Recent Results on Open Heavy Flavour Observables in Relativistic Nuclear Collisions

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Quark Matter 2014
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What’s special about heavy quarks

- Large mass ($m_q \gg \Lambda_{QCD}$) → produced in the early stages of the HI collision with short formation time ($t_{charm} \sim 1/m_c \sim 0.1$ fm/c $\ll \tau_{QGP} \sim O(10$ fm/c), traverse the medium interacting with its constituents
  - natural probe of the hot medium created in HI interactions
- Interactions with QGP don’t change flavour identity
- Uniqueness of heavy quarks: cannot be destroyed/created in the medium
  - transported through the full system evolution

$q$: colour triplet
- $u,d,s$: $m \sim 0$, $C_R = 4/3$
  - (difficult to tag at LHC)
- $g$: colour octet
  - $g$: $m = 0$, $C_R = 3$
  - $g$: $m = 0$, $C_R = 3$
  - $g$: $m = 0$, $C_R = 3$
  - $g$: $m = 0$, $C_R = 3$
- $Q$: colour triplet
  - $c$: $m \sim 1.5$ GeV, $C_R = 4/3$
  - small $m$, tagged by $D$'s
  - $b$: $m \sim 5$ GeV, $C_R = 4/3$
  - large mass → dead cone
  - $b$: $m \sim 5$ GeV, $C_R = 4/3$

Parton Energy Loss by
- medium-induced gluon radiation
- collisions with medium constituents

$$\Delta E(e_{medium}; C_R, m, L)$$

Prediction:
$$\Delta E_g > \Delta E_{c \approx q} > \Delta E_b$$

At both RHIC and LHC: suppressed as much as ...

**200 GeV**

**PHENIX Heavy Flavor : 2014-05-19**

Alan Dion

\( R_{AA} \), \( R_{dA} \) versus \( p_T [\text{GeV/c}] \)

- **\( e^{-}_{HF} R_{dA} \)**
- **\( \pi^{0} R_{dA} \)**
- **\( e^{-}_{HF} R_{AA} \)**
- **\( \pi^{0} R_{AA} \)**

**Pb-Pb, \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)**

- Average \( D^0, D^+, D^{*-} \) \( |y|<0.5, 0-7.5\% \)
- with pp \( p_T \)-extrapolated reference
- Charged particles, \( |y|<0.8, 0-10\% \)
- Charged pions, \( |y|<0.8, 0-10\% \)
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Suppressed → Answers to more differential questions

**STAR Preliminary**

- U+U 193 GeV $D_s^0$, $|y|<1$, $3<p_T<5$ GeV/c
- Au+Au 200 GeV $D_s^0$, $|y|<1$, $3<p_T<5$ GeV/c, arXiv:1404.6185 (submitted to PRL)

![Graph showing nuclear modification factor ($R_{AA}$) for variousAu+Au, d+Au, Cu+Cu, Au+Au energies](image)

**System size & beam energy dependence**

- Au+Au, 62 GeV
- d+Au, 200 GeV
- Cu+Cu, 200 GeV
- Au+Au, 200 GeV

![Graph showing $<R_{AA}>$ for different $p_T^<3$ GeV/c](image)

**Mass effect?**

- ALICE Preliminary D mesons
  - $8<p_T<16$ GeV/c, $|y|<0.5$
  - Correlated systematic uncertainties
  - Uncorrelated systematic uncertainties
- CMS Preliminary Non-prompt $J/\psi$
  - $6.5<p_T<30$ GeV/c, $|y|<1.2$
  - Systematic uncertainties

![Graph showing $R_{AA}$ for ALICE and CMS data](image)

**Final state effect?**

- Average $D_s^0$, $D^+$, $D^-$
  - $|y_{CM}|<0.04$
- CGC (Fuji-Watanabe)
- pQCD NLO (MNR) with CTEQ6M+EPS09 PDF
- Vitev: power corr. + $k_T$ broad + CNM Eloss

![Graph showing final state effect](image)

