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# Search for $B_s^0 \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$ decays in pp collisions at $\sqrt{s} = 7 \text{ TeV}$

The CMS Collaboration\*

## Abstract

A search for the rare decays  $B_s^0 \rightarrow \mu^+ \mu^-$  and  $B^0 \rightarrow \mu^+ \mu^-$  is performed in pp collisions at  $\sqrt{s} = 7 \text{ TeV}$ , with a data sample corresponding to an integrated luminosity of  $1.14 \text{ fb}^{-1}$ , collected by the CMS experiment at the LHC. In both cases, the number of events observed after all selection requirements is consistent with expectations from background and standard-model signal predictions. The resulting upper limits on the branching fractions are  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 1.9 \times 10^{-8}$  and  $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 4.6 \times 10^{-9}$ , at 95% confidence level.

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\*See Appendix A for the list of collaboration members



In the standard model (SM) of particle physics, flavor-changing neutral current (FCNC) decays are forbidden at tree level and can only proceed through higher-order loop diagrams. The decays  $B_{d(s)} \rightarrow \ell^+ \ell^-$  (where  $\ell = e, \mu$ ), besides involving  $b \rightarrow s(d)$  FCNC transitions through Penguin and box diagrams, are helicity suppressed by factors of  $(m_\ell/m_B)^2$ , where  $m_\ell$  and  $m_B$  are the masses of the lepton and B meson, respectively. They also require an internal quark annihilation within the B meson that further reduces the decay rate by  $(f_B/m_B)^2$ , where  $f_B$  is the decay constant of the B meson.

The SM-predicted branching fractions,  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.2 \pm 0.2) \times 10^{-9}$  and  $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.0 \pm 0.1) \times 10^{-10}$  [1], are significantly enhanced in several extensions of the SM, although in some cases the decay rates are lowered [2]. For example, in the minimal supersymmetric extension of the SM, the rates are strongly enhanced at large values of  $\tan \beta$  [3, 4]. In specific models involving leptoquarks [5] and in supersymmetric models with non-universal Higgs masses [6], the  $B_s^0 \rightarrow \mu^+ \mu^-$  and  $B^0 \rightarrow \mu^+ \mu^-$  branching fractions can be enhanced by different factors and, therefore, both channels must be studied in parallel. Several experiments have published upper limits at 95% confidence level (CL) on these decays:  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 5.1 \times 10^{-8}$  by D0 [7];  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 5.8 \times 10^{-8}$  and  $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 1.8 \times 10^{-8}$  by CDF [8];  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 5.6 \times 10^{-8}$  and  $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 1.5 \times 10^{-8}$  by LHCb [9]. CDF recently reported a new limit of  $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 6.0 \times 10^{-9}$  and an excess of  $B_s^0 \rightarrow \mu^+ \mu^-$  events, corresponding to  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (1.8_{-0.9}^{+1.1}) \times 10^{-8}$  [10].

In this Letter, a simultaneous search for the  $B_s^0 \rightarrow \mu^+ \mu^-$  and  $B^0 \rightarrow \mu^+ \mu^-$  decays is presented, using a data sample of pp collisions at  $\sqrt{s} = 7$  TeV, corresponding to an integrated luminosity of  $(1.14 \pm 0.07) \text{ fb}^{-1}$ , collected in the first half of 2011 by the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC). An event-counting experiment is performed in dimuon mass regions around the  $B_s^0$  and  $B^0$  masses. To avoid any possible bias, the signal region was kept blind until after all selection criteria were established. The backgrounds are evaluated from the yields measured in data mass sidebands and from Monte Carlo (MC) simulations for rare hadronic two-body B decays. The MC event samples are generated with PYTHIA 6.409 [11], the unstable particles are decayed via EVTGEN [12], and the detector response is simulated with GEANT4 [13]. Events of the type  $B^\pm \rightarrow J/\psi K^\pm$ ,  $J/\psi \rightarrow \mu^+ \mu^-$  are used as a normalization sample to minimize uncertainties related to the  $b\bar{b}$  production cross section and to the integrated luminosity. The signal and normalization efficiencies are determined with MC simulation studies. A control sample of reconstructed  $B^0 \rightarrow J/\psi \phi$ ,  $J/\psi \rightarrow \mu^+ \mu^-$  events is used to validate the MC simulation (such as the  $B_s^0$  transverse momentum  $p_T$  spectrum) and to evaluate potential effects resulting from differences in fragmentation between  $B^+$  and  $B_s^0$ . The analysis is not affected by multiple pp collisions in the same bunch crossing (pileup) because the spatial vertex resolution is good enough to correctly identify the pp vertex from which signal candidates originate. In the present data set, an average of 5.5 primary vertices are reconstructed per event.

A detailed description of the CMS experiment can be found in Ref. [14]. The main subdetectors used in this analysis are the silicon tracker, composed of pixel and strip layers immersed in a 3.8 T axial magnetic field, and the muon stations, made of gas-ionization detectors embedded in the steel return yoke, and divided into a barrel section and two endcaps. The muons are tracked within the pseudorapidity region  $|\eta| < 2.4$ , where  $\eta = -\ln[\tan(\theta/2)]$  and  $\theta$  is the polar angle with respect to the counterclockwise beam direction. A muon  $p_T$  resolution of about 1.5% is obtained for muons in this analysis. The events are selected with a two-level trigger system. The first level only requires two muon candidates, without an explicit  $p_T$  requirement, while the high-level trigger (HLT) uses additional information from the silicon tracker. The HLT selection for the signal data sample requires two muons each with  $p_T > 2$  GeV, dimuon

$p_T > 4 \text{ GeV}$ , invariant mass within  $4.8 < m_{\mu\mu} < 6.0 \text{ GeV}$ , and a three-dimensional (3D) distance of closest approach to each other  $d'_{ca} < 5 \text{ mm}$ .

The normalization ( $B^\pm \rightarrow J/\psi K^\pm$ ) and control ( $B^0 \rightarrow J/\psi \phi$ ) samples were collected with HLT requirements gradually tightened as the LHC luminosity increased. This time evolution does not affect the analysis presented here, which uses selection criteria significantly tighter than any trigger requirements. More than 95% of the normalization and control sample events were collected by requiring two muons each with  $p_T > 3 \text{ GeV}$ , dimuon  $p_T > 6.9 \text{ GeV}$ , invariant mass within  $2.9 < m_{\mu\mu} < 3.3 \text{ GeV}$ ,  $d'_{ca} < 5 \text{ mm}$ , and a larger than 0.5% probability of the  $\chi^2$  per degree of freedom (dof) of the dimuon vertex fit. Two additional trigger requirements, measured in the transverse plane, significantly reduce the rate of prompt  $J/\psi$  candidates: the significance of the flight distance  $\ell_{xy}/\sigma(\ell_{xy})$  must be larger than 3, where  $\ell_{xy}$  is the distance between the primary and dimuon vertices and  $\sigma(\ell_{xy})$  is its uncertainty; and the pointing angle  $\alpha_{xy}$  between the B candidate momentum and the vector from the primary vertex to the dimuon vertex must fulfill  $\cos \alpha_{xy} > 0.9$ . The average trigger efficiency for events in the signal and normalization samples is about 80%, as determined from MC simulation. The uncertainty on the ratio of trigger efficiencies between the signal and normalization samples is estimated to be 2% by comparing these ratios in simulation studies and in data.

Muon candidates are required to be reconstructed by two different algorithms, one matching silicon-tracker tracks to segments in the muon stations, and the other performing global fits using tracks in both detector systems [15]. The uncertainty on the ratio of muon identification efficiencies between the signal and normalization samples is estimated to be 5%.

