CDF Wjj anomaly as a non-perturbative effect of the electro-weak interaction

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The recently reported CDF excess at 120 – 160 GeV in invariant mass distribution of jet pairs accompanying W-boson \(^1\) is tentatively interpreted as a bound state of two W decaying to quark-anti-quark pair. Non-perturbative effects of EW interaction obtained by application of Bogoliubov compensation approach lead to such bound state due to existence of anomalous three-boson gauge-invariant effective interaction. The application of this scheme gives satisfactory agreement with existing data without any adjusting parameter but the bound state mass 145 GeV.

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In works \(^2\)–\(^8\), N.N. Bogoliubov compensation principle \(^9\), \(^10\) was applied to studies of a spontaneous generation of effective non-local interactions in renormalizable gauge theories.

In particular, papers \(^7\), \(^8\) deal with an application of the approach to the electro-weak interaction and a possibility of spontaneous generation of effective anomalous three-boson interaction of the form

\[
\frac{G}{3!} \epsilon_{abc} W^a_{\mu
u} W^b_{\nu\rho} W^c_{\rho\mu},
\]

(1)

with uniquely defined form-factor \(F(p_i)\). It was done of course in the framework of an approximate scheme, which accuracy was estimated to be \(\simeq (10 - 15)\%\) \(^2\). Effective interaction \(^1\) is usually called anomalous three-boson interaction and it is considered for long time on phenomenological grounds \(^1\), \(^11\), \(^12\). Note, that the first attempt to obtain the anomalous three-boson interaction in the framework of Bogoliubov approach was done in work \(^13\). Our interaction constant \(G\) is connected with conventional definitions in the following way

\[
G = - \frac{g \lambda}{M_W};
\]

(2)

where \(g \simeq 0.65\) is the electro-weak coupling. The current limitations for parameter \(\lambda\) read \(^14\)

\[
\lambda = -0.016^{+0.021}_{-0.023};
-0.059 < \lambda < 0.026 (95\% C.L.).
\]

(3)

Interaction \(^1\) increases with increasing momenta \(p\) and corresponds to effective dimensionless coupling being of the following order of magnitude

\[
g_{eff} = \frac{g \lambda p^2}{M_W}.
\]

(4)

Thus for sufficiently large momentum interaction \(^1\) becomes strong and may lead to physical consequences analogous to that of the usual strong interaction (QCD). In particular bound states and resonances constituting of W-s (W-hadrons) may appear. Let us estimate the typical scale for the effect. We know that in QCD upper bound of a region of really strong interaction (non-perturbative region) is around 600 MeV where \(\alpha_s \simeq 0.5\) that is coupling \(g_s = \sqrt{4\pi\alpha_s} = 2.5\). So we have to equate \(g_{eff} \) to this value and define the typical value \(p_{typ}\) that gives

\[
p_{typ} = M_W \sqrt{\frac{g_{eff}}{g \lambda}} \simeq 650 \text{ GeV};
\]

(5)

where we have taken for modulus of \(\lambda\) its maximal value from limitation \(^3\). Now we have the lightest hadron – the pion with mass \(\simeq 140 \text{ MeV}\) in QCD and for estimated \(p_{typ}\) \(^4\) we have possible mass of the lightest W-hadron

\[
M_{min} = \frac{p_{typ} M_W}{600 \text{ MeV}} \simeq 150 \text{ GeV};
\]

(6)

The excess detected in work \(^1\) is situated just in this region. So one might try to consider interpretation of effect \(^1\) as a manifestation of a W-hadron.

In the present work we apply these considerations along with some results of work \(^8\) to data indicating on an excess in jet pair production accompanied by W at TEVATRON \(^1\) in region of \(jj\) invariant mass 120 – 160 GeV. Some indications for state with the same mass at LHC are discussed in work \(^15\).

