JOINT INSTITUTE FOR NUCLEAR RESEARCH

Veksler and Baldin laboratory of High Energy Physics

Final report on the summer student program

«Simulation the production of microscopic black holes at LHC energies»

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Participation period:

July 09 – August 31

Dubna, 2018

Contents

Abstract

The work performed within the framework of the problem of search of limits on the minimum mass depending on the model and the number of extra dimensions of microscopic black holes, which is performed by the physical group of JINR CMS.

Within the framework of the summer student program the following tasks were performed:

1)Simulations were made production of microscopic black holes on the brane without tension in proton collisions at energies of 8 and 14 TeV in the event generator BlackMax; 2) Estimate the expected number of black holes.

The results obtained in the simulation are compared with the previously obtained results also in BlackMax.

2. Introduction

There is a problem of scale hierarchy - a huge difference between the electroweak scale and Planck mass of Mpl, which determines the limit of applicability of quantum field theory and the transition to quantum gravity. To solve it, scenarios with large additional dimensions were proposed. The peculiarity of these models is the reduction of the fundamental scale of gravity from the value of 10^{19} GeV to a much smaller value in multidimensional models. This is achieved by considering a sufficiently large volume of additional compact spatial measurements (with a radius from a micron to values of the order of 10^{-16} mm). In such models, the true fundamental value is the multidimensional scale of gravity [3]

The four-dimensional gravitational constant becomes an effective constant related to the fundamental multidimensional constant through the volume and shape of the extra dimensions.

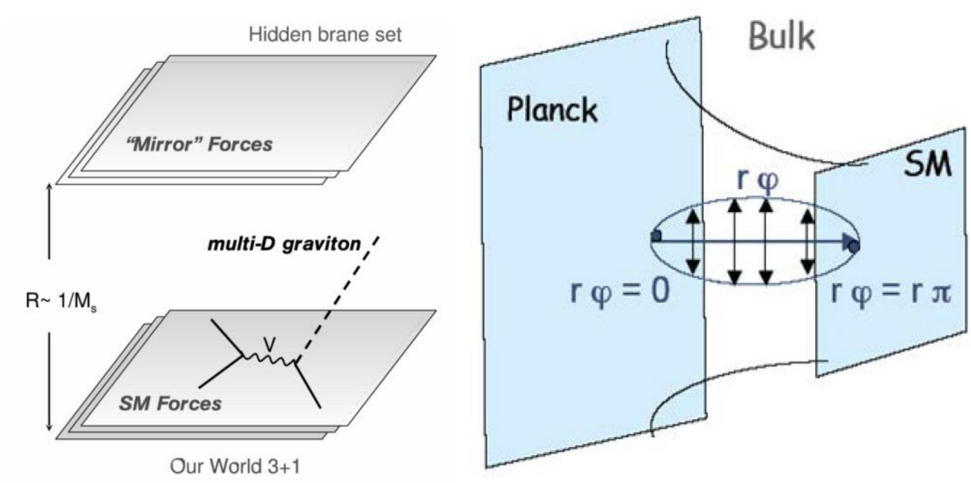
The multidimensional energy scale may even become a value in the TeV region. In this case, effects of multidimensional physics may be observable at accelerators — in particular, at the Large Hadron Collider (LHC).

This immediately entails a number of important implications. The first of these is the production of Kaluza–Klein excitations of those fields that are not localized in the three-dimensional brane. Owing to a high multiplicity [1] or owing to the geometry of the space [2], these excitations are strongly coupled to ordinary matter, contributing to all particle-interaction processes, and this can be observed in accelerator experiments. The second implication has a direct bearing on the present study — this is the production of microscopic black holes at accelerators that is followed by their fast evaporation. Processes of this kind may become possible when the impact parameter of colliding particles (for example, protons in the case of LHC) becomes smaller than the Schwarzschild radius of a black hole whose mass corresponds roughly to the collision energy. This class of events is thought to be an even more spectacular manifestation of the existence of extra dimensions since the production rates for black holes are at least several orders of magnitude higher than those for Kaluza–Klein modes.

A correct description of the process involving the formation of black holes and their further evolution requires invoking quantum gravity as a full theory.

2.1 Models of multidimensional gravity

Models of multidimensional gravity whose characteristic energy scale is substantially lower than the Planck scale, about one or several TeV units, were proposed in [1, 2] and, since then, have been referred to in the literature as models of the Arkani – Hamed – Dimopoulos – Dvali (ADD) class or models of the Randall – Sundrum (RS) class (in the first case, use is made of the metric of a flat multidimensional space, while, in the second case, where curvature is taken into account in a full multidimensional volume, models are written for a “piece” taken in five-dimensional anti-de-Sitter space and bounded by three-dimensional branes).



a) b)

Figure1. a) Model of the world of ADD - type with two "packages" of branes, spaced in the space additional measurements [3]. One set of branes reproduces our world, the second - a hidden sector, through which it is possible to implement the mechanisms of "soft" symmetry breaking;

b) A world with two branes in the RS1 model [3]. Two (3 + 1) branes are located at fixed points of the orbifold and reproduce, one is our world with SM fields, and the second is a hidden sector from which interactions can be transmitted. The fixed points have coordinates $\varphi = 0, \pi$, where φ is the angle parametrizing the fifth compact measurement.

