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**

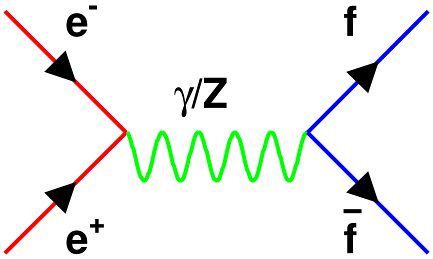
Plan of Talk

- **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:

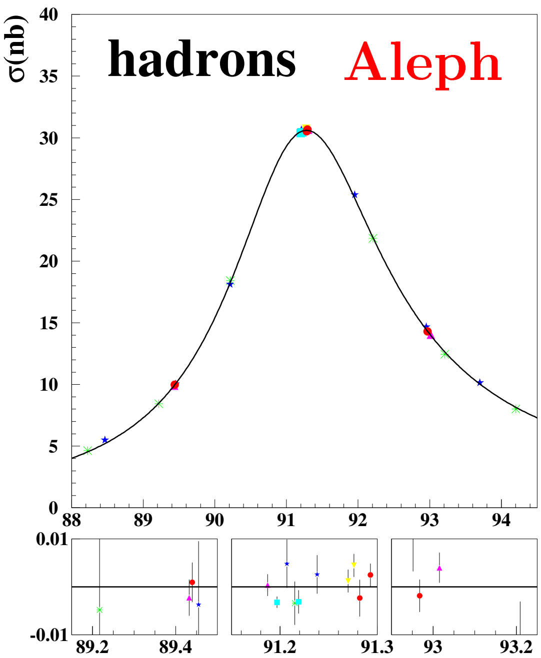
Precision measurements of cross sections & lepton forward-backward asymmetries

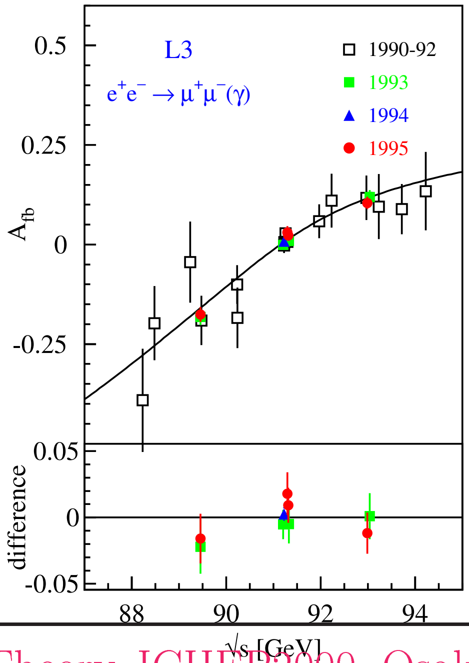


$\mathrm{f} \equiv \mathrm{e}, \mu, \tau, \mathrm{q}$

$\mathrm{e^+e^-} \to \ell^+\ell^-$, hadrons

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





L3

$\mathbf{A_{FB}^{\circ,\mu}}$

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), $e^+e^- \to e^+e^-(\gamma)$**
  - **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; $\Delta\sigma^0_h : \pm 0.02\%$ **(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)

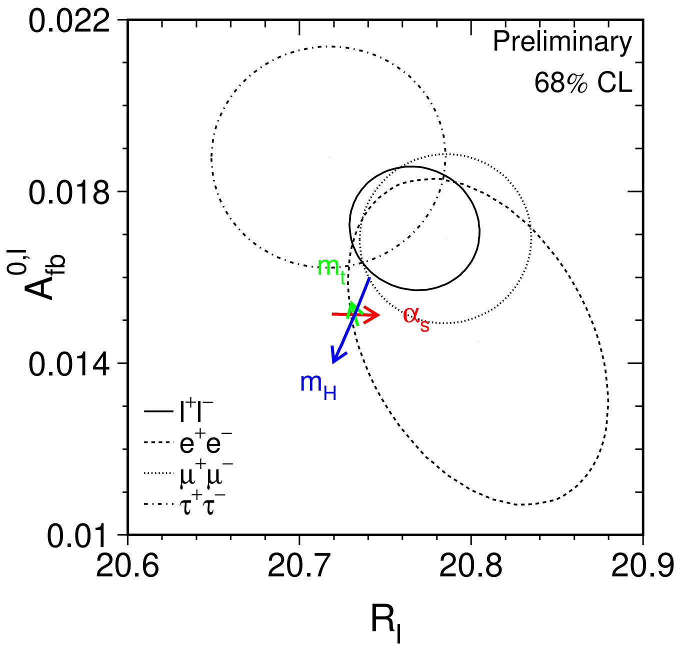
Extraction of Z parameters

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

$$A_{FB}^{\circ,\ell} = \frac{3}{4}A_e A_\ell, \quad A_\ell = \frac{2\bar{g}_V^\ell \bar{g}_A^\ell}{(\bar{g}_V^\ell)^2 + (\bar{g}_A^\ell)^2}$$

	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
$\sigma^{\circ}_{\mathrm{had}}$	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
$A_{FB}^{\circ,e}$	0.0145 ± 0.0025	0.0004	see
$A_{FB}^{\circ,\mu}$	0.0169 ± 0.0013	0.0003	$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$
$A_{FB}^{\circ,e}$	0.0188 ± 0.0017	0.0003	- do -

Extraction of Z parameters



Test of Lepton UNIVERSALITY

$$\mathbf{R}_\ell = \mathbf{20.767 \pm 0.025}$$
$$\mathbf{A}_{\mathbf{FB}}^{\circ,\ell} = \mathbf{0.01714 \pm 0.00095}$$

	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**

$$\boxed{\mathbf{N}_\nu = \mathbf{2.984 \pm 0.008}}$$

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

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

at 95% C.L.

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

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 $\cos\theta \Rightarrow A_\tau$

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

[NEW RESULT FROM OPAL TO CONF.]

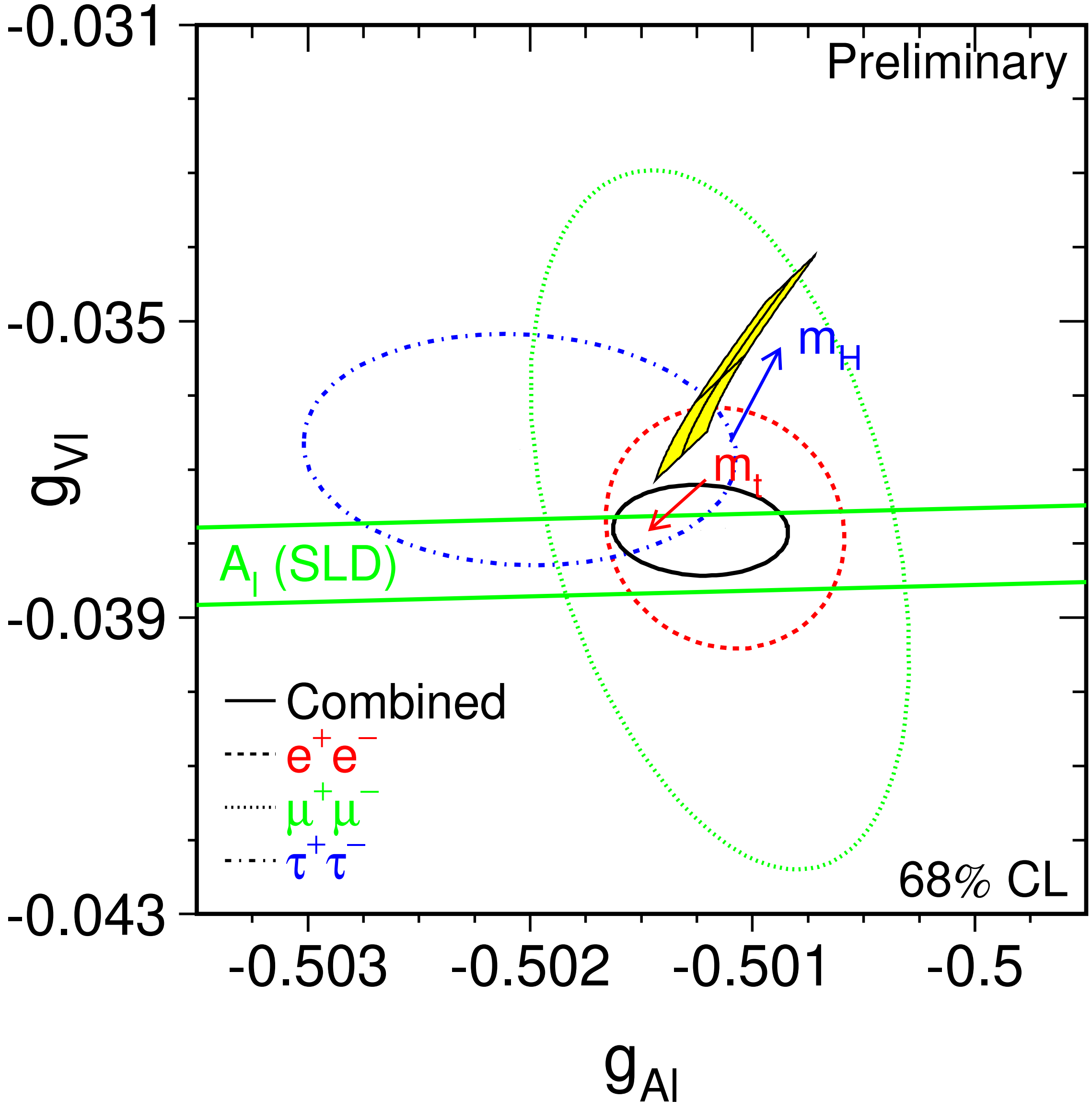
LEP: $A_\tau = 0.1439 \pm 0.0042 \quad A_e = 0.1498 \pm 0.0048$
$\Rightarrow A_\ell = 0.1464 \pm 0.0032$

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

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:
$\Rightarrow A_\ell(\mathrm{SLD}) = 0.1513 \pm 0.0021$



$$\mathbf{A}_\ell = \frac{2\overline{\mathbf{g}}_{\mathbf{V}}^{\ell}\overline{\mathbf{g}}_{\mathbf{A}}^{\ell}}{(\overline{\mathbf{g}}_{\mathbf{V}}^{\ell})^2 + (\overline{\mathbf{g}}_{\mathbf{A}}^{\ell})^2}$$

$$\Gamma_\ell = \frac{\mathbf{G_F M_Z^3}}{\mathbf{6\pi\sqrt{2}}}[(\overline{\mathbf{g}}_{\mathbf{V}}^{\ell})^2 + (\overline{\mathbf{g}}_{\mathbf{A}}^{\ell})^2] \times \ (\mathbf{1} + \delta_\ell^{\mathbf{QED}})$$

LEP & SLD: Cross sections R_b, R_c

$$\mathbf{R_q} = \frac{\Gamma(\mathbf{Z}\to\mathbf{q\bar{q}})}{\Gamma(\mathbf{Z}\to\mathbf{hadrons})}, \Gamma_\mathbf{q} \propto [(\bar{\mathbf{g}}^\mathbf{q}_\mathbf{V})^2 + (\bar{\mathbf{g}}^\mathbf{q}_\mathbf{A})^2]$$

LEP: Forward-Backward Asymmetries $A^{\circ,b}_{FB}$, $\mathbf{A^{\circ,c}_{FB}}$

$$\mathbf{A^{\circ,q}_{FB}} = \frac{3}{4}\mathbf{A_e A_q}$$

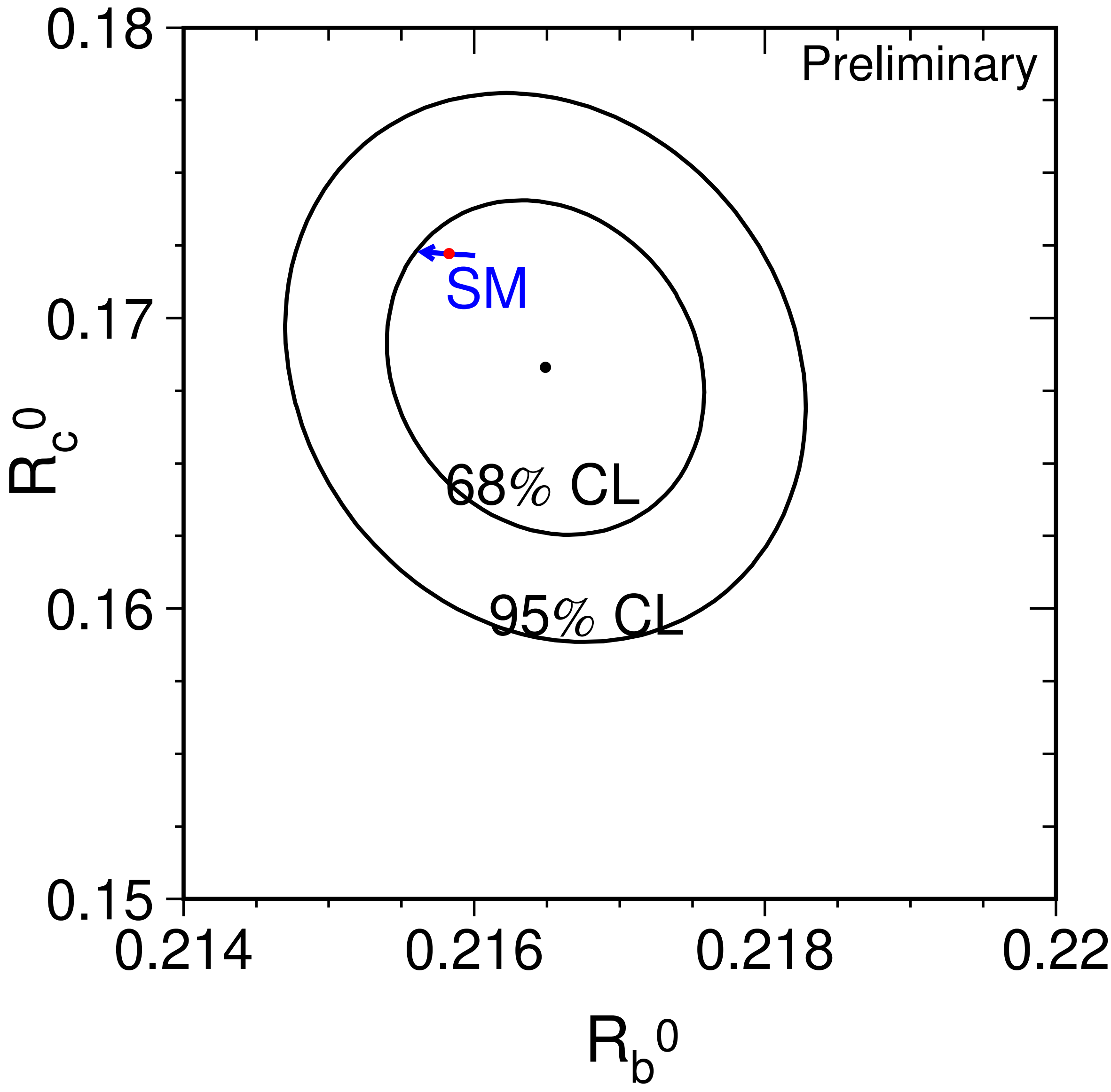
SLD: Left-Right Forward-Backward Asymmetries, $\mathbf{A_b}$, $\mathbf{A_c}$

$$\mathbf{A_q} = \frac{2\bar{\mathbf{g}}^\mathbf{q}_\mathbf{V}\bar{\mathbf{g}}^\mathbf{q}_\mathbf{A}}{(\bar{\mathbf{g}}^\mathbf{q}_\mathbf{V})^2+(\bar{\mathbf{g}}^\mathbf{q}_\mathbf{A})^2}$$

Combining LEP + SLD data:

R_b=	**0.21649**	± **0.00072**	R_c=	**0.1683**	± **0.0038**
$A^{\circ,b}_{FB}$=	**0.0989**	± **0.0020**	$\mathbf{A^{\circ,c}_{FB}}$=	**0.0689**	± **0.0035**
$\mathbf{A_b}$=	**0.922**	± **0.023**	$\mathbf{A_c}$=	**0.632**	± **0.026**

Z Couplings to b, c quarks



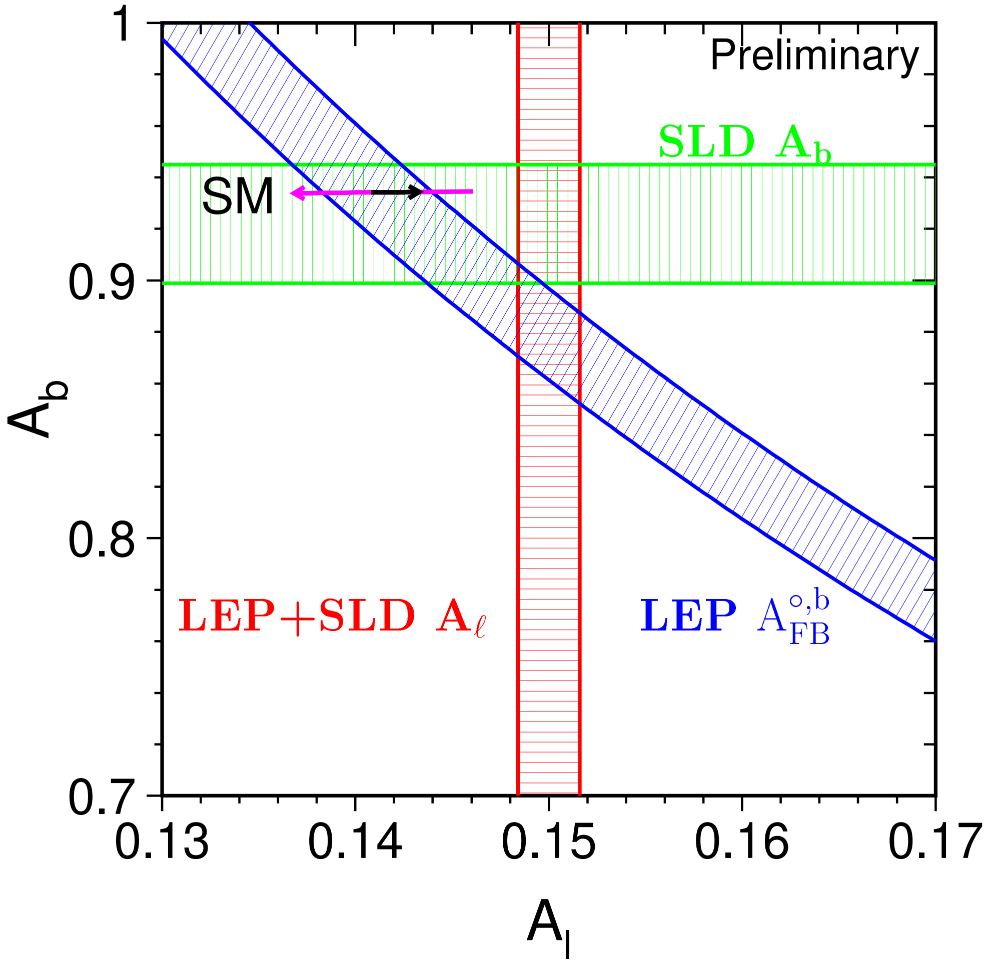
R_b, R_c now within 1σ of SM prediction

(SM R_b, R_c: 0.21583, 0.1674)

Z Couplings to b, c quarks

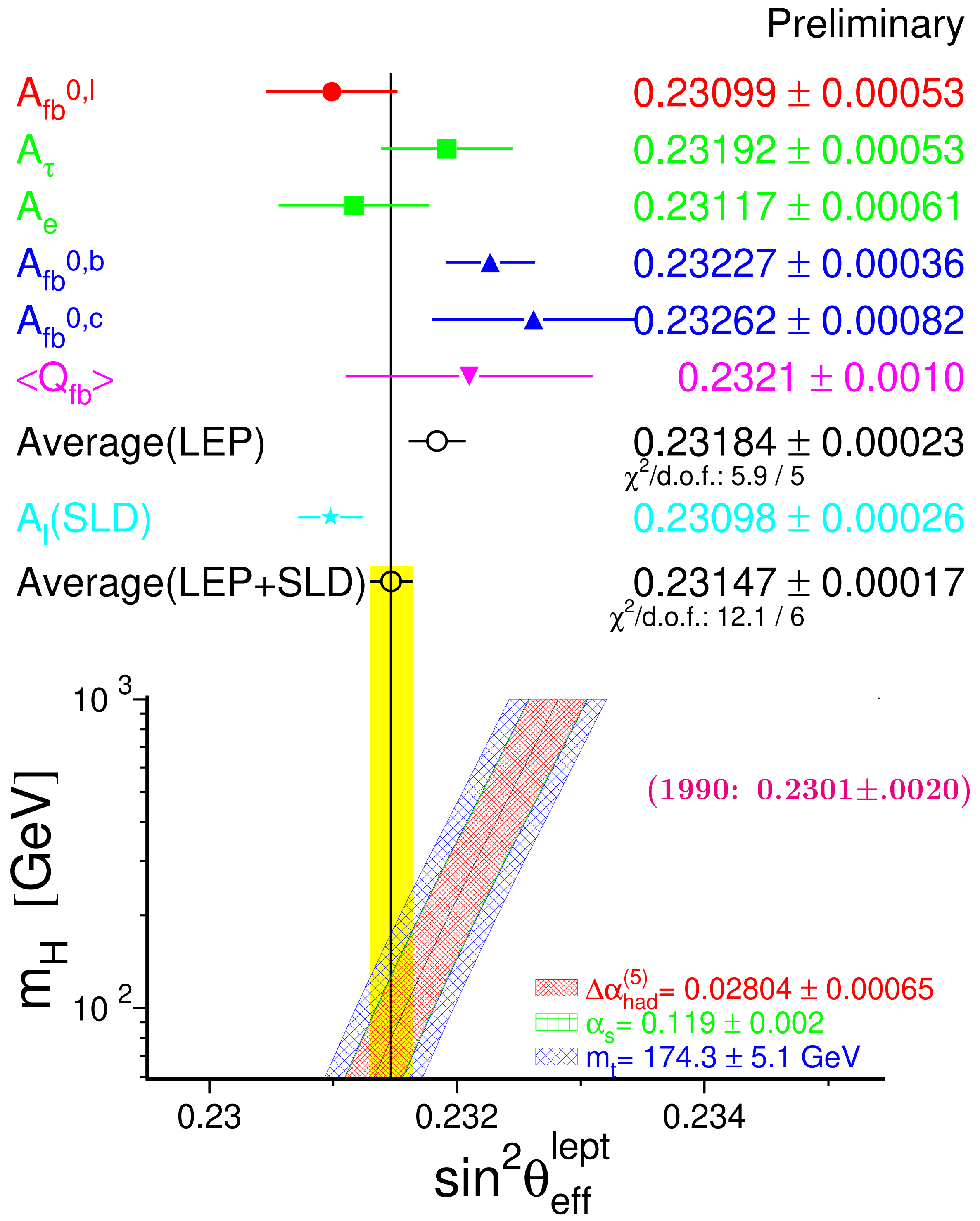
	LEP (A_ℓ= 0.1481±.0026)	SLD	LEP + SLD (A_ℓ= 0.1500±.0016)
A_b	0.890 ±.024	0.922 ±.023	0.898 ±.015
A_c	0.619 ±.035	0.632 ±.026	0.624 ±.020

