Constraining CP-Violating TGCs and Measuring W-polarization at OPAL

Presented by: Isabel Trigger,
CERN EP Division
(for the OPAL collaboration)[a]

OUTLINE

- spin density matrix W^+W^- analysis
- sensitive to CP-violating TGCs
- fraction of longitudinally polarized W

[a] Additional info available from: Jonathan Couchman, jpc@hep.ucl.ac.uk

The Spin Density Matrix for $\mathrm{W^+W^-}$

... describes the polarization properties of the W bosons

2-particle joint SDM describes contribution of each of the helicity states of the 2 W bosons to the $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-}$ cross-section:

$$\rho_{\tau_-\tau'_-\tau_+\tau'_+}(s, \cos\theta_\mathrm{W}) = \frac{\sum_\lambda F^{(\lambda)}_{\tau_-\tau_+}(F^{(\lambda)}_{\tau'_-\tau'_+})^*}{\sum_{\lambda\tau_+\tau_-}|F^{(\lambda)}_{\tau_-\tau_+}|^2}$$

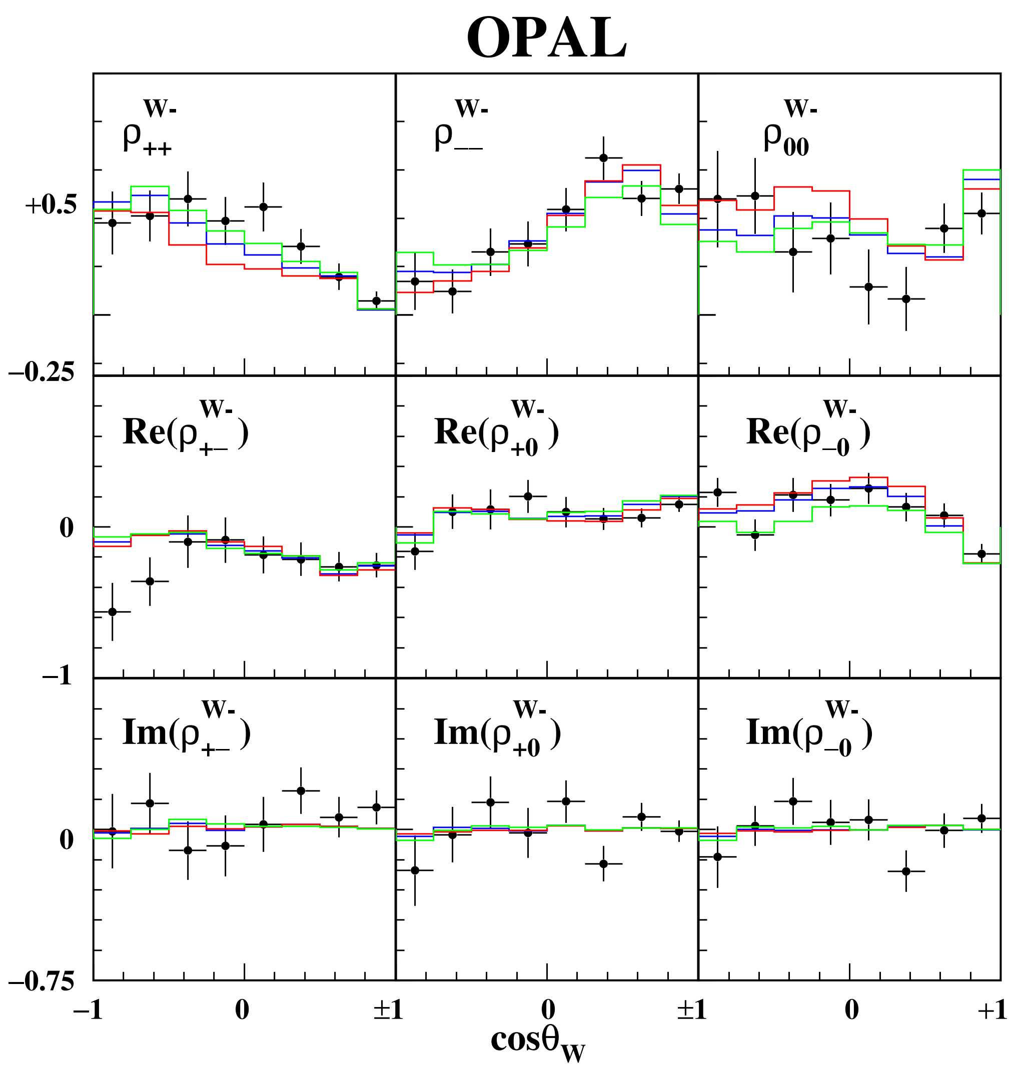
81 elements... diagonal elements = probability of producing W pairs with that helicity combination

