MODEL-INDEPENDENT Z' SEARCHES AT MODERN COLLIDERS

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(Received October 31, 2011)

The model-independent constraints on the Abelian Z' couplings from the LEP data are applied to estimate the Z' production in experiments at hadron colliders. The Z' contribution to the Drell-Yan process at modern hadron colliders is analyzed. The results are compared with model-dependent predictions and present experimental data from the Tevatron and the LHC. The lower bounds on the Z' mass are derived and the Z' discovery limit in the LHC experiments is found.

PACS: 11.10.Gh, 12.60.Cn, 14.70.Pw

1. INTRODUCTION

A new heavy neutral vector boson (Z' boson) is probably the most perspective intermediate state in scattering processes of quarks and leptons which could be discovered in experiments at modern hadron colliders. At the parton level it can appear in the annihilation channel carrying a large part of energy of the colliding particles, its mass is allowed to be of order 1 TeV by current experimental constraints, and it is a necessary component of popular grand unification theories and other models with extended gauge sector (see [1–3] for review).

The most accurate description of resonances requires to calculate scattering amplitudes with intermediate virtual states. But if the resonance is a narrow one, then it can be described by the production cross-section of the on-shell particle and by the decay widths (total and partial). These parameters can be easily constrained from previous experiments giving a possibility to estimate the perspectives of the current experiments.

The Tevatron and LHC collaborations usually perform the model-dependent fits trying to discover Z' boson hints. Of course, effects of Z' boson can be calculated in details for each specific model beyond the SM. Some set of popular E_6 based models and left-right models is usually considered in this approach. However, probing the set we can still miss the actual Z' model. In this regard, it is useful to complement model-dependent Z' searching by some kind of model-independent analysis, i.e. the analysis covering a lot of models.

Almost all of the usually considered models belong to the models with so-called Abelian Z' boson. In Ref. [4,5] we found the relations which hold in any model containing the Abelian Z' boson and satisfying the following conditions: 1) only one neutral vector boson exists at the energy scale about 1...10 TeV; 2) the Z' boson can be phenomenologically described by the effective Lagrangian [1–3] at low energies; 3) the Z' boson and other possible heavy particles are decoupled at considered energies, and the theory beyond the Z' decoupling scale is either one- or two-Higgs-doublet standard model (THDM); 4) the SM gauge group is a subgroup of a possible extended gauge group of the underlying theory. So, the only origin of possible tree-level Z' interactions to the SM vector bosons is the Z–Z' mixing. The relations reduce significantly the number of unknown Z' parameters. This allows to constrain the parameters by existing experiments as well as to predict the quantities used in the analysis of the Tevatron and LHC experiments.

Recently we summarized the information about Z' couplings to leptons and quarks which can be extracted from the LEP experiments [7, 8]. The Z' coupling to axial-vector currents was constrained by both LEP I and LEP II $\mu^+\mu^-, \tau^+\tau^-$ data. In different processes it shows hints at about 1σ confidence level (CL) with approximately the same maximum-likelihood value. This value can be used in estimates of observables in the Tevatron and LHC experiments. As for the couplings to vector currents, the Z' coupling constant to electron can be constrained by the LEP II e^+e^- data only. Although the backward scattering shows a signal at the 2σ CL, the maximum-likelihood value is outside of the 95% CL interval calculated by the complete set of bins. In this situation we refrain from using that maximum-likelihood value

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in our estimates. Nevertheless, the vector coupling is constrained at the 95% CL. The upper bound on the electron vector coupling agrees closely with the corresponding upper bound on the axial-vector coupling. This fact allows us to suppose the rest of vector couplings to be constrained by the same value, since no evident signals were discovered in other scattering processes measured by the LEP collaborations. It is worth to note that all the conclusions derived from the LEP data are also valid if one considers the THDM as the low-energy theory instead of the usual minimal SM.

Our main goal is to obtain estimates for the Z' parameters used in searching for the narrow resonance by applying the LEP constraints on the Z' couplings. Both the minimal SM and the THDM will be considered as the low-energy theory. Also we compare these results to the Tevatron and the LHC experimental data and model-dependent predictions.

