Distinguishing between Z' and anomalous trilinear gauge coupling signatures in $e^+e^- \to W^+W^-$ at ILC with polarized beams

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Outline

- Introduction
- Effects of Z' bosons in W^+W^- production at ILC with
  - * Ecm=0.5 TeV and 1 TeV, Lint=500 fb^{-1} – $1ab^{-1}$;
  - * low energy option: Ecm= 250GeV, 350 GeV with 100 fb^{-1}.
- High sensitivity of $e^+e^- \rightarrow W^+W^-$ to Z' at $2M_W \ll Ecm \ll M_{Z'}$ (violation of the SM gauge cancellation mechanism).
- "Conventional" Z' models: (E_6, LR, SSM).
- Discovery reach on $M_{Z'}$ and Z-Z' mixing angle $\rightarrow$ compare with current limits.
- Analogous effects in $e^+e^- \rightarrow W^+W^-$ from competitor model -- anomalous gauge couplings (AGC).
- **Main goal** – disdinguishing Z' effects from AGC.
- Role of longitudinally polarized beams.
- 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(7TeV): M(Z') >1.5—1.7 TeV.

For ILC with Ecm $\leq$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.

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 propose such a technique that makes use of the specific modifications in angular distributions of the process $e^+e^- \rightarrow W^+W^-$ induced by Z-Z′ mixing and Z′ exchange from those caused by AGC.

Models of Z'-bosons:

The list of ***Z'***-models that will be considered in our analysis is the following:

1) E_6 models: $$E_6 \to SO(10)\times U(1)_\psi \to SU(5)\times U(1)_\chi \times U(1)_\psi$$

$$Z'(\beta) = \chi\cos\beta + \psi\sin\beta$$

three popular possible U(1) Z' scenarios originating from the exceptional group E_6 breaking:

$$\chi-\text{model}\ \ (\cos\beta = 0);\ \psi-\text{model}\ (\cos\beta = 1);\ \eta-\text{model}\ (\tan\beta = -\sqrt{5/3})$$

2) Left-Right models (LR): $$SO(10) \to SU(3)_C\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}$$

$$J_{LR}^{\beta} = \sqrt{\frac{5}{3}}\left(\alpha_{LR}J_{3R}^{\beta} - \frac{1}{2\alpha_{LR}}J_{B-L}^{\beta}\right),\quad \alpha_{LR} \equiv \sqrt{\frac{c_W^2}{s_W^2}\frac{g_R^2}{g_L^2} - 1},\quad \sqrt{\frac{2}{3}} \le \alpha_{LR} \le \sqrt{\frac{c_W^2}{s_W^2} - 1}$$

3) Sequential Standard Model (SSM), where the couplings to fermions are the same as those of the SM Z.

Z-Z′-mixing

The mass eigenstates Z_1 and Z_2 are:

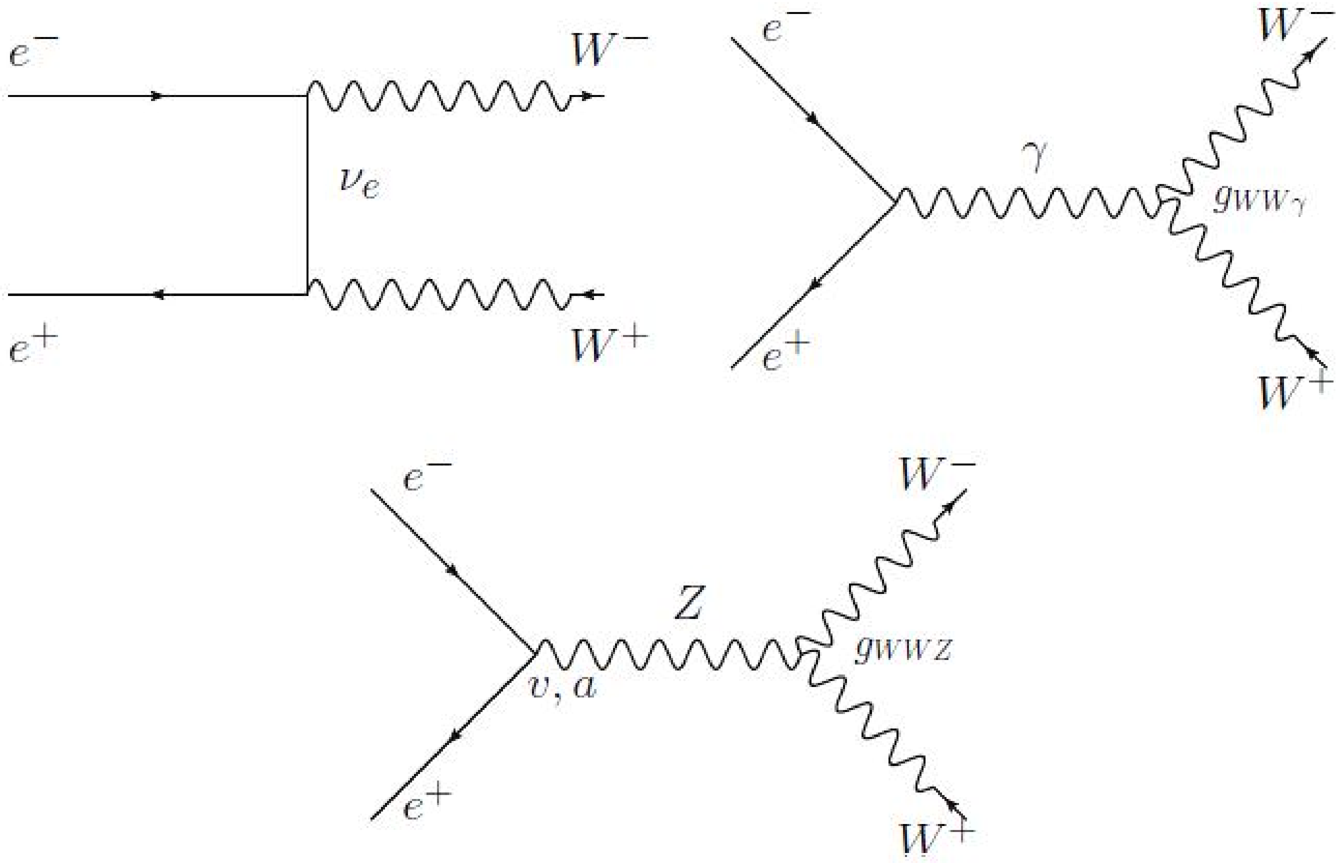
$$Z_1 = Z\cos\phi + Z'\sin\phi$$

$$Z_2 = -Z\sin\phi + Z'\cos\phi$$

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

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

$e^+e^- \to W^+W^-$ in SM



Feynman diagrams for the process $e^-e^+ \to \gamma, Z \to W^-W^+$ in the Born approximation

