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

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Measurements of the total and differential cross sections $d\sigma/dp_T^B$ and $d\sigma/dy^B$ for B^+ mesons produced in pp collisions at $\sqrt{s} = 7$ TeV are presented. The data correspond to an integrated luminosity of 5.8 pb^{-1} collected by the CMS experiment operating at the LHC. The exclusive decay $B^+ \rightarrow J/\psi K^+$, with $J/\psi \rightarrow \mu^+\mu^-$, is used to detect B^+ mesons and to measure the production cross section as a function of p_T^B and y^B. The total cross section for $p_T^B > 5$ GeV and $|y^B| < 2.4$ is measured to be $28.1 \pm 2.4 \pm 2.0 \pm 3.1$ μb, where the first uncertainty is statistical, the second is systematic, and the last is from the luminosity measurement.

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The study of heavy-quark production in high-energy hadronic interactions plays a critical role in testing next-to-leading order (NLO) quantum chromodynamics (QCD) calculations [1]. The first such measurements were made more than two decades ago by the UA1 Collaboration at the CERN S$\bar{p}p$S collider [2,3] operating at a center of mass energy of $\sqrt{s} = 0.63$ TeV, while more recent measurements have been made by the CDF and D0 Collaborations at the Fermilab Tevatron for $\sqrt{s} = 1.8$ and 1.96 TeV [4–11]. Substantial progress has been achieved in the understanding of heavy-quark production at Tevatron energies [12], but large theoretical uncertainties remain due to the dependence on the renormalization and factorization scales. Particularly important in the perturbative expansion are terms that scale as powers of $\ln(\sqrt{s}/m_b)$ at low transverse momentum p_T of the b quark [13,14], or as powers of $\ln(p_T/m_b)$ when $p_T \gg m_b$ [15], where m_b is the mass of the b quark. Measurements of b-hadron production at the higher energies provided by the Large Hadron Collider (LHC) represent an important new test of theoretical calculations [16,17].

Recently, the LHCb Collaboration measured the production cross section for b hadrons at the LHC in the forward region using partially reconstructed decays [18]. This Letter presents the first measurement of exclusive B-meson production in pp collisions at $\sqrt{s} = 7$ TeV. A sample of $B^\pm \rightarrow J/\psi K^\pm$ decays, with $J/\psi \rightarrow \mu^+\mu^-$, is reconstructed in 5.84 ± 0.64 pb^{-1} of data collected by the Compact Muon Solenoid (CMS) experiment operating at the LHC. Charge conjugation is assumed in the remainder of this Letter, where B^+ will be used to refer to both charge states. The signal yield in bins of transverse momentum p_T^B and rapidity $|y^B|$ is measured with a maximum-likelihood fit to the reconstructed invariant mass M_B and proper decay length ct of the B^+ candidates. These yields are corrected for detection efficiencies and luminosity to compute the differential production cross sections $d\sigma/dp_T^B$ and $d\sigma/dy^B$. The results are compared to theoretical predictions based on NLO QCD.

A detailed description of the CMS detector can be found elsewhere [19]. The main subdetectors used in this analysis are the silicon tracker and muon systems. The tracker consists of silicon pixel and strip detector modules and is immersed in a 3.8 T magnetic field that enables the measurement of charged particle momenta over the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln\tan(\theta/2)$ and θ is the polar angle of the track relative to the counterclockwise beam direction. Muons are identified in the range $|\eta| < 2.4$ by gas-ionization detectors embedded in the steel return yoke. The first level of the CMS trigger system consists of custom hardware processors and uses information from the calorimeters and muon system to select the most interesting events in less than 1 μs. The high level trigger (HLT) processor farm further decreases the event rate to less than 300 Hz before data storage. The events used in the measurement reported here were collected with a trigger requiring the presence of two muons at HLT with no explicit momentum threshold.

Reconstruction of $B^+ \rightarrow J/\psi K^+$ candidates begins by identifying $J/\psi \rightarrow \mu^+\mu^-$ decays. The muon candidates are required to have at least one reconstructed segment in the muon system that matches the extrapolated position of a track reconstructed in the tracker. Muons within $|\eta| < 2.4$ that pass the trigger are selected and further required to satisfy a kinematic threshold that depends on pseudorapidity: $p_T^\mu > 3.3$ GeV for $|\eta^\mu| < 1.3$; $p > 2.9$ GeV for $1.3 < |\eta^\mu| < 2.2$; and $p_T > 0.8$ GeV for $2.2 < |\eta^\mu| < 2.4$. Candidate J/ψ mesons are reconstructed by combining pairs of oppositely charged muons having an invariant mass within 150 MeV of the nominal J/ψ mass [20].

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If more than one muon pair in an event satisfies this selection, the one closest to the J/ψ mass is selected.

Candidate B^+ mesons are reconstructed by combining a J/ψ candidate with a track having $p_T > 0.9$ GeV, at least four hits in the tracker (of which one must be in the pixel detector), and a track-fit χ^2 less than 5 times the number of degrees of freedom. A kinematic fit is performed to the dimuon-track combination, constraining the dimuon mass to equal the J/ψ mass and assuming the third track to be a kaon. The selected events must have a resulting χ^2 confidence level greater than 0.1% and a reconstructed B^+ mass satisfying $4.95 < M_B < 5.55$ GeV. In events with at least one B^+ candidate, the average number of such candidates is approximately 1.7. When multiple candidates exist, the one with the highest p_T is retained, which results in the correct choice 95% of the time in simulated events containing a true signal decay. A total of 35 406 B^+ candidates pass all the selection criteria.

The efficiencies corresponding to this selection range from a few percent for $p_T^B \sim 5$ GeV, to approximately 40% for $p_T^B > 24$ GeV, as determined in large samples of signal events generated by PYTHIA 6.422 [21], decayed by EVTGEN [22], and processed by a detailed simulation of the CMS detector based on GEANT4 [23]. The efficiencies for hadron-track reconstruction [24] and the vertex quality requirement are found to be consistent between data and simulation within the available precision, which is used to set the systematic uncertainty of these quantities. Correction factors for trigger and muon-reconstruction efficiencies are obtained from a large sample of inclusive $J/\psi \to \mu^+\mu^-$ decays using a technique similar to that described in [25], where one muon is identified with stringent quality requirements and the second muon is identified using information separately from the tracker or from the muon system.

The proper decay length of each B^+ 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 [26] to the secondary vertex projected onto the B^+ transverse momentum: $L_{xy} = (\vec{s} \cdot \vec{p}_T^B)/|\vec{p}_T^B|$. The core resolution on ct is approximately 30 μm for correctly reconstructed signal decays.

Backgrounds are dominated by prompt and nonprompt inclusive J/ψ production. Additional backgrounds arise from misreconstructed b-hadron decays, such as $B \to J/\psi K^*(892)$, that produce a broad peaking structure in the region $M_B < 5.2$ GeV. Contamination from muon pairs that do not originate from J/ψ decay is negligible after all selection criteria are applied.

The number n_{sig} of signal decays in each p_T^B and $|y^B|$ bin is 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. Five individual components are considered: signal, $B^+ \to J/\psi\pi^+$, misreconstructed $b\bar{b}$ events that peak in M_B, nonprompt J/ψ, and prompt J/ψ. The extended likelihood function is then the product of likelihoods for all events:

$$L = \exp\Bigl(-\sum_i n_i\Bigr)\prod_j\Bigl[\sum_i n_i \mathcal{P}_i(M_B; \vec{\alpha}_i)\mathcal{P}_i(ct; \vec{\beta}_i)\Bigr]. \quad (1)$$

The probabilities $\mathcal{P}_i$ are the probability density functions (PDFs) with shape parameters $\vec{\alpha}_i$ for M_B, and $\vec{\beta}_i$ for ct, evaluated separately for each of the i fit components. The yields n_i are then determined by maximizing $\mathcal{L}$ with respect to the yields and a subset of the PDF parameters. The yield for $J/\psi\pi^+$ is constrained to equal the $J/\psi K^+$ yield times the ratio of branching fractions for the two decay modes [20].

The M_B PDFs are the sum of three (two) Gaussians for the signal ($J/\psi\pi$) with parameters obtained from simulation; an exponential for both prompt and nonprompt J/ψ; and a combination of two Gaussians and an exponential for the peaking $b\bar{b}$ background. The resolution on M_B for signal decays is approximately 30 MeV. The ct PDFs are a single exponential convolved with the resolution function to describe the signal, $J/\psi\pi$, and peaking background components, where the lifetime is allowed to be different for the latter; the sum of two exponentials convolved with the resolution function for the nonprompt J/ψ component; and the pure resolution function for the prompt J/ψ component. The resolution function is common for signal and background, and is described by the sum of two or three Gaussian functions, depending on p_T^B and $|y^B|$.

