Electroweak Results from LEP2

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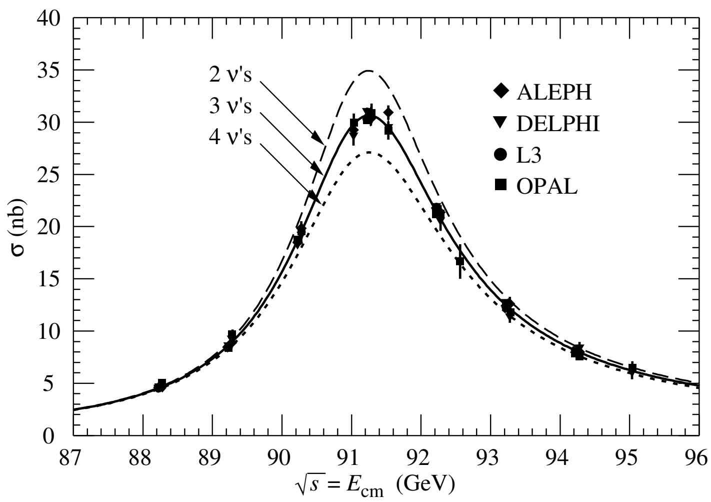
Testing the Standard Model

- Success of the Standard Model over the last two decades has (perhaps) obscured the importance of thoroughly investigating the weak interaction.
- The situation 15 years ago looked like this:
  - $\sin^2\theta_\mathrm{W} = 0.217 \pm 0.014$
  - $\mathrm{M_W(indirect)} = 83.0 \pm 2.8$ GeV
  - $\mathrm{M_{Z^0}(indirect)} = 93.8 \pm 2.3$ GeV
- Today, we have *measured* $\Delta\sin^2\theta_\mathrm{W} = 0.0002$, $\Delta\mathrm{M_{Z^0}} = 0.002$ GeV, and $\Delta\mathrm{M_W} = 0.06$ GeV !

  The SM success is so thorough, can only be wrong at the quantum loop level... and even then beyond leading order.

Nevertheless, measuring fundamental parameters of the SM and comparing them with the theoretical expectations is no less important today than it was 20 years ago. SM success just makes it more difficult.



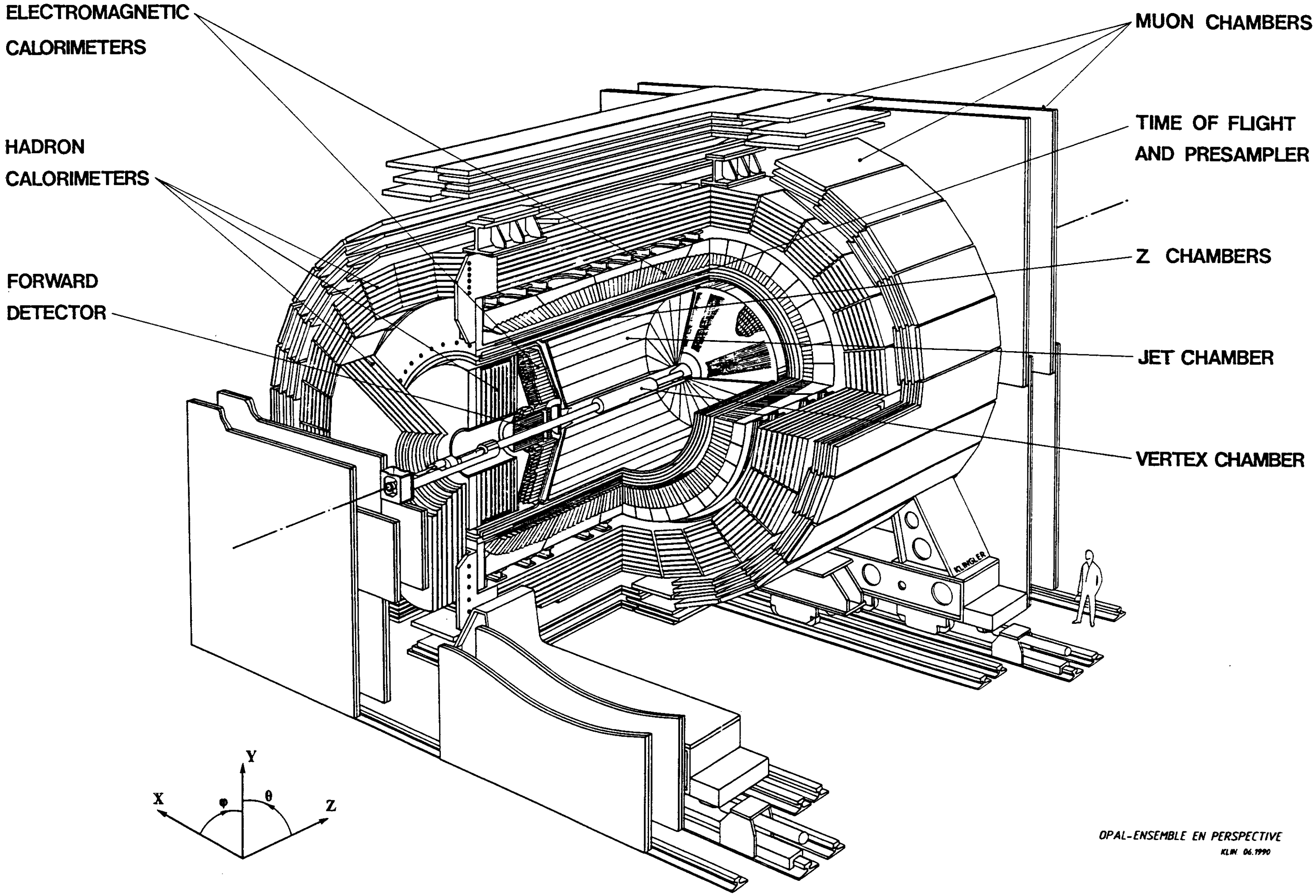
SM at LEP2 Highlights

Outline:

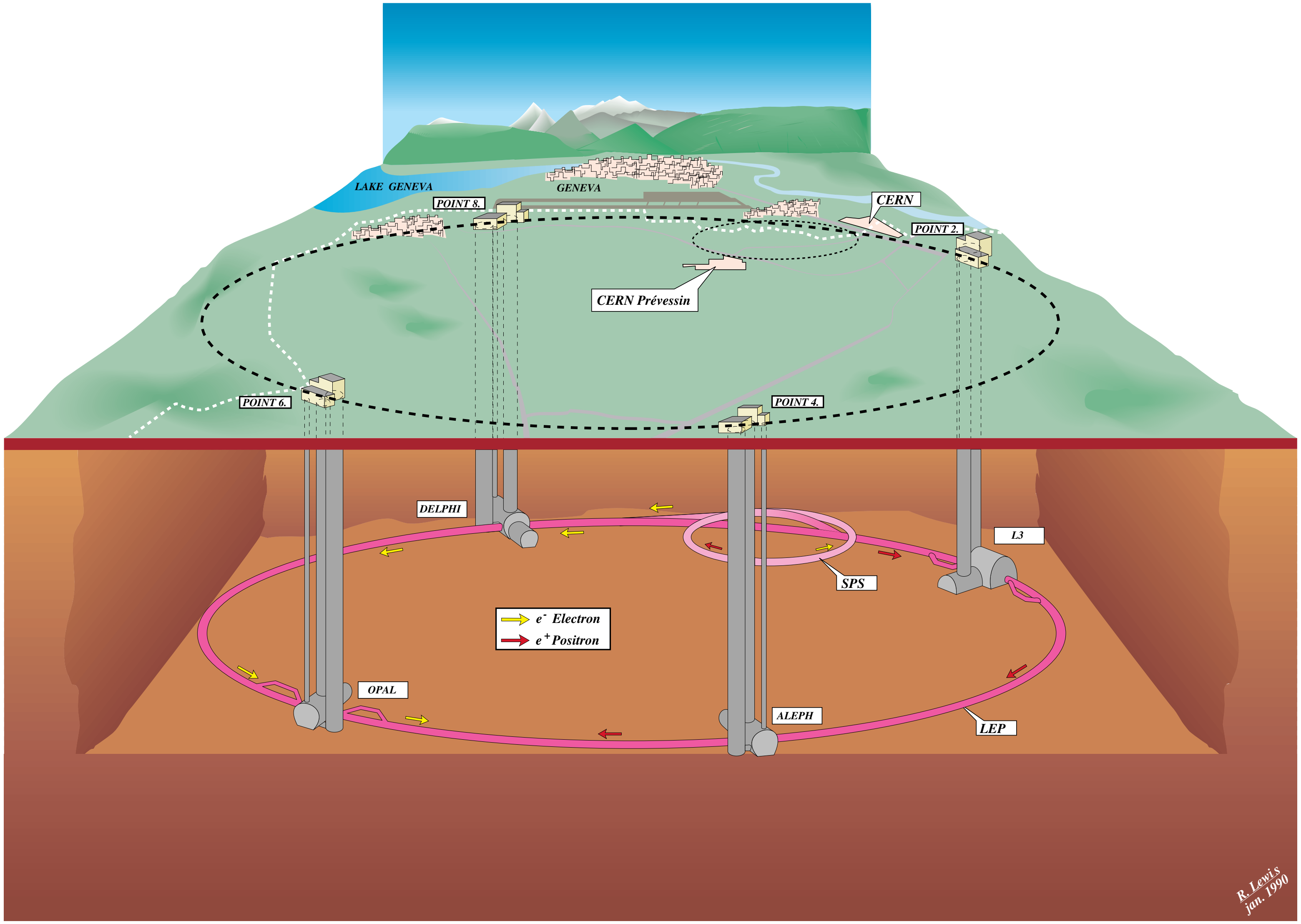
- Introduction: OPAL & LEP
- 2-Fermions Production
  - $\mathrm{e}^+\mathrm{e}^- \to \mathrm{Z}^0(\gamma) \to \mathrm{f\bar{f}}(\gamma)$ with $f = q, \ell, \mu, \tau, \nu$
  - $\alpha_{\mathrm{EM}}(\mathrm{M_{Z^0}})$ and Asymmetries
- QCD
  - Event Shape and α_{s}
- $\mathrm{e}^+\mathrm{e}^- \to \mathrm{ZZ}$
  - Cross-Section
  - Anomalous Couplings
- $\mathrm{e}^+\mathrm{e}^- \to \mathrm{We}\overline{\nu}$
  - Cross-Section
- $\mathrm{e}^+\mathrm{e}^- \to \mathrm{WW}$
  - Cross-Section and BR's
  - Charm tagging and $|V_{\mathrm{cs}}|$
  - W Mass and Width
- Trilinear Gauge Couplings: $\gamma\mathrm{WW}$ & ZWW
- Conclusions

The OPAL Detector

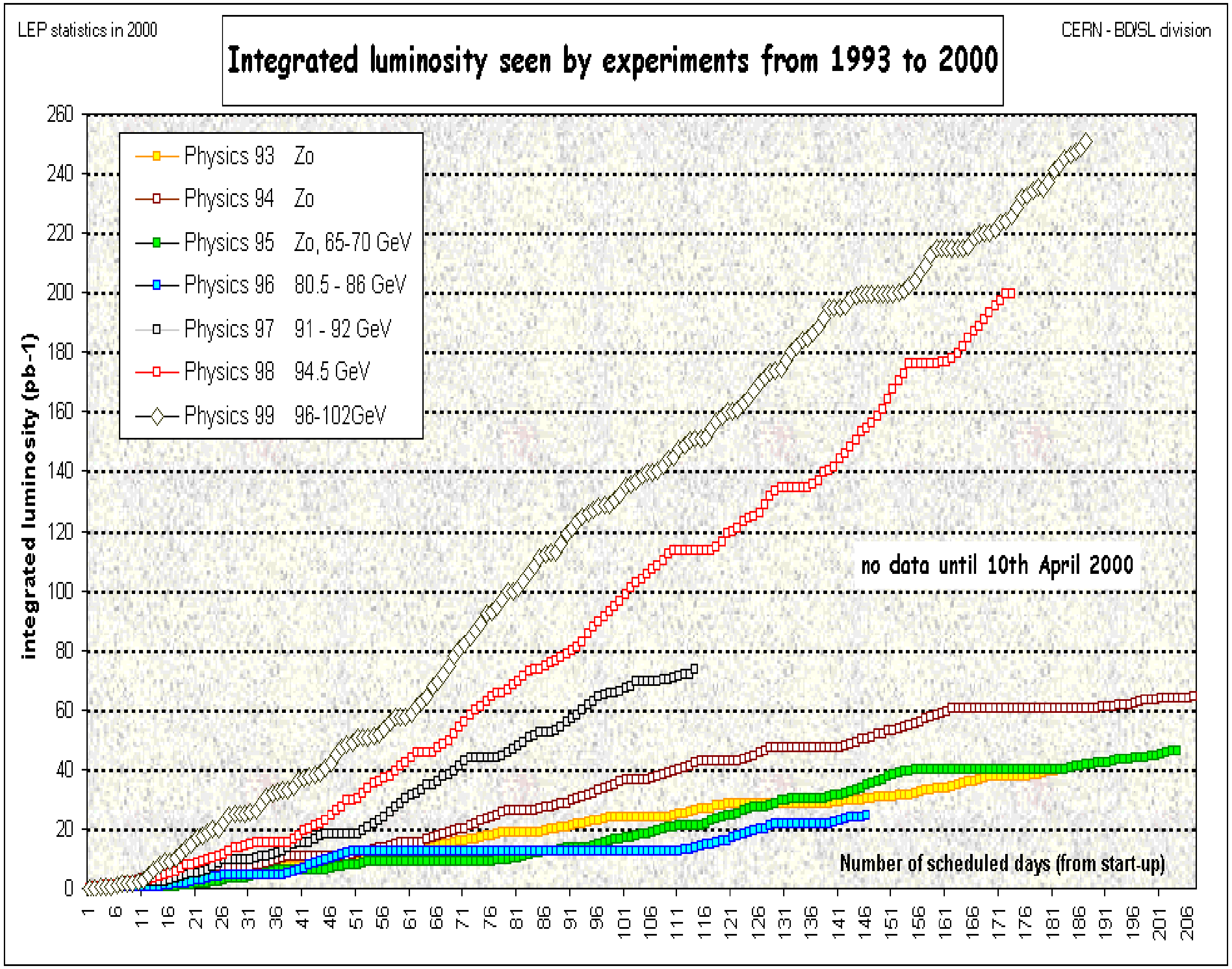
Data: Integrated luminosity used is about $488\mathrm{pb}^{-1}$ recorded at $\sqrt{s} = 161 - 202$ GeV.