Let us assume that this excess is due to existence of bound state \(X\) of two \(W\). This state \(X\) is assumed to have spin 1 and weak isotopic spin also 1. Then vertex of \(XWW\) interaction has the following form

\[
\frac{G_X}{2} \epsilon_{abc} W^a_{\mu
u} W^b_{\nu\rho} X^c_{\rho\mu} \Psi;
\]

(7)

where \(\Psi\) is a Bethe-Salpeter wave function of the bound state. The main interactions forming the bound state are just non-perturbative interactions \(^1\), \(^7\). This means that we take into account exchange of vector boson \(W\) as
well as of vector bound state $X$ itself. In diagram form the corresponding Bethe-Salpeter equation is presented in Fig. 1. For small mass $M_X$ of state $X$ we expand the kernel of the equation in powers of $M_W^2$ and $M_X^2$ and obtain the following equation

$$
\Psi(x) = \frac{G^2 + G_X^2}{32\pi^2} \int_0^{Y_0} \Psi(y) y dy - \frac{G^2 + G_X^2}{32\pi^2} \left( \frac{1}{12x^2} \int_0^x \Psi(y)y^3 dy - \frac{1}{6x} \int_0^x \Psi(y)y^2 dy - \frac{x}{6} \int_0^x \Psi(y)dy + \frac{x^2}{12} \int_x^0 \Psi(y) \frac{y}{y^2} dy \right) + \frac{g G}{4\pi^2} \left( \int_0^x \Psi(y)dy - \frac{3}{8\pi^2} \int_0^x \Psi(y)y^2 dy + \frac{7}{8\pi^2} \int_0^x \Psi(y)y^3 dy - \frac{1}{2x} \int_0^x \Psi(y)dy + \frac{x}{8} \int_x^{Y_0} \Psi(y) \frac{y}{y^2} dy - \frac{x^2}{12} \int_x^0 \Psi(y) \frac{y}{y^2} dy \right) - \frac{\mu G\sqrt{2}}{\pi} \left( \int_0^Y \Psi(y)dy - \frac{1}{12x^2} \int_0^x \Psi(y)y^2 dy + \frac{1}{6x} \int_0^x \Psi(y)dy + \frac{1}{64x} \int_0^x \Psi(y)dy + \frac{x}{64} \int_x^{Y_0} \Psi(y) \frac{y}{y^2} dy - \frac{x^3}{192} \int_x^0 \Psi(y) y^3 dy \right). \quad (8)
$$

Here $x = p^2$ is the external momentum squared and $y$ is the integration momentum squared. Gauge electro-weak coupling $g$ enters due to diagrams of the second line of Fig. 1. Upper limit $Y_0$ is introduced for the sake of generality due the experience of works [2–8], according to which $Y_0$ may be either $\infty$ or some finite quantity. That is $Y_0$ is defined in a process of solving an equation. From the physical point of view an effective cut-off $Y_0$ bounds a "low-momentum" region where our non-perturbative effects act and we consider the equation at interval $[0, Y_0]$ under condition

$$
\Psi(Y) = 0. \quad (9)
$$

For interaction (1) $Y_0$ is defined in work [8].

We shall solve equation (8) by iterations. Let us perform the following substitution

$$
Z = \frac{(G^2 + G_X^2)x^2}{512\pi^2}, \quad T = \frac{(G^2 + G_X^2)y^2}{512\pi^2}; \quad \pi = \frac{GM_X}{16\pi^2}; \quad \chi = \frac{G M_W}{16\pi^2}; \quad G = \sqrt{G^2 + G_X^2}.
$$

