Electroweak Precision Tests and Alternative Theories

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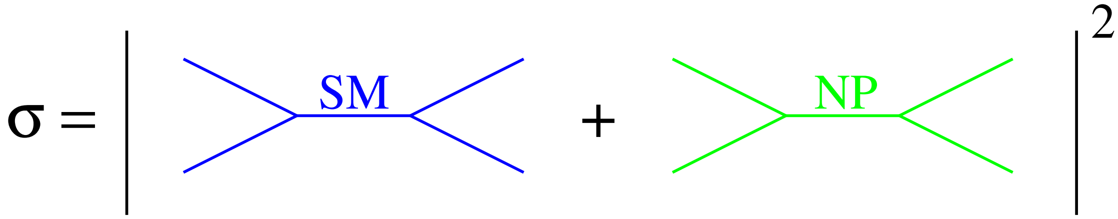
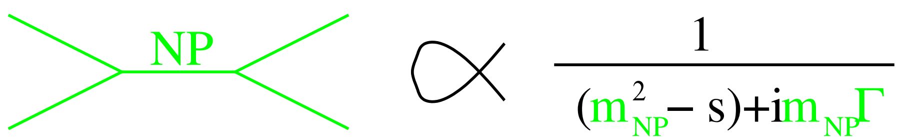
Why very high precision tests of the Standard Model?

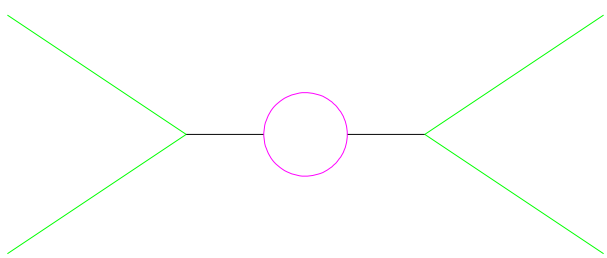
- We all believe that the SM is not the final answer
- Nevertheless it describes the data with an impressive accuracy
- Aim: see the breakdown of the SM or exclude alternatives by very high precision measurements
- (typically) two possibilities:
  - New physics at Born level, but very heavy





➠ suppressed by s/m_{NP}^2

  - New physics appears in loops

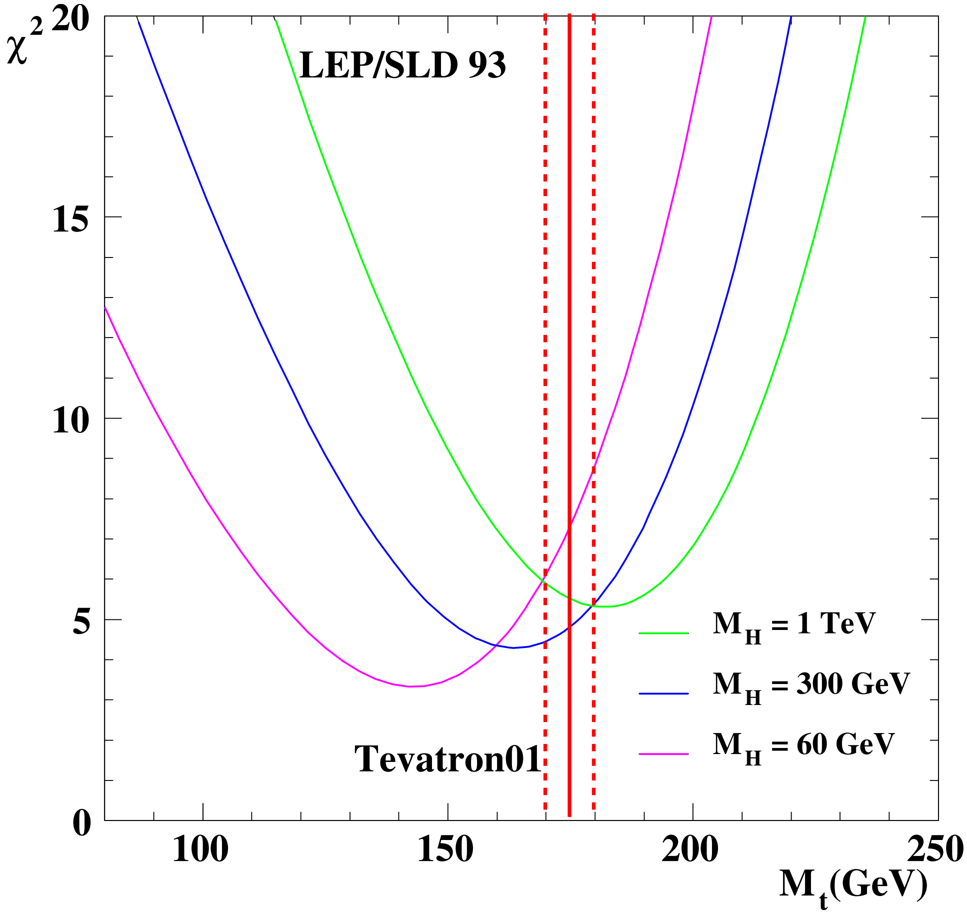


➠ typically suppressed by loop factor $\frac{\alpha}{4\pi}$

Ten years ago...

Fit to all electroweak precision data gave

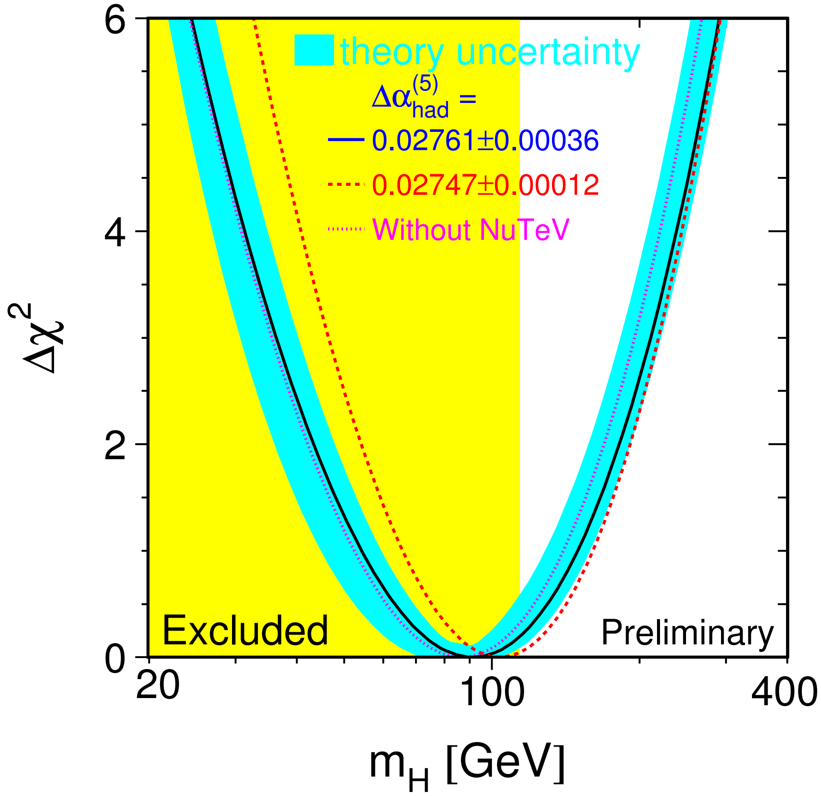
$$m_{\mathrm{t}} = (164 \pm 17(exp.) \pm 20(m_{\mathrm{H}}))\,\mathrm{GeV}$$