The fit proceeds in several steps so that all background shapes are obtained directly from data, except for the peaking component. This technique relies on the assumption that in the signal-free region $5.40 < M_B < 5.55$ GeV (upper sideband) there are only two contributions: prompt and nonprompt J/ψ background (ignoring the small contribution from $J/\psi\pi$). To obtain the effective lifetime of the nonprompt J/ψ background, the ct distribution is fitted for events in the inclusive B^+ sample defined by $p_T^B > 5$ GeV and $|y^B| < 2.4$ that lie in the M_B upper sideband region, allowing the resolution function parameters to vary freely. The resolution function is then fixed and the signal B^+ lifetime in the inclusive sample is obtained by fitting ct and M_B simultaneously. The result, $c\tau = 481 \pm 22$ μm (statistical uncertainty only), is in good agreement with the world-average value of 491 ± 9 μm [20]. With the effective lifetime for signal and nonprompt background fixed, the resolution function parameters are then determined separately in each bin of p_T^B and $|y^B|$. Finally, with all ct resolution and background lifetime parameters fixed, the signal and background yields are fitted in each bin, together with the parameters describing the shape of the prompt and nonprompt J/ψ components in M_B.

The accuracy and robustness of the fit strategy were checked with a set of 400 pseudoexperiments where signal

TABLE I. Bin ranges for p_T^B and $|y^B|$, signal yields $n_{\rm sig}$, efficiencies ϵ, and measured differential cross sections $d\sigma/dp_T^B$ and $d\sigma/dy^B$, compared to the MC@NLO [27] and PYTHIA predictions. The uncertainties in the measured cross sections are statistical and systematic, respectively, excluding the common branching fraction (3.5%) and luminosity (11%) uncertainties. The result for $p_T^B > 30$ GeV is quoted as an integrated cross section in μb.

p_T^B (GeV)	$n_{\rm sig}$	ϵ (%)	$d\sigma/dp_T^B$ (μb/GeV)	MC@NLO	PYTHIA
5–10	223 ± 26	1.56 ± 0.02	$4.07 \pm 0.47 \pm 0.31$	$3.72^{+1.46}_{-0.89}$	6.68
10–13	236 ± 21	7.62 ± 0.11	$1.47 \pm 0.13 \pm 0.09$	$1.17^{+0.31}_{-0.24}$	2.66
13–17	169 ± 17	14.6 ± 0.2	$0.412 \pm 0.041 \pm 0.026$	$0.47^{+0.10}_{-0.05}$	1.01
17–240	207 ± 17	23.3 ± 0.6	$0.181 \pm 0.015 \pm 0.012$	$0.15^{+0.04}_{-0.03}$	0.28
24–30	56 ± 9	31.9 ± 1.5	$0.042 \pm 0.007 \pm 0.004$	$0.048^{+0.029}_{-0.018}$	0.08
>30	44 ± 8	33.4 ± 2.0	$0.188 \pm 0.034 \pm 0.018$	$0.20^{+0.11}_{-0.02}$	0.27
$\lvert y^B\rvert$	$n_{\rm sig}$	ϵ(%)	$d\sigma/dy^B$(μb)	MC@NLO	PYTHIA
0.00–0.60	187 ± 17	3.01 ± 0.06	$7.39 \pm 0.65 \pm 0.53$	$5.98^{+2.2}_{-1.31}$	11.1
0.60–1.10	164 ± 17	3.81 ± 0.08	$6.11 \pm 0.64 \pm 0.47$	$5.85^{+1.78}_{-1.37}$	10.8
1.010–1.45	207 ± 20	5.92 ± 0.12	$7.11 \pm 0.69 \pm 0.59$	$5.59^{+1.71}_{-1.31}$	10.2
1.45–1.80	203 ± 22	8.24 ± 0.15	$5.01 \pm 0.55 \pm 0.42$	$4.96^{+1.88}_{-1.10}$	9.5
1.80–2.40	176 ± 22	6.31 ± 0.12	$3.31 \pm 0.42 \pm 0.28$	$4.29^{+1.73}_{-1.14}$	8.5

and background events were generated randomly from the PDFs in each bin. The fitted yields were unbiased and the uncertainties were estimated properly. The effects of correlations between M_B and ct were studied by mixing together fully simulated signal and background events to produce 100 pseudoexperiments. No significant evidence of bias in the signal yield was found, and the observed deviations (a few percent) between fitted and generated yields are taken as the systematic uncertainty due to potential biases in the fit method.

Table I summarizes the fitted signal yield in each bin of p_T^B and $|y^B|$, while Fig. 1 shows the fit projections for M_B and ct from the inclusive sample with $p_T^B > 5$ GeV and $|y^B| < 2.4$. The total number of signal events is 912 ± 47, where the error is statistical only.

The differential cross sections for B^+ production as a function of p_T^B and y^B (averaged for positive and negative rapidities) are defined as

$$\frac{d\sigma(pp \to B^+X)}{dp_T^B} = \frac{n_{\rm sig}(p_T^B)}{2\epsilon(p_T^B)\mathcal{B}\mathcal{L}\Delta p_T^B},$$
$$\frac{d\sigma(pp \to B^+X)}{dy^B} = \frac{n_{\rm sig}(|y^B|)}{2\epsilon(|y^B|)\mathcal{B}\mathcal{L}\Delta y^B}, \qquad (2)$$

where $n_{\rm sig}(p_T^B)$ and $n_{\rm sig}(|y^B|)$ are the fitted signal yields in the given bin, $\epsilon(p_T^B)$ and $\epsilon(|y^B|)$ are the efficiencies in each bin for a B^+ meson produced with $p_T^B > 5$ GeV and $|y^B| < 2.4$ to pass all the selection criteria, Δp_T^B is the bin size in p_T^B, and $\Delta y^B = 2\Delta|y^B|$ is the bin size in y^B. The total branching fraction $\mathcal{B}$ is the product of the individual branching fractions $\mathcal{B}(B^+ \to J/\psi K^+) = (1.014 \pm 0.034) \times 10^{-3}$ and $\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.93 \pm 0.06) \times 10^{-2}$ [20]. The factor of 2 in the denominator of Eq. (2) takes into account the choice of quoting the cross section for a single charge (taken to be B^+), while $n_{\rm sig}$ includes both charge states. All efficiencies, $\epsilon(p_T^B)$ or $\epsilon(|y^B|)$, are calculated separately in each bin, and account for bin-to-bin migrations (a few percent) due to the resolution on the measured momentum and rapidity.

The cross section is affected by several sources of systematic uncertainty arising from the signal yields, efficiencies, branching fractions, and luminosity. Uncertainties of the signal yields arise from potential fit biases and imperfect knowledge of the PDF parameters (2%–5%), ct resolution function (1%–2%), and the effects of final-state radiation on the signal shape in M_B (< 1%). Uncertainties of the trigger (2%), muon identification (1%), and tracking (1%–4%) efficiencies are all determined directly from data. The contribution (1%–4%) related to the B^+ momentum spectrum is evaluated by reweighting the shape of the p_T^B distribution generated with PYTHIA to match the spectrum predicted by MC@NLO 3.4 [27]. An uncertainty of 1.5% is assigned to the efficiency of the vertex quality requirement. The effect of tracker misalignment on the cross sections due to variations in the signal yields and efficiencies is estimated to be approximately 2% using samples simulated with a different alignment than the nominal one. The total systematic uncertainty of the cross section measurement in each bin is computed as the sum in quadrature of the individual uncertainties, and is summarized in Table I. In addition, there are common uncertainties of 3.5% from the branching fractions and 11% from the luminosity measurement [28].

The differential cross sections as functions of p_T^B and $|y^B|$ are shown in Fig. 2 and Table I. They are compared with the predictions of MC@NLO using a b-quark mass of 4.75 GeV, renormalization and factorization scales $\mu = \sqrt{m_b^2 + p_T^2}$, and the CTEQ6M parton distribution

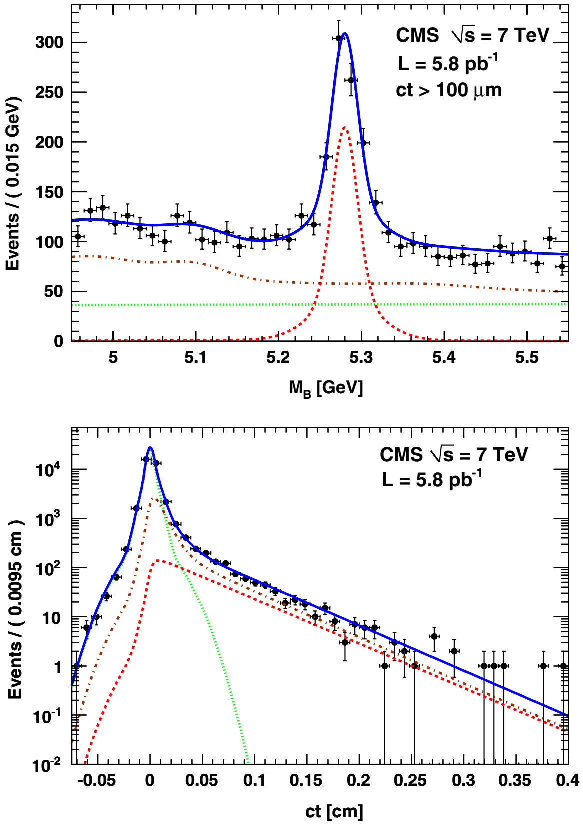

FIG. 1 (color online). Projections of the fit results in M_B (top) and ct (bottom) for $p_T^B > 5$ GeV and $|y^B| < 2.4$. The curves in each plot are the sum of all contributions (solid blue line); signal (dashed red); prompt J/ψ (dotted green); and the sum of nonprompt J/ψ, peaking $b\bar{b}$, and $J/\psi\pi^+$ (dot-dashed brown). For better visibility of the individual contributions, the M_B plot includes a requirement of $ct > 100\ \mu$m.

