# ESTIMATION OF THE CROSS-SECTION FOR THE PRODUCTION OF MICRO BLACK HOLES AT THE LARGE HADRON COLLIDER


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## ABSTRACT


We have studied the cross-section of the reaction of micro black holes (MBH) formation at Large Hadron Collider in this paper. We models for multiple production processes at high energies for the estimation: model of MBH formation, the simplest parton model and a parton model for superhigh energies. On the basis of such a models we have made the conclusion, that the threshold of MBH formation by proton collisions is by 35-36 decimal orders larger than the energy, that was reached today at the Large Hadron Collider (LHC) (14 TeV). It explains the absence of MBH observations at proton collisions at LHC.

We have also studied MBH formation cross-section in collisions of protons with nuclei $Pb$ in this paper. On the basis of hydrodynamic model of *hN*-interaction it was shown, that the threshold energy of protons in a system of equal speeds (S - system) is of the order of $10^{35}$ TeV. That corresponds to the energy of the order of $10^{74}$ TeV at laboratory system ($\vec{p}_{Pb} = 0$). Such proton energy can not be reached at elementary particles accelerators.

Possibly, a calculation of quantum effects will lead to a decrease of the threshold energy of MBH formation.

## KEYWORDS

Black holes; formation; Collider.

## INTRODUCTION

The successes of quantum field theory [6-8, 12-13, 15-17, 19, 22-31] and the classical theory of gravity [1-2, 9-11, 14, 18] make it possible to carry out a comprehensive theoretical study of the properties of singularities in solutions of Einstein's equations [1], which, in particular, are black holes [2, 20-21]. We have valued the cross-section of the reaction of micro black holes (MBH) formation at Large Hadron Collider in this paper. We used models of multiple production processes on high energies for estimation: evristic model of MBH formation, simplest parton model and parton model for superhigh energies. On the basis of this models we have made the conclusion, that threshold of MBH formation by proton collisions is larger by 35-36 decimal orders than energy, that was reached today at Large Hadron Collider (LHC) (14 $TeV$). That explains the absence of MBH observations on proton collisions at LHC.

We have also valued MBH formation cross-section on proton with Pb nucleus collisions in this paper. On the basis of hN-interaction hydrodynamic model it was shown, that threshold energy of protons at the system of equal speeds (S-system) is the value of $10^{35}$ $TeV$ order. That corresponds to energy of $10^{74}$ $TeV$ order at laboratory system ($\vec{p}_{Pb} = 0$). Such an energy of protons can not be reached at elementary particles accelerators.

## I. EVRISTIC MBH FORMATION MODEL

The processes of black holes formation at the LHC were investigated in [3-5] and other papers. In work [3], potentially dangerous events in collisions of heavy ions at the LHC were studied. The article [4] reviews the safety of particle collisions at the LHC. In work [5], the astrophysical consequences of hypothetical stable black holes of the TeV – scale were considered. The authors come to the conclusion about the safety of possible processes of black hole formation at the LHC.

We shall consider reaction p+p→MBH. Radius of the sphere, where deconfainment realizes and virtual and real particles are formed by proton collisions at centre of inertia system, may be estimated by formula

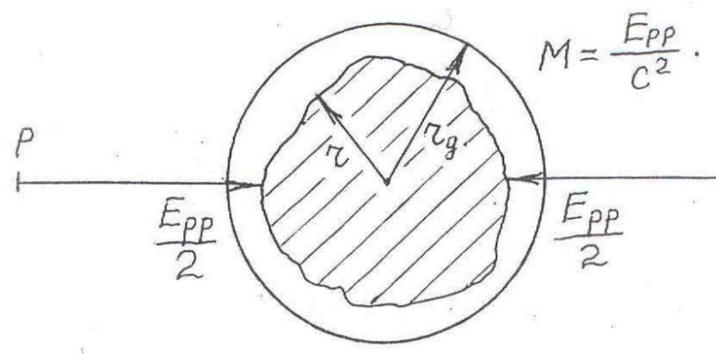
$$r = \sqrt{\frac{\sigma_{tot}(pp)}{\pi}}, \quad (1)$$

here $\sigma_{tot}(pp)$ is total cross-section of pp-interaction. Contemporary experimental data testify, that value of $\sigma_{tot}(pp)$ is constant at great interval of energies. When energy is very great, $\sigma_{tot}(pp)$ increases slowly with energy $E_{pp}$ growth ($E_{pp}$ is full protons energy at centre of inertia system).