Single-particle SDM sums over helicity states of 1 W:

$$\rho^{W^-}_{\tau_-\tau'_-}(s, \cos\theta_\mathrm{W}) = \sum_{\tau_+} \rho_{\tau_-\tau'_-\tau_+\tau_+}(s, \cos\theta_\mathrm{W})$$

9 elements; diagonal elements = probability of producing a W with helicity $+1, 0, -1$

Measured Single W SDM Elements



- ● OPAL data
- Standard Model (blue)
- $\Delta g_1^Z = -0.5$ (green)
- $\Delta g_1^Z = +0.5$ (red)

Note that CPT transforms are used to include events where it is the W^+ which decays leptonically.

What does CP constrain?

CPT-invariance imposes (at tree level):

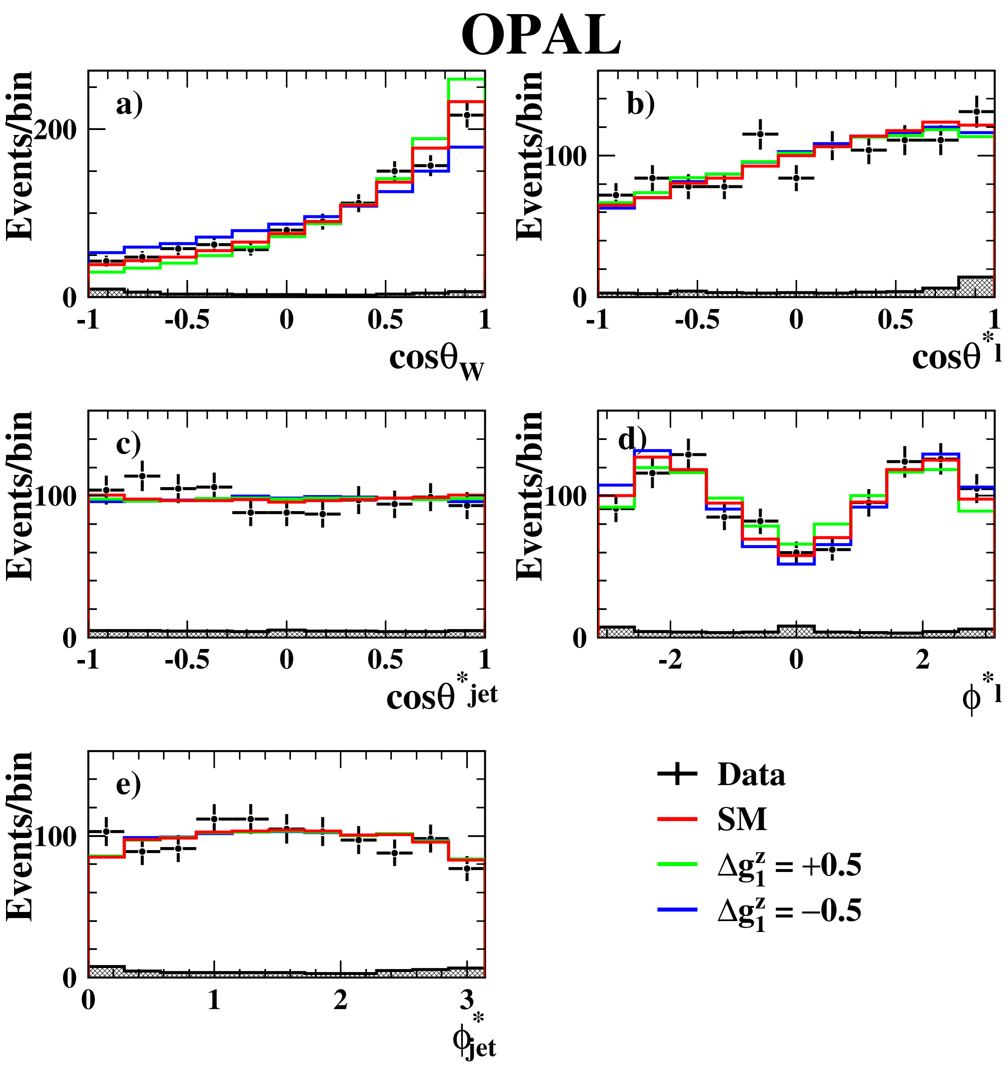
$$\begin{aligned} \mathrm{Re}(\rho^{W^-}_{\tau_1\tau_2}) &- \mathrm{Re}(\rho^{W^+}_{-\tau_1-\tau_2}) = 0 \\ \mathrm{Im}(\rho^{W^-}_{\tau_1\tau_2}) &+ \mathrm{Im}(\rho^{W^+}_{-\tau_1-\tau_2}) = 0 \end{aligned}$$

