OPAL results on $\mathbf{WW}$ cross section and Triple Gauge Boson Couplings

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- $\mathbf{WW}$ events / cross section
- $\mathbf{W}$ branching ratios
- $|\mathbf{V_{cs}}|$
- triple gauge couplings
- spin density matirix elements
- summary

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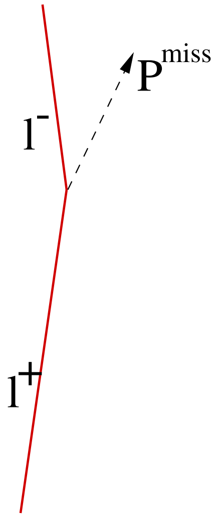
$\mathbf{WW}$ Event Topologies

$e^+e^- \rightarrow \ W^+W^- \ \rightarrow$

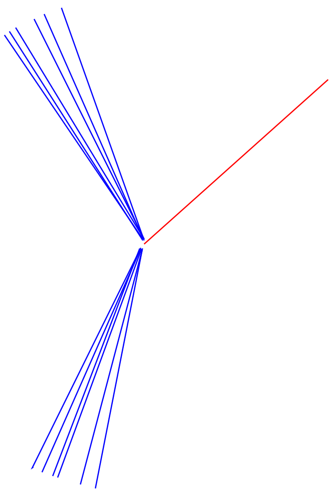


$\rightarrow \ l\bar{\nu}\bar{l}\nu$ **:**

- **2 narrow jets (1-3 tracks)**
- **missing (transverse) momentum**

eff. = $(78.0 \pm 2.3)\%$, purity =93.8%

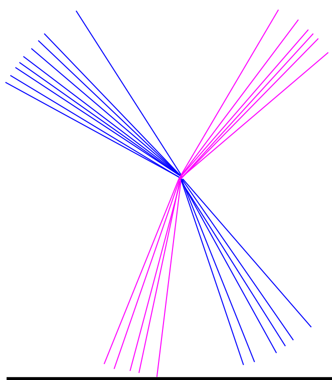
$\rightarrow \ q\bar{q}l\bar{\nu}$ **:**



- **2 jets**
- **high energy lepton**
  or 3rd low multiplicity jet ($q\bar{q}\tau\bar{\nu}_\tau$)
- **missing momentum**

