Evidence for WW Spin Correlations with L3 at LEP

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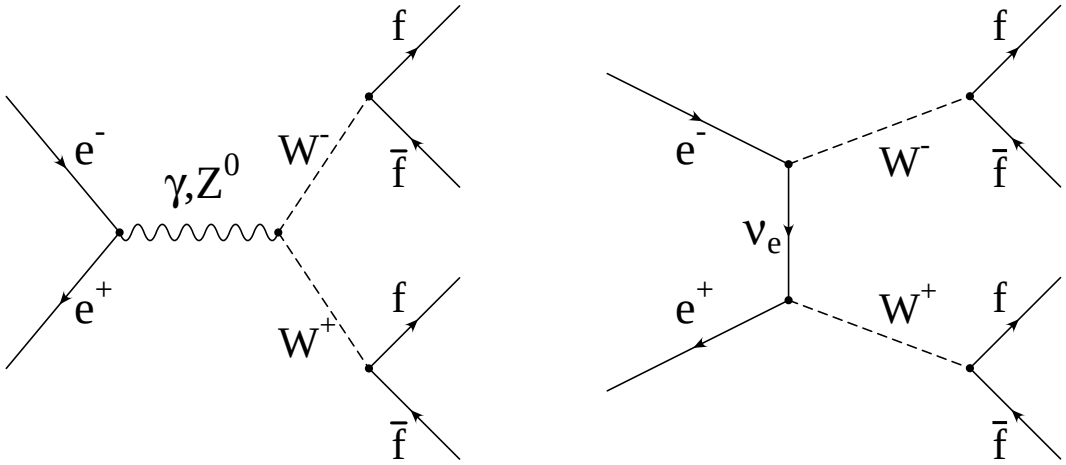
- Introduction
- Inclusive W helicity analysis
- How to measure WW spin correlations
- Data analysis
- Decay plane correlations
- Summary

$e^+e^- \to W^+W^- \to 4f$

Standard Model:



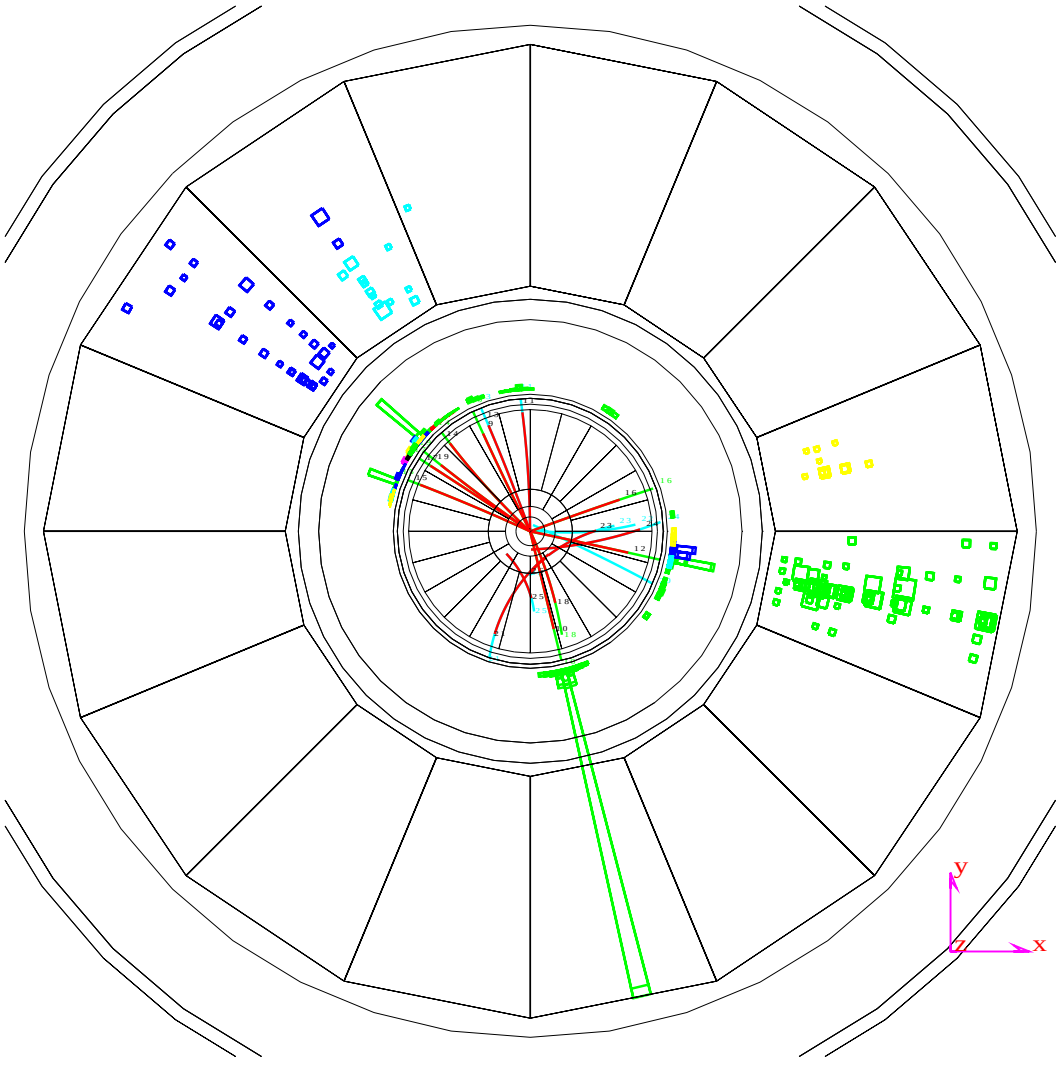
$$f\bar{f}f\bar{f} = \begin{cases} \ell\nu q\bar{q} & 3 \cdot 14.6\% \\ q\bar{q}q\bar{q} & 45.6\% \\ \ell\nu\ell\nu & 10.6\% \end{cases}$$

Semileptonic channel:

- low background,
- only one neutrino,
- hadronic and leptonic W decays well separated,
- $W^\pm$ charge assignment from $\ell^\pm$,
- $\frac{BR(W^+W^- \to e(\mu)\nu q\bar{q})}{BR(W^+W^- \to \text{all})} = 29.2\%$.

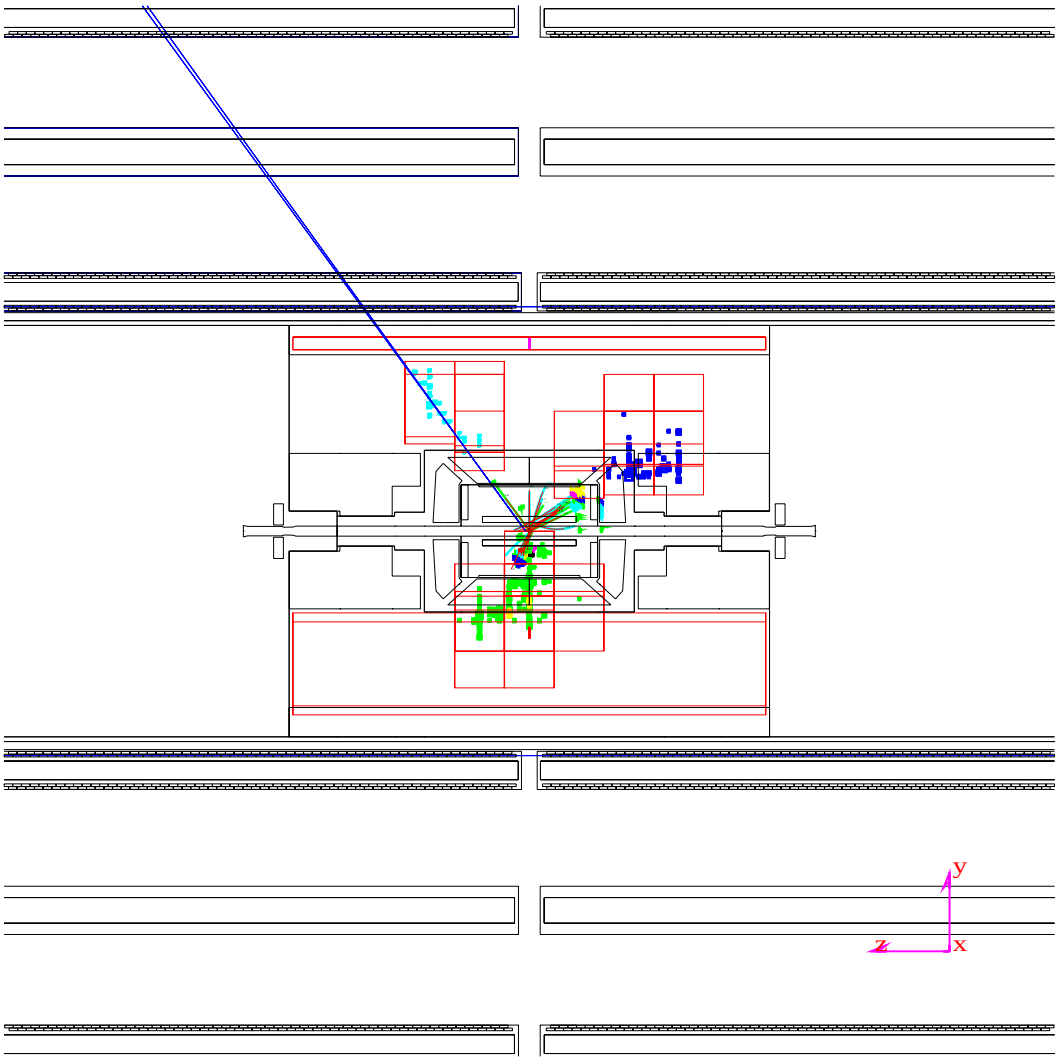
$W^+W^- \to e\nu_e q\bar{q}$ Event in the L3 Detector

