Probing and identifying new physics scenarios at a linear collider with polarized beams

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Outline

- Introduction
- Effects of heavy lepton mixing (*E* and *N*) and *Z-Z'* mixing within E_6 models in W^+W^{--} production at ILC with
  - * E_{cm}=0.5 TeV and 1 TeV, L_{int}=500 fb^{-1} – 1ab^{-1} ;
  - * low energy option: E_{cm}= 350 GeV.
- High sensitivity of $e^+e^- \rightarrow W^+W^-$ to *NP* at $E_{cm} >> 2M_W$ (violation of the SM gauge cancellation mechanism).
- Discovery reach on heavy lepton couplings and masses.
- Main goal: lepton mixing effects vs *Z'*, AGC, LED in W^+W^- production.
- Identification of heavy lepton effects with A_{double}.
- Conclusion

Introduction

• Heavy neutral gauge ***Z'***-bosons, are predicted by many theoretical schemes of physics beyond the SM, and their properties represent important tests of such extended models.

Current limits on Z' mass from LHC(8TeV):

M(Z') >2.6—2.9 TeV.

• For ILC with E_{cm} = 0.5 TeV and 1 TeV only indirect signatures of ***Z'*** exchanges may occur at future colliders, through deviations of the measured observables (cross sections, asymmetries etc.) from the SM predictions.

• Another characteristic of extended models is the existence of new matter, new heavy leptons and quarks (the **27** fundamental representation **in E_6**).

Two heavy left- and righthanded *SU(2)* exotic lepton doublets:

$$\begin{pmatrix} N \\ E^- \end{pmatrix}_L , \qquad \begin{pmatrix} N \\ E^- \end{pmatrix}_R .$$

• In the case of indirect discovery the effects may be subtle and many different new physics (NP) scenarios may lead to the same or similar experimental signatures.

It is clear that determination of the origin of the NP in these cases will prove more difficult and new tools must be available to deal with this potentiality.

• Here, we consider the possibility of uniquely identifying the effects of heavy neutral lepton exchange from *Z'* effects mixing within the same class of E_6 models and analogous ones due to competitor models (AGC, LED) with a double polarization asymmetry A_{double}. [arXiv:1303.3845v1 [hep-ph], to appear in PRD]

[see also talk by J. Kalinowski, this workshop]

Lepton and Z-Z' mixing

Weak basis

In the weak-eigenstate basis, the leptonic $SU(2)\times U(1)\times U(1)'$ interaction:

$$-L = e\left(\tilde{J}^{\mu}_{\text{em}}A_{\mu} + \tilde{J}^{\mu}_{Z}Z_{\mu} + \tilde{J}^{\mu}_{Z'}Z'_{\mu}\right) + \frac{g}{\sqrt{2}}\left(\tilde{J}^{\mu}_{W}W_{\mu} + \text{h.c.}\right),$$

$$\tilde{J}^{\mu}_{V} = \sum_{a} \bar{\varepsilon}^{0}_{a}\gamma^{\mu}Q^{\varepsilon^0}_{a}\varepsilon^{0}_{a}, \qquad \tilde{J}^{\mu}_{W} = \sum_{a} \bar{\eta}^{0}_{a}\gamma^{\mu}G^{\eta^0}_{a}\varepsilon^{0}_{a},$$

$$\varepsilon^{0}_{a} = \begin{pmatrix} e^{0}_{a} \\ E^{0}_{a} \end{pmatrix}, \qquad \eta^{0}_{a} = \begin{pmatrix} \nu^{0}_{a} \\ N^{0}_{a} \end{pmatrix},$$

coupling matrices: $Q^{\varepsilon^0}_{\text{em},a} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}, \quad g^{\varepsilon^0}_{a} = \begin{pmatrix} g^{e^0}_{a} & 0 \\ 0 & g^{E^0}_{a} \end{pmatrix}, \quad g'^{\varepsilon^0}_{a} = \begin{pmatrix} g'^{e^0}_{a} & 0 \\ 0 & g'^{E^0}_{a} \end{pmatrix},$

$$G^{\eta^0}_{a} = \begin{pmatrix} G^{\nu^0}_{a} & 0 \\ 0 & G^{N^0}_{a} \end{pmatrix}$$

$$g^{\varepsilon^0}_{a} = (T^{\varepsilon^0}_{3a} - Q^{\varepsilon^0}_{\text{em},a}s^2_W)g_Z, \qquad g_Z = 1/s_W c_W$$

$$e = \sqrt{4\pi\alpha_{\text{em}}} \qquad g = e/s_W$$

Z' couplings to fermions in E_6

$$g_L^{\prime e^0} = (3A + B) g_{Z'}, \quad g_R^{\prime e^0} = (A - B) g_{Z'},$$

$$g_L^{\prime E^0} = (-2A - 2B) g_{Z'}, \quad g_R^{\prime E^0} = (-2A + 2B) g_{Z'},$$

$$g_{Z'} = 1/c_W \quad A = \cos\beta/(2\sqrt{6}) \qquad B = \sqrt{10}\sin\beta/12$$

$$J_W: \quad G_L^{\nu^0} = 1 \qquad G_R^{\nu^0} = 0 \qquad G_a^{N^0} = -2T_{3a}^E$$

β species the orientation of the *U(1)'* generator in the E_6 group space:

$$Z'_\chi \qquad \beta = 0$$

$$Z'_\psi \qquad \beta = \pi/2$$

$$Z'_\eta \qquad \beta = -\arctan\sqrt{5/3}$$

Fermion mass basis

Assumption: "exotic" fermions only mix with the standard ones within the **same family**, which assures the absence of tree-level generation-changing neutral currents.

