Thoughts on HF measurements and flavor dependence of jet quenching

Yen-Jie Lee (MIT)

HI Physics in the 2020’s
MIT, Cambridge, USA
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Major issues related to HF meson

- Heavy quark production cross-section
- The role of shadowing
- Hardronization mechanism
- Collisional energy loss vs. radiative energy loss
- Could we see the flavor dependence of $E_{\text{loss}}$?
Major issues related to HF meson

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• Could we see the flavor dependence of $E_{\text{loss}}$?
Calculations are in agreement with FONLL calculations. However, the theoretical uncertainty at low $p_T$ is very large (up to 50%)
D⁰ and B⁺ meson in pp

What is really used in the models are the c quark or b quark p_T spectra...
Motivates D meson and B meson jet fragmentation function measurements to validate our understanding.
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• Could we see the flavor dependence of $E_{\text{loss}}$?
Direct measurement of $D_{pPb}$, sensitivity limited by the current uncertainties
Could be done by ALICE, LHCb and CMS data taken in 2016 pPb run
( + pp ref run for ALICE)
LHCb $D^0$ meson measurement

Precise measurement from LHCb: data consistent with the lower edge of the pQCD calculation using EPS09.

Forward backward ratio: ~ shadowing / EMC region
CMS dijet $\eta$ data at large $Q^2$

Consistent with EPS09 at the edge of the uncertainty band. Deviation in the EMC region. Consistent picture between CMS dijet data and LHCb $D^0$ data.
PHSD with shadowing gives a better description of the CMS preliminary result.
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Interpretation of $v_2$ data

- Significant flow signal observed in D0, $v_2$ vs $p_T$ different from charged particles
- Need theoretical calculations at LHC energy without c quark $v_2$ to answer if the charm quarks flows
- Correlation analysis between D$^0$ and charged particle $v_2$
- 2020s: Follow up on the real measurement $B(b \rightarrow J/\psi) v_2$ at RHIC and LHC
ALICE will update the $D_s$ measurements with 2015 data
(In principle, CMS could also contribute to $D_s$ measurement)
Expect high statistics measurement from RHIC
Now - 2020s: $B_s$, $\Lambda_c$, $\Lambda_b$ measurements are becoming feasible by LHC experiments
Projected performance for $B_s$ and $\Lambda_b$ with 10/nb

$B_s$: Projected statistical uncertainty is around 3% in PbPb $p_T = 7$-10 GeV/c ($L = 10/nb$)

[~30-60x of the statistics shown in this plot]

$\Lambda_b$: Projected statistical uncertainty is around 15% in PbPb $p_T = 7$-10 GeV/c ($L = 10/nb$)

[~ 1/4 – 1/8 of the statistics shown in this plot]

Run IV data would help to provide those rate probes
Charged Hadron $R_{pA}$ is consistent with the published jet $R_{pA}$
Relevant for the interpretation of the charged particle $R_{AA}$

To be submitted to JHEP
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D-Dbar correlation

- D-hadron correlation has been studied by ALICE in pp and pPb collisions

- DD(bar) correlation in pp was studied by LHCb, to be done in PbPb by ALICE / CMS

- Difference between prediction with collisional and radiative energy loss goes away quickly as $p_T$ increases…
D/B-jet and D/B-photon correlation

- Propose to study D/B-jet and D/B-photon correlation at RHIC and LHC
- D meson and B meson as a tool to study the fate of the intermediate $p_T$ HF partons
- Relatively less likely to come from medium response, mass scale >> medium scale
- Jet and photon as a proxy to the initial parton direction
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No significant difference between CMS B\(^+\)
D\(^0\) and charged hadron \(R_{AA}\) in PbPb
at 5.02 TeV
No significant difference between CMS $B^+$ and $D^0$ $R_{AA}$ in PbPb at 5.02 TeV

Significant difference between CMS non-prompt $J/\psi$ and ALICE D meson in PbPb at 2.76 TeV
No significant difference between $B^+$, non-prompt $J/\psi$ $R_{AA}$
The reason could be associated with the rapidity dependence of the suppression. To be followed up with $B^+ R_{AA}$ with $|y|<1$ and its the rapidity.
Future (Run II+III) ~20-30x more data

- High precision charged particle, $D^0$ and $B^+ R_{AA}$ and $\nu_N$ data!
- Access to multiple $B^+$, $B^0$ and $B_s$ decay channels
- Jet / photon tagged HF mesons: provide multiple checks on medium modifications of the HF meson kinematics distributions
• Jets are modified in medium
• Separate quark and gluon: use high $p_T$ jets (and groomed jet substructure) to increase the scale difference between medium and the hard scattering
• Can we separate quark and gluon jets without touching the jets?
Z decay kinematics in Collins–Soper Frame

\[ A_0 = \left\langle \sin^2 \theta_1 \right\rangle \]
\[ A_1 = \frac{1}{2} \left\langle \sin 2\theta_1 \cos \phi_1 \right\rangle \]
\[ A_2 = \left\langle \sin^2 \theta_1 \cos 2\phi_1 \right\rangle \]
\[ A_3 = a \left\langle \sin \theta_1 \cos \phi_1 \right\rangle \]
\[ A_4 = a \left\langle \cos \theta_1 \right\rangle \]
\[ A_5 = \frac{1}{2} \left\langle \sin^2 \theta_1 \sin 2\phi_1 \right\rangle \]
\[ A_6 = \frac{1}{2} \left\langle \sin 2\theta_1 \sin \phi_1 \right\rangle \]
\[ A_7 = a \left\langle \sin \theta_1 \sin \phi_1 \right\rangle \]

