From Polarimetry to Anomalous Triple Gauge Couplings A Precision Study at the ILC

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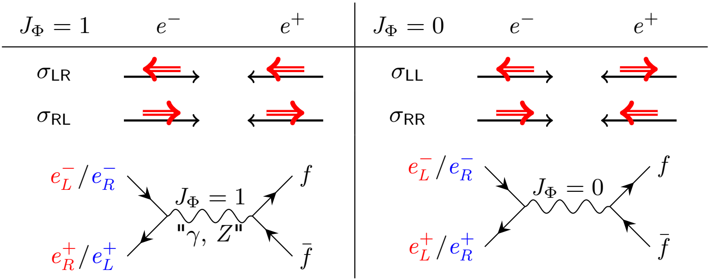
Outline

Polarization at a $e^- e^+$ Collider

- Helicity is the projection of the spin vector on the direction of motion
- In case of massless particles, helicity is equal to chirality
- If $E_{\text{kin}} \gg E_0 \quad \longrightarrow \quad m_e \approx 0$



- For a bunch of particles the polarization is defined as:

$$P := \frac{N_R - N_L}{N_R + N_L}$$

Beam Polarization Dependent Cross Section

- Theoretical polarized cross section in general:

$$\sigma_{\text{theory}}\left(P_{e^-}, P_{e^+}\right) = \frac{\left(1-P_{e^-}\right)}{2}\frac{\left(1-P_{e^+}\right)}{2}\cdot\sigma_{\text{LL}} + \frac{\left(1+P_{e^-}\right)}{2}\frac{\left(1+P_{e^+}\right)}{2}\cdot\sigma_{\text{RR}}$$
$$+\frac{\left(1-P_{e^-}\right)}{2}\frac{\left(1+P_{e^+}\right)}{2}\cdot\sigma_{\text{LR}} + \frac{\left(1+P_{e^-}\right)}{2}\frac{\left(1-P_{e^+}\right)}{2}\cdot\sigma_{\text{RL}}$$

- Nominal ILC Polarization values

$$\underbrace{P_{e^-}^- = -80\%,}_{\text{"left"-handed } e^-\text{-beam}} \quad \underbrace{P_{e^-}^+ = 80\%,}_{\text{"right"-handed } e^-\text{-beam}} \quad \underbrace{P_{e^+}^- = -30\%,}_{\text{"left"-handed } e^+\text{-beam}} \quad \underbrace{P_{e^+}^+ = 30\%,}_{\text{"right"-handed } e^+\text{-beam}}$$

- Cross section of the 4 polarization configurations

$$\sigma_{--} := \sigma\left(P_{e^-}^-, P_{e^+}^-\right) \qquad \sigma_{++} := \sigma\left(P_{e^-}^+, P_{e^+}^+\right)$$
$$\sigma_{-+} := \sigma\left(P_{e^-}^-, P_{e^+}^+\right) \qquad \sigma_{+-} := \sigma\left(P_{e^-}^+, P_{e^+}^-\right)$$

- σ_{LL}, σ_{RR}, σ_{LR}, σ_{RL} calculated by WHIZARD including ISR and beam spectrum

Polarized Cross Section Measurement

- Measured polarized cross section:

$$\sigma_{\text{data}} = \frac{D - \mathfrak{B}}{\varepsilon \cdot \mathcal{L}}$$

D:	Number of signal events	$\mathfrak{B}$:	Background expectation value
ε:	Detector selection efficiency	$\mathcal{L}$:	Integrated luminosity

Remark:
All of them can variate between the different data sets $(\sigma_{-+},\ \sigma_{+-},\ \sigma_{--},\ \sigma_{++})$

- Uncertainty of the polarized cross section calculated via error propagation

$$\text{e.g.}\quad (\Xi_{\mathcal{L}})_{ij} = \text{corr}\left(\sigma_i^{\mathcal{L}},\ \sigma_j^{\mathcal{L}}\right) \frac{\partial \sigma_i}{\partial \mathcal{L}_i} \frac{\partial \sigma_j}{\partial \mathcal{L}_j} \Delta\mathcal{L}_i \Delta\mathcal{L}_j \qquad i,j \in \{-+,+-,--,++\}$$

$$\Xi := \underbrace{\Xi_D}_{\text{statistical uncertainty}} + \underbrace{\Xi_{\mathfrak{B}} + \Xi_{\varepsilon} + \Xi_{\mathcal{L}}}_{\text{systematic uncertainty}};$$

Remark:
Statistical uncertainty is always uncorrelated: corr $\left(\sigma_i^D,\ \sigma_j^D\right) \equiv \delta_{ij}$
And it is determined by Poisson fluctuations:
$\Delta D \equiv \sqrt{D}$

Fit Procedure

- **Consider the 4 ILC polarization as independent:**

$$\underbrace{P^{-}_{e^-} = -80\%,}_{\text{"left"-handed } e^- \text{-beam}} \quad \underbrace{P^{+}_{e^-} = 80\%,}_{\text{"right"-handed } e^- \text{-beam}} \quad \underbrace{P^{-}_{e^+} = -30\%,}_{\text{"left"-handed } e^+ \text{-beam}} \quad \underbrace{P^{+}_{e^+} = 30\%,}_{\text{"right"-handed } e^+ \text{-beam}}$$

- **Using the method of least squares:**

$$\chi^2 = \sum_{\text{process}} \left(\vec{\sigma}_{\text{data}} - \vec{\sigma}_{\text{theory}}\right)^T \Xi^{-1} \left(\vec{\sigma}_{\text{data}} - \vec{\sigma}_{\text{theory}}\right);$$

$$\vec{\sigma} := \begin{pmatrix} \sigma_{-+} & \sigma_{+-} & \sigma_{--} & \sigma_{++} \end{pmatrix}^T$$

Process	Channel
single $W^{\pm}$	$e\nu l\nu,\ e\nu q\bar{q}$
WW	$q\bar{q}q\bar{q},\ q\bar{q}l\nu,\ l\nu l\nu$
ZZ	$q\bar{q}q\bar{q},\ q\bar{q}ll,\ llll$
$ZZWW$Mix	$q\bar{q}q\bar{q},\ l\nu l\nu$
Z	$q\bar{q},\ ll$

