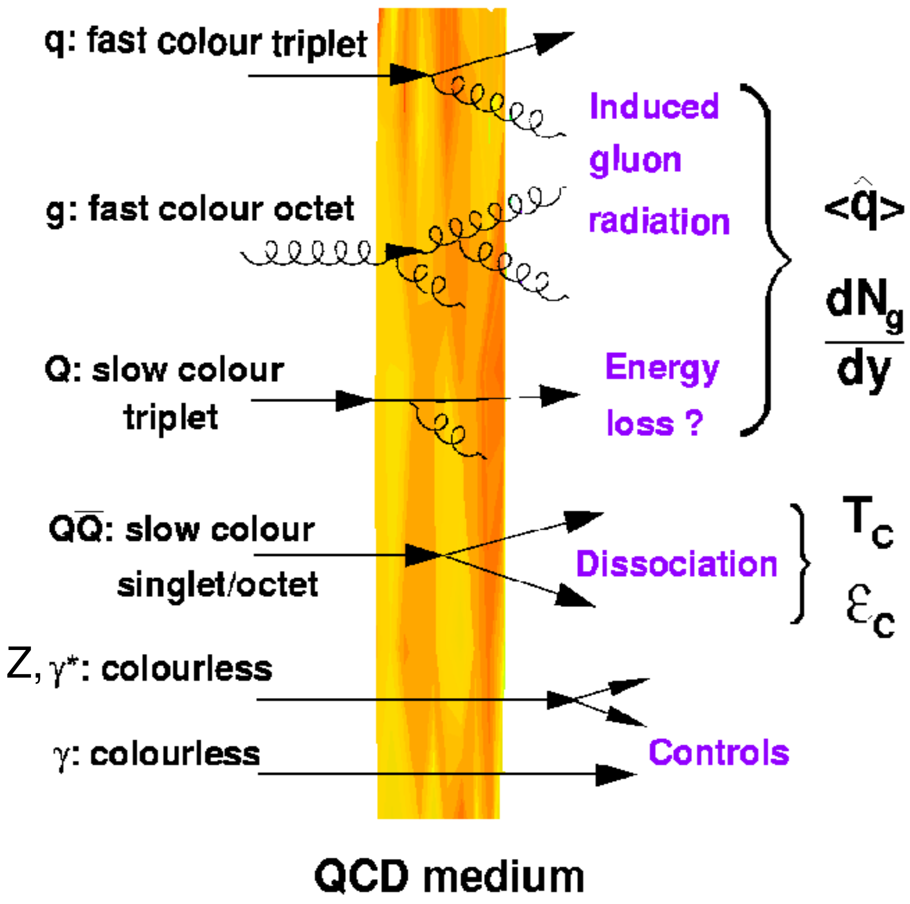
# Hard Tomographic Probes of QCD Matter II

Why are hard probes interesting?

- The creation process is to a large extent calculable within pQCD
- While the production (of a high-$p_T$ particle, a heavy QQ-pair) is insensitive to the presence of a medium, however the probe then has to travel through the medium, and possibly be modified at that stage

- Eventually, before the hard process, its "progenitors" had to travel through the medium: here as well, some modification is possible
- Tomographic probes of hottest & densest phases of medium

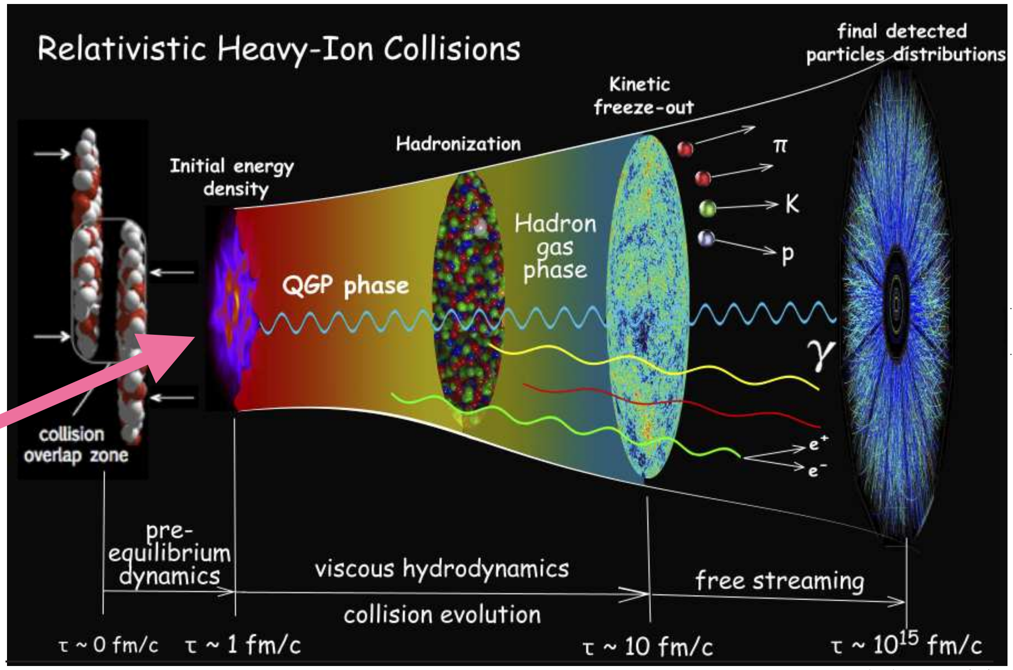


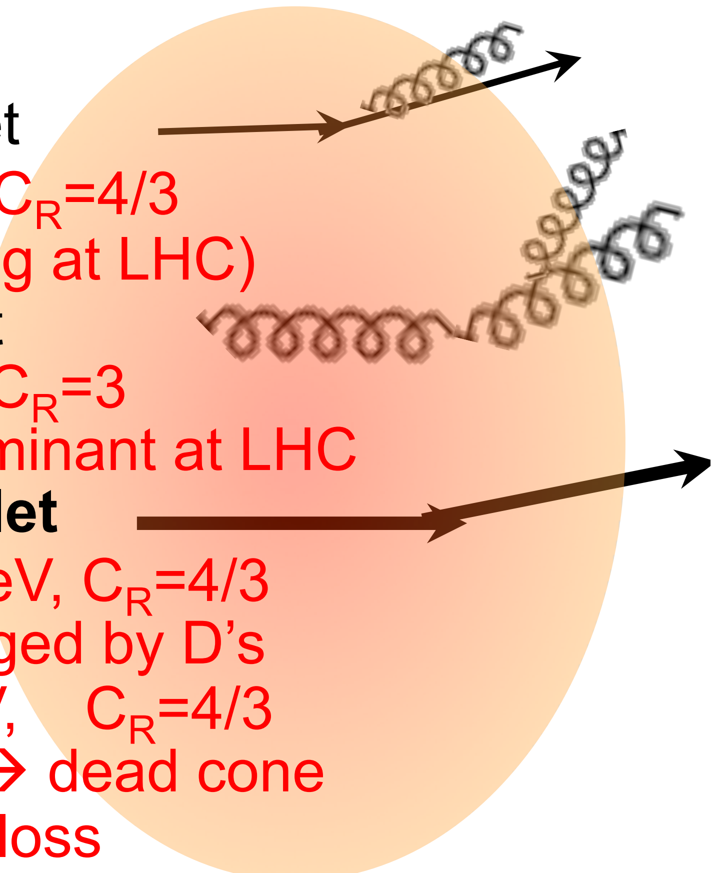
# What's special about heavy quarks

- Heavy-ion (HI) collisions at LHC energies
  - QGP phase expected (lifetime ~ O(10 fm/c))
- Heavy quarks
  - Large mass ($m_q \gg \Lambda_{QCD}$) → produced in the early stages of the HI collision with short formation time( $t_{charm} \sim 1/m_c \sim 0.1$ fm/c << $\tau_{QGP} \sim$ O(10 fm/c) ), traverse the medium interacting with its constituents
    - ➡ natural probe of the hot medium created in HI interactions
  - Interactions with QGP don't change flavour identity
  - Uniqueness of heavy quarks: cannot be destroyed/created in the medium
    - ➡ transported through the full system evolution

**Hard processes:**
- Charm, Beauty, W, Z, photons, Jets
- Probe the whole evolution of the collision



# Heavy quarks as medium probes



q: colour triplet

**u,d,s:** m~0, $C_R$=4/3
(difficult to tag at LHC)

g: colour octet

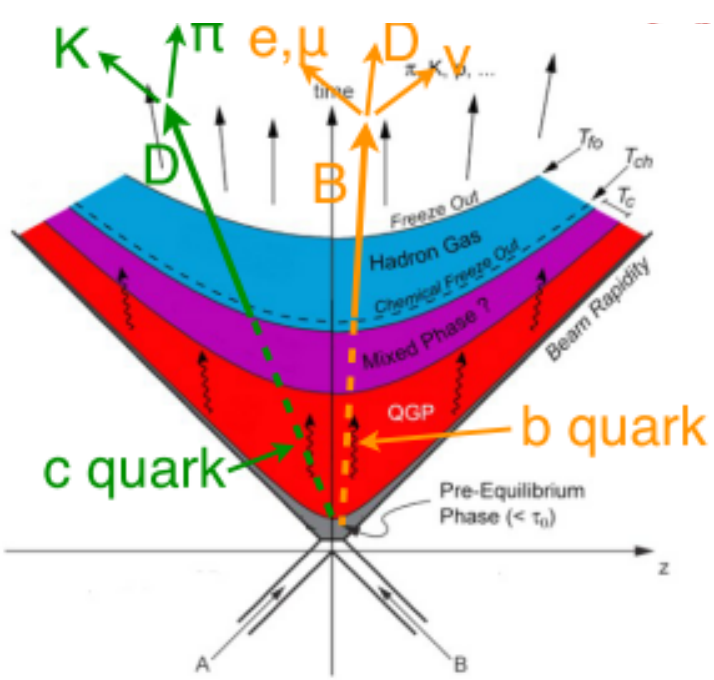
**g:** m=0, $C_R$=3
> E loss, dominant at LHC

**Q: colour triplet**

**c:** m~1.5 GeV, $C_R$=4/3
small m, tagged by D's

**b:** m~5 GeV, $C_R$=4/3
large mass → dead cone
→ < E loss

**'Quark Matter'**




**Parton Energy Loss by**

→ **medium-induced gluon radiation**

→ **collisions with medium constituents**

$$\Delta E(\varepsilon_{medium}; C_R, m, L)$$

**Prediction:** $\Delta E_g > \Delta E_{c \approx q} > \Delta E_b$

**Might translate into a hierarchy of nuclear modification factors**

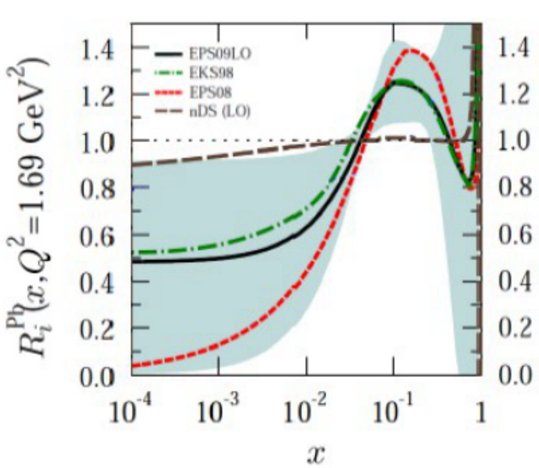
$$R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}?$$

## 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**

# Heavy-flavour physics programs in pp, p-A, A-A collisions

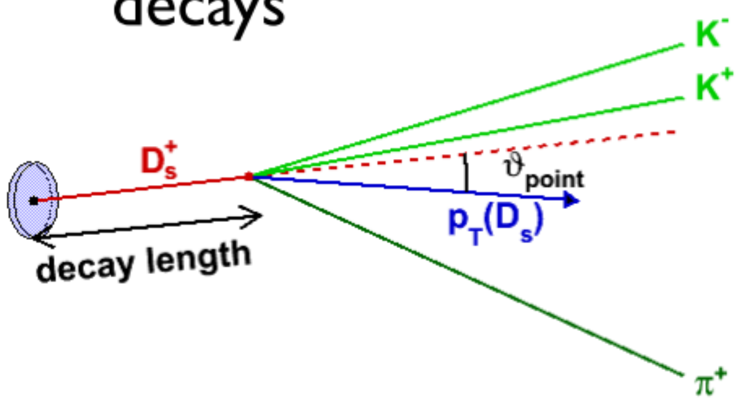
- Pb-Pb collisions
  - Study the interaction of heavy quarks with the medium
    - Color charge and mass dependence of parton energy loss
  - Collectivity in the medium
    - Initial spatial asymmetry
    - Thermalization via sufficient rescattering due to large mass ($v_2$(b)<$v_2$(c)?)
    - Path length dependence of energy loss at high $p_T$
- p-p collisions
  - Test understanding of heavy-quark production
    - Which are the relevant production mechanisms on the parton level: LO, NLO, or even more complex (ex. Multi parton interactions)
    - Test of pQCD-based predictions: theoretical uncertainties are driven by renormalization and factorization scales and quark masses
    - Investigate production mechanisms via more differential measurements (ex. multiplicity dependence of production cross section)
  - Reference for p-Pb and Pb-Pb measurements
- p-Pb collisions
  - Control experiment for the Pb-Pb measurement: indication for final state effect?
  - Address cold nuclear matter effects
    - Nuclear modification of parton distribution function
      - 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



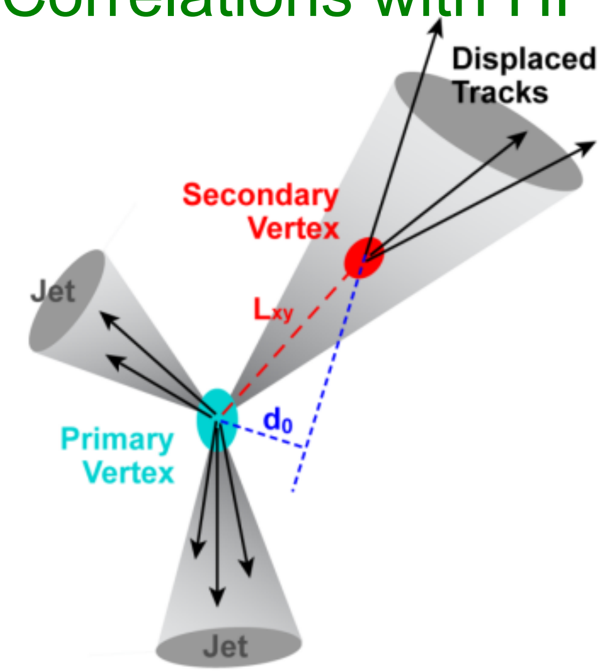
# Heavy-flavour hadrons decay via weak interaction: measure decay products

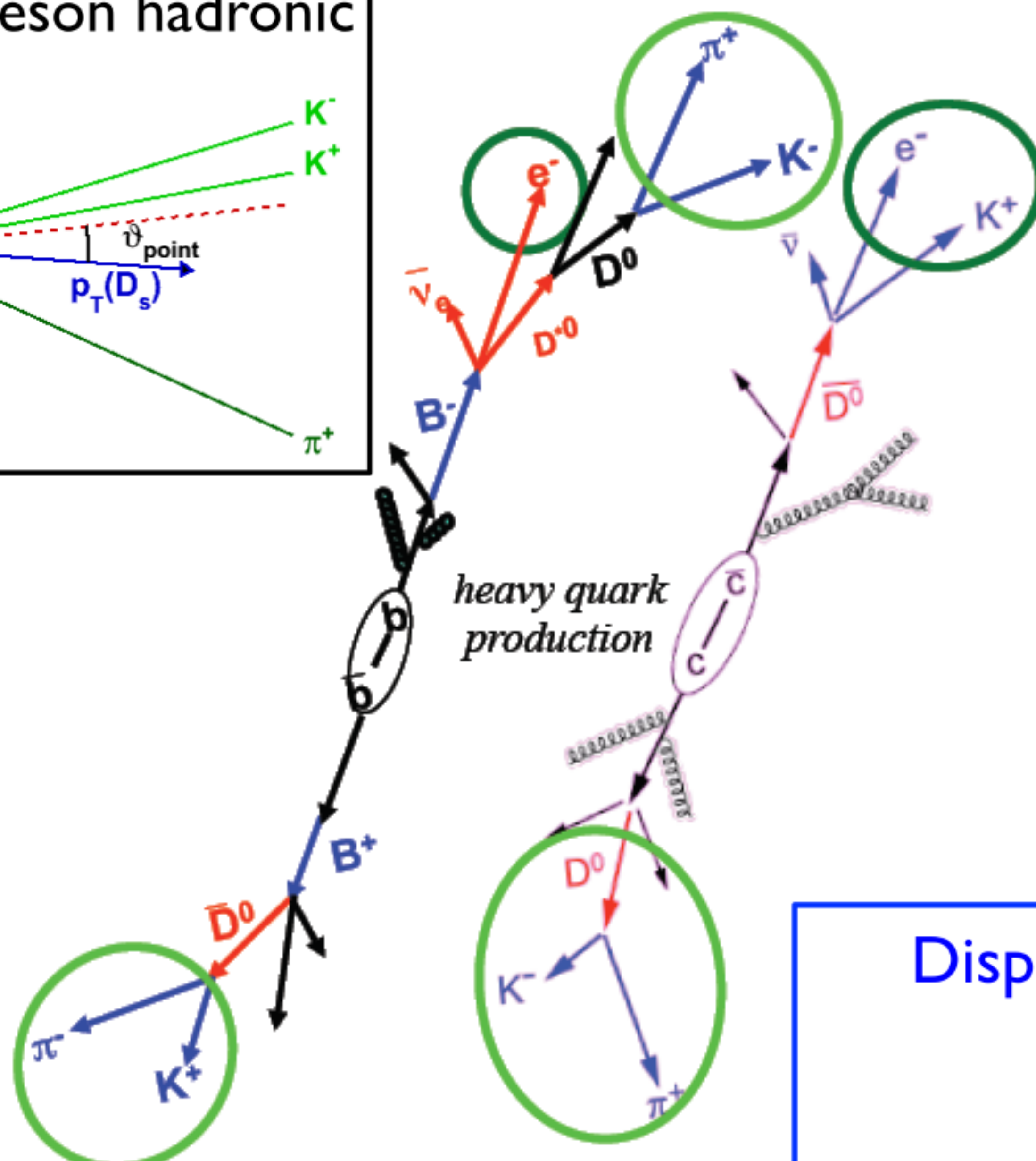
## Full reconstruction of D meson hadronic decays

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

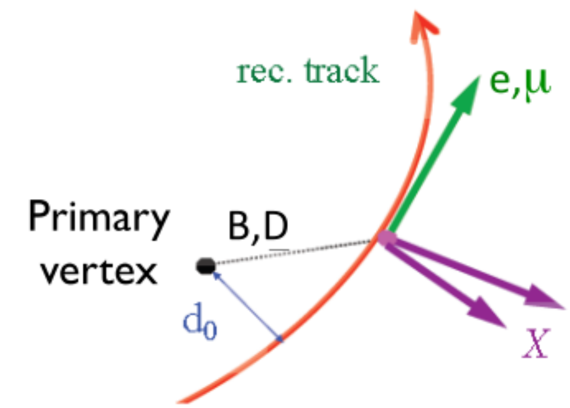



## HF jets
## Correlations with HF

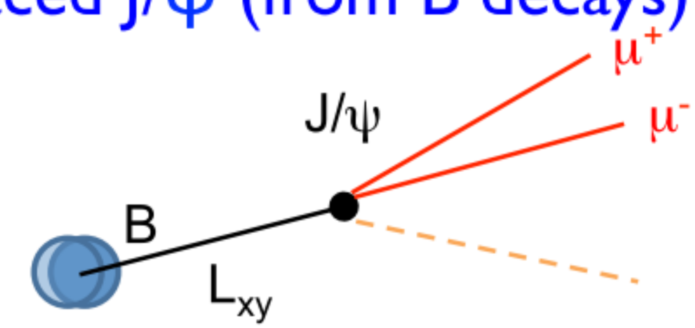



## Semi-leptonic decays (c,b)



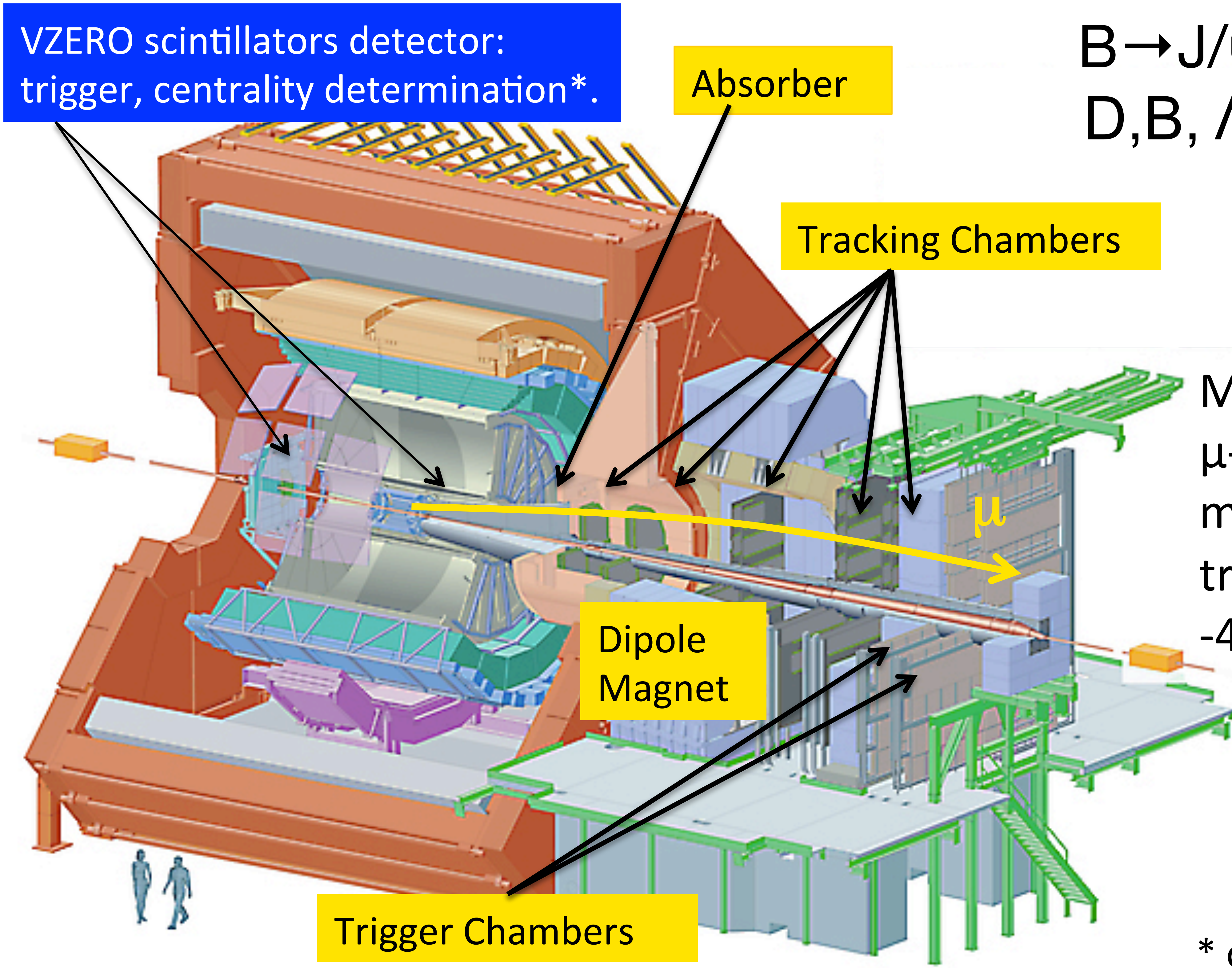

## Displaced J/ψ (from B decays)



# Heavy-flavour and Quarkonium decay muons in ALICE

$B \rightarrow J/\psi$ (displaced)$+X$

$D, B, \Lambda_{c}, \ldots \rightarrow \mu + X$

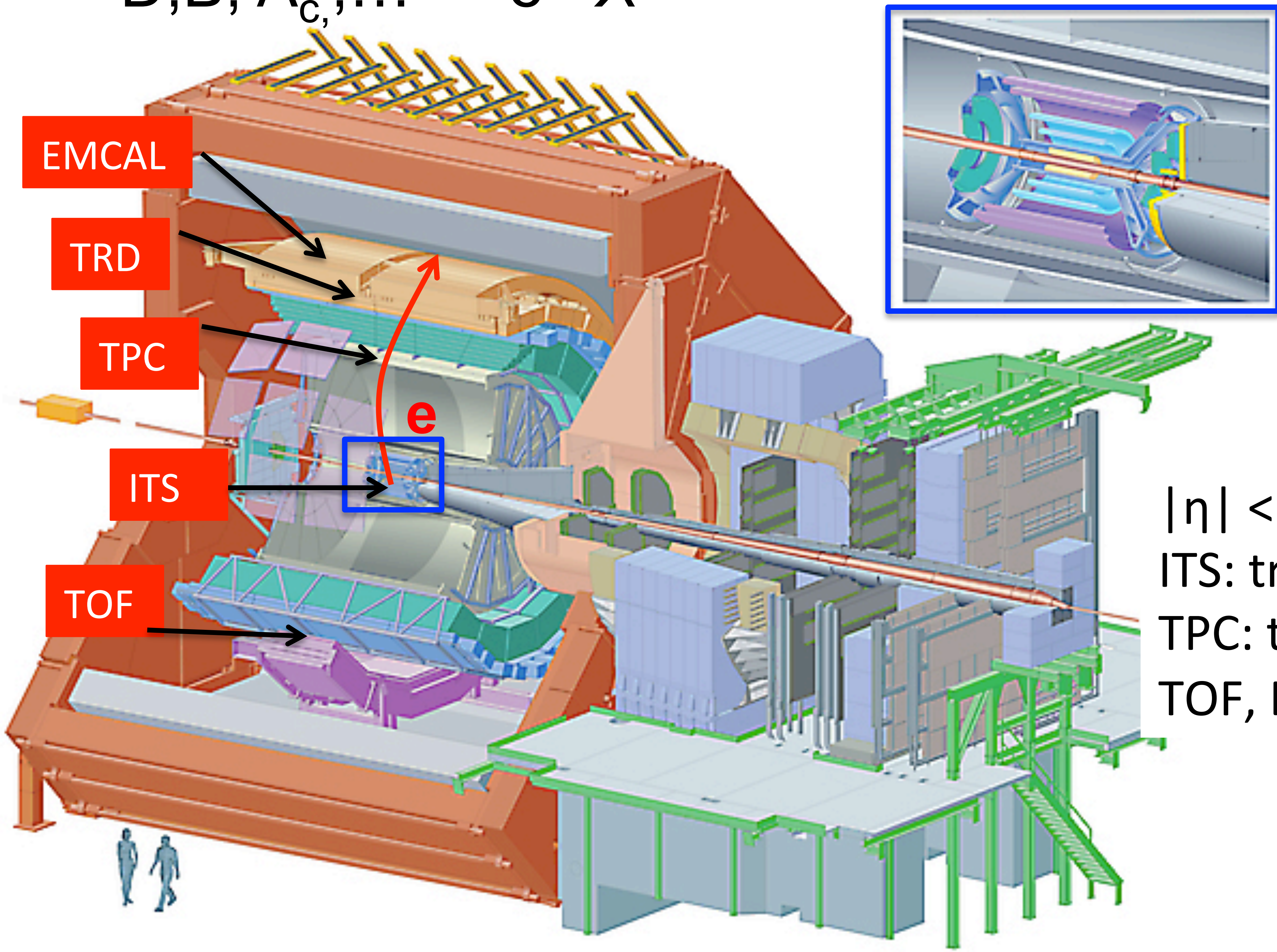



Muon spectrometer:
μ-ID via tracks
matched with and
trigger system
$-4 < \eta < -2.5$

* common for all analyses

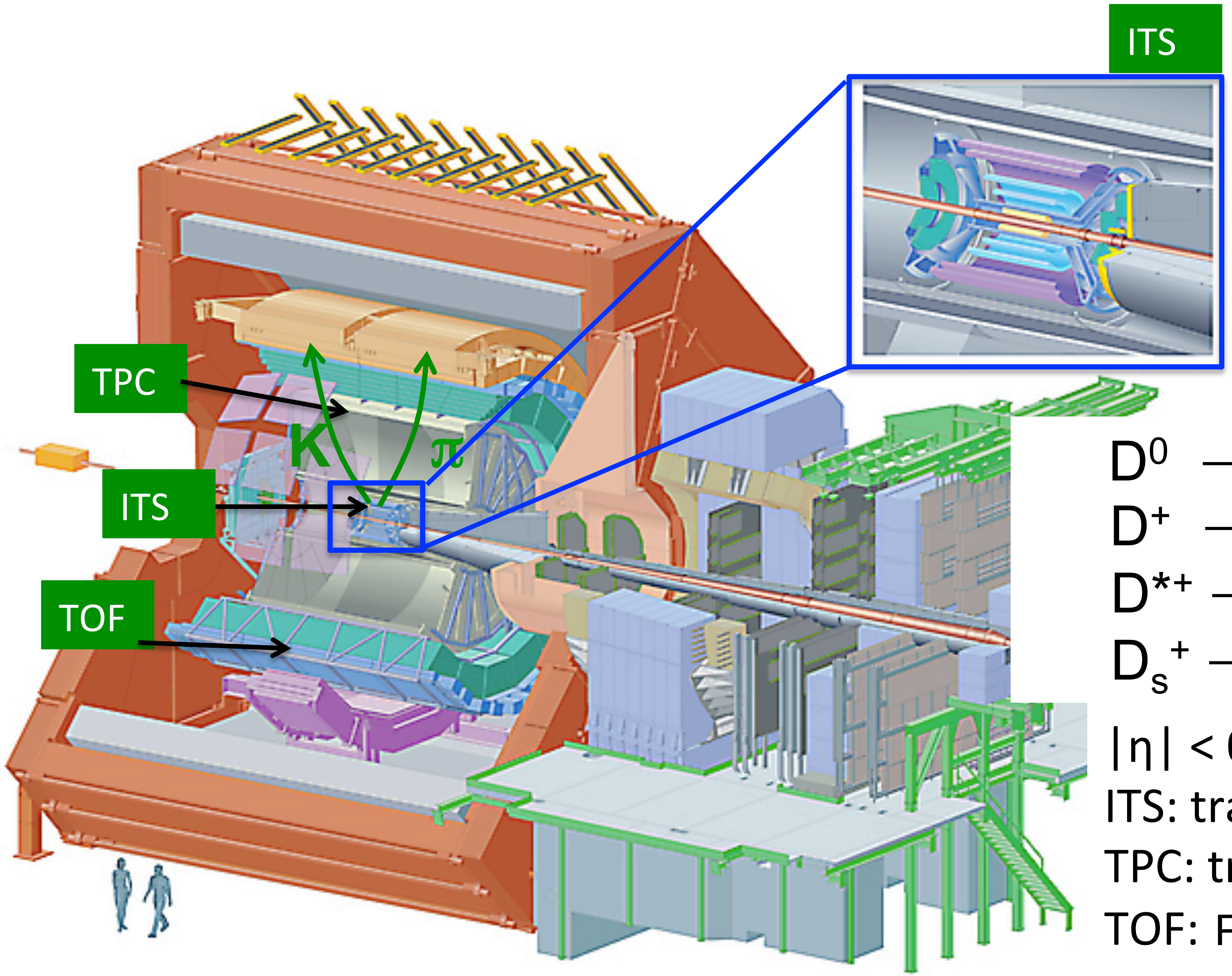
# Heavy-flavour and Quarkonium decay electrons in ALICE