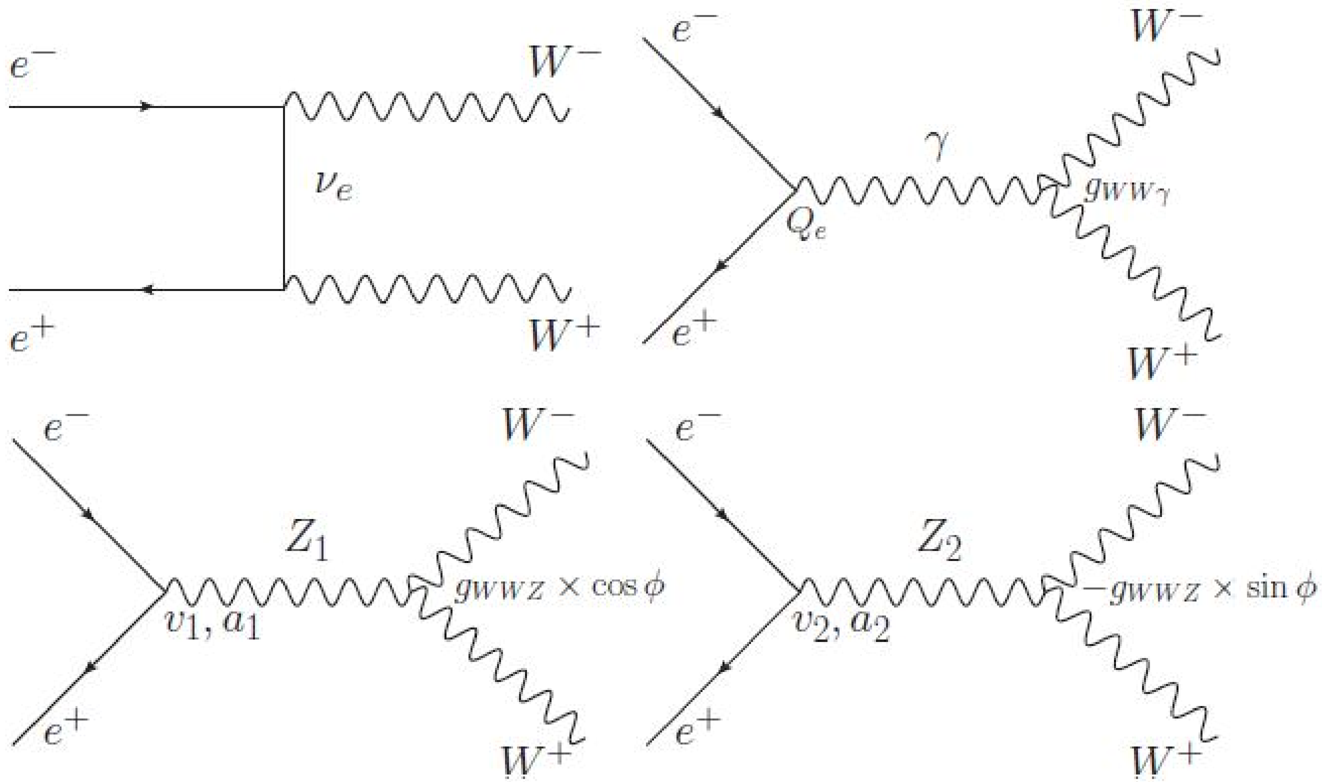
Matrix element of s-channel component in the **SM** can be written as:

$$\mathcal{M}_s^\lambda = \left(-\frac{g_{WW\gamma}}{s} + \frac{g_{WWZ}(v - 2\lambda a)}{s - M_Z^2} \right) \times G^\lambda(s, \theta) \ ,$$

where s and θ are the total c.m. squared energy and W^- production angle; λ denotes helicity of electrons, $G^\lambda(s,\theta)$– kinematical coefficient. Triple gauge boson constants are defined as (in units *e*):

$$g_{WW\gamma} = 1 \ , \quad g_{WWZ} = \cot\theta_W \ .$$

Parametrization of Z′-boson effects



Feynman diagrams for the process $e^-e^+ \to \gamma, Z_1, Z_2 \to W^-W^+$ in the Born approximation

Matrix element

Matrix element of s-channel component for process

$$e^+e^- \to \gamma, Z_1, Z_2 \to W^+W^-$$

$$\mathcal{M}_s^\lambda = \left(-\frac{g_{WW\gamma}}{s} + \frac{g_{WWZ_1}(v_1 - 2\lambda a_1)}{s - M_1^2} + \frac{g_{WWZ_2}(v_2 - 2\lambda a_2)}{s - M_2^2} \right) \times G^\lambda(s,\theta)\ .$$

$$v_{1f} = v_f \cos\phi + v'_f \sin\phi\ , \quad a_{1f} = a_f \cos\phi + a'_f \sin\phi\ ,$$
$$v_{2f} = -v_f \sin\phi + v'_f \cos\phi\ , \quad a_{2f} = -a_f \sin\phi + a'_f \cos\phi,$$

$$g_{WWZ_1} = \cos\phi\ g_{WWZ}\ ,$$
$$g_{WWZ_2} = -\sin\phi\ g_{WWZ}$$

Note: if $\phi = 0$, **no** Z' effects occur in $e^+e^- \to W^+W^-$

(in contrast to $e^+e^- \to f^+f^-$)

The matrix element can be rewritten in terms of two independent parameters Δ_γ and Δ_Z

[A.P., N. Paver, C.Verzegnassi] :

$$\mathcal{M}_s^\lambda = \left(-\frac{\tilde{g}_{WW\gamma}}{s} + \frac{\tilde{g}_{WWZ}(v - 2\lambda a)}{s - M_Z^2} \right) \times G^\lambda(s, \theta) ,$$

$$\tilde{g}_{WW\gamma} = 1 + \Delta_\gamma , \ \tilde{g}_{WWZ} = \cot\theta_W + \Delta_Z .$$

Parameters Δ_γ and Δ_Z “absorb” Z'-boson effects:

$$\Delta_\gamma = v\cot\theta_W\left(\frac{\Delta a}{a}-\frac{\Delta v}{v}\right)(1+\Delta\chi)\,\chi + v\,g_{WWZ_2}\left(\frac{a_2}{a}-\frac{v_2}{v}\right)\chi_2\,,$$

$$\Delta_Z = \Delta g_{WWZ} + \cot\theta_W\left(\frac{\Delta a}{a}+\Delta\chi\right) + g_{WWZ_2}\frac{a_2}{a}\frac{\chi_2}{\chi}\,.$$

Here

$$\Delta a = a_1 - a,\ \Delta v = v_1 - v,\ \Delta g_{WWZ} = g_{WWZ_1} - \cot\theta_W$$

$$\chi = \frac{s}{s-M_Z^2}\,,\quad \chi_2 = \frac{s}{s-M_{Z_2}^2}\,,\quad \Delta\chi = \frac{\chi_1-\chi}{\chi} = -\frac{2M_Z\Delta M}{s-M_Z^2}\,,$$

($\Delta M = M_Z - M_1$ mass shift).

Model-independent parametrization of the Z’ effects in terms of Δ_γ and Δ_Z is both general and useful for phenomenological purposes, in particular to compare different sources of NP effects,

Z’ vs. AGC.

Current data [Erler, et al., Langacker et al., 2009]:

$$\Delta M < 100\ MeV \Rightarrow \Delta\chi(s) \ll 1,$$

$$|\phi| < few \cdot 10^{-3}.$$

Simplified form for Δ_γ and Δ_Z (couplings to first order in ϕ and $\Delta\chi(s) \ll 1$):

$$(v_1, a_1) \simeq (v + v'\phi, a + a'\phi) \Rightarrow (\Delta v, \Delta a) \simeq (v'\phi, a'\phi),$$

$$(v_2, a_2) \simeq (-v\phi + v', -a\phi + a'),$$

$$g_{WWZ_1} \simeq g_{WWZ}; \qquad g_{WWZ_2} \simeq -g_{WWZ}\,\phi.$$

$$\Delta_\gamma = \phi \cdot v \cot\theta_W \left(\frac{a'}{a} - \frac{v'}{v}\right)\left(1 - \frac{\chi_2}{\chi}\right)\chi,$$

$$\Delta_Z = \phi \cdot \cot\theta_W \frac{a'}{a}\left(1 - \frac{\chi_2}{\chi}\right).$$

For specific Z' models (with fixed v' and a') there is a relation between Δ_γ and Δ_Z :

$$\boxed{\Delta_Z = \Delta_\gamma \cdot \frac{1}{\mathrm{v}\chi} \frac{(a'/a)}{(a'/a) - (\mathrm{v}'/\mathrm{v})}}$$

(independent of ϕ and M_2).

Parametrization of AGC effects

Notations [G. Gounaris et al., 1992].