eff. = $(84.7 \pm 1.3)\%$, purity = 90.2%

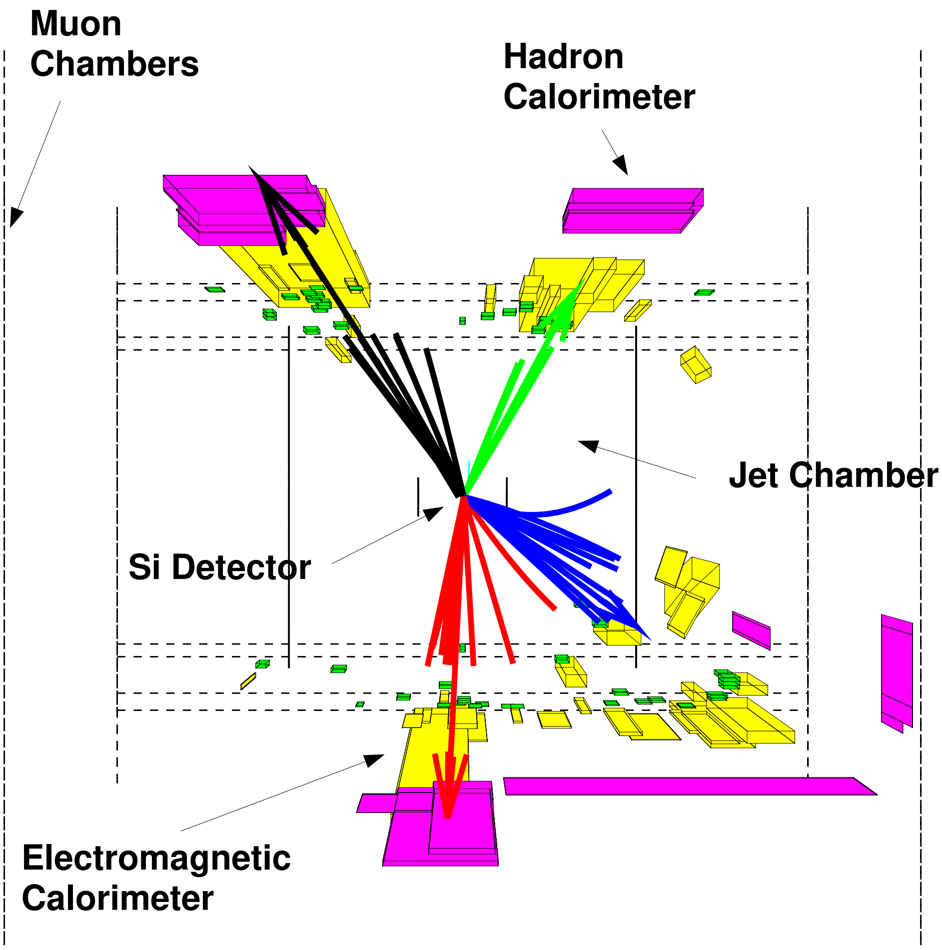
$\rightarrow \ q\bar{q}q\bar{q}$ **:**



- **4 jets**
- **no missing momentum**

eff. = $(84.6 \pm 1.0)\%$, purity = 78.3%

Reconstructed Events

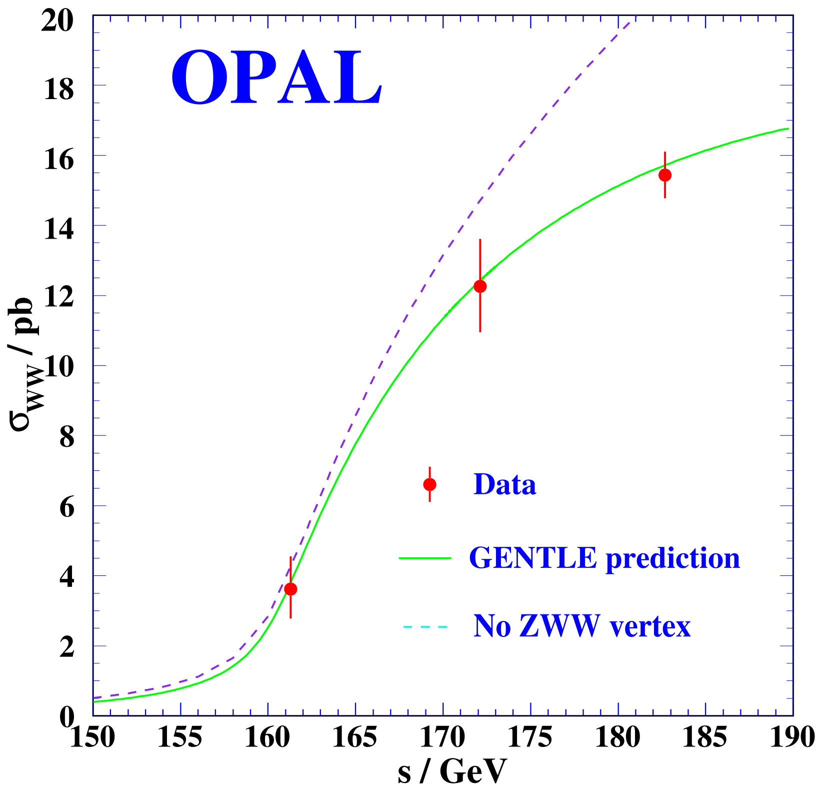


$57\mathrm{pb}^{-1}$ at 182.6 GeV $\Rightarrow$

	Signal	Background	Observed
$W^+W^- \to \ell\bar{\nu}_\ell \bar{\ell}'\nu_{\ell'}$	74.1	4.7	78
$W^+W^- \to q\bar{q}e\bar{\nu}_e$	118.4	11.3	140
$W^+W^- \to q\bar{q}\mu\bar{\nu}_\mu$	119.8	3.4	120
$W^+W^- \to q\bar{q}\tau\bar{\nu}_\tau$	99.1	19.2	101
$W^+W^- \to q\bar{q}q\bar{q}$	347.1	95.5	438
Combined	758.4	134.3	877

WW Coss section and Branching Ratios

Br($W \rightarrow e\overline{\nu}_e$)	=	$0.117 \pm .009 \pm .002$
Br($W \rightarrow \mu\overline{\nu}_\mu$)	=	$0.102 \pm .008 \pm .002$
Br($W \rightarrow \tau\overline{\nu}_\tau$)	=	$0.101 \pm .010 \pm .003$
Br($W \rightarrow q\overline{q}$)	=	$0.680 \pm .012 \pm .005$

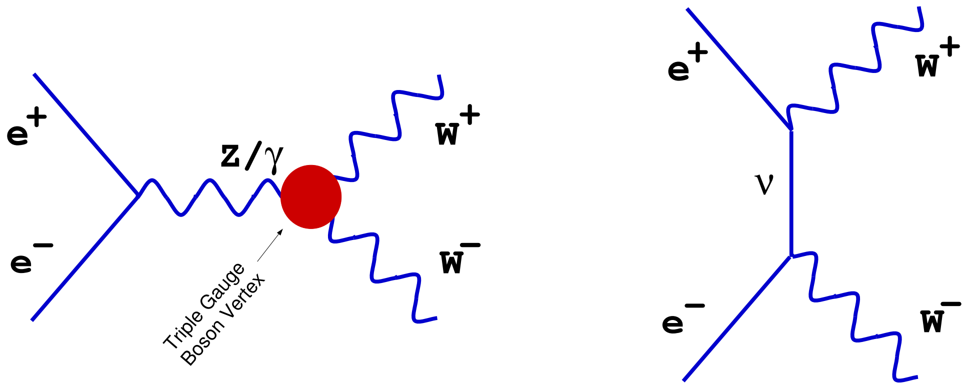


$$\sigma_{WW} = (15.43 \pm 0.61 \pm 0.26)\ \text{pb}$$

$$\frac{\mathrm{Br}(W\rightarrow \text{hadr.})}{\mathrm{Br}(W\rightarrow \text{lept.})} = \left(1 + \frac{\alpha_s}{\pi}\right) \sum |V_{ij}|^2$$

$$|V_{cs}| = 0.99 \pm 0.06 \pm 0.02$$

Triple Gauge Couplings



- most general Lagrangian $\Rightarrow$ 14 coupling constants (TGC's)
  (7 WWZ , 7 WWγ)

