W Physics in e+ e- collisions

at sqrt(s)=161 and 172 GeV

at LEP

Takayuki SAEKI

CERN

Contents

Introduction

LEP2 started in 1996 at sqrt(s)=161 GeV

W pair-production threshold ~ 160 GeV
---->First WW events are observed in e+e- collisions

Integrated Luminosity ~ 11 pb^{-1}
(per experiment)

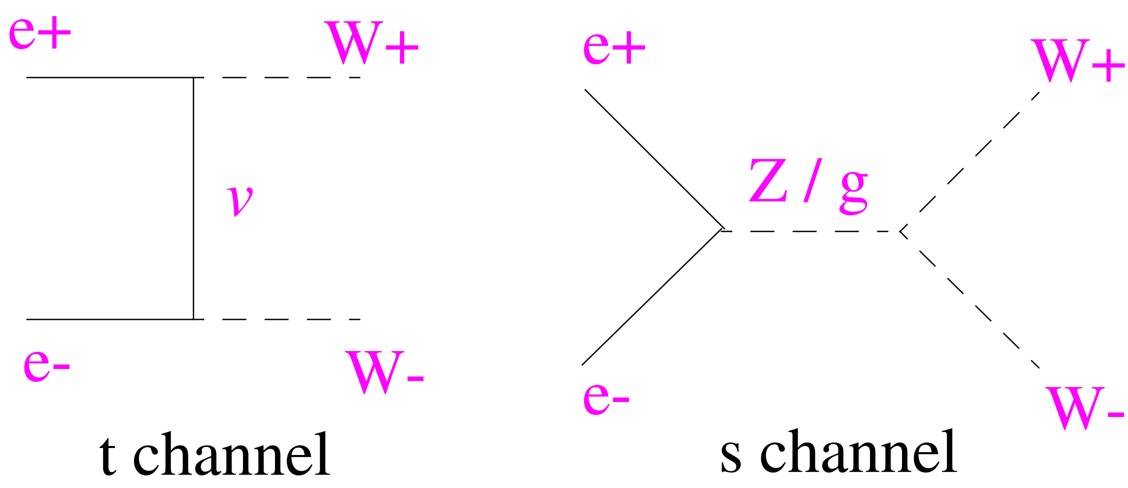
In autmun, sqrt(s)=172 GeV

Integrated Luminosity ~ 10 pb^{-1}
(per experiment)

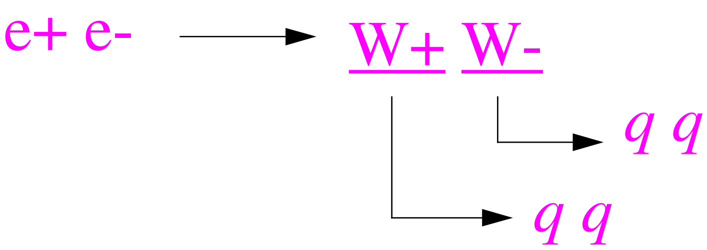
In 1997, sqrt(s)=183 GeV

Running ......

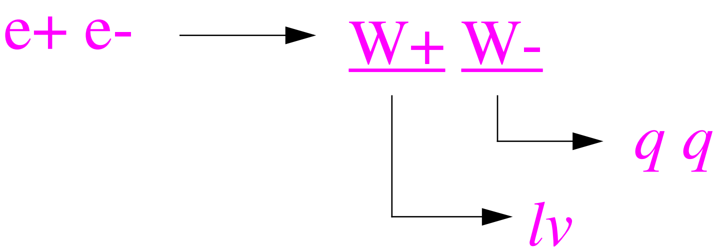
CC03 diagram



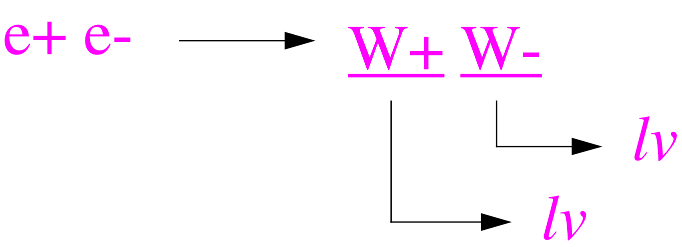
1. *qqqq* channel

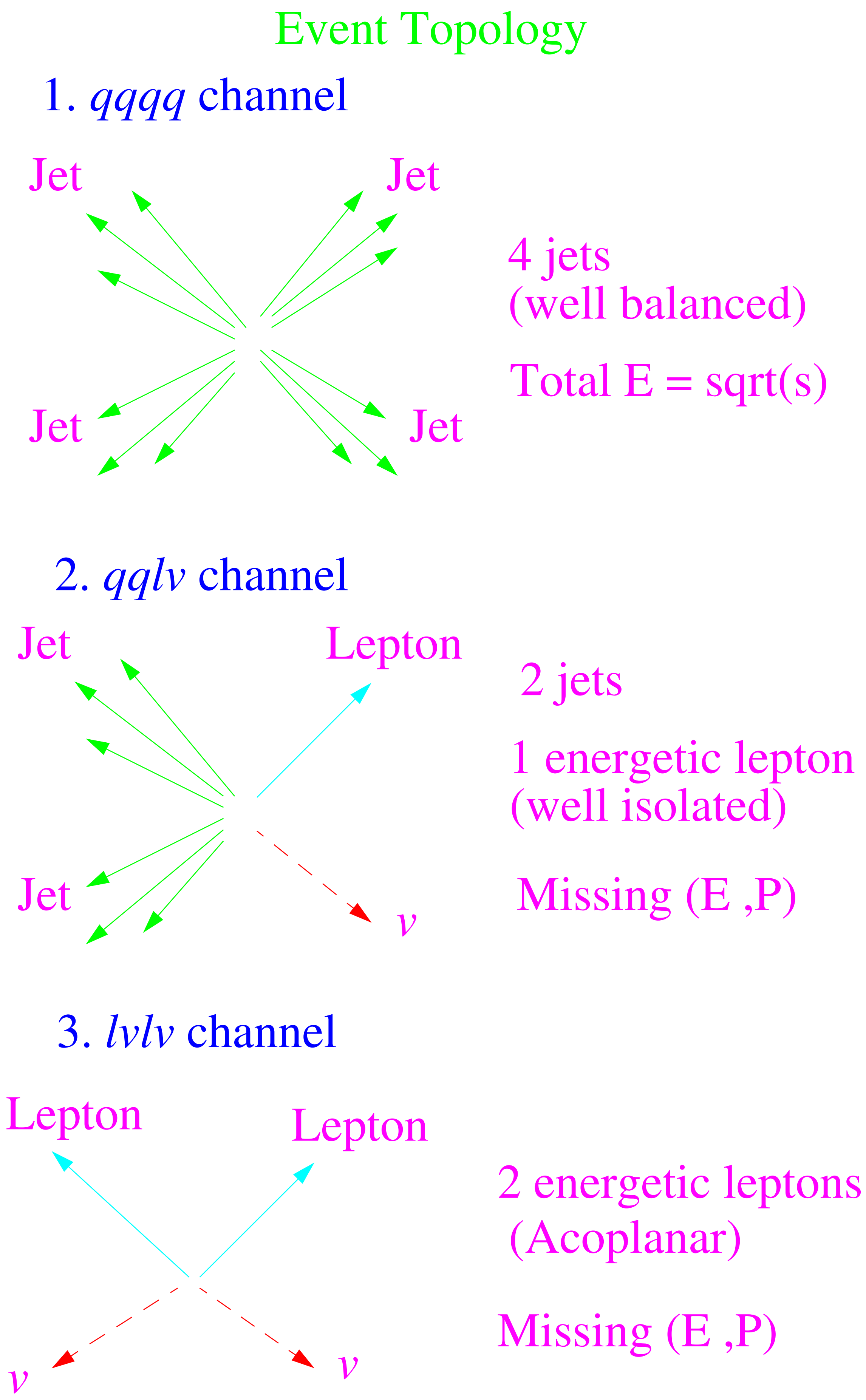


2. *qqlv* channel



3. *lvlv* channel





Event Topology
1. qqqq channel
Jet
Jet
Jet
Jet
4 jets
(well balanced)
Total E = sqrt(s)
2. qqlv channel
Jet
Lepton
Jet
v
2 jets
1 energetic lepton
(well isolated)
Missing (E ,P)
3. lvlv channel
Lepton
Lepton
v
v
2 energetic leptons
(Acoplanar)
Missing (E ,P)

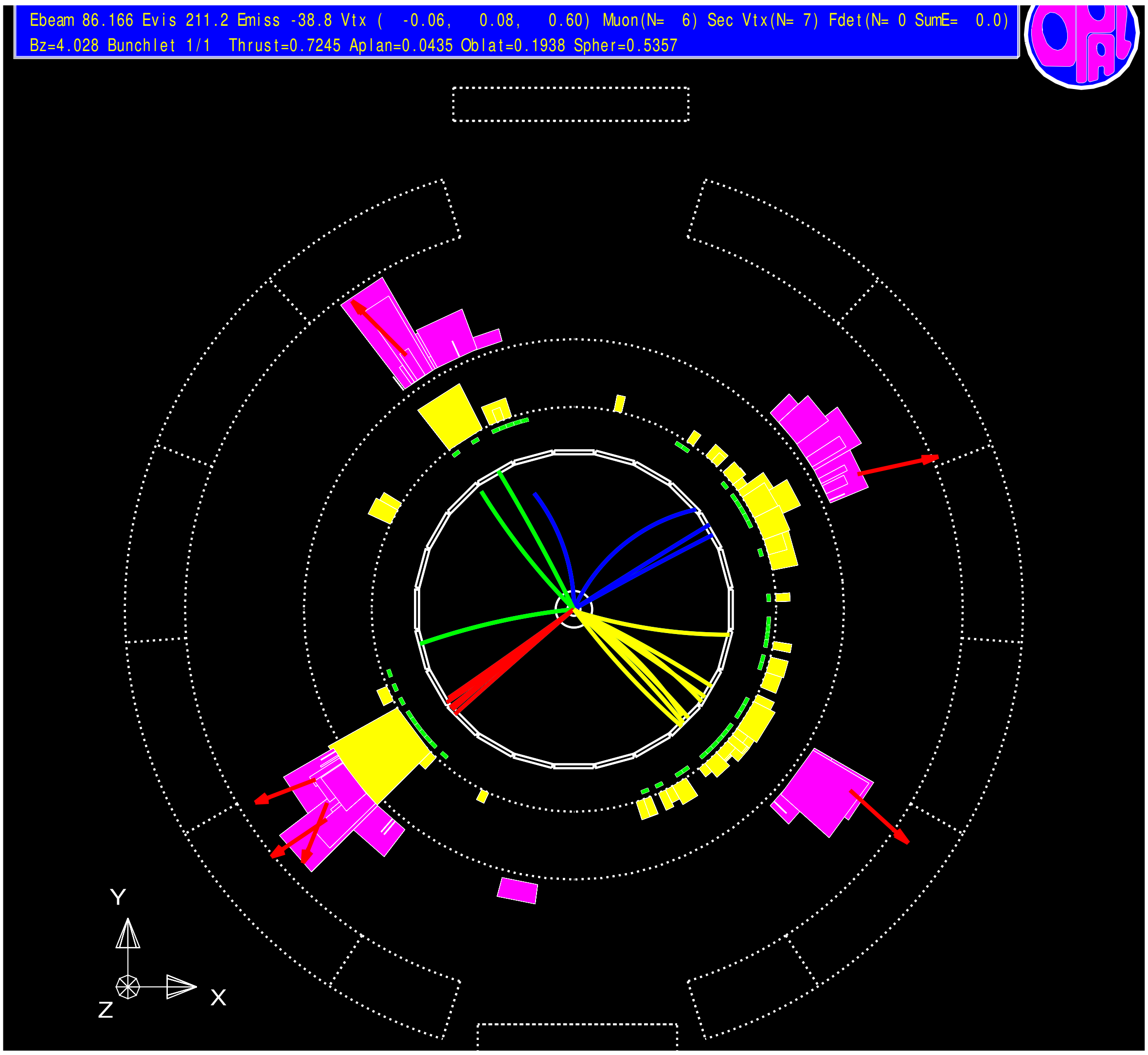
Cross-section and branching franction of W pair-production

1. *qqqq* cahnnel

main background Z/g ---> *qq*

Two order of magnitude larger than for the signal(161GeV)
Order of magnitude larger than for the signal(172GeV)

sqrt(s') cut, Eg cut ....
(for example, Eg=54.7 GeV at sqrt(s)=161 GeV)



e.g. DELPHI

(a) Jet Clustering using LUCLUS argorithm with

d_{join}(differencial 3-jet rate)>6.5 GeV

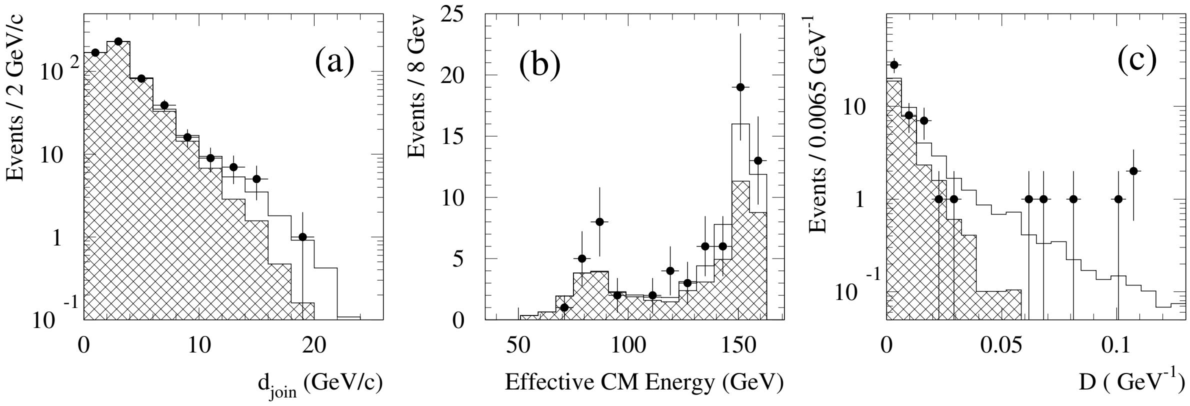
(b) Effective center-of-mass energy cut

sqrt(s') > 115 GeV

(c) D variable cut, where

$$D = \frac{E_{min}}{E_{max}} \times \frac{\theta_{min}}{(E_{max} - E_{min})}$$

$D > 0.0013\ \mathrm{GeV}^{-1}$



Multi-dimentional selection (ALEPH)

Neural network selection (L3)

Likelihood selection (OPAL)

2. *qqlv* cahnnel

main background Z/g ---> *qq*

(Misidentification of ISR photon as a lepton)

