P O S T E R 63

IN WHAT CONDITION CAN THE 125 GEV HIGGS BOSON DECAY TO A PAIR OF ON-SHELL W-BOSONS?

PRESENTER(S): Rasmiyya Gasimova[1,2,3], Vali A. Huseynov*[2,3,4]

[1] Shamakhy Astrophysical Observatory National Academy of Sciences of Azerbaijan,
Y. Mammadaliyev Settlement, Shamakhy District, AZ5618, Azerbaijan;
[2] Department of Theoretical Physics, Baku State University, Z. Khalilov 23, AZ 1148, Baku, Azerbaijan;
[3] Department of Physics, Qafqaz University, Baku-Sumgayit Road, 16 km., Khirdalan, Baku, AZ0101, Azerbaijan;
[4] Department of General and Theoretical Physics, Nakhchivan State University, University Campus, AZ 7012, Nakhchivan, Azerbaijan;

E-mail: gasimovar@yahoo.co.uk
E-mail: vgusseinov@yahoo.com

*In my previous journal papers my surname was written as Guseinov.

Abstract

We investigate the decay of the neutral boson at a mass around 125 GeV observed in the LHC ATLAS and CMS experiments into a pair of on-shell W-bosons in a uniform magnetic field. We have determined that the decay of the neutral boson at a mass around 125 GeV into an on-shell W^-W^+-pair in a uniform magnetic field becomes, in principle, possible and the new decay channel of this boson in a magnetic field is allowed by the energy and total angular momentum conservation laws. The required magnetic field strength for observation of the measurable effect is $\sim 10^{23} G$ (or in Teslas $\sim 10^{19} T$). The existence of the other neutral boson with the spin $J = 0$ and with the other mass is not either excluded in the mass range below $2m_W \cong 160.77 GeV$. We hope that the possibility of the decay of the neutral boson at a mass around 125 GeV into a pair of on-shell W-bosons in a uniform magnetic field will attract the experimental physicists' attention in future collider experiments.

Keywords: Higgs boson, W-boson in a magnetic field, parity, charge conjugation, neutral boson at a mass around 125 GeV

PACS numbers: 14.80.-j, 14.80.Bn, 13.88.+e, 11.30.Er

1. INTRODUCTION

Recently a new neutral boson (NB) at a mass around $125\,GeV$ [1, 2] with properties compatible with the Standard Model Higgs boson [3-8] was discovered in the LHC ATLAS and CMS experiments. This boson is described with $J^{PC} = 0^{++}$ where P is the parity, C is the charge conjugation, J is the spin. One of the decay channels of the discovered Higgs-like boson is $H \to WW^*$. One of these $W^\mp$-bosons is on-shell, the other one (W^*) is off-shell. According to the energy conservation law the decay of this NB into the on-shell W^-W^+-boson pair is impossible because of $m_H < 2m_W$, where $m_W \cong 80.385\,GeV$ [9] is the W-boson mass. Therefore, this NB decays into one on-shell W-boson and one off-shell W^*-boson. The following natural questions arise. In what condition can the $125\,GeV$ Higgs boson decay to a pair of on-shell W-bosons? How is realistic and promising the decay of the NB at a mass around $125\,GeV$ into the two on-shell W-bosons in a magnetic field (MF)? Search for the answers to these questions determines the motivation for the presented investigation. We investigate the decay of the NB at a mass around $125\,GeV$ observed at the LHC into a pair of on-shell W-bosons in a MF. The main purpose of this work is to determine the condition in what the NB at a mass around $125\,GeV$ can decay to a pair of on-shell W-bosons?

