Beam Polarization Measurement Using Single Bosons with Missing Energy

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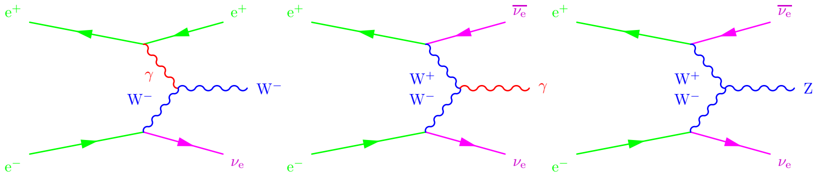


Outline

Why have longitudinally polarized beams?

Advantages

- Measure polarized cross-sections and asymmetries to better understand new and old physics
- Improve statistical errors by preferentially selecting preferred beam helicities (best with high $|P|$)
- Reduce backgrounds in new physics searches

Requirements

- Need to measure beam polarization
- Upstream Compton polarimetry
- In-situ measurements
- Previous studies with WW
- Here look at single boson production
- Study initiated during LCWS11 discussion of beam polarization at CLIC
- Current study for CLIC - also very applicable to ILC

Overview

Use measurements of the event rates in the following four channels ($j = 1, 4$), with different beam helicity configurations to measure the beam polarization

- 1. Single photon
- Single Z
  - 2. Di-muon channel
- Single W
  - 3. Single μ^-
  - 4. Single μ^+

Final states 1 and 2 are dominated by $\nu_{\rm e}\overline{\nu_{\rm e}}{\rm V}$ with V=$(\gamma, {\rm Z})$ and final states 3-4 are dominated by Weν_e. All result from the V-A structure of the W-e-ν_e coupling. For each channel the experimental issues are relatively straightforward. Therefore studies so far are simply at generator level.
Studies so far for CLIC at $\sqrt{s} = 3$ TeV, using WhiZard, with assistance from Stephane Poss.

Single photon channel

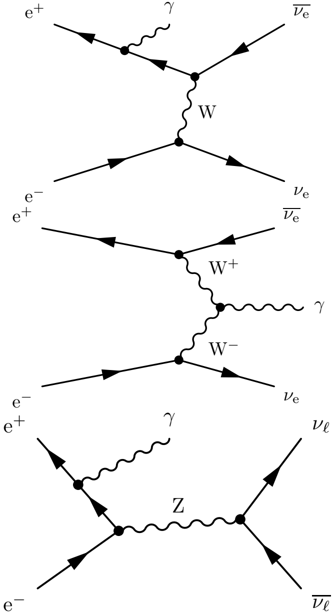
Event Selection

Apply following acceptance cuts:

- Photon $x_T = p_T / E_{\mathrm{beam}} > 0.04$
- Photon $\sin\theta > 0.12$
- Photon $x = E / E_{\mathrm{beam}} < 0.5$

Accepted cross-sections (fb)

Process	σ_{LR}	σ_{RL}
$\gamma\nu_e\overline{\nu_e}$	3072 ± 32	8.4 ± 0.1
$\gamma\nu_\mu\overline{\nu_\mu}$	13.1 ± 0.2	8.5 ± 0.1
$\gamma\nu_\tau\overline{\nu_\tau}$	13.1 ± 0.2	8.5 ± 0.1
Total	3098 ± 32	25.3 ± 0.2



Single Z channel

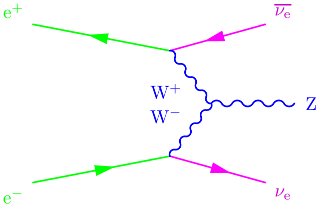
Event Selection

Apply following acceptance cuts:

- Di-muon, $x_T = p_T/E_{\mathrm{beam}} > 0.04$
- Muon $\sin\theta > 0.12$
- Di-muon mass within 10 GeV of M_Z

Accepted cross-sections (fb)

Process	σ_{LR}	σ_{RL}
$\mu^-\mu^+\nu_e\overline{\nu_e}$	158.5 $\pm$ 1.7	0.152 $\pm$ 0.002
$\mu^-\mu^+\nu_\mu\overline{\nu_\mu}$	0.49 $\pm$ 0.02	0.159 $\pm$ 0.003
$\mu^-\mu^+\nu_\tau\overline{\nu_\tau}$	0.364 $\pm$ 0.005	0.154 $\pm$ 0.002
Total	159.4 $\pm$ 1.7	0.465 $\pm$ 0.004

