

# CP-Violating TGC Analysis Update

Ian Bailey

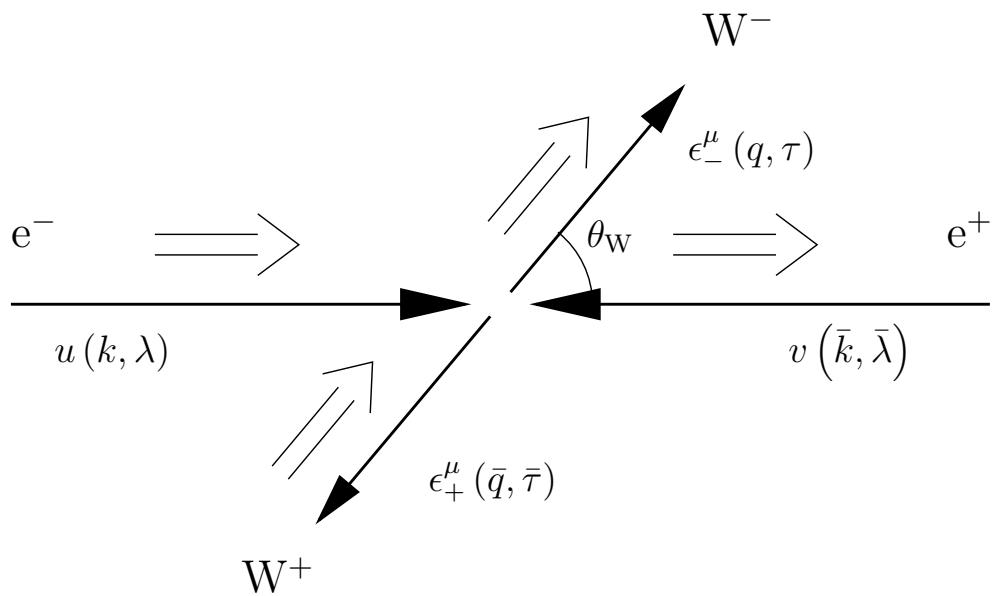


University of Victoria

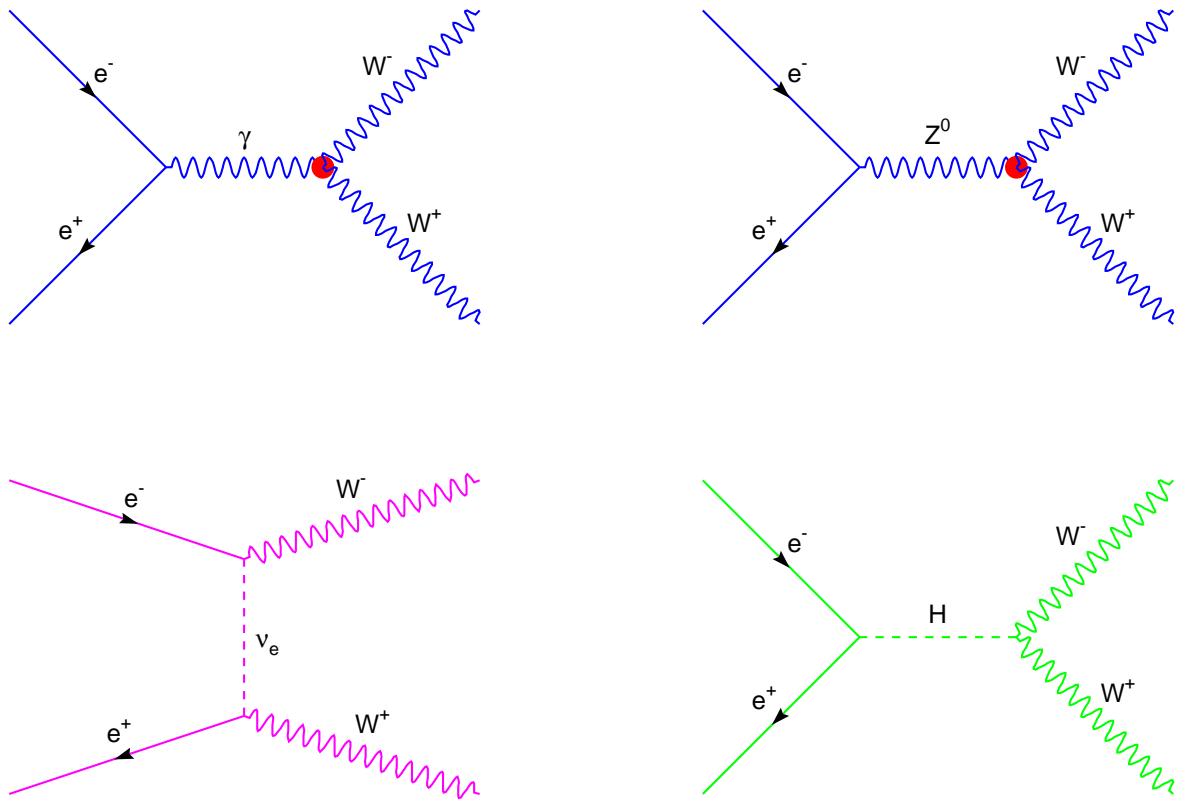
December plenary 2004

- WW Spin Density Matrix (SDM) review
- Reweighting fit
  - Bilenky (CC03)
  - Erato (4f)
- Current results (a first glimpse)
- Remaining work
- Conclusions

## The reaction $e^+e^- \rightarrow W^+W^-$



Standard Model tree-level Feynman diagrams



- - Triple Gauge Coupling vertex (TGC)

## cTGC phenomenological Lagrangian

---

$$\begin{aligned}
\frac{i\mathcal{L}_{\text{eff}}^{\text{WWV}}}{g_{\text{WWV}}} &= g_1^V V^\mu (W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu}) \\
&+ \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} \\
&+ \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^- \\
&+ ig_5^V \epsilon_{\mu\nu\rho\sigma} ((\partial^\rho W^{-\mu}) W^{+\nu} - W^{-\mu} (\partial^\rho W^{+\nu})) V^\sigma \\
&+ ig_4^V W_\mu^- W_\nu^+ (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
&- \frac{\tilde{\kappa}_V}{2} W_\mu^- W_\nu^+ \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} \\
&- \frac{\tilde{\lambda}_V}{2m_W^2} W_{\rho\mu}^- W_\nu^{+\mu} \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}
\end{aligned}$$

Standard Model Term  
 ‘Anapole’ Moment Term  
 CP Violating Term

$$\left( \begin{array}{lcl} g_{\text{WW}\gamma} & = & e \\ g_{\text{WWZ}} & = & e \cot \theta_{\text{wma}} \end{array} \right)$$

## W multipole moments

- Electric charge

$$q_W = e g_1^\gamma$$

- Magnetic dipole moment

$$\mu_W = \frac{e}{2m_W} (g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$$

