W physics at LEP

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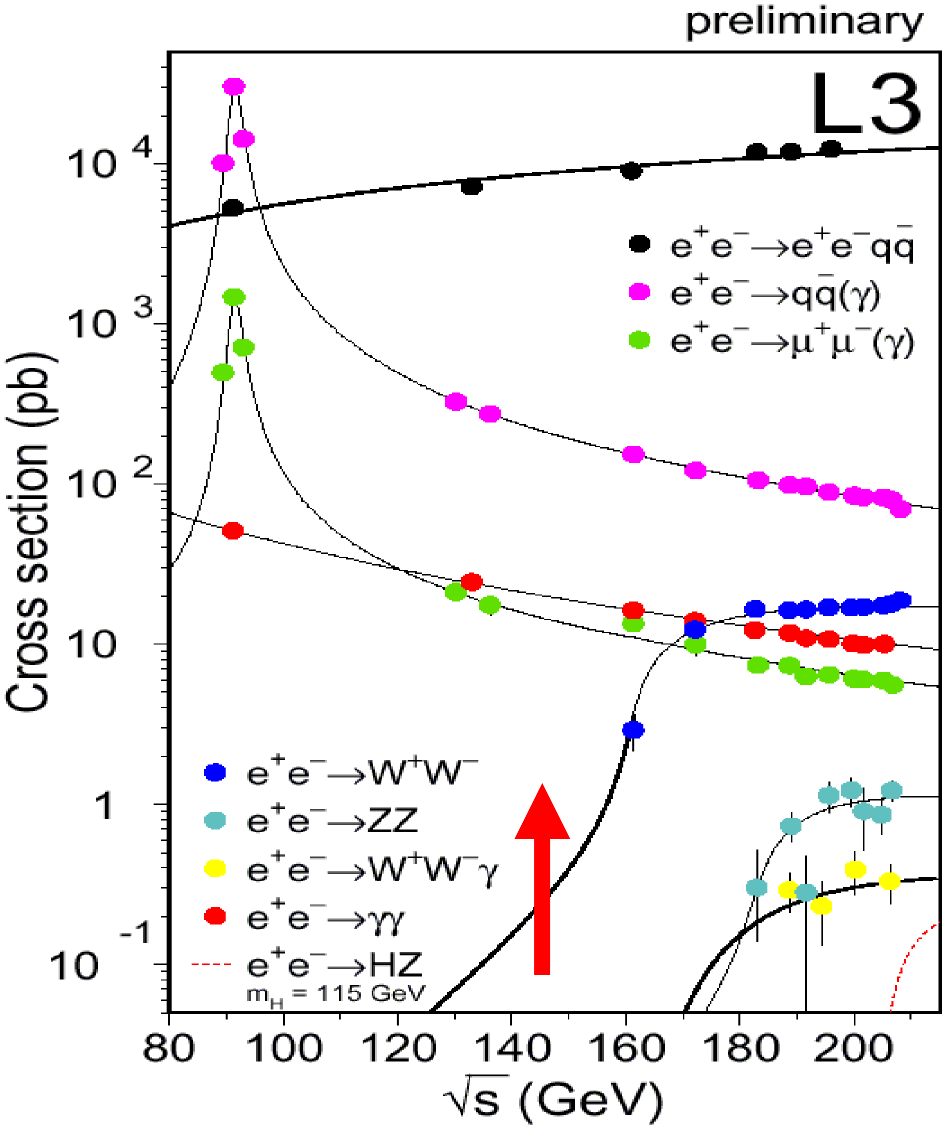
University of Geneva

On behalf of the LEP collaborations

The LEP scan (1989-2000)



- **LEPI(1989-1995):**
  - **$\sqrt{s}$~91 GeV**
  - **Z physics**
- **LEPII(1996-2000):**
  - **$\sqrt{s}$~160-209 GeV**
  - **W physics**

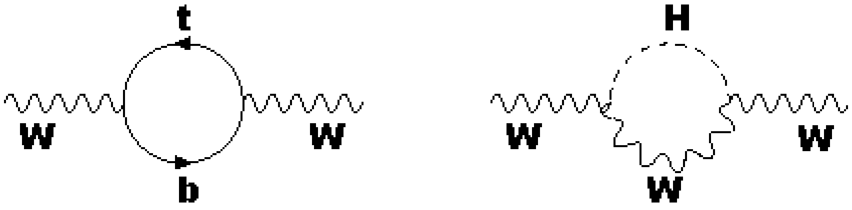
WW threshold
@ ~160 GeV

At LEPI

- **Indirect measurement of the W mass with an accuracy ~25 MeV**

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}\left(1+\Delta r_w(m_t,m_H)+\Delta\alpha_{em}\right)$$

- **First evidence of contribution of gauge-boson loops to gauge-boson self energies**
  - →**Indirect confirmation of the existence of triple gauge boson couplings (TGC's)**



At LEPII

ECFA WORKSHOP ON LEP 200

Aachen, Federal Republic of Germany
29 September – 1 October 1986

LEP200 WORKSHOP SUMMARY

D.H. Perkins,

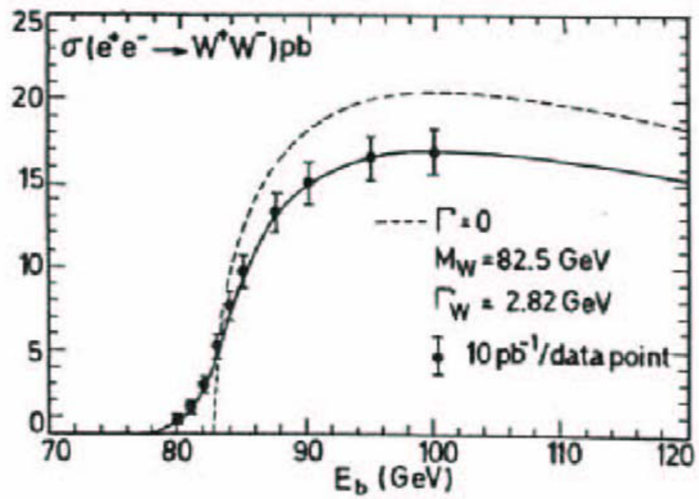
University of Oxford, Nuclear Physics Laboratory, Oxford.

4. W PAIR PRODUCTION AND THE W MASS

For an integrated luminosity of 500pb^{-1} we expe
for $\sigma = \sigma_{\text{max}}$, 5–10,000 events for each of the 4 LEP experiments.

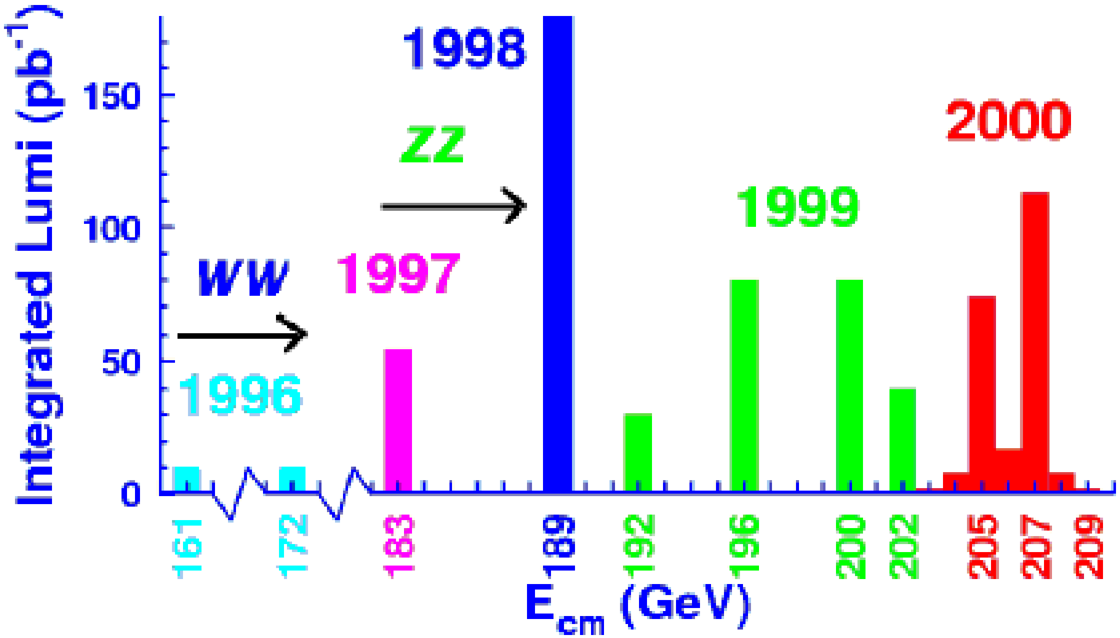
This constitutes the "final check" of the EWI theory via:

- $e^+e^- \to W^+W^-$; checking the gauge vertices.
- precise $M_{W^\pm}$; radiative corrections sensitive to M_H etc.
- measurement of σ_L and σ_T for the W from production angular distribution, detection of anomalies in electric and magnetic moments.
- study of $W \to \ell\nu$, $Q\bar{Q}$; precise measurements of KM matrix element, and of lepton universality.



ΔM_W=60MeV

Luminosity per experiment



Events/exp:

- **WW ~10000**

Total integrated luminosity from 1996-2000:

$$\int \mathbf{Ldt} \approx 700\,\mathbf{pb}^{-1} / \exp$$

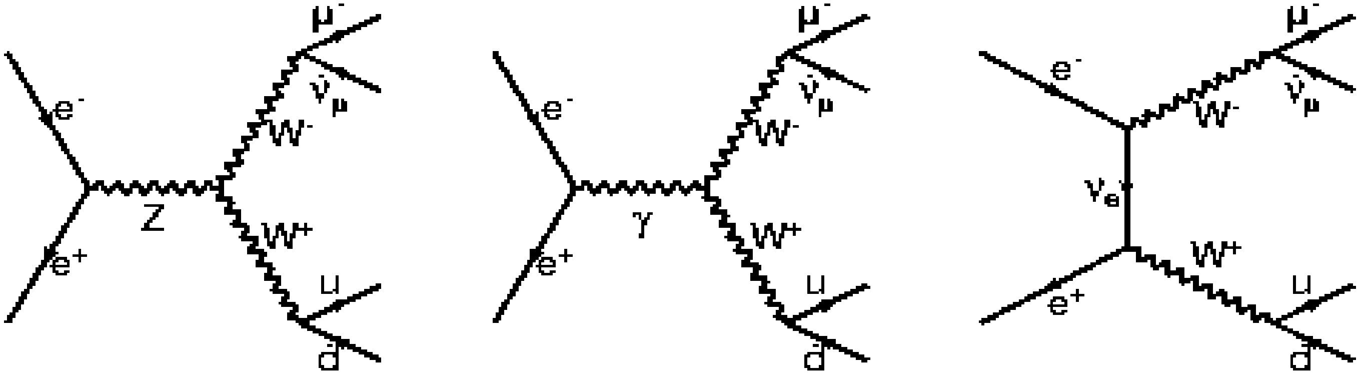
@ √s~161-209 GeV

W production and selection

W production at LEP

Ws are pair produced

Dominates at threshold



So called CC03 processes

$\sigma \propto \beta_W^3$

$\sigma \propto \beta_W$

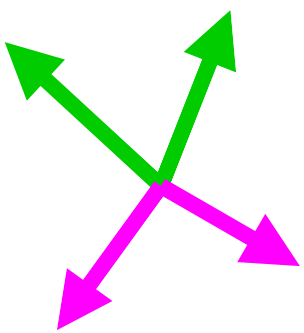
P_W = average W momentum

$\sqrt{s}$ (GeV)	172	183	189	200	208
P_W (GeV)	30	44	50	60	66

Topologies

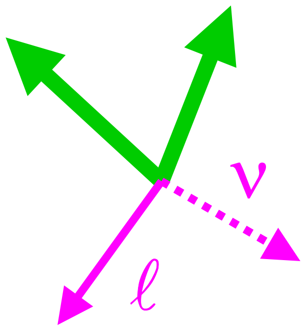
B(W->qq') ≈ 68%

Hadronic



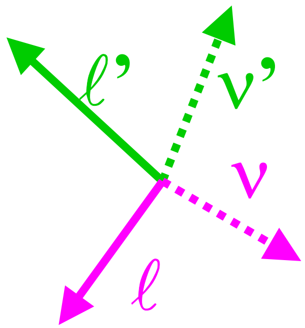
45.6%

Semi-leptonic



43.8%

Fully leptonic

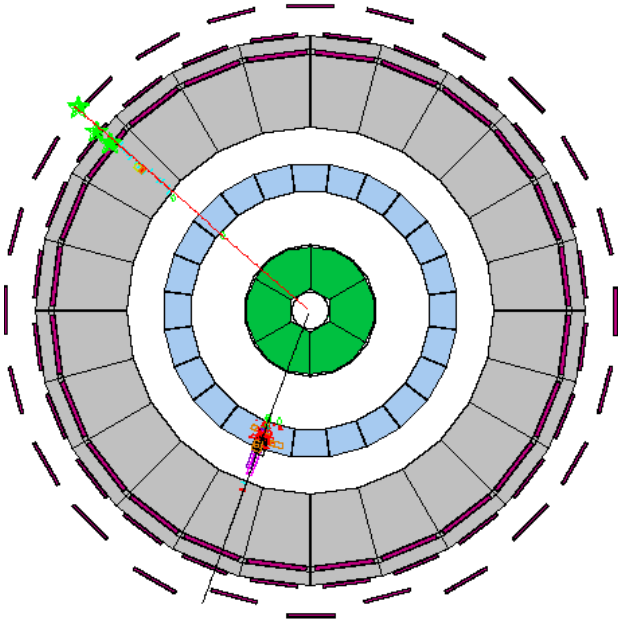


10.6%

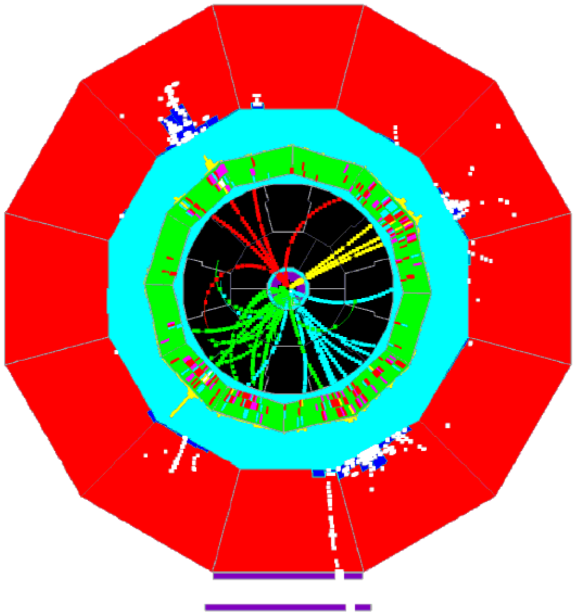
Very limited use for the mass analysis

WW events

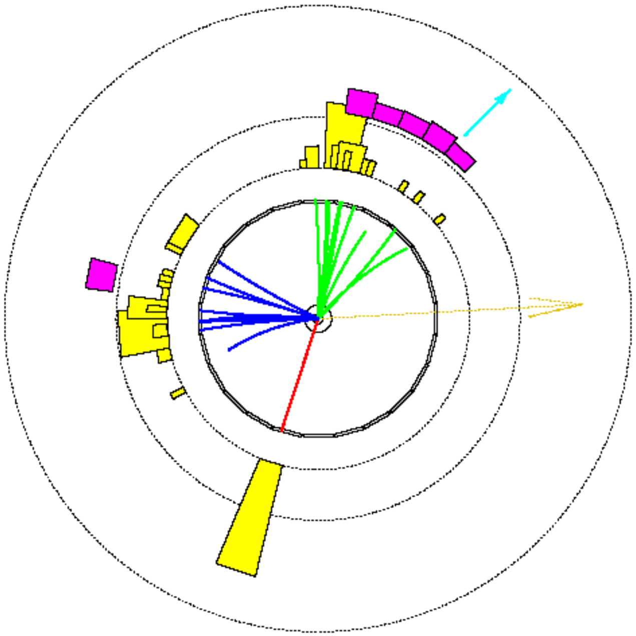
WW→lνlν **WW→qqqq** **WW→eνqq**



DELPHI

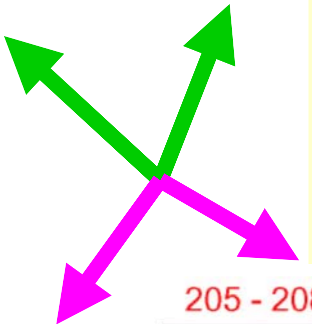


ALEPH

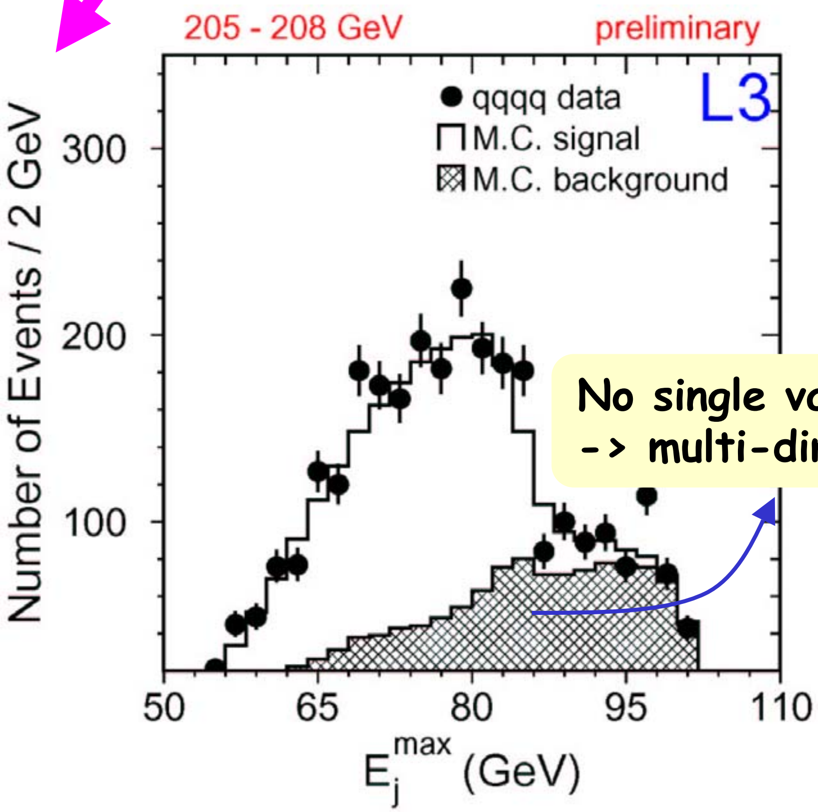


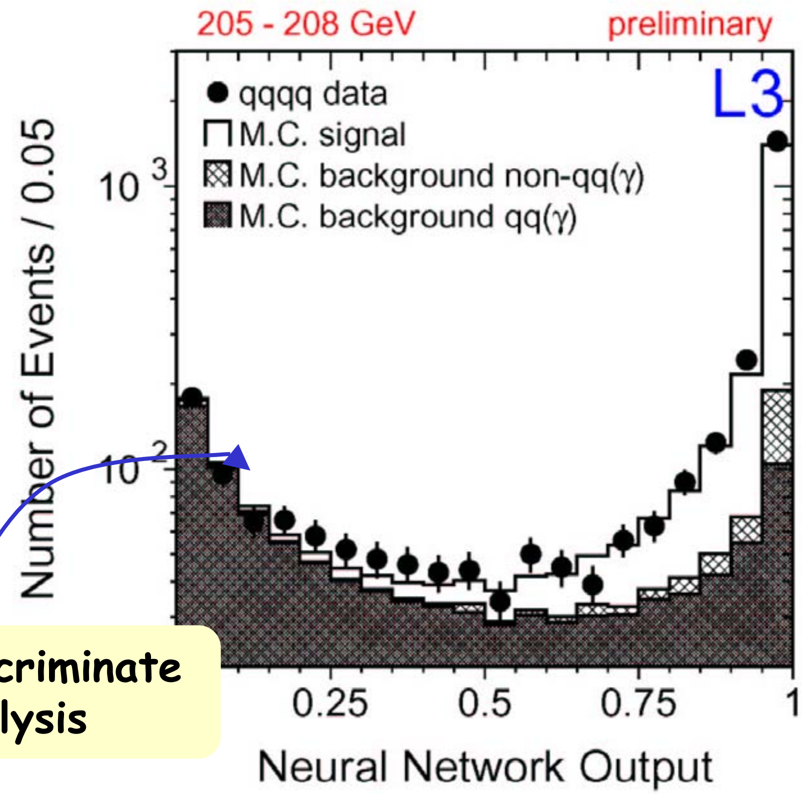
OPAL

qqqq selection



- ➲ large multiplicity
- ➲ no missing E
- ➲ multi-dimensional analysis
  - ➲ to separate qq bkg



