# Physics of the W Boson at LEP 2

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- Results mainly from $\sqrt{s} = 189\ \mathrm{GeV}$ data
- Opalcentric Viewpoint !

Topics covered:

➊ Introduction $\mathrm{W^+W^-}$ at LEP

➋ $\mathrm{W^+W^-}$ Cross Section

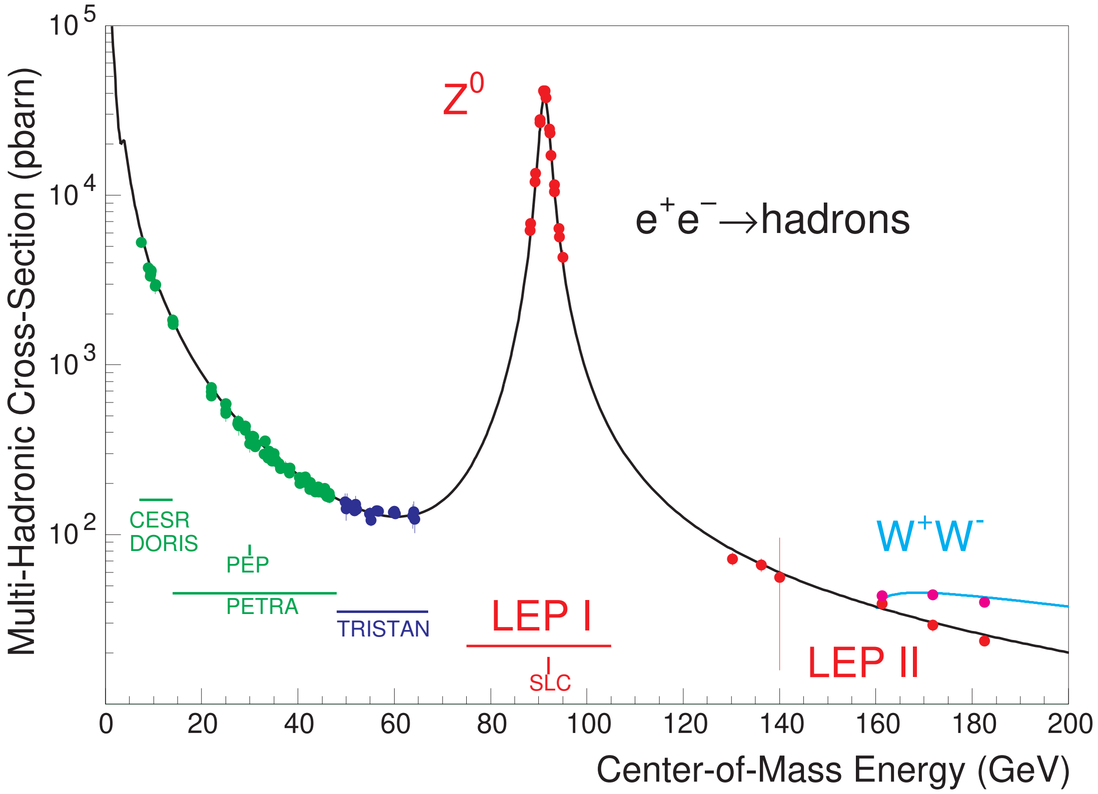
➌ W-boson Couplings

➍ W-boson Mass

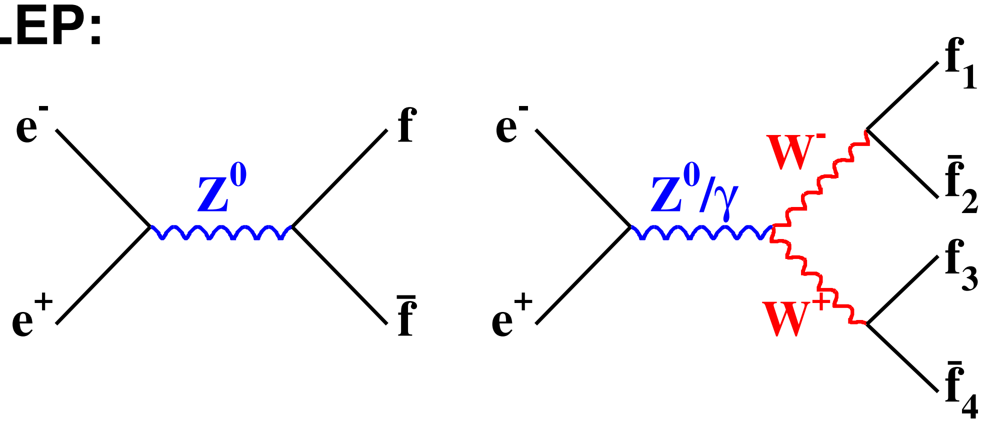
➎ Outlook

# ❶ INTRODUCTION

## A Brief History of $e^+e^- \rightarrow$ hadrons




## At LEP:




## LEP (four experiments) Combined:

- ★ **LEP 1 : 16,000,000 $Z^0$**
- ★ **LEP 2 : 30,000 $W^+W^-$**

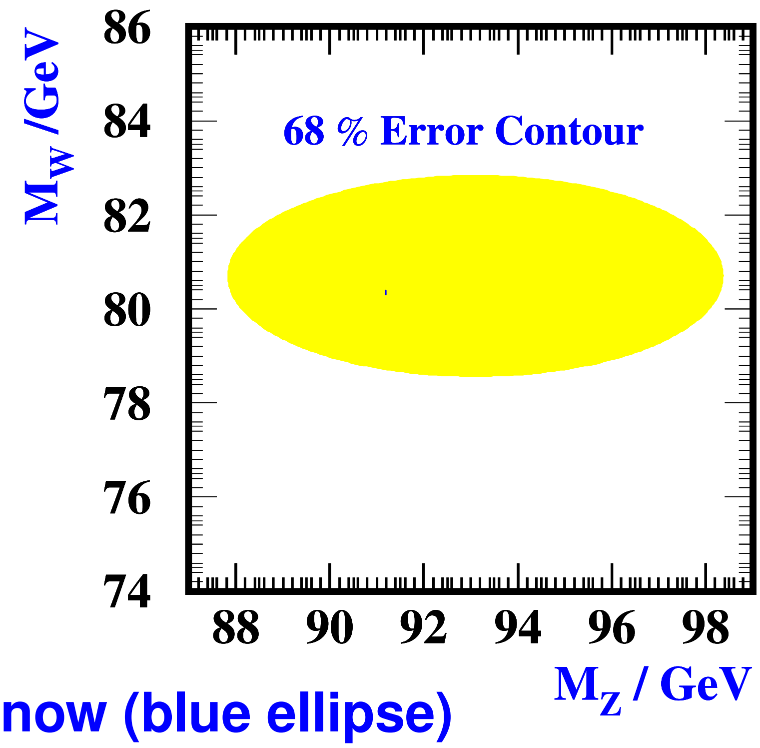
# LEP Physics

★ (In the absence of a discovery) LEP physics will be summarised as:

**"…. precise measurements of the mass and couplings of the $Z^0$ and $W^{\pm}$ …"**

PERKINS $V^{th}$ EDITION (2007)

**The situation in 1989 (yellow ellipse)….**

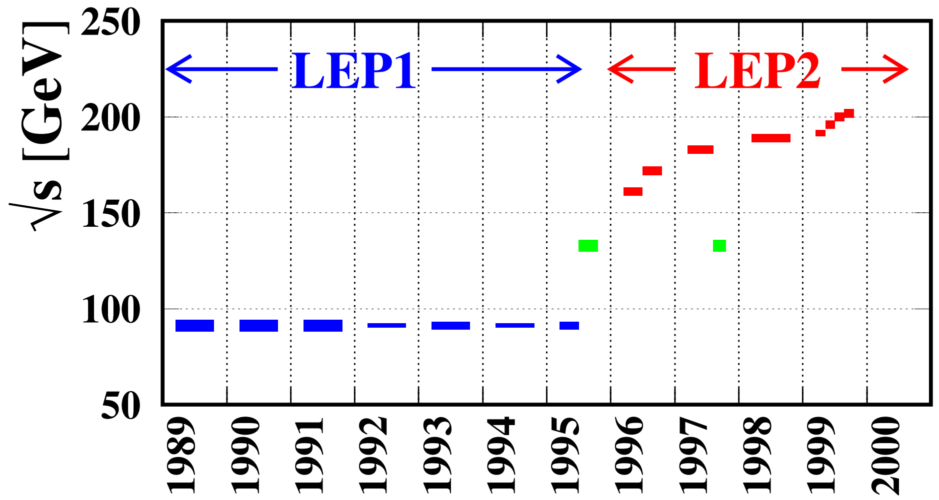


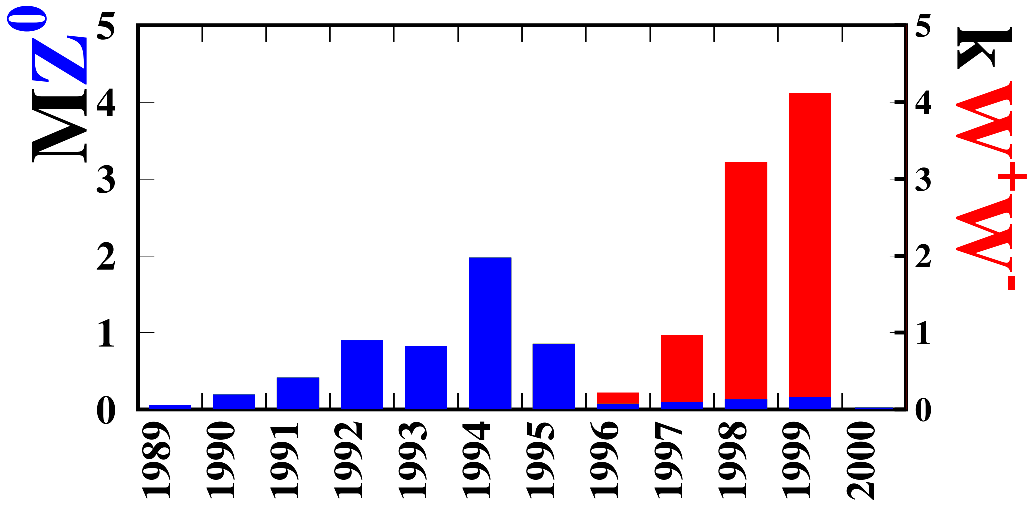

**….and now (blue ellipse)**

# A Brief History of LEP: 1989-2000

★ born.. Autumn 1989

★ R.I.P. Autumn 2000




★ Most results use 260 pb$^{-1}$ of data at $\sqrt{s} = 161 - 189$ GeV

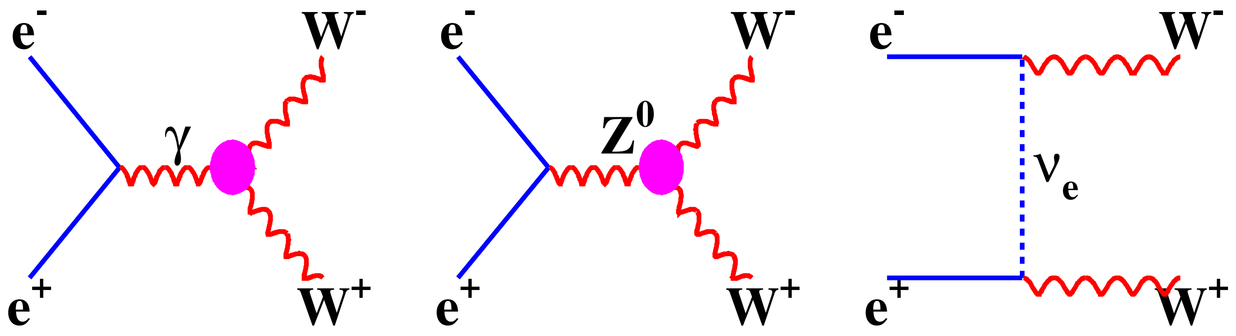
★ Final LEP 2 total 550-600 pb$^{-1}$ at $\sqrt{s} = 161 - 205$ GeV

★ Slight OPAL bias...

# $W^+W^-$ Production at LEP

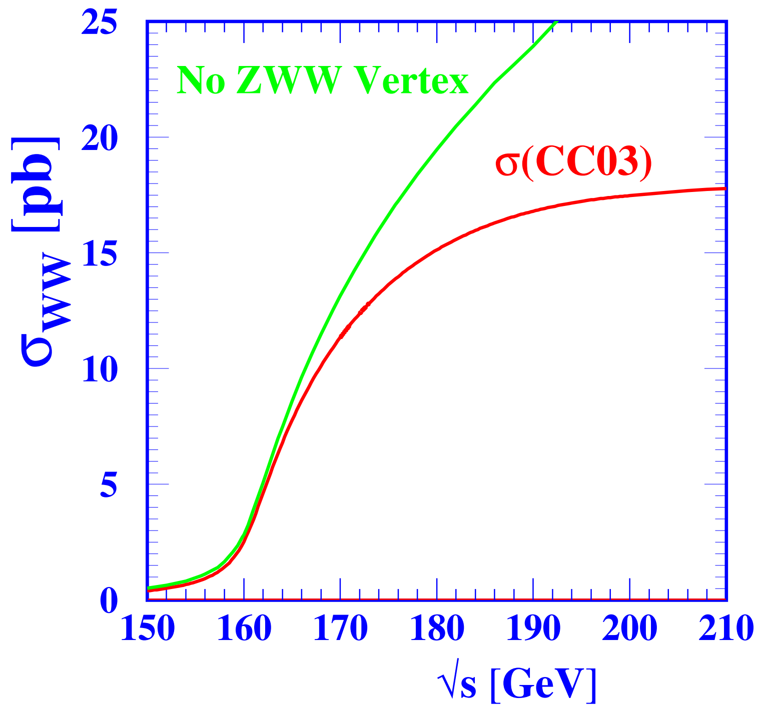
**Three Diagrams (CC03):**

- t-channel $\nu$ exchange
- s-channel $Z^0$ excgange
- s-channel $\gamma$ exchange




★ t-channel dominates - $W^-$ produced preferentially in direction of $e^-$

★ Main effect of s-channel is -ve interference



# $W^{\pm}$ Decay at LEP

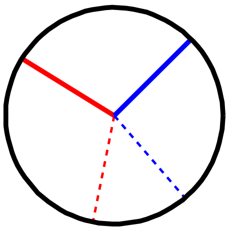
In SM: $W^{\pm}\ell\nu$ and $W^{\pm}q\overline{q}$ couplings are equal.

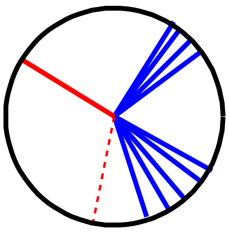
| | | | 3 TIMES | | |
|---|---|---|---|---|---|
| e | μ | τ | u | c | ~~t~~ |
| $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ | d | s | ~~b~~ |

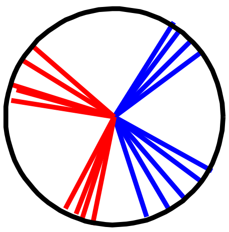
- ★ Br($W^{\pm} \rightarrow q\overline{q}$) = $\frac{2}{3}$
- ★ Br($W^{\pm} \rightarrow \ell\nu$) = $\frac{1}{3}$

QCD corrections enhance hadronic decay fraction by $\sim (1 + \alpha_s/\pi)$:

➡ Br($W^{\pm} \rightarrow q\overline{q}$) = 0.675

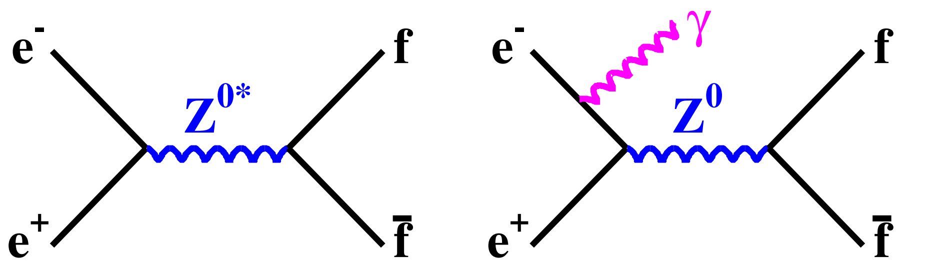
WW→lνlν  10.5 %

WW→qqlν  43.9 %

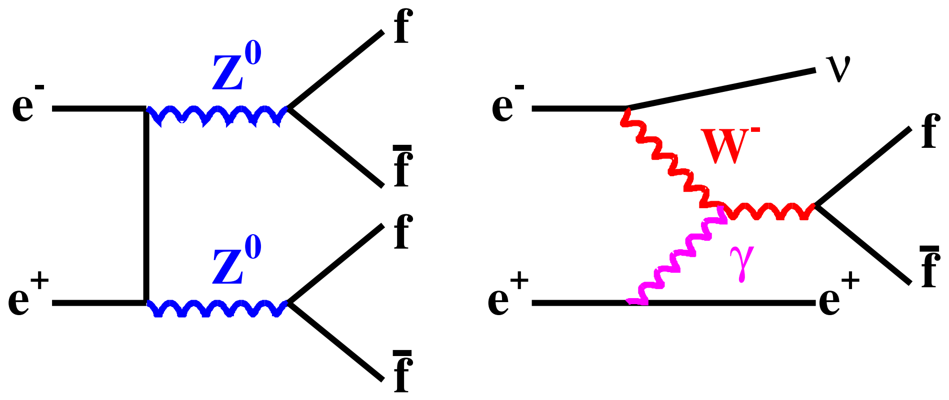
WW→qqqq  45.6 %

# Backgrounds to $W^+W^-$

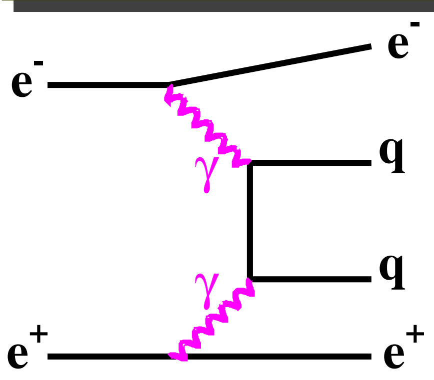
## 2F




## 4F

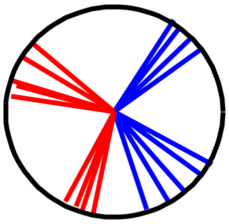



## TWO-PHOTON



# $W^+W^- \to q\bar{q}q\bar{q}$ Selection

**WW→qqqq**



- **Multivariate analysis to separate**

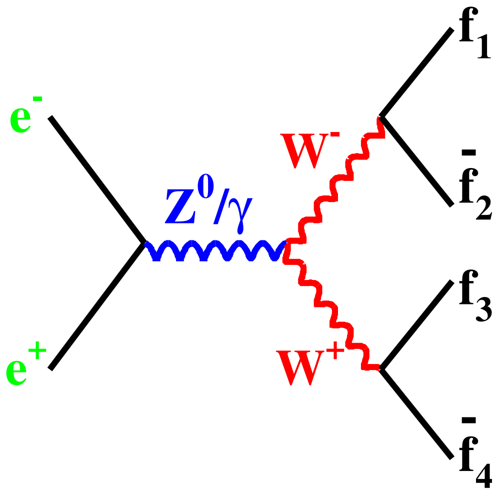
  $W^+W^- \to q\bar{q}q\bar{q}$ **and**

  $Z^0/\gamma \to q\bar{q} \to$ **4 jets**

**SIGNAL:**

**WW→qqqq**

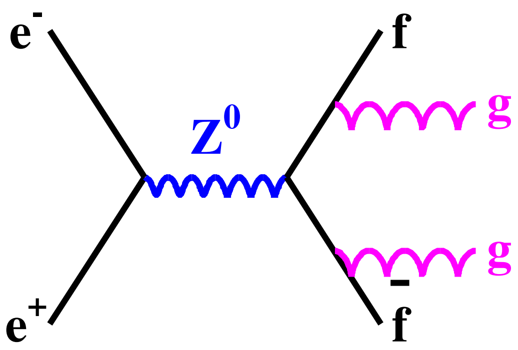
**σ ~ 8 pb**




**BACKGROUND**

**$Z \to qq\,gg$**

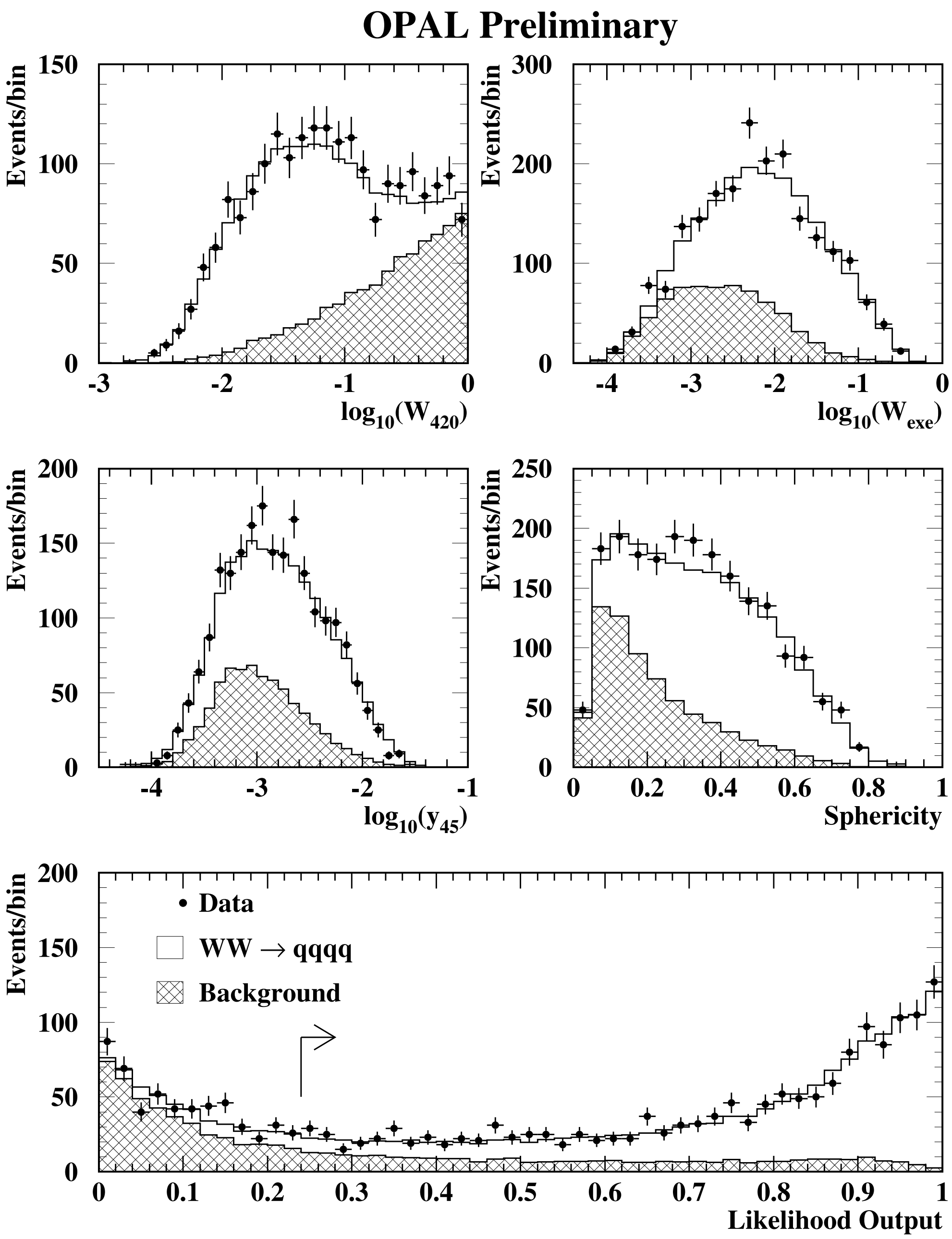
**$\sigma_{qq(gg)} \sim 100$ pb**



# SELECTION:

## Loose Cuts to select 4-jet events

## Likelihood Using 4 variables

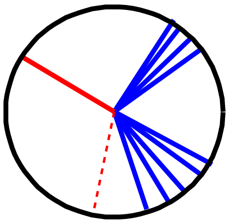



## For $\sqrt{s} = 189$ GeV:

| | Efficiency | Purity |
|---|---|---|
| OPAL | $\sim 86\%$ | $\sim 79\%$ |

# $W^+W^- \rightarrow q\overline{q}\ell\overline{\nu}_\ell$ Selection

$WW \rightarrow qql\nu$

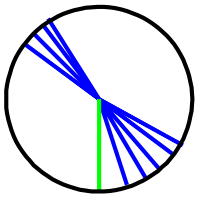


$\sigma \sim 7$ pb

## MAIN BACKGROUNDS :

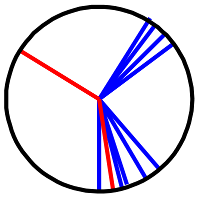
$e^+e^- \rightarrow qq$

(+fragmentation track)



$\sigma \sim 100$ pb

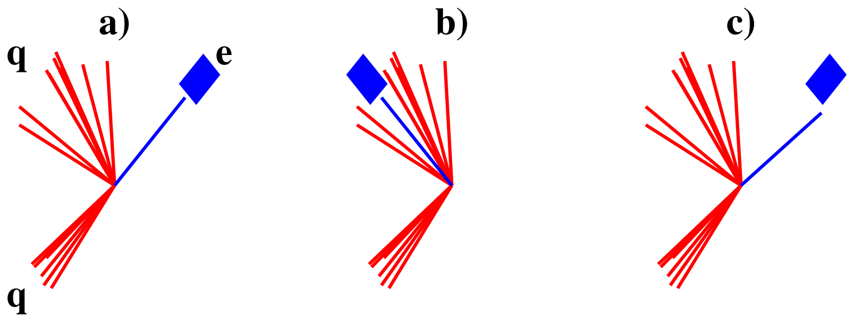
$ZZ \rightarrow qqll$



$\sigma \sim 140$ fb

**Selection:** Find most probable lepton candidate

**No explicit lepton ID/lepton isolation cuts**

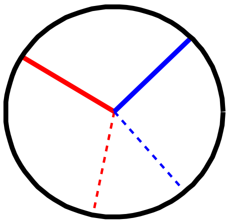



## Followed by multivariate likelihood

| | Efficiency | Purity |
|---|---|---|
| OPAL | 87% | 90% |

# $W^+W^- \to \ell\overline{\nu}_\ell \ell\overline{\nu}_\ell$ Selection

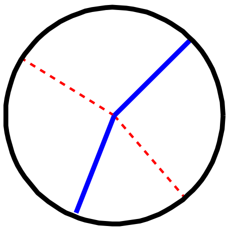
$WW \to l\nu l\nu$



$\sigma \sim 1.5$ pb

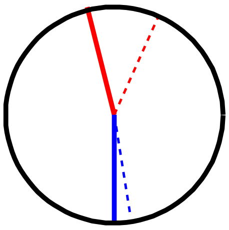
## MAIN BACKGROUNDS :

$ZZ \to ll\nu\nu$



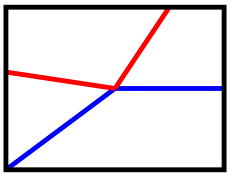
$\sigma \sim 50$ fb

$e^+e^- \to \tau^+\tau^-$



$\sigma \sim 8$ pb

$e^+e^- \to e^+e^-\mu^+\mu^-$



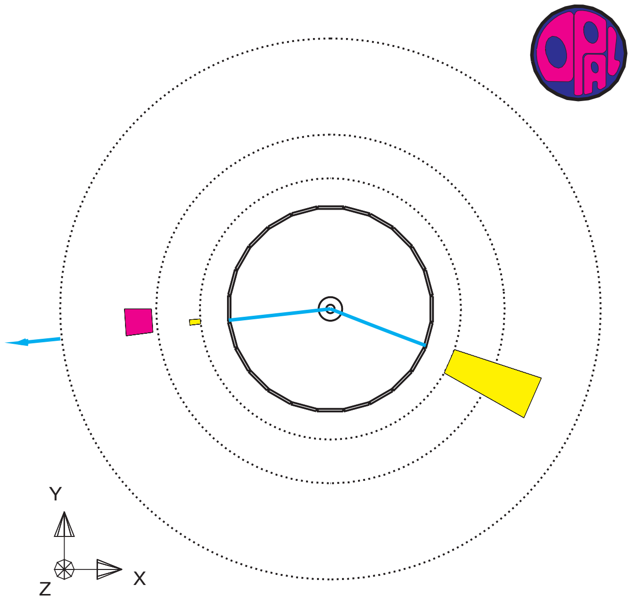
$\sigma \sim$ large

**SELECTION: (cuts) Acoplanar Leptons with significant missing $E_T$**

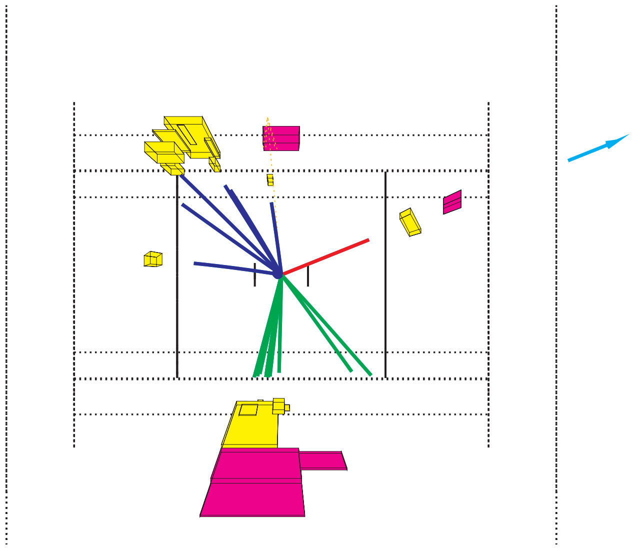
| | Efficiency | Purity |
|---|---|---|
| OPAL | 82% | 90% |

# $W^+W^-$ Events

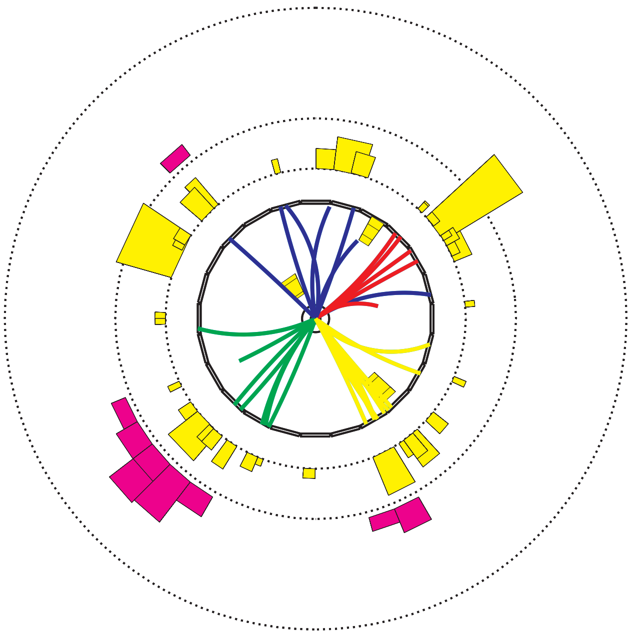
- Efficient Selections for all WW final states:



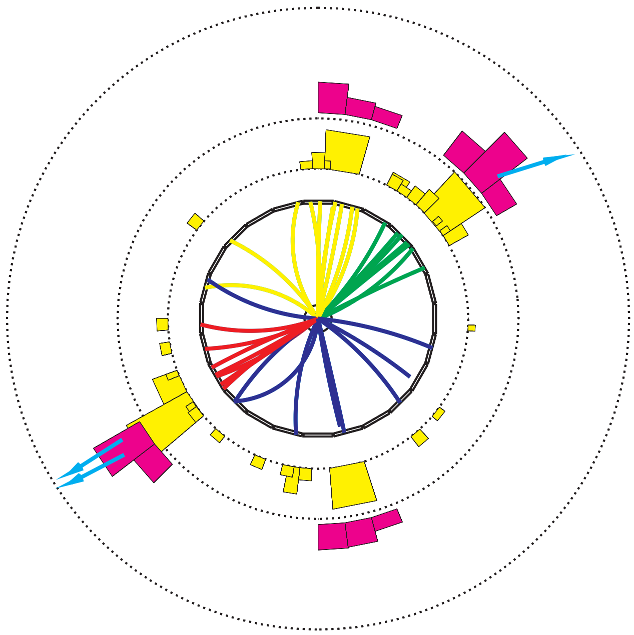

$W^+W^- \to \ell\overline{\nu}_\ell\ell\overline{\nu}_\ell$



$W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$



$W^+W^- \to q\overline{q}q\overline{q}$

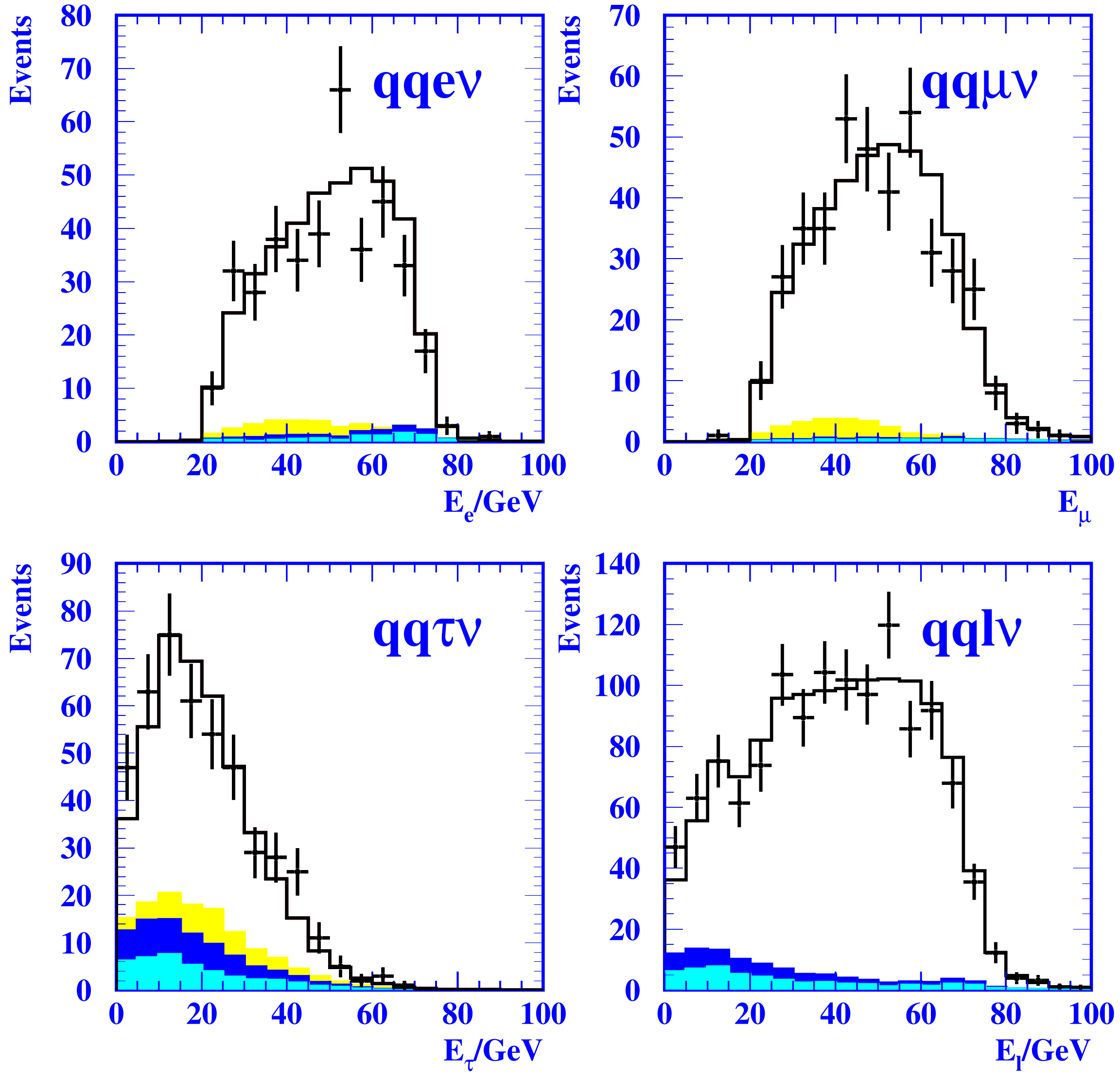


$W^+W^- \to q\overline{q}q\overline{q}$

# OPAL at 189 GeV

| Selection | Effic. | Purity | Expect | Observe |
|---|---|---|---|---|
| $W^+W^- \rightarrow \ell\overline{\nu}_\ell\ell\overline{\nu}_\ell$ | 82% | 90% | 290.0 | 278 |
| $W^+W^- \rightarrow q\overline{q}\ell\overline{\nu}_\ell$ | 87% | 90% | 1287.2 | 1252 |
| $W^+W^- \rightarrow q\overline{q}q\overline{q}$ | 86% | 79% | 1511.1 | 1546 |
| Combined | 87% | 85% | 3088.3 | 3076 |

- **Good agreement between data and MC....e.g.**



# W Decay Branching Fractions

★ **Use numbers of events to determine W Decay Branching Fractions**

## LEP COMBINED RESULTS

(Assuming W decays only to SM fermions)

$$\mathbf{BR(W \to e\nu) = 10.61 \pm 0.25\%}$$
$$\mathbf{BR(W \to \mu\nu) = 10.65 \pm 0.24\%}$$
$$\mathbf{BR(W \to \tau\nu) = 10.82 \pm 0.32\%}$$

BR(W$\to l\nu$) = 10.83 % (Standard Model)

Assuming lepton univerality

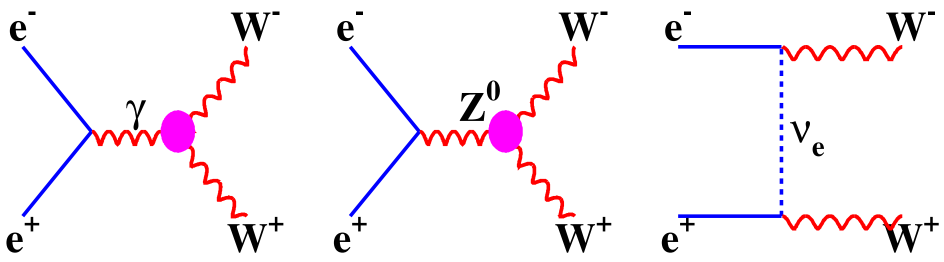
$$\mathbf{BR(W \to q\overline{q}) = 67.96 \pm 0.41\%}$$

