Muons from Open Heavy-flavour Decays in pp, Pb-Pb and p-Pb Collisions with ALICE

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Outline

- Heavy-Flavour Physics at the LHC
- Heavy-Flavour Measurements with ALICE
- Muon analysis results in p-p, Pb-Pb and p-Pb collisions
- Conclusions and Outlooks
Part 1:
Introduction
Heavy-Flavour Physics at the LHC

- Heavy flavours in pp collisions
  - baseline for pA and AA collisions
  - test NLO pQCD in a new energy domain

- Heavy flavours in AA collisions: tomography of QCD medium
  - Nuclear modification factor
    - mass and color charge dependence of parton energy loss;
  - azimuthal anisotropic flow
    - low $p_T$ region: initial conditions of QCD medium, degree of thermalization of heavy quarks in QGP,
    - high $p_T$ region: path length dependence of heavy flavour energy loss;

- Heavy flavours in pA collisions
  - “correct” $R_{AA}$ for shadowing effects: deviation of $R_{pA}$ from unity reveals the presence of cold nuclear matter (CNM) effect

\[
R_{AA} = \frac{1}{<T_{AA}>} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}
\]

\[
\triangle E_g > \triangle E_{q=c} > \triangle E_b
\]

\[
R^h_{AA} < R^D_{AA} < R^B_{AA}
\]
Heavy-flavour Measurements with ALICE

ITS, TPC, TRD, ToF, EMCal (|η|<0.9)
(di-)electrons: J/ψ, ψ’, Υ, Υ’, Υ”
open charm, open bottom, W±, Z0

muon spectrometer (-4<η<-2.5)
(di-)muons: J/ψ, ψ’, Υ, Υ’, Υ”
open charm, open bottom, W±, Z0

The heavy-flavour physics is investigated in several decay channels and large rapidity coverage with ALICE.

ITS, TPC, ToF (|η|<0.9)
hadrons: D⁰, D±, D*…
electron-muon coincidences:
open charm & bottom

no 2nd vertex
2nd vertex

μ ± (GeV)

D (GeV)

0 2 4 6 8

-4 -2 0 2 4

μ electrons hadrons
Data samples

• pp collisions @ $\sqrt{S_{NN}} = 7$ TeV: data collected in 2010, muon trigger events;

• Pb-Pb collisions @ $\sqrt{S_{NN}} = 2.76$ TeV
  ✓ $R_{AA}$: data collected in 2010, min.bias events;
  ✓ $v_2$: data collected in 2011, central and semi-central events;

• p-Pb/Pb-p collisions @ $\sqrt{S_{NN}} = 5.02$ TeV: data collected in 2013, muon trigger events.
Muon selection

Track selection
- $-4 < \eta_{lab} < -2.5$: acceptance of ALICE MUON spectrometer;
- $170^0 < \theta_{abs} < 178^0$: geometry of the spectrometer;
- muon trigger matching: reject hadrons that cross the absorber;
- $p_x\text{DCA}$: remove beam-gas and particles produced in the absorber.
Decay Muon Subtraction in p-p Collisions

● **Strategy:**
  ✓ extract $dN/dp_T$ of $K/\pi$ decay muons from simulation (PYTHIA or Phojet);
  ✓ normalize it to measured muon yield at low $p_T$;
  ✓ subtract from inclusive $dN/dp_T$ to obtain heavy flavour decay muon spectrum;

● **Systematic uncertainty:**
  ✓ models: estimated by using different inputs;
  ✓ transport codes, estimated by varying yield of muons from secondary $K/\pi$ between 0 and 200%.
Strategy:


- extrapolate $K/\pi$ spectra in pp collisions to forward rapidity by means of Monte-Carlo simulations according to

$$d^2N_{pp}^{\pi^\pm,K^\pm}/dp_tdy = [d^2N_{pp}^{\pi^\pm,K^\pm}/dp_tdy]_{y=0} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)$$

- get $K/\pi$ spectra in Pb–Pb collisions at forward rapidity by scaling the extrapolated charged $K/\pi$ spectra with their $R_{AA}$ at central rapidity

$$dN_{PbPb}^{\pi^\pm,K^\pm}/dp_t = \langle T_{AA} \rangle (d\sigma_{pp}^{\pi^\pm,K^\pm}/dp_t) [R_{AA}^{\pi^\pm,K^\pm}(p_t)]_{y=0}$$

- vary $K/\pi R_{AA}$ between 0 and 200% to estimate the systematic uncertainty on unknown quenching effect at forward rapidity;

- produce the $K/\pi$ decay muon background by means of fast simulation.
Decay Muon Subtraction in p-Pb Collisions

