Physics Letters B 713 (2012) 68–90

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Search for neutral Higgs bosons decaying to tau pairs in pp collisions at $\sqrt{s} = 7$ TeV ☆

CMS Collaboration *

CERN, Switzerland

ARTICLE INFO

Article history:
Received 18 February 2012
Received in revised form 17 April 2012
Accepted 13 May 2012
Available online 17 May 2012
Editor: M. Doser

Keywords:
CMS
Physics
Higgs

ABSTRACT

A search for neutral Higgs bosons decaying to tau pairs at a center-of-mass energy of 7 TeV is performed using a dataset corresponding to an integrated luminosity of 4.6 fb^{-1} recorded by the CMS experiment at the LHC. The search is sensitive to both the standard model Higgs boson and to the neutral Higgs bosons predicted by the minimal supersymmetric extension of the standard model (MSSM). No excess of events is observed in the tau-pair invariant-mass spectrum. For a standard model Higgs boson in the mass range of 110–145 GeV upper limits at 95% confidence level (CL) on the production cross section are determined. We exclude a Higgs boson with $m_{\mathrm{H}} = 115$ GeV with a production cross section 3.2 times of that predicted by the standard model. In the MSSM, upper limits on the neutral Higgs boson production cross section times branching fraction to tau pairs, as a function of the pseudoscalar Higgs boson mass, m_{A}, sets stringent new bounds in the parameter space, excluding at 95% CL values of $\tan\beta$ as low as 7.1 at $m_{\mathrm{A}} = 160$ GeV in the $m_{\mathrm{h}}^{\mathrm{max}}$ benchmark scenario.

© 2012 CERN. Published by Elsevier B.V. Open access under CC BY-NC-ND license.

1. Introduction

An important goal of the LHC physics program is to ascertain the mechanism of electroweak symmetry breaking, through which the W and Z bosons attain mass, while the photon remains massless. In the standard model (SM) [1–3], this is achieved via the Higgs mechanism [4–9], which also predicts the existence of a scalar Higgs boson. However, this particle has not yet been observed by experiments. Moreover, the mass of the Higgs boson is quadratically divergent at high energies [10]. Supersymmetry [11] is a well known extension to the SM which allows the cancellation of this divergence.

The minimal supersymmetric standard model (MSSM) contains two Higgs doublets, giving rise to five physical states: a light neutral CP-even state (h), a heavy neutral CP-even state (H), a neutral CP-odd state (A), and a pair of charged states ($\mathrm{H}^{\pm}$) [12–15]. The mass relations between these particles depend on the MSSM parameter $\tan\beta$, the ratio of the Higgs fields vacuum expectation values. We focus on the $m_{\mathrm{h}}^{\mathrm{max}}$ [16,17] benchmark scenario in which $M_{\mathrm{SUSY}} = 1$ TeV; $X_t = 2M_{\mathrm{SUSY}}$; $\mu = 200$ GeV; $M_{\tilde{g}} = 800$ GeV; $M_2 = 200$ GeV; and $A_b = A_t$. Here, M_{SUSY} denotes the common soft-SUSY-breaking squark mass of the third generation; $X_t = A_t - \mu/\tan\beta$ is the stop mixing parameter; A_t and A_b are the stop and sbottom trilinear couplings, respectively; μ the Higgsino mass parameter; $M_{\tilde{g}}$ the gluino mass; and M_2 is the SU(2)-gaugino mass parameter. The value of M_1 is fixed via the unification relation $M_1 = (5/3)M_2 \sin\theta_{\mathrm{W}}/\cos\theta_{\mathrm{W}}$. In this scenario for values of $\tan\beta \gtrsim 15$, if $m_{\mathrm{A}} \lesssim 130$ GeV the masses of the h and A are almost degenerate, while the mass of the H is around 130 GeV. Conversely, if $m_{\mathrm{A}} \gtrsim 130$ GeV, the masses of the A and H are almost degenerate, while the mass of the h remains near 130 GeV. This will thus always lead to one neutral Higgs boson at 130 GeV and two neutral Higgs bosons with almost degenerate mass of m_{A}.

Direct searches for the SM Higgs boson at the Large Electron–Positron Collider (LEP) set a limit on the mass $m_{\mathrm{H}} > 114.4$ GeV at 95% confidence level (CL) [18]. The Tevatron collider experiments exclude the SM Higgs boson in the mass range 162–166 GeV [19], and the ATLAS experiment in the mass ranges 112.9–115.5, 131–238, and 251–466 GeV [20]. Precision electroweak data constrain the mass of the SM Higgs boson to be less than 158 GeV [21]. Direct searches for neutral MSSM Higgs bosons have been reported by LEP, the Tevatron, and both LHC experiments, and set limits on the MSSM parameter space in the $\tan\beta$–m_{A} plane [22–26].

This Letter reports a search for the SM and the neutral MSSM Higgs bosons using final states with tau pairs in proton–proton collisions at $\sqrt{s} = 7$ TeV at the LHC. We use a data sample collected in 2011 corresponding to an integrated luminosity of 4.6 fb^{-1} recorded by the Compact Muon Solenoid (CMS) [27] experiment. Three independent tau-pair final states where one or both taus decay leptonically are studied: $\mathrm{e}\tau_h + \mathrm{X}$, $\mu\tau_h + \mathrm{X}$, and $\mathrm{e}\mu + \mathrm{X}$, where we use the symbol τ_h to indicate a reconstructed hadronic decay of a tau.

☆ © CERN for the benefit of the CMS Collaboration.
* *E-mail address:* cms-publication-committee-chair@cern.ch.

0370-2693 © 2012 CERN. Published by Elsevier B.V. Open access under CC BY-NC-ND license.
http://dx.doi.org/10.1016/j.physletb.2012.05.028

In the case of the SM Higgs boson, the gluon-fusion production mechanism has the largest cross section. However, in the mass region of interest, background from Drell–Yan production of tau pairs overwhelms the expected Higgs boson signal. This search therefore relies upon the signature of Higgs bosons produced via vector boson fusion (VBF) or in association with a high-p_T jet. In the former case, the distinct topology of two jets with a large rapidity separation greatly reduces the background. In the latter, requiring a high-p_T jet both suppresses background, and improves the measurement of the tau-pair invariant mass.

In the MSSM case, two main production processes contribute to $pp \to \phi + X$, where $\phi = h$, H, or A: gluon fusion through a b-quark loop and direct $b\bar{b}$ annihilation from the b-quark content of the beam protons. In the latter case, there is a significant probability that a b-quark jet is produced centrally in association with the Higgs boson due to the enhanced $b\bar{b}\phi$ coupling. Requiring a b-quark jet increases the sensitivity of the search by reducing the $Z +$ jets background.

2. CMS detector

The CMS detector is described in detail elsewhere [27]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid are the silicon pixel and strip tracker, which cover a pseudorapidity region of $|\eta| < 2.5$. Here, the pseudorapidity is defined as $\eta = -\ln(\tan\theta/2)$, where θ is the polar angle of the trajectory of the particle with respect to the direction of the counterclockwise beam. The lead tungstate crystal electromagnetic calorimeter and the brass-scintillator hadron calorimeter surround the tracking volume and cover $|\eta| < 3$. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry which extends the coverage to $|\eta| < 5$. Muons are measured in gas-ionization detectors embedded in the steel return yoke, with a coverage of $|\eta| < 2.4$.

3. Trigger and event selection

The analysis makes use of the three independent tau-pair final states, $e\tau_h + X$, $\mu\tau_h + X$, and $e\mu + X$. In all three channels, there is substantial background, both from processes with similar experimental signatures, and from unrelated hadronic activity in the detector.

The trigger selection required a combination of electron, muon and tau trigger objects [28–30]. The identification criteria and p_T thresholds of these objects were progressively tightened as the LHC instantaneous luminosity increased over the data-taking period.

A particle-flow algorithm [31–33] is used to combine information from all CMS subdetectors to identify and reconstruct individual particles in the event, namely muons, electrons, photons, and charged and neutral hadrons. From the resulting particle list jets, hadronically-decaying taus, and missing transverse energy (E_T^{miss}), defined as the negative of the vector sum of the transverse momenta, are reconstructed. The jets are identified using the anti-k_T jet algorithm [34,35] with a distance parameter of $R = 0.5$. Hadronically-decaying taus are reconstructed using the hadron plus strips (HPS) algorithm, which considers candidates with one or three charged pions and up to two neutral pions [36].

For the $e\tau_h + X$ and $\mu\tau_h + X$ final states, in the region $|\eta| < 2.1$, we select events with an electron of $p_T > 20$ GeV or a muon of $p_T > 17$ GeV, together with an oppositely charged τ_h of $p_T >$ 20 GeV within the range $|\eta| < 2.3$. For the $e\mu + X$ final state, we select events with an electron of $|\eta| < 2.3$ and an oppositely charged muon of $|\eta| < 2.1$, requiring $p_T > 20$ GeV for the highest-p_T lepton and $p_T > 10$ GeV for the next-to-highest-p_T lepton. For the $e\tau_h + X$ and $\mu\tau_h + X$ final states, we reject events with more than one electron or more than one muon of $p_T > 15$ GeV.

Taus from Higgs boson decays are typically isolated from the rest of the event activity, in contrast to background from jets, which are typically immersed in considerable hadronic activity. For each lepton candidate (e, μ, or τ_h), a cone is constructed around the lepton direction at the event vertex. An isolation variable is constructed from the scalar sum of the transverse energy of all reconstructed particles contained within the cone, excluding the contribution from the lepton candidate itself.