- Electric quadrupole moment

$$Q_W = -\frac{e}{m_W^2} (\kappa_\gamma - \lambda_\gamma)$$

- Electric dipole moment

$$d_W = \frac{e}{2m_W} (\tilde{\kappa}_\gamma + \tilde{\lambda}_\gamma)$$

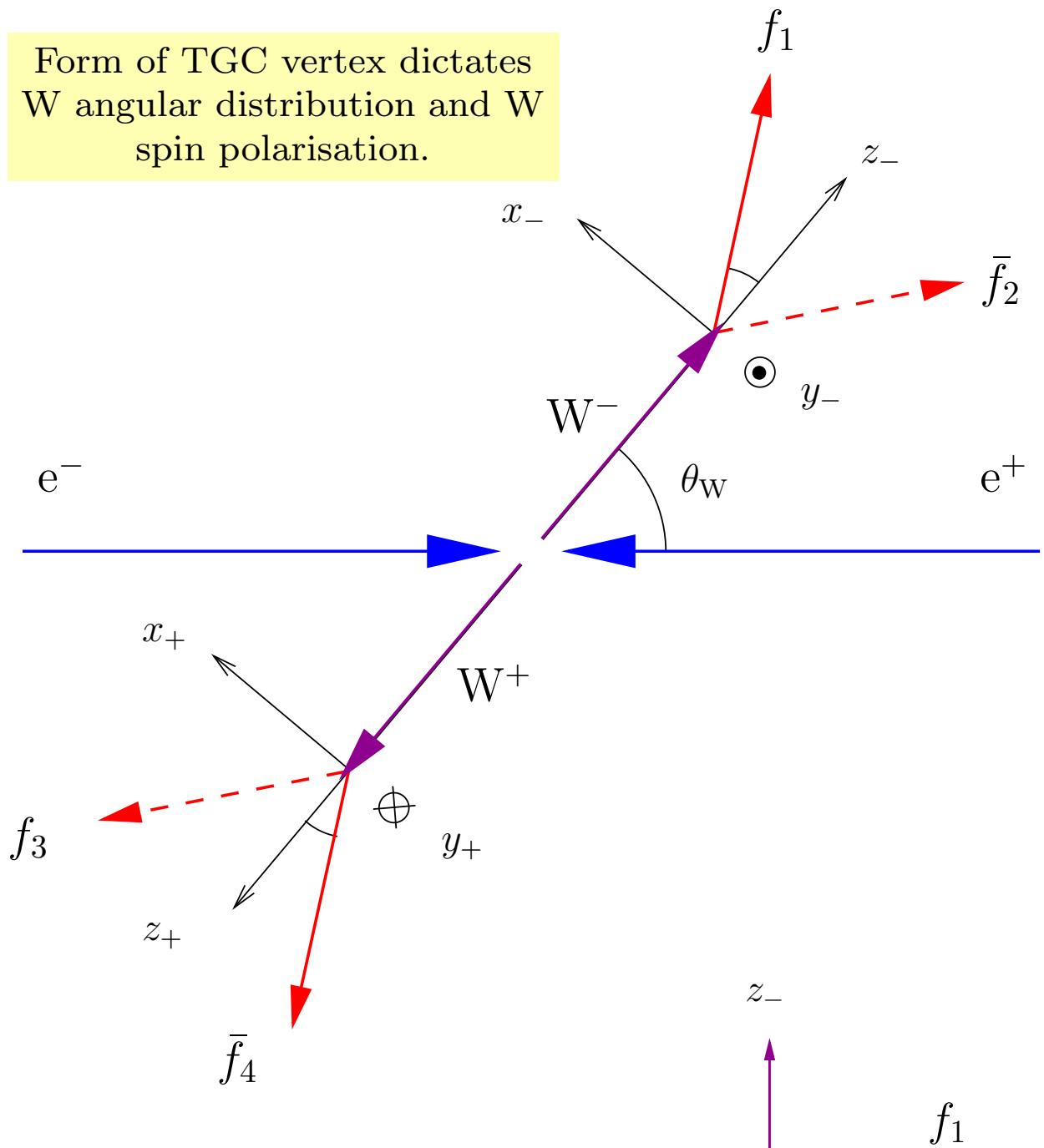
- Magnetic quadrupole moment

$$\tilde{Q}_W = -\frac{e}{m_W^2} (\tilde{\kappa}_\gamma - \tilde{\lambda}_\gamma)$$

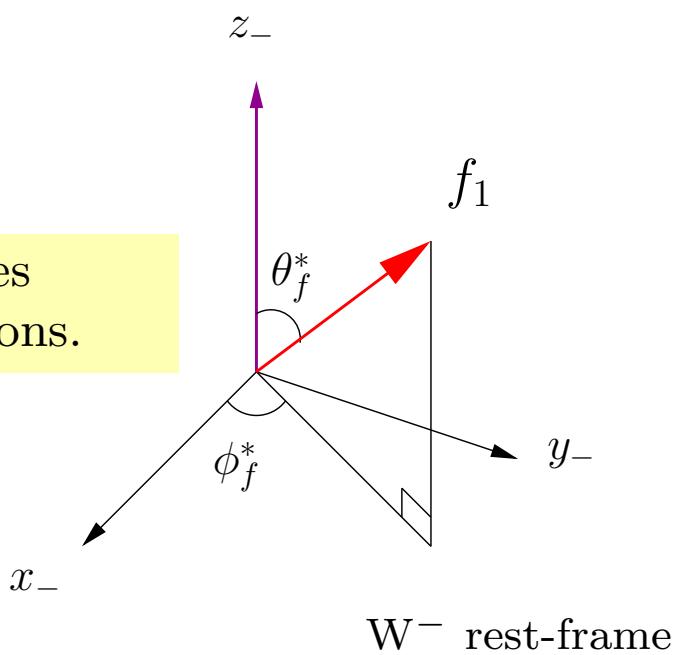
- WWZ coupling parameters  $\Rightarrow$  ‘weak’ multipole moments.

## W-pair event topology

Form of TGC vertex dictates W angular distribution and W spin polarisation.

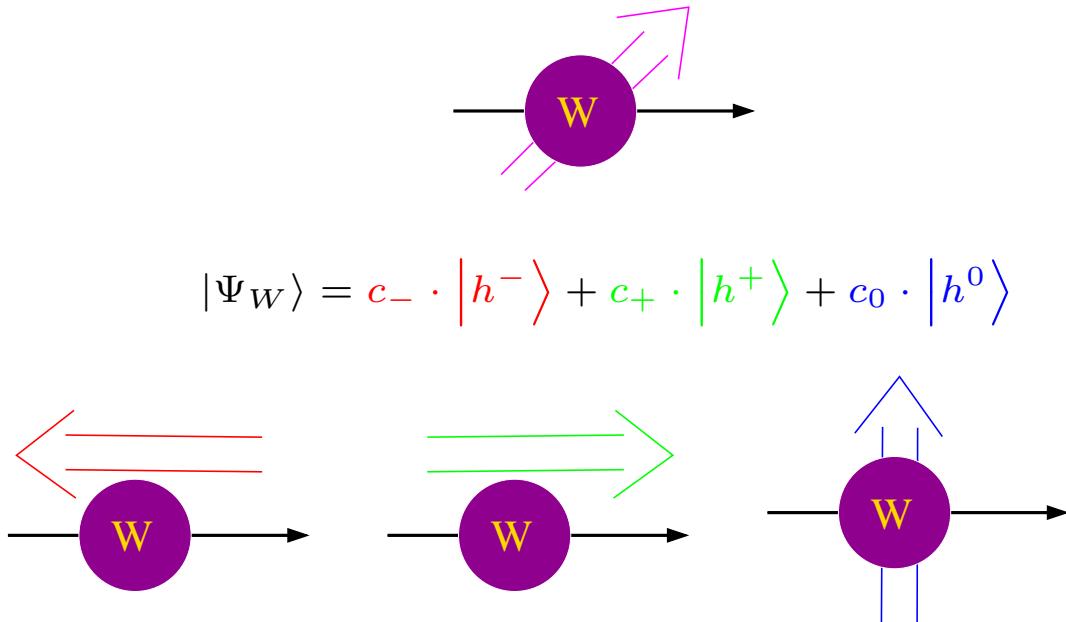


W polarisation dictates decay-product distributions.



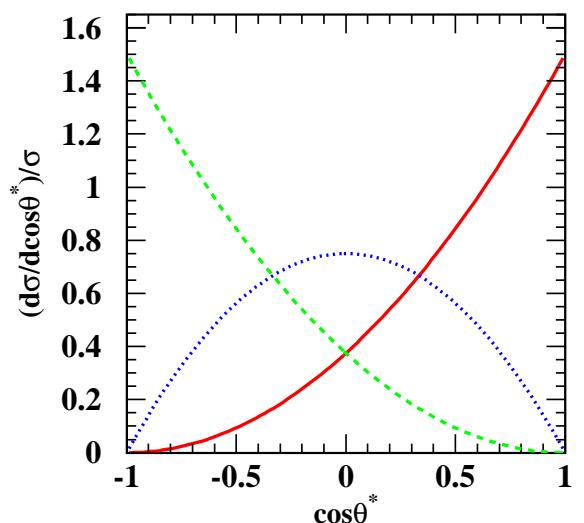
## W decay distributions

Each W is produced in a superposition of three helicity states...



...each giving a characteristic angular decay distribution.