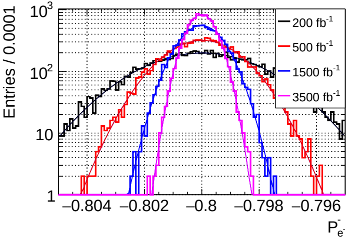
- **Determine the polarization:**
  - Find $P^{-}_{e^-}$, $P^{+}_{e^-}$, $P^{-}_{e^+}$, $P^{+}_{e^+}$ that minimizes χ^2
  - Parameter uncertainties provides also the polarization uncertainties:

    $\Delta P^{-}_{e^-}$, $\Delta P^{+}_{e^-}$, $\Delta P^{-}_{e^+}$, $\Delta P^{+}_{e^+}$

Toy Monte Carlo

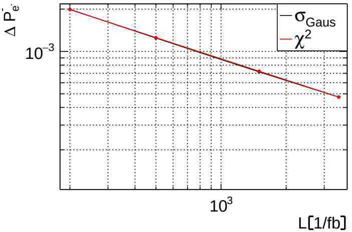
Toy measurement:

- Signal expectation value:
  $\langle D \rangle = \sigma_{\text{theory}} \cdot \varepsilon \cdot \mathcal{L} + \mathfrak{B}$
- One toy experiment:
  Random Poisson number around each $\langle D \rangle$
- Determine $P_{e^\pm}^{\pm}$ for each toy experiment
- Simplified case for illustration:
  - $\mathfrak{B} = 0$ and $\varepsilon = 1$
  - Statistical uncertainties only
  - Using 10^4 toy measruements

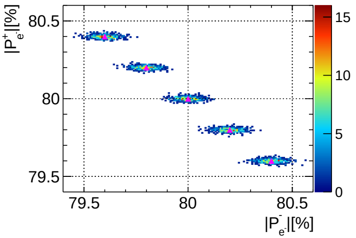


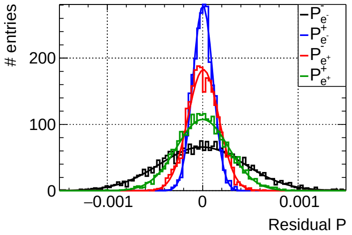
Polarization uncertainty:

- Gaussian fit of toy measurement distribution
- Perfect match between Gaussian width and polarization error



Testing for a Non-Perfect Helicity Reversal





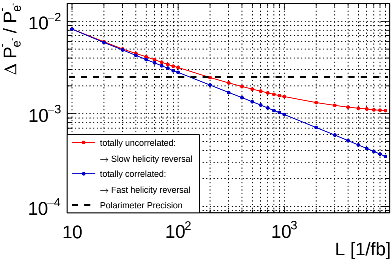
- **Variation in the absolute polarization**
  - Toy Measurement for 5 different polarization discrepancies for both beams (magenta triangle)
  - Nominal initial polarizations: $|P_{e-}| = 80\%$, $|P_{e+}| = 30\%$
  - Statistical uncertainties only
- **χ^2-minimization:**
  - No difference between the residuals:
    - with equal absolute values (solid lines) and
    - without equal absolute values (histograms)
  - Correct determination of the 4 polarization values

✓ **Can compensate for a non-perfect helicity reversal**

Systematic Uncertainties and their Correlations

- **Systematic Uncertainties are inter alia influenced by**
  - Detector calibration and alignment
  - Machine performance
  - ⇒ Time dependent uncertainties
- **Example:**

$$\Delta\varepsilon/\varepsilon = 0.5\%; \quad \varepsilon = 0.8;$$
$$\Delta\mathcal{L}/\mathcal{L} = 1 \cdot 10^{-4}$$



- **Data set are taken one at a time:**
  - Slow frequency of helicity reversals: $\mathcal{O}$ (weeks to months)
  - Data sets are independent
  - → Completely uncorrelated
  - ✘ Lead to saturation at systematic precision
- **Data sets taken concurrently:**
  - Fast frequency of helicity reversals: $\mathcal{O}$ (train-by-train)
  - → Faster than changes in calibration/alignment
  - → Generate correlations
  - ✓ Lead to cancellation of systematic uncertainties

Consideration of the Addition Information from the Angular Distribution

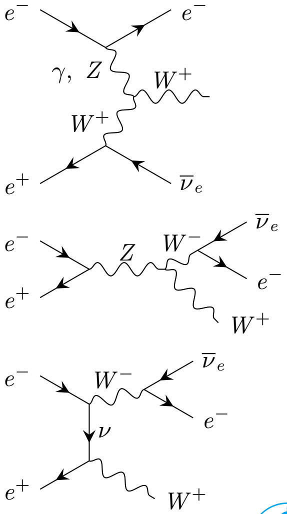
- Total cross section
  - Rely on theoretical calculation
  - ⇒ Susceptible to BSM effects
- Differential cross section
  - Additional usage of the angular information
  - ⇒ Increase of the robustness against BSM effects
- Currently implemented processes for differential cross section

Process	Channel
single $W^{\pm}$	$e\nu l\nu,\ e\nu q\bar{q}$
WW	$q\bar{q}q\bar{q},\ q\bar{q}l\nu,\ l\nu l\nu$
Z	$q\bar{q},\ ll$

- The other processes used with total cross section

⇒ This can easily be changed!

e.g.: $e^+e^- \rightarrow e^-\bar{\nu}_e W^+$

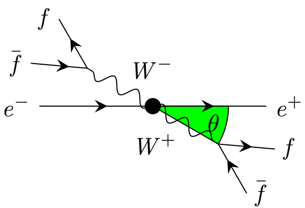


Usage of the Differential Polarized Cross Section

Choice of the angle:

- ✓ Individual for each process and channel
- ✓ High dependence of the angular distribution on the chiral structure
- ✘ Angle has to be well measurable
  $\rightarrow$ Not jet verified for all processes

e.g.: $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}l\nu$



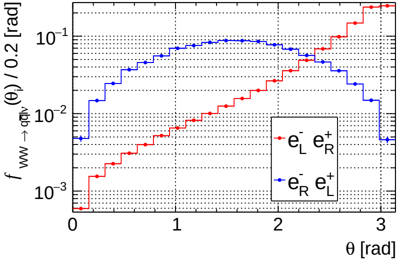
Bin-wise cross section calculation:

$$\overbrace{\partial\sigma/\partial\theta}^{\text{differential cross section}} \rightarrow \overbrace{\delta_i\sigma_{\text{data}}}^{\text{cross section of the } i\text{-th bin}} := \delta_i N/\mathcal{L}$$

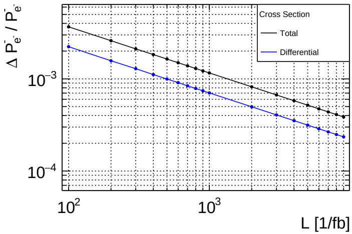
$$\rightarrow \delta_i\sigma_{LR} := f_{LR}(\theta_i)\cdot\sigma_{LR}$$

Analog: RL, LL, RR

- $\delta_i N = (\delta_i D - \delta_i \mathfrak{B})/\delta_i\varepsilon$:
  events of i-th bin
- $f(\theta_i)$: fraction of the total cross section



Statistical Results with Differential Cross Section



Using the following configuration:

- Using 20 equal bins in a θ range of $[0,\ \pi]$
- Signal determination bin-by-bin:
  $\langle \delta_k D \rangle = \delta_k \sigma_{\text{theory}} \cdot \delta_k \varepsilon \cdot \mathcal{L} + \delta_k \mathfrak{B}$
- For the start:
  Statistical error only + no background
- Using H-20 integrated luminosity sharing due to energy

- Differential cross section have a lower statistic uncertainty:
  - Expectation of $\delta_k D$ can be for some bins $\mathcal{O}(1)$
  - Some zero diagonal entries of the covariance matrix $\rightarrow$ not invertible
  - $\Rightarrow$ Dropping χ^2-terms with $\delta_k D = 0$
- Further steps:
  - Implementing differential cross section for all processes
  - Implementing multi-differential cross section
    (only implemented for $e^+e^- \rightarrow q\bar{q}\mu\nu$)

Simultaneous Chiral Cross Section measurement

- Define the ratio R between the "actual" cross section σ_{actual} and the SM cross section σ_{SM}

$$R(\vec{x}) := \frac{\sigma_{\text{actual}}}{\sigma_{\text{SM}}}$$

- In general R can be parameterized by an arbitrary set of parameters $\vec{x}$

$$\begin{aligned}\delta_i\sigma^{\text{theory}}(P_{e^-}, P_{e^+}, \vec{x}) = & \frac{(1-P_{e^-})}{2}\frac{(1+P_{e^+})}{2} \cdot R_{\text{LR}}(\vec{x}) \cdot \delta_i\sigma_{\text{LR}} \\ & + \frac{(1+P_{e^-})}{2}\frac{(1-P_{e^+})}{2} \cdot R_{\text{RL}}(\vec{x}) \cdot \delta_i\sigma_{\text{RL}} \\ & + \frac{(1-P_{e^-})}{2}\frac{(1-P_{e^+})}{2} \cdot R_{\text{LL}}(\vec{x}) \cdot \delta_i\sigma_{\text{LL}} \\ & + \frac{(1+P_{e^-})}{2}\frac{(1+P_{e^+})}{2} \cdot R_{\text{RR}}(\vec{x}) \cdot \delta_i\sigma_{\text{RR}}\end{aligned}$$

- Introducing Pseudo Nuisance Parameters for cross section measurement
  - Unpolarized Cross section scaling α:

$$\sigma_0 \quad \longrightarrow \quad \alpha \cdot \sigma_0 = 0.25 \cdot (\alpha \cdot \sigma_{\text{LR}} + \alpha \cdot \sigma_{\text{RL}} + \alpha \cdot \sigma_{\text{LL}} + \alpha \cdot \sigma_{\text{RR}}) \qquad \alpha \in \mathbb{R}^+$$

  - Asymmetry discrepancy β

$$A \quad \longrightarrow \quad A + \beta$$

Implementing the *Pseudo Nuisance Parameters* α, β

- The ratio R is defined as multiplicative quantity: $R\left(\alpha,\beta\right) = R\left(\alpha\right) \cdot R\left(\beta\right)$

- Calculation of $R\left(\alpha\right)$

$$R_{\text{LR}}\left(\vec{x}\right) \equiv R_{\text{RL}}\left(\vec{x}\right) \equiv R_{\text{LL}}\left(\vec{x}\right) \equiv R_{\text{RR}}\left(\vec{x}\right) \equiv \alpha$$

- Calculation of $R\left(\beta\right)$, e.g. for $A_{\text{RL}}^{\text{LR}}$, analog for other asymmetries

$$R_{\text{LR}}\left(\beta\right) := 1 + 0.5 \cdot \frac{\sigma_{\text{LR}}+\sigma_{\text{RL}}}{\sigma_{\text{LR}}} \cdot \beta \qquad R_{\text{RL}}\left(\beta\right) := 1 - 0.5 \cdot \frac{\sigma_{\text{LR}}+\sigma_{\text{RL}}}{\sigma_{\text{RL}}} \cdot \beta$$

