Quantum Interference Effects Among Helicities at LEP-II and Tevatron

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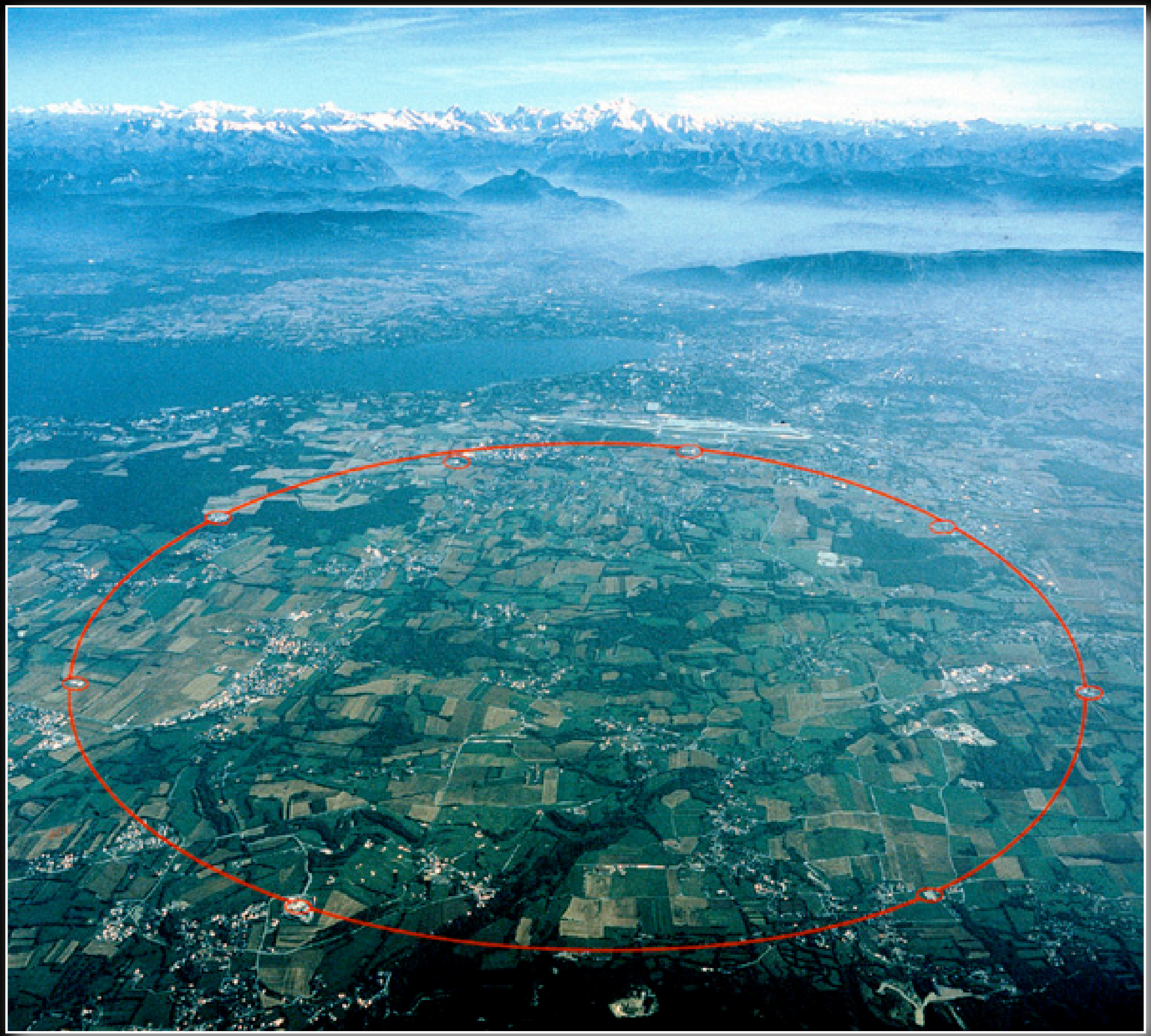
The LHC Era

- Finally have access to TeV-scale physics
  - Solution to the Hierarchy Problem?
  - Dark Matter?

  $\Longrightarrow$ New Particles

  - SUSY, Extra-Dimensions, Little Higgs? Something totally different?