Trilinear WWV interaction which conserves

$U(1)_{em}$, C and P, can be written as ($e = \sqrt{4\pi\alpha_{em}}$):

$$
\begin{aligned}
\mathcal{L}_{\mathrm{eff}} \; = \; & -ie\left[A_\mu\left(W^{-\mu\nu}W^+_\nu - W^{+\mu\nu}W^-_\nu\right) + F_{\mu\nu}W^{+\mu}W^{-\nu}\right] \\
- \; & ie\left(\cot\theta_W + \delta_Z\right)\left[Z_\mu\left(W^{-\mu\nu}W^+_\nu - W^{+\mu\nu}W^-_\nu\right) + Z_{\mu\nu}W^{+\mu}W^{-\nu}\right] \\
- \; & ie\, x_\gamma\, F_{\mu\nu}W^{+\mu}W^{-\nu} - ie\, x_Z\, Z_{\mu\nu}W^{+\mu}W^{-\nu} \\
+ \; & ie\,\frac{y_\gamma}{M_W^2}\, F^{\nu\lambda}W^-_{\lambda\mu}W^{+\mu}_{\ \nu} + ie\,\frac{y_Z}{M_W^2}\, Z^{\nu\lambda}W^-_{\lambda\mu}W^{+\mu}_{\ \nu}\,,
\end{aligned}
$$

where $W^\pm_{\mu\nu} = \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu$ and $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$.

Lagrangian: 2 SM terms and 5 terms with AGC's

$$\delta_Z\,, x_\gamma\,, x_Z\,, y_\gamma\,, y_Z\,.$$

(δ_γ =0 , $U(1)_{em}$ symmetry*)*.

Alternative parametrization: $\Delta g_1^Z\,, \Delta k_\gamma\,, \Delta k_Z\,, \lambda_\gamma\,, \lambda_Z$

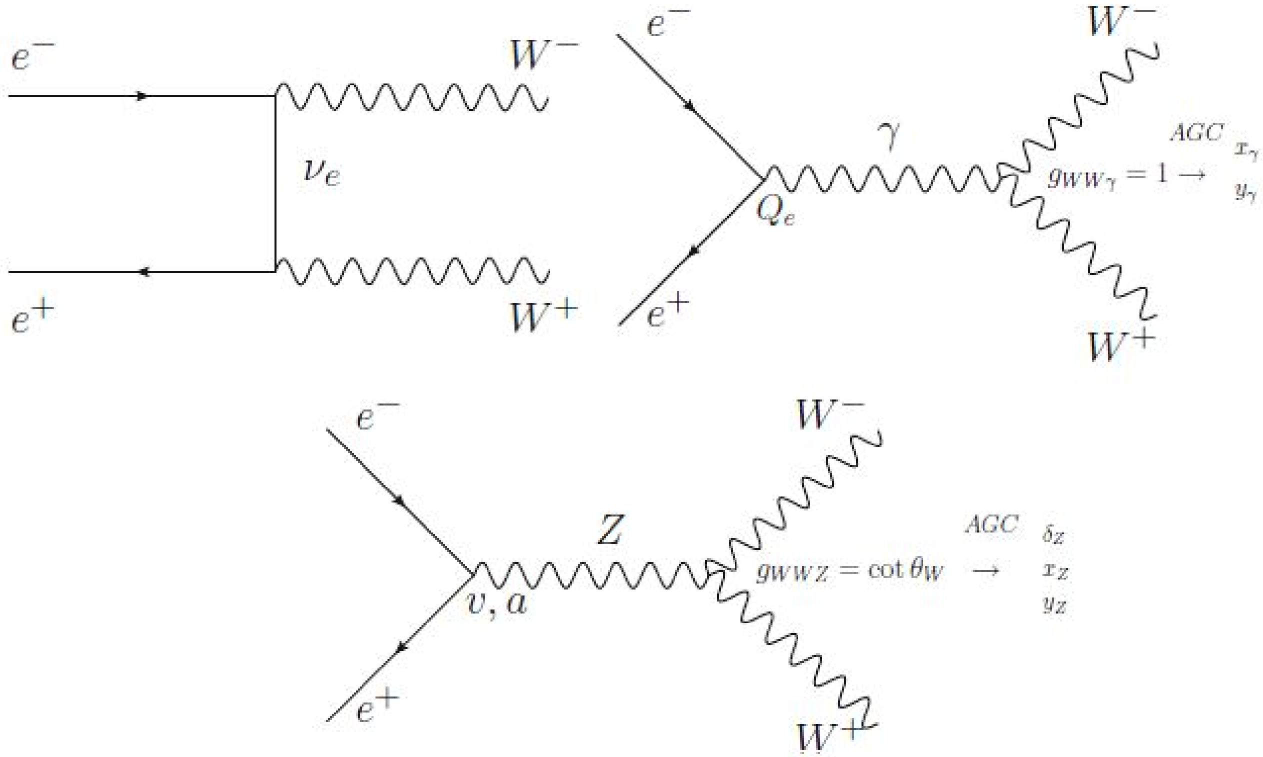
They are related as:

$$\Delta g_1^Z = \left(g_1^Z - 1\right) \equiv \tan\theta_W \delta_Z\ ,\quad \Delta k_Z = (k_Z - 1) \equiv \tan\theta_W\,(x_Z + \delta_Z)\ ,$$

$$\Delta k_\gamma = (k_\gamma - 1) \equiv x_\gamma\ ,\quad \lambda_\gamma \equiv y_\gamma\ ,\quad \lambda_Z \equiv \tan\theta_W\ y_Z\ .$$

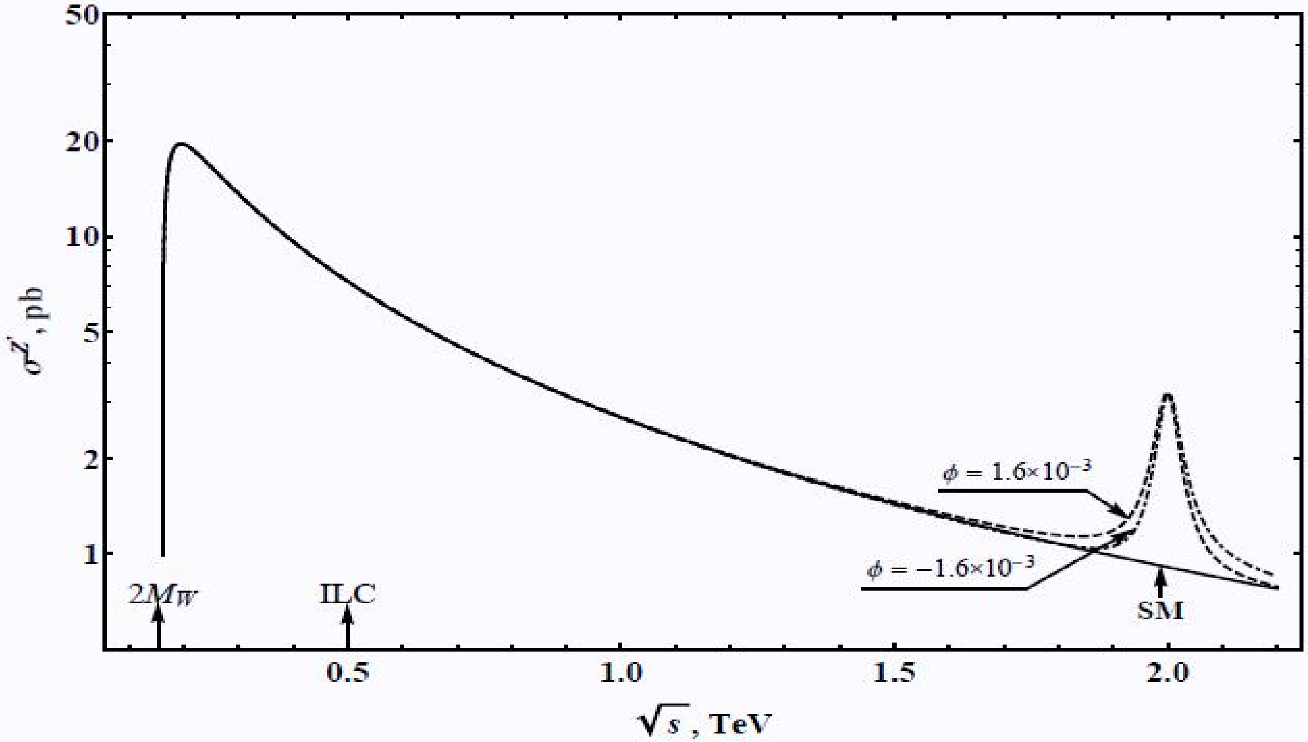
$e^+e^- \to W^+W^-$ with AGC

(see also I. Marchesini, this section)