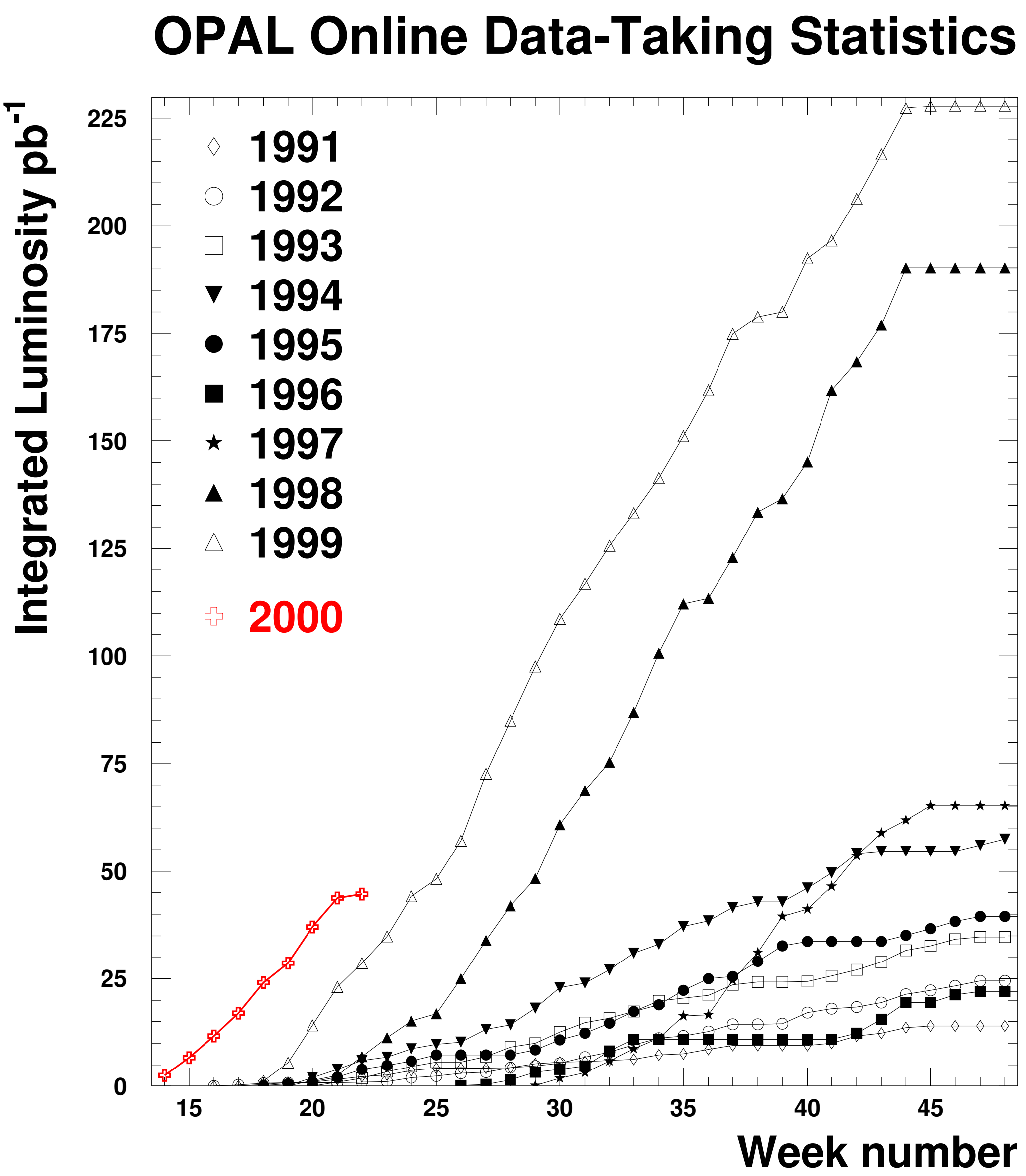
Large Electron-Positron collider at CERN



LEP Performance



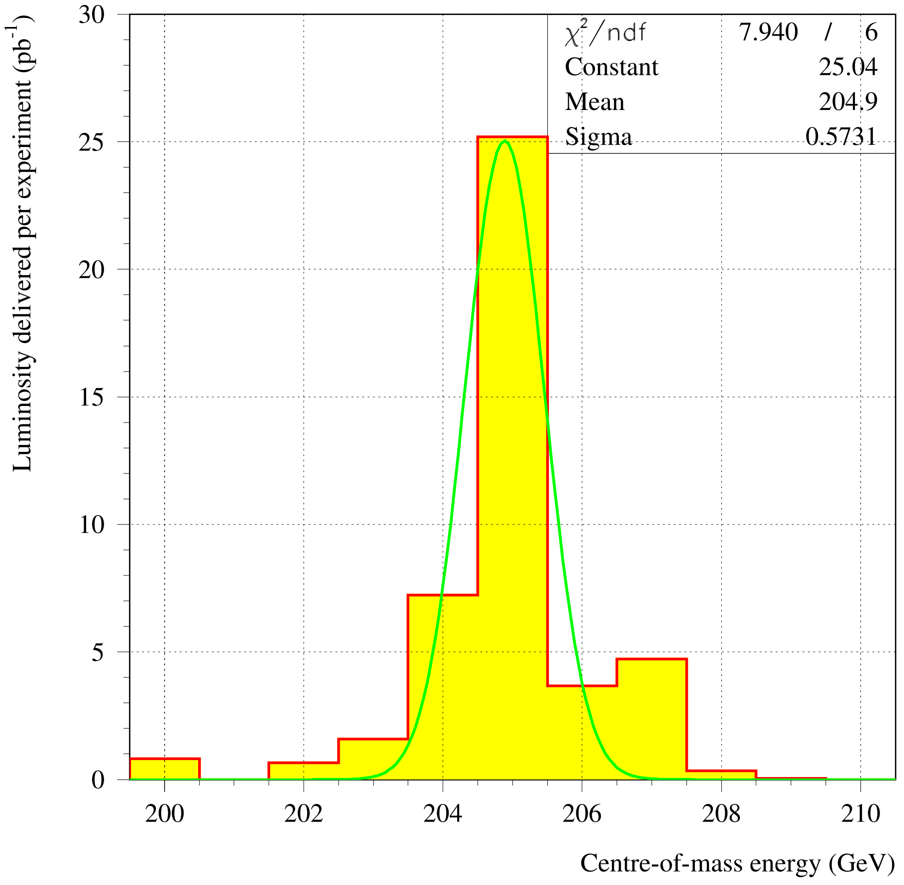
LEP Performance in 2000

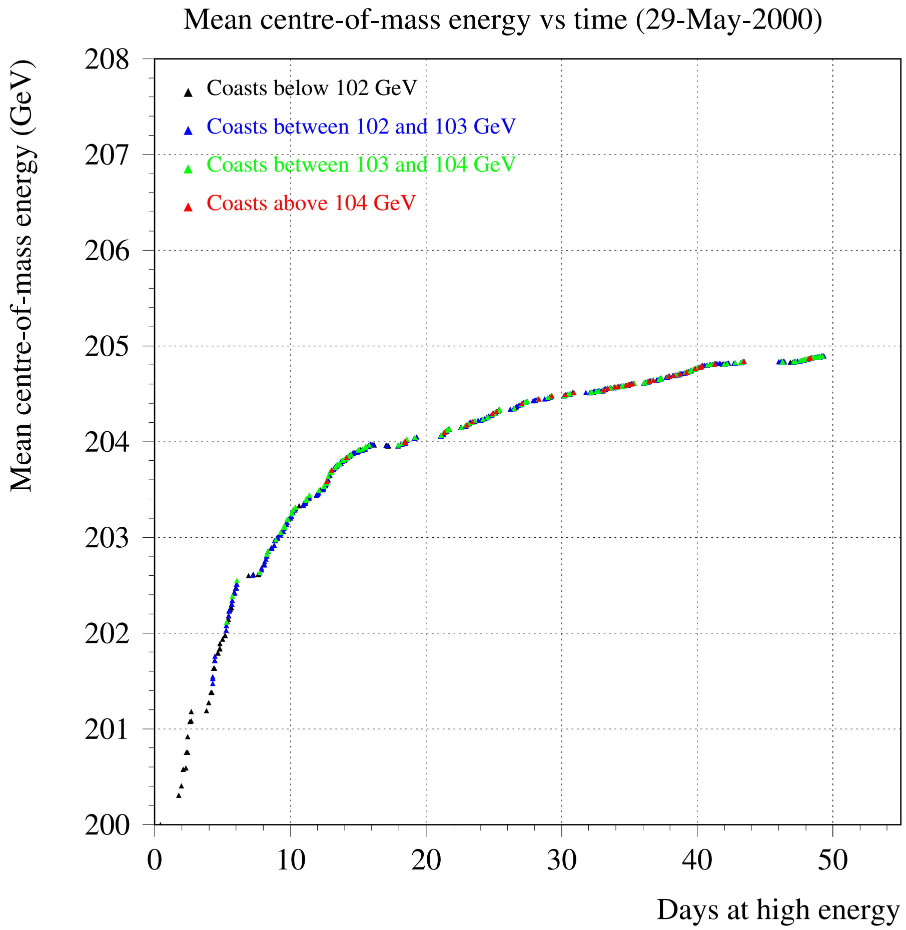


OPAL data used for results presented here(1996-1999):

$\sqrt{s}$ (GeV)	$\mathcal{L}_{\mathrm{tot}}$ (pb^{-1})
161	10
172	10
183	57
189	187
192-202	224
161-202	488

LEP Energies in 2000





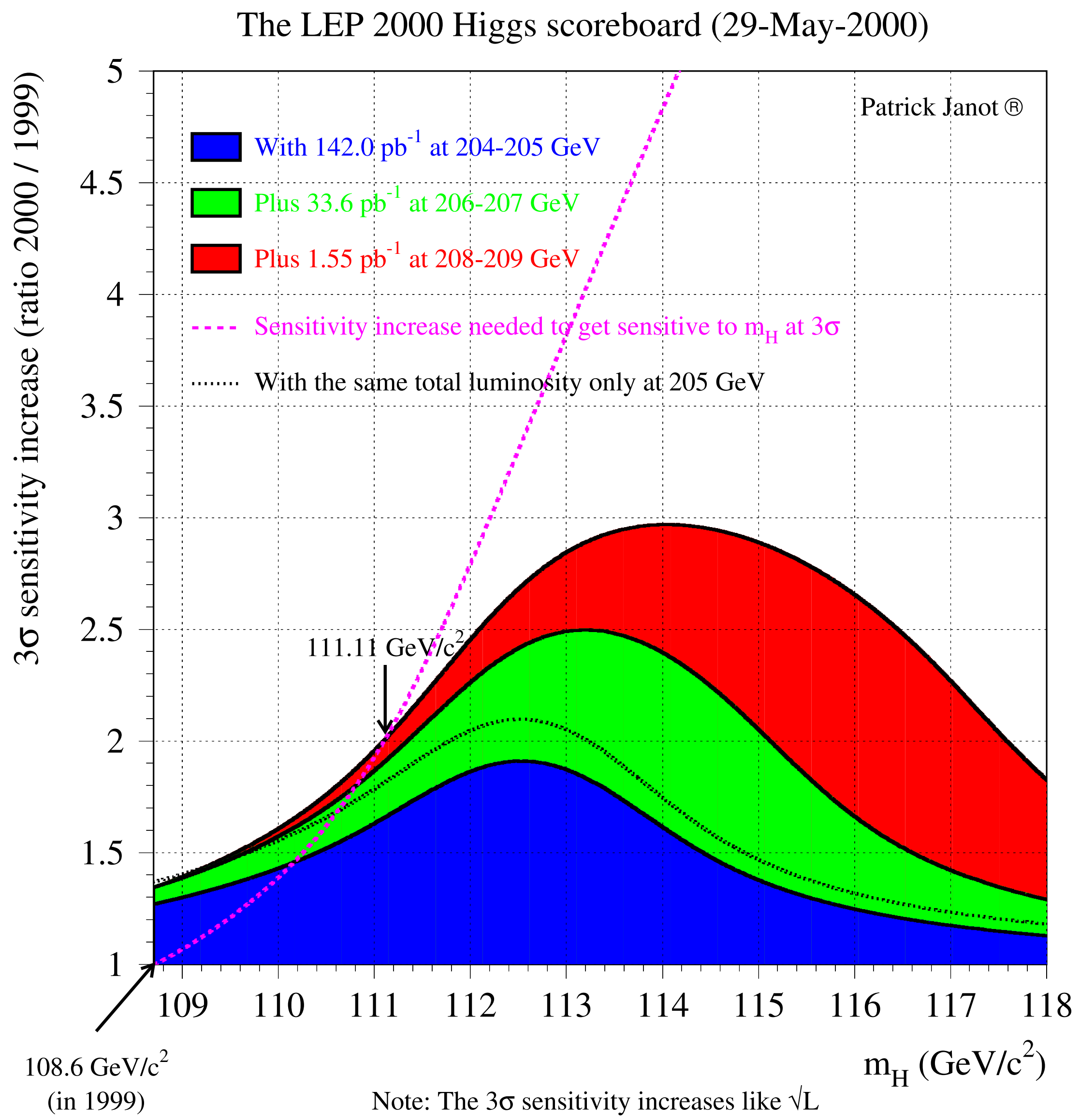
SM Higgs Search

PRELIMINARY Limit on the SM Higgs mass with data collected at $\sqrt{s} = 161 - 202$ GeV:

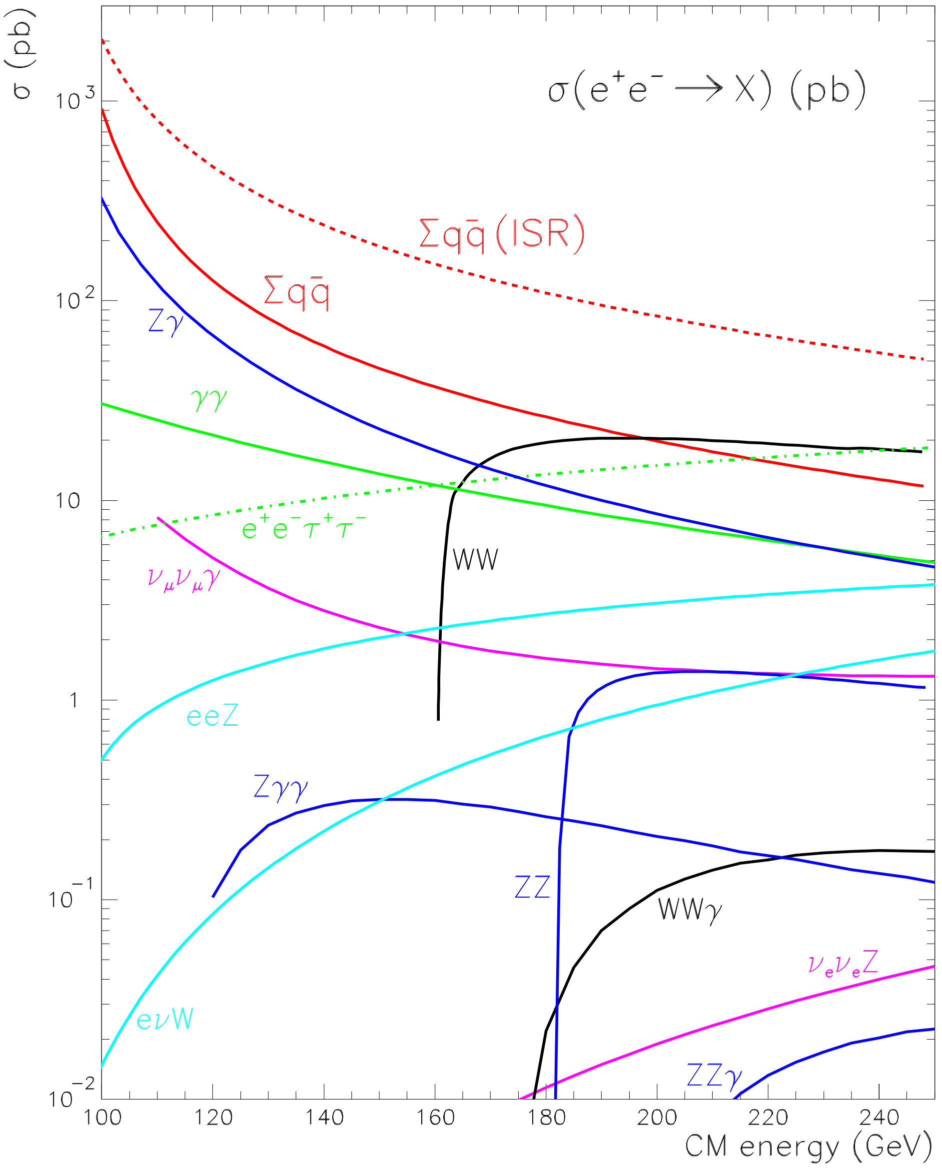
At the end of 99 run experiments reported preliminary limits up to:

$$m_H > 107.9 \text{ GeV } (95\% \text{ CL})$$

The story in 2000 up to now (expected sensitivity)...



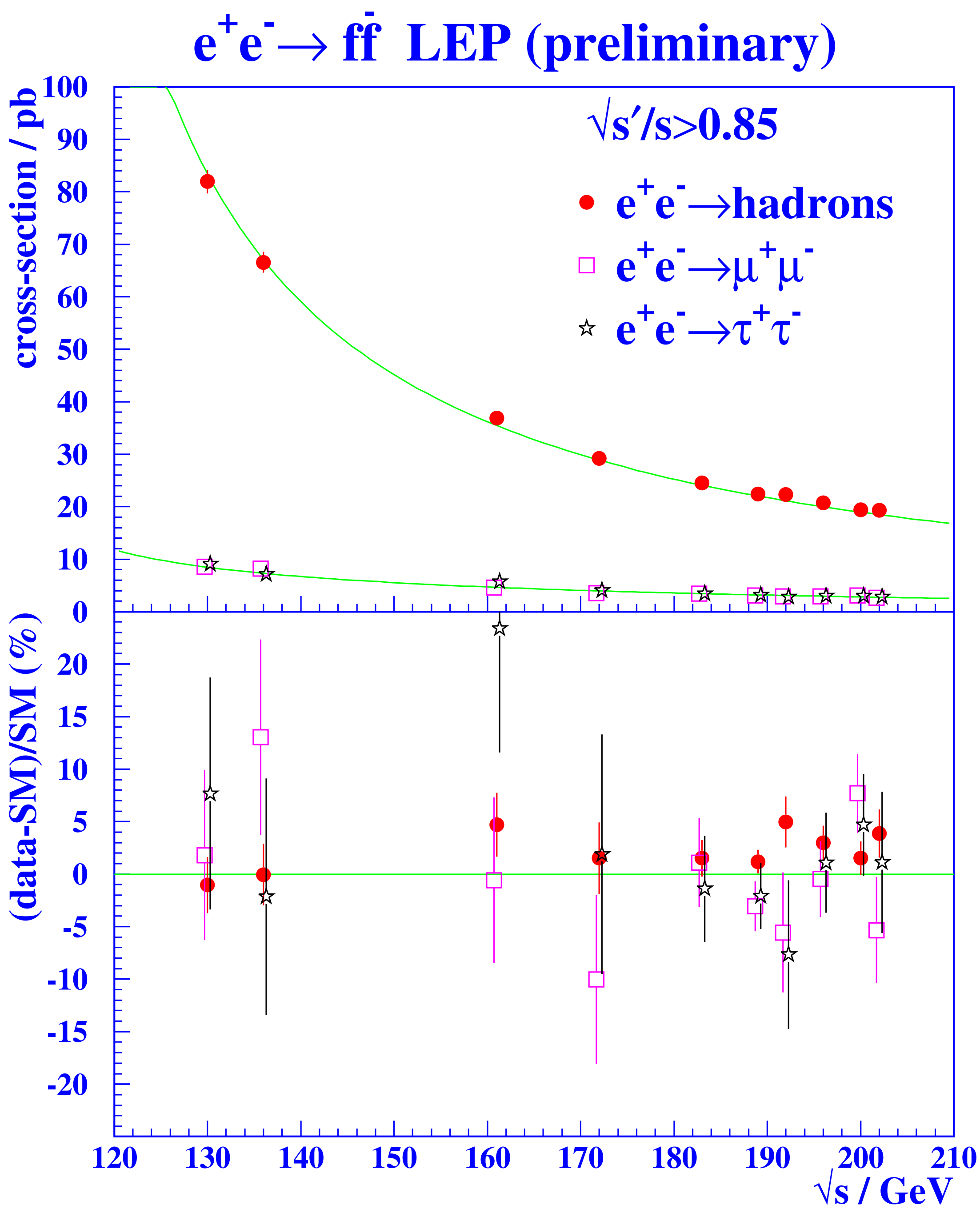
Physics Processes



Processes	$\sigma(\sqrt{s} = 183)$
$e^+e^- \longrightarrow Z/\gamma \longrightarrow q\bar{q}$	107 pb
$e^+e^- \longrightarrow WW$	15.7 pb
$e^+e^- \longrightarrow Ze^+e^-$	2.8 pb
$e^+e^- \longrightarrow (Z/\gamma)^*(Z/\gamma)^*$	0.6 pb
$e^+e^- \longrightarrow We\nu$	0.6 pb

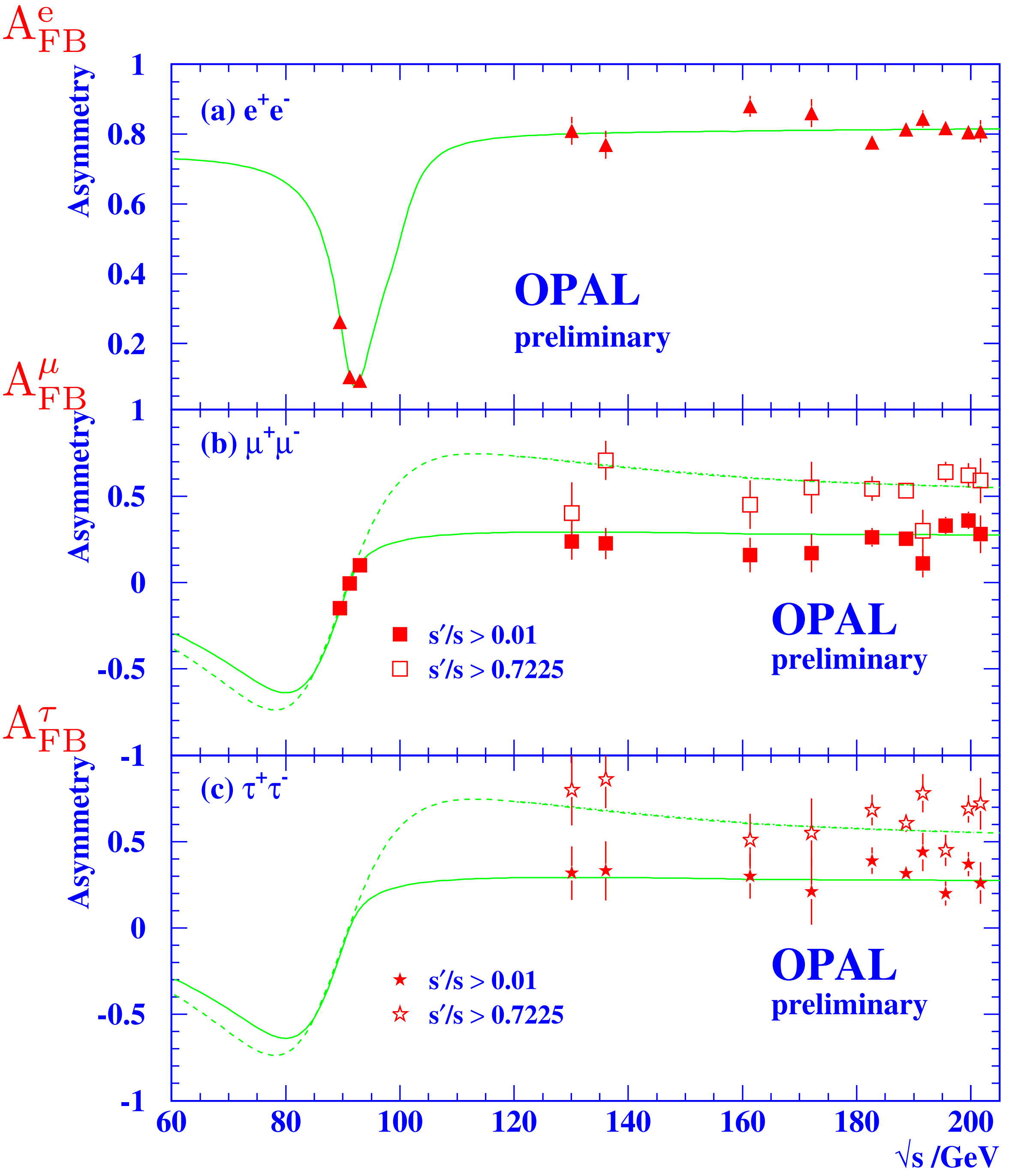
2-Fermion Physics: LEP Average

ALEPH + DELPHI + L3 + OPAL



Lepton Asymmetries

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



The forward (F) and backward (B) hemispheres are defined with respect to the e^- beam direction.