**Mass ordering?**

- Pb-Pb, $\sqrt{s_{NN}}=2.76$ TeV
  - 0-20% centrality
  - $|p_T|<0.5$ GeV/c, $|y|<0.5$
  - $|p_T|$, $|y|$ in bins of $35<p_T<40$
  - $<N_{coll}>$ weighted

![Graph showing mass ordering](image)

**Medium effect on production mechanism?**

- Pb-Pb, $\sqrt{s_{NN}}=200$ GeV
  - $|p_T|<0.5$ GeV/c, $|y|<0.5$
  - $|p_T|$, $|y|$ in bins of $35<p_T<40$
  - $d^2N/dy^2$ vs $d^2N/dy^2$ (rad)

![Graph showing medium effect on production mechanism](image)
pp collisions at $\sqrt{s} = 0.2$, 0.5, 2.76 and 7 TeV

Baseline for AA, pA
Test pQCD: more differentially...
**$p_T$-differential cross sections in pp collisions**

- Heavy flavour cross section measurements: extended kinetic reaches, beam energy dependences

- pQCD-based calculations (FONLL, GM-VFNS, $k_T$ factorization) compatible with data
  - $D^0$, $D^{**}$ (mid rapidity, down to $p_T \sim 0.4$ GeV/c at 200 GeV) at 200 & 500 GeV

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[Diagram showing $p_T$-differential cross sections]
• Heavy flavour cross section measurements: **extended kinetic reaches, beam energy dependences**

• pQCD-based calculations (FONLL, GM-VFNS, $k_T$ factorization) compatible with data
  - $D^0$, $D^{**}$ (mid rapidity, down to $p_T \sim 0.4$ GeV/$c$ at 200 GeV) at **200 & 500 GeV** STAR
  - $D^0$, $D^+$, $D^{**}$ mesons (mid rapidity) at 2.76 & 7 TeV
  - $c,b \rightarrow e$ (mid rapidity, down to $p_T \sim 0.5$ GeV/$c$) at **2.76 & 7 TeV**
  - $c,b \rightarrow \mu$ (forward rapidity) at 2.76 & 7 TeV

**STAR**

**ALICE**


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p_T-differential cross sections in pp collisions

- Heavy flavour cross section measurements: extended kinetic reaches, beam energy dependences

- pQCD-based calculations (FONLL, GM-VFNS, k_T factorization) compatible with data
  - D^0, D^{*+} (mid rapidity, down to p_T\sim0.4 GeV/c at 200 GeV) at 200 & 500 GeV
  - D^0, D^+, D^{*+} mesons (mid rapidity) at 2.76 & 7 TeV
  - c,b\rightarrow e (mid rapidity, down to p_T\sim0.5 GeV/c) at 2.76 & 7 TeV
  - c,b\rightarrow \mu (forward rapidity) at 2.76 & 7 TeV
  - b\rightarrow e (mid rapidity, down to p_T\sim1 GeV/c) at 2.76 & 7 TeV

k_T factorisation: arXiv:1301.3033

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Heavy flavour production cross sections

- Calculation based on pQCD (ex. FONLL) describes consistently energy dependence of total cross sections

- Charm (beauty) x~10 (~100) from RHIC (200 GeV) to LHC
More on production mechanism: Multiplicity dependences of charm production

Particle production in pp collisions at LHC shows better agreement with models including MPIs


For heavy flavours:

• LHCb: double charm production agrees better with models including double parton scattering


MPIs involving only light quarks and gluons?