2. THEORETICAL AND EXPERIMENTAL CONSTRAINTS ON THE Z' COUPLINGS

In this paper we discuss mainly the Z' couplings to the vector and axial-vector fermion currents described by the Lagrangian

$$\begin{aligned}\mathcal{L}_{Z\bar{f}f} &= \frac{1}{2}Z_\mu \bar{f}\gamma^\mu \left[(v^{\rm SM}_{fZ} + \gamma^5 a^{\rm SM}_{fZ})\cos\theta_0 + \right. \\ &\quad \left. +(v_f + \gamma^5 a_f)\sin\theta_0\right] f, \\ \mathcal{L}_{Z'\bar{f}f} &= \frac{1}{2}Z'_\mu \bar{f}\gamma^\mu \left[(v_f + \gamma^5 a_f)\cos\theta_0 - \right. \\ &\quad \left. -(v^{\rm SM}_{fZ} + \gamma^5 a^{\rm SM}_{fZ})\sin\theta_0\right] f, \end{aligned} \quad (1)$$

where f is an arbitrary SM fermion state; a_f and v_f are the Z' couplings to the axial-vector and vector fermion currents; θ_0 is the Z–Z' mixing angle; $v^{\rm SM}_{fZ}$, $a^{\rm SM}_{fZ}$ are the SM couplings of the Z-boson. Such a parametrization is suggested by a number of natural conditions. First of all, the Z' interactions of renormalizable types are to be dominant at low energies $\sim m_W$. The non-renormalizable interactions generated at high energies due to radiation corrections are suppressed by the inverse heavy mass $1/m_{Z'}$ (or by other heavier scales $1/\Lambda_i \ll 1/m_{Z'}$) and therefore at low energies can be neglected. It is also assumed that the Z' is the only neutral vector boson with the mass $\sim m_{Z'}$. The Z' interactions to the SM gauge fields at the tree level are possible due to the Z–Z' mixing only. The explicit Lagrangian describing Z' couplings to the SM fields can be found in [6].

The parameters a_f, v_f, and θ_0 must be fitted in experiments. In a particular model, one has some specific values for them. In case when the model is unknown, these parameters remain potentially arbitrary numbers. In most investigations they are usually considered as independent ones. However, this is not the case if one assumes that the underlying extended model is a renormalizable one. In Refs. [4, 5] it was shown that these parameters are correlated as

$$v_f - a_f = v_{f^*} - a_{f^*}, \qquad a_f = T_{3f}\tilde{g}\tilde{Y}_\phi, \quad (2)$$

where f and f^* are the partners of the $SU(2)_L$ fermion doublet ($l^* = \nu_l, \nu^* = l, q^*_u = q_d$ and $q^*_d = q_u$), T_{3f} is the third component of the weak isospin, and $\tilde{g}\tilde{Y}_\phi$ determines the Z' interactions to the SM scalar fields (see [7] for details). The parameter $\tilde{g}\tilde{Y}_\phi$ defines also the Z–Z' mixing angle in (1).

As it was discussed in [7,8], the relations (2) cover a popular class of models based on the E_6 group (the so called LR, χ-ψ models) and other models, such as the Sequential SM. Thus, they describe correlations between Z' couplings for a wide set of models beyond the SM. That is the reason to call the relations model-independent ones.

At low energies the Z' couplings enter the cross-section together with the inverse Z' mass, so it is convenient to introduce the dimensionless couplings

$$\bar{a}_f = \frac{m_Z}{\sqrt{4\pi}m_{Z'}}a_f, \quad \bar{v}_f = \frac{m_Z}{\sqrt{4\pi}m_{Z'}}v_f, \quad (3)$$

which are constrained by experiments. Since the axial-vector coupling is universal, we will use the notation

$$\bar{a} = \bar{a}_d = \bar{a}_{e^-} = -\bar{a}_u = -\bar{a}_\nu. \quad (4)$$

Then the Z–Z' mixing is

$$\theta_0 \approx -2\bar{a}\frac{\sin\theta_W\cos\theta_W}{\sqrt{\alpha_{\rm em}}}\frac{m_Z}{m_{Z'}}. \quad (5)$$

It also follows from (2) that for each fermion doublet only one vector coupling is independent:

$$\bar{v}_{f_d} = \bar{v}_{f_u} + 2\bar{a}. \quad (6)$$

As a result, Z' couplings can be parameterized by seven independent constants $\bar{a}$, $\bar{v}_u$, $\bar{v}_c$, $\bar{v}_t$, $\bar{v}_e$, $\bar{v}_\mu$, $\bar{v}_\tau$.