2.2 Black Hole Production

We assume that the fundamental quantum-gravity energy scale M_D is not too far above the electroweak scale. Consider two particles colliding with a center-of-mass energy E_{CM}. They will also have an angular momentum J in their center-of-mass (CM) frame. By the hoop conjecture [3], if the impact parameter, b, between the two colliding particles is smaller than the diameter of the horizon of a (d + 1) - dimensional black-hole (where d is the total number of space-like dimensions) of mass $M = E_{CM}$ and angular momentum J,

$$b < 2r_h(d, M, J) \qquad (2.2.1)$$

Then a black-hole with r_h will form. The cross section for this process is approximately equal to the interaction area $\pi(2r_h)^2$.

In Boyer-Lindquist coordinates, the metric for a (d+1) - dimensional rotating black - hole (with angular momentum parallel to the $\hat{\omega}$ in the rest frame of the black-hole) is:

$$ds^2 = \left(1 - \frac{\mu r^{4-d}}{\Sigma(r,\theta)}\right) dt^2 - sin^2\theta \left(r^2 + a^2 \left(+sin^2\theta \frac{\mu r^{4-d}}{\Sigma(r,\theta)}\right)\right) d\phi^2 + 2asin^2\theta \frac{\mu r^{4-d}}{\Sigma(r,\theta)} dtd\phi - \frac{\Sigma(r,\theta)}{\Delta} dr^2 - \Sigma(r,\theta)d\theta^2 - r^2cos^2\theta d^{d-3}\Omega \quad (2.2.2)$$

Where μ is a parameter related to mass of the black hole, while

$$\Sigma = r^2 + a^2cos^2\theta \quad (2.2.3)$$

And

$$\Delta = r^2 + a^2 - \mu r^{4-d} \quad (2.2.4)$$

The mass of the black-hole is

$$M = \frac{(d-1)A_{d-1}}{16\pi G_d}\mu \quad (2.2.5)$$

And

$$J = \frac{2Ma}{d-1} \quad (2.2.6)$$

Is its angular momentum. Here,

$$A_{d-1} = \frac{2\pi^{d/2}}{\Gamma(d/2)} \quad (2.2.7)$$

Is the hyper-surface area of a (d−1)-dimensional unit sphere. The higher-dimensional gravitational constant G_d is defined as

$$G_d = \frac{(2\pi)^{d-4}}{4M_D^{d-1}} \quad (2.2.8)$$

The horizon occurs when $\Delta = 0$. That is at a radius given implicitly by

$$r_h^{(d)} = [\frac{\mu}{1+(a/r_h^{(d)})^2}]^{\frac{1}{d-2}} = \frac{r_s^{(d)}}{[1+(a/r_h^{(d)})^2]^{\frac{1}{d-2}}} \quad (2.2.9)$$

Here

$$r_s^{(d)} \equiv \mu^{1/(d-2)} \quad (2.2.10)$$

Is the Schwarzschild radius of a (d + 1) - dimensional black hole, i.e. the horizon radius of a nonrotating black hole. Equation (2.2.10) can be rewritten as:

$$r_s^{(d)}(E_{CM}, d, M_D) = k(d) M_D^{-1} (E_{CM}/M_D)^{1/(d-2)} \quad (2.2.11)$$

Where

$$k(d) \equiv \left[2^{d-3}\pi^{(d-6)/2}\frac{\Gamma[d/2]}{d-1}\right]^{1/(d-2)} \quad (2.2.12)$$

The Hawking temperature of a black-hole is

$$T_H = \frac{d-2}{4\pi r_h} \quad (2.2.13)$$

If two highly relativistic particles collide with center-of-mass energy E_{CM}, and impact parameter b, then their angular momentum in the center-of-mass frame before the collision is $L_{in} = bE_{CM}/2$.

