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Model-dependent constraints on the mass of extra Z'-boson at the next-generation electron-positron colliders

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Introduction

The extra neutral boson (Z') is a spin-one hypothetical particle without charge.
The existence of the Z' is the natural consequence of the extensions of the SM based on larger gauge symmetry groups.
The goal of Z' search is relevant because it is contained in the ILC (Japan) and CLIC (CERN) research program.
Taking into account the lower bound on the $M_{Z'} \sim 5$ TeV from 'direct' searches at the LHC, only 'indirect' signatures of the Z' exchanges can be expected at the ILC and CLIC.

The main goal:

estimate the possibility of improving constraints on the Z' at the ILC and CLIC based on the developed methodology.

Planned parameters at the ILC and CLIC

$\sqrt{s}$, TeV	ILC	0.25	Upgrade	0.35	Upgrade	0.5	Upgrade	1
$\mathcal{L}_{int}$, ab^{-1}		2		0.2		4		8
Run time, years		10		1		9		?

beam polarization e^+/e^- : $\pm$ 30(60?)/80 %.

Tab. 1: The ILC parameters.

$\sqrt{s}$, TeV	CLIC	0.35	Upgrade	1.5	Upgrade	3
$\mathcal{L}_{int}$, ab^{-1}		1		2.5		5
Run time, years		8		8		8

beam polarization e^+/e^- : $\pm$ 0/80 %.

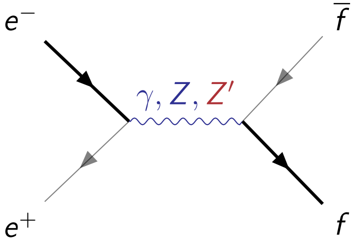
Tab. 2: The CLIC parameters.

Why ILC and CLIC?

1. *Small background;*
2. *High integral luminosity;*
3. *Collision energy on the order of TeV;*
4. *The possibility of polarization e^+ and e^- beam;*

For Z' search:

1. *All fermion couplings to the Z' can be constrained separately;*
2. *Different observables (cross section, A_{FB}, A_{LR} and others).*



Methodology

Stages:

1. *Derive the differential cross section for the process* $e^+e^- \to \bar{f}f$ *($f \neq e$) with new linear* Z' *parameters;*
2. *Use statistical hypothesis test to obtain constraints on the* $\Delta Q_{1,2,3}$ *deviation parameters;*
3. *Perform statistical processing of the result and obtain confidence intervals for the required confidence level;*
4. *Use two observables to compose a system of equations and obtain constraints on the* $\Delta q_{\lambda_e\lambda_f}$ *deviation parameters;*
5. *Use the total width* $\Gamma(Z' \to \bar{f}f)$ *to obtain model-dependent constraints (lower limits) on the* Z' *mass for the SSM, LRS and* $E_6(\chi, \psi, \eta)$ *models.*

Differential cross section

$$\frac{d\sigma^{SM+Z'}}{dz}(P_{e^-}, P_{e^+}) = N_C(1 - P_{e^-}P_{e^+})\frac{\alpha^2\beta\pi}{8s}\times$$
$$\times\left[(1 - z\beta_f)^2 Q_1^{SM+Z'} + (1 + z\beta_f)^2 Q_2^{SM+Z'} + Q_3^{SM+Z'}\right] \ . \ (1)$$

where $z \equiv \cos\theta$, $\beta_f = (1 - 4m_f^2/s)^{\frac{1}{2}}$.

$$Q_1^{SM+Z'} = p_{eff}^- |q_{LR}^{SM+Z'}|^2 + p_{eff}^+ |q_{RL}^{SM+Z'}|^2 \ ,$$
$$Q_2^{SM+Z'} = p_{eff}^- |q_{LL}^{SM+Z'}|^2 + p_{eff}^+ |q_{RR}^{SM+Z'}|^2 \ ,$$
$$Q_3^{SM+Z'} = 2\eta_f^2 \left(p_{eff}^- \Re[q_{LL}^{SM+Z'} q_{LR}^{*SM+Z'}] + p_{eff}^+ \Re[q_{RL}^{SM+Z'} q_{RR}^{*SM+Z'}]\right) \ , \qquad (2)$$

here $\eta_f = (1 - \beta_f^2)^{\frac{1}{2}}$, $p_{eff}^{\pm} = 1 \pm P_{eff}$ *where* $P_{eff} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^-}P_{e^+}}$.