2. BASIC IDEA IN THIS WORK

The energy spectrum of a $W^\mp$-boson in an external uniform MF is discussed in a number of papers or review articles (See: e.g., [10-14]). Here we use the formula

$$E^2 = p_{\mp z}^2 + \left(2n_\mp + 1 - 2q_\mp s_{\mp z}\right)eB + m_W^2\,, \qquad (1)$$

for the energy spectrum of a $W^\mp$-boson in an external uniform MF [10, 11], where $B = \left|\vec{B}\right|$ is the strength of a MF whose intensity vector $\vec{B}$ is directed along the Oz-axis, $p_{\mp z}$ and $s_{\mp z}$ are the third component of the momentum and the third component of the spin of a $W^\mp$-boson, respectively, $n_\mp = 0,1,2,...$ enumerates the Landau energy levels of a $W^\mp$-boson, $q_+ = +1$ ($q_- = -1$) is the sign of the electric charge of a W^+ $\left(W^-\right)$-boson. The formula (1) is written in the $\hbar = c = 1$ system of units.

A $W^\mp$-boson has three polarization states: $\left|W^\mp(s_\mp = 1,\ s_{\mp z} = +1)\right\rangle = \left|1,+1\right\rangle$, $\left|W^\mp(s_\mp = 1,\ s_{\mp z} = 0)\right\rangle = \left|1,0\right\rangle$, $\left|W^\mp(s_\mp = 1,\ s_{\mp z} = -1)\right\rangle = \left|1,-1\right\rangle$, where $s_\mp$ is the spin of a $W^\mp$-

boson. Hereafter we will consider the case $n_{\mp}=0,\ p_{\mp z}=0$. Let us consider the case $q_{\mp}s_{\mp z}=+1$ in the formula (1). The case $n_{\mp}=0,\ p_{\mp z}=0$ and $q_{\mp}s_{\mp z}=+1$ corresponds to the ground Landau level of the $W^{+}\left(W^{-}\right)$-boson. When the $W^{+}\left(W^{-}\right)$-boson spin is oriented along (against) the MF direction, i.e. when $s_{+z}=+1$ ($s_{-z}=-1$), the $W^{\mp}$-boson energy satisfies the inequality

$$E=\sqrt{m_W^2-eB}\le m_W \tag{2}$$

for an arbitrary B taken from the range $0\le B\le B_{0W}$ where $B_{0W}=m_W^2/e$.

The NB at a mass around 125 GeV observed at the LHC is produced in the pp-collisions at $\sqrt{s}=7TeV$ and $\sqrt{s}=8TeV$ via the one of the following main reaction channels: the gluon-gluon fusion channel, the vector boson fusion channel, the Higgs-strahlung channel and the channel of the associated production with a $t\bar{t}$ quark-antiquark pair [15-19]. The main decay channels of the NB at a mass around 125 GeV are $Y\to\gamma\gamma$, $Y\to ZZ^{*}\to 4l$, $Y\to WW^{*}\to l\nu l\nu$, $Y\to\tau^{-}\tau^{+}$, $Y\to b\bar{b}$.

So, one of the main decay modes of the NB at a mass around 125 GeV observed at the ATLAS and CMS experiments is the $H\to WW^{*}\to l\nu l\nu$ channel [20]. As we have already noted one of these $W^{\mp}$-bosons is on-shell, the other one (W^{*}) is off-shell. According to the energy conservation law the decay of this NB into the on-shell $W^{-}W^{+}$-boson pair is impossible. Therefore, this NB decays into one on-shell W-boson and one off-shell W^{*}-boson. However, if we place this NB in a uniform MF, the MF will affect on the W^{+}- and W^{-}-bosons that are the products of the decay $Y\to W^{-}W^{+}$. If we consider the NB at a mass around 125 GeV in the rest frame and take into account the relation $E=\sqrt{m_W^2-eB}\le m_W$ for the W^{+} (W^{-})-boson with $s_{+z}=+1$ ($s_{-z}=-1$) in the energy conservation law $m_H=E_H=E_{W^-}+E_{W^+}$, we can see that in a sufficiently strong MF with the strength B_H the equality $m_H=2\sqrt{m_W^2-eB_H}$ is satisfied and the decay of the NB with the mass around 125 GeV into the two on-shell $W^{\mp}$-bosons becomes, in principle, energetically possible. So, as a result of the decay reaction $H\to W^{-}W^{+}$ in a MF we have the final diboson system H' that consists of the on-shell W^{-}- and W^{+}-bosons situating in a MF.