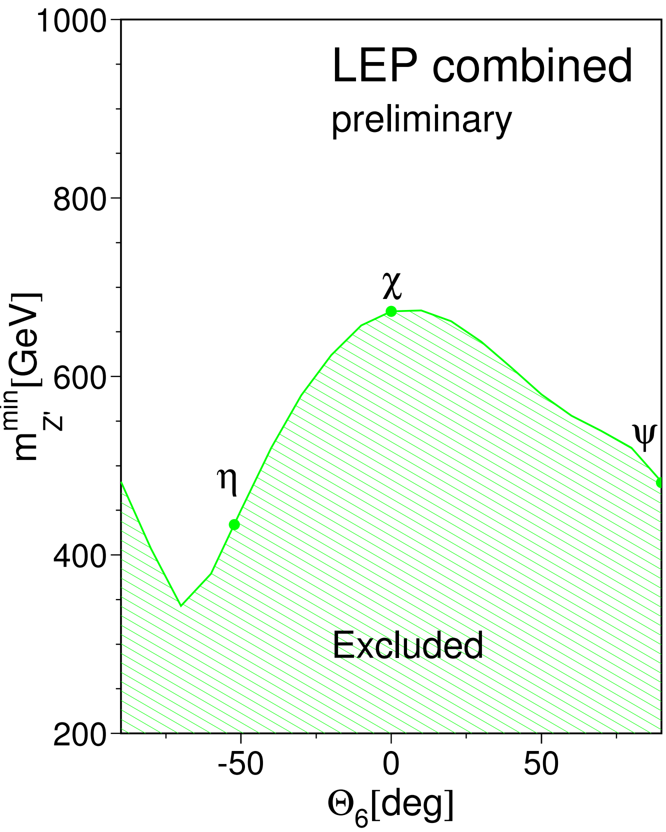
...where the TEVATRON discovered the top two years later

Today...

e.g. prediction that the Higgs is close

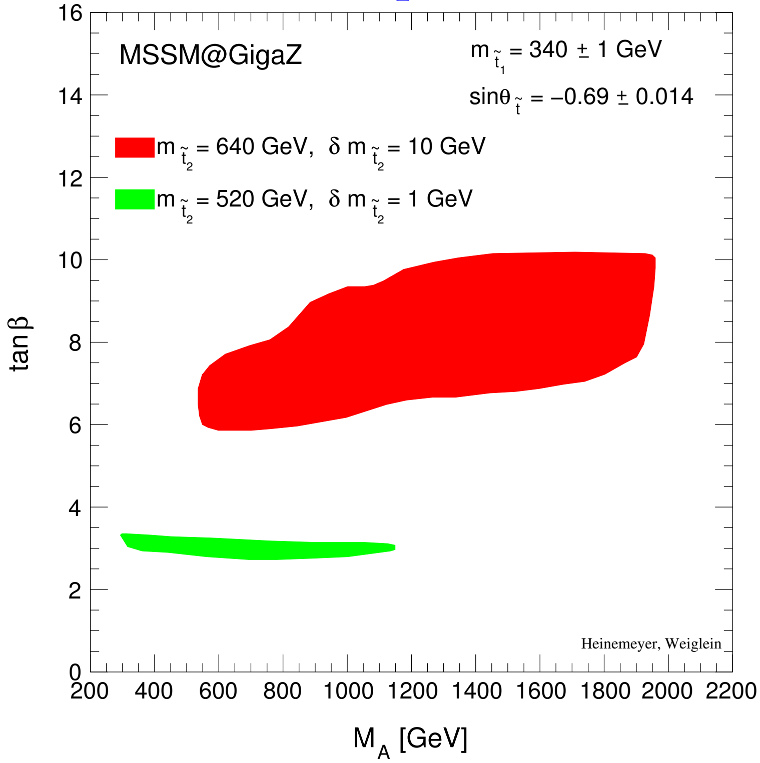


e.g. exclusion of Z' in different models

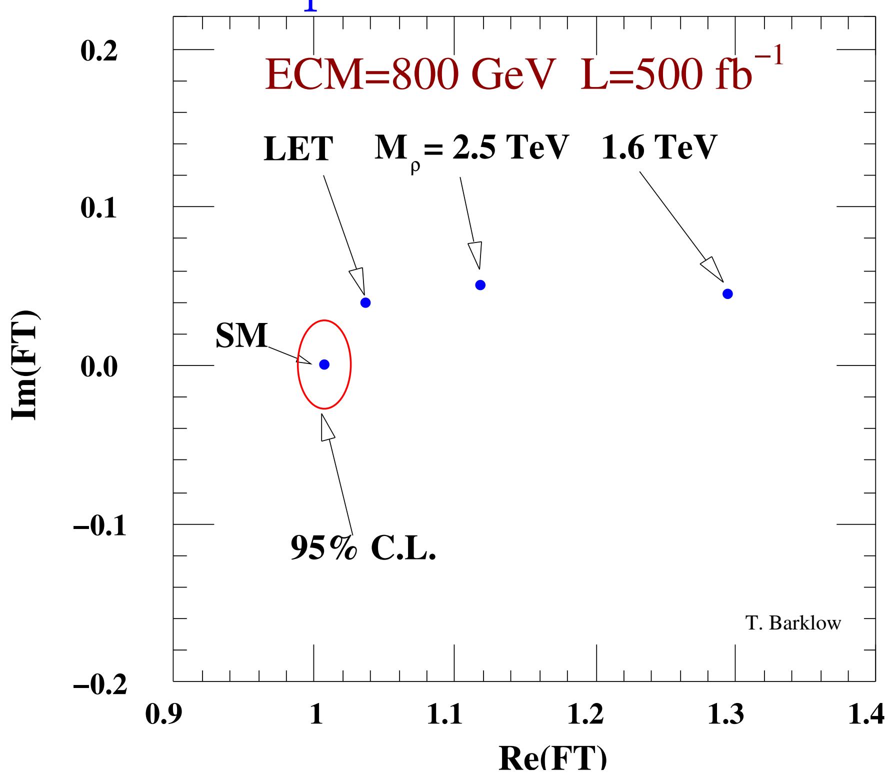


10 years from now...

