❺ Electroweak Gauge-Bosons

- Introduction
- Measurement of the W-mass $\longrightarrow$ later
- Triple gauge-couplings
- Strong interaction of electroweak gauge bosons

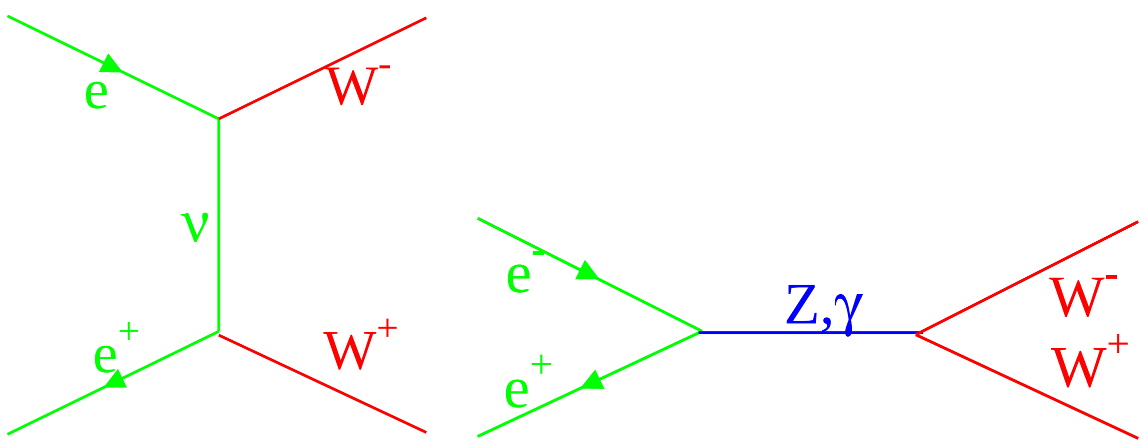
Introduction

- Self-interactions among gauge-bosons are directly given by structure of gauge group

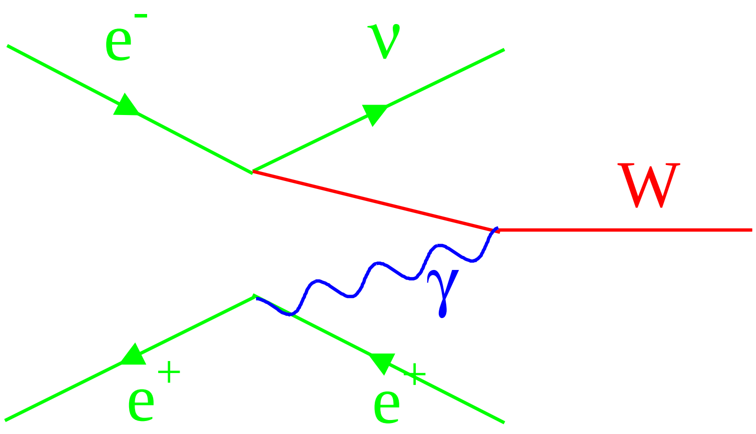
➡ study of gauge-boson interactions can show details of the gauge group.

Two main classes of processes:

Pair production (e.g. W pairs):



Fusion processes (e.g. single W production):



Or combination of both for quartic couplings

Pair production:

- Cross sections fall like $1/s$
- The scale of the interesting interaction is $\sqrt{s}$
- the events are fully contained in the detector

Fusion processes:

- the total cross section rises with energy
- the scale of the interesting interaction remains low
- particles from the incoming fermion are often lost in the beampipe or as neutrinos

Triple gauge couplings

Usual parameterization for WWV (V=Z,γ) couplings:

$$
\begin{aligned}
i\mathcal{L}_{eff}^{WWV} = g_{WWV} \cdot [\\
& g_1^V V^\mu \left(W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu} \right) + \\
& \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \\
& \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^- + \\
& i g_5^V \epsilon_{\mu\nu\rho\sigma} \left(\left(\partial^\rho W^{-\mu} \right) W^{+\nu} - \right. \\
& \qquad \left. W^{-\mu} \left(\partial^\rho W^{+\nu} \right) \right) V^\sigma + \\
& i g_4^V W_\mu^- W_\nu^+ \left(\partial^\mu V^\nu + \partial^\nu V^\mu \right) - \\
& \frac{\tilde{\kappa}_V}{2} W_\mu^- W_\nu^+ \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \\
& \frac{\tilde{\lambda}_V}{2m_W^2} W_{\rho\mu}^- W^{+\mu}{}_\nu \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}]
\end{aligned}
$$

With $V = \gamma,\ Z,\ g_{WW\gamma} = e,\ g_{WWZ} = e \cot\theta_W$ and $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$

Gauge invariance: $g_1^\gamma(q^2 = 0) = 1,\ g_5^\gamma(q^2 = 0) = 0$

SM: $g_1^V = \kappa_V = 1$ all other couplings $= 0$

Static quantities:

- magn. dipole-moment: $\mu_W = \frac{e}{2m_W}(1+\kappa_\gamma+\lambda_\gamma)$
- elec. quadr.-moment: $q_W = -\frac{e}{m_W^2}(\kappa_\gamma-\lambda_\gamma)$

Symmetries:

- $g_1,\ \kappa,\ \lambda$ C,P-conserving
- g_5 C,P-violating, CP-conserving
- $g_4,\ \tilde{\kappa},\ \tilde{\lambda}$ CP-violating

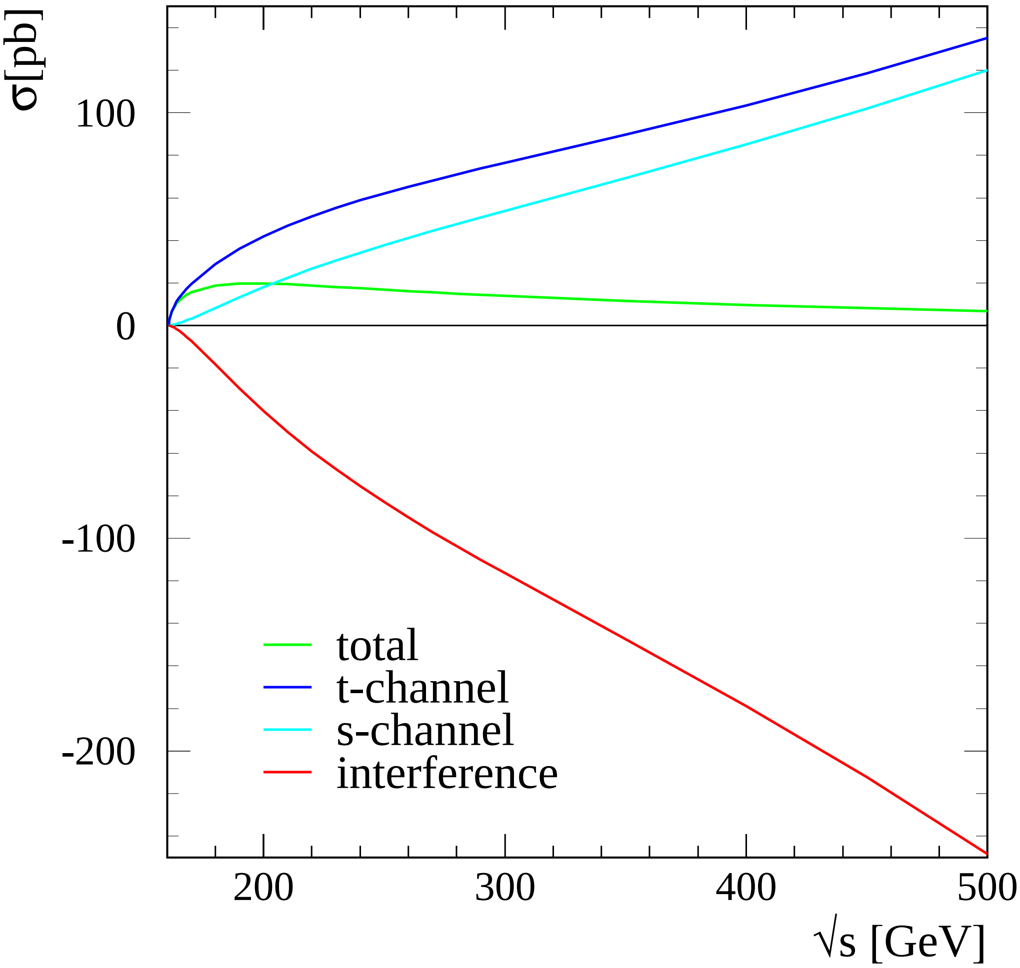
Expect largest experimental sensitivity and largest deviations in C,P-conserving couplings

➠ mainly studied up to now

However construction of C,CP-violating observables measures the other couplings independent from the C,P-conserving ones

Gauge cancellations:

- W-pair production via t-channel ν-exchange and s-channel Z,γ-exchange violates unitarity individually
- unitarity gets restored by s-t interference



➠ sensitivity increases with energy

➠ anomalous couplings have to vanish for $\sqrt{s} \to \infty$

LC:

