Electroweak Gauge Bosons

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- Introduction
- High precision measurements at lower energies
- W production at high energies
- measurements of the CKM matrix

Introduction

- The measurement of gauge boson properties has influenced our physics knowledge since long
- The measurement of radiative corrections opens a window into energies that are not accessible directly
- TESLA offers three ways to study gauge boson properties
  - The masses and couplings of W and Z can be measured with much higher precision than at LEP/SLD
  - Couplings amongst gauge boson can be measured at high energies
  - The CKM matrix can be probes in W-decays at the high energy and in B-decays at Giga-Z

The gauge-boson propagator corrections can be divided into three types of measurements:

- partial/total widths of the Z (Γ_ℓ)
- effective weak mixing angle from v/a ($\sin^2\theta_{\mathrm{eff}}^{\ell}$)
- mass of the W (m_{W})
- (and m_{Z} to define the input parameters)

Physics wise there are three parameters to describe this sector:

- ε_1 (or T): mainly sensitive to isospin splitting ($\propto m_{\mathrm{t}}^2$) $\leftarrow \Gamma_\ell$
- ε_3 (or S): mainly sensitive to logarithmic effects $\propto \log m_{\mathrm{H}} \leftarrow \Gamma_\ell, \sin^2\theta_{\mathrm{eff}}^{\ell}$
- ε_2 (or U): basically constant in the Standard Model $\leftarrow \Gamma_\ell, \sin^2\theta_{\mathrm{eff}}^{\ell}, m_{\mathrm{W}}$

In addition there are variables sensitive to the interesting bb-vertex corrections ($R_{\mathrm{b}}, \mathcal{A}_{\mathrm{b}}$)

TESLA contributions

m_Z, Γ_ℓ:

- m_Z needs an absolute calibration of the energy scale to 10^{-5} which is probably not possible
- Γ_Z might be improved by a factor two if a relative beam energy calibration of 10^{-5} can be achieved
  This needs to be verified!
- the hadronic event selection, the leptonic event selection and the experimental luminosity systematics may improve a factor three
  (New study by M. Winter)
- the theory systematics on the luminosity we assume constant

Improvement on lineshape related quantities:

	LEP	TESLA
m_Z	91.1874 ± 0.0021 GeV	± 0.0021 GeV
$\alpha_s(m_Z^2)$	0.1183 ± 0.0027	± 0.0009
$\Delta\rho$	$(0.55 \pm 0.10) \cdot 10^{-2}$	$\pm 0.05 \cdot 10^{-2}$
N_ν	2.984 ± 0.008	± 0.004

$\sin^2\theta^\ell_{\rm eff}$:

Most sensitive observable is $A_{\rm LR}$, so only this is discussed

- $A_{\rm LR} = \frac{1}{\mathcal{P}}\frac{\sigma_L-\sigma_R}{\sigma_L+\sigma_R} = \mathcal{A}_{\rm e} = \frac{2v_e a_e}{v_e^2+a_e^2}$
  $v_e/a_e = 1 - 4\sin^2\theta^\ell_{\rm eff}$
  independent of the final state
- Statistical error with 10^9 Zs: $\Delta A_{\rm LR} = 3 \cdot 10^{-5}$
- Error from polarization: $\Delta A_{\rm LR}/A_{\rm LR} = \Delta\mathcal{P}/\mathcal{P}$
  - only electron polarization with $\Delta\mathcal{P}/\mathcal{P} = 0.5\%$ would completely dominate the measurement
  - with positron polarization $\mathcal{P}_{\rm eff} = \frac{\mathcal{P}_+ + \mathcal{P}_-}{1+\mathcal{P}_+\mathcal{P}_-}$
    $\Rightarrow$ gain a factor four for $\mathcal{P}_-/\mathcal{P}_+ = 80\%/60\%$ due to error propagation
  - even better with Blondel scheme:

$$\sigma = \sigma_u\left[1 - \mathcal{P}_+\mathcal{P}_- + A_{\rm LR}(\mathcal{P}_+ - \mathcal{P}_-)\right]$$

$$A_{\rm LR} = \sqrt{\frac{(\sigma_{++}+\sigma_{-+}-\sigma_{+-}-\sigma_{--})(-\sigma_{++}+\sigma_{-+}-\sigma_{+-}+\sigma_{--})}{(\sigma_{++}+\sigma_{-+}+\sigma_{+-}+\sigma_{--})(-\sigma_{++}+\sigma_{-+}+\sigma_{+-}-\sigma_{--})}}$$

    can measure $A_{\rm LR}$ independent from polarimeters with very small loss in precision and only 10% of the luminosity on the small cross sections
    however still need polarimeters for relative measurements

- other systematics
  - Beam energy: $\mathrm{dA_{LR}/d\sqrt{s}} = 2 \cdot 10^{-2}/\,\mathrm{GeV}$ from $\gamma - Z$-interference
    $\Rightarrow$ need $\Delta\sqrt{s} = 1\,\mathrm{MeV}$ relative to m_{Z}
  - Beamstrahlung: $\Delta A_{\mathrm{LR}} = 9 \cdot 10^{-4}$
    $\Rightarrow$ need to know beamstrahlung to a few %
    However if beamstrahlung is the same in m_{Z}-scan and A_{LR}-running corrections are automatic
  - other systematics should be small
- In total $\Delta A_{\mathrm{LR}} = 10^{-4} \Rightarrow \Delta \sin^2\theta^{\ell}_{\mathrm{eff}} = 0.000013$
  Factor 13 to LEP/SLD

b-quark observables

- R_{b}: factor five to LEP/SLD due to higher statistics and better efficiency/purity of b-tagging
- $\mathcal{A}_{\mathrm{b}}$: factor 20 to LEP/SLD due to polarization, higher statistics and better b-tagging

m_W

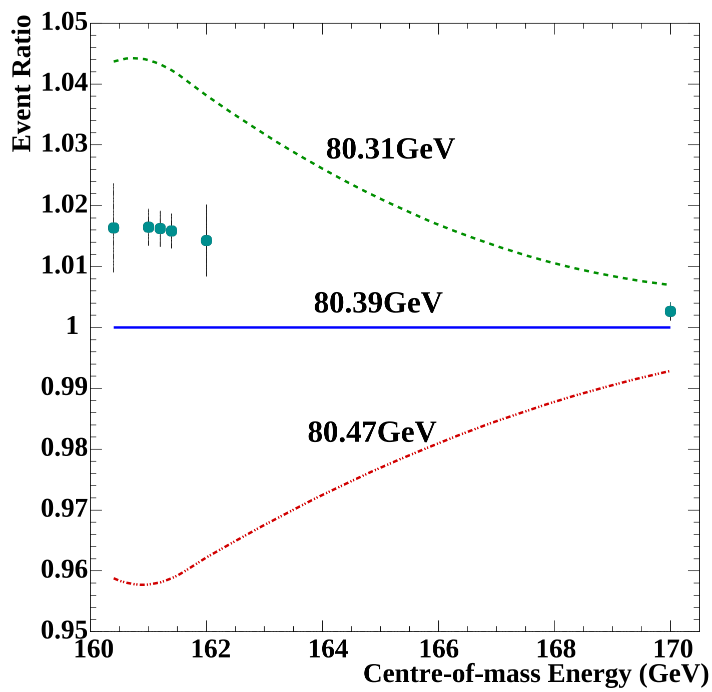
Threshold scan:

- Near threshold W-pair production is dominated by neutrino t-channel exchange

$\Rightarrow$ β-suppression gives high sensitivity to m_W

$\Rightarrow$ no (unknown) triple gauge couplings involved

- A six point scan around $\sqrt{s} = 161\,\text{GeV}$ has been simulated with $\mathcal{L} = 100\,\text{fb}^{-1}$ (one year!!!)