Suppose for now that the black-hole that is formed retains all this energy and angular momentum. Then the mass and angular momentum of the black-hole will be $M_{in} = E_{CM}$ and $J_{in} = L_{in}$. A black-hole will form if:

$$b < b_{max} \equiv 2r_h^{(d)}(E_{CM}, b_{max}E_{CM}/2) \quad (2.2.14)$$

We see that b_{max} is a function of both E_{CM} and the number of extra dimensions. We can rewrite condition (2.2.14) as

$$b_{max}(E_{CM}; d) = 2\frac{r_s^{(d)}(E_{CM})}{[1+(\frac{d-1}{2})^2]^{\frac{1}{d-2}}} \quad (2.2.15)$$

There is one exception to this condition. In the case where we are including the effects of the brane tension, the metric (and hence gray-body factors) for a rotating black-hole are not known. In this case we consider only non-rotating black-holes. For the model with non-zero tension brane, the radius of the black hole is defined as

$$r_h = \frac{r_s}{B^{1/3}} \quad (2.2.16)$$

With B the deficit-angle parameter which is inverse proportional to the tension of the brane $B = 1 - \frac{\lambda}{2\pi M_d^{d-2}}$. Therefore, for branes with tension

$$b_{max}^{tension}(E_{CM}, d) = 2r_h^{(d)}(E_{CM}) \quad (2.2.17)$$

Also, for branes with positive tension only the d = 5 metric is known.

Black hole geometric section for assuming that the entire initial energy ECM was below the horizon, is given by

$$\sigma = \pi r_s^2 \quad (2.2.18)$$

The entire approach to BH as a multidimensional object is correct provided that its Schwarzschild radius is much smaller than the dimensions of additional(AD) measurements: $r_s \ll R$. Then the microscopic black hole is completely in the AD, and the description is correct.

On the other hand, it turned out that not all the initial collision energy (and angular momentum) was captured under the horizon being formed. Thus, strong inelasticity was inherent in the formation of BH. The inelasticity must be taken into account in the calculation of the cross sections.

3 Calculation of the cross sections for BH generation processes for energy LHC

LHC conditions, cross sections were obtained for the production processes black hole. The simulation was performed using the BlackMax event generator. We considered nonrotating black holes and rotating black holes with branes without tension at a center-of-mass energy of 8 and 14 TeV.

With the increase in the number of extra dimensions, n processes with the birth of black holes become more likely.

3.1 Modeling the production of black holes at collision energies 8 TeV

In Fig. 2 show the simulation results of the nonrotating black hole cross sections of the number of extra dimensions n=2,4,6 with collision energy 8 TeV. The graphics were obtained using the Root package.