Mass eigenstates:

$$\varepsilon_a = \begin{pmatrix} e_a \\ E_a \end{pmatrix}, \qquad \eta_a = \begin{pmatrix} \nu_a \\ N_a \end{pmatrix}.$$

relation with weak eigenstates: $\varepsilon_a = U(\psi_{1a})\varepsilon_a^0; \qquad \eta_a = U(\psi_{2a})\eta_a^0,$

unitary mixing matrices $U(\psi_{1a})$ and $U(\psi_{2a})$ diagonalize the charged and neutral fermion mass matrices, respectively:

$$U(\psi_{1a}) = \begin{pmatrix} \cos\psi_{1a} & \sin\psi_{1a} \\ -\sin\psi_{1a} & \cos\psi_{1a} \end{pmatrix} \equiv \begin{pmatrix} c_{1a} & s_{1a} \\ -s_{1a} & c_{1a} \end{pmatrix}, \qquad U(\psi_{2a}) = \begin{pmatrix} \cos\psi_{2a} & \sin\psi_{2a} \\ -\sin\psi_{2a} & \cos\psi_{2a} \end{pmatrix} \equiv \begin{pmatrix} c_{2a} & s_{2a} \\ -s_{2a} & c_{2a} \end{pmatrix}.$$

In the fermion-mass-eigenstate basis:

$$-L = e\left(J^{\mu}_{\rm em} A_{\mu} + J^{\mu}_{Z} Z_{\mu} + J^{\mu}_{Z'} Z'_{\mu}\right) + \frac{g}{\sqrt{2}}\left(J^{\mu}_{W} W_{\mu} + \text{h.c.}\right)$$

$$J^{\mu}_{V} = \sum_a \bar{\varepsilon}_a \gamma^{\mu} Q^{\varepsilon}_a \varepsilon_a, \qquad J^{\mu}_{W} = \sum_a \bar{\eta}_a \gamma^{\mu} G^{\eta}_a \varepsilon_a.$$

$$g_a^{\varepsilon} = \begin{pmatrix} g_a^{e} & g_a^{eE} \\ g_a^{eE} & g_a^{E} \end{pmatrix}, \qquad g_a^{\prime\varepsilon} = \begin{pmatrix} g_a^{\prime e} & g_a^{\prime eE} \\ g_a^{\prime eE} & g_a^{\prime E} \end{pmatrix}, \quad G_a^{\eta} = \begin{pmatrix} G_a^{\nu} & G_a^{\nu E} \\ G_a^{Ne} & G_a^{N} \end{pmatrix}.$$

In J_W^{μ} the exotic-lepton mixings modify:

1) left-handed currents,

2) induce an admixture with the right-handed currents,

3) off-diagonal term in J_W^{μ} induces NWe couplings ➔

additional *t*-channel exotic-lepton-exchange in $e^+e^- \to W^+W^-$.

$$g_a^{e} = g_a^{e^0} c_{1a}^2 + g_a^{E^0} s_{1a}^2, \qquad g_a^{\prime e} = g_a^{\prime e^0} c_{1a}^2 + g_a^{\prime E^0} s_{1a}^2;$$

$$G_L^{\nu} = c_{1L} c_{2L} - 2\, T_{3L}^{E}\, s_{1L}\, s_{2L}, \qquad G_R^{\nu} = -2\, T_{3R}^{E}\, s_{1R} s_{2R};$$

$$G_L^{Ne} = -s_{2L} c_{1L} - 2\, T_{3L}^{E} c_{2L}\, s_{1L}, \qquad G_R^{Ne} = -2\, T_{3R}^{E}\, c_{2R} s_{1R}.$$

Present limits: $s_{1a}^2\,,\ s_{2a}^2 \sim 0.01,\qquad m_N > 100\ \text{GeV}$

Z-Z' mixing

$$\begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix} = \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} Z \\ Z' \end{pmatrix},$$

Z, Z' - weak eigenstates, Z_1, Z_2 – mass eigenstates, ϕ - mixing angle.

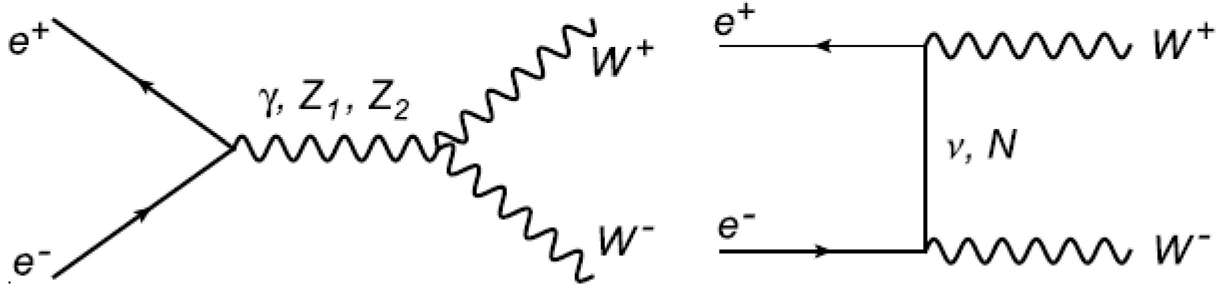
$$g_{1a}^{e} = g_{a}^{e} \cos\phi + g_{a}^{\prime e} \sin\phi; \qquad g_{2a}^{e} = -g_{a}^{e} \sin\phi + g_{a}^{\prime e} \cos\phi.$$

Current limits are of the order $|\phi| \sim \text{few} \times 10^{-3}.$

$$\tan^2\phi = \frac{M_Z^2 - M_1^2}{M_2^2 - M_Z^2} \simeq \frac{2M_Z \Delta M}{M_2^2}$$

$\Delta M = M_Z - M_1 > 0,$ mass shift due to Z-Z' mixing.