The  $B \rightarrow \mu^+ \mu^-$  candidates require two oppositely charged muons with an invariant mass in the region  $4.9 < m_{\mu\mu} < 5.9 \text{ GeV}$ , after constraining their tracks to come from a common vertex. The B candidate momentum and vertex position are used to choose a primary vertex based on the distance of closest approach. Since the background level depends significantly on the pseudorapidity of the B candidate, the events are separated into two categories: the ‘‘barrel channel’’ contains the candidates where both muons have  $|\eta| < 1.4$  and the ‘‘endcap channel’’ contains those where at least one muon has  $|\eta| > 1.4$ . An isolation variable  $I = p_T(B)/(p_T(B) + \sum_{\text{trk}} p_T)$  is calculated from the transverse momentum of the B candidate  $p_T(B)$  and the transverse momenta of all other charged tracks satisfying  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1$ , where  $\Delta\eta$  and  $\Delta\phi$  are the differences in pseudorapidity and azimuthal angle between a charged track and the B candidate momentum. The sum includes all tracks with  $p_T > 0.9 \text{ GeV}$  that are consistent with originating from the same primary vertex as the B candidate or have a distance of closest approach  $d_{ca} < 0.5 \text{ mm}$  with respect to the B vertex. The minimum distance of closest approach with respect to the B vertex among all tracks in the event,  $d_{ca}^{\text{min}}$ , is also determined as a complementary isolation variable. Figure 1 illustrates the transverse momentum, the 3D pointing angle  $\alpha_{3D}$ , the 3D flight length significance  $\ell_{3D}/\sigma(\ell_{3D})$ , and the isolation distributions for signal MC and for sideband background data events. The sideband covers the range  $4.9 < m_{\mu\mu} < 5.9 \text{ GeV}$ , excluding the signal window  $5.2 < m_{\mu\mu} < 5.45 \text{ GeV}$ .

The following selection requirements were optimized for the best expected upper limit using MC signal events and data sideband events. The requirements were established before observing the number of data events in the signal region. The optimized requirements include  $p_T > 4.5 \text{ GeV}$  on one muon and  $p_T > 4.0 \text{ GeV}$  on the other, B candidate  $p_T > 6.5 \text{ GeV}$ ,  $I > 0.75$ , and B-vertex fit  $\chi^2/\text{dof} < 1.6$ . Two requirements are different for the barrel and endcap channels:  $\alpha_{3D} < 0.050$  (0.025) and  $\ell_{3D}/\sigma(\ell_{3D}) > 15.0$  (20.0) for the barrel (endcap). Furthermore, for events in the endcap there is an additional requirement,  $d_{ca}^{\text{min}} > 0.15 \text{ mm}$ . The signal efficiencies  $\varepsilon_{\text{tot}}$  of these selections are provided in Table 1. The dimuon mass resolution for signal

Table 1: The event selection efficiencies for signal events  $\varepsilon_{\text{tot}}$ , the SM-predicted number of signal events  $N_{\text{signal}}^{\text{exp}}$ , the expected number of combinatorial background events  $N_{\text{comb}}^{\text{exp}}$  and peaking background events  $N_{\text{peak}}^{\text{exp}}$ , and the number of observed events  $N_{\text{obs}}$  in the barrel and endcap channels for  $B_s^0 \rightarrow \mu^+ \mu^-$  and  $B^0 \rightarrow \mu^+ \mu^-$ .

	Barrel		Endcap	
	$B^0 \rightarrow \mu^+ \mu^-$	$B_s^0 \rightarrow \mu^+ \mu^-$	$B^0 \rightarrow \mu^+ \mu^-$	$B_s^0 \rightarrow \mu^+ \mu^-$
$\varepsilon_{\text{tot}}$	$(3.6 \pm 0.4) \times 10^{-3}$	$(3.6 \pm 0.4) \times 10^{-3}$	$(2.1 \pm 0.2) \times 10^{-3}$	$(2.1 \pm 0.2) \times 10^{-3}$
$N_{\text{signal}}^{\text{exp}}$	$0.065 \pm 0.011$	$0.80 \pm 0.16$	$0.025 \pm 0.004$	$0.36 \pm 0.07$
$N_{\text{comb}}^{\text{exp}}$	$0.40 \pm 0.23$	$0.60 \pm 0.35$	$0.53 \pm 0.27$	$0.80 \pm 0.40$
$N_{\text{peak}}^{\text{exp}}$	$0.25 \pm 0.06$	$0.07 \pm 0.02$	$0.16 \pm 0.04$	$0.04 \pm 0.01$
$N_{\text{obs}}$	0	2	1	1

events depends on the pseudorapidity of the B candidate and ranges from 36 MeV for  $\eta \approx 0$ , to 85 MeV for  $|\eta| > 1.8$ , as determined from simulated signal.

The reconstruction of  $B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+ \mu^- K^\pm$  ( $B^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ ) candidates requires two oppositely-charged muons with an invariant mass in the range 3.0–3.2 GeV, which are combined with one (two) track(s), assumed to be (a) kaon(s), fulfilling  $p_T > 0.5$  GeV and  $|\eta| < 2.4$ . To ensure a well-measured trigger efficiency, the selected candidates must have dimuon  $p_T > 7$  GeV and the two muons must bend away from each other in the magnetic field (to avoid spurious detector-induced pair correlations). The  $d'_{\text{ca}}$  between all pairs among the three (four) tracks is required to be less than 1 mm. For  $B^0 \rightarrow J/\psi \phi$  candidates the two assumed kaon tracks must have an invariant mass in the range 0.995–1.045 GeV and  $\Delta R(K^+, K^-) < 0.25$ . The tracks from all decay products are used in the B-vertex fit and only B candidates with an invariant mass in the range 4.8–6.0 GeV are considered. The efficiencies of individual selection criteria agree to better than 4% (6%) between data and MC simulation for the normalization (control) sample. Figure 2 compares several distributions for  $B^0 \rightarrow J/\psi \phi$  candidates between MC simulation and sideband-subtracted data.

The total efficiency for  $B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+ \mu^- K^\pm$ , including the detector acceptance, is  $\varepsilon_{\text{tot}}^{B^\pm} = (7.7 \pm 0.8) \times 10^{-4}$  and  $(2.7 \pm 0.3) \times 10^{-4}$ , respectively for the barrel and endcap channels, where statistical and systematic uncertainties are combined. The acceptance has a systematic uncertainty of 4%, estimated by comparing the values obtained with different  $b\bar{b}$  production mechanisms (gluon splitting, flavor excitation, and flavor creation). The uncertainty on the event selection efficiency for the  $B^\pm \rightarrow J/\psi K^\pm$  normalization sample is 4%, evaluated from differences between measured and simulated  $B^\pm \rightarrow J/\psi K^\pm$  events. The uncertainty on the signal efficiency (7.9%) is evaluated using the  $B^0 \rightarrow J/\psi \phi$  control sample. The invariant mass distributions are fitted with a Gaussian function for the signal and an exponential (barrel) or a first-degree polynomial (endcap) plus an error function for the background, as shown in Fig. 3. Applying the same selection requirements as for the signal sample, the observed number of  $B^\pm \rightarrow J/\psi K^\pm$  candidates in the barrel (endcap) channel is  $N_{\text{obs}}^{B^\pm} = 13\,045 \pm 652$  ( $4450 \pm 222$ ). The uncertainty includes a systematic term caused by fit and background parametrization effects, estimated to be 5% from MC studies.