BR(W$\to q\overline{q}$) = 67.51 % (Standard Model)

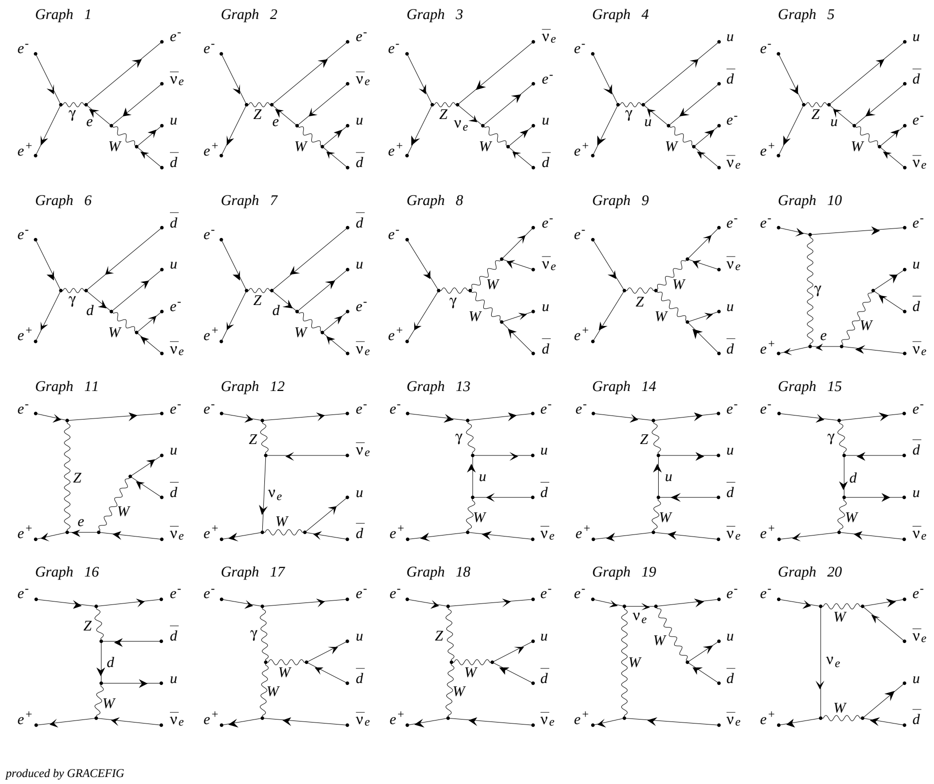
★ $\mathrm{W^{\pm}f\overline{f}}$ **couplings consistent with SM**

# ❷ $\mathrm{W^+W^-}$ Cross Section

Want measure $\mathrm{W^+W^-}$ Cross section (CC03)




Correct for background and interference from other four-fermion diagrams, e.g. $\mathrm{q\overline{q}e\overline{\nu}_e}$




★ **Effective 4f background:**

$$\sigma(4f)^{ACC} - \sigma(CC03)^{ACC}$$

**'CC03' Cross-section not Gauge Invariant**

# It could be worse....

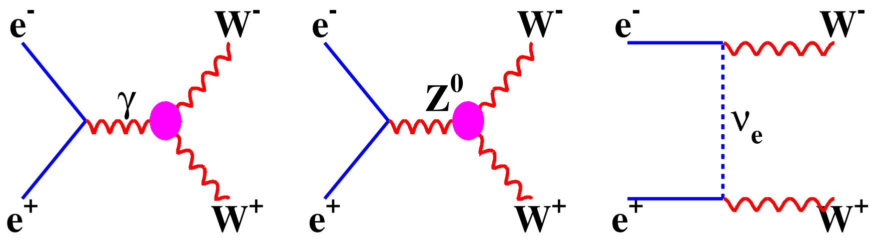
## 144 diagrams for $e^+e^- \rightarrow e^+e^-e^+e^-$

*produced by GRACEFIG*

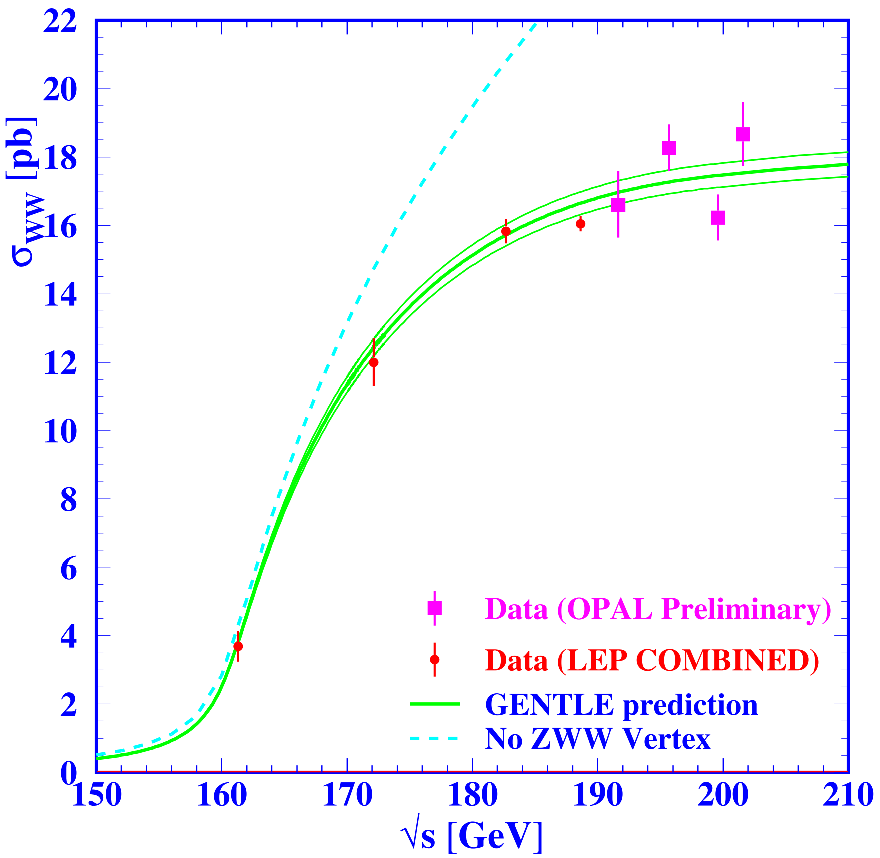
★ **Wait until 500 GeV linear collider:**

$e^+e^- \rightarrow 6$ **fermions**

# $W^+W^-$ Cross Section Results




## LEP COM COMBINED CC03 Cross Section




**Expt. Error $\sim 1.0\ \%$ vs Theory Error $2.0\ \%$**

**RacoonWW: $\sim 2.5\ \%$ lower than GENTLE**

- ★ **At Threshold : $\sigma_{W^+W^-}$ Sensitive to $M_W$**
- ★ **$\sigma_{W^+W^-}$ sensitive to Triple Gauge Couplings**

# ❸ $W^+W^-$ COUPLINGS

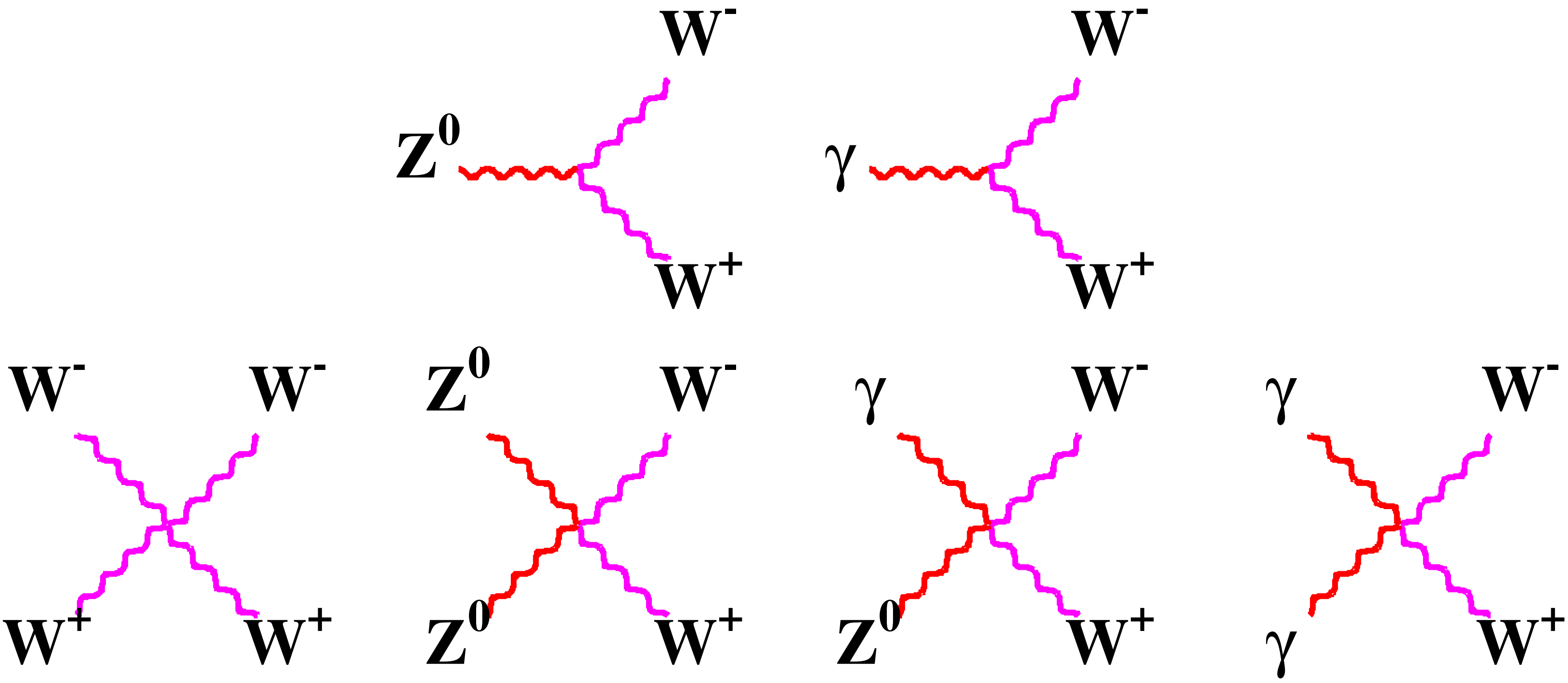
$SU(2) \times U(1)$ Gauge Invariance $\Rightarrow$ Vector Boson Self-Interactions

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

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

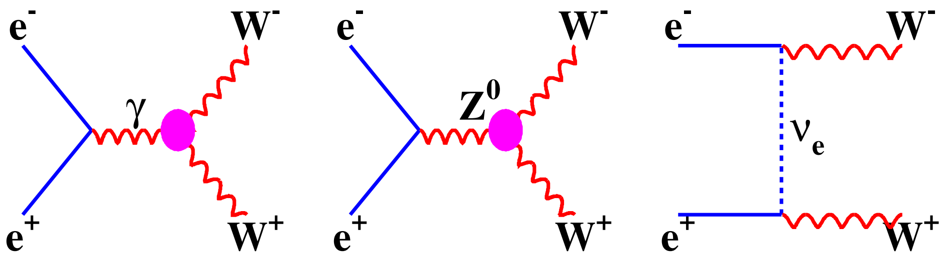
➡ TGCs and QGCs

In the Standard Model:




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

# Triple Gauge Couplings




★ Non-SM physics Parameterised by additional terms in the Lagrangian

★ 7 independent parameters in a general Lorentz-invariant Langrangian which describes the $\mathrm{Z^0W^+W^-}$ or $\gamma\mathrm{W^+W^-}$ vertex

★ 4 are C,P, or CP non-conserving: assumed zero

$$
\begin{aligned}
i\frac{\mathcal{L}_{\mathrm{TGC}}}{g_{WWV}} = \quad & g_1^V V_\mu (W^{-\mu\nu} W_\nu^+ + W^{+\mu\nu} W_\nu^-) \\
& \kappa_V V^{\mu\nu} W_\mu^- W_\nu^+ \\
& \lambda_V / M_{\mathrm{W}}{}^2 V^{\mu\nu} W_\nu^{+\rho} W_{\rho\nu}^-
\end{aligned}
$$

with $V = \gamma/\mathrm{Z}^0, g_{WWV} = e, g_{WW\gamma} = e\cot\theta_W$.

★ SM : $g_1^V = 1, \kappa_V = 1, \lambda_V = 0$

# Standard LEP TGC Parameters

★ **At LEP non-SM TGC are considered as deviations from the SM values.**

$$\Delta g_1^V = g_1^V - 1$$
$$\Delta \kappa_V = \kappa_V - 1$$
$$\lambda_V$$

**i.e. non-zero values ➡ SM = R.I.P**

Further Assumptions:

★ $U(1)_{em}$ **Invariance :**

$$q_W = e\, g_1^V = e \Rightarrow g_1^\gamma = 1$$

★ **Requiring** $SU(2)_L \times U(1)_Y$ **Invariance ➡:**

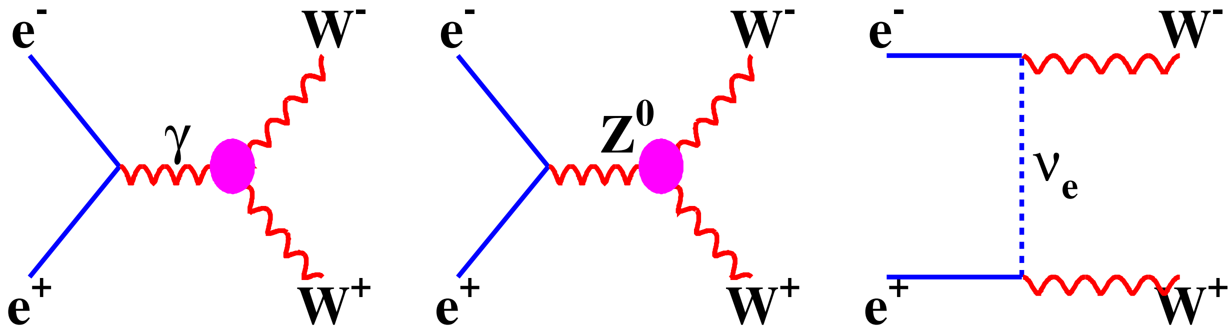
$$\Delta\kappa_Z = \Delta g_1^Z - \tan^2\theta_W \Delta\kappa_\gamma$$
$$\lambda_Z = \lambda_\gamma = \lambda$$

Leaving Three Parameters:

$$\boxed{\Delta\kappa_\gamma, \Delta g_1^Z, \lambda}$$

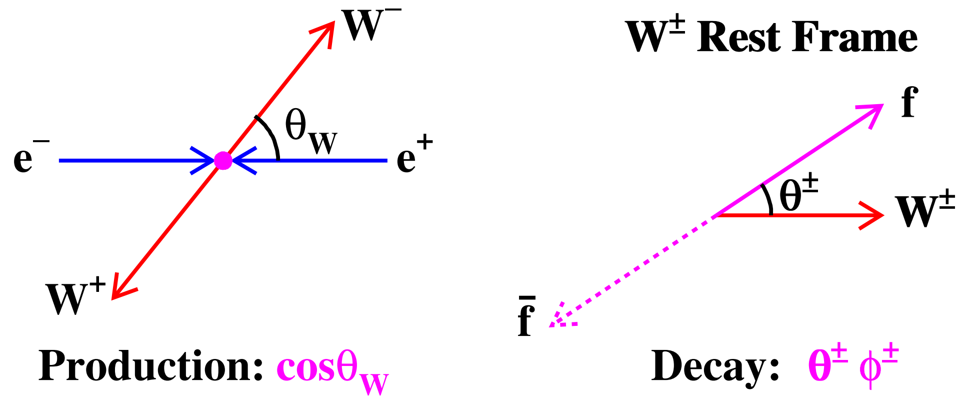
★ **all zero in SM**

# Measuring the TGCs




**TGC Sensitive Observables :**

- ☆ $W^+W^-$ **Production Cross Section**
- ❤ $W^+W^-$ **Production Angle,** $\cos\theta_{W^-}$
- ★ $W^\pm$ **Decay Angles (helicity of** $W^\pm$**)**

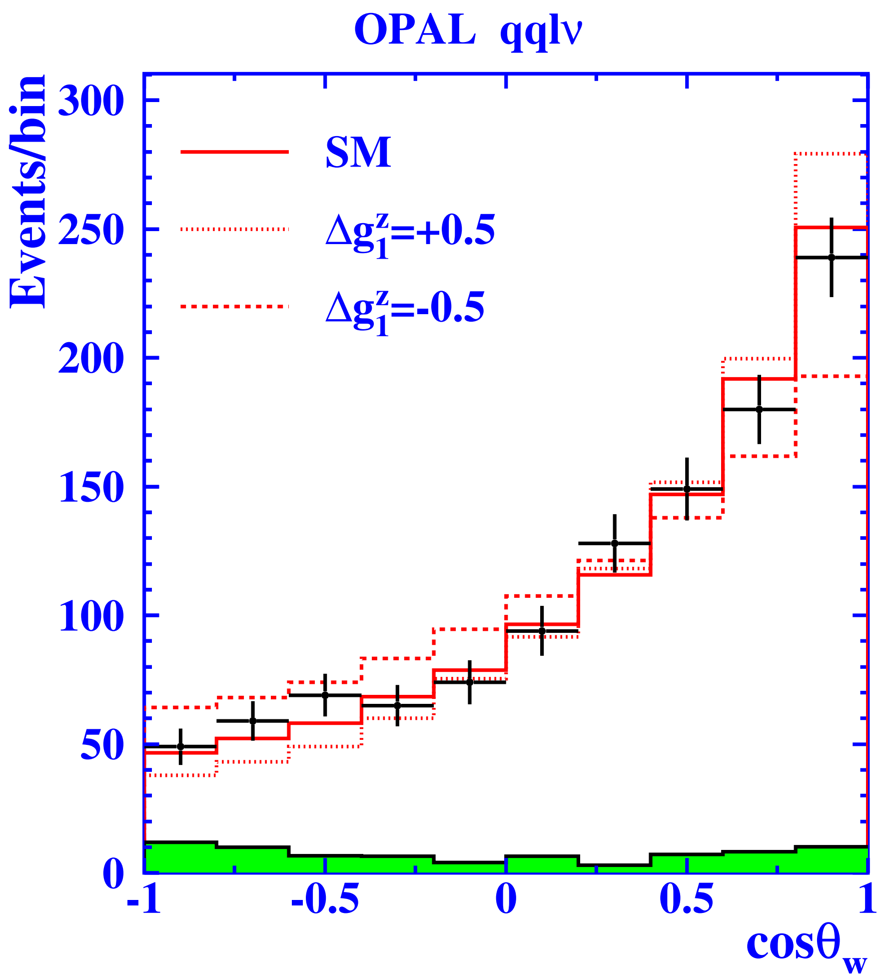



**EXPERIMENTALLY:**

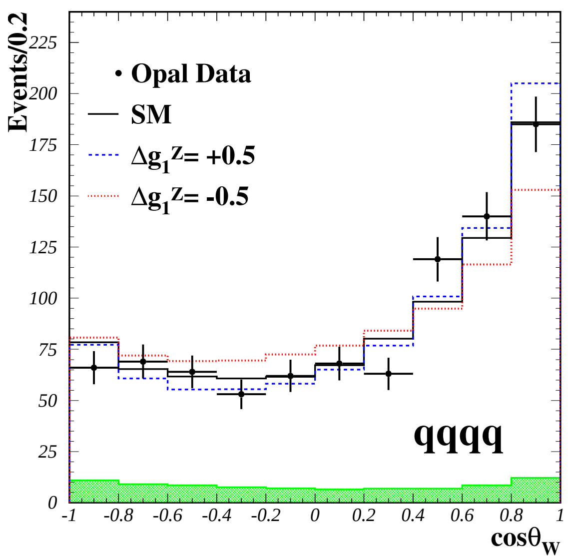
- ★ **Kinematic fit $\Rightarrow$ W production and decay angles**
- ★ **Different channels sensitive to different angles**
- ★ $W^+W^- \rightarrow q\bar{q}\ell\overline{\nu}_\ell$ **'golden' channel: lepton**
  ➨ **W charge**