- main sensitivity from W-pair production

➡ measurement of TGCs at fixed scale ($=\sqrt{s}$)

➡ take energy dependence into account in interpretation of results

LHC:

- main sensitivity in Wγ and WZ pair production
- $\sqrt{s}$ varies event by event due to PDFs

➡ have to take energy dependence into account in analysis

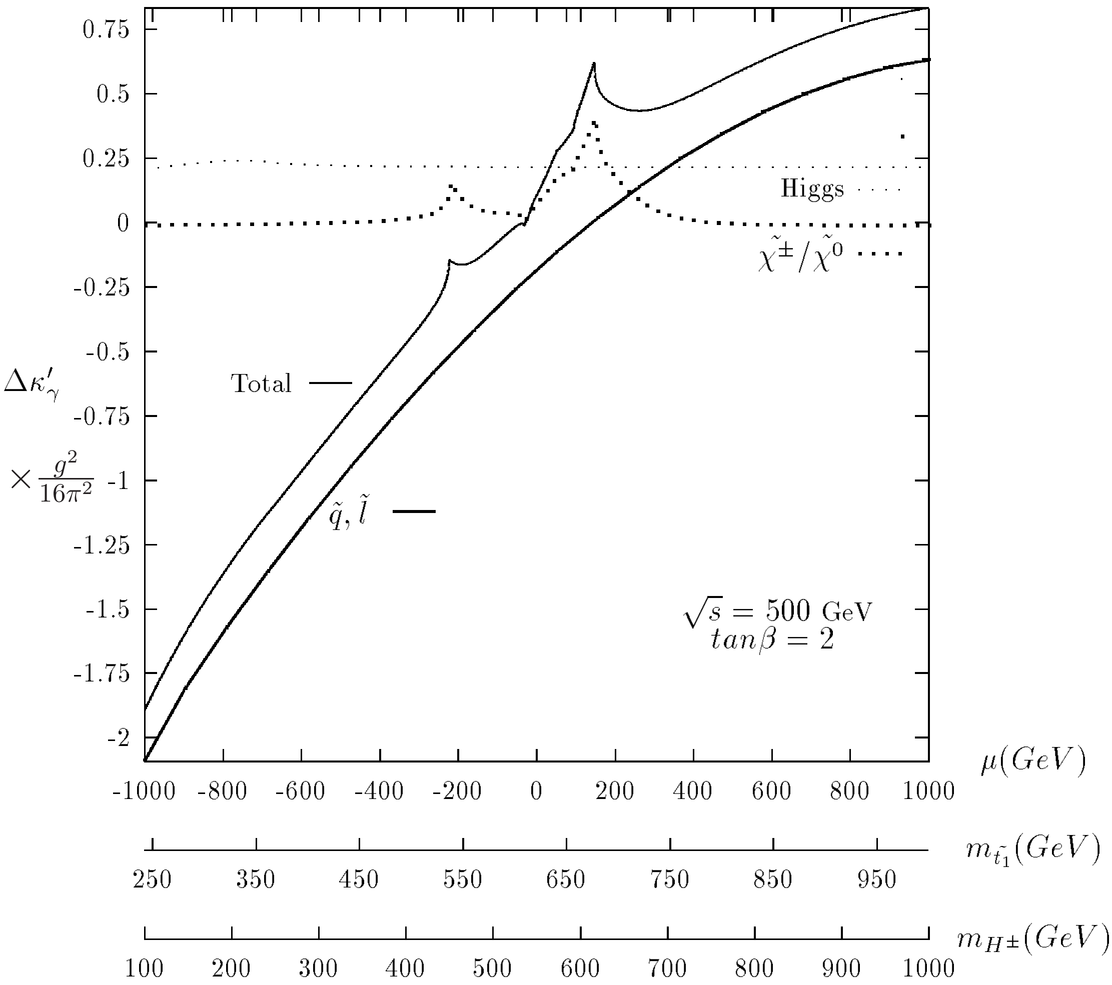
- typically regularize coupling by form factor: $x' = \frac{x}{(1+s/\Lambda^2)^n}$, $n > 0.5$ for $\Delta\kappa$, $n > 1$ for λ
- Λ can be viewed as scale where new physics sets in, so it makes sense to compare experiments for very high Λ
- in case anomalous couplings are found, have to measure detailed shape with $\sqrt{s}$ (LHC+LC!)

Theoretical expectations:

Triple gauge couplings should be modified on 1-loop level

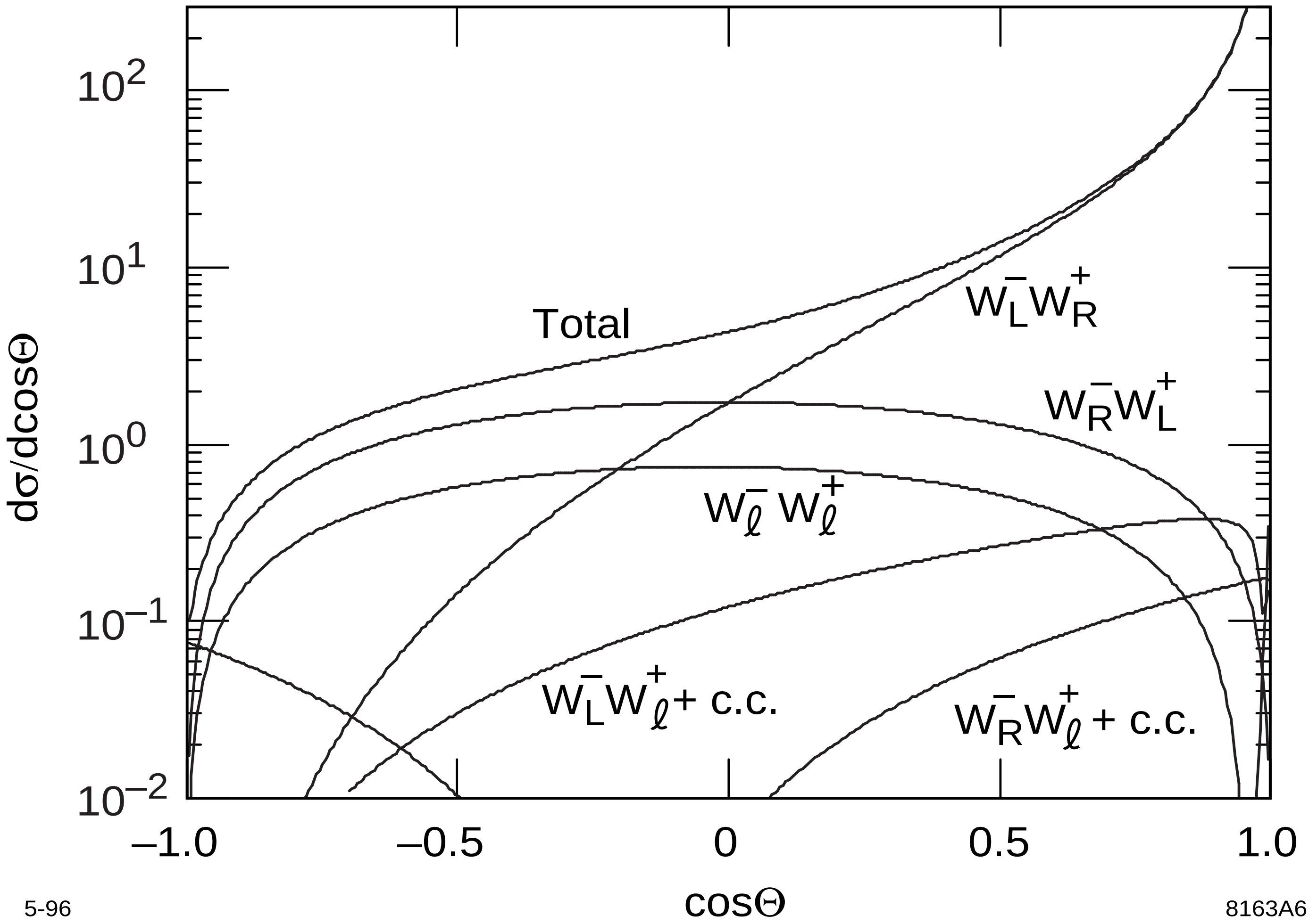
$\Rightarrow$ expect deviations of order $g^2/16\pi^2 \approx 2.7 \cdot 10^{-3}$

E.g. MSSM contributions to $\Delta\kappa_\gamma$:



Experimental analyzes (all very similar to LEP II)

