Status of M_W Measurement at LEP

Douglas A. Glenzinski
Enrico Fermi Institute,
University of Chicago
(representing the LEP Collaborations)

OUTLINE

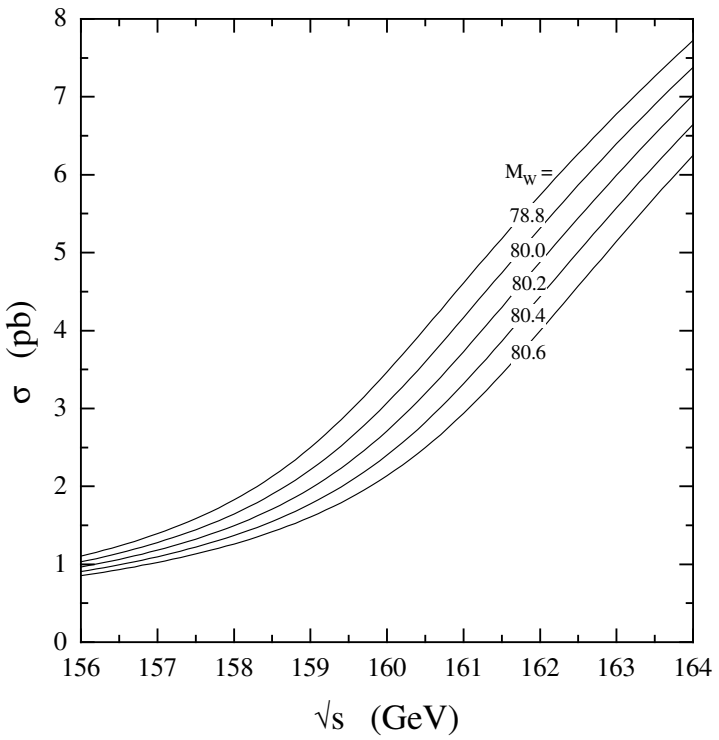
- Introduction
- Selection
- Reconstruction
- Results
- Prospects and Conclusions

LEP Methods for Measuring M_W

Two Methods for Extracting M_W

1) for $\sqrt{s} \approx 2\,M_W$, Threshold (TH):

$$M_W \sim 1/\sigma(e^+e^- \to W^+W^-)$$



1996: $10\ \mathrm{pb}^{-1}$/experiment @ $\sqrt{s} = 161$ GeV

$\Longrightarrow \approx 30$ WW events / experiment

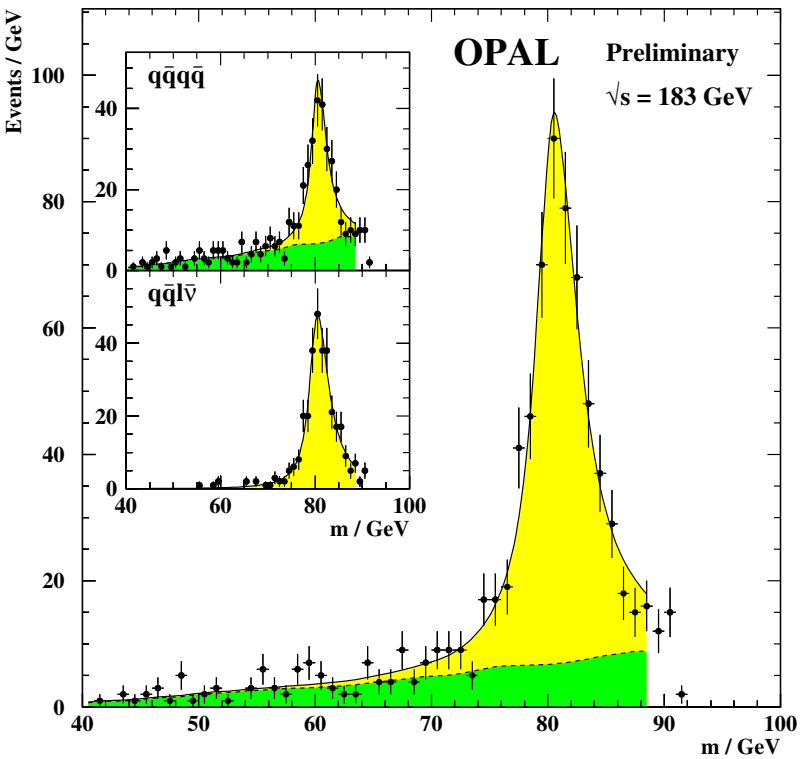
LEP average :

$$M_W = 80.40 \pm 0.20(\mathrm{exp}) \pm 0.03(E_{\mathrm{bm}})\ \mathrm{GeV}$$

LEP Methods for Measuring M_W

2) for $\sqrt{s} \geq 170$ GeV, Direct Reconstruction (DR):

$$\mathrm{PDF}(m_{rec}) \sim \frac{m_{rec}^2}{(m_{rec}^2 - M_W^2)^2 + (m_{rec}^4 \Gamma_W^2 / M_W^2)}$$



1996: $10\ \mathrm{pb}^{-1}$/experiment @ $\sqrt{s} = 172$ GeV

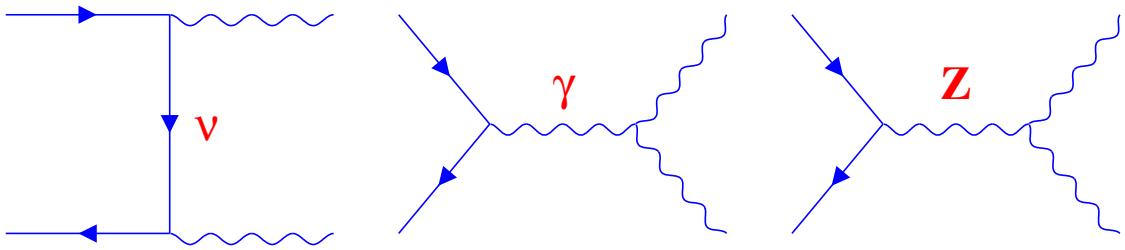
1997: $55\ \mathrm{pb}^{-1}$/experiment @ $\sqrt{s} = 183$ GeV

$\Longrightarrow \approx 850$ WW events / experiment

Concentrate on DR method as it dominates LEP M_W measurements

Procedure

$e^+e^- \to W^+W^-$ production dominated by CC03 diagrams:



Each $W^\pm$ decays into an $f\bar{f}$ pair. The $f\bar{f}f\bar{f}$ final states are:

final state	BR
$q\bar{q}q\bar{q}$	46%
$q\bar{q}\ell\bar{\nu}$	44%
$\ell\bar{\nu}\ell\bar{\nu}$	10%

(presently, $\ell\bar{\nu}\ell\bar{\nu}$ channel is not exploited – a factor 6-7 less sensitive)

To measure M_W:

1. select $W^+W^- \to f\bar{f}f\bar{f}$ events
2. get reconstructed invariant mass for each event, m_{rec}
3. from m_{rec} distributions, extract measure of M_W

Selection of $\mathrm{W^+W^-}$ Events

The expected statistical error on $\mathrm{M_W}$ varies as:

$$\Delta \mathrm{M_W(stat)} \sim \frac{1}{\sqrt{\mathrm{N_{WW}}}} \cdot \frac{1}{\sqrt{\mathrm{Purity}}}$$

so high efficiency (ε), high purity ($\mathcal{P}$) selections are important.

