Status of EW Results at $\mathrm{e^+e^-}$: What has happened in the last year?

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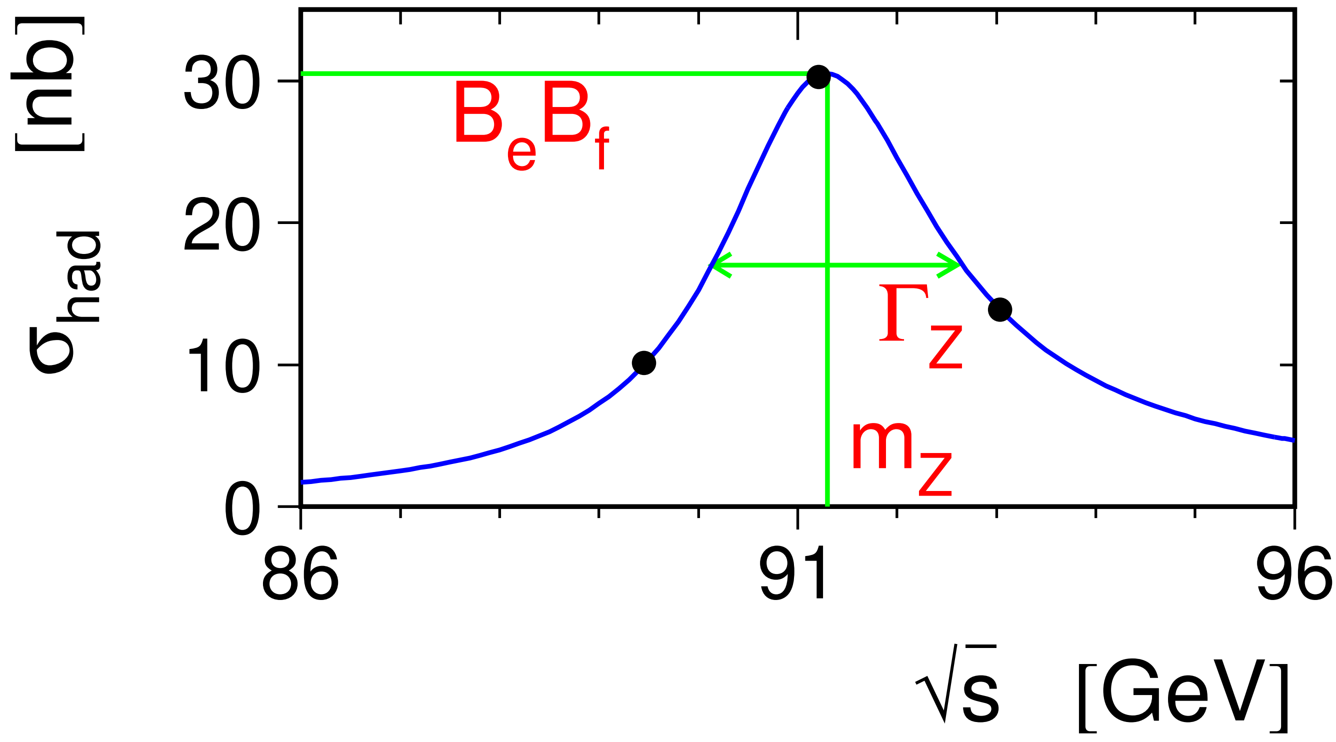
- **Intro**
- **What has changed?**
- **SM fits and m_{H}**
- m_{W}

Many thanks to my colleagues in the LEP EW Working Group.

Visit us at: http://www.cern.ch/LEPEWWG

Excitation Curve of the Z Boson



Properties of the Z boson:

Peak position: m_Z

Peak width: Γ_Z

Peak height: $B_e B_f = \Gamma_{ee}\Gamma_{ff}/\Gamma_Z^2$

QED corrections included by convolution:

$$\sigma(s) = \int_0^1 dz R(z,s)\sigma^0(zs)$$

Peak cross section reduced by $\sim$ 25 %

Fitting procedure

Fit measured cross sections to:

- m_Z
- Γ_Z
- $\sigma^0_{had} \equiv \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}$ **(“peak” cross section)**
- $R_\ell \equiv \Gamma_{had}/\Gamma_{\ell\ell}$, **for** ℓ = e, μ, τ

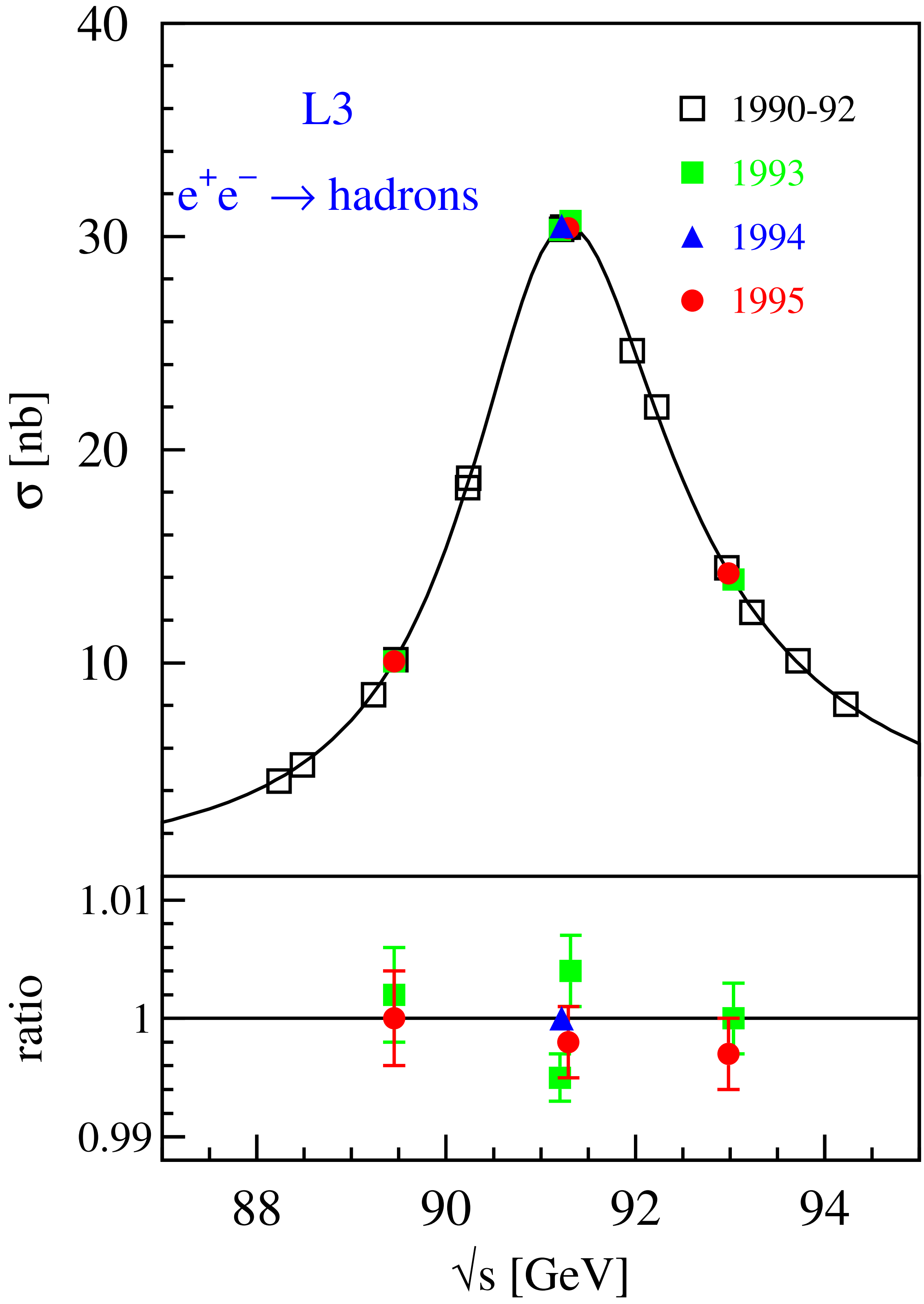
These quantities were chosen to reduce the correlations between the parameters.

“Model independent,” *i.e.*, **no assumptions on** m_t, *etc.*

One can then derive other important parameters such as

- $\Gamma_{\ell\ell} \propto (g_V^2 + g_A^2)$
- $\Gamma_{inv} = \Gamma_Z - \Gamma_{had} - 3\Gamma_{\ell\ell}$
- $N_\nu = \frac{\Gamma_{inv}}{\Gamma_{\ell\ell}}\left(\frac{\Gamma_{\ell\ell}}{\Gamma_{\nu\nu}}\right)_{SM}$ **(in the SM only!!)**
- α_s **from QCD corrections to** Γ_{had}.

Data Example



Result of Lineshape fits

Based on 14.4M hadronic events; 1.6M leptonic events:

$$m_Z \quad 91.1863 \pm 0.0020 \quad \text{GeV}$$
$$\Gamma_Z \quad 2.4946 \pm 0.0027 \quad \text{GeV}$$

$$\sigma^0_{\text{had}} \quad 41.508 \pm 0.056 \quad \text{nb}$$
$$R_\ell \quad 20.778 \pm 0.029$$

$$\left(\begin{array}{ll} R_e & 20.754 \pm 0.057 \\ R_\mu & 20.796 \pm 0.040 \\ R_\tau & 20.814 \pm 0.055 \end{array}\right)$$

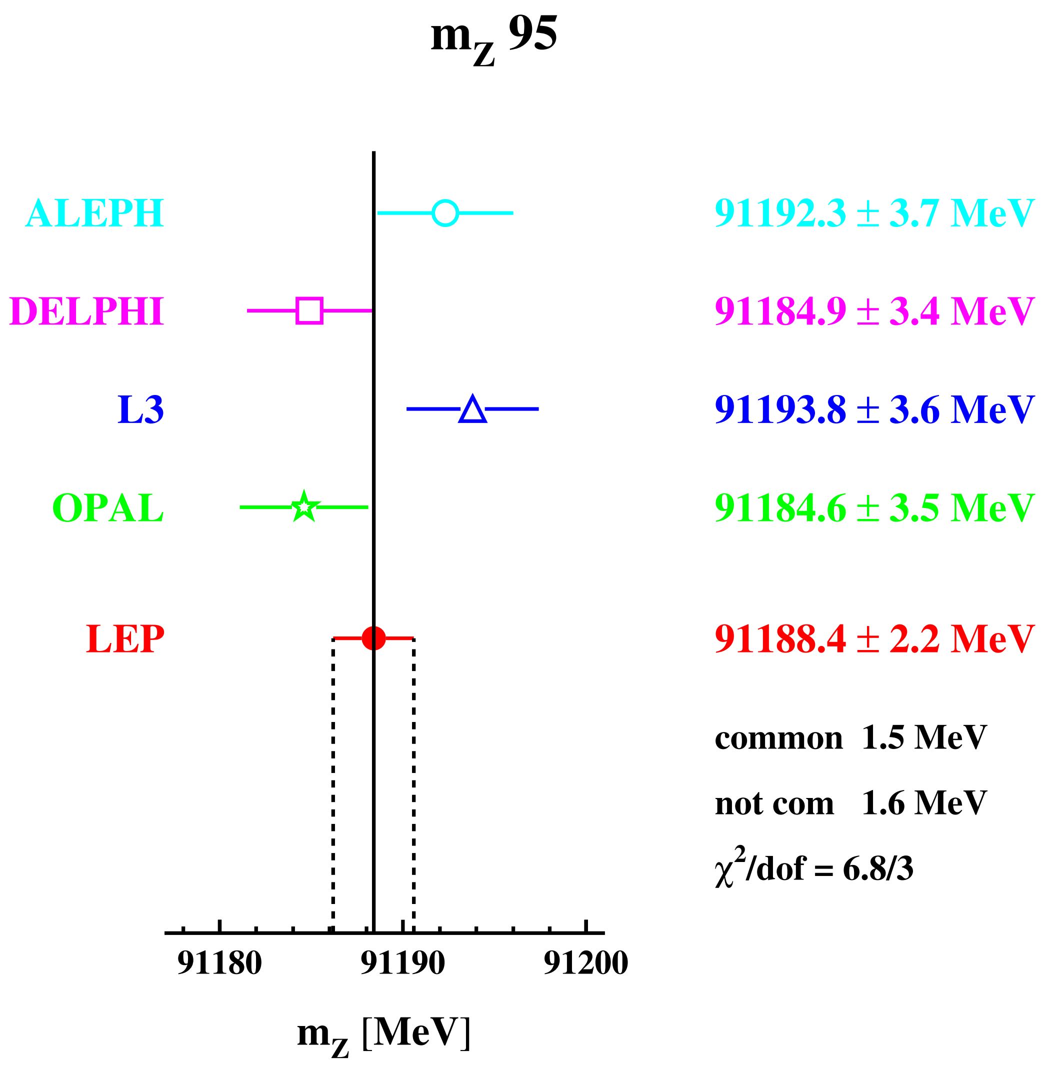
Partial widths:

$$\Gamma_{\text{had}} = 1743.6 \pm 2.5 \text{ MeV}$$
$$\Gamma_{\ell\ell} = 83.91 \pm 0.11 \text{ MeV}$$

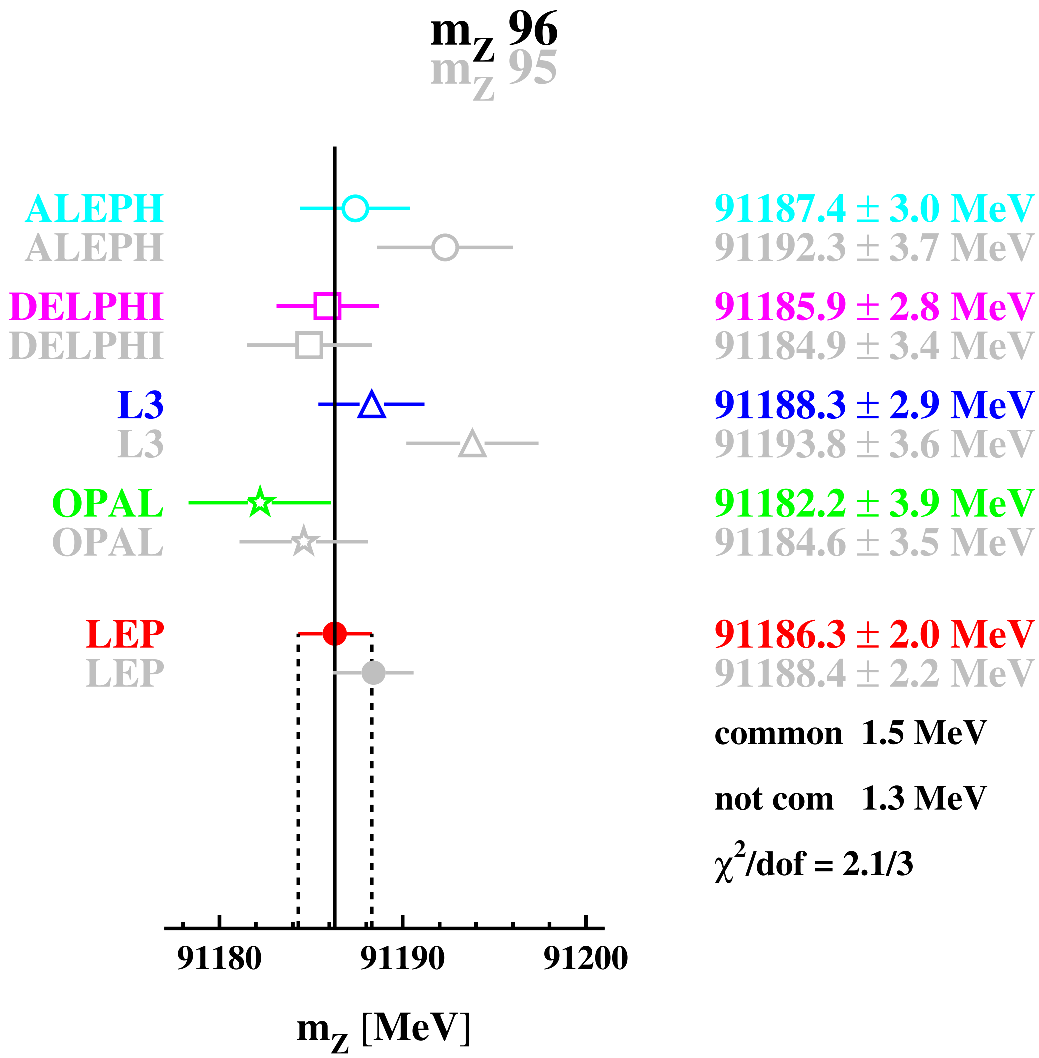
$$\Gamma_{\text{inv}} = 499.5 \pm 2.0 \text{ MeV}$$

$$N_\nu = 2.989 \pm 0.012$$

m_Z in 1995


m_Z 95
ALEPH
DELPHI
L3
OPAL
LEP
91192.3 ± 3.7 MeV
91184.9 ± 3.4 MeV
91193.8 ± 3.6 MeV
91184.6 ± 3.5 MeV
91188.4 ± 2.2 MeV
common 1.5 MeV
not com 1.6 MeV
χ²/dof = 6.8/3
91180
91190
91200
m_Z [MeV]

m_Z in 1996

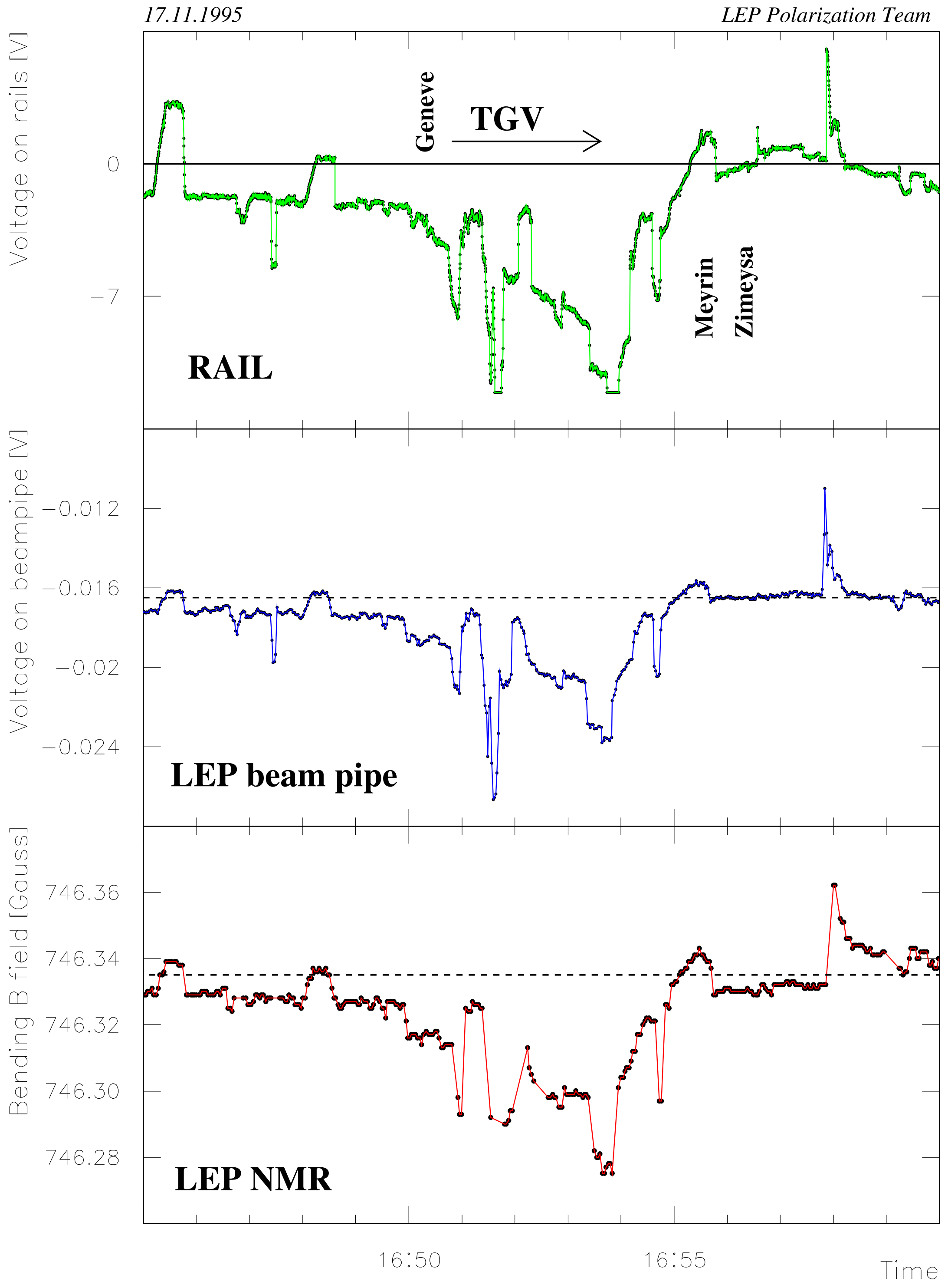


The differences:

