Search for microscopic black hole signatures at the Large Hadron Collider

Klimkovich, T; Klingebiel, D; Kreuzer, P; Lanske, D; Magass, C; Masetti, G; Merschmeyer, M; Meyer, A; Papacz, P; Pieta, H; Reithler, H; Schmitz, Sa; Sonnenschein, L; Steggemann, J; Teyssier, D; Bontenackels, M; Davids, M; Duda, M; Flugge, G; Geenen, H; Giffels, M; Ahmad, Wh; Heydhausen, D; Kress, T; Kuessel, Y; Linn, A; Nowack, A; Perchalla, L; Pooth, O; Rennefeld, J; Sauerland, P; Stahl, A; Thomas, M; Tornier, D; Zoeller, Mh; Martin, Ma; Behrenhoff, W; Behrens, U; Bergholz, M; Borras, K; Cakir, A; Campbell, A; Castro, E; Dammann, D; Eckerlin, G; Eckstein, D; Flossdorf, A; Flucke, G; Geiser, A; Glushkov, I; Hauk, J; Jung, H; Kasemann, M; Katkov, I; Katsas, P; Kleinwort, C; Kluge, H; Knutsson, A; Krucker, D; Kuznetsova, E; Lange, W; Lohmann, W; Mankel, R; Marienfeld, M; Melzer Pellmann, Ia; Meyer, Ab; Mnich, J; Mussgiller, A; Olzem, J; Parenti, A; Raspereza, A; Raval, A; Schmidt, R; Schoerner Sadenius, T; Sen, N; Stein, M; Tomaszewska, J; Volyanskyy, D; Walsh, R; Wissing, C; Autermann, C; Bobrovskyi, S; Draeger, J; Enderle, H; Gebbert, U; Kaschube, K; Kaussen, G; Klanner, R; Lange, J; Mura, B; Naumann Emme, S; Nowak, F; Pietsch, N; Sander, C; Schettler, H; Schleper, P; Schroder, M; Schum, T; Schwandt, J; Srivastava, Ak; Stadie, H; Steinbruck, G; Thomsen, J; Wolf, R; Barth, C; Bauer, J; Buege, V; Chwalek, T; De Boer, W; Dierlamm, A; Dirkes, G; Feindt, M; Gruschke, J; Hackstein, C; Hartmann, F; Heindl, Sm; Heinrich, M; Held, H; Hoffmann, Kh; Honc, S; Kuhr, T; Martschei, D; Mueller, S; Muller, T; Niegel, M; Oberst, O; Oehler, A; Ott, J; Peiffer, T; Piparo, D; Quast, G; Rabbertz, K; Ratnikov, F; Renz, M; Saout, C; Scheurer, A; Schieferdecker, P; Schilling, Fp; Schott, G; Simonis, Hj; Stober, Fm; Troendle, D; Wagner Kuhr, J; Zeise, M; Zhukov, V; Ziebarth, Eb; Daskalakis, G; Geralis, T; Kesisoglou, S; Kyriakis, A; Loukas, D; Manolakos, I; Markou, A; Markou, C; Mavrommatis, C; Ntomari, E; Petrakou, E; Gouskos, L; Mertzinmekis, Tj; Panagiotou, A; Evangelou, I; Foudas, C; Kokkas, P; Manthos, N; Papadopoulos, I; Patras, V; Triantis, Fa; Aranyi, A; Bencze, G; Boldizsar, L; Debreczeni, G; Hajdu, C; Horvath, D; Kapusi, A; Krajczar, K; Laszlo, A; Sikler, F; Vesztergombi, G; Beni, N; Molnar, J; Palinkas, J; Szillasi, Z; Veszpremi, V; Raics, P; Trocsanyi, Zl; Ujvari, B; Bansal, S; Beri, Sb; Bhatnagar, V; Dhingra, N; Jindal, M; Kaur, M; Kohli, Jm; Mehta, Mz; Nishu, N; Saini, Lk; Sharma, A; Singh, Ap; Singh, Jb; Singh, Sp; Ahuja, S; Bhattacharya, S; Choudhary, Bc; Gupta, P; Jain, S; Jain, S; Kumar, A; Shivpuri, Rk; Choudhury, Rk; Dutta, D; Kailas, S; Kataria, Sk; Mohanty, Ak; Pant, Lm; Shukla, P; Aziz, T; Guchait, M; Gurtu, A; Maity, M; Majumder, D; Majumder, G; Mazumdar, K; Mohanty, Gb; Saha, A; Sudhakar, K; Wickramage, N; Banerjee, S; Dugad, S; Mondal, Nk; Arfaei, H; Bakhshiansohi, H; Etesami, Sm; Fahim, A; Hashemi, M; Jafari, A; Khakzad, M; Mohammadi, A; Najafabadi, Mm; Mehdiabadi, Sp; Safarzadeh, B; Zeinali, M; Abbrescia, M; Barbone, L; Calabria, C; Colaleo, A; Creanza, Donato Maria; DE FILIPPIS, Nicola; De Palma, M; Dimitrov, A; Fiore, L; Iaselli, Giuseppe; Lusito, L; Maggi, Giorgio Pietro; Maggi, M; Manna, N; Marangelli, B; My, Salvatore; Nuzzo, S; Pacifico, N; Pierro, Ga; Pompili, A; Pugliese, Gabriella Maria Incoronata; Romano, F; Roselli, G; Selvaggi, G; Silvestris, L; Trentadue, R; Tupputi, S; Zito, G; Abbiendi, G; Benvenuti, Ac; Bonacorsi, D; Braibant