Search for heavy, top-like quark pair production in the dilepton final state in pp collisions at s = 7 TeV

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Search for heavy, top-like quark pair production in the dilepton final state in pp collisions at $\sqrt{s} = 7$ TeV

CMS Collaboration

1. Introduction

Since the discovery of the top quark at the Tevatron [1,2], there have been many searches for a possible new generation of fermions. Those searches have found no evidence of new fermions beyond the standard model (SM). However, based on present knowledge, there is no compelling reason for the number of fermion generations to be limited to three [3]. Additional generations of fermions may have a significant effect on neutrino, flavor, and Higgs physics. A fourth generation of quarks, $t'$, may result in enough intrinsic matter and anti-matter asymmetry to explain the baryon asymmetry of the universe [4]. Therefore, there is continued theoretical and experimental interest in the search for a fourth generation fermion [3].

Previous direct searches restrict the masses of quarks in the fourth generation, $M_{t'}$ and $M_{b'}$, to be greater than 404 and 372 GeV/c², respectively, at the $95\%$ confidence level [5,6], and the measurement of the Z lineshape at the Large Electron–Positron collider excludes a fourth generation of light neutrinos [7–10]. At the Large Hadron Collider (LHC), the quantum chromodynamics (QCD) production cross section as a function of $t'$ mass is measured, and $t'$ masses below 557 GeV/c² are excluded at the $95\%$ confidence level.

The results of a search for pair production of a heavy, top-like quark, $t'$, in the decay mode $t'\rightarrow bW^+\rightarrow b\ell^+\nu$ are presented. The search is performed with a data sample corresponding to an integrated luminosity of $5.0$ fb⁻¹ in pp collisions at a center-of-mass energy of 7 TeV, collected by the CMS experiment at the LHC. The observed number of events agrees with the expectation from standard model processes, and no evidence of $t'$ production is found. Upper limits on the production cross section as a function of $t'$ mass are presented, and $t'$ masses below 557 GeV/c² are excluded at the $95\%$ confidence level.

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jets. Muons are identified and measured in gas-ionization detectors embedded in the steel flux return yoke of the solenoid. The CMS detector is nearly hermetic, allowing momentum balance measurements in the plane transverse to the beam direction. A two-tier trigger system selects pp collision events of interest for use in physics analyses. A more detailed description of the CMS detector can be found elsewhere [14].

3. Event samples, reconstruction, and preselection

The data used for this measurement were collected using one of the ee, eμ, or μμ high-p_T double-lepton triggers. Muon candidates are reconstructed using two algorithms that require consistent signals in the tracker and muon systems: one matches the extrapolated trajectories from the silicon tracker to signals in the muon system (tracker-based muons), and the second performs a global fit requiring consistent patterns in the tracker and the muon system (globally fitted muons) [15]. Electron candidates are reconstructed starting from a cluster of energy deposits in the electromagnetic calorimeter. The cluster is then matched to signals in the silicon tracker. A selection using electron identification variables based on shower shape and track-cluster matching is applied to the reconstructed candidates [16]. Electron candidates within ∆R ≡ √((Δη)² + (Δϕ)²) < 0.1 from a muon are rejected to remove candidates due to muon bremsstrahlung and final-state radiation. Both electrons and muons are required to be isolated from other activity in the event. This is achieved by imposing a maximum allowed value of 0.15 on the ratio of the scalar sum of track transverse momenta and calorimeter transverse energy deposits within a cone of ∆R < 0.3 around the lepton candidate direction at the origin (the transverse momentum of the candidate is excluded), to the transverse momentum of the candidate.

