CP Violation in the
Heaviest Leptons, Quarks, and Bosons

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Two Caveats

1. CP Violation will be addressed in more general framework of anomalous gauge Boson and Fermion couplings

2. Lectures will not form comprehensive review:
   - Subject too vast for detailed coverage
   - Instead, will focus pedagogically on particular approaches & signatures
   - Will touch on other topics you can pursue on your own

Outline (1)

Gauge Boson Couplings

- Standard Model
  - Lagrangian terms
    $\Longrightarrow$ Expected triple- and quadruple-Boson couplings

- Beyond the Standard Model
  - More general $WW\gamma$ and WWZ Lagrangian terms
    $\Longrightarrow$ Many possible couplings, including $\not{C}\not{P}$
  - Possible treatments of anomalous couplings
    * Effective Lagrangian with light Higgs (linear)
    * Chiral Lagrangian with strong coupling (non-linear)

- Experimental signatures for $WW\gamma$, WWZ couplings
  - Low-energy experiments
  - e^+e^- colliders
  - Hadron colliders

- Other gauge Boson couplings ($\not{C}\not{P}$)
  - Sampling of couplings & signatures

Outline (2)

Top Quark Couplings

- Standard Model
- Possible sources of non-SM couplings
- Experimental signatures

Tau Lepton Couplings

- Standard Model
- Possible sources of non-SM couplings
- Experimental signatures

Standard Model

S.M. Electroweak Lagrangian – Bosonic interactions:

(following notation/convention of Renton text)

Unbroken $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$:

$$\begin{aligned} \mathcal{L}_{\text{Bosons}} &= -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} \vec{W}_{\mu\nu(NA)} \cdot \vec{W}^{\mu\nu}_{(NA)} \\ &\quad + [D_\mu \phi]^\dagger [D^\mu \phi] - \mu^2 \phi^\dagger \phi - \lambda [\phi^\dagger \phi]^2 \end{aligned}$$

where

$$\begin{aligned} D^\mu &\equiv \partial^\mu + i\frac{g}{2}\vec{\tau} \cdot \vec{W}^\mu + i\frac{g'}{2} y B^\mu \\ B^{\mu\nu} &\equiv \partial^\mu B^\nu - \partial^\nu B^\mu \\ \vec{W}^{\mu\nu}_{(NA)} &\equiv \partial^\mu \vec{W}^\nu_{(NA)} - \partial^\nu \vec{W}^\mu_{(NA)} - g \vec{W}^\mu_{(NA)} \times \vec{W}^\nu_{(NA)} \end{aligned}$$

where

$$\begin{aligned} \phi &\equiv \text{Complex scalar doublet} \\ \vec{W} &\equiv \text{Unbroken } \mathrm{SU}(2)_L \text{ field} \\ B &\equiv \text{Unbroken } \mathrm{U}(1)_Y \text{ field} \end{aligned}$$

Physical fields:

$$\begin{aligned} A^\mu &= c_W B^\mu + s_W W_3^\mu && \text{(Electromagnetic)} \\ Z^\mu &= -s_W B^\mu + c_W W_3^\mu && \text{(Weak neutral)} \\ W^{\pm\mu} &= \frac{1}{\sqrt{2}}(W_1^\mu \pm i W_2^\mu) && \text{(Weak charged)} \end{aligned}$$

where

$$s_W \equiv \sin\theta_W \qquad c_W \equiv \cos\theta_W$$

Standard Model

Consider Gauge Boson self interactions (ignore Higgs terms):

- Invert relations to obtain B^μ, W_1^μ, W_2^μ and W_3^μ in terms of physical fields A^μ, Z^μ and $W^{\pm\mu}$
- Substitute into first two terms of unbroken Lagrangian

$$\mathcal{L}_{\rm Gauge} \quad = \quad \mathcal{L}_{\rm Abelian} + \mathcal{L}_{\rm TGC} + \mathcal{L}_{\rm QGC}$$

where

$$\mathcal{L}_{\rm Abelian} = -\frac{1}{4}\,{}^{(\gamma)}F_{\mu\nu}\,{}^{(\gamma)}F^{\mu\nu} - \frac{1}{4}\,{}^{(z)}F_{\mu\nu}\,{}^{(z)}F^{\mu\nu} - \frac{1}{2}\,{}^{(w)}F^\dagger_{\mu\nu}\,{}^{(w)}F^{\mu\nu}$$

$\Longrightarrow$ Abelian kinetic energy

$$\begin{aligned}\mathcal{L}_{\rm TGC} = \;& i\,g\,(\partial_\mu W^+_\nu - \partial_\nu W^+_\mu)\,W^{-\nu}\,(c_W Z^\mu + s_W A^\mu)\\ &+ i\,g\,(\partial_\mu W^-_\nu - \partial_\nu W^-_\mu)\,W^{+\mu}\,(c_W Z^\nu + s_W A^\nu)\\ &+ i\,g\,(W^{-\mu}W^{+\nu} - W^{+\mu}W^{-\nu})\,\partial_\mu\,(c_W Z_\nu + s_W A_\nu)\end{aligned}$$

$\Longrightarrow$ Non-Abelian Triple-Gauge-Couplings:
$WW\gamma$, WWZ

$$\begin{aligned}\mathcal{L}_{\rm QGC} = \;& -g^2\,W^+_\mu W^{-\mu}\,(c_W Z_\nu + s_W A_\nu)\,(c_W Z^\nu + s_W A^\nu)\\ &+ g^2\,W^{+\nu}W^{-\mu}\,(c_W Z_\mu + s_W A_\mu)\,(c_W Z_\nu + s_W A_\nu)\\ &+ \frac{1}{2}g^2\,W^-_\nu W^+_\mu\,(W^{-\nu}W^{+\mu} - W^{-\mu}W^{+\nu})\end{aligned}$$

$\Longrightarrow$ Non-Abelian Quadruple-Gauge-Couplings:
$WW\gamma\gamma$, $WWZZ$, $WW\gamma Z$, $WWWW$

where

$${}^{(\gamma)}F^{\mu\nu} \equiv \partial^\mu A^\nu - \partial^\nu A^\mu, \quad {}^{(z)}F^{\mu\nu} \equiv \partial^\mu Z^\nu - \partial^\nu Z^\mu, \quad {}^{(w)}F^{\mu\nu} \equiv \partial^\mu W^{-\nu} - \partial^\nu W^{-\mu}$$

Standard Model

Focus on Triple Gauge Couplings (TGC):

$$WW\gamma,\, WWZ$$

Rewrite $\mathcal{L}_{\mathrm{TGC}}$:

$$\mathcal{L}_{\mathrm{TGC}} = \sum_{V=\gamma,Z} i\, g_{WWV}[\,{}^{(w)}F^{\dagger}_{\mu\nu} W^{-\mu} V^{\nu} - W^{-\dagger}_{\mu} V_{\nu}\, {}^{(w)}F^{\mu\nu} + W^{-\dagger}_{\mu} W^{-}_{\nu}\, {}^{(v)}F^{\mu\nu}]$$

where

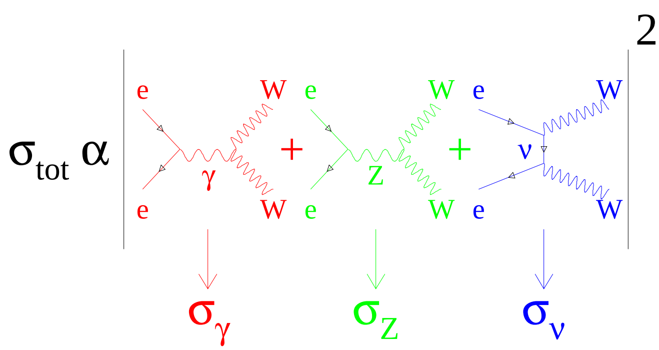
$$\begin{aligned} g_{WW\gamma} &= -g\,\sin\theta_W &= -e \\ g_{WWZ} &= -g\,\cos\theta_W &= -e\cot\theta_W \end{aligned}$$

Remarks:

- Gauge invariance explicitly retained
- TGC (and QGC) strengths predicted by Standard Model from measured e and $\sin^2\theta_W$
- All S.M. terms contain one derivative (momentum)

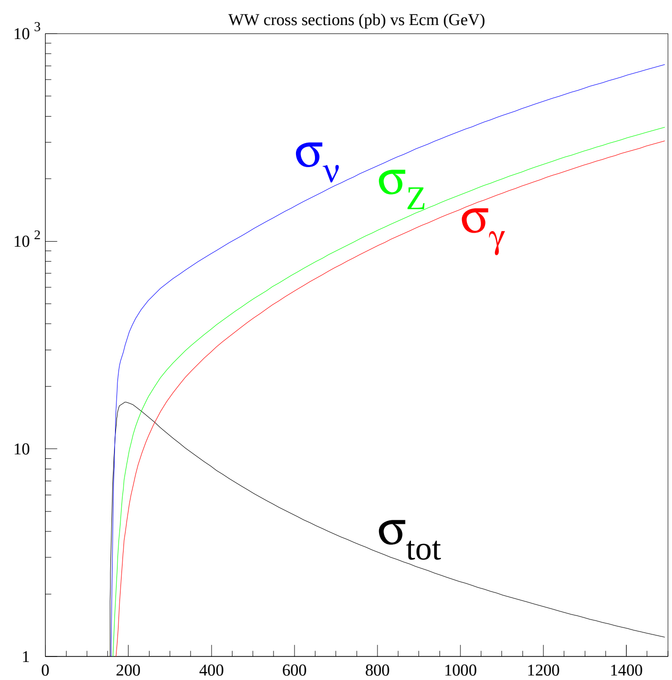
Application: $e^+e^{\Leftrightarrow} \rightarrow W^+W^{\Leftrightarrow}$

Three diagrams contribute to $e^+e^- \rightarrow W^+W^-$:



Each diverges with increasing $\sqrt{s}$

But the sum is finite (in Standard Model):



$\Longrightarrow$ σ_{tot} sensitive to tiny deviations in WWV couplings

Beyond the Standard Model

Generic Lagrangian form for triple Boson vertex

(Hagiwara, Peccei, Zeppenfeld, Hikasa, NPB 282: 253 (1987))

$$
\begin{aligned}
\pounds_{WWV}/g_{WWV} \quad = & \quad i\, g_1^V (\, {}^{(w)}F_{\mu\nu}{}^{\dagger} W^{-\mu} V^{\nu} - W_{\mu}^{-\dagger} V_{\nu} \; {}^{(w)}F^{\mu\nu}) \\
+ & \quad i\, \kappa_V W_{\mu}^{-\dagger} W_{\nu}^{-} \; {}^{(v)}F^{\mu\nu} \\
+ & \quad \frac{i\, \lambda_V}{M_W^2} \; {}^{(w)}F^{\dagger}_{\lambda\mu} W_{\nu}^{-} \; {}^{(v)}F^{\nu\lambda} \\
- & \quad g_4^V W_{\mu}^{-\dagger} W_{\nu}^{-} (\partial^{\mu} V^{\nu} + \partial^{\nu} V^{\mu}) \\
+ & \quad g_5^V \epsilon^{\mu\nu\rho\sigma} (W_{\mu}^{-\dagger} \overleftrightarrow{\partial}_{\rho} W_{\nu}^{-}) V_{\sigma} \\
+ & \quad \tilde{\kappa}_V W_{\mu}^{-\dagger} W_{\nu}^{-} \; {}^{(v)}\tilde{F}^{\mu\nu} \\
+ & \quad \frac{i\, \tilde{\lambda}_V}{M_W^2} \; {}^{(w)}F^{\dagger}_{\lambda\mu} W_{\nu}^{-} \; {}^{(v)}\tilde{F}^{\nu\lambda} \tilde{V}^{\nu\lambda}
\end{aligned}
$$

where

$$
\begin{aligned}
(A \overleftrightarrow{\partial}_{\mu} B) \quad & \equiv \quad A(\partial_{\mu} B) - (\partial_{\mu} A) B \\
{}^{(v)}\tilde{F}_{\mu\nu} \quad & \equiv \quad \frac{1}{2}\, \epsilon_{\mu\nu\rho\sigma} \; {}^{(v)}F^{\rho\sigma}
\end{aligned}
$$

Beyond the Standard Model

Seven $\times$ two independent couplings

with

g_4^V, $\tilde{\kappa}_V$, $\tilde{\lambda}_V$ terms CP-violating

g_5^V term C, P violating

(these terms often ignored in studies)

Standard Model:

$$g_1^V = \kappa_V = 1 \qquad \lambda_V = g_4^V = g_5^V = \tilde{\kappa}_V = \tilde{\lambda}_V = 0$$

Higher order operators with additional derivatives equivalent to momentum-dependent couplings:

$$\kappa_V \quad = \quad \kappa_V(q^2/\Lambda^2) \qquad \text{Form factor couplings}$$

$\Rightarrow$ Important at hadron colliders

In more familiar terminology ...

W magnetic dipole moment:

$$\mu_W \quad \equiv \quad \frac{e}{2\,M_W}(1 + \kappa_\gamma + \lambda_\gamma)$$

W electric quadrupole moment:

$$Q_W \quad \equiv \quad \Leftrightarrow \frac{e}{M_W^2}(\kappa_\gamma \Leftrightarrow \lambda_\gamma)$$

W electric dipole moment:

$$d_W \quad \equiv \quad \frac{e}{2\,M_W}(\tilde{\kappa}_\gamma + \tilde{\lambda}_\gamma)$$

W magnetic quadrupole moment:

$$\tilde{Q}_W \quad \equiv \quad \Leftrightarrow \frac{e}{M_W^2}(\tilde{\kappa}_\gamma \Leftrightarrow \tilde{\lambda}_\gamma)$$

Deviations from SM:

$$\Delta g_1^Z \quad \equiv \quad g_1^Z \Leftrightarrow 1 \qquad\qquad \Delta\kappa_V \quad \equiv \quad \kappa_V \Leftrightarrow 1$$

$$g_1^\gamma(q^2 \to 0) \quad \equiv \quad 1 \qquad - \qquad \text{W electric charge}$$

Beyond the Standard Model

Many possibilities!

But what is reasonable?

Two common model types:

- Effective Lagrangian with light Higgs (linear model)
- Chiral Lagrangian with strong coupling (non-linear model)

Model parameters can be mapped to generic set:

$$\Delta\kappa_\gamma,\ \lambda_\gamma,\ etc.$$

Beyond the Standard Model

Effective Lagrangian:

$$L_{eff} \quad = \quad L_{SM} \quad + \quad L_{NR}$$

(NR $\equiv$ Non-Renormalizable in finite order)

where (Einhorn / Wudka notation)

$$L_{NR} \quad \equiv \quad \frac{1}{\Lambda}\sum_i \alpha_i^{(5)} O_i^{(5)} \quad + \quad \frac{1}{\Lambda^2}\sum_i \alpha_i^{(6)} O_i^{(6)} \quad + \quad \ldots$$

and

$$O_i^{(N)} \quad \equiv \quad \text{Local operator of dimension } N$$
$$\Lambda \quad \equiv \quad \text{Scale of new physics}$$

$O_i^{(5)}$ not physical

$\Longrightarrow$ Dimension 6 operators next in line

$\Longrightarrow$ Keep terms to this order (Λ large)

Beyond the Standard Model

Example

(Hagiwara, Ishihara, Szalapski, Zeppenfeld)

Use only known light fields (gauge Bosons plus Higgs) and covariant derivatives:

(only C, P conserving operators listed)

$$
\begin{aligned}
L_{NR} \quad = \quad & \sum_{i=1}^{7} \frac{f_i}{\Lambda^2} O_i \quad = \quad \frac{1}{\Lambda^2} \times \\
& (\quad f_{\Phi,1} \, (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D^\mu \Phi) \\
& + f_{BW} \, \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \\
& + f_{DW} \, Tr([D_\mu, \hat{W}_{\nu\rho}][D^\mu, \hat{W}^{\nu\rho}]) \\
& \Leftrightarrow f_{DB} \, \frac{g'^2}{2} (\partial_\mu B_{\nu\rho})(\partial^\mu B^{\nu\rho}) \\
& + f_B \, (D_\mu \Phi)^\dagger \hat{B}_{\mu\nu} (D_\nu \Phi) \\
& + f_W \, (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \\
& + f_{WWW} \, Tr[\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu])
\end{aligned}
$$

where

$$
[D_\mu, D_\nu] \quad = \quad \hat{B}_{\mu\nu} + \hat{W}_{\mu\nu} \quad \equiv \quad i\frac{g'}{2} B_{\mu\nu} + ig\frac{\sigma^a}{2} W^a_{\mu\nu}
$$

Beyond the Standard Model

First four operators $(O_{\Phi,1}, O_{BW}, O_{DW}, O_{DB})$ affect 2-point boson functions at tree level

$\Rightarrow$ Severely constrained by LEP and other data

(*c.f.* S, T, U parameters of Peskin / Takeuchi)

Remaining operators (O_B, O_W, O_{WWW}) contribute to anomalous triple boson couplings

"Relaxed" HISZ Scenario:

$$\begin{aligned}
\Delta\kappa_\gamma &= (f_B + f_W)\,\frac{M_W^2}{2\,\Lambda^2} \\
\Delta\kappa_Z &= (f_W \Leftrightarrow s_W^2(f_B + f_W))\,\frac{M_Z^2}{2\,\Lambda^2} \\
\Delta g_1^Z &= f_W\,\frac{M_Z^2}{2\,\Lambda^2} = \Delta\kappa_Z + \frac{s_W^2}{c_W^2}\Delta\kappa_\gamma \\
\lambda_\gamma &= f_{WWW}\,\frac{3\,M_W^2 g^2}{2\,\Lambda^2} = \lambda_Z
\end{aligned}$$

"Full" H.I.S.Z. Scenario adds the constraint:

$$f_B = f_W$$

Beyond the Standard Model

Remarks on Full HISZ scenario:

- Only two free parameters:

$$\kappa_\gamma, \qquad \lambda_\gamma$$

- Anomalous couplings are of order $f_i \, \frac{M_W^2}{\Lambda^2}$

  $\Rightarrow$ If $f_i \approx O(1)$, then

$$\begin{aligned} \Delta\kappa_V &\approx O(\frac{M_W^2}{\Lambda^2}) \\ &\approx 10^{-1} \qquad \text{for } \Lambda \approx 250 \text{ GeV} \\ &\approx 10^{-2} \qquad \text{for } \Lambda \approx 1 \text{ TeV} \end{aligned}$$

- It gets worse...

  No renormalizable underlying theory for this effective Lagrangian can generate non-vanishing O_W, O_B, O_{WWW} at tree level (Artz / Einhorn / Wudka)

  $\Rightarrow$ Loop diagrams needed

  $\Rightarrow$ Further large suppression $[O(\frac{1}{16\,\pi^2})]$

Beyond the Standard Model

Alternative model to go beyond Standard Model:

Chiral Lagrangian with strong coupling

What exactly is strong coupling?

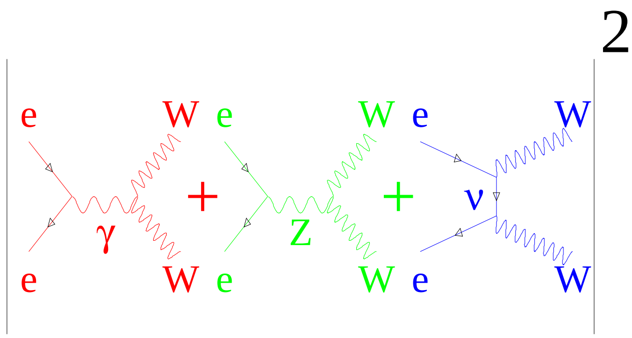
Useful to consider earlier $e^+e^- \to W^+W^-$ example:

- I claimed that $\sigma_{\rm tot}$ is well behaved at large s because diagrams cancel
- But that was a lie...

Beyond the Standard Model

Previous calculation neglected electron mass (m_e)!

Residual axial vector term gives:

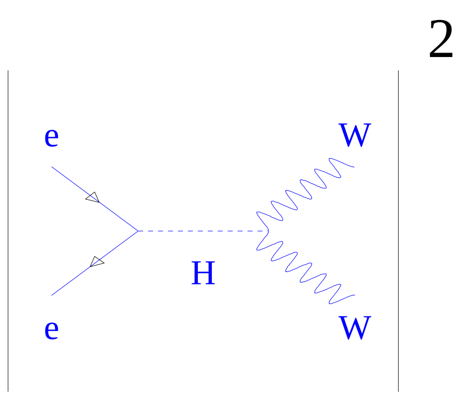


$\alpha \;\; m_e^2 \; s$

⇒ Divergence at very high S

⇒ Not a practical problem in our lifetimes

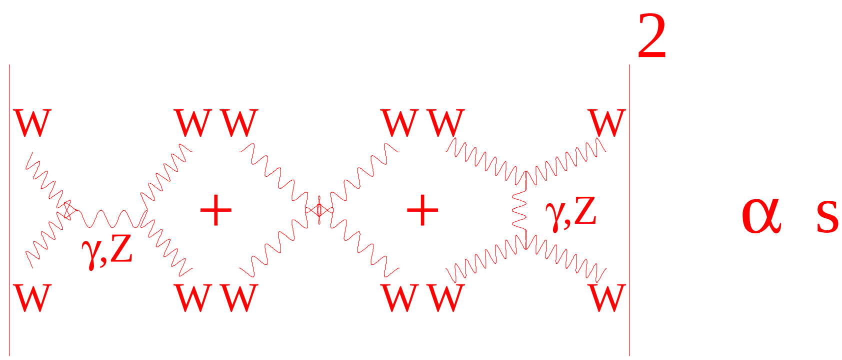
⇒ But suggests eventual need for Higgs cancellation:



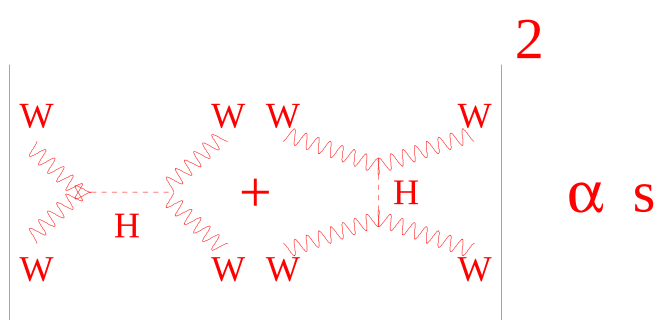
$\alpha \;\; m_e^2 \; s$

Beyond the Standard Model

More pressing divergence:



Again, need something Higgs-like for cancellation:



This works in perturbation theory if

$$m_H \quad < \quad 800 \quad \text{GeV}$$

Beyond the Standard Model

What if $m_H > 1$ TeV?

Or if no fundamental Higgs exists?

Use Equivalence Theorem to relate $W_L W_L$ scattering to Goldstone Boson scattering:

$$W_L W_L \text{ scattering} \quad \Leftrightarrow \quad \phi\phi \text{ scattering}$$

One can go further...