In 2011, an average of ten proton–proton interactions occurred per LHC bunch crossing, making the assignment of the vertex of the hard-scattering process non-trivial. For each reconstructed collision vertex, the sum of the p_T^2 of all tracks associated to the vertex is computed. The vertex for which this quantity is the largest is assumed to correspond to the hard-scattering process, and is referred to as the primary vertex. A correction is applied to the isolation variable to account for effects of additional interactions. For charged particles, only those associated with the primary vertex are considered in the isolation variable. For neutral particles, a correction is applied by subtracting the energy deposited in the isolation cone by charged particles not associated with the primary vertex, multiplied by a factor of 0.5. This factor corresponds approximately to the ratio of neutral to charged hadron production in the hadronization process of pile-up interactions. An η, p_T, and lepton-flavor dependent threshold on the isolation variable of less than roughly 10% of the candidate p_T is applied.

To correct for the contribution to the jet energy due to pile-up, a median energy density (ρ) is determined event by event. The pile-up contribution to the jet energy is estimated as the product of ρ and the area of the jet and subsequently subtracted from the jet transverse energy [37]. In the fiducial region for jets of $|\eta| <$ 4.7, jet energy corrections are also applied as a function of the jet E_T and η [38].

In this analysis, due to the small mass of the tau and the large transverse momentum, the neutrinos produced in the decay tend to be produced nearly collinear with the visible products. Conversely, in $W +$ jets events, one of the main backgrounds, the high mass of the W results in a neutrino approximately opposite to the lepton in the transverse plane, while a jet is misidentified as a tau. In the $e\tau_h + X$ and $\mu\tau_h + X$ channels of the SM Higgs boson search, which focuses on lower masses (less than 145 GeV), we therefore require the transverse mass

$$m_T = \sqrt{2 p_T E_T^{miss}(1 - \cos(\Delta\phi))} \tag{1}$$

to be less than 40 GeV, where p_T is the lepton transverse momentum, and $\Delta\phi$ is the difference in ϕ of the lepton and E_T^{miss} vector.

In the MSSM search channels and in the $e\mu + X$ SM search channel, we use a discriminator formed by considering the bisector of the directions of the visible tau decay products transverse to the beam direction, denoted as the ζ axis [39]. From the projections of the visible decay product momenta and the E_T^{miss} vector onto the ζ axis, two values are calculated:

$$P_\zeta = p_{T,1} \cdot \zeta + p_{T,2} \cdot \zeta + E_T^{miss} \cdot \zeta, \tag{2}$$

$$P_\zeta^{vis} = p_{T,1} \cdot \zeta + p_{T,2} \cdot \zeta, \tag{3}$$

where the indices $p_{T,1}$ and $p_{T,2}$ indicate the transverse momentum of two reconstructed leptons. For the $e\tau_h + X$ and $\mu\tau_h + X$ channels in the MSSM search we require $P_\zeta - 0.5 \cdot P_\zeta^{vis} > -20$ GeV and for the $e\mu + X$ channel we require $P_\zeta - 0.85 \cdot P_\zeta^{vis} > -25$ GeV.

To further enhance the sensitivity of the search for Higgs bosons both in the MSSM and in the SM, we split the sample of

Table 1
Numbers of expected and observed events in the event categories as described in the text for the $e\tau_h + X$ channel. Also given are the expected signal yields and efficiencies for an MSSM Higgs boson with $m_A = 120$ GeV and $\tan\beta = 10$, and for an SM Higgs boson with $m_A = 120$ GeV. Combined statistical and systematic uncertainties on each estimate are reported. For the yield estimates for the Higgs signal the production cross sections for h and A, which have almost degenerate masses, are taken into account. The quoted efficiencies do not include the branching fraction into $\tau\tau$.

Process	SM			MSSM	
	0/1-Jet	Boosted	VBF	Non-b-Tag	b-Tag
$Z \to \tau\tau$	$13\,438 \pm 977$	190 ± 14	19 ± 1	$14\,259 \pm 1037$	135 ± 9
Multijets	6365 ± 299	27 ± 3	15 ± 2	6404 ± 301	100 ± 7
W + jets	2983 ± 216	62 ± 4	4.2 ± 0.4	5432 ± 377	39 ± 3
$Z \to ll$	5170 ± 464	28 ± 4	5 ± 1	6146 ± 502	28 ± 4
$t\bar{t}$	63 ± 7	42 ± 6	2 ± 1	47 ± 7	75 ± 11
Dibosons	68 ± 21	5 ± 2	0.1 ± 0.1	105 ± 22	1 ± 1
Total background	$28\,087 \pm 1142$	354 ± 17	45 ± 2.9	$32\,392 \pm 1249$	378 ± 17
$H \to \tau\tau$	53 ± 9	2.7 ± 0.6	2.0 ± 0.2	279 ± 29	26 ± 4
Data	27 727	318	43	32 051	391
Signal efficiency					
$gg \to \phi$	–	–	–	$1.0 \cdot 10^{-2}$	$9.0 \cdot 10^{-5}$
$gg \to bb\phi$	–	–	–	$1.1 \cdot 10^{-2}$	$1.5 \cdot 10^{-3}$
$gg \to H$	$9.1 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	$2.9 \cdot 10^{-5}$	–	–
$qq \to qqH$	$5.2 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	$3.3 \cdot 10^{-3}$	–	–
$qq \to Ht\bar{t}$ or VH	$7.8 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$	$2.8 \cdot 10^{-5}$	–	–

Table 2
Numbers of expected and observed events in the event categories as described in the text for the $\mu\tau_h + X$ channel. Also given are the expected signal yields and efficiencies for an MSSM Higgs boson with $m_A = 120$ GeV and $\tan\beta = 10$, and for an SM Higgs boson with $m_A = 120$ GeV. Combined statistical and systematic uncertainties on each estimate are reported. For the yield estimates for the Higgs signal the production cross sections for h and A, which have almost degenerate masses, are taken into account. The quoted efficiencies do not include the branching fraction into $\tau\tau$.

Process	SM			MSSM	
	0/1-Jet	Boosted	VBF	Non-b-Tag	b-Tag
$Z \to \tau\tau$	$28\,955 \pm 2054$	295 ± 22	36 ± 2	$29\,795 \pm 2114$	259 ± 18
Multijets	7841 ± 141	36 ± 2	23 ± 2	6387 ± 115	160 ± 9
W + jets	5827 ± 392	65 ± 4	9 ± 1	9563 ± 628	110 ± 9
$Z \to ll$	777 ± 70	5 ± 1	1.0 ± 0.2	924 ± 115	3 ± 1
$t\bar{t}$	147 ± 15	94 ± 12	4 ± 1	101 ± 15	145 ± 20
Dibosons	178 ± 55	9 ± 4	0.4 ± 0.4	217 ± 46	5 ± 2
Total background	$43\,725 \pm 2097$	504 ± 26	73 ± 3.9	$46\,987 \pm 2211$	681 ± 30
$H \to \tau\tau$	96 ± 17	3.9 ± 0.8	3.0 ± 0.5	502 ± 52	45 ± 6
Data	43 612	500	76	47 178	680
Signal efficiency					
$gg \to \phi$	–	–	–	$1.8 \cdot 10^{-2}$	$1.8 \cdot 10^{-4}$
$gg \to bb\phi$	–	–	–	$2.0 \cdot 10^{-2}$	$2.6 \cdot 10^{-3}$
$gg \to H$	$1.7 \cdot 10^{-2}$	$3.9 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	–	–
$qq \to qqH$	$8.6 \cdot 10^{-3}$	$2.6 \cdot 10^{-3}$	$5.2 \cdot 10^{-3}$	–	–
$qq \to Ht\bar{t}$ or VH	$1.5 \cdot 10^{-2}$	$3.3 \cdot 10^{-3}$	$4.2 \cdot 10^{-5}$	–	–

selected events into several mutually exclusive categories based on the jet multiplicity and b-jet content.

In the MSSM case, there is a large probability for having a b-tagged jet in the central region. We use an algorithm based on the impact parameter of the tracks associated to the event vertex to identify b-tagged jets [40]. The MSSM search has two categories:

b-Tag category: We require at most one jet with $p_T > 30$ GeV and at least one b-tagged jet with $p_T > 20$ GeV.

Non-b-Tag category: We require at most one jet with $p_T > 30$ GeV and no b-tagged jet with $p_T > 20$ GeV.

The SM search has three categories:

VBF category: We require at least two jets with $p_T > 30$ GeV, $|\Delta\eta_{jj}| > 4.0$, $\eta_1 \cdot \eta_2 < 0$, and a dijet invariant mass $m_{jj} > 400$ GeV, with no other jet with $p_T > 30$ GeV in the rapidity region between the two jets.

Boosted category: We require one jet with $p_T > 150$ GeV, and, in the $e\mu$ channel, no b-tagged jet with $p_T > 20$ GeV.

0/1-Jet category: We require no more than one jet with $p_T > 30$ GeV, and if such a jet is present, it must have $p_T < 150$ GeV.

The observed number of events for each category, as well as the expected number of events from various background processes are shown in Tables 1–3 together with expected signal yields and efficiencies. The largest source of events selected with these requirements is $Z \to \tau\tau$ decays. We estimate the contribution from this process using an observed sample of $Z \to \mu\mu$ events, where the reconstructed muons are replaced by the reconstructed particles from simulated tau decays, a procedure called 'embedding'.

Table 3
Numbers of expected and observed events in the event categories as described in the text for the $e\mu + X$ channel. Also given are the expected signal yields and efficiencies for an MSSM Higgs boson with $m_A = 120$ GeV and $\tan\beta = 10$, and for an SM Higgs boson with $m_A = 120$ GeV. Combined statistical and systematic uncertainties on each estimate are reported. For the yield estimates for the Higgs signal the production cross sections for h and A, which have almost degenerate masses, are taken into account. The quoted efficiencies do not include the branching fraction into $\tau\tau$.

