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Anomalously interacting Z* bosons: an example of JINR's contribution to physics at the LHC

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Abstract. **Fundamental particle physics research at the Joint Institute for Nuclear Research (JINR) has always included the use of highest-energy accelerator machines, and it is only natural that from its very beginning, the institute played an active role in work on developing, assembling, and upgrading both the Large Hadron Collider itself and its detectors. Along with providing hardware and software support to secure the failure-free operation of detectors and the gathering and processing of experimental data, JINR sets as its primary goal to effectively participate in the unprecedentedly comprehensive and important LHC research program. As part of this program, the experimental search for new heavy chiral Z* and W* bosons is carried out by the ATLAS collaboration, an effort whose necessity was fully justified and strategy exhaustively developed by JINR physicists. The search results from the first run of the LHC are briefly discussed, together with the decisive contribution from JINR and future prospects.**

Keywords: Z* boson, LHC, ATLAS, JINR, heavy boson, lepton

1. Introduction

Experimental research at the Large Hadron Collider (LHC) [1] has resulted in the most important and interesting results over recent years in the field of high-energy physics: the discovery of the Higgs boson, high-precision measurements of the Standard Model (SM) parameters, and new (currently the best) bounds on the parameters of theories beyond the SM. Increasing the collider luminosity and energies of proton–proton collisions shows that the experiments at the LHC are currently most topical and promising in many aspects, such as the discovery of new physical phenomena, confirmation or refutation of various theoretical models, and, finally, improvement of experimental research technologies.

JINR has taken an active part in constructing the accelerator, developing and manufacturing detector systems for experimental setups, and their technical support. But the main task for JINR is to carry out research regarding all the main objectives of the physical experimental program: the study of Higgs boson physics, the investigation of processes with the production of heavy quarks, the search for supersymmetry effects and various physical mechanisms beyond the SM, etc.

While participating in the physical research, JINR does all kinds of work regarding data analysis on various problems: it performs theoretical investigations, develops effective strategies for experimental research, creates and optimizes algorithms for the reconstruction of experimental events, performs modeling of physical processes in the setup in order to estimate and improve its quality, conducts final analysis of experimental data, etc. The need to solve these problems resulted in the creation of a corresponding infrastructure at JINR in order to store and process data, attract and train new specialists, and regularly hold seminars and conferences on the LHC physics.

As a successful example of JINR's contribution to the ATLAS (A Toroidal LHC ApparatuS) project [2], we discuss a new physical model. Physicists from Dubna played a decisive role in the justification of this model, in the development of search strategies, and directly in the experimental research. This model describes heavy 'chiral' Z* and W* bosons [3–6] anomalously coupled to matter.

The actual theoretical background for the existence of such particles is mainly connected with the so-called hierarchy problem of the SM, or the fine-tuning problem. It is caused by the unnaturally large difference between energy scales of electroweak and gravitational interactions or, in other words, by the unexplained stability of the relatively small observed mass of the Higgs boson (125 GeV) compared to the Planck scale (10^{19} GeV). This stability can be explained by the

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existence of mechanisms that either weaken the observed value of the gravitational interaction or decrease radiation corrections to the Higgs boson mass and govern its natural stabilization on the level of ~ 125 GeV (which should then manifest themselves at energies of the order of several TeV).

One of the possible solutions to the hierarchy problem is realized in theories where the Higgs boson is not an elementary particle, for example, in composite Higgs boson models (see [7, 8]). These models postulate the existence of a new strong interaction that binds some new fundamental particles in the observed SM particles. Such theoretical scenarios are similar to quantum chromodynamics (QCD), and neutral bosons like Z^*, together with charged W^* bosons, within these models are the excited states of bosons from the electroweak sector of the SM.

Another candidate for a theory that does not have a hierarchy problem has been suggested quite recently and assumes the existence of an extended electroweak interaction symmetry group. Some of these models are related to the 'little Higgs' model class (see [9–11]). These models assume various extensions of the SM symmetry groups, which lead to the existence of new gauge bosons and an extension of both fermion and Higgs sectors of the SM. Two of the new particles predicted within these models are Z^* and W^* bosons.

Other theoretical models that predict the observation of new heavy resonances and provide matching of the scales of electroweak and gravitational interactions can also be mentioned. For example, a set of theories that assume the existence of additional space–time dimensions predict so-called Kaluza–Klein excited states [12–14], which can be experimentally observed as heavy resonances with a mass of several TeV.

Finally, as was shown in [5], the existence of new-type heavy particles Z^* and W^* can be connected with the existence of fundamental tensor quantum fields. The interaction of these fields with matter fields can have various interesting properties that can give rise to new observed effects, such as a chirality change for particles that participate in interactions of this type. This is why the new particles are called chiral bosons.

If we manage to confirm the realization of these new theoretical ideas in nature by experimentally discovering the resonant production of Z^* and W^* type bosons, we will open broad perspectives for the development of theoretical and experimental high-energy physics. JINR searches for new types of particles and these experiments, on the one hand, are a thorough test for the SM and, on the other hand, motivate further active development of theories beyond the SM framework.