- $\underbrace{\kappa_\gamma , \kappa_z , g_1^z}_{=1} , \underbrace{\lambda_\gamma , \lambda_z}_{=0}$ are P, C and CP invariant in the SM

- SU(2)$\times$U(1) gauge invariance
  not affecting tree level propagators (LEP constraints from Z^0 data)

$$\Rightarrow \Delta\kappa_\gamma , \Delta g_1^z , \lambda$$

$$\Delta\kappa_\gamma = 1 - \kappa_\gamma$$
$$\Delta g_1^z = 1 - g_1^z$$
$$\Delta\kappa_z = -\Delta\kappa_\gamma \tan^2\theta_w + \Delta g_1^z$$
$$\lambda = \lambda_z = \lambda_\gamma$$

anomalous couplings affect the distribution of:

- W-production angle
- W-helicities (decay angles in W-rest frame)
- WW-production cross section

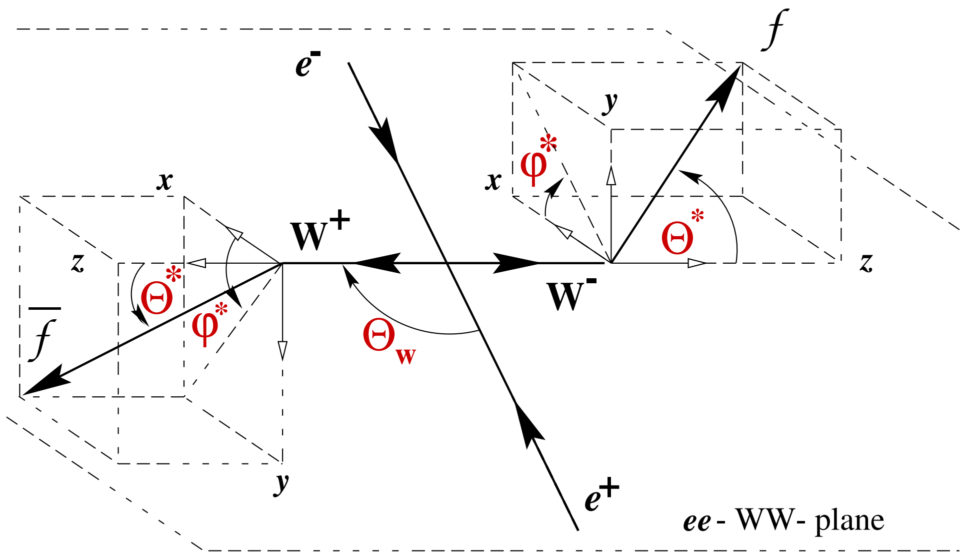
TGC Analysis

- reconstruct kinematics of the event
- apply kinematic fit to improve resolution

$\Rightarrow$ W production angle $\cos\theta_{\mathrm{W}}$

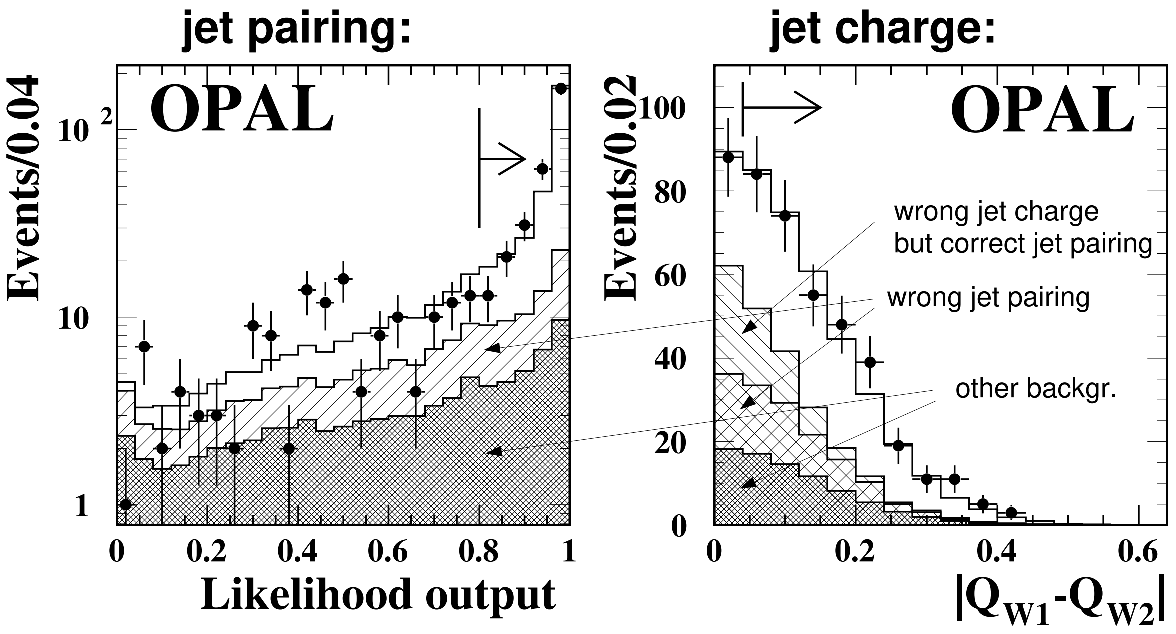
W helicities: decay angles in W-rest frame
($\cos\theta^*_f$, ϕ^*_f, $\cos\theta^*_{\bar{f}}$, $\phi^*_{\bar{f}}$)

