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

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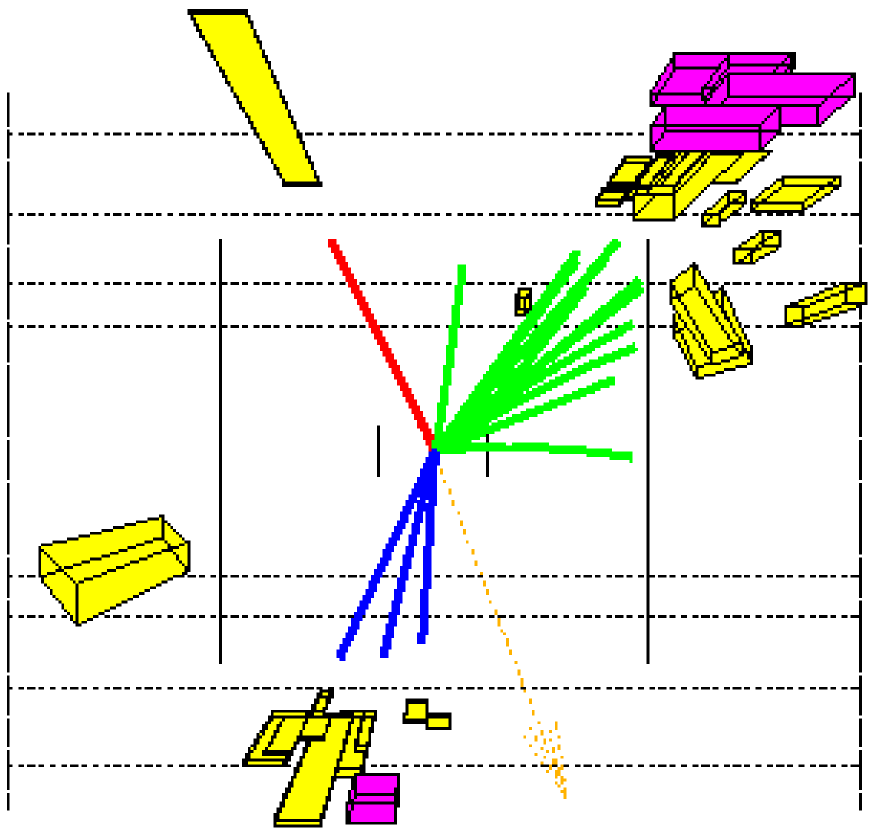
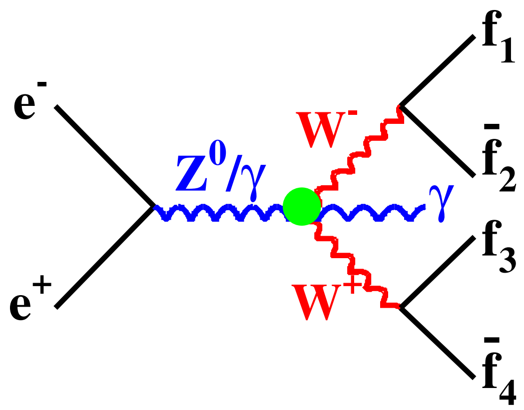


- **OPAL analysis of $\sim 183\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 189\,\mathrm{GeV}$**

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

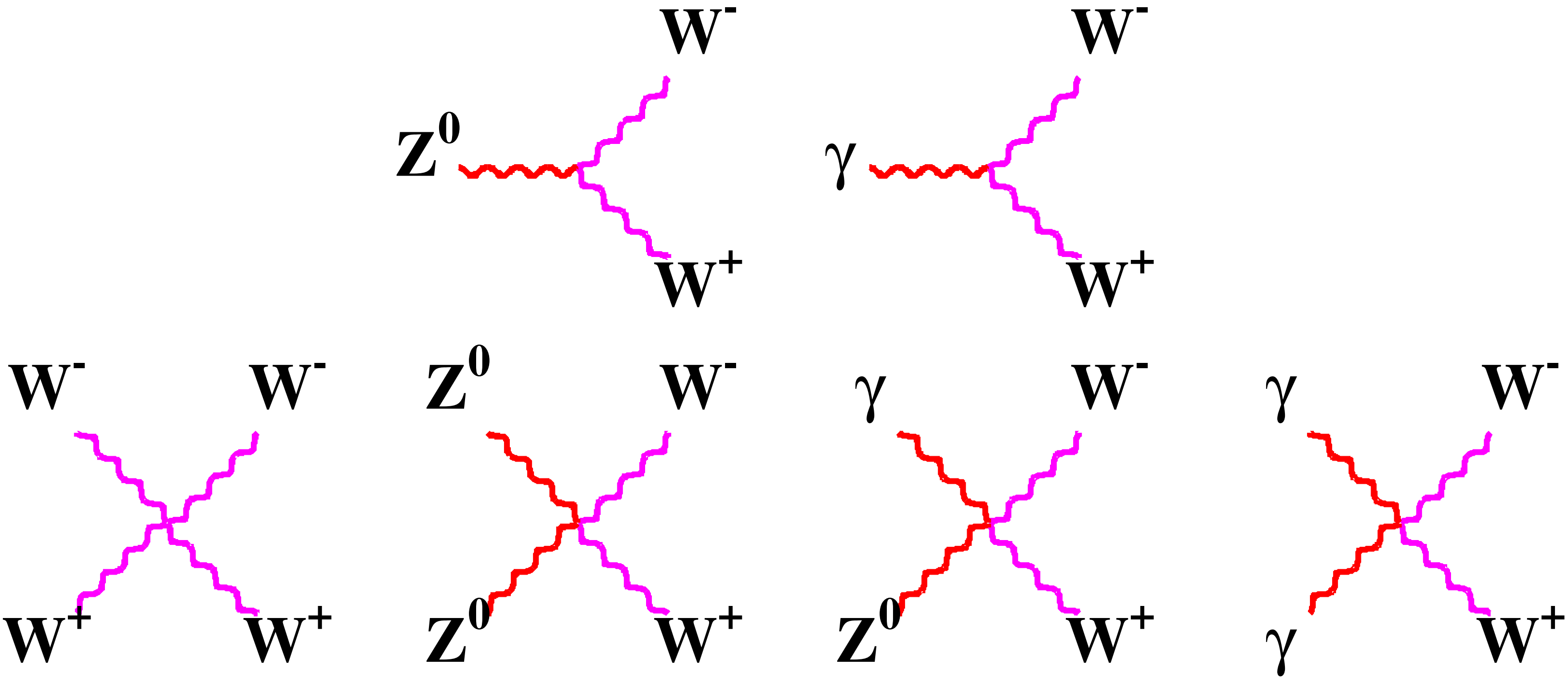
$SU(2) \times U(1)$ Gauge Invariance $\Rightarrow$ Vector Boson Self-Interactions