LEP+SLD A_b is 2.7σ below SM: 0.935



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

$$\boxed{\sin^2\theta^{\rm lept}_{\rm eff} = \frac{1}{4}\left(1 - \frac{\bar{g}^{\ell}_{V}}{\bar{g}^{\ell}_{A}}\right)}$$

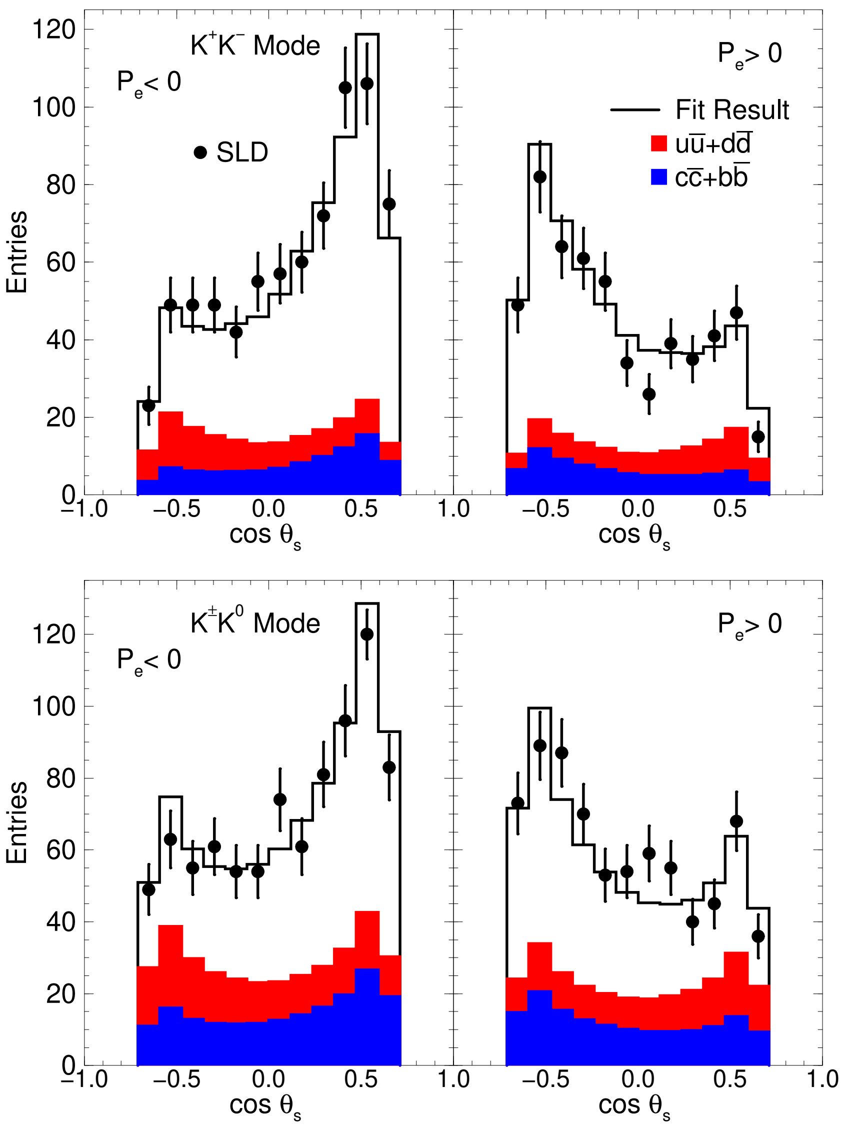


Z Couplings to s quarks

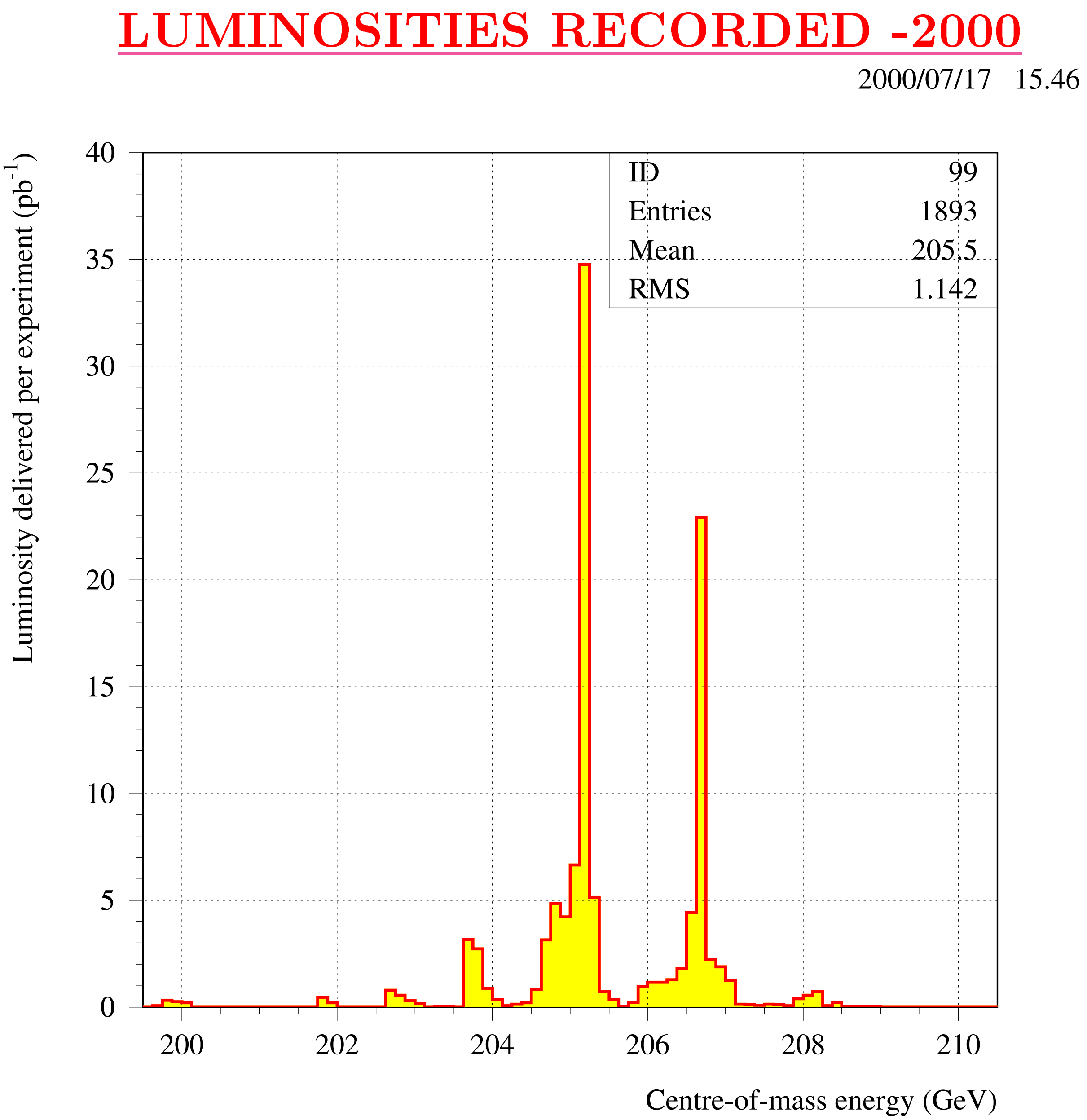
New result from SLD: 550k hadronic events; s-quark tagged by high momentum $K^{\pm}, K^0_S$ & absence of B, D mesons.

Left-Right Forward-Backward asym:

$\boxed{A_s = 0.895^{+0.066}_{-0.063}}$ $\Rightarrow$ $\boxed{A_b/A_s = 1.02 \pm 0.10}$



LEPII: Operation



2000: Luminosity Collected/ Expt: $\sim$115 pb^{-1}

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

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**

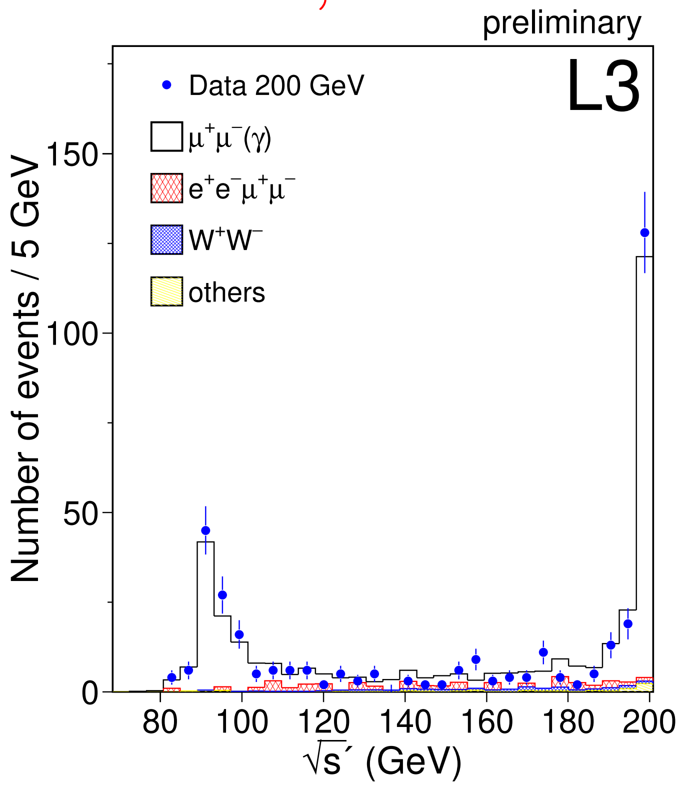
2-fermion processes

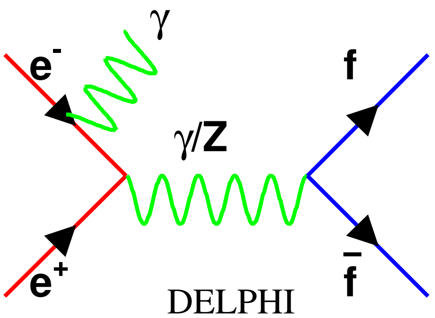
ZFITTER, KKMC give
better than 0.2% accuracy in σ(tot), of hadrons, leptons
0.2-0.4% on A_{FB}

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

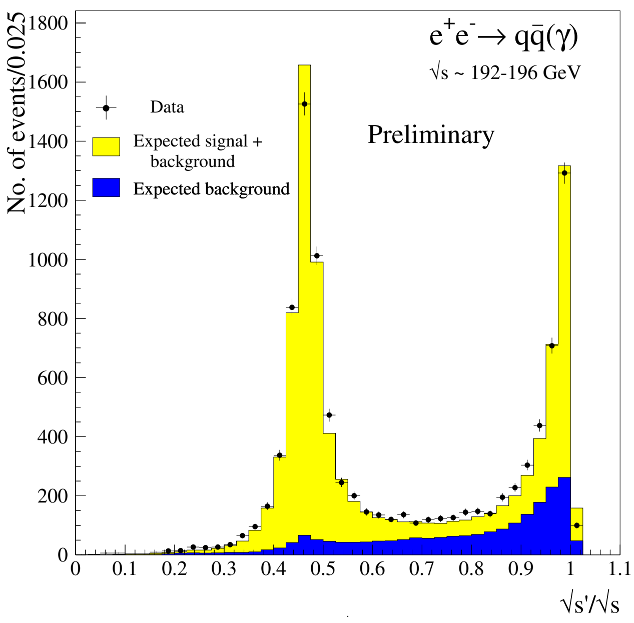
Overall Excellent $\boxed{\text{EXPT} \Longleftrightarrow \text{THEORY}}$ Match

Far above Z, return of Z:





DELPHI



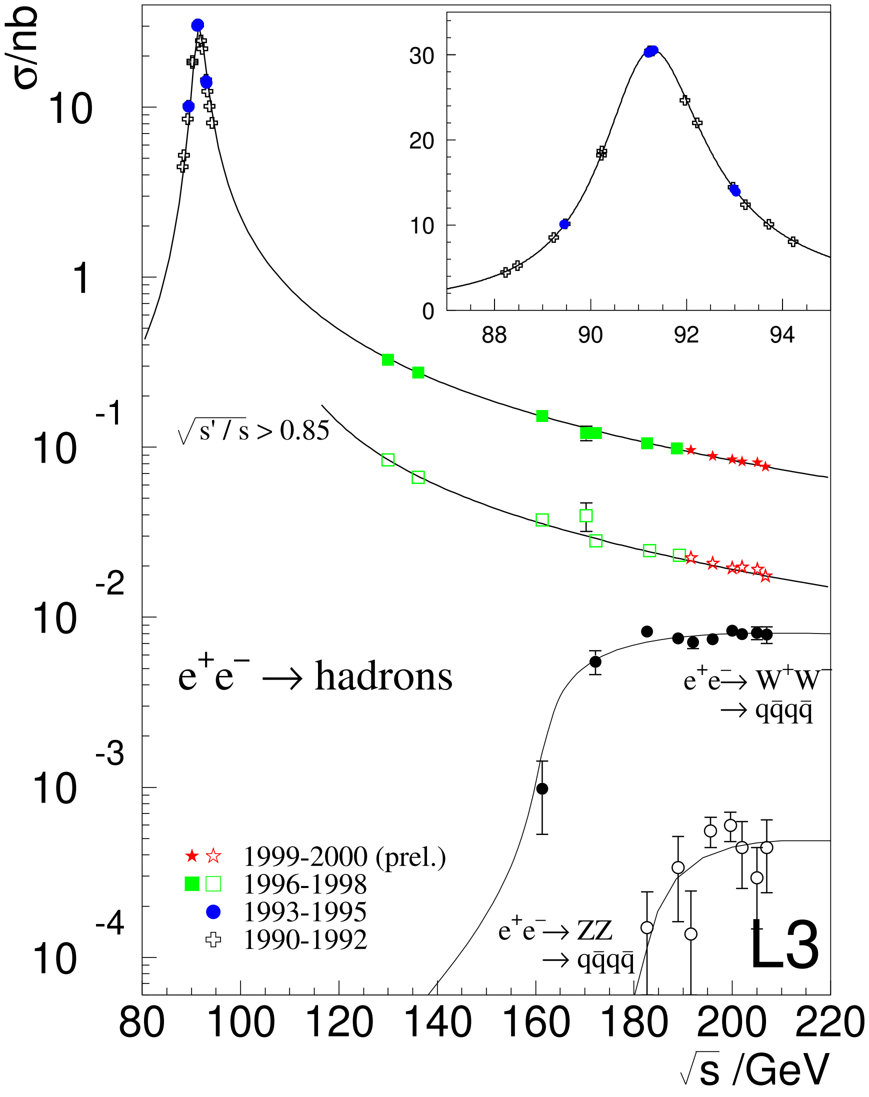
$\sqrt{s'}$ = mass of outgoing lepton pair or Z/γ^* propagator,

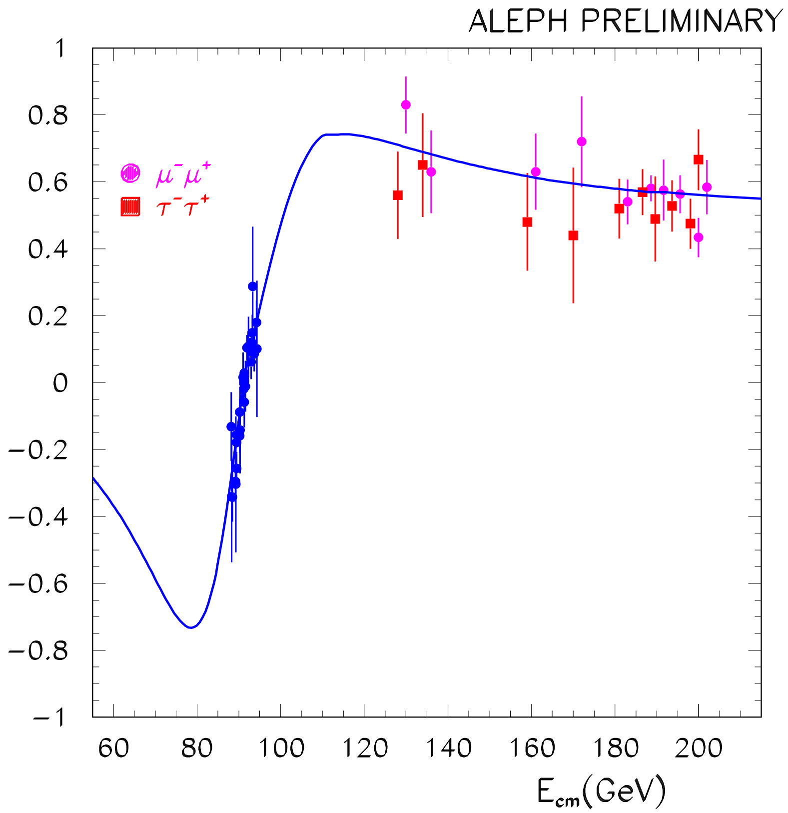
– **Inclusive Production: $s'/s > 0.01$**
– **Exclusive (high energy): $s'/s > 0.7$-0.8**

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

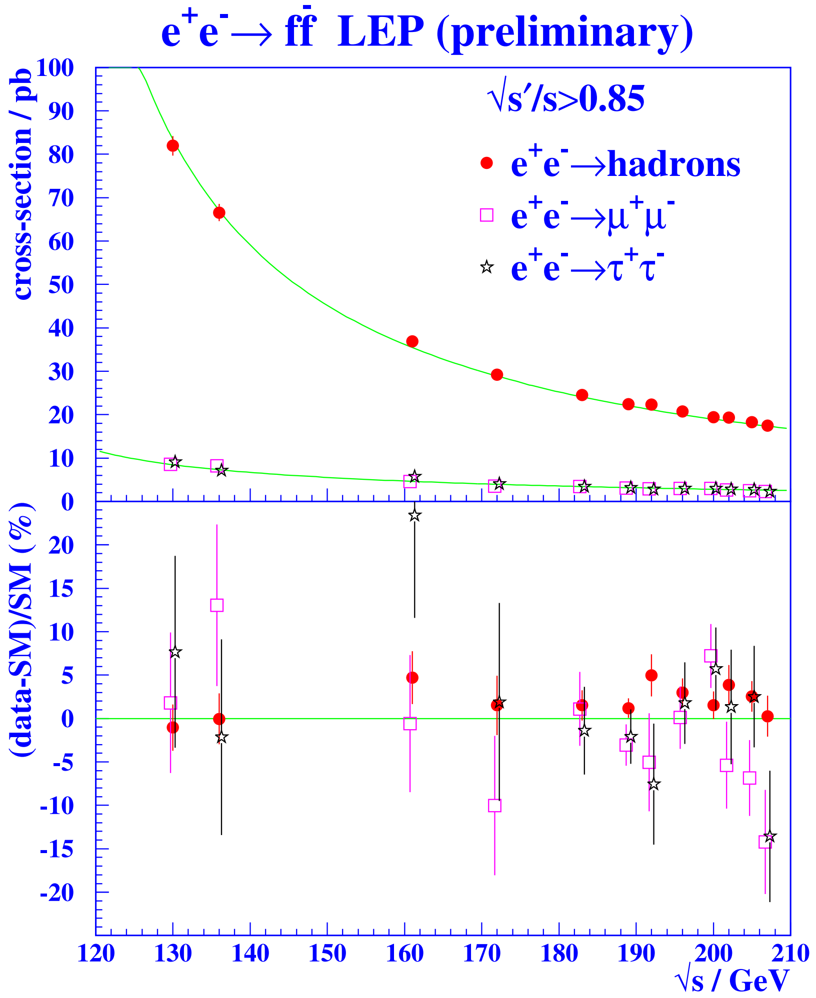
Comparison with SM provides limits on new physics:
(Contact Interactions, Z', $\tilde{\nu}$ exchange, extra dimensions,...)