accessibility depends on $\mathrm{q\bar{q}q\bar{q}}$
$\mathrm{q\bar{q}l\bar{\nu}}$
$\mathrm{l\bar{\nu}\bar{l}\nu}$



TGC Analysis in $W^+W^- \to q\bar{q}q\bar{q}$

- cannot determine individual quark flavor
- jet pairing, jet charge to determine $\cos\theta_{W^-}$

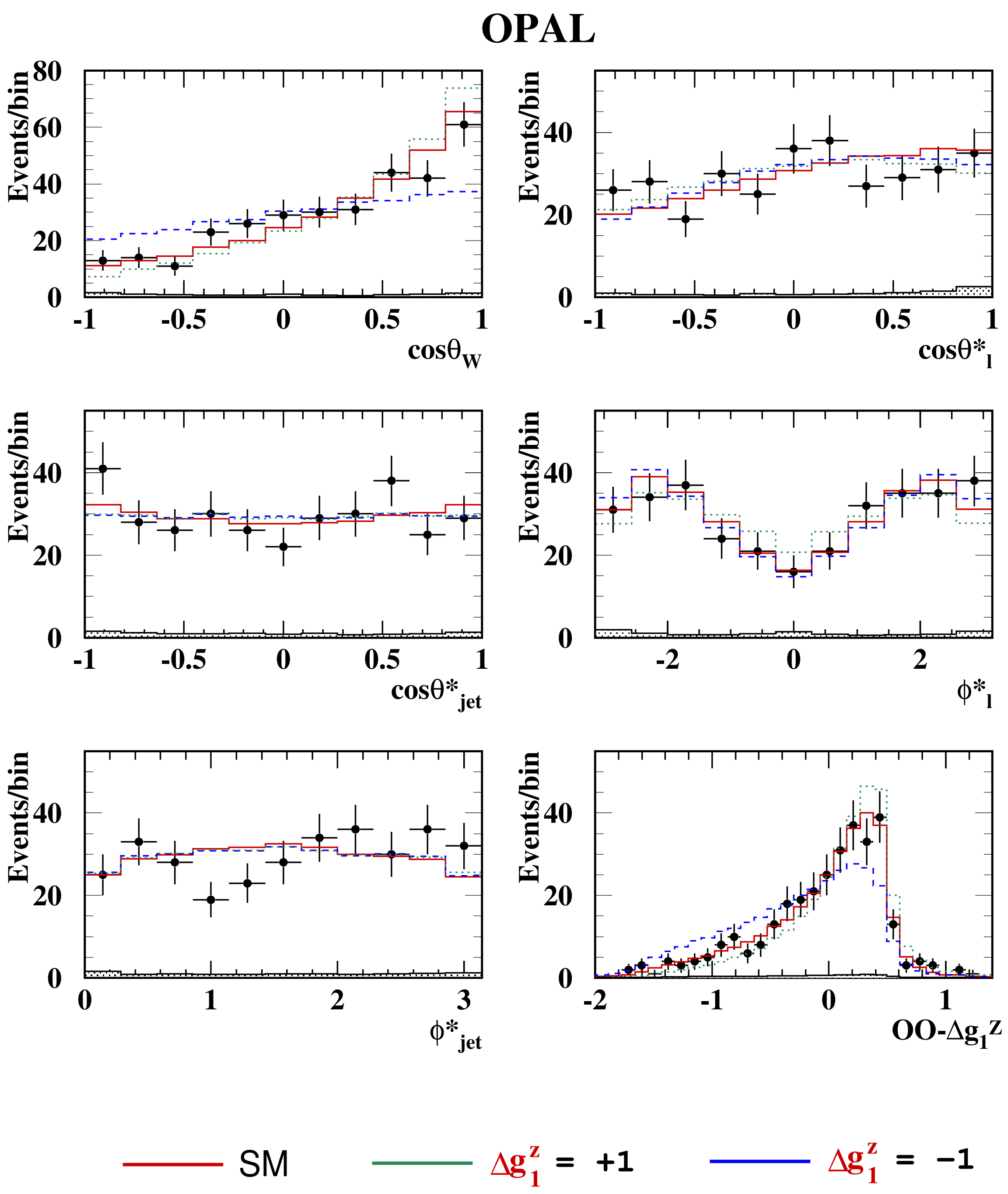


binned Maximum Likelihood Fit in $\cos\theta_{W^-}$

	$\Delta\kappa_\gamma$	Δg_1^z	λ_γ
in data (183 GeV)	$1.15^{+1.28}_{-1.25}$	$0.68^{+0.91}_{-0.64}$	$0.76^{+0.78}_{-0.67}$
expected errors	±1.13	±0.43	±0.52
including systematics	$1.16^{+1.39}_{-1.34}$	$0.73^{+0.88}_{-0.72}$	$0.79^{+0.79}_{-0.78}$
main syst. err.:			
fragmentation model	0.30	0.10	0.20

TGC Analysis in $W^+W^- \to q\bar{q}\ell\bar{\nu}_\ell$

- all angles accessible
  (ambiguity in quark flavor)



TGC Analysis in $\mathrm{W^+W^-} \to \mathrm{q\bar{q}}\ell\bar{\nu}_\ell$

Use optimal observable to project the

5 kinematic variables onto 1 observable.