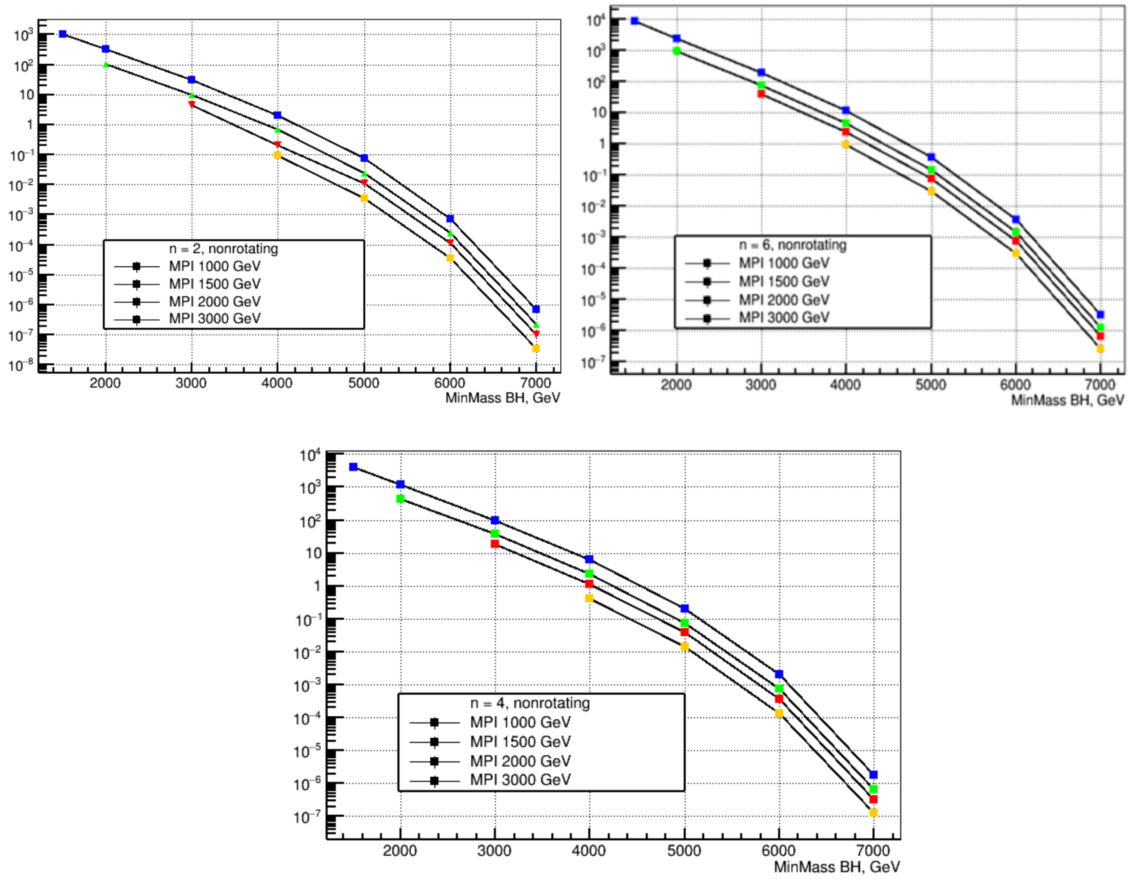


Figure2. A Plot of the dependence of the cross section of production BH from the minimum mass with E_{MC} = 8 TeV

In Fig. 3 show the simulation results the rotating black hole cross sections of the number of extra dimensions n=2,4,6 with collision energy 8 TeV

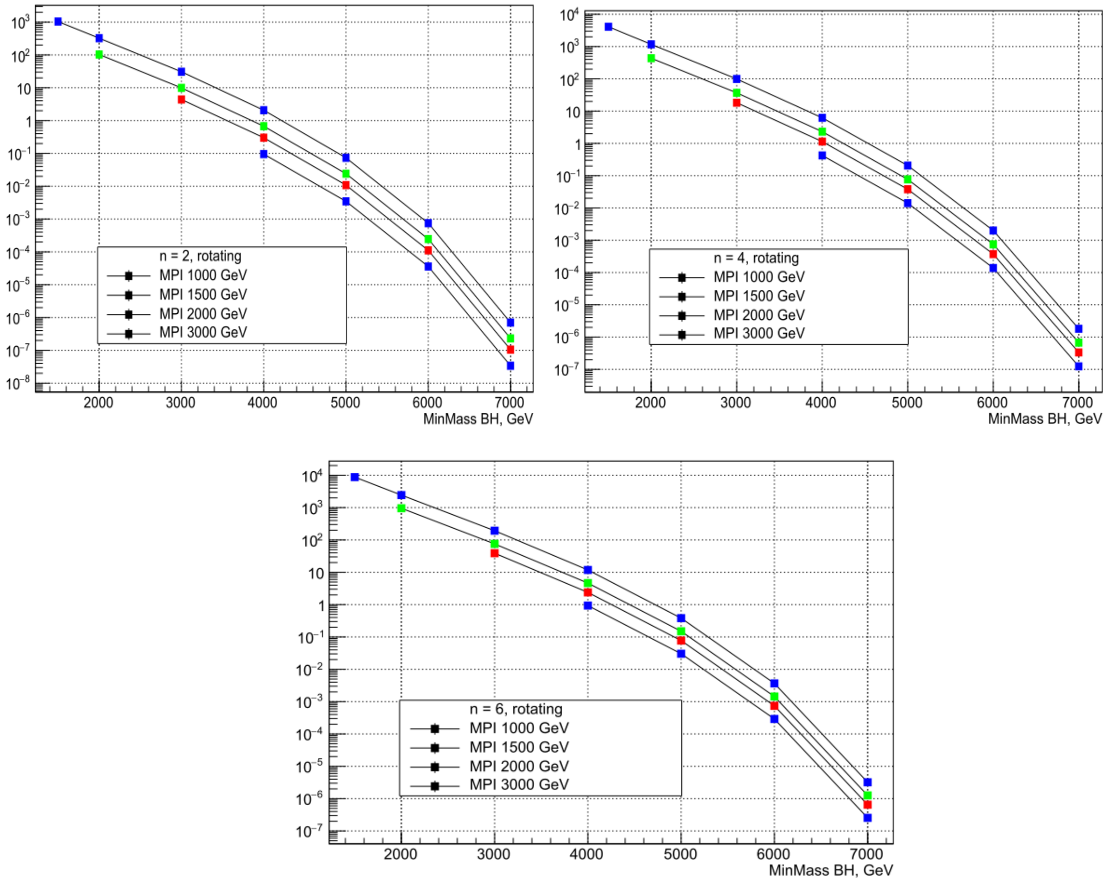


Figure 3. A Plot of the dependence of the cross section of production BH from the minimum mass with E_{MC} = 8 TeV

3.2 Modeling the production of black holes at collision energies 14 TeV

In Fig. 4 show the results of simulation the nonrotating black hole cross sections of the number of extra dimensions n=2,4,6 with collision energy14 TeV