W helicity	Decay Distribution
-	$\frac{3}{8} (1 + \cos \theta_f^*)^2$
+	$\frac{3}{8} (1 - \cos \theta_f^*)^2$
0	$\frac{3}{4} \sin^2 \theta_f^*$



## Helicity state projection operators

Spin state of the  $W^-$ :

$$|\Psi_W\rangle = \textcolor{red}{c}_- \cdot |h^-\rangle + \textcolor{green}{c}_+ \cdot |h^+\rangle + \textcolor{blue}{c}_0 \cdot |h^0\rangle$$

Define projection operators  $\Lambda_{\tau\tau'}$ :

$$\frac{1}{\sigma} \int \Lambda_{\tau\tau'} \frac{d\sigma}{d\Omega} d\cos\theta_f^* d\phi_f^* = c_\tau c_{\tau'}^* = \rho_{\tau\tau'}$$

$$\begin{aligned} \langle \cos\theta_f^*, \phi_f^* | h^-\rangle &\equiv \sqrt{\frac{3}{8}} \cdot (1 + \cos\theta_f^*) \cdot e^{i\phi_f^*} \\ \langle \cos\theta_f^*, \phi_f^* | h^+\rangle &\equiv \sqrt{\frac{3}{8}} \cdot (1 - \cos\theta_f^*) \cdot e^{-i\phi_f^*} \\ \langle \cos\theta_f^*, \phi_f^* | h^0\rangle &\equiv \sqrt{\frac{3}{4}} \cdot \sin\theta_f^* \end{aligned}$$

Gives a set of (9) linear equations for each  $\Lambda_{\tau\tau'}$

Solution...

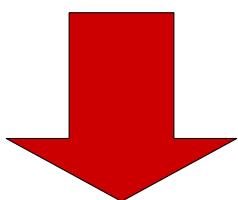
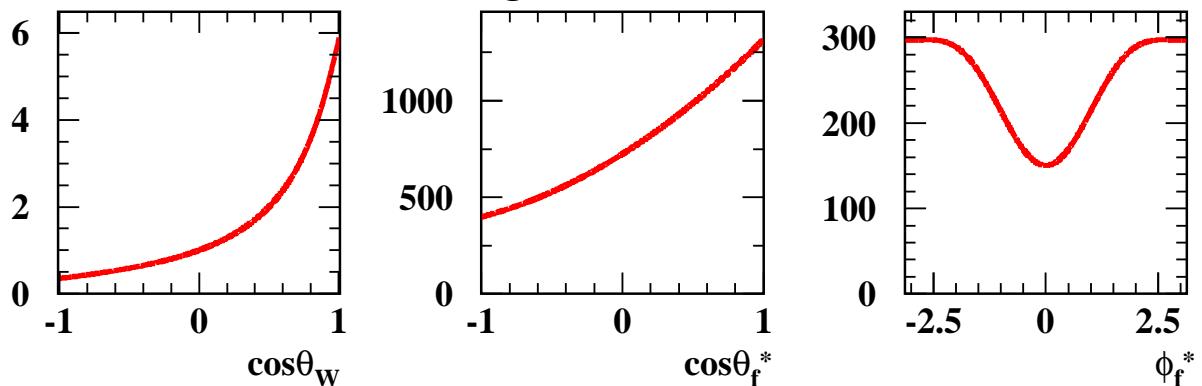
$$\begin{aligned} \Lambda_{--} &= \frac{1}{2} \left( 5 \cos^2 \theta_f^* + 2 \cos \theta_f^* - 1 \right) \\ \Lambda_{++} &= \frac{1}{2} \left( 5 \cos^2 \theta_f^* - 2 \cos \theta_f^* - 1 \right) \\ \Lambda_{00} &= 2 - 5 \cos^2 \theta_f^* \\ \Lambda_{+-} &= 2 e^{-2i\phi_f^*} \end{aligned}$$

Etc...

## Helicity states

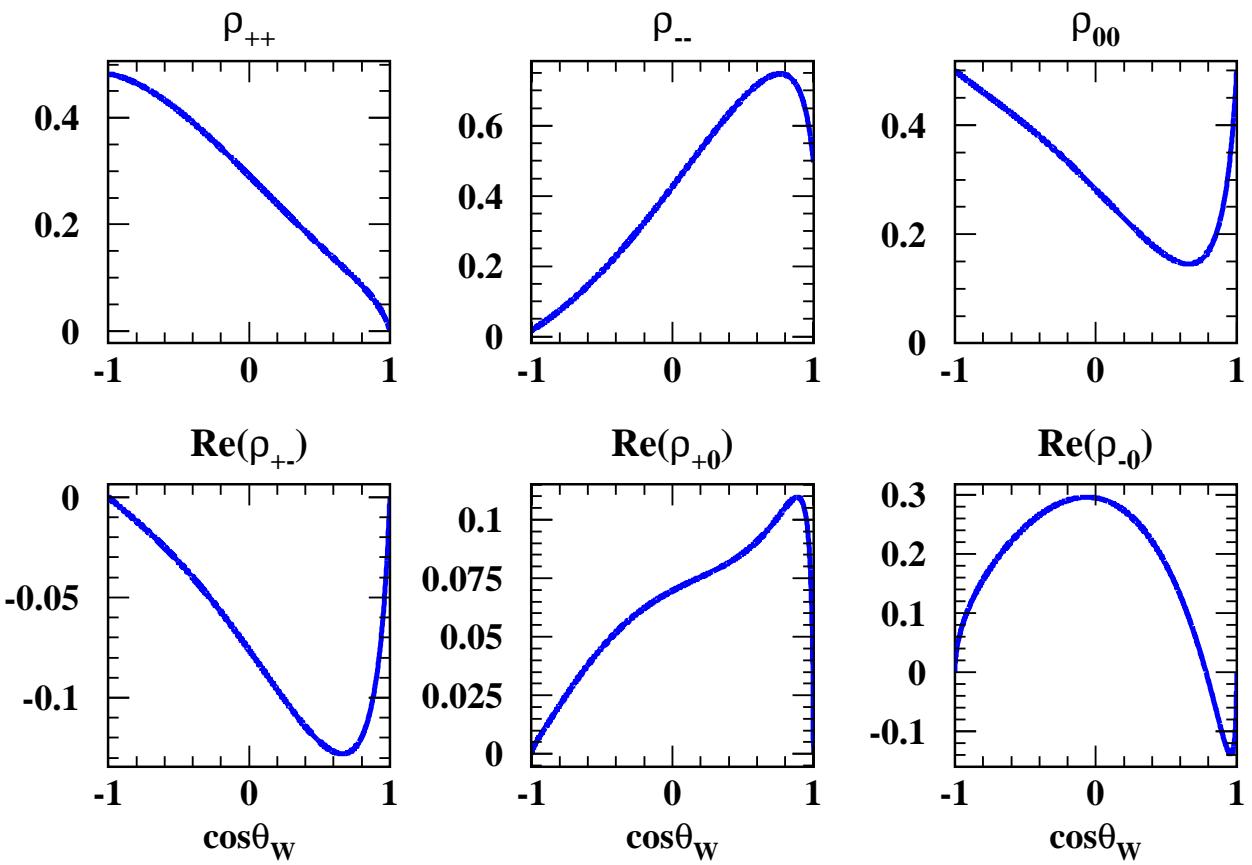
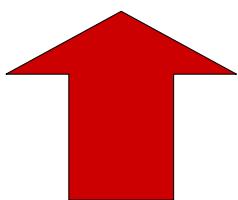
---