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

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

➡ **TGCs and QGCs**

In the Standard Model:



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

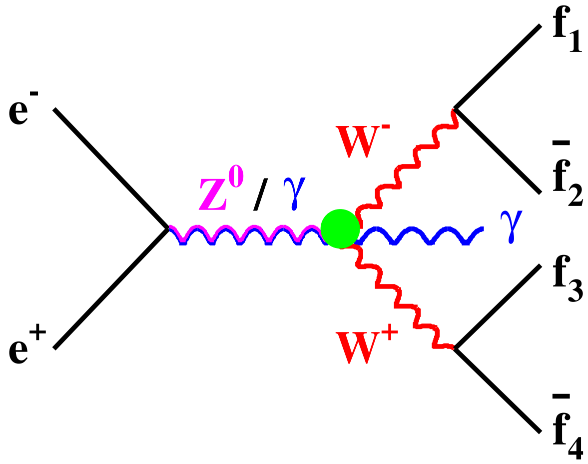
QGCs at LEP

SM QGCs at LEP ?

$W^+W^-\gamma$

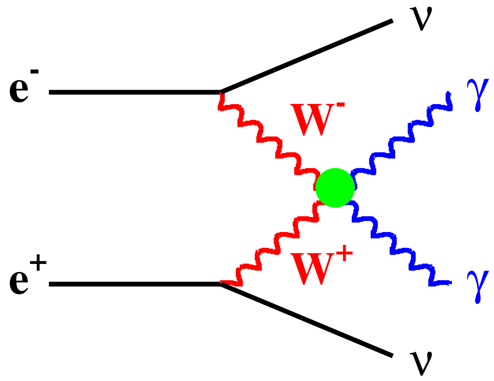
$\rightarrow$ $WW\gamma\gamma$

& $WWZ\gamma$



$\nu\nu\gamma\gamma$

$\rightarrow$ $WW\gamma\gamma$



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)

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

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

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

In addition, we consider CP violating term

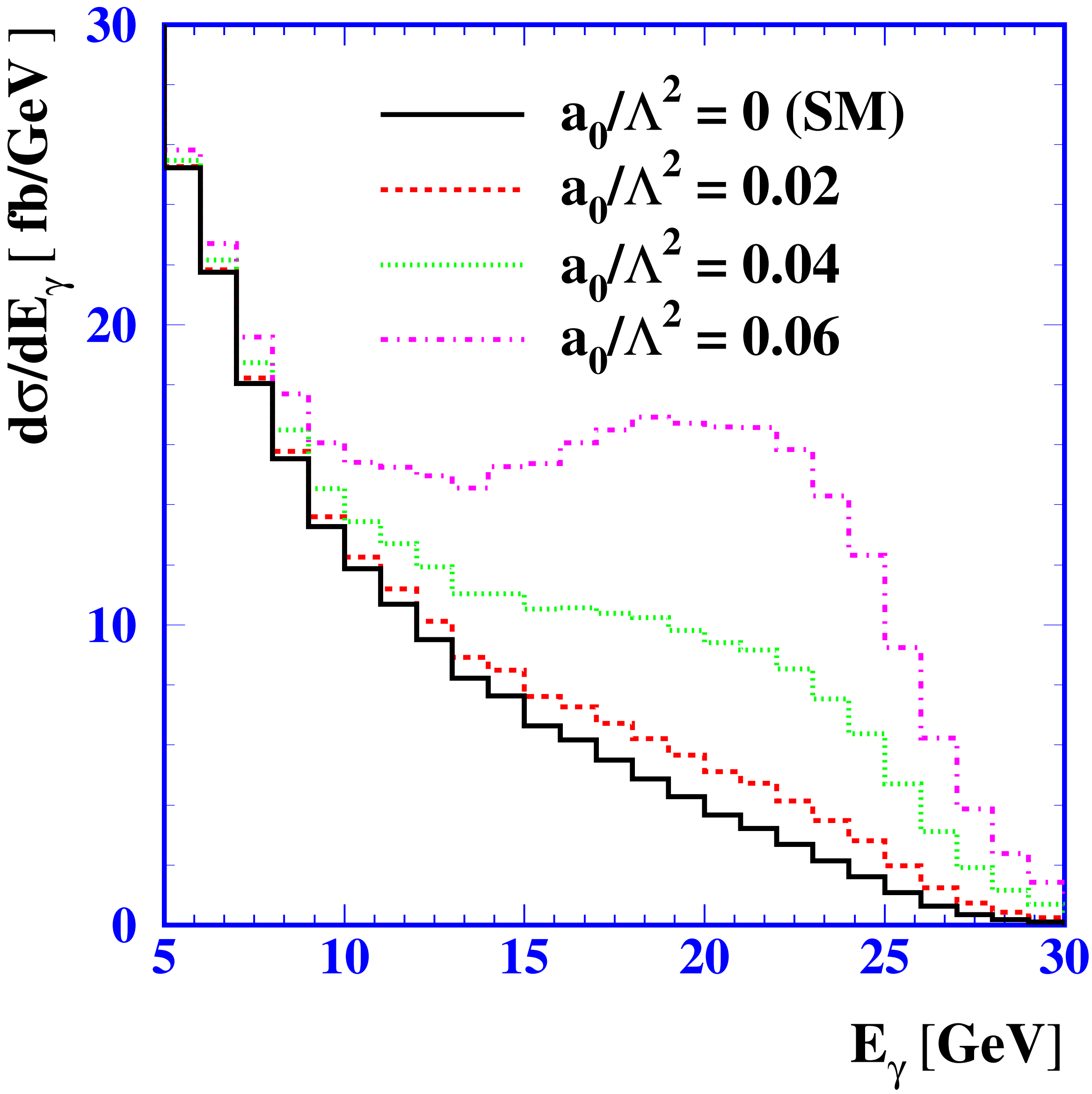
$$\mathcal{L}^n = -\frac{e^2}{16}\frac{a_n}{\Lambda^2}\epsilon_{ijk}W_{\mu\alpha}{}^{(i)}W_{\nu}{}^{(j)}W^{(k)\alpha}\mathrm{F}_{\mu\nu}$$