CP-invariance imposes the condition:

$$\mathrm{Im}(\rho^{W^-}_{\tau_1\tau_2}) - \mathrm{Im}(\rho^{W^+}_{-\tau_1-\tau_2}) = 0$$

Thus CPT- and CP-conservation together dictate that all coefficients from $\rho^{W}_{\tau_1\tau_2}$ are real.

Kinematic Variables



Experimentally... Polarization Cross-Sections

Consider only $\mathrm{W}^+\mathrm{W}^- \rightarrow qq\ell\nu$ events

$\Rightarrow$ measure angles ϕ^* and θ^* unambiguously for leptonic part

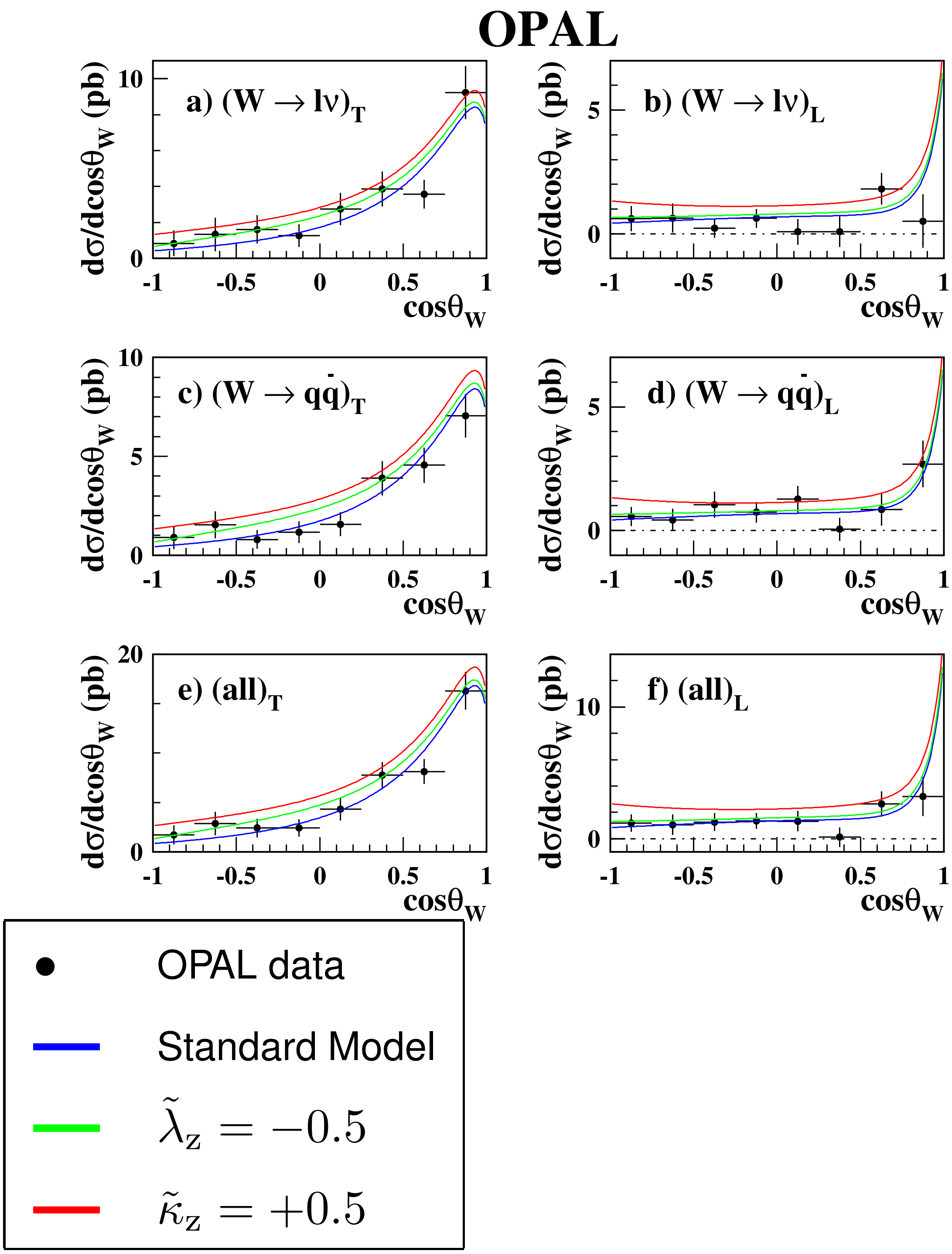