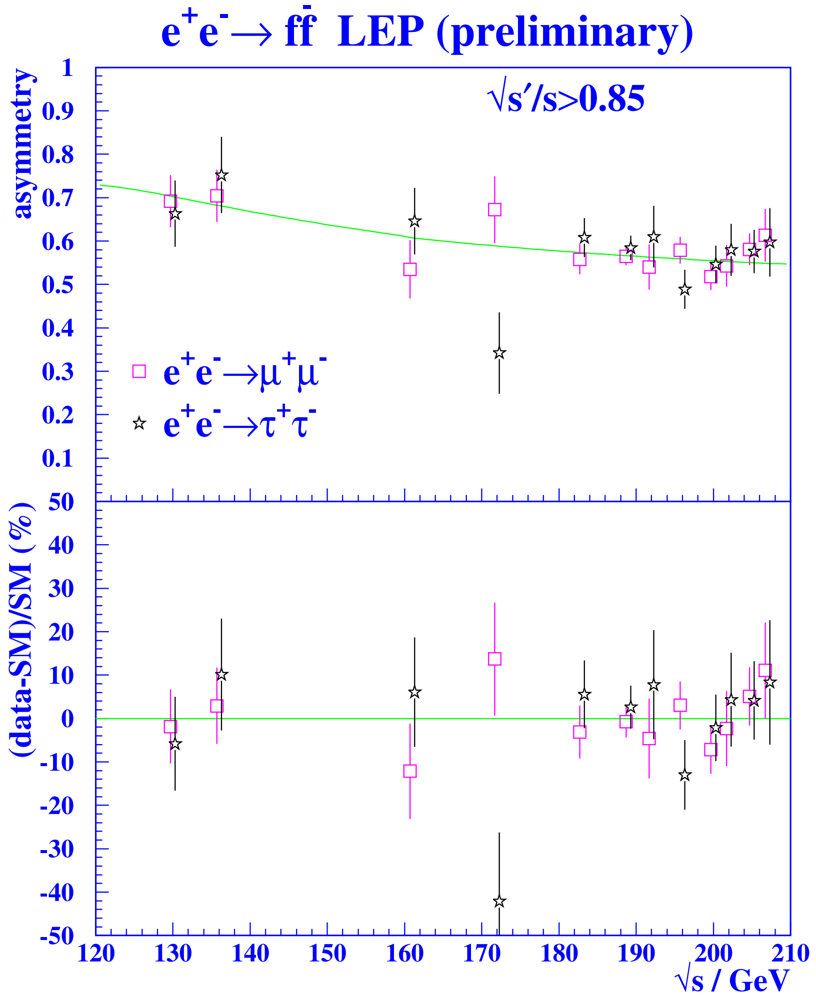
LEPII: 2-fermion

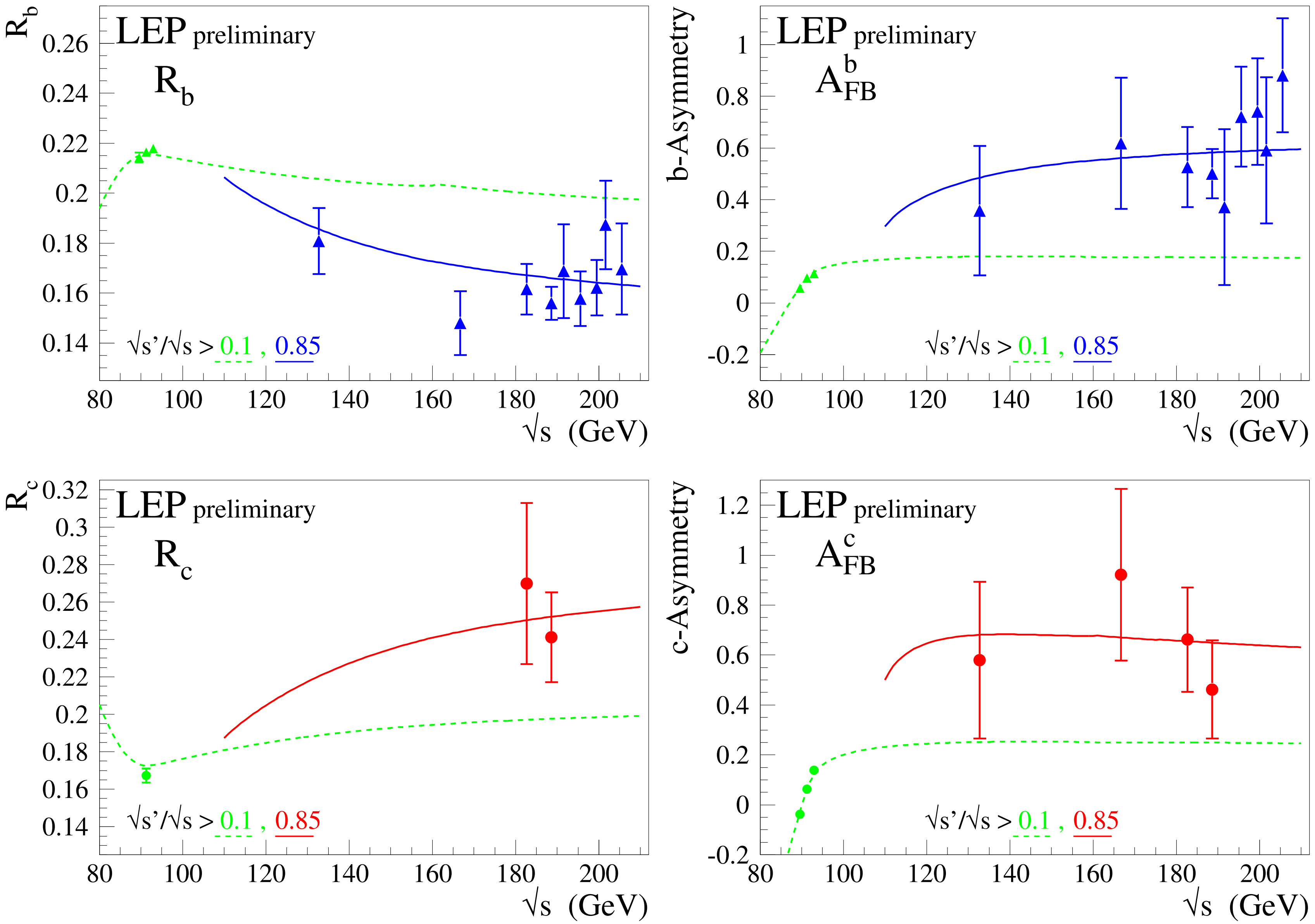


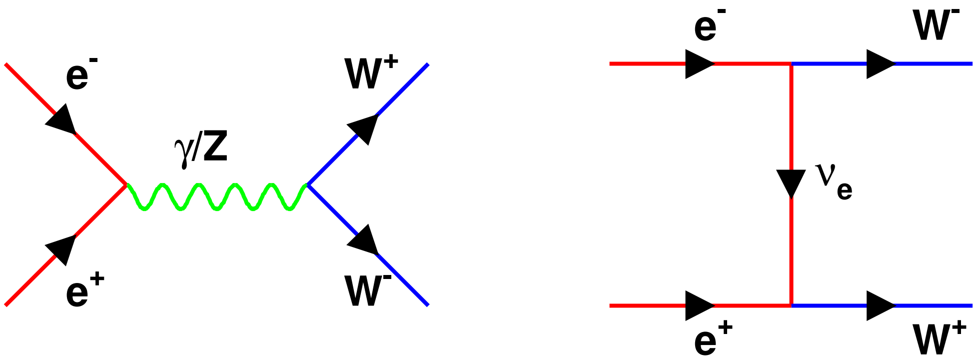


LEPII: 2-fermion






LEP preliminary
R_b
$\sqrt{s'}/\sqrt{s} >$ 0.1 , 0.85
$\sqrt{s}$ (GeV)
LEP preliminary
A_{FB}^{b}
b-Asymmetry
$\sqrt{s'}/\sqrt{s} >$ 0.1 , 0.85
$\sqrt{s}$ (GeV)
LEP preliminary
R_c
$\sqrt{s'}/\sqrt{s} >$ 0.1 , 0.85
$\sqrt{s}$ (GeV)
LEP preliminary
A_{FB}^{c}
c-Asymmetry
$\sqrt{s'}/\sqrt{s} >$ 0.1 , 0.85
$\sqrt{s}$ (GeV)

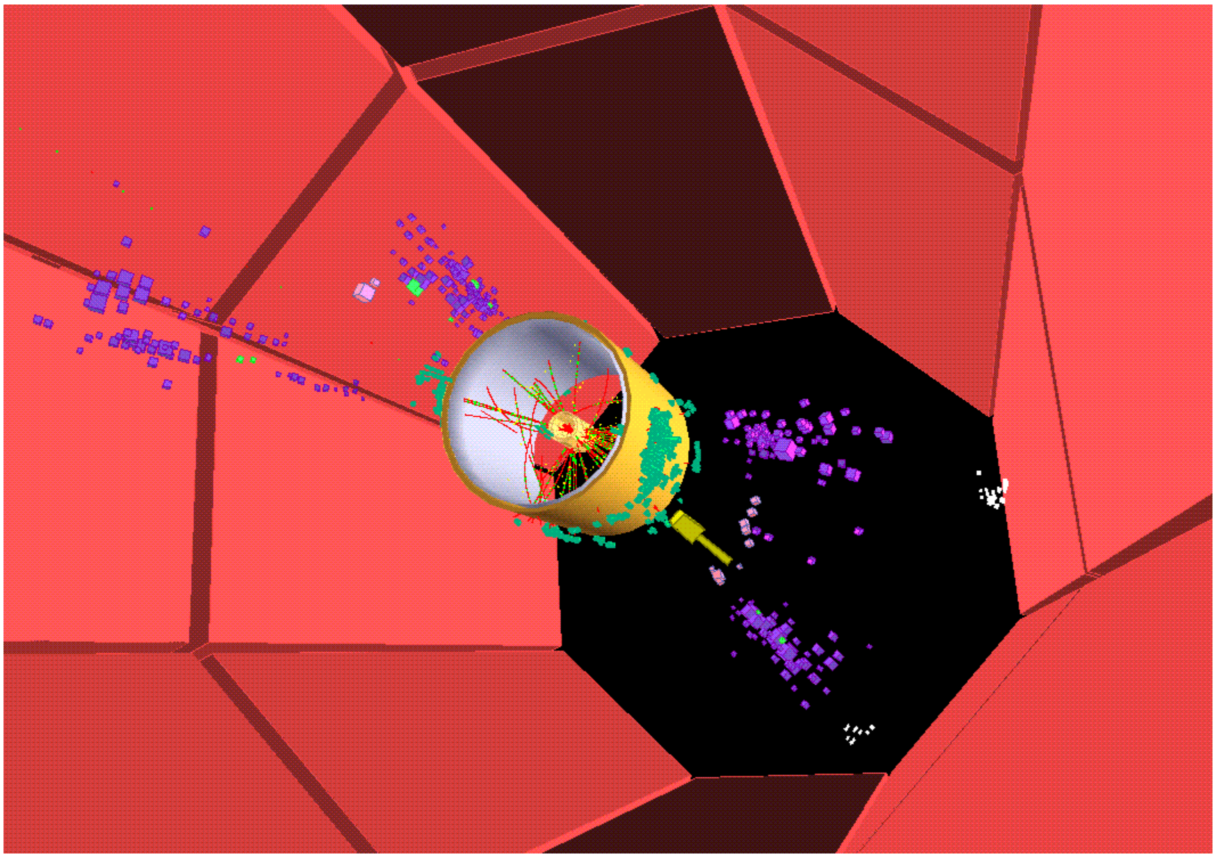


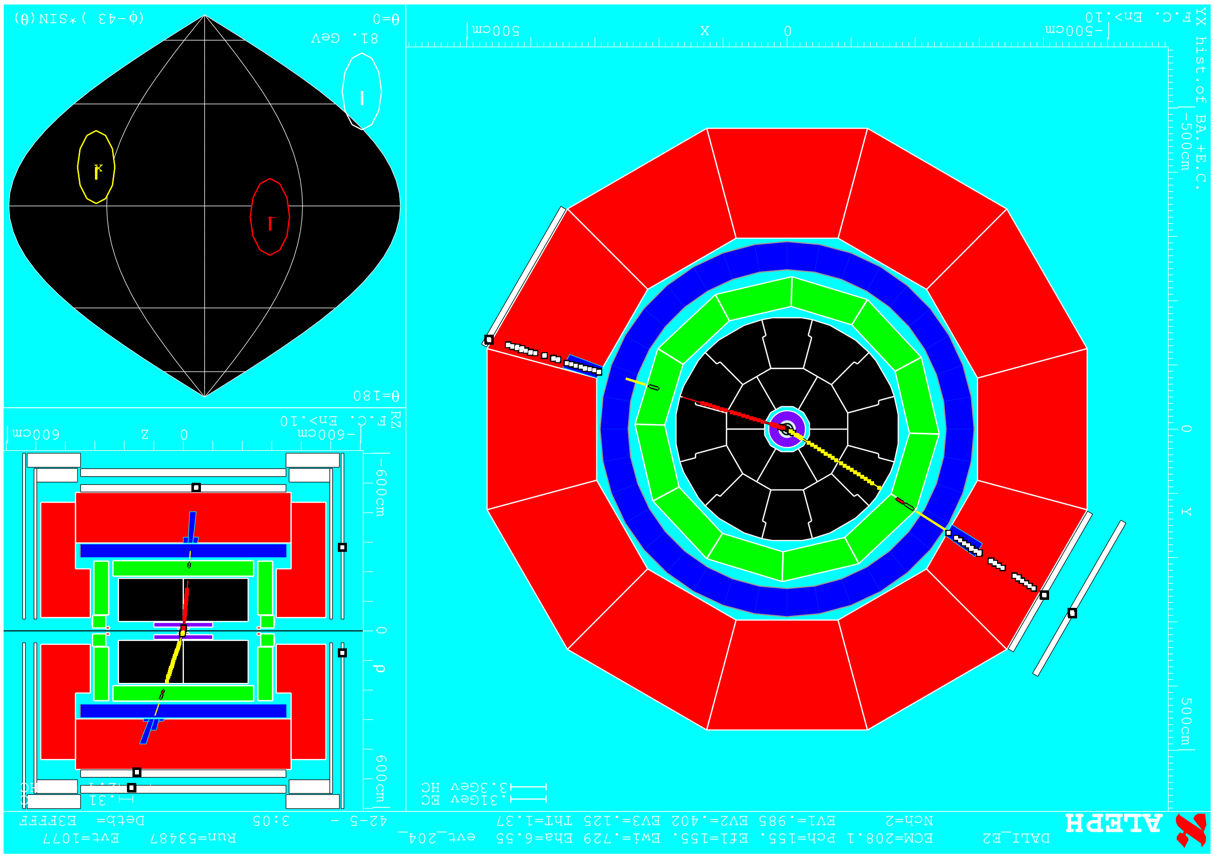
SM branchings $B(W\to q\overline{q'}) = 67.6\%$,
$B(W\to \ell\,\overline{\nu}) = 10.8\%$ per lepton flavour:

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

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

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





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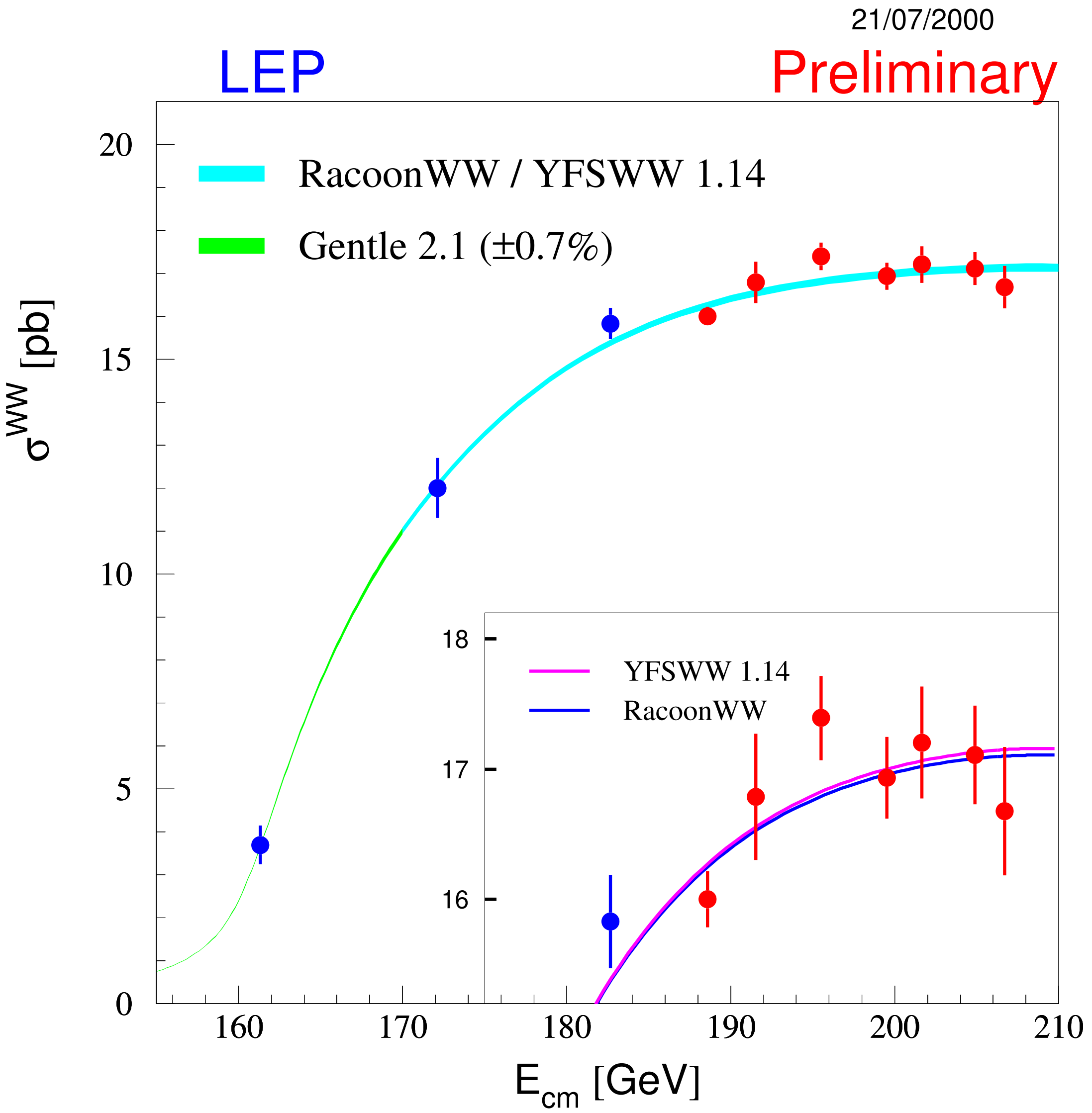
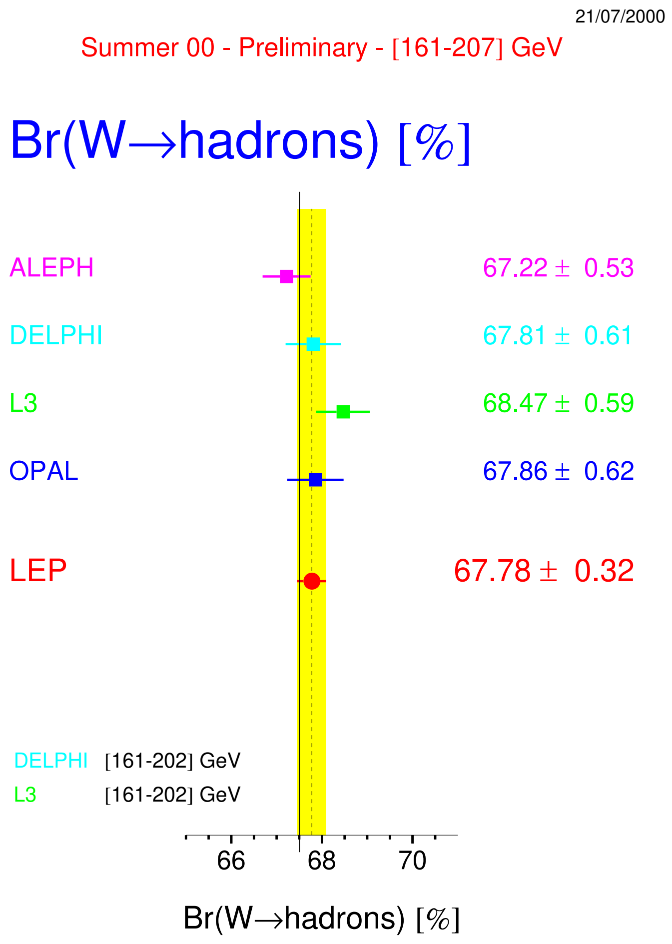
Energy dependence: combined LEP W^+W^- cross sections



Excellent agreement with SM

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

LEPII: W-Physics, W hadronic BR



Determination of $|V_{cs}|$:

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

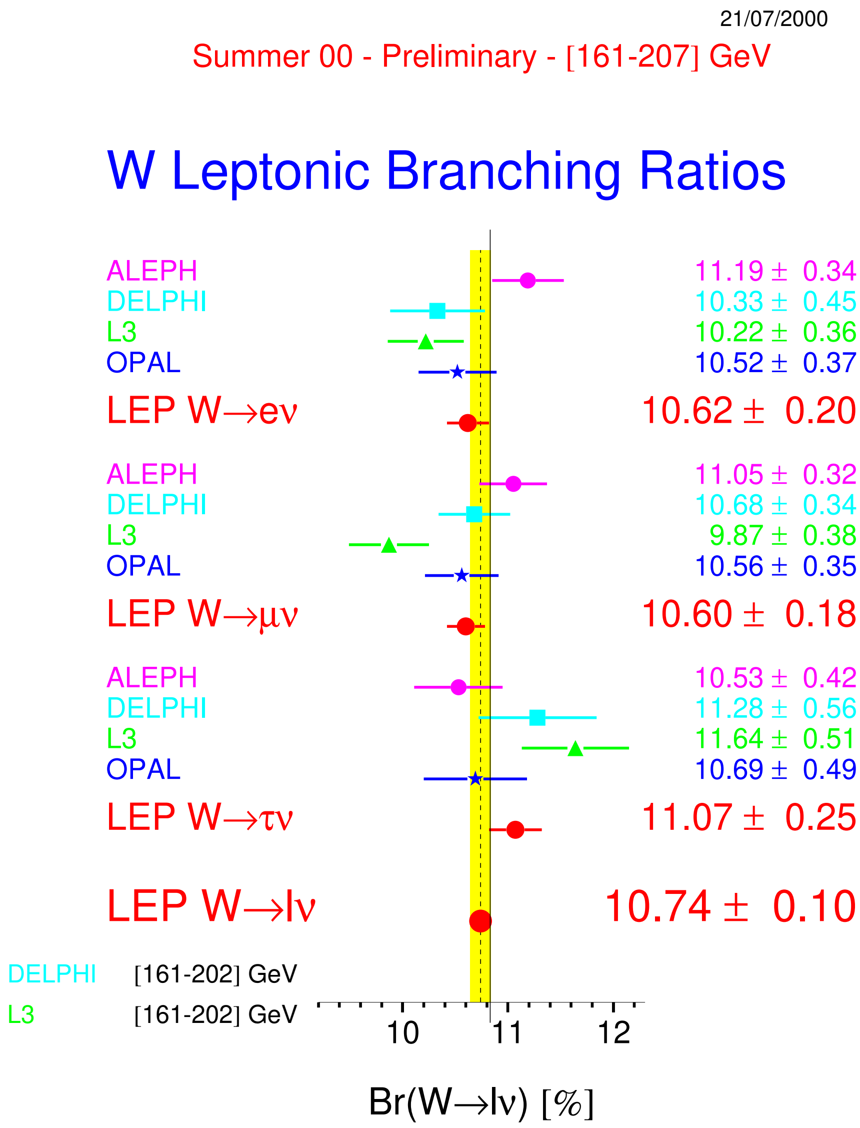
$$\boxed{|V_{cs}| = \mathbf{0.989 \pm 0.016}}$$

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

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

$\boxed{\Rightarrow |\mathbf{V_{cs}}| = \mathbf{0.91 \pm 0.07 \pm 0.11}}$ $\boxed{\textbf{LEP: } \mathbf{0.95 \pm 0.08}}$

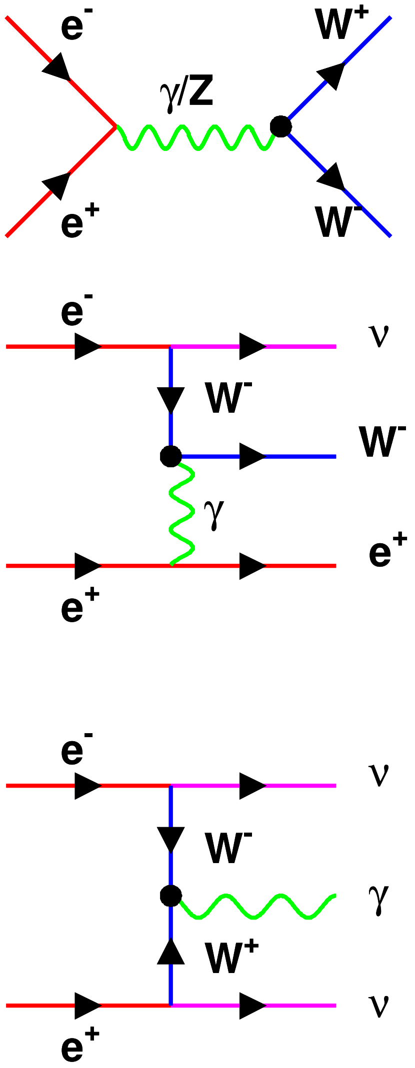
LEPII: W-Physics, W leptonic BR



Tevatron W$\rightarrow$ eν B.R.

D0: 10.50±0.30%; CDF: 10.39±0.35%

Combined: 10.43±0.25%



γWW, 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 $\equiv$ SM values)

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

LEPII: VWW - Triple Gauge Couplings

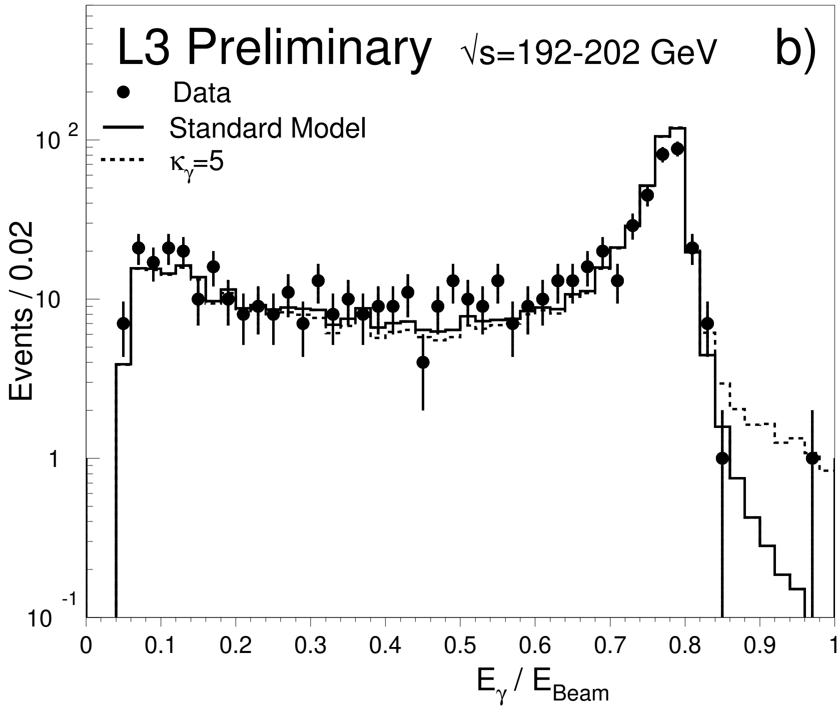
Now higher statistics:

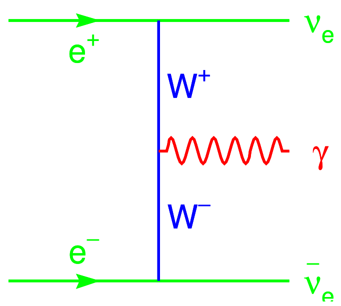
C-, P-, CP- violating couplings under study
2- and 3- parameter fits being carried out

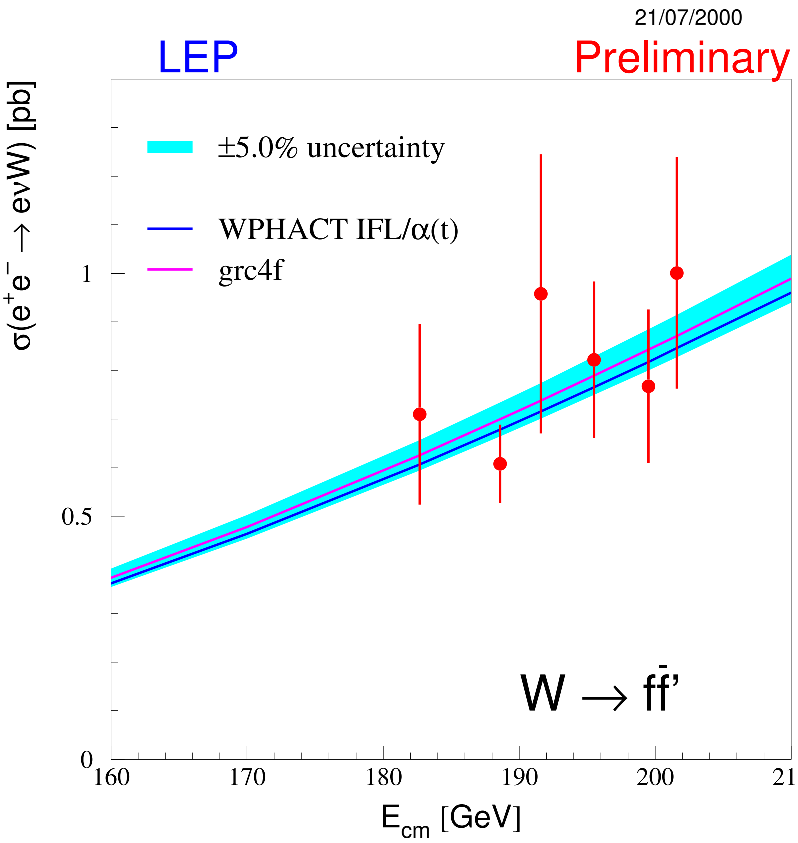
Sensitive Observables:

Cross sections, energy, angular distributions

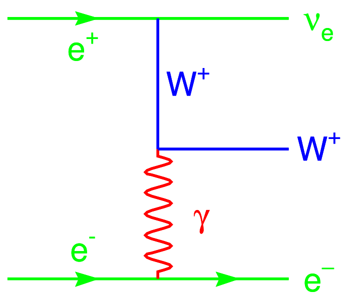
Example of single γ study: L3





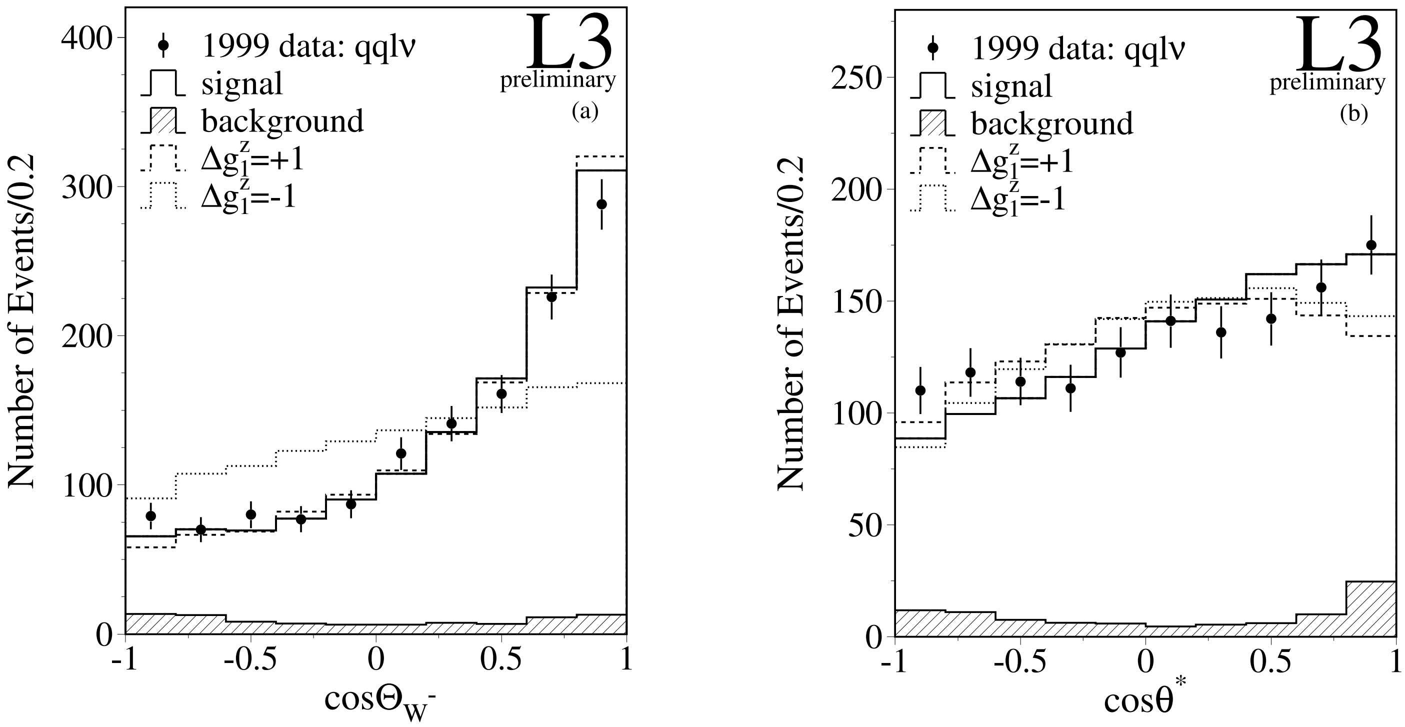


LEP single W Cross section



LEPII: VWW - Triple Gauge Couplings

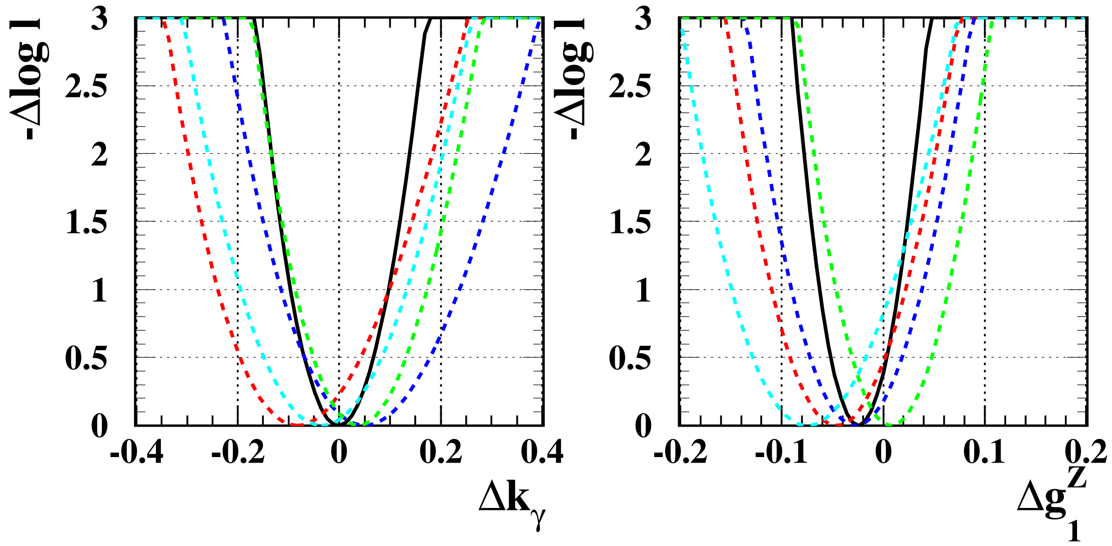
Example of W-pair study: L3

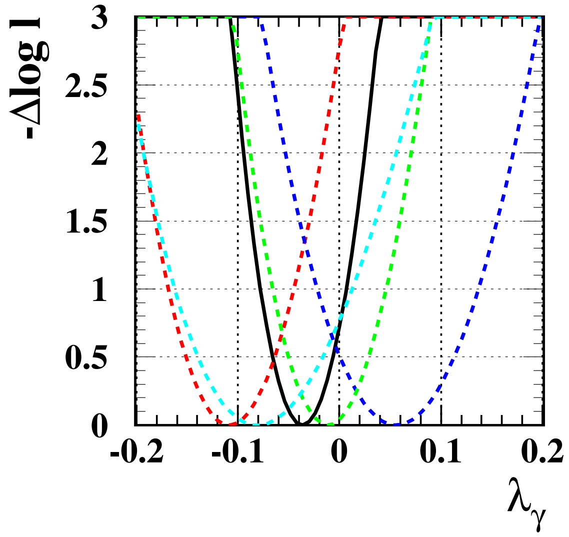


Extensive studies by all LEP collaborations
$\Rightarrow$ LEP combination of data

From Tevatron: no submission to the conference.
D0 Published results combining
$W\gamma$; WW $\rightarrow$ dilepton; WW/WZ $\rightarrow$ $e\nu jj, \mu\nu jj$; WZ $\rightarrow$ 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.**

ALEPH + DELPHI +L3 + OPAL





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

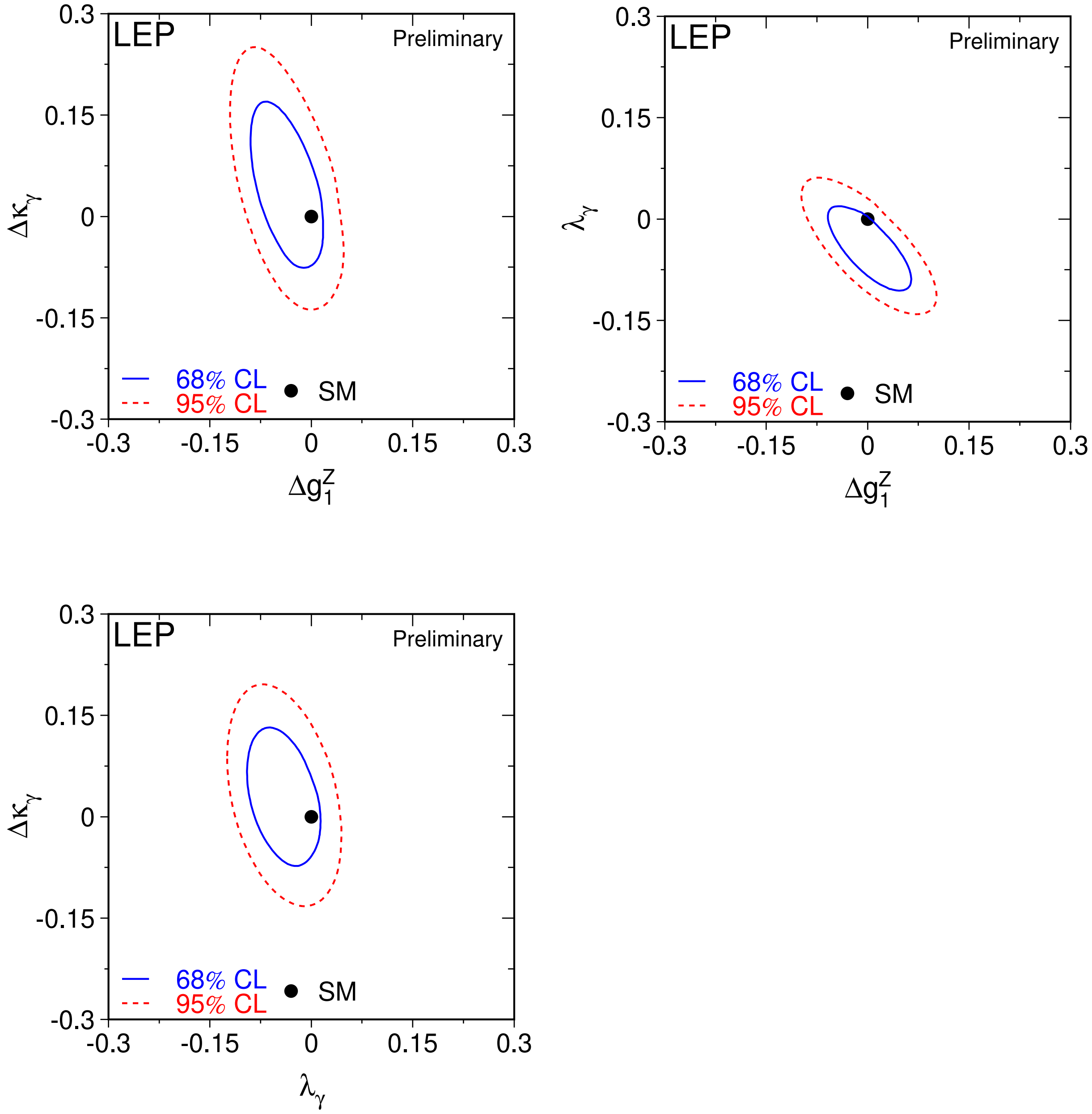
$$\Delta g_1^Z = -0.025^{+0.028}_{-0.027}$$

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

Preliminary

(1-PARAMETER FITS)

LEPII: VWW - Triple Gauge Couplings



(2-PARAMETER FITS)

LEPII: VWW - Triple Gauge Couplings

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	$g_4^Z=g_4^\gamma$	$-0.02^{+0.32}_{-0.32}$

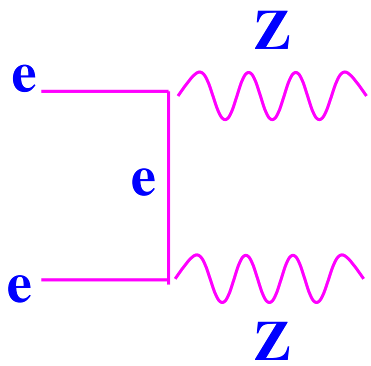
Good agreement with Standard Model

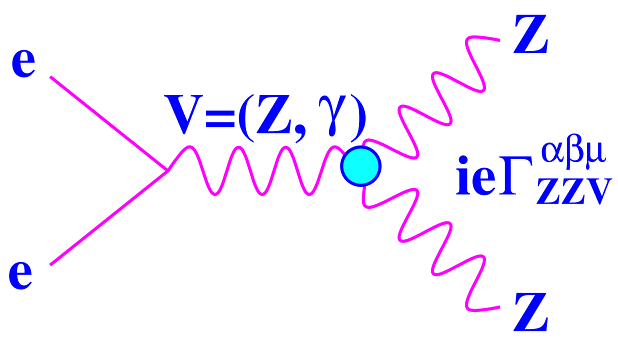
LEPII: ZZ & ZZV Couplings

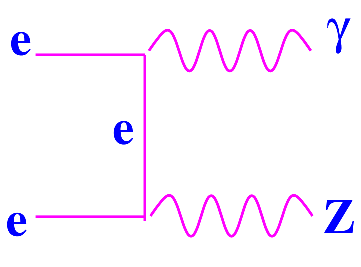
ZZV couplings studied via ZZ, Zγ production