Process	SM			MSSM	
	0/1-Jet	Boosted	VBF	Non-b-Tag	b-Tag
$Z \to \tau\tau$	$11\,787 \pm 790$	98 ± 11	16 ± 4	$11\,718 \pm 797$	112 ± 11
Multijet and W + jets	483 ± 145	9 ± 3	2 ± 1	474 ± 147	15 ± 5
$t\bar{t}$	427 ± 41	70 ± 8	14 ± 3	161 ± 15	289 ± 35
Dibosons	570 ± 91	21 ± 4	2.0 ± 0.6	527 ± 84	55 ± 10
Total background	$13\,267 \pm 809$	197 ± 14	34 ± 5	$12\,881 \pm 815$	471 ± 38
$H \to \tau\tau$	36 ± 6	1.0 ± 0.3	1.0 ± 0.2	161 ± 10	17 ± 1.6
Data	13 152	189	26	12 761	468
Signal efficiency					
$gg \to \phi$	–	–	–	$6.4 \cdot 10^{-3}$	$9.4 \cdot 10^{-5}$
$bb \to bb\phi$	–	–	–	$5.8 \cdot 10^{-3}$	$9.8 \cdot 10^{-4}$
$gg \to H$	$6.3 \cdot 10^{-3}$	$1.8 \cdot 10^{-4}$	$3.0 \cdot 10^{-5}$	–	–
$qq \to qqH$	$3.0 \cdot 10^{-3}$	$8.1 \cdot 10^{-4}$	$2.0 \cdot 10^{-3}$	–	–
$qq \to Ht\bar{t}$ or VH	$3.8 \cdot 10^{-3}$	$6.8 \cdot 10^{-4}$	$1.5 \cdot 10^{-6}$	–	–

The normalization for this process is determined from the measurement of the $Z \to ee$ and $Z \to \mu\mu$ cross section [41].

Another significant source of background is multijet events in which there is one jet misidentified as an isolated electron or muon, and a second jet misidentified as τ_h. W + jets events in which there is a jet misidentified as a τ_h are also a source of background. The rates for these processes are estimated using the number of observed same-charge tau pair events, and from events with large transverse mass, respectively. Other background processes include $t\bar{t}$ production and $Z \to ee/\mu\mu$ events, particularly in the $e\tau_h + X$ channel due to the 2–3% probability for electrons to be misidentified as τ_h [36]. The small background from W + jets and multijet events for the $e\mu$ channel where jets are misidentified as isolated leptons is derived by measuring the number of events with one good lepton and a second which passes relaxed selection criteria, but fails the nominal lepton selection. This sample is extrapolated to the signal region using the efficiencies for such loose lepton candidates to pass the nominal lepton selection. These efficiencies are measured in data using multijet events. Backgrounds from $t\bar{t}$ and di-boson production are estimated from simulation using the MadGraph [42] event generator to simulate the shapes for $t\bar{t}$ events and pythia 6.424 [43] to simulate the shapes for di-boson events. The event yields are normalized to the inclusive cross sections: $\sigma_{t\bar{t}} = 164.4 \pm 14.3$ pb and $\sigma_{WW} = 55.3 \pm 8.3$ pb as measured with an analysis similar to that described in [44,45] using a larger data sample.

To model the MSSM and SM Higgs boson signals the event generators pythia and powheg [46] are used, respectively. The tauola [47] package is used for tau decays in all cases. Additional next-to-next-to-leading order (NNLO) K-factors from FeHiPro [48,49] are applied to the Higgs boson p_T spectrum from Higgs boson events produced via gluon fusion.

The presence of pile-up is incorporated by simulating additional interactions and then reweighting the simulated events to match the distribution of additional interactions observed in data. The events in the embedded $Z \to \tau\tau$ sample and in other background samples obtained from data contain the correct distribution of pile-up interactions. The missing transverse energy response from simulation is corrected using a prescription, based on data, developed for inclusive W and Z cross section measurements [41], where Z bosons are reconstructed in the dimuon channel, and the missing transverse energy scale and resolution calibrated as a function of the Z boson transverse momentum.

4. Tau-pair invariant mass reconstruction

To distinguish the Higgs boson signal from the background, we reconstruct the tau-pair mass using a maximum likelihood technique [26]. The algorithm estimates the original momentum components of the two taus by maximizing a likelihood with respect to free parameters corresponding to the missing neutrino momenta, subject to kinematic constraints. Other terms in the likelihood take into account the tau-decay phase space and the probability density in the tau transverse momentum, parametrized as a function of the tau-pair mass. This algorithm yields a tau-pair mass with a mean consistent with the true value, and a distribution with a nearly Gaussian shape. The standard deviation of the mass resolution is estimated to be 21% at a Higgs boson mass of 130 GeV, compared with 24% for the (non-Gaussian) distribution of the invariant mass spectrum reconstructed from the visible tau-decay products in the inclusive selection. The resolution improves to 15% in the b-Tag category in the MSSM analysis and in the Boosted and VBF categories in the SM analysis where the Higgs boson is produced with significant transverse momentum.

5. Systematic uncertainties

Various imperfectly known or simulated effects can alter the shape and normalization of the invariant mass spectrum. The main contributions to the normalization uncertainty include the uncertainty in the total integrated luminosity (4.5%) [50], jet energy scale (2–5% depending on η and p_T), background normalization (Tables 1–3), Z boson production cross section (2.5%) [41], lepton identification and isolation efficiency (1.0%), and trigger efficiency (1.0%). The tau-identification efficiency uncertainty is estimated to be 6% from an independent study using a tag-and-probe technique [41]. The lepton identification and isolation efficiencies are stable as a function of the number of additional interactions in the bunch crossing in data and in Monte Carlo simulation. The b-tagging efficiency carries an uncertainty of 10%, and the b-mistag rate is accurate to 30% [51]. Uncertainties that contribute to mass spectrum shape variations include the tau (3%), muon (1%), and electron (1% in the barrel region, 2.5% in the endcap region) energy scales. The effect of the uncertainty on the E_T^{miss} scale, mainly due to pile-up effects, is incorporated by varying the mass spectrum shape as described in the next section.

The various production cross sections and branching fractions for SM and MSSM Higgs bosons and corresponding uncertainties are taken from [52–77]. Theoretical uncertainties on the Higgs production cross section are included in the SM and the MSSM search. For the SM signal, these uncertainties range from 12 to 30% for gluon fusion, depending on the event category, and 10% for VBF production. The uncertainty for the MSSM signal depends on $\tan\beta$ and m_A and ranges from 20 to 25%.

6. Maximum likelihood fit

To search for the presence of a Higgs boson signal in the selected events, we perform a binned maximum likelihood fit to the tau-pair invariant-mass spectrum, $m_{\tau\tau}$. The fit is performed jointly across the three SM and two MSSM event categories, but independently in the two cases.

Systematic uncertainties are represented by nuisance parameters in the fitting process. We assume log-normal priors for normalization parameters, and Gaussian priors for mass-spectrum shape uncertainties. The uncertainties that affect the shape of the mass spectrum, mainly those corresponding to the energy scales, are represented by nuisance parameters whose variation results in a continuous perturbation of the spectrum shape [78].

7. Results

Figs. 1 and 2 show for the SM and MSSM, respectively, the distributions of the tau-pair mass $m_{\tau\tau}$ summed over the three search channels, for each category, compared with the background prediction. The background mass distributions show the results of the fit using the background-only hypothesis.

The invariant mass spectra for both the MSSM and SM categories show no evidence for the presence of a Higgs boson signal, and we therefore set 95% CL upper bounds on the Higgs boson cross section times the branching fraction into a tau pair. For calculations of exclusion limits, we use the modified frequentist construction CL_s [79–81]. Theoretical uncertainties on the Higgs boson production cross sections are taken into account as systematic uncertainties in the limit calculations.

7.1. Limits on MSSM Higgs boson production

For the m_h^{max} benchmark scenario as described above we set a 95% CL upper limit on $\tan\beta$ as a function of the pseudoscalar Higgs boson mass m_A from the observed di-tau mass distributions in the b-Tag and non-b-Tag event categories (see Table 4). Signal contributions from h, H and A production are considered. The mass values of h and H, as well as the ratio between the gluon fusion process and the associated production with b quarks, depend on the value of $\tan\beta$. To account for this, we perform a scan of $\tan\beta$ for each mass hypothesis, using the Higgs boson cross sections as a function of $\tan\beta$ as reported by the LHC Cross Section Working Group [52]. For the gluon-fusion process these cross sections have been obtained from the GGH@NNLO [56,82,83] and HIGLU [84] programs. For the $b\bar{b} \to \phi$ process, the four-flavor calculation [85,86] and the five-flavor calculation as implemented in the BBH@NNLO [87] program have been combined using the Santander scheme [88]. Rescaling of the corresponding Yukawa couplings by the MSSM factors calculated with FeynHiggs [89–91] has been applied.

Fig. 3 also shows the region excluded by the LEP experiments [22]. The results reported in this Letter considerably extend the exclusion region of the MSSM parameter space and supersede limits reported by CMS using a smaller data sample collected in 2010 [26].

