"Measurement of the B0 production cross section in pp Collisions at sqrt(s) = 7 TeV"

CMS Collaboration ; Quertenmont, Loic ; Chatrchyan, Serguei ; Basegmez, Suzan ; Bruno, Giacomo ; Caudron, Julien ; Ceard, Ludivine ; Cortina Gil, Eduardo ; de Favereau de Jeneret, Jérôme ; Delaere, Christophe ; Favart, Denis ; Forthomme, Laurent ; Giammanco, Andrea ; Grégoire, Ghislain ; Hollar, Jonathan ; Lemaitre, Vincent ; Liao, Junhui ; Militaru, Otilia ; Nuttens, Claude ; Ovyn, Séverine ; Pagano, Davide ; Pin, Arnaud ; Piotrzkowski, Krzysztof ; Schul, Nicolas

ABSTRACT

Measurements of the differential production cross sections in transverse momentum and rapidity for B0 mesons produced in pp collisions at sqrt(s) = 7 TeV are presented. The dataset used was collected by the CMS experiment at the LHC and corresponds to an integrated luminosity of 40 inverse picobarns. The production cross section is measured from B0 meson decays reconstructed in the exclusive final state J/Psi K-short, with the subsequent decays J/Psi to mu^+ mu^- and K-short to pi^+ pi^- . The total cross section for pt(B0) > 5 GeV and y(B0) < 2.2 is measured to be 33.2 +/- 2.5 +/- 3.5 microbarns, where the first uncertainty is statistical and the second is systematic.

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Measurement of the $B^0$ Production Cross Section in $pp$ Collisions at $\sqrt{s} = 7$ TeV

S. Chatrchyan et al.\textsuperscript{a}\textsuperscript{*}
(CMS Collaboration)

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Measurements of the differential production cross sections $d\sigma/dp_T^B$ and $d\sigma/dy^B$ for $B^0$ mesons produced in $pp$ collisions at $\sqrt{s} = 7$ TeV are presented. The data set was collected by the CMS experiment at the LHC and corresponds to an integrated luminosity of 40 pb\textsuperscript{-1}. The production cross section is measured from $B^0$ meson decays reconstructed in the exclusive final state $J/\psi K_S^0$, with the subsequent decays $J/\psi \to \mu^+\mu^-$ and $K_S^0 \to \pi^+\pi^-$. The total cross section for $p_T^B > 5$ GeV and $|y^B| < 2.2$ is measured to be $33.2 \pm 2.5 \pm 3.5 \mu$b, where the first uncertainty is statistical and the second is systematic.

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Cross sections for heavy quark production in hard scattering interactions have been studied at $p\bar{p}$ colliders at center-of-mass energies from 630 GeV [1] to 1.96 TeV [2–4] and in $p$-nucleus collisions with beam energies from 800 to 920 GeV [5]. The expected cross sections can be calculated in perturbative quantum chromodynamics. The comparison between data and predictions provides a critical test of next-to-leading order (NLO) calculations [6]. Considerable progress has been achieved in understanding heavy quark production at Tevatron energies, largely resolving earlier discrepancies [7], but substantial theoretical uncertainties remain due to the dependence on the renormalization and factorization scales. Measurements of $b$-hadron production at 7 TeV provided by the Large Hadron Collider (LHC) [8–10] represent a test at a new center-of-mass energy of theoretical approaches that aim to describe heavy flavor production [11,12].

This Letter presents the first measurement of the $B^0$ cross section in $pp$ collisions at $\sqrt{s} = 7$ TeV. Events with $B^0$ mesons reconstructed from their decays to the final state $J/\psi K_S^0$, with $J/\psi \to \mu^+\mu^-$ and $K_S^0 \to \pi^+\pi^-$, are used to measure $d\sigma/dp_T^B$, $d\sigma/dy^B$, and the integrated cross section for transverse momentum $p_T^B > 5$ GeV and rapidity $|y^B| < 2.2$, where $y$ is defined as $\frac{1}{2} \ln \frac{E+p_T}{E-p_T}$, $E$ is the particle energy, and $p_T$ is the particle momentum along the counterclockwise beam direction. As the $B^0$ and $\bar{B}^0$ are indistinguishable in this analysis, both mesons are referred to as $B^0$ for the purposes of reconstruction and the final results are divided by two to obtain an average.