Event preselection is applied to reject events other than those from tt or t′t′ in the dilepton final state. Events are required to have two opposite-sign, isolated leptons (e⁺e⁻, e⁺μ⁻, or μ⁺μ⁻). Both leptons must have transverse momentum p_T > 20 GeV/c, and the electrons (muons) must have |η| < 2.5 (2.4). The reconstructed lepton trajectories must be consistent with a common interaction vertex. In the rare case (< 0.1%) of events with more than two such leptons, the two leptons with the highest p_T are selected. Events with an e⁺e⁻ or μ⁺μ⁻ pair with invariant mass between 76 and 106 GeV/c² or below 12 GeV/c² are removed to suppress Drell–Yan (DY) events (Z/γ* → e⁺e⁻) as well as low mass dilepton resonances. The jets and the missing transverse energy E_T^{miss} are reconstructed with a particle-flow technique [17]. The anti-kt clustering algorithm [18] with a distance parameter of 0.5 is used for jet clustering. At least two jets with p_T > 30 GeV/c and |η| < 2.5, separated by ∆R > 0.4 from leptons passing the analysis selection, are required in each event. Exactly two of these jets are required to be consistent with coming from the decay of heavy flavor hadrons and be identified as b jets by the TCHM b-tagging algorithm [19], which relies on tracks with large impact parameters. The E_T^{miss} in the event is required to exceed 50 GeV, consistent with the presence of two undetected neutrinos with large p_T.

Signal and background events are generated using the MADGRAPH 4.4.12 [20] and PYTHIA 6.4.22 [21] event generators. The samples of tt, W+jets, DY with M_ℓτ > 50 GeV/c², diboson (WW, WZ, and ZZ only: the contribution from WW is assumed to be negligible), and single top quark events are generated using MADGRAPH. The DY event samples with M_ℓτ < 50 GeV/c² are generated using PYTHIA. The samples of t′t′ events are generated using MADGRAPH, but decayed using PYTHIA. The τ → Wb decay is modeled assuming a V–A structure of the interaction. Events are then simulated using a GEANT4-based model [22] of the CMS detector, and finally reconstructed and analyzed with the same software used to process collision data. The cross section for tt production is taken from a recent CMS measurement [23], while next-to-leading order (NLO) cross sections are used for the remaining SM background samples. The t′t′ cross sections are calculated to approximate next-to-NLO (NNLO) using HATHOR [24].

With the steadily increasing LHC instantaneous luminosity, the mean number of interactions in a single bunch crossing also increased over the course of data taking, reaching about 15 at the end of the 2011 running period. In the following, the yields of simulated events are weighted such that the distribution of reconstructed vertices observed in data is reproduced. The average efficiency for events containing two leptons satisfying the analysis selection to pass at least one of the double-lepton triggers is measured to be approximately 100%, 95%, and 90% for the ee, eμ, and μμ triggers, respectively, and corresponding weights are applied to the simulated event yields. In addition, b-tagging scale factors are applied to simulated events for each jet, to account for the difference between b-tagging efficiencies in data and simulation [19].

The observed and simulated yields after the above event preselection are listed in Table 1, in which the categories t′t′ → ℓ⁺ℓ⁻ and DY → ℓ⁺ℓ⁻ correspond to dileptonic tt and DY decays, including τ leptons only when they also decay leptonically. All other t′ decay modes are included in the category t′ → other. The yields are dominated by top-pair production in the dilepton final state, and agreement is observed between data and simulation. The expected yields from t′t′ are also shown for different values of M_{t′}.

4. Signal region

After preselection, the sample is dominated by SM tt events. Since a τ′ quark is expected to have a much larger mass than that of the top quark, variables that are correlated with the decaying quark mass can help distinguish t′t′ events from tt events. The mass of the system defined by the lepton and b jet (M_{ℓb}) from the quark decay is chosen for this purpose. In the decay of a given top quark, M_{ℓb} is less than √(M_{t′}² – M_W²), where M_t and M_W are the masses of the top quark and W boson. In contrast, most τ′ decays have M_{ℓb} larger than that value. At the reconstruction level, however, there are two ways to combine the two leptons and two b jets in each event, giving four possible values of M_{ℓb}. The minimum value of the four masses (M_{ℓb}^{min}) is found to be a good variable for distinguishing t′t′ events from tt events. A comparison between t′t′ events and tt events for this variable is shown in Fig. 1.