Run # **696408** **Event #** **1935** Total Energy : 134.25 GeV



$W^+W^- \to \mu\nu_\mu q\bar{q}$ Event in the L3 Detector

Run # 720712 Event # 2154 Total Energy : 136.75 GeV



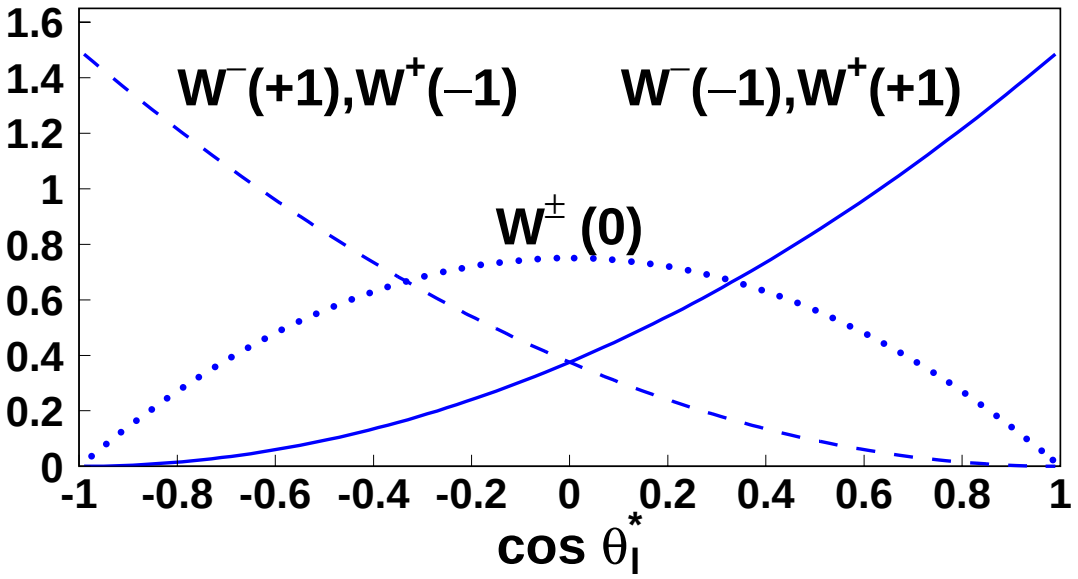
The Longitudinally Polarized W Boson

- Massless photon $\Rightarrow$ helicity ± 1
  only transverse polarisations
- Electroweak theory:
  Higgs mechanism $\Rightarrow$ massive W boson
- Massive W boson $\Rightarrow$ helicity ± 1 and 0
  transverse and longitudinal polarisations
- Quantum field theory: in the limit of high energy, the amplitude for producing a longitudinally polarised W is given precisely by the amplitude for producing the charged Goldstone boson associated with SU(2)×U(1) symmetry breaking.

Analysis of W $\to \ell\nu$ helicity

- extract W helicities $(+1), (-1), (0)$
- fit function for W$\to \ell\nu$:

$$\frac{1}{N}\frac{dN}{d\cos\theta^*} = f_- \frac{3}{8}(1+\cos\theta^*)^2 + f_+ \frac{3}{8}(1-\cos\theta^*)^2 + f_0 \frac{3}{4}\sin^2\theta^*$$



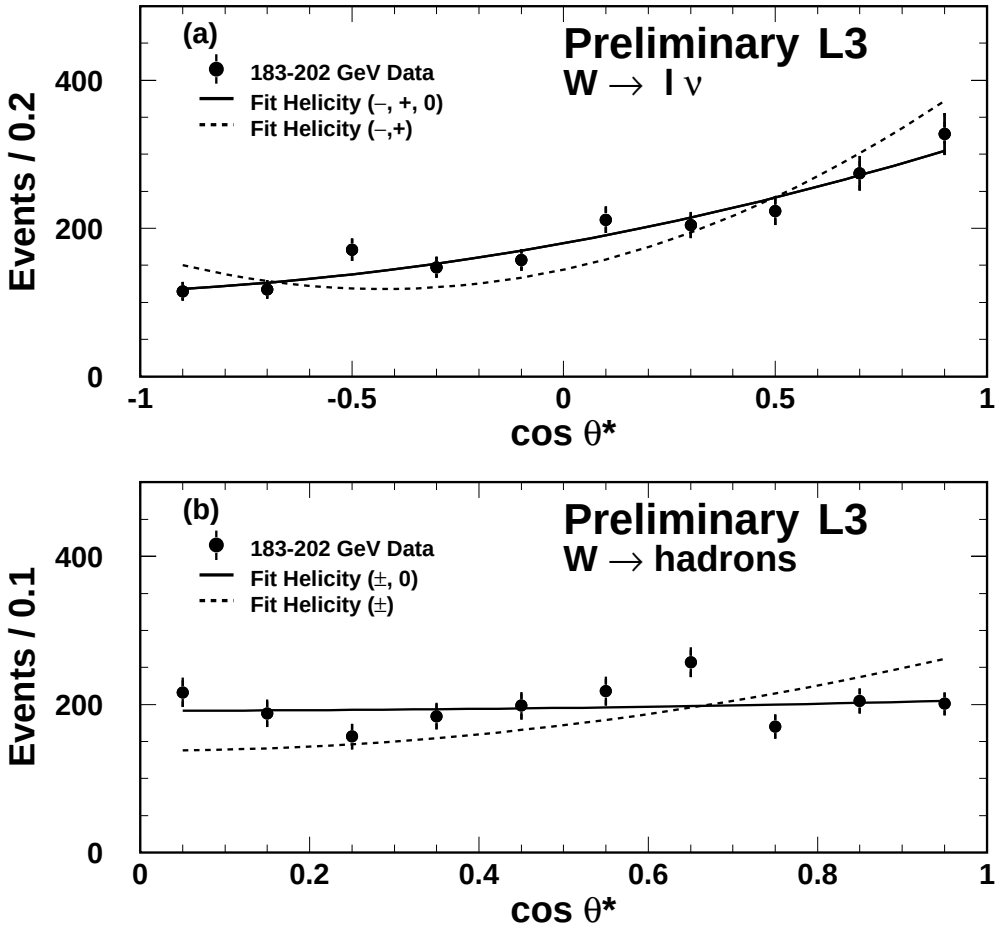
- fit distribution of polar decay angle
  $\Rightarrow$ helicity fractions of W$\to\ell\nu$

Measurement of Longitudinally Polarized $W^{\pm}$ Bosons(1)

- L3 note 2574, *Improved Studies with Longitudinally and Transversely Polarised* $W^{\pm}$ *Bosons.* (Update for 1999 data of L3 paper 195)
- Full statistics ($\sqrt{s} = 183 - 202$ GeV):
  1375 events of the type $e^+e^- \to W^+W^- \to \begin{cases} e\nu_e q\bar{q} \\ \mu\nu_\mu q\bar{q} \end{cases}$
- Background from:
  $e^+e^- \to q\bar{q}(\gamma)$ (1.3%), and
  $e^+e^- \to W^+W^- \to \tau\nu_\tau q\bar{q}$ (2.6%).