e.g. prediction of SUSY parameters from GigaZ



e.g. "measurement" of techni-ρ mass from W-pair production



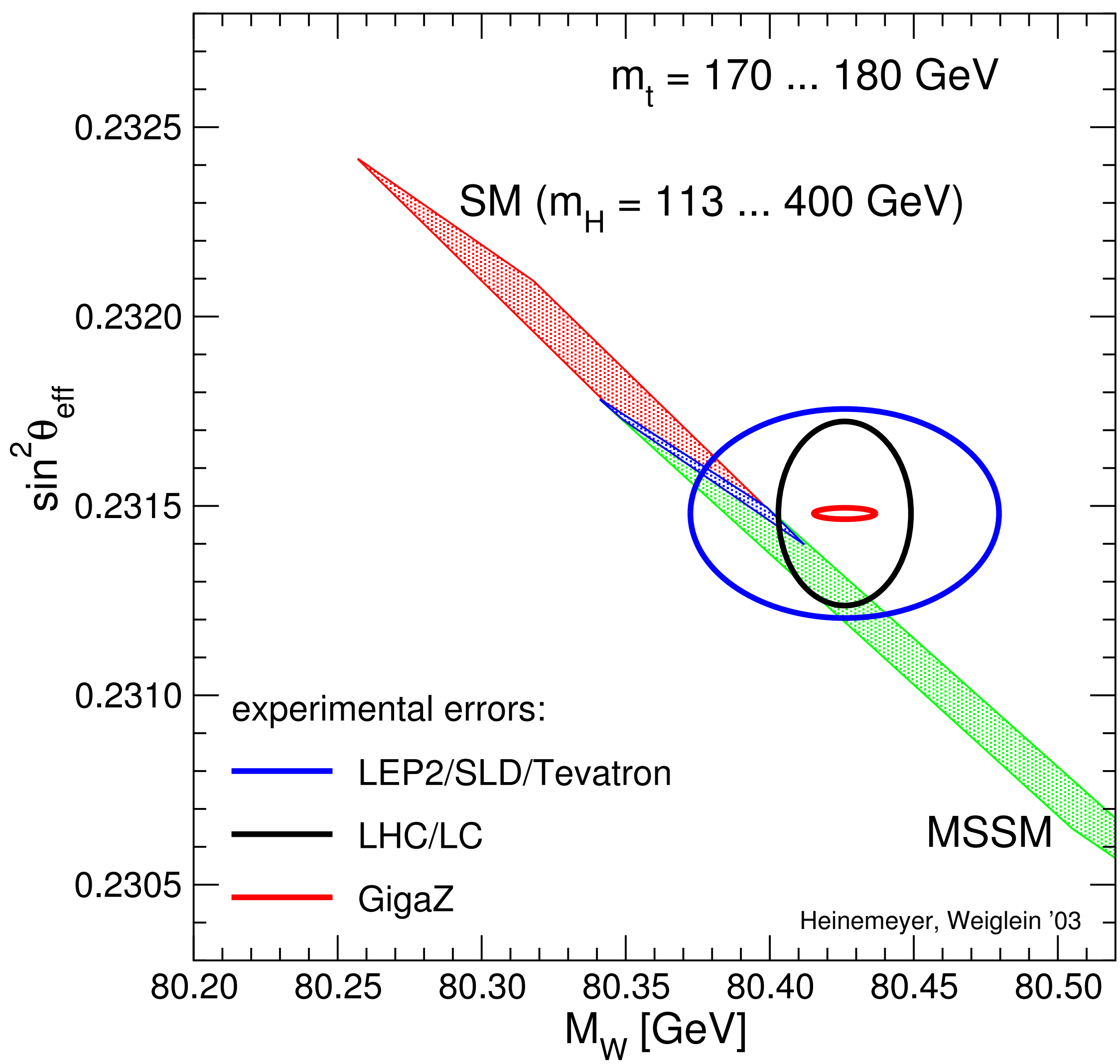
Main reactions used for precision tests:

- $e^+e^- \to f\bar{f}$, $(4f)$ at $\sqrt{s} \approx m_Z\,(2m_W)$ (GigaZ)
  - LEP/SLD physics with much better precision
  - test of theories with loop corrections to W,Z propagator and gauge boson-fermion vertices
- $e^+e^- \to f\bar{f}$ at high energy
  - general test of contact interactions
  - search for Z'
  - search for extra space dimensions
- $e^+e^- \to$ WW, WW$\nu\nu$...
  - high precision test of gauge boson self-interactions
  - window to strong electroweak symmetry breaking if no light Higgs exists

The GigaZ scenario

Physics goals

- $\Delta \sin^2 \theta^l_{eff} = 0.000013$ from left-right asymmetry,
  factor 13 to LEP/SLD
  No competition on that number
- $\Delta m_\mathrm{W} = 6\,\mathrm{MeV}$, factor 6 to LEP/SLD
  LHC goal: 15 MeV
- plus some more



Experimental requirements:

- $\mathcal{L} \approx 5 \cdot 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $\sqrt{s} \sim m_\mathrm{Z}$ (10^9 Zs)
- need electron and positron polarization to measure polarization (mainly) from data
  No problems with beam-beam effects on polarization expected
- still need excellent polarimeters for relative measurements
- $\Delta\sqrt{s} = 1\,\mathrm{MeV}$ relative to m_Z close to Z-peak and $\Delta\sqrt{s}/\sqrt{s} < 5 \cdot 10^{-5}$ for extrapolation from m_Z to $2m_\mathrm{W}$
  under study if this is possible
- control of beamstrahlung on the few % level
- $\Delta\mathcal{L}/\mathcal{L} = 10^{-4}$ if also $\Gamma(\mathrm{Z} \rightarrow \ell^+\ell^-)$ shall be improved

Theoretical progress:

- $\alpha(m_\mathrm{Z})$
  - need $\sigma(\mathrm{e^+e^-} \to \mathrm{q\bar{q}})$ to 1% up to Υ region
  - basically achieved already in ρ region in Novosibirsk
  - however contradiction between $\mathrm{e^+e^-}$ and τ data
  - BESS-II improved R in $2-5\,\mathrm{GeV}$ region from 20% to 7% accuracy, further progress possible
  - can expect also precise results from radiative return experiments at DAΦNE, CESR and b-factories in near future
- predictions for m_W and $\sin^2\theta^l_{eff}$
  - m_W now complete at 2-loop plus m_t dependent 3-loop corrections
  - residual uncertainty $\mathcal{O}(2\,\mathrm{MeV})$
  - $\sin^2\theta^l_{eff}$ not yet at full 2-loop
  - estimated uncertainty $\Delta\sin^2\theta^l_{eff} = 0.00008$
  - need $\sin^2\theta^l_{eff}$ at same level as m_W

(many more calculations needed)

$e^+e^- \to f\bar{f}$ at high energy

Most general approach: contact interactions

- propagator for very large masses:

$$\frac{1}{s-M^2}, \frac{1}{t-M^2} \approx \frac{1}{M^2}$$

- contact term $\frac{1}{\Lambda^2}$ e.g. $\frac{g^2}{16\pi M^2}$ in gauge theories (e.g. μ decay $\Lambda = \sqrt{4\pi\sqrt{2}/G_\mu} \sim 1.2\,\mathrm{TeV}$, $m_\mathrm{W} = 80\,\mathrm{GeV}$)
- TDR studies gave limits on Λ around 50 TeV for $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to b\bar{b}$
- LHC has similar reach, but for complementary couplings
- recent studies give $\sim$ 20% better limits for $e^+e^- \to e^+e^-$ and $e^-e^- \to e^-e^-$

Models with Z'

