Open heavy-flavor measurements

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Heavy flavor: a unique probe

- heavy quarks: charm ($m_c \sim 1.5$ GeV), beauty ($m_b \sim 5$ GeV)
- $m_{c,b} > \Lambda_{QCD}$
  - heavy quarks = genuine hard probes, even at low $p_T$
- large mass $\rightarrow$ short formation time:
  $\tau_{c,b} \sim 1/2m_{c,b} < 0.1$ fm $\ll \tau_{QGP} \sim 5-10$ fm

- heavy quarks are unique
  - interactions with produced QCD medium don’t change the flavor but can modify the phase-space distribution of heavy quarks
  - thermal production rate in the QGP is “small“ (may be measurable $\rightarrow T$)
  - destruction or creation in the medium is difficult
  - transported through the whole evolution of the system
Open heavy-flavor measurements

- heavy-flavor hadron decays via weak interaction:
  - decay lengths $c\tau \sim \text{few } 100 \mu m \rightarrow \text{measure decay products}$

**Full reconstruction of D meson hadronic decays**

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

**Semi-leptonic decays (c,b)**

**HF jets**

Correlations with HF

**Displaced J/ψ (from B decays)**

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Testing pQCD calculations in pp collisions

RHIC: $\sqrt{s} = 200, 500$ GeV
LHC: $\sqrt{s} = 2.76, 7, 13$ TeV
Heavy quarks in pp collisions

- testing ground for perturbative QCD calculations
- relevant production mechanisms on the parton level
  - LO: gluon fusion, quark-antiquark annihilation
  - NLO: gluon splitting, flavor excitation
  - or even more complex, e.g. Multi Parton Interactions (MPI)

- reference for p(d)-A and A-A collisions
Heavy-flavor hadron production

- **STAR: \( D^0 \rightarrow K\pi, D^* \rightarrow D^0\pi \)**
  - STAR preliminary
  - pp \( \sqrt{s} = 200 \text{ GeV} \)

- **LHCb (at forward rapidity): \( D^0 \rightarrow K\pi \)**
  - \( \sqrt{s} = 13 \text{ TeV} \)
  - LHCb-PAPER-2015-041

- **ALICE: \( D^+ \rightarrow K\pi\pi \)**
  - ALICE
  - pp \( \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 5 \text{ nb}^{-1} \)
  - JHEP 1201(2012)128

- **CMS: \( B^+ \rightarrow J/\psi K^+ \)**
  - CMS \( \sqrt{s} = 7 \text{ TeV} \)
  - L = 5.8 \text{ pb}^{-1}
  - BF (3.5%) and Lumi (11%) uncertainties not shown
  - PRL 108(2011)112001

- **\( \bullet \) pQCD calculations**
  - FONLL: JHEP 1210(2012)37
  - \( k_T \) factorization: PRD 87(2013)094022

- **\( \bullet \) pQCD calculations in agreement with measurements within substantial exp. and theor. uncertainties**
Leptons from heavy-flavor decays

- $e^\pm (\mu^\pm)$ from HF decays at mid (forward) rapidity
- pQCD calculations in reasonable agreement with data within uncertainties
Beauty production

- $b \rightarrow e^\pm X$
- $b \rightarrow J/\psi X$

- Also beauty production described by pQCD calculations

**NEW**

**NEW**

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Total charm & beauty cross sections

- Experimental precision not yet satisfactory (e.g. for quarkonia reference!)
  - Extend kinematic coverage (low $p_T$!)
  - Larger data samples
  - Improved control of systematic uncertainties

- Can data constrain pQCD parameters?
- Further constraints: more differential measurements

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D-meson yields vs. multiplicity

- do Multi-Parton Interactions (MPI) play a role on the hard scale relevant for heavy-flavor production?

- D-meson yields increase more than linear with $dN_{\text{ch}}/d\eta$
- similar increase for open and hidden charm → behavior driven by production mechanism, not hadronization
- similar trend for non-prompt $J/\psi$ from open-beauty decays
- models including MPI describe observed trend

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Cold nuclear matter effects in p(d)-A collisions

RHIC: d-Au collisions at $\sqrt{s_{NN}} = 200$ GeV
LHC: p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
Heavy quarks in p(d)-A collisions

- quantify cold nuclear matter effects
  - nuclear modification of Parton Distribution Functions (shadowing, gluon saturation)
  - $k_T$ broadening
  - energy loss in cold nuclear matter
  - multiple binary collisions

- final state effects?

- reference for A-A collisions

K.J. Eskola et al., JHEP 0904(2009)65
Electrons from HF decays at RHIC

- $R_{dA} > 1$ for low-$p_T$ electrons at mid rapidity (also for muons at backward rapidity)
- no “large” enhancement via anti-shadowing expected
- consistent with radial flow
  - $\rightarrow$ D-meson measurement highly desirable
HF decay electron $R_{\text{pPb}}$ at the LHC

- $R_{\text{pPb}}$ consistent with unity and described by models including initial-state effects or radial flow within uncertainties
- $R_{\text{pPb}}$ of beauty-hadron decay electrons consistent with inclusive HF decay electron $R_{\text{pPb}}$ and with unity
- no indication for suppression at intermediate/high $p_T$


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HF decay muon $R_{p\text{Pb}}$ at the LHC

$R_{p\text{Pb}}$ of HF decay muons is consistent with unity at forward rapidity and slightly larger than unity at backward rapidity for $2 < p_T < 4$ GeV/c described within uncertainties by models including cold nuclear matter effects.


