W Polarisation and Spin Density Matrix Measurements at LEP

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- **Introduction**
- **Polarised Cross Section**
- **SDM measurements**
- **Spin Correlations**
- **CP Test**
- **Summary**

Why Studying W Polarisation ?

- model independent approach to Triple Gauge Couplings:

  $\longleftrightarrow$ anomalous TGCs change W-helicity distributions

  see EW-3 S. Jezequel

- longitudinal component of W-Bosons

  $\longleftrightarrow$ electroweak symmetry breaking

e.g. new physics with composite W's

$\longrightarrow$ other mass generation mechanism

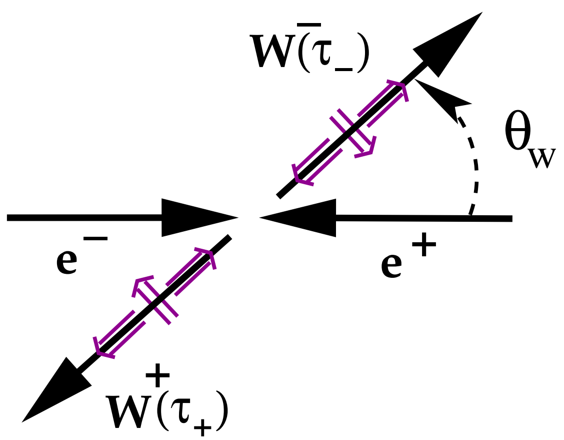
$\longrightarrow$ anomalous electric, magnetic moment (aTGCs)

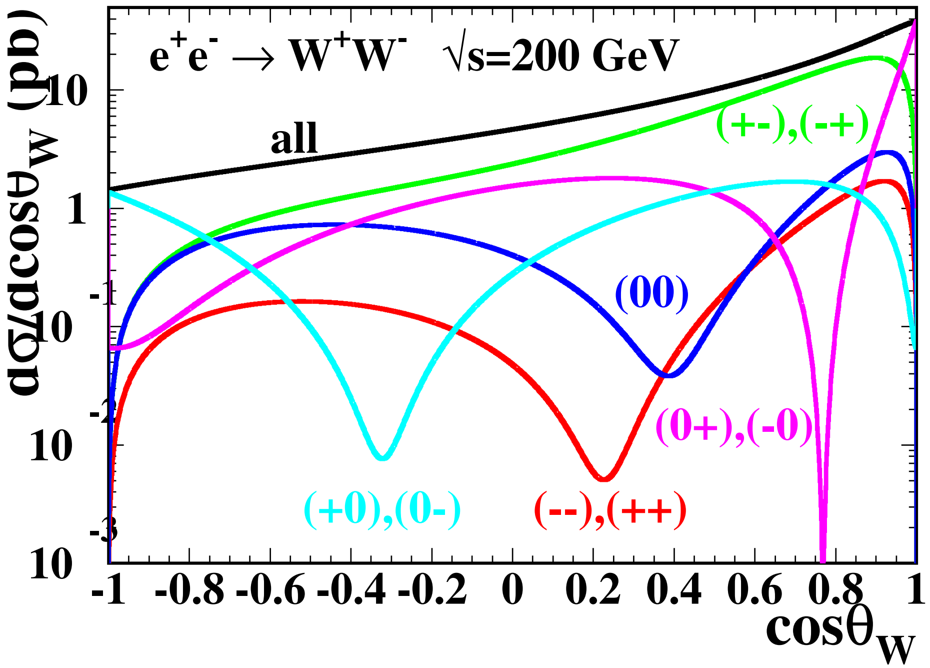
What's it all about

- W-Bosons: 3 spin (helicity) states
- observe individually and in correlation
- helicity content depends on W-production angle $\cos\theta_{\mathrm{W}}$