The data sample collected by the Compact Muon Solenoid (CMS) detector at the LHC corresponds to an integrated luminosity of $39.6 \pm 1.6$ pb\textsuperscript{-1} and represents the entire 2010 data set. A detailed description of the detector may be found elsewhere [13]. The main detector components used in this analysis are the silicon tracker and the muon systems.

The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln \tan(\frac{\theta}{2})$ and $\theta$ is the polar angle of the track relative to the counterclockwise beam direction. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules and is located in the 3.8 T field of the superconducting solenoid. It provides an impact parameter resolution of $\sim 15 \mu$\text{m}$ and a $p_T$ resolution of about 1.5% for particles with transverse momenta up to 100 GeV. Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers.

Events are selected by a trigger requiring two muons without any explicit requirement on the muon momentum. The muon candidates are fully reconstructed offline, combining information from the silicon tracker and muon detectors, and are required to be within the following kinematic acceptance region: $p_T^\mu > 3.3$ GeV for $|\eta^\mu| < 1.3$; total momentum $p^\mu > 2.9$ GeV for $1.3 < |\eta^\mu| < 2.2$; and $p^\mu_T > 0.8$ GeV for $2.2 < |\eta^\mu| < 2.4$. Opposite-sign muon pairs are fit to a common vertex to form $J/\psi$ candidates, which are required to be within 150 MeV of the world-average $J/\psi$ mass [14].

The $K_S^0$ candidates are formed by fitting oppositely charged tracks reconstructed with the CMS tracking algorithm [15] to a common vertex. Each track is required to have at least 6 hits in the silicon tracker, a normalized $\chi^2 < 5$, and a transverse impact parameter with respect to the luminous region greater than 0.5 times its uncertainty. The reconstructed $K_S^0$ decay vertex must have a normalized $\chi^2 < 7$ and a transverse separation from the luminous region at least 5 times larger than the uncertainty on the separation. The $\pi^+\pi^-$ invariant mass $m_{K_S^0}$ is required to satisfy $478 < m_{K_S^0} < 518$ MeV, and the reconstructed...
mass distribution is found to be in good agreement with the world-average value [14].

The $B^0$ candidates are formed by combining a $J/\psi$ candidate with a $K_S^0$ candidate. A kinematic fit is performed with the two muons and the $K_S^0$ candidate, in which the invariant masses of the $J/\psi$ and $K_S^0$ candidates are constrained to their world-average values [14]. The $B^0$ vertex fit confidence level is required to be greater than 1% and the reconstructed $B^0$ mass $m_B$ must satisfy $4.9 < m_B < 5.7$ GeV. When more than one candidate in a single event passes all the selection criteria, only the candidate with the highest $B^0$ vertex fit confidence level is retained, which results in the correct choice 99% of the time in simulated events containing a true signal candidate. A total of 23 174 $B^0$ candidates pass all selection criteria.

The efficiency of the $B^0$ reconstruction is computed with a combination of techniques using the data and large samples of fully simulated signal events generated by PYTHIA 6.422 [16], decayed by EVTGEN [17], and simulated by GEANT4 [18]. The trigger and muon-reconstruction efficiencies are calculated as the product of the measured single muon efficiencies, a correction (1%–6%), obtained from the silicon tracking efficiency. Since the dimuon efficiencies are calculated as the product of the measured single muon efficiencies, a correction (1%–6%), obtained from the simulation, is applied to take into account efficiency correlations between the two muons. The probabilities for the muons to lie within the kinematic acceptance region and for the $B^0$ and $K_S^0$ candidates to pass the selection requirements are determined from the simulated events. To minimize the effect of the PYTHIA modeling of the $p_T^B$ and $|y^B|$ distributions on the efficiency calculation, the simulated events are reweighted to match the kinematic distributions observed in the data. The efficiencies for hadron-track reconstruction [20], $K_S^0$ reconstruction [21], and for fulfilling the vertex quality requirement are found to be consistent between data and simulation within the available precision (up to 5%).