$\Rightarrow$ single W SDM elements all measurable

$\Rightarrow$ can derive $\frac{\mathrm{d}\sigma_\mathrm{T}}{\mathrm{d}\cos\theta_\mathrm{W}}, \frac{\mathrm{d}\sigma_\mathrm{L}}{\mathrm{d}\cos\theta_\mathrm{W}}, \sigma_\mathrm{T}, \sigma_\mathrm{L}$

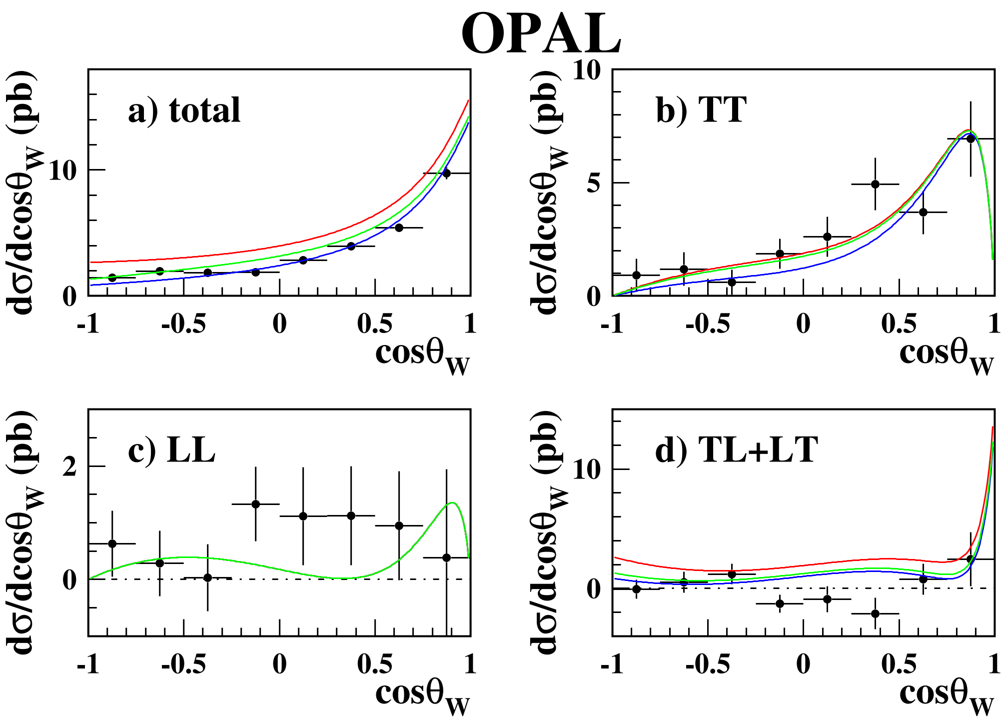
$\Rightarrow$ can measure from hadronic part all combinations of joint 2-W SDM elements which are symmetric under $\cos\theta^* \rightarrow -\cos\theta^*$, $\phi^* \rightarrow \phi^* + \pi$

