

# Polarization, Triple Gauge Couplings and W Mass Precision Measurement @250 GeV

## ILD Analysis/Software Meeting

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# Outline

Polarization Measurement with Simultaneous Cross Section Determination

Triple Gauge Coupling Extrapolation to 250 GeV

W Mass Precision @250 GeV

# Polarization Measurement Reminder

- Determine the *pull term*:

$$\left| \frac{\sigma^{\text{data}} - \sigma^{\text{theory}}(P_{e-}, P_{e+})}{\Delta\sigma} \right|$$

- Calculating  $P_{e-}, P_{e+}$  by minimizing all *pull term*:

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

- ⇒ Relay on precise knowledge on  $\sigma_{\text{LR}}, \sigma_{\text{RL}}, \sigma_{\text{LL}}, \sigma_{\text{RR}}$

# Unpolarized Cross Section Discrepancy

- ▶ Assume precise knowledge of the left-right-asymmetry  $A_{RL}$  but the unpolarized cross section  $\sigma_0$  is uncertain

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

- ▶ Polarization Determination for different  $\alpha$ 's

- ▶ All processes scaled with the same  $\alpha$
- ▶ Unscaled cross sections used for the minimization ( $\alpha \equiv 1$ )
- ▶ Polarization in red corresponds to a deviation larger than  $5\sigma$  from the true value
- ⇒ For  $\alpha \neq 1$  minimization fails to evaluate correct polarization value

| $\alpha$              | 0.5                               | 1               | 1.1                       |
|-----------------------|-----------------------------------|-----------------|---------------------------|
| $\chi^2 / \text{NDF}$ | $3.9453 \cdot 10^7 / 736$         | 739.17 / 736    | $8.3034 \cdot 10^5 / 736$ |
| $P_{e^-}^- [\%]$      | $(-1.5 \pm 3600) \cdot 10^{-12}$  | $-80 \pm 0.027$ | $-90.6 \pm 0.027$         |
| $P_{e^-}^+ [\%]$      | $95.41 \pm 0.0057$                | $80 \pm 0.01$   | $77 \pm 0.01$             |
| $P_{e^+}^- [\%]$      | $(-2.2 \pm 36000) \cdot 10^{-13}$ | $-30 \pm 0.012$ | $-27 \pm 0.012$           |
| $P_{e^+}^+ [\%]$      | $54.7 \pm 0.013$                  | $30 \pm 0.018$  | $32.6 \pm 0.017$          |

# Introducing the *Pseudo Nuisance Parameter Vector* $\vec{x}$

- ▶ Define the ratio  $R$  between the "actual" cross section  $\sigma_{\text{actual}}$  and the SM cross section  $\sigma_{\text{SM}}$

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

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

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

- ▶ Unpolarized cross section scaling: *Pseudo Nuisance Parameter Vector*  $\vec{x} \equiv \alpha$

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

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

# Fit of the Polarization with Scaling Parameter

| $\chi^2 / \text{NDF}$             | 755.18 / 722 |                                 |
|-----------------------------------|--------------|---------------------------------|
| Parameter                         | Actual Value | Fit Value                       |
| $P_{e^-}^- [\%]$                  | -80          | $-80.1 \pm 0.035$               |
| $P_{e^-}^+ [\%]$                  | 80           | $80 \pm 0.012$                  |
| $P_{e^+}^- [\%]$                  | -30          | $-30 \pm 0.014$                 |
| $P_{e^+}^+ [\%]$                  | 30           | $30 \pm 0.02$                   |
| $\alpha_{W+}(e\nu l\nu)$          | 0.84         | $0.84 \pm 0.001$                |
| $\alpha_{W-}(e\nu l\nu)$          | 0.87         | $0.87 \pm 0.001$                |
| $\alpha_{W+}(e\nu q\bar{q})$      | 0.84         | $0.84 \pm 0.00059$              |
| $\alpha_{W-}(e\nu q\bar{q})$      | 1            | $1 \pm 0.00065$                 |
| $\alpha_{WW}(q\bar{q}q\bar{q})$   | 1.2          | $1.2 \pm 0.00047$               |
| $\alpha_{WW}(l\nu l\nu)$          | 0.98         | $0.98 \pm 0.0011$               |
| $\alpha_{WW}(l\nu q\bar{q})$      | 0.8          | $0.8 \pm 0.00033$               |
| $\alpha_{ZZ}(q\bar{q}q\bar{q})$   | 1.1          | $1.1 \pm 0.0011$                |
| $\alpha_{ZZ}(llll)$               | 0.99         | $0.99 \pm 0.0028$               |
| $\alpha_{ZZ}(llq\bar{q})$         | 0.91         | $0.912 \pm 0.00093$             |
| $\alpha_{ZZWW}(q\bar{q}q\bar{q})$ | 0.75         | $0.75 \pm 0.00038$              |
| $\alpha_{ZZWW}(l\nu l\nu)$        | 0.77         | $0.77 \pm 0.00097$              |
| $\alpha_Z(q\bar{q})$              | 0.78         | $0.7799 \pm (10 \cdot 10^{-5})$ |
| $\alpha_Z(l^+l^-)$                | 1.2          | $1.2 \pm 0.00025$               |