The proper decay length of each selected $B^0$ candidate is calculated as $ct = (m_B/p_T^B)L_{xy}$, where the transverse decay length $L_{xy}$ is the vector $\vec{s}$ pointing from the primary vertex [15] to the $B^0$ vertex projected onto the $B^0$ transverse momentum vector: $L_{xy} = (\vec{s} \cdot \vec{p}_T^B)/|\vec{p}_T^B|$. Backgrounds are dominated by prompt and nonprompt $J/\psi$ production, with nonprompt contributions from sources peaking and nonpeaking in $m_B$, as shown in Fig. 1. In particular, misreconstructed $b$-hadron decays to final states with a $J/\psi$, such as $B \rightarrow J/\psi K^*(892)$, produce a broadly peaking structure in the region $m_B < 5.2$ GeV. A study of the dimuon invariant mass distribution confirms that the contamination from events containing a misidentified $J/\psi$ is negligible after all selection criteria have been applied.

The signal yields in each $p_T^B$ and $|y^B|$ bin are obtained using an unbinned extended maximum-likelihood fit to $m_B$ and $ct$. The likelihood for event $j$ is obtained by summing the product of yield $n_i$ and probability density $P_i$ for each of the signal and background hypotheses $i$. Four individual components are considered: signal events, prompt $J/\psi$ events, nonprompt $b \rightarrow J/\psi$ events that peak in $m_B$ (peaking), and nonprompt $b \rightarrow J/\psi$ events that do not peak in $m_B$ (nonpeaking). The extended likelihood function is the product of likelihoods for all events:

$$L = \exp\left(-\sum_{i=1}^{4} n_i \prod_{j=1}^{4} \frac{n_i}{\bar{n}_i} P_i(m_B; \bar{\alpha}_i) P_i(ct; \bar{\beta}_i)\right).$$

The probability density functions (PDFs), $P_i$, with shape parameters $\bar{\alpha}_i$ for $m_B$ and $\bar{\beta}_i$ for $ct$, are evaluated...
separately for each of the \(i\) fit components. The yields \(n_i\) are determined by maximizing \(L\) with respect to the yields and a subset of the PDF parameters.

The PDF shapes are described below with the parameters obtained from data when possible. The \(m_B\) PDFs are as follows: the sum of two Gaussian functions for the signal; exponential functions for the prompt and nonpeaking backgrounds; and a sum of three Gaussian functions for the peaking background. The resolution on \(m_B\) for correctly reconstructed signal events from simulation is approximately 20 MeV. The \(ct\) PDFs are as follows: a single exponential function convolved with the resolution function to describe the signal and peaking background components, where the lifetimes are allowed to be different; the sum of two exponential functions convolved with the resolution function for the nonpeaking component; and the pure resolution function for the prompt \(J/\psi\) component. The resolution function, a sum of two Gaussian functions, is common for signal and background and is measured in data to have an average resolution of 71 \(\mu\)m.

The fit proceeds in several steps such that all background shapes are obtained directly from data, except for the peaking component which is taken from simulation, as are the signal \(m_B\) shapes. This technique relies on the assumption that in the region \(5.4 < m_B < 5.7\) GeV (sideband) there are only two contributions: prompt \(J/\psi\) and nonpeaking background. To obtain the effective lifetime distribution of the nonpeaking background, the \(m_B\) and \(ct\) distributions in the \(m_B\) sideband region are fit simultaneously for events in the inclusive \(B^0\) sample defined by \(p_T^B > 5\) GeV and \(|y^B| < 2.2\). In the second step, the signal \(B^0\) lifetime in the inclusive sample is determined by fitting \(ct\) and \(m_B\) simultaneously in the full \(m_B\) range. The result, \(c\tau = 479 \pm 22\) \(\mu\)m (statistical uncertainty only), is in agreement with the world-average value, 457 \(\pm 3\) \(\mu\)m [14]. With the effective lifetimes for signal and nonprompt background fixed, the signal and background yields are fit in each bin of \(p_T^B\) and \(|y^B|\), together with the parameters describing the \(ct\) resolution and the shapes of the prompt and nonpeaking components in \(m_B\).

