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

The CMS Collaboration*

Abstract

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 $\sqrt{s} = 7\,\text{TeV}$ are presented. The dataset used was collected by the CMS experiment at the LHC and corresponds to an integrated luminosity of $40\,\text{pb}^{-1}$. 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 $p_T^B > 5\,\text{GeV}$ and $|y^B| < 2.2$ is measured to be $33.2 \pm 2.5 \pm 3.5\ \mu\text{b}$, where the first uncertainty is statistical and the second is systematic.

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*See Appendix 1 for the list of collaboration members

Cross sections for heavy quark production in hard scattering interactions have been studied at $p\overline{p}$ colliders at center-of-mass energies from 630 GeV [1] to 1.96 TeV [2–4] and in p−nucleus collisons 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 $\sqrt{s} = 7\,\mathrm{TeV}$. Events with B^0 mesons reconstructed from their decays to the final state $J/\psi\, K^0_S$, with $J/\psi \to \mu^+\mu^-$ and $K^0_S \to \pi^+\pi^-$, are used to measure $d\sigma/dp_T^B$, $d\sigma/dy^B$, and the integrated cross section for transverse momentum $p_T^B > 5\,\mathrm{GeV}$ and rapidity $|y^B| < 2.2$, where y is defined as $\frac{1}{2}\ln\frac{E+p_L}{E-p_L}$, E is the particle energy, and p_L is the particle momentum along the counterclockwise beam direction. As the B^0 and $\overline{B}^0$ 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 $39.6 \pm 1.6\,\mathrm{pb}^{-1}$ and represents the entire 2010 dataset. 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 $\eta = -\ln\tan\left(\frac{\theta}{2}\right)$ and θ 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 $\sim 15\,\mu$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: $p_T^\mu > 3.3\,\mathrm{GeV}$ for $|\eta^\mu| < 1.3$; total momentum $p^\mu > 2.9\,\mathrm{GeV}$ for $1.3 < |\eta^\mu| < 2.2$; and $p_T^\mu > 0.8\,\mathrm{GeV}$ for $2.2 < |\eta^\mu| < 2.4$. Opposite-sign muon pairs are fit to a common vertex to form J/ψ candidates, which are required to be within 150 MeV of the world-average J/ψ mass [14].

The K^0_S 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^0_S 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 $m_{K^0_S}$ is required to satisfy $478 < m_{K^0_S} < 518\,\mathrm{MeV}$, 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/ψ candidate with a K^0_S candidate. A kinematic fit is performed with the two muons and the K^0_S candidate, in which the invariant masses of the J/ψ and K^0_S 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 $4.9 < m_B < 5.7\,\text{GeV}$. 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 obtained from a large sample of inclusive $J/\psi \to \mu^+\mu^-$ decays in data using a technique similar to that described in Ref. [19], where one muon is identified with stringent quality requirements, and the second muon is identified using information either exclusively from the tracker (to measure the trigger and muon-identification efficiencies), or from the muon system (to measure 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^0_S 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^0_S 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 total efficiency of this selection, defined as the fraction of $B^0 \to J/\psi\, K^0_S$ decays produced with $p_T^B > 5\,\text{GeV}$ and $|y^B| < 2.2$ that pass all criteria, is 1.7%. The efficiency ranges from 0.7% for $p_T^B \sim 5\,\text{GeV}$, to 11.4% for $p_T^B > 24\,\text{GeV}$, with roughly equal losses due to the dimuon kinematic acceptance, the dimuon trigger, and the K^0_S reconstruction.

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 non-prompt J/ψ production, with non-prompt 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/ψ, such as $B \to J/\psi K^*(892)$, produce a broadly peaking structure in the region $m_B < 5.2\,\text{GeV}$. A study of the dimuon invariant mass distribution confirms that the contamination from events containing a misidentified J/ψ 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 $\mathcal{P}_i$ for each of the signal and background hypotheses i. Four individual components are considered: signal events, prompt J/ψ events, non-prompt $b \to J/\psi$ events that peak in m_B (peaking), and non-prompt $b \to J/\psi$ events that do not peak in m_B (nonpeaking). The extended likelihood function is the product of likelihoods for all events:

$$\mathcal{L} = \exp\left(-\sum_{i=1}^{4} n_i\right)\prod_j\left[\sum_{i=1}^{4} n_i\mathcal{P}_i(m_B;\,\vec{\alpha}_i)\mathcal{P}_i(ct;\,\vec{\beta}_i)\right]. \quad (1)$$

The probability density functions (PDFs), $\mathcal{P}_i$, with shape parameters $\vec{\alpha}_i$ for m_{B} and $\vec{\beta}_i$ for ct, are evaluated separately for each of the i fit components. The yields n_i are determined by maximizing $\mathcal{L}$ 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/ψ 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 μm.