- efficiencies/purities assumed as at LEP
- $\Delta m_W = 6\,\text{MeV}$ possible with 0.25% error on luminosity and efficiencies
- error increases only to 7 MeV if efficiencies are fitted

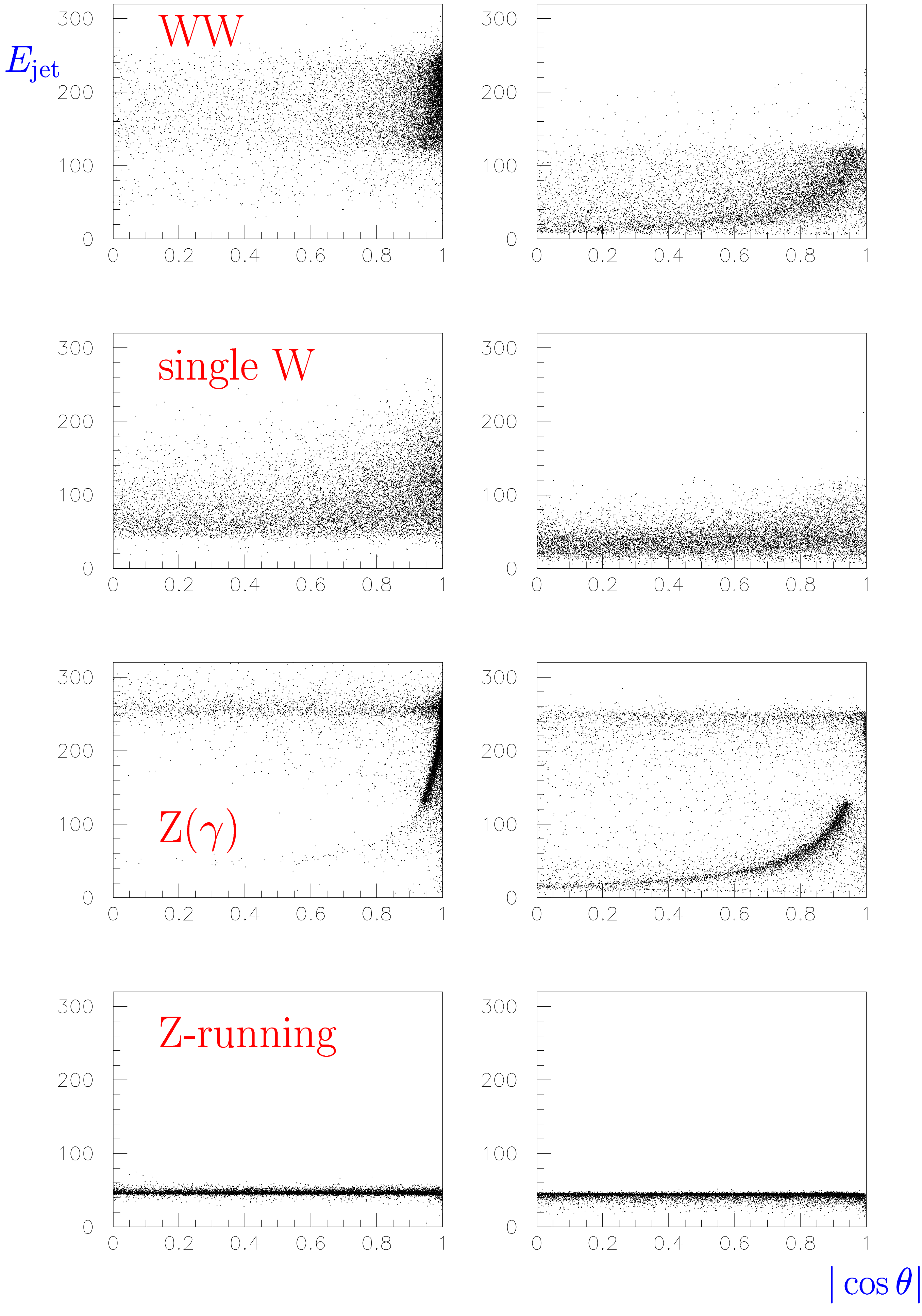
Direct reconstruction at high energy:

- preliminary study exists for $e^+e^- \to W^+W^- \to$ 2jets, ℓ, ν and $e^+e^- \to We\nu \to$ 2jets, $e\nu$
- statistical error ~ 3 MeV in both channels
- statistical error on calibration using 2-jet events at 500 GeV, from radiative return and from Z-running
- however we are not sure if we understand systematics in time for the TDR

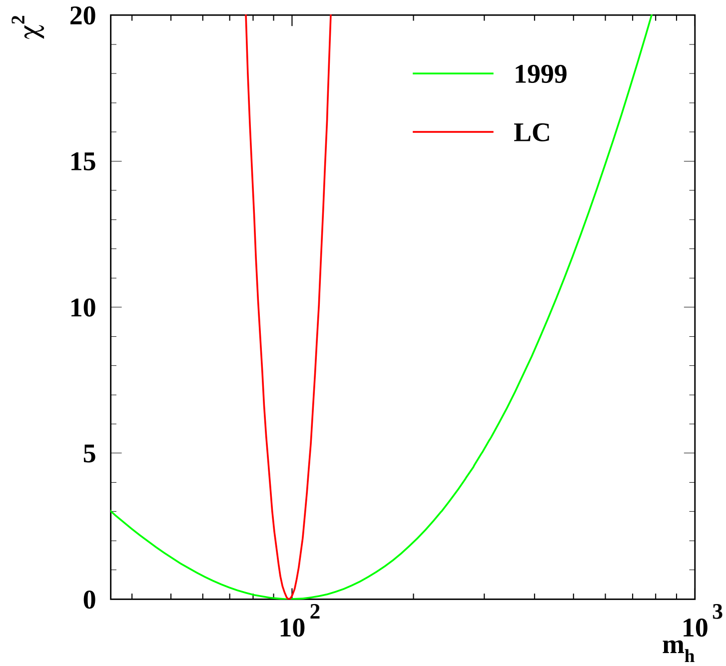
Interpretation of precision measurements