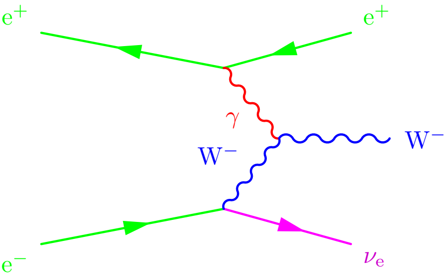


Single W^- channel

Event Selection ($\mathrm{W}^- \to \mu^- \overline{\nu_\mu}$)

Apply following acceptance cuts:

- Muon $x_T = p_T / E_{\mathrm{beam}} > 0.04$
- Muon $\sin\theta > 0.12$
- No electron/positron with $\sin\theta > 0.04$
- No additional muon with $\sin\theta > 0.12$



Accepted cross-sections (fb)

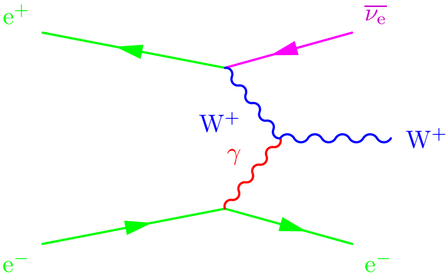
Process	σ_{LR}	σ_{RL}	σ_{LL}
$\mu^- \overline{\nu_\mu} \mathrm{e}^+ \nu_\mathrm{e}$	570.9 ± 10.5	0.0004 ± 0.0001	657.4 ± 10.0
$\mu^- \mu^+ \nu_\mathrm{e} \overline{\nu_\mathrm{e}}$	6.35 ± 0.29	0.0204 ± 0.0008	0
$\mu^- \mu^+ \nu_\mu \overline{\nu_\mu}$	3.58 ± 0.09	0.0235 ± 0.0011	0
$\mu^- \mu^+ \nu_\tau \overline{\nu_\tau}$	0.045 ± 0.002	0.0214 ± 0.0008	0
Total	580.9 ± 10.5	0.0657 ± 0.0016	657.4 ± 10.0

Single W^+ channel

Event Selection ($W^+ \to \mu^+ \nu_\mu$)

Apply following acceptance cuts:

- Muon $x_T = p_T / E_{\mathrm{beam}} > 0.04$
- Muon $\sin\theta > 0.12$
- No electron/positron with $\sin\theta > 0.04$
- No additional muon with $\sin\theta > 0.12$



Accepted cross-sections (fb)

Process	σ_{LR}	σ_{RL}	σ_{RR}
$\mu^+\nu_\mu e^- \overline{\nu_e}$	570.9 ± 10.5	0.0004 ± 0.0001	657.4 ± 10.0
$\mu^-\mu^+\nu_e\overline{\nu_e}$	6.35 ± 0.29	0.0204 ± 0.0008	0
$\mu^-\mu^+\nu_\mu\overline{\nu_\mu}$	3.58 ± 0.09	0.0235 ± 0.0011	0
$\mu^-\mu^+\nu_\tau\overline{\nu_\tau}$	0.045 ± 0.002	0.0214 ± 0.0008	0
Total	580.9 ± 10.5	0.0657 ± 0.0016	657.4 ± 10.0

Beam Polarization Scenarios

Beam Polarization Scenarios Considered

- 4 polarization configurations with two-beam polarization (LR,RL,LL,RR)
- 2 and 3 configurations with only electron-beam polarization (L0,R0,00)
- 9 configurations with two-beam polarization (All of above + 0L, 0R)

Ansatz

The expected event number, μ, in a particular channel, j, with a particular configuration of signed beam polarizations, $(P_{\mathrm{e}^-}, P_{\mathrm{e}^+})$, exposed to an integrated luminosity $\mathcal{L}$ is

$$\mu = \sigma(P_{\mathrm{e}^-}, P_{\mathrm{e}^+})\, \mathcal{L}$$

where

$$\begin{aligned}\sigma(P_{\mathrm{e}^-}, P_{\mathrm{e}^+}) &= \frac{1}{4}\{(1 - P_{\mathrm{e}^-})(1 + P_{\mathrm{e}^+})\sigma_{LR} + (1 + P_{\mathrm{e}^-})(1 - P_{\mathrm{e}^+})\sigma_{RL} + \\ &\quad (1 - P_{\mathrm{e}^-})(1 - P_{\mathrm{e}^+})\sigma_{LL} + (1 + P_{\mathrm{e}^-})(1 + P_{\mathrm{e}^+})\sigma_{RR}\}\end{aligned}$$

and σ_k ($k =$ LR, RL, LL and RR) are the fully polarized cross-sections.

