



## Journal Article

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## Search for Heavy Neutrinos and $W_R$ Bosons with Right-Handed Couplings in a Left-Right Symmetric Model in $pp$ Collisions at $\sqrt{s} = 7$ TeV

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Results are presented from a search for heavy, right-handed muon neutrinos,  $N_\mu$ , and right-handed  $W_R$  bosons, which arise in the left-right symmetric extensions of the standard model. The analysis is based on a  $5.0 \text{ fb}^{-1}$  sample of proton-proton collisions at a center-of-mass energy of 7 TeV, collected by the CMS detector at the Large Hadron Collider. No evidence is observed for an excess of events over the standard model expectation. For models with exact left-right symmetry, heavy right-handed neutrinos are excluded at 95% confidence level for a range of neutrino masses below the  $W_R$  mass, dependent on the value of  $M_{W_R}$ . The excluded region in the two-dimensional  $(M_{W_R}, M_{N_\mu})$  mass plane extends to  $M_{W_R} = 2.5$  TeV.

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The maximal violation of parity conservation is a prominent feature of neutrino interactions that is included in the standard model (SM) in terms of purely left-handed couplings to the  $W$  boson. In addition, the observation of neutrino oscillations (see e.g. [1]), together with direct limits on neutrino masses [2], has demonstrated that neutrinos have tiny but nonvanishing masses, suggesting a distinct origin from the masses of the quarks and leptons.

The left-right (LR) symmetric extension of the standard model [3–6] provides a possible explanation for neutrino mass through the seesaw mechanism [7]. The LR symmetry is spontaneously broken at a multi-TeV mass scale, leading to parity violation in weak interactions as described by the SM. By introducing a right-handed SU(2) symmetry group, the LR model incorporates heavy right-handed Majorana neutrinos ( $N_\ell$ ,  $\ell = e, \mu, \tau$ ) as well as additional charged ( $W_R^\pm$ ) and neutral ( $Z_R$ ) gauge bosons.

We search for the production of  $W_R$  bosons from proton-proton collisions at the Large Hadron Collider (LHC). The  $W_R$  boson is assumed to decay to a muon and to a right-handed neutrino  $N_\mu$ , which subsequently decays to produce a second muon together with a virtual  $W_R^*$ . If the  $N_\mu$  is a Majorana particle as predicted in the LR model, the two final state muons may have the same sign. The virtual  $W_R^*$  decays to a pair of quarks which hadronize into jets ( $j$ ), resulting in a final state with two muons and two jets,

$$W_R \rightarrow \mu_1 N_\mu \rightarrow \mu_1 \mu_2 W_R^* \rightarrow \mu_1 \mu_2 q q' \rightarrow \mu_1 \mu_2 j_1 j_2.$$

The search presented in this Letter is characterized by the  $W_R$  and  $N_\mu$  masses,  $M_{W_R}$  and  $M_{N_\mu}$ , which are allowed to vary independently. Although  $M_{N_\mu} > M_{W_R}$  is allowed, it

is not considered in this analysis. The branching fraction for  $W_R \rightarrow \mu N_\mu$  depends on the number of heavy neutrino flavors that are accessible at LHC energies. To simplify the interpretation of the results,  $N_\mu$  is assumed to be the only heavy neutrino flavor light enough to contribute significantly to the  $W_R$  decay width. CMS recently performed a search for heavy Majorana neutrinos in the final state containing two jets and two same-sign electrons or muons and set limits on the coupling between such a neutrino and the left-handed  $W$  of the SM as a function of  $M_{N_\mu}$  [8], while this analysis considers on-shell production of a right-handed  $W_R$  boson. No charge requirements are imposed on the final state muons in this analysis.

For given  $W_R$  and  $N_\mu$  masses, the signal cross section can be predicted from the assumed value of the coupling constant  $g_R$ , which denotes the strength of the gauge interactions of  $W_R^\pm$  bosons. Strict left-right symmetry implies that  $g_R$  is equal to the (left-handed) weak interaction coupling strength  $g_L$  at  $M_{W_R}$ , which will be assumed throughout this Letter. Consequently, the  $W_R$  production cross section can be calculated by the FEWZ program [9] using the left-handed  $W$  model [10,11]. As an additional simplification, the left-right boson and lepton mixing angles are assumed to be small.

