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ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА. ТЕОРИЯ

# A REFERENCE MODEL FOR ANOMALOUSLY INTERACTING BOSONS

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A simple reference model for anomalously interacting bosons is proposed and implemented in the CompHEP package. This allows preparing for an experimental search of these bosons at powerful colliders, such as Tevatron and LHC. New signatures and some experimental consequences are shortly considered.

В работе предложена простая для пользователей монте-карловских генераторов модель для поиска аномально взаимодействующих бозонов на современных мощных ускорителях (LHC и тэватроне). Модель использует программный пакет CompHEP. Указаны специфические сигналы в сечениях для новых бозонных резонансов.

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## INTRODUCTION

The hypothetical heavy neutral bosons, $Z'$, interacting with the known fermions, quark and leptons, should have a clear signature at the hadron colliders. Due to their resonance production, a peak in the dilepton invariant high-mass distribution of the Drell–Yan process can be expected. In the case of leptophobic bosons their decay in the heavy quarks, $t$ and $b$, allowing tagging and almost a full kinematics reconstruction, can be investigated.

The extra gauge bosons, $Z'$, occur in any extensions of the Standard Model (SM) gauge group. If such extensions are motivated by the Hierarchy Problem, they lead to a new physics around TeV energies not far above the weak scale. Needless to say, understanding experimental consequences of the latter is of a fundamental importance.

However, usually only the gauge bosons, which have minimal couplings with the SM fermions

$$\mathcal{L}_{Z'} = \sum_f \left( g^f_{LL} \overline{\psi^f_L} \gamma^\mu \psi^f_L + g^f_{RR} \overline{\psi^f_R} \gamma^\mu \psi^f_R \right) Z'_\mu \,, \tag{1}$$

are considered in literature. In the recent paper [1] it was shown that there are at least three different classes of theories, all motivated by the hierarchy problem, which predict also the appearance of new spin-1 weak doublets, $V_\mu \equiv (Z^*_\mu, W^*_\mu)$, with the internal quantum numbers identical to the SM Higgs doublet.

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In contrast to the well-known $Z'$ and $W'$ bosons, they possess only effective anomalous (magnetic moment type) couplings with ordinary light fermions [2]

$$\mathcal{L}_V = \frac{1}{M} \sum_f \left( g^f_{LR} \overline{\Psi^f_L} \sigma^{\mu\nu} \psi^f_R D_{[\mu} V_{\nu]} + g^f_{RL} D^\dagger_{[\mu} V^\dagger_{\nu]} \overline{\psi^f_R} \sigma^{\mu\nu} \Psi^f_L \right), \quad (2)$$

where $M$ is the scale of the new physics; $\psi^f_R$ are the right-handed singlets and $\Psi^f_L$ are the left-handed doublets. $D_\mu$ are the usual $SU(2)_W \times U(1)_Y$ covariant derivatives, and the obvious group and family indexes are suppressed.

Although many Beyond the Standard Models (BSM) have been implemented in Monte Carlo (MC) Generators like PYTHIA, the new bosons are not yet even assigned to any number within the MC particle numbering scheme. The aim of this paper is to suggest a simple reference model and implement it in one of the most reliable among Matrix Element MC Generators, the CompHEP package [3]. This will allow one to perform simple calculations of the processes involving the new bosons. In agreement with Les Houches Accord [4] the corresponding generated event files can be passed to PYTHIA for showering/hadronization and further also for simulation and reconstruction within the real experimental software framework.

## 1. THE REFERENCE MODEL AND ITS IMPLEMENTATION

In order to construct the simple reference model for experimental verifications, we need to derive the main features of the new spin-1 bosons from a whole variety of possible models. For example, the doublet structure always introduces new particles in pairs: neutral $Z^*$ and charged $W^*$ spin-1 bosons. Moreover, due to nonzero hypercharge of the doublet, the minimal particle set consists of the four spin-1 bosons: the two charged $W^{*\pm}$ states and the two neutral $CP$-even Re $Z^*$ and $CP$-odd Im $Z^*$ states.

The crucial common feature of all approaches considered in [1] is that the lightness of the Higgs doublets is guaranteed, because they are related to the spin-1 $V_\mu$ bosons by symmetry. It means that each spin-0 Higgs doublet is associated with the corresponding spin-1 doublet and vice versa. In the supersymmetric SM extensions at least two Higgs doublets are needed, which demands introduction of more than one new spin-1 weak doublet. In order to prevent the appearance of flavor-changing neutral currents, one doublet should couple only to up-type quarks, while the other should couple to down-type quarks and charged leptons only [5].