- New data
- New LEP energy scale

LEP energy scale

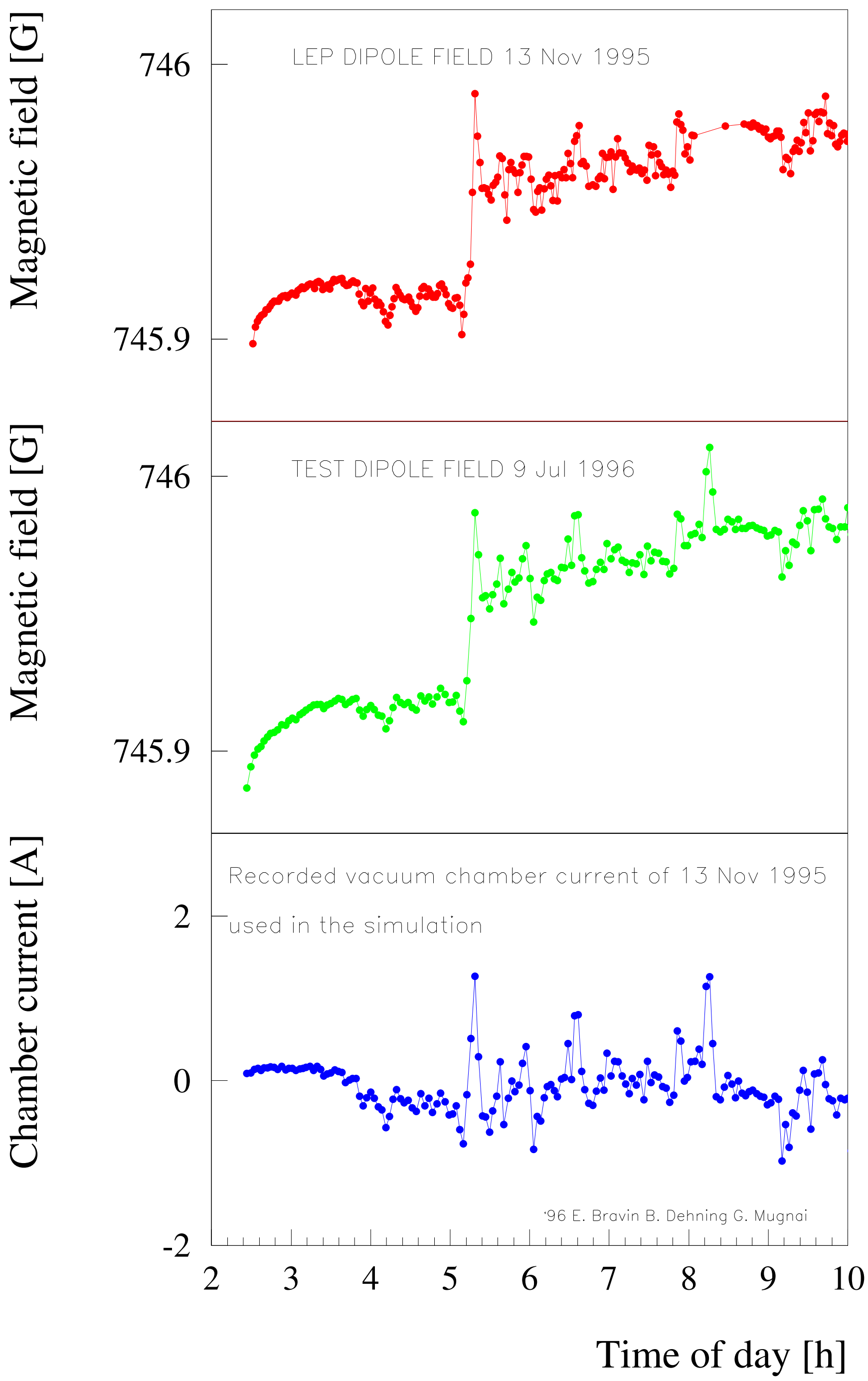
The famous trains:



LEP energy scale

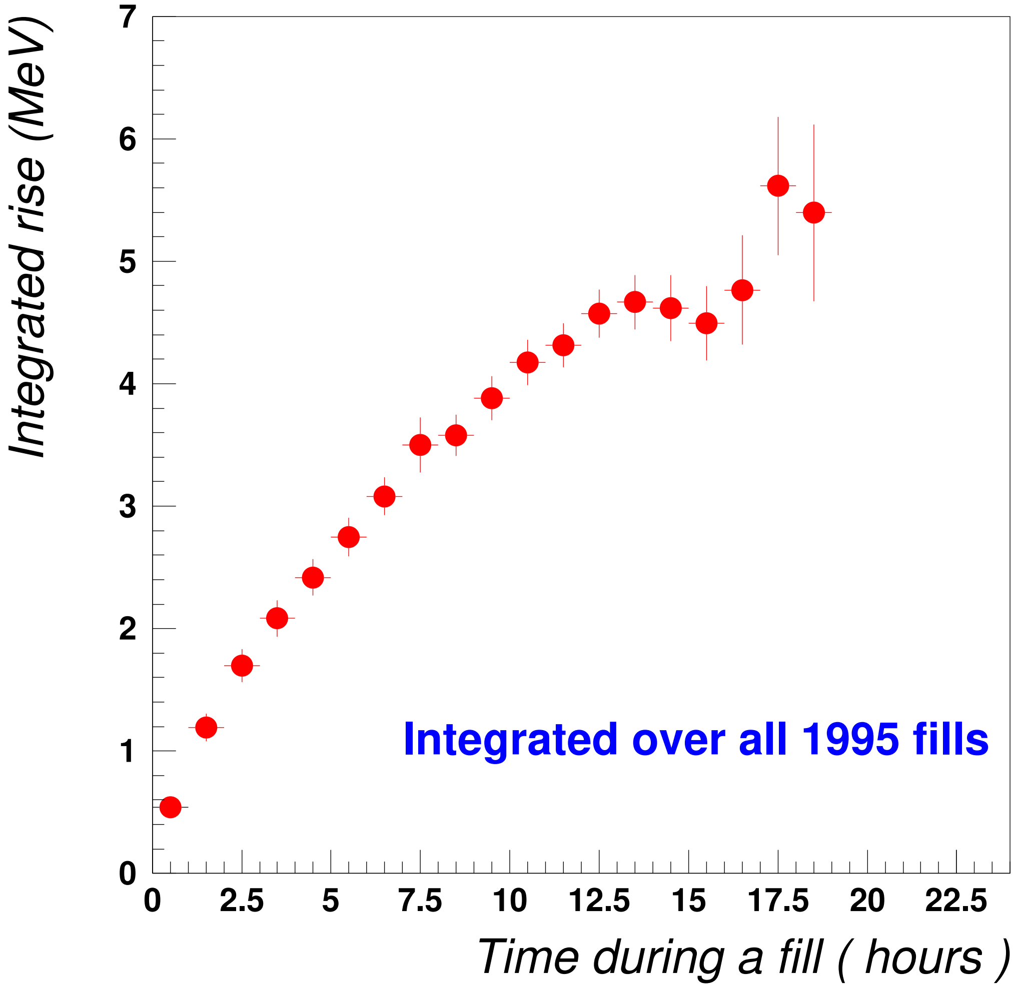
...have now been reproduced in the lab:

Train effect simulation



LEP energy scale

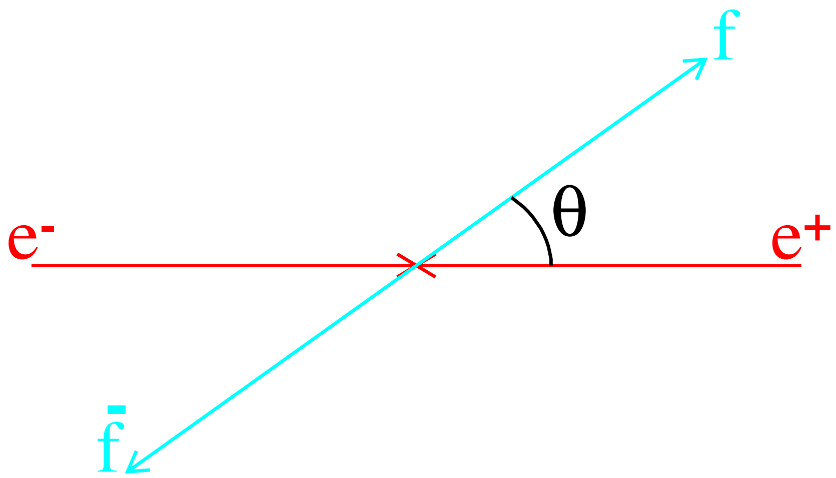
During 1995 the energy was seen to rise during the fill:



In 1993 energy calibrations were performed at the end of fills

$\Rightarrow$ 1993 energy was overestimated by ≈ -4 MeV.

Asymmetries



$$A_{\rm FB} = \frac{\sigma_F - \sigma_B}{\sigma_{\rm tot}}$$

Angular dependence:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{3}{8}(1+\cos^2\theta) + A_{\rm FB}\cos\theta$$

The asymmetry at the Z peak can be expressed as

$$A_{\rm FB}^{0,\rm f} \equiv \frac{3}{4}\mathcal{A}_{\rm e}\mathcal{A}_{\rm f},$$

where

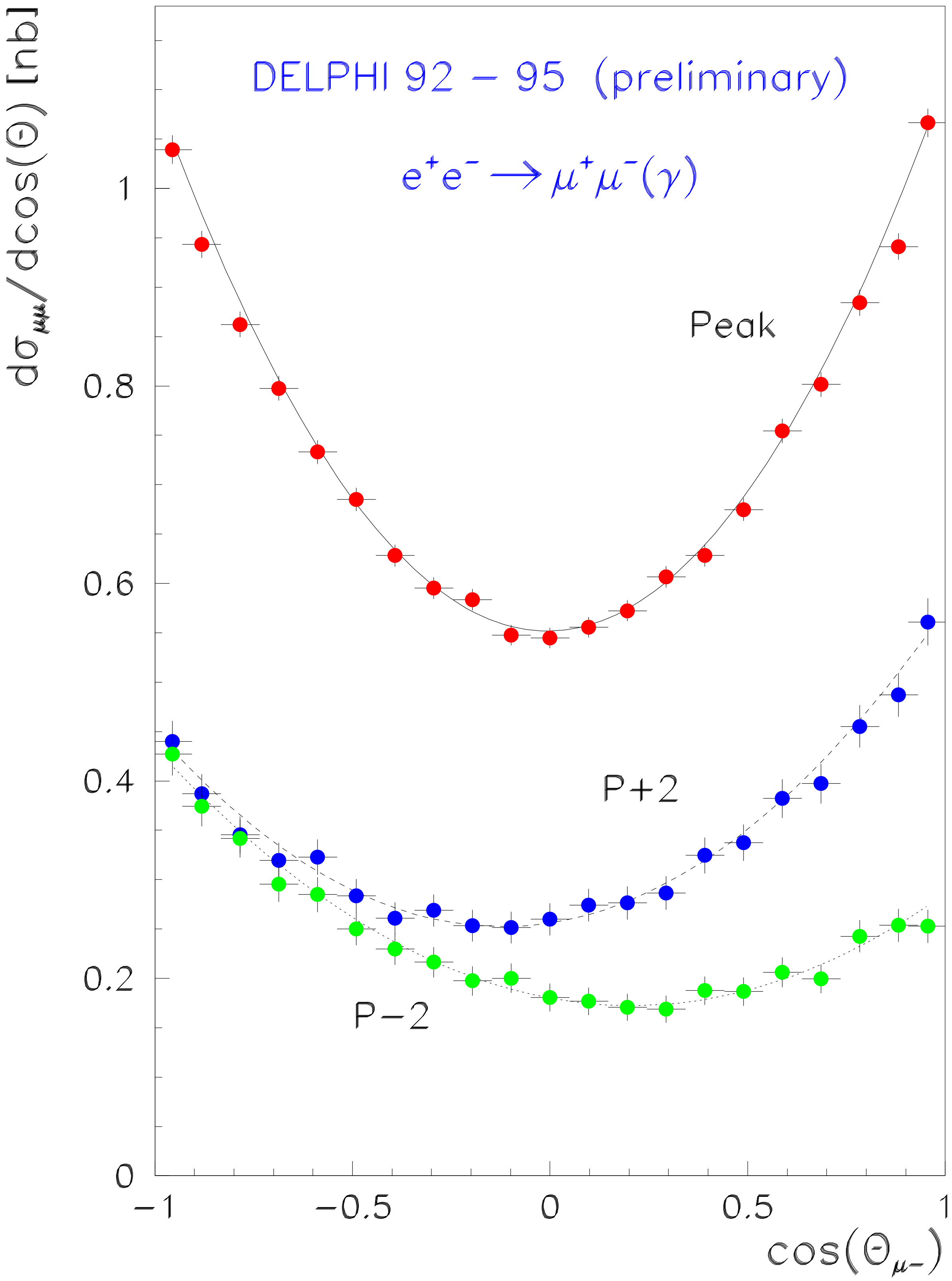
$$\mathcal{A}_{\rm f} = \frac{2g_{\rm Vf}g_{\rm Af}}{g_{\rm Vf}^2 + g_{\rm Af}^2}$$

The asymmetries provide a direct measurement of

$$\sin^2\theta_{\rm eff}^{\rm lept} \equiv \frac{1}{4}(1 - g_{\rm V}/g_{\rm A})$$

In combination with $\Gamma_{\ell\ell}$, the coupling constants $g_{\rm A}$ and $g_{\rm V}$ can be determined. Note: these are effective couplings.

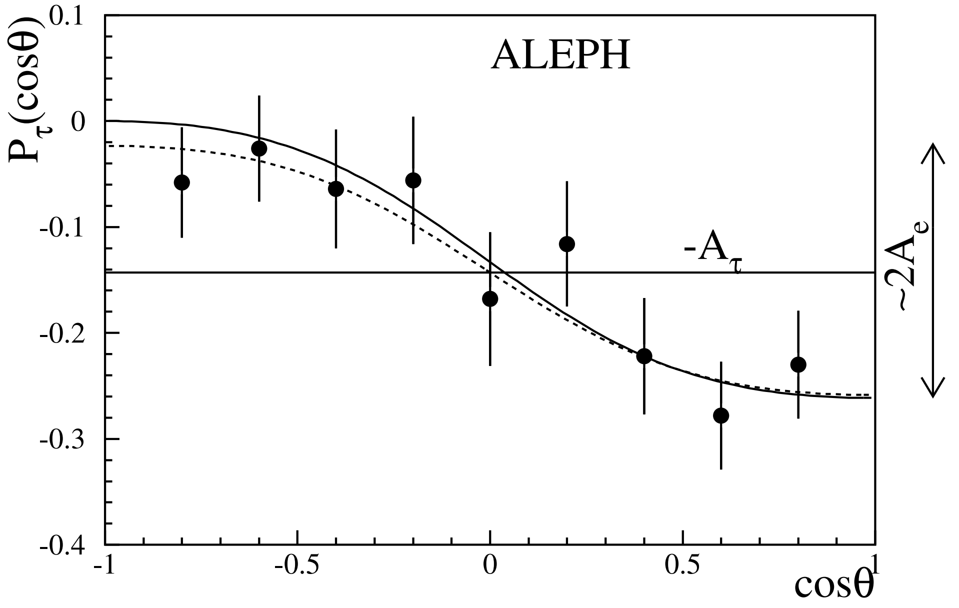
Data Examples



Tau Polarization

Parity violation in Z production and decay produces polarized final states.
At LEP only the $\tau^+\tau^-$ final state can be used as a polarimeter.

$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{1+\cos^2\theta + 2\mathcal{A}_\tau\mathcal{A}_e\cos\theta}$$

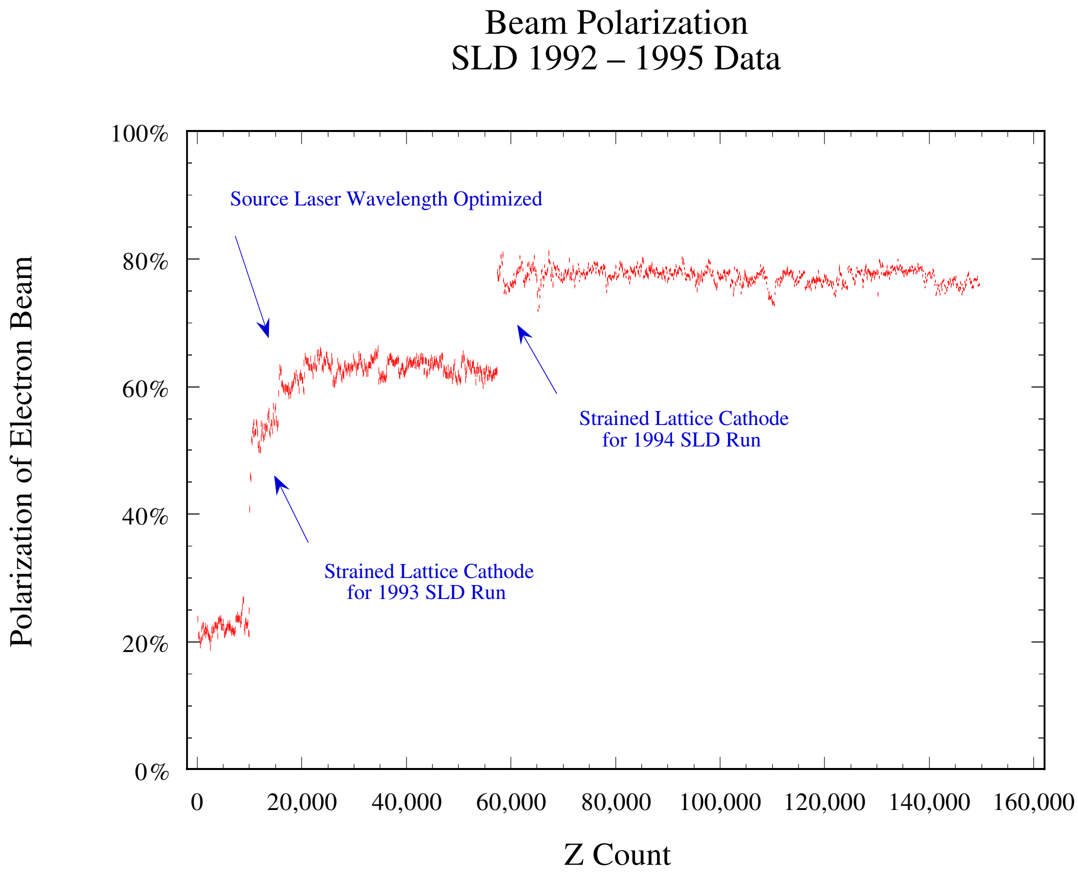


Tau polarization gives independent measurements of $\mathcal{A}_\tau$ and $\mathcal{A}_e$.

Since the measurement is linear in $\mathcal{A}_\tau$ and $\mathcal{A}_e$, the relative sign of g_A and g_V is also determined.

Polarized Asymmetries at SLD

At SLC, the electron beam is highly polarized.