Anothoer source of BG : four-fermion process

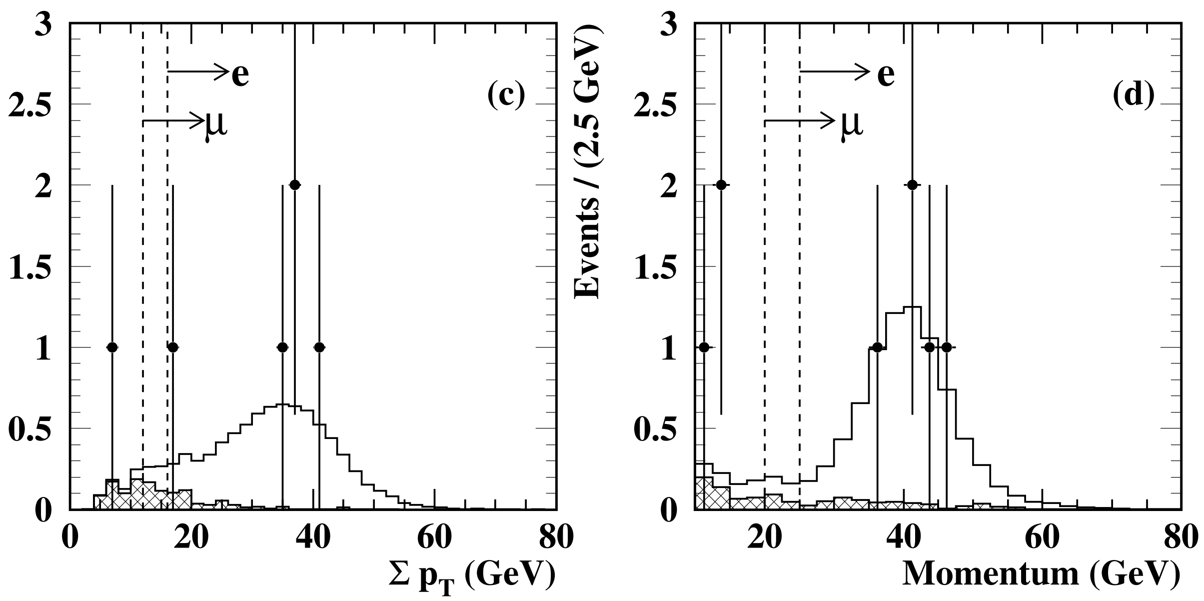
Z0 e+e-, W ev, off-shell ZZ ---> 2 jets and 1 id-lepton

OPAL

Lepton ID : E > 25 GeV (e), p > 20 GeV (muon)

Well isolated (200 mrad cone)

Large missing p, off beam direction



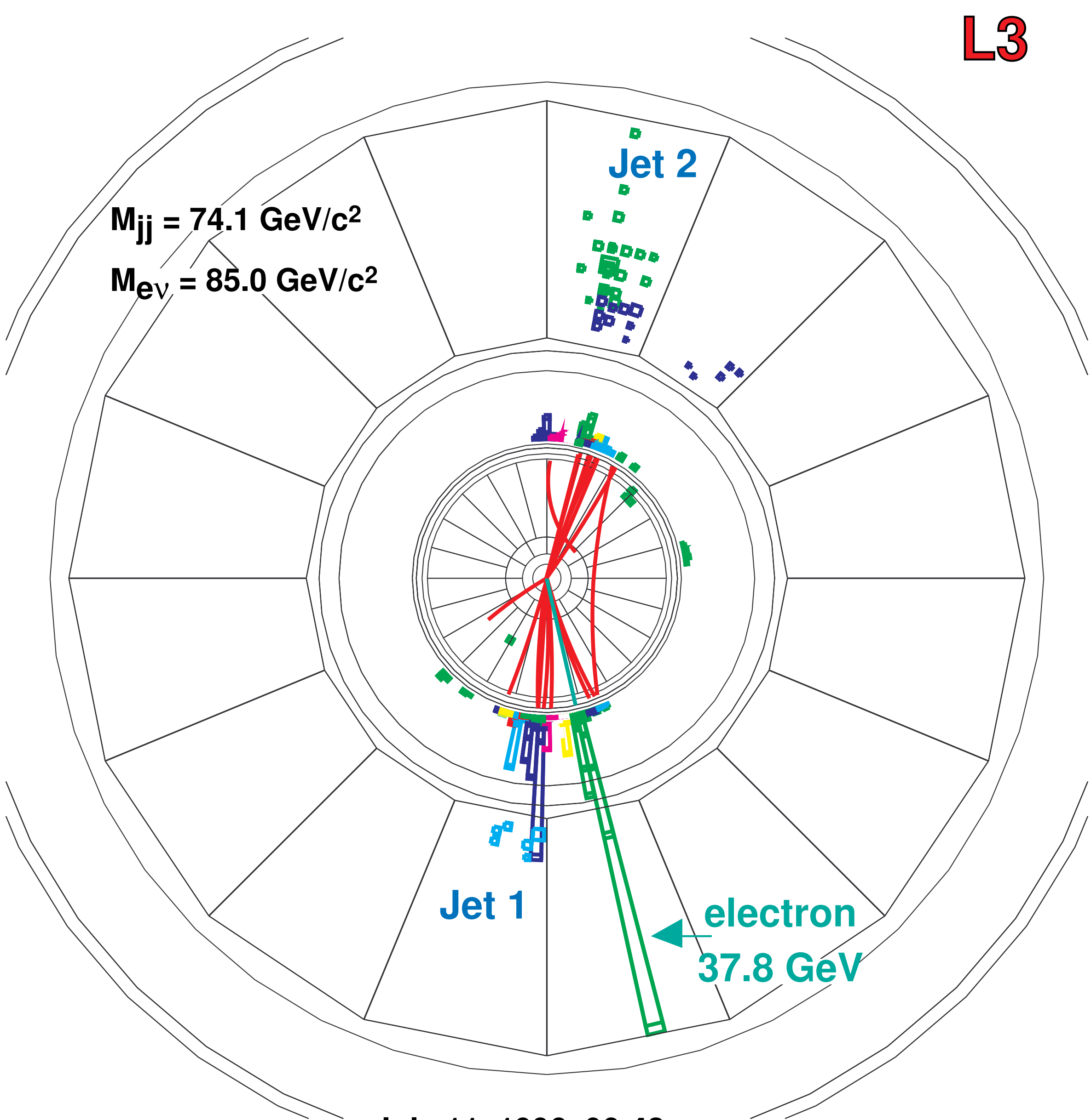
Sytematic check was done using

diffrent MC models and high statistics LEP1 data

Table 1: Numver of events at 161 GeV (OPAL)

	Expected signal	Expected BG	Observed
qqev	3.89 +- 0.44	0.18 +- 0.27	3
qqmv	4.19 +- 0.46	0.27 +- 0.15	2
qqtv	2.32 +- 0.28	0.96 +- 0.34	7

L3



July 11, 1996 06:42am

First W pair event observed by the L3 Experiment at LEP 2.

$$e^+ e^- \rightarrow W^+ W^-$$

$$W^- \rightarrow e^- \bar{\nu}$$

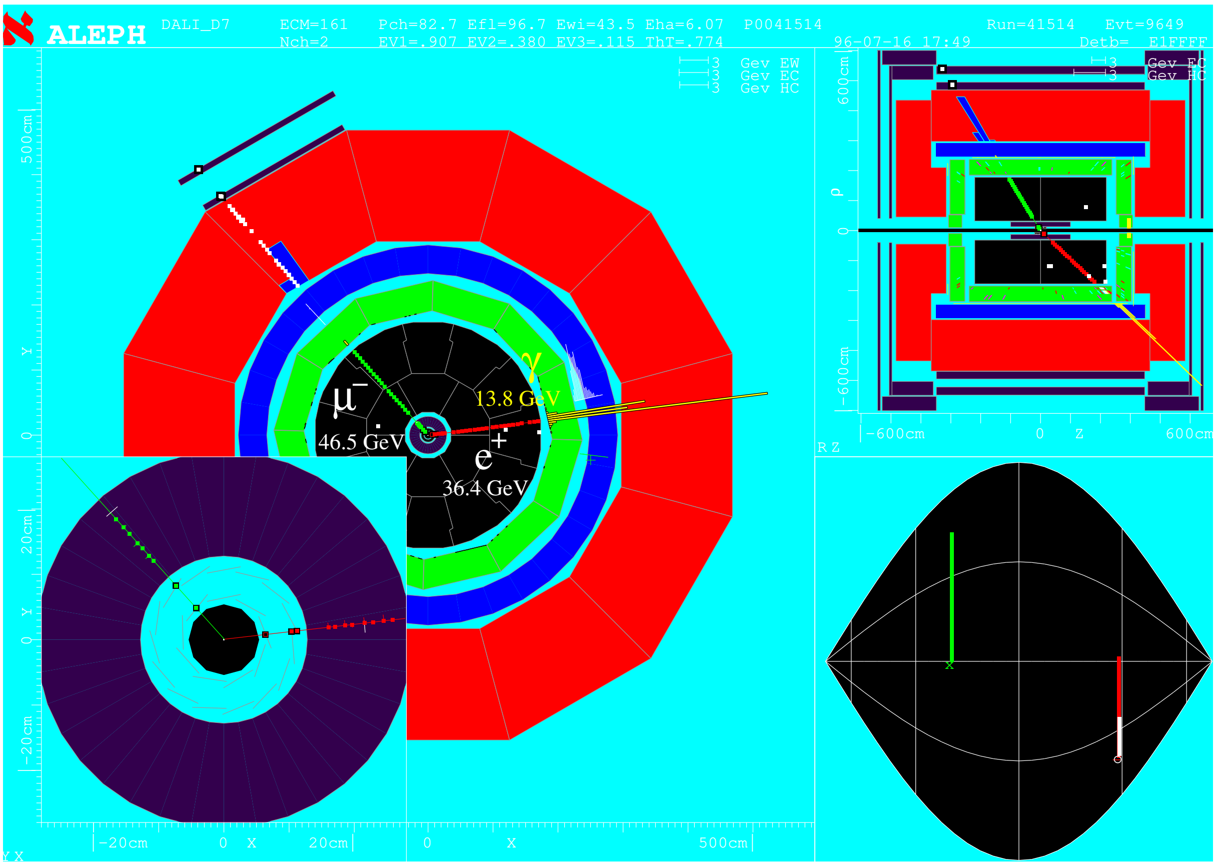
$$W^+ \rightarrow \text{jet} + \text{jet}$$

Applying energy and momentum conservation to the event shows that the two jets and the electron-neutrino originate from the decay of two W bosons.

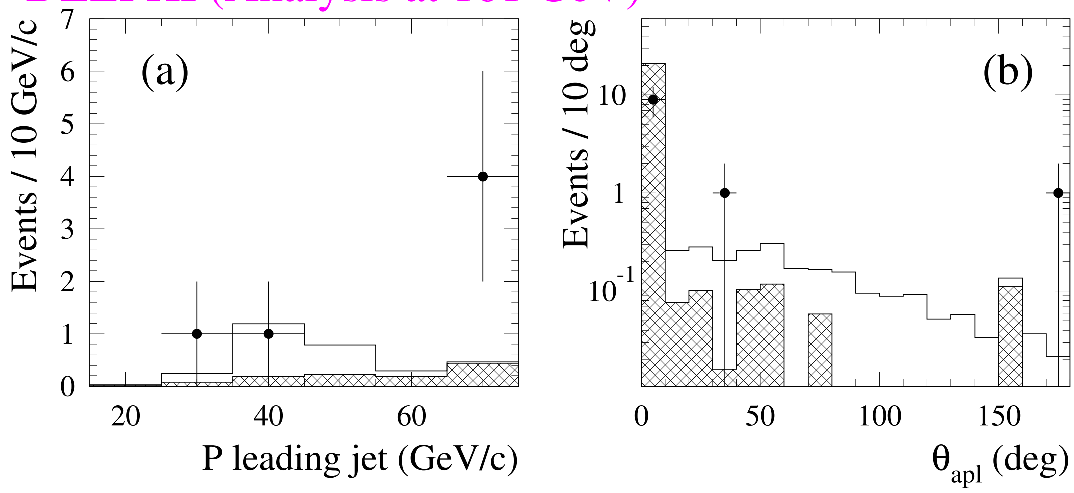
3. *lvlv* cahnnel

main background is e+e- ---> *Z*(g),
Bhabha scattering, and two-photon events

APLEPH



DELPHI (Analysis at 161 GeV)



All particles were clustered into 2 jets

Selection efficeincy matrix for 172GeV L3

Table 2: Selection Efficiencies(%)

	qqev	qqmv	qqtv	lv lv	qqqq
ee --> qqev	79.3	0.16	1.74		
ee -->qqmv	0.11	74.1	3.50		
ee --> qq tv	5.62	6.89	46.6		0.14
ee --> lv lv				45.1	
ee --> qqqq	0.08	0.04	2.14		84.1

Number of selected events

Table 3: Number of events at 161 GeV

	qqlv	lvlv	qqqq	Total of exp.
ALEPH	16	6	16	38
DELPHI	12	2	15	29
L3	11	2	9	22
OPAL	12	2	14	28
Total of chan	51	12	54	117

Table 4: Number of events at 172 GeV

	qqev	lvlv	qqqq	Total of exp.
ALEPH	44	10	65	119
DELPHI	45	8	65	118
L3	40	9	61	110
OPAL	55	8	57	120
Total of chan	184	35	248	467

Determination of cross-section

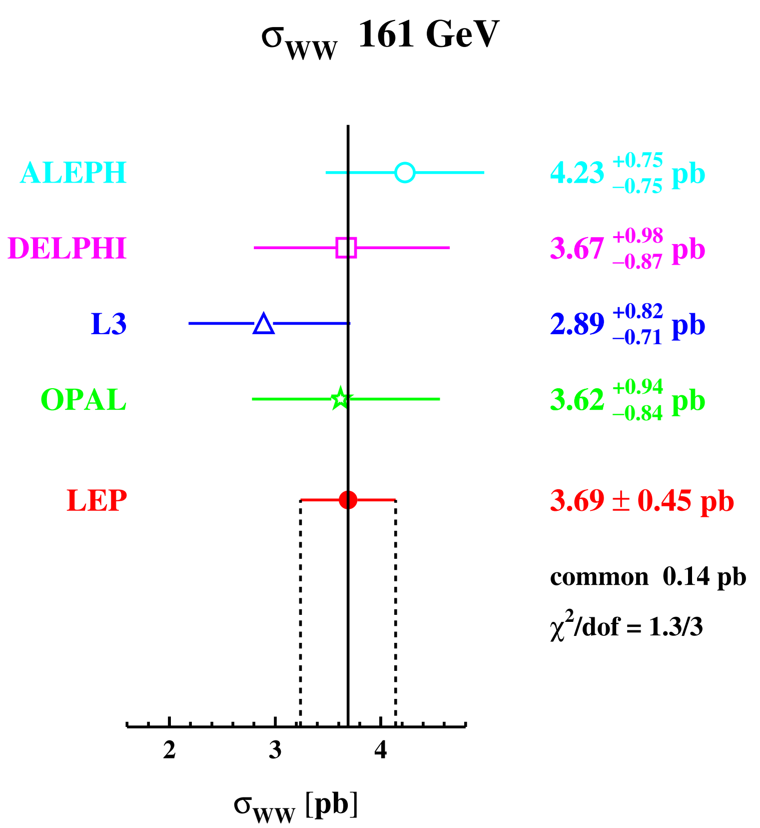
Likelihood fit using a function of WW x-sec,