Recently we obtained limits on Z' couplings from the LEP I and LEP II data [7, 8]. We found some hints of Z' boson at 1-2σ CL. Namely, the constants $\bar{a}$ and $\bar{v}_e$ show non-zero maximum-likelihood (ML) values. The axial-vector coupling $\bar{a}$ can be constrained by the LEP I data (through the mixing angle) and by the LEP II $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$ data. The corresponding ML values are very close to each other. This value

$$\bar{a}^2 = 1.3 \times 10^{-5} \quad (7)$$

will be used in our estimates. The 95% CL intervals were also obtained by the experimental data:

$$\begin{aligned} 0 < \bar{a}^2 < 3.61 \times 10^{-4}, \\ 4 \times 10^{-5} < \bar{v}_e^2 < 1.69 \times 10^{-4}. \end{aligned} \quad (8)$$

Other Z' coupling constants cannot be severely constrained by existing data. Among them $\bar{v}_u$, $\bar{v}_c$, and $\bar{v}_\mu$ play an important role in the process $q\bar{q} \to Z' \to \mu^+\mu^-$ which is most perspective to discover the Z' resonance. Taking into account that no evident signals of new physics were found by the LEP collaborations in the processes involving quarks, muons and tau-leptons, we constrain the values of $\bar{v}_u$, $\bar{v}_c$, $\bar{v}_t$,

$\bar{v}_\mu$, and $\bar{v}_\tau$ by the widest interval from the 95% CL intervals for $\bar{a}$ and $\bar{v}_e$:

$$0 < \bar{v}^2_{\text{other } f} < 4 \times 10^{-4}. \qquad (9)$$

Due to the existence of the ML value for the axial-vector coupling we perform the so called *maximum-likelihood estimate* for the production cross-section and decay widths. In this approach the axial-vector coupling is substituted by its ML value $\bar{a} = \sqrt{1.3 \times 10^{-5}}$. The vector coupling $\bar{v}_u$ is varied in its 95% CL interval. The uncertainty from the parton distribution functions should be also added. This estimate scheme can be considered as an 'optimistic' scenario to discover the Z' boson.

The knowledge of possible values of the Z' couplings allows to estimate the Z' production cross-section at the LHC and Tevatron and the Z' decay width without specifying the model beyond the SM.

3. Z' PRODUCTION CROSS-SECTION AND WIDTH

In modern experiments Z' bosons are expected to be produced in proton-antiproton collisions $p\bar{p} \to Z'$ (Tevatron) or proton-proton collisions $pp \to Z'$ (LHC). At the parton level both the processes are described by the annihilation of a quark-antiquark pair, $q\bar{q} \to Z'$. The Z' production cross-section is the result of usual integration of the partonic cross-section $\sigma_{q\bar{q}\to Z'}$ with the parton distribution functions. We use the parton distribution functions provided by the MSTW PDF package [9] taking into account the 90% CL uncertainties of the parton distribution functions provided by the package.

The Z' decay width $\Gamma_{Z'}$ can be calculated by using the optical theorem:

$$\Gamma_{Z'} = -\text{Im}\, G(m^2_{Z'})/m_{Z'}, \qquad (10)$$

where $G(p^2)$ is the two-point one-particle-irreducible Green's function. We compute $\Gamma_{Z'}$ at the one-loop level with the help of the FeynArts, FormCalc and LoopTools software [10, 11]. As a result, we obtain also all the partial widths corresponding to Z' decays into two SM particles.

All the Z' couplings to the SM scalar and vector bosons can be determined by the universal axial-vector constant a_f and can be constrained. Then the partial widths corresponding to Z' decays into scalar and vector bosons are proportional to a_f^2. As for the fermionic decays, the width can be written in the form

$$\Gamma_{Z'\to\bar{f}f} = a_f^2 \Gamma_{a_f^2} + a_f v_f \Gamma_{a_f v_f} + v_f^2 \Gamma_{v_f^2}. \qquad (11)$$

Now we are able to estimate the Z' contribution to the Drell-Yan process at the Tevatron and the LHC.

4. COMPARISON TO TEVATRON AND LHC DATA

The recent experiments at the LEP gave some hints of the Abelian Z' boson. It is interesting to speculate about the question how can those hints look like at Tevatron and LHC experiments. Taking the LEP ML value of the axial-vector coupling we can give predictions under the assumption that a signal of the Abelian Z' boson has been probably observed in the LEP data.