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

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

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

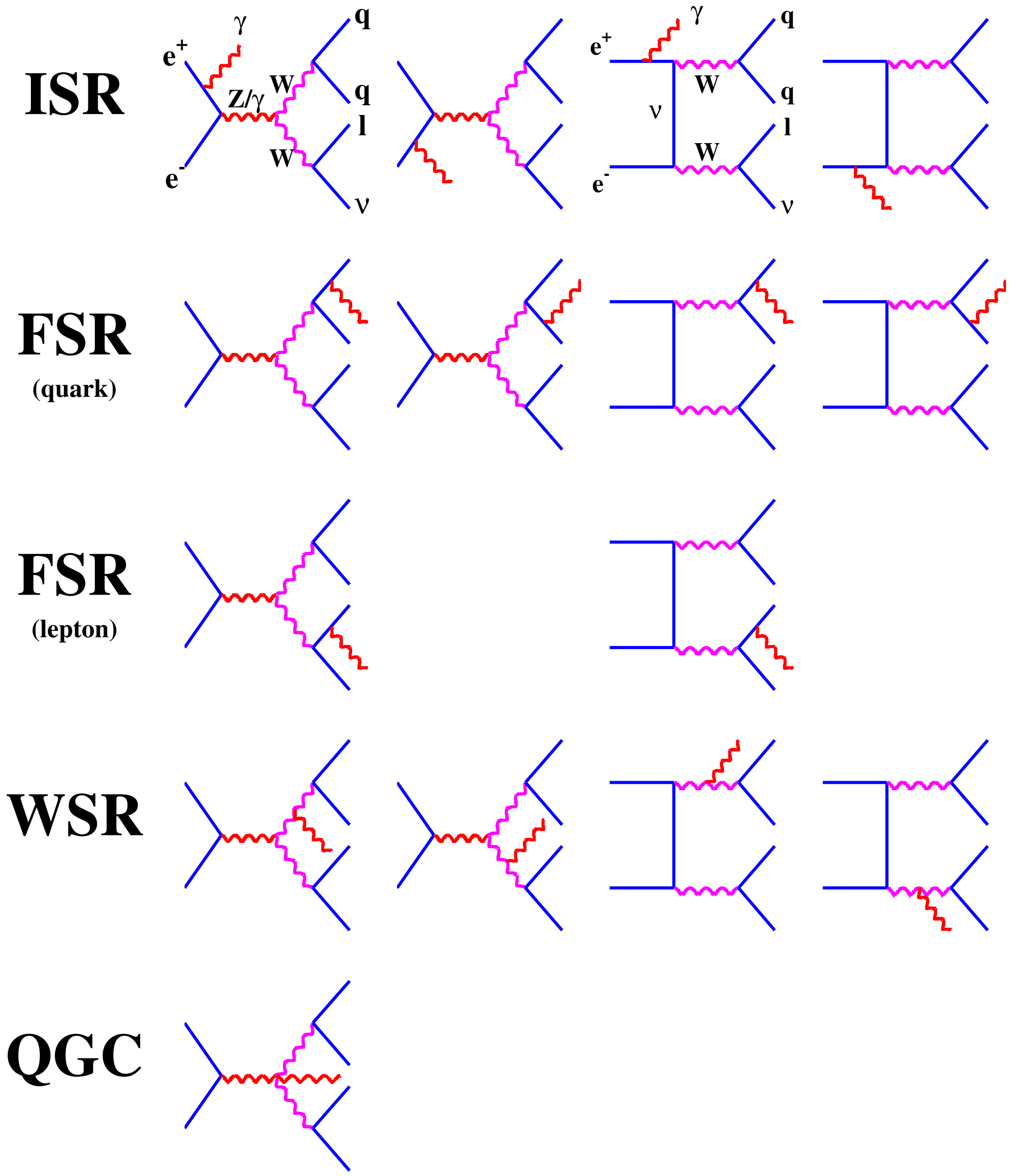
calculation of Stirling and Werthenbach, hep-ph/9903315



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

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

e.g. $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-}(\gamma) \rightarrow \mathrm{q\overline{q}}\ell\overline{\nu}_\ell\gamma$