The signal region is defined by adding the requirement for the minimum mass of lepton and jet pairs to be M_{ℓb}^{min} > 170 GeV/c². This additional selection reduces the expected number of tt events by four orders of magnitude compared with the preselection prediction given in Table 1. The simulated yields of ℓ⁺ℓ⁻ events are typically reduced by 50%; they are given for different values of M_{t′} in Table 2.

5. Background estimation

One of the main sources of background events in the signal region is the misidentification of b jets and leptons. A misidentified lepton is defined as a lepton candidate not originating from a prompt decay, such as a lepton from a semileptonic b or c quark decay, a muon from a pion or kaon decay, an unidentified photon conversion, or a pion misidentified as an electron. Misidentified b jets are referred to as “mistags”, and occur when a non-b jet satisfies the b-tagging requirements.

The background events in the signal region can be divided into the following categories:
For each category, an estimate of the combined yield of ee, $\ell\ell$, and $\mu\mu$ events is made.

To predict the number of events with mistagged b jet(s) (Category I), control regions in data are used where events pass all selection requirements except the number of b-tagged jets. The number of background events with one mistag, $N_{1\text{mistags}}$, is estimated from events with one b tag. Each event is weighted based on the mistag rate $r_1$ for each untagged jet in the event, where $r_1$ gives the $p_T$- and $\eta$-dependent probability (with a mean of 0.02) for a non-b jet to be b-tagged [19]. Where there are no untagged jets passing the $MT_{1b}^\text{min}$ selection, the event weight is zero, and for each untagged jet $i$ passing the selection the event weight is increased by $r_1(1-r_1)$. The subtraction of $r_1$ in the denominator is necessary to account for non-b jets that were mistagged, and are thus missing from the sample of untagged jets. A similar calculation is made using events with no b tags to estimate the number of events with two mistags, $N_{2\text{mistags}}$. This time a weight of $r_1(1-r_1)\times r_2(1-r_2)$ is used for each pair of untagged jets passing selection, where $r_1$ and $r_2$ are the mistag rates for the two untagged jets. The final prediction is obtained as $N_{\text{mistags}} = N_{1\text{mistags}} - N_{2\text{mistags}}$, which takes into account that $N_{2\text{mistags}}$ is counted twice in $N_{1\text{mistags}}$. The performance of the method is checked using simulated events, and an under-prediction of up to 50% is observed. We therefore assign a large systematic uncertainty, 100%, to this prediction. In data, the predicted number of events with mistags in the signal region is $N_{\text{mistags}} = 0.7 \pm 0.3 \pm 0.7$, where the uncertainties are statistical and systematic, respectively. The Category I yield in the simulation, taken as a cross-check using the samples mentioned in Section 3, is $1.0 \pm 0.3$, and is consistent with the prediction based on data.

The background from events with misidentified leptons (Category II) is predicted based on the number of events in data with a candidate lepton that can pass only loosened selection criteria [25].

Using a measurement of the fraction of such “loose” leptons that go on to pass the selection requirements, the number of misidentified leptons in the event sample can be estimated. However, there are no observed data events where one or more of the lepton candidates passes only the loosened selection criteria, resulting in a prediction of $0.0^{+0.7}_{-0.4}$ events where the upper uncertainty corresponds to the prediction of the method, had there been one such event. The Category II event yield is also zero in the simulation.

6. Systematic uncertainties

The systematic uncertainty on the overall selection efficiency is dominated by the uncertainty on the b-tagging efficiency. This uncertainty is 15% for b jets with $p_T > 240$ GeV/c, and 4% for b jets with $p_T < 240$ GeV/c [19]. Other uncertainties include those on trigger efficiency (2%), lepton selection (2%), and jet $E_{T}\text{miss}$. 

### Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>ee</th>
<th>$\mu\mu$</th>
<th>$\ell\ell$</th>
<th>all</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$, $M_T = 400$ GeV/c²</td>
<td>$10.6 \pm 0.9$</td>
<td>$13.9 \pm 1.0$</td>
<td>$29.4 \pm 1.5$</td>
<td>$53.9 \pm 2.0$</td>
</tr>
<tr>
<td>$t\bar{t}$, $M_T = 500$ GeV/c²</td>
<td>$3.0 \pm 0.2$</td>
<td>$3.3 \pm 0.2$</td>
<td>$6.7 \pm 0.44$</td>
<td>$12.9 \pm 0.5$</td>
</tr>
<tr>
<td>$t\bar{t}$, $M_T = 600$ GeV/c²</td>
<td>$0.9 \pm 0.1$</td>
<td>$1.0 \pm 0.1$</td>
<td>$2.2 \pm 0.1$</td>
<td>$4.1 \pm 0.2$</td>
</tr>
<tr>
<td>$t\ell \rightarrow t\ell^<em>\ell^</em>$</td>
<td>$488 \pm 11$</td>
<td>$615 \pm 12$</td>
<td>$1472 \pm 19$</td>
<td>$2575 \pm 25$</td>
</tr>
<tr>
<td>$t\ell \rightarrow$ other</td>
<td>$7.2 \pm 1.3$</td>
<td>$0.5 \pm 0.3$</td>
<td>$10.5 \pm 1.6$</td>
<td>$18.2 \pm 2.1$</td>
</tr>
<tr>
<td>W + jets</td>
<td>$-1.9$</td>
<td>$-1.9$</td>
<td>$-1.9$</td>
<td>$-1.9$</td>
</tr>
<tr>
<td>DY → $t\ell^<em>\ell^</em>$</td>
<td>$2.9 \pm 1.5$</td>
<td>$1.6 \pm 1.0$</td>
<td>$0.6 \pm 0.5$</td>
<td>$5.1 \pm 1.8$</td>
</tr>
<tr>
<td>Diboson</td>
<td>$0.5 \pm 0.1$</td>
<td>$1.1 \pm 0.2$</td>
<td>$1.9 \pm 0.2$</td>
<td>$3.6 \pm 0.3$</td>
</tr>
<tr>
<td>Single top quark</td>
<td>$15.6 \pm 1.0$</td>
<td>$19.5 \pm 1.1$</td>
<td>$46.9 \pm 1.7$</td>
<td>$82.0 \pm 2.2$</td>
</tr>
<tr>
<td>Total background</td>
<td>$514 \pm 54$</td>
<td>$637 \pm 67$</td>
<td>$1532 \pm 162$</td>
<td>$2683 \pm 284$</td>
</tr>
<tr>
<td>Data</td>
<td>$510$</td>
<td>$615$</td>
<td>$1487$</td>
<td>$2612$</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>$t\bar{t}$ sample</th>
<th>ee</th>
<th>$\mu\mu$</th>
<th>$\ell\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_T = 400$ GeV/c²</td>
<td>$3.5 \pm 0.5$</td>
<td>$5.5 \pm 0.6$</td>
<td>$11.2 \pm 0.9$</td>
</tr>
<tr>
<td>$M_T = 500$ GeV/c²</td>
<td>$1.4 \pm 0.2$</td>
<td>$1.9 \pm 0.2$</td>
<td>$3.3 \pm 0.2$</td>
</tr>
<tr>
<td>$M_T = 600$ GeV/c²</td>
<td>$0.6 \pm 0.1$</td>
<td>$0.6 \pm 0.1$</td>
<td>$1.3 \pm 0.1$</td>
</tr>
</tbody>
</table>

