Global search for Z' bososon at modern colliders

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Abstract

We discuss the general approaches of searching for the Z' gauge boson beyond the Standard model of elementary particles.

The construction principles of the renormalizable extended models are described. The popular (benchmark) models and the model-dependent and model-independent methods of searching for new heave particles are presented. The latter one is described in more details. In the renormalizable Z' models, the proper relations between the interaction couplings are derived. They could be used for decreasing the number of independent parameters which have to be fitted in experiments and uniquely fix the kinematics of the scattering process. The off-peak resonance and direct searches for the Z' boson are applied in treating the data of the LHC experiments on the Drell-Yan scattering process at beam energies 7, 8 and 13 TeV. The role of the mixing angle θ_0 of the Z and Z' fields and the width $\Gamma_{Z'}$ as well as applicability of the narrow width approximation are also discussed. The comparison with the results obtained at the LEP experiments is given. As it occures, they are in a good agreement with each other.

Outline

- Z' boson models
- Renormalization group relations (RGR)
- MI interference and direct searches at the LHC
- A_{FB} of Drell-Yan process at 7 and 8 TeV
- Direct searchs in Drell-Yan process at 13 TeV
- Role of the mixing θ_0 and the width $\Gamma_{Z'}$
- MI search for Z' at LEP, comparisons
- Propositions and approaches for Z' searches
- Conclusion

1 Z' boson models

- Present day status of Abelian Z'

All the considered models of particles are expected to be local gauge invariant and renormalizable.

For them the form of interactions is of the type

$$Current \times Potential, \tag{1}$$

where Current J_μ^a is formed out of matter fields and Potential G_μ^a corresponds to the gauge fields. Upper index "a" corresponds to the relevant internal symmetry group.

The interactions are introduced via the substitution of derivative

$$\frac{\partial}{\partial x_\mu} \to D_\mu = \frac{\partial}{\partial x_\mu} - igG_\mu. \tag{2}$$

This form is the result of all known experimental data. 5

The Abelian Z' gauge boson is related withthe extra phase of the standard model gauge group

$$\Big(SU(2)_{ew} \times U(1)_Y \times SU(3)_c\Big) \times \tilde{U}(1)_{\tilde{Y}} \tag{3}$$

Abelian Z' boson at LEP

- determined the SM parameters and particle masses at the level of radiation corrections
- searching for signals of new heavy particles beyond the SM.

At LEP2 experiments. No new particles were discovered,
the energy scale of new physics was estimated as of the order 1 TeV.

- Experiments at LHC - next stage in high energy physics.

A lot of extended models includes Z' gauge boson – a massive neutral vector particle associated usually with an extra $U(1)$ subgroup of the underlying group.

Z' is predicted by a number of GUTs (the E_6 and $SO(10)$ based models – LR, , $\chi - \psi$ and so on are often discussed).

Model-dependent search for Z' at LEP2 gave: $m_{Z'} > 400 - 800$ GeV.

Model-dependent results from Tevatron: $m_{Z'} > 800$ GeV,

and LHC: $m_{Z'} > 3 - 4$ TeV.

Approaches of searches for Z'

- Model-dependent (MD) searching for Z'

Effects of Z' are calculated within a specific model beyond SM. Free parameters are $m_{Z'}$ and $\Gamma_{Z'}$. All the couplings are fixed.
It is assumed Z' is a narrow state : $\Gamma/m_{Z'} \sim 1-3$ per cent.
About 100 Z' models are discussed.

- Model-independent (MI) searching for Z'

Analysis is covering a lot of models.

Effects of Z' are calculated within a specific low energy effective Lagrangian.

2 Renormalization group relations (RGR)

1) Only one Z' exists at energy scale $1 - 10$ TeV;

2) It is described by the known effective Lagrangian;

3) SM is the subgroup of the extended gauge group. The only origin of the three-level interaction Z' with the SM particles is $Z - Z'$ mixing.

These relations (RG relations) are the consequences of a renormalizability (see review Gulov, Skalozub (2010)).

Effective Lagrangian at low energies

At low energies, the Z'-boson can manifest itself by means of the couplings to the SM fermions and scalars as a virtual intermediate state. The Z-boson couplings are also modified due to a Z–Z' mixing.