Polarized cross section



The polarized cross section:

$$\frac{d\sigma\left(P_L^-,P_L^+\right)}{d\cos\theta}=\frac{1}{4}\left[\left(1+P_L^-\right)\left(1-P_L^+\right)\frac{d\sigma^{RL}}{d\cos\theta}+\left(1-P_L^-\right)\left(1+P_L^+\right)\frac{d\sigma^{LR}}{d\cos\theta}\right.$$
$$\left.+\left(1+P_L^-\right)\left(1+P_L^+\right)\frac{d\sigma^{RR}}{d\cos\theta}+\left(1-P_L^-\right)\left(1-P_L^+\right)\frac{d\sigma^{LL}}{d\cos\theta}\right],$$

P_L^- (P_L^+) are degrees of longitudinal polarization of e^- (e^+),

θ the scattering angle of the W^-.

For $e_a^- e_b^+ \to W_\alpha^- W_\beta^+$:

$$\frac{d\sigma_{\alpha\beta}^{ab}}{d\cos\theta} = C \sum_{k=0}^{k=2} F_k^{ab} O_{k\,\alpha\beta},$$

where $C = \pi \alpha_{e.m.}^2 \beta_W / 2s$, $\beta_W = (1 - 4M_W^2/s)^{1/2}$ the W velocity in the CM frame,

and the helicities of the initial $e^- e^+$ and final $W^- W^+$ states:

$$ab = (RL,\ LR,\ LL,\ RR), \qquad \alpha\beta = (LL,\ TT,\ TL),$$

O_k - kinematical functions.

LR case:

t-channel ν, *N*:

$$F_0^{LR} = \frac{1}{16 s_W^4}\left[\left(G_L^{\nu}\right)^2 + r_N\left(G_L^{Ne}\right)^2\right]^2,$$

s-channel γ, Z_1, Z_2:

$$F_1^{LR} = 2\left[1 - g_{WWZ_1} g_{1L}^e \chi_1 - g_{WWZ_2} g_{2L}^e \chi_2\right]^2,$$

Interference of *s*- and *t*-channels:

$$F_2^{LR} = -\frac{1}{2 s_W^2}\left[\left(G_L^{\nu}\right)^2 + r_N\left(G_L^{Ne}\right)^2\right]\left[1 - g_{WWZ_1} g_{1L}^e \chi_1 - g_{WWZ_2} g_{2L}^e \chi_2\right],$$

$$\chi_j = s/(s - M_j^2 + iM_j\Gamma_j), \quad r_N = t/(t - m_N^2), \quad t = M_W^2 - s/2 + s\cos\theta\beta_W/2,$$

m_N is the mass of *N*, $g_{WWZ_1} = g_{WWZ}\cos\phi$, $g_{WWZ_2} = -g_{WWZ}\sin\phi$, $g_{WWZ} = \cot\theta_W$

RL case: *L* → *R*

LL and RR cases: there is only N-exchange contribution

$$F_0^{LL} = F_0^{RR} = \frac{1}{16 s_W^4} r_N^2 \left(G_L^{Ne} G_R^{Ne}\right)^2.$$

Discovery reach on heavy lepton couplings

No Z-Z' mixing

Only lepton mixing and no *Z-Z'* mixing, i.e. $\phi = 0$. Since $s_i^2 \sim 0.01$, we can expect that retaining only the terms of order s_1^2, s_2^2 and $s_1 s_2$ in the cross section should be an adequate approximation.

$$G_L^{Ne} = s_{1L} - s_{2L}, \qquad G_R^{Ne} = s_{1R}$$

$$g_L^e = g_L^{e^0}, \qquad g_R^e = g_R^{e^0} - \frac{1}{2}(G_R^{Ne})^2 g_Z,$$

$$G_L^\nu = G_L^{\nu^0} - \frac{1}{2}(G_L^{Ne})^2, \qquad G_R^\nu = s_{1R} s_{2R}.$$

in the adopted approximation the cross section allows to constrain basically the pair of heavy lepton couplings squared, $((G_L^{Ne})^2, (G_R^{Ne})^2)$

χ^2 – *analysis:*

The sensitivity of the polarized differential cross section to the couplings $(G_L^{Ne})^2$ and $(G_R^{Ne})^2$: divide the angular range $|\cos\theta| \leq 0.98$ into 10 equal bins:

$$N(i) = L_{\text{int}}\, \sigma_i\, \varepsilon_W ,$$

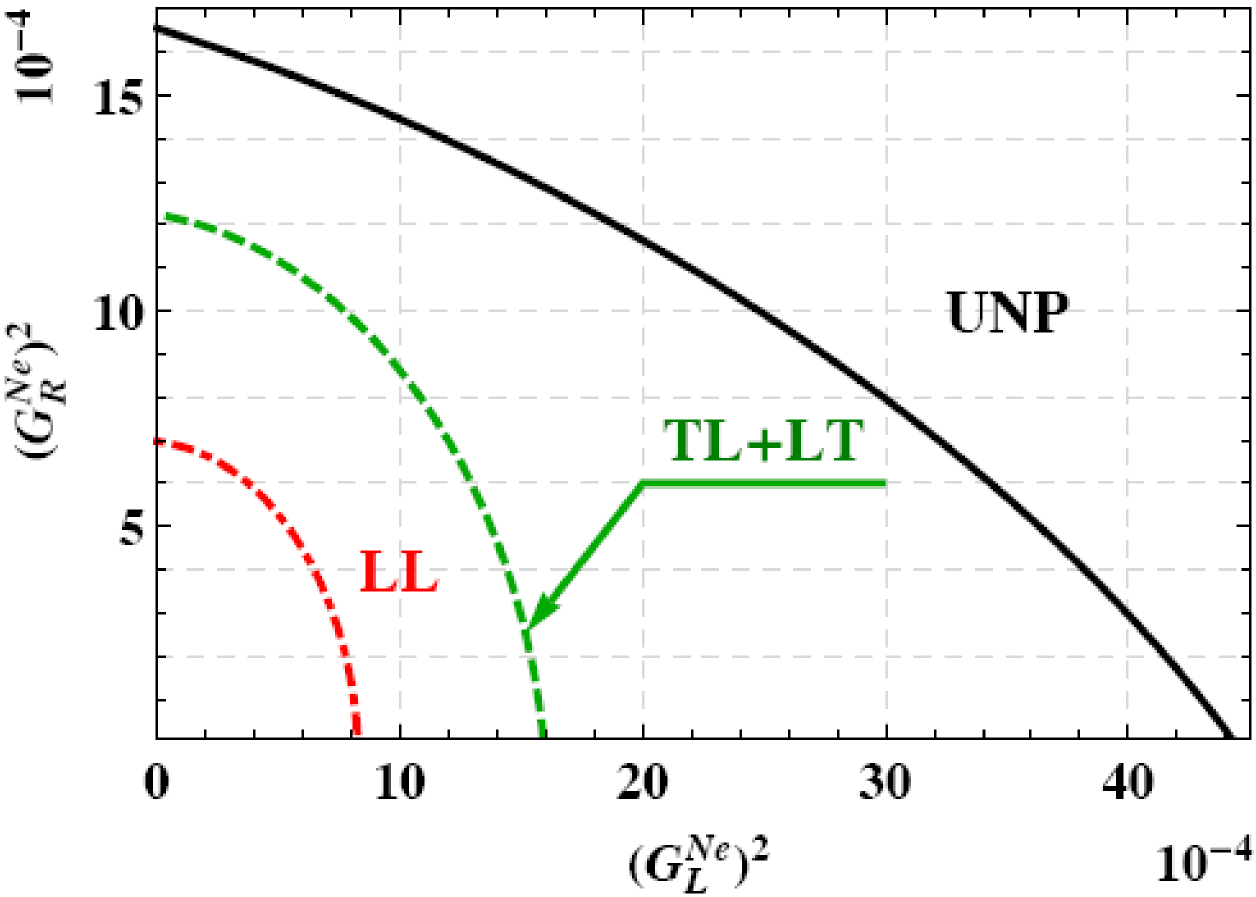
ε_W (≈ 0.3) - efficiency for $W^+W^- \to l\,\nu + 2j$ *(l=e, μ)* reconstruction.

$$\delta P_L^-/P_L^- = \delta P_L^+/P_L^+ = 0.5\%, \quad |P_L^-| = 0.8, \quad |P_L^+| = 0.6, \quad \delta\varepsilon_W/\varepsilon_W = 0.5\%.$$

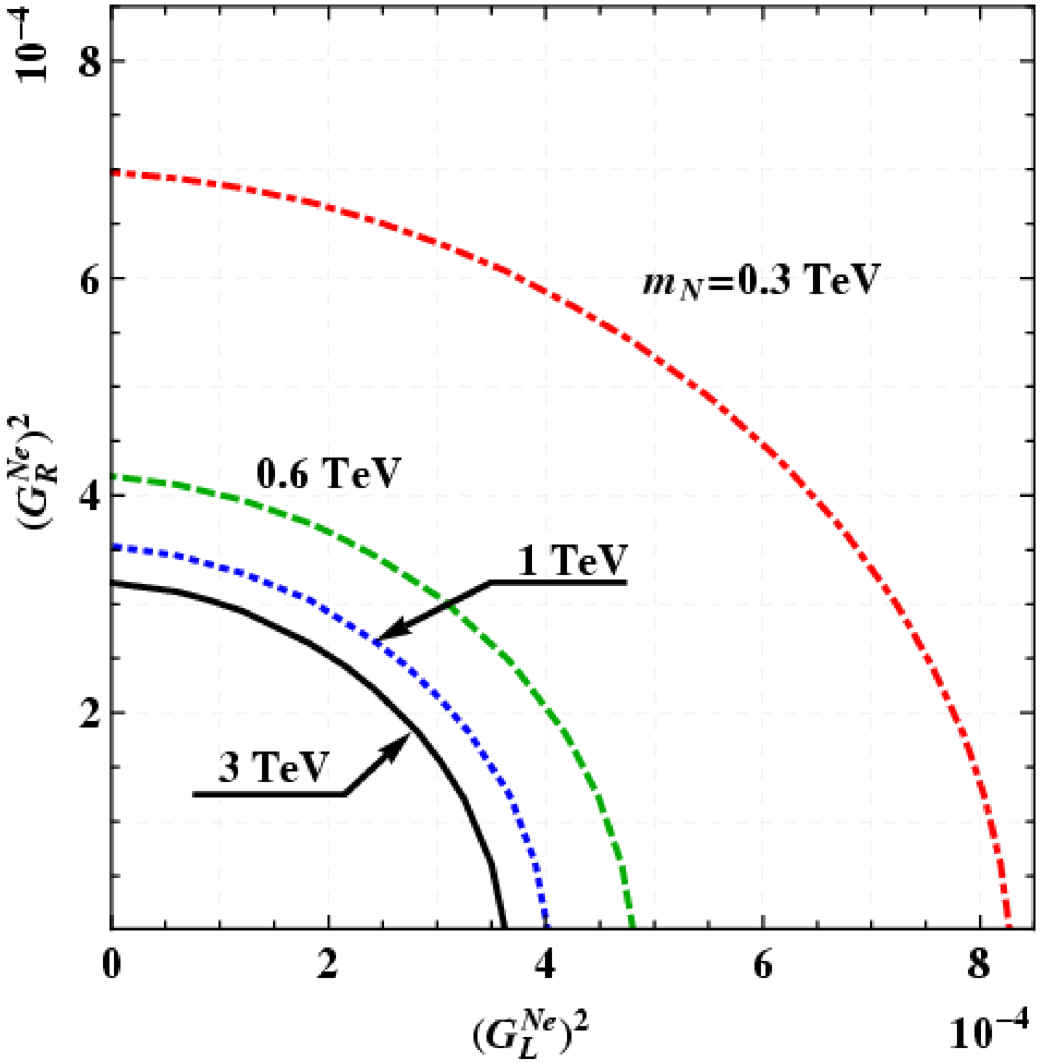
Initial-state QED corrections to on-shell $W^\pm$ pair production in the flux function approach.