• D-meson yields increase with charged-particle multiplicity → presence of MPI and contribution on the a harder scale?
More differential information: Heavy flavour correlations

Heavy flavour jet properties

- Near Side
  - in Pb-Pb
  - trigger hadron

- Away side
  - Path length dependence

- D-hadron correlations in pp show good agreement with expectations from Pythia (different tunes)
p-A collisions at $\sqrt{s} = 0.2$ and 5.02 TeV

d-Au, p-Pb

Cold nuclear matter effect

$$\frac{dN_{PbPb}^{D}}{dp_{T}} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_{T}} \otimes P(\Delta E) \otimes D_{c\rightarrow D}(z)$$
Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- $R_{pPb}$ measured in various channels
- $R_{pPb}$ consistent with unity within uncertainties

D$^0$, D$^+$, D$^{*+}$ mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and $k_T$-broadening
Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- $R_{pPb}$ measured in various channels
- $R_{pPb}$ consistent with unity within uncertainties

**ALICE**
- D⁰, D⁺, D*⁺ mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and kₜ-broadening

**ALICE**
- c,b→e & b→e (mid rapidity)
Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- $R_{pPb}$ measured in various channels
- $R_{pPb}$ consistent with unity within uncertainties

**ALICE**
- $D^0$, $D^+$, $D^{*+}$ mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and $k_T$-broadening

**ALICE**
- $c,b \rightarrow e$ & $b \rightarrow e$ (mid rapidity)

**CMS**
- $B^+$, $B^0$, $B_s$ (mid rapidity): FONLL expectation as a pp reference
Heavy flavour in p-Pb at LHC (at 5.02 TeV)

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**ALICE**
- $c,b\rightarrow e$ & $b\rightarrow e$ (mid rapidity)

**CMS**
- $B^+$, $B^0$, $B_s$ (mid rapidity): FONLL expectation as a pp reference

**Consistency with b jet measurement**

$B^0$: $J/\psi + K^+ + \pi^-$

$B_s$: $J/\psi + K^+ + K^-$

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Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- $R_{pPb}$ measured in various channels
- Slight rapidity dependence
  - non-prompt $J/\psi$:
    - at forward, modest suppression
    - at backward, consistent with unity within uncertainties
Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- $R_{pPb}$ measured in various channels

- Slight rapidity dependence

LHCb
  - non-prompt J/$\psi$:  
    - at forward, modest suppression  
    - at backward, consistent with unity within uncertainties

ALICE
  - c,b→μ:  
    - at forward, consistent with unity within uncertainties  
    - at backward, slightly larger than unity in 2<$p_T<$4 GeV

Within uncertainties, data can be described by pQCD calculations with EPS09 parameterization of shadowing
Heavy flavour in pA at LHC and RHIC

**ALICE**

- p-Pb $\sqrt{s_{NN}} = 5.02$ TeV, $\mu^+\leftrightarrow c,b$ decays
- $2.5 < y_{\text{cmss}} < 3.54$
- $-4 < y_{\text{cmss}} < -2.96$

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- $R_{dA}$
- $0-100\%$ centrality

At RHIC, fail to reproduce the data at both rapidity simultaneously

**arXiv:1310.1005**
Heavy flavour in pA at LHC and RHIC

ALICE

- p-Pb √s_{NN} = 5.02 TeV, μ⁻⁻→c,b decays
  - 2.96<|y_{cms}|<3.54

ALICE Preliminary

Minimum bias

PHENIX

- HF μ⁻, Fwd/Bwd
- PYTHIA + EPS09s LO, D →μ

0-100% centrality
d+Au

At RHIC, fail to reproduce the data at both rapidity simultaneously
Enhancement in central d+Au

Large enhancement (x2)

FIG. 3. The relative probability to for a heavy meson to decay into an electron at a given $p_T$. The dashed lines show the changes in the blast-wave expectations from the uncertainties on the blast-wave parameters discussed above.

FIG. 2. (left) Scaling added at high $p_T$. Results for electrons and heavy flavor mesons are shown in the right panel. The blast-wave calculations presented in this work (curve). The dashed lines show the changes in the blast-wave expectations from the comparison of the blast-wave and FONLL curves in the left panel with binary effects!

Fail to reproduce the data with combinations of initial-state broadening $<k_T^2>$=2.25 GeV$^2$/c$^2$

Enhancement at mid- and backward rapidity possibly due to hydrodynamics?
The double ridge also observed in heavy-flavour sector!