Giacomelli, S; Brigliadori, L; Capiluppi, P; Castro, A; Cavallo, Fr; Cuffiani, M; Dallavalle, Gm; Fabbri, F; Fanfani, A; Fasanella, D; Giacomelli, R; Giunta, M; Marcellini, S; Meneghelli, M; Montanari, A; Navarria, Fl; Odorici, F; Perrotta, A; Primavera, F; Rossi, Am; Rovelli, T; Siroli, G; Travaglini, R; Albergo, S; Cappello, G; Chiorboli, M; Costa, S; Tricomi, A; Tuve, C; Barbagli, G; Ciulli, V; Civinini, C; D'Alessandro, R; Focardi, E; Frosali, S; Gallo, E; Genta, C; Lenzi, P; Meschini, M; Paoletti, S; Sguazzoni, G; Tropiano, A; Benussi, L; Bianco, S; Colafranceschi, S; Fabbri, F; Piccolo, D; Fabbricatore, P; Musenich, R; Benaglia, A; De Guio, F; Di Matteo, L; Ghezzi, A; Malberti, M; Malvezzi, S; Martelli, A; Massironi, A; Menasce, D; Moroni, L; Paganoni, M; Pedrini, D; Ragazzi, S; Redaelli, N; Sala, S; de Fatis, Tt; Tancini, V; Buontempo, S; Montoya, Cac; Cimmino, A; De Cosa, A; De Gruttola, M; Fabozzi, F; Iorio, Aom; Lista, L; Merola, M; Noli, P; Paolucci, P; Azzi, P; Bacchetta, N; Bellan, P; Bisello, D; Branca, A; Carlin, R; Checchia, R; Conti, E; De Mattia, M; Dorigo, T; Dosselli, U; Fanzago, F; Gasparini, F; Gasparini, U; Giubilato, P; Gresele, A; Lacaprara, S; Lazzizzera, I; Margoni, M; Mazzucato, M; Meneguzzo, At; Perrozzi, L; Pozzobon, N; Ronchese, P; Simonetto, F; Torassa, E; Tosi, M; Vanini, S; Zotto, P; Zumerle, G; Baesso, P; Berzano, U; Riccardi, C; Torre, P; Vitulo, P; Viviani, C; Biasini, M; Bilei, Gm; Caponeri, B; Fano, L; Lariccia, R; Lucaroni, A; Mantovani, G; Menichelli, M; Nappi, A; Santocchia, A; Servoli, L; Taroni, S; Valdata, M; Volpe, R; Azzurri, P; Bagliesi, G; Bernardini, J; Boccali, T; Broccolo, G; Castaldi, R; D'Agnolo, Rt; Dell'Orso, R; Fiori, F; Foa, L; Giassi, A; Kraan, A; Ligabue, F; Lomtadze, T; Martini, L; Messineo, A; Palla, F; Palmonari, F; Sarkar, S; Segneri, G; Serban, At; Spagnolo, P; Tenchini, R; Tonelli, G; Venturi, A; Verdini, Pg; Barone, L; Cavallari, F; Del Re, D; Di Marco, E; Diemoz, M; Franci, D; Grassi, M; Longo, E; Organtini, G; Palma, A; Pandolfi, F; Paramatti, R; Rahatlou, S; Amapane, N; Arcidiacono, R; Argiro, S; Arneodo, M; Biino, C; Botta, C; Cartiglia, N; Castello, R; Costa, M; Demaria, N; Graziano, A; Mariotti, C; Marone, M; Maselli, S; Migliore, E; Mila, G; Monaco, V; Musich, M; Obertino, Mm; Pastrone, N; Pelliccioni, M; Romero, A; Ruspa, M; Sacchi, R; Sola, V; Solano, A; Staiano, A; Trocino, D; Pereira, Av; Ambroglini, F; Belforte, S; Cossutti, F; Della Ricca, G; Gobbo, B; Montanino, D; Penzo, A; Heo, Sg; Chang, S; Chung, J; Kim, Dh; Kim, Gn; Kim, Je; Kong, Dj; Park, H; Son, D; Son, Dc; Kim, Z; Kim, Jy; Song, S; Choi, S; Hong, B; Jo, M; Kim, H; Kim, Jh; Kim, Tj; Lee, Ks; Moon, Dh; Park, Sk; Rhee, Hb; Seo, E; Shin, S; Sim, Ks; Choi, M; Kang, S; Kim, H; Park, C; Park, Ic; Park, S; Ryu, G; Choi, Y; Choi, Yk; Goh, J; Lee, J; Lee, S; Seo, H; Yu, I; Bilinskas, Mj; Grigelionis, I; Janulis, M; Martisiute, D; Petrov, P; Sabonis, T; Valdez, Hc; Burelo, Ed; Lopez Fernandez, R; Hernandez, As; Villasenor Cendejas, Lm; Moreno, Sc; Valencia, Fv; Ibarguen, Has; Linares, Ec; Pineda, Am; Reyes Santos, Ma; Allfrey, P; Krofcheck, D; Butler, Ph; Doesburg, R; Silverwood, H; Ahmad, M; Ahmed, I; Asghar, Mi; Hoorani, Hr; Khan, Wa; Khurshid, T; Qazi, S; Cwiok, M; Dominik, W; Doroba, K; Kalinowski, A; Konecki, M; Krolikowski, J; Frueboes, T; Gokieli, R; Gorski, M; Kazana, M; Nawrocki, K; Romanowska Rybinska, K; Szleper, M; Wrochna, G; Zalewski, R; Almeida, N; David, A; Faccioli, P; Parracho, Pgf; Gallinaro, M; Martins, P; Musella, P; Nayak, A; Ribeiro, Pq; Seixas, J; Silva, P; Varela, J; Wohri, Hk; Belotelov, I; Bunin, P; Finger, M; Finger, M; Golutvin, I; Kamenev, A; Karjavin, V; Kozlov, G; Lanev, A; Moisenz, P; Palichik, V; Perelygin, V; Shmatov, S; Smirnov, V; Volodko, A; Zarubin, A; Bondar, N; Golovtsov, V; Ivanov, Y; Kim, V; Levchenko, P; Murzin, V; Oreshkin,