functions [29]. The uncertainty on the predicted cross section is calculated by varying the renormalization and factorization scales by a factor of 2, m_b by ±0.25 GeV, and by using the CTEQ6.6 parton distribution set. For reference, the prediction of PYTHIA is also included, using a b-quark mass of 4.8 GeV, CTEQ6L1 parton distributions [29], and the D6T tune [30] to simulate the underlying event. The total integrated cross section for $p_T^B > 5$ GeV and $|y^B| < 2.4$ is calculated as the sum over all p_T^B bins and is found to be $28.1 \pm 2.4 \pm 2.0 \pm 3.1\ \mu$b, where the first uncertainty is statistical, the second is systematic (including the branching fraction uncertainty), and the last is from the luminosity measurement. This result lies between the predictions of MC@NLO, $25.5^{+8.8}_{-5.4}(\text{scale})^{+2.5}_{-1.8} \times (\text{mass}) \pm 0.8(\text{PDF})\ \mu$b, and PYTHIA ($48.1\ \mu$b).

In summary, first measurements of the total and differential cross sections for charged B production in pp collisions at $\sqrt{s} = 7$ TeV using the decay $B^{\pm} \rightarrow J/\psi K^{\pm}$ have been presented. The measurements cover the range $|y^B| < 2.4$ and p_T^B from 5 GeV to greater than 30 GeV. The result is in reasonable agreement with the predictions of MC@NLO in terms of shape and absolute normalization.

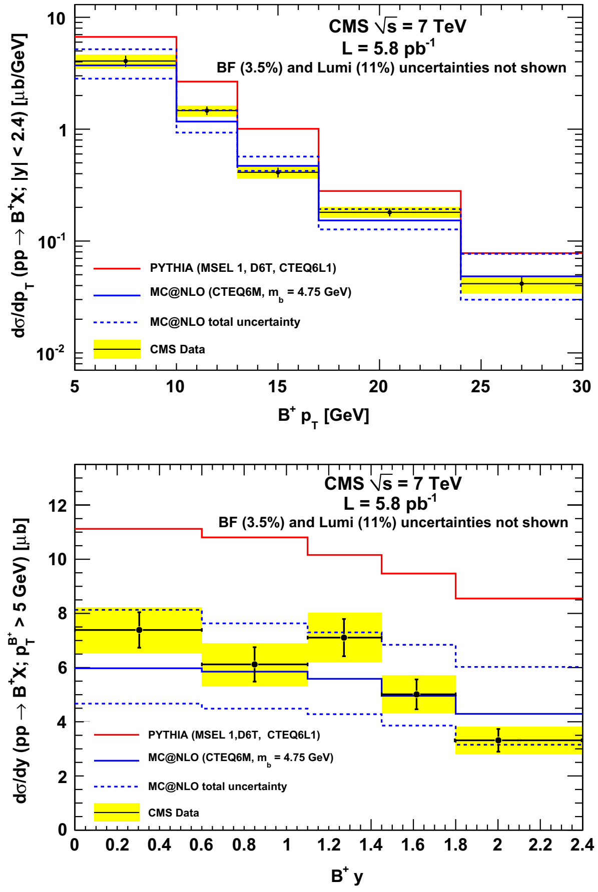

FIG. 2 (color online). Measured differential cross sections $d\sigma/dp_T^B$ (top) and $d\sigma/dy^B$ (bottom) compared with the theory predictions. The error bars are the statistical uncertainties, while the (yellow or light gray) band represents the sum in quadrature of statistical and systematic uncertainties, excluding the common branching fraction and luminosity uncertainties. The solid and dashed blue lines are the MC@NLO prediction and its uncertainty, respectively. The solid red line is the PYTHIA prediction.