Estimates based on  $K_L$ - $K_S$  mixing results imply a theoretical lower limit of  $M_{W_R} \gtrsim 2.5$  TeV [12,13]. Searches for  $W_R \rightarrow tb$  decays at the Tevatron [14–16] and at the LHC [17,18] exclude  $W_R$  masses below 1.85 TeV. An ATLAS search for  $W_R \rightarrow \ell N_\ell$  using similar model assumptions as those in this Letter, but allowing  $W_R$  decays to both  $N_e$  and  $N_\mu$ , excluded a region in the two-dimensional parameter  $(M_{W_R}, M_{N_\ell})$  space extending to nearly  $M_{W_R} = 2.5$  TeV [19].

The analysis is based on a  $5.0 \text{ fb}^{-1}$  sample of proton-proton collision data at a center-of-mass energy of 7 TeV, collected by the Compact Muon Solenoid (CMS) detector [20] at the LHC. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the

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silicon pixel and strip trackers, the lead-tungstate crystal electromagnetic calorimeter, and the brass and scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke, with detection planes made of three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. The CMS trigger system, composed of custom hardware processors at the first level followed by a processor farm at the next level, selects  $\mathcal{O}(100 \text{ Hz})$  of the most interesting events. The events used in this analysis were collected with single-muon triggers whose  $p_T$  thresholds ranged from 24 GeV to 40 GeV, depending on the instantaneous luminosity.

The  $W_R \rightarrow \mu N_\mu$  signal samples are generated using PYTHIA 6.4.24 [21], which includes the LR symmetric model with the standard assumptions mentioned previously, with CTEQ6L1 parton distribution functions [22]. We also study SM background processes using simulated samples:  $t\bar{t}$  and single-top (both generated using POWHEG [23]),  $W$  and Drell-Yan production in association with jets (SHERPA [24]), and diboson production (PYTHIA). Generated events pass through the full CMS detector simulation based on GEANT [25].

The muon identification strategy is based on both the muon detectors and the inner tracker, described in Ref. [26]. At least one of the two muons used to define the  $W_R$  candidate is required to be matched to a muon candidate found by the trigger, and both muons are required to satisfy the tight identification criteria discussed in Ref. [27]. The muon identification requirements ensure good consistency between the measurements of the muon detector and the inner tracker, and suppress muons from decay-in-flight of hadrons as well as from shower punch-through. Nonisolated muon backgrounds are controlled by computing the sum of the transverse momentum of tracks within a cone about the muon direction of  $\Delta R < 0.3$ , with  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ , given the azimuthal angle  $\phi$  and  $\eta = -\ln[\tan(\theta/2)]$ , where  $\theta$  is the polar angle with respect to the beam direction. The final  $p_T$  sum must be less than 10% of the muon transverse momentum.

Jets are reconstructed by forming clusters of charged and neutral hadrons, photons, and leptons that are first reconstructed based on the CMS particle-flow technique [28], using the anti- $k_T$  clustering algorithm [29] with a radius

parameter  $R = 0.5$ . Energy deposits in the calorimeter with characteristics that match those of noise or beam halo tracks are identified, and events are rejected if either of the two highest- $p_T$  jet candidates was produced by such energy deposits. To suppress backgrounds from heavy-flavor-quark decays, any muon is rejected if found near a jet, with  $\Delta R(\mu, j) < 0.5$ .

In approximately 95% of simulated signal event samples, the  $W_R$  final state decay products are the highest  $p_T$  muons and jets in the event.  $W_R \rightarrow \mu N_\mu$  candidates are thus formed from the two highest- $p_T$  muons and the two highest- $p_T$  jets in the event. As the initial two-body decay  $W_R \rightarrow \mu N_\mu$  tends to produce a high-momentum muon, events are selected in which the leading muon has  $p_T > 60 \text{ GeV}$  and the subleading muon has  $p_T > 30 \text{ GeV}$ . A minimum transverse momentum requirement of 40 GeV is imposed on the jet candidates after correcting for the effects of the extra  $pp$  collisions in the event and the jet energy response of the detector. Backgrounds are suppressed by requiring the invariant mass of the dimuon system  $M_{\mu\mu} > 200 \text{ GeV}$  and the four-object mass  $M_{\mu\mu jj} > 600 \text{ GeV}$ .

The signal acceptance is found to be typically near 80% at  $M_{N_\mu} \sim M_{W_R}/2$  and decreases rapidly for  $M_{N_\mu} \leq 0.10M_{W_R}$ . At low neutrino mass, the  $N_\mu \rightarrow \mu jj$  decay products tend to overlap due to the boost from  $W_R$  decay, and the two jets may not be distinguishable or the muon from  $N_\mu$  decay may be too close to a jet. For  $W_R$  signal events which meet the kinematic acceptance requirements, the efficiency to reconstruct the four high- $p_T$  objects using the CMS detector ranges between 75% and 80% as a function of  $W_R$  and  $N_\mu$  mass.