ISR/QGC : $m_{\ell\nu} \sim m_{\mathrm{q\overline{q}}} \sim M_{\mathrm{W}}$

FSR(lepton) : $m_{\ell\nu\gamma} \sim m_{\mathrm{q\overline{q}}} \sim M_{\mathrm{W}}$

★ **For $\mathrm{E}_\gamma > \Gamma_{\mathrm{W}}$, FSR treated as BACKGROUND**

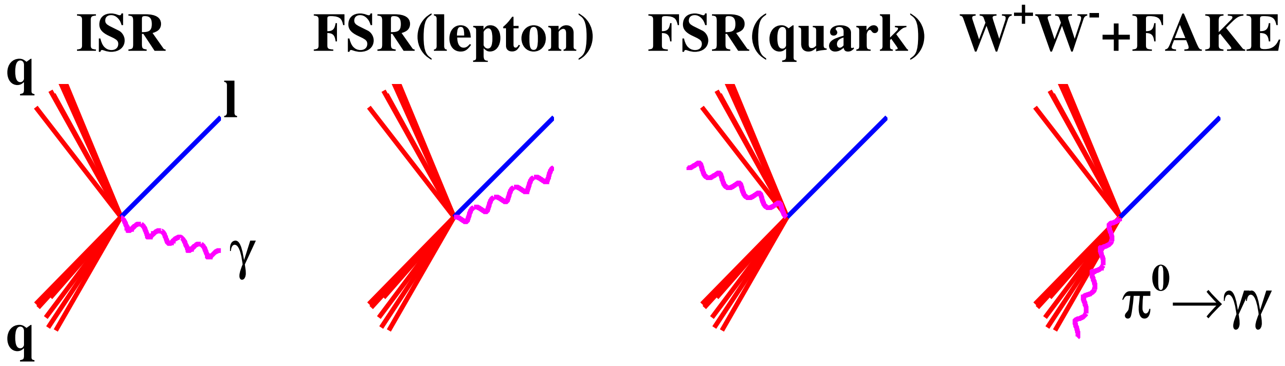
$W^+W^-\gamma$ Event Selection

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 ?



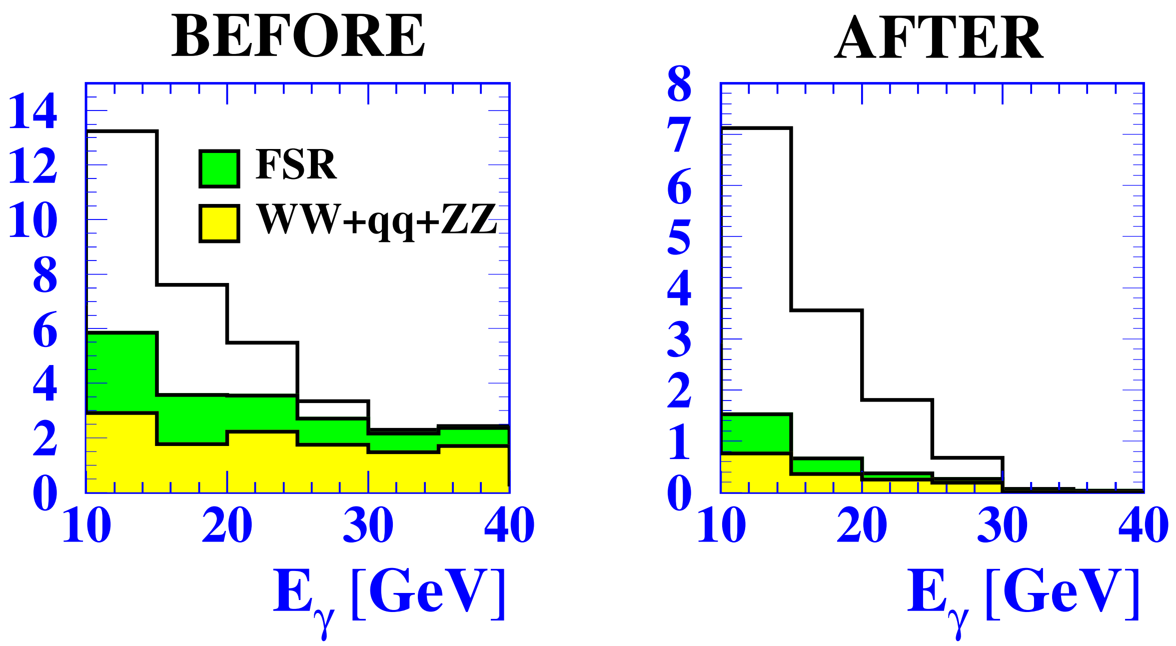
Use Kinematic Fits:

★ **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

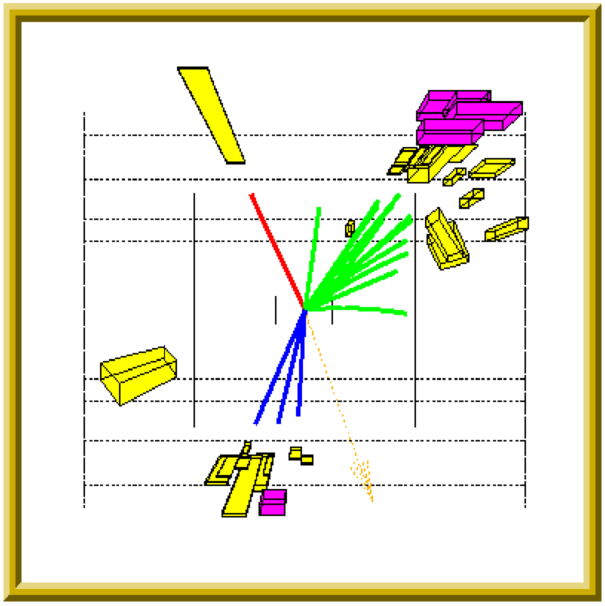
Efficiency	48.7 ± 1.8 %
Background	9.9 ± 2.2 fb

