PRECISION TESTS OF THE ELECTROWEAK GAUGE THEORY

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New Results from

- **LEP I and LEP II**
- **SLD**
- **BES II at BEPC (Beijing)**
- Theoretical Developments
- **GLOBAL FIT TO EW DATA**

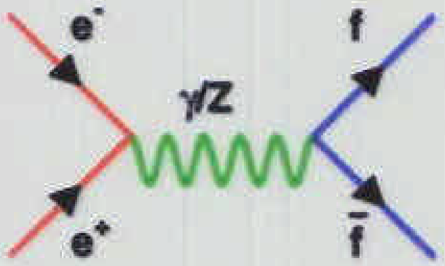
Plan of Talk

- **LEP I & SLD:**
  Precision Measurements around the Z
- **LEP II:**
  - **Fermion Pair production including heavy quark production & asymmetries**
  - **$W^{\pm}$, $W^{+}W^{-}$, ZZ cross sections/ BR's**
  - **Triple/ Quartic Gauge Couplings**
  - **Other topics**
  - **W Mass and Width**
- **Global Fits to EW data $\Longrightarrow$** M_{Higgs}
- **Future Prospects - Tevatron and LHC**

Z Lineshape

Experimental Input:

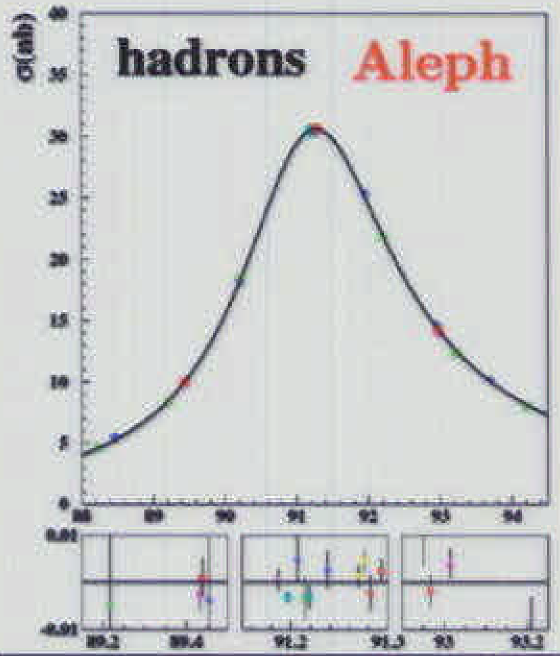
Precision measurements of cross sections & lepton forward-backward asymmetries

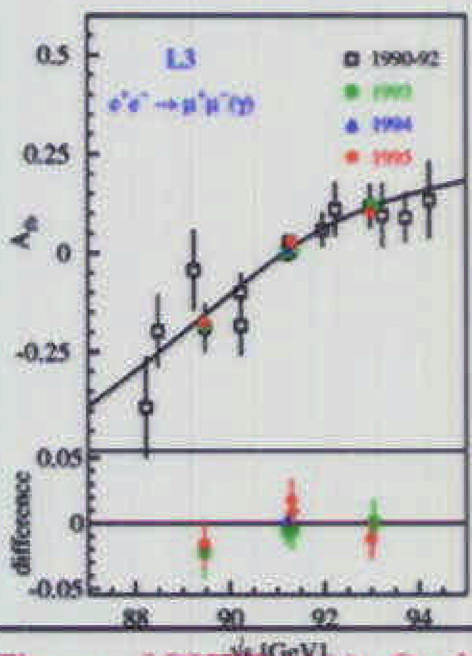


$f \equiv e, \mu, \tau, q$

$e^+e^- \to \ell^+\ell^-$, hadrons

- 17 million Z studied (15.5M hadronic; 1.7M leptonic)
- Aleph, Delphi, L3: Final; Opal: near Final Analysis





L3

$A_{FB}^{0,\mu}$

Extraction of Z parameters

Heroic efforts to Reduce SYSTEMATIC ERRORS

- **Experiments: Detector Upgrades (LUMI)**
- **LEP machine/energy groups: Model incorporating environmental effects - Earth Tide effects, Leakage currents due to passing trains**
- **Theoretical improvements:**
  - **ZFITTER 6.23 (D.Bardin et al)**
  - **TOPAZ0 4.4 (G.Passarino et al)**
  - **ALIBABA (W. Beenaker et al), $e^+e^- \rightarrow e^+e^-(\gamma)$**
  - **BHLUMI 4.04 (S.Jadach et al)**
  - **Contributions from G.Degrassi et al, G.Montagna et al, B. Kniehl, J.Kuhn et al, F.A.Berends et al, B.Ward, Z.Was, ...**

  Overall theoretical errors very small

  $\Delta M_Z : \pm 0.3$ MeV; $\Delta\Gamma_Z : \pm 0.2$ MeV; $\Delta\sigma_h^0 : \pm 0.02\%$ **(different options for photonic and fermion pair radiation)**

  $\Delta R_\ell : \pm 0.004$ **(ZFITTER-TOPAZ0 differences in parametrising observables)**

Extraction of Z parameters

- **LEP EWWG: Procedures for Combining LEP data including Common Errors**

  (LEP energy, theoretical errors in t-channel correction for e^+e^- final state and in Luminosity determination)

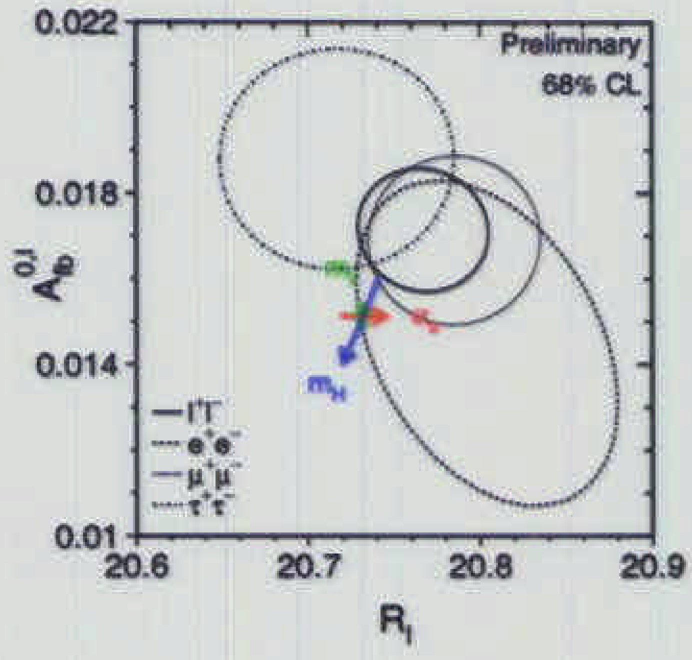
Extraction of Z parameters

$\sigma^{\circ}_{\rm had} = \frac{12\pi}{M_Z^2}\frac{\Gamma_e \Gamma_{\rm had}}{\Gamma_Z^2}$, $R_\ell = \frac{\Gamma_{\rm had}}{\Gamma_\ell}$

$A^{\circ,\ell}_{FB} = \frac{3}{4} A_e A_\ell$, $A_\ell = \frac{2 g^\ell_V g^\ell_A}{(g^\ell_V)^2 + (g^\ell_A)^2}$

	Value	Comm. syst Error	1990 Error
M_Z	91187.6 ± 2.1 MeV	1.7	21
Γ_Z	2495.2 ± 2.3 MeV	1.2	14
$\sigma^{\circ}_{\rm had}$	41.541 ± 0.037 nb	0.014	0.52
R_e	20.804 ± 0.050	0.014	see
R_μ	20.785 ± 0.033	0.004	partial
R_τ	20.764 ± 0.045	0.004	widths
$A^{\circ,e}_{FB}$	0.0145 ± 0.0025	0.0004	see
$A^{\circ,\mu}_{FB}$	0.0169 ± 0.0013	0.0003	$\sin^2\theta^{\rm lept}_{\rm eff}$
$A^{\circ,\tau}_{FB}$	0.0188 ± 0.0017	0.0003	- do -

Extraction of Z parameters



Test of Lepton UNIVERSALITY

$R_\ell = 20.767 \pm 0.025$
$A_{FB}^{0,\ell} = 0.01714 \pm 0.00095$

	Partial Width (MeV)	1990 Error
Γ_e	83.92 ± 0.12	1.0
Γ_μ	83.99 ± 0.18	1.3
Γ_τ	84.08 ± 0.22	1.4
Γ_ℓ	83.984 ± 0.086	0.7
Γ_{had}	1744.4 ± 2.0	16.0
Γ_{inv}	499.0 ± 1.5	13

$N_\nu = 2.984 \pm 0.008$

Using $\Gamma_{inv}^{SM} = 501.7^{+0.1}_{-0.9}$,

$\Delta\Gamma_{inv}^{x} = -2.7^{+1.7}_{-1.5}$ MeV

at 95% C.L.

$\Rightarrow \Delta\Gamma_{inv}^{x} < 2.0$

Z Couplings to Leptons

τ Polarisation at LEP

$$P_\tau(\cos\theta) = -\frac{A_\tau(1+\cos^2\theta) + 2A_e\cos\theta}{1+\cos^2\theta + 2A_\tau A_e\cos\theta}$$

Averaged over $\cos\theta \Rightarrow A_\tau$

[NEW RESULT FROM OPAL TO CONF.]

As function of $\cos\theta$, $P_\tau(\cos\theta) \Rightarrow$
almost uncorrelated measurements of A_τ, A_e

LEP: $A_\tau = 0.1439 \pm 0.0042$ $A_e = 0.1498 \pm 0.0048$
$\Rightarrow A_\ell = 0.1464 \pm 0.0032$

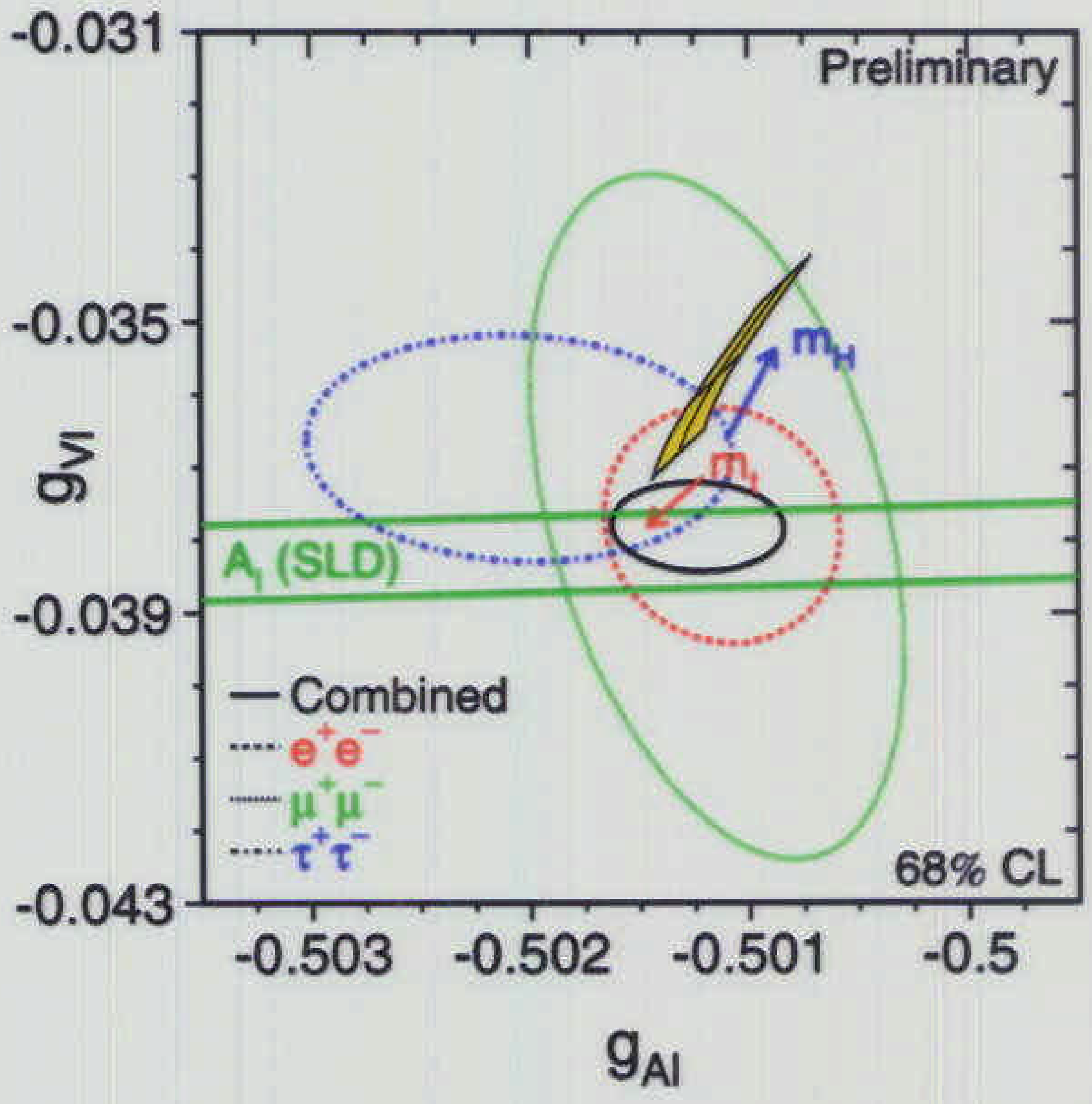
Combine with A_ℓ from $A_{FB}^{0,\ell}$ measurements:
$\Rightarrow A_\ell(\text{LEP}) = 0.1481 \pm 0.0026$

SLD: 550k $e^+e^- \to$ hadrons events with polarised e^-,
Left-Right Asym: $A_{LR} \equiv A_e = 0.1514 \pm 0.0022$

Left-Right Forw-Back Asym in $e^+e^- \to \ell^+\ell^-$ events:
$A_e = 0.1544 \pm 0.0060$; $A_\mu = 0.142 \pm 0.015$;
$A_\tau = 0.136 \pm 0.015$

Combine with A_e from A_{LR} measurement:
$\Rightarrow A_\ell(\text{SLD}) = 0.1513 \pm 0.0021$

Z Couplings to Leptons



$$A_\ell = \frac{2\bar{g}^\ell_V \bar{g}^\ell_A}{(\bar{g}^\ell_V)^2 + (\bar{g}^\ell_A)^2}$$

$$\Gamma_\ell = \frac{G_F M_Z^3}{6\pi\sqrt{2}}[(\bar{g}^\ell_V)^2 + (\bar{g}^\ell_A)^2] \times (1 + \delta^{QED}_\ell)$$

Z Couplings to b, c quarks

LEP & SLD: **Cross sections** R_b, R_c

$$R_q = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \text{hadrons})}, \Gamma_q \propto [(\bar{g}_V^q)^2 + (\bar{g}_A^q)^2]$$

LEP: **Forward-Backward Asymmetries** $A_{FB}^{0,b}$, $A_{FB}^{0,c}$

$$A_{FB}^{0,q} = \frac{3}{4} A_e A_q$$

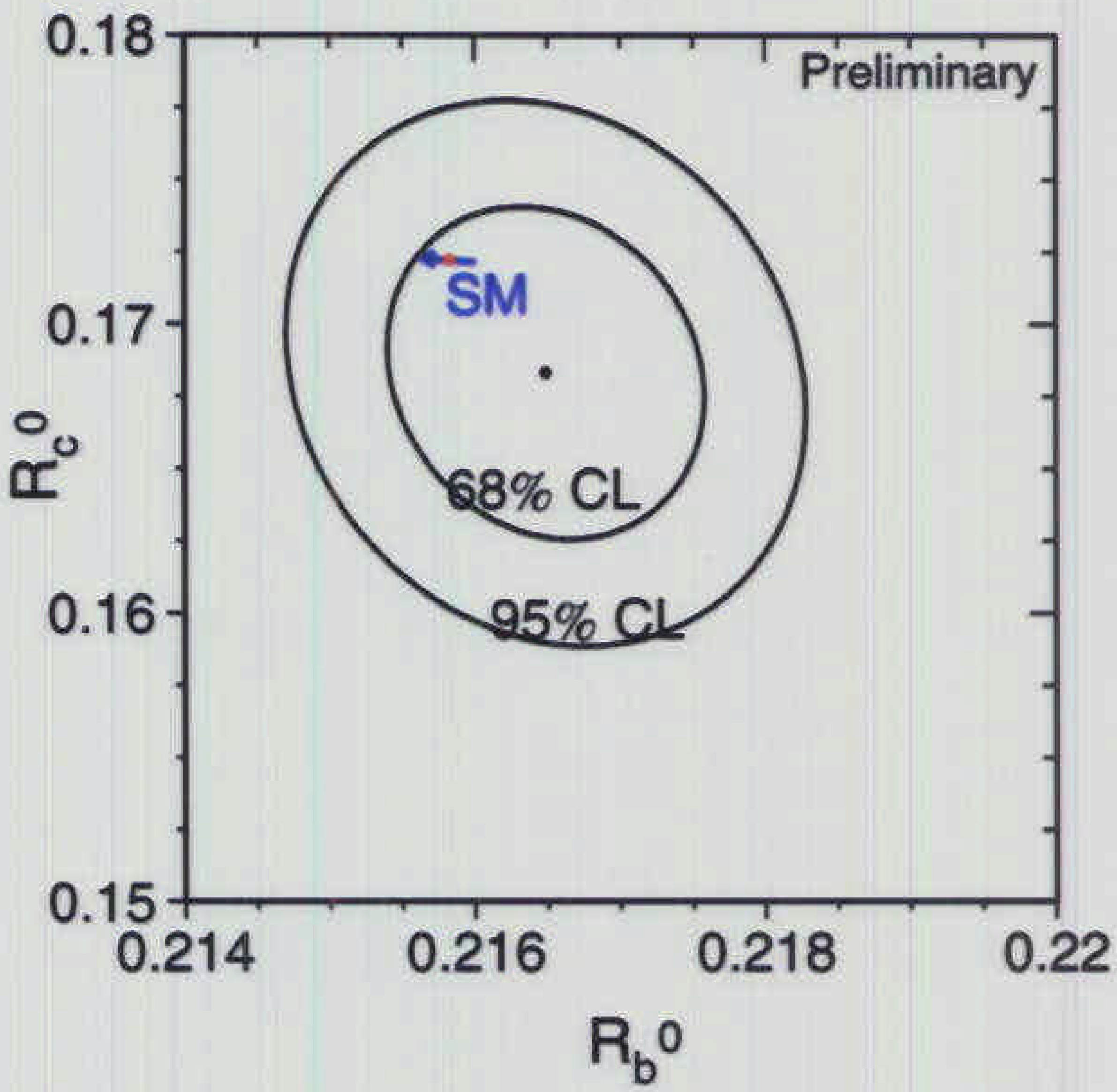
SLD: **Left-Right Forward-Backward Asymmetries,** A_b, A_c

$$A_q = \frac{2\bar{g}_V^q \bar{g}_A^q}{(\bar{g}_V^q)^2 + (\bar{g}_A^q)^2}$$

Combining LEP + SLD data:

$R_b = 0.21649 \pm 0.00072$	$R_c = 0.1683 \pm 0.0038$
$A_{FB}^{0,b} = 0.0989 \pm 0.0020$	$A_{FB}^{0,c} = 0.0689 \pm 0.0035$
$A_b = 0.922 \pm 0.023$	$A_c = 0.632 \pm 0.026$

Z Couplings to b, c quarks



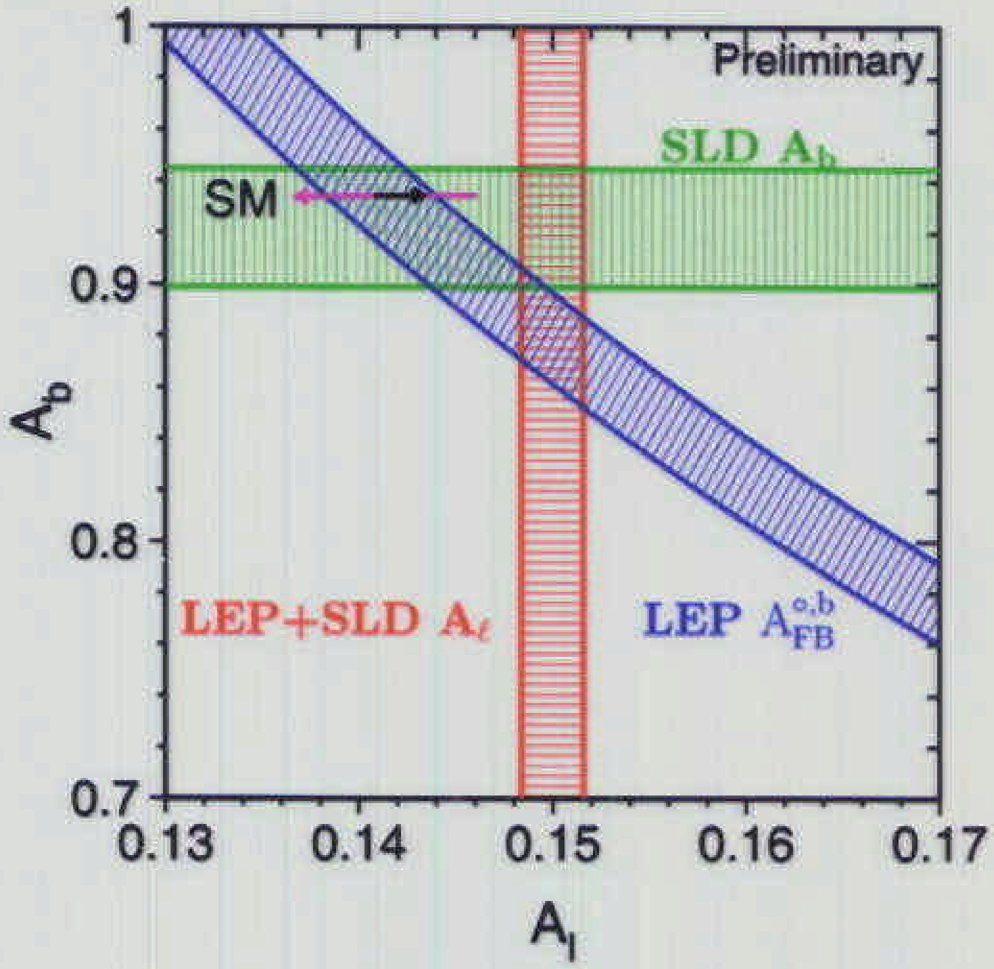
R_b, R_c now within 1σ of SM prediction

(SM R_b, R_c: 0.21583, 0.1674)

