Measurement of Electroweak Gauge Boson Self-couplings at LEP

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- **Introduction to Triple Gauge Couplings (TGC)**
- **Charged Current TGC**
- **Neutral Current TGC**
- **Summary**

Triple Gauge Couplings

The Standard Model predicts self-couplings of electroweak gauge bosons

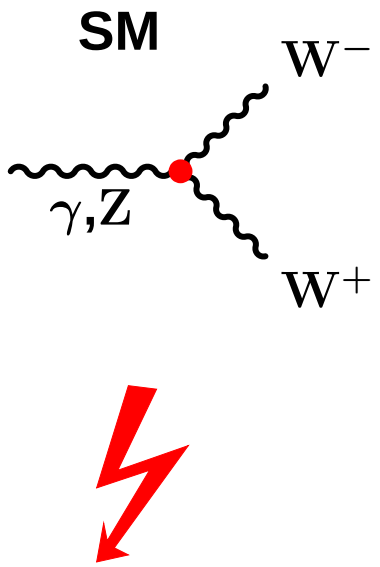
non-Abelian structure

charged

$W^+W^-\gamma$, W^+W^-Z

neutral

$Z\gamma\gamma$, $ZZ\gamma$, ZZZ



The study of gauge self-couplings:

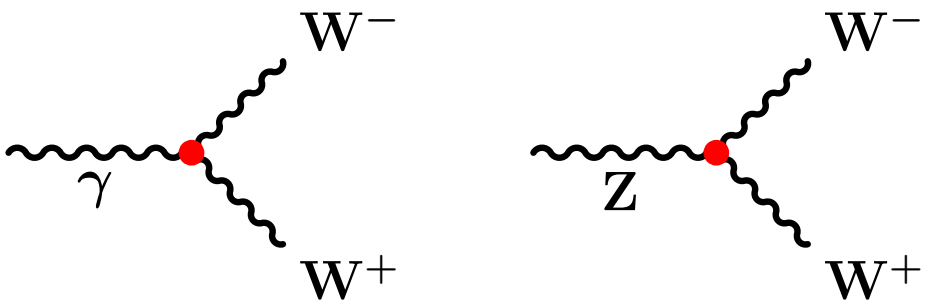
- **test the electroweak sector of the SM**
- **probe for new physics (new particles/coupling structure)**

→ **modify existing couplings**
→ **introduce non-SM couplings**

} **anomalous couplings**

Charge Current TGCs

Describe vertex by effective Lagrangian:



7 parameters **7 parameters**

[Hagiwara et al., Nucl.Phys.B282(1987)253]

	g_1^V	κ_V	λ_V	g_5^V	g_4^V	$\tilde{\kappa}_V$	$\tilde{\lambda}_V$
C	+	+	+	-	-	+	+
P	+	+	+	-	+	-	-
SM	1	1	0	0	0	0	0

$V = \gamma, \mathrm{Z}$

At LEP restricted to:

→ C and P invariance

→ $\mathrm{U}(1)_Q$ invariance

→ $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ invariance

→ $g_1^Z, \kappa_\gamma, \lambda_\gamma$

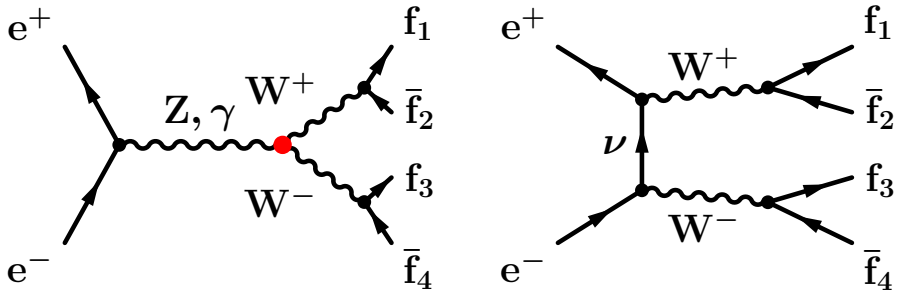
$$g_1^\gamma = 1$$
$$\kappa_Z = (1 - \kappa_\gamma)\tan\theta_w + g_1^Z$$
$$\lambda_Z = \lambda_\gamma$$

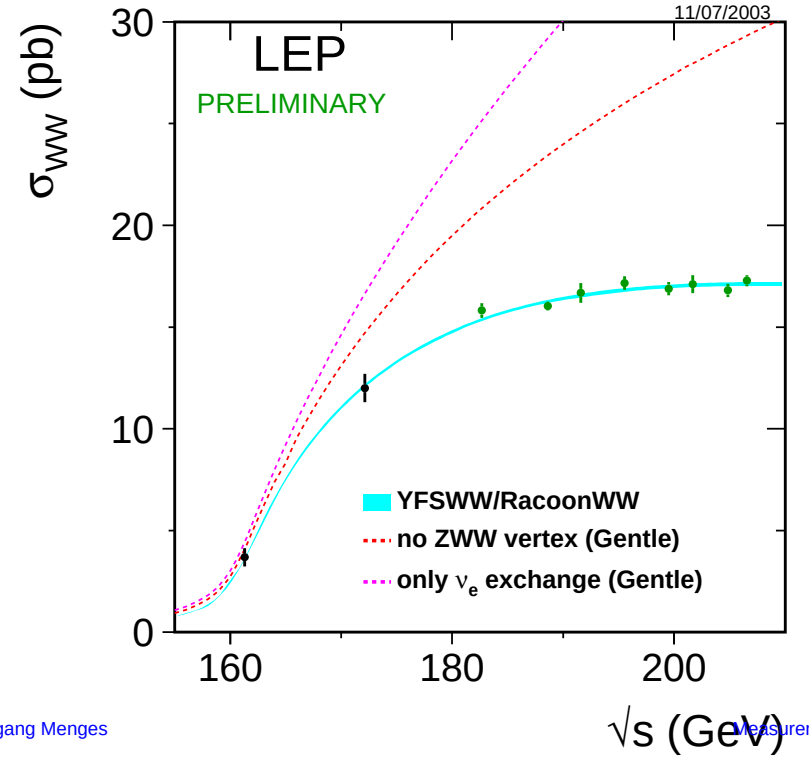
Three processes involve TGC:

- W-pair production
- single W production
- single γ production

W-Pair Production

$e^+e^- \to W^+W^-$ (CC03)



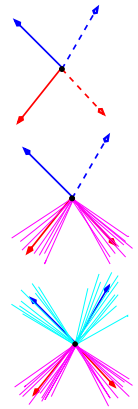


sensitive to g_1^Z, κ_γ, λ_γ

- **cross-section sensitive**
- **diff distributions more sensitive**

W-pair decays

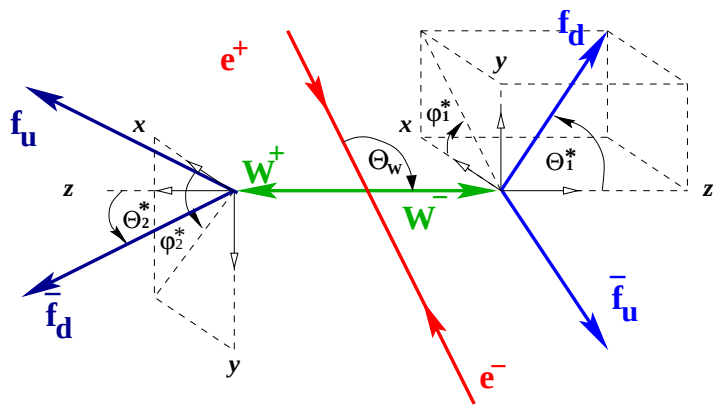
- **leptonic (10.5%)**
  $W^+W^- \to \ell\bar{\nu}_\ell\ell'\nu_{\ell'}$
- **semileptonic (43.9%)**
  $W^+W^- \to q\bar{q}\ell\bar{\nu}_\ell$
- **hadronic (45.6%)**
  $W^+W^- \to q\bar{q}q\bar{q}$