### Table 3

Summary of the predicted background yields and the measured yield in data. Statistical and systematic uncertainties are combined.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category I (from data)</td>
<td>$0.7 \pm 0.8$</td>
</tr>
<tr>
<td>Category II (from data)</td>
<td>$0.0^{+0.7}_{-0.4}$</td>
</tr>
<tr>
<td>Category III (simulated)</td>
<td>$1.0 \pm 0.7$</td>
</tr>
<tr>
<td>Total prediction</td>
<td>$1.8 \pm 1.1$</td>
</tr>
<tr>
<td>Data</td>
<td>1</td>
</tr>
</tbody>
</table>
energy scale (8%) \cite{26}. These four sources combine to yield a 19% relative uncertainty on the overall selection efficiency for signal events. There is a further 2.2% uncertainty on the luminosity measurement \cite{27}.

The systematic uncertainty on the background estimate is dominated by the uncertainty on the estimate of events with mistagged b jets from data (100%), and by the lack of selected events in the loose-lepton control region. The systematic uncertainties on these sources of background are included in the summary of background predictions given in Table 3.

7. Results and summary

The number of expected events from background processes is 1.8 \pm 1.1, and one event is observed in the \( e\mu \) channel. There is thus no evidence for an excess of events above SM expectations.

<table>
<thead>
<tr>
<th>( M_\ell (\text{GeV} / c^2) )</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
<th>550</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical cross section (pb)</td>
<td>3.20</td>
<td>1.41</td>
<td>0.62</td>
<td>0.33</td>
<td>0.17</td>
<td>0.09</td>
</tr>
<tr>
<td>Expected limit (pb)</td>
<td>0.53</td>
<td>0.29</td>
<td>0.24</td>
<td>0.21</td>
<td>0.18</td>
<td>0.16</td>
</tr>
<tr>
<td>Observed limit (pb)</td>
<td>0.47</td>
<td>0.26</td>
<td>0.22</td>
<td>0.18</td>
<td>0.16</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Table 4

Overall selection efficiency in simulated events for different \( \ell \) masses. The branching fraction of 6.5% for the dilepton decay mode of \( \ell' \) is included. The uncertainties are calculated using the systematic uncertainty of 19% from Section 6.

<table>
<thead>
<tr>
<th>( \ell' ) sample</th>
<th>Eff \times Acc \times Br (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_\ell = 350 \text{ GeV} / c^2 )</td>
<td>0.16 \pm 0.03</td>
</tr>
<tr>
<td>( M_\ell = 400 \text{ GeV} / c^2 )</td>
<td>0.29 \pm 0.06</td>
</tr>
<tr>
<td>( M_\ell = 450 \text{ GeV} / c^2 )</td>
<td>0.35 \pm 0.07</td>
</tr>
<tr>
<td>( M_\ell = 500 \text{ GeV} / c^2 )</td>
<td>0.41 \pm 0.08</td>
</tr>
<tr>
<td>( M_\ell = 550 \text{ GeV} / c^2 )</td>
<td>0.48 \pm 0.09</td>
</tr>
<tr>
<td>( M_\ell = 600 \text{ GeV} / c^2 )</td>
<td>0.54 \pm 0.10</td>
</tr>
</tbody>
</table>

A summary of the observed and predicted yields is presented in Table 3.

The simulated distribution of \( M_{bW}^{\text{min}} \) from background processes is compared with the data in Fig. 1, where the expected distribution for a \( \ell' \) signal with \( M_\ell = 450 \text{ GeV} / c^2 \) is also shown.

Finally, 95% confidence level (CL) upper limits on the production cross section of \( \ell' \) as a function of \( \ell' \) mass are set, using the CL\(_b\) method \cite{28,29}, where nuisance parameters are varied in the ensemble tests using log-normal distributions.

The limit calculation is based on the information provided by the observed event count combined with the values and the uncertainties of the luminosity measurement, the background prediction, and the fraction of \( \ell' \) events expected to be selected. This fraction (the overall selection efficiency) is taken as the product of efficiency, acceptance, and the branching fraction for simulated signal events, and is given in Table 4 for different values of \( M_\ell \).