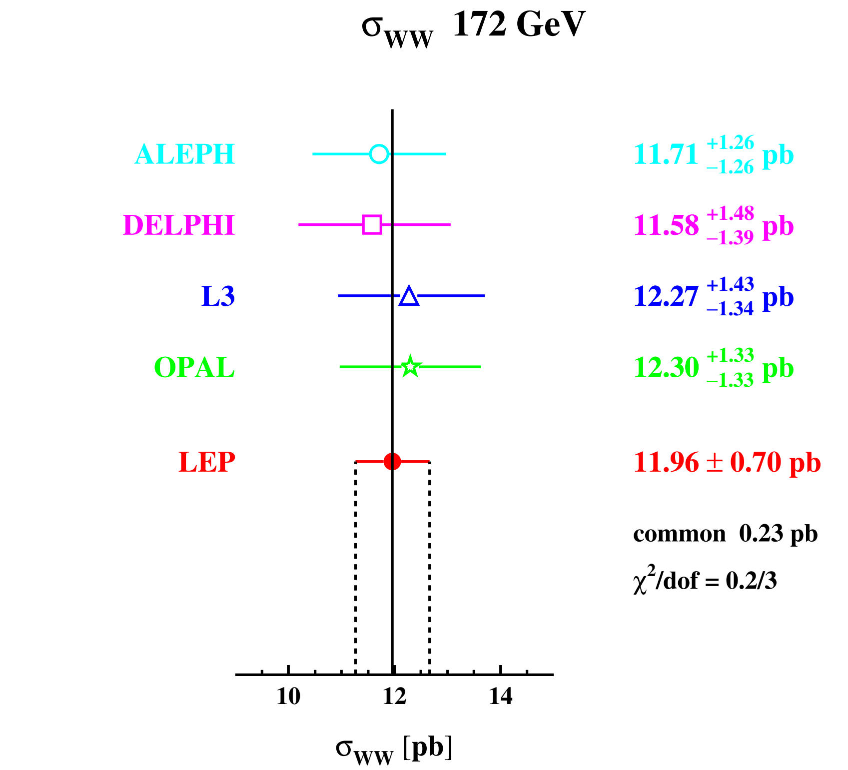
$$L = \prod_i P_i(N_i, \mu_i(\sigma_{WW})) = \prod_i \frac{\mu_i(\sigma_{WW})^{N_i} \cdot e^{-\mu_i(\sigma_{WW})}}{N_i!}$$

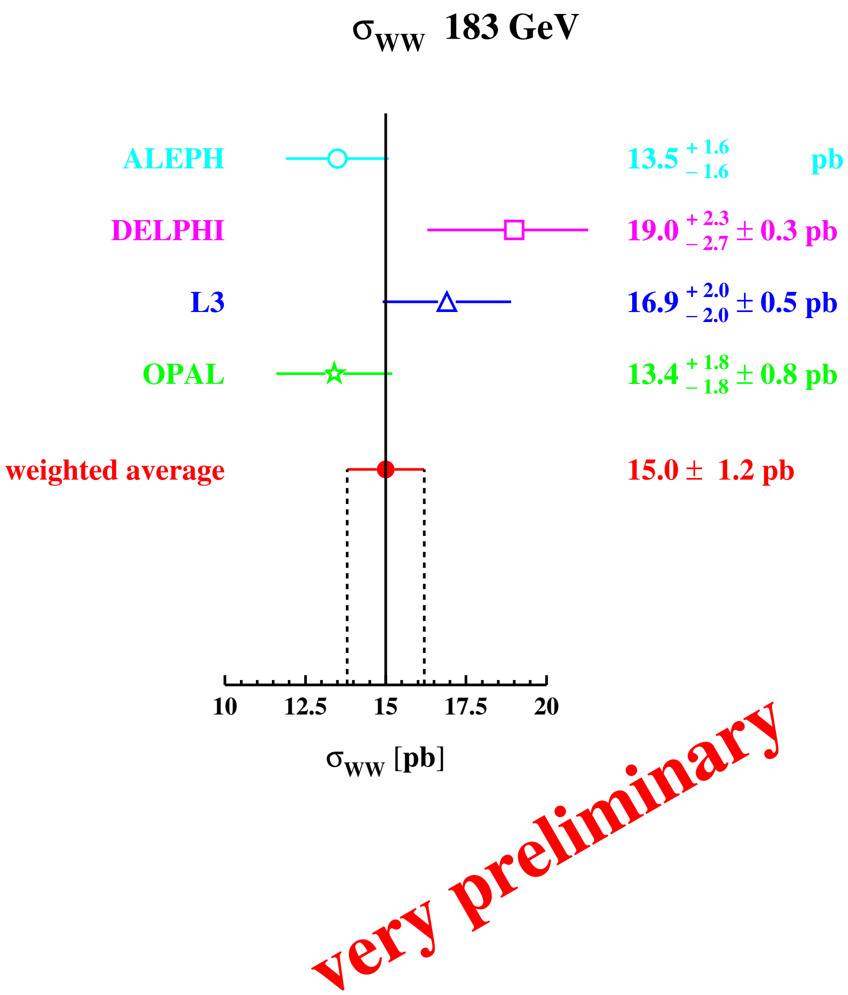
N_i = Observed number of events

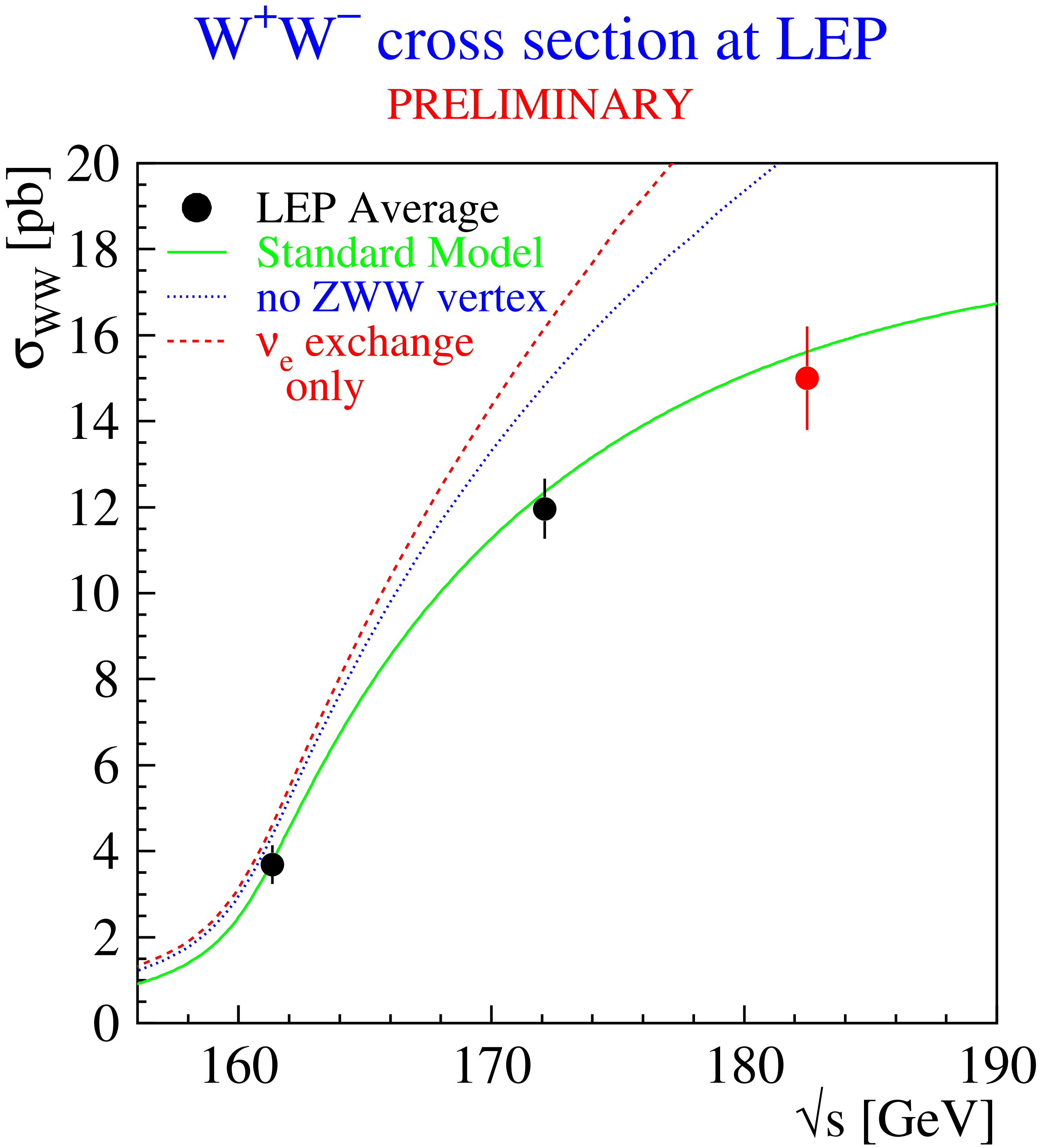
$\mu_i(\sigma_{WW})$ = Expected number of events

i runs over all of WW decay channels



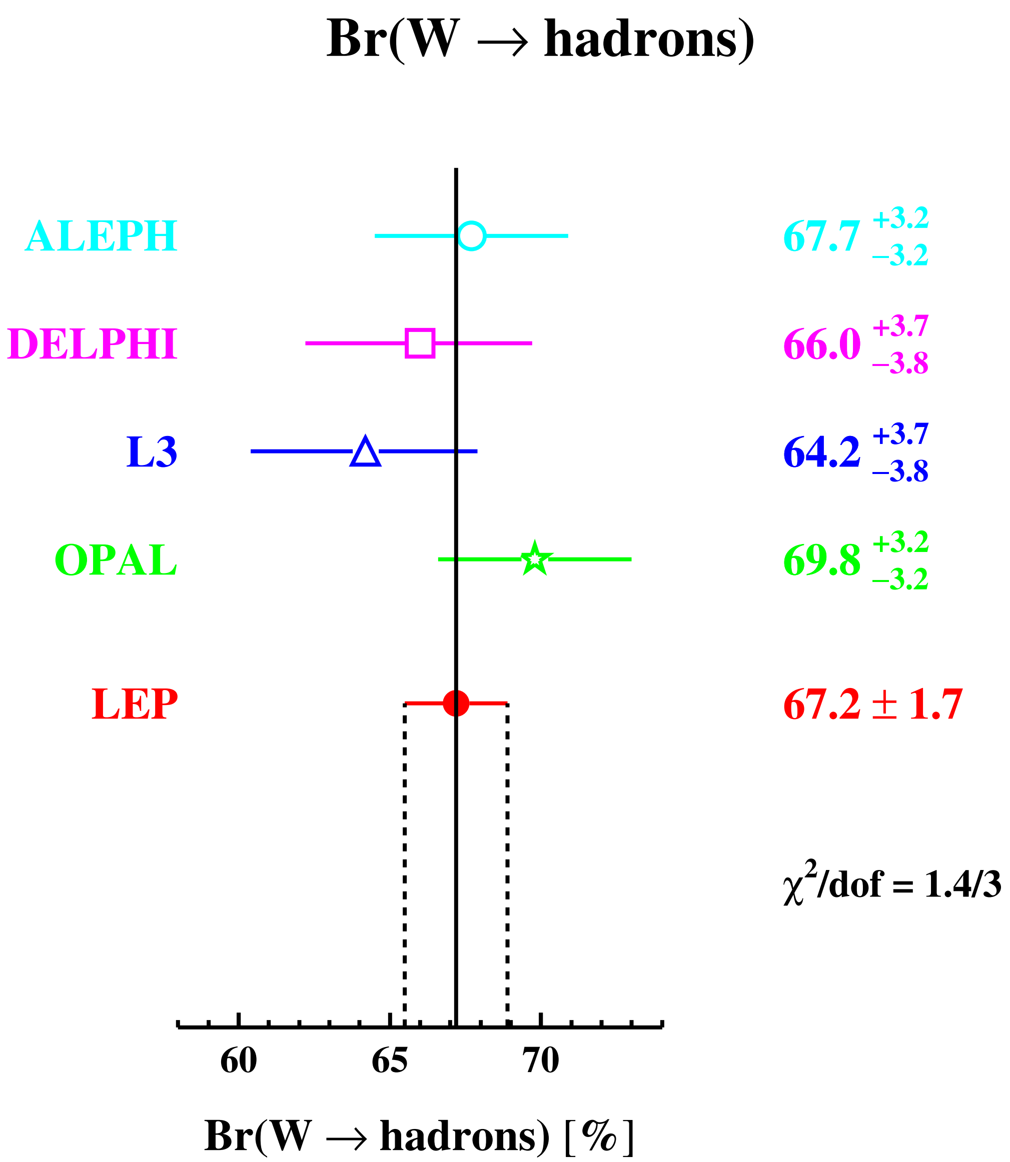

σWW 172 GeV
ALEPH
DELPHI
L3
OPAL
LEP
11.71 +1.26 −1.26 pb
11.58 +1.48 −1.39 pb
12.27 +1.43 −1.34 pb
12.30 +1.33 −1.33 pb
11.96 ± 0.70 pb
common 0.23 pb
χ2/dof = 0.2/3
10
12
14
σWW [pb]