Exploit similarity between Goldstone Boson scattering and low-energy pion scattering:

$$W_L W_L \text{ scattering} \quad \Leftrightarrow \quad \pi\pi \text{ scattering}$$

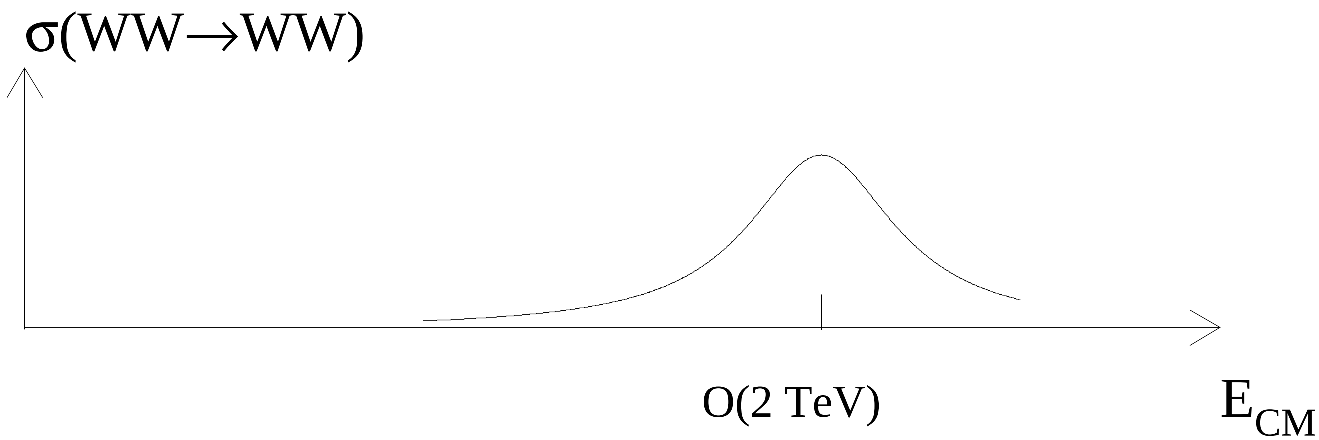
$$v \text{ (250 GeV)} \quad \Leftrightarrow \quad f_\pi \text{ (90 MeV)}$$

$\Rightarrow$ Just scale everything up by

$$\frac{250}{0.09} \quad \approx \quad 2800\,!$$

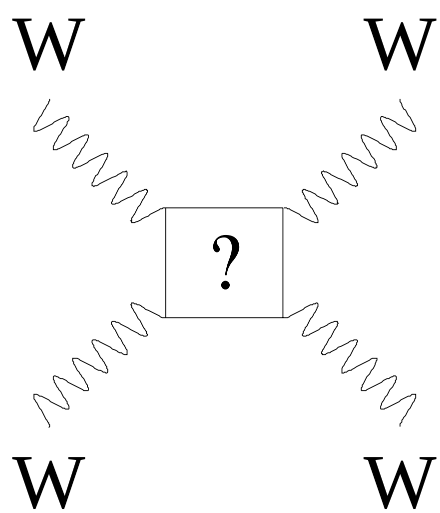
Beyond the Standard Model

Easy to imagine a "ρ" resonance:



This is not guaranteed

But a resonance would probably indicate higher-mass states occuring in loops:



Beyond the Standard Model

TECHNICOLOR

(QCD all over again...)

Take the $\pi\pi$ analogy to logical extreme:

Longitudinal boson = techi-fermion condensate

$W_L \quad \Leftrightarrow \quad$ "π" $\quad \Leftrightarrow \quad$ "$q\bar{q}$" (techni-pion)

$W_L W_L$ resonance $\quad \Leftrightarrow \quad$ "$(q\bar{q})_V$" (techni-rho)

In general, techicolor models have many difficulties
(theoretical and experimental)

But variants still cling to life

Beyond the Standard Model

Chiral Lagrangian Approach

(only C, P conserving terms shown here)

- No Standard Model Higgs

  But retain would-be-Goldstone-Boson fields w_i

- Define non-linear 2×2 matrix:

$$\Sigma \quad \equiv \quad e^{i\vec{w}\cdot\vec{\sigma}/v}$$

  with covariant derivative:

$$D_\mu\Sigma \quad = \quad \partial_\mu\Sigma + \frac{i}{2}gW_\mu^a\sigma^a\Sigma - \frac{i}{2}g'B_\mu\Sigma\sigma_3$$

- Construct effective Lagrangian from the fields and covariant derivatives

  Dimension 6 terms giving anomalous WWV couplings:

$$-ig\frac{v^2}{\Lambda^2} \;\; L_{9L} \;\; Tr[W^{\mu\nu}D_\mu\Sigma D_\nu\Sigma^\dagger]$$
$$-ig'\frac{v^2}{\Lambda^2} \;\; L_{9R} \;\; Tr[B^{\mu\nu}D_\mu\Sigma^\dagger D_\nu\Sigma]$$

Beyond the Standard Model

Coupling parameters L_{9L}, L_{9R} can be mapped onto generic set:

$$\Delta g_1^Z = \frac{e^2}{2\,c_W^2\,s_W^2}\frac{v^2}{\Lambda^2}\,L_{9L}$$

$$\Delta\kappa_\gamma = \frac{e^2}{2\,s_W^2}\frac{v^2}{\Lambda^2}\,(L_{9L}+L_{9R})$$

$$\Delta\kappa_Z = \frac{e^2}{2\,c_W^2\,s_W^2}\frac{v^2}{\Lambda^2}\,(L_{9L}\,c_W^2+L_{9R}\,s_W^2)$$

No λ_V terms in dimension 6

Parametrizing a $W_L W_L$ Vector Resonance

Alternative parametrization of techni-rho resonance via complex form factor (Peskin)

Multiply Standard Model $e^+e^- \to W^+W^-$ amplitude by

$$F_T \quad = \quad \exp[\frac{1}{\pi}\int_0^\infty ds'\delta(s', M_{\rho}, \, , \; _{\rho})\{\frac{1}{s' \Leftrightarrow s \Leftrightarrow i\epsilon} \Leftrightarrow \frac{1}{s'}\}]$$

where

$$\delta(s) \quad = \quad \frac{1}{96\,\pi}\frac{s}{v^2} + \frac{3\,\pi}{8}[\tanh(\frac{s \Leftrightarrow M_\rho^2}{M_{\rho}, \; _{\rho}}) + 1]$$

and

$$M_{\rho}, \, , \; _{\rho} \quad = \quad \text{techni-rho mass, width}$$

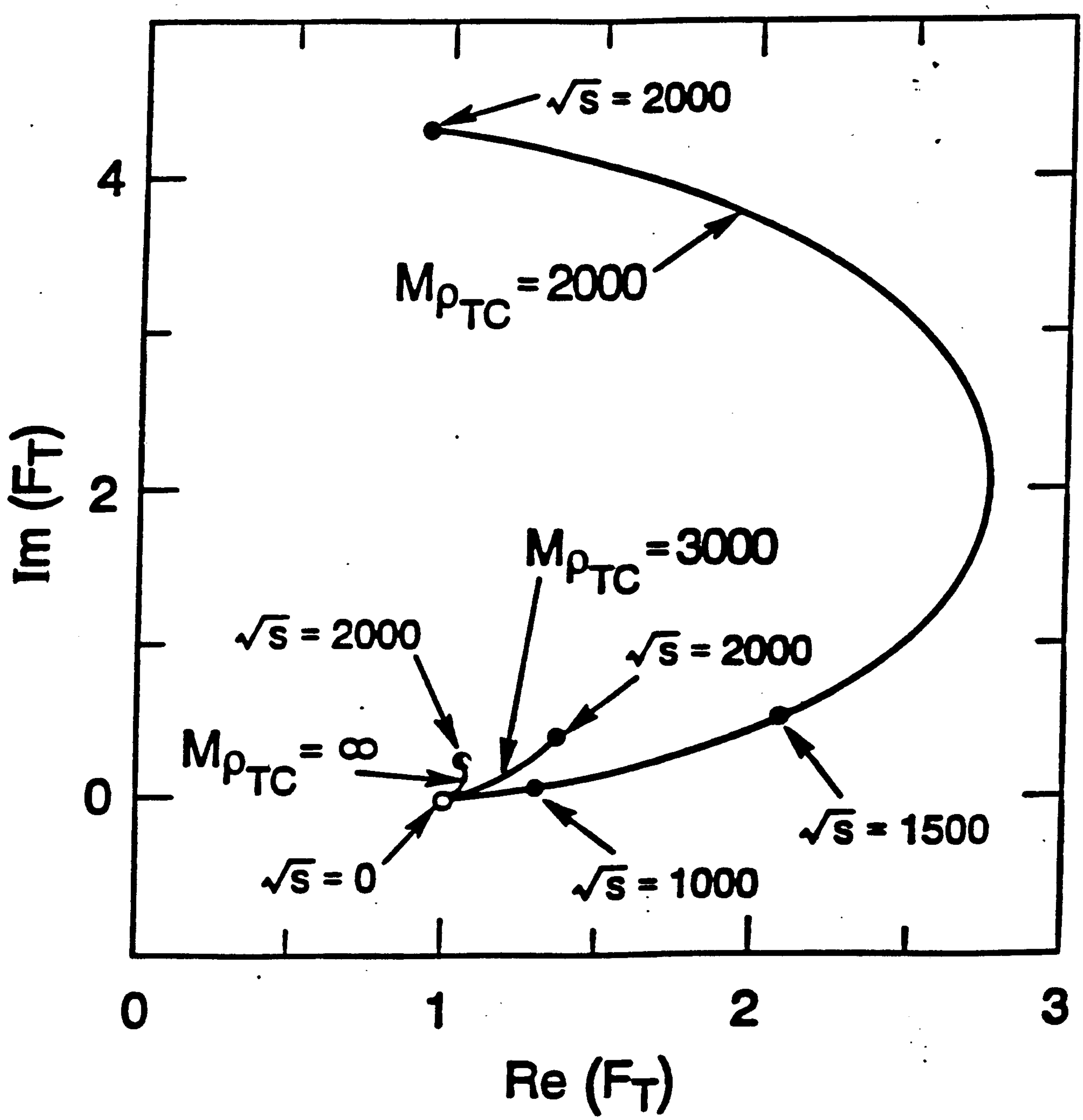
[Note:

$$\text{As } M_\rho \to \infty, \qquad \delta(s) \to \tfrac{1}{96\,\pi}\tfrac{s}{v^2} \qquad\qquad \text{(L.E.T.)}]$$

Extract Re(F_T), Im(F_T) from data

$\Rightarrow$ Limits / evidence for techni-rho

What do we expect for F_T in this model?



Experimental Signatures

Low-Energy Experimentss

(Indirect – based on loop corrections)

CP-Conserving Couplings:

- Limits from $b \to s\gamma \quad \Rightarrow \quad O(1)$
- Limits from $(g \Leftrightarrow 2)_\mu \quad \Rightarrow \quad O(10^{-1})$–$O(1)$
(will improve soon to $O(10^{-2})$–$O(10^{-1})$
- Limits from "oblique" corrections to $W/\gamma/Z$
propagators $\quad \Rightarrow \quad O(10^{-2})$

CP-Violating Couplings:

- Limits from neutron EDM $\quad \Rightarrow \quad O(10^{-4})$

Remarks:

- Indirect constraints from loop processes can be
  - Powerful within a given model
  - Persuasive under "naturalness"
  - Irrelevant in general case

$\Longrightarrow$ Above limits are model dependent

Experimental Signatures

Return to $e^+e^- \to W^+W^-$

- Total cross section sensitive to anomalous couplings

- Additional information in angular distributions of four-Fermion final state

- Seven possible W^-W^+ helicity states (λ_-, λ_+) for s channel production via γ, Z:

$$(+,0) \quad (+,+) \quad (0,+) \quad (0,0) \quad (0,\Leftrightarrow) \quad (\Leftrightarrow,0) \quad (\Leftrightarrow,\Leftrightarrow)$$

- Note: five states involve longitudinal W's

- Two additional helicity combinations allowed by t-channel ν_e exchange diagram:

$$(+,\Leftrightarrow) \quad (\Leftrightarrow,+)$$

(forbidden by $\vec{J}$ conservation in s channel)

Experimental Signatures

- Total of nine helicity combinations (3×3) in matrix element amplitude

- But we don't detect W's; we detect Fermion daughters
  $\Longrightarrow$ Interference possible
  $\Longrightarrow$ 9×9 = 81 components in production tensor:

$$d\sigma \quad \propto \quad P^{\lambda_-\lambda_+}_{\lambda'_-\lambda'_+}\, D^{\lambda_-}_{\lambda'_-}\, D^{\lambda_+}_{\lambda'_+}$$

  where

$$P^{\lambda_-\lambda_+}_{\lambda'_-\lambda'_+} \quad = \quad \text{Production tensor}$$

$$D^{\lambda_-}_{\lambda'_-} \quad = \quad \text{Decay tensor}$$

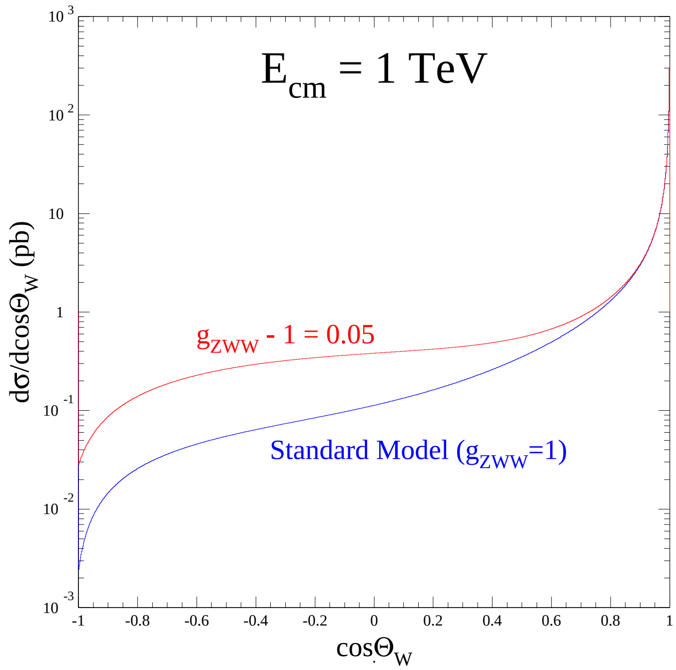
  (see Hagiwara *et al.* for explicit expressions)

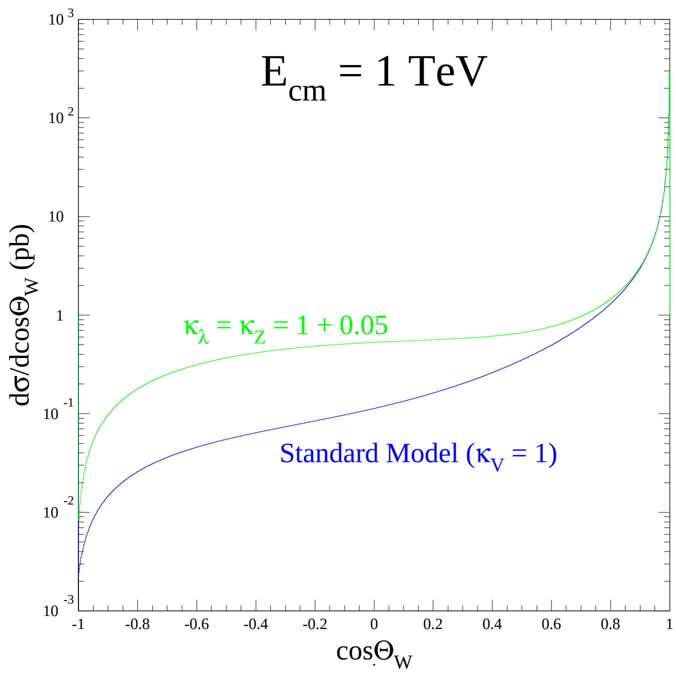
- In principle, can measure all components from 81 different angular distributions defined by projection operators

- In practice, one chooses smaller set of parameters and angular distributions

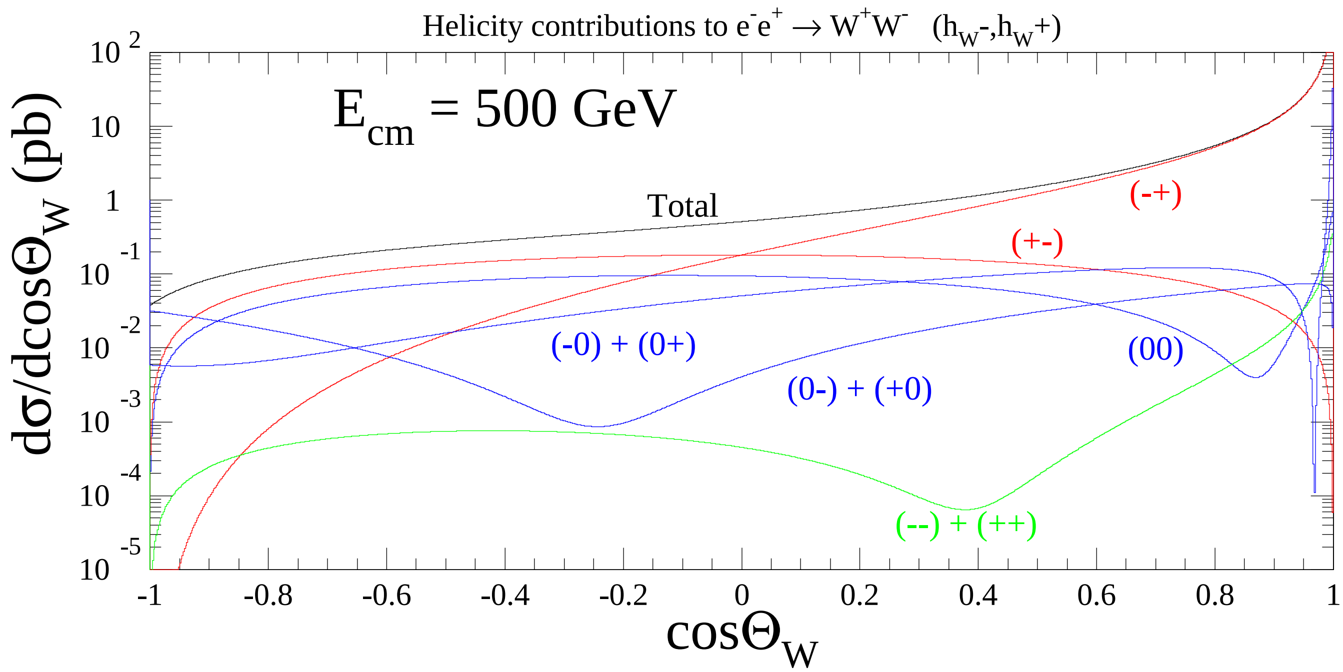
Experimental Signatures

Example: Polar production angle of W^-:

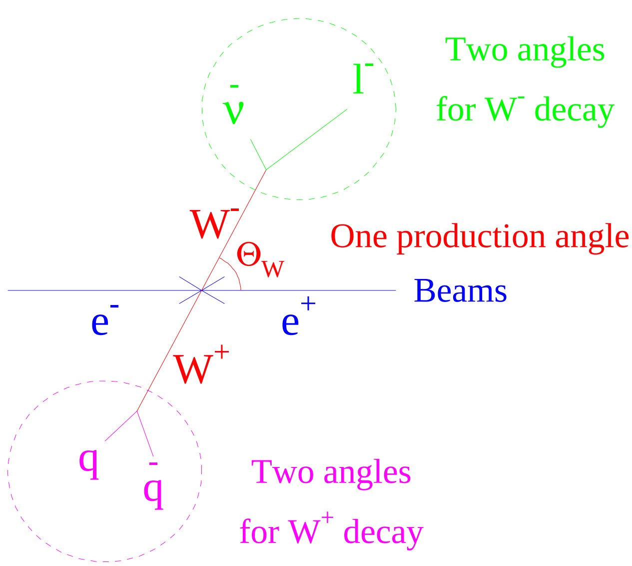




Single $d\sigma/d\cos\Theta_W$ distribution hides complex structure:



Use five production / decay angles to extract helicity amplitudes:



Experimental Signatures

Which WW decay channel is most useful?

- $WW \to q_1\bar{q}_2q_3\bar{q}_4$ (4-jet final state)
  - Branching ratio product $\approx (\frac{2}{3})^2$ (SM = 46%)
  - 3-fold ambiguity in jet assignment
  - 2-fold ambiguity in θ_W
  - 2-fold ambiguity in θ_1, ϕ_1
  - 2-fold ambiguity in θ_2, ϕ_2
    (jet charge tagging helps resolve angle ambiguities)
  - 6-C kinematic fit improves experimental resolution
    (E, $\vec{p}$ conservation + two M_W constraints)
- $WW \to q_1\bar{q}_2\ell\bar{\nu}$ (2-jet + lepton + $\not{E}$ final state)
  - Branching ratio product $\approx 2 \times (\frac{2}{3}) \times (\frac{1}{3})$ (SM = 44%)
  - 2-fold ambiguity in θ_1, ϕ_1
  - 3-C (2-C) kinematic fit improves resolution for e/μ (τ)
- $WW \to \ell\bar{\nu}\bar{\ell}\nu$ (2-lepton + $\not{E}$ final state)
  - Branching ratio product $\approx (\frac{2}{3})^2$ (SM = 10%)
  - WW reconstruction possible only for $\ell = e, \mu$
  - 0-C "fit" leaves 2-fold global angular ambiguity,
    no improvement in experimental resolution

Experimental Signatures

Examples of analysis methods for extracting couplings or testing Standard Model

- Fits to 1-D angular distributions (Θ_W, θ_1, ϕ_1, θ_2, ϕ_2)
- Fits to 2-D (and higher) angular distributions (statistics limited – requires great care)
- Optimal observables:

$$d\sigma(\Omega, \vec{\alpha}) = s^{(0)}(\Omega) \ + \sum_i \alpha_i \cdot s_i^{(1)}(\Omega) \ + \sum_{i,j} \alpha_i \alpha_j \cdot s_{ij}^{(2)}(\Omega)$$

where $\vec{\alpha} \equiv$ set of coupling parameters and $s^{(0)}$, $s^{(1)}$ and $s^{(2)}$ are known functions.
All available information contained in observables:

$$o_i^{(1)}(\Omega) = s_i^{(1)}(\Omega)/s^{(0)}(\Omega) \qquad o_{ij}^{(2)}(\Omega) = s_{ij}^{(2)}(\Omega)/s^{(0)}(\Omega)$$

Can look at distributions or moments of observables

Experimental Signatures

- Decay spin density matrix: Reduce 81-component WW production tensor to 9-component $W^- \to \ell^- \bar{\nu}$
  Single-W spin density matrix:

$$\rho_{\lambda\lambda'}(\Omega) \quad \equiv \quad \frac{\Sigma_{\lambda_+,\lambda'_+} P^{\lambda_-\lambda_+}_{\lambda'_-\lambda'_+} D^{\lambda_-}_{\lambda'_-} D^{\lambda_+}_{\lambda'_+}}{\Sigma_{\lambda_-,\lambda_+,\lambda'_-\lambda'_+} P^{\lambda_-\lambda_+}_{\lambda'_-\lambda'_+} D^{\lambda_-}_{\lambda'_-} D^{\lambda_+}_{\lambda'_+}}$$

  Measured experimentally from projection operators:

$$\rho_{\lambda\lambda'}(\Omega) \quad = \quad \frac{1}{N}\sum_{i=1}^{N} \Lambda_{\lambda\lambda'}(\cos\theta_1, \phi_1)$$

  (see Gounaris *et al.* for explicit $\Lambda_{\lambda\lambda'}$ expressions)

Remarks

- First three methods used to extract coupling parameters
- Spin density matrix is model independent
  $\Longrightarrow$ Test of Standard Model
- Off-diagonal spin matrix elements complex in general
  $\Longrightarrow$ CP violation gives non-zero imaginary components

Experimental Signatures

So what anomalous couplings do we try to fit?

Many free parameters to determine...