Two approaches

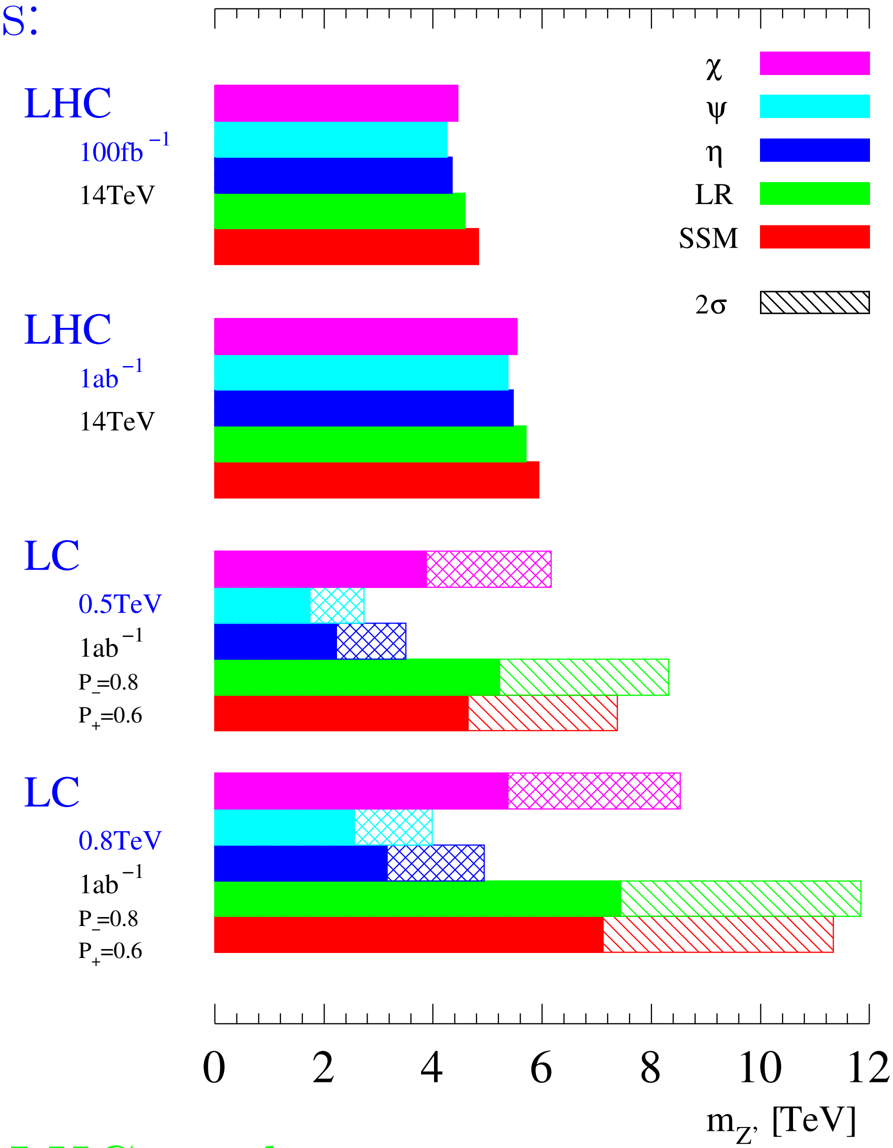
a) model dependent

- fix a model

➠ everything apart from the Z' mass is fixed

➠ can measure a mass or set a limit using all events

- results:



LC and LHC similar

b) model independent

- LC sensitive to normalized couplings

$$a_f^N = a'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}$$

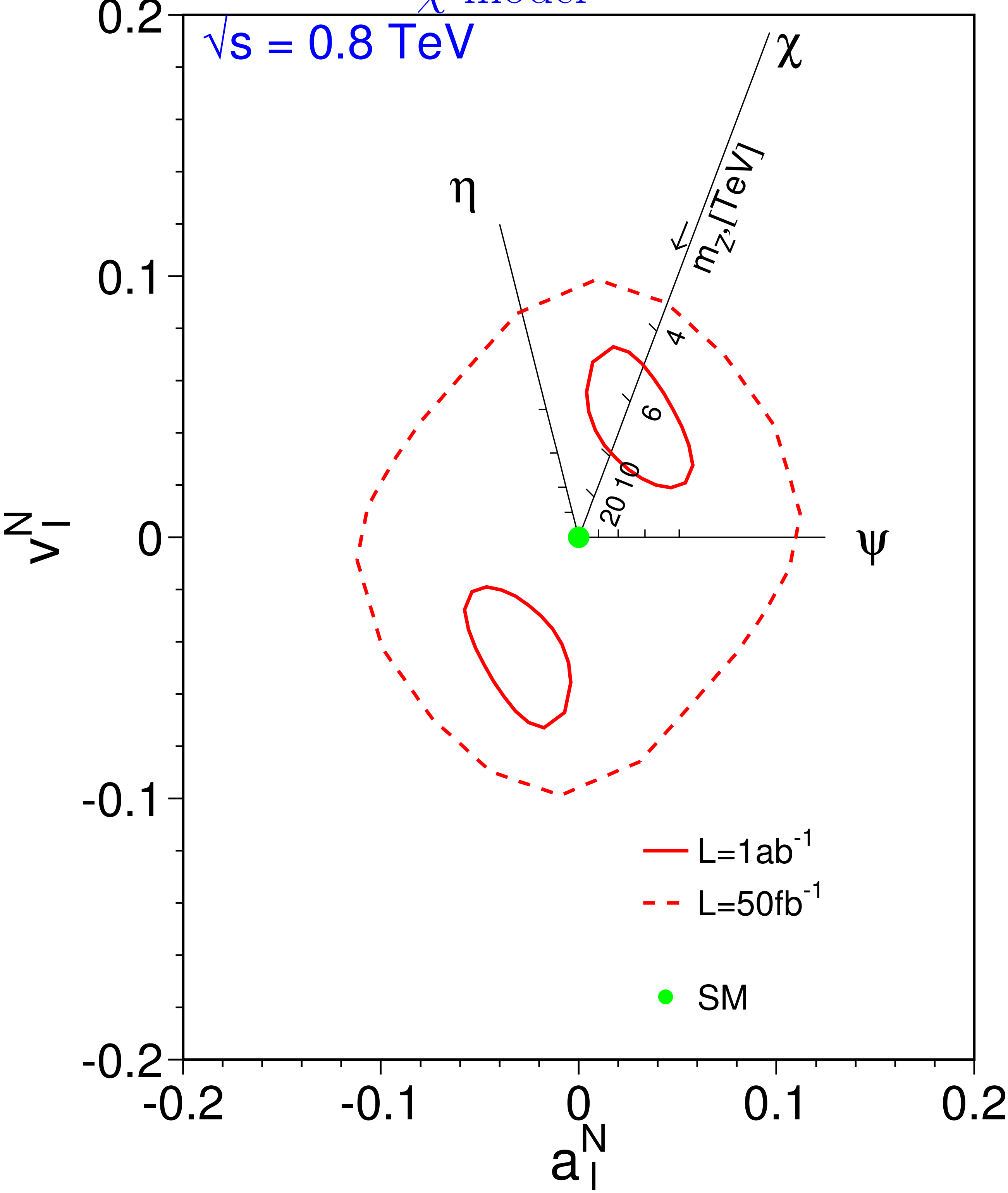
$$v_f^N = v'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}$$

- for leptons can obtain model independent limits/measurements on normalized couplings
- all hadronic observables depend on product of leptonic couplings (Z'-production) and hadronic couplings (Z'-decay)

➠ can measure hadronic couplings only if leptonic couplings deviate significantly from zero

