$\sigma_{WW\gamma}$ and First Direct Limits on Anomalous QGCs

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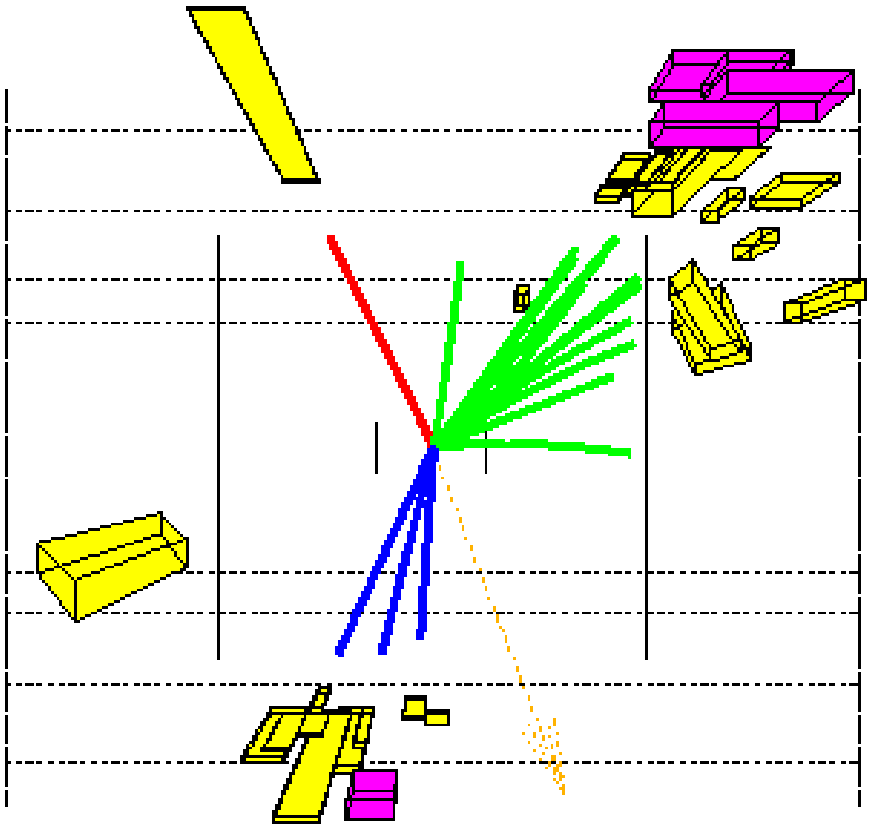
CERN



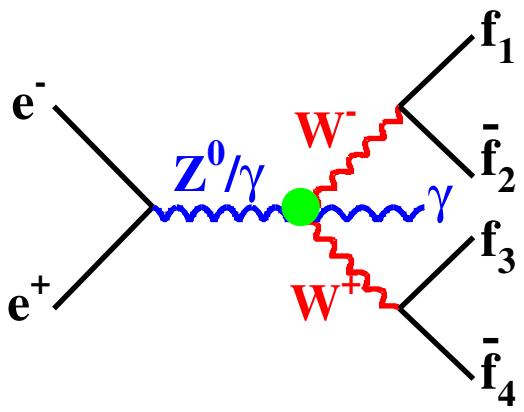
- OPAL analysis of $\sim 183\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 189\,\mathrm{GeV}$

Introduction

★ First look at $e^+e^- \to W^+W^-\gamma$

★ Sensitive to new Physics ?

★ Results expressed in terms of possible Anomalous Quartic Gauge Couplings (QGCs)



★ Currently no Direct limits on Anom QGCs

★ Indirect limits from precise Z^0 data

Monte Carlo/Calculations

- **EEWWG (Stirling and Werthenbach):**
  $W^+W^-\gamma$ Calculation including Anomalous QGCs
- **WWF (van Oldenborgh *et al*):**
  Exact $O(\alpha)$ $W^+W^-\gamma$ Monte Carlo
- **KoralW (Skrzypek *et al*):**
  "Standard" LEP $W^+W^-(\gamma)$ Monte Carlo

Vector Boson Self-Interactions

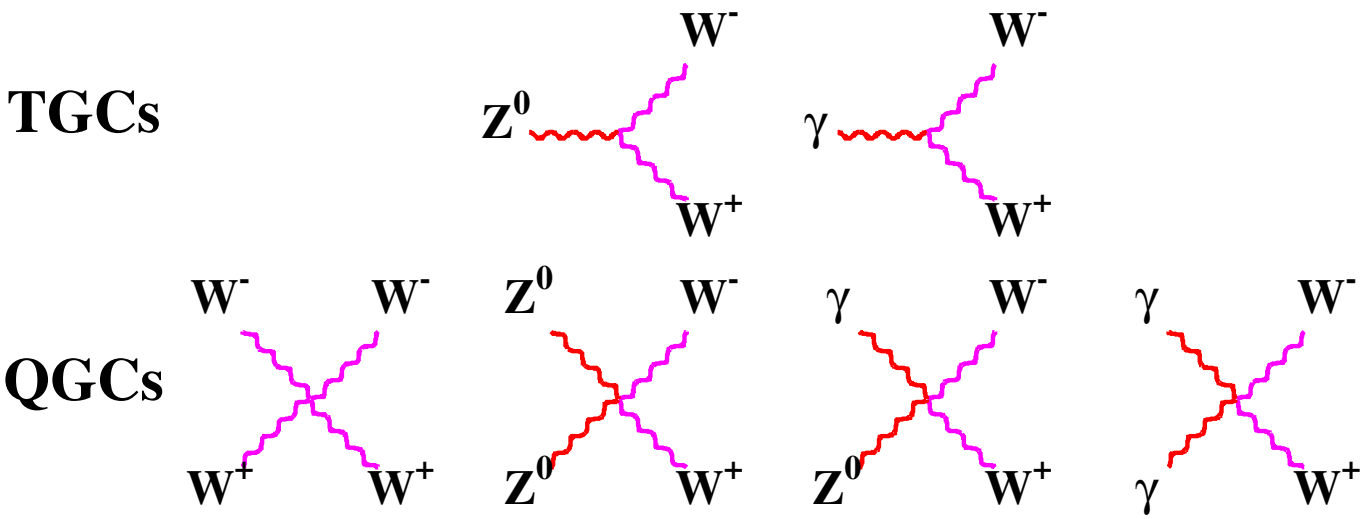
$SU(2) \times U(1)$ **Gauge Invariance** $\Rightarrow$ **Vector Boson Self-Interactions**

$$\mathcal{L} = -\frac{1}{4} W^{\mu\nu} . W_{\mu\nu},$$

$$\text{with} \quad W^{\mu\nu} = \partial^\nu W^\nu - \partial^\mu W^\mu - g\, W^\mu \times W^\nu,$$

