Measurements of heavy-flavour decay leptons with ALICE

Shingo Sakai for the ALICE collaboration, INFN-Frascati

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Heavy-Flavour (HF) in pp, p-Pb & Pb-Pb

- **Heavy-flavour (charm & beauty) in pp collisions**
  - test for perturbative QCD (pQCD)
    - produced on a short timescale in hard partonic scatterings
  - reference for Pb-Pb collisions

- **Heavy-flavour in heavy-ion collisions**
  - created in initial parton-parton scattering
  - traverse and interact with the hot & dense QCD matter
    - a good probe to study the properties of the medium
    - nuclear modification factor
      - Sensitive to colour charge and mass dependence of in-medium parton energy loss
    - azimuthal anisotropy in non-central collisions
      - strong coupling, participation in the collective expansion of medium
      - energy loss at high $p_T$

- **Heavy-flavour in p-A collisions**
  - control measurement for heavy-ion collisions to disentangle initial from final state effects
Charm & Beauty Energy Loss

- In-medium parton energy loss
  - Radiative energy loss (Djordjevic et al. PLB 632, 81)
    - gluon bremsstrahlung
    - smaller energy loss for heavy than for light quarks
due to “dead cone” effect (Dokshitzer & Kharzeev, PLB 519 (2001) 199.)
    - energy loss depends on the colour charge and is
larger for gluons than for quarks
  - Collisional energy loss (Adil & Vitev PLB 649, 139)
    - energy loss via elastic scattering
- Experimental observable = nuclear modification factor:

\[ R_{AA}(p_T) = \frac{d N_{AA}/dp_T}{\langle T_{AA} \rangle \times d\sigma_{pp}/dp_T} \]

Hierarchy in g, light quarks, c, b quark energy loss reflected into

\[ E_{\text{loss}}(g) > E_{\text{loss}}(u,d,s) > E_{\text{loss}}(c) > E_{\text{loss}}(b) \rightarrow R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B} \]
Electron reconstruction & identification (mid-rapidity)
- ITS: track & vertex reconstruction
- TPC: tracking & PID via dE/dx
- TOF: time of flight
- TRD: transition radiation
- EMCal: energy (E/p), trigger
- background: conversion & Dalitz decay
  - estimated by two method: cocktail (MC) & invariant mass

Muon Spectrometer (-4 < η < -2.5)
- tracking and trigger of muons
- background: dominated by μ from π, K decaying upstream from the absorber
  - estimated via fast MC based on measured π & K spectra at mid-rapidity
HF -> e,μ production in pp collisions

- Heavy-flavour production (c+b, b) at mid-rapidity and forward rapidity (c+b) well described by pQCD calculations
- Reference for Pb-Pb collisions
  - due to limited statistics of pp collisions at 2.76 TeV, a pQCD-based √s-extrapolation of the cross section measured at 7 TeV is performed for HF->e & b (arXiv 1107.3243)
  - for HF->μ the pp reference is taken from the measurement at 2.76 TeV
HF production in Pb-Pb collisions

- $R_{AA}$ of HF-$e$ (mid-rapidity: $|y|<0.6$) & HF-$\mu$ (forward-rapidity: $2.5<y<4.0$) in most-central & mid-central collisions
  - strong suppression ($p_T>3$ GeV/c) of HFE & HFM in central collisions
  - similar suppression of HFE & HFM in different rapidity regions
- Suggest significant energy loss of c and b quarks in the medium
R$_{AA}$ of beauty decay electrons

- Charm & beauty separation is crucial to understand HF energy loss in the hot & dense QCD matter
- Beauty-decay electrons in Pb-Pb via impact parameter measurement
  - $c\tau \sim 500\mu$m for B hadron
- A hint of beauty suppression in central collisions (0-20%)
$v_2$ of HF->e and HF->μ

\[ dN/d(\varphi-\psi_{RP}) = N_0 \{1 + \ldots + 2v_2 \cos(2(\varphi-\psi_{RP})) + \ldots \} \]

