Status of $\mathrm{M_W}$ Measurement at LEP2

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OUTLINE

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

Why should we care?

- 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[a]:
  - $\sin^2\theta_W = 0.217 \pm 0.014$
  - $\mathrm{M_W(indirect)} = 83.0 \pm 2.8$ GeV
  - $\mathrm{M_{Z^0}(indirect)} = 93.8 \pm 2.3$ GeV
  - TREE LEVEL deviations from the GSW EWK theory could be accommodated in those errors!
  - authors looked forward to a "very precise determination of $\mathrm{M_{Z^0}}$ to within ± 0.10 GeV"
- Today, we have *measured* $\Delta\sin^2\theta_W = 0.0002$, $\Delta\mathrm{M_{Z^0}} = 0.002$ GeV, and $\Delta\mathrm{M_W} = 0.06$ GeV ! $\longrightarrow$ 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 (ie. $\mathrm{M_W}$) and comparing to theory is no less important today than it was 20 years ago. SM success just makes it more difficult.

[a] Taken from W.J.Marciano and A.Sirlin, Phys.Rev. **D29** (1984) 945.

Why $\mathrm{M_W}$ is still important...

The SM EWK theory starts from here:

$$\sin^2\theta_W\, M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_\mu}\cdot(1+\Delta r)$$

where:

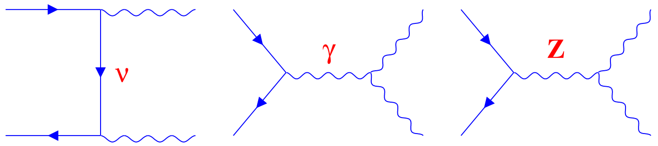
$$\Delta r = \Delta\alpha(\Pi^{\gamma\gamma}) + a\cdot\Delta\rho(M_t^2) + \Delta r_{rem}(\ln\left(M_t^2\right), \ln\left(M_H^2\right))$$

$\longrightarrow$ use precision EKW data (α, G_μ,M_{Z^0}) and SM to predict experimental observables, whose measurements can then be used to set constraints on M_t, M_H

- Asymmetries (A_{FB}^b, A_{FB}^l, A_{LR},...) $\Rightarrow \sin^2\theta_{eff}$
  - large sensitivity to $\Delta\alpha$
  - medium sensitivity to M_t
  - large sensitivity to M_H
- Widths (R_ℓ, R_b, R_c,...)
  - very small sensitivity to $\Delta\alpha$
  - large sensitivity to M_t
  - medium sensitivity to M_H
- M_W
  - small sensitivity to $\Delta\alpha$
  - large sensitivity to M_t
  - large sensitivity to M_H

Signal Process

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



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

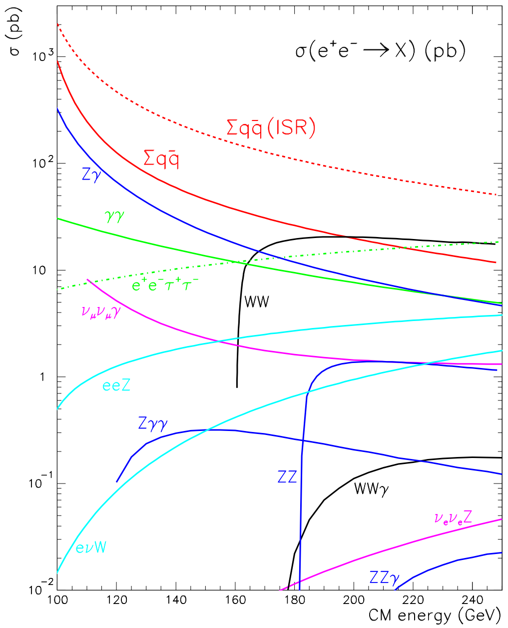
final state	BR
$q\overline{q}q\overline{q}$	45%
$q\overline{q}\ell\overline{\nu}$	44%
$\ell\overline{\nu}\ell\overline{\nu}$	11%

The CC03 production cross-sections are:

$\sqrt{s}$	$\sigma(e^+e^- \to W^+W^-)$
161 GeV	3.6 pb
172 GeV	12.4 pb
183 GeV	15.7 pb
189 GeV	16.7 pb

Background Processes

In contrast to LEP1, many 4-fermion final states turn-on for $\sqrt{s} \geq 2\mathrm{M_W}$



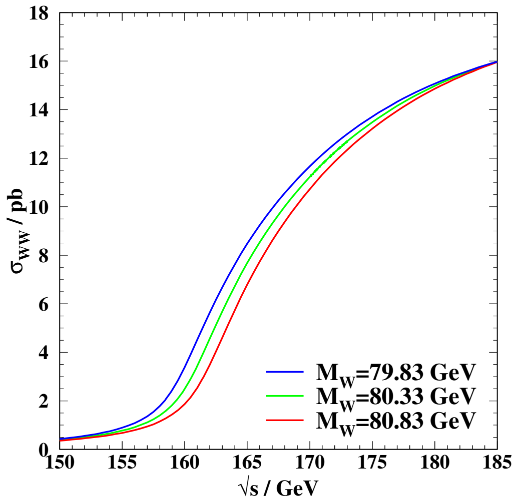
background	$\sigma(\sqrt{s} = 183)$
$\mathrm{e^+e^-} \longrightarrow \mathrm{Z}/\gamma \longrightarrow \mathrm{q\bar{q}}$	107 pb
$\mathrm{e^+e^-} \longrightarrow \mathrm{Ze^+e^-}$	2.8 pb
$\mathrm{e^+e^-} \longrightarrow (\mathrm{Z}/\gamma)^*(\mathrm{Z}/\gamma)^*$	0.6 pb
$\mathrm{e^+e^-} \longrightarrow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

LEP Methods for Measuring $\mathrm{M_W}$

Two Methods for Extracting $\mathrm{M_W}$

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

$$\mathrm{M_W} \sim 1/\sigma(\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-})$$



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

$\Longrightarrow \approx$ 30 WW events / experiment

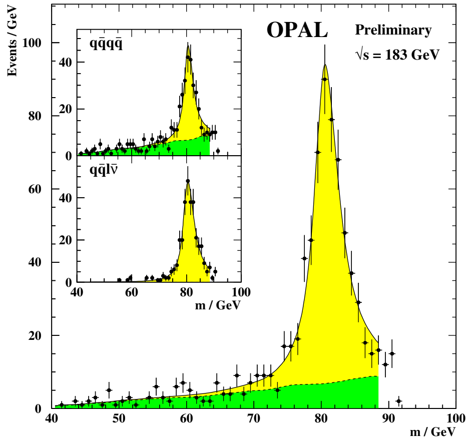
LEP average :