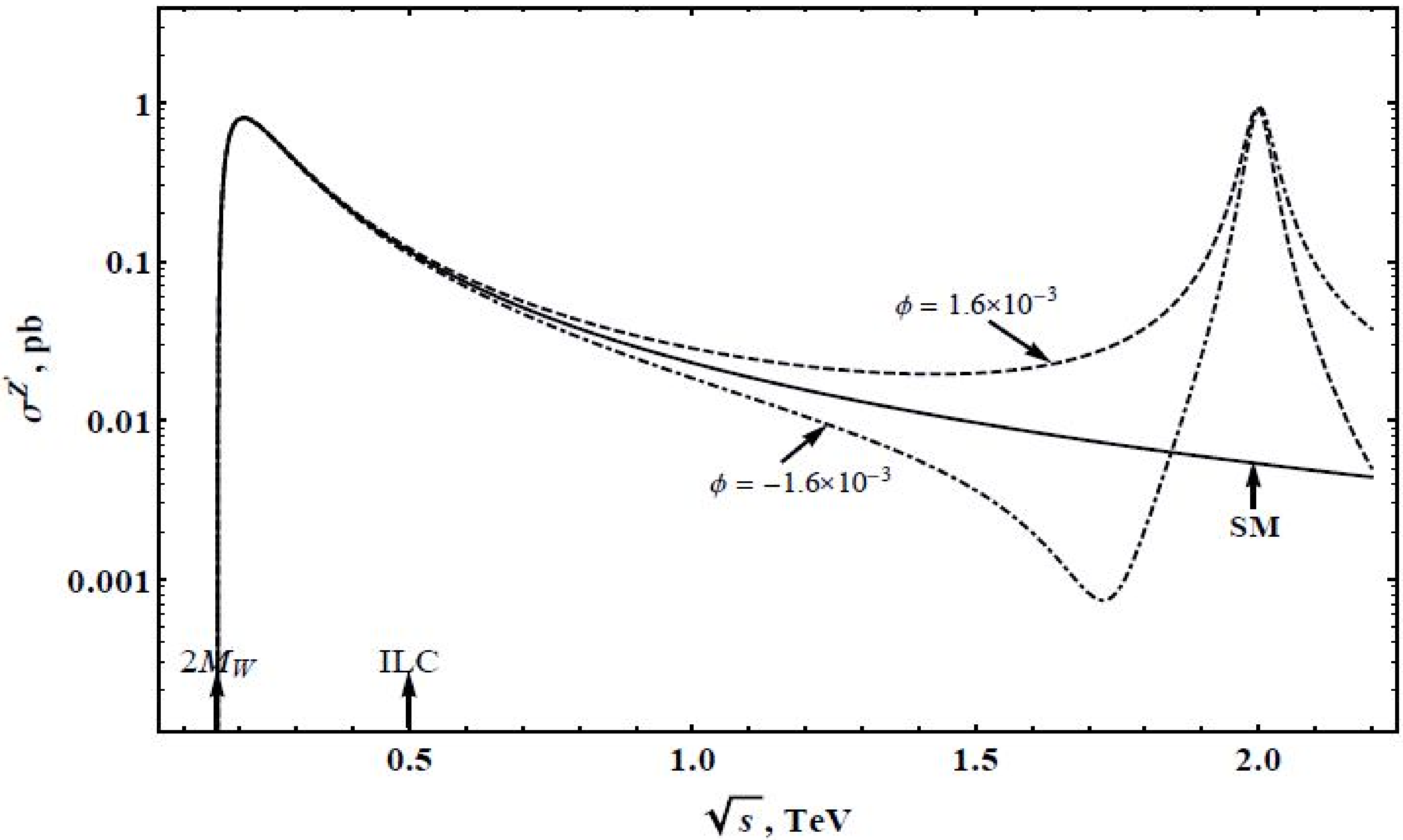
Feynman diagrams for the process $e^+e^- \to W^+W^-$ in the Standard Model and with anomalous trilinear gauge couplings

Z' illustrations

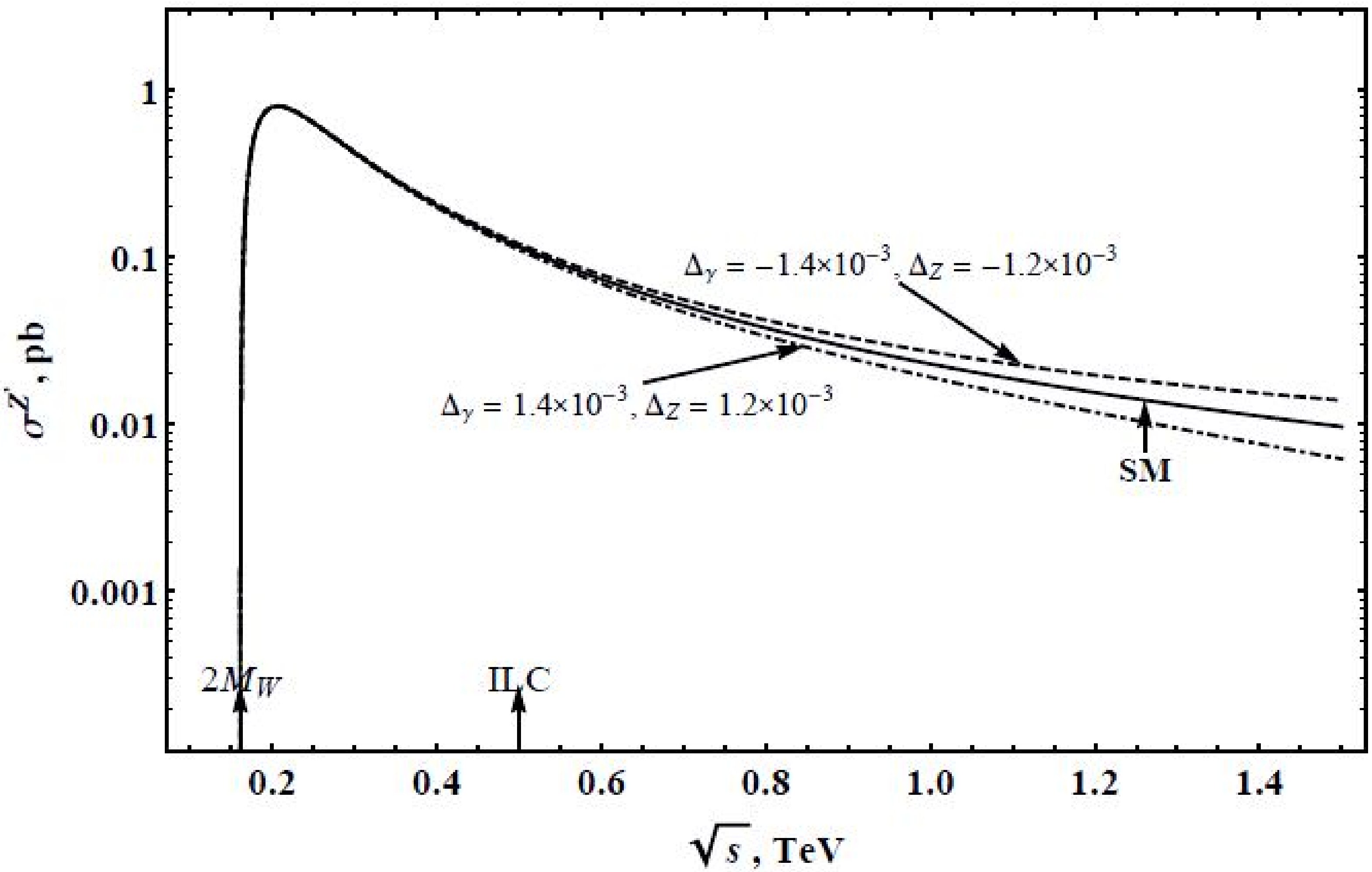


$$|\cos\theta| \leq 0.98 \ .$$

Unpolarized total cross section for the process $e^+e^- \to W^+W^-$ for Z'_χ from E_6. Solid line corresponds to the SM case. Dashed (dash-dotted) lines correspond to a Z' model with $\phi = 1.6 \cdot 10^{-3}$ ($\phi = -1.6 \cdot 10^{-3}$) and $M_2 = 2$ TeV