If

$$r \leq r_g = \frac{2GM}{c^2} \ \left(M = \frac{E_{pp}}{c^2}\right), \quad (2)$$

then second particles don't form on the outside of gravitational sphere [1-2], which is expected, and protons under collision come to gravitational sphere, which is expected, without energy loss for radiation. In that case protons pass full their energy $E_{pp}$ to the volume inside of sphere $r_g$. In that case MBH with gravitational sphere $r_g$ and with imaginary second particles inside of gravitational sphere is formed. This process is represented at picture 1.




Picture 1. MBH formation by proton collisions, when $r \leq r_g$.

From formulas (1) and (2) we have:

$$E_{pp}^2 \geq \frac{c^8 \sigma_{tot}(pp)}{4\pi G^2}\,. \qquad (3)$$

Values of $\sigma_{tot}(pp)$ are represented at table 1.

Table 1. Values of $\sigma_{tot}(pp)$.

| $E_{pp}, TeV$ | $\sigma_{tot}(pp), mb$ |
|---|---|
| 1,0 | 67 |
| 7,0 | 95,35 |
| 10,0 | 107 |
| 60,0 | 144 (extrapolation) |

We approximate $\sigma_{tot}(pp)$ by formula

$$\sigma_{tot}\,(pp) = a_0 + a_1 lgx + a_2 (lgx)^2, \qquad (4)$$

$$x = \frac{E_{pp}}{2m_N c^2}\,,$$

here

$a_0$ = 77,3515 *mb*,

$a_1$= –32,2941 *mb*,

$a_2$=10,4550 *mb*.

On such an approximation inequality (3) admits a solution

$$E_{pp} \geq E_{ppth} = 8{,}32 \cdot 10^{36}\ TeV.$$

It is estimation of protons energy at centre of inertia system, when MBH begin to form. But protons energy at centre of inertia system, which was reached at LHC, is only 14 *TeV*. That explains the absence of MBH observations on proton collisions at LHC.

If $r > r_g = \frac{2GM}{c^2}(M = \frac{E_{pp}}{c^2})$, then MBH don't form. It is illustrated by picture 2. Shaded domain with radius $r$ is domain of virtual and real particles intensive formation. Real particles take away energy from shaded domain. So far as $r > r_g$, then radiation of energy by share of shaded domain, which is disposed on the outside of expected gravitational sphere $r_g$, decreases initial energy of protons $E_{pp}$ and only energy $E_{pp1} < E_{pp}$ comes to sphere $r_g$. Energy $E_{pp1}$ is not enough for MBH formation with gravitational sphere $r_g$. Because of that we decrease radius of expected gravitational sphere to $r_1 = \frac{2GM_1}{c^2}(M_1 = \frac{E_{pp1}}{c^2})$. But share of shaded domain between spheres $r_{g1}$ and $r_g$ also radiates energy. Because of that only energy $E_{pp2} < E_{pp1}$ comes to sphere $r_{g1}$. Energy $E_{pp2}$ is not enough for MBH formation with gravitational sphere $r_{g1}$, because of that we decrease radius of gravitational sphere of expected MBH to $r_{g2} = \frac{2GM_2}{c^2}(M_2 = \frac{E_{pp2}}{c^2})$. But share of shaded domain between spheres $r_{g2}$ and $r_{g1}$ also radiates energy. Because of that only energy $E_{pp3} < E_{pp2}$ comes to sphere $r_{g2}$. Energy $E_{pp3}$ is not enough for MBH formation with gravitational sphere $r_{g2}$, because of that we decrease radius of gravitational sphere of expected MBH to $r_{g3} = \frac{2GM_3}{c^2}(M_3 = \frac{E_{pp3}}{c^2})$ and so on. It will last like that until radius of gravitational sphere of probable MBH will turn into zero.

So, gravitational sphere of expected MBH decreases continuously, when shaded domain radiates the energy; particles, which find oneself inside of given sphere, have not enough energy for formation of MBH, which has given sphere as its gravitational sphere.

