LHC and ILC Measurements of Strong Electroweak Symmetry Breaking

Tim Barklow

SLAC

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Outline

- Anomalous quartic couplings
- WW→tt
- Resonances
- Example of LHC/ILC Interplay

The bosonic part of the lowest-order chiral Lagrangian reads

$$\mathcal{L}_0 = -\frac{1}{2}\,\mathrm{tr}\,\{\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\} - \frac{1}{2}\,\mathrm{tr}\,\{\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu}\} - \frac{v^2}{4}\,\mathrm{tr}\,\{\mathbf{V}_{\mu}\mathbf{V}^{\mu}\} + \beta_1\mathcal{L}_0' + \sum_i \alpha_i\mathcal{L}_i$$

$$\mathcal{L}_0' = \tfrac{v^2}{4}\,\mathrm{tr}\,\{\mathbf{T}\mathbf{V}_\mu\}\,\mathrm{tr}\,\{\mathbf{T}\mathbf{V}^\mu\}$$
$$\mathcal{L}_1 = gg'\,\mathrm{tr}\,\{\mathbf{B}_{\mu\nu}\mathbf{W}^{\mu\nu}\}$$
$$\mathcal{L}_2 = \mathrm{i}g'\,\mathrm{tr}\,\{\mathbf{B}_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu]\}$$
$$\mathcal{L}_3 = \mathrm{i}g\,\mathrm{tr}\,\{\mathbf{W}_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu]\}$$

Conserve $SU(2)_c$ and induce anomalous quartic couplings →

$$\mathcal{L}_4 = (\mathrm{tr}\,\{\mathbf{V}_\mu\mathbf{V}_\nu\})^2$$
$$\mathcal{L}_5 = (\mathrm{tr}\,\{\mathbf{V}_\mu\mathbf{V}^\mu\})^2$$

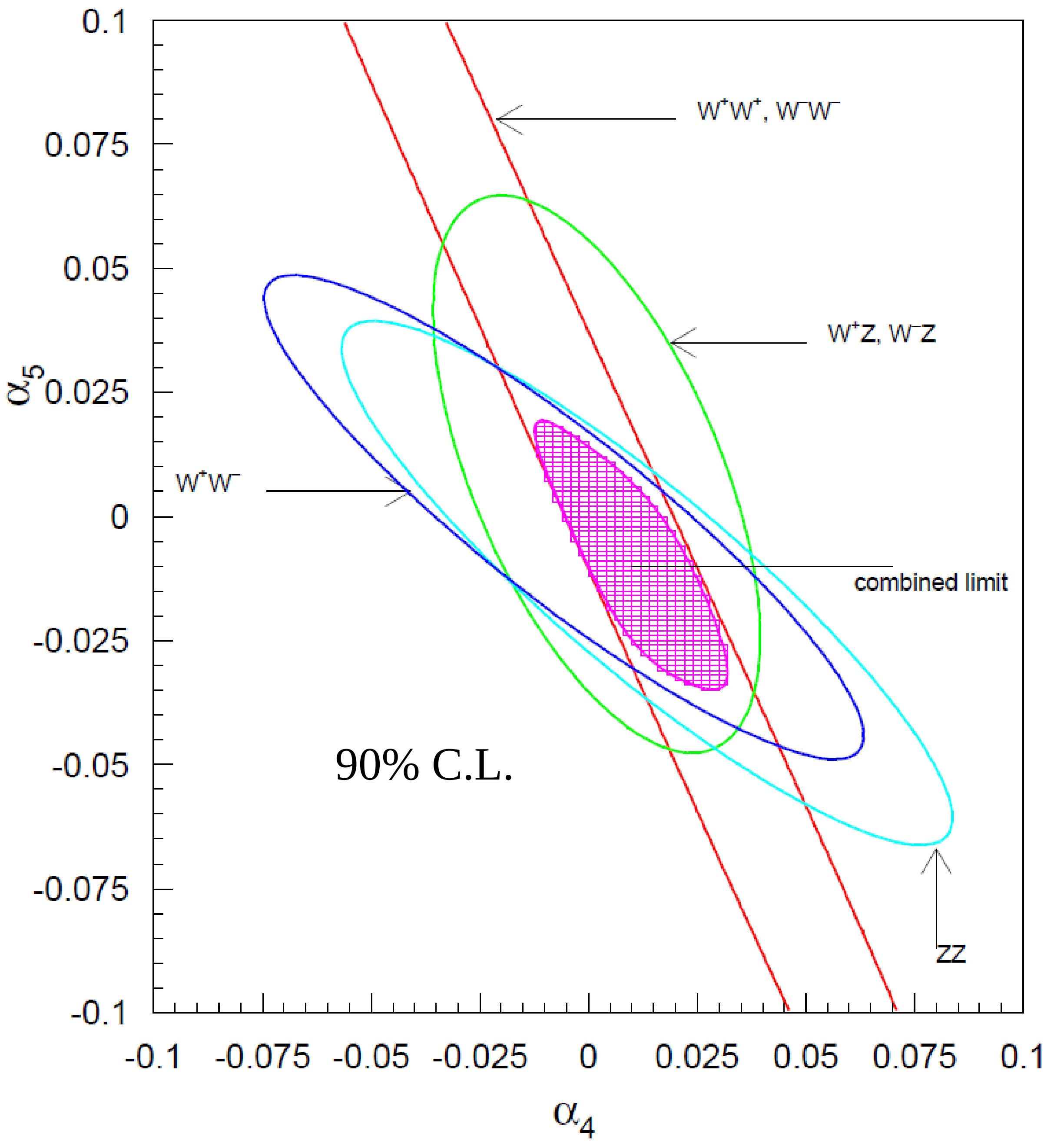
$$\mathcal{L}_6 = \mathrm{tr}\,\{\mathbf{V}_\mu\mathbf{V}_\nu\}\,\mathrm{tr}\,\{\mathbf{T}\mathbf{V}^\mu\}\,\mathrm{tr}\,\{\mathbf{T}\mathbf{V}^\nu\}$$
$$\mathcal{L}_7 = \mathrm{tr}\,\{\mathbf{V}_\mu\mathbf{V}^\mu\}\,(\mathrm{tr}\,\{\mathbf{T}\mathbf{V}_\nu\})^2$$
$$\mathcal{L}_8 = \tfrac{1}{4}g^2\,(\mathrm{tr}\,\{\mathbf{T}\mathbf{W}_{\mu\nu}\})^2$$
$$\mathcal{L}_9 = \tfrac{1}{2}\mathrm{i}g\,\mathrm{tr}\,\{\mathbf{T}\mathbf{W}_{\mu\nu}\}\,\mathrm{tr}\,\{\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu]\}$$
$$\mathcal{L}_{10} = \tfrac{1}{2}\,(\mathrm{tr}\,\{\mathbf{T}\mathbf{V}_\mu\})^2\,(\mathrm{tr}\,\{\mathbf{T}\mathbf{V}_\nu\})^2$$