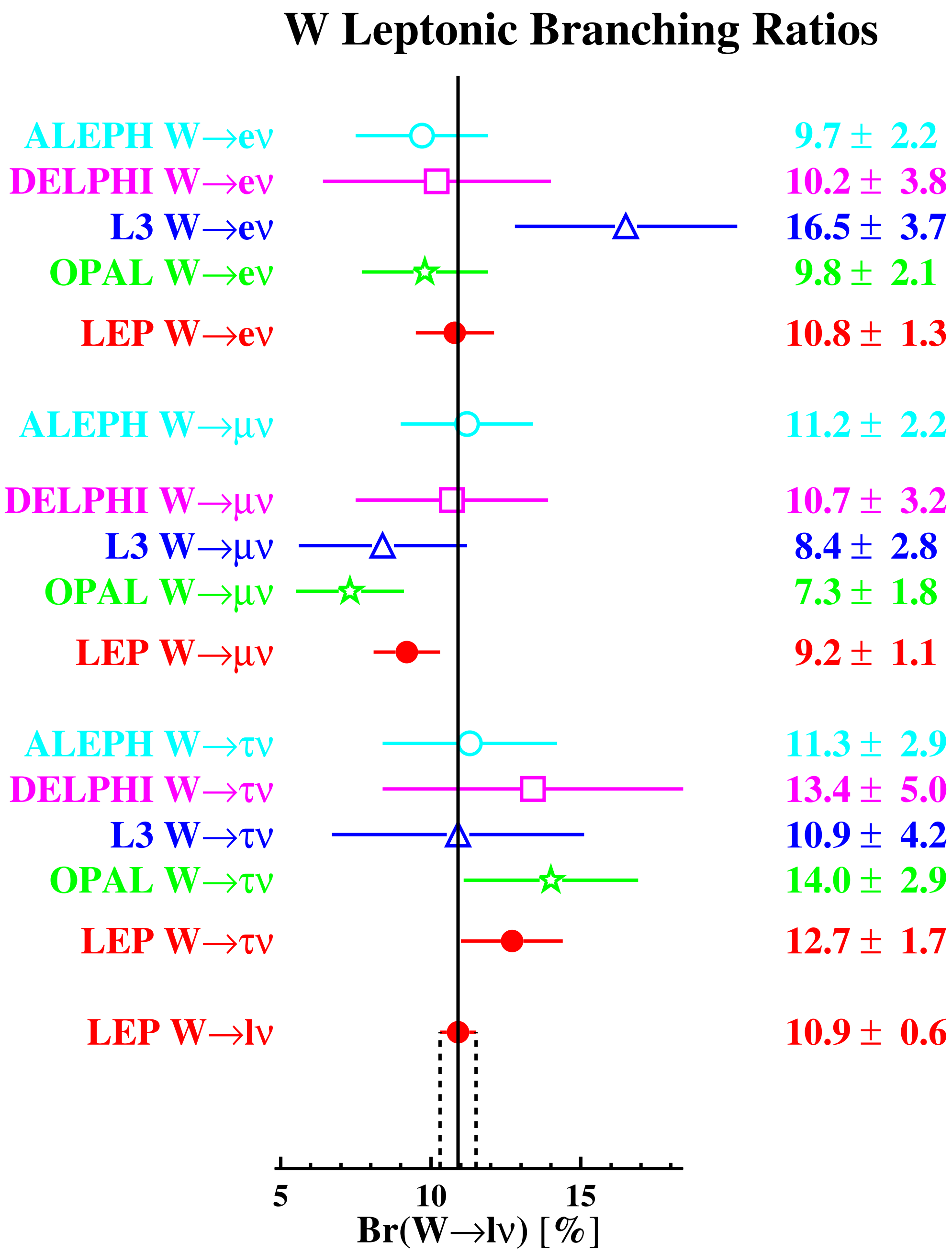

σWW 183 GeV
ALEPH
DELPHI
L3
OPAL
weighted average
13.5 + 1.6 − 1.6 pb
19.0 + 2.3 − 2.7 ± 0.3 pb
16.9 + 2.0 − 2.0 ± 0.5 pb
13.4 + 1.8 − 1.8 ± 0.8 pb
15.0 ± 1.2 pb
10
12.5
15
17.5
20
σWW [pb]
very preliminary



W+W− cross section at LEP
PRELIMINARY
LEP Average
Standard Model
no ZWW vertex
νe exchange only
σWW [pb]
√s [GeV]
0
2
4
6
8
10
12
14
16
18
20
160
170
180
190

Branching fractions were also determined by likelihood fit using a function of Br.




W Leptonic Branching Ratios
ALEPH W→eν
9.7 ± 2.2
DELPHI W→eν
10.2 ± 3.8
L3 W→eν
16.5 ± 3.7
OPAL W→eν
9.8 ± 2.1
LEP W→eν
10.8 ± 1.3
ALEPH W→μν
11.2 ± 2.2
DELPHI W→μν
10.7 ± 3.2
L3 W→μν
8.4 ± 2.8
OPAL W→μν
7.3 ± 1.8
LEP W→μν
9.2 ± 1.1
ALEPH W→τν
11.3 ± 2.9
DELPHI W→τν
13.4 ± 5.0
L3 W→τν
10.9 ± 4.2
OPAL W→τν
14.0 ± 2.9
LEP W→τν
12.7 ± 1.7
LEP W→lν
10.9 ± 0.6
5
10
15
Br(W→lν) [%]

Improvement on CKM-matrix element Vcs

Vcs : the least well determined element of CKM-matrix

Table 5: Absolute error on |Vcs|

	Vcs
D --> Klν	1.01+-0.18
CKM unitarity	0.9493+-0.0008

Whithin the framework of SM;

$$\frac{Br(W \to qq)}{1 - Br(W \to qq)} = \left(1 + \frac{\alpha_s}{\pi}\right) \sum_{i=u,c\,;\,j=d,s,b} |V_{ij}|^2$$

From LEP combined Br(W-->qq):

$$\sum_{i=u,c\,;\,j=d,s,b} |V_{ij}|^2 = 1.97 \pm 0.15$$

(=2.0 in SM)

Using the measured value of the other elements.

$$Vcs = 0.96 \pm 0.08$$

ALEPH, DELPHI measured Rcs and Vcs directly by tagging the flavour of jets

Table 6: Vcs from direct mesurement

	Rcs	Vcs
ALEPH	0.57+-0.18+-0.04	1.18+-0.43+-0.10
DELPHI	0.42+-0.13+-0.06	0.87+-0.24+-0.11
Avaraged	0.47+-0.11	0.95+-0.20

Mass of W

Motivation

- Precision test of Standard Model
- Higgs mass constraint

$$G_\mu = \frac{\alpha\pi}{\sqrt{2}M_W^2}\left(1 - \frac{M_W^2}{M_Z^2}\right)^{-1}\frac{1}{1-\Delta r}$$

where Δr is m_t- and m_{H}-dependent,

when loop corrections are included

Method for Mw measurement

- WW cross-section to Mw
  at qrt(s)=161 GeV
- Direct mass reconstruction
  at sqrt(s)=172 GeV

W mass measurement by WW x-sec

Estimate of the error on the W mass

$$\Delta M_W = \sqrt{\sigma_{WW}} \left| \frac{dM_W}{d\sigma_{WW}} \right| \sqrt{\frac{1}{\varepsilon_{WW} \cdot L}}$$

ε_{WW} = Overall signal efficiency

L = Integrated luminosity

ΔM_W is changed as a function of $\sqrt{s}$

$\downarrow$

$$\sqrt{s}^{\text{Optimal}} \cong 2M_W + 0.5 \text{ GeV}$$

$\downarrow$

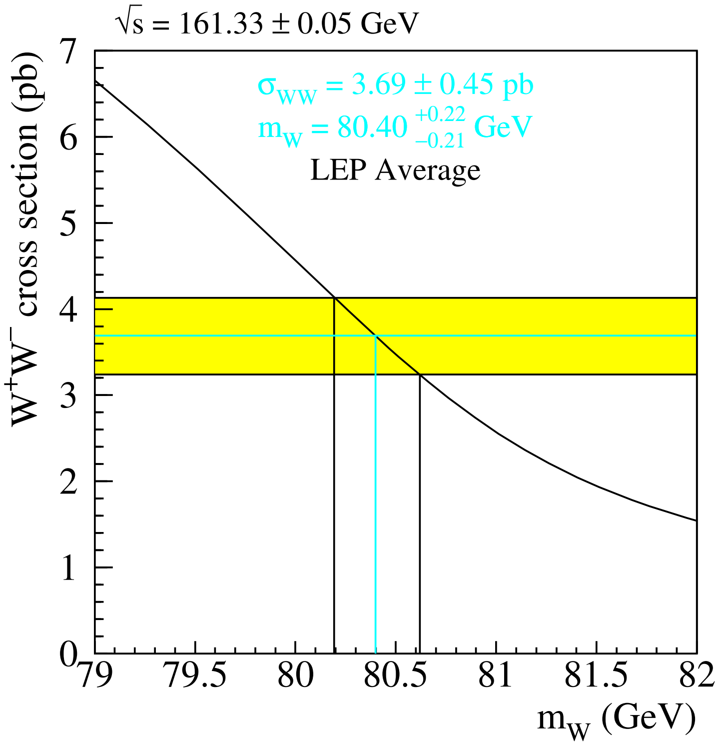
161 GeV

Likelihood fit

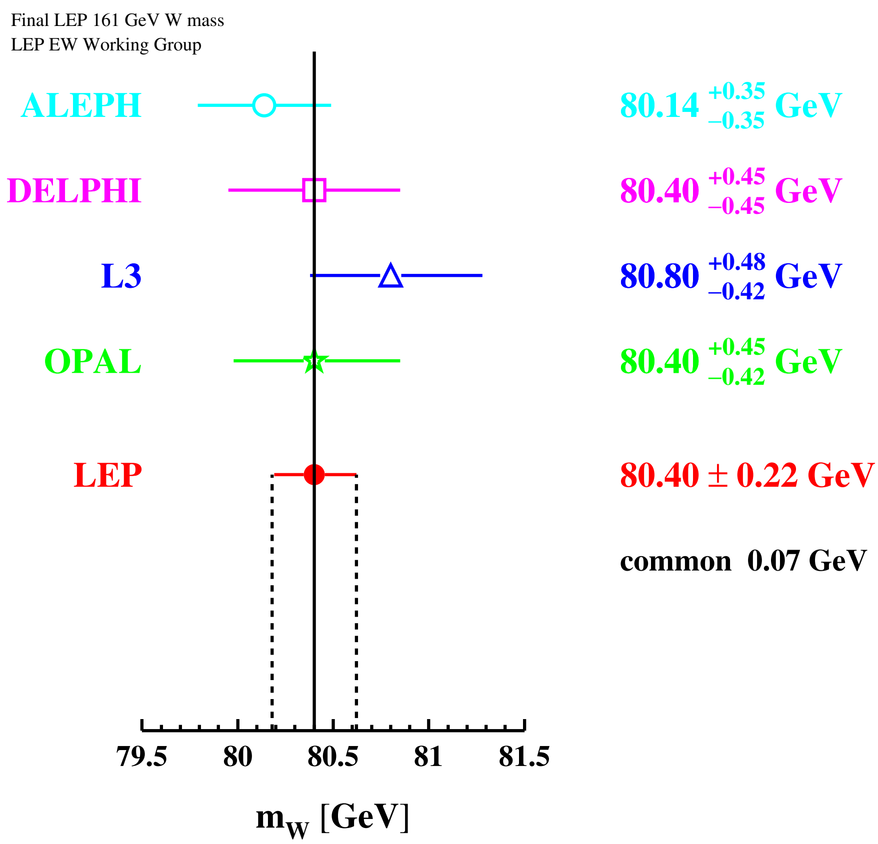
$$L = \prod_i P_i(N_i, \mu_i(\sigma_{WW})) = \prod_i \frac{\mu_i(\sigma_{WW})^{N_i} \cdot e^{-\mu_i(\sigma_{WW})}}{N_i!}$$

$$\mu_i(\sigma_{WW}) = \mu_i(\sigma_{WW}(M_W))$$

m_W from σ_{WW} at 161 GeV

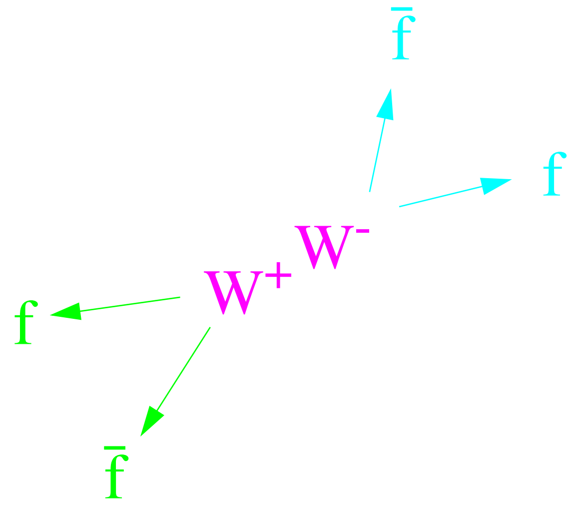


LEP 161 GeV W mass



Mw mesurement by direct reconstruction

172 GeV



Invariant mass of the $f\bar{f}$ / $f\bar{f}$ is reconstructed

ff=qq ---> (E,P) of each jet
ff=lv ----> (E,P) of a lepton
Error on (E,P)

Input

Kinematic fit with constrains

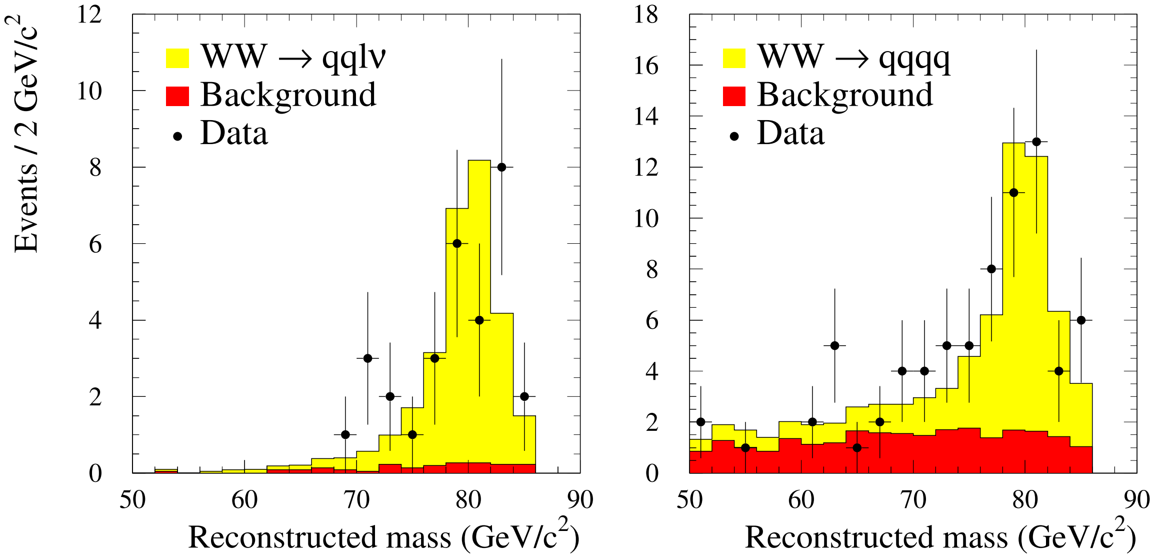
- (E, P) conservation
- Equal mass on WW or E-beam rescaling

improves mass resolution

Output

Reconstructed M_{inv}, event by event

DELPHI



Fitting method

Generating MC samples with various Mw's

Comparing Minv histogram of data
to that of MC's

Find best matching Mw !
(by binned or unbinned likelihood)

However, generating a large number of MC's with diffent Mw's is unfeasible in practice

Reweighting Method

ALEPH, L3, OPAL

e.g. L3 rewighting ratio *Ri* is given by

$$R_i(m_1, m_2, \Psi\mathrm{fit}, \Psi\mathrm{gen}) = \frac{d^2\sigma_i(s, m_1, m_2, \Psi\mathrm{fit}) / dm_1 m_2}{d^2\sigma_i(s, m_1, m_2, \Psi\mathrm{gen}) / dm_1 m_2}$$