To quantify a possible dependence on the pileup, the efficiencies of the isolation and the flight length significance requirements are calculated as functions of the number of reconstructed primary vertices. No dependence is observed for events with up to 12 primary vertices for the

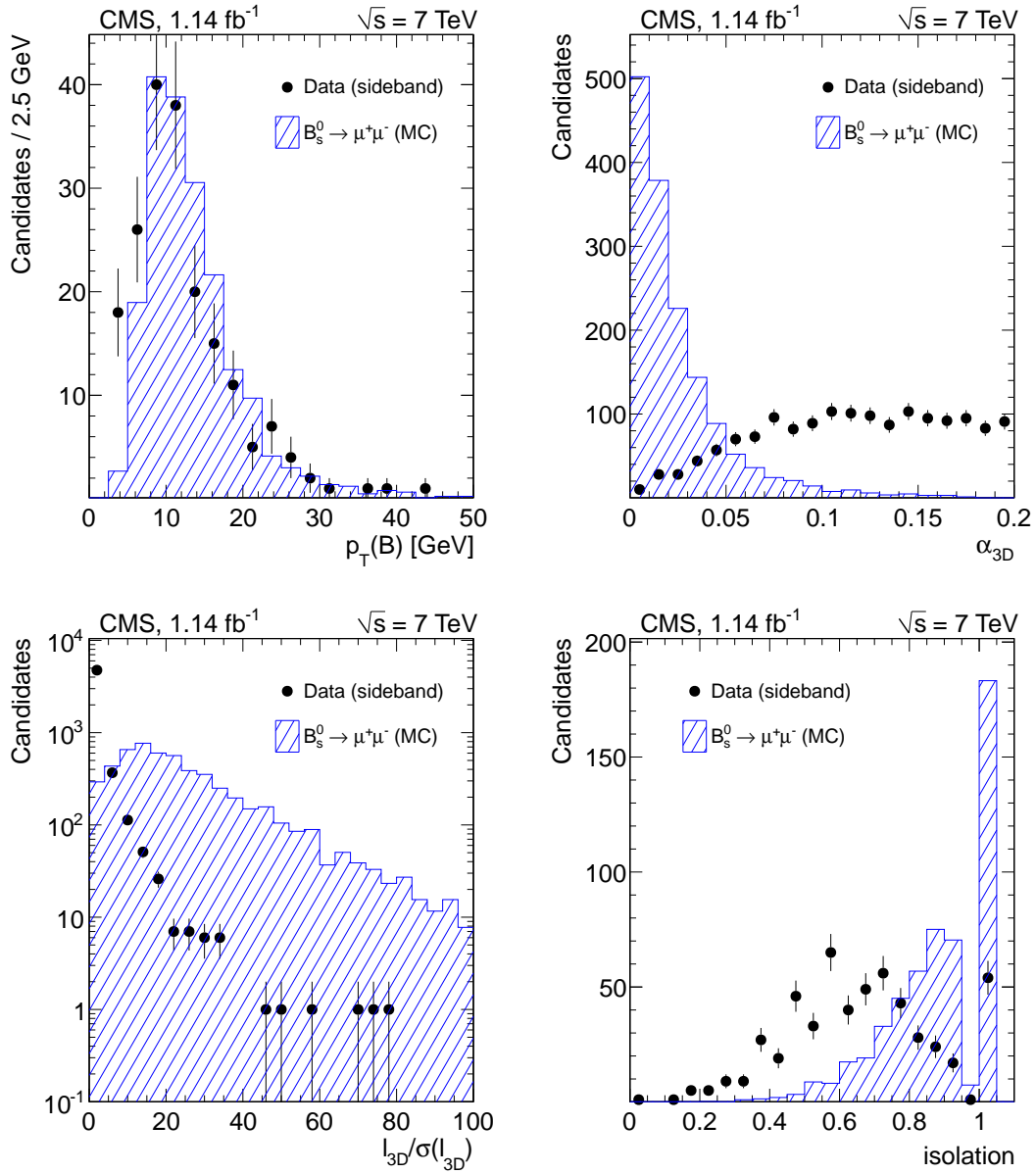


Figure 1: Comparison of MC signal and sideband data distributions, for the transverse momentum (top left), the 3D pointing angle (top right), the flight length significance (bottom left), and the isolation (bottom right). The MC histograms are normalized to the number of events in the data.

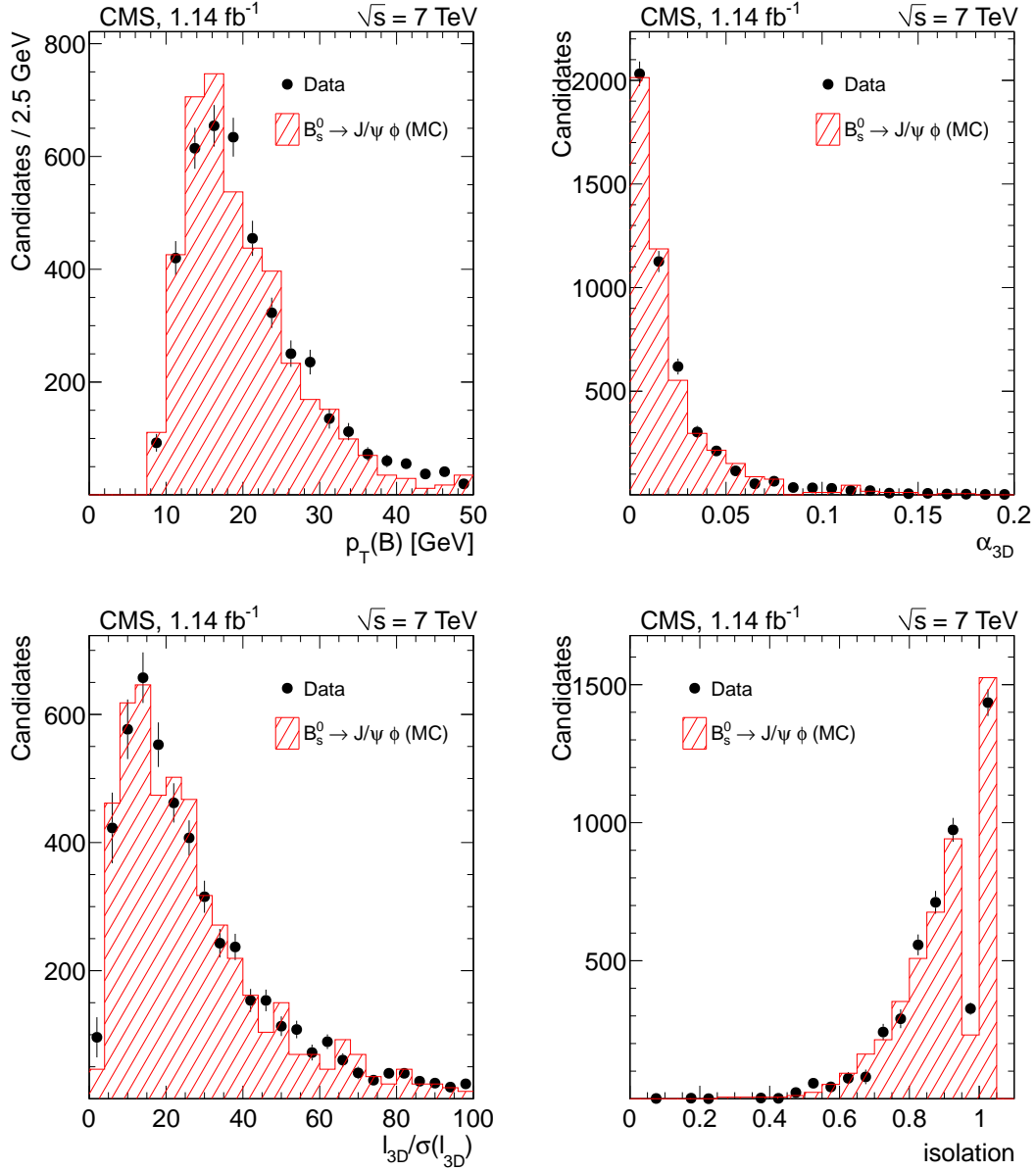


Figure 2: Comparison of measured and simulated  $B^0 \rightarrow J/\psi \phi$  distributions, for the transverse momentum (top left), the 3D pointing angle (top right), the flight length significance (bottom left), and the isolation (bottom right). The MC histograms are normalized to the number of events in the data.

normalization and control samples.