Discussion with Jen-Chieh Peng
Z boson decay kinematics

1) \( q\bar{q} \rightarrow \gamma^*(Z^0)g \)

In \( \gamma^* \) rest frame (C-S):

\[
\sin^2 \beta = \frac{q_T^2}{Q^2 + q_T^2}
\]

\( \theta_1 = \beta \) and \( \phi_1 = 0; \quad A_0 = A_2 = \sin^2 \beta \)

\[
\chi = \frac{2 - 3A_0}{2 + A_0} = \frac{2Q^2 - q_T^2}{2Q^2 + 3q_T^2}; \quad \nu = \frac{2A_2}{2 + A_0} = \frac{2q_T^2}{2Q^2 + 3q_T^2}
\]
2) $qg \rightarrow \gamma^*(Z^0)q$

In $\gamma^*$ rest frame (C-S)

$\theta_1 = \beta$ and $\phi_1 = 0$

$\theta_1 > \beta$ and $\phi_1 = 0$; $A_0 = A_2 \approx 5q_T^2/(Q^2 + 5q_T^2)$

$\lambda = \frac{2 - 3A_0}{2 + A_0} = \frac{2Q^2 - 5q_T^2}{2Q^2 + 15q_T^2}$; $\nu = \frac{2A_2}{2 + A_0} = \frac{10q_T^2}{2Q^2 + 15q_T^2}$
Quark and Gluon Jet Fraction

\[ \lambda = \frac{2Q^2 - q_T^2}{2Q^2 + 3q_T^2} \quad \text{for } q\bar{q} \to Zg \]

\[ \lambda = \frac{2Q^2 - 5q_T^2}{2Q^2 + 15q_T^2} \quad \text{for } qG \to Zq \]

For both processes
\[ \lambda = 1 \text{ at } q_T = 0 \quad (\theta_1 = 0^\circ) \]
\[ \lambda = -1/3 \text{ at } q_T = \infty \quad (\theta_1 = 90^\circ) \]

Data can be well described with a mixture of 58.5% $qG$ and 41.5% $q\bar{q}$ processes.

Jen-Chieh Peng
PLB758 (2016) 384
Idea: Selection on the away side jet could change the fraction of Z boson coming from qq and qG scattering.

With Z polarization studies, one could measure possible modification of:

1. Z production in pPb and PbPb compared to pp
2. The flavor dependence of the jet modification in [pT spectra, shape and fragmentation function]

To be done with high statistics Run II+III data (and Run IV data)

Possible caveat: consideration of NLO corrections
~40% better impact parameter resolution at low track $p_T$

Significant reduction of the fake track rate, and improvement of the $b(c)$-jet tagging and $D^0$ meson reconstruction efficiency
CMS Phase 2 upgrade (2024)

Phase 2 Tracker

- Strip/Strip Modules
  - 90 μm pitch/5 cm length

- Inner Pixel
  - Covers up to η=4.0

- Strip/Pixel Modules
  - 100 μm pitch/2.5 cm length
  - 100 μm x 1.5 mm “macropixels”

- Tracking capability up to η=4
- Possible muon tagging up to η=3-4
Summary

- Heavy quark production cross-section
  - Precise measurement of B and D spectra down to low $p_T$ in pp
  - D and B fragmentation function in pp, pPb and PbPb

- The role of shadowing
  - D and B $R_{pA}$ from ALICE, LHCb and CMS
  - Dijet $\eta$ with Run II data from CMS (ATLAS)

- Hardronization mechanism
  - $D v_2$ measurement in pPb vs. event size
  - Charm+X: $D_s, \Lambda_c$
  - Bottom+X: $B_s, \Lambda_b$ with CMS Run II+III (+IV) data

- Collisional energy loss vs. radiative energy loss
  - Precision measurement of D, B and non-prompt J/$\psi$ RAAs at RHIC and LHC
  - D-photon, D-jet measurement (CMS / ATLAS / sPHENIX)
  - D-D and D-hadron measurements (ALICE, CMS)

- Could we see the flavor dependence of $E_{loss}$?
  - Precision measurement of HF RAAs at RHIC and LHC
  - High $p_T$ jet substructure for the separation of quark and gluons, (bbar) jets
  - High statistics Z-tagged jet studies (Run II+II (+IV))
Z-jet production in $O(\alpha_s)$

1) $q\bar{q} \rightarrow \gamma^* (Z^0) g$

2) $qg \rightarrow \gamma^* (Z^0) q$
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