2. Model for heavy chiral Z^* bosons

One of the key properties of neutral and charged Z^* and W^* bosons is the tensor type of their coupling to SM fermions, which distinguishes them from other types of heavy bosons. This follows from the SM symmetry, because the chiral bosons are introduced as doublets $V_\mu = (Z^*_\mu, W^*_\mu)$. The coupling of new-type particles to the SM fermions is described by the Lagrangian

$$\mathcal{L}_{\text{int}} \sim t\,\bar{\psi}_2 \sigma^{\mu\nu} \psi_1 \partial_{[\mu} V_{\nu]}\,, \tag{2.1}$$

where $\bar{\psi}_2$ are left-handed doublets, ψ_1 are right-handed singlets of fermionic fields, t is the coupling constant, $\sigma^{\mu\nu}$ is a second-rank antisymmetric tensor, and V_ν is the field that describes heavy vector bosons.

This type of coupling between the new bosons V_ν and the SM fermions can effectively appear due to the existence of heavy fermions and scalars in intermediate states in theories with an extended symmetry (see [4]):

$$\begin{aligned}\mathcal{L} = & -D_{[\mu} V^\dagger_{\nu]} D^{[\mu} V^{\nu]} + M_V^2 V^\dagger_\mu V^\mu + \partial_\mu \phi^* \partial^\mu \phi - M^2 \phi^* \phi \\ & + \sum_{k=1,2} \bar{\psi}'_k (\mathrm{i}\not{D} - m) \psi'_k + g \bar{\psi}'_2 \gamma^\mu \psi'_1 V_\mu + g V^\dagger_\mu \bar{\psi}'_1 \gamma^\mu \psi'_2 \\ & + \sum_{k=1,2} \bar{\psi}_k \mathrm{i}\not{D} \psi_k + \frac{h}{2} \bar{\psi}_2 (1+\gamma^5) \psi'_2 \phi + \frac{h}{2} \bar{\psi}'_1 (1+\gamma^5) \psi_1 \phi^* \\ & + \frac{h}{2} \bar{\psi}'_2 (1-\gamma^5) \psi_2 \phi^* + \frac{h}{2} \bar{\psi}_1 (1-\gamma^5) \psi'_1 \phi\,, \end{aligned} \tag{2.2}$$

where V_μ is the vector field of new gauge bosons, ψ'_1 and ψ'_2 are singlets and doublets of heavy fermionic fields, ϕ is a heavy scalar field, ψ_1 and ψ_2 are singlets and doublets of the SM fermionic fields, g and h are coupling constants, M_V is the mass of heavy bosons V_μ, M is the mass of the scalar field ϕ, m is the mass of the fermionic fields ψ', $\not{D}$ is the covariant derivative, and γ^μ and γ^5 are Dirac gamma matrices. In such models, the coupling of V_μ bosons to SM fermions is possible only for higher orders of interaction in (2.2). Accordingly, the effective operator for the coupling of heavy bosons and SM fermions has the form

$$\begin{aligned}\mathcal{L}_{\text{eff}} = & \frac{\mathrm{i}gh^2}{4} \bar{\psi}_2 \int \frac{\mathrm{d}^4 k}{(2\pi)^4} (1+\gamma^5) \frac{\not{p}' - \not{k} + m}{(p'-k)^2 - m^2} \gamma^\mu \\ & \times \frac{\not{p} - \not{k} + m}{(p-k)^2 - m^2} (1+\gamma^5) \frac{1}{k^2 - M^2} \psi_1 V_\mu \\ = & \frac{gh^2}{32\pi^2 m} \mathcal{I}(q^2, m^2, M^2) \bar{\psi}_2 \sigma^{\mu\nu} (1+\gamma^5) \psi_1 \partial_{[\mu} V_{\nu]}\,, \end{aligned} \tag{2.3}$$

where k is the boson momentum, p and p' are fermion momenta, and $\not{p}$ and $\not{k}$ are convolutions of momenta with the gamma matrices,

$$\mathcal{I} = \int_0^1 x^2\,\mathrm{d}x \int_0^1 \frac{y\,\mathrm{d}y}{x + (M^2/m^2)(1-x) - (q^2/m^2)x^2 y(1-y)}\,. \tag{2.4}$$

Interaction operator (2.3) has the same form as (2.1).

Besides the discussed possibility, Z^* and W^* bosons can be described by new fundamental antisymmetric tensor fields $T_{\mu\nu} \sim \partial_{[\mu} V_{\nu]}$. A detailed discussion of the possible existence of new fundamental bosons, which are different from the SM gauge bosons and are described by tensor fields, is given in [5]. Such fields are the ingredients of string theory or extended supergravity models and can be used to eliminate anomalies from these theories. It was shown in [15] that a renormalizable theory that includes this kind of fields can be constructed in the framework of conformal field theory. A special feature of antisymmetric tensor fields is that the corresponding states transform under the Lorentz group representations $(1,0)$ and $(0,1)$, unlike gauge bosons, which transform under the representation $(1/2, 1/2)$. Bosons associated with the tensor fields bind fermions of different chiralities and are therefore called 'chiral' bosons.