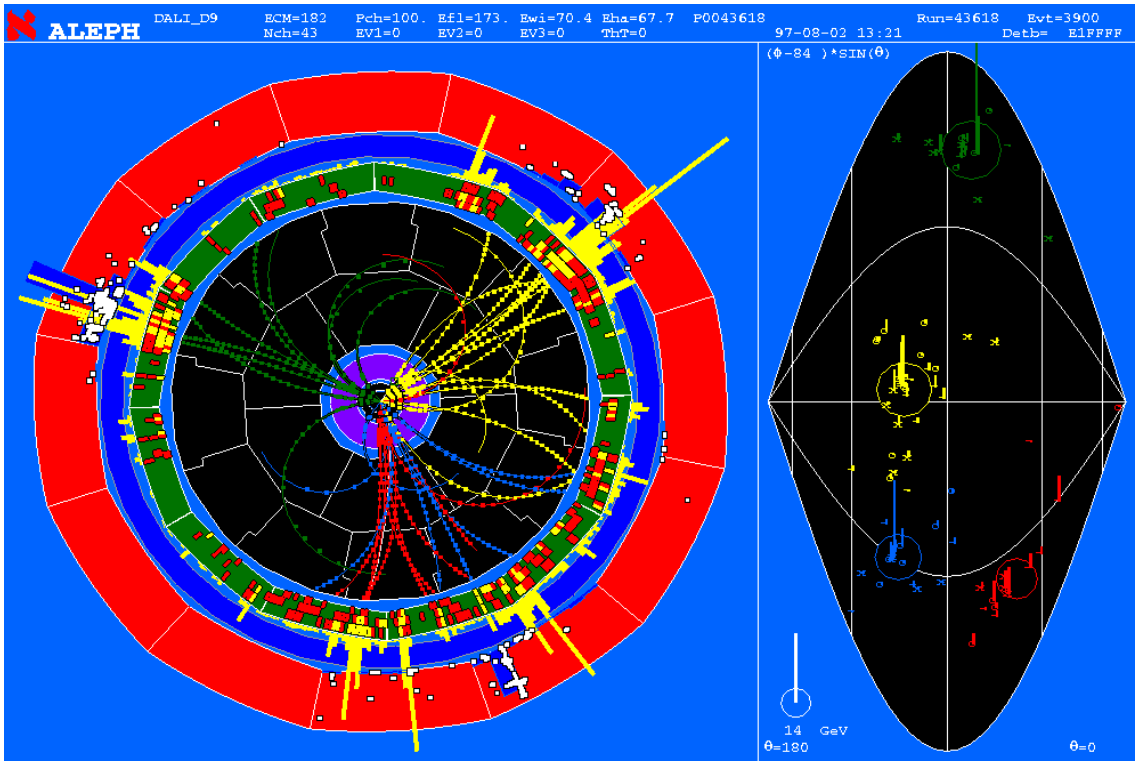
channel		experiment A	D	L	O
$\mathrm{q\bar{q}q\bar{q}}$	ε (%)	83	85	88	85
	$\mathcal{P}$ (%)	83	65	80	80
$\mathrm{q\bar{q}e\bar{\nu}(\mu\bar{\nu})}$	ε (%)	89	71	87	90
	$\mathcal{P}$ (%)	96	94	96	94
$\mathrm{q\bar{q}\tau\bar{\nu}}$	ε (%)	64	–	59	75
	$\mathcal{P}$ (%)	93	–	87	83

For 1997 @ $\sqrt{s} = 183$ GeV this gives (excluding $\ell\bar{\nu}\ell\bar{\nu}$):

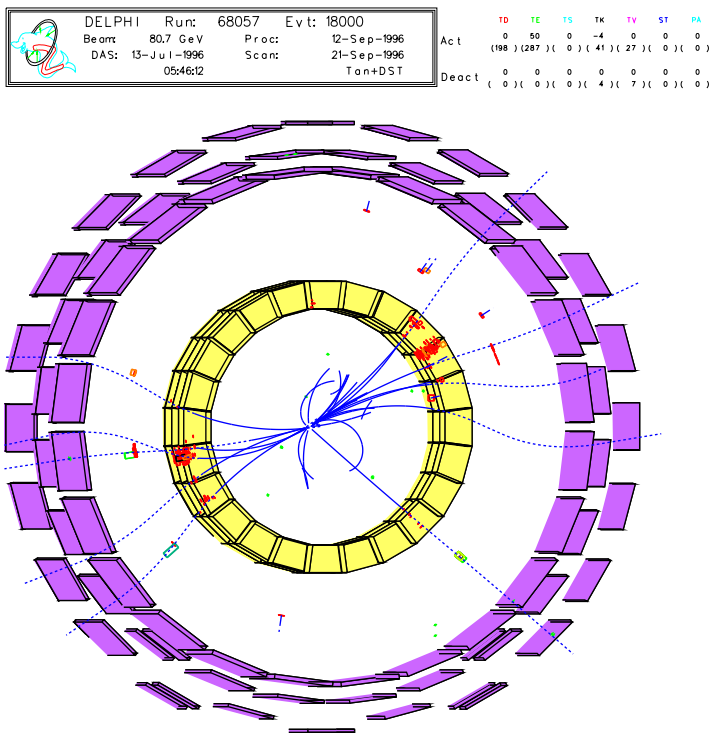
$$< \mathrm{N_{WW}} > /\mathrm{experiment} \approx 600$$
$$< \mathrm{N_{bgd}} > /\mathrm{experiment} \approx 100$$