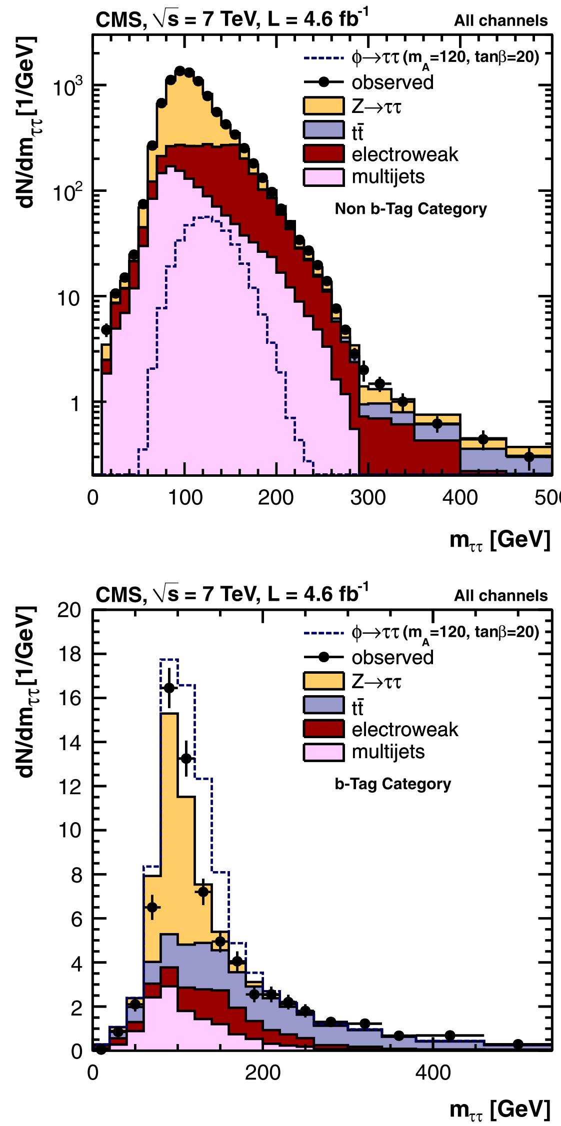

Fig. 1. Distribution of the tau-pair invariant mass, $m_{\tau\tau}$, in the MSSM Higgs boson search categories: Non-b-Tag category (top), b-Tag category (bottom). The background labeled 'electroweak' combines the contribution from W + jets, $Z \to ll$, and diboson processes.

7.2. Limits on SM Higgs boson production

The 0/1-Jet, VBF and Boosted categories are used to set a 95% CL upper limit on the product of the Higgs boson production cross section and the $H \to \tau\tau$ branching fraction, $\sigma_H \times \mathrm{BR}(H \to \tau\tau)$, with respect to the SM Higgs expectation, σ/σ_{SM}. Fig. 4 shows the observed and the mean expected 95% CL upper limits for Higgs boson mass hypotheses ranging from 110 to 145 GeV. The bands represent the one- and two-standard-deviation probability intervals around the expected limit. Table 5 shows the results for selected mass values. We set a 95% upper limit on σ/σ_{SM} in the range of 3–7.

8. Summary

We have reported a search for SM and neutral MSSM Higgs bosons, using a sample of CMS data from proton–proton collisions at a center-of-mass energy of 7 TeV at the LHC, corresponding to an integrated luminosity of 4.6 fb^{-1}. The tau-pair decay mode in final states with one e or μ plus a hadronic decay of a tau, and

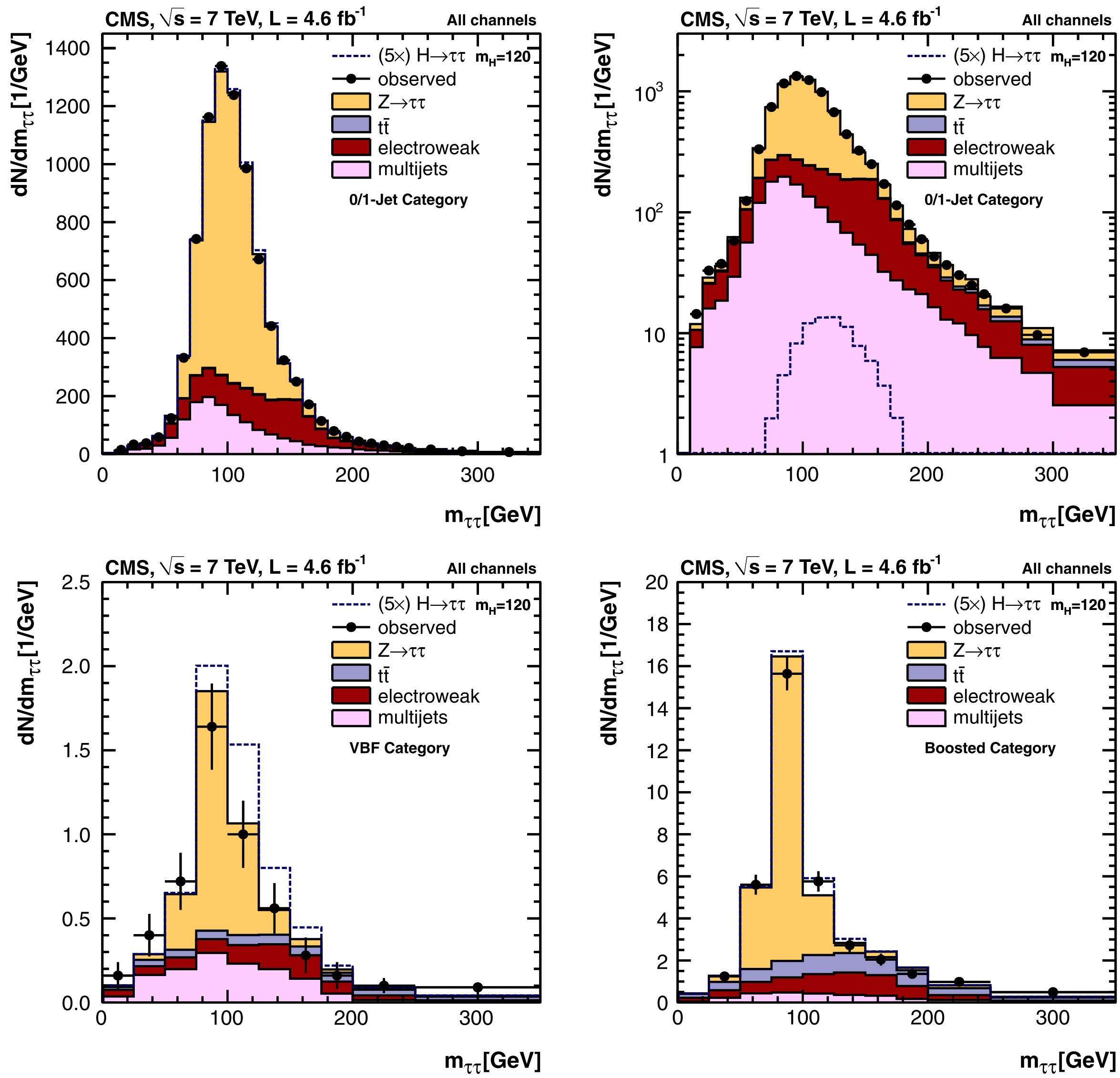

Fig. 2. Distribution of the tau-pair invariant mass, $m_{\tau\tau}$, in the SM Higgs boson search categories: 0/1-Jet (top row, linear and log vertical scale), VBF (lower left), and Boosted (lower right). The background labeled 'electroweak' combines the contribution from W + jets, $Z \to ll$, and diboson processes.

Table 4
Expected range and observed 95% CL upper limits for $\tan\beta$ as a function of m_A, for the MSSM search.

MSSM Higgs	Expected $\tan\beta$ limit					Obs. $\tan\beta$ limit
m_A [GeV]	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	
90	5.19	7.01	8.37	10.6	12.8	12.2
100	6.49	7.45	8.78	10.8	13.4	11.8
120	4.50	6.47	8.09	9.89	12.0	9.84
130	5.37	6.71	7.85	9.69	11.5	9.03
140	5.62	6.63	7.90	9.69	11.6	8.03
160	5.57	6.99	8.51	10.4	12.5	7.11
180	6.75	8.14	9.53	11.3	13.8	7.50
200	7.84	9.12	10.5	12.8	15.0	8.46
250	10.3	12.3	13.9	16.8	19.4	13.8
300	13.5	15.7	18.4	21.4	24.5	20.9
350	17.7	20.1	23.0	26.9	31.1	29.1
400	21.9	24.3	27.9	32.4	37.3	37.3
450	25.0	29.2	33.3	38.8	44.7	45.2
500	30.3	35.7	40.5	47.1	55.0	51.9

the $e\mu$ final state are used. The observed tau-pair mass spectra reveal no evidence for neutral Higgs boson production. In the SM case we determine a 95% CL upper limit in the mass range of 110–145 GeV on the Higgs boson production cross section. We exclude a Higgs boson with $m_A = 115$ GeV with a production cross section 3.2 times of that predicted by the standard model. In the MSSM

Table 5
Expected range and observed 95% CL upper limits on the cross section, divided by the expected SM Higgs cross section as a function of m_A, for the SM search.