The  $B_s^0 \rightarrow \mu^+ \mu^-$  branching fraction is measured separately in the barrel and endcap channels using

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = \frac{N_S}{N_{\text{obs}}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{\text{tot}}^{B^+}}{\varepsilon_{\text{tot}}} \mathcal{B}(B^+), \quad (1)$$

and analogously for the  $B^0 \rightarrow \mu^+ \mu^-$  case, where  $N_S$  is the background-subtracted number of observed  $B_{d(s)} \rightarrow \mu^+ \mu^-$  candidates in the signal window ( $5.3 < m_{\mu\mu} < 5.45$  GeV for  $B_s^0$  and  $5.2 < m_{\mu\mu} < 5.3$  GeV for  $B^0$ ) and  $\varepsilon_{\text{tot}}$  is the total signal efficiency of all selection requirements. The ratio of the  $B_s^0$  and  $B^+$  meson production fractions is  $f_s/f_u = 0.282 \pm 0.037$  and  $\mathcal{B}(B^+) \equiv \mathcal{B}(B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+) = (6.0 \pm 0.2) \times 10^{-5}$  [16]. (We use  $f_s = 0.113 \pm 0.013$  and  $f_u = 0.401 \pm 0.013$  from the main section of Ref. [16] and account for the correlations in the ratio.)

Events in the signal window can result from real signal decays, combinatorial background, and ‘‘peaking’’ background from decays of the type  $B_{d(s)} \rightarrow hh'$ , where  $h, h'$  are charged hadrons misidentified as muons. The expected number of signal events,  $N_{\text{signal}}^{\text{exp}}$ , is calculated assuming the SM branching fraction and is normalized to the  $B^+$  yield. The expected number of combinatorial background events,  $N_{\text{comb}}^{\text{exp}} = 3(4)$  in the barrel (endcap), is evaluated by interpolating to the signal window the number of events observed in the sideband regions. The interpolation procedure assumes a flat background shape and has a systematic uncertainty of 4%, evaluated by varying the flight length significance selections and by using a floating slope. The expected number of peaking background events,  $N_{\text{peak}}^{\text{exp}}$ , is evaluated from MC simulation and muon misidentification rates measured in  $K_S^0 \rightarrow \pi^+ \pi^-$ ,  $\phi \rightarrow K^+ K^-$ , and  $\Lambda \rightarrow p \pi^-$  samples [15].

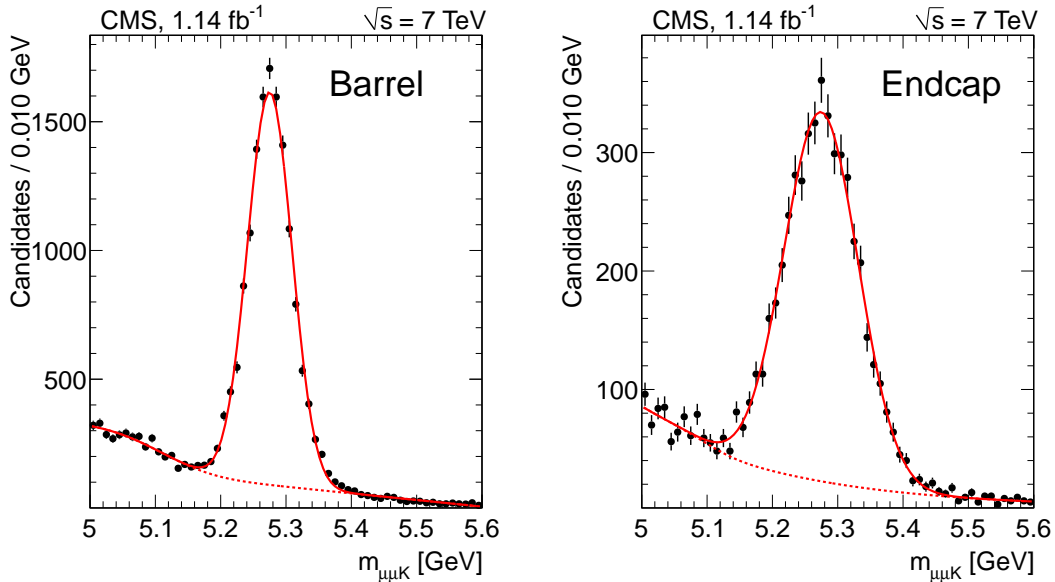


Figure 3:  $B^\pm \rightarrow J/\psi K^\pm$  invariant mass distributions in the barrel (left) and endcap (right) channels. The solid (dashed) lines show the fits to the data (background).

Figure 4 shows the measured dimuon invariant mass distributions. Three events are observed in the  $B_s^0 \rightarrow \mu^+ \mu^-$  signal windows (two in the barrel and one in the endcap), while only one event is observed in the  $B^0 \rightarrow \mu^+ \mu^-$  endcap channel. This observation is consistent with the



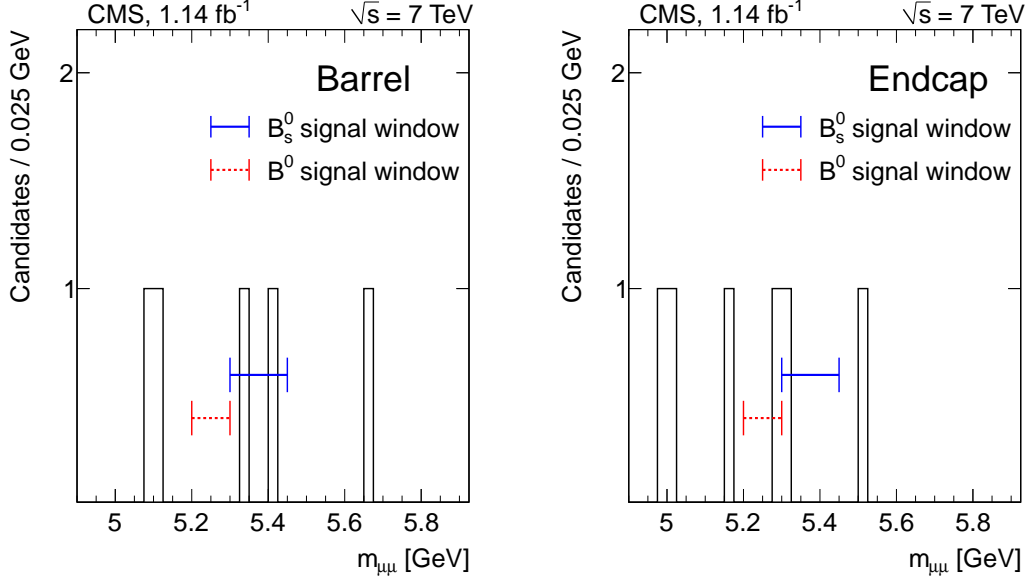


Figure 4: Dimuon invariant mass distributions in the barrel (left) and endcap (right) channels. The signal windows for  $B_s^0$  and  $B^0$  are indicated by horizontal lines.

SM expectation for signal plus background. Upper limits are determined with the  $CL_s$  approach [17]. Table 1 shows the values needed for the extraction of the results, separately for the barrel and endcap channels. The obtained upper limits on the branching fractions are  $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) < 1.9 \times 10^{-8}$  ( $1.6 \times 10^{-8}$ ) and  $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 4.6 \times 10^{-9}$  ( $3.7 \times 10^{-9}$ ), at 95% (90%) CL. The median expected upper limits at 95% CL are  $1.8 \times 10^{-8}$  ( $4.8 \times 10^{-9}$ ) for  $B_s^0 \rightarrow \mu^+\mu^-$  ( $B^0 \rightarrow \mu^+\mu^-$ ). The background-only  $p$  value is 0.11 (0.40) for  $B_s^0 \rightarrow \mu^+\mu^-$  ( $B^0 \rightarrow \mu^+\mu^-$ ), corresponding to 1.2 (0.27) standard deviations. The  $p$  value is 0.053 when assuming a  $B_s^0 \rightarrow \mu^+\mu^-$  signal at 5.6 times the SM value, as reported in Ref. [10].

In summary, a search for the rare decays  $B_s^0 \rightarrow \mu^+\mu^-$  and  $B^0 \rightarrow \mu^+\mu^-$  has been performed on a data sample of pp collisions at  $\sqrt{s} = 7$  TeV corresponding to an integrated luminosity of  $1.14 \text{ fb}^{-1}$ . The observed event yields are consistent with those expected adding background and SM signals. Upper limits on the branching fractions have been determined at 90% and 95% CL.