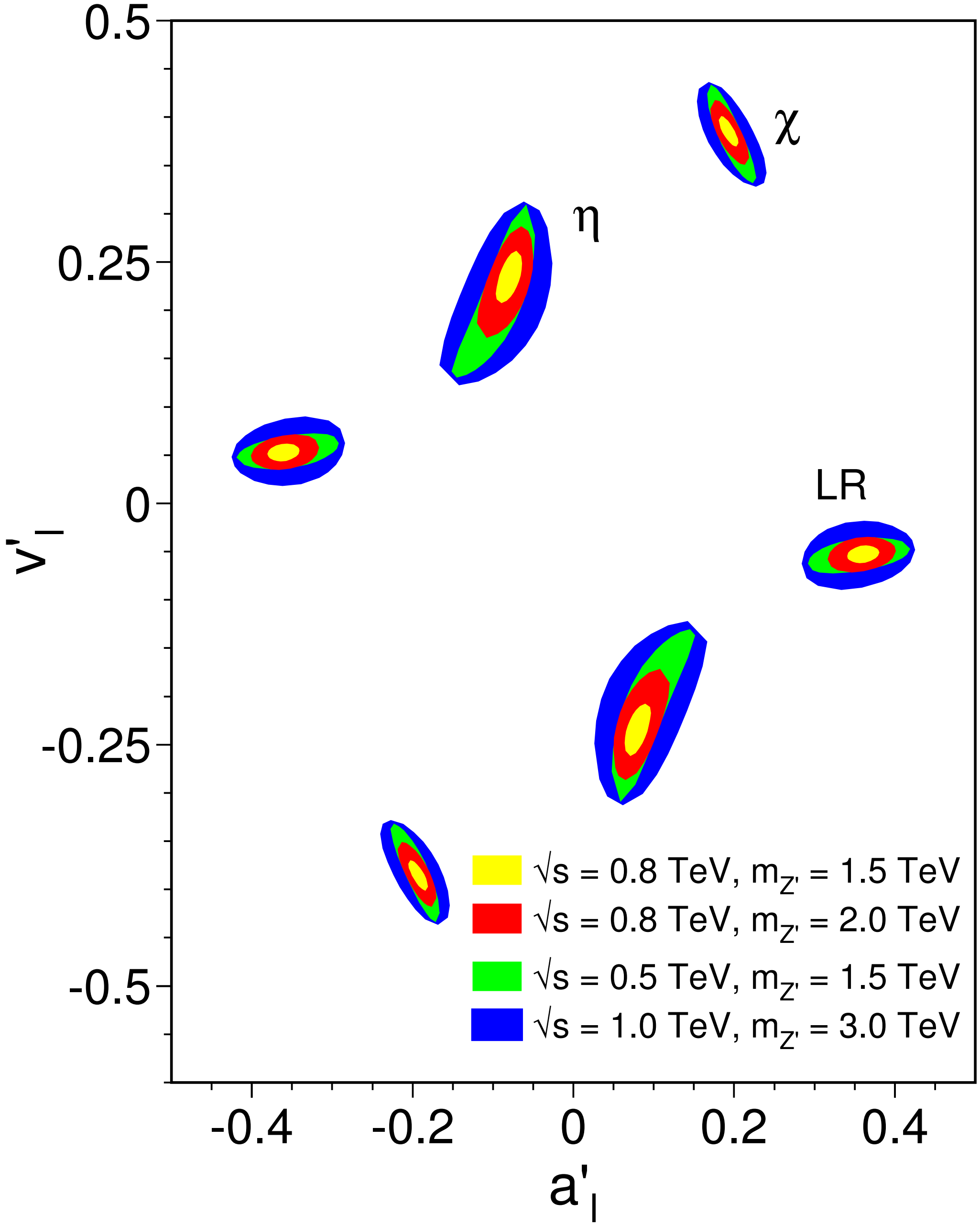
LC can distinguish models even outside LHC discovery reach

LC measurement for $m(Z') = 6\,\text{TeV}$ in the χ-model



Ideal case: LHC measures mass and LC measures coupling

95% c.l. contours for $\mathcal{L} = 1000\,\mathrm{pb}^{-1}$



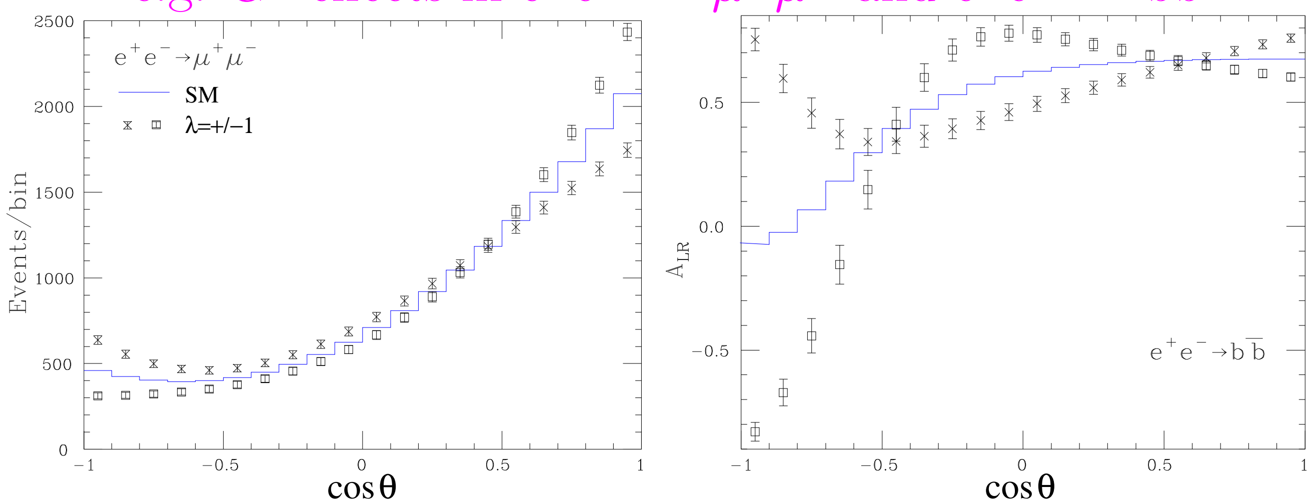
Measure couplings to few %

Extra space dimensions

LC (and LHC) is sensitive to effects from KK graviton excitations (G^*)

- TDR status: visible effects from $e^+e^- \rightarrow \gamma G^*$ and $e^+e^- \rightarrow G^* \rightarrow f\bar{f}$ for $M_D < 8\,\mathrm{TeV}$ ($\sqrt{s} = 800\,\mathrm{GeV}$), similar to LHC

e.g. G^*-effects in $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow b\bar{b}$



- recent development: how can one distinguish extra dimensions from e.g. Z'?
- key: G^* has spin 2
- define moments $< P_n >= \int dz \frac{1}{\sigma}\frac{d\sigma}{dz} P_n(z)$ (P_n = Legendre polynomials)
- $s \leq 1$ exchange: $< P_n >= 0$ for $n > 2$
- $s = 2$ exchange: $< P_{3,4} > \neq 0$

⇒ unique identification of $s = 2$ up to $4 - 5\,\mathrm{TeV}$

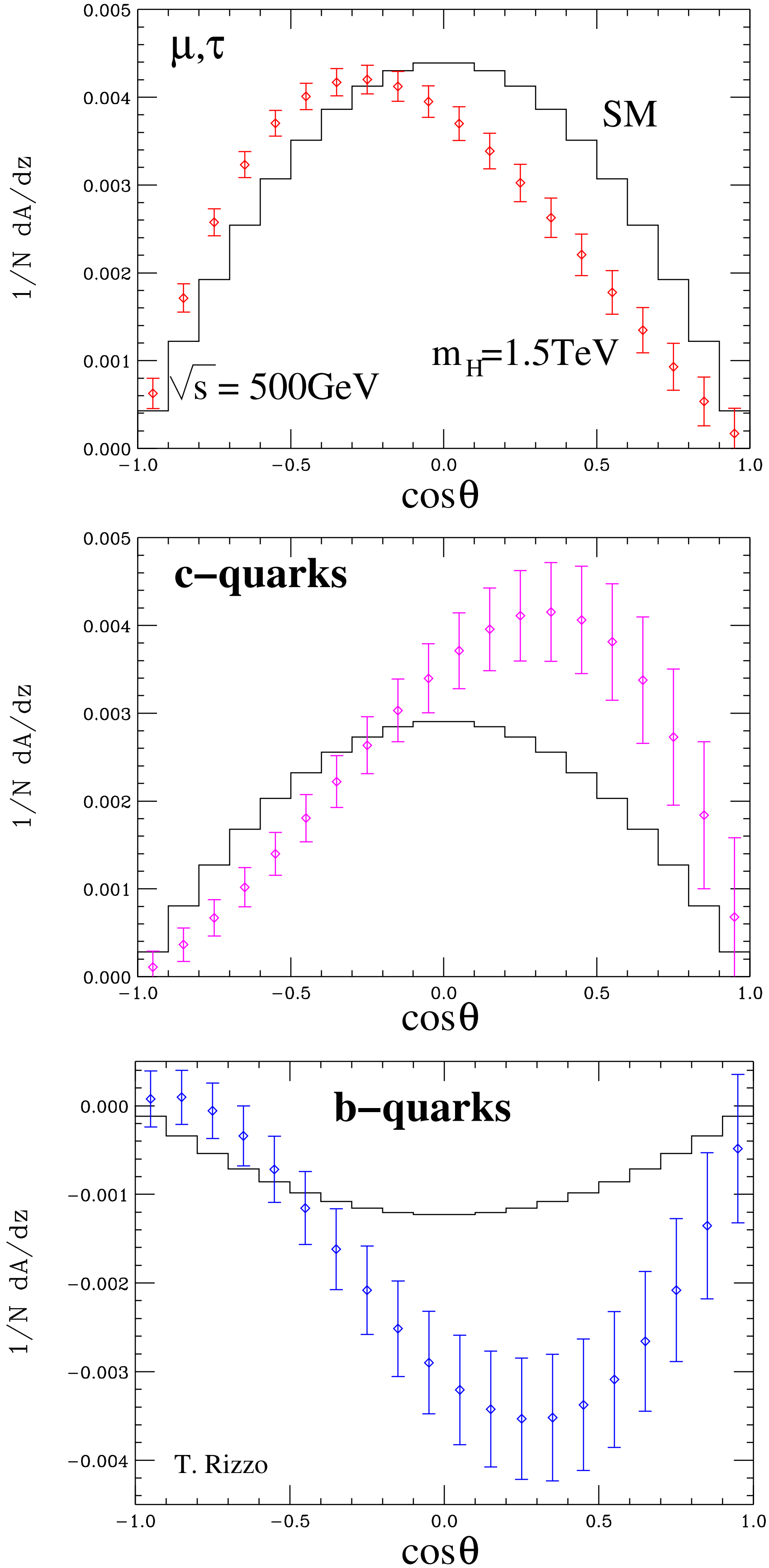
Additional possibility: transverse polarization