Quartic Couplings at LHC

$L = 100\ fb^{-1}$

Older analysis (1998) using equivalence theorem and/or equivalent W approximation

A.S. Belyaev et al. hep-ph/9805229

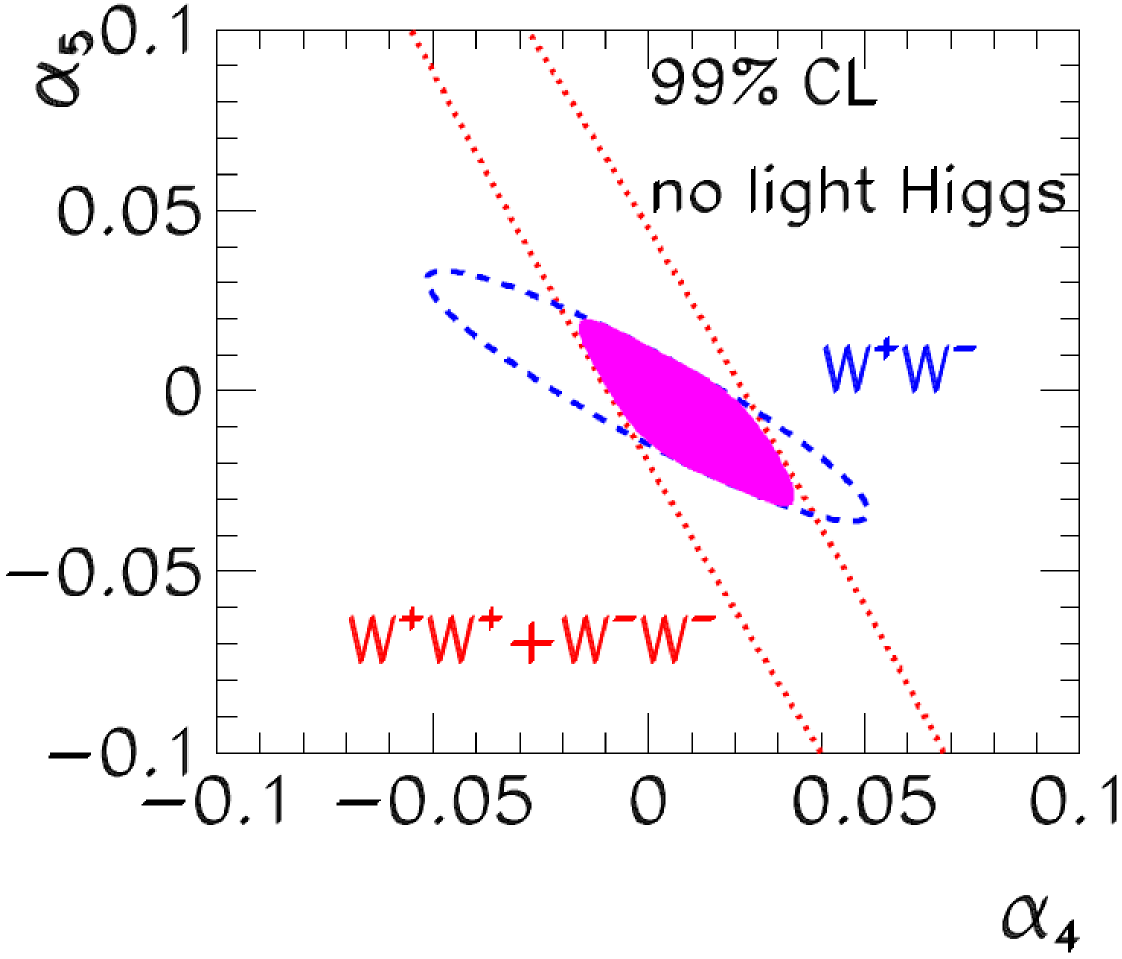


Quartic Couplings at LHC

$L = 100 \ fb^{-1}$

New analysis with full matrix element calculation for all 6-fermion final states at $O(\alpha_{em}^6)$ and $O(\alpha_{em}^4 \alpha_s^2)$