## Minimization:

- ▶ All processes scaled by a random  $\alpha$  value
- ▶ For each process and channel an individual free scaling parameter was included
- ▶ All  $\alpha$ 's initialized with 1 within the minimization
- ⇒ Correct determination of the polarization and the scaling parameters
- Tested for various  $\alpha$  values



# Discrepancy of the Asymmetry

In general 6 different asymmetries of the total chiral cross sections:

$$A_{RL}^{LR} := \frac{\sigma_{LR} - \sigma_{RL}}{\sigma_{LR} + \sigma_{RL}}$$

$$A_{LL}^{LR} := \frac{\sigma_{LR} - \sigma_{LL}}{\sigma_{LR} + \sigma_{LL}}$$

$$A_{RR}^{LR} := \frac{\sigma_{LR} - \sigma_{RR}}{\sigma_{LR} + \sigma_{RR}}$$

$$A_{LL}^{RL} := \frac{\sigma_{RL} - \sigma_{LL}}{\sigma_{RL} + \sigma_{LL}}$$

$$A_{RR}^{RL} := \frac{\sigma_{RL} - \sigma_{RR}}{\sigma_{RL} + \sigma_{RR}}$$

$$A_{LL}^{RR} := \frac{\sigma_{RR} - \sigma_{LL}}{\sigma_{RR} + \sigma_{LL}}$$

Including a new Pseudo Nuisance Parameter  $\beta$   
 (Shown for  $A_{RL}^{LR}$ , analog for other asymmetries)

$$R_{LR}(\beta) := 1 + 0.5 \cdot \frac{\sigma_{LR} + \sigma_{RL}}{\sigma_{LR}} \cdot \beta$$

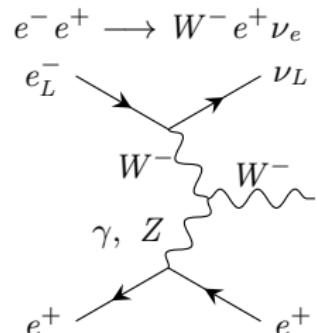
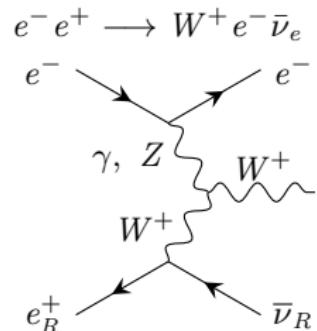
$$R_{RL}(\beta) := 1 - 0.5 \cdot \frac{\sigma_{LR} + \sigma_{RL}}{\sigma_{RL}} \cdot \beta$$

