"Search for Microscopic Black Hole Signatures at the Large Hadron Collider"

CMS Collaboration; Quertenmont, Loic; Khachatryan, Vardan; Basegmez, Suzan; Bruno, Giacomo Luca; Caudron, Julien; Ceard, Ludivine; Cortina Gil, Eduardo; de Favereau de Jeneret, Jérôme; Delaere, Christophe; Favart, Denis; Forthomme, Laurent; Giammanco, Andrea; Grégoire, Ghislain; Hollar, Jonathan; Lemaître, Vincent; Liao, Junhui; Militaru, Otilia; Nuttens, Claude; Ovyn, Séverine; Pagano, Davide; Pin, Arnaud; Piotrzkowski, Krzysztof; Schul, Nicolas

ABSTRACT

A search for microscopic black hole production and decay in pp collisions at a center-of-mass energy of 7 TeV has been conducted by the CMS Collaboration at the LHC, using a data sample corresponding to an integrated luminosity of 35 inverse picobarns. Events with large total transverse energy are analyzed for the presence of multiple high-energy jets, leptons, and photons, typical of a signal expected from a microscopic black hole. Good agreement with the expected standard model backgrounds, dominated by QCD multijet production, is observed for various final-state multiplicities. Limits on the minimum black hole mass are set, in the range 3.5 -- 4.5 TeV, for a variety of parameters in a model with large extra dimensions, along with model-independent limits on new physics in these final states. These are the first direct limits on black hole production at a particle accelerator.

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One of the exciting predictions of theoretical models with extra spatial dimensions and low-scale quantum gravity is the possibility of copious production of microscopic black holes in particle collisions at the CERN Large Hadron Collider (LHC) [1,2]. Models with low-scale gravity are aimed at solving the hierarchy problem, the puzzlingly large difference between the electroweak and Planck scales.

In this Letter we focus on microscopic black hole production in a model with large, flat, extra spatial dimensions, proposed by Arkani-Hamed, Dimopoulos, and Dvali, and referred to as the ADD model [3,4]. This model alleviates the hierarchy problem by introducing n extra dimensions in space, compactified on an n-dimensional torus or sphere with radius r. The multidimensional space–time is only open to the gravitational interaction, while the r-dimensional torus or sphere with radius n dimensions (\(M_D\)) is consequently lowered to the electroweak scale, much smaller than the apparent Planck scale of \(M_{Pl}\) seen by a 3 + 1 space–time observer. The “true” Planck scale is given by solving Einstein’s general relativity equations and is given by [6–8]:

\[
\frac{1}{\sqrt{\pi M_D}} \left[ \frac{M_{BH}}{M_D} \right]^{\frac{1}{n+2}} \sim \frac{1}{\pi r_S^2}.
\]

The parton-level cross section of black hole production is derived from geometrical considerations and is given by \(\sigma \sim \pi r_S^2\) [1,2]. At LHC energies, this cross section can reach 100 pb for \(M_D\) of 1 TeV. The exact cross section cannot be calculated without knowledge of the underlying theory of quantum gravity and is subject to significant uncertainty. It is commonly accepted [1,2] that the minimum black hole mass \(M_{BH, min}\) cannot be smaller than \(M_D\); although the formation threshold can be significantly larger than this. When a black hole is formed, some fraction of the colliding parton energy may not be trapped within the event horizon and will be emitted in the form of gravitational shock waves, which results in energy, momentum, and angular momentum loss [9–11]. This effect is particularly model-dependent for black hole masses close to \(M_D\). In general, black holes in particle collisions are produced with non-zero angular momentum, which also affects their properties and production cross section.

Once produced, the microscopic black holes would decay thermally via Hawking radiation [12], approximately democratically (with equal probabilities) to all standard model (SM) degrees of freedom rather than \(M_{Pl}\), which is the case for a 3 + 1 space–time. Colliding particles would collapse in a black hole if their impact parameter were smaller than approximately the Schwarzschild radius of a black hole with mass \(M_{BH}\) equal to the total energy accessible in the collision. The Schwarzschild radius of a black hole with mass \(M_{BH}\) embedded in 4 + n space–time can be found by solving Einstein’s general relativity equations and is given by [6–8]:

\[
\frac{1}{\sqrt{\pi M_D}} \left[ \frac{M_{BH}}{M_D} \right]^{\frac{1}{n+2}} \sim \frac{1}{\pi r_S^2}.
\]
freedom. Quarks and gluons are the dominant particles produced in the black hole evaporation (~75%) because they have a large number of color degrees of freedom. The remaining fraction is accounted for by leptons, W and Z bosons, photons, and possibly Higgs bosons. Emission of gravitons by a black hole in the bulk space is generally expected to be suppressed [13], although in some models it can be enhanced for rotating black holes for bly Higgs bosons. Emission of gravitons by a black hole in the formation of the counterclockwise beam, and
cay may become very important, if not dominant, for known quantum corrections to the black hole production and decay. While we expect that unknown quantum corrections to the black hole production and decay may become very important, if not dominant, for MBH ≈ 2MBH, we still use semi-classical approximation as a benchmark due to the lack of a better, quantum model of black hole production and decay.

The microscopic black holes produced at the LHC would be distinguished by high multiplicity, democratic, and highly isotropic decays with the final-state particles carrying hundreds of GeV of energy. Most of these particles would be reconstructed as jets of hadrons. Observation of such spectacular signatures would provide direct information on the nature of black holes as well as the structure and dimensionality of space–time [1]. Microscopic black hole properties are reviewed in more detail in [10,11].

The search for black holes is based on \( \sqrt{s} = 7 \) TeV pp collision data recorded by the Compact Muon Solenoid (CMS) detector at the LHC between March and October 2010, which correspond to an integrated luminosity of 34.7 ± 3.8 pb\(^{-1}\). A detailed description of the CMS experiment can be found elsewhere [21]. The central feature of the CMS detector is the 3.8 T superconducting solenoid enclosing the silicon pixel and strip tracker, the electromagnetic calorimeter (ECAL), and the brass-scintillator hadronic calorimeter (HCAL). For triggering purposes and to facilitate jet reconstruction, the calorimeter cells are grouped in projective towers, of granularity Delta \( \Delta \eta \times \Delta \phi = 0.087 \times 0.087 \) at central rapidities and 0.175 \times 0.175 in the forward region. Here, the pseudorapidity \( \eta \) is defined as \(- \ln(\tan(\frac{\theta}{2}))\), where \( \theta \) is the polar angle with respect to the direction of the counterclockwise beam, and \( \phi \) is the azimuthal angle. Muons are measured in the pseudorapidity window \( |\eta| < 2.4 \) in gaseous detectors embedded in the steel return yoke.

The CMS trigger system consists of two levels. The first level (L1), composed of custom hardware, uses information from the calorimeters and muon detectors to select the most interesting events for more refined selection and analysis at a rate of up to 80 kHz. The software-based High Level Trigger (HLT) further decreases the rate to a maximum of ~300 Hz for data storage. The instantaneous luminosity is measured using information from forward hadronic calorimeters [22].

We use data collected with a dedicated trigger on the total jet activity, \( H_T \), where \( H_T \) is defined as the scalar sum of the transverse energies \( E_T \) of the jets above a preprogrammed threshold. At L1 this jet \( E_T \) threshold was 10 GeV, and the \( H_T \) threshold was 50 GeV. At HLT, the jet \( E_T \) threshold varied between 20 and 30 GeV, and the \( H_T \) threshold between 100 and 200 GeV. The trigger is fully efficient for the offline analysis selections described below. Energetic electrons and photons are also reconstructed as jets at the trigger level and are thus included in the \( H_T \) sum.

Jets are reconstructed using energy deposits in the HCAL and ECAL, clustered using a collinear and infrared safe anti-k_{t} algorithm with a distance parameter of 0.5 [23]. The jet energy resolution is \( \Delta E/E \approx 0.5/\sqrt{E[GeV]} \mp 5\% \). Jets are required to pass quality requirements to remove those consistent with calorimeter noise. Jet energies are corrected for the non-uniformity and non-linearity of the calorimeter response, as derived using Monte Carlo (MC) samples and collision data [24]. Jets are required to have \( E_T > 20 \) GeV before the jet-energy-scale corrections and to have \( |\eta| < 2.6 \). Missing transverse energy \( E_T \) is reconstructed as the negative of the vector sum of transverse energies in the individual calorimeter towers. This quantity is further corrected to account for muons in the event, which deposit little energy in the calorimeters, and for the jet energy scale [25].