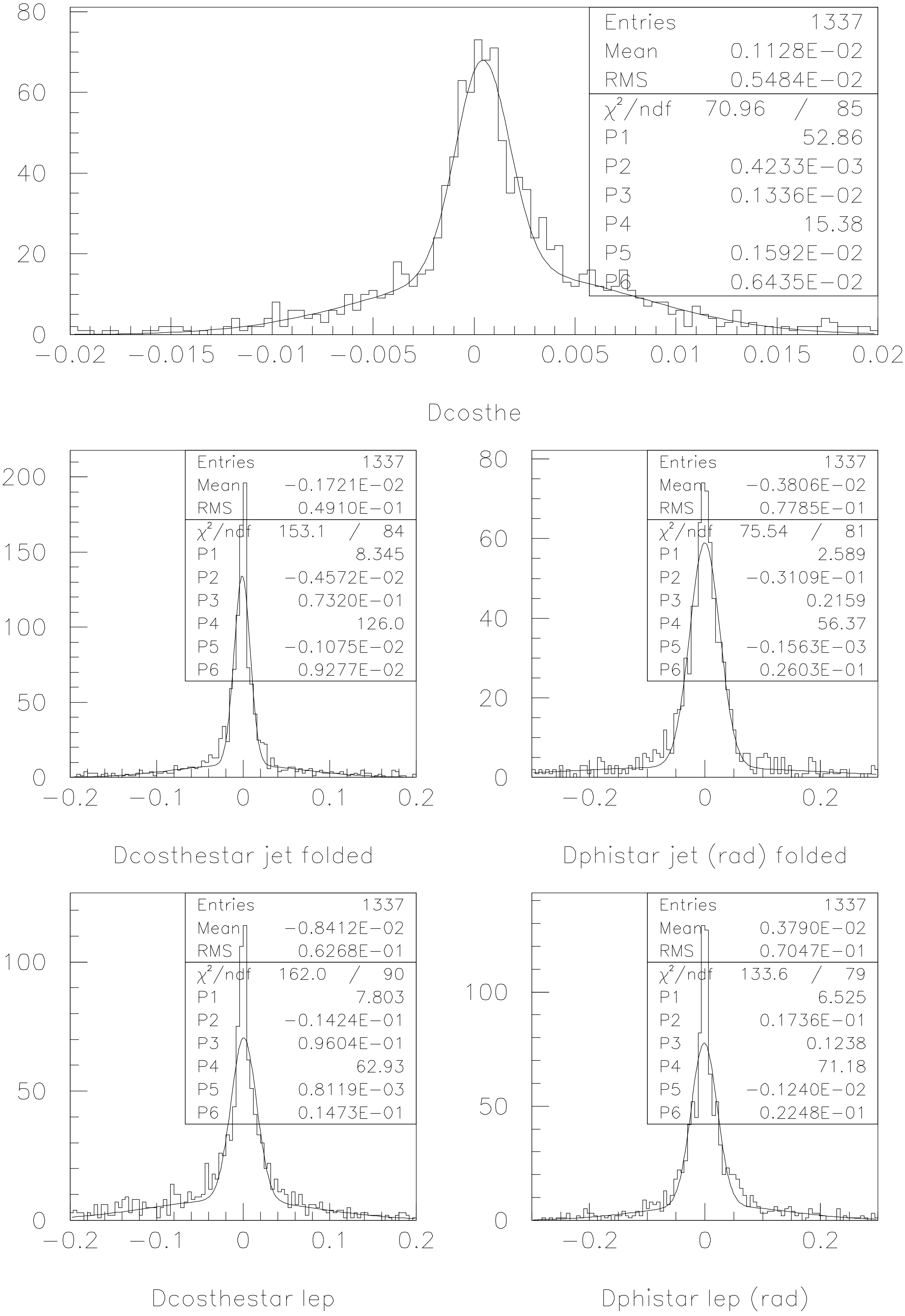
- sensitive quantities
  - cross section
  - W-production angle
  - W polarization $\rightarrow$ W-decay angles



- huge peak in forward region,insensitive to anomalous coupling
  $\Rightarrow$ cross section dependence contained in angular dependence

- Ws have much larger boost than at LEP:
  - the two Ws are well separated
  - the resolution in the production angle is better than at LEP $\longrightarrow$ plot
  - the resolution in the decay angles is somewhat worse $\longrightarrow$ plot
  - however detector resolution does not effect the analysis strongly
- up to now only mixed decays WW $\rightarrow \ell\nu \mathrm{q\bar{q}}'$
  - about $\sim 40\%$ of the statistics
  - W^+, W^- can be separated without ambiguity
  - decay angles of leptonically decaying W can be measured without ambiguity
  - decay angles of hadronically decaying W can be measured with twofold ambiguity
- analysis methods similar as at LEP:
  optimal observables, spin density matrix, maximum likelihood fits
- expect factor 100 smaller errors
  - factor 10 from sensitivity $\longrightarrow$ applies also to systematics
  - factor 10 from luminosity $\longrightarrow$ have to improve systematics by that amount

Angular resolutions for $\theta_W > 20^\circ$

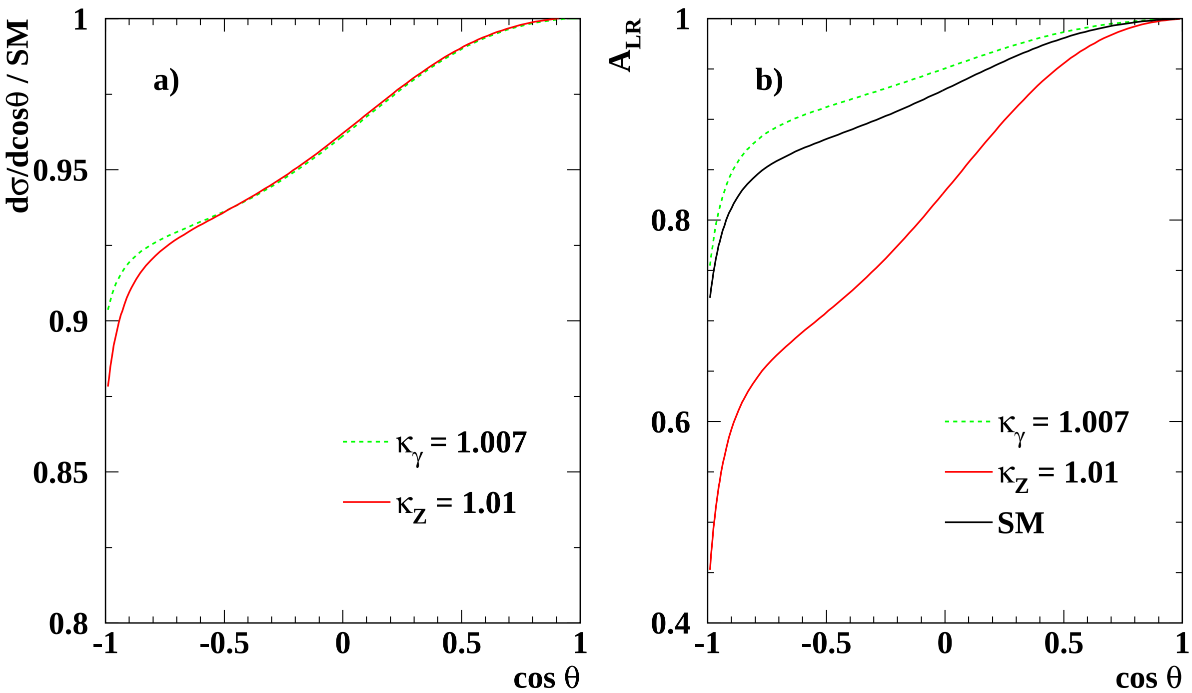


Separation of WWγ and WWZ couplings

- for the W-pairs WWγ and WWZ couplings cannot be separated from the event information
- however initial state $e^+e^-\gamma$ and e^+e^-Z couplings are different for different electron polarization

➡ can use beam polarization to separate the two

total cross section $\qquad\qquad$ A_{LR}



- (for fits relating the WWγ and WWZ couplings polarization also reduces the error by more than a factor 2)
- in addition single W production, $e\gamma$- and $\gamma\gamma$-collider measure WWγ coupling only

Results:

Statistical precision for $\sqrt{s} = 500\,\mathrm{GeV}$, $\mathcal{L} = 500\,\mathrm{fb}^{-1}$, $\mathcal{P}_{\mathrm{e}^-} = \pm 80\%$:

$$\begin{aligned} \Delta\kappa_\gamma, \Delta\kappa_Z, \Delta\lambda_\gamma, \Delta\lambda_Z &\approx (3-4)\times 10^{-4} \\ \Delta g_1^Z &\approx (8-13)\times 10^{-4} \end{aligned}$$

depending on the number of fit parameters

$\sqrt{s} = 800\,\mathrm{GeV}$ ~factor 2 better

Systematics:

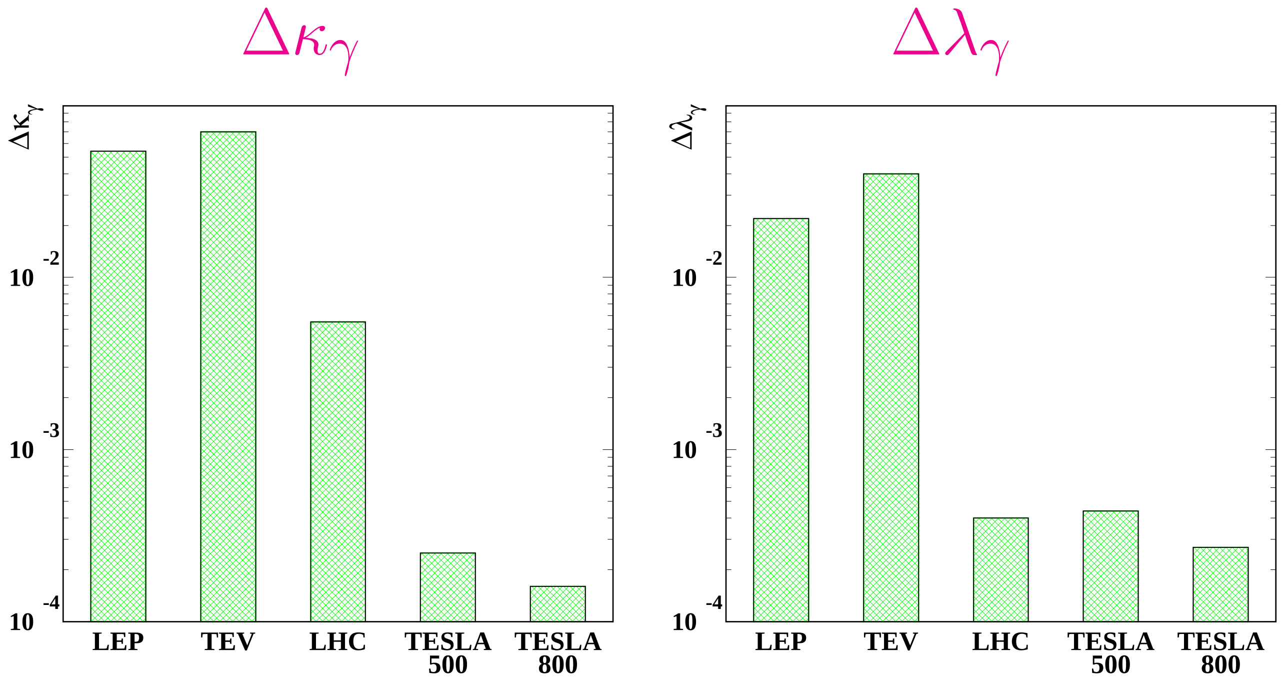
- ISR needs to be known to the 1% level
- beamstrahlung seems no problem
- detector effects should also be under control due to better θ_W resolution
- with the standard parameterization polarization can be obtained from A_{LR} in forward peak

CP-violating couplings

$$\Delta\tilde{\kappa}, \Delta\tilde{\lambda} = (1-2)\times 10^{-2}$$

from CP-odd observables

Comparison with LHC etc.:

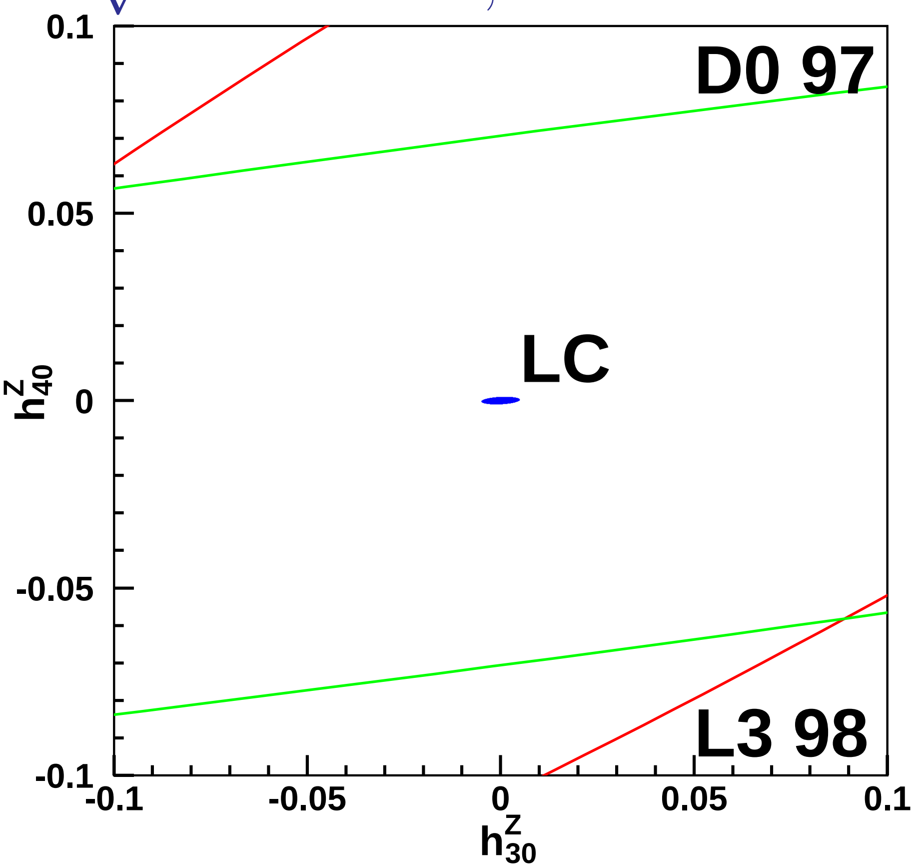


- LC much better than LHC for κ, somewhat better for λ
- if new physics scale is high, effects are expected in κ because of lower dimension
  ➠ big advantage for LC
- if new physics scale is low, both couplings can show effects and LHC probes at higher scales where new physics might be visible directly
  ➠ advantage for LHC
- if some effect is found somewhere it is definitely invaluable to have complementary information

Measurements of neutral TGCs

- neutral TGCs forbidden in the SM at loop level
- possible anomalous couplings only come in at higher dimensions (8)
- studies exist e.g. for γZZ- and $\gamma\gamma Z$-couplings in $Z\gamma$ events with high p_t photons
- dramatic improvement compared to existing machines

$\sqrt{s} = 500\,\text{GeV},\ \mathcal{L} = 100\,\text{fb}^{-1}$



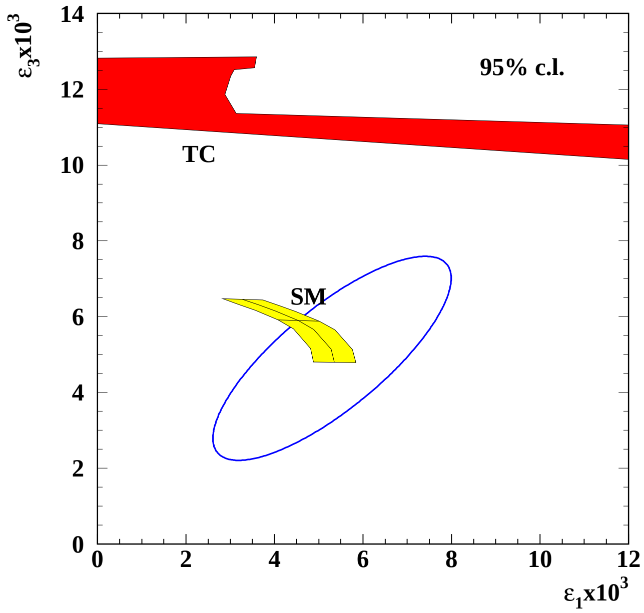
- however still factor 10 worse than SM prediction and LHC

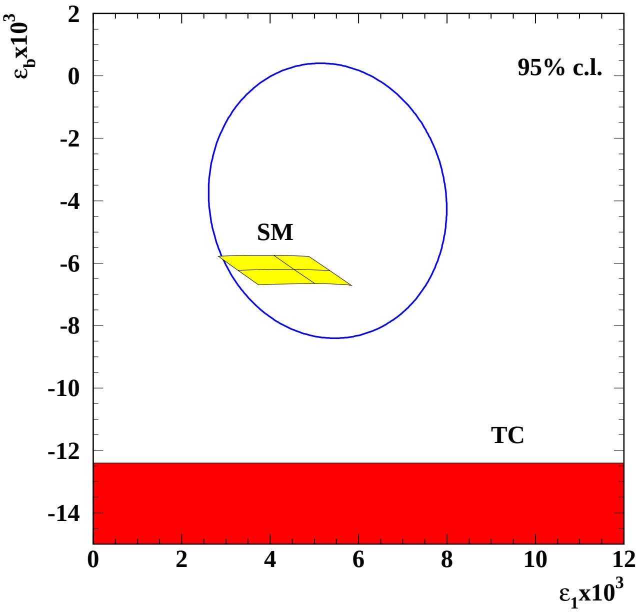
Strong Electroweak Symmetry Breaking

- If no Higgs exists electroweak interactions become strong at high energy and e.g. WW scattering violates unitarity at $\sqrt{s_{WW}} \sim 1.2\,\mathrm{TeV}$.

