Open heavy flavour measurements at LHC with CMS

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Heavy Quark Physics in Heavy-Ion collisions: experiments, phenomenology and theory
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Introduction

• HF measurements in CMS

• What was done so far:
  → b-jet measurement in PbPb
  → non-prompt J/Psi
  → B meson in pPb collisions as a proof of feasibility

• Plans for new analyses with Run2:
  → D/B meson measurement in PbPb collisions
  → c/b jets, b-jet correlations, di-b-jets analysis
Heavy-flavour interactions with the medium

Heavy quarks produced in hard scatterings (described by pQCD) at the early stages of the collisions → Experience the full evolution of the medium

• Once produced, they strongly interact with the deconfined medium (hot nuclear matter effects):

→ In-medium energy loss as a consequence of radiative and collisional processes

Flavour-dependence of radiative energy loss:

• Larger for gluons than for quarks
  E.g. in BDMPS model [1]  \( <\Delta E> \propto \alpha_s C_R q L^2 \)

• Dead cone effect: gluon radiation suppressed at small angles for massive quarks

\[ \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \]

\[ R_{AA}^B > R_{AA}^D > R_{AA}^{\text{light}} \]
**CMS detector**

- **Inner tracker**: for charged track and vertex reconstruction
- **EM and hadron calorimeters**: for jet, photon reconstruction and isolation
- **Muon system**: for muon reconstruction and triggering

| Component  | $|\eta| < $  |
|------------|-------------|
| Muon       | 2.4         |
| HCAL       | 5.2         |
| ECAL       | 3.0         |
| Tracker    | 2.5         |
How to measure heavy-flavour quarks in CMS

Non-prompt $J/\psi$
$O(0.1\%)$ of b-cross section

Exclusive $B$ meson decays,
$O(0.01\%)$ of b-cross section

$b$-jet, $O(100\%)$ of total b-cross section
b-jet measurements

What is a b-jet?

→ A b-jet is a jet where a b-quark is identified within $\Delta R<0.3$ from jet axis
→ HF hadron does not need to be fully reconstructed

CAVEAT: b-quarks don't need to be primary. This definition of b-jet includes jets in which b-quark is produced e.g. by gluon splitting $g \rightarrow b\bar{b}$
b-jet analysis strategy

Jet reconstruction → b-jet tagging → Purity determination → Efficiency correction and resolution unfolding

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b-jet tagging

→ based on kinematic variables related to the long lifetime and large mass of b hadrons

“Secondary Vertex Tagger”

- Secondary vertex (SV) reconstructed with charged tracks with $p_T > 1$ GeV/c in the jet cone ($R=0.2$)

- b-jet contribution enhanced by requiring SVs far enough from the primary interaction vertex

- Displaced SVs identified by using a selection on the significance of the 3D flight distance
In each $p_T$ bin we need to evaluate the fraction of genuine b-jets that pass the “Secondary vertex tagger” criteria.
- First $b$-jet $R_{AA}$ measurement in PbPb collisions.
- Evidence of $b$-jet suppression in central PbPb events
- $b$-jet $R_{AA}$ favours pQCD models that include strong jet-medium coupling
non-prompt $J/\psi$

JHEP 1205 (2012) 063
non-prompt $J/\psi$ measurement

Getting closer to the $b$-quark kinematics!
Identification of $J/\psi \rightarrow B$ based on the measurement of displaced secondary $\mu^+\mu^-$ vertices

- The fraction of non-prompt $J/\psi$ extracted with a simultaneous fit of invariant mass distribution of $\mu^+\mu^-$ pairs and pseudo-proper decay length $l_{J/\psi}$
non-prompt $J/\psi$ measurement

- Clear suppression pattern vs centrality and $p_T$
B-meson measurements

CMS-PAS-HIN-14-004
B-meson measurement

How do we reconstruct B mesons in CMS?

→ Clean and high statistics sample collected by triggering on muons!

• \( J/\psi \rightarrow \mu^+\mu^- \) reconstruction
• Tracks are associated to \( J/\psi \) candidate to build B-meson candidates

Candidate selection variables:
• \( \chi^2 \) confidence level of B-vertex fit
• standardised decay length in XY plane
• cosine of the pointing angle

In \( B^0 \) and \( B^0_s \) case, selection on the invariant mass of the track-track system w.r.t. mass of the resonance (\( K^{0*} \) or \( \phi \))
B-meson production in pPb as a proof of feasibility

- Fit to the invariant mass distributions of B-meson candidates. Three components:
  - 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*)
B-meson cross sections in pPb at 5.02 TeV

- $d\sigma/dp_T$ of $B^+, B^0, B_s^0$ and $d\sigma/dy$ of $B^+$ in $|y_{CM}|<1.93$ and $10<p_T<60$ GeV/c
- measurements compared to FONLL predictions at 5.02 TeV scaled by $A$
What have we learnt in pPb?