The definitions of the cross section ratios  $R$  are set that the asymmetry differs by  $\beta$

$$\begin{aligned} A' &= \frac{\sigma'_{LR} - \sigma'_{RL}}{\sigma'_{LR} + \sigma'_{RL}} = \frac{R_{LR}\sigma_{LR} - R_{RL}\sigma_{RL}}{R_{LR}\sigma_{LR} + R_{RL}\sigma_{RL}} = \frac{\left(\sigma_{LR} + \frac{\sigma_{LR} + \sigma_{RL}}{2} \cdot \beta\right) - \left(\sigma_{RL} - \frac{\sigma_{LR} + \sigma_{RL}}{2} \cdot \beta\right)}{\left(\sigma_{LR} + \frac{\sigma_{LR} + \sigma_{RL}}{2} \cdot \beta\right) + \left(\sigma_{RL} - \frac{\sigma_{LR} + \sigma_{RL}}{2} \cdot \beta\right)} = \\ &= \dots = \underline{A + \beta} \end{aligned}$$

# Choice of the Asymmetry for each process

|                                  |               |  |
|----------------------------------|---------------|--|
| $\beta_{W+}(e\nu l\nu)$          | $A_{RR}^{LR}$ | single $W^+$ requires a right-handed positron            |
| $\beta_{W+}(e\nu q\bar{q})$      | $A_{RL}^{LR}$ |  |
| $\beta_{W-}(e\nu l\nu)$          | $A_{LL}^{LR}$ | single $W^-$ requires a left-handed electron             |
| $\beta_{W-}(e\nu q\bar{q})$      | $A_{LL}^{LR}$ |  |
| $\beta_{WW}(q\bar{q}q\bar{q})$   | $A_{RL}^{LR}$ |  |
| $\beta_{WW}(l\nu l\nu)$          | $A_{RL}^{LR}$ |  |
| $\beta_{WW}(l\nu q\bar{q})$      | $A_{RL}^{LR}$ | All those processes have $\sigma_{LL} = \sigma_{RR} = 0$ |
| $\beta_{ZZ}(q\bar{q}q\bar{q})$   | $A_{RL}^{LR}$ |  |
| $\beta_{ZZ}(llll)$               | $A_{RL}^{LR}$ | So only $A_{RL}^{LR}$ is meaningful                      |
| $\beta_{ZZ}(llq\bar{q})$         | $A_{RL}^{LR}$ |  |
| $\beta_{ZZWW}(q\bar{q}q\bar{q})$ | $A_{RL}^{LR}$ | All other asymmetries are either 0 or 1                  |
| $\beta_{ZZWW}(l\nu l\nu)$        | $A_{RL}^{LR}$ |  |
| $\beta_Z(q\bar{q})$              | $A_{RL}^{LR}$ |  |
| $\beta_Z(l^+l^-)$                | $A_{RL}^{LR}$ |  |



# Polarization, Scaling Parameters $\alpha$ And Asymmetry Deviation $\beta$ Combined

Results for statistical uncertainties only

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

## Preview: Triple Gauge Couplings Fit

- ▶ Set Triple Gauge Couplings as free parameters  $\vec{x} = (\delta g \quad \delta\kappa \quad \delta\lambda)$ :

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

- ▶ The coefficients  $A, B, C, D, E, F, G, H, I$  are fixed but depend on:
  - ▶ The chiral structure  $A_{LR}, A_{RL}, A_{LL}, A_{RR}, B_{RL}, \dots$
  - ▶ The individual process and the channel
  - ▶ The angular distribution according to the differential cross section
- ▶ The coefficients have to be calculated from MC simulations
  - ▶ Using whizard to determine the coefficients but method will deviate from previous studies
  - ▶ Still only work in progress



## Polarization Measurement with Simultaneous Cross Section Determination

### Triple Gauge Coupling Extrapolation to 250 GeV

W Mass Precision @250 GeV



# Triple Gauge Coupling Notations

► TGC:

$$\begin{aligned} g_1^Z(\text{data}) - g_1^Z(\text{SM}) &= \delta g \pm \Delta g & \kappa_\gamma(\text{data}) - \kappa_\gamma(\text{SM}) &= \delta \kappa \pm \Delta \kappa \\ \lambda_\gamma(\text{data}) - \lambda_\gamma(\text{SM}) &= \delta \lambda \pm \Delta \lambda \end{aligned}$$

