Westfälische
Wilhelms-Universität
Münster

ALICE

# Measurements of open heavy flavours with ALICE at the LHC

Denise Moreira de Godoy
for the ALICE Collaboration

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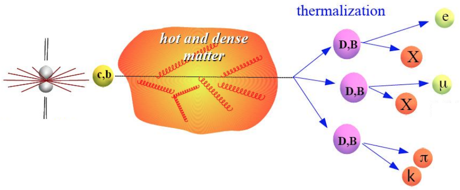
# Heavy flavours

- Heavy quarks (charm and beauty) are produced in initial hard scattering processes at the early stage of collisions




In Pb-Pb collisions:

- Experience the full evolution of the system
- Interact with the hot and dense QCD matter
- Sensitivity to the medium properties

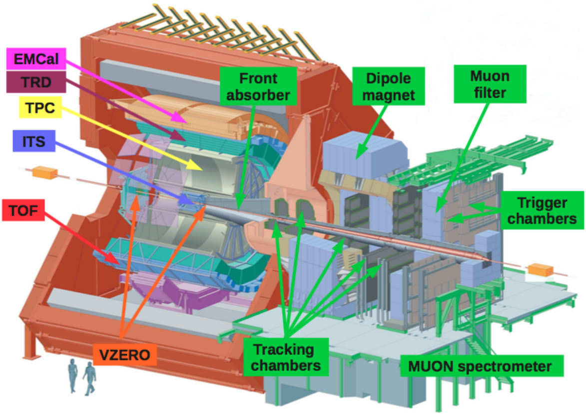
In p-Pb collisions:

- Disentangle hot and dense matter effects from initial-state effects: nuclear modification of PDFs, saturation for small-x gluons, $k_{\mathrm{T}}$ broadening, energy loss in cold nuclear matter, ...
  - ◇ Measurements in the light-quark sector in p-Pb collisions show hints for the establishment of a collective behavior in this system

In pp collisions:

- Reference to study effects in Pb-Pb and p-Pb collisions
- Test of perturbative QCD

# ALICE detector




VZEROA ($2.8 < \eta < 5.1$)

VZEROC ($-3.7 < \eta < -1.7$)

- multiplicity trigger, event plane

ITS ($|\eta| < 0.9$)

- vertexing, tracking, PID

TPC ($|\eta| < 0.9$)

- tracking, PID, event plane

TOF ($|\eta| < 0.9$)

- PID

TRD ($|\eta| < 0.9$)

- PID, trigger

EMCal ($|\eta| < 0.7$)

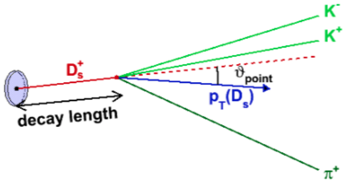
- electron ID, trigger

Muon spectrometer ($-4 < \eta < -2.5$)

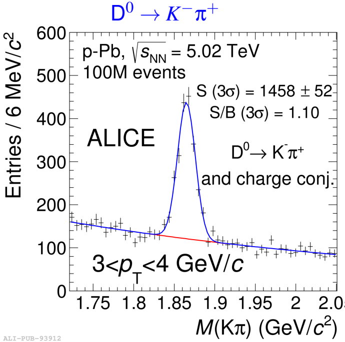
- tracking, muon ID, trigger

# D-meson reconstruction

| | |
|---|---|
| $D^0 \to K^-\pi^+$ | BR: 3.87% |
| $D^+ \to K^-\pi^+\pi^+$ | BR: 9.13% |
| $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ | BR: 67.7% |
| $D_s^+ \to \phi(\to K^-K^+)\pi^+$ | BR: 2.28% |



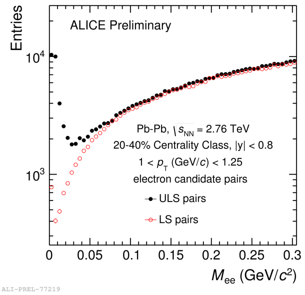

- Analysis based on the reconstruction of decay vertex topologies ($c\tau \approx$ 100-300 $\mu$m) displaced from the primary vertex
- Signal extracted from fits to invariant mass distributions
- Feed down from B hadrons subtracted using pQCD (FONLL) predictions



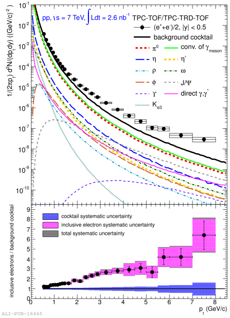
# Heavy-flavour decay electron reconstruction