SM Angular Distributions



Projection  
Operators

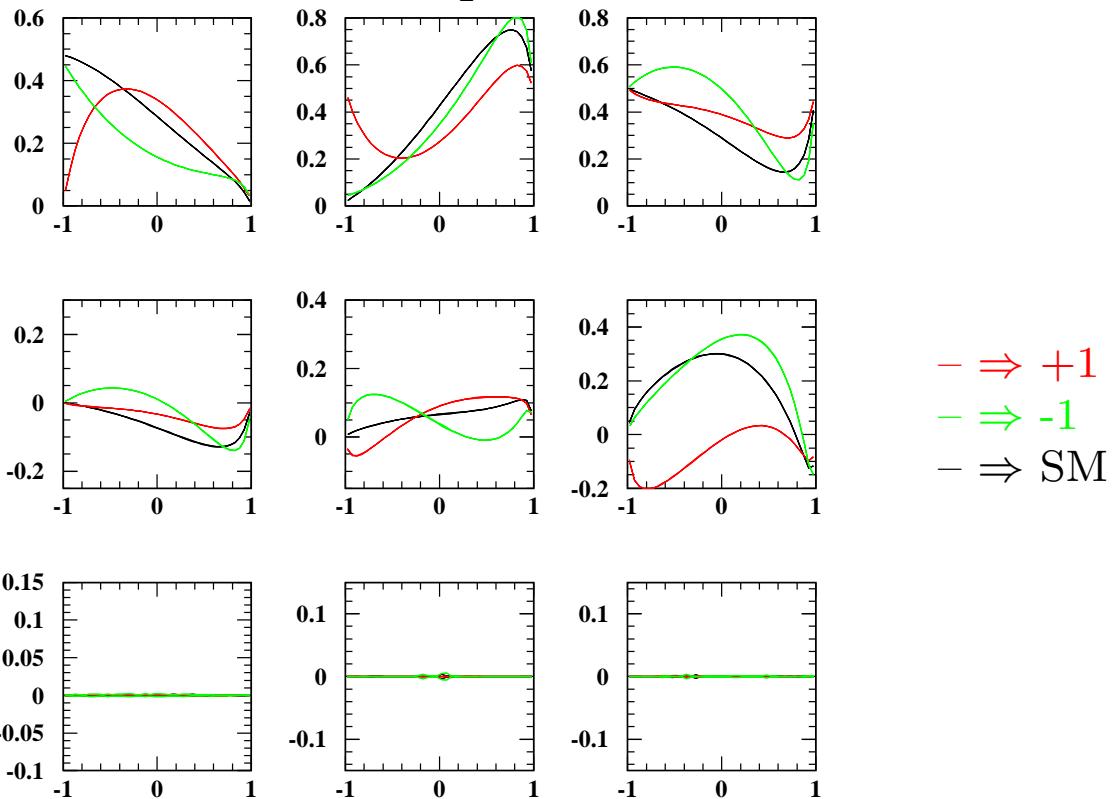
D-Functions



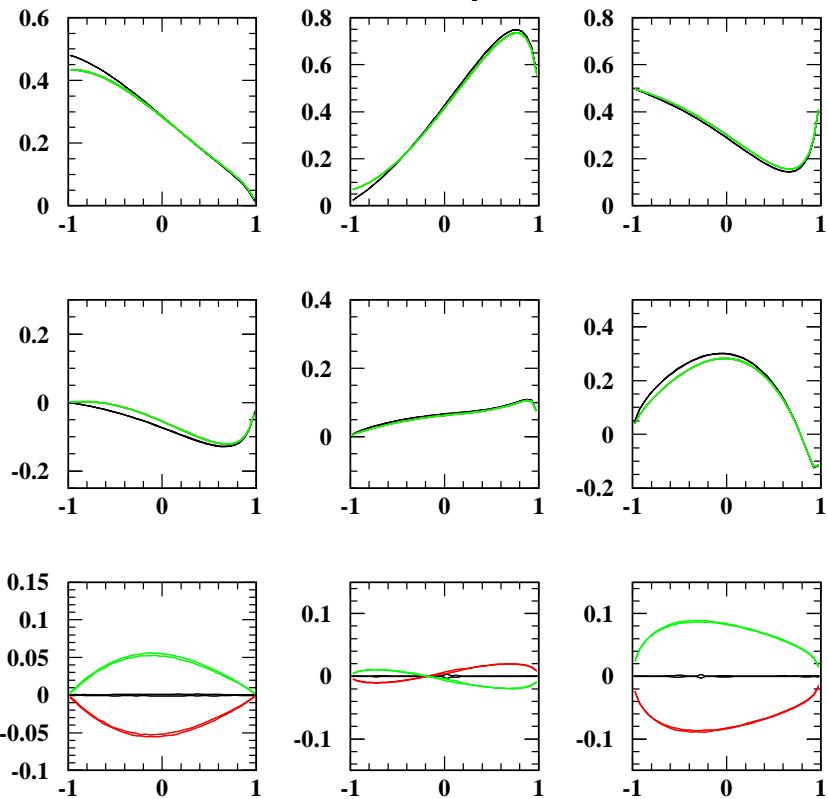
SM Spin Density Matrix

## Anomalous TGC effects

$\Delta g_1^z$



$\Delta g_4^z$



## Spin density matrix (SDM) overview

Definition (reduced matrix for  $W^-$ )

$$\rho_{\tau, \tau'}^{W^-}(s, \cos \theta_W) = \frac{\sum_{\lambda, \bar{\lambda}, \bar{\tau}} F^{(\tau, \bar{\tau}; \lambda, \bar{\lambda})} (F^{(\tau', \bar{\tau}; \lambda, \bar{\lambda})})^*}{\sum_{\lambda, \bar{\lambda}, \tau, \bar{\tau}} |F^{(\tau, \bar{\tau}; \lambda, \bar{\lambda})}|^2}$$

- Normalised Hermitean matrix (8 d.o.f.)
- $F$  denotes the helicity amplitude
- $\tau$  denotes  $W^-$  helicity state
- $\bar{\tau}$  denotes  $W^+$  helicity state
- $\lambda$  denotes  $e^-$  helicity state
- $\bar{\lambda}$  denotes  $e^+$  helicity state

Longitudinal W Polarisation ( $\rho_{00}$ ) - In PR394

Model Independent CP Tests - In PR394

CP Violating TGC's - This talk

- $\tilde{\lambda}_Z$
- $g_4^Z$
- $\tilde{\kappa}_Z$

Doubly Polarised Cross-sections - No plans

- $\sigma_{TT}/\sigma_{total}$
- $\sigma_{LL}/\sigma_{total}$
- $\sigma_{TL}/\sigma_{total}$

# CP-Violating TGC Analysis Strategy

## Measure SDM

- Use OPAL ‘WW’  $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}'\ell\nu_\ell$  selection
- Measure the angular distributions from the data
- Apply projection operators (using 8 bins in  $\cos\theta_W$ )

$$\rho_{\tau\tau'}^k = \frac{1}{n_k} \sum_{i=1}^{n_k} \Lambda_{\tau\tau'}(\Omega_i)$$

- Simltaneously fit reweighted MC to
  - SDM ( 64 d.o.f. )
  - $\cos(\theta_W)$  distribution ( 8 d.o.f.)

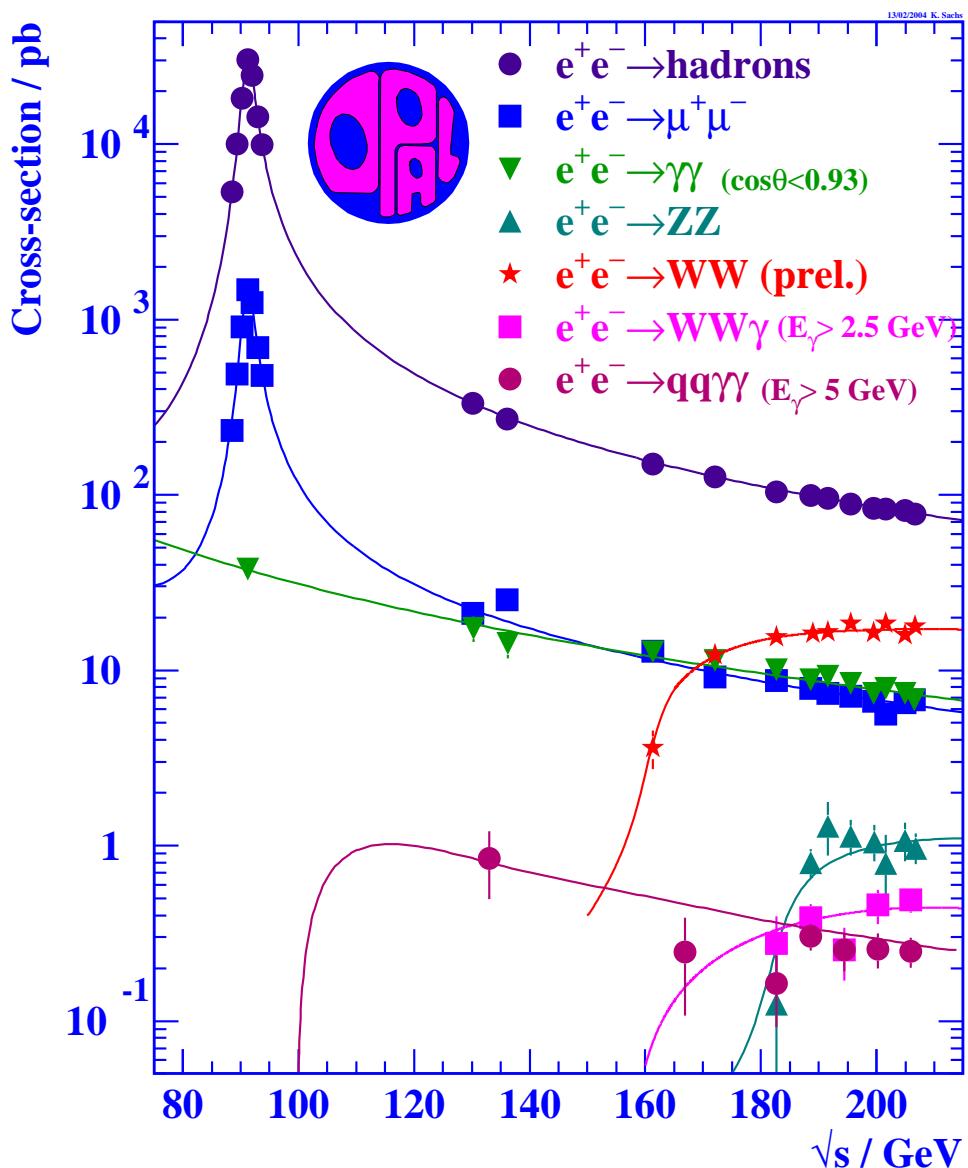
## Fit using ‘raw’ data and GOPALised MC (KandY)