The prohibition of flavor-changing neutral currents leads to additional constraints on the properties of new particles. To ensure the compatibility with these constraints, an assumption can be introduced that neutral components of one tensor field doublet can interact only with up-type fermions, and neutral components of the other doublet can interact only with down-type fermions. The Glashow–Iliopulos–Maiani (GIM) mechanism works in the model of Z^* and W^* bosons similarly to how it works in the SM if we assume that mixing is the same for right-handed and left-handed fermions. This means that the coupling of tensor bosons to the SM fermions can be described as

$$\mathcal{L} = t\bar{Q}\sigma^{\mu\nu}u_{\rm R}U_{\mu\nu} + t(\bar{Q}\sigma^{\mu\nu}d_{\rm R} + \bar{L}\sigma^{\mu\nu}e_{\rm R})T_{\mu\nu}\,, \qquad (2.5)$$

where $\bar{Q} = (u_{\rm L}, d_{\rm L})$ are left-handed quark doublets, $\bar{L} = (\nu_{\rm L}, e_{\rm L})$ are left-handed lepton doublets, $e_{\rm R}$ are right-handed lepton singlets, $u_{\rm R}$ and $d_{\rm R}$ are right-handed quark singlets, U and T are the new tensor fields, and t is the coupling constant.

In experimental search for Z^*-type heavy resonances, new bosons were associated with the neutral components of the tensor fields $T_{\mu\nu}$ coupled to down-type quarks and charged leptons. Thus, the following experimentally observed Z^* decay modes are predicted in the leading order in the coupling: the lepton one $Z^* \to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ and the quark one $Z^* \to d\bar{d}$, $s\bar{s}$, $b\bar{b}$. The probability of decay through each lepton channel is predicted to be around 8.3% for Z^*. This follows from assuming the universality of the quark and lepton coupling constant. The Z^* resonance is narrow and the Z^* decay width is on the level of 3.4% of its pole mass. In the range of cross sections predicted by various theories with Z^* and W^* bosons, the cross section of Z^* production with its mass being equal to the Z-boson mass is set close to the cross section of Z production. It is important to note that for the problem of the experimental search for new particles, this choice is conventional because the experimental search is aimed at discovering tensor bosons with various cross sections and masses. The key experimental parameters of the Z^* model (for example, the shape and width of the resonance) are determined by the kinematics of the new boson decay into leptons.

As in other theoretically predicted models of heavy resonances (Z', G^*, Kaluza–Klein particles, technimesons, quantum black holes, etc.), the observation of Z^* is possible in the form of a heavy resonance in the invariant mass distribution for leptons or hadron jets (Fig. 1).

One of the possible properties of the new particles is that with the couplings as in (2.1), transitions between fermions of various chiralities can be observed [3, 5].

Other properties of couplings like those in (2.1) and (2.3) manifest themselves in the observed properties of the Z^* and $W^{\pm *}$ bosons. In particular, these bosons are characterized by a unique angular distribution of their decay products. Fermions that are produced in the decay of Z or Z' bosons on 'symmetric' pp colliders in the center-of-mass system are characterized by an angular distribution of the form $d\sigma/d\cos\theta \sim (1 + \cos^2\theta)$. On the other hand, Z^* chiral bosons described by tensor interaction (2.3) produce fermions in the final state with the angular distribution of the form $d\sigma/d\cos\theta \sim \cos^2\theta$, where θ is the scattering angle between the direction of the beam and the outgoing fermions (see [5]).

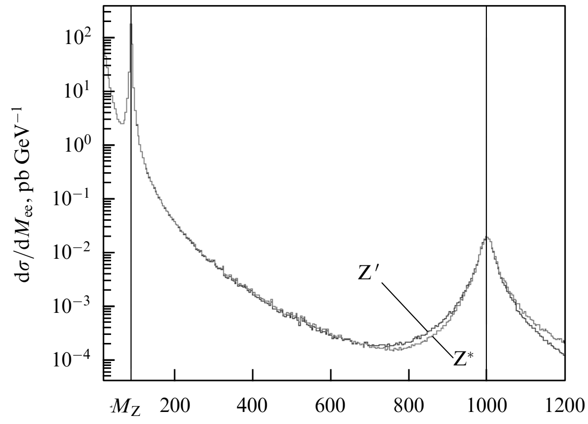

Figure 1. Distribution of leptons (in this case, electron–positron pairs) produced in proton–proton collisions over the invariant mass of the pair M_{ee}. Lines show the expected peaks of new Z' and Z^* bosons with a mass of 1 TeV.

Table 1. Distribution of fermions in two-particle decays of various types of resonances over the escape angle in the Collins–Soper system.

Resonance type*	Spin	Distribution of decay particles
Z, Z'	1	$1 + \cos^2\theta$
H	0	1
G^*	2	$1 - 3\cos^2\theta + 4\cos^4\theta$ $1 - \cos^4\theta$
Z^*	1	$\cos^2\theta$

* Z and Z' are vector gauge bosons, H is the Higgs boson, G^* is the Randall–Sundrum graviton.

Table 1 shows the angular distributions of decay fermions for neutral resonances of various types. Figures 2 and 3 show a comparison of decay lepton distributions over the transverse momentum and cosine of the angle in the Collins–Soper system for the Z' and Z^* models, obtained from theoretical calculations.

From the standpoint of high-energy experimental physics, a convenient angular characteristic of decay leptons is the difference between their pseudorapidities $\Delta\eta$. This variable has a useful property for experimental physics on particle colliders: it is constant for Lorentz boost transformations along the beam axis. Figure 4 shows the distributions of this variable in the decays of neutral bosons (with the mass of 1 TeV) of different types. The distributions are obtained from theoretical calculations. The Z^*-type resonance is characterized by a unique distribution of the lepton pseudorapidity difference, unlike resonances of other types. In the case of Z^*, this distribution has a maximum at $\Delta\eta \approx 1.8$.