Discovery reach: $\chi^2 \leq \chi^2_{min} + \chi^2_{\text{CL}}$.

$$\Delta\sigma_{LR} \equiv \sigma_{\text{NP}} - \sigma_{\text{SM}} \propto (G_L^{Ne})^2\,(1 - r_N).$$



Discovery reach (95% C.L.) on the heavy neutral lepton couplings $(G_L^{Ne})^2$ and $(G_R^{Ne})^2$ obtained from differential polarized cross sections with ($P_L^- = \pm 0.8,\ P_L^+ = \mp 0.6$) and different sets of $W^\pm$ polarizations. Here, $\sqrt{s} = 0.5$ TeV, $\mathcal{L}_{\rm int} = 0.5$ ab^{-1} and $m_N = 0.3$ TeV.

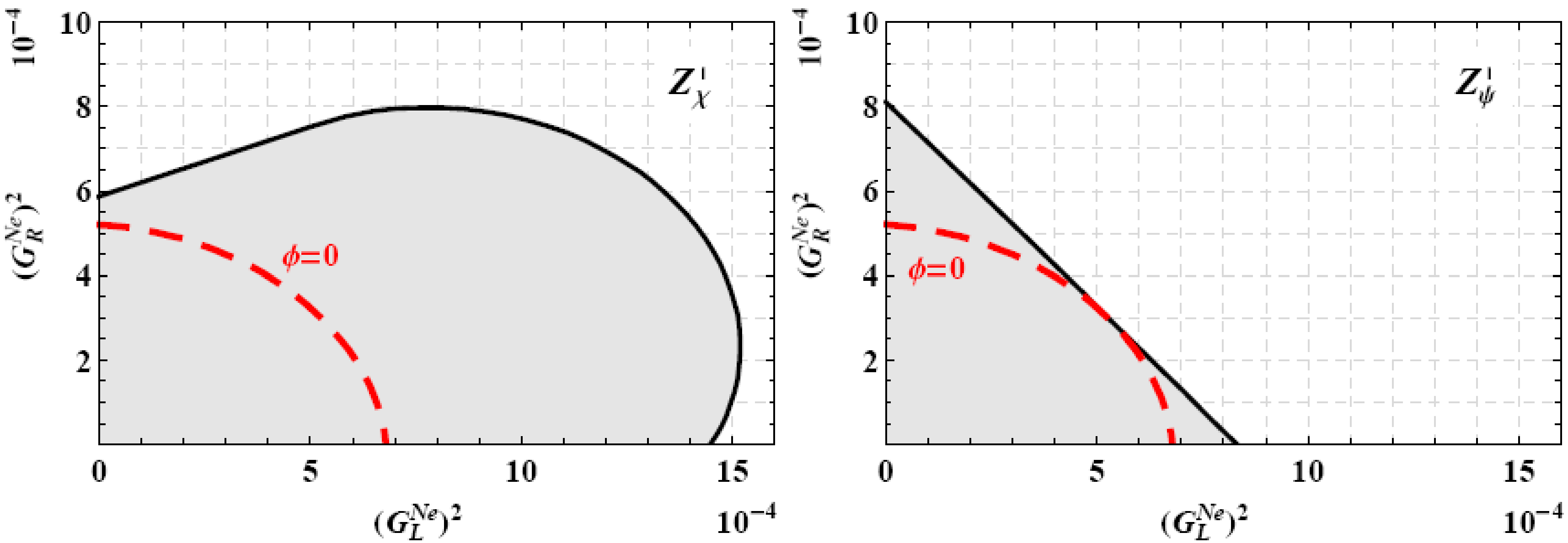


Same as in prev. fig. but obtained from the differential polarized cross sections $d\sigma(W_L^+W_L^-)/dz$ only, with $(P_L^- = \pm 0.8,\ P_L^+ = \mp 0.6)$ and different values of the lepton mass $m_N = 0.3$ TeV, 0.6 TeV, 1 TeV and 3 TeV. Here, $\sqrt{s} = 0.5$ TeV and $\mathcal{L}_{\rm int} = 0.5$ ab^{-1}.

Including Z-Z' mixing

For Z'_ψ - model: $-0.0018 < \phi < 0.0009$, for Z'_χ: $-0.0016 < \phi < 0.0006$

Within a specific *Z'* model and with fixed m_N, the χ^2 function basically depends on three parameters: $\phi,\ (G_L^{Ne})^2,\ (G_R^{Ne})^2$.