- Positive $v_2$ measured
  - $3\sigma$ effect in $2<p_T<3$ GeV/c in 20-40% centrality class
- Measurement indicates centrality dependence of strength of $v_2$
  - Increase of $v_2$ from central (0-10%) to mid-central (20-40%) collisions
- $v_2$ of HF->e at mid-rapidity and HF->μ at forward-rapidity compatible within uncertainties
  - No significant rapidity dependence
- Suggests that charm quarks take part in the collective expansion in medium
Comparison with models

- Theoretical calculations predict strong suppression of HF->e yield at high $p_T$ in Pb-Pb collisions
- Significantly different strength of HF->e $v_2$ in models especially at low $p_T$
- Simultaneous description of $R_{AA}$ and $v_2$ constraints models
Heavy-flavour in p-A collisions
- control measurement for heavy-ion collisions to disentangle initial (cold nuclear matter effects) from final state effects

Cold nuclear matter effects
- nuclear modification of Parton distribution Functions (PDF): shadowing or gluon saturation
  - K.J. Eskola et al., JHEP 0904(2009)65
  - H. Fuji & K. Watanabe, NPA 915 (2013) 1
- energy loss
  - I. Vitev et al., PRC 75(2007) 064906
- $k_T$ broadening
- multiple collisions
  - A.M. Glenn et al., PLB 644(2007)119
HF production in p-Pb collisions at mid-rapidity

- $R_{pPb}$ of HF-$\rightarrow$e and b-$\rightarrow$e are consistent with unity within uncertainties
- Suppression of HF-$\rightarrow$e & b-$\rightarrow$e ($R_{AA}<1$) in Pb-Pb collisions is due to interaction with the hot and dense medium
HF production in p-Pb collisions at forward rapidity

- $R_{p\text{Pb}}$ of HF-$\mu$ at forward ($2.5<y_{\text{CMS}}<3.54$) and backward ($-4<y_{\text{CMS}}<-2.96$) rapidity
  - forward (proton going): consistent with unity
  - backward (Pb going): consistent with unity, however, slightly larger 1 for $p_T<4$ GeV/c

- Strong suppression of HF-$\mu$ in Pb-Pb collisions is due to interaction with the hot and dense medium
Comparison with models in p-Pb collisions

- Comparison with MNR pQCD calculations for heavy-flavour production with EPS09 parametrization of shadowing
  - EPS09: JHEP 0904 (2009) 065
  - calculations in agreement with data (HF->e & HF->µ) within uncertainties in different rapidity regions
  - seems to under-predict \( R_{pPb} \) of HF->µ at low \( p_T \)

\[ R_{pPb} \text{ vs. } p_T (GeV/c) \]

\( p_{Pb} s_{NN} = 5.02 \text{ TeV, } \mu^\pm \rightarrow c,b \) decays

2.5<\( y_{\text{cms}} <3.54 \)

\( R_{pPb} \text{ vs. } p_T (GeV/c) \]

\( p_{Pb} s_{NN} = 5.02 \text{ TeV, } \mu^\pm \rightarrow c,b \) decays

-4<\( y_{\text{cms}} <2.96 \)
Azimuthal correlations of HF->e - hadron in p-Pb collisions (I)

- Azimuthal correlation between HF->e and hadrons
  - trigger particle: heavy flavour decay electrons
  - clear correlation on near & away side: jet like structure
- Enhancement in high (0-20%) w.r.t. low-multiplicity (60-100%) collisions
Azimuthal correlations of HF->e - hadron in p-Pb collisions (2)

- Subtract low mult. correlations from high mult. to remove jet contributions
- Observed long-range ridge structures on the near-side and away-side in heavy-flavour production in p-Pb collisions
  - similar structure observed hadron-hadron correlations: PLB 719(2013)29-41 [ALICE]
- Possible origins:
  - Color Glass Condensate (CGC) in the initial state
  - collective (hydrodynamic) expansion in the final state
Summary