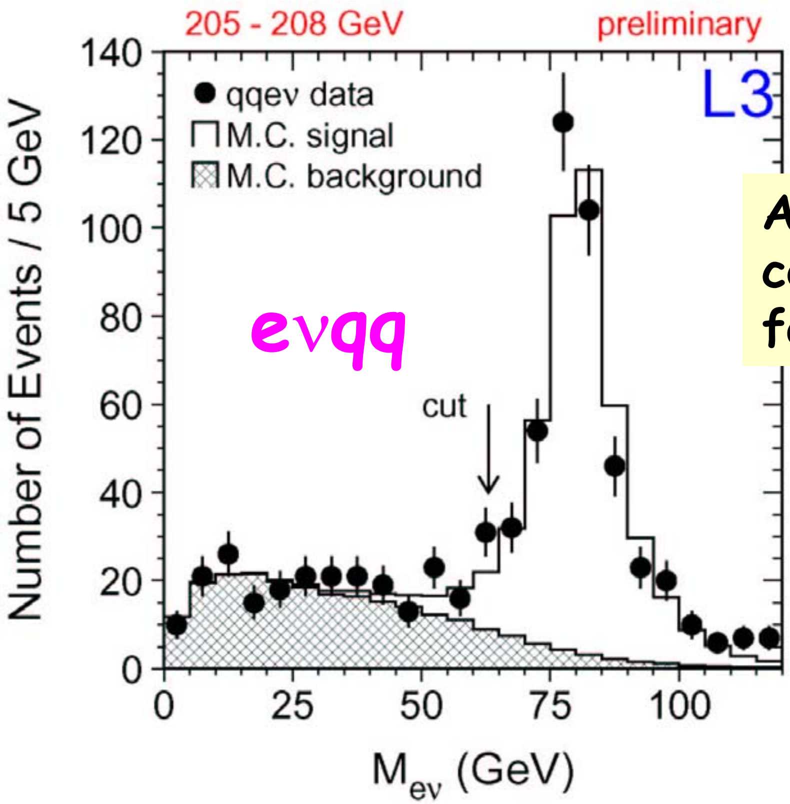


No single variable to discriminate
-> multi-dimensional analysis

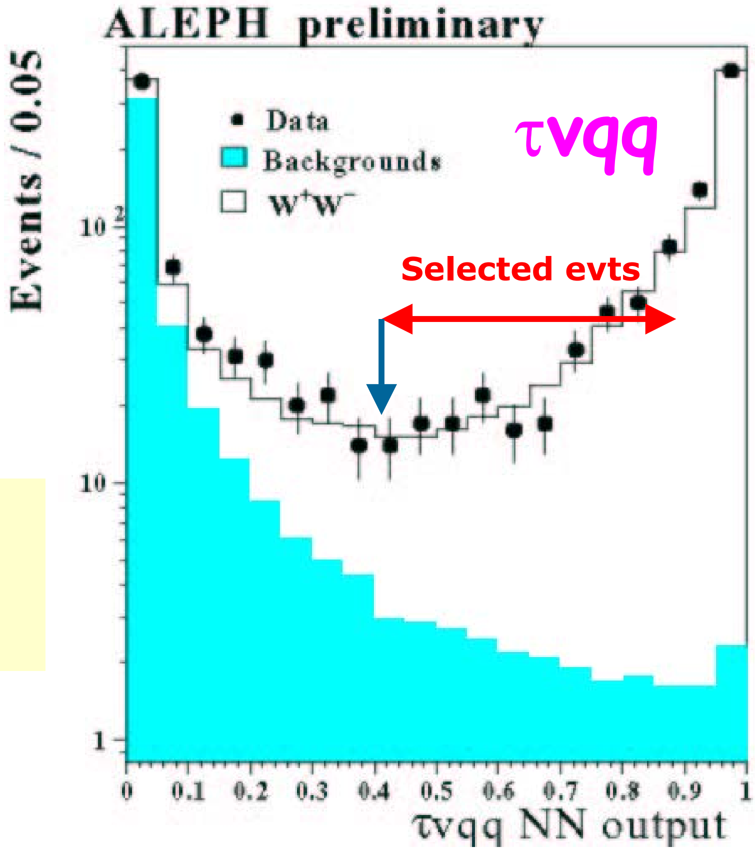
'Typical'	4q
Efficiency (%)	90
Purity (%)	85

lνqq selection

- ➲ isolated high P lepton
- ➲ missing E
- ➲ 2 jets



A bit more complicated for τ channel

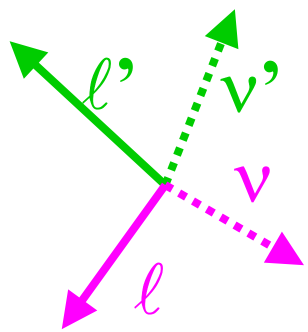


'typical'	e,μ	τ
Efficiency (%)	85	50-80
Purity (%)	95	85

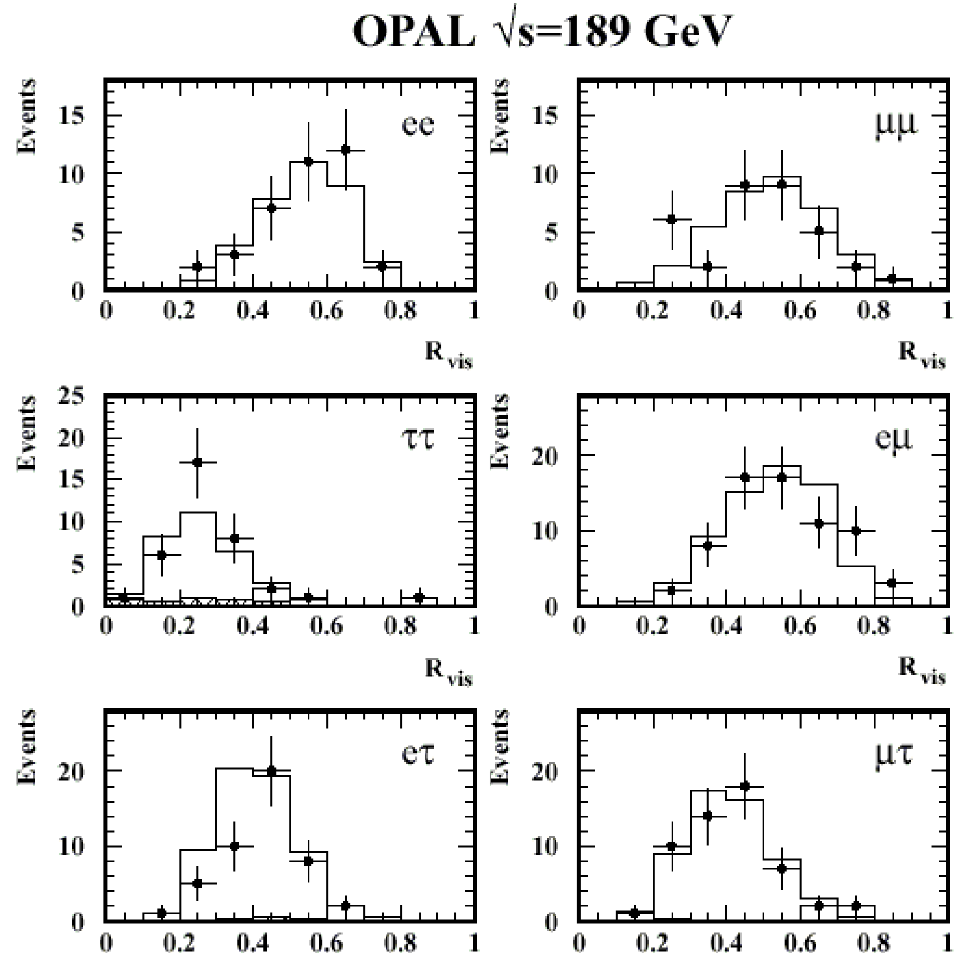
$l\nu l\nu$ selection

6 topologies (ee, eμ, eτ, μμ, μτ, ττ)

- ➲ 2 acoplanar, acollinear high P leptons
- ➲ misssing E



'Typical'	eμ, ee, μμ	eτ, μτ	ττ
Efficiency (%)	60-70	40-60	20-45
Purity (%)	95	90	80

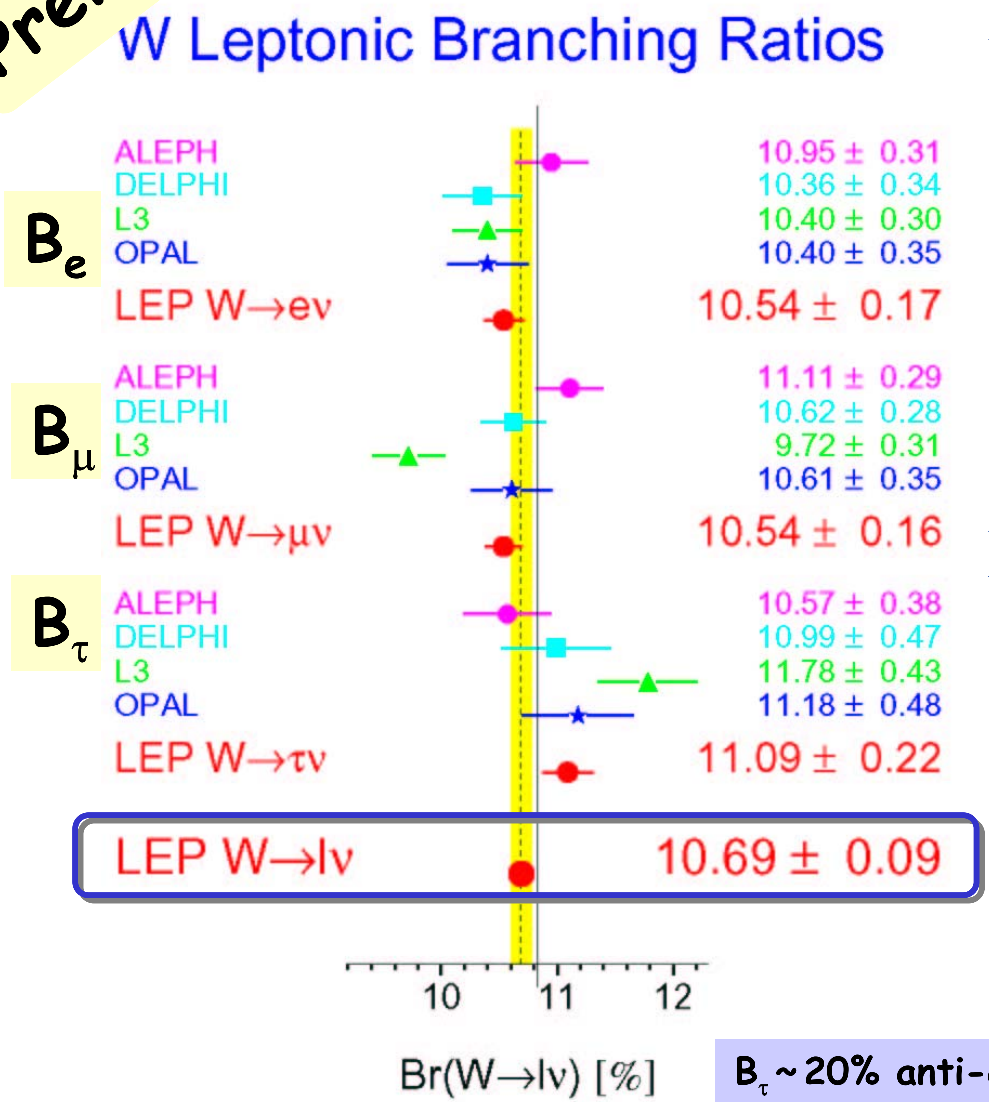


Rescaled visible energy

Branching Ratios
Cross sections

Preliminary

W branching ratios



- **Test of lepton universality at 3% level**

$$\mathbf{B}_\mu / \mathbf{B}_e = 1.000 \pm 0.021$$
$$\mathbf{B}_\tau / \mathbf{B}_e = 1.052 \pm 0.029$$
$$\mathbf{B}_\tau / \mathbf{B}_\mu = 1.052 \pm 0.028$$

- **W decay into hadrons**

Lepton universality assumed

$$\mathbf{B}(\mathbf{W} \to \mathbf{q}\bar{\mathbf{q}}') = 67.92 \pm 0.27\%$$

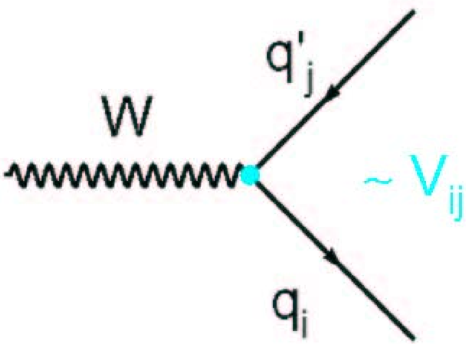
  - **SM prediction 67.51%**

B_τ ~ 20% anti-correlated to B_e and B_μ

Preliminary

Vcs CKM matrix element

- SM relation between hadronic branching ratio and CKM matrix elements:



$$\frac{B_h}{1-B_h} = \left(1 + \frac{\alpha_s\left(M_W^2\right)}{\pi}\right) \sum_{\substack{i=u,c \\ j=d,s,b}} \left|V_{ij}^2\right|$$

$$\alpha_s = 0.121 \pm 0.002$$

$$\sum_{\substack{\mathbf{i=u,c} \\ \mathbf{j=d,s,b}}} \left|\mathbf{V}_{\mathbf{ij}}^2\right| = 2.039 \pm 0.025(\mathbf{B}_{\mathbf{W\to l\nu}}) + 0.001(\alpha_s)$$

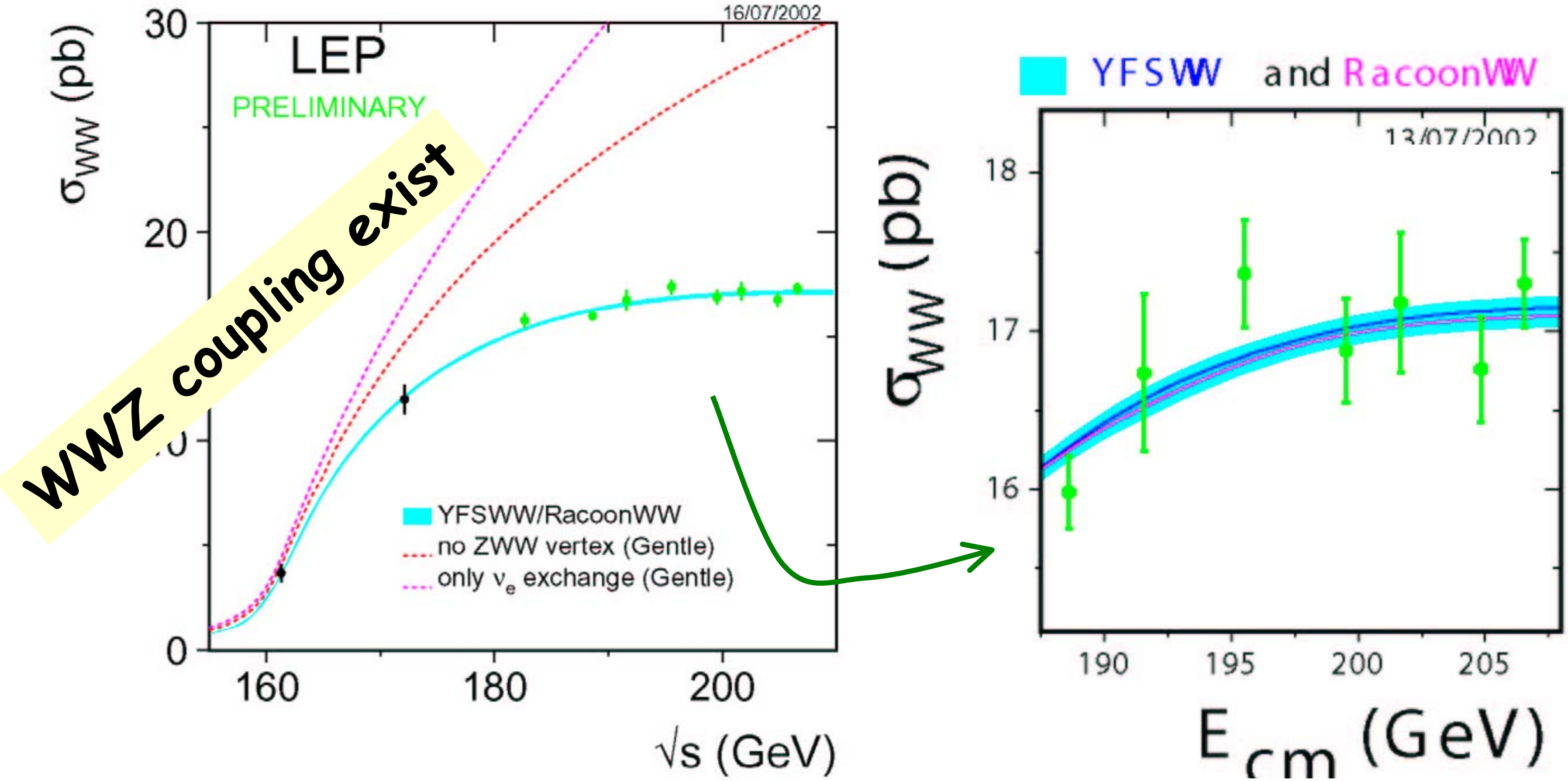
- V_{cs} : the least known CKM matrix element
- Using experimental values of the other CKM elements:

$$\left|\mathbf{V}_{\mathbf{cs}}\right| = 0.996 \pm 0.013$$

Best measurement of Vcs

WW cross section

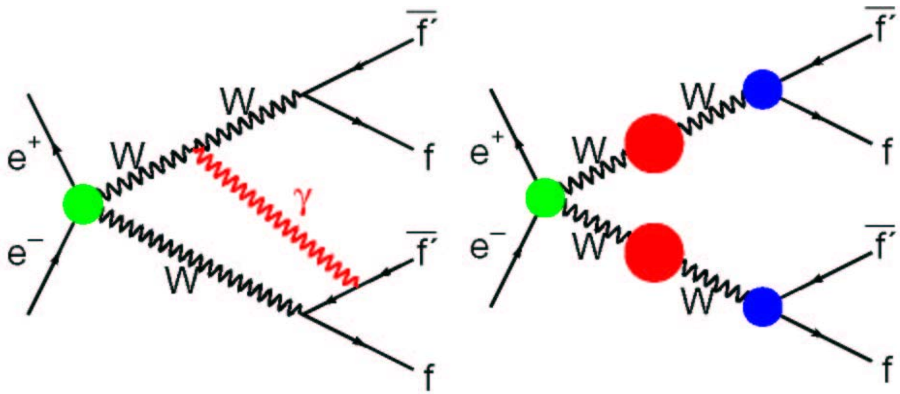
Clear evidence of SU(2)xU(1) gauge structure



