Recent Open Heavy Flavor Results from ATLAS and CMS Experiment at LHC

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For the ATLAS and CMS collaboration

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Study of open heavy flavor production at the LHC (1/4)

Leptons from heavy quarks

Secondary vertex

Primary vertex

Sample $O(10\%)$ of b cross-section
Study of open heavy flavor production at the LHC (2/4)

Leptons from heavy quarks

Non-prompt J/ψ

Dileptons channel sample $O(0.1\%)$ of $b$ cross-section
Leptons from heavy quarks

Non-prompt $J/\psi$

Exclusive $B$ meson decays

$J/\psi + 1(2)$ tracks decay channels sample $O(0.01\%)$ of $b$ cross-section
Study of open heavy flavor production at the LHC (4/4)

Leptons from heavy quarks

Secondary vertex

Primary vertex

Non-prompt J/ψ

Exclusive B meson decays

b-jet reconstruction

b-tagged jet sample $O(100\%)$ of $b$ cross-section and ~70-90% of the $b$ quark energy
Requirements

Leptons from heavy quarks

Non-prompt J/ψ

Exclusive B meson decays

b-jet reconstruction

**Requirement:** flexible trigger system, muon / electron detection, secondary vertex reconstruction, jet reconstruction
ATLAS detector

Barrel: $|\eta| < 1.05$
End cap: $1.05 < |\eta| < 2.7$

Centrality determination

Muon measurement

Pixel, SCT, TRT

$|\eta| < 2.5$

3.2 < $|\eta| < 4.9$
CMS detector

EM and Hadron calorimeters
photons, isolation, jet reco

Inner tracker:
charged particles
vertex, isolation

Muon
|\eta|< 2.4

HCAL
|\eta|< 5.2

ECAL
|\eta|< 3.0

Tracker
|\eta|< 2.5
Bottom production at the LHC

- LO $b\bar{b}$ production (FCR) not dominant at the LHC

At NLO

- Excitation of sea quarks $\rightarrow b(\bar{b}) +$ light dijet, w/ $b(\bar{b})$ at beam rapidity
- Gluon splitting into $b$ and $\bar{b}$ which can also be reconstructed as a single jet

Herwig 6.5, arXiv:0705.1937

GSP

FEX

pp @ 14 TeV

$p_t$ [GeV]
Flavor Creation Candidate (pp @ 7 TeV)

Secondary Vertices with their tracks

Reconstructed secondary vertices from b and c quarks

Secondary Vertex with its Tracks

Jets

Reconstructed

CMS Experiment at LHC, CERN
Data recorded: Sun Aug 15 04:08:48 2010 CEST
Run/Event: 142971 / 343407290
Lumi section: 372
Gluon Splitting Candidate (pp @ 7 TeV)

Secondary Vertices with their Tracks

Muon

jets

CMS Experiment at LHC, CERN
Data recorded: Fri Jul 30 07:23:52 2010 CEST
Run/Event: 141961 / 45761100
Lumi section: 74
1. Leptons from heavy quarks

Primary vertex

Secondary vertex

$\mu^+$

$\mu^-$

$b$

$K^+$
Heavy flavor muon identification

- **Separate signal muons** (heavy flavor meson decay) from pion and kaon decays

- **Momentum balance**

  \[
  \frac{\Delta p_{\text{loss}}}{p_{\text{ID}}} = \frac{p_{\text{ID}} - p_{\text{MS}} - \Delta p_{\text{calo}}(p, \eta, \phi)}{p_{\text{ID}}}
  \]

- **Scattering angle significance**

  \[
  s_i \equiv q\Delta \phi_i / \phi_{\text{msc}} \\
  S(k) = \frac{1}{\sqrt{n}} \left( \sum_{i=1}^{k} s_i - \sum_{j=k+1}^{n} s_j \right)
  \]

  Take the maximum: \( S = \max \{|S(k)|, k = 1, 2, \ldots\} \)
Heavy flavor muon signal extraction

- Composite discriminant

\[ C = \left| \frac{\Delta p_{\text{loss}}}{p_{\text{ID}}} \right| + rS \]

\[ r = 0.07 \]

- **Signal** extracted from a two component fit

ATLAS-CONF-2012-050
• Suppression of heavy flavor muons in central PbPb collisions with respect to peripheral events is observed ($R_{CP} \sim 0.4$)
• $R_{CP} \sim$ constant vs. muon $p_T$
2. Non-prompt J/ψ