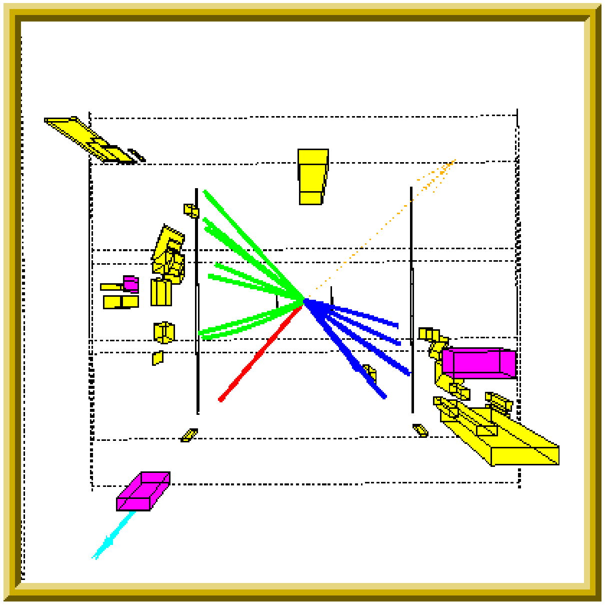
➨ 17 Events with $E_\gamma > 10$ GeV

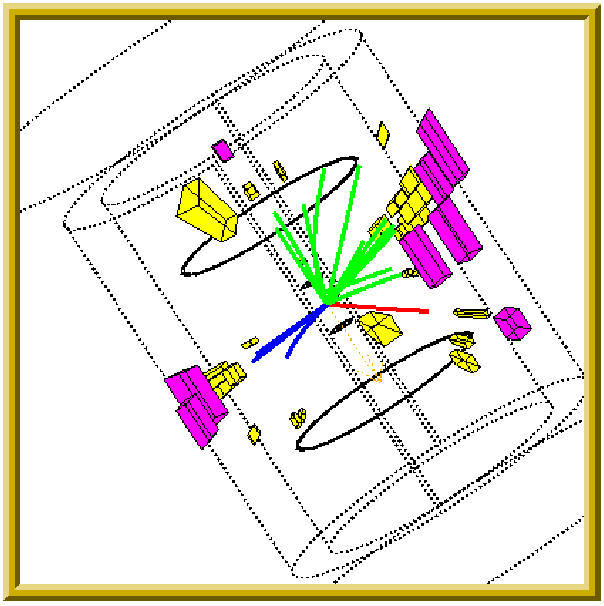
$W^+W^-\gamma$ Events ($E_\gamma > 10$ GeV)