- No unfolding
- Used in published OPAL 189 GeV paper (PR323)
- Avoids bias and correlation problems

## Reweighting calculator

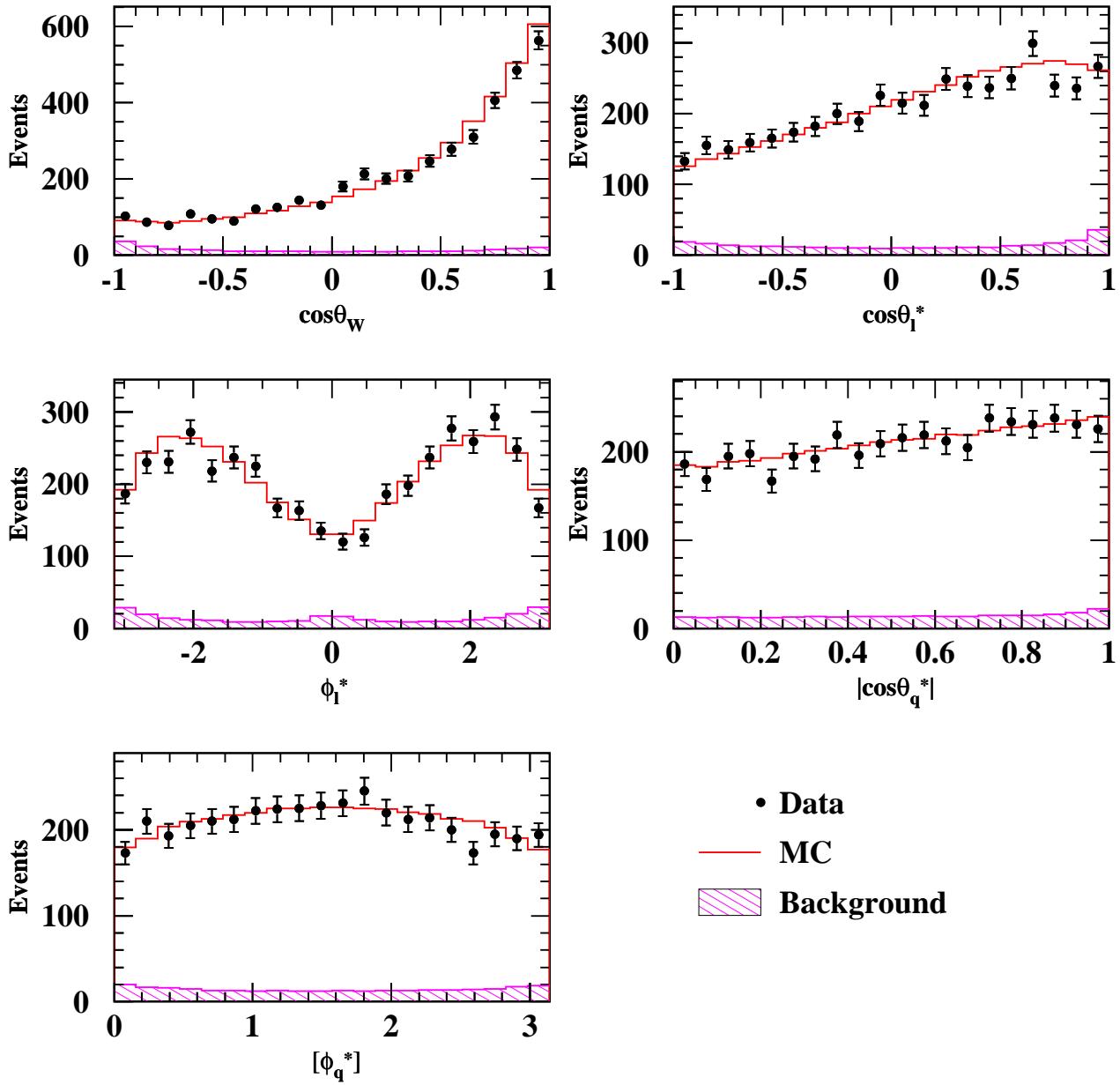
- Bilenky (WVC) calculator
  - Doesn’t include ISR, off-shell W’s, etc
- Erato
  - 4-fermion MC generator with all TGC parameters
  - Previously used to generate four-vectors at 189 GeV
  - Convert to a reweighting calculator
- Reweight with one calculator, and fit with the other
  - Bias tests, etc...

## Event selection and reconstruction



- Track quality selection
- $q\bar{q}'\ell\nu$  pre-selection
- Lepton track identification
- Lepton-specific selections ( $q\bar{q}'e\nu$ ,  $q\bar{q}'\mu\nu$ ,  $q\bar{q}'\tau\nu$ )
  - Pre-selection
  - Likelihood selection
- Kinematic fit
- Final selection
  - 4176 events
  - Efficiency  $\approx 80\%$
  - Purity  $\approx 94\%$

## Measured distributions



	$\cos\theta_W$	$\cos\theta_{l^*}$	$\phi_{l^*}$	$ \cos\theta_{q^*} $	$[\phi_{q^*}]$
$\chi^2/\text{d.o.f.}$	1.69	1.22	1.51	0.57	0.80

## Erato Status

- Migrated from HP to Linux
  - Non-standard F77
  - Non-standard compiler flags
  - Tested against demonstration job  
(‘perfect’ agreement)
- Extracted matrix element calculators
  - Erato uses separate files for each final state (e.g. qqqq)
  - Have combined all files into one Patchy cradle
  - Resolved name conflicts
  - Matched input parameters (e.g.  $m_W$ ) with KandY
  - Tested CC03 prediction against Bilenky  
(sub-percent agreement)
- Interfaced to pre-existing SDM fitting code  
(work ongoing)
  - REAL (ntuple) v DOUBLE PRECISION (Erato)
  - Fermion masses (ERAMAS)
  - ISR boost
  - Flavour ID

## Fit results

Simultaneous fits to SDM and  $\cos \theta_W$   
Bilenky

	183	189	192	196	200	202	205	207
$\Delta g_1^Z$	0.46	-0.33	0.92	-0.90	-0.53	-0.16	0.16	-0.25
+ve error	0.90	0.38	0.61	0.43	0.40	0.71	0.36	0.49
-ve error	-1.16	-0.33	-0.80	-0.34	-0.33	-0.56	-0.35	-0.34
$\chi^2/\text{d.o.f.}$	0.99	0.98	1.26	1.16	1.42	1.29	1.37	0.91