- Theoretical cross section calculation:

$$\begin{aligned}\delta_i\sigma^{\text{theory}}\left(P_{e^-},P_{e^+},\alpha,\beta\right) = &\frac{\left(1-P_{e^-}\right)}{2}\frac{\left(1+P_{e^+}\right)}{2}\cdot\alpha\cdot\left(1+0.5\cdot\frac{\sigma_{\text{LR}}+\sigma_{\text{RL}}}{\sigma_{\text{LR}}}\cdot\beta\right)\cdot\delta_i\sigma_{\text{LR}}\\ &+\frac{\left(1+P_{e^-}\right)}{2}\frac{\left(1-P_{e^+}\right)}{2}\cdot\alpha\cdot\left(1-0.5\cdot\frac{\sigma_{\text{LR}}+\sigma_{\text{RL}}}{\sigma_{\text{RL}}}\cdot\beta\right)\cdot\delta_i\sigma_{\text{RL}}\\ &+\frac{\left(1-P_{e^-}\right)}{2}\frac{\left(1-P_{e^+}\right)}{2}\cdot\alpha\cdot\delta_i\sigma_{\text{LL}}+\frac{\left(1+P_{e^-}\right)}{2}\frac{\left(1+P_{e^+}\right)}{2}\cdot\alpha\cdot\delta_i\sigma_{\text{RR}}\end{aligned}$$

- **Remark:** For each process and channel one α and β will be introduced

Polarization, Scaling Parameters α And Asymmetry Deviation β Combined

Results for statistical uncertainties only

χ^2 / NDF	727.42 / 708				
Parameter	Actual Value	Fit Value	Parameter	Actual Value	Fit Value
$P^-_{e^-}$ [%]	-80	-80.1 ± 0.038	$P^-_{e^+}$ [%]	-30	-30 ± 0.032
$P^+_{e^-}$ [%]	80	80 ± 0.013	$P^+_{e^+}$ [%]	30	30 ± 0.043
$\alpha_{W^+(e\nu l\nu)}$	0.8	0.8 ± 0.001	$\beta_{W^+(e\nu l\nu)}$	0	$(6.4 \pm 7) \cdot 10^{-4}$
$\alpha_{W^-(e\nu l\nu)}$	1.1	1.1 ± 0.0012	$\beta_{W^-(e\nu l\nu)}$	0	$(8.7 \pm 12) \cdot 10^{-4}$
$\alpha_{W^+(e\nu q\bar{q})}$	0.79	0.79 ± 0.00066	$\beta_{W^+(e\nu q\bar{q})}$	0	$(1.9 \pm 4.1) \cdot 10^{-4}$
$\alpha_{W^-(e\nu q\bar{q})}$	1.2	1.198 ± 0.00087	$\beta_{W^-(e\nu q\bar{q})}$	0	$(-4.6 \pm 7) \cdot 10^{-4}$
$\alpha_{WW(q\bar{q}q\bar{q})}$	1.2	1.2 ± 0.00069	$\beta_{WW(q\bar{q}q\bar{q})}$	0	$(-4.1 \pm 15) \cdot 10^{-5}$
$\alpha_{WW(l\nu l\nu)}$	0.78	0.78 ± 0.0011	$\beta_{WW(l\nu l\nu)}$	0	$(1 \pm 0.55) \cdot 10^{-3}$
$\alpha_{WW(l\nu q\bar{q})}$	0.9	0.9 ± 0.00052	$\beta_{WW(l\nu q\bar{q})}$	0	$(-2.8 \pm 1.5) \cdot 10^{-4}$
$\alpha_{ZZ(q\bar{q}q\bar{q})}$	1.1	1.1 ± 0.0011	$\beta_{ZZ(q\bar{q}q\bar{q})}$	0	$(5.1 \pm 120) \cdot 10^{-5}$
$\alpha_{ZZ(llll)}$	0.91	0.91 ± 0.0027	$\beta_{ZZ(llll)}$	0	-0.011 ± 0.0036
$\alpha_{ZZ(llq\bar{q})}$	1	0.999 ± 0.00098	$\beta_{ZZ(llq\bar{q})}$	0	$(-2.7 \pm 12) \cdot 10^{-4}$
$\alpha_{ZZWW(q\bar{q}q\bar{q})}$	0.93	0.93 ± 0.00058	$\beta_{ZZWW(q\bar{q}q\bar{q})}$	0	$(1.2 \pm 3) \cdot 10^{-4}$
$\alpha_{ZZWW(l\nu l\nu)}$	0.82	0.82 ± 0.0011	$\beta_{ZZWW(l\nu l\nu)}$	0	$(-2.1 \pm 0.89) \cdot 10^{-3}$
$\alpha_{Z(q\bar{q})}$	0.79	0.79 ± 0.00014	$\beta_{Z(q\bar{q})}$	0	$(-2.9 \pm 3.6) \cdot 10^{-4}$
$\alpha_{Z(l^+l^-)}$	0.88	0.88 ± 0.00022	$\beta_{Z(l^+l^-)}$	0	$(-2.8 \pm 4.6) \cdot 10^{-4}$

Polarization, Scaling Parameters α And Asymmetry Deviation β Combined

Results for statistical uncertainties only

χ^2 / NDF	727.42 / 708				
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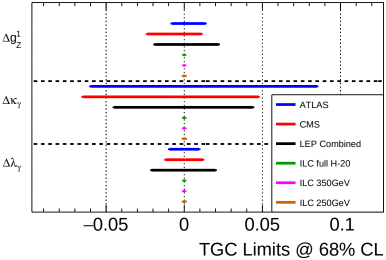
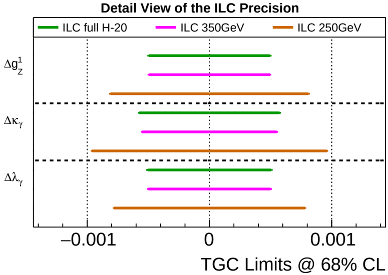
$\alpha_{W^+}(e\nu q\bar{q})$	[illegible]	[illegible]	[illegible]	[illegible]	$\ldots 10^{-4}$
$\alpha_{W^-}(e\nu q\bar{q})$	[illegible]	[illegible]	[illegible]	[illegible]	$\ldots 10^{-4}$
$\alpha_{WW}(q\bar{q}q\bar{q})$	[illegible]	[illegible]	[illegible]	[illegible]	$\ldots 10^{-5}$
$\alpha_{WW}(l\nu l\nu)$	[illegible]	[illegible]	[illegible]	[illegible]	$\ldots 10^{-3}$
$\alpha_{WW}(l\nu q\bar{q})$	[illegible]	[illegible]	[illegible]	[illegible]	$\ldots 10^{-4}$
$\alpha_{ZZ}(q\bar{q}q\bar{q})$	[illegible]	[illegible]	[illegible]	[illegible]	$\ldots 10^{-5}$
$\alpha_{ZZ}(llll)$	[illegible]	[illegible]	[illegible]	[illegible]	…036
$\alpha_{ZZ}(llq\bar{q})$	1	0.999 ± 0.00098	$\beta_{ZZ}(llq\bar{q})$	0	$(-2.7 \pm 12) \cdot 10^{-4}$
$\alpha_{ZZWW}(q\bar{q}q\bar{q})$	0.93	0.93 ± 0.00058	$\beta_{ZZWW}(q\bar{q}q\bar{q})$	0	$(1.2 \pm 3) \cdot 10^{-4}$
$\alpha_{ZZWW}(l\nu l\nu)$	0.82	0.82 ± 0.0011	$\beta_{ZZWW}(l\nu l\nu)$	0	$(-2.1 \pm 0.89) \cdot 10^{-3}$
$\alpha_Z(q\bar{q})$	0.79	0.79 ± 0.00014	$\beta_Z(q\bar{q})$	0	$(-2.9 \pm 3.6) \cdot 10^{-4}$
$\alpha_Z(l^+l^-)$	0.88	0.88 ± 0.00022	$\beta_Z(l^+l^-)$	0	$(-2.8 \pm 4.6) \cdot 10^{-4}$