→ First that we can measure fully reconstructed B mesons in CMS!
→ \( R_{pA} \) consistent with unity within uncertainty
→ Important reference for the PbPb analysis
... and $B^0$ and $B^{0s}$

$\rightarrow R_{pA}$ of $B^0$ and $B^{0s}$ was also measured even if with larger uncertainties

$\rightarrow$ Both consistent with unity
Flavour-dependence of jet quenching

\[ R_{AA}(b\text{-jets}) = R_{AA}(\text{inclusive jets}) \text{ at high } p_T. \]
No strong indication of flavour-dependence

\[ R_{AA}(J/\psi \leftarrow B) > R_{AA}(D) \approx R_{AA}(\text{lights}) \]

Possible interpretation?
- flavour dependence relevant for \( p_T < 75 \text{ GeV/c} \)
- In GSP, energy loss as for a “massive” gluon

Huang, Kang and Vitev
PLB726 (2013) 251-256!
Prospects for future analyses
Fully reconstructed D/B mesons in PbPb

**B-meson in PbPb**
- Large statistics will be available next year with Run2 (1.5 nb⁻¹)
- Clean sample thanks to muon triggers
- We expect to measure B mesons in PbPb from 5-10 GeV/c to ≈100 GeV/c
- $B_s/B$ ratio

**D-meson in PbPb**
- We will measure D meson production via hadronic decay in a wide $p_T$ range
- At high-$p_T$ we can profit from large samples collected with jet triggers
Heavy-flavour jets

**b-jet in PbPb**
- With 2015 data sample, we will extend the 2011 measurement down to lower $p_T$ (about 50 GeV/c)
- Reduce uncertainty to give insights on the flavour dependence of energy loss

**c-jet in PbPb**
- much more difficult to be tagged
  - Shorter $\tau \approx 100-300$ μm
  - Smaller multiplicity
  - Softer vertices

*Plots from Matthew Nguyen*
b-jet correlations

Angular correlations of di-b-jets are sensitive to production mechanisms!

Gluon splitting processes characterised by small angle within bb pairs

- By selecting couple of b-jets with large $\Delta \Phi$ we select a sample of b di-jet mainly produced by flavour creation processes
- Most of the generators tend to under-predict the gluon splitting contribution

JHEP 1103 (2011) 136
b-jet $p_T$ asymmetry

- The advantage of measuring asymmetry vs inclusive spectrum is reduced systematics

- By using large $\Delta \Phi$ selection we “kill” the contribution of gluon splitting processes

 CMS projection for PbPb double tagged b-jets

CMS PAS FTR 13-025

$A_J = \frac{(p_{T,1} - p_{T,2})}{(p_{T,1} + p_{T,2})}$

Projected $\sqrt{s}=5.5$ TeV, $L = 10$ nb$^{-1}$

stat. uncert. for 160 $\mu$b$^{-1}$

$p_{T,1} > 100$ GeV

$p_{T,2} > 30$ GeV

centrality : 0-10%
What do we need?

“Regional” tracking algorithm:
• standard HI tracking algorithm optimised for reconstructing tracks coming from primary vertex to reduce combinatorial background
• “regional” tracking algorithm based on sequential iterations to recover displaced tracks → the new strategy will increase reconstruction efficiency of HF topologies

HLT HF trigger developments:
→ Wide upgrade of the ECAL and HCAL trigger system in Run2

• Heavy-flavour jets:
  HF jet-triggers based on Jet trigger + b-tagging algorithms
• D mesons:
  Similar strategy based on Jet trigger + D meson filters

→ This will allow to record in 2015 the largest HF sample ever collected in HI collisions!
Call for models!

- D meson predictions from 5-10 GeV/c up to 100 GeV/c
- B meson predictions from 10 GeV/c up to 100 GeV/c
- b-jets from about 50 to 300 GeV/c
- $p_T$ asymmetry of b-jets
- ....?

Please contact us in case you can provide any of these predictions!
Conclusions

• Many ways of measuring heavy-flavour production in HI in CMS!
  → Fully reconstructed D/B mesons
  → Non-prompt B → J/ψ
  → Heavy-flavoured jets

• First b-jet measurement performed in HI collisions
  → strong suppression observed in central PbPb events

• New analyses and prospects for Run2
  → Fully reconstructed B/D mesons in PbPb
  → HF jets
  → b-jet correlations

• Strong effort on heavy-flavour trigger developments for Run2
  → plans to trigger on b-jets, D and B mesons in HLT
BACKUP SLIDES
Heavy-flavour production mechanisms in pp collisions

**LO process: Flavour Creation (FCR)**
- gluon fusion or light $q\bar{q}$ annihilation
- $b\bar{b}$ produced back-to-back in azimuthal plane and symmetric in $p_T$

**NLO process: Flavour Excitation (FEX)**
- excitation of $b/\bar{b}$ sea quark by gluon or light quark/anti-quark
- $b\bar{b}$ pairs produced asymmetric in $p_T$ and with a broad opening angle