$\tau = +1$
$\tau = 0$
$\tau = -1$

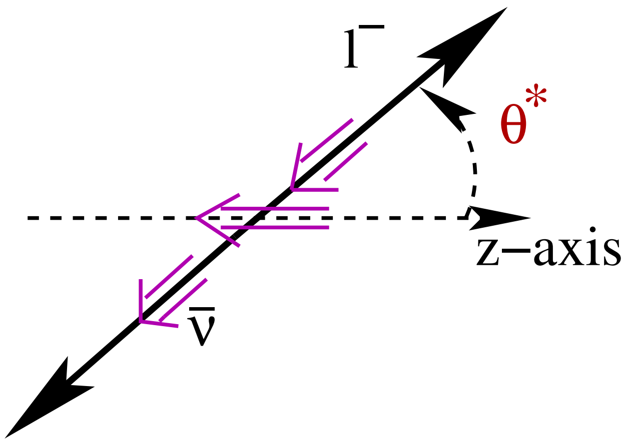
LEP: $e^+e^- \rightarrow W^+W^-$





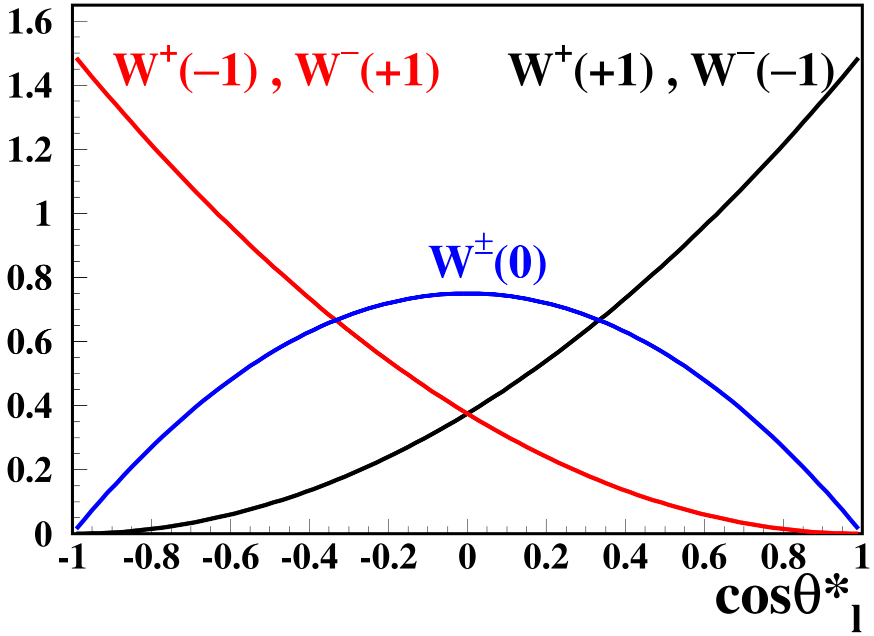
W Polarisation - Signatures

- V-A structure of W decay reflects polarisation
- $\cos\theta^*$: polar angle in W rest frame of charged lepton, d-type quark



decay distribution in W rest-frame

W^--helicity	decay distribution
-1	$\frac{3}{8}(1+\cos\theta^*)^2$
$+1$	$\frac{3}{8}(1-\cos\theta^*)^2$
0	$\frac{3}{4}\sin^2\theta^*$

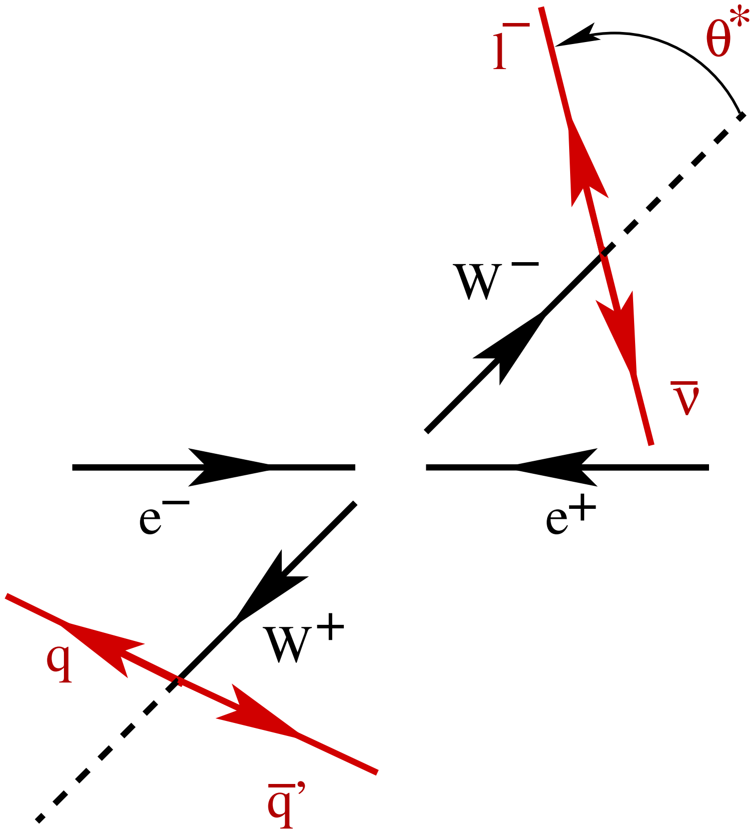


W Polarisation - Experimental Access

- $WW \to q\bar{q}q\bar{q}$, $q\bar{q}\ell\bar{\nu}_\ell$, $\ell\bar{\nu}_\ell\bar{\ell}'\nu_{\ell'}$

use: $W^+W^- \to q\bar{q}\ell\bar{\nu}_\ell$

- identification of W
- $\cos\theta^*_\ell$ without ambiguity



access to helicities:

- $W \to \ell\nu$: $\Rightarrow$ τ= (-1), (+1), (0)
- $W \to q\bar{q}$: $\Rightarrow$ τ= ($\pm$1), (0)

Polarisation - SDM measurements

- direct measurement (L3) $\sqrt{s} =$ (183-208) GeV
  $\longrightarrow$ fit analytical helicity distribution to $\cos\theta^*$
- Spin Density Matrix (SDM) (DELPHI, L3, OPAL) $\sqrt{s} =$ 189 GeV
  $\longrightarrow$ projection onto "squares" of helicity amplitudes

Comparison with theoretical distributions:

bin by bin correction for efficiency and bin-migration

Longitudinal W Helicity Fractions

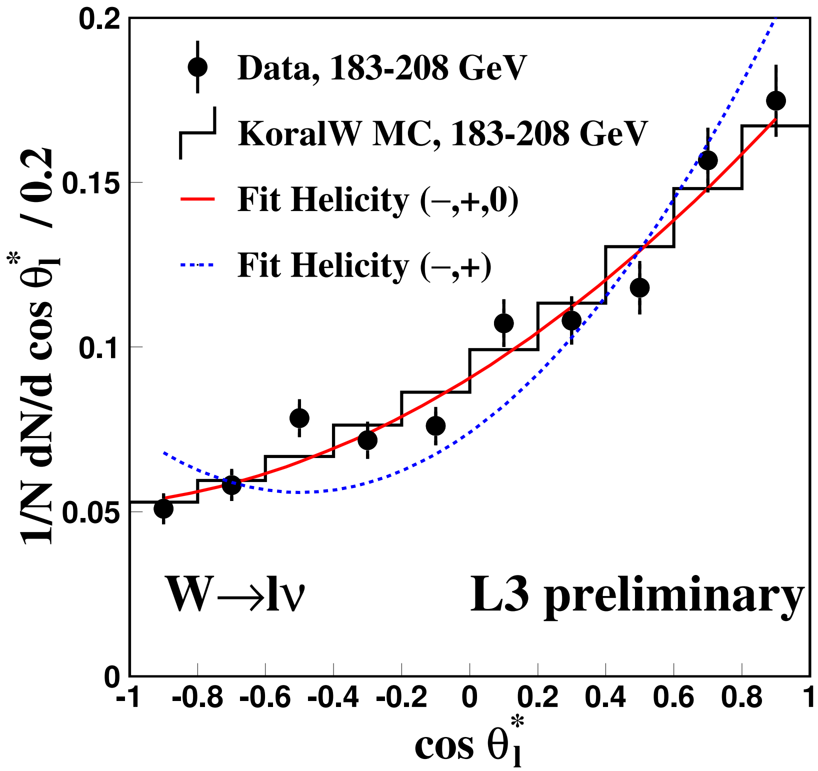
longitudinally polarised W-Bosons

L3 $\sqrt{s} =$ (183-208) GeV

DATA	0.228 ±0.027 ±0.012
expected	0.241

OPAL $\sqrt{s} =$ 189 GeV

DATA	0.210 ±0.033 ±0.016
expected	0.257 ±0.004



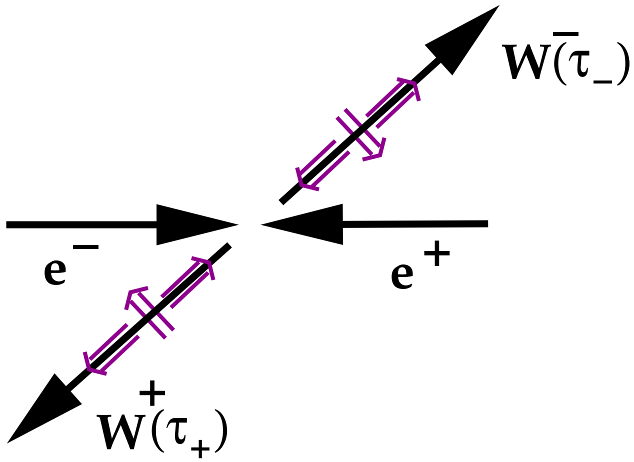
- Fit without longitudinal component fails to describe the data

Spin Density Matrix

SDM: normalized product of helicity amplitudes

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

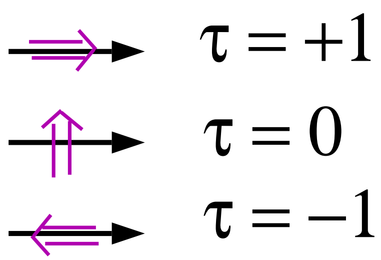
$\tau_\pm$: helicity of $\mathrm{W}^\pm$ λ: spin of $\mathrm{e}^+\mathrm{e}^-$-system



hermitic: 80 independent real coefficents

$\sum \mathrm{W}^+ \Rightarrow$ **single particle matrix element** W^-

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



$\rho^{\mathrm{W}^-}_{\tau_-\tau_-}$: **probability of producing a** W^- **with helicity** τ_-

Spin Density Matrix

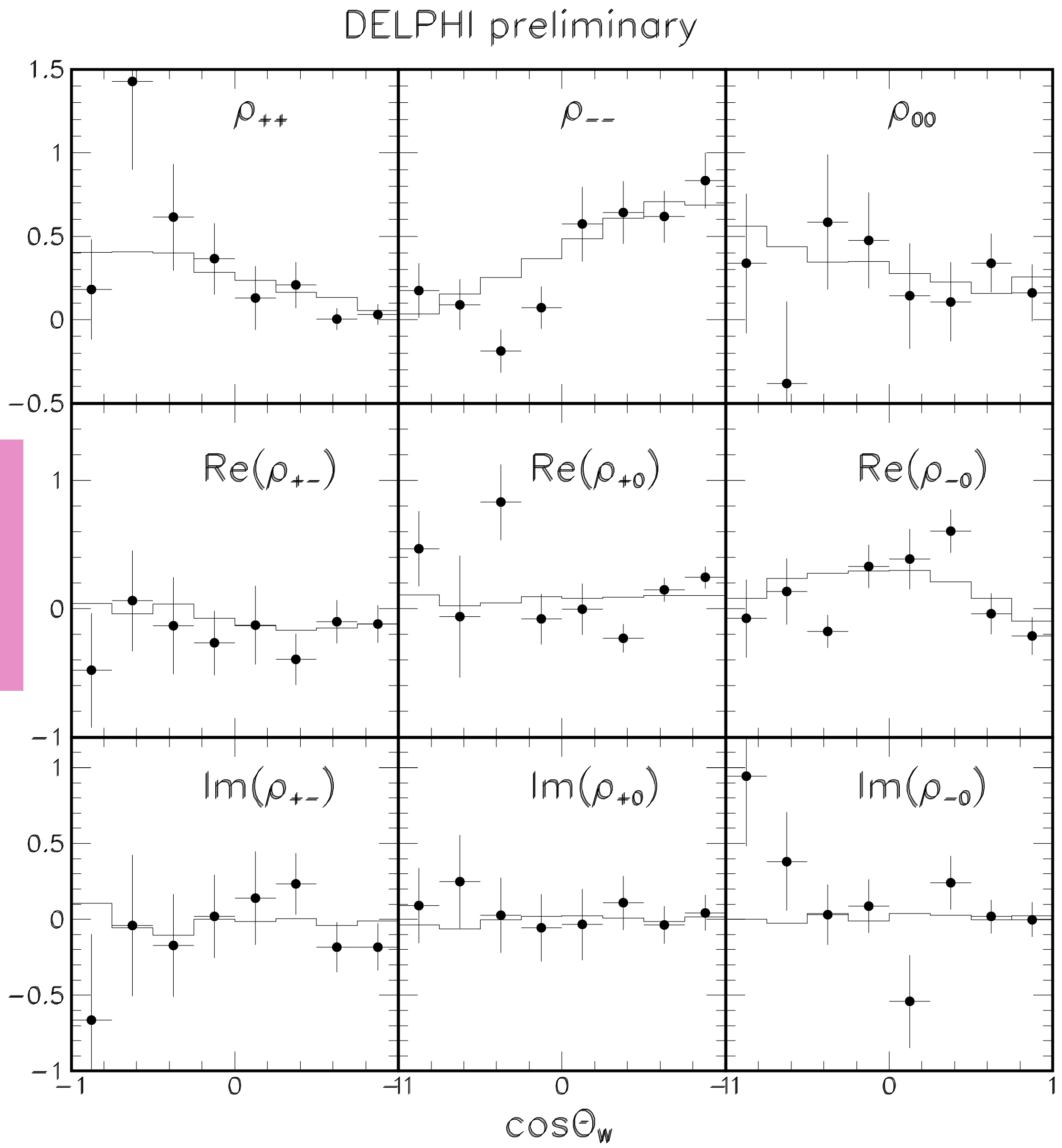
each helicity amplitude $\longrightarrow$