Polarized total cross section for the process $e^+e^- \to W^+W^-$ for Z'_χ from E_6 with perfectly polarized electrons and positrons ($P_L = 1, \bar{P}_L = -1$) and unpolarized final states. Solid line corresponds to the SM. Dashed (dash-dotted) lines correspond to a Z' model with $\phi = 1.6 \cdot 10^{-3}$ ($\phi = -1.6 \cdot 10^{-3}$) and $M_2 = 2$ TeV



Polarized total cross section for the process $e^+e^- \to W^+W^-$ as a function of $\sqrt{s}$ with perfectly polarized electrons and positrons ($P_L = 1, \bar{P}_L = -1$) and unpolarized final states. Solid line corresponds to the SM. Contribution to the cross section caused by Z' is determined by different sets of parameters $(\Delta_\gamma, \Delta_Z) = (1.4 \cdot 10^{-3}, 1.2 \cdot 10^{-3})$ and $(-1.4 \cdot 10^{-3}, -1.2 \cdot 10^{-3})$

Discovery reach on Z′ parameters

- Channel: $W^+W^- \to (e\nu + \mu\nu) + 2j$

- Angular range $|\cos\theta| \le 0.98$ is divided into 10 equal size bins.
- χ^2 function is defined in terms of the expected number of events $N(i)$ in each bin:

$$\chi^2 = \sum_{\{P_L, \bar{P}_L\}} \sum_i^{\text{bins}} \left[\frac{N_{\text{SM}}(i) - N_{\text{NP}}(i)}{\delta N_{\text{SM}}(i)} \right]^2,$$

where $N(i) = \mathcal{L}_{\text{int}}\, \sigma_i\, \varepsilon_W$ with $\mathcal{L}_{\text{int}}$ the time-integrated luminosity, and ($z = \cos\theta$)

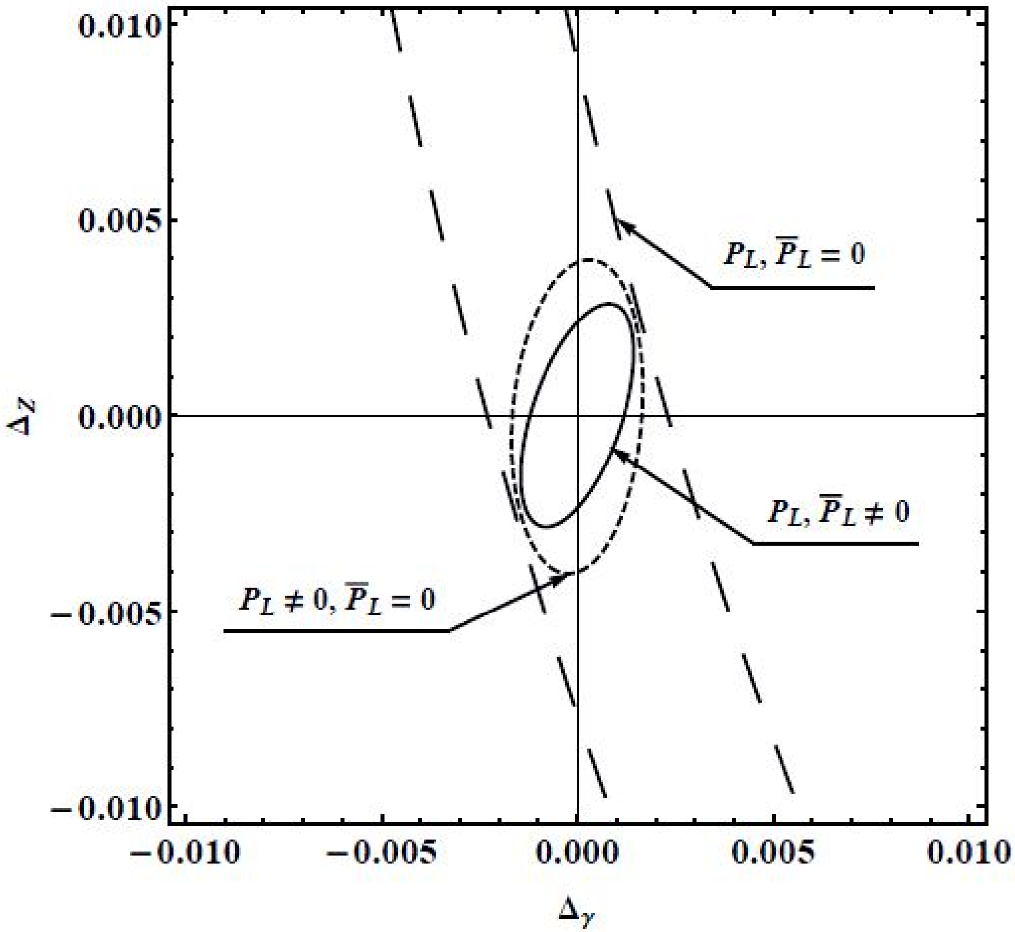
$$\sigma_i = \sigma(z_i, z_{i+1}) = \int_{z_i}^{z_{i+1}} \left(\frac{d\sigma}{dz} \right) dz.$$

Experimental Inputs

- $\sqrt{s}$ = 0.5 (1) TeV (and also low energy option)
- Integrated Luminosity: L_{int}= 500 (1000) fb^{-1}
- Polarization: $\left|P_L\right| = 0.8$, $\left|\overline{P}_L\right| = 0.5$
- Efficiency: $\varepsilon_W \simeq 0.3$
- Systematics: $\delta\varepsilon_W/\varepsilon_W$=0.5%, $\delta P_L/P_L$= 0.5%
- Rad. corrections:

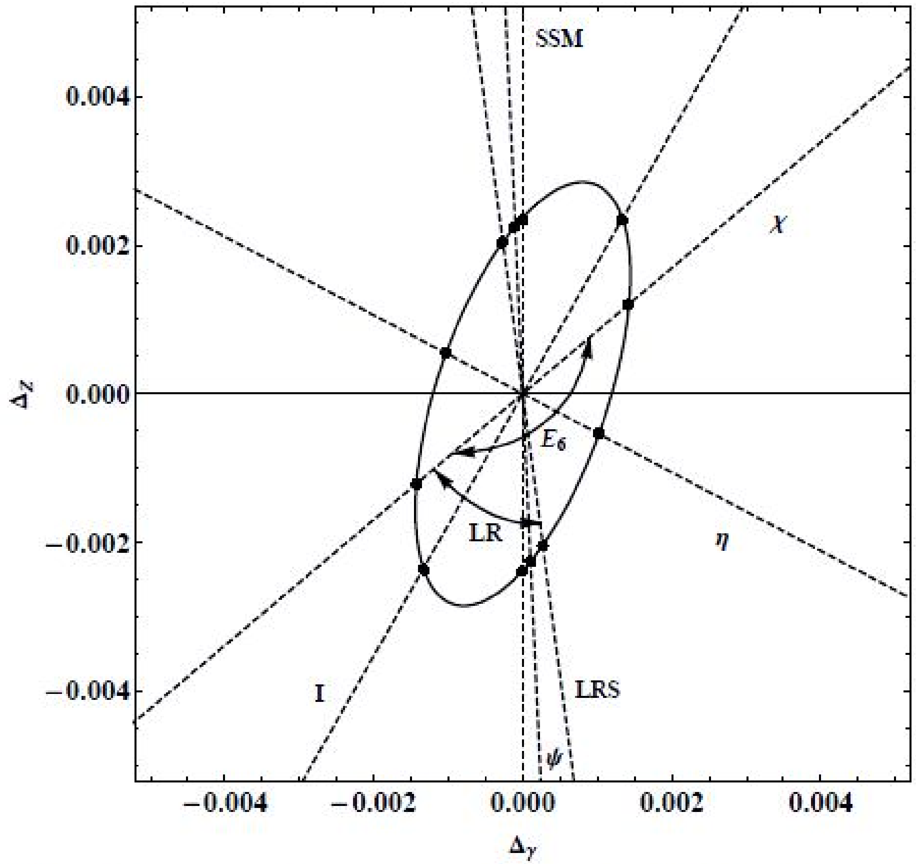
(Initial-state QED corrections (ISR) to on-shell W pair production

in the flux function approach)



Discovery reach at 95% CL on the Z' parameters $\Delta_{\gamma,Z}$ obtained from polarized differential cross sections at different sets of initial beams polarization: $P_L = \pm 0.8,\ \bar{P}_L = \mp 0.5$ (solid line), $P_L = \pm 0.8,\ \bar{P}_L = 0$ (short-dashed line), unpolarized beams $P_L = 0,\ \bar{P}_L = 0$ (long-dashed line) and $\mathcal{L}_{\rm int} = 500$ fb^{-1}

$$Z' \; models \; lines: \quad \Delta_Z = \Delta_\gamma \frac{1}{v\chi} \frac{a'/a}{(a'/a - v'/v)}$$



Discovery reach (95% C.L.) on Z' parameters $(\Delta_\gamma,\, \Delta_Z)$ obtained from differential polarized cross sections with $(P_L = \pm 0.8,\ \bar{P}_L = \mp 0.5)$. Dashed straight lines correspond to specific extended gauge models (χ, ψ, η, I and LRS). The segments of the ellipse correspond to the whole classes of E_6 and LR-models, respectively

Distinguishing between Z′ and AGC

- Model-independent analysis

!

Z’	Δ_γ	Δ_Z	–	–	–	–
AGC	$\delta_\gamma=0$	δ_Z	x_γ	x_Z	y_γ	y_Z

Consequences:

- models with $\Delta_\gamma=0$ and $\Delta_Z\neq0$ $\rightarrow$ Z’ and AGC indistinguishable (e.g. Z'_{SSM})

- models with $\Delta_\gamma\neq0$, Z’: distinguishable from AGC.

Goal: Differentiate various Z' models from similar effects caused by AGC , e.g. x_γ :

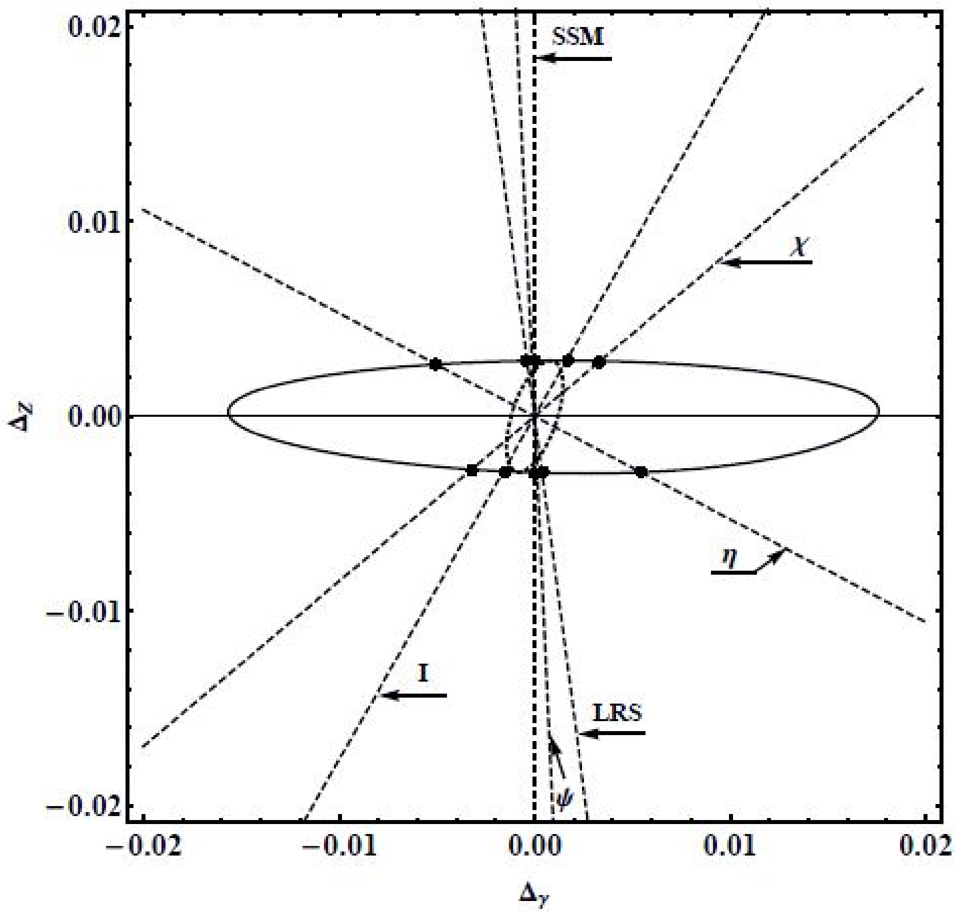
Z' (Δ_γ, Δ_Z) vs AGC (x_γ) (others AGC =0).

Assumption: a Z' model is consistent with the data ("true" model),
AGC ("tested" model)

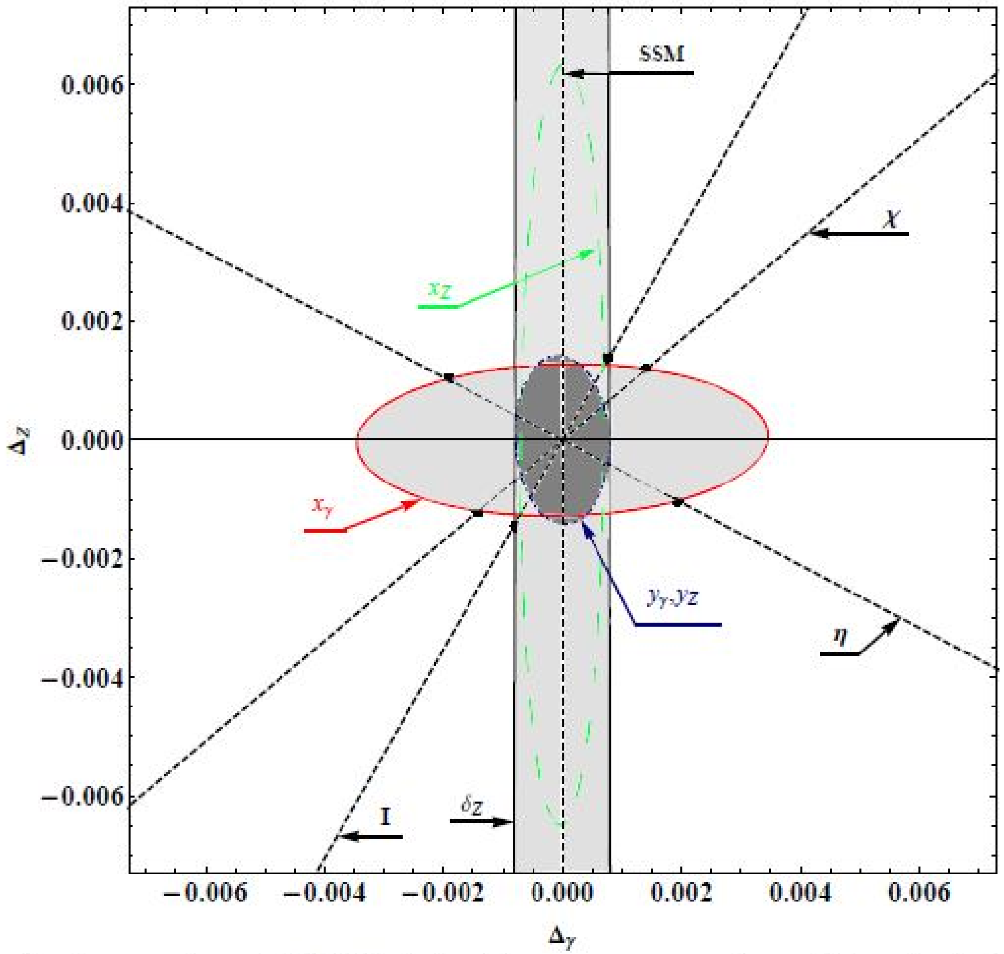
$$\chi^2 = \sum_{\{P_L,P_L\}} \sum_i^{\text{bins}} \left[\frac{N_{Z'}(i) - N_{\text{AGC}}(i)}{\delta N_{Z'}(i)} \right]^2,$$