Z Couplings to b, c quarks

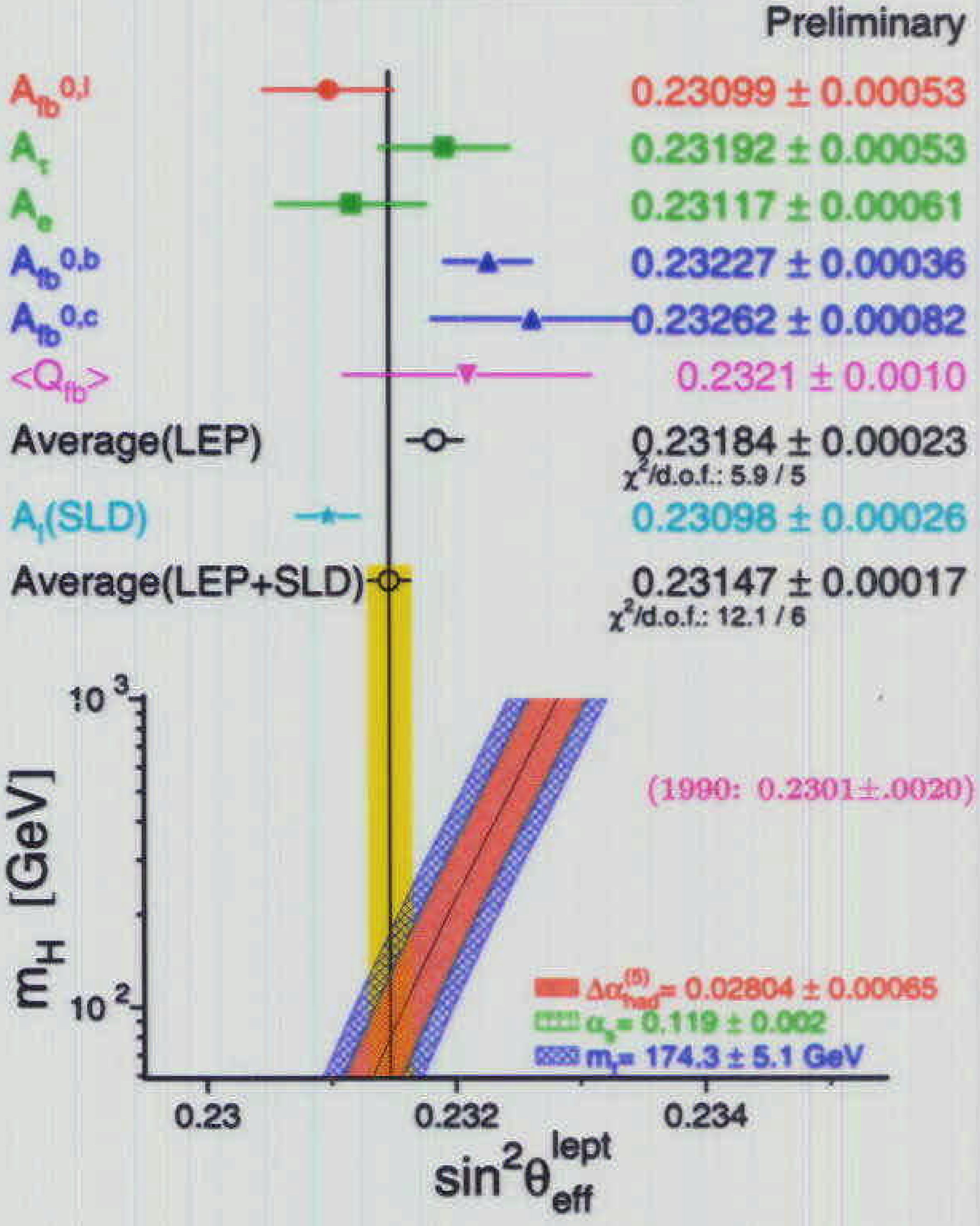
	LEP (A_ℓ= 0.1481±.0026)	SLD	LEP + SLD (A_ℓ= 0.1500±.0016)
A_b	0.890 ±.024	0.922 ±.023	0.898 ±.015
A_c	0.619 ±.035	0.632 ±.026	0.624 ±.020

LEP+SLD A_b is 2.7σ below SM: 0.935



$\sin^2\theta_{\rm eff}^{\rm lept}$ from Asymmetries

$$\sin^2\theta_{\rm eff}^{\rm lept} = \frac{1}{4}\left(1 - \frac{g_V^\ell}{g_A^\ell}\right)$$



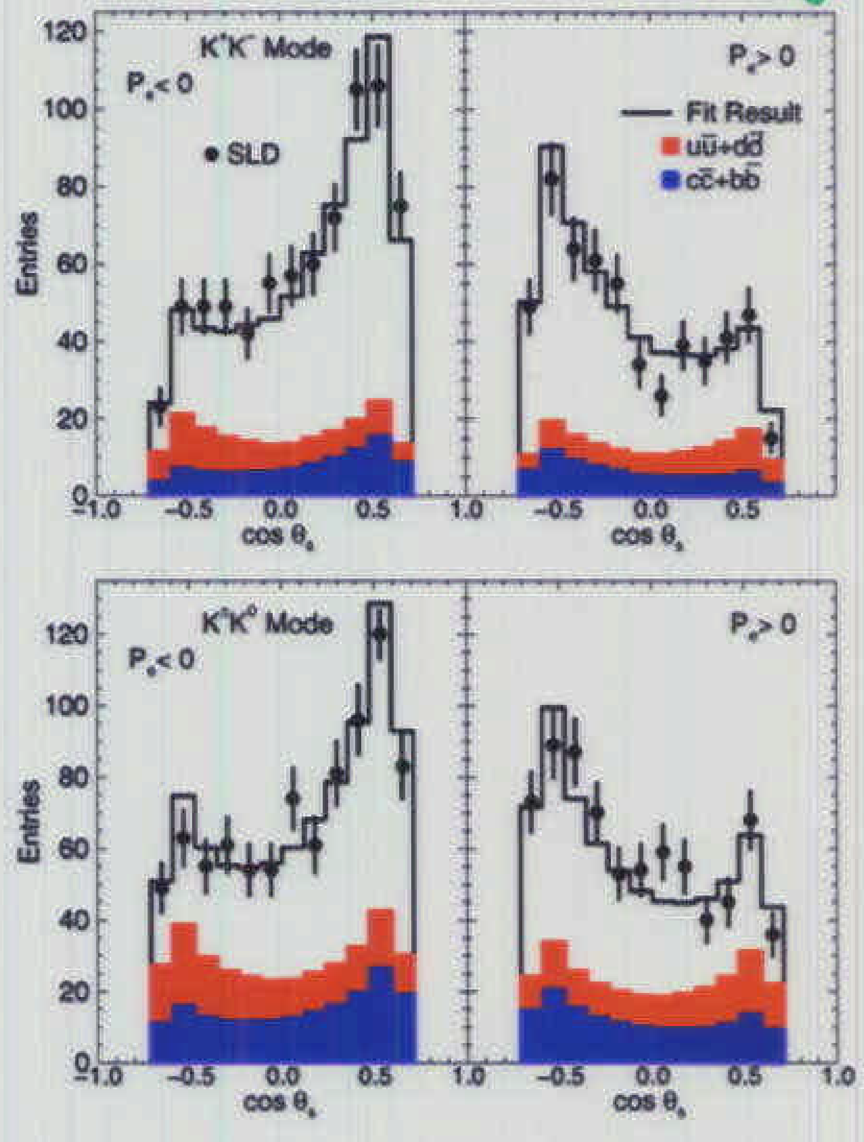
Z Couplings to s quarks

<u>New result from SLD:</u> 550k hadronic events; s-quark tagged by high momentum $K^{\pm}, K^0_S$ & absence of B, D mesons.

Left-Right Forward-Backward asym:

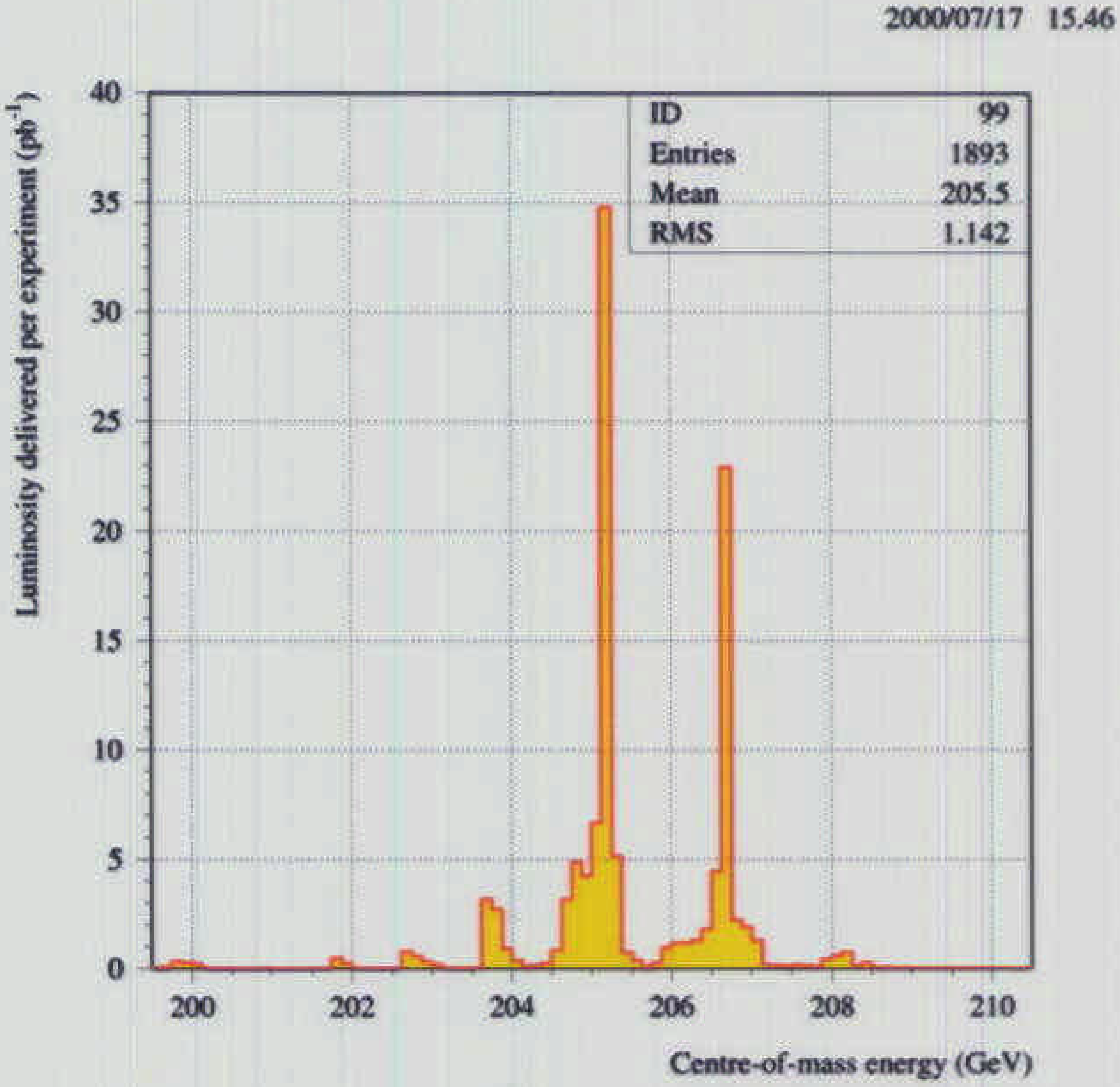
$$A_s = 0.895^{+0.066}_{-0.063}$$

$$\frac{A_b}{A_s} = 1.02 \pm 0.10$$



LEPII: Operation

LUMINOSITIES RECORDED -2000



2000: LUMINOSITY COLLECTED/EXPT NOW ~ 115 pb^{-1}

(1996-1999: 475 pb^{-1}/EXPT)

Theoretical Developments

To match

- superb performance of machines (LEP,SLC,Tevatron,...),
- excellent high resolution detectors, experimental analyses,
- **need matching THEORETICAL predictions**

4-fermion processes

(see LEP2MC workshop proceedings hep-ph/0005309)

- – $\sigma(W^+W^-)$ to 0.4%: (Use of Double-Pole Approx - valid much above threshold) (RacoonWW, YFSWW3)
  – σ(1-W) to 4-5% (Use of Fermion Loop Scheme) (WPHACT, grc4f)
  – σ (ZZ) to 2% (YFSZZ, ZZTO)
- GENTLE v2.10 now corrects for overestimated Coulomb correction; agrees well with RacoonWW; still ~0.75% ISR related uncertainty

2-fermion processes

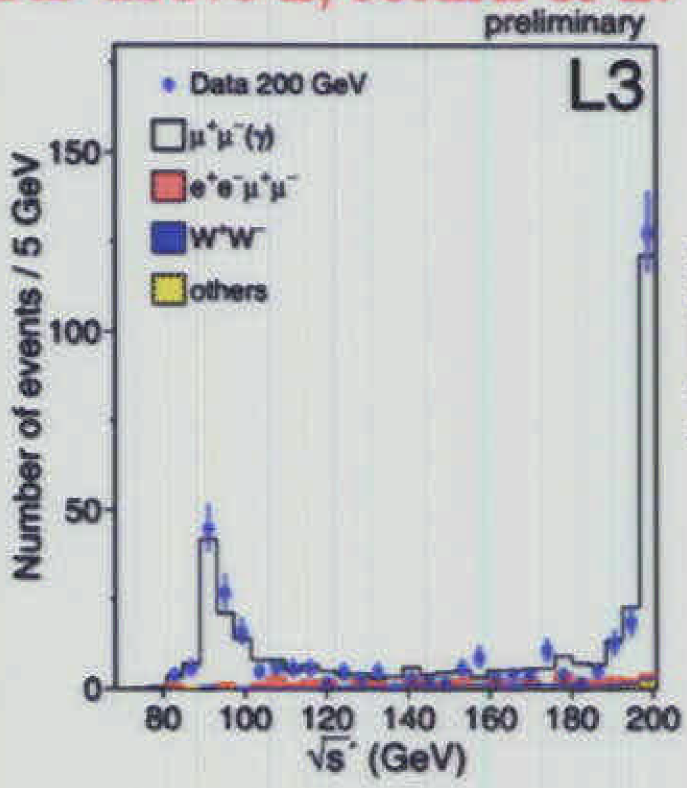
ZFITTER, KKMC give
better than 0.2% accuracy in σ(tot), of hadrons, leptons
0.2-0.4% on A_{FB}

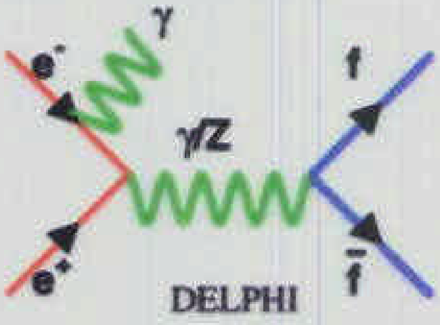
KKMC 1st MC for LEP, LC, μ-colliders, τ, b factories

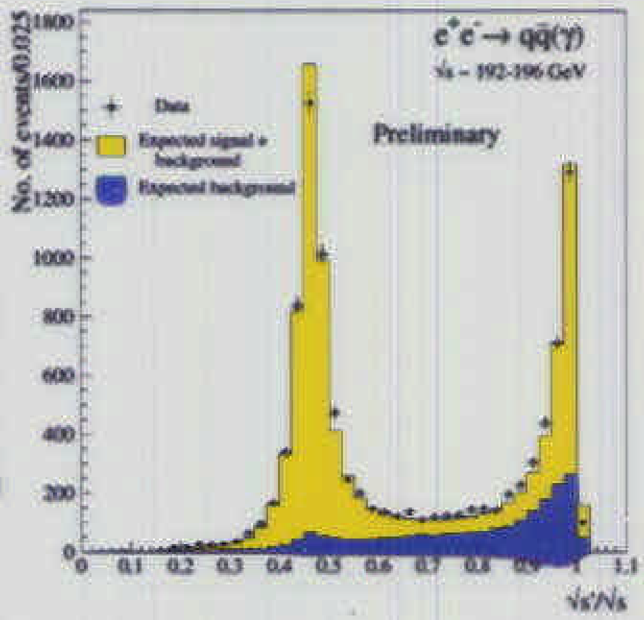
Overall Excellent [EXPT $\Longleftrightarrow$ THEORY] Match

LEPII: 2-fermion

Far above Z, return of Z:







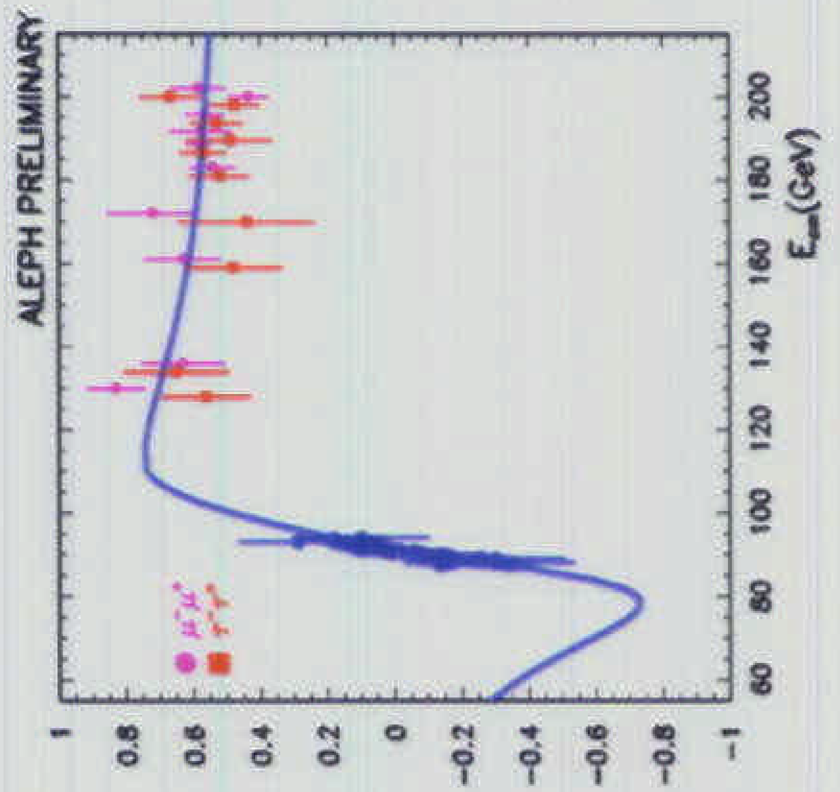
$\sqrt{s'}$ = mass of outgoing lepton pair or Z/γ^* propagator,

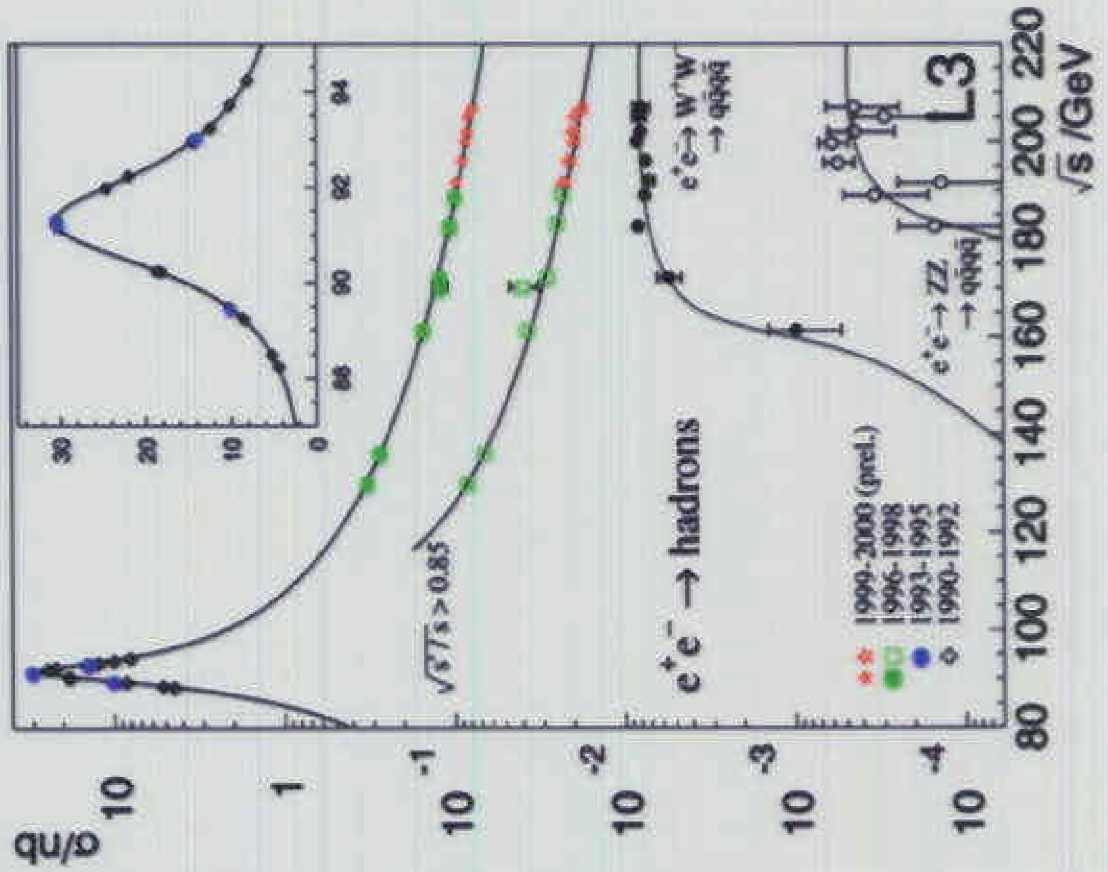
– **Inclusive Production: $s'/s > 0.01$**
– **Exclusive (high energy): $s'/s >$ 0.7-0.8**

Cross sections, asymmetries determined for hadronic, leptonic events & heavy flavours (b,c)

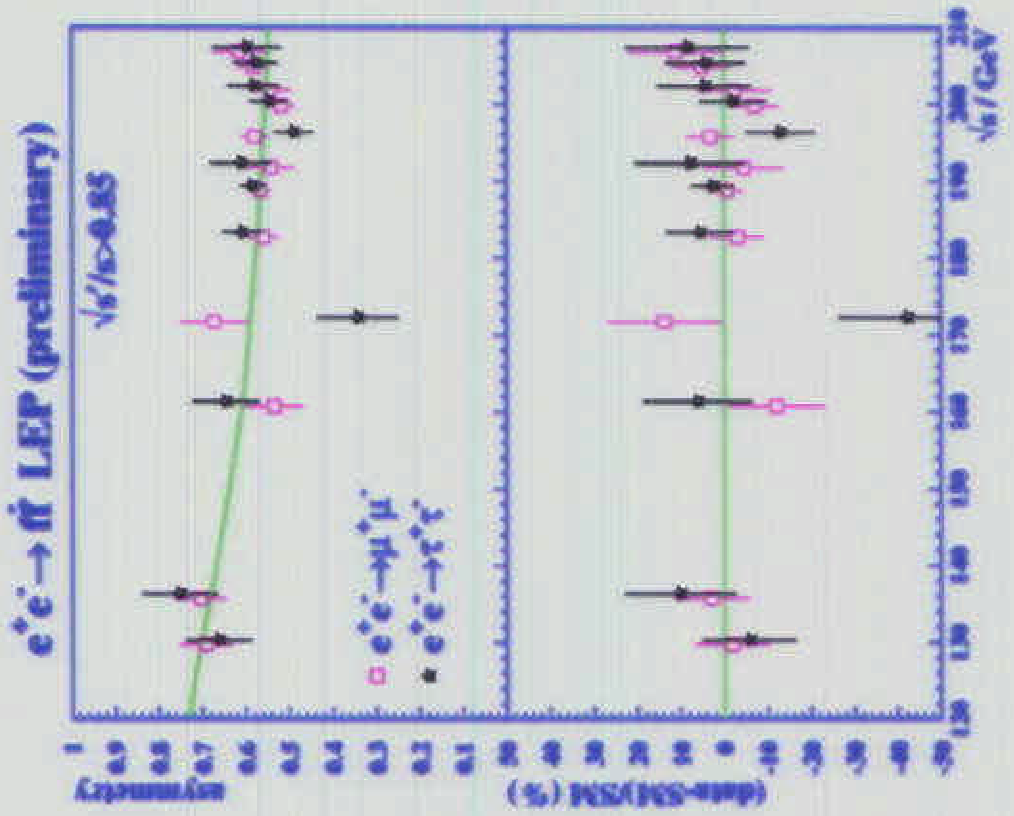
Comparison with SM provides limits on new physics:
(Contact Interactions, Z', $\tilde{\nu}$ exchange, extra dimensions,...)