**Remark:** No guarantee for same sign of  $\delta g$ ,  $\delta \kappa$ ,  $\delta \lambda$  as Ivan and Aura

- 'δ' refer to the actual deviation from the SM parameter, while 'Δ' refer to its uncertainty
- $\theta_W$ : polar angle of the  $W^-$
- $\theta_x^*$ ,  $\phi_x^*$  : are the polar and azimuth angle, respectively, of the down-type decay product in the rest frame of the  $W$ -boson  
(charged leptons are considered as down types)
- The index  $x$  is  $l$  for the leptonic channel and  $h$  for the hadronic channel of the  $W$ -decay

# Triple Gauge Coupling Overview

- ▶ Result @  $\sqrt{s} = 500 \text{ GeV}$  ( Ivan Marchesini )
  - ▶ Integrated luminosity  $\mathcal{L} = 500 \text{ 1/fb}$
  - ▶  $P_{e^-} = \pm 80\%$ ,  $P_{e^+} = \pm 30\%$ , equal luminosity sharing between  $\sigma_{\pm\pm}$
  - ▶ Binning in  $\cos(\theta_W)$ ,  $\cos(\theta_l^*)$ ,  $\phi_l^*$ : **20-10-10**
  - ▶  $\Delta g = 6.1 \cdot 10^{-4}$ ,  $\Delta \kappa = 6.4 \cdot 10^{-4}$ ,  $\Delta \lambda = 7.2 \cdot 10^{-4}$   
thesis table 5.7 [1]
  
- ▶ Result @  $\sqrt{s} = 1 \text{ TeV}$  ( Aura Rosca )
  - ▶ Integrated luminosity  $\mathcal{L} = 1000 \text{ 1/fb}$
  - ▶  $P_{e^-} = \pm 80\%$ ,  $P_{e^+} = \pm 20\%$ , equal luminosity sharing between  $\sigma_{\pm\pm}$
  - ▶ Binning in  $\cos(\theta_W)$ ,  $\cos(\theta_l^*)$ ,  $\phi_l^*$ : **20-20-20**
  - ▶  $\Delta g = 1.88 \cdot 10^{-4}$ ,  $\Delta \kappa = 1.73 \cdot 10^{-4}$ ,  $\Delta \lambda = 2.66 \cdot 10^{-4}$   
paper table 2 [2]
  
- ▶ **blue** marks taken into account, **red** ignored

# Simplified Triple Gauge Coupling Precision Scaling to $\sqrt{s} = 250 \text{ GeV}$

► Concept in a Nutshell:

1. 2 reference points: @  $\sqrt{s} = 500 \text{ GeV}$  and @  $\sqrt{s} = 1 \text{ TeV}$
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  $\Delta x$  by a factor  $f$

$$\Delta x(\sqrt{s}) = f(\sqrt{s}) \cdot \Delta x(500 \text{ GeV})$$

$$f(\sqrt{s}) = f_{\text{theory}}(\sqrt{s}) \cdot f_{\text{statistic}}(\sqrt{s}) \cdot f_{\text{detector}}(\sqrt{s})$$

► Scaling parameter determination (overview):

$$f_{\text{theory}}(\sqrt{s}) = \frac{(500 \text{ GeV})^2}{s}: \quad \text{BSM uncertainty scales with } m_W^2/s$$

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

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

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

- Theoretical contribution:

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

- Statistical contribution:

$$\begin{aligned} f_{\text{statistic}}(\sqrt{s}) &= \sqrt{\frac{N(500 \text{ GeV})}{N(1 \text{ TeV})}} = \sqrt{\frac{\mathcal{L}(500 \text{ GeV}) \cdot \sigma(500 \text{ GeV})}{\mathcal{L}(1 \text{ TeV}) \cdot \sigma(1 \text{ TeV})}} = \\ &= \sqrt{\frac{500 \text{ fb}^{-1} \cdot (9521.45 \text{ fb} + 45.58 \text{ fb})}{1000 \text{ fb}^{-1} \cdot (4116.63 \text{ fb} + 14.00 \text{ fb})}} \approx 1.08 \end{aligned}$$