$\Longrightarrow$ Tempting / customary to allow only one / two parameter(s) to vary at a time

Example:

Fit for $\Delta\kappa_\gamma$ with all other couplings fixed by SM

Complications:

- Convenient but not well motivated theoretically
- $\kappa_V, \lambda_V, g_1^V$ strongly correlated in observables
- Unnatural to vary only γ or only Z couplings
- Hard to separate γ, Z couplings in $e^+e^- \to W^+W^-$ without polarized beams

  (bad for LEP II, okay for Linear Collider)

Common choices – Full (relaxed) HISZ scenario

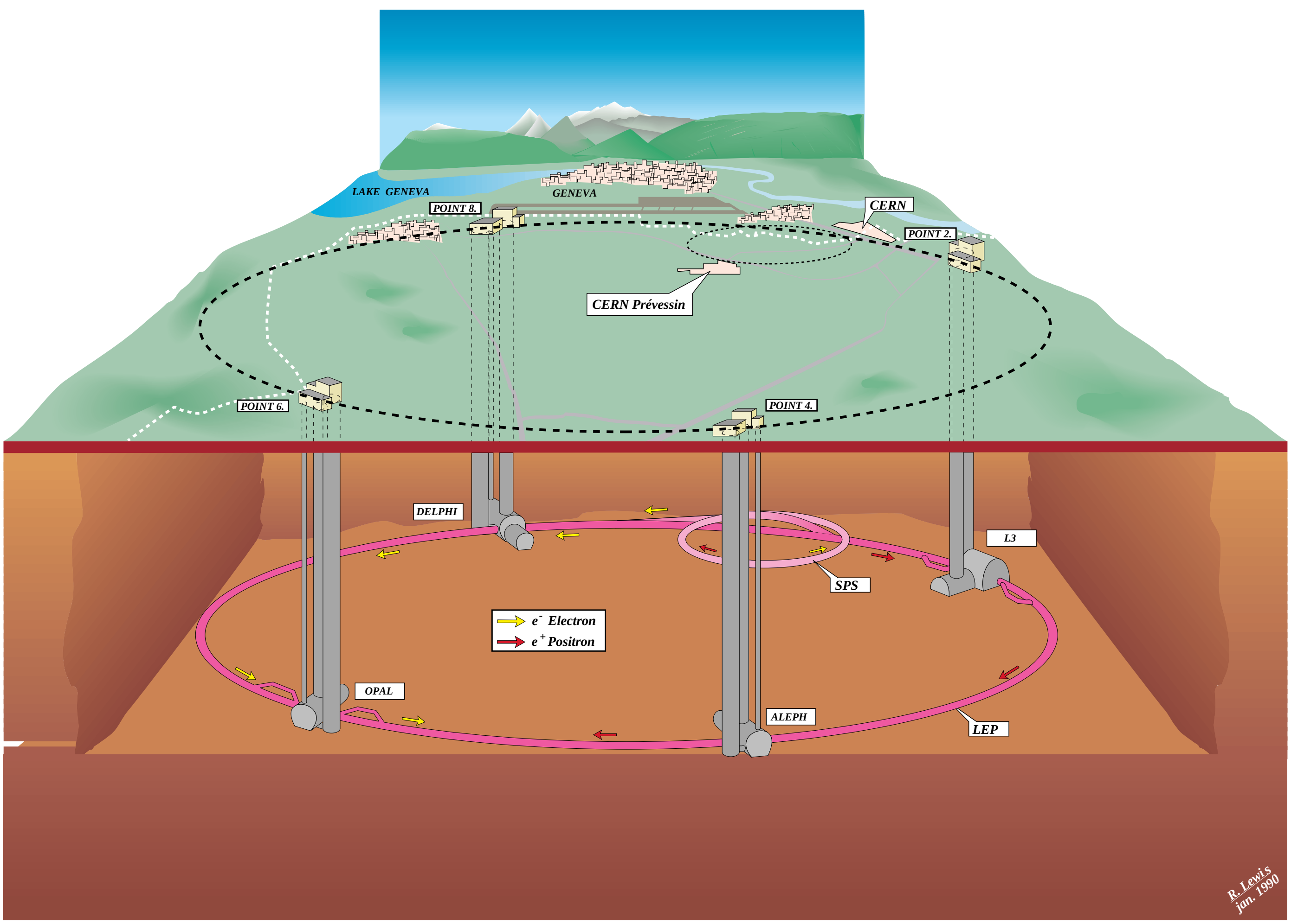
$\Rightarrow$ Two (three) free parameters to fit:

$$\kappa_\gamma, \quad \lambda_\gamma \quad (g_1^Z)$$

Experimental Signatures

LEP Ring:

- Electron-positron synchrotron
- 27-km circumference (see figure)
- Four major detectors: ALEPH, DELPHI, L3, OPAL
- Ring magnets permit $\sqrt{s} \approx 240$ GeV
- RF cavities / power (\$) = real limitations



Experimental Signatures

LEP Running History:

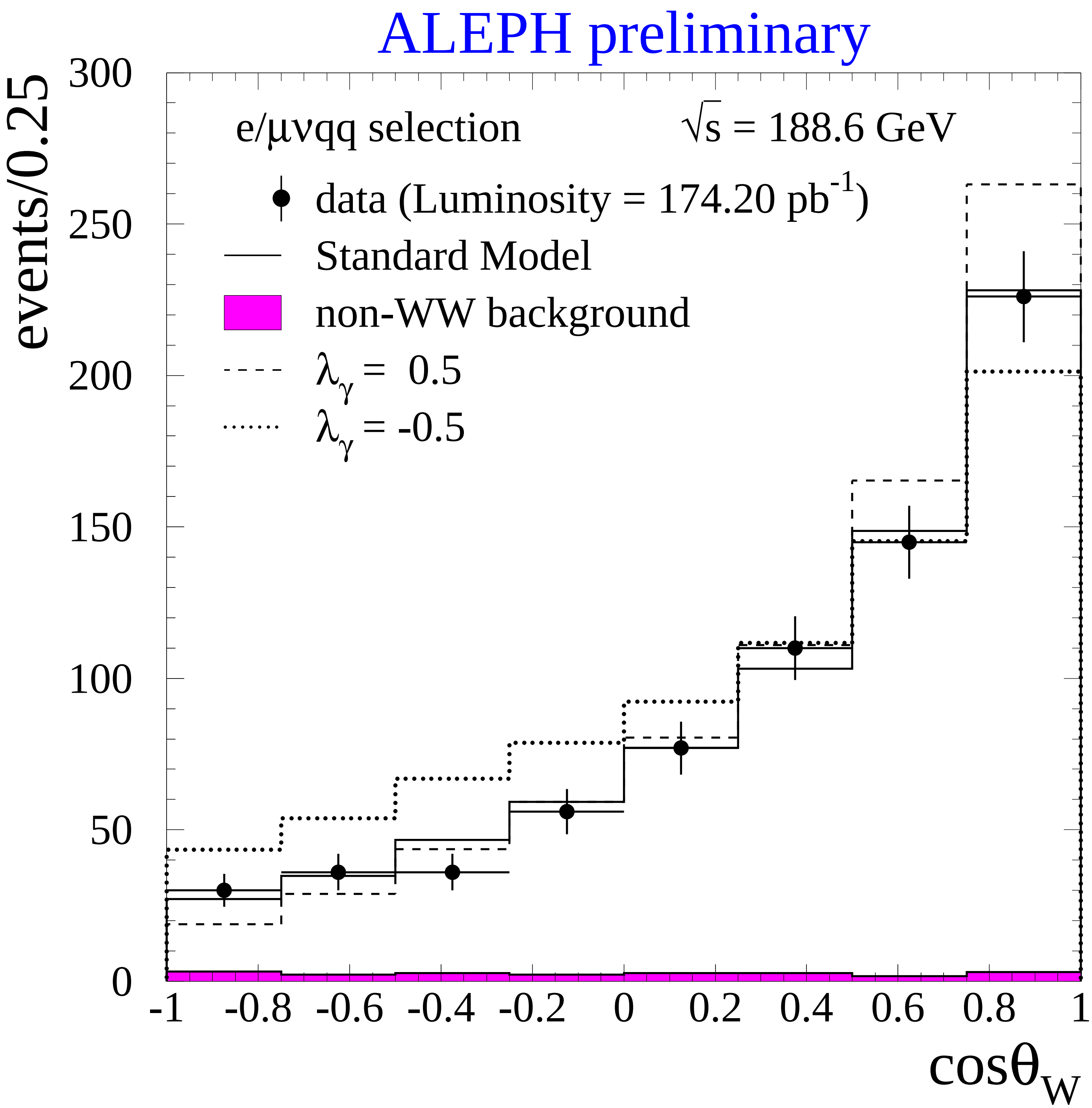
- Turned on in 1989
- Ran at 91 ± 3 GeV 1989-1995
- Provided millions of Z's / experiment
  Standard Model confirmed with depressingly high precision
- Short run at 130-140 GeV in November 1995 ("LEP 1.5")
- LEP II began in summer 1996 with 25 pb^{-1} at 161 GeV
- Subsequent runs at 172, 183, 189 GeV (1996-1998)
- Started 1999 at 192 GeV, now running at 196 GeV
- LEP II integrated luminosity / experiment > 350 pb^{-1}

LEP Running Plans:

- Collect data through 2000 with
  - $\sqrt{s} > 200$ GeV
  - Total LEP II luminosity > 500 pb^{-1}
- Shut down for 2001 LHC tunnel construction
- If dramatic new physics seen by end of 2000,
  running in 2002 possible

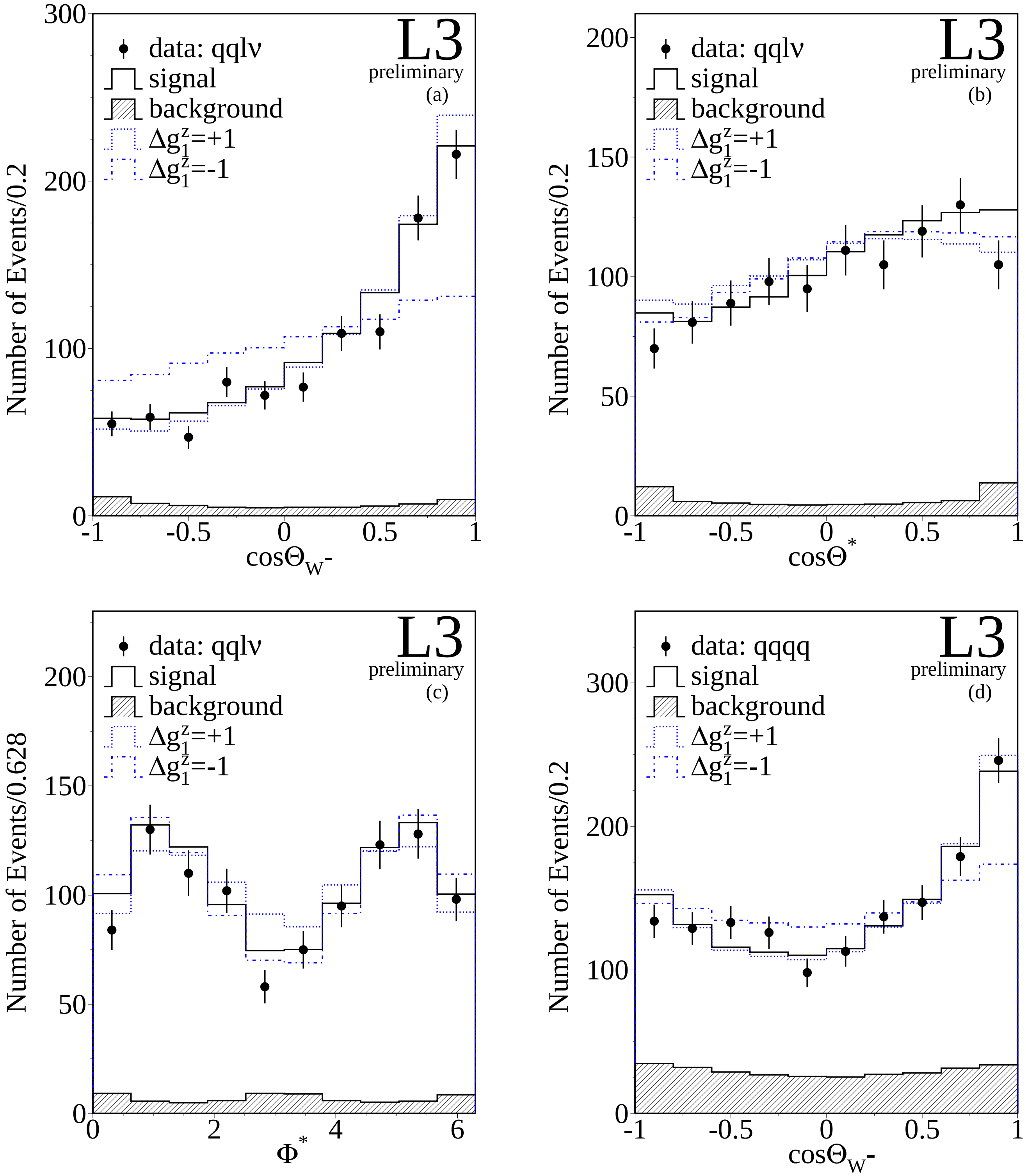
Experimental Signatures

Measurement from ALEPH of $\cos\Theta_W$ distribution:



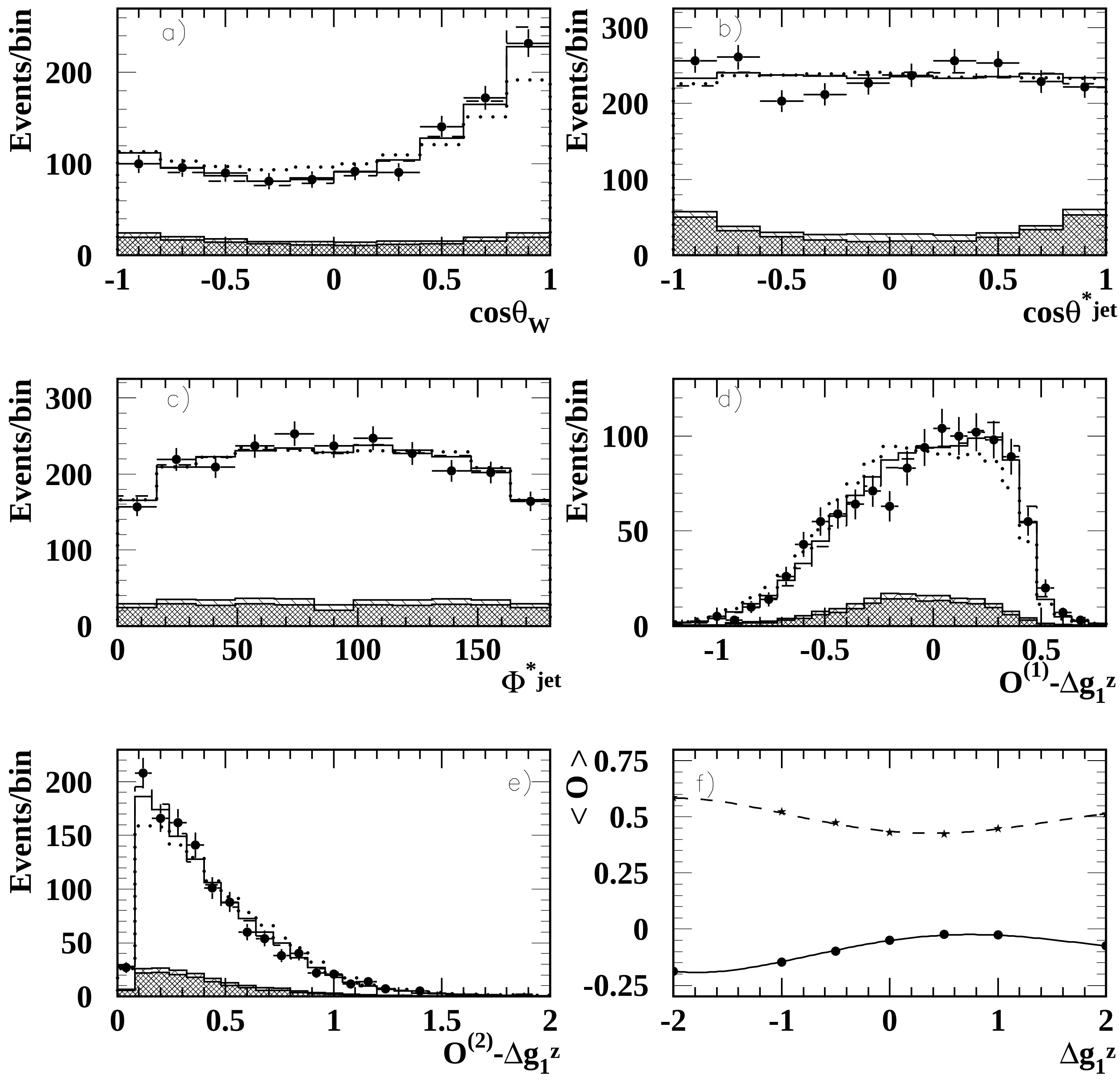
Experimental Signatures

Measurement from L3 of several 1-D distributions:



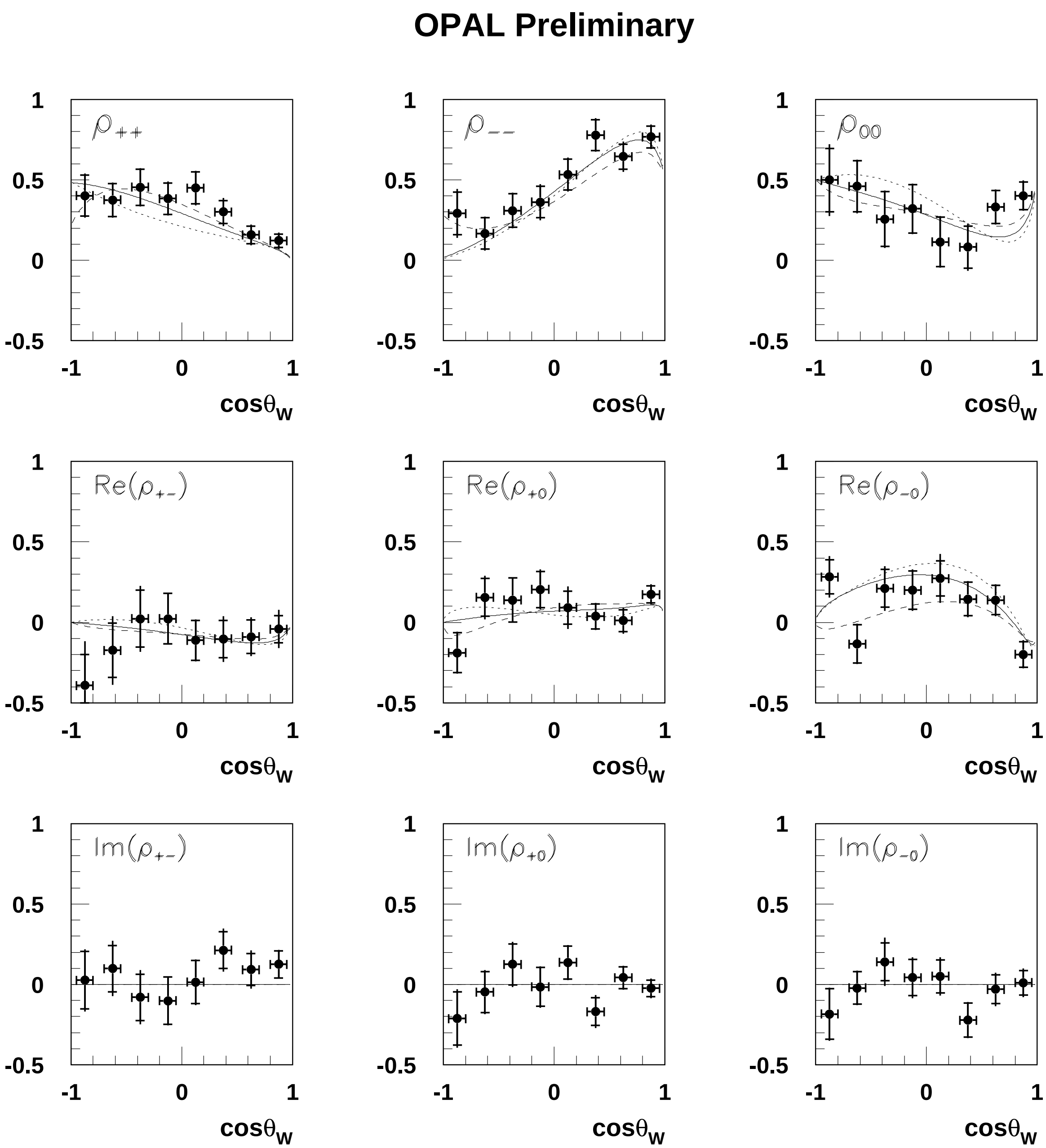
OPAL angular distributions & optimal observables (prelim)

(curves for Δg_1^Z = ⇔0.5(dotted), 0(solid), +0.5(dashed))



Experimental Signatures

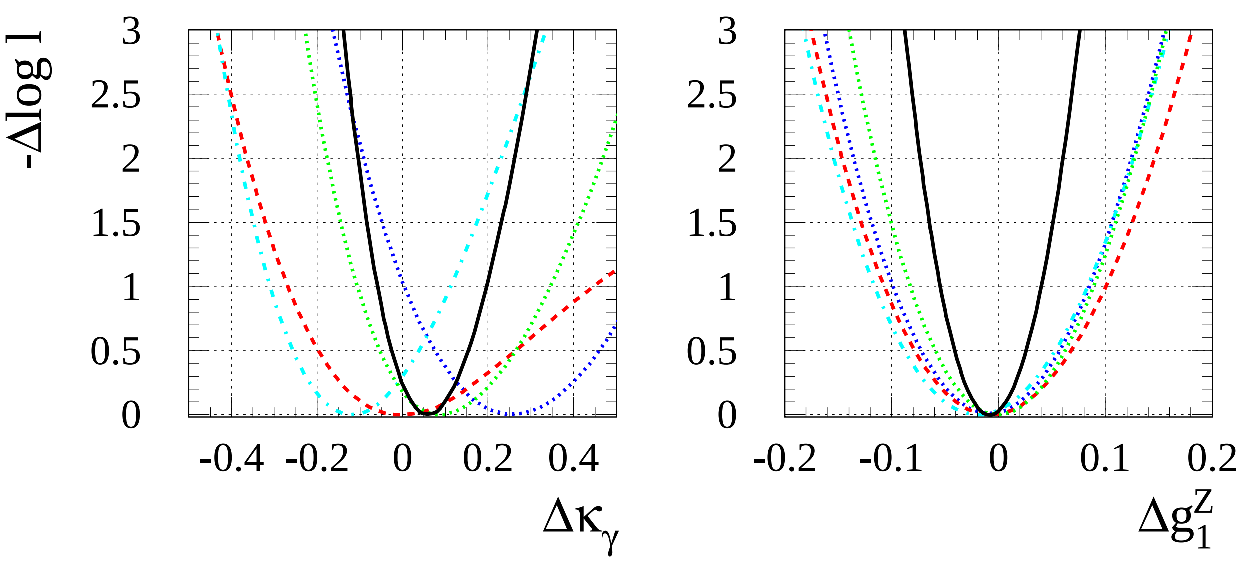
OPAL spin density matrix measurements:

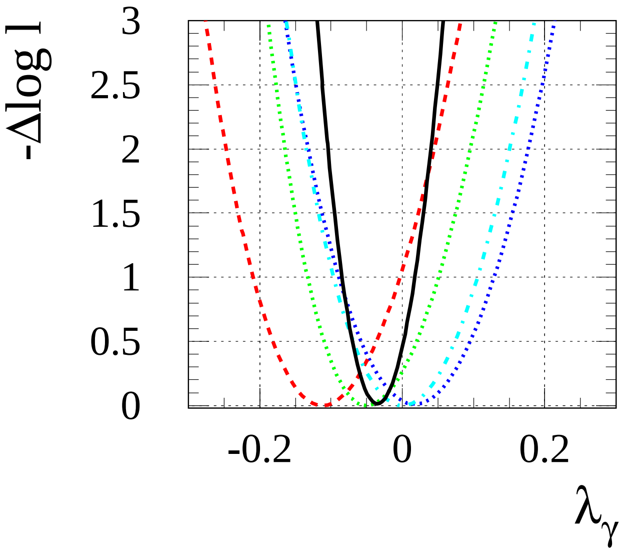


Experimental Signatures

Results for HISZ coupling parameters:

ALEPH + DELPHI + L3 + OPAL





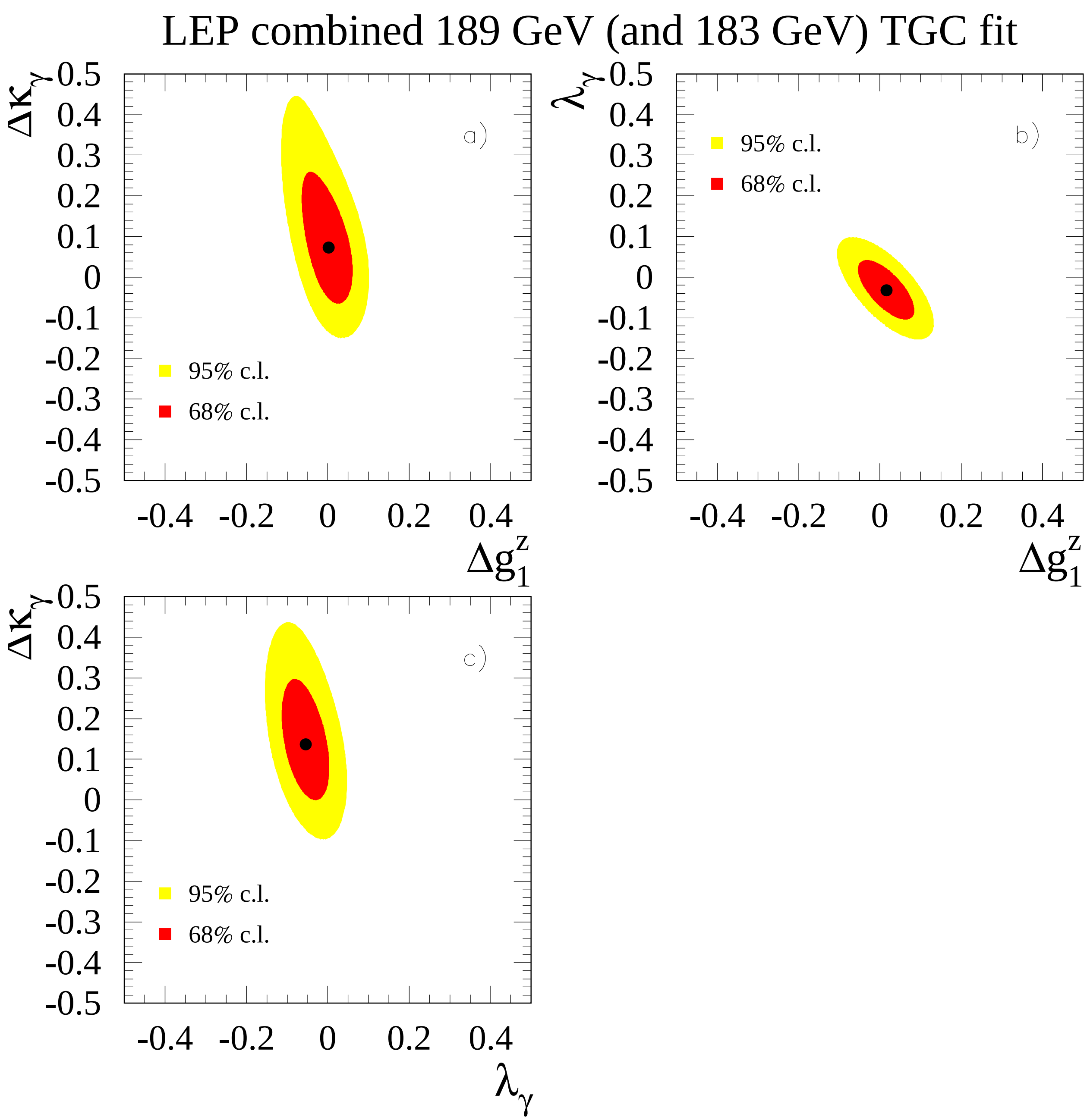
$\Delta\kappa_\gamma = 0.06\ ^{+0.09}_{-0.09}$

$\Delta g_1^Z = -0.01\ ^{+0.03}_{-0.03}$

$\lambda_\gamma = -0.03\ ^{+0.04}_{-0.04}$

(Fits courtesy of LEP Electroweak Working Group)

Correlations cannot be neglected:



(Fits courtesy of LEP Electroweak Working Group)

Experimental Signatures

A Next Linear Collider

Who will build it?