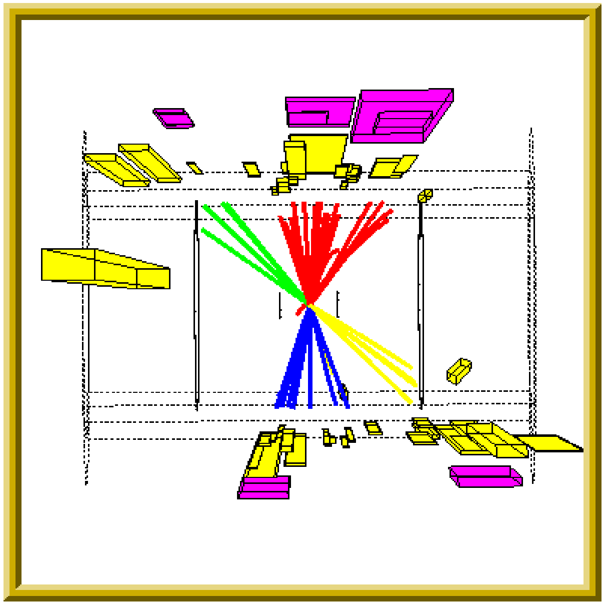
Data	17
KORALW	13.4
WWF	11.6
EEWWG	11.9

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









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

Measurement of $\sigma_{WW\gamma}$

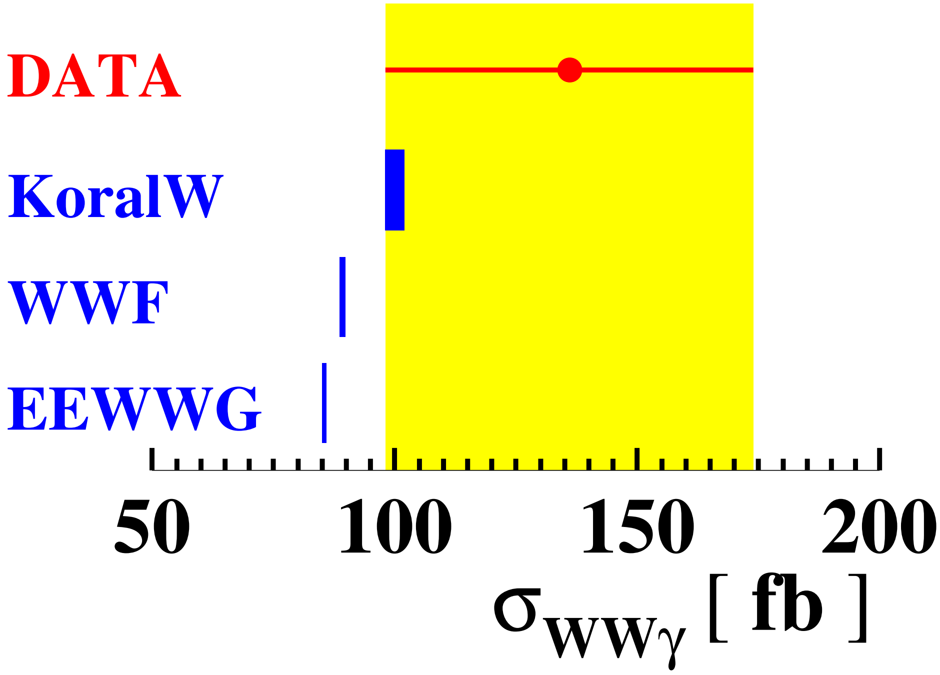
17 Selected $W^+W^-\gamma$ Events →

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

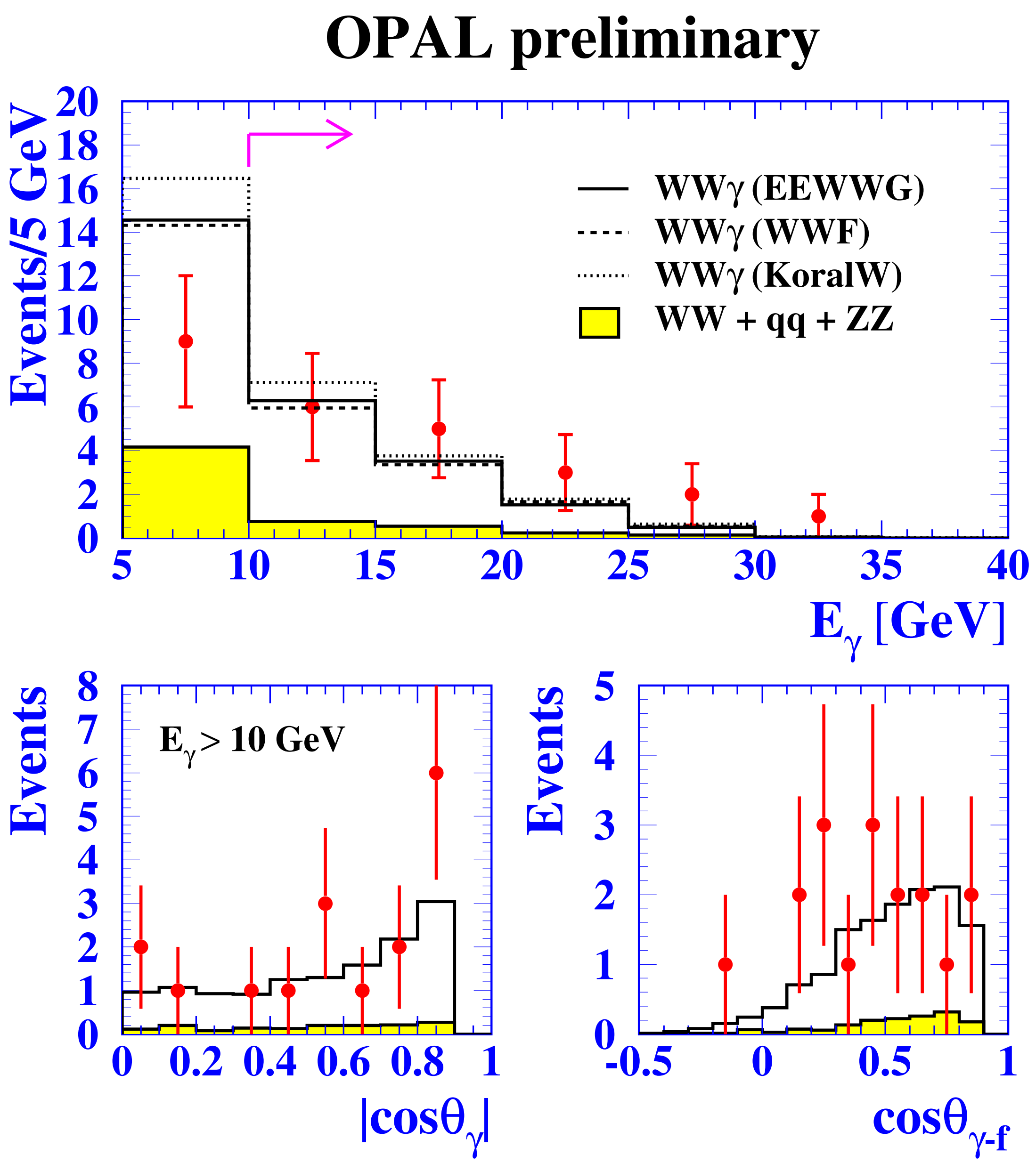
within $f_1\overline{f}_2 f_3\overline{f}_4\gamma$ acceptance:

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

★ **Consistent with SM expectation:**



Differential Cross sections



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

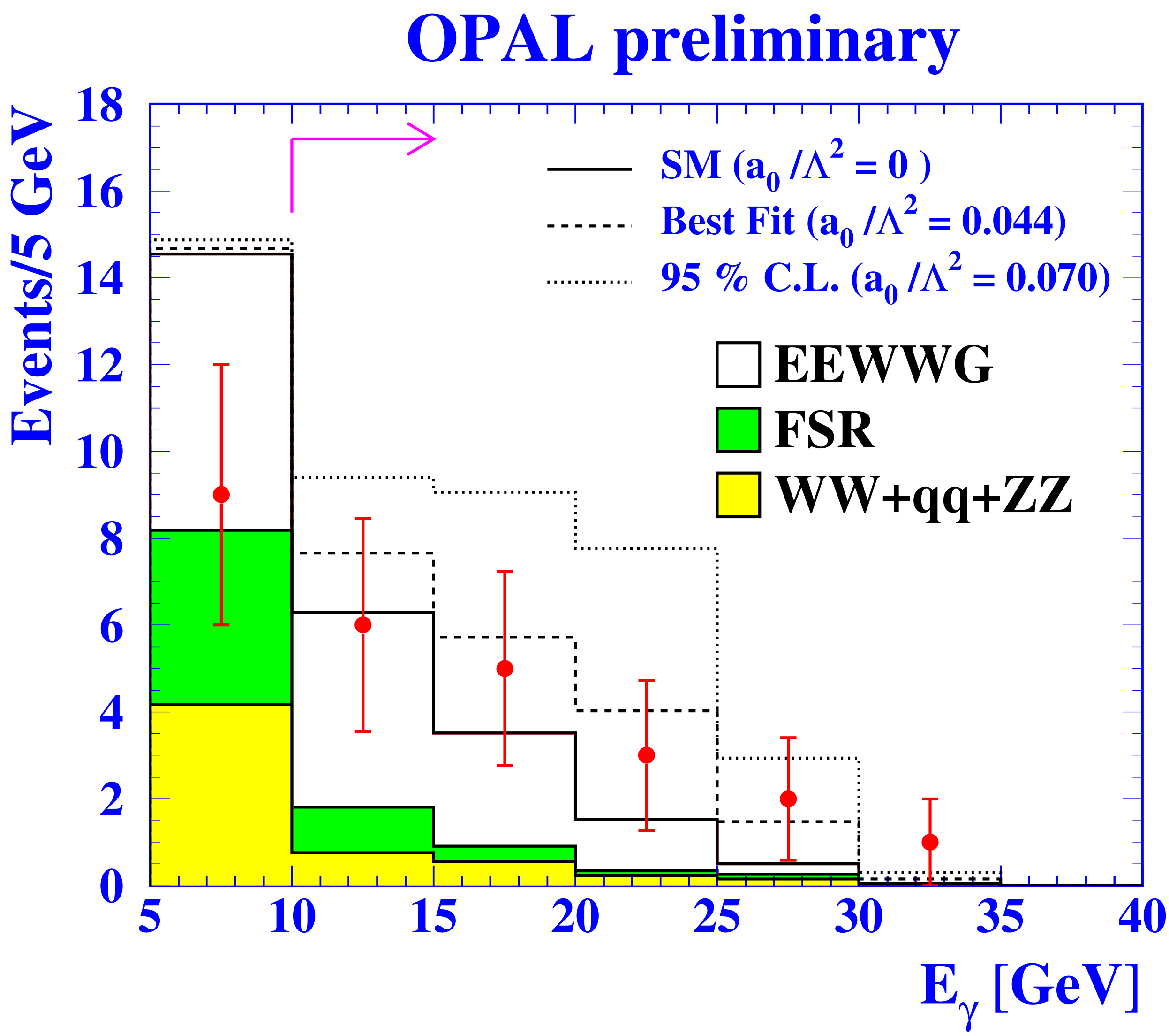
Monte Carlo Recipe:

❶ **EEWWG for ISR, WSR, SM QGC + AQGCs**

❷ **KORALW for FSR and WW+fake**

❸ **PYTHIA for non-WW (qq,ZZ,Wev)**

Anomalous QGC Fits



★ **95 % Confidence Limits:**

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

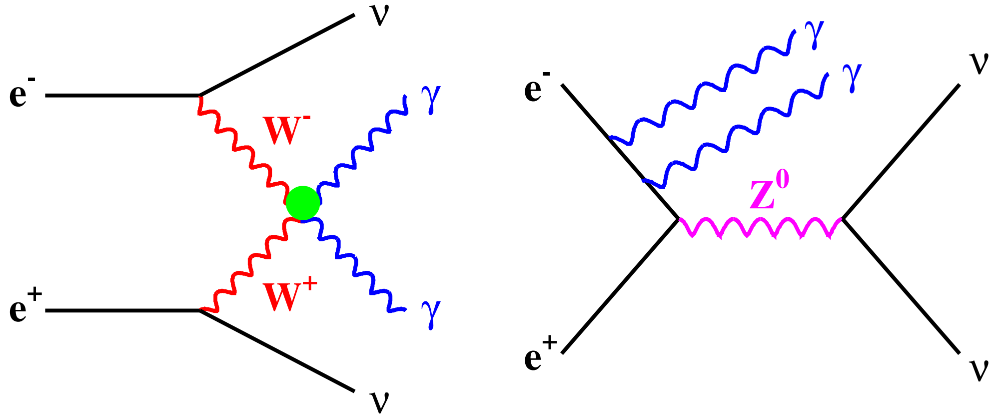
$$-0.13\,\mathrm{GeV}^{-2} < \quad a_c/\Lambda^2 \quad < 0.19\,\mathrm{GeV}^{-2}$$