The mechanism (CGC? Hydro?) that generates it affects also HF
More differential information: Heavy-flavour electron-muon correlation in d+Au

Access to the g-PDF?

\[ \sigma_{cc} = 538 \pm 46(\text{stat}) \pm 197(\text{data syst}) \pm 174(\text{model syst}) \mu b \]

Peak by leading order gluon fusion
Continuum by higher order processes

\[ J_{dA} = \frac{d + \text{Au pair yield}}{\langle N_{\text{coll}} \rangle \text{ p + p pair yield}} \]

x \approx 10^{-2} \text{ at } Q^2 \approx 10 \text{ GeV}^2, \text{ on the edge of the shadowing region}

Cold nuclear medium modifies the c\bar{c} correlations

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PHENIX dilepton (\langle \text{model syst} \rangle)

\[ \text{d}^3N/(\text{d}y^{e^+}d^{\phi}d\Delta y^{e^-}) \] (rad\(^{-1}\))

\[ \times 10^{-9} \]

p+p \sqrt{s} = 200 \text{ GeV}

- POWHEG
- PYTHIA
- PYTHIA (NO LO)
- MC@NLO

\( \Delta \phi \) (rad)

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

\[ \langle N_{\text{coll}} \rangle \text{ scaled p+p} \]

\[ \text{d+Au} \]

\[ e^\pm: p_T > 0.5 \text{ GeV/c, } |y| < 0.5 \]

\[ \mu^\pm: p_T > 1 \text{ GeV/c, } 1.4 < |y| < 2.1 \]

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

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More differential information: Multiplicity dependence of modification

Investigate the scaling of charm production in p-Pb collisions w.r.t. pp collisions

\[ Q_{pPb}^{V0A}(p_T) = \frac{dN_{pPb}^{\text{mult}}/dp_T}{N_{\text{Glauber}}^{\text{coll}} dN_{pp}^{\text{mult}}/dp_T} \]

No multiplicity dependent modification of the \( p_T \) spectra in p-Pb

Similar pattern for D mesons and high-\( p_T \) charged particles
More differential information: Multiplicity dependence of modification

Investigate the scaling of charm production in p-Pb collisions w.r.t. pp collisions

\[ Q^{V0A}_{p\text{Pb}}(p_T) = \frac{dN_{\text{pp}}^{\text{pPb}}}{dp_T} / \frac{dN_{\text{coll}}^{\text{mult}}}{dN_{\text{pp}}^{\text{mult}}/dp_T} \]

ALICE

Production rates in high-multiplicity p-Pb collisions doesn’t exhibit any effect like suppression.

No multiplicity dependent modification of the \( p_T \) spectra in p-Pb

Similar pattern for D mesons and high-\( p_T \) charged particles
Bottom measurement in d+Au via di-electrons

**PHENIX**

![Plot](plot.png)

- Low mass, high $p_T$ region is dominated by the decay from a single B meson
- For $m_q \gg p$, less model dependent

$p+p$ equivalent cross sections extracted from PYTHIA and MCNLO as

$$\sigma_{bb} = 3.4 \pm 0.28(stat) \pm 0.46(sys) \mu b$$

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Bottom measurement in d+Au via di-electrons

p+p equivalent cross sections extracted from PYTHIA and MCNLO as

\[ \sigma_{bb} = 3.4 \pm 0.28(\text{stat}) \pm 0.46(\text{sys}) \mu b \]
A-A collisions at $\sqrt{s} = 0.2$ and 2.76 TeV

Cu-Cu, Au-Au, Pb-Pb, U-U
Initial & final state effect
D-meson $R_{AA}$ at LHC and RHIC

- Significant suppression at high $p_T$
  
  **ALICE**
  - $D^0$, $D^+$, $D^{*+}$ mesons (mid rapidity): 0-7.5 % & 30-50 % centrality
  
  **STAR**
  - $D^0$ mesons (mid rapidity): 0-10 % centrality

$\star$ \hspace{1cm} \star \hspace{1cm} \star$

![Graph](ALICE_Preliminary_Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV)

- Similar at high $p_T$, different at low $p_T$ (1-2 GeV/c)
- Shadowing? recombination? radial flow?