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## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

### Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer<sup>1</sup>, S. Häsnel, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, B. Rahbaran, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, F. Teischinger, C. Trauner, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

### National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

### Universiteit Antwerpen, Antwerpen, Belgium

S. Bansal, L. Benucci, E.A. De Wolf, X. Janssen, S. Luyckx, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

### Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

### Université Libre de Bruxelles, Bruxelles, Belgium

O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, G.H. Hammad, T. Hreus, P.E. Marage, A. Raval, L. Thomas, G. Vander Marcken, C. Vander Velde, P. Vanlaer

### Ghent University, Ghent, Belgium

V. Adler, A. Cimmino, S. Costantini, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. McCartin, D. Ryckbosch, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, N. Zaganidis

### Université Catholique de Louvain, Louvain-la-Neuve, Belgium

S. Basegmez, G. Bruno, J. Caudron, L. Ceard, E. Cortina Gil, J. De Favereau De Jeneret, C. Delaere, D. Favart, A. Giammanco, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, S. Owyn, D. Pagano, A. Pin, K. Piotrkowski, N. Schul

### Université de Mons, Mons, Belgium

N. Bely, T. Caebergs, E. Daubie

### Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, L. Brito, D. De Jesus Damiao, M.E. Pol, M.H.G. Souza

### Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, A. Sznajder

### Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

C.A. Bernardes<sup>2</sup>, F.A. Dias<sup>3</sup>, T. Dos Anjos Costa<sup>2</sup>, T.R. Fernandez Perez Tomei, E. M. Gregores<sup>2</sup>, C. Lagana, F. Marinho, P.G. Mercadante<sup>2</sup>, S.F. Novaes, Sandra S. Padula

### Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

N. Darmenov<sup>1</sup>, V. Genchev<sup>1</sup>, P. Iaydjiev<sup>1</sup>, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

**University of Sofia, Sofia, Bulgaria**

A. Dimitrov, R. Hadjiiska, A. Karadzhinova, V. Kozhuharov, L. Litov, M. Mateev, B. Pavlov, P. Petkov

**Institute of High Energy Physics, Beijing, China**

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

**State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China**

Y. Ban, S. Guo, Y. Guo, W. Li, Y. Mao, S.J. Qian, H. Teng, B. Zhu, W. Zou

**Universidad de Los Andes, Bogota, Colombia**

A. Cabrera, B. Gomez Moreno, A.A. Ocampo Rios, A.F. Osorio Oliveros, J.C. Sanabria

**Technical University of Split, Split, Croatia**

N. Godinovic, D. Lelas, K. Lelas, R. Plestina<sup>4</sup>, D. Polic, I. Puljak

**University of Split, Split, Croatia**

Z. Antunovic, M. Dzelalija, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

**University of Cyprus, Nicosia, Cyprus**

A. Attikis, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

**Charles University, Prague, Czech Republic**

M. Finger, M. Finger Jr.

**Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt**

Y. Assran<sup>5</sup>, A. Ellithi Kamel, S. Khalil<sup>6</sup>, M.A. Mahmoud<sup>7</sup>, A. Radi<sup>8</sup>

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

A. Hektor, M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

**Department of Physics, University of Helsinki, Helsinki, Finland**

V. Azzolini, P. Eerola, G. Fedi, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

**Lappeenranta University of Technology, Lappeenranta, Finland**

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

**Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France**

D. Sillou

**DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France**

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, F.X. Gentit, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, M. Marionneau, L. Millischer, J. Rander, A. Rosowsky, I. Shreyber, M. Titov, P. Verrecchia

**Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France**

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj<sup>9</sup>, C. Broutin, P. Busson, C. Charlot, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Haguenaer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaut, B. Wyslouch<sup>10</sup>, A. Zabi

**Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France**

J.-L. Agram<sup>11</sup>, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte<sup>11</sup>, F. Drouhin<sup>11</sup>, C. Ferro, J.-C. Fontaine<sup>11</sup>, D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim<sup>11</sup>, A.-C. Le Bihan, Y. Mikami, P. Van Hove

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France**

F. Fassi, D. Mercier

**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France**

C. Baty, S. Beauceron, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret

**Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia**

D. Lomidze

**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**

G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, N. Mohr, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, M. Weber, B. Wittmer

**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

M. Ata, E. Dietz-Laursonn, M. Erdmann, T. Hebbeker, C. Heidemann, A. Hinzmann, K. Hoepfner, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske<sup>†</sup>, J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier

**RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**

M. Bontenackels, V. Cherepanov, M. Davids, M. Duda, G. Flügge, H. Geenen, M. Giffels, W. Haj Ahmad, D. Heydhausen, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl, D. Tornier, M.H. Zoeller

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz<sup>12</sup>, A. Bethani, K. Borras, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, J. Hauk, H. Jung<sup>1</sup>, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann<sup>12</sup>, R. Mankel, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, J. Olzem, A. Petrukhin, D. Pitzl, A. Raspereza, M. Rosin, R. Schmidt<sup>12</sup>, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszewska, R. Walsh, C. Wissing

**University of Hamburg, Hamburg, Germany**

C. Autermann, V. Blobel, S. Bobrovskyi, J. Draeger, H. Enderle, U. Gebbert, M. Görner,

T. Hermanns, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, S. Naumann-Emme, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, M. Schröder, T. Schum, H. Stadie, G. Steinbrück, J. Thomsen

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

C. Barth, J. Bauer, J. Berger, V. Buege, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, C. Hackstein, F. Hartmann, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov<sup>13</sup>, J.R. Komaragiri, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, T. Weiler, M. Zeise, V. Zhukov<sup>13</sup>, E.B. Ziebarth

**Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece**

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari, E. Petrakou

**University of Athens, Athens, Greece**

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou, E. Stiliaris

**University of Ioánnina, Ioánnina, Greece**

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

**KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary**

A. Aranyi, G. Bencze, L. Boldizsar, C. Hajdu<sup>1</sup>, P. Hidas, D. Horvath<sup>14</sup>, A. Kapusi, K. Krajczar<sup>15</sup>, F. Sikler<sup>1</sup>, G.I. Veres<sup>15</sup>, G. Vesztergombi<sup>15</sup>

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

N. Beni, J. Molnar, J. Palinkas, Z. Szillasi, V. Veszpremi

**University of Debrecen, Debrecen, Hungary**

P. Raics, Z.L. Trocsanyi, B. Ujvari

**Panjab University, Chandigarh, India**

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, A.P. Singh, J. Singh, S.P. Singh

**University of Delhi, Delhi, India**

S. Ahuja, B.C. Choudhary, P. Gupta, A. Kumar, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R.K. Shivpuri

**Saha Institute of Nuclear Physics, Kolkata, India**

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, S. Jain, S. Jain, R. Khurana, S. Sarkar

**Bhabha Atomic Research Centre, Mumbai, India**

R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty<sup>1</sup>, L.M. Pant, P. Shukla

**Tata Institute of Fundamental Research - EHEP, Mumbai, India**

T. Aziz, M. Guchait<sup>16</sup>, A. Gurtu, M. Maity<sup>17</sup>, D. Majumder, G. Majumder, K. Mazumdar, G.B. Mohanty, A. Saha, K. Sudhakar, N. Wickramage

**Tata Institute of Fundamental Research - HECR, Mumbai, India**

S. Banerjee, S. Dugad, N.K. Mondal

**Institute for Research and Fundamental Sciences (IPM), Tehran, Iran**

H. Arfaei, H. Bakhshiansohi<sup>18</sup>, S.M. Etesami<sup>19</sup>, A. Fahim<sup>18</sup>, M. Hashemi, H. Hesari, A. Jafari<sup>18</sup>,



M. Khakzad, A. Mohammadi<sup>20</sup>, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali<sup>19</sup>

**INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup>, L. Barbone<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, N. De Filippis<sup>a,c,1</sup>, M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, L. Lusito<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, N. Manna<sup>a,b</sup>, B. Marangelli<sup>a,b</sup>, S. My<sup>a,c</sup>, S. Nuzzo<sup>a,b</sup>, N. Pacifico<sup>a,b</sup>, G.A. Pierro<sup>a</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, F. Romano<sup>a,c</sup>, G. Roselli<sup>a,b</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a</sup>, R. Trentadue<sup>a</sup>, S. Tuppiti<sup>a,b</sup>, G. Zito<sup>a</sup>