To summarize, in the case of the experimental observation of a new resonance, the characteristics of the kinematic distributions allow distinguishing the Z^* resonance from the scalar and vector bosons at an early stage, even if the statistics of the observed events are low.

3. Experimental data analysis

The experimental search for Z^* resonance production was based on the data obtained at the ATLAS facility during the proton–proton collisions at the LHC in 2011–2012. In 2011, the energy of proton–proton collisions in the center-of-mass

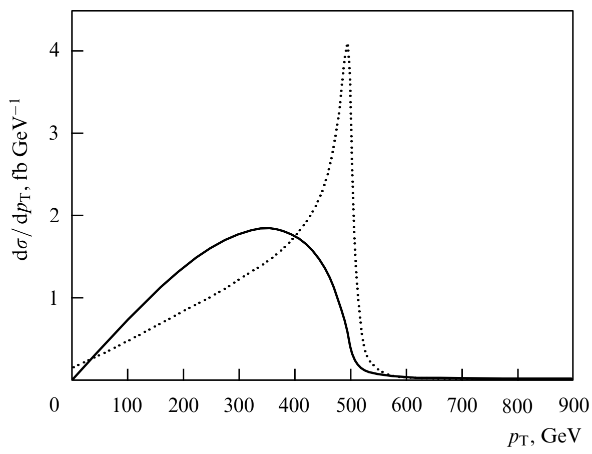

Figure 2. Distribution of decay leptons over the transverse momentum for Z′ bosons (dotted curve) and Z* bosons (solid curve) with a mass of 1 TeV.

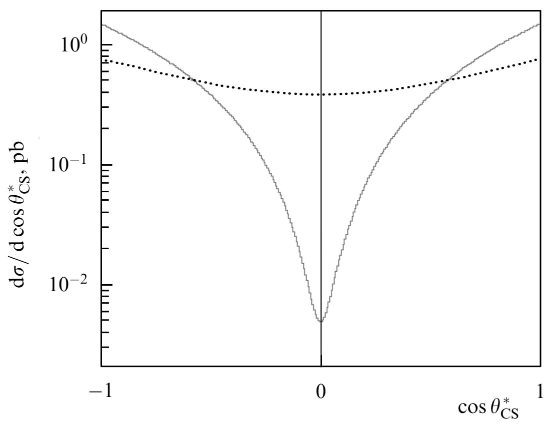

Figure 3. Distribution of the cosine of the angle between the decay lepton escape direction and the heavy boson propagation direction in the rest frame of the heavy boson (Collins–Soper reference frame) for Z′ bosons (dotted curve) and Z* bosons (solid curve) with a mass of 1 TeV.

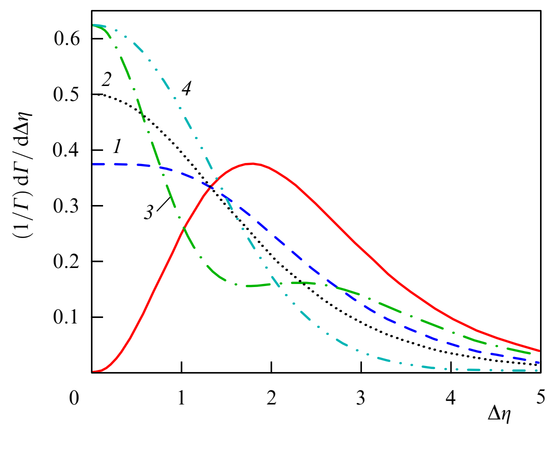

Figure 4. Distribution of the pseudorapidity difference between decay leptons for neutral bosons of different types with a mass of 1 TeV. Curve *1* corresponds to bosons of type Z, Z′ with spin 1; curve *2* corresponds to resonances with spin 0, such as the Higgs boson; curve *3* corresponds to resonances with spin 2 (for example, G*), which are produced in quark collisions; curve *4* corresponds to resonances with spin 2 produced in gluon collisions. The solid curve shows the pseudorapidity difference for leptons in the Z* boson decay.

system was 7 TeV, and the collision statistics accumulated at ATLAS by the end of the year reached a value that corresponds to the integrated luminosity 5.2 fb^{-1}. In 2012, the collision energy at LHS reached 8 TeV. During that year, the ATLAS detector accumulated data statistics that correspond to the integrated luminosity 21.3 fb^{-1}.

Selection criteria for events with two leptons were mainly aimed at improving the lepton reconstruction quality (in particular, providing a high accuracy of the momentum reconstruction), reducing the number of falsely reconstructed leptons, and, finally, eliminating a number of background processes.

For the channel with two electrons, the condition was that one of the electrons should have a transverse energy not less than 40 GeV and the other electron, not less than 30 GeV. The muons had a bound of the transverse momentum of each muon in the pair: not less than 25 GeV. The following requirements were applied to both electrons and muons: good compatibility of their trajectories with the primary vertex, isolation from other particle tracks (this allowed significantly suppressing the background processes that involve hadron jets); the presence of a particular number of counts that correspond to registration of leptons in different detector subsystems (this allowed improving the quality of the reconstruction and determining lepton kinematic parameters), and a number of other conditions, which are mostly related to the specifics of the facility operation.

