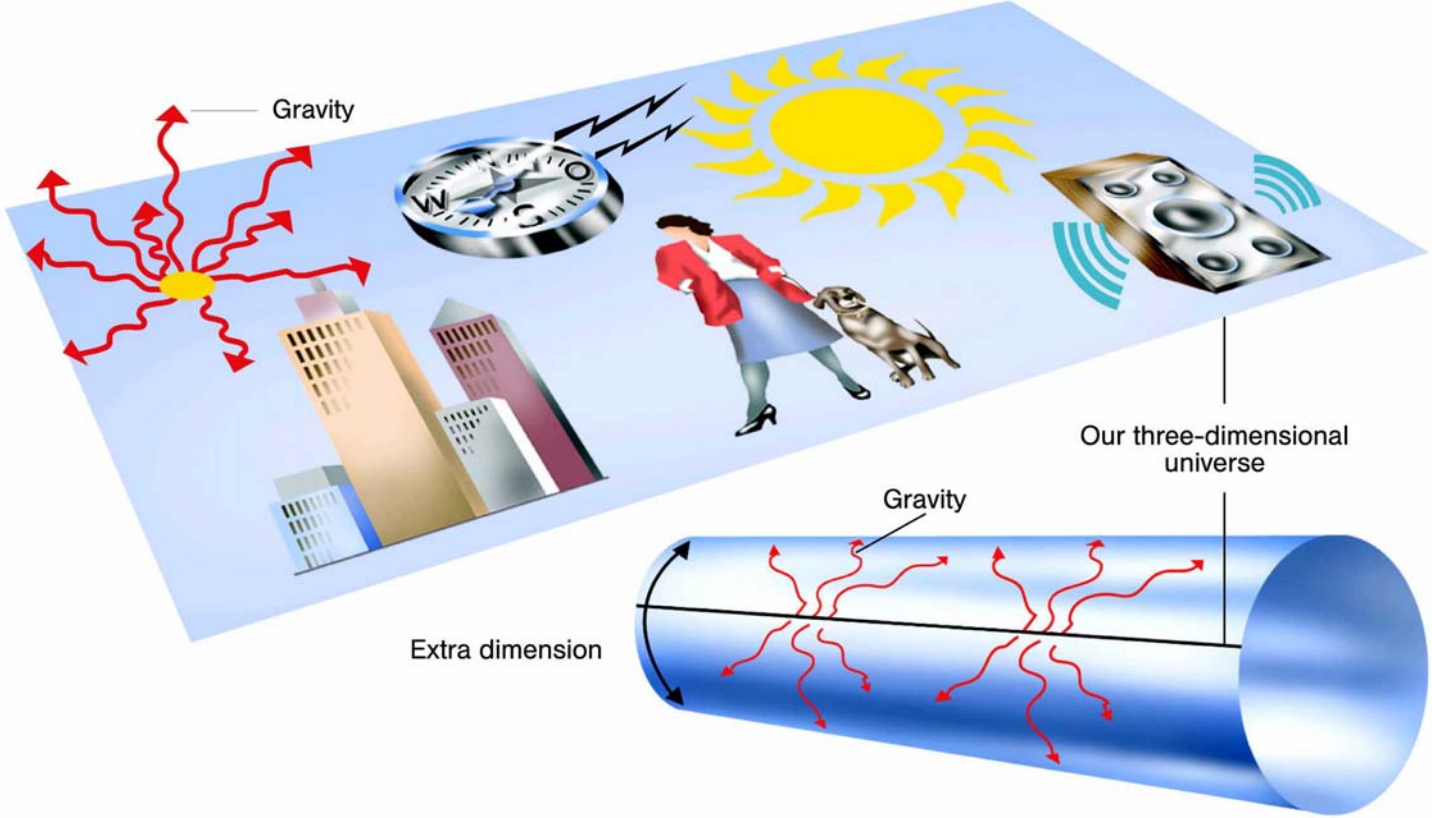
4. Extra Dimensions — “Large” Extra Dimensions

- Completely alternative approach to solve the hierarchy problem: ‘There is no hierarchy problem’
- Suppose, the SM fields live in ‘normal’ 3+1D space
- Gravity lives in 4 + δ Dimensions
- δ extra Dimensions are curled to a small volume (radius R):



“Large” Extra Dimensions

For r < R, gravity follows Newtons law in 4+δ dimensions:

$$V(r) = \frac{G_S}{r^{\delta+1}}$$

For r > R, gravity follows effectively Newton’s law in 4 dimensions, since the ‘distance’ in the extra dimensions does not rise anymore:

$$V(r) = \frac{G_S}{R^\delta r} = \frac{G_N}{r} \text{ with } G_N = \frac{G_S}{R^\delta}$$

The Planck-Mass $M^2_{Planck} = \hbar c / G_N$ only effectively appears so high at large distances. The true scale of gravity is

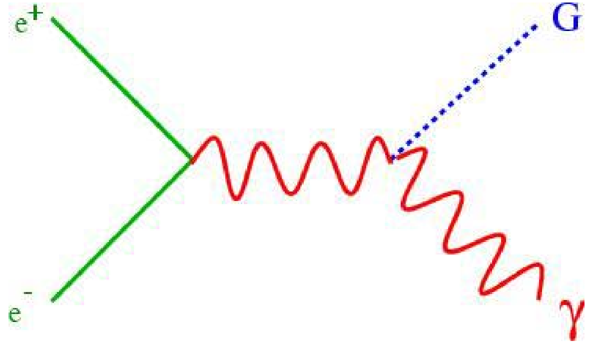
$$M_S^2 = \hbar c / G_S = \hbar c R^\delta / G_N$$

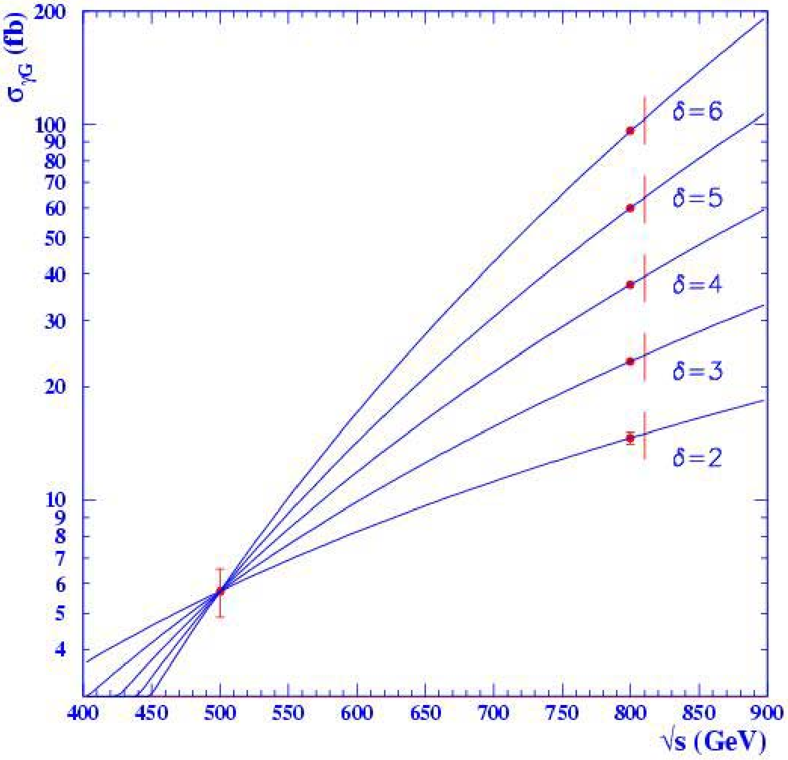
If e.g. R ~ o(100 μm) and $\delta=2$ one obtains $M_S = o(1\,\mathrm{TeV})$!

⇨ Gravity might become visible in TeV-scale colliders!

"Large" Extra Dimensions

Effects from real graviton emission:

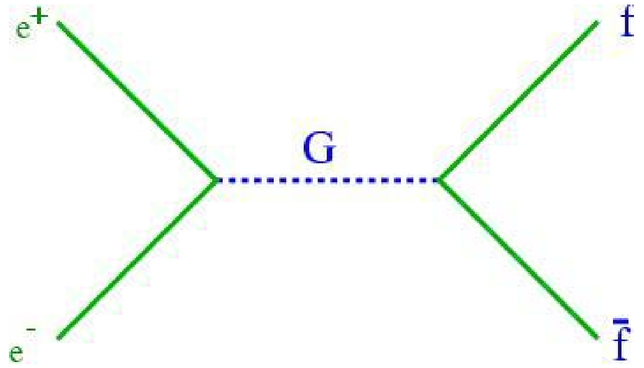




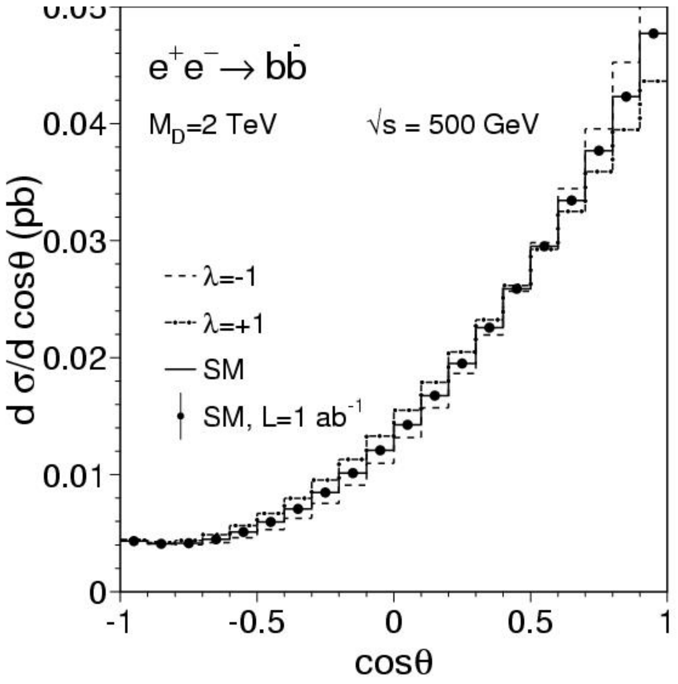
measures the number
of extra dimensions!