➡ **TGCs and QGCs**

In the Standard Model:



$SU(2) \times U(1)$ **Gauge Invariance** ➡
exact FORM and STRENGTH of Gauge Couplings

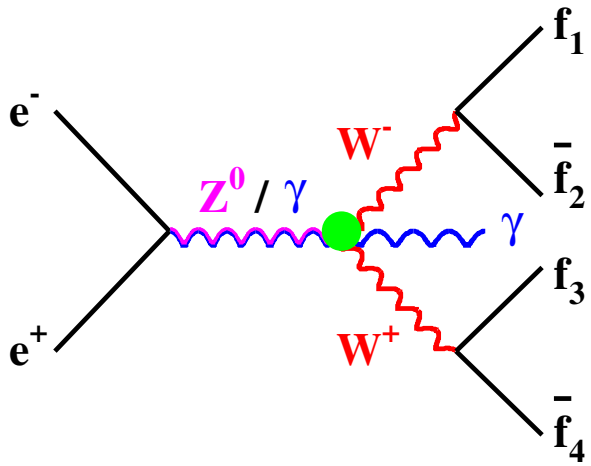
QGCs at LEP

SM QGCs at LEP ?

$W^+W^-\gamma$

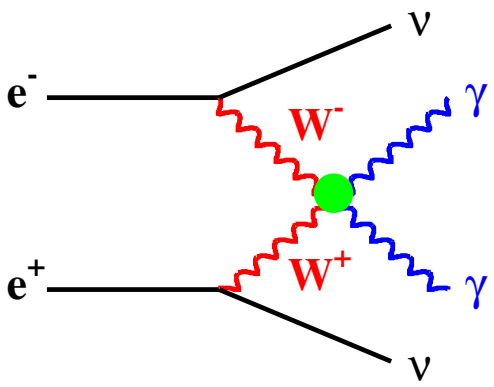
$\rightarrow WW\gamma\gamma$

& $WWZ\gamma$



$\nu\nu\gamma\gamma$

$\rightarrow WW\gamma\gamma$



In the SM: effects of QGCs too small to be observable at LEP ➡

★ Look for anomalous contributions★

Genuine Anomalous Quartic Gauge Couplings

Anomalous QGCs parametrised by additional terms in Lagrangian, require $SU(2)_c$ Symmetry

★ Only consider terms $\Rightarrow$ QGCs

but $\not\Rightarrow$ (TGCs)

★ 3 Commonly used terms $\mathcal{L}^0$, $\mathcal{L}^c$, $\mathcal{L}^n$

C and P conserving (Bélanger and Boudjema)

$$\mathcal{L}^0 = -\frac{e^2}{16}\frac{a_0}{\Lambda^2}\mathbf{F}^{\mu\nu}\mathbf{F}_{\mu\nu}\,\vec{W}^\alpha \,.\, \vec{W}_\alpha$$

$$\mathcal{L}^c = -\frac{e^2}{16}\frac{a_c}{\Lambda^2}\mathbf{F}^{\mu\alpha}\mathbf{F}_{\mu\beta}\,\vec{W}^\beta \,.\, \vec{W}_\alpha$$

$\Rightarrow \mathbf{W^+W^-\gamma\gamma}$

In addition, we consider CP violating term

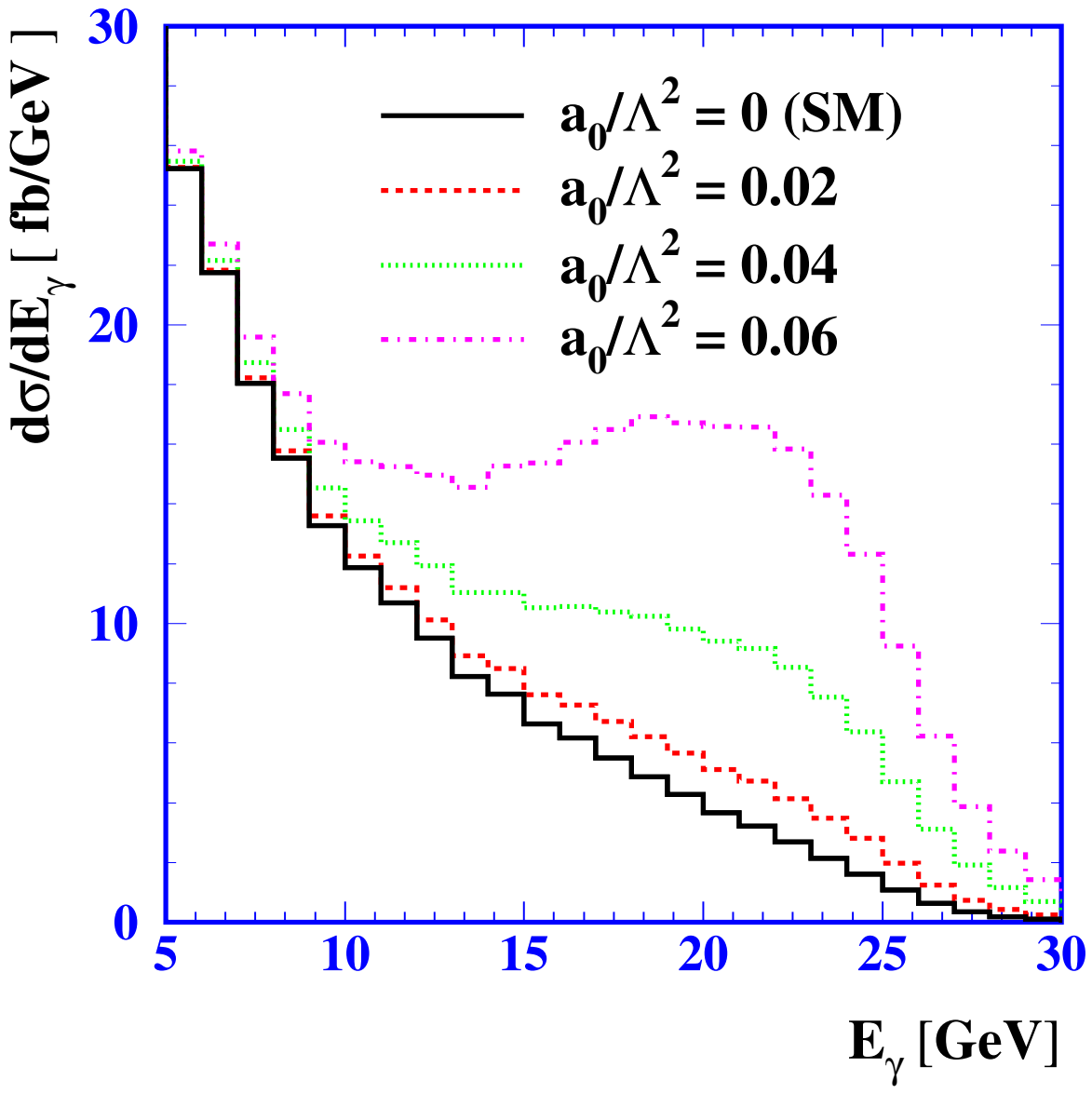
$$\mathcal{L}^n = -\frac{e^2}{16}\frac{a_n}{\Lambda^2}\epsilon_{ijk}W_{\mu\alpha}{}^{(i)}W_\nu{}^{(j)}W^{(k)\alpha}\mathbf{F}_{\mu\nu}$$