Putting the ingredients together

Use a general implementation using MINUIT of beam polarization measurements using these processes.

In general, one can, (and may want to) assign some integrated luminosity to all 9 possible configurations, i, of beam polarization where $i = -+, +-, --, ++, -0, +0, 0-, 0+, 00$.

For the 4 channels, this leads to potentially 36 measurements of the produced number of events, N_{ij}, where i refers to the beam polarization configuration and its associated integrated luminosity exposure, and j to the channel.

Essentially the problem is to find the best fit to the 9×4 matrix, N, of *observed* event numbers with a model which takes into account the beam characteristics, (integrated luminosities and beam polarizations), in a 9×4 matrix, B, and the predicted fully polarized cross-sections for each channel, represented by a 4×4 matrix, C, where the matrix of *expected* event numbers, M is equal to BC.

Fitting and fit parameters

Observation matrix, N. Expectation matrix, $M = BC$.

Minimize,

$$\chi^2 = \sum_{i=1}^{9} \sum_{j=1}^{4} (n_{ij} - m_{ij})^2 / m_{ij}$$

Fit parameters are encapsulated in matrices, B and C.

Beam Matrix, B

So far, focussed on the standard case, where one assumes that one can exactly flip the helicity of each beam retaining the same value of $|P|$ per beam. Possible to also fit for distinct values, but then need integrated luminosity devoted to polarization configurations 5-9.

The beam matrix has rows simply related to the left and right helicity fractions of each beam which are simple functions of the beam polarization. Each row is essentially:

$$f_L^- f_R^+ \quad f_R^- f_L^+ \quad f_L^- f_L^+ \quad f_R^- f_R^+$$

with

$$f_L^- = \frac{1}{2}(1 - P_{\mathrm{e}^-}), f_R^- = \frac{1}{2}(1 + P_{\mathrm{e}^-})$$

$$f_L^+ = \frac{1}{2}(1 - P_{\mathrm{e}^+}), f_R^+ = \frac{1}{2}(1 + P_{\mathrm{e}^+})$$

Cross-section Matrix, C

Here we specify the fully-polarized visible cross-sections for each channel. Shown for illustration are the expected values in fb from the draft LCD note http://heplx3.phsx.ku.edu/~graham/BeamPol/BeamPolMeasurement.pdf

$$\begin{pmatrix} 3098 & 159.4 & 580.9 & 580.9 \\ 25.3 & 0.465 & 0.066 & 0.066 \\ 0.0 & 0.0 & 657.4 & 0.0 \\ 0.0 & 0.0 & 0.0 & 657.4 \end{pmatrix}$$

Fit Parameters and Method

Choose a running scenario with a particular mix of polarization configurations with assigned integrated luminosity fractions.

The fit uses the four physics channels and in general depends on up to 9 parameters. Usually 5 free parameters ($\sigma^{\gamma}_{LR}, \sigma^{\gamma}_{RL}, \sigma^{Z}_{LR}, \sigma^{\mu}_{LR}, \sigma^{\mu}_{SS}$), for the larger elements of the cross-section matrix and up to 4 parameters for the polarization value of each beam and helicity choice (see next slide).

$$\begin{pmatrix} \sigma^{\gamma}_{LR} & \sigma^{Z}_{LR} & \sigma^{\mu}_{LR} & \sigma^{\mu}_{LR} \\ \sigma^{\gamma}_{RL} & 0.465 & 0.066 & 0.066 \\ 0.0 & 0.0 & \sigma^{\mu}_{SS} & 0.0 \\ 0.0 & 0.0 & 0.0 & \sigma^{\mu}_{SS} \end{pmatrix}$$

Six of the elements are zero on physics grounds (for the backgrounds considered so far). The non-zero elements that are not fit parameters are visible background cross-sections (fb). They are fixed to their expected value, and should be varied to estimate associated systematic errors. These backgrounds are predominantly neutral current backgrounds which should be under relatively good control. Assuming CP conservation (and charge symmetric cuts) two pairs of elements have been equated ($\sigma^{\mu^-}_{LR} = \sigma^{\mu^+}_{LR}$ and $\sigma^{\mu^-}_{LL} = \sigma^{\mu^+}_{RR}$).