The different doublets are associated with the different vacuum expectation values of the Higgs doublets and, in general, acquire different masses. Let us choose them according to the estimations in [2]

$$M_{Z^*_u} \simeq 700 \text{ GeV}, \quad M_{Z^*_d} \simeq 1000 \text{ GeV}. \quad (3)$$

In contrast to the case of neutral bosons the charged bosons can mix, which results in an additional mass splitting. So, the mass of the lightest boson can be estimated as $M_{W^*} \simeq$ 500 GeV [2]. It will be shown that all properties of the new bosons can be described by the following independent input parameters: coupling constant, masses and mixing of the charged bosons. All input parameters of the model called _ESM are summarized in Table 1.

*Table* 1. **Independent parameters of the _ESM model (varsX.mdl)**

Variables

| Name | Value | > Comment < |
|---|---|---|
| GW | 0.652 | new coupling constant = EE/SW |
| MZd | 1000. | mass of down-type Z* |
| MZu | 700. | mass of up-type Z* |
| MWX | 500. | mass of W* |
| SX | 0.5 | sin of charged boson mixing |

*Table* 2. **List of particles of the _ESM model and their properties (prtclsX.mdl)**

Particles

| Full name | P | aP | 2*spin | Mass | Width | Color | aux | > LaTex(A) < | > LaTex(A+) < |
|---|---|---|---|---|---|---|---|---|---|
| down-type Z* | Zd | Zd | 2 | MZd | wZd | 1 | | Z^*_d | Z^*_d |
| up-type ReZ* | Zr | Zr | 2 | MZu | wZr | 1 | | ReZ^*_u | ReZ^*_u |
| up-type ImZ* | Zi | Zi | 2 | MZu | wZi | 1 | | ImZ^*_u | ImZ^*_u |
| W* | X+ | X- | 2 | MWX | wWX | 1 | | W^{*+} | W^{*-} |

*Table* 3. **Parameters depending on the basic ones (funcX.mdl)**

Constraints

| Name | > Expression < | > Comment < |
|---|---|---|
| CX | sqrt(1-SX^2) | cos of charged boson mixing |
| pi | acos(-1) | Pi |
| Sqrt3 | sqrt(3) | sqrt of 3 |
| rtZ | Mtop^2/MZu^2 | (Mtop/MZu)^2 ratio |
| rtW | Mtop^2/MWX^2 | (Mtop/MWX)^2 ratio |
| wZd | GW^2*MZd/(4*pi) | width of down-type Z* |
| wZr | GW^2*MZu/(12*pi)*(2+(1+8*rtZ)*sqrt(1-4*rtZ)) | width of up-type ReZ* |
| wZi | GW^2*MZu/(12*pi)*(2+sqrt((1-4*rtZ)^3)) | width of up-type ImZ* |
| wWX | GW^2*MWX/(4*pi)*(1+SX^2*rtW^2*(3-2*rtW)/12) | width of W* |

Table 2 includes all characteristic representatives of the _ESM model and their properties. Their interactions can be derived from (2)

$$\mathcal{L}_{\rm ref} = \frac{g}{\sqrt{2}M_{Z^*_d}}\left(\bar{d}\sigma^{\mu\nu}d + \bar{e}\sigma^{\mu\nu}e\right)\partial_\mu Z^*_{d\,\nu} + \\ + \frac{\sqrt{2}g}{\sqrt{3}M_{Z^*_u}}\left(\bar{u}\sigma^{\mu\nu}u\partial_\mu {\rm Re}\, Z^*_{u^\nu} + i\bar{u}\sigma^{\mu\nu}\gamma^5 u\partial_\mu {\rm Im}\, Z^*_{u\,\nu}\right) + \\ + \frac{g}{M_{W^*}}\left(\sin\theta_X\overline{u_L}\sigma^{\mu\nu}d_R + \frac{2}{\sqrt{3}}\cos\theta_X\overline{u_R}\sigma^{\mu\nu}d_L + \sin\theta_X\overline{\nu_L}\sigma^{\mu\nu}e_R\right)\partial_\mu W^{*\,+}_{X\,\nu} + {\rm h.c.}, \quad (4)$$