$$q_{LL}^{SM+Z'} = \sum_i \frac{g_{i,e}^{L} g_{i,f}^{L} s}{s - M_i^2 + iM_i\Gamma_i}\ , \quad q_{RR}^{SM+Z'} = \sum_i \frac{g_{i,e}^{R} g_{i,f}^{R} s}{s - M_i^2 + iM_i\Gamma_i},$$

$$q_{LR}^{SM+Z'} = \sum_i \frac{g_{i,e}^{L} g_{i,f}^{R} s}{s - M_i^2 + iM_i\Gamma_i}\ , \quad q_{RL}^{SM+Z'} = \sum_i \frac{g_{i,e}^{R} g_{i,f}^{L} s}{s - M_i^2 + iM_i\Gamma_i}\ , \tag{3}$$

$$where \quad i \equiv \gamma, Z^0, Z'.$$

$$g_{\gamma,f}^{\lambda_f} = -Q_f\ ,$$

$$g_{Z^0,f}^{\lambda_f} = \left(\delta_{\lambda_f,-} t_f/2 - Q_f s_w^2\right)/(s_w c_w)\ , \quad \lambda_f = \ +\ (R)\ or\ -\ \ (L)\ . \tag{4}$$

χ^2 test and deviation parameters

$$\chi^2(\Delta Q_i) = \sum_{i=1}^{bins} \left[\frac{\Delta N_i(\Delta Q_i)}{\delta N_i^{SM}} \right]^2 \leq \chi^2_{min} + \chi^2_{C.L.} \ , \tag{5}$$

$$\text{where} \quad \Delta N_i = N_i^{SM+Z'}(Q_i^{SM+Z'}) - N_i^{SM} \ ,$$

$$\delta N_i^{SM} = \sqrt{N_i^{SM}(1 + \delta^2_{syst} N_i^{SM})}, \quad \chi^2_{min} = \chi^2(0) = 0 \ .$$

$$N_i^{model} = \mathcal{L}_{int} \times c_P \times \varepsilon_f \times \int_{z_i}^{z_{i+1}} \left(\frac{d\sigma^{model}}{dz} \right) dz. \tag{6}$$

$$\begin{aligned} \Delta Q_1 \left(p^-_{eff}, p^+_{eff}\right) &= Q_1^{SM+Z'} - Q_1^{SM} = p^-_{eff} \Delta q_{LR} + p^+_{eff} \Delta q_{RL} \ , \\ \Delta Q_2 \left(p^-_{eff}, p^+_{eff}\right) &= Q_2^{SM+Z'} - Q_2^{SM} = p^-_{eff} \Delta q_{LL} + p^+_{eff} \Delta q_{RR} \ , \end{aligned} \tag{7}$$

$$\text{where} \quad \Delta q_{\lambda_e \lambda_f} = |q_{\lambda_e \lambda_f}^{SM+Z'}|^2 - |q_{\lambda_e \lambda_f}^{SM}|^2.$$

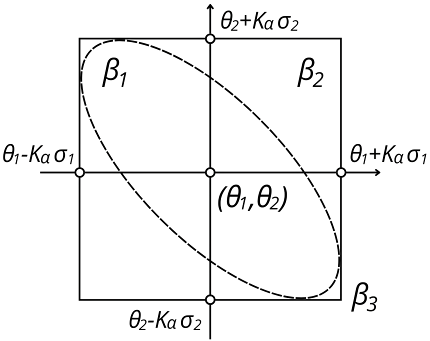


Fig. 2 – Standard error ellipse.

β_1 *is the probability of being in the ellipse;*

$$\beta_2(\rho_{12}) = Prob[\theta_1 - K_\alpha\sigma_1 \leq \Delta Q_1 \leq \theta_1 + K_\alpha\sigma_1 \text{ and } \theta_2 - K_\alpha\sigma_2 \leq \Delta Q_2 \leq \theta_2 + K_\alpha\sigma_2]\ ;$$

$$\beta_3 = Prob[\theta_1 - K_\alpha\sigma_1 \leq \Delta Q_1 \leq \theta_1 + K_\alpha\sigma_1 \text{ or } \theta_2 - K_\alpha\sigma_2 \leq \Delta Q_2 \leq \theta_2 + K_\alpha\sigma_2]\ .$$

For our case: $\rho_{12} \approx -0.2$;
for $\beta_2 = 68$ %, $\beta_1 \approx 59.7$ %;
for $\beta_2 = 95$ %, ≈ 91.7 %.
We introduce two observables ΔN_i^a *and* ΔN_i^b *for different polarization (a and b), to obtain:*

$$\Delta q_{LR} = \frac{p_{eff}^{+,b}\Delta Q_1^a - p_{eff}^{+,a}\Delta Q_1^b}{p_{eff}^{-,a}p_{eff}^{+,b} - p_{eff}^{+,a}p_{eff}^{-,b}}\ ,$$

$$\Delta q_{RL} = \frac{p_{eff}^{-,a}\Delta Q_1^b - p_{eff}^{-,b}\Delta Q_1^a}{p_{eff}^{-,a}p_{eff}^{+,b} - p_{eff}^{+,a}p_{eff}^{-,b}}\ ,$$

$$\Delta q_{LL} = \frac{p_{eff}^{+,b}\Delta Q_2^a - p_{eff}^{+,a}\Delta Q_2^b}{p_{eff}^{-,a}p_{eff}^{+,b} - p_{eff}^{+,a}p_{eff}^{-,b}}\ ,$$

$$\Delta q_{RR} = \frac{p_{eff}^{-,a}\Delta Q_2^b - p_{eff}^{-,b}\Delta Q_2^a}{p_{eff}^{-,a}p_{eff}^{+,b} - p_{eff}^{+,a}p_{eff}^{-,b}}\ . \tag{8}$$

