Measurements of heavy-flavour decay leptons with ALICE

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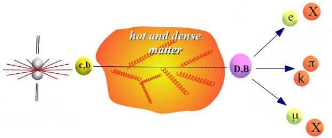
Outline

- Physics motivation
- ALICE
  - ALICE detector
  - Particle identification
- Nuclear modification factor (R_{AA})
  - Heavy-flavour decay electrons
  - Beauty-decay electrons
  - Heavy-flavour decay muons
- Elliptic azimuthal anisotropy (v_2)
  - Heavy-flavour decay electrons
  - Heavy-flavour decay muons
- Correlations
  - Heavy-flavour decay electrons and charged particles
- Conclusions

Heavy flavours

- Heavy quarks are produced in initial hard scattering processes
- They experience the full evolution of the system formed in ultra-relativistic heavy-ion collisions



In Pb-Pb collisions:

- Interact with the hot and dense QCD medium
- Sensitivity to the medium properties

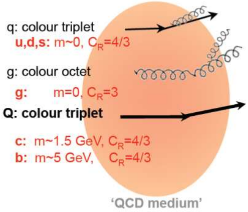
In pp collisions:

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

In p-Pb collisions:

- Disentangle hot and dense matter effects from initial state effects: nuclear modification of PDFs, saturation for small-x gluons, ...
- Measurements of correlations in the light-quark sector in p-Pb collisions show hints for the establishment of a collective behavior in this system (Phys.Lett. B719 (2013) 29-41)

Nuclear modification factor



- Heavy quarks propagate through the medium and interact with its constituents
- In-medium parton energy loss:
  - collisional and radiative processes
  - dependence on medium density and volume
  - dependence on colour charge (Casimir factor): $\Delta E(\text{gluon}) > \Delta E(\text{quark})$
  - dependence on quark mass (dead cone effect): $\Delta E(\text{light quark}) > \Delta E(\text{charm}) > \Delta E(\text{beauty})$

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 an observable sensitive to the parton energy loss:

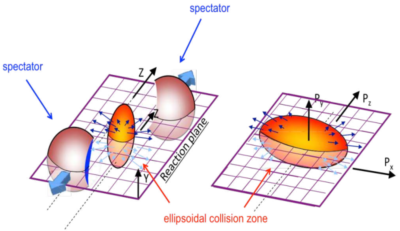
$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

◇ R_{AA} = 1 indicates no nuclear modification

◇ Energy loss hierarchy $\rightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?

- There are caveats on the R_{AA} hierarchy due to the different production spectrum of gluons, light and heavy quarks, as well as different fragmentation function

Elliptic azimuthal anisotropy



initial spatial anisotropy → momentum space anisotropy

- Elliptic azimuthal anisotropy 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

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

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

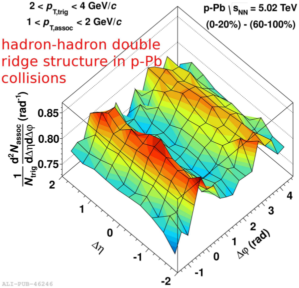
- Heavy-flavour hadron v_2 can be described with transport models, since heavy quarks traverse all the expanding medium (in-medium production and annihilation of heavy quarks are negligible)

Correlations between heavy-flavour and charged particles

In pp collisions:

- Reference for correlations in Pb-Pb and p-Pb collisions
- Address charm and beauty jet properties
- Correlations between heavy-flavour decay electrons and charged hadrons allow us to estimate the relative contributions of electrons from charm and beauty hadron decays to the heavy-flavour decay electron yield

Phys.Lett. B719 (2013) 29-41

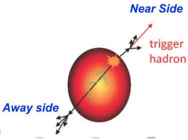


In p-Pb collisions:

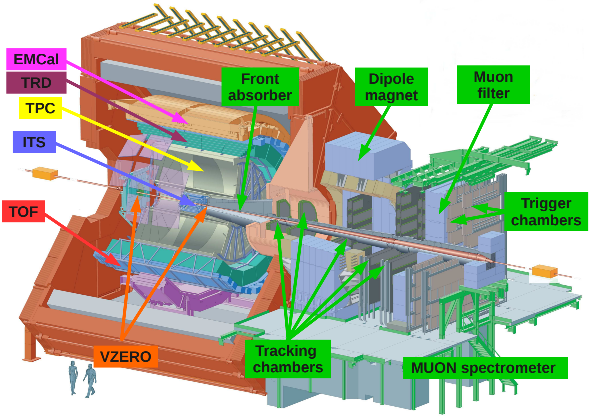
- Study possible modifications of heavy-flavour jet structure due to initial state effects
- Is the double-ridge structure observed in hadron-hadron correlations present also in the heavy-flavour sector?
  - CGC (arXiv:hep-ph/0303204, arXiv:1211.3701)
  - Hydrodynamics (arXiv:1211.0845)

In Pb-Pb collisions:

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



ALICE detector



VZERO (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

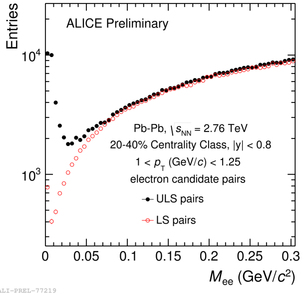
EMCal ($|\eta| < 0.7$)
- electron ID, trigger

Muon spectrometer (-4 $< \eta <$ -2.5)
- tracking, muon ID, trigger

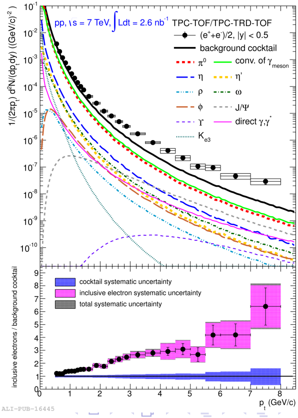
Heavy-flavour decay electron reconstruction

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

1) **Invariant mass:** remove π^0 and η Dalitz decays and photon conversions by selecting on the mass of $e^- e^+$ pairs



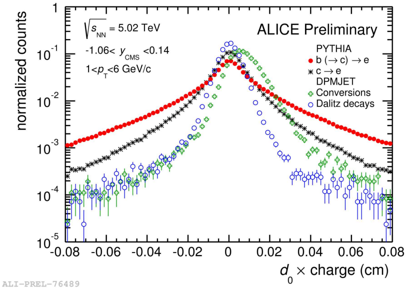
2) **Cocktail:** estimate background sources using Monte Carlo simulations based on data (π^0, η)



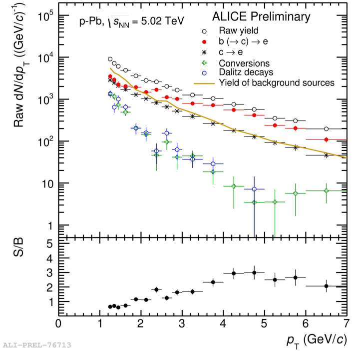
Beauty-decay electron reconstruction

- 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

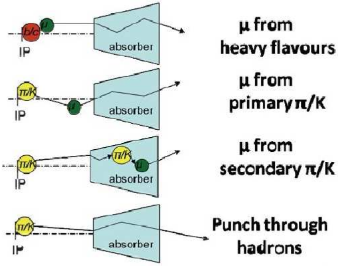


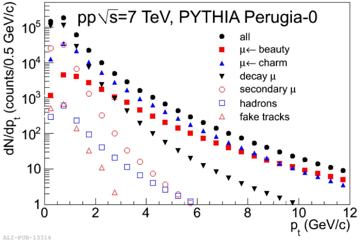
- Remaining background estimated by weighting relevant electron source yields in MC simulations using measured spectra



Heavy-flavour decay muon reconstruction

- Inclusive muons are reconstructed with muon tracking chambers and identified requiring a match between the track in the tracking chambers and the track segment in the trigger chambers
  - p $\times$ DCA cut is applied to reject tracks from beam-gas interaction
- Background muons are estimated with:
  - **cocktail** technique in pp collisions based on Pythia and Phojet
  - **extrapolation** of muons from π and K decays measured at mid-rapidity in p-Pb and Pb-Pb collisions (CMS measurements of asymmetry are used in the extrapolation in p-Pb analysis)