Discovery reach at 95% CL on the heavy neutral lepton coupling plane $((G_L^{Ne})^2, (G_R^{Ne})^2)$ at $m_N = 0.3$ TeV in the case where both lepton mixing and Z-Z' mixing are simultaneously allowed for the Z'_χ model (left panel) and the Z'_ψ model (right panel), obtained from combined analysis of polarized differential cross sections $d\sigma(W_L^+W_L^-)/dz$ at different sets of polarization, $P_L^- = \pm 0.8$, $P_L^+ = \mp 0.6$, at the ILC with $\sqrt{s} = 0.5$ TeV and $\mathcal{L}_{\rm int} = 1$ ab^{-1}. The dashed curves labelled "$\phi = 0$" refer to the case of no Z-Z' mixing.

Identification of heavy lepton effects with A_{double}

$$A_{\text{double}}=\frac{\sigma(P_1,-P_2)+\sigma(-P_1,P_2)-\sigma(P_1,P_2)-\sigma(-P_1,-P_2)}{\sigma(P_1,-P_2)+\sigma(-P_1,P_2)+\sigma(P_1,P_2)+\sigma(-P_1,-P_2)},\quad \text{where}\quad P_1=|P_L^-|,\ P_2=|P_L^+|,$$

$$A_{\text{double}}=P_1P_2\frac{(\sigma^{RL}+\sigma^{LR})-(\sigma^{RR}+\sigma^{LL})}{(\sigma^{RL}+\sigma^{LR})+(\sigma^{RR}+\sigma^{LL})}.$$

$$\sigma_{\text{SM}}=\frac{1}{4}\left[\left(1+P_L^-\right)\left(1-P_L^+\right)\sigma_{\text{SM}}^{RL}+\left(1-P_L^-\right)\left(1+P_L^+\right)\sigma_{\text{SM}}^{LR}\right].$$

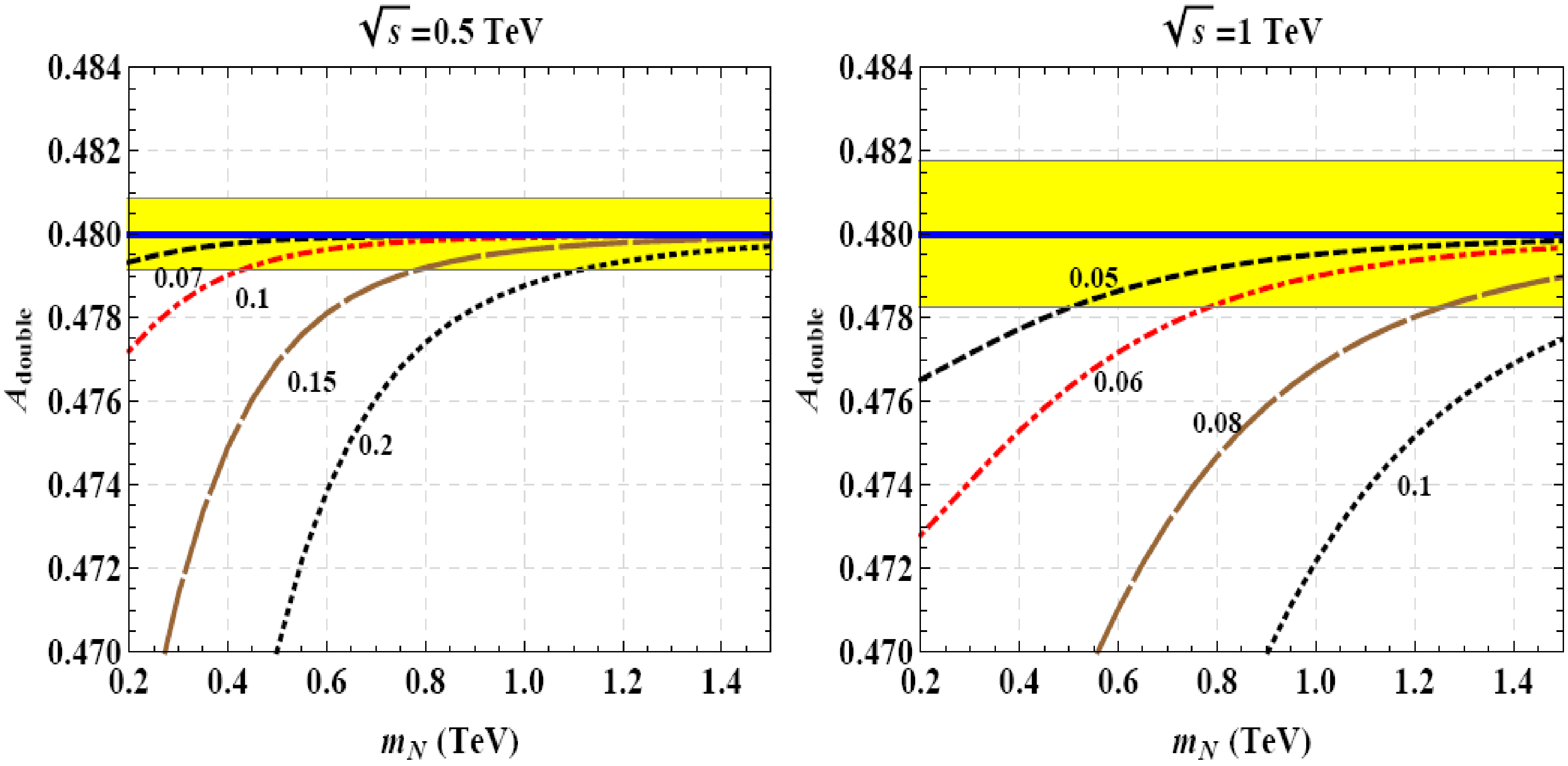
Anomalous gauge couplings (AGC), large extra dimensions (LED), *Z'*-boson effects (including *Z-Z'* mixing and Z_2 exchange):