Measurement of Longitudinally Polarized $W^{\pm}$ Bosons(2)

Corrected $\cos\theta^*$ distributions for
(a) leptonic W decays and (b) for hadronic W decays

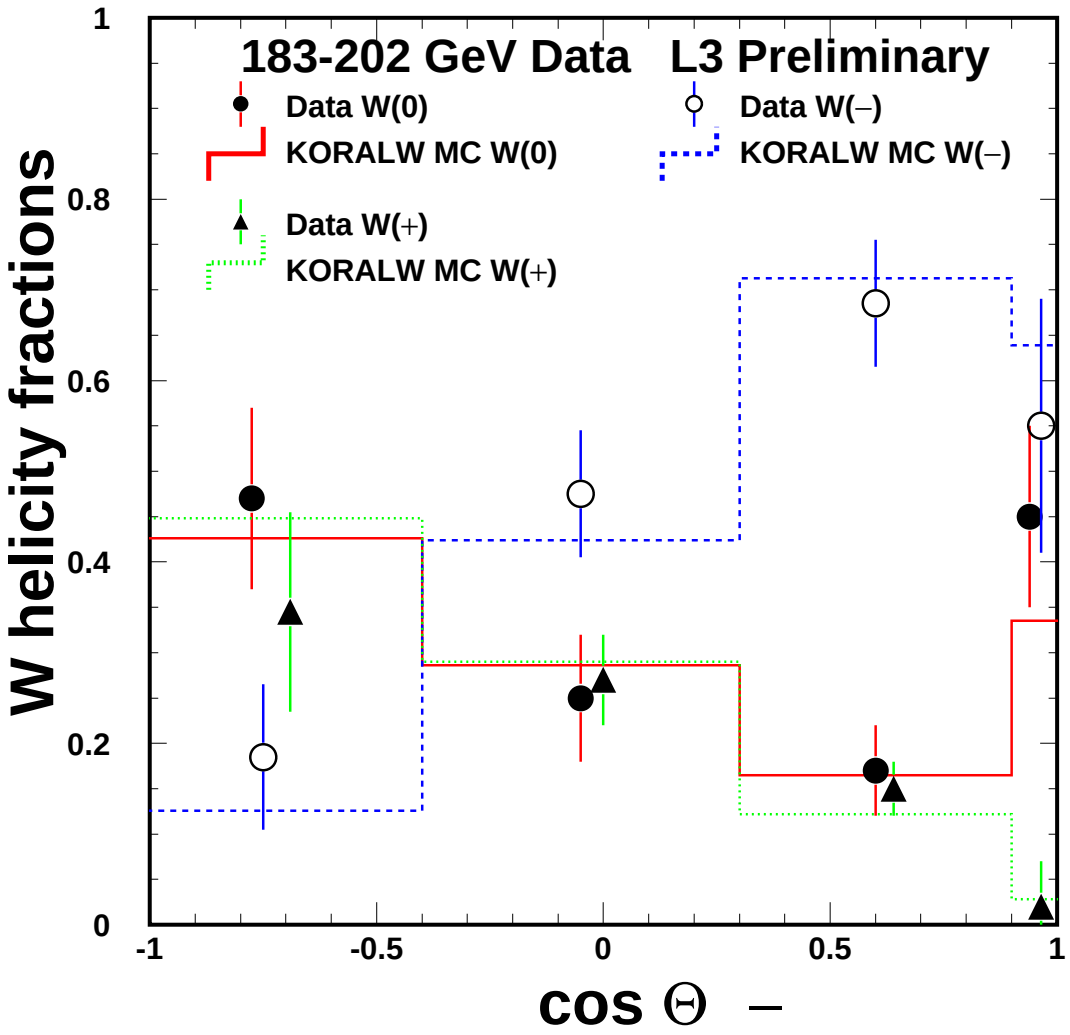


Measured W helicity fractions, combining the leptonic and hadronic W decays.

	-1	$+1$	0
Data	0.562 ± 0.045	0.179 ± 0.023	0.259 ± 0.035
MC	0.576	0.176	0.248

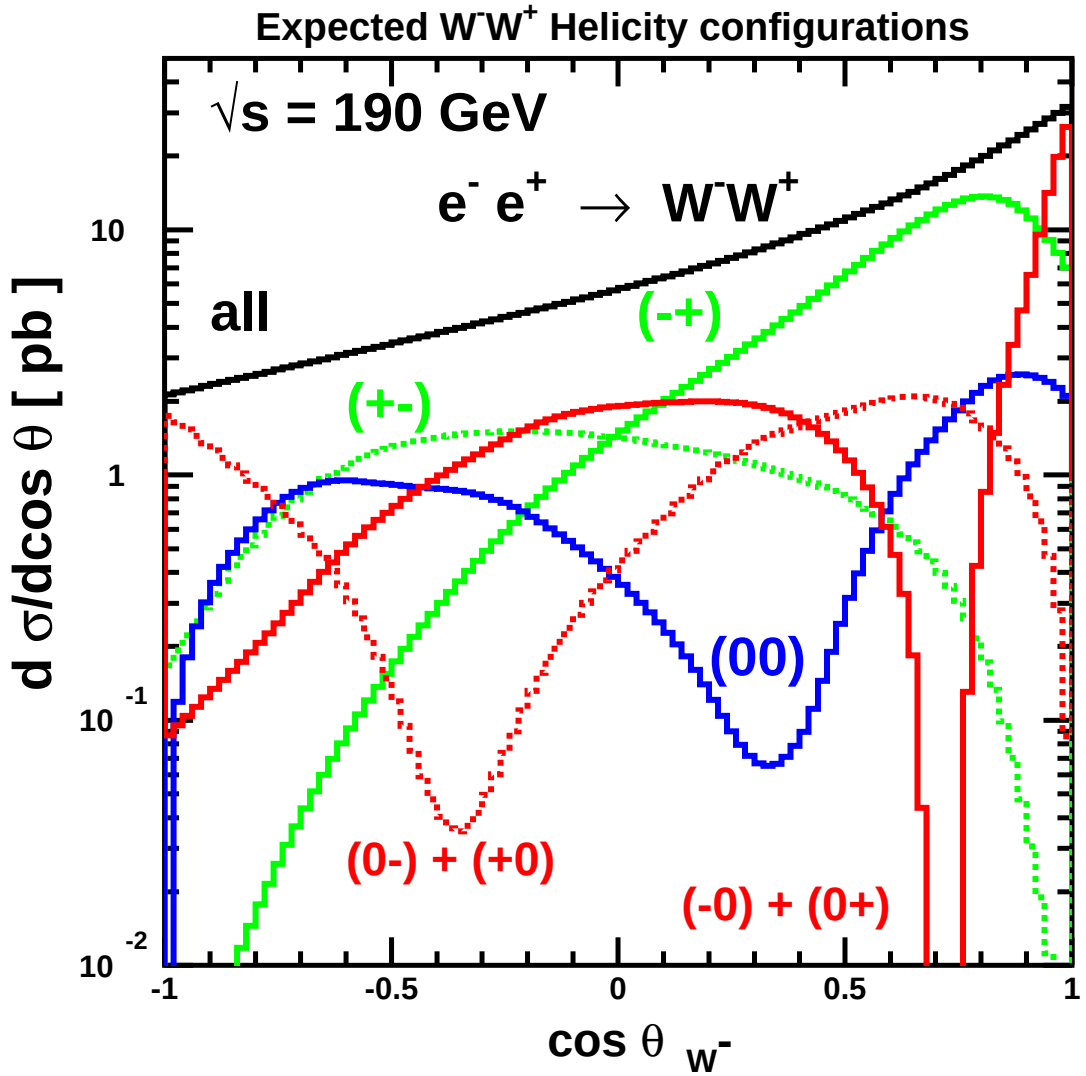
Measurement of Longitudinally Polarized $W^{\pm}$ Bosons(3)

- Fractions of W^- helicities (0) and (–) as a function of the W^- scattering angle.