SM Higgs	Expected limit					Obs. limit
m_A [GeV]	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	
110	1.83	2.36	3.30	4.76	6.63	3.20
115	1.61	2.13	2.97	4.23	5.86	3.19
120	1.65	2.17	3.03	4.33	6.07	3.62
125	1.75	2.19	3.05	4.38	6.01	4.27
130	1.82	2.37	3.31	4.72	6.43	5.08
135	2.25	2.96	4.06	5.77	7.87	5.39
140	2.39	2.99	4.17	5.85	7.99	5.46
145	3.06	3.97	5.45	7.65	10.7	7.00

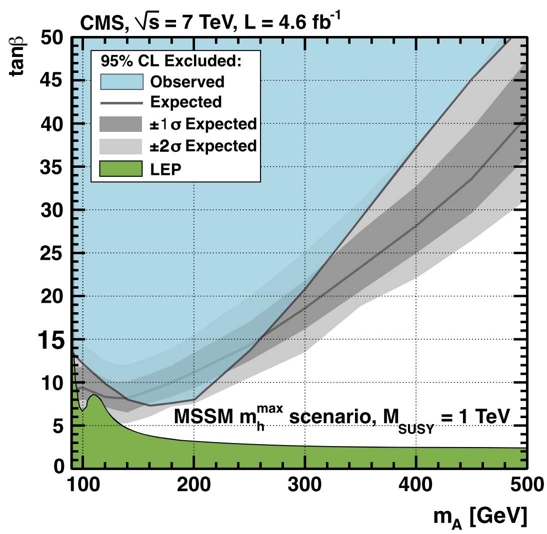

Fig. 3. Region in the parameter space of $\tan\beta$ versus m_A excluded at 95% CL in the context of the MSSM m_h^{max} scenario. The expected one- and two-standard-deviation ranges and the observed 95% CL upper limits are shown together with the observed excluded region.

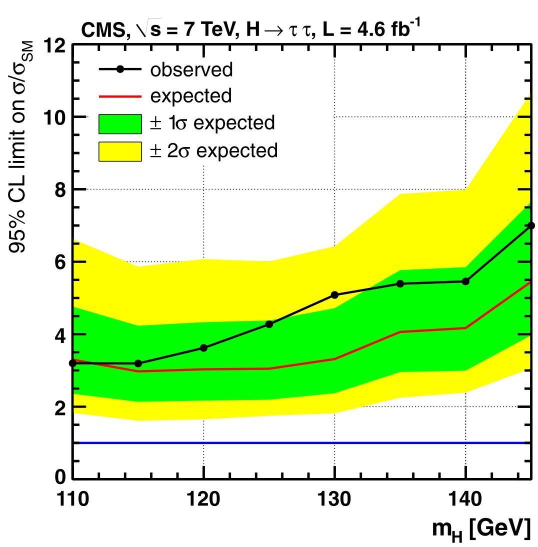

Fig. 4. The expected one- and two-standard-deviation ranges are shown together with the observed 95% CL upper limits on the cross section, normalized to the SM expectation for Higgs boson production, as a function of m_A.

case, we determine a 95% CL upper bound on the value of $\tan\beta$ as a function of m_A, for the m_h^{max} scenario. This search excludes a previously unexplored region reaching as low as $\tan\beta = 7.1$ at $m_A = 160$ GeV.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie program and the European Research Council (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA – Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT – Belgium); the Council of Science and Industrial Research, India; and the HOMING PLUS program of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund.

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References

[1] S.L. Glashow, Nucl. Phys. 22 (1961) 579, http://dx.doi.org/10.1016/0029-5582(61)90469-2.
[2] S. Weinberg, Phys. Rev. Lett. 19 (1967) 1264, http://dx.doi.org/10.1103/PhysRevLett.19.1264.
[3] A. Salam, in: N. Svartholm (Ed.), Elementary Particle Physics: Relativistic Groups and Analyticity, Almqvist & Wiskell, Stockholm, 1968, p. 367, Proceedings of the eighth Nobel symposium.
[4] F. Englert, R. Brout, Phys. Rev. Lett. 13 (1964) 321, http://dx.doi.org/10.1103/PhysRevLett.13.321.
[5] P.W. Higgs, Phys. Lett. 12 (1964) 132, http://dx.doi.org/10.1016/0031-9163(64)91136-9.
[6] P.W. Higgs, Phys. Rev. Lett. 13 (1964) 508, http://dx.doi.org/10.1103/PhysRevLett.13.508.