$$\text{SM}\to\text{AGC},\ \text{LED},\ Z'$$

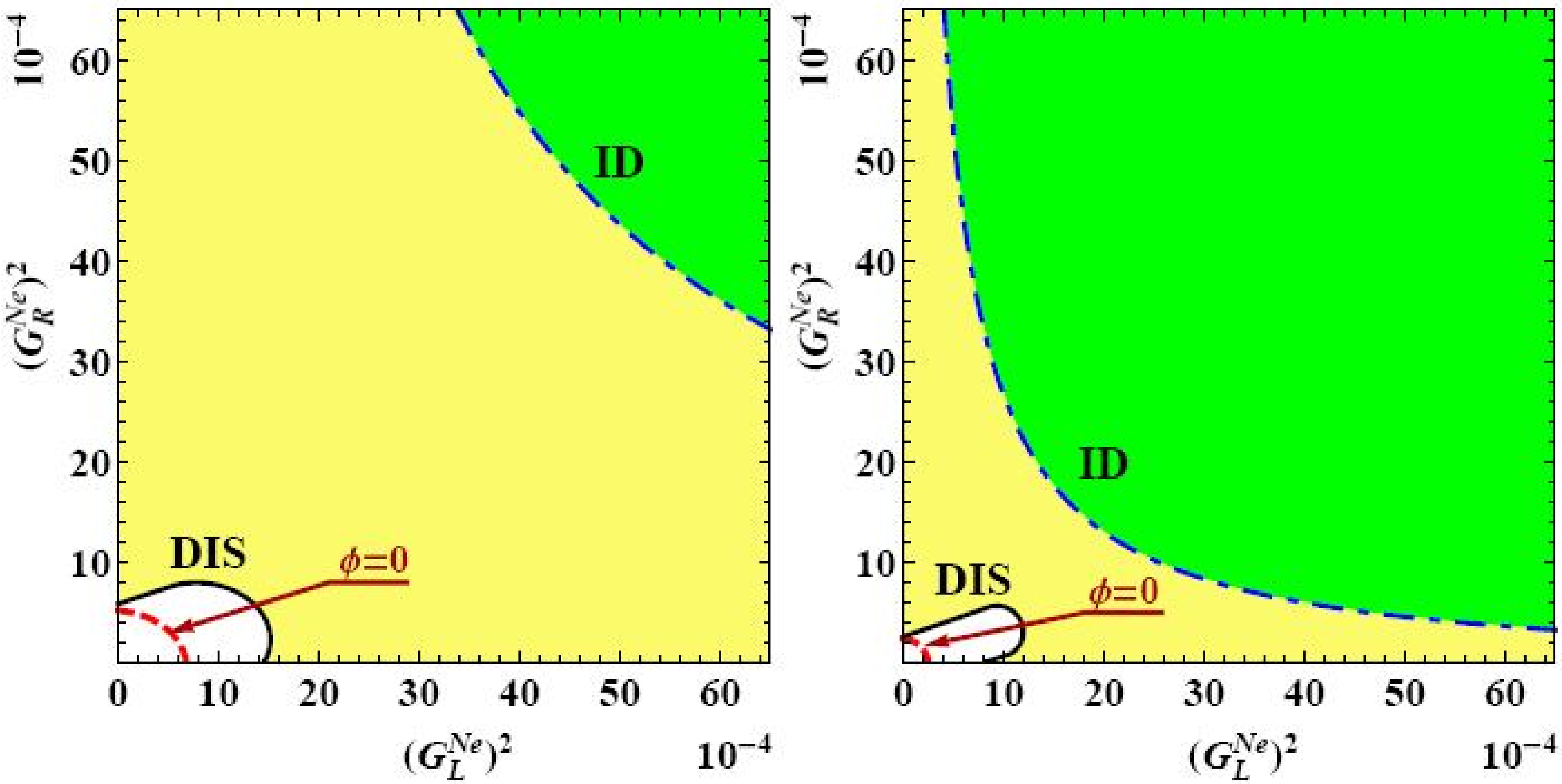
$$A_{\text{double}}^{\text{SM}}=A_{\text{double}}^{\text{AGC}}=A_{\text{double}}^{\text{LED}}=A_{\text{double}}^{Z'}=P_1P_2=0.48,\qquad P_1=0.8,\quad P_2=0.6$$

$$\Delta A_{\text{double}}=A_{\text{double}}^{\text{AGC}}-A_{\text{double}}^{\text{SM}}=A_{\text{double}}^{\text{LED}}-A_{\text{double}}^{\text{SM}}=A_{\text{double}}^{Z'}-A_{\text{double}}^{\text{SM}}=0$$

N-exchange in the *t*-channel: $\Delta A_{\text{double}}=A_{\text{double}}^{N}-A_{\text{double}}^{\text{SM}}\propto -P_1P_2\,r_N^2\left(G_L^{Ne}G_R^{Ne}\right)^2<0$

