Inclusive and exclusive B production cross-sections at CMS

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on behalf of the CMS collaboration
outline

• the CMS detector:
  ★ general overview (see K. Hoepfners talk yesterday)
  ★ tracker performance

• inclusive B cross-sections:
  ★ inclusive B production with muons  (L=85nb$^{-1}$)
  ★ inclusive B -jet production with secondary vertices (L=60nb$^{-1}$)

• exclusive B cross-sections:
  ★ $B^+ \rightarrow J/\psi (\mu^+ \mu^-) K^+$  (L=5.8pb$^{-1}$)
  ★ $B^0 \rightarrow J/\psi (\mu^+ \mu^-) K_s (\pi^+ \pi^-)$  (L=40pb$^{-1}$)
  ★ $B_s \rightarrow J/\psi (\mu^+ \mu^-) \Phi (K^+ K^-)$  (L=40pb$^{-1}$)
CMS tracker performance

pixel barrel detector radiography from conversions

tracking efficiency from tag+probe method with di-muons from J/ψ

primary vertex efficiency and resolution from split method

data-driven impact parameter resolution

all agrees well with simulation!

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DIS 2011

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b quark production at the LHC

QCD:
- Gluon splitting
- Flavour creation

Electroweak: \(Z \rightarrow b \bar{b}\)

TOP:
- SUSY???
- Higgs???
b quark production at the LHC

test of perturbative QCD:
➔ measurements at LHC beyond theory uncertainties

good understanding of B production is mandatory for searches for new physics
➔ B is background in many searches
➔ dynamics and topology is relevant (see A. Rizzi’s talk on bb correlations)

new physics may also show up in B decays!
➔ examples: CP violation in $B_s \rightarrow J/\psi \Phi$
branching fraction of $B_s \rightarrow \mu^+\mu^-$
Inclusive B production with muons

JHEP 1103:090,2011
B mesons are heavy ($m=5\text{GeV}/c^2$) $\rightarrow$ decay products have large relative momenta

$\muon p_{t,\text{rel}}$

$\rightarrow$ characteristic $p_{t,\text{rel}}$ spectrum for muons from B decays
$\rightarrow$ extract B fraction with template fit
results

inclusive cross-section: \[ \sigma \equiv \sigma(pp \rightarrow b + X \rightarrow \mu + X') = \frac{N_b}{\mathcal{L} \varepsilon} \]

with \( N_b \) = observed events; \( \mathcal{L} \) = int. luminosity; \( \varepsilon \) = reco+trigger eff.

\[
\sigma = 1.32 \pm 0.01\text{(stat)} \pm 0.30\text{(syst)} \pm 0.15\text{(lumi)} \mu b
\]

\[
\sigma_{MC@NLO} = 0.84^{+0.36}_{-0.19}\text{(scale)} \pm 0.08(m_b) \pm 0.04(pdf) \mu b
\]

\[
\sigma_{PYTHIA} = 1.8 \mu b
\]
Inclusive B production using b-tagging with secondary vertices

CMS PAS BPH-10-009
secondary vertex b-tagging:

- define region around jet direction \(dR=0.5\)
- use tracks in this cone as input to vertex search
- separation between primary and secondary vertex is discriminator
b-jet tagging

b-tag efficiency determined from simulation, validation with data-driven methods

CMS simulation \( \sqrt{s} = 7 \text{ TeV} \)

- \( \text{b-tagging efficiency} \)
- \( p_T \) (GeV)
- \( \text{Number of jets / 0.25 GeV} \)
- \( \text{Secondary vertex mass (GeV)} \)

\( \Rightarrow \) uncertainty only 20% (right from the start)

\( \Rightarrow \) purity \( f_b = 75\% \)

b-tagged sample purity obtained from vertex mass fit

CMS preliminary, 60 nb\(^{-1} \) \( \sqrt{s} = 7 \text{ TeV} \)

- Data
- \( b \) template
- \( c \) template
- light template

\( 37 \leq p_T < 56 \text{ GeV} \)
\( \chi^2 / \text{NDF} = 18.9 / 17 \)
results

differential cross-section:

\[
\frac{d^2\sigma_{b-jets}}{dp_T dy} = \frac{N_{tagged f_b C_{smear}}}{\epsilon_{jet} \epsilon_b \Delta p_T \Delta y \mathcal{L}}
\]

measured events  
jet reco. eff.  
b-tag eff.  
fitted purity  
unfolding correction  
luminosity

ratio to inclusive jets:

CMS preliminary, 60 nb\(^{-1}\)  \(\sqrt{s} = 7\) TeV

\[
\text{b-jet } \frac{d^2\sigma}{dp_T dy} \text{ (pb/GeV)}
\]

\[
\text{Anti-}k_T \text{ R=0.5 PF}
\]

\[
\text{b-jet/inclusive jet}
\]

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exclusive decay $B^+ \rightarrow J/\psi (\mu^+ \mu^-) K^+$

PRL 106, 112001 (2011)
event reconstruction

- di-muon trigger (efficiency from tag + probe method)
- two opposite-sign muons within $J/\psi$ mass window 150 MeV
- muon acceptance cuts:

| $|\eta| < 1.3$ | $p_T > 3.3$ GeV |
|--------------|-----------------|
| $1.3 < |\eta| < 2.2$ | $p > 2.9$ GeV |
| $2.2 < |\eta| < 2.4$ | $p_T > 0.8$ GeV |

- $p_T(K^+) > 0.9$ GeV

- kinematic constrained vertex fit with $\mu^+\mu^-$ and $K^+$
  (the $J/\psi$ mass is constrained to the PDG value)

- three track vertex fit probability $> 0.1\%$

**Signal**

prompt $J/\psi$

b background
2D unbinned maximum likelihood fit to inv. mass ($\mu^+\mu^- K^+$) and $c\tau$

- extract number of signal events in $p_t$ and $|\eta|$ bins
- obtain background PDF parameters from sidebands
- validated with toy MC
- lifetime measured:
  $c\tau = 481 \pm 22\mu m$ (stat.)
  $c\tau$(PDG) = 491 $\pm$ 9µm
- fitted signal events: 912 $\pm$ 47

PDF uncertainties and fit bias:
2% - 5% systematic error
**results**

**diff. cross-sections:**

\[
\frac{d\sigma(pp \rightarrow B^+X)}{dp_T^{B^+}} = \frac{n_{\text{sig}}(p_T^{B^+})}{2 \epsilon(p_T^{B^+}) B \mathcal{L} \Delta p_T^{B^+}}
\]

\[
\frac{d\sigma(pp \rightarrow B^+X)}{dy^{B^+}} = \frac{n_{\text{sig}}(|y^{B^+}|)}{2 \epsilon(|y^{B^+}|) B \mathcal{L} \Delta y^{B^+}}
\]

trigger+reco eff.

\(B(B^+ \rightarrow J/\psi K^+)^{\ast}\) \(B(J/\psi \rightarrow \mu^+ \mu^-)\)

**trigger+reco eff.**

**total cross-section**

for \(p_T > 5\text{GeV}\) and \(|y^{B^+}| < 2.4\):

\[\sigma(pp \rightarrow B^+X) = 28.3 \pm 2.4\text{(stat)} \pm 2.0\text{(syst.)} \pm 1.1\text{(lumi.)} \mu\text{b}\]

\[MC@NLO : 25.5^{+9.2}_{-5.7} \mu\text{b}\]
exclusive decay $B^0 \to J/\psi (\mu^+ \mu^-) K_s (\pi^+ \pi^-)$
event reconstruction

- **di-muon trigger** (efficiency from tag + probe method)
- **two opposite-sign muons within J/ψ mass window 150 MeV**
- **muon acceptance cuts:**

  | |eta| < 1.3 | p_T > 3.3 GeV |
  |---|---|---|
  | 1.3 < |eta| < 2.2 | p > 2.9 GeV |
  | 2.2 < |eta| < 2.4 | p_T > 0.8 GeV |

- **additional difficulty:**
  - K_s reconstruction: find vtx. + resonance using all displaced opposite-sign tracks

- **kinematic fit with**
  - \(\mu^+\mu^-\) and K_s candidates
  (the J/ψ mass and K_s mass are constrained to the PDG values)

- **fit probability > 1%**
2D unbinned maximum likelihood fit to inv. mass ($\mu^+\mu^- K_s$) and cT

- extract number of signal events in $p_t$ and $|\eta|$ bins

- PDF functions:
  - **mass**: two gaussians for signal polynomial for non-peaking background
  - **lifetime**: exponential decay convolved with resolution function (two gaussians) for signal
    double exponential for B background, pure resolution for prompt backgr.

- background PDF parameters obtained from sidebands (except for peaking background)

- fitted signal events: 809 ± 39

- lifetime measured:
  - $cT = 479\pm 22\mu$m (stat.)
  - $cT$(PDG) = 453 ±3µm
diff. cross-section:

\[
\frac{d\sigma(pp \rightarrow B^0 X)}{dp_T^B} = \frac{n_{\text{sig}}}{2 \cdot \epsilon \cdot B \cdot L \cdot \Delta p_T^B}
\]

fitted yields

trigger+reco eff.