Destructive interaction of WWZ and γWW diagrams

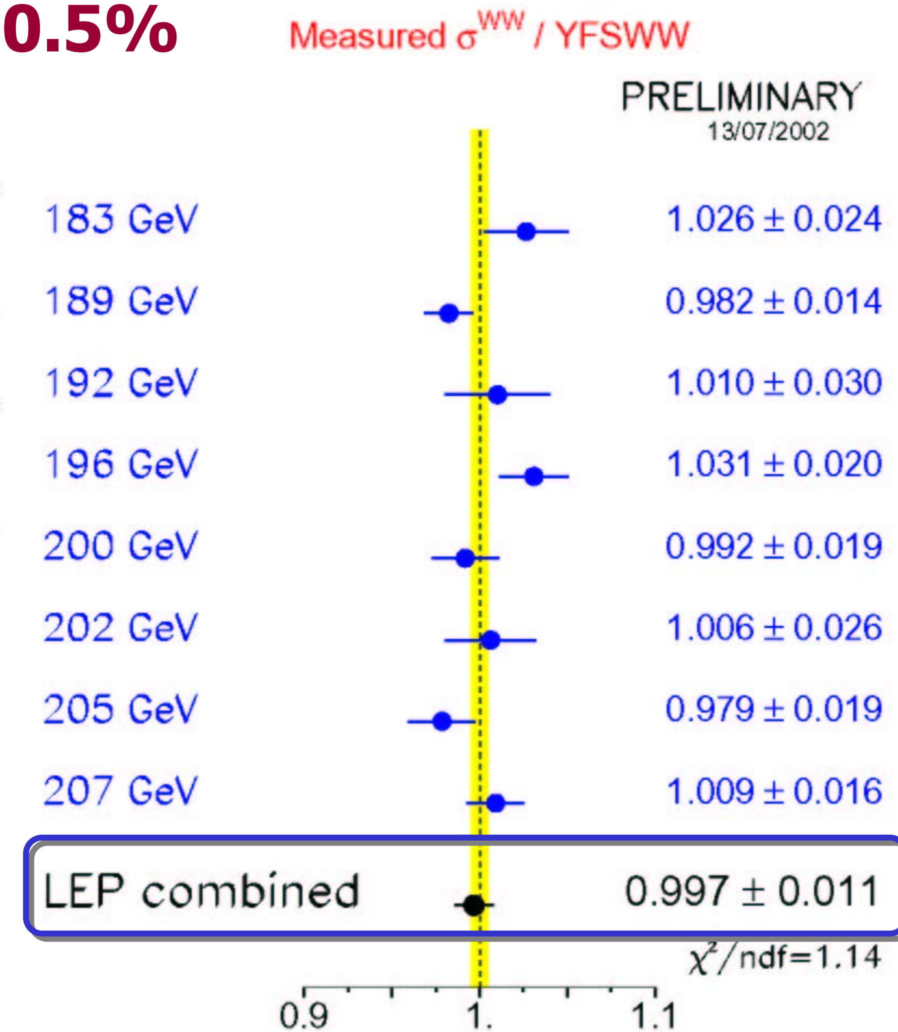
WW cross section

- **Computed to better than 0.5%**
  - **2% beginning of LEPII**



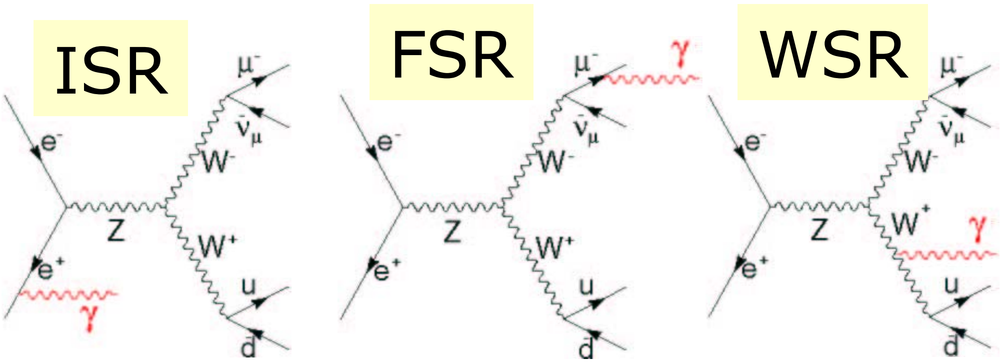
YFSWW / RacoonWW
➲ O(α) corrections
➲ Double Pole Approximation

Include consistently Γ_W

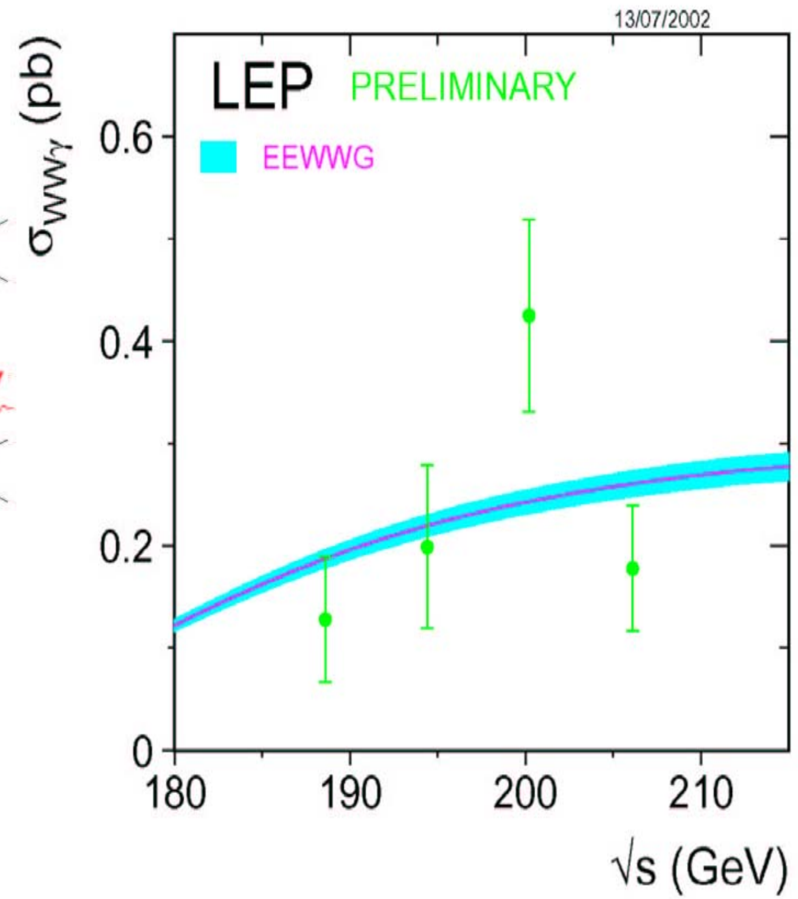


WWγ cross section

- **Final states with a detected photon**



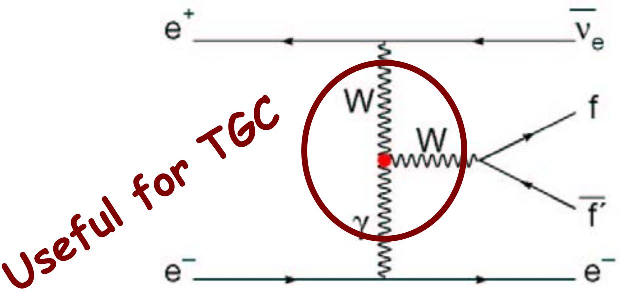
- **Test theoretical implementation of radiation**
- **Used for anomalous WWγγ and WWZγ couplings**