*Table* 4. **Vertices of interactions of the _ESM model (lgrngX.mdl)**

Lagrangian

| P1 | P2 | P3 | P4 | > Factor < | > dLagrangian/ dA(p1) dA(p2) dA(p3) < |
|---|---|---|---|---|---|
| B | b | Zd | | GW/(2*Sqrt2*MZd) | G(m3)*G(p3)-G(p3)*G(m3) |
| D | d | Zd | | GW/(2*Sqrt2*MZd) | G(m3)*G(p3)-G(p3)*G(m3) |
| E | e | Zd | | GW/(2*Sqrt2*MZd) | G(m3)*G(p3)-G(p3)*G(m3) |
| L | l | Zd | | GW/(2*Sqrt2*MZd) | G(m3)*G(p3)-G(p3)*G(m3) |
| M | m | Zd | | GW/(2*Sqrt2*MZd) | G(m3)*G(p3)-G(p3)*G(m3) |
| S | s | Zd | | GW/(2*Sqrt2*MZd) | G(m3)*G(p3)-G(p3)*G(m3) |
| C | c | Zr | | GW/(Sqrt2*Sqrt3*MZu) | G(m3)*G(p3)-G(p3)*G(m3) |
| T | t | Zr | | GW/(Sqrt2*Sqrt3*MZu) | G(m3)*G(p3)-G(p3)*G(m3) |
| U | u | Zr | | GW/(Sqrt2*Sqrt3*MZu) | G(m3)*G(p3)-G(p3)*G(m3) |
| C | c | Zi | | GW/(Sqrt2*Sqrt3*MZu) | (G(m3)*G(p3)-G(p3)*G(m3))*G5 |
| T | t | Zi | | GW/(Sqrt2*Sqrt3*MZu) | (G(m3)*G(p3)-G(p3)*G(m3))*G5 |
| U | u | Zi | | GW/(Sqrt2*Sqrt3*MZu) | (G(m3)*G(p3)-G(p3)*G(m3))*G5 |
| B | t | X- | | GW/(4*Sqrt3*MWX) | (G(m3)*G(p3)-G(p3)*G(m3))*(Sqrt3*SX*(1-G5)+2*CX*(1+G5)) |
| C | s | X+ | | GW/(4*Sqrt3*MWX) | (G(m3)*G(p3)-G(p3)*G(m3))*(Sqrt3*SX*(1+G5)+2*CX*(1-G5)) |
| D | u | X- | | GW/(4*Sqrt3*MWX) | (G(m3)*G(p3)-G(p3)*G(m3))*(Sqrt3*SX*(1-G5)+2*CX*(1+G5)) |
| E | nu | X- | | GW/(4*MWX) | (G(m3)*G(p3)-G(p3)*G(m3))*SX*(1-G5) |
| L | nl | X- | | GW/(4*MWX) | (G(m3)*G(p3)-G(p3)*G(m3))*SX*(1-G5) |
| M | nm | X- | | GW/(4*MWX) | (G(m3)*G(p3)-G(p3)*G(m3))*SX*(1-G5) |
| Ne | e | X+ | | GW/(4*MWX) | (G(m3)*G(p3)-G(p3)*G(m3))*SX*(1+G5) |
| Nl | l | X+ | | GW/(4*MWX) | (G(m3)*G(p3)-G(p3)*G(m3))*SX*(1+G5) |
| Nm | m | X+ | | GW/(4*MWX) | (G(m3)*G(p3)-G(p3)*G(m3))*SX*(1+G5) |
| S | c | X- | | GW/(4*Sqrt3*MWX) | (G(m3)*G(p3)-G(p3)*G(m3))*(Sqrt3*SX*(1-G5)+2*CX*(1+G5)) |
| T | b | X+ | | GW/(4*Sqrt3*MWX) | (G(m3)*G(p3)-G(p3)*G(m3))*(Sqrt3*SX*(1+G5)+2*CX*(1-G5)) |
| U | d | X+ | | GW/(4*Sqrt3*MWX) | (G(m3)*G(p3)-G(p3)*G(m3))*(Sqrt3*SX*(1+G5)+2*CX*(1-G5)) |

where for simplicity the scale of the new physics is equal to the mass of the corresponding boson and $g$ being the coupling constant of the $SU(2)_W$ weak gauge group. The flavor universality is assumed and the family indexes are omitted. The coupling constants are chosen in such a way that all fermionic decay widths of the new bosons are the same in the Born approximation and in the massless quarks limit. This value coincides with the total decay width of the heavy $W'$ boson of the same mass. The corresponding decay widths are presented in Table 3 taking into account the top quark mass only.