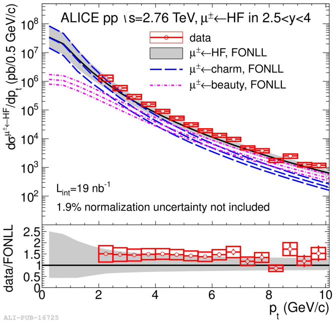




R_{AA}: analysis strategy

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

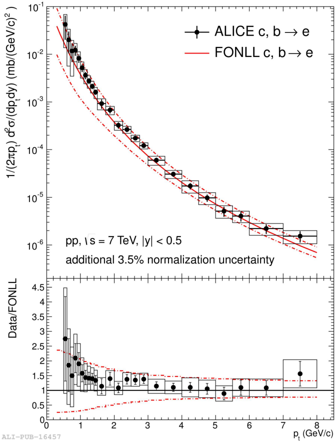
- Yield measured in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV
- Reference in pp collisions:
  - **Heavy-flavour decay muon analysis:** $d\sigma_{pp}/dp_{\mathrm{T}}$ measured in pp collisions at $\sqrt{s}$ = 2.76 TeV (Phys. Rev. Lett. 109, 112301 (2012))
  - **Heavy-flavour decay electron analysis:**
    - ◇ $p_T < 8$ GeV/c: $d\sigma_{pp}/dp_{\mathrm{T}}$ 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
    - ◇ $p_T > 8$ GeV/c: FONLL calculations
  - **Beauty-decay electron analysis:** $d\sigma_{pp}/dp_{\mathrm{T}}$ 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 $\langle T_{\mathrm{AA}} \rangle$ is calculated using Glauber model (arXiv:0805.4411)



R_{pPb}: analysis strategy

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

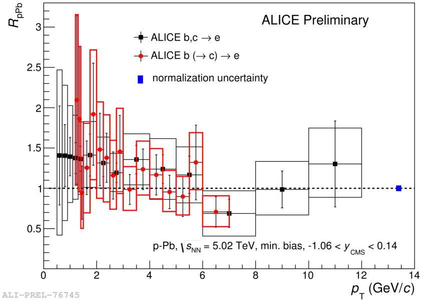
- $d\sigma_{pA}/dp_{\mathrm{T}}$ measured in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV
- Reference in pp collisions:
  - **Heavy-flavour decay muon analysis:** $d\sigma_{pp}/dp_{\mathrm{T}}$ measured in pp collisions at $\sqrt{s}$ = 2.76 TeV (Phys. Rev. Lett. 109, 112301 (2012)) and 7 TeV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

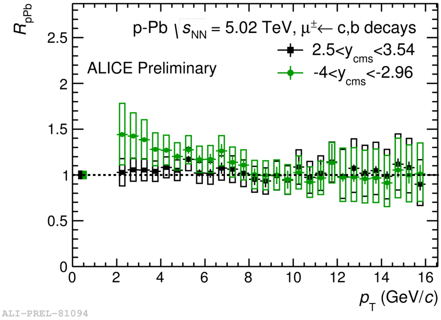


Heavy-flavour decay lepton R_{pPb} at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

$e \leftarrow HF$, mid-rapidity
$e \leftarrow b$, mid-rapidity

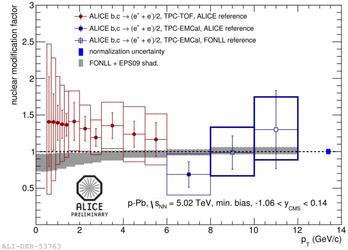
$\mu \leftarrow HF$, forward rapidity
$\mu \leftarrow HF$, backward rapidity