After the muon requirements are applied, the SM backgrounds for  $W_R \rightarrow \mu N_\mu$  consist primarily of events from processes with two isolated high- $p_T$  muons, namely  $t\bar{t} \rightarrow bW + \bar{b}W^-$  and  $Z + \text{jets}$  processes. The impact of the selection criteria on background processes is shown in Table I.

The  $t\bar{t}$  background contribution is estimated using a control sample of  $e\mu jj$  events reconstructed in data and simulation. This sample is dominated by  $t\bar{t}$  events, with small contributions from other SM processes estimated using simulation. The simulated  $t\bar{t}$  background

TABLE I. The total number of events reconstructed in data, and the expected contributions from signal and background (bkgd) samples, after different stages of the selection requirements are applied. The first selection given below requires two muons with  $p_T > 30 \text{ GeV}$  and two jets with  $p_T > 40 \text{ GeV}$  meeting all requirements described in the text. The ‘‘Signal’’ column indicates the expected contribution for  $M_{W_R} = 1800 \text{ GeV}$ , with  $M_{N_\mu} = 1000 \text{ GeV}$ . The uncertainties for the background expectation are derived for the final stage of selection and more details are given in the text. The yields from earlier stages of the selection have greater relative uncertainty than that for the full selection.

Selection stage	Data	Signal	Total bkgd	$t\bar{t}$	$Z + \text{jets}$	Other
Two muons, two jets	21 769	50	21 061	1603	19 136	322
$\mu_1 p_T > 60 \text{ GeV}$	13 328	50	12 862	1106	11 531	225
$M_{\mu\mu} > 200 \text{ GeV}$	365	48	341	211	116	14
$M_{\mu\mu jj} > 600 \text{ GeV}$	164	$48 \pm 13$	$152 \pm 22$	$81 \pm 18$	$65 \pm 9$	$6 \pm 3$

contribution is scaled to data using events satisfying  $M_{e\mu} > 200$  GeV, which is equivalent to the third selection stage in Table I. The scale factor for the simulated  $t\bar{t}$  sample, relative to the  $t\bar{t}$  cross section measured by CMS [30], is  $0.97 \pm 0.06$ . The uncertainty on this scale factor reflects the number of events in data with  $M_{e\mu} > 200$  GeV. Applying this scale factor to the  $t\bar{t}$  simulation, the  $M_{e\mu,jj}$  distributions in data and simulation are found to be in agreement. This scale factor is applied to the simulated  $t\bar{t}$  event sample at all stages of selection in order to estimate the expected number of  $pp \rightarrow t\bar{t} + X$  events that survive successive selection criteria.

The  $Z + \text{jets}$  background contribution is estimated from  $Z \rightarrow \mu\mu$  decays reconstructed in simulation and data. The simulated  $Z + \text{jets}$  background contribution is normalized to data using events in the dimuon mass region  $60 \text{ GeV} < M_{\mu\mu} < 120 \text{ GeV}$  after requiring  $\mu_1 p_T > 60 \text{ GeV}$  as indicated in Table I. Accounting for other SM background processes, the simulated  $Z + \text{jets}$  scale factor is  $1.43 \pm 0.01$  relative to inclusive next-to-next-to-leading order calculations. The uncertainty on this value reflects the number of events from data with  $60 \text{ GeV} < M_{\mu\mu} < 120 \text{ GeV}$ . After rescaling the  $Z + \text{jets}$  simulation, the shape of the  $M_{\mu\mu}$  distribution for data is in agreement with simulation for  $M_{\mu\mu} > 60 \text{ GeV}$ .

After all selection criteria are applied, the  $t\bar{t}$  and  $Z + \text{jets}$  processes dominate the total SM background contribution. Other SM processes, mostly diboson and single top, comprise less than 5% of the total background and their contributions are estimated from simulation. Background from  $W + \text{jets}$  processes, also estimated from simulation, is negligible. The background contribution from multijet processes is estimated using control samples from data and is roughly 0.1% of the total SM background after all selection requirements are applied.

The observed and expected number of events surviving the selections are summarized in Table I. The yields reflect the number of background events surviving each selection stage, with normalization factors obtained from control sample studies ( $t\bar{t}$ ,  $Z + \text{jets}$ , and multijet processes) or taken directly from simulation. The data are found to be in agreement with SM expectations.