- Inclusive electrons are identified with ITS, TPC, TOF, TRD, and EMCal
- Two techniques are used to obtain background electrons:

Invariant mass: remove Dalitz decays from neutral mesons and photon conversions by applying cuts on the mass of $e^-e^+$ pairs



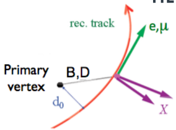

Cocktail: estimate background sources using Monte Carlo simulations based on data ($\pi^0$,$\eta$)




PRD 86 (2012) 112007

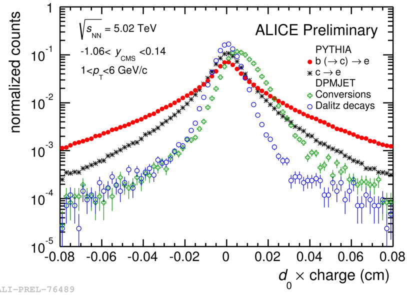
# Beauty-decay electron reconstruction

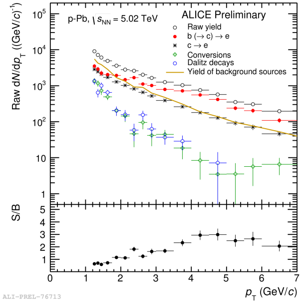
- Inclusive electrons are identified with TOF and TPC
- $c\tau$ = 500 $\mu$m for beauty hadrons $\rightarrow$ impact parameter of beauty-decay electrons is larger than background electrons (photon conversions, Dalitz decays, and charm-hadron decays)




Beauty-decay electrons selected with $p_T$-dependent cut on minimum impact parameter ($d_0$) or by fitting the impact parameter distribution with MC templates

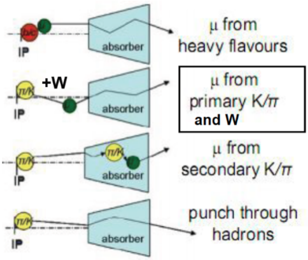
In the impact parameter cut approach, the remaining background is estimated by weighting relevant electron source yields in MC simulations using measured spectra

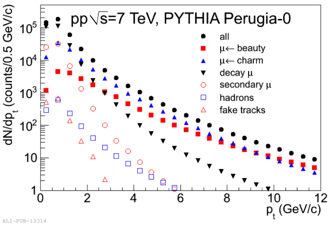


# Heavy-flavour decay muon reconstruction

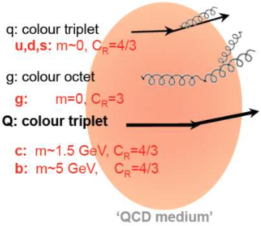
- Inclusive muons are reconstructed with muon tracking chambers
- Acceptance and geometrical cuts and track matching with trigger chambers (from tracking chambers) are applied on the identified muons
- $p \times$ DCA cut is applied to reject tracks from beam-gas interaction
- Background muons (mainly muons from primary $K$ and $\pi$ decays) are estimated with:
  - cocktail technique in pp collisions based on Pythia and Phojet
  - data-tuned MC cocktail in p-Pb and Pb-Pb collisions
- At high $p_{\mathrm{T}}$ ($p_{\mathrm{T}} \gtrsim 15$ GeV/$c$), muons from $W$ decays need to be subtracted using MC simulations




PLB 708 (2012) 265

# Nuclear modification factor




- In-medium parton energy loss:
  - collisional and radiative processes
  - dependence on:
    - ◇ medium density and volume
    - ◇ colour charge (Casimir factor): $\Delta E$(gluon) $> \Delta E$ (quark)
    - ◇ quark mass (dead cone effect): $\Delta E$(light quark) $> \Delta E$(charm) $> \Delta E$(beauty)

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

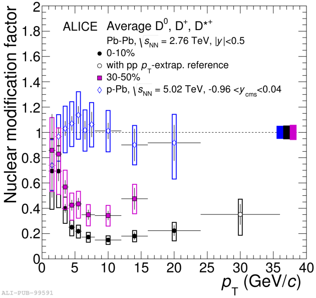
M. Djordjevic, Phys. G 32 (2006); M. Djordjevic, U. Heinz arXiv: 0705.3439 (2007); Dokshitzer et al., PLB 519 (2001) 199; Armesto et al., PRD 69 (2004) 114003; Djordjevic et al., NPA 783 (2007) 493