- with transverse beam polarization there exists an azimuthal asymmetry depending on $\cos\theta$ → plot
- this asymmetry is symmetric in $\cos\theta$ for vector or scalar particle exchange
- for tensor exchange (gravitons) it receives an asymmetric component

➡ Graviton and Z' exchange can be distinguished up to $M < 10\sqrt{s}$

- extra dimensions can be excluded up to $M_D <$ 10(22) TeV for $\sqrt{s} = 0.5(1)$ TeV (highest reach at next generation colliders)

Azimuthal asymmetry as function of polar angle in SM and with extra dimensions



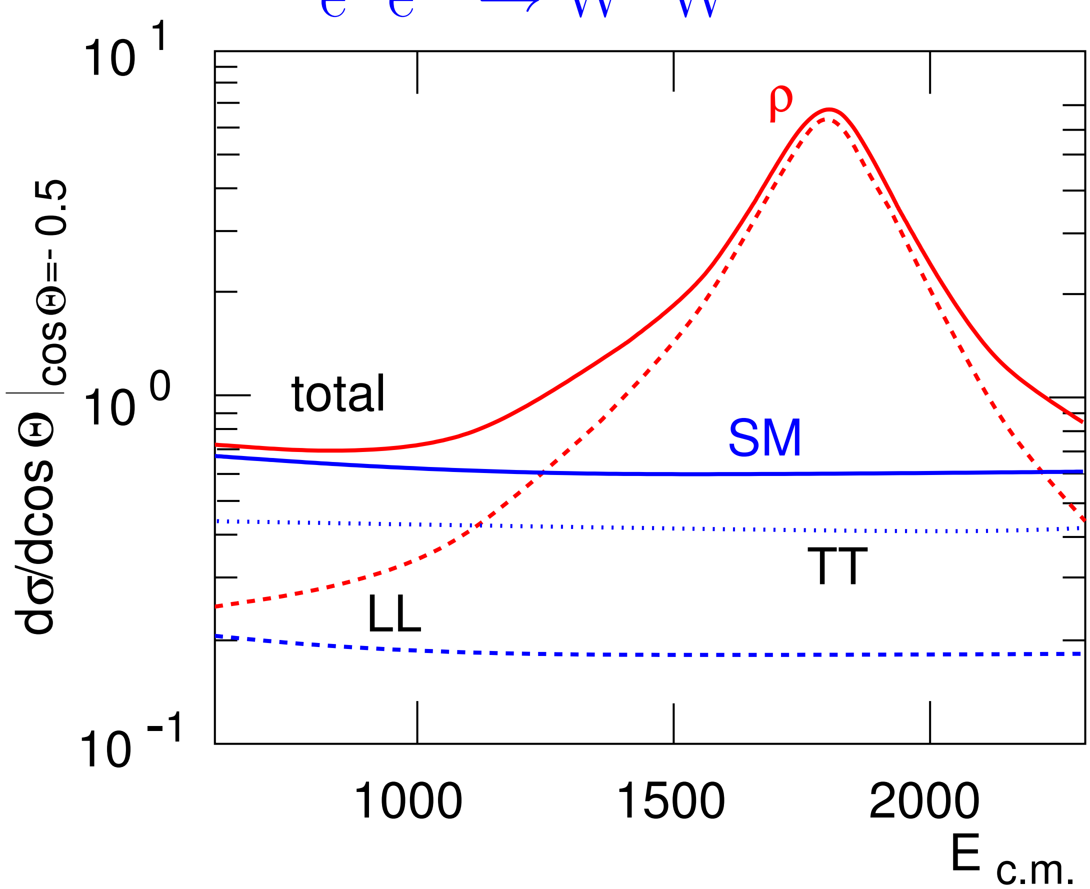
Gauge Boson interactions

Why are gauge boson interactions interesting?

- gauge boson interactions are directly given by the structure of the gauge group
- the longitudinal gauge bosons are connected to mechanism of mass generation
- in a weakly interacting theory gauge boson self-interactions receive loop corrections of $\mathcal{O}(\frac{g^2}{16\pi^2}) \sim 3 \cdot 10^{-3}$

- in a strongly interacting theory the longitudinal components of the gauge bosons are expected to have similar interactions as the pions in QCD (at much higher energy)
  ➟ expect to see effects from the dynamics of the new theory in the interaction of the longitudinal gauge bosons