Parametric errors

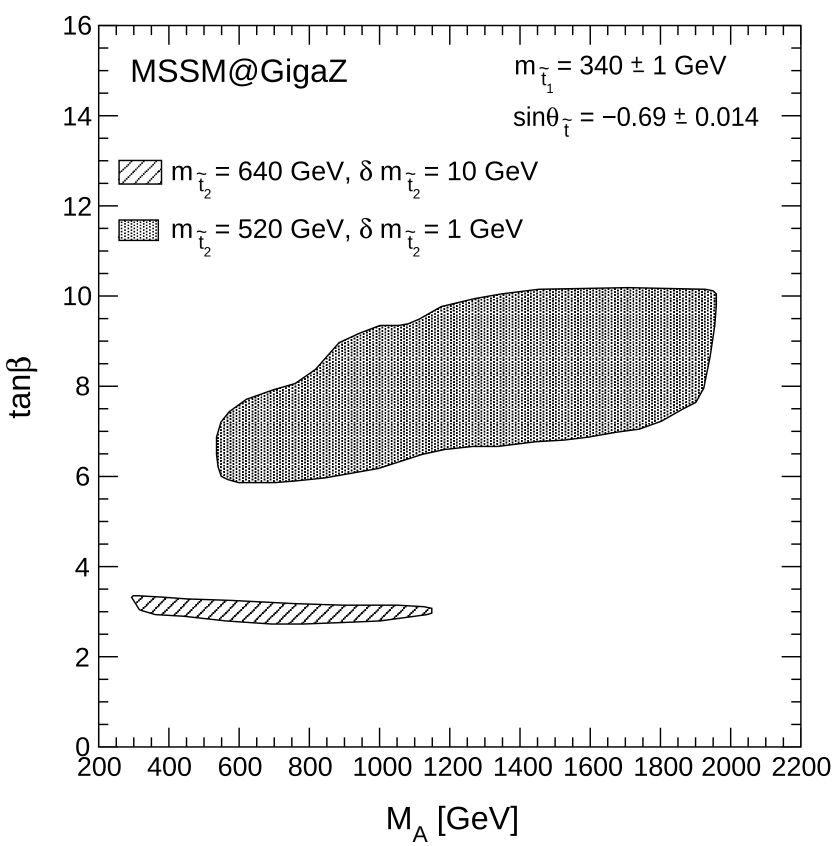
- largest effect: Running of α on $\sin^2\theta^\ell_{\rm eff}$
  - Using data only: $\Delta\sin^2\theta^\ell_{\rm eff} = 0.00023$
  - $\sim$ factor three improvement using perturbative QCD at low energy
  - with $\sigma(e^+e^- \to \text{had})$ below the Υ to 1% $\Delta\sin^2\theta^\ell_{\rm eff} = 0.000017$
- 2 MeV error on m_Z gives $\Delta\sin^2\theta^\ell_{\rm eff} = 0.000014$ and $\Delta m_W = 1$ MeV (if W-mass calibrated to m_Z)
- m_t no problem with TESLA precision of m_t


WW
single W
Z(γ)
Z-running
$E_{\rm jet}$
$|\cos\theta|$
0
100
200
300
0.2
0.4
0.6
0.8
1

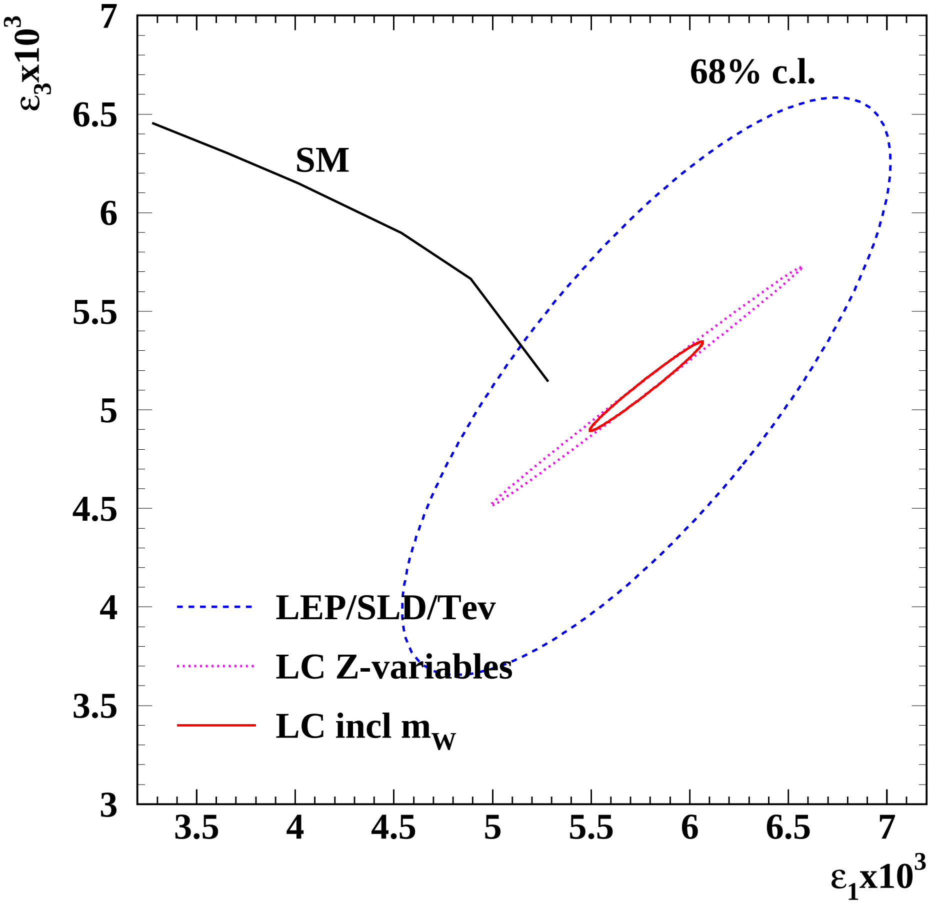
Within SM m_{H} can be predicted to 5% from precision data



Within the MSSM the data can be used to measure model parameters



Model independent analysis (ε parameters)

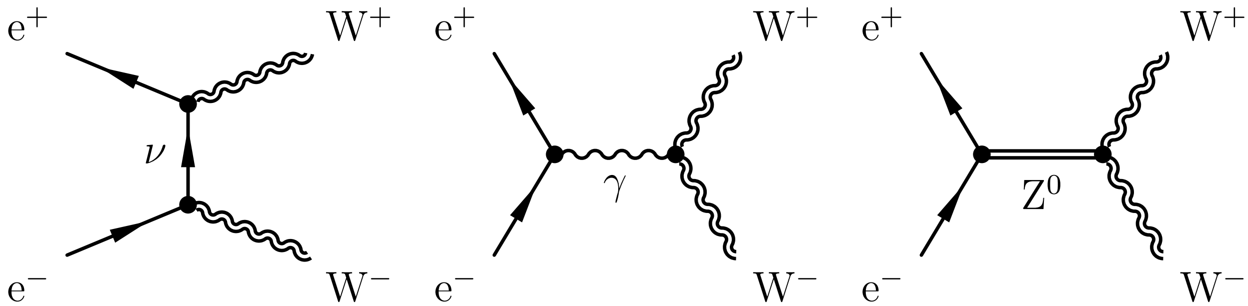


- dramatic improvement wrt. LEP/SLD in m_{H} direction
- improvement perpendicular to m_{H} from pure Z-variables not so dramatic (Γ_ℓ)
- only inclusion of m_{W} allows Higgs constraint independent of ε_1