- ✓ Simultaneous fit of the 4 beam polarizations and the 28 pseudo nuisance parameter possible
- ✓ All pseudo nuisance parameter correctly determined
- ✓ No effect on the polarization precision

ILC Extrapolation in Comparison LEP and LHC





ILD full simulation		Extrapolations		
E_{CMS}	500 GeV	250 GeV	350 GeV	H-20
Δg_1^Z	$4.3 \cdot 10^{-4}$	$8.1 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$
$\Delta\kappa_\gamma$	$4.4 \cdot 10^{-4}$	$9.6 \cdot 10^{-4}$	$5.5 \cdot 10^{-4}$	$5.7 \cdot 10^{-4}$
$\Delta\lambda_\gamma$	$4.1 \cdot 10^{-4}$	$7.8 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$

LEP combined from ALEPH, L3 and OPAL [arXiv:1708.08912]
LHC TGC limits for $\sqrt{s} = 8$ TeV data,
$\mathcal{L}_I = 20.3\,\mathrm{fb}^{-1} (19.4\,\mathrm{fb}^{-1})$ for ATLAS (CMS)

Direct Study of TGC Precision at 250 GeV

Determination of the TGC within an Effective Field Theory (EFT):

$$R(\delta g, \delta\kappa, \delta\lambda) = 1 + A \cdot \delta g + B \cdot \delta\kappa + C \cdot \delta\lambda + D \cdot \delta g^2 + E \cdot \delta\kappa^2 + F \cdot \delta\lambda^2 + G \cdot \delta g \cdot \delta\kappa + H \cdot \delta g \cdot \delta\lambda + I \cdot \delta\kappa \cdot \delta\lambda$$

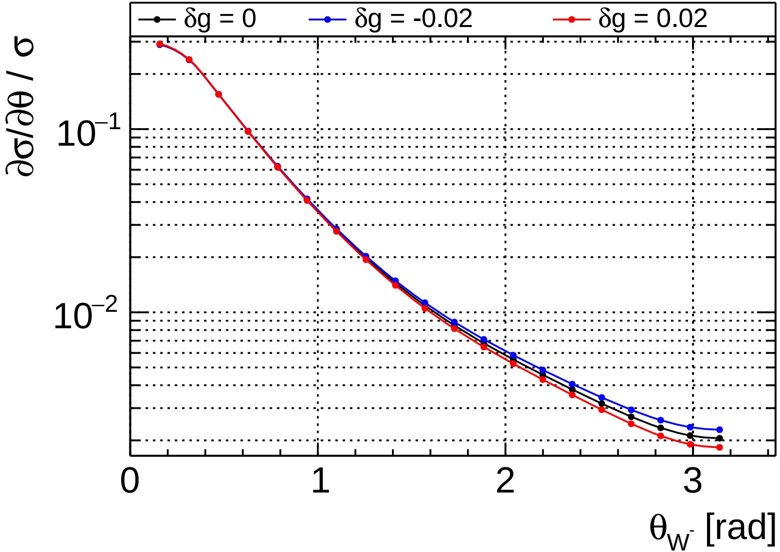
Determination of $A, B, \ldots$ with 9 different MC-Samples (R_0 only for reference):

TGC	R_0	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9
δg	**0**	$+\delta x$	0	0	$-\delta x$	0	0	$+\delta x$	0	$+\delta x$
$\delta\kappa$	0	0	$+\delta x$	0	0	$-\delta x$	0	$+\delta x$	$+\delta x$	0
$\delta\lambda$	0	0	0	$+\delta x$	0	0	$-\delta x$	0	$+\delta x$	$+\delta x$

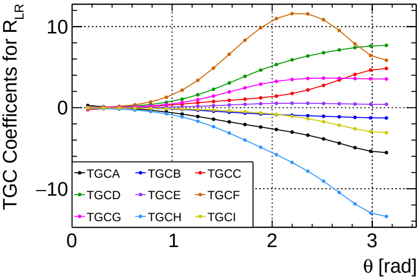
$\delta x > 0$

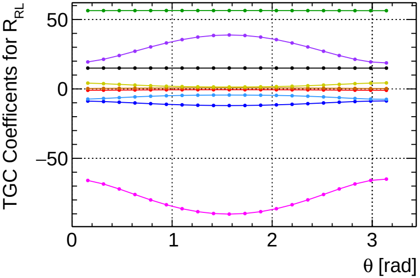
LEP Limit: $\delta x \approx 0.02$

Effect of TGC g_1^Z WW semileptonic $e_L^- e_R^+$ at 250 GeV



TGC Coefficients





- Study the change of the differential cross section for W-pair production in the semileptonic channel
- In this channel using the cross section dependence of
  - Polar angle of the W^- θ_{W-}
  - Polar angle of the charged lepton θ_l^*
  - Azimuth angle of the charged lepton φ_l^*
  - θ_l^* and φ_l^* are measured in the rest-frame of the W
- With a respective binning of $20 \times 10 \times 10$
- Left plots shows the projection of the TGC coefficients on the θ_{W-} axis