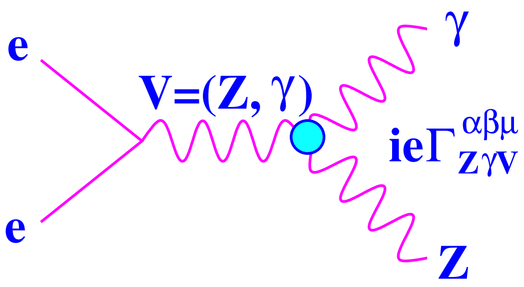
ZZ production above $\sqrt{s} = 183$ GeV at LEP

Standard Model **Anomalous**





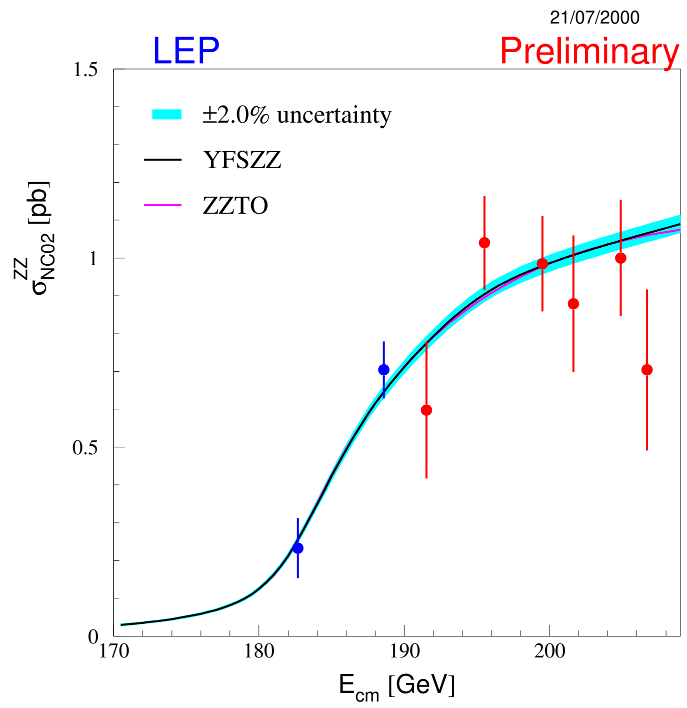


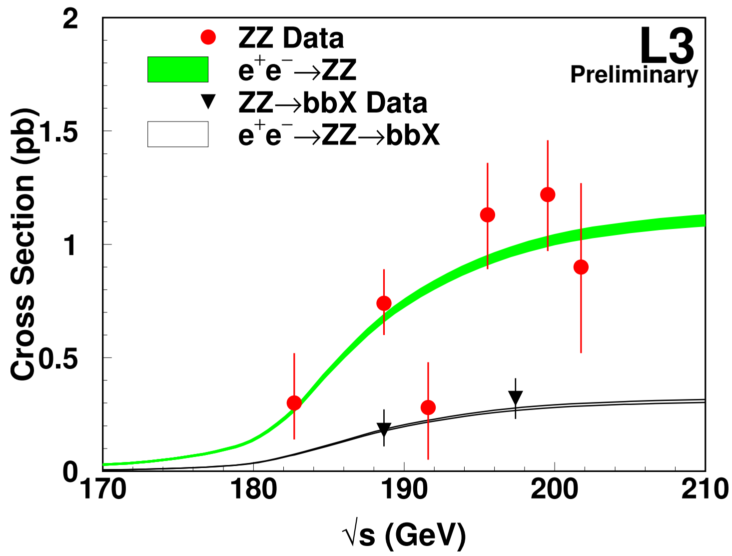


SM: ZZV coupling is zero

Anomalous ZZγ, 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:

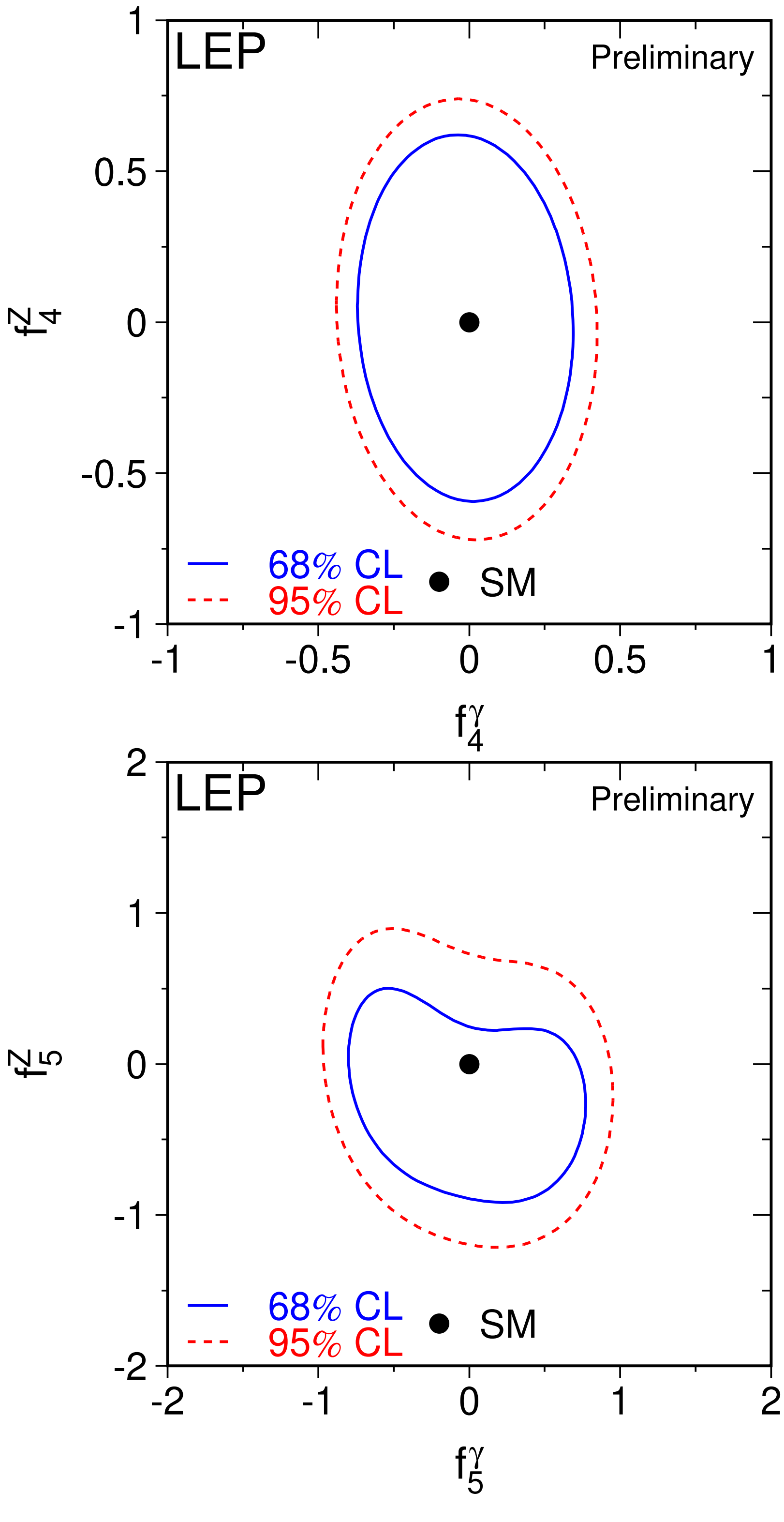
$$\frac{\sqrt{\alpha} h_i^V}{m_Z^2} \equiv \frac{1}{\Lambda_{iV}^2}, i = 1,3$$

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

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

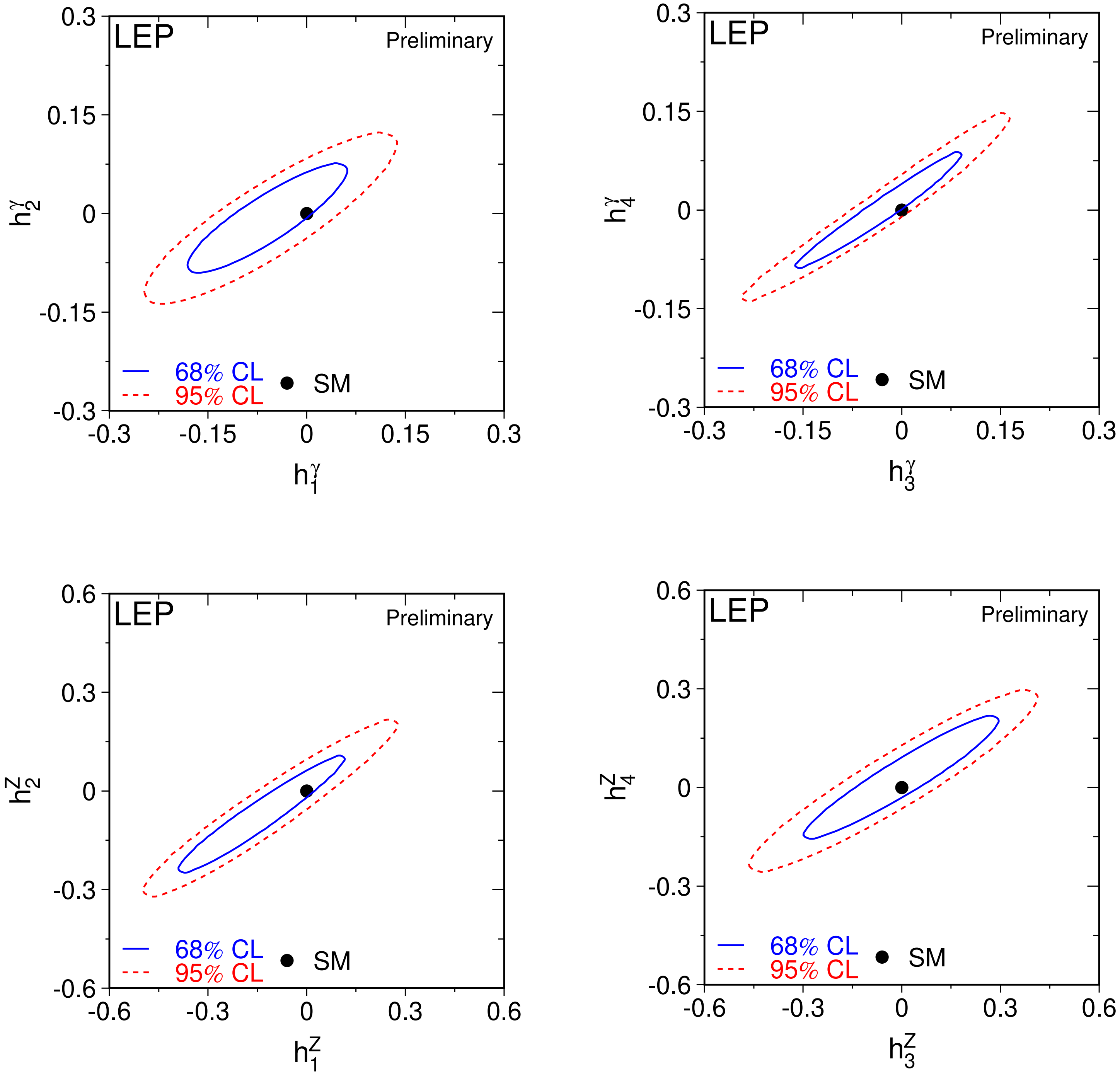
LEPII: ZZ & ZZV Couplings

FROM ZZ PRODUCTION



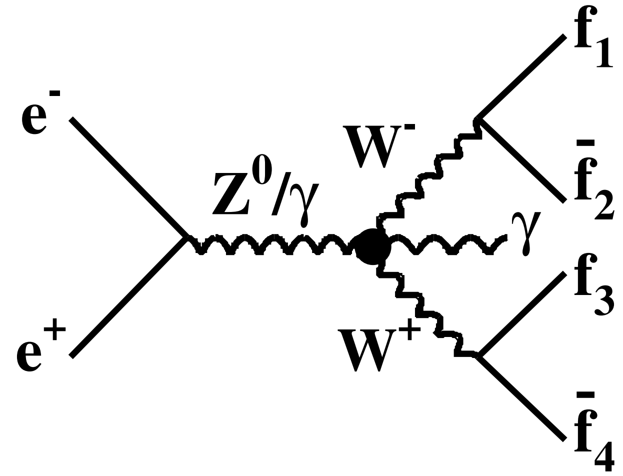
LEPII: ZZ & ZZV Couplings

FROM $Z\gamma$ PRODUCTION



SM predicts WWWW, WWZZ, WWZγ, WW$\gamma\gamma$ Couplings

Small at LEP, important at TeV linear Collider

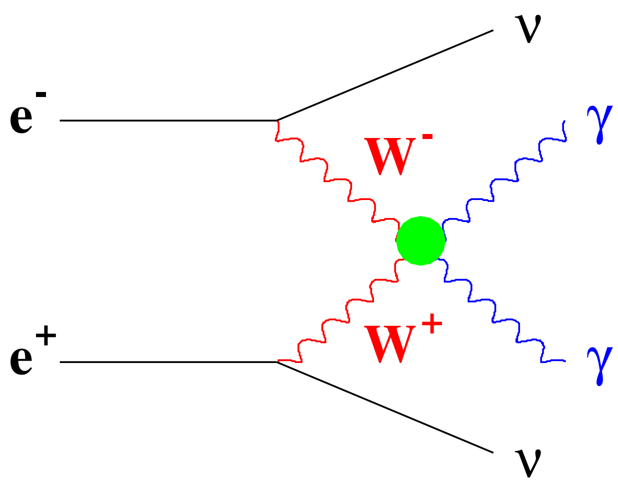


Six dimension operators:

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

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

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



$\mathbf{a_0, a_c, a_n}$: Anomalous Quartic Couplings "Outside" SM

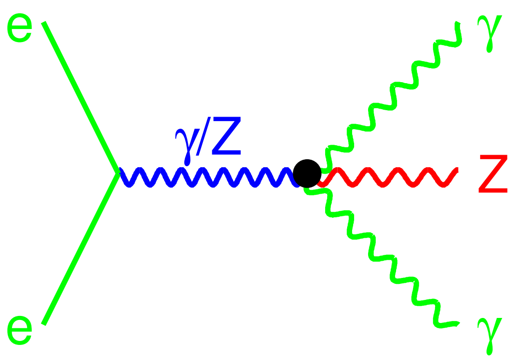
F, W **are photon and W fields**

L_6^0, L_6^c: **conserve C-, P- separately,** L_6^n **violates CP.**

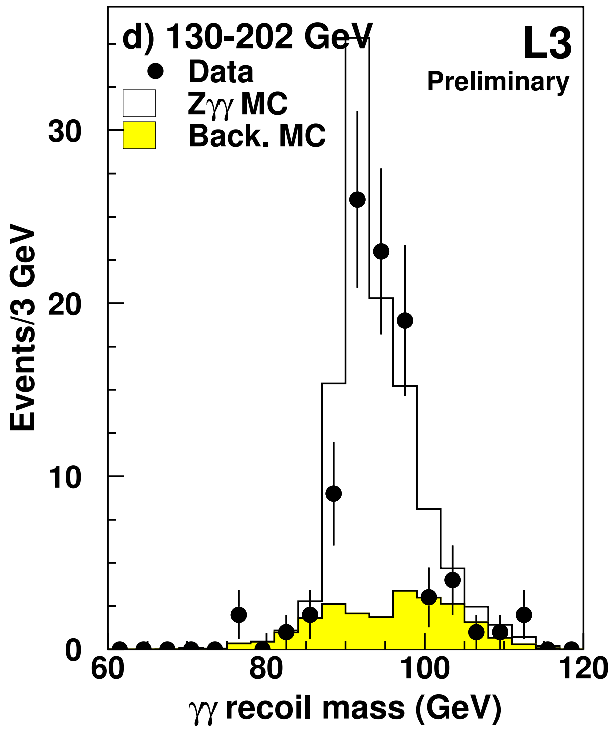
Λ : **scale for new physics**

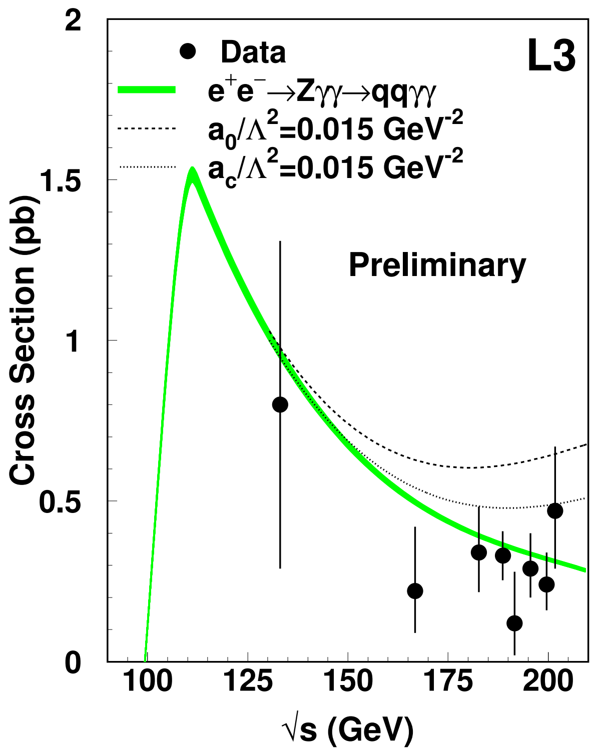
LEPII: $Z\gamma\gamma\gamma$ - Quartic Coupling

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



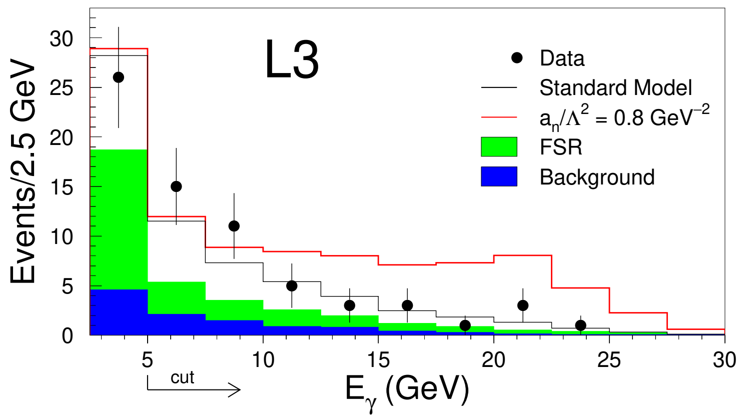


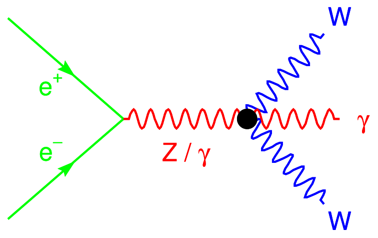
Results

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

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

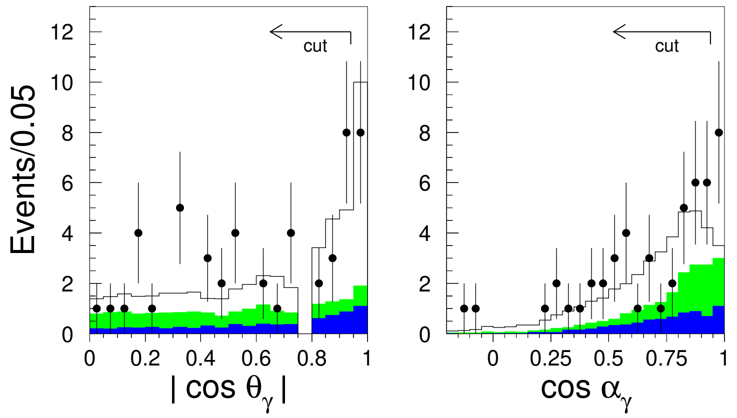
L3 use $WW\gamma$ (at 189 GeV) & $\gamma\gamma\nu\nu$ (at 183-202 GeV)

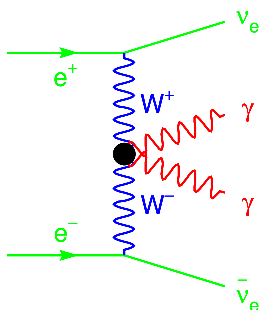


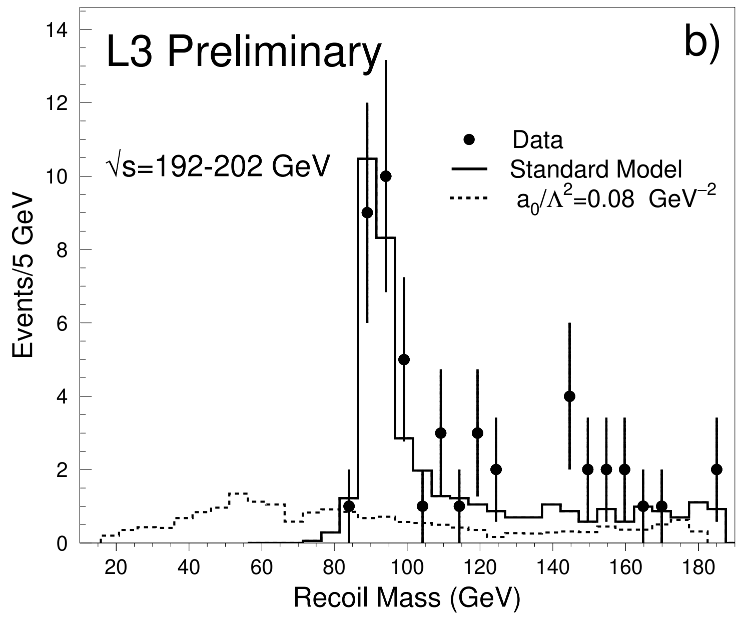


$WW\gamma$, 42 evts,

$\sigma = 290 \pm 80 \pm 16$ **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: Z$\gamma\gamma\gamma$ - Quartic Coupling