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 $5.4 < m_{\mathrm{B}} < 5.7\,\mathrm{GeV}$ (sideband) there are only two contributions: prompt J/ψ 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 $p_{\mathrm{T}}^{\mathrm{B}} > 5\,\mathrm{GeV}$ and $|y^{\mathrm{B}}| < 2.2$. 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, $c\tau = 479 \pm 22\,\mu\mathrm{m}$ (statistical uncertainty only), is in agreement with the world-average value, $457 \pm 3\,\mu\mathrm{m}$ [14]. With the effective lifetimes for signal and non-prompt background fixed, the signal and background yields are fit in each bin of $p_{\mathrm{T}}^{\mathrm{B}}$ and $|y^{\mathrm{B}}|$, 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 pseudo-experiments, 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 $p_{\mathrm{T}}^{\mathrm{B}}$ and $|y^{\mathrm{B}}|$ are summarized in Table 1. Figure 1 shows the fit projections for m_{B} and ct from the inclusive sample with $p_{\mathrm{T}}^{\mathrm{B}} > 5\,\mathrm{GeV}$ and $|y^{\mathrm{B}}| < 2.2$. The total number of signal events is 809 ± 39, where the uncertainty is statistical only.

The differential cross section is calculated in bins of $p_{\mathrm{T}}^{\mathrm{B}}$ as

$$\frac{d\sigma(\mathrm{pp} \to \mathrm{B}^0 X)}{dp_{\mathrm{T}}^{\mathrm{B}}} = \frac{n_{\mathrm{sig}}}{2 \cdot \epsilon \cdot \mathcal{B} \cdot L \cdot \Delta p_{\mathrm{T}}^{\mathrm{B}}}, \quad (2)$$

and similarly for $|y^{\mathrm{B}}|$, where n_{sig} is the fitted number of signal events in the given bin, ϵ is the efficiency for a B^0 meson to pass all the selection criteria, L is the integrated luminosity, $\Delta p_{\mathrm{T}}^{\mathrm{B}}$ is the bin size, and $\mathcal{B}$ is the product of branching fractions $\mathcal{B}(\mathrm{B}^0 \to \mathrm{J}/\psi\,\mathrm{K}_{\mathrm{S}}^0) = (4.36 \pm 0.16) \times 10^{-4}$, $\mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-) = (5.93 \pm 0.06) \times 10^{-2}$, and $\mathcal{B}(\mathrm{K}_{\mathrm{S}}^0 \to \pi^+\pi^-) = 0.6920 \pm 0.0005$ [14]. The additional factor of two in the denominator accounts for our choice of quoting the cross section for B^0 production only, while n_{sig} includes both B^0 and $\overline{\mathrm{B}}^0$. The efficiencies are calculated separately for each bin, always considering only mesons produced with $|y^{\mathrm{B}}| < 2.2$ ($p_{\mathrm{T}}^{\mathrm{B}} > 5\,\mathrm{GeV}$) for