Polarization Fit Parameters

Method

For each beam, we have three potential choices of polarization value. For the electron-beam, preferentially negative helicity ($P^L_{e^-}$), unpolarized, and preferentially positive helicity ($P^R_{e^-}$) and similarly for the positron beam.

We assume that the unpolarized values are exactly zero, and parameterise the four non-zero polarizations in terms of the respective beam's mean absolute polarization $|P|$ and (signed) polarization difference δ

$$\begin{array}{ll} P^L_{e^-} = -|P_{e^-}| + \frac{1}{2}\delta_- & P^L_{e^+} = -|P_{e^+}| + \frac{1}{2}\delta_+ \\ P^R_{e^-} = \ \ |P_{e^-}| + \frac{1}{2}\delta_- & P^R_{e^+} = \ \ |P_{e^+}| + \frac{1}{2}\delta_+ \end{array}$$

Fit Types

We perform three types of fit to investigate the sensitivity to the δ values. Firstly, a "Standard" equal-magnitude 2 polarization parameters fit with both δ values fixed to zero. Secondly a "General" 4 polarization parameter fit where the δ values float and are measured from the data which is equivalent to measuring all 4 polarizations. And lastly, a fit where small polarization differences are allowed, but are "Constrained" by an assumed uncertainty (0.1%) and the data.

50% Opposite Helicities Fit ($\delta_- = \delta_+ = 0$)

7-parameter fit with 16 measurements

2 ab^{-1} equally distributed amongst polarization configurations 1-4 (statistical errors only)

$\lvert P_{\mathrm{e}^-}\rvert$	$80.000 \pm 0.056\%$
$\lvert P_{\mathrm{e}^+}\rvert$	$30.000 \pm 0.065\%$
σ^{γ}_{LR}	$3098.0 \pm 2.7\ \mathrm{fb}$
σ^{γ}_{RL}	$25.3 \pm 1.1\ \mathrm{fb}$
σ^{Z}_{LR}	$159.40 \pm 0.57\ \mathrm{fb}$
σ^{μ}_{LR}	$580.9 \pm 1.1\ \mathrm{fb}$
σ^{μ}_{SS}	$657.4 \pm 1.1\ \mathrm{fb}$

Beam polarizations are measured with little correlation.

$$\rho(\lvert P_{\mathrm{e}^-}\rvert, \lvert P_{\mathrm{e}^+}\rvert) = 14\%$$

See backup slides for details of other scenarios.

Systematics

Background systematics were estimated by changing the background cross-section estimates coherently up and down by a factor of 1.1 corresponding to a presumed reasonably conservative 10% error.

For some time it looked like the single-electron and single-photon measurements were systematically limited with these statistics. Single-electron has worse statistics and much lower purity - so that was removed.
Now the single-photon background is fitted without significant precision loss and backgrounds are no longer a big issue for any of the four remaining channels.

Summary Table (Both Beams Polarized)

Polarization statistical errors for various opposite helicities fractions. Standard and Constrained only use beam configurations with both beams polarized.

		50%	80%	90%
Standard	$\|P_{e^-}\|$	0.056%	0.064%	0.069%
	$\|P_{e^+}\|$	0.065%	0.085%	0.113%
Constrained	$\|P_{e^-}\|$	0.068%	0.074%	0.079%
	$\|P_{e^+}\|$	0.067%	0.087%	0.114%
	δ_-	0.096%	0.096%	0.096%
	δ_+	0.096%	0.096%	0.096%
General	$\|P_{e^-}\|$	0.127%	0.155%	0.195%
	$\|P_{e^+}\|$	0.091%	0.122%	0.162%
	δ_-	0.27%	0.35%	0.47%
	δ_+	0.27%	0.35%	0.47%

Summary Table (Electron Polarization Only)

Polarization statistical errors for the two (5,6) and three (5,6,9) helicity configuration running scenarios