# TGC from $q\overline{q}\ell\overline{\nu}_\ell$ and $q\overline{q}q\overline{q}$

★ **Extract TGCs by fitting angular distributions**

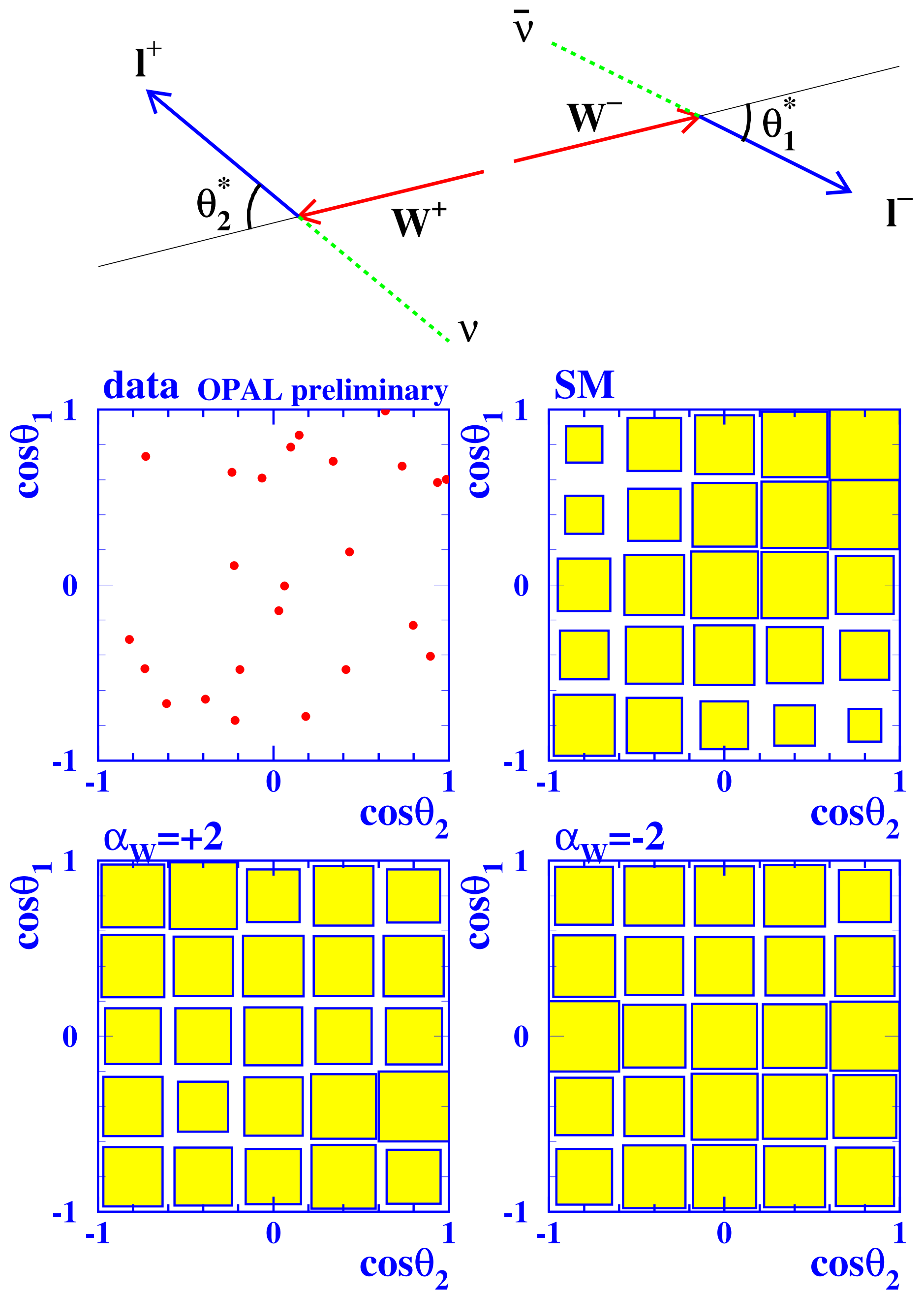



- $q\overline{q}q\overline{q}$ **channel more difficult: e.g. jet charge to get sign of $\cos\theta_W$**



# TGCs from $W^+W^- \rightarrow \ell^+\nu_\ell \ell'^- \overline{\nu}_{\ell'}$

- BR($W^+W^- \rightarrow \ell^+\nu_\ell \ell'^- \overline{\nu}_{\ell'}$) $\sim 11\%$
- Final states with $\tau$s not useful
- Useful BR $\sim 5\%$ **BUT** sensitive to different angles.
- Both W-decay polar angles be determined.

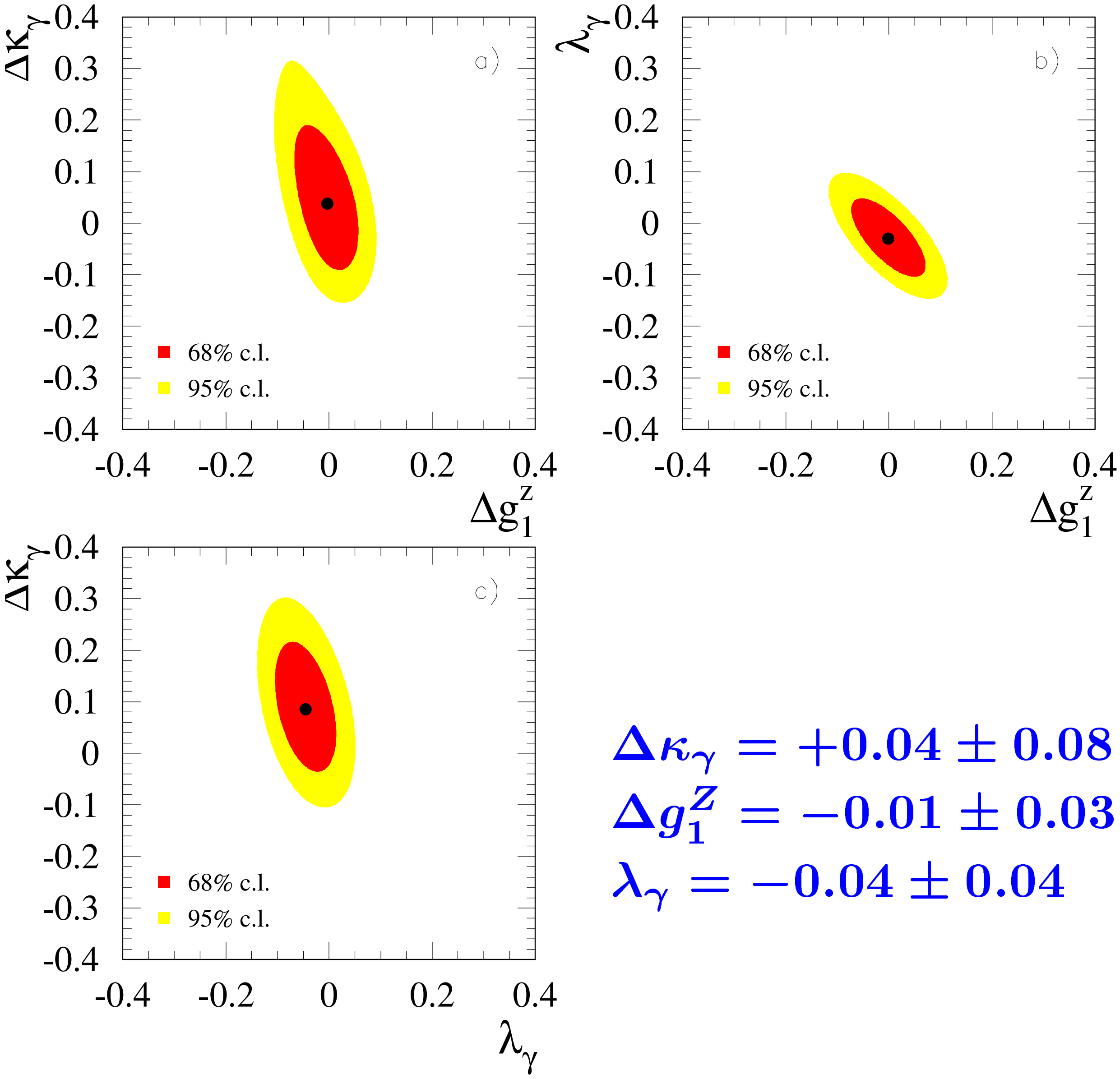


# Combined TGC Results

**4 LEP Collaborations fit 5D angular ➡ TGCs:**

- ★ **Binned Maximum Likelihood**
- ★ **Optimal Observables**
- ★ **Spin Density Matrix**

## LEP COMBINED 161-189 GeV data




$$\Delta\kappa_\gamma = +0.04 \pm 0.08$$
$$\Delta g_1^Z = -0.01 \pm 0.03$$
$$\lambda_\gamma = -0.04 \pm 0.04$$

**No indication of anomalous TGCs**

# Interpretation

★ **This is not another failed search !**

★ **Measuring the strength of $W^+W^-Z^0$ and $W^+W^-\gamma$ couplings**

**LEP Combined:**

$$\kappa_\gamma = 1.04 \pm 0.08$$
$$g_1^Z = 0.99 \pm 0.03$$
$$\lambda_\gamma = -0.04 \pm 0.04$$

(1,1,0) in SM.

$$
\begin{aligned}
i\frac{\mathcal{L}_{\mathrm{TGC}}}{g_{WWV}} = \quad & (1.04 \pm 0.08) \quad V_\mu(W^{-\mu\nu}W^+_\nu + W^{+\mu\nu}W^-_\nu) \\
& (0.99 \pm 0.03) \quad V^{\mu\nu}W^-_\mu W^+_\nu \\
& (-0.04 \pm 0.04) \quad /{M_{\mathrm{W}}}^2 V^{\mu\nu}W^{+\rho}_\nu W^-_{\rho\nu}
\end{aligned}
$$

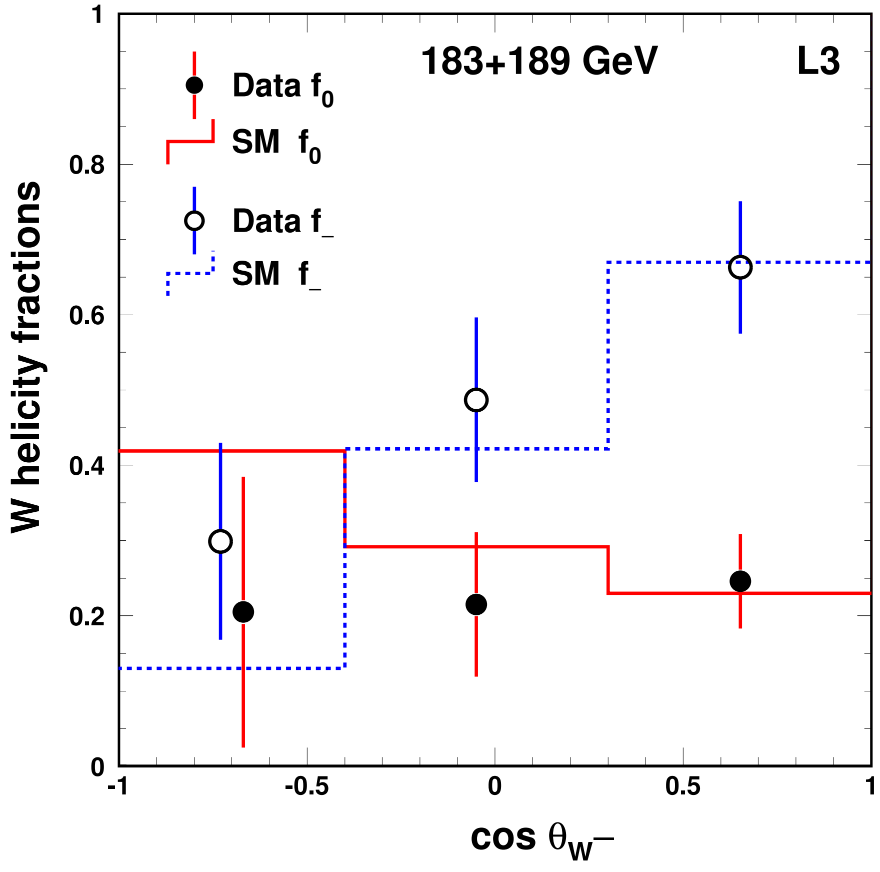
**5 % MEASUREMENT OF TGCs**

# Longitudanal W Boson Production

## Helicity Analysis (W decay angles alone)

$$\frac{1}{N}\frac{dN}{dx} = f_{-}\frac{3}{8}(1+x)^2 + f_{+}\frac{3}{8}(1-x)^2 + f_L\frac{3}{4}(1-x^2)$$

with $x = \cos\theta^*$




$$f(\mathrm{W}^{\pm}{}_L) = 0.261 \pm 0.053$$

0.26 in SM.

★ $5\sigma$ observation of $W_L$

# Quartic Gauge Couplings at LEP

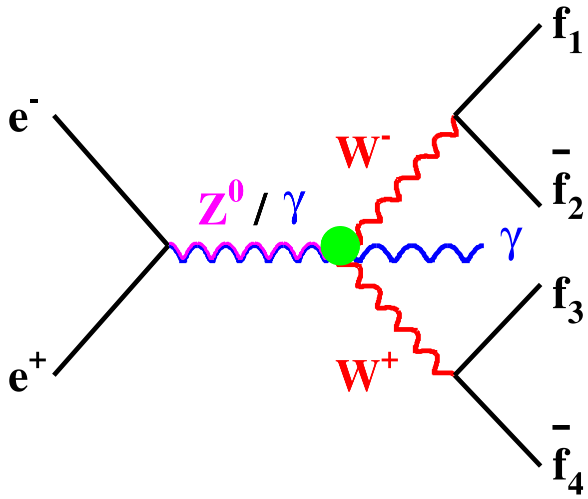
**SM Lagrangian ➡ TGCs and QGCs**

**Senstive to SM QGCs at LEP ?**

$W^+W^-\gamma$

$\rightarrow$ $WW\gamma\gamma$

& $WWZ\gamma$




**NO ! In the SM: effects too small to be observable at LEP ➡**

**★ Look for anomalous contributions ★**

**★ Previously no Direct limits on Anom QGCs**

**Parameterise by additional terms in Lagrangian:**

**(Bélanger and Boudjema)**

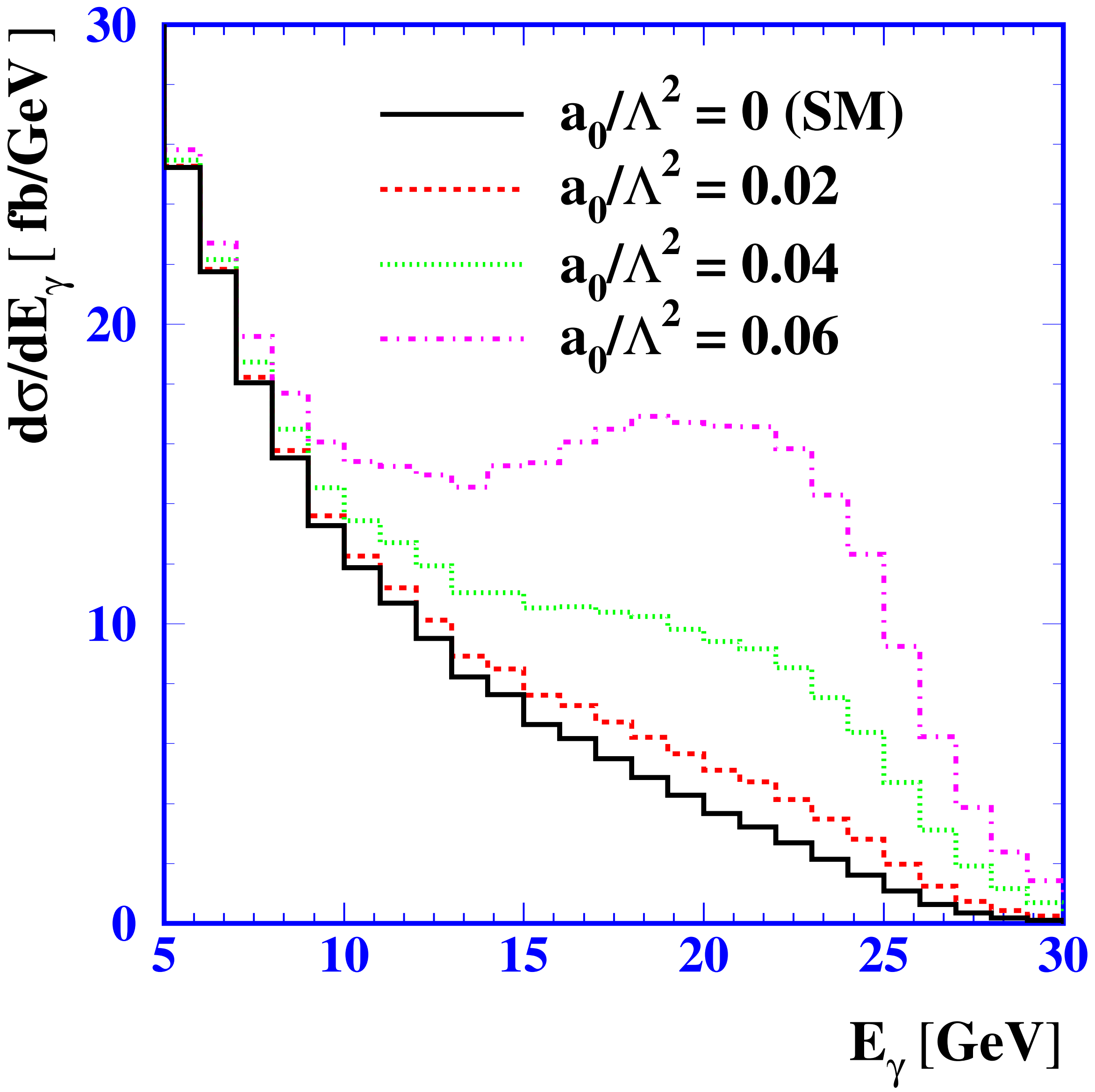
$$\mathcal{L}^0 = -\frac{e^2}{16}\frac{a_0}{\Lambda^2}F^{\mu\nu}F_{\mu\nu}\,\vec{W}^{\alpha}\,.\,\vec{W}_{\alpha}$$