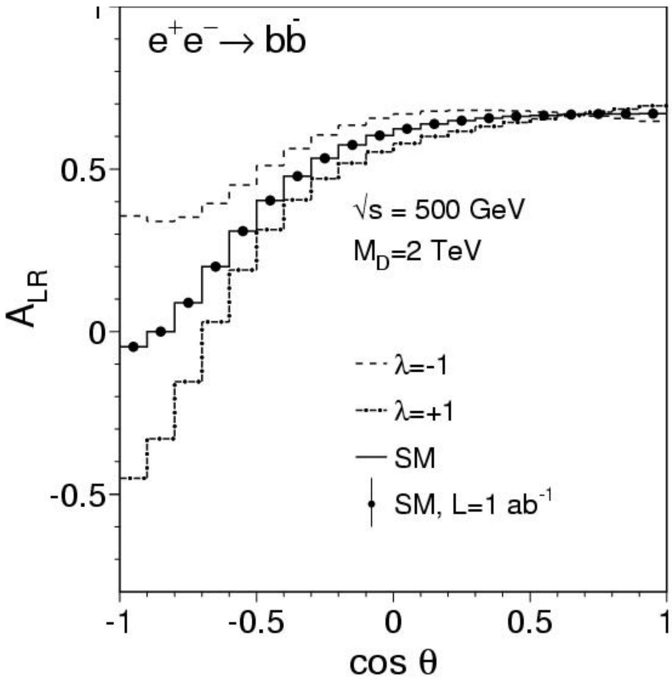
4. Extra Dimensions “Large” Extra Dimensions

Effects from virtual graviton exchange:

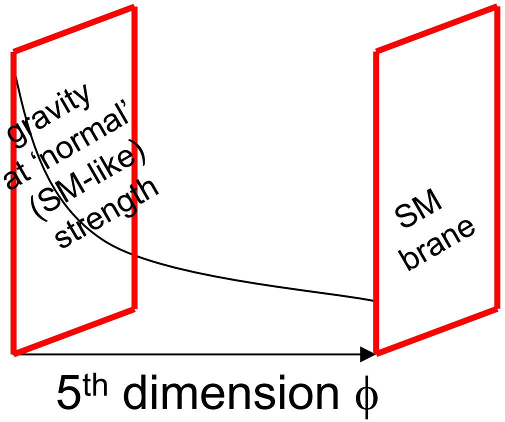


can prove Spin-2 exchange!



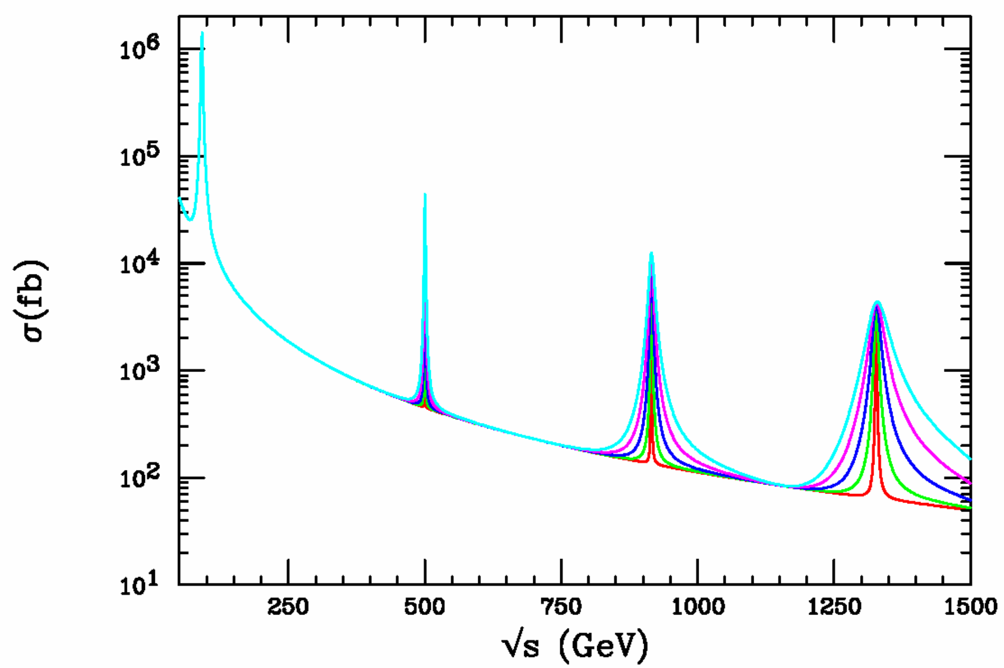


“Warped” Extra Dimensions



gravity appears weak on SM brane (in our world) due to exponentially ‘warped’ metric in 5th dimension

$$ds^2 = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2$$



Discovery through precision

Precision measurements of SM processes are a telescope to higher scale physics

Plan:

1. top quark
2. 2f production: contact interactions
3. 2f production: Z' and similar heavy vector resoncances
4. 4f production: anomalous TGC's
5. Alternative EWSB:
    - effective Lagrangian
    - TGCs reinterpreted
    - Quartic gauge couplings

6. Giga-Z / Mega-W

5. Top quark

Top is the heaviest fermion → want to its mass as precise as possible

Why?

- Crucial input parameters to any future theory of flavour

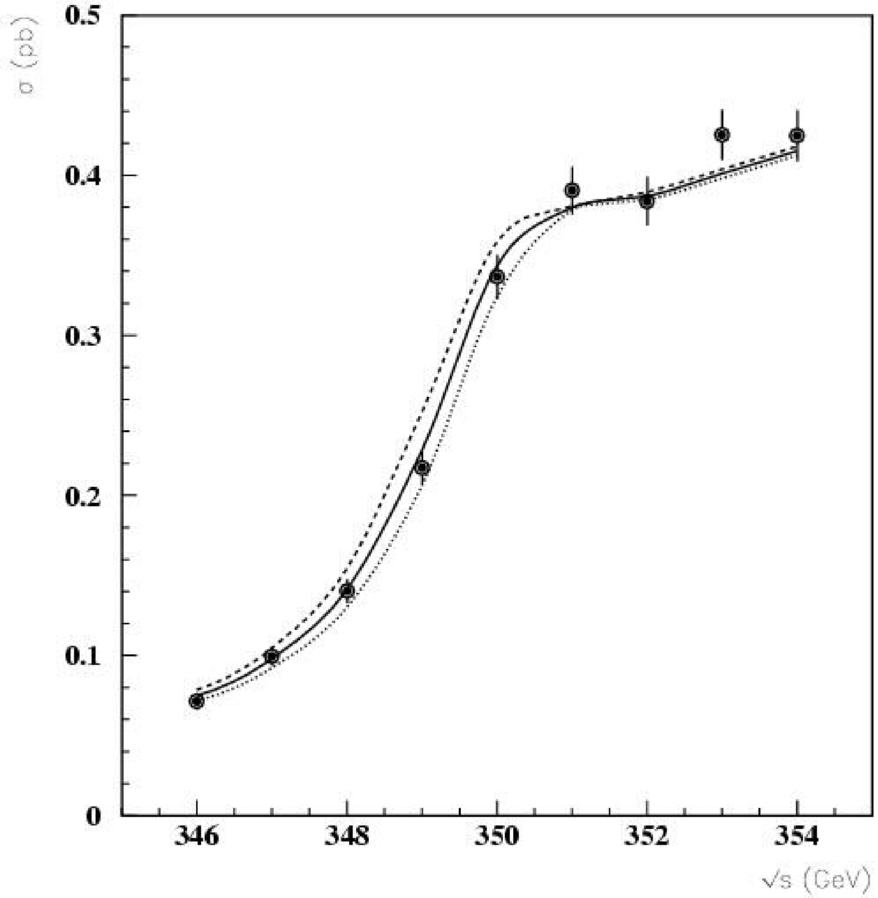
- Already today the largest uncertainty in the calculation of many SM observables. With improved precision on m_W (Δm_W=6 MeV, later) even more important

- In any model where m_h can be calculated (e.g. SUSY), always large large contribution from m_t. In MSSM typically shift of 1 GeV in m_t means shift of 1 GeV in m_h. If Δm_h= 50 MeV, Δm_t will be limiting again.

