Heavy flavor probes of the Quark Gluon Plasma with ATLAS

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SQM2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

June 15, 2022
Motivation

• Heavy flavor (HF) quarks \((b/c)\): large masses compared to the quark-gluon plasma (QGP) temperature
  ➢ Produced primarily at early times in the collisions
  ➢ May not completely thermalize
Motivation

• Heavy flavor (HF) quarks \((b/c)\): large masses compared to the quark-gluon plasma (QGP) temperature
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• Color screening from the deconfined medium
• Three \(\Upsilon\) meson states (quarkonia) have different binding energies.
  - Their "sequential melting" serves as a QGP "thermometer".
Heavy flavor (HF) quarks ($b/c$): large masses compared to the quark-gluon plasma (QGP) temperature

- Produced primarily at early times in the collisions
- May not completely thermalize

Open HF quarks lose energy and deflect in the QGP and these probe the properties of the medium.
\( \Upsilon \) signal extraction

- \( \Upsilon \) states measured in the di-muon channel at midrapidity.

**2017 pp**

- Data, \( \Upsilon(1S) \), \( \Upsilon(2S) \), \( \Upsilon(3S) \)
  - Fit
  - Bkg

**2018 Pb+Pb**

- Data, \( \Upsilon(1S) \), \( \Upsilon(2S) \), \( \Upsilon(3S) \)
  - Fit
  - Bkg

**HION-2021-12**
• Stronger suppression in central collisions
• Sequential suppression: $\Upsilon(1S) > \Upsilon(2S) > \Upsilon(2S+3S)$
  • 3S combined due to its low statistics
Double ratio

\[ \rho _{AA}^{\Upsilon(nS)/\Upsilon(1S)} = R_{AA}(\Upsilon(nS))/R_{AA}(\Upsilon(1S)) \]

- Double ratio cancel out some common systematic uncertainties.
- Sequential suppression is significant (below unity).
- Slightly decreasing trend toward more central collisions; no significant \( p_T \) dependence.
From quarkonium, $W/Z...$ (small)

Pion, kaon decay

ID-MS random combination

Template fit to remove the background: based on the ID-MS momentum imbalance:

$$\rho = \frac{p^{ID} - p^{MS}}{p^{ID}}$$

Muon from HF semi-leptonic decay

From Qipeng Hu
Open HF ($b/c$) muon

Template fit to separate $b/c$: based on muon $d_0$ (ID impact parameter on the transverse plane) <- due to slightly different lifetime
• $c$ is more suppressed than $b$ at low $p_T$
• Consistent above $\sim 10$ GeV
• $v_2(c) > v_2(b)$
• Strong centrality dependence observed
• No theory model describes $b/c \ R_{AA}/v_2$ simultaneously.
• Large uncertainties due to anti-correlation between $b$ and $c$

• Charm is more suppressed at low $p_T$; comparable at higher $p_T$.
  • Model captures the qualitative behavior but underestimates $c R_{AA}$ and thus also the double ratio at low $p_T$ in 0-10%.
Yield suppression double ratio

- Large uncertainties due to anti-correlation between $b$ and $c$
- Charm is more suppressed at low $p_T$; comparable at higher $p_T$.
  - Model underestimates $c$ quark $R_{AA}$ and thus also the double ratio at low $p_T$ in 0-10%.
- Mass ordering consistent with the dead-cone effect in the radiative energy loss
HF muon pair

- Measure back-to-back muon pair production from semi-leptonic decays of HF quarks:
  - $|\Delta \eta| > 0.8$ to remove the near-side jet peak
  - Invariant mass cuts to remove $J/\psi, \Upsilon$ etc. (only on opposite sign pairs)
  - $b\bar{b}$ dominates in the same-sign and inclusive di-muon pairs (according to the MC).

Theory prediction for broadening

![Diagram showing broadening of muon pairs](image-url)
The following fit function is used to extract the signal:

$$dN/d\Delta\phi = N_0 + N_{\text{flow}} \cos(2\Delta\phi) + Y_{\text{corr}}(\Delta\phi),$$

With (Lorentzian)

$$Y_{\text{corr}}(\Delta\phi) = \frac{N_{\text{corr}}}{(\Delta\phi - \pi)^2 + \tau^2} - N_{\text{pedestal}},$$

Yield = integral of $Y$
Width = std deviation of $Y$

(pedestal term chosen such that $Y(0) = 0$)
Di-muon correlation: yields

- $T_{AA}$ scaled yields suggest stronger suppression in the more central collisions.
- Similar trend for both the same sign and opposite sign.
Di-muon correlation: width

- Centrality-independent width indicates no significant change in the width.
Both collisional and collisional + radiative lead to the broadening <- not observed
  - Although with the radiative, the broadening is weaker.

However, some recent new results suggest that the radiative may largely cancel out broadening from the collisional.
• *b*-jets (quark jets) are expected to lose less energy via radiation compared to gluon-initiated jets.

• Due to the dead-cone effect, radiation is suppressed for *b* compared to lighter quarks.

> Both reduce the (radiative) energy loss.
**b-jet signal extraction**

- **b-jet reconstruction:** containing muons from the semi-leptonic decay
  - *b*-quark directly produced in the hard scattering or from a gluon splitting

- **Template fit:**
  - Jet + \( \mu \) axis:
    
    \[
    \mu_{\text{jet}+\mu} = \frac{p_T^{\mu} + p_T^{\text{jet}}}{|p_T^{\mu} + p_T^{\text{jet}}|}
    \]

  - Muon \( p_T \) projection:
    
    \[
    p_T^{\text{rel}} = |p_T^{\mu} \times \mu_{\text{jet}+\mu}|
    \]

- **Muon candidates:**
  - \( p_T > 4 \text{ GeV} \)
  - Within the jet cone (\( R \))

- **Pb+Pb combinatoric term** estimated from event mixing

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From S. Tapia Araya
• Both b-jets and inclusive jets are suppressed, especially in more central collisions.