Electrons and photons are identified as isolated energy deposits in the ECAL, with a shape consistent with that expected for electromagnetic showers. Photons are required to have no matching hits in the inner pixel detector layers, while electrons are required to have a matching track. Electrons and photons are required to have \( E_T > 20 \) GeV and to be reconstructed in the fiducial volume of the barrel (\( |\eta| < 1.44 \)) or the endcap (1.56 < |\eta| < 2.4). The ECAL has an ultimate energy resolution better than 0.5% for unconverted photons or electrons with transverse energies above 100 GeV [26]. In 2010 collision data, for \( E_T > 20 \) GeV, this resolution is better than 1% in the barrel.

Muons are required to have matched tracks in the central tracker and the muon spectrometer, to be within \( |\eta| < 2.1 \), be consistent with the interaction vertex to suppress backgrounds from cosmic ray muons, be isolated from other tracks, and have transverse momentum \( p_T \) above 20 GeV. The combined fit using tracks measured in the central tracker and the muon spectrometer results in \( p_T \) resolution between 1% and 5% for \( p_T \) values up to 1 TeV.

The separation between any two objects (jet, lepton, or photon) is required to be

\[ \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} > 0.3. \]

Black hole signal events are simulated using the parton-level BlackMax [27] generator (v2.01.03), followed by a parton-showering fragmentation with PYTHIA [28] (v6.420), and a fast parametric simulation of the CMS detector response [29], which has been extensively validated for signal events using detailed detector simulation via GEANT4 [30].

Several parameters govern black hole production and decay in the ADD model in addition to \( M_D \) and \( n \). For each value of \( M_D \), we consider a range of the minimum black hole masses, \( M_{BH}^{min} \), between \( M_D \) and the kinematic limit of the LHC. We assume that no parton–collision energy is lost in gravitational shock waves, i.e. it is all trapped within the event horizon of the forming black hole. We consider both rotating and non-rotating black holes in this analysis, although the description of rotating black holes in the existing MC generators is only approximate. Graviton radiation by the black hole is not considered. For most of the signal samples we assume full Hawking evaporation without a stable non-interacting remnant.

The parameters used in the simulations are listed in Table 1 for a number of characteristic model points. The MSTW2008lo68 [31] parton distribution functions (PDF) were used. In addition we compare the BlackMax results with those of the CHARYBDIS 2 MC...
Table 1

| $M_0$ (TeV) | $M_{\text{Min}}^\text{ST}$ (TeV) | $n$ | $\sigma$ (pb) | $N^\text{Min}$ | $S^\text{Min}$ (TeV) | $A$ (%) | $n^\text{bg}$ | $n^\text{data}$ | $\sigma^\text{95}$ (pb) | $\sigma^\text{95}_{\text{exp}}$ (pb) |
|-----------|-----------------|----|----------|-------------|----------------|--------|----------|----------------|----------------|----------------|----------------|
| 1.5       | 2.5             | 6  | 118      | 3           | 1.5           | 3671   | 203      | 241 ± 45        | 1.69            | 2.52            |
| 1.5       | 3.0             | 6  | 25.9     | 3           | 1.8           | 91.3   | 823      | 46             | 66.2 ± 22.2    | 0.62            | 1.13           |
| 1.5       | 3.5             | 6  | 4.97     | 2           | 4.1           | 88.3   | 153      | 6              | 12.1 ± 6.3     | 0.21            | 0.39           |
| 1.5       | 4.0             | 6  | 0.77      | 5           | 2.4           | 84.4   | 22.5     | 0              | 2.01 ± 1.48    | 0.11            | 0.18           |
| 1.5       | 4.5             | 6  | 0.09      | 5           | 2.9           | 80.9   | 2.55     | 0              | 0.46 ± 0.54    | 0.11            | 0.13           |
| 1.5       | 5.0             | 6  | 0.007    | 5           | 3.4           | 75.2   | 0.19     | 0              | 0.13 ± 0.21    | 0.12            | 0.13           |
| 2.0       | 2.5             | 4  | 28.9     | 3           | 1.7           | 81.4   | 817      | 82             | 95.7 ± 28.1    | 1.16            | 1.64           |
| 2.0       | 3.0             | 4  | 6.45     | 3           | 2.0           | 83.2   | 186      | 21             | 30.8 ± 14.0    | 0.47            | 0.76           |
| 2.0       | 3.5             | 4  | 1.26     | 4           | 2.3           | 77.9   | 34.0     | 3              | 6.12 ± 4.05    | 0.20            | 0.31           |
| 2.0       | 4.0             | 4  | 0.20     | 4           | 2.8           | 73.4   | 5.07     | 0              | 1.35 ± 1.35    | 0.12            | 0.19           |
| 2.0       | 4.5             | 4  | 0.02     | 5           | 3.2           | 64.4   | 0.53     | 0              | 0.21 ± 0.32    | 0.14            | 0.15           |
| 2.0       | 5.0             | 4  | 0.002    | 5           | 3.7           | 59.6   | 0.04     | 0              | 0.06 ± 0.06    | 0.15            | 0.15           |
| 3.0       | 3.0             | 2  | 0.59     | 3           | 2.4           | 62.1   | 12.8     | 2              | 7.88 ± 5.80    | 0.21            | 0.46           |
| 3.0       | 3.5             | 2  | 0.12     | 3           | 2.8           | 58.9   | 2.41     | 0              | 2.40 ± 2.37    | 0.15            | 0.28           |
| 3.0       | 4.0             | 2  | 0.02     | 4           | 3.2           | 47.3   | 0.32     | 0              | 0.46 ± 0.46    | 0.19            | 0.23           |
| 3.0       | 4.5             | 2  | 0.005    | 5           | 3.6           | 33.6   | 0.03     | 0              | 0.08 ± 0.08    | 0.26            | 0.28           |
| 3.0       | 5.0             | 2  | 0.0002   | 5           | 4.0           | 34.5   | 0.002    | 0              | 0.03 ± 0.07    | 0.26            | 0.26           |