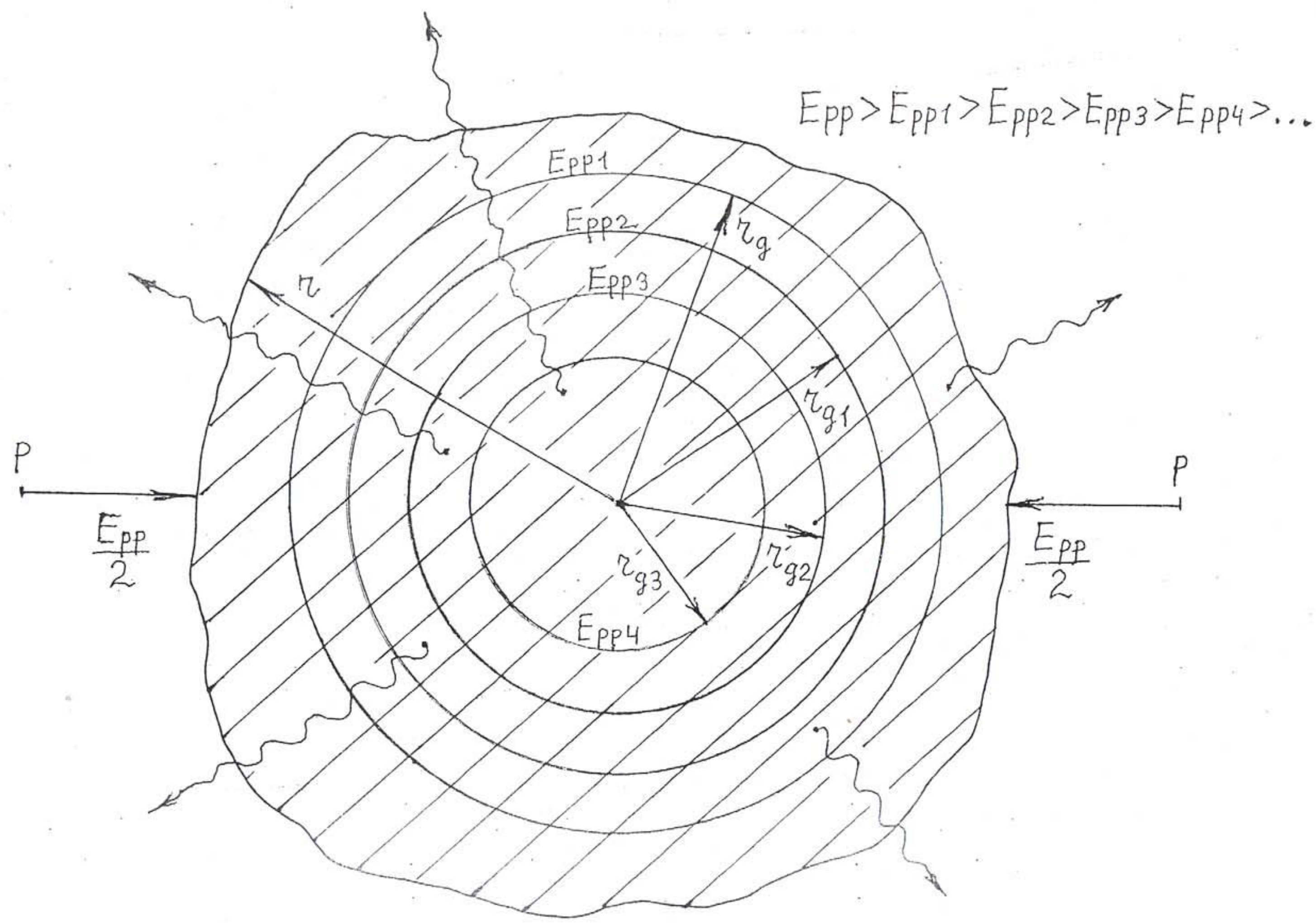
So, if $r > r_g$, then MBH don't form, if one assume, that radiation of energy realizes continuously from the whole domaine of virtual and real particles formation.

Cross-section of MBH formation on two protons collisions at centre of inertia system may be estimated in such a way:

$$\sigma \approx \pi\left(2r_g\right)^2 = \frac{16 \cdot \pi \cdot G^2}{c^8} \cdot E_{pp}^2. \qquad (5)$$

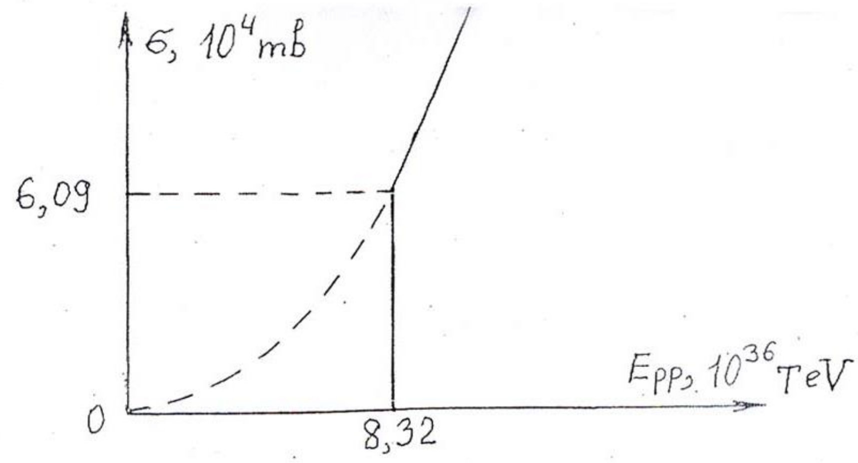
Cross-section of MBH formation on threshold energy is equal to

$$\sigma_{th} = \sigma\left(E_{ppth}\right) = 6{,}09 \cdot 10^4\ mb.$$




Picture 2. Process of decrease of expected MBH gravitational sphere on second particles formation, when $r > r_g$.