V; Smirnov, I; Sulimov, V; Uvarov, L; Vavilov, S; Vorobyev, A; Andreev, Y; Gninenko, S; Golubev, N; Kirsanov, M; Krasnikov, N; Matveev, V; Pashenkov, A; Toropin, A; Troitsky, S; Epshteyn, V; Gavrilov, V; Kaftanov, V; Kossov, M; Krokhotin, A; Lychkovskaya, N; Safronov, G; Semenov, S; Stolin, V; Vlasov, E; Zhokin, A; Boos, E; Dubinin, M; Dudko, L; Ershov, A; Gribushin, A; Kodolova, O; Lokhtin, I; Obraztsov, S; Petrushanko, S; Sarycheva, L; Savrin, V; Shigirev, A; Andreev, V; Azarkin, M; Dremin, I; Kirakosyan, M; Rusakov, Sv; Vinogradov, A; Azhgirey, I; Bitioukov, S; Grishin, V; Kachanov, V; Konstantinov, D; Korablev, A; Krychkine, V; Petrov, V; Ryutin, R; Slabospitsky, S; Sobol, A; Tourtchanovitch, L; Troshin, S; Tyurin, N; Uzunian, A; Volkov, A; Adzic, P; Djordjevic, M; Krpic, D; Milosevic, J; Aguilar Benitez, M; Maestre, Ja; Arce, P; Battilana, C; Calvo, E; Cepeda, M; Cerrada, M; Colino, N; De La Cruz, B; Pardos, Cd; Vazquez, Dd; Bedoya, Cf; Ramos, Jpf; Ferrando, A; Flix, J; Fouz, Mc; Garcia Abia, P; Lopez, Og; Lopez, Sg; Hernandez, Jm; Josa, Mi; Merino, G; Pelayo, Jp; Redondo, I; Romero, L; Santaolalla, J; Willmott, C; Albajar, C; Codispoti, G; de Troconiz, Jf; Cuevas, J; Menendez, Jf; Folgueras, S; Caballero, Ig; Iglesias, Ll; Garcia, Jmv; Cifuentes, Jab; Cabrillo, Ij; Calderon, A; Llatas, Mc; Chuang, Sh; Campderros, Jd; Felcini, M; Fernandez, M; Gomez, G; Sanchez, Jg; Jorda, C; Pardo, Pl; Virto, Al; Marco, J; Marco, R; Rivero, Cm; Matorras, F; Sanchez, Fjm; Gomez, Jp; Rodrigo, T; Jimeno, Ar; Scodellaro, L; Sanudo, Ms; Vila, I; Cortabitarte, Rv; Abbaneo, D; Auffray, E; Auzinger, G; Baillon, P; Ball, Ah; Barney, D; Bell, Aj; Benedetti, D; Bernet, C; Bialas, W; Bloch, P; Bocci, A; Bolognesi, S; Breuker, H; Brona, G; Bunkowski, K; Camporesi, T; Cano, E; Cerminara, G; Christiansen, T; Perez, Jac; Cure, B; D'Enterria, D; De Roeck, A; Ramos, Fd; Elliott Peisert, A; Frisch, B; Funk, W; Gaddi, A; Gennai, S; Georgiou, G; Gerwig, H; Gigi, D; Gill, K; Giordano, D; Glege, F; Garrido, Rgr; Gouzevitch, M; Govoni, P; Gowdy, S; Guiducci, L; Hansen, M; Harvey, J; Hegeman, J; Hegner, B; Henderson, C; Hesketh, G; Hoffmann, Hf; Honma, A; Innocente, V; Janot, P; Karavakis, E; Lecoq, P; Leonidopoulos, C; Lourenco, C; Macpherson, A; Maki, T; Malgeri, L; Mannelli, M; Masetti, L; Meijers, F; Mersi, S; Meschi, E; Moser, R; Mozer, Mu; Mulders, M; Nesvold, E; Nguyen, M; Orimoto, T; Orsini, L; Perez, E; Petrilli, A; Pfeiffer, A; Pierini, M; Pimia, M; Polese, G; Racz, A; Rolandi, G; Rommerskirchen, T; Rovelli, C; Rovere, M; Sakulin, H; Schafer, C; Schwick, C; Segoni, I; Sharma, A; Siegrist, P; Simon, M; Sphicas, P; Spiga, D; Spiropulu, M; Stockli, F; Stoye, M; Tropea, P; Tsirou, A; Tsyganov, A; Veres, Gi; Vichoudis, P; Voutilainen, M; Zeuner, Wd; Bertl, W; Deiters, K; Erdmann, W; Gabathuler, K; Horisberger, R; Ingram, Q; Kaestli, Hc; Konig, S; Kotlinski, D; Langenegger, U; Meier, F; Renker, D; Rohe, T; Sibille, J; Starodumov, A; Bortignon, P; Caminada, L; Chen, Z; Cittolin, S; Dissertori, G; Dittmar, M; Eugster, J; Freudenreich, K; Grab, C; Herve, A; Hintz, W; Lecomte, P; Lustermann, W; Marchica, C; del Arbol, Rmr; Meridiani, P; Milenovic, P; Moortgat, F; Nef, P; Nessi Tedaldi, F; Pape, L; Pauss, F; Punz, T; Rizzi, A; Ronga, Fj; Rossini, M; Sala, L; Sanchez, Ak; Sawley, Mc; Stieger, B; Tauscher, L; Thea, A; Theofilatos, K; Treille, D; Urscheler, C; Wallny, R; Weber, M; Wehrli, L; Weng, J; Aguilo, E; Amsler, C; Chiochia, V; De Visscher, S; Favaro, C; Rikova, Mi; Mejias, Bm; Regenfus, C; Robmann, P; Schmidt, A; Snoek, H; Wilke, L; Chang, Yh; Chen, Kh; Chen, Wt; Dutta, S; Go, A; Kuo, Cm; Li, Sw; Lin, W; Liu, Mh; Liu, Zk; Lu, Yj; Wu, Jh; Yu, Ss; Bartalini, P; Chang, P; Chang, Yh; Chang, Yw; Chao, Y; Chen, Kf; Hou, Ws; Hsiung, Y; Kao, Ky; Lei, Yj; Lu, Rs; Shiu, Jg; Tzeng, Ym; Wang, M; Adiguzel, A; Bakirci, Mn; Cerci, S; Demir, Z; Dozen, C; Dumanoglu, I; Eskut, E; Girgis, S; Gokbulut, G; Guler, Y; Gurpinar, E; Hos, I; Kangal, Ee; Karaman, T; Topaksu, Ak; Nart, A; Onengut, G; Ozdemir, K; Ozturk, S; Polatoz, A; Sogut, K; Tali, B; Topakli, H; Uzun, D; Vergili, Ln; Vergili, M; Zorbilmez, C; Akin, Iv; Aliev, T; Bilmis, S; Deniz, M; Gamsizkan, H; Guler, Am; Ocalan, K; Ozpineci, A; Serin, M; Sever, R; Surat, Ue; Yildirim, E; Zeyrek, M; Deliomeroglu, M; Demir, D; Gulmez, E; Halu, A; Isildak, B; Kaya, M; Kaya, O; Ozkorucuklu, S; Sonmez, N; Levchuk, L; Bell, P; Bostock, F; Brooke, Jj; Cheng, Tl; Clement, E; Cussans, D; Frazier, R; Goldstein, J; Grimes, M; Hansen, M; Hartley, D; Heath, Gp; Heath, Hf; Huckvale, B; Jackson, J; Kreczko, L; Metson, S; Newbold, Dm; Nirunpong, K; Poll, A; Senkin, S; Smith, Vj; Ward, S; Basso, L; Bell, Kw; Belyaev, A; Brew, C; Brown, Rm; Camanzi, B; Cockerill, Dja; Coughlan, Ja; Harder, K; Harper, S; Kennedy, Bw; Olaiya, E; Petyt, D; Radburn Smith, Bc; Shepherd