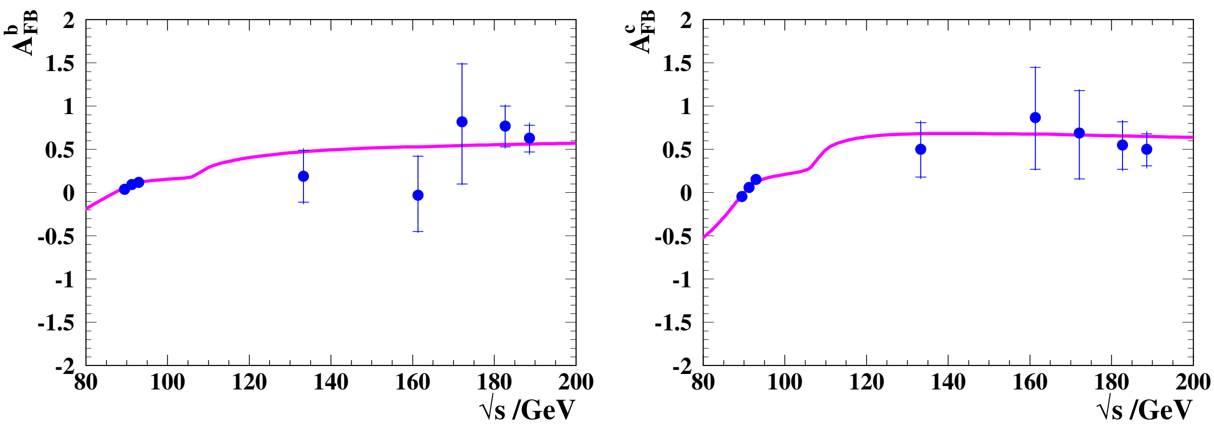
Heavy Quark Asymmetries & Decay Rate

OPAL

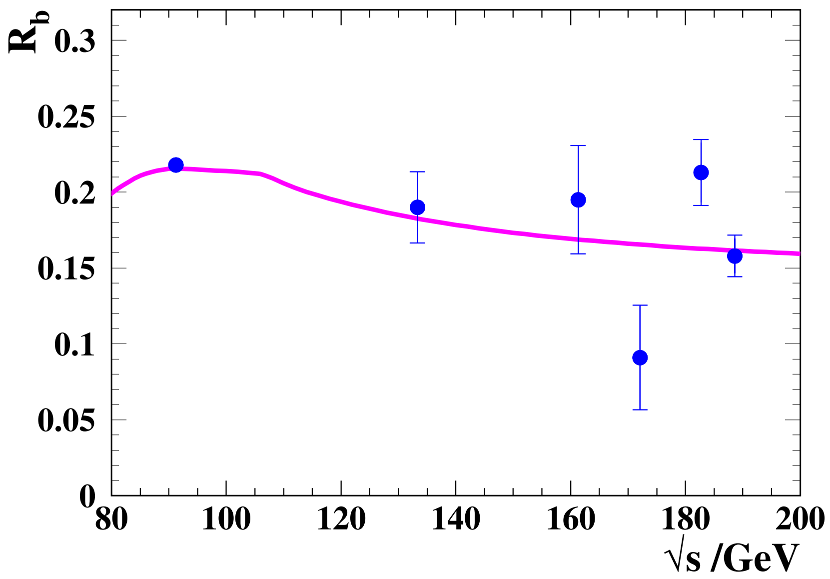
Heavy Flavour Tag: Based on secondary vertices of long lived hadrons, high p_t lepton from semileptonic decays, hemisphere charge, and pions from $D^{*+} \rightarrow D^0\pi^+$ decays.

$$\mathrm{A_{FB}} = \frac{\sigma_\mathrm{F} - \sigma_\mathrm{B}}{\sigma_\mathrm{F} + \sigma_\mathrm{B}}$$

$\mathrm{A^b_{FB}}$ $\mathrm{A^c_{FB}}$



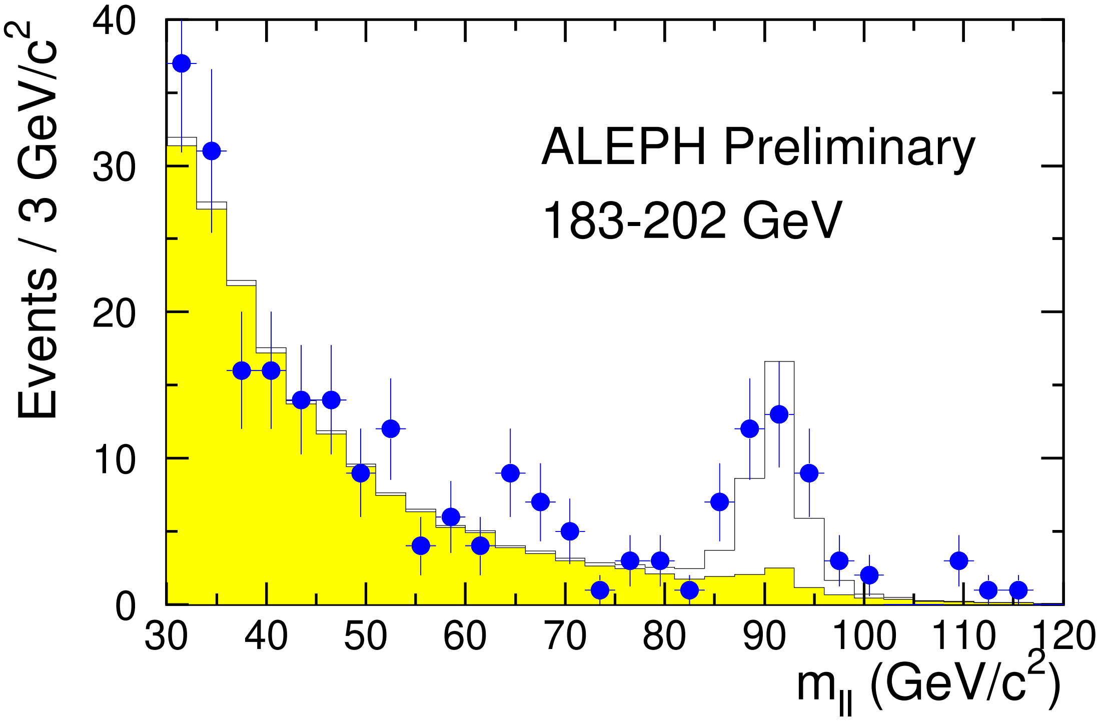
$$\mathrm{R_b} = \frac{\Gamma(\mathrm{Z^0} \rightarrow \mathrm{b\bar{b}})}{\Gamma(\mathrm{Z^0} \rightarrow \mathrm{q\bar{q}})}$$



Z^0 Pair Production

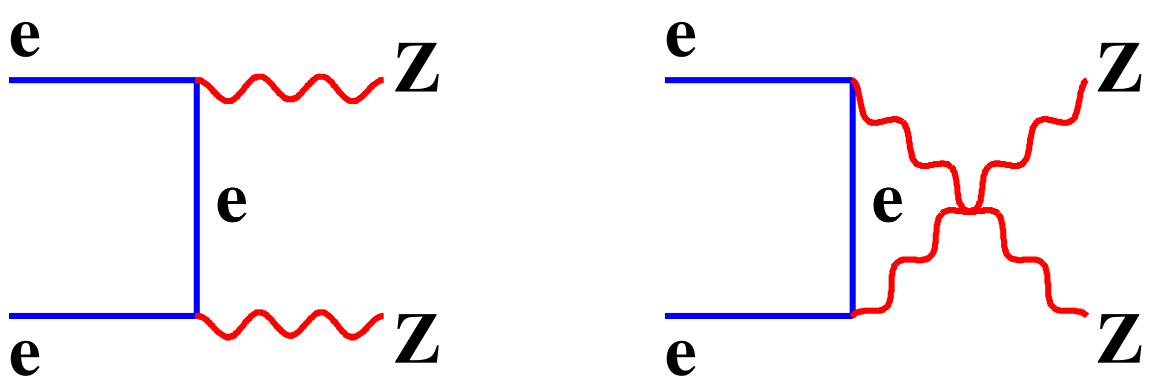
Decay Channel	Br (%)	Signature	Main Background
$q\bar{q}q\bar{q}$	49	4 hadronic jets	Very large $\mathrm{WW} \to q\bar{q}q\bar{q}$ and $Z^0/\gamma \to q\bar{q}(n\gamma)$
$q\bar{q}\ell^+\ell^-$	14	2 jets + 2 leptons	Low $Z^0\gamma^* \to q\bar{q}\ell^+\ell^-$
$\ell^+\ell^-\ell^+\ell^-$	1	4 energetic leptons	Medium non resonant $e^+e^-\ell^+\ell^-$
$q\bar{q}\nu\bar{\nu}$	28	2 jets + missing E	Large $Z^0/\gamma \to q\bar{q}(n\gamma)$ and $e^+e^- \to \mathrm{W}e\bar{\nu}$
$\ell^+\ell^-\nu\bar{\nu}$	4	2 leptons + missing E	Medium $\mathrm{WW} \to \ell\bar{\nu}\ell\bar{\nu}$
$\nu\bar{\nu}\nu\bar{\nu}$	4	invisible	

- dijet and dilepton invariant mass close to Z^0 mass.
- b tagging for jets to improve signal/noise.

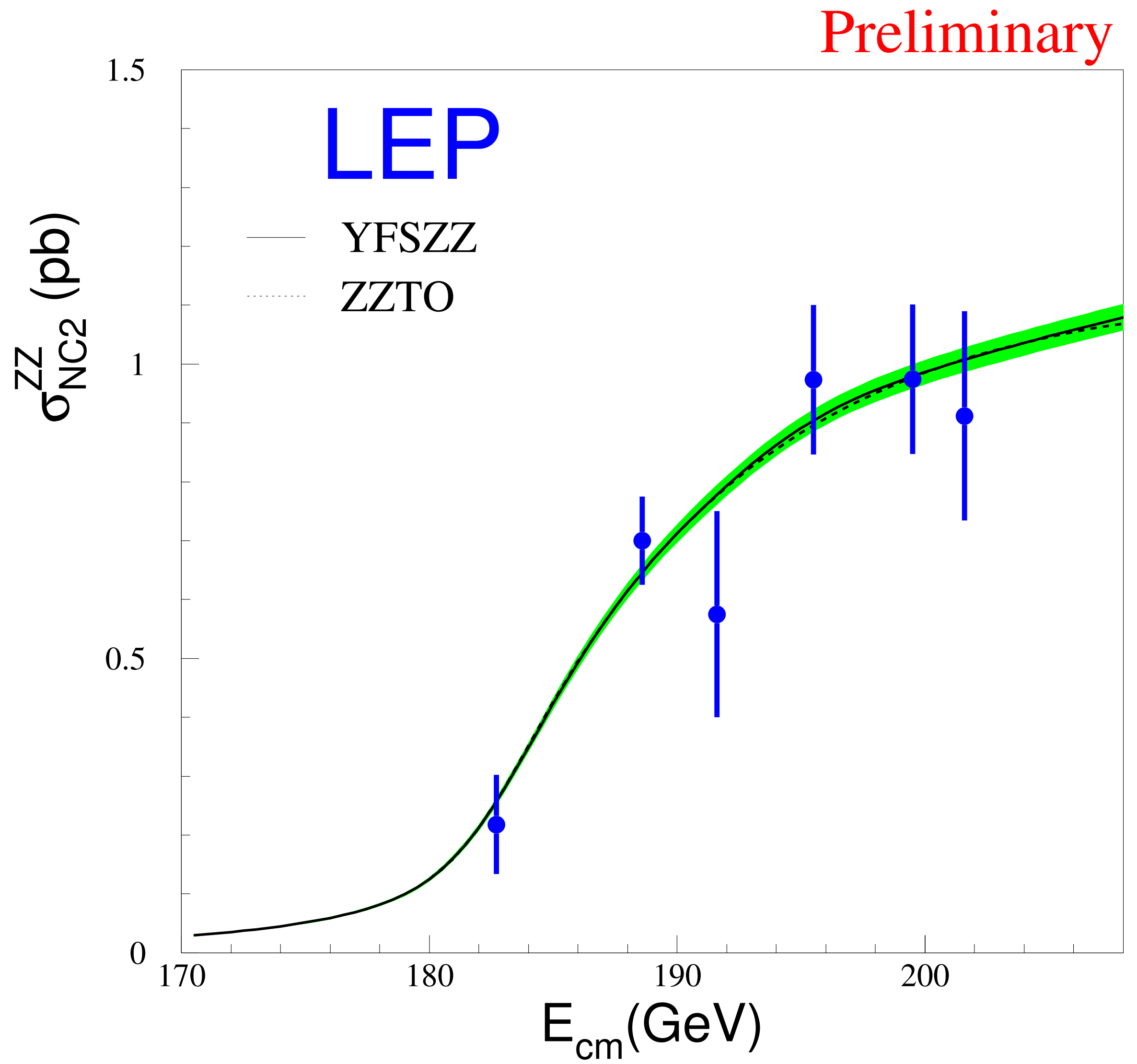


ZZ Cross-Section

Main background for Higgs searches if $m_{\mathrm{Higgs}} \simeq \mathrm{M}_{\mathrm{Z^0}}$.

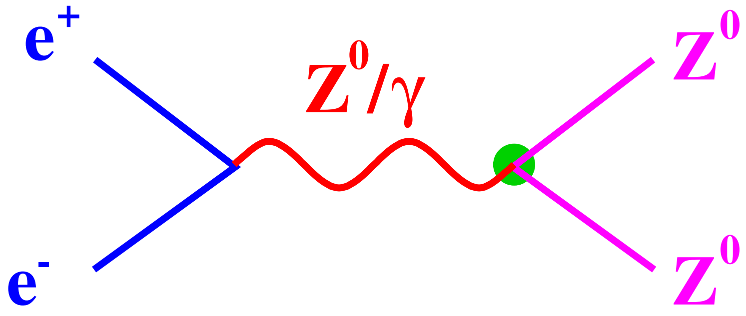


Capability to test anomalous couplings among neutral bosons.