The present paper discusses only the resonance production of the heavy bosons and their subsequent decay into fermion pairs, which is important for early discoveries. In the case of the light fermions, it is impossible to discriminate the multiplicative quantum numbers of the neutral boson, $P$ and $C$, because they have identical signatures. Therefore, we will consider only one of the down-type neutral bosons, for instance, $\mathrm{Re}\, Z^*_d$. Table 4 describes the vertex structures of the new interactions (4).

These four tables completely describe the model and can be used for process evaluations within the CompHEP package.

## 2. CONSEQUENCES FOR COLLIDERS

Due to their biggest center-of-momentum (CM) energy $\sqrt{s} \sim$ several TeV and their relatively compact sizes, the hadron colliders still remain the main tools for discoveries of very heavy particles. Since the production mechanism for new heavy bosons at a hadron collider is the $q\bar{q}$ resonance fusion, the presence of partons with a broad range of different momenta allows one to flush the entire energetically accessible region, roughly, up to $\sqrt{s}/2$. This, in a way, fixes the dominant production and decay mechanisms.

In paper [6] it has been found that tensor interactions lead to a new angular distribution of the outgoing fermions

$$\frac{d\sigma(q\bar{q} \to Z^*/W^* \to f\bar{f})}{d\cos\theta} \propto \cos^2\theta, \tag{5}$$

in comparison with the well-known vector interactions

$$\frac{d\sigma(q\bar{q} \to Z'/W' \to f\bar{f})}{d\cos\theta} \propto 1 + \cos^2\theta. \tag{6}$$

It was realized later [2] that this property ensures distinctive signature for the detection of the new interactions at the hadron colliders. At first glance, the small difference between the distributions (5) and (6) seems unimportant. However, the absence of the constant term in the first case results in new experimental signatures.

First of all, since the angular distribution for vector interactions (6) includes a nonzero constant term, this leads to the kinematical singularity in $p_T$ distribution of the final fermion

$$\frac{1}{\cos\theta} \propto \frac{1}{\sqrt{(M/2)^2 - p_T^2}} \tag{7}$$

in the narrow width approximation $\Gamma \ll M$

$$\frac{1}{(s - M^2)^2 + M^2\Gamma^2} \approx \frac{\pi}{M\Gamma}\delta(s - M^2). \tag{8}$$

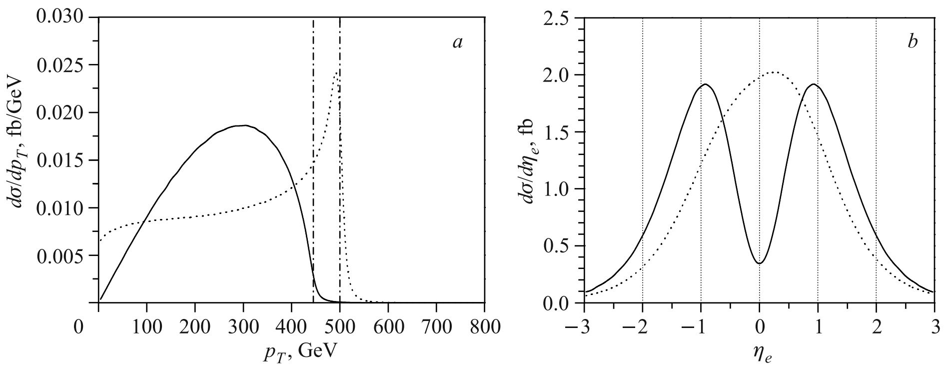


Fig. 1. *a*) The final electron $p_T$ distributions from the $Z_d^*$ (solid) and $Z'_{\rm SSM}$ (dotted) bosons decays. *b*) The differential cross sections for the $Z^*$ (solid) and $Z'_{\rm SSM}$ (dotted) bosons as functions of the pseudorapidity of the final electron

This singularity is transformed into the well-known Jacobian peak due to a finite width of the resonance. In contrast to this, the pole in the decay distribution of the $Z^*/W^*$ bosons is canceled out and the fermion $p_T$ distribution reaches even zero at the kinematical endpoint $p_T = M/2$. Therefore, the $Z^*/W^*$ boson decay distribution has a broad smooth hump with a maximum below the kinematical endpoint, instead of a sharp Jacobian peak (Fig. 1, *a*)[1].