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

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

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

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

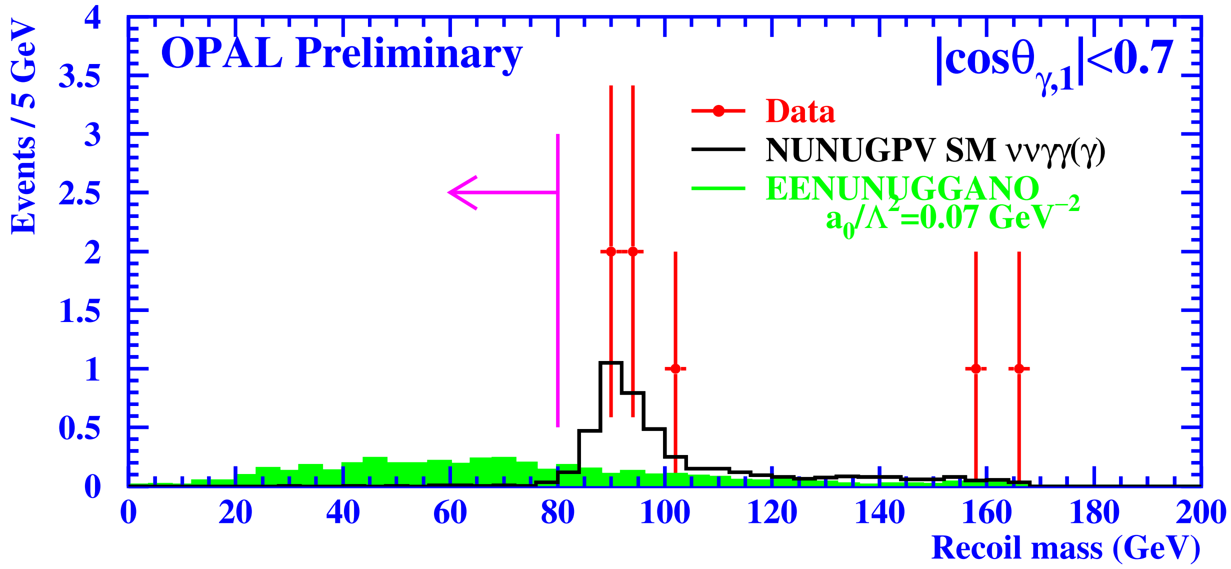


★ Final State: Two photons + Missing Energy

☆ Background: Radiative return to Z^0

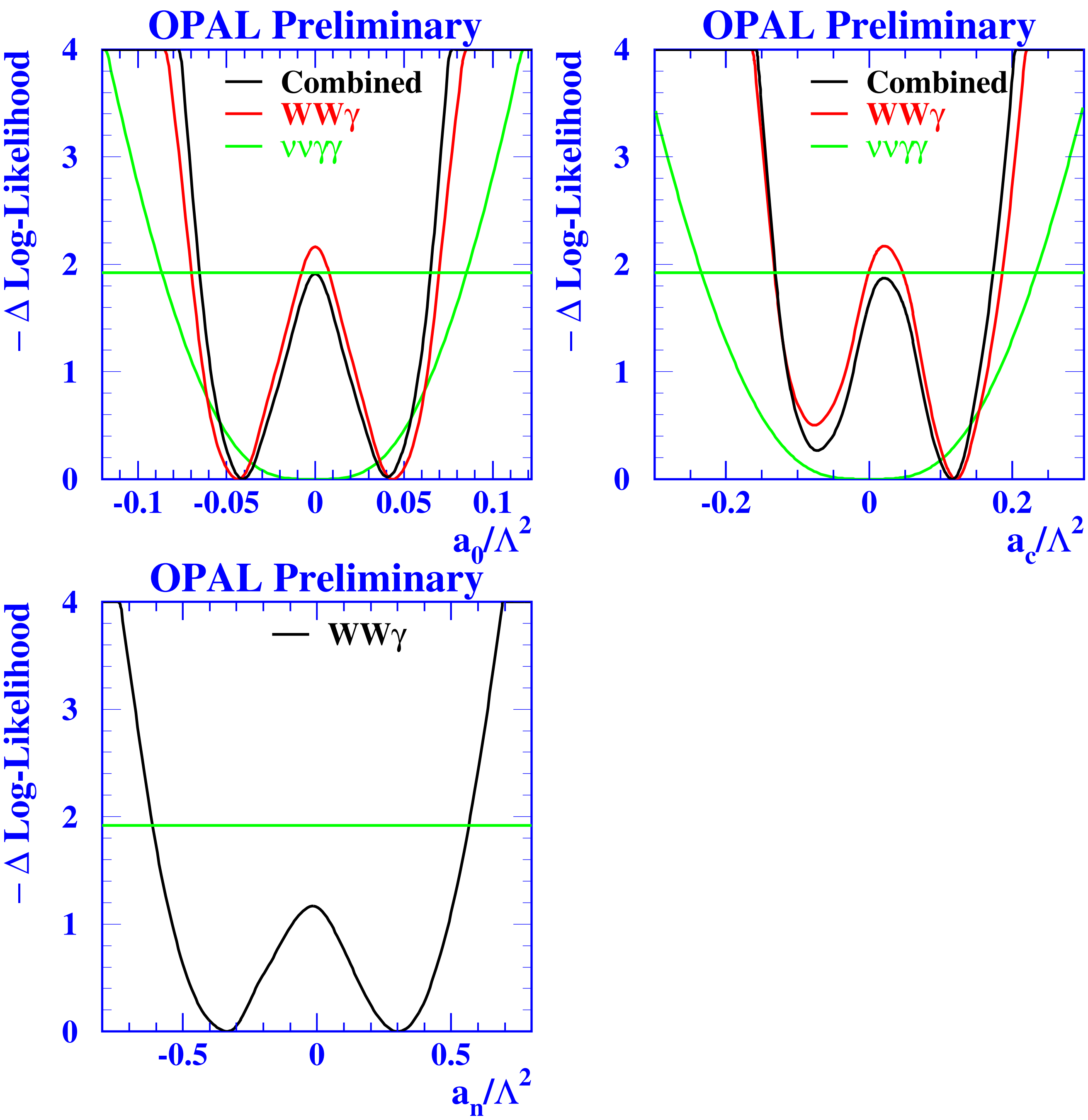
★ EENUNUGGANO (Stirling and Werthenbach hep-ph/9907235) includes Anomalous QGCs

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



★ No event ⇒ limits

Combined Limits



Combined Limits $\mathbf{W^+W^-\gamma\gamma}$

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

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

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

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

Conclusions/Outlook

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

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