Simulations of dilepton events have shown that the selection efficiency as a function of the lepton invariant mass is around 70% for the channel with two electrons and around 45% for the dimuon channel.

The search strategy for a signal of the Z* resonance production consists in comparing the lepton invariant mass distributions in the dilepton event with the same distributions for the simulated SM background processes. The main background process relative to the required new-physics signals is the Drell–Yan process, when a Z boson or a virtual γ quantum decay into a lepton–antilepton pair. Another class of background processes is the production of several weakly interacting bosons (WW, WZ, ZZ), which can decay and produce several leptons in the final state. The next less significant background process is the one with the production of one or two top quarks, which decay into leptons. Finally, the processes of associated production of jets and W bosons, as well as processes with the creation of several heavy jets (b, c) that decay into leptons, must be strongly suppressed by the selection criteria regarding the compatibility of trajectories with the primary vertex and lepton isolation.

An important parameter for the problem of the signal search is the uncertainty in simulations of background processes. The main systematic errors for estimations of the SM background are as follows: theoretical uncertainties in the distribution functions for partons in the proton, which have a big influence on the cross sections of all considered processes; the uncertainty in the distribution function for photons in the proton, which lead to errors in the cross sections of the processes induced by photons in the initial state [16]; uncertainties in the SM parameters used in the simulations (renormalization and factorization scales); simulation errors for the lepton reconstruction efficiency, lepton momentum resolution and uncertainty of the LHC proton beam energy; errors connected with the extrapolation of several background process distributions to the large mass

Table 2. Systematic errors from different uncertainty sources for the SM background cross section for the distributions of dimuon events in proton–proton collisions with the energy of 8 TeV. The reconstructed invariant mass of leptons m_l is 1, 2, and 3 TeV.

Source	Error*, %		
	$m_l = 1$ TeV	$m_l = 2$ TeV	$m_l = 3$ TeV
Parton function parameters	5	12	17
Choice of the parton function	—	6	12
α_s	1	3	4
Muon reconstruction efficiency	—	—	
Corrections to electroweak processes	—	3	3
Processes with photons in the initial state	2	3	4
Beam energy	2	3	3
Detector resolution of the muon momentum	3	3	8
Extrapolation of background processes with top-quark production	3	—	—
Total	7	15	23

* Dashes indicate that the corresponding contributions to the systematic error are assumed to be negligible.

Table 3. Systematic errors from different uncertainty sources for the SM background cross section for the distributions of dielectron events in proton–proton collisions with the energy of 8 TeV. The reconstructed invariant mass of leptons m_l is 1, 2, and 3 TeV.

Source	Error*, %		
	$m_l = 1$ TeV	$m_l = 2$ TeV	$m_l = 3$ TeV
Parton function parameters	5	11	30
Choice of the parton function	—	7	22
α_s	1	3	5
Muon reconstruction efficiency	—	—	
Corrections to electroweak processes	—	2	4
Processes with photons in the initial state	2	3	6
Beam energy	1	3	5
Detector resolution of the electron energy	—	—	—
Extrapolation of background processes with top-quark production	—	—	—
Total	6	15	44

* Dashes indicate that the corresponding contributions to the systematic error are assumed to be negligible.

range; the integrated luminosity uncertainty. The last uncertainty is eliminated by normalizing the number of events summed over all background processes to the number of observed events in the region of the Z boson peak (the so-called normalization region, 80–110 GeV).

It is assumed that all systematic uncertainties are correlated in the background and signal processes. The error of the Z/γ^* production cross section in the normalization region is attributed to the cross section of the signal process $Z^* \to ll$. This error is determined to be 5% for the 2011 data and 4% for the 2012 data.

Systematic errors less than 3% in the entire range of analyzed invariant masses were not taken into account. In estimating the compatibility of data with hypotheses of different masses, the theoretical errors of Z^* cross section estimates were not taken into account either.

The values of systematic background uncertainties for dimuon and dielectron channels used in the analysis of the 2012 data are shown in Tables 2 and 3.

4. Comparison of experimental data with simulation results for Standard Model processes

Figures 5 and 6 [17–19] show the invariant mass distribution of selected lepton pairs from the 2011 and 2012 data, together with the distributions of SM processes. As an example, the distribution plots show the signals of Z^* bosons with different masses.

Analysis of the presented distributions indicates that the data can be satisfactorily described by the SM for both 7 TeV and 8 TeV collision energies. Local data deviations from the background (calculated in each column of the invariant mass distribution) do not exceed two standard deviations with systematic and statistical uncertainties of the data and the background taken into account. A comparison of data and simulation results was performed not only for the invariant mass distributions but also for all key kinematic variables of dilepton events: pseudorapidity, the azimuthal angle, the transverse momentum of individual leptons, and the transverse energy lost during the event, the rapidity and the transverse momentum of a muon pair. These comparisons have also shown agreement of the data with the simulation results for SM processes.

Besides investigations of the data and background compatibility, several methods were used to investigate the compatibility of observed data with signals of new resonances, taking their shape and width into account. One such method is the data fitting by modeling the event distributions for the signal and for the SM physics. As the criterion for data compatibility with different hypotheses, we have chosen a likelihood function. This function is defined in the entire range of the invariant mass distribution as the product of likelihood values in all distribution columns.