then equation (8) takes the following form

$$
\Pi(x) = \Pi_0(z) = 8 \int_0^{z_0} \Pi_0(t)dt - \frac{2}{3z} \int_0^z \Pi_0(t)\sqrt{t} dt + \frac{4}{3\sqrt{2}} \int_0^z \Pi_0(t) dt + \frac{4\sqrt{2}}{3} \int_0^{z_0} \Pi_0(t) \frac{1}{\sqrt{t}} dt - \frac{2z}{3} \int_z^{z_0} \Pi_0(y) \frac{y}{y^2} dy + \frac{g'\sqrt{2}}{4\pi} \left( 8 \int_0^{z_0} \Pi_0(t) \frac{1}{\sqrt{t}} dt - \frac{3}{z\sqrt{2}} \int_0^z \Pi_0(t) dt + \frac{7}{z} \int_0^z \Pi_0(t) \sqrt{t} dt - \frac{4}{\sqrt{2}} \int_0^z \Pi_0(t)dt + \sqrt{2} \int_z^{z_0} \Pi_0(t) \frac{1}{t} dt - z \int_z^{z_0} \Pi_0(t) \frac{1}{t\sqrt{t}} dt \right) - \mu \left( 16 \int_0^{z_0} \Pi_0(t) \frac{1}{\sqrt{t}} dt - \frac{4}{3z} \int_0^z \Pi_0(t) dt + \frac{8}{3\sqrt{2}} \int_0^{z_0} \Pi_0(t) \sqrt{t} dt - \frac{4}{\sqrt{2}} \int_0^z \Pi_0(t)dt + \frac{8\sqrt{2}}{3} \int_z^{z_0} \Pi_0(t) \frac{1}{t} dt - \frac{4z}{3} \int_z^{z_0} \Pi_0(t) \frac{1}{t\sqrt{t}} dt \right) - \chi \left( \frac{2}{3} \int_0^{z_0} \Pi_0(t) \frac{1}{\sqrt{t}} dt - \frac{1}{12\sqrt{2}} \int_0^z \Pi_0(t) dt + \frac{1}{4\sqrt{2}} \int_0^z \Pi_0(t)dt + \frac{\sqrt{2}}{4} \int_z^{z_0} \Pi_0(t) \frac{1}{t} dt - \frac{z\sqrt{2}}{12} \int_z^{z_0} \Pi_0(t) \frac{1}{t^2} dt \right); \quad \Pi_0(0) = 1; \quad R = \frac{G_X}{G^2}; \quad z_0' = \frac{(G^2 + G_X^2)Y_0^2}{512\pi^2} = (1 + R) z_0; \quad g' = \frac{g}{\sqrt{1+R}}.
$$

Here we shall use results of work [8] according to which consideration of the compensation equation for effective

$$
\Psi(Y) = 0.
$$
interaction \[1\] we obtain definite value for \(z_0 = 9.6175\) and value for \(g(M_W)\) being consistent with experimental value \(g(M_W) = 0.65\). Thus, we use these values in the forthcoming calculations.

\[ z_0 = 9.6175; \quad g = g(M_W) = 0.65. \quad (13) \]

Let us formulate the first approximation to equation \[11\]. The first five terms of rhs of \[11\] will present the simplest zero approximation. Then we substitute into terms being proportional to \(g', \mu', \chi'\) a solution of the zero approximation and take into account constant terms and terms being proportional to \(\sqrt{z}, \sqrt{z} \ln z\). Terms being \(O(z \ln z)\) and smaller (for small \(z\)) are neglected. Just this approximation was used in works \[2, 3\].

The zero approximation evidently reads

\[ \Psi_{00}(z) = \frac{\pi}{2} G_{15}^{21}(z')_{0,0,1/2,-1/2,-1}. \quad (14) \]

Here the solution is expressed in terms of a Meijer function \[10\]. Then set of equations \[11\] takes the form

\[ \Psi_0(z) = \text{INH} - \frac{2}{3z} \int_0^z \Psi_0(t) dt + \frac{4}{3} \int_0^z \Psi_0(t) \sqrt{t} \, dt + \frac{4 \sqrt{z}}{3} \int_z^{z_0} \Psi_0(t) \sqrt{t} \, dt - \frac{2z}{3} \int_z^{z_0} \Psi_0(y) \frac{dy}{y}; \]

\[ \text{INH} = 1 - \sqrt{z} \left( \frac{g' \sqrt{2}}{8 \pi} + \frac{8 \mu}{3} - \frac{\chi}{4} \right) (\ln z + 4 \gamma + 4 \ln 2 + \frac{\pi}{2} G_{15}^{21}(z'_{00})_{0,0,1/2,-1/2,-1}) + \]

\[ \sqrt{z} \left( \frac{g' \sqrt{2}}{48 \pi} + \frac{68 \mu}{9} - \frac{25 \chi}{32} \right); \]

\[ 1 = 8 \int_0^{z_0} \Psi_0(t) dt - \left( \frac{g' \sqrt{2}}{\pi} - 16 \mu + \frac{2 \chi}{3} \right) \int_0^{z_0} \frac{\Psi_0(t)}{\sqrt{t}} \, dt \]

where \(\gamma\) is the Euler constant. Now we look for solutions of set \[15\] bearing in mind conditions \[12\] and values \[13\]. We have relation

\[ M_X = M_W \sqrt{\frac{\chi}{\mu}}; \quad M_W = 80.4 \text{ GeV}. \quad (16) \]