The accuracy and robustness of the fit strategy were demonstrated by performing a large set of pseudoexperiments, with each one corresponding to the yields observed in data, where signal and background events were generated randomly from the PDFs in each bin. No significant biases were observed on the yields, and the statistical precision of the test was taken as the systematic uncertainty due to potential biases in the fit method. The fit uncertainties were also observed to be estimated properly.

The fitted signal yields in each bin of \(p_T^B\) and \(|y^B|\) are summarized in Table I. Figure 1 shows the fit projections for \(m_B\) and \(ct\) from the inclusive sample with \(p_T^B > 5\) GeV and \(|y^B| < 2.2\). The total number of signal events is 809 \(\pm\) 39, where the uncertainty is statistical only.

The differential cross section is calculated in bins of \(p_T^B\) as

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

and similarly for \(|y^B|\), where \(n_{\text{sig}}\) is the fitted number of signal events in the given bin, \(\epsilon\) is the efficiency for a \(B^0\) meson to pass all the selection criteria, \(L\) is the integrated luminosity, \(\Delta p_T^B\) is the bin size, and \(B\) is the product of branching fractions \(B(B^0 \rightarrow J/\psi K_S^0) = (4.36 \pm 0.16) \times 10^{-4}\), \(B(J/\psi \rightarrow \mu^+\mu^-) = (5.93 \pm 0.06) \times 10^{-2}\), and \(B(K_S^0 \rightarrow \pi^+\pi^-) = 0.6920 \pm 0.0005\) [14]. The additional factor of 2 in the denominator accounts for our choice of quoting the cross section for \(B^0\) production only, while \(n_{\text{sig}}\) includes both \(B^0\) and \(\bar{B}^0\). The efficiencies are calculated separately for each bin, always considering only mesons produced with \(|y^B| < 2.2\) (\(p_T^B > 5\) GeV) for \(p_T^B (|y^B|)\) bins, and take into account bin-to-bin migrations (\(< 1\%\)) due to the resolution on the measured \(p_T^B\) and \(|y^B|\).

### Table I. Signal yield \(n_{\text{sig}}\), efficiency \(\epsilon\), and measured differential cross sections \(d\sigma/dp_T^B\) and \(d\sigma/d|y^B|\), compared to the MC@NLO [22] and PYTHIA [16] predictions. The uncertainties in the measured cross sections are statistical and systematic, respectively, excluding the common luminosity (4\%) and branching fraction (3.8\%) uncertainties. The uncertainties on the signal yields are statistical only, while those on the efficiencies are systematic.