Effective Z' Lagrangian

Such couplings can be described by adding new $\tilde{U}(1)$-terms to EW covariant derivatives D^{ew} in the Lagrangian Cvetic (1986), Degrassi (1989)

$$L_f = i \sum_{f_L} \bar{f}_L \gamma^\mu \left(\partial_\mu - \frac{ig}{2}\sigma_a W^a_\mu - \frac{ig'}{2} B_\mu Y_{f_L} - \frac{i\tilde{g}}{2}\tilde{B}_\mu \tilde{Y}_{f_L} \right) f_L \quad (4)$$

$$+ \; i \sum_{f_R} \bar{f}_R \gamma^\mu \left(\partial_\mu - ig' B_\mu Q_f - \frac{i\tilde{g}}{2}\tilde{B}_\mu \tilde{Y}_{f_R} \right) f_R,$$

$$L_\phi = \left| \left(\partial_\mu - \frac{ig}{2}\sigma_a W^a_\mu - \frac{ig'}{2} B_\mu Y_\phi - \frac{i\tilde{g}}{2}\tilde{B}_\mu \tilde{Y}_\phi \right) \phi \right|^2, \quad (5)$$

where left-handed doublets, $f_L = (f_u)_L, (f_d)_L$,

right-handed singlets, $f_R = (f_u)_R, (f_d)_R$.

$g, g', \tilde{g}$ are the charges associated with the $SU(2)_L, U(1)_Y$, and the Z' gauge groups, respectively,

σ_a are the Pauli matrices, Q_f denotes the charge of f in positron charge units, Y_ϕ is the $U(1)_Y$ hypercharge, and $Y_{f_L} = -1$ for leptons and 1/3 for quarks.

Generators $\tilde{Y}_{f_L}$= diag($\tilde{Y}_{f_u}, \tilde{Y}_{f_d}$) and $\tilde{Y}_\phi$ = diag($\tilde{Y}_{\phi,1}, \tilde{Y}_{\phi,2}$) are diagonal 2×2 matrices.

the Lagrangian can be simply generalized for the case of

SM with two Higgs doublets (THDM).

Lagrangian (5) leads to the Z–Z' mixing.

The mixing angle θ_0 is

$$\theta_0 = \frac{\tilde{g} \sin\theta_W \cos\theta_W}{\sqrt{4\pi\alpha_{\rm em}}} \frac{m_Z^2}{m_{Z'}^2} \tilde{Y}_\phi + O\left(\frac{m_Z^4}{m_{Z'}^4}\right), \tag{6}$$

where θ_W is the SM Weinberg angle, and $\alpha_{\rm em}$ is the electromagnetic fine structure constant.

Other Z' couplings

$$v_f = \tilde{g} \frac{\tilde{Y}_{L,f} + \tilde{Y}_{R,f}}{2}, \qquad a_f = \tilde{g} \frac{\tilde{Y}_{R,f} - \tilde{Y}_{L,f}}{2}. \tag{7}$$

Lagrangian (4) leads to the interactions:

$$\begin{aligned}\mathcal{L}_{Z\bar{f}f} &= \frac{1}{2} Z_\mu \bar{f}\gamma^\mu \left[(v^{\rm SM}_{fZ} + \gamma^5 a^{\rm SM}_{fZ})\cos\theta_0 + (v_f + \gamma^5 a_f)\sin\theta_0\right] f, \\ \mathcal{L}_{Z'\bar{f}f} &= \frac{1}{2} Z'_\mu \bar{f}\gamma^\mu \left[(v_f + \gamma^5 a_f)\cos\theta_0 - (v^{\rm SM}_{fZ} + \gamma^5 a^{\rm SM}_{fZ})\sin\theta_0\right] f, \quad (8)\end{aligned}$$

where f is a SM fermion state; $v^{\rm SM}_{fZ}$, $a^{\rm SM}_{fZ}$ are the SM couplings of the Z-boson. The dimensionless couplings

$$\bar{a}_f = \frac{m_Z}{\sqrt{4\pi} m_{Z'}} a_f, \quad \bar{v}_f = \frac{m_Z}{\sqrt{4\pi} m_{Z'}} v_f, \quad (9)$$

can be constrained by experiments.