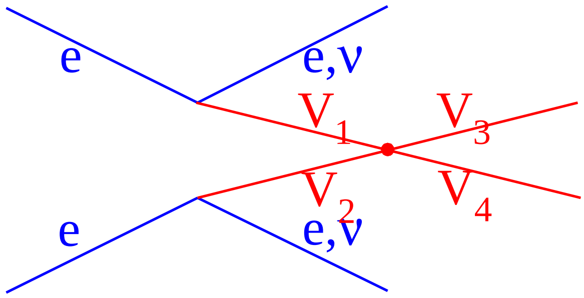
➠ expect new effects at this energy

- Typical models invoke a new strong interaction at the TeV scale (Technicolor)
- The Goldstone-bosons (Pions) of the new theory become the longitudinal degrees of freedom of the vector-bosons
- Warning: simple copy of QCD is excluded by LEP/SLD precision data

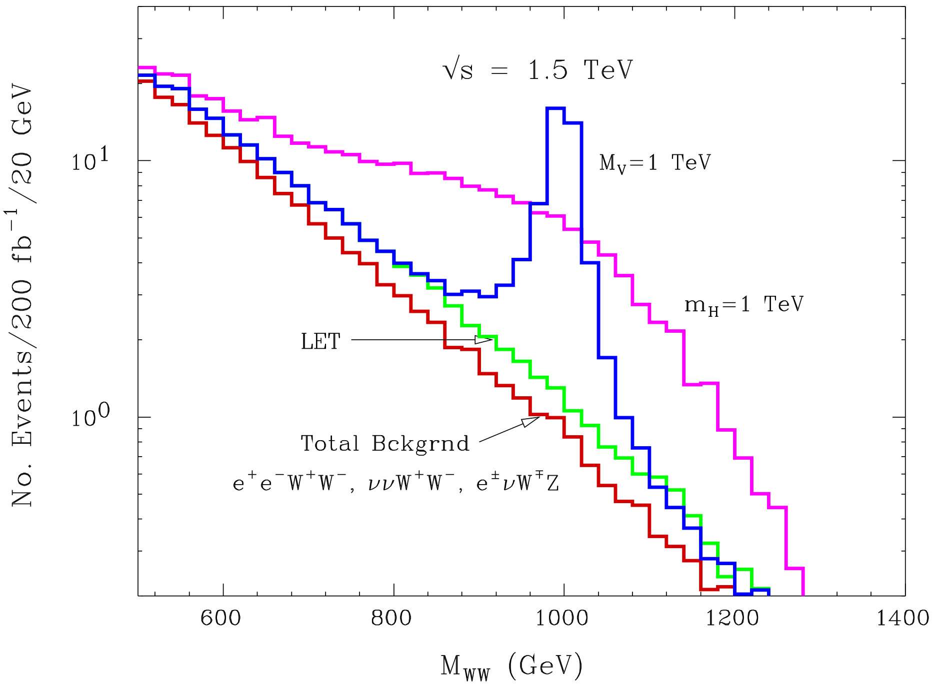




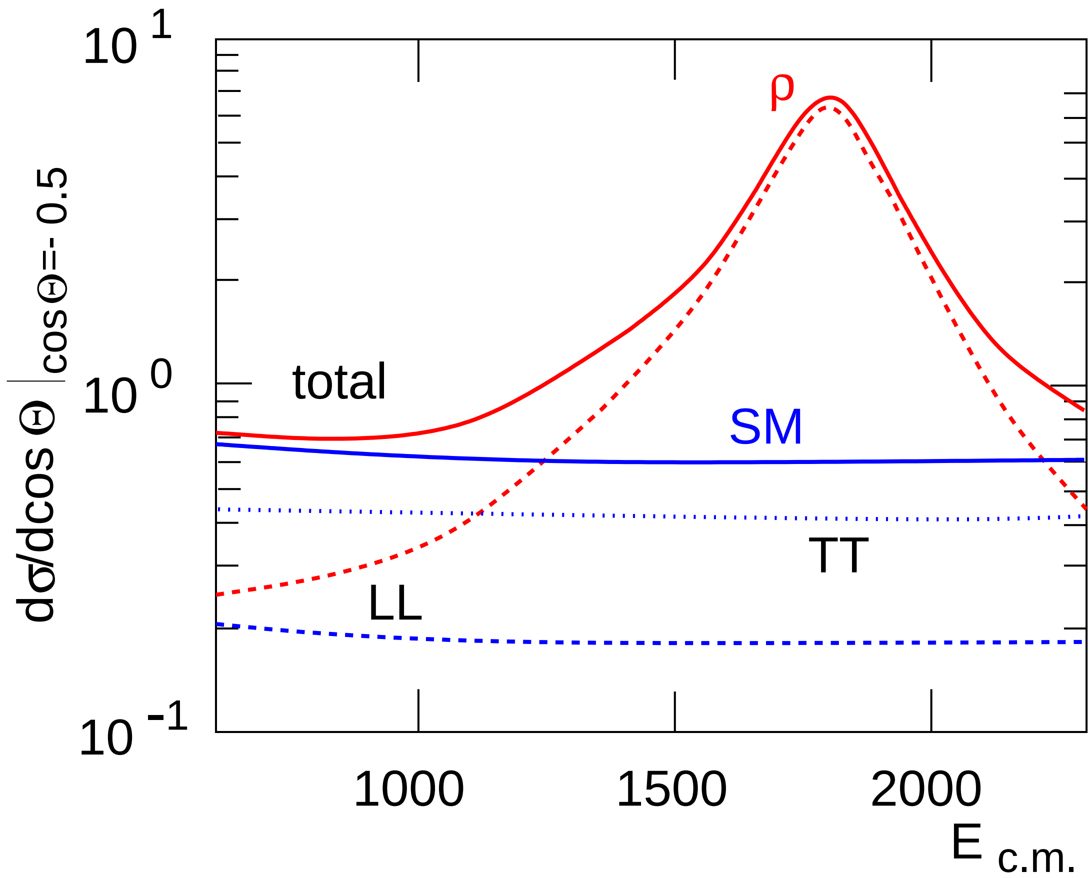
- interpretations within this model are certainly a very useful indication but should not be taken literally, however no other concrete model exists
- most intuitive channel: VV scattering V=W,Z



- ideally find resonances (like ρ, ω, etc.)
- however also if no resonances are found the LET says that longitudinal VV-scattering at high energy behaves like $\pi\pi$-scattering at low energy



also in W-pair production effects from J=1 resonances should be visible (like in $e^+e^- \rightarrow \rho \rightarrow \pi^+\pi^-$)



with high precision resonance effects remain visible at lower energy

Systematic approach: Effective Lagrangian

- symmetry breaking is realized non-linearly
- expand Lagrangian in the dimension of the field operators ($\propto \sqrt{s}$)
- keep lowest order that contains analyzed interaction

Trilinear couplings:

$$
\begin{aligned}
\mathcal{L}_{TGC} = & \frac{\alpha_1}{16\pi^2}\frac{gg'}{2}B_{\mu\nu}\,\mathrm{tr}(\sigma_3 W^{\mu\nu}) + \\
& \frac{\alpha_2}{16\pi^2}\mathrm{i}g' B_{\mu\nu}\,\mathrm{tr}(\sigma_3 V^{\mu}V^{\nu}) + \\
& \frac{\alpha_3}{16\pi^2}2\mathrm{i}g\,\mathrm{tr}(W_{\mu\nu}V^{\mu}V^{\nu})
\end{aligned}
$$

Strong interaction:

$$
\frac{\alpha_i}{16\pi^2} = \left(\frac{v}{\Lambda_i^*}\right)^2
$$

Unitarity requires:

$$
\Lambda^* \approx 3\,\mathrm{TeV}
$$

α's can be expressed in terms of g_1, κ:

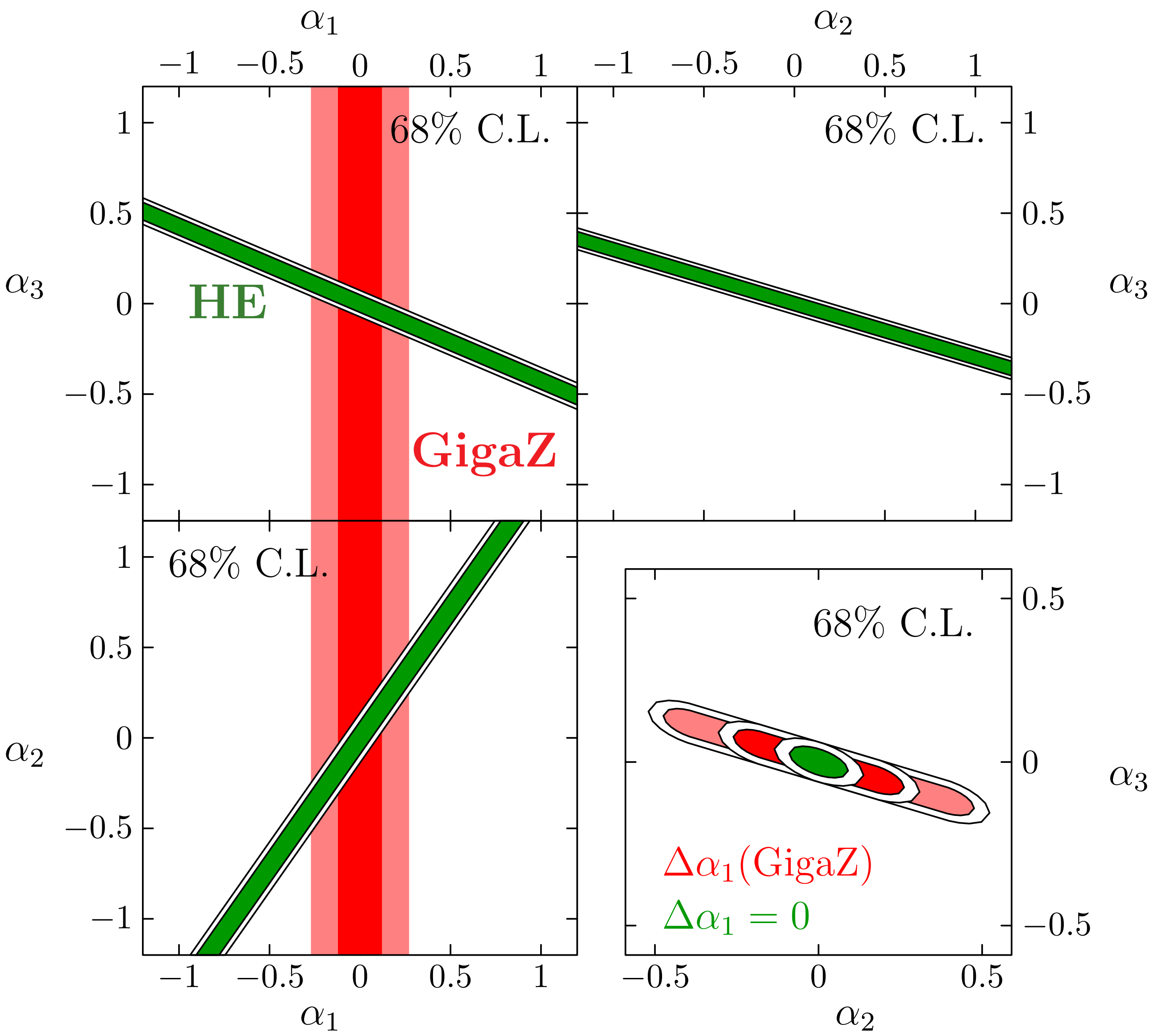
$$\Delta g_1^Z = \frac{e^2}{\cos^2\theta_W(\cos^2\theta_W - \sin^2\theta_W)}\frac{\alpha_1}{16\pi^2} + \frac{e^2}{\sin^2\theta_W\cos^2\theta_W}\frac{\alpha_3}{16\pi^2}$$

$$\Delta\kappa_\gamma = -\frac{e^2}{\sin^2\theta_W}\frac{\alpha_1}{16\pi^2} + \frac{e^2}{\sin^2\theta_W}\frac{\alpha_2}{16\pi^2} + \frac{e^2}{\sin^2\theta_W}\frac{\alpha_3}{16\pi^2}$$

$$\Delta\kappa_Z = \frac{2e^2}{\cos^2\theta_W - \sin^2\theta_W}\frac{\alpha_1}{16\pi^2} - \frac{e^2}{\cos^2\theta_W}\frac{\alpha_2}{16\pi^2} + \frac{e^2}{\sin^2\theta_W}\frac{\alpha_3}{16\pi^2}$$

System is degenerate, but α_1 can be tightly constrained with m_{W} and $\sin^2\theta^l_{eff}$ measurements at GigaZ

Results for $\sqrt{s} = 800\,\mathrm{GeV}$, $\mathcal{L} = 1000\,\mathrm{fb}^{-1}$

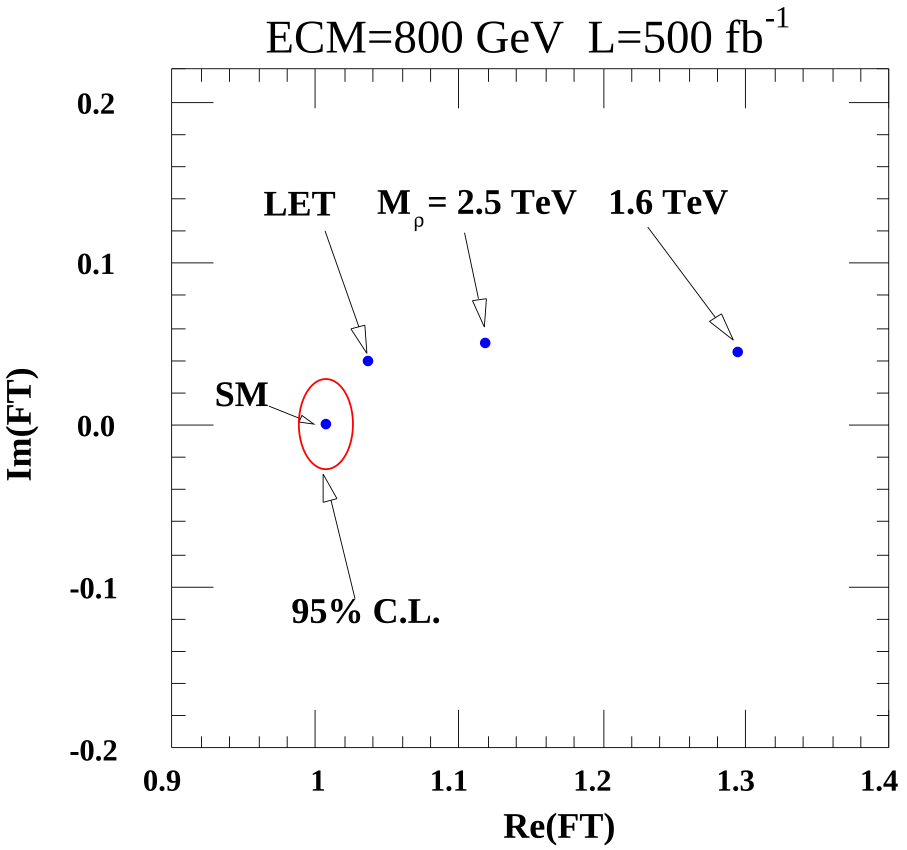


α-limits correspond to $\Lambda^* = \mathcal{O}(10\,\mathrm{TeV}) \gg 3\,\mathrm{TeV}$

SEWSB should be seen in triple gauge couplings at LC

Analysis within technicolor models

- Parameterize $e^+e^- \rightarrow WW$ with a form factor similar to $e^+e^- \rightarrow \pi^+\pi^-$
- can predict form factor as a function of m_ρ
- LET is limit for large m_ρ



- Linear Collider is sensitive to techni-ρ masses up to $\sim 2.5\,\mathrm{TeV}$ and can distinguish LET from SM
- The LHC has a similar reach
- however the information is very complementary since the LHC measures the mass of a resonance and the LC measures the couplings

Quartic couplings:

Luminosity spectrum of “W beam”:

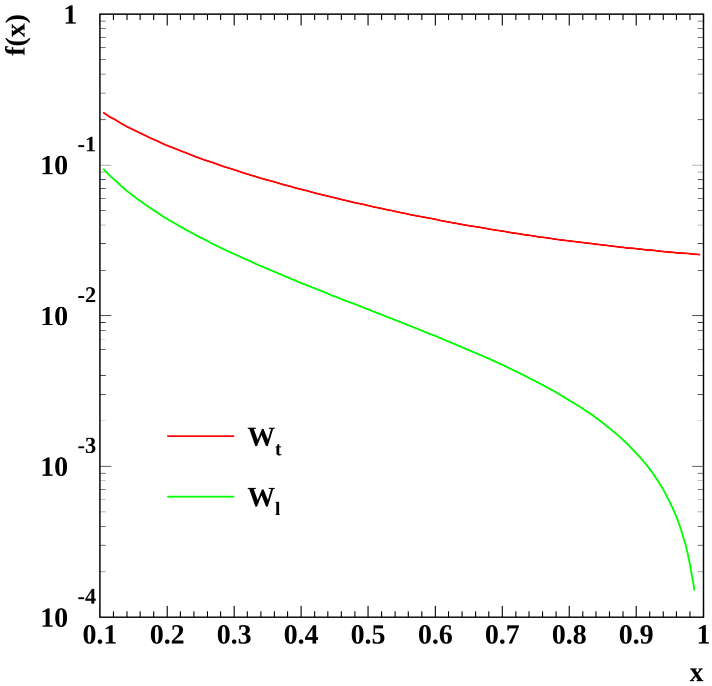
Effective W approximation

- Transversely polarized Ws:

$$f_W^T(x) = \frac{\alpha}{4\pi s_w^2} \frac{1+(1-x)^2}{2x} \ln \frac{xs}{M_W^2}$$