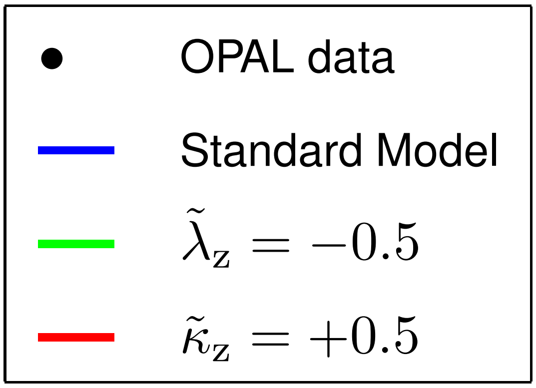
$\Rightarrow$ can derive $\frac{\mathrm{d}\sigma_\mathrm{TT}}{\mathrm{d}\cos\theta_\mathrm{W}}, \frac{\mathrm{d}\sigma_\mathrm{LL}}{\mathrm{d}\cos\theta_\mathrm{W}}, \frac{\mathrm{d}\sigma_\mathrm{TL}}{\mathrm{d}\cos\theta_\mathrm{W}}, \sigma_\mathrm{TT}, \sigma_\mathrm{LL}, \sigma_\mathrm{TL}$

Polarized W Production Cross-Sections



Cross-Sections for Different W Helicity States





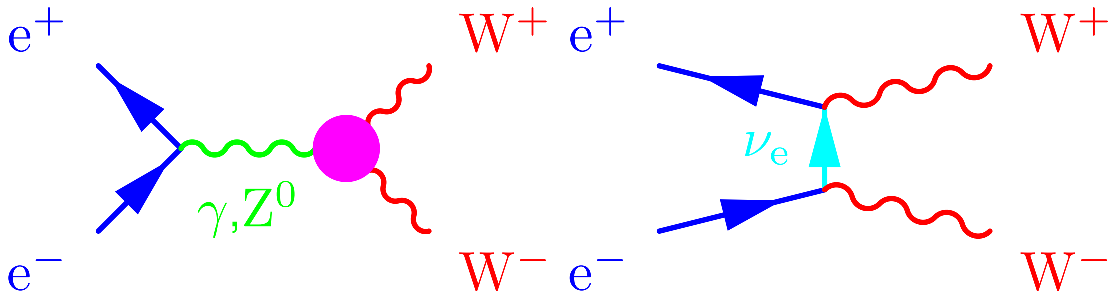
W Polarization & Helicity Fractions

	Data	SM Exp.
$\sigma_{\mathrm{T}}/\sigma_{\mathrm{total}}$		
W$\longrightarrow \ell\nu$	$0.842 \pm 0.048 \pm 0.023$	0.746 ± 0.006
W$\longrightarrow$ qq	$0.738 \pm 0.045 \pm 0.025$	0.741 ± 0.006
All	$0.790 \pm 0.033 \pm 0.016$	0.743 ± 0.004
$\sigma_{\mathrm{L}}/\sigma_{\mathrm{total}}$		
W$\longrightarrow \ell\nu$	$0.158 \pm 0.048 \pm 0.023$	0.254 ± 0.006
W$\longrightarrow$ qq	$0.262 \pm 0.045 \pm 0.025$	0.259 ± 0.006
All	$0.210 \pm 0.033 \pm 0.016$	0.257 ± 0.004