- Combination:  $1.08 \cdot 0.25 = 0.27$

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

# Comparison between the extrapolation and the full simulation results

The actual full simulation results have the following ratios:

$$\frac{\Delta g_{1 \text{ TeV}}}{\Delta g_{500 \text{ GeV}}} = 0.31$$

$$\frac{\Delta \kappa_{1 \text{ TeV}}}{\Delta \kappa_{500 \text{ GeV}}} = 0.27$$

$$\frac{\Delta \lambda_{1 \text{ TeV}}}{\Delta \lambda_{500 \text{ GeV}}} = 0.37$$

This gives for the detector contribution  $f_{\text{det},i}$ :

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

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

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

# Calculation of the Scaling Factor @ $\sqrt{s} = 250 \text{ GeV}$

- ▶ Statistical precision:

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

- ▶ Coupling sensitivity:

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

- ▶ Detector contribution:

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

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

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

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

$$\Delta g(250 \text{ GeV}, 2 \text{ ab}^{-1}) = f_{\text{theo}}(250 \text{ GeV}) \cdot f_{\text{stat}}(250 \text{ GeV}, 2 \text{ ab}^{-1}) \cdot f_{\text{det}, \Delta g}(250 \text{ GeV}) \cdot \Delta g(500 \text{ GeV})$$

$$= 4 \cdot 0.355 \cdot 0.87 \cdot 6.1 \cdot 10^{-4} = \underline{\underline{7.5 \cdot 10^{-4}}}$$

$$\Delta \kappa(250 \text{ GeV}, 2 \text{ ab}^{-1}) = f_{\text{theo}}(250 \text{ GeV}) \cdot f_{\text{stat}}(250 \text{ GeV}, 2 \text{ ab}^{-1}) \cdot f_{\text{det}, \Delta \kappa}(250 \text{ GeV}) \cdot \Delta \kappa(500 \text{ GeV})$$

$$= 4 \cdot 0.355 \cdot 1 \cdot 6.4 \cdot 10^{-4} = \underline{\underline{9.1 \cdot 10^{-4}}}$$

$$\Delta \lambda(250 \text{ GeV}, 2 \text{ ab}^{-1}) = f_{\text{theo}}(250 \text{ GeV}) \cdot f_{\text{stat}}(250 \text{ GeV}, 2 \text{ ab}^{-1}) \cdot f_{\text{det}}(250 \text{ GeV}) \cdot \Delta \lambda(500 \text{ GeV})$$

$$= 4 \cdot 0.355 \cdot 0.73 \cdot 7.2 \cdot 10^{-4} = \underline{\underline{7.5 \cdot 10^{-4}}}$$

# Systematic Uncertainties

## ► Polarization:

- ▶ Previous analysis assumed equal absolute polarization values after helicity reversal
- ▶ Non-perfect helicity reversal is an additional uncertainty  $\mathcal{O}$  (polarimeter precision)
- ⇒ Using several processes with different  $A_{RL}$  can compensate for a non-perfect helicity reversal without loss of precision

## ► Luminosity:

- ▶ Train-by-train helicity reversal is implemented in the ILC lattice also for the  $e^+$  beam
- ▶ Correlated uncertainties leads to a substantially reduction of uncertainties
- Assuming that the uncertainty on the luminosity can be neglected

## ► Selection Efficiencies:

- ▶ Consider  $\Delta\epsilon/\epsilon = 0.2\%$  and  $\Delta B/B = 1\%$  [1]

$$\Delta g_{sys} = 6 \cdot 10^{-4} \quad \Delta \kappa_{sys} = 7 \cdot 10^{-4} \quad \Delta \lambda_{sys} = 2 \cdot 10^{-4}$$

- ▶ Reducing  $\Delta\epsilon/\epsilon$  to 0.1% (already achieved by LEP for W pair production)
- ⇒ Systematic uncertainty for  $\mathcal{L} = 1 \text{ ab}^{-1}$  can be reduced to:

$$\Delta g_{sys} = 3 \cdot 10^{-4} \quad \Delta \kappa_{sys} = 3 \cdot 10^{-4} \quad \Delta \lambda_{sys} = 2 \cdot 10^{-4}$$