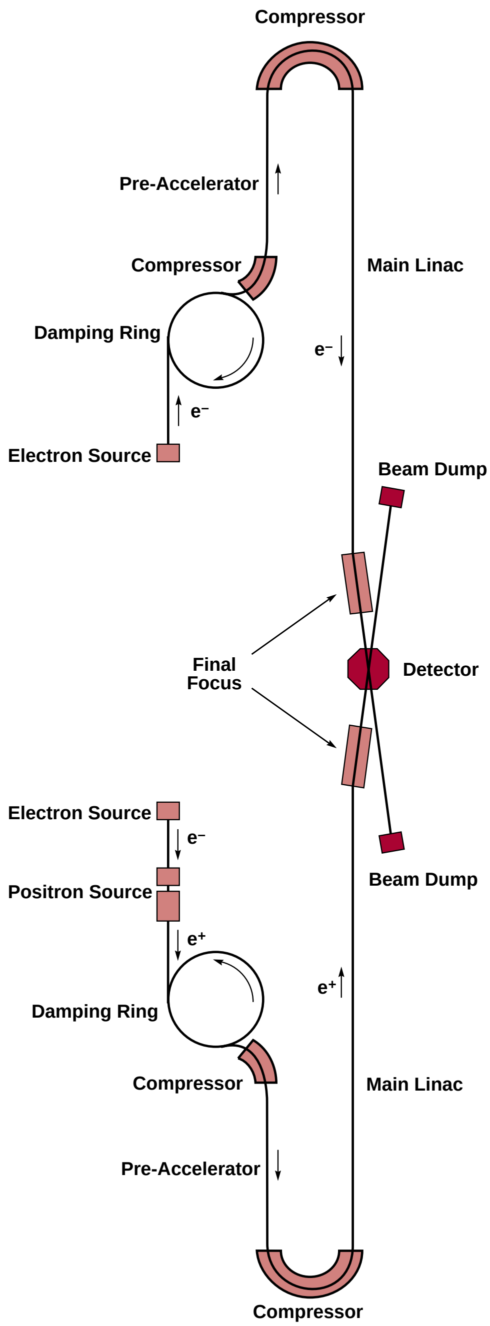
- Germany? – TESLA or SBLC
- Japan? – JLC (S, C, or X)
- Russia? – VLEPP
- Europe? – CLIC
- U.S.A.? – NLC

⇒ World-wide, collaborative R & D effort

U.S. R & D effort centered at SLAC

- Three-stage concept:
  - Turn on with $\sqrt{s} = 500$ GeV
  - Increase $\sqrt{s}$ "adiabatically" to 1 TeV (more/better klystrons)
  - Lengthen machine to achieve 1.5 TeV

Layout of NLC



Experimental Signatures

Some NLC machine parameters:

$\sqrt{s}$	500 GeV	1 TeV
Length (km)	16	18
RF Frequency (GHz)	11	11
Klystron Power (MW)	50	72
# Klystrons	3900	9200
Gradient (MV/m)	50	85
Wall Plug Power (MW)	105	200
Beam spot σ_x (nm)	320	250
Beam spot σ_y (nm)	5.5	4.3
£ ($cm^{-2}s^{-1}$	5×10^{33}	1.4×10^{34}

$\Rightarrow \approx$ 6 years construction

- "Zero-order" Design Report (ZDR) completed 1996
- Detailed engineering work has begun at SLAC

Experimental Signatures

Other Accelerator Options:

- e^-e^- Collider (Get for "free")
- $e^-\gamma$ Collider
- $\gamma\gamma$ Collider

γ colliders based on backscattered laser photons
(Ginzburg *et al.*, Akerlof 1981)

Some advantages:

- Opens up new Physics channels
  (Spin, Isospin, Charge)
- Isolation of γ from Z contributions
- Look for $\gamma\gamma \to H$
- Look for Majorana neutrinos ($e^-e^- \to \nu\nu W^-W^-$)

Potential pitfall:

- Making γ beams with competitive luminosity

Experimental Signatures

Early studies by Barklow of $q\bar{q}\ell\bar{\nu}$ channel

Use:

Measured energy of lepton

Angles of lepton, jets (require $|\cos\Theta_W| < 0.8$)

Velocities of jets ($\beta_i = p_i/E_i$)

Kinematic constraint to $\ell\bar{\nu}j_1j_2$

Require:

$$\chi^2 \quad \equiv \quad \frac{(M_{\ell\bar{\nu}}^{fit} \Leftrightarrow M_W)^2}{,^2_W} + \frac{(M_{j_1j_2}^{fit} \Leftrightarrow M_W)^2}{,^2_W} \quad < \quad 2$$

Perform unbinned maximum likelihood fit in five reconstructed angles to extract coupling parameters

- No detector smearing*
- But realistic efficiencies used
- Following exclusion contours defined by covariance matrix elements

*Studies for Snowmass 96 (KR) confirmed that planned detector resolutions cause no serious degradation

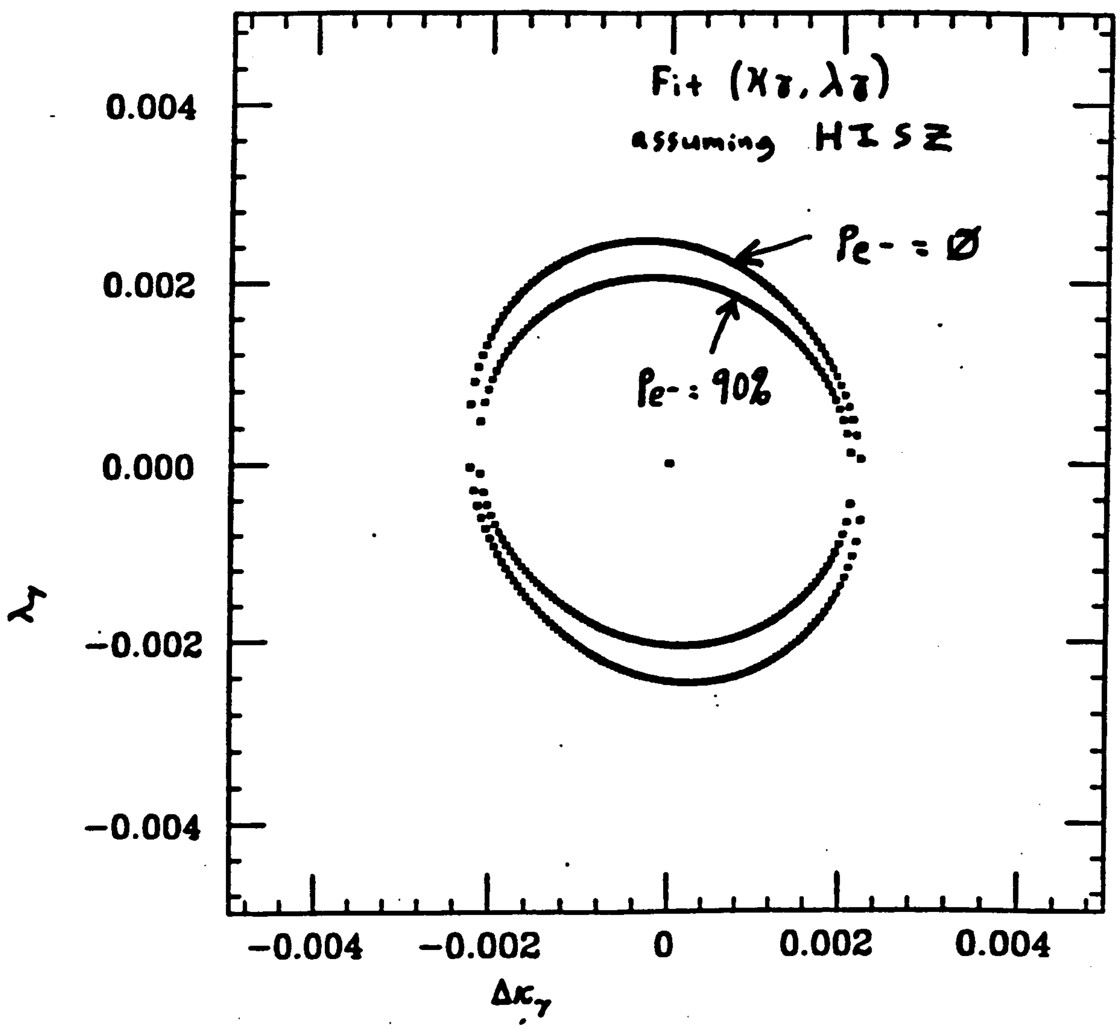
Experimental Signatures

NLC studies (Barklow)

With and without e^- beam polarization

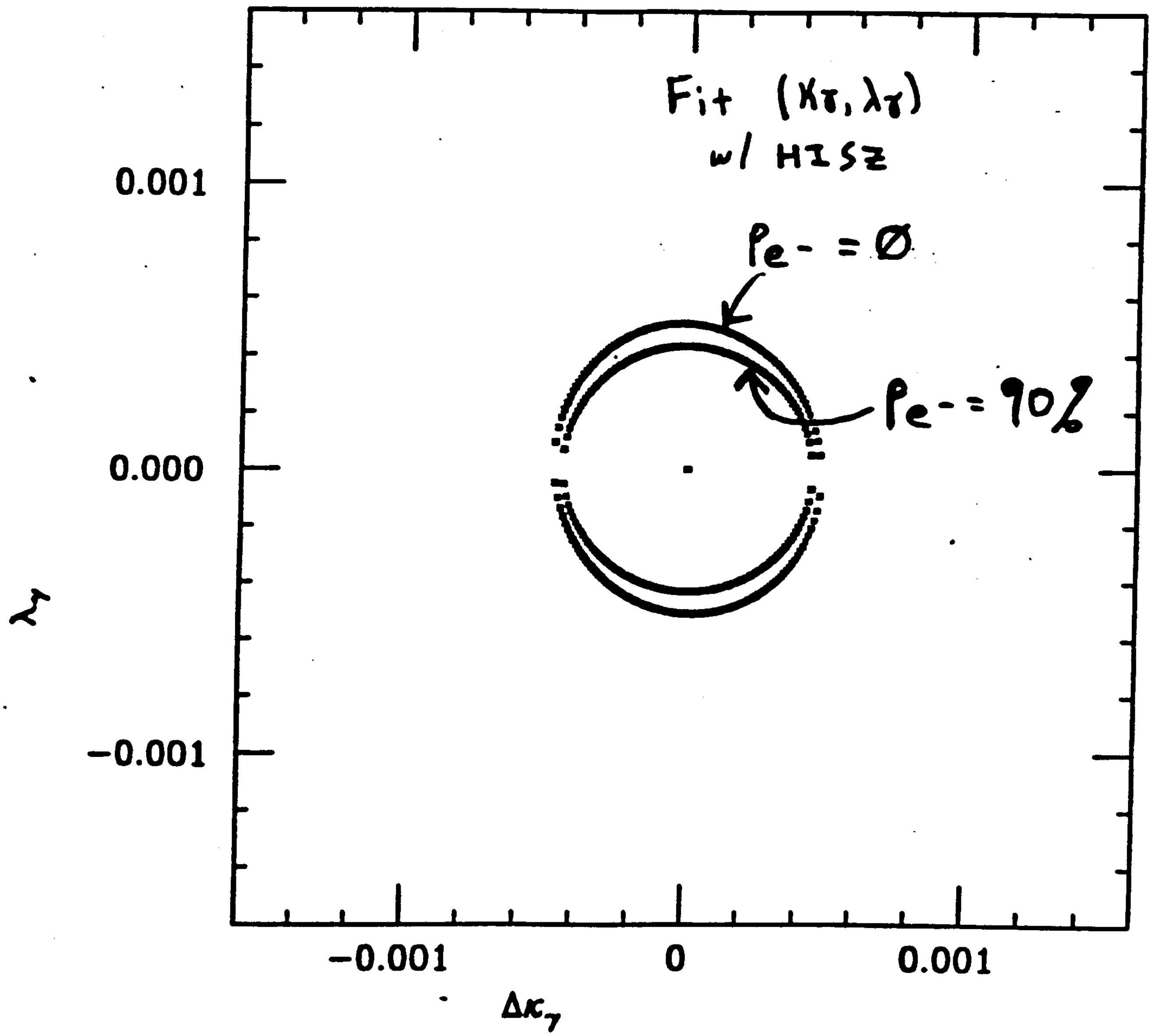
80 fb^{-1} at $\sqrt{s} = 500$ GeV

Assumes HISZ scenario



Experimental Signatures

Same plots with 190 fb^{-1} at $\sqrt{s} = 1.5$ TeV



Conclusion:

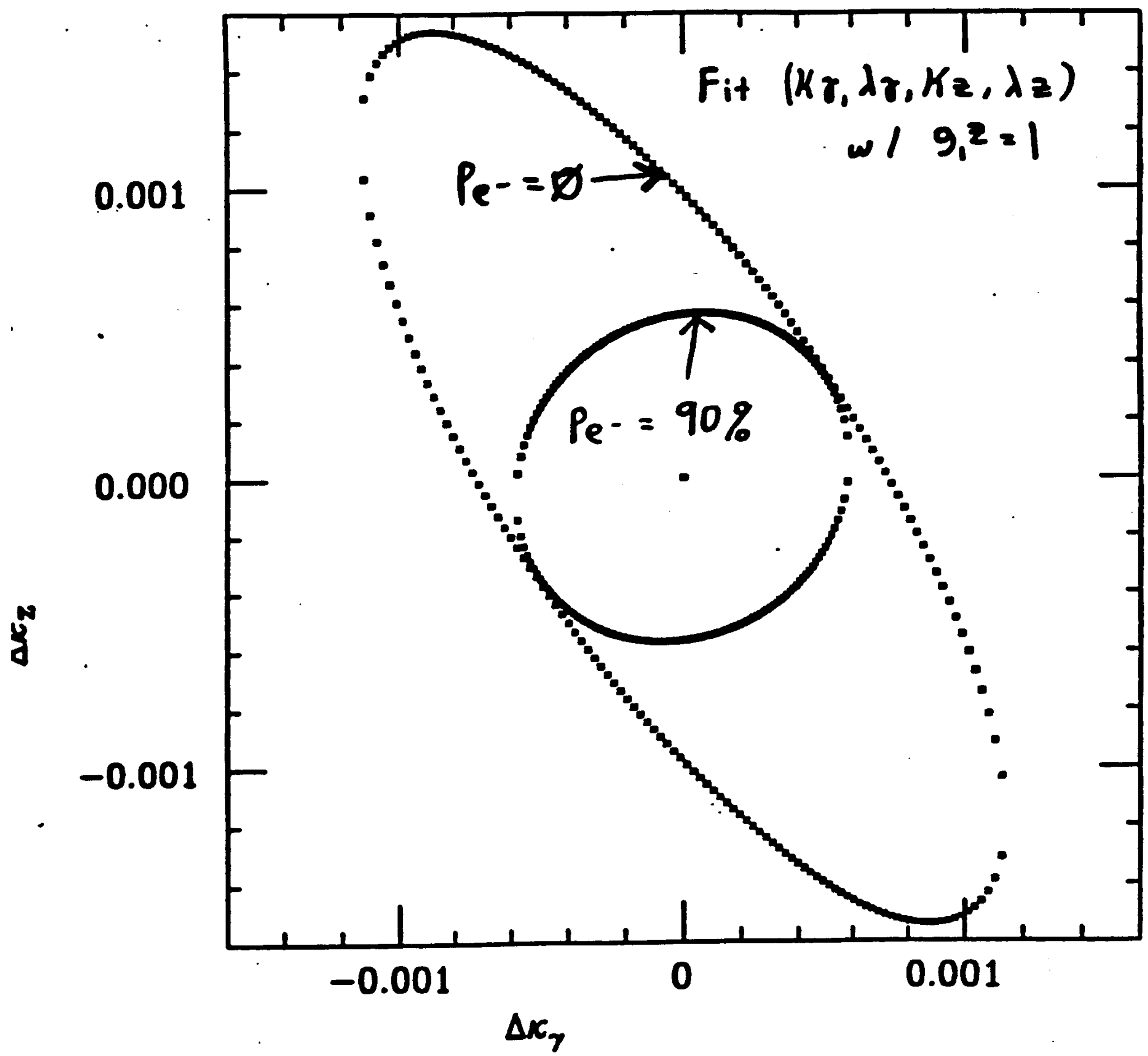
Beam polarization useful even in HISZ Scenario

Experimental Signatures

In more general model, however,

beam polarization critical

in disentangling γ, Z couplings

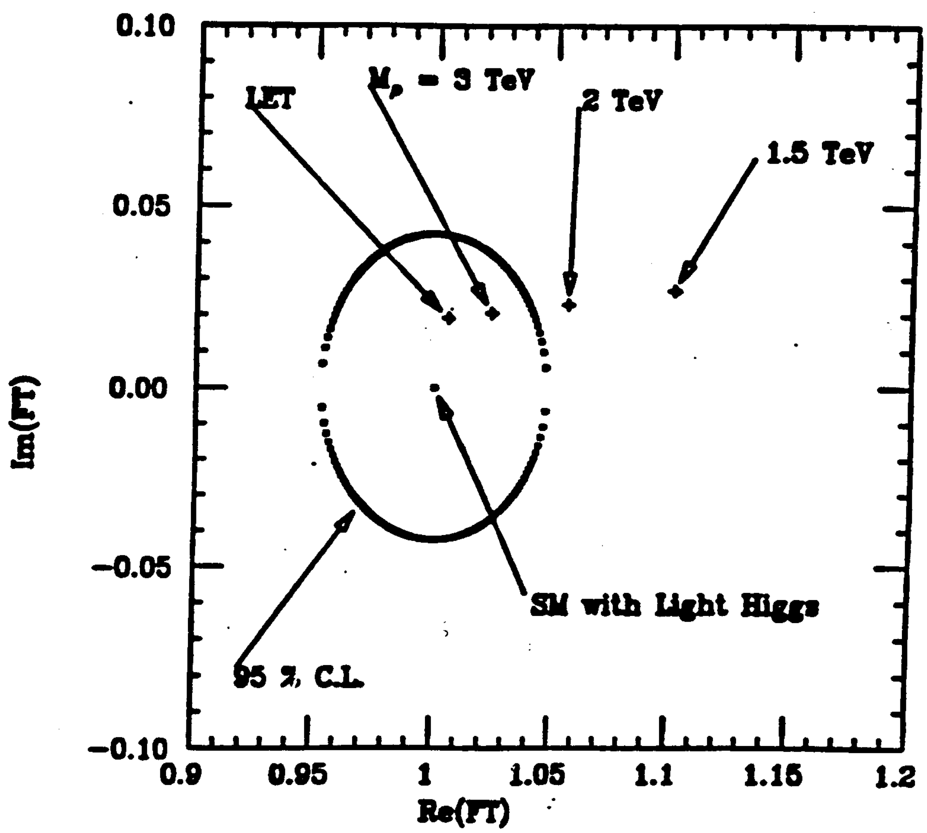


Experimental Signatures

Can one start to see a techni-rho at NLC?

Preceding helicity analysis (Barklow) of $e^+e^- \to W^+W^-$ extended to fit for real/imaginary components of complex form factor:

(S.M. $W_L W_L$ amplitude multiplied by F_T)

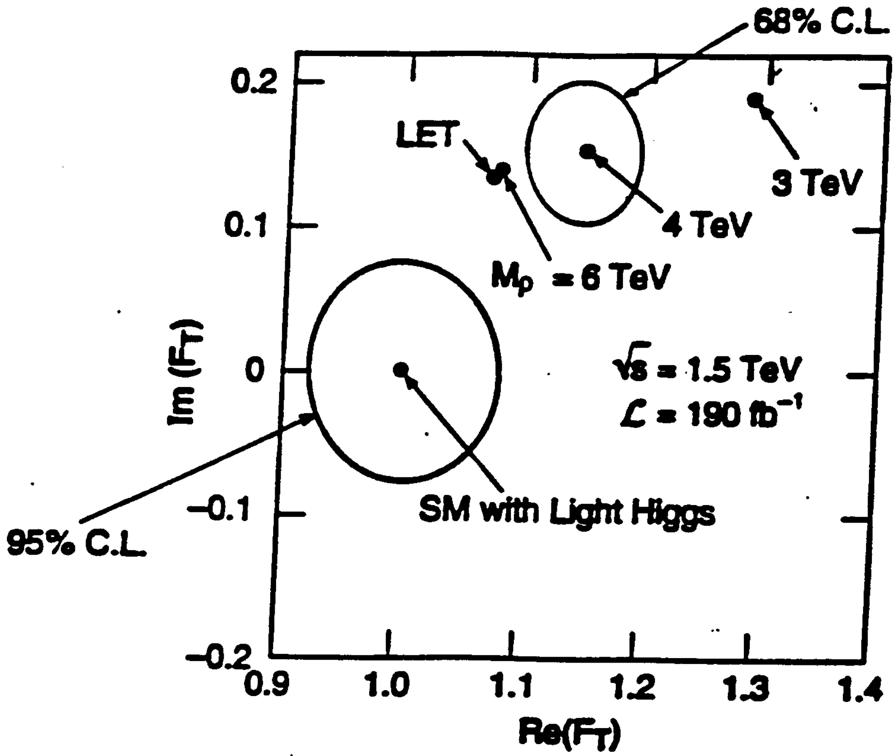


⇒ At 500 GeV:

- Exclude techni-rho with $M_\rho < 2.5$ TeV (95% CL)
- Discover techni-rho with $M_\rho < 1.5$ TeV ($5\,\sigma$)

Experimental Signatures

At higher $\sqrt{s}$, expected deviations of F_T from (1,0) become larger for given M_{ρ}, , $_{\rho}$:



$\Rightarrow$ At 1.5 TeV:

- Exclude <u>any</u> techni-rho in this model
- Discovery potential:

  4.5 σ for L.E.T.

  4.8 σ for $M_\rho = 6$ TeV

  6.5 σ for $M_\rho = 4$ TeV

- Distinguish L.E.T. from $M_\rho < 4$ TeV

Experimental Signatures

What about $W_L W_L$ fusion?