The dependence $\sigma(E_{pp})$ is adduced at picture 3.




Picture 3. The graph of dependence of MBH formation cross-section $\sigma$ on full energy of protons, which are colliding, $E_{pp}$.

MBH life time at vacuum is equal to

$$\Delta t = \frac{5120 \cdot \pi \cdot G^2 \cdot M^3}{\hbar \cdot c^4}, \qquad M = \frac{E_{pp}}{c^2}. \tag{6}$$

The indeterminacy of MBH formation energy is equal to

$$\Delta E_{pp} \approx \frac{\hbar}{\Delta t} = \frac{\hbar^2 \cdot \mathrm{c}^{10}}{5120 \cdot \pi \cdot G^2 \cdot E_{pp}^3}. \tag{7}$$

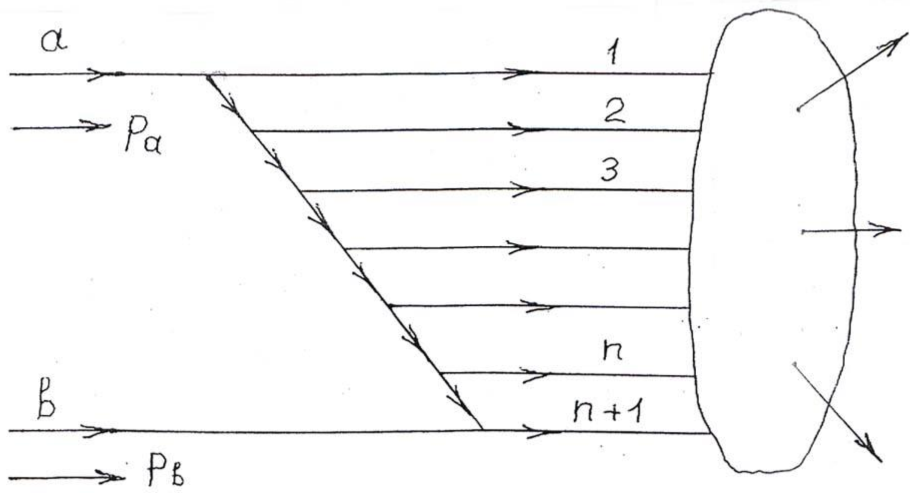
The indeterminacy of MBH formation energy decreases, when protons energy $E_{pp}$ increases. On threshold energy

$$\Delta E_{ppth} = 2{,}40 \cdot 10^{-51}\, TeV.$$

The adduced estimations are approximate ones because we combined mechanically quantum theory formulas with formulas from general relativity. For carefully investigation of MBH formation one have to use quantum theory of gravitation; but such a theory is not worked out enough today. Besides that, we don't know whether approximation (4) is correct on very high energies.

# II. PARTON MODEL

We shall consider reaction p+p→MBH+X at centre of inertia system of protons, which collide. Scheme of pp-interaction process in parton model is adduced at picture 4.




Picture 4. Scheme of pp-interaction process in parton model.

In accordance with parton model free proton a dissociates virtually to system of partons until slow parton with impulse

$$p_q = \frac{p_a}{2^n} \approx < m_{q\perp} > \quad (8)$$

will form; such a parton may to interact with slow parton from other proton b. We use mark $m_{q_\perp} = (k_{q_\perp}^2 + m_q^2)^{1/2}$. At simplest parton model they suppose $< m_{q_\perp} > \approx m_N$. From formula (8) we have

$$n = \frac{ln(p_a/< m_{q_\perp} >)}{ln2}.$$

The dimension of parton fluctuation in diametrical direction is

$$|\vec{b}| \approx < m_{q_\perp} >^{-1} \cdot \sqrt{n} = < m_{q_\perp} >^{-1} \cdot \left(\frac{ln(p_a/< m_{q_\perp} >)}{ln2}\right)^{1/2}.$$

It is hadron disk radius. Slow parton is disposed at the border of the disk.