The two generators yield different values of total cross section, as BlackMax introduces additional $n$-dependent factor applied on top of the geometrical cross section. The CHARYBDIS cross sections are a factor of 1.36, 1.59, and 1.78 smaller than those from BlackMax for $n = 2$, 4, and 6, respectively. In addition, CHARYBDIS has been used to simulate black hole evaporation resulting in a stable non-interacting remnant with mass $M_D$ (this model is not implemented in BlackMax). In the generation, we use the Particle Data Group [5] definition of the Planck scale $M_P$. (Using another popular choice for $M_D$ from Dimopoulos and Landsberg [1] would result in a suppression of the production cross section by a factor of 1.35, 5.21, or 9.29 for $n = 2$, 4, or 6, respectively.)

We employ a selection based on total transverse energy to separate black hole candidate events from the backgrounds. The variable $S_T$ is defined as a scalar sum of the $E_T$ of the $N$ individual objects (jets, electrons, photons, and muons) passing the above selections. Only objects with $E_T > 50$ GeV are included in the calculation of $S_T$, in order to suppress the SM backgrounds and to be insensitive to jets from pile-up, while being efficiently for black hole decays. Further, the missing transverse energy in the event is added to $S_T$, if the missing transverse energy value exceeds 50 GeV. Note that while $E_T$ is counted toward $S_T$, it is not considered in the determination of $N$.

The main background to black hole signals arises from QCD multijet events. Other backgrounds from direct photon, W/Z+jets, and tt production were estimated from MC simulations, using the MadGRAPH [34] leading-order parton-level event generator with CTEQ6L PDF set [35]; followed by PYTHIA [28] parton showering and full CMS detector simulation via GEANT4 [30]. These additional backgrounds are negligible at large values of $S_T$ and contribute less than 1% to the total background after the final selection.

The dominant multijet background can only be estimated reliably from data. For QCD events, $S_T$ is almost completely determined by the hard $2 \to 2$ parton scattering process. Further splitting of the jets due to final-state radiation, as well as additional jets due to initial-state radiation – most often nearly collinear with either incoming or outgoing partons – does not change the $S_T$ value considerably. Consequently, the shape of the $S_T$ distribution is expected to be independent of the event multiplicity $N$, as long as $S_T$ is sufficiently above the turn-on region (i.e., much higher than $N \times 50$ GeV). This shape invariance offers a direct way of extracting the expected number of background events in the search for black hole production.