Analysis by Barger / Cheung / Han / Phillips uses $e^+e^- \to \nu\bar{\nu}W^+W^-$, $e^+e^- \to \nu\bar{\nu}ZZ$ channels at 1.5 TeV to measure ratio

$$R_{W/Z} \equiv \frac{\sigma(W_L^+ W_L^- \to W^+ W^-)}{\sigma(W_L^+ W_L^- \to ZZ)}$$

Ratio varies with strong coupling model

- S.M. with $M_H = 1$ TeV: expect $R_{W/Z} \approx 2$
- L.E.T. ($M_H \to \infty$): expect $R_{W/Z} \approx 2/3$
- Technicolor: expect $R_{W/Z}$ very large (no resonance for $Z_L Z_L$)

e^+e^- cleanliness allows selection of hadronic decays with modest backgrounds

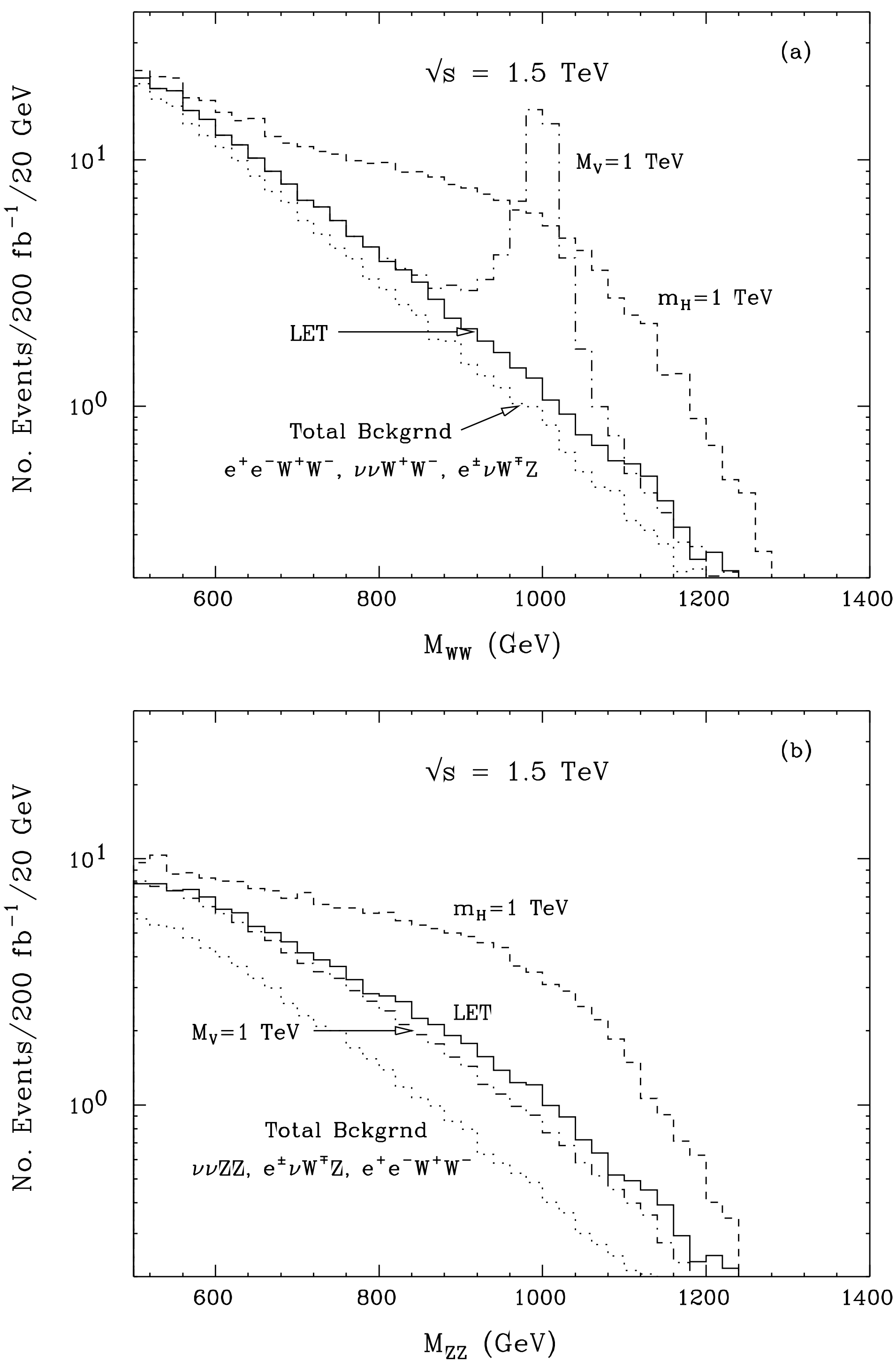
W^+W^- and ZZ separated statistically by dijet mass:

$$68 \text{ Gev} < M_W < 86 \text{ GeV} \qquad 86 < M_Z < 105 \text{ GeV}$$

Experimental Signatures

How many events?

Following figure assumes 200 fb^{-1} at 1.5 TeV



Experimental Signatures

Other Coupling Measurements at e^+e^- Collider:

Process	Couplings probed
$e^+e^- \to Z\gamma$	$ZZ\gamma$, $Z\gamma\gamma$
$e^+e^- \to WW\gamma$	$WW\gamma$, $WWZ\gamma$, $WW\gamma\gamma$
$e^+e^- \to WWZ$	WWZ, $WWZZ$, $WWZ\gamma$
$e^+e^- \to e\bar{\nu}W$	WWZ, $WW\gamma$
$e^+e^- \to \nu\bar{\nu}\gamma$	$WW\gamma$
$e^+e^- \to \nu\bar{\nu}Z$	WWZ

Coupling Measurements at e^-e^-, $\gamma\gamma$, $e^-\gamma$ Colliders:

Process	Couplings probed
$e^-e^- \to e^-\nu W^-$	$WW\gamma$, WWZ
$e^-e^- \to e^-e^-Z$	$ZZ\gamma$, $Z\gamma\gamma$
$e^-e^- \to e^-\nu W^-\gamma$	$WW\gamma$, WWZ
$e^-e^- \to \nu\nu W^-W^-$	$WWWW$ (Isospin 2 poss.)
$\gamma\gamma \to W^+W^-$	$WW\gamma$
$\gamma\gamma \to W^+W^-Z$	WWZ, $WW\gamma$
$\gamma\gamma \to ZZ$	$ZZ\gamma$, $Z\gamma\gamma$
$\gamma\gamma \to W^+W^-W^+W^-$	$WWWW$ (Isospin 2 poss.)
$\gamma\gamma \to W^+W^-ZZ$	$WWZZ$
$e^-\gamma \to W^-\nu$	$WW\gamma$
$e^-\gamma \to e^-Z$	$ZZ\gamma$, $Z\gamma\gamma$
$e^-\gamma \to W^+W^-e^-$	WWZ, $WW\gamma$, $WWZ\gamma$

Note: can polarize both beams in e^-e^-

Experimental Signatures

WHAT CAN HADRON COLLIDERS TELL US?

Sampling of accessible couplings / processes:

Coupling	Processes
$WW\gamma$	$q\bar{q}' \to W^* \to W\gamma$
$WW\gamma/WWZ$	$q\bar{q} \to \gamma^*/Z^* \to WW$
WWZ	$q\bar{q}' \to W^* \to WZ$

Complications:

- Parton initial state energies / longitudinal momenta unknown *a priori*
- Parton collisions have poorly defined maximum $\sqrt{s'}$ (unlike at e^+e^-, e^-e^-, $\gamma\gamma$ colliders)
- Form-factor dependence critical in setting sensible limits

  Example:

$$\Delta\kappa_V(s') \quad = \quad \frac{\Delta\kappa_\gamma^0}{(1+\frac{s'}{\Lambda_{FF}^2})^2}$$

  where $\Lambda_{FF} \approx$ scale of new physics

  Quoted limits must specify assumed Λ_{FF}

  Typical choices: 1.0, 1.5, 2.0 TeV

Experimental Signatures

The Tevatron Collider

Two Detectors: CDF D0

Run 1 (1992-95)

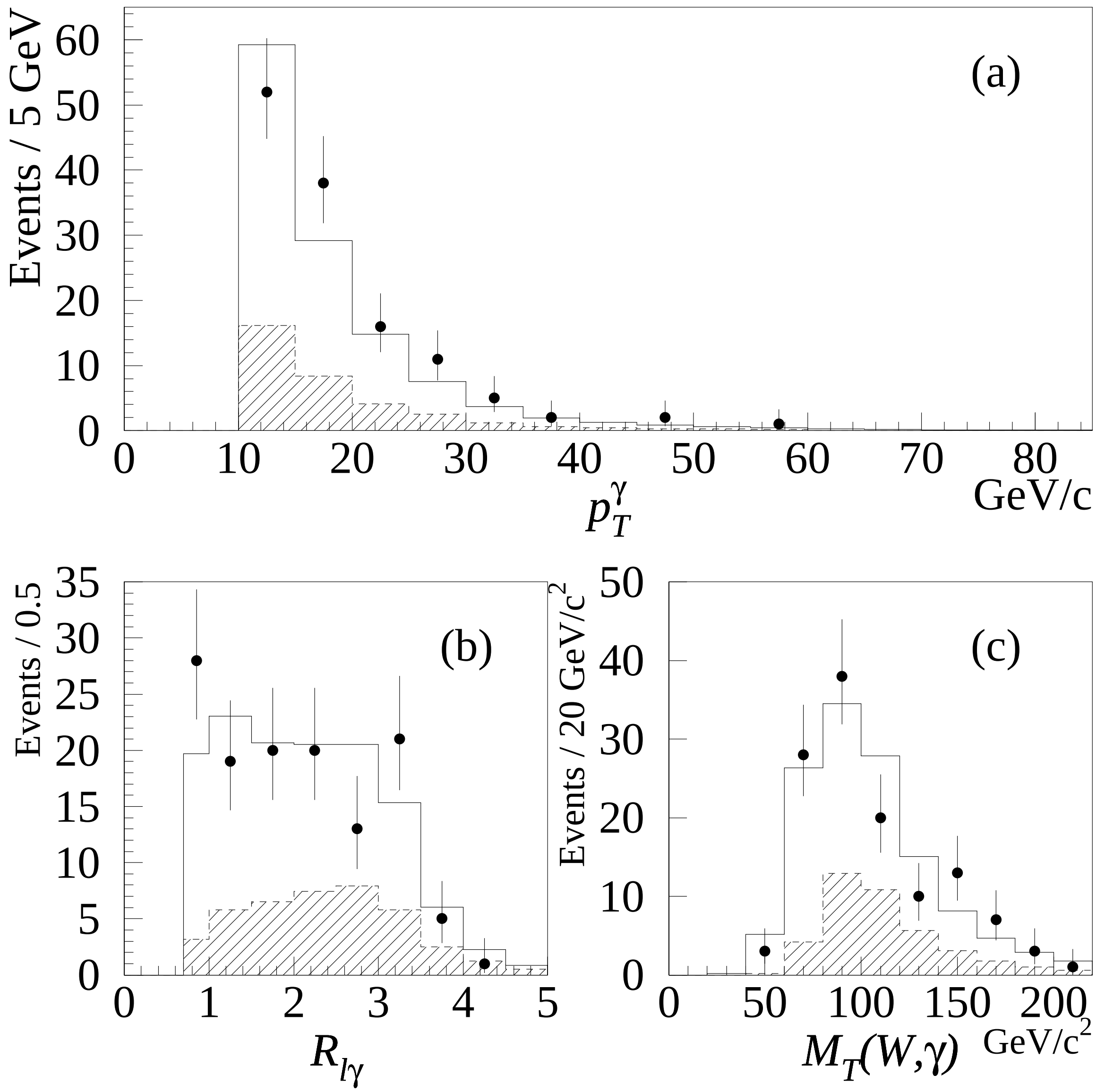
- >100 pb^{-1} at $\sqrt{s_{p\bar{p}}} = 1.8$ TeV
- Many TGC results now final & published

Run 2 (2000-200?)

- >2 fb^{-1} at $\sqrt{s_{p\bar{p}}} = 2.0$ TeV
- Extension to $\geq$10-30 fb^{-1} (TEV33)

Experimental Signatures

Measurement of $W\gamma$ production from D0:

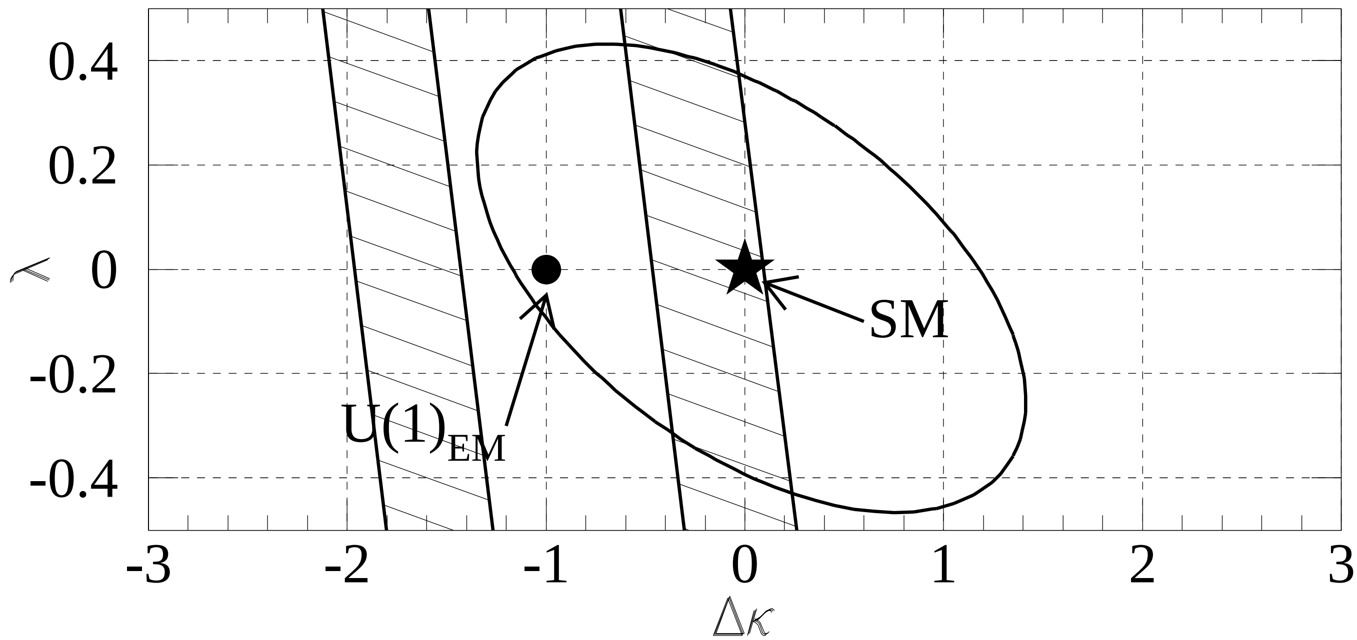


$$R_{\ell\gamma} \quad \equiv \quad \sqrt{(\delta\eta)^2 + (\delta\phi)^2}$$

$$M_T(W,\gamma) \quad = \quad W\text{–}\gamma \text{ transverse mass}$$

Experimental Signatures

Resulting D0 limits on $\Delta\kappa_\gamma$, λ_γ: ($b \to s\gamma$ limits shown too)



Remarks:

- Better sensitivity to λ_V than to $\Delta\kappa_V$ (like LEP)
- $WW\gamma$ cleanly isolated from WWZ (unlike LEP)
- Assumes $\Lambda_{FF} = 1.5$ TeV

CDF limits from WW, WZ production:

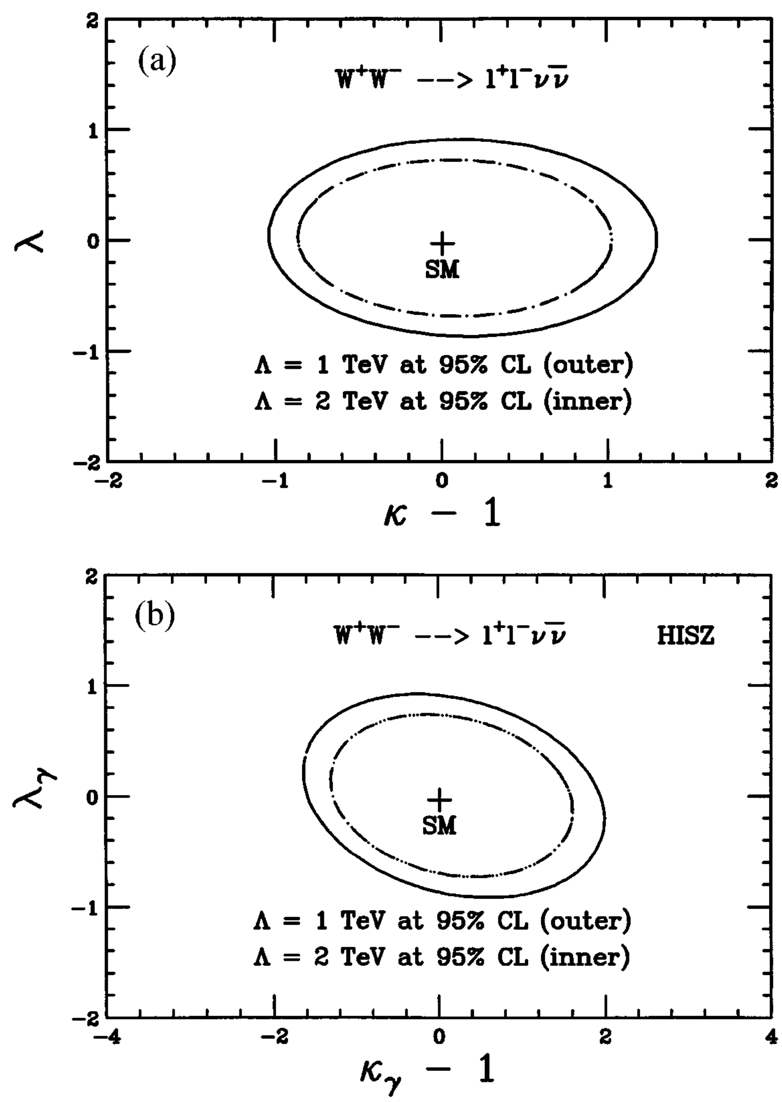


FIG. 2. Limits on anomalous couplings: (a) Assuming $\kappa_\gamma = \kappa_Z = \kappa$ and $\lambda_\gamma = \lambda_Z = \lambda$. (b) The HISZ scenario where κ_γ and λ_γ are used as independent parameters. The standard model value is located at the center. The outer (inner) contour is the 95% CL limits with the energy scale $\Lambda =$ 1 TeV (2 TeV).

Experimental Signatures

Tevatron – Run 2

Expect 1-10 fb^{-1} at $\sqrt{s} = 1.8/2.0$ TeV

Analysis by Errede

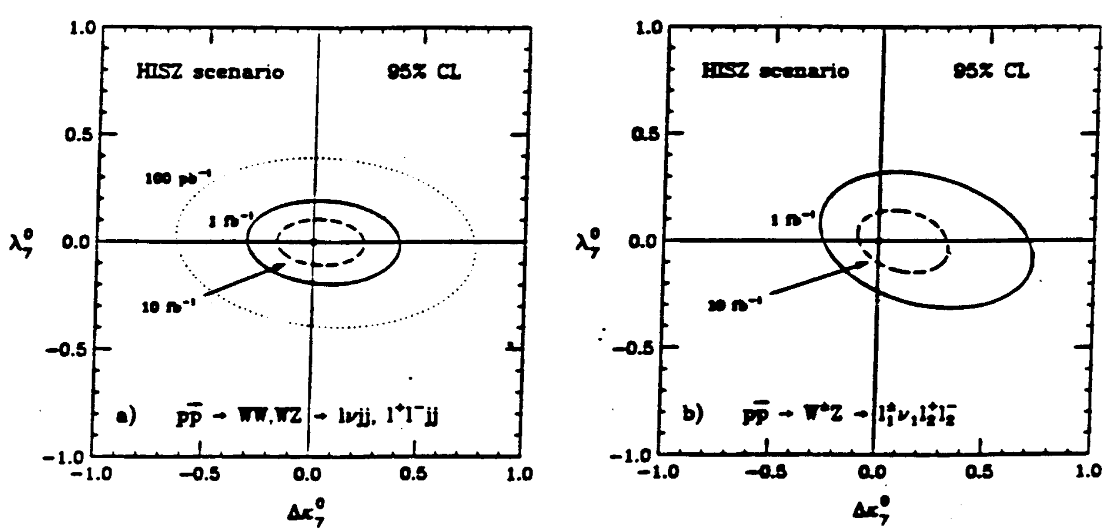
Assumes full HISZ scenario

For 1 fb^{-1}:

$$\Leftrightarrow\!0.31 < \Delta\kappa_\gamma < 0.41\ (\lambda_\gamma = 0)$$
$$\Leftrightarrow\!0.19 < \lambda_\gamma < 0.19\ (\Delta\kappa_\gamma = 0)$$

For 10 fb^{-1}:

$$\Leftrightarrow\!0.17 < \Delta\kappa_\gamma < 0.24\ (\lambda_\gamma = 0)$$
$$\Leftrightarrow\!0.10 < \lambda_\gamma < 0.11\ (\Delta\kappa_\gamma = 0)$$



Experimental Signatures

What about the LHC?

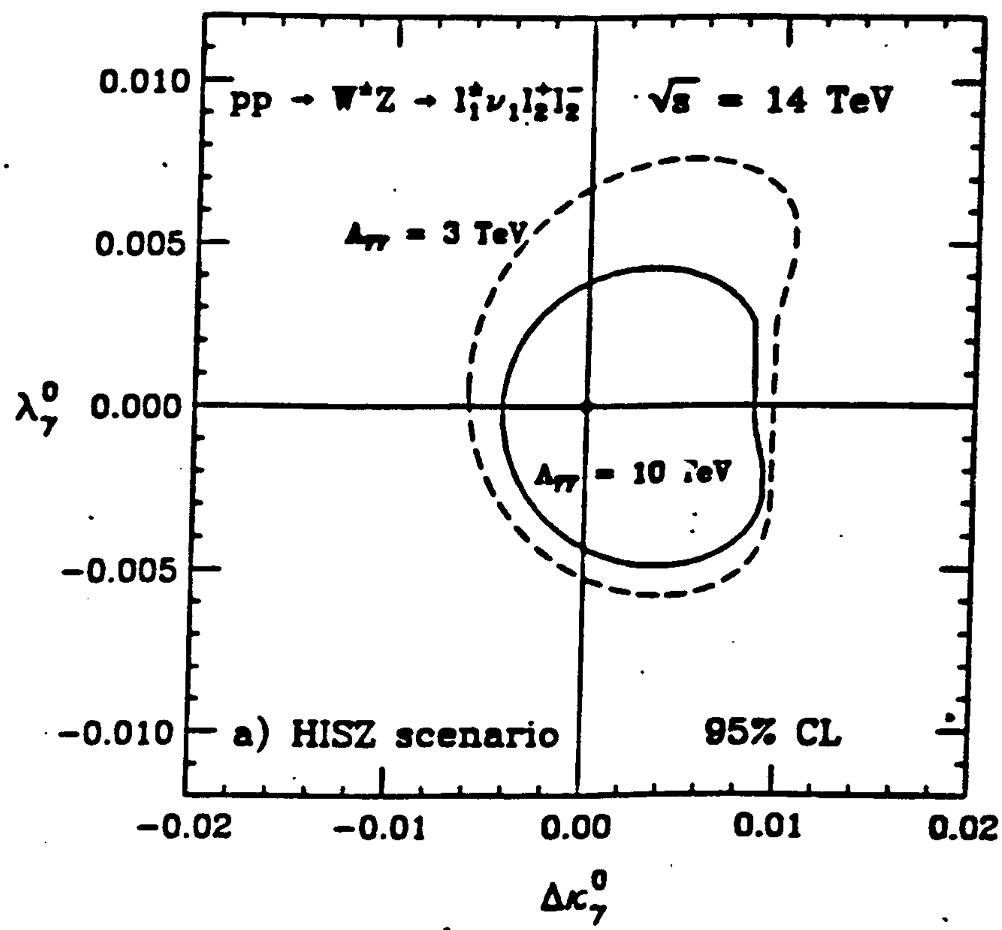
Assume 100 fb^{-1} at $\sqrt{s} = 14$ TeV

Analysis for ATLAS TDR

Assumes HISZ scenario

For 100 fb^{-1}:

$$\Leftrightarrow 0.006 < \Delta\kappa_\gamma < 0.0097 \; (\lambda_\gamma = 0)$$
$$\Leftrightarrow 0.0053 < \lambda_\gamma < 0.0067 \; (\Delta\kappa_\gamma = 0)$$

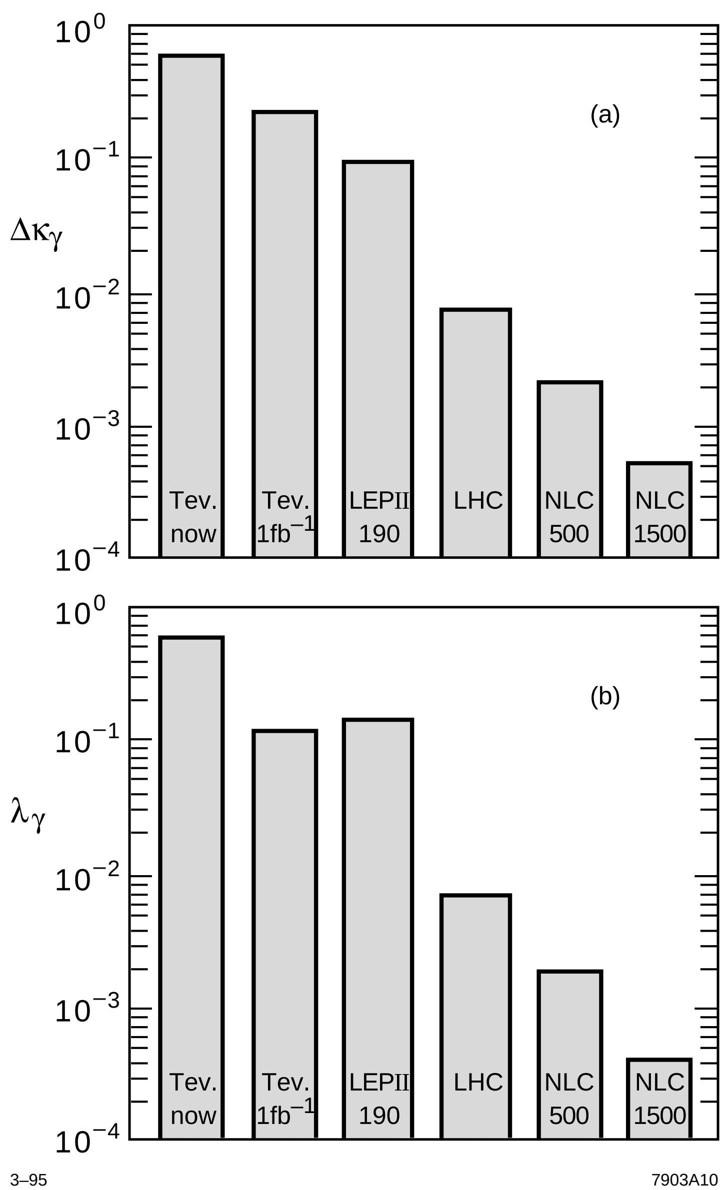


Experimental Signatures

Summary of CP-conserving WWV measurement prospects

NLC should improve dramatically upon LEP II / Tevatron and substantially upon LHC

Figure from Barklow/Dawson/Haber/Siegrist:



Experimental Signatures

What about CP violation? (!)