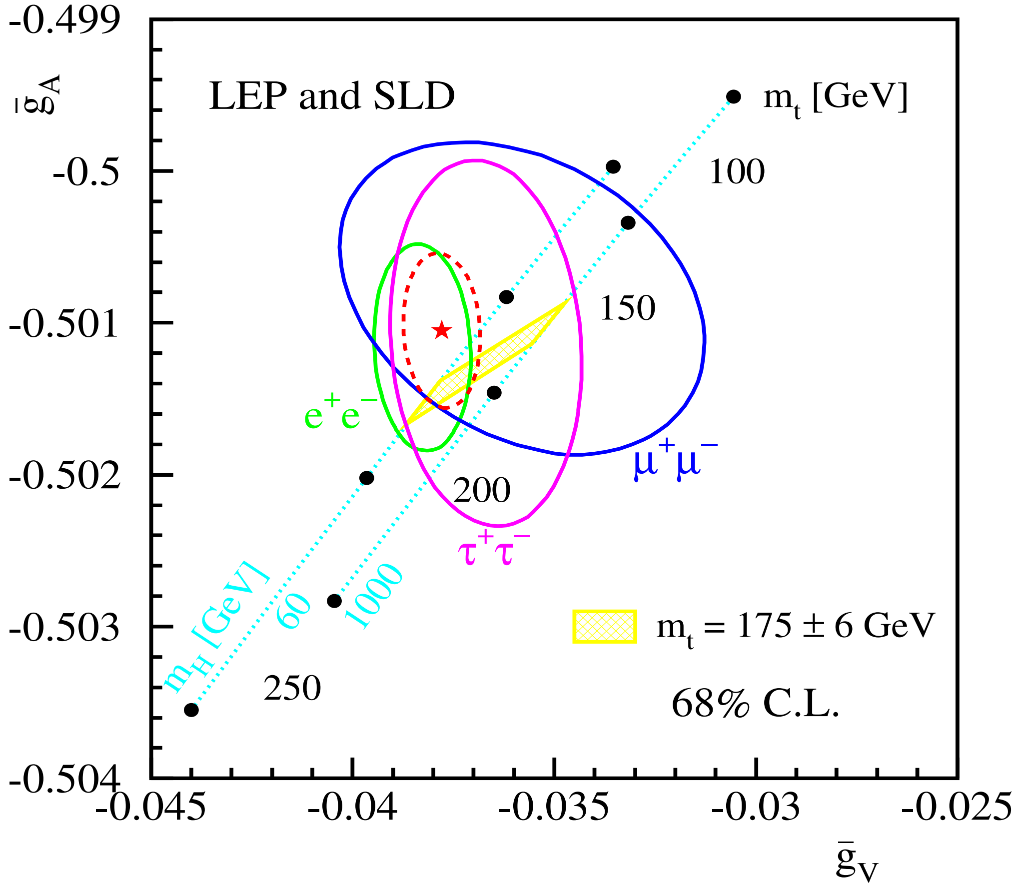


A straight-forward measurement of the hadronic cross-section for left and right polarized electrons gives a precise determination of $\mathcal{A}_e$:

$$A_{\mathrm{LR}} = \frac{1}{\mathcal{P}} \frac{\sigma_L - \sigma_R}{\sigma_{\mathrm{tot}}} = \mathcal{A}_e$$

$\mathcal{P}_\tau$ in reverse, BUT 77% polarization of the electron beam, compared to 14% for $\mathcal{P}_\tau$

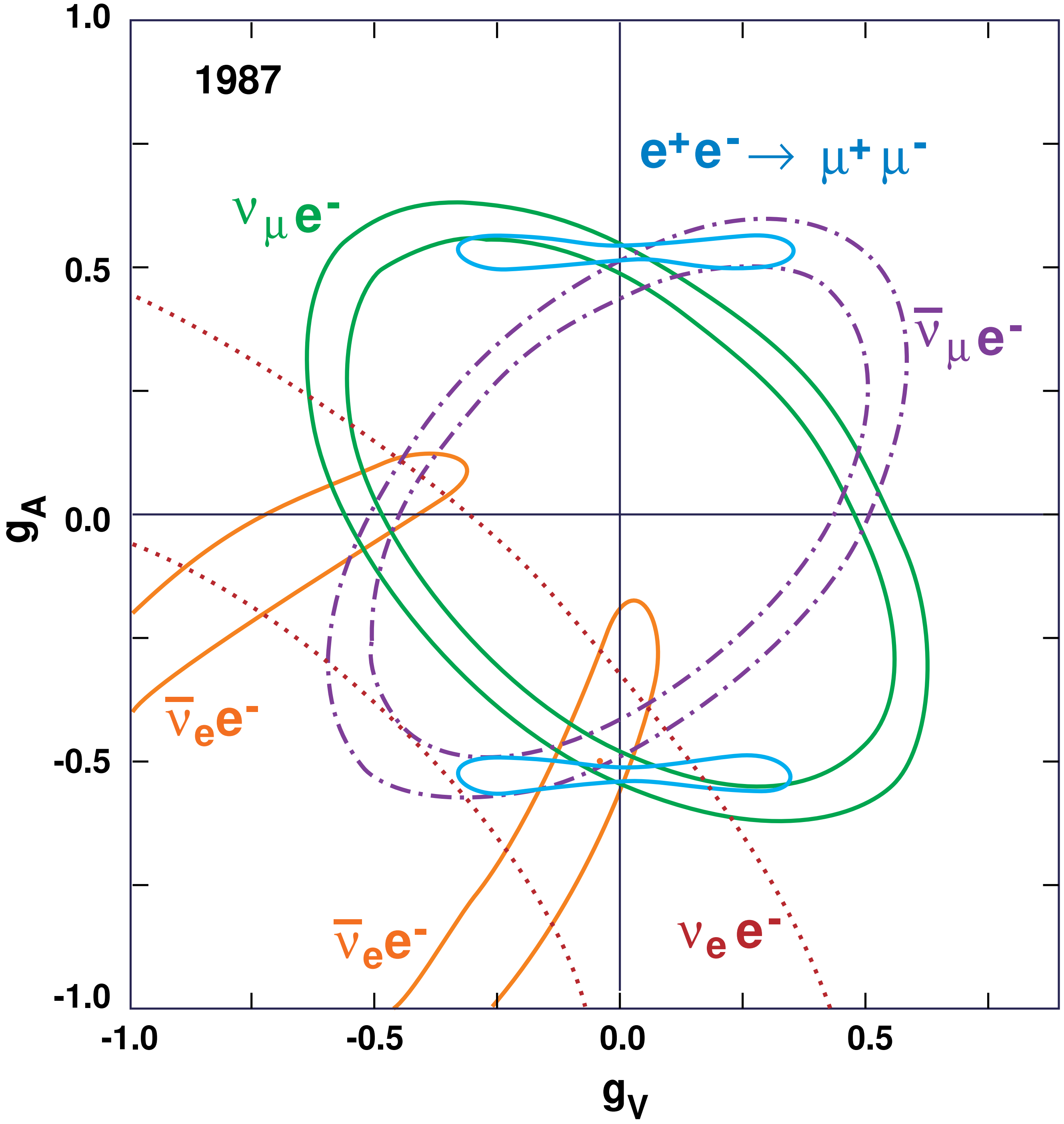
Combining the lepton asymmetry measurements, the τ polarization, the $\Gamma_{\ell\ell}$ and the SLD A_{LR} results determines the lepton g_V and g_A:



Assuming lepton universality

$$g_{V\ell} = -0.03776 \pm 0.00062$$
$$g_{A\ell} = -0.50108 \pm 0.00034$$

g_V and g_A 10 years ago



Heavy Flavor EW Physics

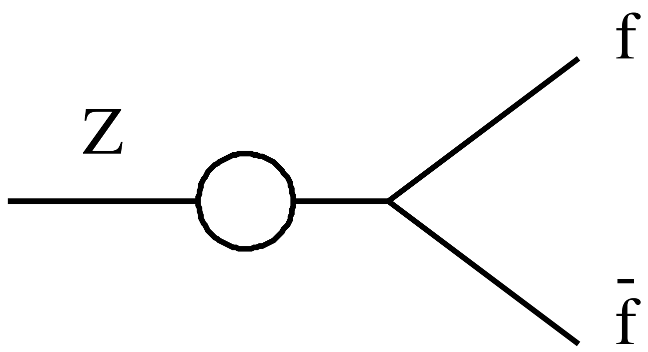
Using the properties of heavy quarks, one can isolate samples of $\mathrm{b\bar{b}}$ and $\mathrm{c\bar{c}}$ events.

These can be used to extract:

- $\Gamma_{\mathrm{b\bar{b}}}$ **and** $\Gamma_{\mathrm{c\bar{c}}}$
- $A_{\mathrm{FB}}^{\mathrm{b}}$ **and** $A_{\mathrm{FB}}^{\mathrm{c}}$

$\Gamma_{\mathrm{b\bar{b}}}$ **is especially interesting:**

All Z decays have radiative corrections of the form

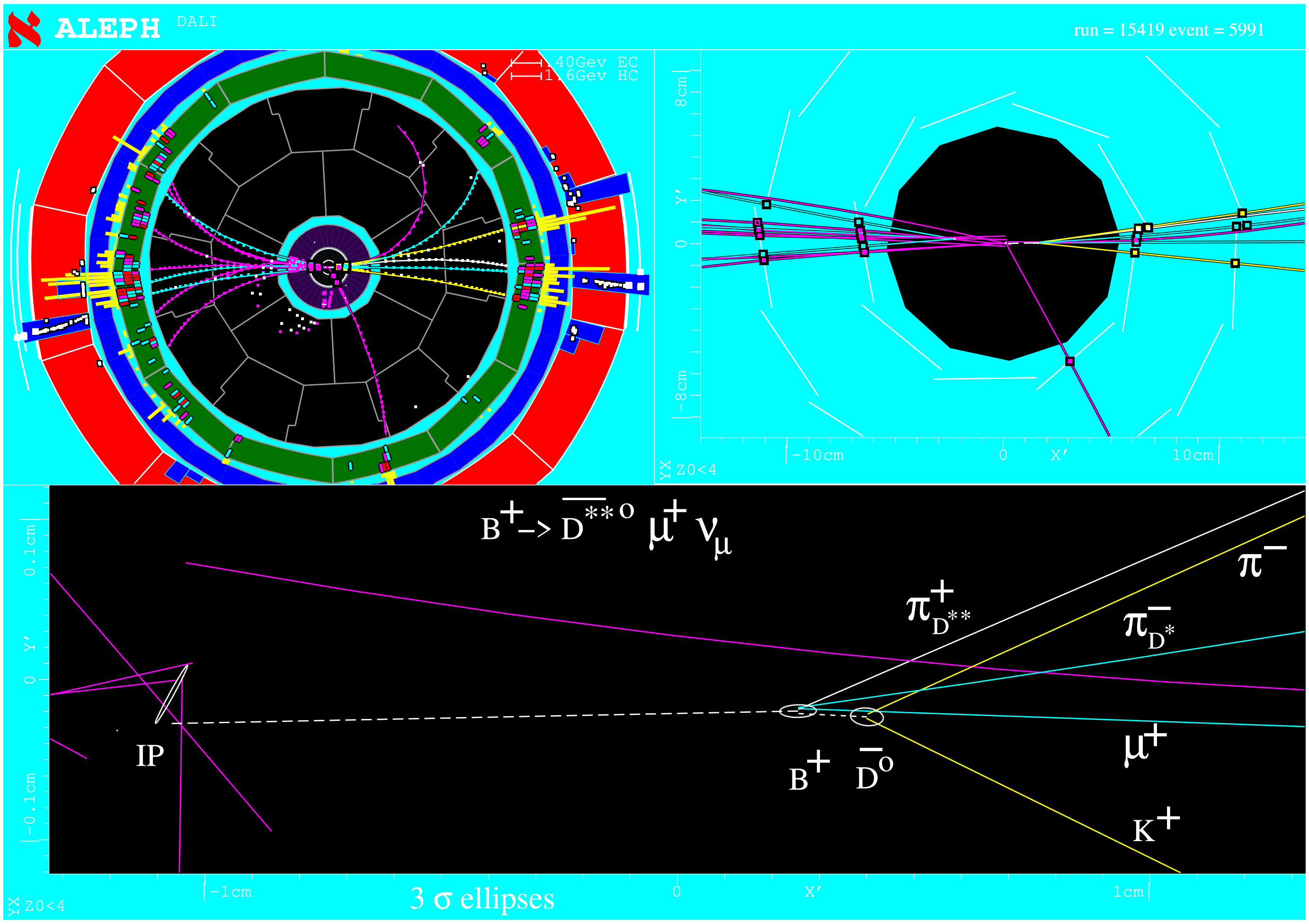


$\mathrm{Z} \rightarrow \mathrm{b\bar{b}}$ **receives additional contributions from**

The ratio $R_{\mathrm{b\bar{b}}} = \Gamma_{\mathrm{b\bar{b}}}/\Gamma_{\mathrm{had}}$ **has a different sensitivity to** m_{t} **(and** m_{H}**) than other quantities.**

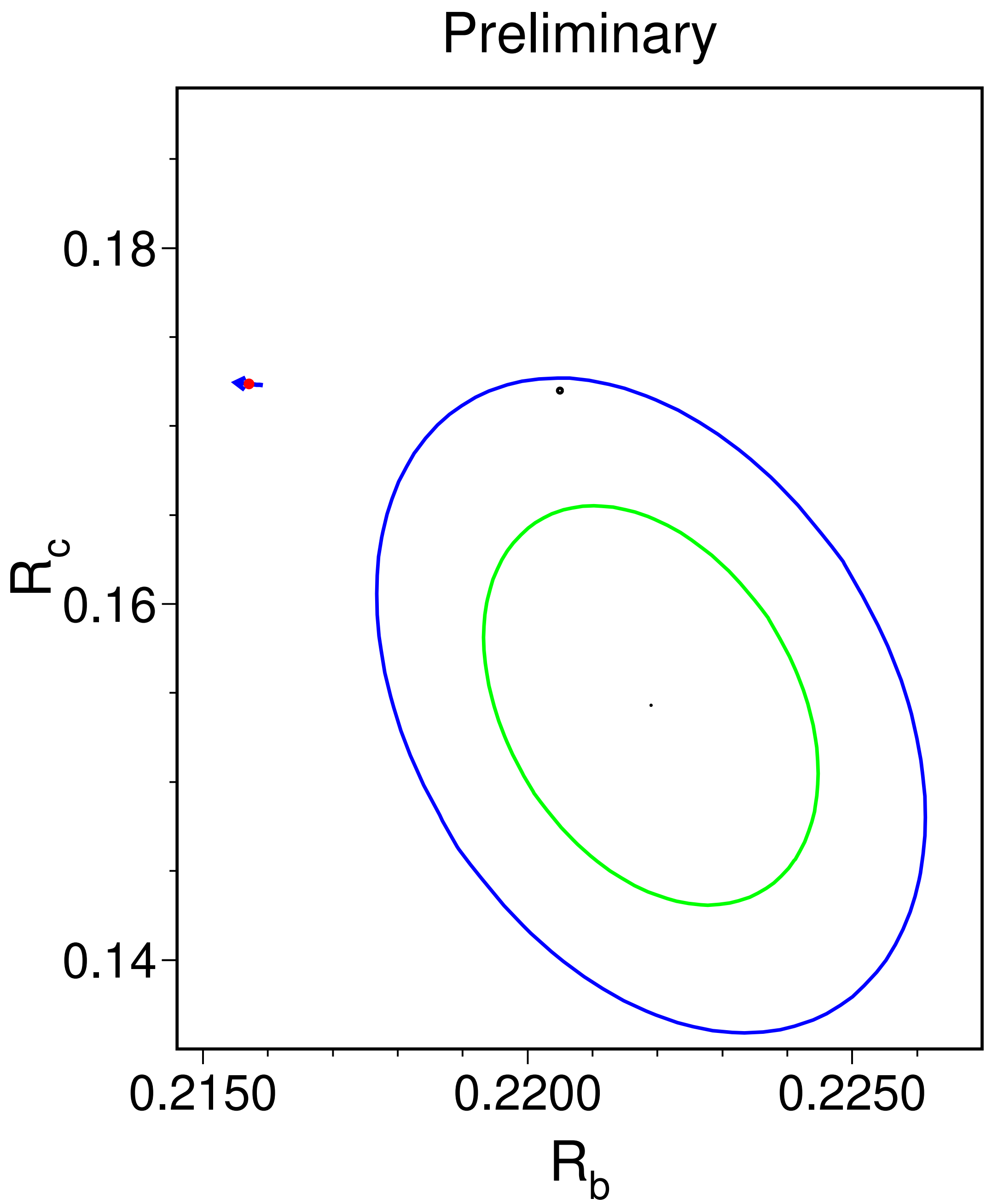
Heavy Flavor EW Physics

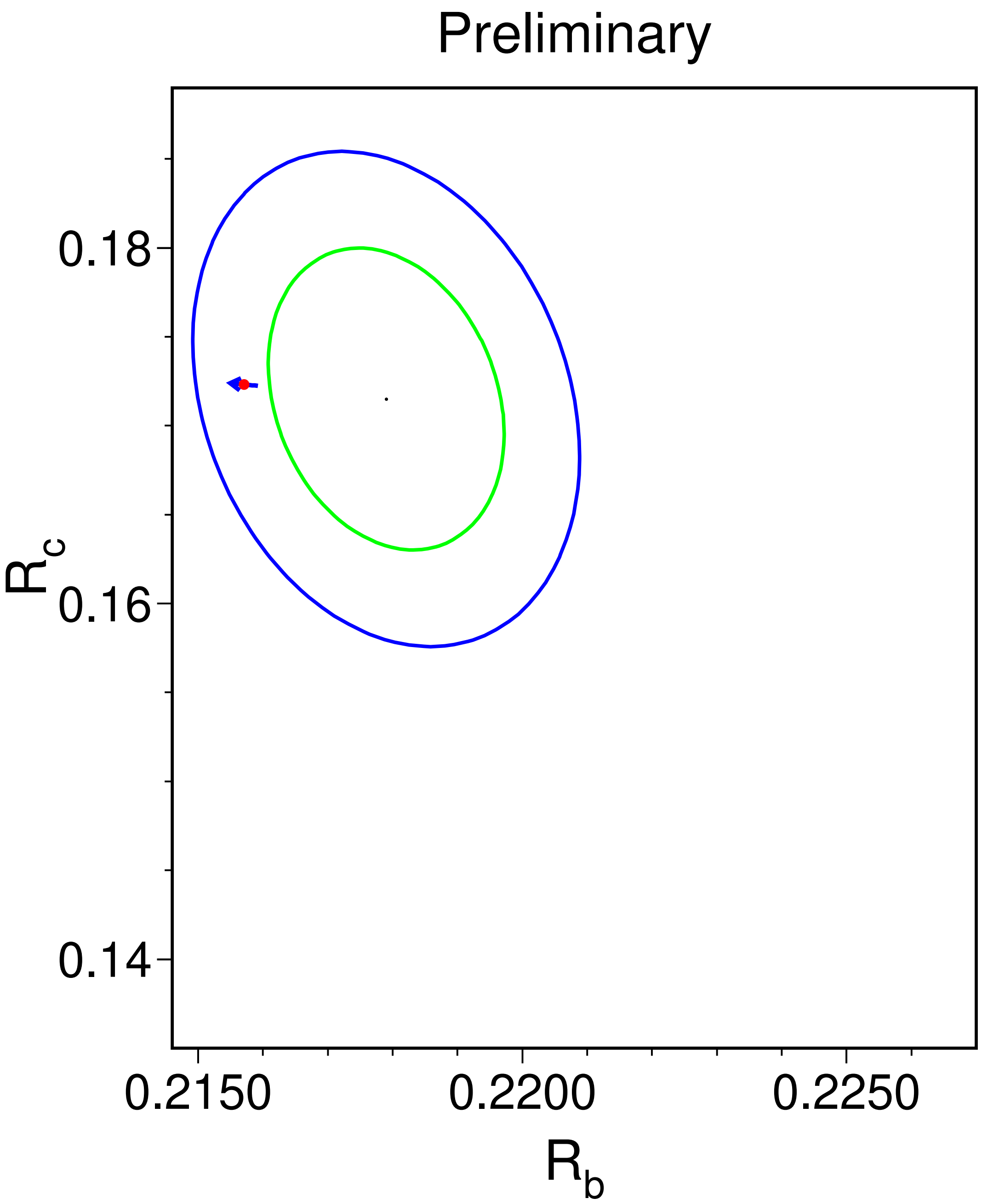
Summary of heavy flavor tags with a “typical”! event:



- **Long lifetimes**
- **Charmed final states**
- **Leptonic final states**
- **Broad (massive) jets**

$R_{b\bar{b}}$, $R_{c\bar{c}}$ in 1995

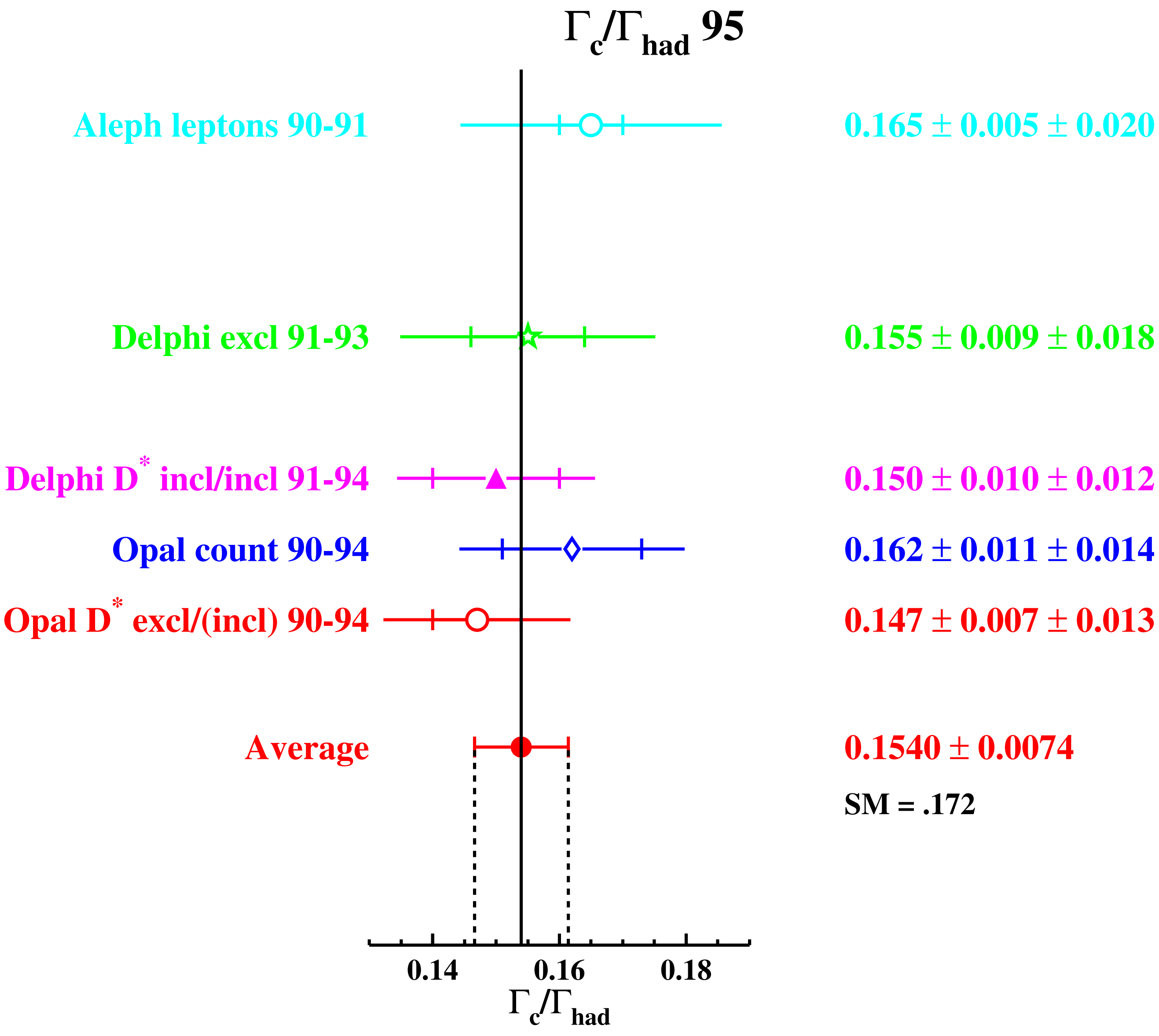




What happened?

$R_{c\bar{c}}$

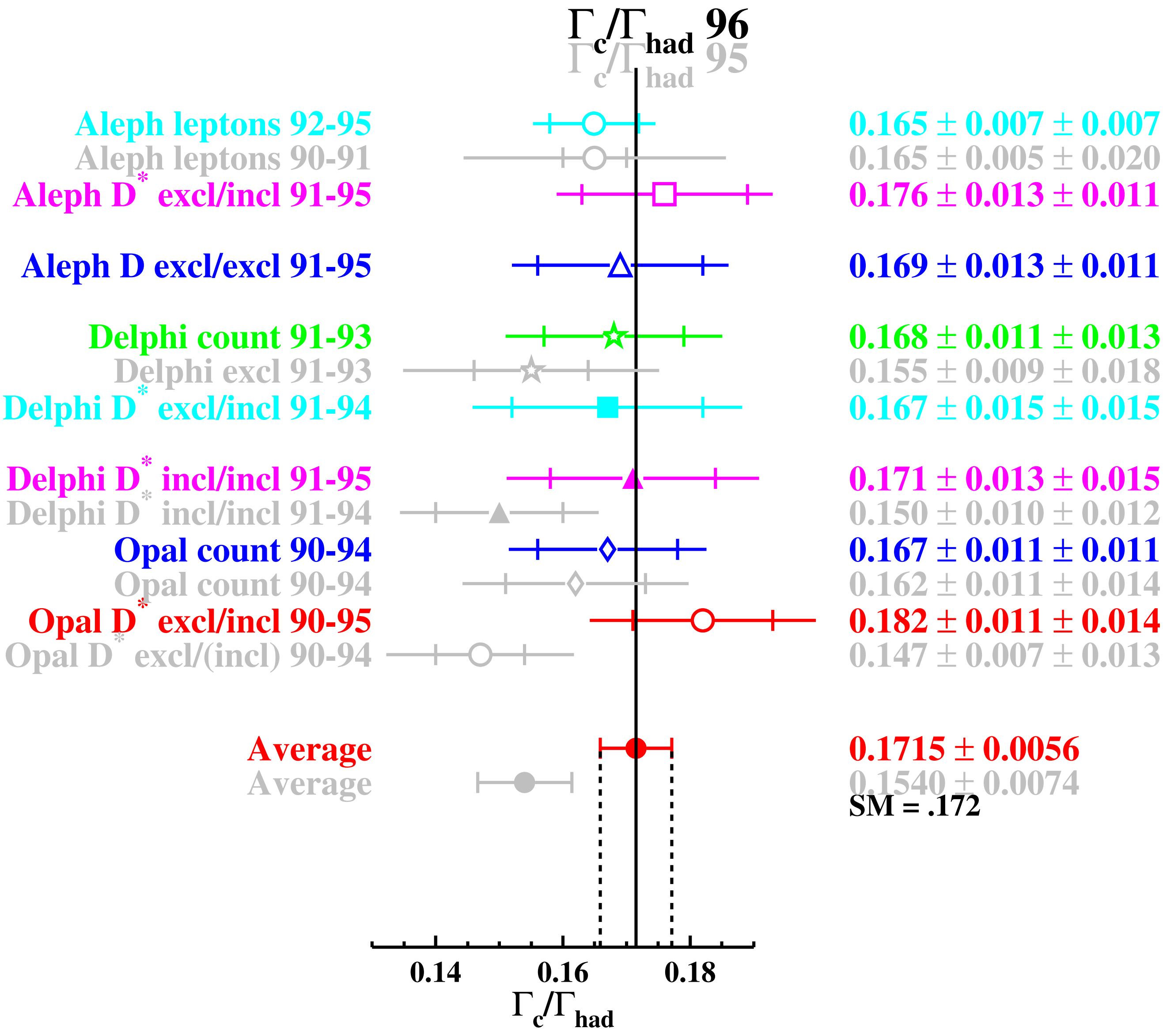
Don't quote: modified results![1]



[1] For the purposes of these graphical comparisons, the results have been modified by hand to common input parameters. The averages quoted have been correctly determined with the complete combination procedure.

$R_{c\bar{c}}$

Don't quote: modified results!



$R_{c\bar{c}}$

The differences:

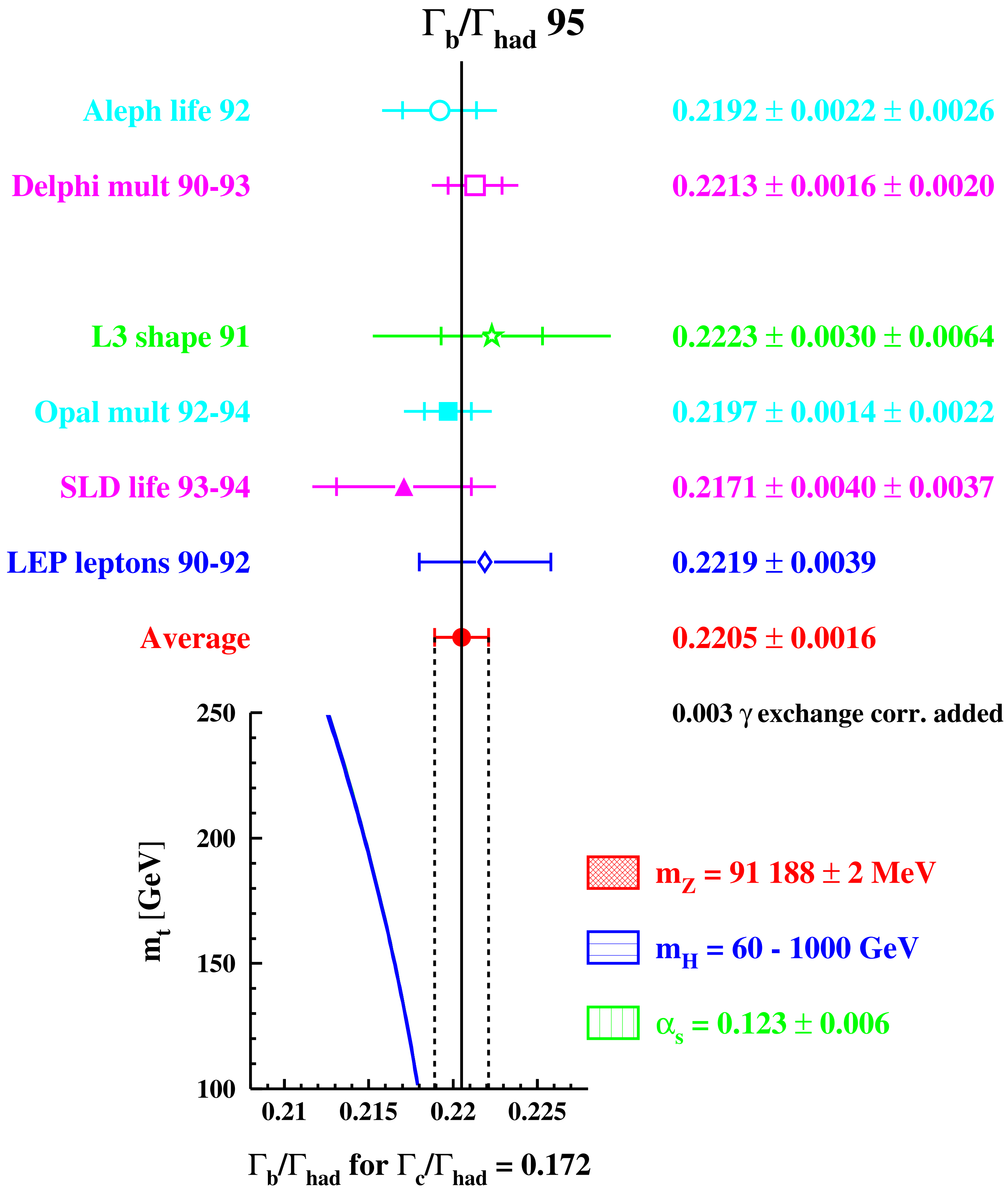
- Several results depend on the value of $P(\mathrm{c} \to \mathrm{D}^{*+}) \times BR(\mathrm{D}^{*+} \to \pi^{+}\mathrm{D}^{0})$. Last year the low energy result (0.178) was used; this year the result from LEP (0.163) is used. This is the largest systematic effect. (The current average of 0.1715 would change to 0.1637).
- Several input parameters have changed (*e.g.*, branching ratios and gluon splitting).
- Several analyses have been improved.
- The data sample has increased significantly.

Dominant errors:

$$\begin{array}{ll} \text{Statistics:} & 0.0037 \\ \text{Uncorrelated systematics:} & 0.0029 \\ BR(\mathrm{c} \to \ell) & 0.0022 \\ BR(\mathrm{D_s} \to \phi\pi) & 0.0011 \end{array} \Bigg\} \; 0.0053$$

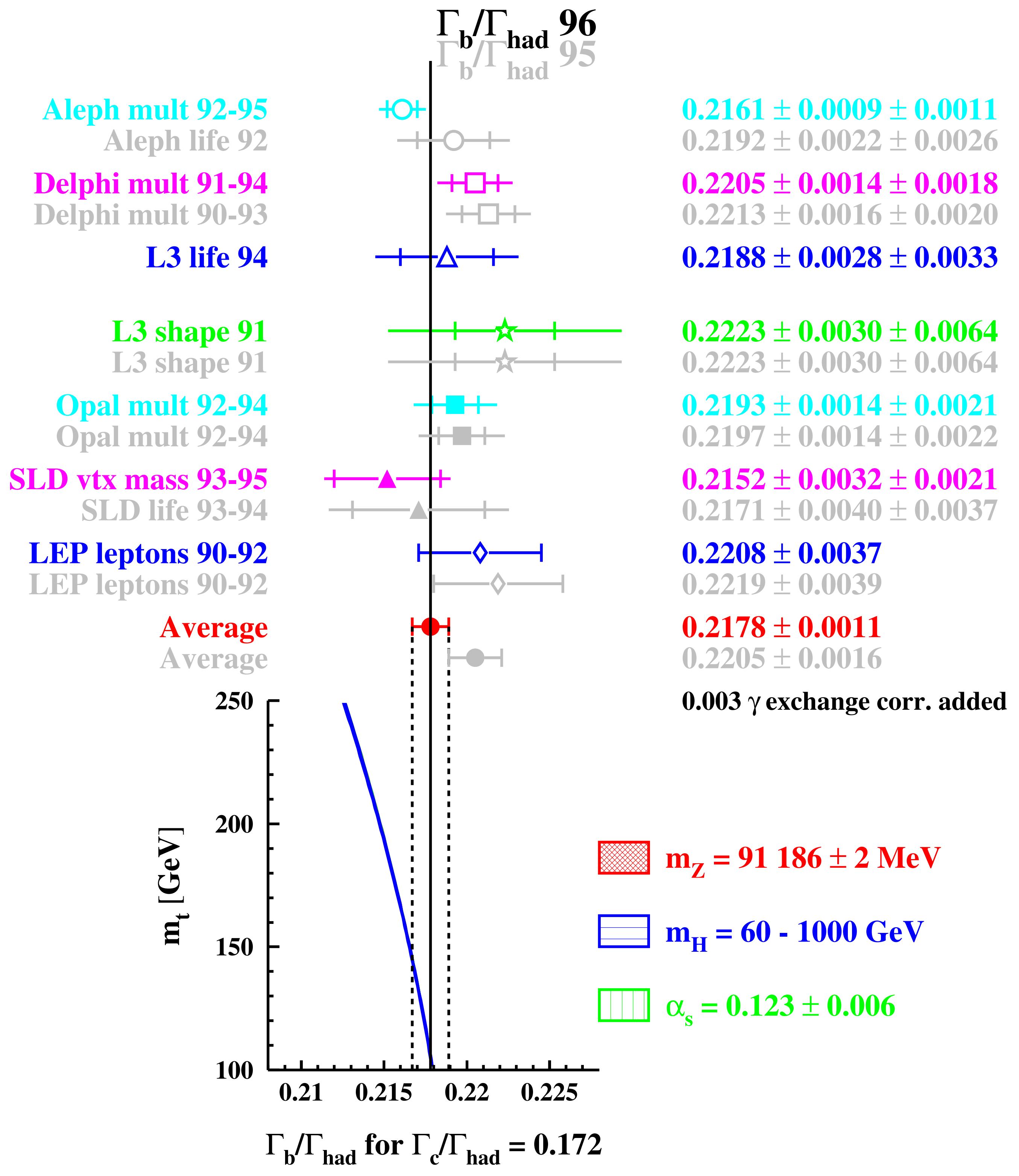
$R_{b\bar{b}}$

Don't quote: modified results!



$R_{b\bar{b}}$

Don’t quote: modified results!



$R_{b\bar{b}}$

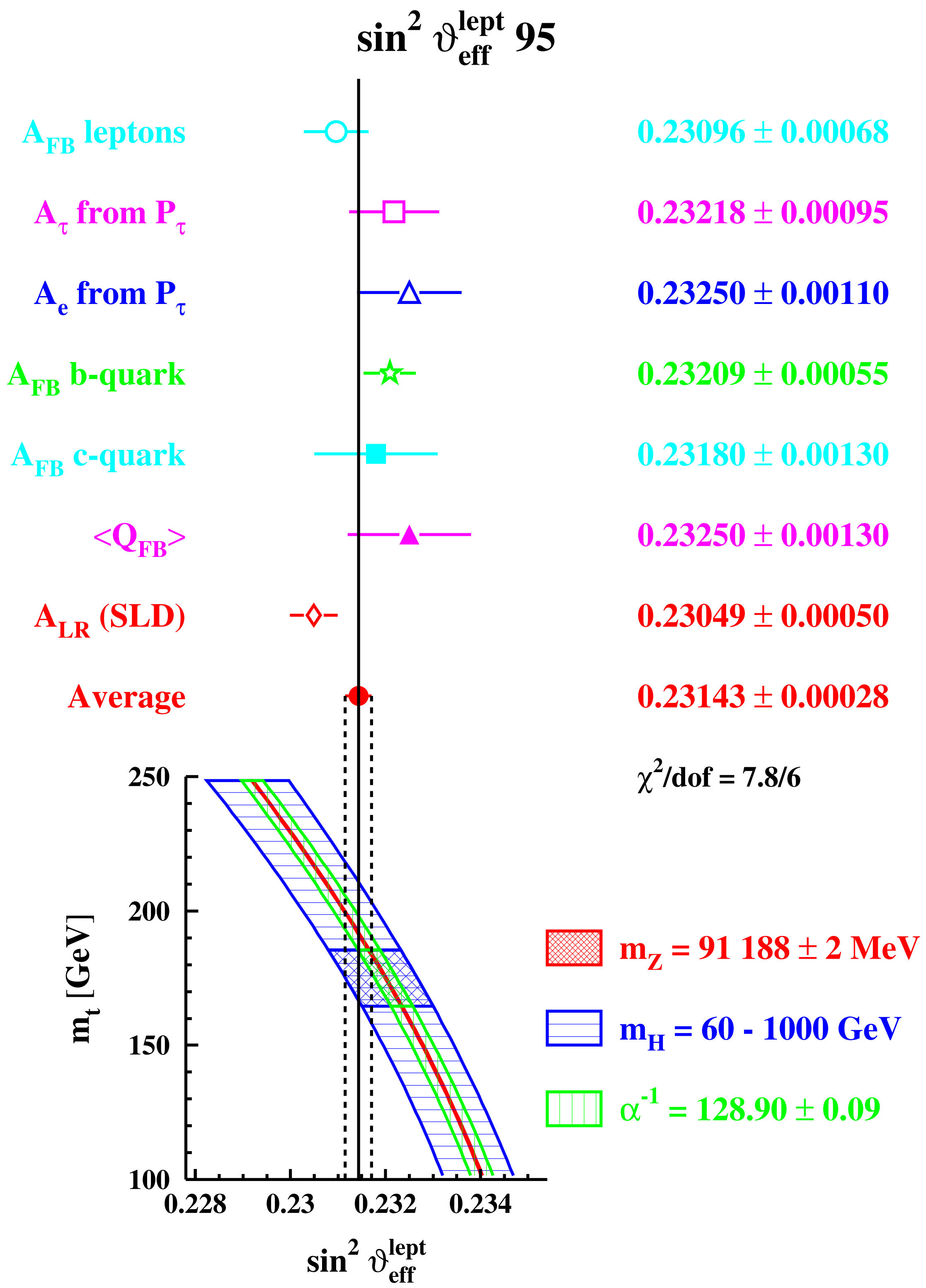
The differences:

- New data:
  - ALEPH: 92 $\rightarrow$ 92-95
  - DELPHI: 90-93 $\rightarrow$ 90-94
  - L3: new 94 result
- New analyses:
  - SLD: vertex mass tag: VERY high purity (97% pure at 37% eff)
  - ALEPH: multi-tag including vertex mass tag $\Rightarrow$ VERY small systematics
- Some minor changes to input parameters (*e.g.*, g$\rightarrow$ $b\bar{b}$, $c\bar{c}$).