Some Selected Events

$$W^+W^- \to q\bar{q}q\bar{q}$$



$$W^+W^- \to q\bar{q}\mu\bar{\nu}$$

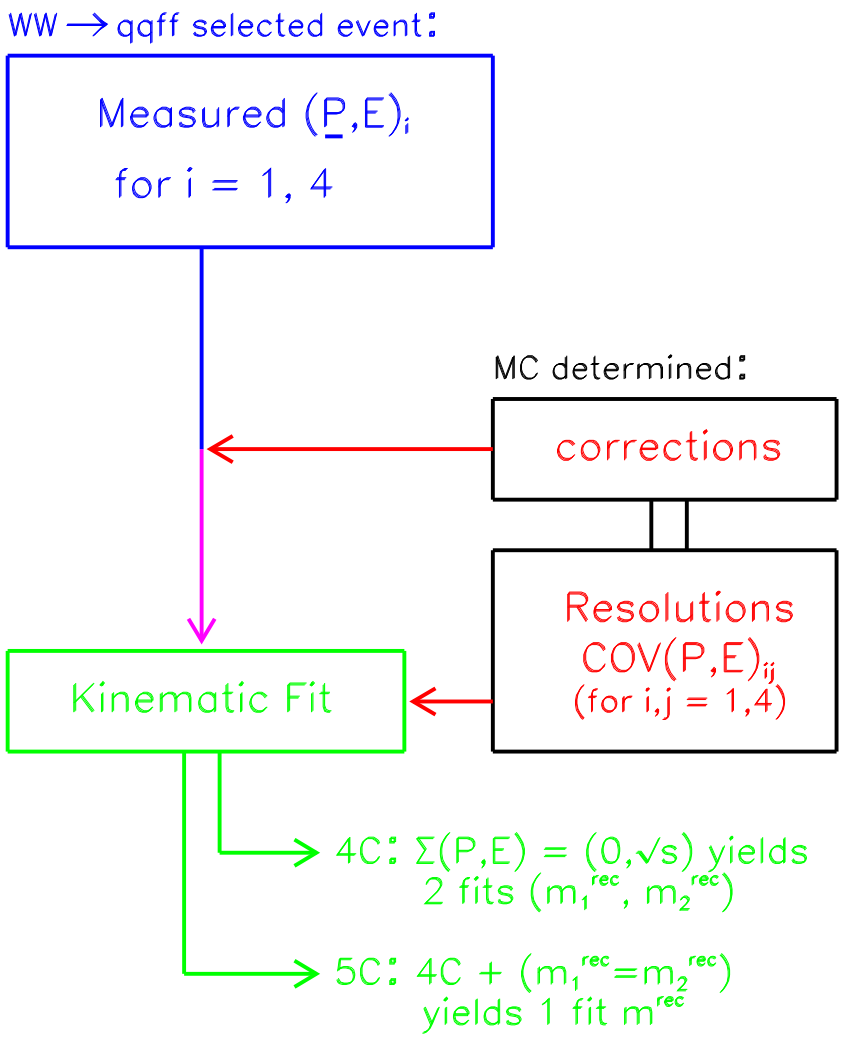


Invariant Mass Reconstruction

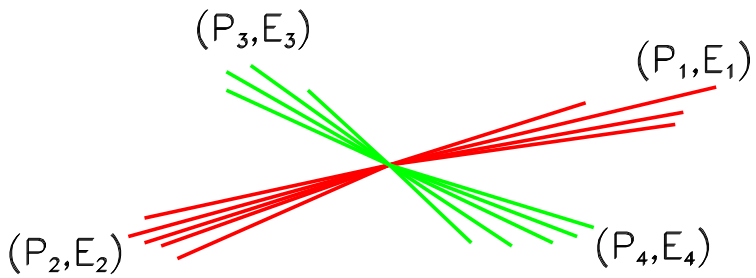
Several methods available:

- A) simple $\mathrm{M_{f\bar{f}}} = \sqrt{2\mathrm{E_1}\mathrm{E_2}(1-\cos\theta_{12})}$
- B) scaled $\mathrm{M'_{f\bar{f}}} = \mathrm{M_{f\bar{f}}} \cdot \left(\frac{\mathrm{E_{bm}}}{\mathrm{E_1}+\mathrm{E_2}}\right)$
- C) kinematic fit exploiting niceties of $\mathrm{e^+e^-}$ machines

Method C gives best resolution and is employed by ADLO.



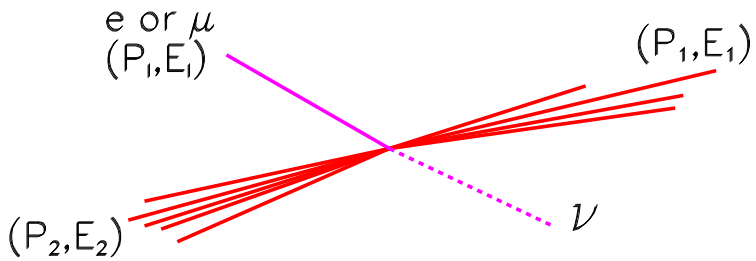
Invariant Mass Reconstruction



$\underline{\mathrm{q\bar{q}q\bar{q}}}$: force 4-jets

use a 4C- or 5C-fit

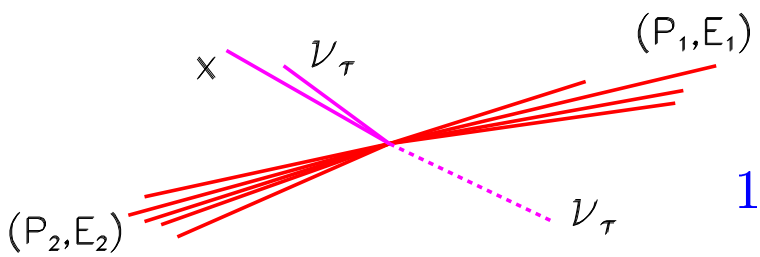
3 jet-jet pairings



$\underline{\mathrm{q\bar{q}e\bar{\nu}}}$ or $\underline{\mathrm{q\bar{q}}\mu\bar{\nu}}$:

$1\mathrm{C} = 4\mathrm{C} - \mathbf{P}_\nu$ fit or

$2\mathrm{C} = 5\mathrm{C} - \mathbf{P}_\nu$ fit



$\underline{\mathrm{q\bar{q}}\tau\bar{\nu}}$: use either

$1\mathrm{C} = 5\mathrm{C} - \mathbf{P}_\nu - \mathrm{E}_\tau$

or $\mathrm{M}'_{\mathrm{q\bar{q}}}$ info only

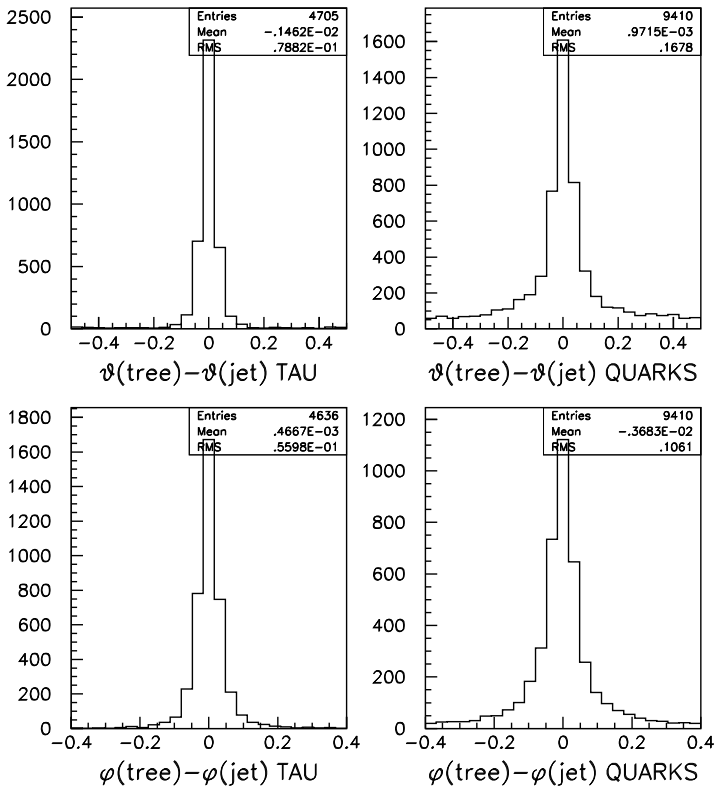
- two types of kinematic fits
  - 4C fit: $\sum(\underline{\mathrm{P}}, \mathrm{E}) = (0, \sqrt{s})$; yields two masses $(\mathrm{m_{rec_1}}, \mathrm{m_{rec_2}})$
  - 5C fit: 4C $+(\mathrm{m_{rec_1}} = \mathrm{m_{rec_2}})$; yields a single $\mathrm{m_{rec}}$

An Aside: $\mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$ Combinatorics

- assuming 4-jet: jet pairing ambiguity yields 3 combinations of $(\mathrm{m_{rec_1}}, \mathrm{m_{rec_2}})$ (5-jet final state yields 10!)
- only the correct combination contains $\mathrm{M_W}$ information
  - OL use 5C kinematic fit probabilities to order pairings:
    - $\mathcal{P}_1 > \mathcal{P}_2 > \mathcal{P}_3$
    - $\mathcal{P}_1$ correct $\approx 65\%$ and $\mathcal{P}_2$ correct $\approx 25\%$
    - use $\mathcal{P}_1$ and $\mathcal{P}_2$ at cost of additional combinatorics
  - DA use $\Delta\mathrm{m_{rec}}$ and $\sum \theta_{jj}$ information from 4C fit to choose best combination
    - D uses all combinations
    - A only use 1 combination per event
    - A choose correctly $\approx 85\%$
    - caveat: A biases shape of background distribution slightly
  - OD employ weights to suppress $\mathcal{P}_2 \ll \mathcal{P}_1$

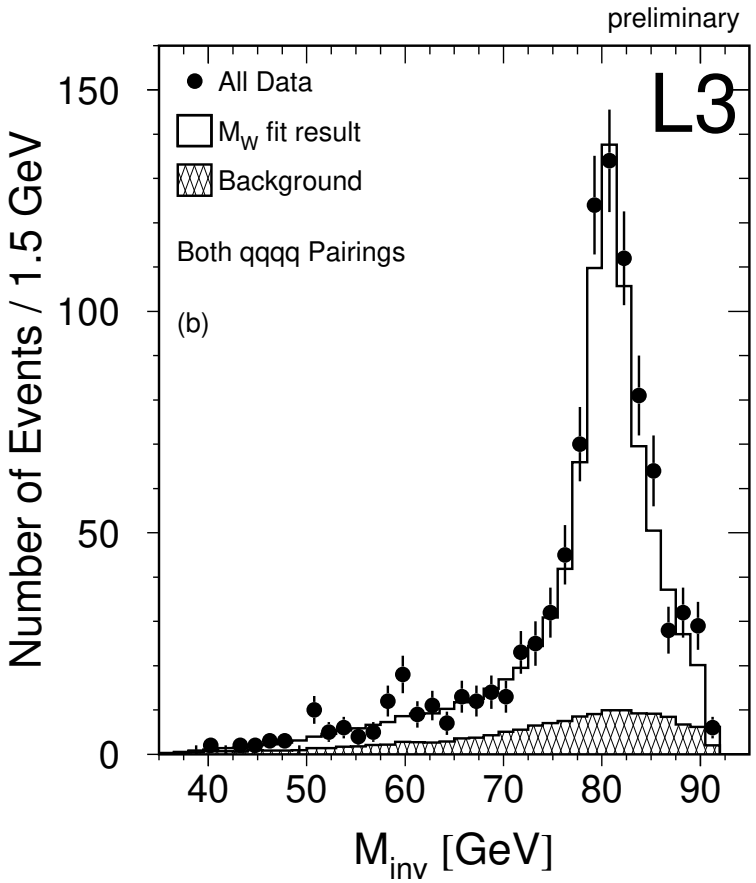
An Aside: $\mathrm{W^+W^-} \to \mathrm{q\overline{q}}\tau\overline{\nu}$ Fits

- a kinematic fit more difficult since $\sum \mathrm{P}^{\tau}_{\mathrm{vis}} \neq \mathrm{P}_{\tau}$
- still possible if
  - assume $\sum \widehat{\mathrm{P}^{\tau}_{\mathrm{vis}}} = \widehat{\mathrm{P}_{\tau}}$
  - employ a 5C fit to determine P_{ν}, E_{τ}, and $\mathrm{m}_{\mathrm{rec}}$



- or, can simply use information from hadronic system (scaled $\mathrm{M}_{\mathrm{q\overline{q}}}$)
- OA use 5C fit. L uses scaled $\mathrm{M}_{\mathrm{q\overline{q}}}$ and *calculated* $\mathrm{M}_{\tau\overline{\nu}}$. D does not use $\mathrm{q\overline{q}}\tau\overline{\nu}$.

Ensemble of selected events yields a m_{rec} distribution.



Various methods to extract M_W from m_{rec} distribution:

- a) analytic fit to Breit-Wigner + background

$$f(m_{rec}) \sim \frac{m_{rec}^2}{(m_{rec}^2 - M_W^2)^2 + (m_{rec}^4 \Gamma_W^2 / M_W^2)}$$

- b) maximum likelihood comparison of data to MC spectra corresponding to various M_W

$$\ln(\mathcal{L}) = \sum_{i=1}^{N_{bins}} n_i \ln(f_b P_b^i + (1 - f_b) P_s^i(M_W, \Gamma_W))$$

- c) convolution techniques

$$\mathcal{L} = (1 - f_b) \left(\int R(\hat{m} \mid m_{rec}) \cdot BW(\hat{m} \mid M_W) \cdot dm \right) + f_b P_b(m_{rec})$$

Extracting $\mathrm{M_W}$

- a) analytic fit to Breit-Wigner + background

  + simple

  - biased (*a posteriori* correction necessary)

  - choice of fit function is arbitrary

  - does not make optimal use of all information

- b) maximum likelihood comparison of data to MC spectra corresponding to various $\mathrm{M_W}$

  + simple and unbiased

  - requires lots of MC

  - does not make optimal use of all information

- c) convolution techniques

  + makes use of all available information

  - many functions are approximate (ie. $\mathrm{R}(\hat{\mathbf{m}}; \mathrm{m_{rec}})$)

  - requires lots of MC

  $\pm$ may or may not require bias correction depending on whether or not all effects (ie. ISR) included

ALO use method b). D uses method c). All employ a) as a cross-check.