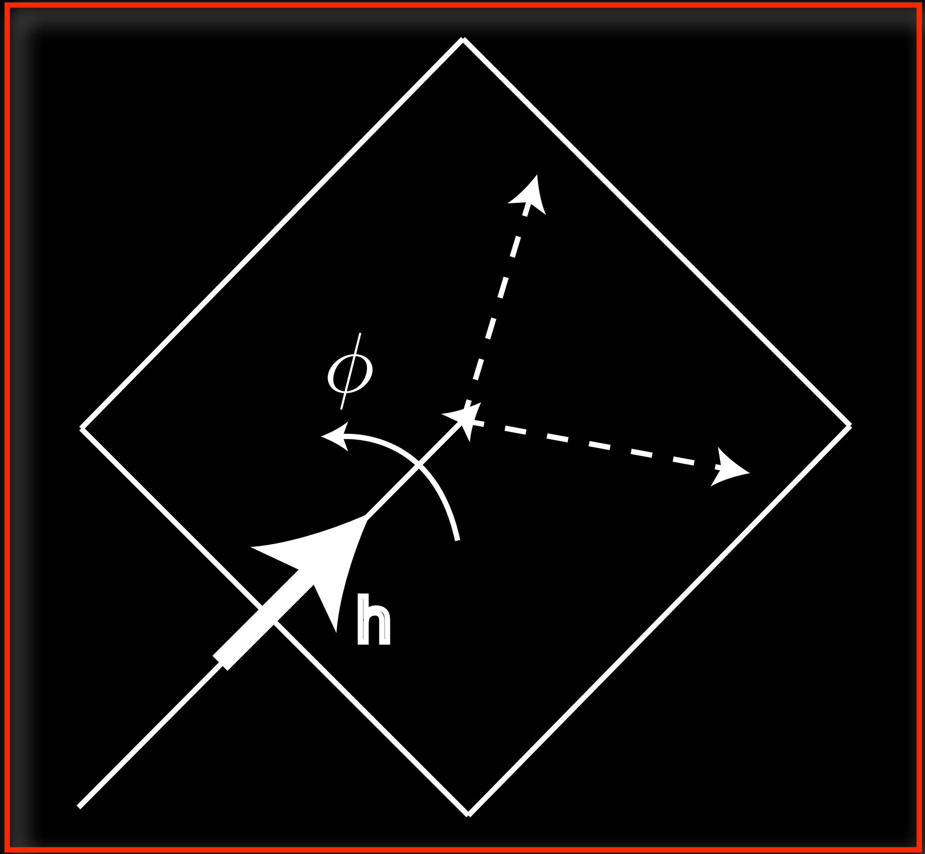
Spin Measurements

- Most techniques for next-generation colliders concentrate on distinguishing models:
  - Comparison of total cross section
  - Look for higher KK modes in UED
- At a linear collider can use threshold scans
  - Reconstruct production/polar decay angle
  - With long decay chains, can be used at hadron collider.

Spin and Quantum Interference

- Want a spin measurement with as few assumptions as possible.
- Back to Quantum Mechanics!
- Decay of particle with helicity h
  - Rotations about the z-axis (particle momentum) implies that

$$\mathcal{M}_{\mathrm{decay}} \propto e^{iJ_z\phi} = e^{ih\phi}$$



Spin and Quantum Interference

- If particle is produced in multiple helicity states and then decays, then decay amplitudes interfere coherently:

$$\sigma \propto \left| \sum \mathcal{M}_{\mathrm{prod.}} \mathcal{M}_{\mathrm{decay}} \right|^2$$

$$\mathcal{M}_{\mathrm{decay}}(h, \phi) = e^{ih\phi} \mathcal{M}_{\mathrm{decay}}(h, \phi = 0)$$

- Sum runs over all helicities produced, generically $h = -s, \cdots, s$ in which case

$$\sigma = A_0 + A_1 \cos\phi + \cdots + A_n \cos n\phi, \;\; n = 2s$$

(with H.Murayama, W. Klemm, and B.Heinemann)

Applications

- Demonstration of technique using data already on tape, from LEP-II and Tevatron