5. Top quark

Best method to measure m_t:

Threshold scan of $e^+e^- \rightarrow t\bar{t}$



Experimental precision ~40 MeV

Precision limited by theoretical uncertainty from huge QCD corrections at threshold:

Δm(top) ~ 50-100 MeV

$\Delta\Gamma$(top)/Γ(top) ~ 3-5%

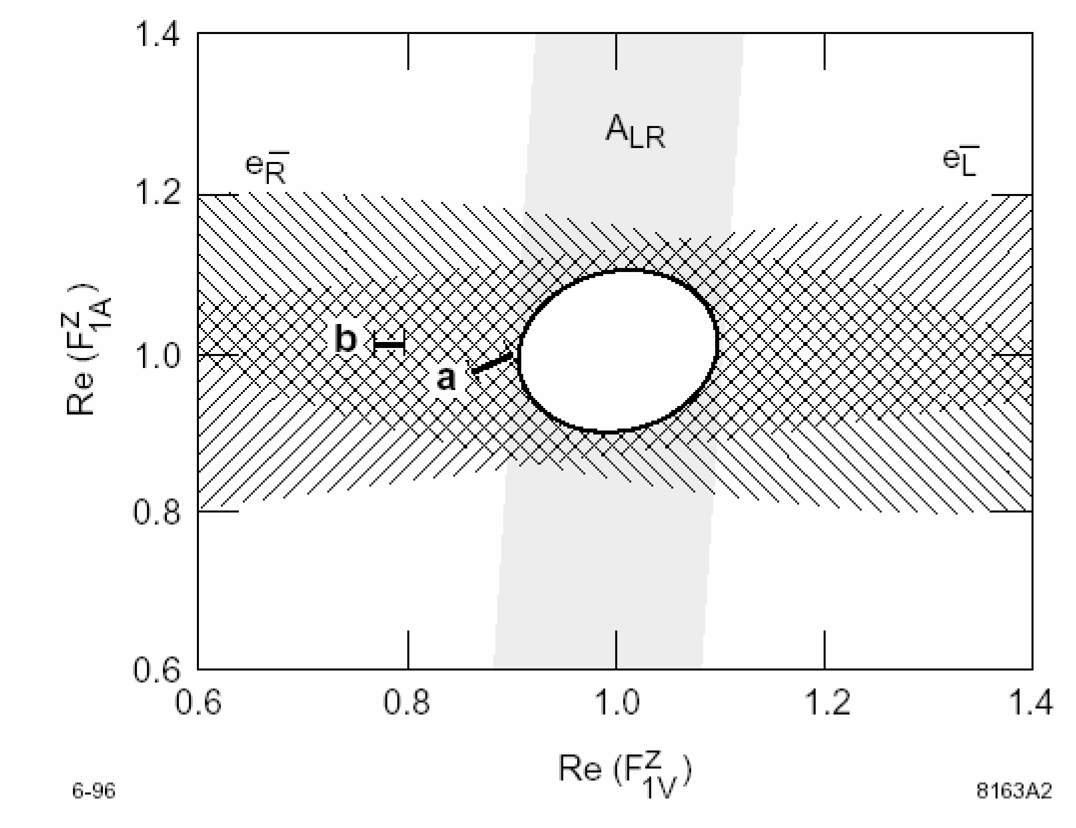
simultaneously fit

$\Delta\alpha_s$ ~ 0.0025

5. Top quark

Further possibilities by studying top decays in continuum:

e.g. top-Coupling to Z (hard at LHC due to strong production)



6. Two-fermion

The process $e^+e^- \rightarrow f\bar{f} \quad f = e, \mu, \tau, uds, c, b$

can be predicted within the SM to high precision. Any deviation is a definitive sign of new physics

Precision allow for tests at the loop level → sensitivity far beyond cms energy!

Large variety of observables (σ_{tot}, A_{FB}, A_{LR}) + flavour dependence allows to find out details about the new physics contribution

Interpretation in models of:

- contact interactions
- new gauge bosons (Z')
- large extra dimensions

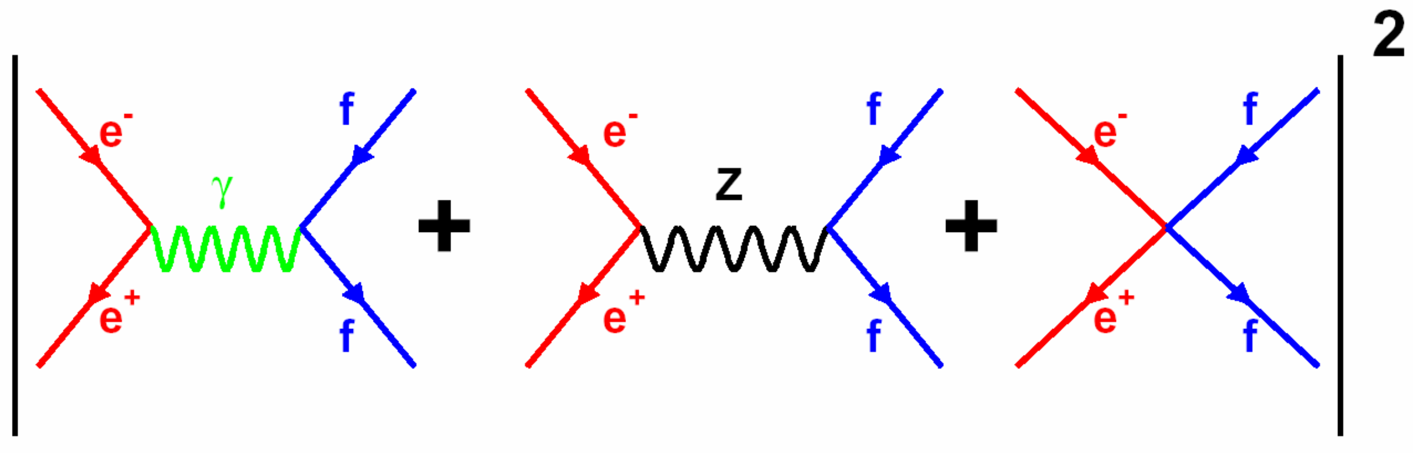
6. Two-fermion

Contact Interactions

Exchange of very heavy new particle can be parametrized by an effective 4-Fermion vertex (like for μ-decay where W propagator can be ignored)

$$L_{\mathrm{eff}} = \sum_{i,k=L,R} \frac{\lambda_{ik}^{2}}{M} \alpha_{ik} (\bar{e}_i \gamma^{\mu} e_i)(\bar{f}_k \gamma_{\mu} f_k) \quad \alpha_{ik} = \pm 1$$

Introduce scale-parameter $\Lambda^2 = \dfrac{4\pi M^2}{\lambda^2}$



Differential cross-section $\dfrac{d\sigma}{d\cos\theta} = SM(s,t) + C_{\mathrm{int}}(s,t)\dfrac{1}{\Lambda^2} + C_{\mathrm{cont}}(s,t)\dfrac{1}{\Lambda^4}$

Interference term dominates

Contact Interactions

Observables at the LC:

$$\begin{aligned} &\sigma_{tot} \\ A_{FB} &= \tfrac{3}{4}\sigma_{FB}/\sigma_{tot} \\ A_{LR} &= \sigma_{LR}/\sigma_{tot} \\ A_{LR}^{FB} &= \tfrac{3}{4}\sigma_{LR}^{FB}/\sigma_{tot} \end{aligned}$$

Scaling law for stat. errors:

$$\Lambda \approx M_X/g \propto (s \cdot L_{int})^{1/4}$$

LC sensitivities 50 – 100 TeV
+ different channels than LHC
+ flavour dependent sensitivity