One may estimate radius of domain, where real and virtual particles form on pp – interaction, in such a way: $r \approx 2|\vec{b}|$. The condition of MBH formation is

$$r \leq r_g\,;$$

$$\frac{2}{<m_{q_\perp}>} \cdot \left(\frac{ln\left(p_a/<m_{q_\perp}>\right)}{ln2}\right)^{1/2} \leq 2G\,E_{pp}.$$

For usual units we have inequality

$$\frac{2\hbar}{m_N \cdot c}\left(\frac{ln(E_{pp}/2m_N c^2)}{ln2}\right)^{1/2} \leq \frac{2G\,E_{pp}}{c^4}.$$

This inequality admits the solution

$$E_{pp} \geq E_{ppth} = 1{,}81 \cdot 10^{36}\ TeV.$$

So, reaction p+p→MBH+X threshold is larger by 35 decimal orders than energy, that was reached today at LHC $(14\,TeV)$.

Cross-section of MBH formation reaction, when threshold of reaction is reached, determines by formula (5). At threshold of reaction cross-section is equal to

$$\sigma_{th} = \sigma\left(E_{ppth}\right) = 2{,}88 \cdot 10^3\,mb.$$

Indeterminacy of MBH formation energy determines by formula (7). At threshold of reaction indeterminacy of energy is equal to

$$\Delta E_{ppth} = 2{,}34 \cdot 10^{-49}\,TeV.$$

If energy is very high, then in a multitude of fluctuations the particular fluctuation may realizes. For particular fluctuation development of parton picture until slow parton formations will be carried out, in the main, in one direction at plane of sighting parameters. In that case effective diametrical dimension of parton fluctuation is equal to

$$\left|\vec{b}\right|_{eff} \approx < m_{q_\perp} >^{-1} \cdot n = < m_{q_\perp} >^{-1} \frac{ln(p_a / < m_{q_\perp} >)}{ln2}.$$

The condition of MBH formation is

$$r \approx 2\left|\vec{b}\right|_{eff} \leq r_g$$

or for usual units

$$\frac{2\hbar}{m_N \cdot c} \frac{ln(E_{pp}/2m_N c^2)}{ln2} \leq \frac{2G\, E_{pp}}{c^4}. \qquad (9)$$

The inequality (9) solution is

$$E_{pp} \geq E_{ppth} = 2{,}11 \cdot 10^{37} \; TeV.$$

So, reaction threshold $E_{ppth}$ on superhigh energies is larger by 36 decimal orders than energy, that was reached today at LHC.

From formulas (5) and (7) we obtain reaction cross-section at threshold of reaction and MBH formation energy indeterminacy at threshold of reaction:

$$\sigma_{th} = \sigma\left(E_{ppth}\right) = 3{,}93 \cdot 10^5 \, mb;$$
$$\Delta E_{ppth} = 1{,}46 \cdot 10^{-52} \, TeV.$$

For three considered models values of threshold energy $E_{ppth}$ , cross-section at threshold $\sigma_{th}$ and MBH formation energy indeterminacy at threshold of reaction p+p→MBH+X $\Delta E_{ppth}$ are adduced at table 2.

Table 2. Values of $E_{ppth}$, $\sigma_{th}$ and $\Delta E_{ppth}$ for different models at centre of inertia system of protons, which collide.

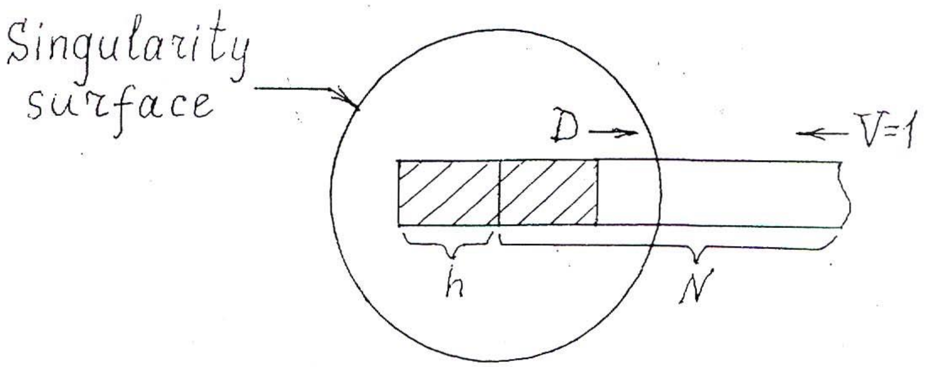
| **Model** | $\boldsymbol{E_{ppth}}$ **, TeV** | $\boldsymbol{\sigma_{th}}$**, mb** | $\boldsymbol{\Delta E_{ppth}}$ **, TeV** |
|---|---|---|---|
| 1.Evristic MBH formation model. | $8{,}32 \cdot 10^{36}$ | $6{,}09 \cdot 10^4$ | $2{,}40 \cdot 10^{-51}$ |

| | | | |
|---|---|---|---|
| 2.Simplest parton model. | $1{,}81 \cdot 10^{36}$ | $2{,}88 \cdot 10^{3}$ | $2{,}34 \cdot 10^{-49}$ |
| 3.Parton model for superhigh energies. | $2{,}11 \cdot 10^{37}$ | $3{,}93 \cdot 10^{5}$ | $1{,}46 \cdot 10^{-52}$ |