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D-meson $R_{AA}$ at LHC and RHIC

- Significant suppression at high $p_T$
  
  **ALICE**  
  $D^0$, $D^+$, $D^{*+}$ mesons (mid rapidity): 0-7.5 % & 30-50 % centrality

  **STAR**  
  $D^0$ mesons (mid rapidity): 0-10 % centrality

STAR Au+Au $\rightarrow D^0 + X$ @ 200 GeV Central 0-10%

- Similar at high $p_T$, different at low $p_T$(1-2 GeV/c)
- Shadowing? recombination? radial flow?
HF-decay lepton $R_{AA}$ at LHC and RHIC

- Significant suppression at high $p_T$ down to 200 GeV

- $c,b \rightarrow e$ (mid rapidity) & $c,b \rightarrow \mu$ (forward rapidity)

![Graph showing $R_{AA}$ versus $p_T$](image)

$\text{Pb-Pb, } \sqrt{s_{NN}} = 2.76 \text{ TeV}$

- $\Delta$ Heavy flavour decay $\mu^\pm$ 0-10% central, $2.5 < y < 4.0$
- Heavy flavour decay $e^\pm$ 0-10% central, $|y| < 0.6$
- with pp ref. from scaled cross section at $\sqrt{s} = 7 \text{ TeV}$
- with pp ref. from FONLL calculation at $\sqrt{s} = 2.76 \text{ TeV}$

S. Li talk, 15:00

- Significant suppression at high $p_T$ down to 200 GeV
- $c,b \rightarrow e$ (mid rapidity) & $c,b \rightarrow \mu$ (forward rapidity)
- $B^+ +, B^0, B_s$ (mid rapidity): FONLL expectation as a pp reference

ALI-DER-36791
HF-decay lepton $R_{AA}$ at LHC and RHIC

- Significant suppression at high $p_T$ down to 200 GeV
  - $c,b \rightarrow e$ (mid rapidity) & $c,b \rightarrow \mu$ (forward rapidity)
  - $b \rightarrow e$ (mid rapidity) hint of suppression

ALICE Preliminary

Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV, 0-20% centrality

$R_{AA}$ vs. $p_T$ (GeV/c)

ALICE Preliminary

NEW

$R_{AA}$ vs. $p_T$ (GeV/c)

Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV, 0-20% centrality

- $b \rightarrow e$, $|y| < 0.8$
- $c \rightarrow e$, $|y| < 0.8$
- systematic uncertainty
- normalization uncertainty

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HF-decay lepton $R_{AA}$ at LHC and RHIC

- Significant suppression at high $p_T$ down to 200 GeV
  - $c,b \rightarrow e$ (mid rapidity) & $c,b \rightarrow \mu$ (forward rapidity)
  - $b \rightarrow e$ (mid rapidity) hint of suppression
  - $c,b \rightarrow e$ (mid rapidity) PHENIX

Not the same story for 62 GeV
Color charge dependence?: D-meson $R_{AA}$ vs. $\pi^\pm$

- Comparable results for $\pi$ and D mesons suppressions within uncertainties
- Is it consistent with the colour charge dependence picture?
Excellent agreement!

Calculation by M. Djordjevic (rad+coll energy loss) can describe both $R_{AA}$

Shows strong colour charge effect in partonic $R_{AA}$ (g vs. light and c)

$R_{AA} (D) = R_{AA} (charm)$

$R_{AA} (light \text{ quarks}) = R_{AA} (charm)$

$R_{AA} (h^{\pm}) = R_{AA} (D)$

Colour charge effect plays!
Quark mass dependence?: D-meson $R_{AA}$ vs. non-prompt $J/\psi$

- ALICE prompt D mesons & CMS non-prompt $J/\psi$:
  - B and D mesons $<p_T> \sim 10$ GeV/c
  - Clear indication of a dependence on quark mass: $R_{AA}^B > R_{AA}^D$

![Graph showing the comparison between ALICE and CMS results for D-meson $R_{AA}$ and non-prompt $J/\psi$ at different centrality and $p_T$ ranges.](image)

Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV

$\langle N_{part} \rangle$ weighted with $N_{coll}$

Centrality

ALICE Preliminary D mesons $8<p_T<16$ GeV/c, $|y|<0.5$

CMS Preliminary Non-prompt $J/\psi$ $6.5<p_T<30$ GeV/c, $|y|<1.2$

Correlated systematic uncertainties

Uncorrelated systematic uncertainties

Systematic uncertainties

CMS-PAS-HIN-12-014

ALICE $D$ mesons results compared with CMS non-prompt $J/\psi$ in a similar kinematic range:

- Central rapidity region

$\Delta E_c > \Delta E_u,d,s > \Delta E_b$

Could be reflected in a hierarchy of $R_{AA}$:$R_{AA}^B > R_{AA}^D >$ consistent with the expectation for $\Delta E_c > \Delta E_b$
Quark mass dependence?: D-meson $R_{AA}$ vs. non-prompt $J/\psi$

- ALICE prompt D mesons & CMS non-prompt $J/\psi$:
  - $B$ and $D$ mesons $<p_T> \sim 10$ GeV/c
  - Clear indication of a dependence on quark mass: $R_{AA}^B > R_{AA}^D$

- Djordjevic: non-prompt $J/\psi$ $R_{AA}$ considering for energy loss
  - $b$ quark mass
  - $c$ quark mass

- Djordjevic: $D$ meson $R_{AA}$

Calculation by M. Djordjevic (including mass-dependent rad+coll energy loss) predict a difference

Similar pattern from other calculations (e.g. BAMPS, WHDG, Vitev et al.).

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System size dependence of $R_{AA}$

\begin{align*}
\text{CENTRAL } d+Au & \approx \text{PERIPHERAL } Cu+Cu \\
\text{CENTRAL } Cu+Cu & \approx \text{MID } Au+Au
\end{align*}
System size dependence of $R_{AA}$

TREND FROM $d+Au$ and peripheral $Cu+Cu$ collisions where enhancement effects are dominating

TO central $Cu+Cu$ and $Au+Au$ collisions where suppression effects take over

Central $U+U$ collisions have higher energy density: ~20% increase over $Au+Au$ collisions
System size dependence of $R_{AA}$

TREND FROM $d+Au$ and peripheral Cu+Cu collisions where enhancement effects are dominating
TO central Cu+Cu and Au+Au collisions where suppression effects take over

STAR Preliminary
- U+U 193 GeV
- $D^0$: $|y|<1$, $3<p_T<5$ GeV/c
- Au+Au 200 GeV $D^0$: $|y|<1$, $3<p_T<8$ GeV/c, arXiv:1404.6185 (submitted to PRL)

Central U+U collisions have higher energy density: ~20% increase over Au+Au collisions
**Heavy flavour $v_2$ at RHIC & LHC**

- Charm does flow (at low energy, questionable!)
- Confirm significant interaction of charm quarks with the medium
- Suggest collective motion of low-$p_T$ charm quarks in the expanding fireball
Path length dependence of $R_{AA}$

$R_{AA}$ measured in-plane and out-of-plane, sensitive to

- high $p_T$: path length dependence of parton energy loss
- low $p_T$: collectivity
Observables constraining models

Various observables provide constraints for the models

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Observables constraining models

Various observables provide constraints for the models

TAMU elastic: arXiv:1401.3817
Djordjevic: arXiv:1307.4098
Cao, Qin, Bass: PRC 88 (2013) 044907

MC@sHQ+EPOS: PRC 89 (2014) 014905
Vitev, rad+dissoc: PRC 80 (2009) 054902
POWLANGE: JPG 38 (2011) 124144
BAMPS: PLB 717 (2012) 430
**Outlook**