**Strategy:**

- input: $K/\pi$ spectra in p-Pb collisions at central rapidity measured with ALICE;
- extrapolate $K/\pi$ spectra in p-Pb collisions to forward rapidity by means of Monte-Carlo simulations according to

$$\left. \frac{1}{N_{AA}^{ev}} \frac{dN_{pA}^{k/\pi}}{dp_t} \right|_{FW (\Delta p_t)} = \left. \frac{1}{N_{AA}^{ev}} \frac{dN_{pA}^{k/\pi}}{dp_t} \right|_{CB} \times F_{\text{extra.}}$$

$$F_{\text{extra.}} = \frac{1}{N_{AA}^{ev}} \frac{dN_{pA}^{k/\pi}}{dp_t} \bigg|_{a}^{b} \left/ \left. \frac{1}{N_{AA}^{ev}} \frac{dN_{pA}^{k/\pi}}{dp_t} \right|_{0}^{0.5} \right.$$ 

by using the *non-parameterized* rapidity extrapolation factor;

- produce the $K/\pi$ decay muon background by means of fast simulation.

$$\left. \frac{1}{N_{AA}^{ev}} \frac{dN_{pA}^{\mu^{-}-k/\pi}}{dp_t} \right|_{FW (\Delta p_t)} = \left\{ \left. \frac{1}{N_{AA}^{ev}} \frac{dN_{pA}^{k/\pi}}{dp_t} \right|_{FW (\Delta p_t)} \right\} \times \left. \frac{dN_{pA}^{\mu^{-}\text{flat}}}{dp_t} \right|_{FW (\Delta p_t)} (\Delta p_t)$$
Normalization to Min. Bias events

**Strategy:** two methods are used to obtain the number of equivalent Min. Bias events from the MSL/MSH triggers: about 1% difference

- Offline method from AOD

\[
F_{\text{norm}}(\text{MSL}) = \frac{N_{\text{MB}} \times F_{\text{pile-up}}}{N_{(\text{MB} \& 0\text{MSL})}}
\]

\[
F_{\text{norm}}(\text{MSH}) = \frac{N_{\text{MB}} \times F_{\text{pile-up}}}{N_{(\text{MB} \& 0\text{MSL})}} \times \frac{N_{\text{MSL}}}{N_{(\text{MSL} \& 0\text{MSH})}}
\]

- Scaler method from OCDB: used in the following

\[
F_{\text{norm}} = \frac{L0b_{\text{MB}} \times \text{purity}_{\text{MB}} \times F_{\text{pile-up}}}{L0b_{\text{MSL}(\text{MSH})} \times PS_{\text{MSL}(\text{MSH})}}
\]

**N.B.** $L0b$ is the value of $L0b$ counter for selected trigger;

$PS$ is the fraction of physics selection accepted triggers;

$purity$ is the fraction of events which satisfy V0 timing cut (that is better than 99% for most of the runs)

\[
F_{\text{pile-up}} = \mu / e^{-\mu}, \quad \mu = -\ln(1 - \text{purity}_{\text{MB}} \times \frac{L0b\text{Rate}_{\text{MB}}}{N_{\text{colliding}} \times f_{\text{LHC}}})
\]

<table>
<thead>
<tr>
<th>$F_{\text{norm}}(0-100%)$</th>
<th>p-Pb</th>
<th>Pb-p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Offline</td>
<td>Scaler</td>
</tr>
<tr>
<td>MSL</td>
<td>28.1</td>
<td>28.5</td>
</tr>
<tr>
<td>MSH</td>
<td>1024.3</td>
<td>1040.8</td>
</tr>
</tbody>
</table>
Acceptance x Efficiency Correction

➢ Reminder for Pb-Pb collisions
  • the centrality dependence of tracking efficiency is estimated via embedding procedure
  • efficiency drops by $4 \pm 1\%$ in the 10% most central collisions w.r.t. peripheral collisions

➢ Follow same strategy as in pp collisions
  • no dependence on centrality expected
    (Javier, Jpsi2mumu PAG meeting, 31/05/2013)
  • simulations using beauty signals with realistic detector condition as inputs
  • systematic uncertainty on misalignment: $1\% \times p_T$ ($p_T$ in GeV/c)
Part 2:
Results & Discussions
p-p collisions

--- cross section

- $p_T$-differential cross sections of muon from heavy-flavour decays measured at 2.76 and 7 TeV;
- The FONLL pQCD calculations are in good agreement with data within experimental and theoretical uncertainties;
- baseline for the study of heavy quark in-medium effects in Pb-Pb and p-Pb collisions.
Pb-Pb collisions