The significance of the possible new physics signal, i.e., the production of heavy bosons, was estimated using the *P*-value — the probability of statistical variation in the invariant mass distribution under the assumption that there is no signal whose significance is the same as or greater than the one in the observed distribution. There is common agreement that a *P*-value lower than 1.35×10^{-3} indicates a statistically significant excess of observations over the predictions, and a *P*-value lower than 2.87×10^{-7} indicates a discovery. When the *P*-value exceeds 0.1, the data is considered to be properly described by the background.

Signal distributions for the Z' model and the background were simulated and compared with the data. The resulting *P*-value turned out to be 0.70 for 2011 data and 0.28 for 2012 data. These values indicate that there are no statistically significant deviations (compatible with the shape of new resonances) of the observed data distributions from the simulated distribution of SM processes.

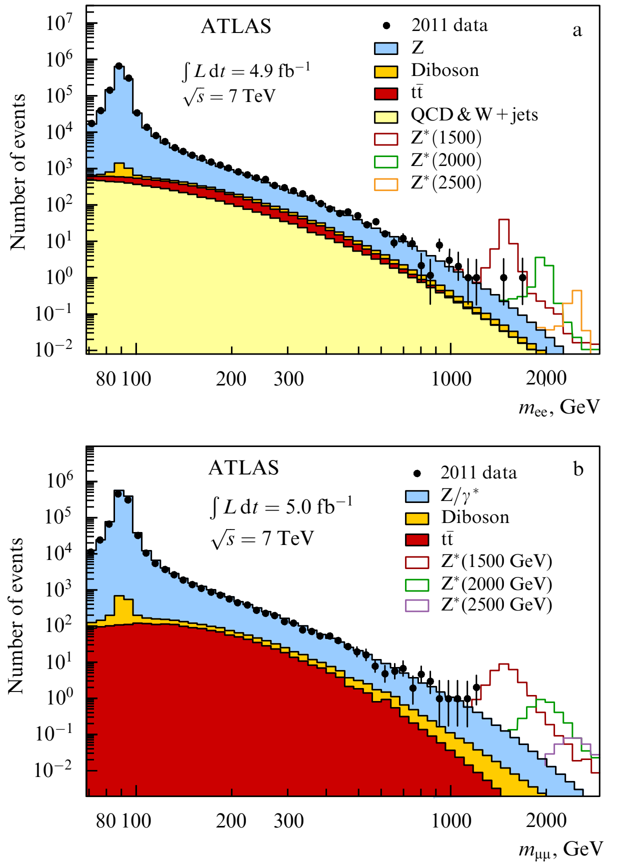

Figure 5. Distribution of events over the invariant masses of (a) electrons and (b) muons in the final state for the ATLAS 2011 data. Black circles show the lepton distributions in the data. Histograms are the distributions of background processes: Drell–Yan (Z/γ^*), production of several Z and W bosons (Diboson), processes involving top quarks ($t\bar{t}$), and QCD processes (QCD & W + jets). Contour plots show the resonance production signals for Z' type bosons with different masses. (From [17].)

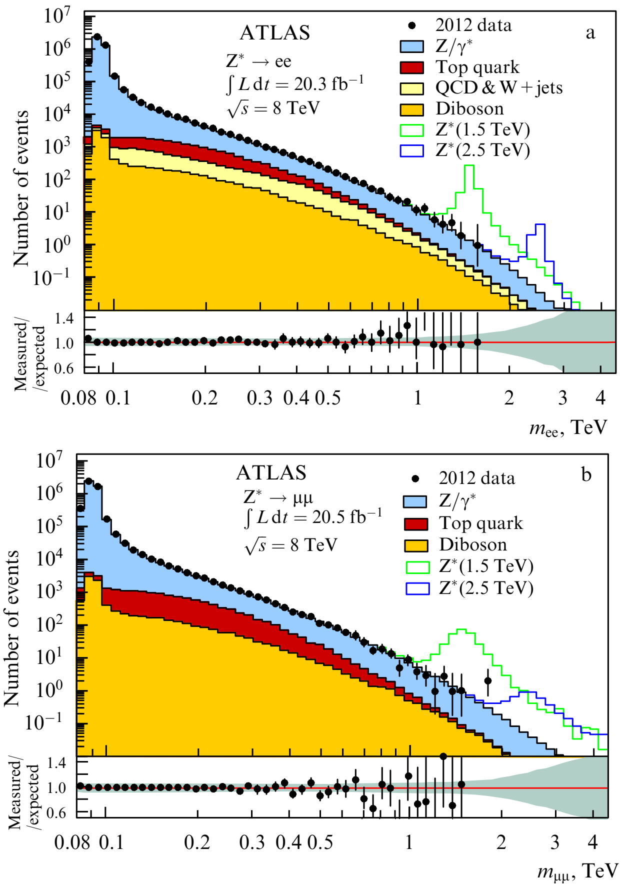

Figure 6. Distribution of events over the invariant masses of (a) electrons and (b) muons in the final state for the ATLAS 2012 data. Black circles show the lepton distributions in the data. Histograms are the distributions of background processes: Drell–Yan (Z/γ^*), production of several Z and W bosons (Diboson), processes involving top quarks, and QCD processes (QCD & W + jets). Contour plots show the resonance production signals for Z' type bosons with different masses. (From [18].)