➡ **decays have different sensitivity**

W Pair Decay

kinematic variables: 5 angles



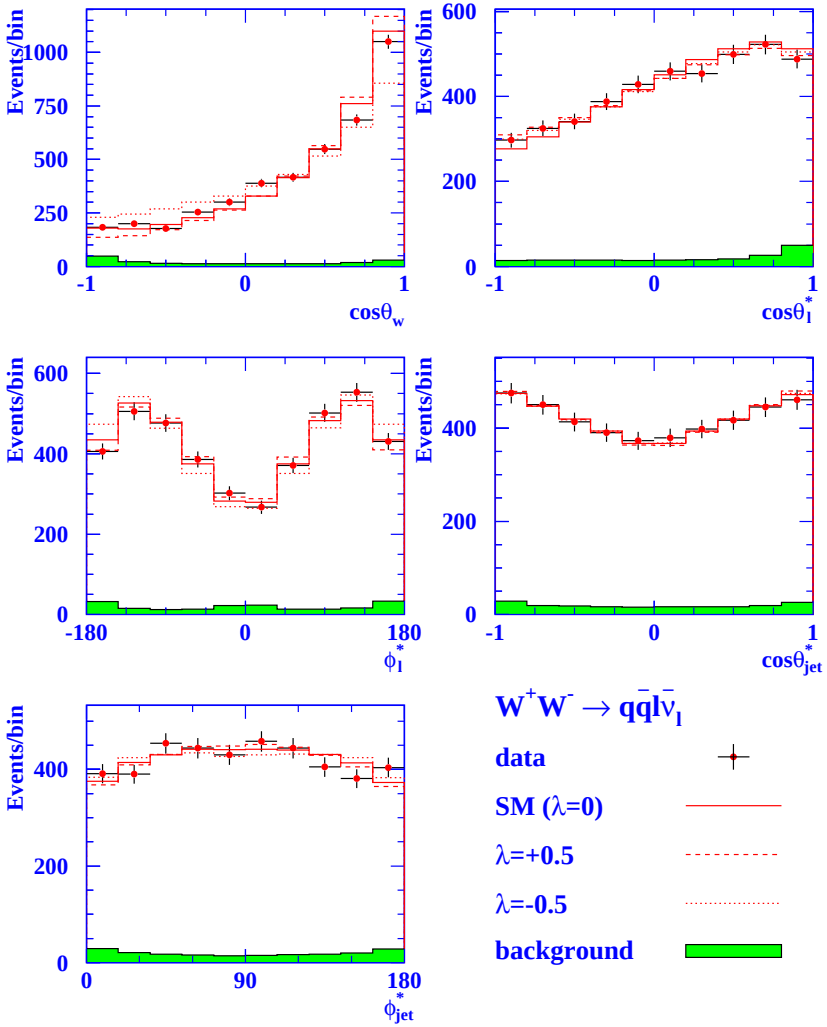
- most information in $\cos\theta_W$
- no flavour tagging
- jet pairing and W charge tagging in $W^+W^- \to q\bar{q}q\bar{q}$ is $\sim 80\%$

differential distributions:

→ angular distribution (up to 5)

→ optimal observables

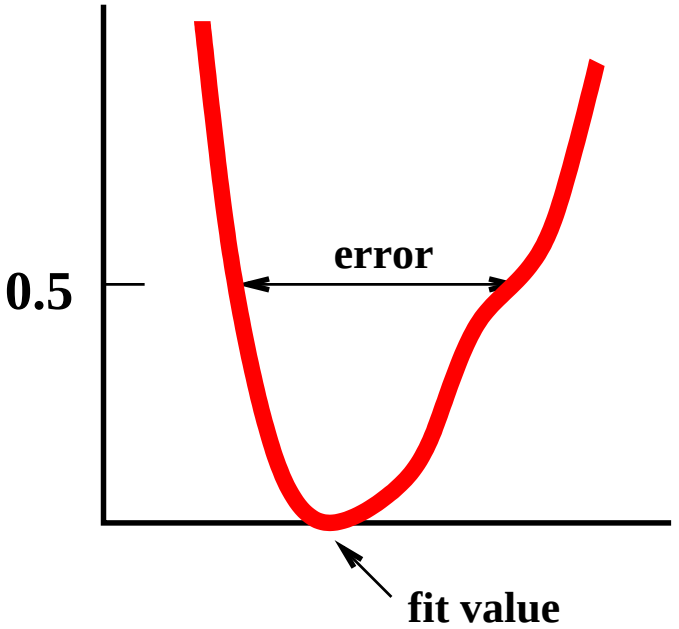
OPAL 183 – 209 GeV



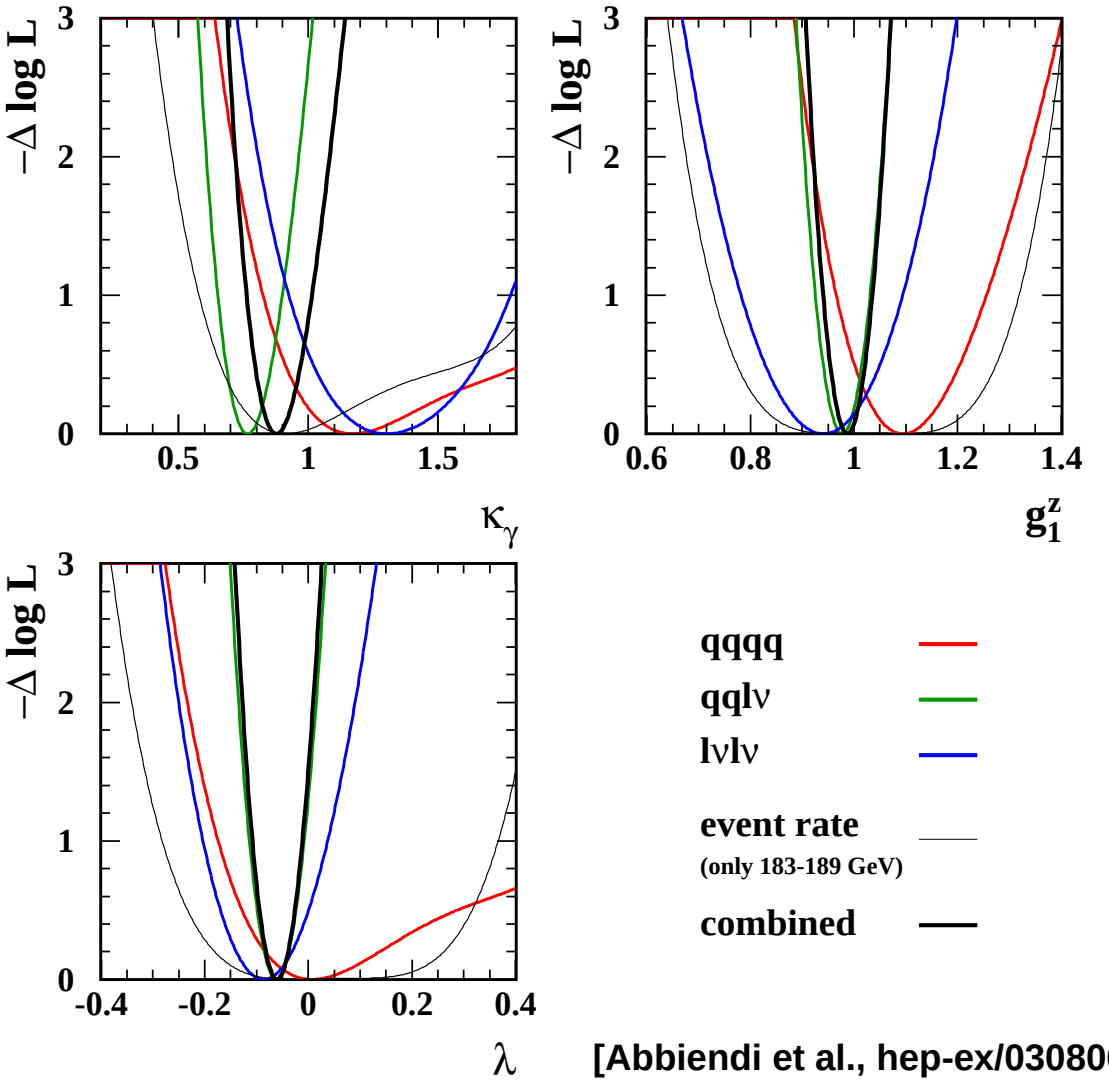
[Abbiendi et al., hep-ex/0308067]