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

LEP Methods for Measuring $\mathrm{M_W}$

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

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



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

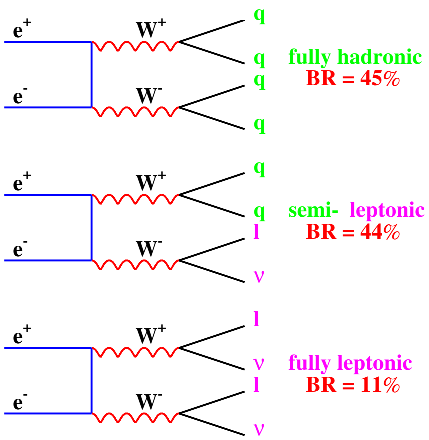
1998: $180\ \mathrm{pb}^{-1}$/experiment @ $\sqrt{s} = 189$ GeV
(an additional ≈ 2.5k WW events / experiment)

Concentrate on DR method as it dominates LEP $\mathrm{M_W}$ measurements

Procedure

To measure $\mathrm{M_W}$:

1. select $\mathrm{W^+W^-} \to \mathrm{f\bar{f}f\bar{f}}$ events
   - final state specific
   - small source of systematics
2. get reconstructed invariant mass for each event, $\mathrm{m_{rec}}$
   - final state specific
   - source of largest systematics
3. from $\mathrm{m_{rec}}$ distributions, extract measure of $\mathrm{M_W}$
   - final state independent
   - small-ish source of systematics



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

Selection of W^+W^- Events

The expected statistical error on M_W varies as:

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

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

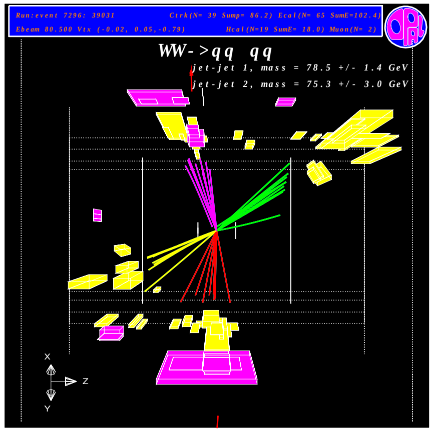
channel		experiment			
		A	D	L	O
$q\bar{q}q\bar{q}$	ε (%)	83	85	88	85
	$\mathcal{P}$ (%)	83	65	80	80
$q\bar{q}e\bar{\nu}(\mu\bar{\nu})$	ε (%)	89	71	87	90
	$\mathcal{P}$ (%)	96	94	96	94
$q\bar{q}\tau\bar{\nu}$	ε (%)	64	–	59	75
	$\mathcal{P}$ (%)	93	–	87	83

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

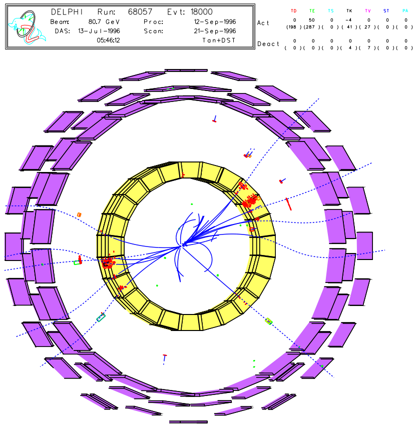
$$< N_{WW} > /\mathrm{experiment} \approx 600$$
$$< N_{bgd} > /\mathrm{experiment} \approx 100$$

Some Selected Events

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



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



Selection Uncertainties

Systematics of selection efficiency (%)

Source of uncertainty	Event Selection $W^+W^- \to$ $q\bar{q}e\bar{\nu}$	$q\bar{q}\mu\bar{\nu}$	$q\bar{q}\tau\bar{\nu}$	$q\bar{q}q\bar{q}$
Statistical	0.3	0.3	0.4	0.2
MC modelling	0.9	0.8	0.9	0.8
Fragmentation	0.2	0.1	0.6	0.8
M_W dependence	0.1	0.2	0.1	0.1
ΔE_{beam}	0.1	0.1	0.1	0.1
Total	1.0	0.9	1.2	1.1

$\longrightarrow$ Dominant systematic uncertainty on selection efficiency from MC modelling.

Accepted background cross sections (fb)

Source	Event Selection $W^+W^- \to$ $q\bar{q}e\bar{\nu}$	$q\bar{q}\mu\bar{\nu}$	$q\bar{q}\tau\bar{\nu}$	$q\bar{q}q\bar{q}$
$q\bar{q}q\bar{q}$	1 ± 2	1 ± 2	7 ± 7	190 ± 92
$q\bar{q}e\bar{\nu}$	91 ± 58	3 ± 3	76 ± 7	0 ± 0
$q\bar{q}\ell\ell$	66 ± 19	25 ± 5	70 ± 12	62 ± 6
$q\bar{q}\nu\nu$	0 ± 0	0 ± 0	9 ± 2	0 ± 0
$Zq\bar{q}$	53 ± 10	29 ± 5	184 ± 22	1350 ± 230
$Z\ell\ell$	2 ± 1	1 ± 1	6 ± 1	0 ± 0
$\gamma\gamma$	13 ± 13	0 ± 0	5 ± 5	2 ± 2
Total	226 ± 63	59 ± 8	357 ± 28	1604 ± 248

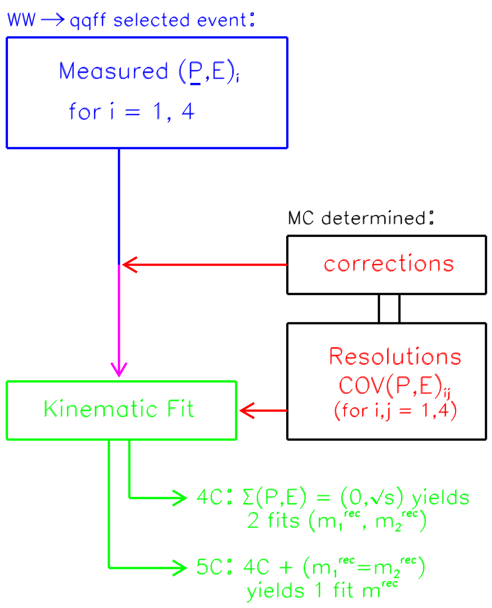
$\longrightarrow$ Dominant systematic uncertainty on accepted background from fragmentation uncertainties.