3. POLARIZATION STATES OF $W^{-}W^{+}$-SYSTEM

We denote an arbitrary polarization state of the system H' as $|S_{H'}, S_{H'z}\rangle$ where $S_{H'} = S_{W^-W^+}$ is the total spin of the system H' and $S_{H'z}$ is the third component of the total spin vector $\vec{S}_{H'} = \vec{S}_{W^-W^+}$. The quantum states of the system H' can have the spin equal to 0, 1, 2. Using the three possible polarization states of $W^{\mp}$-bosons, the addition rule of spins and the Clebsch-Gordan coefficients [9, 21] we obtain nine polarization states $|S_{H'}, S_{H'z}\rangle$ of the system H': $|2,+2\rangle$, $|2,+1\rangle$, $|2,0\rangle$, $|2,-1\rangle$, $|2,-2\rangle$, $|1,+1\rangle$, $|1,0\rangle$, $|1,-1\rangle$, $|0,0\rangle$. The total angular momentum vector $\vec{J}$ of the W^-W^+-system is determined with the total spin vector $\vec{S}_{W^-W^+}$ of the W^-W^+-system and the orbital angular momentum vector $\vec{L}_{W^-W^+}$ of the relative motion performed by the W^-- and W^+-bosons on the plane perpendicular to the MF intensity vector which is oriented along the Oz-axis. It should be noted that in case of the longitudinal polarization of the spin of the $W^{\mp}$-boson we have $s_{\mp z} = 0$ and from the formula (1) we derive $E = \sqrt{m_W^2 + eB} \geq m_W$ for an arbitrary B taken from the range $0 \leq B < B_{0W}$. In this case we obtain the relation $m = 2\sqrt{m_W^2 + eB} \geq 2m_W$ for the mass of the decaying NB. The last relation contradicts to the condition $m_H \cong 125\,GeV \leq 2m_W$. So, in the mass range $0 < m \leq 2m_W$ there is no sense to investigate the case of the longitudinal polarization of the spin of the on-shell W^- (W^+)-boson in a MF. In case of the transverse polarization the spin vector $\vec{S}_{W^-W^+}$ in a MF is strictly oriented along or against the MF (Oz-axis) direction. So, in case of the transverse polarization the relations $|\vec{J}| = J = const$ and $|J_z| = const$ can be written for the total angular momentum J and its projection J_z. Therefore here we investigate the case of the transverse polarization of the spins of the on-shell $W^{\mp}$-bosons in a MF. In this case the polarization states $|W^{\pm}(s_{\pm} = 1,\ s_{\pm z} = +1)\rangle = |1,+1\rangle$ and $|W^{\pm}(s_{\pm} = 1,\ s_{\pm z} = -1)\rangle = |1,-1\rangle$ only contributes to the transverse polarization of the system H' that has five different polarization states:

$$|2,+2\rangle = |1,+1;1,+1\rangle,\ |2,0\rangle = (1/\sqrt{6})(|1,+1;1,-1\rangle + |1,-1;1,+1\rangle),\ |2,-2\rangle = |1,-1;1,-1\rangle,$$

$$|1,0\rangle = (1/\sqrt{2})(|1,+1;1,-1\rangle - |1,-1;1,+1\rangle), |0,0\rangle = \frac{1}{\sqrt{3}}(|1,+1;1,-1\rangle + |1,-1;1,+1\rangle).$$

The states $|2,0\rangle$, $|1,0\rangle$ and $|0,0\rangle$ are formed from $W^-(s_- = 1, s_{-z} = +1)$ and