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D-meson $R_{pPb}$ at the LHC

- $R_{pPb}$ consistent with unity for all D-meson species
- described within uncertainties by models including initial-state effects
- no indication for suppression at intermediate/high $p_T$

Multiplicity (in)dependence: $Q^{\text{mult}}_{pPb}$

- multiplicity dependent nuclear modification factor $Q^{\text{mult}}_{pPb}$
  - nuclear overlap function $<T^{\text{mult}}_{pPb}>$ determined based on energy deposited by neutrons in Zero Degree Calorimeters
  - prompt D-meson $Q^{\text{mult}}_{pPb}$
    - no multiplicity dependence
    - no $p_T$ dependence in any multiplicity class

\[
Q^{\text{mult}}_{pPb} = \frac{dN_{pPb} / dp_T}{\left< T^{\text{mult}}_{pPb} \right> d\sigma_{pp} / dp_T}
\]
B-meson $R_{pPb}$ at the LHC

- B-meson $R_{pPb}$ for various species
  - pp reference from FONLL pQCD
  - consistent with unity
    → no indication for significant cold nuclear matter effects
- capability to reconstruct B mesons in Pb-Pb collisions as well!

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Beauty and charm jets

- **b-jet** $R_{pPb}$ consistent with unity within uncertainties
  - no significant suppression due to cold nuclear matter effects

- **first c-jet measurement in nuclear collisions**
  - PYTHIA agrees with measured spectrum
Dense/hot QCD matter effects in A-A collisions

RHIC: Au-Au (U-U) collisions at $\sqrt{s_{NN}} = 200 \ (193) \ GeV$

LHC: Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\ TeV$
Heavy quarks in A-A collisions

- Interaction of heavy quarks with hot/dense medium
  - Parton energy loss via radiative and collisional processes
    - Depends on
      - Color charge
      - Quark mass
      - Path length in the medium
      - Medium density and temperature
  
  \[ \rightarrow \text{expect: } \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \]

  \[ \rightarrow R_{AA}\text{(light hadron)} < R_{AA}\text{(D)} < R_{AA}\text{(B)}? \]
    - Caveats:
      - Different shapes of parton $p_T$ distributions in pp collisions
      - Different fragmentation functions
      - Role of soft particle production at low $p_T$

- Collectivity in the QGP
  - Initial spatial asymmetry
    \[ \rightarrow \text{Azimuthal asymmetry of particle emission in momentum space} \]
  - Heavy quarks participate in collectivity of the medium in case of sufficient re-scattering \[ \rightarrow \text{Approach to thermalization} \]
  - High $p_T$: Path-length dependence of energy loss \[ \rightarrow \text{Azimuthal asymmetry} \]

\[
R_{AA} = \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \times \frac{< T_{AA}>}{N_0} \]

\[
dN/d\varphi = \frac{N_0}{2\pi} (1 + 2\nu_1 \cos(\varphi - \Psi_1) + 2\nu_2 \cos(\varphi - \Psi_2) + ...)\]
B-jet suppression at the LHC

- fully reconstructed b jets in Pb-Pb collisions at 2.76 TeV
  - suppressed compared to measured pp reference
  - qualitatively consistent with light-flavor jet suppression
  - b-jet suppression shows strong centrality dependence

PRL 113(2014)132301
Electrons at RHIC

- electrons from HF decays in Au-Au collisions at 200 GeV
- suppression of the yield at high $p_T$
- binary scaling of the total yield
- positive $v_2$
- model comparison: constrain transport properties of the produced medium

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Electrons in U-U collisions at RHIC

- New pp reference from STAR for electrons from HF decays
  - $p_T$ reach extended to higher and lower $p_T$
- U-U collisions
  - Energy density ~20% larger than in same centrality Au-Au collisions

- $R_{AA}$ for electrons from HF decays in 5% most central collisions systematically lower than for Au-Au collisions, but still within uncertainties

[Graphs and data plots illustrating the comparison between U-U and Au-Au collisions]
c$\rightarrow$e vs. b$\rightarrow$e at RHIC

- PHENIX Silicon Vertex Detector (VTX)
  - DCA$_T$ resolution $\sim 60$ $\mu$m
- unfolding of measured electron $dN/dp_T$ and DCA$_T$ distributions
- $dN/dp_T$ of c & b hadrons
- $p_T^e < 4$ GeV/c
  - electrons from beauty decays suppressed less than those from charm decays
- new constraints for models

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HF decay leptons at the LHC: $R_{AA}$