O.J.P. Eboli et al. hep-ph/0606118



Quartic Couplings at ILC

$e^+e^- \rightarrow WWZ$

case A: $e^-_{pol} = 0\%$

$e^+_{pol} = 0\%$

case B: $e^-_{pol} = 80\%\,R$

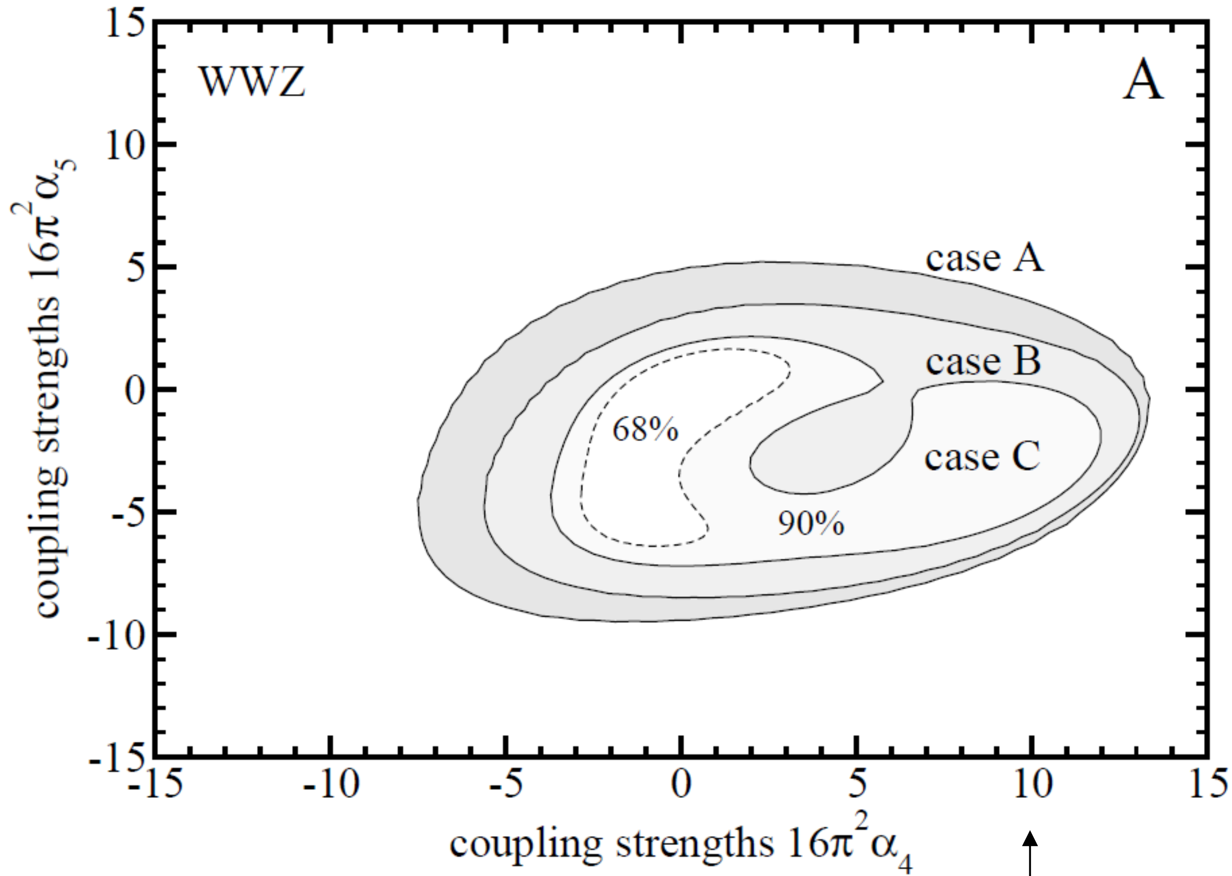
$e^+_{pol} = 0\%\,L$

case C: $e^-_{pol} = 80\%\,R$

$e^+_{pol} = 60\%\,L$

$\sqrt{s} = 1000\,GeV$

$L = 1000\ fb^{-1}$



$\alpha_4 = 0.063$

M. Beyer et al. hep-ph/0604048