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L. Litov,[14] E. Marinova,[14] M. Mateev,[14] B. Pavlov,[14] P. Petkov,[14] J. G. Bian,[15] G. M. Chen,[15] H. S. Chen,[15]
C. H. Jiang,[15] D. Liang,[15] S. Liang,[15] J. Wang,[15] J. Wang,[15] X. Wang,[15] Z. Wang,[15] M. Xu,[15] M. Yang,[15] J. Zang,[15]
Z. Zhang,[15] Y. Ban,[16] S. Guo,[16] Y. Guo,[16] W. Li,[16] Y. Mao,[16] S. J. Qian,[16] H. Teng,[16] L. Zhang,[16] B. Zhu,[16] W. Zou,[16]
A. Cabrera,[17] B. Gomez Moreno,[17] A. A. Ocampo Rios,[17] A. F. Osorio Oliveros,[17] J. C. Sanabria,[17] N. Godinovic,[18]
D. Lelas,[18] K. Lelas,[18] R. Plestina,[18,d] D. Polic,[18] I. Puljak,[18] Z. Antunovic,[19] M. Dzelalija,[19] V. Brigljevic,[20]
S. Duric,[20] K. Kadija,[20] S. Morovic,[20] A. Attikis,[21] M. Galanti,[21] J. Mousa,[21] C. Nicolaou,[21] F. Ptochos,[21]
P. A. Razis,[21] H. Rykaczewski,[21] Y. Assran,[22,e] M. A. Mahmoud,[22,f] A. Hektor,[23] M. Kadastik,[23] K. Kannike,[23]
M. Müntel,[23] M. Raidal,[23] L. Rebane,[23] V. Azzolini,[24] P. Eerola,[24] S. Czellar,[25] J. Härkönen,[25] A. Heikkinen,[25]
V. Karimäki,[25] R. Kinnunen,[25] J. Klem,[25] M. J. Kortelainen,[25] T. Lampén,[25] K. Lassila-Perini,[25] S. Lehti,[25]
T. Lindén,[25] P. Luukka,[25] T. Mäenpää,[25] E. Tuominen,[25] J. Tuominiemi,[25] E. Tuovinen,[25] D. Ungaro,[25]
L. Wendland,[25] K. Banzuzi,[26] A. Korpela,[26] T. Tuuva,[26] D. Sillou,[27] M. Besancon,[28] S. Choudhury,[28] M. Dejardin,[28]
D. Denegri,[28] B. Fabbro,[28] J. L. Faure,[28] F. Ferri,[28] S. Ganjour,[28] F. X. Gentit,[28] A. Givernaud,[28] P. Gras,[28]
G. Hamel de Monchenault,[28] P. Jarry,[28] E. Locci,[28] J. Malcles,[28] M. Marionneau,[28] L. Millischer,[28] J. Rander,[28]
A. Rosowsky,[28] I. Shreyber,[28] M. Titov,[28] P. Verrecchia,[28] S. Baffioni,[29] F. Beaudette,[29] L. Bianchini,[29] M. Bluj,[29,g]
C. Broutin,[29] P. Busson,[29] C. Charlot,[29] T. Dahms,[29] L. Dobrzynski,[29] R. Granier de Cassagnac,[29] M. Haguenauer,[29]
P. Miné,[29] C. Mironov,[29] C. Ochando,[29] P. Paganini,[29] D. Sabes,[29] R. Salerno,[29] Y. Sirois,[29] C. Thiebaux,[29]
B. Wyslouch,[29,h] A. Zabi,[29] J.-L. Agram,[30,i] J. Andrea,[30] A. Besson,[30] D. Bloch,[30] D. Bodin,[30] J.-M. Brom,[30]
M. Cardaci,[30] E. C. Chabert,[30] C. Collard,[30] E. Conte,[30,i] F. Drouhin,[30,i] C. Ferro,[30] J.-C. Fontaine,[30,i] D. Gelé,[30]
U. Goerlach,[30] S. Greder,[30] P. Juillot,[30] M. Karim,[30,i] A.-C. Le Bihan,[30] Y. Mikami,[30] P. Van Hove,[30] F. Fassi,[31]
D. Mercier,[31] C. Baty,[32] N. Beaupere,[32] M. Bedjidian,[32] O. Bondu,[32] G. Boudoul,[32] D. Boumediene,[32] H. Brun,[32]
N. Chanon,[32] R. Chierici,[32] D. Contardo,[32] P. Depasse,[32] H. El Mamouni,[32] A. Falkiewicz,[32] J. Fay,[32] S. Gascon,[32]
B. Ille,[32] T. Kurca,[32] T. Le Grand,[32] M. Lethuillier,[32] L. Mirabito,[32] S. Perries,[32] V. Sordini,[32] S. Tosi,[32] Y. Tschudi,[32]
P. Verdier,[32] H. Xiao,[32] V. Roinishvili,[33] D. Lomidze,[34] G. Anagnostou,[35] M. Edelhoff,[35] L. Feld,[35] N. Heracleous,[35]
O. Hindrichs,[35] R. Jussen,[35] K. Klein,[35] J. Merz,[35] N. Mohr,[35] A. Ostapchuk,[35] A. Perieanu,[35] F. Raupach,[35]
J. Sammet,[35] S. Schael,[35] D. Sprenger,[35] H. Weber,[35] M. Weber,[35] B. Wittmer,[35] M. Ata,[36] W. Bender,[36]
M. Erdmann,[36] J. Frangenheim,[36] T. Hebbeker,[36] A. Hinzmann,[36] K. Hoepfner,[36] C. Hof,[36] T. Klimkovich,[36]
D. Klingebiel,[36] P. Kreuzer,[36] D. Lanske,[36,a] C. Magass,[36] G. Masetti,[36] M. Merschmeyer,[36] A. Meyer,[36] P. Papacz,[36]
H. Pieta,[36] H. Reithler,[36] S. A. Schmitz,[36] L. Sonnenschein,[36] J. Steggemann,[36] D. Teyssier,[36] M. Bontenackels,[37]
M. Davids,[37] M. Duda,[37] G. Flügge,[37] H. Geenen,[37] M. Giffels,[37] W. Haj Ahmad,[37] D. Heydhausen,[37] T. Kress,[37]
Y. Kuessel,[37] A. Linn,[37] A. Nowack,[37] L. Perchalla,[37] O. Pooth,[37] J. Rennefeld,[37] P. Sauerland,[37] A. Stahl,[37]
M. Thomas,[37] D. Tornier,[37] M. H. Zoeller,[37] M. Aldaya Martin,[38] W. Behrenhoff,[38] U. Behrens,[38] M. Bergholz,[38,j]
K. Borras,[38] A. Cakir,[38] A. Campbell,[38] E. Castro,[38] D. Dammann,[38] G. Eckerlin,[38] D. Eckstein,[38] A. Flossdorf,[38]
G. Flucke,[38] A. Geiser,[38] I. Glushkov,[38] J. Hauk,[38] H. Jung,[38] M. Kasemann,[38] I. Katkov,[38] P. Katsas,[38]
C. Kleinwort,[38] H. Kluge,[38] A. Knutsson,[38] D. Krücker,[38] E. Kuznetsova,[38] W. Lange,[38] W. Lohmann,[38,j]
R. Mankel,[38] M. Marienfeld,[38] I.-A. Melzer-Pellmann,[38] A. B. Meyer,[38] J. Mnich,[38] A. Mussgiller,[38] J. Olzem,[38]
A. Parenti,[38] A. Raspereza,[38] A. Raval,[38] R. Schmidt,[38,j] T. Schoerner-Sadenius,[38] N. Sen,[38] M. Stein,[38]
J. Tomaszewska,[38] D. Volyanskyy,[38] R. Walsh,[38] C. Wissing,[38] C. Autermann,[39] S. Bobrovskyi,[39] J. Draeger,[39]
H. Enderle,[39] U. Gebbert,[39] K. Kaschube,[39] G. Kaussen,[39] R. Klanner,[39] J. Lange,[39] B. Mura,[39]
S. Naumann-Emme,[39] F. Nowak,[39] N. Pietsch,[39] C. Sander,[39] H. Schettler,[39] P. Schleper,[39] M. Schröder,[39]
T. Schum,[39] J. Schwandt,[39] A. K. Srivastava,[39] H. Stadie,[39] G. Steinbrück,[39] J. Thomsen,[39] R. Wolf,[39] C. Barth,[40]
J. Bauer,[40] V. Buege,[40] T. Chwalek,[40] W. De Boer,[40] A. Dierlamm,[40] G. Dirkes,[40] M. Feindt,[40] J. Gruschke,[40]
C. Hackstein,[40] F. Hartmann,[40] S. M. Heindl,[40] M. Heinrich,[40] H. Held,[40] K. H. Hoffmann,[40] S. Honc,[40] T. Kuhr,[40]
D. Martschei,[40] S. Mueller,[40] Th. Müller,[40] M. Niegel,[40] O. Oberst,[40] A. Oehler,[40] J. Ott,[40] T. Peiffer,[40] D. Piparo,[40]
G. Quast,[40] K. Rabbertz,[40] F. Ratnikov,[40] M. Renz,[40] C. Saout,[40] A. Scheurer,[40] P. Schieferdecker,[40] F.-P. Schilling,[40]
G. Schott,[40] H. J. Simonis,[40] F. M. Stober,[40] D. Troendle,[40] J. Wagner-Kuhr,[40] M. Zeise,[40] V. Zhukov,[40,k]
E. B. Ziebarth,[40] G. Daskalakis,[41] T. Geralis,[41] S. Kesisoglou,[41] A. Kyriakis,[41] D. Loukas,[41] I. Manolakos,[41]
A. Markou,[41] C. Markou,[41] C. Mavrommatis,[41] E. Ntomari,[41] E. Petrakou,[41] L. Gouskos,[42] T. J. Mertzimekis,[42]
A. Panagiotou,[42,b] I. Evangelou,[43] C. Foudas,[43] P. Kokkas,[43] N. Manthos,[43] I. Papadopoulos,[43] V. Patras,[43]
F. A. Triantis,[43] A. Aranyi,[44] G. Bencze,[44] L. Boldizsar,[44] G. Debreczeni,[44] C. Hajdu,[44,b] D. Horvath,[44,l] A. Kapusi,[44]
K. Krajczar,[44,m] A. Laszlo,[44] F. Sikler,[44] G. Vesztergombi,[44,m] N. Beni,[45] J. Molnar,[45] J. Palinkas,[45] Z. Szillasi,[45]
V. Veszpremi,[45] P. Raics,[46] Z. L. Trocsanyi,[46] B. Ujvari,[46] S. Bansal,[47] S. B. Beri,[47] V. Bhatnagar,[47] N. Dhingra,[47]