Opal (1999)

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

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

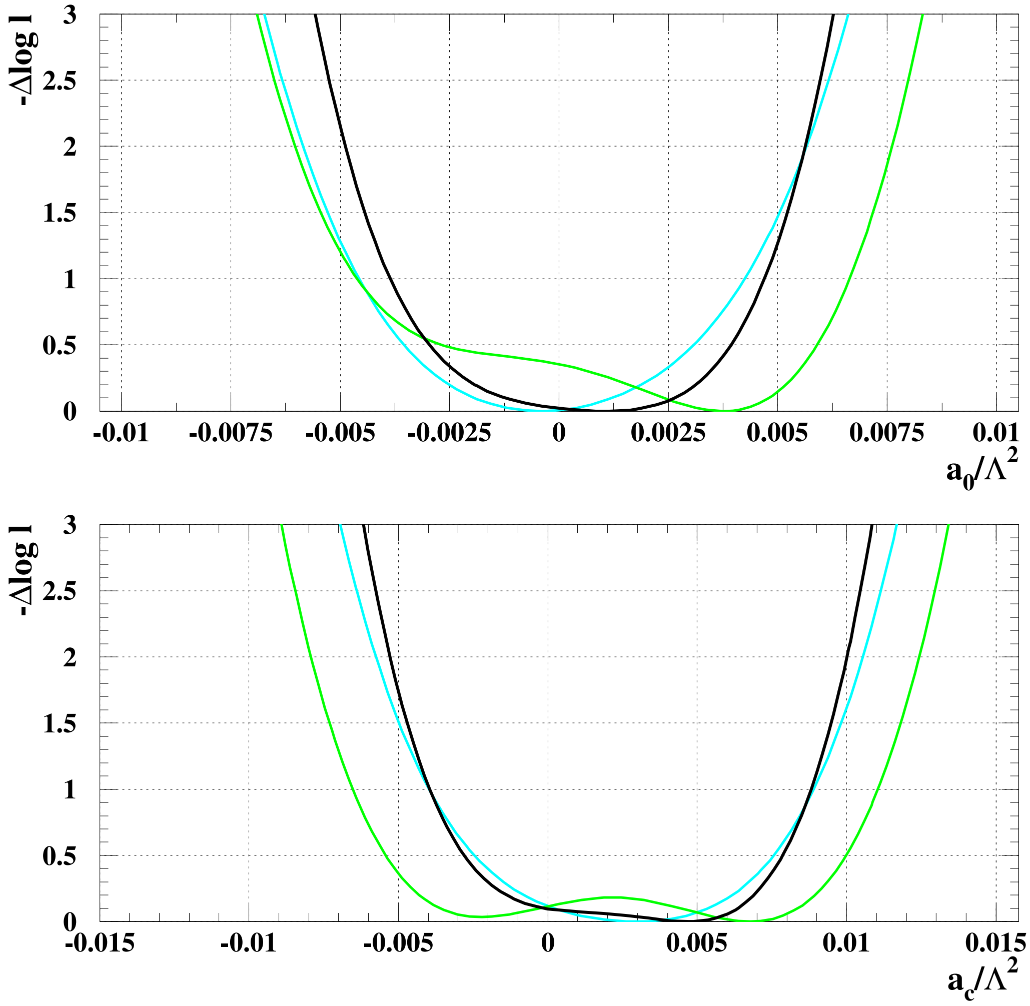
Aleph

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

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

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

Preliminary **L3+OPAL**

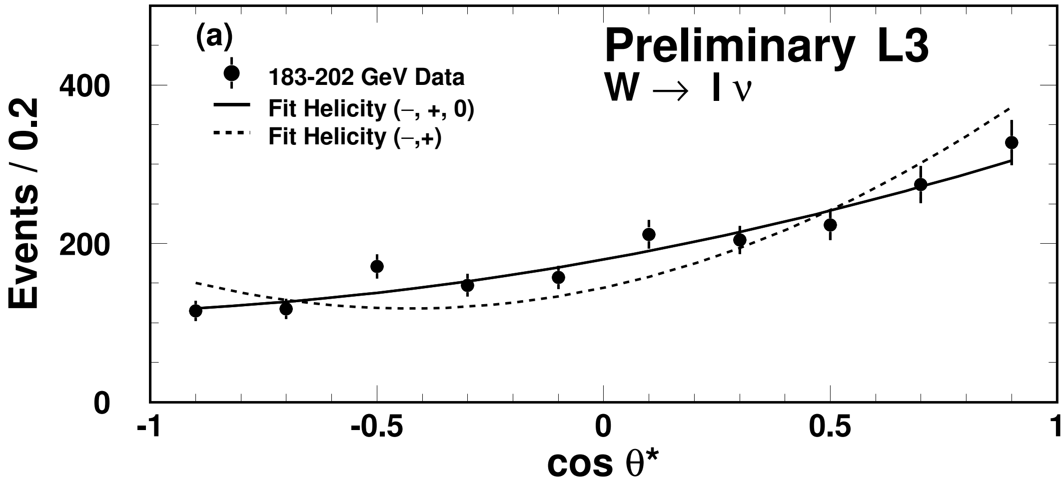


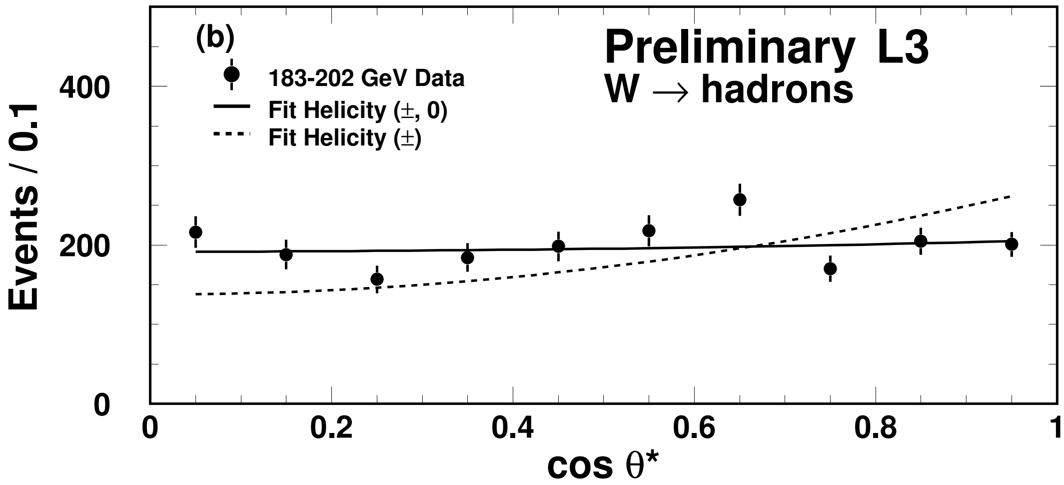
LEP Combined values ($\nu\nu\gamma\gamma + \mathbf{WW}\gamma + \mathbf{Z}\gamma\gamma$):

$$-0.0049 < a_0/\Lambda^2 < 0.0056$$
$$-0.0054 < a_c/\Lambda^2 < 0.0098$$

SM conserves CP in $e^+e^- \to W^+W^-$:
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^-)	**$0.565 \pm .060$**	**$0.181 \pm .032$**	**$0.254 \pm .049$**
W^+ helicity	**$+1$**	**-1**	**0**
Data (W^-)	**$0.559 \pm .068$**	**$0.177 \pm .036$**	**$0.264 \pm .049$**
Monte Carlo	**0.576**	**0.176**	**0.248**

Agreement with SM:

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

OPAL

Spin-density method on $W \to q\overline{q'}$ & $W \to \ell\nu$:

$$\sigma_L/\sigma_{TOT} = 21.0 \pm 3.3 \pm 1.3\%$$

(SM: 25.7%)

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

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

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 $\gamma Z \to t\overline{c}(\overline{u})$:

$$\Gamma^{\gamma}_{\mu} = \kappa_{\gamma}\frac{ee_q}{\Lambda}\sigma_{\mu\nu}q^{\nu}; \qquad \Gamma^{Z}_{\mu} = \kappa_{Z}\frac{e}{\sin 2\theta_W}\gamma_{\mu}$$

Λ: **new physics cutoff scale** $\equiv M_{top}$, $\kappa_{\gamma}, \kappa_{Z}$ **define strength of anomalous coupling.**

$$\text{CDF: } \kappa^2_{\gamma} < 0.176, \kappa^2_{Z} < 0.533$$

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.

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

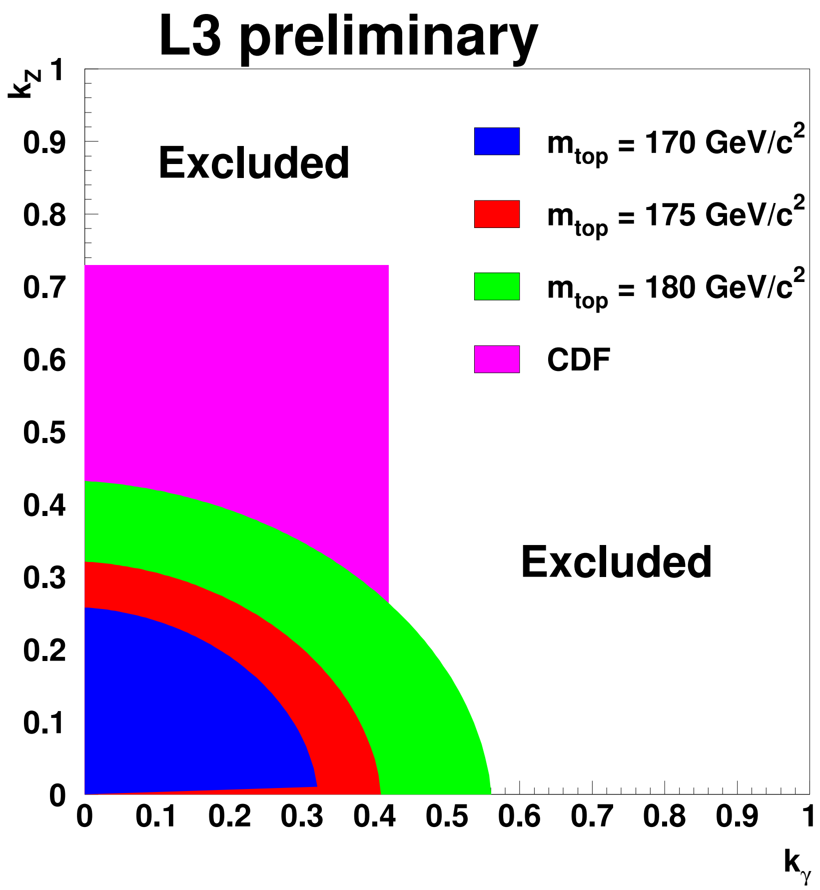
$$\boxed{\text{Opal } \sigma(e^+e^- \to t\bar{q}) < 390 \text{ fb, } 95\% \text{ CL}}$$

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

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

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

LEPII: FCNC via single top



LEPI: CPT test

Opal: 1st Test of CPT with τ Leptons

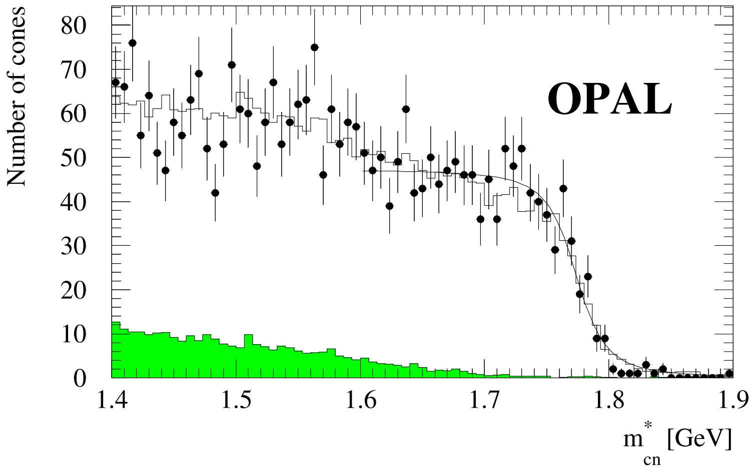
Data: 159K τ-pair evts 1990-95 around Z.

Pseudomass method

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

$h \equiv$ **hadronic system,** $\psi =$ **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 $m^\star_{cn}$ for
$\tau \to 3\pi^\pm\nu_\tau$

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

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

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

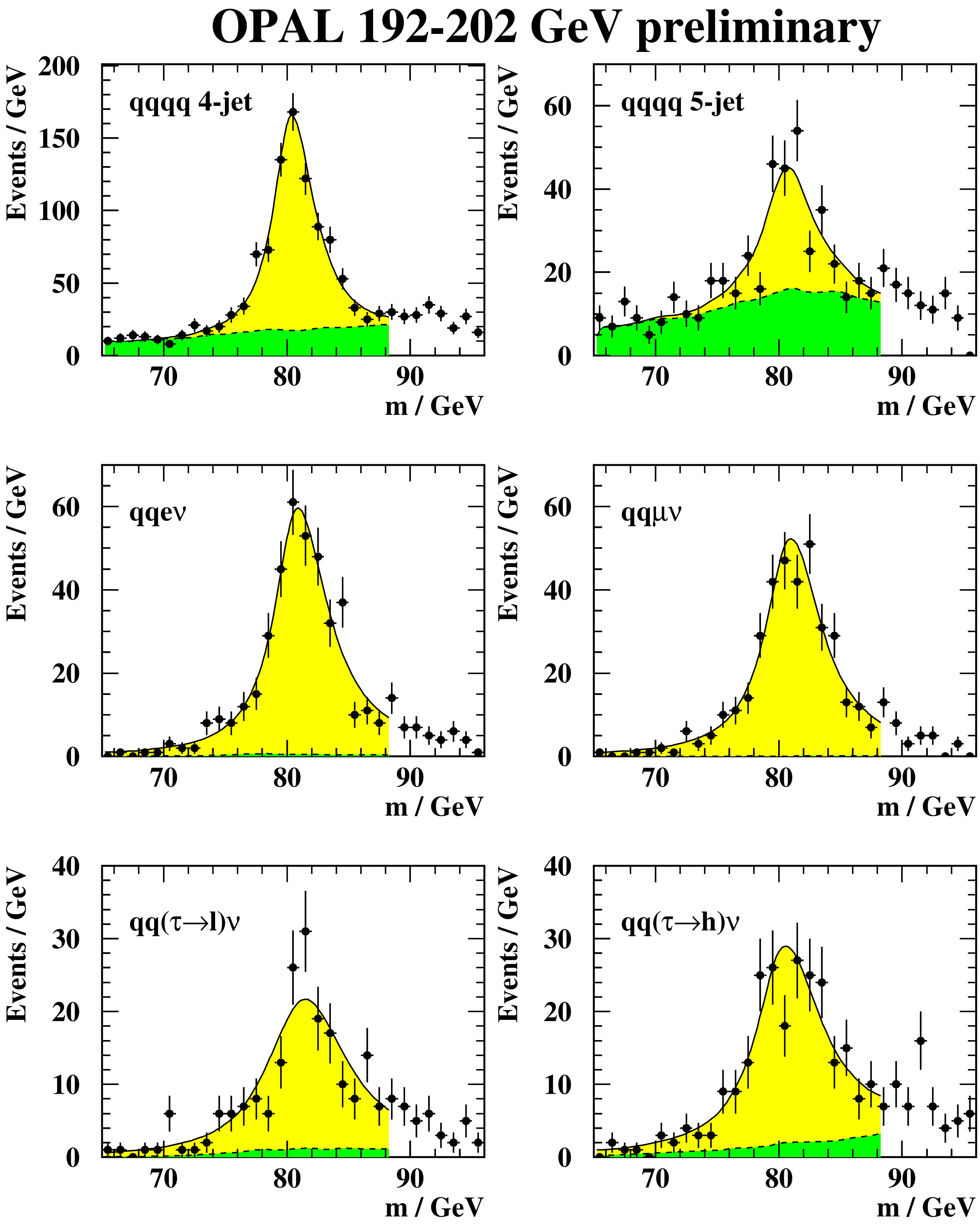
Precision determination of M_W, Γ_W:
A major goal of LEP II

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

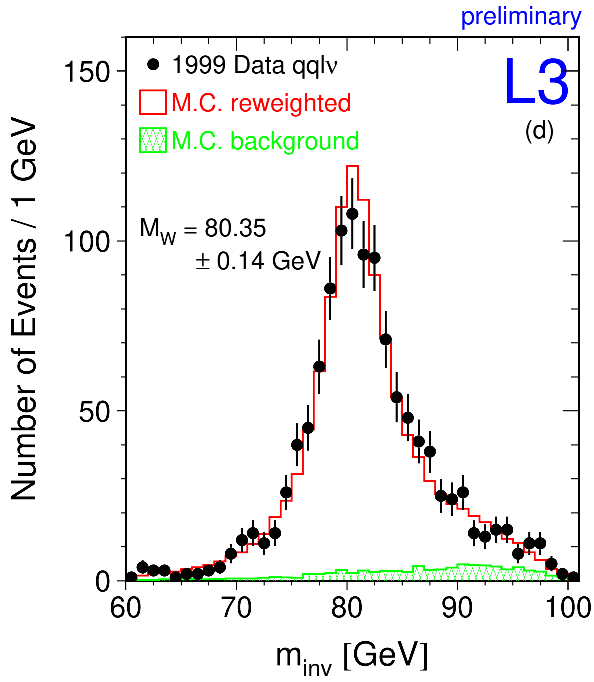
M_W determination

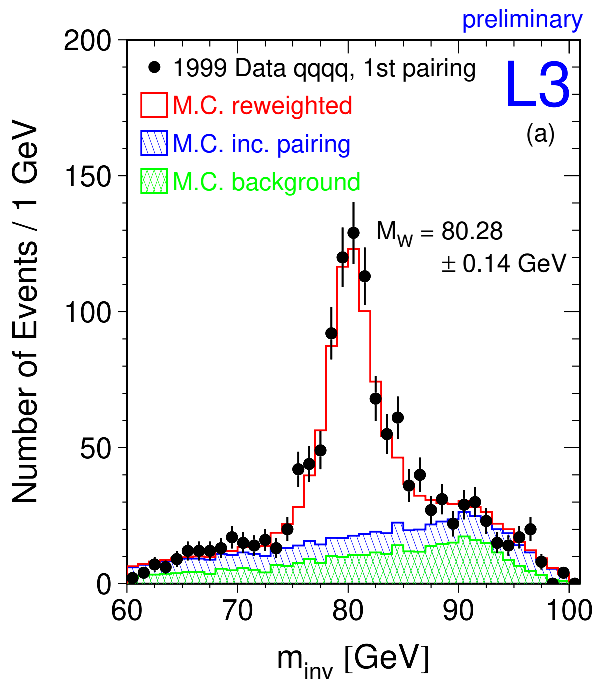
Known CM energy:
reconstruct the W's using kinematic fits,
fit the invariant mass distribution

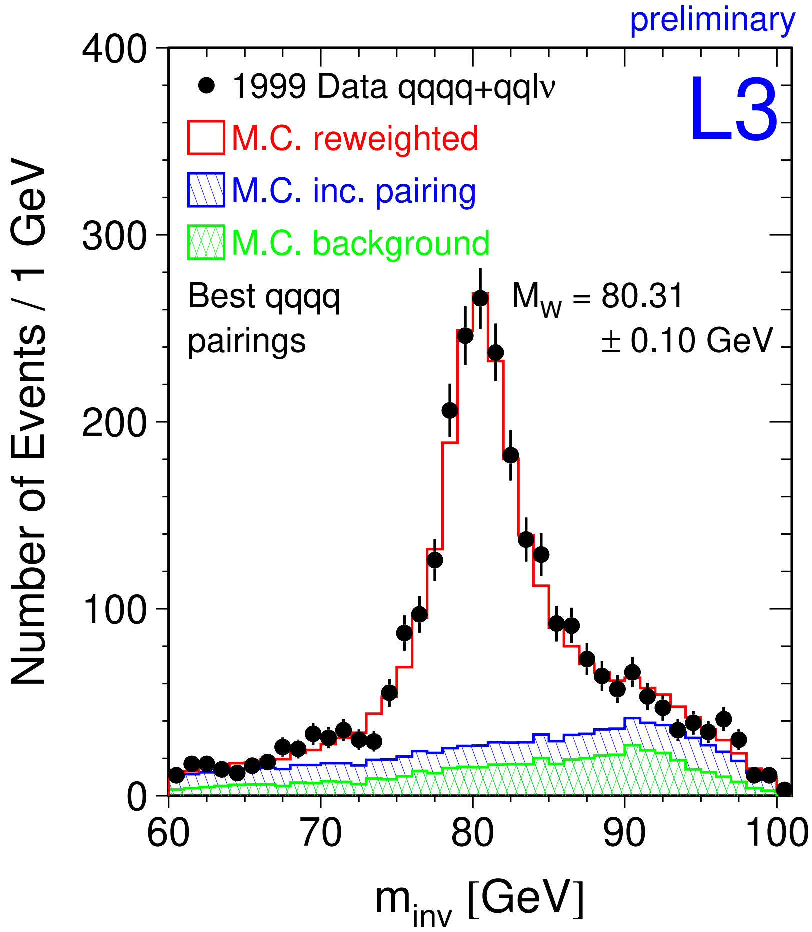
Individual LEP expts: syst err $\simeq$ stat err $\simeq$50 MeV
Combined LEP:
common systematics now dominates


OPAL 192-202 GeV preliminary
qqqq 4-jet
qqqq 5-jet
qqeν
qqμν
qq(τ→l)ν
qq(τ→h)ν
Events / GeV
m / GeV

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 on M_W correlated between experiments

– LEP energy error: $\sim$17 MeV,
may decrease to $\sim$ 12 MeV.