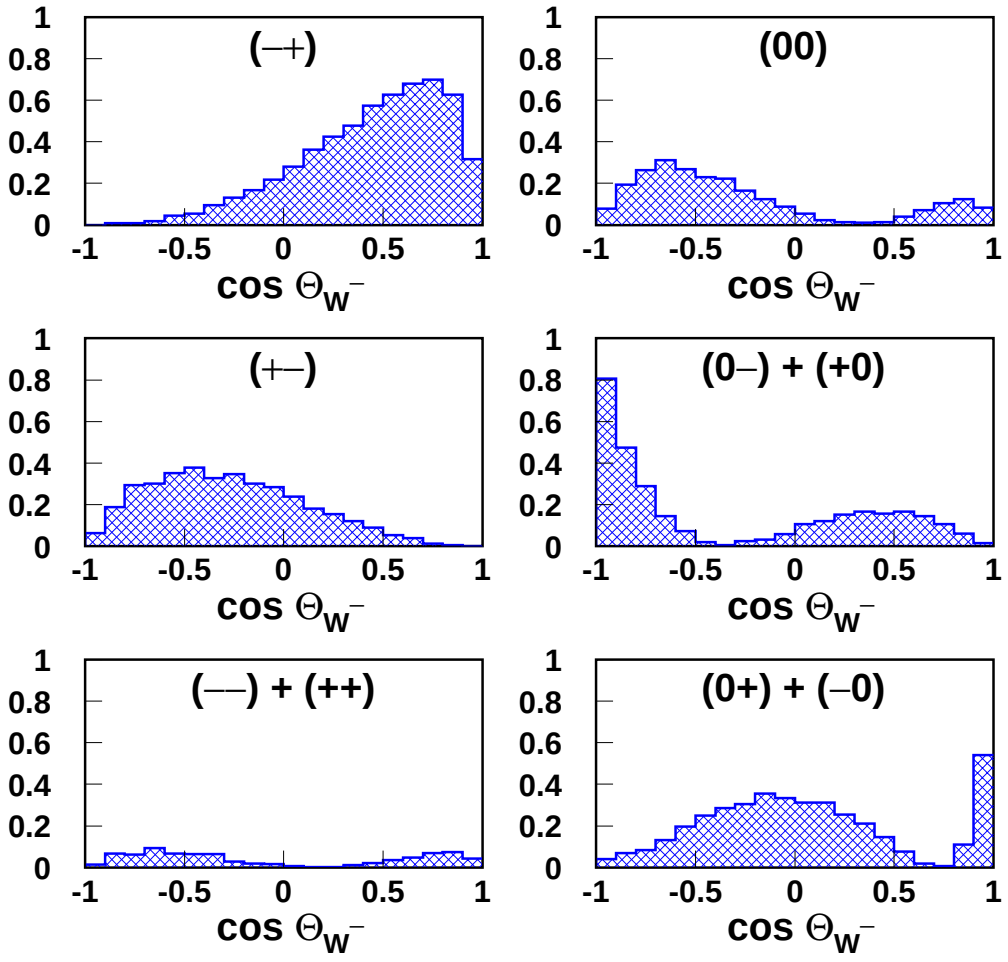
Searching for W^+W^- Spin Correlations

Angular distribution of cross section of $e^+e^- \to W^+W^-$:



Searching for W^+W^- Spin Correlations

Relative cross section contributions from particular helicity combinations (EEWW MC):



Cut on W^- scattering angle — Enrichment of

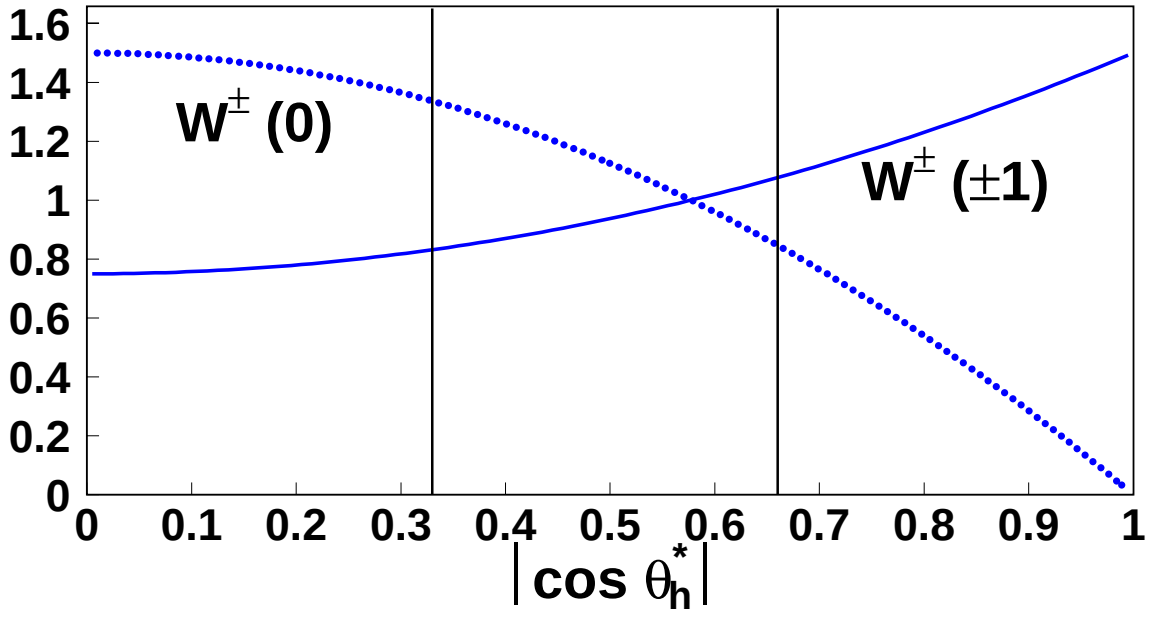
$0.3 < \cos\Theta_{W^-} < 0.9$ — $(-+) \sim 63\%$ (43% average)

$-0.3 < \cos\Theta_{W^-} < 0.3$ — no effect expected

$-0.9 < \cos\Theta_{W^-} < -0.3$ — $(00) \sim 25\%$ (9% average)

How to Observe W^+W^- Spin Correlations

- $W \to q\bar{q}$: helicities $(\pm 1), (0)$



- Cut on polar decay angle of $W \to q\bar{q}$
  - $(0.0, 0.33)$ $\Rightarrow (\pm 1)$ depleted W sample
  - $(0.66, 1.0)$ $\Rightarrow (\pm 1)$ enriched W sample

  For $0.3 \leq \cos\Theta_{W^-} \leq 0.9$ expect:
  (± 1) W helicity fraction varies from 75% to 90%
  (compared to average 80%)

- $W \to \ell\nu$: Compare / fit the resulting $\cos\theta^*$ distributions.

Event Selection

$e^+e^- \to W^+W^- \to e(\mu)\nu q\bar{q}$

- large multiplicity events (jet events)
- isolated electrons and muons ($p > 15 - 20$ GeV)
- large missing momentum ($p > 10$ GeV), pointing well into detector ($|\cos\Theta_\nu| < 0.95$)
- mass of jets $\approx m_W$
- mass of lepton-neutrino system $\approx m_W$,

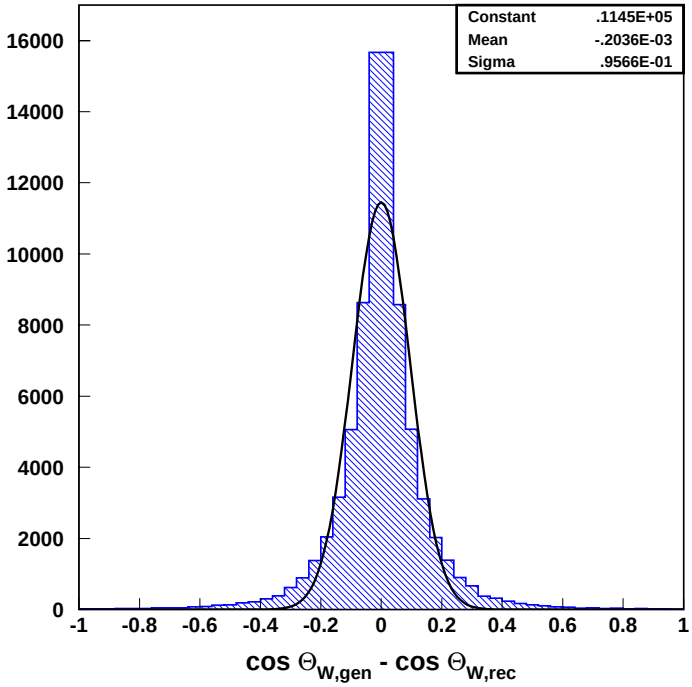
$W \to \ell\nu$:

- reconstruct neutrino from missing momentum,
- boost charged lepton to W rest frame.

$W \to q\bar{q}$:

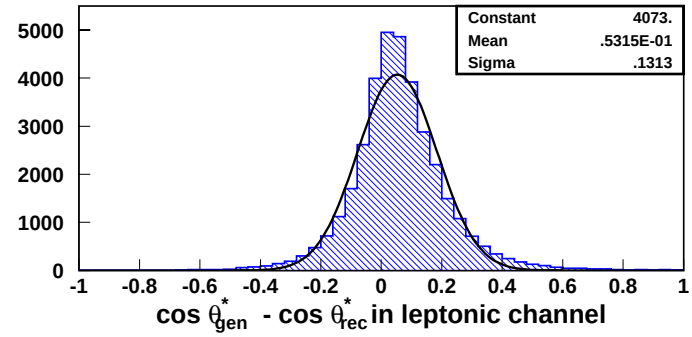
- boost all hadrons to W rest frame,
- determine thrust vector in rest frame,
- thrust vector gives direction of quark momentum vector.