• b-jets are less suppressed compared to inclusive jets in central collisions.
Some common uncertainties are cancelled out in the double ratio.
The double ratio is consistent with unity in peripheral and about 20% above unity in central collisions.
b-jets are less suppressed compared to inclusive jets in central collisions.
Is it a color effect or a mass effect (dead cone)?
Photon-tagged jets vs inclusive jets

- **Photon-tagged jets:**
  - More likely to be initiated by a quark
  - Colorless photon not significantly modified by the QGP

\[ pp (or \ NN) \rightarrow \gamma + \text{jet}(+X) \quad (\Delta\phi > \pi/2) \]

(Enhancement) ~0.15 inclusive
• *b*-jets and photon-tagged jets are close (e.g.: ~0.6 at 100 GeV).

• This might be a sign that *b*-jets are less suppressed more because of the color-charge effect than the parton mass (dead cone) effect.
  • *b*-jet spectrum falls more steeply so close $R_{AA}$ might indicate a smaller energy loss.
  • Isospin/nPDF effect reduces the Compton scattering in Pb+Pb -> $\gamma$-jet $R_{AA}$ decreases by ~0.05-0.1.
Summary

- Quarkonium:
  - Sequential suppression for the three $\Upsilon$ states observed.
Summary

- Open heavy flavor and hard-probes:
  - Suppression on $b/c$ muon, with $c$ more suppressed than $b$ at lower $p_T$.
  - HF back-to-back muon pairs: no significant open angle broadening observed.
  - $b$-jets and photon-tagged jets less suppressed than inclusive jets in central collisions.
Backup
Cross-sections in \( pp \) and \( \text{Pb+Pb} \)

- \( \Upsilon(3S) \) not shown in \( \text{Pb+Pb} \) due to its low statistics.
Nuclear modification factor

- No significant rapidity or pT dependence observed
HF muon
ATLAS
$pp$, 5.02 TeV, 1.17 pb$^{-1}$

\[ \frac{d^2 \sigma}{dp_T^2} \text{ [pb GeV}^{-1}] \]

$c \to \mu$ data
FONLL $c \to \mu$

Data / FONLL

$5 \leq p_T [\text{GeV}] \leq 30$

\[ \frac{d^2 \sigma}{dp_T^2} \text{ [pb GeV}^{-1}] \]

$b \to \mu$ data
FONLL $b \to \mu$

Data / FONLL

$5 \leq p_T [\text{GeV}] \leq 30$
pp v2

ATLAS

pp $\sqrt{s}=13$ TeV, $150 \text{ pb}^{-1}$

$4<p_T<6$ GeV

$1.5<|\Delta\eta|<5$

- $c\rightarrow\mu$
- $b\rightarrow\mu$

$V_2$ vs $N_{\text{rec}}^\text{ch}$
$c$ RAA

**ATLAS**

Pb+Pb, 5.02 TeV, 246 μb⁻¹

$pp$, 5.02 TeV, 1.17 pb⁻¹

$c \rightarrow \mu$
Di-muon correlation: yields

**ATLAS** Preliminary

Pb+Pb 5.02 TeV, 1.93 nb⁻¹

- Same-sign pairs: $p_T^{a,b} > 4$ GeV
- Opp-sign pairs: $p_T^{a,b} > 4$ GeV
- All pairs: $p_T^{a,b} > 4$ GeV

Yield per percentile [$10^3$] vs Centrality [%]
• b-jet to inclusive ratio in pp consistent with simulation and the CMS result
• No significant pT dependence observed
Photon-tagged jet

**Atlas Preliminary**

2017 pp 257 pb^{-1} \( \sqrt{s} = 5.02 \text{ TeV} \)

- anti-\( k_T \) R = 0.4 jets
- \( |\eta| < 2.8 \)
- \( p_T^\gamma > 50 \text{ GeV}, |\eta^\gamma| < 2.37 \)
- \( \Delta\phi(\gamma, \text{jet}) > \pi/2 \)

**Atlas Preliminary**

2018 Pb+Pb 1.7 nb^{-1}, 2017 pp 260 pb^{-1}

- \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
- anti-\( k_T \) R = 0.4 jets
- \( |\eta^\text{jet}| < 2.8 \)
- \( p_T^\gamma > 50 \text{ GeV}, |\eta^\gamma| < 2.37 \)
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**MC/Data**

- pp data
- PYTHIA
- SHERPA
- HERWIG

**\( \gamma \)-tagged jet**

\[ \frac{d^3\sigma}{dp_T d\eta} \text{ (GeV)} \]

**0-10\% \( \gamma \)-jet**
- 10-30\% \( \gamma \)-jet (x10)
- 30-80\% \( \gamma \)-jet (x10^3)

\[ \frac{d^2N_{\gamma\text{-jet}}}{dp_T dp_T'} \]

**pp inc. jet** [PLB 790 (2019) 108]
• Double ratio above unity: $\gamma$-tagged jets are less suppressed.

• This could indicate a reduced energy loss of quark-initiated jets compared to gluon-initiated (or inclusive) jets.
  • However, 2 other effects of opposite sign and likely similar magnitude should be taken into consideration when interpreting this result.
  • $\gamma$-tagged jet spectrum is steeper -> RAA increases by $\sim 0.1$ (same energy loss, a simple model of fractional energy loss).
  • Isospin/nPDF effect reduces the Compton scattering in Pb+Pb -> RAA decreases by $\sim 0.05-0.1$. 