Erato

	183	189	192	196	200	202	205	207
$\Delta g_1^Z$	0.46	0.15	0.36	0.36	0.09	-0.44	-0.33	0.00
+ve error	0.34	0.23	0.38	0.28	0.28	0.59	0.33	0.00
-ve error	-0.53	-0.34	-2.08	-0.46	-0.46	-0.63	-0.39	0.00
$\chi^2/\text{d.o.f.}$	0.98	0.99	1.27	1.20	1.44	1.28	1.35	0.00

Bilenky

	183	189	192	196	200	202	205	207
$g_4^Z$	0.75	0.00	0.97	-1.30	-0.58	0.29	0.00	-0.72
+ve error	0.88	0.80	0.73	0.65	0.75	0.91	0.48	0.72
-ve error	-1.47	-0.81	-1.08	-0.46	-0.53	-1.27	-0.48	-0.40
$\chi^2/\text{d.o.f.}$	0.99	0.99	1.26	1.17	1.43	1.29	1.37	0.90

Erato

	183	189	192	196	200	202	205	207
$g_4^Z$	-0.57	-0.02	-1.52	1.34	0.96	-0.02	0.12	0.00
+ve error	1.58	0.75	1.42	0.87	0.68	1.39	0.61	0.00
-ve error	-1.25	-0.74	-0.97	-1.77	-0.82	-1.39	-0.63	0.00
$\chi^2/\text{d.o.f.}$	0.99	0.99	1.26	1.20	1.42	1.29	1.37	0.00

Statistical uncertainty only. No  $SU(2)_c$  constraints. Preliminary!

## Fit results (2)

Simultaneous fits to SDM and  $\cos \theta_W$   
 Bilenky

	183	189	192	196	200	202	205	207
$\Delta \kappa_\gamma$	-0.60	-0.32	2.40	-0.58	-0.45	0.08	0.35	-0.30
+ve error	1.04	0.38	0.52	0.46	0.38	0.75	0.54	0.30
-ve error	-0.64	-0.32	-0.68	-0.37	-0.31	-0.53	-0.41	-0.24
$\chi^2/\text{d.o.f.}$	0.99	0.98	1.21	1.18	1.42	1.29	1.36	0.90

Erato

	183	189	192	196	200	202	205	207
$\Delta \kappa_\gamma$	-0.74	-0.61	1.23	-0.80	-0.54	0.25	0.15	0.00
+ve error	1.60	0.64	1.17	1.52	0.78	0.97	0.59	0.00
-ve error	-1.38	-0.60	-2.29	-1.09	-0.72	-1.04	-0.60	0.00
$\chi^2/\text{d.o.f.}$	0.99	0.98	1.27	1.20	1.43	1.29	1.37	0.00

Bilenky

	183	189	192	196	200	202	205	207
$\tilde{\kappa}_Z$	-0.42	0.22	-0.35	0.68	0.45	-0.10	-0.02	0.51
+ve error	1.16	0.27	0.57	0.23	0.25	0.65	0.25	0.18
-ve error	-0.36	-0.50	-0.39	-0.34	-0.38	-0.52	-0.25	-0.26
$\chi^2/\text{d.o.f.}$	0.99	0.99	1.27	1.18	1.42	1.29	1.37	0.88

Erato

	183	189	192	196	200	202	205	207
$\tilde{\kappa}_Z$	-0.35	0.02	-0.67	0.74	0.40	0.02	0.02	0.00
+ve error	1.01	0.37	0.91	0.36	0.36	0.65	0.32	0.00
-ve error	-0.51	-0.38	-0.46	-0.71	-0.49	-0.68	-0.33	0.00
$\chi^2/\text{d.o.f.}$	0.99	0.99	1.26	1.19	1.43	1.29	1.37	0.00

Statistical uncertainty only. No  $SU(2)_c$  constraints. Preliminary!

## Fit results (3)

Simultaneous fits to SDM and  $\cos \theta_W$   
 Bilenky

	183	189	192	196	200	202	205	207
$\lambda_\gamma$	-0.41	-0.28	0.79	-0.81	-0.37	-0.19	0.18	-0.16
+ve error	2.26	0.44	0.67	0.35	0.40	0.81	0.31	0.72
-ve error	-0.66	-0.32	-1.00	-0.28	-0.30	-0.45	-0.30	-0.27
$\chi^2/\text{d.o.f.}$	0.99	0.99	1.27	1.16	1.43	1.29	1.36	0.91

Erato

	183	189	192	196	200	202	205	207
$\lambda_\gamma$	-0.09	-0.42	0.43	-1.36	-0.19	-0.09	0.11	0.00
+ve error	1.52	0.59	1.00	0.64	0.60	0.84	0.44	0.00
-ve error	-1.38	-0.50	-1.27	-0.49	-0.55	-0.76	-0.44	0.00
$\chi^2/\text{d.o.f.}$	0.99	0.99	1.27	1.16	1.44	1.29	1.37	0.00

Bilenky

	183	189	192	196	200	202	205	207
$\tilde{\lambda}_Z$	-0.43	-0.19	0.27	-0.55	-0.27	0.23	0.03	-0.31
+ve error	1.05	0.40	0.32	0.23	0.41	0.27	0.17	0.22
-ve error	-0.27	-0.21	-0.48	-0.16	-0.21	-0.45	-0.18	-0.14
$\chi^2/\text{d.o.f.}$	0.99	0.99	1.27	1.17	1.43	1.29	1.37	0.89

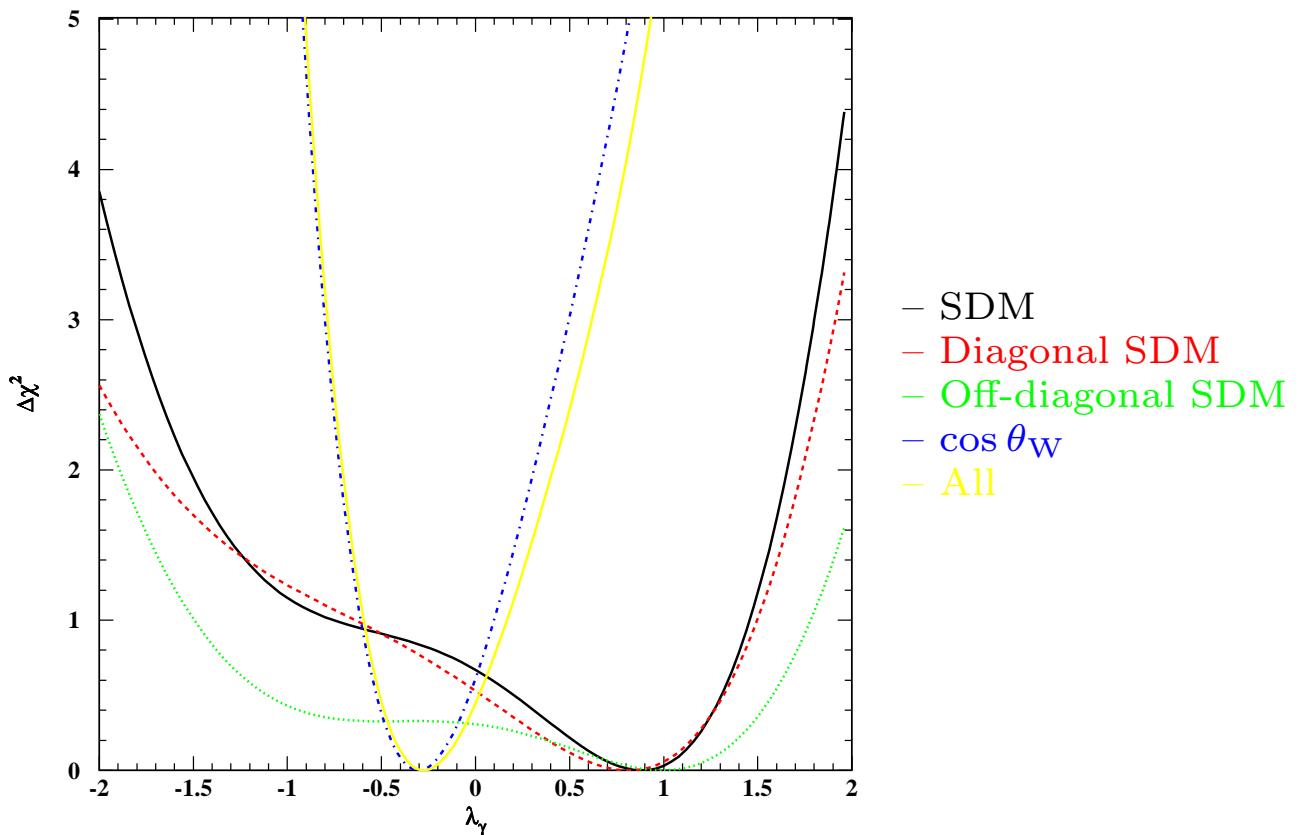
Erato

	183	189	192	196	200	202	205	207
$\tilde{\lambda}_Z$	0.45	-0.06	0.51	-0.65	-0.18	0.04	-0.02	0.00
+ve error	0.35	0.36	0.37	0.42	0.39	0.44	0.24	0.00
-ve error	-0.88	-0.33	-0.69	-0.26	-0.31	-0.47	-0.24	0.00
$\chi^2/\text{d.o.f.}$	0.99	0.99	1.27	1.18	1.44	1.29	1.37	0.00

Statistical uncertainty only. No  $SU(2)_c$  constraints. Preliminary!