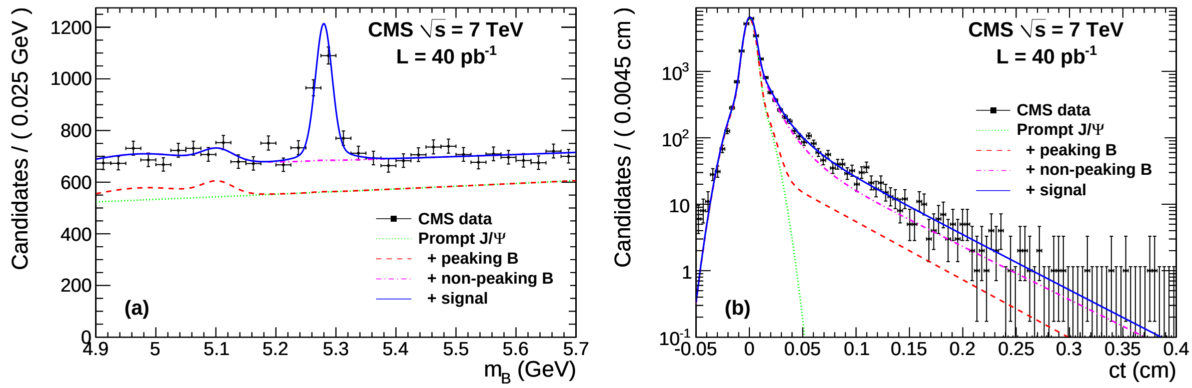

Figure 1: Projections of the fit results in (a) m_{B} and (b) ct for $p_{\mathrm{T}}^{\mathrm{B}} > 5\,\mathrm{GeV}$ and $|y^{\mathrm{B}}| < 2.2$. The curves in each plot are as follows: the sum of all contributions (blue solid line); the prompt J/ψ (green dotted); the sum of the prompt J/ψ and peaking background (red dashed), and the sum of all backgrounds (purple dot-dashed).

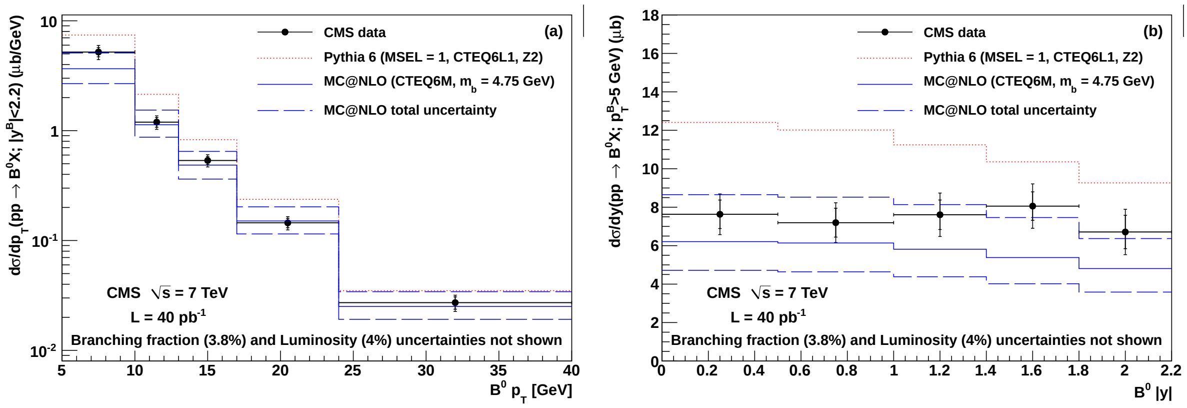

Figure 2: Measured differential cross sections (a) $d\sigma/dp_{\mathrm{T}}^{\mathrm{B}}$ and (b) $d\sigma/dy^{\mathrm{B}}$ compared to the theoretical predictions. The inner error bars correspond to the statistical uncertainties and the outer error bars represents the uncorrelated systematic uncertainties added in quadrature to the statistical uncertainties. Overall uncertainties of 4% for the luminosity and 3.8% for the branching fractions are not shown. The solid and dashed (blue) lines are the MC@NLO prediction and its uncertainty, respectively. The dotted (red) line is the PYTHIA prediction.

$p_{\mathrm{T}}^{\mathrm{B}}$ ($|y^{\mathrm{B}}|$) bins, and take into account bin-to-bin migrations ($< 1\%$) due to the resolution on the measured $p_{\mathrm{T}}^{\mathrm{B}}$ and $|y^{\mathrm{B}}|$.

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%), $\mathrm{K_S^0}$ (5%) and $\mathrm{B^0}$ (3%) candidate selection requirements, acceptance (2–3%), dimuon correlations (1–5%) and $p_{\mathrm{T}}^{\mathrm{B}}$ and $|y^{\mathrm{B}}|$ 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 arrise from the $\mathrm{K_S^0}$ reconstruction, which is dominated by the

Table 1: Signal yield $n_{\rm sig}$, efficiency ϵ, and measured differential cross sections $d\sigma/dp_T^B$ and $d\sigma/dy^B$, 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.