	Measured	Expected
$\sigma_{\mathrm{TT}}/\sigma_{\mathrm{total}}$	$0.781 \pm 0.090 \pm 0.033$	0.572 ± 0.010
$\sigma_{\mathrm{LL}}/\sigma_{\mathrm{total}}$	$0.201 \pm 0.072 \pm 0.018$	0.086 ± 0.008
$\sigma_{\mathrm{TL}}/\sigma_{\mathrm{total}}$	$0.018 \pm 0.147 \pm 0.038$	0.342 ± 0.016

Corresponds to a χ^2 probability of 10% for SM compatibility.

Triple Gauge Couplings and the SDM



Vertex coupling strength is described as function of many parameters. In SM $\kappa_\gamma = g_1^Z = 1$, $\lambda = \tilde{\kappa_V} = g_4^V = g_5^V = \tilde{\lambda} = 0$.

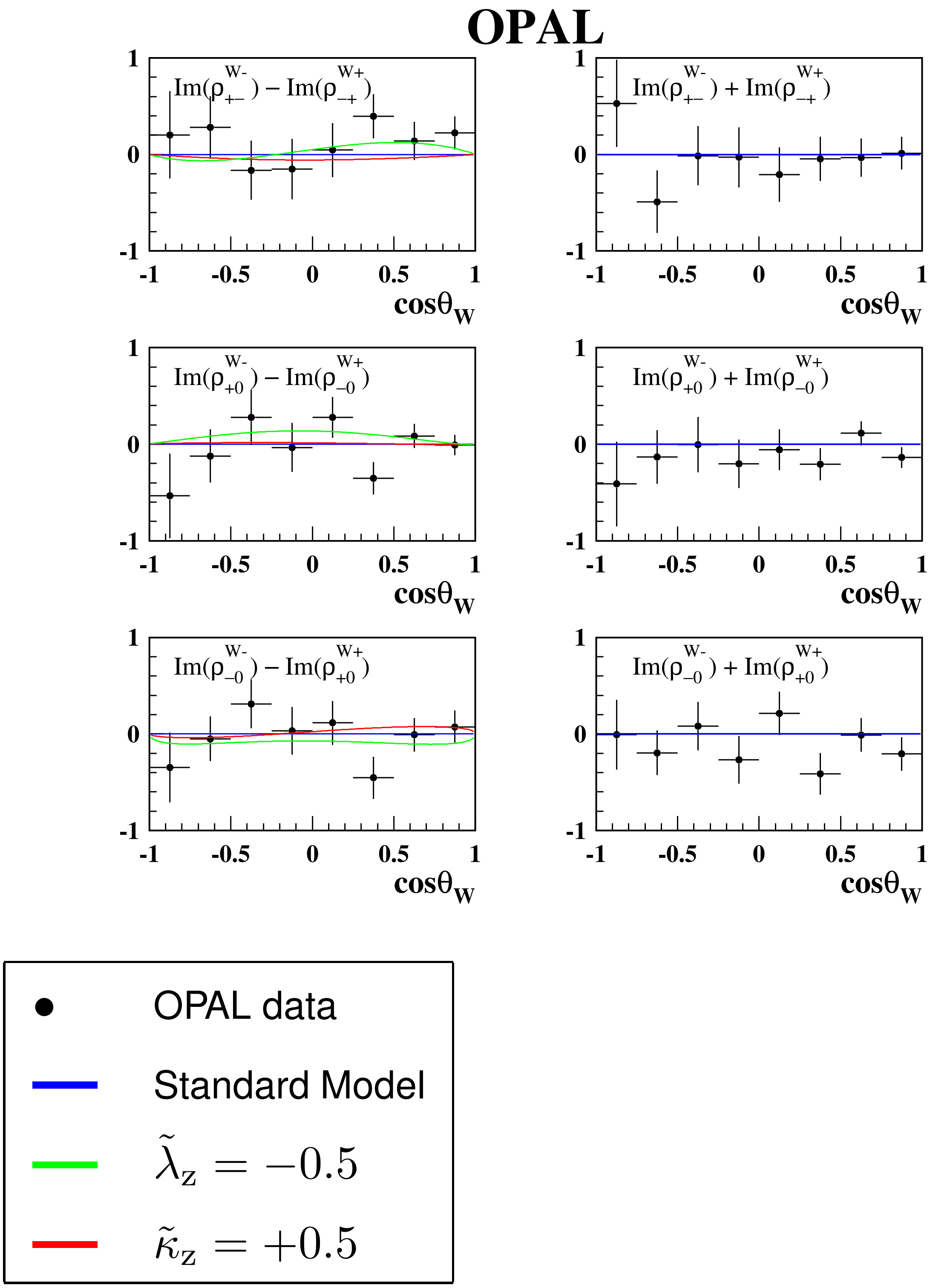
⇒ the 6 real elements of the single-W SDM are sensitive to all TGCs