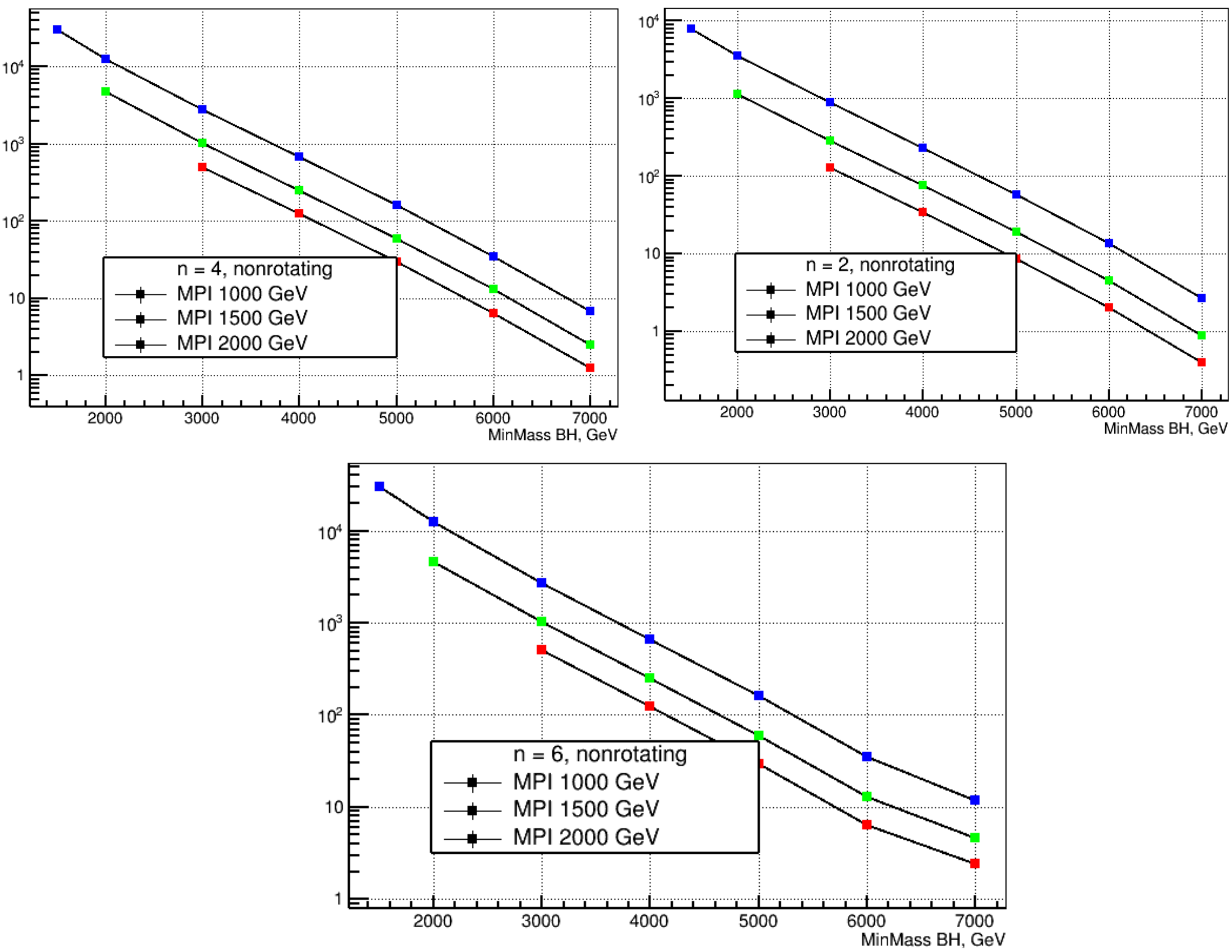


Figure4. A Plot of the dependence of the cross section of production BH from the minimum mass with E_{MC} = 14 TeV

In Fig. 5 show the results of simulation the rotating black hole cross sections of the number of extra dimensions n=2,4,6 with collision energy 14 TeV

