Measurements of leptons from heavy-flavor decays

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Heavy quarks carry information about early stage of collisions:

- Charm(c) and bottom(b) quarks are massive
- Formation takes place only early in the collision.
- Sensitivity to initial gluon density and gluon distribution

Selected results on HF in next slides
Correlations: jets/flow and Quarkonia (in brief)
Why they are good probes?

Heavy Quarks : Why good probes?

Large Mass : $m_{c,b} \gg \Lambda_{QCD}$

Are hard probes, even at low $p_T$

Do not change flavor while interacting with the QCD medium, although the phase-space distribution does change

$\tau_{prod} \sim 1/2m \sim 0.1 \text{ fm} \ll \tau_{QGP} \sim 5-10 \text{ fm}$

Nuclear modification factor:

$$R_{AA}(p_T) = \frac{\text{Yield} (A + A)}{\text{Yield} (p + p) \times \langle N_{coll} \rangle}$$

• Knowing system properties in a simple way
  - calibrated probe
  - calibrated interaction
  - suppression pattern tells about density profile of the medium

• Heavy-ion (AA) collisions
  - hard processes : calibrated probe
  - transported through the whole
  - evolution of the system
  - suppression provides density measurements
Heavy quarks in pp and pA collisions

**pp**: test understanding of heavy-quark production

- parton level production processes
  - LO contributions:
    - gluon fusion, quark-antiquark annihilation
  - NLO contributions:
    - gluon splitting, flavor excitation
  - also complex mechanisms, like, Multi Parton Interactions (MPI)

- understand perturbative QCD calculations where theoretical uncertainties are due to
  - renormalization and factorization scales
  - quark masses

- production mechanisms using differential measurements
  - multiplicity dependence of heavy-flavor production cross sections
  - angular correlation measurements

- pp collisions act as a reference for pA and AA collisions

**pA collisions**: Useful as there is no QGP expected while there are some high density effects

- Nuclear modification of Parton Density Functions

- Saturation and shadowing effects

- Energy loss in Cold Nuclear Matter (CNM)

- Multiple binary collisions and $k_T$ broadening

- Help to compare AA collisions

**EIC Physics Connections!**
Measuring heavy-flavor particles

Heavy-Flavor (HF) hadrons decay via weak interaction:
- decay length $c\tau \sim$ few 100 $\mu$m
- measure decay products
- signal on invariant mass distribution
- difficulty is in understanding the background
- need good event mixing and vertex information

Measurements of electrons and muons from heavy flavor decays
- $D \rightarrow e/\mu + X$, BR $\sim$ 10%
- $B \rightarrow e/\mu + X$, BR $\sim$ 11%

ALICE: Mid-rapidity electrons and Forward rapidity muons
Single electron spectra (RHIC)

- Single electron spectra (from HF decays) shown till 10 GeV/c
- Integrated yield scale with binary collisions
- Yield strongly suppressed at high $p_T$ in central Au+Au collisions
Electron and Muon spectra at LHC

- Left plot: the electrons from semi-leptonic decays of HF hadrons at mid-rapidity in Pb-Pb collisions
- Right plot shows the pQCD calculations in agreement with data at forward rapidity in pp collisions
Electron and Muon spectra at LHC

Spectra

ATLAS


• pQCD calculations agree with $e^\pm$ & $\mu^\pm$ (from HF) at high $p_T$
The results for p+p at 200 GeV

Such results for Au+Au will be much harder
Electrons from beauty decays: RHIC & LHC

- Near-side peak for electron-hadron angular correlation
  - Wider for electrons from beauty decays than those from charm decays

STAR, PRL 105, 202301 (2010)  

Separation of e± from charm and beauty decays
Open charmed mesons (first measured) in heavy-ion collisions
Open charmed mesons (first) detail studies in heavy-ion collisions

Also the $p_T$ spectra at different centrality classes are fitted
Open charmed mesons detail studies in pp collisions at 13 TeV