Invariant Mass Reconstruction

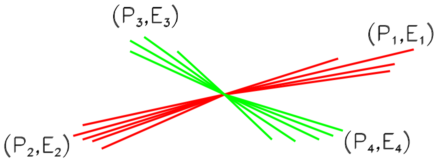
Several methods available:

- A) simple $M_{f\bar{f}} = \sqrt{2E_1E_2(1-\cos\theta_{12})}$
- B) scaled $M'_{f\bar{f}} = M_{f\bar{f}} \cdot \left(\frac{E_{bm}}{E_1+E_2}\right)$
- C) kinematic fit exploiting niceties of e^+e^- machines

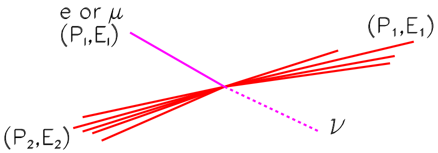
Method C gives best resolution and is employed by ADLO.



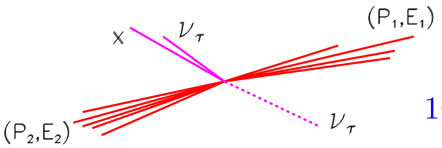
Invariant Mass Reconstruction



$q\bar{q}q\bar{q}$: force 4-jets
use a 4C- or 5C-fit
3 jet-jet pairings



$q\bar{q}e\bar{\nu}$ or $q\bar{q}\mu\bar{\nu}$:
$1C = 4C - \mathbf{P}_\nu$ fit or
$2C = 5C - \mathbf{P}_\nu$ fit

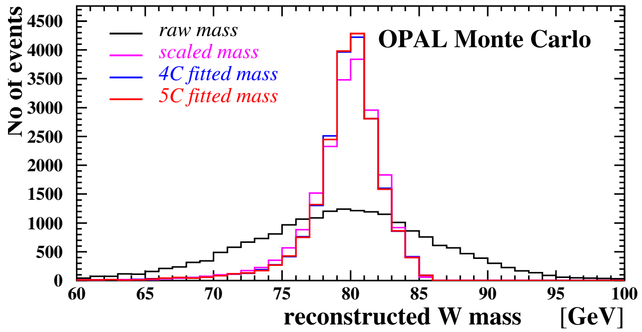


$q\bar{q}\tau\bar{\nu}$: use either
$1C = 5C - \mathbf{P}_\nu - E_\tau$
or $M'_{q\bar{q}}$ info only

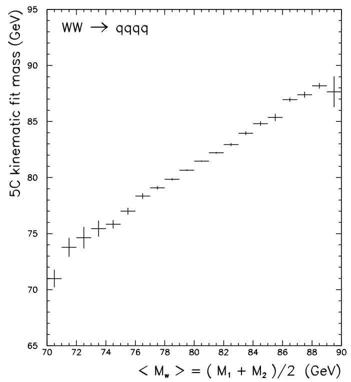
- two types of kinematic fits
  - "4C" fit: $\sum(\underline{P}, E) = (0, \sqrt{s})$; yields two masses (m_{rec_1}, m_{rec_2})
  - "5C" fit: 4C $+(m_{rec_1} = m_{rec_2})$; yields a single m_{rec}

Invariant Mass Reconstruction Resolutions

The various methods for calculating the invariant mass(es) per event have differing resolutions.



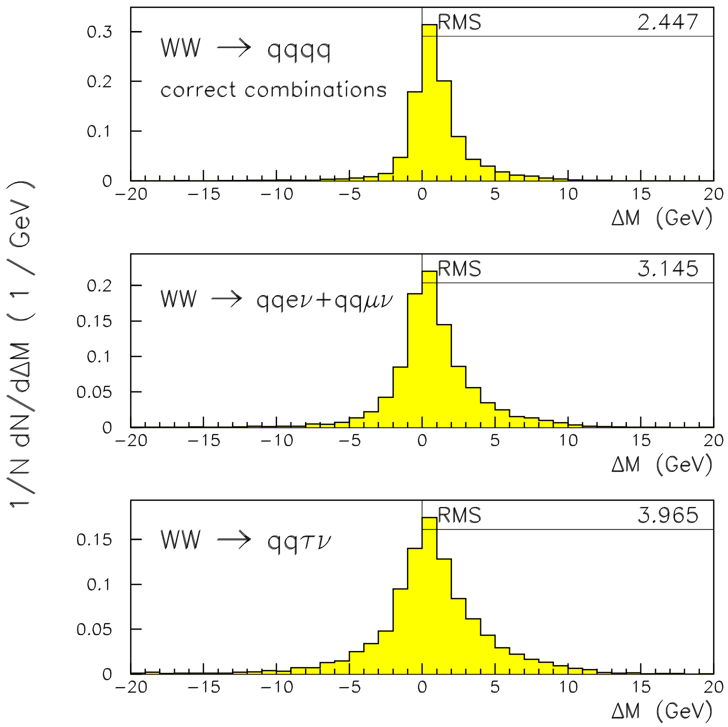
$\sigma(5C) \leq \sigma(4C) < \sigma(\text{scaled}) < \sigma(\text{raw})$



invariant mass from 5C fit $\approx < M_W >$

Invariant Mass Reconstruction Resolutions

The various channels also have differing resolutions.