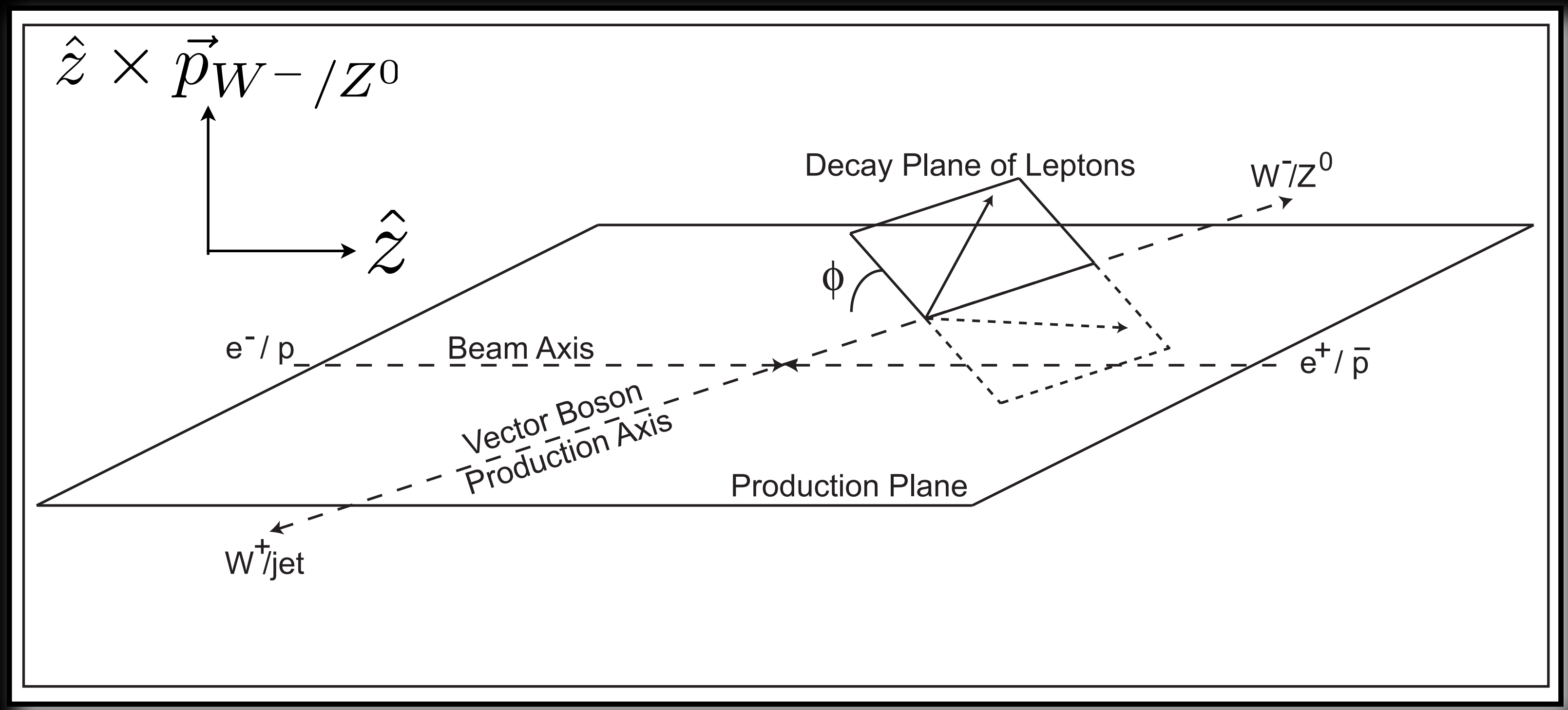
- $p\bar{p} \to Z + \text{jet},\ \ Z \to e^- e^+$
- $\sigma = 7\ \text{pb}$ with
  $p_{T\text{jet}} > 30\ \text{GeV},\ \ |\eta_{\text{jet}}| < 2.1$
  and cuts on lepton $p_T,\ \eta$
- $1.7(8.0)\ \text{fb}^{-1}$ total luminosity

- $e^- e^+ \to W^- W^+ \to jj\ell^\pm\nu$
- 3150 events with $\sqrt{s}$ from
  $182 - 207\ \text{GeV}$

In both cases, expect non-zero

$$A_0, A_1, A_2$$

Kinematics



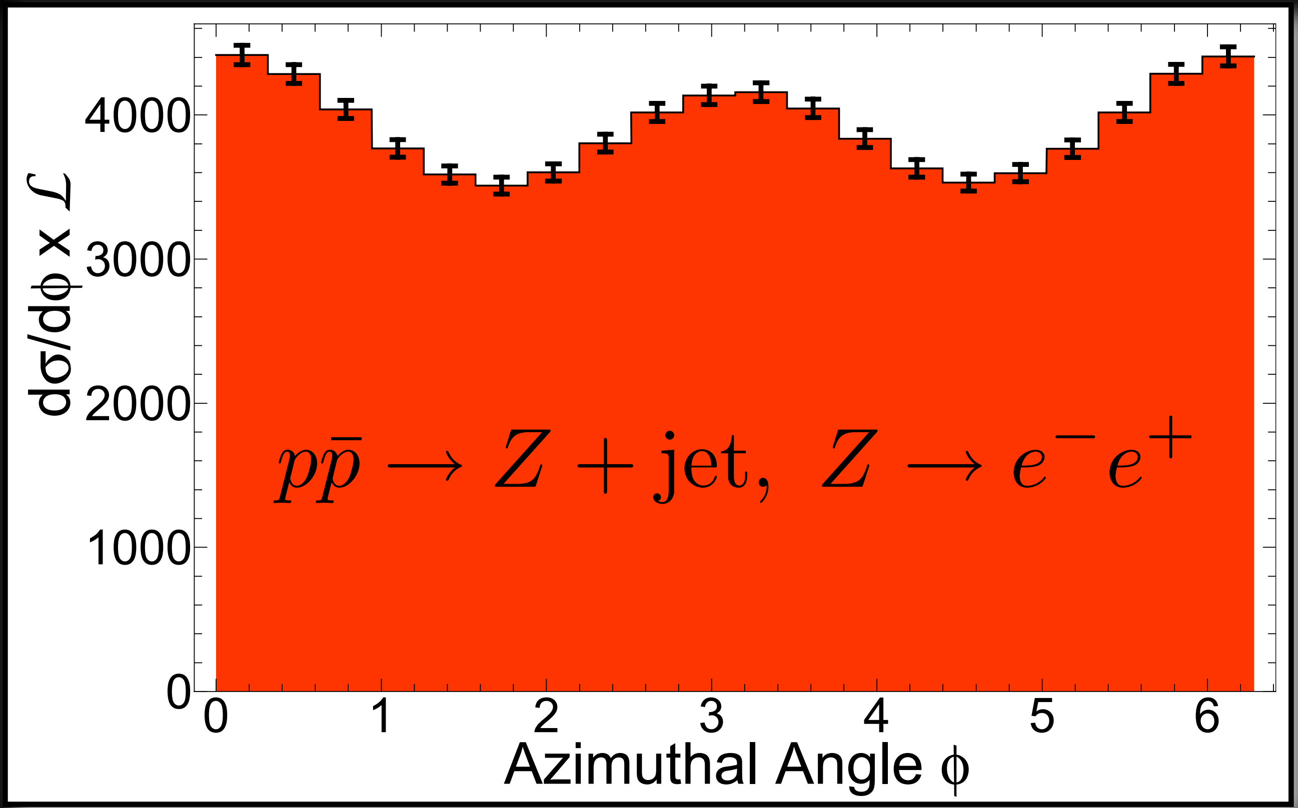
$$\cos\phi = \frac{\hat{z} \times \vec{p}_{W^\pm/Z^0}}{|\hat{z} \times \vec{p}_{W^\pm/Z^0}|} \cdot \frac{\vec{p}_{W^\pm/Z^0} \times \vec{p}_{\ell^\pm/e^-}}{|\vec{p}_{W^\pm/Z^0} \times \vec{p}_{\ell^\pm/e^-}|}$$