Two processes with large cross section

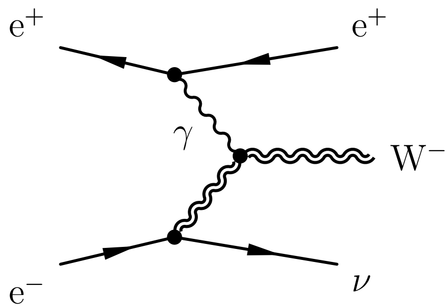
W-pair production:

Superposition of t-channel ν-exchange and s-channel Z, γ-exchange

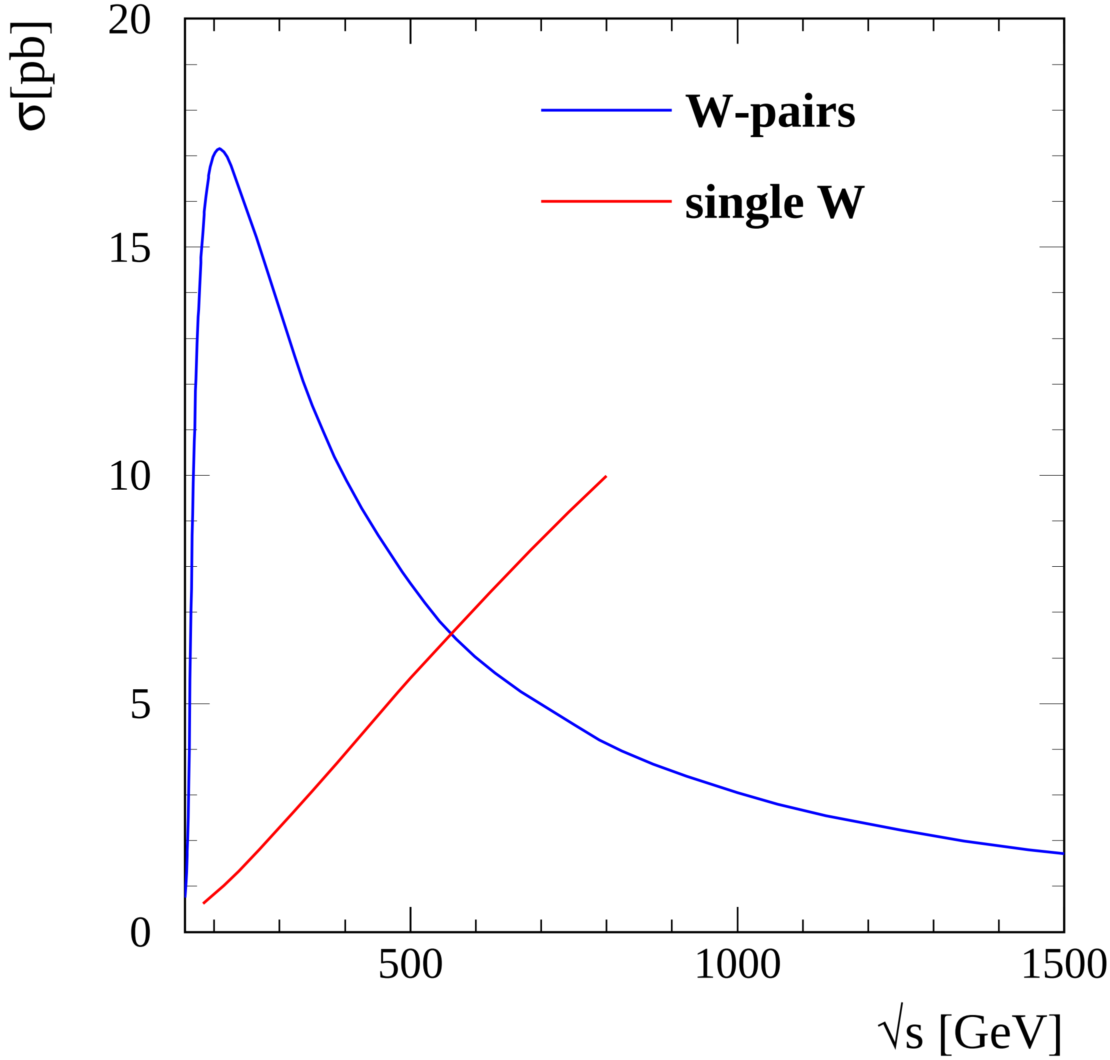


Single W production

Main diagram contains WWγ coupling



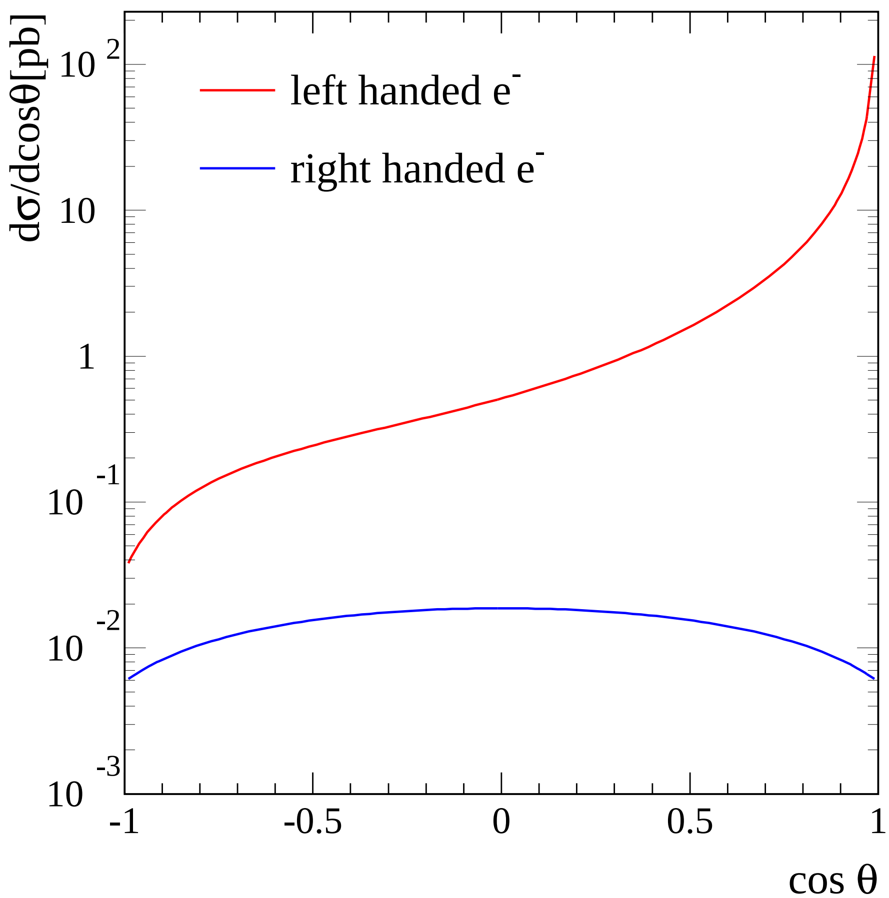
Cross sections at TESLA energies about equal



Single W^- (W^+) only for left handed e^- (right handed e^+)