So, different fenomenological models lead to essentially different values of $E_{ppth}$, $\sigma_{th}$ and $\Delta E_{ppth}$, but all models testify, that $E_{ppth}$ is essentially larger, than energy, which was reached today at LHC. That explains the absence of MBH observations on proton collisions at LHC.

## III. MBH FORMATION ON PROTONS WITH PB NUCLEUSES COLLISIONS

We shall consider reaction p+Pb→MBH+X at the system of equal speeds (S - system). In accordance with hN – interaction hydrodynamic model the collision of hadron with nucleus leads to the tube with radius $r_o = m_\pi^{-1}$ formation. The length of this tube is equal to longitudinal dimension of nucleus. At first stage of multiple production process two disks come into contact, after that to both sides from plane of contact blow waves begin to spread through hadron liquid with speed D. When blow wave comes to hadron “border”, hadron substance between fronts of waves is resting and has mass $M \approx 2E$. Here $E$ is hadron energy at S – system. Just at that moment one have to expect for singularity surface formation around of hadron substance between fronts of waves, if such a surface had not formed still earlier.




Picture 5. Moment of hadron with nucleus interaction, when blow wave have came to hadron “border”.

If singularity surface have formed, then it means MBH formation on hadron with nucleus collision. The condition $r_o \leq r_g$ have to be executed for MBH formation; for usual units this condition is wrote as

$$\frac{\hbar}{m_\pi c} \leq \frac{4GE}{c^4};$$

$$E \geq E_{th} = \frac{\hbar c^3}{4Gm_\pi} = 2{,}67 \cdot 10^{35}\ TeV.$$

One may estimate reaction p+Pb→MBH+X cross-section in such a way:

$$\sigma = \pi \cdot r_{Pb}^2 = 1{,}70 \cdot 10^3\ mb.$$

Cross-section doesn’t depend on energy, when threshold energy is reached.

The energy indeterminacy is defined by formula (7). At reaction threshold for S-system

$$\Delta E_{th} = \frac{Gm_\pi^3 \cdot c}{640 \cdot \pi \cdot \hbar} = 9{,}07 \cdot 10^{-48}\ TeV.$$

Transition to laboratory system (L-system), where nucleus is at state of rest, is realized by formula

$$E' = \frac{2A \cdot E^2}{m_{Pb} \cdot c^2},$$

here $A$ is quantity of nucleons in nucleus (for Pb $A$=207), $m_{Pb}$ is nucleus mass ($m_{Pb} = 3{,}44 \times 10^{-25}$ kg), $E'$ is hadron energy at laboratory system. The calculations give:

$$E'_{th} = 1{,}53 \cdot 10^{74}\ TeV.$$

Of course, such an energy of protons can not be reached at elementary particles accelerators.

The estimations, which were realized in this paper, are founded on famous fenomenological models of multiple production. Possibly, calculation of quantum effects will lead to decrease of MBH formation threshold energy.

In papers [25, 30], field theories in space–time with additional dimensions were considered. If additional dimensions do exist, then there is the theoretical possibility of creating micro black holes on particle accelerators. Therefore, if the MBH is still found on particle accelerators, this will become a serious argument in favor of the space–time theories with N > 4.

## IV. MODELING THE PROCESS OF BLACK HOLE FORMATION IN COLLISIONS OF QUARKS AND ANTIQUARKS

The literature suggests that all particles with a Compton wavelength less than the gravitational radius are black holes:

$$\lambda_c \lesssim r_g; \quad \frac{hc}{2G} \lesssim M^2.$$

An example of such a micro black hole is the Planck black hole (maximon) with Planck mass

$$M_p = \sqrt{\frac{\hbar c}{G}}\ .$$

It is suggested that the Planck mass is the lower limit of the masses of black holes and the upper limit for the masses of elementary particles [32, 33]. However, the stability of the maximon and the absence of Hawking radiation contradict the predictions of the quantum theory of gravity.