The reconstructed four-object mass in data and simulation is used to estimate limits on  $W_R$  production. The  $M_{\mu\mu,jj}$  distribution for  $W_R \rightarrow \mu\mu jj$  signal events, for each  $W_R$  mass assumption, is included together with the SM background distributions to search for evidence of  $W_R$  production.

The dominant uncertainty related to  $W_R \rightarrow \mu N_\mu$  production arises from the variation in the predicted signal production cross section as a result of the uncertainties in the parton distribution functions (PDFs) of the proton. This uncertainty varies between 4% and 22%, depending on the  $W_R$  mass hypothesis, following the PDF4LHC prescriptions [31] for the CT10 [32] and MSTW2008 [33] PDF sets.

The uncertainties associated with muon reconstruction and identification are determined from  $Z \rightarrow \mu^+ \mu^-$  events reconstructed in both data and simulation. The size of this uncertainty is about 15% for signal and 5% for background processes.

The shape of each SM background  $M_{\mu\mu,jj}$  distribution is modeled by an exponential ( $e^{a+bM_{\mu\mu,jj}}$ ) line shape, and the background contributions as a function of mass are determined from the result of fits applied to each background type:  $t\bar{t}$ ,  $Z + \text{jets}$ , and other SM backgrounds. The background uncertainty is dominated by the uncertainty in the background modeling and is computed as a function of  $\mu\mu,jj$  mass.

The uncertainty in the exponential fit is taken as the uncertainty due to background modeling. Each background distribution is also fit with an alternative suite of exponential functions to allow for deviations from the assumed shape at high mass. For a given  $M_{\mu\mu,jj}$  range, we take the maximum of the deviation, relative to the nominal exponential fit, from any alternative fit result as the uncertainty due to background modeling if this deviation exceeds the nominal fit uncertainty.

Uncertainties in the jet energy scale and resolution impact the shape of the signal and background  $M_{\mu\mu,jj}$  distributions, contributing less than 10% to the signal and background uncertainties. The normalization of the various background samples contributes 5% to the total uncertainty. Muon resolution and trigger efficiency uncertainties, and additional factorization and scale theoretical uncertainties, contribute to the total uncertainty to a lesser extent. The uncertainties in the total number of background events are derived taking into account the relative contribution of all background events after the full event selection, and the correlation of each effect between all background processes.

The total uncertainty for signal and background is summarized in Table I. The  $M_{\mu\mu,jj}$  distribution for events with  $M_{\mu\mu} > 200$  GeV is presented in Fig. 1, which also summarizes the background uncertainty as a function of  $M_{\mu\mu,jj}$  and demonstrates the dominant background model uncertainty relative to the total background uncertainty.

As no evidence for  $W_R \rightarrow \mu N_\mu$  decay is found, limits on  $W_R$  production are estimated using a multibin technique based on the ROOSTATS package [34]. The bin width of 200 GeV, comparable to the mass resolution for a reconstructed  $W_R$  boson with mass below 2.5 TeV, is chosen for the  $M_{\mu\mu,jj}$  distributions used to compute the limits. The background inputs to the limit calculation use the results of the exponential fit, while the signal input is taken directly from the  $M_{\mu\mu,jj}$  distribution for each signal  $W_R$  mass assumption. Uncertainties are included as nuisance parameters in the limit calculations. A  $\text{CL}_S$  limit setting technique [35,36] is used to estimate the 95% confidence level (CL) excluded region as a function of the  $W_R$  cross section multiplied by the  $W_R \rightarrow \mu\mu,jj$  branching fraction