The couplings are correlated(Gulov, Skalozub (2000)):

$$\tilde{Y}_{\phi,1} = \tilde{Y}_{\phi,2} \equiv \tilde{Y}_\phi, \qquad \tilde{Y}_{L,f} = \tilde{Y}_{L,f^*}, \quad \tilde{Y}_{R,f} = \tilde{Y}_{L,f} + 2T_{3f}\, \tilde{Y}_\phi. \qquad (10)$$

Here 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 weak isospin.
Z' couplings to the vector and axial-vector fermion currents (7),

$$v_f - a_f = v_{f^*} - a_{f^*}, \qquad a_f = T_{3f}\tilde{g}\tilde{Y}_\phi. \qquad (11)$$

Hence it follows:

- The couplings of Z' , a_f, have the universal absolute value proportional to the Z' coupling to the scalar doublet.
- Z–Z' mixing angle θ_0 is determined by the a_f.

Since a_f is universal, we introduce the notation

$$\bar{a} = \bar{a}_d = \bar{a}_{e^-} = -\bar{a}_u = -\bar{a}_\nu, \tag{12}$$

and find

$$\theta_0 = -2\bar{a}\frac{\sin\theta_W \cos\theta_W}{\sqrt{\alpha_{em}}}\frac{m_Z}{m_{Z'}}. \tag{13}$$

From (11) it follows for each fermion doublet

$$\bar{v}_{f_d} = \bar{v}_{f_u} + 2\bar{a}. \tag{14}$$

Thus, Z' couplings can be parameterized by seven independent couplings

$$\bar{a}, \bar{v}_u, \bar{v}_c, \bar{v}_t, \bar{v}_e, \bar{v}_\mu, \bar{v}_\tau. \tag{15}$$

These relations (between numerically arbitrary parameters) are similar to the ones from the SM (for the specific values of the parameters)!.

Estimates from LEP1 and LEP2 experiments

MinD limits on Z' couplings from LEP1 and LEP2 at $1-2\sigma$ CL (Gulov, Skalozub (2010))

- Axial-vector coupling $\bar{a}$ can be constrained by LEP1 (through the mixing angle) and LEP2 ($e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$) data with ML value

$$\bar{a}^2 = 1.3 \times 10^{-5} \tag{16}$$

and 2σ CL interval:

$$0 < \bar{a}^2 < 3.61 \times 10^{-4}. \tag{17}$$

- Electron vector coupling $\bar{v}_e$ can be constrained by LEP2 ($e^+e^- \to e^+e^-$)

2σ CL interval:

$$4 \times 10^{-5} < \bar{v}_e^2 < 1.69 \times 10^{-4}. \tag{18}$$

Constrain $\bar{v}_u, \bar{v}_c, \bar{v}_t, \bar{v}_\mu, \bar{v}_\tau$ by the widest interval from 2σ CL intervals for $\bar{v}_e$, $\bar{a}$:

$$0 < \bar{v}_{other}^2 < 4 \times 10^{-4}. \tag{19}$$

Expected parameters for Z' searching

- spin 1
- charge 0
- mass $m_{Z'} \leq 2 - 3$ TeV, width $\Gamma_{Z'} = 150 - 200$ GeV
- mixing angle Θ_0
- coupling $\tilde{g}$
- axial-vector coupling constant $\bar{a}^2 = 1.3 \times 10^{-5}$
- vector coupling constant $4 \times 10^{-5} < \bar{v}_e^2 < 1.69 \times 10^{-4} (2\sigma\ CL)$

Observable for $\bar{a}$ in Drell-Yan process

- Cross-section (CS) $q\bar{q} \to l\bar{l}$

At parton level, Drell-Yan process

$$p\bar{p}(pp) \to Z' \to l\bar{l} + X \tag{20}$$

is reduced to quark annihilations $q\bar{q} \to (Z, \gamma, Z') \to l\bar{l}$.