Themistocleous, Ch; Tomalin, Ir; Womersley, Wj; Worm, Sd; Bainbridge, R; Ball, G; Ballin, J; Beuselinck, R; Buchmuller, O; Colling, D; Cripps, N; Cutajar, M; Davies, G; Della Negra, M; Fulcher, J; Futyan, D; Bryer, Ag; Hall, G; Hatherell, Z; Hays, J; Iles, G; Karapostoli, G; Lyons, L; Magnan, Am; Marrouche, J; Nandi, R; Nash, J; Nikitenko, A; Papageorgiou, A; Pesaresi, M; Petridis, K; Pioppi, M; Raymond, Dm; Rompotis, N; Rose, A; Ryan, Mj; Seez, C; Sharp, P; Sparrow, A; Tapper, A; Tourneur, S; Acosta, Mv; Virdee, T; Wakefield, S; Wardrope, D; Whyntie, T; Barrett, M; Chadwick, M; Cole, Je; Hobson, Pr; Khan, A; Kyberd, P; Leslie, D; Martin, W; Reid, Id; Teodorescu, L; Hatakeyama, K; Bose, T; Jarrin, Ec; Clough, A; Fantasia, C; Heister, A; St John, J; Lawson, P; Lazic, D; Rohlf, J; Sperka, D; Sulak, L; Avetisyan, A; Bhattacharya, S; Chou, Jp; Cutts, D; Ferapontov, A; Heintz, U; Jabeen, S; Kukartsev, G; Landsberg, G; Narain, M; Nguyen, D; Segala, M; Speer, T; Tsang, Kv; Borgia, Ma; Breedon, R; Sanchez, Mcd; Cebra, D; Chauhan, S; Chertok, M; Conway, J; Cox, Pt; Dolen, J; Erbacher, R; Friis, E; Ko, W; Kopecky, A; Lander, R; Liu, H; Maruyama, S; Miceli, T; Nikolic, M; Pellett, D; Robles, J; Salur, S; Schwarz, T; Searle, M; Smith, J; Squires, M; Tripathi, M; Sierra, Rv; Veelken, C; Andreev, V; Arisaka, K; Cline, D; Cousins, R; Deisher, A; Duris, J; Erhan, S; Farrell, C; Hauser, J; Ignatenko, M; Jarvis, C; Plager, C; Rakness, G; Schlein, P; Tucker, J; Valuev, V; Babb, J; Clare, R; Ellison, J; Gary, Jw; Giordano, F; Hanson, G; Jeng, Gy; Kao, Sc; Liu, F; Liu, H; Luthra, A; Nguyen, H; Pasztor, G; Satpathy, A; Shen, Bc; Stringer, R; Sturdy, J; Sumowidagdo, S; Wilken, R; Wimpenny, S; Andrews, W; Branson, Jg; Cerati, Gb; Dusinberre, E; Evans, D; Golf, F; Holzner, A; Kelley, R; Lebourgeois, M; Letts, J; Mangano, B; Muelmenstaedt, J; Padhi, S; Palmer, C; Petrucciani, G; Pi, H; Pieri, M; Ranieri, R; Sani, M; Sharma, V; Simon, S; Tu, Y; Vartak, A; Wurthwein, F; Yagil, A; Barge, D; Bellan, R; Campagnari, C; D'Alfonso, M; Danielson, T; Flowers, K; Geffert, P; Incandela, J; Justus, C; Kalavase, P; Koay, Sa; Kovalskyi, D; Krutelyov, V; Lowette, S; Mccoll, N; Pavlunin, V; Rebassoo, F; Ribnik, J; Richman, J; Rossin, R; Stuart, D; To, W; Vimant, Jr; Bornheim, A; Bunn, J; Chen, Y; Gataullin, M; Kcira, D; Litvine, V; Ma, Y; Mott, A; Newman, Hb; Rogan, C; Timciuc, V; Traczyk, P; Veverka, J; Wilkinson, R; Yang, Y; Zhu, Ry;