$D, B, \Lambda_c, \ldots \rightarrow e + X$




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

# D mesons in ALICE




$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow K^-\pi^+\pi^+$

$D^{*+} \rightarrow D^0\pi^+$

$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$

$|\eta| < 0.9$

ITS: tracking, vertexing

TPC: tracking, PID

TOF: PID

# Heavy flavours

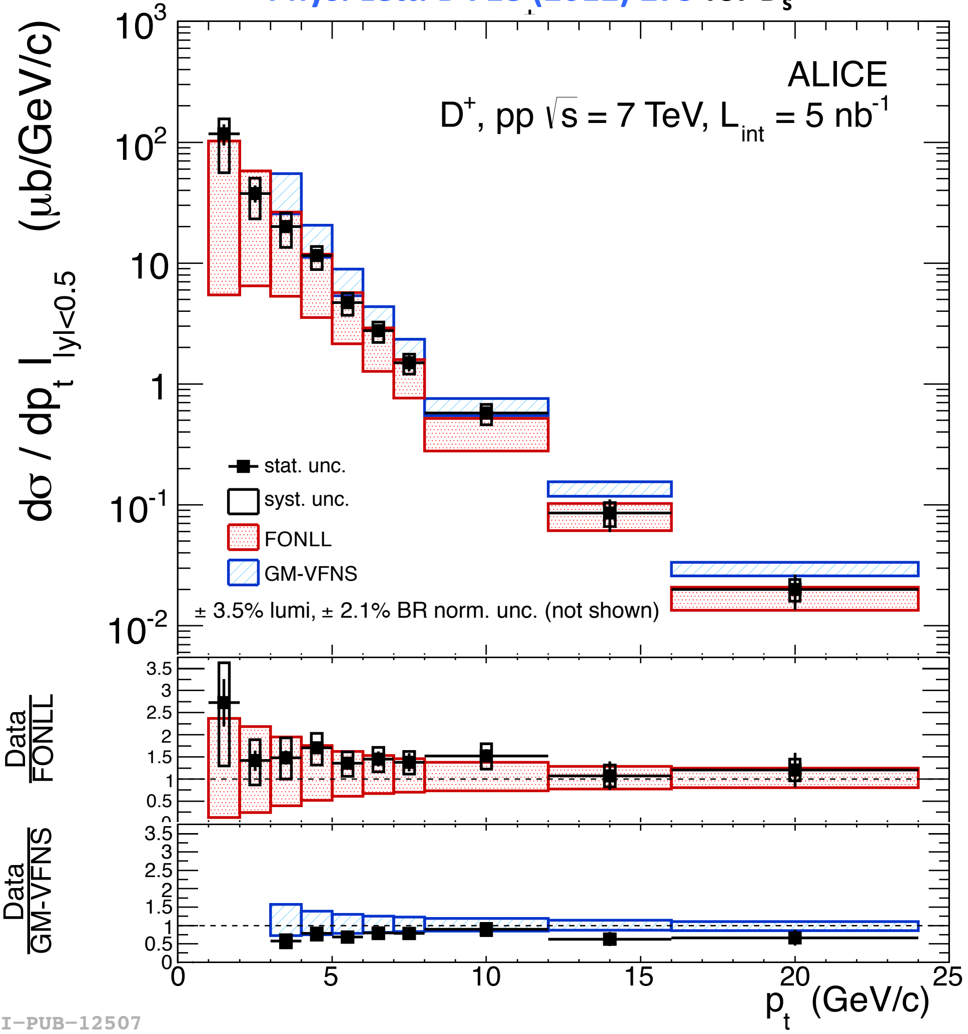
# Results in pp collisions at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 2.76 TeV

# Heavy-flavour cross section in pp at $\sqrt{s}$ = 2.76, 7 TeV

## D mesons

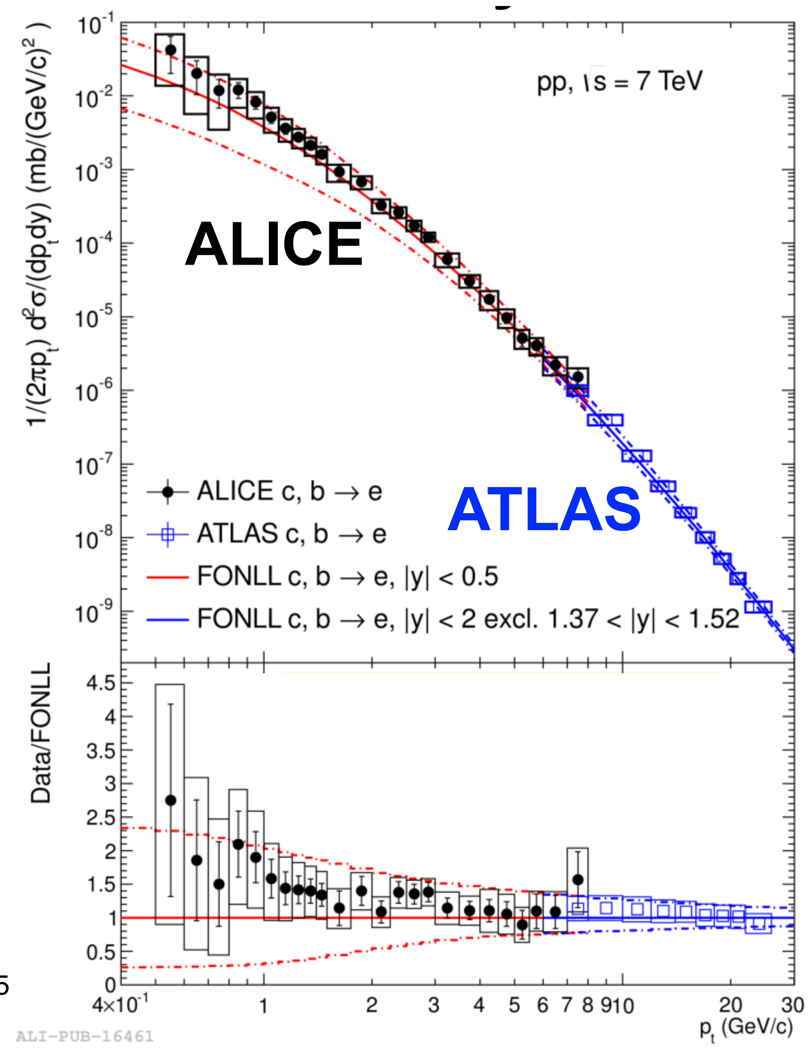
JHEP 1201 (2012) 128

Phys. Lett. B 718 (2012) 279 for $D_s$



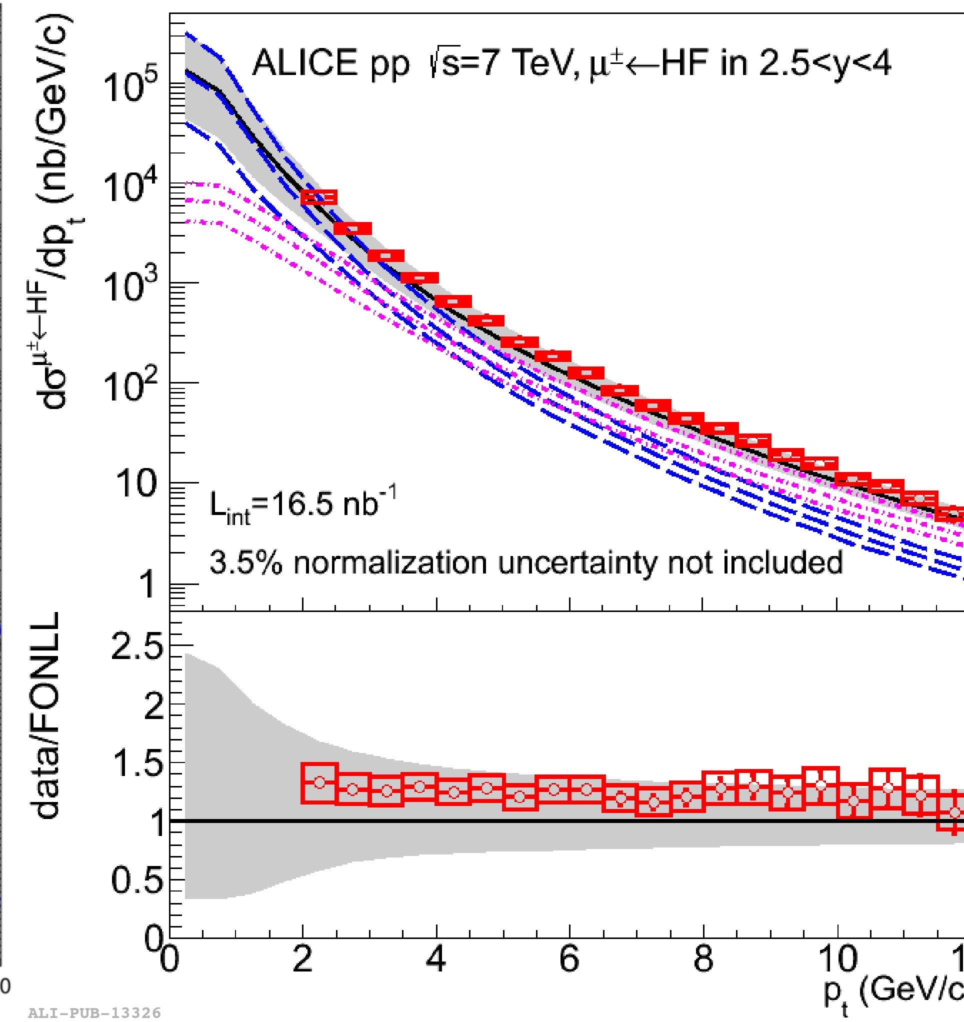

## HF decay electrons

Phys. Rev. D 86, 112007 (2012)




## HF decay muons

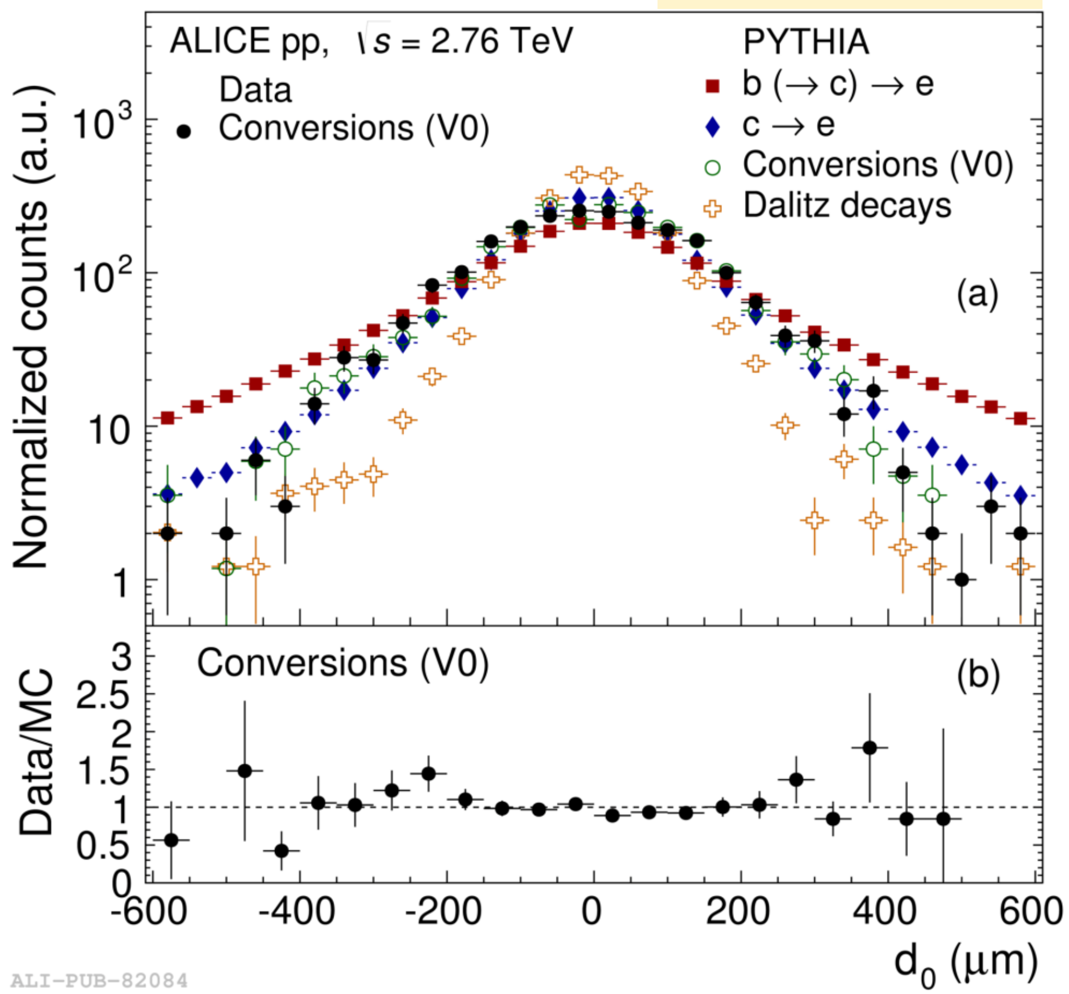
Phys. Lett. B 708 (2012) 265



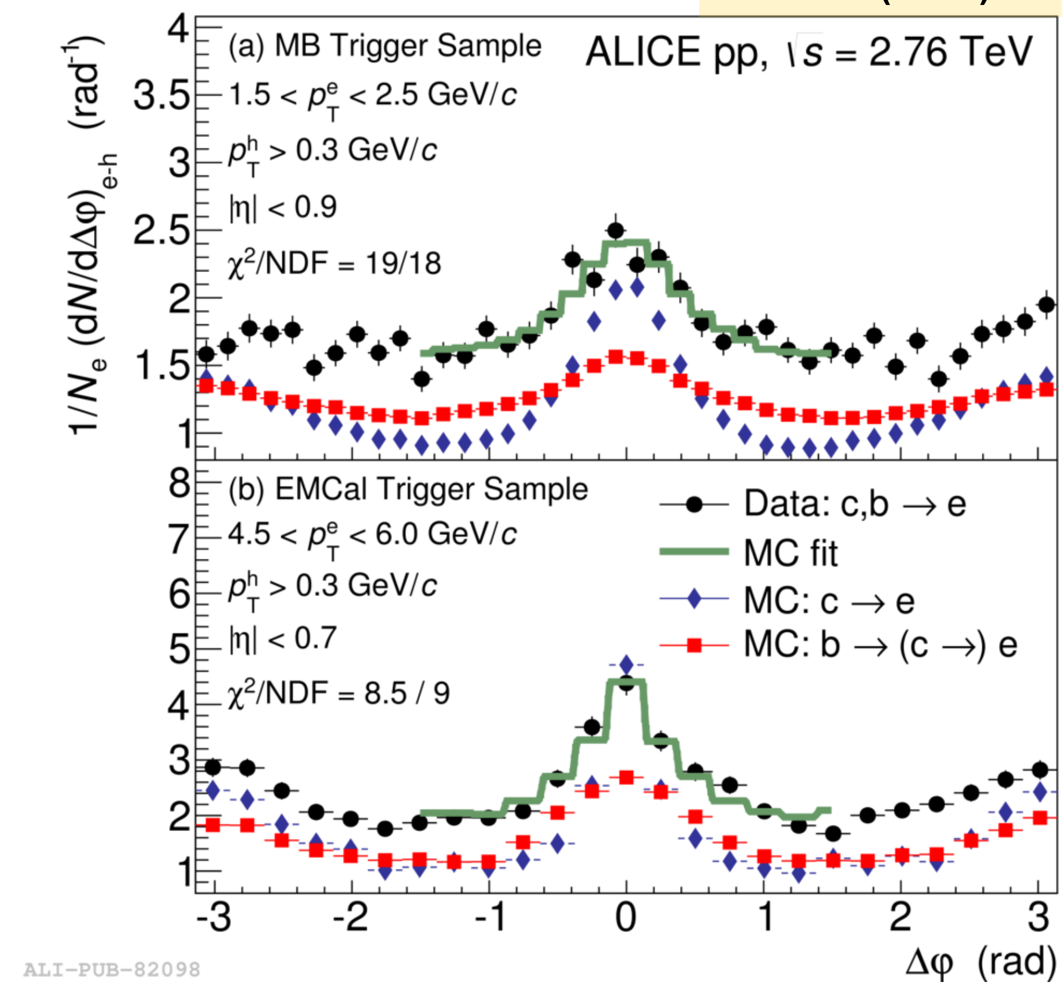

- Heavy flavour cross section measured in various channels
- pQCD-based calculations (FONLL, GM-VFNS, $k_T$ factorization) compatible with data FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082, $k_T$ factorisation: arXiv:1301.3033
- Similar situation at $\sqrt{s}$ = 2.76 TeV

## Beauty decay electrons

PLB 708(2012)265




PLB 738(2014)97

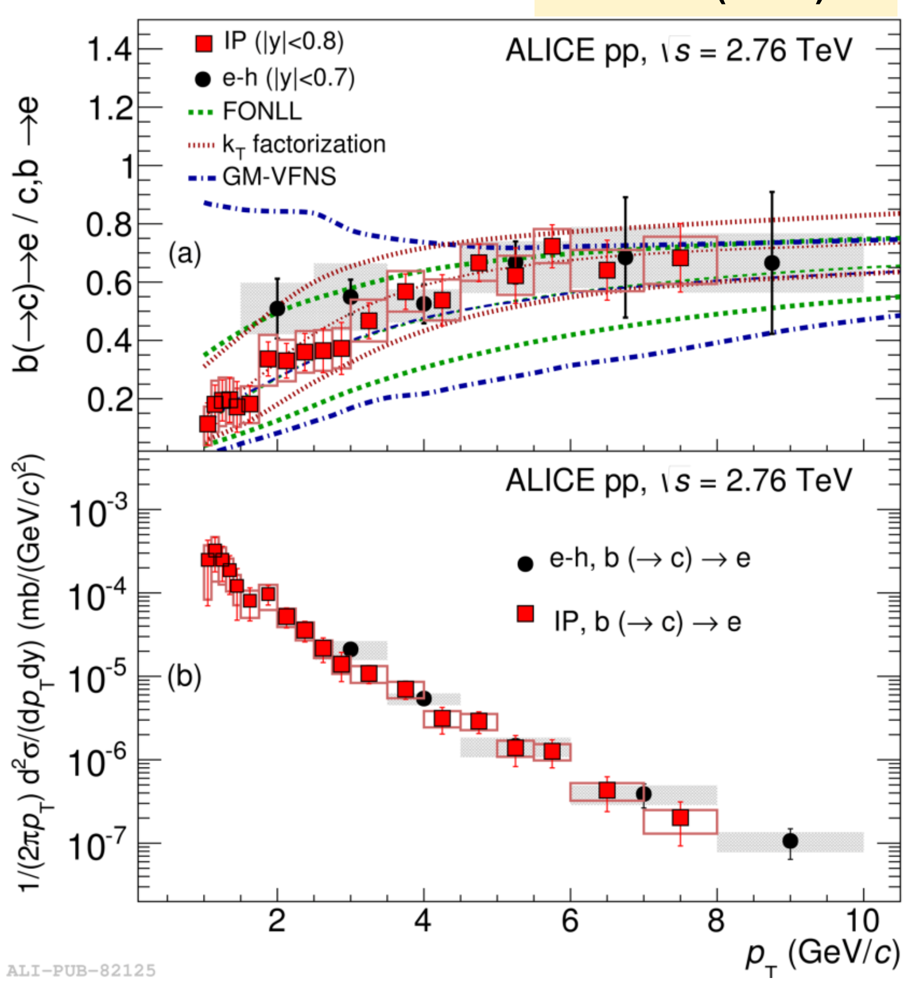



- Statistical separation of $e^{\pm}$ from charm and beauty decays using displaced secondary vertex and electron-hadron angular correlation

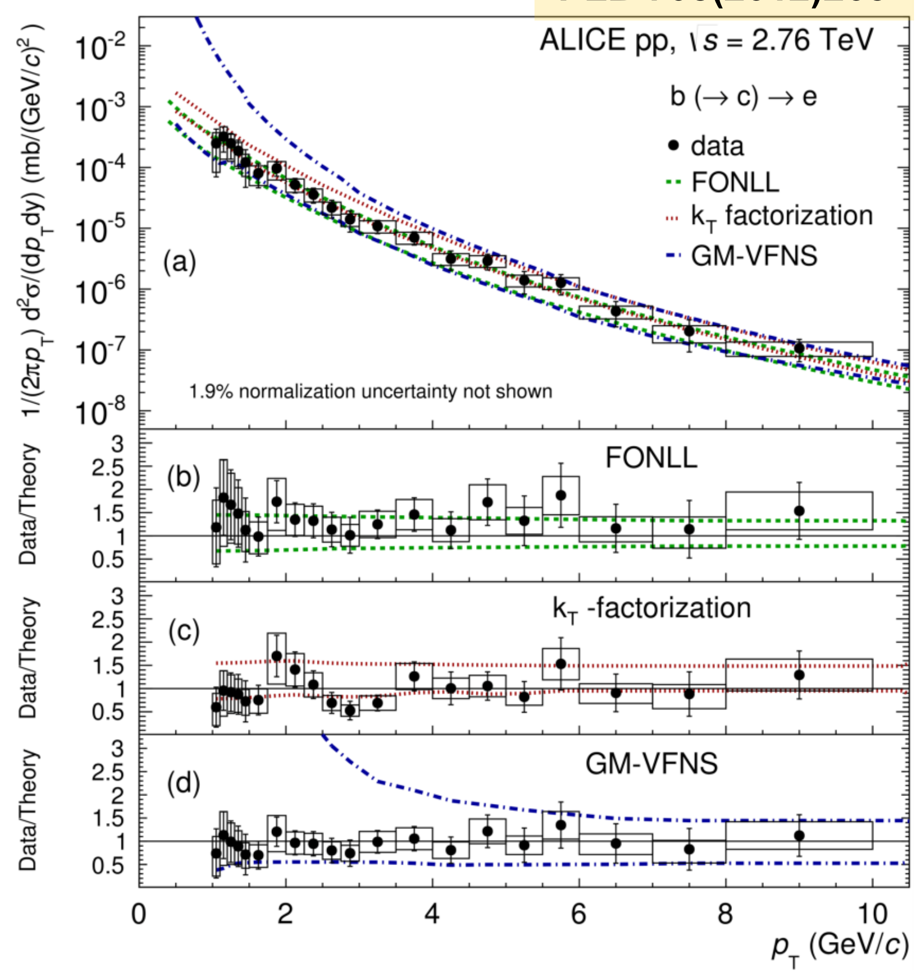
# Heavy-flavour cross section in pp at $\sqrt{s}$ = 2.76, 7 TeV

## Beauty decay electrons

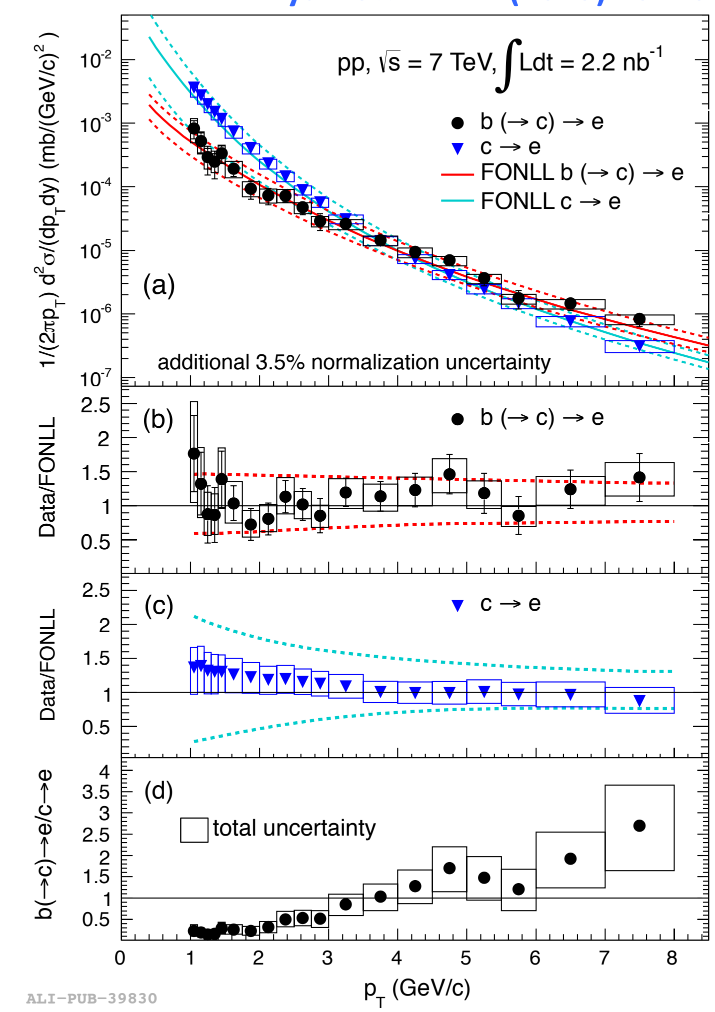
**PLB 738(2014)97**




**PLB 708(2012)265**



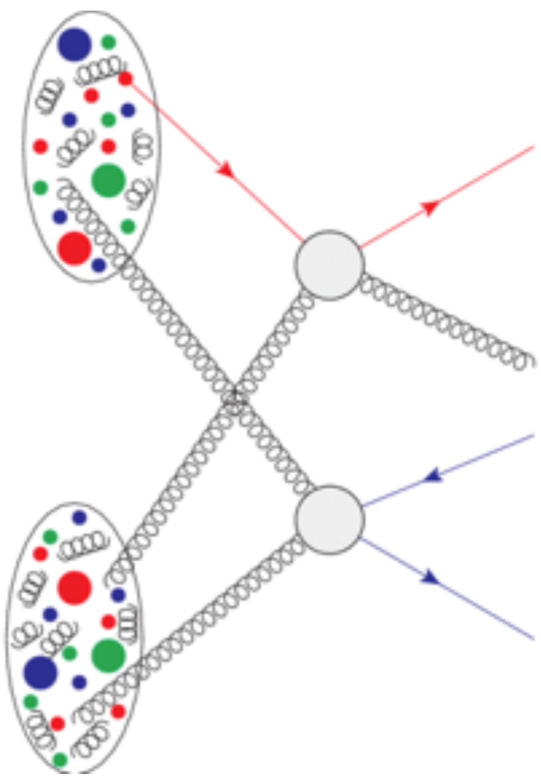

**Phys. Lett. B 721 (2013) 13–23**




- Statistical separation of $e^{\pm}$ from charm and beauty decays using displaced secondary vertex and electron-hadron angular correlation
- Relative contributions of charm and beauty decays as well as beauty decay electron cross section reproduced by pQCD-based calculations (FONLL, GM-VFNS, $k_T$ factorization)

FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082, $k_T$ factorisation: arXiv:1301.3033

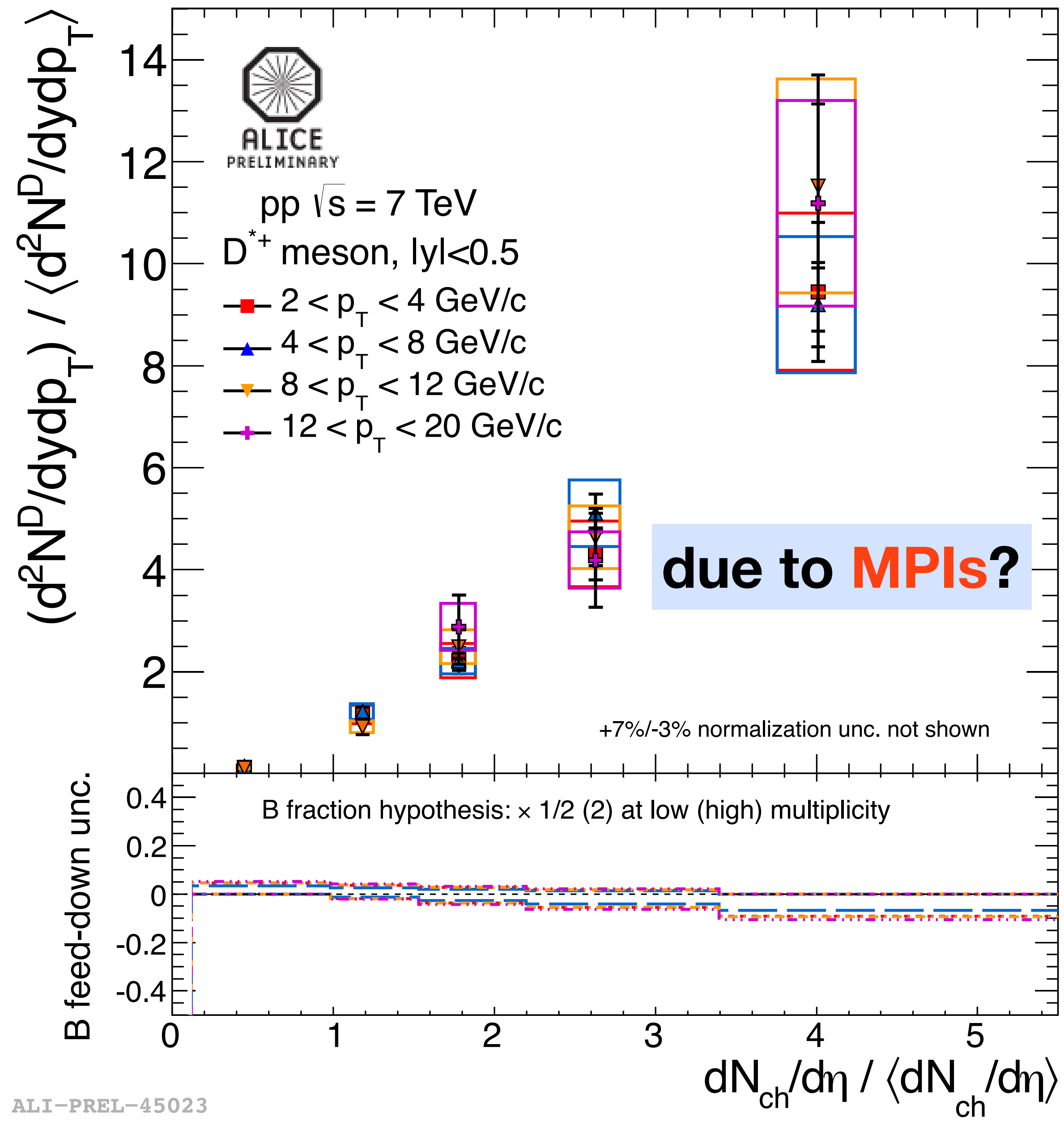
# More on production mechanism:
# Multiplicity dependences of charm production