Polarization dependence of W-pair production

- t-channel only for left handed e^- and right handed e^+
- for s-channel at high energy pure W^0 exchange $\Rightarrow$ same polarization behavior
- for TESLA energies already large left-right asymmetry



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:

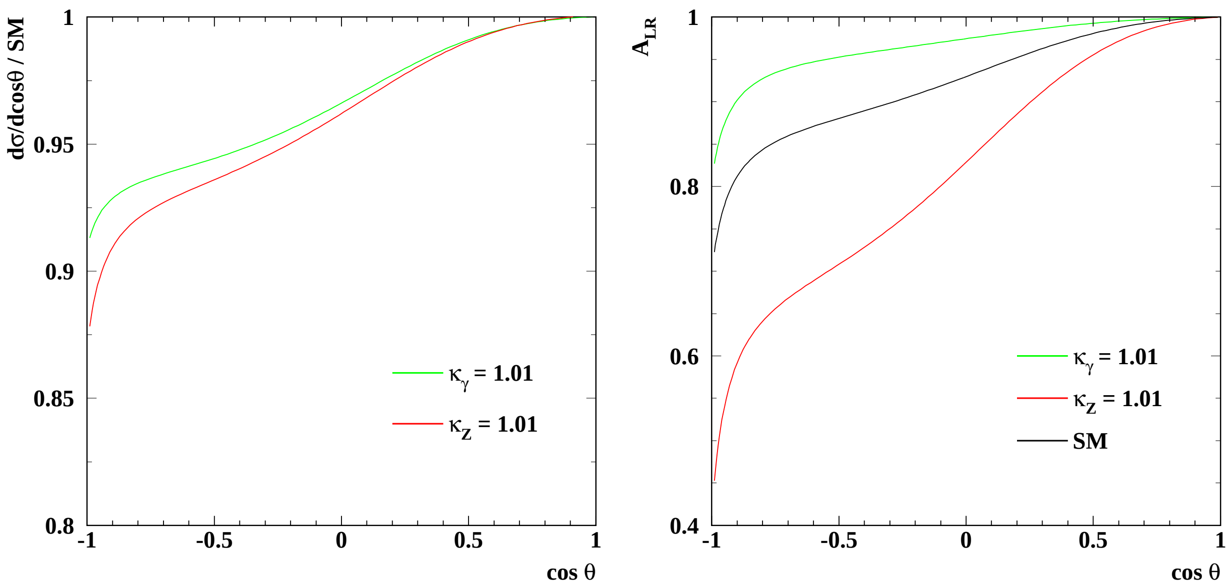
- g_1, κ, λ C,P-conserving
- g_5 C,P-violating, CP-conserving
- g_4, $\tilde{\kappa}$, $\tilde{\lambda}$ CP-violating

Up to now C,P-conserving couplings mainly studied

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

With unpolarized beams W-pair production measures a mixture of ZWW and γWW-couplings

However beam polarization can separate the two



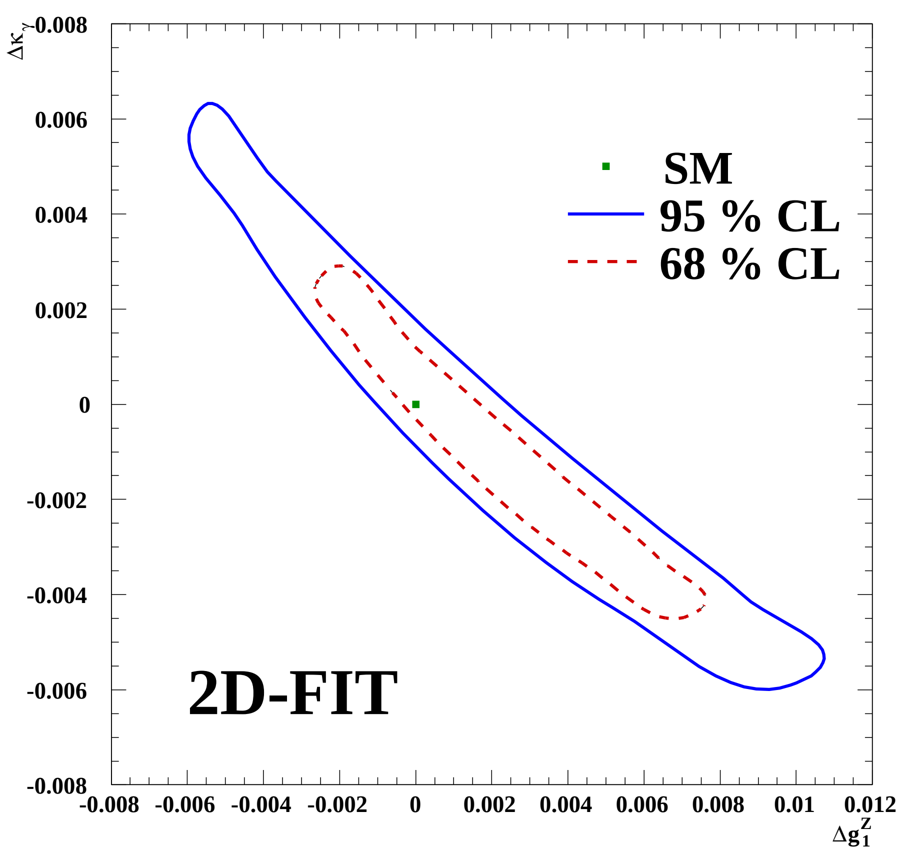
- Undocumented results from W-pairs (Burgard, Petzold) exist since long
- New results start to arrive (W. Menges)
  - old results seem confirmed
  - detector, beamstrahlung seems no problem
  - radiative corrections needed to $< 1\%$
  - first priority: understand polarization systematics
- Analysis on single Ws has started (S. Roth)
- No quantitative results on $\gamma\gamma \to W^+W^- \Rightarrow$ only some qualitative statements in TDR

Results for $\mathcal{L} = 500\,\mathrm{fb}^{-1}$, without polarization:

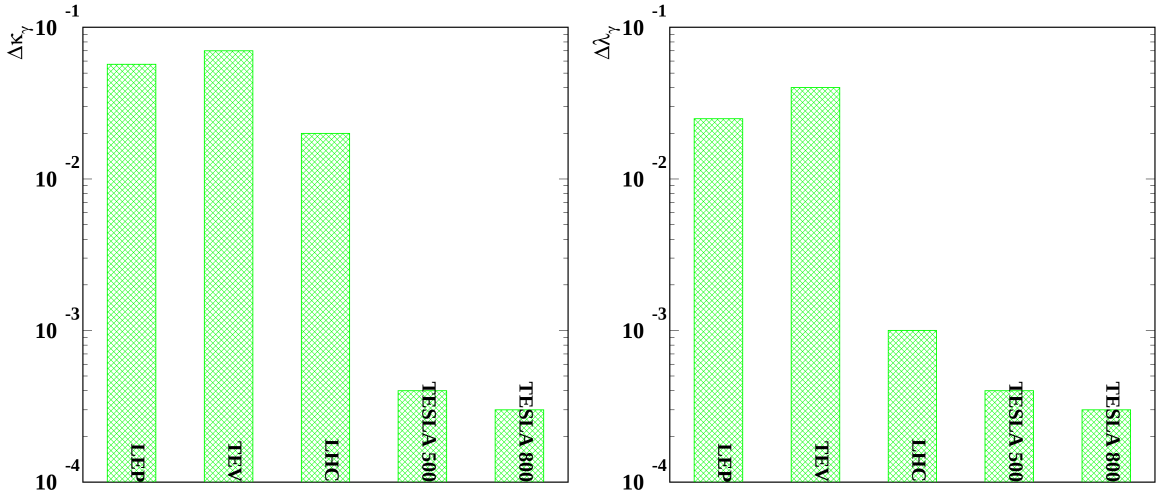
expected errors (10^{-4}) for 1d fits:

		500 GeV	1000 GeV
$CP(3)$	Δg_1^Z	7.3	6.2
	$\Delta\kappa_\gamma$	5.7	4.2
	λ_γ	6.1	3.4
$\not{C}, \not{P}, CP$	g_5^Z	27.7	41.4
$\not{CP}$	g_4^Z	85.8	40.1
	$\tilde{\kappa}_Z$	64.9	30.5
	$\tilde{\lambda}_Z$	11.4	5.3

2D $\Delta g_1^Z - \Delta\kappa_\gamma$ fit

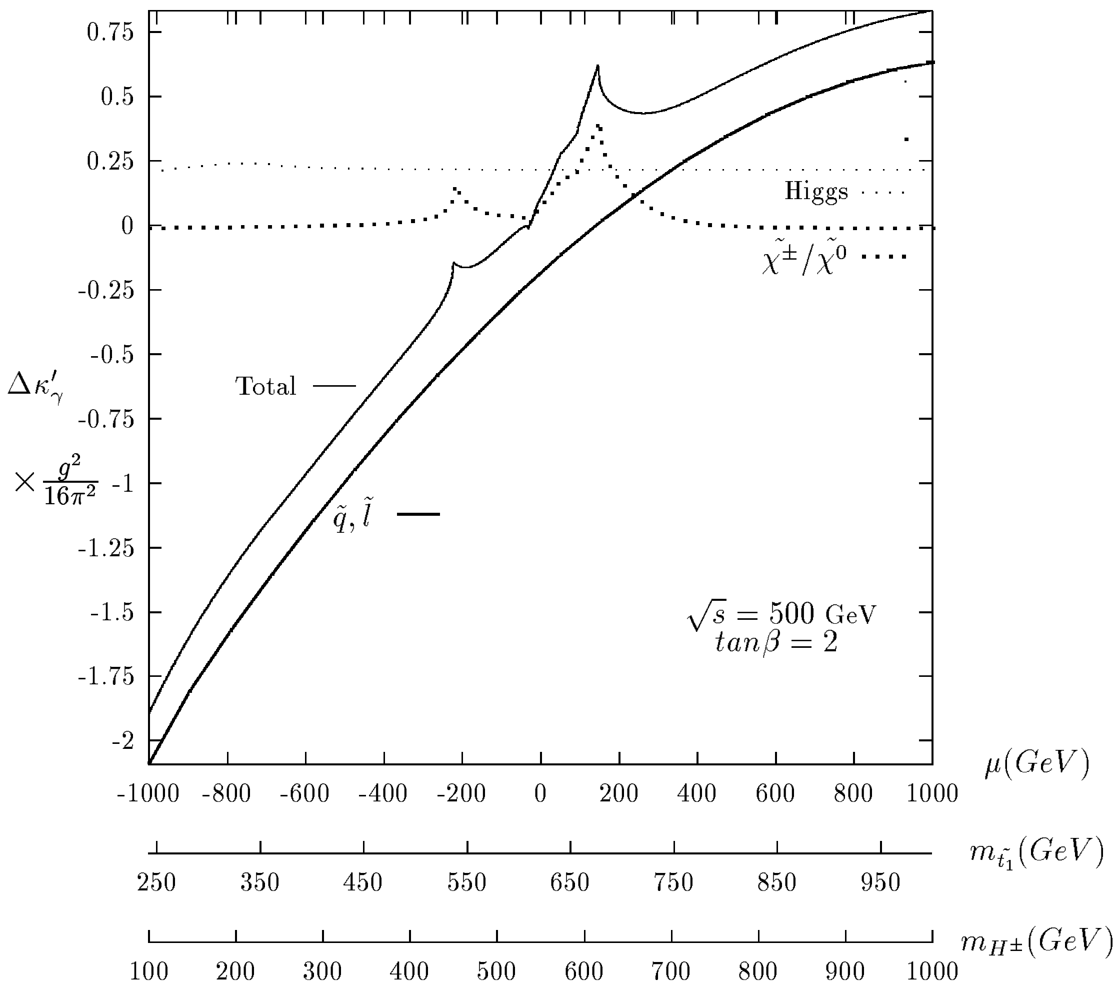


Comparison with LHC

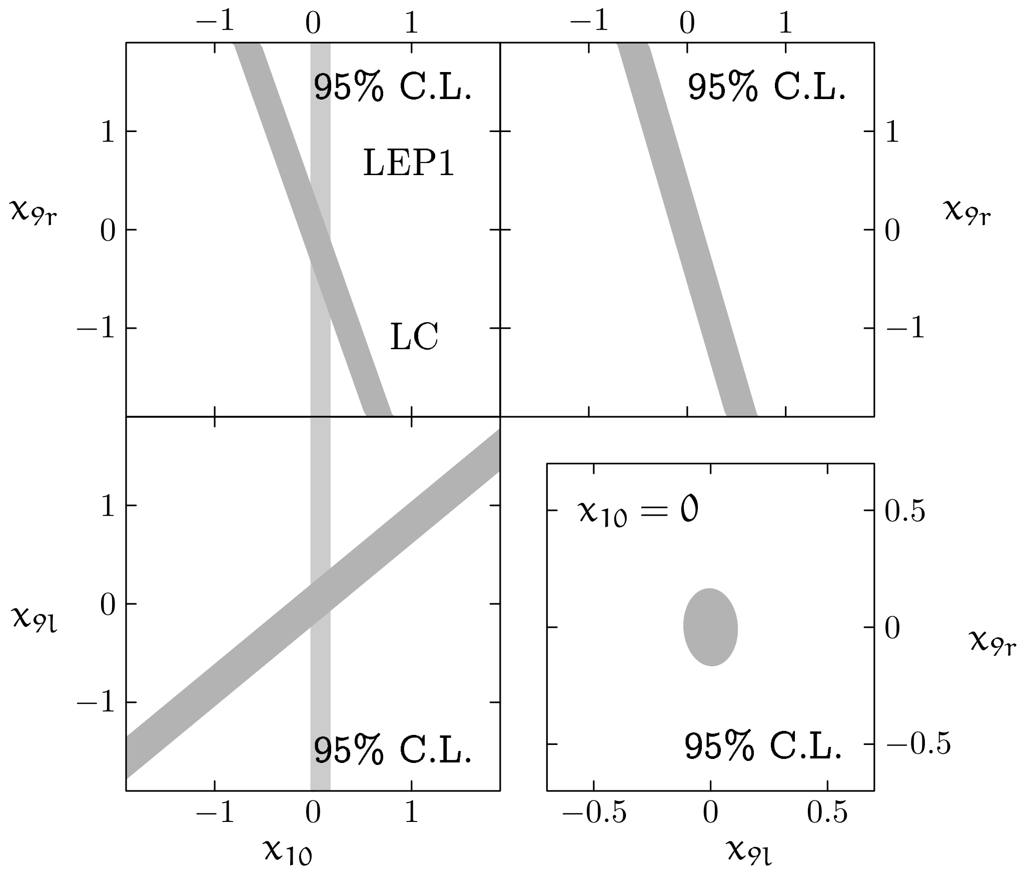


Especially for κ large advantage for TESLA

The precision is e.g. good enough to see MSSM loop contributions



Triple gauge couplings expressed in terms of x_9, x_{10} from high energy effective Lagrangian