<table>
<thead>
<tr>
<th>(p_T^B) (GeV)</th>
<th>(n_{\text{sig}})</th>
<th>(\epsilon) (%)</th>
<th>(d\sigma/dp_T^B) ((\mu)b/GeV)</th>
<th>MC@NLO</th>
<th>PYTHIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>5–10</td>
<td>240 \pm 23</td>
<td>0.65 \pm 0.05</td>
<td>5.20 \pm 0.50 \pm 0.59</td>
<td>3.66</td>
<td>7.42</td>
</tr>
<tr>
<td>10–13</td>
<td>169 \pm 17</td>
<td>3.32 \pm 0.28</td>
<td>1.196 \pm 0.121 \pm 0.117</td>
<td>1.13</td>
<td>2.14</td>
</tr>
<tr>
<td>13–17</td>
<td>193 \pm 16</td>
<td>6.37 \pm 0.51</td>
<td>0.535 \pm 0.045 \pm 0.051</td>
<td>0.49</td>
<td>0.83</td>
</tr>
<tr>
<td>17–24</td>
<td>138 \pm 13</td>
<td>9.60 \pm 0.76</td>
<td>0.145 \pm 0.014 \pm 0.014</td>
<td>0.15</td>
<td>0.24</td>
</tr>
<tr>
<td>24–40</td>
<td>70 \pm 9</td>
<td>11.40 \pm 1.04</td>
<td>0.027 \pm 0.003 \pm 0.003</td>
<td>0.025</td>
<td>0.035</td>
</tr>
<tr>
<td>(</td>
<td>y^B</td>
<td>)</td>
<td>(n_{\text{sig}})</td>
<td>(\epsilon) (%)</td>
<td>(d\sigma/d</td>
</tr>
<tr>
<td>0.0–0.5</td>
<td>145 \pm 14</td>
<td>1.34 \pm 0.10</td>
<td>7.63 \pm 0.74 \pm 0.76</td>
<td>6.21</td>
<td>12.41</td>
</tr>
<tr>
<td>0.5–1.0</td>
<td>141 \pm 15</td>
<td>1.38 \pm 0.10</td>
<td>7.20 \pm 0.75 \pm 0.71</td>
<td>6.14</td>
<td>12.01</td>
</tr>
<tr>
<td>1.0–1.4</td>
<td>167 \pm 17</td>
<td>1.93 \pm 0.15</td>
<td>7.61 \pm 0.77 \pm 0.83</td>
<td>5.81</td>
<td>11.24</td>
</tr>
<tr>
<td>1.4–1.8</td>
<td>229 \pm 21</td>
<td>2.51 \pm 0.21</td>
<td>8.06 \pm 0.74 \pm 0.89</td>
<td>5.38</td>
<td>10.36</td>
</tr>
<tr>
<td>1.8–2.2</td>
<td>128 \pm 17</td>
<td>1.69 \pm 0.14</td>
<td>6.71 \pm 0.87 \pm 0.80</td>
<td>4.81</td>
<td>9.26</td>
</tr>
</tbody>
</table>
The cross section is affected by systematic uncertainties on the signal yield and efficiencies, which are uncorrelated bin-to-bin and can affect the shapes of the distributions, and by uncertainties on the branching fractions and luminosity, which are common to all bins and only affect the overall normalization. The uncertainty on the signal yield arises from potential fit biases and imperfect knowledge of the PDF parameters (4%–7%), and from effects of final-state radiation and mismeasured track momenta on the signal shape in \( m_B \) (1%). Uncertainties on the efficiencies arise from the trigger (2%–3%), muon identification (1%), muon tracking (1%), \( K_0^0 \) (5%) and \( B^0 \) (3%) candidate selection requirements, acceptance (2%–3%), dimuon correlations (1%–5%) and \( p_T^B \) and \(|y^B|\) mismeasurement (1%). The first five efficiency uncertainties are determined directly from data, while the last three are determined by simulation. The largest uncertainties on the efficiency arise from the \( K_0^0 \) reconstruction, which is dominated by the displaced hadronic track efficiency and is measured by comparing the reconstructed \( K_0^0 \) lifetime with the known value, and the dimuon correlation uncertainty, which is taken as 100% of the correction applied to account for the correlations. The difference between the kinematically reweighted and unreweighted results (3%–5%) is taken as an additional systematic uncertainty. The bin-to-bin systematic uncertainty is computed as the sum in quadrature of the individual uncertainties, and is summarized in Table I. In addition, there are normalization uncertainties of 4% from the luminosity measurement and of 3.8% from the branching fractions [14].

