Heavy Flavor Production at CMS

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Heavy flavor production

- Provides a testing ground for QCD calculations in a new energy regime
  - NLO contributions dominate at LHC
  - Large uncertainties remain due to factorization and renormalization scales

- b-jet tagging is crucial in many new physics studies, and we must understand these SM backgrounds

- Many heavy flavor production results from CMS
  - J/Ψ and Y production
  - Inclusive b production, including b\bar{b} angular correlations
  - Exclusive B⁺, B⁰, Bₛ production

New!
The CMS detector

- All silicon inner tracker with $p_T$ resolution $\sim 1\%$ and $d_0$ resolution $\sim 20 \, \mu m$ for tracks in analyses presented

- Tracking efficiency $> 99\%$ for central muons

- Redundant muon system triggers and records muons with $p_T > 1-3$ GeV and $|\eta| < 2.4$
Quarkonia production

- First heavy flavor production results from CMS
  - $J/\Psi$ and $\Upsilon$ double differential cross sections vs $p_T$ and $\gamma$
  - Including lifetime fit for $J/\Psi$ fraction from $b$ decays

$J/\Psi$ production: [arXiv:1011.4193](http://arxiv.org/abs/1011.4193) (accepted by EPJC)

$\Upsilon$ production: [arXiv:1012.5545](http://arxiv.org/abs/1012.5545) (submitted to PRD)

Complete results and more details in backup slides
Inclusive beauty production

- Use semi-leptonic decays to separate $b$ from udscg jets
- Trigger on muon ($p_T > 3$ GeV) and require $p_T > 6$ GeV, $|\eta| < 2.1$ offline
- Jets clustered with anti-$k_T$ ($R=0.5$) from tracks with $p_T > 300$ MeV
- Muon further from jet axis on average for heavier $b$ decays provides discrimination power
- $p_T^{\text{rel}}$ templates from MC (data) for $b$ and c (udsg), with signal validated in $b$-enriched data
- Background templates combined in fit

$\sqrt{s}=7$ TeV
$\mathcal{L}=85$ nb$^{-1}$

$b$ fraction from fit = 46%
Inclusive beauty cross section

- Measure visible cross section: $\mu p_T > 6$ GeV, $|\eta| < 2.1$
  \[
  \sigma(pp\rightarrow b+X\rightarrow\mu+X) = 1.32 \pm 0.01\text{(stat.)} \pm 0.30\text{(syst.)} \pm 0.15\text{(lumi.)} \ \mu b
  \]

  \[
  \sigma_{\text{MC@NLO}} = 0.95^{+0.42}_{-0.21} \ \mu b, \quad \sigma_{\text{PYTHIA}} = 1.9 \ \mu b
  \]

- Systematics limited: signal and background $p_T^{\text{rel}}$ shapes dominate uncertainty

- Measured $\sigma$ higher than MC@NLO, particularly at low $p_T$; lower than PYTHIA

- Pseudorapidity shape in good agreement with models

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JHEP 1103 (2011) 090
Inclusive b from jet tagging

- Use secondary vertex tagging to identify b jets
  - Jets from anti-$k_T$ algorithm using tracks and calorimeter information
  - Displaced vertices selected with $\geq 3$ tracks to identify b events
  - Significantly extends the measurement in $p_T$: Tagging efficiency 50-60% for jet $p_T = 100$ GeV, with 0.1% contamination

- Uncertainties dominated by b-tag efficiency and jet energy scale

- Fewer b jets measured than predicted by MC@NLO at high rapidity

- Ratio of b jets/all jets described well by Pythia

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CMS-PAS-BPH-10-009

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**bb correlations**

- Use secondary vertex finding to study correlations between two B hadrons
  - Require exactly two secondary vertices, with $\geq 3$ tracks, 3D flight length $\geq 5\sigma$
  - Calculate $\Delta R = \sqrt{(\Delta \phi^2 + \Delta \eta^2)}$ from directions from primary vertex to each secondary
- Correct measured momentum to true B hadron momentum with MC
- Report visible spectrum with both B’s in $|\eta| < 2.0$, $p_T > 15$ GeV
- Results shown in different ranges for the leading jet $p_T$

- Flavor creation expected to dominate at high $\Delta R$, gluon splitting contributes more at low $\Delta R$
- Normalize MC in high $\Delta R$ region
- Data shows excess at low $\Delta R$ over Pythia

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*arXiv:1102.3194 (accepted by JHEP)*
Exclusive beauty production

- Reconstruct B hadrons in exclusive final states
  - $B^+ \to J/\Psi K^+$
  - $B^0 \to J/\Psi K_s$
  - $B_s \to J/\Psi \phi$

- Trigger on dimuon events from $J/\Psi \Rightarrow \mu^+\mu^-$

- Small branching fractions ($2-6 \times 10^{-5}$, including product branching fractions)

- High $b\bar{b}$ cross section at the LHC already allows for measurements with early data
Use 2D maximum likelihood fit to $B^0$ mass and lifetime to separate signal events from background.