In this section of the article, modeling of the process of black hole formation during collisions of quarks and antiquarks is carried out. The simulation consists in identifying a black hole with a real scalar field $H(x)$, which is introduced into the Lagrangian of chromodynamics:

$$\mathcal{L} = -\frac{1}{2}\,TrG^{\mu\upsilon}G_{\mu\upsilon} + \bar{q}\big(i\gamma^{\mu}\partial_{\mu} + g\gamma^{\mu}A_{\mu} - m\big)q + \mathcal{L}_H;$$

$$\mathcal{L}_H = \frac{1}{2}(\partial^{\mu}H)\big(\partial_{\mu}H\big) - \frac{M^2}{2}H^2 + \lambda\bar{q}qH.$$

The new vertex has a maximum index $\Omega = 0$, the dimension of the constant λ: $[\lambda] = [m]^o$. This justifies the conservation of the renormalizability of the theory.

Consider the reaction $u(p_1) + \tilde{u}(p_2) \to H(p)$. The matrix element is equal to

$$\Phi^{+}_{\vec{p}}S\Phi_{\vec{p}_1,\vec{p}_2} = \frac{i\lambda}{2p^o}\cdot\frac{1}{(2\pi)^{1/2}}\cdot\delta^{(4)}(p_1 + p_2 - p)\bar{v}^{\mu,-}(\vec{p}_2)v^{\nu,-}(\vec{p}_1).$$

The effective cross-section invariant under Lorents transformations is determined by the formula

$$\sigma\big(p^o_{1,}\,p^o_{2,}\,cos\theta\big) = \frac{2\pi\cdot\lambda^2 p^o_1 p^o_2}{8\,p^{03}}\left(\frac{(p_1p_2) - m^2}{(p_1p_2) + m^2}\right)^{1/2}\cdot\delta(p^o_1 + p^o_2 - p^o);$$

$$p^o = \left(p^o_1 + p^o_2 + 2\sqrt{p^{o^2}_1 - m^2}\cdot\sqrt{p^{o^2}_2 - m^2}\cdot cos\theta + M^2 - 2m^2\right)^{1/2}. \qquad (10)$$

In the experiment, the δ-function “broadens” due to the uncertainty of its argument $p^o_*$:

$$p^o_* = p^o_1 + p^o_2 - p^o. \qquad (11)$$

We have

$$\sigma\left(p_{1,}^{o}\,p_{2}^{o},cos\theta\right)=\frac{2\pi\cdot\lambda^{2}p_{1}^{o}p_{2}^{o}}{8\,p^{03}}\left(\frac{(p_{1}p_{2})-m^{2}}{(p_{1}p_{2})+m^{2}}\right)^{1/2}\cdot Ae^{-\alpha p_{*}^{o2}}. \qquad (12)$$

Uncertainty $p_{*}^{o}$ is given by the formula

$$\Delta p_{*}^{o}=\frac{\partial p_{*}^{o}}{\partial p_{1}^{o}}\Delta p_{1}^{o}+\frac{\partial p_{*}^{o}}{\partial p_{2}^{o}}\,\Delta p_{2}^{o}+\frac{\partial p_{*}^{o}}{\partial(cos\theta)}\,\Delta(cos\theta)+\frac{\partial p_{*}^{o}}{\partial M}\Delta M; \qquad (13)$$

$$\frac{\partial p_{*}^{o}}{\partial p_{1}^{o}}=1-\frac{p_{1}^{o}}{p^{o}}\left(1+\sqrt{\frac{p_{2}^{02}-m^{2}}{p_{1}^{02}-m^{2}}}\cdot cos\theta\right); \qquad (14)$$

$$\frac{\partial p_{*}^{o}}{\partial p_{2}^{o}}=1-\frac{p_{2}^{o}}{p^{o}}\left(1+\sqrt{\frac{p_{1}^{02}-m^{2}}{p_{2}^{02}-m^{2}}}\cdot cos\theta\right); \qquad (15)$$

$$\frac{\partial p_{*}^{o}}{\partial(cos\theta)}=-\frac{1}{p^{o}}\,(p_{1}^{02}-m^{2})^{1/2}\cdot(p_{2}^{02}-m^{2})^{1/2}; \qquad (16)$$

$$\frac{\partial p_{*}^{o}}{\partial M}=-\frac{M}{p^{o}}. \qquad (17)$$

The values of $\Delta p_{1}^{0}$, $\Delta p_{2}^{0}$ and $\Delta(\cos\theta)$ are determined by the technical characteristics of the accelerator. The uncertainty of the boson mass is

$$\Delta M\approx\frac{\hbar}{2\Delta t}=\frac{\hbar^{2}c^{4}}{10240\cdot\pi\cdot G^{2}\cdot M^{3}}, \qquad (18)$$

$\Delta t$ – time life of a black hole in its rest system. In addition, in the usual way we obtain the relations:

$$\alpha=\frac{ln2}{(\Delta p_{*}^{o})^{2}}\;;\qquad A=\frac{1}{|\Delta p_{*}^{o}|}\cdot\sqrt{\frac{ln2}{\pi}}. \qquad (19)$$

Thus, the total invariant cross-section of the reaction of the formation of a black hole in a collision of a quark and an antiquark is determined by formula (12) taking into account formulas (10), (11), (19), (13-18).