Primary vertex

Secondary vertex

\[ \mu^+ \]

\[ \mu^- \]

\[ J/ψ \]

\[ K^+ \]
Inclusive J/ψ production in PbPb

CMS Preliminary

PbPb $\sqrt{s_{NN}} = 2.76$ TeV

$N_{J/\psi} = 2291 \pm 97$

$\sigma = 46 \pm 1$ MeV/c$^2$

$L_{\text{int}} = 150 \mu$b$^{-1}$

1.6 $< |y| < 2.4$

6.5 $< p_T < 30$ GeV/c

Cent. 0-100%

Non-prompt J/ψ to dimuon channel

inclusive J/ψ

J/ψ $\leftrightarrow$ B

prompt J/ψ

direct J/ψ

J/ψ $\leftrightarrow$ ψ', $\chi_C$

CMS PAS HIN-12-014
Non-prompt J/$\psi$ suppression in PbPb collisions

Suppression of non-prompt J/$\psi$ in central PbPb collisions with respect to pp reference is observed ($R_{AA} \sim 0.4$)

CMS Preliminary
$PbPb \sqrt{s_{NN}} = 2.76$ TeV

CMS PAS HIN-12-014
Study of open heavy flavor production at the LHC (3/4)

3. Exclusive B meson decays

Primary vertex

Secondary vertex

$J/\psi$

$K^+$

$\mu^+$

$\mu^-$
B meson reconstruction

- B-meson reconstructed by combination of
  - $J/\psi$ (decay to dimuon)
  - tracks (assigned pion or kaon mass, w/o PID)

- $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$
- $B^0 \rightarrow J/\psi K^0* \rightarrow \mu^+ \mu^- K^+ \pi^-$
- $B_s \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$

Primary Collision Vertex

B$^+$

$B^0$ Decay Vertex

$B^0$

$m = 3.10 \text{ GeV/c}^2$

$B^+$

$m = 3.10 \text{ GeV/c}^2$

$B_s$ Decay Vertex

$B_s$

$m = 1.02 \text{ GeV/c}^2$

$B^0$ Decay Vertex

J/ψ

K$^+$

$m = 0.89 \text{ GeV/c}^2$

π$^-$

Primary Collision Vertex

Primary Collision Vertex

$B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$

$B^0 \rightarrow J/\psi K^0* \rightarrow \mu^+ \mu^- K^+ \pi^-$

$B_s \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$

$J/\psi$

$K^+$

$\mu^+$

$\mu^-$

$K^-$

$\pi^-$

$\phi$

$\mu^+$

$\mu^-$

$K^+$

$K^-$

$\pi^-$
Open heavy flavor production in pp collisions

ATLAS and CMS have reported B meson (b baryon) cross-section measurements in pp collisions ($p_T = 5$ GeV to 100 GeV)

Good agreement between pp data and FONLL calculation
Three component fit for signal extraction:

- Signal
- Combinatorial background from J/ψ-track(s)
- Non-prompt component from other B-meson decays that form peaking structures (e.g. in B⁺ analysis, bkg from B⁰ → J/ψ K⁰*)

First fully reconstructed B meson signal in heavy ion collisions!
B meson production in pPb collisions

Raw yields are corrected by acceptance and efficiency

Acceptance

Efficiency

CMS Preliminary p+Pb $\sqrt{s_{NN}}=5.02$ TeV
PYTHIA+EvtGen+PHOTOS

CMS Preliminary p+Pb $\sqrt{s_{NN}}=5.02$ TeV
PYTHIA+EvtGen+PHOTOS
HIJING minbias embedded
Differential cross-section

\[
\frac{d\sigma^B}{dp_T} \bigg|_{|y_{CM}|<1.93} = \frac{1}{2} \frac{1}{\Delta y \Delta p_T} \frac{N^B}{(Acc \times \epsilon) \cdot BR \cdot L_{int}}
\]

pp reference: FONLL calculation is used

(agreement with CDF, ATLAS and CMS data)

http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html
Nuclear modification factor: $R_{pA}^{FONLL}$

$$R_{pA}^{FONLL}(p_T) = \frac{(\frac{d\sigma}{dp_T})_{pPb}}{A \times (\frac{d\sigma^{FONLL}}{dp_T})_{pp}}$$

$R_{pA}^{FONLL}$ is compatible with unity within given uncertainties for the three $B$-mesons

$|y_{CM}| < 1.93$

CMS Preliminary $p+Pb \sqrt{s_{NN}} = 5.02$ TeV

$L_{int} = 34.8$ nb$^{-1}$

CMS PAS HIN-14-004
4. b-jet reconstruction (Anti-$k_T$ r=0.3) UE background subtracted
Tagging and counting b-quark jets

Secondary vertex tagged using flight distance significance

Tagging efficiency estimated in a **data-driven** way

Purity from **template fits** to (tagged) secondary vtx mass distributions

![Secondary vertex diagram]