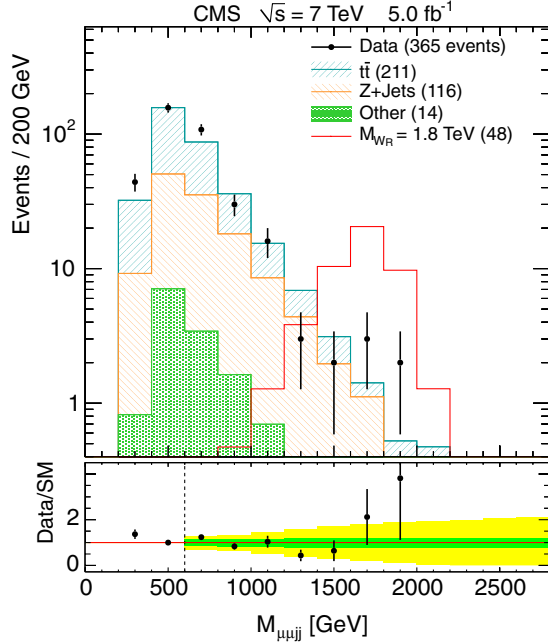


FIG. 1 (color online). Distribution of the invariant mass  $M_{\mu\mu jj}$  for events in data (points with error bars) with  $M_{\mu\mu} > 200$  GeV and for simulated background contributions (hatched stacked histograms). The signal mass point  $M_{W_R} = 1800$  GeV,  $M_{N_\mu} = 1000$  GeV, is included for comparison (open red histogram). The number of events from each background process (and the expected number of signal events) is included in parentheses in the legend. The data are compared to SM expectations in the lower portion of the figure. The total background uncertainty (outer band) and the background uncertainty after neglecting the uncertainty due to background modeling (inner band) are included as a function of  $M_{\mu\mu jj}$  for  $M_{\mu\mu jj} > 600$  GeV.

and  $W_R$  mass. The observed and expected limits are found to be in agreement. These results (available in tabular form in the Supplemental Material [37]) can be used for the evaluation of models other than those considered in this Letter.

Limits as a function of  $W_R$  mass for a right-handed neutrino with  $M_N = \frac{1}{2}M_{W_R}$  are presented in Fig. 2. The theoretical expectation in Fig. 2 assumes that only  $N_\mu$  contributes to the  $W_R$  decay width, as mentioned previously. Assuming degenerate  $N_\ell$  ( $\ell = e, \mu, \tau$ ) masses allows  $W_R \rightarrow eN_e$  and  $W_R \rightarrow \tau N_\tau$  decays in addition to  $W_R \rightarrow q\bar{q}$  and  $W_R \rightarrow \mu N_\mu$  and effectively decreases the expected  $W_R \rightarrow \mu\mu jj$  production rate by approximately 15%.

For the model considered in this Letter, Fig. 3 indicates the range of excluded  $N_\mu$  masses as a function of  $W_R$  mass by comparing the observed (expected) upper limit and the predicted cross section for each mass point. These limits extend to  $M_{W_R} = 2.5$  TeV, and exclude a wide range of heavy neutrino masses for  $W_R$  mass assumptions below this maximal value.

In summary, we have presented a search for the right-handed heavy muon neutrinos ( $N_\mu$ ) and bosons ( $W_R$ ) of the

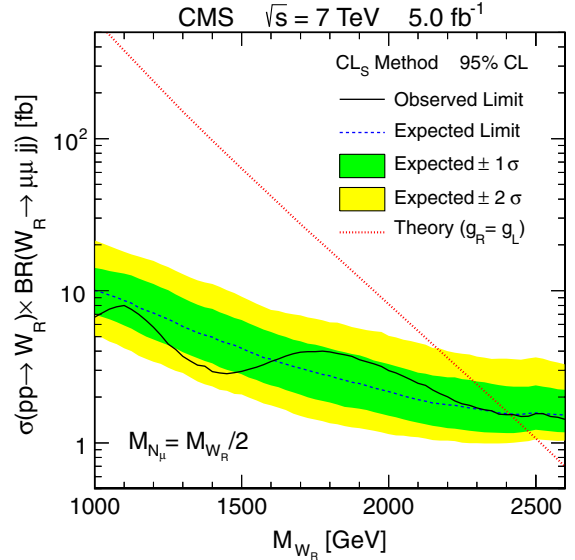


FIG. 2 (color online). The 95% confidence level exclusion limit on the  $W_R$  production cross section times branching fraction for  $W_R \rightarrow \mu\mu jj$  as a function of  $M_{W_R}$  for  $M_{N_\mu} = \frac{1}{2}M_{W_R}$ . This limit is compared to expectations given the theoretical model described in the text.

left-right symmetric extension of the standard model. We find that our data sample is in agreement with expectations from standard model processes and therefore set a limit on the  $W_R$  and  $N_\mu$  masses. For models with exact left-right symmetry (the same coupling to the right-handed and left-handed sectors), we exclude heavy right-handed neutrinos for a range of  $M_{N_\mu} < M_{W_R}$ , dependent on the value of  $M_{W_R}$ . For these models, the excluded region in the two-dimensional parameter space  $(M_{W_R}, M_{N_\mu})$  extends to  $M_{W_R} = 2.5$  TeV.

