Heavy-flavor hadron measurement with ALICE

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Outline

- Physics motivation
- ALICE detector
- Results
  - Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV, $L_{int} \sim 0.1$ nb$^{-1}$ (2011 run)
  - p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV, $L_{int} \sim 30$ nb$^{-1}$ (2013 run)
- Summary
Heavy quark production

- **pp**
  - Test of perturbative QCD in vacuum
  - Reference for p-Pb and Pb-Pb
- **p-Pb**
  - Initial state effects (gluon saturation/shadowing)
  - Indication of flow and final state effects
  - Is it reference for Pb-Pb?
- **Pb-Pb**
  - Heavy quarks are ideal to probe the QGP ($\tau_{\text{prod}} = 1/2m \ll \tau_{\text{QGP}} \sim 10$ fm/c)
  - Study the interaction of heavy quarks with dense and hot QCD medium
    - Energy loss dependence on color charge ($\Delta E_g > \Delta E_{q,Q}$) and mass “dead cone” ($\Delta E_q > \Delta E_c > \Delta E_b$) [Dokshitzer and Kharzeev, PLB 519 (2001) 199]
    - Test of collectivity in QGP – do heavy quarks participate in flow?
    - Probe the level of heavy quark thermalization – heavy flavor production mechanism [Kuznetsova and Rafelski, EPJC 51 (2007) 113]
Quarkonium production in HI collisions

- Quarkonia – bound states \((c\bar{c}, b\bar{b})\) produced in the early stage of HI collisions
- Charmonia production via regeneration \((c\bar{c} \text{ combination})\) in the QGP or at the phase boundary \((T \sim T_{ch})\) [Braun-Munzinger and Stachel, PLB 490 (2000) 196; Thews et al., PRC 63 (2000) 054905]

Central Pb-Pb collisions at LHC:
- \(N_{c\bar{c}}/\text{event} \sim 115, N_{b\bar{b}}/\text{event} \sim 3\) (10x more than at RHIC)

\(\rightarrow\) Enhancement of charmonium production via regeneration (depending on open charm cross section)?
\(\rightarrow\) Evidence for charm thermalization?
\(\rightarrow\) Charmonium inherits flow from charm?
\(\rightarrow\) Small regeneration for bottomonia?
Heavy-flavor hadrons and quarkonia in ALICE

- $D, B \ldots \rightarrow e + X$ and quarkonia (e.g. $J/\psi \rightarrow e^+e^-$) in central rapidity $|\eta| < 0.9$
- $D, B \ldots \rightarrow \mu + X$ and quarkonia (e.g. $J/\psi \rightarrow \mu^+\mu^-$) in forward rapidity $-4.0 < \eta < -2.5$

Central barrel tracking and PID $|\eta| < 0.9$

MUON arm $-4.0 < \eta < -2.5$
D mesons in ALICE

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

Central barrel tracking and PID $|\eta| < 0.9$
RESULTS FROM PB-PB COLLISIONS
D-meson $R_{AA}$ vs. $p_T$

$$R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{AA}}{dp_T} / \frac{dN_{pp}}{dp_T}$$

$R_{AA} = 1 \rightarrow$ no modification

- Strong suppression of all D mesons at high-$p_T$ (factor $\sim 5$ at $p_T=10$ GeV/c) in central collisions
- Different $D_s^+$ $R_{AA}$ compared to other mesons (first measurement in HI collisions, large uncertainties)? Expected if $D_s^+$ production via coalescence in QGP [Kuznetsova and Rafelski, EPJC 51 (2007) 113; Andronic et. al, PLB 659 (2008) 149]
$R_{AA}$ - D mesons vs. pions

$\Delta E_{g,q} > \Delta E_c \Rightarrow R_{AA}(\pi) < R_{AA}(D)$?