"Confusion" regions of $\Delta_{\gamma,Z}$ and x_γ values where AGC (x_γ) model can be indistinguishable from the Z' scenario:

$$\chi^2 \le \chi^2_{\text{min}} + \chi^2_{\text{CL}}.$$



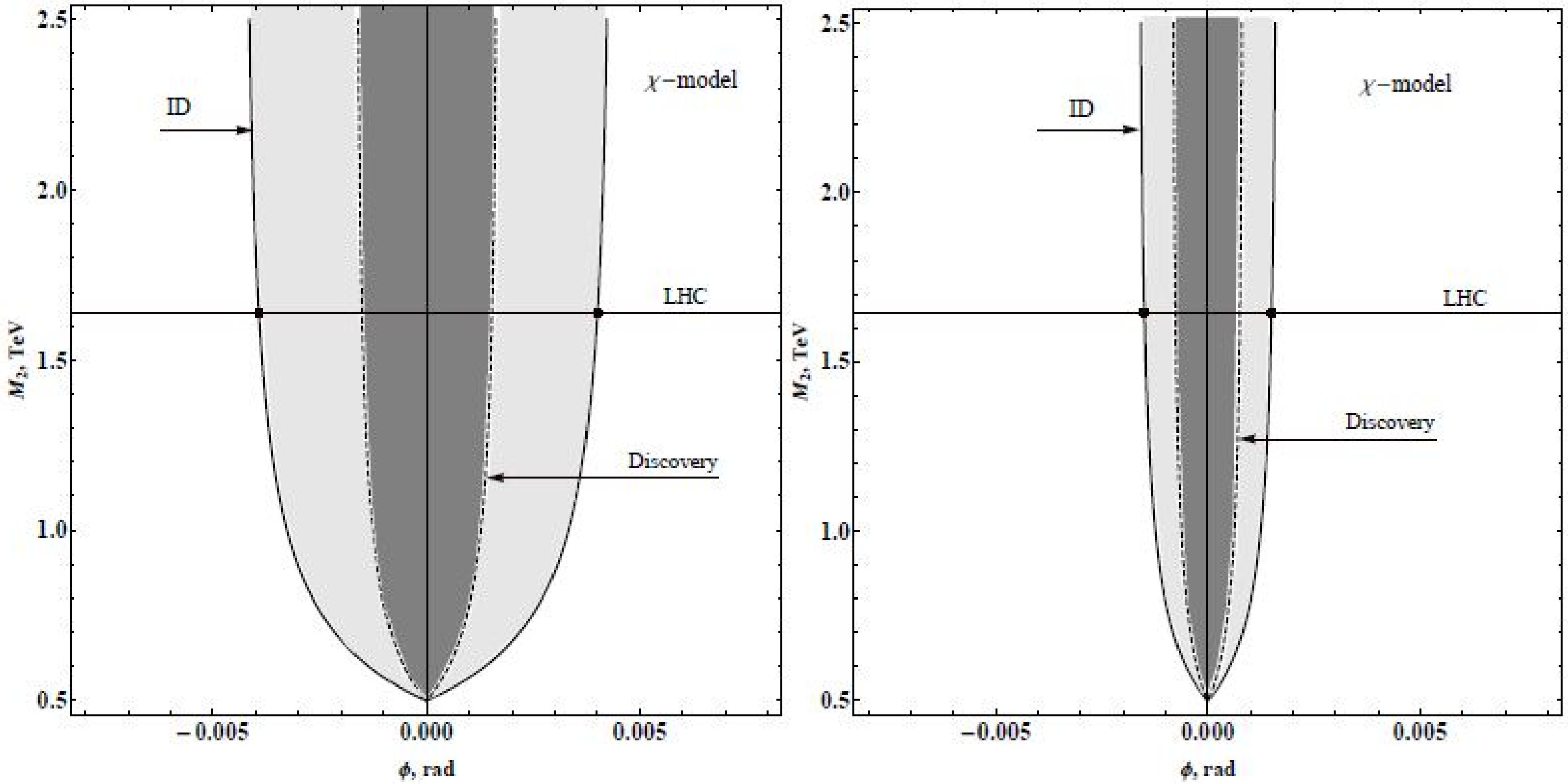
The big ellipse (solid) shows the confusion region (95% C.L.) in the parameter plane $(\Delta_\gamma, \Delta_Z)$ for a generic Z' model and the AGC model with nonvanishing parameter x_γ obtained from the polarized cross section with $P_L = \pm 0.8$ and $\bar{P}_L = \mp 0.5$. The inner ellipse (dashed) corresponds to the discovery reach on Z' obtained from a comparison with AGC at $x_\gamma = 0$. The dashed straight lines correspond to specific extended gauge models (χ, ψ, η, I and LRS)



Overlapping confusion regions (95%C.L.) in the parameter plane $(\Delta_\gamma, \Delta_Z)$ for a generic Z' model and AGC models with parameters taking nonvanishing values, one at a time: x_γ, x_Z, y_γ, y_Z and δ_Z obtained from polarized cross sections with $P_L = \pm 0.8$, $\bar{P}_L = \mp 0.5$ and polarized final states (solid line). Dashed lines correspond to specific Z' models (χ, ψ, η, I and LRS)

Model dependent analysis

$$\sqrt{s} = 500\ \mathrm{GeV}\ ,\quad \mathcal{L}_{\mathrm{int}} = 500\ \mathrm{fb}^{-1}$$



Left: Discovery (dashed line) and identification (solid line) reach for the χ model in the (ϕ, M_2) plane obtained from polarized initial e^+ and e^- beams with $(P_L = \pm 0.8,\ \bar{P}_L = \mp 0.5)$ and unpolarized final $W^\pm$ states. Right: The same with polarized final $W^\pm$ states

$$\sqrt{s} = 500\ \mathrm{GeV}\ , \quad \mathcal{L}_{\rm int} = 500\ \mathrm{fb}^{-1}$$

Discovery and identification reach on the Z-Z' mixing angle ϕ for Z' models with $M_2 = 2$ TeV obtained from the polarized differential cross section with ($P_L = \pm 0.8,\ \bar{P_L} = \mp 0.5$) and unpolarized final states.

(In parenthesis are given corresponding values for the case of polarized final-state Ws.)