Accuracy of Reconstruction

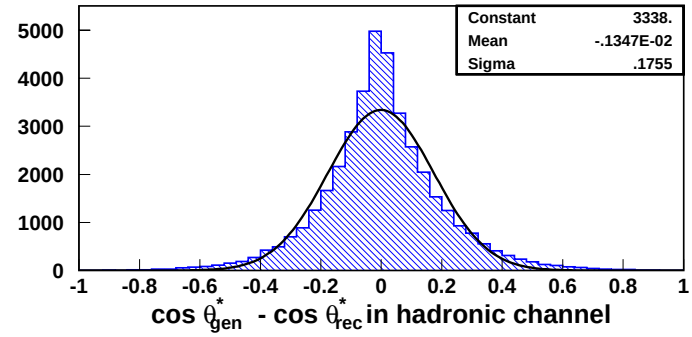


$$\text{shift} = -2 \cdot 10^{-4}$$

$$\sigma = 0.096$$



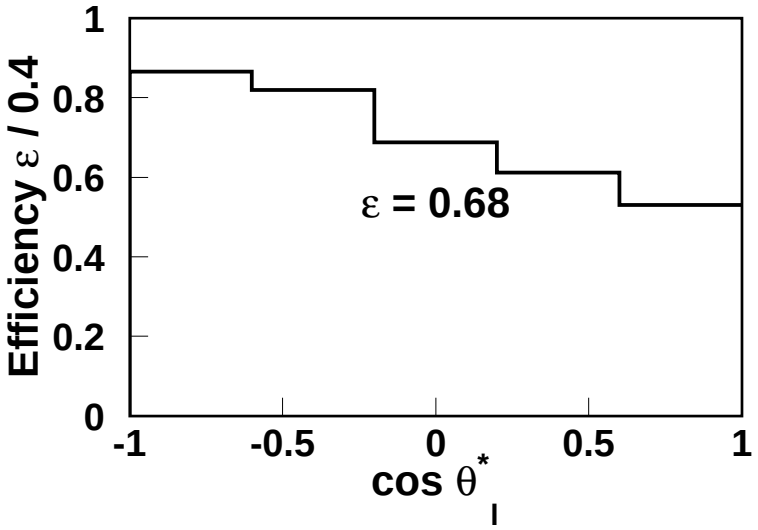
$$\text{shift} = 0.05$$
$$\sigma = 0.13$$



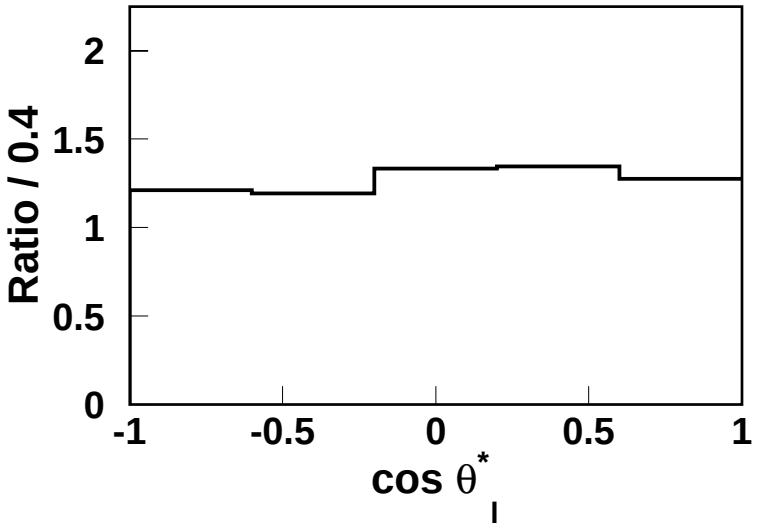
$$\text{shift} = -0.001$$
$$\sigma = 0.18$$

Efficiencies

in the forward scattering angle interval
$(0.3 \leq \cos\Theta_{W^-} \leq 0.9)$.



Inclusive efficiency,



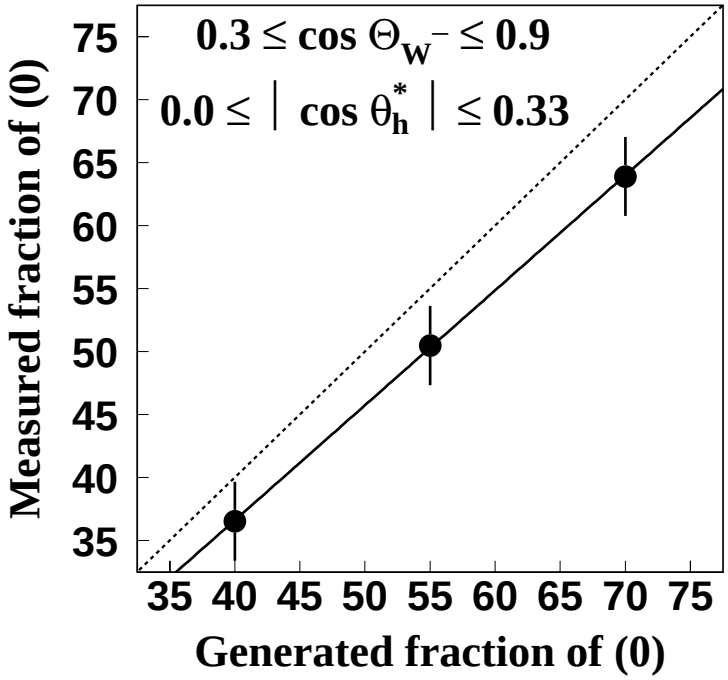
$|\cos\theta_h^*|$:

Ratio =

$$\frac{\text{efficiency in bin } (0.66, 1.0)}{\text{efficiency in bin } (0.0, 0.33)}.$$

Effects of Resolution and Efficiency: Bias Correction

- Use Monte Carlo with known helicity fractions (EEWW).

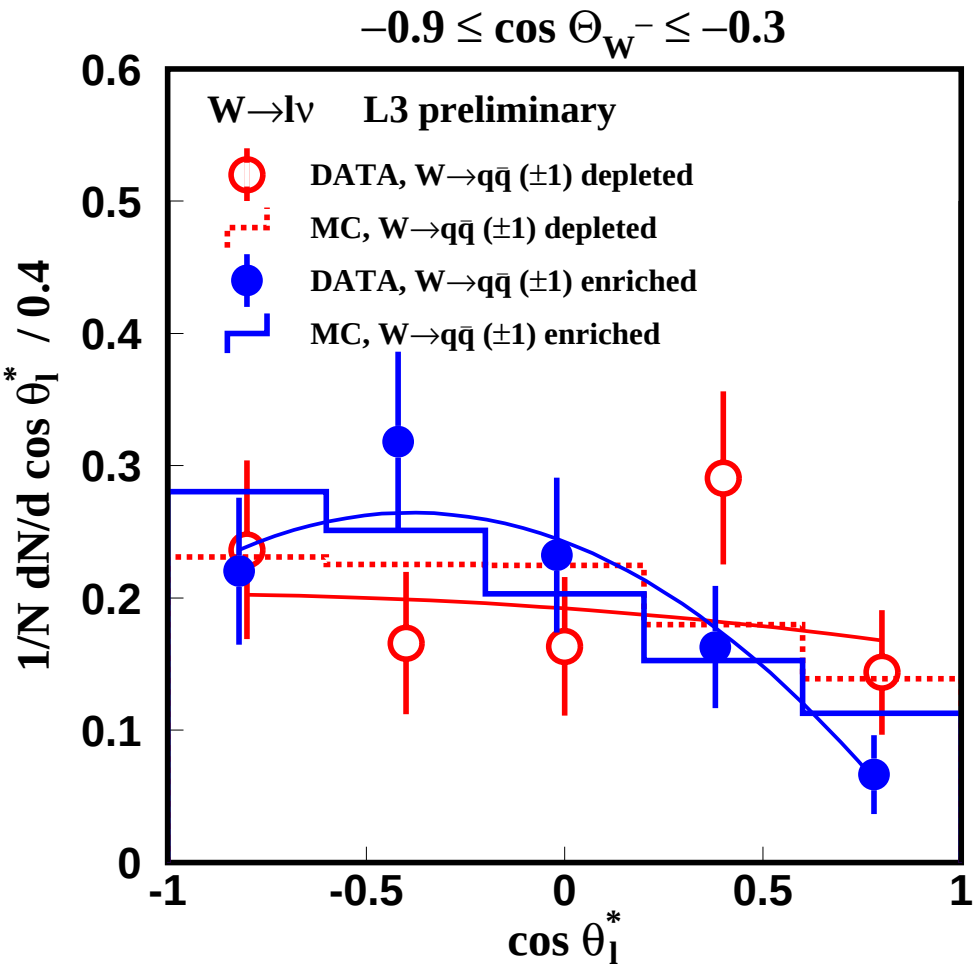


- Bias correction depends on $|\cos\theta^*_h|$ - slice, and slightly on fraction of other helicities.

- In each $|\cos\theta^*_h|$ slice, bias is almost linear for constant ratio of fractions of other helicities.