Quartic Couplings at ILC

$e^+e^- \to WWZ$

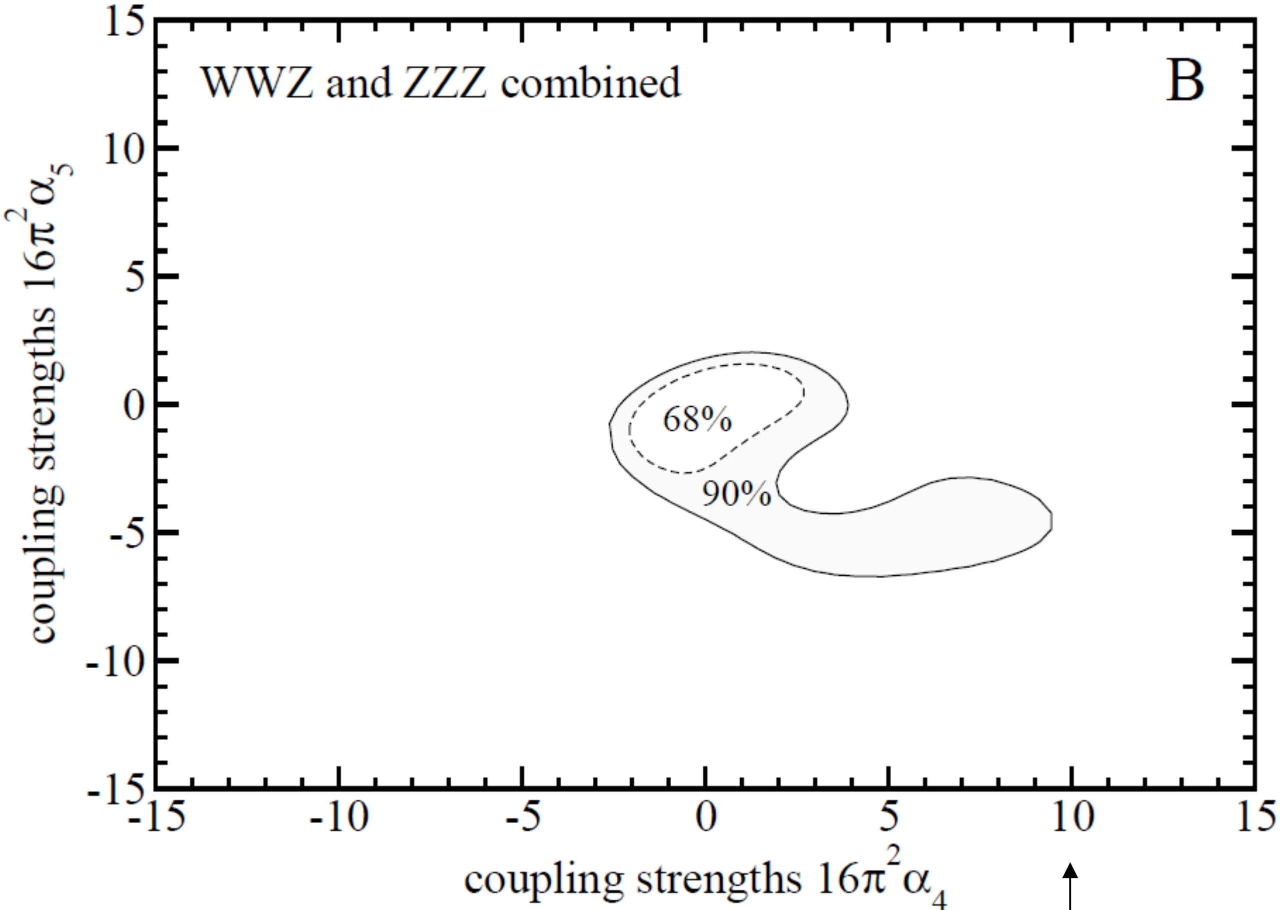
$e^+e^- \to ZZZ$

$e^-_{pol} = 80\%\,\mathrm{R}$

$e^+_{pol} = 60\%\,\mathrm{L}$

$\sqrt{s} = 1000\,GeV$

$L = 1000\ fb^{-1}$



$\alpha_4 = 0.063$

M. Beyer et al. hep-ph/0604048

Quartic couplings at ILC

$e^+e^- \to \nu_e \nu_e WW$

$e^+e^- \to \nu_e \nu_e ZZ$

$e^+e^- \to eeWW$