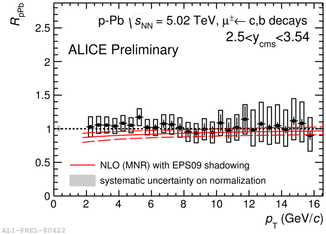


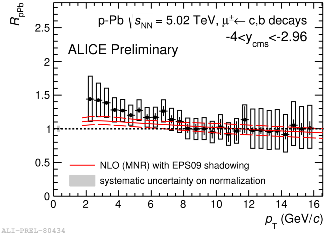


- R_{pPb} of heavy-flavour decay leptons are compatible with unity within uncertainties
- Possible indication of $R_{\mathrm{pPb}} > 1$ for heavy-flavour decay muons at low p_T at backward rapidity, but trend is not conclusive with current uncertainties

Comparison with models: heavy-flavour decay lepton $R_{\rm pPb}$ at $\sqrt{s_{\rm NN}}$ = 5.02 TeV







- Calculations in agreement with data within uncertainties in different rapidity regions

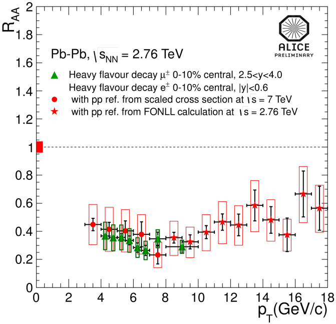
MNR: Nucl. Phys. B 373 (1992) 295; EPS09: JHEP 0904 (2009) 065

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

$\mu \leftarrow HF$, 0-10% centrality

Phys. Rev. Lett. 109, 112301 (2012)

$e \leftarrow HF$, 0-10% centrality

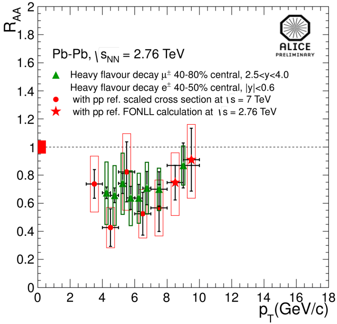


ALI-DER-36791

$\mu \leftarrow HF$, 40-80% centrality

Phys. Rev. Lett. 109, 112301 (2012)

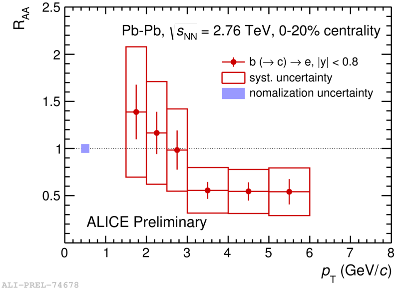
$e \leftarrow HF$, 40-50% centrality



ALI-DER-53851

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

Beauty-decay electron R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV



- Separation of charm and beauty is crucial to understand heavy-flavour energy loss in the QGP
- Hint of suppression of beauty-decay electrons for $p_T > 3$ GeV/c in 0-20% central Pb-Pb collisions due to the b-quark in-medium energy loss

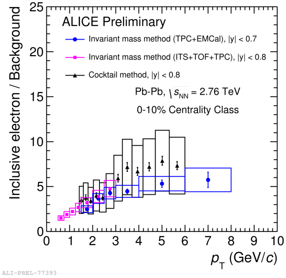
Heavy-flavour decay electron v_2: analysis strategy

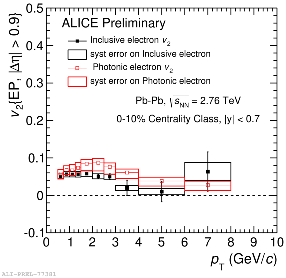
- v_2 of heavy-flavour decay electrons is obtained with the event plane method
- v_2 of inclusive electrons is measured in the central barrel ($|\eta| < 0.7$)
- v_2 of background electrons is obtained with 2 methods:
  - invariant mass method for p_T <1.5 GeV/c
  - cocktail based on data for p_T >1.5 GeV/c
- The heavy-flavour decay electron v_2 is obtained as:

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

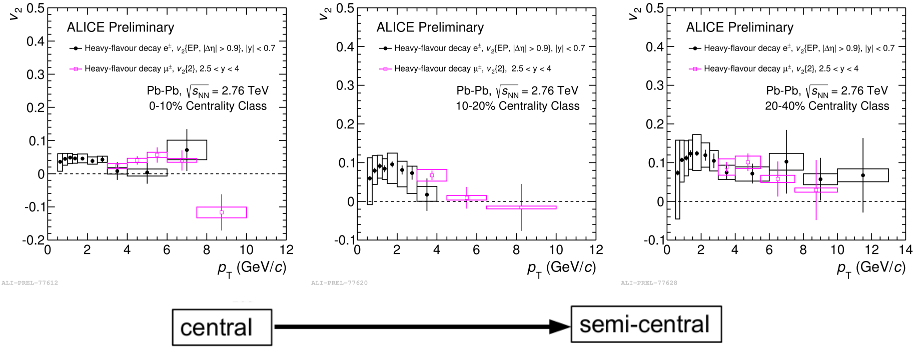
where $R = N^{incl.e}/N^{\text{backg.}e} - 1$.

- Similar strategy for heavy-flavour decay muon v_2



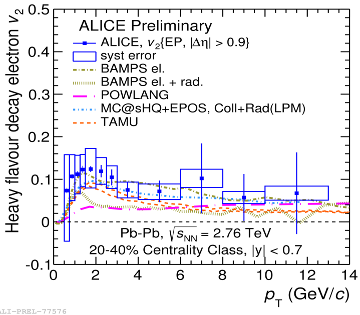


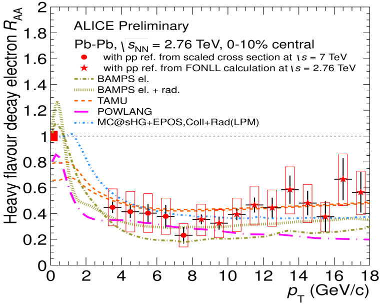
Heavy-flavour decay lepton v_2 in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV



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

Comparison with models: $v_2^{e\leftarrow HF}$ and $R_{AA}^{e\leftarrow HF}$ in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV



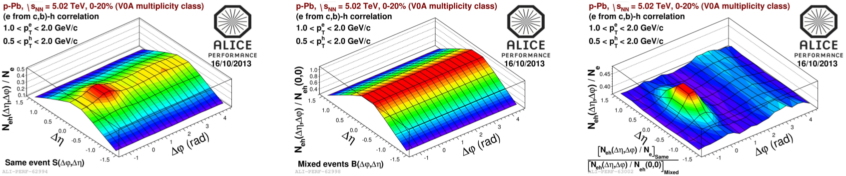


- $v_2^{e\leftarrow HF}$ and $R_{AA}^{e\leftarrow HF}$ measurements together start to provide constraints for the models
- Same behavior observed in heavy-flavour decay muon results

BAMPS:Phys. Lett. B 717 (2012) 430; arXiv:1310.3597v1 [hep-ph]; POWLANG: Eur. Phys. J. C71 (201) 1666, J.Phys. G 38 (2011) 124144; MC@sHQ+EPOS, Coll+Rad(LPM): Phys. Rec. C89 (2004) 014905; TAMU elastic:: arXiv:1401.3817[nucl-th] (2014);

HF-hadron correlations: analysis strategy

- Angular correlation of the heavy-flavour decay electron with other particles
- Correction for detector inhomogeneities and pair acceptance via the event mixing technique
- Efficiency corrections for trigger and associated particles



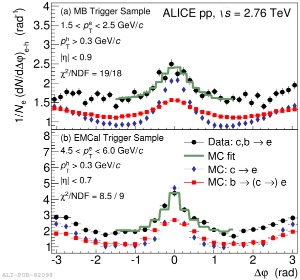
- Study of the correlation distribution as a function of kinematical variables (transverse momentum of the trigger/associated particle) or event properties (multiplicity)

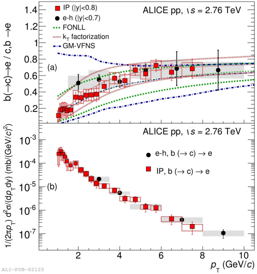
$e \leftarrow HF$-hadron azimuthal correlations in pp collisions