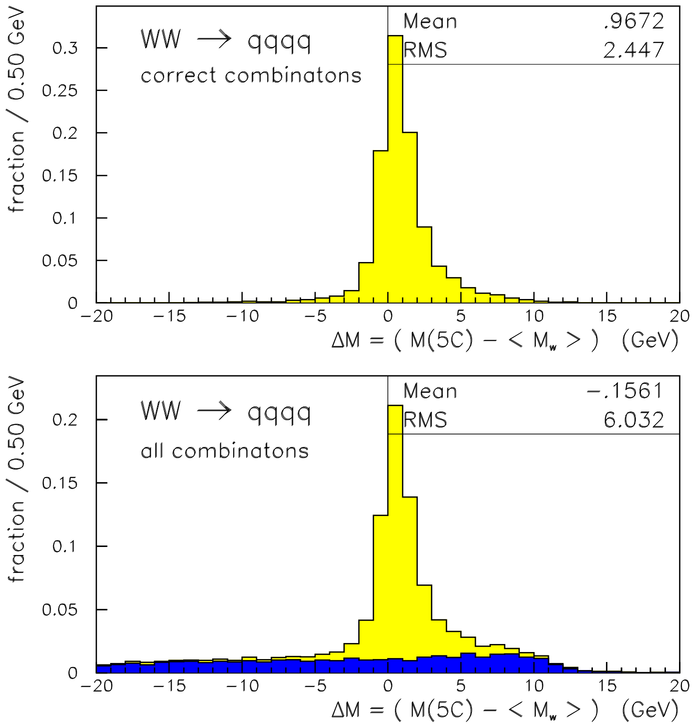
→ But the addition of backgrounds changes their relative sensitivities... more later on this.

An Aside: $\mathrm{W^+W^-} \longrightarrow \mathrm{q\bar{q}q\bar{q}}$ 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
  - L uses 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
  - ADO use $\Delta\mathrm{m_{rec}}$ and $\sum\theta_{jj}$ and information from 4C fit to choose best combination
    - D uses all combinations
    - AO only use 1 combination per event
    - AO choose correctly $\approx 85\%$
    - caveat: AO bias shape of background distribution slightly
  - D employs weights to suppress $\mathcal{P}_2 \ll \mathcal{P}_1$

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

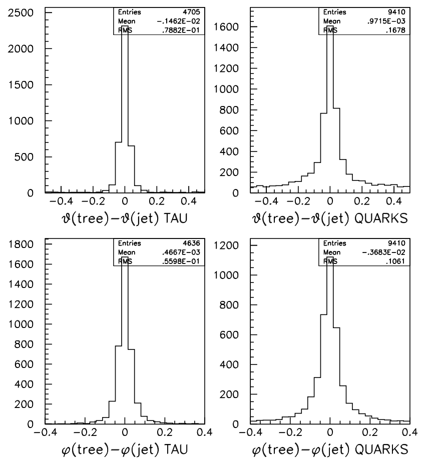
The effect of the combinatoric background is illustrated here:



- RMS is increased by a factor of $\approx\ 2.5$
- Shape(combinatorics) $\neq$ Shape(signal)

An Aside: $W^+W^- \longrightarrow q\bar{q}\tau\bar{\nu}$ Fits

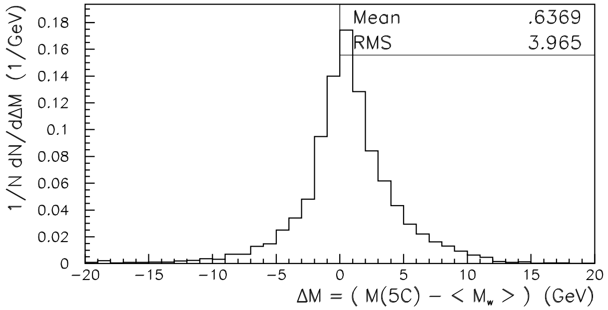
- a kinematic fit more difficult since $\sum P^{\tau}_{\rm vis} \neq P_{\tau}$
- still possible if
  - assume $\widehat{\sum P^{\tau}_{\rm vis}} = \widehat{P_{\tau}}$
  - employ a 5C fit to determine P_{ν}, E_{τ}, and $m_{\rm rec}$

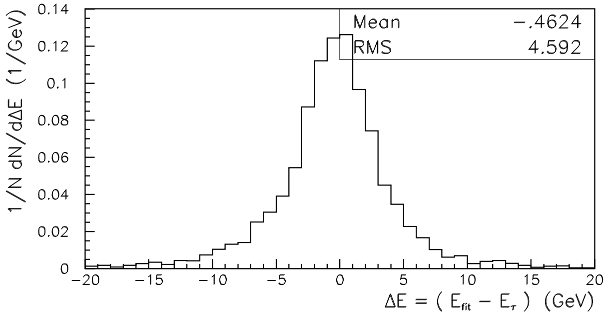


- or, can simply use information from hadronic system (scaled $M_{q\bar{q}}$)
- OA use 5C fit. L uses scaled $M_{q\bar{q}}$ and *calculated* $M_{\tau\bar{\nu}}$. D does not use $q\bar{q}\tau\bar{\nu}$.

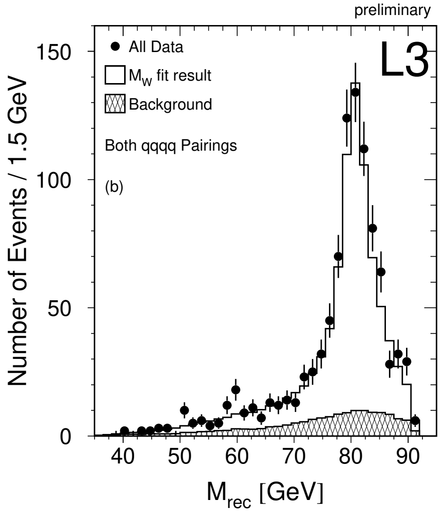
An Aside: $W^+W^- \to q\bar{q}\tau\bar{\nu}$ Fits

Employing kinematic fit improves ΔM_W and ΔE_τ for $q\bar{q}\tau\bar{\nu}$ channel by 10-20% relative to using $M_{q\bar{q}}$ information only.





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

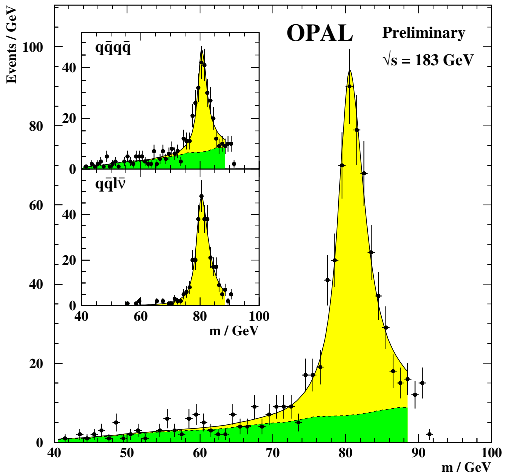
$$\ln(\mathcal{L}) = \sum_{i=1}^{N_{bins}} n_i \ln(f_b P_b^i + (1 - f_b) P_s^i(M_W, \Gamma_W))$$

- 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



$$f_{sig}(\mathrm{m_{rec}}) \sim \frac{\mathrm{m^2_{rec}}}{(\mathrm{m^2_{rec}}-\mathrm{M^2_W})^2+(\mathrm{m^4_{rec}}\Gamma^2_W/\mathrm{M^2_W})}$$

$$f_{bgd}(\mathrm{m_{rec}}) \sim a + b\mathrm{m_{rec}} + c\mathrm{m^2_{rec}}$$

+ simple
- biased (*a posteriori* correction necessary)
- choice of fit function is arbitrary
- does not make optimal use of all information

- ADLO use method a) as cross-check.