$W^+(s_+ = 1, s_{+z} = -1)$ or from $W^-(s_- = 1, s_{-z} = -1)$ and $W^+(s_+ = 1, s_{+z} = +1)$ as a result of the transition reactions $H \to H'(S_{H'} = 2,\ S_{H'z} = 0)$, $H \to H'(S_{H'} = 1,\ S_{H'z} = 0)$, $H \to H'(S_{H'} = 0,\ S_{H'z} = 0)$, respectively. According to the energy conservation law the energy of the final W^+W^--system $E_{W^-W^+}$ is to be in the range $0 \le E_{W^-W^+} \le 2m_W$ and $E_{W^-W^+}$ can not be more than $2m_W$. The polarization states $\left|W^+(s_+ = 1,\ s_{+z} = +1)\right\rangle = \left|1, +1\right\rangle$ and $\left|W^-(s_- = 1,\ s_{-z} = -1)\right\rangle = \left|1, -1\right\rangle$ only satisfy the condition $0 \le E_{W^-W^+} \le 2m_W$. Therefore we assume that the $W^\mp$-bosons are produced on the ground Landau level and we consider the contributions from the polarization states $\left|W^+(s_+ = 1,\ s_{+z} = +1)\right\rangle = \left|1, +1\right\rangle$ and $\left|W^-(s_- = 1,\ s_{-z} = -1)\right\rangle = \left|1, -1\right\rangle$.

The energy conservation law is as $m = m_H = 2\sqrt{m_W^2 - eB_H}$ for the transition reactions $H \to H'(S_{H'} = 2,\ S_{H'z} = 0)$, $H \to H'(S_{H'} = 1,\ S_{H'z} = 0)$, $H \to H'(S_{H'} = 0,\ S_{H'z} = 0)$ when $W^-(s_- = 1, s_{-z} = -1)$ and $W^+(s_+ = 1, s_{+z} = +1)$ are produced on the ground Landau level. Since we consider a NB in the rest frame, the mass of the decaying NB can not be zero: $m \ne 0$. Taking into account the condition $m \ne 0$ we obtain from the formula $m = m_H = 2\sqrt{m_W^2 - eB_H}$ that $B_H \ne B_{0W}$ and $B_H < B_{0W}$. So, the mass of the NB at a mass around 125 GeV satisfies the condition $0 < m_H \le 2m_W$ ($0 < m_H \le 160.77\ GeV$) for an arbitrary B taken from the range $0 \le B_H < B_{0W}$.

4. QUANTUM CHARACTERISTICS OF W^-W^+-PAIR AND SPIN OF 125 GeV BOSON

Introducing the intrinsic parity $P_{W^-}\left(P_{W^+}\right)$ for the $W^-\left(W^+\right)$-boson, the orbital quantum number $L_{W^-W^+}$ and the total spin $S_{W^-W^+}$ for the W^-W^+-system we can determine the charge conjugation $C_{W^-W^+}$, the parity $P_{W^-W^+}$ and the total angular momentum J for the W^-W^+-system by the following formulas, respectively:

$$C_{W^-W^+} = (-1)^{L_{W^-W^+} + S_{W^-W^+}}, \tag{3}$$

$$P_{W^-W^+} = (-1)^{L_{W^-W^+}} P_{W^-} P_{W^+} = (-1)^{L_{W^-W^+}}, \tag{4}$$

$$J = L_{W^-W^+} + S_{W^-W^+},\ L_{W^-W^+} + S_{W^-W^+} - 1, \ldots, \left|L_{W^-W^+} - S_{W^-W^+}\right|. \tag{5}$$