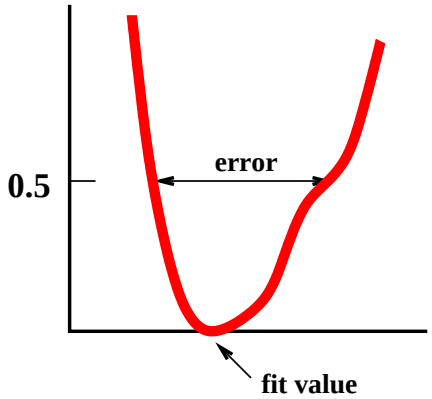
Sensitivity of the W Decays

Likelihood function



Sensitivity of the W Decays





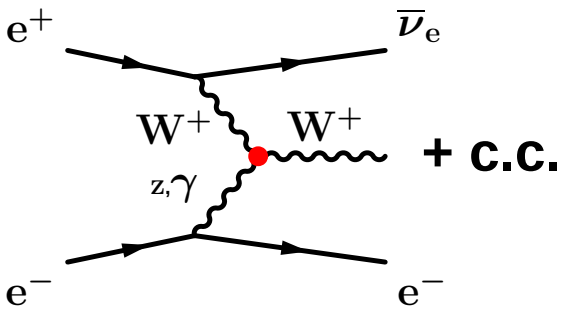
W-pair decays
OPAL 183 - 209 GeV

→ $q\bar{q}\ell\bar{\nu}_\ell$ **highest sensitivity**

→ **cross-section needed for excluding large couplings**

[Abbiendi et al., hep-ex/0308067]

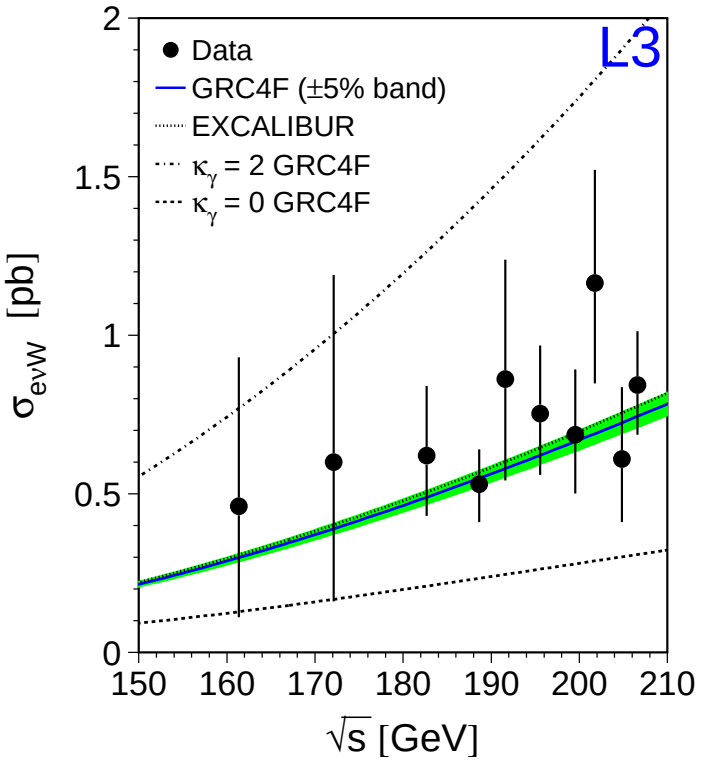
Single W & Single γ Production



single W

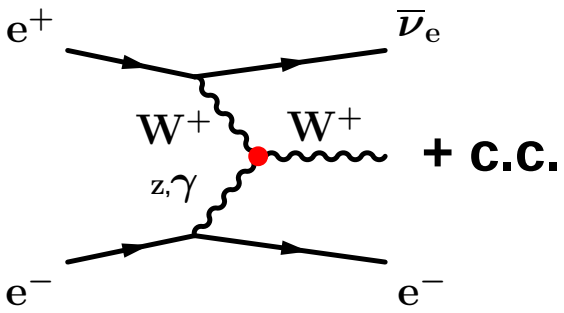
mainly sensitive to κ_γ & λ_γ

- **total cross-section**
- **diff distributions**
  - → $q\bar{q}e\bar{\nu}_e$: jet angle, p_t
  - → $\ell\bar{\nu}_\ell e\bar{\nu}_e$: E_ℓ, $\cos\theta_\ell$, P_t^ℓ



[Achard et al., Phy.Lett.B547 (2002) 151]

Single W & Single γ Production



single W

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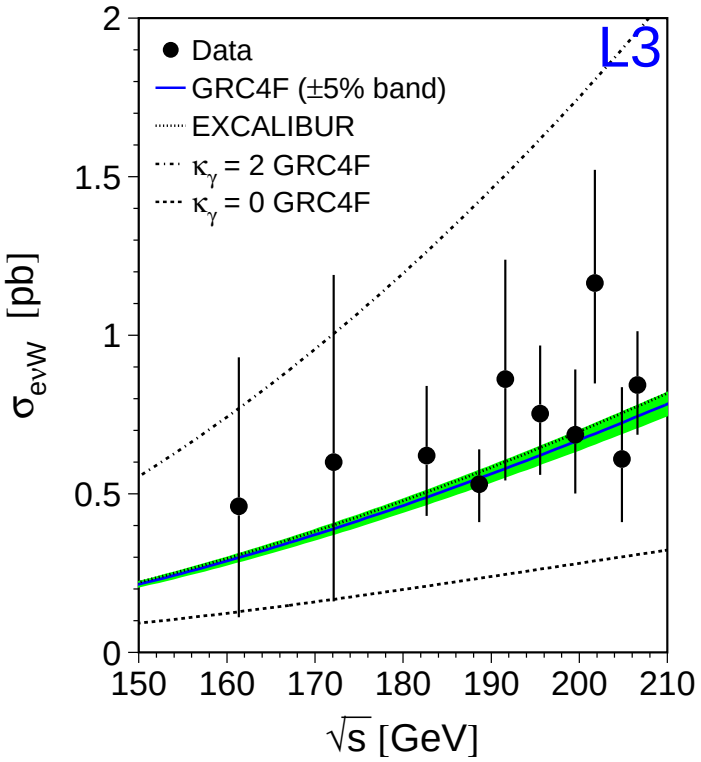

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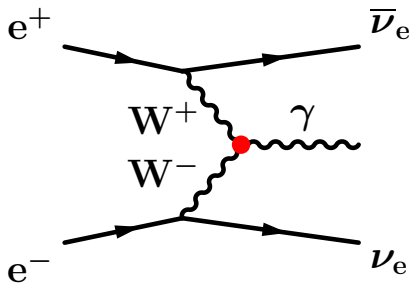