– ISR: small, Fragmentation: 20-30 MeV

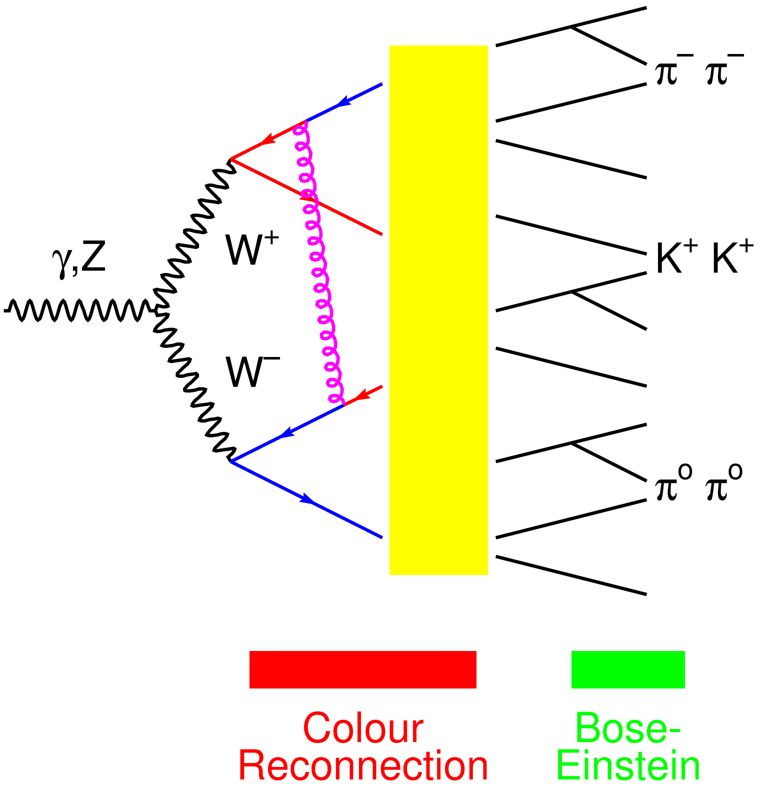
$\Rightarrow$BE, CR effects: $\sim$ 25, 50 MeV for qqqq !!

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

$\boxed{\textbf{Contribution of BE and CR to } \Delta M_W \sim \textbf{30 MeV}}$

LEPII: W Mass and width

Color Reconnection, Bose-Einstein studies



Distortion of M_{inv} distribution in qqqq state.

$\Downarrow$

POSSIBLE SHIFT in FITTED M_W

Color Reconnection:

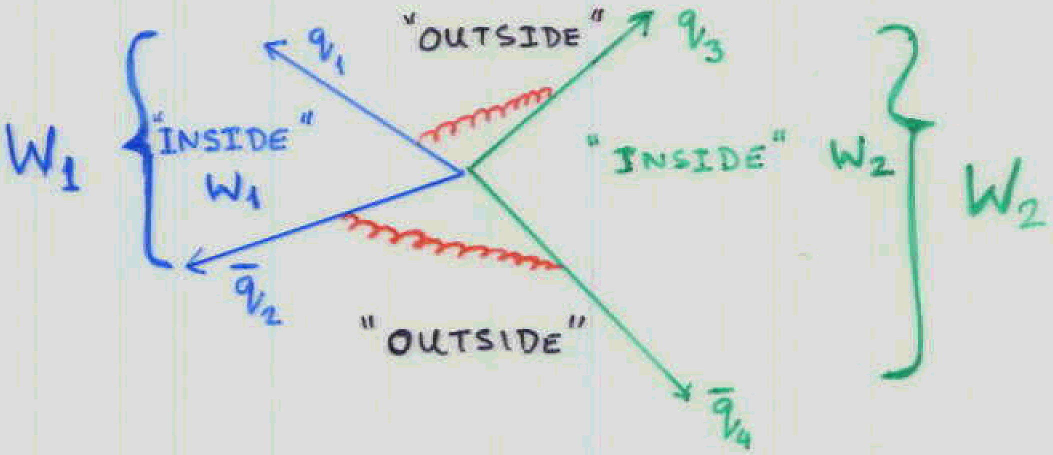
Non-perturbative: models used e.g.,:
Sjostrand-Khoze (SK), Gustafson-Hakkinen (GH)

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.

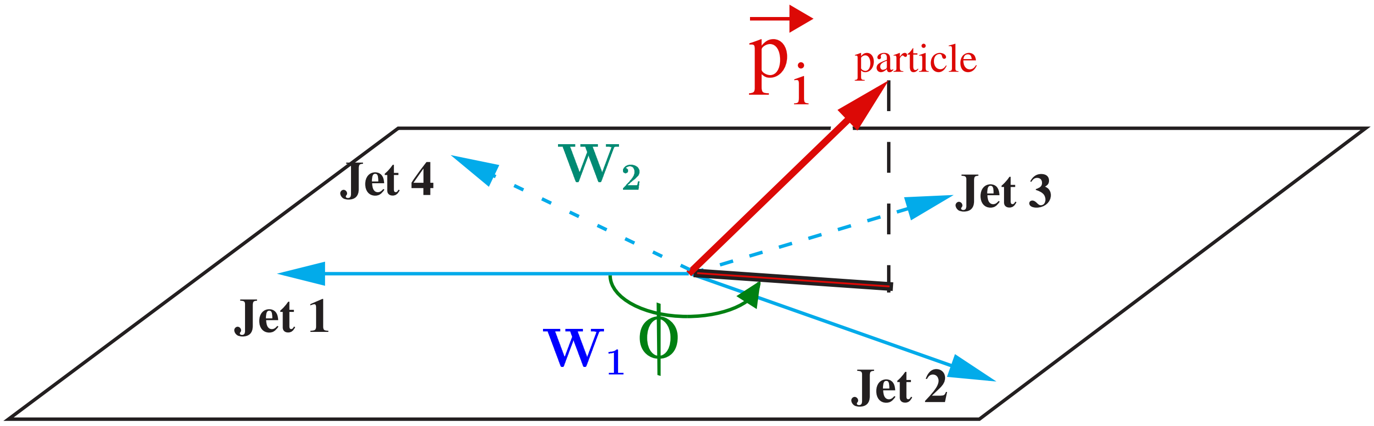


TAKE RATIO OF PARTICLES

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

STUDY OF INTER-JET PARTICLE & ENERGY FLOW

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

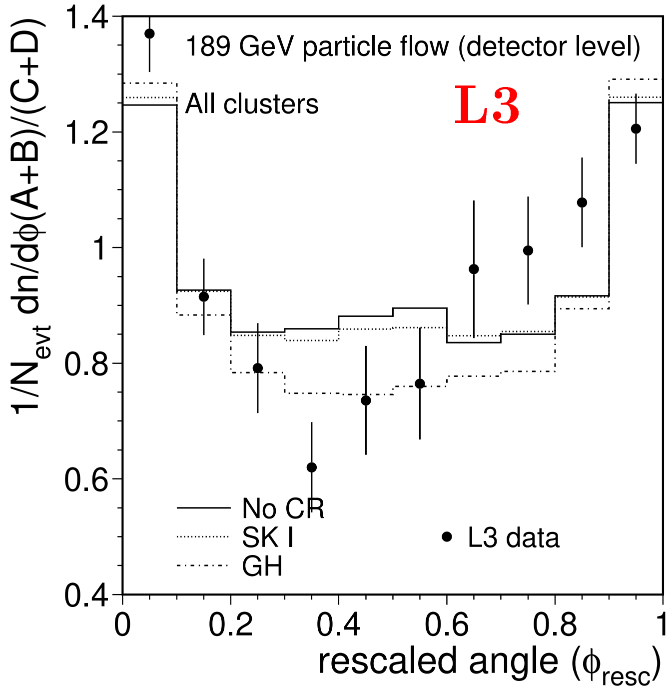
Jets 3 & 4 from W_2

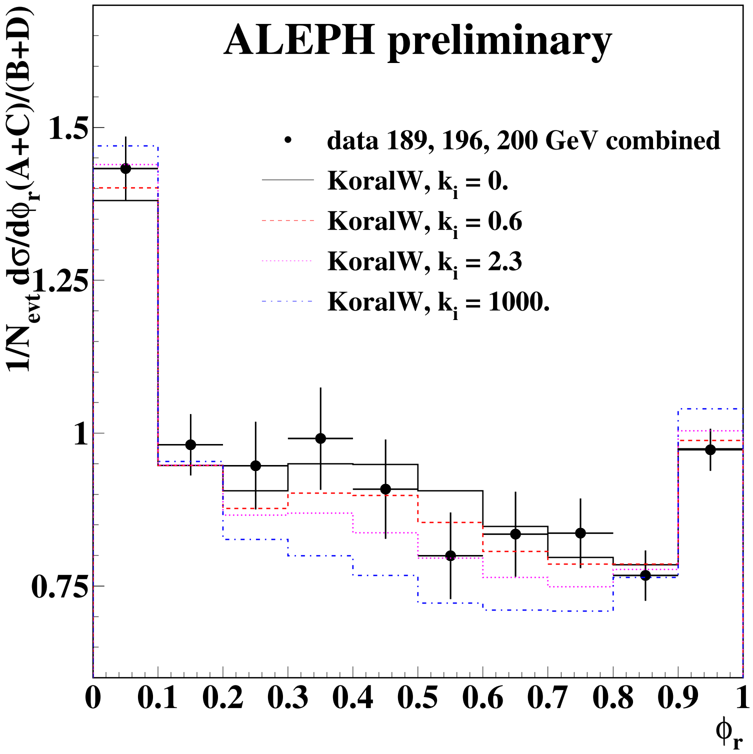
Four angular regions (A, B, C, D):

(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

$\boxed{\textbf{Currently LEP expts use } \Delta M_W(\text{CR}) = 50 \textbf{ MeV}}$

(End of LEP run: $\sim 600\text{pb}^{-1}$/expt should see a 3.5σ effect if CR prob is 35% in SK-I model)

– 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.
(Aleph, L3 disfavour)

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

Studying the BEC effect

Correlation function

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

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

LEPII: W Mass and width

Parametrized as

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

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

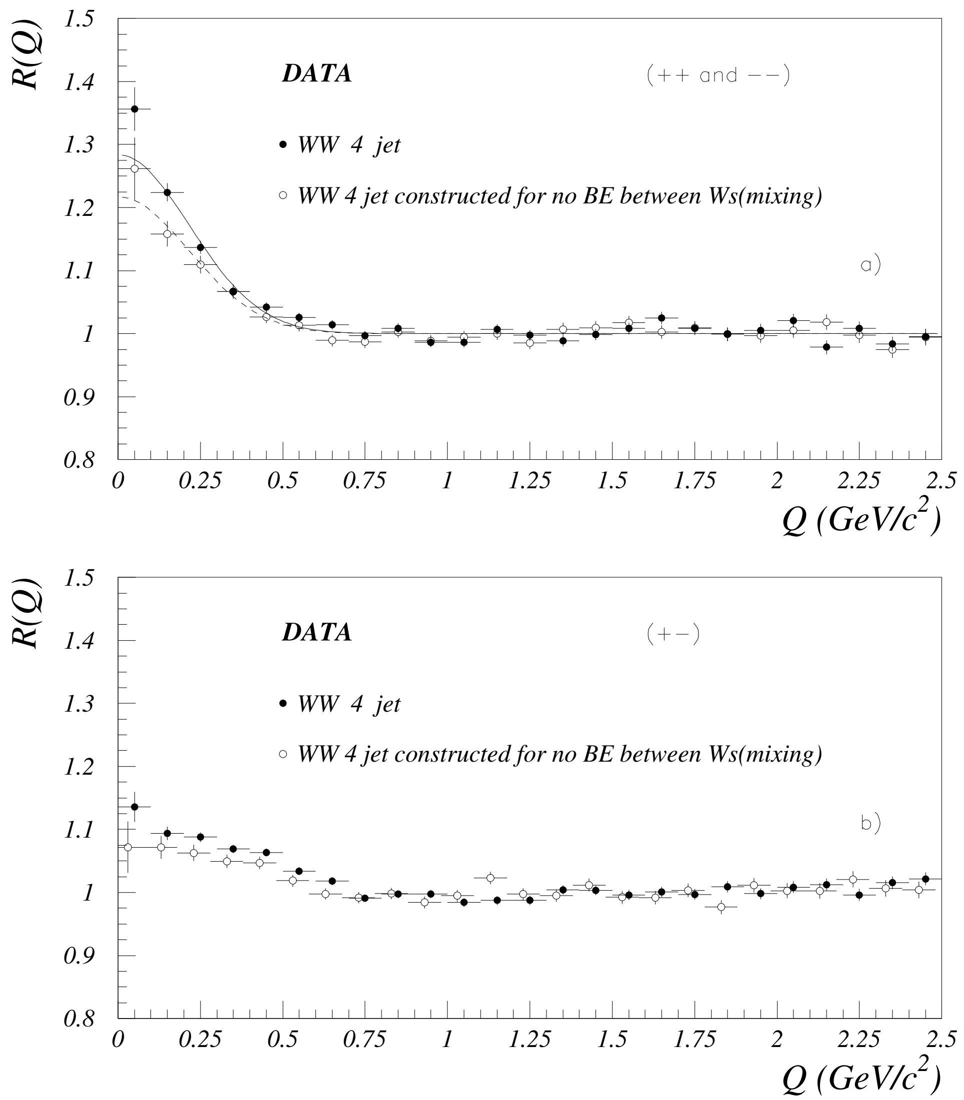
Delphi measured R(Q) in:

- **hadronic Z decays,**
- **WW**$\rightarrow$**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

DELPHI(preliminary)



Correlation strength diff. between 4q data and

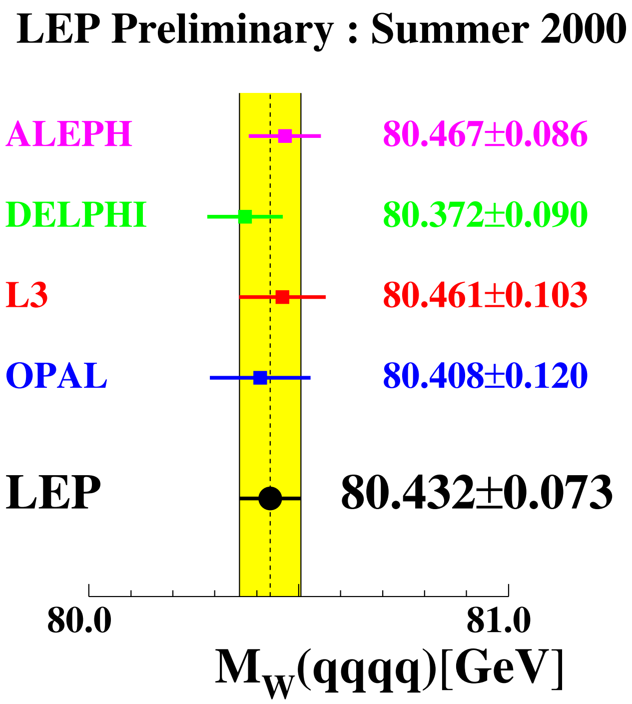
– Mixed events $\Delta\lambda = 0.062 \pm .025 \pm .021$

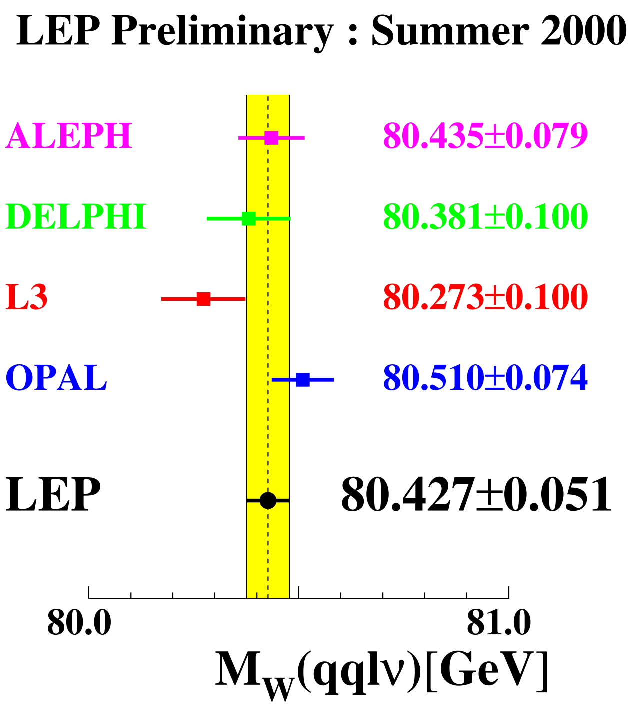
– qq$\ell\nu$ $\Delta\lambda = 0.077 \pm .026 \pm .020$

Needs further study, confirmation by ADO

$\boxed{\textbf{Currently LEP expts use } \Delta M_W(BE) = 25 \textbf{ MeV.}}$

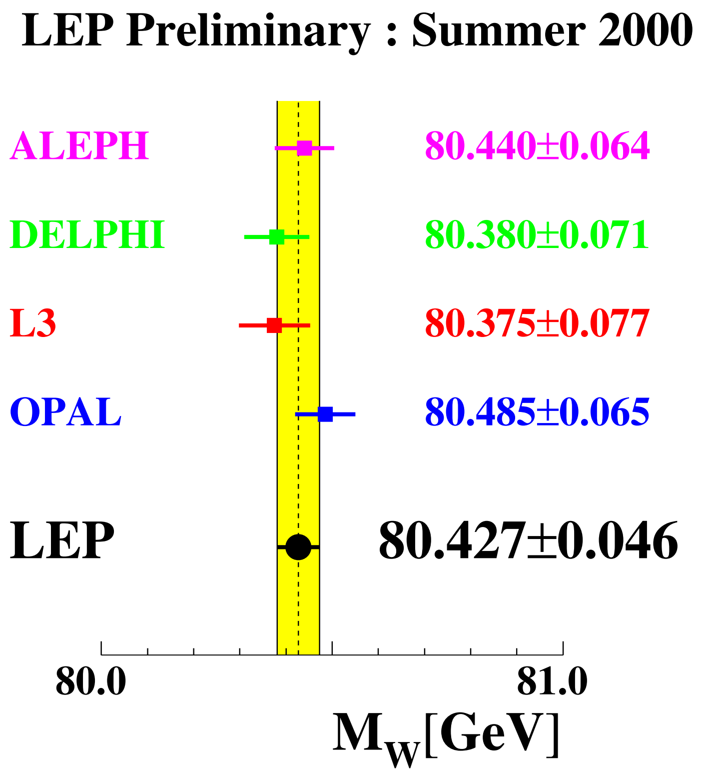
LEPII: W Mass and width

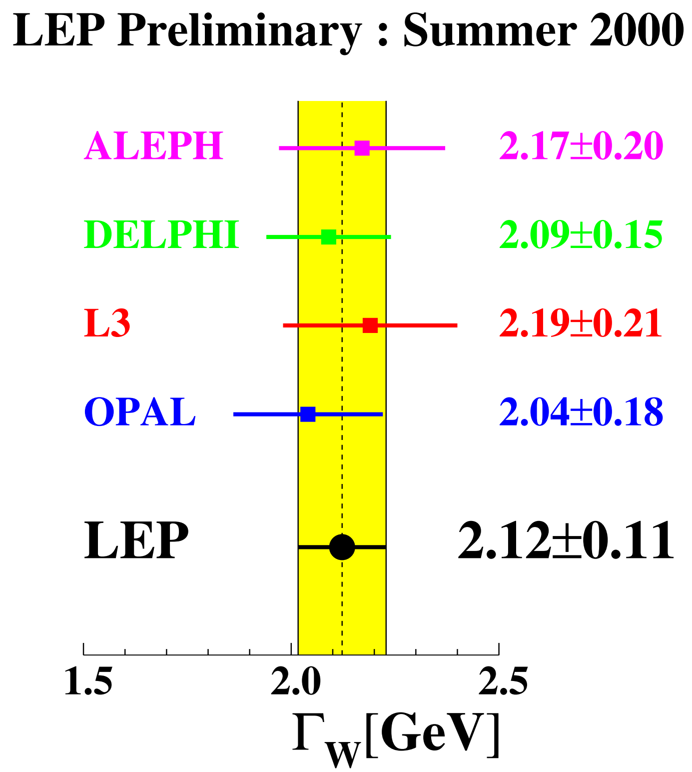




$$\mathbf{M_W(qqqq) - M_W(qq\ell\nu) = 5{\pm}51\ MeV}$$
$$\Longrightarrow \mathbf{CR + BE\ effects \neq large}$$