Remarks

- Total cross section less sensitive to small $\not{C}\not{P}$ couplings
- Why?

$$\sigma \quad \propto \quad |M_{\mathrm{tot}}|^2$$

  where

$$M_{\mathrm{tot}} \quad = \quad M_{\mathrm{S.M.}} + M_{\not{C}\not{P}}$$

  At tree level,

$$\Im\{M_{\mathrm{S.M.}}\} = 0 \qquad \Re\{M_{\not{C}\not{P}}\} = 0$$

  $\Longrightarrow \sigma_{\mathrm{tot}} = \sigma_{\mathrm{S.M.}} + \sigma_{\not{C}\not{P}}$

  $\Longrightarrow$ No interference

- Contrast with CP-even anomalous couplings which disturb large destructive interference in S.M.
- Similar problem occurs in simple angular distributions
- Better sensitivity from
  - Correlations between W^+ and W^- decay distributions
  - Manifestly CP-odd observables

Experimental Signatures

Examples in $e^+e^- \to W^+W^-$:

- Multi-dimensional maximum likelihood fitting
- Look at following 1-D distributions (Hagiwara *et al.*)
  - $\sin\theta_1 \sin\theta_2$
  - $\sin(\phi_1 \Leftrightarrow 2\,\phi_2) \Leftrightarrow \sin(2\,\phi_1 \Leftrightarrow \phi_2)$
  - $\sin(\phi_1 \Leftrightarrow \phi_2)$
- Look at imaginary components of off-diagonal single-W spin density matrix elements (Gounaris *et al.*)
  - $\Im\{\rho_{+-}^{W^+}\} + \Im\{\rho_{+-}^{W^-}\}$
  - $\Im\{\rho_{+0}^{W^+}\} \Leftrightarrow \Im\{\rho_{-0}^{W^-}\}$
  - $\Im\{\rho_{-0}^{W^+}\} \Leftrightarrow \Im\{\rho_{+0}^{W^-}\}$

Experimental Signatures

Present *direct* limits on $\not{CP}$ $WW\gamma$ couplings:

- D0 used $p\bar{p} \to W\gamma + X$ to derive

$$-0.92 < \tilde{\kappa}_\gamma < 0.92 \qquad -0.31 < \tilde{\lambda}_\gamma < 0.30$$

  from the p_t^γ spectrum

- DELPHI used $e^+e^- \to W^+W^-$ and $e^+e^- \to e\bar{\nu}W$ events to derive

$$\tilde{\kappa}_\gamma = 0.11^{+0.71}_{-0.88} \pm 0.09 \qquad \tilde{\lambda}_\gamma = 0.19^{+0.28}_{-0.41} \pm 0.11$$

  (based on small 161-172 GeV data sample)

- OPAL verified imaginary components of off-diagonal single-W spin density matrix consistent with zero, but no explicit limit on $\not{CP}$ couplings derived

Remarks:

- More stringent limits possible from present LEP II data
- Many experimentalists regard such limits are artificial, since they require setting other anomalous couplings to zero
- Indirect neutron EDM limits on $\tilde{\kappa}_\gamma$ and $\tilde{\lambda}_\gamma$ encourage confidence (complacency?) in considering only CP conserving couplings

Other Gauge Boson Couplings ($\not{C}\not{P}$)

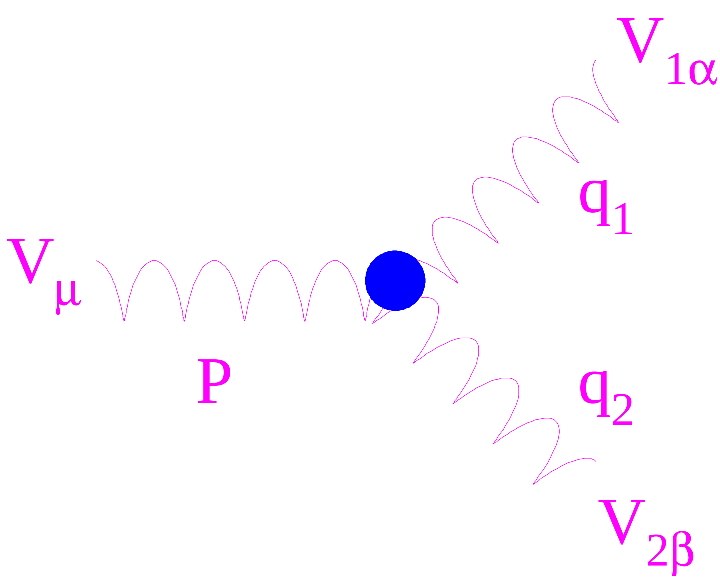
Anomalous $ZZ\gamma$, $Z\gamma\gamma$ Couplings

- Couplings vanish at tree-level in SM
- Bose symmetry / gauge invariance forbid non-zero values when all bosons on mass shell
- Parametrization of $Z\gamma V$ vertex function: ($V \equiv Z\gamma$)

$$,{}^{\alpha\beta\mu}_{Z\gamma V}(q_1, q_2, P) \quad \equiv \quad \frac{P^2 \Leftrightarrow m_V^2}{m_Z^2} \times$$

$$[h_1^V(q_2^\mu g^{\alpha\beta} \Leftrightarrow q_2^\alpha g^{\mu\beta}) + \frac{h_2}{m_Z^2} P^\alpha (P \cdot q_2 g^{\mu\beta} \Leftrightarrow q_2^\mu P^\beta)$$

$$+ h_3^V \epsilon^{\mu\alpha\beta\rho} q_{2_\rho} + \frac{h_4^V}{m_Z^2} P^\alpha \epsilon^{\mu\beta\rho\sigma} P_\rho q_{2_\sigma}]$$



Other Gauge Boson Couplings ($\not{C}\not{P}$)

Anomalous $Z\gamma V$ couplings:

- CP-odd couplings: h_1^V, h_2^V

- CP-even couplings: h_3^V, h_4^V

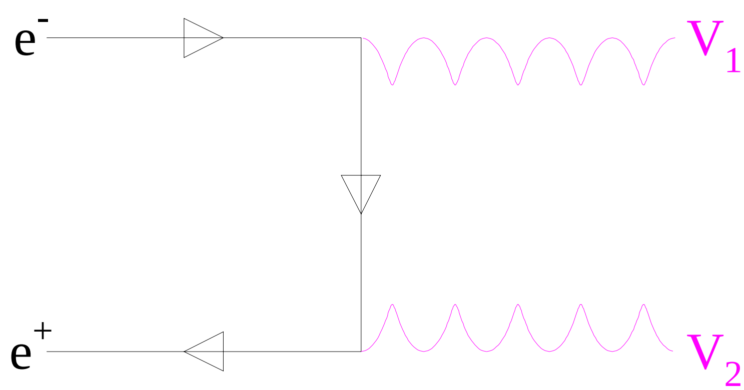
- The h_i^V couplings are really form factors:

$$h_i^v(P^2) \qquad \equiv \qquad \frac{h_{i0}^V}{(1+\frac{P^2}{\Lambda_V^2})^{n_i^V}}$$

- Unitarity requires $\quad n_1^V,\ n_3^V, \geq 3, \qquad n_2^V,\ n_4^V \geq 4$

- Signatures at e^+e^- collider: $\gamma\gamma$, $Z\gamma$, ZZ production

- Standard Model background:



Other Gauge Boson Couplings ($\not{C}P$)

Example from L3:

Probe all eight h_i^V couplings via $Z\gamma$ production

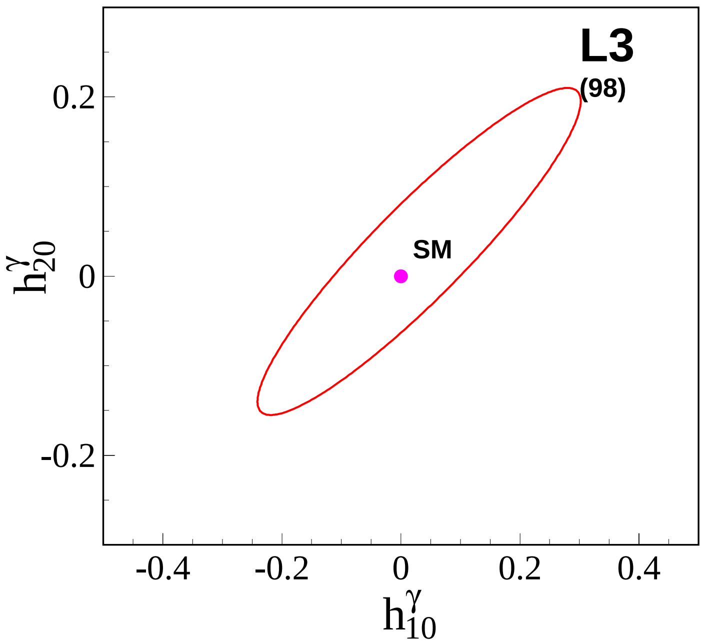
- Look at final state $q\bar{q}\gamma$ (2 jets + hard photon)
- Look at final state $\nu\bar{\nu}\gamma$ (single hard photon)
- Couplings determined by matrix element reweighting of Monte Carlo events to match data
- Five kinematic variables used in $q\bar{q}\gamma$ analysis (E_γ, θ_γ, ϕ_γ, θ_q^*, ϕ_q^*)
- The three photon variables used in $\nu\bar{\nu}\gamma$ analysis

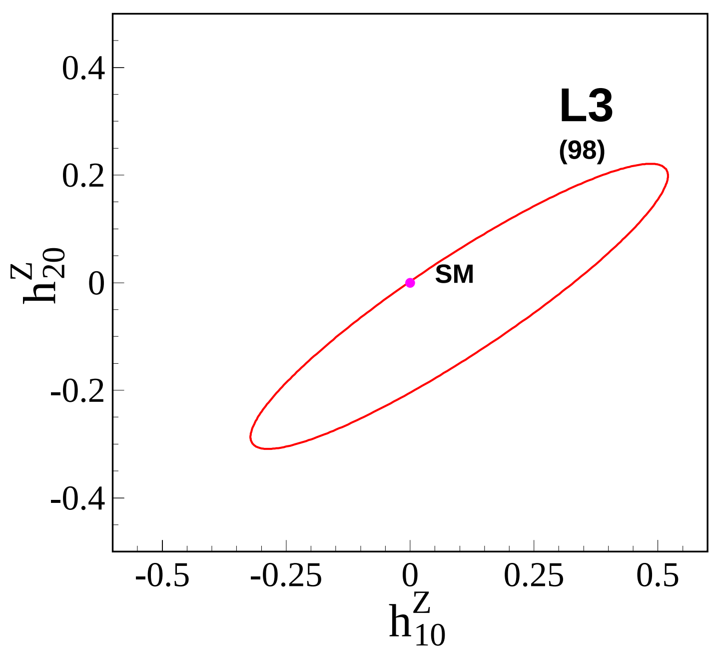
Preliminary Results:

95% CL Limits
$\Leftrightarrow 0.09 < h_1^Z < 0.20$
$\Leftrightarrow 0.12 < h_2^Z < 0.06$
$\Leftrightarrow 0.16 < h_3^Z < 0.15$
$\Leftrightarrow 0.09 < h_4^Z < 0.10$
$\Leftrightarrow 0.09 < h_1^\gamma < 0.08$
$\Leftrightarrow 0.05 < h_2^\gamma < 0.07$
$\Leftrightarrow 0.09 < h_3^\gamma < 0.07$
$\Leftrightarrow 0.05 < h_4^\gamma < 0.06$

Other Gauge Boson Couplings ($\not{CP}$)

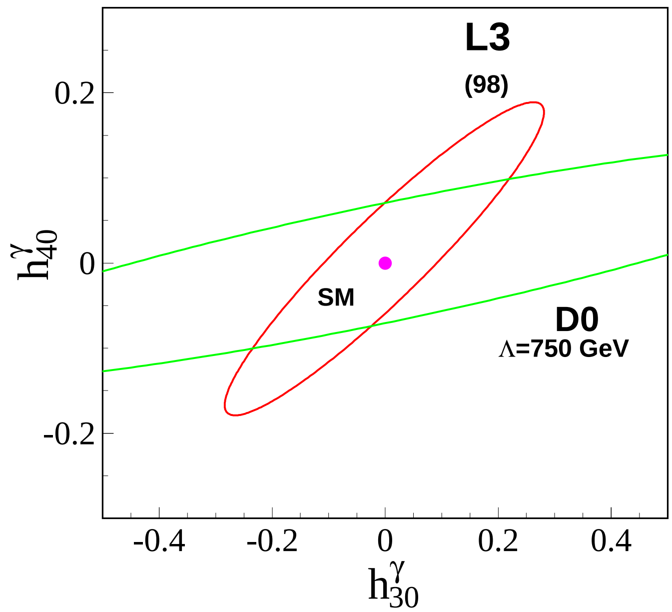
2-Dimensional contour limits on $\not{CP}$ couplings: (preliminary)

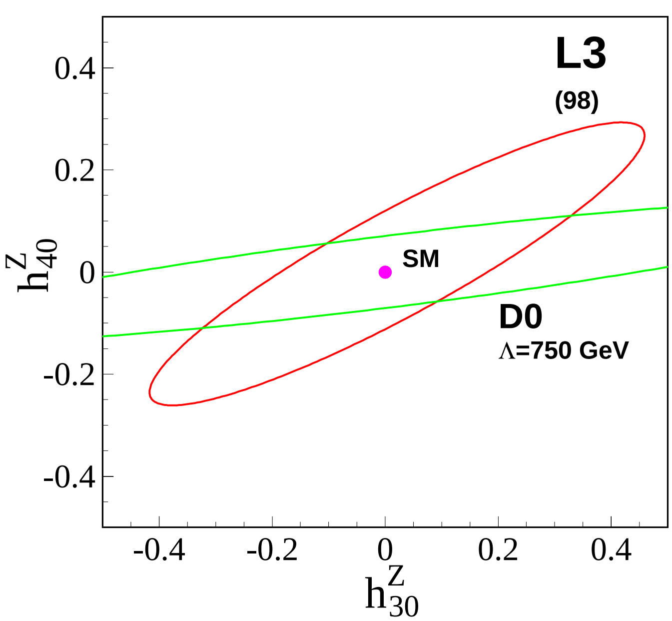




Other Gauge Boson Couplings ($\not{C}\not{P}$)

2-Dimensional contour limits on CP conserving couplings from D0 and L3 (L3 limits preliminary)





Other Gauge Boson Couplings ($\not{C}P$)

Anomalous $ZZ\gamma$, ZZZ Couplings (ZZ production)

- Bose symmetry permits two couplings
- Parametrization of ZZV vertex function:

$$\Gamma^{\alpha\beta\mu}_{ZZV}(q_1, q_2, P) \quad \equiv \quad \frac{P^2 - m_V^2}{m_Z^2} \times$$

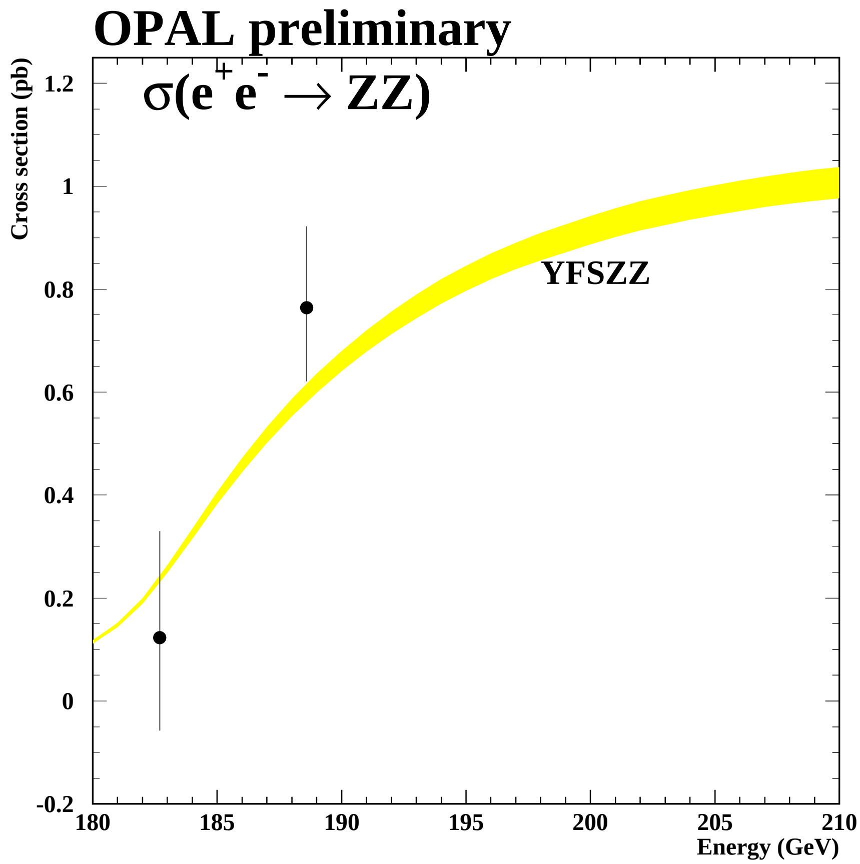
$$\left[i\, f_4^{ZZV}(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) \; + \; i\, f_5^{ZZV} \epsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho\right]$$

- CP-Violating: f_4^{ZZV}
- CP-Conserving: f_5^{ZZV}

Preliminary analysis from OPAL:

- Examines total cross section and $d\sigma/d\cos\theta_Z$ distribution
- Probes both real & imaginary f_i^{ZZV} components
- Severely limited by ZZ statistics ($\sqrt{s} \leq 189$ GeV)

Other Gauge Boson Couplings ($\not{C}P$)



Resulting limits on f_i^{ZZV}:

95% CL Limits
$\Leftrightarrow 2.0 < \Re\{f_4^{ZZZ}\} < 2.0$
$\Leftrightarrow 2.0 < \Im\{f_4^{ZZZ}\} < 1.9$
$\Leftrightarrow 5.1 < \Re\{f_5^{ZZZ}\} < 3.6$
$\Leftrightarrow 5.2 < \Im\{f_5^{ZZZ}\} < 5.4$
$\Leftrightarrow 1.2 < \Re\{f_4^{ZZ\gamma}\} < 1.2$
$\Leftrightarrow 1.2 < \Im\{f_4^{ZZ\gamma}\} < 1.2$
$\Leftrightarrow 3.2 < \Re\{f_5^{ZZ\gamma}\} < 3.0$
$\Leftrightarrow 3.2 < \Im\{f_5^{ZZ\gamma}\} < 3.2$

Gauge Boson Couplings

Summary

- Anomalous TGC and QGC probed most directly at e^+e^- and hadron colliders
- Best sensitivity: High energy e^+e^-, e^-e^-, $\gamma\gamma$, $e^-\gamma$ colliders
- LEP I and low-energy measurements suggest anomalous couplings will not be observed soon

  Especially $\not{CP}$ $WW\gamma$ couplings

- LEP II measurements confirm analysis techniques, but do not challenge Standard Model
- Optimistic perspective:

  If non-zero anomalous couplings measured,
  Then dramatic New Physics imminent

Top Quark $\not{CP}$ Couplings

Standard Model: (see Nir lectures):

Expect $\not{CP}$ in only charged-current quark interactions

Cabibbo-Kobayashi-Maskawa Matrix:

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Standard parametrization:

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{KM}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\mathrm{KM}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\mathrm{KM}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\mathrm{KM}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\mathrm{KM}}} & c_{23}c_{13} \end{pmatrix}$$

$\Longrightarrow$ Explicit $\not{CP}$ phase in V_{td}, V_{ts} elements

$\Longrightarrow$ Easy to see CP violation in top decay?

Nope...