Particle production in pp collisions at LHC shows **better agreement with models including MPIs**

**Eur. Phys. J. C 73 (2013) 2674**

**Self-normalized D-meson yields vs. charged-particle multiplicity**




## For heavy flavours:

- LHCb: double charm production agrees better with models including double parton scattering

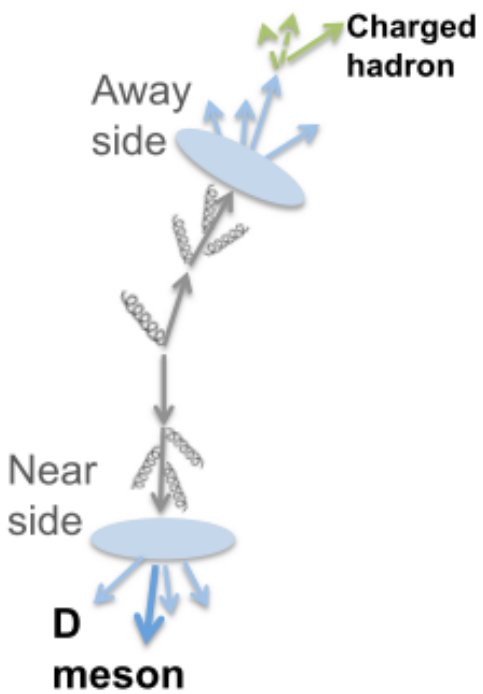
**J. High Energy Phys., 06 (2012) 141**

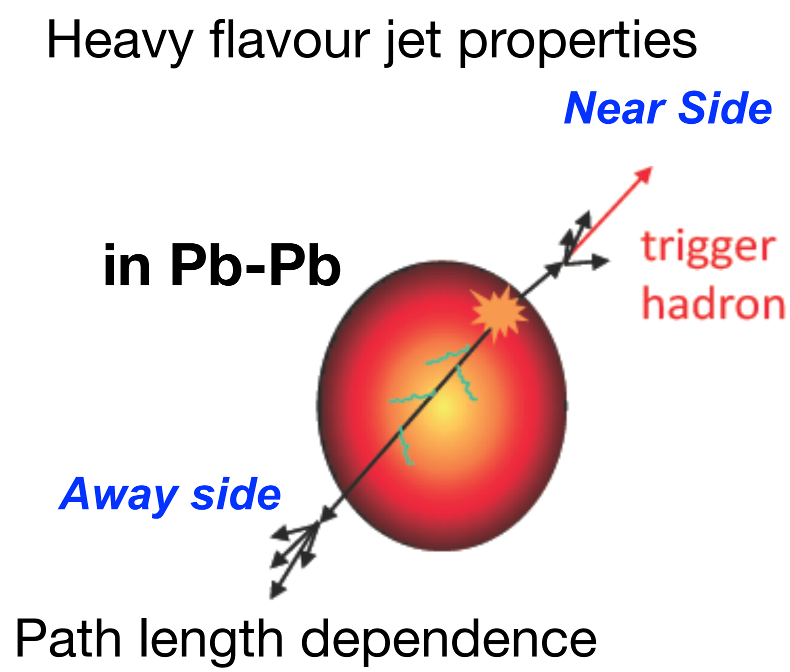
**MPIs involving only light quarks and gluons?**

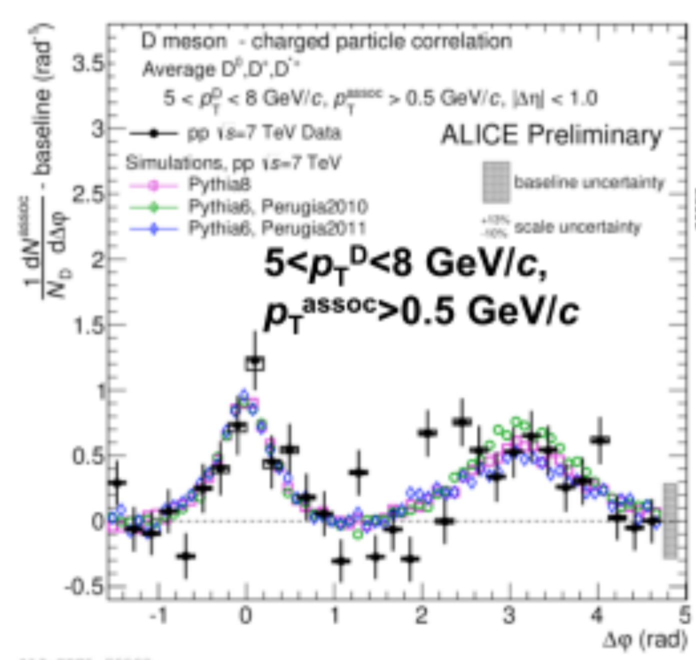
- D-meson yields increase with charged-particle multiplicity
→ presence of MPI and contribution on the a harder scale?

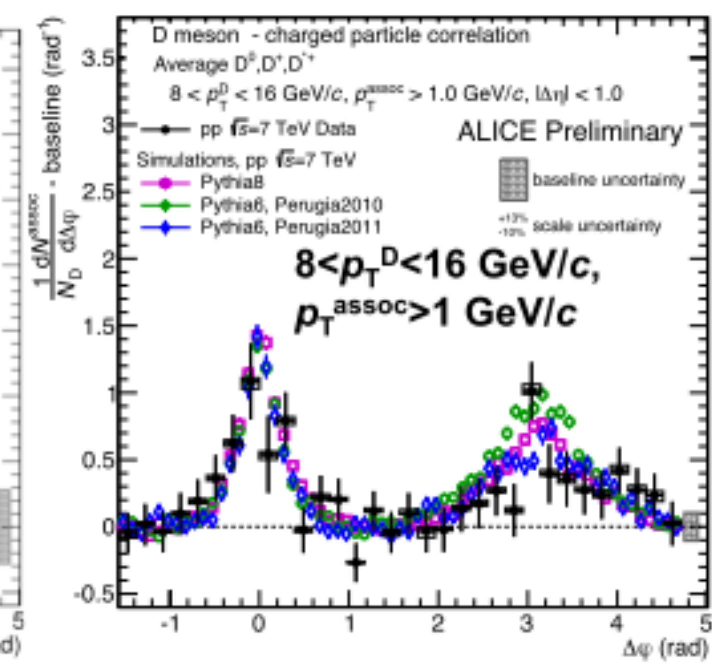
# More differential information: Heavy flavour correlations

- **Measurement of associated hadron yields on the near and away side**
- **Sensitive to charm production mechanism and fragmentation**
  - → **charm jet properties**
  - → **constrain models**



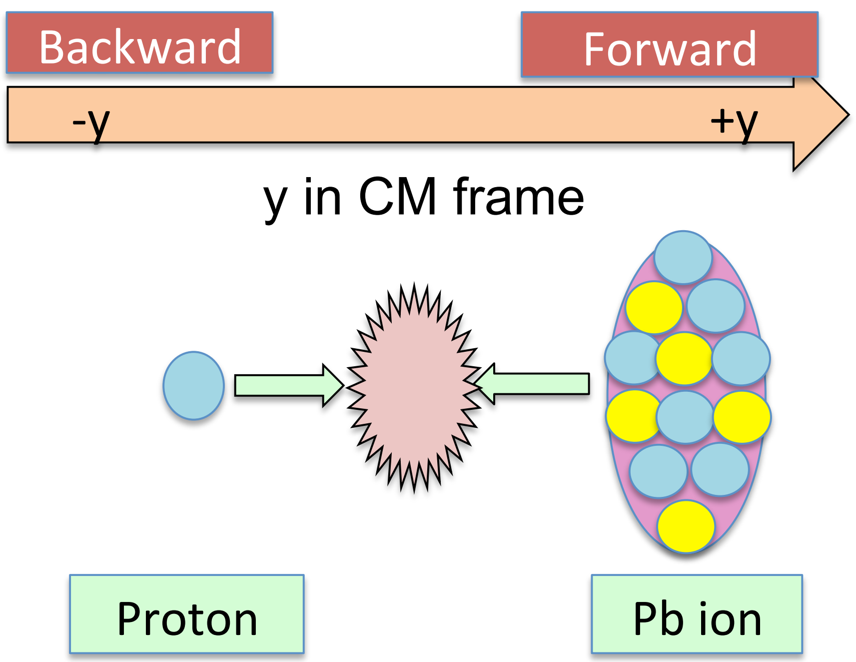




- D-hadron correlations in pp show good agreement with expectations from Pythia (different tunes)
- Better precision requires more data

# Heavy flavours

## Results in p-Pb collisions




**$y_{CMS}$ = 0.465 in the p-beam direction**

## Cold nuclear matter effect

$$\frac{dN^{D}_{PbPb}}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T} \otimes P(\Delta E) \otimes D_{c \to D}(z)$$

### Nuclear modification factor

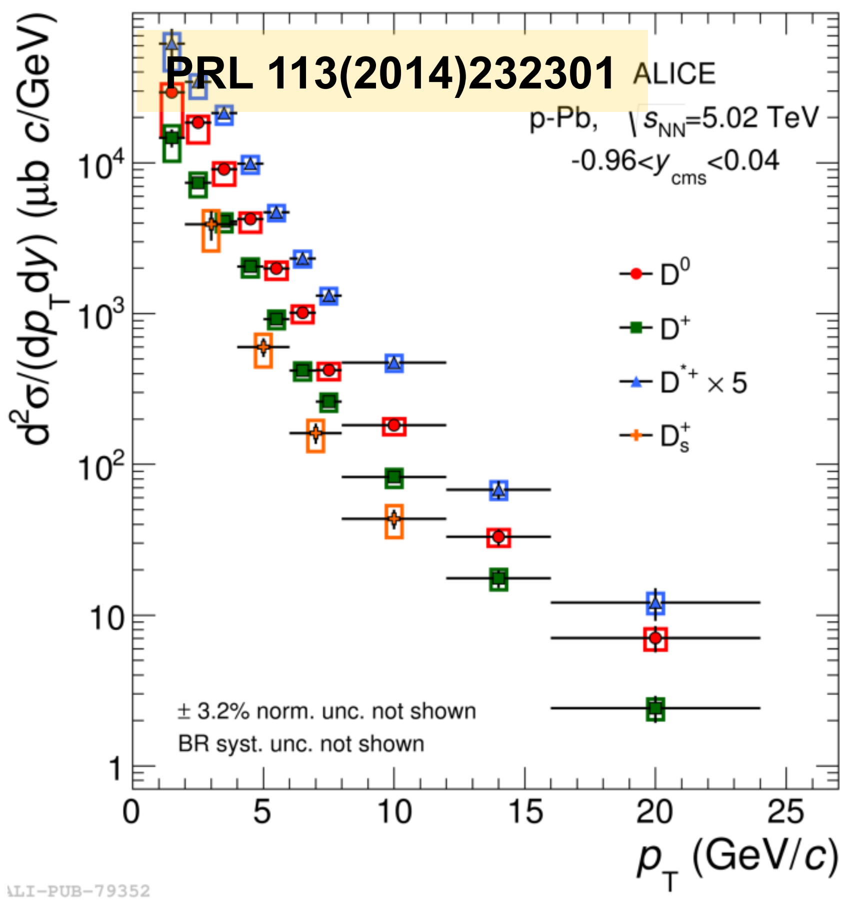
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle \times dN_{pp}/dp_T} = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle \times d\sigma_{pp}/dp_T}$$

**Binary scaling based on the Glauber Model**

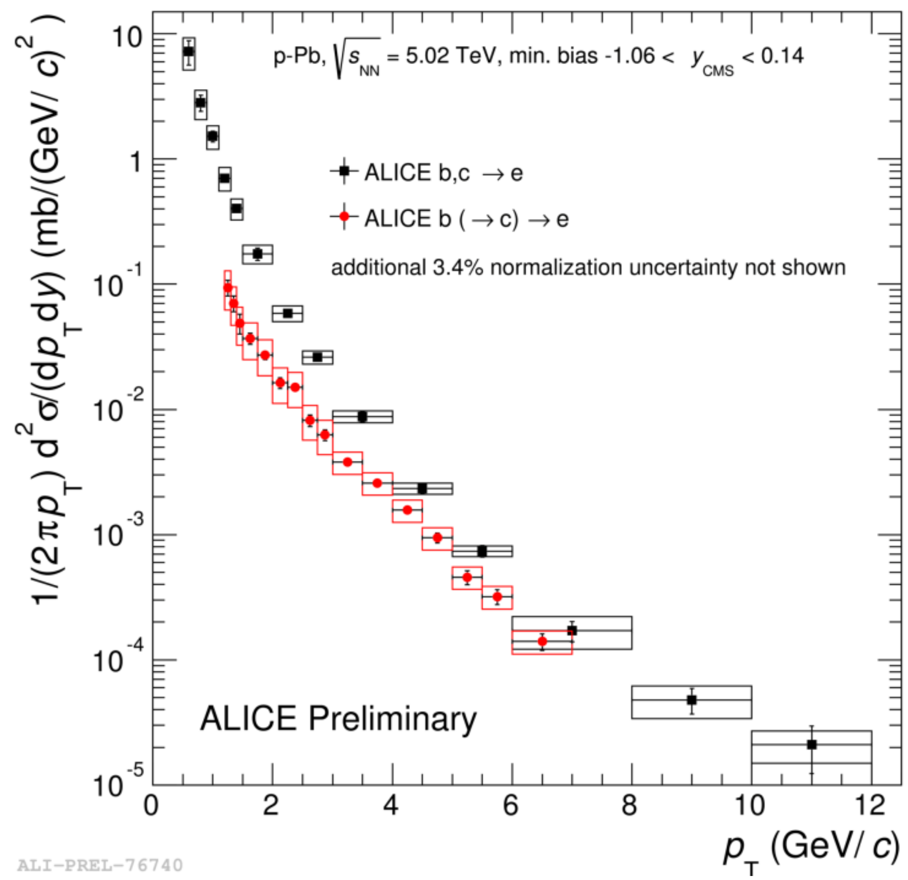
- **$R_{AA}$ = 1: binary scaling**
- **$R_{AA} \neq$ 1: medium effect**

# Heavy flavour in p-Pb

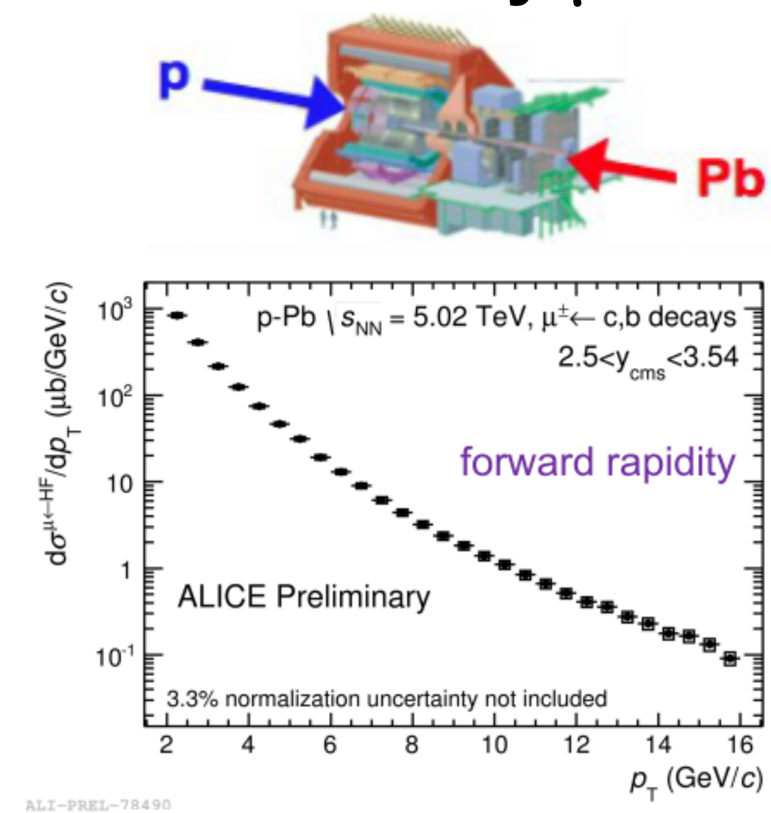
## D mesons

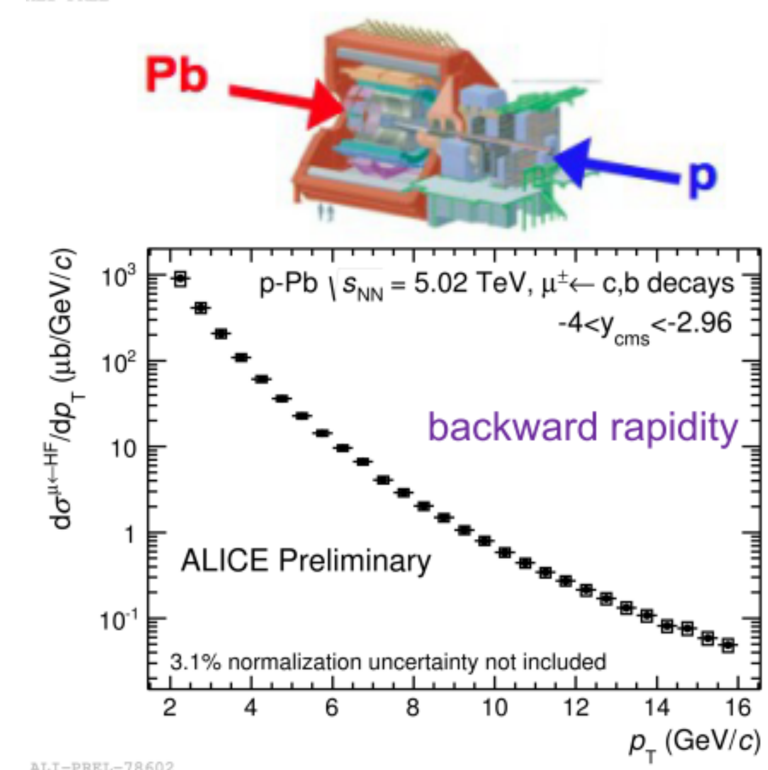



## HF decay e±




## HF decay μ±



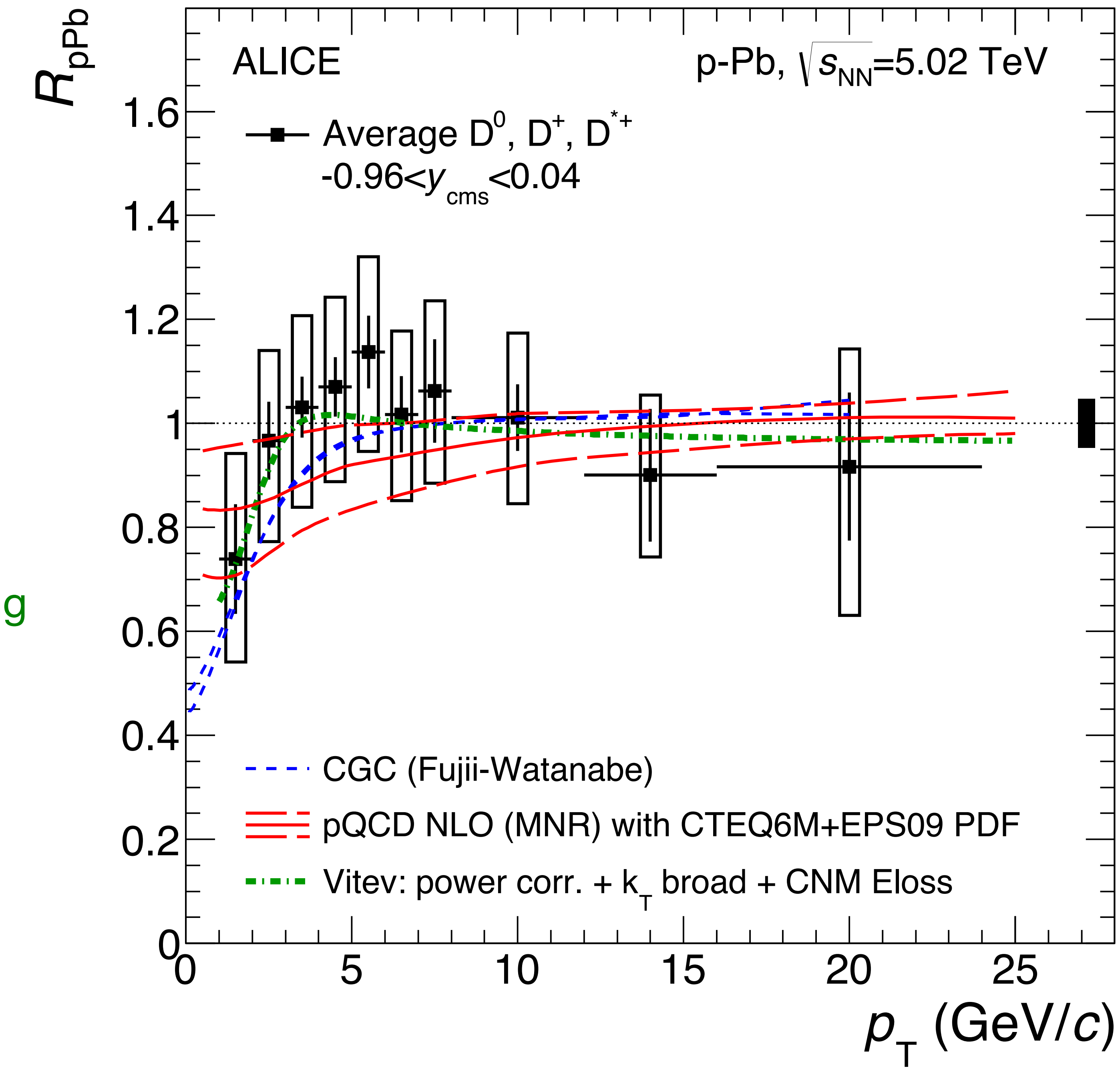




- Heavy-flavor production in p-Pb collisions are measured in all channels!

# Heavy flavour in p-Pb

arXiv:1405.3452

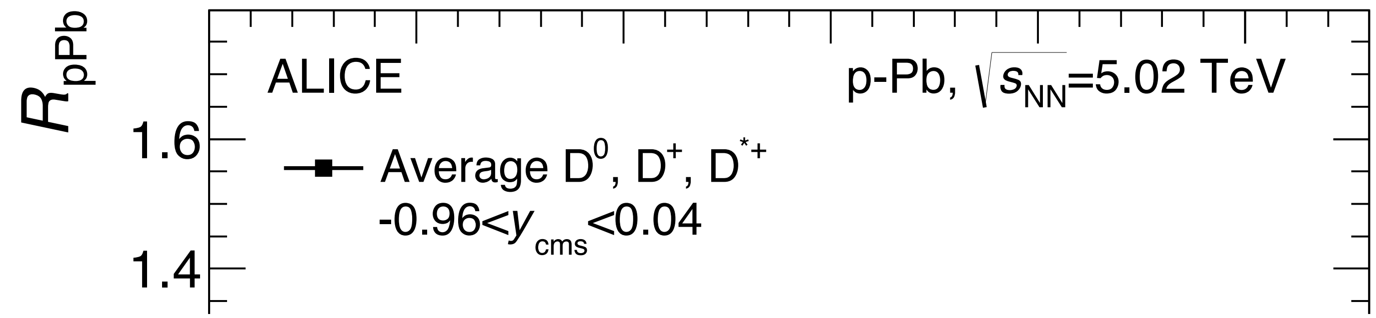
- $R_{pPb}$ measured in various channels
- $R_{pPb}$ consistent with unity within uncertainties
  - ◉ $D^0$, $D^+$, $D^{*+}$ mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and $k_T$-broadening

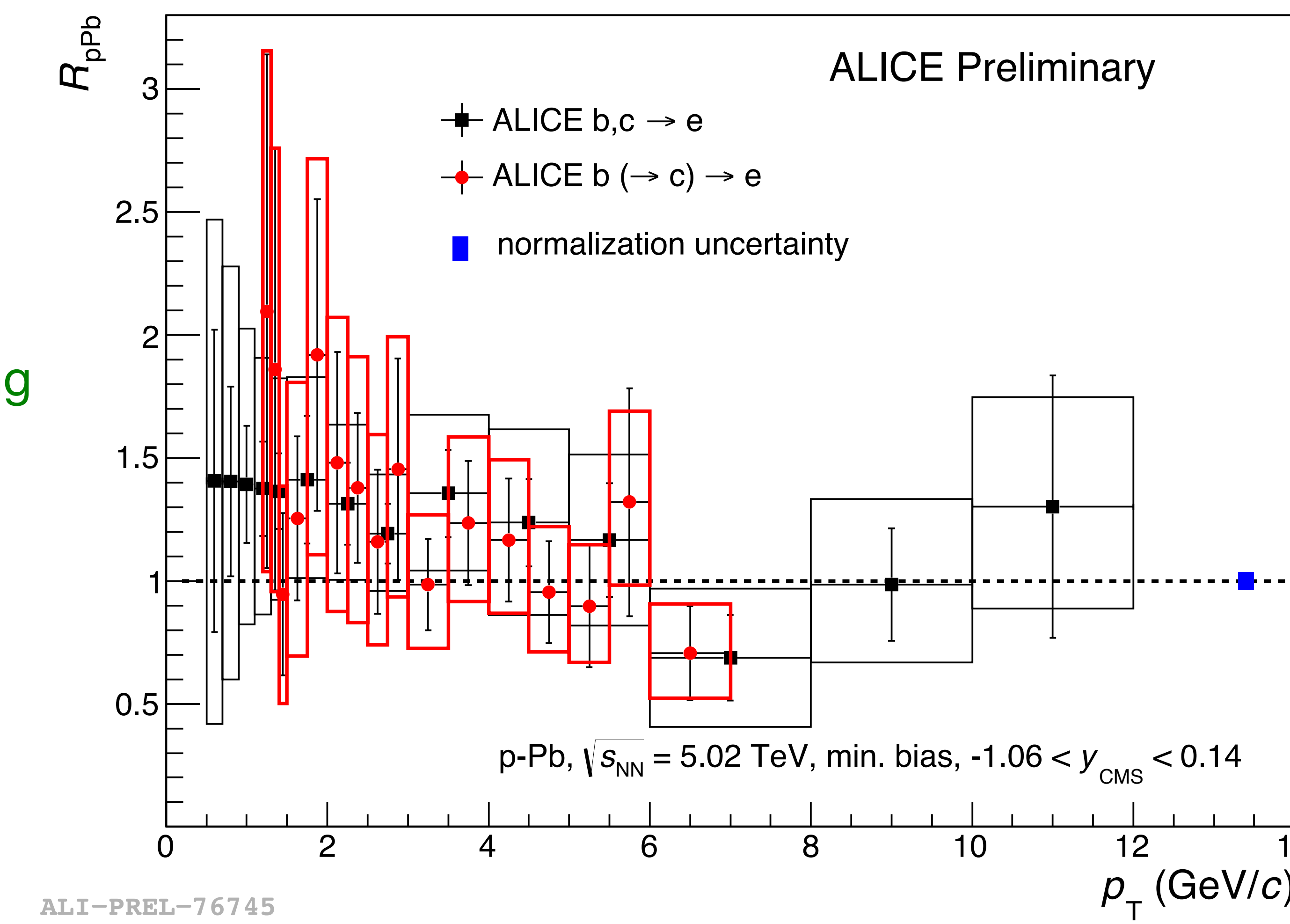


# Heavy flavour in p-Pb

arXiv:1405.3452

- $R_{pPb}$ measured in various channels
- $R_{pPb}$ consistent with unity within uncertainties
  - ◉ $D^0$, $D^+$, $D^{*+}$ mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and $k_T$-broadening
  - ◉ c,b→e & b→e (mid rapidity)