Open charm at LHC: TeV regime

LHCb

Forward rapidity

JHEP 1603 (2016) 159
Erratum: JHEP 1705 (2017) 074

\[ \sqrt{s} = 13 \text{ TeV} \]

\[ D^0 \]

\[ D^+ \]

\[ D_s \]

\[ D^{*+} \]
Open charm at LHC: TeV regime

Mid-rapidity, ALICE


Pb+Pb 2.76 TeV, JHEP 03 (2016) 081

- Open charmed mesons detail studies in pp and also in Pb-Pb collisions.
D^0 p_T spectra in pp collisions : LHC

ALICE

LHCb


LHCb D^0 p_T spectra in pp collisions : LHC

JHEP 1603 (2016) 159
Erratum: JHEP 1705 (2017) 074

• ALICE and LHCb D^0 p_T spectra

• Both data within FONLL uncertainty band (for p_T < 3 GeV/c)

• Both data on FONLL band upper edge (for p_T > 3 GeV/c)
ATLAS data in agreement with GM-VFNS

Both data (ATLAS & CMS) at $p_T > 20$ GeV/c higher than FONLL

ATLAS

CMS-PAS-HIN-16-001

CMS

pp at 5.02 TeV

CMS

$\sqrt{s} = 7$ TeV, 280 nb$^{-1}$

ATLAS

Data, $|y(D^{*+})| < 2.1$

FONLL

GM-VFNS

POWHEG+PYTHIA

POWHEG+HERWIG

MC@NLO

CMS

$|y| < 1.0$

Preliminary

Global uncert. 12.1%

25.8 pb$^{-1}$ (5.02 TeV pp)

CMS

pp at 7 TeV

$\sqrt{s} = 7$ TeV, 280 nb$^{-1}$
Charm content in Jets: The ratio \( \frac{N(D^{*+} + D^{*-})}{N(\text{jet})} \) is measured to be 0.015 ± 0.008(stat) ± 0.007(sys) for \( D^* \) mesons with fractional momenta \( 0.2 < z < 0.5 \) in jets with a mean transverse energy of 11.5 GeV.

Charm content in Jets: \( \frac{N(D^{*+})}{N(\text{jet})} \) is 0.025 ± 0.001(stat) ± 0.004(sys) for jets with transverse momentum between 25 and 70 GeV in \( |\eta| < 2.5 \) and \( D^{*\pm} \) mesons with fractional momenta \( 0.3 < z < 1.0 \).

EIC Physics Connections!
Open bottom mesons detail studies in pp collisions at 7 TeV

Open bottom at LHC : TeV regime

LHCb, Forward rapidity

pp at 7 TeV
B$^+$ $p_T$ spectra at LHC

CMS

Mid - rapidity

- FONLL describes the pp data well for CMS
- FONLL agrees with LHCb (forward rapidity)
- FONLL explains ATLAS & CMS data at 7 TeV

The last two bullets from previous slide 7 TeV pp data-sets
Nuclear modification factor
Single electron $R_{AA}$: RHIC

- Strong suppression for $p_T > 4$ GeV/c in central collisions but less towards more peripheral collisions
- Likely enhancement at low $p_T$ in both central and peripheral collisions
yields of leptons from heavy-flavor decays show suppression at high $p_T$ in central Pb-Pb collisions, compared with binary scaled pp collisions

less suppression in more peripheral collisions
**D⁰ mesons in pA collisions : LHC**

ALICE, PHYSICAL REVIEW C 94, 054908 (2016)

- ALICE $R_{pA}$ data are consistent with 1 within uncertainties
  - We see no major modification in pPb and also similar with LHCb
- We need more precise data to be able to separate between the models
D mesons in AA collisions: LHC

ALICE, Pb+Pb 2.76 TeV
JHEP 03 (2016) 081

CMS, Pb+Pb 5.02 TeV, CMS-PAS-HIN-16-001, arXiv:1708.04962

● Similar suppression in Pb+Pb at 2.76 TeV and 5.02 TeV
Consistent with various models
But we need more precise data to extract detailed underlying mechanism from the various models
Color Singlet Model [NPA470 (2013) 910]