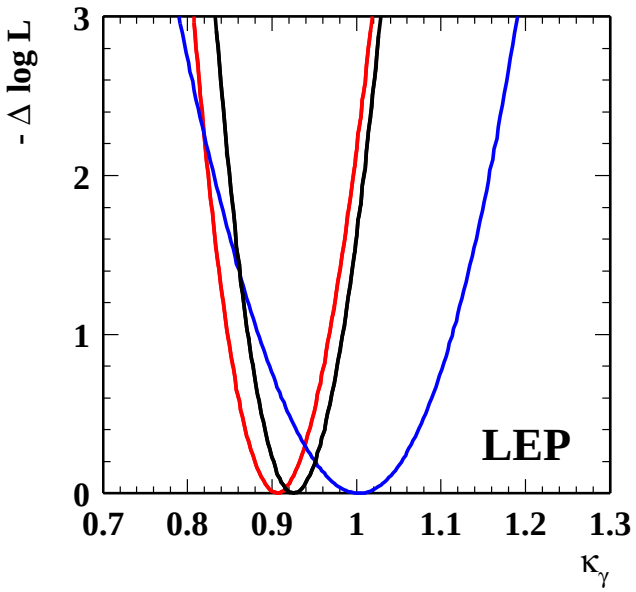
single γ

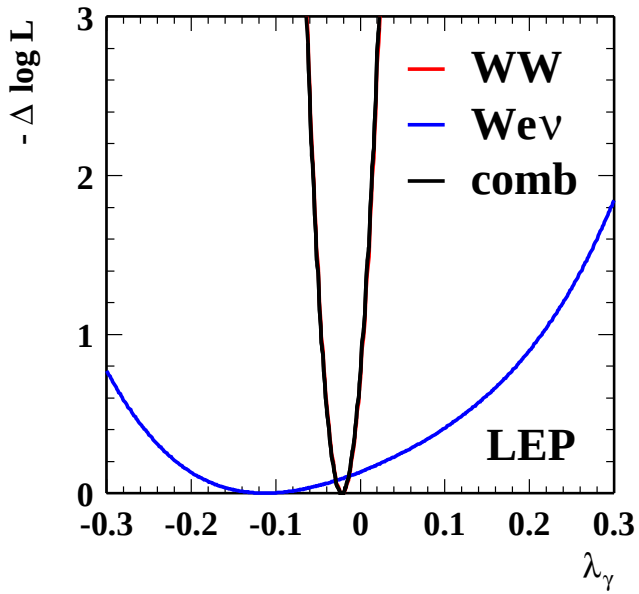
sensitive to κ_γ & λ_γ

- **simple topology → high efficiency**
- **low rate → low sensitivity**

- **total cross-section**
- **differential distributions:**
  - → E_γ, $\cos\theta_\gamma$

Qualitative Sensitivity Comparision





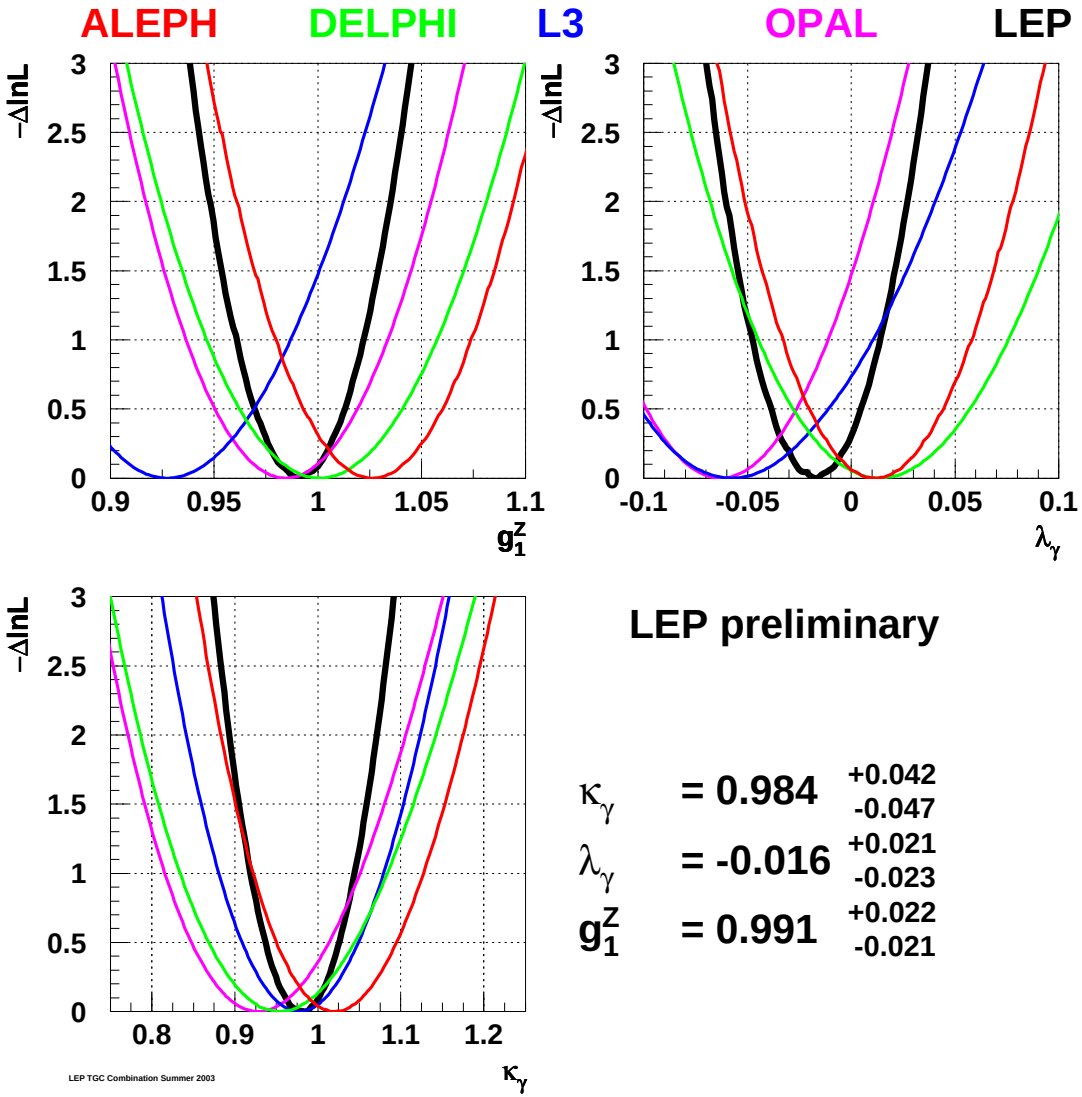
LEP combination

- **W pair results combined**
- **single W results combined**
- **single γ results not shown**

→ W pairs highest sensitivity

→ single W has small impact but good cross check

LEP Combination



LEP preliminary

$\kappa_\gamma = 0.984\ ^{+0.042}_{-0.047}$

$\lambda_\gamma = -0.016\ ^{+0.021}_{-0.023}$

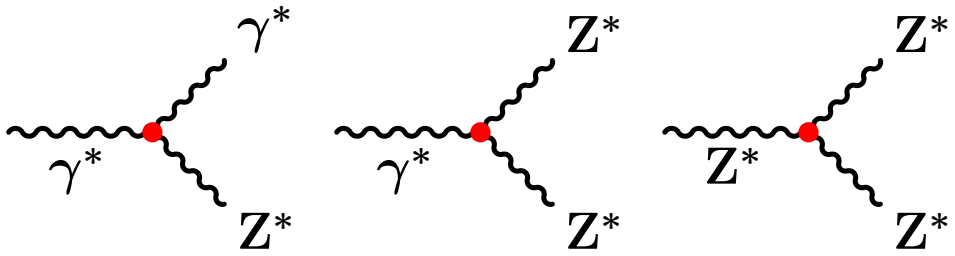
$g_1^Z = 0.991\ ^{+0.022}_{-0.021}$

Only one free parameter
Others fixed at SM values

- **experimental proof of triple gauge couplings**
- **consistent with the Standard Model**
- **sensitive to radiative corrections** $(\sim 10^{-2})$
- $\mathcal{O}(\alpha)$ **radiative corrections from YFSWW & RacoonWW**

Neutral Current TGCs

The electroweak gauge structure prohibits neutral triple gauge couplings at tree level.