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

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

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

calculation of Stirling and Werthenbach, hep-ph/9903315



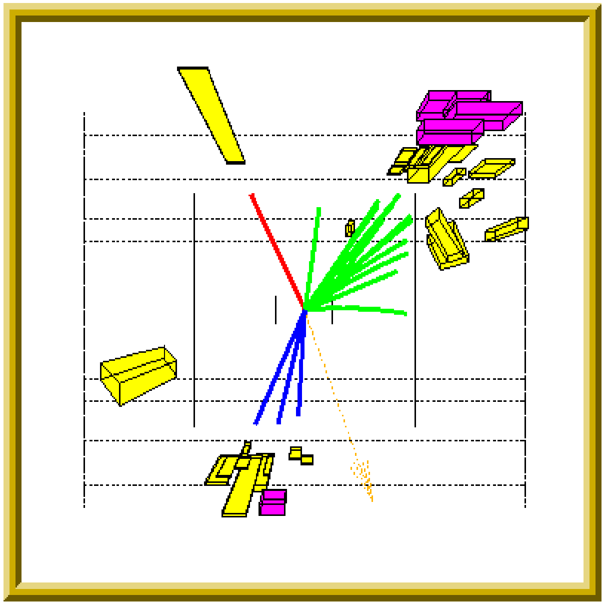

**Anomalous QGCs $\Rightarrow$ Excess of high energy photons in $W^+W^-$ Events**

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

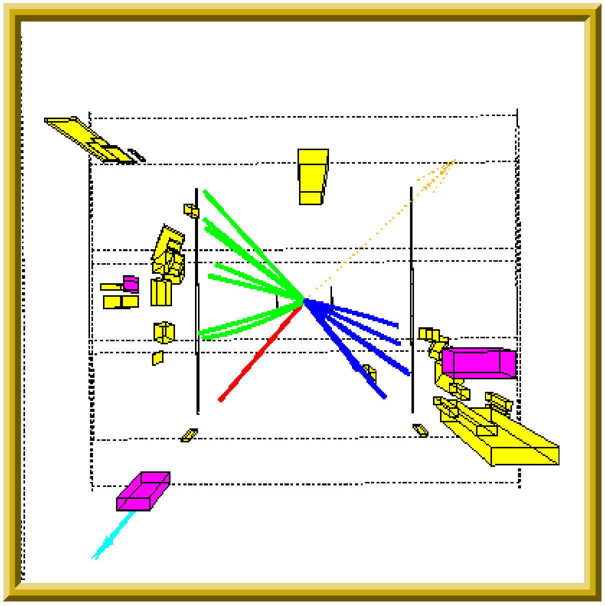
$W^+W^-\gamma$ **Selection Requires :**

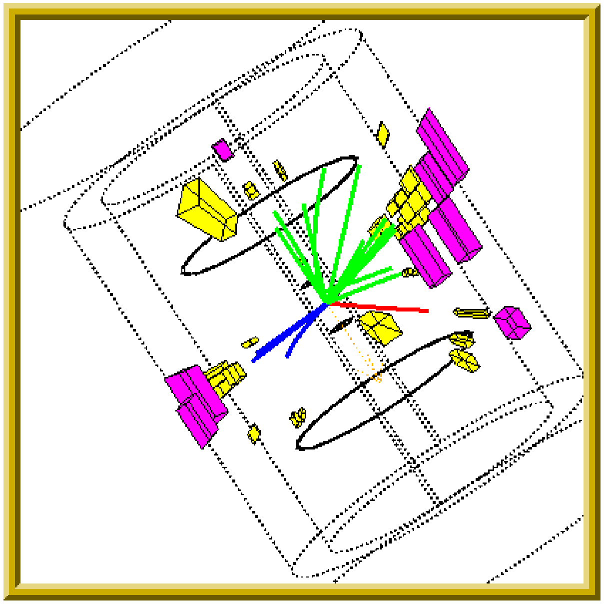
- $E_\gamma > 10$ **GeV**
- $|cos\theta_\gamma| < 0.9$ **(reduce ISR)**
- $cos\theta_{\gamma f} < 0.9$ **(reduce FSR)**

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

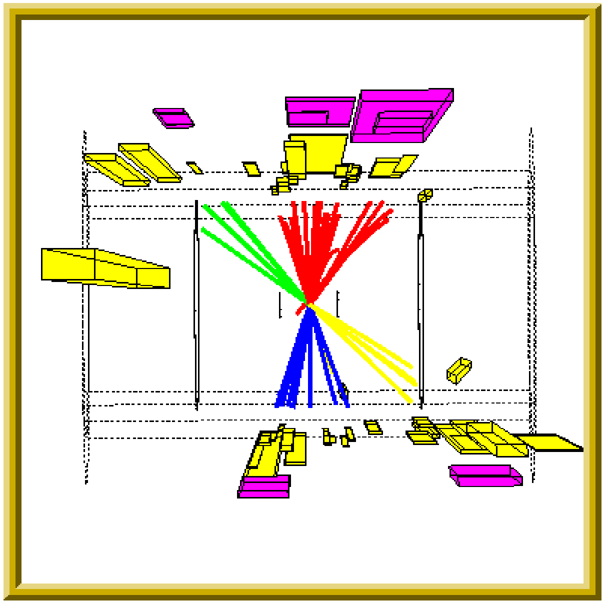


$W^+W^- \rightarrow qq\mu\nu\gamma$





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



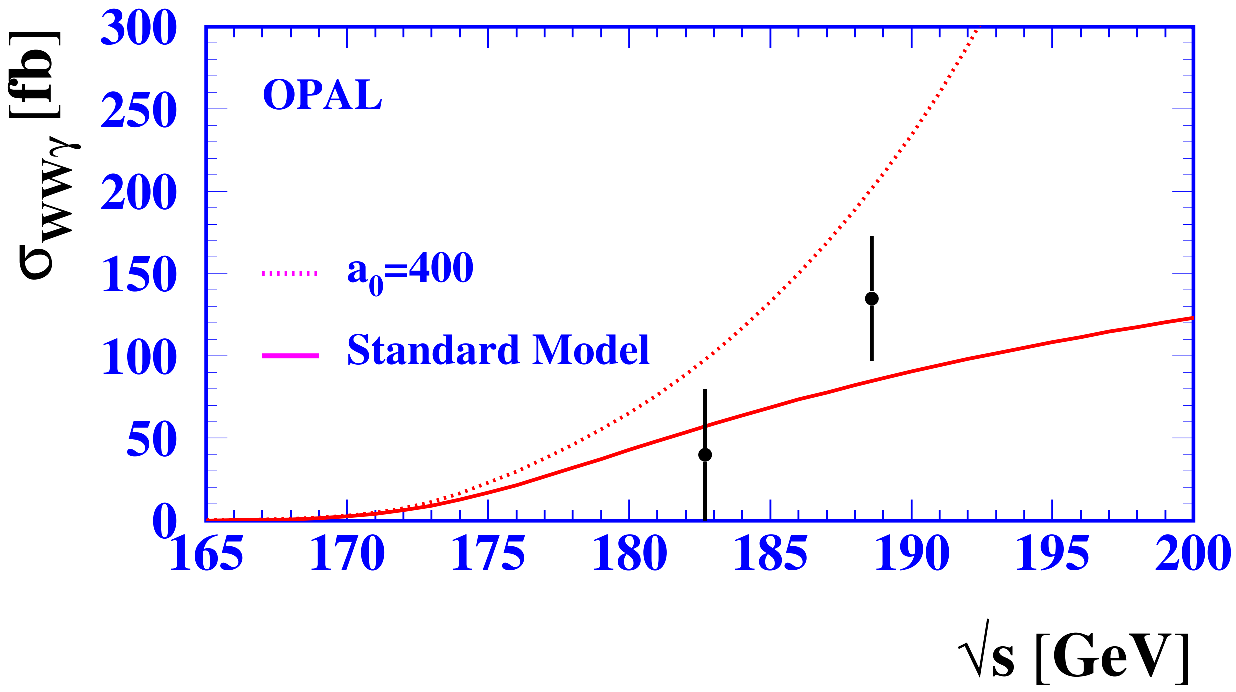
$W^+W^- \rightarrow qqqq\gamma$

# OPAL $\sigma_{WW\gamma}$ Study

| OPALData | 17 |
|---|---|
| KORALW | 13.4 |
| WWF | 11.6 |
| EEWWG | 11.9 |

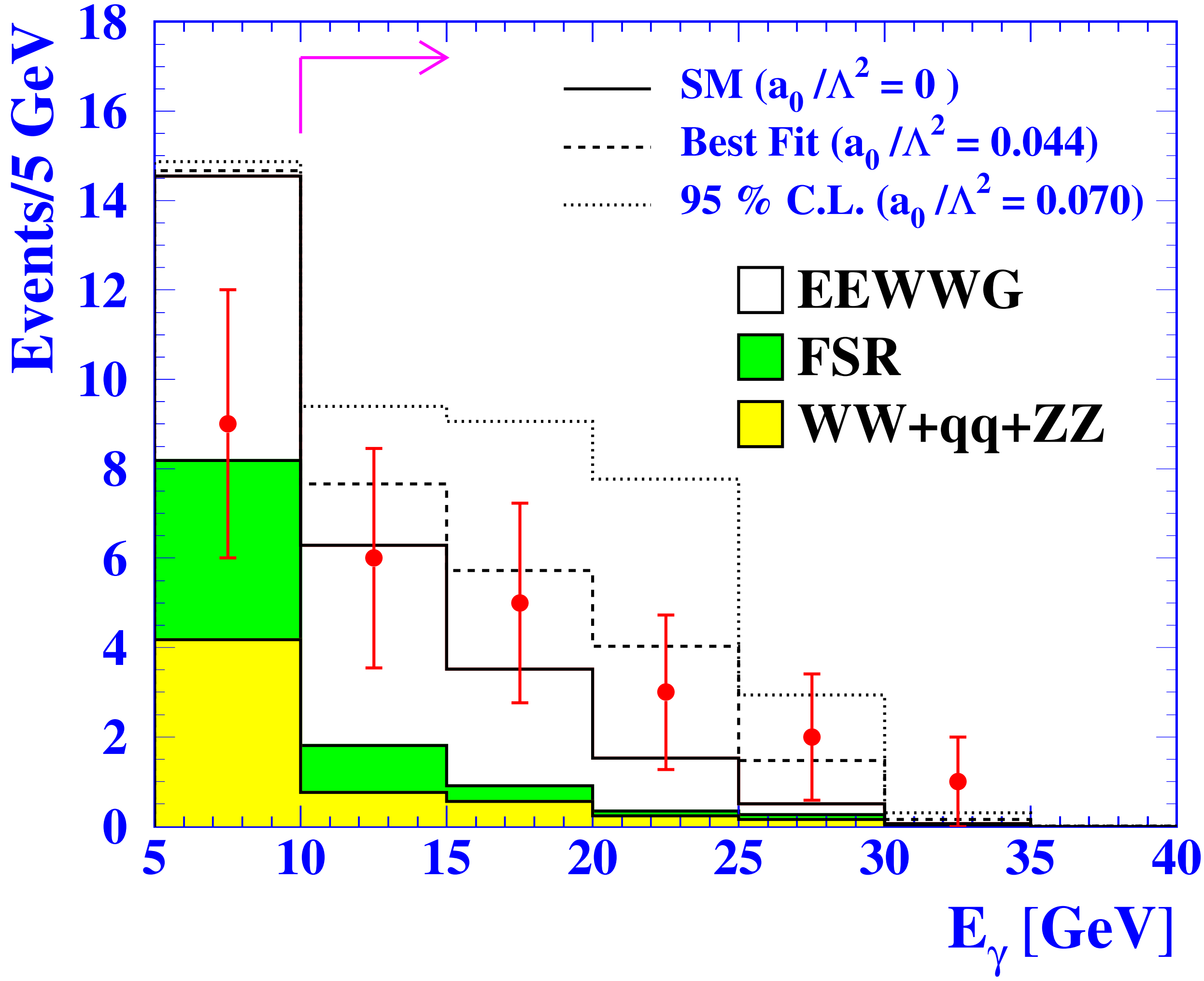
$$\sigma_{WW\gamma} = 136 \pm 37 \pm 8 \text{ fb}$$

(compare to $W^+W^-$ cross-section of 16.5 pb)




★Consistent with **SM** expectation

# Anomalous QGC Fits




★ **95 % Confidence Limits:**

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

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

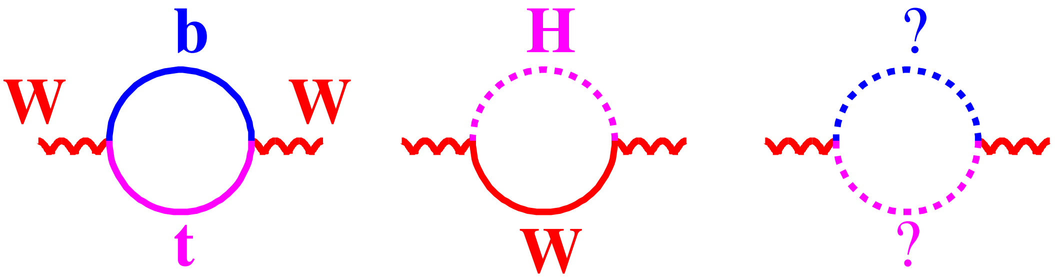
★ **First Direct limits on AQGCs**

**COUPLINGS OK....** $M_{\mathrm{W}}$ **?**

# ❹ $W$ MASS

## WHY MEASURE $M_W$ ?

- ★ Its there !
- ★ Test the self-consistency of SM
- ★ Sensitive to $m_H$ through radiative corrections



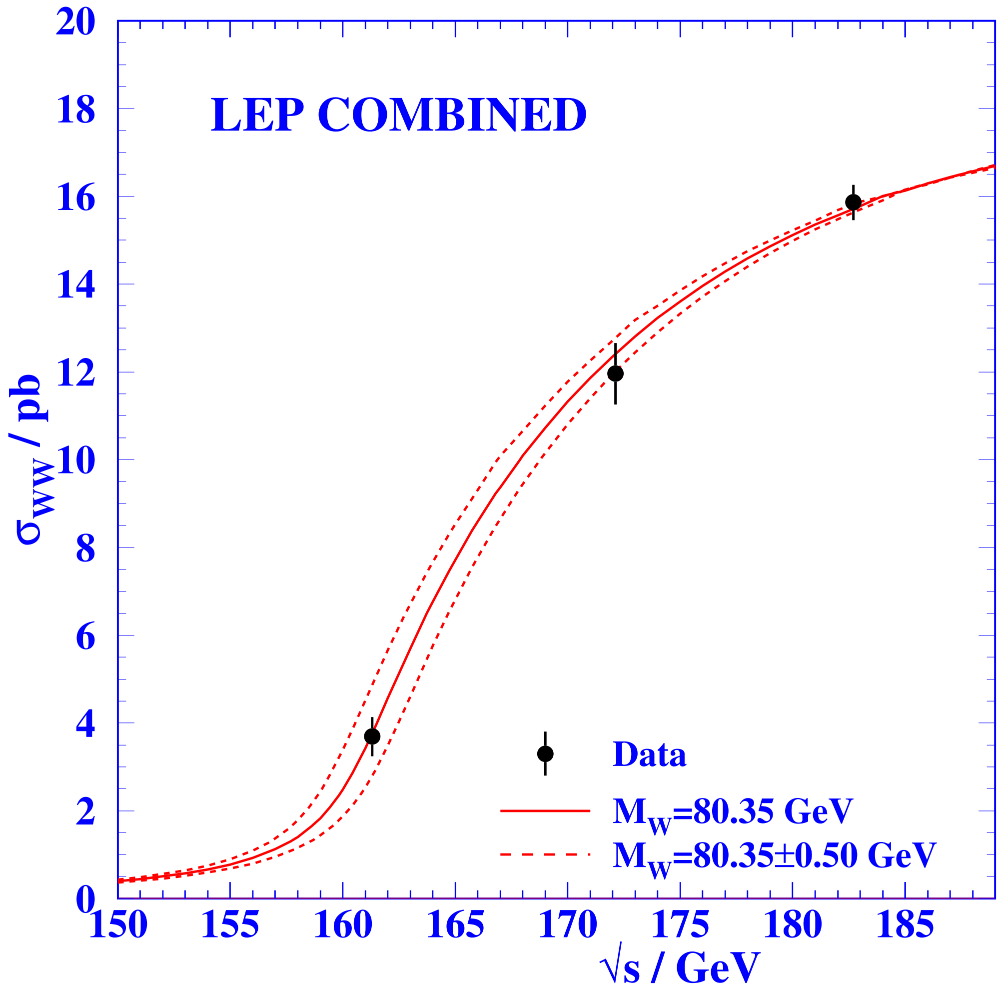

$\propto m_t^2$ $\propto \ln(m_H)$ $\propto ?$

## HOW ?

- ★ Threshold Cross-section ($\sqrt{s} \sim 161$ GeV)
- ★ Direct Reconstruction ($\sqrt{s} > 161$ GeV)

# $M_W$ from Threshold Cross Section

- At threshold: $W^+W^-$ cross-section sensitive to $M_W$




**LEP COMBINED** (10 pb$^{-1}$/expt. at 161 GeV)

$$M_W^{\text{threshold}} = 80.40 \pm 0.22 \text{ GeV}$$

# $M_W$ from Direct Reconstruction

★ $M_W$ deterimined from the kinematic reconstruction of the invariant mass of the $W^+W^-$ decay products

**Leading order $\sigma$ for $W^+W^-$ production:**

$$d^2\sigma(\sqrt{s}, m_1, m_2) = \sigma_0(\sqrt{s}, m_1, m_2)\rho(m_1)\rho(m_2)dm_1 dm_2$$

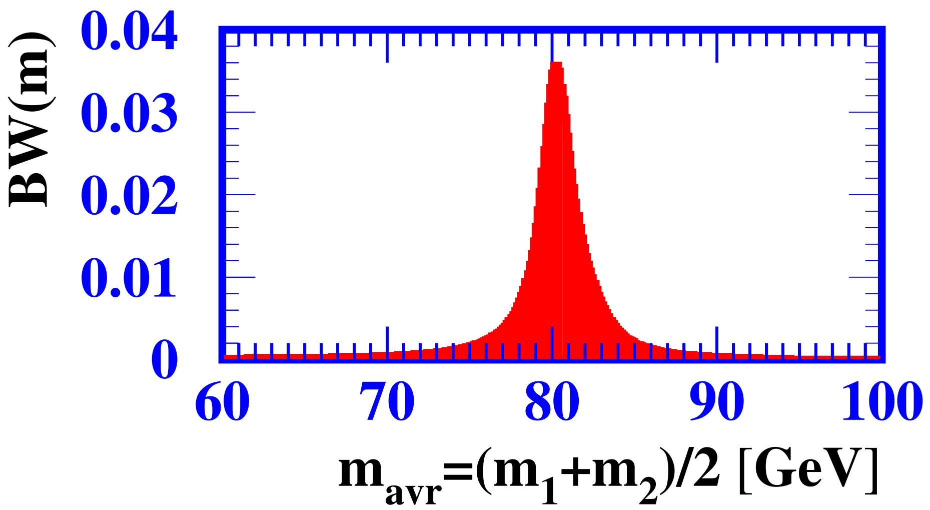
★ $m_1, m_2$ are invariant masses of the decay products of the two W bosons