The total width of the Z'

$$\Gamma(Z' \to f\bar{f}) = \sum_f N_C \frac{\alpha M_{Z'}}{6} \left(1 - 4\frac{m_f^2}{M_{Z'}^2}\right)^{\frac{1}{2}} \times$$
$$\times \left[\left({g^L_{Z',f}}^2 + {g^R_{Z',f}}^2\right)\left(1 - \frac{m_f^2}{M_{Z'}^2}\right) + 6 g^L_{Z',f} g^R_{Z',f} \frac{m_f^2}{M_{Z'}^2} \right]. \tag{9}$$

In the SSM, all couplings are equal SM.

f	e, μ, τ	d, s, b	u, c, t
$g^L_{Z',f}/g_{Z'}$	$\frac{1}{2\alpha_{LRS}}$	$-\frac{1}{6\alpha_{LR}}$	$-\frac{1}{6\alpha_{LRS}}$
$g^R_{Z',f}/g_{Z'}$	$\frac{1}{2\alpha_{LRS}} - \frac{\alpha_{LRS}}{2}$	$-\frac{1}{6\alpha_{LRS}} - \frac{\alpha_{LRS}}{2}$	$-\frac{1}{6\alpha_{LRS}} + \frac{\alpha_{LRS}}{2}$

: LRS model

where $\alpha_{LRS} = \sqrt{c_W^2/s_W^2 - 1}$ $(g_{Z'} = 1/c_w)$.

f	e, μ, τ	d, s, b	u, c, t
$g^L_{Z',f}/g_{Z'}$	$3A + B$	$-A + B$	$-A + B$
$g^R_{Z',f}/g_{Z'}$	$A - B$	$-3A - B$	$A - B$

: E_6 models

where $A = \cos\beta/2\sqrt{6}$ *and* $B = \sqrt{10}/12 \sin\beta$
$(\beta_\chi = 0,\ \beta_\psi = \pi/2$ *and* $\beta_\eta = \pi - \arctan\sqrt{5/3})$.

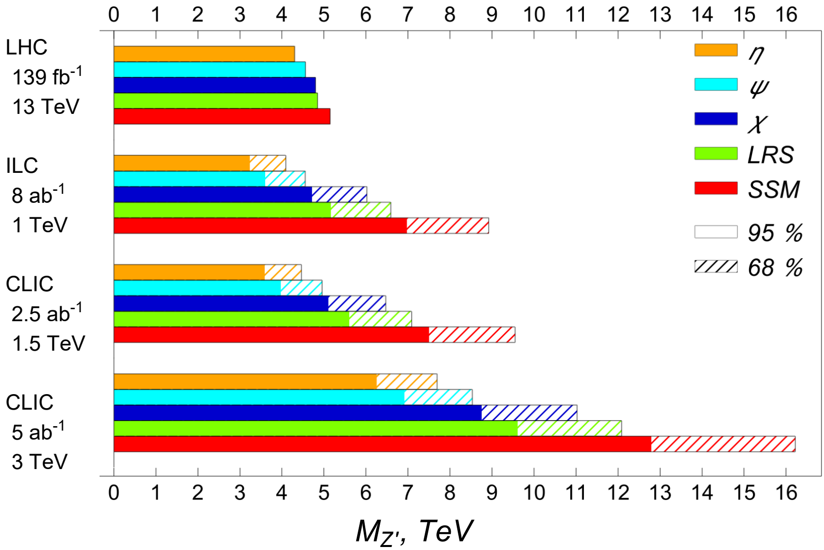


Fig. 3 – The comparison of Z' discovery reaches at the LHC and the model-dependent constraints at the ILC and CLIC for the $e^+e^- \to \tau^+\tau^-$.

Conclusion

- *The methodology of model-dependent Z' analysis is presented;*
- *Model-dependent constraints (lower bounds) on the Z' mass are obtained for a possible experiments at the ILC and CLIC (without $Z - Z'$ mixing).*

Analyzing the obtained phenomenological constraints, we can conclude that potential possibilities of the ILC and CLIC allow us to improve the LHC constraints on the Z'.

Thank you for attention!

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