5. Calculations of bounds for cross sections and masses of new resonances

Because the signal was not observed, the search results were considered to be statistical bounds on the number of dilepton events that follow the Z^* resonance decay and the related product of the Z^* production cross section and the relative width of the decay to leptons. This was done (for 2011 and 2012 data) using the Bayesian approach.

The bounds on the cross section times the probability of a new-resonance decay into leptons were calculated using specific statistics of pseudoexperimental data bins (around 1000). Each bin was used to randomly distribute background systematic variations and the number of signal process events. The likelihood function was estimated for each pseudoexperiment as the product of Poisson probabilities for each column of the invariant mass distribution:

$$P(N, \mu) = \frac{\exp(-\mu)\, \mu^N}{N!}\,, \qquad (5.1)$$

where μ is the expected number of events considering systematic and statistical background uncertainties together with the signal process cross section, and N is the observed number of events.

Based on these calculations, we estimate the upper bound on the new resonance cross section with a 95% confidence level, meaning that the integral over the likelihood function reaches 0.95 for this cross-section value. The so-called observed exclusion bounds were calculated for the new resonance by comparing the compatibility of pseudoexperiments with the detector data, while the 'expected bounds' (and also their uncertainties on the level of one or two standard deviations) were found from a comparison of distributions of the detector data and the background. The described procedure was applied to each separate channel, as well as to the combination of all channels under analysis, dimuon and dielectron. The joint likelihood function was calculated as the product of likelihood functions of all channel.

The cross-section bound and its uncertainty at the level of one or two standard deviations are estimated for all values of the pole mass in the search range, i.e., in the range 0.15–4.5 TeV.

Figure 7 [17–19] shows the observed (solid curve) and expected (dotted curve) bounds on the Z^* resonance cross sections with various masses obtained by analyzing the 2011 and 2012 data. Uncertainties of the expected bounds, connected with errors in the background distribution estimates ($\pm 1\sigma$, $\pm 2\sigma$), are shown as a shaded area around the expected bound curve.

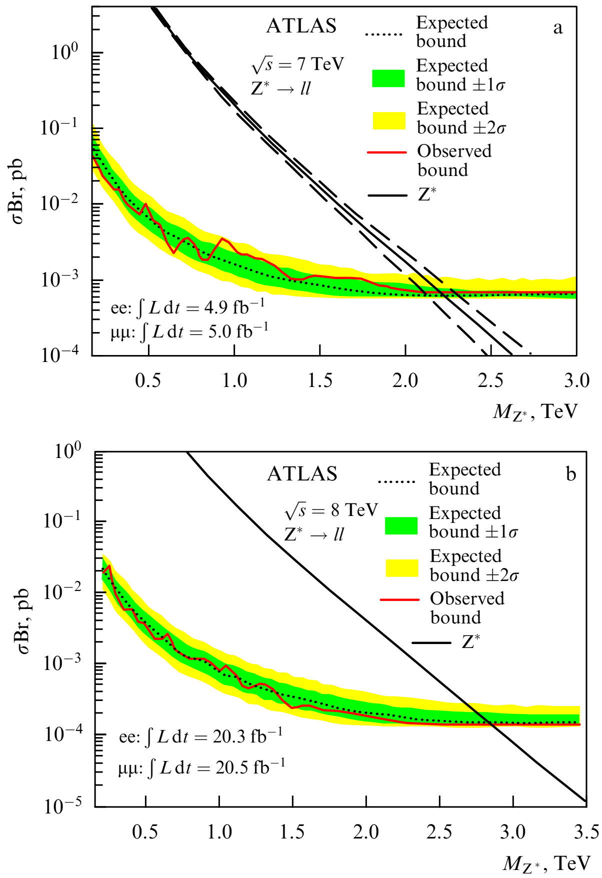

Figure 7. Bounds of the Z* resonance cross section for various pole masses, obtained from the statistical analysis of (a) 2011 and (b) 2012 data in a combination of dimuon and dielectron channels. (From [17, 18].)

To compare limiting cross sections with the theoretical ones for all resonance masses, the figure shows the theoretically predicted product of the Z* cross section and the probability of decay into leptons (solid grey curve), together with the theoretical uncertainty.

Bounds on possible cross sections and masses of Z*-type bosons were significantly improved in the 2012 data analysis. This was due to the higher energy of proton–proton collisions and the corresponding increase in the parton luminosity for higher invariant masses and the higher integrated luminosity of the collider.

Table 4 shows the observed bounds with a 95% confidence level for cross sections of Z* bosons with different masses, calculated from the ATLAS 2012 data for a combination of dimuon and dielectron channels.

The crossing of the curve for an observed (expected) cross-section bound by the curve for a theoretical cross section gives the observed (expected) bound for the new resonance mass. Tables 5 and 6 show the values of mass bounds obtained from the analysis of 2011 and 2012 data.

The proton–proton collision energy and luminosity at the LHC increase, which increases the chances to observe heavy neutral resonances in the forthcoming ATLAS data collection periods.