- The nuclear modification factor is defined as:

$$\boxed{R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{dN_{\mathrm{AA}}/dp_{\mathrm{T}}}{d\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}}}$$

- ◇ $R_{\mathrm{AA}} = 1$ indicates no nuclear modification
- ◇ $R_{\mathrm{AA}} < 1$ at high $p_{\mathrm{T}}$ indicates a suppression of particle production
- ◇ Energy loss hierarchy $\rightarrow R_{\mathrm{AA}}(\pi) < R_{\mathrm{AA}}(\mathrm{D}) < \mathrm{R}_{\mathrm{AA}}(\mathrm{B})$ ?

# Nuclear modification factor of D mesons in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV and p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

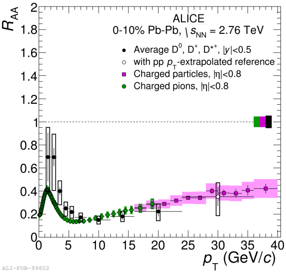



arXiv:1509.06888

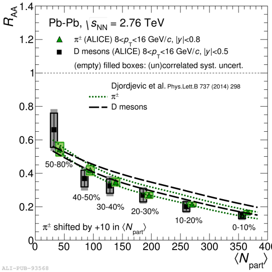
- No strong modification of D-meson spectra in p-Pb collisions relative to pp collisions ($R_{pPb}$ compatible with unity, within uncertainties, for $p_T > 2$ GeV/$c$)
- Large suppression of D mesons at high $p_T$ in Pb-Pb collisions
- Hint for an increase of suppression from semi-central to central Pb-Pb collisions
- Results on $R_{pPb}$ and $R_{AA}$ of D mesons indicate that the strong suppression observed in Pb-Pb collisions is due to the hot and dense medium

# D-meson $R_{AA}$ in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

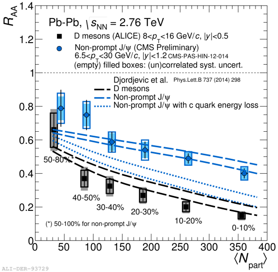
D-meson, charged-particle, and $\pi^{\pm}$ $R_{AA}$




D-meson and $\pi^{\pm}$ $R_{AA}$



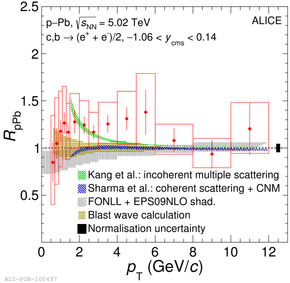

D-meson and non-prompt J/$\Psi$ $R_{AA}$



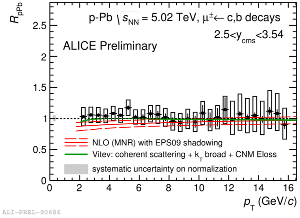

arXiv:1509.06888, JHEP 1511 (2015) 205

- D-meson and $\pi^{\pm}$ $R_{AA}$ as a function of $p_T$ and $\langle N_{part} \rangle$ are compatible within uncertainties (colour-charge energy loss dependence, softer fragmentation of gluons, different shapes of the $p_T$ distributions of partons)
- CMS non-prompt J/$\Psi$ measured in the range $6.5 < p_T < 30$ GeV/$c$ and in a narrower rapidity interval $|y| <$1.2 (CMS-PAS-HIN-12-014)
- Hint of $R_{AA}$ (beauty) $>$ $R_{AA}$ (charm) in central collisions
- Results are compatible with pQCD model including mass-dependent radiative and collisional energy loss

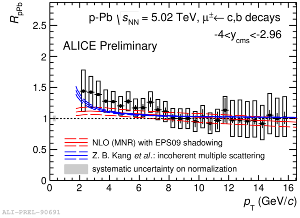
# Heavy-flavour decay lepton $R_{\mathrm{pPb}}$ at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV




p-going (forward rapidity)




Pb-going (backward rapidity)




- No strong modification of heavy-flavour decay lepton spectra in p-Pb collisions relative to pp collisions
- Heavy-flavour decay muon $R_{\mathrm{pPb}}$ is slightly larger than unity in $2 < p_{\mathrm{T}} < 4$ GeV/$c$ at backward rapidity, but trend is not conclusive with current uncertainties
- Nuclear modification factor of heavy-flavour decay leptons are described by models including cold nuclear matter effects