[Gounaris et al., Phys.Rev.D62:073013,2000]

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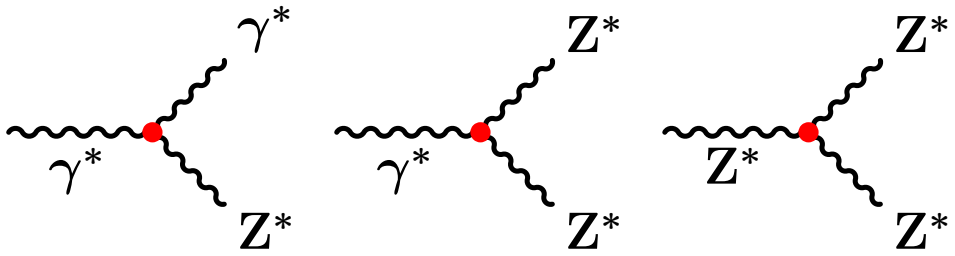

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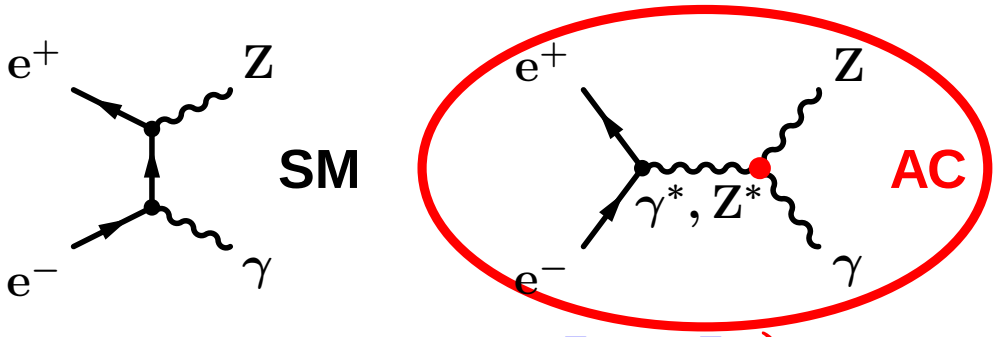
$e^+e^- \to Z\gamma$



CP violating: $h_1^{\gamma,Z}$, $h_2^{\gamma,Z}$

CP conserving: $h_3^{\gamma,Z}$, $h_4^{\gamma,Z}$

} 8

SM: $h_i^{\gamma,Z} = 0$ **loop:** $h_i^{\gamma,Z} \sim 10^{-4}$

Neutral Current TGCs

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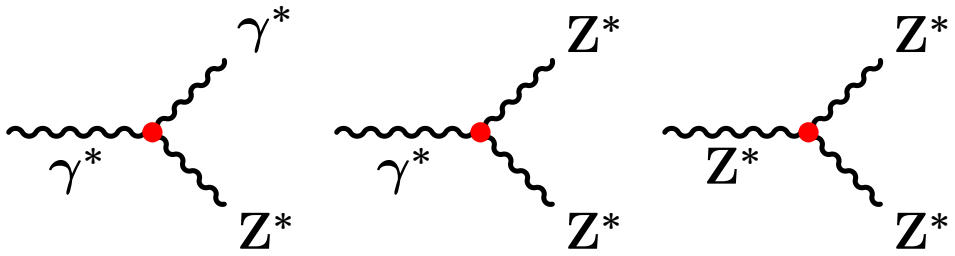

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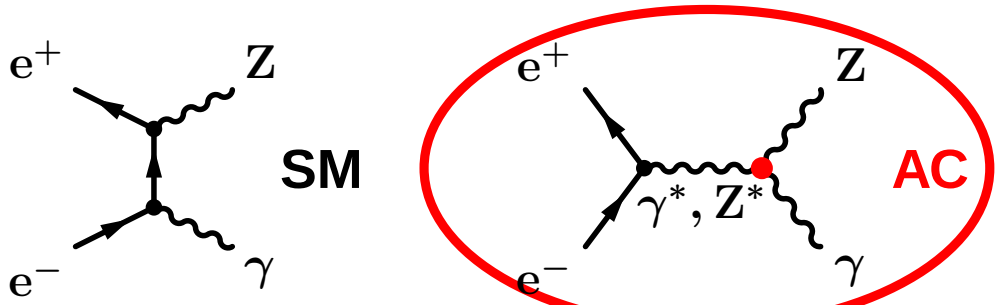

CP violating: $h_1^{\gamma,Z}$, $h_2^{\gamma,Z}$

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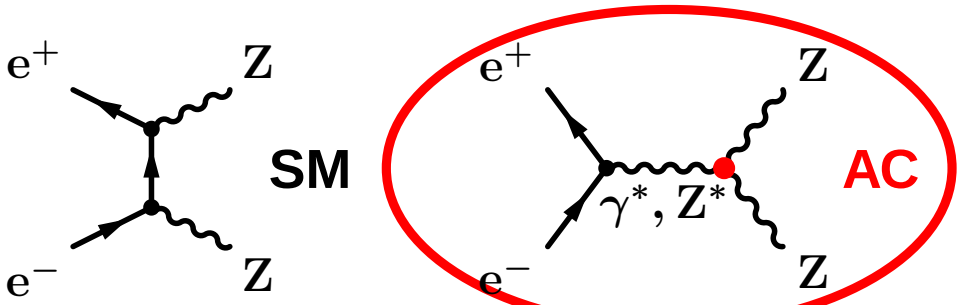
$e^+e^- \to ZZ$

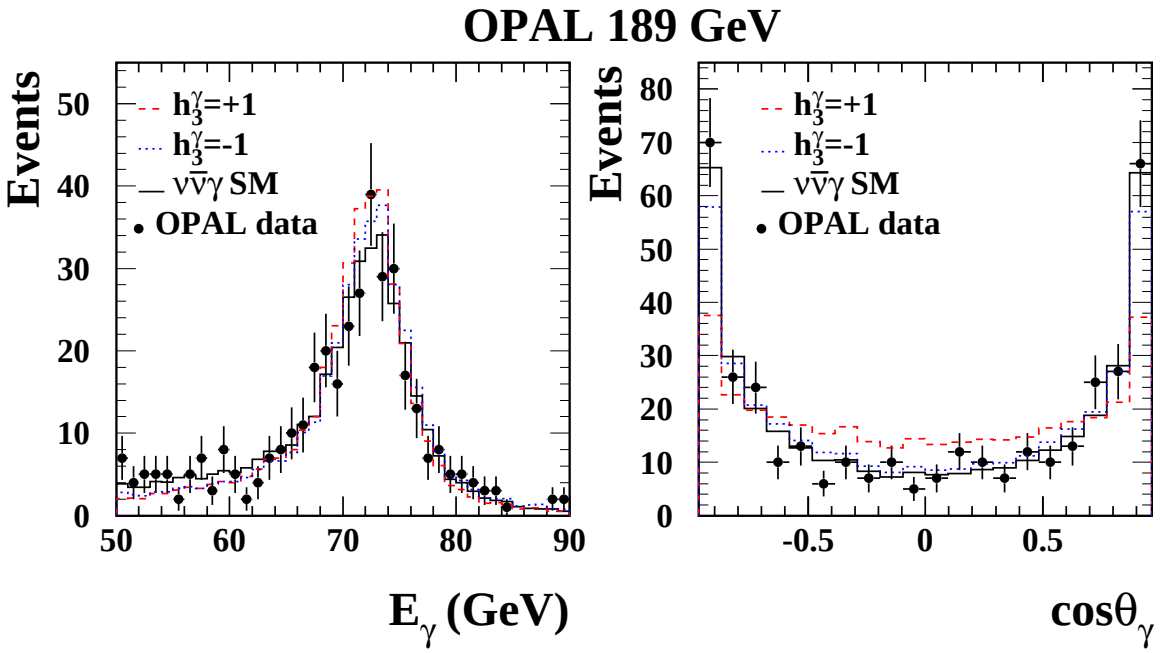


CP violating: $f_4^{\gamma,Z}$

CP conserving: $f_5^{\gamma,Z}$ } 4

SM: $h_i^{\gamma,Z} = 0$ **loop:** $h_i^{\gamma,Z} \sim 10^{-4}$ **SM:** $f_i^{\gamma,Z} = 0$ **loop:** $f_i^{\gamma,Z} \sim 10^{-4}$

$e^+e^- \to \gamma^*/Z^* \to \nu\bar{\nu}\gamma$



[Abbiendi et al., Eur.Phys.J. C17 (2000) 553]

- total cross-section
- differential distributions
  - → $|\cos\theta_\gamma|$, E_γ, $\alpha(\gamma, \text{jet})$
  - → optimal observables

LEP combined results Summer03 (95% CL)