**INFN Sezione di Bologna <sup>a</sup>, Università di Bologna <sup>b</sup>, Bologna, Italy**

G. Abbiendi<sup>a</sup>, A.C. Benvenuti<sup>a</sup>, D. Bonacorsi<sup>a</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a</sup>, P. Giacomelli<sup>a</sup>, M. Giunta<sup>a</sup>, C. Grandi<sup>a</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>b</sup>, M. Meneghelli<sup>a,b</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, F. Odoricci<sup>a</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G. Siroli<sup>a,b</sup>, R. Travaglini<sup>a,b</sup>

**INFN Sezione di Catania <sup>a</sup>, Università di Catania <sup>b</sup>, Catania, Italy**

S. Albergo<sup>a,b</sup>, G. Cappello<sup>a,b</sup>, M. Chiorboli<sup>a,b,1</sup>, S. Costa<sup>a,b</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

**INFN Sezione di Firenze <sup>a</sup>, Università di Firenze <sup>b</sup>, Firenze, Italy**

G. Barbagli<sup>a</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, S. Frosali<sup>a,b</sup>, E. Gallo<sup>a</sup>, S. Gonzi<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, G. Sguazzoni<sup>a</sup>, A. Tropiano<sup>a,1</sup>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi, S. Bianco, S. Colafranceschi<sup>21</sup>, F. Fabbri, D. Piccolo

**INFN Sezione di Genova, Genova, Italy**

P. Fabbriatore, R. Musenich

**INFN Sezione di Milano-Bicocca <sup>a</sup>, Università di Milano-Bicocca <sup>b</sup>, Milano, Italy**

A. Benaglia<sup>a,b</sup>, F. De Guio<sup>a,b,1</sup>, L. Di Matteo<sup>a,b</sup>, S. Gennai<sup>1</sup>, A. Ghezzi<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, A. Martelli<sup>a,b</sup>, A. Massironi<sup>a,b</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, N. Redaelli<sup>a</sup>, S. Sala<sup>a</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

**INFN Sezione di Napoli <sup>a</sup>, Università di Napoli "Federico II" <sup>b</sup>, Napoli, Italy**

S. Buontempo<sup>a</sup>, C.A. Carrillo Montoya<sup>a,1</sup>, N. Cavallo<sup>a,22</sup>, A. De Cosa<sup>a,b</sup>, F. Fabozzi<sup>a,22</sup>, A.O.M. Iorio<sup>a,1</sup>, L. Lista<sup>a</sup>, M. Merola<sup>a,b</sup>, P. Paolucci<sup>a</sup>

**INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Università di Trento (Trento) <sup>c</sup>, Padova, Italy**

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, P. Bellan<sup>a,b</sup>, D. Bisello<sup>a,b</sup>, A. Branca<sup>a</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, F. Fanzago<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino, S. Lacaprara<sup>a,23</sup>, I. Lazzizzera<sup>a,c</sup>, M. Margoni<sup>a,b</sup>, M. Mazzucato<sup>a</sup>, A.T. Meneguzzo<sup>a,b</sup>, M. Nespolo<sup>a,1</sup>, L. Perrozzi<sup>a,1</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, M. Tosi<sup>a,b</sup>, S. Vanini<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

**INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy**

P. Baesso<sup>a,b</sup>, U. Berzano<sup>a</sup>, S.P. Ratti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Torre<sup>a,b</sup>, P. Vitulo<sup>a,b</sup>, C. Viviani<sup>a,b</sup>

**INFN Sezione di Perugia <sup>a</sup>, Università di Perugia <sup>b</sup>, Perugia, Italy**

M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, B. Caponeri<sup>a,b</sup>, L. Fano<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, A. Lucaroni<sup>a,b,1</sup>, G. Mantovani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Nappi<sup>a,b</sup>, F. Romeo<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, S. Taroni<sup>a,b,1</sup>, M. Valdata<sup>a,b</sup>

**INFN Sezione di Pisa <sup>a</sup>, Università di Pisa <sup>b</sup>, Scuola Normale Superiore di Pisa <sup>c</sup>, Pisa, Italy**  
 P. Azzurri<sup>a,c</sup>, G. Bagliesi<sup>a</sup>, J. Bernardini<sup>a,b</sup>, T. Boccali<sup>a</sup>, G. Broccolo<sup>a,c</sup>, R. Castaldi<sup>a</sup>,  
 R.T. D’Agnolo<sup>a,c</sup>, R. Dell’Orso<sup>a</sup>, F. Fiori<sup>a,b</sup>, L. Foà<sup>a,c</sup>, A. Giassi<sup>a</sup>, A. Kraan<sup>a</sup>, F. Ligabue<sup>a,c</sup>,  
 T. Lomtadze<sup>a</sup>, L. Martini<sup>a,24</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, F. Palmonari, G. Segneri<sup>a</sup>, A.T. Serban<sup>a</sup>,  
 P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b,1</sup>, A. Venturi<sup>a,1</sup>, P.G. Verdini<sup>a</sup>

**INFN Sezione di Roma <sup>a</sup>, Università di Roma “La Sapienza” <sup>b</sup>, Roma, Italy**  
 L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, D. Del Re<sup>a,b</sup>, E. Di Marco<sup>a,b</sup>, M. Diemoz<sup>a</sup>, D. Franci<sup>a,b</sup>, M. Grassi<sup>a,1</sup>,  
 E. Longo<sup>a,b</sup>, P. Meridiani, S. Nourbakhsh<sup>a</sup>, G. Organtini<sup>a,b</sup>, F. Pandolfi<sup>a,b,1</sup>, R. Paramatti<sup>a</sup>,  
 S. Rahatlou<sup>a,b</sup>, M. Sigamani<sup>a</sup>

**INFN Sezione di Torino <sup>a</sup>, Università di Torino <sup>b</sup>, Università del Piemonte Orientale (No-  
 vara) <sup>c</sup>, Torino, Italy**  
 N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, C. Biino<sup>a</sup>, C. Botta<sup>a,b,1</sup>,  
 N. Cartiglia<sup>a</sup>, R. Castello<sup>a,b</sup>, M. Costa<sup>a,b</sup>, N. Demaria<sup>a</sup>, A. Graziano<sup>a,b,1</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>,  
 E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, M. Musich<sup>a</sup>, M.M. Obertino<sup>a,c</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a,b</sup>,  
 A. Potenza<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, V. Sola<sup>a,b</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>,  
 A. Vilela Pereira<sup>a</sup>

**INFN Sezione di Trieste <sup>a</sup>, Università di Trieste <sup>b</sup>, Trieste, Italy**  
 S. Belforte<sup>a</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, B. Gobbo<sup>a</sup>, M. Marone<sup>a,b</sup>, D. Montanino<sup>a,b</sup>, A. Penzo<sup>a</sup>

**Kangwon National University, Chunchon, Korea**  
 S.G. Heo, S.K. Nam

**Kyungpook National University, Daegu, Korea**  
 S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

**Chonnam National University, Institute for Universe and Elementary Particles, Kwangju,  
 Korea**  
 J.Y. Kim, Zero J. Kim, S. Song

**Konkuk University, Seoul, Korea**  
 H.Y. Jo

**Korea University, Seoul, Korea**  
 S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, J.H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park,  
 E. Seo, K.S. Sim

**University of Seoul, Seoul, Korea**  
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**Sungkyunkwan University, Suwon, Korea**  
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**Vilnius University, Vilnius, Lithuania**  
 M.J. Bilinskas, I. Grigelionis, M. Janulis, D. Martisiute, P. Petrov, M. Polujanskas, T. Sabonis

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**  
 H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez,  
 R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

**Universidad Iberoamericana, Mexico City, Mexico**  
 S. Carrillo Moreno, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