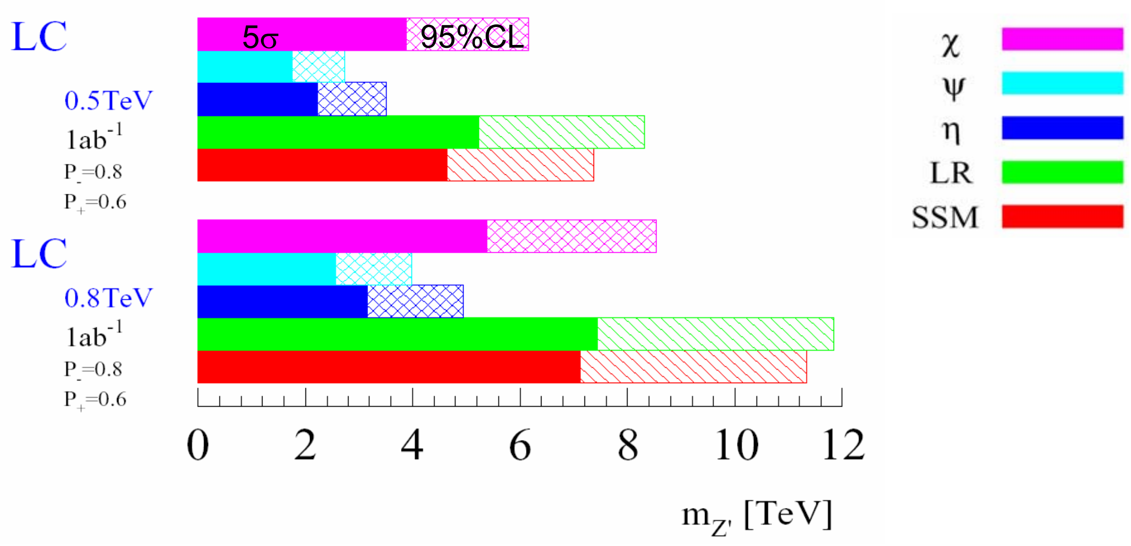
		LHC Λ [TeV]				LC Λ [TeV] (500 fb^{-1} at 500 GeV)			
model		LL	RR	LR	RL	LL	RR	LR	RL
eeqq:	Λ_+	20.1	20.2	22.1	21.8	64	24	92	22
	Λ_-	33.8	33.7	29.2	29.7	63	35	92	24
ee$\mu\mu$:	Λ_+					90	88	72	72
	Λ_-					90	88	72	72
eeee:	Λ_+					44.9	43.4	52.4	52.4
	Λ_-					43.5	42.1	50.7	50.7

6. Two-fermion | New Gauge Bosons (Z')

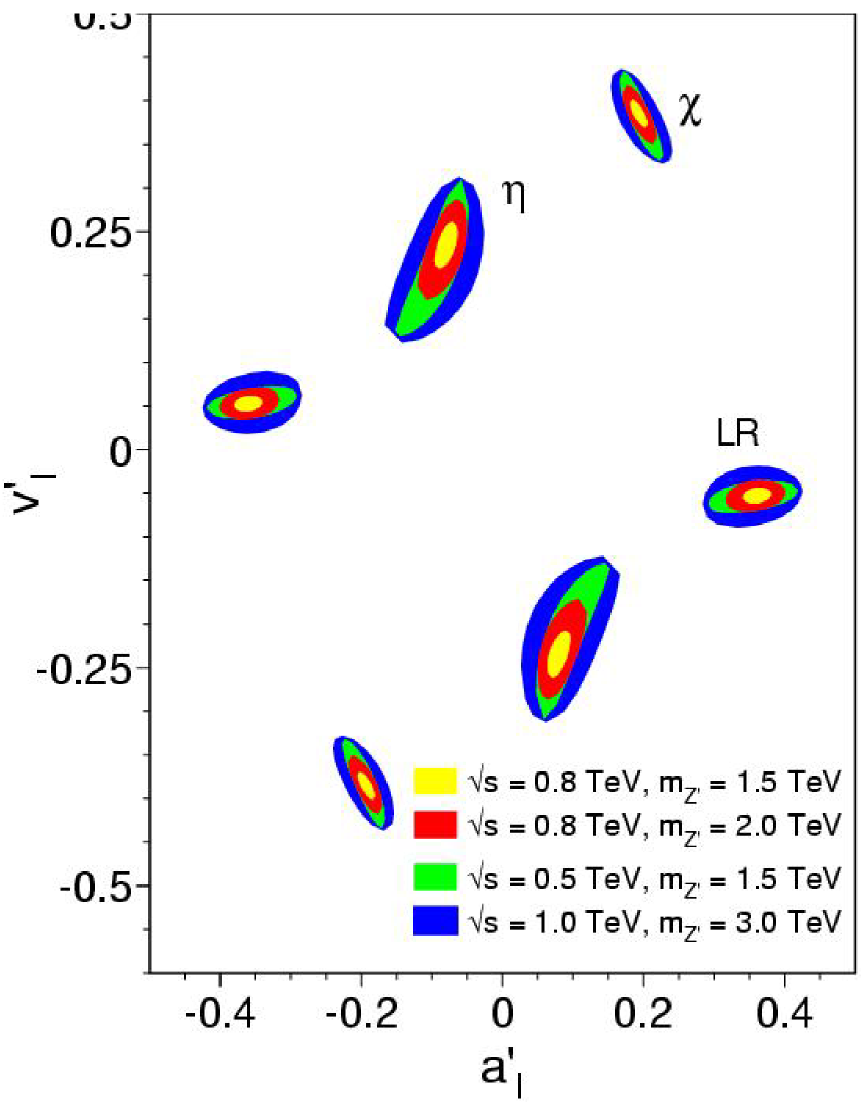
New U(1) gauge bosons (Z') often appear when in models of step-by-step symmetry breaking of GUT groups, e.g. E(6), LR-symmetric models
Some of the subgroups may stay intact down to the TeV scale

Unlikely for LC to directly produce a Z' (Tevatron limits approaching 1 TeV)
LHC reach typically ~3-5 TeV for SM-like couplings

LC can discover a Z' by measuring its interference with Z,γ exchange
(PETRA could measure Z properties without producing Z's)



New Gauge Bosons (Z')



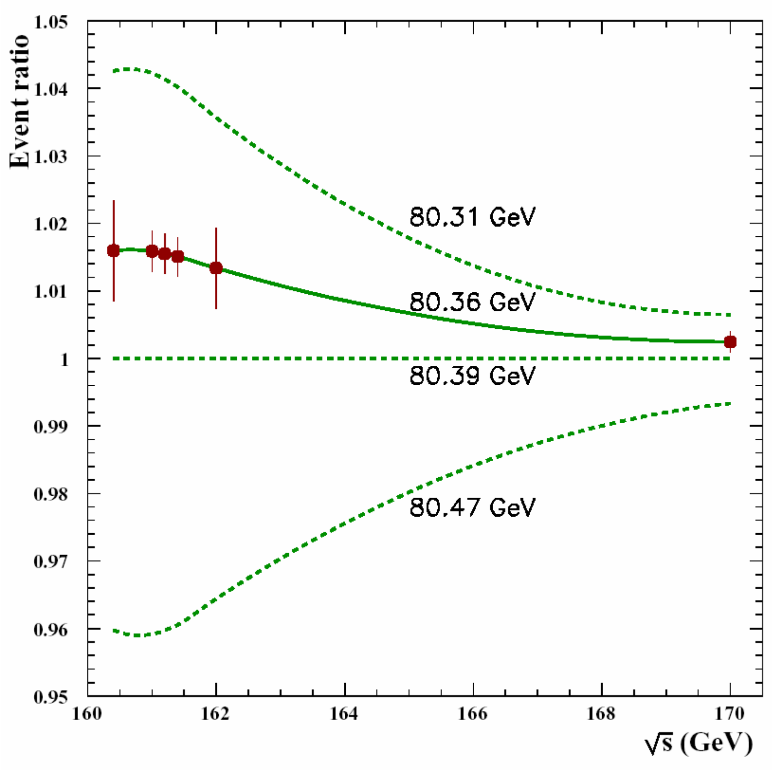
If Z' mass is known (e.g. from LHC) ILC can measure the vector and axial-vector couplings an pin down the nature of the Z'

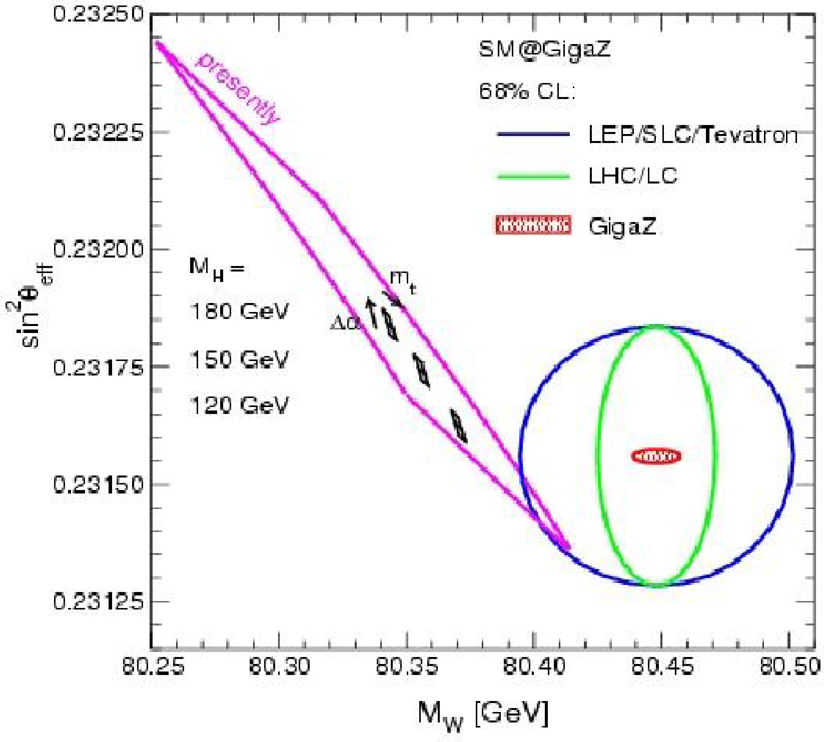
By measuring at two different √s, ILC can measure both mass and couplings