expect new couplings to be of $\mathcal{O}(1)$

Multiple gauge boson production

- Three gauge boson production will be visible at TESLA
- Cross section $\mathcal{O}(10 fb)$ for WWZ and $\mathcal{O}(1 fb)$ for ZZZ
- Both processes have maximum around 500 GeV
- Several anomalous coupling parameters that are not visible elsewhere can be measured to the 0.1 level

Two ways to access CKM matrix

- study of hadronic W decays
- study of b-decays at Giga-Z

CKM matrix elements in hadronic Z decays

- in principle can measure absolute values of all elements $|V_{ij}|$ with $i = u, c,\ j = d, s, b$ in W decays when all flavors can be tagged
- can measure without CKM-unitarity by normalizing to the leptonic W decays or with CKM-unitarity
- analysis of W-pairs with mixed decays and single Ws
- flavor tagging:
  - b,c-tagging in usual way with microvertex
  - u,d,s tagging with leading hadrons (mainly K, π)
  - tagging efficiencies can be calibrated on the Z
  - only assumption is the small extrapolation of fragmentation from the Z-scale to the W-scale

- uncertainties are dominantly experimental in this approach
- Results

  without CKM-unitarity:

  – $|V_{ui}|$ not competitive with PDG value

  – $|V_{cd}|, |V_{cb}|$ about factor two better

  – $|V_{cs}|$ about factor 70 better

  with CKM unitarity:

  – $|V_{cb}|$ stays completive with the expectation of BaBar, however with completely different error sources

  – other elements are worse than PDG value

B-physics at Giga-Z

Available statistics: 10^8 B-hadrons

Comparison with e^+e^--B-factories

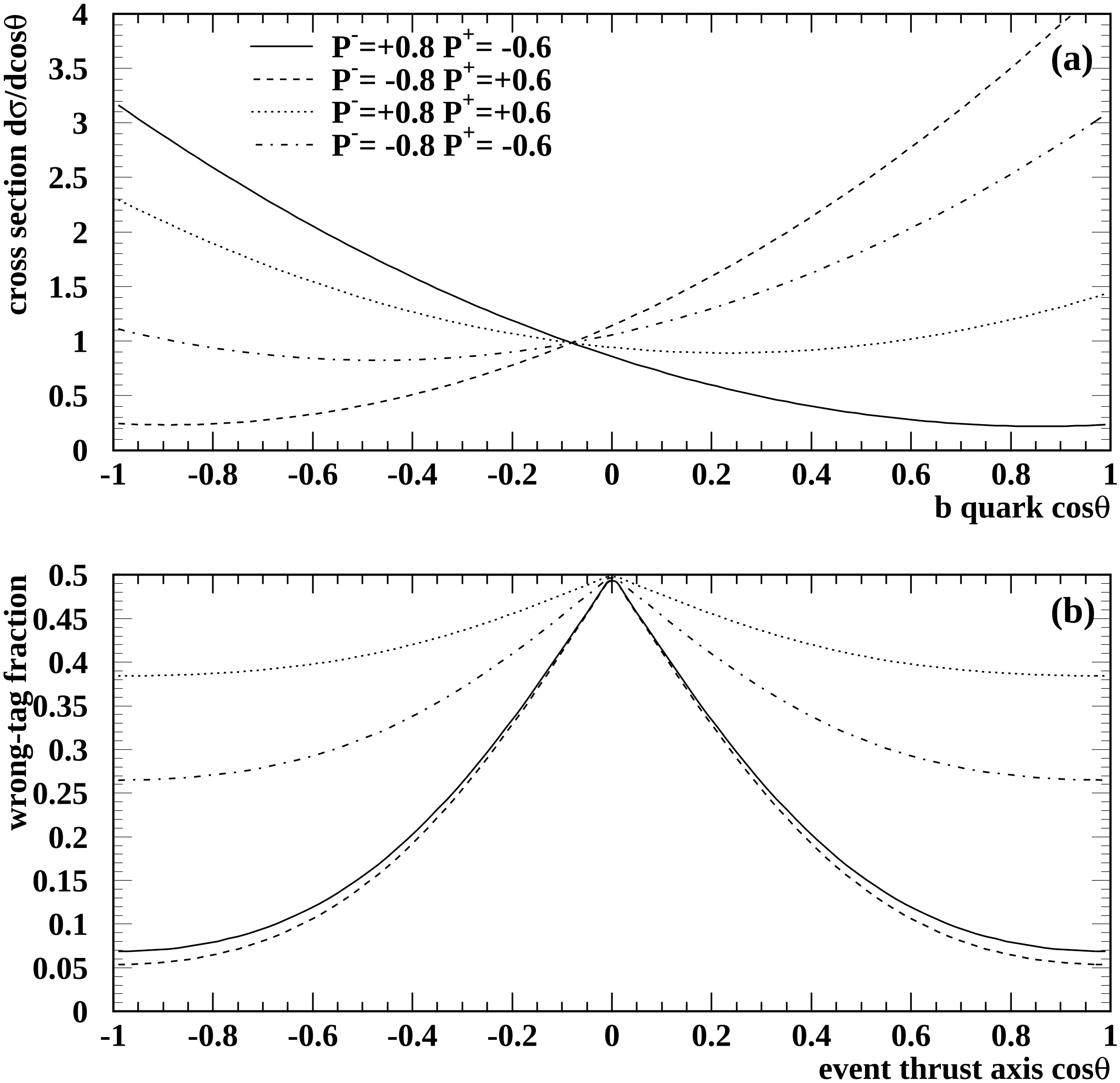
- comparable statistics
- large boost allows separation of the two Bs
- large boost gives much better decay length resolution
- also B_s and Λ_b produced
- large A_{FB} with polarized beams gives very good initial state charge tagging

Comparison with LHCb,B-TeV

- much lower statistics
- however all Bs are triggered and can be reconstructed
- much cleaner environment