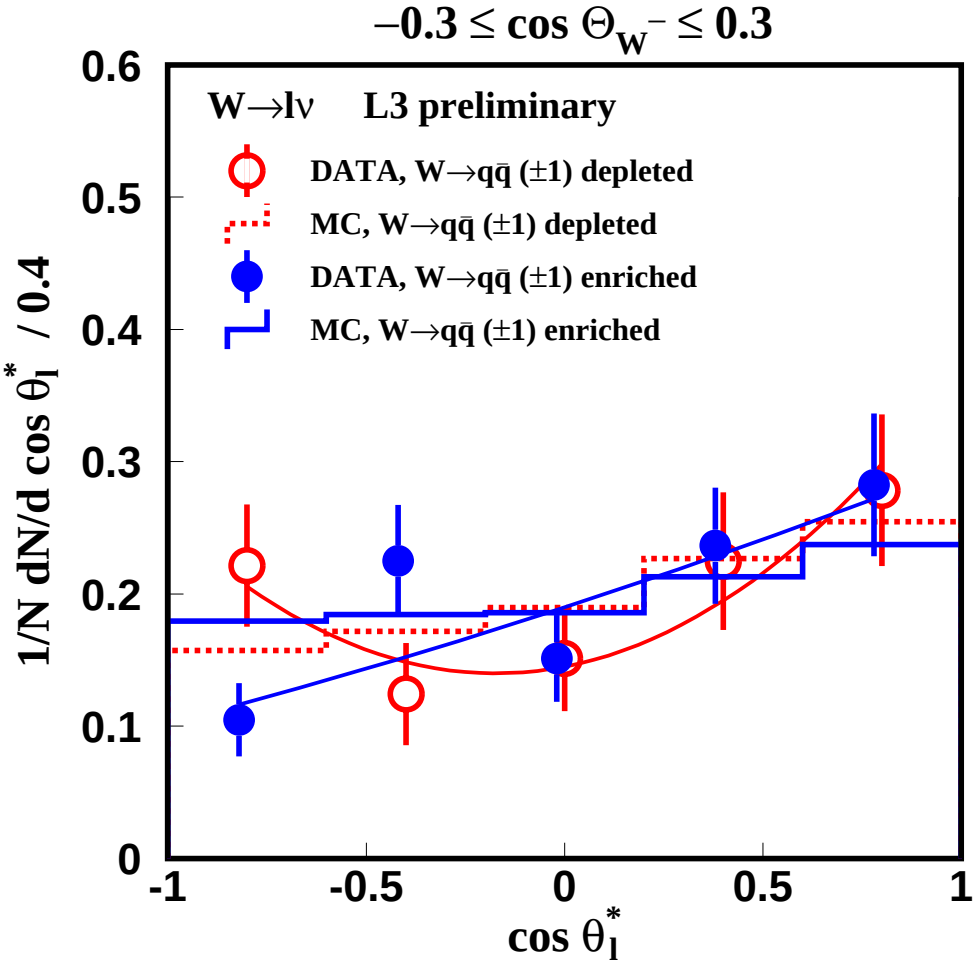
Data (183 – 202GeV) : Backward W^- Scattering Angle

W→ hadrons:	$W^- \to \ell\nu$ helicity		
	−1	+1	0
±1 depleted	24.0±9.5	34.9±13.8	41.1±19.8
±1 enriched	6.0±6.0	25.2±16.3	68.8±19.2
difference Data	18.0±11.2	9.7±21.4	-27.7±27.6
difference MC	3.6	-13.3	9.6



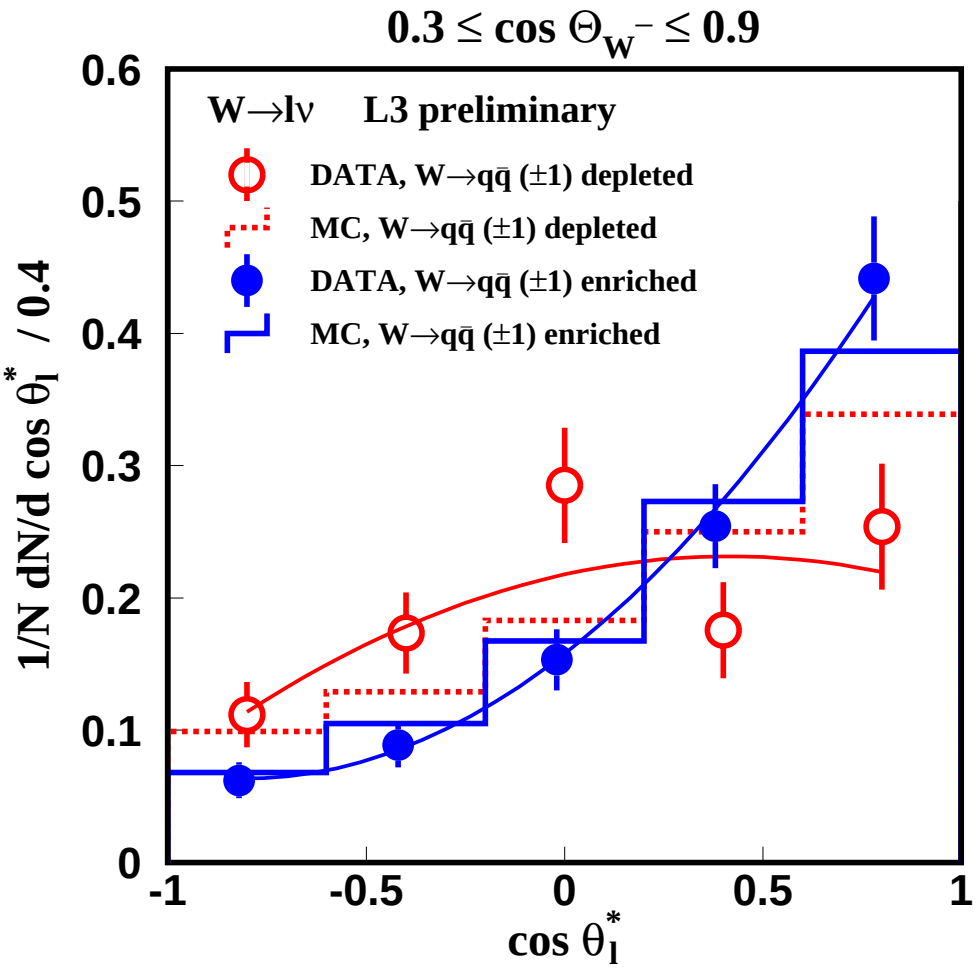
Data (183 – 202GeV) : Central W^- Scattering Angle

W→ hadrons:	$W^- \to \ell\nu$ helicity		
	−1	+1	0
±1 depleted	54.9±13.1	45.1±11.3	0.0±17.9
±1 enriched	50.5±13.0	20.2±8.5	29.3±15.2
difference Data	4.4±18.5	24.9±14.1	-29.3±23.5
difference MC	3.5	-5.2	1.7