- Correlations of electrons from heavy-flavour decays and charged hadrons in pp collisions allow one to statistically separate the charm and beauty contributions to the inclusive yield of heavy-flavour decay electron
- Wider correlation distribution for electrons from beauty-hadron decays

ALICE collaboration, arXiv:1405.4117

r_b

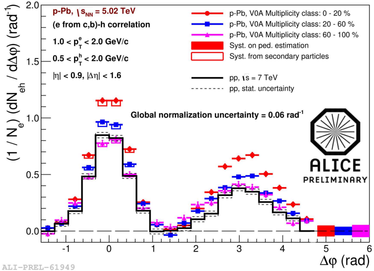


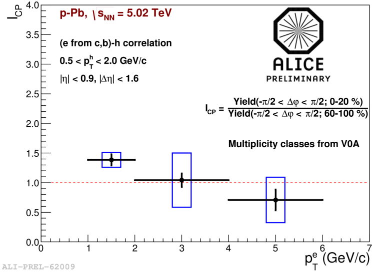


$$\frac{1}{N_{e\leftarrow c,b}}\left(\frac{dN}{d\Delta\varphi}\right)_{e\leftarrow c,b-h} = C + r_b\frac{1}{N_{e\leftarrow c}}\left(\frac{dN}{d\Delta\varphi}\right)_{e\leftarrow c-h} + (1-r_b)\frac{1}{N_{e\leftarrow b}}\left(\frac{dN}{d\Delta\varphi}\right)_{e\leftarrow b-h}$$

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

$e \leftarrow HF$-hadron azimuthal correlations in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV

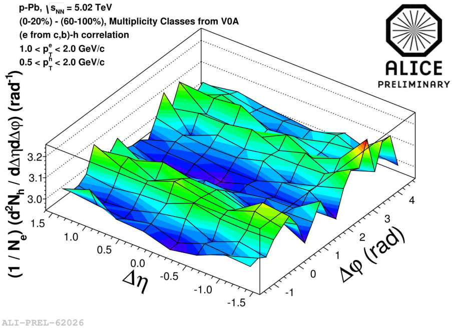




$$I_{CP} = \frac{Y\left(-\pi/2 < \Delta\varphi < \pi/2\right)_{0-20\%}}{Y\left(-\pi/2 < \Delta\varphi < \pi/2\right)_{60-100\%}}$$

- An increase in the yield of associated particles per heavy-flavour decay electron at low p_T on the near- and away-side in high-multiplicity p-Pb collisions, after subtraction of the baseline, is observed with respect to pp and low-multiplicity p-Pb collisions
- An enhacement of the total number of associated particles per trigger on the near side (I_{CP}) is observed in the range $1 < p_T^e < 2$ GeV/c

$e \leftarrow HF$-hadron azimuthal correlations in p-Pb at $\sqrt{s_{\rm NN}}$ = 5.02 TeV



- Removal of jet peak via subtraction of multiplicity classes: (0-20%) - (60-100%)
- Long range correlation featuring a double ridge structure observed for 1 $< p_{\rm T}^{e} <$ 2 GeV/c and 0.5 $< p_{\rm T}^{h} <$ 2 GeV/c
- The double ridge observed in light hadrons (Phys.Lett. B719 (2013) 29-41) is also observed in heavy-flavour sector. The mechanism (CGC? Hydro?) that generates it affects also heavy flavours

Conclusions

Nuclear modification factor

- Strong suppression of heavy-flavour decay leptons at intermediate-high p_{T} observed in central Pb-Pb collisions
- Hint of suppression of beauty-decay electrons for $p_T > 3$ GeV/c in 0-20% central Pb-Pb collisions due to b-quark in-medium energy loss
- R_{pPb} of heavy-flavour decay leptons are compatible with unity within uncertainties, which confirms that the suppression observed in Pb-Pb collisions is due to the hot and dense medium.
- Simultaneous description of v_2 and R_{AA} remains a challenge for models