not trivial relation: parton p$_T$ spectral shape and fragmentation

- $R_{AA}(\pi) \sim R_{AA}(D)$ for p$_T > 7$ GeV/c
- Sign of $R_{AA}(\pi) < R_{AA}(D)$ for 2 < p$_T$ < 3 GeV/c in central collisions

$\rightarrow$ Color charge dependence? Data not conclusive yet (large systematic uncertainties)
\( R_{AA} \) - D vs. B mesons

\[ \Delta E_c > \Delta E_b \rightarrow R_{AA}(D) < R_{AA}(B) ? \]

energy loss mass dependence

- D \(< p_T \sim 10 \text{ GeV/c}: \text{ALICE} \)
- B (non prompt J/\(\psi\)) \(< p_T \sim 11 \text{ GeV/c}: \text{CMS} \)

\( R_{AA}(D) > R_{AA}(B) \rightarrow \) indication of larger energy loss for charm than for beauty
Heavy-flavor elliptic flow $v_2$

D mesons [ALICE PRL 111, 102301 (2013)]

- All channels show elliptic flow $v_2 > 0$ at intermediate $p_T$
- D-meson $v_2$ comparable to pion $v_2$
- Similar values of $v_2$ in central and forward rapidity
→ Charm participates in flow

Heavy-flavor decay electrons and muons
QUARKONIA FROM PB-PB COLLISIONS
Sequential $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ suppression at the LHC

$\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ $p_T>0$: CMS, PRL 109 (2012) 222301

$J/\psi$ $p_T > 6.5$ GeV/c: CMS, PAS HIN-12-014

- Suppression of $\Upsilon(2S)$
- Suppression of $\Upsilon(1S)$ consistent with excited state suppression (50% feed down)

Centrality 0-100%
- $R_{AA}(\Upsilon(1S)) \sim 0.56 \pm 0.08$ (stat.) $\pm 0.07$ (syst.)
- $R_{AA}(\Upsilon(2S)) \sim 0.12 \pm 0.04$ (stat.) $\pm 0.02$ (syst.)
- $R_{AA}(\Upsilon(3S)) < 0.1$ (at 95% C.L.)

Sequential suppression of $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ states in order of their binding energy
\( J/\psi \) \( R_{AA} \) in ALICE

ALICE, arXiv:1311.0214

- \( J/\psi \) suppressed at forward and central rapidity
- Suppression increasing with rapidity
Different suppression pattern compared to RHIC at central and forward rapidity

→ Different source of J/ψ in central collisions at the LHC
→ Indication of regeneration in central collisions?

ALICE, arXiv:1311.0214
PHENIX, PRC 84 (2011) 054912
At low $p_T$: different suppression compared to RHIC at central and forward rapidity
At high $p_T$: similar suppression compared to RHIC

Different source of low-$p_T$ $J/\psi$ in central collisions at the LHC (regeneration?)
J/ψ $R_{AA}$ vs. collision centrality vs. models

Central rapidity

Forward rapidity

Statistical hadronization model:
Andronic et al. (J/ψ production at chemical freeze-out)

Transport models:
Liu et al. (J/ψ dissociation + regeneration + $p_T$ broadening + shadowing)
Zhao at al. (J/ψ dissociation + regeneration + shadowing)
Ferreiro (J/ψ comover dissociation + regeneration + shadowing)
$J/\psi$ $R_{AA}$ vs. $p_T$ vs. models

ALICE, arXiv:1311.0214

Transport model: Liu et al. ($J/\psi$ dissociation + regeneration + $p_T$ broadening + shadowing) consistent with data

$\rightarrow$ Production of low-$p_T$ $J/\psi$ via regeneration
J/ψ $v_2$ vs. $p_T$

Transport models (Liu et al. / Zhao et al.):
- J/ψ dissociation and regeneration

J/ψ elliptic flow $v_2 > 0$ at intermediate $p_T$ in semi-central Pb-Pb collisions