$\Rightarrow \mathbf{W^+W^-Z^0\gamma}$

Anomalous QGCs in $W^+W^-\gamma$ at LEP

For LEP at $\sqrt{s} = 189$ GeV

calculation of Stirling and Werthenbach, hep-ph/9903315

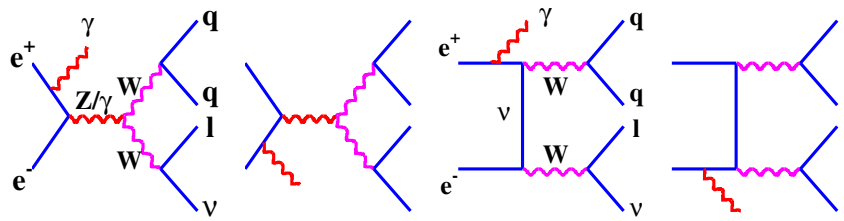


Anomalous QGCs $\Rightarrow$ Excess of high energy photons in $W^+W^-\gamma$

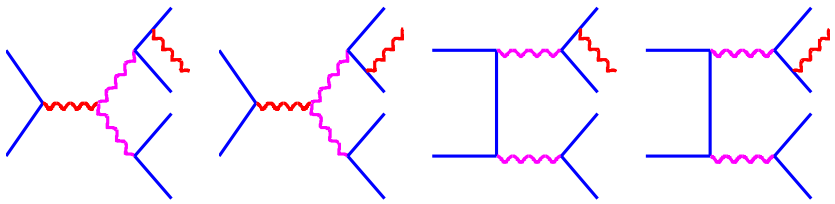
$W^+W^-\gamma$ at $O(\alpha)$

e.g. $e^+e^- \to W^+W^-(\gamma) \to q\bar{q}\ell\bar{\nu}_\ell\gamma$

ISR

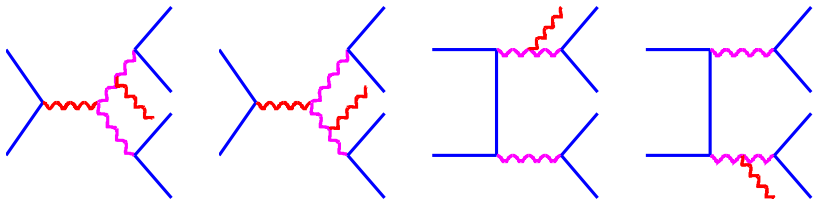


FSR (quark)

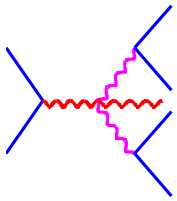


FSR (lepton)

WSR



QGC



ISR/QGC : $m_{\ell\nu} \sim m_{q\bar{q}} \sim M_W$

FSR(lepton) : $m_{\ell\nu\gamma} \sim m_{q\bar{q}} \sim M_W$

✶ **For $E_\gamma > \Gamma_W$, FSR treated as BACKGROUND**

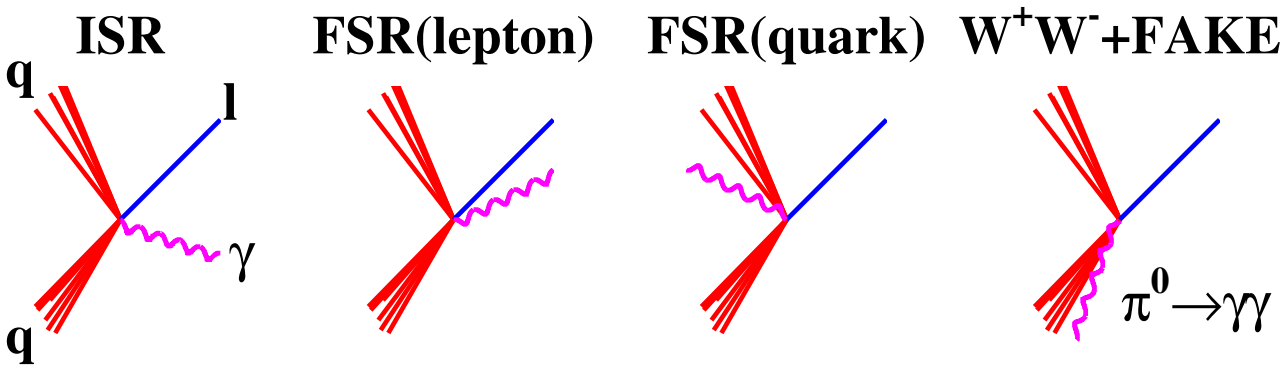
$W^+W^-\gamma$ Event Selection

OPAL DATA: 183 pb^{-1} at $\sqrt{s} = 189$ GeV

Event Selection:

- **W^+W^- Selection (not $\ell\nu\ell\nu$)**
- **Isolated Photon, $E_\gamma > 10$ GeV**
- **γ Polar Angle: $|cos\theta_\gamma| < 0.9$**
- **γ—fermion : $cos\theta_{\gamma f} < 0.9$**

What kind of photon ?