Elliptic azimuthal anisotropy

- Observed positive heavy-flavour decay electron v_2 and heavy-flavour decay muon v_2 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_{T} heavy quarks (mainly charm)

Correlations

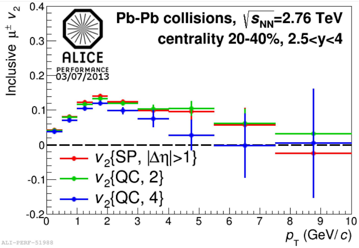
- Multiplicity dependence in HF decay electron-hadron correlations in p-Pb collisions
- Double-ridge structure also observed in HF decay electron - hadron correlations (same origin as for light flavours? CGC? Hydrodynamics?)

Heavy-flavour decay muon v_2: analysis strategy

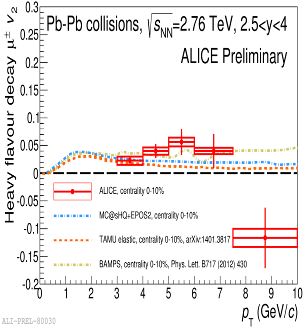
- v_2 of heavy-flavour decay muon is obtained with different methods
- v_2 of inclusive muons is measured at forward rapidity (2.5$< y <$4)
- v_2 of background muons, mainly from π and K decays, is estimated by cocktail method based on extrapolation from mid-rapidity
- The heavy-flavour decay muon v_2 is obtained as:

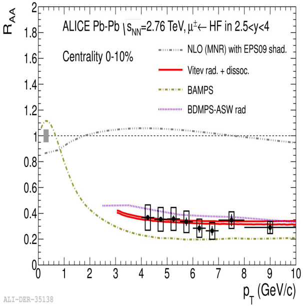
$$v_2^{\mu \leftarrow HF} = \frac{v_2^{\text{incl.}\mu} - f v_2^{\text{back.}\mu}}{1-f}$$

where f is the fraction of decay muons in the inclusive muon sample



Comparison with models: $v_2^{\mu\leftarrow HF}$ and $R_{AA}^{\mu\leftarrow HF}$



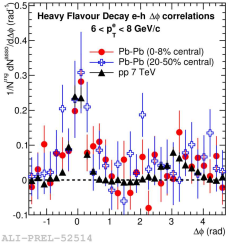


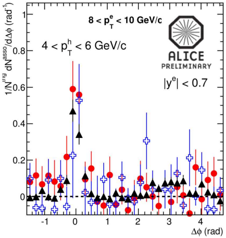
$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

- $v_2^{\mu\leftarrow HF}$ and $R_{AA}^{\mu\leftarrow HF}$ measurements together start to provide constraints for the models

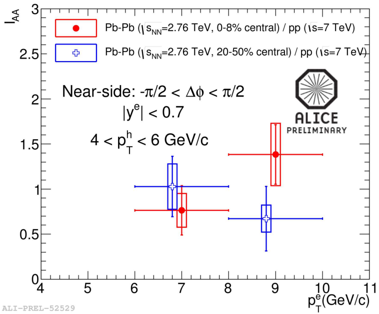
MC@sHQ+EPOS, Coll+Rad(LPM): Phys. Rec. C89 (2004) 014905; TAMU elastic: arXiv:1401.3817 [nucl-th]; BAMPS: Phys. Rev. C 84 (2011) 024908; J. Phys. G38 (2011) 124152 Phys. Lett. B 717 (2012) 430; arXiv:1310.3597v1[hep-ph];

$e \leftarrow HF$-hadron azimuthal correlations in Pb-Pb at $\sqrt{s_{\rm NN}}$ = 2.76 TeV





$$I_{\rm AA} = \frac{Y_{\rm AA}}{Y_{\rm pp}}$$



- The comparison of azimuthal angular correlation distributions in pp and Pb-Pb is quantified by the near-side yields ($I_{\rm AA}$)
- $I_{\rm AA}$ is compatible with unity within uncertainties
- Possible medium induced modification of the fragmentation is not conclusive due to the limited statistics