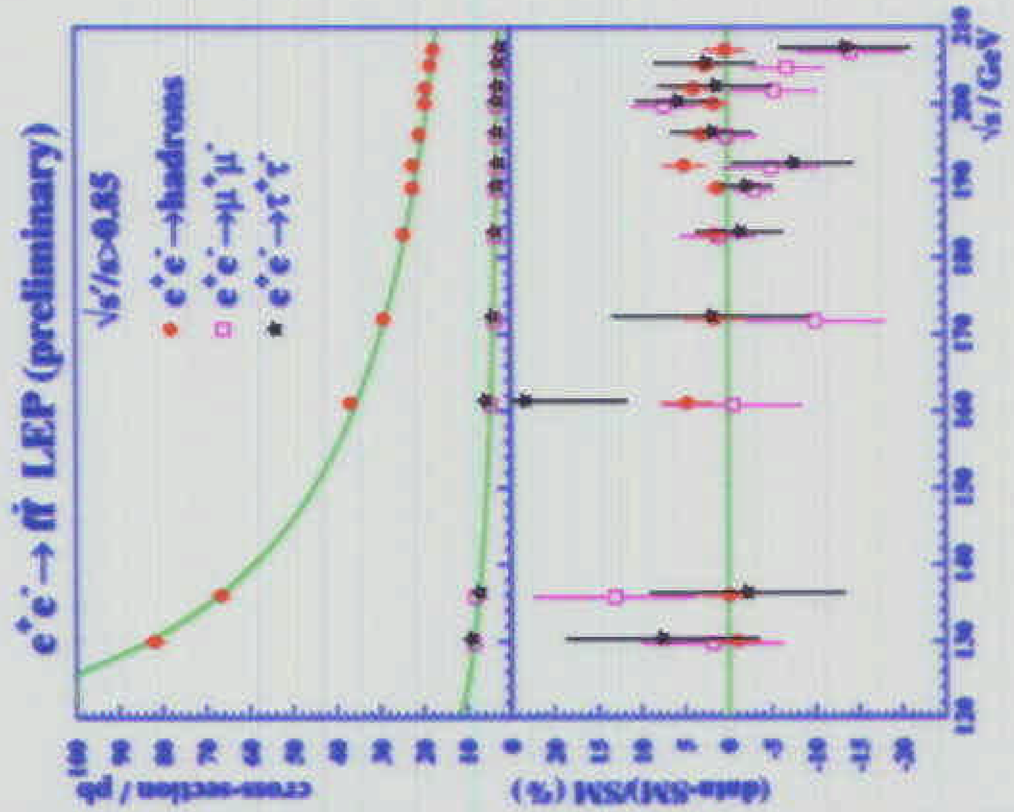
LEPII: 2-fermion



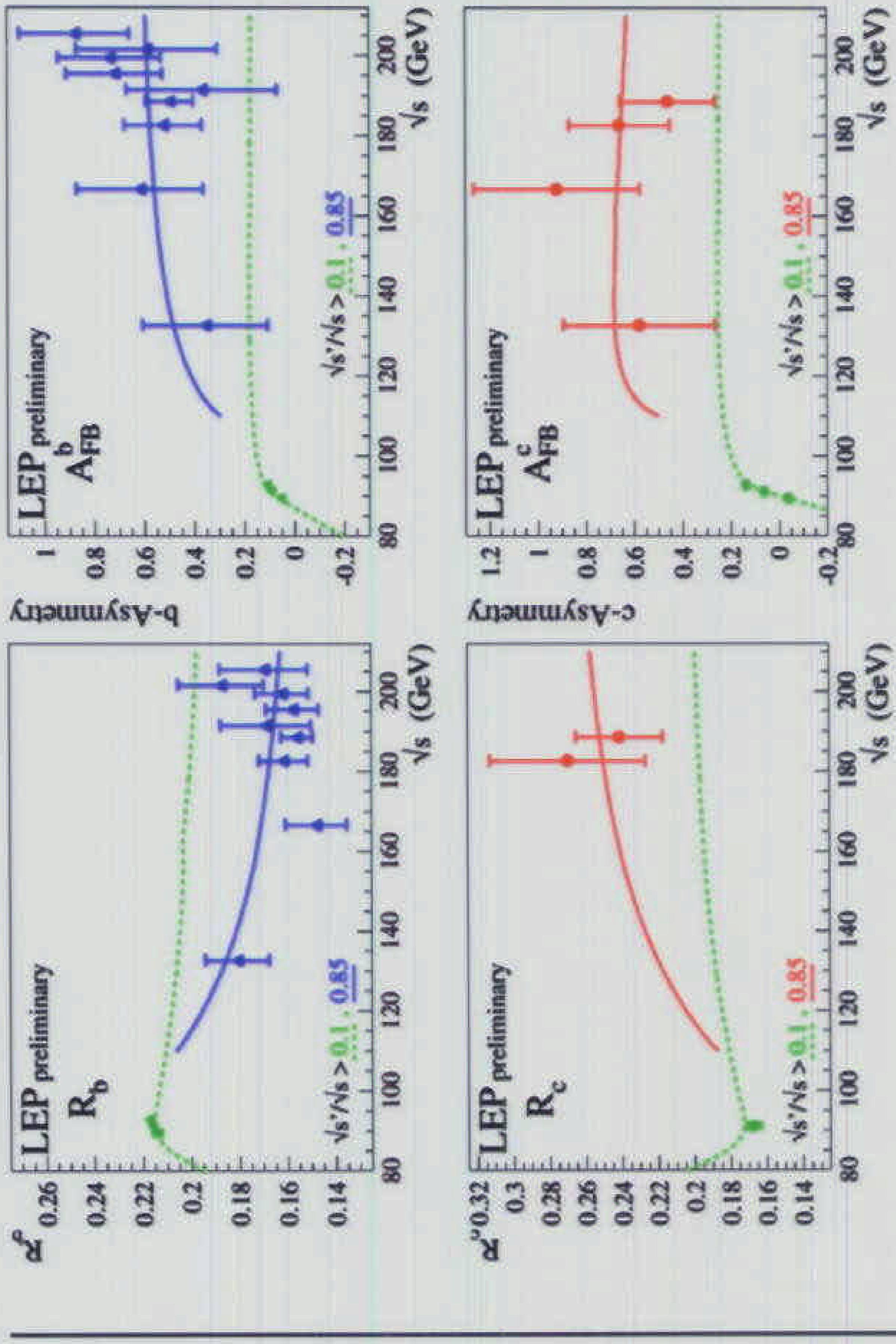


LEPII: 2-fermion

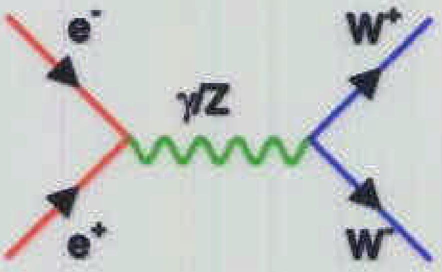


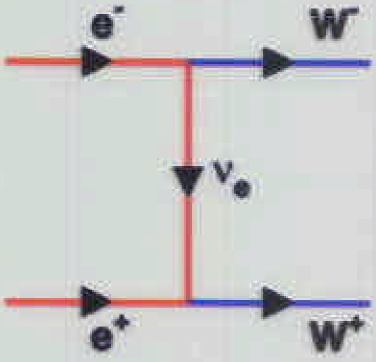


LEPII: 2-fermion



LEPII: W-Physics, W^+W^-





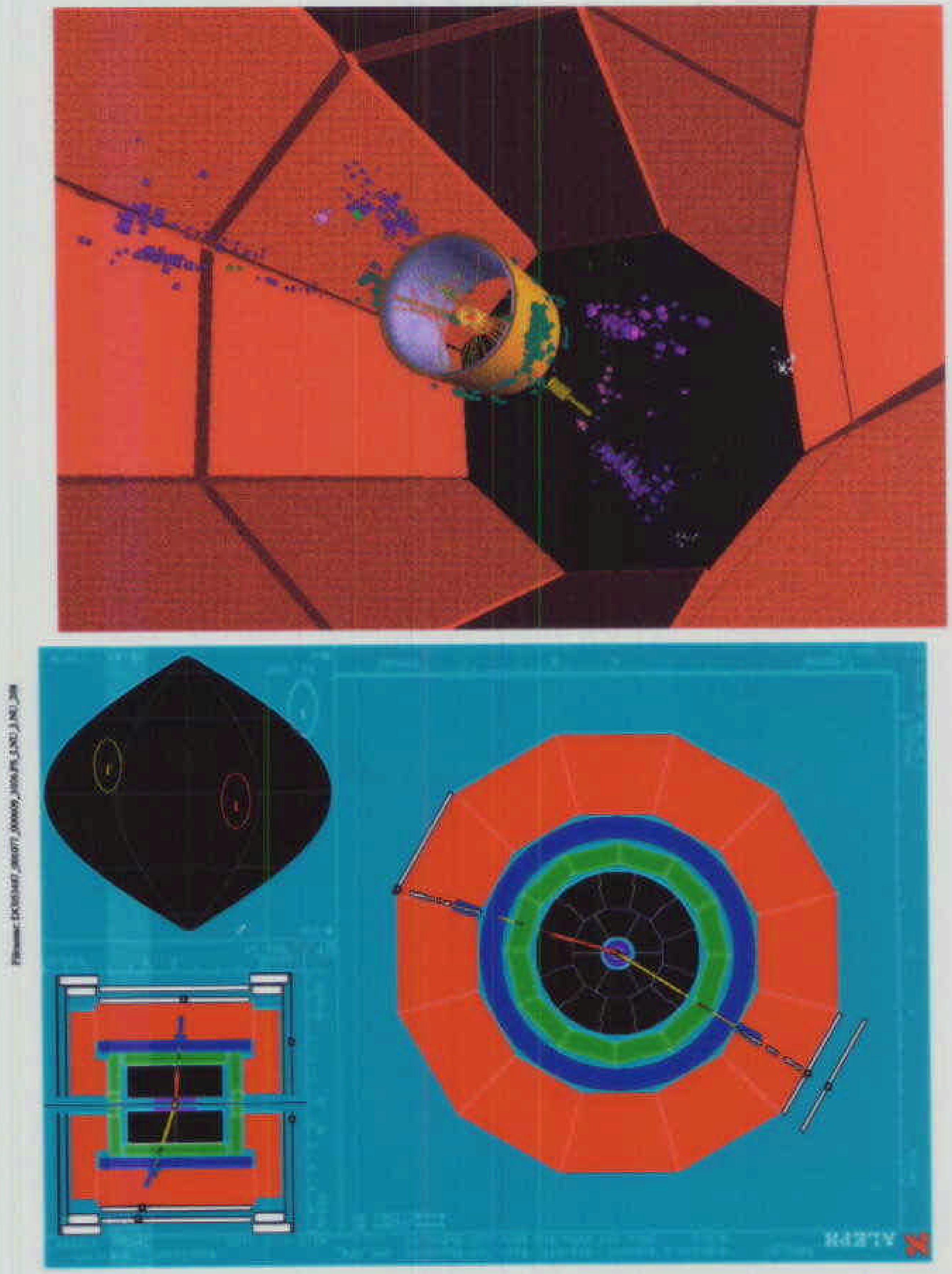
SM branchings $B(W \to q\bar{q}') = 67.6\%$,
$B(W \to \ell\,\bar{\nu}) = 10.8\%$ per lepton flavour:

- **$B(W^+W^- \to q\bar{q}'q\bar{q}') = 45.6\%$ 4 jets**
  High Multiplicity, balanced events.

- **$B(W^+W^- \to q\bar{q}'\ell\,\bar{\nu}) = 14.6\%$ 2 jets, 1 lepton for each lepton flavour**
  Hadronic events with energetic lepton or narrow jet (τ)

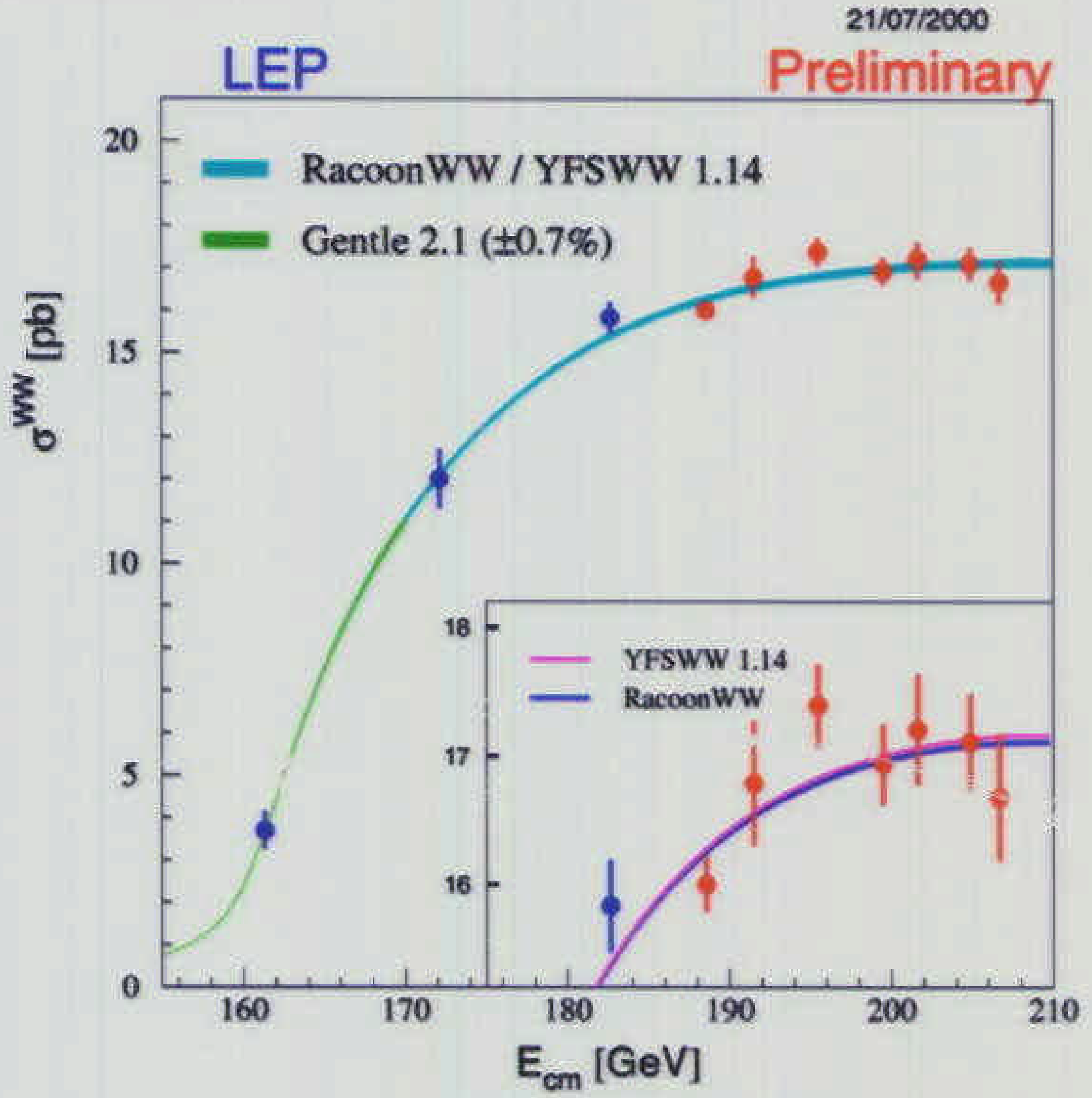
- **$B(W^+W^- \to \ell\,\bar{\nu}\bar{\ell}\,\nu') = 10.6\%$ 2 leptons, summed over lepton flavours**
  Low multiplicity non-hadronic events, acoplanar isolated leptons

LEPII: W-Physics, W^+W^-



LEPII: W-Physics, W^+W^-

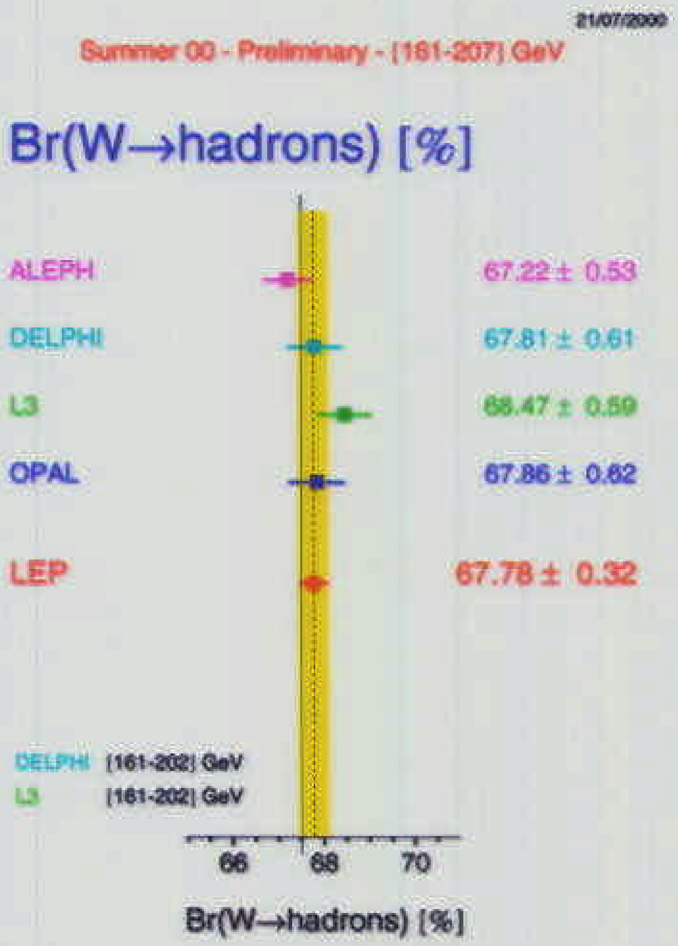
Energy dependence: combined LEP W^+W^- cross sections



Excellent agreement with SM

Theory error improved: 0.7 - 0.4% (170 -200 GeV)

LEPII: W-Physics, W hadronic BR



Determination of $|V_{cs}|$:

$$\frac{BR_{had}}{1-BR_{had}} = \sum |V_{ij}^2| (1+\frac{\alpha_s}{\pi})$$

$$\boxed{|V_{cs}| = \mathbf{0.989 \pm 0.016}}$$

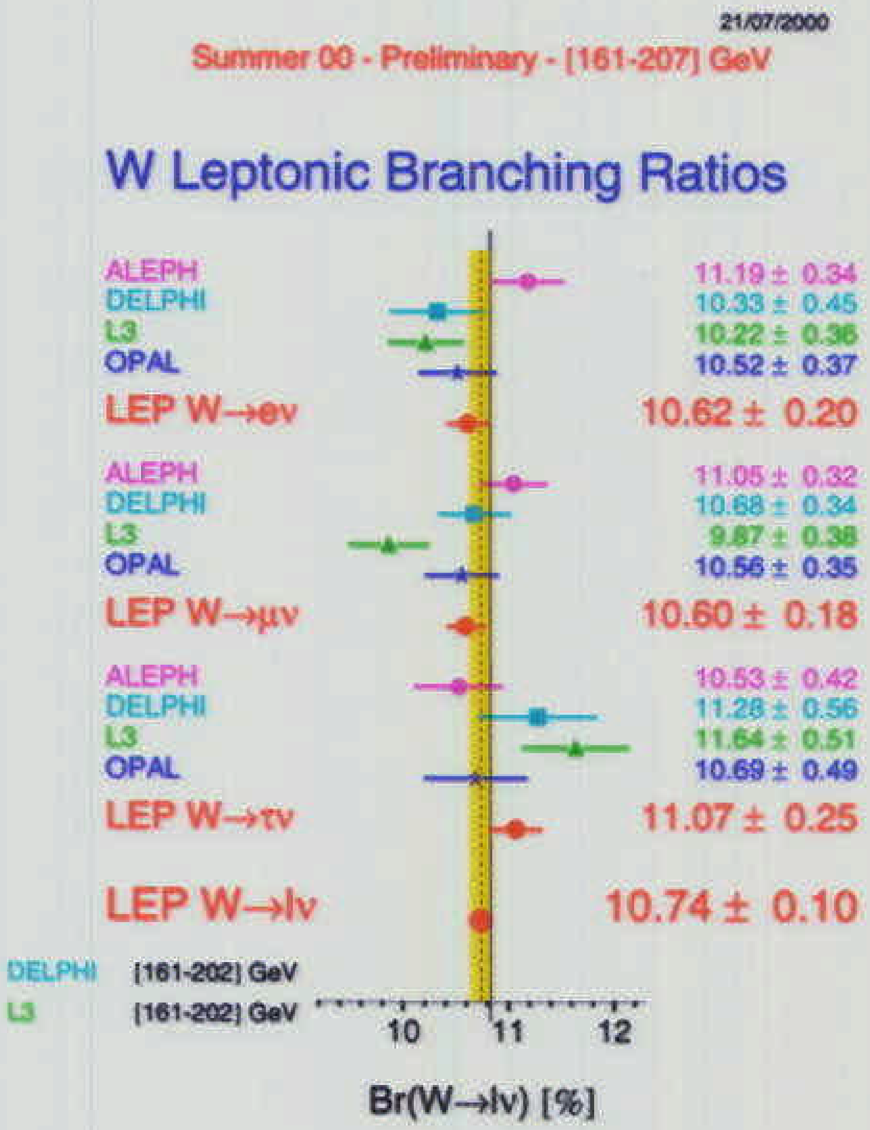
Direct determination of $|V_{cs}|$: identify charm in W-jets ($W \to c\bar{s}$)

OPAL: $\frac{\Gamma(W\to cX)}{\Gamma(W\to had)} = 0.47 \pm 0.04 \pm 0.06$

$$\boxed{\Rightarrow |V_{cs}| = 0.91 \pm 0.07 \pm 0.11}$$

LEP
$|V_{cs}| =$
0.95 ± 0.08

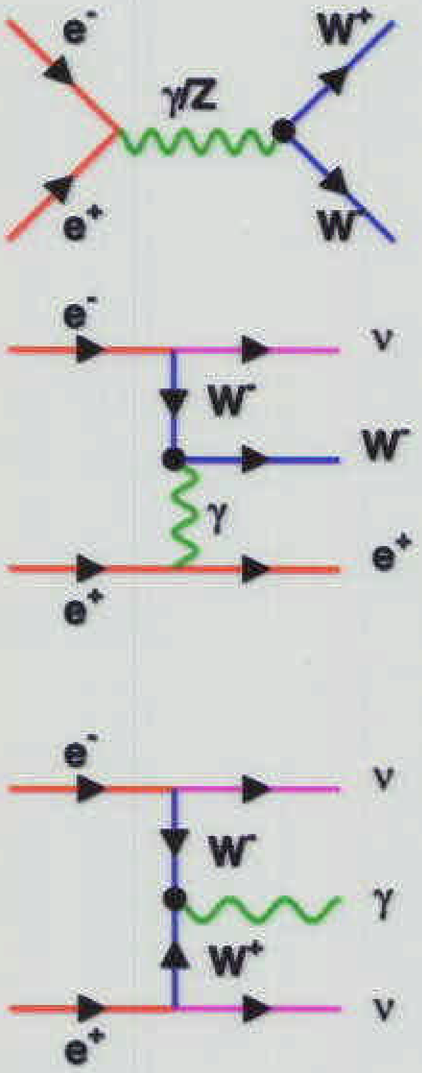
LEPII: W-Physics, W leptonic BR



W → eν B.R.
DØ: 10.50 ± 0.30
CDF: 10.39 ± 0.35

TEVATRON: 10.43 ± 0.25

LEPII: VWW - Triple Gauge Couplings



γ**WW**, **ZWW couplings**

7 Complex couplings for each:

$(g_1^V, g_4^V, g_5^V, \kappa_V, \lambda_V, \tilde{\kappa}_V, \tilde{\lambda}_V)$

3 Conserve C- & P-

3 violate CP

1 violates C-, P-
but conserves CP (g_5^V)

Initial studies: only CP conserving TGC's:

g_1^Z, κ_γ, λ_γ

& fitted ONE TGC at a time (others ≡ SM values)

SM Values: $g_1^Z = 1$, $\kappa_\gamma = 1$, $\lambda_\gamma = 0$

LEPII: VWW - Triple Gauge Couplings

Now higher statistics:

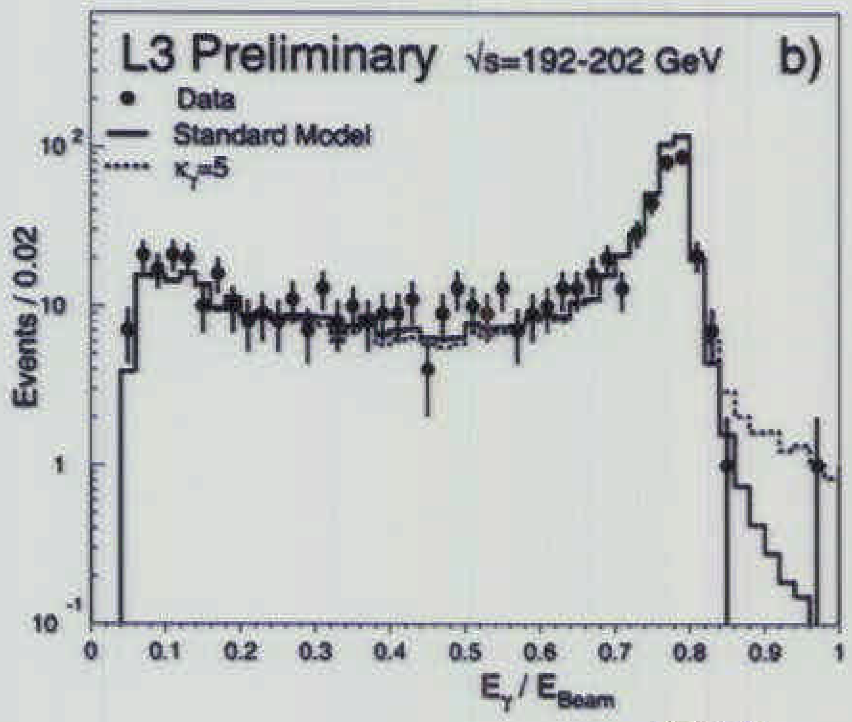
C-, P-, CP- violating couplings under study
2- and 3- parameter fits being carried out