specific angular symmetry:

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

for each bin in $\cos\theta_{\mathrm{W}}$:

$$\rho^W_{\tau\tau'} = \frac{1}{N_{ev.}} \sum_i^{ev.} \Lambda_{\tau\tau'}(\cos\theta^*{}_i,\ \phi^*{}_i)$$



- **9 SDM-elements $\rho^W_{\tau\tau'}$**

  hermitian matrix

  $\Longrightarrow$ 6 independent parameters

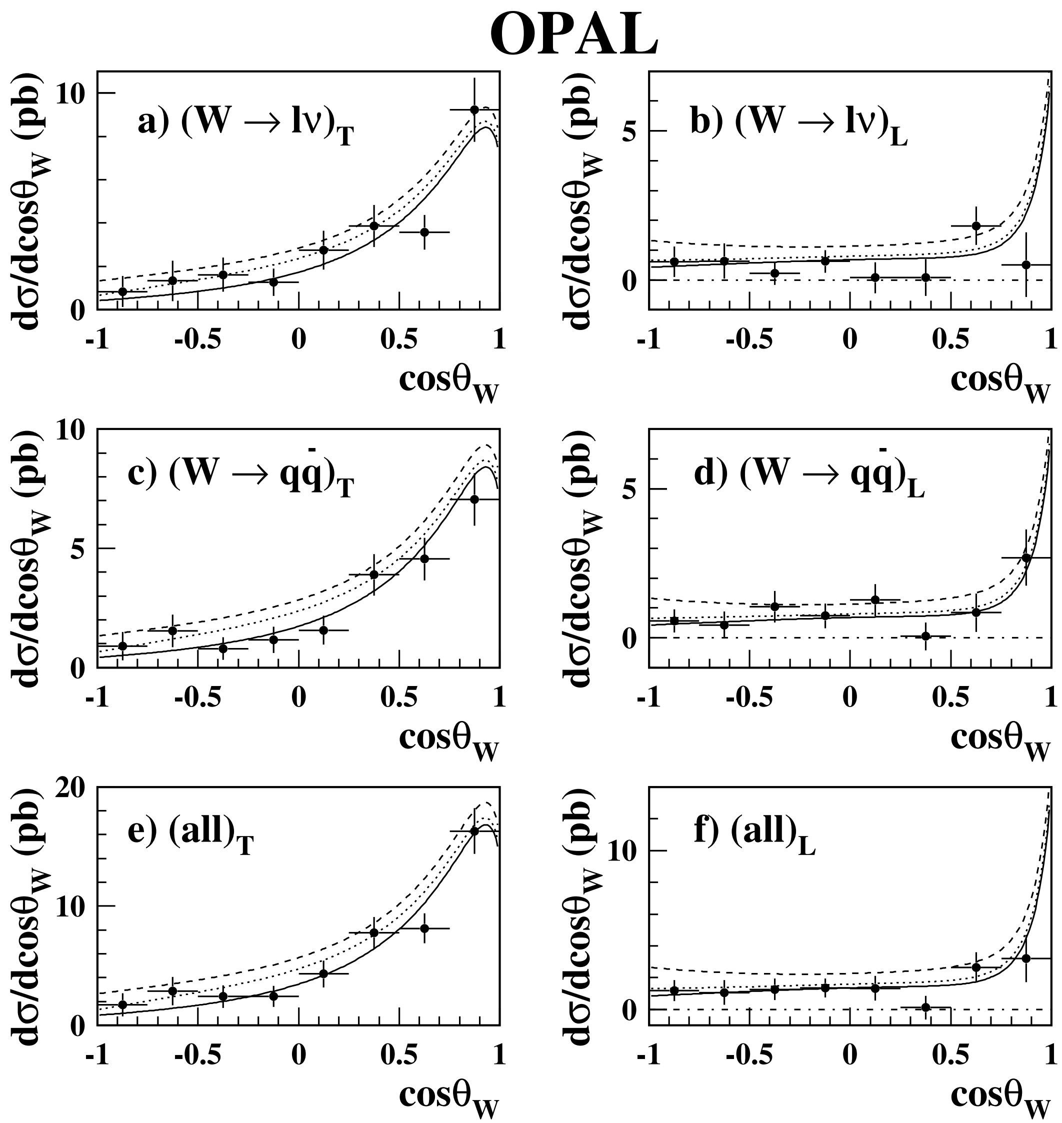
Polarised Differential W Cross Sections

$\rho_{\tau_-\tau_-}(\cos\theta_W) \Rightarrow$

e.g.