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

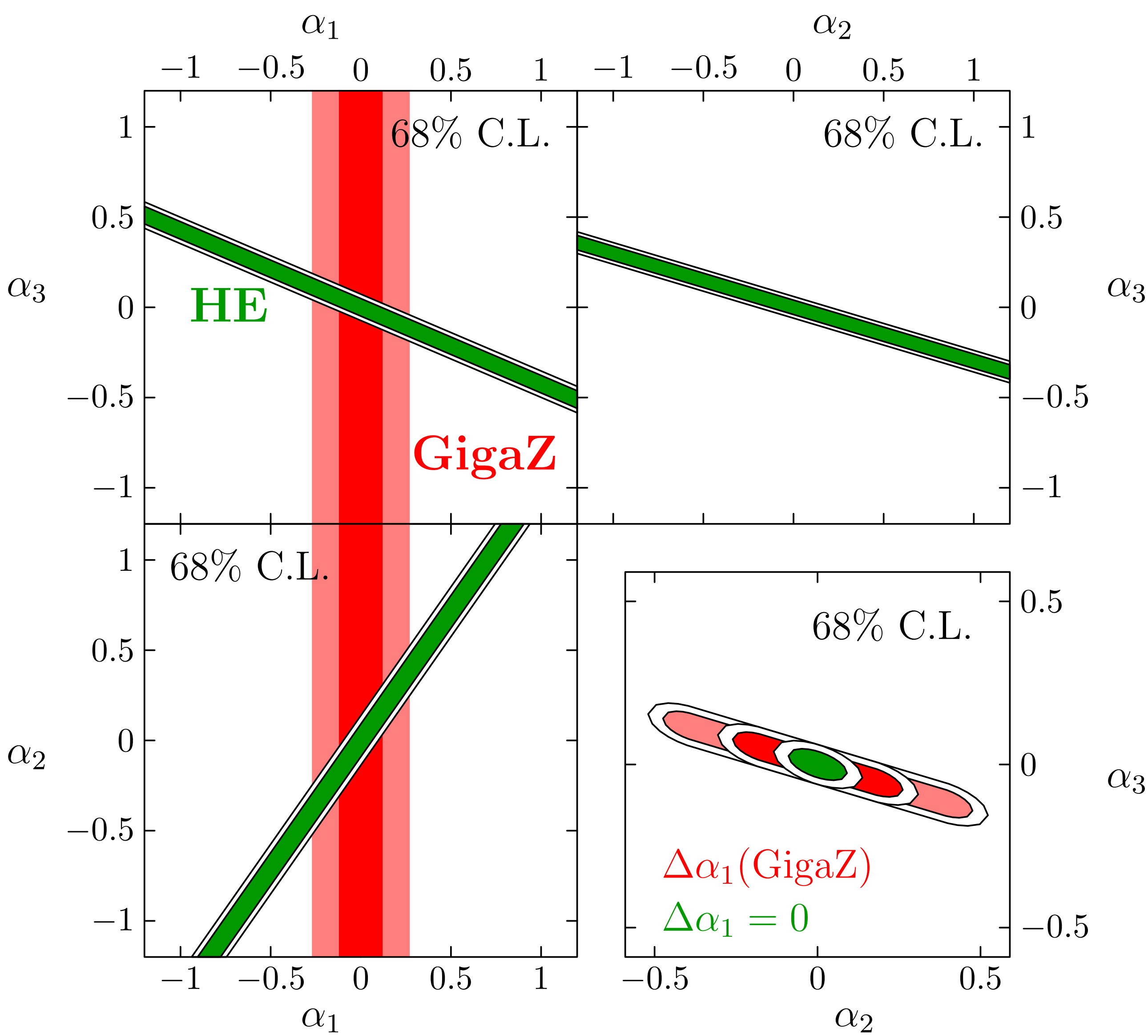


TDR status

Triple gauge couplings

- full experimental analysis of TGCs
- C,P conserving couplings can be measured with $3 - 15 \cdot 10^{-4}$ precision in e^+e^- at $\sqrt{s} = 500\,\mathrm{GeV}$
  ∼factor 2 better at $\sqrt{s} = 800\,\mathrm{GeV}$
  much better than the $3 \cdot 10^{-3}$ expectation from loop corrections
- C,P violating couplings are up to one order of magnitude worse
- the TGC precisions translate into a $\Lambda > 10\,\mathrm{TeV}$ limit for the scale of strong electroweak symmetry breaking, significantly above the $\Lambda \leq 3\,\mathrm{TeV}$ limit from unitarity

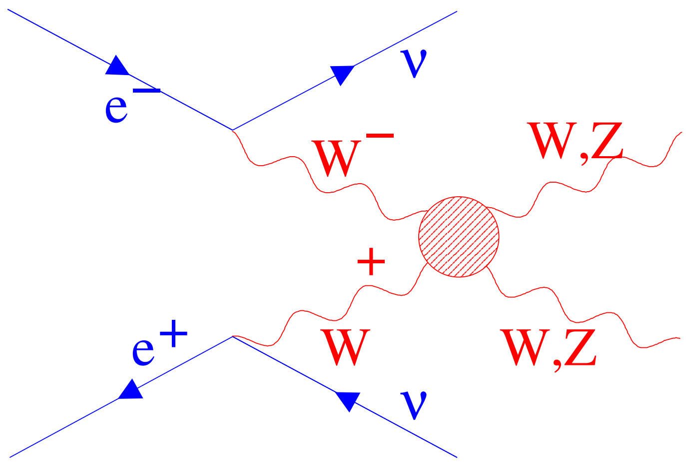
TGC limits in terms of α couplings ($\frac{\alpha}{16\pi^2} = \left(\frac{v}{\Lambda}\right)$)



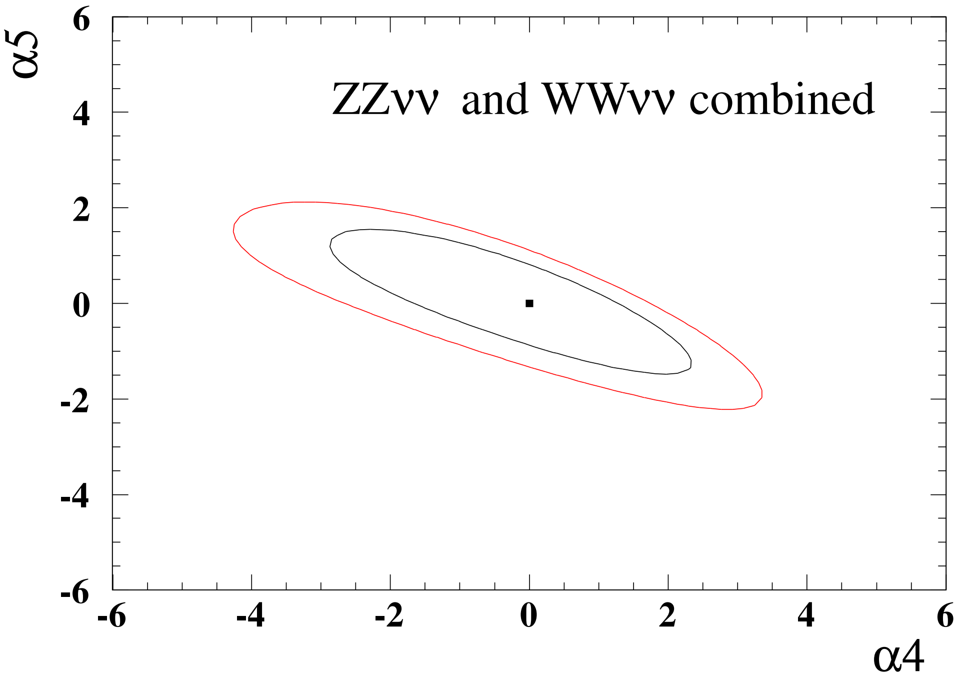
TGC limits on Λ are the highest ones anywhere

Quartic couplings

- $WW \to WW$ and $WW \to ZZ$ has been studied at $\sqrt{s} = 800\,\mathrm{GeV}$



- this channel probes directly the Goldstone boson dynamics (like $\pi\pi$ scattering in QCD)
- it is sensitive to $\Lambda > 3-5\,\mathrm{TeV}$, slightly better than LHC