p_T^B (GeV)	$n_{\rm sig}$	ϵ (%)	$d\sigma/dp_T^B$ (μb/GeV)	MC@NLO	PYTHIA
$5-10$	240 ± 23	0.65 ± 0.05	$5.20 \pm 0.50 \pm 0.59$	3.66	7.42
$10-13$	169 ± 17	3.32 ± 0.28	$1.196 \pm 0.121 \pm 0.117$	1.13	2.14
$13-17$	193 ± 16	6.37 ± 0.51	$0.535 \pm 0.045 \pm 0.051$	0.49	0.83
$17-24$	138 ± 13	9.60 ± 0.76	$0.145 \pm 0.014 \pm 0.014$	0.15	0.24
$24-40$	70 ± 9	11.40 ± 1.04	$0.027 \pm 0.003 \pm 0.003$	0.025	0.035
$\|y^B\|$	$n_{\rm sig}$	ϵ (%)	$d\sigma/dy^B$ (μb)	MC@NLO	PYTHIA
$0.0-0.5$	145 ± 14	1.34 ± 0.10	$7.63 \pm 0.74 \pm 0.76$	6.21	12.41
$0.5-1.0$	141 ± 15	1.38 ± 0.10	$7.20 \pm 0.75 \pm 0.71$	6.14	12.01
$1.0-1.4$	167 ± 17	1.93 ± 0.15	$7.61 \pm 0.77 \pm 0.83$	5.81	11.24
$1.4-1.8$	229 ± 21	2.51 ± 0.21	$8.06 \pm 0.74 \pm 0.89$	5.38	10.36
$1.8-2.2$	128 ± 17	1.69 ± 0.14	$6.71 \pm 0.87 \pm 0.80$	4.81	9.26

displaced hadronic track efficiency and is measured by comparing the reconstructed K_S^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 1. 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 1. They are compared to the predictions of 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 by independently 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 MC@NLO, while the y spectrum is measured to be flatter than the PYTHIA prediction and in agreement with the MC@NLO prediction within uncertainties. The integrated cross section for $p_T^B > 5$ 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 $33.2 \pm 2.5 \pm 3.5$ μb, where the first uncertainty is statistical and the second is systematic. The result is compatible with the prediction from MC@NLO ($25.2^{+9.6}_{-6.2}$ μb) and below the prediction from PYTHIA (49.1 μb).

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 $\sqrt{s} = 7$ TeV have been presented using the decay $B^0 \to J/\psi K_S^0$. 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 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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3: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
4: Also at Suez Canal University, Suez, Egypt
5: Also at British University, Cairo, Egypt
6: Also at Fayoum University, El-Fayoum, Egypt
7: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
8: Also at Massachusetts Institute of Technology, Cambridge, USA

9: Also at Université de Haute-Alsace, Mulhouse, France
10: Also at Brandenburg University of Technology, Cottbus, Germany
11: Also at Moscow State University, Moscow, Russia
12: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
13: Also at Eötvös Loránd University, Budapest, Hungary
14: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
15: Also at University of Visva-Bharati, Santiniketan, India
16: Also at Sharif University of Technology, Tehran, Iran
17: Also at Shiraz University, Shiraz, Iran
18: Also at Isfahan University of Technology, Isfahan, Iran
19: Also at Facoltà Ingegneria Università di Roma "La Sapienza", Roma, Italy
20: Also at Università della Basilicata, Potenza, Italy
21: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
22: Also at Università degli studi di Siena, Siena, Italy
23: Also at California Institute of Technology, Pasadena, USA
24: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
25: Also at University of California, Los Angeles, Los Angeles, USA
26: Also at University of Florida, Gainesville, USA
27: Also at Université de Genève, Geneva, Switzerland
28: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
29: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
30: Also at University of Athens, Athens, Greece
31: Also at The University of Kansas, Lawrence, USA
32: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
33: Also at Paul Scherrer Institut, Villigen, Switzerland
34: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
35: Also at Gaziosmanpasa University, Tokat, Turkey
36: Also at Adiyaman University, Adiyaman, Turkey
37: Also at Mersin University, Mersin, Turkey
38: Also at Izmir Institute of Technology, Izmir, Turkey
39: Also at Kafkas University, Kars, Turkey
40: Also at Suleyman Demirel University, Isparta, Turkey
41: Also at Ege University, Izmir, Turkey
42: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
43: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
44: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
45: Also at Utah Valley University, Orem, USA
46: Also at Institute for Nuclear Research, Moscow, Russia
47: Also at Los Alamos National Laboratory, Los Alamos, USA
48: Also at Erzincan University, Erzincan, Turkey