Backgrounds from prompt $J/\Psi$, peaking and non-peaking $B$ events.

Most fit shapes derived directly from data; peaking background and signal $B$ mass from MC.

Keep candidates with $B^0 p_T > 5$ GeV and $|B^0$ rapidity$| < 2.4$.

Total yield $= 912 \pm 47$.

Efficiency of candidate reconstruction (1.5-33%) determined from data-driven and MC techniques.
Inclusive $B^+$ cross section

- Total $\sigma(pp \rightarrow B^+X) = 28.1 \pm 2.4$ (stat.) $\pm 2.0$ (syst.) $\pm 3.1$ (lumi.) $\mu$b for $p_T > 5$ GeV, $|y| < 2.4$
- Between predictions from MC@NLO ($25.5^{+9.2}_{-5.7}$ $\mu$b) and Pythia (48.1 $\mu$b)
- Use fits in bins of $B^+$ $p_T$ and $y$ to measure $B^+$ differential cross section

$$\frac{d\sigma(pp \rightarrow B^+X)}{dp_T^{B^+}} = \frac{n_{\text{sig}}(p_T^{B^+})}{2e(p_T^{B^+})B L \Delta p_T^{B^+}}$$

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Similar techniques used for $B^0$ and $B_S$
- $K_s$ reconstructed in $\pi^+\pi^-$, and $\phi$ in $K^+K^-$ final state
- New results based on the full 2010 CMS dataset with 39.6 pb$^{-1}$
- Signal yields: 809±39 for $B^0$, 549±32 for $B_S$
- Signal $m_B$ resolution ~20 μm, ct resolution ~45 μm

B$^0$ mass projection
$p_T > 5$ GeV, $|y| < 2.2$

$B_S$ mass projection
$p_T > 8$ GeV, $|y| < 2.4$
B⁰ cross section results

- Total $\sigma(pp \rightarrow B^0X) = 33.2 \pm 2.5$ (stat.) $\pm 3.5$ (syst.) $\mu$b for $p_T > 5$ GeV, $|y| < 2.2$
- Between predictions from MC@NLO ($25.2^{+9.6}_{-6.2}$ $\mu$b) and Pythia (49.1$\mu$b)
- $p_T$ shape in reasonable agreement with the models
- Rapidity shape more flat than Pythia and MC@NLO
**B_s** cross section results

- Total $\sigma(pp \Rightarrow B_s X) \times BF(B_s \Rightarrow J/\Psi \phi) = 6.9 \pm 0.6$ (stat.) $\pm 0.5$ (syst.) $\pm 0.3$ (lumi.) nb, for $p_T > 8$ GeV, $|y| < 2.4$
  - 30% uncertainty on $B_s \Rightarrow J/\Psi \phi$ factored out of measurement
- Between predictions from MC@NLO ($4.6_{-1.7}^{+1.9}$ nb) and Pythia (9.4 nb)
- $p_T$ shapes falls faster than MC@NLO
- Rapidity distribution flatter than either model

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Data: PYTHIA (MSEL 1, CTEQ6L1, Z2 tuning) = 4.75 GeV

MC@NLO (CTEQ6M, m_{MC@NLO scale variation (0.5-2)}

CMS Preliminary $\sqrt{s}=7$ TeV, L=40pb$^{-1}$
Conclusions

- CMS has measured heavy flavor production with a wide variety of techniques
  - Quarkonia production, including fraction of J/Ψ’s from B hadrons
  - Open b production from multiple inclusive and exclusive reconstruction techniques
- Different methods are complementary with different sensitivities and different limiting uncertainties
- Wealth of new data now being used to refine theoretical models and improve MC simulation
- Many more interesting results to come…
References

- J/Ψ production: arXiv:1011.4193 (accepted by EPJC)
- Y production: arXiv:1012.5545 (submitted to PRD)
- Inclusive b from muons: JHEP 1103 (2011) 090
- Inclusive b from jets: CMS-PAS-BPH-10-009
- bb correlations: arXiv:1102.3194 (accepted by JHEP)
J/ψ production

- Reconstruct J/ψ from decays to two muons
- Cross section determined in p_T and y intervals with yields corrected for efficiency and acceptance
- Measure muon efficiency directly in data
  \[ \sigma(6.5<p_T<30 \text{ GeV}, |y|<2.4) \times B(J/\psi \rightarrow \mu\mu) = 97.5 \pm 1.5 \pm 3.4 \pm 10.7 \text{ nb}, \text{ for unpolarized } J/\psi \]
  - Different polarizations shift results as much as 20%
- Prompt J/ψ production at low p_T and high rapidity exceeds predictions from models

\[ B \times d^2\sigma / dp_T dy \text{ (nb/GeV/c)} \]

\[ \sigma \text{ (6.5<p_T<30 GeV, } |y|<2.4) \times B(J/\psi \rightarrow \mu\mu) = 97.5 \pm 1.5 \pm 3.4 \pm 10.7 \text{ nb}, \text{ for unpolarized } J/\psi \]
Fraction of $J/\psi$’s from b decays