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Search for microscopic black hole signatures at the Large Hadron Collider ☆

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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 pb^{-1}. 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 standard model backgrounds, dominated by QCD multijet production, is observed for various final-state multiplicities and model-independent limits on new physics in these final states are set. Using simple semi-classical approximation, limits on the minimum black hole mass are derived as well, in the range 3.5–4.5 TeV. These are the first direct limits on black hole production at a particle accelerator.

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 gauge interactions are localized on the $3+1$ space–time membrane. As a result, the effective gravitational coupling is enhanced at distances smaller than r, and Newton's law of gravitation is modified at short distances. The "true" Planck scale in $4+n$ dimensions (M_D) is consequently lowered to the electroweak scale, much smaller than the apparent Planck scale of $M_{\text{Pl}} \sim 10^{16}$ TeV seen by a $3+1$ space–time observer. The relationship between M_D and M_{Pl} follows from Gauss's law and is given as $M_{\text{Pl}}^2 = 8\pi M_D^{n+2} r^n$, using the Particle Data Group (PDG) definition [5].

Since in the ADD model gravity is enhanced by many orders of magnitude at distances much smaller than r, black hole formation in particle collisions could happen at energies greater than M_D, 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 the 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]:

$$r_S = \frac{1}{\sqrt{\pi} M_D} \left[\frac{M_{\text{BH}}}{M_D} \frac{8\Gamma(\frac{n+3}{2})}{n+2} \right]^{\frac{1}{n+1}}.$$

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 $M_{\text{BH}}^{\min}$ 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

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freedom. Quarks and gluons are the dominant particles produced in the black hole evaporation ($\sim 75\%$) 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 the case of large n [10,11,14]. In some models the evaporation is terminated earlier, when the black hole mass reaches M_D, with the formation of a stable non-interacting and non-accreting remnant [15]. The Hawking temperature for a black hole in $4+n$ space–time is given by [1,2,7,8]: $T_H = \frac{n+1}{4\pi r_S}$ (in Planck units $\hbar = c = k_B = 1$, where k_B is the Boltzmann constant) and is typically in the range of a few hundred GeV. The lifetime for such a microscopic black hole is $\sim 10^{-27}$ s [1,2,8].

Here we consider semi-classical black holes, whose properties are similar to those for classical black holes described by general relativity and whose mass is close enough to M_D so that quantum effects can not be ignored completely. There are also models [16–18] of quantum black holes that decay before they thermalize, mainly into two-jet final states. We do not consider this signature here, leaving it for dedicated searches in the dijet channel [19,20].

In what follows, we further assume that the semi-classical approximation, which is strictly valid only for $M_{\mathrm{BH}} \gg M_D$, still holds even for the BH masses as low as M_D. While we expect that unknown quantum corrections to the black hole production and decay may become very important, if not dominant, for $M_{\mathrm{BH}} \approx M_D$, 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 $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ at central rapidities and 0.175×0.175 in the forward region. Here, the pseudorapidity η is defined as $-\ln(\tan\frac{\theta}{2})$, where θ is the polar angle with respect to the direction of the counterclockwise beam, and ϕ 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 $\Delta E/E \approx 100\%/\sqrt{E[\mathrm{GeV}]} \oplus 5\%$. 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 $\not{E}_{\mathrm{T}}$ 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, $M_{\mathrm{BH}}^{\mathrm{min}}$, 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
Monte Carlo signal points for some of the model parameters probed, corresponding leading order cross sections (σ), and the minimum required values for the event multiplicity ($N \geqslant N^{\min}$) and S_T ($S_T > S_T^{\min}$), as well as the signal acceptance (A), the expected number of signal events (n^{sig}), the number of observed events (n^{data}) in data, the expected number of background events (n^{bkg}), and the observed (σ^{95}) and expected ($\sigma^{95}_{\text{exp.}}$) limits on the signal cross section at 95% confidence level.

M_D (TeV)	$M_{\text{BH}}^{\min}$ (TeV)	n	σ (pb)	$N^{\min}$	$S_T^{\min}$ (TeV)	A (%)	n^{sig}	n^{data}	n^{bkg}	σ^{95} (pb)	$\sigma^{95}_{\text{exp.}}$ (pb)
1.5	2.5	6	118	3	1.5	90.6	3713	203	241 ± 45	1.69	2.52
1.5	3.0	6	25.9	3	1.8	91.3	823	45	66.2 ± 22.2	0.62	1.13
1.5	3.5	6	4.97	4	2.1	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	$0.46^{+0.54}_{-0.46}$	0.11	0.13
1.5	5.0	6	0.007	5	3.4	75.2	0.19	0	$0.13^{+0.21}_{-0.13}$	0.12	0.13
2.0	2.5	4	28.9	3	1.7	81.4	817	82	99.7 ± 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	$1.35^{+1.45}_{-1.35}$	0.12	0.19
2.0	4.5	4	0.02	5	3.2	64.4	0.53	0	$0.21^{+0.31}_{-0.21}$	0.14	0.15
2.0	5.0	4	0.002	5	3.7	59.6	0.04	0	$0.06^{+0.12}_{-0.06}$	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	$2.40^{+2.57}_{-2.40}$	0.15	0.28
3.0	4.0	2	0.02	4	3.2	47.3	0.32	0	$0.46^{+0.67}_{-0.46}$	0.19	0.23
3.0	4.5	2	0.002	5	3.6	33.6	0.03	0	$0.08^{+0.15}_{-0.08}$	0.26	0.28
3.0	5.0	2	0.0002	5	4.0	34.5	0.002	0	$0.03^{+0.07}_{-0.03}$	0.26	0.26

generator (v1.0.3) [32,33]. The two generators yield different values of total cross section, as BlackMax introduces an 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_D. (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 fully efficient 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 $\not{E}_{\text{T}}$ 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 $t\bar{t}$ 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 $\frac{P_0(1+x)^{P_1}}{x^{P_2+P_3\log(x)}}$, which is shown with the solid line in Fig. 1. To check the systematic uncertainty of the fit, we use two additional ansatz functions, $\frac{P_0}{(P_1+P_2x+x^2)^{P_3}}$ and $\frac{P_0}{(P_1+x)^{P_2}}$ [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 $N \geqslant 3$, 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