$\gamma^*Z\gamma$

h_1^γ	$[-0.056; +0.055]$
h_2^γ	$[-0.045; +0.025]$
h_3^γ	$[-0.049; -0.008]$
h_4^γ	$[-0.002; +0.034]$

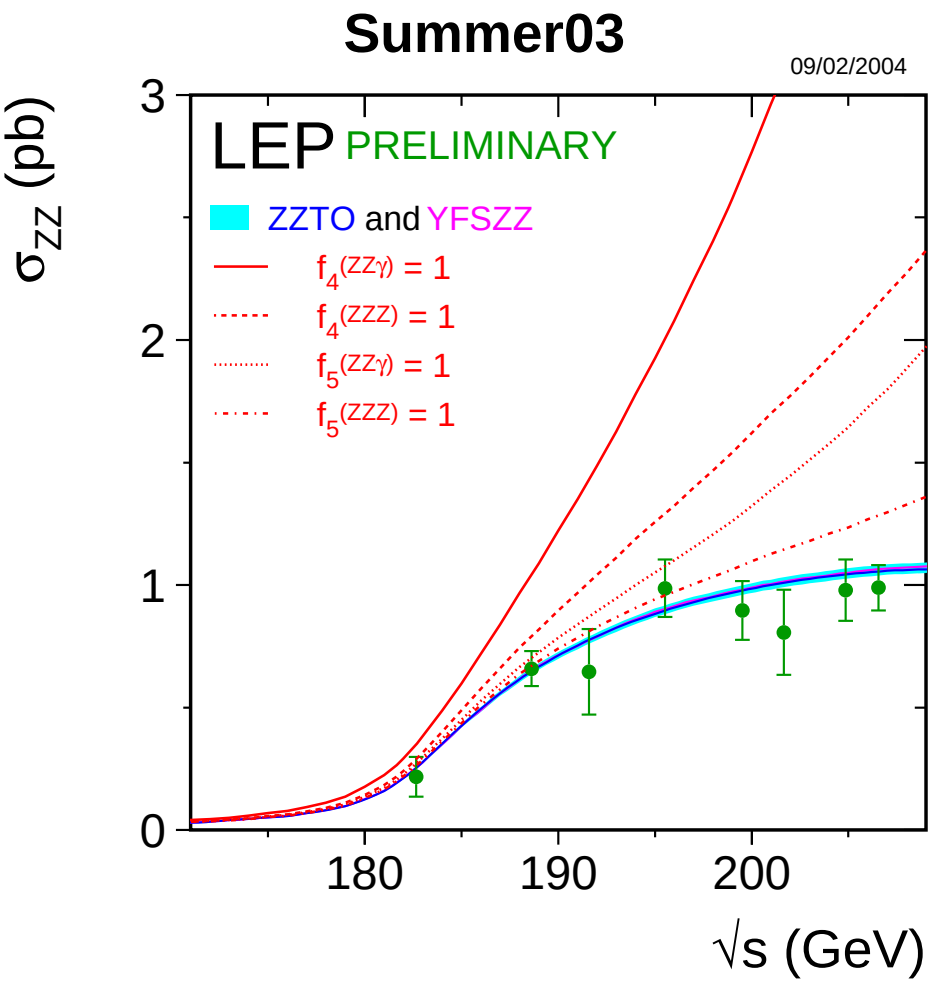
$Z^*Z\gamma$

h_1^Z	$[-0.13; +0.13]$
h_2^Z	$[-0.08; +0.07]$
h_3^Z	$[-0.20; +0.07]$
h_4^Z	$[-0.05; +0.12]$

- **total cross-section**
- **differential distributions**
  - → $|\cos\theta_Z|$
  - → **optimal observables**

LEP combined results (95% CL)

γ^*ZZ	f_4^γ	$[-0.17; +0.19]$
	f_5^γ	$[-0.32; +0.36]$
Z^*ZZ	f_4^Z	$[-0.30; +0.30]$
	f_5^Z	$[-0.34; +0.38]$



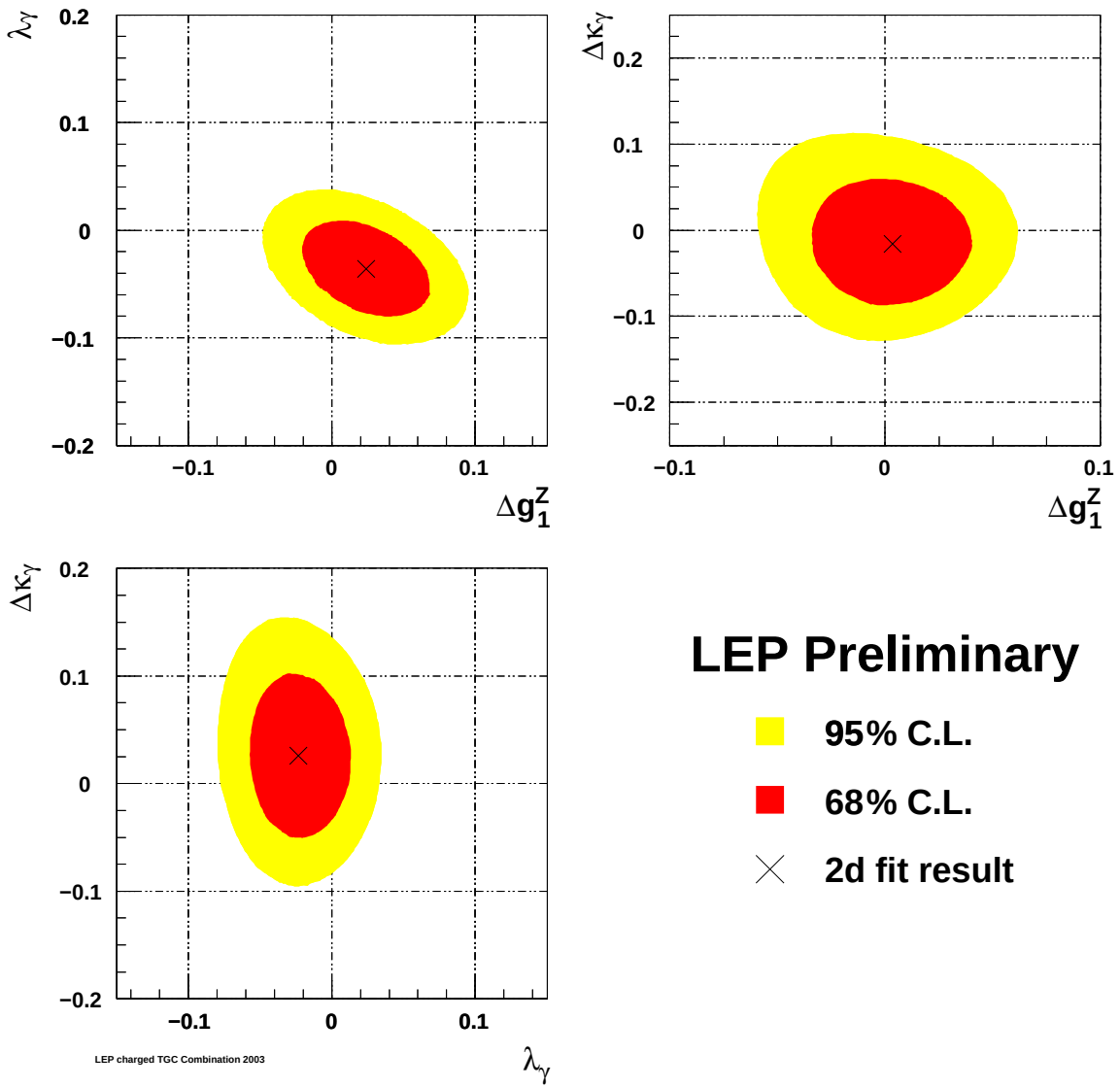
Summary

- **the SM predicts charged TGC but prohibits neutral TGC**

- **all four LEP experiments have measured charged TGC in W-pair, single W and single γ production**
  - **→ results show good agreement with SM expectations**
  - **→ proof of non-Abelian gauge structure of electroweak sector**