Z' model	χ	ψ	η	I	LRS	SSM
$\phi^{\rm DIS}, 10^{-3}$	$\pm 1.5(0.8)$	$\pm 2.3(1.4)$	$\pm 1.6(1.3)$	$\pm 2.0(0.8)$	$\pm 1.4(1.0)$	$\pm 1.2(0.7)$
$\phi^{\rm ID}, 10^{-3}$	$\pm 3.8(1.5)$	$\pm 37(19)$	$\pm 17(3.2)$	$\pm 4.3(1.2)$	$\pm 8.1(4.2)$	–

$$\sqrt{s} = 1000\ \mathrm{GeV}\ , \quad \mathcal{L}_{\rm int} = 1000\ \mathrm{fb}^{-1}$$

Z' model	χ	ψ	η	I	LRS	SSM
$\phi^{\rm DIS}, 10^{-4}$	$\pm 3.8(1.8)$	$\pm 5.8(3.4)$	$\pm 4.6(3.2)$	$\pm 4.4(1.9)$	$\pm 3.7(2.4)$	$\pm 3.1(1.7)$
$\phi^{\rm ID}, 10^{-4}$	$\pm 9.0(4.2)$	$\pm 94(45)$	$\pm 24(9.5)$	$\pm 6.1(2.8)$	$\pm 18(10)$	–

$\sqrt{s} = \mathbf{250}$ GeV , $\mathcal{L}_{\rm int} = \mathbf{100\ fb}^{-1}$

Discovery and identification reach on the Z-Z' mixing angle ϕ for Z' models with $M_2 = 2$ TeV obtained from the polarized differential cross section with ($P_L = \pm 0.8,\ \bar{P_L} = \mp 0.5$) and unpolarized final states.

(In parenthesis are given corresponding values for the case of polarized final-state Ws.)

Z' model	χ	ψ	η	I	LRS	SSM
$\phi^{\rm DIS}, 10^{-3}$	$\pm 5.1(3.8)$	$\pm 8.4(7.0)$	$\pm 6.8(6.7)$	$\pm 5.7(3.9)$	$\pm 5.4(4.9)$	$\pm 4.4(3.6)$
$\phi^{\rm ID}, 10^{-3}$	$\pm 14(6.8)$	$\pm 109(86)$	$\pm 29(14)$	$\pm 7.8(5.9)$	$\pm 45(21)$	–

$\sqrt{s} = \mathbf{350}$ GeV , $\mathcal{L}_{\rm int} = \mathbf{100\ fb}^{-1}$

Z' model	χ	ψ	η	I	LRS	SSM
$\phi^{\rm DIS}, 10^{-3}$	$\pm 3.7(2.4)$	$\pm 6.0(4.5)$	$\pm 4.9(4.3)$	$\pm 4.1(2.5)$	$\pm 3.9(3.1)$	$\pm 3.2(2.3)$
$\phi^{\rm ID}, 10^{-3}$	$\pm 8.4(4.6)$	$\pm 77(61)$	$\pm 27(9.4)$	$\pm 13.5(3.8)$	$\pm 19(14)$	–

Concluding remarks

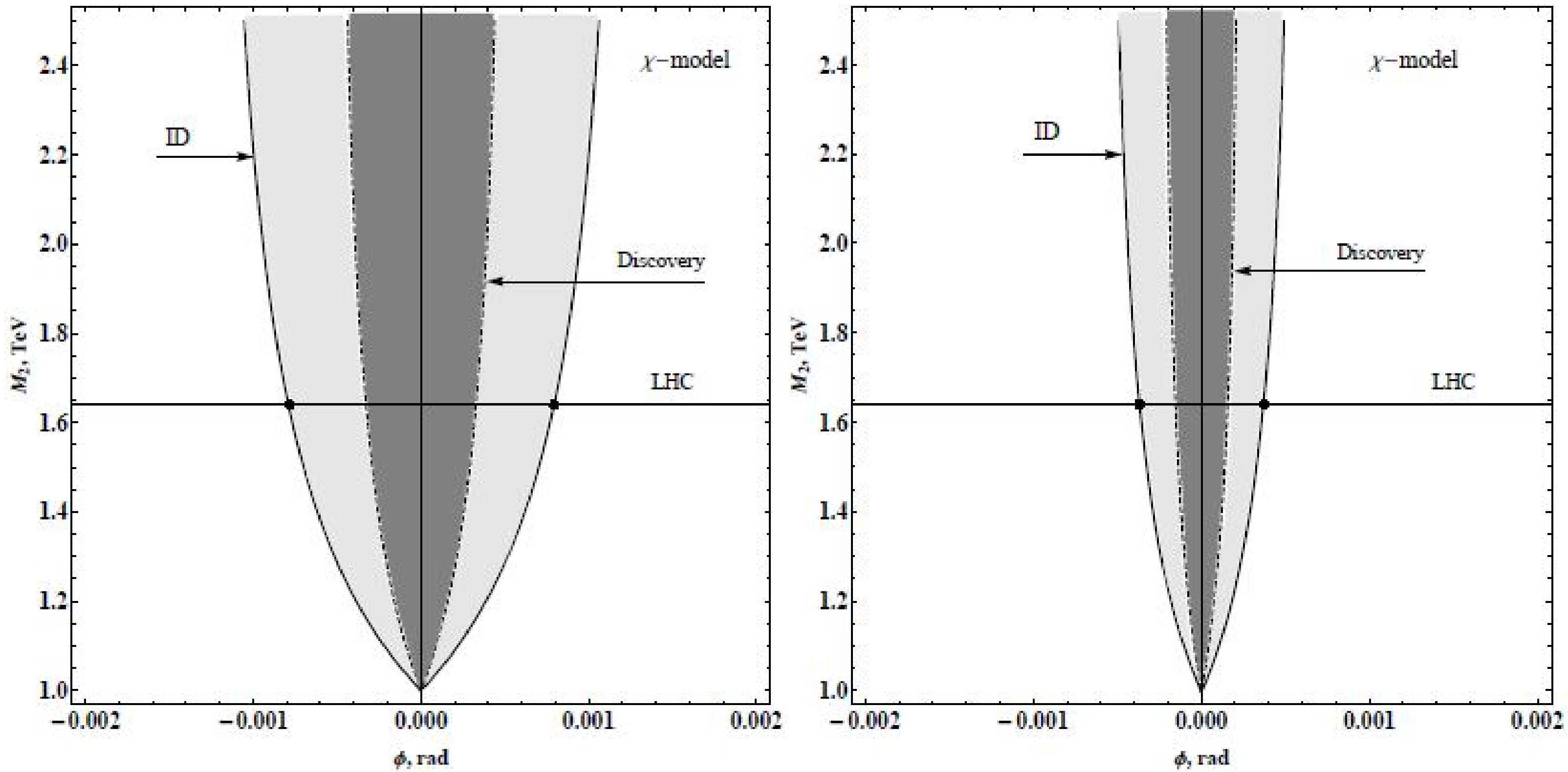
•We discussed the foreseeable sensitivity to Z’s of W-pair production cross sections at ILC, especially as regards the potential of distinguishing observable effects of the Z' from analogous ones due to competitor models with AGC that can lead to the same or similar new physics experimental signatures.

• We shown that the sensitivity of ILC for probing the Z-Z' mixing and its capability to distinguish these two new physics scenarios is substantially enhanced when the polarization of the initial beams (and also, possibly produced $W^{\pm}$ bosons) are considered.

• ILC (0.25TeV) and ILC(0.35TeV) allow to obtain bounds on Z-Z’ mixing at the same level as those of current experimental limits (derived mostly from on Z resonance LEP1 and SLC data), and therefore provide complementary information; differentiating Z’ from AGC is impossible.

• ILC (0.5TeV) and ILC(1 TeV) allow to improve current bounds on Z-Z’ mixing; differentiating Z’ from AGC is feasible.

$$\sqrt{s} = 1000 \text{ GeV}\ , \ \ \mathcal{L}_{\rm int} = 1000 \text{ fb}^{-1}$$



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