According to Eq. (5), for the $Z^*/W^*$ bosons there exists a characteristic plane, perpendicular to the beam axis in the parton rest frame, where the emission of the final-state pairs is forbidden. The nonzero probability in the perpendicular direction in the laboratory frame is only due to the longitudinal boosts of the colliding partons. This property is responsible for the additional dips in the middle of the final fermion pseudorapidity distributions of the anomalously interacting bosons, in contrast to the $Z'/W'$ bosons with the minimal gauge couplings (Fig. 1, *b*).

While the maximum of the gauge boson distribution is centered at the small lepton pseudorapidities, which correspond to the central part of the detector, the chiral boson distribution has minimum in this region and its maxima are placed at the edges of the CDF and D0 central calorimeters $|\eta| \simeq 1$. Based on the fact that the major part of the leptons, stemming from the $Z'$ decays, are emitted in the central detector region, both collaborations have analyzed the spectrum of the transverse high-energy electrons only in the central electromagnetic calorimeters $|\eta_e| \leqslant \eta_{\rm cut} \simeq 1$. The acceptances for the processes with the chiral $Z_d^*$ bosons and the sequential $Z'_{\rm SSM}$ bosons are shown in Fig. 2, *a*.

The cuts in the backward-forward regions lead to a miss in an essential part of the events from the chiral boson decays due to the previously mentioned specific angular distribution. As seen from Fig. 2, *a*, the curve for the chiral $Z_d^*$ boson mostly lies under the $Z'_{\rm SSM}$ curve, and at $\eta_{\rm cut} \simeq 1$ there are around 65% detected events in the case of the sequential $Z'_{\rm SSM}$ bosons decays and only 45% in the case of the chiral $Z_d^*$ bosons decays.

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[1]All calculations are performed for the resonant production of the down-type chiral $Z_d^*$ bosons with the mass $M = 890$ GeV and for the sequential $Z'_{\rm SSM}$ bosons with the mass $M = 1000$ GeV and their subsequent decays into $e^+e^-$ pairs in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using the CompHEP package 4.5.1. Thus, the chosen masses lead to identical cross sections of 5.6 fb.

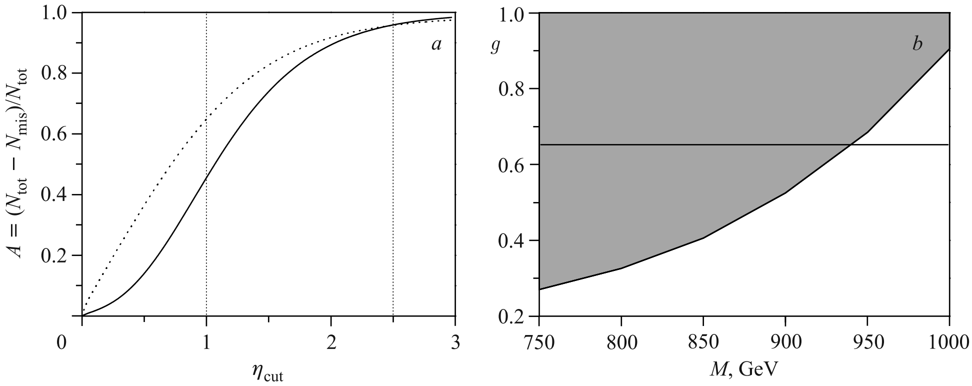


Fig. 2. *a*) The acceptances for the $Z_d^*$ (solid) and $Z'_{\rm SSM}$ (dotted) bosons as function of $|\eta_e| < \eta_{\rm cut}$ cut. *b*) The allowed region (white) for the coupling constant–mass relation of the $Z_d^*$ resonance from the D0 Tevatron constraints [7]. The horizontal line corresponds to the ordinary value of the $SU(2)_W$ coupling constant $g$

Taking into account this fact, we can correct and apply experimental constraints of the D0 collaboration (Table II from [7]) on production cross section in the case of the chiral $Z_d^*$ bosons with arbitrary coupling constant $g$ (Fig. 2, *b*). One can see that due to a smaller acceptance for the $Z_d^*$ bosons than for the $Z'_{\rm SSM}$ bosons, even for the same production cross sections more lighter $Z_d^*$ masses are allowed. For example, in the case when the coupling constant $g$ is equal to the ordinary value of the $SU(2)_W$ coupling constant, we obtain $M_{Z_d^*} > 940$ GeV, in comparison with D0 result $M_{Z'_{\rm SSM}} > 1023$ GeV.

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