⇒ the 3 imaginary elements are sensitive to CP-violating TGCs

We test one coupling at a time, and set all the others to their Standard Model values, except those related to the tested coupling via $SU(2) \times U(1)$ symmetry:

$$\begin{aligned} \tilde{\kappa}_{\mathrm{z}} &= -\tan^2\theta_{\mathrm{w}}\tilde{\kappa}_\gamma \\ \tilde{\lambda}_{\mathrm{z}} &= \tilde{\lambda}_\gamma \\ g_4^{\mathrm{z}} &= g_4^\gamma \end{aligned} \quad (1)$$

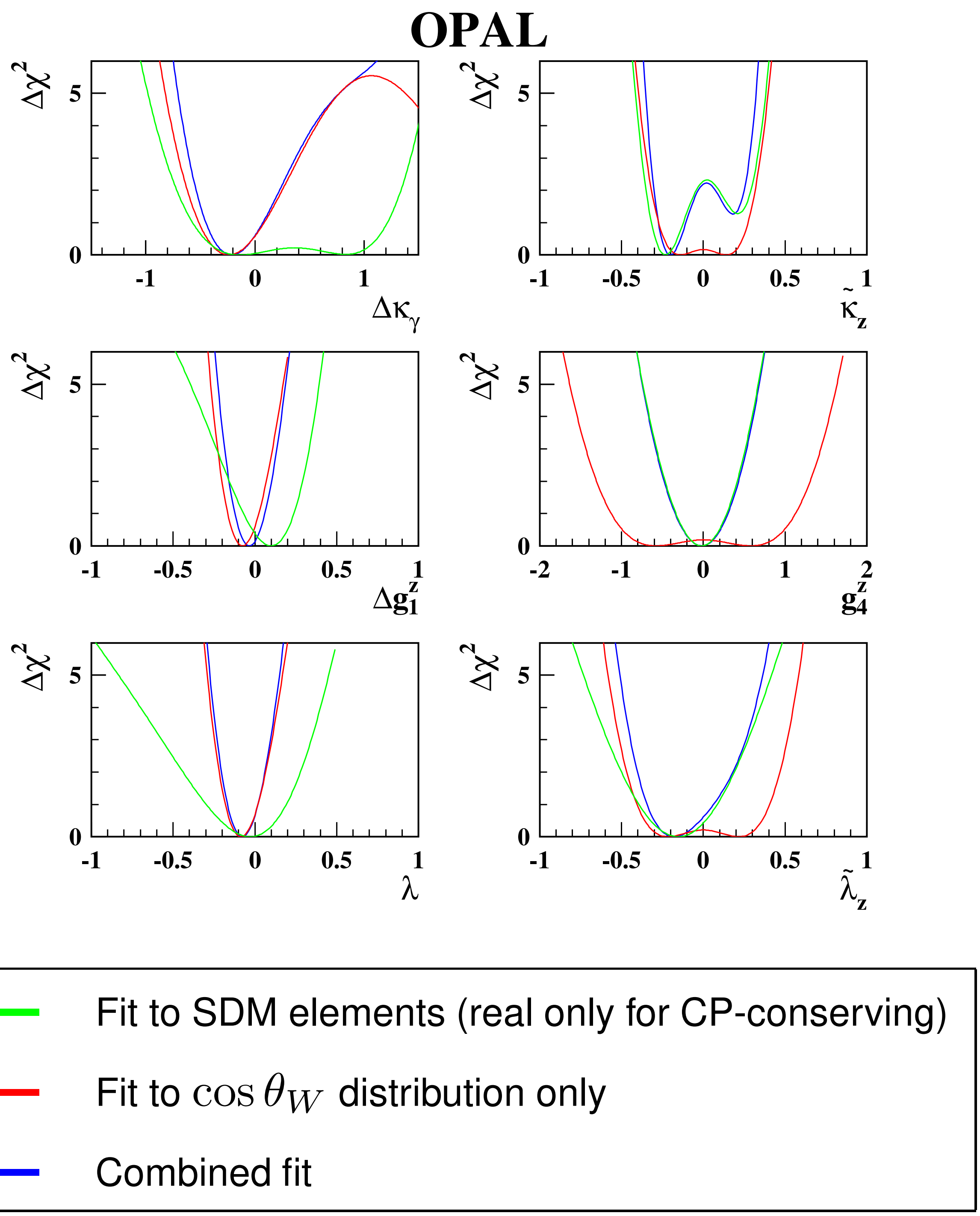
Sensitive Combinations of SDM Coefficients