First Results for Statistical Precision of the TGC Measurement

Using the following parameter values:

$$\varepsilon = 0.6 \qquad \pi = \frac{D - \mathfrak{B}}{D} = 0.8$$

$$\mathcal{L} = 2\,\mathrm{ab}^{-1} \qquad \Delta\varepsilon = \Delta\pi = \Delta\mathcal{L} = 0$$

Luminosity sharing:

$$(-+ : 45\%, +- : 45\%, -- : 5\%, ++ : 5\%)$$

Used with the following channels:

process	channel	bins	TGC
W-pair	semileptonic	2000	yes
s-channel Z	leptonic	20	no
	hadronic	20	no

Polarization precision in $\left[10^{-3}\right]$

$$\Delta P^{-}_{e^-}/P = 0.89$$

$$\Delta P^{+}_{e^-}/P = 0.37$$

$$\Delta P^{-}_{e^+}/P = 0.99$$

$$\Delta P^{+}_{e^+}/P = 1.5$$

TGC precision in $\left[10^{-4}\right]$

Fit Results:	Theoretical limit*
$\Delta g = 11.9$	$\Delta g = 4.14$
$\Delta\kappa = 14.9$	$\Delta\kappa = 6.22$
$\Delta\lambda = 22.4$	$\Delta\lambda = 3.74$

* Theoretical limit is calculated on MC level with Optimal Observables

Outlook

- Current results are preliminary
  - Still work in progress → Realistic description on systematic uncertainties needed
  - Currently very promising results, but the reference is till the extrapolation

$$\Delta g_1^Z = 8.1 \cdot 10^{-4} \qquad \Delta\kappa_\gamma = 9.6 \cdot 10^{-4} \qquad \Delta\lambda_\gamma = 7.8 \cdot 10^{-4}$$

- Include differential cross sections for more processes for polarization constraint (e.g. Z-pair production)
- Include TGC dependence for more channels:
  - W pair hadronic: $e^+e^- \to q\bar{q}q\bar{q}$
  - single W^+ semileptonic: $e^+e^- \to q\bar{q}e^+\nu$
  - single W^- semileptonic: $e^+e^- \to q\bar{q}e^-\nu$
- Combination with the other nuisance parameters α, β

Conclusion

- **Beam Polarization Determination via Cross Section Measurement**
  - The framework works perfectly
  - Non-perfect helicity reversal, correlations of systematics and angular information are included
- **Electroweak Precision Measurements**
  - Simultaneous measurement of unpolarized cross section, the left-right asymmetry and the beam polarization works perfectly
  - Simultaneous measurement of TGCs is implemented for $e^+e^- \rightarrow q\bar{q}\mu\nu$ channel and the study in ongoing
- **Remarks:**
  - Including the polarimeter information still yields an improvement on the precision, especially for low luminosity runs
  - A test of the framework on "real" data still has to be done

Backup Slides

Coefficient Calculation

$$R\left(\delta g, \delta\kappa, \delta\lambda\right) = 1 + A \cdot \delta g + B \cdot \delta\kappa + C \cdot \delta\lambda + D \cdot \delta g^2 + E \cdot \delta\kappa^2 + F \cdot \delta\lambda^2 + G \cdot \delta g \cdot \delta\kappa + H \cdot \delta g \cdot \delta\lambda + I \cdot \delta\kappa \cdot \delta\lambda$$

$$R_1 = 1 + A \cdot \delta x + D \cdot \delta x^2$$

$$R_2 = 1 + B \cdot \delta x + E \cdot \delta x^2$$

$$R_3 = 1 + C \cdot \delta x + F \cdot \delta x^2$$

$$R_4 = 1 - A \cdot \delta x + D \cdot \delta x^2$$

$$R_5 = 1 - B \cdot \delta x + E \cdot \delta x^2$$

$$R_6 = 1 - C \cdot \delta x + F \cdot \delta x^2$$

$$R_7 = 1 + A \cdot \delta x + B \cdot \delta x + D \cdot \delta x^2 + E \cdot \delta x^2 + G \cdot \delta x^2$$

$$R_8 = 1 + B \cdot \delta x + C \cdot \delta x + E \cdot \delta x^2 + F \cdot \delta x^2 + I \cdot \delta x^2$$

$$R_9 = 1 + A \cdot \delta x + C \cdot \delta x + D \cdot \delta x^2 + F \cdot \delta x^2 + H \cdot \delta x^2$$

$$A = 0.5 \cdot \left(R_1 - R_4\right) / \delta x$$

$$B = 0.5 \cdot \left(R_2 - R_5\right) / \delta x$$

$$C = 0.5 \cdot \left(R_3 - R_6\right) / \delta x$$

$$D = 0.5 \cdot \left(R_1 + R_4 - 2\right) / \delta x^2$$

$$E = 0.5 \cdot \left(R_2 + R_5 - 2\right) / \delta x^2$$

$$F = 0.5 \cdot \left(R_3 + R_6 - 2\right) / \delta x^2$$

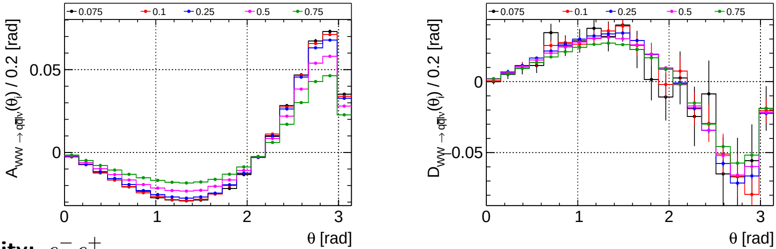
$$G = \left(R_7 - R_1 - R_2 + 1\right) / \delta x^2$$

$$I = \left(R_8 - R_2 - R_3 + 1\right) / \delta x^2$$

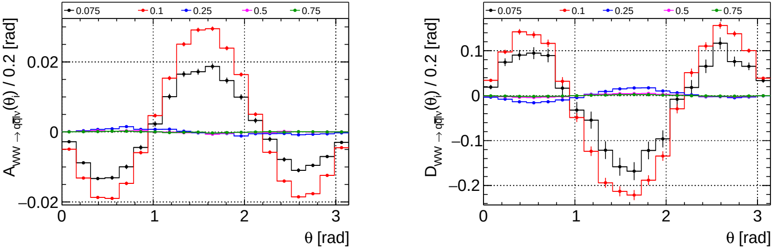
$$H = \left(R_9 - R_1 - R_3 + 1\right) / \delta x^2$$