Top Quark $\not{C}P$ Couplings

Obstacles:

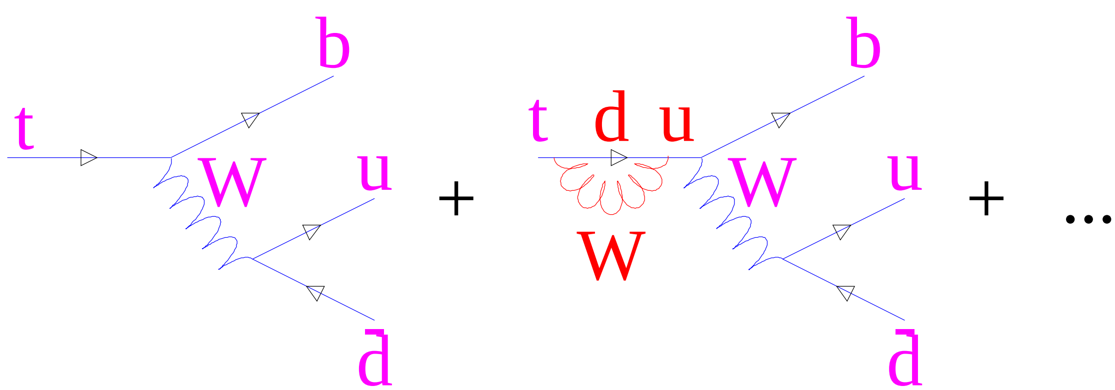
- Max($|V_{td}|$, $|V_{ts}|$) $<$ $\approx$0.01

- t decays ($\Gamma \approx$1.8 GeV) before neutral $t\bar{c}$, $t\bar{u}$ states can form
  $\Longrightarrow$ No time for mixing effects

- Any identifiable exclusive decay is "rare"

- Interference possible between tree + loop diagrams

  Example:



(exploit imaginary term from on-shell W in tree diagram)

Top Quark $C\!\!\!/P\!\!\!/$ Couplings

- Can look for Partial Rate Asymmetry (PRA):

$$\mathrm{PRA} \quad \equiv \quad \frac{,\,(t \to X_i) \Leftrightarrow ,\,(\bar{t} \to \bar{X}_i)}{,\,(t \to X_i) + ,\,(\bar{t} \to \bar{X}_i)}$$

  for some X_i final state

- But loop contribution suppressed by off-diagonal CKM elements and by GIM mechanism

- Result: $(\mathrm{PRA})^2 \times B(t \to X_i) \quad < \quad \approx 10^{-15}$

  $\Longrightarrow$ $C\!\!\!/P\!\!\!/$ not visible in S.M. top decay / production

  $\Longrightarrow$ If $C\!\!\!/P\!\!\!/$ seen in top sector, new physics at work

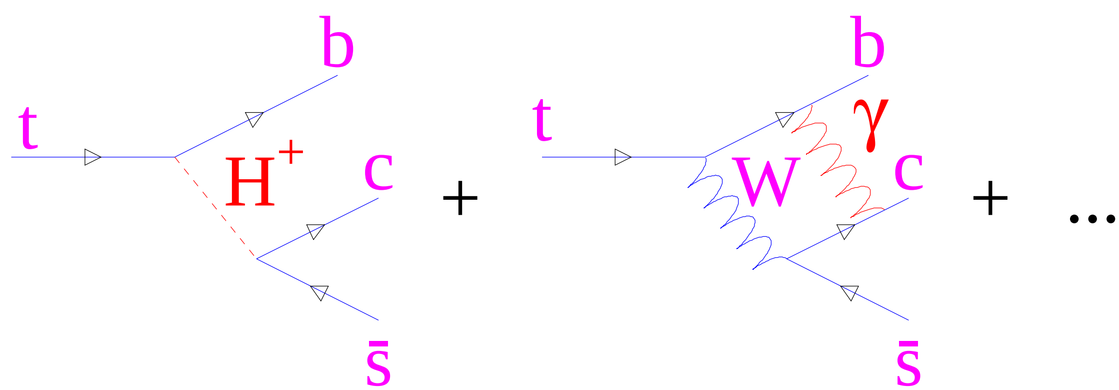
Top Quark $\not{CP}$ Couplings

Beyond the Standard Model

$\not{CP}$ in the top sector:

- Charged current processes:
  - Add charged Higgs to decay route

Example:



Remarks:

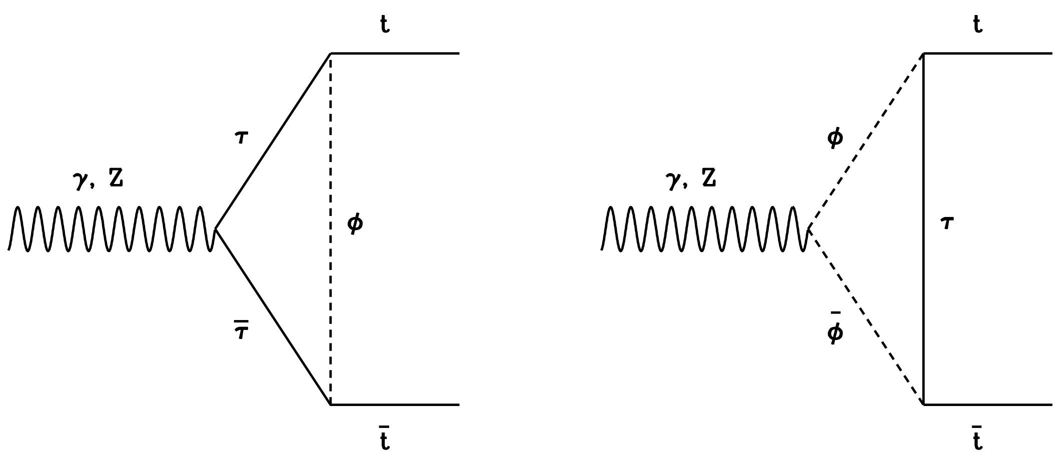
- Non-SM Higgs gives large effects because m_t large
- Fast t decay has important advantage:
  - Spin of t undiluted by hadronization
    $\Longrightarrow$ Polarimetry feasible via $V\Leftrightarrow A$ coupling in decay

Top Quark $\not{C}\not{P}$ Couplings

$\not{C}\not{P}$ in the top sector:

- Neutral current processes:
  - Electric dipole moment (SM prediction $\approx 10^{-30}$ e-cm)
  - Weak and Chromo analogs
  - Much larger moments can arise from
    * $\not{C}\not{P}$ in neutral Higgs sector (multi-Higgs models)
    * $\not{C}\not{P}$ in charged Higgs sector (" " ")
    * $\not{C}\not{P}$ in MSSM: $\tilde{t}_L$, $\tilde{t}_R$ mixing
    * Scalar leptoquarks

Example:



(figure from Poulose & Rindani)

Top Quark $\not{C}$P Couplings

Comparing single t decay to single $\bar{t}$ decay...
(correlations in $t\bar{t}$ production discussed below)

PRA enhanced in many non-SM scenarios, but still tiny

One can go beyond partial decay widths:

- Energy asymmetry in $t \to b\bar{\ell}\nu$ *vs* $\bar{t} \to \bar{b}\ell\bar{\nu}$

$$A_E \quad \equiv \quad \frac{< E_\ell > \Leftrightarrow < E_{\bar{\ell}} >}{< E_\ell > + < E_{\bar{\ell}} >}$$

  - $\ell = e$ (Schmidt & Peskin, 1992)
  - $\ell = \tau$ (Atwood *et al.*, 1993)
    (enhanced over $\ell = e$ if Higgs-induced)

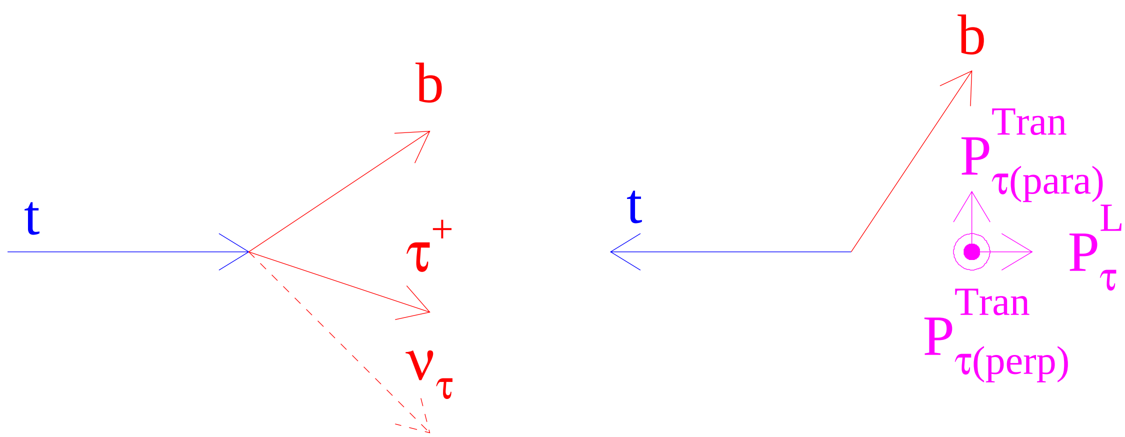
- T-odd W polarization asymmetry in $t \to bW$ (t *vs* $\bar{t}$)
  (Ma and Brandenburg, 1992)

- Partially Integrated Rate Asymmetry (PIRA)
  (partial phase space integration, Atwood *et al.*, 1993)

- Tau transverse polarization asymmetry in $t \to b\bar{\tau}\nu$
  (Atwood, Eilam & Soni, 1993)

Top Quark $\not{C}\not{P}$ Couplings

Example – Tau transverse polarization in $t \to b\bar{\tau}\nu_\tau$
(Atwood, Eilam & Soni, 1993)



Lab frame

τ frame

Look for difference between $< P^{\mathrm{Tran}}_{\tau(\mathrm{para})} >$, $< P^{\mathrm{Tran}}_{\tau(\mathrm{perp})} >$
for t *vs* $\bar{t}$ decays

Quoted precision on asymmetry for 500 GeV NLC:

$$3\sigma \text{ for } A_{pol} \approx 6\%$$

For charged Higgs of $m_{H^+} = 400$ GeV,
"might" expect $A_{pol} \approx$ 5–20%

Can reach ≈50% for $m_{H^+} = 200$ GeV

Top Quark $\not{CP}$ Couplings

$\not{CP}$ easier to see in $t\bar{t}$ production

Especially at lepton, photon colliders

As with gauge bosons, $\not{CP}$ couplings fall under more general category of anomalous couplings

$\Longrightarrow$ Parametrized as multipole moments

Electroweak neutral current: (notation of Frey *et al.*, 1996)

$$
\begin{aligned}
,\,^{\mu}_{tt(\gamma/Z)} \quad = \quad & e\,\bar{t}\,\{\gamma^{\mu}\,[Q_V^{\gamma,Z} F_{1V}^{\gamma,Z} \; + \; Q_A^{\gamma,Z} F_{1A}^{\gamma,Z}\gamma_5] \\
& + \frac{i\,e}{2\,m_t}\,\sigma^{\mu\nu}k_{\nu}\,[Q_V^{\gamma,Z} F_{2V}^{\gamma,Z} \; + \; Q_A^{\gamma,Z} F_{2A}^{\gamma,Z}\gamma_5]\}\,t
\end{aligned}
$$

where in the S.M. $F_{1V}^{\gamma} = F_{2V}^{Z} = F_{2A}^{Z} = 1$
and all other form factors are zero

Normalization:

$$
\begin{aligned}
Q_V^{\gamma} \quad &= \quad Q_A^{\gamma} \quad = \quad \frac{2}{3} \\
Q_V^{Z} \quad &= \quad (1 \Leftrightarrow \frac{8}{3}\sin^2\theta_W)/(4\,\sin\theta_W\,\cos\theta_W) \\
Q_A^{Z} \quad &= \quad \Leftrightarrow 1/(4\,\sin\theta_W\,\cos\theta_W)
\end{aligned}
$$

$F_{2V}^{\gamma,Z}$, $F_{2A}^{\gamma,Z}$ = E.W. magnetic, electric dipole form factors

Top Quark $\not{C}P$ Couplings

Weak charged current: (neglecting flavor violation)

$$
\begin{aligned}
,^{\mu}_{tbW} \quad = \quad & \frac{g}{\sqrt{2}}\,\bar{b}\,\{\gamma^{\mu}\,[P_L F^{W}_{1L} \, + \, P_R F^{W}_{1R}] \\
& + \frac{i}{2m_t}\sigma^{\mu\nu}k_{\nu}[P_L F^{W}_{2L} \, + \, P_R F^{W}_{2R}]\}\,t
\end{aligned}
$$

where P_L, P_R = left, right projection operators
and where in the Standard Model $F^{W}_{1L} = 1$ and all other form factors are zero. (F_{1R} describes $V{+}A$ coupling)

SU(3) current: (notation of Rizzo, 1996)

$$
\pounds_{ttg} \quad = \quad g_s\,\bar{t}\,T_{\alpha}(\gamma^{\mu} \, + \, \frac{i}{2m_t}\sigma^{\mu\nu}(\kappa - i\,\tilde{\kappa}\gamma_5)\,q_{\nu})\,t\,G^{\mu}_{\alpha}
$$

where g_s = strong coupling constant,
T_{α} = color generators,
G^{μ}_{α} = gluon field

κ, $\tilde{\kappa}$ = chromo-magnetic, chromo-electric dipole moments (form factors in general)

Top Quark $\not{C}\not{P}$ Couplings

Looking for $\not{C}\not{P}$ in top production (a sampling)
(some techniques automatically probe $\not{C}\not{P}$ in top decay too)

- Top polarization asymmetry in $e^+e^- \to t\bar{t}$ and $gg \to t\bar{t}$
  (from W kinematics, Kane, Ladinsky, & Yuan, 1992)

- Azimuthal W correlations in $e^+e^- \to t\bar{t}$
  (Kane, Ladinsky, & Yuan, 1992)

- Energy asymmetry A_E (Schmidt & Peskin, 1992)

- Manifestly CP-odd observables in $e^+e^- \to t\bar{t}$
  Correlation Tensor:

$$\hat{T}_{ij} \quad \equiv \quad (\hat{q}_- \Leftrightarrow \hat{q}_+)_i \frac{(\hat{q}_- \times \hat{q}_+)_j}{|\hat{q}_- \times \hat{q}_+|} \; + \; (i \Leftrightarrow j)$$

  where $\hat{q}_-$, $\hat{q}_+$ = unit vectors along, e.g., b, $\bar{b}$ directions
  (Bernreuther, Schröder & Pham, 1992)

Top Quark $\not{C}\not{P}$ Couplings

- Optimal observables in $e^+e^- \to t\bar{t} \to b\bar{b}\bar{\ell}\ell'\nu_\ell\bar{\nu}_{\ell'}$
  Analogous to TGC observables discussed earlier, but with terms projecting out $\Re\{d_t^{\gamma,Z}\}$, $\Im\{d_t^{\gamma,Z}\}$ where

$$d_t^{\gamma,Z} = \text{Electric, weak electric dipole moment}$$
$$\equiv \frac{e}{2\,m_t} F_{2A}^{\gamma,Z}$$

  (Atwood & Soni, 1992)

- Decay lepton up/down asymmetry in $gg \to t\bar{t} \to b\bar{\ell}\nu X$
  (Grzadkowski & Gunion, 1992)
  (Up/down refers to $\vec{p}_e$ in W rest frame w.r.t. $t \Leftrightarrow b$ plane)

- Manifestly CP-odd observables in $e^+e^- \to t\bar{t} \to b\bar{b}X\bar{X}$ with polarized beams (Cuypers & Rindani, 1994)

$$O_1 \equiv (\vec{p}_b \times \vec{p}_{\bar{b}}) \cdot \hat{p}_{e^+}$$
$$O_2 \equiv (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot \hat{p}_{e^+}$$

- Multi-distribution fitting with matrix element reweighting
  (reweighting by one or more form factor parameters)
  (Frey *et al.*, 1996)

Top Quark $\not{C}\not{P}$ Couplings

More exotic possibilities: (sampling)

- CP-odd observables in $e^+e^- \to t\bar{t}H$, $e^+e^- \to t\bar{t}Z$
  – need hefty $\sqrt{s}$ for this! (Bar-Shalom *et al.*, 1996; Bar-Shalom, Atwood & Soni, 1998)

$$O \quad \equiv \quad \vec{p}_{e^-} \cdot (\vec{p}_t \times \vec{p}_{\bar{t}})$$

- Charge and forward/backward asymmetries of $\ell^+\ell'^-$ in $\gamma\gamma \to t\bar{t} \to b\bar{b}\,\ell^+\ell'^-\,\nu_\ell\bar{\nu}_{\ell'}$ (Poulose & Rindani, 1998)

Top Quark $\not{C}P$ Couplings

What about chromo-magnetic/electric dipole moments?

- Gluon energy spectrum in $e^+e^- \to t\bar{t}g$ (NLC)
  (Rizzo, 1996)

- Top quark polarization & polarization asymmetry in $e^+e^- \to t\bar{t}$ (NLC)
  (Rindani & Tung, 1999)

- $M_{t\bar{t}}$, $p_t^{t,\bar{t}}$ distributions in $gg \to t\bar{t}$
  (Sensitive to anomalous couplings at LHC,
  sensitive to low-scale gravity theory at Tevatron Run II)
  (Review by Rizzo, 1999)

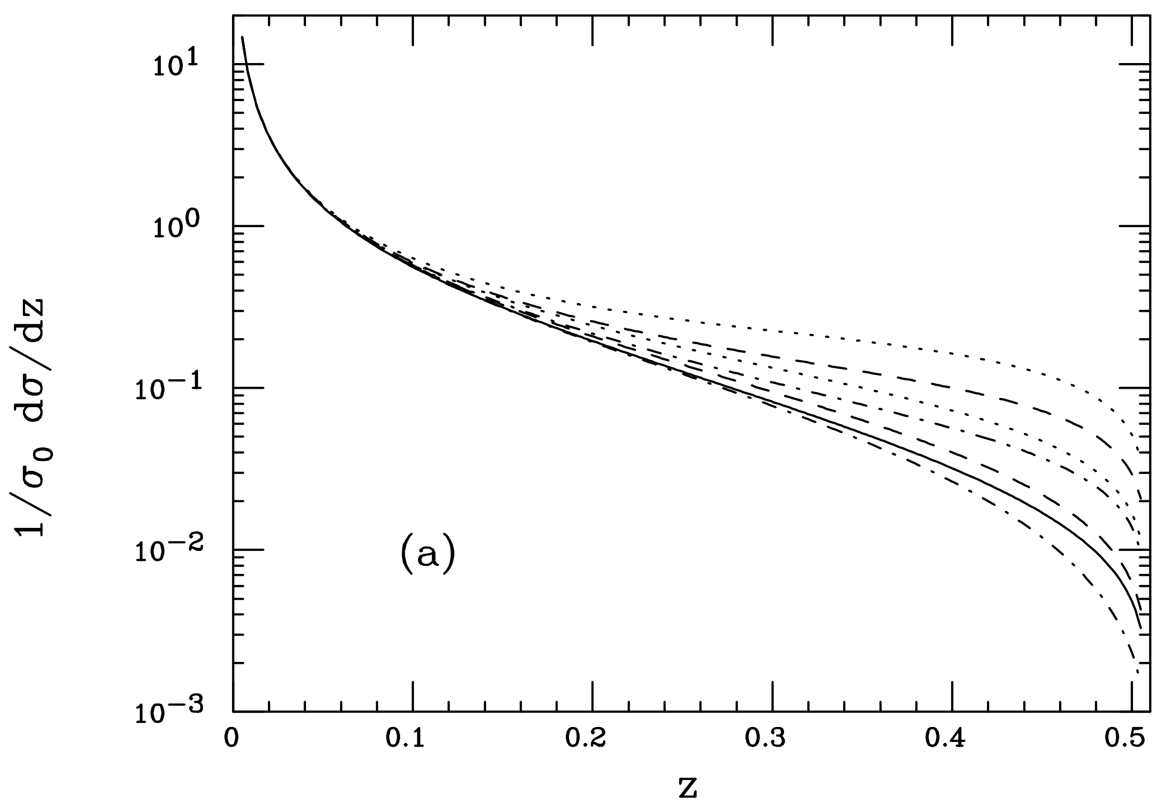
Top Quark $\not{C}P$ Couplings

Example (Rizzo, 1996)

Chromo-magnetic(κ), Chromo-electric($\tilde{\kappa}$) dipole moments

Measure gluon energy distributions at a e^+e^- linear collider

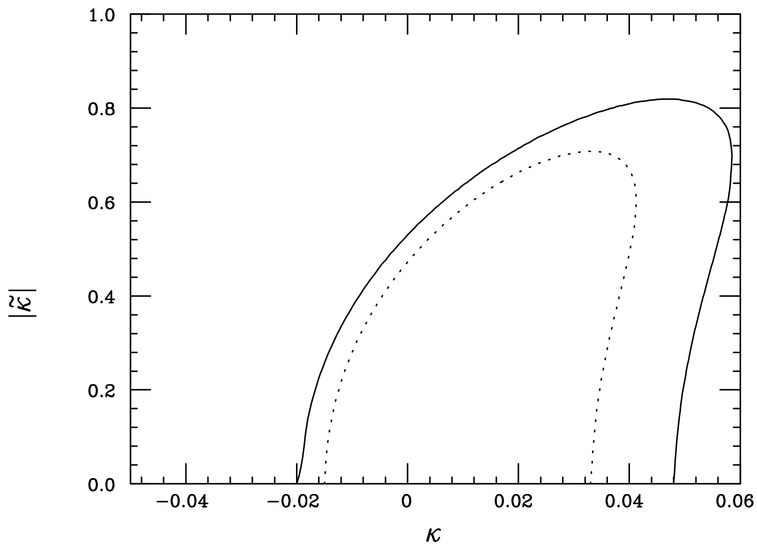
E_g shapes at 500 GeV NLC for $\kappa = 0, \pm1, \pm2, \pm3$



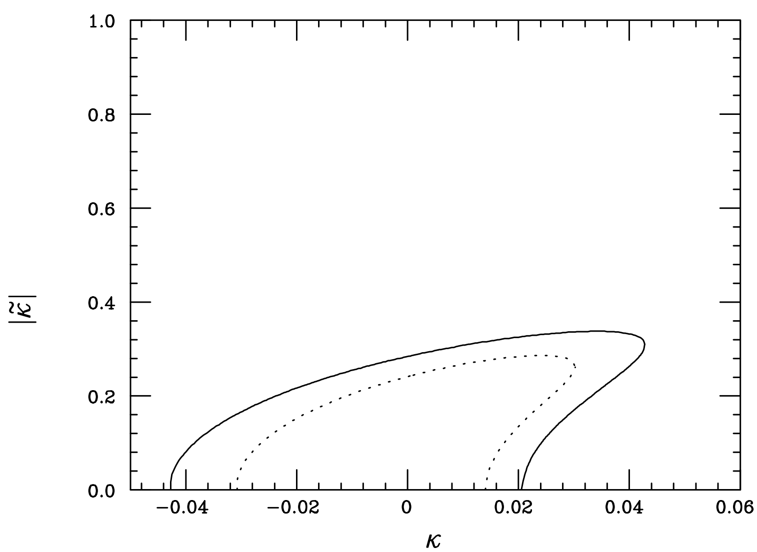
where $z \equiv E_g/E_{\rm beam}$

Top Quark $\not{C}P$ Couplings

Resulting limits at a 500 GeV NLC ($\int \mathcal{L}\, dt = 50,\ 100\ \mathrm{fb}^{-1}$)



and at a 1 TeV NLC ($\int \mathcal{L}\, dt = 100,\ 200\ \mathrm{fb}^{-1}$)



Top Quark $\not{C}P$ Couplings

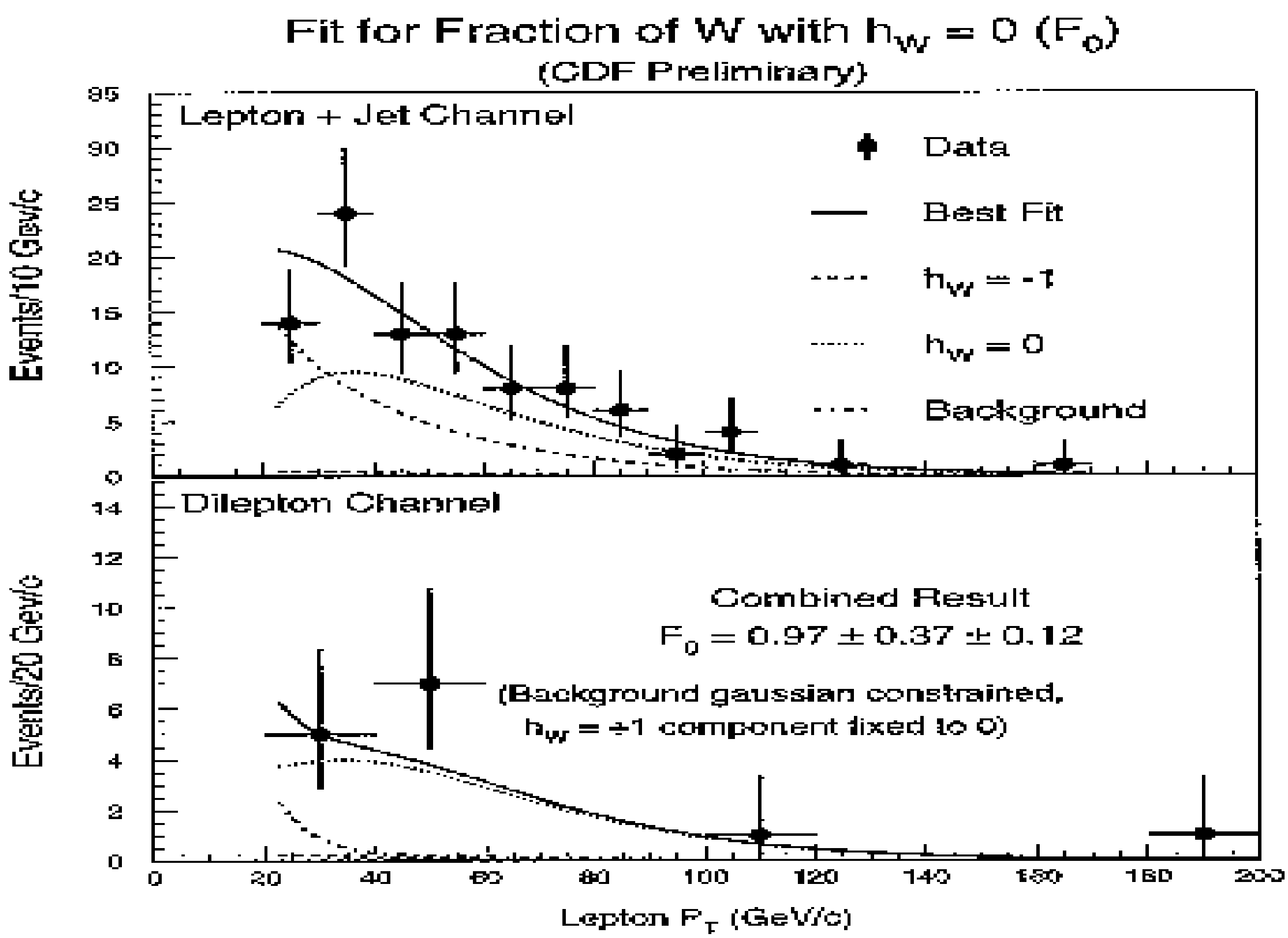
Can any Tevatron Run I data be used?