We look for the exact solution of set of equations \[15\] in the following form

\[ \Psi_0(z) = \frac{\pi}{2} G_{15}^{21}(z')_{0,0,1/2,-1/2,-1} + \]

\[ C_1 G_{15}^{21}(z')_{1/2,1/2,-1/2,-1} + \]

\[ C_2 G_{15}^{00}(z')_{1/2,1/2,-1/2,-1} + \]

\[ C_3 G_{15}^{00}(-z')_{1/2,1/2,-1/2,-1}. \quad (17) \]

Let us choose a solution with "experimental" \(M_X = 145 \text{ GeV} \[11\], then we have solution with the following parameters

\[ C_1 = -0.015282; \quad C_2 = -3.26512; \]

\[ C_3 = 1.27962 \times 10^{-11}; \quad g' = 0.03932; \quad (18) \]

\[ \chi = 0.0074995; \quad z_0' = 2627.975; \]

\[ \mu = 0.002305. \]

Parameters \[18\] defines the following physical parameters

\[ G = \frac{0.0099}{M_W^2}; \quad \lambda = -\frac{G M_W^2}{g} = -0.0152; \]

\[ M_X = 145 \text{ GeV}; \quad |G_X| = \frac{0.1639}{M_W^2}. \quad (19) \]

Value \(\lambda \[19\] agrees with restrictions \[3\]. With value of \(G \) from \[19\] we have additional solutions for "radial excitations" \(X_i\) with the following masses and coupling constants

\[ M_{X_1} = 180.7 \text{ GeV}; \quad |G_{X_1}| = \frac{0.0628}{M_W^2}; \]

\[ M_{X_2} = 205.1 \text{ GeV}; \quad |G_{X_2}| = \frac{0.1155}{M_W^2}. \quad (20) \]

\[ M_{X_3} = 244.2 \text{ GeV}; \quad |G_{X_3}| = \frac{0.1837}{M_W^2}. \]

With these masses \(X_{1,2,3}\) decay into pair of W-s, i.e.

\[ X_{1,2,3}^+ \rightarrow W^+ + (Z, \gamma); \quad X_{1,2,3}^0 \rightarrow W^+ + W^-; \]

\[ \Gamma(X_1^0) = 0.0086 \text{ GeV}; \quad \Gamma(X_2^+ + X_2^-) = 0.0051 \text{ GeV}; \]

\[ \Gamma(X_3^0) = 0.126 \text{ GeV}; \quad \Gamma(X_3^+ + X_3^-) = 0.083 \text{ GeV}; \]

\[ \Gamma(X_3^0) = 1.26 \text{ GeV}; \quad \Gamma(X_3^0) = 0.89 \text{ GeV}; \quad (21) \]

\[ BR(X_1^+ \rightarrow W^+ Z) = 0.44; \quad BR(X_1^+ \rightarrow W^-) = 0.56. \]

\[ BR(X_2^+ \rightarrow W^+ Z) = 0.80; \quad BR(X_2^+ \rightarrow W^-) = 0.20. \]

\[ BR(X_3^+ \rightarrow W^+ Z) = 0.91; \quad BR(X_3^+ \rightarrow W^-) = 0.09. \]