longitudinal diff. cross section:

$$\frac{d\sigma_L}{d\cos\theta_W} = \rho_{00}\frac{d\sigma}{d\cos\theta_W}$$

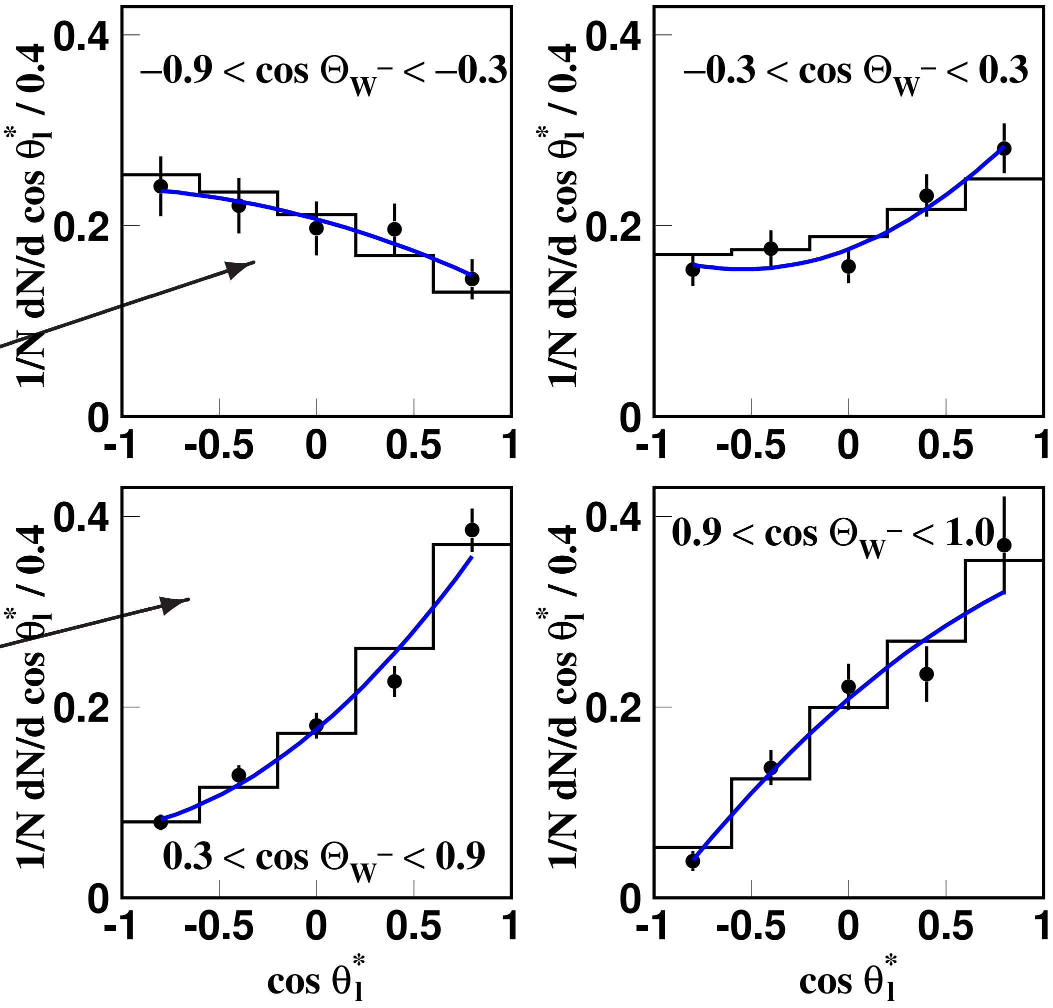


Polarised Differential W Cross Sections

L3 preliminary

helicity composition in 4 $\cos\theta_W$ regions

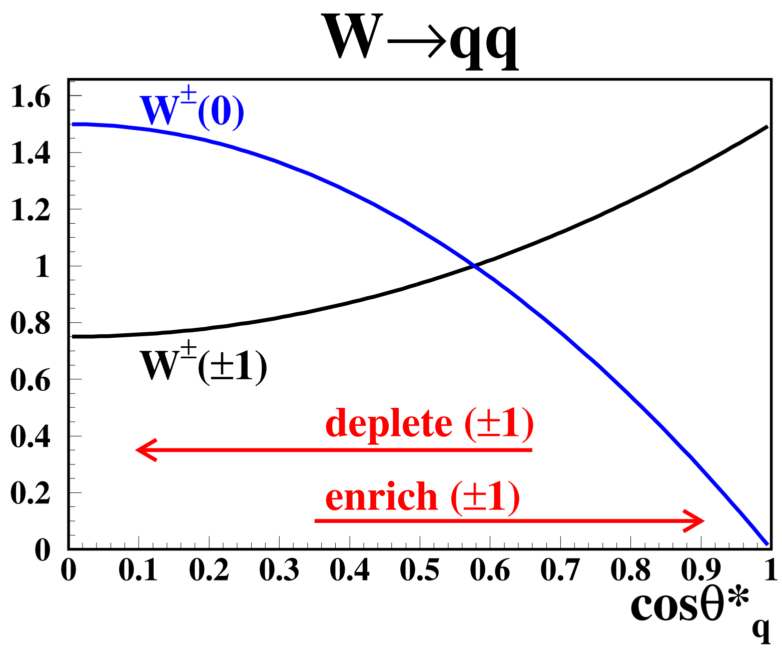
- negative $\cos\theta_W$ (backward)
  $\longrightarrow$ (τ_-= +1,τ_+= -1) large
- positive $\cos\theta_W$ (forward)
  $\longrightarrow$ (τ_-= -1,τ_+= +1) large