Estimates for signal and background process cross sections in 13 TeV proton–proton collisions, together with preliminary estimates for the systematic error in the background simulation, selection efficiency for two-lepton events, and the detector resolution for the lepton momentum, were

Table 4. Observed bounds for the cross section of Z* with different masses calculated at a 95% confidence level from 2012 data for a dimuon channel and for a combination of dimuon and dielectron channels.

Mass Z*, TeV	Bound σBr(Z* → μμ), fb	Bound σBr(Z* → μμ, ee), fb
0.3	14.4	8.37
0.5	6.31	5.03
0.7	2.99	1.86
1.0	2.41	0.424
1.5	0.492	0.312
2.0	0.459	0.229
2.5	0.431	0.194
3.0	0.351	0.152
3.5	0.388	0.138

Table 5. Observed and expected bounds for the Z* mass calculated at a 95% confidence level from 2011 data for a dimuon channel and for a combination of dimuon and dielectron channels.

Channel	Z* mass bound, TeV	
	Observed	Expected
Z* → μμ	1.97	1.99
Z* → μμ, ee	2.20	2.22

Table 6. Observed and expected bounds for the Z* mass calculated at a 95% confidence level from 2012 data for a dimuon channel and for a combination of dimuon and dielectron channels.

Channel	Z* mass bound, TeV	
	Observed	Expected
Z* → μμ	2.58	2.58
Z* → μμ, ee	2.82	2.85

obtained using the ATLAS 2011–2012 data. This information allows estimating the possibility of observing or excluding Z* type bosons [20]. Figure 8 shows the integrated luminosity of the collider required for observing or excluding Z* bosons in the two-lepton channel. If the collision energy is 13 TeV, the required amount of data corresponds to 1–2 fb^{-1} of the integrated luminosity in order to reach the same or greater sensitivity to the observation of new heavy bosons as in the case of the 8 TeV energy. As the collision energy increases, the main problems of data analysis that greatly influence the possibility of observing new physics are as follows: improving the quality and efficiency of lepton reconstruction (in particular, improving the experimental setup resolution of the lepton momentum and energy), increasing the accuracy of the SM background process simulations (in particular, reducing systematic errors in the background simulation for large values of the invariant mass), and optimizing present and developing new strategies for experimental search.

6. Conclusions

The experimental search for signatures of physics beyond the SM framework at energy scales of several TeV is the main area of physics research at the LHC. These searches are very important for explaining the physics of fundamental interactions and for developing theoretical understanding of the processes of high energies up to the Planck scales. Besides supersymmetry models, there are a number of theories that extend the SM and assume the existence of new fundamental interactions, space–time dimensions, etc., and predict the existence of heavy vector bosons, fermions, and scalars.

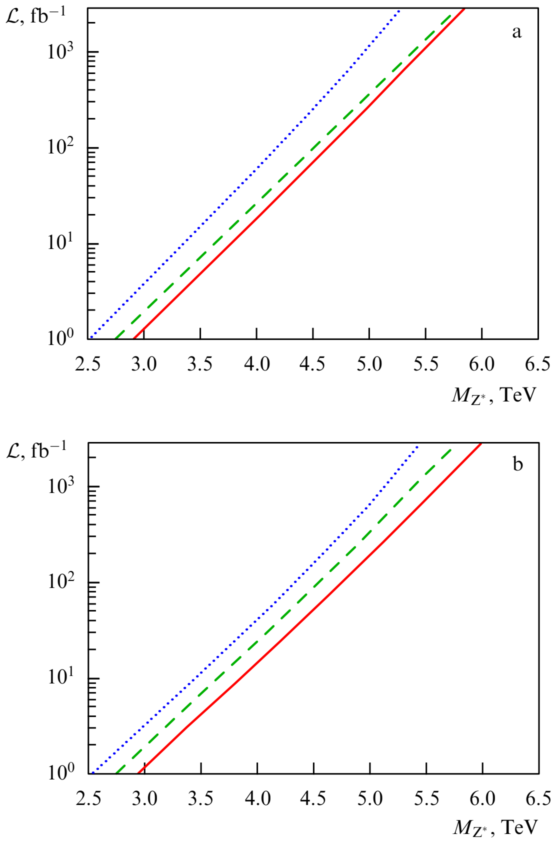

Figure 8. Illustration of the possibilities of (a) discovering and (b) excluding Z^* bosons in the data from proton–proton collisions with the energy of 13 TeV based on the center-of-mass system. Plots show the integrated luminosity of collisions $\mathcal{L}$, which is needed to discover or exclude Z^*, for channels with two muons (dotted line), two electrons (dashed line), and a combination of dimuon and dielectron channels (solid line). (From [20].)

Prospects such as the discovery of new particles, the exclusion of their existence, or the imposition of strict bounds on their masses and cross sections are a great motivation for the development of new theoretical models of TeV physics and for the search for new physical mechanisms that would hold beyond the SM. Anomalously interacting Z^* and W^* chiral bosons were suggested at JINR [3–6] and are related to one such particle type. The authors of this article took part in the analysis of the ATLAS data, which resulted in new experimental bounds on the parameters of these particles. We also predict the prospects for future searches.

With the new LHC run, the nominal energies of proton–proton collisions will reach 13–14 TeV and the search for new-physics manifestations, including the production of heavy chiral Z^* and W^* bosons, will continue with new motivations and new expectations.

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