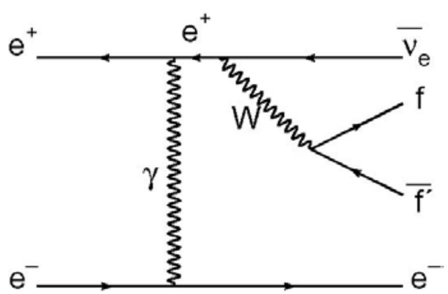
- **Only L3 and DELPHI combined**

Single W

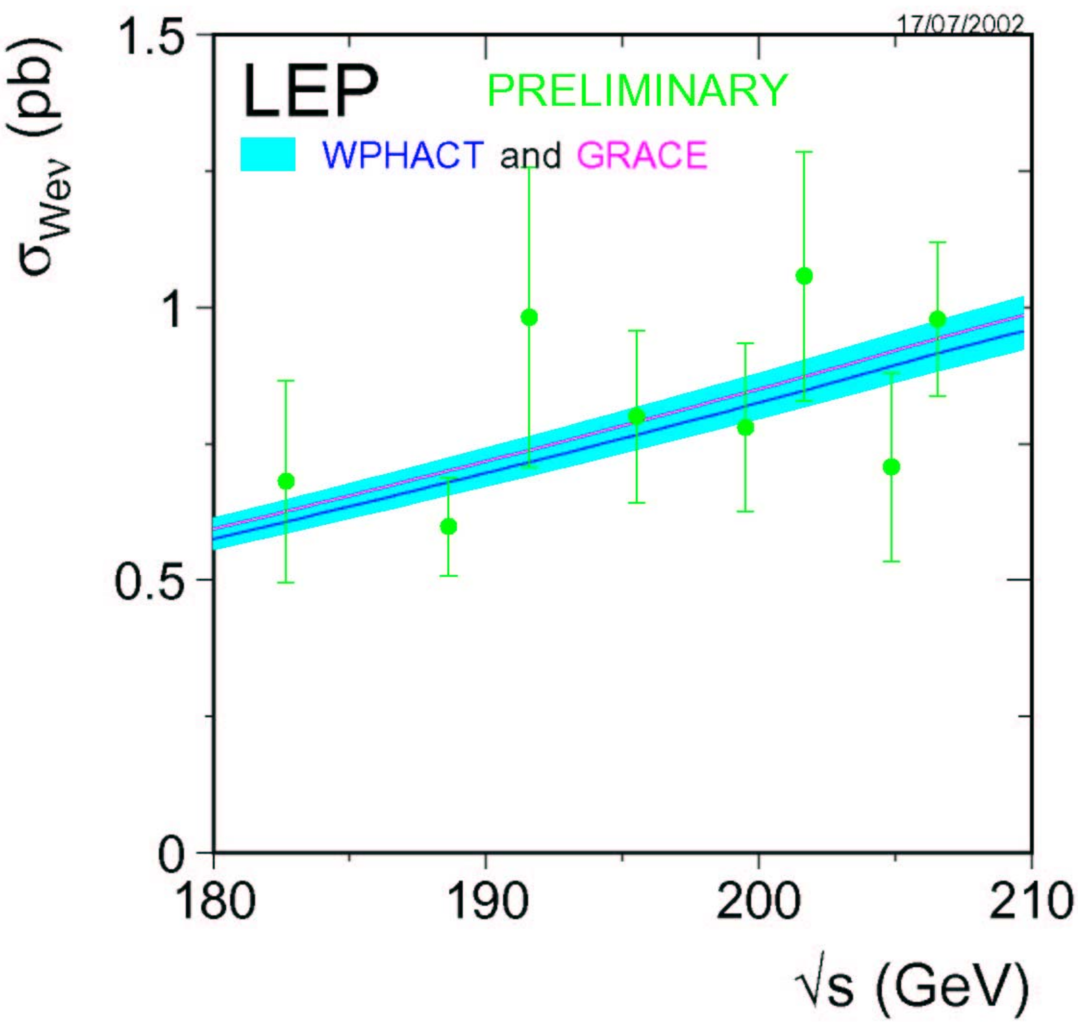
- γW fusion



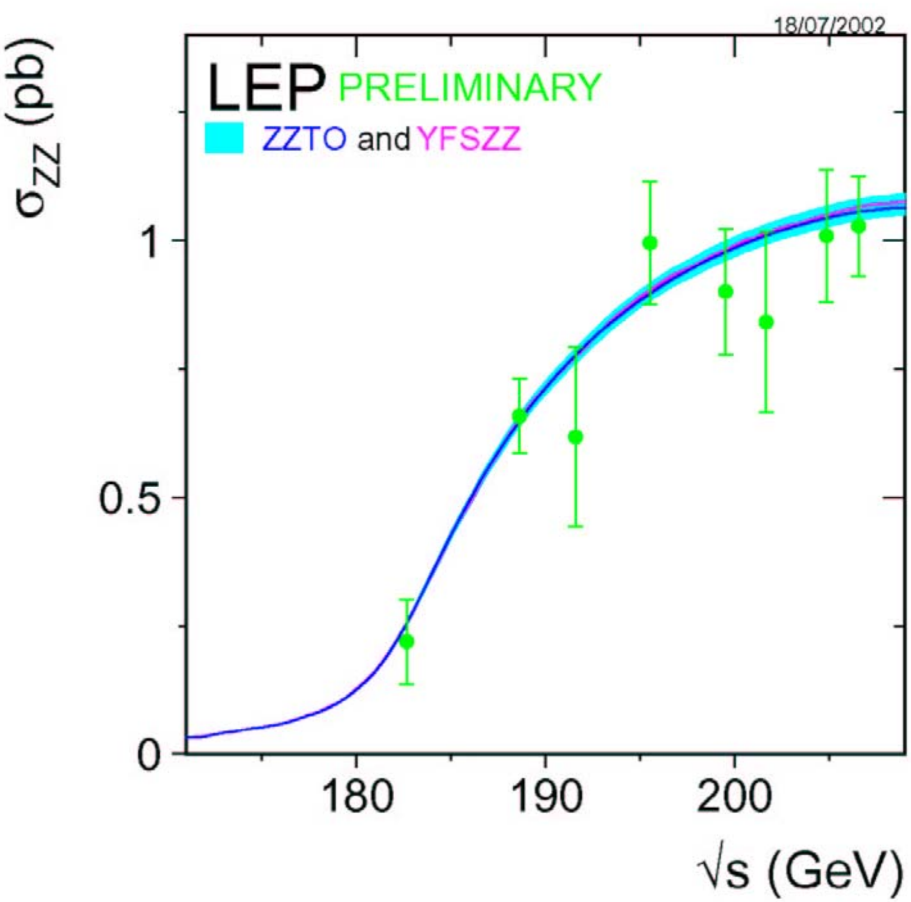
- W-bremsstrahlung

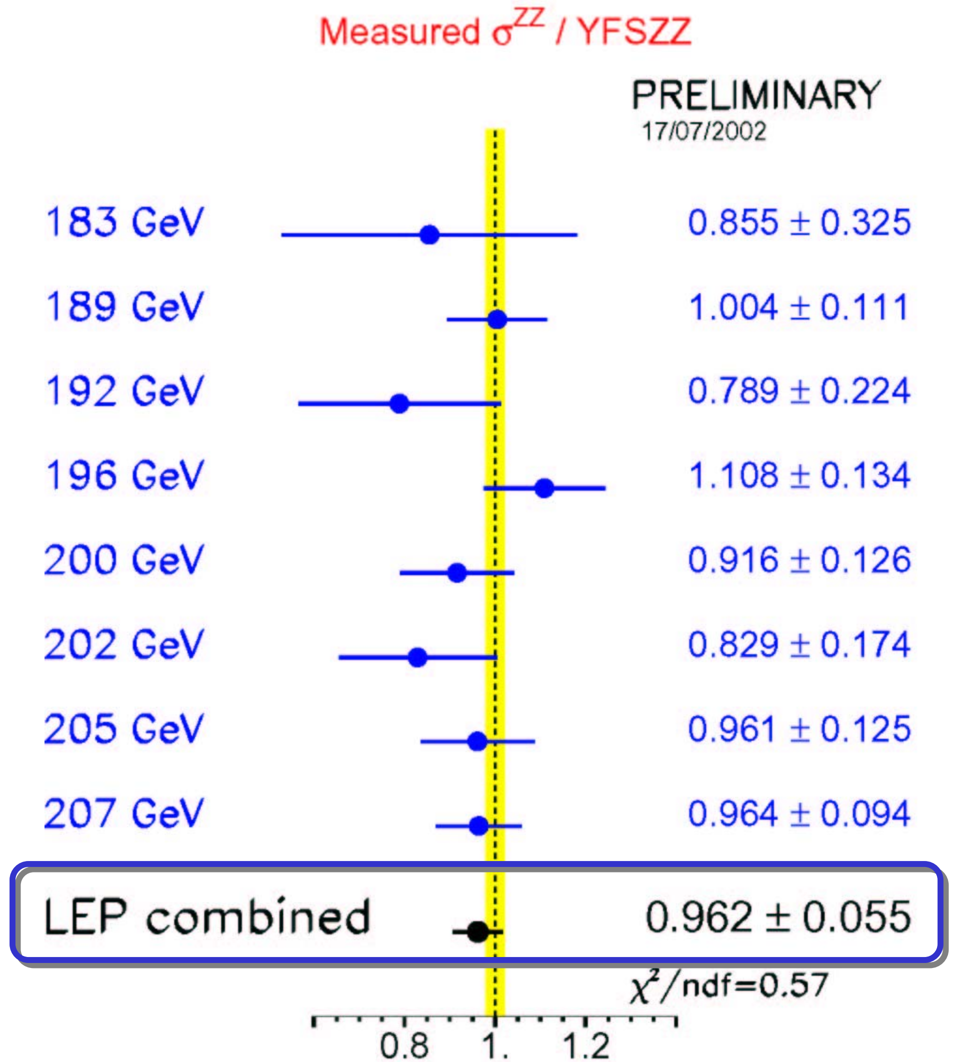


- e escapes undetect



ZZ production

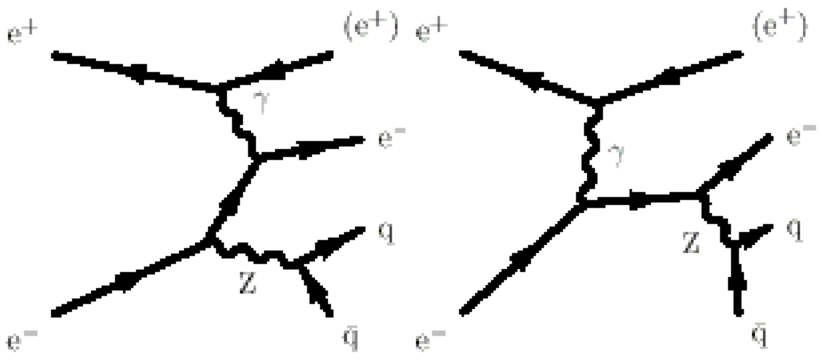


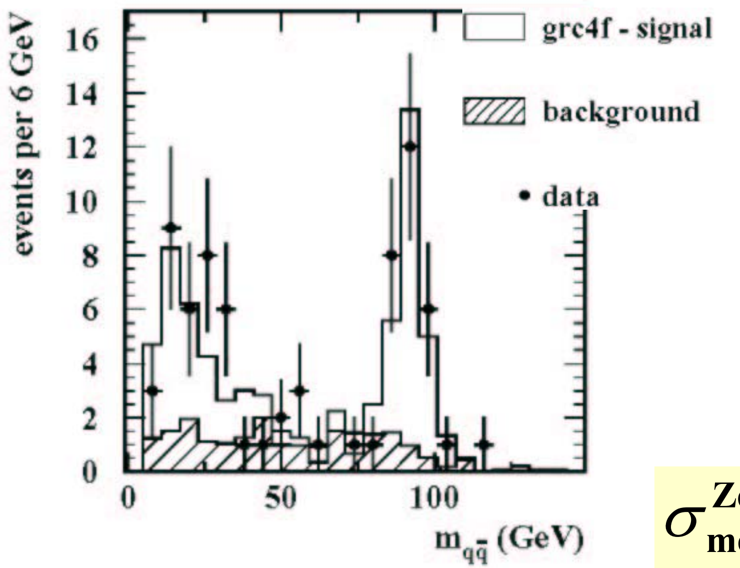


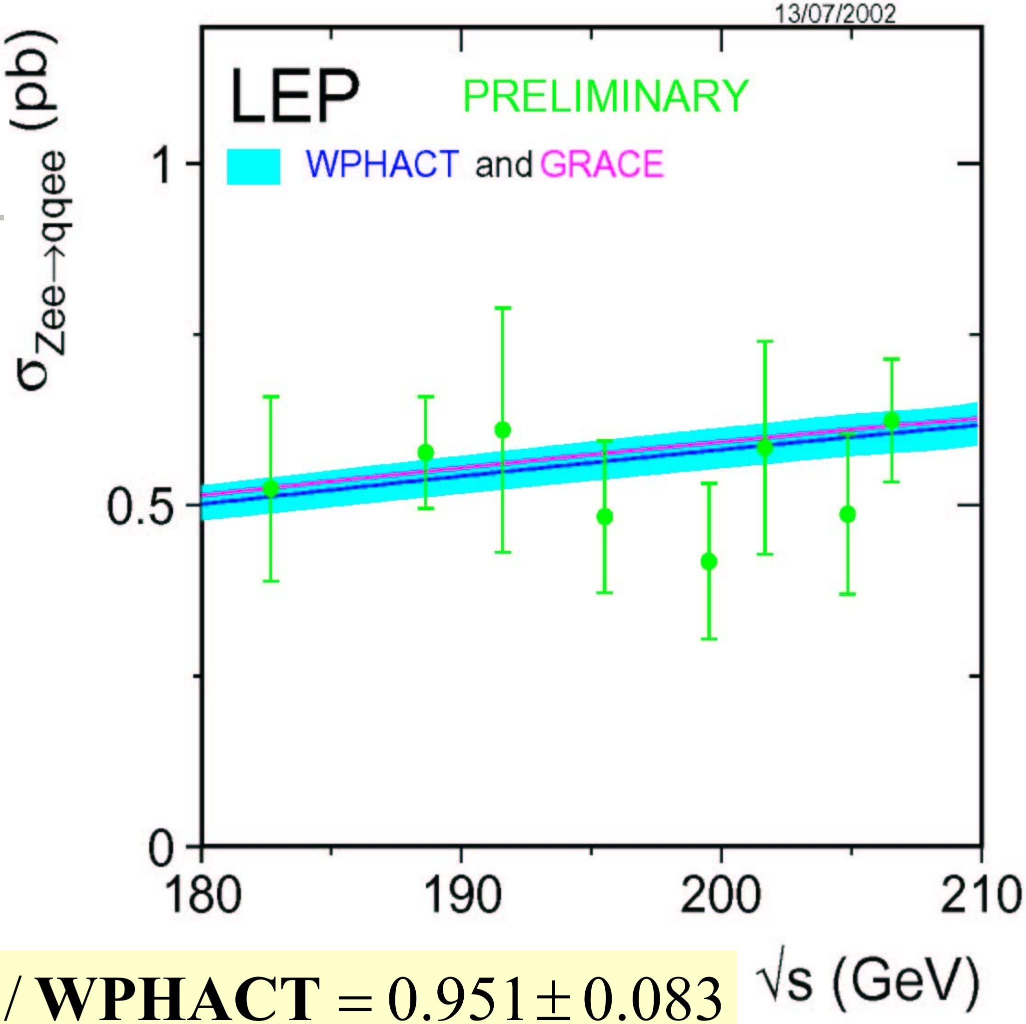
- **Test at 5% level**

Zee production

- ➢ **e scapes undetected**





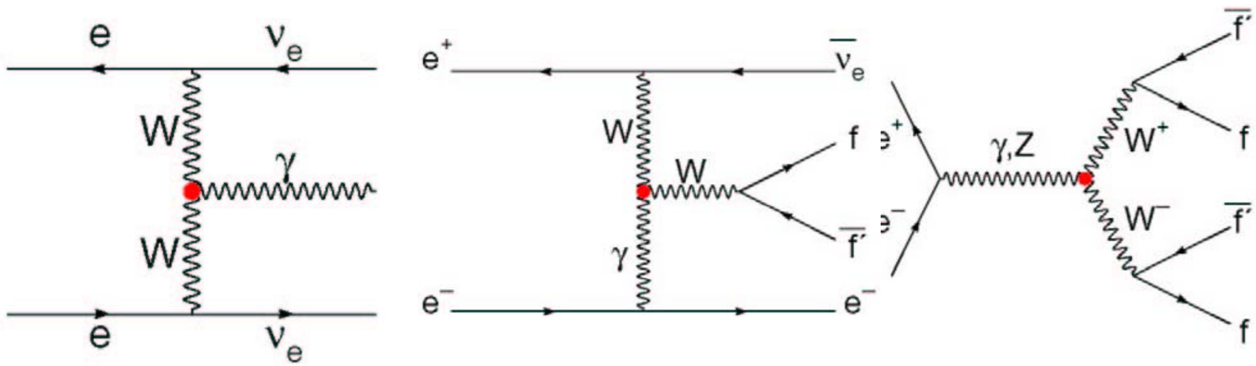


$$\sigma^{Zee}_{measu} \, / \, \mathbf{WPHACT} = 0.951 \pm 0.083$$

Gauge Couplings

Triple Gauge Couplings (TGC)

- **Accessible in single-γ, single-W, and W-pair production**



Effective lagrangian CP conserving (V=Z,γ)

$$\frac{i\mathrm{L}_{\mathrm{eff}}}{g_{\mathrm{VWW}}} = g_1^{V} V^{\mu} W^{-}_{\mu\nu} W^{+\nu}_{\mu\nu} + \kappa_V W^{+}_{\mu} W^{-}_{\nu} V^{\mu\nu} + \frac{\lambda_V}{M_W^2} V^{\mu\nu} W^{+}_{\nu} W^{-}_{\mu}$$

- **Gauge invariance→ only** $g_1^Z, \kappa_\gamma, \lambda_\gamma$ **are free**

Triple Gauge Couplings (TGC)

- **Related to the properties of the W boson**
  - **Magnetic dipole moment**

$$\mu_W = \frac{e}{2M_W^2}(1+\kappa_\gamma+\lambda_\gamma)$$

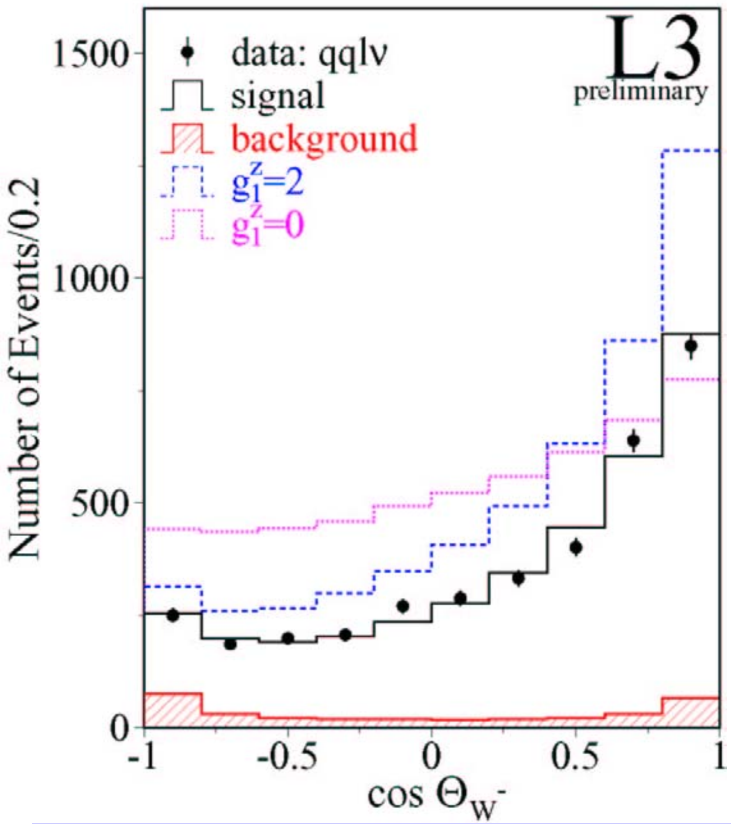
  - **Electric quadrupole moment**

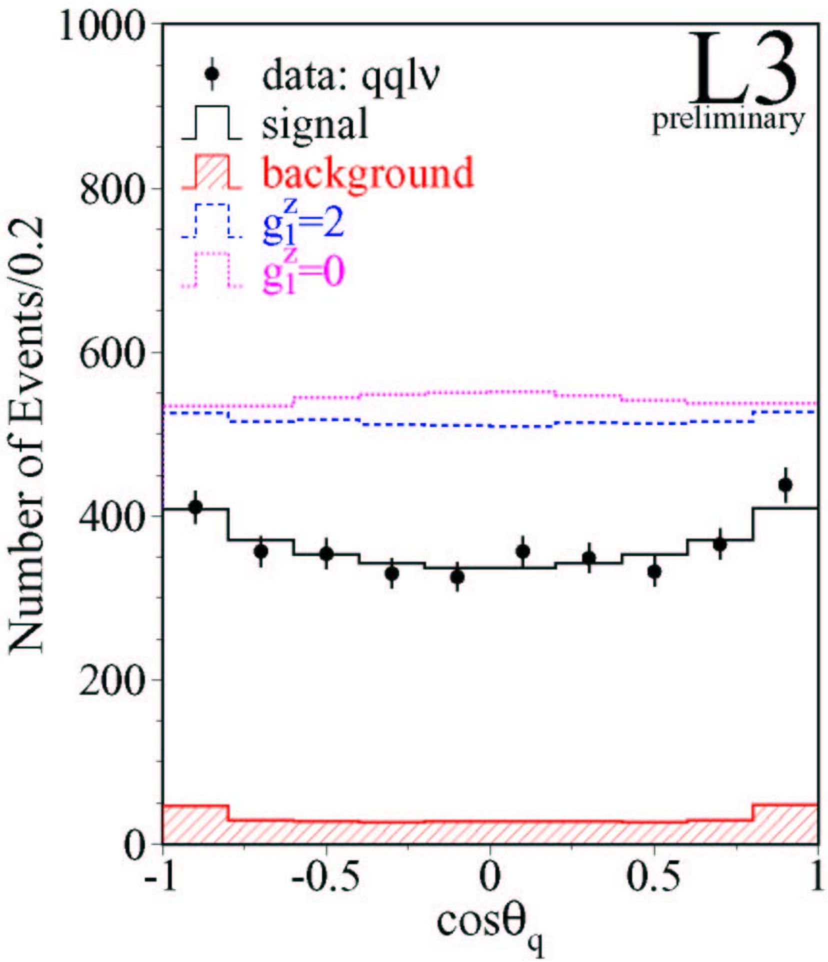
$$q_W = -\frac{e}{M_W^2}(\kappa_\gamma-\lambda_\gamma)$$

- **WW→ 4f sensitive to:** κ_γ λ_γ g_1^Z
- **Single W, single γ** κ_γ

- **In the Standard Model:** $\kappa_\gamma = 1$ $\lambda_\gamma = 0$ $g_1^Z = 1$

TGCs from W pairs



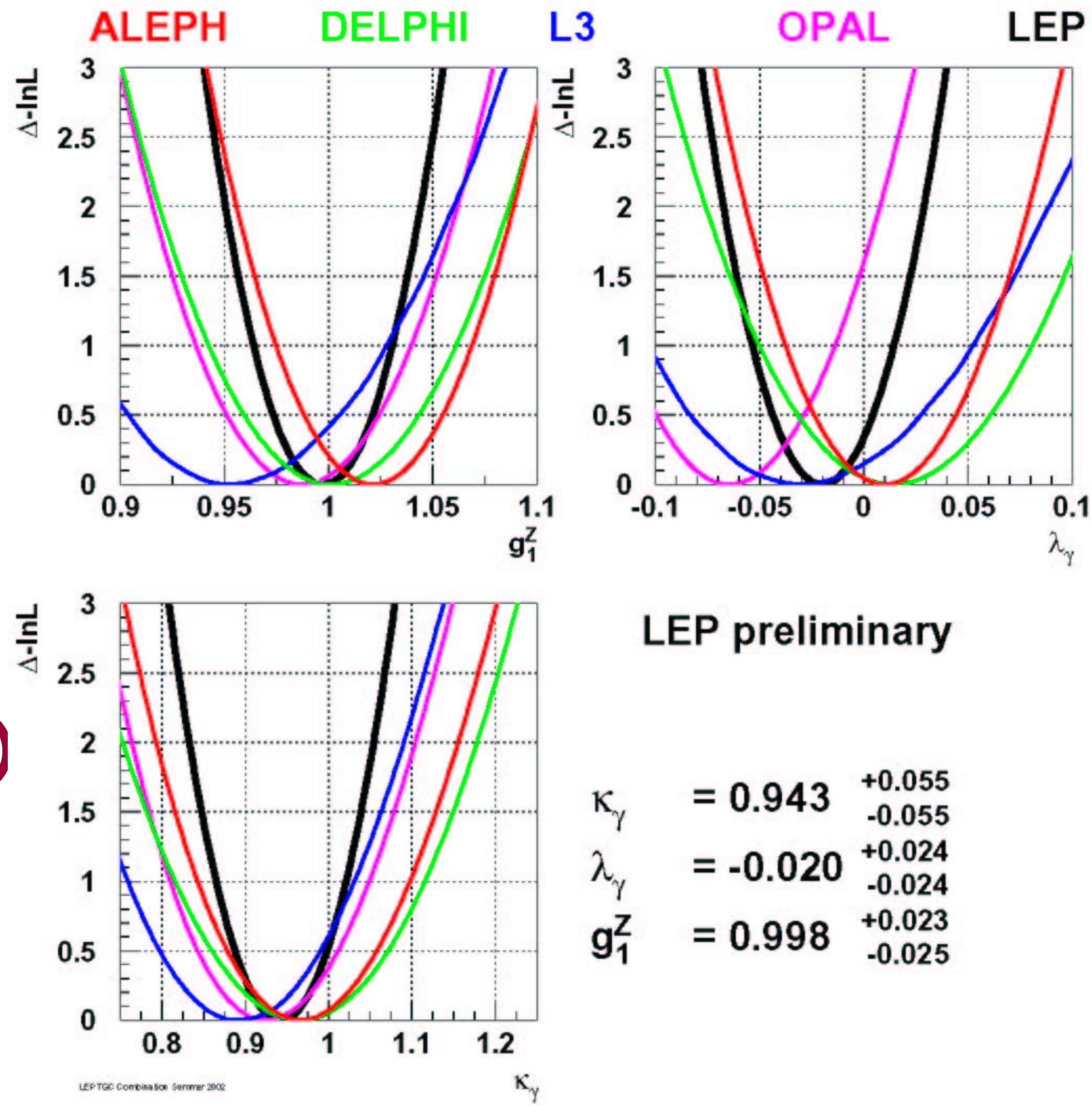


Sensitive to:

- **Angular distribution**
- **Event rate**

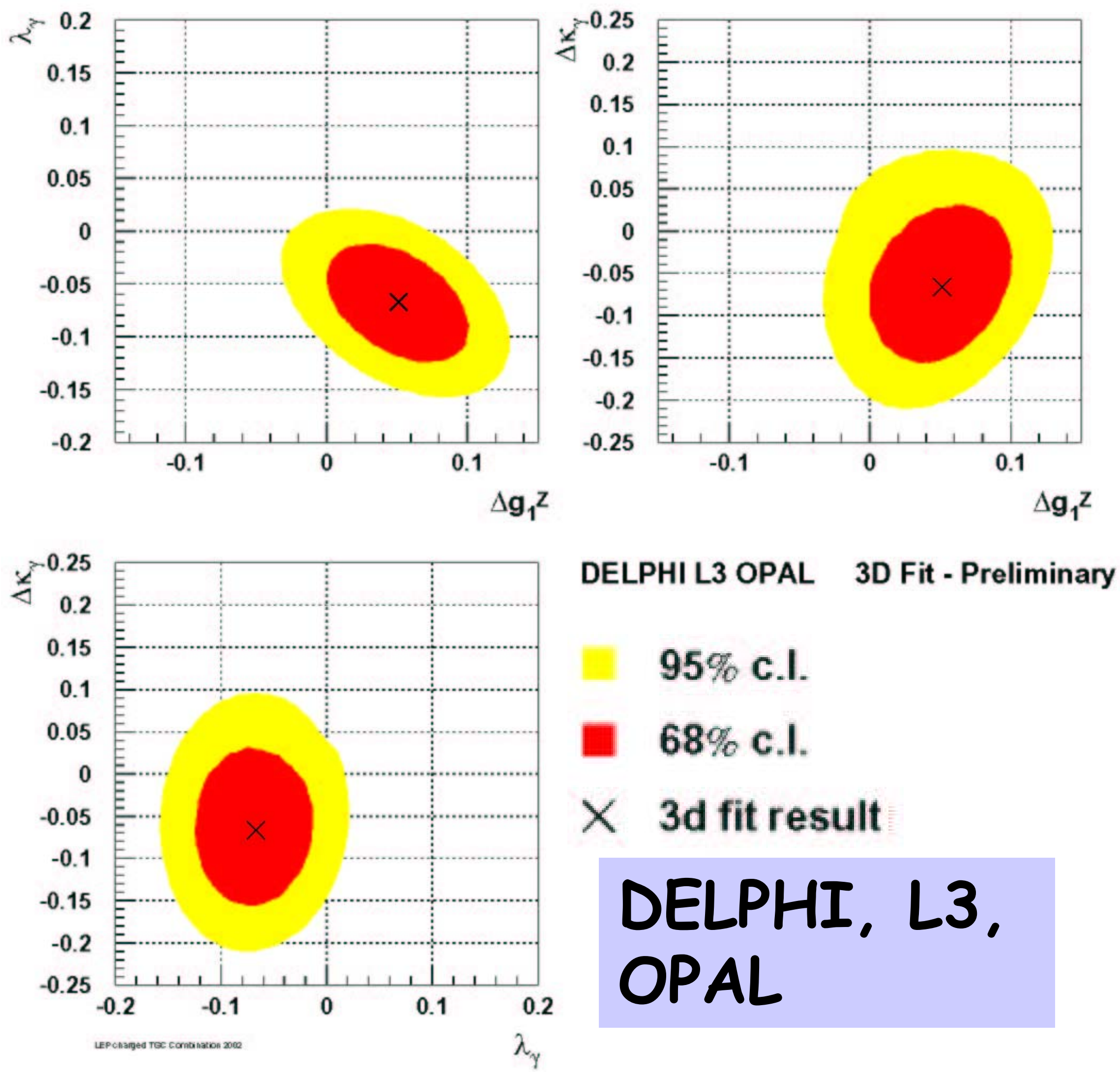
TGCs: 1 dimensional fit

- **1 parameter fitted**
- **The others fixed to their SM value**
- **Fit to qqqq, qlν,lνlν, single W, single γ**
- **Main correlated systematic from O(α) corrections**
  - **0.015 on** g_1^Z λ_γ
  - **0.039 on** κ_γ



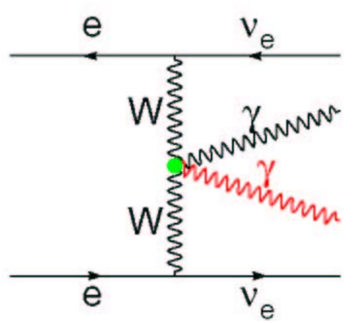
TGCs: 3 Dimensional fits

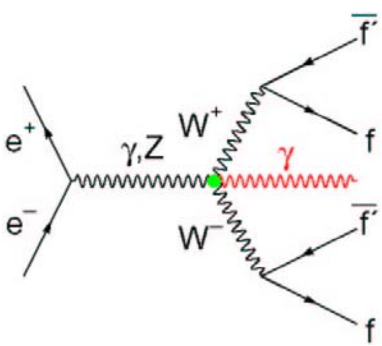
- **All parameters free**
- Δg_1^Z $\Delta\kappa_\gamma$ **: deviations from SM**
- **2D contours when the 3rd parameter is at minimum**



Quartic Gauge Couplings(QGC)

- **Predicted by SM**





Accesible via:

$\nu\nu\gamma\gamma$

And

$WW\gamma$

Final states

- **Negligible at LEPII energies**

- **Deviations from SM**
  - **Increase of WWγ cross section**
  - **Modify the energy spectrum and rate of γ production**
- **New physics lagrangian**

$$\mathcal{L}_0 = -\frac{e^2}{16}\frac{a_0^{W,Z}}{\Lambda^2} F^{\mu\nu} F_{\mu\nu} \vec{W}^{\alpha} \vec{W}_{\alpha}$$

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

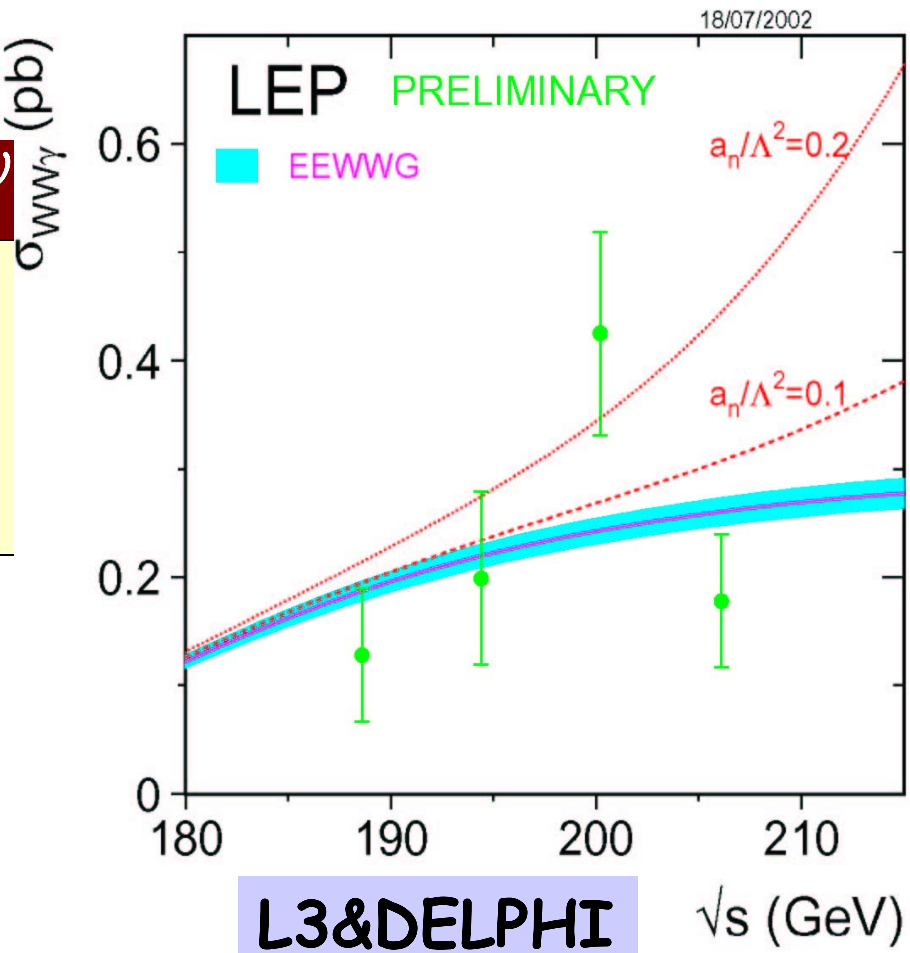
$$\mathcal{L}_n = -\frac{e^2}{16}\frac{a_n}{\Lambda^2} \vec{W}_{\mu\alpha} \cdot (\vec{W}_{\nu} \times \vec{W}^{\alpha}) F^{\mu\nu}$$

Λ energy scale

Quartic Gauge Couplings(QGC)

	$a^W_0/\Lambda^2 (GeV^{-2})$	$a^W_c/\Lambda^2 (GeV^{-2})$	$a_n/\Lambda^2 (GeV^{-2})$
ALEPH	[-0.045,0.042]	[-0.115,0.115]	
DELPHI	[-0.018,0.018]	[-0.057,0.030]	[-0.16,0.12]
L3	[-0.015,0.015]	[-0.048,0.026]	[-0.14,0.13]
OPAL	[-0.054,0.052]	[-0.15,0.14]	[-0.61,0.57]

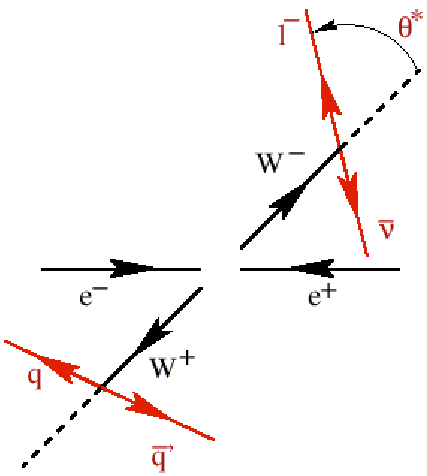
Limits at 95% CL



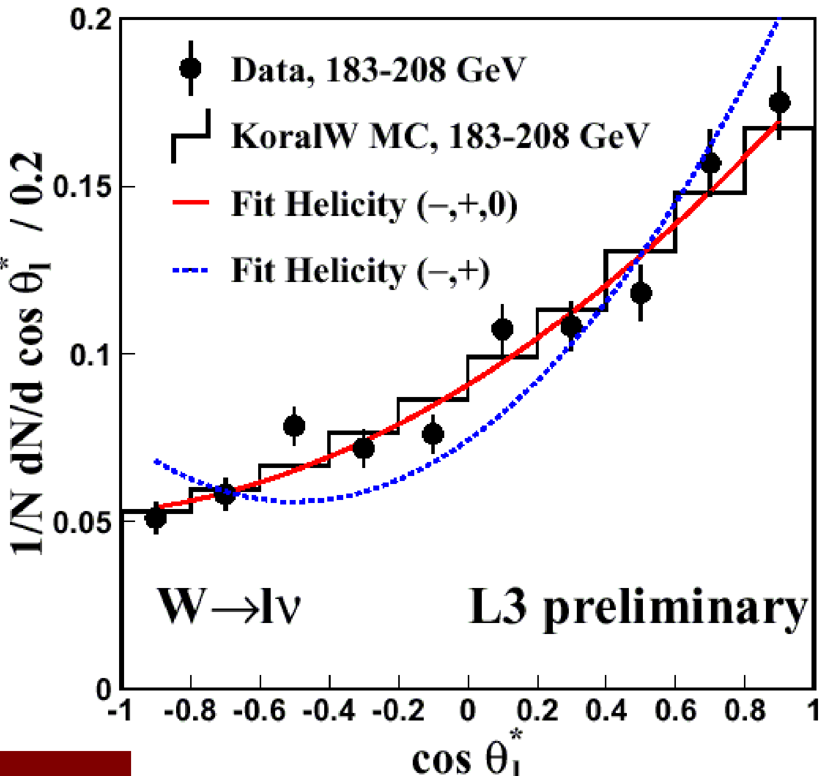
L3&DELPHI

W polarization

- The 0 helicity state of W is related to the Higgs mechanism



- Measured from the angular distribution of the decay products of W
- In the rest frame of W



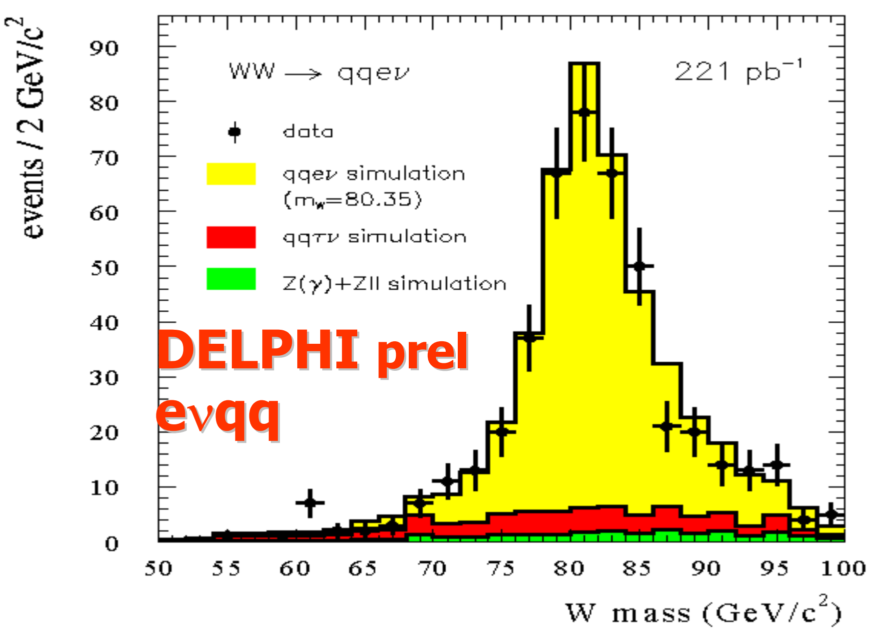
	σ_L/σ	SM
L3	0.228±0.027±0.012	0.241 @ <√s>=197 GeV
OPAL	0.210±0.033±0.016	0.257 @ √s=189 GeV

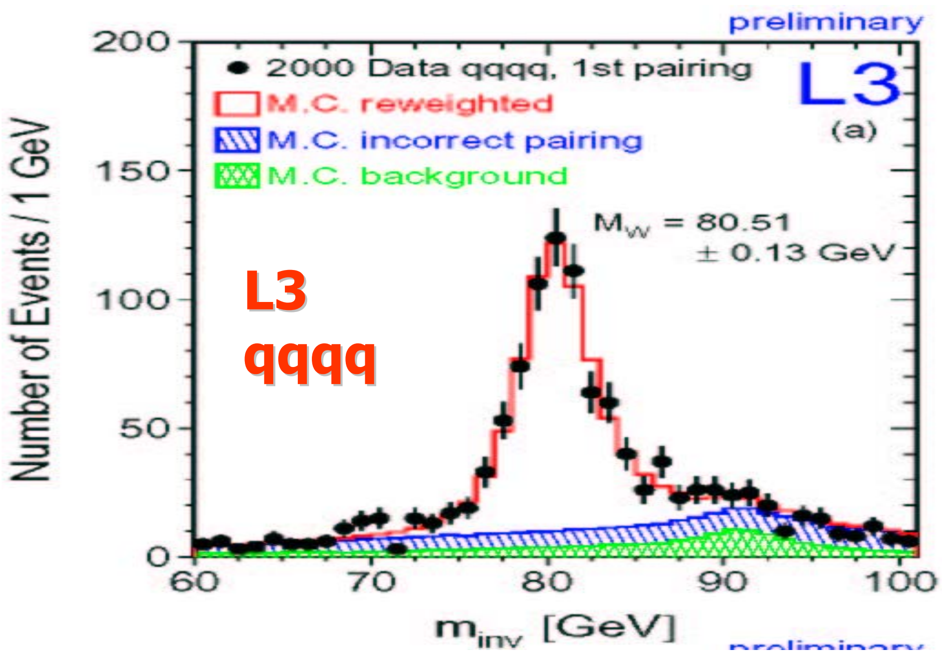
Fit without longitudinal component fails to describe data

W mass and width

M_W from direct reconstruction

- **Estimator of the W mass/event** $M_{qq}^{inv}, M_{l\nu}^{inv}, \langle M_W \rangle, \ldots$
- **Constrained fit to improve resolution**
  - **E, P conservation**
  - **Mw1=Mw2**
- **3 solutions for qqqq**





Mass Extraction – 3 Methods

- **Monte Carlo Reweighting technique** (ALO)
  - Compare data distributions to Monte Carlo distributions reweighted to different M_W
  - Estimators used : $< M_W>$, M_{qq}^{inv}, σ_{mw},...(n-dimensional reweighting)

- **Convolution technique** (D,O for cross check)
  - Build event likelihood:

  PDF:=Breit-Wigner $\oplus$ ISR $\oplus$ phase space

- **Breit-Wigner method** (OALD for cross check)
  - Fit analytical Breit-Wigner function to data distributions

Systematic error on Mw(MeV)

- **Total statistical error:**
  - **30 MeV**
- **Reduced weight of the qqqq channel :**
  - **9%**
- **Large effect from Final State Interactions**

Preliminary
Summer '02

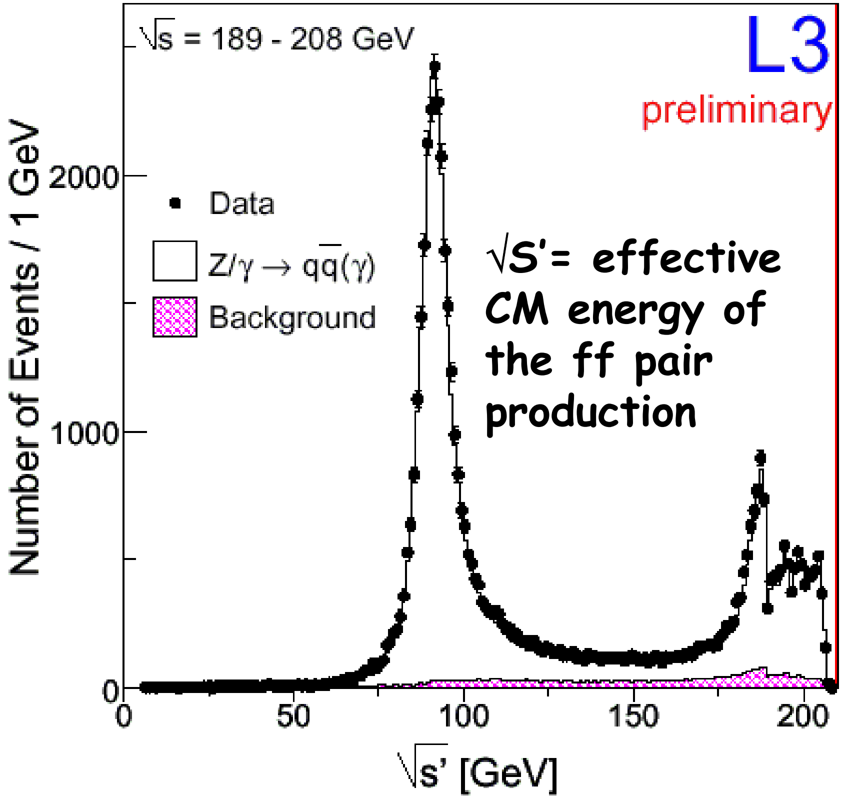
source	*qqln*	*qqqq*	*Combined*
ISR/FSR	8	8	8
Hadronization	19	18	18
Detector	12	8	11
LEP beam energy	17	17	17
Colour Reconnection	-	90	9
Bose-Einstein	-	35	3
Other	4	5	4
Total Systematic	29	101	30
Statistical	33	36	30
Total	44	107	42