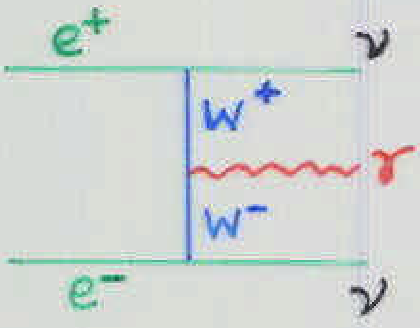
Sensitive Observables:

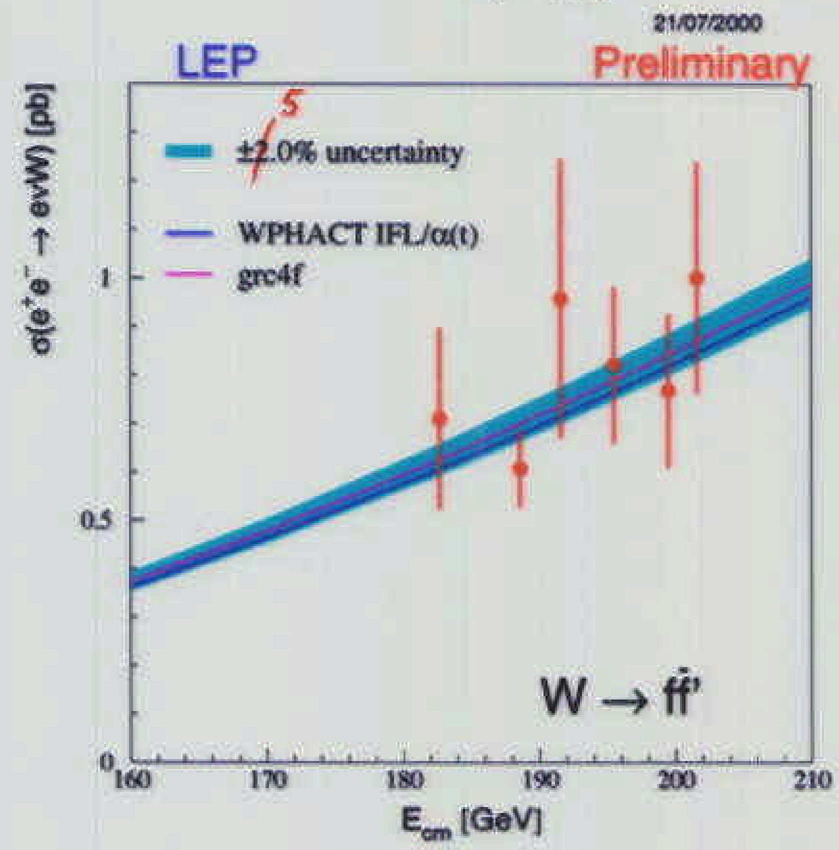
Cross sections, energy, angular distributions

LEPII: VWW - Triple Gauge Couplings

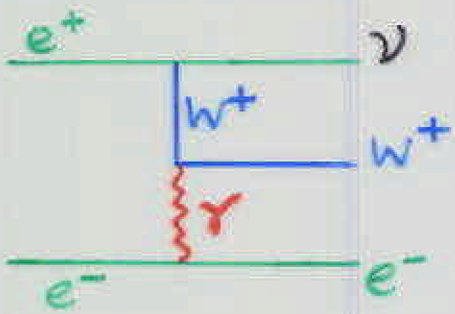
Example of single γ study: L3





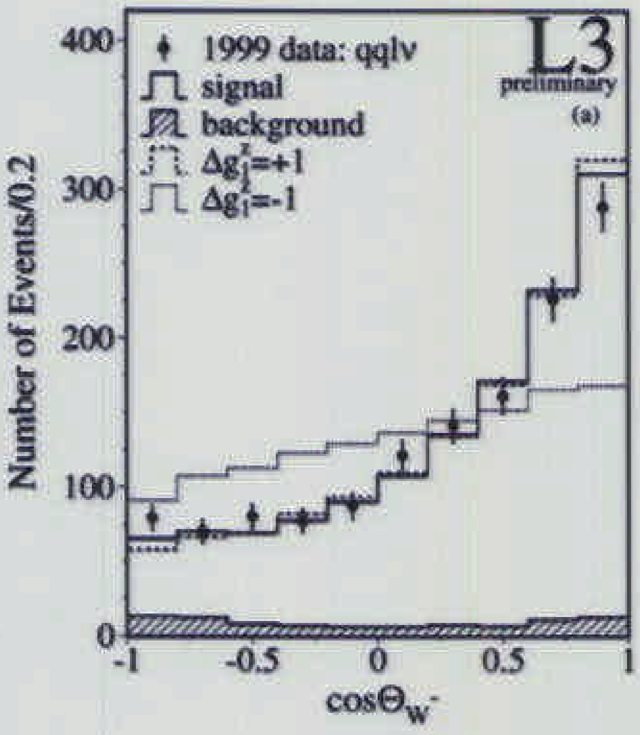


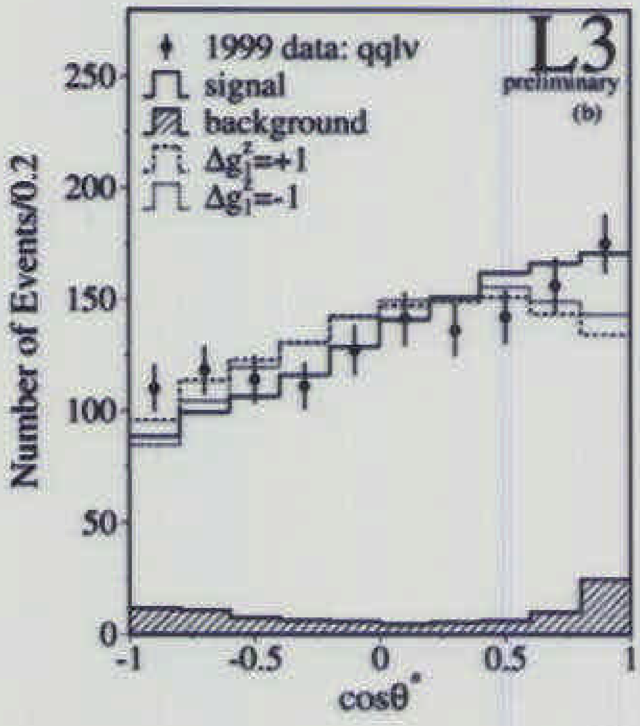
LEP single W Cross section



LEPII: VWW - Triple Gauge Couplings

Example of W-pair study: L3



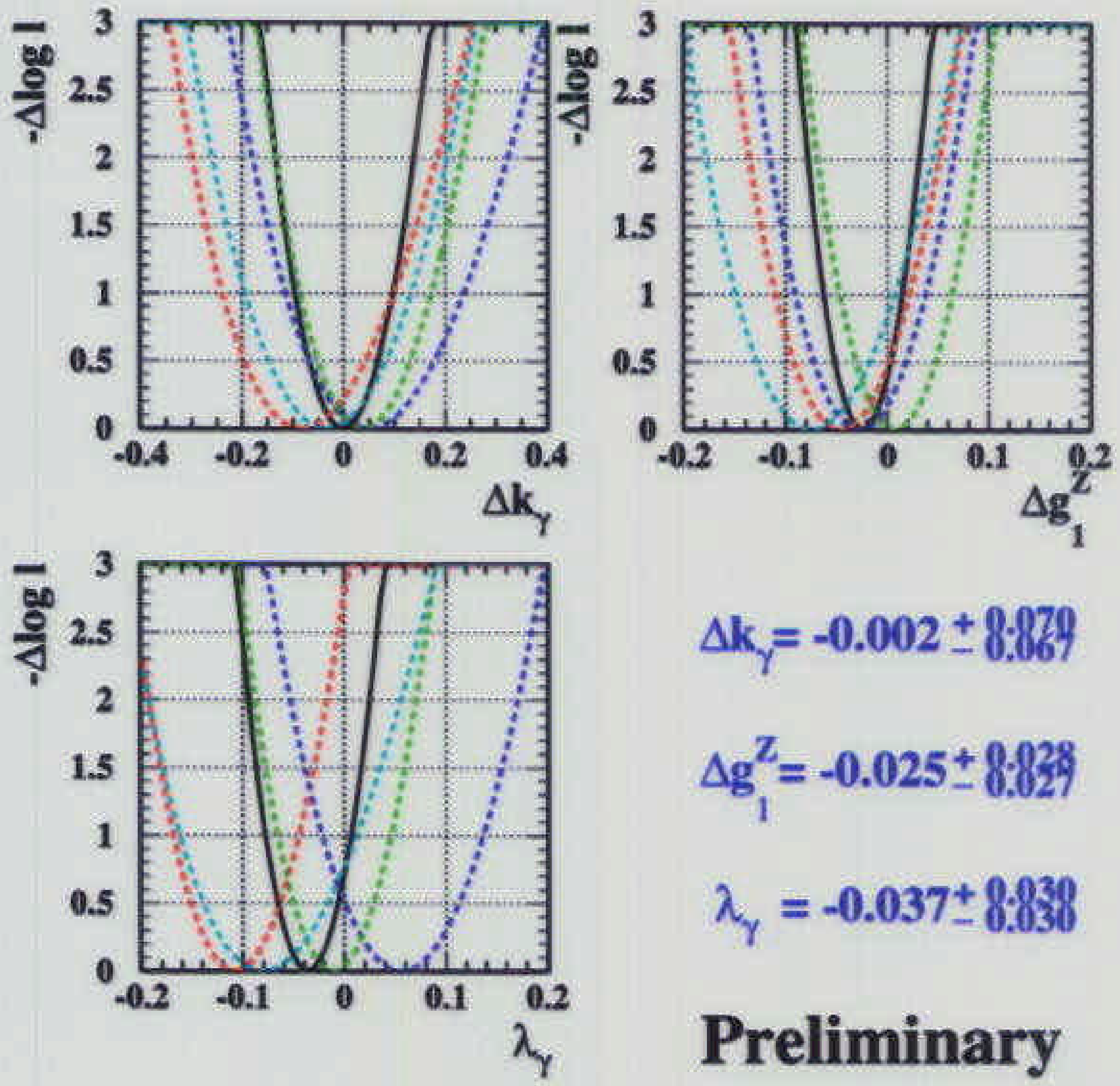


Extensive studies by all LEP collaborations
⇒ LEP combination of data

From Tevatron: no submission to the conference.
D0 Published results combining
$W\gamma$; WW → dilepton; WW/WZ → $e\nu jj$, $\mu\nu jj$; WZ → trilepton data,
$\Delta\kappa_\gamma = -0.08 \pm 0.34$, $\lambda_\gamma = 0.00^{+0.10}_{-0.09}$, and
$-0.37 < \Delta g_1^Z < 0.57$, fixing $\lambda_Z = \Delta\kappa_Z = 0$ & assuming SM values for $WW\gamma$ couplings.

LEPII: VWW - Triple Gauge Couplings

ALEPH + DELPHI + L3 + OPAL



$\Delta k_\gamma = -0.002^{+0.070}_{-0.067}$

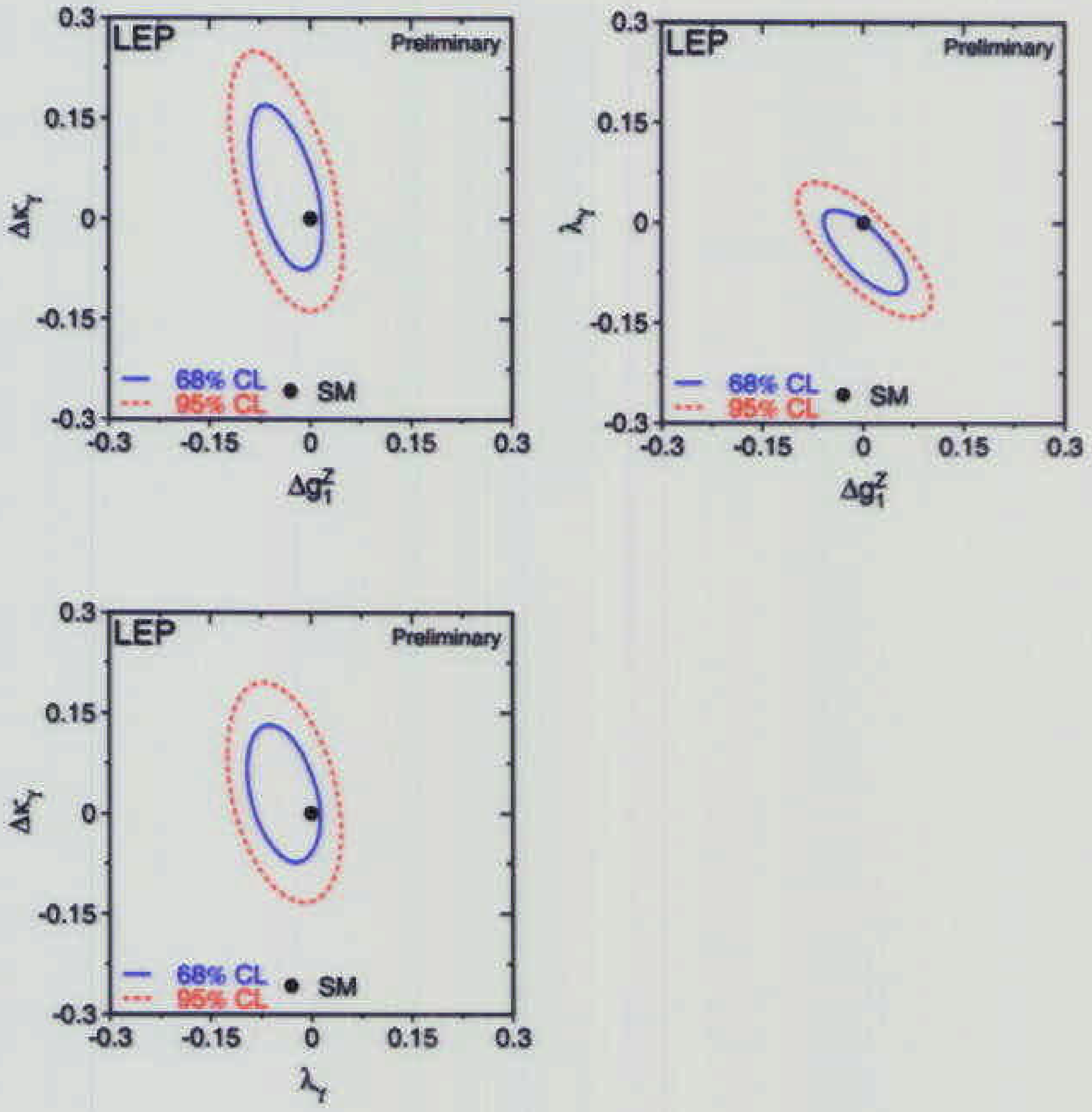
$\Delta g_1^Z = -0.025^{+0.028}_{-0.027}$

$\lambda_\gamma = -0.037^{+0.030}_{-0.030}$

Preliminary

(1- PARAMETER FITS)

LEPII: VWW - Triple Gauge Couplings



(2- PARAMETER FITS)

C,P and CP violating parameters

▹Analysis extended to all TGC parameters

▹One dimension fit with all other couplings at S.M. value

	fit result	95% confidence limits
ALEPH @ 183-202 GeV (lνqq)		
$\tilde{\kappa}_\gamma$	$-0.192^{+0.178}_{-0.159}{}^{+0.057}_{-0.057}$	[-0.507, 0.183]
$\tilde{\lambda}_\gamma$	$0.167^{+0.130}_{-0.147}{}^{+0.051}_{-0.051}$	[-0.147, 0.427]
$\tilde{\kappa}_Z$	$-0.085^{+0.115}_{-0.109}{}^{+0.023}_{-0.023}$	[-0.296, 0.144]
$\tilde{\lambda}_Z$	$0.073^{+0.090}_{-0.095}{}^{+0.022}_{-0.022}$	[-0.119, 0.248]
g_4^γ	$0.063^{+0.340}_{-0.347}{}^{+0.053}_{-0.053}$	[-0.619, 0.721]
g_5^γ	$-0.020^{+0.502}_{-0.502}{}^{+0.093}_{-0.093}$	[-1.018, 0.979]
g_4^Z	$0.067^{+0.224}_{-0.228}{}^{+0.039}_{-0.039}$	[-0.384, 0.503]
L3 @ 189-202 GeV (all WW channels)		
$\Delta\kappa_Z$	$-0.013^{+0.08}_{-0.07}\pm0.09$	[-0.34, 0.12]
λ_Z	$-0.014^{+0.11}_{-0.06}\pm0.09$	[-0.34, 0.16]
ALEPH+L3		
g_5^Z	$0.05\pm0.17\pm0.08$	[-0.29, 0.37]

▹ OPAL : Based on Spin Density Matrix analysis

	constraint	fit result
$\tilde{\kappa}_Z$	$\tilde{\kappa}_Z=-\tan^2\theta_w\tilde{\kappa}_\gamma$	$-0.20^{+0.10}_{-0.07}$
$\tilde{\lambda}_Z$	$\tilde{\lambda}_Z=\tilde{\lambda}_\gamma$	$-0.18^{+0.24}_{-0.16}$
g_4^Z	$g_4^Z=g_4^\gamma$	$-0.02^{+0.32}_{-0.32}$

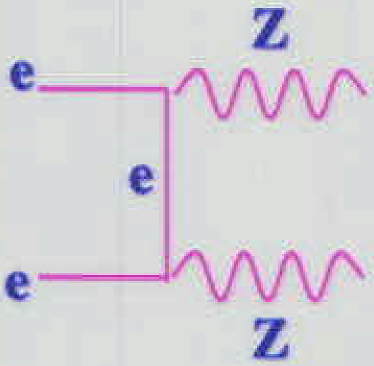
Good agreement with Standard Model

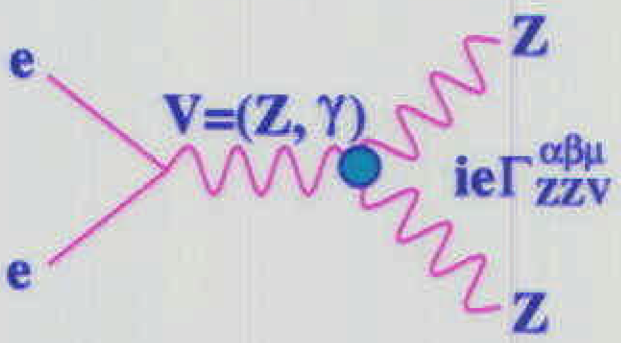
LEPII: ZZ & ZZV Couplings

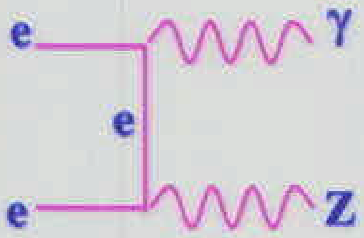
ZZV couplings studied via ZZ, $Z\gamma$ production

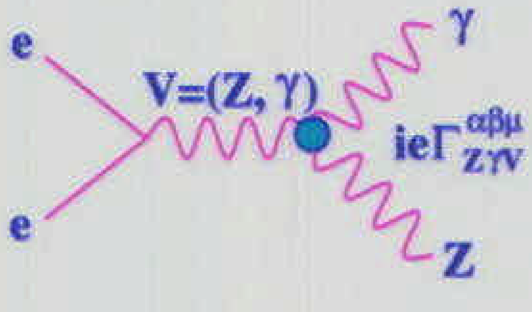
ZZ production above $\sqrt{s} = 183$ GeV at LEP

Standard Model **Anomalous**





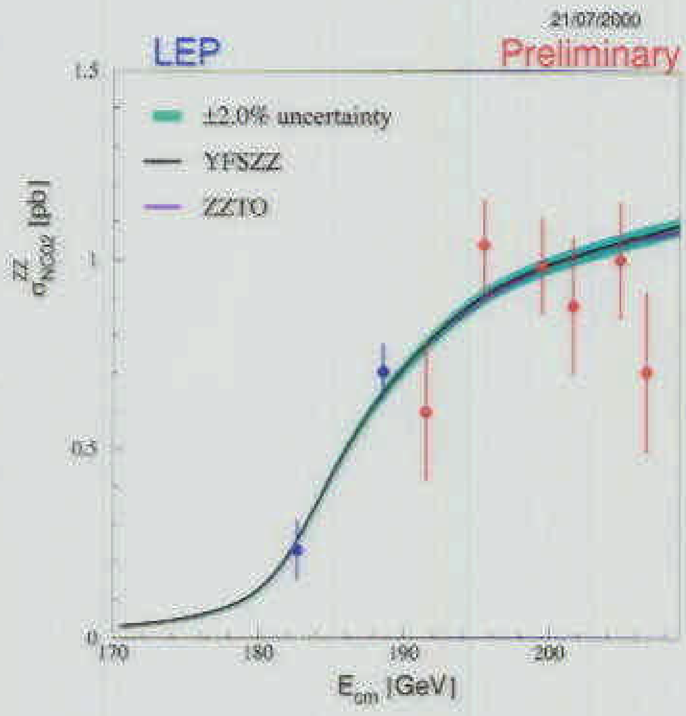


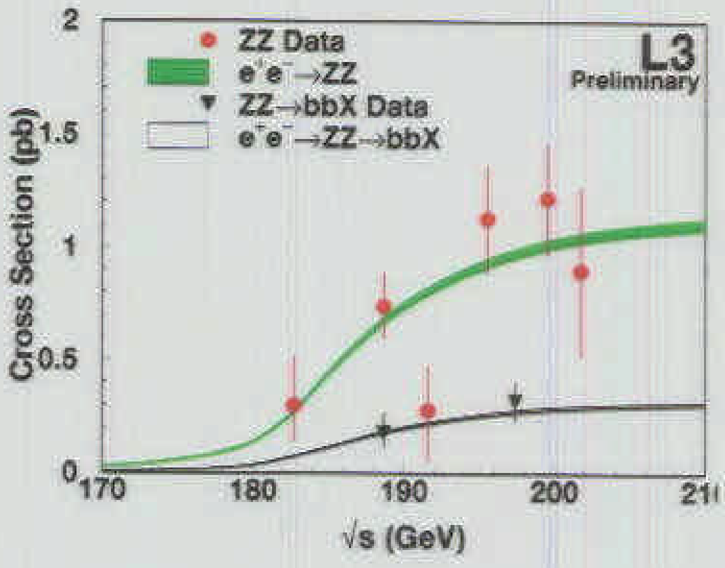


SM: ZZV coupling is zero

Anomalous $ZZ\gamma$, $Z\gamma\gamma$ couplings
– increase production cross sections
– modify γ polar angle θ at large θ

LEPII: ZZ & ZZV Couplings





– **For ZZV (ZZ prodn.) Hagiwara et al.,**
Four couplings: f_4^V : **CP– violating;**
f_5^V : **CP– conserving**