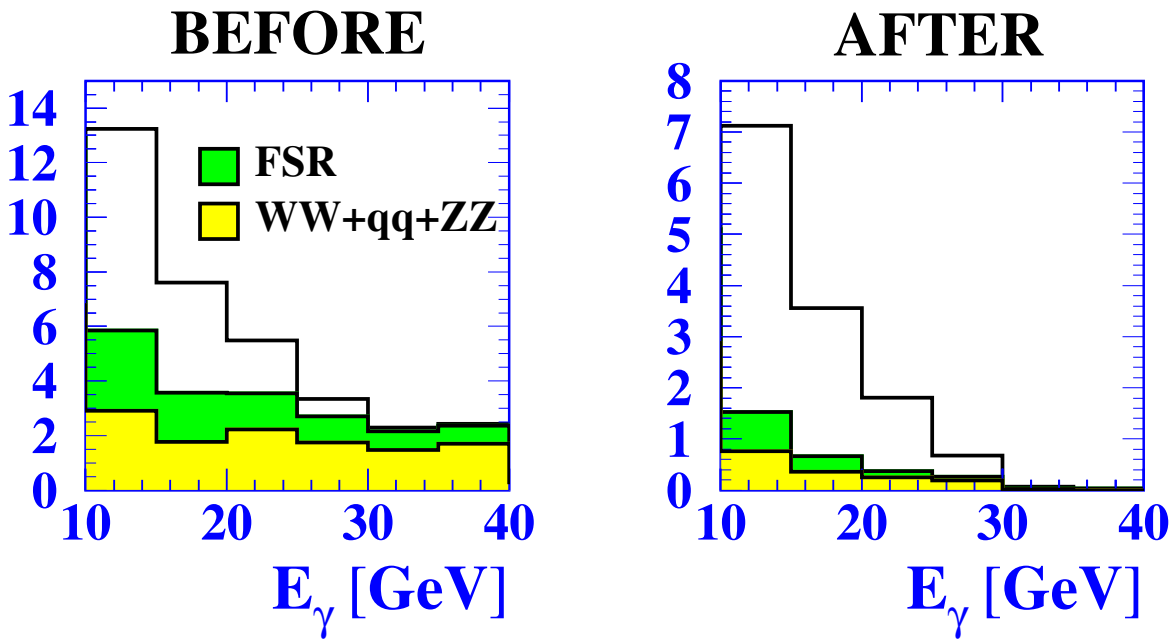


Use Kinematic Fits:

- ★ **ISR/QGC : 3-body $W^+W^-\gamma$ final state**
- ★ **FSR : 2-body W^+W^- final state, $\gamma \rightarrow \ell$/jet**

Effect of Kinematic Cuts

Kinematic cuts: "Event more consistent with $W^+W^-\gamma$ final state than with W^+W^-" ➜



Kinematic Requirements:

- ★ **Reduce Background/Systematics**
- ★ **Increase sensitiviy to QGCs**

($\ell\nu\ell\nu$ not used, because no kinematic rejection of FSR)

Selection Performance

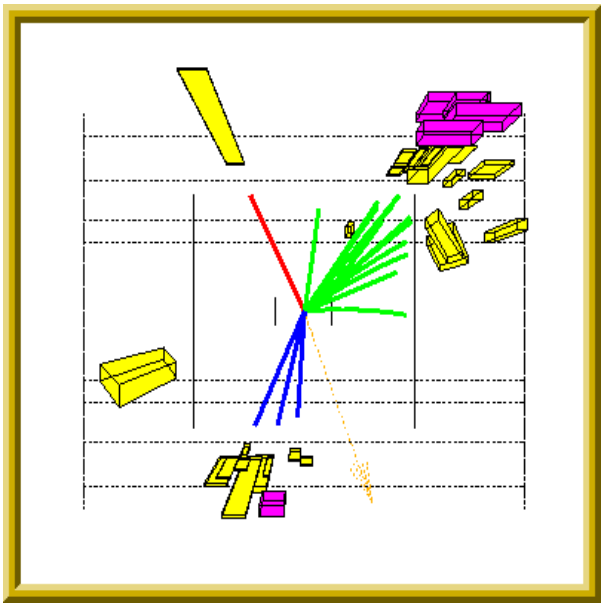
Efficiency	$48.7 \pm 1.8\ \%$
Background	9.9 ± 2.2 fb

➨ **17 Events with $E_\gamma > 10$ GeV**

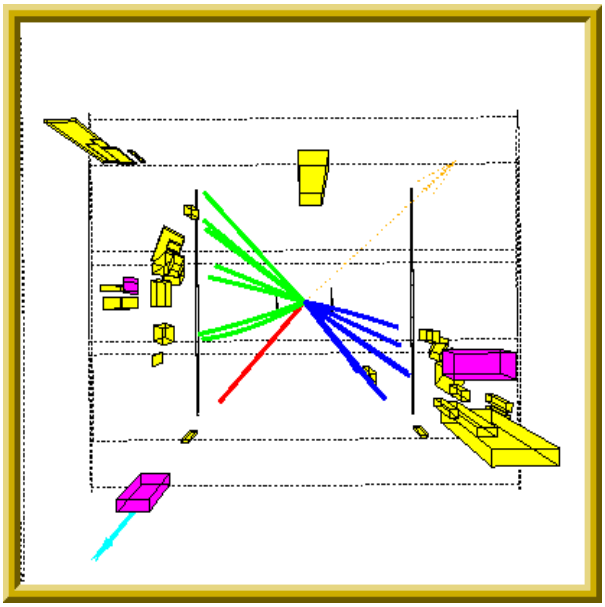
$W^+W^-\gamma$ Events ($E_\gamma > 10$ GeV)