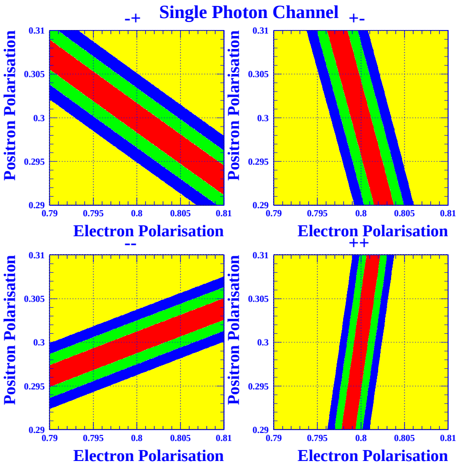
		Two	Three
Standard	$\lvert P_{\mathrm{e}^-}\rvert$	0.072%	0.088%
Constrained	$\lvert P_{\mathrm{e}^-}\rvert$	0.082%	0.096%
	δ_-	0.096%	0.093%
General	$\lvert P_{\mathrm{e}^-}\rvert$	0.153%	0.133%
	δ_-	0.339%	0.249%

Summary

- Have demonstrated that single-boson processes can be very effective in measuring the beam polarization at high energy $\mathrm{e}^+\mathrm{e}^-$ colliders where single-boson processes have high cross-sections.
- Precisions at the 0.2% level appear feasible.

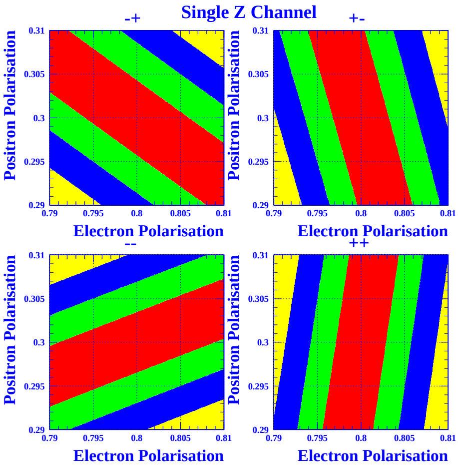
Backup Slides

Single photon channel



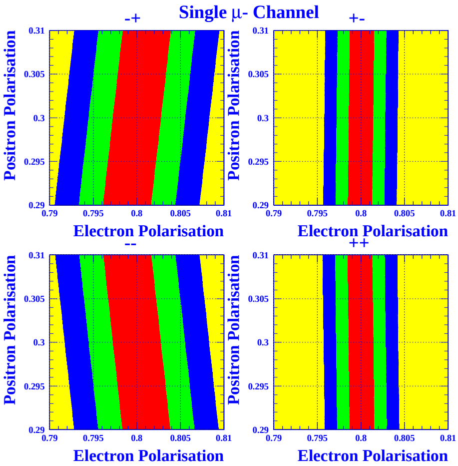
Polarization configurations 1-4 with 2 ab^{-1} equally distributed. For illustration using expected σ values. Contours show $\Delta\chi^2 = 1, 4, 9$.

Single Z channel



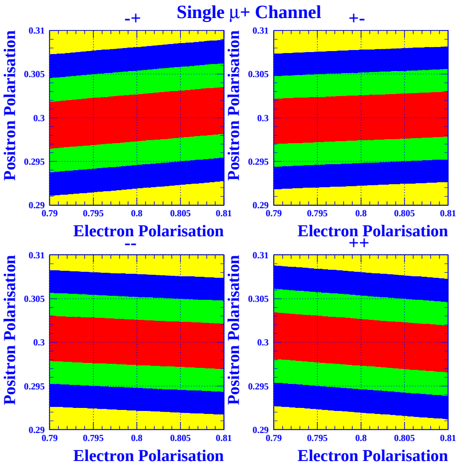
Polarization configurations 1-4 with 2 ab^{-1} equally distributed. For illustration using expected σ values. Contours show $\Delta\chi^2 = 1, 4, 9$.

Single μ^- channel : Measure e^- polarization



Polarization configurations 1-4 with 2 ab^{-1} equally distributed. For illustration using expected σ values. Contours show $\Delta\chi^2 = 1, 4, 9$.

Single μ^+ channel : Measure e^+ polarization



Polarization configurations 1-4 with 2 ab^{-1} equally distributed. For illustration using expected σ values. Contours show $\Delta\chi^2 = 1, 4, 9$.