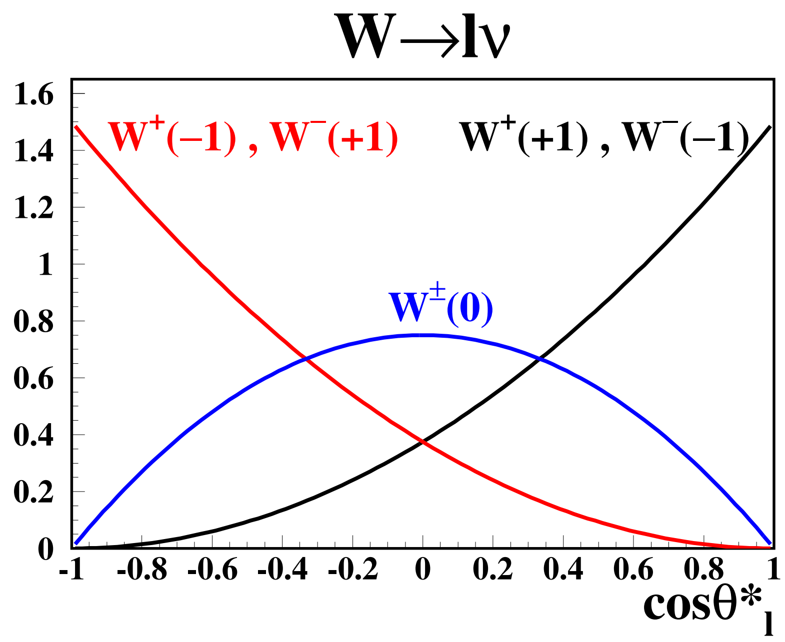


Spin Correlations

- does the helicity of W_2 depend on the helicity of W_1 ?

  fractions of $(\tau^{\mathrm{W}^-}, \tau^{\mathrm{W}^+})$ = (-,+), (-,0), (0,0), ...
- enrich (deplete) helicity τ = ±1 of $\mathrm{W} \rightarrow \mathrm{q}\overline{\mathrm{q}}$
- measure helicity of $\mathrm{W} \rightarrow \ell \overline{\nu}_\ell$



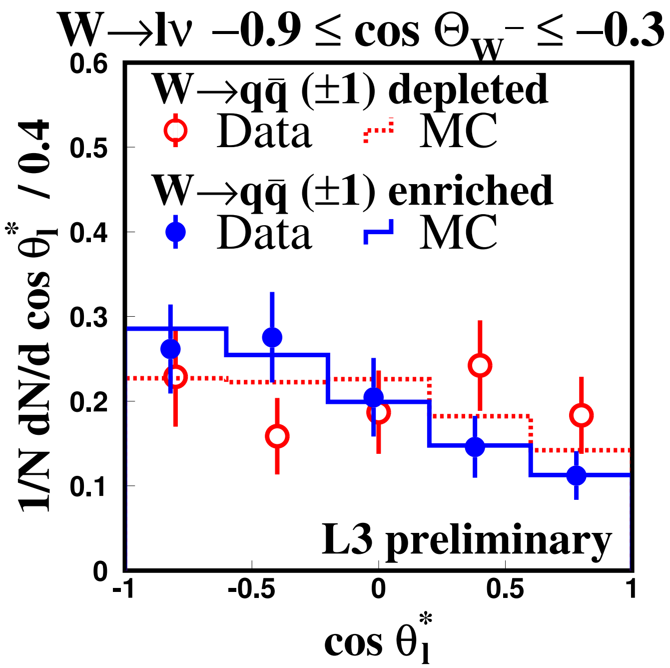


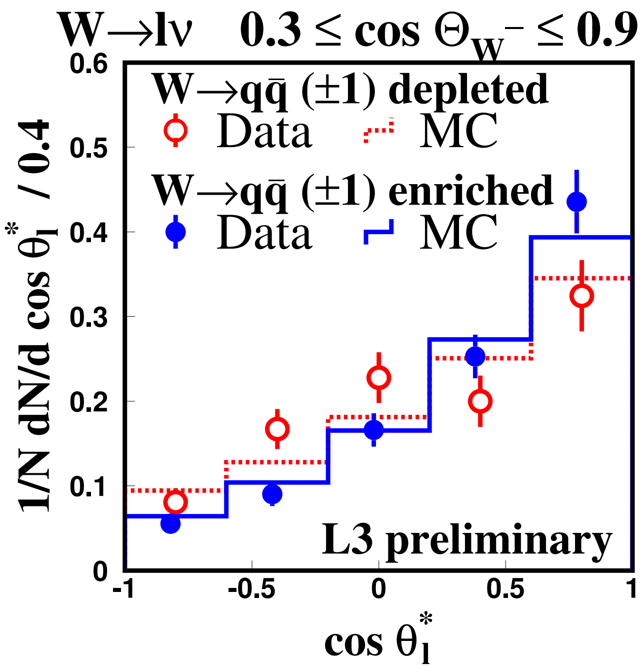
Measurement of Spin Correlations

- $\cos\theta_W$ region with small (large) (transverse,transverse) W-pair helicity fraction
- "select" $\cos\theta^*_q$ region to deplete (enrich) transverse helicity in $W\rightarrow q\bar{q}$

helicity fractions L3 $0.3 < \cos\theta_W < 0.9$

	τ= -1	τ= +1	τ= 0
±1 depleted	0.46 ±0.10 ±0.06	0.11 ±0.06 ±0.04	0.44 ±0.12 ±0.07
±1 enriched	0.83 ±0.09 ±0.00	0.09 ±0.03 ±0.03	0.08 ±0.08 ±0.03
difference	−0.38 ±0.13 ±0.06	0.01 ±0.07 ±0.05	0.36 ±0.14 ±0.08