We confirmed the assumption of the $S_T$ shape invariance of $N$ up to high multiplicities using MC generators capable of simulating multijet final states from either matrix elements [36] or parton showers [28]. The conjecture that the $S_T$ shape is independent of the multiplicity has been also checked with data using the exclusive multiplicities of $N = 2$ and $N = 3$. Even in the presence of a black hole signal with a mass of a few TeV, the decays of these black holes result in events with half-a-dozen objects in the final state. Hence, the signal contribution to the $N = 2$ and $N = 3$ data is expected to be small and only seen at large values of $S_T$, so these samples still can be used for the background prediction at higher multiplicities. Moreover, since dedicated analyses of the dijet invariant mass spectrum have been conducted [19,20], we know that there are no appreciable contributions from new physics to the dijet final state up to invariant masses of about 1.5 TeV, which, for central jets, translates to a similar range of $S_T$.

We fit the $S_T$ distributions between 600 and 1100 GeV, where no black hole signal is expected, for data events with $N = 2$ and $N = 3$ using an ansatz function $\sigma_{\text{95}} = \frac{P_0 + x^2}{(P_1 + P_2 + x^2)^{\gamma}}$, which is shown with the solid line in Fig. 1. To check the systematic uncertainty of the fit, we use two additional ansatz functions, $\sigma_{\text{95}} = \frac{P_0}{(P_1 + P_2 + x^2)^{\gamma}}$ and $\sigma_{\text{95}} = \frac{P_0}{(P_1 + x)^{\gamma}}$ [19], which are shown as the upper and lower boundaries of the shaded band in Fig. 1. The default choice of the ansatz function was made based on the best-fit to the $S_T$ distribution for $N = 2$. Additional systematic uncertainty arises from a slight difference between the best-fit shapes for $N = 2$ and $N = 3$. Nevertheless, the fits for these two exclusive multiplicities agree with each other within the uncertainties, demonstrating that the shape of the $S_T$ distribution is independent of the final-state multiplicity.

The $S_T$ distributions for data events with multiplicities $N \geq 3$, 4, and 5 are shown in Figs. 2a, b, and c, respectively. The solid curves in the figures are the predicted background shapes, found by normalizing the fits of the $N = 2$ $S_T$ distribution to the range...
Fig. 1. Total transverse energy $S_T$, for events with the multiplicities of a) $N = 2$, and b) $N = 3$ objects in the final state. Data are depicted as solid circles with error bars; the shaded band is the background prediction obtained from data (solid line) with its uncertainty. Non-multijet backgrounds are shown as colored histograms. Also shown is the predicted black hole signal for three different parameter sets.

$S_T = 1000–1100$ GeV, where no black hole signal contribution is expected.

Since no excess is observed above the predicted background, we set limits on the black hole production. We assign a systematic uncertainty on the background estimate of 6% to 125% for the $S_T$ range used in this search. This uncertainty comes from the normalization uncertainty (4–12%, dominated by the statistics in the normalization region) added in quadrature to the uncertainties arising from using various ansatz fit functions and the difference between the shapes obtained from the $N = 2$ and $N = 3$ samples. The integrated luminosity is measured with an uncertainty of 11% [22]. The uncertainty on the signal yield is dominated by the jet-energy-scale uncertainty of $\approx 5\%$ [24] which translates into a 5% uncertainty on the signal. An additional 2% uncertainty on
the signal acceptance comes from the variation of PDFs within the CTEQ6 error set [35]. The particle identification efficiency does not affect the signal distribution, since an electron failing the identification requirements would be classified either as a photon or a jet; a photon failing the selection would become a jet; a rejected muon would contribute to the jet; a photon failing the selection would become a jet; a rejected muon would contribute to the jet. In any case the total value of $S_T$ is not affected.

We set limits on black hole production with the optimized $S_T$ and $N$ selections by counting events with $S_T > S^{\text{min}}_T$ and $N > N^{\text{min}}$. We optimized the signal ($S$) significance in the presence of background ($B$) using the ratio $S/\sqrt{S+B}$ for each set. The optimum choice of parameters is listed in Table 1, as well as the predicted number of background events, the expected number of signal events, and the observed number of events in data. Note that the background uncertainty, dominated by the choice of the fitting function, is highly correlated for various working points listed in Table 1 and also bin-to-bin for the $S_T$ distributions shown in Figs. 1 and 2.