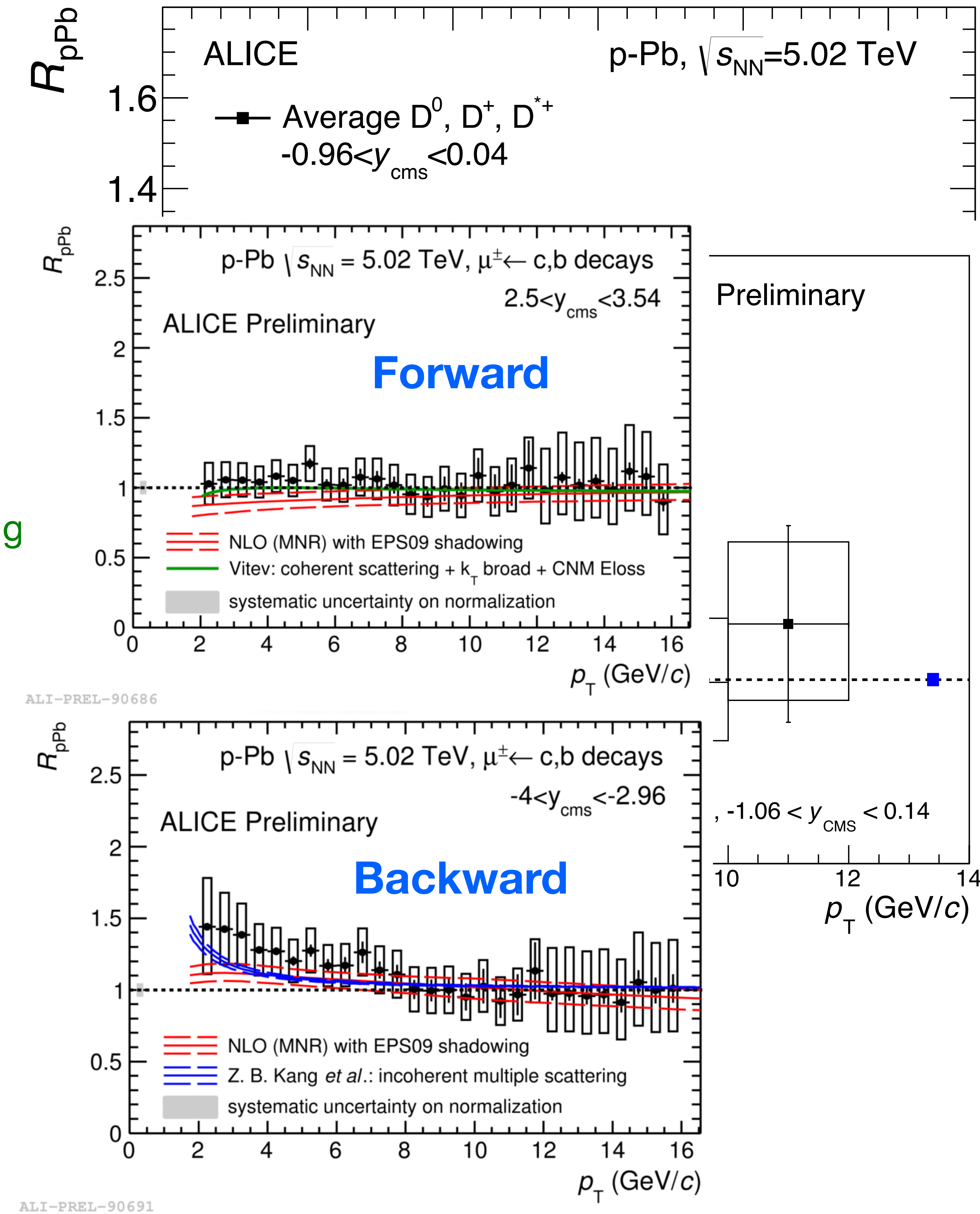



# Heavy flavour in p-Pb

- $R_{pPb}$ measured in various channels
- $R_{pPb}$ consistent with unity within uncertainties
  - ◉ $D^0$, $D^+$, $D^{*+}$ mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and $k_T$-broadening
  - ◉ c,b→e & b→e (mid rapidity)
  - ◉ c,b→μ:
    - at forward, consistent with unity within uncertainties
    - at backward, slightly larger than unity in $2<p_T<4$ GeV

Within uncertainties, data can be described by pQCD calculations with EPS09 parameterization of shadowing

arXiv:1405.3452



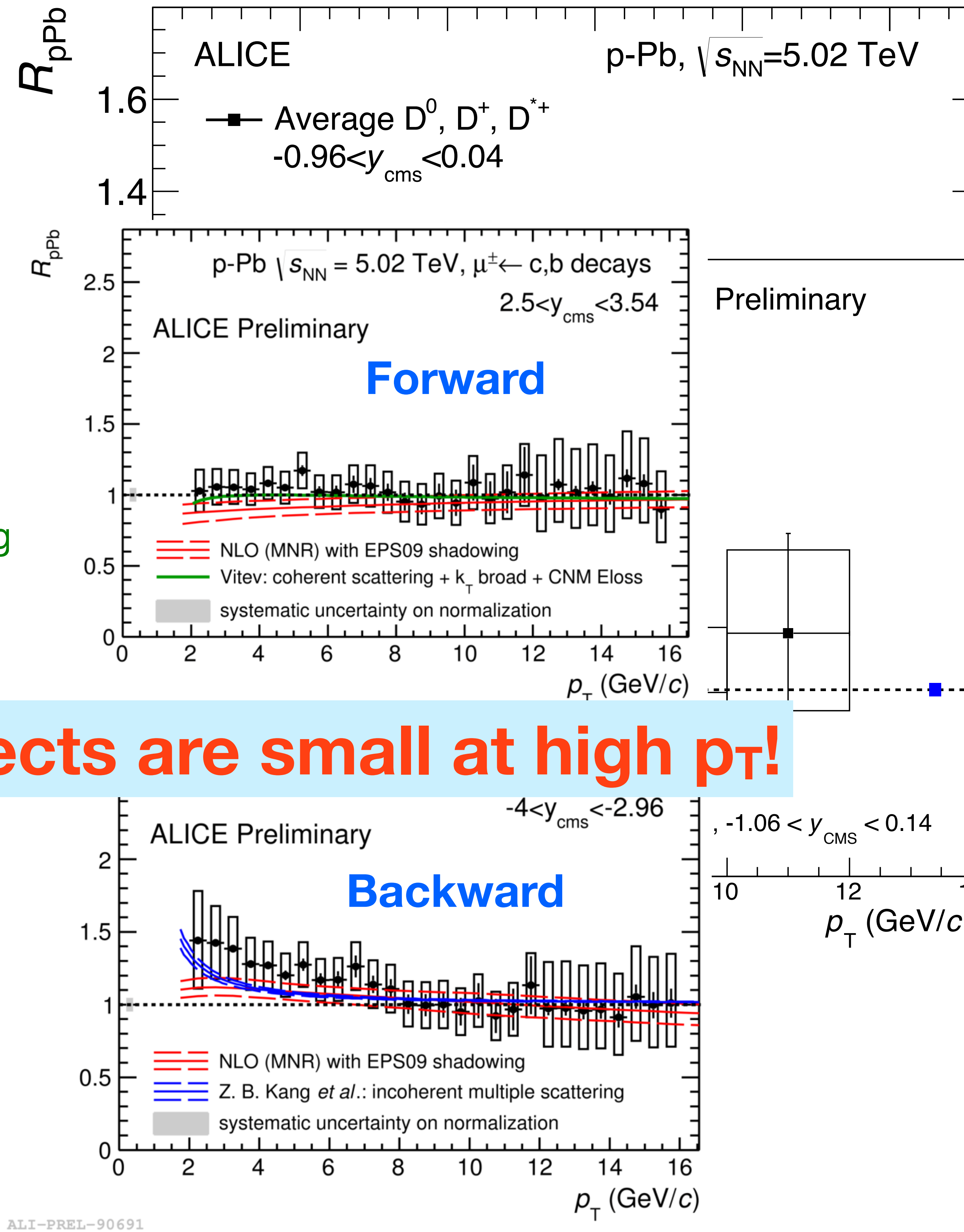
# Heavy flavour in p-Pb

arXiv:1405.3452

- $R_{pPb}$ measured in various channels
- $R_{pPb}$ consistent with unity within uncertainties
  - ◉ $D^0$, $D^+$, $D^{*+}$ mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and $k_T$-broadening
  - ◉ c,b→e & b→e (mid rapidity)
  - ◉ c,b→μ:
    - within uncertainties
    - at backward, slightly larger than unity in $2<p_T<4$ GeV

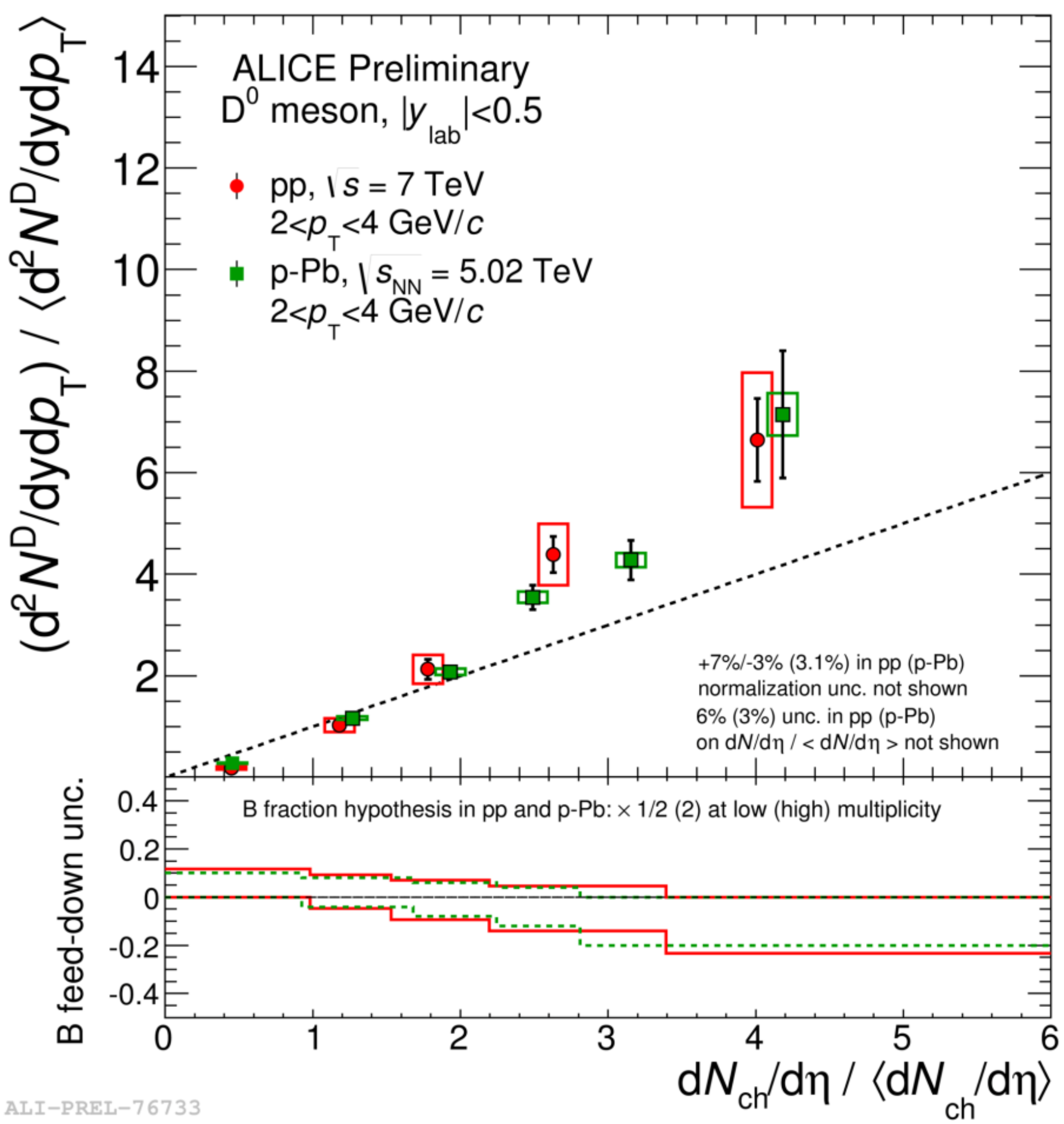
Within uncertainties, data can be described by pQCD calculations with EPS09 parameterization of shadowing

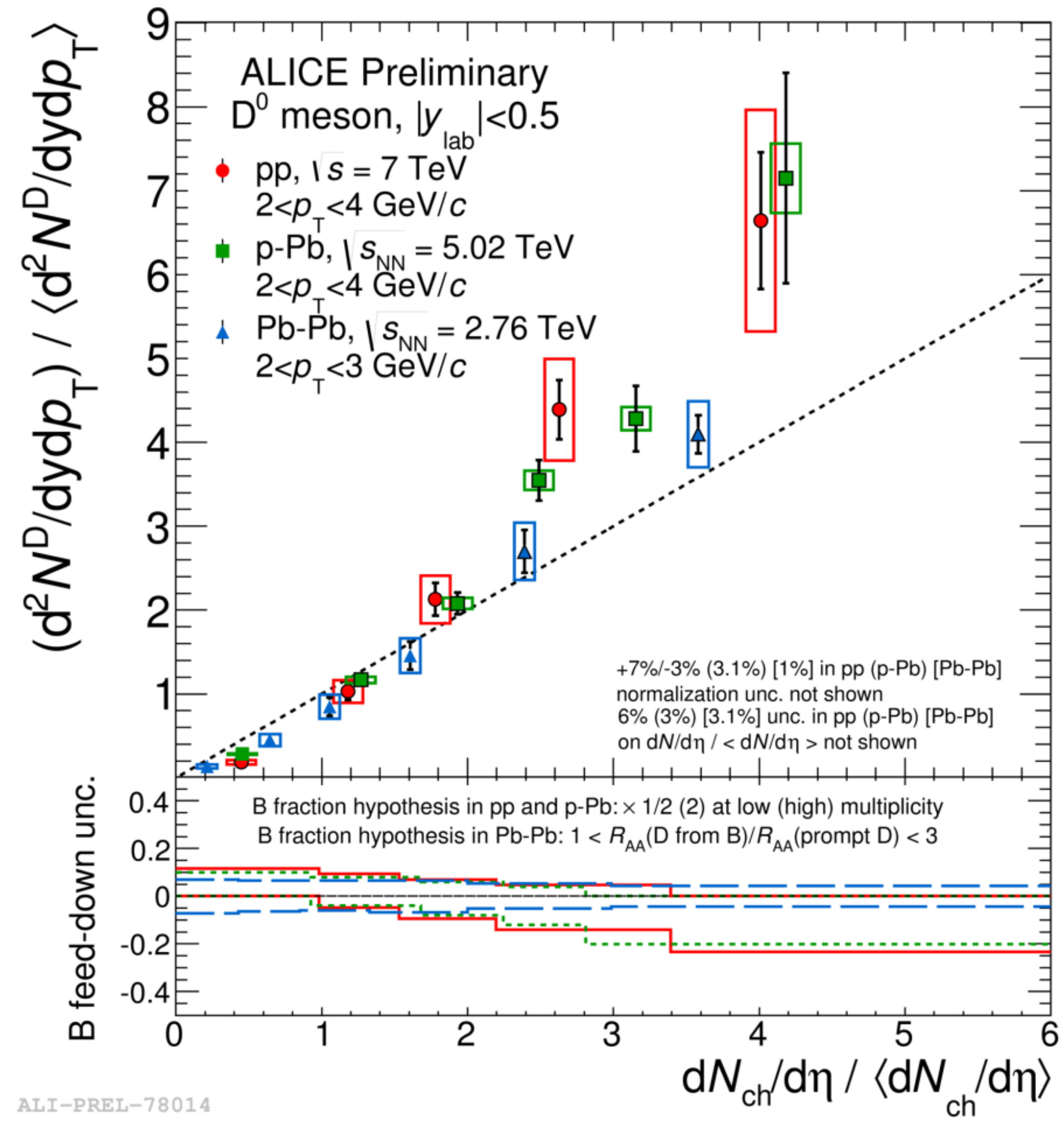
**Cold nuclear matter effects are small at high $p_T$!**



# More on production mechanism:
# Multiplicity dependences of D-meson yields

## Self-normalized D-meson yields vs. charged-particle multiplicity



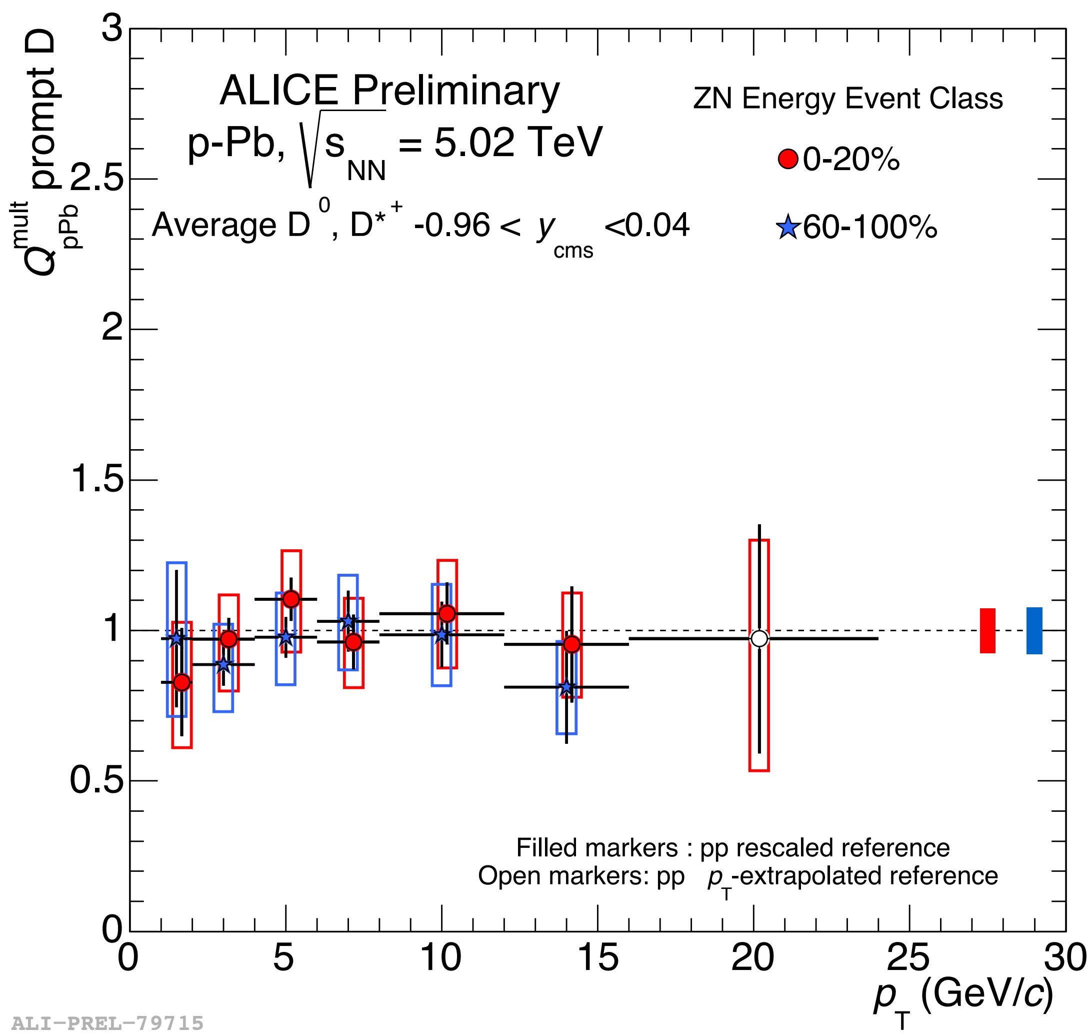



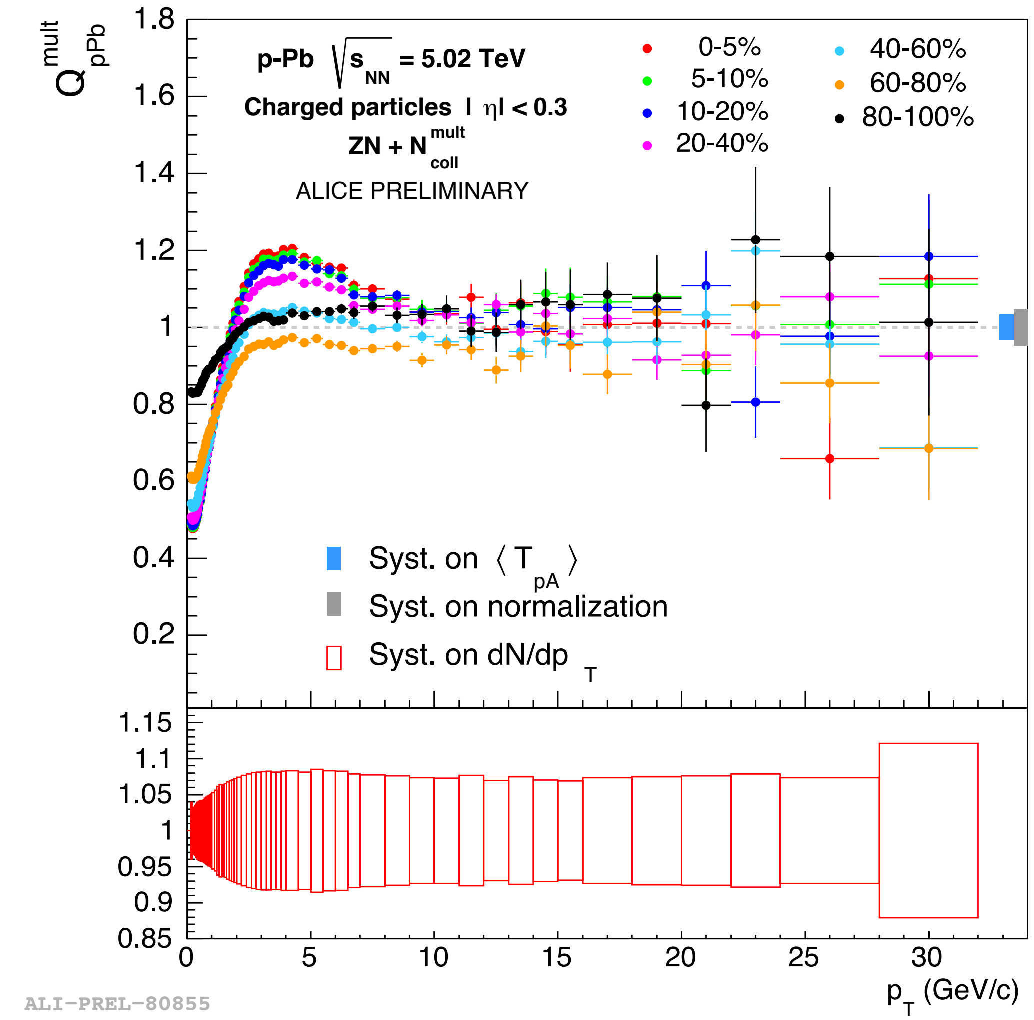

- **similar trend of D-meson yields vs. multiplicity in pp and p-Pb collisions**
  - **pp collisions: high-multiplicity events mainly from MPI**
  - **p-Pb collisions: high multiplicity events also due to $N_{coll} > 1$**
- **similar trend also in Pb-Pb collisions**
  - **highest multiplicity bin in Pb-Pb (pp) collisions: 10% (1%) of the total cross section**

# More differential information:
# Multiplicity dependence of modification

Investigate the scaling of charm production in p-Pb collisions w.r.t. pp collisions

$$Q_{\rm pPb}^{\rm V0A}(p_{\rm T}) = \frac{{\rm d}N^{\rm pPb}_{\rm mult}/{\rm d}p_{\rm T}}{N_{\rm coll}^{\rm Glauber}\,{\rm d}N^{\rm pp}/{\rm d}p_{\rm T}}$$



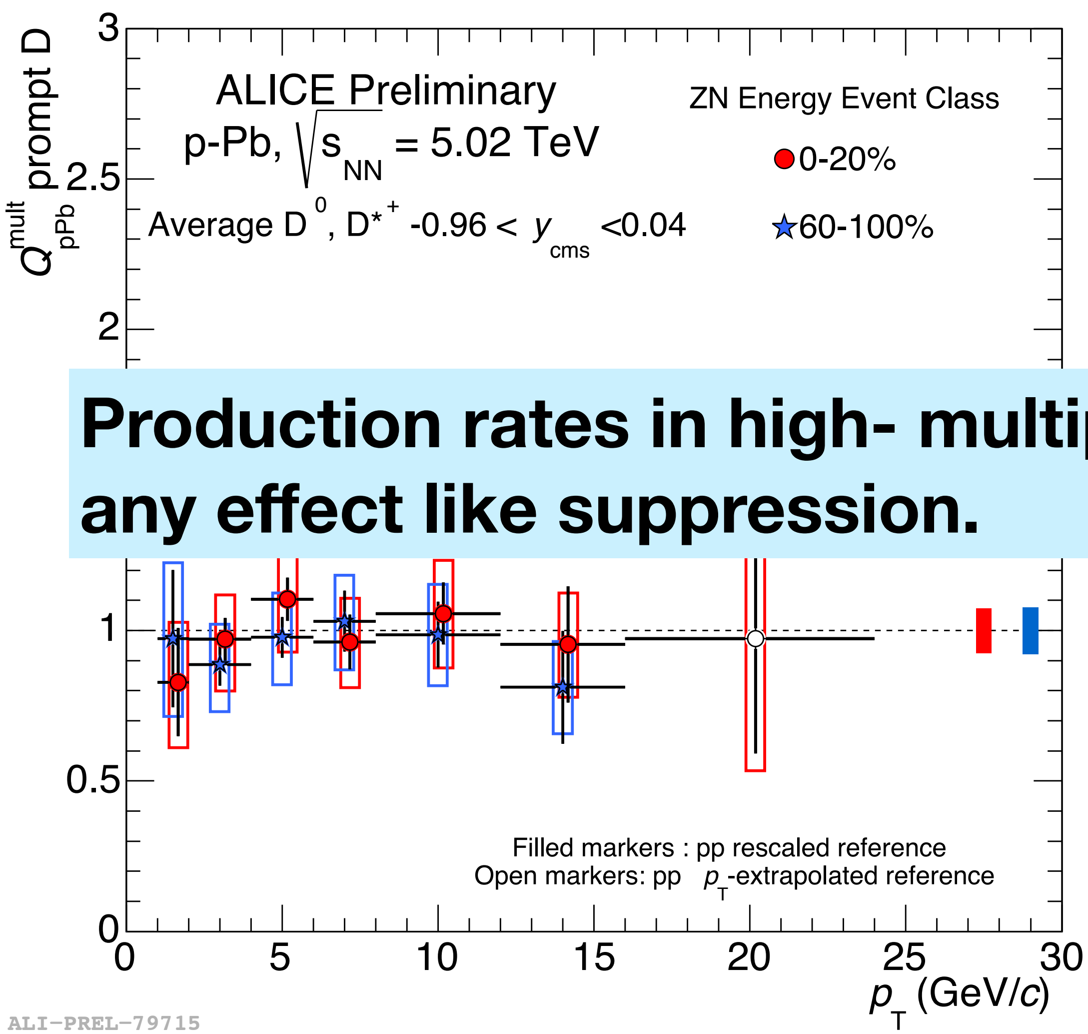

For charm, no multiplicity dependent modification of the $p_T$ spectra in p-Pb

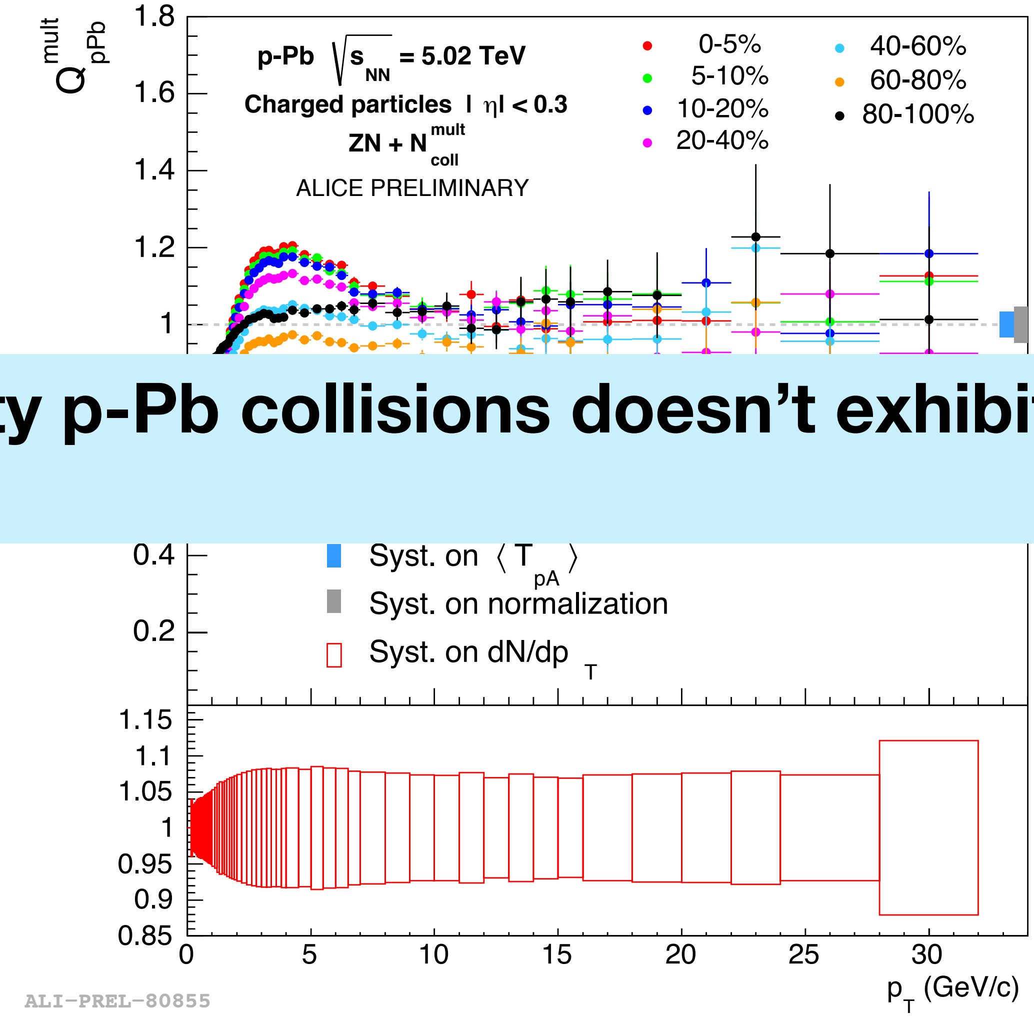
Similar pattern for D mesons and high-$p_T$ charged particles

# More differential information:
# Multiplicity dependence of modification

Investigate the scaling of charm production in p-Pb collisions w.r.t. pp collisions

$$\boxed{Q^{\mathrm{V0A}}_{\mathrm{pPb}}(p_{\mathrm{T}})} = \frac{\mathrm{d}N^{\mathrm{pPb}}_{\mathrm{mult}}/\mathrm{d}p_{\mathrm{T}}}{N^{\mathrm{Glauber}}_{\mathrm{coll}}\mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$




**Production rates in high- multiplicity p-Pb collisions doesn't exhibit any effect like suppression.**

For charm, no multiplicity dependent modification of the $p_{\mathrm{T}}$ spectra in p-Pb