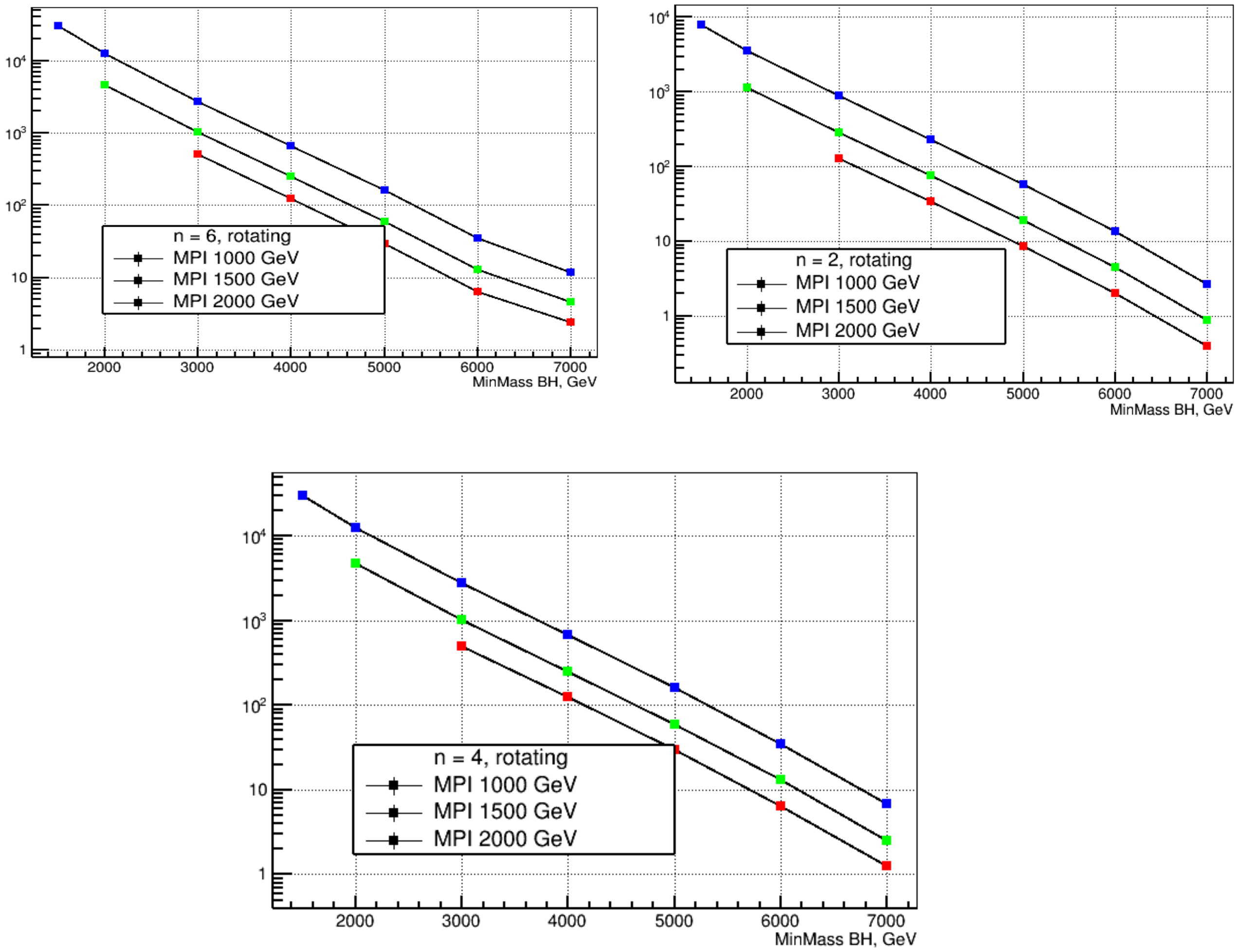


Figure 5. A Plot of the dependence of the cross section of production BH from the minimum mass with E_{MC} = 14 TeV

3.3 Estimating the number of black holes

The number of interactions is obtained from the expression:

$$N = \sigma L \qquad (3.3.1)$$

Where L - integral luminosity LHC, σ - the cross section for the production of black holes that were obtained in BlackMax;

The calculation of the number of black holes was obtained for the parameters E_{CM} = 8, 14 TeV for the number extra dimensions n = 2, 4, 6. The report presents the results of calculations for n = 4 for the pp - collision energy of 8 TeV (Table 1) and 14 TeV (Table 2), since this takes up a lot of space.

As can be seen from Tables 1 and 2, the expected number of black holes, and, consequently, the cross section (Figures 3-6) for scenarios of a rotating and non-rotating BH.

Table1. The expected number of black holes of the pp - collision 14 TeV

Luminosity =12,1 fb^{-1}								
n=4	M_{pl}, GeV							
	Nonrotating black hole				Rotating black hole			
Minmass BH	1000	1500	2000	3000	1000	1500	2000	3000
1500	4,98E+07	-	-	-	4,98E+07	-	-	-
2000	1,42E+07	5,27E+06	-	-	1,42E+07	5,27E+06	-	-
3000	1,20E+06	4,46E+05	2,21E+05	-	1,20E+06	4,46E+05	2,21E+05	-
4000	7,51E+04	2,80E+04	1,38E+04	5,13E+03	7,51E+04	2,80E+04	1,38E+04	5,13E+03
5000	2,49E+03	9,28E+02	4,60E+02	1,71E+02	2,49E+03	9,28E+02	4,60E+02	1,71E+02
6000	2,42E+01	9,04E+00	4,49E+00	1,67E+00	2,42E+01	9,04E+00	4,49E+00	1,67E+00
7000	2,19E-02	8,16E-03	4,05E-03	1,51E-03	2,19E-02	8,16E-03	4,05E-03	1,51E-03