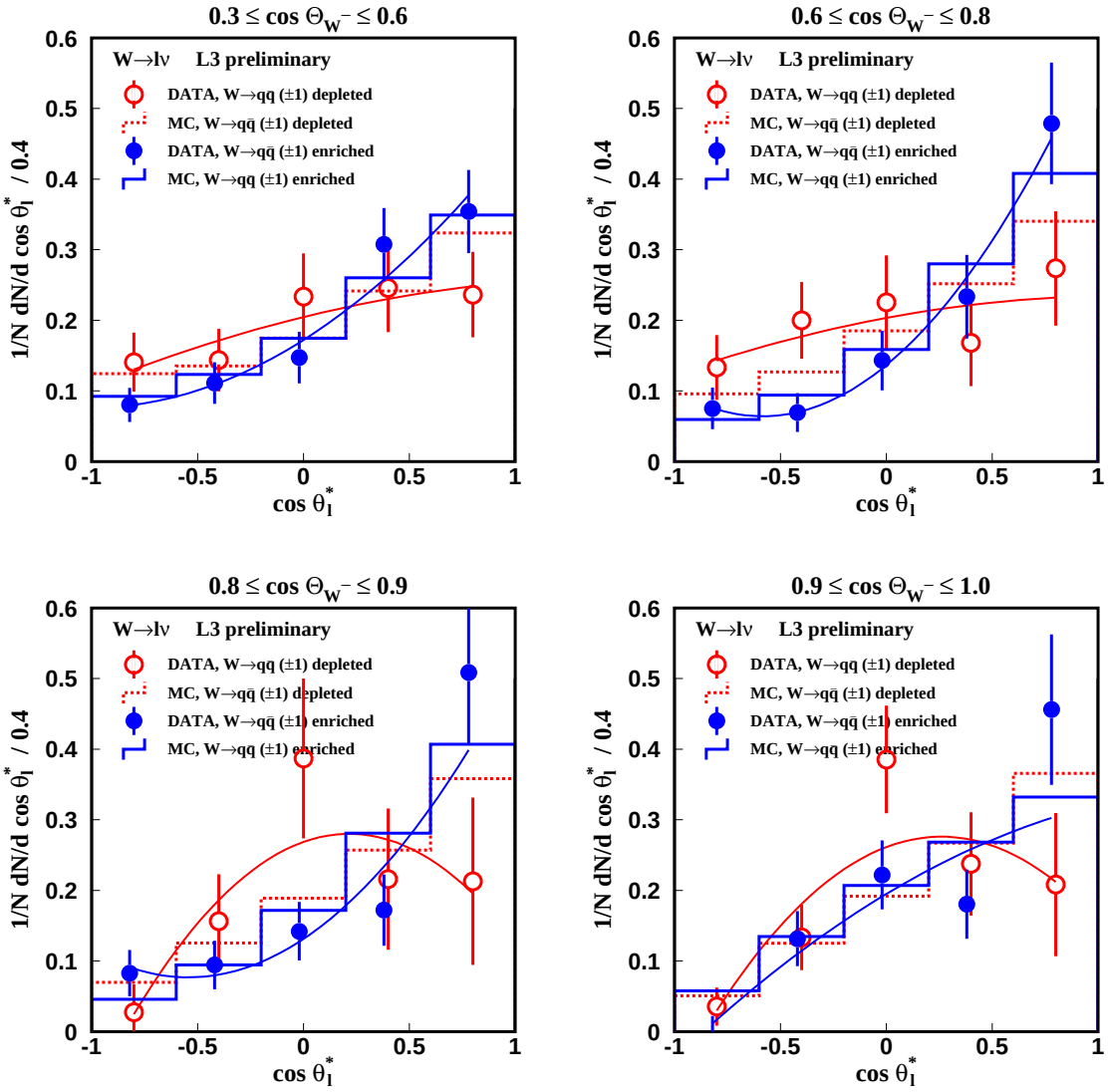


Data (183 – 202GeV) :
Forward W^- Scattering Angle

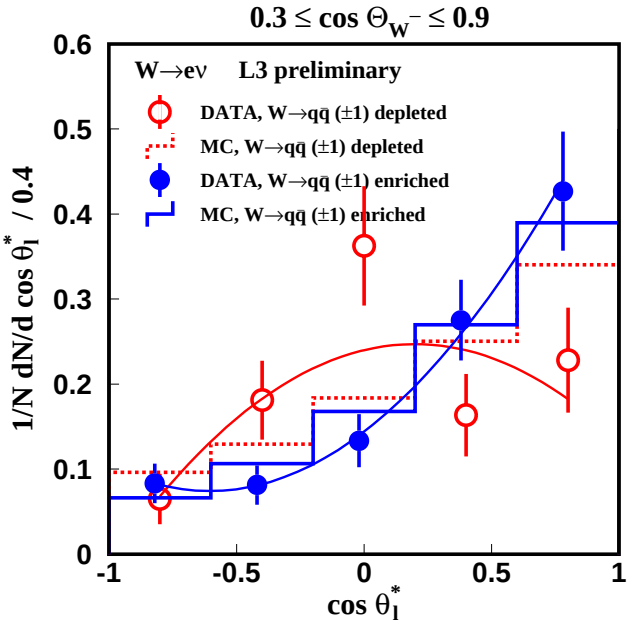
W→ hadrons:	$W^- \to \ell\nu$ helicity		
	−1	+1	0
±1 depleted	26.2±12.7	16.9±9.0	57.0±16.1
±1 enriched	86.2±13.1	12.7±4.1	1.1±8.6
difference Data	-60.0±18.2	4.2±9.9	55.9±18.3
difference MC	-12.0	4.9	7.0



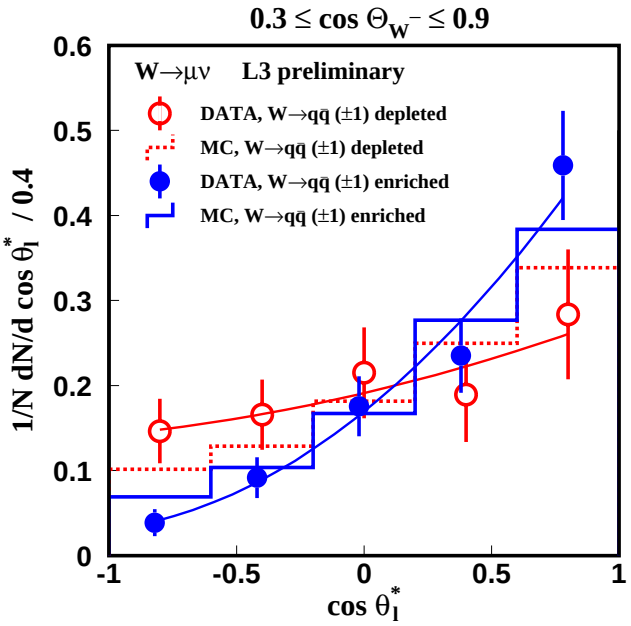
Forward W^- Scattering Angle: Subsamples



Forward W^- Scattering Angle: Electrons and Muons



electrons only



muons only

Systematic Studies

- Variation of background: $\frac{1}{2}$ to $1\frac{1}{2}$ of nominal,
- variation of selection cuts for $m_{\ell\nu}$, $m_{\mathrm{q\bar{q}}}$ and p_{miss},
- variation of cuts on W$\rightarrow$q$\bar{\mathrm{q}}$,
- dependence on center-of-mass energy,
- uncertainties from efficiency and bias corrections.

Result:

- no significant systematic effect found,
- systematic uncertainties $< \frac{1}{2} \times$ statistical errors.