**NLO process: Gluon splitting (GSP)**
- gluon splits in a $b\bar{b}$ pair
- produced with small opening angles and asymmetric in $p_T$
- In this case, $b\bar{b}$ are not involved in the hard scattering but produced later
Heavy-flavour production mechanisms in pp collisions

LO production mechanisms are not dominant at the LHC energies

EPJC 73 (2013) 2301
Flavour creation process (FCR) in pp collisions at 7 TeV
Gluon splitting process (GSP) in pp collisions at 7 TeV
Heavy-flavour interactions with the medium

The presence of the medium where high energy partons can scatter enhances the probability of gluon radiation (gluonstrahlung)

\[ \langle \Delta E \rangle \propto \alpha_s \, C_R \, q \, L^2 \]

- \( \alpha_s \) is the QCD coupling constant
- \( L \) is the in-medium path length
- \( C_R \) is the Casimir factor
  - \( C_R = 3 \) for gluons, \( C_R = 4/3 \) for quarks
- \( \hat{q} \) is the transport coefficient, proportional to the medium density

**Dead cone effect**: gluon radiation suppressed at small angles for massive quarks

\[ \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \]

A hierarchy in the nuclear modification factors of lights and heavy quarks is also expected:

\[ R_{AA}^B > R_{AA}^D > R_{AA}^{\text{light}} \]

Jet reconstruction and composition

Optimise the use of calorimeter and tracker by using “Particle Flow” method

Anti-$k_T$ algorithm with $R=0.3$

A typical high-$p_T$ jet composition
Background subtraction

1) Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

Estimate background for each tower ring of constant $\eta$
estimated background = $<p_T> + \sigma(p_T)$

- Captures $dN/d\eta$ of background
- Misses $\phi$ modulation – to be improved
Background subtraction

1) Background energy per tower calculated in strips of \( \eta \). Pedestal subtraction

Background level
Background subtraction

1) Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

2) Run anti $k_T$ algorithm on background subtracted towers

Background level
1) Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

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Background level
Background subtraction

1) Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

2) Run anti $k_T$ algorithm on background subtracted towers

3) Exclude reconstructed jets
Background subtraction

1) Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

2) Run anti $k_T$ algorithm on background subtracted towers

3) Exclude reconstructed jets. Recalculate the background energy

Background level
Background subtraction

1) Background energy per tower calculated in strips of $\eta$. pedestal subtraction

2) Run anti $k_T$ algorithm on background subtracted towers

3) Exclude reconstructed jets. Recalculate the background energy

4) Run anti $k_T$ algorithm on background subtracted towers to get final jets
Jet analysis workflow

- Raw jet energy
- Background subtraction: Remove underlying events contribution
- Jet energy correction: MC Simulation PYTHIA
- Jet energy
Gluon splitting matters!

b jets

D mesons, non-prompt J/ψ

- A non-negligible fraction of b-jets at the LHC come from gluon splitting
- Even more important for charm than for bottom at LHC energy!

Plots from Matthew Nguyen
PbPb b-jet spectra

- Spectra obtained by correcting b-jets yields for efficiency and resolution unfolding.
- Clear suppression of b-jets observed for central events
• $R_{pA}$ is consistent with unity within the systematic uncertainty
• No suppression observed in pPb collisions at 5.02 TeV!

→ **Suppression in PbPb collisions due to interaction with the QGP**
b-jet to inclusive jet ratio

\[ \text{b-jet fraction} = \frac{\text{# of tagged jets} \times \text{purity}}{\text{efficiency}} \]

- b-jet fraction consistent within pp and PbPb within uncertainty
- Both measurements consistent with MC predictions
Tracking in heavy-ion collisions

“Standard” HI Tracking (2011)

- Efficiency
- Fake track rate

- Pythia
- Pythia + Hydjet, centrality: 30-100%
- Pythia + Hydjet, centrality: 0-30%

CMS-PAS-HIN-12-013
b-jet efficiency vs misidentification

- b-jet tagging working point: reject 99% of the light jet rejection and 90% of the charm jet
• Alternative tagger used as a cross-check on SSV
• Each track assigned a probability to be from primary vertex
• Determined separately for Data and MC using negative IP tracks
• JP= probability that all tracks originate from primary vertex

\[
P_N = \prod \cdot \sum_{j=0}^{N-1} \frac{-\log \Pi}{j!}
\]

with

\[
\Pi = \prod_{i=1}^{N} P(S^i)
\]
Excellent pixel spacial resolution
• \( \approx 100 \, \mu\text{m} \) at 1 GeV/c, 20 \( \mu\text{m} \) at 20 GeV/c
• well described by MC simulations based on GEANT
b-jet cross section

Double differential cross section ($y$ and $p_T$)

- MC@NLO agreement at the edge of uncertainties
- Pythia overshoots at low $p_T$, agrees well at high $p_T$