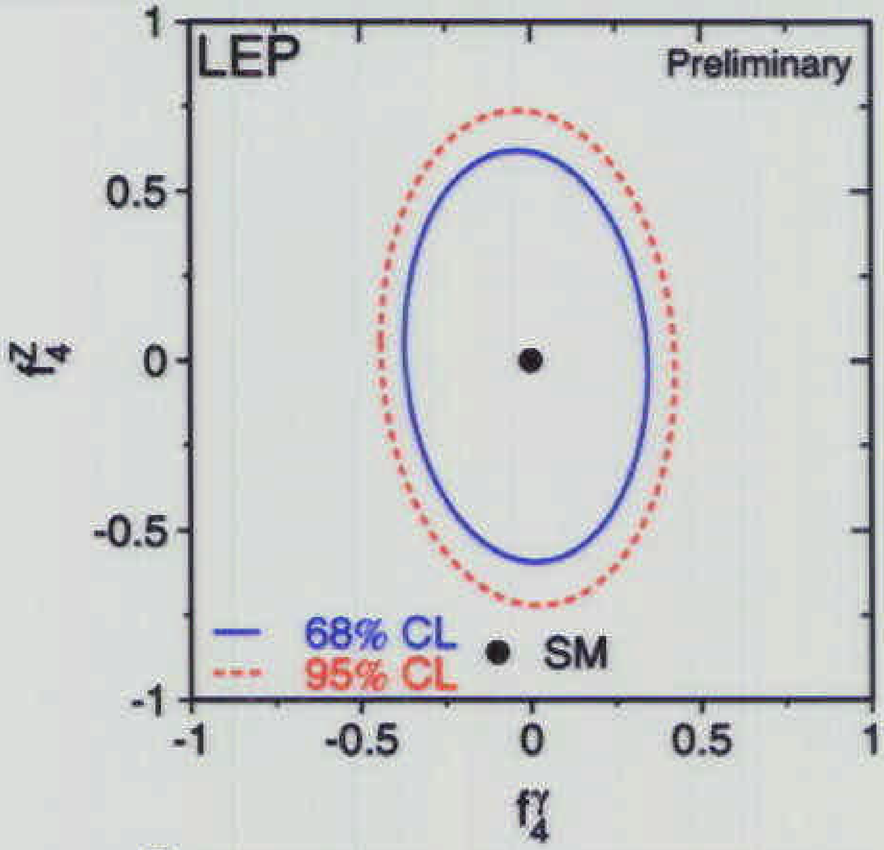
– **For ZγV (Zγ prodn.) P.Mery et al.,** GOUNARIS et al
General formalism incorporating energy scale (Λ) of new physics:

$$\frac{\sqrt{\alpha} h_i^V}{m_Z^2} \equiv \frac{1}{\Lambda_{iV}^2}, i = 1,3$$

$$\frac{\sqrt{\alpha} h_i^V}{m_Z^4} \equiv \frac{1}{\Lambda_{iV}^4}, i = 2,4$$

i = 1,2: CP violating; i = 3,4: CP conserving.
Unitarity: $h_i^V \to 0$ **as** $s \to \infty$

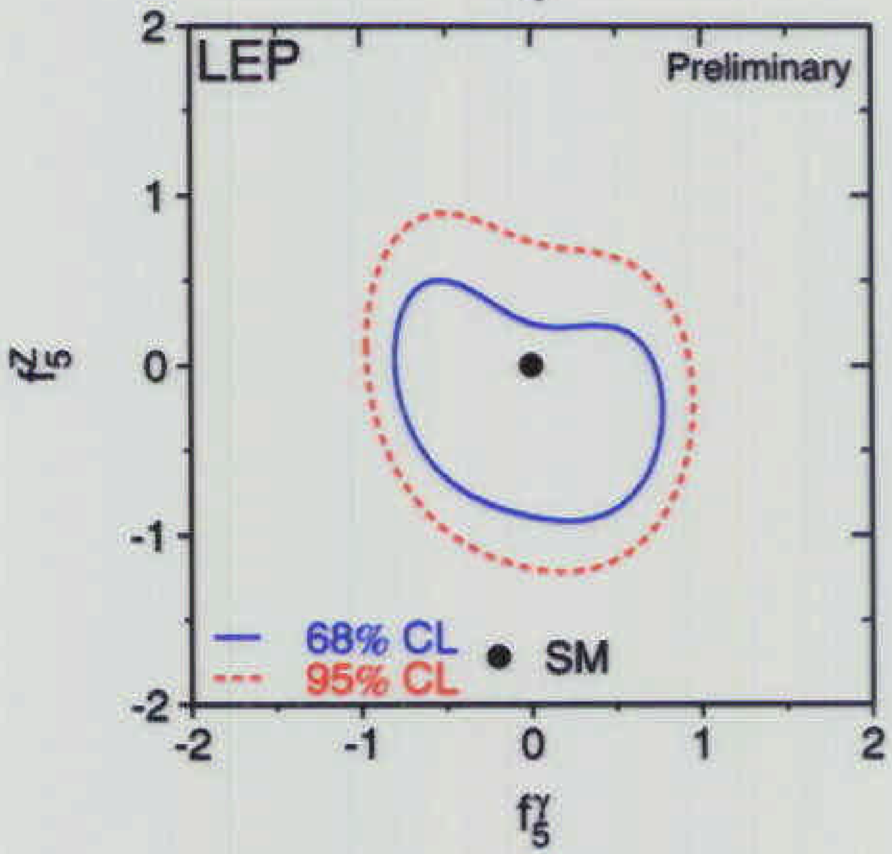
LEPII: ZZ & ZZV Couplings



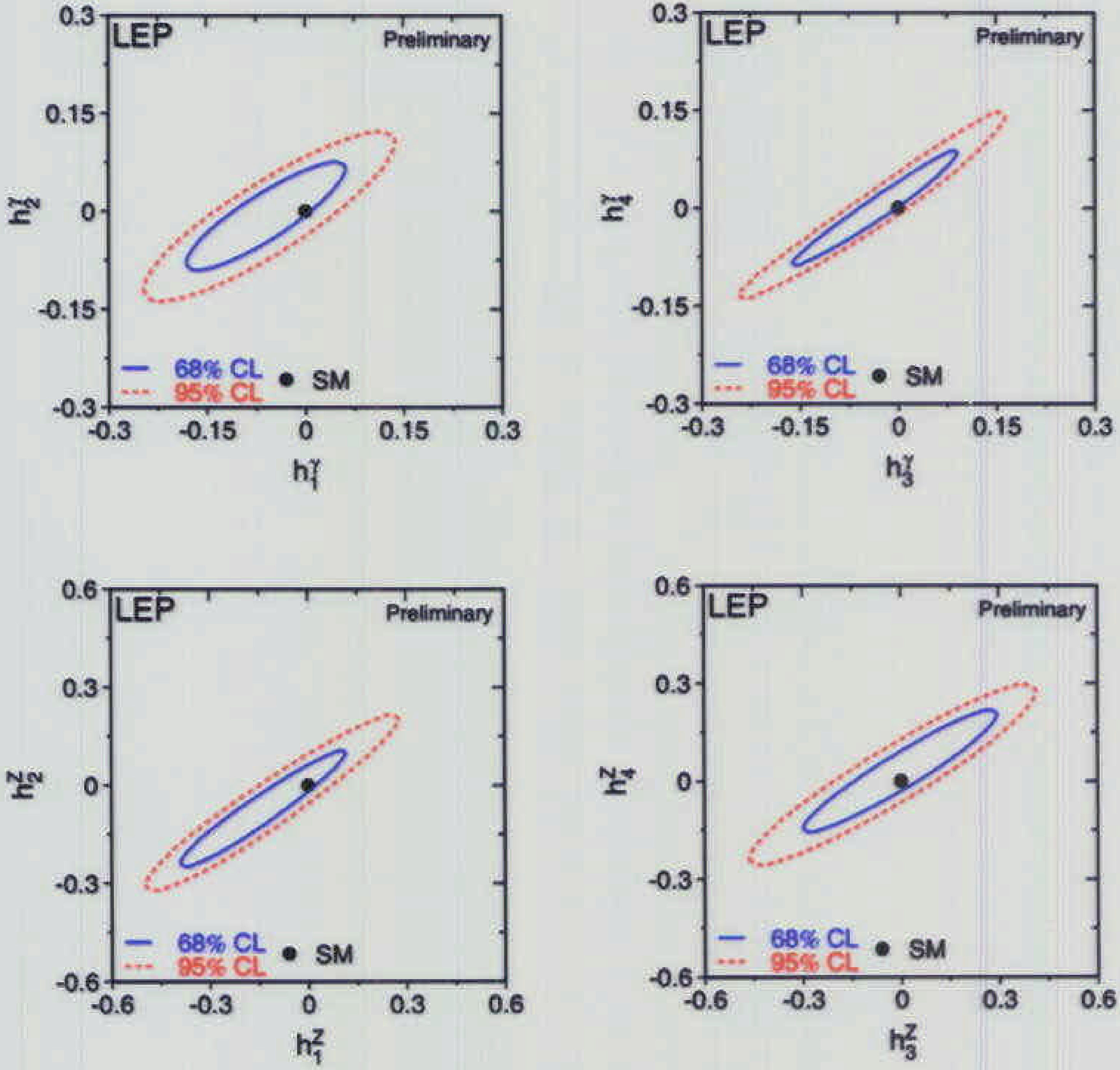
FROM

ZZ

PRODN.



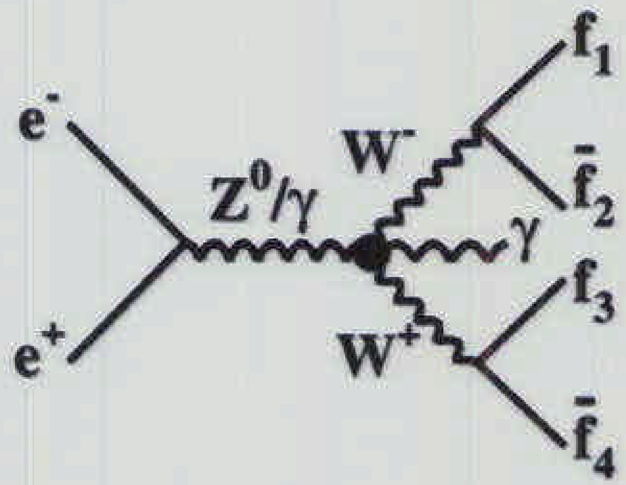
LEPII: ZZ & ZZV Couplings



FROM $Z\gamma$ PRODUCTION

LEPII: W/Z - Quartic Gauge Couplings

SM predicts WWWW, WWZZ, WWZγ, WW$\gamma\gamma$
Couplings
Small at LEP, important at TeV linear Collider



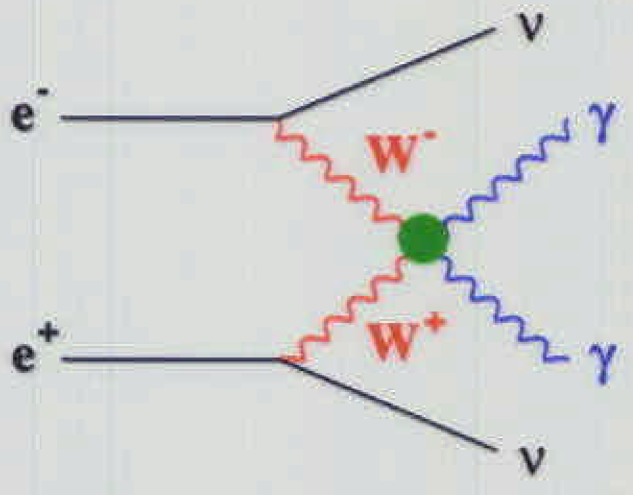
Six dimension operators:

$$L_6^0 = -\frac{e^2}{16\Lambda^2} a_0 F^{\mu\nu} F_{\mu\nu} \vec{W}^{\alpha} \cdot \vec{W}_{\alpha},$$

$$L_6^c = -\frac{e^2}{16\Lambda^2} a_c F^{\mu\alpha} F_{\mu\beta} \vec{W}^{\beta} \cdot \vec{W}_{\alpha},$$

$$L_6^n = -\frac{e^2}{16\Lambda^2} a_n \epsilon_{ijk} W^{(i)}_{\mu\alpha} W^{(j)}_{\nu} W^{(k)\alpha} F^{\mu\nu}$$

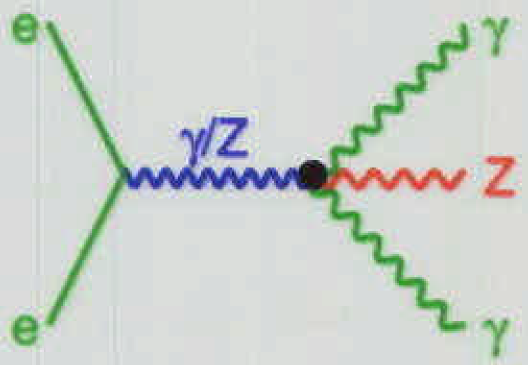
↑
Anomalous Quartic Coupling "Outside" SM



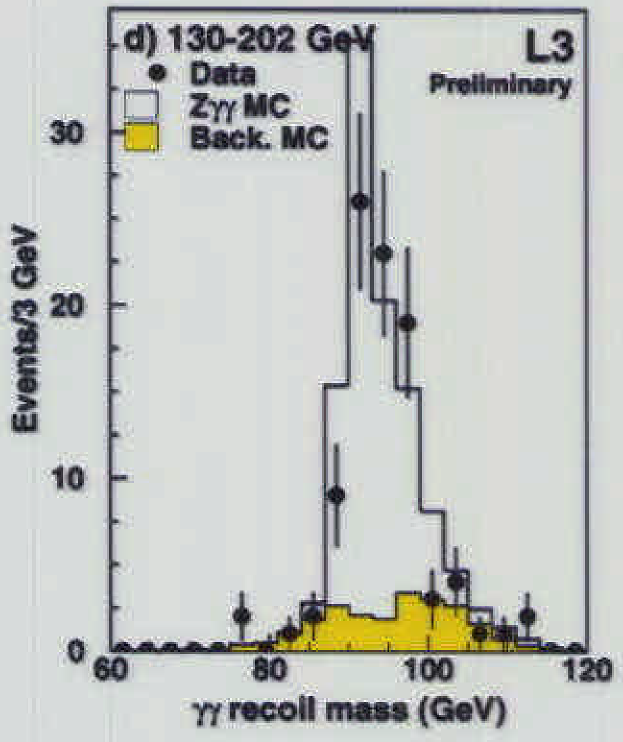
F, W are photon and W fields
L_6^0, L_6^c: conserve C-, P- separately, L_6^n violates CP.
Λ : scale for new physics,
a_0, a_c, a_n: Couplings

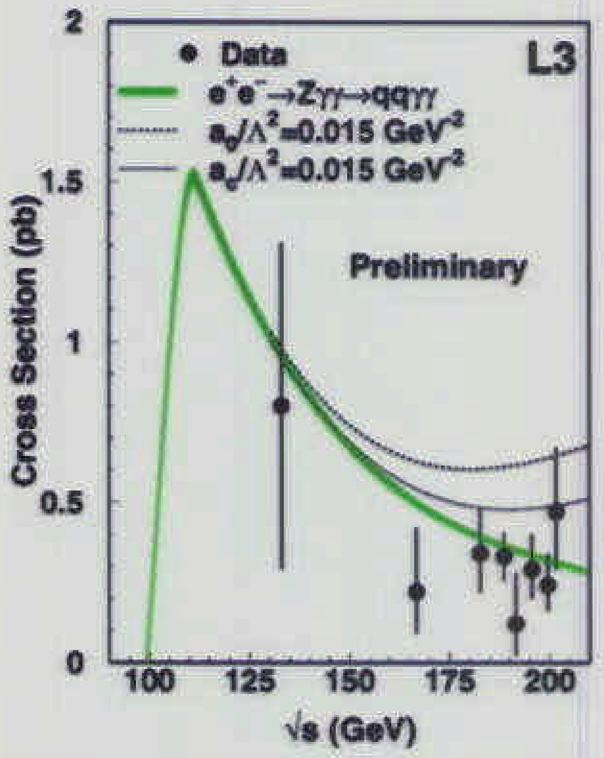
LEPII: $Z\gamma\gamma\gamma$ - Quartic Coupling

L3: All LEP II data, 130-202 GeV, $Z\gamma\gamma$ state
$Z \to qq$ decay mode



Same dimension-6 operator formulae:
couplings a_0/Λ^2, a_c/Λ^2



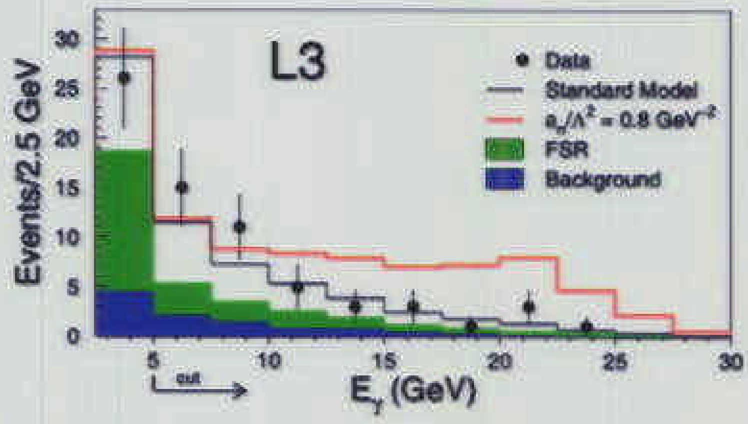


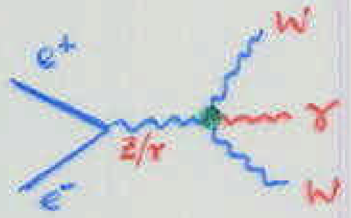
Results

$$-0.007 < a_0/\Lambda^2 < 0.005;$$
$$-0.006 < a_c/\Lambda^2 < 0.011 \text{ GeV}^{-2}$$

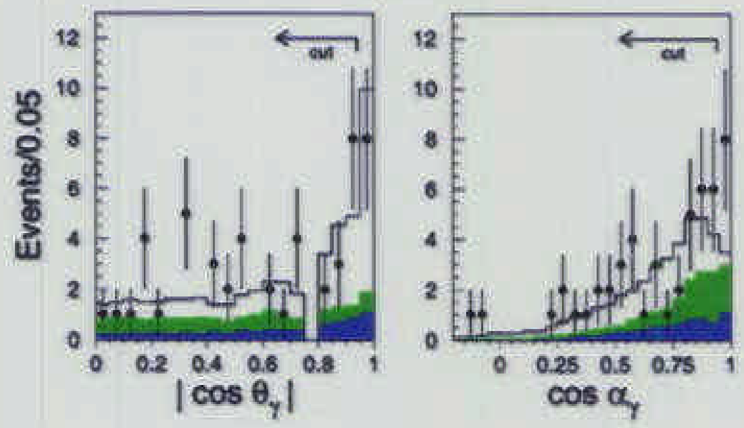
LEPII: W/Z - Quartic Gauge Couplings

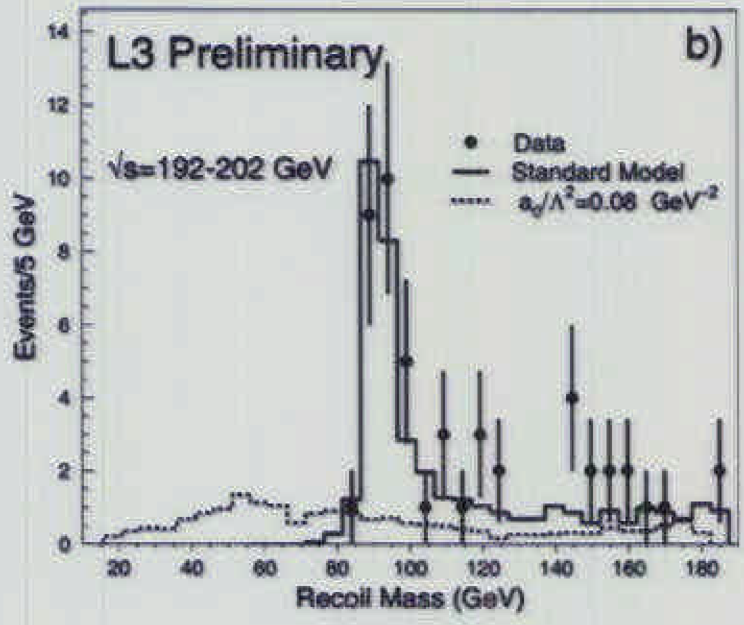
L3 use WWγ (at 189 GeV) & $\gamma\gamma\nu\nu$ (at 183-202 GeV)





WWγ, 42 evts,
$\sigma = 290 \pm 80 \pm 16$ fb





$\gamma\gamma\nu\nu$, 84 evts,
E_γ >5, 1 GeV
After final cuts: 0 data evt.

Combined analysis:

$-0.035 < a_0/\Lambda^2 < 0.034$ GeV^{-2},
$-0.07 < a_c/\Lambda^2 < 0.11$ GeV^{-2},
$-0.41 < a_n/\Lambda^2 < 0.37$ GeV^{-2}

LEPII: W/Z - Quartic Gauge Couplings

Opal (1999)

$\hat{\sigma}(WW\gamma) = 136 \pm 36 \pm 8$ **fb**

$$0.070 < a_0/\Lambda^2 < 0.070 \ \mathbf{GeV^{-2}}$$
$$0.13 < a_c/\Lambda^2 < 0.19 \ \mathbf{GeV^{-2}}$$
$$0.61 < a_n/\Lambda^2 < 0.57 \ \mathbf{GeV^{-2}}$$

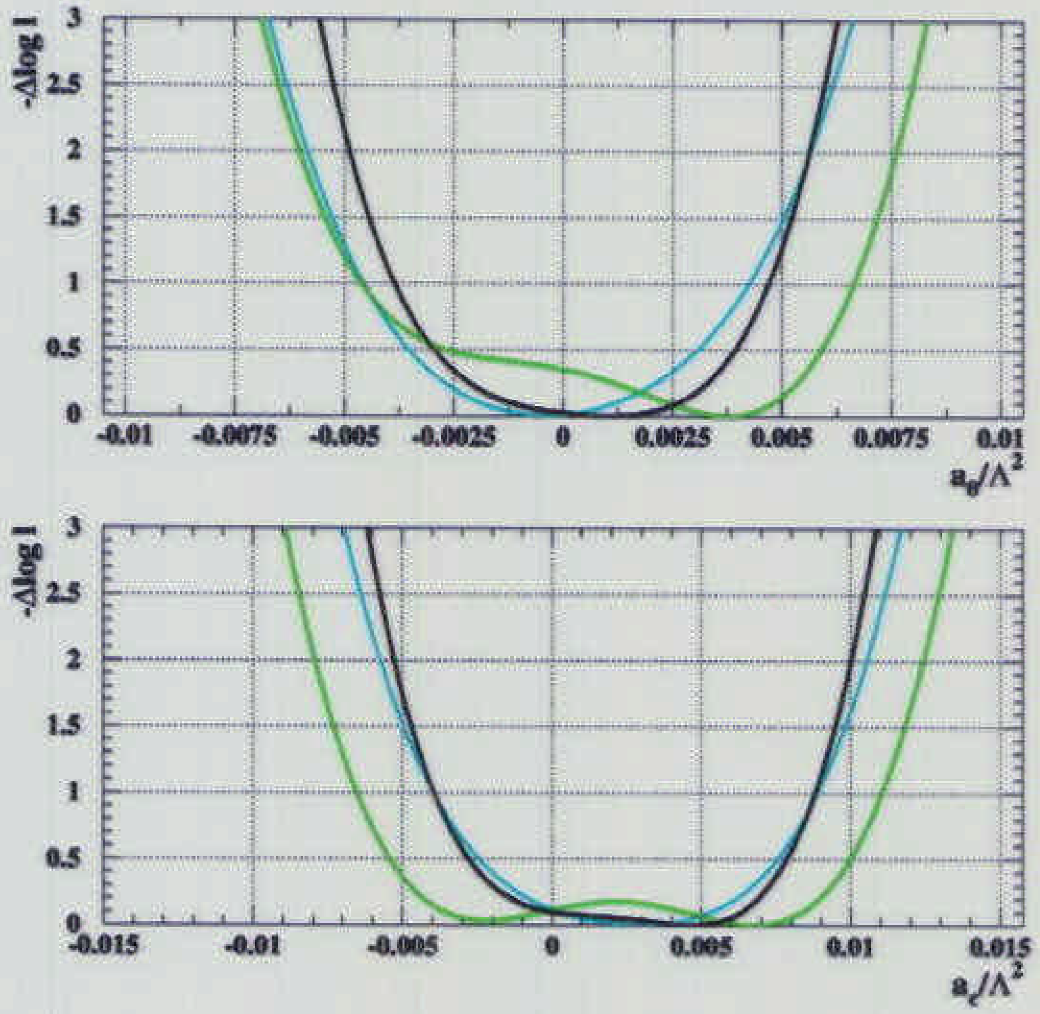
Aleph

189-202 GeV $\gamma\gamma(\nu\nu)$ cross section data

$$0.045 < a_0/\Lambda^2 < 0.042 \ \mathbf{GeV^{-2}}$$
$$0.115 < a_c/\Lambda^2 < 0.115 \ \mathbf{GeV^{-2}}$$