- Longitudinally polarized Ws:

$$f_{W/e}^L(x) = \frac{\alpha}{4\pi s_w^2} \frac{1-x}{x}$$

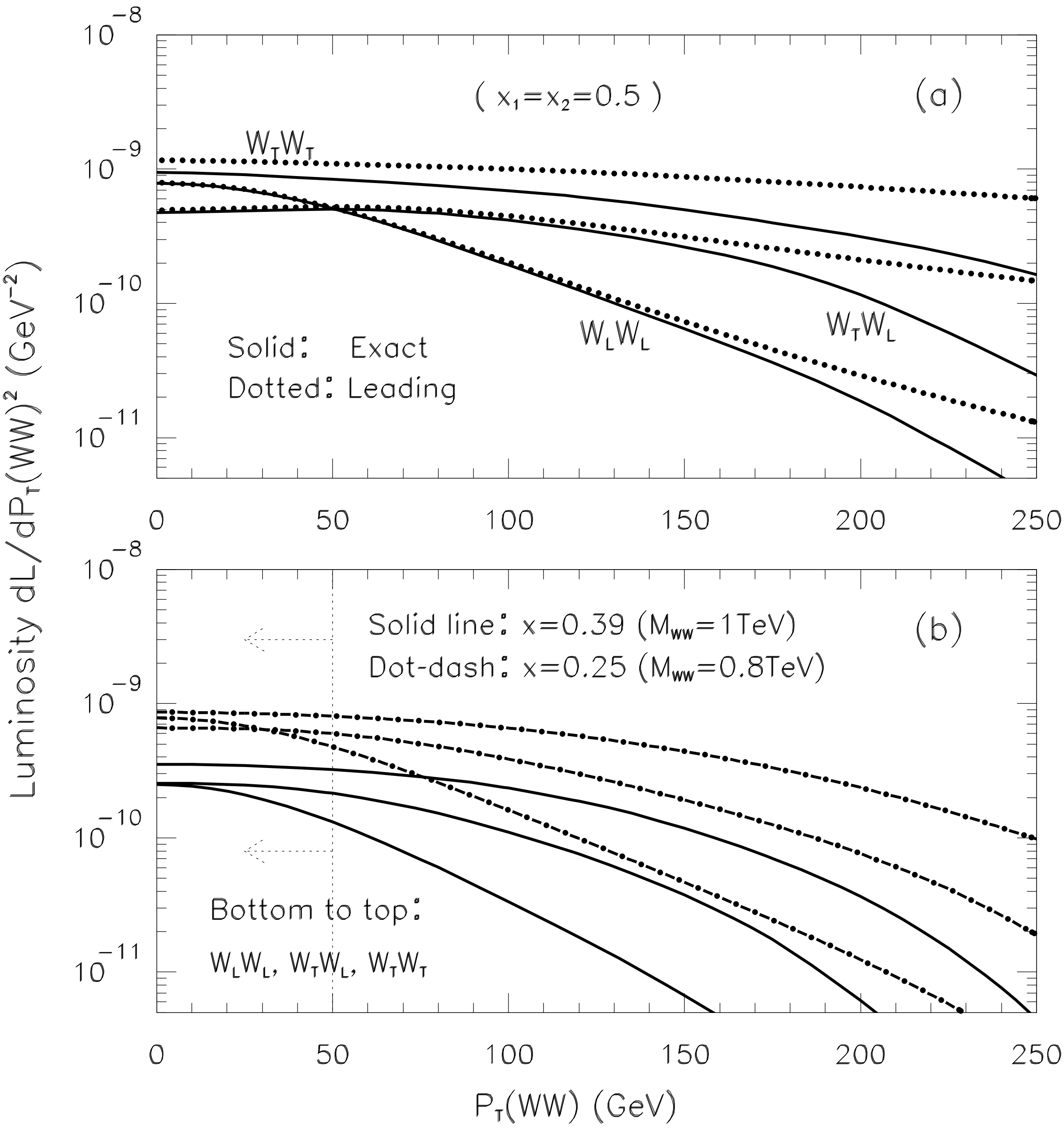


(Calculations use improved W spectra)

Longitudinal Ws are suppressed in the interesting region at large x

Suppression is mainly at large p_t

$$\sqrt{s} = 1.6\,\mathrm{TeV}$$



Have to cut low p_t to reject $\gamma\gamma \to \mathrm{W}^+\mathrm{W}^-$ background

Effective Lagrangian:

Two terms not already constrained by TGCs:

$$\mathcal{L}_4 = \frac{\alpha_4}{16\pi^2}\left[\frac{g^4}{2}\left[(W^+_\mu W^{-\mu})^2 + (W^+_\mu W^{+\mu})(W^-_\nu W^{-\nu})\right]\right.$$
$$\left. + \frac{g^4}{c_w^2}(W^+_\mu Z^\mu)(W^-_\nu Z^\nu) + \frac{g^4}{4c_w^4}(Z_\mu Z^\mu)^2\right]$$
$$\mathcal{L}_5 = \frac{\alpha_5}{16\pi^2}\left[g^4(W^+_\mu W^{-\mu})^2 + \frac{g^4}{c_w^2}(W^+_\mu W^{-\mu})(Z_\nu Z^\nu)\right.$$
$$\left. + \frac{g^4}{4c_w^4}(Z_\mu Z^\mu)^2\right]$$

Again with $\frac{\alpha_i}{16\pi^2} = \left(\frac{v}{\Lambda_i^*}\right)^2$

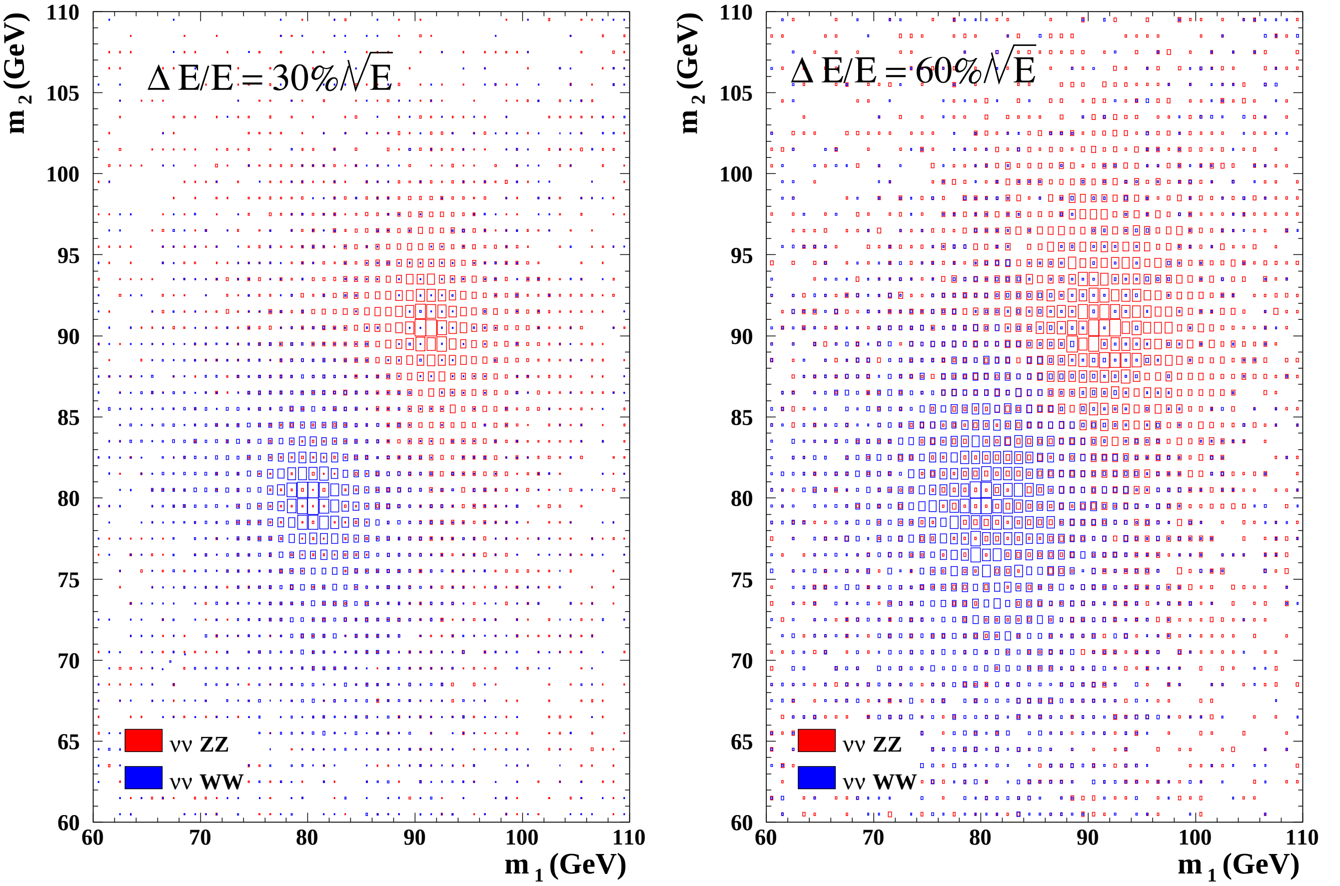
Three sensitive observables for two unknowns:

$$\begin{aligned} e^+e^- &\to \nu\nu W^+W^- \\ e^+e^- &\to \nu\nu ZZ \\ e^-e^- &\to \nu\nu W^-W^- \end{aligned}$$