$\Psi\mathrm{fit}$ = Mw and Γw to fit

$\Psi\mathrm{gen}$ = Mw and Γw of generated MC

s, m_1, m_2 = CME squared, Invariant mass 1, 2

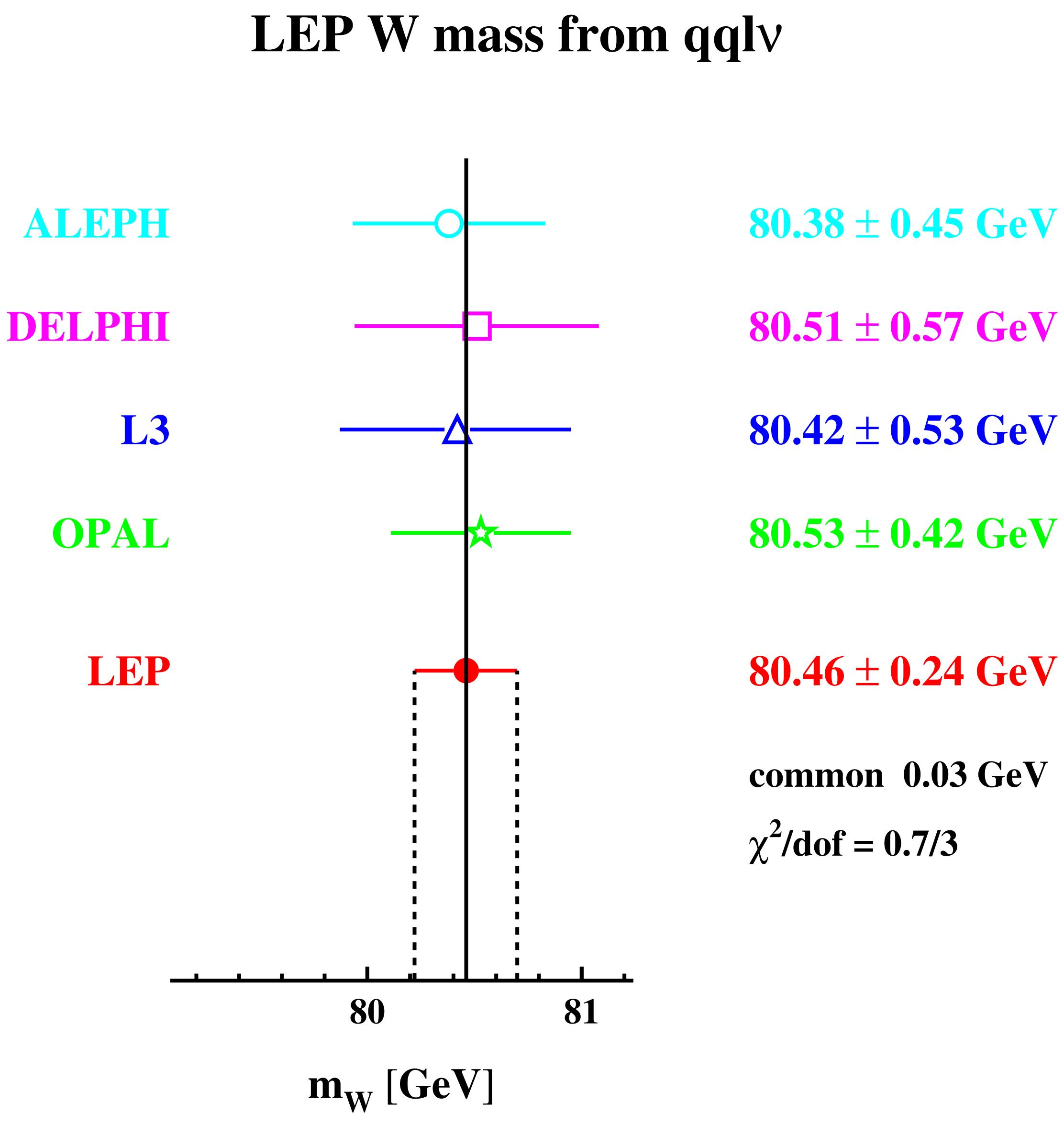
BW x PS modeling

DELPHI

Likelihood *L*(Mw) includes all information,

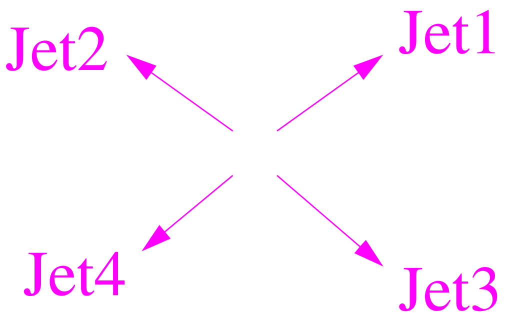
detector resolution, BWxPS, Purity,
correct jet clustring efficiency .....

qqlν channel



qqqq channel

Difficulty of jet pairing --> multiple solutions



3 combinations for 4 jets
10 combinations for 5 jets

ALEPH

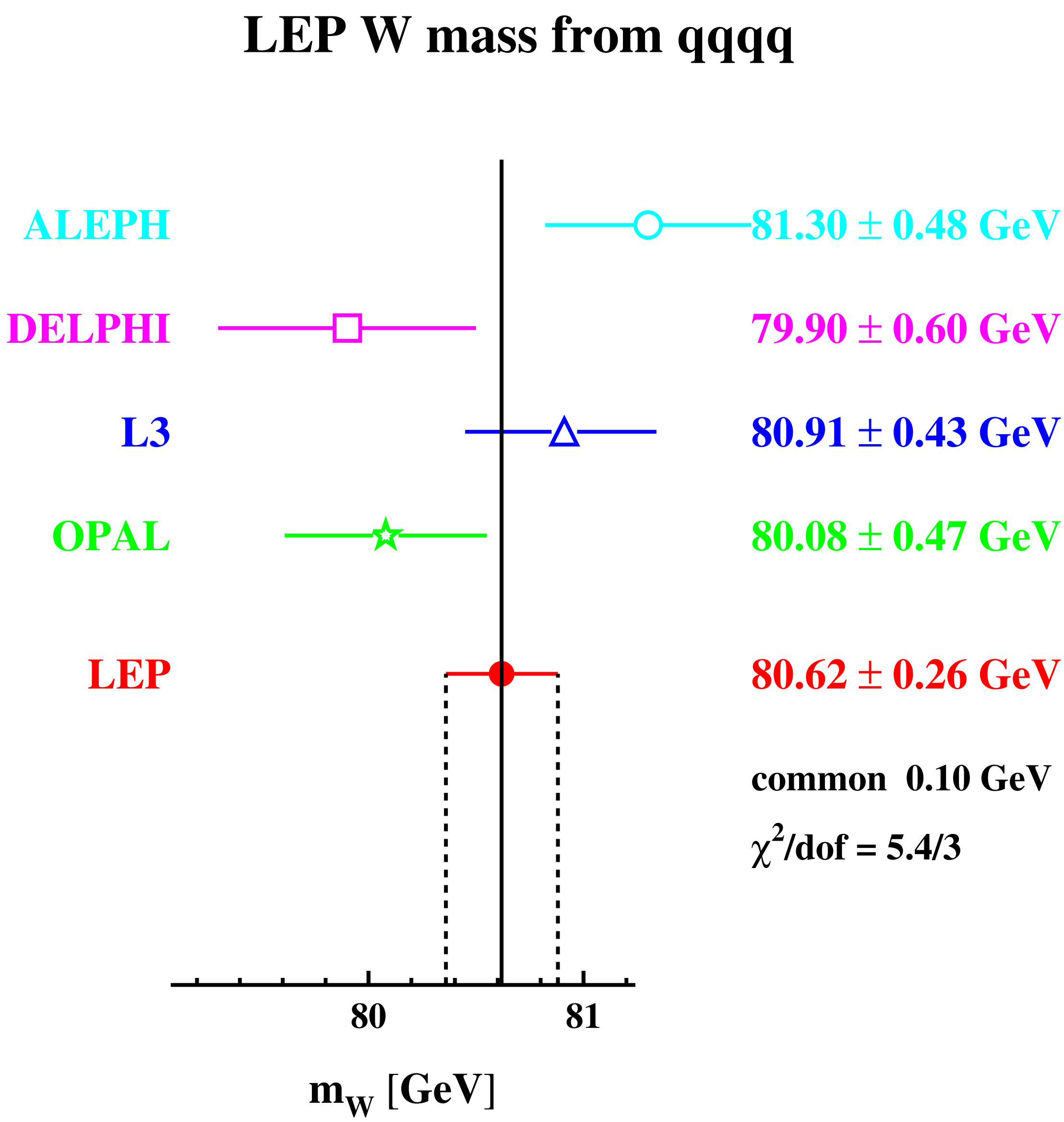
Choose one combination by (Minv1-Minv2), and use two Minv's

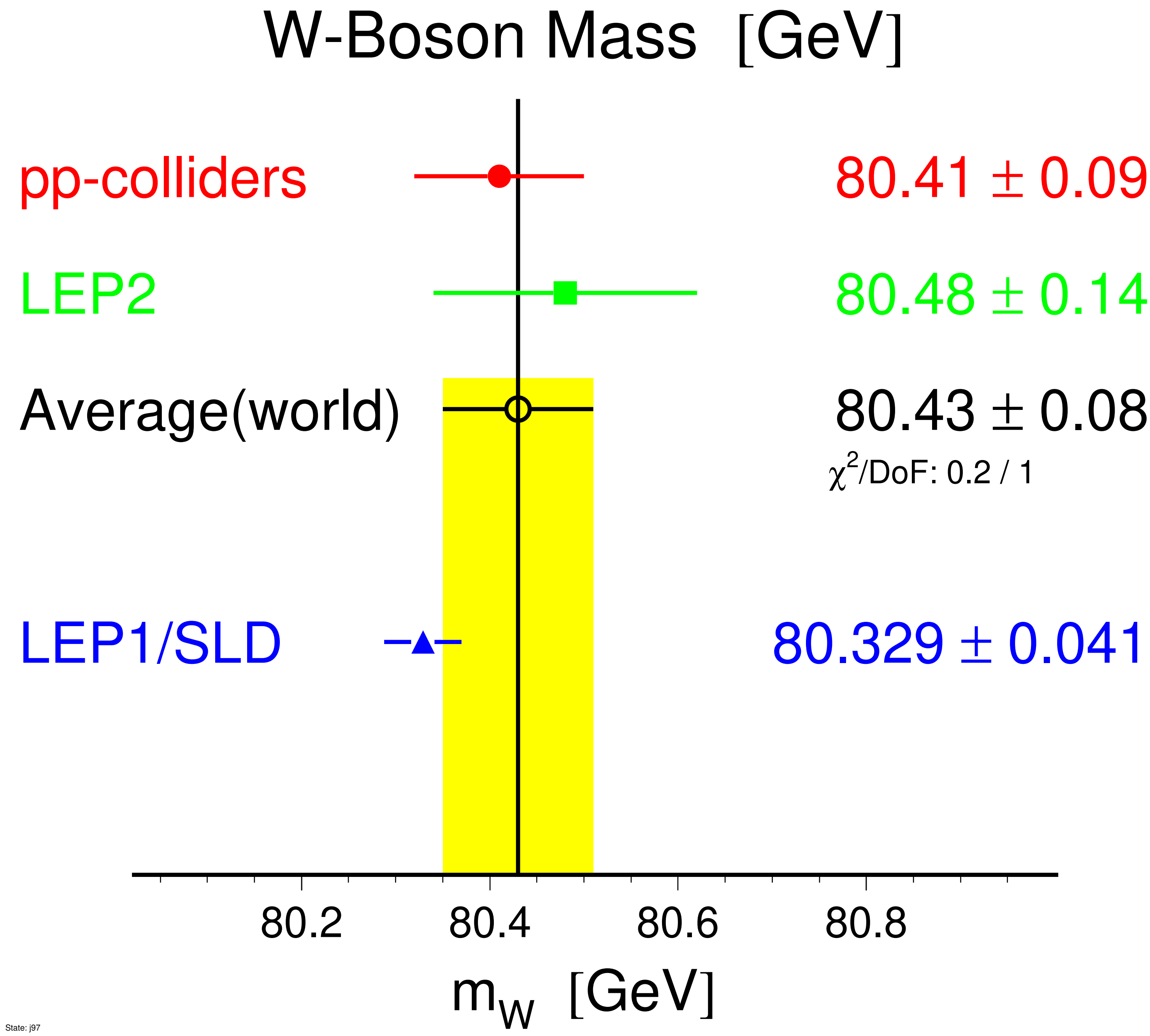
DELPHI

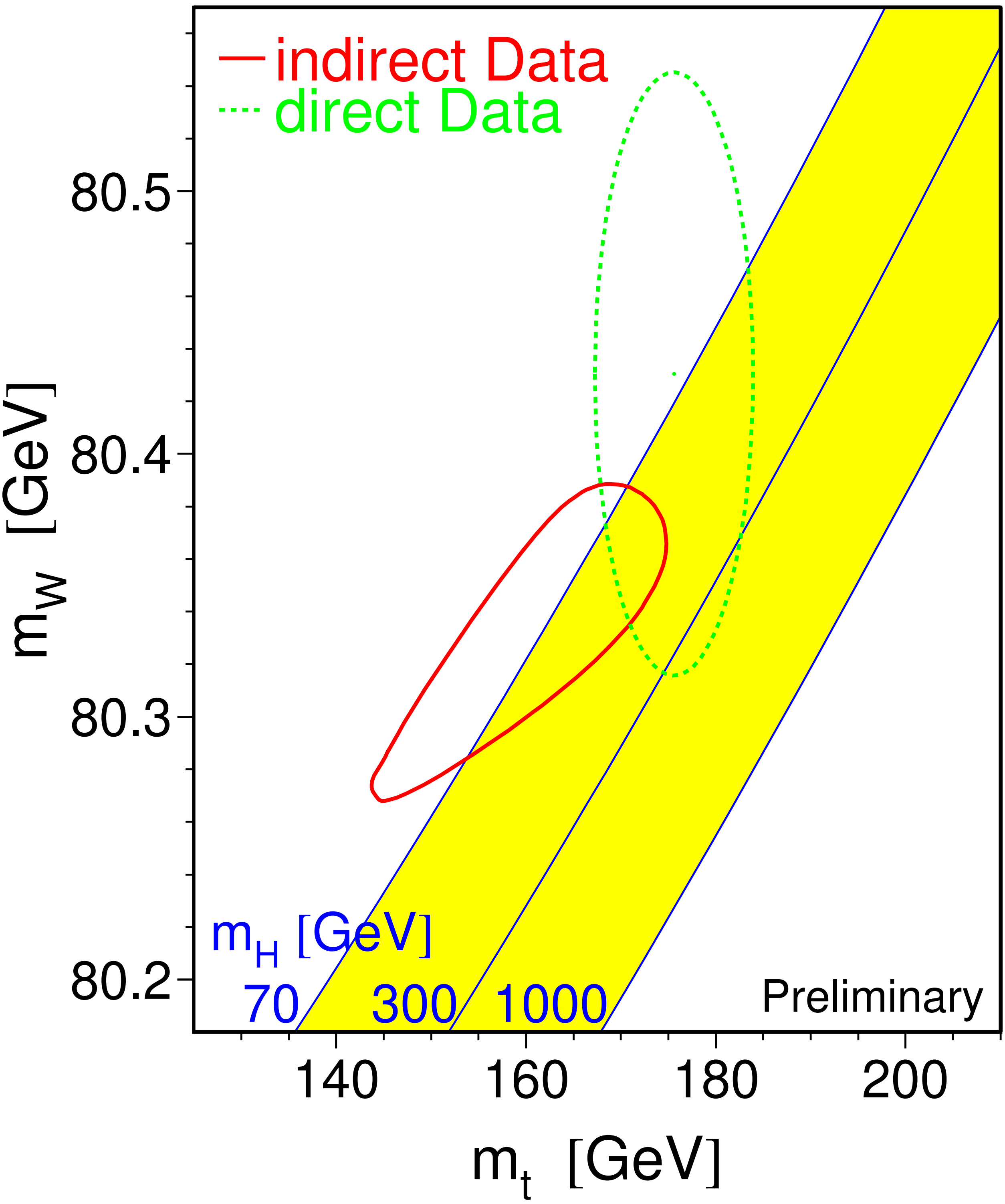
Use all combinations and two Minv's for each, and gluon radiation probability for 5 jets.