The calculated limits are shown in Table 5 and Fig. 2.

In summary, assuming a branching fraction of 100% for \( \ell' \to bW \), the expected and observed 95% CL lower bounds on the \( M_\ell \) mass are 547 and 557 GeV/c\(^2\), respectively, from the analysis of a data sample of pp collisions at \( \sqrt{s} = 7 \text{ TeV} \), corresponding to an integrated luminosity of 5.0 fb\(^{-1}\).

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Universiteit Antwerpen, Antwerpen, Belgium


Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium


Ghent University, Ghent, Belgium


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

N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Université de Mons, Mons, Belgium


Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil


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


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

V. Genchev, P. Iaydjiev, 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, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria


Institute of High Energy Physics, Beijing, China


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

C. Avila, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria
Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, R. Plestina, D. Polic, I. Puljak

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 Radjer Boskovic, Zagreb, Croatia

A. Attikis, M. Galanti, G. Mavromanolakis, 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, S. Elgammal, A. Ellithi Kamel, S. Khalil, M.A. Mahmoud, A. Radi

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

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


Helsinki Institute of Physics, Helsinki, Finland

K. Banzuzi, A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland


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


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


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

University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, P. Hidas, D. Horvath, K. Krajcar, B. Radics, F. Sikler, V. Vespremi, G. Vesztergombi

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

N. Beni, S. Czellar, 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


Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India


Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, A.K. Mohaney, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India


Tata Institute of Fundamental Research – EHEP, Mumbai, India

S. Banerjee, S. Dugad

Tata Institute of Fundamental Research – HECR, Mumbai, India


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


a INFN Sezione di Bari, Bari, Italy
b Università di Bari, Bari, Italy
c Politecnico di Bari, Bari, Italy

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

\textsuperscript{a} INFN Sezione di Bologna, Bologna, Italy
\textsuperscript{b} Università di Bologna, Bologna, Italy
\textsuperscript{1} INFN Sezione di Padova, Padova, Italy

S. Albergo\textsuperscript{a,b}, G. Cappello\textsuperscript{a,b}, M. Chiorboli\textsuperscript{a,b}, S. Costa\textsuperscript{a,b}, R. Potenza\textsuperscript{a,b}, A. Tricomi\textsuperscript{a,b}, C. Tuve\textsuperscript{a,b}

\textsuperscript{a} INFN Sezione di Catania, Catania, Italy
\textsuperscript{b} Università di Catania, Catania, Italy

G. Barbaglia\textsuperscript{a}, V. Ciulli\textsuperscript{a,b}, C. Civinini\textsuperscript{a}, R. D'Alessandro\textsuperscript{a,b}, E. Focardi\textsuperscript{a,b}, S. Frosali\textsuperscript{a,b}, E. Gallo\textsuperscript{a}, S. Gonzi\textsuperscript{a,b}, M. Meschini\textsuperscript{a}, S. Paoletti\textsuperscript{a}, G. Sguazzoni\textsuperscript{a}, A. Tropiano\textsuperscript{a,1}

\textsuperscript{a} INFN Sezione di Firenze, Firenze, Italy
\textsuperscript{b} Università di Firenze, Firenze, Italy

L. Benussi\textsuperscript{a}, S. Bianco\textsuperscript{a}, S. Colafranceschi\textsuperscript{24}, F. Fabbri\textsuperscript{a}, D. Piccolo\textsuperscript{a}

\textsuperscript{a} INFN Sezione di Genova, Genova, Italy

P. Fabbricatore\textsuperscript{a}, R. Musenich\textsuperscript{a}

\textsuperscript{a} INFN Sezione di Napoli, Napoli, Italy
\textsuperscript{b} Università di Napoli “Federico II”, Napoli, Italy