R. Gupta,[47] M. Jindal,[47] M. Kaur,[47] J. M. Kohli,[47] M. Z. Mehta,[47] N. Nishu,[47] L. K. Saini,[47] A. Sharma,[47]
R. Sharma,[47] A. P. Singh,[47] J. B. Singh,[47] S. P. Singh,[47] S. Ahuja,[48] S. Bhattacharya,[48] B. C. Choudhary,[48] P. Gupta,[48]
S. Jain,[48] S. Jain,[48] A. Kumar,[48] R. K. Shivpuri,[48] R. K. Choudhury,[49] D. Dutta,[49] S. Kailas,[49] S. K. Kataria,[49]
A. K. Mohanty,[49,b] L. M. Pant,[49] P. Shukla,[49] T. Aziz,[50] M. Guchait,[50,n] A. Gurtu,[50] M. Maity,[50,o] D. Majumder,[50]
G. Majumder,[50] K. Mazumdar,[50] G. B. Mohanty,[50] A. Saha,[50] K. Sudhakar,[50] N. Wickramage,[50] S. Banerjee,[51]
S. Dugad,[51] N. K. Mondal,[51] H. Arfaei,[52] H. Bakhshiansohi,[52] S. M. Etesami,[52] A. Fahim,[52] M. Hashemi,[52]
A. Jafari,[52] M. Khakzad,[52] A. Mohammadi,[52] M. Mohammadi Najafabadi,[52] S. Paktinat Mehdiabadi,[52]
B. Safarzadeh,[52] M. Zeinali,[52] M. Abbrescia,[53a,53b] L. Barbone,[53a,53b] C. Calabria,[53a,53b] A. Colaleo,[53a]
D. Creanza,[53a,53c] N. De Filippis,[53a,53c] M. De Palma,[53a,53b] A. Dimitrov,[53a] L. Fiore,[53a] G. Iaselli,[53a,53c]
L. Lusito,[53a,53b,b] G. Maggi,[53a,53c] M. Maggi,[53a] N. Manna,[53a,53b] B. Marangelli,[53a,53b] S. My,[53a,53c] S. Nuzzo,[53a,53b]
N. Pacifico,[53a,53b] G. A. Pierro,[53a] A. Pompili,[53a,53b] G. Pugliese,[53a,53c] F. Romano,[53a,53c] G. Roselli,[53a,53b]
G. Selvaggi,[53a,53b] L. Silvestris,[53a] R. Trentadue,[53a] S. Tupputi,[53a,53b] G. Zito,[53a] G. Abbiendi,[54a] A. C. Benvenuti,[54a]
D. Bonacorsi,[54a] S. Braibant-Giacomelli,[54a,54b] L. Brigliadori,[54a] P. Capiluppi,[54a,54b] A. Castro,[54a,54b]
F. R. Cavallo,[54a] M. Cuffiani,[54a,54b] G. M. Dallavalle,[54a] F. Fabbri,[54a] A. Fanfani,[54a,54b] D. Fasanella,[54a]
P. Giacomelli,[54a] M. Giunta,[54a] S. Marcellini,[54a] M. Meneghelli,[54a,54b] A. Montanari,[54a] F. L. Navarria,[54a,54b]
F. Odorici,[54a] A. Perrotta,[54a] F. Primavera,[54a] A. M. Rossi,[54a,54b] T. Rovelli,[54a,54b] G. Siroli,[54a,54b]
R. Travaglini,[54a,54b] S. Albergo,[55a,55b] G. Cappello,[55a,55b] M. Chiorboli,[55a,55b,b] S. Costa,[55a,55b] A. Tricomi,[55a,55b]
C. Tuve,[55a] G. Barbagli,[56a] V. Ciulli,[56a,56b] C. Civinini,[56a] R. D'Alessandro,[56a,56b] E. Focardi,[56a,56b] S. Frosali,[56a,56b]
E. Gallo,[56a] C. Genta,[56a] P. Lenzi,[56a,56b] M. Meschini,[56a] S. Paoletti,[56a] G. Sguazzoni,[56a] A. Tropiano,[56a,b]
L. Benussi,[57] S. Bianco,[57] S. Colafranceschi,[57,p] F. Fabbri,[57] D. Piccolo,[57] P. Fabbricatore,[58] R. Musenich,[58]
A. Benaglia,[59a,59b] F. De Guio,[59a,59b,b] L. Di Matteo,[59a,59b] A. Ghezzi,[59a,59b,b] M. Malberti,[59a,59b] S. Malvezzi,[59a]
A. Martelli,[59a,59b] A. Massironi,[59a,59b] D. Menasce,[59a] L. Moroni,[59a] M. Paganoni,[59a,59b] D. Pedrini,[59a]
S. Ragazzi,[59a,59b] N. Redaelli,[59a] S. Sala,[59a] T. Tabarelli de Fatis,[59a,59b] V. Tancini,[59a,59b] S. Buontempo,[60a]
C. A. Carrillo Montoya,[60a] A. Cimmino,[60a,60b] A. De Cosa,[60a,60b] M. De Gruttola,[60a,60b] F. Fabozzi,[60a,q]
A. O. M. Iorio,[60a] L. Lista,[60a] M. Merola,[60a,60b] P. Noli,[60a,60b] P. Paolucci,[60a] P. Azzi,[61a] N. Bacchetta,[61a]
P. Bellan,[61a,61b] D. Bisello,[61a,61b] A. Branca,[61a] R. Carlin,[61a,61b] P. Checchia,[61a] E. Conti,[61a] M. De Mattia,[61a,61b]
T. Dorigo,[61a] U. Dosselli,[61a] F. Fanzago,[61a] F. Gasparini,[61a,61b] U. Gasparini,[61a,61b] P. Giubilato,[61a,61b]
A. Gresele,[61a,61c] S. Lacaprara,[61a,qq] I. Lazzizzera,[61a,61c] M. Margoni,[61a,61b] M. Mazzucato,[61a]
A. T. Meneguzzo,[61a,61b] L. Perrozzi,[61a,b] N. Pozzobon,[61a,61b] P. Ronchese,[61a,61b] F. Simonetto,[61a,61b] E. Torassa,[61a]
M. Tosi,[61a,61b] S. Vanini,[61a,61b] P. Zotto,[61a,61b] G. Zumerle,[61a,61b] P. Baesso,[62a,62b] U. Berzano,[62a] C. Riccardi,[62a,62b]
P. Torre,[62a,62b] P. Vitulo,[62a,62b] C. Viviani,[62a,62b] M. Biasini,[63a,63b] G. M. Bilei,[63a] B. Caponeri,[63a,63b] L. Fanò,[63a,63b]
P. Lariccia,[63a,63b] A. Lucaroni,[63a,63b,b] G. Mantovani,[63a,63b] M. Menichelli,[63a] A. Nappi,[63a,63b] A. Santocchia,[63a,63b]
L. Servoli,[63a] S. Taroni,[63a,63b] M. Valdata,[63a,63b] R. Volpe,[63a,63b,b] P. Azzurri,[64a,64c] G. Bagliesi,[64a]
J. Bernardini,[64a,64b] T. Boccali,[64a,b] G. Broccolo,[64a,64c] R. Castaldi,[64a] R. T. D'Agnolo,[64a,64c] R. Dell'Orso,[64a]
F. Fiori,[64a,64b] L. Foà,[64a,64c] A. Giassi,[64a] A. Kraan,[64a] F. Ligabue,[64a,64c] T. Lomtadze,[64a] L. Martini,[64a]
A. Messineo,[64a,64b] F. Palla,[64a] F. Palmonari,[64a] S. Sarkar,[64a,64c] G. Segneri,[64a] A. T. Serban,[64a] P. Spagnolo,[64a]
R. Tenchini,[64a] G. Tonelli,[64a,64b,b] A. Venturi,[64a,b] P. G. Verdini,[64a] L. Barone,[65a,65b] F. Cavallari,[65a] D. Del Re,[65a,65b]
E. Di Marco,[65a,65b] M. Diemoz,[65a] D. Franci,[65a,65b] M. Grassi,[65a] E. Longo,[65a,65b] G. Organtini,[65a,65b]
A. Palma,[65a,65b] F. Pandolfi,[65a,65b,b] R. Paramatti,[65a] S. Rahatlou,[65a,65b] N. Amapane,[66a,66b] R. Arcidiacono,[66a,66c]
S. Argiro,[66a,66b] M. Arneodo,[66a,66c] C. Biino,[66a] C. Botta,[66a,66b,b] N. Cartiglia,[66a] R. Castello,[66a,66b] M. Costa,[66a,66b]
N. Demaria,[66a] A. Graziano,[66a,66b,b] C. Mariotti,[66a] M. Marone,[66a,66b] S. Maselli,[66a] E. Migliore,[66a,66b] G. Mila,[66a,66b]
V. Monaco,[66a,66b] M. Musich,[66a,66b] M. M. Obertino,[66a,66c] N. Pastrone,[66a] M. Pelliccioni,[66a,66b,b] A. Romero,[66a,66b]
M. Ruspa,[66a,66c] R. Sacchi,[66a,66b] V. Sola,[66a,66b] A. Solano,[66a,66b] A. Staiano,[66a] D. Trocino,[66a,66b]
A. Vilela Pereira,[66a,66b,b] F. Ambroglini,[67a,67b] S. Belforte,[67a] F. Cossutti,[67a] G. Della Ricca,[67a,67b] B. Gobbo,[67a]
D. Montanino,[67a,67b] A. Penzo,[67a] S. G. Heo,[68] S. Chang,[69] J. Chung,[69] D. H. Kim,[69] G. N. Kim,[69] J. E. Kim,[69]
D. J. Kong,[69] H. Park,[69] D. Son,[69] D. C. Son,[69] Zero Kim,[70] J. Y. Kim,[70] S. Song,[70] S. Choi,[71] B. Hong,[71] M. Jo,[71]
H. Kim,[71] J. H. Kim,[71] T. J. Kim,[71] K. S. Lee,[71] D. H. Moon,[71] S. K. Park,[71] H. B. Rhee,[71] E. Seo,[71] S. Shin,[71]
K. S. Sim,[71] M. Choi,[72] S. Kang,[72] H. Kim,[72] C. Park,[72] I. C. Park,[72] S. Park,[72] G. Ryu,[72] Y. Choi,[73] Y. K. Choi,[73]
J. Goh,[73] J. Lee,[73] S. Lee,[73] H. Seo,[73] I. Yu,[73] M. J. Bilinskas,[74] I. Grigelionis,[74] M. Janulis,[74] D. Martisiute,[74]
P. Petrov,[74] T. Sabonis,[74] H. Castilla Valdez,[75] E. De La Cruz Burelo,[75] R. Lopez-Fernandez,[75]
A. Sánchez Hernández,[75] L. M. Villasenor-Cendejas,[75] S. Carrillo Moreno,[76] F. Vazquez Valencia,[76]