L3, OPAL

Choose two combinations by kinematic fit probability, and use one Minv for each

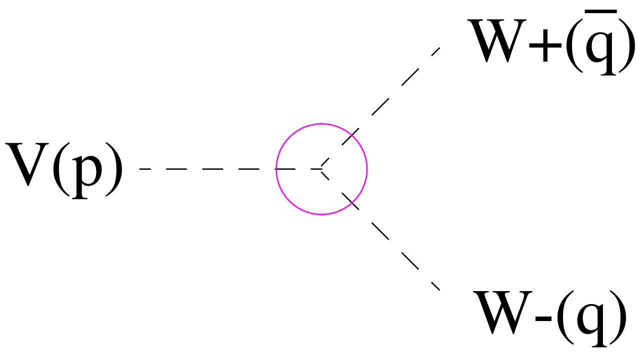

LEP W mass from qqqq
ALEPH
DELPHI
L3
OPAL
LEP
81.30 ± 0.48 GeV
79.90 ± 0.60 GeV
80.91 ± 0.43 GeV
80.08 ± 0.47 GeV
80.62 ± 0.26 GeV
common 0.10 GeV
χ^2/dof = 5.4/3
80
81
m_W [GeV]


W-Boson Mass [GeV]
pp-colliders
80.41 ± 0.09
LEP2
80.48 ± 0.14
Average(world)
80.43 ± 0.08
χ2/DoF: 0.2 / 1
LEP1/SLD
80.329 ± 0.041
80.2
80.4
80.6
80.8
mW [GeV]
State: j97


indirect Data
direct Data
80.5
80.4
80.3
80.2
m_W [GeV]
m_H [GeV]
70
300
1000
Preliminary
140
160
180
200
m_t [GeV]

Triple gauge coupling

Parameter space



2 x 7 complex coupling constants

Overall couplings : $g_{WW\gamma} = 1$, $g_{WWZ} = \cot\theta_W$

C,P and CP conservations reduce to five

$$g_1^Z,\ \kappa_\gamma,\ \kappa_Z,\ \lambda_\gamma,\ \lambda_Z$$

Blind directions (LEP1 data) ---> Three TGC's

$$\alpha_{W\phi} = \Delta g_1^Z \cos^2\theta_W$$

$$\alpha_W = \lambda_\gamma$$

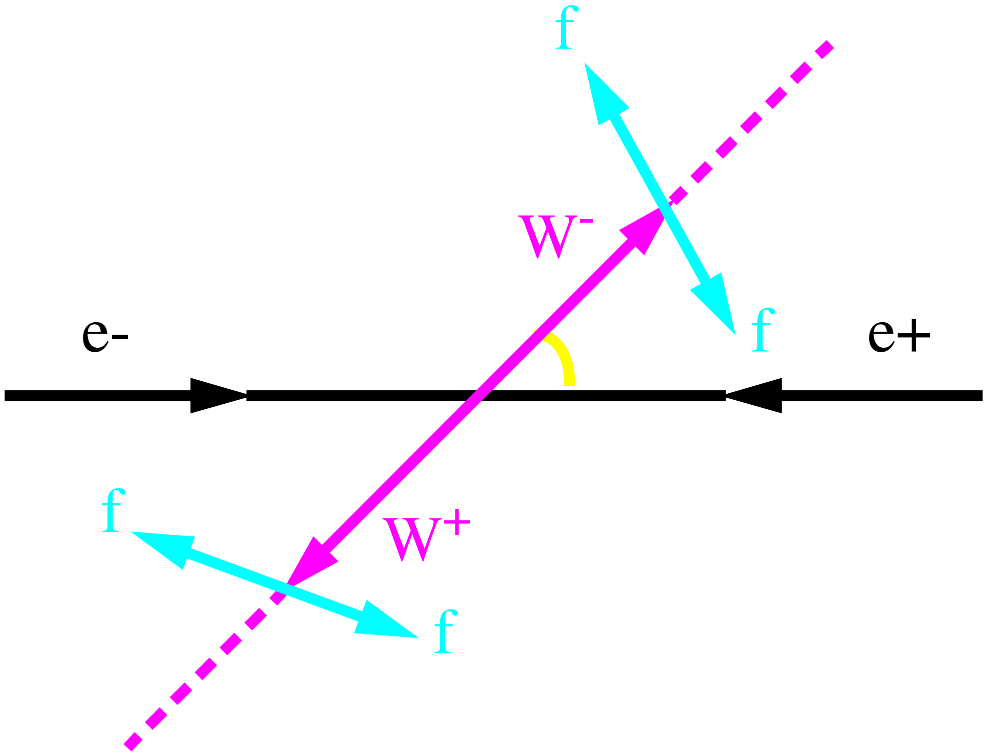
$$\alpha_{B\phi} = \Delta\kappa_\gamma - \Delta g_1^Z \cos^2\theta_W$$

with constrains

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

preserve local $SU(2)_L \times U(1)_Y$ invariance

Experimental variables



W- polar production angle

Polar and azimathal
W decay angle
in W rest frame

- Reconstruction of 4 decay fermions
- Kinematic fit to improve resolution
- Reconstruction of 5 phase-space variables

Diffential cross section

$$d\sigma = d\sigma(\Omega, \alpha)$$

$$\Omega = (\Theta, \theta^{*}_{\pm}, \phi^{*}_{\pm})$$

- contains all possible information
- measure as many angle as possible

W --> lv decay

The sign of the charge of lepton determines unique W- decay angle: $\cos\theta^{*}, \phi^{*}$

W -->qq decay

Flavour and chrage of quak is not measured

two-fold ambiguity

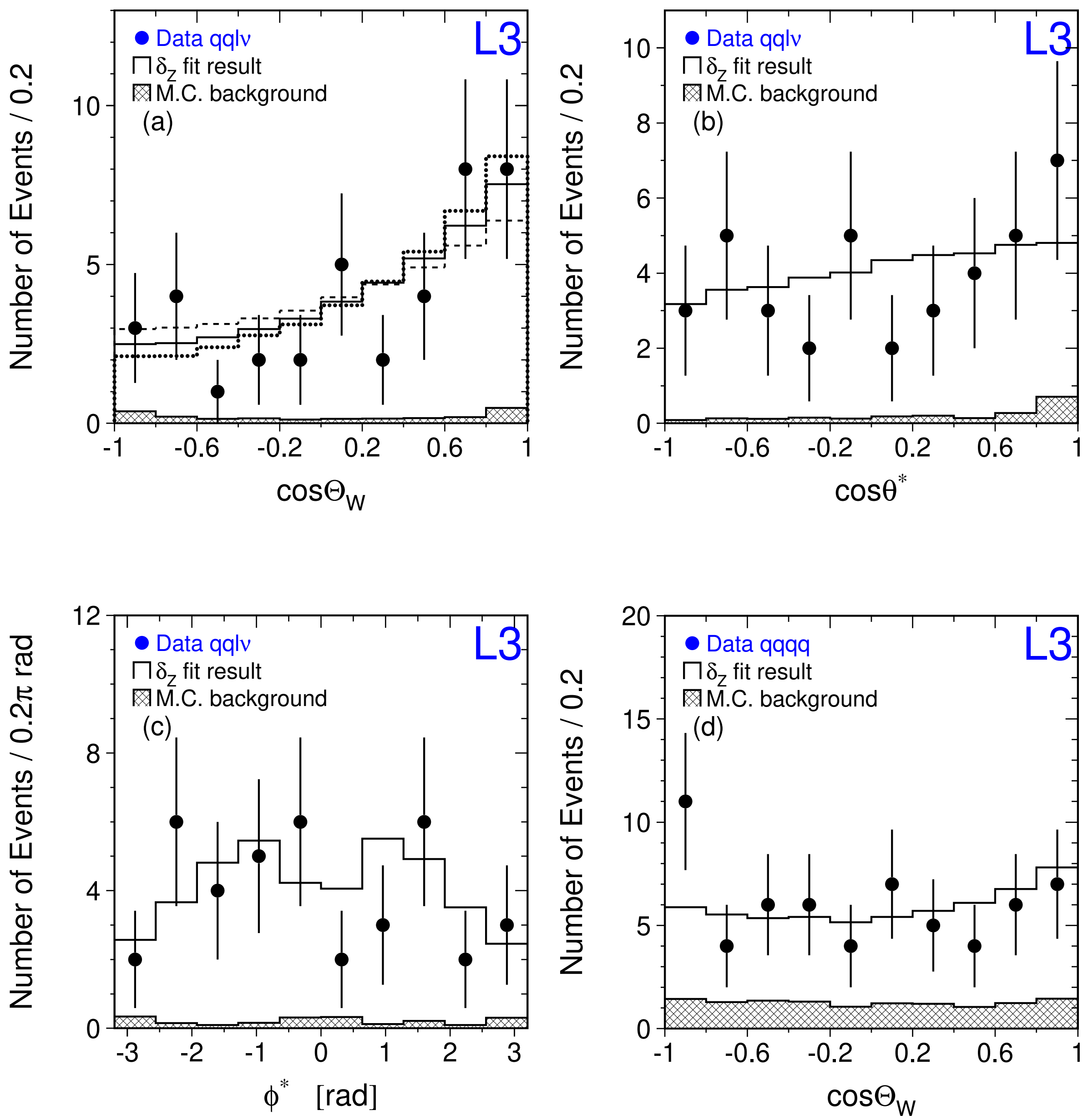
$$\left(\cos\theta^{*}, \phi^{*}\right) \leftrightarrow \left(-\cos\theta^{*}, \phi^{*} + \pi\right)$$

Jet charge determines the sign of $\cos\Theta$

Correct-asignment efficiency = 70 ~ 80 %

$$\cos\Theta \leftrightarrow -\cos\Theta$$

Semileptonic channel is more sensitive



Data qqlν
δ_Z fit result
M.C. background
(a)
L3
Number of Events / 0.2
cosΘ_W
Data qqlν
δ_Z fit result
M.C. background
(b)
L3
Number of Events / 0.2
cosθ*
Data qqlν
δ_Z fit result
M.C. background
(c)
L3
Number of Events / 0.2π rad
φ* [rad]
Data qqqq
δ_Z fit result
M.C. background
(d)
L3
Number of Events / 0.2
cosΘ_W

Optimal Observable

Differential cross-section is expanded as a functions of coupling α

$$\frac{d\sigma}{d\Omega}(\alpha) = C_0 + \alpha C_1 + \alpha^2 C_2$$

$$\frac{1}{C_0}\frac{d}{d\alpha}\frac{d\sigma}{d\Omega} = \frac{C_1}{C_0} + 2\alpha\frac{C_2}{C_0}$$

2-variable space (C1/C0, C2/C0)
retains
the whole infotmation of TGC's

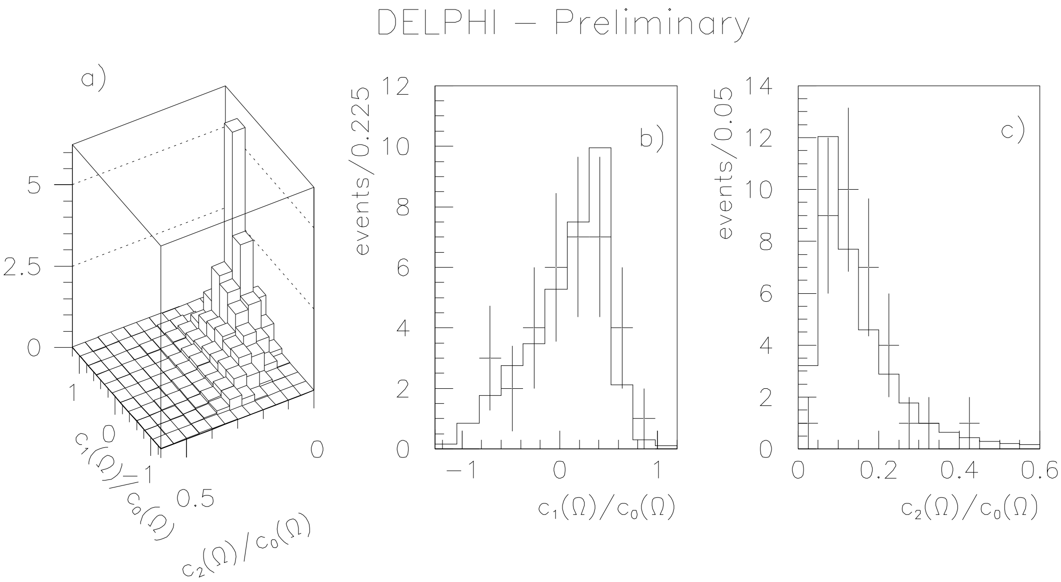
↓

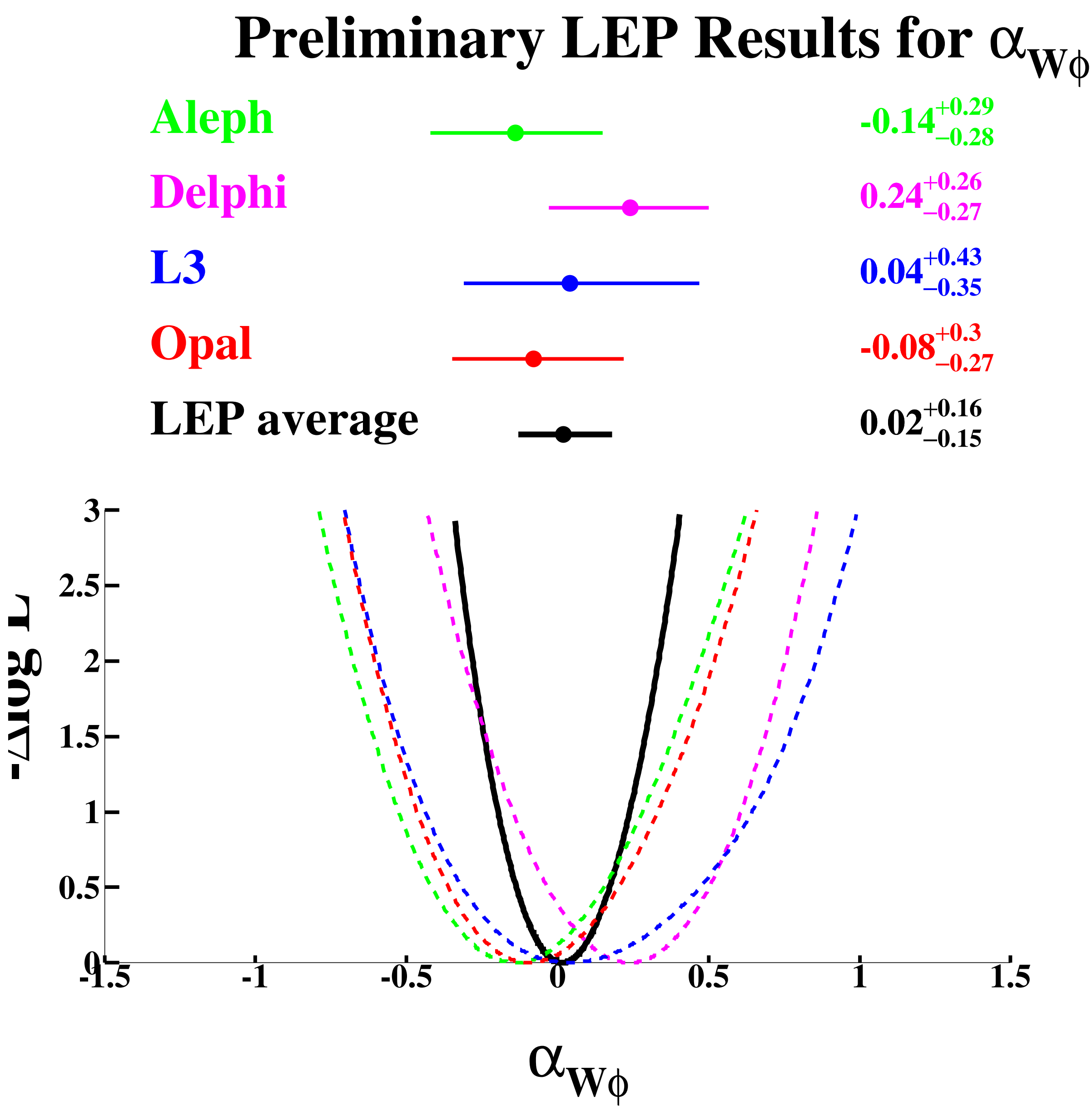
Allows determination of α
with maximum precision