Now interaction \[7\] with parameters \[19\] defines reactions of \(X^\pm, \; X^0\) production at TEVATRON and their decays. Bound states \(X\) interact with fermion doublets \(\psi_L\) due to diagram presented at Fig. 2. The effective interaction is described by the following expression

\[ L_{X^\psi} = g_X X^\psi \bar{\psi}_L \tau^a \gamma^\nu \psi_L; \quad (22) \]

\[ g_X = \frac{g^2 G_X M_X^2}{64 \pi^2} \int_0^{z_0} \Psi_0(t) \frac{dt}{t} = 0.000879. \]
Due to interactions (7,22) there are the following decays of bound states $X$ (in calculations of decay parameters and cross-sections we use CompHEP package [17])

\[ X^\pm \rightarrow W^\pm + \gamma \ (85.9\%); \quad X^\pm \rightarrow j\bar{j} \ (9.5\%); \]
\[ X^0 \rightarrow j\bar{j} \ (71.4\%); \]
(23)

where we associate a jet with each quark. The states are narrow, but small total widths do not contradict to data [1] because the observed width of the enhancement corresponds to experimental resolution. One has also to bear in mind that real masses of neutral and charged $X$ may differ by few GeV.

For estimation of $X$ production cross-sections we have to take into account that according to EW gauge invariance isotopic triplet $X^0$ necessarily interacts with gauge field $W^\pm$ and the interaction vertex is just the gauge one with the same coupling $g$

\[ \Gamma_{abc}(p, q, k) = g \phi_{ab}(p, q, k) \kappa (g_{\mu\nu}k_\mu - g_{\mu\nu}k_\nu) + \Phi(k(p, q, k) (g_{\mu\nu}(q_\mu - p_\mu) - g_{\mu\nu}q_\mu + g_{\mu\nu}p_\mu)); \]
(24)

where $\phi_{ab}(p)$ are form-factors, which are equal to unity for $W$ momentum $k = 0$ and other two momenta $p, q$ on the mass shell, $\kappa$ is the well-known parameter describing quadrupole interaction of a vector particle. In the present approximation $\kappa = 0$. Effective total energy for partons collisions at TEVATRON is around 300 GeV which is essentially smaller than typical value $\sqrt{s}$. Thus, for estimates of cross-sections at TEVATRON we take $\phi_1 = 1$ and $\Psi \simeq \Psi(0) = 1$.

So taking into account all relevant interactions (7,22,24) we obtain the following estimates for cross-sections for energy $\sqrt{s} = 1960$ GeV

\[ \sigma(pp \rightarrow W^\pm X^0 + \ldots) = 1.86 \text{ pb}; \]
\[ \sigma(pp \rightarrow W^\mp X^\pm + \ldots) = 1.71 \text{ pb}; \]
\[ \sigma(pp \rightarrow Z X^\pm + \ldots) = 1.37 \text{ pb}; \]
\[ \sigma(pp \rightarrow X^0 X^\pm + \ldots) = 0.35 \text{ pb}; \]
\[ \sigma(pp \rightarrow X^\mp X^\pm + \ldots) = 0.26 \text{ pb}. \]
(25)

The cross-sections for production of $X^\pm$ and $X^0$ at LHC are estimated to be

\[ \sigma(pp \rightarrow W^\mp X^0 + \ldots) \simeq 7.9 \text{ pb}; \]
\[ \sigma(pp \rightarrow W^\pm X^\mp + \ldots) \simeq 4.7 \text{ pb}; \]
\[ \sigma(pp \rightarrow Z X^\pm + \ldots) \simeq 5.7 \text{ pb}; \]
(31)

These results by no means contradict upper limits of work [21]. Note that $X_i$ production is accompanied by additional boson either $W$ or $Z$. Thus we predict effects in triple weak boson production: $W^\pm W^\mp W^\mp, W^\pm W^\mp Z, W^\pm Z Z$, which are connected with $X_i$ production.