LEP M_W Results at $\sqrt{s} = 183$ GeV

for $q\bar{q}\ell\bar{\nu}$:

all quantities in GeV

exp	$M_W \pm (\text{stat}) \pm (\text{syst})$	$\hat{\sigma}_{\text{stat}}$	s
A	$80.16 \pm 0.20 \pm 0.08$	0.21	3.7
D	$80.50 \pm 0.26 \pm 0.07$	0.25	3.3
L	$80.03 \pm 0.24 \pm 0.07$	0.21	3.8
O	$80.25 \pm 0.18 \pm 0.08$	0.20	3.2
LEP	$80.22 \pm 0.11 \pm 0.05$	$\chi^2 = 1.8/3$	

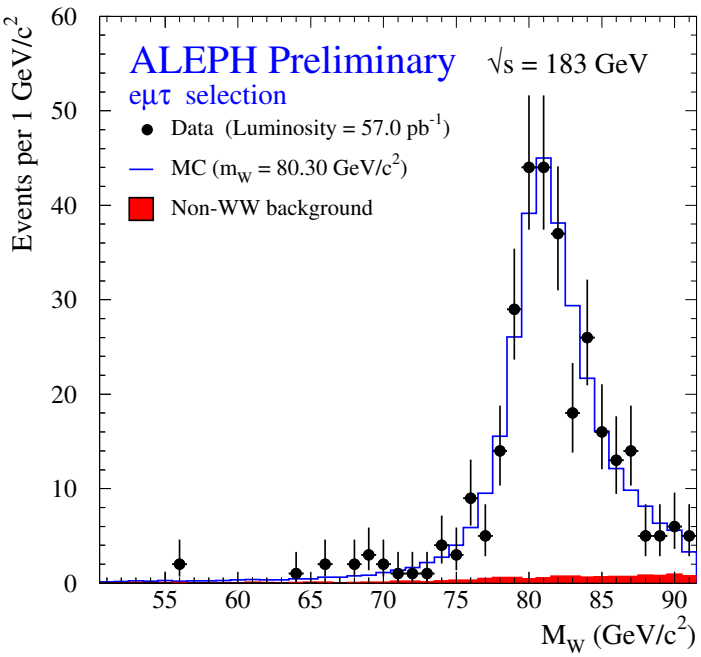
for $q\bar{q}q\bar{q}$:

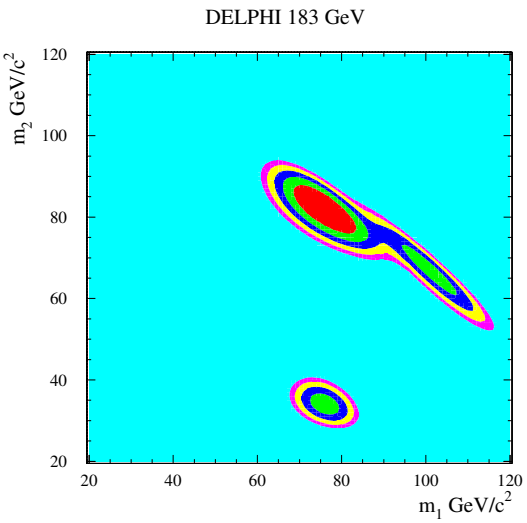
all quantities in GeV

exp	$M_W \pm (\text{stat}) \pm (\text{syst}) \pm (\text{CR})$	$\hat{\sigma}_{\text{stat}}$	s
A	$80.45 \pm 0.18 \pm 0.06 \pm 0.10$	0.18	3.6
D	$80.02 \pm 0.20 \pm 0.05 \pm 0.10$	0.21	4.4
L	$80.51 \pm 0.21 \pm 0.09 \pm 0.10$	0.22	4.5
O	$80.48 \pm 0.23 \pm 0.08 \pm 0.10$	0.20	3.9
LEP	$80.36 \pm 0.10 \pm 0.05 \pm 0.10$	$\chi^2 = 3.8/3$	

- $\hat{\sigma}_{\text{stat}} \equiv$ expected statistical error
- $s \equiv$ per event "sensitivity" $= \hat{\sigma}_{\text{stat}} \cdot \sqrt{\hat{N}_{\text{evt}}}$
- for LEP combination, ISR, hadronization, E_{bm}, and CR/BE uncertainties taken as correlated

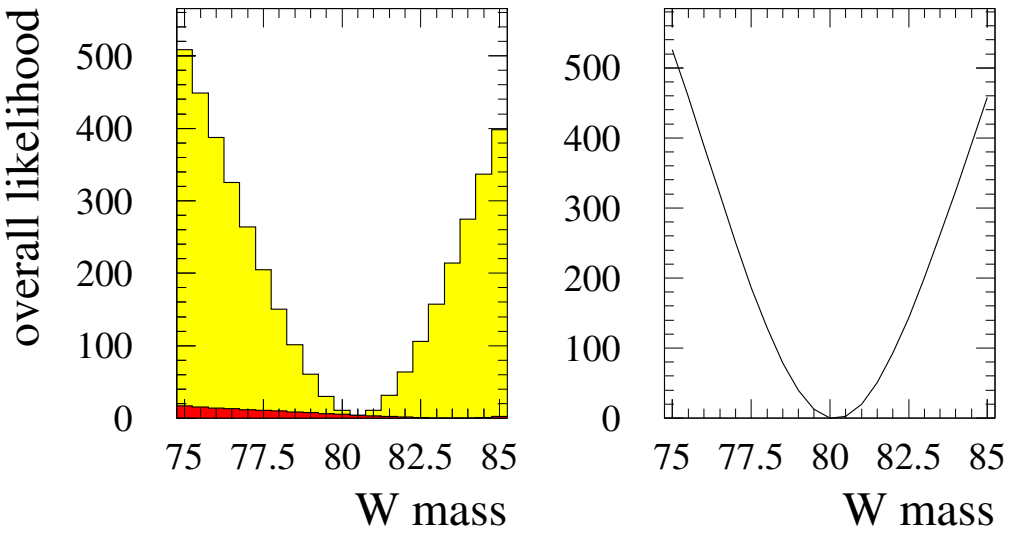
LEP M_W Results at $\sqrt{s} = 183$ GeV





← Delphi

↓



Systematic Errors

for "typical" LEP experiment

systematic source	ΔM_W (MeV) $q\bar{q}\ell\bar{\nu}$	$q\bar{q}q\bar{q}$
initial state radiation	15	15
hadronization	25	30
four fermion	20	20
detector effects	45	50
fit procedure	30	30
Subtotal	65	70
beam energy	30	30
color reconnection	–	100
Total	71	126