We take into account that the NB at a mass around 125 GeV also decays into the two photons. Therefore its spin J can not be 1 according to the Landau-Yang theorem [22, 23] and the charge conjugation C of this NB is $C = C_H = 1$. The decay $H \to W^- W^+$ is a weak process and C is not conserved in this process. It means that if the charge conjugation of the initial neutral H-boson is $C_H = 1$ before the reaction $H \to W^- W^+$, the charge conjugation $C_{W^-W^+}$ might be $+1$ or -1 after the reaction, or it might also go to a state that is not a $C_{W^-W^+}$ eigenstate. Here we assume that $C_{W^-W^+}$ is either $+1$ or -1 after the reaction. We also assume that $P_{W^-W^+}$ is either $+1$ or -1 after the reaction. The following combinations of $C_{W^-W^+}$ and $P_{W^-W^+}$ for the $W^- W^+$-system are possible:

case A: $$C_{W^-W^+} = +1, \quad P_{W^-W^+} = +1, \tag{6}$$

case B: $$C_{W^-W^+} = +1, \quad P_{W^-W^+} = -1, \tag{7}$$

case C: $$C_{W^-W^+} = -1, \quad P_{W^-W^+} = +1, \tag{8}$$

case D: $$C_{W^-W^+} = -1, \quad P_{W^-W^+} = -1. \tag{9}$$

Case A: If $S_{W^-W^+} = 1$, the condition (6) of the case A is not satisfied. When $S_{W^-W^+} = 0$ and $S_{W^-W^+} = 2$, the minimal value for $L_{W^-W^+}$ is $L_{W^-W^+} = 0$. In this case we obtain $J = 0$ and $J = 2$ for the spin of the NB. So, if $C_{W^-W^+} = +1, \quad P_{W^-W^+} = +1$, the NB with the spins $J = 0$ can exist in the mass range $0 < m_H \le 2m_W$. The particle with the spin $J = 0$ in the mass range $0 < m_H \le 2m_W$ corresponds to the Higgs boson at a mass around 126 GeV discovered in 2012 at the LHC [1, 2].

Case B: If $S_{W^-W^+} = 0$ and $S_{W^-W^+} = 2$, the condition (7) of the case B is not satisfied. When $S_{W^-W^+} = 1$, the minimal value for $L_{W^-W^+}$ is $L_{W^-W^+} = 1$. In this case we obtain $J = 0$ and $J = 2$ for the spin of the decaying NB. It means that if $C_{W^-W^+} = +1, \quad P_{W^-W^+} = -1$, the NB with the spins $J = 0$ can exist in the mass range $0 < m_H \le 2m_W$.

Case C: If $S_{W^-W^+} = 0$ and $S_{W^-W^+} = 2$, the condition (8) of the case C is not satisfied. When $S_{W^-W^+} = 1$, the minimal value for $L_{W^-W^+}$ is $L_{W^-W^+} = 2$ (here $L_{W^-W^+} = 0$ is not allowed according to the Landau-Yang theorem). In this case we obtain $J = 2$ and $J = 3$ for the spin of the decaying NB. It means that if $C_{W^-W^+} = -1, \quad P_{W^-W^+} = +1$, the NB with the spin $J = 0$ can not exist in the mass range $0 < m_H \le 2m_W$.

Case D: If $S_{W^-W^+} = 1$, the condition (9) of the case D is not satisfied. When $S_{W^-W^+} = 0$, the corresponding minimal value for $L_{W^-W^+}$ is $L_{W^-W^+} = 3$ (here $L_{W^-W^+} = 1$ is not allowed according to the Landau-Yang theorem) and we obtain $J = 3$ for the spin of the decaying NB. When $S_{W^-W^+} = 2$, the minimal value for $L_{W^-W^+}$ is $L_{W^-W^+} = 1$. In this case we obtain $J = 2$ and $J = 3$ for the spins of the decaying NB. So, if $C_{W^-W^+} = -1$, $P_{W^-W^+} = -1$, the NB with the spin $J = 0$ can not exist in the mass range $0 < m_H \leq 2m_W$.