[7] G.S. Guralnik, C.R. Hagen, T.W.B. Kibble, Phys. Rev. Lett. 13 (1964) 585, http://dx.doi.org/10.1103/PhysRevLett.13.585.
[8] P.W. Higgs, Phys. Rev. 145 (1966) 1156, http://dx.doi.org/10.1103/PhysRev.145.1156.
[9] T.W.B. Kibble, Phys. Rev. 155 (1967) 1554, http://dx.doi.org/10.1103/PhysRev.155.1554.
[10] E. Witten, Phys. Lett. B 105 (1981) 267, http://dx.doi.org/10.1016/0370-2693(81)90885-6.
[11] S.P. Martin, A supersymmetry primer, arXiv:hep-ph/9709356, 1997, see also references therein.
[12] P. Fayet, Nucl. Phys. B 90 (1975) 104, http://dx.doi.org/10.1016/0550-3213(75)90636-7.
[13] P. Fayet, Phys. Lett. B 69 (1977) 489, http://dx.doi.org/10.1016/0370-2693(77)90852-8.
[14] S.L. Glashow, S. Weinberg, Phys. Rev. D 15 (1977) 1958, http://dx.doi.org/10.1103/PhysRevD.15.1958.
[15] N.G. Deshpande, E. Ma, Phys. Rev. D 18 (1978) 2574, http://dx.doi.org/10.1103/PhysRevD.18.2574.
[16] M.S. Carena, et al., Eur. Phys. J. C 26 (2003) 601, http://dx.doi.org/10.1140/epjc/s2002-01084-3.
[17] M.S. Carena, et al., Eur. Phys. J. C 45 (2006) 797, http://dx.doi.org/10.1140/epjc/s2005-02470-y.
[18] R. Barate, et al., Phys. Lett. B 565 (2003) 61, http://dx.doi.org/10.1016/S0370-2693(03)00614-2, arXiv:hep-ex/0306033.
[19] T. Aaltonen, et al., Phys. Rev. Lett. 104 (2010) 061802, http://dx.doi.org/10.1103/PhysRevLett.104.061802. A more recent, unpublished, limit is given in preprint, arXiv:1103.3233.
[20] ATLAS Collaboration, Phys. Lett. B 710 (2012) 49, http://dx.doi.org/10.1016/j.physletb.2012.02.044.
[21] ALEPH, CDF, D0, DELPHI, L3, OPAL, SLDL Collaborations, LEP Working Group, Tevatron Electroweak Working Group, SLD Electroweak and Heavy Flavor Group, Precision electroweak measurements and constraints on the standard model, arXiv:1012.2367 [hep-ex], 2010.
[22] S. Schael, et al., Eur. Phys. J. C 47 (2006) 547, http://dx.doi.org/10.1140/epjc/s2006-02569-7.
[23] T. Aaltonen, et al., Phys. Rev. Lett. 103 (2009) 201801, http://dx.doi.org/10.1103/PhysRevLett.103.201801.
[24] V.M. Abazov, Phys. Lett. B 707 (2012) 323, http://dx.doi.org/10.1016/j.physletb.2011.12.050.
[25] ATLAS Collaboration, Phys. Lett. B 705 (2011) 174, http://dx.doi.org/10.1016/j.physletb.2011.10.001.
[26] S. Chatrchyan, et al., Phys. Rev. Lett. 106 (2011) 231801, http://dx.doi.org/10.1103/PhysRevLett.106.231801.
[27] S. Chatrchyan, et al., JINST 3 (2008) S08004, http://dx.doi.org/10.1088/1748-0221/3/08/S08004.
[28] CMS Collaboration, Electron reconstruction and identification at $\sqrt{s}=7$ TeV, CMS Physics Analysis Summary CMS-PAS-EGM-10-004, 2010, http://cdsweb.cern.ch/record/1299116.
[29] CMS Collaboration, Performance of muon identification in pp collisions at $\sqrt{s}=7$ TeV, CMS Physics Analysis Summary CMS-PAS-MUO-10-002, 2010, http://cdsweb.cern.ch/record/1279140.
[30] S. Chatrchyan, et al., JHEP 1108 (2011) 117, http://dx.doi.org/10.1007/JHEP08(2011)117.
[31] CMS Collaboration, Particle-flow event reconstruction in CMS and performance for jets, taus, and E_T^{miss}, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009, http://cdsweb.cern.ch/record/1194487.
[32] CMS Collaboration, Commissioning of the particle-flow reconstruction in minimum-bias and jet events from pp collisions at 7 TeV, CMS Physics Analysis Summary CMS-PAS-PFT-10-002, 2010, http://cdsweb.cern.ch/record/1279341.
[33] CMS Collaboration, Commissioning of the particle-flow event reconstruction with leptons from J/ψ and W decays at 7 TeV, CMS Physics Analysis Summary CMS-PAS-PFT-10-003, 2010, http://cdsweb.cern.ch/record/1279347.
[34] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, arXiv:1111.6097v1 [hep-ph].
[35] M. Cacciari, G.P. Salam, Phys. Lett. B 641 (2006) 57, http://dx.doi.org/10.1016/j.physletb.2006.08.037, arXiv:hep-ph/0512210.
[36] CMS Collaboration, JINST 7 (2012) P01001, http://dx.doi.org/10.1088/1748-0221/7/01/P01001.
[37] M. Cacciari, G.P. Salam, Phys. Lett. B 659 (2008) 119, http://dx.doi.org/10.1016/j.physletb.2007.09.077, arXiv:0707.1378 [hep-ph].
[38] CMS Collaboration, JINST 6 (2011) 11002, http://dx.doi.org/10.1088/1748-0221/6/11/P11002.
[39] C.C. Almenar, Search for the neutral MSSM Higgs bosons in the $\tau\tau$ decay channels at CDF Run II, Ph.D. thesis, Universitat de València, FERMILAB-THESIS-2008-86, http://dx.doi.org/10.2172/953708.
[40] CMS Collaboration, Commissioning of b-jet identification with pp collisions at $\sqrt{s}=7$ TeV, CMS Physics Analysis Summary CMS-PAS-BTV-10-001, 2010, http://cdsweb.cern.ch/record/1279144.
[41] V. Khachatryan, et al., JHEP 1110 (2011) 132, http://dx.doi.org/10.1007/JHEP01(2011)080.
[42] J. Alwall, et al., JHEP 0709 (2007) 028, http://dx.doi.org/10.1088/1126-6708/2007/09/028, arXiv:0706.2334 [hep-ph].
[43] T. Sjöstrand, S. Mrenna, P. Skands, JHEP 0605 (2006) 026, http://dx.doi.org/10.1088/1126-6708/2006/05/026.
[44] S. Chatrchyan, et al., Phys. Rev. D 84 (2011) 092004, http://dx.doi.org/10.1103/PhysRevD.84.092004.
[45] S. Chatrchyan, et al., Phys. Lett. B 699 (2011) 25, http://dx.doi.org/10.1016/j.physletb.2011.03.056.
[46] S. Frixione, P. Nason, C. Oleari, JHEP 0711 (2007) 070, http://dx.doi.org/10.1088/1126-6708/2007/11/070.
[47] Z. Wąs, Nucl. Phys. B (Proc. Suppl.) 98 (2001) 96, http://dx.doi.org/10.1016/S0920-5632(01)01200-2.
[48] C. Anastasiou, K. Melnikov, F. Petriello, Nucl. Phys. B 724 (2005) 197, http://dx.doi.org/10.1016/j.nuclphysb.2005.06.036.
[49] C. Anastasiou, S. Bucherer, Z. Kunszt, JHEP 0910 (2009) 068, http://dx.doi.org/10.1088/1126-6708/2009/10/068.
[50] CMS Collaboration, Measurement of CMS luminosity, CMS Physics Analysis Summary CMS-PAS-EWK-10-004, 2010, http://cdsweb.cern.ch/record/1279145.
[51] CMS Collaboration, Performance of b-jet identification in CMS, CMS Physics Analysis Summary CMS-PAS-BTV-11-001, 2011, http://cdsweb.cern.ch/record/1366061.
[52] L.H.C. Higgs Cross Section Working Group, Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables, CERN Report CERN-2011-002, 2011, http://cdsweb.cern.ch/record/1318996, arXiv:1101.0593.
[53] A. Djouadi, M. Spira, P.M. Zerwas, Phys. Lett. B 264 (1991) 440, http://dx.doi.org/10.1016/0370-2693(91)90375-Z.
[54] S. Dawson, Nucl. Phys. B 359 (1991) 283, http://dx.doi.org/10.1016/0550-3213(91)90061-2.
[55] M. Spira, A. Djouadi, D. Graudenz, P.M. Zerwas, Nucl. Phys. B 453 (1995) 17, http://dx.doi.org/10.1016/0550-3213(95)00379-7.
[56] R.V. Harlander, W.B. Kilgore, Phys. Rev. Lett. 88 (2002) 201801, http://dx.doi.org/10.1103/PhysRevLett.88.201801, arXiv:hep-ph/0201206.
[57] C. Anastasiou, M. Charalampos, Nucl. Phys. B 646 (2002) 220, http://dx.doi.org/10.1016/S0550-3213(02)00837-4, arXiv:hep-ph/0207004.
[58] V. Ravindran, J. Smith, W.L. van Neerven, Nucl. Phys. B 665 (2003) 325, http://dx.doi.org/10.1016/S0550-3213(03)00457-7, arXiv:hep-ph/0302135.
[59] S. Catani, et al., Soft-gluon resummation for Higgs boson production at hadron colliders, arXiv:hep-ph/0306211, 2003.
[60] U. Aglietti, R. Bonciani, G. Degrassi, A. Vicini, Phys. Lett. B 595 (2004) 432, http://dx.doi.org/10.1016/j.physletb.2004.06.063, arXiv:hep-ph/0404071.
[61] G. Degrassi, F. Maltoni, Phys. Lett. B 600 (2004) 255, http://dx.doi.org/10.1016/j.physletb.2004.09.008, arXiv:hep-ph/0407249.
[62] S. Actis, et al., Phys. Lett. B 670 (2008) 12, http://dx.doi.org/10.1016/j.physletb.2008.10.018, arXiv:0809.1301 [hep-ph].
[63] C. Anastasiou, R. Boughezal, F. Petriello, JHEP 0904 (2009) 003, http://dx.doi.org/10.1088/1126-6708/2009/04/003, arXiv:0811.3458 [hep-ph].
[64] D. de Florian, M. Grazzini, Phys. Lett. B 674 (2009) 291, http://dx.doi.org/10.1016/j.physletb.2009.03.033, arXiv:0901.2427 [hep-ph].
[65] J. Baglio, A. Djouadi, JHEP 1103 (2011) 055, http://dx.doi.org/10.1007/JHEP03(2011)055, arXiv:1012.0530.
[66] M. Ciccolini, A. Denner, S. Dittmaier, Phys. Rev. Lett. 99 (2007) 161803, http://dx.doi.org/10.1103/PhysRevLett.99.161803, arXiv:0707.0381 [hep-ph].
[67] M. Ciccolini, A. Denner, S. Dittmaier, Phys. Rev. D 77 (2008) 013002, http://dx.doi.org/10.1103/PhysRevD.77.013002, arXiv:0710.4749 [hep-ph].
[68] K. Arnold, et al., Comput. Phys. Commun. 180 (2009) 1661, http://dx.doi.org/10.1016/j.cpc.2009.03.006, arXiv:0811.4559 [hep-ph].
[69] O. Brein, A. Djouadi, R. Harlander, Phys. Lett. B 579 (2004) 149, http://dx.doi.org/10.1016/j.physletb.2003.10.112 arXiv:hep-ph/0307206.
[70] M.L. Ciccolini, S. Dittmaier, M. Krämer, Phys. Rev. D 68 (2003) 073003, http://dx.doi.org/10.1103/PhysRevD.68.073003, arXiv:hep-ph/0306234.
[71] A. Djouadi, J. Kalinowski, M. Muhlleitner, M. Spira, An update of the program HDECAY, in: The Les Houches 2009 Workshop on TeV Colliders: The Tools and Monte Carlo Working Group Summary Report, arXiv:1003.1643 [hep-ph], 2010.
[72] A. Denner, S. Heinemeyer, I. Puljak, D. Rebuzzi, M. Spira, Eur. Phys. J. C 71 (2011) 1753, http://dx.doi.org/10.1140/epjc/s10052-011-1753-8, arXiv:1107.5909 [hep-ph].
[73] M. Botje, J. Butterworth, A. Cooper-Sarkar, A. de Roeck, J. Feltesse, et al., The PDF4LHC Working Group Interim Recommendations, arXiv:1101.0538 [hep-ph].
[74] S. Alekhin, S. Alioli, R.D. Ball, V. Bertone, J. Blumlein, et al., The PDF4LHC Working Group Interim Report, arXiv:1101.0536 [hep-ph].
[75] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P.M. Nadolsky, et al., Phys. Rev. D 82 (2010) 074024, http://dx.doi.org/10.1103/PhysRevD.82.074024.
[76] A. Martin, W. Stirling, R. Thorne, G. Watt, Eur. Phys. J. C 63 (2009) 189, http://dx.doi.org/10.1140/epjc/s10052-009-1072-5.
[77] R.D. Ball, V. Bertone, F. Cerutti, L. Del Debbio, S. Forte, et al., Impact of heavy quark masses on parton distributions and LHC phenomenology, arXiv:1101.1300 [hep-ph].

[78] J.S. Conway, in: H. Propser, L. Lyons (Eds.), Proceedings of PHYSTAT 2011 Workshop on Statistical Issues Related to Discovery Claims in Search Experiments and Unfolding, CERN-2011-006, CERN, 2011, pp. 115–120, http://cdsweb.cern.ch/record/1306523.
[79] T. Junk, Nucl. Instrum. Meth. A 434 (1999) 435, http://dx.doi.org/10.1016/S0168-9002(99)00498-2.
[80] A.L. Read, Modified frequentist analysis of search results (the cls method), CERN Report CERN-OPEN-2000-005, 2000, http://cdsweb.cern.ch/record/451614.
[81] ATLAS, CMS Collaborations, LHC Higgs Combination Group, Procedure for the LHC Higgs boson search combination in summer 2011, ATL-PHYS-PUB/CMS NOTE 2011-11, 2011/005, 2011, http://cdsweb.cern.ch/record/1379837.
[82] R.V. Harlander, W.B. Kilgore, JHEP 0210 (2002) 017, http://dx.doi.org/10.1088/1126-6708/2002/10/017.
[83] C. Anastasiou, K. Melnikov, Phys. Rev. D 67 (2003) 037501, http://dx.doi.org/10.1103/PhysRevD.67.037501, arXiv:hep-ph/0208115.
[84] M. Spira, HIGLU: A program for the calculation of the total Higgs production cross section at hadron colliders via gluon fusion including QCD corrections, arXiv:hep-ph/9510347.
[85] S. Dittmaier, M. Kramer, M. Spira, Phys. Rev. D 70 (2004) 074010, http://dx.doi.org/10.1103/PhysRevD.70.074010.
[86] S. Dawson, C. Jackson, L. Reina, D. Wackeroth, Phys. Rev. D 69 (2004) 074027, http://dx.doi.org/10.1103/PhysRevD.69.074027, arXiv:hep-ph/0311067.
[87] R.V. Harlander, W.B. Kilgore, Phys. Rev. D 68 (2003) 013001, http://dx.doi.org/10.1103/PhysRevD.68.013001.
[88] R. Harlander, M. Kramer, M. Schumacher, Bottom-quark associated Higgs-boson production: reconciling the four- and five-flavour scheme approach, CERN-PH-TH/2011-134, FR-PHENO-2011-009, TTK-11-17, WUB/11-04, arXiv:1112.3478 [hep-ph].
[89] S. Heinemeyer, W. Hollik, G. Weiglein, Comput. Phys. Commun. 124 (2000) 76, http://dx.doi.org/10.1016/S0010-4655(99)00364-1.
[90] S. Heinemeyer, W. Hollik, G. Weiglein, Eur. Phys. J. C 9 (1999) 343, http://dx.doi.org/10.1007/s100529900006.
[91] G. Degrassi, et al., Eur. Phys. J. C 28 (2003) 133, http://dx.doi.org/10.1140/epjc/s2003-01152-2.

CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

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

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

S. Bansal, L. Benucci, T. Cornelis, 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, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, 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

Vrije Universiteit Brussel, Brussels, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, G. Bruno, L. Ceard, J. De Favereau De Jeneret, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco [2], G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, N. Schul

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

N. Beliy, T. Caebergs, E. Daubie

Université de Mons, Mons, Belgium

G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, A. Custódio, 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, L. Soares Jorge, A. Sznajder

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

T.S. Anjos [3], C.A. Bernardes [3], F.A. Dias [4], T.R. Fernandez Perez Tomei, E.M. Gregores [3], C. Lagana, F. Marinho, P.G. Mercadante [3], S.F. Novaes, Sandra S. Padula

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

V. Genchev [1], P. Iaydjiev [1], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

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

Institute of High Energy Physics, Beijing, China

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

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

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

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, R. Plestina [5], D. Polic, I. Puljak [1]

Technical University of Split, Split, Croatia

Z. Antunovic, M. Dzelalija, M. Kovac

University of Split, Split, Croatia

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

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

Y. Assran [6], A. Ellithi Kamel [7], S. Khalil [8], M.A. Mahmoud [9], A. Radi [8,10]

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

Department of Physics, University of Helsinki, 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, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

K. Banzuzi, A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

D. Sillou

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

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

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

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj [11], C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaux, C. Veelken, A. Zabi

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

J.-L. Agram [12], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte [12], F. Drouhin [12], C. Ferro, J.-C. Fontaine [12], D. Gelé, U. Goerlach, P. Juillot, M. Karim [12], A.-C. Le Bihan, P. Van Hove

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

F. Fassi, D. Mercier

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

C. Baty, S. Beauceron, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, J. Chasserat, R. Chierici [1], D. Contardo, P. Depasse, H. El Mamouni, A. Falkiewicz, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret

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

D. Lomidze

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

G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov [13]

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

M. Ata, J. Caudron, E. Dietz-Laursonn, M. Erdmann, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske [†], J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer,

M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

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

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

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

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz [14], A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, J. Hauk, H. Jung [1], M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann [14], B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, M. Rosin, J. Salfeld-Nebgen, R. Schmidt [14], T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszewska, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

C. Autermann, V. Blobel, S. Bobrovskyi, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, H. Stadie, G. Steinbrück, J. Thomsen

University of Hamburg, Hamburg, Germany

C. Barth, J. Berger, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, M. Guthoff [1], C. Hackstein, F. Hartmann, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov [13], J.R. Komaragiri, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, T. Peiffer, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, S. Röcker, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, M. Schmanau, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, T. Weiler, M. Zeise, E.B. Ziebarth

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

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

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

University of Athens, Athens, Greece

I. Evangelou, C. Foudas [1], P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

University of Ioánnina, Ioánnina, Greece

A. Aranyi, G. Bencze, L. Boldizsar, C. Hajdu [1], P. Hidas, D. Horvath [15], A. Kapusi, K. Krajczar [16], F. Sikler [1], V. Veszpremi, G. Vesztergombi [16]

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

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

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

University of Debrecen, Debrecen, Hungary

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

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, Kolkata, India

R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty [1], L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait [17], A. Gurtu [18], M. Maity [19], G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, A. Saha, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research – EHEP, Mumbai, India

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

Tata Institute of Fundamental Research – HECR, Mumbai, India

H. Arfaei, H. Bakhshiansohi [20], S.M. Etesami [21], A. Fahim [20], M. Hashemi, H. Hesari, A. Jafari [20], M. Khakzad, A. Mohammadi [22], M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh [23], M. Zeinali [21]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Abbrescia [a,b], L. Barbone [a,b], C. Calabria [a,b], S.S. Chhibra [a,b], A. Colaleo [a], D. Creanza [a,c], N. De Filippis [a,c,1], M. De Palma [a,b], L. Fiore [a], G. Iaselli [a,c], L. Lusito [a,b], G. Maggi [a,c], M. Maggi [a], N. Manna [a,b], B. Marangelli [a,b], S. My [a,c], S. Nuzzo [a,b], N. Pacifico [a,b], A. Pompili [a,b], G. Pugliese [a,c], F. Romano [a,c], G. Selvaggi [a,b], L. Silvestris [a], G. Singh [a,b], S. Tupputi [a,b], G. Zito [a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], A.C. Benvenuti [a], D. Bonacorsi [a], S. Braibant-Giacomelli [a,b], L. Brigliadori [a], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], M. Cuffiani [a,b], G.M. Dallavalle [a], F. Fabbri [a], A. Fanfani [a,b], D. Fasanella [a,1], P. Giacomelli [a], C. Grandi [a], S. Marcellini [a], G. Masetti [a], M. Meneghelli [a,b], A. Montanari [a], F.L. Navarria [a,b], F. Odorici [a], A. Perrotta [a], F. Primavera [a], A.M. Rossi [a,b], T. Rovelli [a,b], G. Siroli [a,b], R. Travaglini [a,b]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo [a,b], G. Cappello [a,b], M. Chiorboli [a,b], S. Costa [a,b], R. Potenza [a,b], A. Tricomi [a,b], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

G. Barbagli [a], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], S. Frosali [a,b], E. Gallo [a], S. Gonzi [a,b], M. Meschini [a], S. Paoletti [a], G. Sguazzoni [a], A. Tropiano [a,1]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, S. Colafranceschi [24], F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbricatore, R. Musenich

INFN Sezione di Genova, Genova, Italy

A. Benaglia [a,b,1], F. De Guio [a,b], L. Di Matteo [a,b], S. Fiorendi [a,b], S. Gennai [a,1], A. Ghezzi [a,b], S. Malvezzi [a], R.A. Manzoni [a,b], A. Martelli [a,b], A. Massironi [a,b,1], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], S. Ragazzi [a,b], N. Redaelli [a], S. Sala [a], T. Tabarelli de Fatis [a,b]

[a] *INFN Sezione di Milano-Bicocca, Milano, Italy*
[b] *Università di Milano-Bicocca, Milano, Italy*

S. Buontempo [a], C.A. Carrillo Montoya [a,1], N. Cavallo [a,25], A. De Cosa [a,b], O. Dogangun [a,b], F. Fabozzi [a,25], A.O.M. Iorio [a,1], L. Lista [a], M. Merola [a,b], P. Paolucci [a]

[a] *INFN Sezione di Napoli, Napoli, Italy*
[b] *Università di Napoli "Federico II", Napoli, Italy*

P. Azzi [a], N. Bacchetta [a,1], P. Bellan [a,b], D. Bisello [a,b], A. Branca [a], R. Carlin [a,b], P. Checchia [a], T. Dorigo [a], U. Dosselli [a], F. Fanzago [a], F. Gasparini [a,b], U. Gasparini [a,b], A. Gozzelino [a], K. Kanishchev, S. Lacaprara [a,26], I. Lazzizzera [a,c], M. Margoni [a,b], M. Mazzucato [a], A.T. Meneguzzo [a,b], M. Nespolo [a,1], L. Perrozzi [a], N. Pozzobon [a,b], P. Ronchese [a,b], F. Simonetto [a,b], E. Torassa [a], M. Tosi [a,b,1], S. Vanini [a,b], P. Zotto [a,b], G. Zumerle [a,b]

[a] *INFN Sezione di Padova, Padova, Italy*
[b] *Università di Padova, Padova, Italy*
[c] *Università di Trento (Trento), Padova, Italy*

U. Berzano [a], M. Gabusi [a,b], S.P. Ratti [a,b], C. Riccardi [a,b], P. Torre [a,b], P. Vitulo [a,b]

[a] *INFN Sezione di Pavia, Pavia, Italy*
[b] *Università di Pavia, Pavia, Italy*

M. Biasini [a,b], G.M. Bilei [a], B. Caponeri [a,b], L. Fanò [a,b], P. Lariccia [a,b], A. Lucaroni [a,b,1], G. Mantovani [a,b], M. Menichelli [a], A. Nappi [a,b], F. Romeo [a,b], A. Santocchia [a,b], S. Taroni [a,b,1], M. Valdata [a,b]

[a] *INFN Sezione di Perugia, Perugia, Italy*
[b] *Università di Perugia, Perugia, Italy*

P. Azzurri [a,c], G. Bagliesi [a], T. Boccali [a], G. Broccolo [a,c], R. Castaldi [a], R.T. D'Agnolo [a,c], R. Dell'Orso [a], F. Fiori [a,b], L. Foà [a,c], A. Giassi [a], A. Kraan [a], F. Ligabue [a,c], T. Lomtadze [a], L. Martini [a,27], A. Messineo [a,b], F. Palla [a], F. Palmonari [a], A. Rizzi, A.T. Serban [a], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b,1], A. Venturi [a,1], P.G. Verdini [a]

[a] *INFN Sezione di Pisa, Pisa, Italy*
[b] *Università di Pisa, Pisa, Italy*
[c] *Scuola Normale Superiore di Pisa, Pisa, Italy*