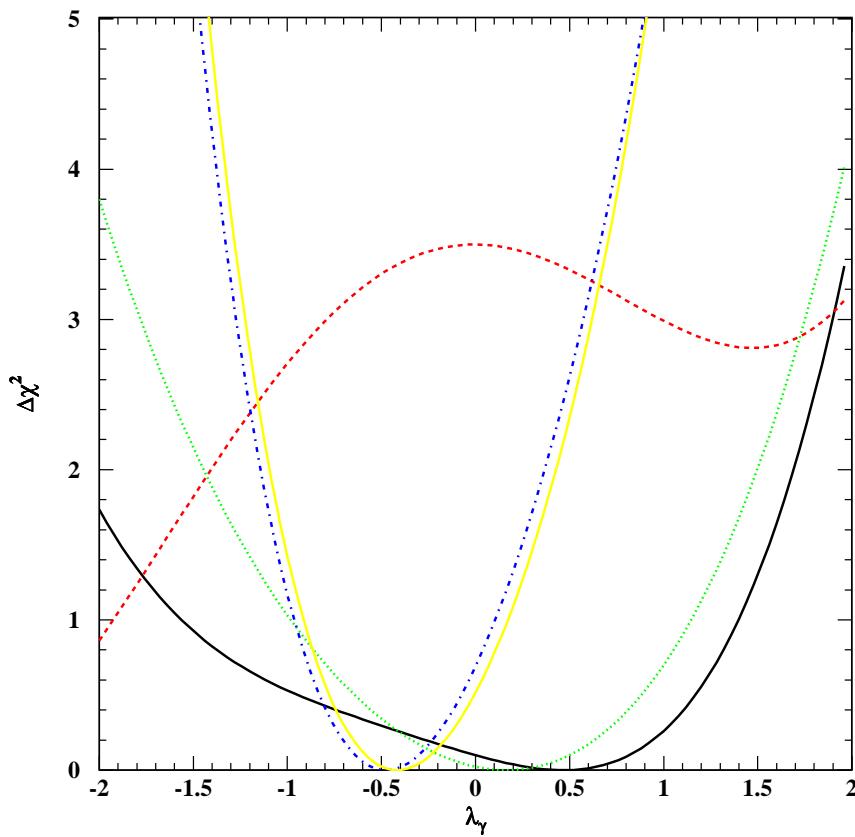
Bilenky

## Fit $\chi^2$ distributions ( $\lambda_\gamma$ 189 GeV)

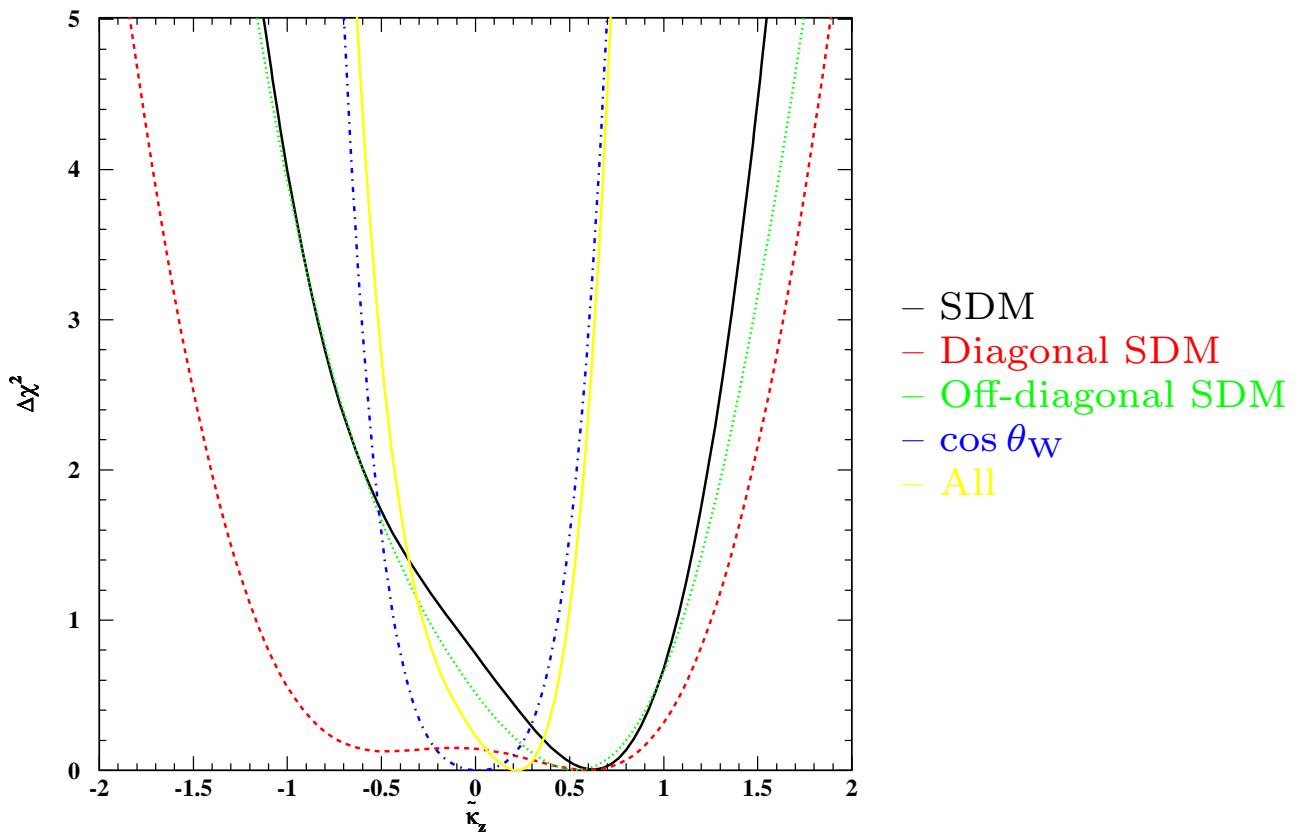


Erato

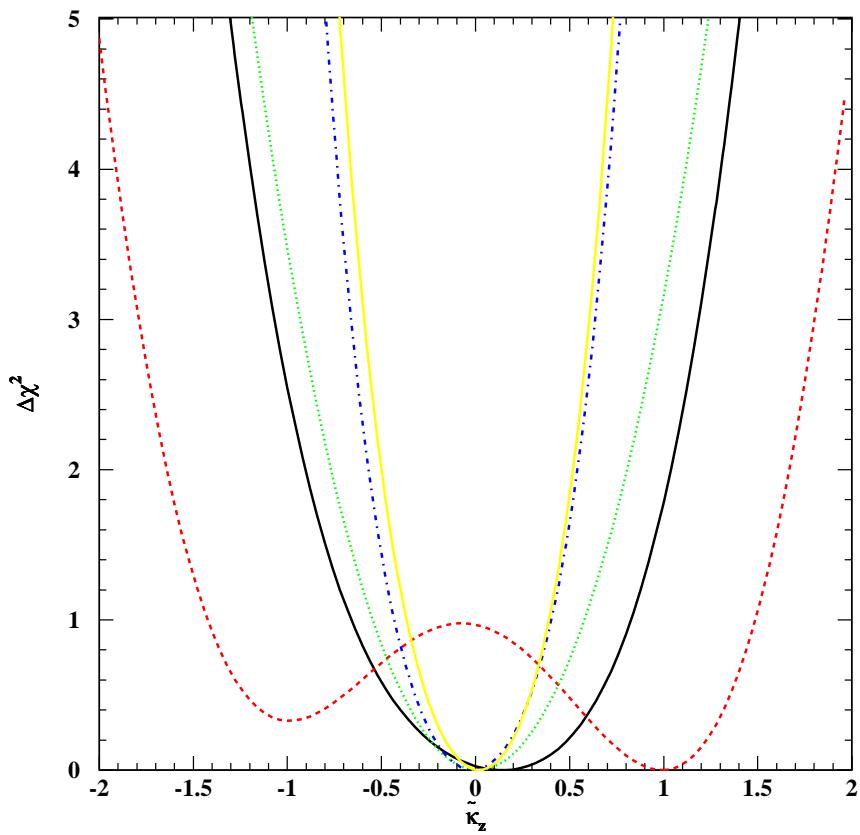
Qualitative agreement...  
Except for diagonal  
elements ??