Up to now no Giga-Z specific CP-studies, only repetition of B-factory/LHCb

Primary flavor tagging from B-direction



measure time dependent asymmetries

$$A(t) = \frac{N_{B^0}(t) - N_{\bar{B}^0}(t)}{N_{B^0}(t) + N_{\bar{B}^0}(t)} = a_{\cos} \cos \Delta mt + a_{\sin} \sin \Delta mt$$

mainly two examined decay modes

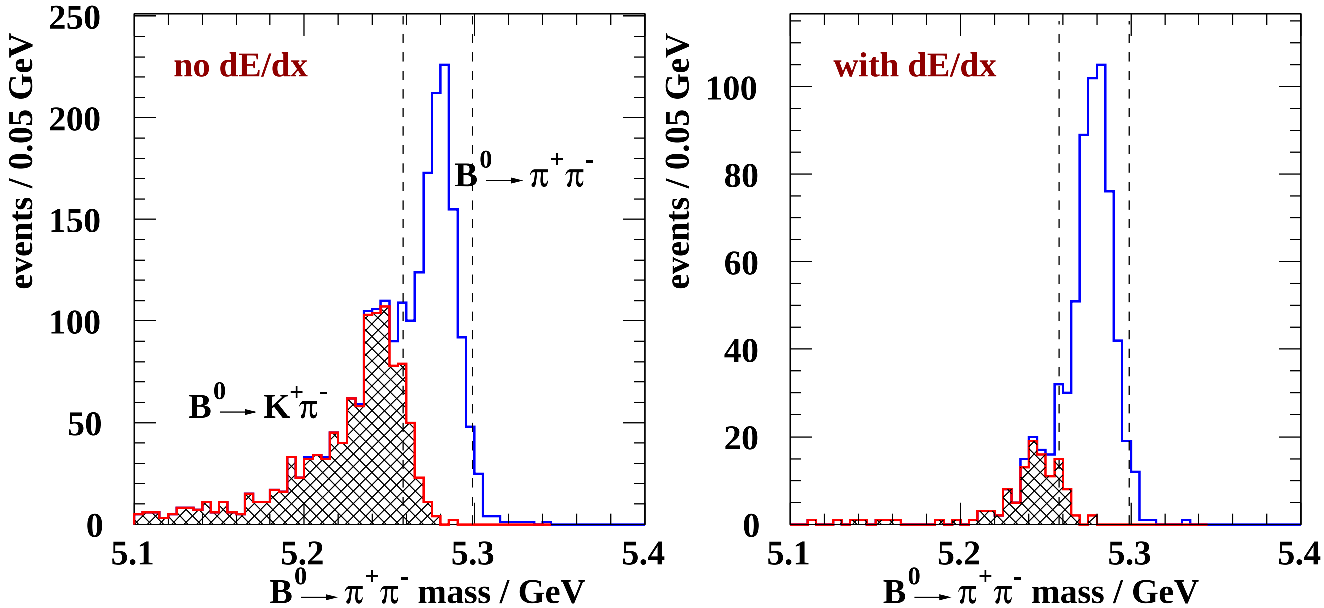
- $B^0 \rightarrow J/\Psi K_s^0$:
  - $a_{\sin} = -\sin 2\beta, \ a_{\cos} = 0$
- $B^0 \rightarrow \pi^+\pi^-$:
  - $a_{\sin} = -\sin 2\alpha, \ a_{\cos} = 0$ if penguin diagrams can be ignored
  - however $a_{\sin}, a_{\cos}$ modified by penguin contributions, hard to calculate
  - can be disentangled by measuring branching ratios $B^0 \rightarrow \pi^+\pi^-$, $B^0 \rightarrow \pi^0\pi^0$, $B^+ \rightarrow \pi^+\pi^0$

Experimental analysis:

- identify initial state b-charge
- reconstruct decay mode
- measure eigentime to decay (easy in LC environment with fully reconstructed decays)

Final state identification:

- Missing particle ID can be replaced by excellent momentum resolution



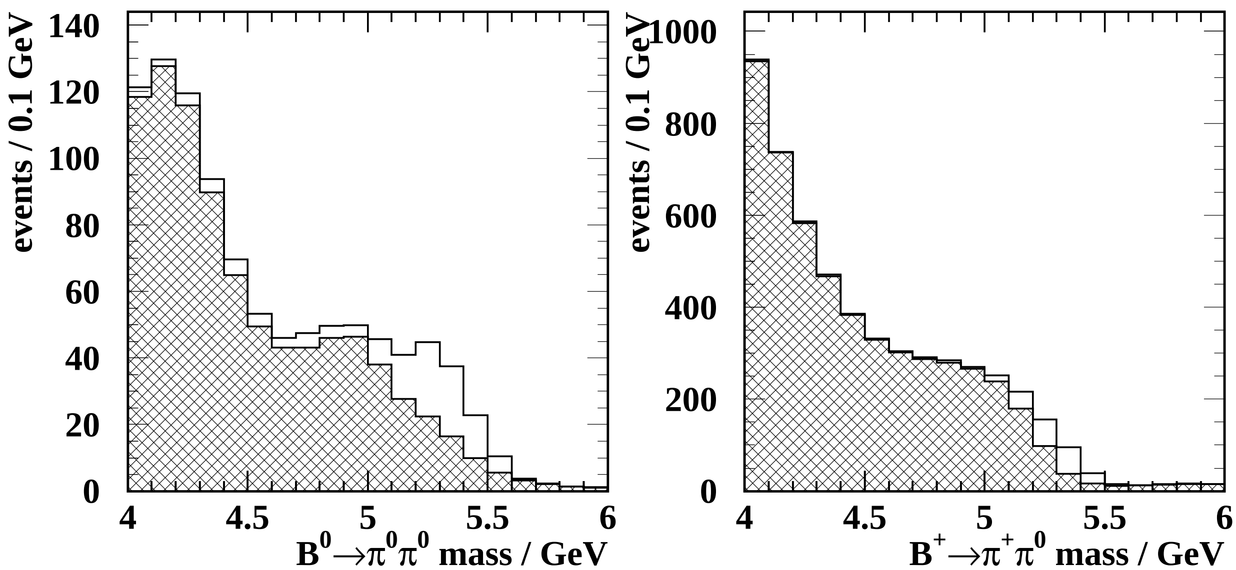
Results

	$\sin 2\beta$	"$\sin 2\alpha$"
BaBar	0.12	0.26
CDF	0.08	0.10
ATLAS	0.02	0.14
LHC-b	0.01	0.05
TESLA	0.04	0.07

Not the best, but interesting cross check!

Branching ratios $B^0 \to \pi^0\pi^0$, $B^+ \to \pi^+\pi^0$

- needed to disentangle direct from penguin contributions in $B^0 \to \pi^+\pi^-$
- only possible in e$^+$e$^-$-machines
- can be done at LC with good calorimetry and good b-tagging/anti-b-tagging



- Competitive results to BaBar can be obtained

Other b-physics topics

- Some rare b-decays might be accessible at TESLA (e.g. $b \to s\nu\nu$)
- tests of quark hadron duality (e.g. V_{cb} in B_s)

Conclusions

- Interesting gauge boson physics is guaranteed at TESLA
- With Giga-Z the consistency of the model can be tested about an order of magnitude better than at LEP/SLD
- Triple gauge couplings offer a window into new physics, especially if the Higgs is NOT there
- In addition TESLA offers some alternatives to understand the CKM matrix
- In summary gauge boson physics adds significantly to the motivation of TESLA