Extracting $\mathrm{M_W}$

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

$$\ln(\mathcal{L}) = \sum_{i=1}^{\mathrm{N_{bins}}} n_i \ln(f_b P^i_b + (1 - f_b)P^i_s(\mathrm{M_W}, \Gamma_\mathrm{W}))$$

+ simple and unbiased
- requires lots of MC
- does not make optimal use of all information

- ALO use method b)

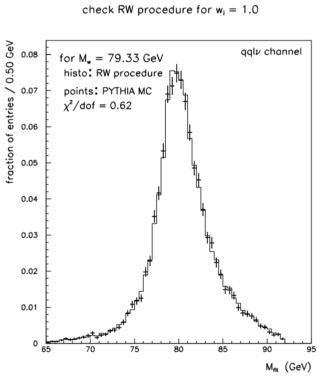
Aside: The “Reweighting” Procedure

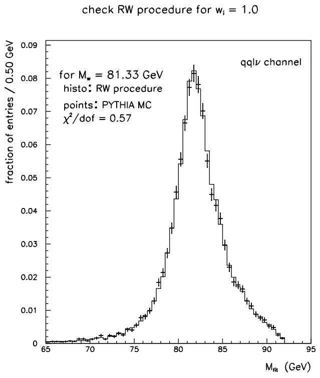
- make optimal use of MC statistics by using a re-weighting procedure to construct $f_{sig}(\mathrm{m_{rec}})$ at an arbitrary $(\mathrm{M_W}, \Gamma_\mathrm{W})$
- a MC sample generated at $(\mathrm{M_W},\Gamma_\mathrm{W})$ can be re-weighted, event-by-event as:

$$w_i = \frac{\sigma_\mathrm{B}(m_1, m_2, s)\cdot \mathrm{BW}(\mathrm{M_W^{new}}, \Gamma_\mathrm{W}^\mathrm{new}, \mathrm{m_1})\cdot \mathrm{BW}(\mathrm{M_W^{new}}, \Gamma_\mathrm{W}^\mathrm{new}, \mathrm{m_2})}{\sigma_\mathrm{B}(m_1, m_2, s)\cdot \mathrm{BW}(\mathrm{M_W^{mc}}, \Gamma_\mathrm{W}^\mathrm{mc}, \mathrm{m_1})\cdot \mathrm{BW}(\mathrm{M_W^{mc}}, \Gamma_\mathrm{W}^\mathrm{mc}, \mathrm{m_2})}$$

where $m_{1(2)} \equiv$ mass of the 1st (2nd) W-boson in the event.

(alternatively could calculate ratio of matrix elements)





Extracting $\mathrm{M_W}$

- c) convolution techniques

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

+ makes use of all available information
- many functions are approximate $(\mathrm{R}(\hat{\mathbf{m}}; \mathrm{m_{rec}}) \approx \mathrm{Gausn})$
- requires lots of MC

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

- D uses method c)

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

for $\mathrm{q\overline{q}}\ell\overline{\nu}$:

all quantities in GeV

exp	$\mathrm{M_W} \pm \mathrm{(stat)} \pm \mathrm{(syst)}$	$\hat{\sigma}_{\mathrm{stat}}$	s
A	$80.34 \pm 0.19 \pm 0.05$	0.20	3.6
D	$80.50 \pm 0.26 \pm 0.07$	0.25	3.3
L	$80.03 \pm 0.24 \pm 0.07$	0.21	3.6
O	$80.33 \pm 0.17 \pm 0.06$	0.19	3.6
LEP	$80.31 \pm 0.10 \pm 0.03$	$\chi^2 = 1.9/3$	

for $\mathrm{q\overline{q}q\overline{q}}$:

all quantities in GeV

exp	$\mathrm{M_W} \pm \mathrm{(stat)} \pm \mathrm{(syst)} \pm \mathrm{(CR)}$	$\hat{\sigma}_{\mathrm{stat}}$	s
A	$80.41 \pm 0.18 \pm 0.05 \pm 0.06$	0.18	3.4
D	$80.02 \pm 0.20 \pm 0.05 \pm 0.06$	0.20	4.3
L	$80.51 \pm 0.21 \pm 0.08 \pm 0.06$	0.19	3.7
O	$80.53 \pm 0.23 \pm 0.07 \pm 0.06$	0.19	3.6
LEP	$80.35 \pm 0.10 \pm 0.04 \pm 0.06$	$\chi^2 = 3.7/3$	

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

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

Considering the $\mathrm{q\overline{q}}\ell\overline{\nu}$ channels separately...

for $\mathrm{q\overline{q}e\overline{\nu}}$ + $\mathrm{q\overline{q}}\mu\overline{\nu}$:

all quantities in GeV

exp	$\mathrm{M_W} \pm \mathrm{(stat)}$	$\hat{\sigma}_{\mathrm{stat}}$	s
A	80.17 ± 0.21	0.22	3.3
D	80.50 ± 0.26	0.25	3.3
L	80.09 ± 0.25	0.25	3.7
O	80.23 ± 0.20	0.22	3.3

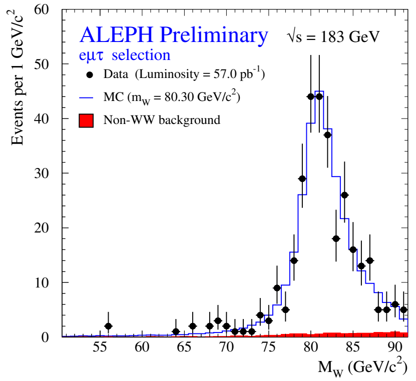
for $\mathrm{q\overline{q}}\tau\overline{\nu}$:

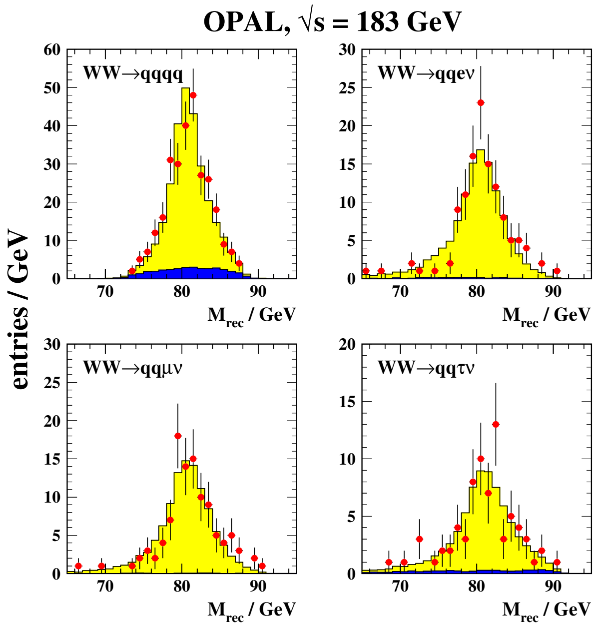
all quantities in GeV

exp	$\mathrm{M_W} \pm \mathrm{(stat)}$	$\hat{\sigma}_{\mathrm{stat}}$	s
A	80.05 ± 0.60	0.59	5.6
D	not used	—	—
L	80.50 ± 0.51	0.50	5.1
O	80.29 ± 0.43	0.45	4.1

- only stat errors as systematics not available from all collaborations for ($\mathrm{q\overline{q}e\overline{\nu}}$ + $\mathrm{q\overline{q}}\mu\overline{\nu}$)

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





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Systematic Errors

for “typical” LEP experiment

systematic source	$\Delta\mathrm{M_W}$ (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	30	35
fit procedure	30	30
bias	25	25
backgnd	$<$5	15
MC stats	10	10
Sub-total	55	60
beam energy	22	22
color reconnection/BEC	–	60
Total	59	88

- isr/hadronization/four-fermion errors all limited by statistics of comparison
- detector effects are large
- “fit procedure” dominated by bias (limited by stats) and background uncertainties (shape and normalization)
- recent work helps reduce CR/BE errors

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Systematic Errors

Color Reconnection Effects:

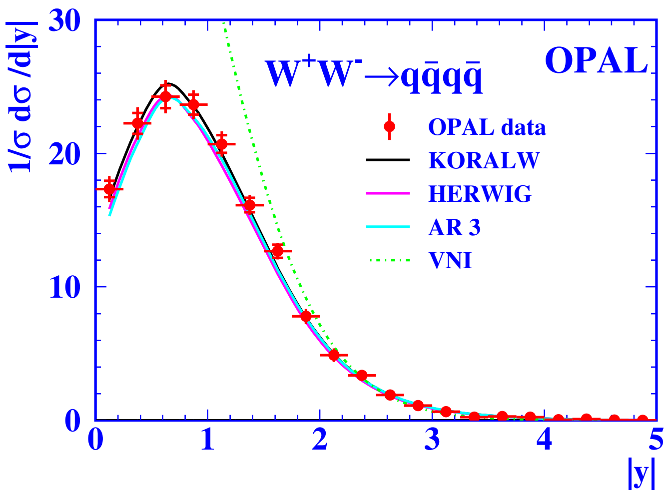
- only effects $\mathrm{q\bar{q}q\bar{q}}$ channel
- standard QCD models assume each W fragments independently
- effects of CR alter this assumption and (might) distort the reconstructed mass spectra
- perturbative effects are small: $\Delta\mathrm{M_W} \leq 5$ MeV
- non-perturbative effects unknown and model dependent

$\Longrightarrow$ requires theoretical and experimental input

Re:Color Reconnection

- CR effects observables other than $\mathrm{M_W}$:

eg. $\mathrm{n_{ch}^{4q}}$, $d\sigma/dx_\mathrm{p}$, $d\sigma/d\,|y|$,...



$\Longrightarrow$ use these observables to constrain available models

- VNI (Ellis-Geiger), AR2, and AR3 models disfavored in data

Color Reconnection Caveats

- implementation of CR models requires a re-tuning of the MC at LEP1
- size of the effects is generally a function of θ_{WW}
- selection efficiency not uniform vs θ_{WW}

  $\longrightarrow$ visible effect on $\mathrm{M_W} \downarrow$

  $\longrightarrow$ visible effect on other observables $\downarrow$

$\Delta\mathrm{M_W}$ from Color Reconnection

- to get $\Delta\mathrm{M_W^{CR}}$ have to employ models:

$$\Delta\mathrm{M_W^{CR}} = (\mathrm{M_{fit}(CR)} - \mathrm{M_{fit}(noCR)})$$

CR model	$\Delta\mathrm{M_W^{CR}}$ (MeV)
SK I	$+10 \pm 25$
SK II	-25 ± 25
SK II$'$	-20 ± 25
HW	-30 ± 25
AR 2	$+50 \pm 15$

- since initial study, a concensus has emerged that
  - $\Delta\mathrm{M_W^{CR}} \sim 100 \cdot \mathcal{P}(\mathrm{recon})$ MeV
  - $\mathcal{P}(\mathrm{recon}) \equiv$ reconnection probability $= 0.20 - 0.40$ in most models

with additional data from 1998:

$\Longrightarrow$ tighter model constraints

$\Longrightarrow$ smaller $\Delta\mathrm{M_W^{CR}}$ (hopefully)

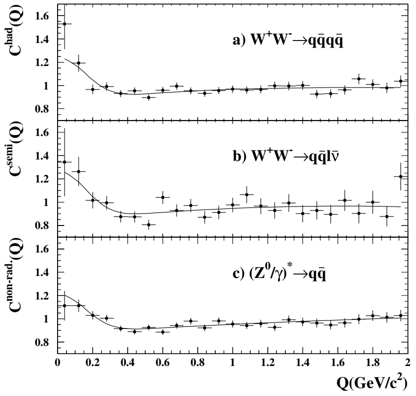
Systematic Errors

Bose-Einstein Correlation Effects:

- only effects $q\bar{q}q\bar{q}$ 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:

OPAL



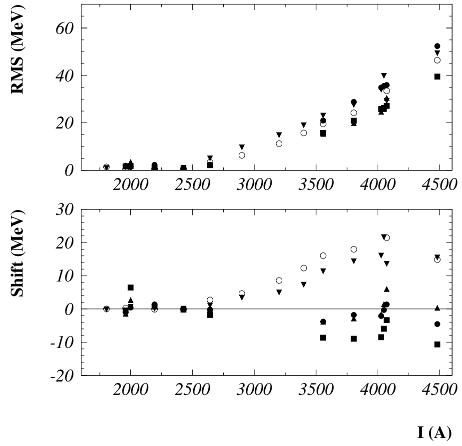
$$\lambda(\mathrm{diff}) = 0.22 \pm 0.53(\mathrm{stat}) \pm 0.14(\mathrm{syst})$$
$$\lambda(\mathrm{same}) = 0.63 \pm 0.19(\mathrm{stat}) \pm 0.14(\mathrm{syst})$$
$$R = 0.92 \pm 0.09(\mathrm{stat}) \pm 0.09(\mathrm{syst})\ \text{fm}$$

(ADL have preliminary results from 172+183 GeV)

Systematic Errors

LEP Beam Energy:

- effects all channels through constraints imposed by kinematic fits
- in 1996 @ $\sqrt{s} = 172$ GeV estimated $\Delta E_{bm} = 30$ MeV based on a conservative “guess”... turned out to be right
- total 1997 @ $\sqrt{s} = 183$ GeV, $\Delta E_{bm} = 25$ 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

Systematic Errors: Detector Effects

How do they enter?

$\longrightarrow$ through kinematic fit

- corrections (energy scales)
- COV(i,j) matrix (resolutions)

How important are they? (or... "the joys of knowing E_{cm}")

	for a 1% change in:	ΔM_W:
for	E_{jet}	4 MeV
$q\bar{q}q\bar{q}$	$\sigma(E)_{jet}$	$<$ 1 MeV
chnl	$\sigma(\phi,\theta)_{jet}$	4 MeV
	E_{jet}	8 MeV
for	$\sigma(E)_{jet}$	$<$ 1 MeV
$q\bar{q}\ell\bar{\nu}$	$\sigma(\phi,\theta)_{jet}$	—
chnl	E_{lept}	40 MeV
	$\sigma(E)_{lept}$	—
	$\sigma(\phi,\theta)_{lept}$	—

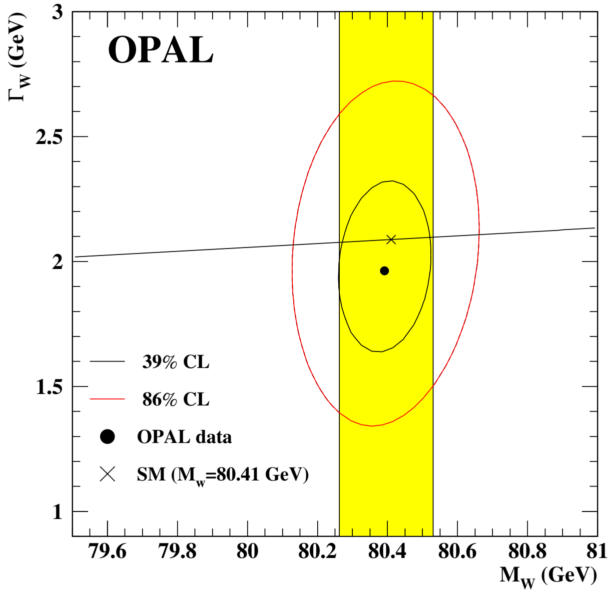
- E scales known to w/i 1%
- resolutions known to w/i 5-15%
- control using $\sqrt{s} \approx M_{Z^0}$ data, $e^+e^- \to e^+e^-$, and $e^+e^- \to Z^0\gamma$ events

$\longrightarrow$ *much* easier than at the TeVatron, where

$$1\%\ \Delta E(\text{scale}) \Rightarrow 1\%\Delta M_W$$

Direct Measurement of Γ_W

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



OPAL: $\Gamma_W = 1.84 \pm 0.32(\text{stat}) \pm 0.20(\text{syst})$ GeV

L3: $\Gamma_W = 1.97 \pm 0.34(\text{stat}) \pm 0.17(\text{syst})$ GeV

DELPHI: $\Gamma_W = 2.50 \pm 0.39(\text{stat}) \pm 0.09(\text{syst})$ GeV

Dominant systematics are from detector effects and background uncertainties.

LEP $\mathrm{M_W}$ from 172+183 GeV

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

all quantities in GeV

exp	$\mathrm{M_W} \pm \mathrm{(stat)} \pm \mathrm{(syst)}$
A	$80.334 \pm 0.170 \pm 0.040$
D	$80.540 \pm 0.245 \pm 0.027$
L	$80.407 \pm 0.214 \pm 0.055$
O	$80.354 \pm 0.154 \pm 0.044$
LEP	$80.376 \pm 0.093 \pm 0.044$ $\chi^2 = 0.6/3$

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

all quantities in GeV

exp	$\mathrm{M_W} \pm \mathrm{(stat)} \pm \mathrm{(syst)} \pm \mathrm{(CR)}$
A	$80.564 \pm 0.167 \pm 0.048 \pm 0.056$
D	$80.103 \pm 0.180 \pm 0.039 \pm 0.054$
L	$80.752 \pm 0.184 \pm 0.073 \pm 0.092$
O	$80.434 \pm 0.202 \pm 0.029 \pm 0.059$
LEP	$80.433 \pm 0.091 \pm 0.059 \pm 0.054$ $\chi^2 = 6.3/3$

- for combination, ISR, hadronization, $\mathrm{E_{bm}}$, and CR/BE uncertainties taken as correlated