Not really...too few events

Interesting proof-of-principle analyses from CDF & D0:

- W polarization from top decay
- Spin-spin correlations from t and $\bar{t}$ decay products

Example – CDF result on W long. polarization (SM = 70%)



Tau Lepton $\not{CP}$ Couplings

Standard Model: (see Nir lectures):

If neutrinos massless, then no $\not{CP}$

But much evidence for ν oscillation

$\Longrightarrow m_{\nu_i} \neq 0$

$\Longrightarrow$ Possible (likely) $\not{CP}$ phase in leptonic CKM matrix

Can we therefore detect "S.M." $\not{CP}$ in τ decay?

Probably not

(cannot use the $\Im\{\text{W}\not\Leftrightarrow\text{tree}\} \times \Re\{\text{loop}\}$ trick because intermediate W far off resonance)

In principle, one can measure $\delta^{\ell}_{\rm KM}$ from high-statistics ν oscillation asymmetries, but not anytime soon...

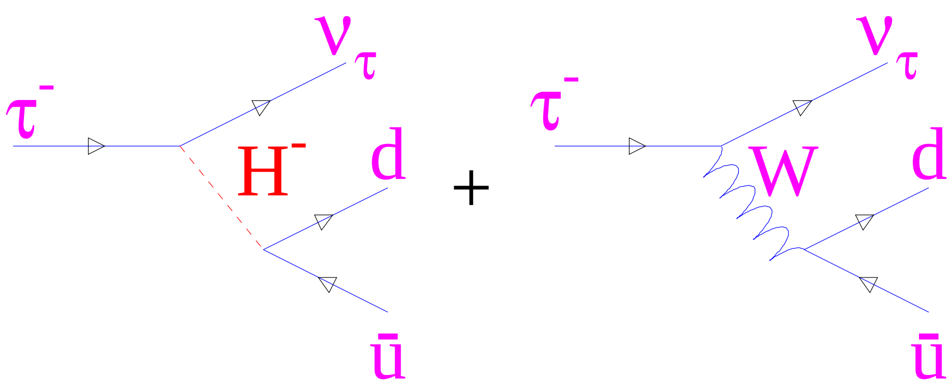
$\Longrightarrow$ As for top decay, any measured $\not{CP}$ means New Physics

Tau Lepton $\not{C}\not{P}$ Couplings

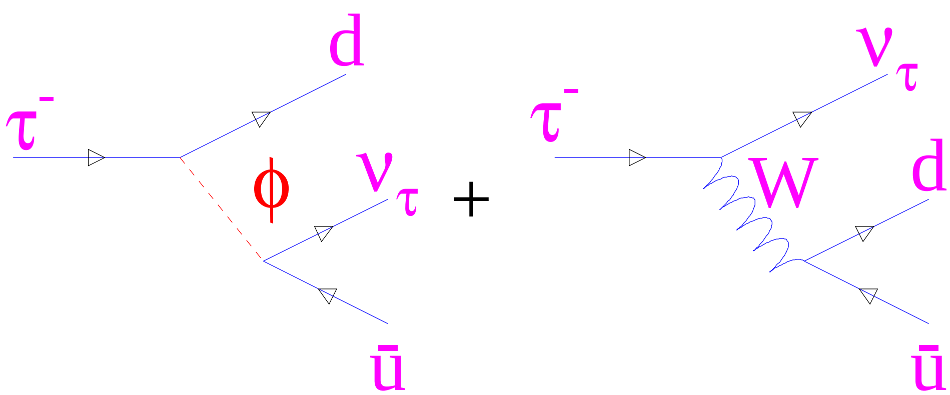
Beyond the Standard Model

$\not{C}\not{P}$ in the tau sector:

- Charged current processes:
  - As for top quark, add charged Higgs to decay route: (Tsai, 1989)



  - Or add a scalar leptoquark: (Choi, Hagiwara & Tanabashi, 1994)



Tau Lepton $\not{C}\not{P}$ Couplings

- Can enhance the $\not{C}\not{P}$ interference with final state containing possible non-zero CP-conserving phase
  - "Stage Two Spin Correlation" in $\tau^- \to \rho^- \to \pi^- \pi^0 \nu_\tau$ (interference of two allowed ρ helicity states)*
    (Nelson, 1994)
  - Double resonance in $\tau^- \to (3\pi)^- \nu_\tau$
    (interference of a_1 (J^P=1^+) and π' (J^P=0^-) states)
    (Choi, Hagiwara & Tanabashi, 1994)
  - Double resonance in $\tau^- \to (K\pi)^- \nu_\tau$
    (interference of $K^*(892)$ (J^P=1^-) and $K_0^*(1430)$ (J^P=0^+) states)
    (Kühn & Mirkes, 1996)

Remark:

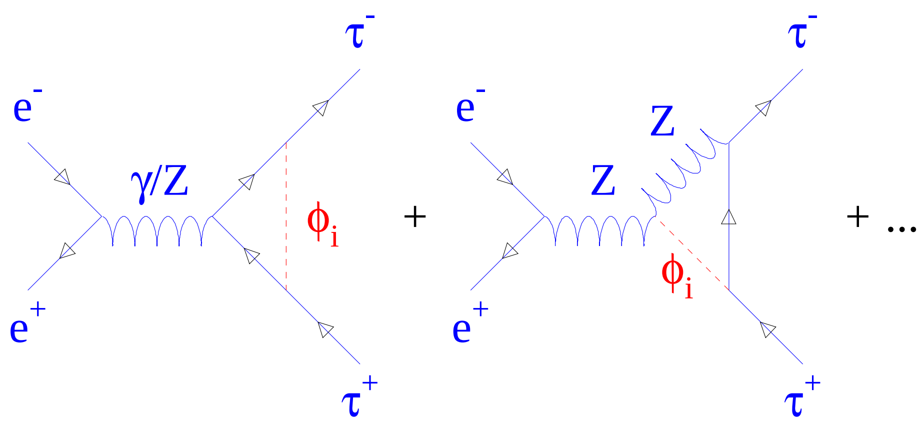
Cabibbo suppression of strange channels offset by mass-dependent coupling for multi-Higgs models

*Requires CPT violation – shown by Tsai, 1996B

Tau Lepton $\not{CP}$ Couplings

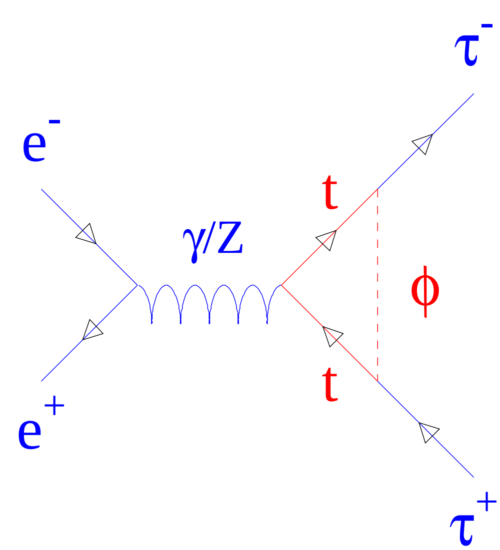
$\not{CP}$ in the tau sector:

- Neutral current processes:
  - Two-Higgs-Doublet models with explicit $\not{CP}$ phase (Bernreuther, Schröder & Pham)



  - Tau-Stau coupling or scalar leptoquarks (Bernreuther, Brandenburg & Overmann, 1997)

Example – Leptoquark loop:



Tau Lepton $\not{C}P$ Couplings

Comparing single τ^- decay to single τ^+ decay...
(correlations in $\tau^-\tau^+$ production discussed below)

- Forward-backward asymmetries and optimal observable in $\tau^- \to \pi^-\pi^+\pi^-$
  (Choi, Hagiwara & Tanabashi, 1994)

- Partial rate asymmetry of $\tau^- \to \pi^-\pi^0\nu_\tau$, $\tau^- \to K \Leftrightarrow \pi^0\nu_\tau$
  (Tsai, 1995)

- μ polarization in τ decay with polarized e^+e^- beams
  (Tsai, 1995)
  Look at
  $$(\vec{w}_{\rm beam} \times \vec{p}_\mu) \cdot \vec{w}_\mu$$
  where $\vec{w}_{\rm beam/\mu}$ = polarization of beam / muon
  Not easy to measure!

- Similar T-odd terms in $\tau \to \nu_\tau + (\geq 2\text{hadrons})$
  with polarized e^+e^- beams (requires $\geq$ 2 final spin states)
  (Tsai, 1996A)

Tau Lepton $\not{C}\not{P}$ Couplings

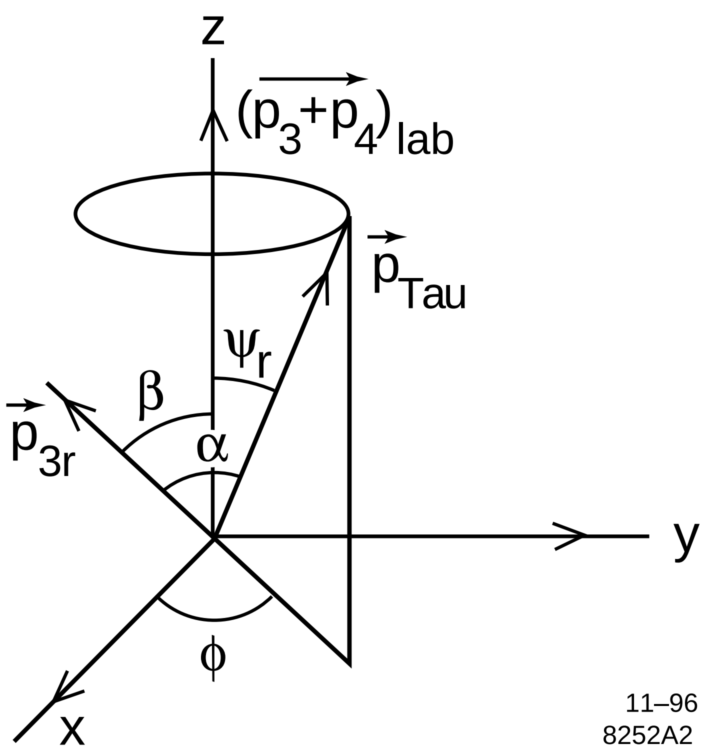
- CP-odd kinematic asymmetries in $\tau^- \to (K\pi)^-\nu_\tau$
  (with and without full τ kinematic reconstruction)
  (Kühn & Mirkes, 1996)

- Enhance $\not{C}\not{P}$ signal in $\tau^- \to (3\pi)^-\nu_\tau$
  with τ polarization (Tsai, 1996A/1998)

Tau Lepton $\not{CP}$ Couplings

Example – $\tau^- \to (K\pi)^- \nu_\tau$
(Tsai, 1996B; based on Kühn & Mirkes, 1996)

Kinematics in K–π rest frame:



where $\vec{p}_3$, $\vec{p}_4 = K, \pi$ momenta and
ψ_r is known even if $\vec{p}_{\rm Tau}$ not reconstructed

Define following observable:

$$O_{\tau^-} \quad \equiv \quad \cos\beta \cos\psi_r$$

Non-KM $\not{CP}$ indicated by differing O_{τ^-}, O_{τ^+} distributions

Tau Lepton $\not\!\!{CP}$ Couplings

Observable O_τ used in search for $\not\!\!{CP}$ by CLEO (1998)

(e^+e^- collisions at $\sqrt{s} = 10.6$ GeV, 4.4×10^6 $\tau^-\tau^+$ events)

- Examined $\tau^\pm \to K^0_s \, \pi^\pm \, \nu_\tau$ events with $K^0_s \to \pi^+\pi^-$
- Defined following asymmetry in bins of O_τ:

$$A \quad \equiv \quad \frac{N^+(\cos\beta \cos\psi_r) \Leftrightarrow N^-(\cos\beta \cos\psi_r)}{N^+(\cos\beta \cos\psi_r) + N^-(\cos\beta \cos\psi_r)}$$

with $N^\pm$ = Number of $\tau^\pm$ decays in $\cos\beta \cos\psi_r$ bin

- Ideally,

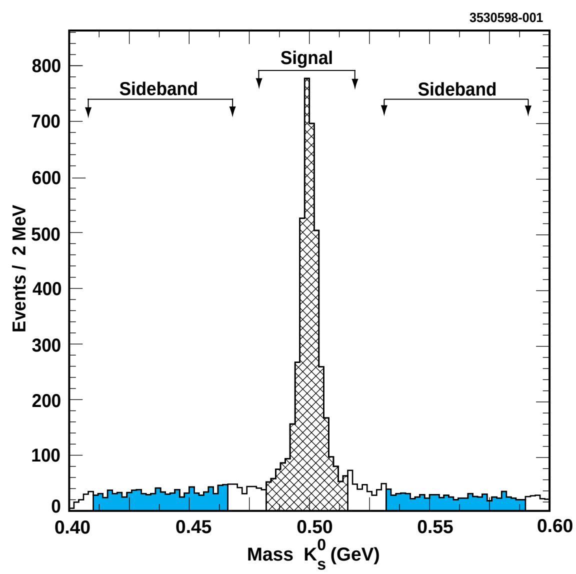
$$A \quad \propto \quad [\cos\beta \cos\psi_r] \, (g \; \sin\theta_{CP})$$

where $g \, e^{i\,\theta_{CP}}$ = scalar/vector coupling strength ratio

($e.g.$, from τ–ν_τ–H^+ vertex)

Tau Lepton $\not{C}\not{P}$ Couplings

- In practice, detector displays "C asymmetry" in $\pi^{\pm}$ reconstruction efficiencies
- To remove fake $\not{C}\not{P}$ due to detector imperfection, carry out sideband subtraction from K_s^0 mass spectrum:



- Raw asymmetries for two bins of $\cos\beta\cos\psi_r$:

	$A_{observed}(\cos\beta\cos\psi < 0)$	$A_{observed}(\cos\beta\cos\psi > 0)$
Signal	0.058±0.023	0.024±0.021
Sideband	0.049±0.030	0.034±0.033

Result:

$$g\sin\theta_{CP} < 1.7 \quad \text{at } 90\% \text{ C.L.}$$

Tau Lepton $\not{C}\not{P}$ Couplings

$\not{C}\not{P}$ easier to see in $\tau^+\tau^-$ production

Again, parametrize as multipole moment form factors

Focus on electromagnetic and neutral weak dipole moments:
(parametrization & notation used by LEP experiments)

- Anomalous magnetic moment $a_\tau^{\gamma,Z}$
  (dimensionless, CP-even; SM(γ, Z): $O(10^{-3})$, $O(10^{-6})$)
- Electric dipole moment $d_\tau^{\gamma,Z}$
  (dimensional, $\not{C}\not{P}$; SM: $O(10^{-37}$ e-cm$)$)

Effective Lagrangian terms:

$$\mathcal{L}^{eff}_{\tau\tau V} = \sum_V [-\frac{i}{2} d_\tau^V \bar{\tau} \sigma^{\mu\nu}\gamma_5 \tau \, {}^{(v)}F_{\mu\nu} + \frac{1}{2} \frac{e\, a_\tau^V}{2\, m_\tau} \bar{\tau} \sigma^{\mu\nu} \tau \, {}^{(v)}F_{\mu\nu}]$$

Tau Lepton $\not{C}\not{P}$ Couplings

Looking for $\not{C}\not{P}$ in $\tau^-\tau^+$ production (a sampling)
(some techniques automatically probe $\not{C}\not{P}$ in τ decay too)

- Deviation from S.M. in $,_{Z\to\tau^+\tau^-}$
  (Bernreuther & Nachtmann, 1989)

- Manifestly CP-odd observables
  Correlation Tensor:

$$\hat{T}_{ij} \quad \equiv \quad (\hat{q}_+ \Leftrightarrow \hat{q}_-)_i \frac{(\hat{q}_+ \times \hat{q}_-)_j}{|\hat{q}_+ \times \hat{q}_-|} \; + \; (i \Leftrightarrow j)$$

  where $\hat{q}_+$, $\hat{q}_-$ = unit vectors along τ daughter momenta
  ($e.g.$, π^+, e^- in $e^+e^- \to \tau^+\tau^- \to \pi^+\bar{\nu}_\tau e^-\bar{\nu}_e\nu_\tau$)
  (Bernreuther & Nachtmann, 1989)

- Optimal observables
  (Atwood & Soni, 1992, see also review by Wermes, 1996)

$$O^{\Re} \quad \equiv \quad \frac{M^{\Re}_{CP}}{M_{SM}}; \qquad O^{\Im} \quad \equiv \quad \frac{M^{\Im}_{CP}}{M_{SM}};$$

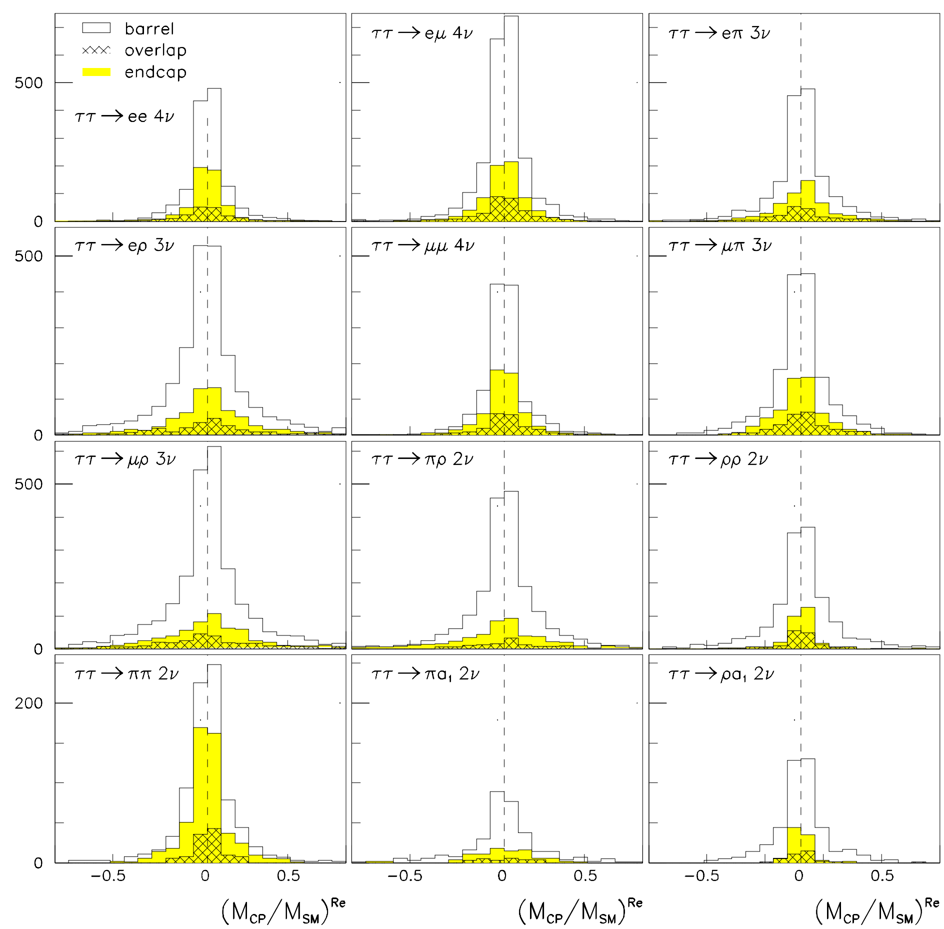
- Photon kinematics in $e^+e^- \to \tau^+\tau^-\gamma$
  (probes d^γ_τ, a^γ_τ at $q^2 = 0$)

Tau Lepton ~~CP~~ Couplings

Example from OPAL (1994):

- Looked at optimal observables derived from $\tau^+\tau^-$ daughter momenta from variety of decay topologies
- Must worry about "CP symmetry" of detector
  - Biggest worry: twisted tracking chamber
  - Nailed down with $e^+e^- \rightarrow \mu^+\mu^-$ events
  - Other detector asymmetries checked with event mixing

Sample of CP-odd observable distributions:



Tau Lepton $\not{C}\not{P}$ Couplings

$\not{C}\not{P}$ results from full LEP data samples

Deviation in , $_{Z\to\tau^+\tau^-}$:

- $|d_\tau^Z| < 1.8 \times 10^{-17}$ e-cm   Wermes review, 1996
- $|d_\tau^\gamma| < 1.1 \times 10^{-17}$ e-cm   Escribano & Massó, 1996

Analyses of optimal observables in $e^+e^- \to \tau^+\tau^-$events:

- $\Re\{d_\tau^Z\} = (-0.29 \pm 2.59 \pm 0.88) \times 10^{-18}$ e-cm   ALEPH
- $\Re\{d_\tau^Z\} = (-1.48 \pm 2.64 \pm 0.27) \times 10^{-18}$ e-cm
  $\Im\{d_\tau^Z\} = (-0.44 \pm 0.77 \pm 0.13) \times 10^{-17}$ e-cm   DELPHI
- $\Re\{d_\tau^Z\} = (0.72 \pm 2.46 \pm 0.24) \times 10^{-18}$ e-cm
  $\Im\{d_\tau^Z\} = (0.35 \pm 0.57 \pm 0.08) \times 10^{-17}$ e-cm   OPAL
- $|\Re\{d_\tau^Z\}| < 3.6 \times 10^{-18}$ e-cm
  $|\Im\{d_\tau^Z\}| < 1.1 \times 10^{-17}$ e-cm   Wermes review, 1996

Analysis of $e^+e^- \to \tau^+\tau^-\gamma$ events:

- $|d_\tau^\gamma| < 3.1 \times 10^{-16}$ e-cm   L3 1998

Tau Lepton ~~CP~~ Couplings

Other determinations of anomalous τ couplings

- Analysis of azimuthal angular asymmetries in $e^+e^- \to \tau^+\tau^- \to h^-h^+\nu_\tau\bar{\nu}_\tau$ L3, 1998

$$|\Re\{a_\tau^Z\}| < 4.5 \times 10^{-3} \qquad |\Im\{a_\tau^Z\}| < 9.9 \times 10^{-3}$$

(same analysis gives weak limits on $|\Re\{d_\tau^Z\}|$)

- Measurements of Michel parameters and ν_τ helicity from LEP, SLD and CLEO

- Limits on charged-current magnetic / electric dipole moment form factors from
  - τ lifetime and lepton energy spectrum E_ℓ in $\tau \to \ell\nu\bar{\nu}$ (Rizzo, 1997)
  - Apparent τ polarization in $\tau \to \pi\pi^0\nu_\tau$ and $B(\tau \to \pi\pi^0\nu_\tau)$ (Dova *et al.*, 1999)

Tau Lepton $\not{C}\not{P}$ Couplings

Summary on top and tau $\not{C}\not{P}$ couplings

- Third generation fermions especially interesting because of possible anomalous couplings from Higgs
- Detecting direct $\not{C}\not{P}$ in top, tau decays difficult
- Detecting $\not{C}\not{P}$ in neutral couplings easier, especially at e^+e^- colliders
- Much work already carried out in τ physics with no hint of signal (LEP, SLD & CLEO)
- Verifying "Standard Model" leptonic $\not{C}\not{P}$ not likely in forseeable future

My prejudice:

$\not{C}\not{P}$ will be seen in top couplings at LHC or NLC before gauge boson or tau effects are seen