Analysis:

Select $e^+e^- \to \nu\nu VV$ events at $\sqrt{s} = 800\,\mathrm{GeV}$

(very good energy flow resolution needed to separate W and Z)

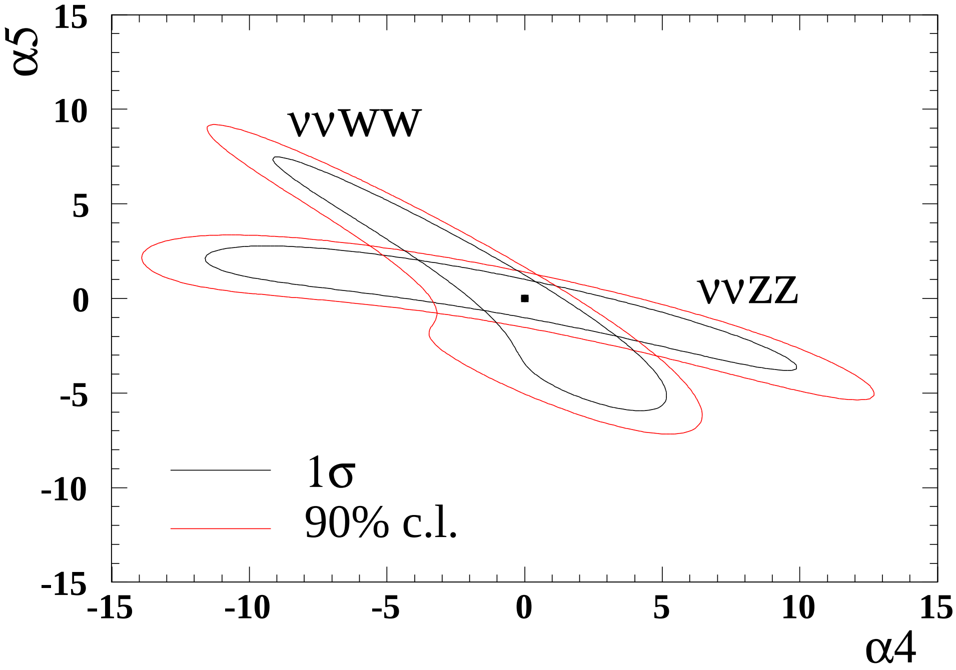


Analyze differential in terms of

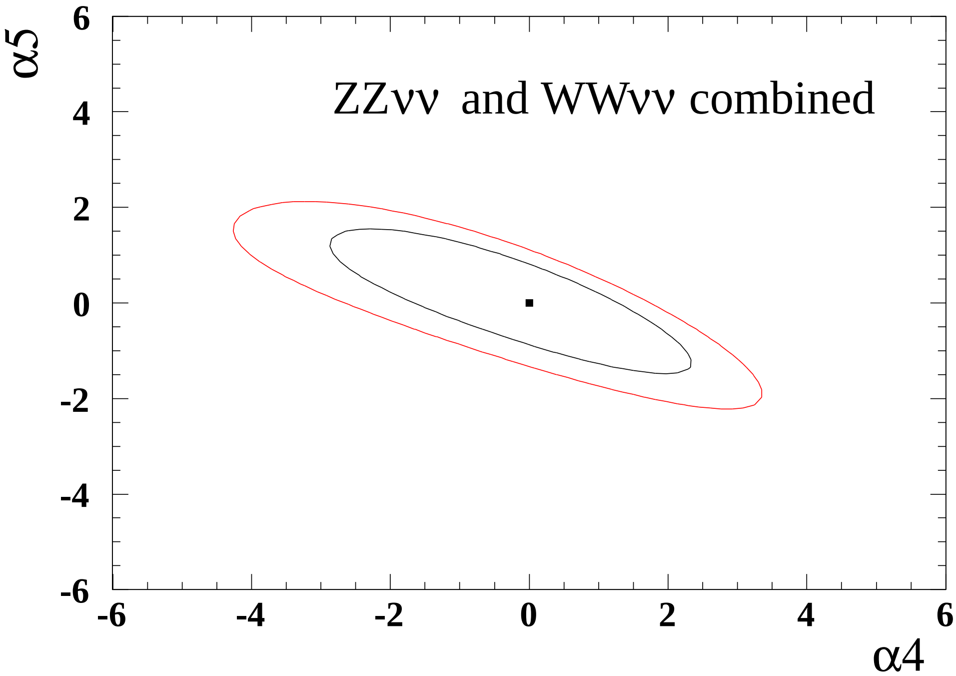
- V-decay angles (to select longitudinal V-polarization)
- V-scattering angle (to select hard scattering)
- VV invariant mass

Results:

Single channels give limits of about $\alpha_i < 10$



Combination of the two channels improves limits to about $\alpha_i < 1$



For single parameter fits one gets

$$\Lambda_4^* > 2.9\,\mathrm{TeV}$$
$$\Lambda_5^* > 4.9\,\mathrm{TeV}$$

- limits ∼factor 1.5 better than LHC
- however weak signals, so all possible redundancy needed
- dramatic improvements, if $\sqrt{s}$ can be increased
- LHC can see resonances up to $m \sim 1 - 2\,\mathrm{TeV}$ dependent on width

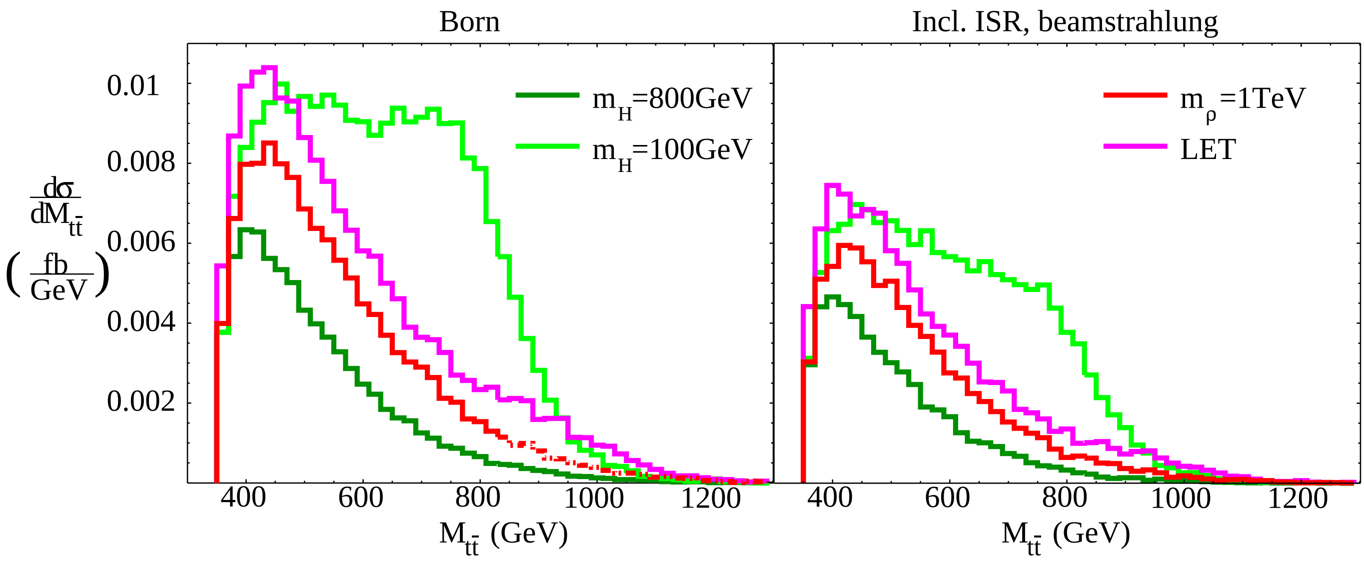
➡ In such a situation the LC could do a precise measurement of quantum numbers and couplings

Signal in $W^+W^- \to t\bar{t}$

- the mechanism simulating the Higgs must also couple to fermions to produce fermion masses

➡ should see a signal in $W^+W^- \to t\bar{t}$

- 1st analysis exists at $\sqrt{s} = 1.5\,\mathrm{TeV}$



- different models can be separated by $> 10\sigma$ with $\mathcal{L} = 200\,\mathrm{fb}^{-1}$
- additional information in t-polarization, but not yet fully analyzed
- also here the LHC is sensitive to resonances up to $\sim 2\,\mathrm{TeV}$

Conclusions Gauge-Boson-interactions

- For triple gauge couplings involving Ws the LC has a unique sensitivity to loop corrections and to a strongly interacting weak sector.
- For purely neutral couplings the sensitivity is still an order of magnitude worse than the expected effects and than the LHC expectation.
- There is a very high chance that the LC can see effects if electroweak symmetry breaking is realized in a strongly interacting scenario.
  If there are resonances in the LHC region, the LHC is the better machine.
  If there are no resonances the LHC and an 800 GeV LC have comparable statistical power, where the LC-backgrounds should be easier to calculate.