# Final Results

**The TGC precision for the different  $E_{\text{CMS}}$ 's and integrated luminosities:**

|                             | $\sqrt{s} = 250 \text{ GeV}$        |                                   | $\sqrt{s} = 500 \text{ GeV}$        |                                   | $\sqrt{s} = 1 \text{ TeV}$        |
|-----------------------------|-------------------------------------|-----------------------------------|-------------------------------------|-----------------------------------|-----------------------------------|
|                             | $\mathcal{L} = 500 \text{ fb}^{-1}$ | $\mathcal{L} = 2 \text{ ab}^{-1}$ | $\mathcal{L} = 500 \text{ fb}^{-1}$ | $\mathcal{L} = 4 \text{ ab}^{-1}$ | $\mathcal{L} = 1 \text{ ab}^{-1}$ |
| $\Delta g \cdot 10^4$       | 16                                  | 8.1                               | 8.6                                 | 3.7                               | 3.6                               |
| $\Delta \kappa \cdot 10^4$  | 19                                  | 9.6                               | 9.5                                 | 3.8                               | 3.4                               |
| $\Delta \lambda \cdot 10^4$ | 15                                  | 7.8                               | 7.5                                 | 3.3                               | 3.4                               |

**The correlation matrix for the TGC:**

$$\begin{matrix} & g & \kappa & \lambda \\ g & 1 & 0.634 & 0.477 \\ \kappa & 0.634 & 1 & 0.354 \\ \lambda & 0.477 & 0.354 & 1 \end{matrix}$$

Polarization Measurement with Simultaneous Cross Section Determination

Triple Gauge Coupling Extrapolation to 250 GeV

W Mass Precision @250 GeV



# W Mass Measurement: Concept in a Nutshell

## As a start:

- ▶ Working with W-pair DST-files in the semileptonic decay channel ( $q\bar{q}l\nu$ )
  - ▶  $P_{e-} = -100\%$        $P_{e+} = +100\%$
  - ▶ choosing only  $q\bar{q}\mu\nu$  events →  $\mu$  selected via truth information
- ▶ Invariant mass calculation
  - ▶ Removing the isolated muon from the PFO collection
  - ▶ Consider the remaining PFO's as decay products of the  $W$  boson
  - ▶ Using kt algorithm the create 4 jets
  - Invariant mass is calculated from the jets
- ▶ Determine  $m_W$  via  $\chi^2$  minimization:

$$\chi^2 = \sum_{\text{events}} \frac{(m_{\text{jet}} - m_W)^2}{\Delta m_{\text{jet}}^2}$$



# Uncertainty of the invariant jet mass

Invariant mass calculation from the 4-momentum of the i-th jet  $p_i^\mu$ :

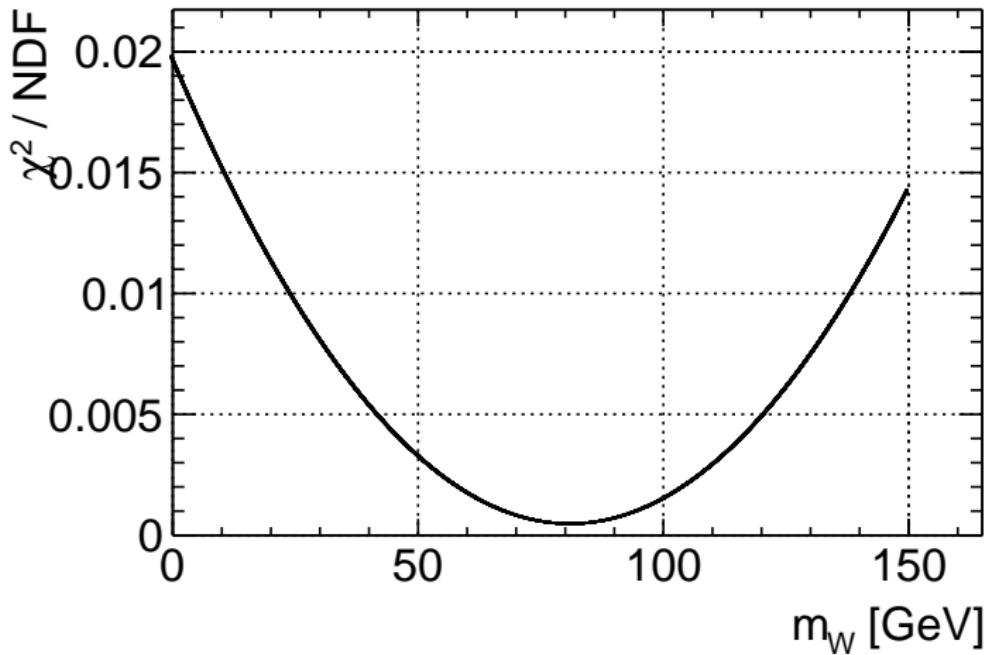
$$m^2 = p^\mu p_\mu = E^2 - |\vec{p}|^2; \quad p^\mu = \sum_i p_i^\mu; \quad p_i^\mu = (E_i \quad p_{x,i} \quad p_{y,i} \quad p_{z,i})^T$$