New Gauge Bosons (Z')

Additional sensitivity from improved measurements of EW parameters ($\sin^2\theta_W$ and m_W) at 'Giga Z'

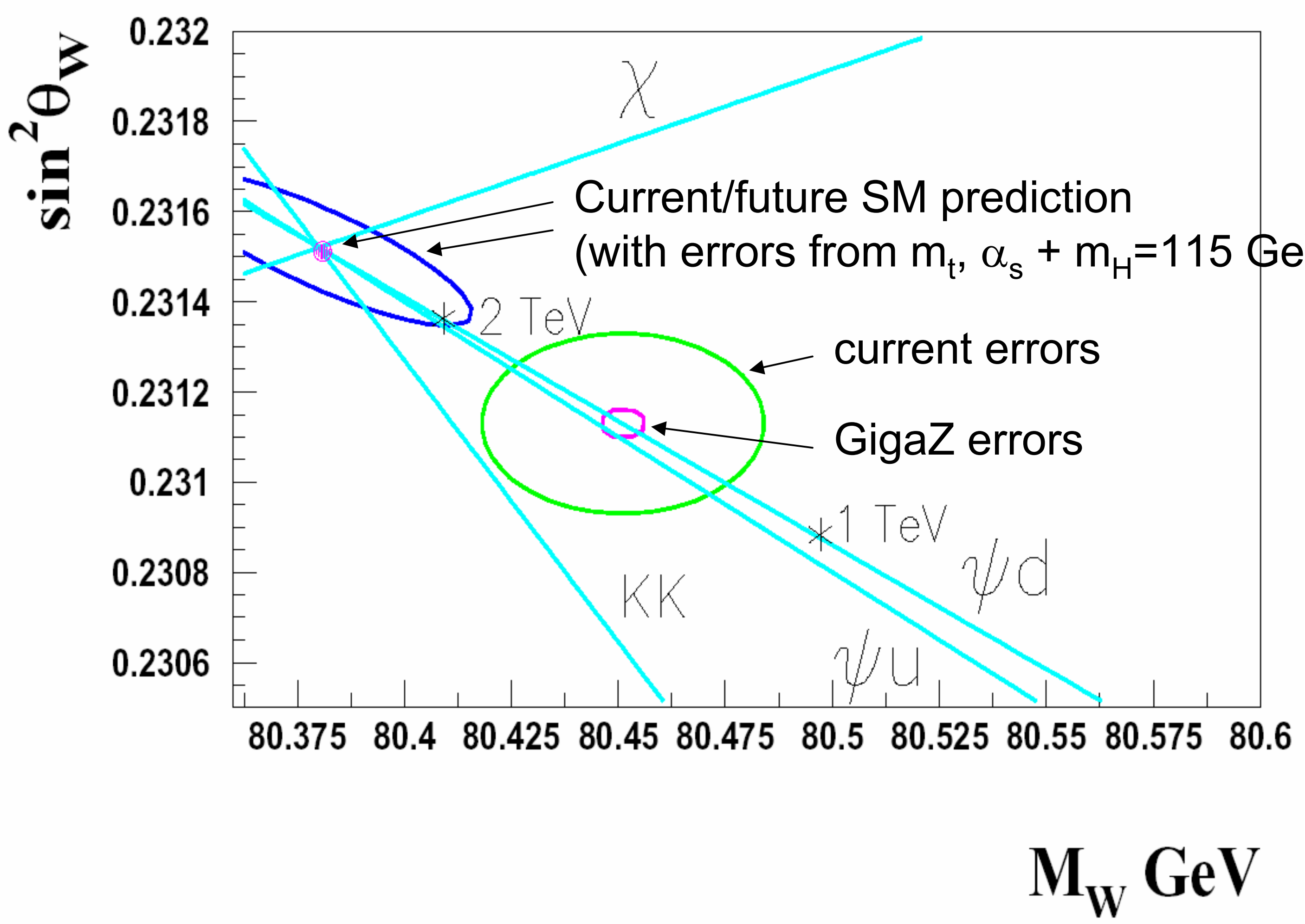
Expect $\Delta \sin^2\theta_W \sim 0.000013$ (factor 10 w.r.t LEP, from A_{LR} measurement of 10^9 Z decays) and $\Delta m_W = 6$ MeV (from threshold scan of $e^+e^- \to W^+W^-$):





New Gauge Bosons (Z')

These measurements are sensitive to Z/Z'- mixing (not interference)



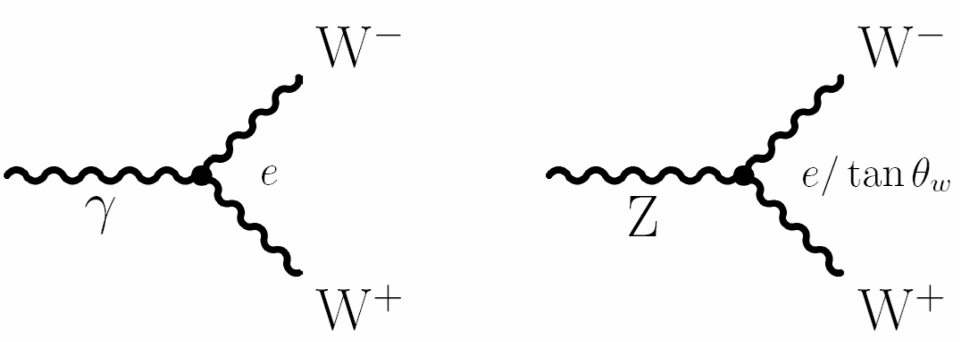
Current/future SM prediction
(with errors from m_t, α_s + m_H=115 GeV)

current errors

GigaZ errors

7. Four-fermion

Triple Gauge Boson Couplings



Gauge boson self-interactions are predicted by the (non-abelian) structure of the gauge group

Deviations parametrized by anoumalous couplings in an effective Lagrangian:

$$
\begin{aligned}
\frac{\mathcal{L}^{WWV}}{i g_{WWV}} &= \underline{g_1^V V^\mu \left(\hat{W}^-_{\mu\nu} W^{+\nu} - \hat{W}^+_{\mu\nu} W^{-\nu} \right)} + \underline{\kappa_V W^-_\mu W^+_\nu \hat{V}^{\mu\nu}} + \frac{\lambda_V}{M_W^2} \hat{V}^{\mu\nu} \hat{W}^{+\rho}_\mu \hat{W}^-_{\rho\nu} \\
&- i g_4^V W^-_\mu W^+_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
&+ i g_5^V \varepsilon^{\mu\nu\rho\sigma} \left[(\partial^\rho W^-_\mu) W^+_\nu - W^-_\mu (\partial^\rho W^+_\nu) \right] V_\sigma \\
&+ \frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma} \hat{V}_{\rho\sigma} + \frac{\tilde{\lambda}_V}{2 M_W^2} \hat{W}^-_{\rho\mu} \hat{W}^{+\mu}_\nu \varepsilon^{\nu\rho\alpha\beta} \hat{V}_{\alpha\beta},
\end{aligned}
$$