H. A. Salazar Ibarguen,[77] E. Casimiro Linares,[78] A. Morelos Pineda,[78] M. A. Reyes-Santos,[78] P. Allfrey,[79]
D. Krofcheck,[79] P. H. Butler,[80] R. Doesburg,[80] H. Silverwood,[80] M. Ahmad,[81] I. Ahmed,[81] M. I. Asghar,[81]
H. R. Hoorani,[81] W. A. Khan,[81] T. Khurshid,[81] S. Qazi,[81] M. Cwiok,[82] W. Dominik,[82] K. Doroba,[82] A. Kalinowski,[82]
M. Konecki,[82] J. Krolikowski,[82] T. Frueboes,[83] R. Gokieli,[83] M. Górski,[83] M. Kazana,[83] K. Nawrocki,[83]
K. Romanowska-Rybinska,[83] M. Szleper,[83] G. Wrochna,[83] P. Zalewski,[83] N. Almeida,[84] A. David,[84] P. Faccioli,[84]
P. G. Ferreira Parracho,[84] M. Gallinaro,[84] P. Martins,[84] P. Musella,[84] A. Nayak,[84] P. Q. Ribeiro,[84] J. Seixas,[84]
P. Silva,[84] J. Varela,[84,b] H. K. Wöhri,[84] I. Belotelov,[85] P. Bunin,[85] M. Finger,[85] M. Finger, Jr.,[85] I. Golutvin,[85]
A. Kamenev,[85] V. Karjavin,[85] G. Kozlov,[85] A. Lanev,[85] P. Moisenz,[85] V. Palichik,[85] V. Perelygin,[85] S. Shmatov,[85]
V. Smirnov,[85] A. Volodko,[85] A. Zarubin,[85] N. Bondar,[86] V. Golovtsov,[86] Y. Ivanov,[86] V. Kim,[86] P. Levchenko,[86]
V. Murzin,[86] V. Oreshkin,[86] I. Smirnov,[86] V. Sulimov,[86] L. Uvarov,[86] S. Vavilov,[86] A. Vorobyev,[86] Yu. Andreev,[87]
S. Gninenko,[87] N. Golubev,[87] M. Kirsanov,[87] N. Krasnikov,[87] V. Matveev,[87] A. Pashenkov,[87] A. Toropin,[87]
S. Troitsky,[87] V. Epshteyn,[88] V. Gavrilov,[88] V. Kaftanov,[88,a] M. Kossov,[88,b] A. Krokhotin,[88] N. Lychkovskaya,[88]
G. Safronov,[88] S. Semenov,[88] V. Stolin,[88] E. Vlasov,[88] A. Zhokin,[88] E. Boos,[89] M. Dubinin,[89,r] L. Dudko,[89]
A. Ershov,[89] A. Gribushin,[89] O. Kodolova,[89] I. Lokhtin,[89] S. Obraztsov,[89] S. Petrushanko,[89] L. Sarycheva,[89]
V. Savrin,[89] A. Snigirev,[89] V. Andreev,[90] M. Azarkin,[90] I. Dremin,[90] M. Kirakosyan,[90] S. V. Rusakov,[90]
A. Vinogradov,[90] I. Azhgirey,[91] S. Bitioukov,[91] V. Grishin,[91,b] V. Kachanov,[91] D. Konstantinov,[91] A. Korablev,[91]
V. Krychkine,[91] V. Petrov,[91] R. Ryutin,[91] S. Slabospitsky,[91] A. Sobol,[91] L. Tourtchanovitch,[91] S. Troshin,[91]
N. Tyurin,[91] A. Uzunian,[91] A. Volkov,[91] P. Adzic,[92,s] M. Djordjevic,[92] D. Krpic,[92,s] J. Milosevic,[92]
M. Aguilar-Benitez,[93] J. Alcaraz Maestre,[93] P. Arce,[93] C. Battilana,[93] E. Calvo,[93] M. Cepeda,[93] M. Cerrada,[93]
N. Colino,[93] B. De La Cruz,[93] C. Diez Pardos,[93] D. Domínguez Vázquez,[93] C. Fernandez Bedoya,[93]
J. P. Fernández Ramos,[93] A. Ferrando,[93] J. Flix,[93] M. C. Fouz,[93] P. Garcia-Abia,[93] O. Gonzalez Lopez,[93]
S. Goy Lopez,[93] J. M. Hernandez,[93] M. I. Josa,[93] G. Merino,[93] J. Puerta Pelayo,[93] I. Redondo,[93] L. Romero,[93]
J. Santaolalla,[93] C. Willmott,[93] C. Albajar,[94] G. Codispoti,[94] J. F. de Trocóniz,[94] J. Cuevas,[95]
J. Fernandez Menendez,[95] S. Folgueras,[95] I. Gonzalez Caballero,[95] L. Lloret Iglesias,[95] J. M. Vizan Garcia,[95]
J. A. Brochero Cifuentes,[96] I. J. Cabrillo,[96] A. Calderon,[96] M. Chamizo Llatas,[96] S. H. Chuang,[96]
J. Duarte Campderros,[96] M. Felcini,[96,t] M. Fernandez,[96] G. Gomez,[96] J. Gonzalez Sanchez,[96] C. Jorda,[96]
P. Lobelle Pardo,[96] A. Lopez Virto,[96] J. Marco,[96] R. Marco,[96] C. Martinez Rivero,[96] F. Matorras,[96]
F. J. Munoz Sanchez,[96] J. Piedra Gomez,[96,u] T. Rodrigo,[96] A. Ruiz Jimeno,[96] L. Scodellaro,[96] M. Sobron Sanudo,[96]
I. Vila,[96] R. Vilar Cortabitarte,[96] D. Abbaneo,[97] E. Auffray,[97] G. Auzinger,[97] P. Baillon,[97] A. H. Ball,[97] D. Barney,[97]
A. J. Bell,[97,v] D. Benedetti,[97] C. Bernet,[97,d] W. Bialas,[97] P. Bloch,[97] A. Bocci,[97] S. Bolognesi,[97] H. Breuker,[97]
G. Brona,[97] K. Bunkowski,[97] T. Camporesi,[97] E. Cano,[97] G. Cerminara,[97] T. Christiansen,[97] J. A. Coarasa Perez,[97]
B. Curé,[97] D. D'Enterria,[97] A. De Roeck,[97] F. Duarte Ramos,[97] A. Elliott-Peisert,[97] B. Frisch,[97] W. Funk,[97]
A. Gaddi,[97] S. Gennai,[97] G. Georgiou,[97] H. Gerwig,[97] D. Gigi,[97] K. Gill,[97] D. Giordano,[97] F. Glege,[97]
R. Gomez-Reino Garrido,[97] M. Gouzevitch,[97] P. Govoni,[97] S. Gowdy,[97] L. Guiducci,[97] M. Hansen,[97] J. Harvey,[97]
J. Hegeman,[97] B. Hegner,[97] C. Henderson,[97] G. Hesketh,[97] H. F. Hoffmann,[97] A. Honma,[97] V. Innocente,[97] P. Janot,[97]
E. Karavakis,[97] P. Lecoq,[97] C. Leonidopoulos,[97] C. Lourenço,[97] A. Macpherson,[97] T. Mäki,[97] L. Malgeri,[97]
M. Mannelli,[97] L. Masetti,[97] F. Meijers,[97] S. Mersi,[97] E. Meschi,[97] R. Moser,[97] M. U. Mozer,[97] M. Mulders,[97]
E. Nesvold,[97,b] M. Nguyen,[97] T. Orimoto,[97] L. Orsini,[97] E. Perez,[97] A. Petrilli,[97] A. Pfeiffer,[97] M. Pierini,[97]
M. Pimiä,[97] G. Polese,[97] A. Racz,[97] J. Rodrigues Antunes,[97] G. Rolandi,[97,w] T. Rommerskirchen,[97] C. Rovelli,[97,x]
M. Rovere,[97] H. Sakulin,[97] C. Schäfer,[97] C. Schwick,[97] I. Segoni,[97] A. Sharma,[97] P. Siegrist,[97] M. Simon,[97]
P. Sphicas,[97,y] D. Spiga,[97] M. Spiropulu,[97,r] F. Stöckli,[97] M. Stoye,[97] P. Tropea,[97] A. Tsirou,[97] A. Tsyganov,[97]
G. I. Veres,[97,m] P. Vichoudis,[97] M. Voutilainen,[97] W. D. Zeuner,[97] W. Bertl,[98] K. Deiters,[98] W. Erdmann,[98]
K. Gabathuler,[98] R. Horisberger,[98] Q. Ingram,[98] H. C. Kaestli,[98] S. König,[98] D. Kotlinski,[98] U. Langenegger,[98]
F. Meier,[98] D. Renker,[98] T. Rohe,[98] J. Sibille,[98,z] A. Starodumov,[98,aa] P. Bortignon,[99] L. Caminada,[99,bb] Z. Chen,[99]
S. Cittolin,[99] G. Dissertori,[99] M. Dittmar,[99] J. Eugster,[99] K. Freudenreich,[99] C. Grab,[99] A. Hervé,[99] W. Hintz,[99]
P. Lecomte,[99] W. Lustermann,[99] C. Marchica,[99,bb] P. Martinez Ruiz del Arbol,[99] P. Meridiani,[99] P. Milenovic,[99,cc]
F. Moortgat,[99] P. Nef,[99] F. Nessi-Tedaldi,[99] L. Pape,[99] F. Pauss,[99] T. Punz,[99] A. Rizzi,[99] F. J. Ronga,[99] M. Rossini,[99]
L. Sala,[99] A. K. Sanchez,[99] M.-C. Sawley,[99] B. Stieger,[99] L. Tauscher,[99,a] A. Thea,[99] K. Theofilatos,[99] D. Treille,[99]
C. Urscheler,[99] R. Wallny,[99] M. Weber,[99] L. Wehrli,[99] J. Weng,[99] E. Aguiló,[100] C. Amsler,[100] V. Chiochia,[100]
S. De Visscher,[100] C. Favaro,[100] M. Ivova Rikova,[100] B. Millan Mejias,[100] C. Regenfus,[100] P. Robmann,[100]
A. Schmidt,[100] H. Snoek,[100] Y. H. Chang,[101] K. H. Chen,[101] W. T. Chen,[101] S. Dutta,[101] A. Go,[101] C. M. Kuo,[101]