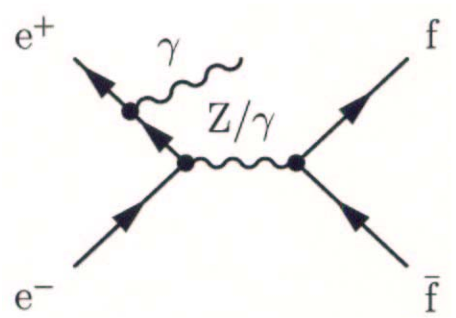
Z0 returns to calibrate E_{beam}

- **LEP2 aim : $\Delta E_{LEP}/E_{LEP} \approx 1.10^{-4}$**

$$\frac{\Delta M_W}{M_W} \propto \frac{\Delta E_{beam}}{E_{beam}}$$

- **E_{LEP} used in the kinematic fit**
  - **absolute scale for W mass**
- **Independent measure of E_{LEP} very important**
  - **Radiative returns to Z^0**





M_Z known to 10^{-5} (LEPI)

ΔE_b=E(rad)-E(LEP)

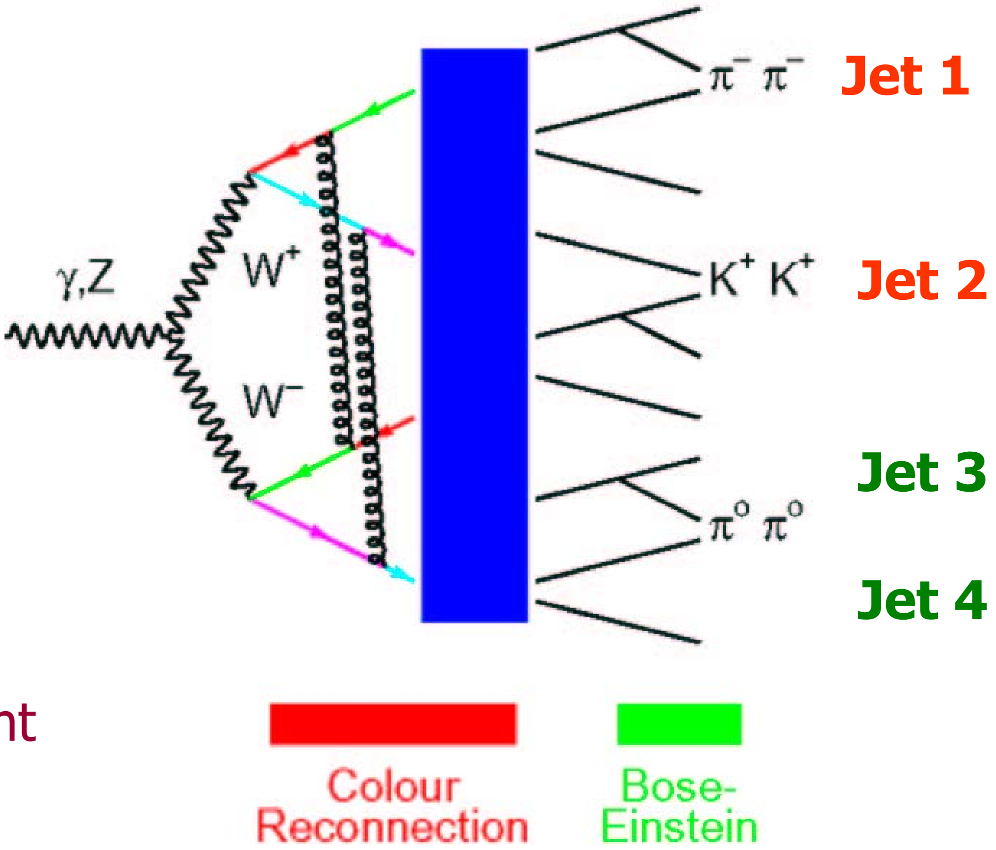
ΔE_b=-10±27(stat) ±26(syst) MeV

Final State Interactions

- **Ws decay distance ~0.1fm**
- **Hadronization scale ~1fm**

Cross-talks between the two hadronic systems ?

- Colour Reconnection
- Bose Einstein Correlations between particles from different Ws



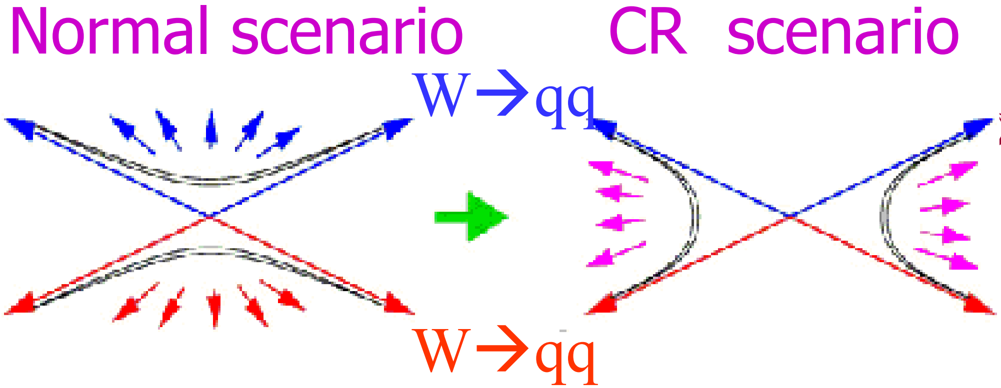
Possible mass shift:

Minv(W) ≠ Minv(jet,jet)

Use data to limit FSI bias on Mw(qqqq)

Colour Reconnection

- Colour flow pattern is modified



- Interaction between decay products (change of colour flow)
- Final hadronic color singlets do not correspond to the initial W bosons

- Bias on the reconstructed W mass by momentum transfer between the two Ws
- CR described by phenomenological models.
  - Try to test the validity of them using sensitive analysis to CR
  - Develop a mass analysis less sensitive to CR

Colour Reconnection

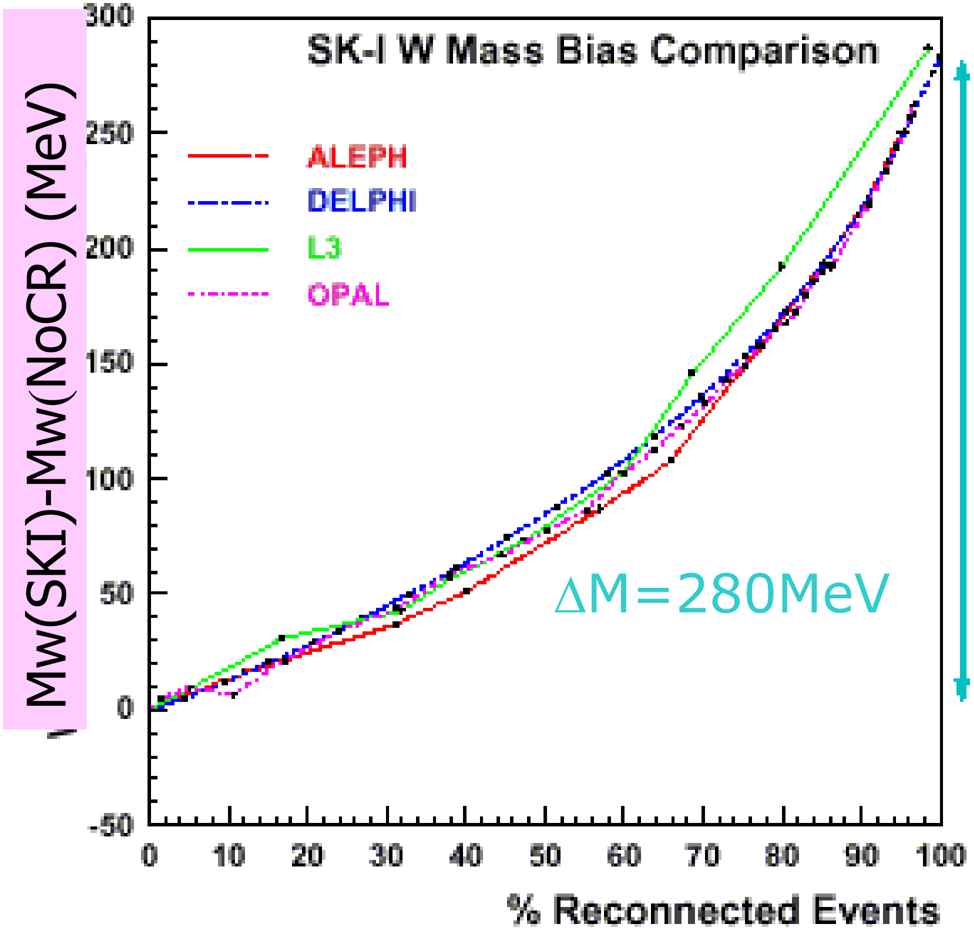
- **Models tested: SKI, Herwig, AR2, Rathsman…**
- **All LEP experiments similar sensitivity**

√s=189 GeV

MeV	SKI	Rathsman	HW	AR2
ΔM_W √s=189	0-300	~60	~30	~60

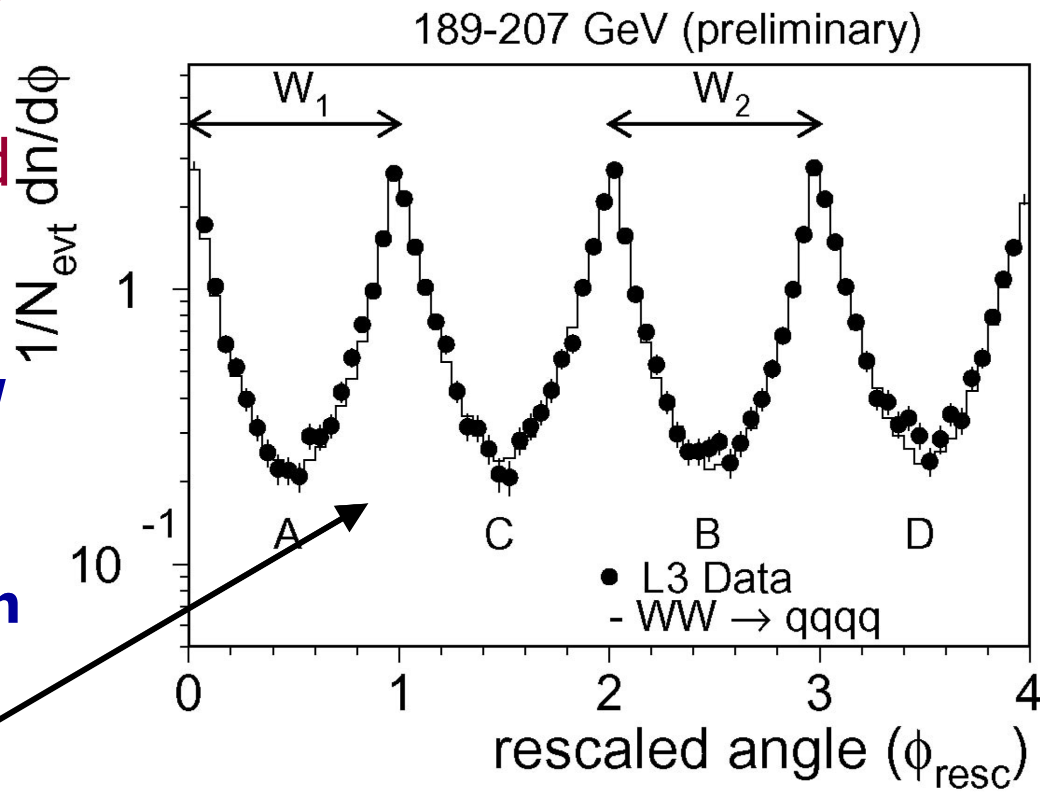
- **CR effect scales with √s**
- **SKI:**
  - **Free strength parameter κ**
  - **Controls reconnection probability**

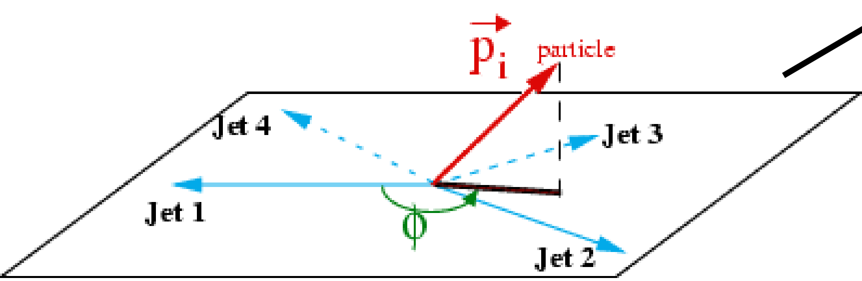
$$P_{reco} = 1 - e^{-f.\sqrt{s}.\kappa}$$



Particle Flow Method

- Compare the particle flow in the regions between jets from the same W and between jets from different Ws
  - **Identify jets from the W decay**
  - **Build the normalized particle flow distribution**

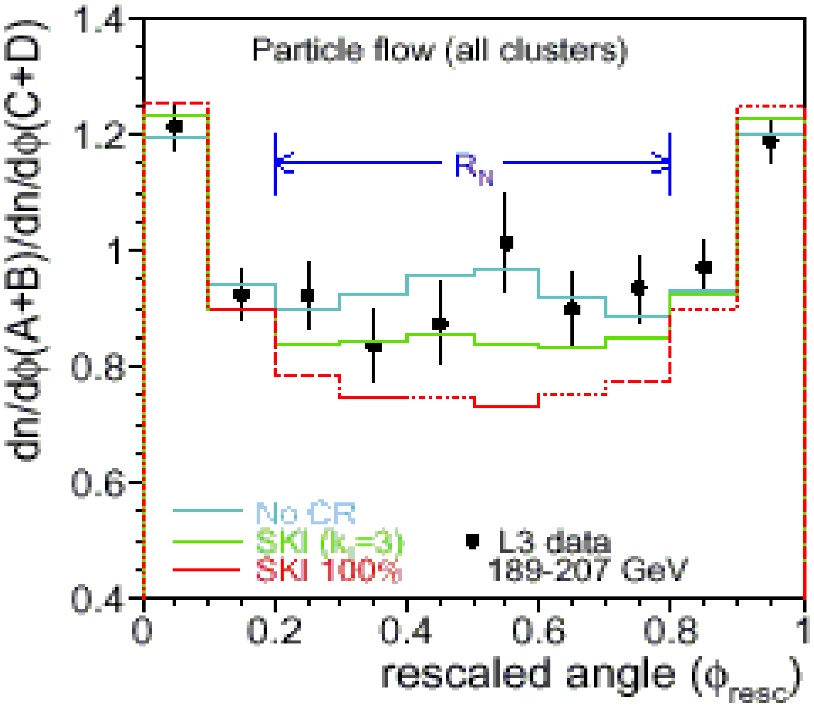




CR should lead to:
- depletion inside W region (A and B)
- enhancement in non W region (C and D)

CR from particle Flow

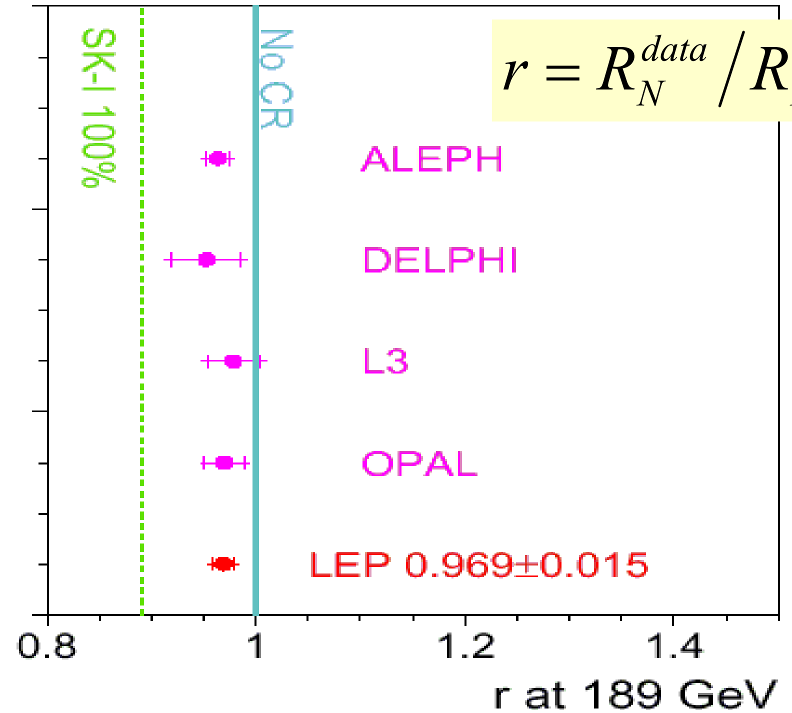
- **Ratio: (A+B)/(C+B)**



- **Most sensitive region [0.2,0.8]**

$$R_N = \int A + B \Big/ \int C + D$$

$$r = R_N^{data} \Big/ R_N^{no-CR}$$

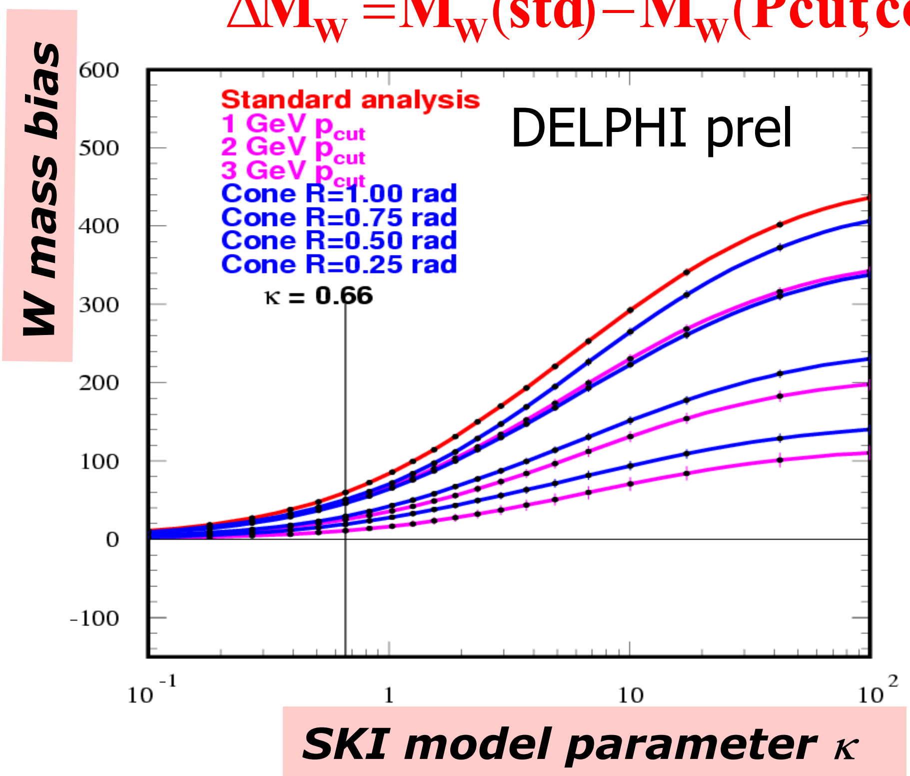


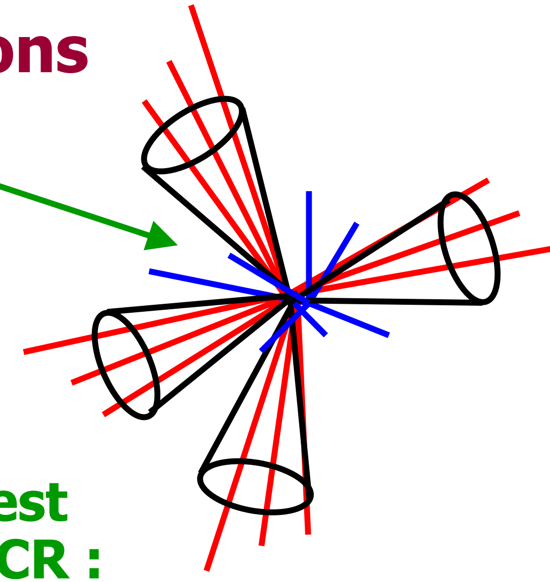
- **κ<2.13 @ 68% CL (P_{reco}≈65%)**
  - **ΔM_W=90 MeV**
- **SKI (100%) disfavoured by 5.2σ**
- AR2 and HW are not sensitive to particle flow method