★ $\rho(m)$ = relativistic Breit-Wigner (BW)

$$\rho(m) = \frac{m^2}{(m^2 - M_W{}^2)^2 + m^2\Gamma_W{}^2}$$

**In Practice Reconstruct :**

$$m_{avr} = (m_1 + m_2)/2$$

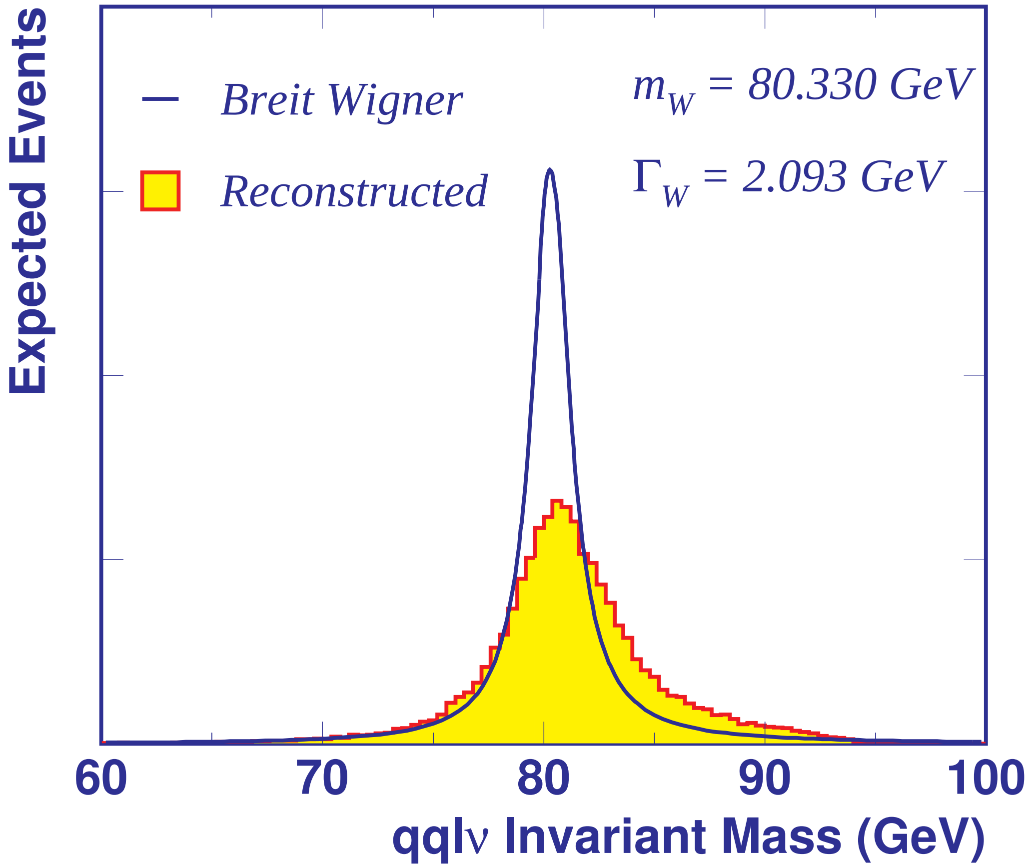


# Mass Reconstruction

**Two Distinct Stages:**

★ **Reconstruct Mass Distribution**

★ **Fit** $M_{\mathrm{W}}$




**Mass Distribution Distorted by**

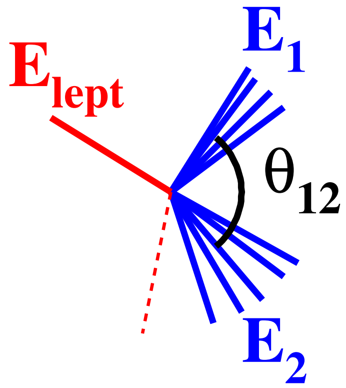
★ **Experimental Resolution**

★ **Event Selection...**

★ **ISR**

➡ **systematics**

# Mass Reconstruction : $W^+W^- \rightarrow q\overline{q}\ell\overline{\nu}_\ell$




★ **Jet angles better measured than energies.**

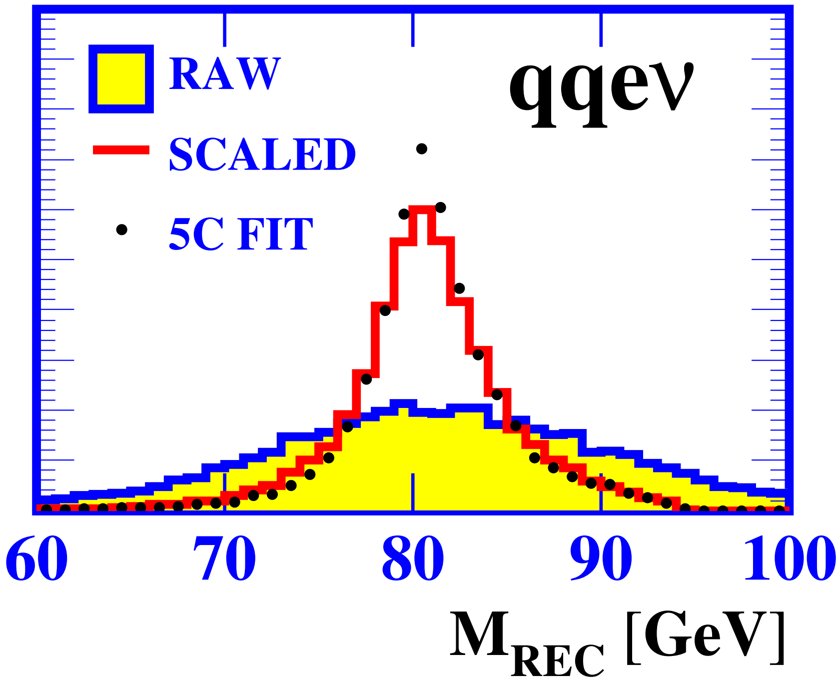
**Mass Reconstruction:**

❶ Raw : $M_{q\overline{q}} = \sqrt{2E_1E_2}(1 - \cos\theta_{12})$

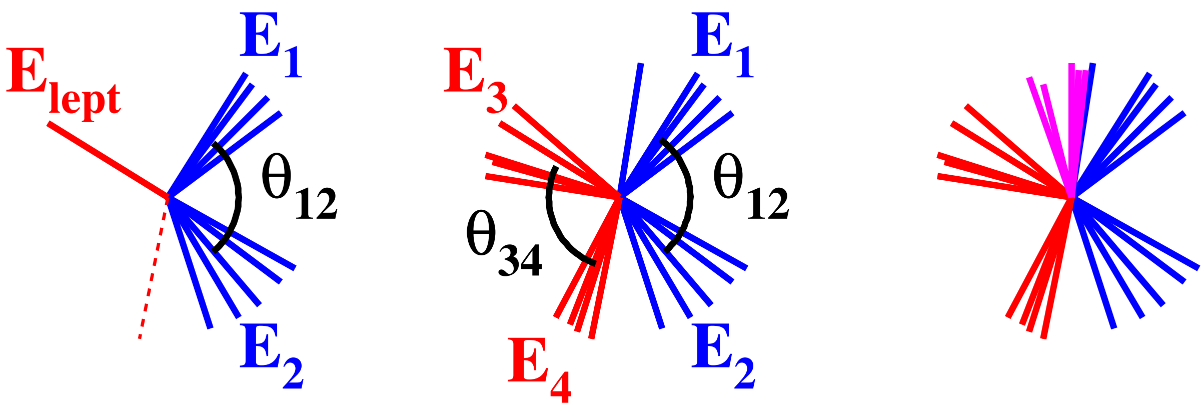
❷ Scaled : $M'_{q\overline{q}} = M_{q\overline{q}}\frac{E_{beam}}{(E_1+E_2)}$

❸ Kinematic fit (4C) using $(E, \underline{p})$ conservation

❹ Kinematic fit (5C) = 4C and $m_1 = m_2$



# Mass Reconstruction : $W^+W^- \rightarrow q\overline{q}q\overline{q}$

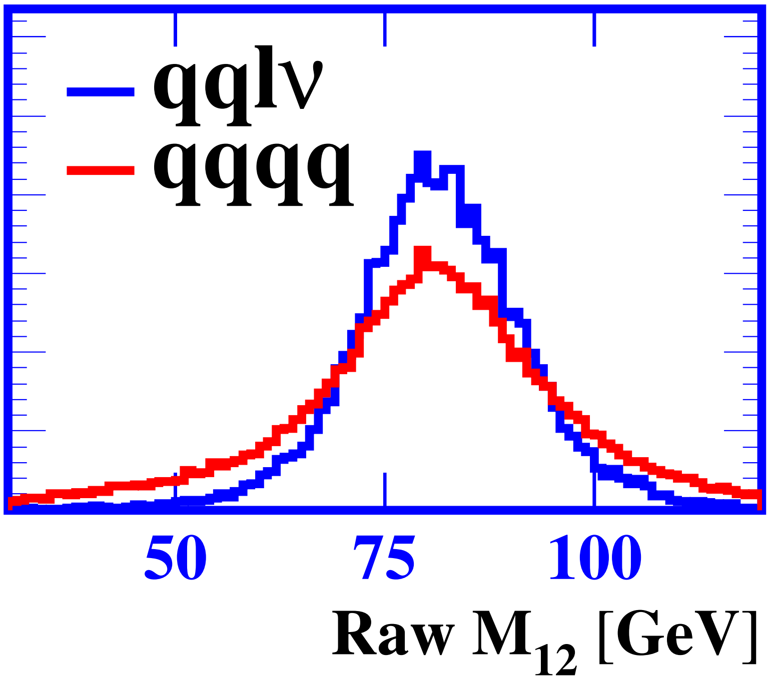



**Detect all fermions ➡ Better Resolution ?**

★ **But some hadrons assigned to wrong jet**

★ $\alpha_s(M_W) \sim 0.12$: **Gluon radiation**

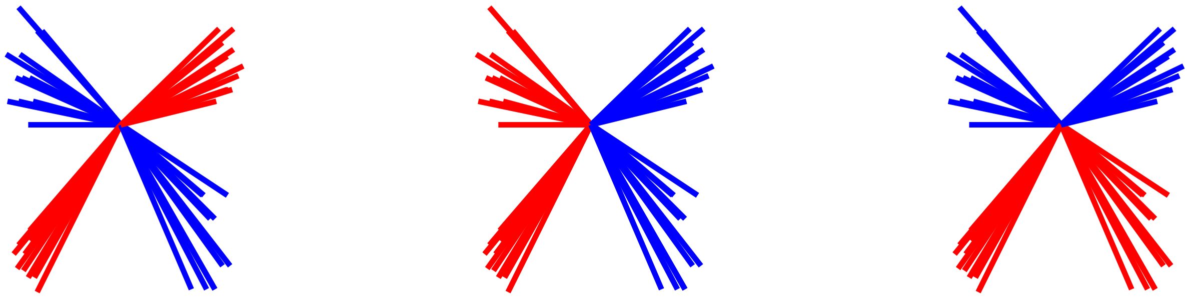
➡ **both effects degrade resolution**

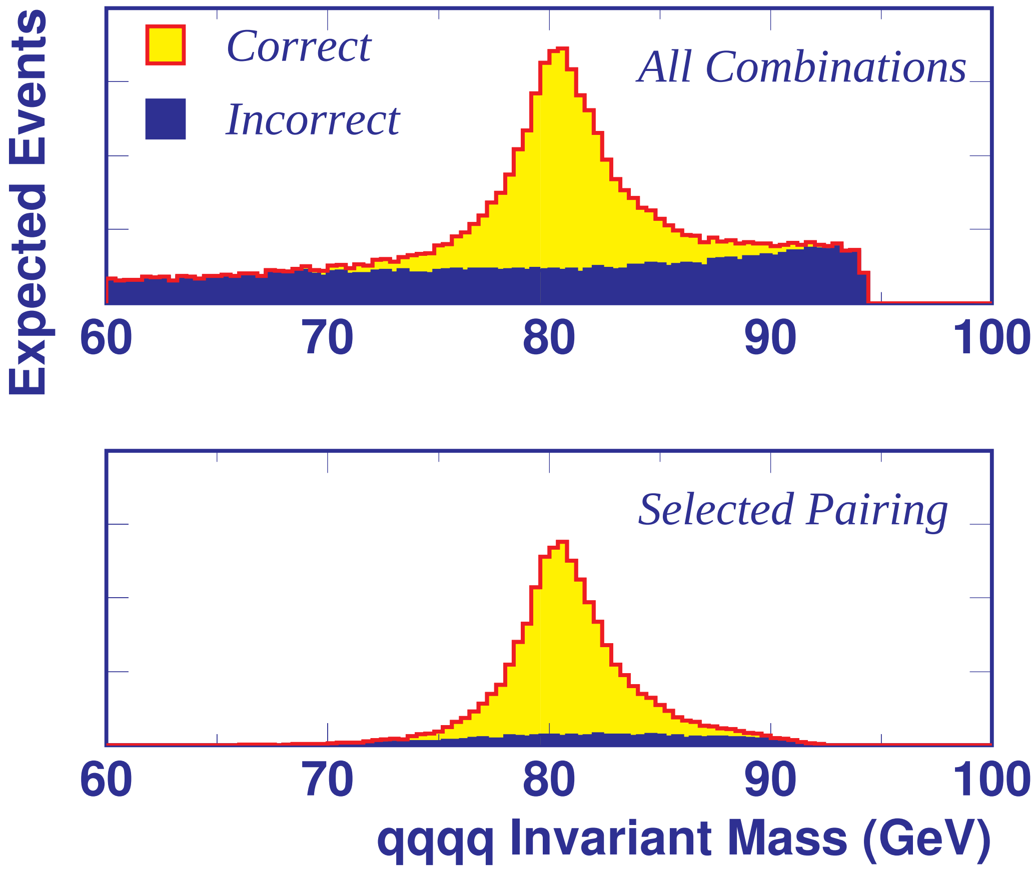



$M_W$ **Resolution : 1** $W^+W^- \rightarrow q\overline{q}q\overline{q}$ **event** $\sim$ **1** $W^+W^- \rightarrow q\overline{q}\ell\overline{\nu}_\ell$ **event**

# $W^+W^- \rightarrow q\bar{q}q\bar{q}$ Jet Pairing

★ 3 pairings of jets to $W^{\pm}W^{\mp}$





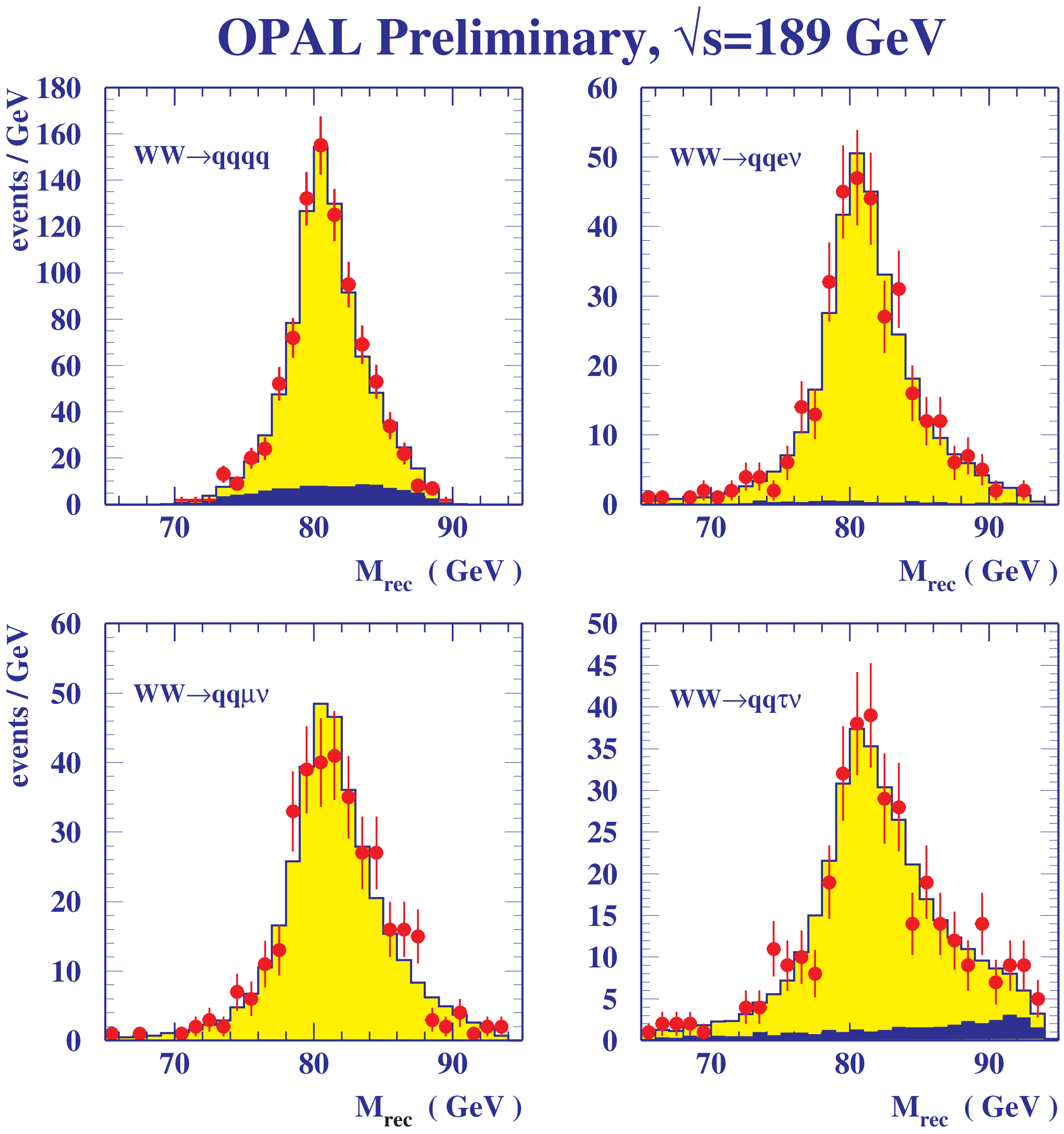

★ Incorrect pairings $\Rightarrow$ Combinatorial BGD.