- **high-$p_T$** leptons suppressed
  - similar for HF decay electrons ($|y| < 0.6$) and muons ($2.5 < y < 4$, $|y| < 1$)
  - pronounced centrality dependence
  - also: hint for suppression of electrons from beauty decays

- **cold nuclear matter effects** small at high $p_T$ → hot/dense medium effect
HF decay leptons at the LHC: $v_2$

- $v_2 > 0$ at intermediate/high $p_T$
  - similar for $e^\pm$ and $\mu^\pm$ at mid rapidity and muons at forward rapidity
  - $v_2$ decreases towards central collisions
  - confirms strong interaction of heavy quarks with the medium
  - charm (even beauty?) quarks participate in the collectivity of the QGP
D-meson suppression

- observed suppression in central Pb-Pb collisions at the LHC is due to the strong interaction of charm quarks with the dense/hot partonic medium

- hint for less suppression of $D_s^+$ compared to non-strange D mesons at LHC/RHIC
  - expected if recombination plays a role in charm hadronization


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D-meson $R_{AA}$ and $v_2$ at RHIC

- STAR Heavy Flavor Tracker (HFT)
- DCA$_T$ resolution $\sim 30 \, \mu$m

- $D^0$ mesons in Au-Au at 200 GeV
  - $v_2 > 0$ for $p_T > 2$ GeV/c
  - yield suppressed at high $p_T$
  - enhancement at $1 < p_T < 2$ GeV/c (charm coalescence with flowing medium)
  - $R_{AA}$ and $v_2$ model comparisons constrain charm diffusion coefficient

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D-meson $v_2$: RHIC vs. LHC

- **RHIC:** $D^0$ $v_2 < \text{light-hadron } v_2$ for $p_T < 3$ GeV/c
- **D-meson $v_2$** measured by ALICE at the LHC
  - $D$-meson $v_2 > 0$ and similar to charged-particle $v_2$
  - Hint for increasing $v_2$ with decreasing centrality
- **significant interaction of charm quarks with the medium**
  $\rightarrow$ collective motion of low-$p_T$ charm quarks with the medium
D-meson $R_{AA}$: RHIC vs. LHC

- D mesons at the LHC and at RHIC
  - different trend for D-meson $R_{AA}$ at low $p_T$?

- differences between
  - Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - Au-Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV
    - different shape of pp reference
    - different modification of nPDFs
    - different radial flow
    - different impact of coalescence

- some models describe both measurements reasonably well (e.g. TAMU, PLB 735(2014)445)

ALICE: arXiv:1509.06888
STAR: PRL 113(2014)142301
D⁰ mesons at the LHC

- D⁰, D⁺, D∗⁺, Dˢ⁺ mesons measured by ALICE
- prompt D⁰ measured by CMS in the range 2.5 < p_T < 40 GeV/c

- R_AA shows suppression in central Pb-Pb collisions relative to data/FONLL based reference

  - significant interaction of charm quarks with the medium
  - pronounced centrality dependence
  - tension with ALICE D-meson R_AA for p_T > 16 GeV/c
  → difference in pp reference
**$R_{AA}$: D-mesons vs. pions**

naively: $\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b) \Rightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

- D-meson and pion $R_{AA}$ are compatible within uncertainties
- agreement consistent with models including
  - energy loss hierarchy: $\Delta E(g) > \Delta E(u,d,s) > \Delta E(c)$
  - different shapes of the parton $p_T$ distributions
  - different fragmentation functions

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$R_{AA}$: D mesons vs. non-prompt J/$\psi$

naively: $\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b) \rightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

- similar $<p_T>$ for D and B mesons
- indication for $R_{AA}(D) < R_{AA}(J/\psi \leftarrow B)$ in central Pb-Pb collisions
- confirmed by CMS D$^0$ measurement

consequence of mass difference of c and b quarks in pQCD based model calculation (Djordjevic, PL B734(2014)286)

- pQCD model including mass-dependent energy loss predicts a difference between the $R_{AA}$ of D mesons and non-prompt J/$\psi$
  similar to the observation
- similar for other calculations (BAMPS, WHDG, Vitev et al.)

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ALICE: arXiv:1506.06604
CMS: CMS-PAS-HIN-12-014
theory: PL B734(2014)286
Summary

- **pp collisions**
  - pQCD calculations describe heavy-flavor cross sections
  - interplay of soft and hard processes under investigation
  - what about correlations?

- **p(d)-A collisions**
  - no indication for substantial cold nuclear matter effects
  - what about collectivity in small systems?

- **A-A collisions**
  - strong interaction of heavy quarks with the medium
    - suppression of yields at high $p_T$ consistent with partonic energy loss
    - indication for charm (maybe beauty?) participating in the medium‘s collective expansion

- **what is missing?**
  - better precision, more statistics, extended $p_T$ coverage (high and low (!) $p_T$)
  - smaller uncertainties and new differential measurements will help to
    - constrain model calculations quantitatively
    - address open questions concerning the energy-loss mechanisms, their path-length dependence, thermalization, coalescence involving heavy quarks ....