We set upper limits on the black hole production cross section using the Bayesian method with flat signal prior and log-normal prior for integration over the nuisance parameters (background, signal acceptance, luminosity) [5,37]. These upper limits at the 95% confidence level (CL) are shown in Fig. 3, as a function of $M^{\text{min}}_{\text{BH}}$. For the three model parameter sets shown in the figure, the observed (expected) lower limits on the black hole mass are 3.5, 4.2 and 4.5 TeV (3.2, 4.0, and 4.5 TeV), respectively.

Translating these upper limits into lower limits on the parameters of the ADD model, we can exclude the production of black holes with minimum mass of 3.5–4.5 TeV for values of the multidimensional Planck scale up to 3.5 TeV at 95% CL. These limits, shown in Fig. 4, do not exhibit significant dependence on the details of the production and evaporation within the set of models we studied. These are the first limits of a dedicated search for black hole production at a particle accelerator.

We point out that the semi-classical approximation used in this search is valid only for the lowest values of the $M_D$, for which the limits on the minimum black hole mass exceed $M_D$ by a factor of a few. For higher values of $M_D$ the limits become comparable with $M_D$, which implies that the approximation is no longer valid and that the BH production cross section may be modified significantly. Nevertheless, due to the exponentially falling nature of production cross section with the black hole mass, even large changes in the cross section translate only in moderate changes in the minimum black hole mass limit, as evident from Fig. 3.

Finally, we produce model-independent upper limits on the cross section times the acceptance for new physics production in high-$S_T$ inclusive final states for $N \geq 3, 4,$ and 5. Fig. 5 shows 95% CL upper limits from a counting experiment for $S_T > S^{\text{min}}_T$ as a function of $S^{\text{min}}_T$, which can be used to test models of new physics that result in these final states. A few examples of such models are production of high-mass $t\bar{t}$ resonances [38] in the six-jet and jet+jet final states, $R$-parity violating gluino decay into three jets, resulting in the six-jet final state [39,40], and a class of models with strong dynamics, with a strongly produced resonance decaying into a pair of resonances further decaying into two jets each, resulting in the four-jet final state [41]. In addition, these limits can be used to constrain black hole production for additional regions of the parameter space of the model, as well as set limits on the existence of string balls [42], which are quantum precursors of black holes predicted in certain string models. We have checked that for the black hole model parameters we probed with the dedicated optimized analysis, the sensitivity of the search in terms of the excluded black hole mass range exceeds that from the model-independent cross section limits by as little as 5–8%. Thus, model-independent limits can be used efficiently to constrain the allowed parameter space in an even broader variety of black hole models than we covered in this Letter.

To conclude, we have performed the first dedicated search for microscopic black holes at a particle accelerator and set limits on their production in the model with large extra dimensions in space using simple semi-classical approximation of the black hole production and decay [1,2]. The lower limits on the black hole mass at 95% CL range from 3.5 to 4.5 TeV for values of the Planck scale up to 3 TeV. Additionally, we have produced model-independent limits on the production of energetic, high-multiplicity final states, which can be used to constrain a variety of models of new physics.

Acknowledgements

We wish to 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); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF...
Fig. 5. Model-independent 95% confidence level upper limits on a signal cross section times acceptance for counting experiments with \( N > S > S_{\text{min}} \) as a function of \( S_{\text{T}} \) for (a) \( N > 3 \), (b) \( N > 4 \), and (c) \( N > 5 \). The solid (dashed) lines correspond to an observed (expected) limit for nominal signal acceptance uncertainty of 5%.

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References

CMS Collaboration

V. Khachatryan, A.M. Sirunyan, A. Tumasyan
Yerevan Physics Institute, Yerevan, Armenia

Institut für Hochenergiephysik der OeAW, Wien, Austria

V. Mossovov, N. Shumeiko, J. Suarez Gonzalez
National Centre for Particle and High Energy Physics, Minsk, Belarus

Universiteit Antwerpen, Antwerpen, Belgium

Vrije Universiteit Brussel, Brussel, Belgium

Université Libre de Bruxelles, Bruxelles, Belgium

Ghent University, Ghent, Belgium

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

N. Beliy, T. Caeberts, E. Daubie
Université de Mons, Mons, Belgium

G.A. Alves, D. De Jesus Damiao, M.E. Pol, M.H.G. Souza
Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