**Status: Heavy Flavor Tracker**

Heavy Flavor Tracker (HFT)
- Physics goal: Precision measurement of heavy quark hadron production in heavy ion collisions
- All 3 sub-detectors (PXL, IST, SSD) were completed, installed prior to Run14
- PXL – heart of the HFT: state-of-art detector, MAPS technology, first time used at a collider experiment.
- Integration time ~ 160μs
- Taking data with STAR detector system, on track towards the physics goal
- With survey and preliminary alignment, Kaons at 750 MeV/c: DCA < 60μm

**PHENIX Silicon Vertex Tracking System**

**Precision measurements**

**p_T~0 using**

**Charm and beauty R_{AA} down to p_T~0 using D^0 and B-decay J/ψ**

**ALICE Upgrade**

Pb-Pb √s_{NN} = 5.5 TeV
L_{int} = 10 nb⁻¹, centrality 0-10%

**Non-prompt J/ψ → e⁺e⁻**

(stat. only)
Thank you for your attention!

Special thanks to:
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Backup
The $Q^2$ dependence of $R_{AF}$ is weaker and has thus been more difficult to measure. Data with high enough precision, however, exist. The NMC collaboration discovered a clear $Q^2$ dependence in the ratio $d\sigma_{\mu Sn}/d\sigma_{\mu C}$ [47], i.e. the scale dependence of the ratio $F_{Sn}^2/F_C^2$, at $x > \sim 0.01$. Since $F_p(n)/A^2 = \sum_q e_q^2 f_p(n)/A + f_p(n)/A \bar{q} + O(\alpha_s)$, then nucleon effects in the ratio $R_{AF}$ directly translate into nuclear effects in the parton distributions: $f_{p/A}/i \neq f_p/i$.

The nPDFs, $f_{p/A}/i$, also obey the DGLA equation in the large-$Q^2$ limit. They can be determined by using a global DGLAP fit procedure similar to the case of the free proton PDFs. Pioneering studies of the DGLAP evolution of the nPDFs are found in e.g. Ref. [48–51]. References for various other studies of perturbative evolution of the nPDFs and also to simpler $Q^2$-independent parametrizations of the nuclear effects in the PDFs can be found e.g. in Refs. [52, 53]. The nuclear case is, however, more complicated because of additional variables, the mass number $A$ and the charge $Z$, and because the number of data points available in the perturbative region is more limited than for the PDFs of the free proton. The DIS data play the dominant role in the nuclear case as well. However, as illustrated by Fig. 8, no data are available from nuclear DIS experiments below $x < \sim 5 \cdot 10^{-3}$ at $Q^2 > \sim 1$ GeV$^2$. This makes the determination of the nuclear gluon distributions especially difficult. Further constraints on the global DGLAP fits of the nPDFs can be obtained from e.g. the Drell-Yan (DY) process measured in fixed-target $pA$ collisions [54, 55]. Currently, there are two sets of nPDFs available which are based on the global DGLAP fits to the data: (i) EKS98 [27, 28] (the code in Refs. [56, 57]), and (ii) HKM [29] (the code in Ref. [58]). We shall compare the main features of these two analyses and comment on their differences below.
D-meson production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

**Figure 3:** Average $R_{pPb}$ of prompt $D^0$, $D^+$, and $D^{*+}$ mesons as a function of $p_T$ compared to model calculations.

**Figure 4:** Average $R_{pPb}$ of prompt $D$ mesons as a function of $p_T$ compared to $D$-meson $R_{AA}$ in the 20% most central and in the 40-80% Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from [6]. Statistical (bars), systematic (empty boxes) and normalization (full boxes) uncertainties are shown.

The present uncertainties of the measurement do not allow sensitivity on this effect. In Fig. 4 the average $R_{AA}$ of prompt $D$ mesons in central (0-20%) and in semi-peripheral (40-80%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [6] is reported along with the average $R_{pPb}$ of prompt $D$ mesons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, showing that cold nuclear matter effects are smaller than the uncertainties for $p_T \gtrsim 3$ GeV/c. In addition, as reported in [6], the same EPS09 nuclear PDF parametrization that describes the D-meson $R_{pPb}$ results predicts small initial state effects (less than 10% for $p_T > 5$ GeV/c) for Pb–Pb collisions. As a consequence, the suppression observed in central Pb–Pb collisions for $p_T \gtrsim 2$ GeV/c is predominantly induced by final-state effects, e.g. the charm energy loss in the...
Is charm actually flowing? or is this $v_2$ just from recombination with a light quark?
FIG. 3: (color online). Comparison of $p_\perp$ near with the EPS09s nPDF is consistent with the data over does not reproduce the data at backward rapidity, partic-