- suppression is observed and is independent of $p_T$ within uncertainties (in the measured $p_T$ interval);
- stronger suppression in central than peripheral collisions, reaching a factor of about 3–4 in the 10% most central collisions;
- in the $p_T$ region ($p_T > 6$ GeV/$c$), beauty contribution is dominant in pp collisions, according to FONLL calculations.
Pb-Pb collisions

---- azimuthal anisotropic flow

- **Left:** differential $v_2$ vs $p_T$
  - $v_2$ of muons from heavy-flavour decays in semi-central collisions (20-40%) is systematically larger than that in central collisions (0-10%);
  - non-zero $v_2$ (3σ effect) in $3<p_T<5$ GeV/c and 20-40% centrality class;

- **Right:** integrated $v_2$ (in $3<p_T<10$ GeV/c) vs centrality
  - $v_2$ of muons from heavy-flavour decays increases from central to peripheral collisions;
  - non-zero $v_2$ (3σ effect) in semi-central collisions (20-40%).
p-Pb collisions

----- nuclear modification factor $R_{pA}$
Conclusion

- **Cross section of muons from heavy-flavour decays measured in pp collisions:**
  - FONLL predictions in good agreement with data within uncertainties;
  - baseline for the study of AA and pA collisions

- **$R_{AA}$ of muons from heavy flavour decays measured as a function of $p_T$ and centrality:**
  - a strong suppression of high $p_T$ muons from heavy-flavour decays is observed in central collisions;
  - no significant dependence on $p_T$ in $4<p_T<10$ GeV/c;

- **$v_2$ of muons from heavy-flavour decays:**
  - $v_2$ in 20-40% centrality class is larger than that in the most central collisions
  - non-zero $v_2$ (3σ effect) in $3<p_T<5$ GeV/c and 20-40% centrality class;

- **$R_{pA}$ of muons from heavy-flavour decays in 0-100%:**
Ongoing work

• implement the similar strategy of the background estimation in Pb-p collisions;
• measure the $R_{Ap}$;
• get the forward to backward ratio $R_{FB}$.
backup
Convert the spectra to muon level

✓ weighting procedure: \( p_t^{\text{flat } k/\pi} \leftrightarrow p_t^{\mu \leftrightarrow \text{flat } k/\pi}; \)

☐ for each muon we get the transverse momentum of its mother K/pi (\( p_t^{\text{flat } k/\pi} \))

☐ weight the above muon spectra according to the bin content at \( p_t = p_t^{\text{flat } k/\pi} \) in the given K/pi distribution, and then re-fill it;

☐ systematics uncertainties on the given K/pi spectrum and rapidity extrapolation factor are taken into account, and also the absorber effect;

☐ finally, we normalize the weighted muon distribution with the total number of generated mother K/pi .

\[
\frac{1}{N_{AA}^{ev}} \left. \frac{dN_{pA}^{\mu \leftrightarrow k/\pi}}{dp_t} \right|_{FW (\Delta p_t)} = \left\{ \frac{1}{N_{AA}^{ev}} \left. \frac{dN_{pA}^{k/\pi}}{dp_t} \right|_{FW (\Delta p_t)} \times \left. \frac{dN_{pA}^{\mu \leftrightarrow \text{flat } k/\pi}}{dp_t} \right|_{FW (\Delta p_t)} \right \}
\]
\( p_T \)-differential \( R_{AA} \) of Heavy Flavours

- Similar HF decay e (\(|y|<0.6\)) and \( \mu \) (2.5<\( y \)<4.0) \( R_{AA} \) in 0-10%;
- difficulty: comparison of \( R_{AA} \) of D mesons and that of HF decay electrons must consider semi-leptonic decay kinematics (\( p_T^{\text{e}} \approx 0.5 \ p_T^{\text{B}} \) at high \( p_T \));
$\rho_T$-differential $v_2$ of Heavy Flavours

- **D mesons:**
  - measured with event plane method; consistency among different D mesons; similar $v_2$ magnitude of D mesons and charged hadrons;
- **Heavy-flavour electron:**
  - measured with event plane method;
- **Non-zero $v_2$ (3 sigma effect) for D mesons in $2<\rho_T<6$ GeV/c, heavy flavour electrons in $2<\rho_T<3$ GeV/c and heavy flavour muons in $3<\rho_T<5$ GeV/c;
- **$v_2$ of heavy-flavour muons at forward rapidity (-4<\eta<-2.5) is consistent with that of heavy-flavour electrons at mid-rapidity (|\eta|<0.9) within uncertainties.
\( \rho_T \)-differential \( R_{pA} \) of Heavy Flavours

D mesons:
- \(-0.04 < y_{CMS} < 0.96\)

Heavy-flavour electrons:
- \(-0.14 < y_{CMS} < 1.06\)

● Within uncertainties, both the results from D mesons and heavy-flavour electrons are around unity, and also consistent with theoretical predictions;