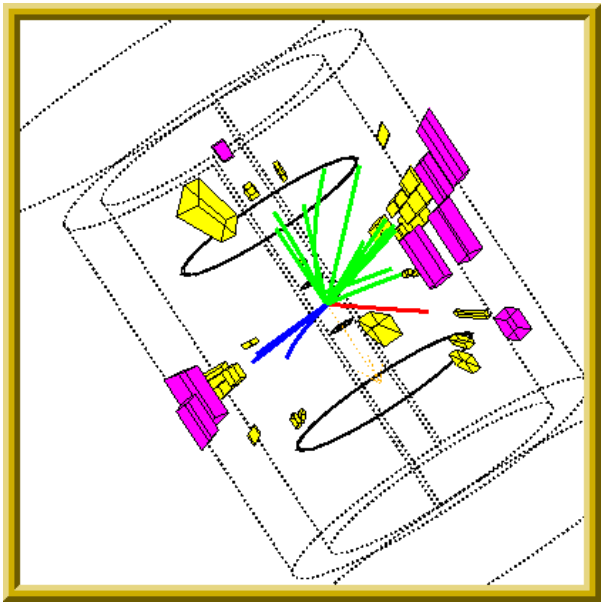
Data	17
KORALW	13.4
WWF	11.6
EEWWG	11.9

$W^+W^- \to qqe\nu\gamma$

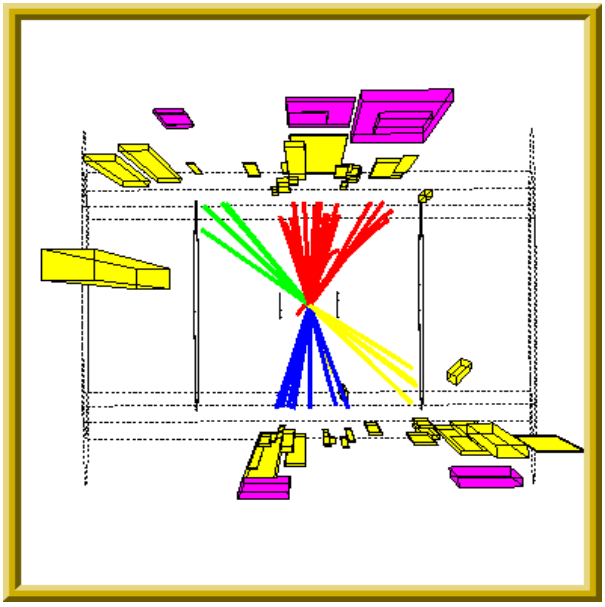


$W^+W^- \to qq\mu\nu\gamma$





$W^+W^- \to qq\tau\nu\gamma$



$W^+W^- \to qqqq\gamma$

Measurement of $\sigma_{WW\gamma}$

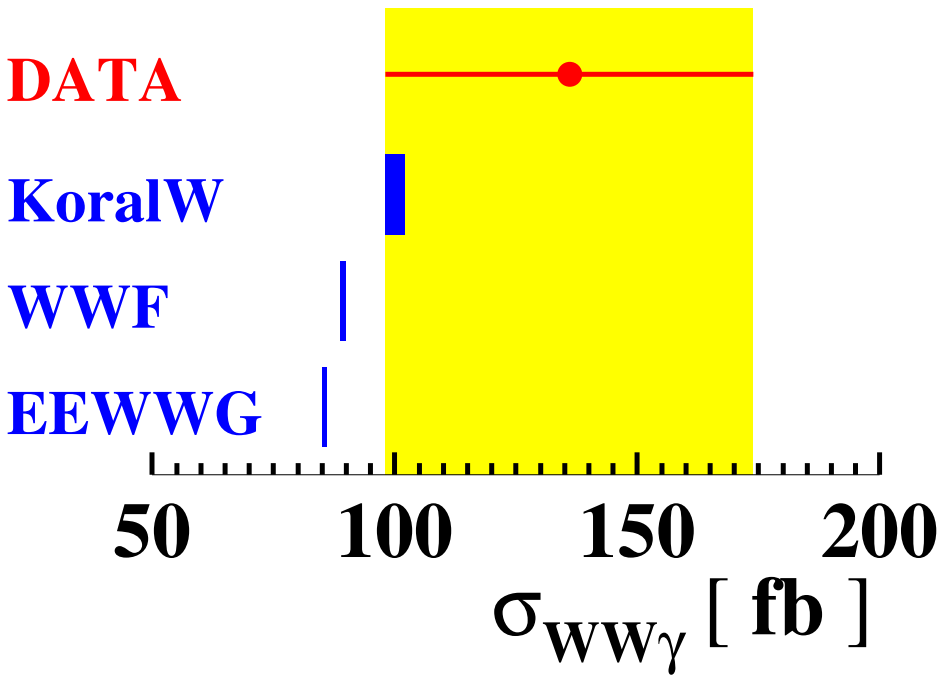