S. W. Li,[101] W. Lin,[101] M. H. Liu,[101] Z. K. Liu,[101] Y. J. Lu,[101] J. H. Wu,[101] S. S. Yu,[101] P. Bartalini,[102] P. Chang,[102] Y. H. Chang,[102] Y. W. Chang,[102] Y. Chao,[102] K. F. Chen,[102] W.-S. Hou,[102] Y. Hsiung,[102] K. Y. Kao,[102] Y. J. Lei,[102] R.-S. Lu,[102] J. G. Shiu,[102] Y. M. Tzeng,[102] M. Wang,[102] A. Adiguzel,[103] M. N. Bakirci,[103,dd] S. Cerci,[103,ee] C. Dozen,[103] I. Dumanoglu,[103] E. Eskut,[103] S. Girgis,[103] G. Gokbulut,[103] Y. Guler,[103] E. Gurpinar,[103] I. Hos,[103] E. E. Kangal,[103] T. Karaman,[103] A. Kayis Topaksu,[103] A. Nart,[103] G. Onengut,[103] K. Ozdemir,[103] S. Ozturk,[103] A. Polatoz,[103] K. Sogut,[103,ff] B. Tali,[103] H. Topakli,[103,dd] D. Uzun,[103] L. N. Vergili,[103] M. Vergili,[103] C. Zorbilmez,[103] I. V. Akin,[104] T. Aliev,[104] S. Bilmis,[104] M. Deniz,[104] H. Gamsizkan,[104] A. M. Guler,[104] K. Ocalan,[104] A. Ozpineci,[104] M. Serin,[104] R. Sever,[104] U. E. Surat,[104] E. Yildirim,[104] M. Zeyrek,[104] M. Deliomeroglu,[105] D. Demir,[105,gg] E. Gülmez,[105] A. Halu,[105] B. Isildak,[105] M. Kaya,[105,hh] O. Kaya,[105,hh] S. Ozkorucuklu,[105,ii] N. Sonmez,[105,jj] L. Levchuk,[106] P. Bell,[107] F. Bostock,[107] J. J. Brooke,[107] T. L. Cheng,[107] E. Clement,[107] D. Cussans,[107] R. Frazier,[107] J. Goldstein,[107] M. Grimes,[107] M. Hansen,[107] D. Hartley,[107] G. P. Heath,[107] H. F. Heath,[107] B. Huckvale,[107] J. Jackson,[107] L. Kreczko,[107] S. Metson,[107] D. M. Newbold,[107,kk] K. Nirunpong,[107] A. Poll,[107] S. Senkin,[107] V. J. Smith,[107] S. Ward,[107] L. Basso,[108] K. W. Bell,[108] A. Belyaev,[108] C. Brew,[108] R. M. Brown,[108] B. Camanzi,[108] D. J. A. Cockerill,[108] J. A. Coughlan,[108] K. Harder,[108] S. Harper,[108] B. W. Kennedy,[108] E. Olaiya,[108] D. Petyt,[108] B. C. Radburn-Smith,[108] C. H. Shepherd-Themistocleous,[108] I. R. Tomalin,[108] W. J. Womersley,[108] S. D. Worm,[108] R. Bainbridge,[109] G. Ball,[109] J. Ballin,[109] R. Beuselinck,[109] O. Buchmuller,[109] D. Colling,[109] N. Cripps,[109] M. Cutajar,[109] G. Davies,[109] M. Della Negra,[109] J. Fulcher,[109] D. Futyan,[109] A. Guneratne Bryer,[109] G. Hall,[109] Z. Hatherell,[109] J. Hays,[109] G. Iles,[109] G. Karapostoli,[109] L. Lyons,[109] A.-M. Magnan,[109] J. Marrouche,[109] R. Nandi,[109] J. Nash,[109] A. Nikitenko,[109,aa] A. Papageorgiou,[109] M. Pesaresi,[109] K. Petridis,[109] M. Pioppi,[109,ll] D. M. Raymond,[109] N. Rompotis,[109] A. Rose,[109] M. J. Ryan,[109] C. Seez,[109] P. Sharp,[109] A. Sparrow,[109] A. Tapper,[109] S. Tourneur,[109] M. Vazquez Acosta,[109] T. Virdee,[109] S. Wakefield,[109] D. Wardrope,[109] T. Whyntie,[109] M. Barrett,[110] M. Chadwick,[110] J. E. Cole,[110] P. R. Hobson,[110] A. Khan,[110] P. Kyberd,[110] D. Leslie,[110] W. Martin,[110] I. D. Reid,[110] L. Teodorescu,[110] K. Hatakeyama,[111] T. Bose,[112] E. Carrera Jarrin,[112] A. Clough,[112] C. Fantasia,[112] A. Heister,[112] J. St. John,[112] P. Lawson,[112] D. Lazic,[112] J. Rohlf,[112] D. Sperka,[112] L. Sulak,[112] A. Avetisyan,[113] S. Bhattacharya,[113] J. P. Chou,[113] D. Cutts,[113] A. Ferapontov,[113] U. Heintz,[113] S. Jabeen,[113] G. Kukartsev,[113] G. Landsberg,[113] M. Narain,[113] D. Nguyen,[113] M. Segala,[113] T. Speer,[113] K. V. Tsang,[113] M. A. Borgia,[114] R. Breedon,[114] M. Calderon De La Barca Sanchez,[114] D. Cebra,[114] S. Chauhan,[114] M. Chertok,[114] J. Conway,[114] P. T. Cox,[114] J. Dolen,[114] R. Erbacher,[114] E. Friis,[114] W. Ko,[114] A. Kopecky,[114] R. Lander,[114] H. Liu,[114] S. Maruyama,[114] T. Miceli,[114] M. Nikolic,[114] D. Pellett,[114] J. Robles,[114] S. Salur,[114] T. Schwarz,[114] M. Searle,[114] J. Smith,[114] M. Squires,[114] M. Tripathi,[114] R. Vasquez Sierra,[114] C. Veelken,[114] V. Andreev,[115] K. Arisaka,[115] D. Cline,[115] R. Cousins,[115] A. Deisher,[115] J. Duris,[115] S. Erhan,[115] C. Farrell,[115] J. Hauser,[115] M. Ignatenko,[115] C. Jarvis,[115] C. Plager,[115] G. Rakness,[115] P. Schlein,[115,a] J. Tucker,[115] V. Valuev,[115] J. Babb,[116] R. Clare,[116] J. Ellison,[116] J. W. Gary,[116] F. Giordano,[116] G. Hanson,[116] G. Y. Jeng,[116] S. C. Kao,[116] F. Liu,[116] H. Liu,[116] A. Luthra,[116] H. Nguyen,[116] G. Pasztor,[116,mm] A. Satpathy,[116] B. C. Shen,[116,a] R. Stringer,[116] J. Sturdy,[116] S. Sumowidagdo,[116] R. Wilken,[116] S. Wimpenny,[116] W. Andrews,[117] J. G. Branson,[117] G. B. Cerati,[117] E. Dusinberre,[117] D. Evans,[117] F. Golf,[117] A. Holzner,[117] R. Kelley,[117] M. Lebourgeois,[117] J. Letts,[117] B. Mangano,[117] J. Muelmenstaedt,[117] S. Padhi,[117] C. Palmer,[117] G. Petrucciani,[117] H. Pi,[117] M. Pieri,[117] R. Ranieri,[117] M. Sani,[117] V. Sharma,[117,b] S. Simon,[117] Y. Tu,[117] A. Vartak,[117] F. Würthwein,[117] A. Yagil,[117] D. Barge,[118] R. Bellan,[118] C. Campagnari,[118] M. D'Alfonso,[118] T. Danielson,[118] K. Flowers,[118] P. Geffert,[118] J. Incandela,[118] C. Justus,[118] P. Kalavase,[118] S. A. Koay,[118] D. Kovalskyi,[118] V. Krutelyov,[118] S. Lowette,[118] N. Mccoll,[118] V. Pavlunin,[118] F. Rebassoo,[118] J. Ribnik,[118] J. Richman,[118] R. Rossin,[118] D. Stuart,[118] W. To,[118] J. R. Vlimant,[118] A. Bornheim,[119] J. Bunn,[119] Y. Chen,[119] M. Gataullin,[119] D. Kcira,[119] V. Litvine,[119] Y. Ma,[119] A. Mott,[119] H. B. Newman,[119] C. Rogan,[119] V. Timciuc,[119] P. Traczyk,[119] J. Veverka,[119] R. Wilkinson,[119] Y. Yang,[119] R. Y. Zhu,[119] B. Akgun,[120] R. Carroll,[120] T. Ferguson,[120] Y. Iiyama,[120] D. W. Jang,[120] S. Y. Jun,[120] Y. F. Liu,[120] M. Paulini,[120] J. Russ,[120] N. Terentyev,[120] H. Vogel,[120] I. Vorobiev,[120] J. P. Cumalat,[121] M. E. Dinardo,[121] B. R. Drell,[121] C. J. Edelmaier,[121] W. T. Ford,[121] B. Heyburn,[121] E. Luiggi Lopez,[121] U. Nauenberg,[121] J. G. Smith,[121] K. Stenson,[121] K. A. Ulmer,[121] S. R. Wagner,[121] S. L. Zang,[121] L. Agostino,[122] J. Alexander,[122] A. Chatterjee,[122] S. Das,[122] N. Eggert,[122] L. J. Fields,[122] L. K. Gibbons,[122] B. Heltsley,[122] W. Hopkins,[122] A. Khukhunaishvili,[122] B. Kreis,[122] V. Kuznetsov,[122] G. Nicolas Kaufman,[122] J. R. Patterson,[122] D. Puigh,[122] D. Riley,[122] A. Ryd,[122] X. Shi,[122] W. Sun,[122] W. D. Teo,[122] J. Thom,[122] J. Thompson,[122] J. Vaughan,[122] Y. Weng,[122] L. Winstrom,[122] P. Wittich,[122] A. Biselli,[123] G. Cirino,[123] D. Winn,[123] S. Abdullin,[124] M. Albrow,[124] J. Anderson,[124] G. Apollinari,[124] M. Atac,[124] J. A. Bakken,[124]