- **all four LEP experiments have searched for neutral TGC in $\mathrm{Z}\gamma$ and ZZ production**
  - **→ results show good agreement with SM expectations**
  - **→ no neutral TGC were found**

LEP Combination - 2D Results



LEP Preliminary

- 95% C.L.
- 68% C.L.
- 2d fit result

- **Two parameters are free**
- **Third parameters fixed at SM**

$$g_1^Z = +1.024^{+0.029}_{-0.029}$$
$$\lambda_\gamma = -0.036^{+0.029}_{-0.029}$$

$$g_1^Z = +1.004^{+0.024}_{-0.025}$$
$$\kappa_\gamma = +0.984^{+0.049}_{-0.049}$$

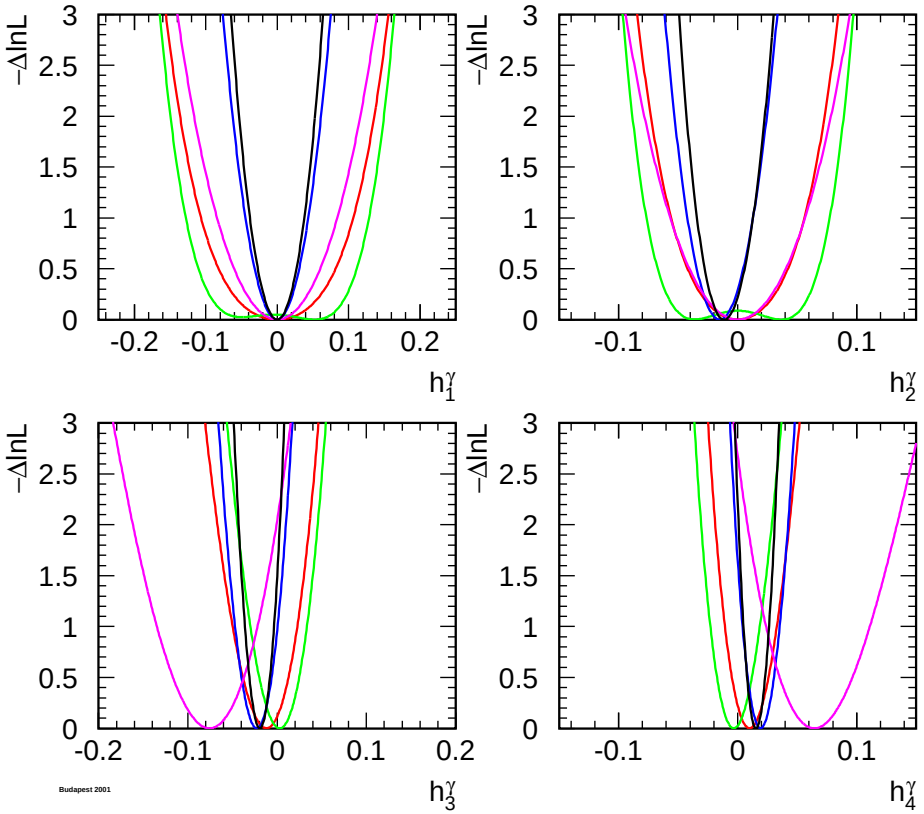
$$\lambda_\gamma = -0.024^{+0.025}_{-0.021}$$
$$\kappa_\gamma = +1.026^{+0.048}_{-0.051}$$