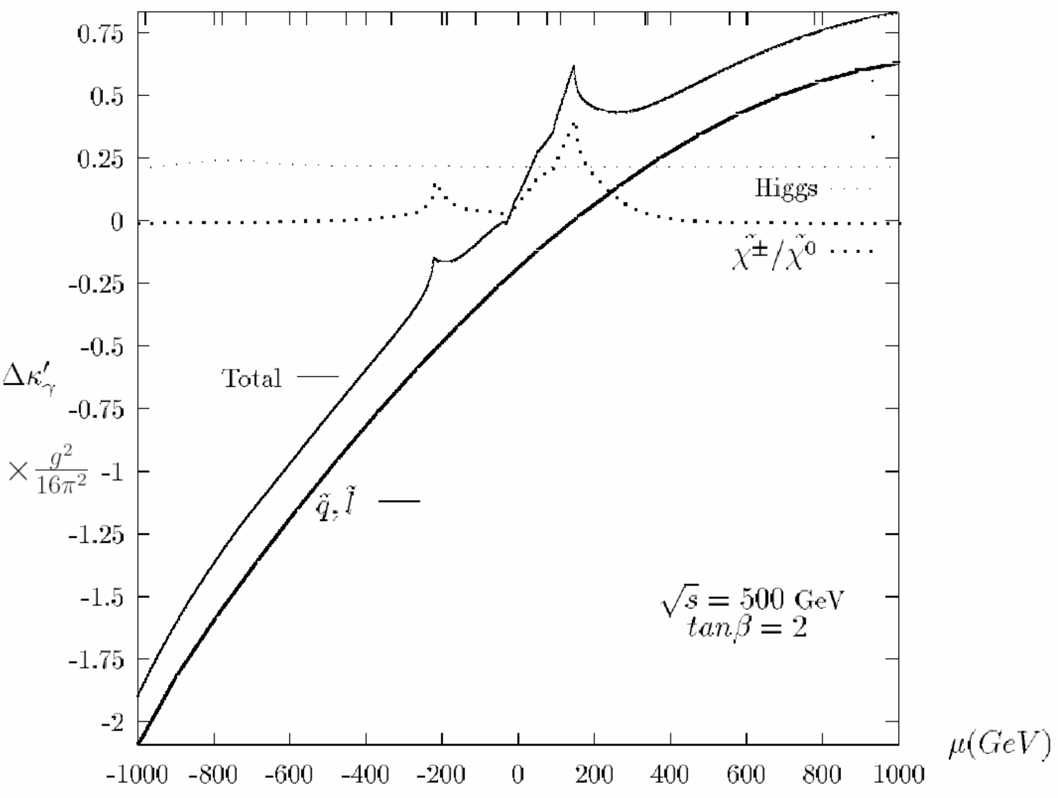
SM: $g_1^V = \kappa_V = 1$
all others 0

V=Z,γ

7. Four-fermion | Triple Gauge Boson Couplings

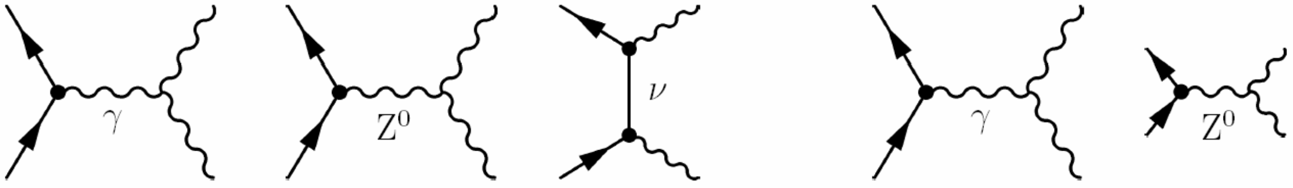
In extended models, deviations occur typically at loop level, i.e. suppressed by $g/16\pi^2 \approx 3\ 10^{-3}$

MSSM contribution to $\Delta\kappa_\gamma$:



Triple Gauge Boson Couplings

At ILC highest sensitivity from W pair production

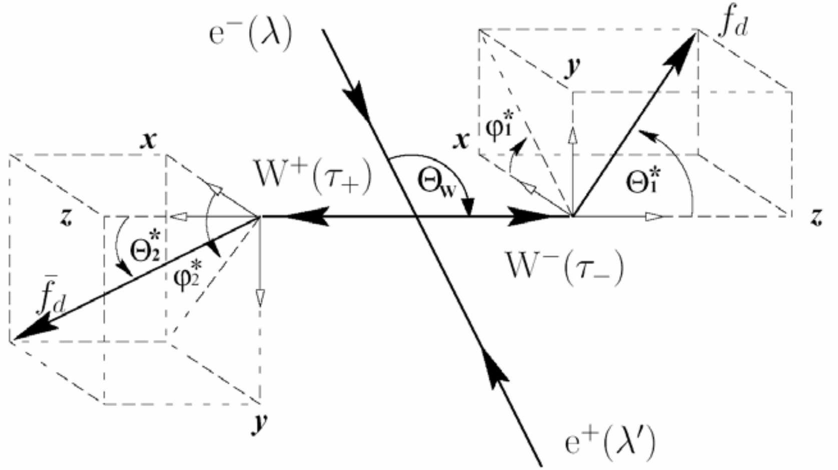


(a) left-handed electrons

(b) right-handed electrons

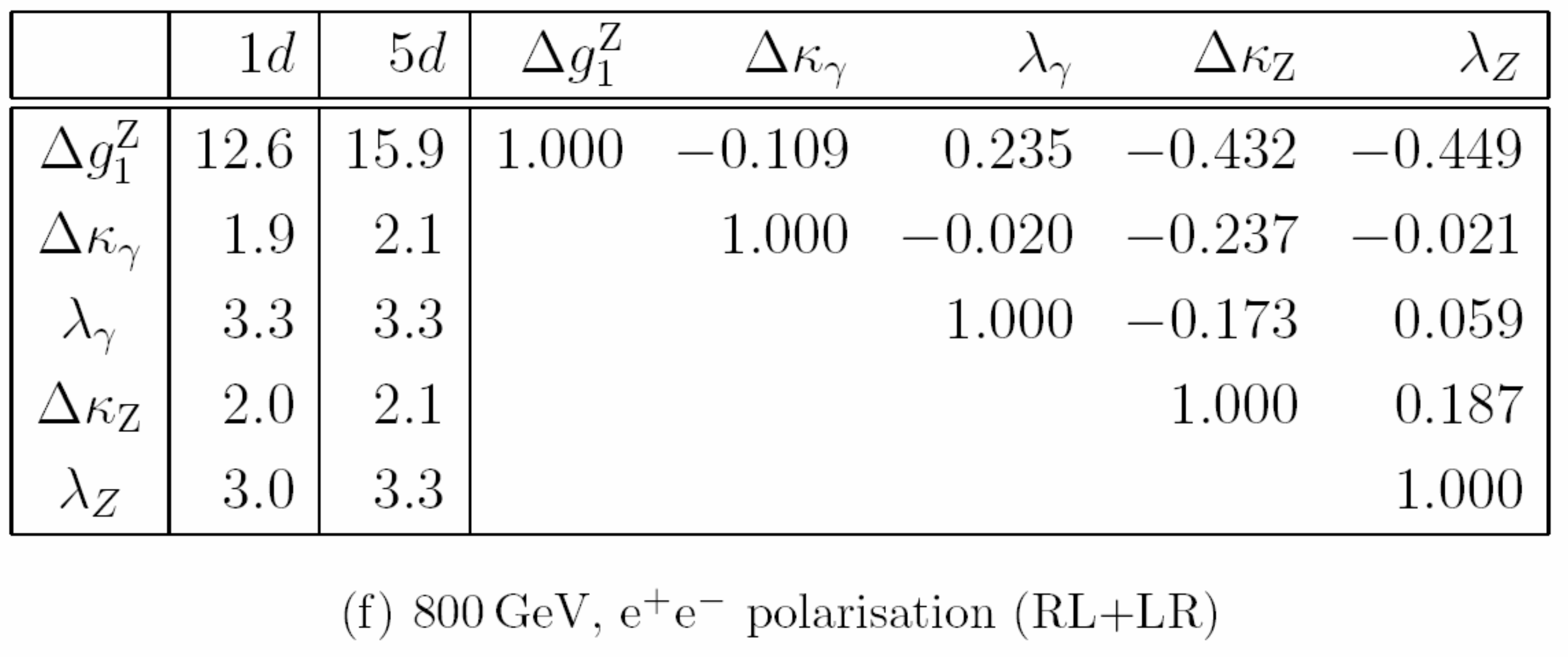
Distentangle Z- and Photon-couplings through polarization

Golden channel: WW→qqlν - can reconstruct all angles up to twofold ambig.



Triple Gauge Boson Couplings

Results (in units 10^{-4}):



	$1d$	$5d$	Δg_1^Z	$\Delta\kappa_\gamma$	λ_γ	$\Delta\kappa_Z$	λ_Z
Δg_1^Z	12.6	15.9	1.000	-0.109	0.235	-0.432	-0.449
$\Delta\kappa_\gamma$	1.9	2.1		1.000	-0.020	-0.237	-0.021
λ_γ	3.3	3.3			1.000	-0.173	0.059
$\Delta\kappa_Z$	2.0	2.1				1.000	0.187
λ_Z	3.0	3.3					1.000

(f) 800 GeV, e^+e^- polarisation (RL+LR)

With polarisation, simultaneous 5-parameter fits can be done without huge degardation of precision

Systematic errors ~ statistical errors if ISR known to 1% and beamstrahlung to ~10% - other syst. errors smaller

Triple Gauge Boson Couplings

Comparison to other colliders:

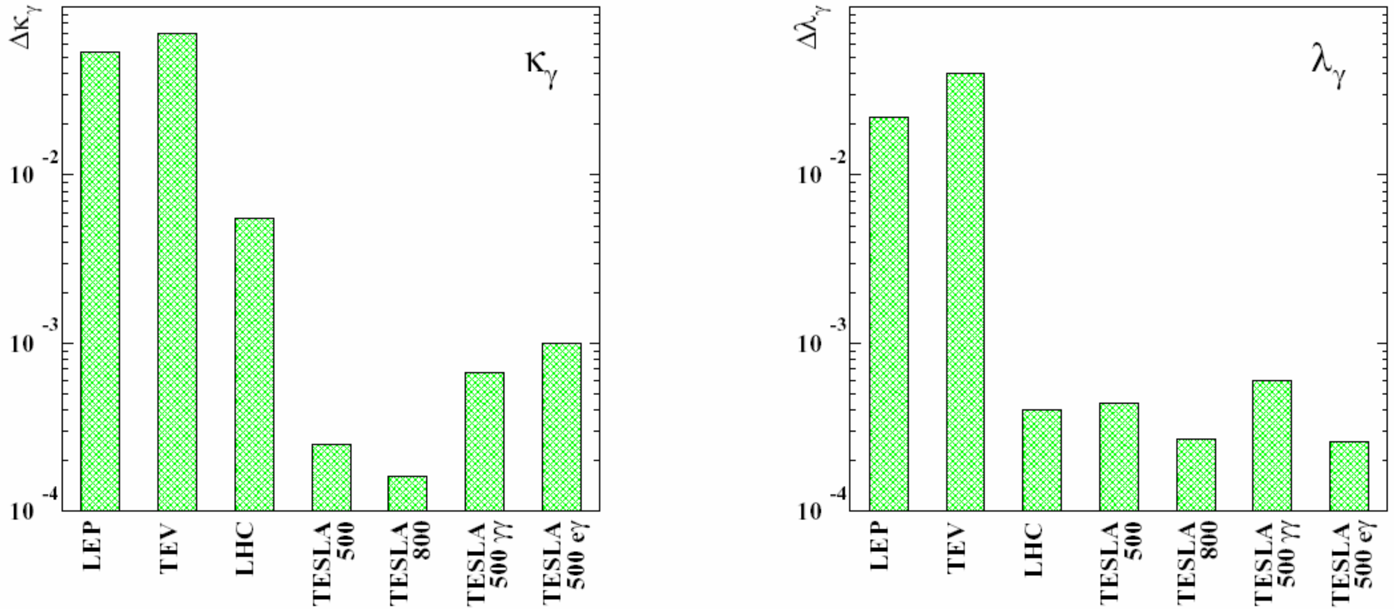
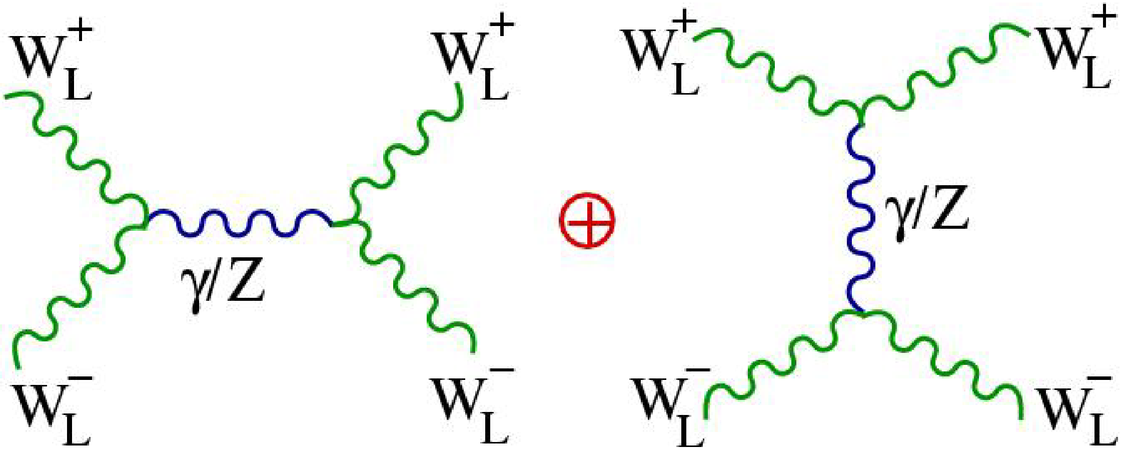


Figure 7.9: Comparison of $\Delta\kappa_\gamma$ and $\Delta\lambda$ at different machines. For LHC and TESLA three years of running are assumed (LHC: $300\,\mathrm{fb}^{-1}$, TESLA $\sqrt{s} = 500$ GeV: $900\,\mathrm{fb}^{-1}$, TESLA $\sqrt{s} = 800$ GeV: $1500\,\mathrm{fb}^{-1}$).

No Higgs Boson?

Quantum Field Theory with massive Quanta fails at high Energies:



Cross section:
$\sigma \sim$ **s**
Violates unitarity at
$\sqrt{\mathbf{s}} \sim 1.2\,\mathbf{TeV}$

(if forces remain weak)

"if nothing happens, something must happen…"

maybe they they don't…

Strong EWSB

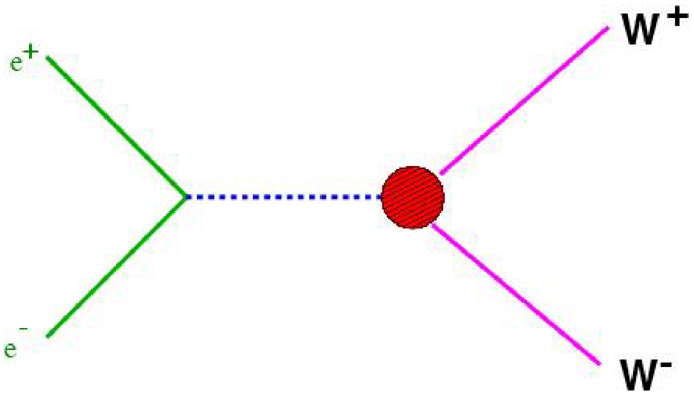
→ divergent $W_L W_L \rightarrow W_L W_L$ amplitude

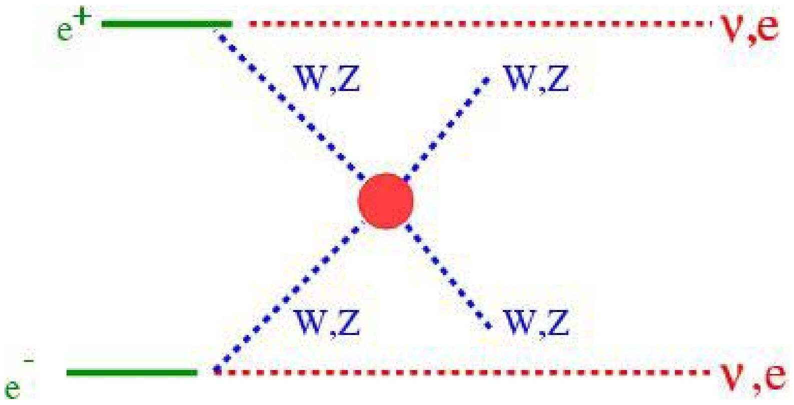
→ new strong QCD-like interaction at $\Lambda^2 \sim o(\frac{4\pi\sqrt{2}}{G_F}) = (1.2\,\mathrm{TeV})^2$

→ Goldstone bosons (“Pions”) = W_L states (“technicolor”)

→ no calculable theory until today in agreement with precision data

Experimental consequences: deviations in triple and quartic gauge





(or direct observation of the new techni-hadrons)

Strong EWSB

- Theoretical approach: assume only that $SU(2)_L \times U(1)_Y$ is broken spontaneously down to $U(1)_Q$
- Effective Lagrangian contains 10 dim-4 Operators
- 5 obey $SU(2)_C$, i.e. they protect $\rho \sim 1$.

$$L_1 = \frac{\alpha_1}{16\pi^2}\frac{gg'}{2}B_{\mu\nu}\,\mathrm{tr}\left(\sigma_3 W^{\mu\nu}\right)$$

$$L_2 = \frac{\alpha_2}{16\pi^2}ig'B_{\mu\nu}\,\mathrm{tr}\left(\sigma_3 V^{\mu}V^{\nu}\right)$$

$$L_3 = \frac{\alpha_3}{16\pi^2}2ig\,\mathrm{tr}\left(W_{\mu\nu}V^{\mu}V^{\nu}\right)$$

$$L_4 = \frac{\alpha_4}{16\pi^2}\mathrm{tr}\left(V_\mu V_\nu\right)\mathrm{tr}\left(V^{\mu}V^{\nu}\right)$$

$$L_5 = \frac{\alpha_5}{16\pi^2}\mathrm{tr}\left(V_\mu V^\mu\right)\mathrm{tr}\left(V_\nu V^{\nu}\right),$$