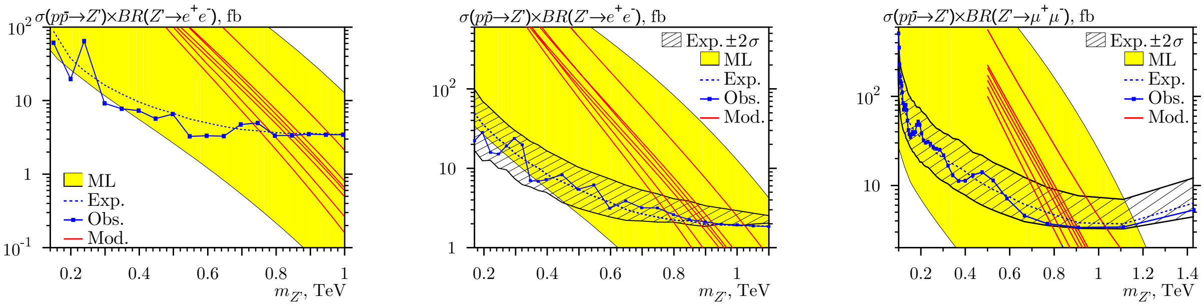

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Fig. 1. *The ML domains for $\sigma(p\bar{p} \to Z') \times BR(Z' \to e^+e^-)$ and $\sigma(p\bar{p} \to Z') \times BR(Z' \to \mu^+\mu^-)$ at $\sqrt{s} = 1.96$ TeV together with the experimentally obtained upper limits on these contributions and E_6-model-based predictions. In all plots the filled areas represent the ML estimates; the E_6-model predictions are plotted in solid lines. The models are (corresponding to the plotted lines from left to right): Z'_{I}, Z'_{sec}, Z'_{N}, Z'_ψ, Z'_χ, Z'_η and SSM Z'. The expected and observed 95% CL upper limits on the Z' contribution are shown as the dashed lines and line charts, respectively, and the hatched areas are the 2σ standard deviation bands for the expected values. The estimates for the dielectron channel compared to the data from CDF [12] and D0 [14] are presented in Figs. (a) and (b). In Fig. (c) the dimuon channel estimate and the CDF results [13] are shown*

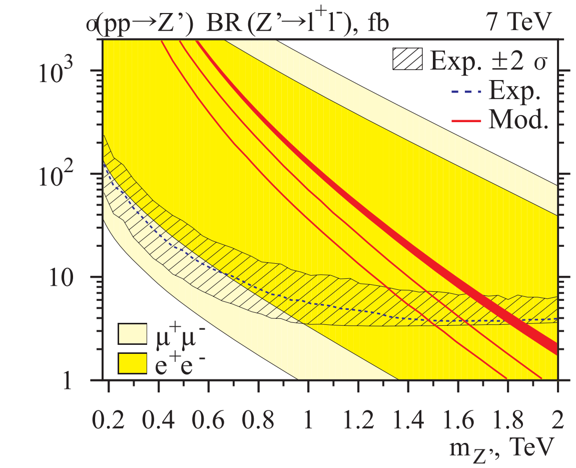

Fig. 2. *The same as in Fig. 1 at $\sqrt{s} = 7$ TeV. The filled areas represent the ML estimates (light filling is for dimuons, dark filling is for dielectrons; the E_6 and SSM model predictions are plotted in solid lines (from left to right: Z'_ψ, Z'_χ, Z'_{SSM}). The expected 95% CL upper limit on the Z' contribution is shown is the dashed lines, and the hatched area is the 2σ standard deviation band for the expected value. The estimates for the combined dilepton channel are compared to the data from ATLAS [15]*

On the other hand the 95% CL bounds on possible Z' couplings to the SM particles are left behind the LEP experiments. Taking these bounds for all the Z' couplings we can exclude some values of the observables at hadron colliders. In this scheme the values outside of the predicted intervals are forbidden for the Abelian Z' boson. Being measured in experiments, such values have to be interpreted as a signal of new physics which is something else than the Z' boson. For example, considering the Z' width, we can expect $\Gamma_{Z'} \times (1\ \text{TeV}/m_{Z'})^3 \simeq 10 \ldots 150$ GeV from the ML estimate, and we can think about the NWA for $m_{Z'} \leq 2$ TeV.

Now let us present the ML estimate for the Drell-Yan cross-section for the Tevatron experiments. As it was mentioned, in this case the NWA can be applied and the Z' contribution to the cross-section of the $pp\,(p\bar{p}) \to l\bar{l}$ process reads $\sigma(pp\,(p\bar{p}) \to Z') \times BR(Z' \to l\bar{l})$ where the branching ratio can be extracted from the total and partial Z' decay widths. The experimental bounds on the Z' contribution to the Drell-Yan process at the Tevatron are available in [12–14] together with the predictions from popular Z' models. The comparison between those results and our ML estimate for $\sigma(p\bar{p} \to Z' \to e^+e^-, \mu^+\mu^-)$ is presented in Fig. 1.