↓

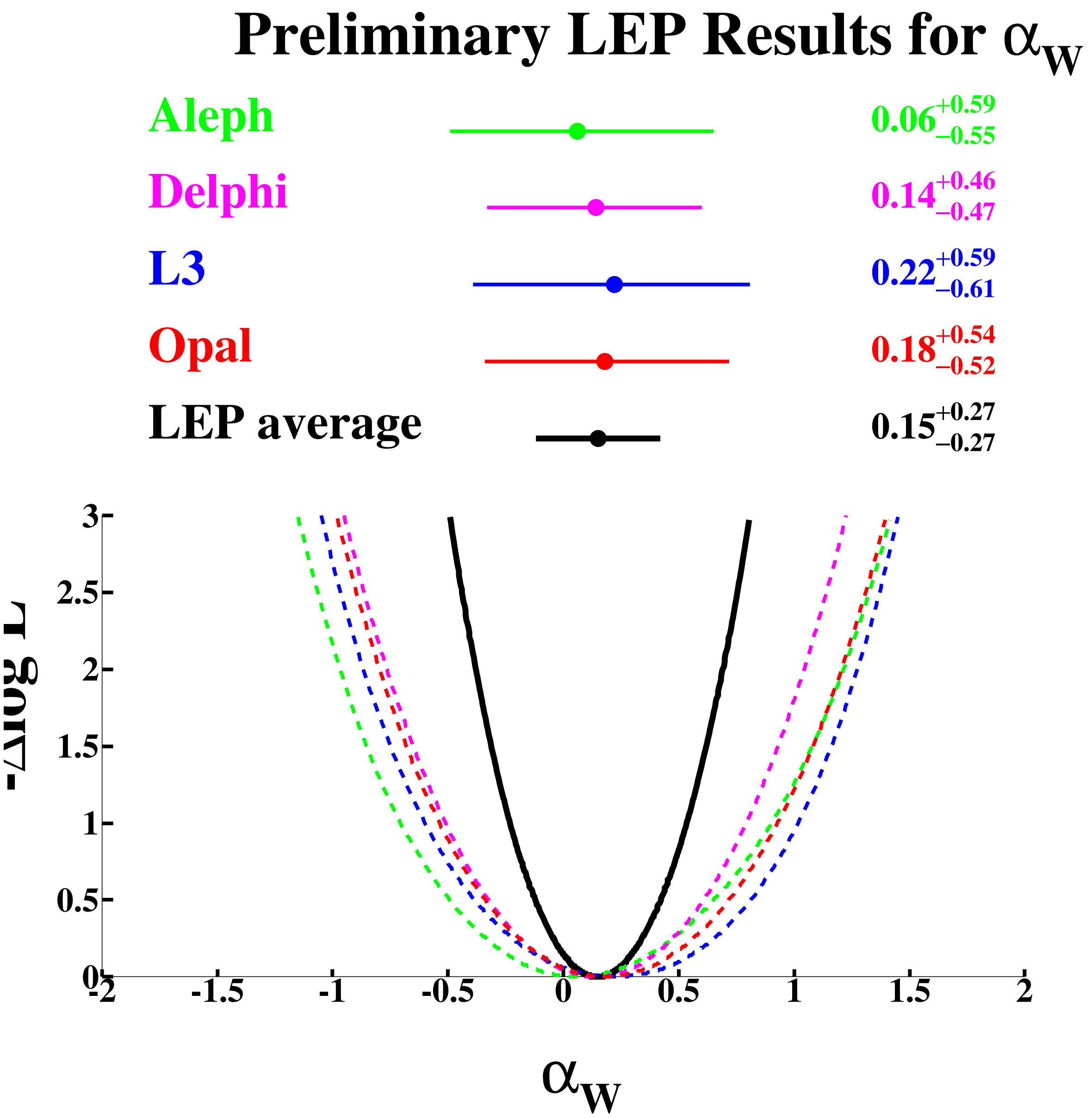
Fits (C1/C0, C2/C0), by likelihood method

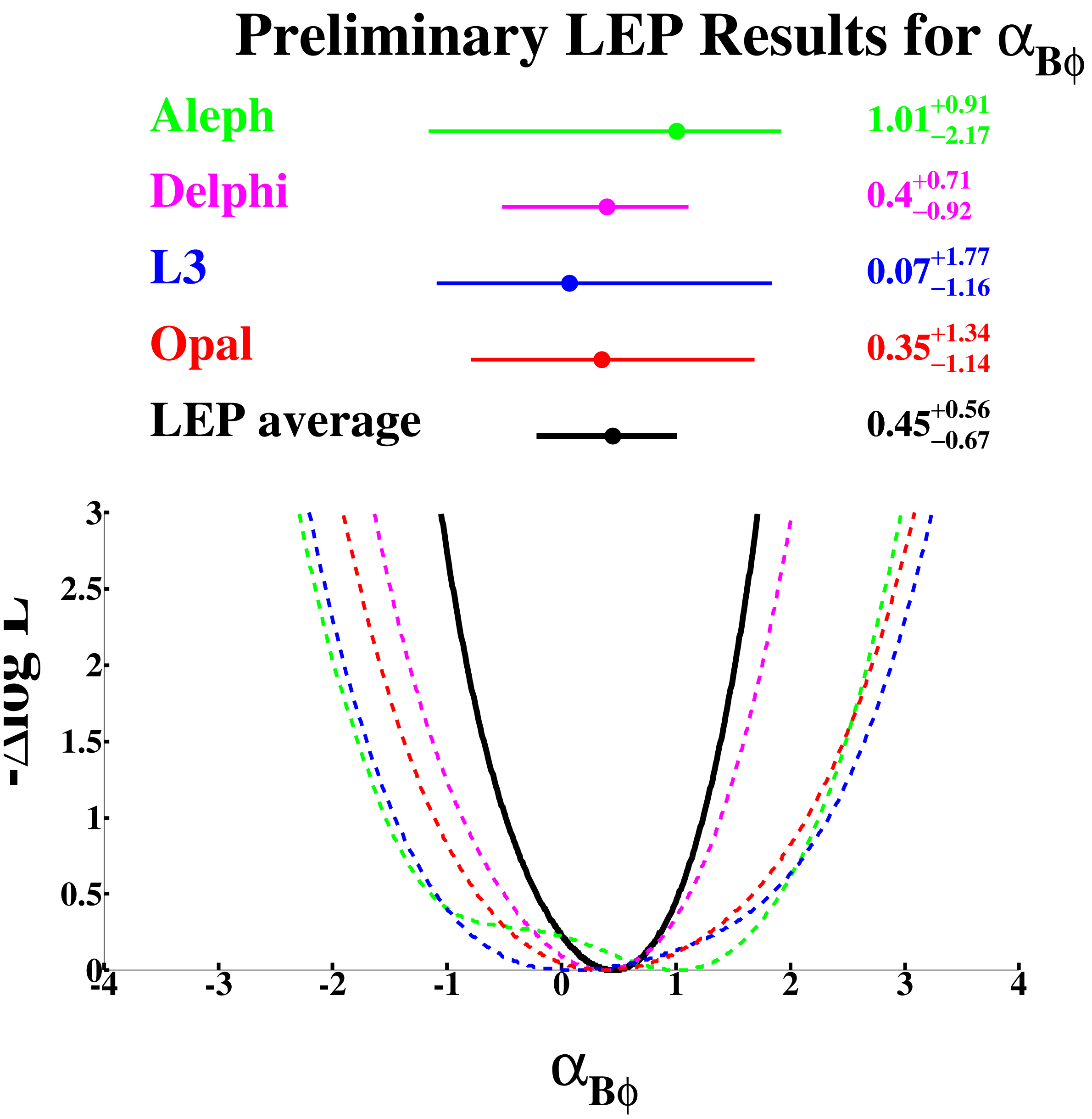
APLEPH OO plots



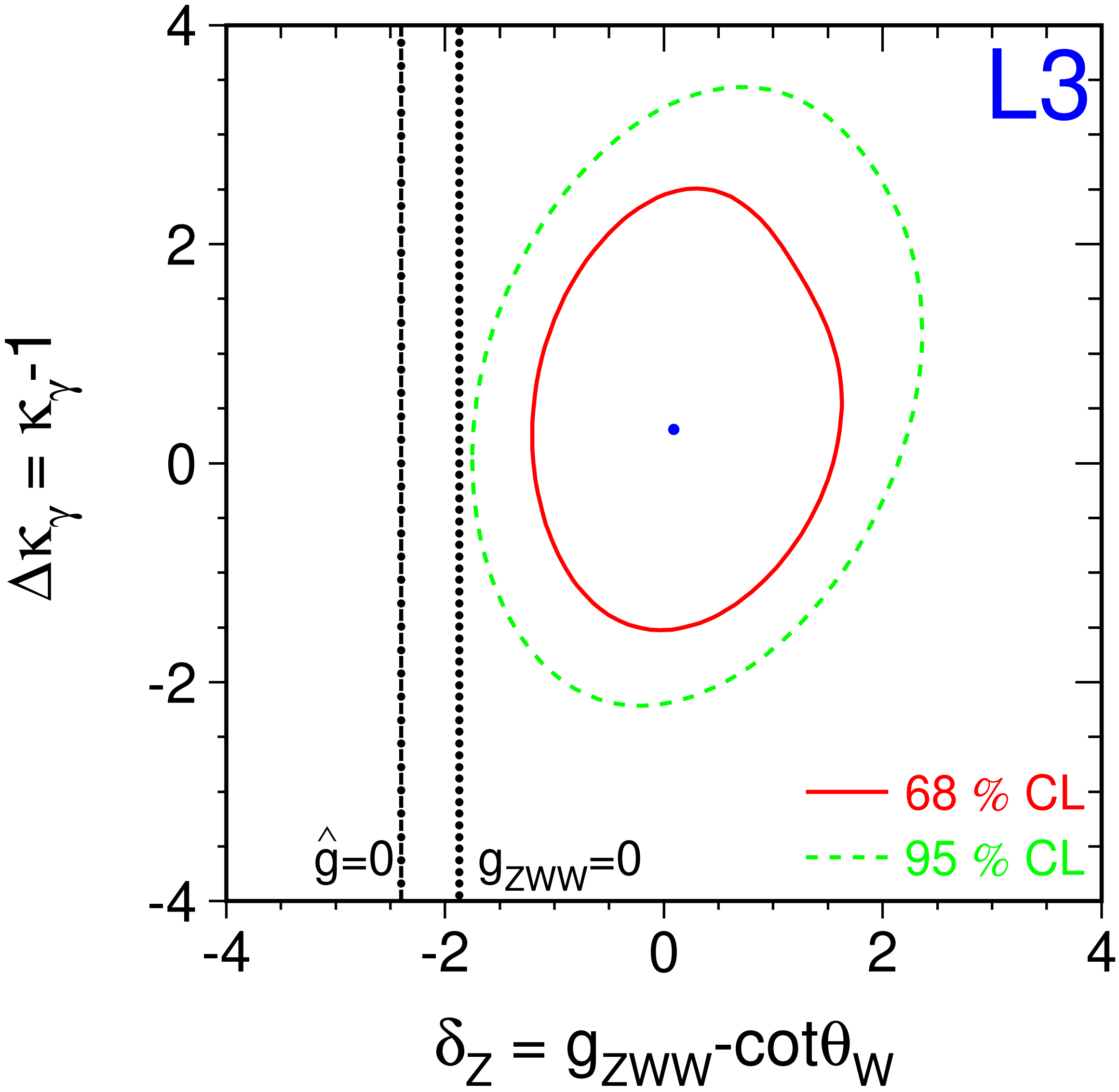


Preliminary LEP Results for $\alpha_{W\phi}$
Aleph
$-0.14^{+0.29}_{-0.28}$
Delphi
$0.24^{+0.26}_{-0.27}$
L3
$0.04^{+0.43}_{-0.35}$
Opal
$-0.08^{+0.3}_{-0.27}$
LEP average
$0.02^{+0.16}_{-0.15}$
$-\Delta \log L$
0
0.5
1
1.5
2
2.5
3
-1.5
-1
-0.5
0
0.5
1
1.5
$\alpha_{W\phi}$


Preliminary LEP Results for α_W
Aleph
$0.06^{+0.59}_{-0.55}$
Delphi
$0.14^{+0.46}_{-0.47}$
L3
$0.22^{+0.59}_{-0.61}$
Opal
$0.18^{+0.54}_{-0.52}$
LEP average
$0.15^{+0.27}_{-0.27}$
-Δlog L
α_W


Preliminary LEP Results for $\alpha_{B\phi}$
Aleph $1.01^{+0.91}_{-2.17}$
Delphi $0.4^{+0.71}_{-0.92}$
L3 $0.07^{+1.77}_{-1.16}$
Opal $0.35^{+1.34}_{-1.14}$
LEP average $0.45^{+0.56}_{-0.67}$
-Δlog L
0
0.5
1
1.5
2
2.5
3
-4
-3
-2
-1
0
1
2
3
4
$\alpha_{B\phi}$