TGC Coefficient from MC Samples

Chirality: $e_L^- e_R^+$



Chirality: $e_R^- e_L^+$



The Problem:

- In fact A is a 5D-histogram $\rightarrow$ the precision per bin of $\mathbf{R_1} - \mathbf{R_4}$ is too small because of too less MC statistics
- How many MC events do we need?

$$\Delta A/A = 1\% \quad \rightarrow \quad \mathcal{O}(A) \approx 0.05 \quad \rightarrow \quad \Delta A = 5 \cdot 10^{-4}$$

$$\Delta(R_1 - R_4) = 2 \cdot \underbrace{\delta x}_{\approx 0.01} \cdot \Delta A = 10^{-5} = 1/\sqrt{N} \quad \rightarrow \quad N = 10^{10}$$

- ΔA calculated only for 1D $\rightarrow$ 5D gives an additional factor of $\approx 10^4$
- $N \approx 10^{14}$ $\rightarrow$ $\mathcal{O}$(100byte/event) $\rightarrow$ $\approx$ 10 petabyte MC data
- Use Complete DESY Bird Cluster $\rightarrow$ 10 terabyte / day $\rightarrow$ ≈ 2.7 years

$\Rightarrow$ Using MC does not work!

The Solution: Using Omega (WHIZARD) directly

- WHIZARD Event Generation:
  1. Start with the matrix element calculation performed by Omega
  2. Use matrix elements to calculated probability distributions
  3. Get random events following the probability distributions

- Instead of MC events using direct the matrix element to calculate the distributions
  - Calculating matrix element as a function of different angles (neglecting ISR and beam spectrum)
  - TGC are implemented as free parameters in Omega

- Compare it with the distribution of MC data
  $\rightarrow$ Study effects of ISR and beam spectrum

- Implementing TGC measurement in the current framework
  $\rightarrow$ Same as for my Pseudo Nuisance Parameter α, β

Electroweak Precision Measurements

Anomalous Triple Gauge Couplings

TGC Extrapolation from 500 GeV to 250 GeV

TGC Extrapolation from 500 GeV to 250 GeV

- Concept in a Nutshell:
  1. 2 reference points:
     @ $\sqrt{s} = 500$ GeV (Ivan Marchesini) and @ $\sqrt{s} = 1$ TeV (Aura Rosca)
  2. Take result for 500 GeV and extrapolate it to 1 TeV
  3. Compare it with the 1 TeV and adjust the extrapolation, if necessary
  4. Use final extrapolation to calculate expected precision at 250 GeV
- Scaling of an arbitrary uncertainty Δx by a factor f

$$\Delta x\left(\sqrt{s}\right) = f\left(\sqrt{s}\right) \cdot \Delta x\,(500\,\text{GeV})$$
$$f\left(\sqrt{s}\right) = f_{\text{theory}}\left(\sqrt{s}\right) \cdot f_{\text{stat}}\left(\sqrt{s}\right) \cdot f_{\text{det}}\left(\sqrt{s}\right)$$

- Scaling parameter determination (overview):

$$f_{\text{theory}}\left(\sqrt{s}\right) = \frac{(500\,\text{GeV})^2}{s}:$$ BSM sensitivity scales with m_W^2/s

$$f_{\text{statistic}}\left(\sqrt{s}\right) = \sqrt{\frac{N(500\,\text{GeV})}{N\left(\sqrt{s}\right)}}:$$ Statistical uncertainty scales with $1/\sqrt{N}$

$$f_{\text{detector}}\left(\sqrt{s}\right) \approx 1:$$ ignored (at the moment)

Calculation of the Scaling Factor @ $\sqrt{s}$ =1 TeV

- Theoretical contribution:

$$f_{\text{theory}}\left(1\,\text{TeV}\right) = \frac{\left(500\,\text{GeV}\right)^2}{\left(1\,\text{TeV}\right)^2} = 0.25$$

- Statistical contribution:

$$f_{\text{stat}}\left(\sqrt{s}\right) = \sqrt{\frac{\mathcal{L}\left(500\,\text{GeV}\right)\cdot\sigma\left(500\,\text{GeV}\right)}{\mathcal{L}\left(1\,\text{TeV}\right)\cdot\sigma\left(1\,\text{TeV}\right)}} \approx 1.08$$

- Comparison with the actual ratio:

$$f\left(1\,\text{TeV}\right) = 1.08 \cdot 0.25 = 0.27$$

$$\frac{\text{TGC}_{\text{Aura}}}{\text{TGC}_{\text{Ivan}}}: \quad \frac{\Delta g_{1\,\text{TeV}}}{\Delta g_{500\,\text{GeV}}} = 0.31 \quad \frac{\Delta\kappa_{1\,\text{TeV}}}{\Delta\kappa_{500\,\text{GeV}}} = 0.27 \quad \frac{\Delta\lambda_{1\,\text{TeV}}}{\Delta\lambda_{500\,\text{GeV}}} = 0.37$$