CP-Violating TGCs

Fit	$\tilde{\kappa}_{\mathrm{z}}$	g_4^{z}	$\tilde{\lambda}_{\mathrm{z}}$
SDM Elements	$-0.19^{+0.08}_{-0.07}$	$0.00^{+0.21}_{-0.20}$	$-0.12^{+0.17}_{-0.16}$
$\cos\theta_{\mathrm{W}}$	$-0.19^{+0.46}_{-0.08}$	$0.7^{+0.4}_{-1.8}$	$-0.29^{+0.69}_{-0.11}$
Combined	$-0.19^{+0.06}_{-0.05}$	$0.01^{+0.22}_{-0.22}$	$-0.19^{+0.18}_{-0.13}$
Expected Stat. Error	±0.11	±0.19	±0.12
Final Fit Including Systematics	$-0.20^{+0.10}_{-0.07}$	$-0.02^{+0.32}_{-0.33}$	$-0.18^{+0.24}_{-0.16}$

χ^2 Fits for Anomalous Couplings



All fits include systematic uncertainties.

TGC Constraints Obtained

For the CP-violating couplings we find:

$$\begin{aligned} \tilde{\kappa}_{\mathrm{z}} &= -0.20^{+0.10}_{-0.07} \\ g_4^{\mathrm{z}} &= -0.02^{+0.32}_{-0.33} \\ \tilde{\lambda}_{\mathrm{z}} &= -0.18^{+0.24}_{-0.16} \end{aligned}$$

and for the CP-conserving couplings (done here as a cross-check) we find:

$$\begin{aligned} \Delta\kappa_{\gamma} &= -0.22^{+0.29}_{-0.24} \\ \Delta g_1^{\mathrm{z}} &= -0.03^{+0.09}_{-0.09} \\ \lambda &= -0.08^{+0.10}_{-0.09} \end{aligned}$$

which is consistent with the results of the OPAL optimal observable analysis

Conclusions

- direct measurement of fraction of W bosons produced with longitudinal polarization
- measurement of joint W pair production fractions $\sigma_{TT}/\sigma_{\mathrm{total}}, \sigma_{LL}/\sigma_{\mathrm{total}}, \sigma_{TL}/\sigma_{\mathrm{total}}$
- constraints on CP-violating TGCs
- all results consistent with Standard Model predictions