H.A. Salazar Ibarguen

**Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico**

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

**University of Auckland, Auckland, New Zealand**

D. Krofcheck, J. Tam

**University of Canterbury, Christchurch, New Zealand**

P.H. Butler, R. Doesburg, H. Silverwood

**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**

M. Ahmad, I. Ahmed, M.H. Ansari, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**

G. Brona, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

**Soltan Institute for Nuclear Studies, Warsaw, Poland**

T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

**Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro<sup>1</sup>, P. Musella, A. Nayak, J. Pela<sup>1</sup>, P.Q. Ribeiro, J. Seixas, J. Varela

**Joint Institute for Nuclear Research, Dubna, Russia**

S. Afanasiev, I. Belotelov, P. Bunin, M. Gavrilenko, I. Golutvin, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

**Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia**

V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

**Institute for Nuclear Research, Moscow, Russia**

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, A. Toropin, S. Troitsky

**Institute for Theoretical and Experimental Physics, Moscow, Russia**

V. Epshteyn, M. Erofeeva, V. Gavrilov, V. Kaftanov<sup>†</sup>, M. Kossov<sup>1</sup>, A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

**Moscow State University, Moscow, Russia**

A. Belyaev, E. Boos, M. Dubinin<sup>3</sup>, L. Dudko, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, L. Sarycheva, V. Savrin, A. Snigirev

**P.N. Lebedev Physical Institute, Moscow, Russia**

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

**State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia**

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin<sup>1</sup>, V. Kachanov, D. Konstantinov, A. Korablev,

V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

**University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia**

P. Adzic<sup>25</sup>, M. Djordjevic, D. Krpic<sup>25</sup>, J. Milosevic

**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

**Universidad Autónoma de Madrid, Madrid, Spain**

C. Albajar, G. Codispoti, J.F. de Trocóniz

**Universidad de Oviedo, Oviedo, Spain**

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J.M. Vizan Garcia

**Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain**

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini<sup>26</sup>, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez<sup>27</sup>, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, A.J. Bell<sup>28</sup>, D. Benedetti, C. Bernet<sup>4</sup>, W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, M. Bona, H. Breuker, K. Bunkowski, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, S. Di Guida, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, G. Georgiou, H. Gerwig, D. Gigi, K. Gill, D. Giordano, F. Glege, R. Gomez-Reino Garrido, M. Gouzevitch, P. Govoni, S. Gowdy, R. Guida, L. Guiducci, M. Hansen, C. Hartl, J. Harvey, J. Hegeman, B. Hegner, H.F. Hoffmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, P. Lecoq, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, A. Maurisset, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold, M. Nguyen, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi<sup>29</sup>, T. Rommerskirchen, C. Rovelli<sup>30</sup>, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas<sup>31</sup>, D. Spiga, M. Spiropulu<sup>3</sup>, M. Stoye, A. Tsiros, P. Vichoudis, H.K. Wöhri, S.D. Worm, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille<sup>32</sup>

**Institute for Particle Physics, ETH Zurich, Zurich, Switzerland**

L. Bäni, P. Bortignon, L. Caminada<sup>33</sup>, B. Casal, N. Chanon, Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, W. Hintz, P. Lecomte, W. Lustermann, C. Marchica<sup>33</sup>, P. Martinez Ruiz del Arbol, P. Milenovic<sup>34</sup>, F. Moortgat, C. Nägeli<sup>33</sup>, P. Nef,

F. Nessi-Tedaldi, L. Pape, F. Pauss, T. Punz, A. Rizzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, A. Starodumov<sup>35</sup>, B. Stieger, M. Takahashi, L. Tauscher<sup>†</sup>, A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, M. Weber, L. Wehrli, J. Weng

**Universität Zürich, Zurich, Switzerland**

E. Aguilo, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, A. Jaeger, B. Millan Mejias, P. Otiougova, P. Robmann, A. Schmidt, H. Snoek

**National Central University, Chung-Li, Taiwan**

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, R. Volpe, S.S. Yu

**National Taiwan University (NTU), Taipei, Taiwan**

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

**Cukurova University, Adana, Turkey**

A. Adiguzel, M.N. Bakirci<sup>36</sup>, S. Cerci<sup>37</sup>, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk<sup>38</sup>, A. Polatoz, K. Sogut<sup>39</sup>, D. Sunar Cerci<sup>37</sup>, B. Tali<sup>37</sup>, H. Topakli<sup>36</sup>, D. Uzun, L.N. Vergili, M. Vergili

**Middle East Technical University, Physics Department, Ankara, Turkey**

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

**Bogazici University, Istanbul, Turkey**

M. Deliomeroglu, D. Demir<sup>40</sup>, E. Gülmez, B. Isildak, M. Kaya<sup>41</sup>, O. Kaya<sup>41</sup>, M. Özbek, S. Ozkorucuklu<sup>42</sup>, N. Sonmez<sup>43</sup>

**National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine**

L. Levchuk

**University of Bristol, Bristol, United Kingdom**

F. Bostock, J.J. Brooke, T.L. Cheng, E. Clement, D. Cussans, R. Frazier, J. Goldstein, M. Grimes, D. Hartley, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold<sup>44</sup>, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith

**Rutherford Appleton Laboratory, Didcot, United Kingdom**

L. Basso<sup>45</sup>, K.W. Bell, A. Belyaev<sup>45</sup>, C. Brew, R.M. Brown, B. Camanzi, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

**Imperial College, London, United Kingdom**

R. Bainbridge, G. Ball, J. Ballin, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, B.C. MacEvoy, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko<sup>35</sup>, A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi<sup>46</sup>, D.M. Raymond, S. Rogerson, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, D. Wardrope, T. Whyntie

**Brunel University, Uxbridge, United Kingdom**

M. Barrett, M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, W. Martin, I.D. Reid, L. Teodorescu

**Baylor University, Waco, USA**

K. Hatakeyama, H. Liu

**The University of Alabama, Tuscaloosa, USA**

C. Henderson

**Boston University, Boston, USA**

T. Bose, E. Carrera Jarrin, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

**Brown University, Providence, USA**

A. Avetisyan, S. Bhattacharya, J.P. Chou, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

**University of California, Davis, Davis, USA**

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, E. Friis, W. Ko, A. Kopecky, R. Lander, H. Liu, S. Maruyama, T. Miceli, M. Nikolic, D. Pellett, J. Robles, B. Rutherford, S. Salur, T. Schwarz, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, C. Veelken

**University of California, Los Angeles, Los Angeles, USA**

V. Andreev, K. Arisaka, D. Cline, R. Cousins, A. Deisher, J. Duris, S. Erhan, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein<sup>†</sup>, J. Tucker, V. Valuev

**University of California, Riverside, Riverside, USA**

J. Babb, A. Chandra, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, B.C. Shen<sup>†</sup>, R. Stringer, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

**University of California, San Diego, La Jolla, USA**

W. Andrews, J.G. Branson, G.B. Cerati, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, H. Pi, M. Pieri, R. Ranieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech<sup>47</sup>, F. Würthwein, A. Yagil, J. Yoo

**University of California, Santa Barbara, Santa Barbara, USA**

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi<sup>1</sup>, V. Krutelyov, S. Lowette, N. Mccoll, E. Mullin, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, J.R. Vlimant, C. West

**California Institute of Technology, Pasadena, USA**

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, K. Shin, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

**Carnegie Mellon University, Pittsburgh, USA**

B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

**University of Colorado at Boulder, Boulder, USA**

J.P. Cumalat, M.E. Dinardo, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner, S.L. Zang

**Cornell University, Ithaca, USA**

L. Agostino, J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, K. Henriksson, W. Hopkins, A. Khukhunaishvili, B. Kreis, Y. Liu, G. Nicolas Kaufman, J.R. Patterson, D. Puigh, A. Ryd, M. Saelim, E. Salvati, X. Shi, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