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{SM}} + \alpha \cdot \mathrm{d}\sigma_{\mathrm{anom.}} \quad \Rightarrow \quad \mathrm{OO} = \frac{\mathrm{d}\sigma_{\mathrm{anom.}}}{\mathrm{d}\sigma_{\mathrm{SM}}}$$

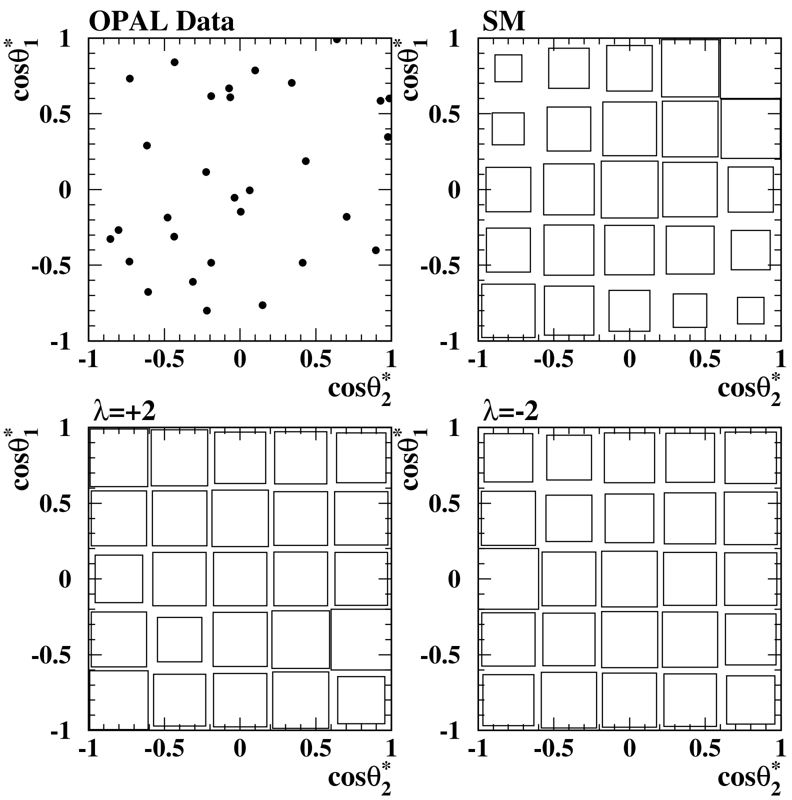
alternatively:

- binned Maximum Likelihood fit in $\cos\theta_{\mathrm{W}}$, $\cos\theta^*_\ell$, ϕ^*_ℓ
- fitting spin density matrix elements

	$\Delta\kappa_\gamma$	Δg_1^z	λ_γ
in data (183 GeV)	$-0.21^{+0.61}_{-0.45}$	0.00 ± 0.14	-0.19 ± 0.15
expected errors, OO	±0.46	±0.13	±0.14
expected errors, BML	±0.56	±0.16	±0.19
expected errors, SDM	±0.50	±0.14	±0.16
including systematics	$-0.18^{+0.77}_{-0.56}$	0.00 ± 0.16	-0.19 ± 0.16
main syst. err.:			
jet reconstruction	0.114	0.029	0.033

TGC Analysis in $\mathrm{W}^+\mathrm{W}^- \rightarrow \ell\overline{\nu}_\ell\overline{\ell}'\nu_{\ell'}$

- all angles accessible
  - ambiguity in sign of $(\cos\theta_\mathrm{W}, \phi^*_{\ell-}$ and $\phi^*_{\ell+})$



unbinned Maximum Likelihood Fit in:

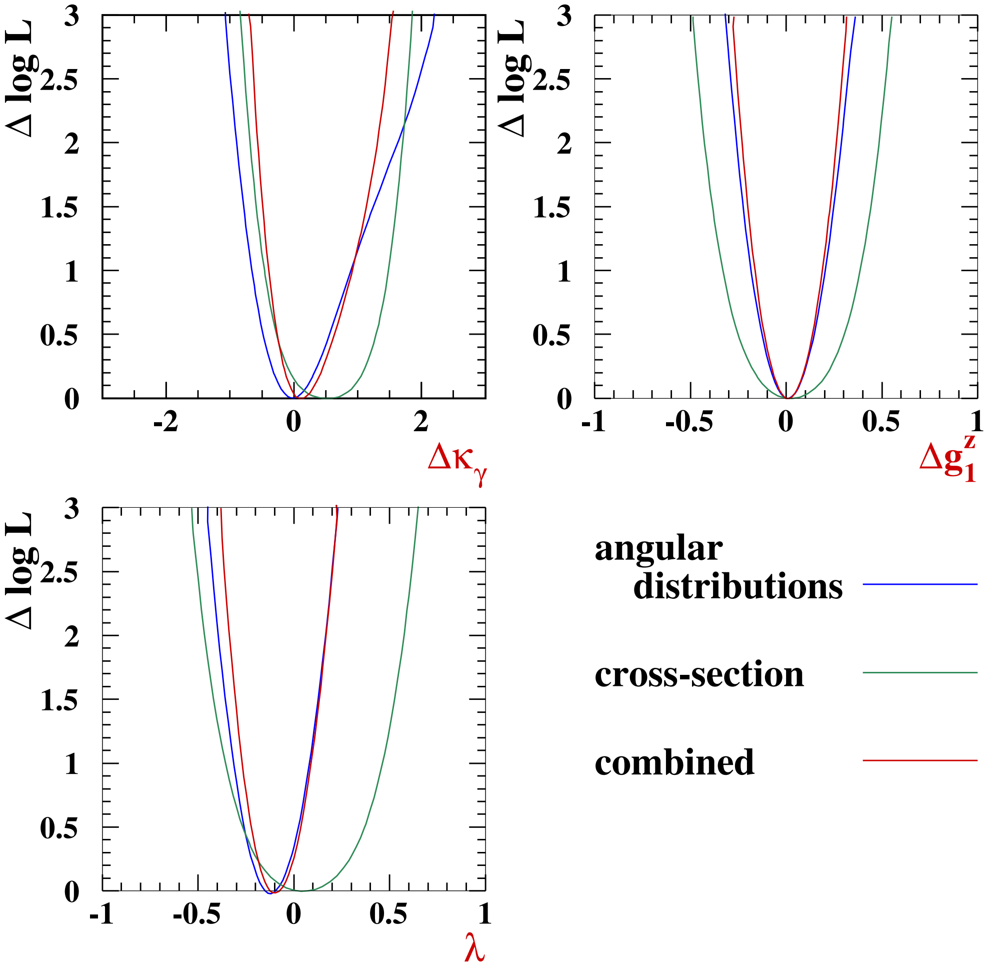
$\cos\theta_{\mathrm{W}-}, \cos\theta^*_{\ell-}, \phi^*_{\ell-}, \cos\theta^*_{\ell+}, \phi^*_{\ell+}$ averaged over ambiguity

	$\Delta\kappa_\gamma$	Δg_1^z	λ_γ
in data (183 GeV)	$-1.00^{+0.94}_{-0.92}$	$-0.79^{+0.56}_{-0.69}$	$-0.29^{+0.34}_{-0.38}$
expected errors	± 1.08	± 0.71	± 0.41
including systematics	$-0.74^{+1.23}_{-1.16}$	$-0.76^{+0.70}_{-0.79}$	$-0.23^{+0.35}_{-0.39}$
main syst. err.:			
Low statistics tests	± 0.56	± 0.05	± 0.03

TGC Results

combining all channels ($161 - 183$ GeV data) and total cross section

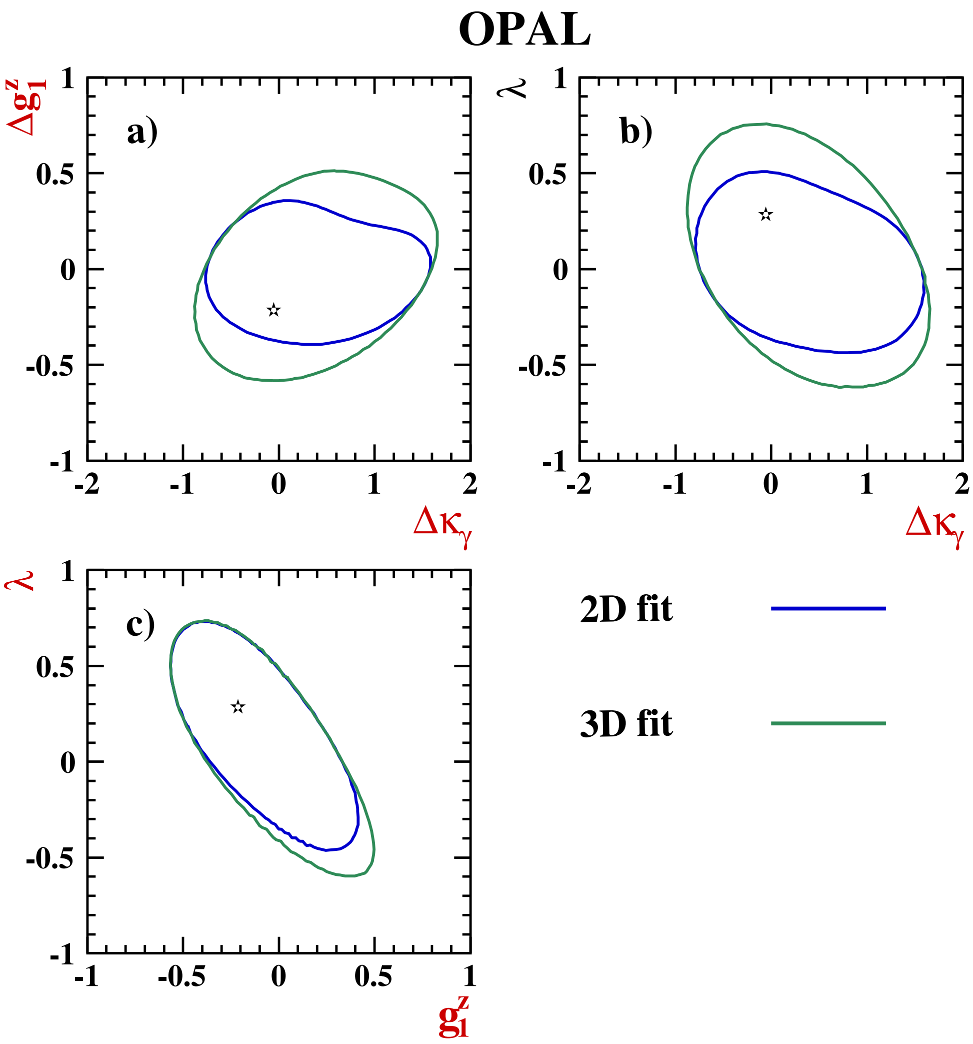
	$\Delta\kappa_\gamma$	Δg_1^z	λ_γ
Combined results	$0.11^{+0.52}_{-0.37}$	$0.01^{+0.13}_{-0.12}$	$-0.10^{+0.13}_{-0.12}$
95% C.L. limits	$[-0.55,\ 1.28]$	$[-0.23,\ 0.26]$	$[-0.33,\ 0.16]$