Structure of the Z' boson contributions

$$\begin{aligned} \Delta\frac{d\sigma}{dz} &= \frac{d\sigma}{dz} - \big(\frac{d\sigma}{dz}\big)_{SM} = F_a(E,z)\bar{a}^2 \\ &+ F_{av}(E,z)a\bar{v}_q + F_{vv}(E,z)\bar{\,}_l\bar{v}_q + ..., z = \cos\theta \end{aligned} \tag{21}$$

where

$$F_a = \sum_{q=u,d} f_a^q(E,z), F_{av} = \sum_{q=u,d} f_{av}^q(E,z), F_{vv} = \sum_{q=u,d} f_{vv}^q(E,z)... \tag{22}$$

3 A_{FB} of Drell-Yan process at 7 and 8 TeV

Forward-backward asymmetry A_{FB}

Accounting for symmetries of form-factors, we introduce A_{FB}:

$$A_{FB} = \frac{\int\limits_{-1}^{0} \Delta \frac{d\sigma}{dz} dz - \int\limits_{0}^{1} \Delta \frac{d\sigma}{dz} dz}{\int\limits_{-1}^{1} \Delta \frac{d\sigma}{dz} dz} \tag{23}$$

It is determined by

$$A_{FB} = \sum_{i=a,av,vv} A^i, \tag{24}$$

and

$$A^a(\int\limits_{-1}^{1} \Delta \frac{d\sigma}{dz} dz) = \int\limits_{-1}^{0} F_a dz - \int\limits_{0}^{1} F_a dz, ... \tag{25}$$

Values of quark asymmetries A^a, A^{av}, A^{vv}

E (GeV)	100	300	600	800	1000
$A^a \times 10^{-7}$	51.7	6.2	6.7	8.7	14.7
$A^{av} \times 10^{-23}$	1610	1.3	1.3	2.6	5.3
$A^{vv} \times 10^{-23}$	74	0	0	0	0

Table 1.

- Differential CS $pp \to l\bar{l}$

$$\sigma_{AB} = \sum_q \int_0^1 dx_1 \int_0^1 dx_2 f_{q,A}(x_1, Q^2) f_{q,B}(x_2, Q^2) \times \sigma(q\bar{q} \to f\bar{f}), \quad (26)$$

$Q^2 = m_{Z'}$. Packet MSTW PDF was used.

Rapidities $y = \frac{1}{2}(y_{l^+} - y_{l^-}); Y = \frac{1}{2}(y_{l^+} - y_{l^-})$.

Variables in lepton CM system
Rapidities $y_{l^+} = -y_{l^-} = y_*$.

Recently, using this MI approach, and the RG relations, we analyze the CMS data on A_{FB} for the Drell-Yan process at 7 TeV and 8 TeV by means of indirect (interference) searches (Pevzner, Skalozub (2016)) and the ATLAS data on the differential cross sections at 13 TeV (Pevzner, Skalozub, Gulov, Pankov (2018)) by means of the direct searches.

The coupling of the Z' to the standard model fermions a_f^2, the couplings of the axial-vector to lepton vector currents $a_f v_l$ and the couplings of the axial-vector to quark vector currents $a_f v_q$ are derived at at 2 σ CL. The optimistic limits on $m_{Z'}$ are established as $3 < m_{Z'} < 7 - 8$ TeV.

The obtained results are in an agreement with that of obtained already for the LEP and Tevatron experiment data.

Role of the mixing θ_0 and the width $\Gamma_{Z'}$

Wide resonances

Interference and direct searches. Any amplitude has the form

$$F_{if} = F_{if}^{SM} + F_{if}^{Z'}, \quad (27)$$

where F^{SM} describes the SM contribution and $F^{Z'}$ the Z' part. In the cross sections, two types of terms present

$$\sigma^{inf.} \sim F_{if}^{SM} \times (F_{if}^{Z'})^{+}, \quad (28)$$

$$\sigma^{res.} \sim F_{if}^{Z'} \times (F_{if}^{Z'})^{+}. \quad (29)$$

The data treating depends on the choices:

1) energy is fare from the Z' mass pole; 2) energy is close to the Z' mass pole. In the case 1)interference the Z' width $\Gamma_{Z'}$ is not important.

For 2) it is important. Usually it is believed that $\Gamma_{Z'}/m_{Z'}$ $1-3$ per cent (NWA). Used for direct searches.

I. Recently, (Pevzner, Skalozub (2018)), it was demonstrated that the width $\Gamma_{Z'}/m_{Z'} \sim 1$ does not influences the Z boson width Γ_Z which is well measured at LEP experiments.

Thus, the wide Z' is not excluded.