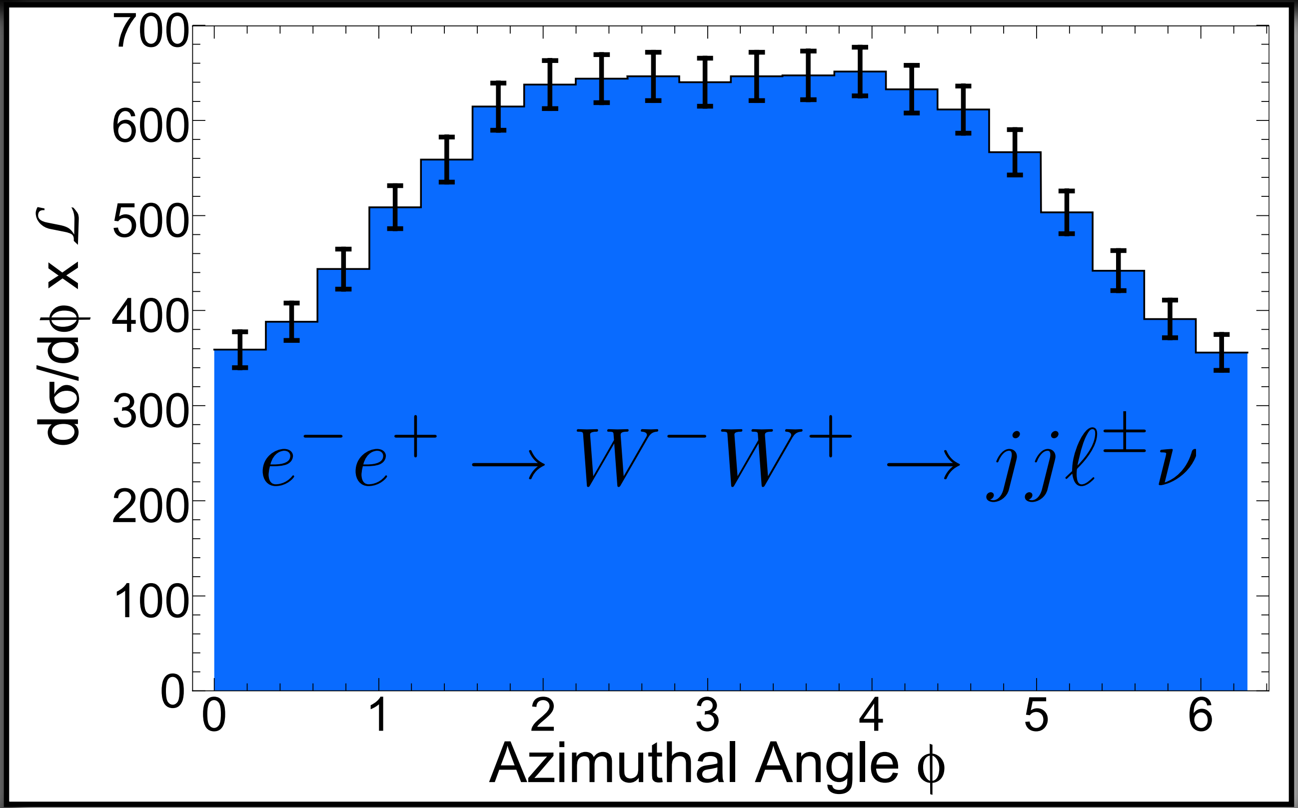
Define positive ϕ to be in the direction of

$$\hat{z} \times \vec{p}_{W^\pm/Z^0}$$

Results

- Calculated cross sections using HELAS and the adaptive Monte-Carlo program BASES.
- With only cuts on jet $p_T,\ \eta$ for Tevatron data, and no cuts on LEP-II:



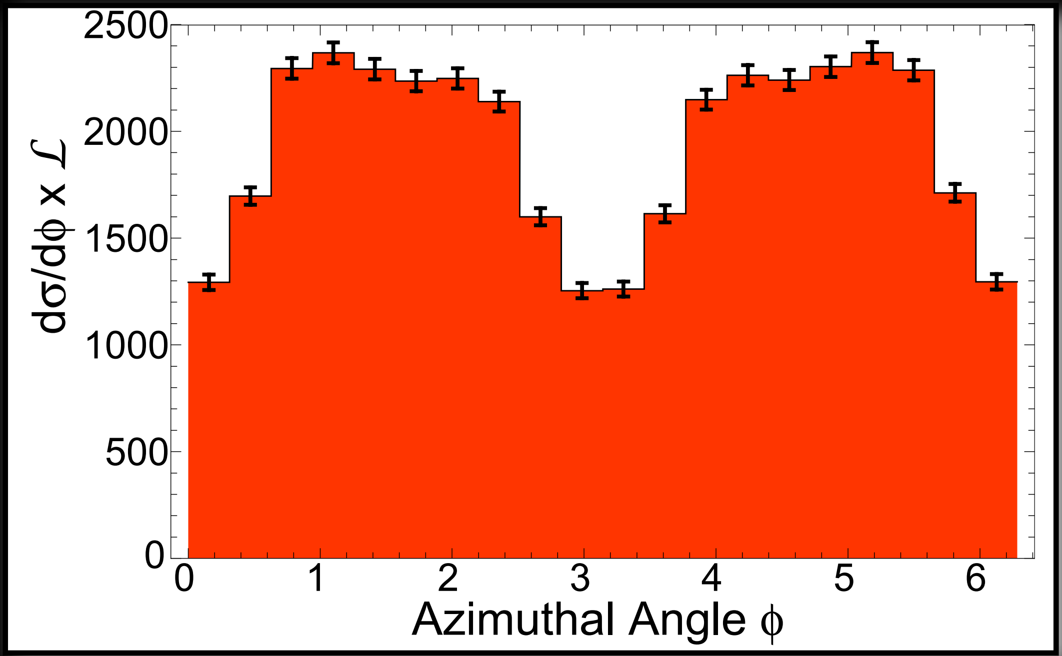


Effects of Cuts

- However, detectors cannot see forward regions, and need isolation cuts on jets/leptons.

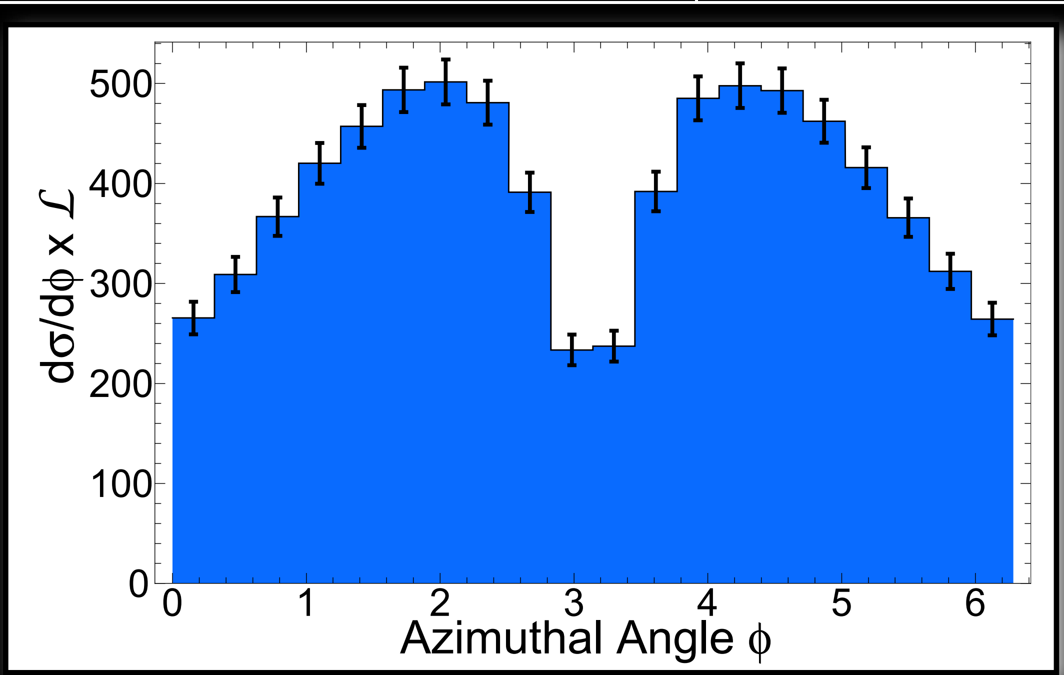
CDF cuts:

Jet transverse momentum	$p_{T,j} > 30$ GeV
Jet η	$\|\eta\| < 2.1$
Invariant mass of lepton pair	$66 < m_{\ell\ell} < 116$
Central electron η	$\|\eta\| < 1$
Second electron η	$\|\eta\| < 1$ or $1.2 < \|\eta\| < 2.8$
Electron E_T	$E_T > 25$ GeV
Electron isolation cuts	$\Delta R_{e-j} > 0.7$



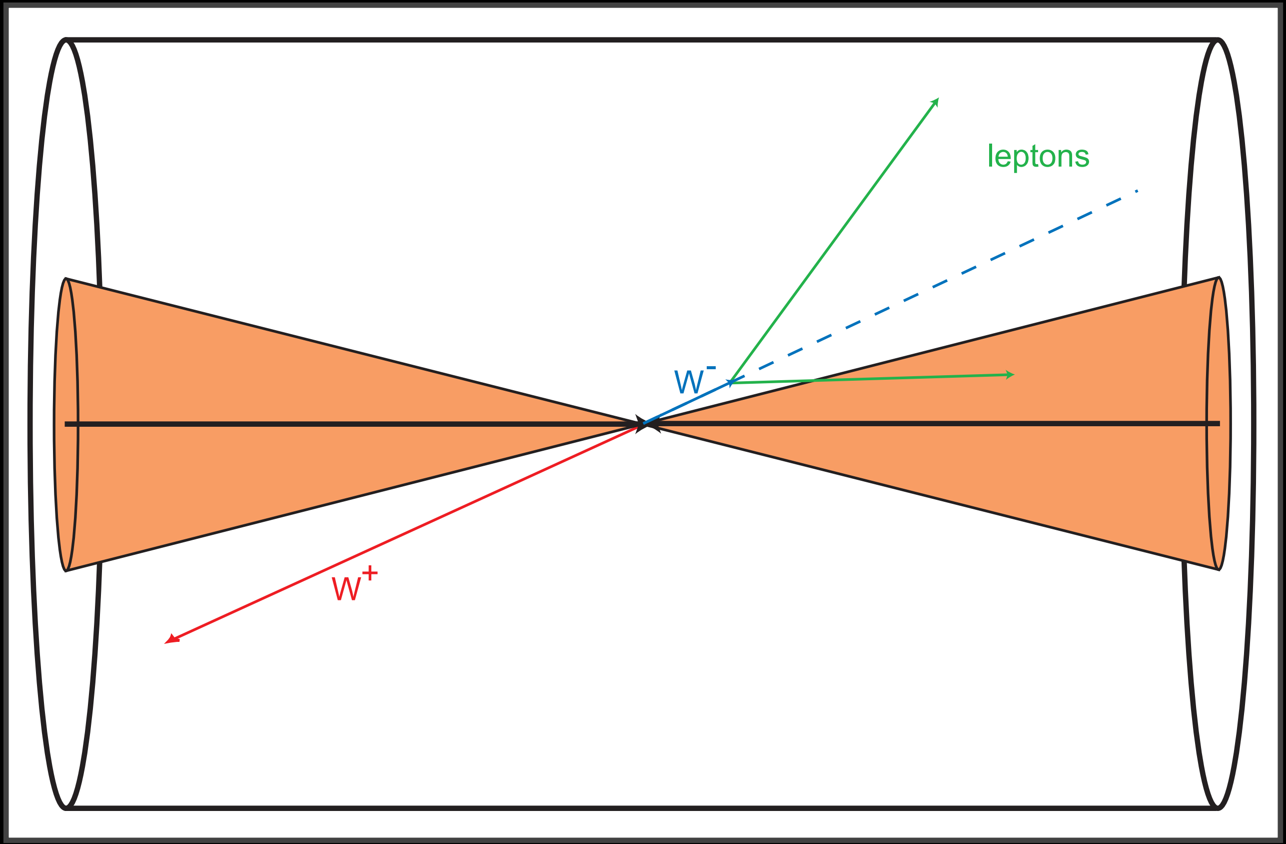
OPAL cuts:

Lepton momentum	$p_\ell > 25$ GeV
Polar angle θ of final state particles	$\|\cos\theta\| < 0.95$
Neutrino energy fraction	$R_\nu > 0.07$
Visible energy fraction	$R_{\text{vis}} > 0.3$
Neutrino transverse momentum	$p_{T,\nu} > 16$ GeV
Lepton isolation	$\Delta R > 0.75, 0.5, 0.2$