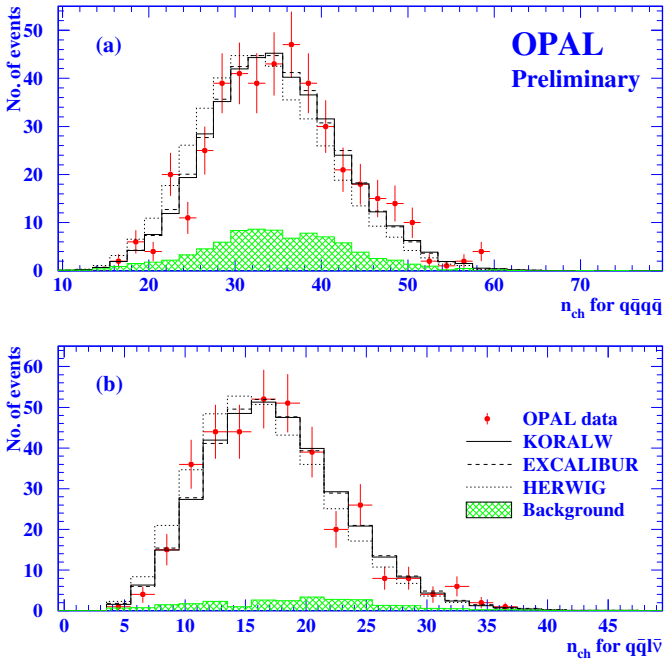
- isr/hadronization/four-fermion errors all limited by statistics of comparison
- detector effects are large
  - compare energy scales and resolutions using $\sqrt{s} \approx M_{Z^0}$ data at start of each year
  - monitor using Bhabha events
  - lots of work to do for future measurements
- "fit procedure" dominated by background shapes and normalizations and finite MC statistics

Systematic Errors

Color Reconnection Effects:

- only effects $\mathrm{q\bar{q}q\bar{q}}$ channel
- standard QCD models assume each W fragments independently
- effects of CR alter this assumption and (might) distort the reconstructed mass spectra
- requires theoretical and experimental input

New using 183 GeV data:



CR may effect other experimental observables ie:

$$\Delta\hat{n}_{\mathrm{ch}} = \hat{n}_{\mathrm{ch}}^{4\mathrm{q}} - 2\hat{n}_{\mathrm{ch}}^{\mathrm{qq}\ell\nu}$$

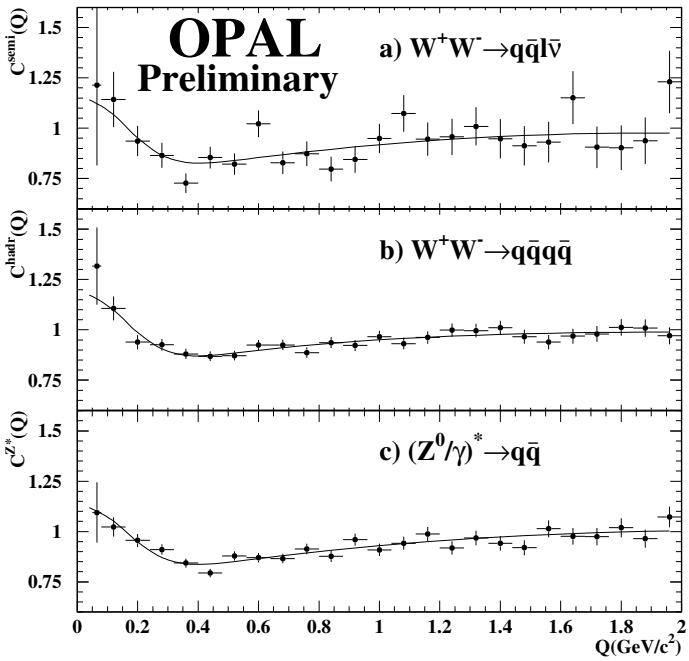
some models predict $\left|\Delta\hat{n}_{\mathrm{ch}}\right| \approx 4$ units while our present sensitivity, including systematics, is < 1 unit (cf. G. Duckeck's talk)

Systematic Errors

Bose-Einstein Correlation Effects:

- only effects $\mathrm{q\bar{q}q\bar{q}}$ channel
- MC models used do not include BE correlations
- correlations between decay products originating from different Ws (might) distort the reconstructed mass spectra
- requires theoretical and experimental input

New using $172 + 183$ GeV data:



$$\lambda(\mathrm{diff}) = 0.40 \pm 0.50(\mathrm{stat}) \pm 0.39(\mathrm{syst})$$

$$\lambda(\mathrm{same}) = 0.72 \pm 0.25(\mathrm{stat}) \pm 0.25(\mathrm{syst})$$

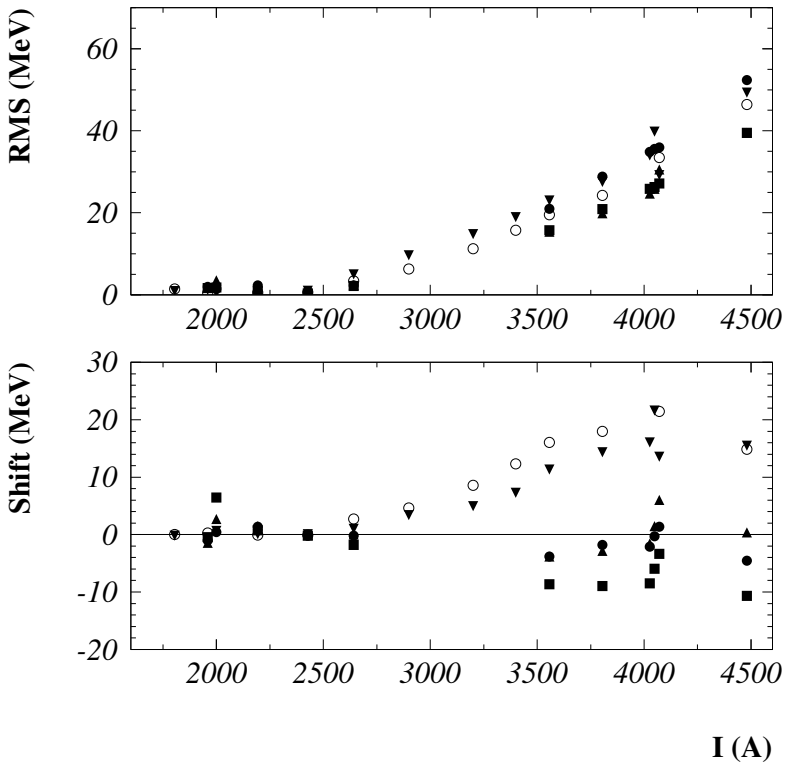
$$R = 0.94 \pm 0.09(\mathrm{stat}) \pm 0.13(\mathrm{syst})\ \mathrm{fm}$$