ALICE, PRL 111 (2013) 162301
RESULTS FROM P-PB COLLISIONS
p-Pb measurements

- Asymmetric p-Pb collisions ($\sqrt{s_{NN}} = 5.02$ TeV): $\Delta y_{NN} = 0.465$ in the p-beam direction
- 2 beam configurations (p-Pb and Pb-p): 2 rapidity ranges for the MUON spectrometer

MUON spectrometer in p-beam direction
Forward rapidity: $2.03 < y_{cms} < 3.53$
$x_{Pb} \sim 10^{-5} - 10^{-4}$

MUON spectrometer in Pb-beam direction
Backward rapidity: $-4.46 < y_{cms} < -2.96$
$x_{Pb} \sim 10^{-2} - 10^{-1}$

Central rapidity: $-1.37 < y_{cms} < 0.43$
$x_{Pb} \sim 10^{-3}$

$p$–Pb

$p$ 4 TeV

$Pb$ 1.58 A TeV

$p$ 4 TeV

$x_{Pb}$ – momentum fraction of probed gluons in Pb nucleus assuming $2 \rightarrow 1$ quarkonia production mechanism
D-meson $R_{pPb}$ vs. $R_{AA}$

\[ R_{pPb} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pPb}}{dp_T} / \frac{dN_{pp}}{dp_T} \]

\[ \langle N_{coll} \rangle = A \cdot \frac{\sigma_{pN}}{\sigma_{pA}} = 208 \cdot \frac{70 \text{ mb}}{2100 \text{ mb}} = 6.9 \]

No modification at high-$p_T$ ($R_{pPb} \sim 1$) in minimum bias $p$-$Pb$

→ Particle production suppression in Pb-Pb central collisions related to final state effects
D-meson $R_{pPb}$ vs. models

Models:

- pQCD NLO (MNR) with EPS09 parameterization of nuclear PDFs

- Color Glass Condensate (CGC)
  [Fuji-Watabe, arXiv:1308.1258]

→ Models including cold nuclear matter effects describe the data
Heavy flavor e-h correlations in p-Pb

Heavy flavor decay electrons correlation with hadrons

Analysis in multiplicity classes defined using V0A detector (2.8 < η < 5.1):
- 0-20% - high multiplicity
- 60-100% - low multiplicity

Double ridge structure as in h-h correlations [ALICE, PLB 719 (2013) 29].

The h-h correlations are consistent with flow [Bożek and Broniowski PLB718 (2013) 1557] or CGC [Dusling and Venugopalan, PRD 87 (2013) 054014].
QUARKONIA FROM P-PB COLLISIONS
\[ \frac{J/\psi}{R_{pPb}} \text{ vs. } y_{\text{cms}} \]

- **Backward rapidity**: No modification $R_{pPb} \sim 1$
- **Suppression at central and forward rapidity** (increasing with rapidity)
$J/\psi \ R_{pPb}$ vs. $y_{\text{cms}}$ vs. models

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**Backward rapidity**

**Central rapidity**

**Forward rapidity**

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Models:

- CEM + EPS09 NLO shadowing

- Gluon saturation [Fuji et al., arXiv:1304.2221]: CGC + LO CEM
  - disagreement

- Coherent energy loss with/without EPS09 NLO shadowing
J/ψ $R_{pPb}$ vs. $p_T$ vs. models

Data:
Backward rapidity: $R_{pPb} = 1$-1.2, small dependence on $p_T$
Central rapidity: $R_{pPb} < 1$ at low $p_T$ and increases with $p_T$
Forward rapidity: $R_{pPb} < 1$ at low $p_T$ and increases with $p_T$, $R_{pPb} \sim 1$ above $p_T = 5$ GeV/c

Comparison with models:
• Data consistent with energy loss (Arleo et al.) and shadowing (Vogt) models at high $p_T$
• Model based on CGC (Fuji et al.) does not describe data
Strong suppression of $\Psi(2S)$ in minimum bias p-Pb collisions ($R_{pPb} \sim 0.5$)