$e^+e^- \to eeZZ$

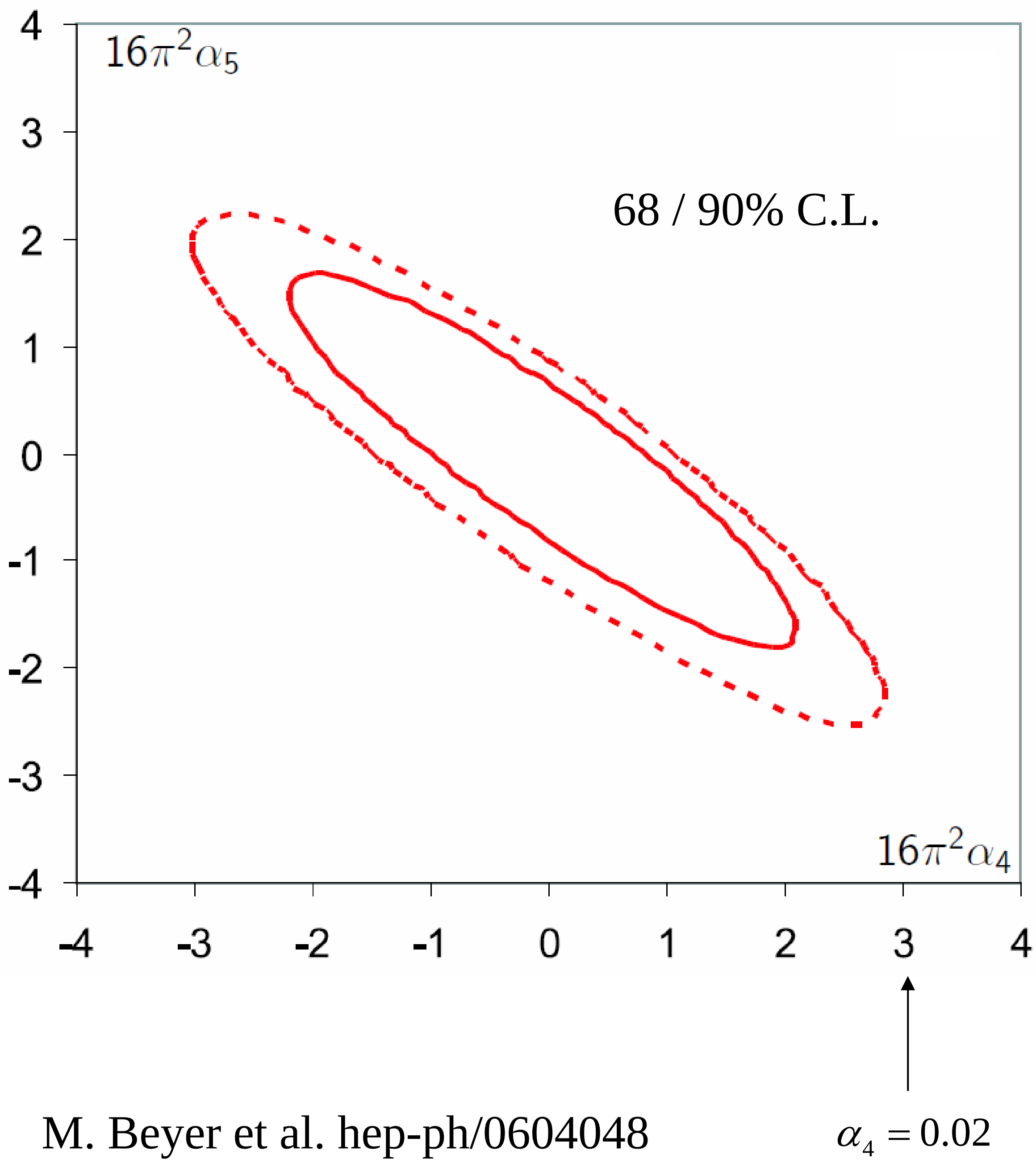
$e^+e^- \to e\nu_e WZ$

$e^-_{pol} = 80\%\,\mathrm{L}$

$e^+_{pol} = 40\%\,\mathrm{R}$

$\sqrt{s} = 1000\ GeV$

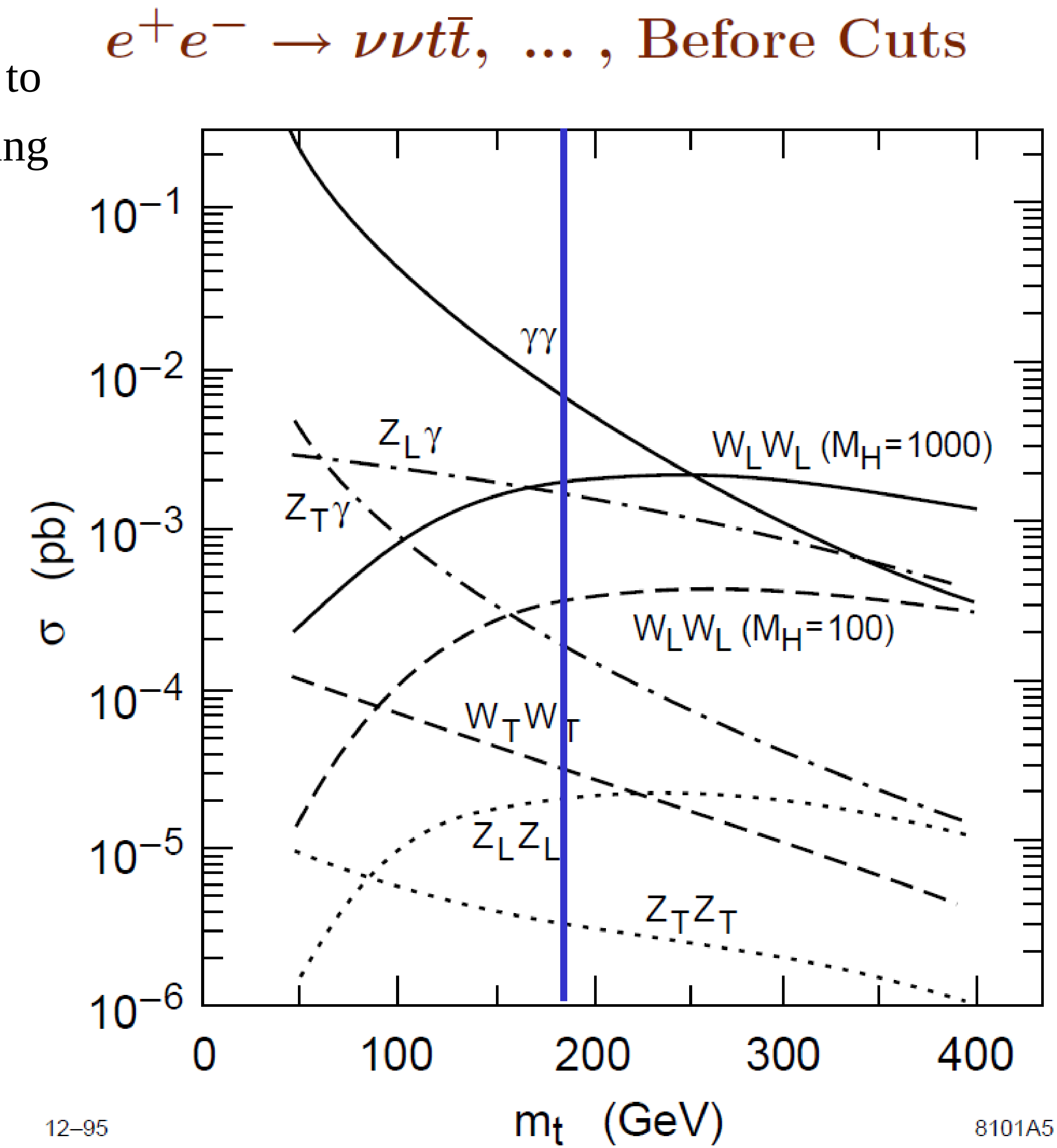
$L = 1000\ fb^{-1}$



M. Beyer et al. hep-ph/0604048

$WW \rightarrow t\bar{t}$ is sensitive to strong symmetry breaking in the fermion sector.

$\sqrt{s} = 2000\,GeV$:

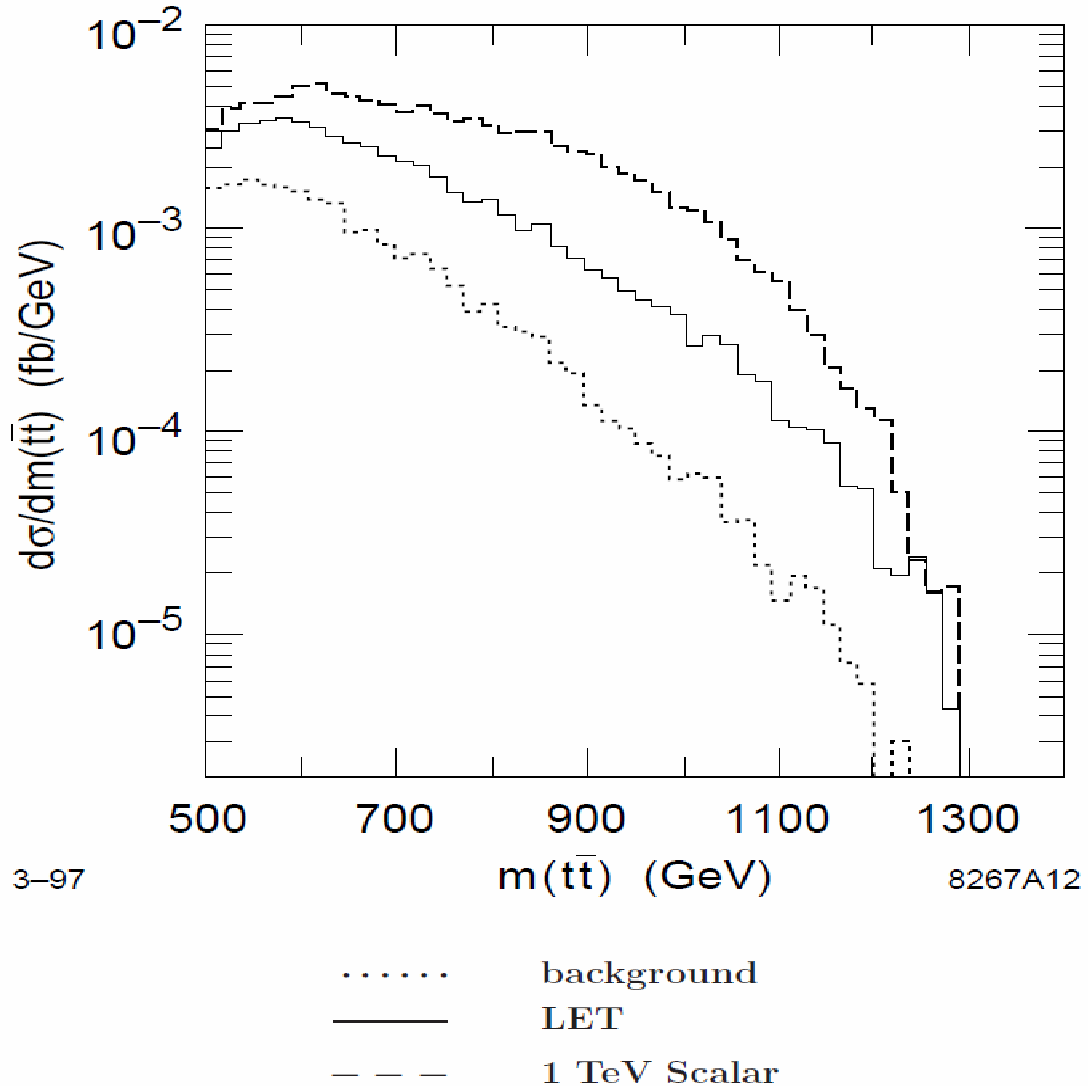


$e^+e^- \to \nu\nu t\bar{t}$ After Cuts

12σ (28σ) LET signal at $\sqrt{s} = 1000$ GeV (1500 GeV) LC with

$\mathcal{L} = 1000 \text{ fb}^{-1}$

$\sqrt{s} = 1500\ GeV:$

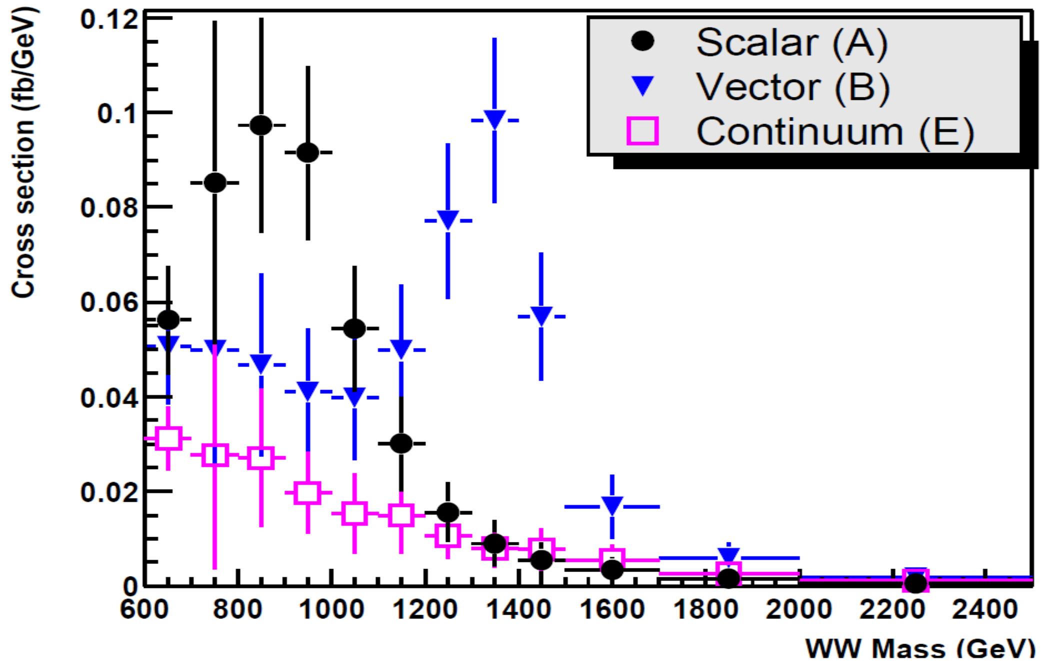


Direct Resonance

Detection at LHC

$L = 100\ fb^{-1}$

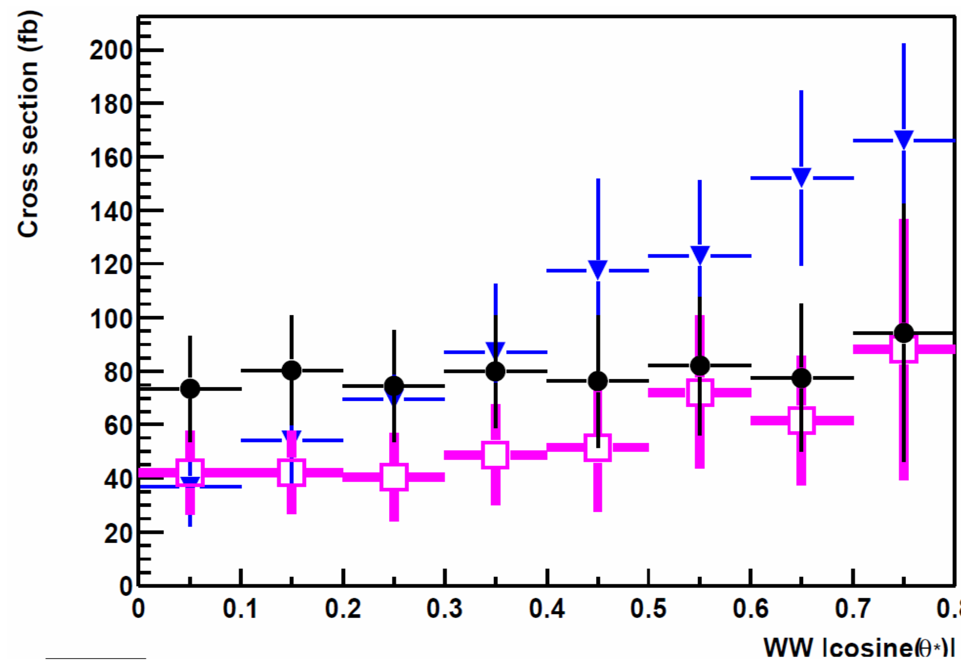
Cross section after cuts:



1 TeV Scalar

1.4 TeV Vector

non resonant



Direct Resonance

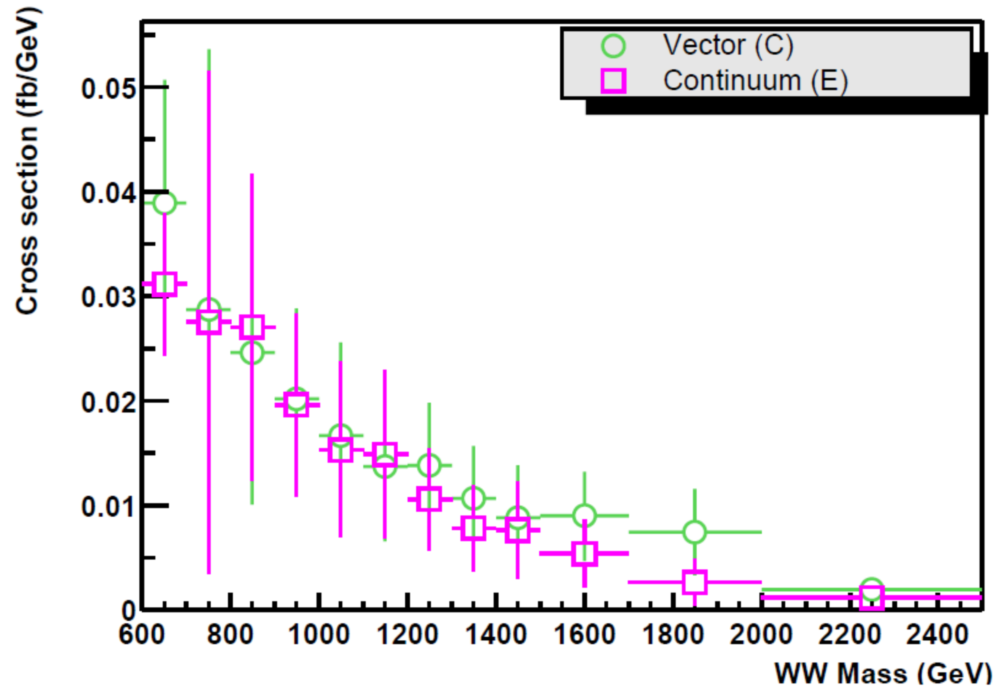
Detection at LHC

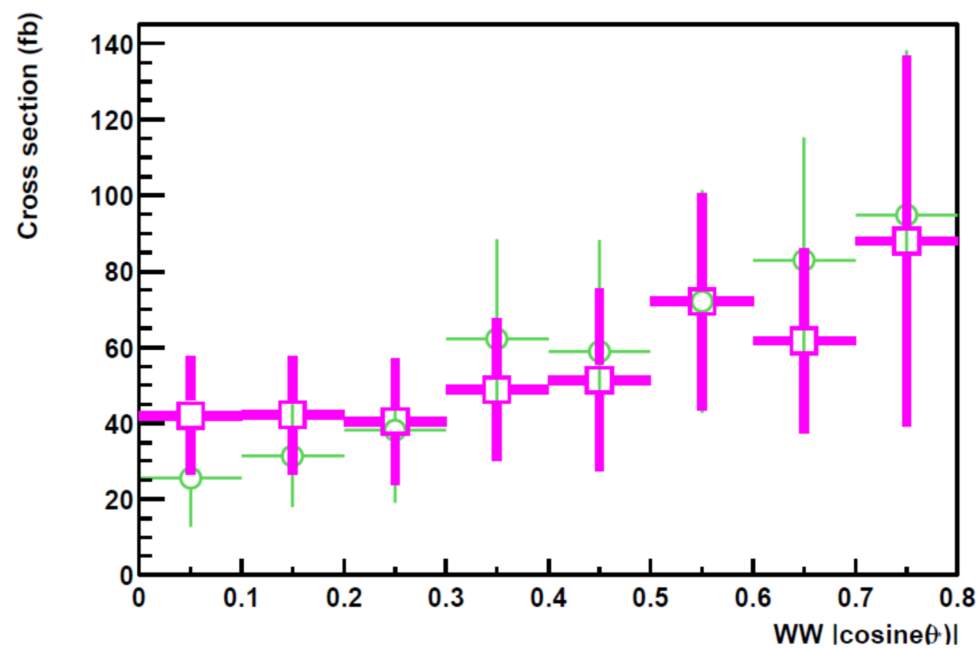
$L = 100 \ fb^{-1}$

Cross section after cuts:

1.9 TeV Vector

non resonant





Indirect Detection of

Heavy ρ-like Vector Resonances

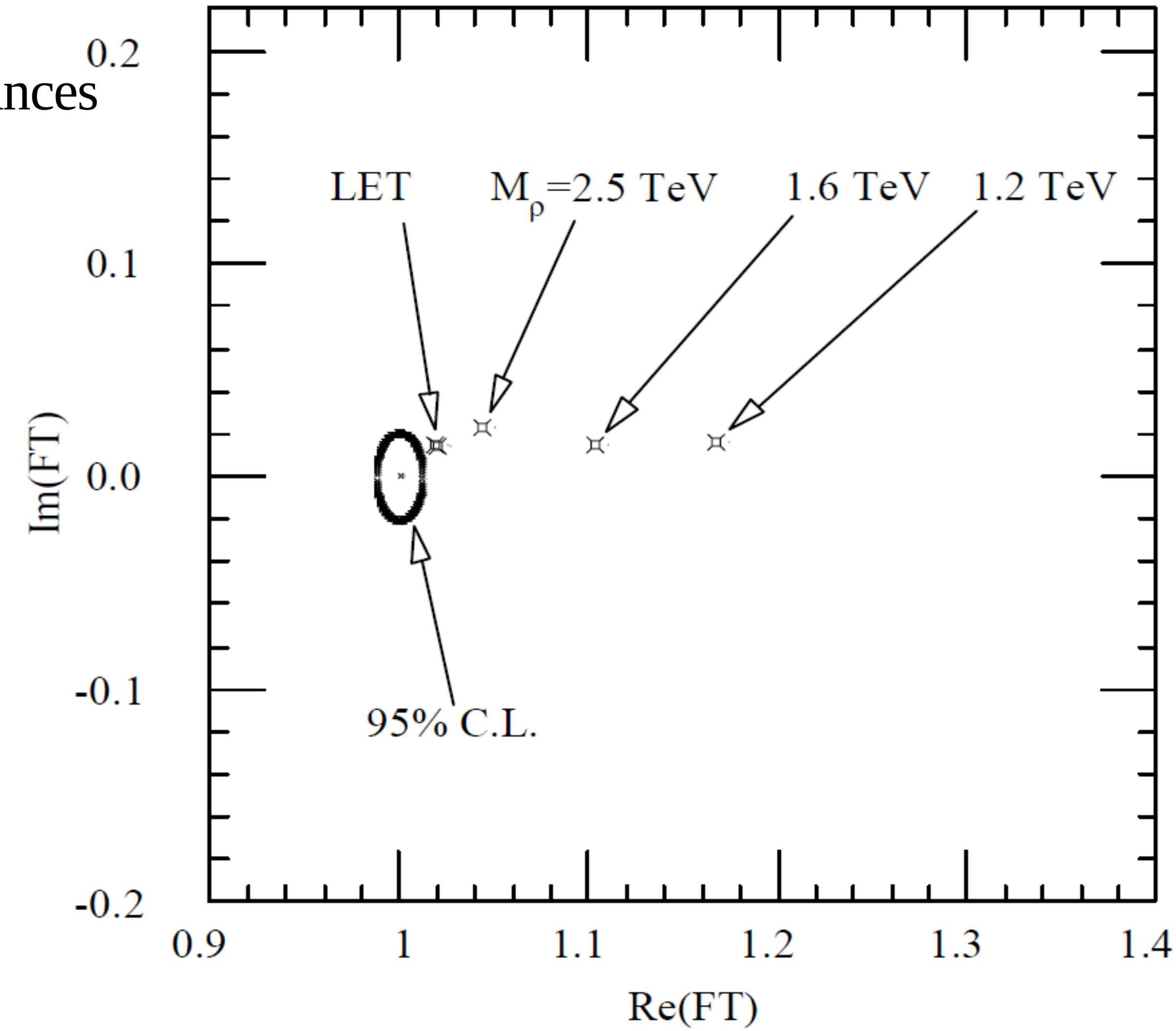
at ILC in $e^+e^- \to W^+W^-$

$\sqrt{s} = 500\ GeV$

$L = 500\ fb^{-1}$

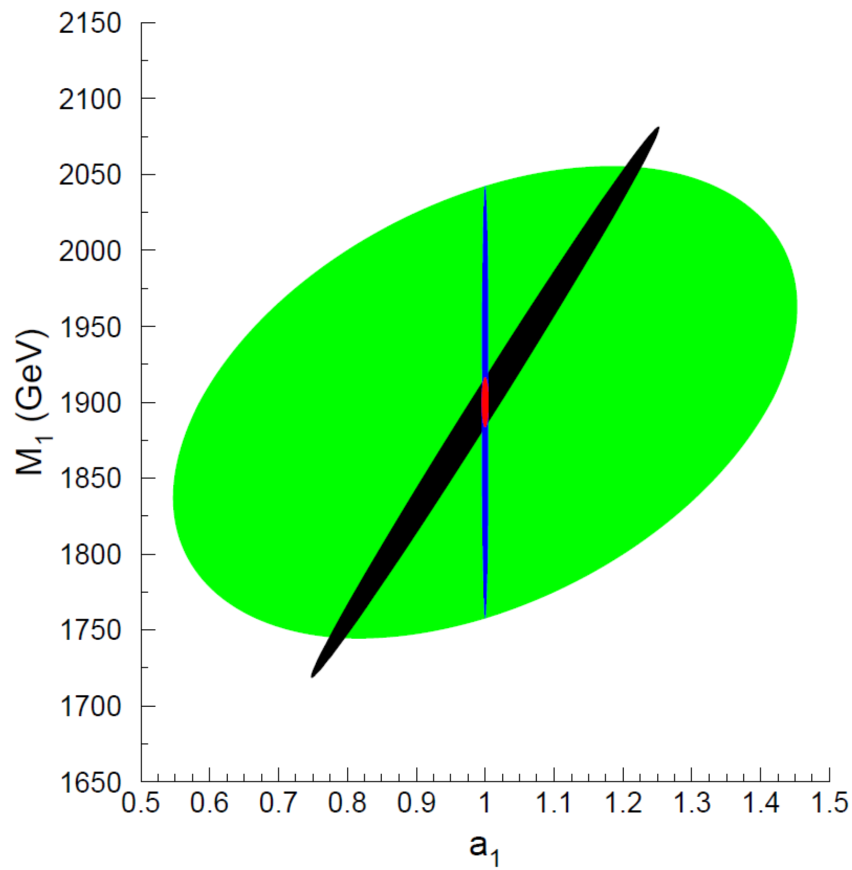
F_T is the form factor for the amplitude $e^+e^- \to W_L^+W_L^-$

$$F_T = 1 + s\sum_k \frac{a_k}{M_k^2}$$



Take example of direct detection of 1.9 TeV resonance at LHC.

Fit LHC mass distribution to Gaussian using resonance mass, width and strength a_1^2 as fit parameters. Project 3-d error ellipse onto Mass - a_1 plane (green):



Measure form factor F_T at the ILC at $\sqrt{s} = 500$ and 1000 GeV and fit for resonance mass, width and a_1 .

If the resonance is a vector you get the narrow black ellipse. If a scalar you get $a_1 = 0$.

$$F_T = 1 + s\sum_k \frac{a_k}{M_k^2}$$

Summary

- Both LHC and the ILC at E_{cm}=1000 GeV measure anomalous quartic couplings α_4, α_5 at the few percent level; systematics of LHC/ILC quite different; ILC quartic coupling reach is now well documented.
- ILC can uniquely measure WW→tt and thereby probe strong symmetry breaking in the fermion sector.
- Only LHC can directly detect strong resonances, although ILC can be indirectly sensitive to vector resonances beyond the reach of LHC.
- An example was given where the ILC helped pin down the spin, coupling strength, and mass of a 1.9 TeV resonance detected in WW scattering at the LHC.