The differential cross sections as functions of \( p_T^B \) and \(|y^B|\) are shown in Fig. 2 and Table I. They are compared to the predictions of \( \text{MC@NLO} \) [22] using a \( b \)-quark mass \( m_b \) of 4.75 GeV, renormalization and factorization scales \( \mu = \sqrt{m_b^2 + p_T^2} \), and the CTEQ6M parton distribution functions [23]. The uncertainty on the predicted cross section is calculated independently by varying the renormalization and factorization scales by factors of two, \( m_b \) by ±0.25 GeV, and by using the CTEQ6.6 parton distribution functions. For reference, the prediction of PYTHIA [16] is also included, using a \( b \)-quark mass of 4.80 GeV, CTEQ6L1 parton distribution functions [23], and the Z2 tune [24] to simulate the underlying event. The measured \( p_T \) spectrum falls slightly faster than predicted by \( \text{MC@NLO} \), while the \( y \) spectrum is measured to be flatter than the PYTHIA prediction and in agreement with the \( \text{MC@NLO} \) prediction within uncertainties. The integrated cross section for \( p_T^B > 5 \text{ GeV} \) and \(|y^B| < 2.2 \) is calculated as the sum over all \( p_T \) bins, without an upper limit for the highest \( p_T \) bin, to be 33.2 ± 2.5 ± 3.5 \( \mu \)b, where the first uncertainty is statistical and the second is systematic. The result is compatible with the prediction from \( \text{MC@NLO} \) (25.2\(_{+9.6}^{-8.2} \) \( \mu \)b) and below the prediction from PYTHIA (49.1 \( \mu \)b).

In summary, the first measurements of the differential cross sections \( d\sigma/dp_T^B \) and \( d\sigma/dy^B \) for \( B^0 \) mesons produced in \( pp \) collisions at \( \sqrt{s} = 7 \text{ TeV} \) have been presented using the decay \( B^0 \rightarrow J/\psi K_0^0 \). The measurements cover a range in \( p_T^B \) from 5 GeV to more than 30 GeV, and the rapidity range \(|y^B| < 2.2 \). The total cross section in this kinematic region lies between the central values of the \( \text{MC@NLO} \) and PYTHIA predictions, with a rapidity distribution that is flatter than PYTHIA. It is also in agreement within uncertainties with the measured \( B^+ \) cross section [9].

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A. Ruiz-Jimeno,
L. Scodellaro,
M. Sobron Sanudo,
I. Vila,
R. Vilar Cortabitarta,
D. Abbaneo,
P. Auffray,
G. Auzeing,
P. Baillon,
A. H. Ball,
D. Barney,
A. J. Bell,
B. Benedetti,
C. Bernet,
W. Bialas,
P. Bloch,
A. Bocci,
S. Bolognesi,
M. Bona,
H. Breuker,
G. Brona,
K. Bunkowski,
T. Camporesi,
G. Cerminara,
J. A. Coarasa Perez,
B. Cure,
D. D’Enterria,
A. De Roeck,
S. Di Guida,
A. Elliott-Peisert,
B. Frisch,
W. Funk,
A. Gaddi,
S. Gennai,
G. Georgiou,
H. Gerwig,
D. Gigi,
K. Gill,
D. Giordano,
F. Glege,
R. Gomez-Reino Garrido,
M. Gouzevitch,
P. Govoni,
S. Gowdy,
L. Guiducci,
M. Hansen,
H. Hartl,
J. Harvey,
H. Hegeman,
B. Hegner,
H. F. Hoffmann,
A. Homma,
V. Innocente,
J. Janot,
K. Kadadze,
E. Karavakis,
P. Lecoq,
C. Lourenço,
T. Maki,
L. Malgeri,
M. Manelli,
L. Masetti,
A. Maurisset,
P. Nef,
F. Nessi-Tedaldi,
L. Pape,
F. Pauss,
T. Punz,
P. Faccioli,
P. G. Ferreira Parracho,
P. Gallinaro,
P. Musella,
P. Nayak,
P. P. Ribeiro,
J. Segoni,
S. Sharma,
F. Sphicas,
P. Stoye,
P. Tropea,
K. Gabathuler,
R. Horisberger,
H. C. Kaestli,
S. König,
D. Kotlinski,
U. Langenegger,
F. Meier,
D. Renker,
T. Rohe,
J. Sibille,
A. Starodumov,
P. Bortignon,
L. Caminada,
N. Chanon,
Z. Chen,
S. Cittolin,
G. Dissertori,
M. Dittmar,
J. Eugster,
K. Freudenreich,
C. Grab,
A. Herve,
W. Hintsch,
P. Leconte,
W. Lustermann,
C. Marchics,
P. Martinez Ruiz del Arbol,
P. Meridiani,
P. Moortgat,
C. Nägeli,
P. Nef,
F. Nessi-Tedaldi,
L. Pape,
F. Pauss,
T. Punz,
A. Riggi,
P. Ronga,
M. Rossini,
L. Sala,
A. K. Sanchez,
M. C. Sawley,
B. Steiger,
L. Tauscher,
P. Faccioli,
P. G. Ferreira Parracho,
P. Gallinaro,
P. Musella,
P. Nef,
P. P. Ribeiro,
J. Segoni,
S. Sharma,
F. Sphicas,
P. Stoye,
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R. Yohay,157 S. Gollapinni,158 R. Harr,158 P. E. Karchin,158 P. Lamichhane,158 M. Mattson,158 C. Milstêne,158
A. Sakharov,158 M. Anderson,159 M. Bachtis,159 J. N. Bellinger,159 D. Carlsmith,159 S. Dasu,159 J. Efron,159
K. Flood,159 L. Gray,159 K. S. Grogg,159 M. Grothe,159 R. Hall-Wilton,159 M. Herndon,159 P. Klabbers,159
J. Klukas,159 A. Lanaro,159 C. Lazaridis,159 J. Leonard,159 R. Loveless,159 A. Mohapatra,159 F. Palmonari,159
D. Reeder,159 I. Ross,159 A. Savin,159 W. H. Smith,159 J. Swanson,159 and M. Weinberg159