F.A. Dias, M.A.F. Dias, T.R. Fernandez Perez Tomei, E.M. Gregores², F. Marinho, S.F. Novaes, Sandra S. Padula
Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil
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. Fabbrì a, A. Fanfani a,b, D. Fasanella a, P. Giacomelli a, M. Giunta a, S. Marcellini a, M. Meneghelli a,b, A. Montanari a, F.L. Navarria a,b, F. Odorici a, A. Perrotta a, F. Primavera a, B. Rovelli a, G. Sirolì a,b, R. Travaglini a,b

a INFN Sezione di Bologna, Bologna, Italy
b Università di Bologna, Bologna, 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, C. Genta a, P. Lenzi a,b, M. Meschini a, S. Paoletti a, G. Sguazzoni a, A. Tropiano a,b

a INFN Sezione di Firenze, Firenze, Italy
b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, S. Colafranceschi 14, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbricatore, R. Musenich

INFN Sezione di Genova, Genova, Italy

S. Buontempo a, C.A. Carrillo Montoya a, A. Cimmino a,b, A. De Cosa a,b, M. De Gruttola a,b, F. Fabozzi a,15, A.O.M. Iorio a, L. Lista a, M. Merola a,b, P. Noli 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, P. Bellan a,b, D. Bisello a,b, A. Branca a, R. Carlin a,b, P. Checchia a, E. Conti a, M. De Mattia a,b, T. Dorigo a, U. Dosselli a, F. Fanzago a, F. Gasparini a,b, U. Gasparini a,b, P. Giubilato a,b, A. Gresele a,c, S. Lacerenza a,c, I. Lazzizzera a,c, M. Margoni a,b, M. Mazzucato a, A.T. Meneguzzo a,b, L. Perrozzi a,1, N. Pozzobon a,b, P. Ronchese a,b, F. Simonetto a,b, E. Torassa a, M. Tosi a,b, 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

P. Baesso a,b, U. Berzano a, C. Riccardi a,b, P. Torre a,b, P. Vitulo a,b, C. Viviani a,b

a INFN Sezione di Pavia, Pavia, Italy
b Università di Pavia, Pavia, Italy

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

E. Aguiló, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, C. Regenfus, P. Robmann, A. Schmidt, H. Snoek, L. Wilke

Universität Zürich, Zurich, Switzerland


National Central University, Chung-Li, Taiwan


National Taiwan University (NTU), Taipei, Taiwan


Cukurova University, Adana, Turkey


Middle East Technical University, Physics Department, Ankara, Turkey

M. Deliomeroglu, D. Demir, E. Gülmez, A. Halu, B. Isildak, M. Kaya, O. Kaya, S. Ozkorucuklu, N. Sonmez

Bogazici University, Istanbul, Turkey

L. Levchuk

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


University of Bristol, Bristol, United Kingdom


Rutherford Appleton Laboratory, Didcot, United Kingdom


Imperial College, London, United Kingdom
S. Gollapinni, R. Harr, P.E. Karchin, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

Wayne State University, Detroit, USA


University of Wisconsin, Madison, USA

* Corresponding author.
E-mail address: Roberto.Tenchini@cern.ch (R. Tenchini).

¹ Deceased.
2 Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
3 Also at Universidade Federal do ABC, Santo Andre, Brazil.
4 Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.
5 Also at Suez Canal University, Suez, Egypt.
6 Also at Solvay Institute for Nuclear Studies, Warsaw, Poland.
7 Also at Massachusetts Institute of Technology, Cambridge, USA.
8 Also at University of Cape Town, Cape Town, South Africa.
9 Also at Université de Haute-Alsace, Mulhouse, France.
10 Also at Brandenburg University of Technology, Cottbus, Germany.
11 Also at Eötvös Loránd University, Budapest, Hungary.
12 Also at Tata Institute of Fundamental Research – HECR, Mumbai, India.
13 Also at University of Visva-Bharati, Santiniketan, India.
14 Also at University of Calabria, Catanzaro, Italy.
15 Also at Università della Basilicata, Potenza, Italy.
16 Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
17 Also at California Institute of Technology, Pasadena, USA.
18 Also at University of California, Los Angeles, Los Angeles, USA.
19 Also at University of Florida, Gainesville, USA.
20 Also at Ege University, Izmir, Turkey.
21 Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy.
22 Also at University of Athens, Athens, Greece.
23 Also at The University of Kansas, Lawrence, USA.
24 Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
25 Also at Paul Scherrer Institut, Villigen, Switzerland.
26 Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
27 Also at Adiyaman University, Adiyaman, Turkey.
28 Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.