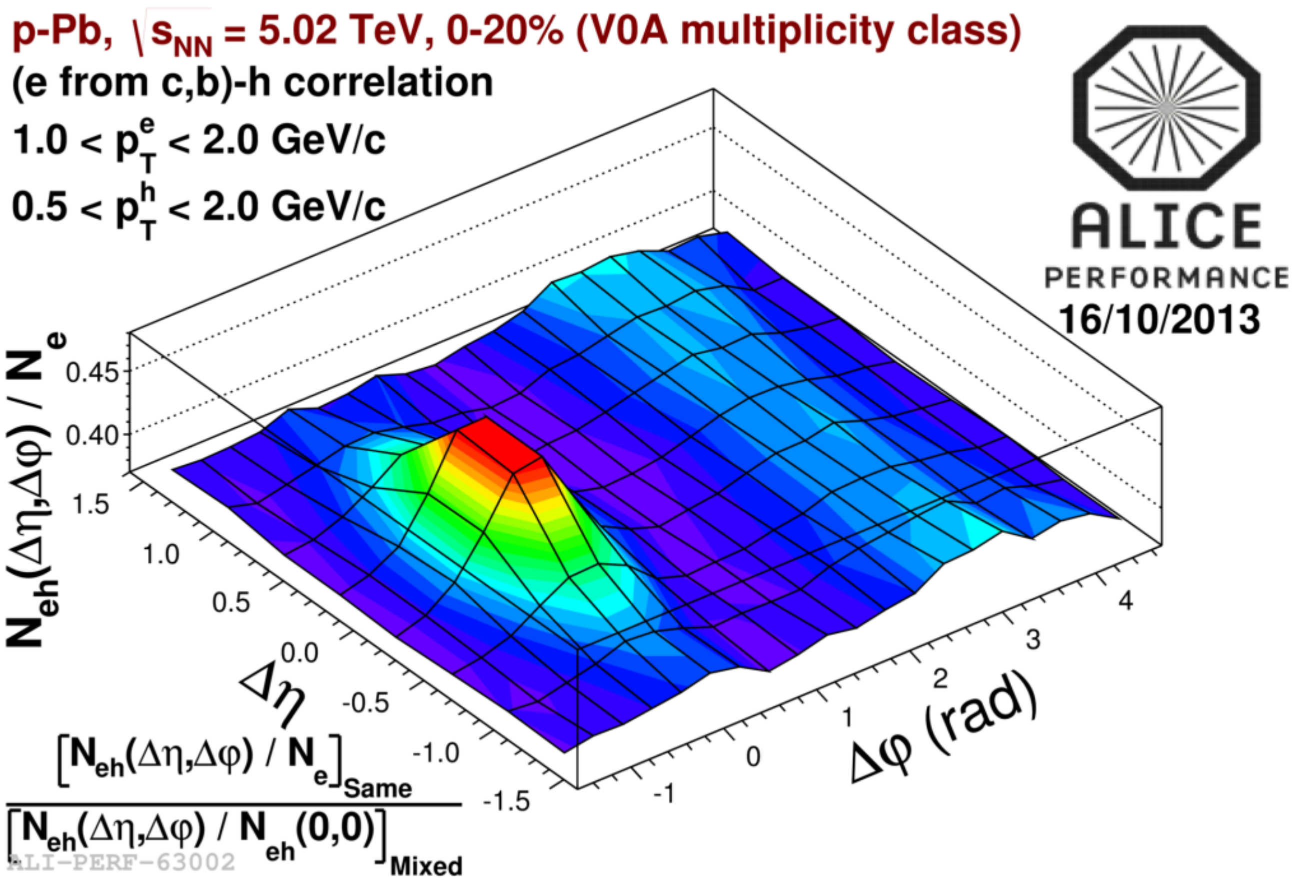
Similar pattern for D mesons and high-$p_{\mathrm{T}}$ charged particles

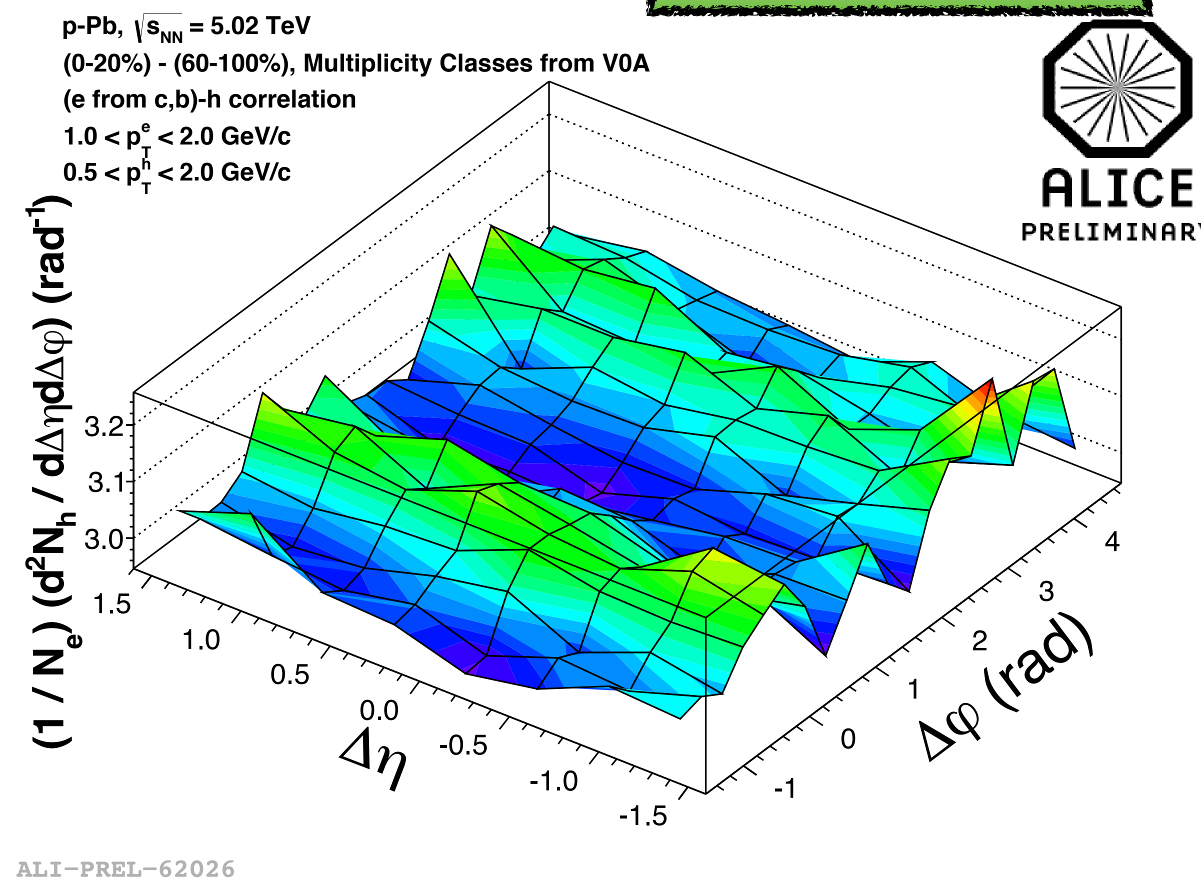
# More differential information:
# Heavy-flavour electron-hadron correlations

## Angular correlation between an electron from heavy-flavor hadron decay (trigger particle) and a charged hadron (associated particle)

- **various electron and hadron $p_T$ ranges in multiplicity classes**

*Multiplicity class:*
*(0-20%) - (60-100%)*




*Resembles the structure that in AA is interpreted in terms of collective flow*

**The double ridge also observed in heavy-flavour sector!**

**The mechanism (CGC? Hydro?) that generates it affects also HF**

# Heavy flavours

## Results in Pb-Pb collisions


**Final state effect**

### Nuclear modification factor

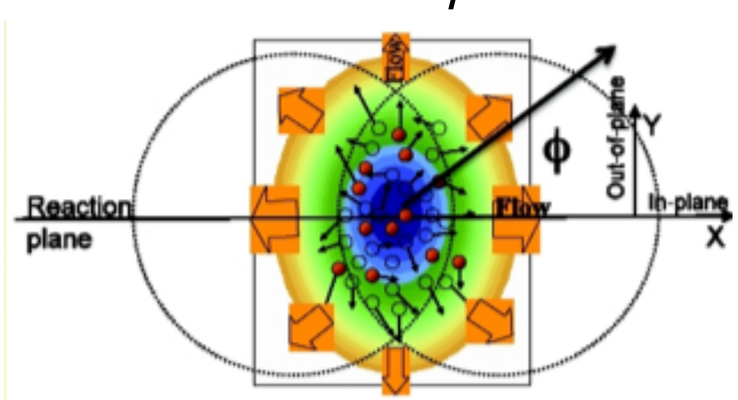
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \times dN_{pp}/dp_T} = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

**Binary scaling based on the Glauber Model**

- **$R_{AA}$ = 1: binary scaling**
- **$R_{AA} \neq 1$: medium effect**

### Anisotropic flow: $v_2$

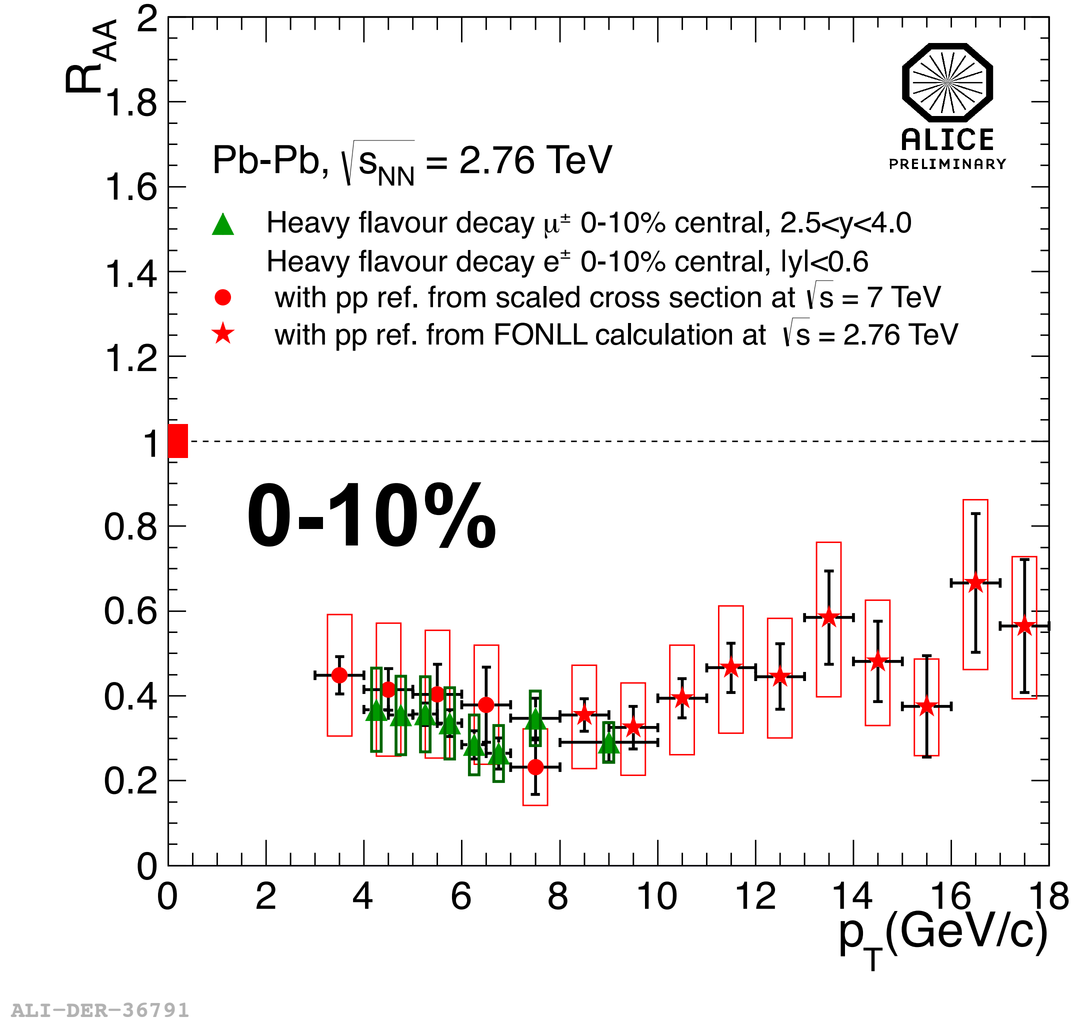
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_{RP}) + \boxed{2v_2\cos[2(\varphi - \Psi_{RP})]} + \ldots\right)$$

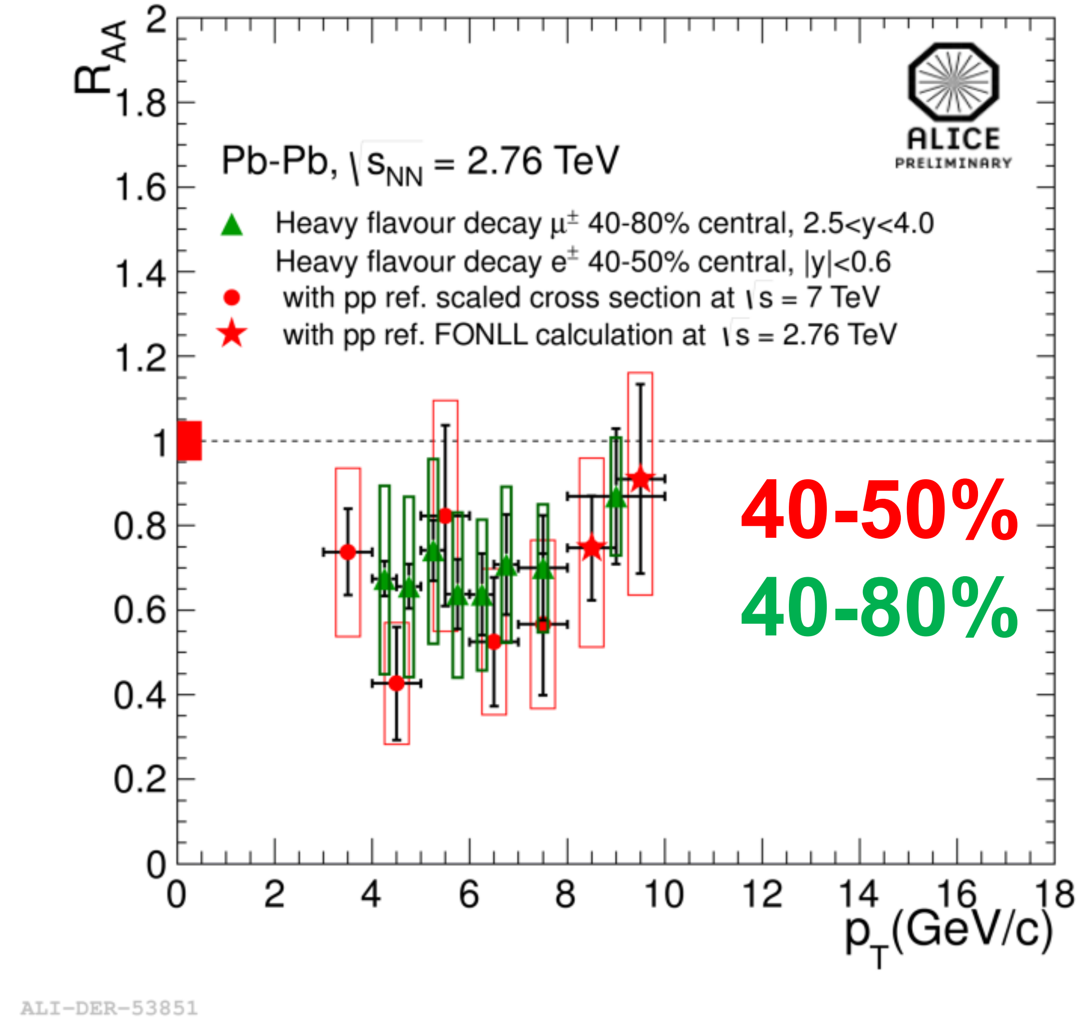



Initial spatial anisotropy $\xrightarrow{\text{via re-scatterings}}$ momentum anisotropy of particle emission

The anisotropy is quantified via a Fourier expansion in azimuthal angle ($\varphi$) with respect to the reaction plane ($\Psi_{RP}$)

# HF-decay lepton $R_{AA}$

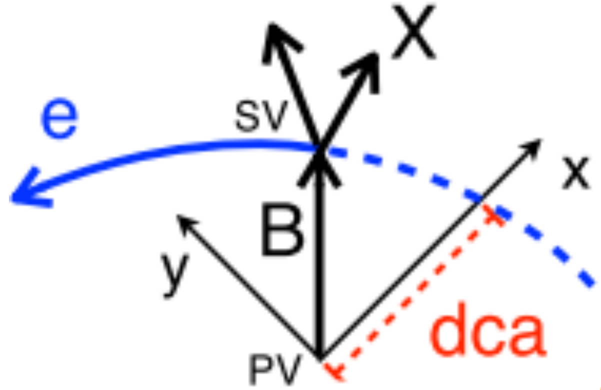


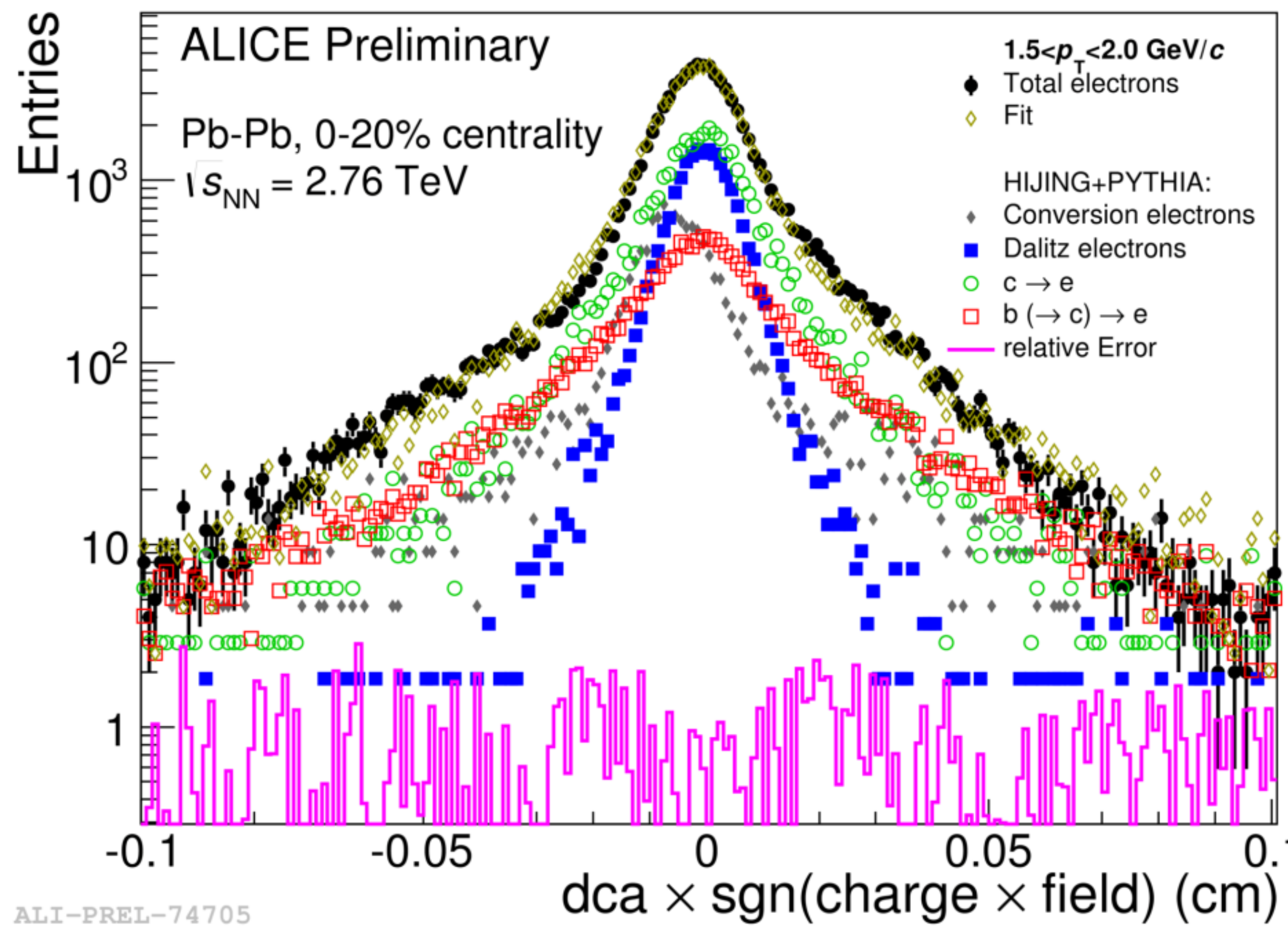




- Significant suppression at high $p_T$ in central Pb-Pb collisions w.r.t. binary scaled pp collisions
  - HF decay electron (|y| < 0.6) and muon (2.5 < y < 4) $R_{AA}$ are similar
  - Less suppression in more peripheral collisions

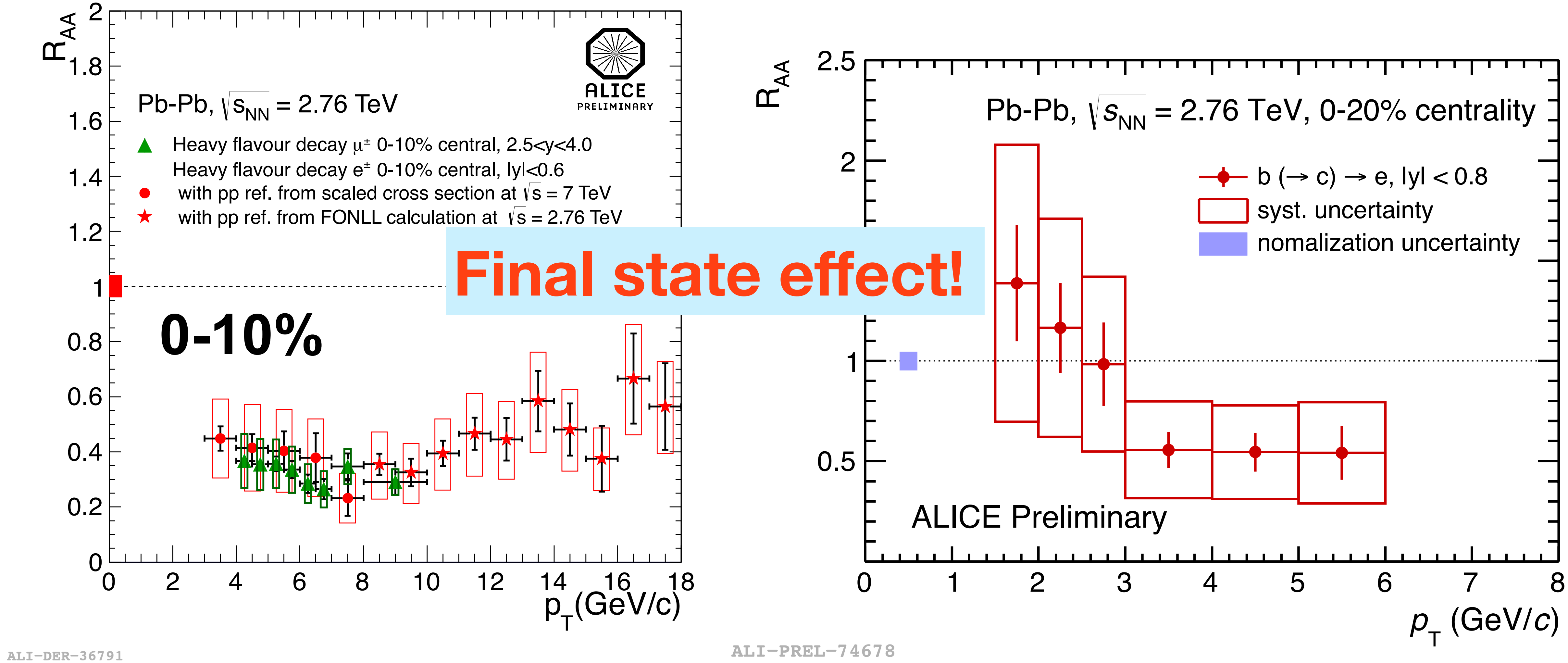
# HF-decay lepton $R_{AA}$

- $R_{AA}$ of electrons from beauty decays in 0-20% central Pb-Pb collisions
  - analysis based on the measured electron impact parameter distribution



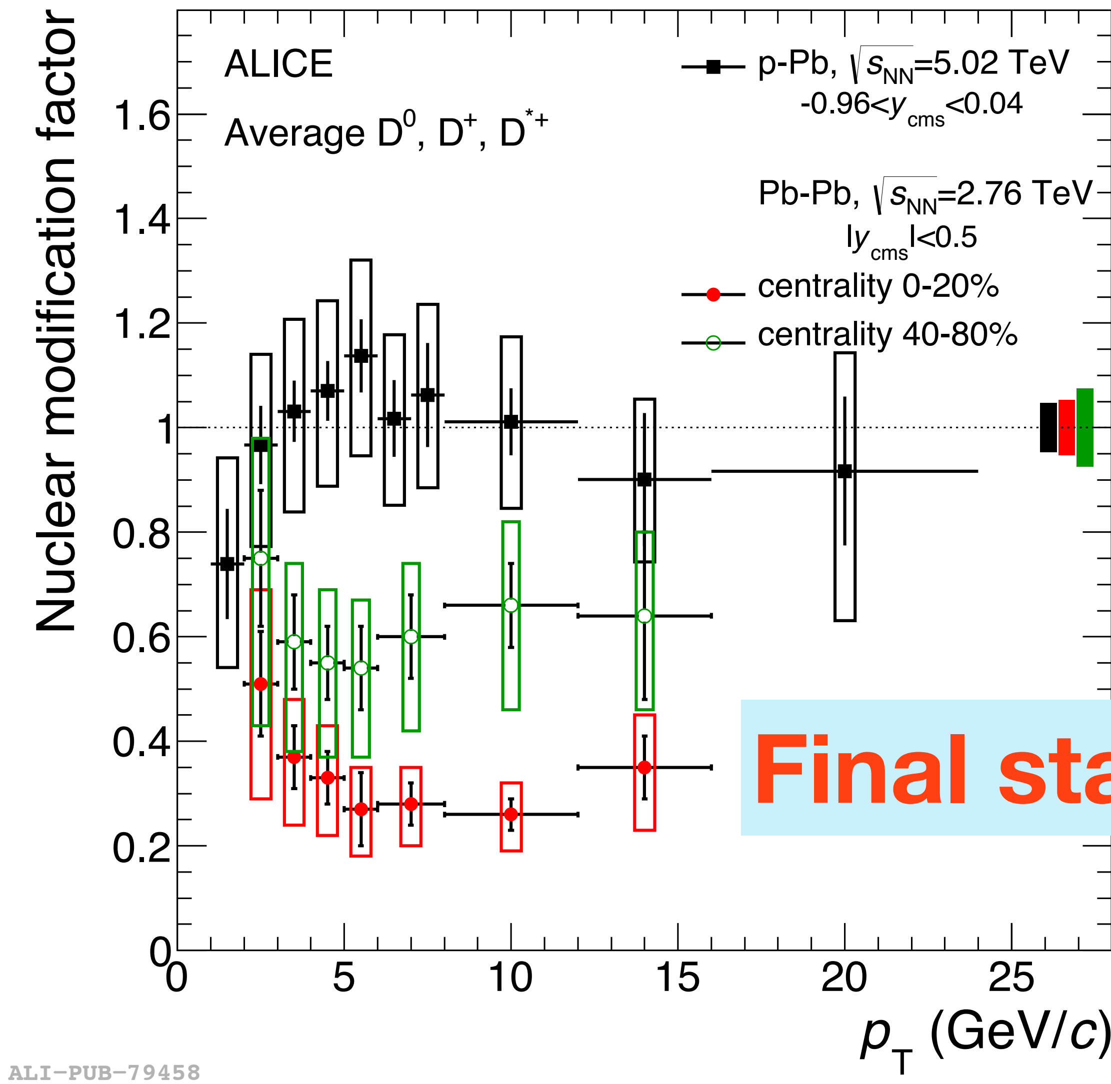



# HF-decay lepton $R_{AA}$

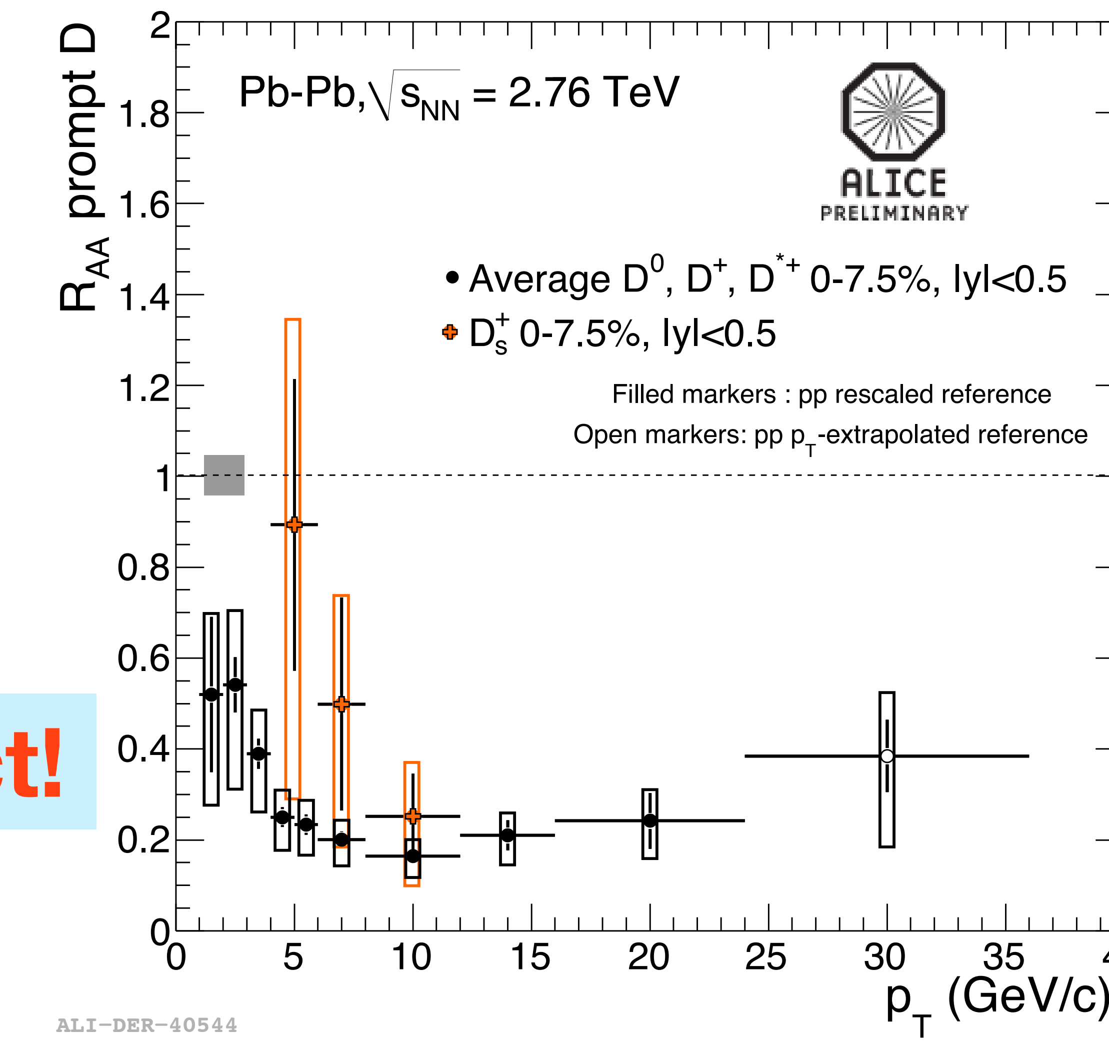



- Significant suppression at high $p_T$ in central Pb-Pb collisions w.r.t. binary scaled pp collisions
  - HF decay electron (|y| < 0.6) and muon (2.5 < y < 4) $R_{AA}$ are similar
  - Less suppression in more peripheral collisions
  - $R_{AA}$ of electrons from beauty decays in 0-20% shows **hint of suppression**
- Cold nuclear matter effects are small ($R_{pPb}$ ~ 1)
- Suppression due to final state effect