- Use 2D proper decay length to separate prompt $J/\psi$ from non-prompt contributions from b decays

$$\sigma(pp \rightarrow bX \rightarrow J/\psi X) \times B(J/\psi \rightarrow \mu\mu) = 26.0 \pm 1.4 \pm 1.6 \pm 2.9 \text{ nb},$$

for unpolarized $J/\psi$, 

$6.5 < p_T < 30 \text{ GeV}, |y| < 2.4$

- Non-prompt contribution in good agreement with models

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Y production

- Y reconstructed in decays to two muons
- 1S, 2S and 3S states all visible
- Mass resolution ~70 MeV for $|\eta| < 1.0$
- Three yields extracted simultaneously with maximum likelihood fits in $p_T$ and $y$ intervals

\[
\sigma(pp \rightarrow Y(1S)X) \cdot B(Y(1S) \rightarrow \mu^+\mu^-) = 7.37 \pm 0.13{\text{(stat.)}}^{+0.61}_{-0.42}{\text{(syst.)}} \pm 0.81{\text{(lumi.)}} \text{ nb},
\]
\[
\sigma(pp \rightarrow Y(2S)X) \cdot B(Y(2S) \rightarrow \mu^+\mu^-) = 1.90 \pm 0.09{\text{(stat.)}}^{+0.20}_{-0.14}{\text{(syst.)}} \pm 0.24{\text{(lumi.)}} \text{ nb},
\]
\[
\sigma(pp \rightarrow Y(3S)X) \cdot B(Y(3S) \rightarrow \mu^+\mu^-) = 1.02 \pm 0.07{\text{(stat.)}}^{+0.11}_{-0.08}{\text{(syst.)}} \pm 0.11{\text{(lumi.)}} \text{ nb}.
\]

- Fraction of 2S and 3S increases with $p_T$
- Results in good agreement with previous Tevatron measurements
The CMS tracker

- Diameter = 2.4m
- Length = 5.4m
- 75 million channels
- 220 m² of silicon
- Design operation -10°C

- Inside 3.8 T field
- Cooler temperature to slow radiation damage
- Coverage up to $|\eta| < 2.4$ with $\geq 3$ pixel hits and $\geq 10$ strip hits
- Efficiency >99% for central muons
Anti-$k_T$ jet reconstruction algorithm

Slide from Francesco Pandolfi’s talk on Thursday

The Anti-$k_T$ Algorithm

- Reference jet algorithm at CMS
- It's a $k_T$ class algorithm (sequential recombination)
  - Infrared/collinear safe
  - One parameter: “cone size” parameter $R$
- But with inverse-momentum weights
  - Clusters soft particles around hard ones
  - Resulting jets are circular
  - Cannot extend beyond $R$
B tagging

- B tagging efficiency measured in MC and verified with semi-leptonic events with $p_T^{rel}$ method
- B tagging fake rate measured in data with secondary vertex mass fit, and found to be in good agreement with MC
Exclusive cross section summary

- **Red** is CMS measurement
  - Inner errors are statistical
  - Outer are statistical + systematic
- **Grey** is MC@NLO prediction

**CMS Preliminary, \(\sqrt{s}=7\) TeV**

- \(pp \rightarrow B^+ X\), \(P_T>5\) GeV, \(|y|<2.4\)
  - Value: \(28.3 \pm 2.4 \pm 2.0 \pm 1.1\) \(\mu b\) (6 pb\(^{-1}\))

- \(pp \rightarrow B^0 X\), \(P_T>5\) GeV, \(|y|<2.2\)
  - Value: \(33.5 \pm 2.5 \pm 3.1 \pm 1.3\) \(\mu b\) (40 pb\(^{-1}\))

- \(pp \rightarrow B_s X \rightarrow J/\psi \phi X\), \(8<p_T<50\) GeV, \(|y|<2.4\) (x1000)
  - Value: \(6.9 \pm 0.6 \pm 0.5 \pm 0.3\) nb (40 pb\(^{-1}\))

**Theory: MC@NLO**

- CTEQ6M PDF, \(\mu=(m_b^2+p_T^2)^{1/2}\), \(m_b=4.75\) GeV

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Additional correlation plots

- Results also shown for azimuthal angle $\Delta \phi$
- Fraction of colinear B’s increases with jet $p_T$

$\sqrt{s} = 7$ TeV, $L = 3.1$ pb$^1$

Ratio to PYTHIA

CMS $\sqrt{s} = 7$ TeV, $L = 3.1$ pb$^1$

$\sigma_{\Delta R < 0.8} / \sigma_{\Delta R > 2.4}$

Leading jet $p_T$ (GeV)
B^0 and B_s lifetime plots

- Lifetime projections for B^0 (left) and B_s (right) from 2D fit to full p_T range