ALICE: arXiv:1509.07491; MNR: Nucl. Phys. B 373 (1992) 295; EPS09: JHEP 0904 (2009) 065; Vitev: PRC 80 (2009) 054902, PRC 87 (2013) 044905; Kang et al.: PLB 740, (2015) 23, PR D 88 (2013) 054010; Sharma et al.: Phys. Rev. C80 (2009) 054902; FONLL: JHEP 05 (1998) 007

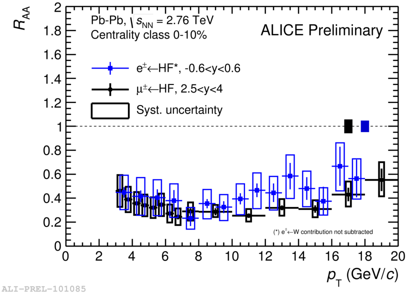
# Heavy-flavour decay lepton $R_{AA}$ in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

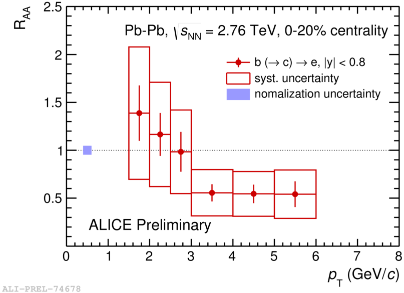
$e \leftarrow$ HF, $|y| < 0.6$

$\mu \leftarrow$ HF, $2.5 < y < 4$

(PRL 109 (2012) 112301 for results in $4 < p_T^{\mu \leftarrow HF} < 10$ GeV/$c$)

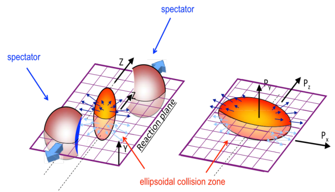
$b(\rightarrow c) \rightarrow e$, $|y| < 0.8$




- Strong suppression of heavy-flavour decay leptons for $p_T > 3$ GeV/$c$ observed in central Pb-Pb collisions
- Compatibility between mid- and forward rapidity results
- Hint of suppression of beauty-decay electrons for $p_T > 3$ GeV/$c$ in 0-20% central Pb-Pb collisions
- Results suggest significant energy loss of heavy quarks in the medium

# Elliptic flow




- Elliptic flow of heavy flavours probes:
  - ◇ at low and intermediate $p_T$: collective motion and possibly heavy-quark thermalization
  - ◇ at high $p_T$: path-length dependence of the heavy-quark energy loss

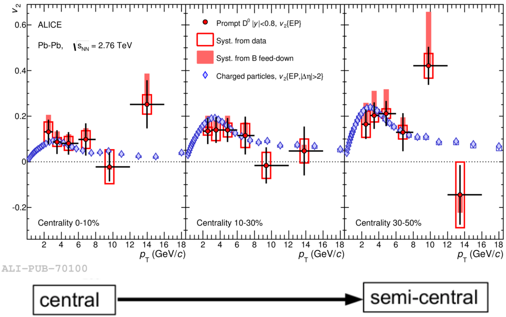
Initial spatial anisotropy → momentum space anisotropy

- The reaction plane is defined by the impact parameter direction and the beam direction
- The particle azimuthal distribution can be expressed as a function of the reaction plane angle ($\Psi_{\mathrm{RP}}$):

$$\boxed{\frac{dN}{d(\varphi - \Psi_{RP})} = \frac{1}{2\pi}\left\{1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n(\varphi - \Psi_{\mathrm{RP}})\right]\right\}}$$

- The second harmonic of the distribution, $v_2 = \langle\cos[2(\varphi - \Psi_{RP})]\rangle$, is the magnitude of the elliptic flow

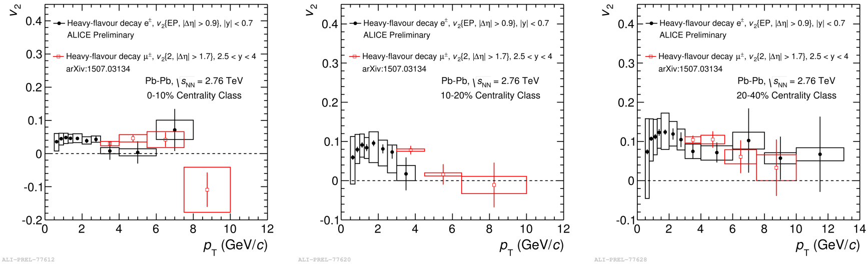
# D-meson $v_2$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV




PRC 90 (2014) 3 034904, PRL 111 (2013) 102301

- Observed positive D-meson $v_2$ in the 30-50% centrality class
  - 5σ effect in $2 < p_T < 6$ GeV/$c$
- Hint for an increase of D-meson $v_2$ from central to semi-central collisions
- D-meson $v_2$ similar to charged-particle $v_2$
- Indication of collective motion of low-$p_T$ charm quarks in the medium

# Heavy-flavour decay lepton $v_2$ in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV

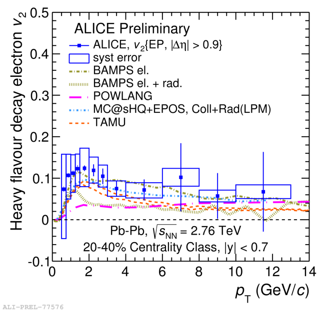


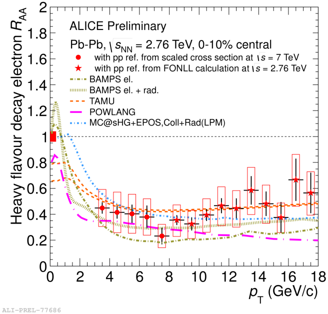

central → semi-central

arxiv:1507.03134 ($\mu \leftarrow$ HF)

- Observed positive $v_2$ in the 20-40% centrality class
  - 3σ effect in $2 < p_{\mathrm{T}}^{e\leftarrow \mathrm{HF}} < 3$ GeV/$c$ and $3 < p_{\mathrm{T}}^{\mu\leftarrow \mathrm{HF}} < 5$ GeV/$c$
- Hint for an increase of $v_2^{e\leftarrow \mathrm{HF}}$ from central to semi-central collisions
- $v_2^{\mu\leftarrow \mathrm{HF}}$ is compatible with $v_2^{e\leftarrow \mathrm{HF}}$ within uncertainties
- Confirmation of significant interaction of heavy quarks with the medium
- Indication of collective motion of low-$p_{\mathrm{T}}$ heavy quarks in the QGP

# Comparison with models in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV

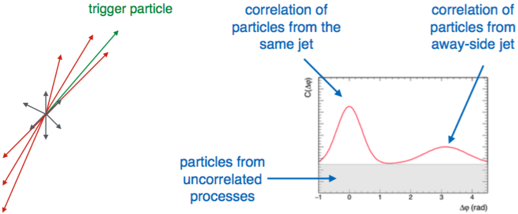



- $v_2^{e\leftarrow\mathrm{HF}}$ and $R_{\mathrm{AA}}^{e\leftarrow\mathrm{HF}}$ measurements together start to provide constraints for the models
- Same picture for D mesons and heavy-flavour decay muons

BAMPS:PLB 717 (2012) 430, arXiv:1310.3597v1 [hep-ph]; POWLANG: Eur. PJC 71 (201) 1666, JPG 38 (2011) 124144; MC@sHQ+EPOS, Coll+Rad(LPM): PRC 89 (2004) 014905; TAMU elastic: arXiv:1401.3817[nucl-th] (2014)

# Correlations between heavy flavours and charged particles




Correlation function is sensitive to the production mechanism of heavy quarks

## In Pb-Pb collisions:

- Near side: modifications of the properties of jets containing heavy flavours
- Away side: path-length dependence of the heavy-quark energy loss (surface bias, away-side suppression)

## In p-Pb collisions:

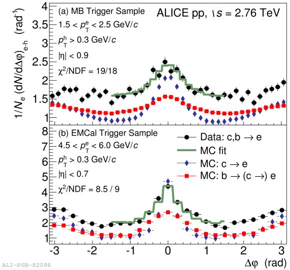
- Study possible modifications of heavy-flavour jet structure due to initial-state effects

## In pp collisions:

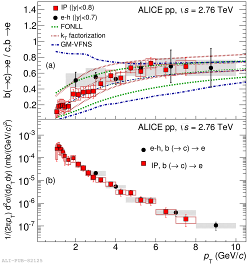
- Reference for correlations in Pb-Pb and p-Pb collisions
- Address charm and beauty jet properties

# $e \leftarrow$ HF-hadron azimuthal correlations in pp collisions at $\sqrt{s}$ = 2.76 TeV

- Possibility to statistically separate the charm and beauty contributions to the inclusive yield of heavy-flavour decay electrons
- Wider correlation distribution for electrons from beauty-hadron decays