Table2. The expected number of black holes of the pp - collision 14 TeV

Luminosity =100 fb^{-1}						
n=4	M_{pl}, GeV					
	Nonrotating black hole			Rotating black hole		
Minmass BH	1000	1500	2000	1000	1500	2000
1500	2.99E+09	-	-	2,99E+09	-	-
2000	1.26E+09	4,68E+08	-	1,26E+09	4,68E+08	-
3000	2.74E+08	1,02E+08	5,05E+07	2,74E+08	1,02E+08	5,05E+07
4000	6.74E+07	2,51E+07	1,24E+07	6,74E+07	2,51E+07	1,24E+07
5000	1.60E+07	5,98E+06	2,97E+06	1,60E+07	5,98E+06	2,97E+06
6000	3.50E+06	1,31E+06	6,49E+05	3,50E+06	1,31E+06	6,49E+05
7000	6.82E+05	2,55E+05	1,27E+05	6,82E+05	2,55E+05	2,27E+05
8000	2.99E+09	3,98E+04	1,98E+04	-		

4 Actual results

In data archive [8], on May 15, 2018, CMS collaboration presents a search in energy, multiple finite states to prove physics beyond the standard model, such as black holes. The data sample corresponds to the integrated luminosity of 35.9 fb^{-1} collected in the CMS experiment at LHC in proton-proton collisions at a center-of-mass energy of 13 TeV in 2016.

In the context of models with large additional dimensions, semiclassical black holes with a minimum mass of up to 10.1 TeV are excluded from this search.

An example of a model-specific limit is given in Fig. 7 for a BLACKMAX benchmark point B1 (nonrotating semiclassical BH) with M_D = 4 TeV, n_{ED} = 6, and M_{BH}^{min} between 5 and 11 TeV. In this case, the optimal inclusive multiplicity N_{min} starts at 7 for the lowest M_{BH}^{min} value of 5 TeV, with the corresponding$S_{min}^{T} = 5$ TeV. As M_{BH}^{min} increases, the optimal point shifts to lower inclusive multiplicities and the corresponding S_{min}^{T} increases, reaching (3, 7.6 TeV) for $M_{BH}^{min} = 11$ TeV .

The corresponding 95% CL upper limit curve and the theoretical cross section for the chosen benchmark point is shown in Fig. 7. The observed (expected) 95% CL lower limit on M_{BH}^{min} in this benchmark model can be read from this plot as the intersection of the theoretical curve with the observed (expected) 95% CL upper limit on the cross section, and is found to be 9.7 (9.7) TeV.