# D meson $R_{AA}$ in p-Pb and Pb-Pb




**Final state effect!**




- p-Pb results indicate that the suppression observed in Pb-Pb comes from strong interaction of charm quarks with the medium

- $D_s^+$ suppressed by a factor ~3 for $8 < p_T < 12$ GeV/c
  - more statistics needed at low $p_T$ where enhancement of $D_s^+/D$ due to coalescence is predicted:

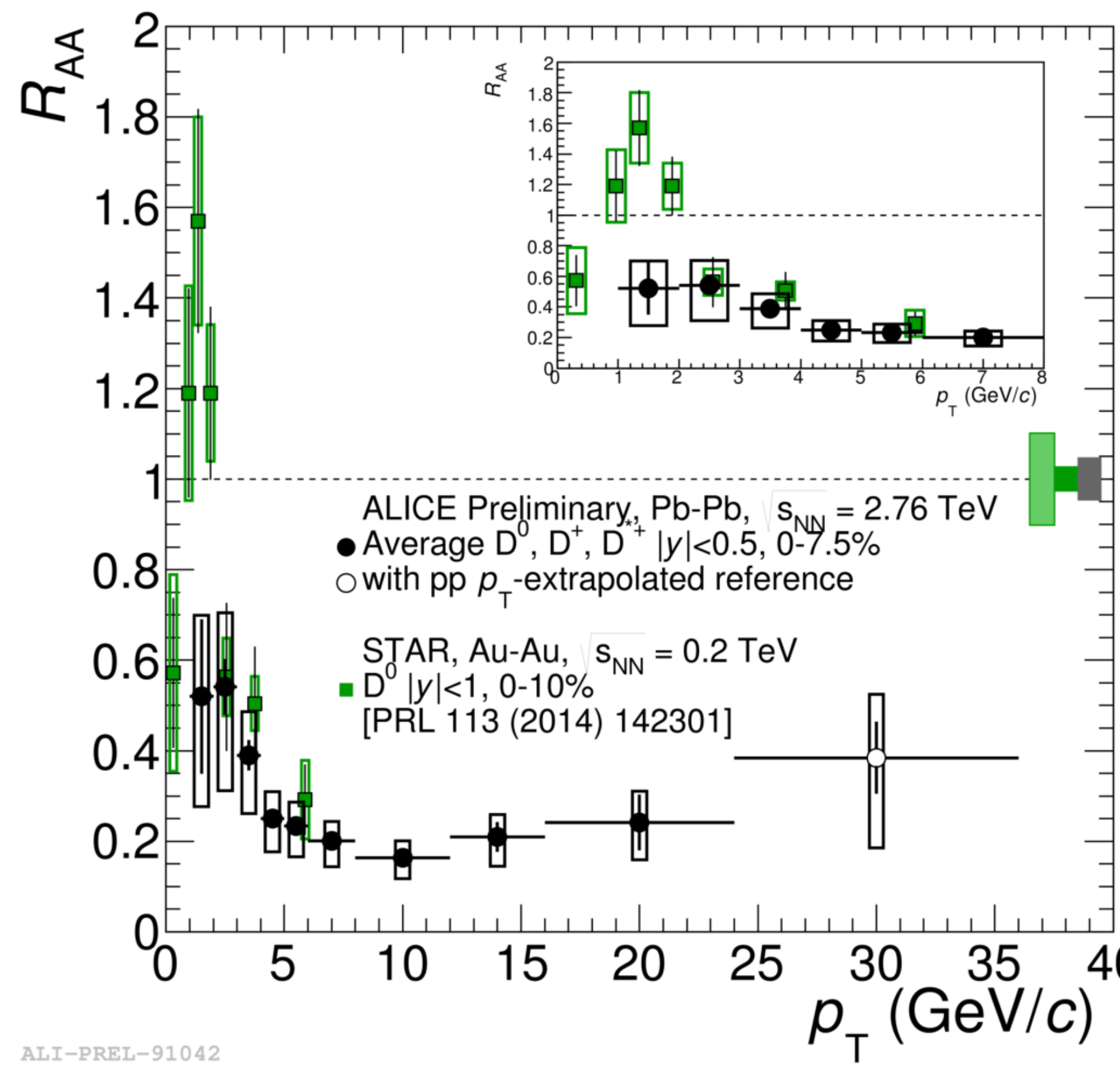
Kuznetsova, Rafelski EPJ C 51 (2007) 113
He et al. PRL 110 (2013) 112301
Andronic et al. PLB 659 (2008) 149

# D meson $R_{AA}$: LHC vs. RHIC

- D mesons at the LHC and at RHIC
  - different trend for $D^0$-meson $R_{AA}$ at $p_T$ ~ 2 GeV/c?
- differences between

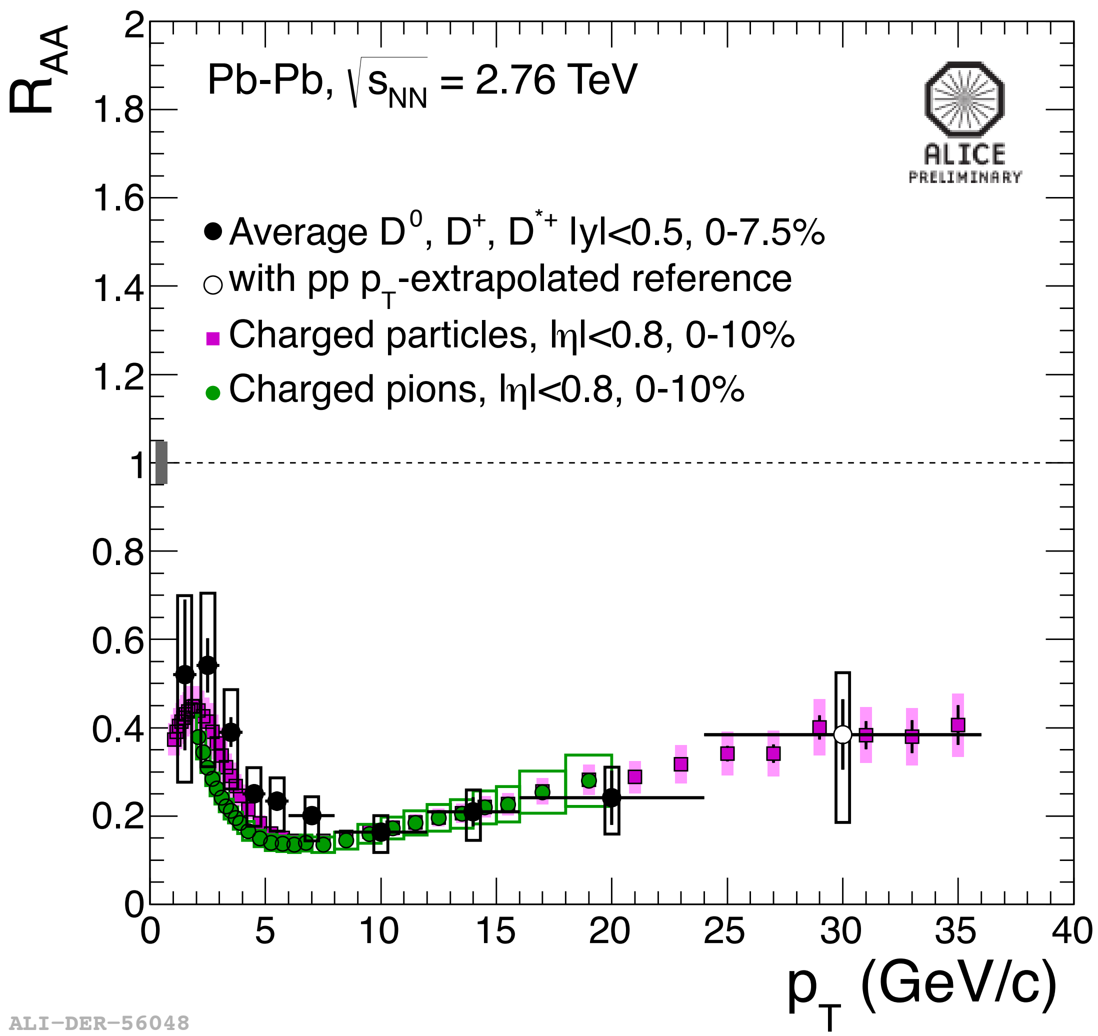
  Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV &

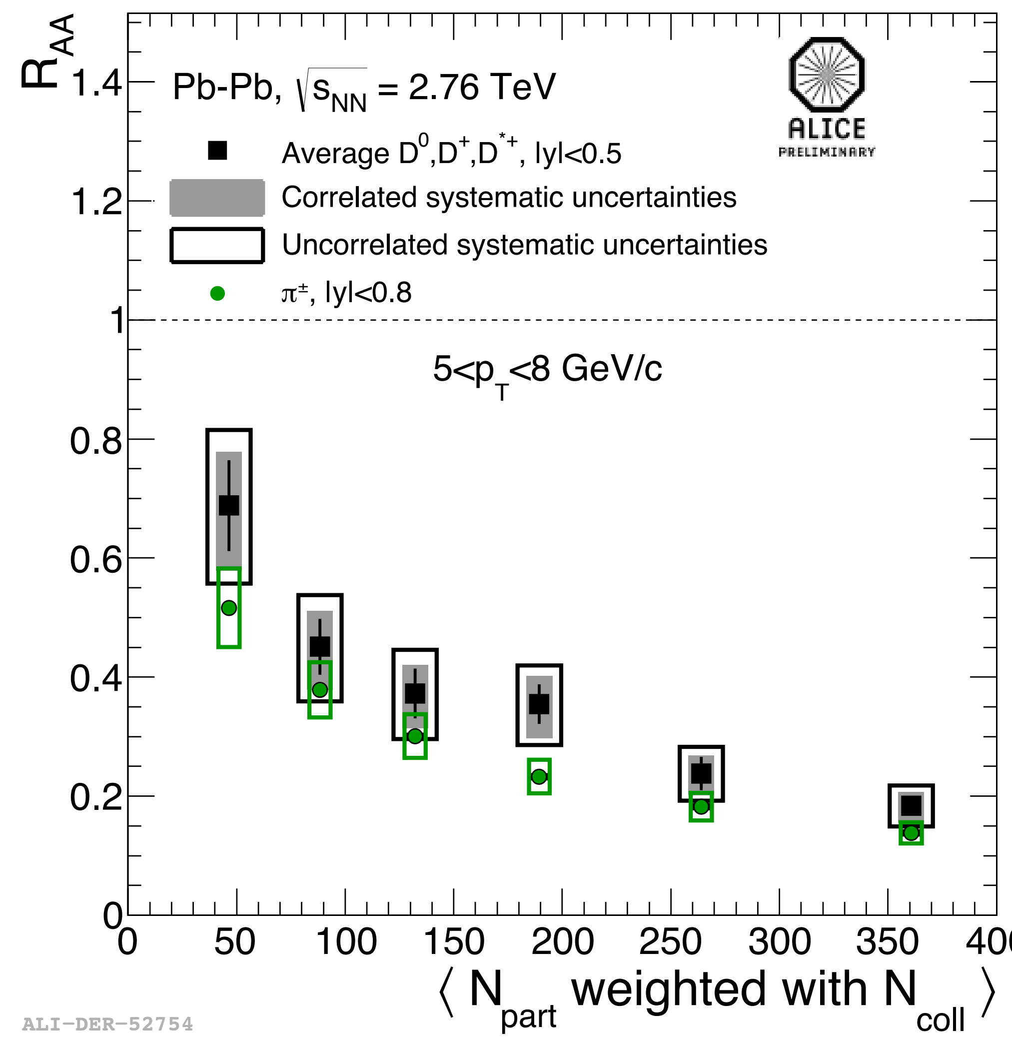
  Au-Au collisions at $\sqrt{s_{NN}}$ = 0.2 TeV
  - different shape of pp reference
  - different modification of nPDFs
  - different radial flow
- some models describe both measurements reasonably well (e.g. TAMU, PLB 735(2014)445)



# Color charge dependence?: D-meson $R_{AA}$ vs. $\pi^{\pm}$

$\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b)$ could reflected in $R_{AA}(B) >$ $R_{AA}(D) > R_{AA}(\pi)$

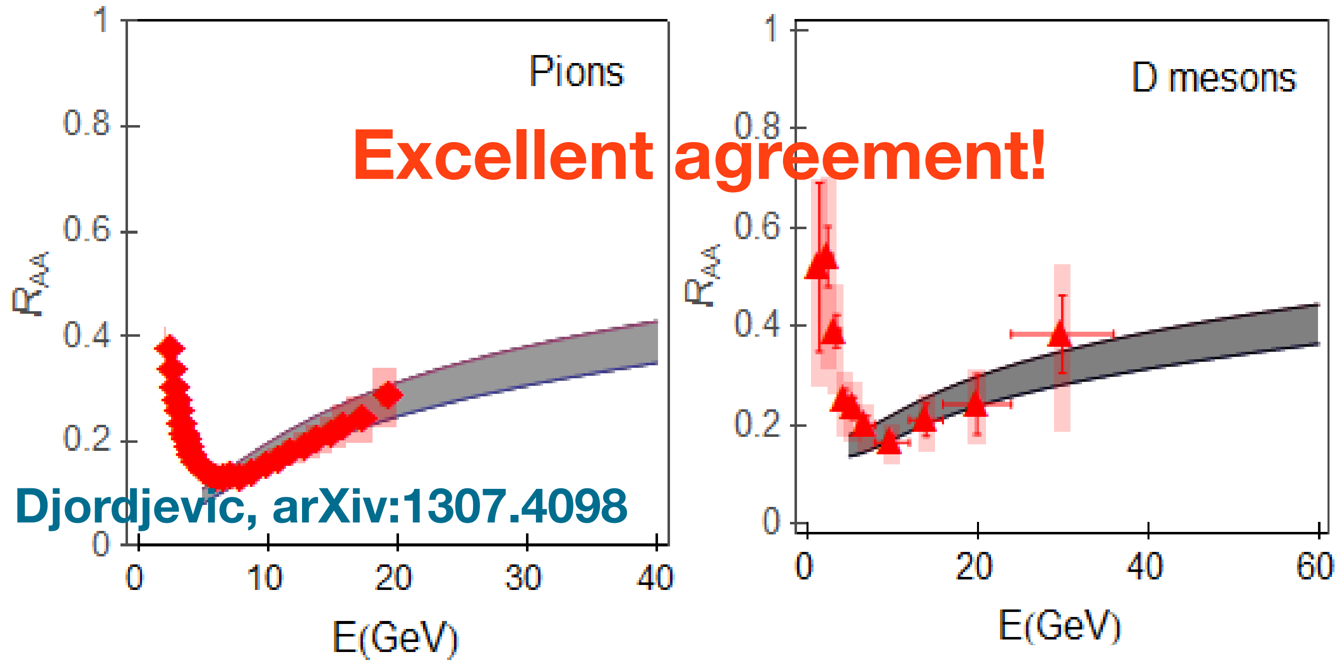



- D-meson and π $R_{AA}$ are compatible within uncertainties
- Measurement not yet conclusive
- Agreement with models including
  - energy loss hierarchy: $\Delta E(g) > \Delta E(u,d,s) > \Delta E(c)$
  - different shapes of the parton $p_T$ distributions
  - different fragmentation functions
  - soft production mechanisms for low-$p_T$ π

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

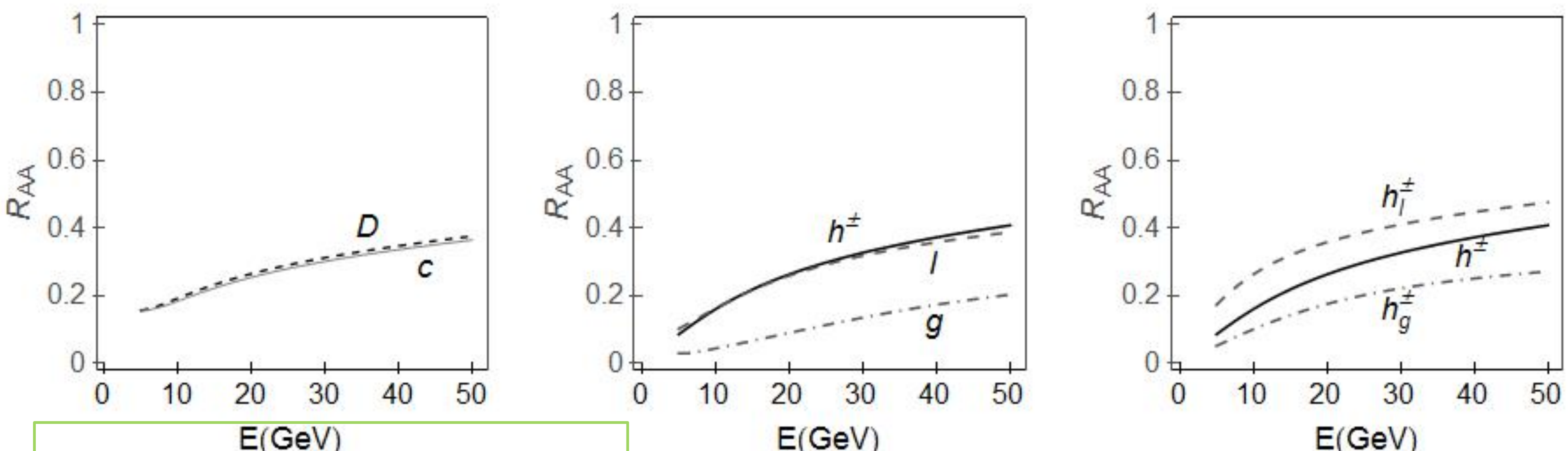
# Color charge dependence?: D-meson $R_{AA}$ vs. $\pi^{\pm}$




**Excellent agreement!**

**Djordjevic, arXiv:1307.4098**

Calculation by M. Djordjevic (rad+coll energy loss) can describe both $R_{AA}$




Shows strong colour charge effect in partonic $R_{AA}$ (g vs. light and c)

**$R_{AA}$ (D) = $R_{AA}$ (charm)**

**$R_{AA}$ (light quarks) = $R_{AA}$ (charm)**

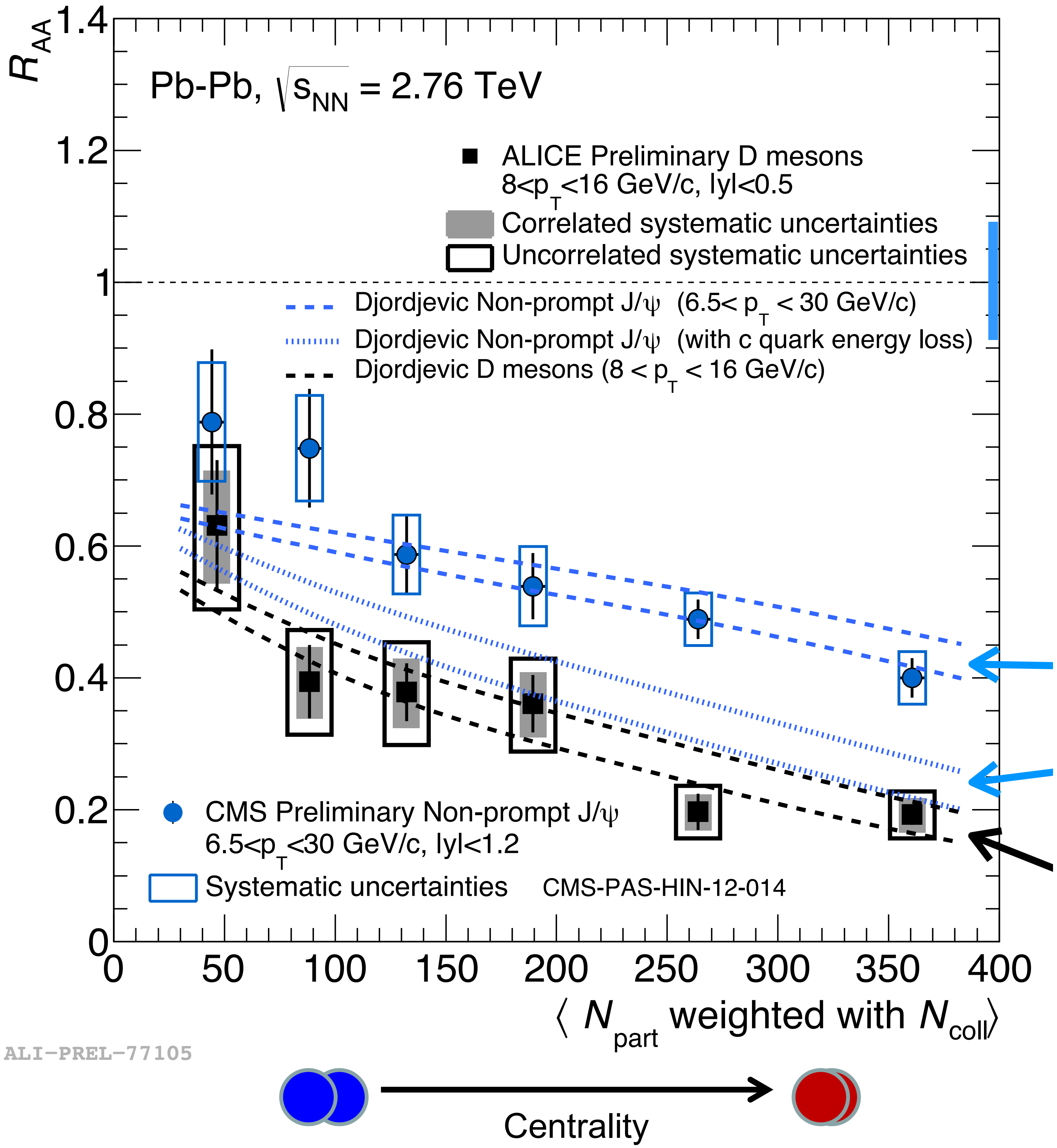
**Distortion by fragmentation!**

**$R_{AA}$ ($h^{\pm}$) = $R_{AA}$ (D)**

**Colour charge effect plays!**

# Quark mass dependence?: D-meson $R_{AA}$ vs. non-prompt J/ψ

ΔE(g) > ΔE(u,d,s) > ΔE(c) > ΔE(b) could reflected in $R_{AA}(B) > R_{AA}(D)$ > $R_{AA}(\pi)$




- ALICE prompt D mesons & CMS non-prompt J/ψ:
  - B and D mesons $\langle p_T \rangle$~10 GeV/c, slightly different rapidity ranges
- **Clear indication of $R_{AA}^{B\leftarrow J/\psi} > R_{AA}^{D}$**

✓ M. Djordjevic: non-prompt J/ψ $R_{AA}$ considering for energy loss
- b quark mass
- c quarkmass

**No trivial relation between ΔE and $R_{AA}$**

✓ M. Djordjevic: D meson $R_{AA}$

**PQCD model including mass-dependent rad+coll energy loss predict a difference**

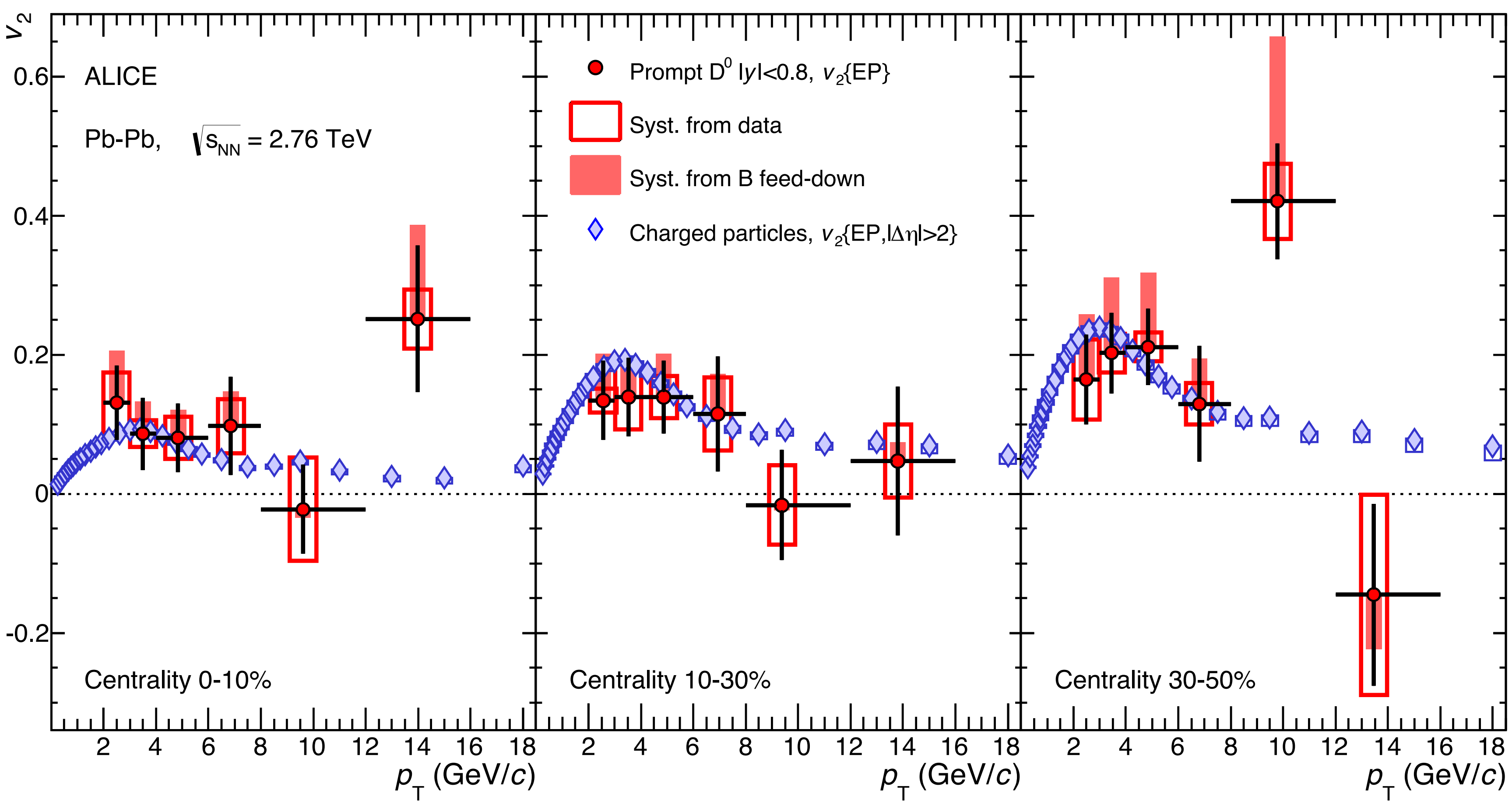
**Similar pattern from other calculations (e.g. BAMPS, WHDG, Vitev et al.).**

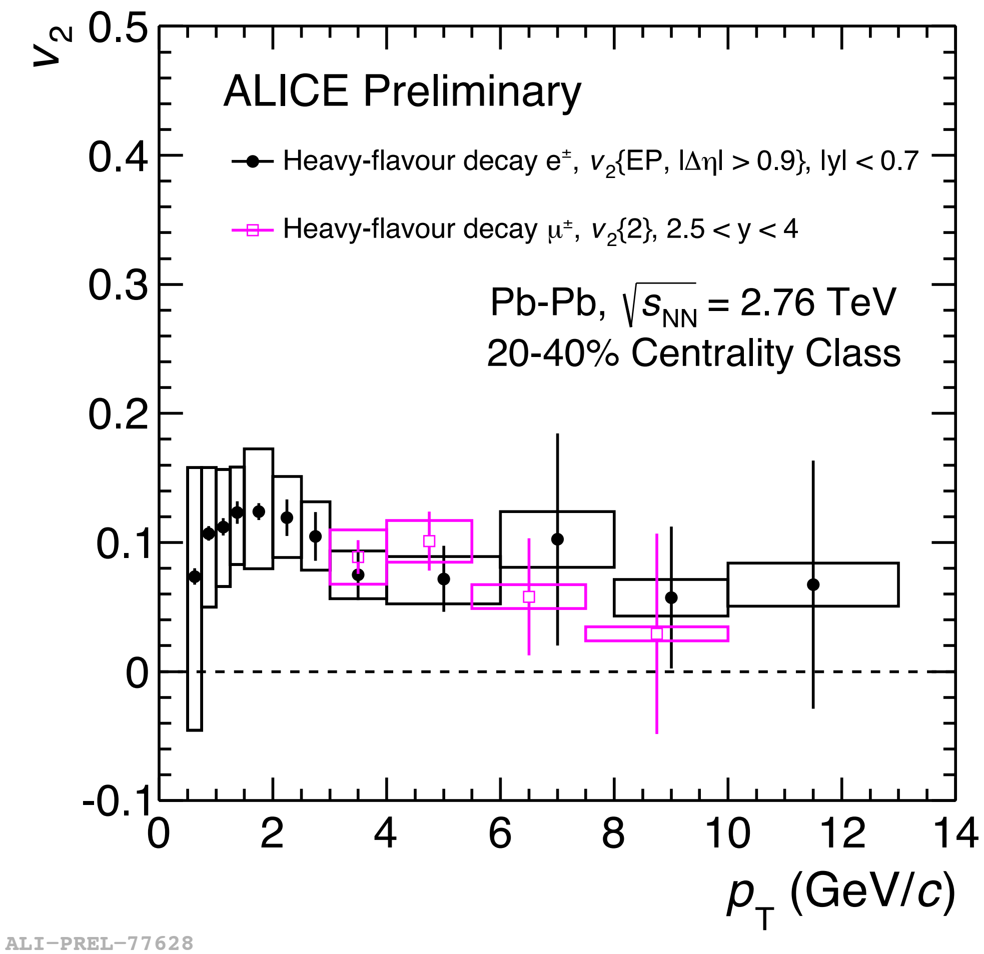
# Azimuthal anisotropy of heavy-flavours