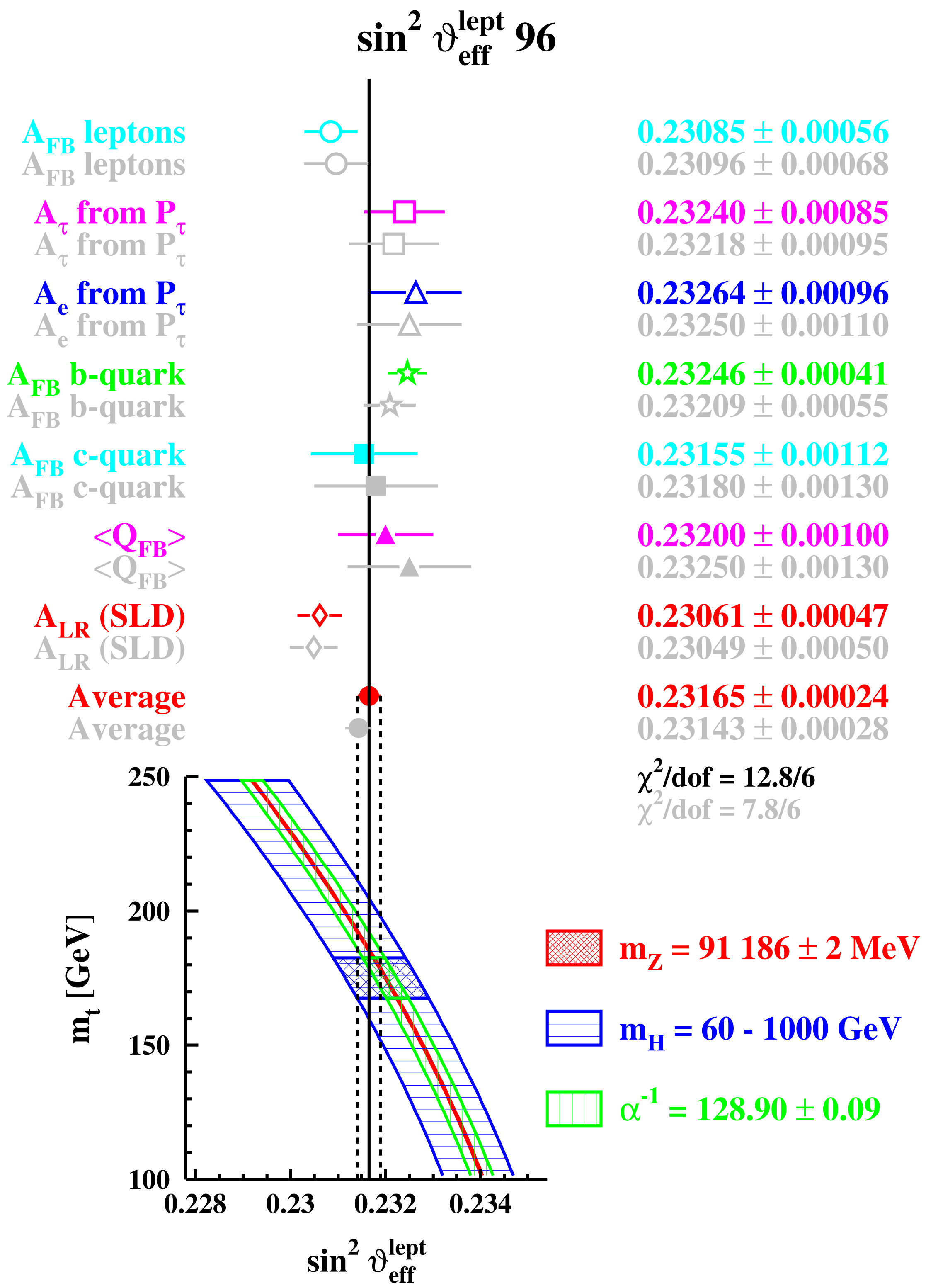
Dominant errors:

Statistics	0.00067	0.0011
Uncorrelated systematics	0.00053	
gluon splitting	0.00044	
QCD hemisphere correlations	0.00031	
D decay multiplicity	0.00029	
$BR(\mathrm{D} \rightarrow \mathrm{K}^0\mathrm{X})$	0.00022	

$\sin^2\theta_{\rm eff}^{\rm lept}$ in 1995



$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ in 1996

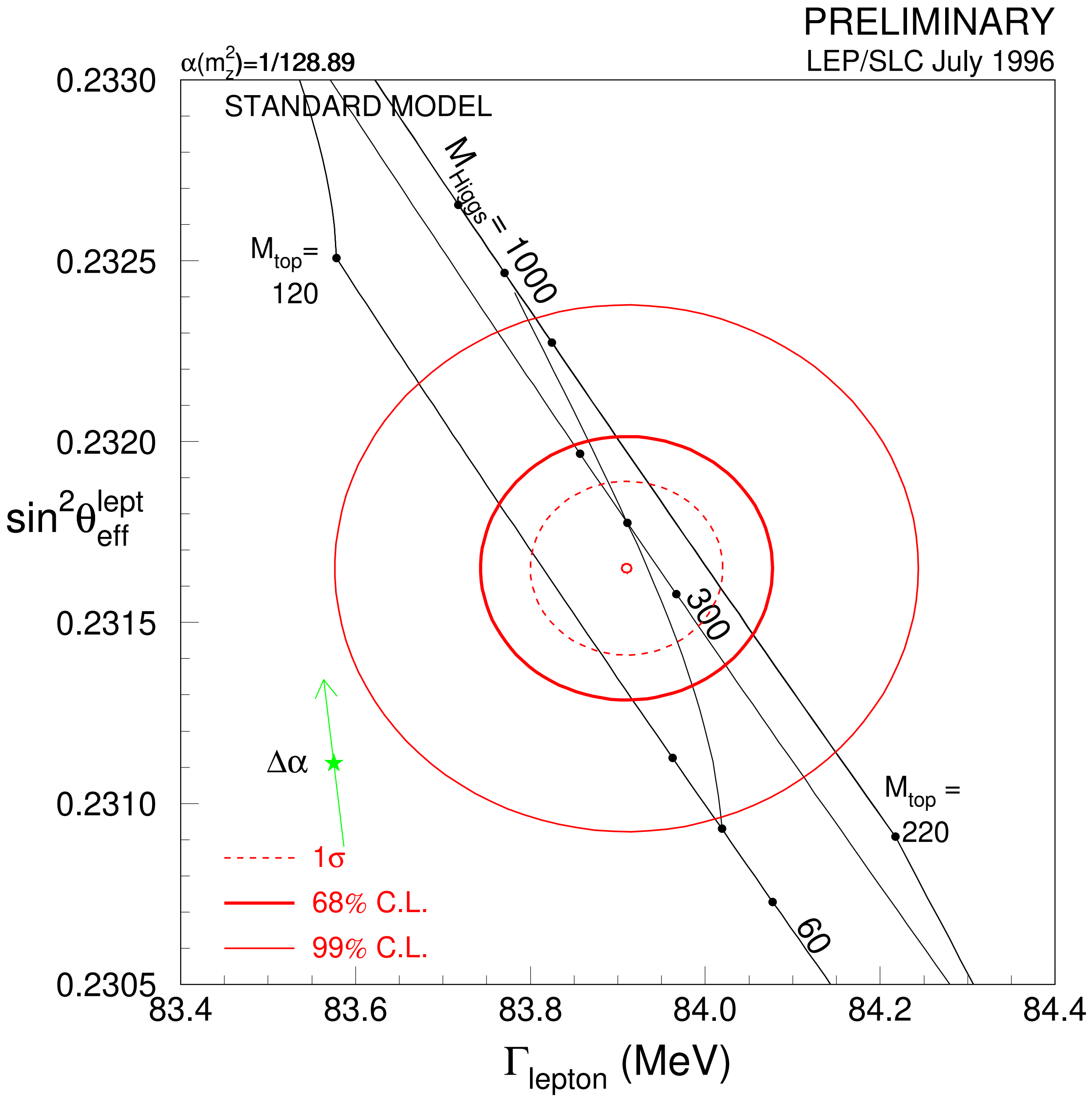


Summary of data

	96	95
$\alpha(m_Z^2)^{-1}$	128.896 ± 0.090	128.896 ± 0.090
LEP		
m_Z [GeV]	91.1863 ± 0.0020	91.1884 ± 0.0022
Γ_Z [GeV]	2.4946 ± 0.0027	2.4963 ± 0.0032
σ^0_{had} [nb]	41.508 ± 0.056	41.488 ± 0.077
R_ℓ	20.778 ± 0.029	20.788 ± 0.032
$A_{FB}^{0,\ell}$	0.0174 ± 0.0010	0.0172 ± 0.0012
+ corr. matrix		
$\mathcal{A}_\tau$	0.1401 ± 0.0067	0.1418 ± 0.0075
$\mathcal{A}_e$	0.1382 ± 0.0076	0.1390 ± 0.0089
$R^0_{b\bar{b}}$	0.2179 ± 0.0012	0.2219 ± 0.0017
$R^0_{c\bar{c}}$	0.1715 ± 0.0056	0.1543 ± 0.0074
$A_{FB}^{0,b}$	0.0979 ± 0.0023	0.0999 ± 0.0031
$A_{FB}^{0,c}$	0.0733 ± 0.0049	0.0725 ± 0.0058
+ corr. matrix		
$\sin^2\theta_{eff}^{lept}$ $(\langle Q_{FB}\rangle)$	0.2320 ± 0.0010	0.2325 ± 0.0013
SLD		
$\sin^2\theta_{eff}^{lept}$ (A_{LR})	0.23061 ± 0.00047	0.23049 ± 0.00050
$R^{0\ (a)}_{b\bar{b}}$	0.2149 ± 0.0038	0.2171 ± 0.0054
$\mathcal{A}_b$	0.863 ± 0.049	0.841 ± 0.053
$\mathcal{A}_c$	0.625 ± 0.084	0.606 ± 0.090
$p\bar{p}$ and νN		
$\sin^2\theta_W(\nu N)$	0.2244 ± 0.0042	0.2257 ± 0.0043
m_W [GeV] $(p\bar{p})$	80.356 ± 0.125	80.26 ± 0.16
m_t [GeV] $(p\bar{p})$	175 ± 6	180 ± 12

What can be said about m_{H}?

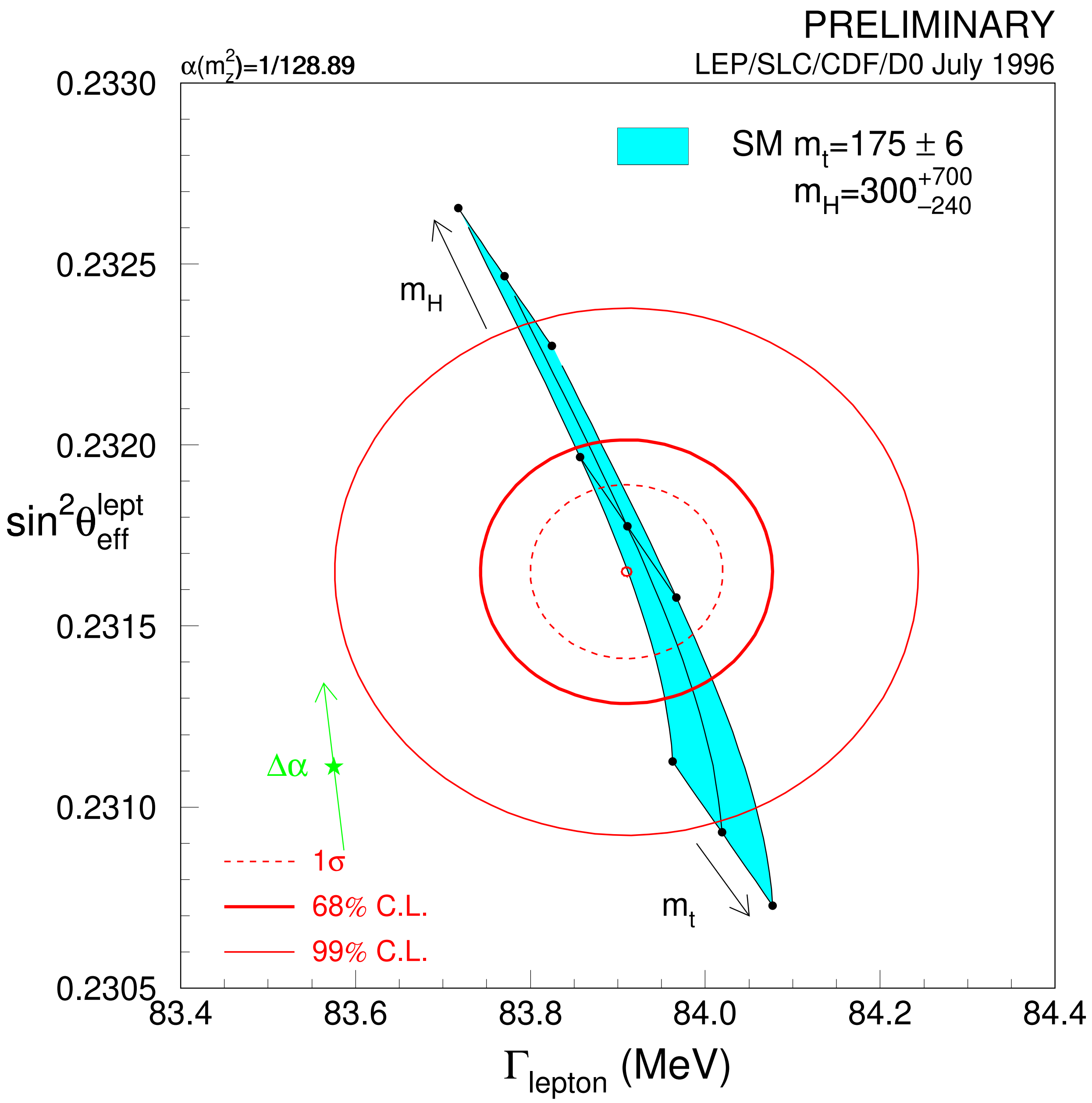
No fit yet, just asymmetries and widths:



Not much to learn without m_{t}!

What can be said about m_{H}?

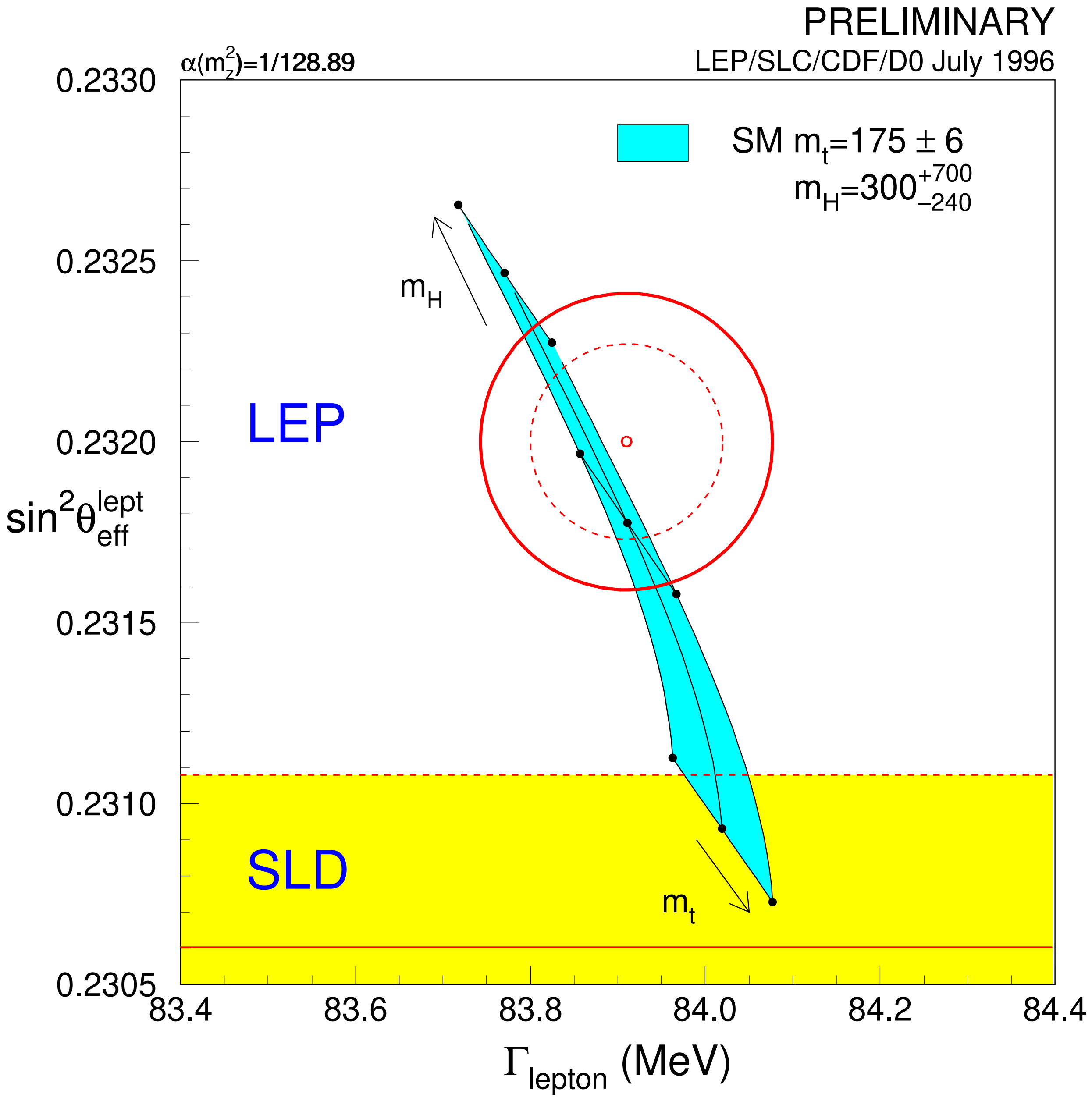
No fit yet, just asymmetries and widths:



But with m_{t} it starts getting interesting!