Rotational Invariance

- Cuts introduce new directional dependences.
- Remove them by requiring events to pass cuts after rotation about boson axis



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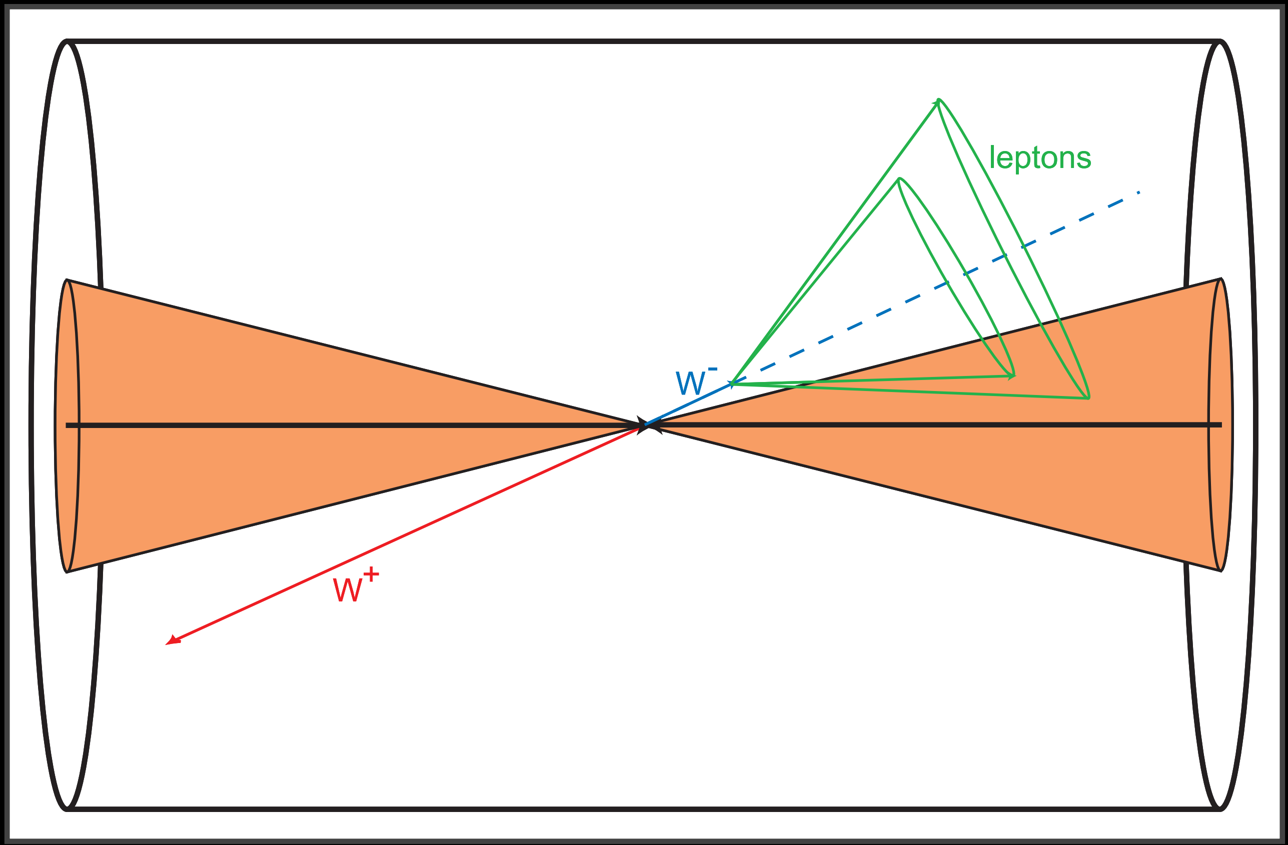
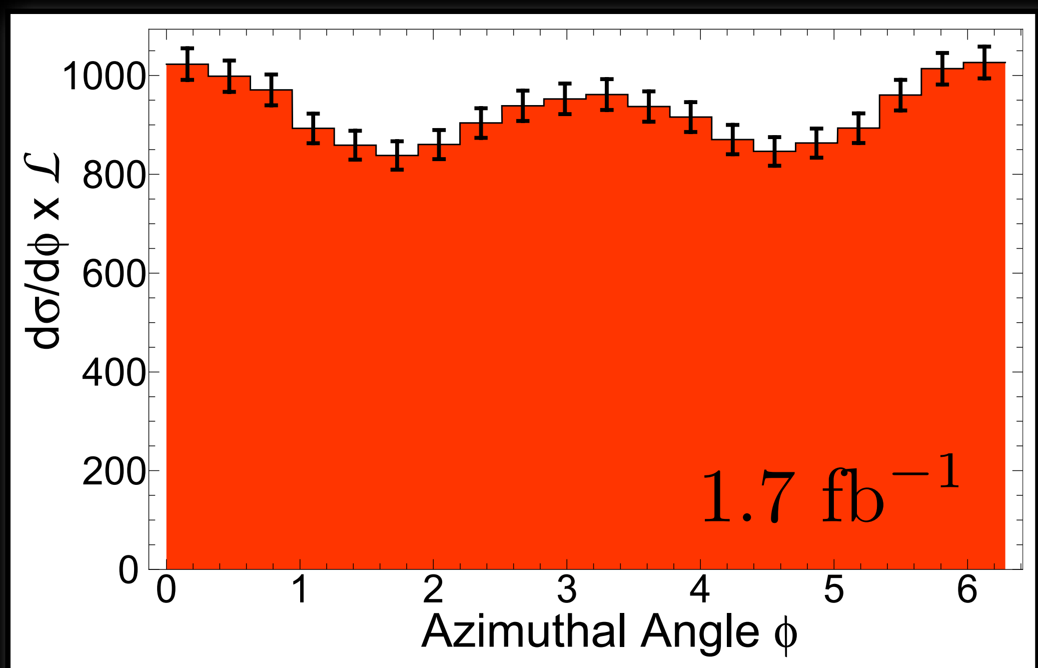
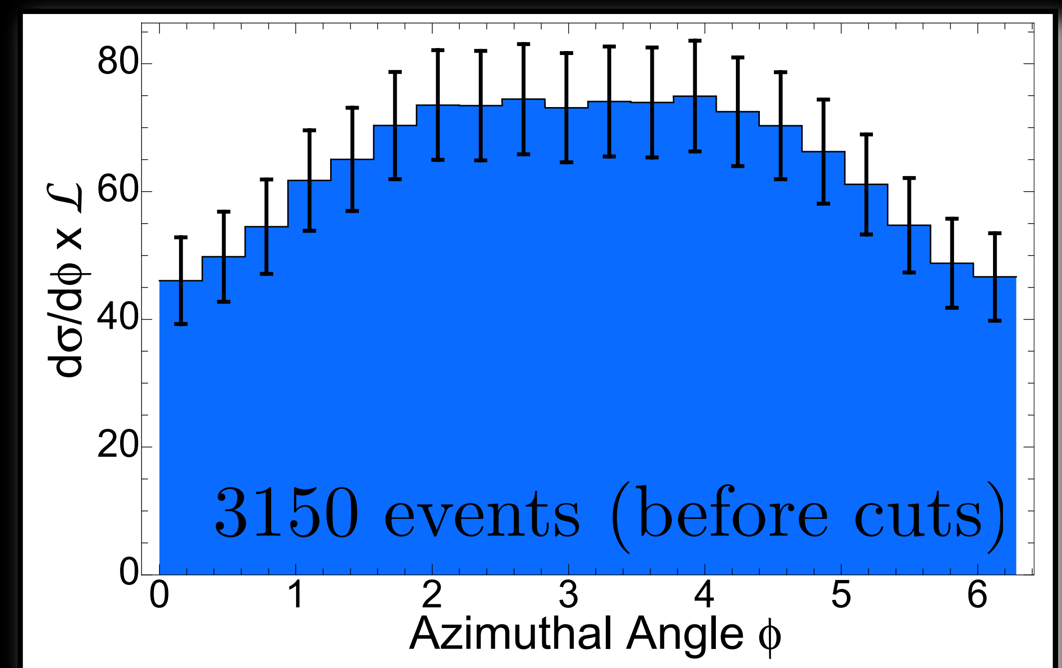