$\Psi(2S)$ suppressed stronger than for $J/\Psi$ (similar observation at RHIC Phys. Rev. Lett. 111, 202301 (2013))

Shadowing (Vogt) and energy loss (Arleo et al.) models cannot explain data

→ Final state effects? Other mechanisms?
Summary

Pb-Pb collisions
- D and B production is strongly suppressed at high-p_T in central Pb-Pb collisions
  - Mass dependence observed
- First D_s^+ R_{AA} measurement in HI collisions
- Charm and beauty v_2 > 0 at intermediate p_T (D meson v_2 comparable to pion v_2)
- Upsilon sequential suppression observed at LHC (color screening)
- J/ψ suppression and regeneration observed in central Pb-Pb collision
- J/ψ elliptic flow v_2 > 0 at intermediate p_T in semi-central Pb-Pb collisions

p-Pb collisions
- D-meson R_{AA} \sim 1 in minimum bias Pb-Pb collisions
- Double ridge in heavy flavor e-h correlations in high multiplicity p-Pb collisions
- J/ψ production is suppressed in central and forward rapidity (p_T < 5 GeV/c), and not at backward rapidity
- Ψ(2S) R_{pPb} < J/ψ R_{pPb} in p-Pb \rightarrow Final state effects? Other mechanisms?

Era of high precision measurements of heavy flavor hadrons has just started!
Backup
Parton energy loss in QCD medium

Radiative and collisional parton energy loss: 
\[ \Delta E (\varepsilon_{\text{medium}}; m, C_R, L) \]
- Color charge dependence \( C_R \): \( \Delta E_g > \Delta E_{q,Q} \)
- Mass dependence \( m \): \( \Delta E_q > \Delta E_c > \Delta E_b \)
\[ \Rightarrow \Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b \]

Not trivial relation between energy loss and \( R_{AA} \):
\[ R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B) \]
- Need to account for different parton \( p_T \) spectra and fragmentation functions

\[
R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{AA} / dp_T}{dN_{pp} / dp_T}
\]

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Dokshitzer, et al., JPG 17 (1991) 1602
Dokshitzer and Kharzeev, PLB 519 (2001) 199
Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003
Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493
D-meson $R_{AA}$ at RHIC and LHC

- Similar D suppression at high-$p_T$ ($\sim 5-6$ GeV/c) at RHIC and LHC
- Different behavior at lower $p_T \sim 1.5$ GeV/c (enhancement at RHIC)
- Model predictions [He, Fries and Rapp, PRL 110 (2013) 112301] (hydro + non-perturbative QCD + coalescence with strange quarks + diffusion in hadronic phase)
  $\Rightarrow$ “D vs. $D_S$ comparison (spectra and flow) helps to disentangle transport properties of QGP and hadronic medium”
$\Delta E_{g,q} > \Delta E_c \rightarrow R_{AA}(\pi) < R_{AA}(D)$?

not trivial relation: parton $p_T$ spectral shape, fragmentation and bulk particles

Model [M. Djordjevic at al.]:

$R_{AA}(\pi) \sim R_{AA}(D)$ for $p_T > 7$ GeV/c

Hint for $R_{AA}(\pi) < R_{AA}(D)$ for $p_T<$
Heavy-flavor $R_{AA}$ in p-Pb vs. models

**D mesons**

- Average $D^0$, $D^+$, $D^{*-}$
- pQCD NLO (MNR) + EPS09 shad.
- CGC (Fujii-Watanabe)

\[ R_{pPb} \text{ prompt } D \]

\[ p\text{-}Pb, \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

\[ -0.96 < y_{CMS} < 0.04 \]

**$b,c \rightarrow e^+ e^-/2$**

\[ -0.14 < y_{CMS} < 1.06 \]
J/ψ cross section in p-Pb

\[ \sigma_{J/\psi} = \frac{N_{J/\psi \rightarrow l^+l^-}}{L_{\text{int}} A \epsilon \text{BR}_{J/\psi \rightarrow l^+l^-}} \]