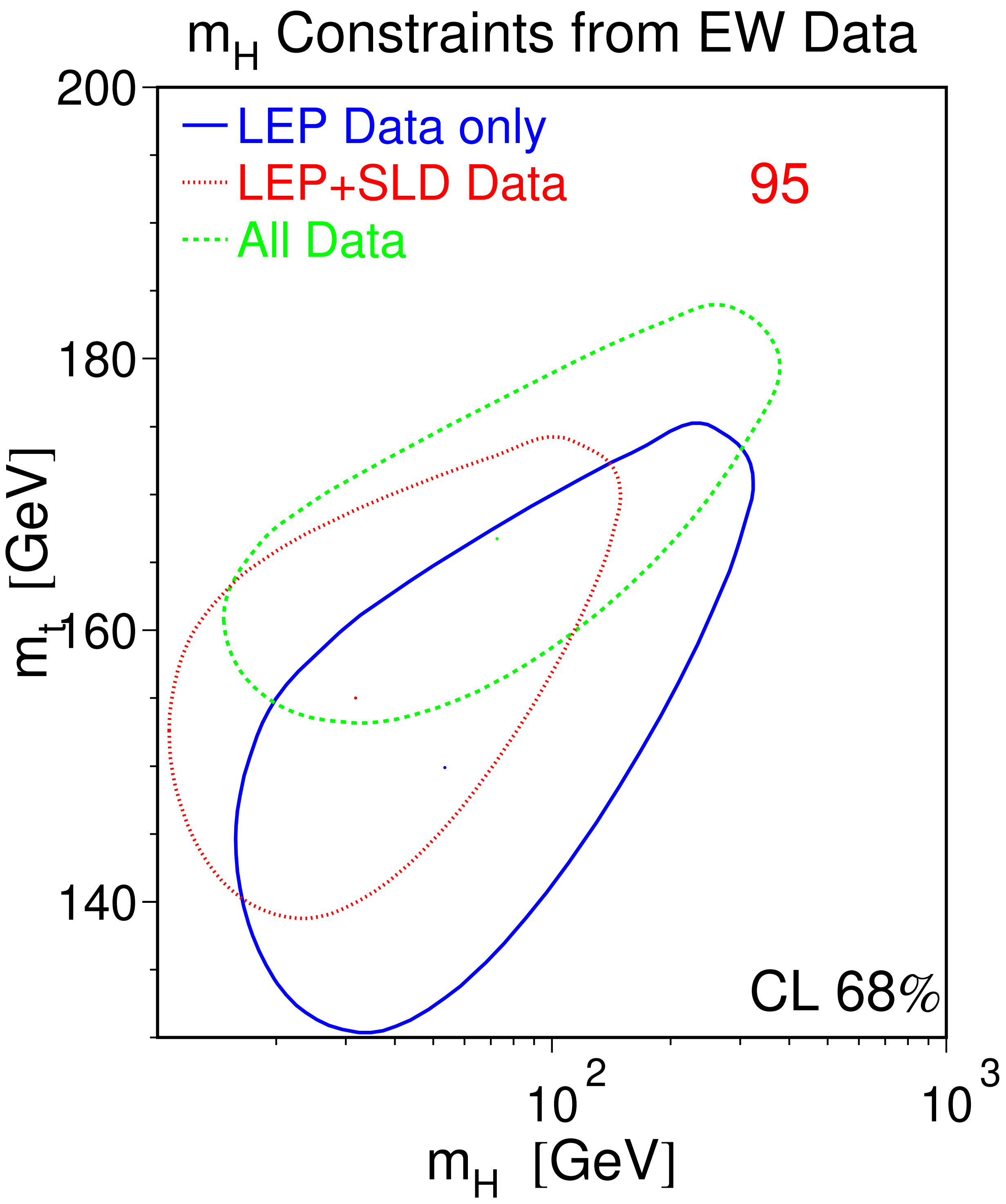
Short aside

LEP *vs.* SLD comparison:



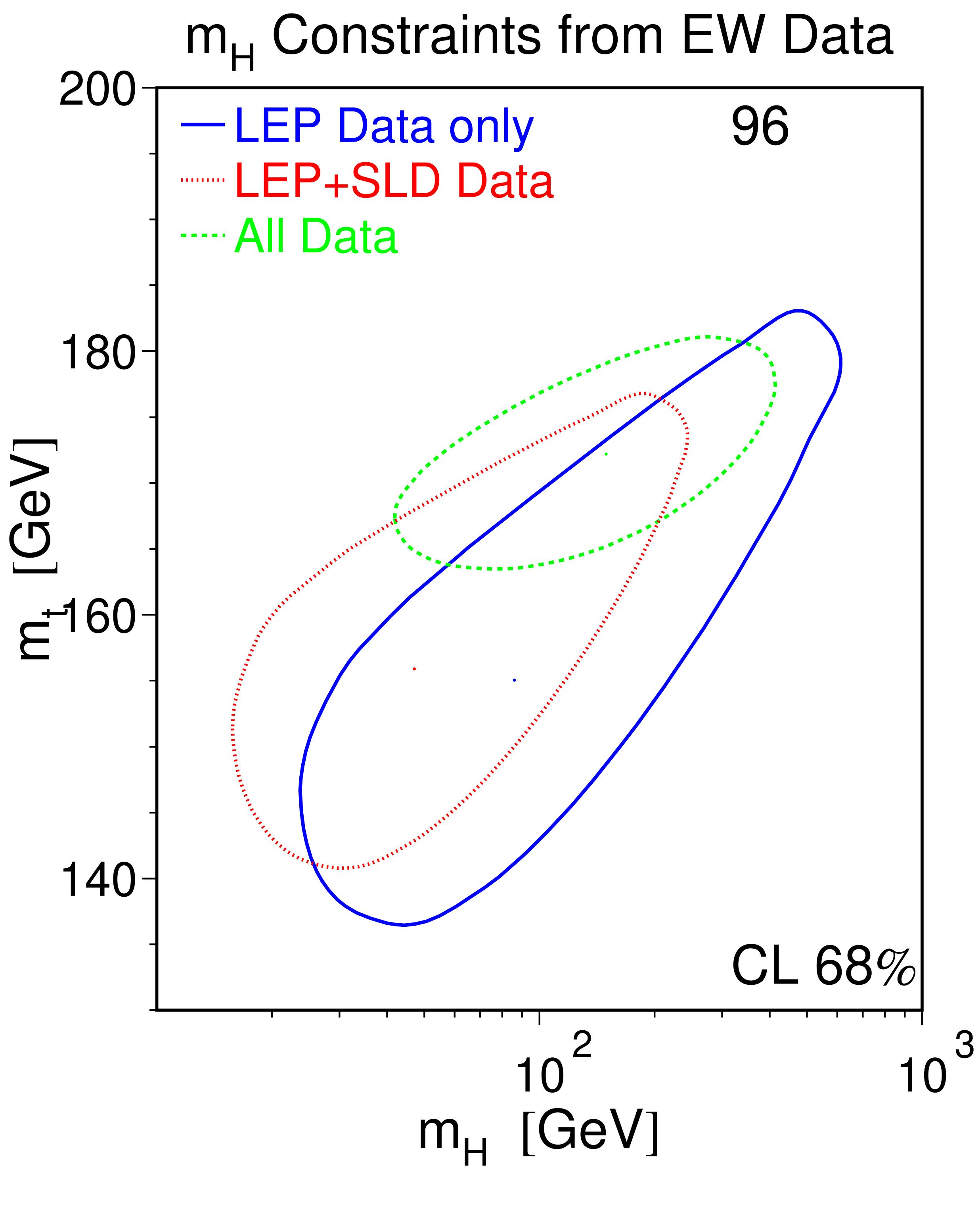
m_H *vs.* m_t

1995…

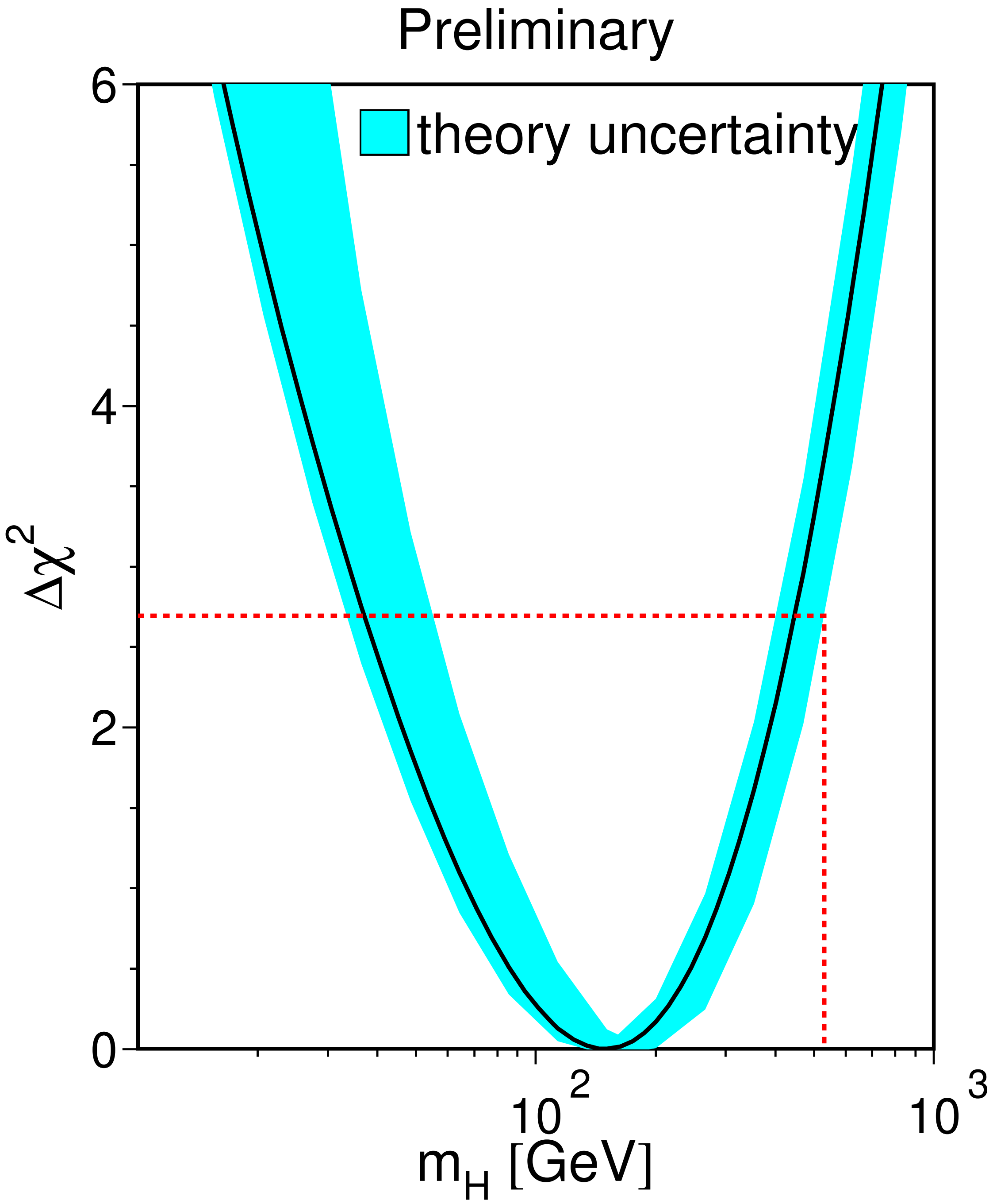


m_H Constraints from EW Data
LEP Data only
LEP+SLD Data
All Data
95
CL 68%
200
180
160
140
m_t [GeV]
10^2
10^3
m_H [GeV]

1996...


mH Constraints from EW Data
LEP Data only
LEP+SLD Data
All Data
96
CL 68%
200
180
160
140
mt [GeV]
10^2
10^3
mH [GeV]

m_H limit?



95% CL upper limit: 550 GeV.

SM fit

	LEP	LEP +SLD + $p\bar{p}$ and νN data + m_t
m_t [GeV]	155^{+18}_{-13}	172 ± 6
m_H [GeV]	86^{+202}_{-51}	149^{+148}_{-82}
$\alpha_s(m_Z^2)$	0.121 ± 0.003	0.120 ± 0.003
χ^2/d.o.f.	$9/8$	$19/14$

Values derived from the above:

$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$	0.23198 ± 0.00026	0.23167 ± 0.00023
$\sin^2\theta_W$	0.2249 ± 0.0009	0.2235 ± 0.0006
m_W(GeV)	80.278 ± 0.049	80.352 ± 0.033

Comments:

- $\alpha_s(m_Z^2)$ is as good as all other measurements of $\alpha_s(m_Z^2)$ together (0.118 ± 0.003)
- The error on m_W is an excellent goal for LEPII!

The LEP 200 Program

LEP 2 (1996-1999):

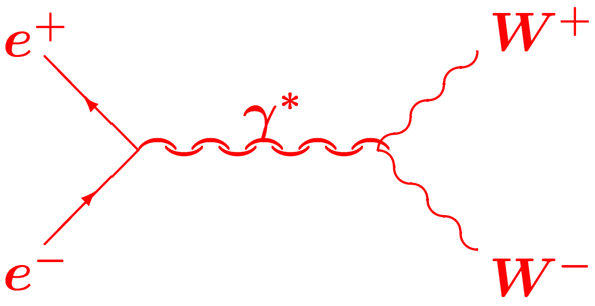
An additional 180 SC Cavities installed in stages

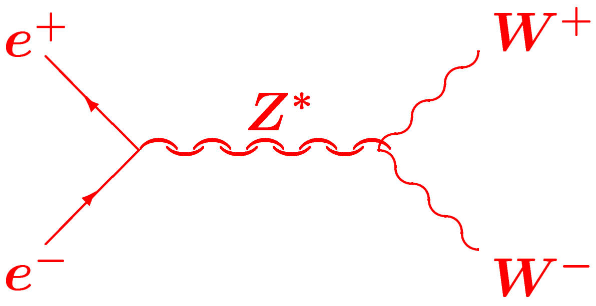
Interactions at $\sqrt{s} \simeq 161 \rightarrow 192$ GeV

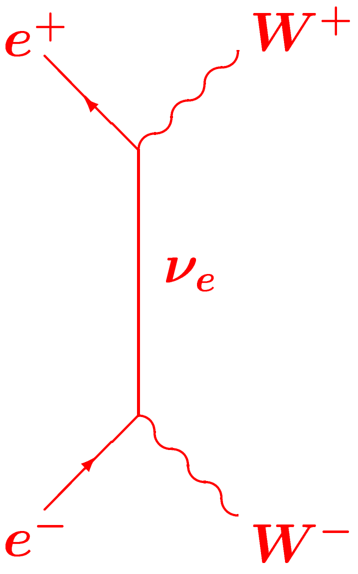
Doubling of the energy compared to LEP 1

Higher energies $\rightarrow$ new physics:

$\sqrt{s} > 2m_{\mathrm{W}}$: pair production of $\mathrm{W}^{\pm}$ bosons



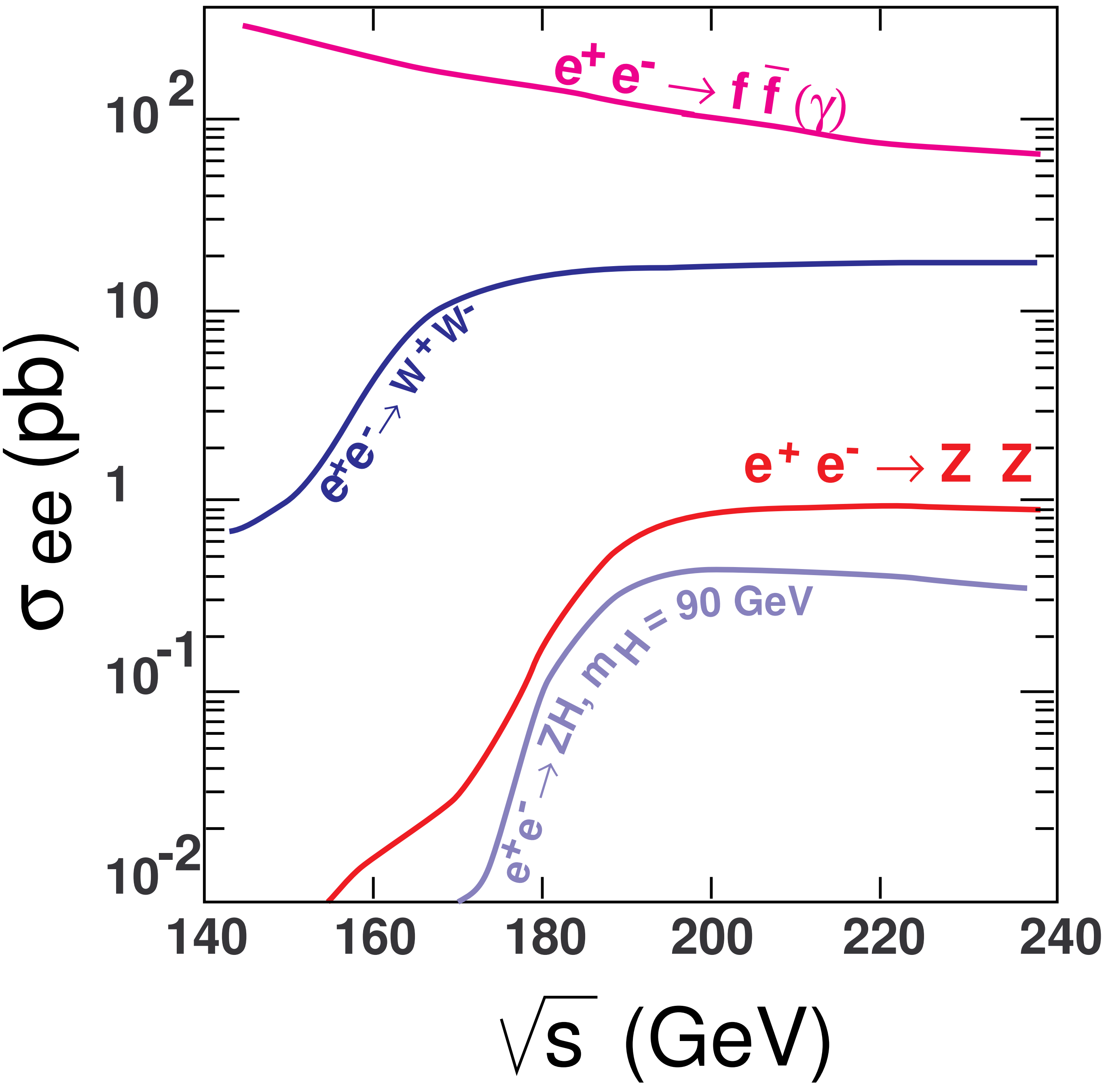




$$\mathrm{W} \rightarrow f\bar{f}'$$

$$\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{W}^+\mathrm{W}^- \rightarrow f_1\bar{f}_2 f_3\bar{f}_4$$

Cross-sections at LEP-2



Total cross-section $\sigma(W^+W^-(\gamma))$:

threshold behavior

Expectations at LEP-2

Expected total LEP-2 luminosity:
$\mathcal{L} \simeq 500\ \mathrm{pb}^{-1}$ / experiment

Expected LEP-2 center-of-mass energies:

June 1996: $\sqrt{s} = 161\ \ \mathrm{GeV} \quad (12\ pb^{-1})$
October 1996: $\sqrt{s} = 172\ \ \mathrm{GeV} \quad (12\ pb^{-1})$
1997: $\sqrt{s} \rightarrow 188\ \ \mathrm{GeV}$
1998: $\sqrt{s} \rightarrow 192\ \ \mathrm{GeV}$

Total cross-section after radiative corrections:
$\sigma(\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{W}^+\mathrm{W}^-(\gamma);\ 192\ \ \mathrm{GeV}) \simeq 17\ pb$

$\mathrm{W}^+\mathrm{W}^-$ events at LEP-2:
Fewer than 8500 events / experiment

W Boson Decays

Produced W bosons decay:

$$\mathrm{W} \to \mathrm{e}\nu,\ \mu\nu,\ \tau\nu,\quad \underbrace{\mathrm{ud}',\ \mathrm{cs}'}_{\times 3\ \text{(color charge)}}$$

$$\mathrm{B}(\mathrm{W} \to \text{leptons}) \simeq 1/3$$
$$\mathrm{B}(\mathrm{W} \to \text{hadrons}) \simeq 2/3$$

Total and partial widths of the W Boson:

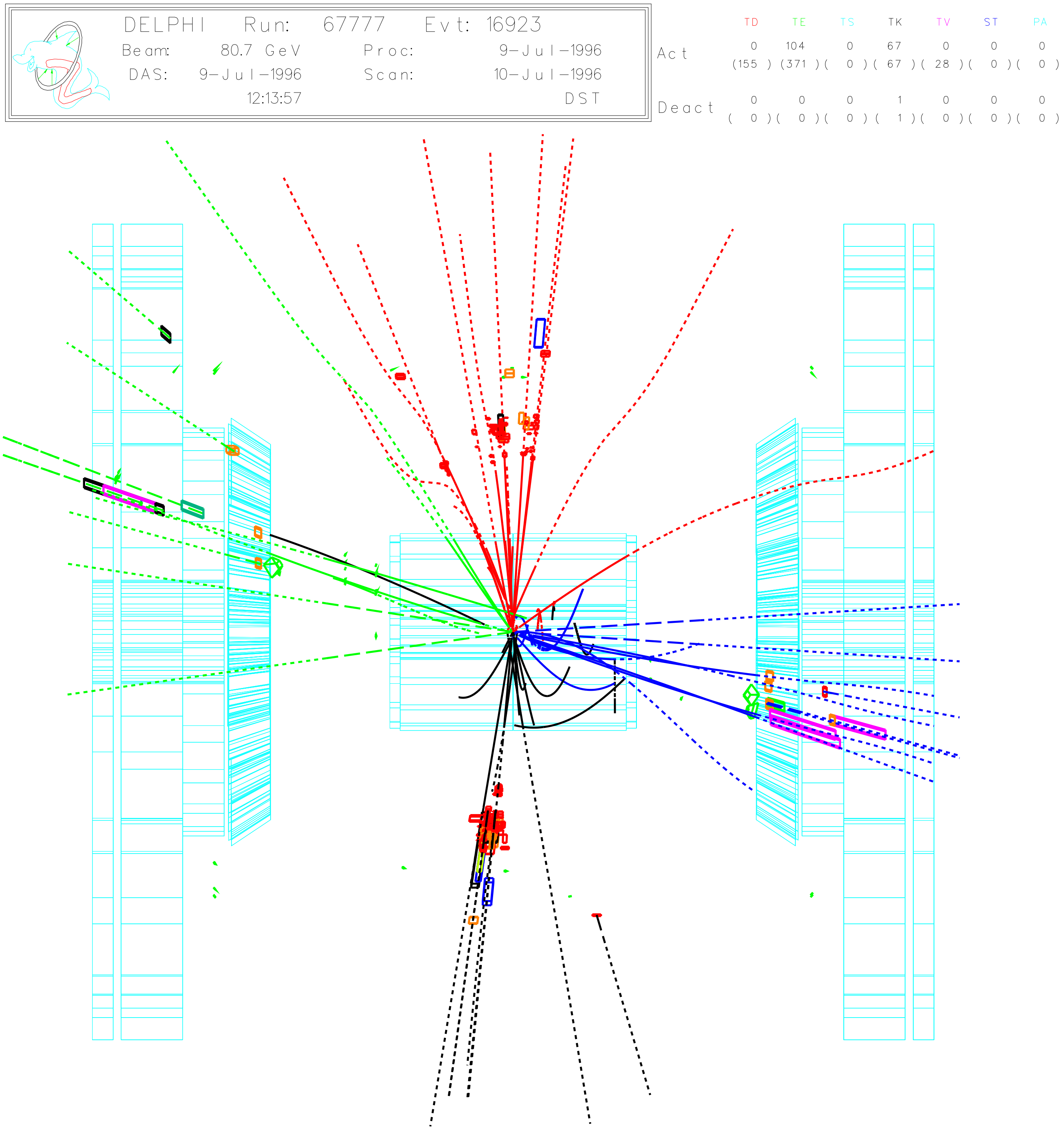
$$\Gamma^{\mathrm{W}}_{\ell\nu} = \frac{G_{\mathrm{F}} m^3_{\mathrm{W}}}{6\sqrt{2}\pi} \simeq 225.5\ \mathrm{MeV}$$
$$\Gamma^{\mathrm{W}}_{ud} = 3\left(1 + \frac{\alpha_S}{\pi}\right)|V_{ud}|^2\Gamma^{\mathrm{W}}_{\ell\nu}$$
$$\Gamma_{\mathrm{W}} = 9\left(1 + \frac{2\alpha_S}{3\pi}\right)\Gamma^{\mathrm{W}}_{\ell\nu} \simeq 2.082\ \mathrm{GeV}$$

Event classes:

$\mathrm{e}^+\mathrm{e}^- \to \mathrm{W}^+\mathrm{W}^- \to$	Class	Fraction
$\mathrm{q}\overline{\mathrm{q}}'\mathrm{q}\overline{\mathrm{q}}' \to$ 4 Jets	hadronic	45.6%
$\mathrm{q}\overline{\mathrm{q}}'\ell\nu \to$ 2 Jets $\ell\nu$	semileptonic	43.8%
$\ell^+\ell^-\nu\overline{\nu}$	leptonic	10.6%

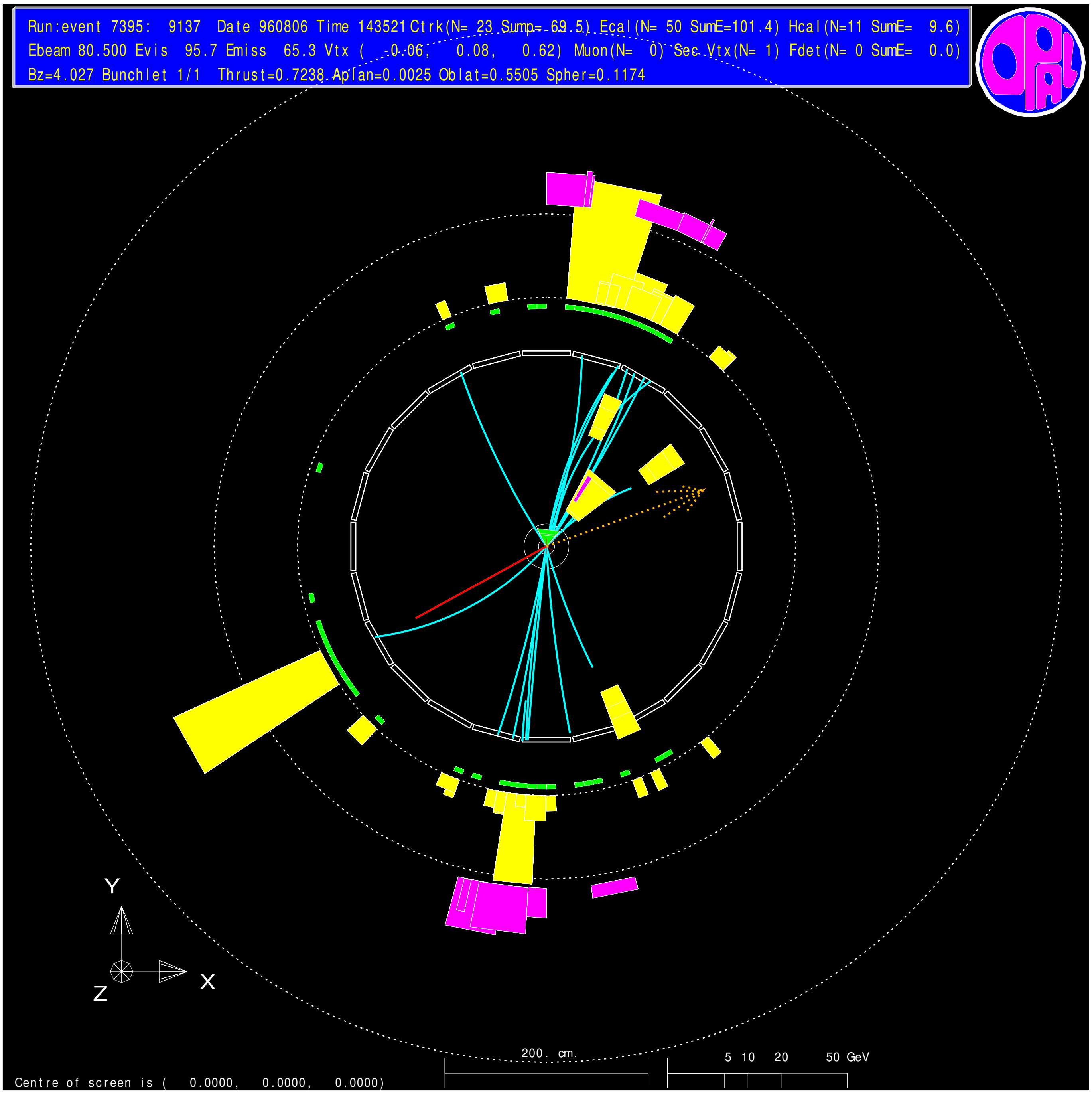
$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}'q\bar{q}' \rightarrow$ 4 Jets

Branching ratio: 45.6%



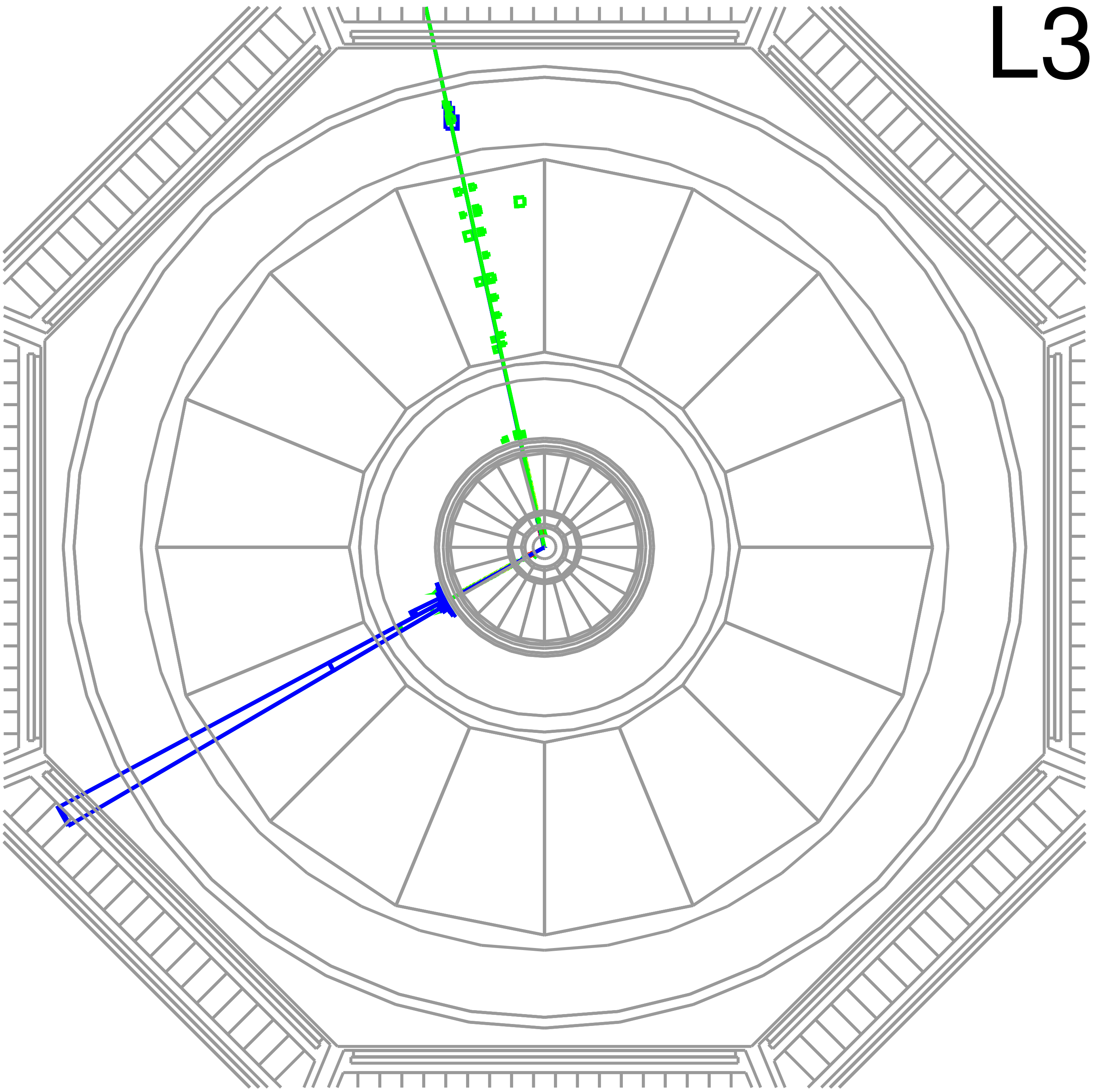
$e^+e^- \to W^+W^- \to q\overline{q}'\ell\nu \to 2\,\text{Jets} + \ell$

Branching ratio: 3×14.6%



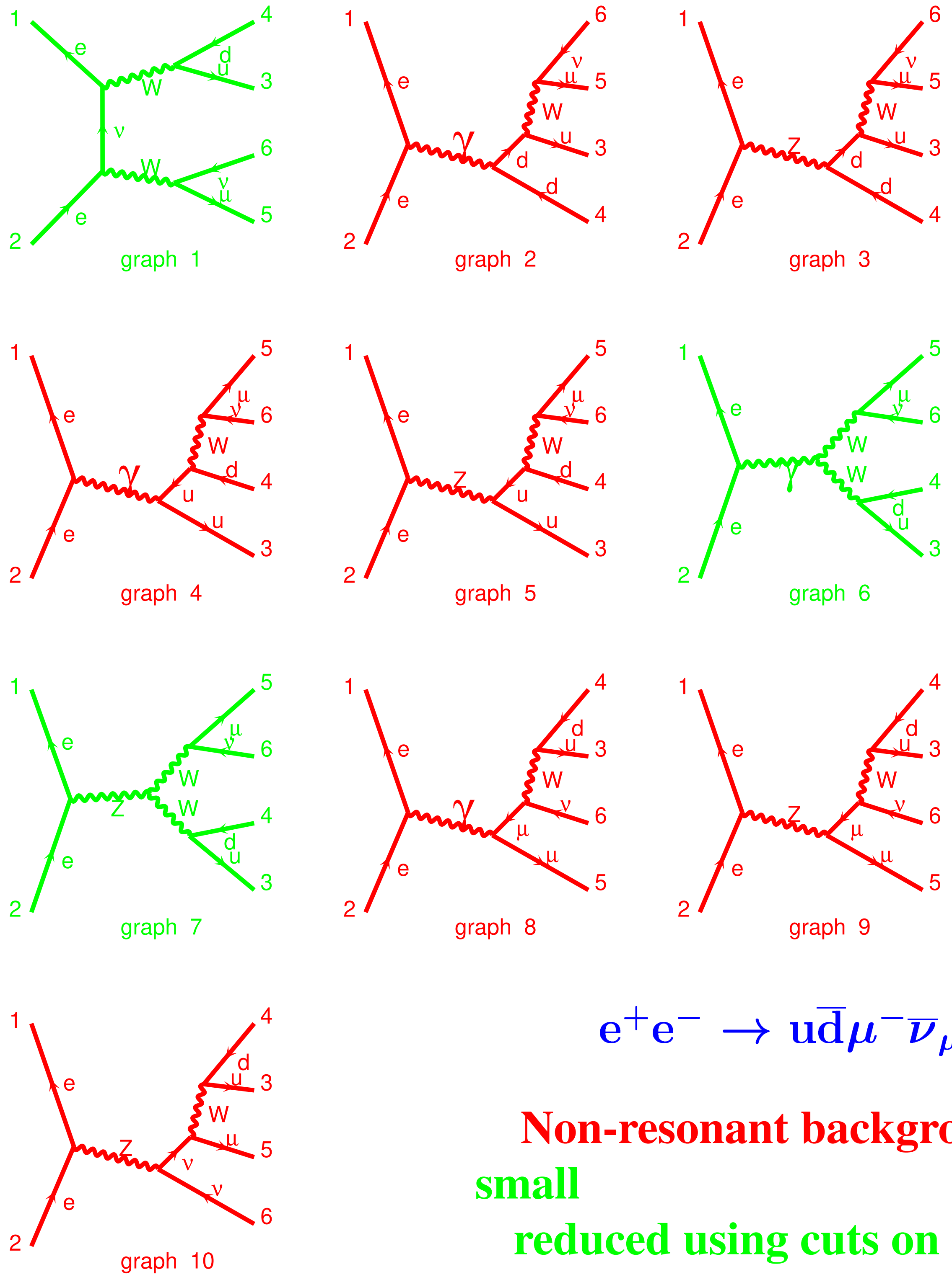
$$e^+e^- \to W^+W^- \to \ell\nu\ell\nu$$

Branching ratio: 10.6%



Four-Fermion Production

Diagrams by MadGraph



$$\mathbf{e^+e^- \to u\bar{d}\mu^-\bar{\nu}_\mu}$$

Non-resonant background:

small

reduced using cuts on M_{inv}

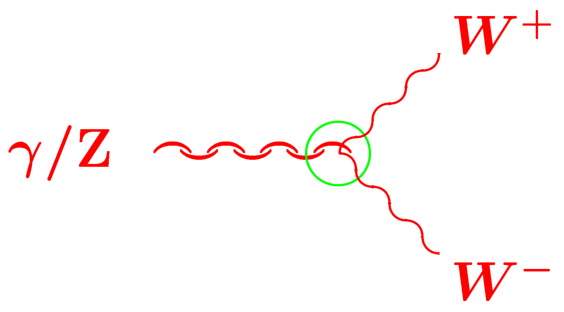
W Physics at LEP 2

Properties of the W Boson:

$m_{\rm W}$	**Mass**
$\Gamma_{\rm W}$	**Total Width**
$\Gamma^{\rm W}_{f\overline{f}'}$	**Partial Widths**
$B({\rm W} \to f\overline{f}')$	**Branching ratios**

New Physics at $\rm e^+e^-$ machines:

Three-Boson Vertices $\gamma {\rm W}^+{\rm W}^-,\ {\rm ZW}^+{\rm W}^-$



Anomalous three-boson couplings

Measurements of the W Mass

Current:
Measurments at Hadron Accelerators
SPS, TEVATRON Experiments: UA2, CDF, DØ

$$m_{\mathrm{W}} = 80.356 \pm 0.125 \ \ \mathrm{GeV}$$

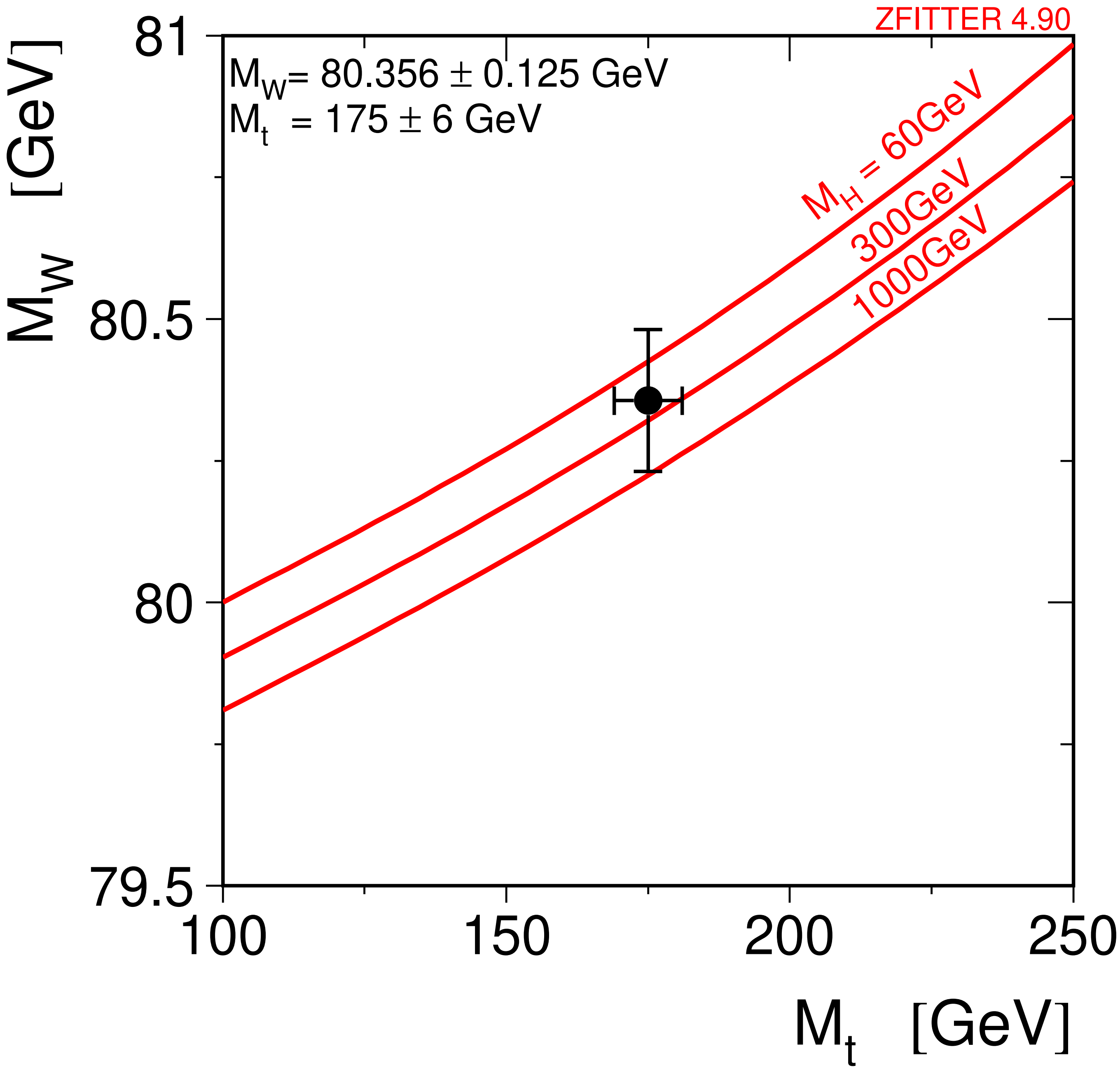
Error: $\delta m_{\mathrm{W}} = 125 \ \ \mathrm{MeV}$

Analysis of all TEVATRON data (1a+1b):
Expected error: $\delta m_{\mathrm{W}} \simeq 100 \ \ \mathrm{MeV}$

Why should we bother to measure m_{W} more precisely at LEP 2?