★ Only correct pairing $\Rightarrow$ $M_{\mathrm{W}}$ info

★ Correct pairing chosen using Likelihood discriminant $\mathcal{L}(P_{FIT}, m_1 - m_2)$

# Mass Distributions

## 5C fit masses:




## Time to extract $M_W$....

**THREE METHODS :**

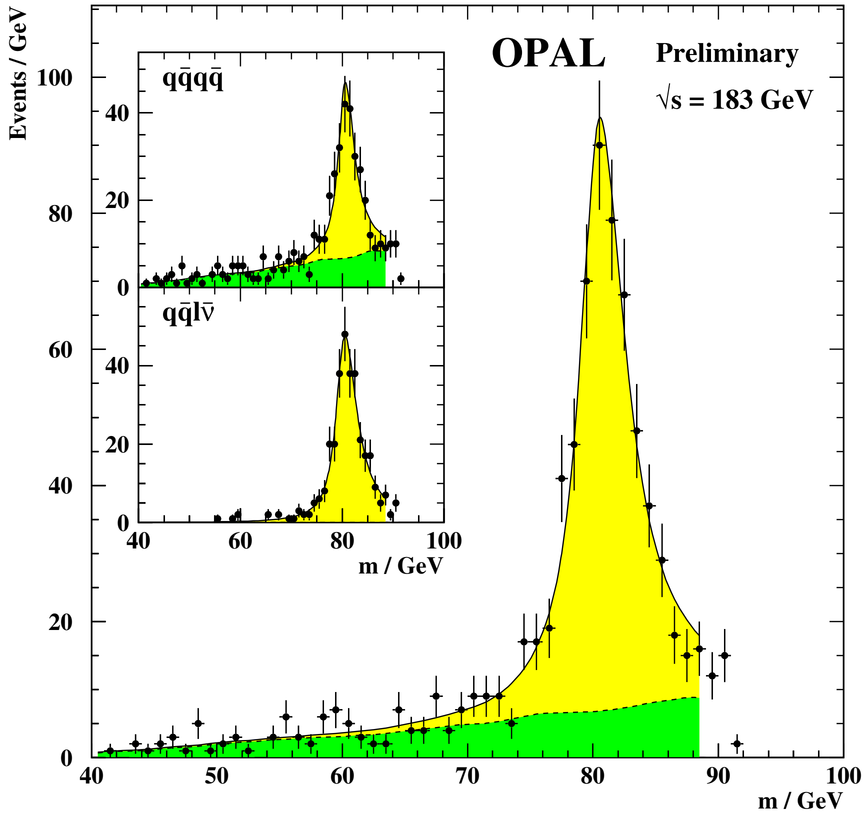
① **Breit-Wigner Fit (ADLO)**

② **Monte Carlo Reweighting (ALO)**

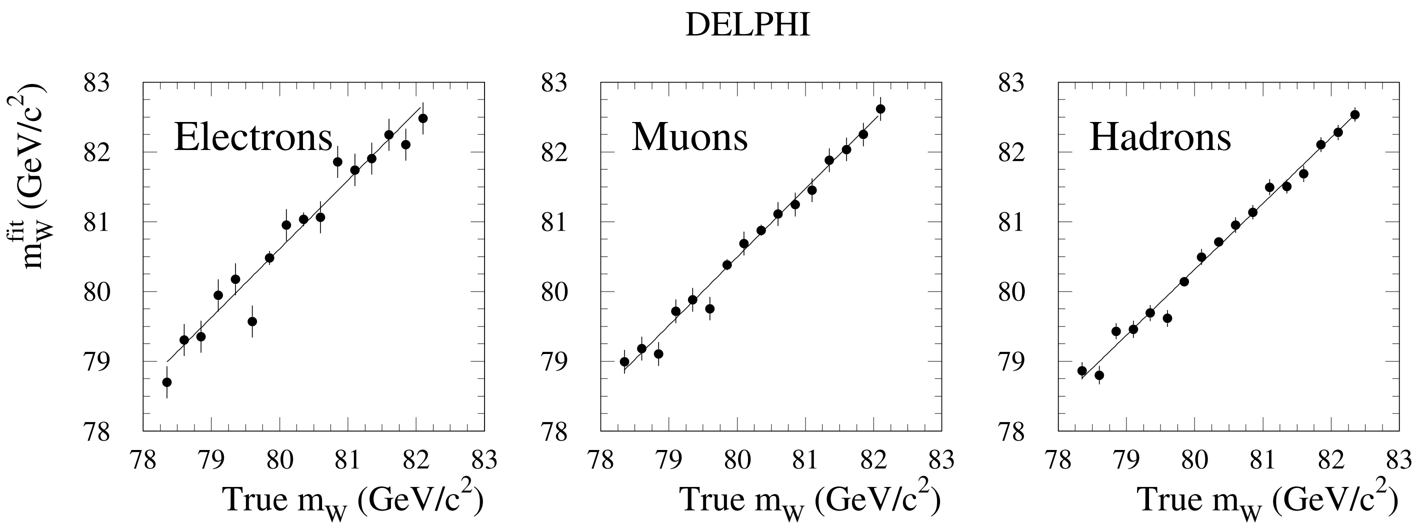
③ **Convolution (D O)**

# ① Breit-Wigner Fit

★ **Parameterise using function based on BW**




★ **Use MC to calibrate fitted mass**



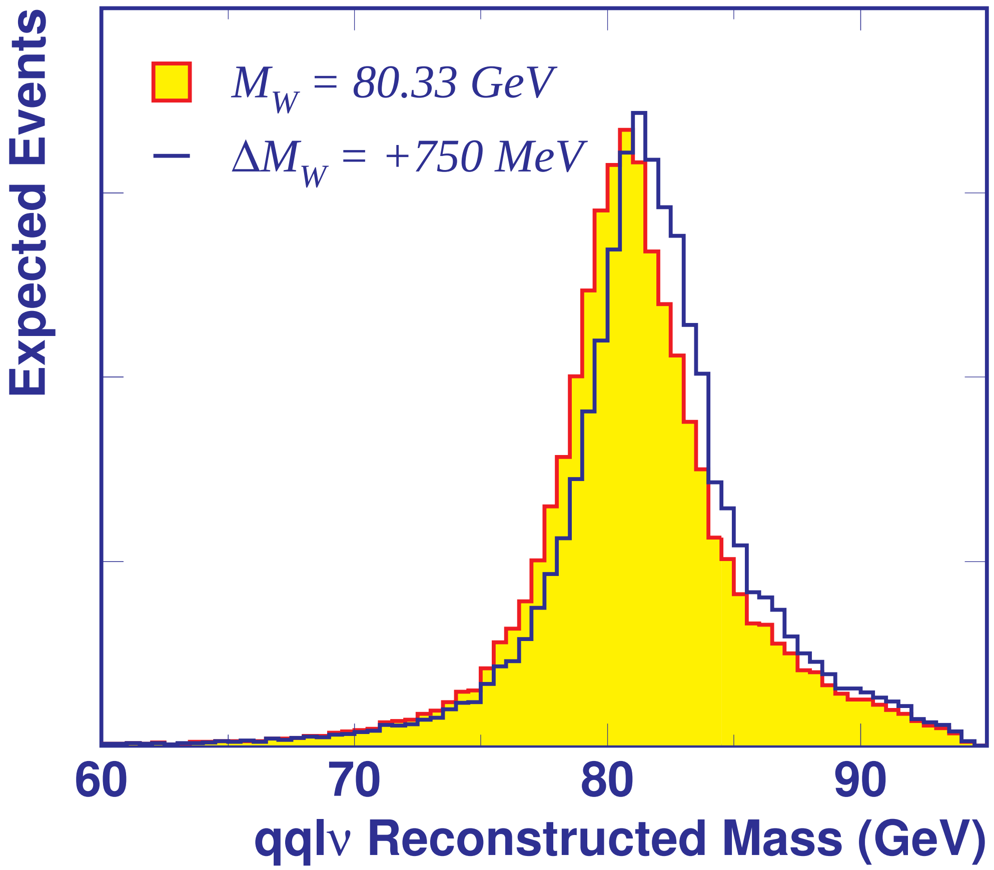

★ **SIMPLE/ROBUST : used by ADLO as cross-check**

# ② Reweighting Fit ALO

★ Compare Data to Monte Carlo distributions with different $M_{\mathrm{W}}$

★ Could generate many MC samples

★ Generate one large sample $(M_{\mathrm{W}}, \Gamma_{\mathrm{W}})$ and REWEIGHT to $(M_{\mathrm{W}}{}', \Gamma_{\mathrm{W}}{}')$

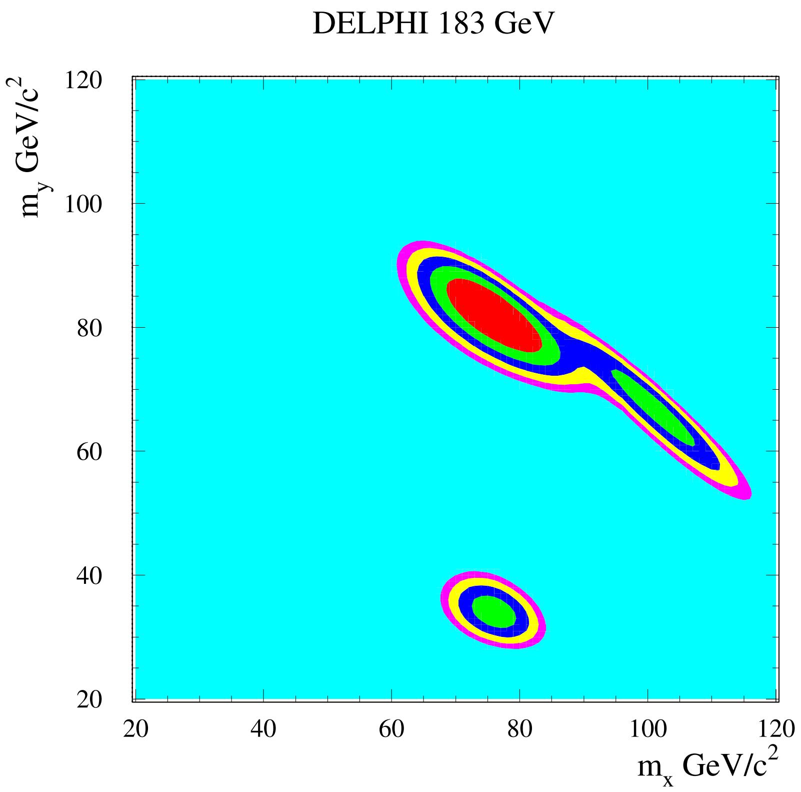


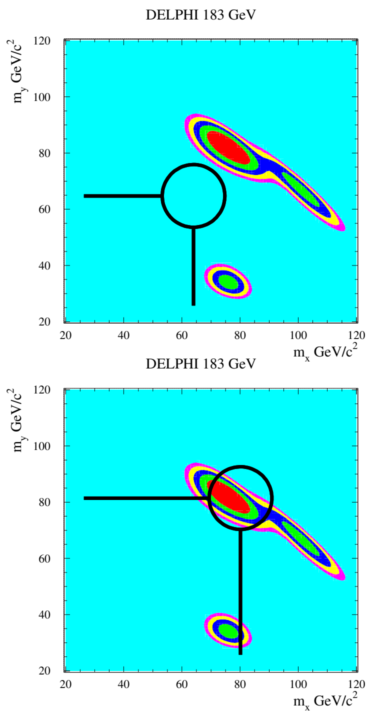

For event $i$ with generated masses $(m_1, m_2)$

$$w^i = \frac{BW(m_1, m_2 : M_{\mathrm{W}}{}', \Gamma_{\mathrm{W}}{}')}{BW(m_1, m_2 : M_{\mathrm{W}}, \Gamma_{\mathrm{W}})}$$

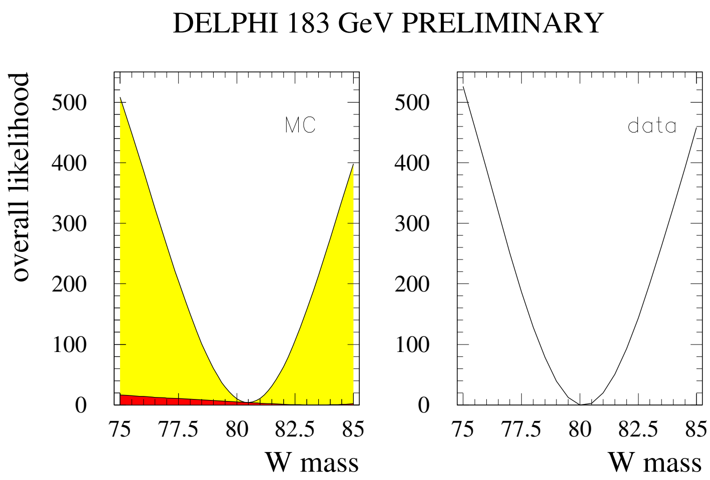
# ③ Convolution Fit : DELPHI

- ★ Use 4C fit $\Rightarrow$ 2 masses for each jet pairing
- ★ $\Rightarrow$ event PDF (all jet pairings used !)
- ★ calculate overlap integral of event PDF with a 2D Breit-Wigner, $\mathcal{BW}(M_W)$ $\Rightarrow$ event likelihood, $\mathcal{L}^i(M_W)$




- ★ $\mathcal{L}(M_W) = \sum_i \mathrm{PDF}_i \otimes \mathcal{BW}(M_W)$



# Advantages/Disadvantages

## Which Method is best ?

**At WW'99 Crete : all methods have similar inherent statistical sensitivity $\pm 5\ \%$**

### Breit-Wigner

- ✔ Simple/Robust
- ✘ Needs Monte Carlo calibration: $M_{fit} \rightarrow M_{true}$
- ✘ Arbitrary Fit function
- ✘ Least statistical power

### Reweighting

- ✔ Simple/Unbiased
- ✔ No calibration
- ✘ Still requires MC describes data
- ✘ Requires lots of MC

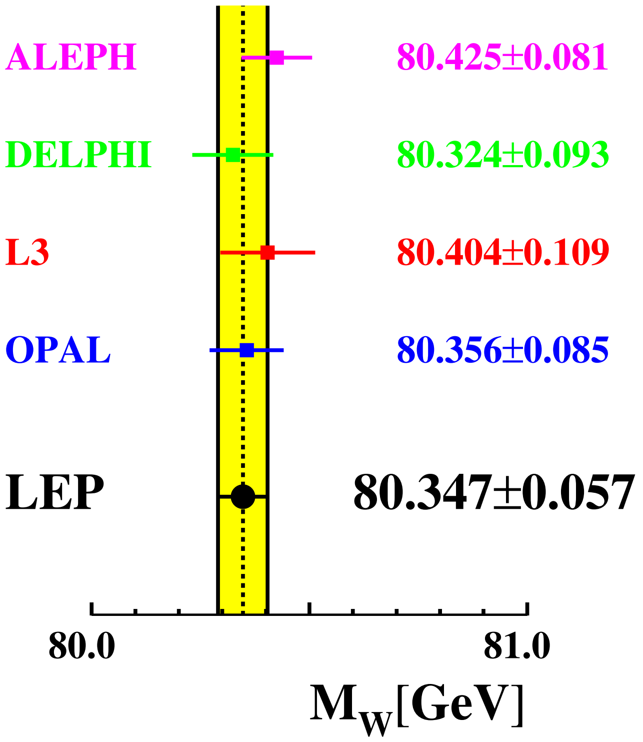
### Convolution

- ✔ Statistical power
- ✔ Elegant...
- ✘ Requires bias correction
- ✘ Slow: computationally intensive

# Direct Reconstruction 172-189 GeV

(189 GeV results all preliminary)

**Combining $q\bar{q}\ell\overline{\nu}_\ell$ and $q\bar{q}q\bar{q}$:**




## LEP COMBINED:

| | |
|---|---|
| $q\bar{q}\ell\overline{\nu}_\ell$ | : 80.313 ± 0.052 ± 0.036 GeV |
| $q\bar{q}q\bar{q}$ | : 80.429 ± 0.049 ± 0.074 GeV |

**$M_W$ from $q\bar{q}\ell\overline{\nu}_\ell$ and $q\bar{q}q\bar{q}$ :**

- ★ **Similar statistical errors**
- ★ **Systematic much larger in $q\bar{q}q\bar{q}$**
- ★ **Weight of $q\bar{q}q\bar{q}$ in combination $\sim \frac{1}{3}$ !**

# Systematic Uncertainties

## Typical Systematic Errors:

| Source | $\Delta M_{\mathrm{W}}$ (MeV) $\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ | $\Delta M_{\mathrm{W}}$ (MeV) $\mathrm{q\overline{q}q\overline{q}}$ |
|---|---|---|
| Detector calibration | 15 | 5 |
| non-WW background | 5 | 5 |
| MC statistics | 10 | 10 |
| Hadronization | 20 | 20 |
| Initial state radiation | 5 | 5 |
| Beam energy | 15 | 15 |
| Final State Interactions (FSI) | 0 | 70 |
| Total | 35 | 80 |

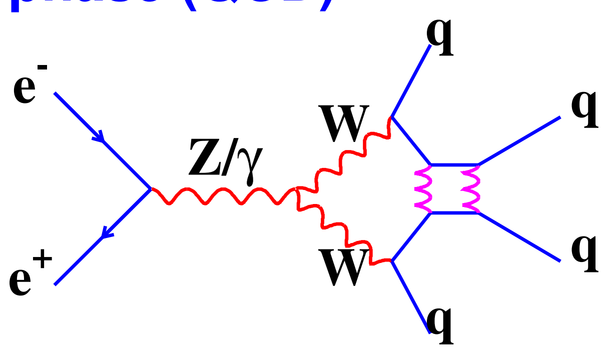
## Largest systematic: FSI

- ★ Only affects $\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}q\overline{q}}$
- ★ Standard MCs assume independent fragmentation for the two W bosons
- ★ W-decay length ~0.1 fm
- ★ Hadronization scale ~1 fm
- ★ Interactions between W-decay productions during fragmentation process ➡ Mass shifts.

# Final State Interactions

## Colour Reconnection

### Perturbative phase (QCD)



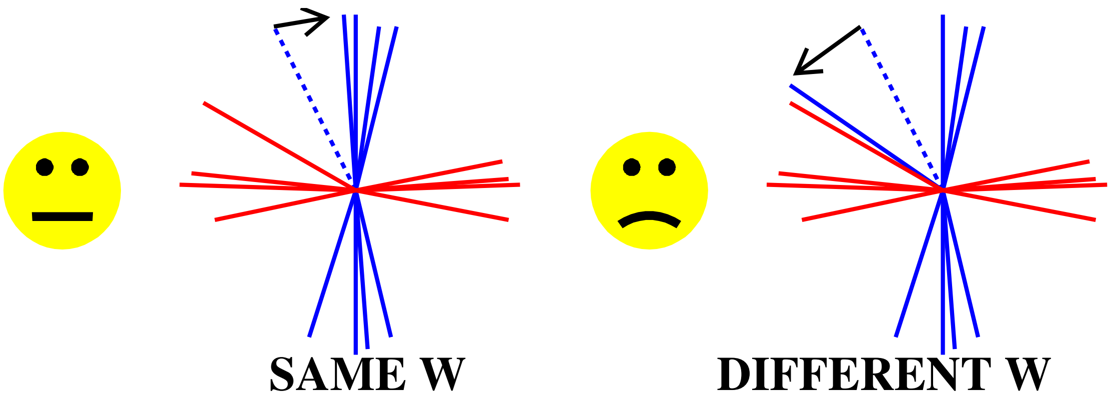

- Suppressed by 2 gluon exchange + colour
- Negligible mass shifts $< 10$ MeV

### Hadronization phase (non-pertubative)

- Rely on models (string, cluster...)
- Mass bias ? : Predictions from 0-100 MeV

## Bose-Einstein Correlations

- BEC - Quantum mechanical effect
- Like-sign pions closer in phase space
- $\mathrm{BEC}$ between pions from different Ws ?