LEPII: $Z\gamma\gamma\gamma$ - Quartic Coupling

Preliminary **L3+OPAL**



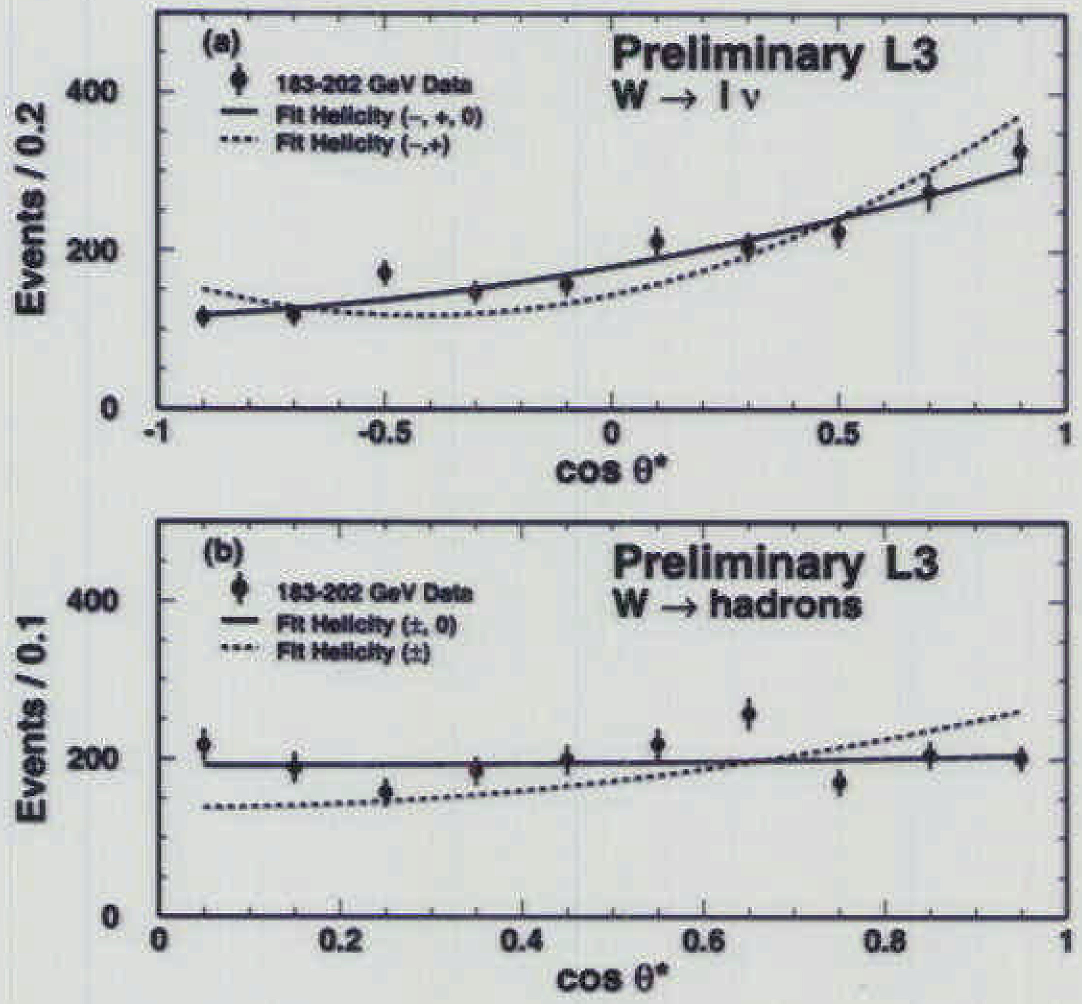
LEP Combined values ($\nu\nu\gamma\gamma + \mathbf{WW}\gamma + \mathbf{Z}\gamma\gamma$):

$$-0.0049 < a_0 < 0.0056$$
$$-0.0054 < a_c < 0.0098$$

LEPII: W Polarization

SM conserves CP in $e^+e^- \rightarrow W^+W^-$:
W^+ helicity fractions $(+1, -1, 0) \equiv$
W^- helicity fractions $(-1, +1, 0)$

L3 updates it's study of W decays.
Full 183-202 GeV data sample



LEPII: W Polarization

W⁻ helicity	−1	+1	0
Data (W^-)	0.565±.060	0.181±.032	0.254±.049
W^+ helicity	+1	−1	0
Data (W^+)	0.559±.068	0.177±.036	0.264±.049
Monte Carlo	0.576	0.176	0.248

Agreement with SM:

1. helicity 0 needed
2. ± helicity fractions of W^- & W^+ flipped as expected

OPAL

Spin-density Method on $W \to l\nu$ and $W \to q\bar{q}'$

$$\frac{\sigma_L}{\sigma_{Tot}} = 21.0 \pm 3.3 \pm 1.3 \ \%$$

SM: 25.7 %

LEPII: FCNC via single top

FCNC in SM: highly suppressed. Higher predictions in multiple higgs, SUSY, quark singlet, composite models (upto BR $\simeq 10^{-2}$).

at LEP: Search for $e^+e^- \to t\bar{c}(\bar{u})$

CDF limits on FCNC t decays:

$$BR(t \to \gamma c/\gamma u) < 3.2\%$$
$$BR(t \to Zc/Zu) < 33\%$$

both at 95% C.L.

FCNC transition vertices $\gamma Z \to t\bar{c}(\bar{u})$:

$$\Gamma_\mu^\gamma = \kappa_\gamma \frac{ee_q}{\Lambda}\sigma_{\mu\nu}q^\nu; \quad \Gamma_\mu^Z = \kappa_Z \frac{e}{\sin 2\theta_W}\gamma_\mu$$

Λ: new physics cutoff scale $\equiv M_{top}$, κ_γ, κ_Z define strength of anomalous coupling.

CDF: $\kappa_\gamma^2 < 0.176, \kappa_Z^2 < 0.533$

LEPII: FCNC via single top

Delphi, L3, Opal: 189-202 GeV data. Final states:

$$e^+e^- \to t\bar{c} \to Wb\bar{c} \to qqbc \text{ or } \ell\nu bc$$

Use b-tagging, E_c, E_b almost fixed (and small).

Both channels main bgds: W^+W^- and QCD evts.

Delphi $\sigma(e^+e^- \to t\bar{q}) < 320$ fb, 95% CL

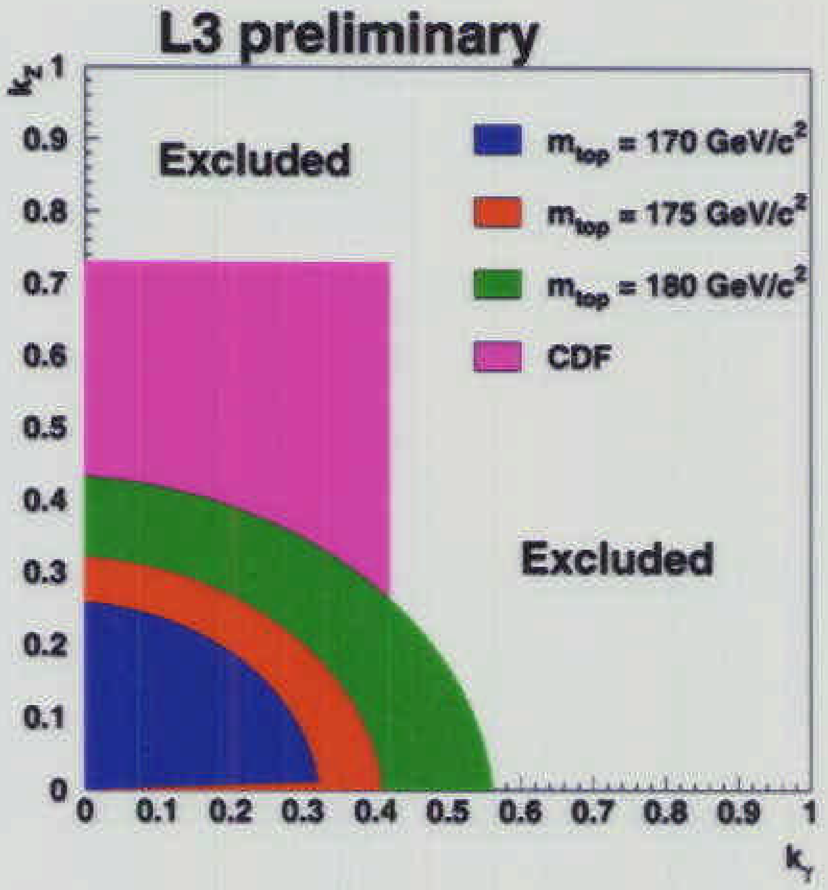
Opal $\sigma(e^+e^- \to t\bar{q}) < 390$ fb, 95% CL

L3 95% C.L. upper limits on the cross section (fb)

	Leptonic	Hadronic	Combined
σ measured	162	344	136
σ expected	199	324	160

L3: $\sigma(e^+e^- \to t\bar{c}) < 136$ fb at 95% C.L.

LEPII: FCNC via single top



LEPI: CPT test

Opal: 1st Test of CPT with τ Leptons

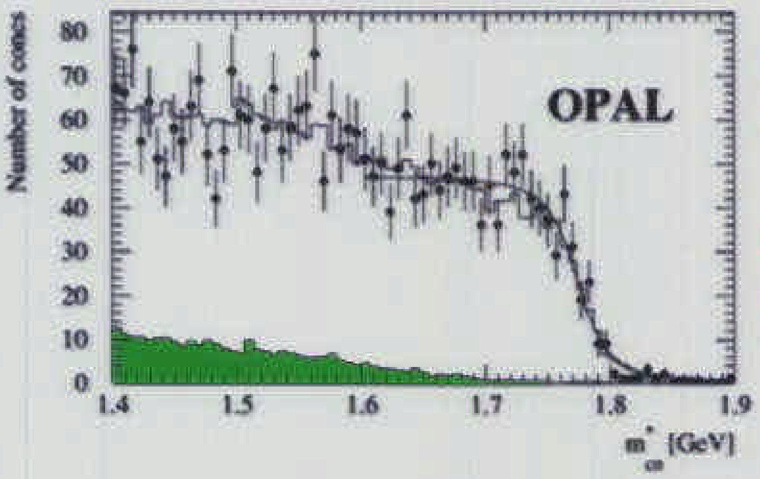
Data: 159K τ-pair evts 1990-95 around Z.

Pseudomass method

$$m_\nu^2 = m_\tau^2 - 2E_\tau E_h + 2\,|\vec{p_\tau}\,||\,\vec{p_h}\,|\cos\psi + m_h^2$$

$h \equiv$ hadronic system, ψ = angle between τ & hadronic system.
Set m_ν =0, $E_\tau = E_{beam}$, ψ unknown; assume = 0

Obtain τ pseudomass using hadronic system within cone of 35° of leading particles in event.



Pseudomass m^*_{cn} for $\tau \to 3\pi^\pm \nu_\tau$

Cut-off gives true mass ψ =0
Tail: bgd, resolution, ISR.

$$\frac{m(\tau^+) - m(\tau^-)}{m(\tau)} = (0.0 \pm 1.8) \times 10^{-3}$$

or $\boxed{\frac{\Delta m(\tau)}{m(\tau)} < 3.0 \times 10^{-3} \text{ at 90\% CL}}$

LEPII: W Mass and width

Precision determination of M_W, Γ_W:
A major goal of LEP II

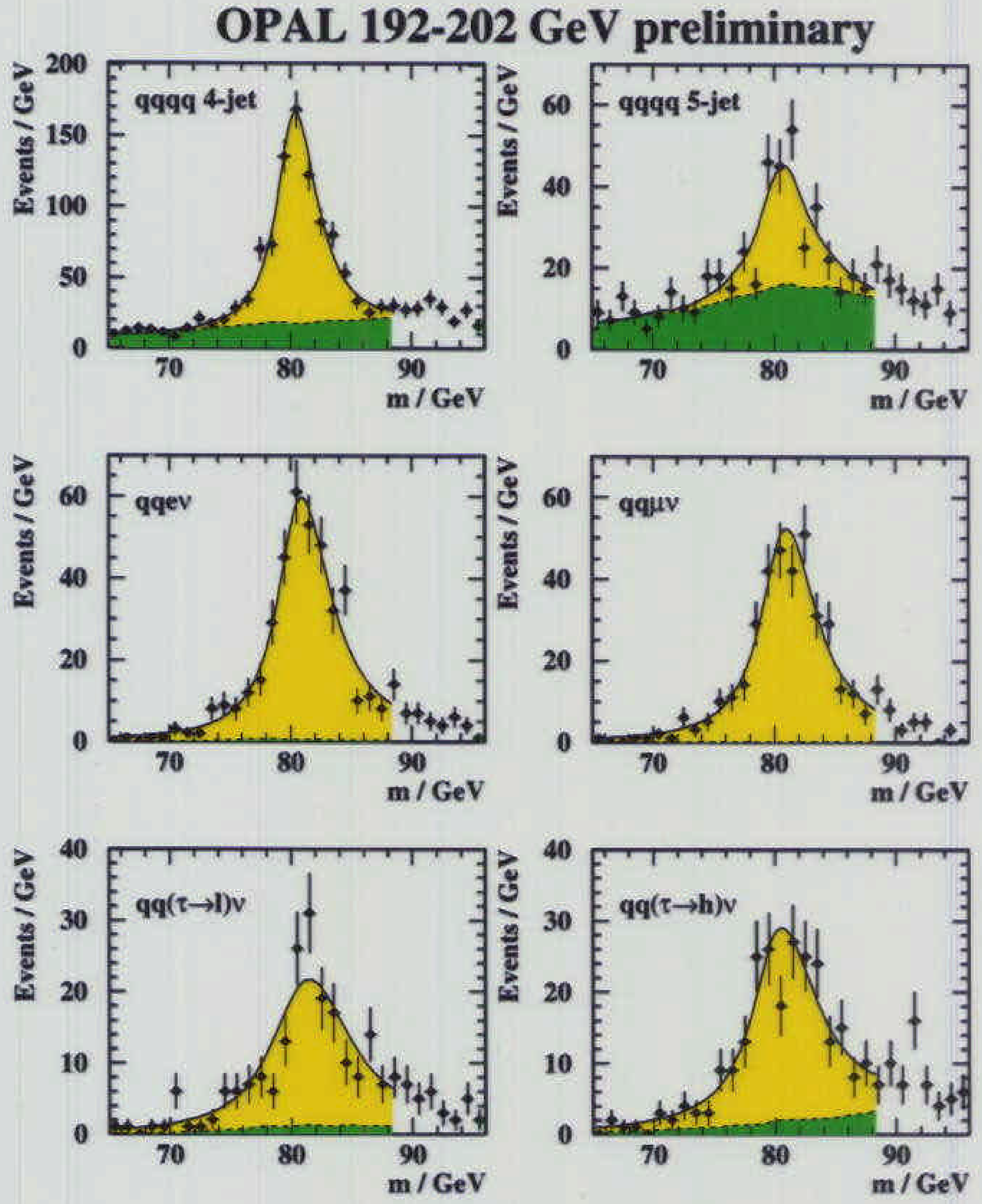
- **Check of internal consistency of the SM**
- **Improvement of M_{Higgs} prediction**

M_W determination

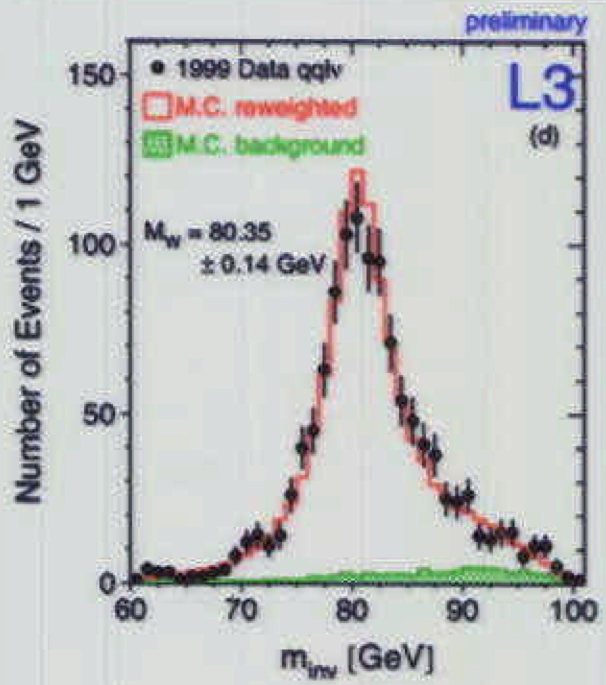
Known CM energy:
reconstruct the W's using kinematic fits,
fit the invariant mass distribution

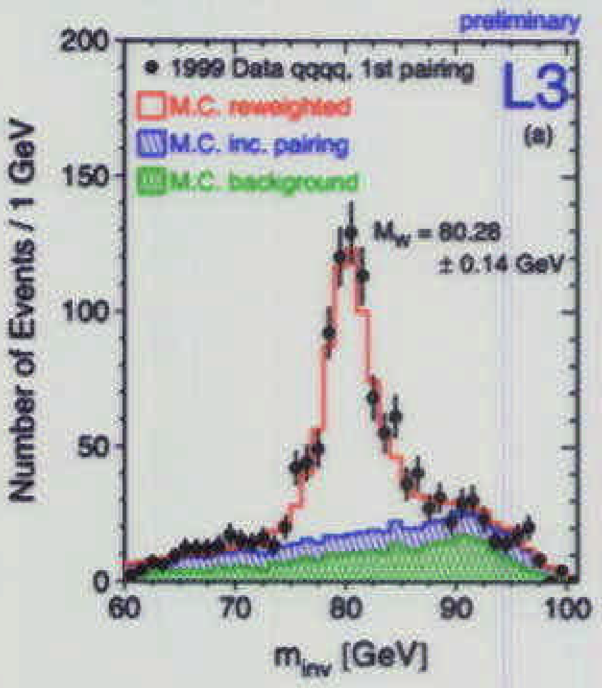
Individual LEP expts: syst err $\simeq$ stat err $\simeq$50 MeV
Combined LEP:
common systematics now dominates

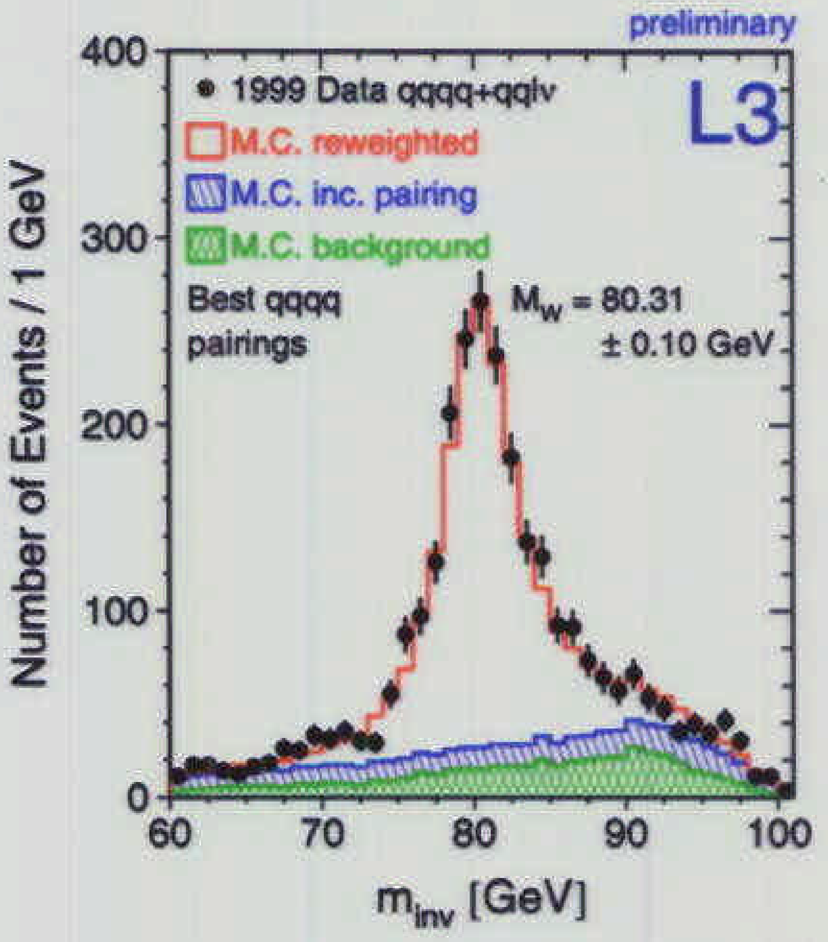
LEPII: W Mass and width



LEPII: W Mass and width







LEPII: W Mass and width

SYSTEMATIC ERRORS ON M_W

- uncorrelated between channels, experiments
- correlated between channels within an experiment e.g., detector calibration, simulation
- correlated between experiments, e.g.,
  (a) Bose-Einstein, Color Reconnection effects in the qqqq channel,
  (b) Initial State Radiation, fragmentation effects
  (c) LEP energy error, its correlation between years

Major concern:
Syst. errors correlated between experiments

ΔM_W DUE TO:

– LEP energy error: ~17 MeV, may decrease to ~ 12 MeV.

– ISR: small, Fragmentation: 20-30 MeV

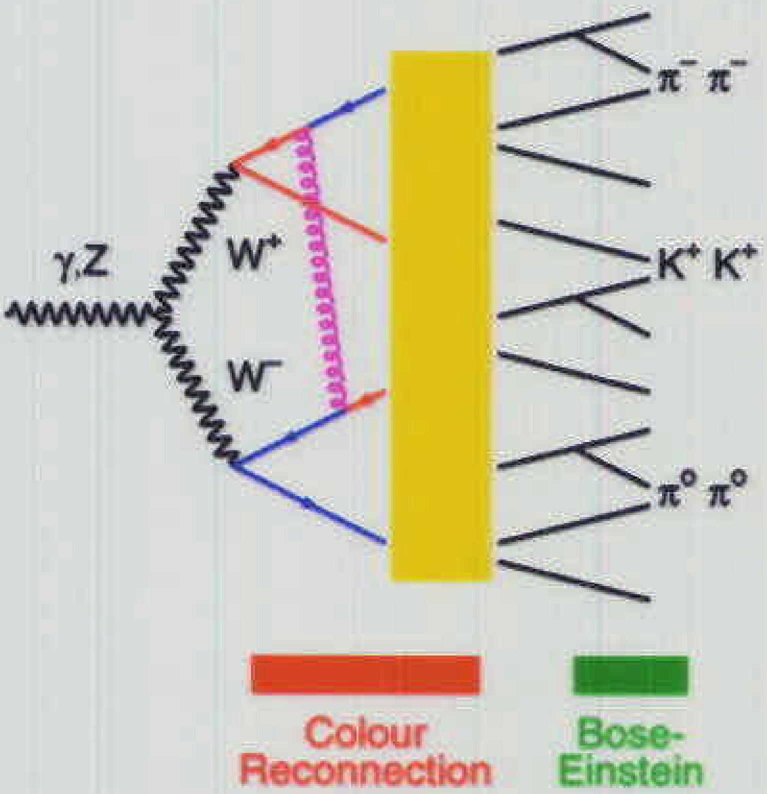
→ BE, CR effects: ~ 25, 50 MeV for qqqq !!