S. Buontempo\textsuperscript{a}, C.A. Carrillo Montoya\textsuperscript{a,1}, N. Cavallo\textsuperscript{a,25}, A. De Cosa\textsuperscript{a,b}, O. Dogangun\textsuperscript{a,b}, F. Fabozzi\textsuperscript{a,25}, A.O.M. Iorio\textsuperscript{a,1}, L. Lista\textsuperscript{a}, S. Meola\textsuperscript{a,26}, M. Merola\textsuperscript{a,b}, P. Paolucci\textsuperscript{a}

\textsuperscript{a} INFN Sezione di Padova, Padova, Italy
\textsuperscript{b} Università di Padova, Padova, Italy
\textsuperscript{c} Università di Trento (Trento), Padova, Italy

M. Gabusi\textsuperscript{a,b}, S.P. Ratti\textsuperscript{a,b}, C. Riccardi\textsuperscript{a,b}, P. Torre\textsuperscript{a,b}, P. Vitulo\textsuperscript{a,b}

\textsuperscript{a} INFN Sezione di Pavia, Pavia, Italy
\textsuperscript{b} Università di Pavia, Pavia, Italy

G.M. Bilei\textsuperscript{a}, L. Fan\textsuperscript{a,b}, P. Lariccia\textsuperscript{a,b}, A. Lucaroni\textsuperscript{a,b,1}, M. Mantovani\textsuperscript{a,b}, M. Menichelli\textsuperscript{a}, A. Nappi\textsuperscript{a,b}, F. Romeo\textsuperscript{a,b}, A. Saha\textsuperscript{a,b}, A. Santocchia\textsuperscript{a,b}, S. Taroni\textsuperscript{a,b,1}

\textsuperscript{a} INFN Sezione di Perugia, Perugia, Italy
\textsuperscript{b} Università di Perugia, Perugia, Italy

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

\textsuperscript{a} INFN Sezione di Pisa, Pisa, Italy
\textsuperscript{b} INFN Sezione di Pisa, Pisa, Italy
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

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

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

Soltan Institute for Nuclear Studies, Warsaw, Poland

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

Joint Institute for Nuclear Research, Dubna, Russia

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

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilon, M. Kossov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin  
Institute for Theoretical and Experimental Physics, Moscow, Russia

Moscow State University, Moscow, Russia

P.N. Lebedev Physical Institute, Moscow, Russia

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

P. Adzic, M. Djordjevic, M. Ekmedzic, D. Krpic, J. Milosevic

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


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

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

Universidad Autónoma de Madrid, Madrid, Spain


Universidad de Oviedo, Oviedo, Spain


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


CERN, European Organization for Nuclear Research, Geneva, Switzerland


Paul Scherrer Institut, Villigen, Switzerland

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


University of Maryland, College Park, USA


Massachusetts Institute of Technology, Cambridge, USA


University of Minnesota, Minneapolis, USA

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

University of Mississippi, University, USA


University of Nebraska-Lincoln, Lincoln, USA


State University of New York at Buffalo, Buffalo, USA


Northeastern University, Boston, USA


Northwestern University, Evanston, USA


University of Notre Dame, Notre Dame, USA

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

The Ohio State University, Columbus, USA
S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

Wayne State University, Detroit, USA


University of Wisconsin, Madison, USA

* Corresponding author.
  E-mail address: cms-publication-committee-chair@cern.ch (P. Sphicas).
  † 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 Also 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 Also at King Abdulaziz University, Jeddah, Saudi Arabia.
  19 Also at University of Västra-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 Università degli Studi Guglielmo Marconi, Roma, 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 Süleyman Demirel University, Isparta, Turkey.
  44 Also at Ege University, İzmir, 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 University of Sydney, Sydney, Australia.
  48 Also at Utah Valley University, Orem, USA.
  49 Also at Institute for Nuclear Research, Moscow, Russia.
  50 Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
  51 Also at Argonne National Laboratory, Argonne, USA.
  52 Also at Erzincan University, Erzincan, Turkey.
  53 Also at Kafkas University, Kars, Turkey.