17 Selected $W^+W^-\gamma$ Events ➜

$$\sigma_{WW\gamma} = 136 \pm 37 \pm 8 \text{ fb}$$

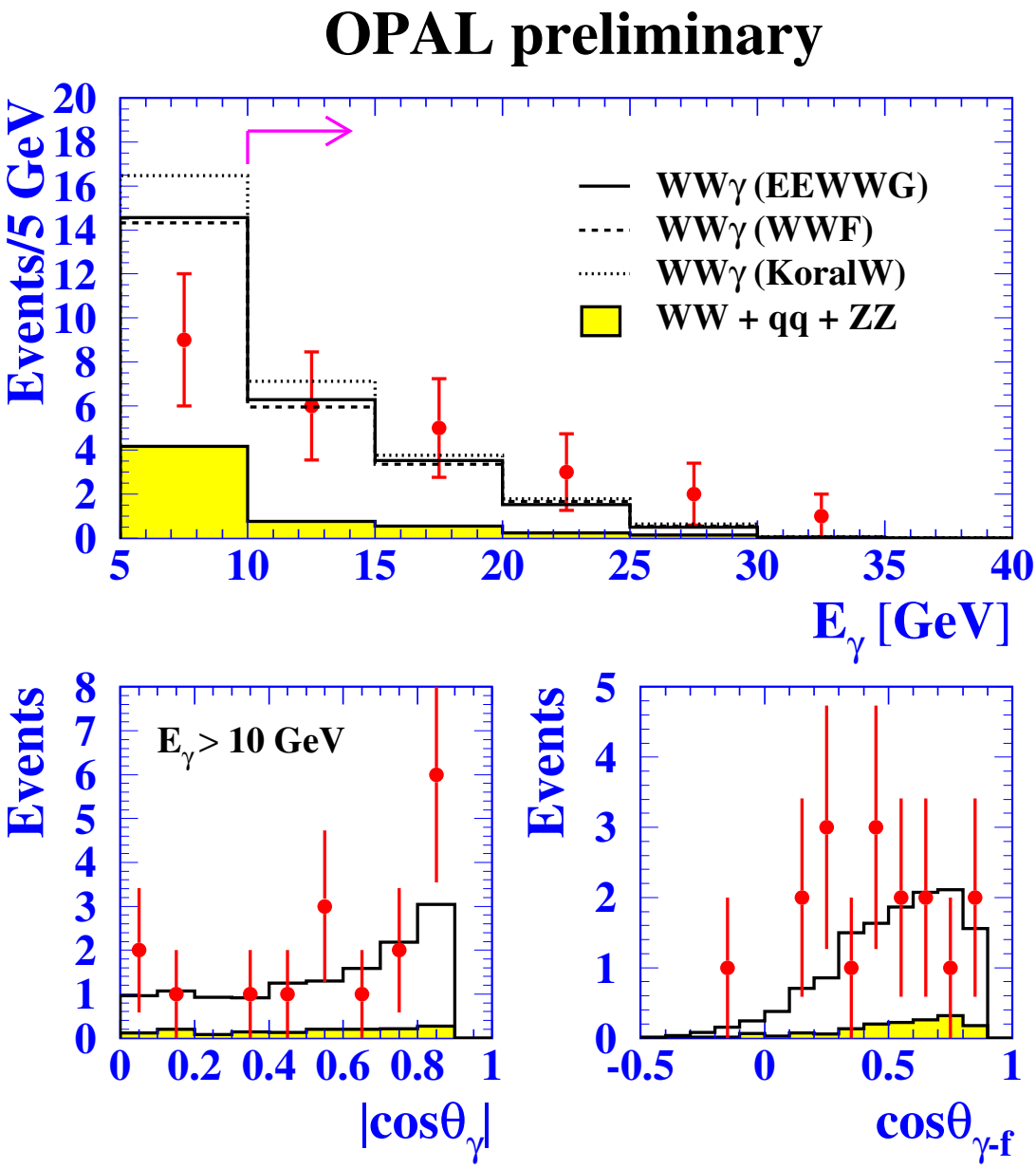
within $f_1\bar{f}_2 f_3\bar{f}_4\gamma$ acceptance:

- $E_\gamma > 10$ GeV
- $|cos\theta_\gamma| < 0.9$
- $cos\theta_{\gamma f} < 0.9$
- $M_{f_1\bar{f}_2}, M_{f_3\bar{f}_4} > 73$ GeV

★Consistent with SM expectation:



Differential Cross sections

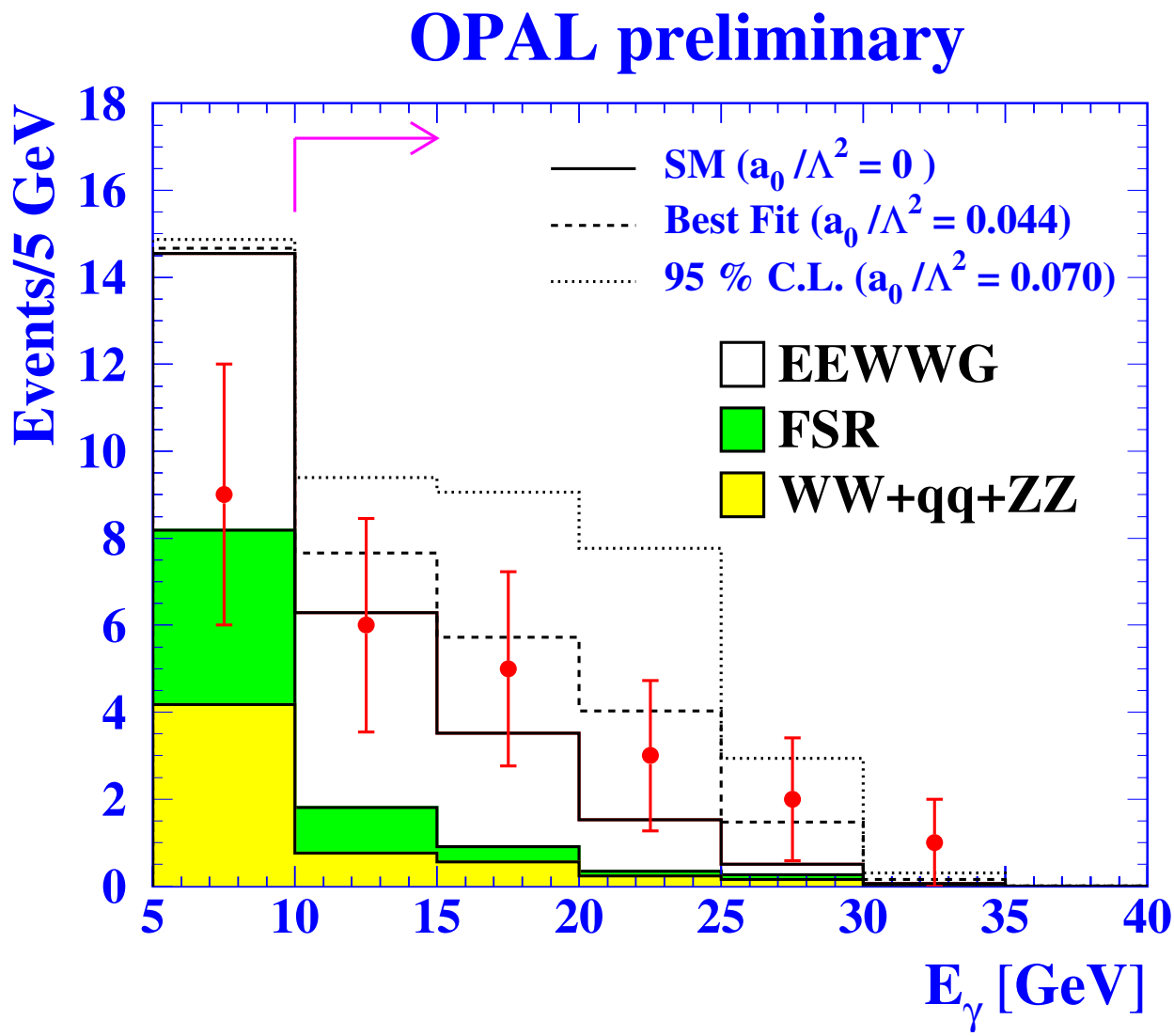


Binned maximum likelihood fit to (E_γ, $cos\theta_\gamma$) distribution ⇒ Limits on Anomalous QGCs.

Monte Carlo Recipe:

1. **EEWWG for ISR, WSR, SM QGC + AQGCs**
2. **KORALW for FSR and WW+fake**
3. **PYTHIA for non-WW (qq,ZZ,Wev)**

Anomalous QGC Fits



★ **95 % Confidence Limits:**

$$-0.07\ \mathrm{GeV}^{-2} < a_0/\Lambda^2 < 0.07\ \mathrm{GeV}^{-2}$$

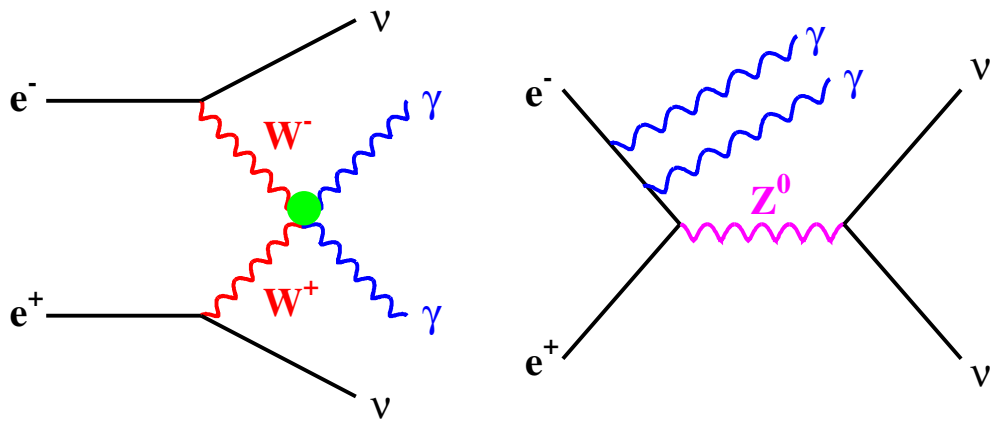
$$-0.13\ \mathrm{GeV}^{-2} < a_c/\Lambda^2 < 0.19\ \mathrm{GeV}^{-2}$$

$$-0.61\ \mathrm{GeV}^{-2} < a_n/\Lambda^2 < 0.57\ \mathrm{GeV}^{-2}$$

★ **Expected limit** $a_0/\Lambda^2 < 0.045$. **Probability of obtaining such high limits** ∼**2 %**