TGC Results

2 and 3 couplings allowed to vary freely

95% C.L results shown as contour plots



Spin Density Matrix (SDM) Elements

- **Model independent measurement of helicity structure**

helicity of $\mathrm{W}^{\pm}$

$\tau = 1$

$\tau = 0$

$\tau = -1$

λ: spin of $\mathrm{e}^+\mathrm{e}^-$-sys.

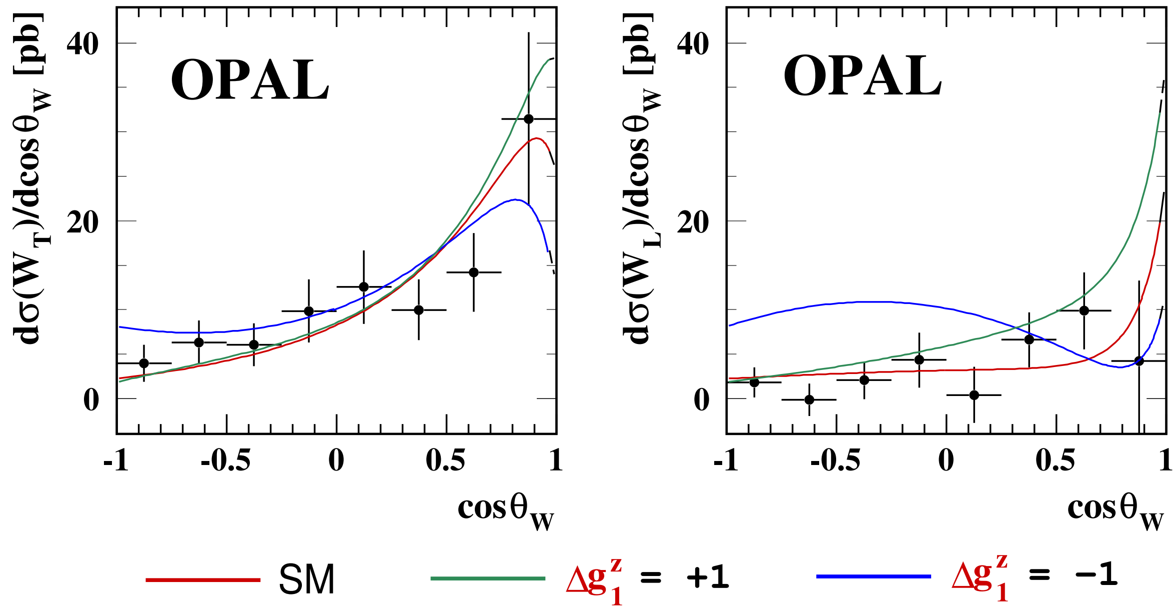
$$\rho_{\tau_-\tau'_-\tau_+\tau'_+}(\cos\theta_\mathrm{W}) = \frac{\sum_\lambda F^{(\lambda)}_{\tau_-\tau_+} (F^{(\lambda)}_{\tau'_-\tau'_+})^*}{\sum_{\lambda\tau_+\tau_-} |F^{(\lambda)}_{\tau_-\tau_+}|^2}$$

summation over $\mathrm{W}^+ \Rightarrow$ single W matrix element

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

diagonal elem. $\rho_{\tau_-\tau_-}$: probability of producing a W^- with helicity τ_-