## D mesons

Phys. Rev. Lett. 111, 102301 (2013)

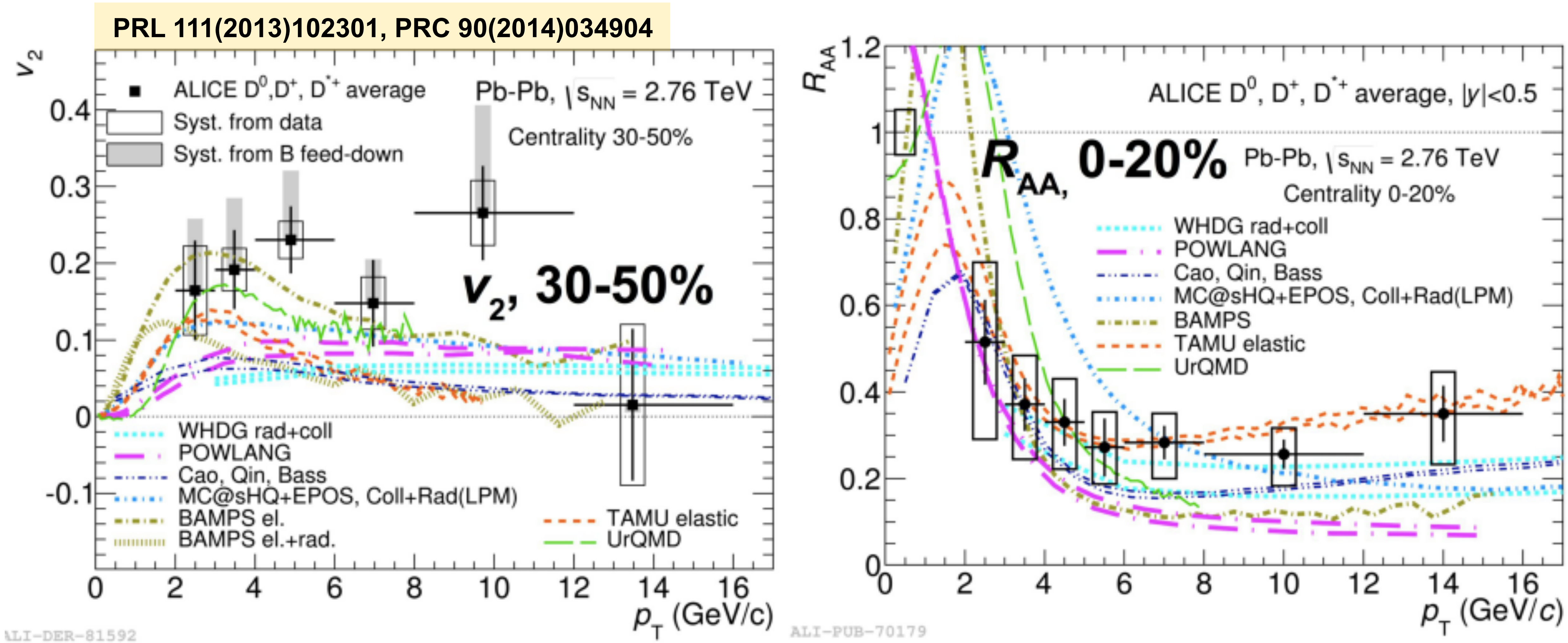
## HF decay electrons, muons




- 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

# $R_{AA}$ and $v_2$: Comparison with models




- Simultaneous measurement and theory description of open charm $R_{AA}$ and $v_2$

⇒ understanding of heavy quark energy loss mechanism, the degree of thermalization of heavy-quarks within the medium

- Task to us: reduction of stat. and sys. uncertainties of data


BAMPS Uphoff et al. arXiv: 1112.1559, Aichelin et al. Aichelin et al. Phys. Rev. C 79 (2009) 044906,
WHDG W. A. Horowitz et al. J. Phys. G38, 124064 (2011), POWLANG W. M. Alberico et al. Eur. Phyis J. C 71, 1666 (2011), TAMU M. He, R. J. Fries and R. Rapp, arXiv:1204.4442[nucl-th],
UrQMD arXiv:1211.6912, J. Phys. Conf. Ser. 426, 012032 (2013), Cao, Quin, Bass arXiv:1308.0617

# Summary

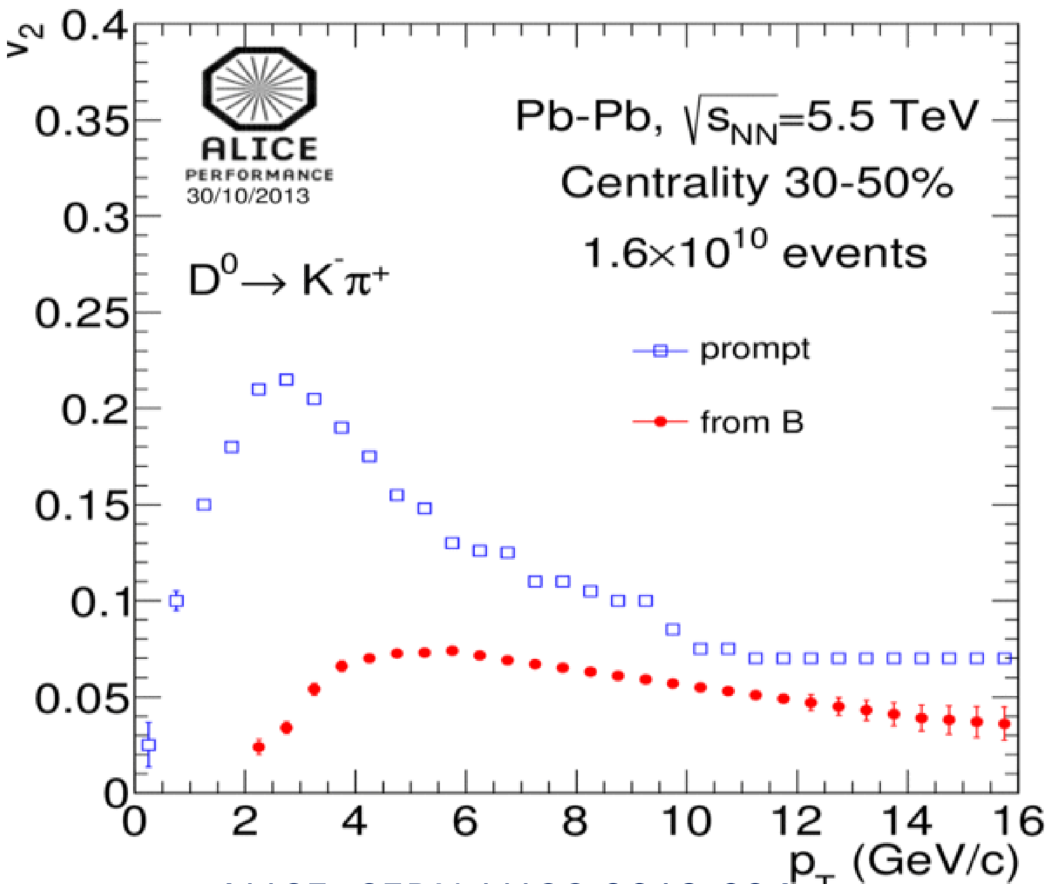
- **ALICE: new quality of Heavy Flavour measurements**
  - pp collisions:
    - described by perturbative QCD ⇒ Heavy-flavours are a calibrated probe
    - investigate heavy flavour fragmentation via correlations
  - Pb-Pb collisions:
    - strong interaction of heavy quarks with the medium
      - ✤ suppression of yields at high $p_T$ consistent with partonic energy loss
      - ✤ indication for charm participating in the medium's collective expansion
    - hints of a stronger suppression for charm than for beauty at intermediate/high $p_T$.
    - no strong conclusions can be drawn from the comparison of D mesons and pions $R_{AA}$, given the large uncertainties
  - p-Pb collisions:
    - results consistent with pQCD + shadowing: the observed suppression in Pb-Pb collisions is a final state effect

- **what is missing?**
  - better precision, more statistics, extended $p_T$ coverage (high and low $p_T$) • smaller uncertainties and new differential measurements will help to
  - constrain model calculations quantitatively
  - address open questions concerning the energy-loss mechanisms, their path- length dependence, thermalization of charm (and beauty?) …

# Outlook

**Precision measurements**

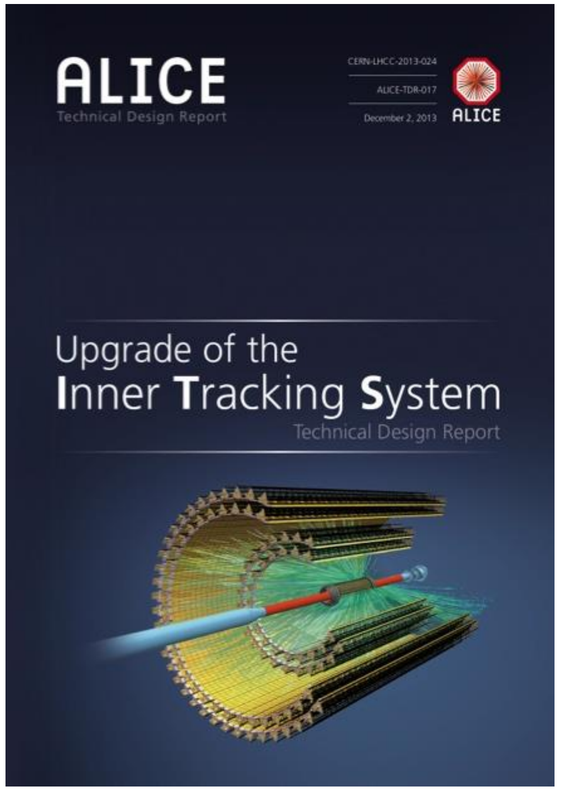
Upgrade



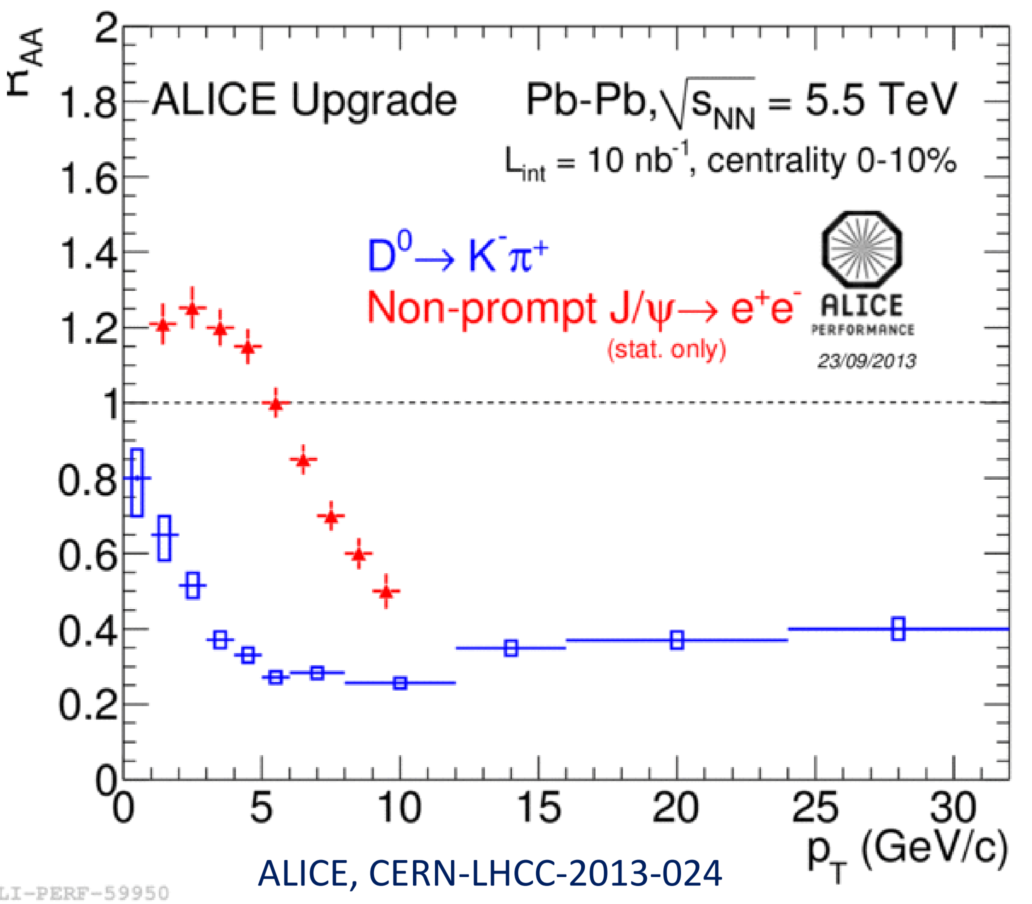

ALICE, CERN-LHCC-2013-024

Input values from BAMPS model: C. Greiner et al. arXiv:1205.4945

Charm $v_2$ down to $p_T$~0 using prompt and beauty $v_2$ down to B $p_T$~0 using B-decay $D^0$




Upgrade




ALICE, CERN-LHCC-2013-024

Charm and beauty $R_{AA}$ down to $p_T$~0 using $D^0$ and B-decay $J/\psi$

Thank you for your attention!

# Extra Slides

# Heavy Quark Energy Loss in Medium

## Radiative energy loss via gluon radiation

**Color charge dependence of energy loss**

*gluon radiation spectrum by the parton propagation in the medium:*

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R f(\omega)$$

$$\text{where} \quad C_R = 3 \ \text{for}\ g, \ \frac{4}{3} \ \text{for}\ q$$

**Dead Cone Effect**

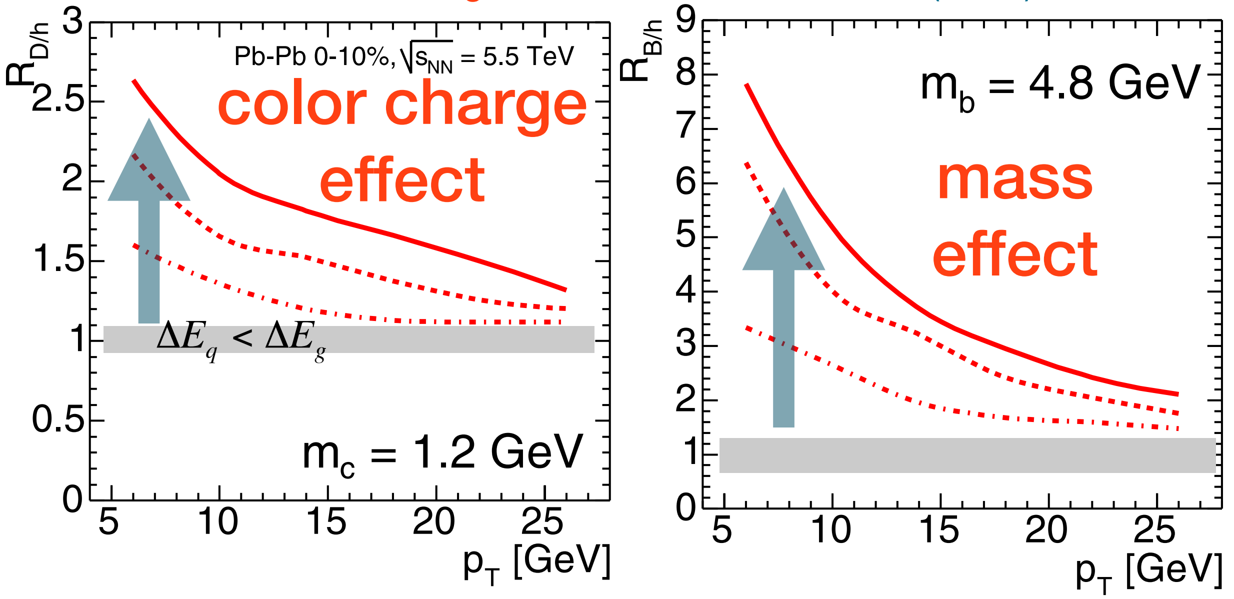
- In vacuum, gluon radiation is suppressed at angles smaller than $M_Q/E_Q$ (ratio of the quark mass to its energy)
- In medium, dead cone implies lower energy loss for massive partons

(Dokshitzer and Kharzeev, PLB 519 (2001) 199.)

$$\Rightarrow R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA} \qquad R_{AA}(p_T) = \frac{1}{<T_{AA}>} \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

$R_{D/h}$: $R^D_{AA}/R^h_{AA}$

Armesto, Dainese, Salgado, Wiedemann, PRD 71 (2005) 054027.




## Elastic energy loss is not negligible?

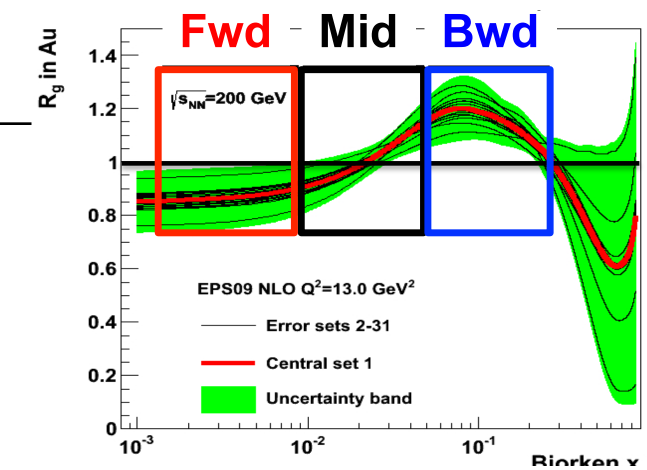
Simon Wicks, William Horowitz, Magdalena Djordjevic, Miklos Gyulassy, Nucl.Phys.A784:426-442,2007

## Collisional dissociation probability of heavy mesons in the QGP?

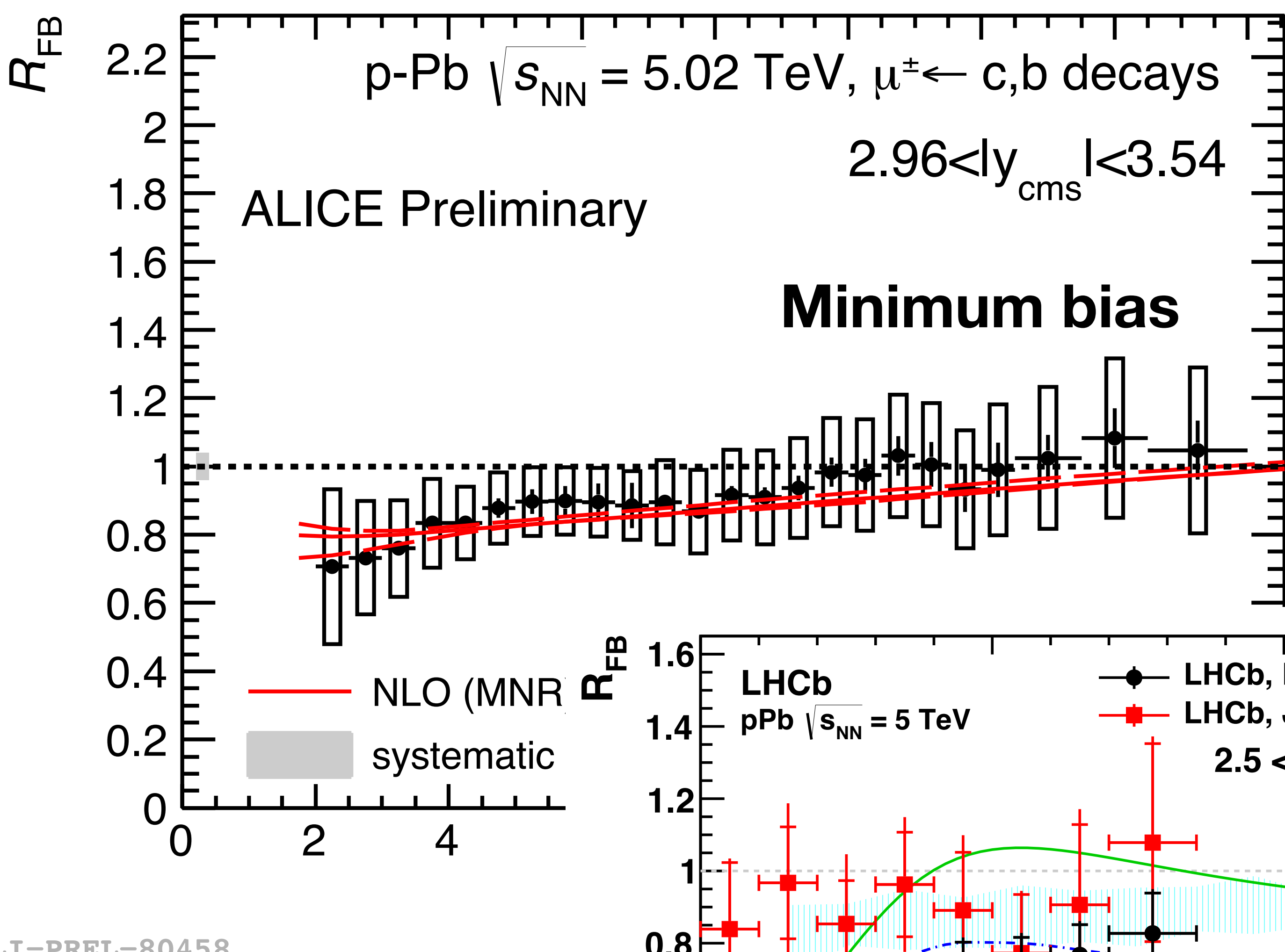
I Vitev, A Adil and H van Hees, J. Phys. G: Nucl. Part. Phys. 34 (2007) S769–S773