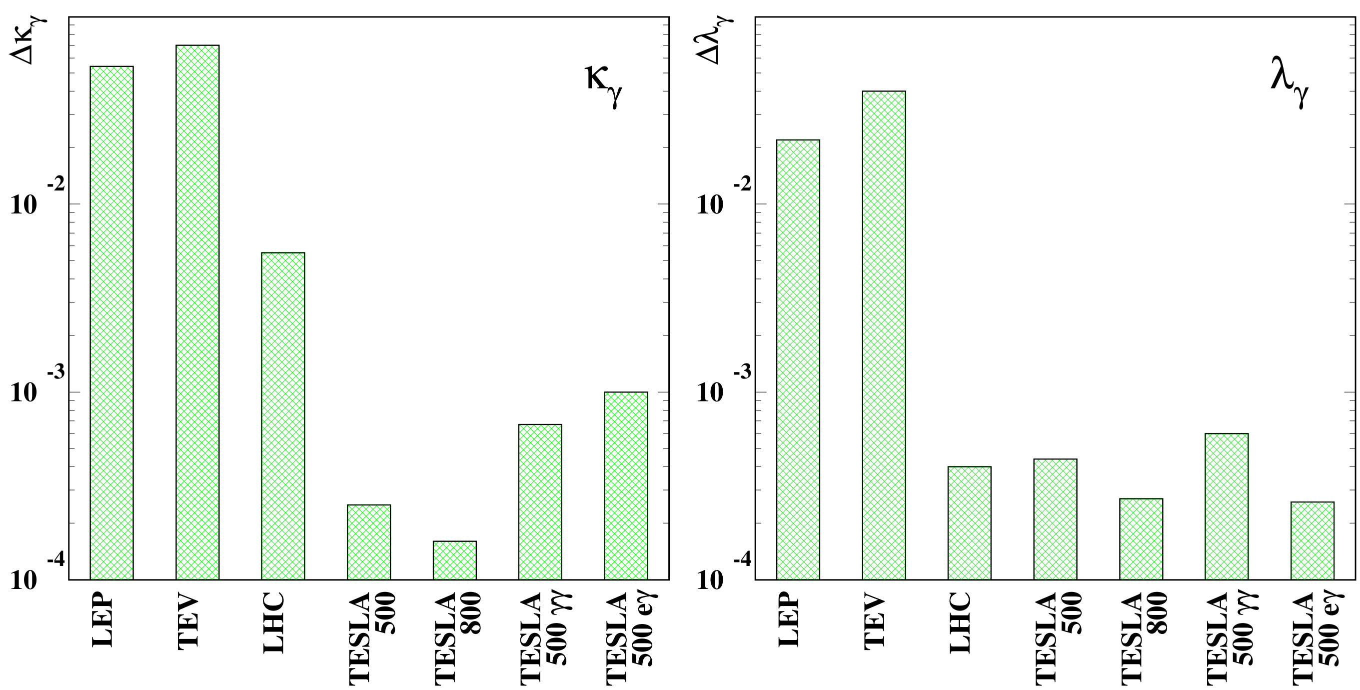
News since the TDR:

Optimal observables study for triple gauge couplings in e^+e^-

- study up to now only on parton level
- using optimal observables additional couplings (e.g. imaginary parts) can be included without a loss in precision
- precision on imaginary parts similar to real parts
- one combination ($\mathrm{Im}(g_1^R + \kappa_R)$) can only be measured with transverse polarization

Study of TGCs in $\gamma\gamma \to WW$ and $e\gamma \to W\nu$

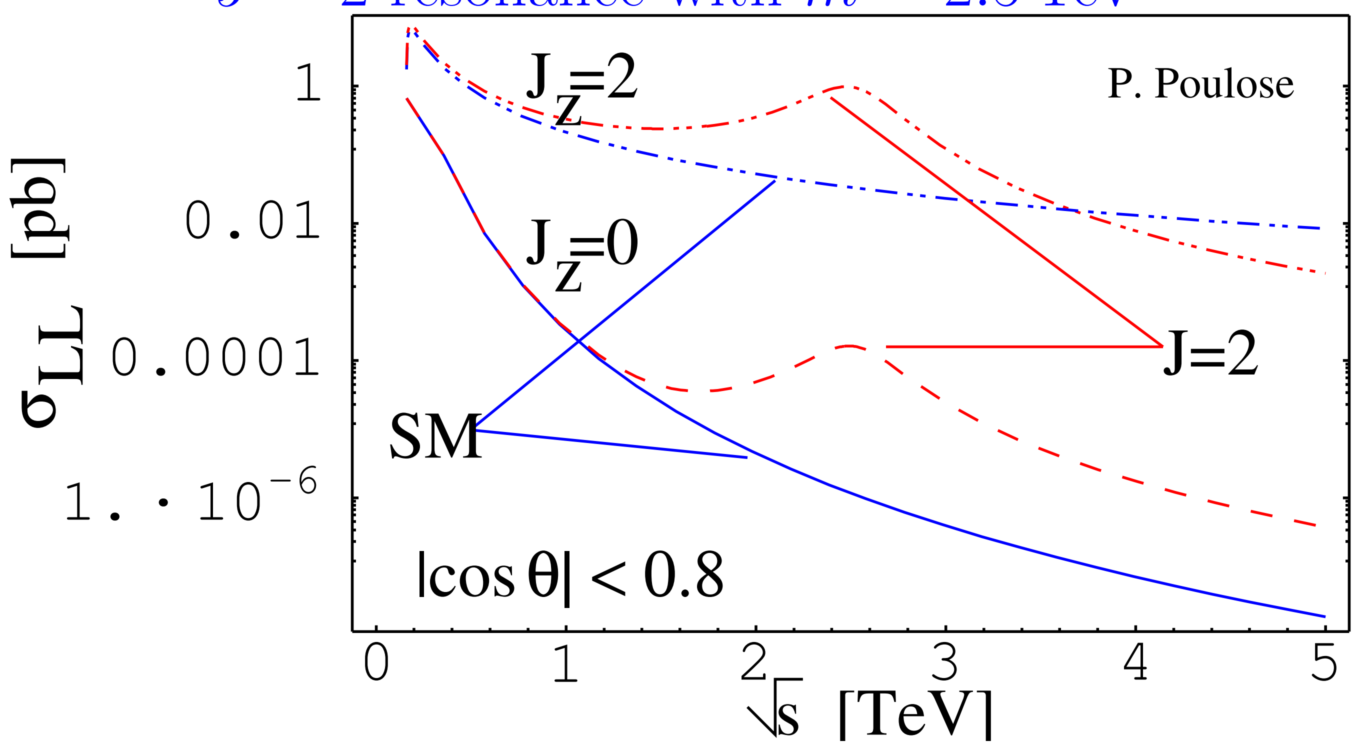
- $e\gamma$ reasonably complete at $\sqrt{s_{ee}} = 500\,\mathrm{GeV}$
- in $\gamma\gamma$ use of ϕ angle (interference of helicity amplitudes) still missing
- the cross sections in these channels are much larger
- however there are no large gauge cancellations
- in the end the sensitivity is comparable to e^+e^-



Rescattering for $\gamma\gamma \to WW$ has been calculated

- $e^+e^- \to WW$ is only sensitive to J=1 resonances (ρ, ω)
- $\gamma\gamma \to WW$ is sensitive to J=0 and J=2
- the cross sections have been calculated
- a study on the experimental sensitivities is planned

$J = 2$ resonance with $m = 2.5\,\mathrm{TeV}$



If anomalous triple gauge couplings are seen somewhere information from all different channels ($e^+e^- \to W^+W^-$, $\gamma\gamma \to W^+W^-$, $e\gamma \to W\nu$, $pp \to W\gamma, WZ$) are needed to understand the mechanism behind it

Conclusions

- electroweak precision tests contribute significantly to the physics at a LC:
  - precision measurements on the Z can test model parameters inside or beyond the Standard Model
  - 2-fermion production at high energy tests a wide class of models beyond the SM
  - W-pair production provides new precision observables on the same level as $\sin^2\theta^l_{eff}$ or m_{W}
  - if no light Higgs exists gauge boson production offers a window to strong electroweak symmetry breaking
- precision tests are an active field of research in the linear collider community
- the combination of the direct studies of the probable extensions of the SM (Higgs and SUSY) with the potential of the precision tests makes the Linear Collider a unique tool to understand the physics of electroweak symmetry breaking