L. Barone [a,b], F. Cavallari [a], D. Del Re [a,b,1], M. Diemoz [a], C. Fanelli, M. Grassi [a,1], E. Longo [a,b], P. Meridiani [a], F. Micheli, S. Nourbakhsh [a], G. Organtini [a,b], F. Pandolfi [a,b], R. Paramatti [a], S. Rahatlou [a,b], M. Sigamani [a], L. Soffi

[a] *INFN Sezione di Roma, Roma, Italy*
[b] *Università di Roma "La Sapienza", Roma, Italy*

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], C. Biino [a], C. Botta [a,b], N. Cartiglia [a], R. Castello [a,b], M. Costa [a,b], N. Demaria [a], A. Graziano [a,b], C. Mariotti [a,1], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], M. Musich [a], M.M. Obertino [a,c], N. Pastrone [a], M. Pelliccioni [a], A. Potenza [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], V. Sola [a,b], A. Solano [a,b], A. Staiano [a], A. Vilela Pereira [a]

[a] *INFN Sezione di Torino, Torino, Italy*
[b] *Università di Torino, Torino, Italy*
[c] *Università del Piemonte Orientale (Novara), Torino, Italy*

S. Belforte [a], F. Cossutti [a], G. Della Ricca [a,b], B. Gobbo [a], M. Marone [a,b], D. Montanino [a,b,1], A. Penzo [a]

[a] INFN Sezione di Trieste, Trieste, Italy
[b] Università di Trieste, Trieste, Italy

S.G. Heo, S.K. Nam

Kangwon National University, Chunchon, Republic of 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

Kyungpook National University, Daegu, Republic of Korea

J.Y. Kim, Zero J. Kim, S. Song

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

H.Y. Jo

Konkuk University, Seoul, Republic of Korea

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

Korea University, Seoul, Republic of Korea

M. Choi, S. Kang, H. Kim, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

M.J. Bilinskas, I. Grigelionis, M. Janulis

Vilnius University, Vilnius, Lithuania

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

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

University of Canterbury, Christchurch, New Zealand

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

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

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

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

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

Soltan Institute for Nuclear Studies, Warsaw, Poland

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Musella, A. Nayak, J. Pela [1], P.Q. Ribeiro, J. Seixas, J. Varela, P. Vischia

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

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

Joint Institute for Nuclear Research, Dubna, Russia

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

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

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

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov [1], A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin [4], L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, L. Sarycheva [†], V. Savrin, A. Snigirev

Moscow State University, Moscow, Russia

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

P.N. Lebedev Physical Institute, Moscow, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin [1], V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic [28], M. Djordjevic, M. Ekmedzic, D. Krpic [28], J. Milosevic

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

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

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

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

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez [29], J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini [30], 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, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, C. Bernet [5], W. Bialas, G. Bianchi, P. Bloch, A. Bocci, 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, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, G. Georgiou, H. Gerwig, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, L. Guiducci, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, H.F. Hoffmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, G. Mavromanolakis, 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 [31], T. Rommerskirchen, C. Rovelli [32], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas [*,33], D. Spiga, M. Spiropulu [4], M. Stoye, A. Tsirou, G.I. Veres [16], P. Vichoudis, H.K. Wöhri, S.D. Worm [34], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, 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 [35]

Paul Scherrer Institut, Villigen, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, Z. Chen, A. Deisher, G. Dissertori, M. Dittmar, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, P. Lecomte, W. Lustermann, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli [36], P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, A. Starodumov [37], B. Stieger, M. Takahashi, L. Tauscher [†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli, J. Weng

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

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

Universität Zürich, Zurich, Switzerland

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 Central University, Chung-Li, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, M. Wang

National Taiwan University (NTU), Taipei, Taiwan

A. Adiguzel, M.N. Bakirci [38], S. Cerci [39], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, I. Hos, E.E. Kangal, G. Karapinar, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk [40], A. Polatoz, K. Sogut [41], D. Sunar Cerci [39], B. Tali [39], H. Topakli [38], D. Uzun, L.N. Vergili, M. Vergili

Cukurova University, Adana, 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

Middle East Technical University, Physics Department, Ankara, Turkey

M. Deliomeroglu, E. Gülmez, B. Isildak, M. Kaya [42], O. Kaya [42], S. Ozkorucuklu [43], N. Sonmez [44]

Bogazici University, Istanbul, Turkey

L. Levchuk

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

F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold [34], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

University of Bristol, Bristol, United Kingdom

L. Basso [45], K.W. Bell, A. Belyaev [45], C. Brew, R.M. Brown, 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

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, 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, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko [37], A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi [46], D.M. Raymond, S. Rogerson, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, D. Wardrope, T. Whyntie

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

K. Hatakeyama, H. Liu, T. Scarborough

Baylor University, Waco, USA

C. Henderson

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

S. Bhattacharya, 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

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, M. Caulfield, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, O. Mall, T. Miceli, R. Nelson, D. Pellett, J. Robles, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

University of California, Davis, Davis, USA

V. Andreev, K. Arisaka, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], J. Tucker, V. Valuev, M. Weber

University of California, Los Angeles, Los Angeles, USA

J. Babb, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, Riverside, Riverside, USA

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

University of California, San Diego, La Jolla, 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[1], V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, J.R. Vlimant, C. West

University of California, Santa Barbara, Santa Barbara, USA

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

California Institute of Technology, Pasadena, 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

Carnegie Mellon University, Pittsburgh, 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

University of Colorado at Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

A. Biselli, D. Winn

Fairfield University, Fairfield, 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, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, H. Jensen, S. Jindariani, M. Johnson, U. Joshi, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, T. Miao, K. Mishra, S. Mrenna, Y. Musienko[48], C. Newman-Holmes, V. O'Dell, J. Pivarski, R. Pordes, O. Prokofyev, T. Schwarz, 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

Fermi National Accelerator Laboratory, Batavia, 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, P. Milenovic [49], G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, M. Snowball, D. Wang, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

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

Florida International University, Miami, 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, M. Weinberg

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, 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 [50], F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, C. Silvestre, D. Strom, N. Varelas

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

U. Akgun, E.A. Albayrak, B. Bilki [51], W. Clarida, F. Duru, S. Griffiths, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya [52], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

The University of Iowa, Iowa City, USA

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

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, M. Boutemeur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, A. Peterman, K. Rossato, P. Rumerio, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

University of Maryland, College Park, USA

B. Alver, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, Y.-J. Lee, W. Li, 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, B. Wyslouch, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

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

University of Mississippi, University, USA

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

University of Nebraska-Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, D. Trocino, D. Wood, J. Zhang

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

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

University of Notre Dame, Notre Dame, USA

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

The Ohio State University, Columbus, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, E. Laird, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

Princeton University, Princeton, USA

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

University of Puerto Rico, Mayaguez, USA

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

Purdue University, West Lafayette, USA

S. Guragain, N. Parashar

Purdue University Calumet, Hammond, USA

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

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

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

The Rockefeller University, New York, USA

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

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

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

University of Tennessee, Knoxville, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon [53], V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas A&M University, College Station, USA

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

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

M. Anderson, M. Bachtis, D. Belknap, J.N. Bellinger, J. Bernardini, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, J. Efron, E. Friis, 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, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

University of Wisconsin, Madison, USA

* Corresponding author.

† Deceased.

1 Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

2 Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

3 Also at Universidade Federal do ABC, Santo Andre, Brazil.

4 Also at California Institute of Technology, Pasadena, USA.

5 Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.

6 Also at Suez Canal University, Suez, Egypt.

7 Also at Cairo University, Cairo, Egypt.

8 Also at British University, Cairo, Egypt.

9 Also at Fayoum University, El-Fayoum, Egypt.

10 Now at Ain Shams University, Cairo, Egypt.

[11] Also at Soltan Institute for Nuclear Studies, Warsaw, Poland.
[12] Also at Université de Haute-Alsace, Mulhouse, France.
[13] Also at Moscow State University, Moscow, Russia.
[14] Also at Brandenburg University of Technology, Cottbus, Germany.
[15] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[16] Also at Eötvös Loránd University, Budapest, Hungary.
[17] Also at Tata Institute of Fundamental Research – HECR, Mumbai, India.
[18] Now at King Abdulaziz University, Jeddah, Saudi Arabia.
[19] Also at University of Visva-Bharati, Santiniketan, India.
[20] Also at Sharif University of Technology, Tehran, Iran.
[21] Also at Isfahan University of Technology, Isfahan, Iran.
[22] Also at Shiraz University, Shiraz, Iran.
[23] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran.
[24] Also at Facoltà Ingegneria Università di Roma, Roma, Italy.
[25] Also at Università della Basilicata, Potenza, Italy.
[26] Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
[27] Also at Università degli studi di Siena, Siena, Italy.
[28] Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
[29] Also at University of Florida, Gainesville, USA.
[30] Also at University of California, Los Angeles, Los Angeles, USA.
[31] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[32] Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy.
[33] Also at University of Athens, Athens, Greece.
[34] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[35] Also at The University of Kansas, Lawrence, USA.
[36] Also at Paul Scherrer Institut, Villigen, Switzerland.
[37] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[38] Also at Gaziosmanpasa University, Tokat, Turkey.
[39] Also at Adiyaman University, Adiyaman, Turkey.
[40] Also at The University of Iowa, Iowa City, USA.
[41] Also at Mersin University, Mersin, Turkey.
[42] Also at Kafkas University, Kars, Turkey.
[43] Also at Suleyman Demirel University, Isparta, Turkey.
[44] Also at Ege University, Izmir, Turkey.
[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 University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[50] Also at Los Alamos National Laboratory, Los Alamos, USA.
[51] Also at Argonne National Laboratory, Argonne, USA.
[52] Also at Erzincan University, Erzincan, Turkey.
[53] Also at Kyungpook National University, Daegu, Republic of Korea.