2 Parameter fit



$g_{ZWW} = 0 \;:\; (\delta_Z = -\cot\theta_W)$

i.e. , vanishing ZWW coupling

$\hat{g} = 0 \;:\; (\delta_Z = -\tan\theta_W - \cot\theta_W)$

i.e. , weak TGC coupling only by γ/Z mixing

Existence of ZWW vertex

Independent of κ_γ

Single photon analysis

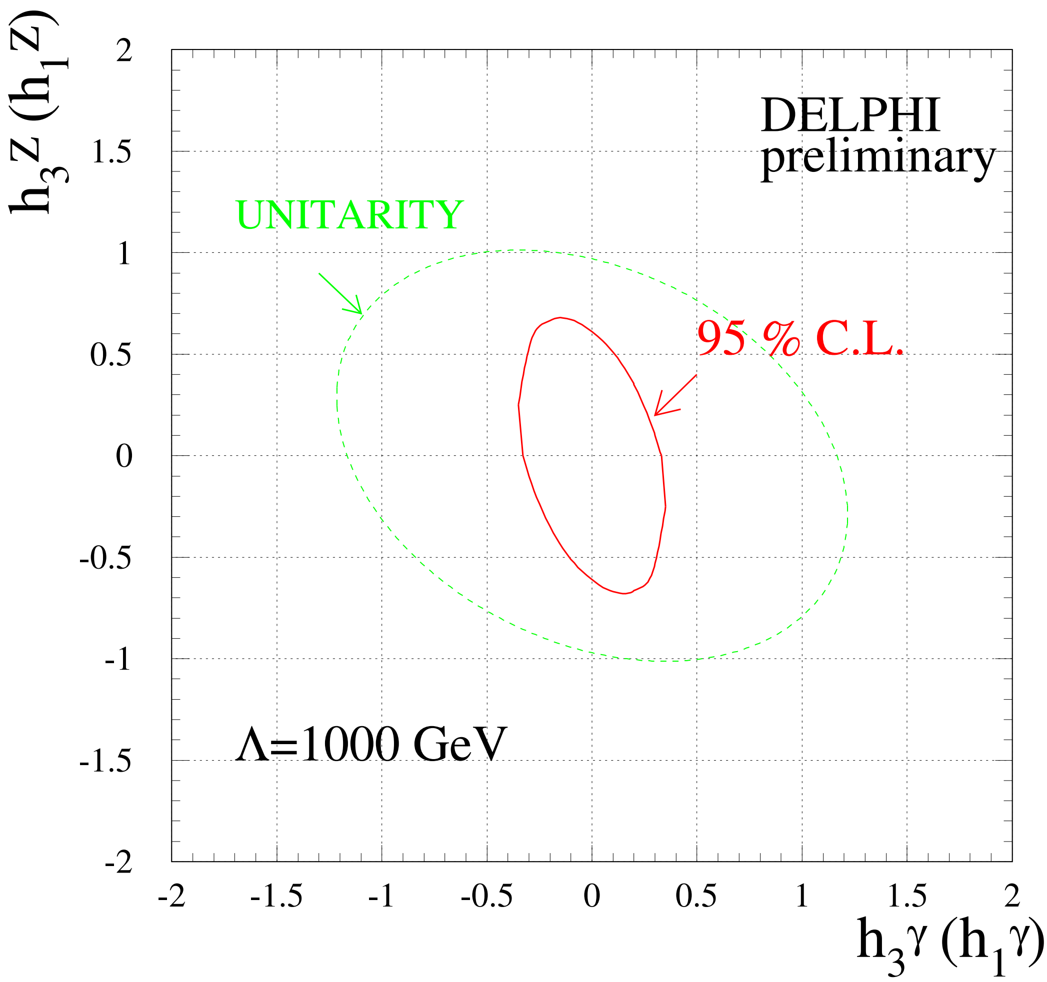
$$e^+e^- \to \gamma + \text{invisible particle}$$

ZVγ vertex

form factor: $$h_i^V(s) = h_{i0}^V / (1 + s/\Lambda^2)^n$$

$(i=1,2,3,4)$

Λ = Energy scale



Single W production

W hadronic decay properties

Colour reconnection

$$\frac{\langle N_{ch}(WW \rightarrow qqqq)\rangle}{2\langle N_{ch}(WW \rightarrow qqlv)\rangle} < 1$$

A reduction of $N_{ch}(WW \rightarrow qqqq)$ is expected

at $(p < 1 \text{ GeV})$

Search for the effects in data

Table 7:

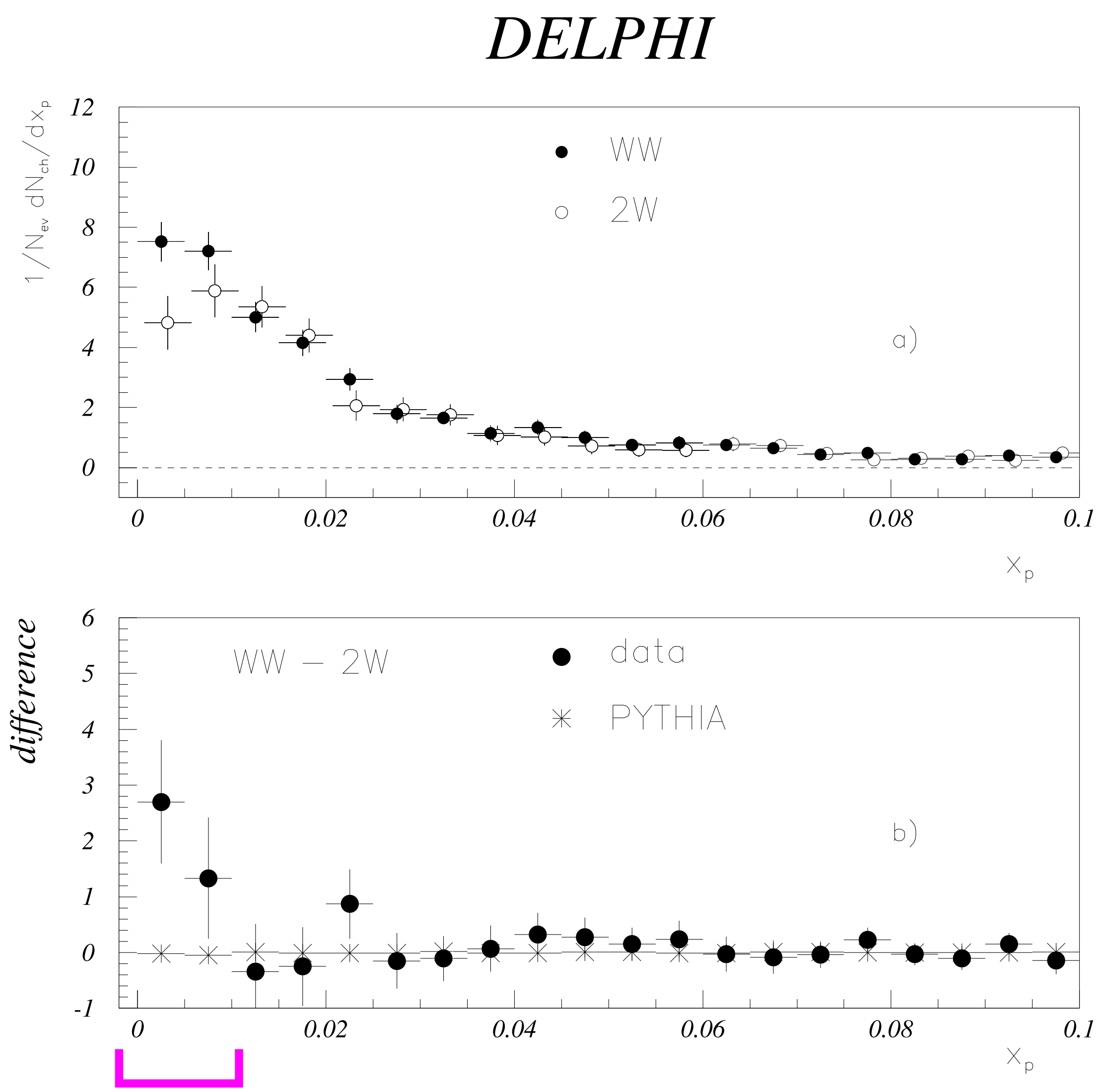
	Nch(qqqq)	2Nch(qqlv)	delta Nch
DELPHI	41.7+-1.8	36.4+-2.2	+5.3+-2.8
L3	37.9+-0.9	38.8+-1.2	-0.9+-1.5
OPAL	38.3+-1.1+-0.6	36.8+-1.8+-0.8	+1.5+-2.2+-0.8

x_p distributions of charged particles

$$x_p = \frac{2p}{\sqrt{s}}$$

for $qqqq$ and $qqlv$ channels

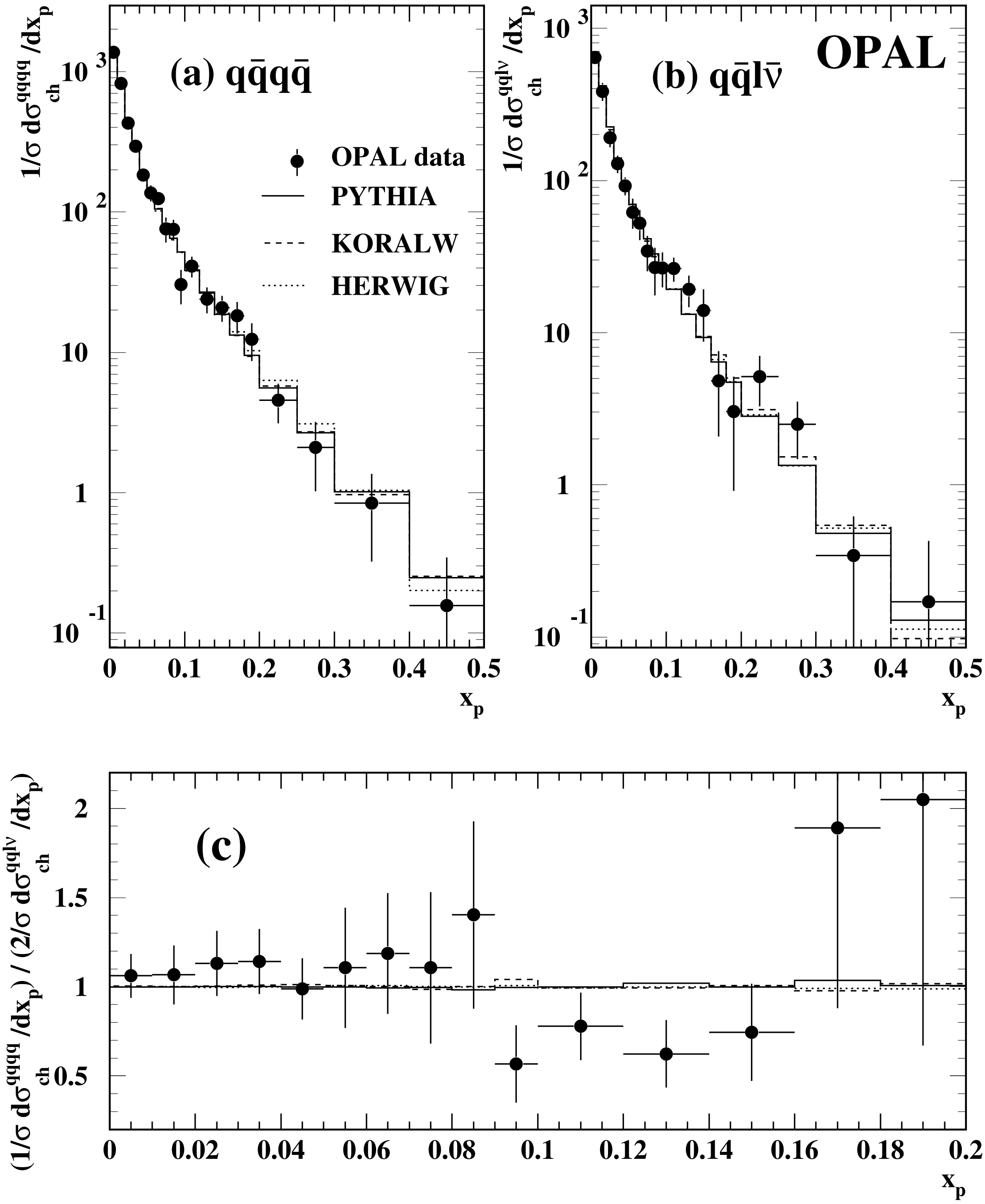
Excess at low x_p (DELPHI)



Excess of 3.9+-1.5+-0.7 (x_p<0.01)

Also in rapidity, P_t^{in}, and P_t^{out} distributions

No excess (OPAL)



We need more data!

Bose-Einstein correlations

Effect on W mass

Jadach & Zalewski : CERN-TH/97-29
Kartveliskvili, Kvatadze & Moller : hep-ph/9704424

$\longrightarrow$ $\Delta M_W < 20$ MeV (B.E.)

B.E. correlations in WW events

$$Q^2 = M^2(\pi\pi) - 4m_\pi^2$$

P(Q) : two-particle probability density

P_0(Q) : reference two-particle distribution

$$R(Q) = \frac{P(Q)}{P_0(Q)}$$

$$R'(Q) = R^{data}(Q)/R^{MC}(Q)$$

or

$$R^{**}(Q) = \frac{\left(\dfrac{N_\pi^{++,--}(qqqq) - 2N_\pi^{++,--}(qql\nu)}{N_\pi^{+-}(qqqq) - 2N_\pi^{+-}(qql\nu)}\right)^{data}}{\left(\dfrac{N_\pi^{++,--}(qqqq) - 2N_\pi^{++,--}(qql\nu)}{N_\pi^{+-}(qqqq) - 2N_\pi^{+-}(qql\nu)}\right)^{MC}}$$

Fit with

$$\kappa(1 + \varepsilon Q)(1 + \lambda \exp(-\sigma^2 Q^2))$$

σ : source radius

correlation function

Table 8:

	qqlv	qqqq
DELPHI	λ = 0.41 +- 0.13 σ = 0.5 fm fixed	λ = 0.09+-0.06 σ = 0.5 fm fixed
ALEPH	λ = 0.96 +- 0.84 σ = 0.96 +- 0.41 fm	λ = 0.12 +- 0.12 σ = 0.64 +- 0.38 fm

In good agreement with the result from Z^0 data

ALEPH plot

Conclusion

- Good start of LEP2

- σ_{WW} = 3.69 +- 0.45 pb (161 GeV)

  σ_{WW} = 11.96 +- 0.70 pb (172 GeV)

  $Br(\mathrm{W} \rightarrow had)$ = 67.2 +- 1.7

  $Br(\mathrm{W} \rightarrow lepton)$ = 10.9 +- 0.6

  V_{cs} = 0.96 +- 0.08

- Mw = 80.48 +- 0.14 GeV

- $\alpha_{W\phi} = 0.02 \begin{smallmatrix} +\ 0.16 \\ -\ 0.15 \end{smallmatrix}$

  $\alpha_{W} = 0.15 \begin{smallmatrix} +\ 0.27 \\ -\ 0.27 \end{smallmatrix}$

  $\alpha_{B\phi} = 0.45 \begin{smallmatrix} +\ 0.56 \\ -\ 0.67 \end{smallmatrix}$

- C. R. : we meed more data

  B. E. : consistent with Z0 data

→ All consistent with SM