Process $p + p \rightarrow W^\pm + \gamma + \ldots$ was studied at LHC for energy $\sqrt{s} = 7$ TeV [22]. The results in comparison to SM calculations are the following

\[ \sigma(W^\pm\gamma) = 56.3 \pm 5.0(st) \pm 5.0(sy) \pm 2.3(lu) \text{ pb}; \]
\[ \sigma(W^\pm\gamma)_{SM} = 49.4 \pm 3.8 \text{ pb}. \]
(30)

Due to branching ratios (23) we obtain for additional $Wjj$ and $Zjj$ production in the region of enhancement the following estimate. We also divide cross-section for jet - jet production into two parts: with accompanying $\gamma$ and without $\gamma$

\[ \sigma(pp \rightarrow W^\pm + \gamma + 2j + \ldots) = 0.26 \text{ pb}; \]
\[ \sigma(pp \rightarrow W^\pm + 2j + \ldots) = 1.49 \text{ pb}; \]
\[ \sigma(pp \rightarrow Z + 2j + \ldots) = 0.13 \text{ pb}. \]
(26)

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\[ \sigma(pp \rightarrow Z + 2j + \ldots) = 0.13 \text{ pb}. \]
(26)

Total cross-section for $Wjj + Wjj\gamma$: $\sigma (Wjj) = 1.75 \text{ pb}$ occurs to be rather smaller than result [1] $\sigma (Wjj) = 4.0 \pm 1.2 \text{ pb}$, whereas small value for $Zjj$ production quite agrees with [1] data. However recent results of D0 [18] do not support large value for $\sigma(Wjj)$ and give upper limit for cross-section under study $\sigma(Wjj) < 1.9 \text{ pb} (95\% \text{ C.L.})$. As a matter of fact our result (26) evidently does not contradict both results, because it differs from CDF number [1] by less than two s.d.

Processes (23) contribute also to observable reactions of pair weak boson production. From (23,25) we have additional contribution

\[ \Delta \sigma(p\bar{p} \rightarrow W^+ W^-) + \sigma(p\bar{p} \rightarrow Z W^\pm) = 2.8 \text{ pb}; \]
(27)

that gives no contradiction to data [19] at TEVATRON

\[ \sigma(W^+ W^-) + \sigma(Z W^\pm) = 17.4 \pm 3.3 \text{ pb}; \]
\[ (\sigma(W^+ W^-) + \sigma(Z W^\pm) )_{SM} = 15.1 \pm 0.9 \text{ pb}; \]
(28)

where the lower line corresponds to SM NLO calculations [21]. We see that possible contribution (27) comfortably fits into error bars of difference between experimental and theoretical (SM) numbers [25].

The production of radial excitations $X_1$ may be compared with data on search of resonant $WW$ and $WZ$ production [21]. The results following from values of parameters [20,21] are the following ($B_i = BR(X_i \rightarrow W Z)$)

\[ X_1 : \sigma B_1 = 0.15 \text{ pb}; \quad X_2 : \sigma B_2 = 0.76 \text{ pb}; \]
\[ X_3 : \sigma B_3 = 1.64 \text{ pb}. \]
(29)

These results by no means contradict upper limits of work [21]. Note that $X_i$ production is accompanied by additional boson either $W$ or $Z$. Thus we predict effects in triple weak boson production: $W^\pm W^\mp W^\mp, W^\pm W^\mp Z, W^\pm Z Z$, which are connected with $X_i$ production.

Process $p + p \rightarrow W^\pm + \gamma + \ldots$ was studied at LHC for energy $\sqrt{s} = 7$ TeV [22]. The results in comparison to SM calculations are the following

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\[ \sigma(W^\pm\gamma)_{SM} = 49.4 \pm 3.8 \text{ pb}. \]
(30)
We see that here we also have no contradiction with data (30). Let us emphasize that this process is quite promising for checking of our scheme, because we not only predict additional contribution (32) but we insist that this additional contribution means production of narrow resonance $X^\pm$ with mass around 145 GeV which decays mostly to $W^\pm + \gamma$.

Let us present also estimate for production of the 145 GeV excess at LHC for $\sqrt{s} = 7$ TeV, which follows from processes (31)

$$
\sigma(pp \to jj + ...) \simeq 0.5 \text{pb};
$$

$$
\sigma(pp \to jj + W^\pm + ...) \simeq 6.1 \text{pb}.
$$

To conclude we once more would emphasize that the would-be resonances being considered here might serve as an evidence for existence of the new family of particles with mass scale of hundreds GeV – W-hadrons.

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