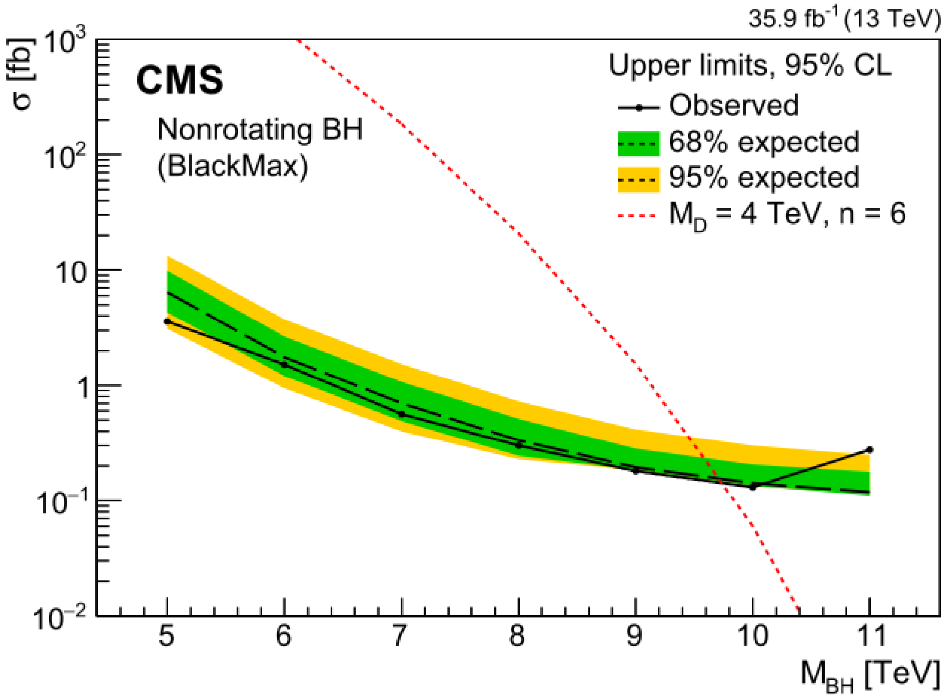


Figure 7. Example of a model-specific limit on M_{BH}^{min} for a semiclassical nonrotating BH model (BLACKMAX point B1) with M_D = 4 TeV n_{ED} = 6, as a function of M_{BH}^{min}. The 95% CL upper exclusion limit on the signal cross section for each M_{BH}^{min} value is obtained at the optimal (N_{min}, S_{min}^{T}) point, which ranges from (7, 5.0 TeV) for M_{BH}^{min} = 5 TeV to (3, 7.6 TeV) forM_{BH}^{min} = 11 TeV.

Also shown with a dashed line are the theoretical cross sections corresponding to these optimal points. The green (yellow) band represents the ±1 (±2) standard deviation uncertainty in the expected limit.

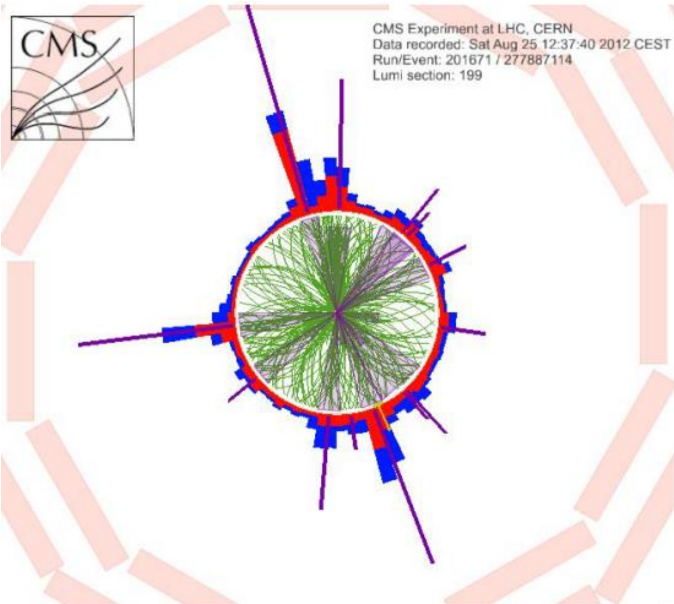


Figure 8. Visualization of a real event - a candidate in BH with 13 objects in the final state, ST = 2.1 TeV, √s = 8 TeV in center of mass system (2012).

For example, in Fig. 8 and 9 are "event monitors" - three- and two-dimensional visualizations of real multi-jet events registered by the CMS installation during the first cycle of work in 2010-2012, having passed all the necessary triggers and selection criteria and recorded in candidates for BH [3].

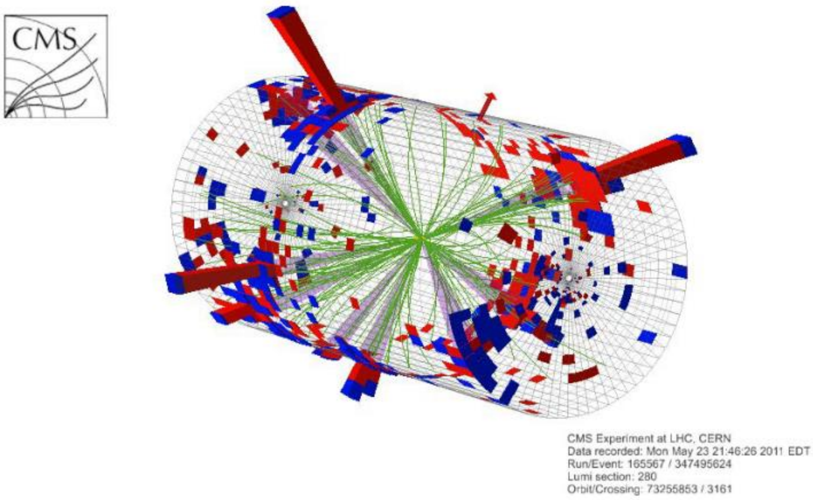


Figure 9. Three-dimensional visualization of a real event - a candidate in BH with 9 objects in the final state, S_T = 2.6 TeV, √s = 7 TeV in center of mass system (2011)

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Acknowledgments.

I would like to express my gratitude to my scientific adviser, the head of the scientific and experimental department of physics at CMS, Dr. Sergei Shmatov, who not only gave me a wonderful opportunity to pass an internship at JINR, but also provided support professional advice and invaluable help in mastering and understanding the material. Moreover, this work could not be carried out without specialized computer programs, which were provided to us.