80% Opposite Helicities Fit ($\delta_- = \delta_+ = 0$)

7-parameter fit with 16 measurements

2 ab^{-1} distributed 40:40:10:10 amongst polarization configurations 1-4.

$\vert P_{e^-}\vert$	$80.000 \pm 0.064\%$
$\vert P_{e^+}\vert$	$30.000 \pm 0.085\%$
σ^{γ}_{LR}	3098.0 ± 3.0 fb
σ^{γ}_{RL}	25.3 ± 1.0 fb
σ^{Z}_{LR}	159.40 ± 0.53 fb
σ^{μ}_{LR}	580.9 ± 1.0 fb
σ^{μ}_{SS}	657.4 ± 1.3 fb

Beam polarization correlation:

$$\rho(|P_{e^-}|, |P_{e^+}|) = 10\%$$

90% Opposite Helicities Fit ($\delta_- = \delta_+ = 0$)

7-parameter fit with 16 measurements

2 ab^{-1} distributed 45:45:5:5 amongst polarization configurations 1-4.

$\lvert P_{e^-}\rvert$	$80.000 \pm 0.069\%$
$\lvert P_{e^+}\rvert$	$30.000 \pm 0.113\%$
σ^{γ}_{LR}	3098.0 ± 3.6 fb
σ^{γ}_{RL}	25.3 ± 1.1 fb
σ^{Z}_{LR}	159.40 ± 0.53 fb
σ^{μ}_{LR}	580.9 ± 1.1 fb
σ^{μ}_{SS}	657.4 ± 1.6 fb

Beam polarization correlation:

$$\rho(|P_{e^-}|, |P_{e^+}|) = 14\%$$

50% Opposite Helicities Fit (Both δ's constrained to 0.1% uncertainty)

9-parameter fit with 16 measurements

2 ab^{-1} equally distributed amongst polarization configurations 1-4 (statistical errors only)

$$
\begin{array}{lr}
|P_{e^-}| & 80.000 \pm 0.068\% \\
|P_{e^+}| & 30.000 \pm 0.067\% \\
\delta_- & 0 \pm 0.096\% \\
\delta_+ & 0 \pm 0.096\%
\end{array}
$$

80% Opposite Helicities Fit (Both δ's constrained to 0.1% uncertainty)

9-parameter fit with 16 measurements

2 ab^{-1} equally distributed amongst polarization configurations 1-4 (statistical errors only)

$\lvert P_{e^-}\rvert$	$80.000 \pm 0.074\%$
$\lvert P_{e^+}\rvert$	$30.000 \pm 0.087\%$
δ_-	$0 \pm 0.096\%$
δ_+	$0 \pm 0.096\%$

90% Opposite Helicities Fit (Both δ's constrained to 0.1% uncertainty)

9-parameter fit with 16 measurements

2 ab^{-1} equally distributed amongst polarization configurations 1-4 (statistical errors only)

$\lvert P_{e^-}\rvert$	$80.000 \pm 0.079\%$
$\lvert P_{e^+}\rvert$	$30.000 \pm 0.114\%$
δ_-	$0 \pm 0.096\%$
δ_+	$0 \pm 0.096\%$

50% Opposite Helicities Fit (Both δ's floating)

9-parameter fit with 36 measurements

2 ab^{-1} distributed 25:25:50 amongst polarization configurations 1,2 and 3-9 (statistical errors only) with the 3-9 int. lumi. split equally.

$\lvert P_{e^-}\rvert$	$80.000 \pm 0.127\%$
$\lvert P_{e^+}\rvert$	$30.000 \pm 0.091\%$
δ_-	$0 \pm 0.27\%$
δ_+	$0 \pm 0.27\%$

80% Opposite Helicities Fit (Both δ's floating)

9-parameter fit with 36 measurements

2 ab^{-1} distributed 40:40:20 amongst polarization configurations 1,2 and 3-9 (statistical errors only) with the 3-9 int. lumi. split equally.

$\lvert P_{e^-}\rvert$	$80.000 \pm 0.155\%$
$\lvert P_{e^+}\rvert$	$30.000 \pm 0.122\%$
δ_-	$0 \pm 0.35\%$
δ_+	$0 \pm 0.35\%$

90% Opposite Helicities Fit (Both δ's floating)

9-parameter fit with 36 measurements

2 ab^{-1} distributed 45:45:10 amongst polarization configurations 1,2 and 3-9 (statistical errors only) with the 3-9 int. lumi. split equally.