CR from ΔM_W

- **Exclude soft particles in inter jet regions**
  - **Cut in particle momentum**
  - **Cut in cone size**
- **ΔMw provides a measurement of CR**

$$\Delta M_W = M_W(std) - M_W(Pcut, cone)$$



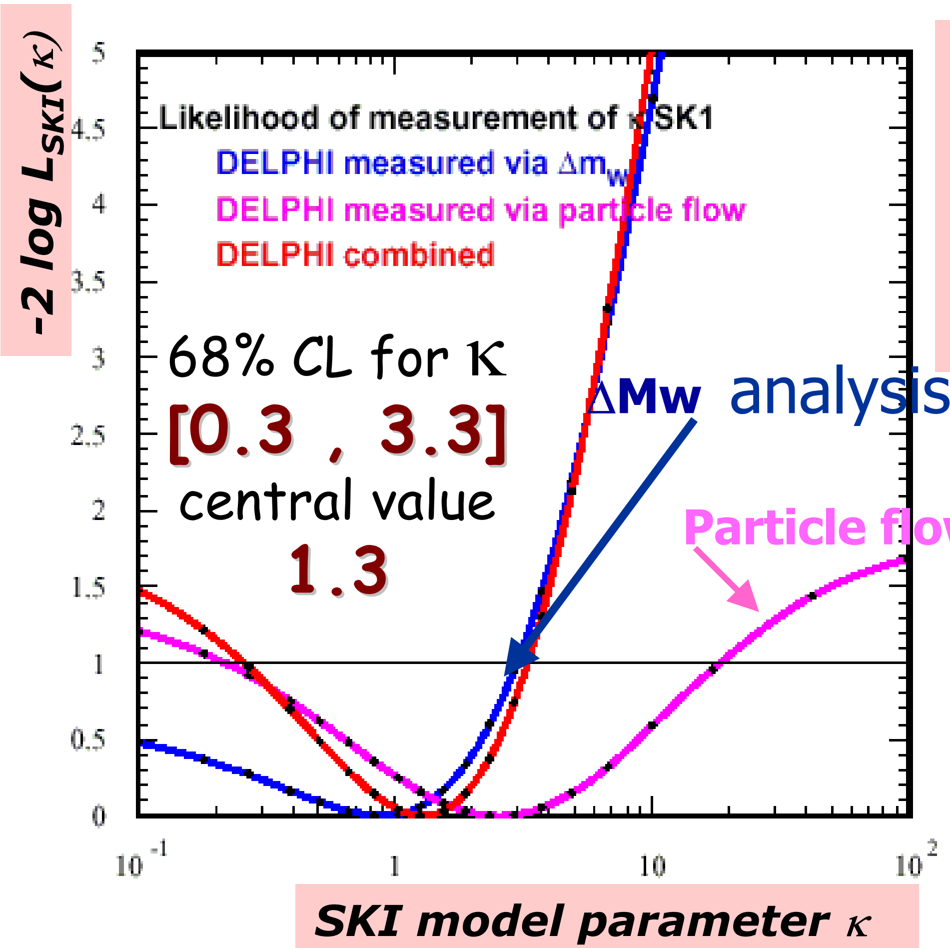


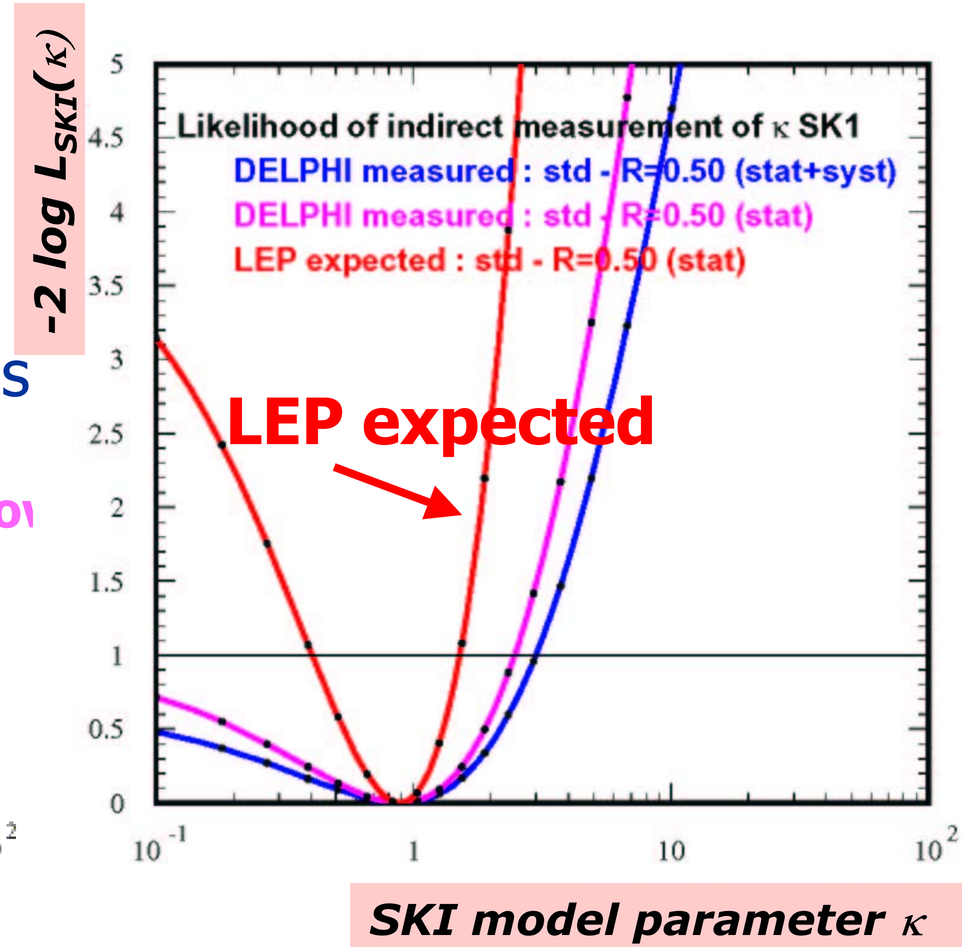
- **DELPHIs largest sensitivity to CR :**
  - **Cone analysis: R_{cone}=0.5 rad**

$$\Delta M_W(std, R_{cone}=0.5\,rad) = 36 \pm 36 \pm 25\,MeV/c^2$$

- Compare with model prediction for each κ …

CR from ΔM_w

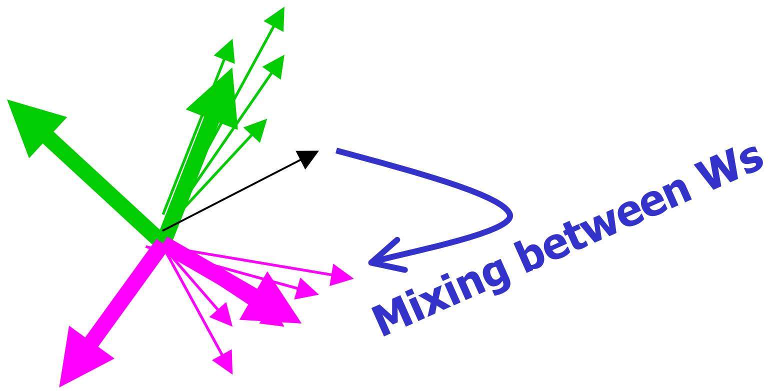




Other LEP experiments working on it

Bose-Einstein Correlations

- **Enhanced production of identical bosons close in phase space**
- **BEC measured at LEPI**

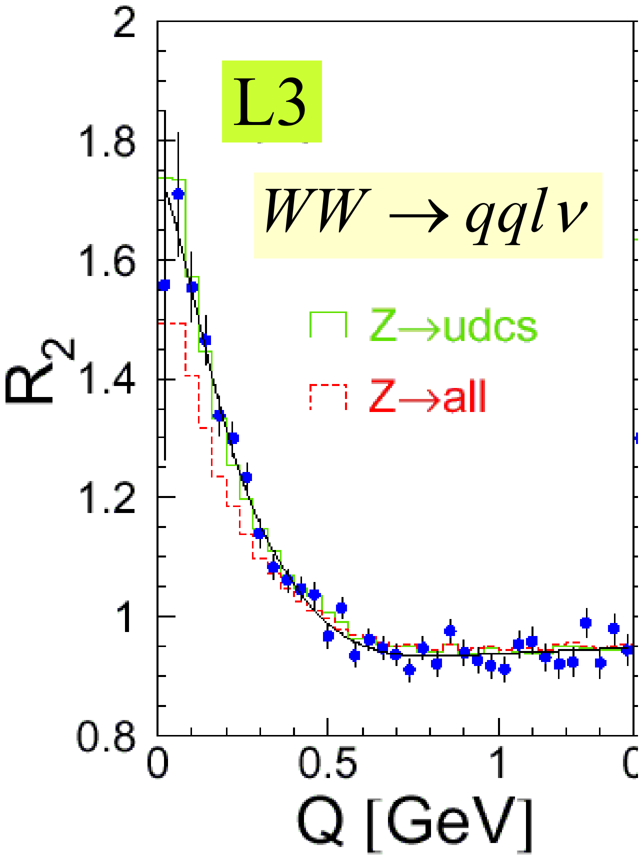


- **Effect similar in Z^0 and W decay ?**
- **BE between Ws?**
- **Systematic effect on W mass (summer 2002)**

ΔMw(MeV)	BEall-BEinside
ALEPH	33±5
DELPHI	-
L3	30±8
OPAL	26±5

Bose-Einstein Effect Inside W

- Enhancement of identical bosons at low Q



- 2-particle density

$$\rho(Q) = \frac{1}{N_{event}} \frac{dn_{pairs}}{dQ}$$

- 2-particle momentum transfer

$$Q = \sqrt{-(p_1 - p_2)^2}$$

- Correlation function

$$R_2(Q) = \rho(data) / \rho(MC)_{noBE}$$

Correlations are equal in light-quark Z decays and inside Ws

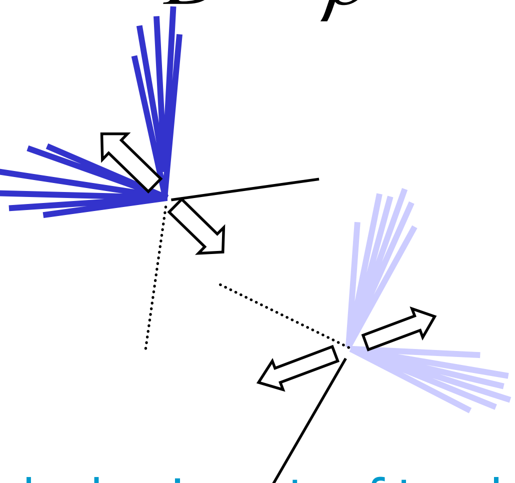
Inter-W BEC

$$\Delta\rho = \rho^{WW\to4q} - 2\rho^{W\to2q} - 2\rho^{WW_{mix}}$$

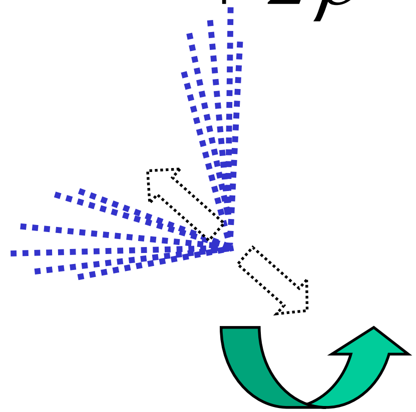
$$D = \rho^{WW\to4q} / (2\rho^{W\to2q} + 2\rho^{WW_{mix}})$$

Δρ=0 , D=1

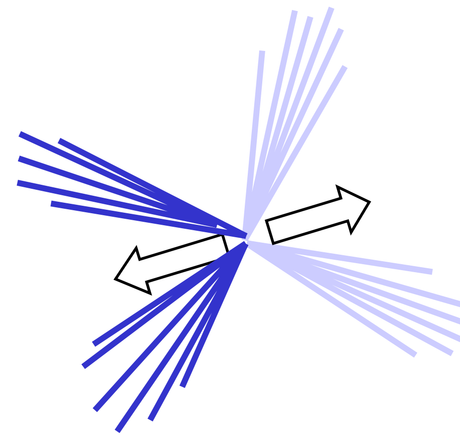
in the absence of inter BEC



hadronic parts of two lνqq evts



rotate/boost to balance momenta

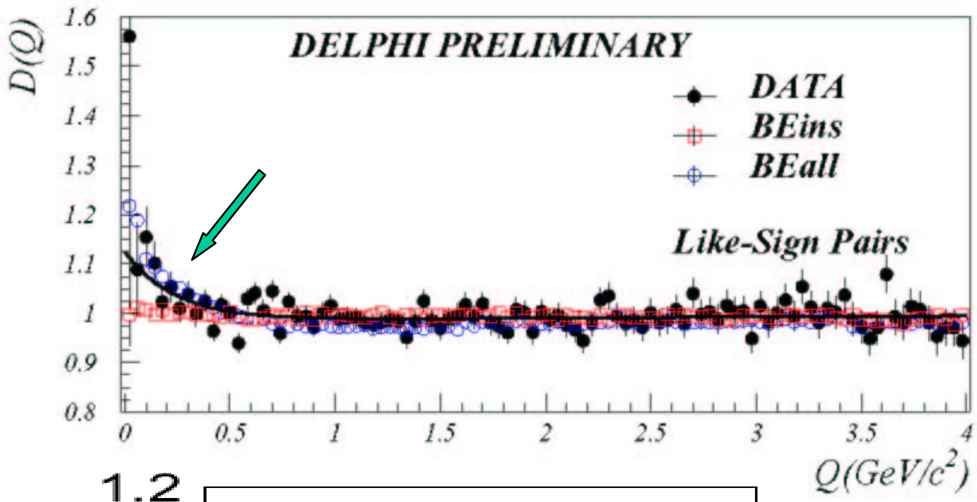


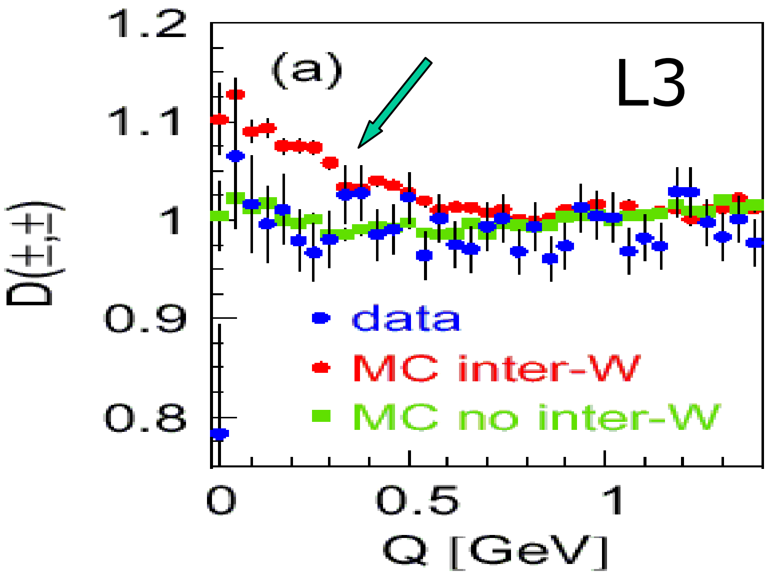
mix => uncorrelated 'WW' event

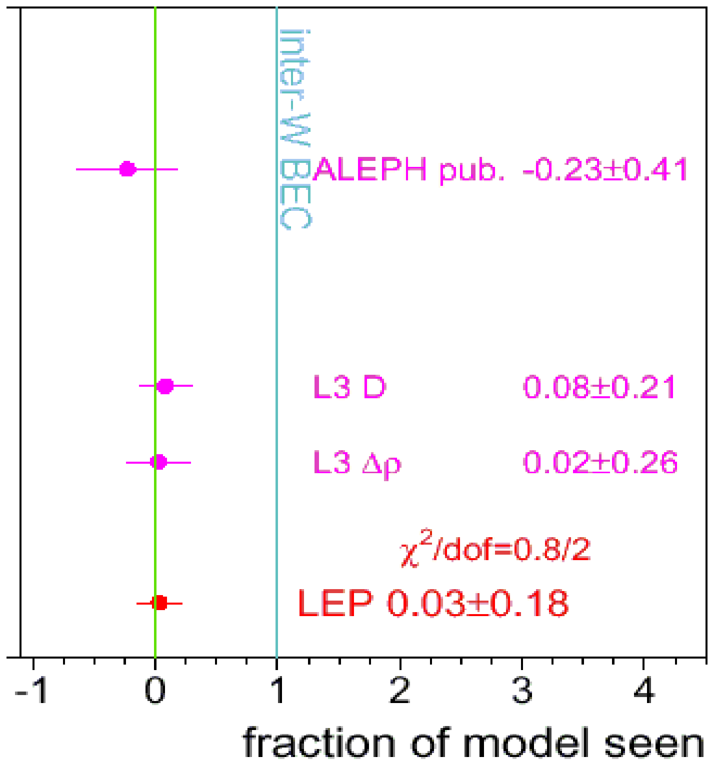
- Experimentally robust (data compared with data)
- Model independent (except for background subtraction)