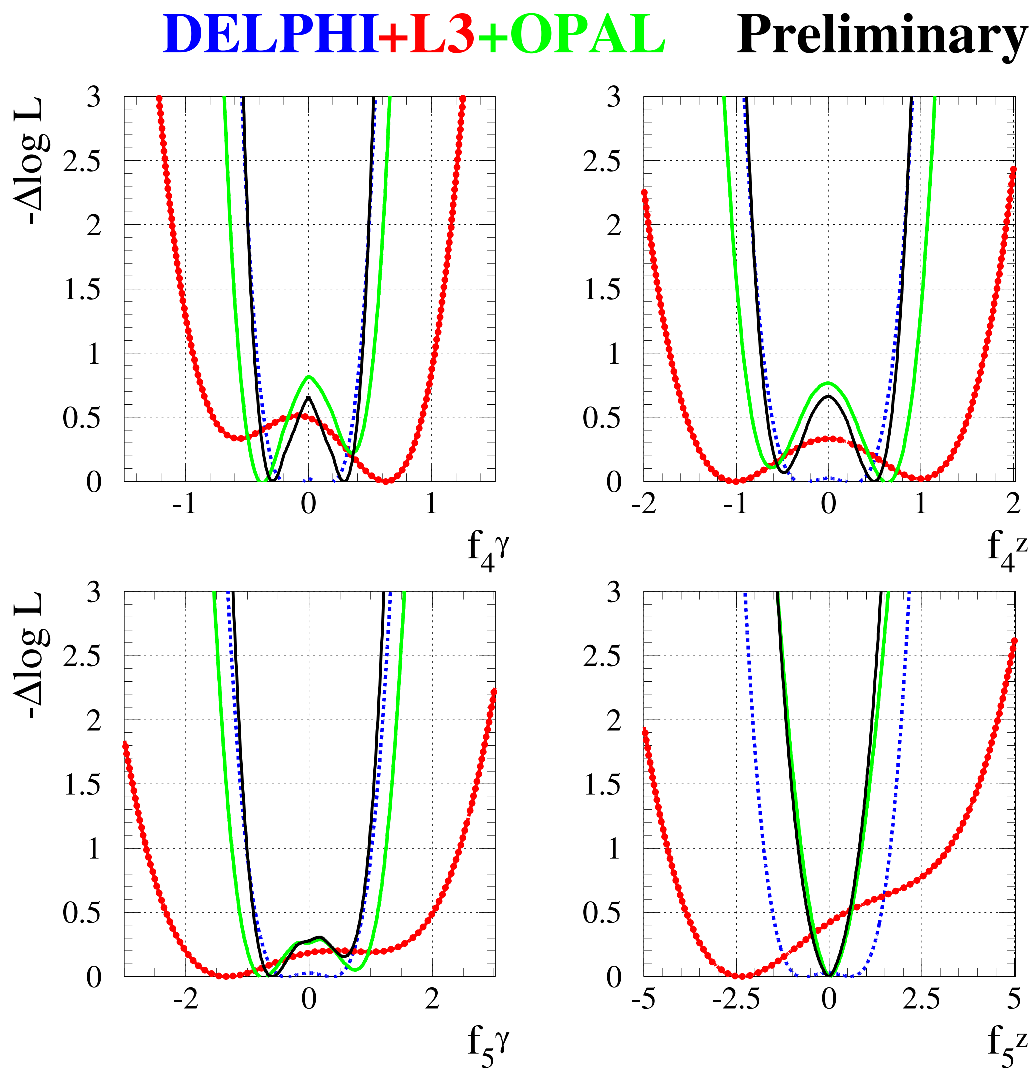


Experimental errors dominated by statistic!

ZZZ and ZZγ Couplings: LEP Limits



Couplings	68% CL	95%CL
f_4^γ	$+0.29^{+0.11}_{-0.21}$	$[\pm 0.49]$
f_4^Z	$+0.49^{+0.19}_{-0.31}$	$[\pm 0.82]$
f_5^γ	$-0.6^{+1.4}_{-0.3}$	$[\pm 1.1]$
f_5^Z	$+0.01^{+0.56}_{-0.57}$	$[\pm 1.1]$

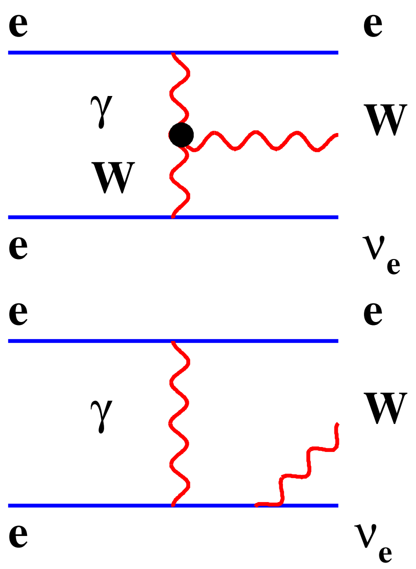


LEP: Delphi=Up to 189 GeV

L3= Up to 189 GeV

OPAL= Up to 202 GeV

Single W Production



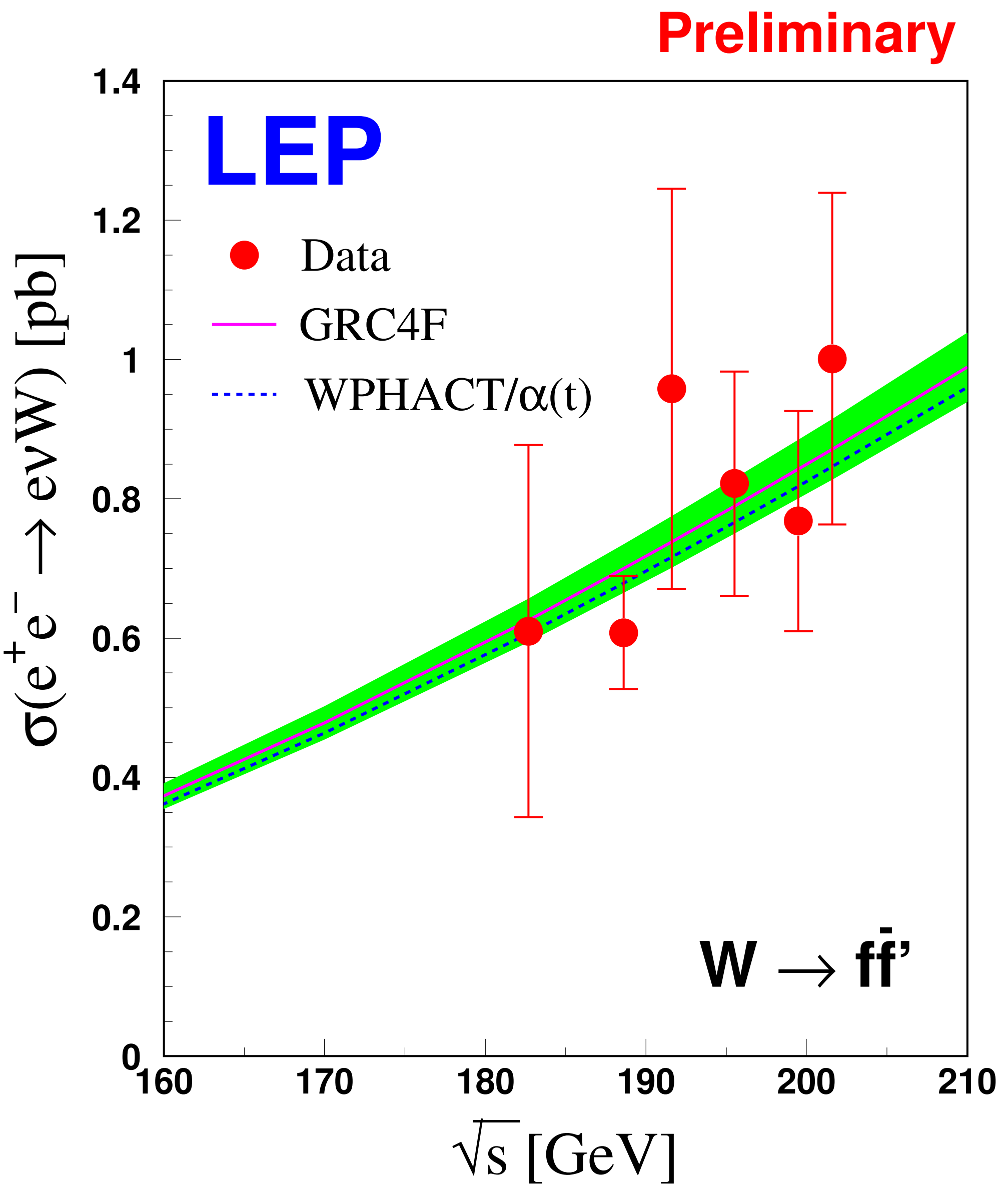
Plus many s- and t-channel diagrams with the same final states.

LEP: ALEPH=183-189 GeV

Delphi=189-202 GeV

L3=189-202 GeV

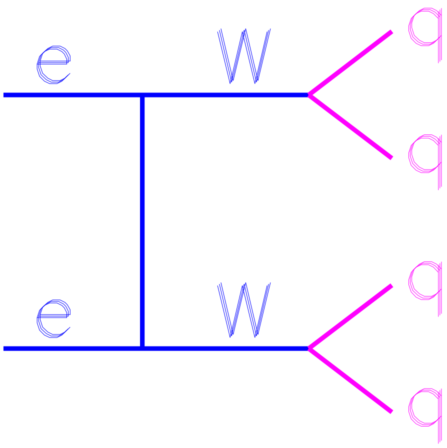
OPAL=189 GeV



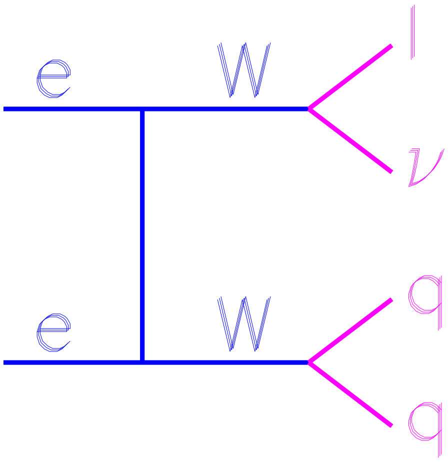
WW Pair Production

- Lots of $\mathrm{W}^{\pm}$ bosons at LEP2!
- Precision $\sigma(\mathrm{WW})$, BR, $|V_{\mathrm{cs}}|$, and $\mathrm{M_W}$
- Tighter TGC constraints

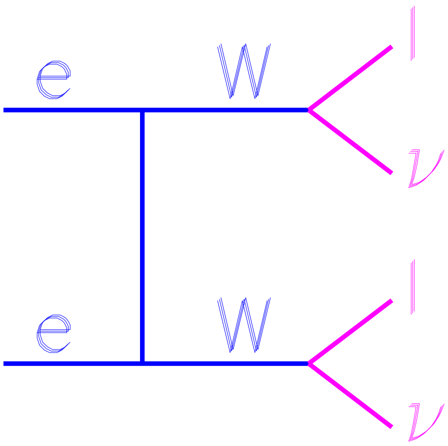
Selections (at 189 GeV)



$\mathrm{BR} \approx 46\%$
$\varepsilon = \mathbf{86}\%$
$\mathbf{P} = \mathbf{79}\%$



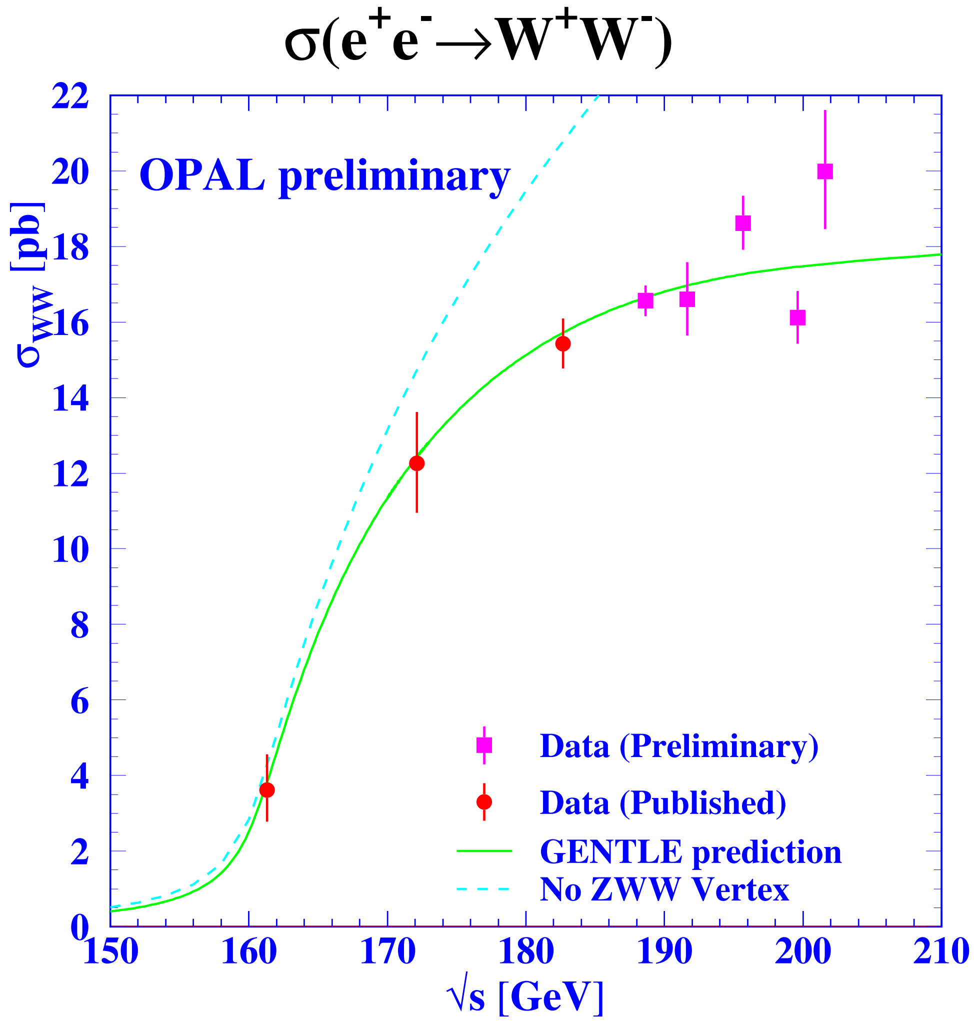
$\mathrm{BR} \approx 45\%$
$\varepsilon = \mathbf{87}\%$
$\mathbf{P} = \mathbf{90}\%$



$\mathrm{BR} \approx 10\%$
$\varepsilon = \mathbf{82}\%$
$\mathbf{P} = \mathbf{90}\%$

OPAL WW Cross-Section

Final state	N_{exp}	N_{obs}
$WW \rightarrow \ell\overline{\nu}\ell\overline{\nu}$	290.0 ± 8.9	278
$WW \rightarrow q\overline{q}\ell\overline{\nu}$	1287.2 ± 29.5	1252
$WW \rightarrow q\overline{q}q\overline{q}$	1511.1 ± 34.9	1546
Combined (189 GeV)	3088.3 ± 62.0	3076