(CMS Collaboration)

1Yerevan Physics Institute, Yerevan, Armenia
2Institut für Hochenergiephysik der OeAW, Wien, Austria
3National Centre for Particle and High Energy Physics, Minsk, Belarus
4Universiteit Antwerpen, Antwerpen, Belgium
5Vrije Universiteit Brussel, Brussel, Belgium
6Université Libre de Bruxelles, Bruxelles, Belgium
7Ghent University, Ghent, Belgium
8Université Catholique de Louvain, Louvain-la-Neuve, Belgium
9Université de Mons, Mons, Belgium
10Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
11Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
12Instituto de Física Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil
13Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
14University of Sofia, Sofia, Bulgaria
15Institute of High Energy Physics, Beijing, China
16State Key Laboratory of Nuclear Physics and Technology., Peking University, Beijing, China
17Universidad de Los Andes, Bogota, Colombia
18Technical University of Split, Split, Croatia
19University of Split, Split, Croatia
20Institut Rudjer Boskovic, Zagreb, Croatia
21University of Cyprus, Nicosia, Cyprus
22Charles University, Prague, Czech Republic
23Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian National Center of High Energy Physics, Cairo, Egypt
24National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
25Department of Physics, University of Helsinki, Helsinki, Finland
26Helsinki Institute of Physics, Helsinki, Finland
27Lappeenranta University of Technology, Lappeenranta, Finland
28Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
29DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