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CMS HIN-12-003
ArXiv 1312.4198

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CMS PAS HIN-14-007

Yen-Jie Lee (MIT)  RHIC & AGS Annual Users' Meeting
b-jet $R_{pA}^{PYTHIA}$ in pPb collisions at 5.02 TeV

b-jet $R_{pA}^{PYTHIA}$ is compatible with unity within given uncertainties.
b-Jet $R_{AA}$ in PbPb collisions at 2.76 TeV

Suppression of b-tagged jets in central PbPb collisions with respect to pp reference was observed ($R_{AA} \sim 0.5$)

CMS HIN-12-003
ArXiv 1312.4198
Summary of open heavy flavor production in ATLAS and CMS

1. Leptons from heavy quarks
2. Non-prompt \( J/\psi \)
3. Exclusive B meson decays
4. \( b \)-jet reconstruction
Summary: $R_{AA}^{CP}$ vs $N_{part}$

CMS Non-prompt J/ψ $R_{AA}$

ATLAS Heavy Flavor Muon $R_{CP}$

($60$-$80\%$ as reference)
Summary: Flavor Dependence of Jet Quenching

Indication of $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$ at low $p_T$

(However, spectra slope are different)
Summary: Flavor Dependence of Jet Quenching

Indication of \( R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi) \) at low \( p_T \)

(However, spectra slope are different)

Replace non-prompt \( J/\psi \) results by exclusive B meson to fix the x axis scale
Summary: Flavor Dependence of Jet Quenching

Indication of $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$ at low $p_T$
(However, spectra slope are different)

Indication of $R_{AA}(b\text{-jet}) \sim R_{AA}(\text{all jets})$ at high jet $p_T$

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**ALICE**
- Average $D^0, D^+, D^{*-} |y|<0.5, 0-7.5%$
- with $pp$ $p_T$-extrapolated reference
- Charged particles, $|\eta|<0.8, 0-10%$
- Charged pions, $|\eta|<0.8, 0-10%$

**CMS Preliminary**
- $b \rightarrow J/\psi$
- $b$ to secondary $J/\psi$
- $|\eta|<2.4, 0-100\%$

$b$ quark jet $\sim$ inclusive jet (mainly gluon jets), contribution from gluon splitting?
Outlook: Statistical Reach in 2015 and beyond

2011 2.76 TeV PbPb data (0.15/nb)
- b-jet

2013 5.02 TeV pPb data (35/nb)
- B meson
- b-jet

2015-17 5.1 TeV PbPb data (1.5/nb)
- B meson
- b-jet

HL-LHC (10/nb): (b)-jet quenching at O(TeV)
ttbar production

Stay tuned!

Yen-Jie Lee (MIT)
Backup slides
Open heavy flavor production in pp collisions

Good agreement between POWHEG+PYTHIA and data

\[ B^+ \rightarrow J/\psi K^+ \]
Figure 1: Projections of the fit results in $M_B$ (left) and $ct$ (right) for $p_T^B > 5 \text{ GeV}$ and $|y^B| < 2.4$. The curves in each plot are the sum of all contributions (solid blue line); signal (dashed red); prompt $J/\psi$ (dotted green); and the sum of non-prompt $J/\psi$, peaking $b\bar{b}$, and $J/\psi\pi^+$ (dot-dashed brown). For better visibility of the individual contributions, the $M_B$ plot includes a requirement of $ct > 100 \mu m$. 
Data agrees with the FONLL expectation at 1.96(p-pbar, CDF) and 7 TeV(p-p, ATLAS, CMS)
Expect the same agreement at 5TeV collision also
## Summary of optimal cuts

<table>
<thead>
<tr>
<th>Variable for B-meson selection</th>
<th>$B^+$</th>
<th>$B^0$</th>
<th>$B_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$ confidence level of B vertex fit</td>
<td>$&gt;0.013$</td>
<td>$&gt;0.16$</td>
<td>$&gt;0.037$</td>
</tr>
<tr>
<td>distance between the primary and the B-decay vertices</td>
<td>$&gt;3.4$</td>
<td>$&gt;4.2$</td>
<td>$&gt;3.4$</td>
</tr>
<tr>
<td>cosine value of angle between the displacement and the momentum of the B-meson in the transverse plane</td>
<td>$&gt;-0.35$</td>
<td>$&gt;0.75$</td>
<td>$&gt;0.26$</td>
</tr>
<tr>
<td>difference of the mass between track-pair and resonant meson (unit : GeV/$c^2$)</td>
<td>$&lt;0.23$</td>
<td>$&lt;0.016$</td>
<td></td>
</tr>
</tbody>
</table>