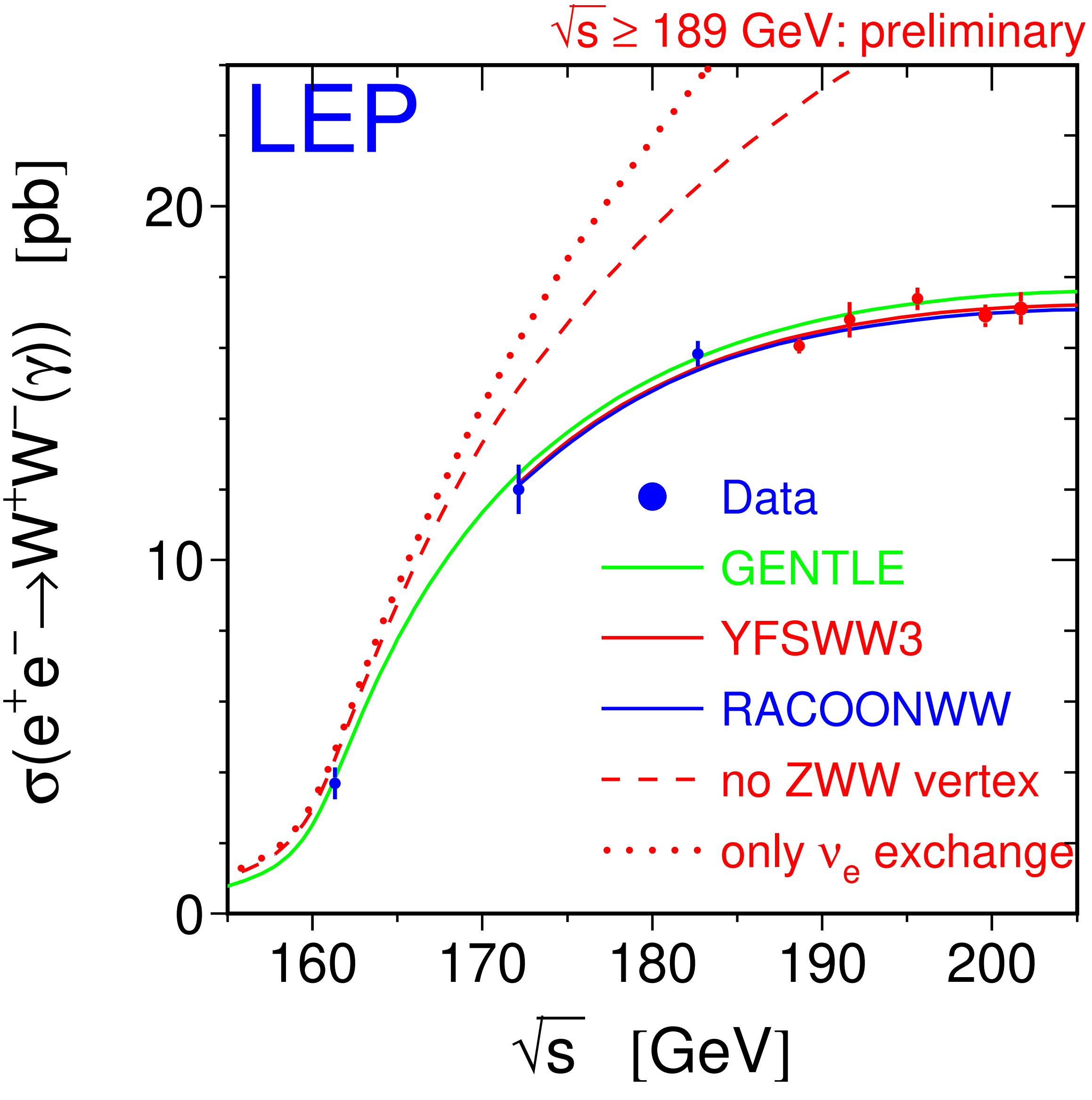


Assuming SM branching fractions (at 189 GeV):

$$\sigma_{WW} = 16.55 \pm 0.35(\mathrm{sta}) \pm 0.20(\mathrm{sys})\,\mathrm{pb}$$

WW Cross-Section: LEP Average

ALEPH + DELPHI + L3 + OPAL

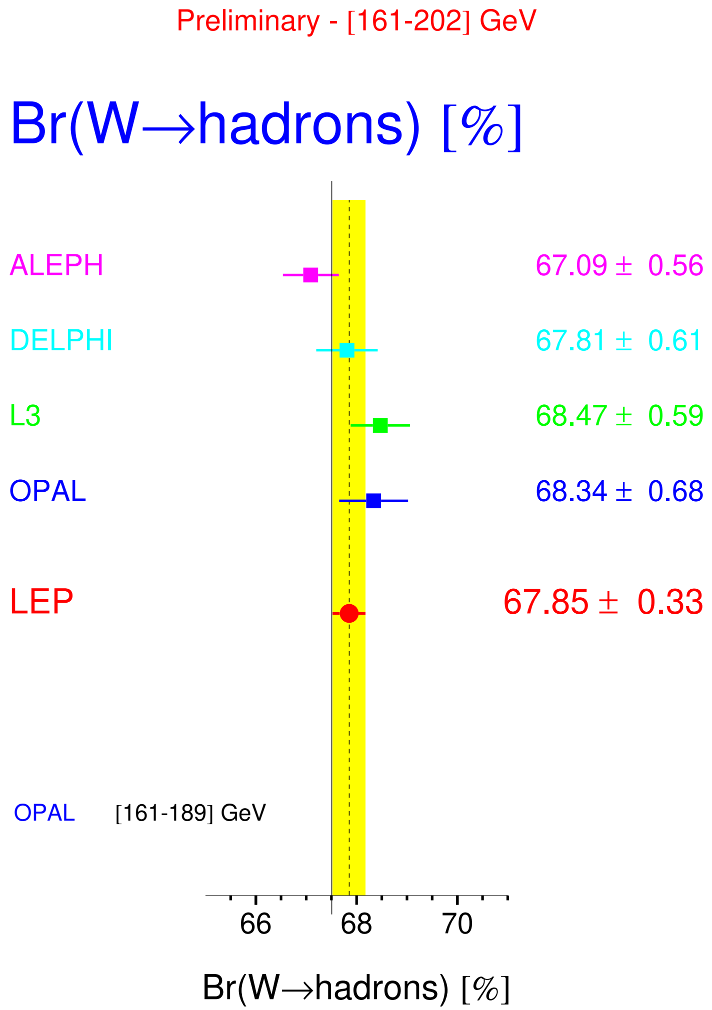


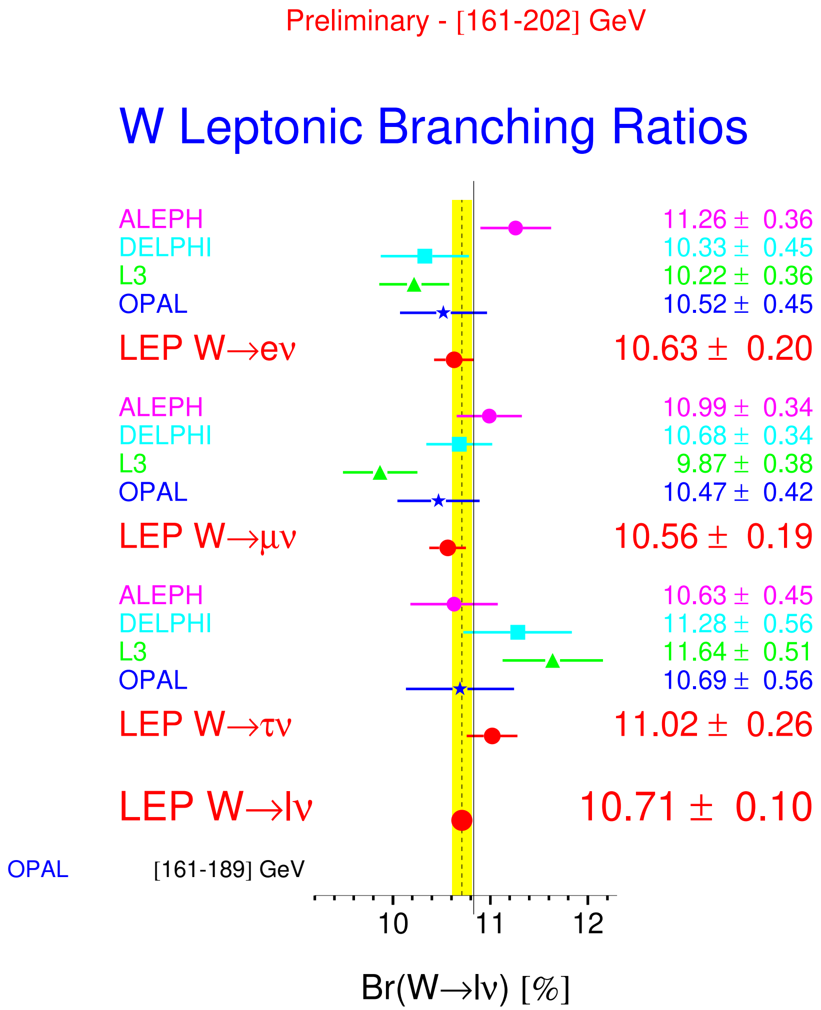
Assuming SM branching fractions (at 189 GeV):

$$\sigma_{\rm WW} = (16.05 \pm 0.22)\,\text{pb}$$

WW BR's: LEP Average

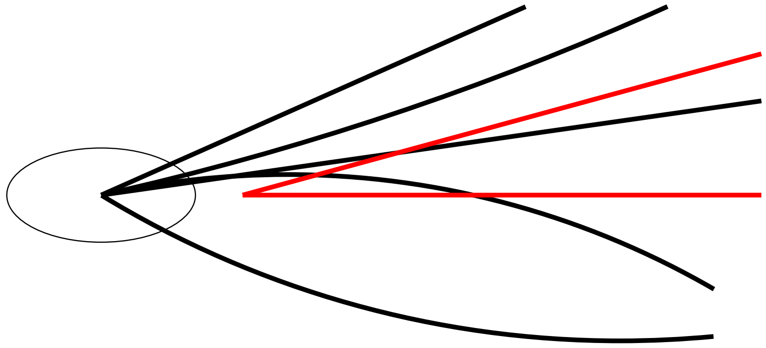
ALEPH + DELPHI + L3 + OPAL





Charm Tagging: Strategy

Reconstruction of the Sub-Jet



Tag the charm flavour with
- lifetime information
- lepton ID
- jet properties

- Inclusive JET BASED charm tag for a better statistical power
- Average charged multiplicity for charm hadron decays: 2-3
- $\tau_{\rm charm} \sim 1$ ps: large flight distance of about 1-2 mm
- Charm hadrons are a source of prompt leptons
- Charm quark heavier than uds-quarks: specific momentum distribution within the jet
- $|V_{\rm ub}|$ and $|V_{\rm cb}|$ are small

OPAL $R_c^W = \frac{\Gamma(W \to cX)}{\Gamma(W \to \text{hadrons})}$

$$-\ln\mathcal{L} = -\sum_{i=1}^{N} n_i \ln\{(1-F_{\rm bkg})[F_c\mathcal{P}_c^i + (1-F_c)\mathcal{P}_{uds}^i] + F_{\rm bkg}\mathcal{P}_{\rm bkg}^i\}$$

with $R_c^W = 2\,F_c$ and

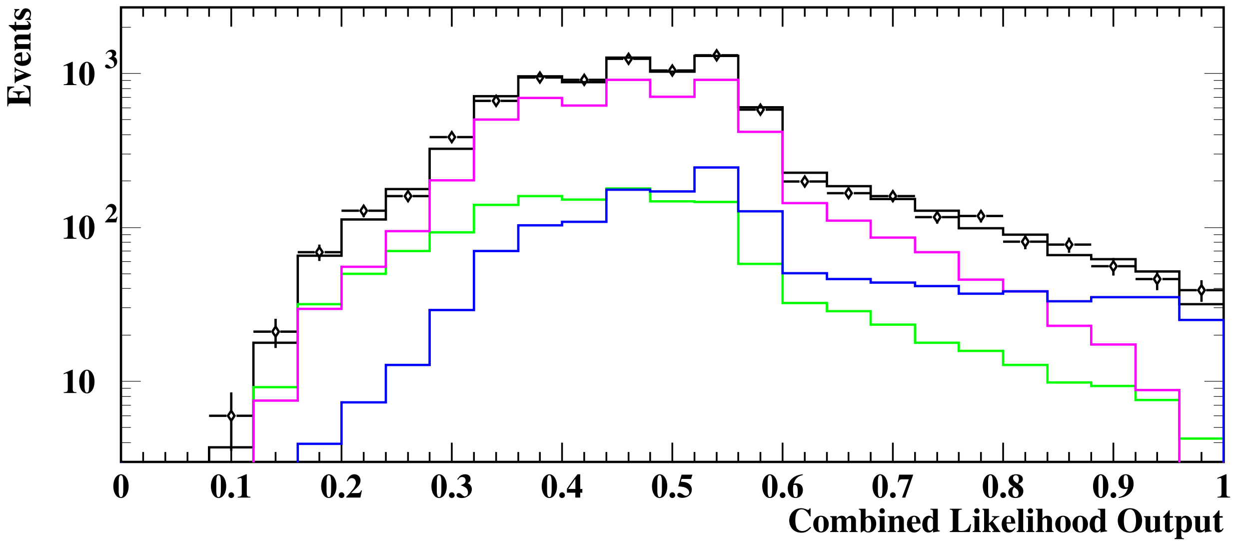
F_c: Fraction of charm jets (float)

$\mathcal{P}_c^i$: Probability to tag Charm in $i^{\rm th}$ bin

$\mathcal{P}_{uds}^i$: Probability to tag uds in $i^{\rm th}$ bin

$F_{\rm bkg}$: Fraction of background jets (float or fixed)

$\mathcal{P}_{\rm bkg}^i$: Probability to tag non-WW bkg in $i^{\rm th}$ bin



$$\boxed{R_c^W = 0.481 \pm 0.042(\text{stat.}) \pm 0.032(\text{syst.})}$$

$|V_{cs}|$ at LEP2

$|V_{cs}|$ from $\mathrm{Br}(\mathrm{W} \to \mathrm{q\bar{q}})$

The hadronic branching fraction $\mathrm{Br}(\mathrm{W} \to \mathrm{q\bar{q}})$ can be interpreted as a measurement of $|V_{cs}|$ since:

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

LEP Preliminary with $\sqrt{s}$=161-202 GeV data:

$$\boxed{|V_{cs}| = 0.993 \pm 0.016}$$

$|V_{cs}|$ from R_c^{W}

In the SM,

$$\Gamma\,(\mathrm{W} \to \mathrm{c\,X}) = \frac{G_\mathrm{F}\mathrm{M}_\mathrm{W}^3}{2\sqrt{2}\pi}\left(|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2\right)$$

with $\frac{G_\mathrm{F}\mathrm{M}_\mathrm{W}^3}{2\sqrt{2}\pi} = (707 \pm 1)\mathrm{MeV}$

Thus:

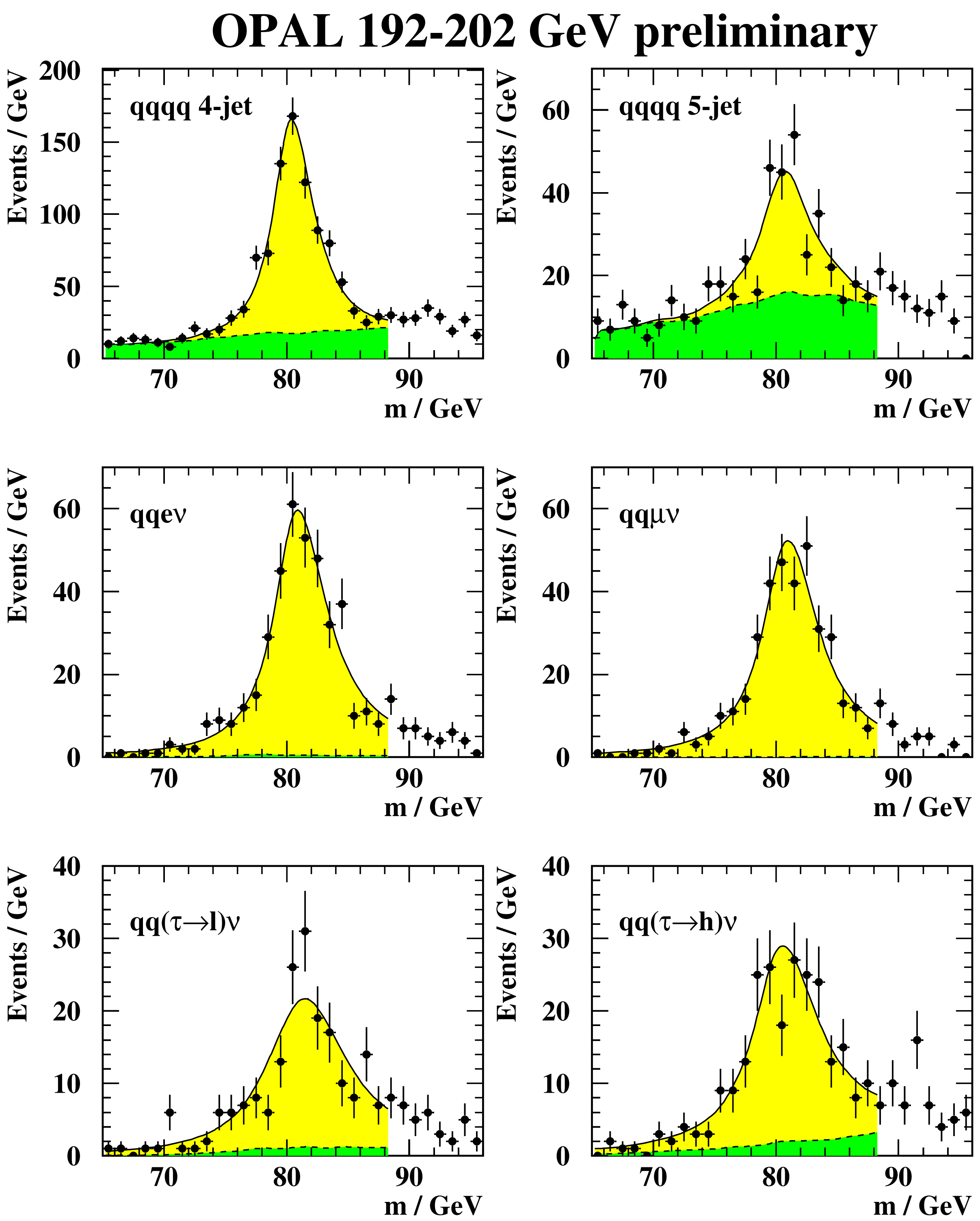
$$\Gamma\,(\mathrm{W} \to \mathrm{c\,X}) = R_c^{\mathrm{W}}\,\mathrm{Br}(\mathrm{W} \to \mathrm{q\bar{q}})\,\Gamma_\mathrm{W}$$

LEP Preliminary with $\sqrt{s}$=161-202 GeV data:

$$\boxed{|V_{cs}| = 0.974 \pm 0.050}$$

Remark: PDG98 from charm semielectronic decays is

W Mass Extraction



⟹ M_W: **Perform maximum likelihood fits to data.**

- Compare Reweighted MC to Data
- Convolute Differential Xsection with the Resolution Function
- Analytic Breit-Wigner Signal Function

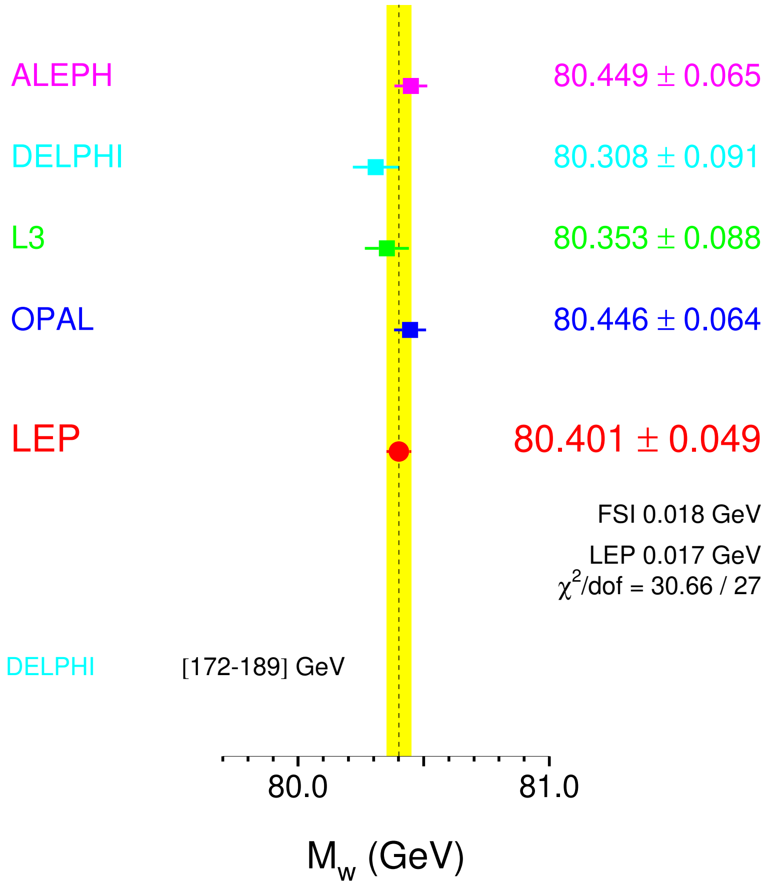
Systematic on M_W

- Preliminary, error overestimated, incomplete...
- Current Statistical Error: 27 MeV
- Current Systematic Error: 49 MeV
- WW99 Workshop Co-operation at LEP2

Source	Error	Correlated
Background	3-15 MeV	No
Detector Effects	9-30 MeV	No
ISR	2-15 MeV	Yes
Beam Energy	17 MeV	Yes
Fragmentation	17-45 MeV	Yes
	FSI Effects	
Colour Reconnection	30-55 MeV	Yes
Bose-Einstein	20-50 MeV	Yes

Mass of the W Boson

M_W (GeV) 172-202 GeV LEP



Preliminary Error LEP2

$\pm 27(\mathrm{stat}) \pm 30(\mathrm{syst})$

$\pm 18(\mathrm{FSI}) \pm 17(\mathrm{LEP})$

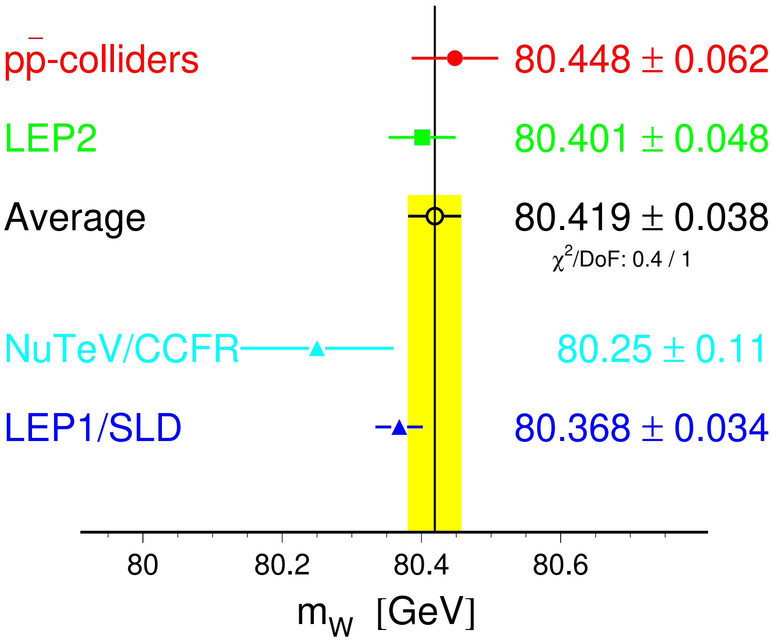
in MeV

Mass Difference

$\mathrm{M_W}(\mathrm{q\bar{q}q\bar{q}} - \mathrm{q\bar{q}}\ell\bar{\nu})$

$= (35 \pm 55)$ MeV

World Average W-Boson Mass [GeV]



World Average

Winter 00

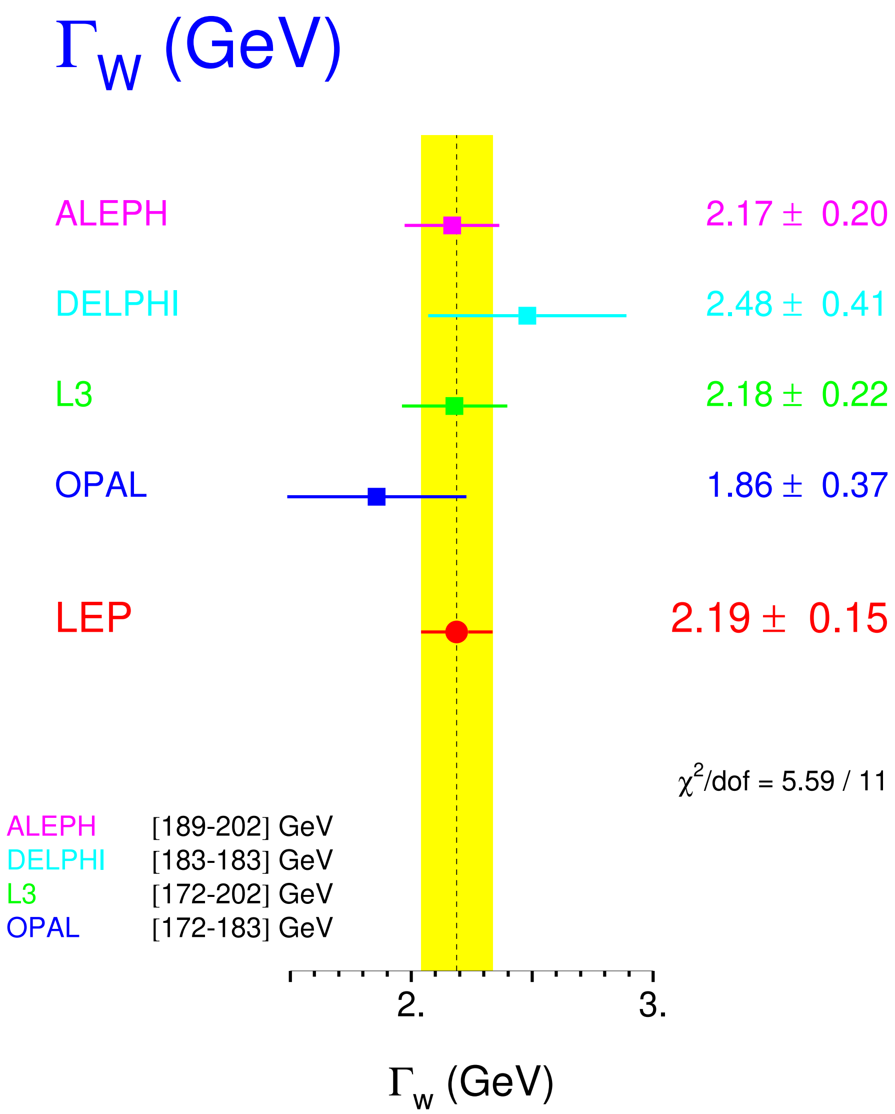
LEP2 includes

Threshold

Width of the W Boson

- Same techniques as for the mass measurement
- Main Systematics: Fragmentation & FSI
- Correlation with the mass is small
- First LEP combination

Preliminary



Comparable accuracy to CDF direct W width determination:

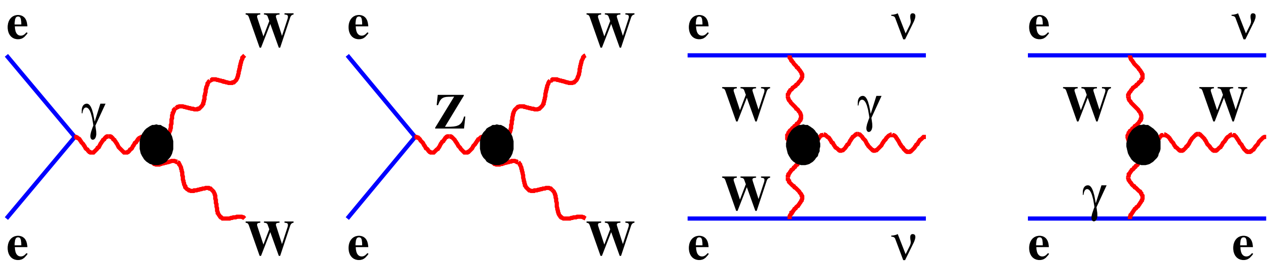
$$\Gamma_\mathrm{W} = (2.055 \pm 0.125) GeV$$

Trilinear Gauge Coupling

Due to non-abelian tructure of $SU(2)_L \otimes U(1)_Y$ gauge theory.