$\lvert P_{e^-} \rvert$	$80.000 \pm 0.195\%$
$\lvert P_{e^+} \rvert$	$30.000 \pm 0.162\%$
δ_-	$0 \pm 0.47\%$
δ_+	$0 \pm 0.47\%$

Only Electron Beam polarization ($\delta_- = 0$)

6-parameter fit with 8 measurements

2 ab^{-1} equally distributed amongst polarization configurations 5 and 6 (statistical errors only)

$\lvert P_{e^-} \rvert$	$80.000 \pm 0.072\%$
σ^{γ}_{LR}	3098.0 ± 3.0 fb
σ^{γ}_{RL}	25.3 ± 1.7 fb
σ^{Z}_{LR}	159.40 ± 0.57 fb
σ^{μ}_{LR}	580.9 ± 1.1 fb
σ^{μ}_{SS}	657.4 ± 1.1 fb

Only Electron Beam polarization (δ_- constrained with 0.1% uncertainty)

7-parameter fit with 8 measurements

2 ab^{-1} equally distributed amongst polarization configurations 5 and 6 (statistical errors only)

$\|P_{e^-}\|$	$80.000 \pm 0.082\%$
σ^{γ}_{LR}	3098.0 ± 3.4 fb
σ^{γ}_{RL}	25.3 ± 1.7 fb
σ^{Z}_{LR}	159.40 ± 0.57 fb
σ^{μ}_{LR}	580.9 ± 1.1 fb
σ^{μ}_{SS}	657.4 ± 1.2 fb
δ_-	$0 \pm 0.096\%$

Only Electron Beam polarization

7-parameter fit with 8 measurements

2 ab^{-1} equally distributed amongst polarization configurations 5 and 6 (statistical errors only)

$\lvert P_{\mathrm{e}^-}\rvert$	$80.000 \pm 0.153\%$
σ^{γ}_{LR}	3098.0 ± 6.0 fb
σ^{γ}_{RL}	25.3 ± 1.7 fb
σ^{Z}_{LR}	159.40 ± 0.63 fb
σ^{μ}_{LR}	580.9 ± 1.2 fb
σ^{μ}_{SS}	657.4 ± 1.3 fb
δ_-	$0 \pm 0.339\%$

Only Electron Beam polarization ($\delta_- = 0$)

6-parameter fit with 12 measurements

2 ab^{-1} equally distributed amongst polarization configurations 5 and 6 and 9 (statistical errors only)

$\|P_{e^-}\|$	$80.000 \pm 0.088\%$
σ^{γ}_{LR}	3098.0 ± 3.2 fb
σ^{γ}_{RL}	25.3 ± 2.1 fb
σ^{Z}_{LR}	159.40 ± 0.57 fb
σ^{μ}_{LR}	580.9 ± 1.3 fb
σ^{μ}_{SS}	657.4 ± 1.3 fb

Only Electron Beam polarization (δ_- constrained with 0.1% uncertainty)

7-parameter fit with 12 measurements

2 ab^{-1} equally distributed amongst polarization configurations 5 and 6 and 9 (statistical errors only)

$\lvert P_{\mathrm{e}^-}\rvert$	$80.000 \pm 0.096\%$
σ^{γ}_{LR}	3098.0 ± 3.4 fb
σ^{γ}_{RL}	25.3 ± 2.1 fb
σ^{Z}_{LR}	159.40 ± 0.57 fb
σ^{μ}_{LR}	580.9 ± 1.3 fb
σ^{μ}_{SS}	657.4 ± 1.4 fb
δ_-	$0 \pm 0.093\%$

Only Electron Beam polarization

7-parameter fit with 12 measurements

2 ab^{-1} equally distributed amongst polarization configurations 5 and 6 and 9 (statistical errors only)

$\lvert P_{\mathrm{e}^-}\rvert$	$80.000 \pm 0.133\%$
σ^{γ}_{LR}	3098.0 ± 4.1 fb
σ^{γ}_{RL}	25.3 ± 2.1 fb
σ^{Z}_{LR}	159.40 ± 0.58 fb
σ^{μ}_{LR}	580.9 ± 1.3 fb
σ^{μ}_{SS}	657.4 ± 1.4 fb
δ_-	$0 \pm 0.249\%$