LEPII: W Mass and width

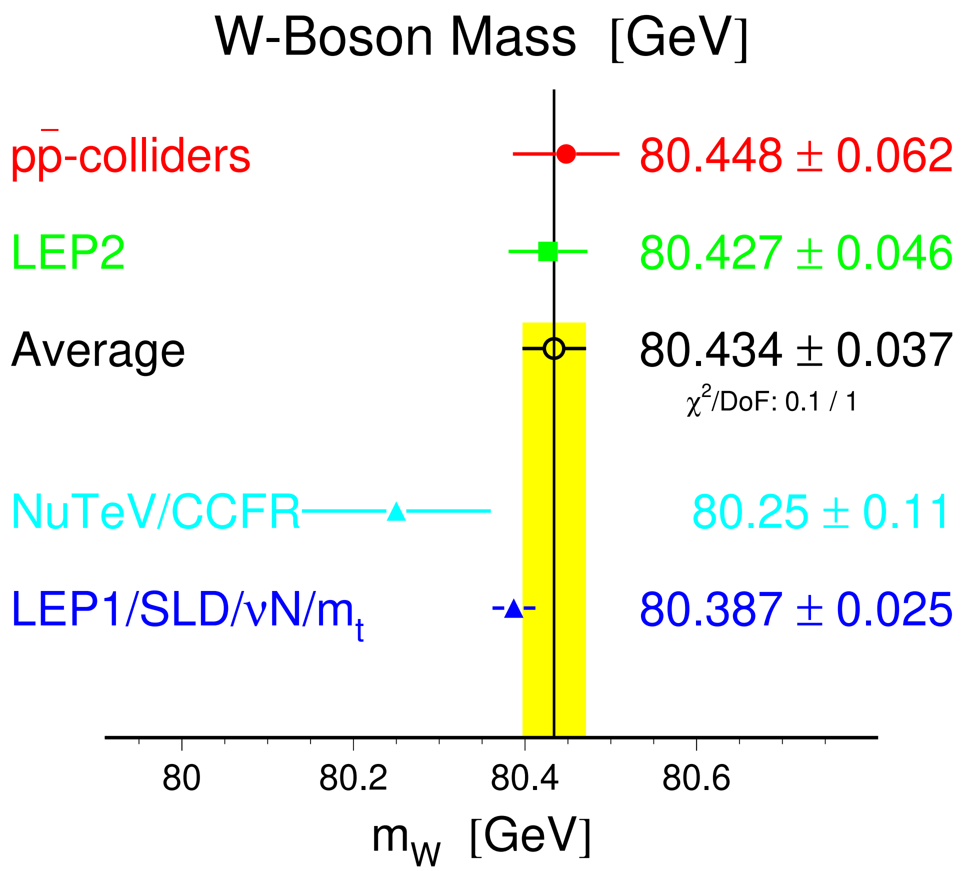




LEP value of Γ_W: 2.12±0.11 GeV

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

WORLD AVERAGE OF W MASS

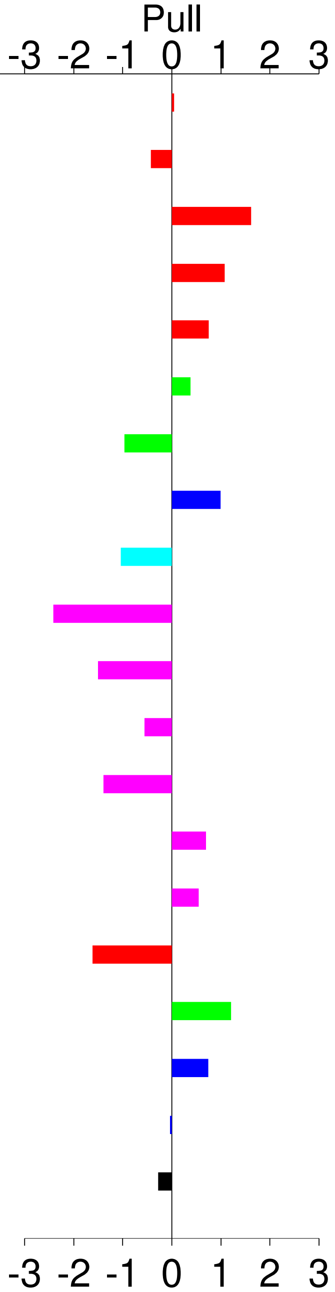


Global Fit to EW data

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

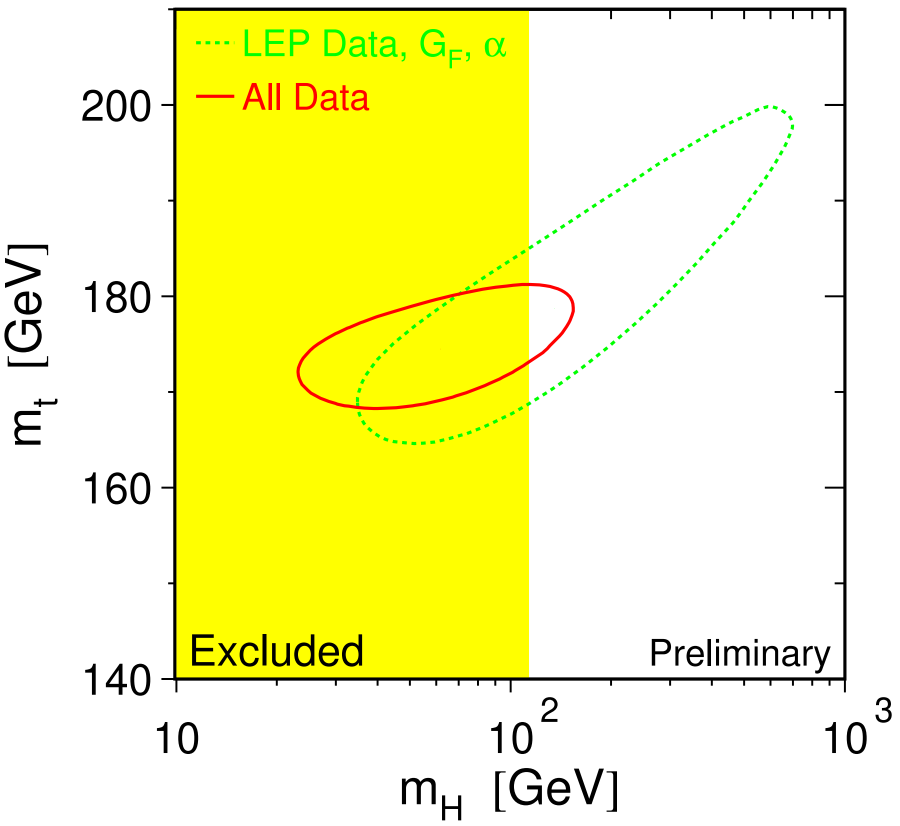
Osaka 2000

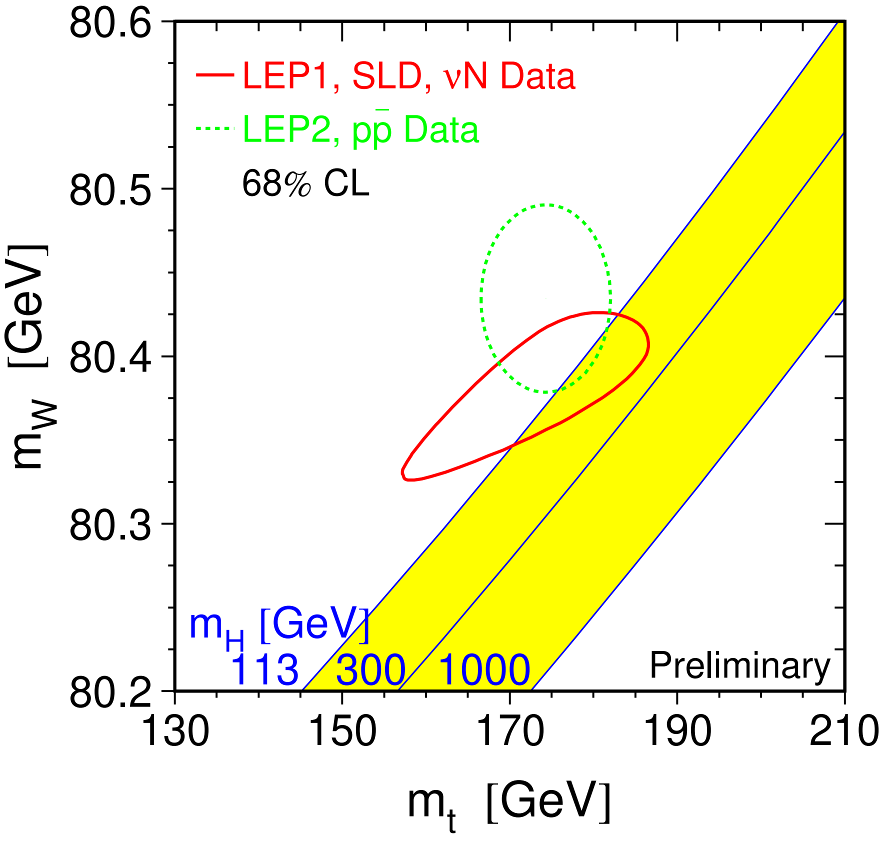
	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.05
Γ_Z [GeV]	2.4952 ± 0.0023	-.43
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.08
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.76
A_e	0.1498 ± 0.0048	.38
A_τ	0.1439 ± 0.0042	-.97
R_b	0.21649 ± 0.00072	1.00
R_c	0.1683 ± 0.0038	-1.04
$A^{0,b}_{fb}$	0.0989 ±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

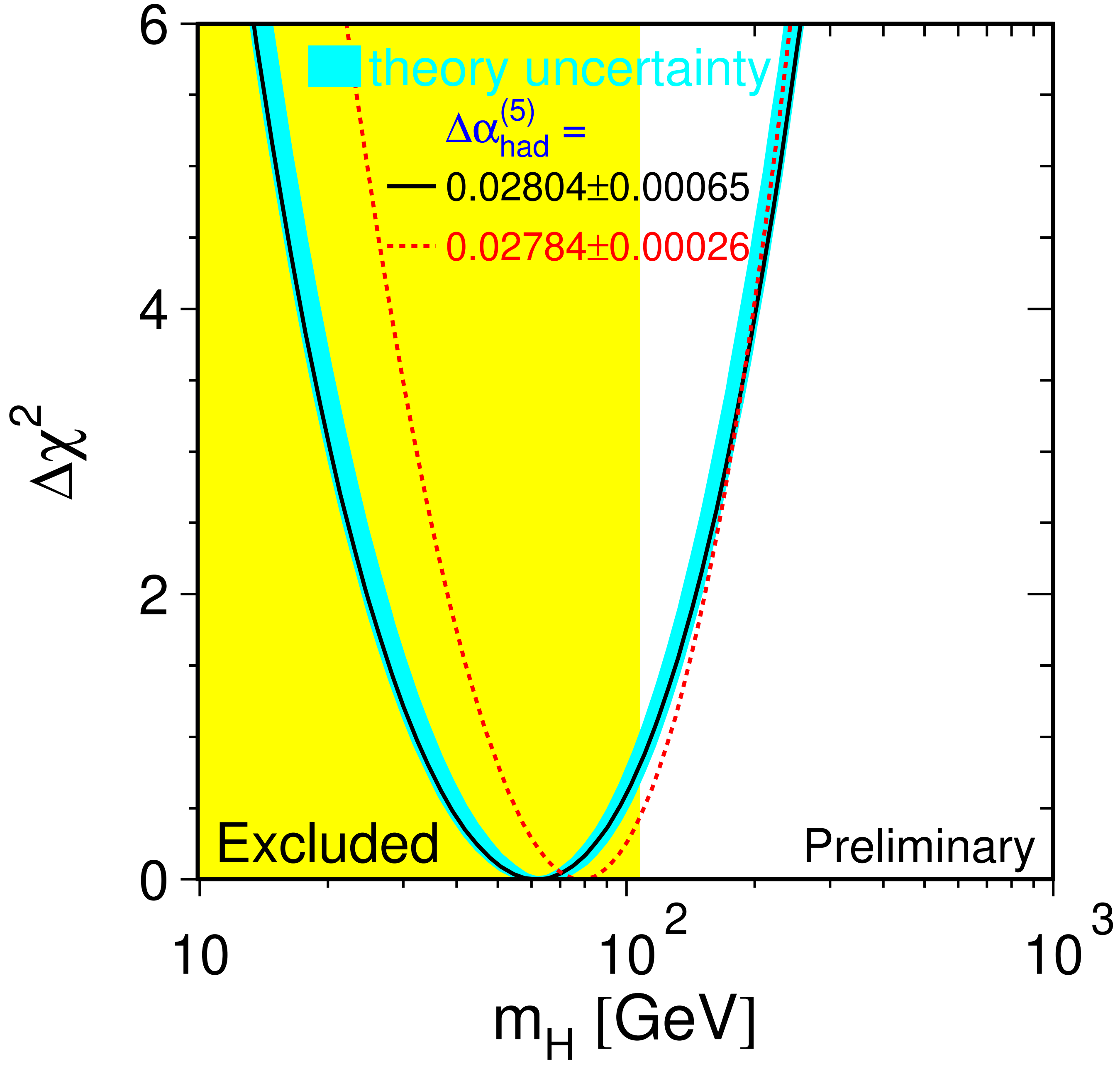


Global Fit to EW data

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


LEP Data, G_F, α
All Data
200
180
160
140
m_t [GeV]
Excluded
Preliminary
10
10^2
10^3
m_H [GeV]


80.6
80.5
80.4
80.3
80.2
m_W [GeV]
LEP1, SLD, νN Data
LEP2, $p\bar{p}$ Data
68% CL
m_H [GeV]
113
300
1000
Preliminary
130
150
170
190
210
m_t [GeV]



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

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

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

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

$$\boxed{\Rightarrow\ \mathbf{1}/\alpha(\mathbf{M_Z^2}) = \mathbf{128.878 \pm 0.090}}$$

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

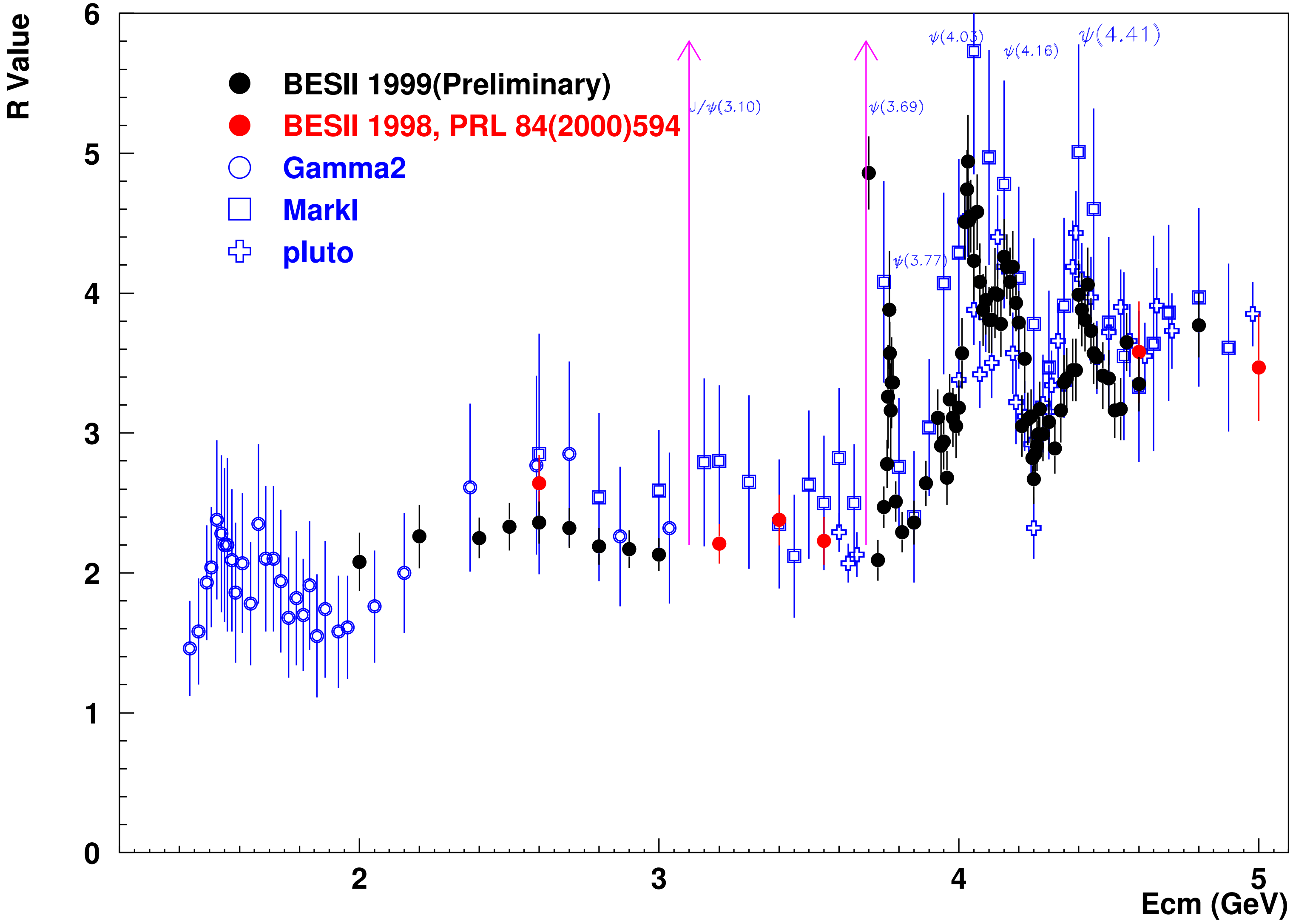
R (hadrons/$\mu^+\mu^-$),
poorly measured from 2.5 to 5 GeV.

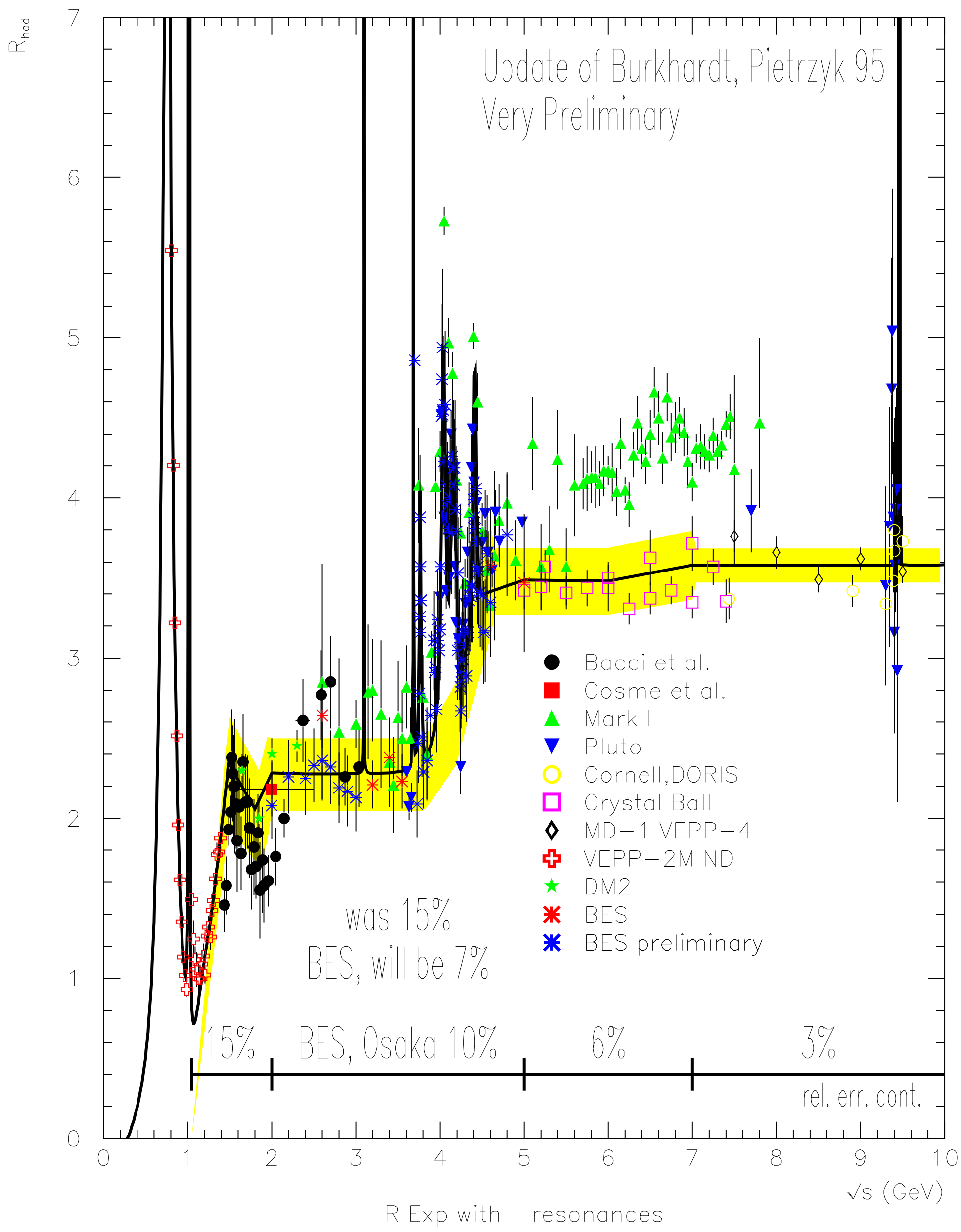
Theory driven approaches:
smaller error (factor 3)

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

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

Global Fit to EW data





To incorporate into determination of α(QED)

V.Prelim (B. Pietrzyk): $\Delta\alpha^{5}_{\mathbf{had}}(\mathbf{M^2_Z}) = \mathbf{0.02755 \pm 0.00046}$

$\mathbf{M_{Higgs}} \leq$210 GeV at 95% C.L.

OUTLOOK, CONCLUSIONS

WHERE DO WE GO FROM HERE ?

- **LEP I, SLD RESULTS (ALMOST) FINAL**
- **LEP II: WILL COLLECT ANOTHER $\sim$100 pb^{-1} DATA AT HIGH ENERGY (205-209 GeV) PER EXPT (already $\sim$ 600pb^{-1}/expt)**
  - **MORE SENSITIVE TESTS OF COUPLINGS**
  - **Hope to resolve CR/BE SYSTEMATICS REDUCED $\Delta M_W \simeq 35$ MeV**
- **INTERPRETATION IN SM FRAMEWORK Digest, Use BESII Data on R: Better M_{Higgs}**
- **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}

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

LHC: Discover/ Rule out HIGGS