Bilenky

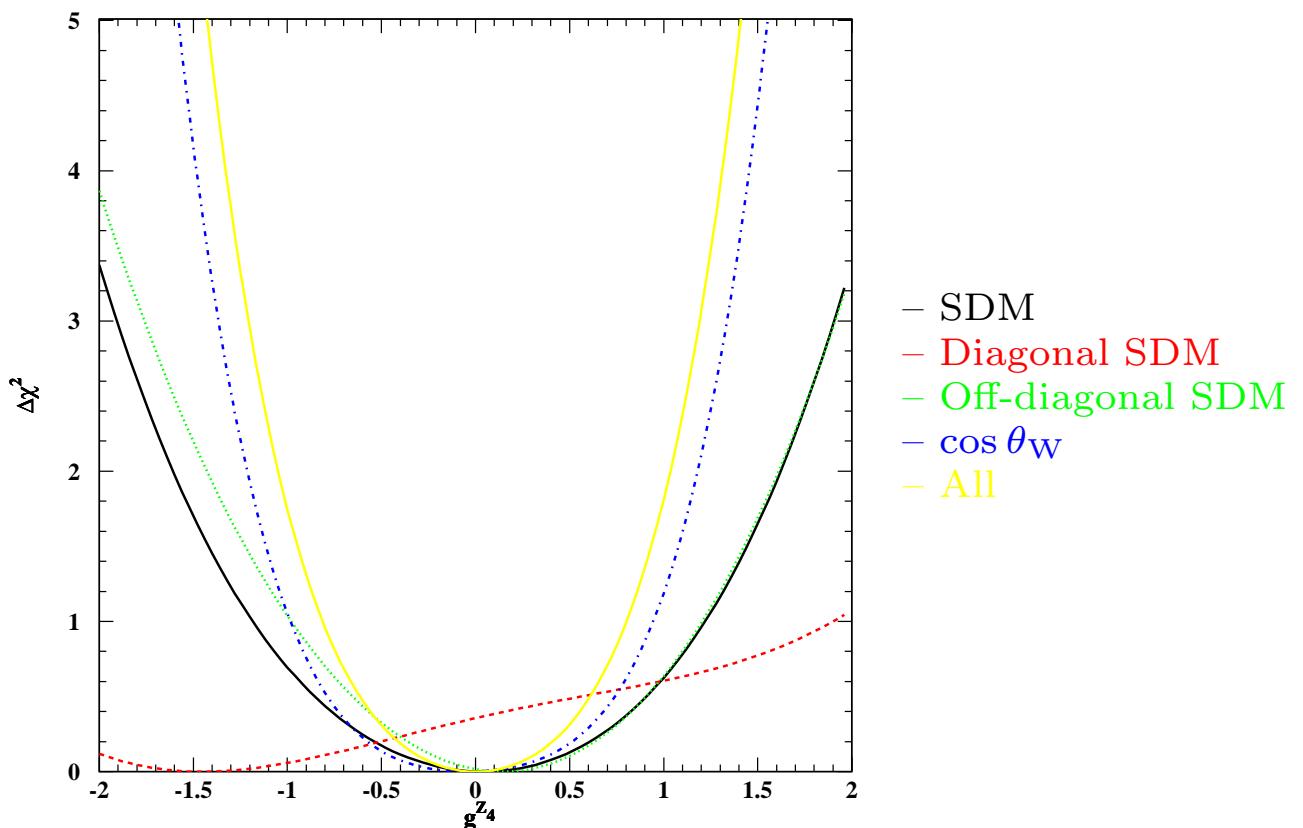


Erato

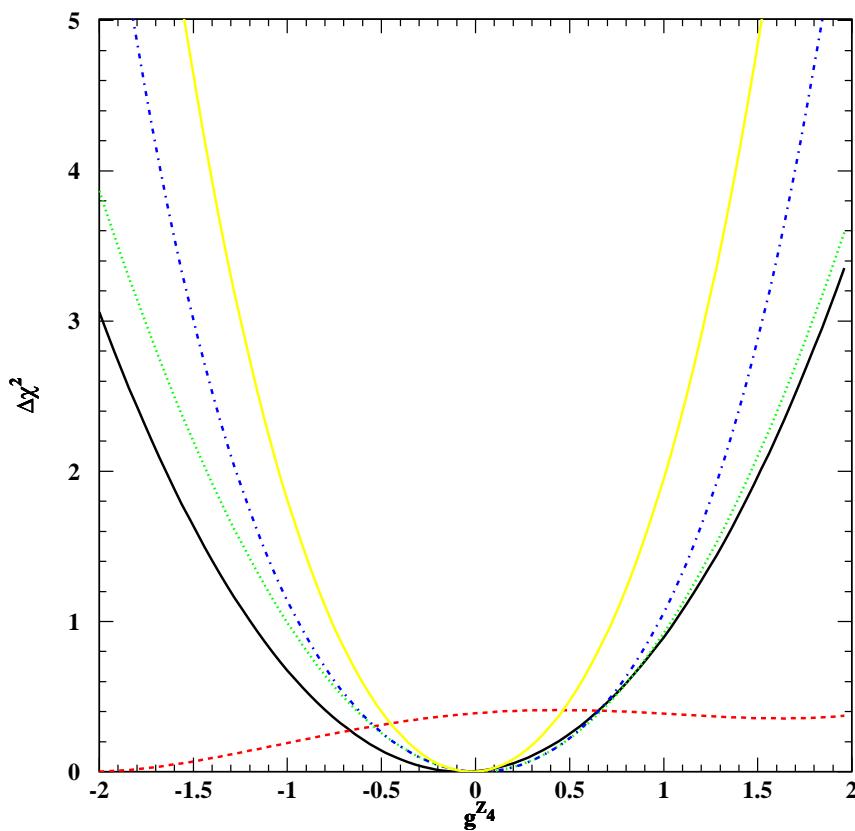


Bilenky

## Fit $\chi^2$ distributions ( $g_4^Z$ 189 GeV)



Erato



## Remaining work

- Systematic uncertainties
  - Necessary ntuples already generated (Hadronisation, ISR,  $\mathcal{O}(\alpha)$ , etc)
  - Method the same as for PR323 and PR387.
- Pull testing
  - Currently running...
- Bias testing
  - Essential to have this cross-check.
  - Erato reweighting implemented. Needs further testing.
  - Excalibur reweighting implemented. Not yet tested.
  - No plans to reweight with KandY.
- $SU(2)_c$  constraints
  - Implemented but not tested.
- Multi-dimensional fits
  - Software development ongoing.
- Combine centre-of-mass energies
  - Calculate weighted averages.
  - Also fit to all data simultaneously?
- Anything else??

## Outlook

- Progress has been quite rapid
- Most analysis code already in place
- Analysis must be complete by mid-February
  - ...or someone else must adopt it
- Other LEP CP-violating TGC analyses
  - Aleph
    - \* Preliminary results (real and imaginary parts)
  - Delphi
    - \* SDM analysis expected complete around Easter
  - L3
    - \* CP-violating TGC aspect of SDM analysis was dropped
    - \* Has become part of mainstream TGC analysis