ABSOLUTE MEASUREMENT OF INTER-W CORRELATIONS

Inter-W BEC



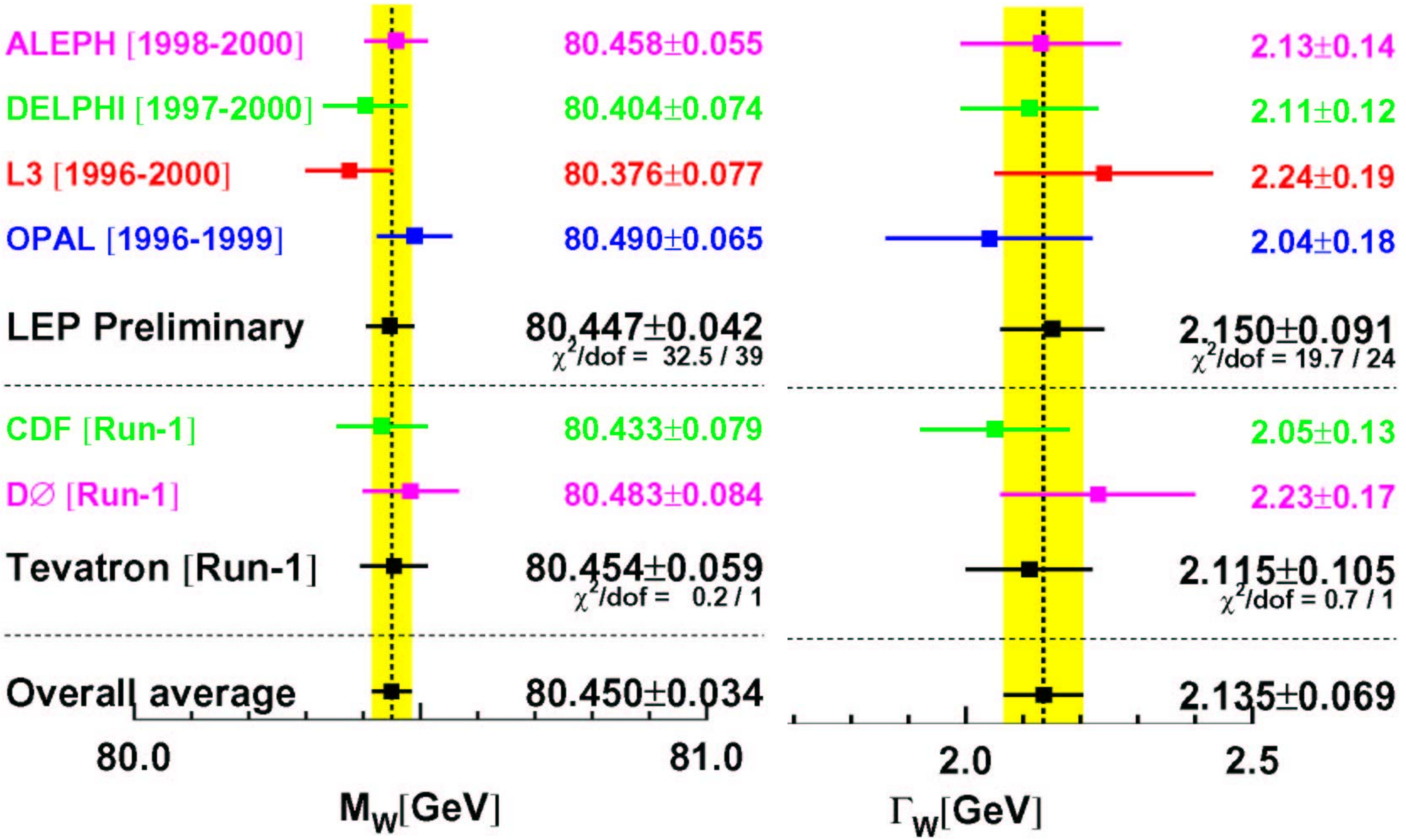




- **Data compatible with 3%±18% of full correlations in LUBOEI**
  - **ΔMw<10 MeV (not yet used)**
- **DELPHI not yet included in fit**

Results

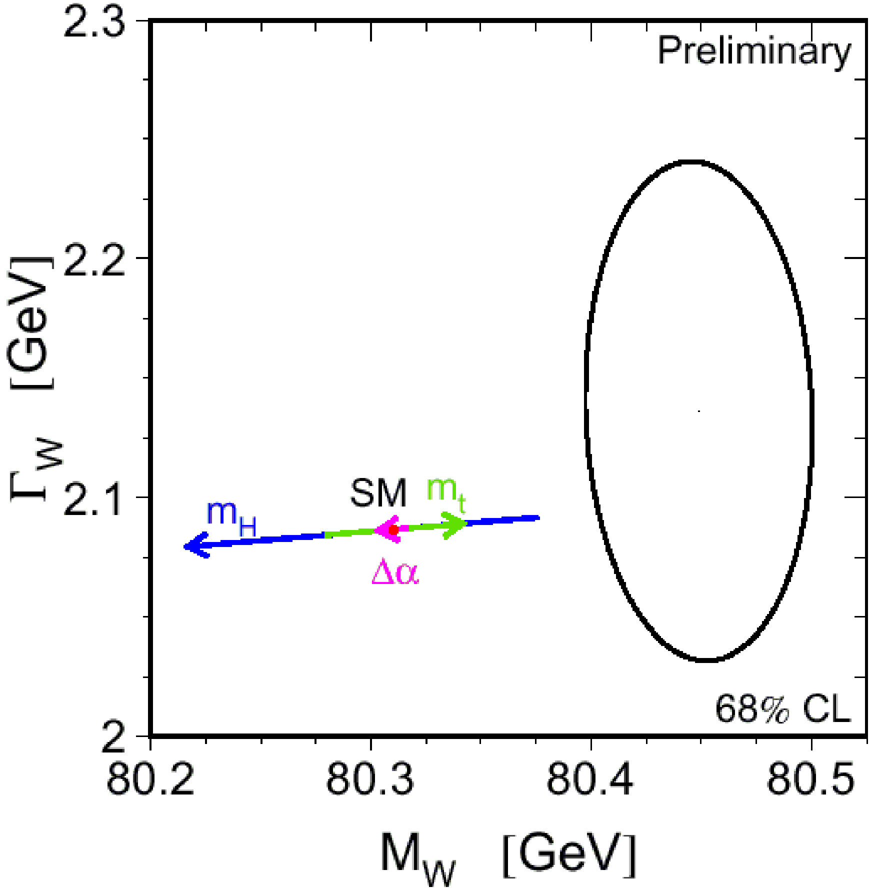
Results

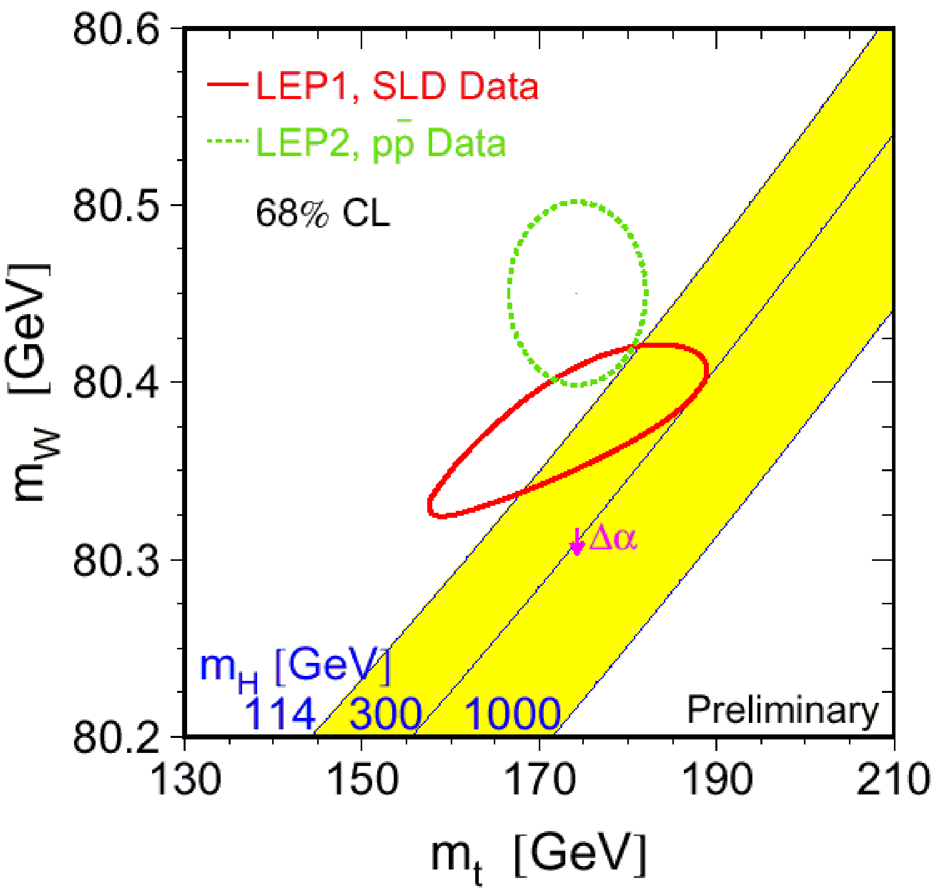


Very good agreement between experiments

Mw(qqqq)-Mw(qqln)=9±44 MeV without FSI error

SM comparison



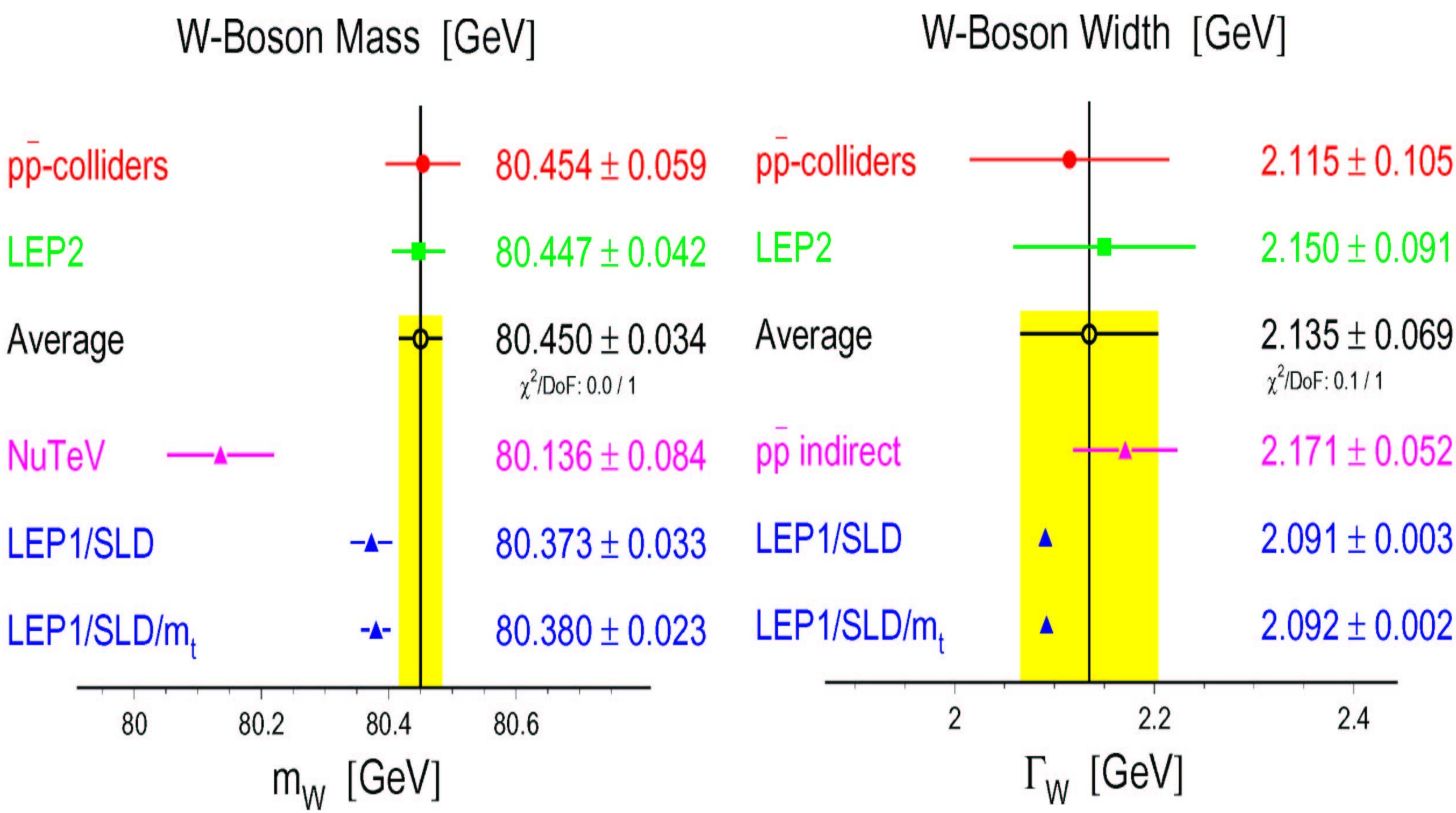


DATA favours small Higgs masses

Conclusions

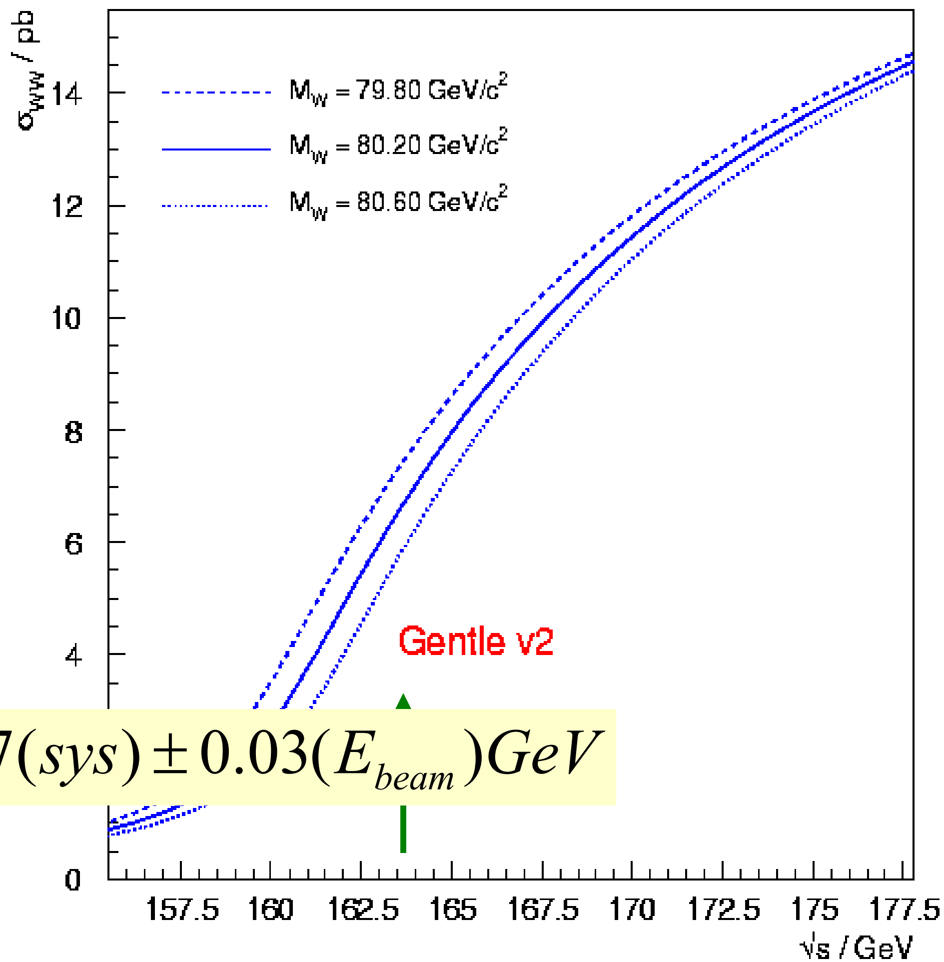
- **LEPII met the expectations and exceeded them**
- **High precision test of the SM performed**
- **Many properties of the W boson measured with high accuracy:**
  - **Cross sections and branching ratios ~ 1%**
  - **Triple gauge couplings 1-5%**
  - **W polarization**
  - **W mass (5×10^{-4}) and W width (~4%)**
- **Data favours low values of Higgs mass**
- **Final analysis still going on…**

Mw and Γw


W-Boson Mass [GeV]
p$\bar{p}$-colliders
80.454 ± 0.059
LEP2
80.447 ± 0.042
Average
80.450 ± 0.034
χ^2/DoF: 0.0 / 1
NuTeV
80.136 ± 0.084
LEP1/SLD
80.373 ± 0.033
LEP1/SLD/m_t
80.380 ± 0.023
80
80.2
80.4
80.6
m_W [GeV]
W-Boson Width [GeV]
p$\bar{p}$-colliders
2.115 ± 0.105
LEP2
2.150 ± 0.091
Average
2.135 ± 0.069
χ^2/DoF: 0.1 / 1
p$\bar{p}$ indirect
2.171 ± 0.052
LEP1/SLD
2.091 ± 0.003
LEP1/SLD/m_t
2.092 ± 0.002
2
2.2
2.4
Γ_W [GeV]

M_W from σ_{WW} at threshold

- **Maximum sensitivity at √s ~ 161 GeV**
  - **No sensitivity far above threshold**
- **Small impact on final LEP result ~ 3%**
  - **10 pb-1 at threshold**



$$Mw = 80.40 \pm 0.20(stat) \pm 0.07(sys) \pm 0.03(E_{beam})GeV$$