Their strength mainly measured with W pair events.

Further information from single W and single γ events.



$$i\,\frac{\mathcal{L}_{TGC}^{V}}{g_{WWV}} = g_1^V V_\mu (W^{-\mu\nu}W_\nu^+ - W^{+\mu\nu}W_\nu^-) + \kappa_V V^{\mu\nu}W_\mu^- W_\nu^+ + \frac{\lambda_V}{M_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^-$$

with $g_{WW\gamma} = e$ and $g_{WWZ} = e\cot\theta_W$.

Asking for $U(1)_{em}$ and $SU(2)_L \otimes U(1)_Y$ invariance:

$$Q_W = e\,g_1^\gamma \Rightarrow g_1^\gamma = 1$$

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

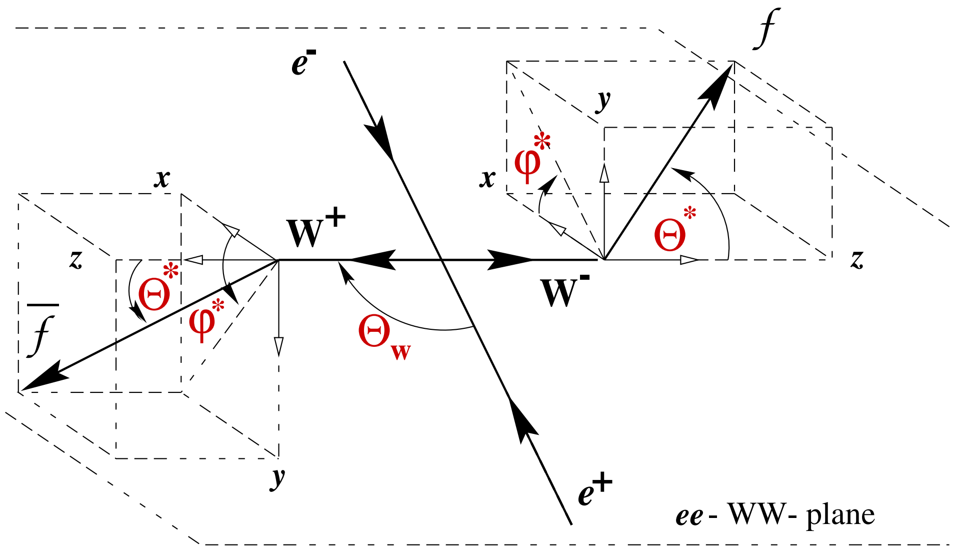
$$\lambda_Z = \lambda_\gamma = \lambda$$

Considering **deviation** for the Standard Model:

$$\Delta g_1^Z = g_1^Z - 1,\ \Delta\kappa_\gamma = \kappa_\gamma - 1,\ \lambda = 0.$$

Three parameters left: $\boldsymbol{\Delta g_1^Z, \Delta\kappa_\gamma, \lambda}$

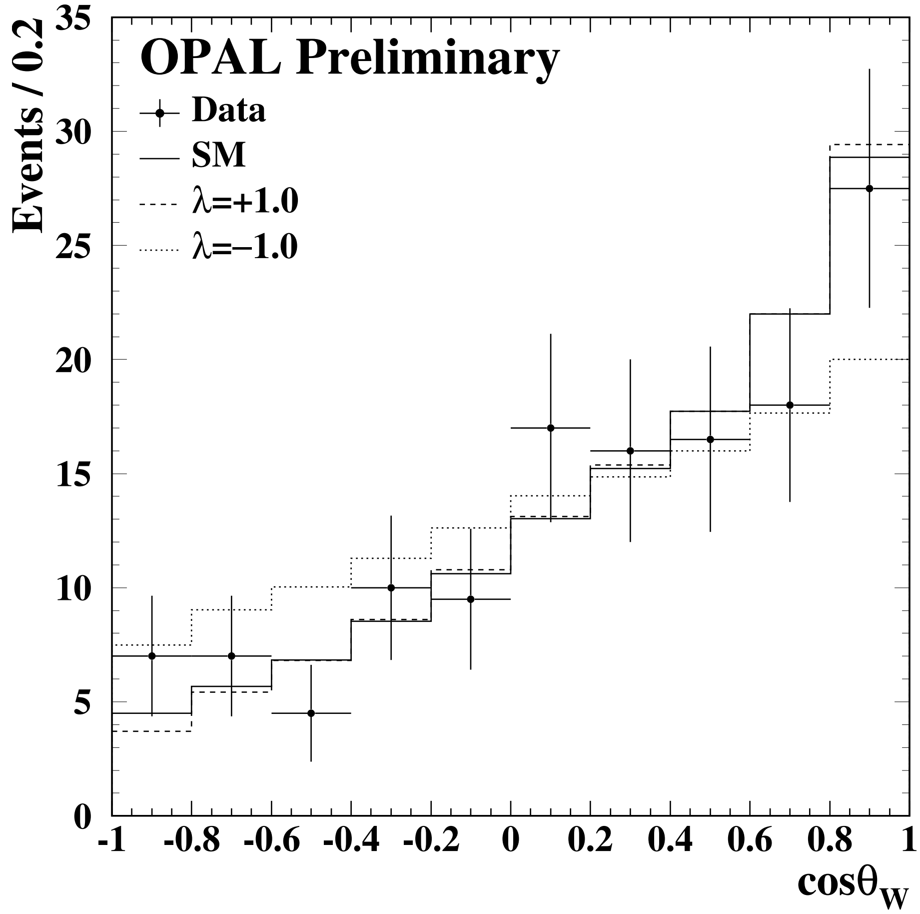
LEP Results on TGC



Sensitivity to couplings: - Total Cross-Section $\sigma_{\rm tot}$

- W^{+} scatering angle (θ_{W+})

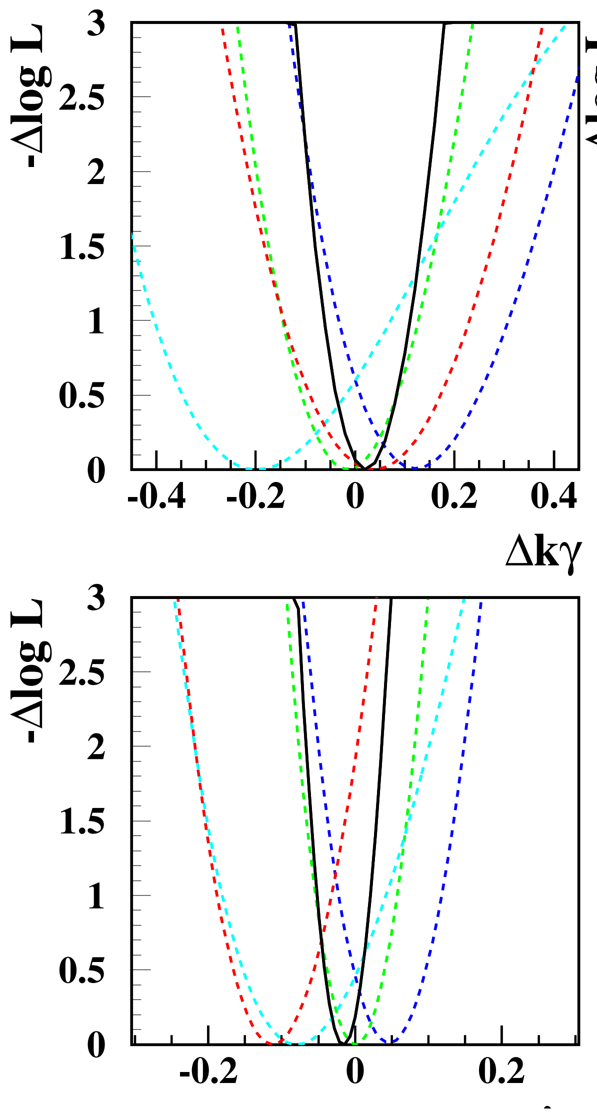
- Wpolarisation $\theta^{*}_{f(\bar{f})}$ and $\phi^{*}_{f(\bar{f})}$



LEP Results on TGC

One parameter fits - Preliminary

ALEPH + DELPHI+ L3 + OPAL



$\Delta k_\gamma = .021 \begin{smallmatrix} +\ 0.063 \\ -\ 0.059 \end{smallmatrix}$

$\Delta g_1^Z = -.024 \begin{smallmatrix} +\ 0.024 \\ -\ 0.024 \end{smallmatrix}$

$\lambda_\gamma = -.016 \begin{smallmatrix} +\ 0.026 \\ -\ 0.026 \end{smallmatrix}$

No single W at 192-202 GeV

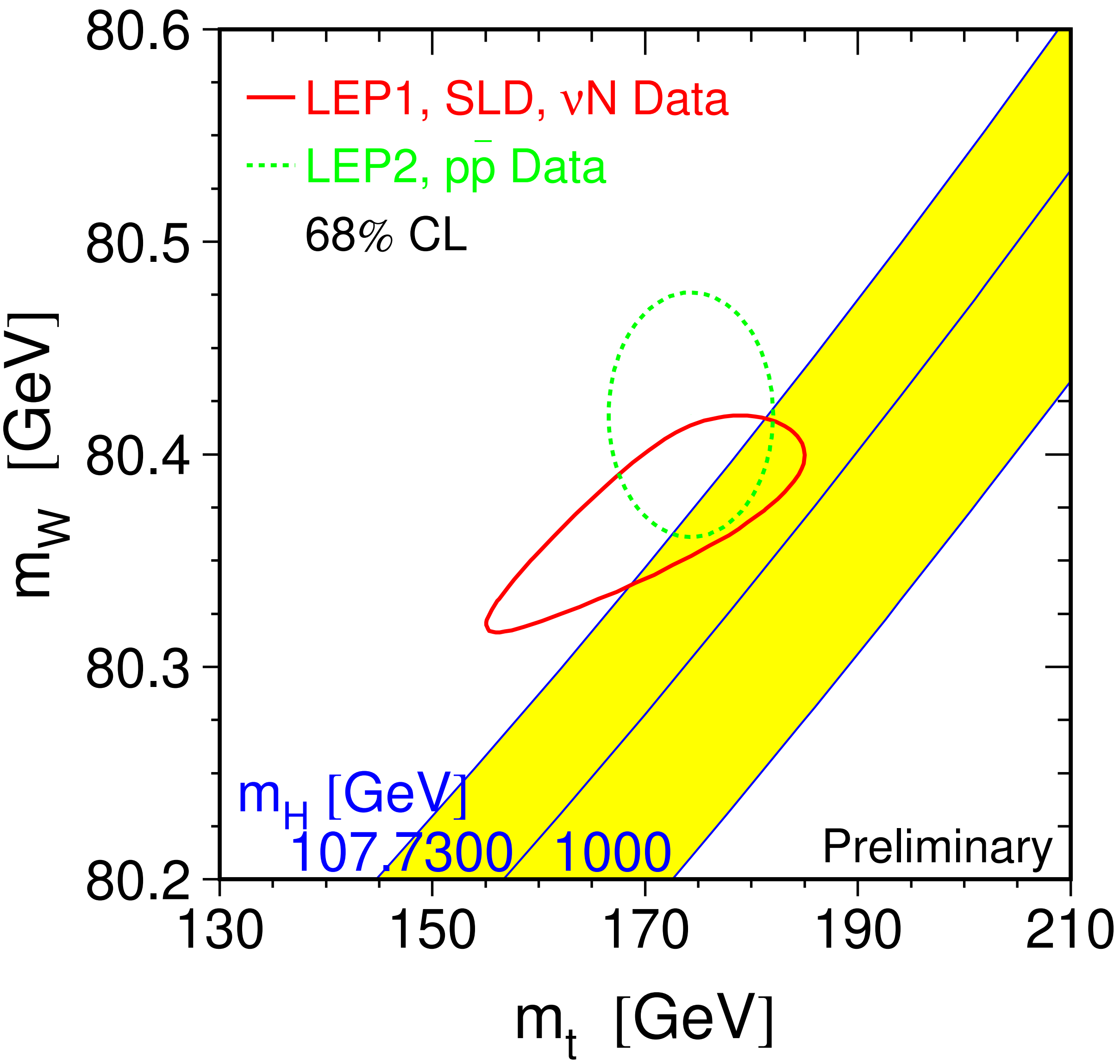
No 192-202 GeV data from OPAL

Not all W decay channels from ALEPH at 192-202 GeV

No $\gamma\gamma\nu$ from OPAL

SM Higgs is light!

PRELIMINARY: Direct and indirect measurement of $m_{\rm top}$ and $\mathrm{M_W}$ for different $m_{\rm Higgs}$:



Standard Model parameter relations confirmed at quantum level that small Higgs masses are preferred.

Conclusions

- Standard Model is looking good !
- LEP2 precision measurements improving with increasing statistics and detailed systematic studies.
- The LEP2 experiments offer a great variety of experimental probes for the study of the weak properties of the neutral and charged mediators of the weak interaction.
- Future: More data for the LEP experiments (at higher energies!).