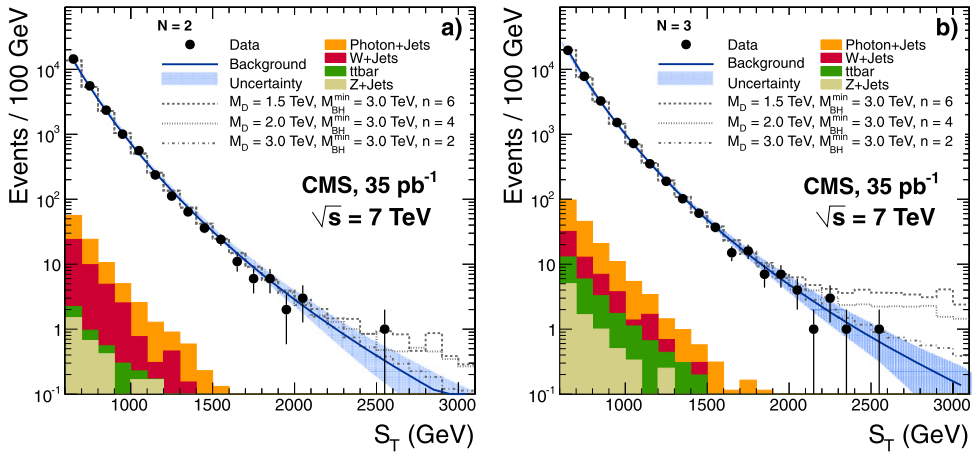

Fig. 1. Total transverse energy S_T, for events with the multiplicities of a) $N = 2$, and b) $N = 3$ objects in the final state. Data are depicted as solid circles with error bars; the shaded band is the background prediction obtained from data (solid line) with its uncertainty. Non-multijet backgrounds are shown as colored histograms. Also shown is the predicted black hole signal for three different parameter sets.

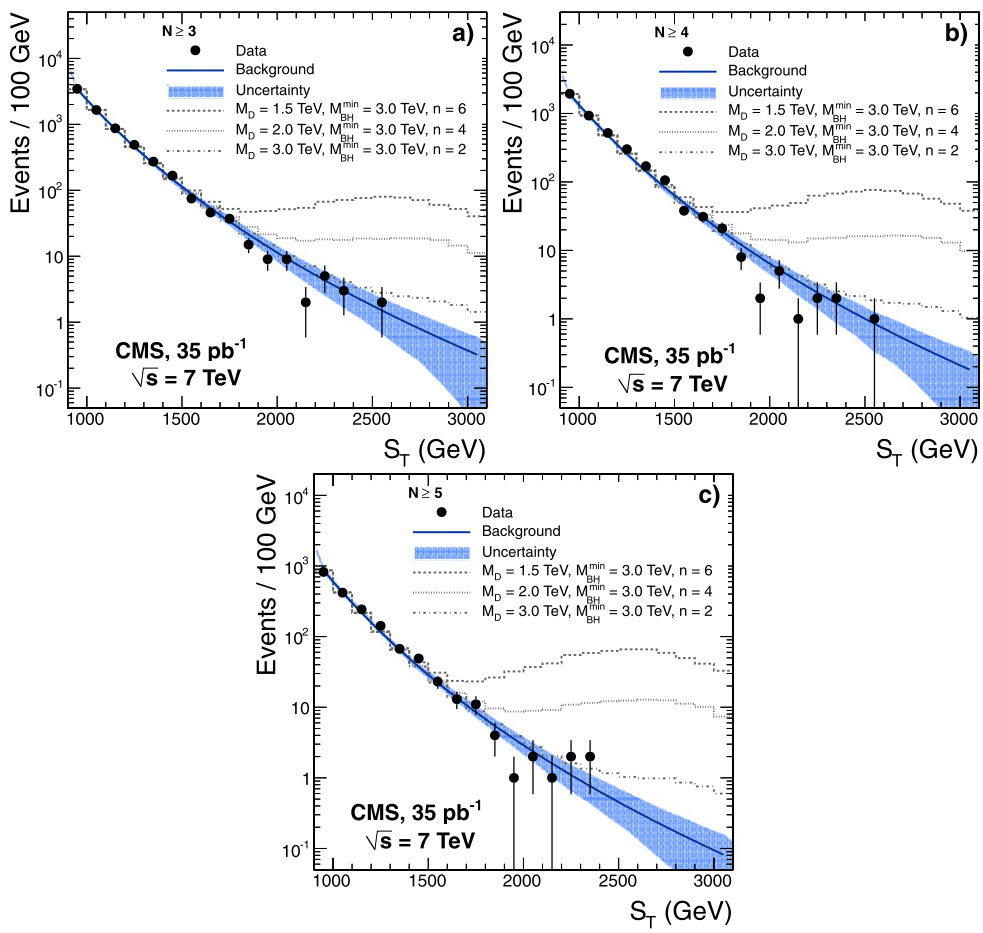

Fig. 2. Total transverse energy S_T, for events with multiplicities a) $N \geqslant 3$, b) $N \geqslant 4$, and c) $N \geqslant 5$ objects in the final state. Data are depicted as solid circles with error bars; the shaded band is the background prediction (solid line) with its uncertainty. Also shown are black hole signals 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