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Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France
Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
Deutsches Elektronen-Synchrotron, Hamburg, Germany
Institut für Experimentelle Kernphysik, Karlsruhe, Germany
Institute of Nuclear Physics "Demokritos," Aghia Paraskevi, Greece
University of Athens, Athens, Greece
University of Ioánnina, Ioánnina, Greece
KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
Institute of Nuclear Research ATOMKI, Debrecen, Hungary
University of Debrecen, Debrecen, Hungary
Panjab University, Chandigarh, India
University of Delhi, Delhi, India
Bhabha Atomic Research Centre, Mumbai, India
Tata Institute of Fundamental Research–EHEP, Mumbai, India
Tata Institute of Fundamental Research–HECR, Mumbai, India
Institute for Research and Fundamental Sciences (IPM), Tehran, Iran
INFN Sezione di Bari, Bari, Italy
Università di Bari, Bari, Italy
Politecnico di Bari, Bari, Italy
INFN Sezione di Bologna, Bologna, Italy
Università di Bologna, Bologna, Italy
INFN Sezione di Catania, Catania, Italy
Università di Catania, Catania, Italy
INFN Sezione di Firenze, Firenze, Italy
Università di Firenze, Firenze, Italy
INFN Laboratori Nazionali di Frascati, Frascati, Italy
INFN Sezione di Genova, Genova, Italy
INFN Sezione di Milano-Bicocca, Milano, Italy
Università di Milano-Bicocca, Milano, Italy
INFN Sezione di Napoli, Napoli, Italy
Università di Napoli “Federico II,” Napoli, Italy
INFN Sezione di Padova, Padova, Italy
Università di Padova, Padova, Italy
Università di Trento (Trento), Padova, Italy
INFN Sezione di Pavia, Pavia, Italy
Università di Pavia, Pavia, Italy
INFN Sezione di Perugia, Perugia, Italy
Università di Perugia, Perugia, Italy
INFN Sezione di Pisa, Pisa, Italy
Università di Pisa, Pisa, Italy
Scuola Normale Superiore di Pisa, Pisa, Italy
INFN Sezione di Roma, Roma, Italy
Università di Roma “La Sapienza,” Roma, Italy
INFN Sezione di Torino, Torino, Italy
Università di Torino, Torino, Italy
Università del Piemonte Orientale (Novara), Torino, Italy
INFN Sezione di Trieste, Trieste, Italy
Università di Trieste, Trieste, Italy
Kangwon National University, Chunchon, Korea
Kyungpook National University, Daegu, Korea
Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
Korea University, Seoul, Korea
University of Seoul, Seoul, Korea
aDeceased.
bAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
cAlso at Universidade Federal do ABC, Santo Andre, Brazil.
dAlso at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
eAlso at Suez Canal University, Suez, Egypt.
fAlso at British University, Cairo, Egypt.
gAlso at Fayoum University, El-Fayoum, Egypt.
hAlso at Sultan Institute for Nuclear Studies, Warsaw, Poland.
iAlso at Massachusetts Institute of Technology, Cambridge, MA, USA.
jAlso at Université de Haute-Alsace, Mulhouse, France.
kAlso at Brandenburg University of Technology, Cottbus, Germany.
lAlso at Moscow State University, Moscow, Russia.
mAlso at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
nAlso at Eötvös Loránd University, Budapest, Hungary.
oAlso at Tata Institute of Fundamental Research - HECR, Mumbai, India.
pAlso at University of Visva-Bharati, Santiniketan, India.
qAlso at Sharif University of Technology, Tehran, Iran.
rAlso at Shiraz University, Shiraz, Iran.
sAlso at Isfahan University of Technology, Isfahan, Iran.
tAlso at Facoltà Ingegneria Università di Roma “La Sapienza,” Roma, Italy.
uAlso at Università della Basilicata, Potenza, Italy.
vAlso at Università degli studi di Siena, Siena, Italy.
wAlso at California Institute of Technology, Pasadena, CA, USA.
xAlso at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
yAlso at University of California, Los Angeles, Los Angeles, CA, USA.
zAlso at University of Florida, Gainesville, FL, USA.
aaAlso at Université de Genève, Geneva, Switzerland.
bbAlso at Scuola Normale e Sezione dell’ INFN, Pisa, Italy.
ccAlso at INFN Sezione di Roma, Università di Roma “La Sapienza”, Roma, Italy.
ndAlso at University of Athens, Athens, Greece.
eAlso at The University of Kansas, Lawrence, KS, USA.
Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
Also at Paul Scherrer Institut, Villigen, Switzerland.
Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
Also at Gaziosmanpasa University, Tokat, Turkey.
Also at Adiyaman University, Adiyaman, Turkey.
Also at Mersin University, Mersin, Turkey.
Also at Izmir Institute of Technology, Izmir, Turkey.
Also at Kafkas University, Kars, Turkey.
Also at Suleyman Demirel University, Isparta, Turkey.
Also at Ege University, Izmir, Turkey.
Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.
Also at Utah Valley University, Orem, UT, USA.
Also at Institute for Nuclear Research, Moscow, Russia.
Also at Erzincan University, Erzincan, Turkey.