As N(qqqq) $\simeq \frac{1}{2}$ N(all):

Contribution of BE and CR to $\Delta M_W \sim$ 30 MeV

LEPII: W Mass and width

Color Reconnection, Bose-Einstein studies



DISTORTION OF M_{inv} DISTRIBUTION IN qqqq STATE.
⇓
POSSIBLE SHIFT IN FITTED M_W

Color Reconnection:

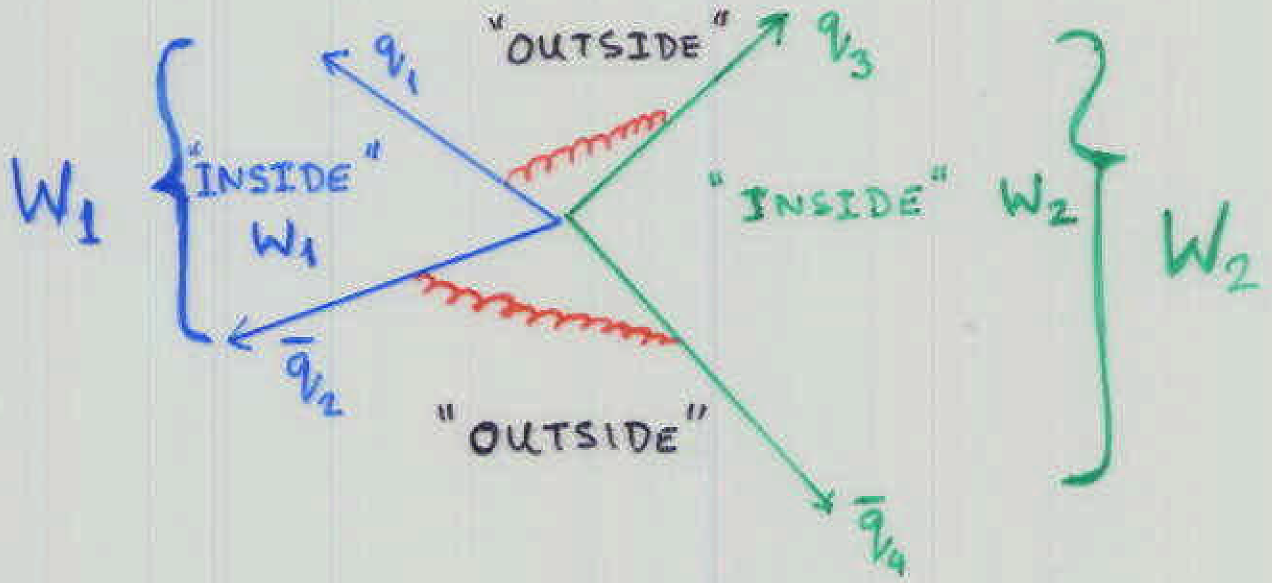
Non-perturbative: models used e.g.,:
Sjostrand-Khoze (SK), Gustafson-Hakkinen (GH)

Try determining Reconnection prob parameter in model.
Simple minded approach,
$< N_{ch}(qqqq) > -2 < N_{ch}(qq\ell\nu) >$ not sensitive, e.g.

L3: $\Delta N = -0.29 \pm .26 \pm .30$

COLOR RECONNECTION

MIGRATES W DECAY PRODUCTS FROM "INSIDE" W's TO "OUTSIDE" W's.



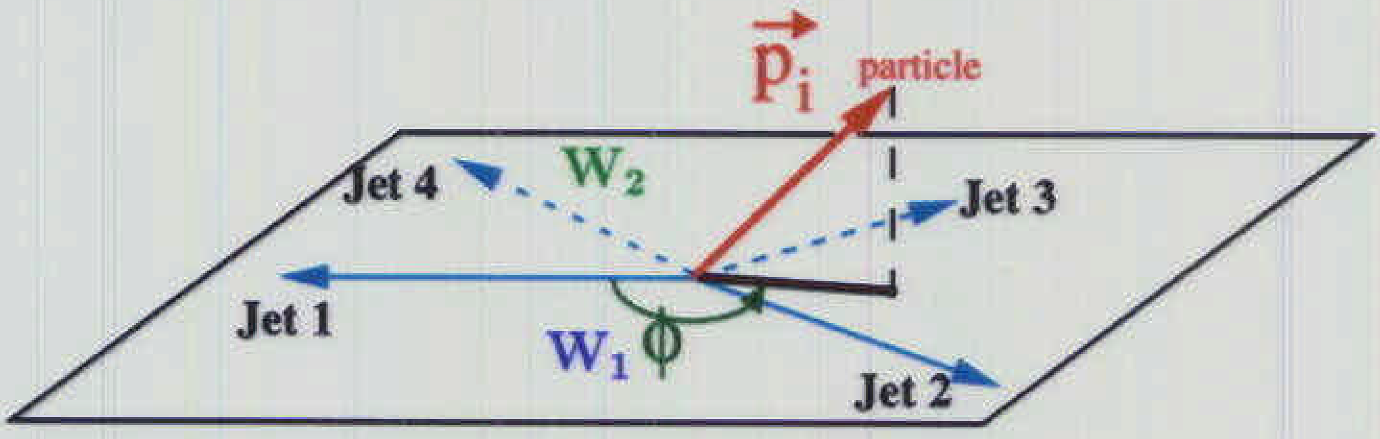
TAKE RATIO OF PARTICLES

$$\frac{\text{"INSIDE"}}{\text{"OUTSIDE"}}$$

STUDY OF INTER-JET PARTICLE & ENERGY FLOW

LEPII: W Mass and width

Inter-jet Particle- & Energy Flow; L3, Aleph



Jet 1: highest energy
Jet 2: jet from same W (W_1)
angles projected in Jet1-Jet2 plane

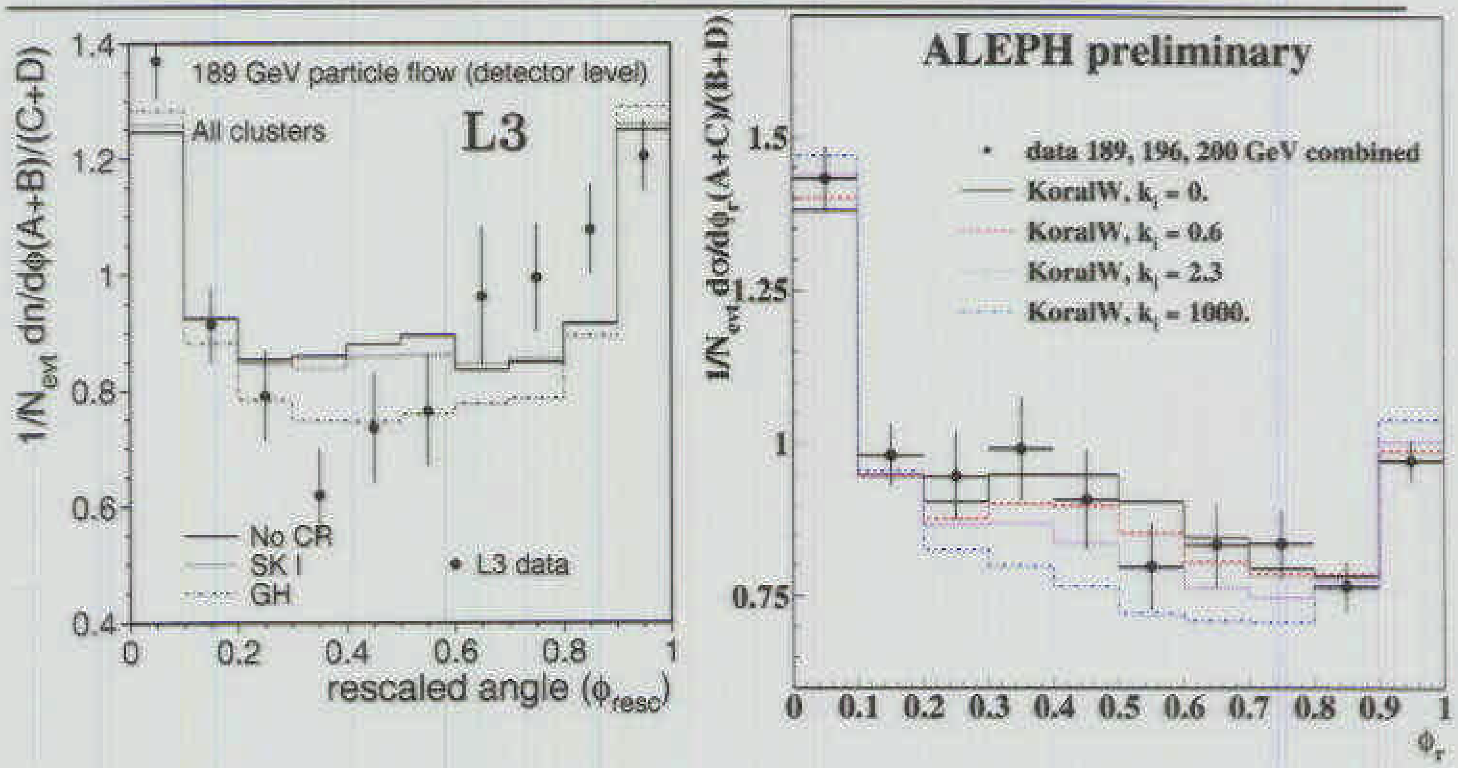
Jets 3 & 4 from W_2

Four angular regions (A, B, C, D):

(2 inside W's)
A: between jets 1 & 2; B: between jets 3 & 4

(2 outside W's)
C: between jets 2 & 3; D: between jets 4 & 1

LEPII: W Mass and width



L3, Aleph:
Determination Reconnnection Probability
L3 189 GeV: $R_N = 0.771 \pm .049 \pm .029$
$\Rightarrow\sim$ 40% Reconnection probability in SK-I model.

Aleph 189 GeV: $R_N = 0.805 \pm .05$
Using also 196+200 GeV
$\Rightarrow\leq$ 45% Reconnection probability at 1σ
(40 MeV shift in M_W) in qqqq channel

STUDIES IN PROGRESS

Currently LEP expts use $\Delta M_W(CR) = 50$ MeV

(~600 pb^{-1}/expt : should see a 3.5 σ effect if CR prob is 35% in SKI model)

LEPII: W Mass and width

– Bose-Einstein Correlations (qqqq evts):
Enhanced production of identical boson pairs at small 4-mom difference.
(LEP I: $\pi^\pm\pi^\pm$, $K_S^0 K_S^0$, $K^\pm K^\pm$)

At LEP: to check if such interference exists between particles from different W's,
if so, its effect on W mass determination

Aleph, L3, Opal: BE effects within same W, e.g., in qq system within $qq\ell\nu$.
But no *inter-W* effects seen in qqqq. (A, L ⇒ DISFAVOUR)

Delphi: seem to see some *inter-W* effects in qqqq

Studying the BEC effect

Correlation function

$$R(p_1, p_2) = \frac{P(p_1, p_2)}{P_0(p_1, p_2)}$$

$P \equiv 2-$particle prob density, $p_i \equiv 4-$mom
$P_0 \equiv$ reference $2-$particle density like P, but without BEC

LEPII: W Mass and width

Parametrized as

$$\mathbf{R(Q) = \gamma(1 + \delta Q)(1 + \lambda e^{-r^2Q^2})}$$

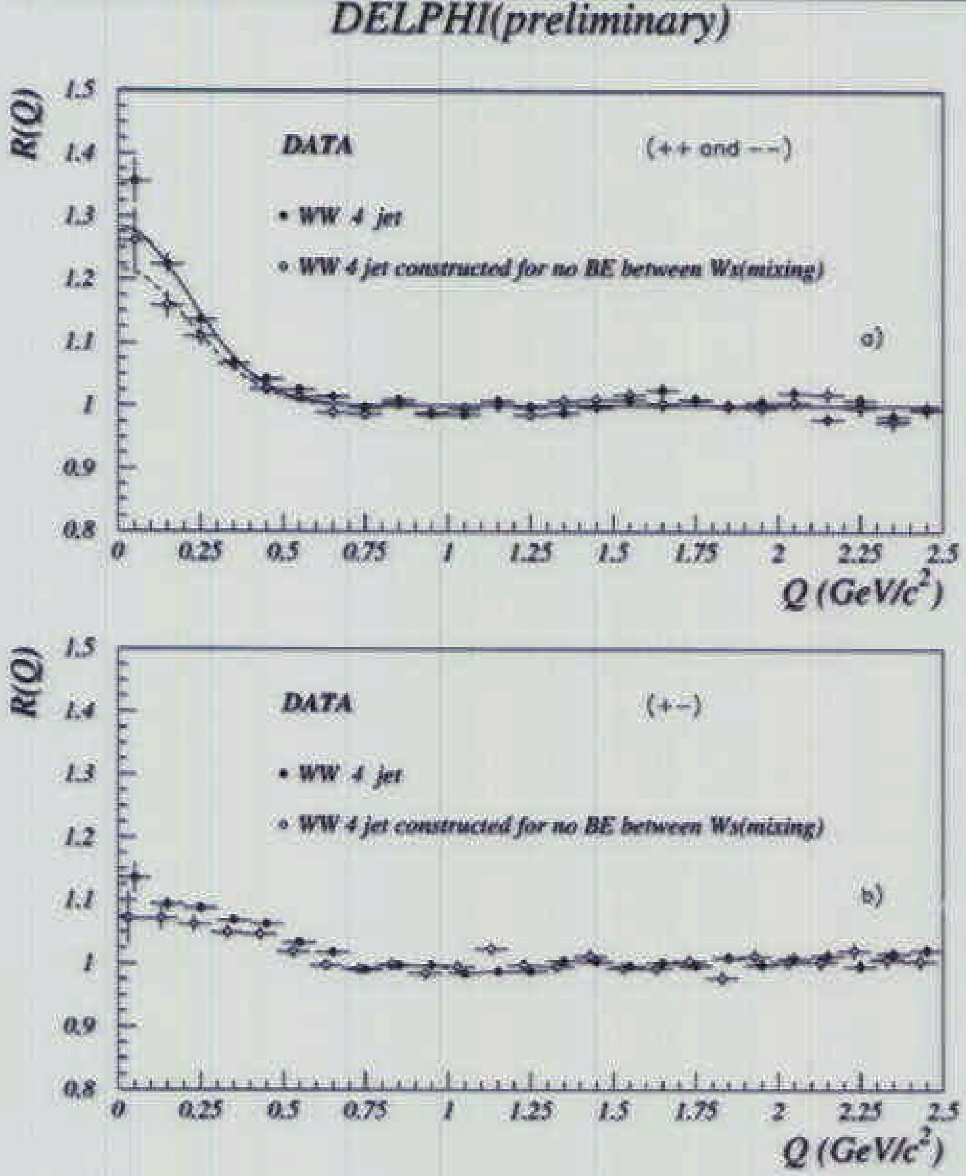
$\mathbf{Q^2 = -(p_1 + p_2)^2 = M^2_{\pi\pi} - 4m^2_{\pi}}$, **r = radius of spherically symmetric pion source, λ= strength of correlation.**

Delphi measured R(Q) in:

- **hadronic Z decays,**
- **WW→qq$\ell\nu$ and qqqq decays**

Comparison sample: event mixing, took (qq)'s from 2 qq$\ell\nu$ events to fake qqqq with no inter-W BEC's

LEPII: W Mass and width

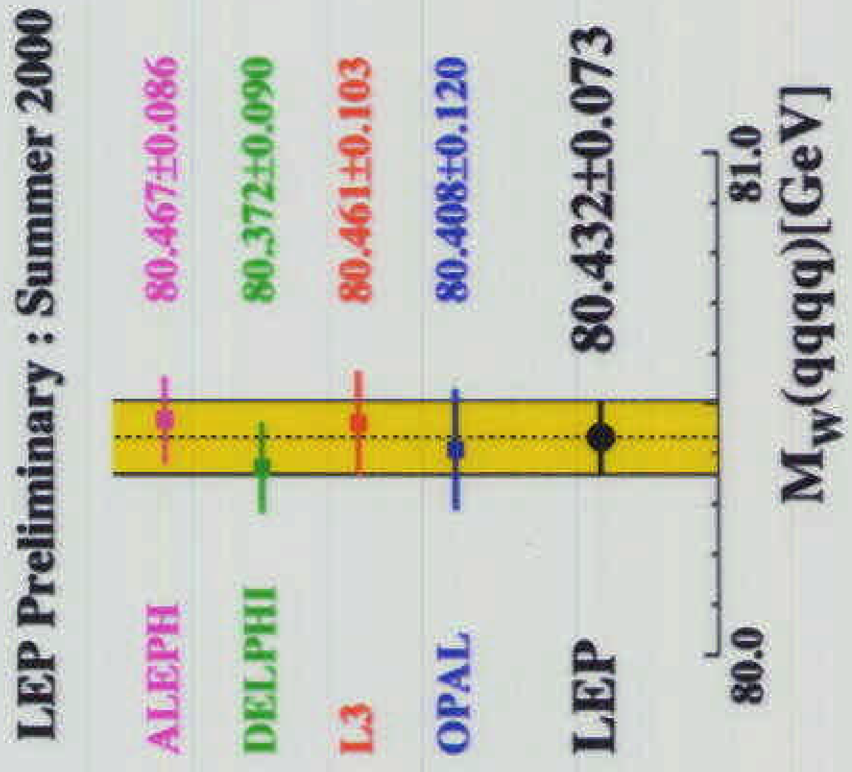


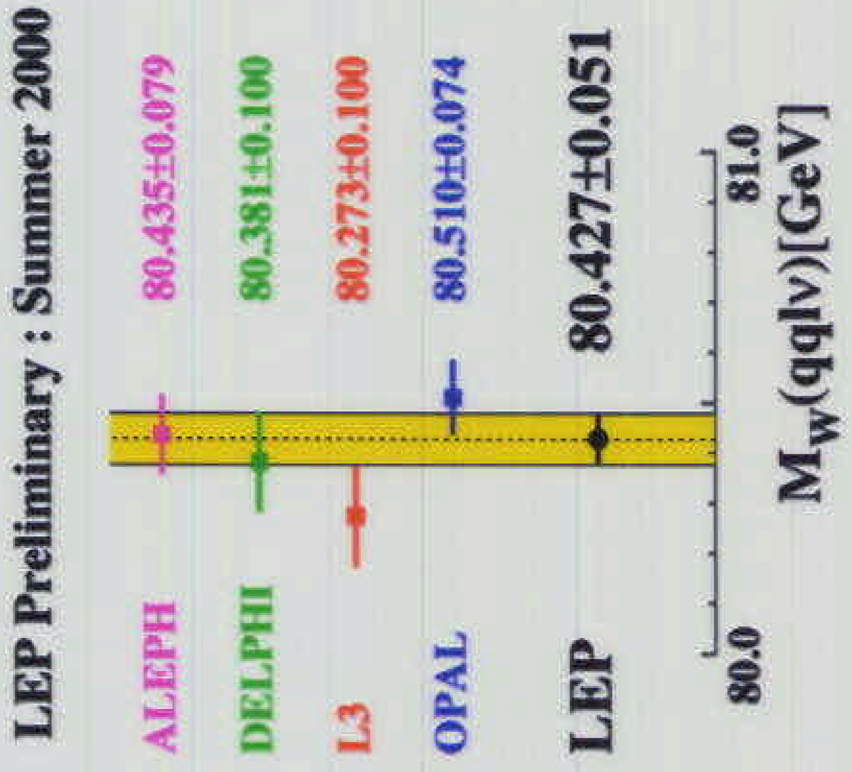
Correlation strength diff. between 4q data and
– Mixed events $\Delta\lambda = 0.062 \pm .025 \pm .021$
– $qq\ell\nu$ $\Delta\lambda = 0.077 \pm .026 \pm .020$

Needs further study, confirmation by ADO

Currently LEP expts use $\Delta M_W(BE) = 25$ MeV.

LEPII: W Mass and width



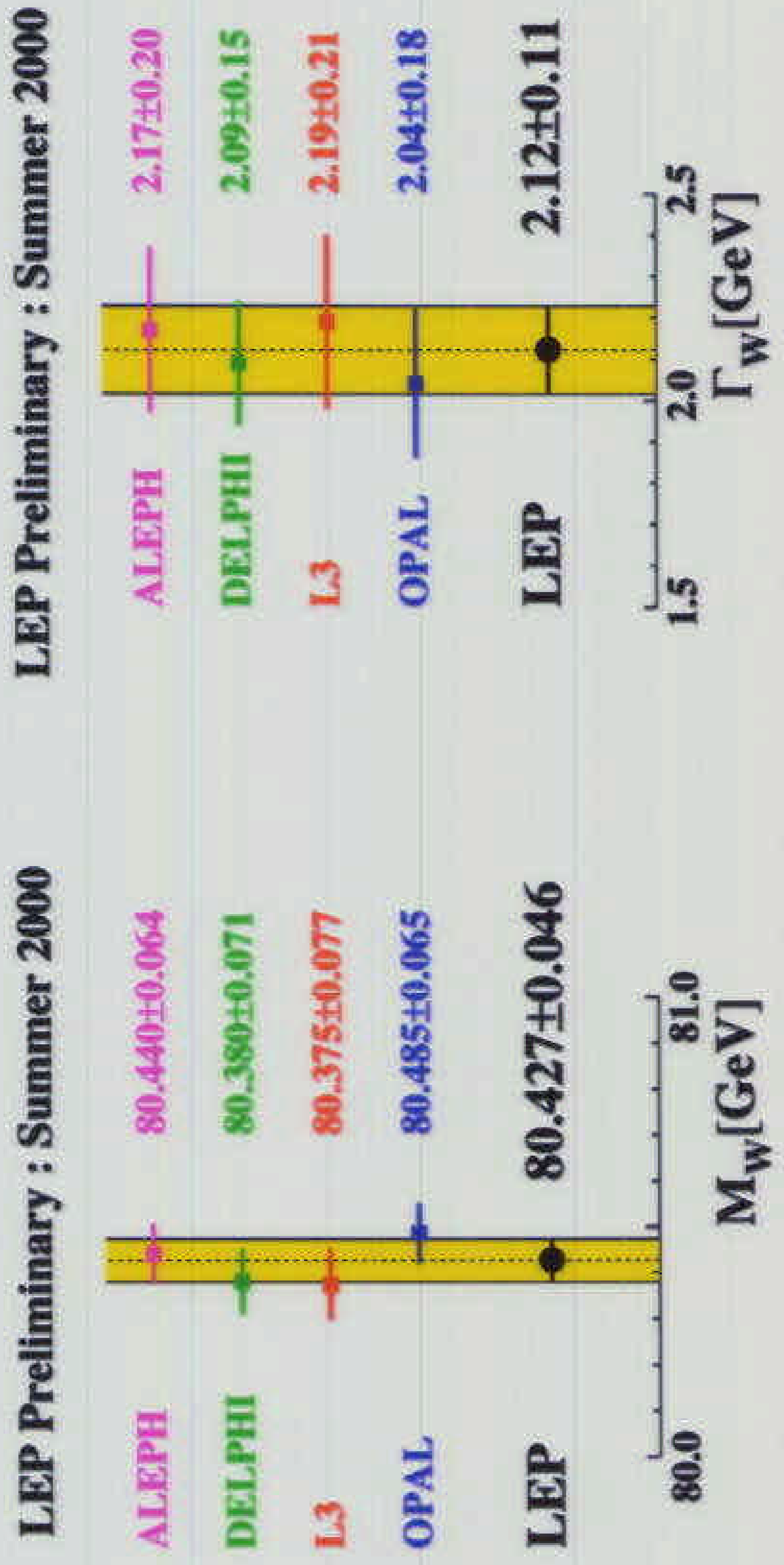


$\Delta M_W = M_W(qqqq) - M_W(qq\ell\nu)$

$= 5 \pm 51$ MeV

$\Longrightarrow$ CR + BE EFFECTS $\neq$ LARGE

LEPII: W Mass and width

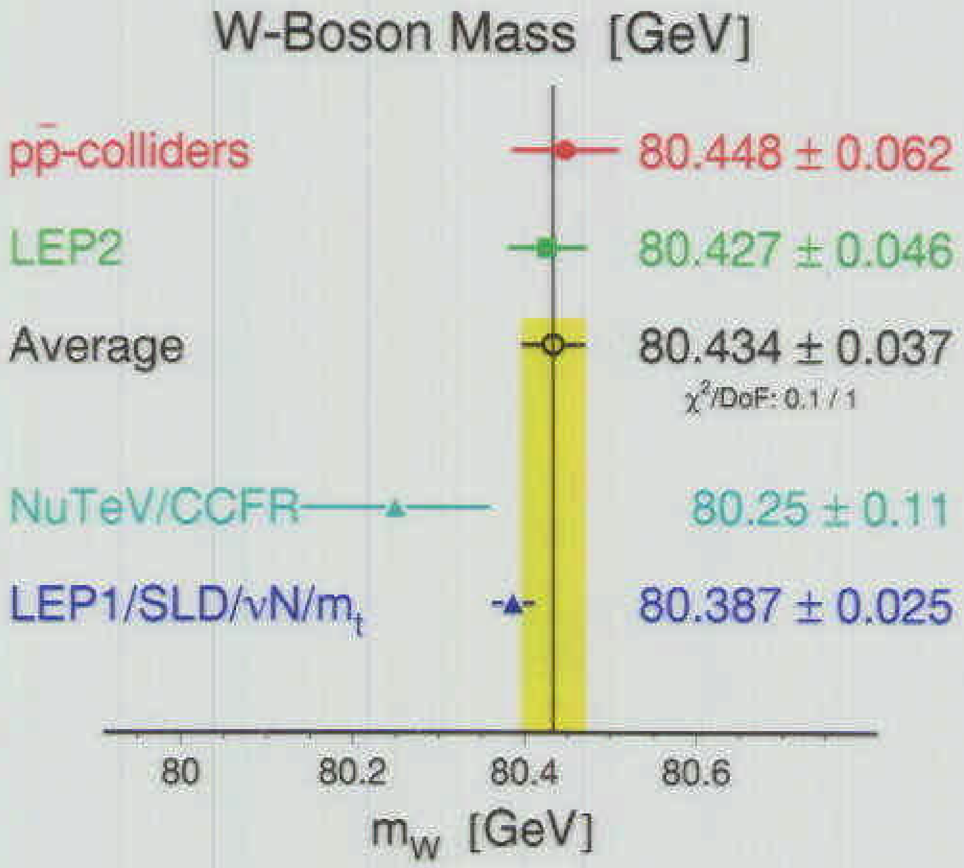


LEPII: W Mass and width

LEP value of Γ_W: 2.12±0.11 GeV

CDF Direct measurement: 2.055 ± 0.125 GeV
CDF+D0 "Extracted" Value: $2.171 \pm .052$ GeV