S. Banerjee,[124] L. A. T. Bauerdick,[124] A. Beretvas,[124] J. Berryhill,[124] P. C. Bhat,[124] I. Bloch,[124] F. Borcherding,[124]
K. Burkett,[124] J. N. Butler,[124] V. Chetluru,[124] H. W. K. Cheung,[124] F. Chlebana,[124] S. Cihangir,[124] M. Demarteau,[124]
D. P. Eartly,[124] V. D. Elvira,[124] S. Esen,[124] I. Fisk,[124] J. Freeman,[124] Y. Gao,[124] E. Gottschalk,[124] D. Green,[124]
K. Gunthoti,[124] O. Gutsche,[124] A. Hahn,[124] J. Hanlon,[124] R. M. Harris,[124] J. Hirschauer,[124] B. Hooberman,[124]
E. James,[124] H. Jensen,[124] M. Johnson,[124] U. Joshi,[124] R. Khatiwada,[124] B. Kilminster,[124] B. Klima,[124]
K. Kousouris,[124] S. Kunori,[124] S. Kwan,[124] P. Limon,[124] R. Lipton,[124] J. Lykken,[124] K. Maeshima,[124]
J. M. Marraffino,[124] D. Mason,[124] P. McBride,[124] T. McCauley,[124] T. Miao,[124] K. Mishra,[124] S. Mrenna,[124]
Y. Musienko,[124,nn] C. Newman-Holmes,[124] V. O'Dell,[124] S. Popescu,[124,oo] R. Pordes,[124] O. Prokofyev,[124]
N. Saoulidou,[124] E. Sexton-Kennedy,[124] S. Sharma,[124] A. Soha,[124] W. J. Spalding,[124] L. Spiegel,[124] P. Tan,[124]
L. Taylor,[124] S. Tkaczyk,[124] L. Uplegger,[124] E. W. Vaandering,[124] R. Vidal,[124] J. Whitmore,[124] W. Wu,[124] F. Yang,[124]
F. Yumiceva,[124] J. C. Yun,[124] D. Acosta,[125] P. Avery,[125] D. Bourilkov,[125] M. Chen,[125] G. P. Di Giovanni,[125]
D. Dobur,[125] A. Drozdetskiy,[125] R. D. Field,[125] M. Fisher,[125] Y. Fu,[125] I. K. Furic,[125] J. Gartner,[125] S. Goldberg,[125]
B. Kim,[125] S. Klimenko,[125] J. Konigsberg,[125] A. Korytov,[125] A. Kropivnitskaya,[125] T. Kypreos,[125] K. Matchev,[125]
G. Mitselmakher,[125] L. Muniz,[125] Y. Pakhotin,[125] C. Prescott,[125] R. Remington,[125] M. Schmitt,[125] B. Scurlock,[125]
P. Sellers,[125] N. Skhirtladze,[125] D. Wang,[125] J. Yelton,[125] M. Zakaria,[125] C. Ceron,[126] V. Gaultney,[126] L. Kramer,[126]
L. M. Lebolo,[126] S. Linn,[126] P. Markowitz,[126] G. Martinez,[126] J. L. Rodriguez,[126] T. Adams,[127] A. Askew,[127]
D. Bandurin,[127] J. Bochenek,[127] J. Chen,[127] B. Diamond,[127] S. V. Gleyzer,[127] J. Haas,[127] S. Hagopian,[127]
V. Hagopian,[127] M. Jenkins,[127] K. F. Johnson,[127] H. Prosper,[127] L. Quertenmont,[127] S. Sekmen,[127]
V. Veeraraghavan,[127] M. M. Baarmand,[128] B. Dorney,[128] S. Guragain,[128] M. Hohlmann,[128] H. Kalakhety,[128]
R. Ralich,[128] I. Vodopiyanov,[128] M. R. Adams,[129] I. M. Anghel,[129] L. Apanasevich,[129] Y. Bai,[129] V. E. Bazterra,[129]
R. R. Betts,[129] J. Callner,[129] R. Cavanaugh,[129] C. Dragoiu,[129] E. J. Garcia-Solis,[129] C. E. Gerber,[129] D. J. Hofman,[129]
S. Khalatyan,[129] F. Lacroix,[129] M. Malek,[129] C. O'Brien,[129] C. Silvestre,[129] A. Smoron,[129] D. Strom,[129]
N. Varelas,[129] U. Akgun,[130] E. A. Albayrak,[130] B. Bilki,[130] K. Cankocak,[130,pp] W. Clarida,[130] F. Duru,[130]
C. K. Lae,[130] E. McCliment,[130] J.-P. Merlo,[130] H. Mermerkaya,[130] A. Mestvirishvili,[130] A. Moeller,[130]
J. Nachtman,[130] C. R. Newsom,[130] E. Norbeck,[130] J. Olson,[130] Y. Onel,[130] F. Ozok,[130] S. Sen,[130] J. Wetzel,[130]
T. Yetkin,[130] K. Yi,[130] B. A. Barnett,[131] B. Blumenfeld,[131] A. Bonato,[131] C. Eskew,[131] D. Fehling,[131] G. Giurgiu,[131]
A. V. Gritsan,[131] Z. J. Guo,[131] G. Hu,[131] P. Maksimovic,[131] S. Rappoccio,[131] M. Swartz,[131] N. V. Tran,[131]
A. Whitbeck,[131] P. Baringer,[132] A. Bean,[132] G. Benelli,[132] O. Grachov,[132] M. Murray,[132] D. Noonan,[132]
V. Radicci,[132] S. Sanders,[132] J. S. Wood,[132] V. Zhukova,[132] T. Bolton,[133] I. Chakaberia,[133] A. Ivanov,[133]
M. Makouski,[133] Y. Maravin,[133] S. Shrestha,[133] I. Svintradze,[133] Z. Wan,[133] J. Gronberg,[134] D. Lange,[134]
D. Wright,[134] A. Baden,[135] M. Boutemeur,[135] S. C. Eno,[135] D. Ferencek,[135] J. A. Gomez,[135] N. J. Hadley,[135]
R. G. Kellogg,[135] M. Kirn,[135] Y. Lu,[135] A. C. Mignerey,[135] K. Rossato,[135] P. Rumerio,[135] F. Santanastasio,[135]
A. Skuja,[135] J. Temple,[135] M. B. Tonjes,[135] S. C. Tonwar,[135] E. Twedt,[135] B. Alver,[136] G. Bauer,[136] J. Bendavid,[136]
W. Busza,[136] E. Butz,[136] I. A. Cali,[136] M. Chan,[136] V. Dutta,[136] P. Everaerts,[136] G. Gomez Ceballos,[136]
M. Goncharov,[136] K. A. Hahn,[136] P. Harris,[136] Y. Kim,[136] M. Klute,[136] Y.-J. Lee,[136] W. Li,[136] C. Loizides,[136]
P. D. Luckey,[136] T. Ma,[136] S. Nahn,[136] C. Paus,[136] D. Ralph,[136] C. Roland,[136] G. Roland,[136] M. Rudolph,[136]
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