(DA also have results from 172 GeV only)

Systematic Errors

LEP Beam Energy:

- effects all channels through constraints imposed by kinematic fits
- in 1996 @ $\sqrt{s} = 172$ GeV estimated $\Delta \mathrm{E_{bm}} = 30$ MeV based on a conservative "guess"... turned out to be right
- total 1997 @ $\sqrt{s} = 183$ GeV, $\Delta \mathrm{E_{bm}} = 29$ MeV
- dominant systematics are:
  - extrapolation procedure: 20 MeV
  - NMR RMS for fits and extrapolations: $(10 \oplus 10)$ MeV

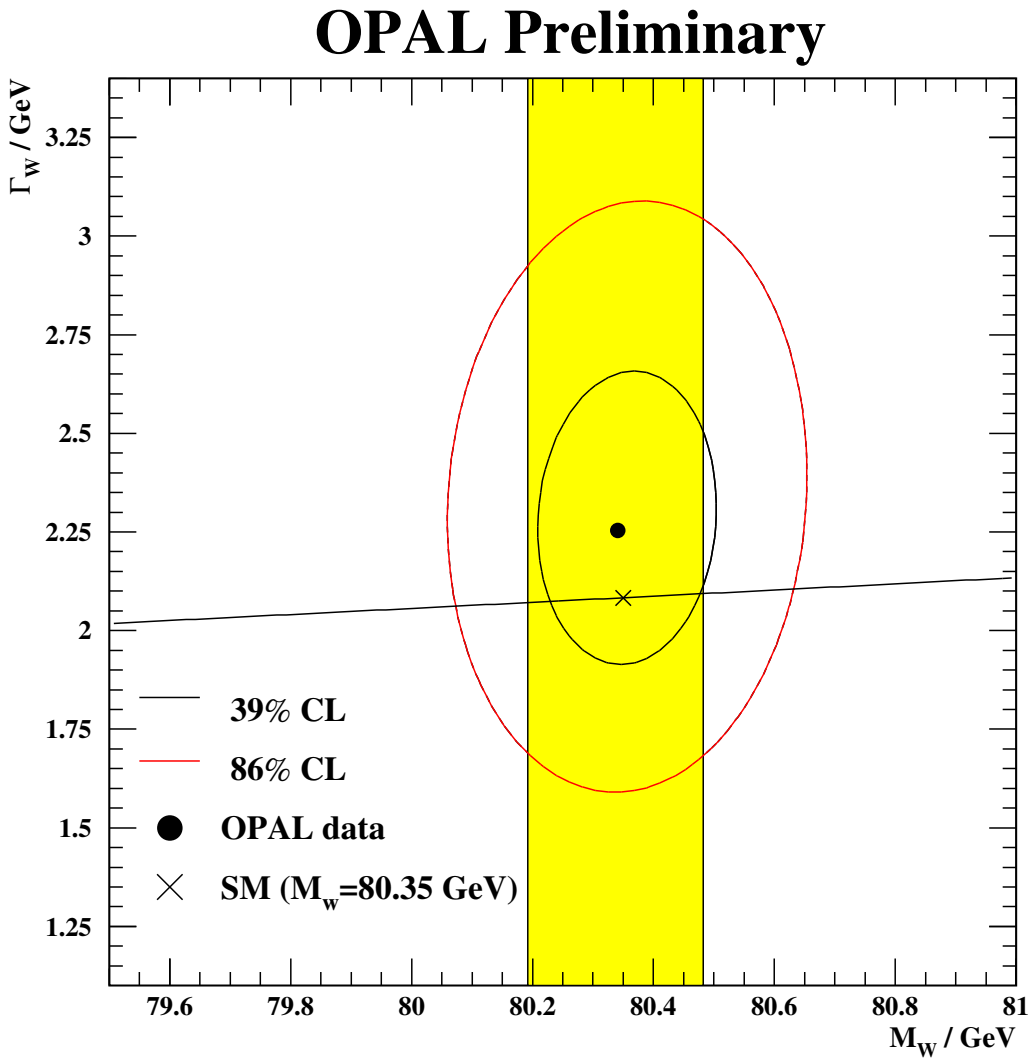


cross-check extrapolation by comparing NMR to flux loop fills

$\Longrightarrow$ more tricks up their sleeve - expect improvements

Direct Measurement of Γ_W

LO also perform simultaneous fits to (M_W, Γ_W):



OPAL: $\Gamma_W = 2.25 \pm 0.37(\text{stat}) \pm 0.17(\text{syst})$

L3: $\Gamma_W = 2.41 \pm 0.39(\text{stat}) \pm 0.25(\text{syst})$

Dominant systematics are from detector effects and background uncertainties.

LEP M_W from 172+183 GeV

for $q\bar{q}\ell\bar{\nu}$:

all quantities in GeV

exp	$M_W \pm (stat) \pm (syst)$
A	$80.20 \pm 0.18 \pm 0.08$
D	$80.50 \pm 0.23 \pm 0.06$
L	$80.09 \pm 0.23 \pm 0.06$
O	$80.29 \pm 0.17 \pm 0.07$
LEP	$80.27 \pm 0.10 \pm 0.04$ $\chi^2 = 1.7/3$

for $q\bar{q}q\bar{q}$:

all quantities in GeV

exp	$M_W \pm (stat) \pm (syst) \pm (CR)$
A	$80.57 \pm 0.17 \pm 0.07 \pm 0.10$
D	$80.01 \pm 0.19 \pm 0.05 \pm 0.10$
L	$80.59 \pm 0.19 \pm 0.09 \pm 0.10$
O	$80.40 \pm 0.20 \pm 0.08 \pm 0.10$
LEP	$80.40 \pm 0.09 \pm 0.05 \pm 0.10$ $\chi^2 = 5.9/3$

Combining with the threshold measurements gives:

$$\text{LEP } M_W(\text{DR} + \text{TH}) =$$
$$80.35 \pm 0.07(\text{exp}) \pm 0.04(\text{CR}) \pm 0.03(E_{\text{bm}})$$