Rotationally Invariant Cuts

- Applying these rotationally invariant cuts
  - (And with looser acceptances at Tevatron)





A_1/A_0	0.039 ± 0.022
A_2/A_0	0.083 ± 0.021
A_3/A_0	0.000 ± 0.022
A_4/A_0	0.000 ± 0.023

A_1/A_0	-0.215 ± 0.069
A_2/A_0	-0.068 ± 0.071
A_3/A_0	0.000 ± 0.073
A_4/A_0	0.000 ± 0.075

LEP-II Efficiencies

- OPAL uses energy deposition cuts to isolate leptons
  - We used ΔR cuts with lower efficiencies.
  - Higher efficiency $\rightarrow$ better statistics
  - Using $\Delta R = 0$, $\epsilon \sim 90\%$ (non-rotational cuts)
    $\epsilon \sim 15\%$ (rotational cuts)

A_1/A_0	-0.211 ± 0.050
A_2/A_0	-0.081 ± 0.052
A_3/A_0	0.000 ± 0.053
A_4/A_0	0.000 ± 0.054

- Combine ALEPH, L3, DELPHI, OPAL:

A_1/A_0	-0.207 ± 0.027
A_2/A_0	-0.072 ± 0.028
A_3/A_0	0.000 ± 0.028
A_4/A_0	0.000 ± 0.029

Conclusions

- Interference of helicity states provides a model-independent method of spin measurements.
  - Method can be tested with current data on vector bosons at Tevatron and LEP-II
  - Should be capable of demonstrating that $W^{\pm}/Z^0$ have spin ≥ 1