QGC Limits from $\nu\nu\gamma\gamma$

★ $e^+e^- \to \nu\nu\gamma\gamma$ also probes $W^+W^-\gamma\gamma$

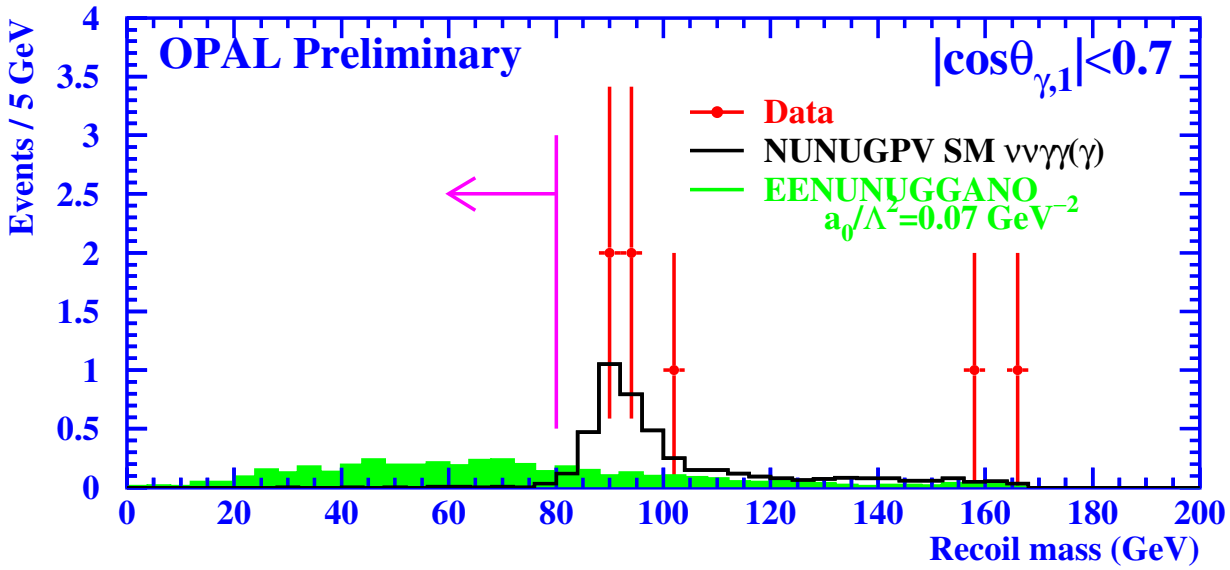


★ Final State: Two photons + Missing Energy

☆ Background: Radiative return to Z^0

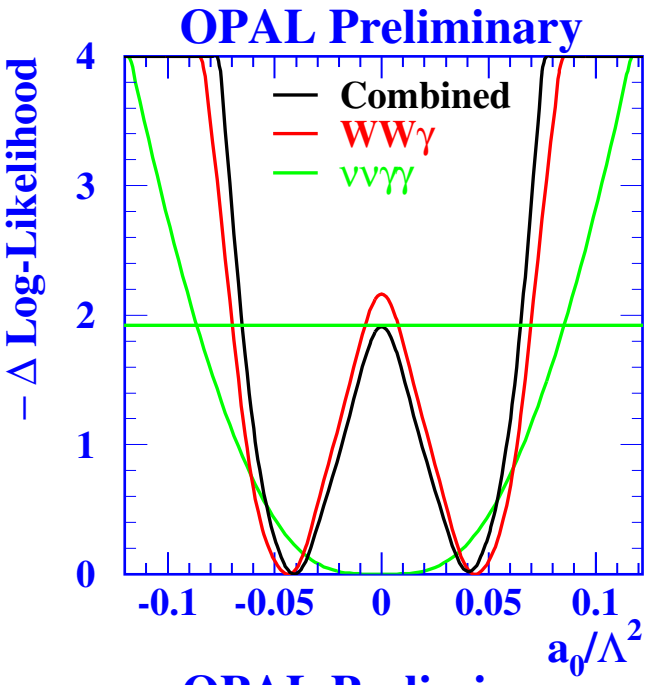
★ EENUNUGGANO (Stirling and Werthenbach hep-ph/9907235) includes Anomalous QGCs

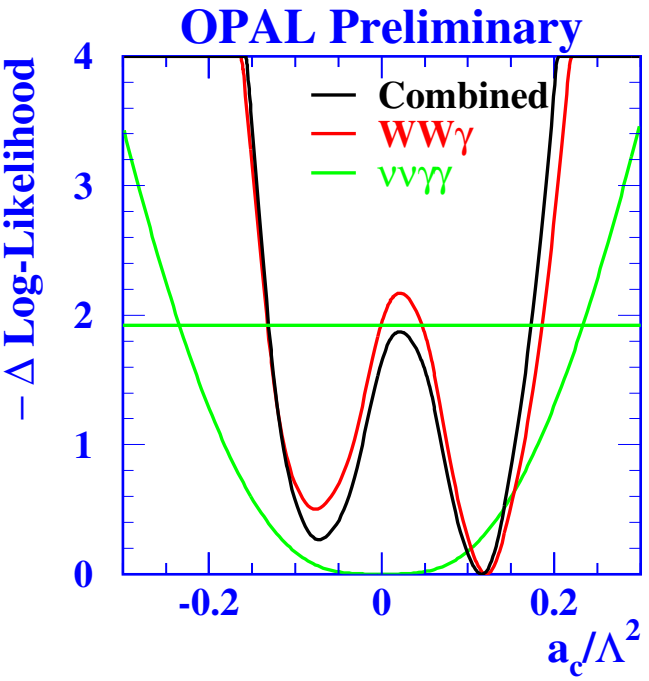
★ For $m_{\nu\nu} < 70$ GeV ∼ background free

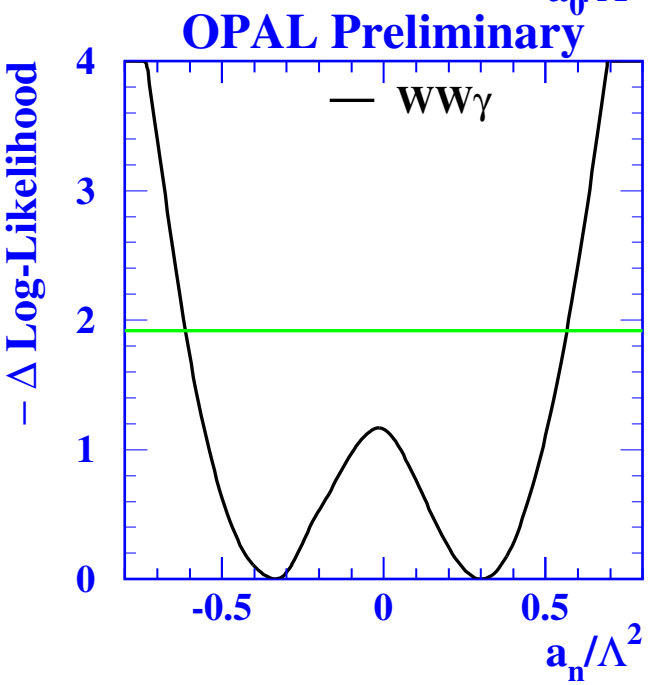


★ No event ⇒ limits

Combined Limits







Combined Limits $W^+W^-\gamma\gamma$

$$-0.065\ \mathrm{GeV}^{-2} < a_0/\Lambda^2 < 0.065\ \mathrm{GeV}^{-2}$$

$$-0.13\ \mathrm{GeV}^{-2} < a_c/\Lambda^2 < 0.17\ \mathrm{GeV}^{-2}$$

Combined Limits $W^+W^-Z^0\gamma$

$$-0.61\ \mathrm{GeV}^{-2} < a_n/\Lambda^2 < 0.57\ \mathrm{GeV}^{-2}$$

Conclusions/Outlook

★ **First Look at Hard Radiation in $\mathbf{W^+W^-}$**

★ $\sigma_{WW\gamma} = 135 \pm 37 \pm 8$ fb

c.f. SM $85 - 110$

★ **First Direct Limits on Anomalous QGCs**

★ **Far from a Complete Study of Anomalous QGCs at LEP**

Particular Thanks to: James Stirling, Anja Werthenbach, Doreen Wackeroth