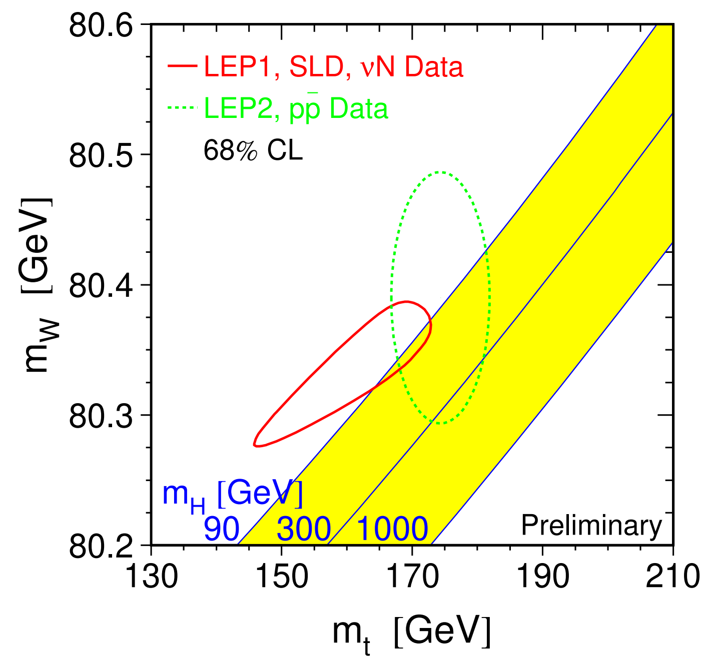
Combining with the threshold measurements gives:

$$\text{LEP } \mathrm{M_W(DR+TH)} =$$
$$80.399 \pm 0.070(\mathrm{exp}) \pm 0.025(\mathrm{CR}) \pm 0.026(\mathrm{E_{bm}})$$

(total error ± 79 MeV)

Indirect 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



Constraints on $\mathrm{M_H}$

Comparing the various means for constraining $\mathrm{M_H}$:

- Asymmetries ($\mathrm{A^b_{FB}}$, $\mathrm{A^l_{FB}}$, $\mathrm{A_{LR}}$,...) $\Rightarrow \sin^2\theta_{\mathrm{eff}}$
  - $\log(\mathrm{M_H}) = 1.94^{+0.29}_{-0.31}$
  - dominated by $\Delta\alpha$
  - statistical contribution large
- Widths (R_ℓ, $\mathrm{R_b}$, $\mathrm{R_c}$,...)
  - $\log(\mathrm{M_H}) = 2.21^{+0.36}_{-1.43}$
  - dominated by $\Delta\mathrm{M_t}$
  - statistical contribution large
- $\mathrm{M_W}$
  - $\log(\mathrm{M_H}) = 2.04^{+0.45}_{-0.84}$
  - dominated completely by statistics !

Putting it all together yields:

$$\mathrm{M_H} = 76^{+85}_{-47}\ \text{GeV}$$

$$\mathrm{M_H} < 267\ \text{GeV @ } 95\%\ \text{CL}$$

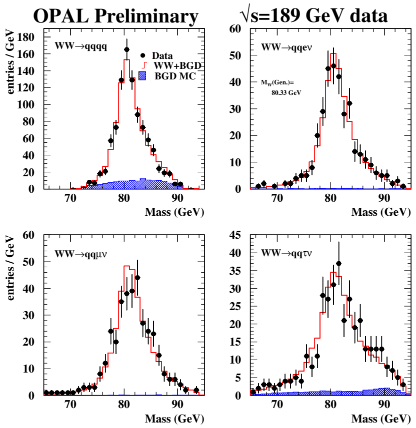
Conclusions

- LEP $\mathrm{M_W}$ will be systematics limited by this time next year. In 1998 we collected:
  - $\int \mathcal{L}dt \geq 180\ \mathrm{pb}^{-1}$ / exp @ $\sqrt{s} \approx 189$ GeV
  - $\Delta\mathrm{M_W}(\mathrm{stat}) \sim 40 - 50$ MeV from LEP
- constraints on CR/BE effects should tighten-up in 1999
- detector effects looming... lots of work
- $\Delta\mathrm{E_{bm}}$ *may* be harder than first guessed... LEP spectrometer should help
- Using data from $\sqrt{s} = 161, 172, 183$ GeV, $\mathrm{M_W} =$ $\boxed{80.399 \pm 0.079\ \text{GeV}}$
- in 1999 we expect $100 - 150\ \mathrm{pb}^{-1}$/experiment @ $\sqrt{s} = 192 - 198$ GeV ($+1.5 - 2.0$k WW/experiment)
- world average direct $\mathrm{M_W}$ will soon give constraints on $\mathrm{M_H}$ among the most stringent

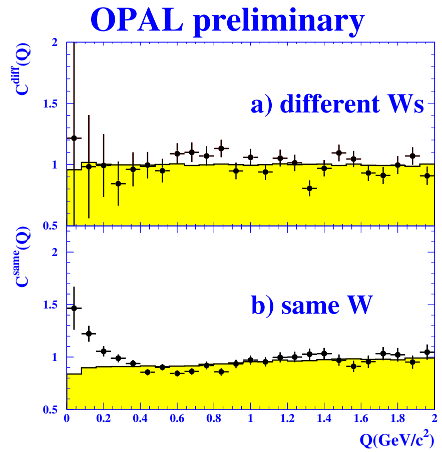
Sneak Preview of 189 GeV Data

in 1998: $180\ \mathrm{pb}^{-1}$/experiment at $\sqrt{s} = 189$ GeV

$\Longrightarrow$ expect $\Delta\mathrm{M_W(stat)} = 80 - 90$ MeV/experiment:



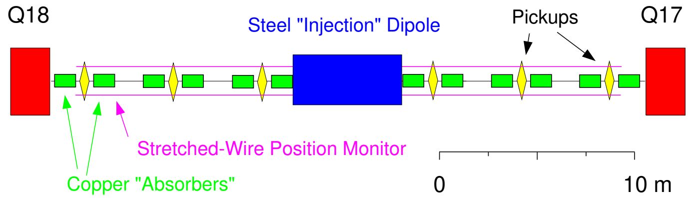
$\Longrightarrow$ expect tighter model constraints:



LEP Spectrometer Project

Aim: to measure $\mathrm{E_{bm}}$ independent of NMR/Flux-loop

How: measure bend angle of e^- through well mapped dipole



$\Longrightarrow$ fully operational in 1999

$\Longrightarrow$ expect precision on $\mathrm{E_{bm}}$ of ± 10 MeV

$\Longrightarrow$ expect to be able to propagate improved understanding of extrapolation procedure to previous years

Extracting $\mathrm{M_W}$

- a) analytic fit to Breit-Wigner + background

  + simple

  - biased (*a posteriori* correction necessary)

  - choice of fit function 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 (eg. $\mathrm{R}(\hat{\mathrm{m}}, \mathrm{m_{rec}})$)

  - requires lots of MC

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

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