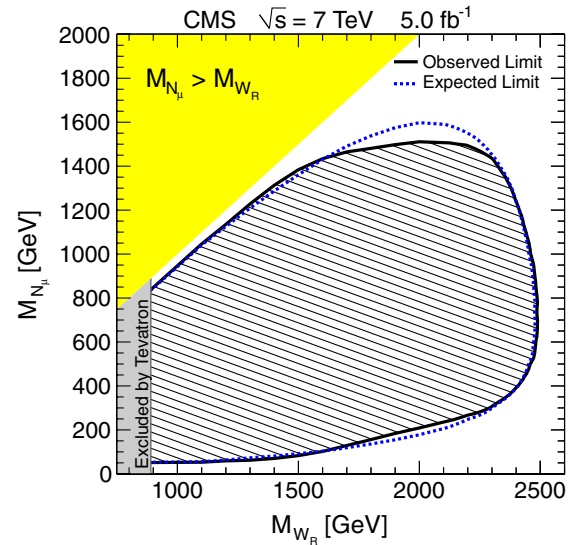


FIG. 3 (color online). The 95% confidence level exclusion region in the  $(M_{W_R}, M_{N_\mu})$  plane, assuming the model described in the text. The Tevatron exclusion region for  $W_R$  production [16] is included in the figure.

These results represent the most sensitive limits to date on  $W_R$  production assuming a single heavy neutrino flavor contributes significantly to the  $W_R$  decay width.

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M. Djordjevic,<sup>92</sup> M. Ekmedzic,<sup>92</sup> D. Krpic,<sup>92,hh</sup> J. Milosevic,<sup>92</sup> M. Aguilar-Benitez,<sup>93</sup> J. Alcaraz Maestre,<sup>93</sup>  
P. Arce,<sup>93</sup> C. Battilana,<sup>93</sup> E. Calvo,<sup>93</sup> M. Cerrada,<sup>93</sup> M. Chamizo Llatas,<sup>93</sup> N. Colino,<sup>93</sup> B. De La Cruz,<sup>93</sup>  
A. Delgado Peris,<sup>93</sup> D. Domínguez Vázquez,<sup>93</sup> C. Fernandez Bedoya,<sup>93</sup> J. P. Fernández Ramos,<sup>93</sup> A. Ferrando,<sup>93</sup>  
J. Flix,<sup>93</sup> M. C. Fouz,<sup>93</sup> P. Garcia-Abia,<sup>93</sup> O. Gonzalez Lopez,<sup>93</sup> S. Goy Lopez,<sup>93</sup> J. M. Hernandez,<sup>93</sup> M. I. Josa,<sup>93</sup>  
G. Merino,<sup>93</sup> J. Puerta Pelayo,<sup>93</sup> A. Quintario Olmeda,<sup>93</sup> I. Redondo,<sup>93</sup> L. Romero,<sup>93</sup> J. Santaolalla,<sup>93</sup> M. S. Soares,<sup>93</sup>  
C. Willmott,<sup>93</sup> C. Albajar,<sup>94</sup> G. Codispoti,<sup>94</sup> J. F. de Trocóniz,<sup>94</sup> H. Brun,<sup>95</sup> J. Cuevas,<sup>95</sup> J. Fernandez Menendez,<sup>95</sup>  
S. Folgueras,<sup>95</sup> I. Gonzalez Caballero,<sup>95</sup> L. Lloret Iglesias,<sup>95</sup> J. Piedra Gomez,<sup>95</sup> J. A. Brochero Cifuentes,<sup>96</sup>  
I. J. Cabrillo,<sup>96</sup> A. Calderon,<sup>96</sup> S. H. Chuang,<sup>96</sup> J. Duarte Campderros,<sup>96</sup> M. Felcini,<sup>96,ii</sup> M. Fernandez,<sup>96</sup> G. Gomez,<sup>96</sup>  
J. Gonzalez Sanchez,<sup>96</sup> A. Graziano,<sup>96</sup> C. Jorda,<sup>96</sup> A. Lopez Virto,<sup>96</sup> J. Marco,<sup>96</sup> R. Marco,<sup>96</sup> C. Martinez Rivero,<sup>96</sup>  
F. Matorras,<sup>96</sup> F. J. Munoz Sanchez,<sup>96</sup> T. Rodrigo,<sup>96</sup> A. Y. Rodríguez-Marrero,<sup>96</sup> A. Ruiz-Jimeno,<sup>96</sup> L. Scodellaro,<sup>96</sup>  
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