$r_b$

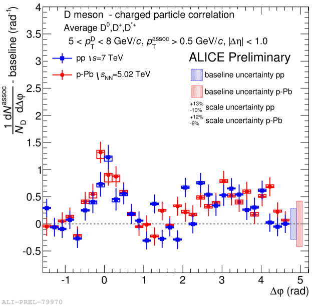


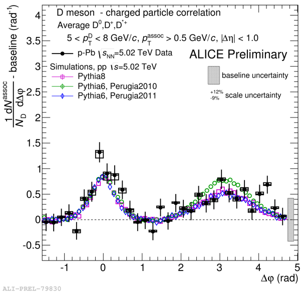

PLB 738 (2014) 97-108

$$\boxed{\frac{1}{N_{e\leftarrow c,b}}\left(\frac{dN}{d\Delta\varphi}\right)_{e\leftarrow c,b-h} = C + r_b\frac{1}{N_{e\leftarrow c}}\left(\frac{dN}{d\Delta\varphi}\right)_{e\leftarrow c-h} + (1-r_b)\frac{1}{N_{e\leftarrow b}}\left(\frac{dN}{d\Delta\varphi}\right)_{e\leftarrow b-h}}$$

- $r_b = N_{e\leftarrow b}/N_{e\leftarrow c,b}$ increases with $p_T$ and reaches $\approx$ 50% at $p_T \approx$ 3 GeV/$c$
- $r_b$ compatible with result obtained via cut on minimum impact parameter to select beauty-decay electrons and with predictions from FONLL, GM-VFNS and $k_T$-factorization

# D-h correlations in pp collisions at $\sqrt{s} = 7$ TeV and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV




- D meson-charged particle azimuthal correlation distributions measured in pp and p-Pb collisions are compatible within uncertainties after baseline subtraction
- Results after baseline subtraction are described by different PYTHIA tunes

# Conclusions

## Nuclear modification factor

- Strong suppression of D mesons and heavy-flavour decay leptons at intermediate-high $p_{\mathrm{T}}$ observed in central Pb-Pb collisions
- Hint of suppression of beauty-decay electrons for $p_{\mathrm{T}} >$3 GeV/$c$ in 0-20% central Pb-Pb collisions
- The suppression observed in Pb-Pb collisions is due to the hot and dense medium ($R_{\mathrm{pPb}} \approx 1$)

## Elliptic flow

- Observed positive $v_2$ of D mesons and heavy-flavour decay leptons in semi-central Pb-Pb collisions
- Hint for an increase of $v_2$ from central to semi-central collisions
- Indication of collective motion of low-$p_{\mathrm{T}}$ heavy quarks (mainly charm quarks)
- Simultaneous description of $v_2$ and $R_{\mathrm{AA}}$ remains a challenge for models

## Angular correlations

- $r_b$ obtained with $e \leftarrow$ HF-h azimuthal correlations in pp collisions is compatible with result obtained via cut on minimum impact parameter approach and with predictions from FONLL, GM-VFNS and $k_{\mathrm{T}}$-factorization
- D-h correlation distributions measured in pp and p-Pb collisions are compatible within uncertainties and described by different PYTHIA tunes

# Nuclear modification factor: analysis strategy

$$R_{\mathrm{pA}}(p_{\mathrm{T}}) = \frac{1}{A}\frac{d\sigma_{\mathrm{pA}}/dp_{\mathrm{T}}}{d\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}}$$

- $d\sigma_{\mathrm{pA}}/dp_{\mathrm{T}}$ measured in **p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV**
- $A$ is the mass number of the Pb nucleus
- $d\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}$ measured in pp collisions at $\sqrt{s}$ = 2.76 TeV and/or 7 TeV scaled to $\sqrt{s}$ = 5.02 TeV based on FONLL calculations (arXiv:1107.3243)
  - ◇ $p_{\mathrm{T}}$-extrapolation based on FONLL calculations

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle T_{\mathrm{AA}}\rangle}\frac{dN_{\mathrm{AA}}/dp_{\mathrm{T}}}{d\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}}$$