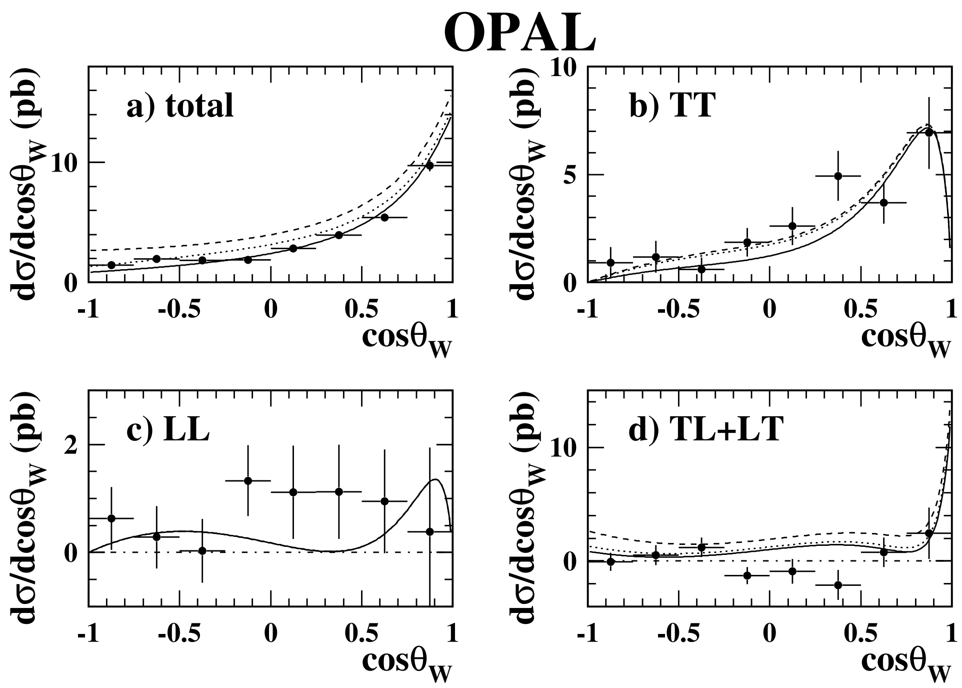


Joint Polarised Cross Sections

some combinations of the full SDM elements are symmetric in $q \leftrightarrow \bar{q}'$

$$(\rho_{++++} + \rho_{++--} + \rho_{--++} + \rho_{----}) \propto \sigma_{TT}$$
$$(\rho_{0000}) \propto \sigma_{LL}$$
$$(\rho_{++00} + \rho_{--00} + \rho_{00++} + \rho_{00--}) \propto \sigma_{TL}$$

	measured	expected
$\frac{\sigma_{\mathrm{TT}}}{\sigma_{\mathrm{total}}}$	0.78 ±0.09 ±0.03	0.57 ±0.01
$\frac{\sigma_{\mathrm{LL}}}{\sigma_{\mathrm{total}}}$	0.20 ±0.07 ±0.02	0.09 ±0.01
$\frac{\sigma_{\mathrm{TL}}}{\sigma_{\mathrm{total}}}$	0.02 ±0.15 ±0.04	0.34 ±0.02



Testing CP Conservation

$$\text{CP} \Rightarrow \begin{array}{cccc} f(\tau=-1) & f(\tau=+1) & f(\tau=0) & \text{for } W^+ \\ & = & & \\ f(\tau=+1) & f(\tau=-1) & f(\tau=0) & \text{for } W^- \end{array}$$

	helicity fractions L3 @ $\sqrt{s}$ = (183-208) GeV		
	τ= -1	τ= +1	τ= 0
W^-	0.547 ±0.046 ±0.012	0.198 ±0.027 ±0.013	0.255 ±0.038 ±0.006
	τ= +1	τ= -1	τ= 0
W^+	0.631 ±0.048 ±0.023	0.180 ±0.024 ±0.014	0.189 ±0.039 ±0.015