Assuming that the 4-momentums of the jet are uncorrelated and the uncertainty of the i-th jet is given by  $\Delta m_i$

$$\Delta m^2 = \sum_i \Delta m_i^2; \quad \Delta m_i^2 = (\vec{\nabla}_i m^2)^T M_i \vec{\nabla}_i m^2$$

$$(\vec{\nabla}_i m^2)^T = \left( \frac{\partial m^2}{\partial E_i} \quad \frac{\partial m^2}{\partial p_{x,i}} \quad \frac{\partial m^2}{\partial p_{y,i}} \quad \frac{\partial m^2}{\partial p_{z,i}} \right) = (2E \quad -2p_x \quad -2p_y \quad -2p_z)$$

$$M_i = \begin{pmatrix} \Delta E_i^2 & \text{cov}(p_{x,i}, E_i) & \text{cov}(p_{y,i}, E_i) & \text{cov}(p_{z,i}, E_i) \\ \text{cov}(E_i, p_{x,i}) & \Delta p_{x,i}^2 & \text{cov}(p_{y,i}, p_{x,i}) & \text{cov}(p_{z,i}, p_{x,i}) \\ \text{cov}(E_i, p_{y,i}) & \text{cov}(p_{x,i}, p_{y,i}) & \Delta p_{y,i}^2 & \text{cov}(p_{z,i}, p_{y,i}) \\ \text{cov}(E_i, p_{z,i}) & \text{cov}(p_{x,i}, p_{z,i}) & \text{cov}(p_{y,i}, p_{z,i}) & \Delta p_{z,i}^2 \end{pmatrix}$$

$\chi^2$  Distribution

NDF = 19625

Robert Karl |  $\mathcal{P} + TGC + m_W$  | 07.06.2017 | 24/26



## W Mass Value and Precision

The mass value that minimize  $\chi^2$  provides the W mass  $m_W$

$$\chi_{\min}^2(m_W)/\text{NDF} = 4.79 \cdot 10^{-4} \quad m_W = 81.275 \text{ GeV}$$

The uncertainty on  $m_W$  is given by the deviation of the  $\chi^2$  from the minimal value

$$1 = |\chi^2(m_W \pm \Delta m_W) - \chi^2(m_W)|$$

$$\Delta m_W = 4.17 \text{ GeV}$$

### Remark:

In general the uncertainty can be asymmetric but in this case the uncertainty is found to be symmetric

### Ongoing Work:

- ▶ One would expect  $\chi^2/\text{NDF} \approx 1$  but here  $\chi_{\min}^2/\text{NDF} = 4.79 \cdot 10^{-4}$
- ▶ The uncertainty on  $m_W$  are huge  $> 5\%$
- Further study on the jet uncertainty is necessary

## References |

- [1] Ivan Marchesini, *Triple Gauge Couplings and Polarization at the ILC and Leakage in a Highly Granular Calorimeter*, Hamburg 2011  
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- [2] Aura Rosca, *Measurement of the charged triple gauge boson couplings at the ILC*,  
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