WORLD AVERAGE OF W MASS

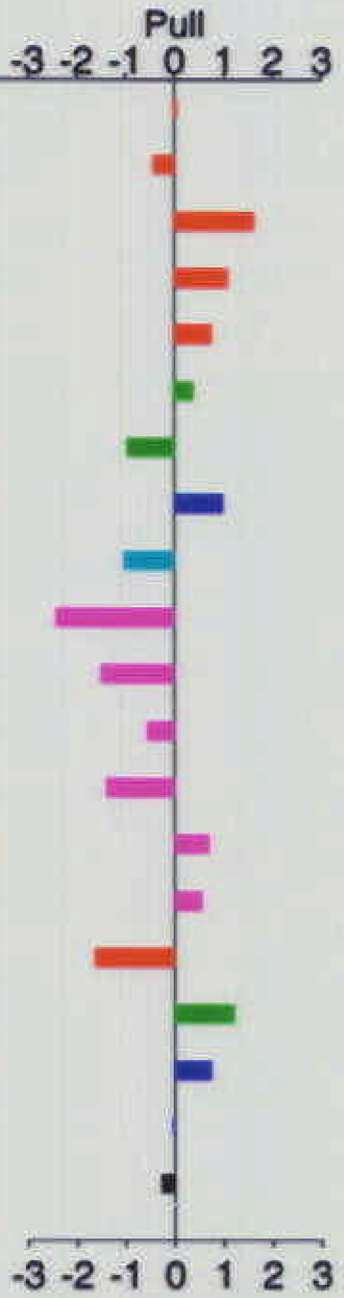


Global Fit to EW data

Fitted SM parameters: M_{top}, M_Z, α_s, $1/\alpha^{(5)}(M_Z^2)$, M_{Higgs}

Osaka 2000

	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.05
Γ_Z [GeV]	2.4952 ± 0.0023	-.43
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.08
$A_{fb}^{0,l}$	0.01714 ± 0.00095	.76
A_e	0.1498 ± 0.0048	.38
A_τ	0.1439 ± 0.0042	-.97
R_b	0.21649 ± 0.00072	1.00
R_c	0.1683 ± 0.0038	-1.04
$A_{fb}^{0,b}$	0.0989 ± 0.0020	-2.42
$A_{fb}^{0,c}$	0.0689 ± 0.0035	-1.50
A_b	0.922 ± 0.023	-.55
A_c	0.632 ± 0.026	-1.40
$\sin^2\theta_{eff}^{lept}$	0.2321 ± 0.0010	.70
m_W [GeV]	80.427 ± 0.046	.55
$\sin^2\theta_{eff}^{lept}$	0.23098 ± 0.00026	-1.62
$\sin^2\theta_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.448 ± 0.062	.75
m_t [GeV]	174.3 ± 5.1	-.04
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02804 ± 0.00065	-.28



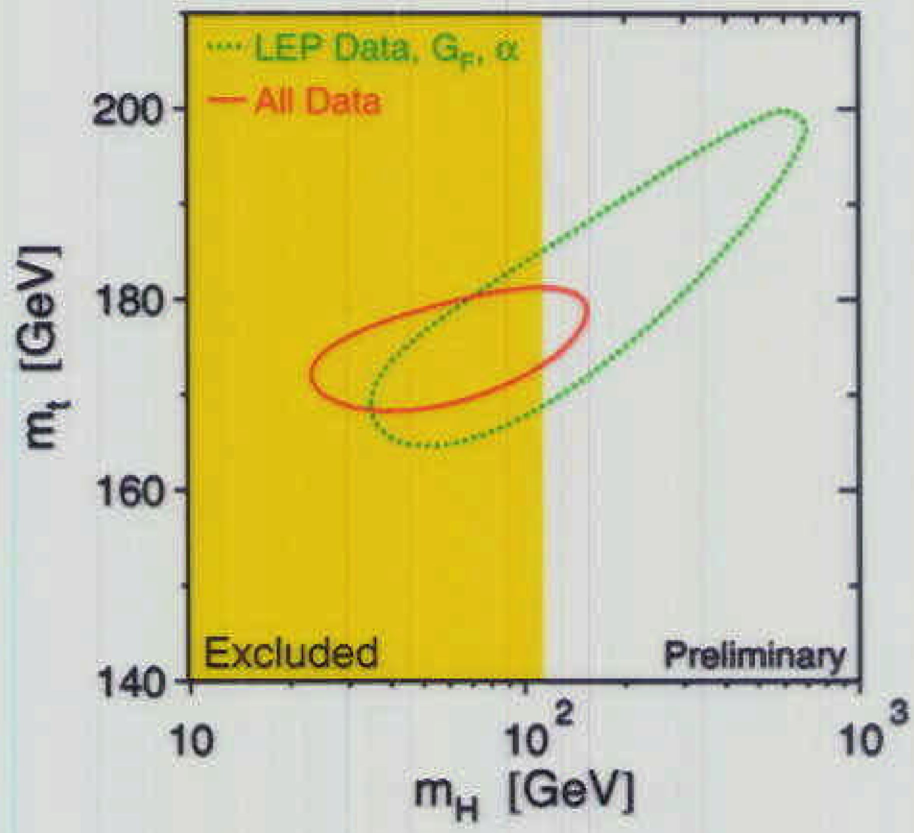
Global Fit to EW data

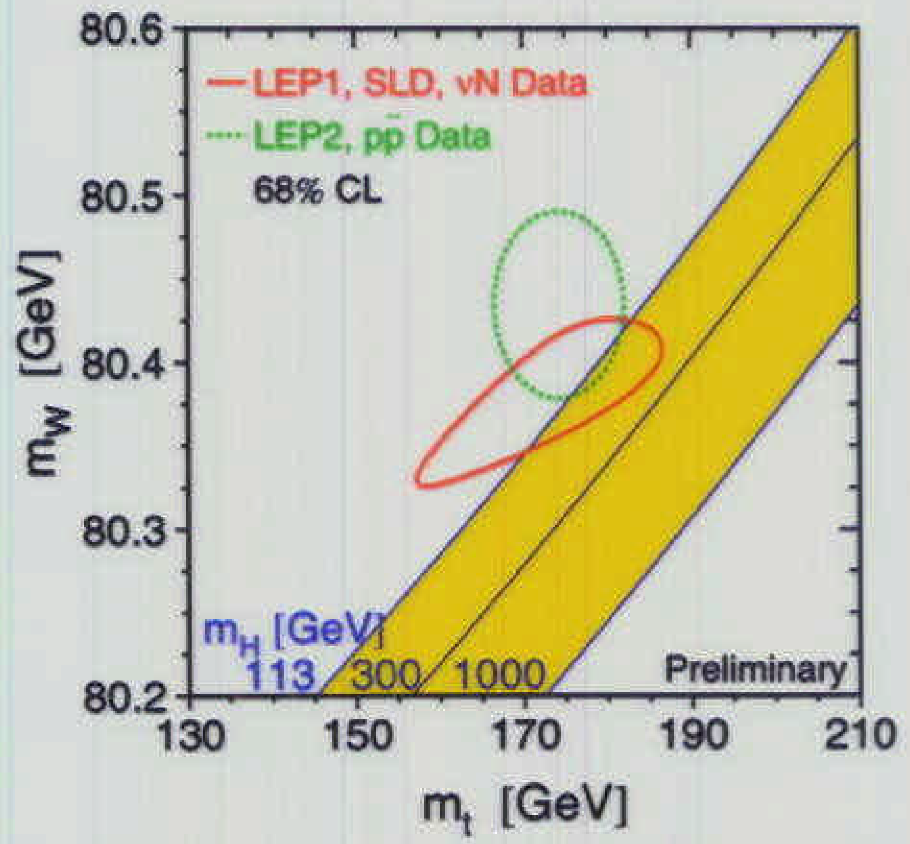
	LEP including LEPII M_W	all data except M_W and M_{top}	all data except M_W	all data
M_{top} [GeV]	179^{+13}_{-10}	169^{+10}_{-8}	$173.2^{+4.7}_{-4.5}$	$174.5^{+4.4}_{-4.2}$
M_{Higgs} [GeV]	135^{+262}_{-83}	59^{+84}_{-29}	75^{+69}_{-37}	62^{+53}_{-30}
$\log(M_{Higgs}/GeV)$	$2.13^{+0.47}_{-0.41}$	$1.77^{+0.39}_{-0.29}$	$1.88^{+0.28}_{-0.30}$	$1.79^{+0.27}_{-0.28}$
α_s	0.1195 ± 0.0029	0.1185 ± 0.0027	$0.1185 \pm .0027$	0.1183 ± 0.0027
χ^2/d.o.f.	13/9	20/12	20/13	21/15
$\sin^2\theta_{eff}^{lept}$	0.23167 ± 0.00020	0.23147 ± 0.00017	0.23147 ± 0.00017	0.23140 ± 0.00016
$1 - M_W^2/M_Z^2$	0.22294 ± 0.00056	0.22306 ± 0.00066	0.22285 ± 0.00048	0.22257 ± 0.00040
M_W [GeV]	80.383 ± 0.029	80.376 ± 0.034	80.387 ± 0.026	80.402 ± 0.021

Tevatron Direct 174.3 ± 5.1

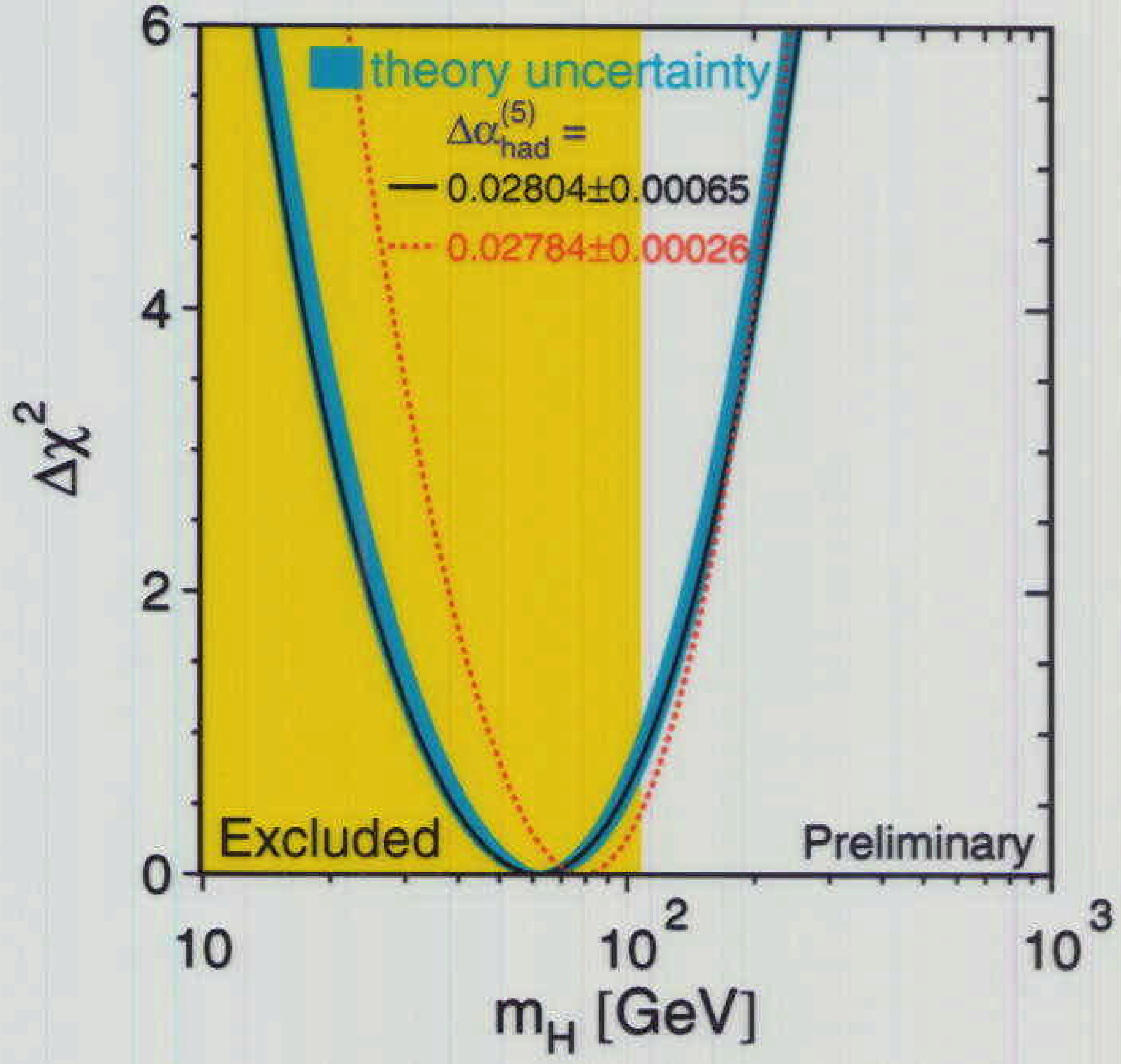
LEP + TEVATRON Direct: 80.434 ± 0.037

Global Fit to EW data





Global Fit to EW data



M_{Higgs} < 170 GeV at 95% C.L.

Global Fit to EW data

$$\alpha(M_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha_\ell(M_Z^2) - \Delta\alpha_{had}^{(5)}(M_Z^2) - \Delta\alpha_{top}(M_Z^2)}$$

Main uncertainty in $\alpha(M_Z^2)$ from $\Delta\alpha_{had}^{(5)}(M_Z^2)$.
Use Eidelmann, Jegerlehner (1995):

$$\Delta\alpha_{had}^{(5)}(M_Z^2) = 0.02804 \pm 0.00065$$

$$\Rightarrow 1/\alpha(M_Z^2) = 128.878 \pm 0.090$$

Important input for $\Delta\alpha_{had}^{(5)}(M_Z^2)$:

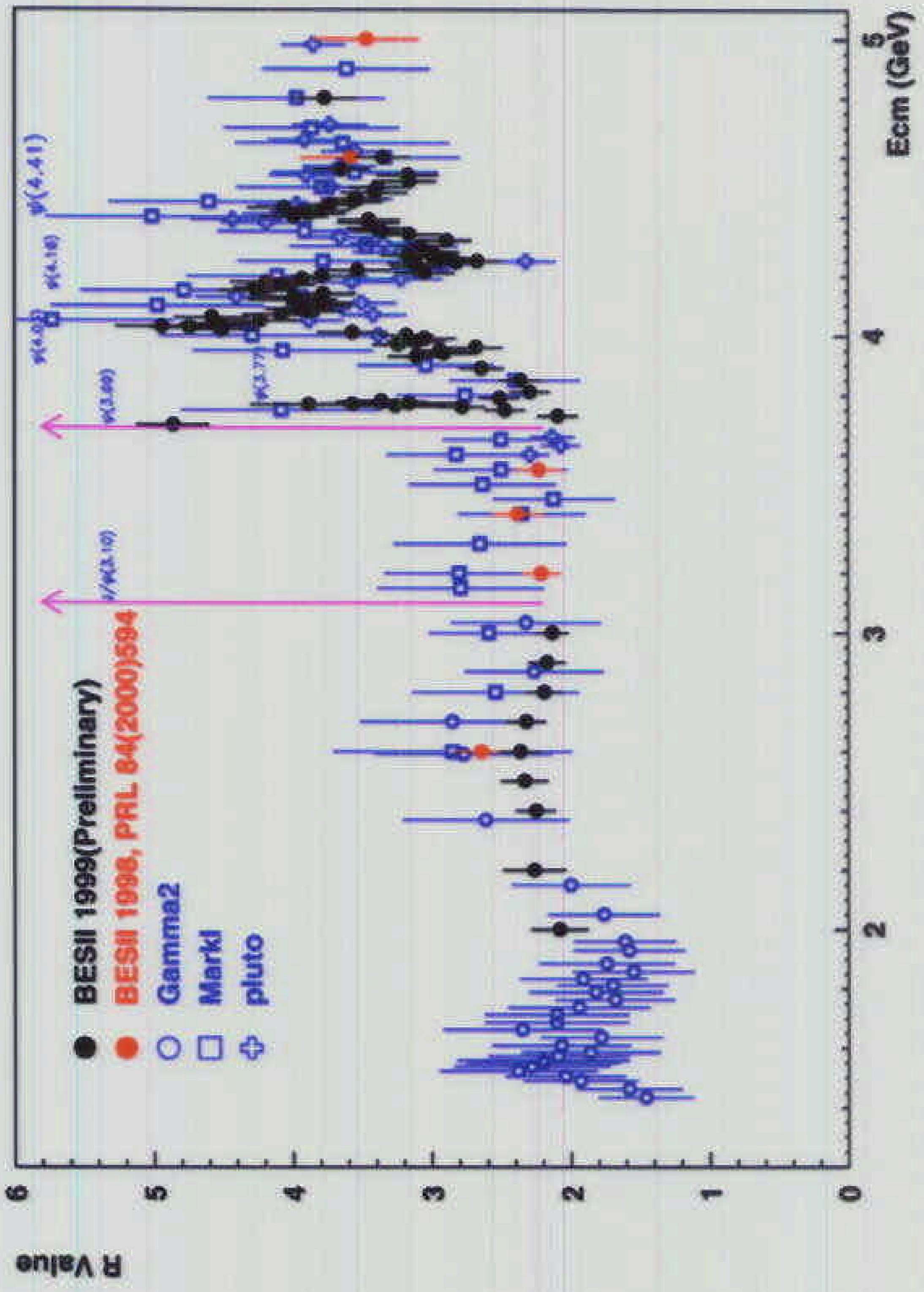
R (hadrons/$\mu^+\mu^-$),
poorly measured from 2.5 to 5 GeV.

Theory driven approaches:
smaller error (factor 3)

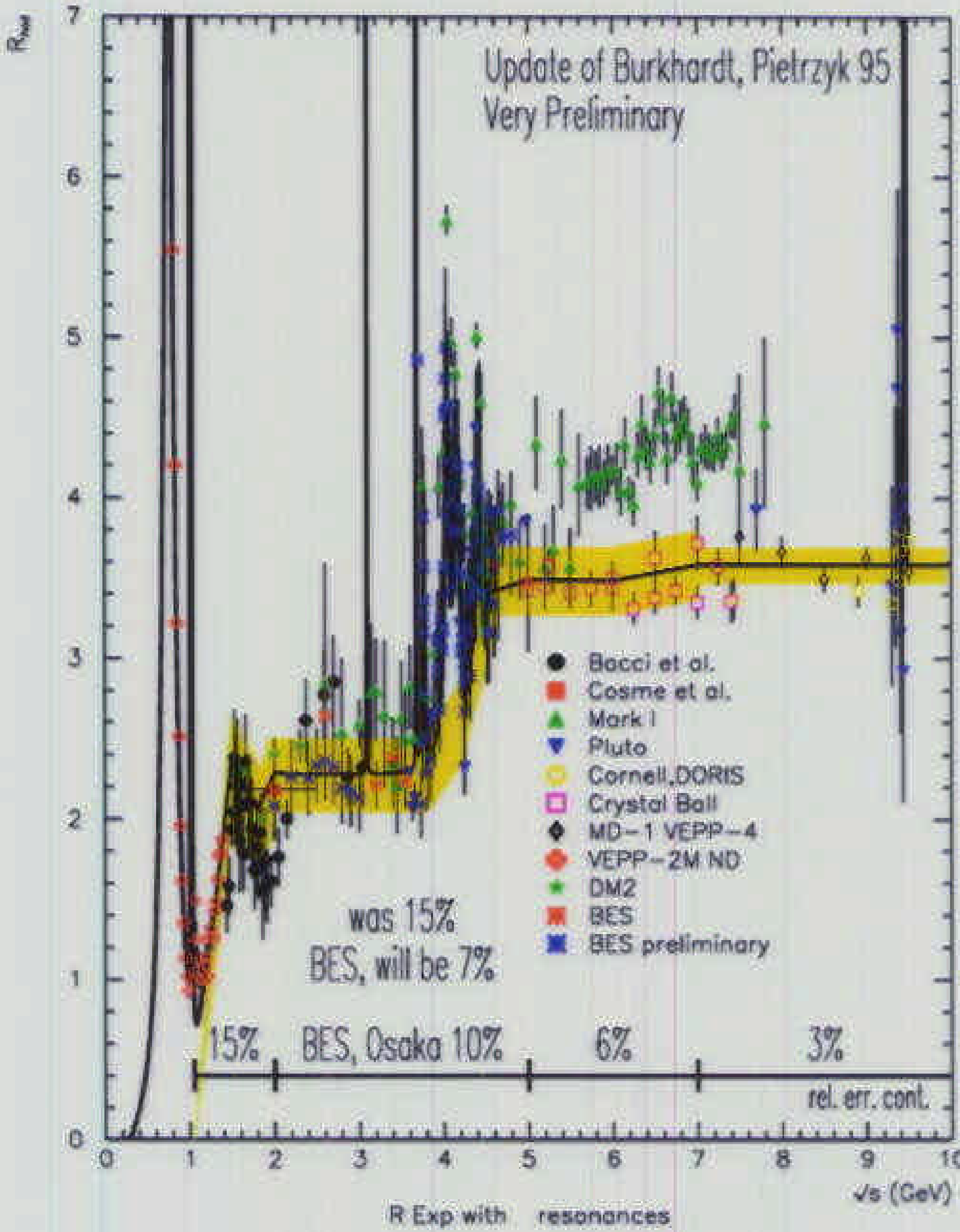
$\Rightarrow\sim$25% reduction of error on log(M_{Higgs})

New measurements of R (hadrons/$\mu^+\mu^-$)
from BESII (BEPC, Beijing)

Global Fit to EW data



Global Fit to EW data



To incorporate into determination of α(QED)

V. PRELIMINARY: $\Delta\alpha^{(5)}_{had}(M_Z^2) = 0.02755 \pm 0.00046$

(B. Pietrzyk) $M_{HIGGS} \lesssim 210$ GeV at 95% C.L.

WHERE DO WE GO FROM HERE?

- LEP I, SLD RESULTS (ALMOST) FINAL
- LEP II: WILL COLLECT ANOTHER ~100 pb^{-1} DATA AT HIGH ENERGY (205 - 209 GeV) (ALREADY HAS ~ 600 pb^{-1} / expt)
  - MORE SENSITIVE TESTS OF COUPLINGS
  - HOPE TO RESOLVE CR/BE SYSTEMATICS
    $\Rightarrow$ REDUCED $\Delta M_W \rightarrow$ ~ 35 MeV
    (CURRENT ΔM_W (LEP) = 46 MeV)
- INTERPRETATION IN SM FRAMEWORK
  DIGEST, USE BES II DATA ON R
  $M_{HIGGS} \uparrow$
- 2001 $\Rightarrow$ TEVATRON RUN II

OUTLOOK, CONCLUSIONS

Men, Machines, Detectors:

Excellent Performance

Upto Last Year: SM in EXCELLENT SHAPE; Higgs LIGHT (< 215 GeV)

Today: modulo ν OSCILLATIONS, SM still in EXCELLENT SHAPE Higgs even LIGHTER (< 170 GeV)

Watch impact of new BESII R-measurements on M_{Higgs} ($\lesssim$ 210 GeV)

Tevatron Run II : reduced errors on M_W, M_{top}: Tighter prediction of M_{Higgs}, possible discovery

LHC: Discover/ Rule out HIGGS