5. DISCUSSION OF THE RESULTS

We have obtained that only in the cases A and B the NB at a mass around $125\ GeV$ with the spin $J = 0$ can exist in the mass range $0 \leq m_H \leq 2m_W$ and it can decay into the on-shell $W^-(s_- = 1, s_{-z} = -1)$- and $W^+(s_+ = 1, s_{+z} = +1)$-bosons in a MF:

case A: if $C_{W^-W^+} = +1$ and $P_{W^-W^+} = +1$, $J = 0,2$ $(S_{W^-W^+} = 0,2;\ L_{W^-W^+} = 0)$, (10)

case B: if $C_{W^-W^+} = +1$ and $P_{W^-W^+} = -1$, $J = 0,2$ $(S_{W^-W^+} = 1;\ L_{W^-W^+} = 1)$, (11)

We have obtained $J = 0, 2$ for the spin of the NB at a mass around $125\ GeV$ if $C_{W^-W^+} = +1$. One NB with the spin $J = 0$ has already been observed in the mass range $0 < m_H \leq 2m_W$ by the ATLAS and CMS Collaborations [1, 2]. However, the existence of the other NB with the spin $J = 0$ and with the other mass is not excluded in the mass range $0 < m_H \leq 2m_W$. The analysis of the above considered cases A, B, C and D show that the existence of the NB at a mass around $125\ GeV$ with the spin $J = 0$ is allowed in the cases A and B. When W^-W^+-pair are produced on the ground Landau level, the orbital quantum number $L_{W^-W^+}$ should be minimal. $L_{W^-W^+}$ is minimal only in the case A. So, the case A is more suitable for the particle with the spin $J = 0$. The existence of the particle with the spin $J \geq 2$ would indicate that the world we live has additional dimensions besides known four ones [24, 25].

The MF strength required for the decay of the NB at a mass around $125\ GeV$ into the on-shell $W^-(s_- = 1, s_{-z} = -1)$- and $W^+(s_+ = 1, s_{+z} = +1)$-bosons is calculated by the formula

$$B_H = B_{0W}\left[1 - \left(\frac{m_H}{2m_W}\right)^2\right]. \tag{12}$$

Let us perform the simple numerical estimations for the strength of the MF required for the decay of the NB at a mass around 125 GeV into the on-shell $W^{-}(s_{-}=1, s_{-z}=-1)$ - and $W^{+}(s_{+}=1, s_{+z}=+1)$ -bosons in a MF. When $m \cong 125 GeV$, the required MF strength is $\sim 10^{23} G$ (or in Teslas it is $\sim 10^{19} T$). The strongest (pulsed) MF ever obtained in a laboratory is $28 MG$ (or $2.8 \times 10^{3} T$) [26] that is much less than $\sim 10^{22} G$ (or $\sim 10^{18} T$). The maximum strength of the produced strong MF in noncentral heavy-ion collisions in the direction perpendicular to the reaction plane is estimated to be $\sim 10^{17}\, G(\sim 10^{13}\, T)$ at the RHIC and $\sim 10^{18}\, G(\sim 10^{14}\, T)$ at the LHC [27-33]. In lead-lead collisions at the LHC, the strength of the generated MF may reach $\sim 10^{20} G(\sim 10^{16}\, T)$ [28, 29]. We hope that in the future collider experiments, when the strength of the produced strong MF reaches the magnitude $\sim 10^{22 \div 23} G$, the decay of the the NB at a mass around 125 GeV into the on shell W^{-} -and W^{+} -bosons can be observed experimentally.

6. CONCLUSIONS

We have investigated the decay of the NB at a mass around 125 GeV with properties compatible with the Standard Model Higgs boson that was discovered in the LHC ATLAS and CMS experiments into a pair of on-shell W -bosons in a uniform MF. We have determined that the decay of the NB at a mass around 125 GeV into an on-shell $W^{-}W^{+}$ -pair in a uniform MF becomes, in principle, possible and the new decay channel of this boson in a MF is allowed by the energy and total angular momentum conservation laws. The required MF strength for observation of the measurable effect is $\sim 10^{23} G$ (or in Teslas $\sim 10^{19} T$). The existence of the other NB with the spin $J=0$ and with the other mass is not either excluded in the mass range below $2m_{W} \cong 160.77 GeV$. We hope that the possibility of the decay of the NB at a mass around 125 GeV into a pair of on-shell W -bosons in a uniform MF will attract the experimental physicists' attention in future collider experiments.