Determination of $f_{\text{det},i}\left(\sqrt{s}\right)$

Calculating $f_{\text{det},i}$ using the TeV results:

$$f_{\text{det},\Delta g}\left(1\,\text{TeV}\right) = \frac{\Delta g_{1\,\text{TeV}}}{\Delta g_{500\,\text{GeV}}} / \left(f_{\text{theo}}\left(1\,\text{TeV}\right) \cdot f_{\text{stat}}\left(1\,\text{TeV};1,\text{ab}^{-1}\right)\right) = 0.31/0.27 = 1.15$$

$$f_{\text{det},\Delta \kappa}\left(1\,\text{TeV}\right) = \frac{\Delta \kappa_{1\,\text{TeV}}}{\Delta \kappa_{500\,\text{GeV}}} / \left(f_{\text{theory}}\left(1\,\text{TeV}\right) \cdot f_{\text{stat}}\left(1\,\text{TeV};1,\text{ab}^{-1}\right)\right) = 0.27/0.27 = 1$$

$$f_{\text{det},\Delta \lambda}\left(1\,\text{TeV}\right) = \frac{\Delta \lambda_{1\,\text{TeV}}}{\Delta \lambda_{500\,\text{GeV}}} / \left(f_{\text{theo}}\left(1\,\text{TeV}\right) \cdot f_{\text{stat}}\left(1\,\text{TeV};1,\text{ab}^{-1}\right)\right) = 0.37/0.27 = 1.37$$

Extrapolation $f_{\text{det},i}$ to 250 GeV

$$f_{\text{det},\Delta g}\left(250\,\text{GeV}\right) = \left(f_{\text{det},\Delta g}\left(1\,\text{TeV}\right)\right)^{-1} = 1.15^{-1} = 0.87$$

$$f_{\text{det},\Delta \kappa}\left(250\,\text{GeV}\right) = \left(f_{\text{det},\Delta \kappa}\left(1\,\text{TeV}\right)\right)^{-1} = 1^{-1} = 1$$

$$f_{\text{det},\Delta \lambda}\left(250\,\text{GeV}\right) = \left(f_{\text{det},\Delta \lambda}\left(1\,\text{TeV}\right)\right)^{-1} = 1.37^{-1} = 0.73$$

Extrapolation to $\sqrt{s} = 250$ GeV

$$f_{\text{stat}}\left(250\ \text{GeV},\ 2000\ \text{fb}^{-1}\right) = \sqrt{\frac{500\ \text{fb}^{-1} \cdot (9521.45\ \text{fb} + 45.58\ \text{fb})}{2000\ \text{fb}^{-1} \cdot (18781.00\ \text{fb} + 172.73\ \text{fb})}} \approx 0.355$$

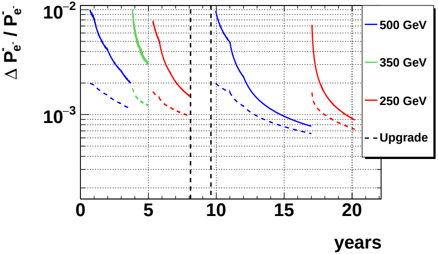
$$f_{\text{theo}}\left(250\ \text{GeV}\right) = \frac{(500\ \text{GeV})^2}{(250\ \text{GeV})^2} = 4$$

$$\begin{aligned}\Delta g\left(250\ \text{GeV},\ 2\ \text{ab}^{-1}\right) =& f_{\text{theo}}\left(250\ \text{GeV}\right) \cdot f_{\text{stat}}\left(250\ \text{GeV},\ 2\ \text{ab}^{-1}\right) \cdot f_{\text{det},\Delta g}\left(250\ \text{GeV}\right) \cdot \Delta g\left(500\ \text{GeV}\right) \\ =& 4 \cdot 0.355 \cdot 0.87 \cdot 6.1 \cdot 10^{-4} = \underline{7.5 \cdot 10^{-4}}\end{aligned}$$

$$\begin{aligned}\Delta \kappa\left(250\ \text{GeV},\ 2\ \text{ab}^{-1}\right) =& f_{\text{theo}}\left(250\ \text{GeV}\right) \cdot f_{\text{stat}}\left(250\ \text{GeV},\ 2\ \text{ab}^{-1}\right) \cdot f_{\text{det},\Delta \kappa}\left(250\ \text{GeV}\right) \cdot \Delta \kappa\left(500\ \text{GeV}\right) \\ =& 4 \cdot 0.355 \cdot 1 \cdot 6.4 \cdot 10^{-4} = \underline{9.1 \cdot 10^{-4}}\end{aligned}$$

$$\begin{aligned}\Delta \lambda\left(250\ \text{GeV},\ 2\ \text{ab}^{-1}\right) =& f_{\text{theo}}\left(250\ \text{GeV}\right) \cdot f_{\text{stat}}\left(250\ \text{GeV},\ 2\ \text{ab}^{-1}\right) \cdot f_{\text{det}}\left(250\ \text{GeV}\right) \cdot \Delta \lambda\left(500\ \text{GeV}\right) \\ =& 4 \cdot 0.355 \cdot 0.73 \cdot 7.2 \cdot 10^{-4} = \underline{7.5 \cdot 10^{-4}}\end{aligned}$$

Consider Constraints from the Polarimeter Measurement



E	500	350	250	500	250
$\mathcal{L}$	500	200	500	3500	1500
Without Constraint					
$P^{-}_{e^-}$	0.2	0.3	0.1	0.08	0.09
With Constraint					
$P^{-}_{e^-}$	0.1	0.1	0.1	0.07	0.07

Simplified approach: (as a first step)

- Neglect spin transport
- Using $\Delta P/P = 0.25\%$:
- Gaussian distribution
  - Mean: $|P_{e-}| = 80\%, |P_{e+}| = 30\%$
  - Width: ΔP

Implementation:

$$\chi^2 += \sum_P \left[\frac{\left(P^{\pm}_{e\pm} - \mathcal{P}^{\pm}_{e\pm}\right)^2}{\Delta\mathcal{P}^2} \right]$$

- $P^{\pm}_{e\pm}$: 4 fitted parameters
- $\mathcal{P}^{\pm}_{e\pm}$: Polarimeter measurement
- $\Delta\mathcal{P}$: Polarimeter uncertainty