- $dN_{\mathrm{AA}}/dp_{\mathrm{T}}$ measured in **Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV**
- $\langle T_{\mathrm{AA}}\rangle$ is calculated using Glauber model (arXiv:0805.4411)
- $d\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}$ obtained with different strategy depending on the analysis:
  - ◇ measured in pp collisions at $\sqrt{s}$ = 2.76 TeV
  - ◇ measured in pp collisions at $\sqrt{s}$ = 7 TeV and scaled to $\sqrt{s}$ = 2.76 TeV based on FONLL calculations (arXiv:1107.3243)
  - ◇ $p_{\mathrm{T}}$-extrapolation based on FONLL calculations

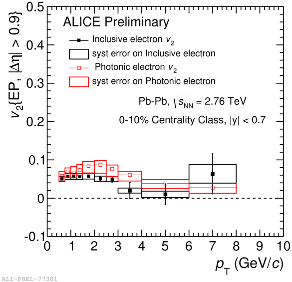
# Elliptic flow: analysis strategy

## Heavy-flavour decay electron $v_2$

- $v_2$ of inclusive electrons measured with the event plane method (PRC 58 (1998) 1671), which requires the reaction plane
- $v_2$ of background electrons is estimated (invariant mass and cocktail methods) and subtracted from the measured $v_2$ of inclusive electrons:

$$v_2^{e\leftarrow \text{HF}} = \frac{(1+R)v_2^{\text{incl. elec.}} - v_2^{\text{back. elec.}}}{R}, \text{where } R = \frac{N^{\text{incl.elec.}}}{N^{\text{backg.elec.}}} - 1$$

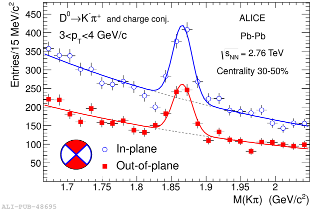
- Similar strategy for heavy-flavour decay muon $v_2$



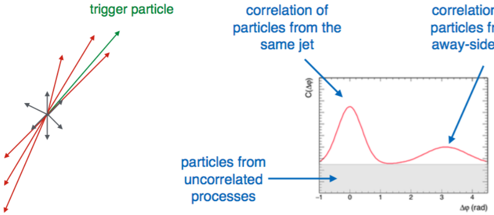

## D-meson $v_2$

- Yield extracted from invariant mass spectra in two bins of azimuthal angle relative to the event plane: PRC 90 (2014) 3 034904

$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in}} - N_{\text{out}}}{N_{\text{in}} + N_{\text{out}}}$$



# Angular correlations: analysis strategy




- Heavy-flavour particles are the trigger particles
- Event mixing technique is used to correct the correlation distribution for detector inhomogeneities and pair acceptance
- Efficiency corrections are applied for trigger and associated particles
- The correlation function is given by:

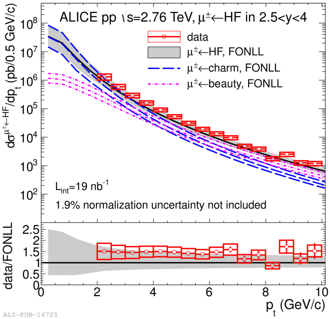
$$C(\Delta\varphi) = \frac{S(\Delta\varphi)}{B(\Delta\varphi)} = \frac{1}{N^{\text{trigger}}} \frac{dN}{d\Delta\varphi}$$

where $S(\Delta\varphi)$ refers to correlations in the same event and $B(\Delta\varphi)$ corresponds to correlations in different events

# $R_{AA}$: analysis strategy

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

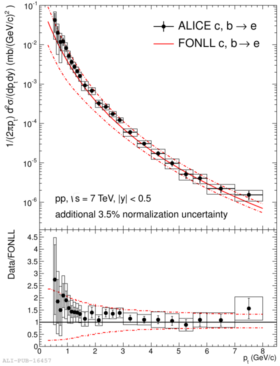
- Yield measured in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
- Reference in pp collisions:
  - **Heavy-flavour decay muon analysis:** $d\sigma_{pp}/dp_T$ measured in pp collisions at $\sqrt{s}$= 2.76 TeV (Phys. Rev. Lett. 109, 112301 (2012))
  - **Heavy-flavour decay electron analysis:**
    - $p_T < 8$ GeV/$c$ : $d\sigma_{pp}/dp_T$ measured in pp collisions at $\sqrt{s}$ = 7 TeV (Phys. Rev. D 86, 112007 (2012)) scaled to $\sqrt{s}$ = 2.76 TeV based on FONLL calculations
    - $p_T > 8$ GeV/$c$ : FONLL calculations
  - **Beauty-decay electron analysis:** $d\sigma_{pp}/dp_T$ measured in pp collisions at $\sqrt{s}$ = 7 TeV (Physics Letters B 721 (2013) 13) scaled to $\sqrt{s}$ = 2.76 TeV based on FONLL calculations
- The average nuclear overlap function $\langle T_{AA} \rangle$ is calculated using Glauber model (arXiv:0805.4411)