**Fairfield University, Fairfield, USA**

A. Biselli, G. Cirino, D. Winn

**Fermi National Accelerator Laboratory, Batavia, USA**

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, M. Atac, J.A. Bakken, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, W. Cooper, D.P. Eartly, V.D. Elvira, S. Esen, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, K. Gunthoti, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, H. Jensen, M. Johnson, U. Joshi, R. Khatiwada, B. Klima, K. Kousouris, S. Kunori, S. Kwan, C. Leonidopoulos, P. Limon, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, T. Miao, K. Mishra, S. Mrenna, Y. Musienko<sup>48</sup>, C. Newman-Holmes, V. O'Dell, J. Pivarski, R. Pordes, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

**University of Florida, Gainesville, USA**

D. Acosta, P. Avery, D. Bourilkov, M. Chen, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, S. Goldberg, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, G. Mitselmakher, L. Muniz, P. Myeonghun, C. Prescott, R. Remington, A. Rinkevicius, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, M. Snowball, D. Wang, J. Yelton, M. Zakaria

**Florida International University, Miami, USA**

V. Gaultney, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

**Florida State University, Tallahassee, USA**

T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, S. Sekmen, V. Veeraraghavan

**Florida Institute of Technology, Melbourne, USA**

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyarov

**University of Illinois at Chicago (UIC), Chicago, USA**

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, G.J. Kunde<sup>49</sup>, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, C. Silvestre, A. Smoron, D. Strom, N. Varelas

**The University of Iowa, Iowa City, USA**

U. Akgun, E.A. Albayrak, B. Bilki, W. Clarida, F. Duru, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya<sup>50</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, J. Wetzel, T. Yetkin, K. Yi

**Johns Hopkins University, Baltimore, USA**

B.A. Barnett, B. Blumenfeld, A. Bonato, C. Eskew, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, N.V. Tran, A. Whitbeck

**The University of Kansas, Lawrence, USA**

P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, J.S. Wood, V. Zhukova

**Kansas State University, Manhattan, USA**

A.f. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze, Z. Wan

**Lawrence Livermore National Laboratory, Livermore, USA**

J. Gronberg, D. Lange, D. Wright

**University of Maryland, College Park, USA**

A. Baden, M. Boutemour, S.C. Eno, D. Ferencek, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, Y. Lu, A.C. Mignerey, K. Rossato, P. Rumerio, F. Santanastasio, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

**Massachusetts Institute of Technology, Cambridge, USA**

B. Alver, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, P. Everaerts, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, P. Harris, Y. Kim, M. Klute, Y.-J. Lee, W. Li, C. Loizides, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

**University of Minnesota, Minneapolis, USA**

S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, J. Haupt, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, V. Rekovic, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

**University of Mississippi, University, USA**

L.M. Cremaldi, R. Godang, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

**University of Nebraska-Lincoln, Lincoln, USA**

K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, P. Jindal, J. Keller, T. Kelly, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

**State University of New York at Buffalo, Buffalo, USA**

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

**Northeastern University, Boston, USA**

G. Alverson, E. Barberis, D. Baumgartel, O. Boeriu, M. Chasco, S. Reucroft, J. Swain, D. Trocino, D. Wood, J. Zhang

**Northwestern University, Evanston, USA**

A. Anastassov, A. Kubik, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

**University of Notre Dame, Notre Dame, USA**

L. Antonelli, D. Berry, A. Brinkerhoff, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, T. Kolberg, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, J. Ziegler

**The Ohio State University, Columbus, USA**

B. Bylsma, L.S. Durkin, J. Gu, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, C. Vuosalo, G. Williams

**Princeton University, Princeton, USA**

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, A. Hunt, E. Laird, D. Lopes



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Pegna, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

**University of Puerto Rico, Mayaguez, USA**

J.G. Acosta, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

**Purdue University, West Lafayette, USA**

E. Alagoz, V.E. Barnes, G. Bolla, L. Borrello, D. Bortoletto, M. De Mattia, A. Everett, A.F. Garfinkel, L. Gutay, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, C. Liu, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, H.D. Yoo, J. Zablocki, Y. Zheng

**Purdue University Calumet, Hammond, USA**

S. Guragain, N. Parashar

**Rice University, Houston, USA**

A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

**University of Rochester, Rochester, USA**

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, H. Flacher, A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, D. Orbaker, G. Petrillo, W. Sakumoto, D. Vishnevskiy, M. Zielinski

**The Rockefeller University, New York, USA**

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulios, G. Lungu, S. Malik, C. Mesropian

**Rutgers, the State University of New Jersey, Piscataway, USA**

S. Arora, O. Atramentov, A. Barker, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, D. Hits, A. Lath, S. Panwalkar, R. Patel, A. Richards, K. Rose, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

**University of Tennessee, Knoxville, USA**

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

**Texas A&M University, College Station, USA**

R. Eusebi, W. Flanagan, J. Gilmore, A. Gurrola, T. Kamon, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Safonov, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

**Texas Tech University, Lubbock, USA**

N. Akchurin, C. Bardak, J. Damgov, P.R. Duderu, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, P. Mane, Y. Roh, A. Sill, I. Volobouev, R. Wigmans, E. Yazgan

**Vanderbilt University, Nashville, USA**

E. Appelt, E. Brownson, D. Engh, C. Florez, W. Gabella, M. Issah, W. Johns, C. Johnston, P. Kurt, C. Maguire, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

**University of Virginia, Charlottesville, USA**

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, S. Goadhouse, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood, R. Yohay

**Wayne State University, Detroit, USA**

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

**University of Wisconsin, Madison, USA**

M. Anderson, M. Bachtis, D. Belknap, J.N. Bellinger, D. Carlsmith, M. Cepeda, S. Dasu, J. Efron, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, W. Parker, I. Ross, A. Savin, W.H. Smith, J. Swanson, M. Weinberg

†: Deceased

- 1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 2: Also at Universidade Federal do ABC, Santo Andre, Brazil
- 3: Also at California Institute of Technology, Pasadena, USA
- 4: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 5: Also at Suez Canal University, Suez, Egypt
- 6: Also at British University, Cairo, Egypt
- 7: Also at Fayoum University, El-Fayoum, Egypt
- 8: Also at Ain Shams University, Cairo, Egypt
- 9: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
- 10: Also at Massachusetts Institute of Technology, Cambridge, USA
- 11: Also at Université de Haute-Alsace, Mulhouse, France
- 12: Also at Brandenburg University of Technology, Cottbus, Germany
- 13: Also at Moscow State University, Moscow, Russia
- 14: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 15: Also at Eötvös Loránd University, Budapest, Hungary
- 16: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 17: Also at University of Visva-Bharati, Santiniketan, India
- 18: Also at Sharif University of Technology, Tehran, Iran
- 19: Also at Isfahan University of Technology, Isfahan, Iran
- 20: Also at Shiraz University, Shiraz, Iran
- 21: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
- 22: Also at Università della Basilicata, Potenza, Italy
- 23: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
- 24: Also at Università degli studi di Siena, Siena, Italy
- 25: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 26: Also at University of California, Los Angeles, Los Angeles, USA
- 27: Also at University of Florida, Gainesville, USA
- 28: Also at Université de Genève, Geneva, Switzerland
- 29: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 30: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
- 31: Also at University of Athens, Athens, Greece
- 32: Also at The University of Kansas, Lawrence, USA
- 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 Institute for Theoretical and Experimental Physics, Moscow, Russia
- 36: Also at Gaziosmanpasa University, Tokat, Turkey
- 37: Also at Adiyaman University, Adiyaman, Turkey
- 38: Also at The University of Iowa, Iowa City, USA
- 39: Also at Mersin University, Mersin, Turkey
- 40: Also at Izmir Institute of Technology, Izmir, Turkey
- 41: Also at Kafkas University, Kars, Turkey
- 42: Also at Suleyman Demirel University, Isparta, Turkey

43: Also at Ege University, Izmir, Turkey

44: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom

45: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

46: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy

47: Also at Utah Valley University, Orem, USA

48: Also at Institute for Nuclear Research, Moscow, Russia

49: Also at Los Alamos National Laboratory, Los Alamos, USA

50: Also at Erzincan University, Erzincan, Turkey