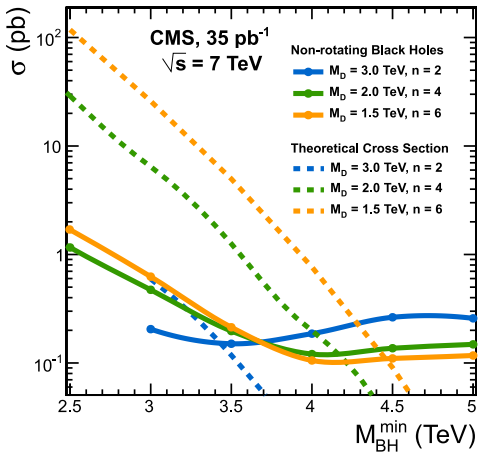

Fig. 3. The 95% confidence level upper limits on the black hole production cross section (solid lines) and three theoretical predictions for the cross section (dashed lines), as a function of the black hole mass.

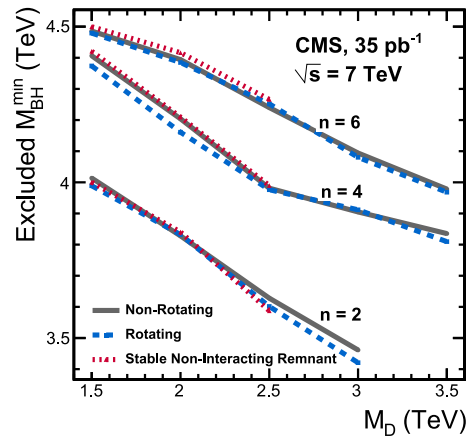

Fig. 4. The 95% confidence level limits on the black hole mass as a function of the multidimensional Planck scale M_D for several benchmark scenarios. The area below each curve is excluded by this search.

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 $\not{E}_T$. 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 $S_T > S_T^{\min}$ and $N > N^{\min}$. 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 $M_{\mathrm{BH}}^{\min}$. 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 $N \geqslant 3$, 4, and 5. Fig. 5 shows 95% CL upper limits from a counting experiment for $S_T > S_T^{\min}$ as a function of $S_T^{\min}$, 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 lepton + 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.

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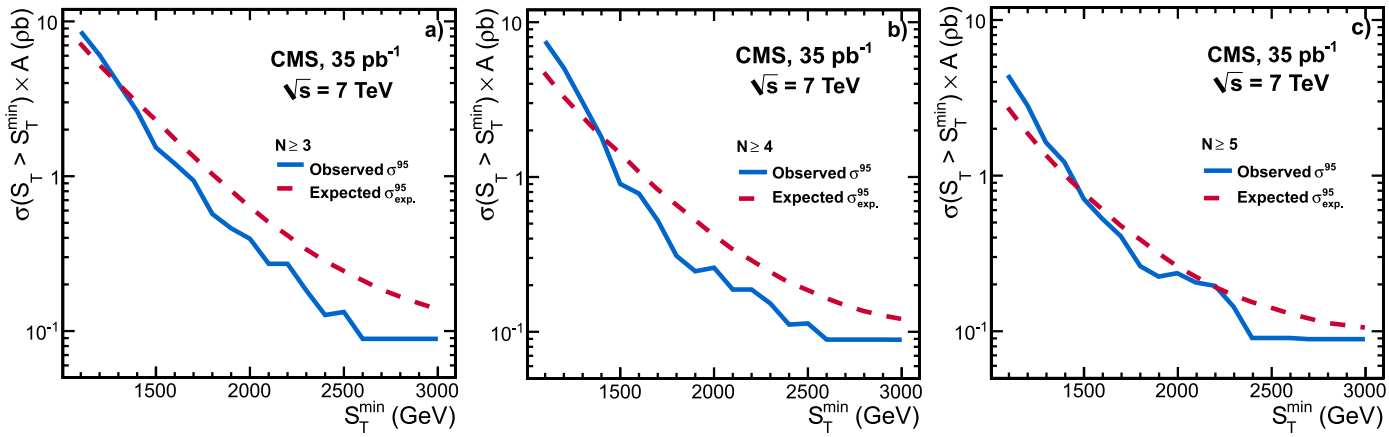

Fig. 5. Model-independent 95% confidence level upper limits on a signal cross section times acceptance for counting experiments with $S_T > S_T^{\min}$ as a function of $S_T^{\min}$ for (a) $N \geqslant 3$, (b) $N \geqslant 4$, and (c) $N \geqslant 5$. The solid (dashed) lines correspond to an observed (expected) limit for nominal signal acceptance uncertainty of 5%.

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