The lack of experimental data makes it impossible to estimate the constant λ. We assume that it is very small. Therefore, in collisions of quarks and marine antiquarks on the LHC, the reaction $u\tilde{u} \to H$ was not observed.

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## REFERENCES

1. Albert Einstein. (25, November, 1915). "Die Feldgleichungen der Gravitation". Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin: 844-847.
2. K. Schwarzschild. Ber das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie. Sitzungsberichte der Kniglich Preussischen Akademie der Wissenschaften 1. – 1916. – 189-196.
3. J. – P. Blaizot, J. Iliopoulos, J. Madsen, G. G. Ross, P. Sonderegger and H. – J. Specht. CERN European Organization for Nuclear Research. CERN Scientific Information Service – 1200 – February 2003.
4. John Ellis, Gian Giudice, Michelangelo Mangano, Igor Tkachev and Urs Wiedemann. LHC Safety Assessment Group. CERN – PH – TH / 2008 - 136.
5. Steven B. Giddings and Michelangelo L. Mangano. CERN – PH – TH / 2008 – 025.
6. Michael E.Peskin und Daniel V. Schroeder. An Introduction to Quantum Field Theory. Addison – Wesley, Reading 1995, ISBN – 0-201-50397-2.

7. M. Peskin, D.Abercrombie, et al. Report of the ATLAS/CMS Dark Matter Forum. arXiv: 1507.00966.
8. Michael E.Peskin. Concepts of Elementary Particle Physics. Oxford University Press, 2019.
9. Robert Geroch. General Relativity from A to B. Chicago. University of Chicago Press (1981). ISBN – 10: 9780226288642.
10. Robert Geroch, Annals of Physics. V. 62(2), p. 582-589 (1971), doi: 10.1016/0003-4916(71) 90104-7.
11. Robert P. Geroch, Gabriel Nagy, Oscar Reula, J. Math. Phys. 42(2001)3789-3808. DOI: 10.1063/1.1364502.
12. EA Baltz, M. Battaglia, ME Peskin, T.Wizansky. Physical Review D. V. 74(10), 103521.
13. ME Peskin, JD Wells. Physical Review D. 64(9), 093003.
14. Robert Geroch, Gary T. Horowitz, Annals of Physics. V. 117(1), p. 1-4 (1979), doi: 10: 1016/0003-4916(79) 90041-1.
15. D.Ya. Petrina. Quantum field theory. Kiev. "Vischa shkola", 1984.
16. A.G. Sitenko, V.K. Tartakovskiy. Lectures by nuclear theory. M. Atomizdat, 1972.
17. O.S. Parasuk, DAN SSSR. V.100, p. 643 (1955).
18. Robert Geroch. General Relativity. Minkowski, Institute Press.
19. Michael E.Peskin, T.Barklow, K.Fujii, S.Jung, R.Karl, J.List, T.Ogawa and J.Tian, Phys. Rev. D97, 053004 (2018).
20. Черная дыра. wikipedia_uk_all. Черные дыры. html. Internet.
21. Horatiu Năstase. "The RHIC fireball as a dual black hole" // arXiv: hep-th/0501068 v3.- 2005.
22. Michael E. Peskin, J.Yoon, Phys. Rev. D96, 115030 (2017).
23. Michael E. Peskin, PNAS. 112, 12256 (2015).
24. J. Cleymans, R.V. Gavai, E. Suhonen, Phys. Rep. V.130, №4, p. 217-292 (1986).

25. R.Kerner, Annales Poincare Phys. Theor. V.9, 143 (1968).

26. S.L.Glashow, Nucl. Phys. V. 22, p. 579 (1961).

27. S.L.Glashow, S.Weinberg, Phys. Rev. V. D15, p. 1958 (1977).

28. M. Thoennessen, Rep. Prog. Phys. V. 67, p. 1187 (2004).

29. M. Thoennessen, et al, Nucl. Phys. A.V. 912, p. 1-6 (2013).

30. L.Randall, R.Sundrum, Phys. Rev. Lett.V. 83, 3370 (1999).

31. Yu.A. Tisenko. Subquarks. Dniepropetrovsk. Society “Prosvita”, Publishing house of UNIAS, 1995.

32. https://ru.wikipedia.org>wiki>Планковская_масса

33. https://bigenc.ru/physics/text/2087635