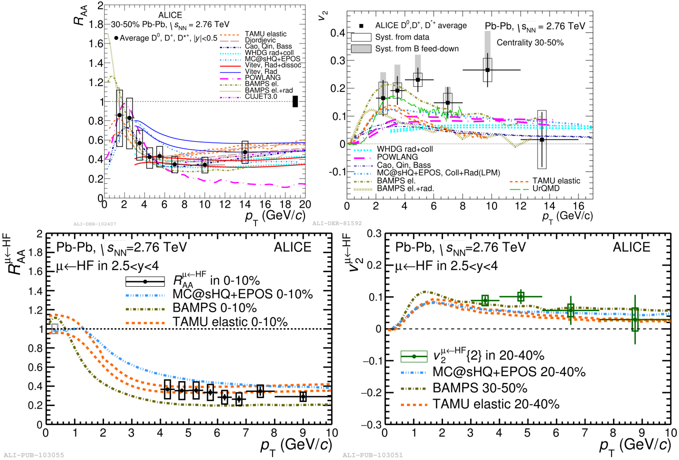
# $R_{\mathrm{pPb}}$: analysis strategy

$$\boxed{R_{\mathrm{pA}}(p_{\mathrm{T}}) = \frac{1}{A}\frac{d\sigma_{\mathrm{pA}}/dp_{\mathrm{T}}}{d\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}}}$$

- $d\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}$ measured in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ =5.02TeV
- Reference in pp collisions:
  - **Heavy-flavour decay muon analysis:** $d\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}$ measured in pp collisions at $\sqrt{s}$ = 2.76 TeV (Phys. Rev. Lett. 109, 112301 (2012)) and 7 TeV (Phys. Lett. B 708 (2012) 265) scaled to $\sqrt{s}$ = 5.02 TeV based on FONLL calculations
  - **Heavy-flavour decay electron analysis:**
    - $p_{\mathrm{T}} < 8$ GeV/$c$ : $d\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}$ measured in pp collisions at $\sqrt{s}$ = 7 TeV (Phys. Rev. D 86, 112007 (2012)) scaled to $\sqrt{s}$ = 2.76 TeV based on FONLL calculations
    - $p_{\mathrm{T}} > 8$ GeV/$c$ :FONLL calculations
  - **Beauty-decay electron analysis:** $d\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}$ measured in pp collisions at $\sqrt{s}$ = 7 TeV (Physics Letters B 721 (2013) 13) scaled to $\sqrt{s}$ = 5.02 TeV based on FONLL calculations
- A is the mass number of the Pb nucleus

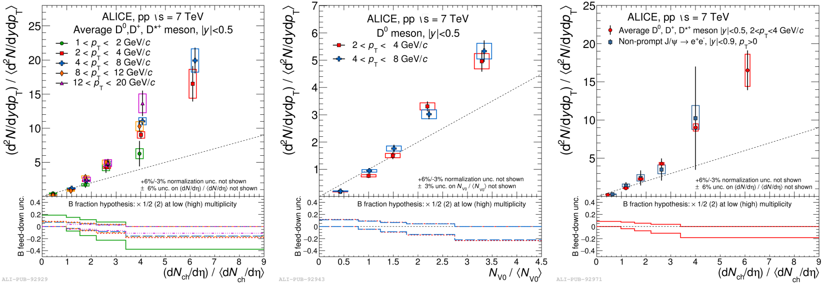


# Comparison with models




ALICE: arXiv:1507.03134, arXiv:1509.06888, PRL 111 (2013) 102301; BAMPS: Fochler et al., JPG 38 (2011) 124152; POWLANG: Alberico et al., Eur.Phys.J C71 (2011) 1666; UrQMD: T. Lang et al, arXiv:1211.6912 [hep-ph], T. Lang et al., arXiv:1212.0696 [hep-ph]; TAMU: Rapp, He et al., PRC 86 (2012) 014903; WHDG: Horowitz et al., JPG 38 (2011) 124114 Aichelin et al.:PRC 79 (2009) 044906, JPG 37 (2010) 094019

# D mesons vs multiplicity

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