$e^+e^- \to Z\gamma$ - *1D Fits*

$\gamma^*Z\gamma$

Preliminary

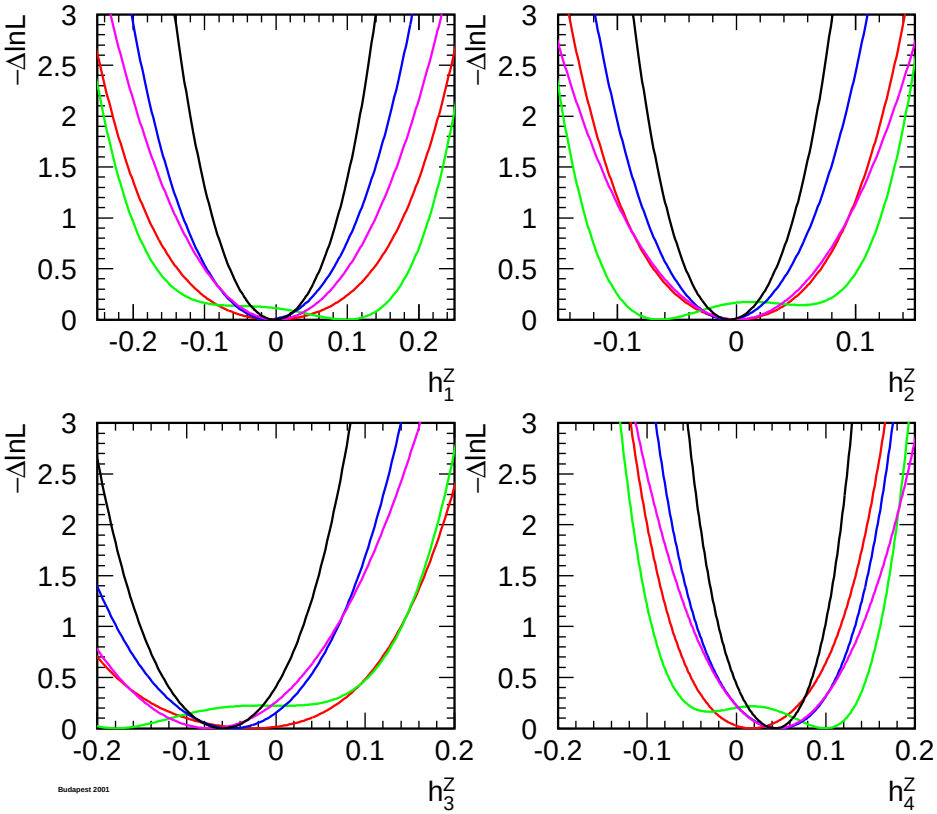
LEP ALEPH+DELPHI+ L3+OPAL



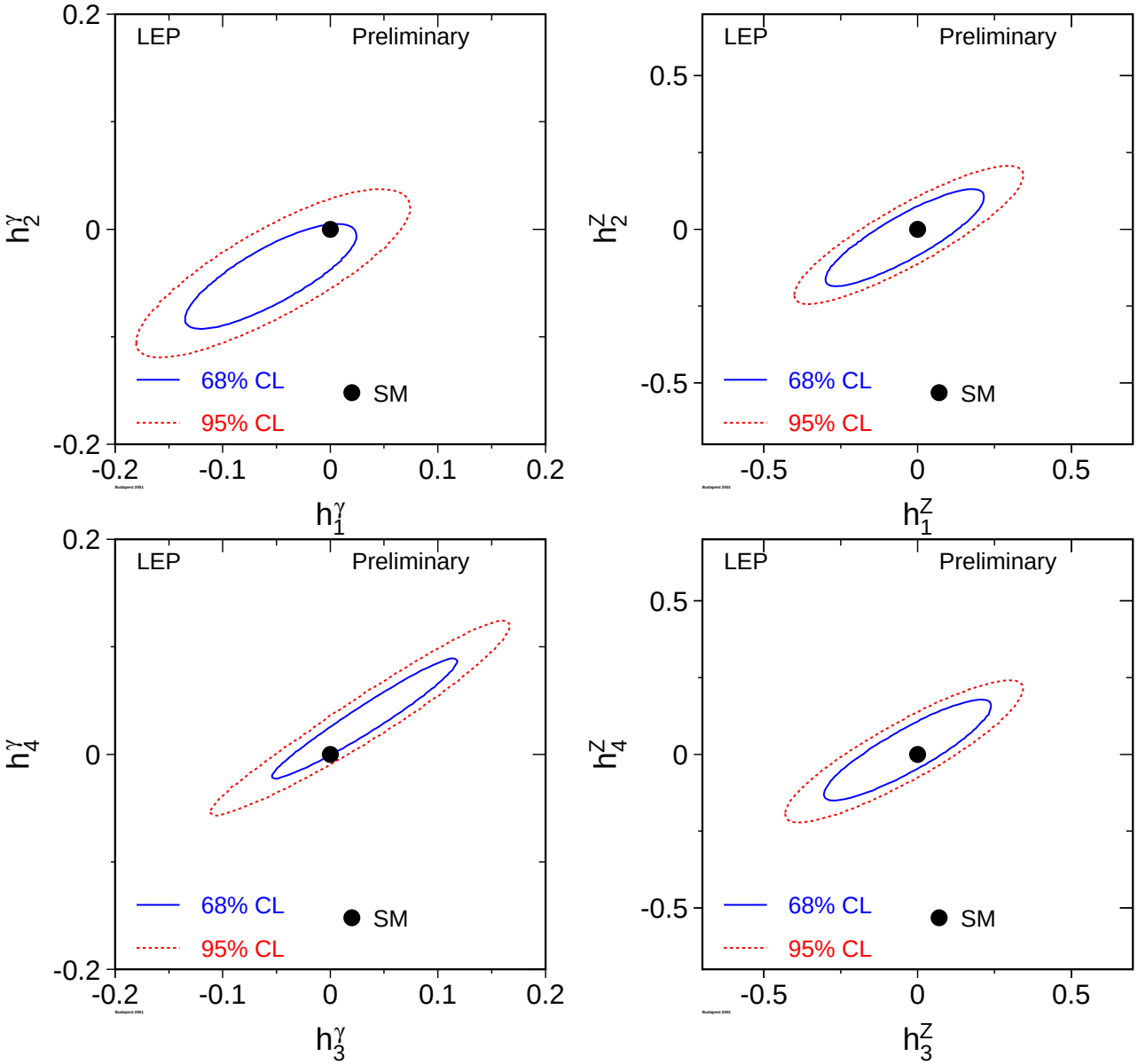
$Z^*Z\gamma$

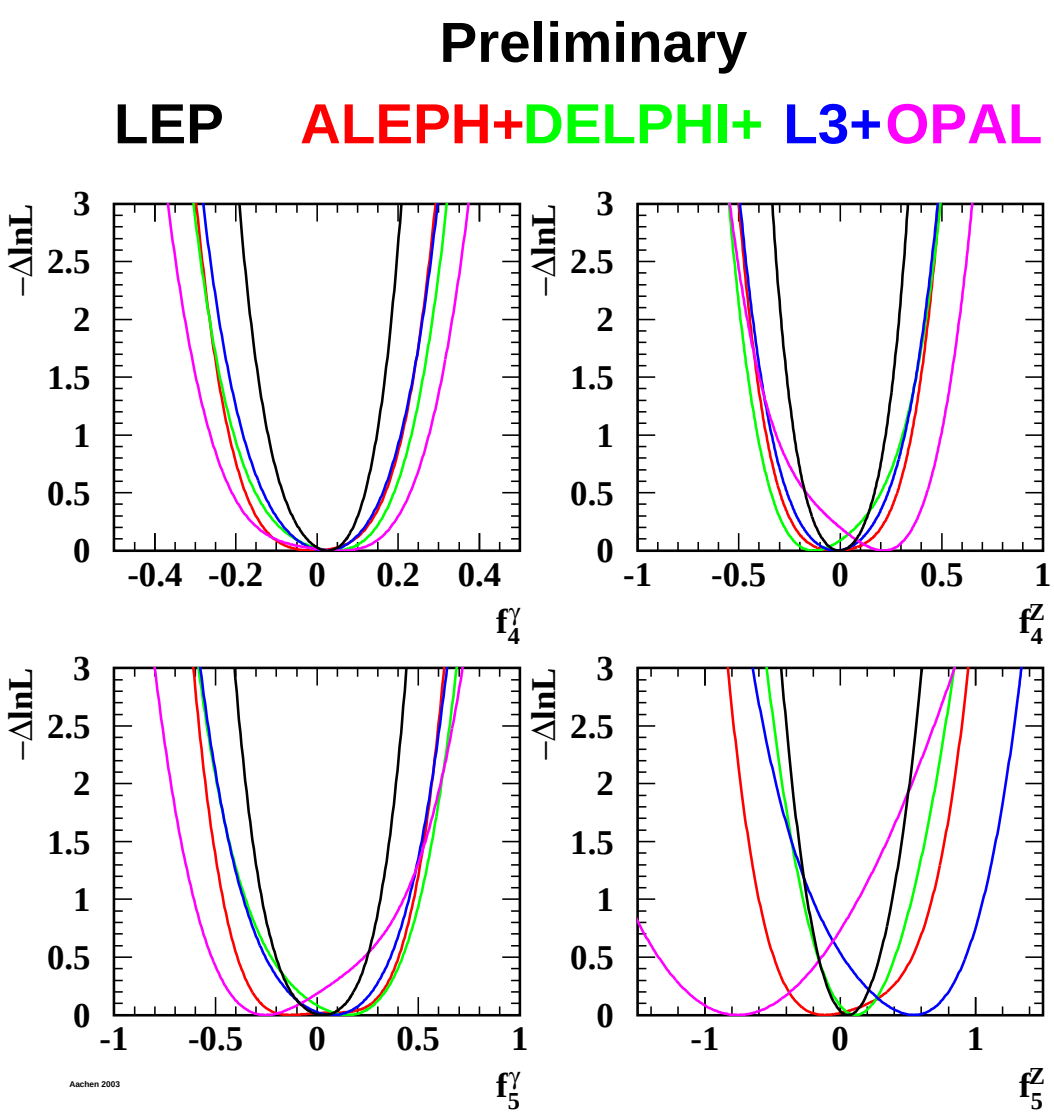
Preliminary

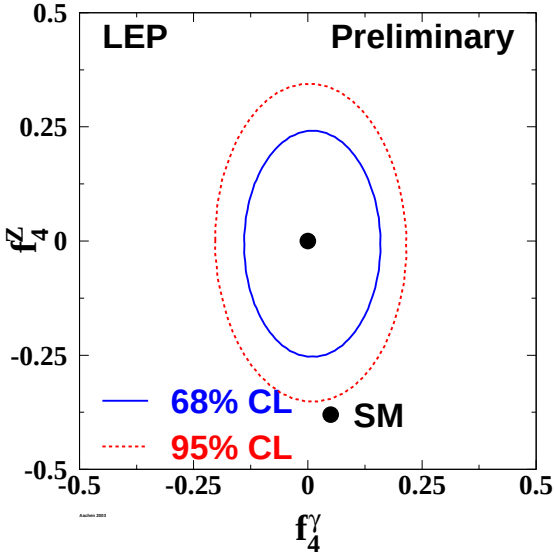
LEP ALEPH+DELPHI+ L3+OPAL

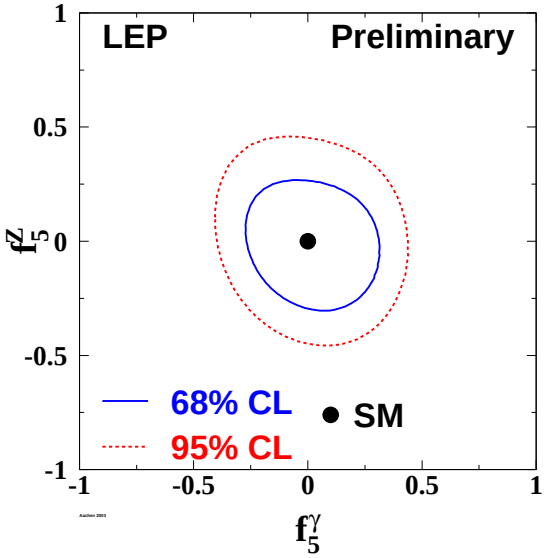


$e^+e^- \to Z\gamma$ - *2D Fits*




Preliminary
LEP ALEPH+DELPHI+ L3+OPAL
−ΔlnL
f_4^γ
f_4^Z
f_5^γ
f_5^Z
Aachen 2003


LEP
Preliminary
68% CL
95% CL
SM
f_4^Z
f_4^γ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