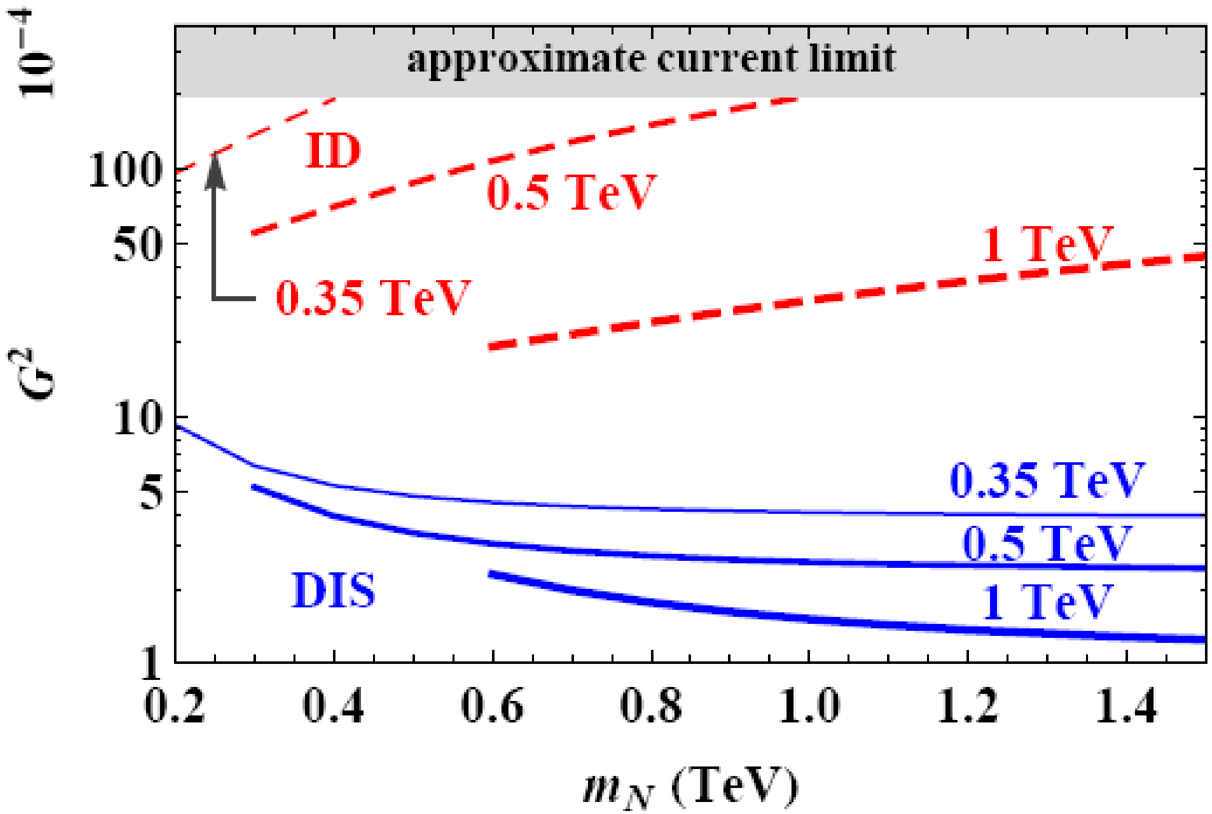


Double beam polarization asymmetry $A_{\rm double}$ for the production of unpolarized $W^{\pm}$ as a function of neutral heavy lepton mass m_N for different choices of couplings $\sqrt{G_L^{Ne}G_R^{Ne}}$ (attached to the lines) at the ILC with $\sqrt{s}=0.5$ TeV (left panel) and $\sqrt{s}=1.0$ TeV (right panel), $\mathcal{L}_{\rm int}=1$ ab^{-1}. The solid horizontal line corresponds to $A_{\rm double}^{\rm SM}=A_{\rm double}^{Z'}=A_{\rm double}^{\rm AGC}$. The error bands indicate the expected uncertainty in the SM case at the 1-σ level.



Left panel: discovery (DIS) and identification (ID) reaches at 95% CL on the heavy neutral lepton coupling plane $((G_L^{Ne})^2, (G_R^{Ne})^2)$, obtained from a combined analysis of polarized differential cross sections $d\sigma(W_L^+W_L^-)/dz$ at different sets of polarization, $P_L^- = \pm 0.8$, $P_L^+ = \mp 0.6$, and exploiting the double polarization asymmetry. Furthermore, $m_N = 0.3$ TeV, $\sqrt{s} = 0.5$ TeV and $\mathcal{L}_{\rm int} = 1$ ab^{-1}. Right panel: similar, with $\sqrt{s} = 1.0$ TeV and for $m_N = 0.6$ TeV. The dashed curves labelled "$\phi = 0$" refer to the case of no Z-Z' mixing, whereas the outer contour labelled "DIS" refer to the minimum discovery reach in the presence of mixing.

Discovery and identification reaches



Discovery (DIS) and identification (ID) reach on $G^2 \equiv (G_L^{Ne})^2 = (G_R^{Ne})^2$. The low-energy case (350 GeV) is compared with the nominal energy cases of 500 GeV and 1 TeV, all at an assumed integrated luminosity of 500 fb^{-1}. The approximate current limit on these couplings is indicated as a grey band.

Concluding remarks

- Here we have studied the effects of neutrino and electron mixing with exotic heavy leptons in the process $e^+e^- \rightarrow W^+W^-$ within E_6 models.

- We examine the possibility of uniquely distinguishing and identifying such effects of heavy neutral lepton exchange from *Z-Z'* mixing within the same class of models and also from analogous ones due to competitor models with AGC and LED that can lead to very similar experimental signatures at the e^+e^- ILC for E_{cm} = 0.35 TeV, 0.5 TeV and 1 TeV.

- Such clear identification of the model is possible by using a certain double polarization asymmetry $\boldsymbol{A_{double}}$. The availability of both beams being polarized plays a crucial role in identifying such exotic-lepton admixture.