Decay Planes of W^+ and W^-

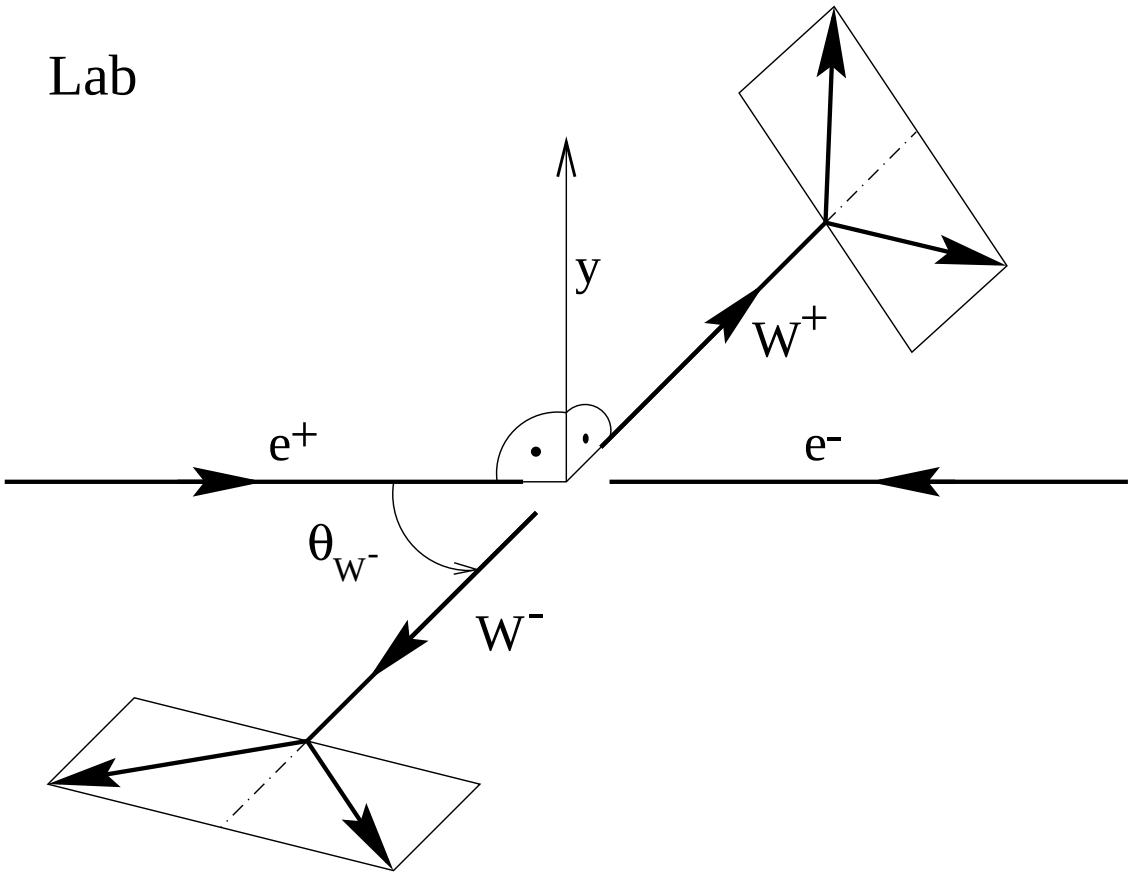
- Studying

$$|\Delta\phi^*| = \left|\phi^*_\ell - \phi^*_h\right|$$

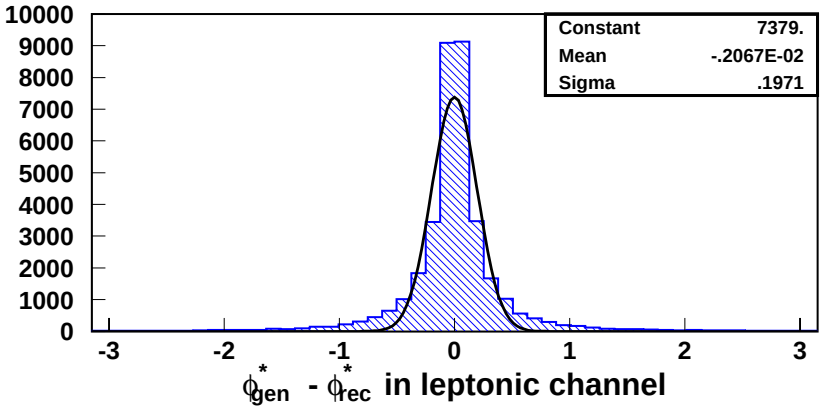
in the range $0° < |\Delta\phi^*| < 90°$.

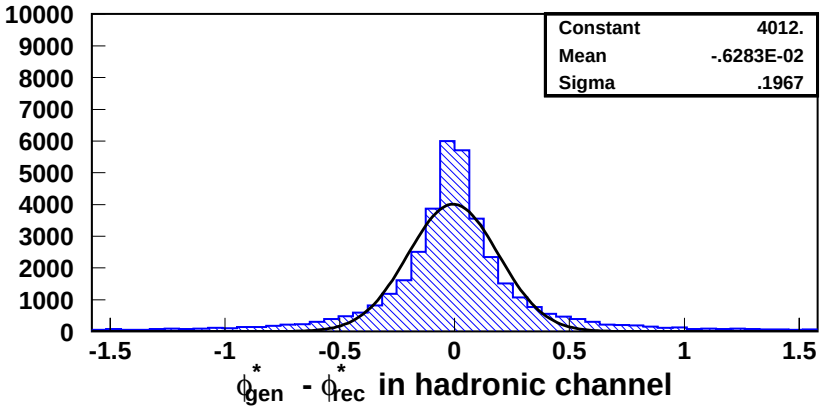
- Fit function: $1 + D \cdot \cos(2 \cdot |\Delta\phi^*|)$

(Reference:
Duncan *et al.*, Phys.Rev.Lett. **55**, 773.)



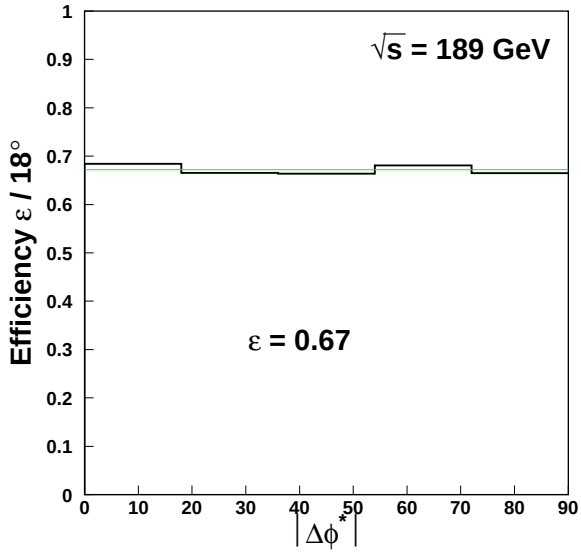
Accuracy of Reconstruction and Efficiency





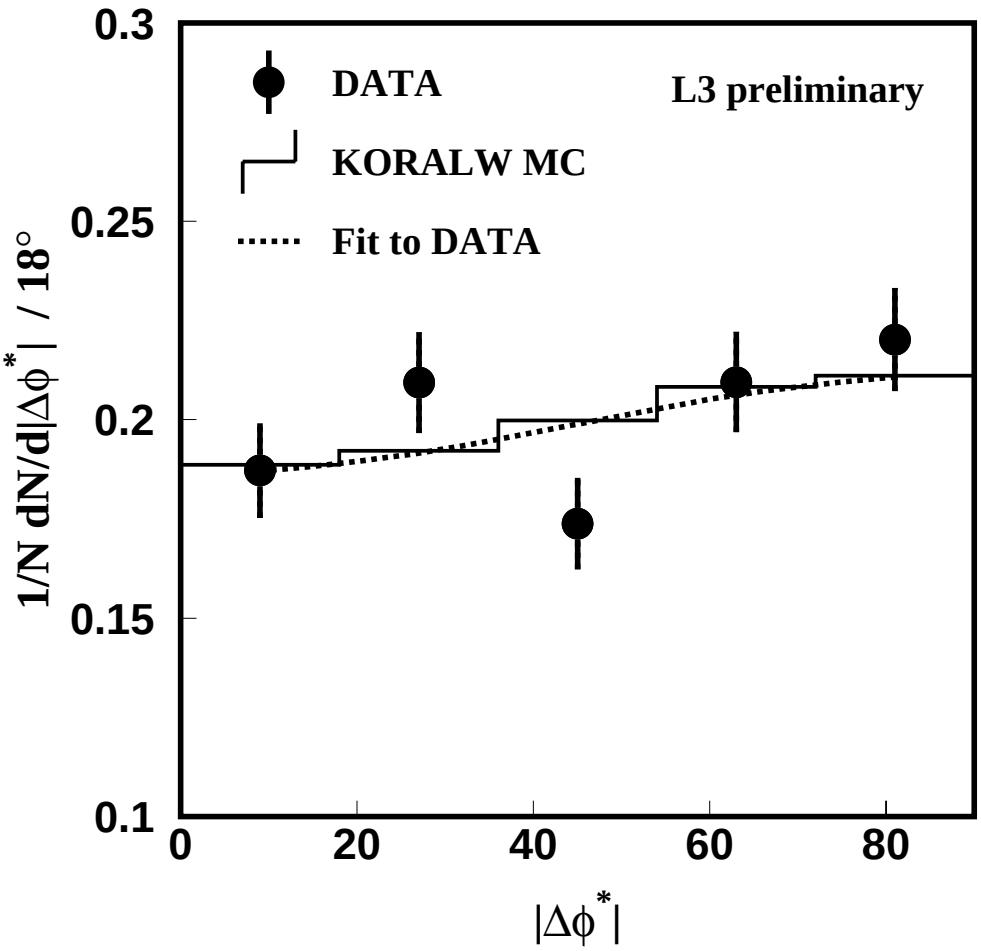
shift $< 1°$

$\sigma \approx 11°$



Decay Planes: Data

- uncorrelated decay: $D = 0$
- fit to KORALW MC: $D = -0.061 \pm 0.006$
- fit to DATA : $D = -0.062 \pm 0.040$



⇒ $|\Delta\phi^*|$ goes into expected direction,
not yet statistically significant.
⇒ Include 2000 data and 4-jet final states.

Summary

- Evidence for spin correlations along W flight direction with 4 standard deviations:
  - Helicity of $W \to \ell\nu$ depends on helicity of $W \to q\bar{q}$.

    $0.3 < \cos\Theta_{W^-} < 0.9 \Rightarrow$
    $W^- \to \ell\nu$ (-1):

    $26.2 \pm 12.7\%$ with $W \to q\bar{q}$ (± 1) depleted

    $86.2 \pm 13.1\%$ with $W \to q\bar{q}$ (± 1) enriched

    $-0.9 < \cos\Theta_{W^-} < -0.3 \Rightarrow$
    $W^- \to \ell\nu$ (-1):

    $24.0 \pm 9.5\%$ with $W \to q\bar{q}$ (± 1) depleted

    $6.0 \pm 6.0\%$ with $W \to q\bar{q}$ (± 1) enriched

  - Reasonable agreement with KORALW Monte Carlo.
    (See some interesting deviations up to $\approx 3\sigma$)

- Spin correlations in decay planes:
  1.5σ deviation from uncorrelated decay,
  in good agreement with KORALW MC.
  Preference of decay under a 90° angle.

- Results written up in L3 note 2574:
  Improved Studies with Longitudinally and Transversely Polarised $W^{\pm}$ *Bosons.*

Outlook

- Include this years data: some 50% or 200pb^{-1} more data – statistical gain $\approx$ 1.2

- Include 4-jet final states (WW$\rightarrow q\bar{q}q\bar{q}$): statistical gain $\approx$ 1.5
  However: systematics not easy.

Definitions in the $W^{\pm}$ Center-of-Mass System