In Fig. 2 the same estimations are presented for the LHC case. The experimental data together with the model predictions are taken from [15].

Our model-independent maximum-likelihood estimates cover the predictions of all the popular Z' models. The model-independent lower bound on the Z' mass is still about 400 GeV for the Tevatron data and 700 GeV for the LHC data whereas the popular models give larger values.

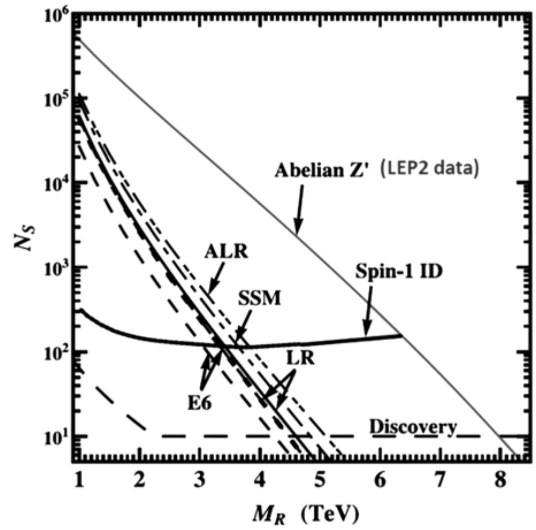

Fig. 3. *The model-independent discovery limit of the Z' boson in the LHC experiments at 14 TeV with the luminosity 100 fb^{-1}. The predictions from the popular models are also shown*

In addition to the lower bound on $m_{Z'}$ we can also estimate the discovery limit for the Abelian Z' boson at the LHC experiments [16]. We define the Z' boson discovery in experiments as at least ten Z' events, and no less than the 5σ excess over the SM background must be detected. At any value of $m_{Z'}$ this condition sets the minimal number of Z' events necessary for the Z' discovery. In Fig. 3 we compare the minimal necessary number of Z' events with the largest number of Z' events which can be realized under the model-independent LEP constraints on the Z' couplings. As it is seen the discovery of the Z' with $m_{Z'} > 8$ TeV is excluded in the LHC experiments at 14 TeV with the luminosity 100 fb^{-1}. The model-independent discovery limit is naturally higher than the values predicted by the popular models also shown in Fig. 3.

5. CONCLUSIONS

The model-independent relations for the Z' couplings give a good possibility to reduce the number of unknown Z' parameters. As a consequence, the Z' width and the production cross-sections of the processes at modern hadron colliders can be estimated using the constraints on the Z' couplings obtained from previous experiments at LEP. A combined analysis of the LEP, Tevatron and LHC data seems to be possible.

Our new model-independent results are complementary to the usual model-dependent schemes. The predictions of all the popular Z' models agree with our model-independent bounds.

Finally the Z' hints observed in the LEP data can be still hidden as the resonance in the Tevatron and LHC experiments. The model-independent lower bound is near 400 GeV/700 GeV from Tevatron/LHC data. The LHC experiments at 14 TeV with the luminosity 100 fb^{-1} can discover the Z' boson with the mass no more than 8 TeV.

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МОДЕЛЬНО-НЕЗАВИСИМЫЕ ПОИСКИ Z'-БОЗОНА НА СОВРЕМЕННЫХ КОЛЛАЙДЕРАХ

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С помощью модельно-независимых ограничений на константы связи абелевого Z'-бозона получены оценки процессов рождения Z' в экспериментах на адронных коллайдерах. Изучен вклад Z'-бозона в процесс Дрелла-Яна. Проведено сравнение полученных результатов с модельно-зависимыми предсказаниями и экспериментальными данными ускорителей Tevatron и LHC. Получена нижняя граница значения массы Z'-бозона, а также предельные значения массы, при которых Z' будет обнаружен в эксперименте LHC.

МОДЕЛЬНО-НЕЗАЛЕЖНІ ПОШУКИ Z'-БОЗОНА НА СУЧАСНИХ КОЛАЙДЕРАХ

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За допомогою модельно-незалежних обмежень констант зв'язку абелевого Z'-бозона отримано оцінки процесів народження Z'-бозона в експериментах на гадронних колайдерах. Досліджено внесок Z' в процес Дрелла-Яна. Виконано порівняння отриманих результатів з модельно-залежними результатами та експериментальними даними прискорювачів Tevatron та LHC. Отримана нижня границя маси Z'-бозона, а також граничні значення маси, при яких Z'-бозон буде знайдено в експериментах LHC.