- **Heavy-flavour production in pp collisions**
  - pQCD calculations describe data within uncertainties

- **Heavy-flavour production in Pb-Pb collisions**
  - Strong suppression of heavy-flavour yield at high $p_T$
    - clear indication for substantial energy loss of heavy-flavour in the hot and dense medium
  - Non-zero $v_2$ in low $p_T$
    - suggests that charm quarks take part in the collective expansion of the medium

- **Heavy-flavour production in p-Pb collisions**
  - $R_{ppb}$ is consistent with unity
    - confirms that the suppression observed in Pb-Pb is due to interactions with the hot and dense medium
  - Long-range ridge structures
    - the mechanisms (CGC or hydro) proposed for light-hadron correlations affect also HF

- Heavy flavours observed to be significantly affected by hot and dense QCD medium (energy loss and $v_2$)

- Constraining the models with our data and learn mechanism of HF productions
Heavy flavour study via electrons

- **Signal Electrons:**
  - From semileptonic decay of charm & beauty hadrons

- **Background Electrons:**
  - From photon conversions
  - From Dalitz decays of neutral mesons
  - From quarkonia decays

- **Background subtraction**
  - **Cocktail method**
    - Background calculated using measured hadron production cross section
  - **Invariant mass method – electrons from ‘photonic’ sources**
    - Reconstruction of electron pairs from the decays of neutral mesons & photon conversions

  - **Heavy Flavour decay Electrons (HFE) dN/dp_T obtained via subtraction of the background from the inclusive electron spectrum**

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<th>Branching Ratios:</th>
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<tr>
<td>$c \rightarrow e + X$</td>
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<td>$b \rightarrow e + X$</td>
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<td>$b \rightarrow c \rightarrow e + X$</td>
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Beauty decay electron separation
- Impact parameter method

- Separation based on displacement from primary vertex
  - Preferential selection via their large impact parameter ($d_0$)
    - $c\tau \sim 500\mu m$ for B hadron
    - $|d_0|>250\mu m$ ($p_T \sim 2.5$ GeV/c) ($p_T$ dependent cut)
  - ITS ; impact parameter resolution $< 75 \mu m$ for $p_T > 1$ GeV/c

- Remaining backgrounds estimated based on measured $\pi^0$, $\eta$ & D

- use in pp & p-Pb analysis
Azimuthal anisotropy

- Elliptic flow
- Transfer initial spatial anisotropy to momentum anisotropy
  - macroscopic: hydro model
    => pressure gradient
  - microscopic
    => scattering in the medium
- At low $p_T$, heavy flavour $v_2$ gives information about the coupling of heavy quarks with the medium and possibly their thermalization in the medium
- Path-length dependence of energy loss at high $p_T$

\[
dN/d(\varphi-\psi_{RP}) = N_0\{1+\ldots+2v_2\cos(2(\varphi-\psi_{RP})) +\ldots\}
\]
Azimuthal anisotropy of electrons

- Elliptic flow ($v_2$); $dN/d(\phi-\psi) = N (1 + 2v_2^{\text{obs}} \cos(2(\phi-\psi_{\text{EP}})))$
- Event plane determined with the VZERO detectors ($2.8<\eta<5.1$, $-3.7<\eta<-1.7$)
- HFE $v_2$ obtained by subtraction of the background electron $v_2$:

$$v_2^{\text{HFE}} = \frac{(1 + R) v_2^{\text{inclusive}} - v_2^{\text{background}}}{R}, \quad R = \frac{N_{\text{HFE}}}{N_{\text{background}}}$$
\( R_{pPb} \) of HF->e

- Compatible with unity within uncertainties
- Similar behaviour observed at PHENIX for d-Au at \( \sqrt{s_{NN}} = 0.2 \) TeV