B(B^0 \rightarrow J/\psi K_s)

*B(J/\psi \rightarrow \mu^+ \mu^-)

total cross-section

for p_t>5GeV and |y_B|<2.2:

\[
\sigma(pp \rightarrow B^0 + X) = 33.2 \pm 2.5 \text{(stat)} \pm 3.1 \text{(syst.)} \pm 1.3 \text{(lumi.)} \mu b
\]

MC@NLO = \[25.5^{+9.6}_{-6.2}\] \mu b
exclusive decay $B_s \rightarrow J/\psi(\mu^+\mu^-) \ \Phi(K^+ K^-)$
oscillation between particle and anti-particle states:

interference between both decays involves CP violating weak phase $\Phi_s$ which is predicted to be small in the SM

new physics (e.g. SUSY) can significantly enhance $\Phi_s$!

roadmap:

$\sim 100\text{pb}^{-1}$: CP even (odd) components (angular analysis)

$\sim 1\text{fb}^{-1}$: CP violation: time dependent angular analysis with flavor tagging
event reconstruction

- di-muon trigger (efficiency from tag + probe method)
- two opposite-sign muons within \( J/\psi \) mass window 150 MeV
- muon acceptance cuts:

| \(|\eta|\) | \( p_T \) |
|----------|-------|
| < 1.3    | > 3.3 GeV |
| 1.3 < \(|\eta|\) < 2.2 | > 2.9 GeV |
| > 2.2    | > 0.8 GeV |

- \( p_T(K^+, K^-) > 0.7 \) GeV
- kinematic constrained vertex fit with \( \mu^+ \mu^- \) and \( K^+ K^- \)
  (the \( \mu^+ \mu^- \) mass is constrained to the PDG value)
- fit probability > 0.1%

CMS Preliminary
\( \sqrt{s} = 7 \) TeV, \( L = 40 \text{pb}^{-1} \)
\( \text{ct} > 0.01 \text{ cm} \)

same as in B+ analysis
fit procedure

2D unbinned maximum likelihood fit to inv. mass ($\mu^+\mu^- K^+ K^-$) and $c\tau$

- Extract number of signal events in $p_t$ and $|\eta|$ bins

- PDF functions:
  - **mass**: two gaussians for signal, polynomial for background
  - **lifetime**: exponential decay convolved with resolution function (two gaussians) for signal
    double exponential for B background, pure resolution for prompt backgr.

- Background PDF parameters obtained from sidebands

- Fitted signal events: $549 \pm 32$

- Lifetime measured:
  $c\tau = 478 \pm 26 \mu$m (stat.)
  $c\tau$(PDG) = 441 $\mu$m
results

**diff. cross-section:**

\[
\frac{d\sigma(pp \rightarrow B_s^0 \rightarrow J/\psi \phi)}{dx} = \frac{n_{\text{sig}}}{2 \cdot \epsilon \cdot B \cdot L \cdot \Delta x}
\]

fitted yields

trigger+reco eff.

\[B(\Phi \rightarrow K^+ K^-)\]
\[\ast B(J/\psi \rightarrow \mu^+ \mu^-)\]

**total cross-section**

for \(8 < p_T < 50 \text{ GeV} \) and \(|y_B| < 2.4\):

\[\sigma(pp \rightarrow B_s \rightarrow J/\psi \Phi) = 6.9 \pm 0.6(\text{stat}) \pm 0.5(\text{syst.}) \pm 0.3(\text{lumi.}) \text{ nb}\]

MC@NLO = \[4.57^{+1.93}_{-1.71} \pm 1.37\text{nb}\]
conclusions

• CMS did precision measurements of b-production cross-sections right from the start

• demonstrates excellent detector performance and MC simulation

• in agreement with MC@NLO within uncertainties:
  • all results more precise than theory predictions: NLO errors dominated by scale uncertainties
  • MC@NLO tends to underestimate at low-\(p_t\) and overestimate at high-\(p_t\) and high-|\(y|\)
  • PYTHIA overestimates B x-section (both D6T and Z2 tunes)

• more results to come soon: \(\Lambda_B\), \(B_c\), ....

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ratio to theory

Inclusive B production with muons:
ratio to MC@NLO
Inclusive B production using b-tagging with secondary vertices:

ratio to MC@NLO