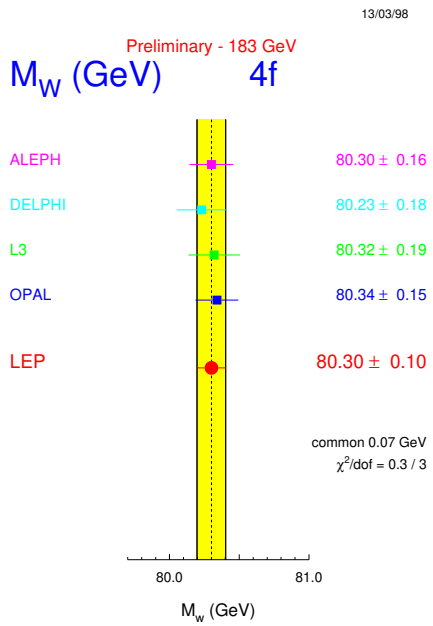
Conclusions

- LEP $\mathrm{M_W}$ will be systematics limited by this time next year. In 1998 we expect:
  - $\int \mathcal{L} dt \geq 150\ \mathrm{pb}^{-1}$ / exp @ $\sqrt{s} \approx 190$ GeV
  - $\Delta \mathrm{M_W(stat)} \sim 50$ MeV from LEP
- constraints on CR/BE effects should tighten-up in 1998
- detector effects looming... lots of work
- $\Delta \mathrm{E_{bm}}$ *may* be harder than first guessed... needs work for next year
- Using data from $\sqrt{s} = 161, 172, 183$ GeV, $\mathrm{M_W} =$

$$80.35 \pm 0.07(\mathrm{exp}) \pm 0.04(\mathrm{CR}) \pm 0.03(\mathrm{E_{bm}})\ \mathrm{GeV}$$

$\mathrm{M_W}$ Measurement at LEP

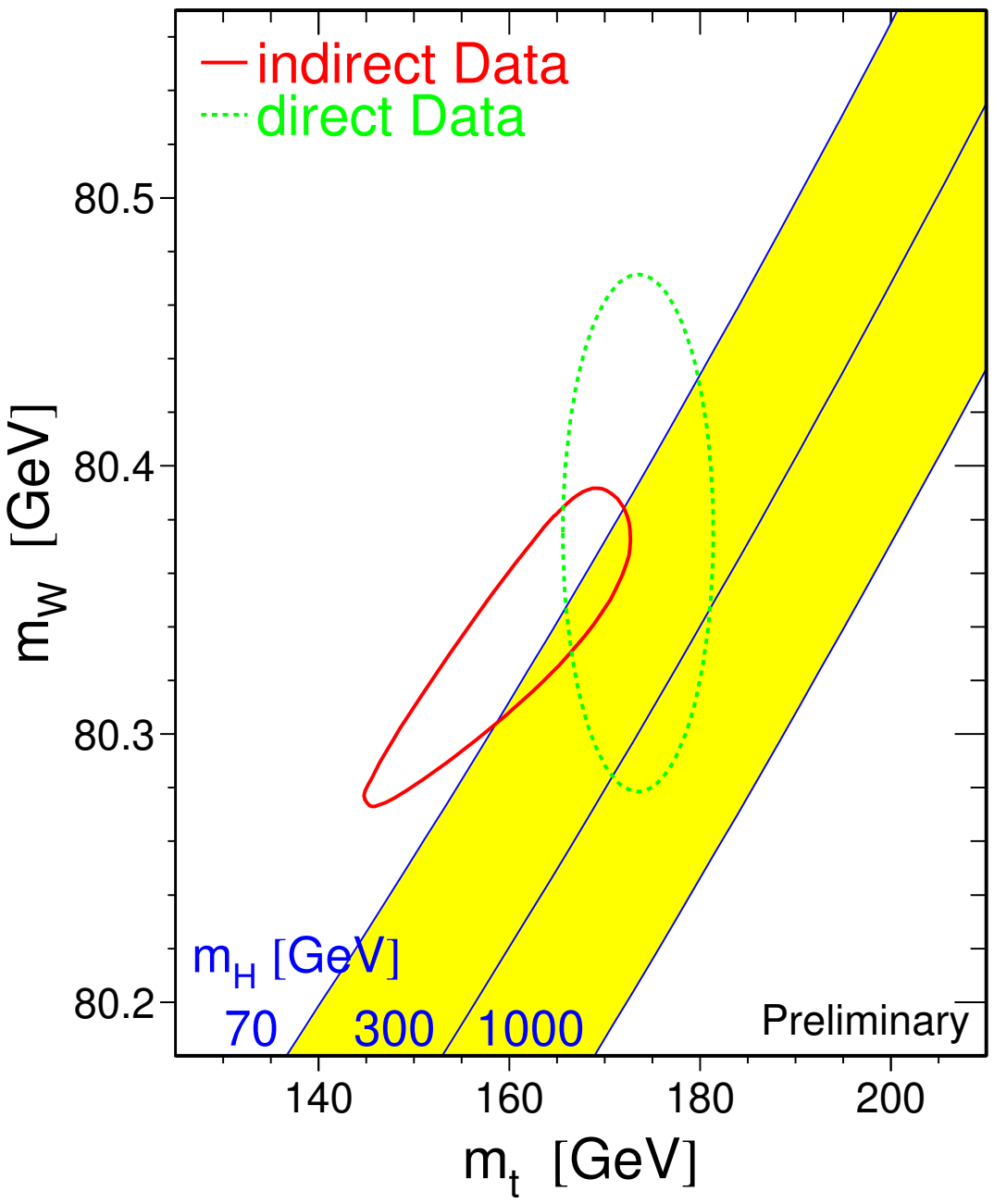
- in 1997 LEP delivered $55\ \mathrm{pb}^{-1}$ to each experiment ($\approx 600\ \mathrm{W^+W^-}$ events/experiment)
- using the distribution of reconstructed invariant masses the LEP average $\mathrm{M_W}$ is:



- dominant systematics are detector effects, $\mathrm{E_{bm}}$, and Color-Reconnection/Bose-Einstein interactions
- Using data from $\sqrt{s} = 161, 172, 183$ GeV, $\mathrm{M_W} =$

$$80.35 \pm 0.07(\mathrm{exp}) \pm 0.04(\mathrm{CR}) \pm 0.03(\mathrm{E_{bm}})\ \mathrm{GeV}$$

- in 1998 expect an additional $150\ \mathrm{pb}^{-1}$ per experiment
- will have enough sensitivity to constrain CR/BE models

Indrect vs Direct

- from a global fit to EWK data, *excluding* direct measurements of $\mathrm{M_W}$ and $\mathrm{M_t}$
- direct measurements of $\mathrm{M_W}$ and $\mathrm{M_t}$ from LEP and the TeVatron