From LEP data and results it follows that the Z - Z' mixing angle $\theta_0 \sim 10^{-4} - 10^{-3}$ is small. And $\Gamma_{Z'}/m_{Z'} \sim 0.1$. These states could be missed in the present day analysis based on NWA. In such a situation the indirect MI searches are preferable.

II. Let us analyze the permissible values of Z' couplings to SM fermions compatible with NWA (Pevzner, Skalozub, Gulov, Pankov (2018)).

We treated in MI method the data on the Drell-Yan processes accumulated at $\sqrt{13}$ TeV , 36.1 fb^{-1} by ATLAS Collaboration and obtained the values of the couplings a^2,..., mixing angle θ_0 and the mass $m_{Z'}$ by using the interference and the direct searching and compare the obtained results.

We performed the analysis of direct Z' search allowing to vary $M_{Z'}$ within the interval 1.25 TeV $< M_{Z'} <$ 4.5 TeV and obtained that $(\bar{a}^2)_{\rm max} \sim 10^{-6}$, $|\bar{a}\bar{v}_e|_{\rm max} \sim 10^{-6} - 10^{-5}$, $|\bar{a}\bar{v}_u|_{\rm max} \sim 10^{-6}$.

The model independent limits on the Z' fermion couplings were obtained for the first time for representative Z' signal mass points of $M_{Z'} =$ 2, 3, and 4 TeV by using the ATLAS data collected at the LHC.

The upper limit for the mixing angle $|\theta_0| < 10^{-4} - 10^{-3}$ was estimated.

This evaluations are consistent with the results obtained from the global LEP data. Direct and indirect searches are in agreement wih each other.

Notice, for all $M_{Z'}$ values of interest for LHC the width $\Gamma_{Z'}$ should be considerably smaller than the mass window ΔM_{ll} in order to meet the NWA condition.

We compute the LHC Z' production CS multiplied by the branching ratio into two leptons l^+l^-, $\sigma(pp \to Z') \cdot \mathrm{B}(Z' \to l^+l^-)$, as a function of three free parameters (a, v_e, v_u) at given Z' mass $M_{Z'}$ and compare it with the limits of $\sigma_{95\%\mathrm{CL}} \cdot B$ obtained from ATLAS data.

Due to the RG relations the CS of $pp \to Z' \to l^+l^- + X$ can be expressed through a, v_e, v_u , only. Hence any constraints on the Z' production CS at a given $M_{Z'}$ yield the corresponding constraints on these couplings.

Table 1: Model-independent upper limits at 95% C.L. on fermion couplings based on ATLAS dilepton production data in direct Z' search at 13 TeV

	$M_{Z'} = 2$ TeV	$M_{Z'} = 3$ TeV	$M_{Z'} = 4$ TeV
$\|a\|$	0.20	0.35	0.35
$\|\bar{a}\|$	0.003	0.002	0.002
$\|v_e\|$	1	1.1	1.1
$\|\bar{v}_e\|$	0.01	0.007	0.005
$\|v_u\|$	0.8	0.9	0.9
$\|\bar{v}_u\|$	0.01	0.007	0.005

Here it is assumed NWA $\Gamma_{Z'}/m_{Z'} \sim 0.01 - 0.03$.

Propositions and approaches for Z' searches

Global MI searches for Z' established at LEP, Tevatron and LHC have determined the same value of the mixing angle $|\theta_0| < 10^{-4} - 10^{-3}$.

Because of the smallness of θ_0, a large values of $\Gamma_{Z'}/m_{Z'} \sim 0.1 - 0.5$ (wide resonances) are not excluded by experiments.

These type of resonances requires other (not NWA) ways of searches.

1. Indirect MI methods with high statistics is of paramount interest.

They are weakly dependent on the $\Gamma_{Z'}$ values.

Due to RG relations, the θ_0 is strictly related with the axial vector coupling a_f. Therefore it is incorrect to neglect the $Z - Z'$ mixing (as it is often doing) in experiment data treating.

In theory

2. Construction of the effective Lagrangians for extended models

with the goal to estimate the actual values of the width $\Gamma_{Z'}$ as the function of the couplings in the hidden sectors

and to investigate the role of the mixing, which is regulated by the universal coupling a_f, in different processes.