**p-Pb \| s_{NN} = 5.02 \text{ TeV}**

- \( L_{\text{int}} = 52 \mu \text{b}^{-1} (e^+e^-) \)
- \( L_{\text{int}} = 5.0 \text{ nb}^{-1} (\mu^+\mu^-, \text{forward}) \)
- \( L_{\text{int}} = 5.8 \text{ nb}^{-1} (\mu^+\mu^-, \text{backward}) \)

ALICE Preliminary:
- Inclusive \( J/\psi \rightarrow e^+e^-; p_T > 0 \text{ GeV/c} \)

ALICE arXiv:1308.6726:
- Inclusive \( J/\psi \rightarrow \mu^+\mu^-; 0 < p_T < 15 \text{ GeV/c} \)

**\( p_{\text{T}} \) (GeV/c)**

**\( y_{\text{cms}} \)**

ALI-DER-60357  ALI-DER-62712
Heavy-flavor decay muon and electron $R_{AA}$

$D+B \rightarrow e, \mu + X$

$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA} / dp_T}{dN_{pp} / dp_T}$

Muons: PRL 109 (2012) 112301

- Strong suppression (factor $\sim 2$) in central collisions ($p_T^{hadron} \sim 2p_T^{lepton}$)
- Smaller suppression in peripheral collisions
- Comparable suppression in central and forward rapidity
- Dominated by beauty at such high-$p_T$ (from FONLL calculations)
Heavy-flavor decay muon and electron $R_{AA}$

$D+B \rightarrow \mu + X$

ALICE, PRL 109 (2012) 112301

ATLAS-CONF-2012-081

- ALICE $R_{AA}$: Suppression increases with centrality for high-$p_T$ muons
- ATLAS $R_{CP}$: Strong suppression in central collisions, and no sign of $p_T$ dependence for muons with $p_T=4-10\text{ GeV}/c$
Different $D_s^+$ $R_{AA}$ expected if production by combination/coalescence in the QGP (*).

Model predictions [He, Fries and Rapp, PRL 110 (2013) 112301]
- Hydro
- non-perturbative QCD
- coalescence with strange quarks
- diffusion in hadronic phase

(*)
Kuznetsova and Rafelski, EPJC 51 (2007) 113
Andronic, Braun-Munzinger, Redlich and Stachel, PLB 659 (2008) 149
$\Delta E_c > \Delta E_B \Rightarrow R_{AA}(D) < R_{AA}(B)$?

energy loss mass dependence

- D $< p_T > \sim 10$ GeV/c: ALICE
- B (non prompt J/$\psi$) $< p_T > \sim 11$ GeV/c: CMS

$R_{AA}(D) > R_{AA}(B)$
$
\Rightarrow \text{indication of larger energy loss for charm than for beauty}$

The difference predicted by energy loss models:

BAMPS: JPG 38 (2011) 124152
WHDG: JPG 38 (2011) 124114
Vitev et al., PRC 80 (2009) 054902
$\Upsilon(1S) \ R_{pPb} \ vs. \ \gamma_{CMS} \ vs. \ models$

$\Upsilon(1S)$ suppressed similar to $J/\Psi$
(large normalisation uncertainties)

Shadowing model ($Vogt$), energy loss models ($Arleo \ et \ al.$) and CGC model ($Fuji \ et \ al.$) consistent with data
J/ψ $R_{AA}$ vs. $p_T$ and rapidity vs. models

Transport model:
Liu et al. (J/ψ dissociation + regeneration + $p_T$ broadening + shadowing) consistent with data
→ production of low-$p_T$ J/ψ via regeneration

Models (Cold Nuclear Matter effects):
• R. Vogt (CEM + EPS09 NLO shadowing)
• Ferreiro et al. (CSM + nDSg NLO shadowing)