shown in Fig. 2(b), the EPS09s nPDF based calculation density modification into account. In central collisions, this calculation, we can take solely the initial parton certainty bands are calculated as described in [13]. From at forward (backward) rapidity.

ranges. Diamonds represent heavy-flavor electrons at midra

ward and backward rapidity is significantly larger in the
effector-charge heavy-flavor muons produced at for-
different rapidity and

Figure 3 shows the heavy-flavor muon

dA

behavior across the entire
coll

Global sys. =

0.5

1.5

1.5

R

1.0 < p

ψ[21] for central collisions. A similar

1.4 < y < 2.0

, 1.0 < y < 1.4

ψ

R

Systematics = systematic uncertainties on

sum of statistical (systematic) uncertainties determined as the quadratic

bars

each centrality class. In both

flavor electron measurement at midrapidity [17]. Bars

event between for-

tainties, showing a large enhancement for more central

This comparison suggests that an additional CNM ef-

terence is seen at backward rapidity, partic-

ularly for

dA

class. The global systematic uncertainty on each distri

Open heavy-flavor production in nuclear collisions [21, 29–34]. Quarkonia and open heavy-flavor hadrons are sensitive

tion can provide a baseline for interpreting the nuclear

in nuclear matter. Therefore, open heavy-flavor produc-
tion is shown as a percentage in the legend.

for heavy-flavor leptons from di

Inelastic scattering of quarkonia. Previous measurements suggest

tion is suggested, because the di

nPDF based calculations are consistent with the data at

bin shows little or no centrality dependence. The EPS09s

iments on heavy-quark production. However,

breakup of quarkonia. Previous measurements suggest

breakup has a significant e

tinction across the entire

coll

Distinctions on heavy-flavor production are induced by breakup

to the same e

ward rapidity within uncertainties. At forward rapidity the low-

tainties, showing a large enhancement for more central

Centrality 0-20%
ing error. The global uncertainty is that on the partonic matter dominating in central collisions.

The centrality dependent cocktail and the ratio of uncertainties cancel in and is shown in Fig. 5. Most of the systematic uncertainties are Type C uncertainties, which include the...
Nuclear modification factor

ALICE Preliminary

$\mu^\pm \leftrightarrow b,c$ decays

p-Pb, $\sqrt{s_{NN}}=5.02$ TeV
- $2.5<y_{\text{cms}}<3.54$
- $-4<y_{\text{cms}}<-2.96$

Pb-Pb, $\sqrt{s_{NN}}=2.76$ TeV
- $2.5<y_{\text{cms}}<4$ (0-10%)

$N_{\text{coll}}$: 10

$N_{\text{PU}}$: 10

$N_{\text{PU}}$: 10

$p_T$ (GeV/$c$)
Heavy Quark Energy Loss in Medium

Radiative energy loss via gluon radiation

Color charge dependence of energy loss

\[ \omega \frac{dI}{d\omega} \propto \alpha_s C_R f(\omega) \]

where \( C_R = 3 \) for \( g \), \( \frac{4}{3} \) for \( q \)

Dead Cone Effect
- In vacuum, gluon radiation is suppressed at angles smaller than \( M_Q/E_Q \) (ratio of the quark mass to its energy)
- In medium, dead cone implies lower energy loss for massive partons

(Dokshitzer and Kharzeev, PLB 519 (2001) 199.)

Elastic energy loss is not negligible?


Collisional dissociation probability of heavy mesons in the QGP?


Proton-proton collisions: provide important test of pQCD in a new energy domain and heavy ion reference

MinJung Kweon, Inha University Quark Matter 2014