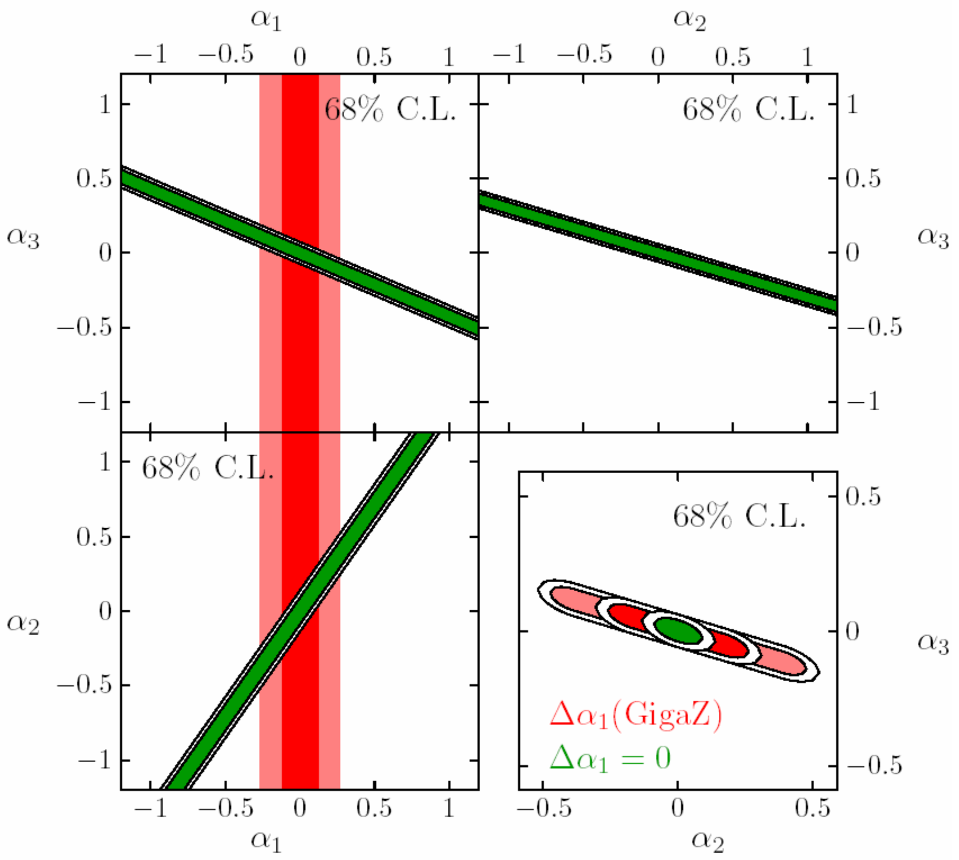
L_1, L_2, L_3 can be probed in W pair production (reinterpretation of anomaluous TGC couplings)

L_4,L_5 probed in VV→VV scattering

couplings α_l relate to scale of new physics $\frac{\alpha_i}{16\pi^2} = \left(\frac{v}{\Lambda_i^*}\right)^2$

Strong EWSB

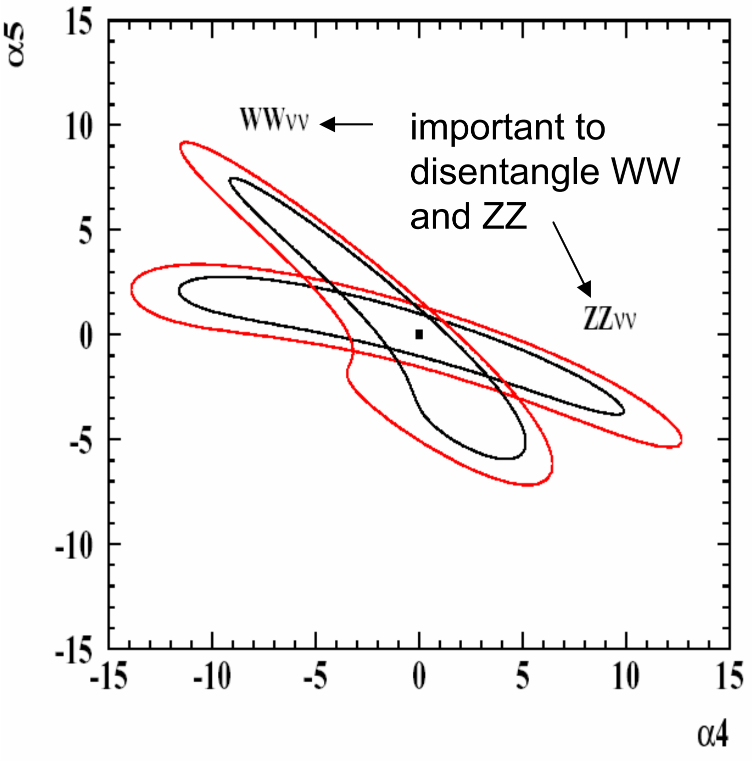
Triple Gauge Couplings



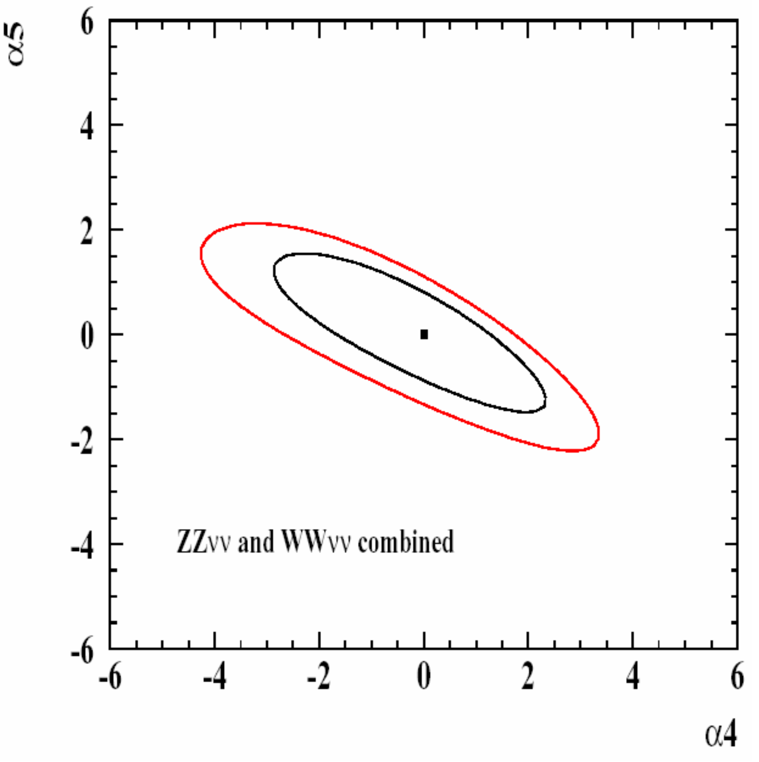
Sensitivity to new physics scale Λ:

$\alpha_1 = 0$	80%+0%	80%+60%
Λ_2^*	5.4 TeV	8.8 TeV
Λ_3^*	8.2 TeV	10.7 TeV

Strong EWSB | Quartic Gauge Couplings



important to disentangle WW and ZZ



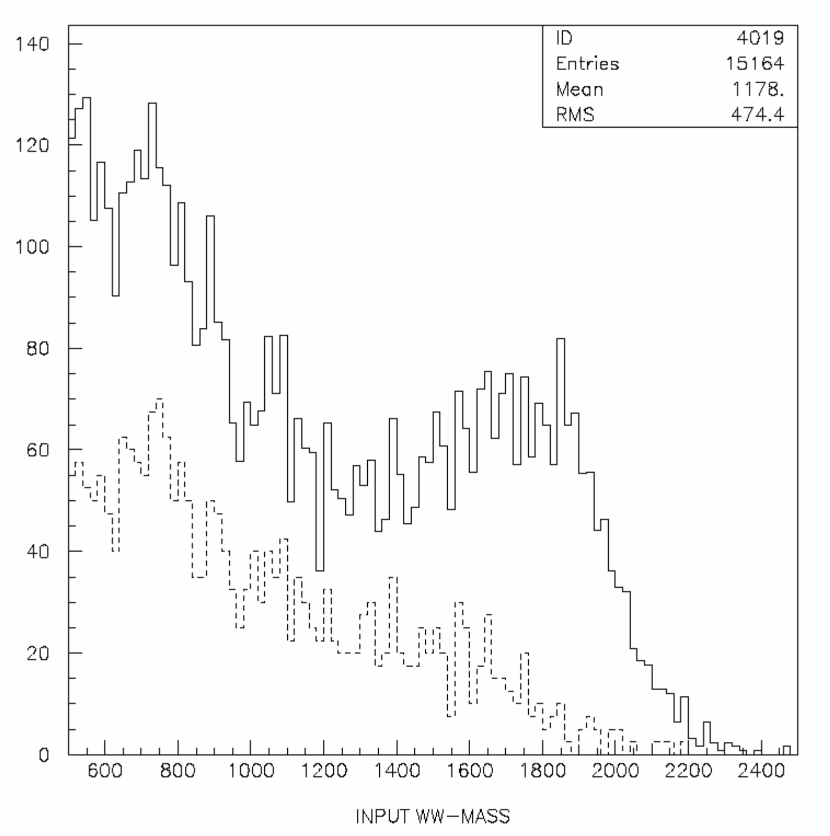
Sensitivity to new physics scale Λ:

complete threshold region of new strong interaction covered

	LHC **100 fb^{-1}**	**LC** **1000 fb^{-1}**
Λ_4^*	**2.3 TeV**	**2.9 TeV**
Λ_5^*	**2.8 TeV**	**4.9 TeV**

Strong EWSB

Observation of heavy resonances at CLIC



heavy resaonance in WW,WZ,ZZ channels at ~2 TeV

with detector simulation
+ backgrounds

at √s = 3 TeV, 1.6 ab^{-1}

Summary of day 4

- Precision measurements of SM processes at the LC complement its ability to study directly produced new particles
- The top-mass measurement with <100 MeV error will be a crucial ingredient for any precise prediction of SM + BSM observables
- The energy reach of ILC through precision measurements goes deep into multi-TeV region
  (C.I. 50-100 TeV, Z' 10 TeV, SEWSB 3-10 TeV)
- This can lead to new discoveries, complement LHC results and guide the planning for multi-TeV colliders