7. ACKNOWLEDGMENTS

R. G. and V. H. are very grateful to the Organizing Committee of the LHCP2014 Conference for the kind invitation to attend this conference.

REFERENCES

1. G. Aad *et al.* (ATLAS Collaboration), Phys. Lett. B **716**, 1 (2012).
2. S. Chatrchyan *et al.* (CMS Collaboration), Phys. Lett. B **716**, 30 (2012).
3. F. Englert and R. Brout, Phys. Rev. Lett. **13,** 321 (1964).
4. P. W. Higgs, Phys. Lett. **12**, 132 (1964).

5 P. W. Higgs, Phys. Rev. Lett. **13**, 508 (1964).

6. G. S. Guralnik, C. R. Hagen and T. W. B. Kibble, Phys. Rev. Lett. **13**, 585 (1964).
7. P. W. Higgs, Phys. Rev. **145**, 1156 (1966).
8. T. W. B. Kibble, Phys. Rev. **155**, 1554 (1967).
9. J. Beringer *et al.*, Particle Data Group, PR D **86**, 010001 (2012).
10. T. Goldman, W. Tsai, and A. Yildiz, Phys. Rev. D **8**, 1926 (1972).
11. A. Salam, J. Strathdee, Nucl. Phys. B **90**, 203 (1975).
12. V. V. Skalozub, Yad. Fiz. **37**, 474 (1983).
13. V. V. Skalozub, Yad. Fiz. 4**3**, 1045 (1986) [Sov. J. Nucl. Phys, **43**, 665 (1986)].
14. D. Grasso, H. R. Rubinstein, Phys. Rept. **348**, 163 (2001).
15. A. Djouadi, Phys. Rept. **457**, 1 (2008), arXiv: 0503172 [hep-ph], 2005.
16. A. Djouadi, Pramana **79**, 513 (2012), arXiv:1203.4199 [hep-ph], 2012.
17. Science, **338**, 1558 (2012).
18. S. Dittmaier et al.,(LHC Higgs Cross Section Working Group), arXiv:1101.0593[hep-ph], 2011.
19. V. Rubakov, Uspekhi fizicheskikh nauk, **182 (10)**, 1017 (2012).
20. ATLAS Collaboration. ATLAS-CONF-2012-098; ATLAS-COM-CONF-2012-138.
21. G. Källén, *Elementary Particle Physics* (Addison-Wesley, Reading, MA, 1964).
22. L. D. Landau, Dokl. Akad. Nauk USSR **60**, 207 (1948).
23. C. N. Yang, Phys. Rev. **77**, 242 (1950).
24. N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **429**, 263 (1998).
25. N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, Phys. Rev. D **59**, 086004(1999).
26. B. A. Boyko et al., in 12th IEEE Intern. Pulsed Power Conf., Monterey, Calif., USA, 1999, Digest of Technical Papers (Eds C. Stallings, H. Kirbie) (New York: IEEE, 1999).
27. V. Skokov, A. Y. Illarionov, V. Toneev, Int. J. Mod. Phys. A **24**, 5925 (2009).
28. W. -T. Deng and X. -G. Huang, Phys. Rev. C **85**, 044907 (2012).
29. A. Bzdak and V. Skokov, Phys. Lett. B **710**, 171 (2012).
30. D. E. Kharzeev, L. D. McLerran and H. J. Warringa, Nucl. Phys. A **803**, 227 (2008).
31. M. N. Chernodub, Phys. Rev. D **82**, 085011 (2010).
32. M. N. Chernodub, Phys. Rev. Lett. **106**, 142003 (2011).
33. M. N. Chernodub, Lect. Notes Phys. **871**, 143 (2013).