DELPHI, L3, OPAL @ $\sqrt{s}$ = 189 GeV

$$\text{CPT:} \quad \rho^{W^+}_{\tau\tau'} = (\rho^{W^-}_{-\tau-\tau'})^*$$

$$\text{CP:} \quad \rho^{W^+}_{\tau\tau'} = \rho^{W^-}_{-\tau-\tau'}$$

CPT + CP $\Rightarrow \rho^{W}$ are real

Test of CP-Violation

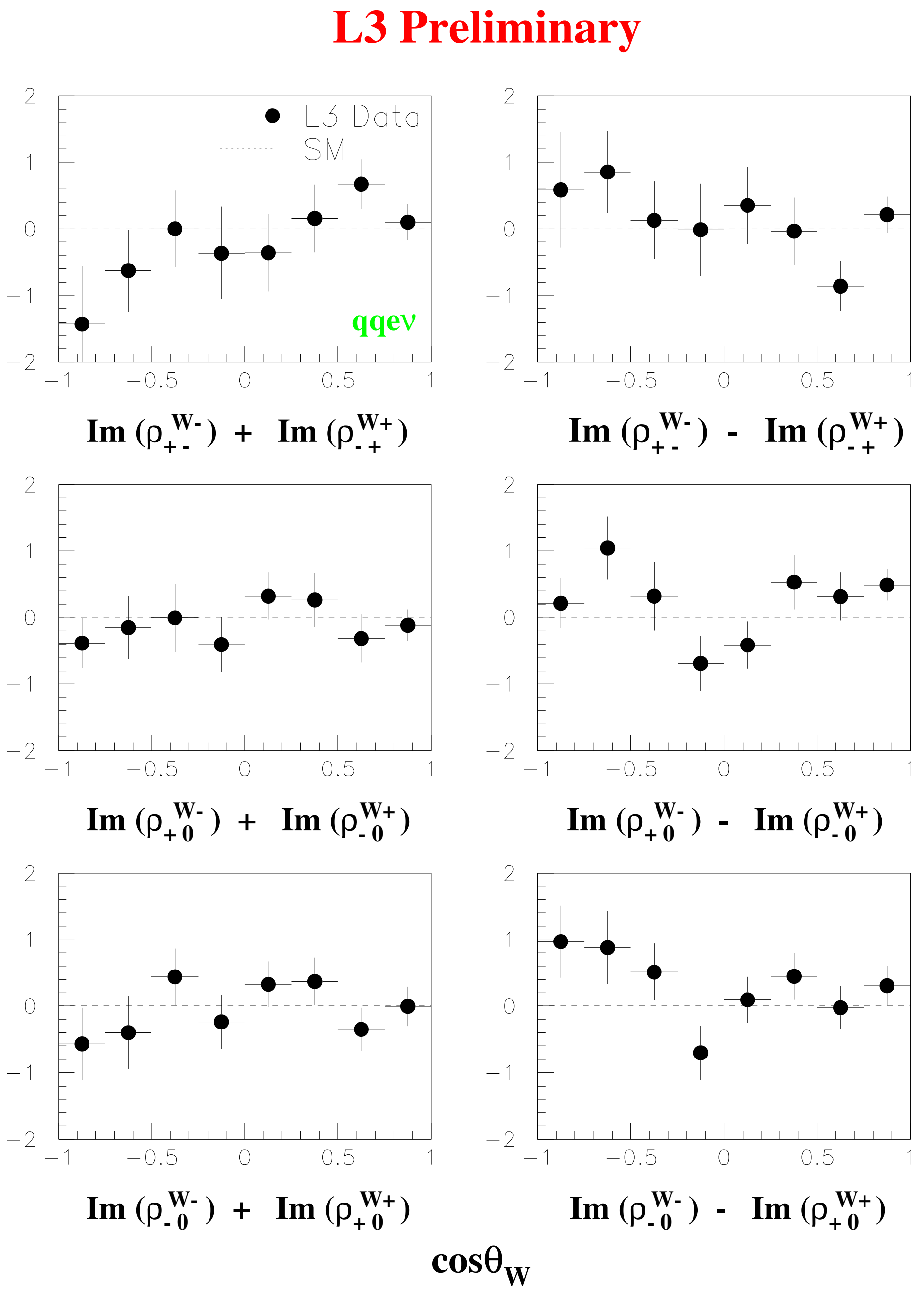
CP violation at tree level:

$$\mathrm{Im}(\rho^{W^+}_{\tau\tau'}) - \mathrm{Im}(\rho^{W^-}_{-\tau-\tau'}) \neq 0$$

CP violation at loop level or

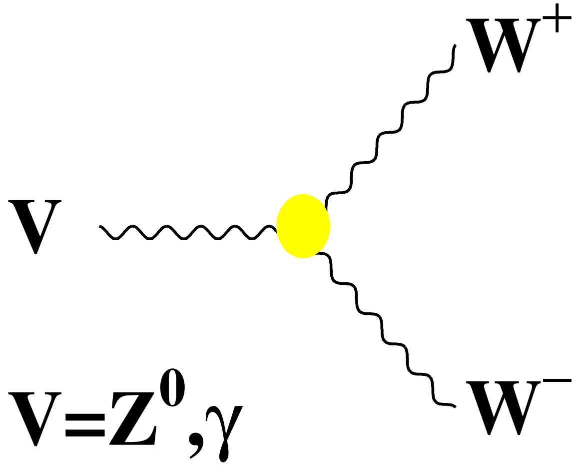
CPT violation at tree level:

$$\mathrm{Im}(\rho^{W^+}_{\tau\tau'}) + \mathrm{Im}(\rho^{W^-}_{-\tau-\tau'}) \neq 0$$



CP-Violating Triple Gauge Couplings

- fitting SDM elements to MC expectations (OPAL)



	$\tilde{\kappa}_Z$	g_4^Z	$\tilde{\lambda}_Z$
SDM elements	$-0.19^{+0.08}_{-0.07}$	$0.00^{+0.21}_{-0.20}$	$-0.12^{+0.17}_{-0.16}$
$\cos\theta_W$	$-0.19^{+0.46}_{-0.08}$	$0.7^{+0.4}_{-1.8}$	$-0.29^{+0.69}_{-0.11}$
combined (+sys)	$-0.20^{+0.10}_{-0.07}$	$-0.02^{+0.32}_{-0.33}$	$-0.18^{+0.24}_{-0.16}$

there are other measurements of CP-violating TGCs by ALEPH, DELPHI that use different methods

Summary

- ee $\longrightarrow \mathrm{WW}$ spin structure from DELPHI, L3, OPAL

- polarised W cross section measured

  longitudinal W-Bosons confirmed

- Spin Density Matrix analysis (more data analysed soon)

- correlated helicity states studied

- CP, CPT tests (and CP - violating TGCs)