- Calculations for LO and NLO
  - Qualitative features like data for low $p_T$ and rapidity dependence
  - Underestimates the data at high $p_T$
- Also the leading-$p_T$ NNLO contributions
  - Better agreement at high $p_T$, but with large uncertainties

Non-Relativistic QCD (NRQCD) [PRD84 (2011) 114001, PRD85 (2012) 114003]
- Theory overestimates the data
- Smaller disagreement at high $p_T$

$\Upsilon(2S)$ -to-$\Upsilon(1S)$ ratio in good agreement with CSM & NRQCD & Hybrid [Mod. Phys. Lett. A 28, 1350120 (2013)]
(L.S.Kisslinger and DD)
Figure 4. Differential cross-sections $\frac{d}{dy} \sigma^{\gamma \rightarrow \mu^+ \mu^-}$ in the range $p_T < 30$ GeV/c for (red solid circles) $\Upsilon(1S)$, (blue open squares) $\Upsilon(2S)$ and (green solid diamonds) $\Upsilon(3S)$ mesons for (left) $\sqrt{s} = 7$ TeV and (right) $\sqrt{s} = 8$ TeV data. Thick lines show fit results with the CO model predictions from refs. [63, 64] in the region $2.5 < y < 4.0$, and dashed lines show the extrapolation to the full region $2.0 < y < 4.5$. The data points are positioned in the bins according to eq. (6) in ref. [62].

(L.S.Kisslinger and DD)
Mod.Phys.Lett. A28 (2013) 1350120. (7.0 TeV)
Mod.Phys.Lett. A29 (2014) 1450082. (8.0 TeV)
Studies of $J/\psi \, v_2$ at RHIC and LHC energies have provided important elements toward the understanding on the production mechanisms and thermalization of charm quarks. Bottomonia has an advantage since it is a cleaner probe. A brief discussion has been provided for $\Upsilon(1S) \, v_2$, which can become the new probe for QGP, including the necessity of studies for small systems.

**ALICE and CMS**

ArXiv: 1812.06772 (December 2018)  YELLOW REPORT

*CERN* Yellow Report on Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

Where lies the challenge?

ALICE, PLB 753 (2016) 41

simultaneous description of HF decay $R_{AA}$ and $v_2$ is a challenge
-- can constrain energy loss models
Colour charge dependence

\[ R_{D/h}(p_t) = R^D_{AA}(p_t)/R^h_{AA}(p_t) \]

Mass hierarchy

\[ R_{B/D}(p_t) = R^e_{AA} \text{ from } B(p_t)/R^e_{AA} \text{ from } D(p_t) \]

- More intricacies on heavy-flavor quenching mechanisms

- \( R^{c}_{AA}/R^{b}_{AA} \) ratio differ as we see for pQCD and AdS/CFT
Unanswered Questions and next steps

• Heavy quarks are particularly good probes to study the properties of hot QCD matter

• pp data are important baseline measurements
  - examine interplay of soft and hard processes

• pA which is more than just a control
  - needed to study the CNM effects in various x ranges

• AA collisions : for understanding dense/hot QCD matter
  - strong interaction of heavy quarks with the QCD medium

• But do we understand fully the suppression at high $p_T$ at RHIC ?

• In this perspective what is the role of collisional energy loss?

• Difference between Pb+Pb at 2.76 TeV and 5.02 TeV ?

• The role of shadowing effect ?  EIC Physics Connections!

• Next steps :
  - Need more statistics, better precision and extended coverage (in terms of $p_T$)
  - Need new differential measurements to constrain models and address open questions
  - New probes like top quarks ?

Liliana Apolinário, José Guilherme Milhano, Gavin P. Salam, Carlos A. Salgado, PRL. 120, 232301(2018)
MORE
Different particle species

Phenix, d-Au

Backward rapidity ($-2.0 < y < -1.4$, Au-going direction)

Forward rapidity ($1.4 < y < 2.0$, d-going direction)
Comparisons at LHC

\[ \frac{dN}{d\varphi} = \frac{N_0}{2\pi} (1 + 2v_1 \cos(\varphi - \Psi_1) + 2v_2 \cos(\varphi - \Psi_2) + \ldots) \]