**Proton-proton collisions**: provide important test of pQCD in a new energy domain and heavy ion reference

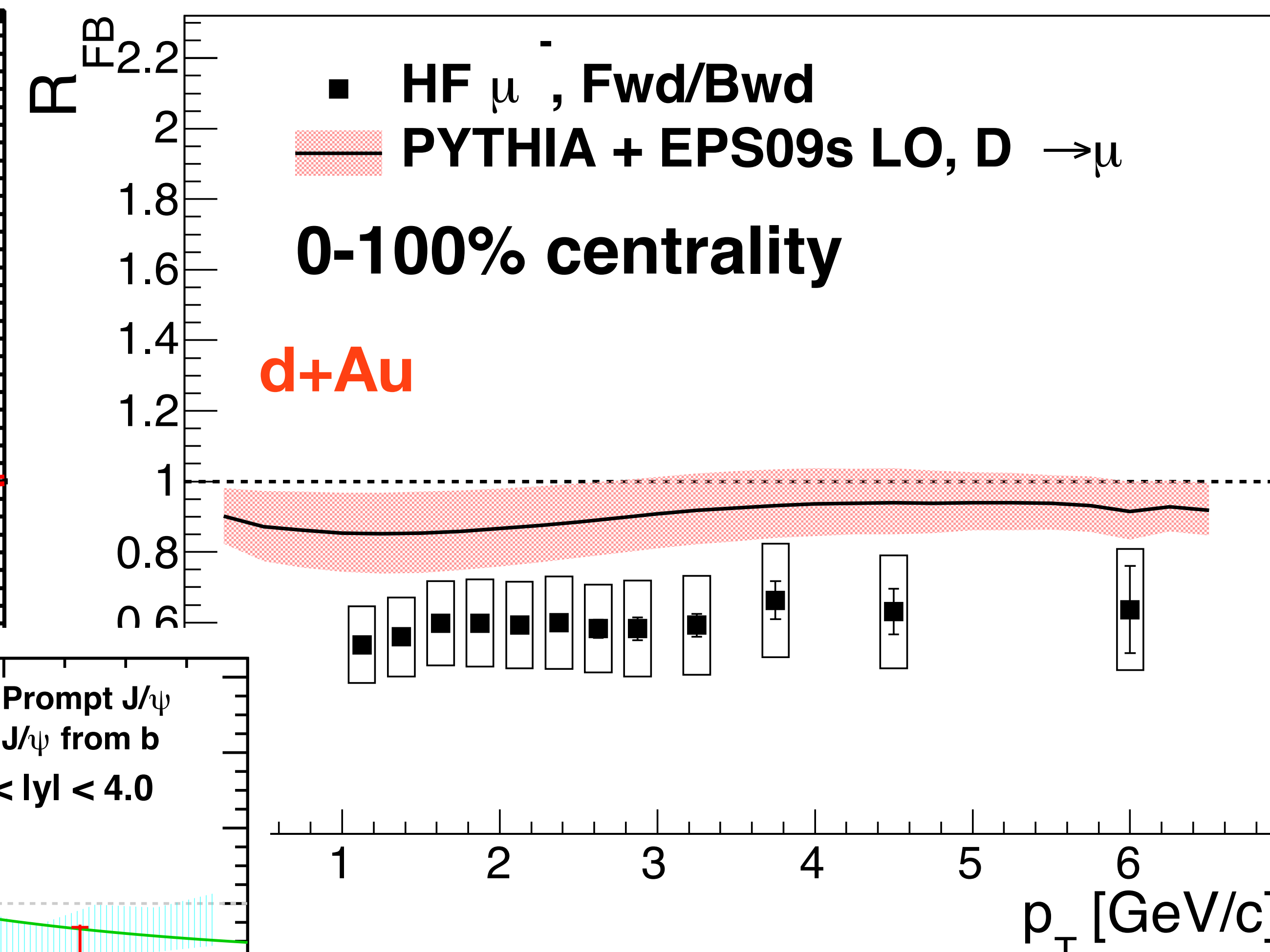
# Heavy flavour in pA at LHC and RHIC

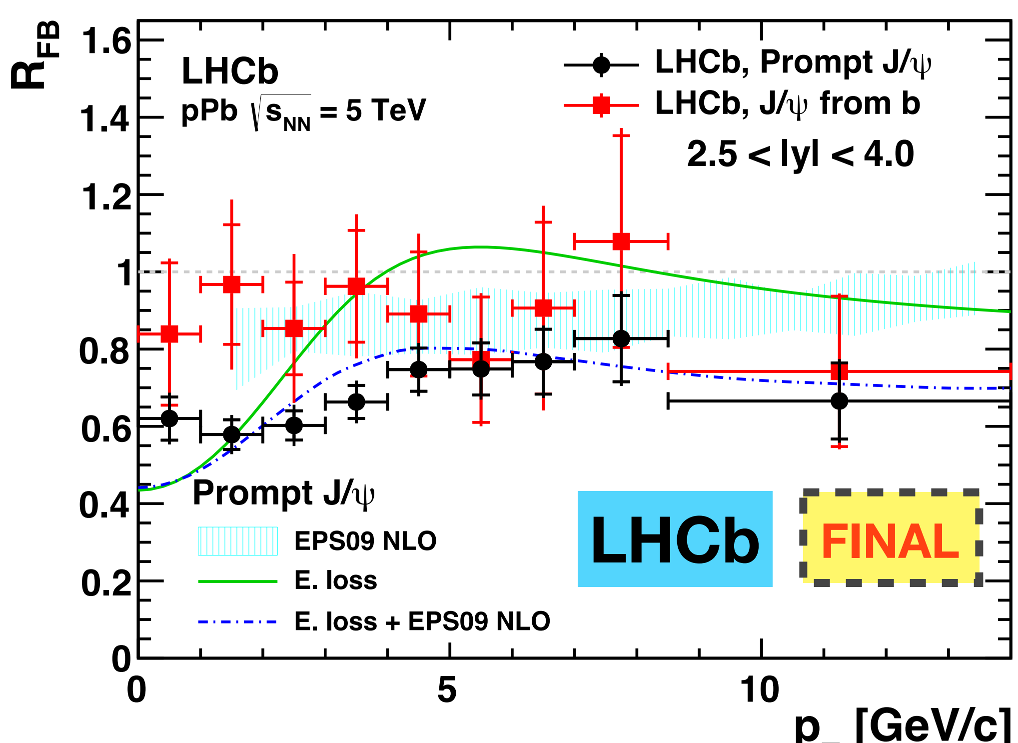



ALICE



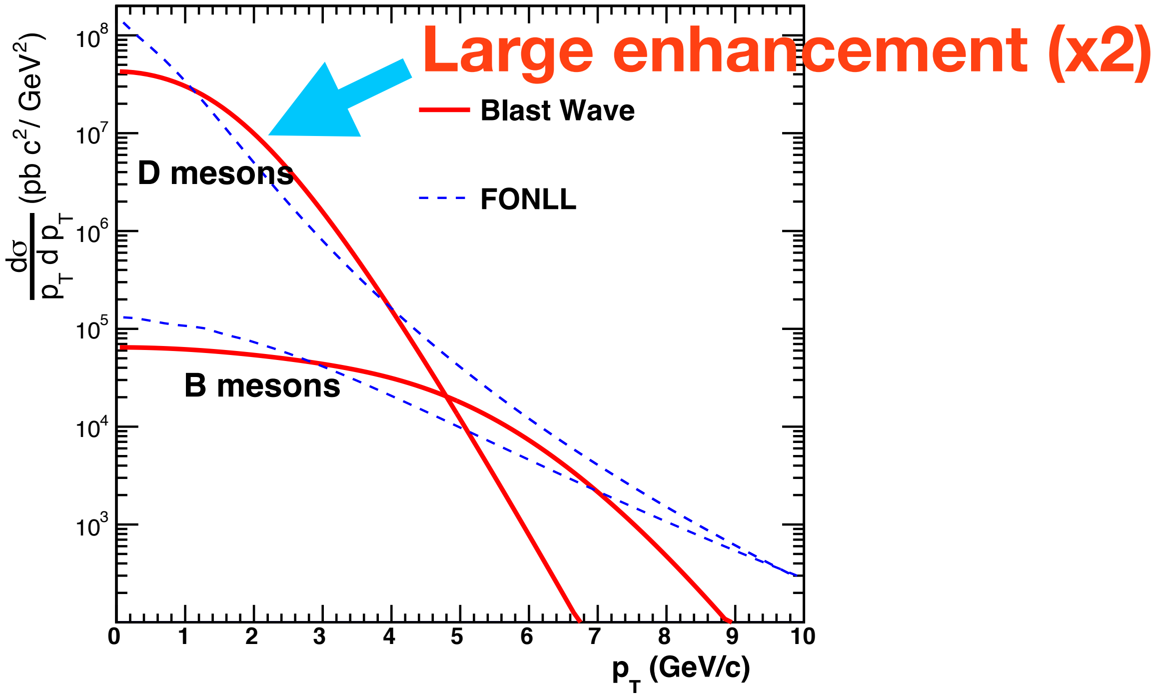

PHENIX

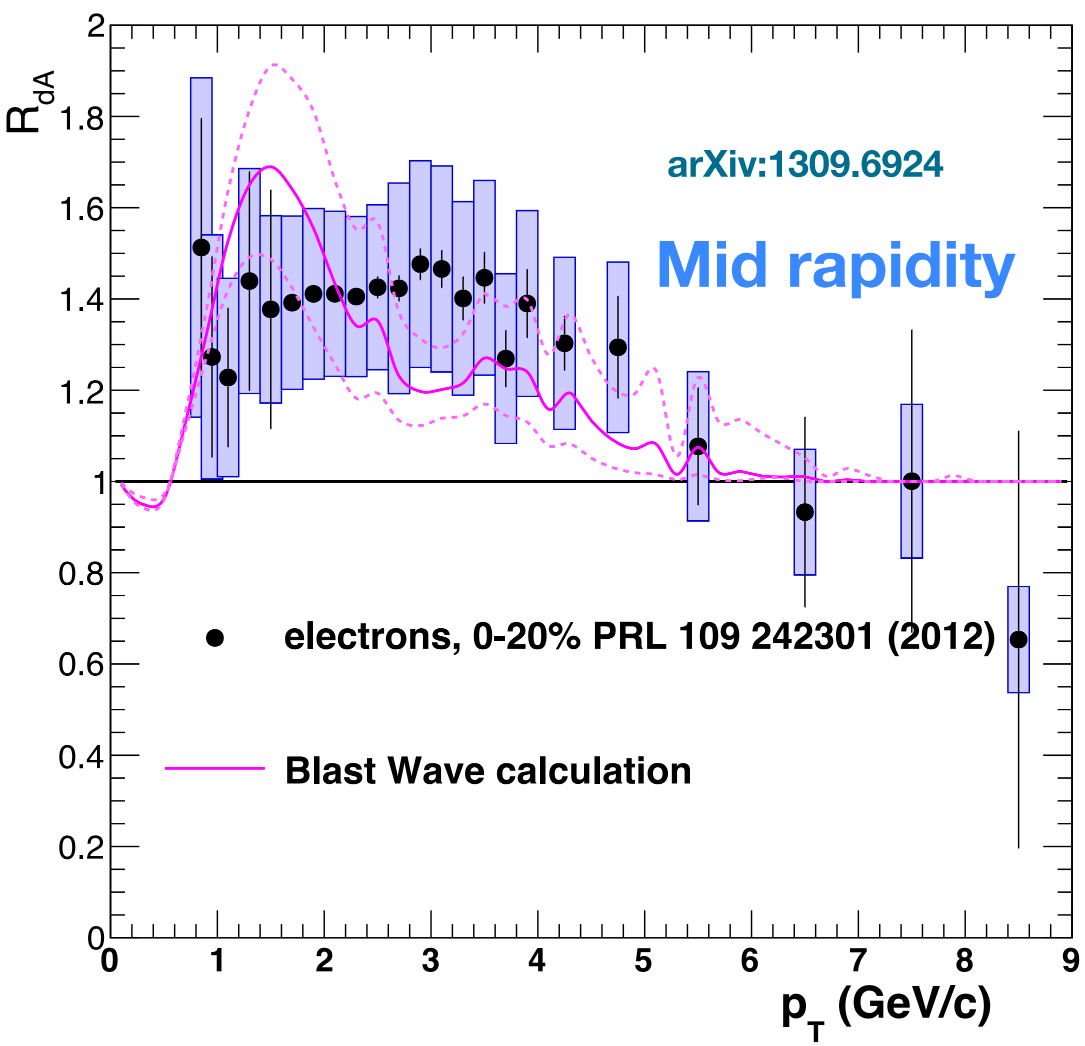


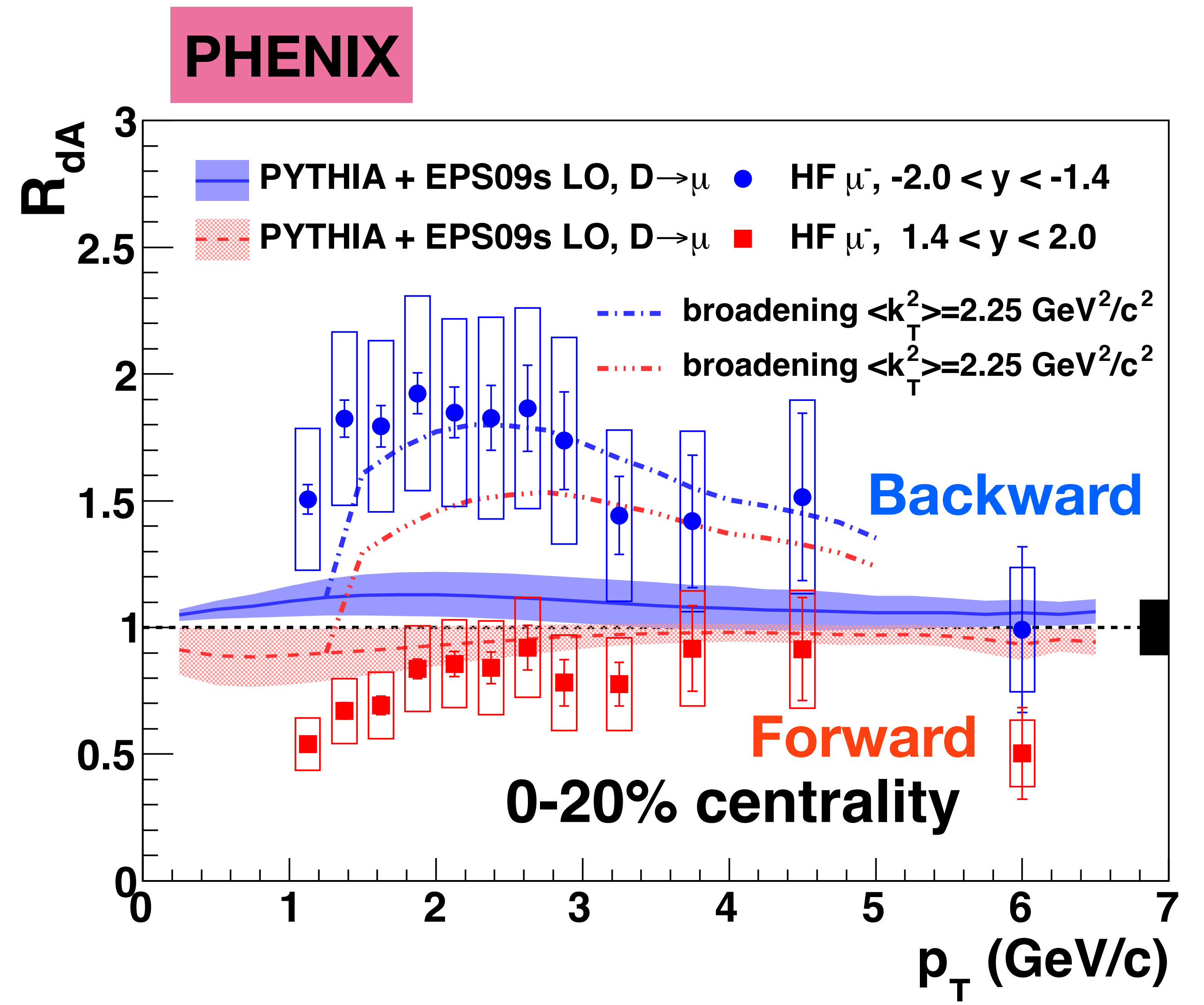




**At RHIC, fail to reproduce the data at both rapidity simultaneously**

# Enhancement in central d+Au




← Radial flow qualitatively reproduces the data!

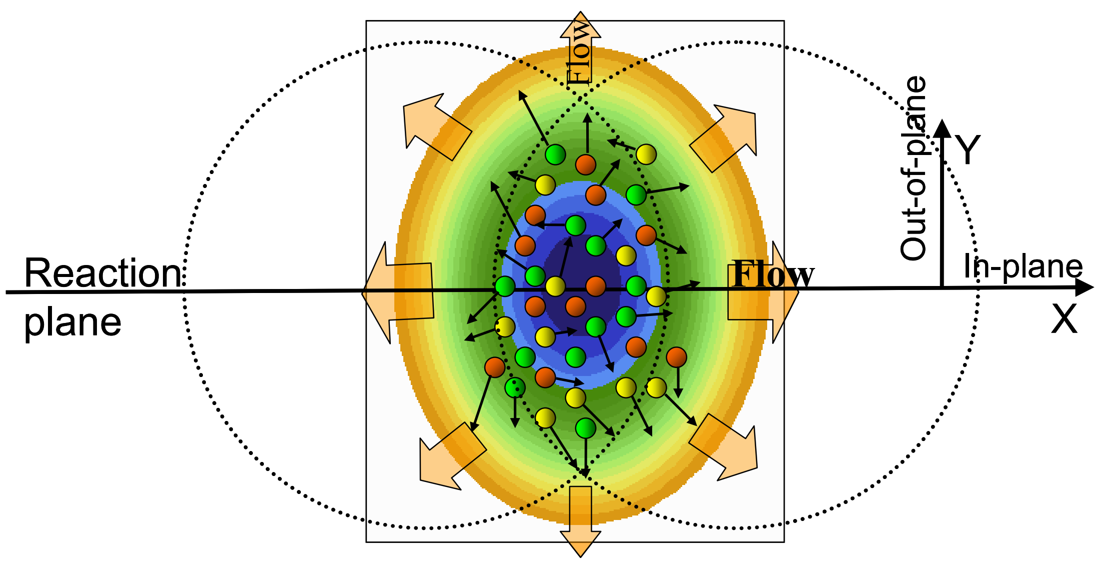
Enhancement at mid- and backward rapidity possibly due to hydrodynamics?

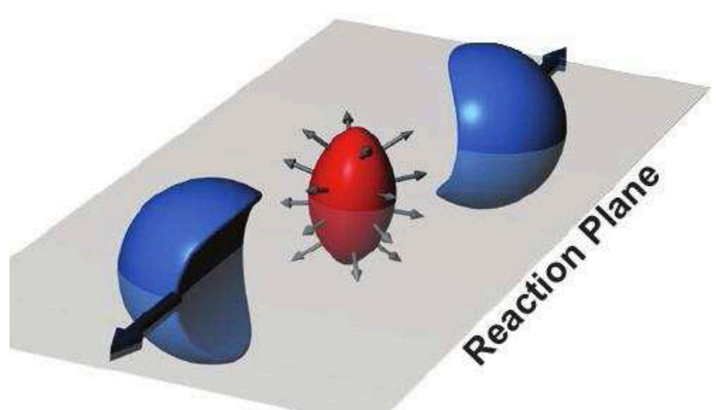
# Anisotropic transverse flow: $v_2$

Initial spatial anisotropy $\xrightarrow[\text{in the medium}]{\text{via re-scatterings}}$ momentum anisotropy of particle emission

The anisotropy is quantified via a Fourier expansion in azimuthal angle ($\varphi$) with respect to the reaction plane ($\Psi_{RP}$)

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}(1 + 2v_1\cos(\varphi - \Psi_{RP}) + 2v_2\cos[2(\varphi - \Psi_{RP})] + \ldots)$$

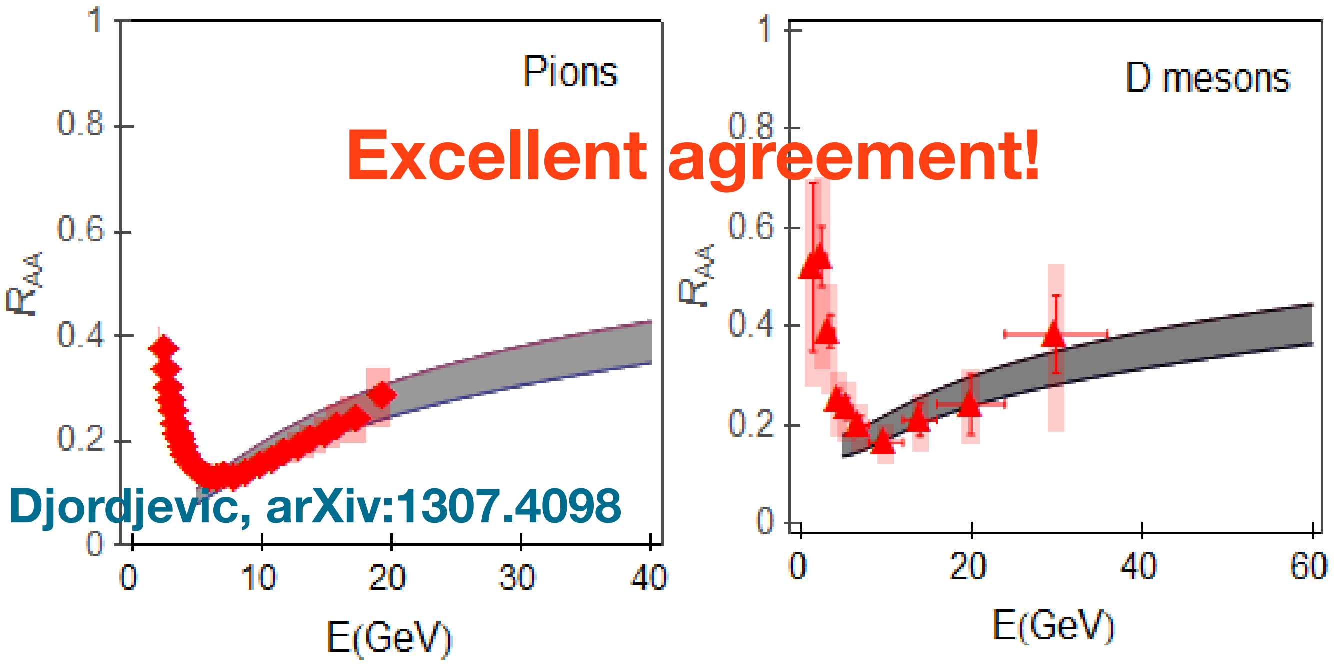



- Due to their large mass, c and b quarks should take longer time (= more re-scatterings) to be influenced by the collective expansion of the medium
  - $v_2(b) < v_2(c)$
- Various methods are available to evaluate v2
  - event plane
  - 2-particle cumulants
  - 4-particle cumulants and Lee-Yang zeros

… not discussed in any detail

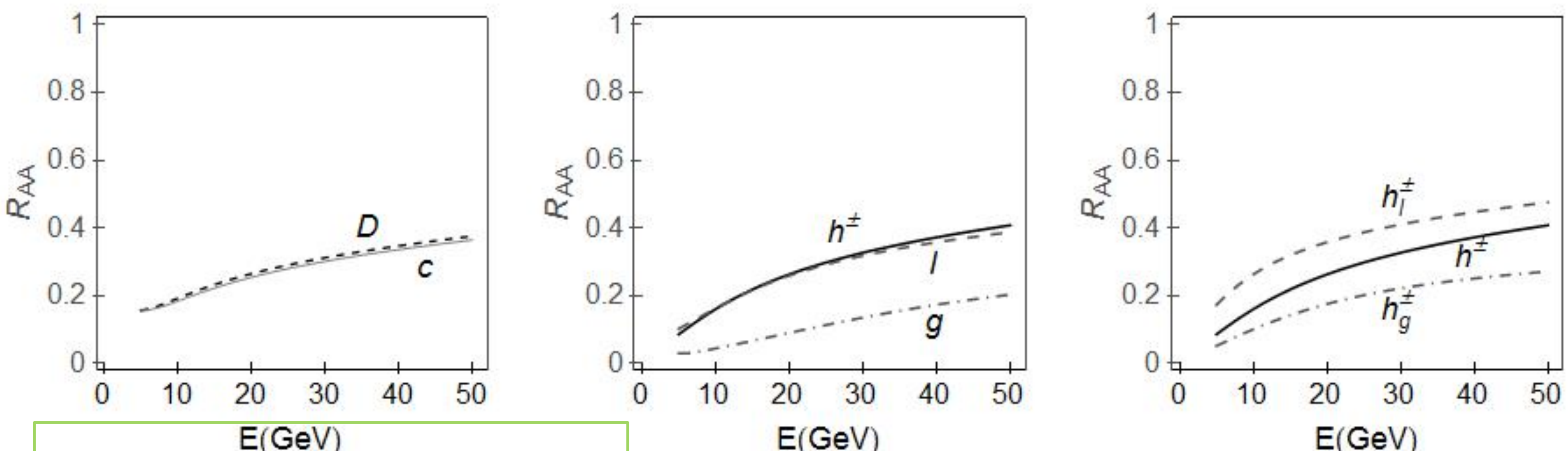
# Color charge dependence?: D-meson $R_{AA}$ vs. $\pi^{\pm}$




**Excellent agreement!**

Djordjevic, arXiv:1307.4098

Calculation by M. Djordjevic (rad+coll energy loss) can describe both $R_{AA}$




Shows strong colour charge effect in partonic $R_{AA}$ (g vs. light and c)

$R_{AA}$ (D) = $R_{AA}$ (charm)

$R_{AA}$ (light quarks) = $R_{AA}$ (charm)

**Distortion by fragmentation!**

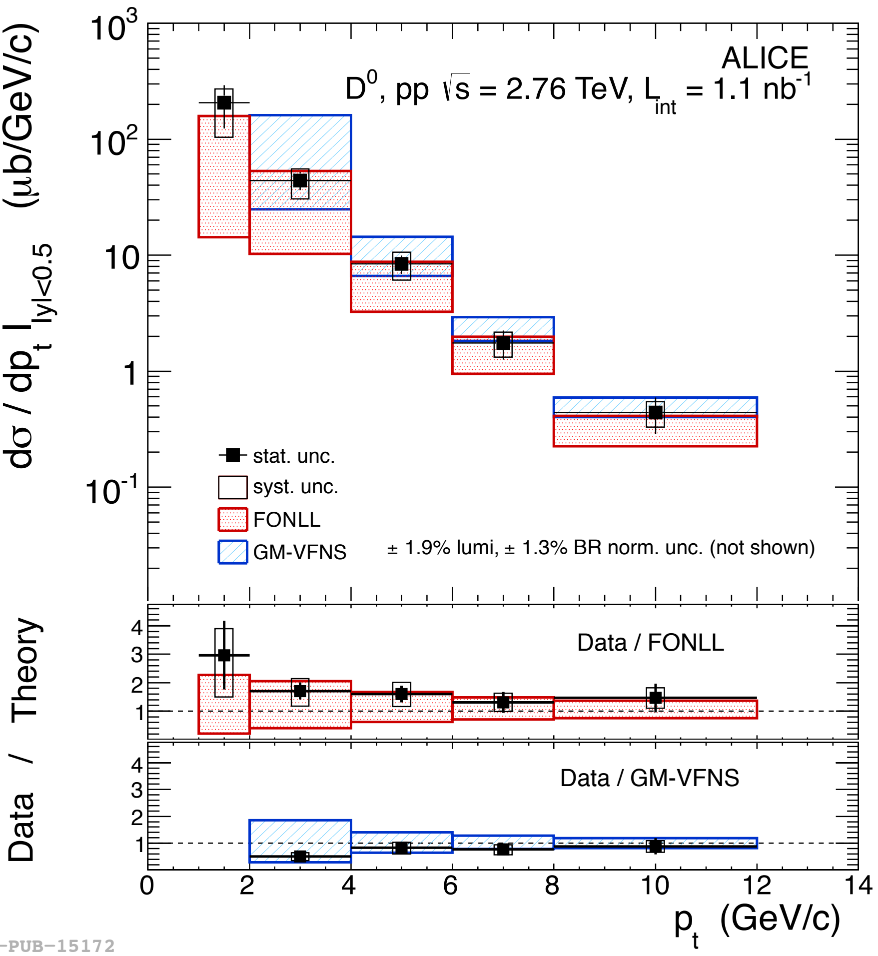
$R_{AA}$ ($h^{\pm}$) = $R_{AA}$ (D)

**Colour charge effect plays!**

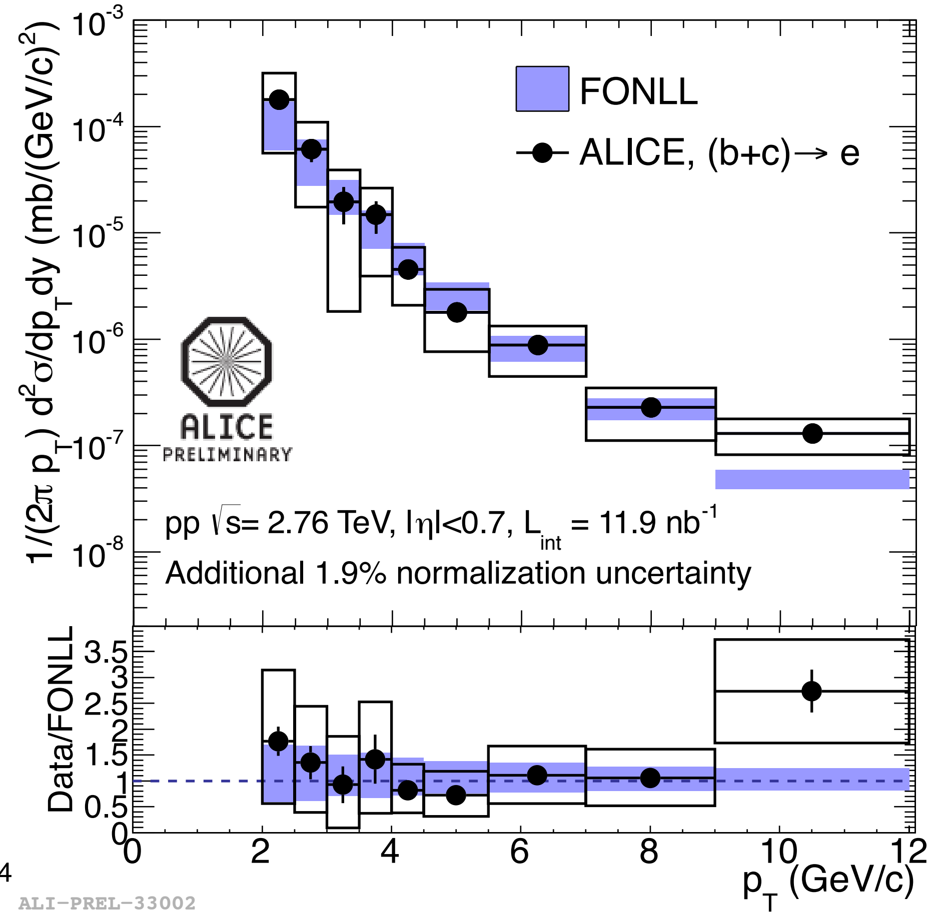
# Heavy-flavour cross section in pp at $\sqrt{s}$ = 2.76 TeV

## D mesons

JHEP 1207 (2012) 191

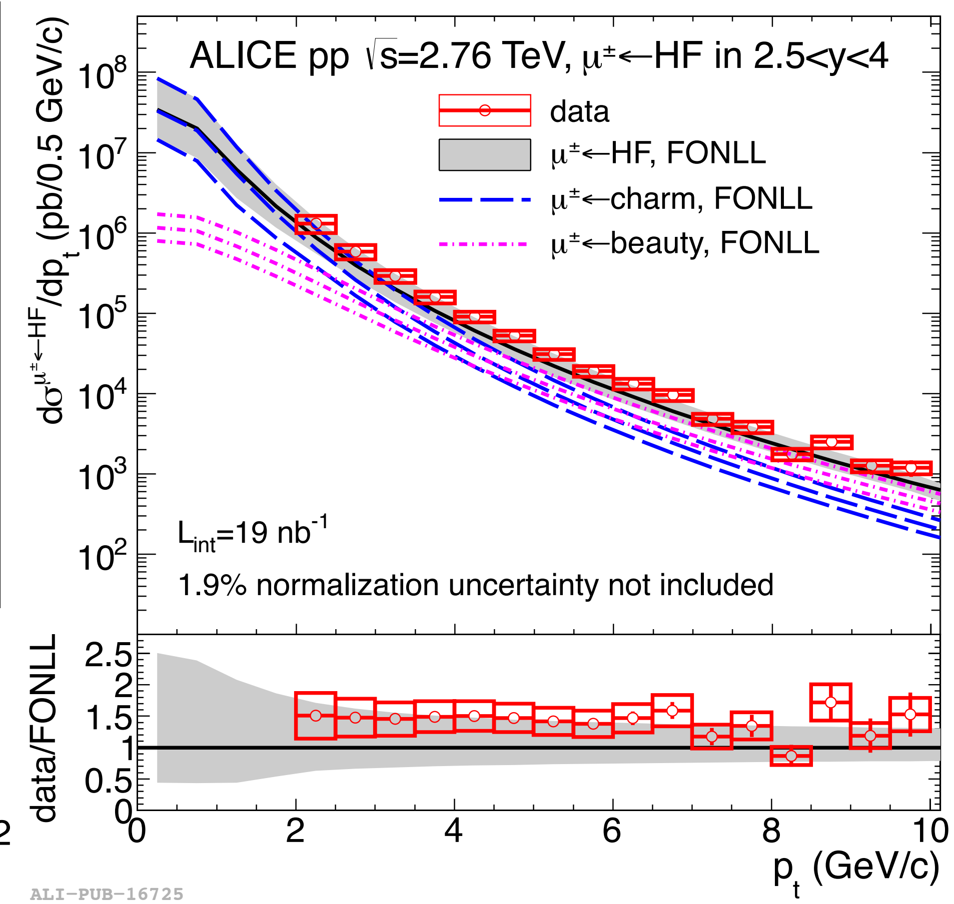



## Heavy flavour decay electrons




## Heavy flavour decay muons

Phys. Rev. Lett. 109 (2012) 112301




R.Averbeck et al., arXiv:1107.3243

Heavy flavour muon data is used as reference for Pb-Pb at the same energy, for the other channels a $\sqrt{s}$ extrapolation based on pQCD calculation is used

**pQCD-based calculations (FONLL, GM-VFNS, $k_T$ factorization) compatible with data**

FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082, $k_T$ factorisation: arXiv:1301.3033

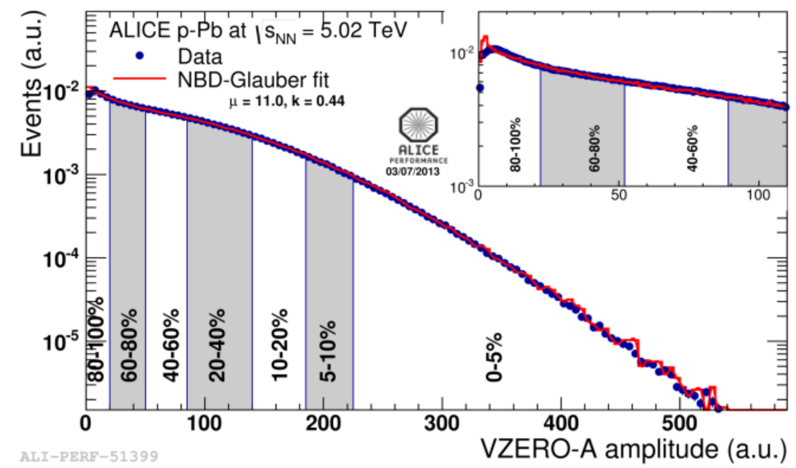
# Nuclear Modification Factor: $Q_{pPb}$

- **investigate multiplicity dependent nuclear modification of the $p_T$ distributions in p-Pb collisions w.r.t. pp collisions**
- **quantified via:**

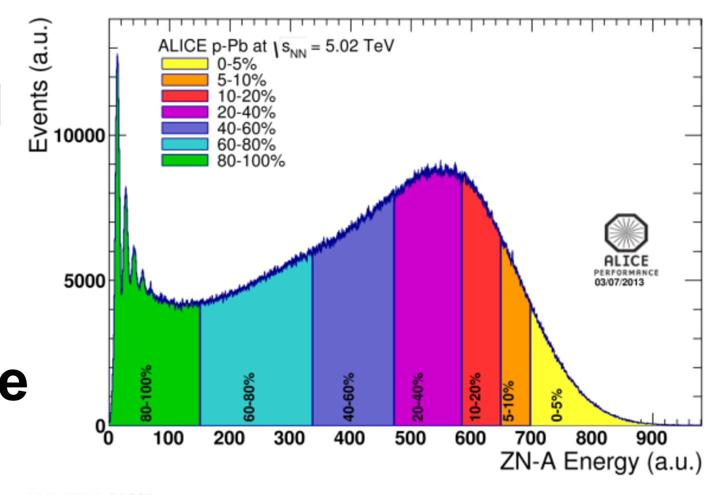
$$Q^{mult}_{pPb}(p_T) = \frac{\left(dN^{mult}_{pPb}/dp_T\right)_i}{\langle N_{coll}\rangle_i \, dN_{pp}/dp_T}$$

- **problem: determination of <$N_{coll}$> suffers from biases in p-Pb collisions**
  - **multiplicity bias**
  - **geometrical bias**
  - **jet veto bias**
- **bias depends on multiplicity estimator**

- **V0A: <$N_{coll}$> from Glauber fit of V0A amplitude**




- **ZN: <$N_{coll}$> from Hybrid approach**
  - **define event classes based on the energy deposited by Pb-spectator neutrons in the ZDC (ZN)**




  - **<$N_{coll}$> obtained by scaling with multiplicity the minimum bias value**

$$\langle N_{coll}\rangle_i = \langle N_{coll}\rangle_{MB} \left( \frac{\langle dN/d\eta\rangle_i}{\langle dN/d\eta\rangle_{MB}} \right)_{-1<\eta<0} -1$$