diff. cross section for transverse, longitudinal polarized W's



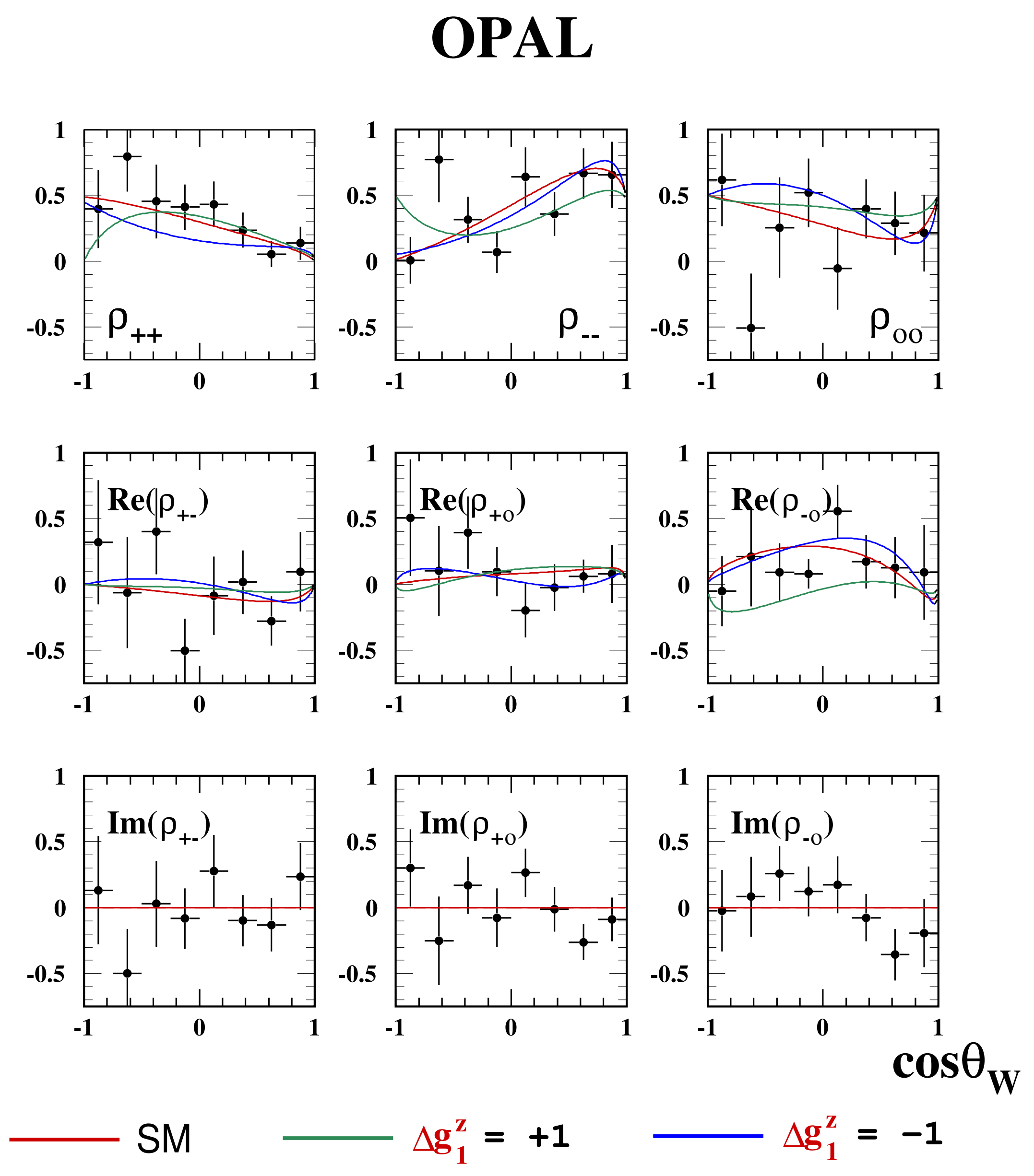
Single W Spin Density Matrix Elements

- 9 SDM-elements $\rho_{\tau_- \tau'_-}$

  hermitian matrix $\Rightarrow$ 6 independent parameters

- imaginary part of off diagonal elments:

  =0 for CP-conserving TGC's



Summary

877 $\mathbf{WW}$-candidates at 182.6 GeV (+ $120/28$ at $172/161$ GeV)

- $\mathbf{WW}$ cross section at 182.6 GeV

$$\sigma_{\mathrm{WW}} = (15.43 \pm 0.61 \pm 0.26)\ \mathrm{pb}$$

- $\mathbf{W}$ branching fraction to hadrons:

Br($\mathbf{WW} \rightarrow \mathrm{q\bar{q}}$) = $0.680 \pm .012 \pm .005$

$$|\mathrm{V_{cs}}| = 0.99 \pm 0.06 \pm 0.02$$

- measurement of TGC's

$\Delta\kappa_\gamma$ = $0.11^{+0.52}_{-0.37}$

Δg_1^z = $0.01^{+0.13}_{-0.12}$

λ_γ = $-0.10^{+0.13}_{-0.12}$

- spin density matirx element measurement

$$\frac{\mathrm{W}_L\mathrm{W}}{\mathrm{W}_L\mathrm{W}+\mathrm{W}_T\mathrm{W}} = (24.2 \pm 9.1 \pm 2.3)\%$$