# Systematic Error from FSI

**Sys. Errors estimated by comparing Models**

Some typical values:

| Model | Effect | Mass shift |
|---|---|---|
| Herwig | CR | $\sim$ 10-30 MeV |
| Pythia | CR | $\sim$ 20-50 MeV |
| Ariadne | CR | $\sim$ 50-100 MeV |
| Pythia | BE | $\sim$ 20-50 MeV |
| KoralW | BE | $\sim$ 20-50 MeV |

## Tests of CR

- ★ **Would like to test above models**
- ★ **For CR most sensitive observable is $M_{\mathrm{W}}$ ?**

**LEP COMBINED**

$$M_{\mathrm{W}}^{\mathrm{q\bar{q}q\bar{q}}} - M_{\mathrm{W}}^{\mathrm{q\bar{q}}\ell\bar{\nu}_\ell} = 152 \pm 74 \text{ MeV}$$

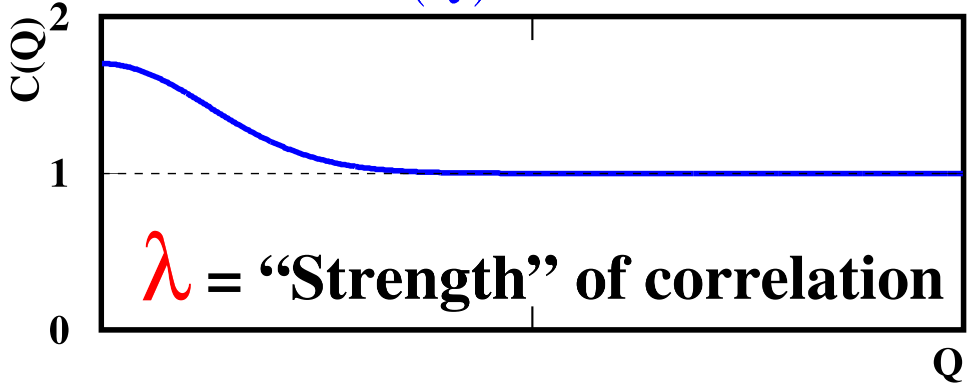
- ★ **Not a useful test !**

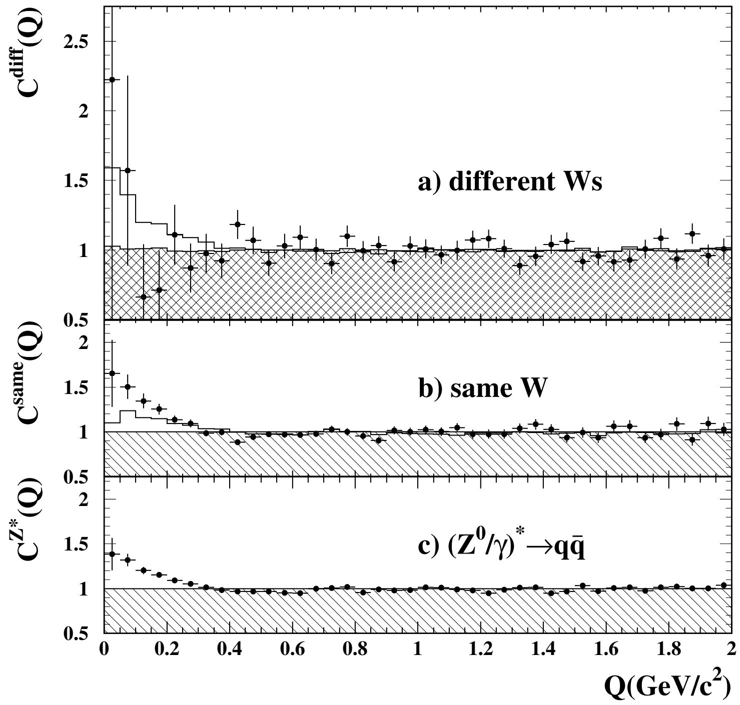
## Tests of BEC

- ★ **More promising....**
- ★ **....but for now not clear**

# Experimental Status of BEC in WW

$$C(Q) = \frac{N^{\pm\pm}(Q)}{N^{+-}(Q)}; \quad Q^2 = M^2(\pi\pi) - 4m_\pi^2$$



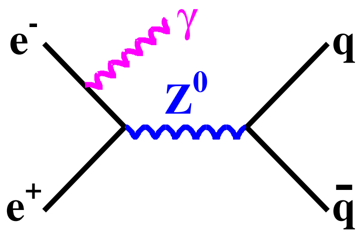

$$\lambda^{\mathrm{same}} = 0.69 \pm 0.12 \pm 0.06$$

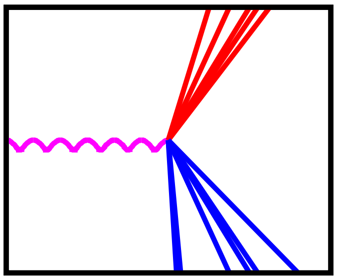
$$\lambda^{\mathrm{diff}} = 0.05 \pm 0.67 \pm 0.35$$

- ★ Current situation unclear
- ★ But by end of LEP ...

# Detector/Hadronization Systematics

**Many Cross-Checks e.g. Radiative $Z^0$**

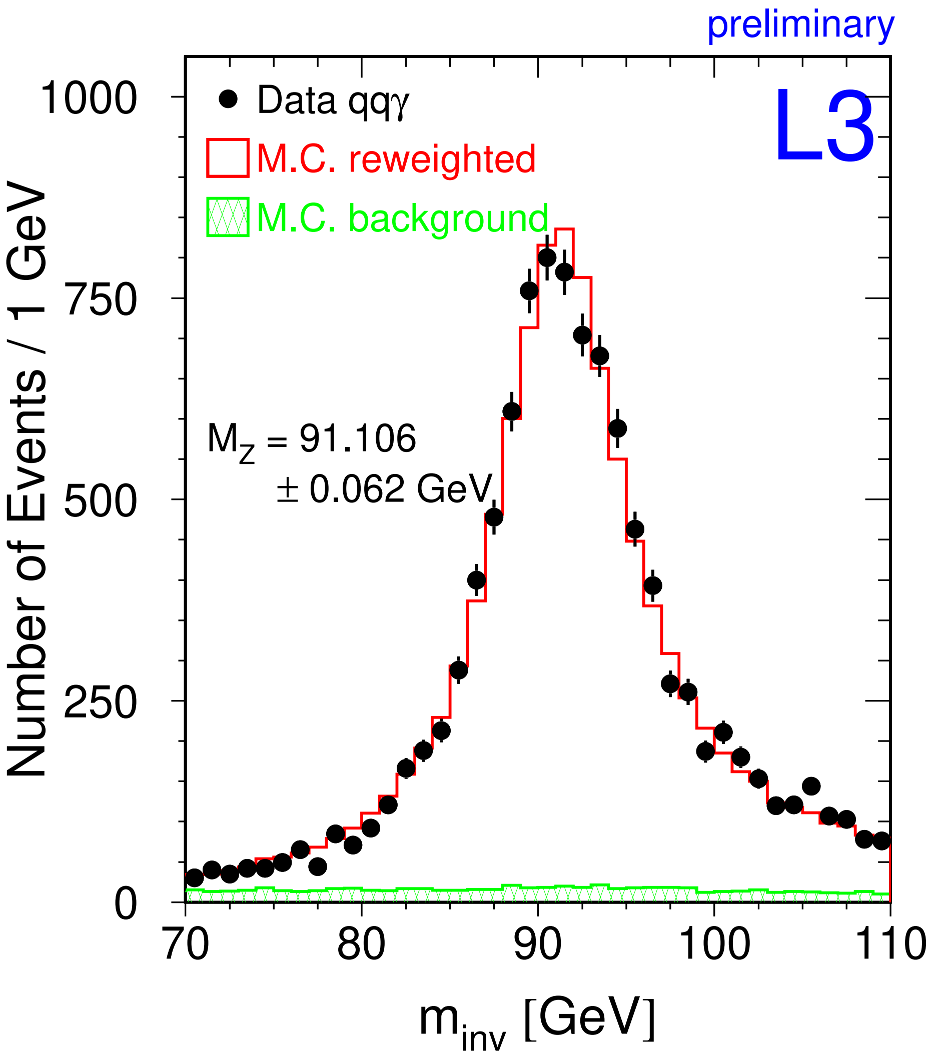


$$M_{q\bar{q}} = M_{Z^0}$$

★ **Reconstruct $M_{q\bar{q}}$ using kinematic fit.**

★ **Fit by reweighting MC**



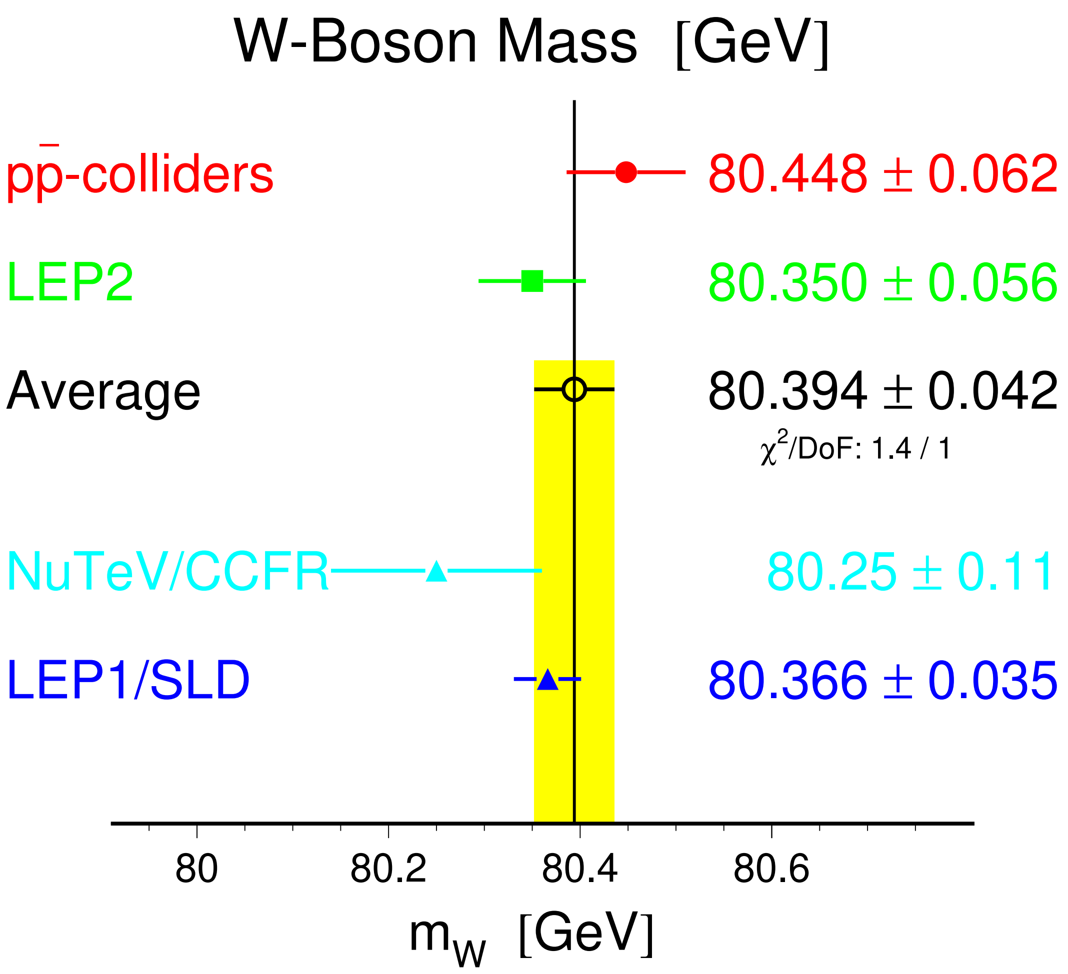
# Combined $M_W$ Result

**LEP Combined $M_W$ from**

- **cross section from $10\ pb^{-1}$/expt @ 161 GeV**
  **80.40$\pm$0.22 GeV**
- **direct reconstruction $250\ pb^{-1}$/expt @ 172-189 GeV**
  **80.347$\pm$0.036(stat)$\pm$ 0.036(sys)$\pm$0.020(fsi)$\pm$0.017(beam) GeV**

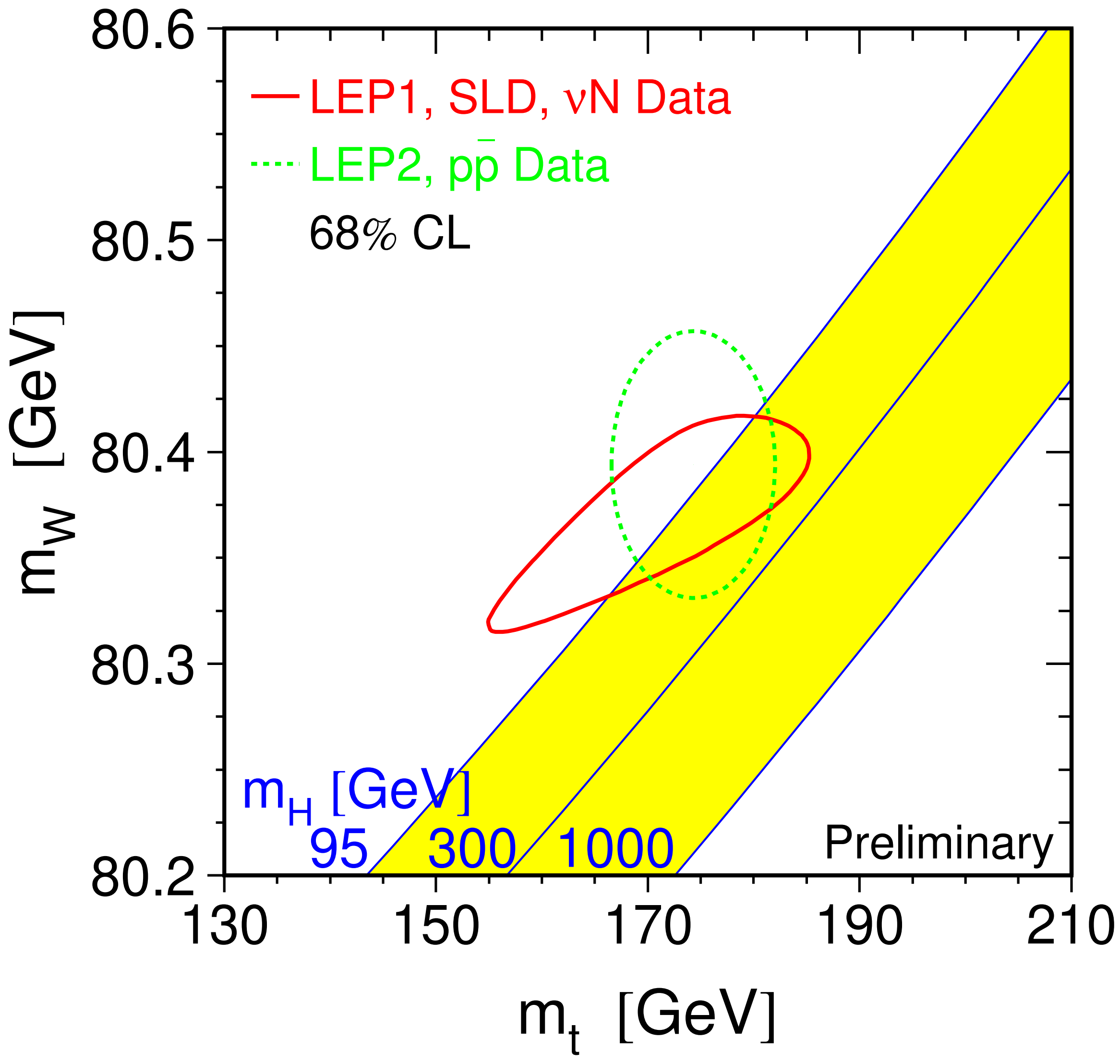
**$M_W$(LEP) = 80.350 $\pm$0.056 GeV**

## CURRENT WORLD AVERAGE



# Direct vs. Indirect

- **DIRECT : measurements of $M_{\mathbf{W}}$ and $M_{\mathbf{top}}$ from TeVatron and LEP**
- **INDIRECT : Electroweak data *excluding* direct measurements of $M_{\mathbf{W}}$ and $M_{\mathbf{top}}$**




Direct measurements of $(M_{\mathbf{W}}, M_{\mathbf{top}})$ + $(\mathrm{M_Z}, \mathrm{G}_\mu, \alpha_\mathrm{s})$ :

- $\mathbf{m_{Higgs} = 74^{+106}_{-55}\,GeV}$

# Electroweak Fit Results

**Direct measurements of ($M_W$, $M_{top}$)**

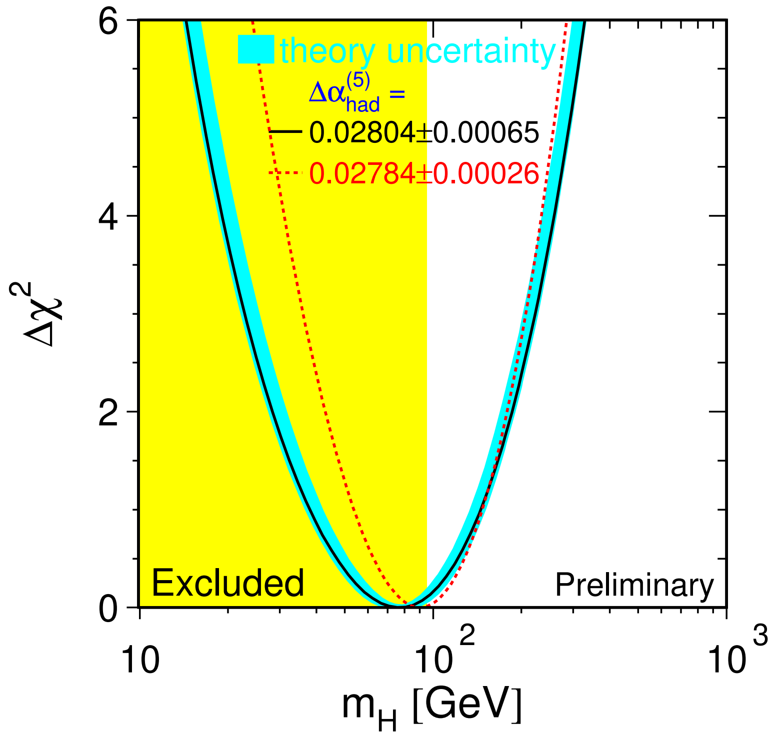
- $m_{Higgs} = 74^{+106}_{-55}\,\mathrm{GeV}$

**Excluding direct measurements of ($M_W$, $M_{top}$)**

- $m_{Higgs} = 55^{+83}_{-33}\,\mathrm{GeV}$

**Direct + Indirect**

- $m_{Higgs} = 76^{+68}_{-38}\,\mathrm{GeV}$




**at 95 % C.L.**

$$m_{Higgs} < 215\ \mathrm{GeV}$$

# $M_W$ Outlook

## Ultimate LEP $M_W$

★ Assume 600 pb$^{-1}$/expt.

★ My guestimates are not pessimistic !

| Source | $\Delta M_W$ (MeV) | | |
|---|---|---|---|
| | $q\bar{q}\ell\bar{\nu}_\ell$ | $q\bar{q}q\bar{q}$ | Comb |
| Detector calibration | 5 | 5 | 5 |
| non-WW background | 5 | 5 | |
| Hadronization | 10 | 5 | 5 |
| $O(\alpha_{em})$ + ISR | 5 | 5 | 5 |
| Beam energy | 12 | 12 | 12 |
| FSI | 0 | 0-100 | 0-10 |
| Statistical | 30 | 30 | 20-30 |
| Systematic | 20 | 15-100 | 15-20 |
| Total | 35 | 35-105 | 25-35 |

★ Final LEP $M_W$ Error $25 - 35$ MeV

★ Depends on FSI error

# Summary

## LEP 2 : THE STORY SO FAR....

- ★ Results from $\sim$ 4000 $\mathrm{W^+W^-}$/expt.
- ★ $\sigma_{\mathrm{W^+W^-}}$ Measured $\sim 1\,\%$
- ★ TGC measurements $\sim 5\,\%$
- ★ $M_{\mathrm{W}}$ measured to 56 MeV

# Outlook

## BY THE END OF LEP 2

- ★ $\sim$ 10000 $\mathrm{W^+W^-}$/expt.
- ★ $M_{\mathrm{W}}$ measured to 25-35 MeV
- ★ Need to understand FSI !