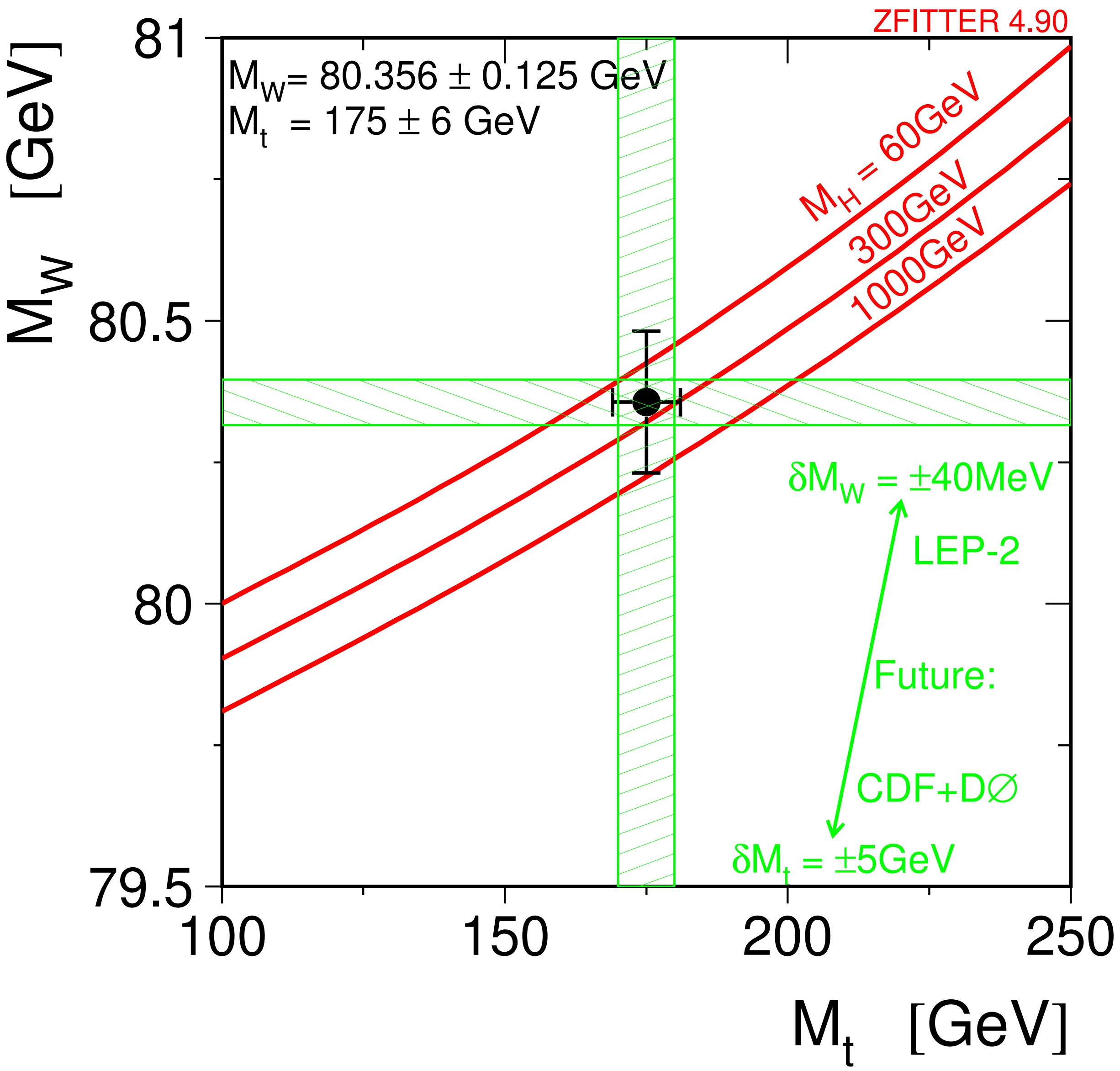
Measurements of the W Mass

m_W is a fundamental parameter of the SM



Measurements of the W Mass

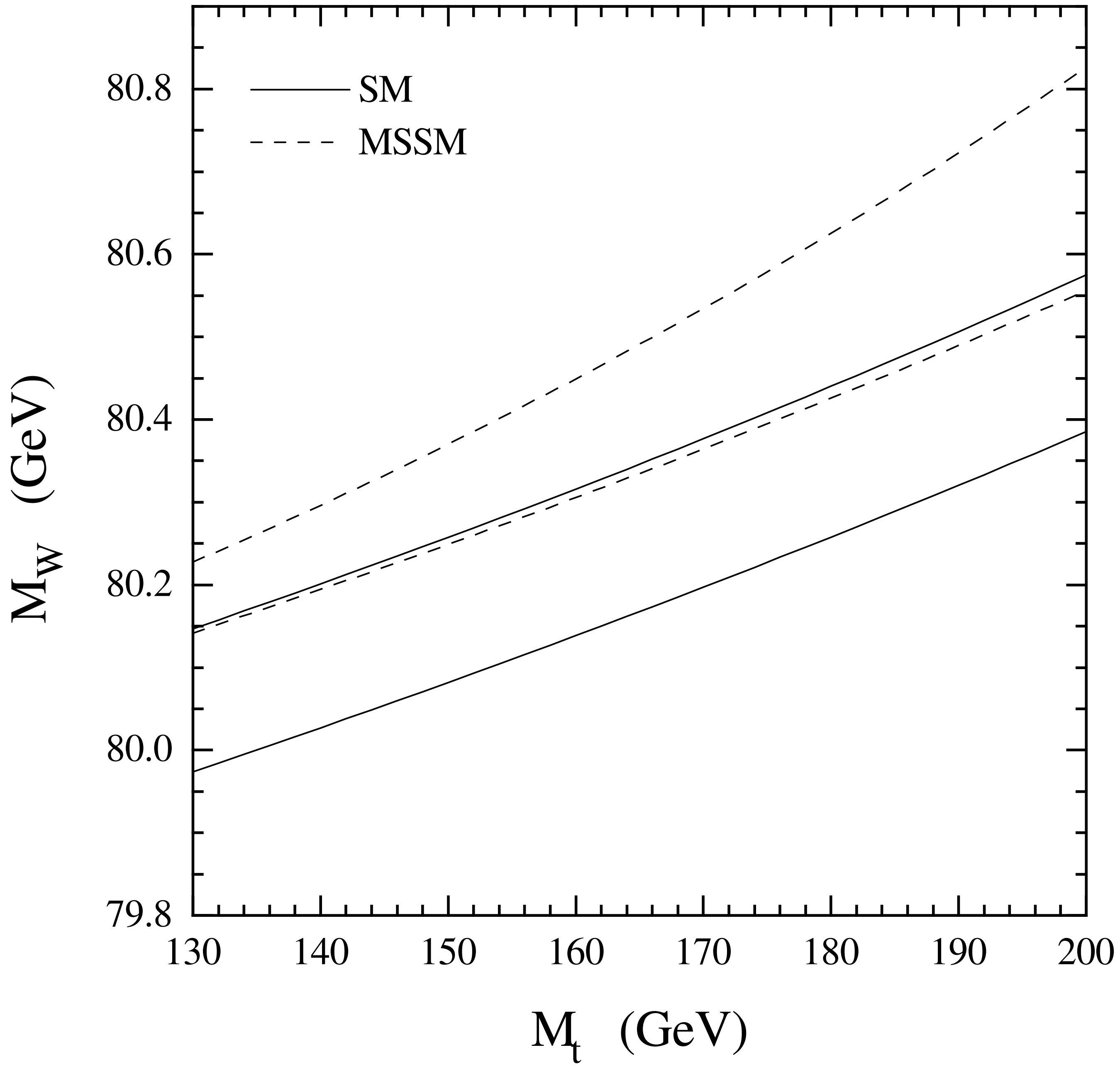
Test the consistency of the Standard Model



***cf* LEP1: $\delta m_{\mathrm{W}} \approx 30$ MeV**

Measurements of the W Mass

m_W in the SM and in supersymmetric SM



Measurements of the W Mass

Two complementary methods at LEP 2:

1. **Threshold behavior of the total cross-section ($\sqrt{s} \simeq 2m_{\mathrm{W}}$):**

$$\sigma(\mathrm{e}^+\mathrm{e}^- \to \mathrm{W}^+\mathrm{W}^-) = \sigma(\sqrt{s}, m_{\mathrm{W}}, \ldots)$$

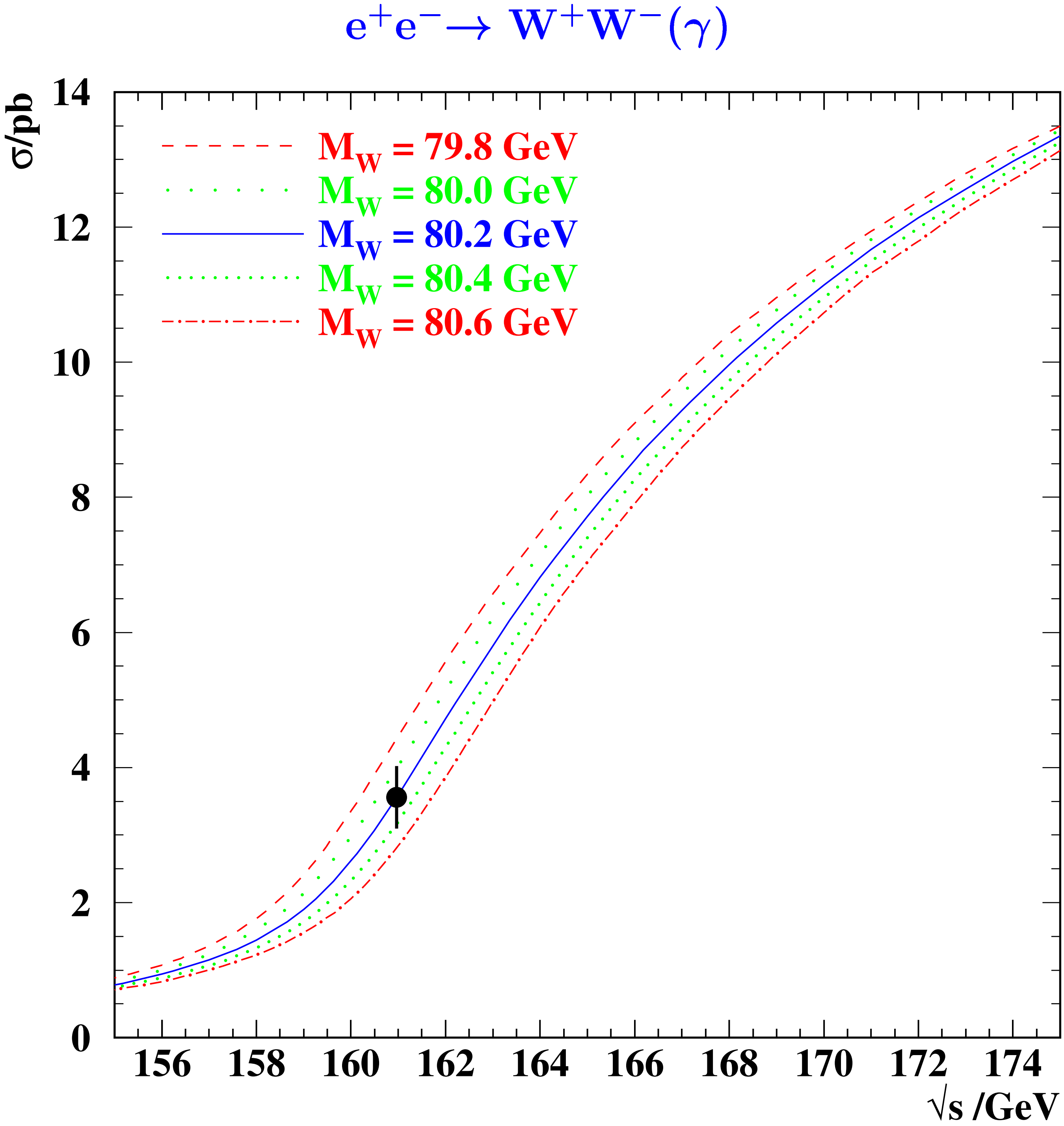
(Similar to m_τ from BES at BEPC)

2. **Direct reconstruction ($\sqrt{s} > 170\ \mathrm{GeV}$):**

$$m_{\mathrm{W}} = M_{\mathrm{invariant}}(\mathrm{W} \to q\overline{q}' \to \mathrm{Jet\ Jet})$$

The two methods have similar statistical sensitivity.

Threshold Method

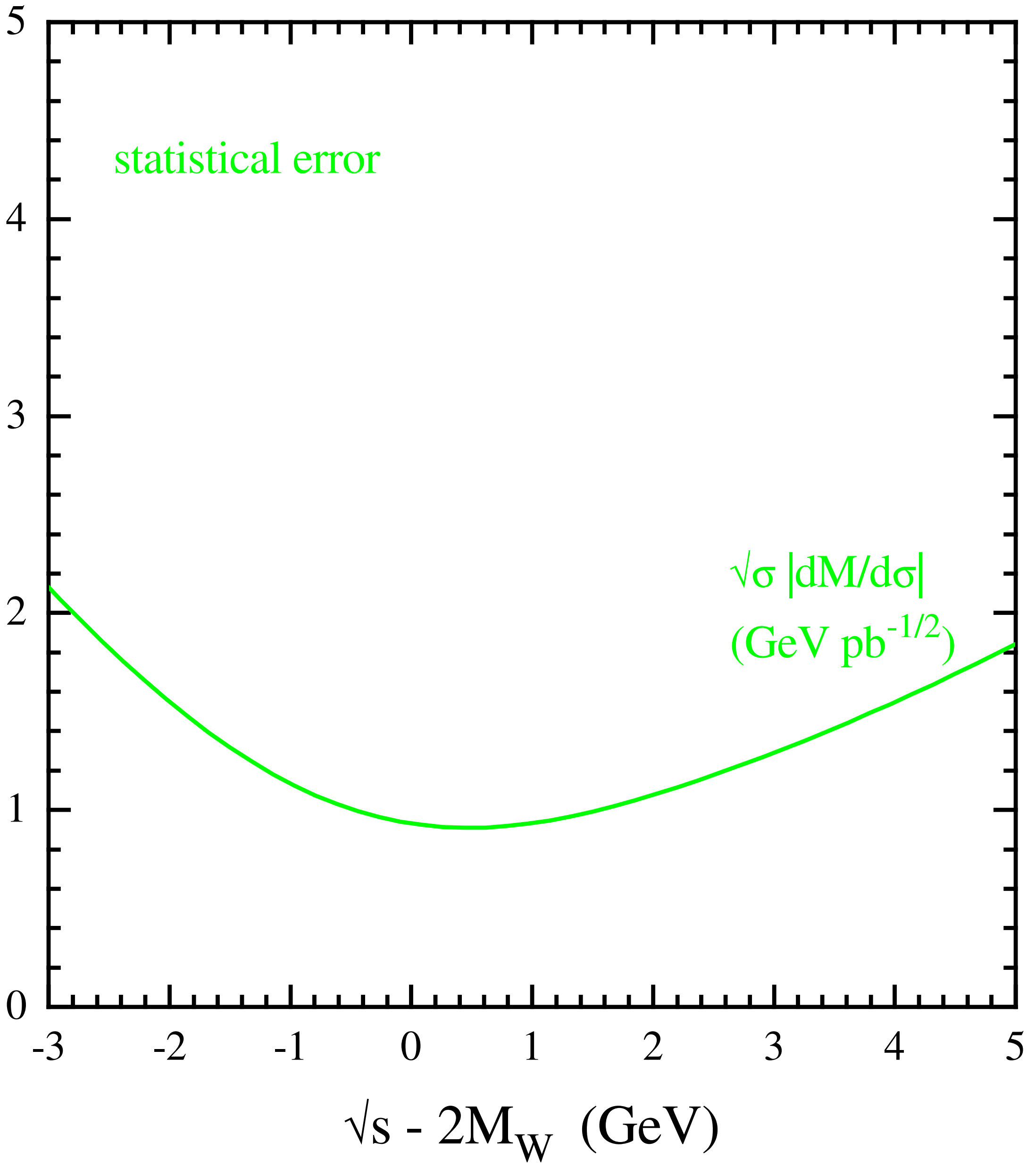


In the vicinity of the nominal threshold ($\sqrt{s} = 2m_W$):

$\sigma = \sigma(\sqrt{s} - 2m_W)$

Threshold Method

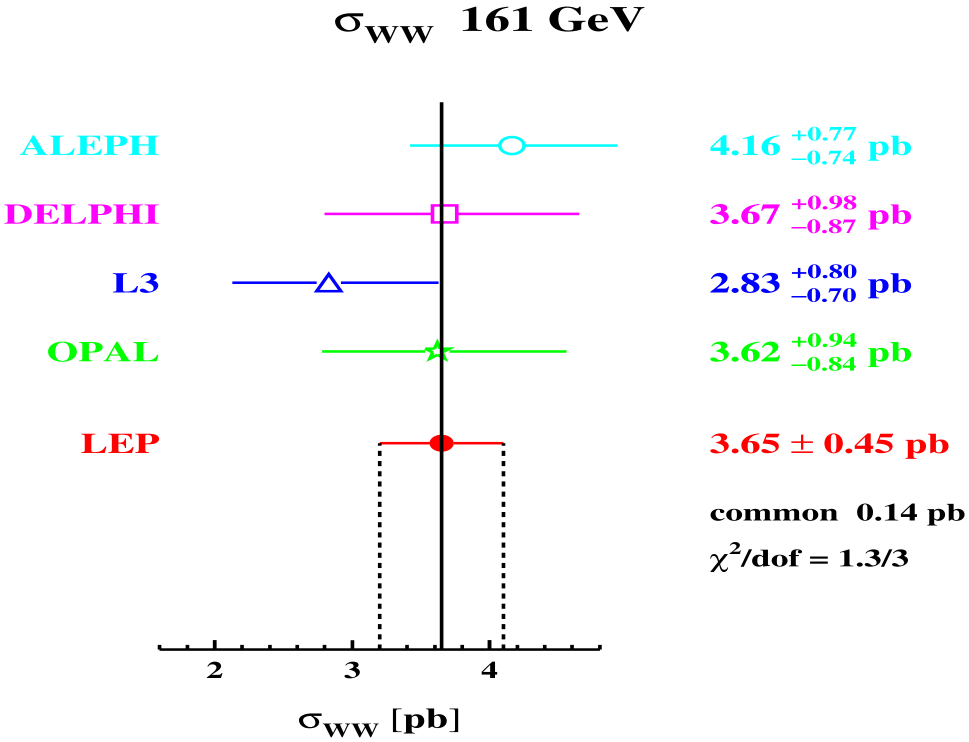
$$\text{Error on } m_W : \quad \delta m_W = \left|\frac{d\,m_W}{d\,\sigma}\right| \delta\sigma$$

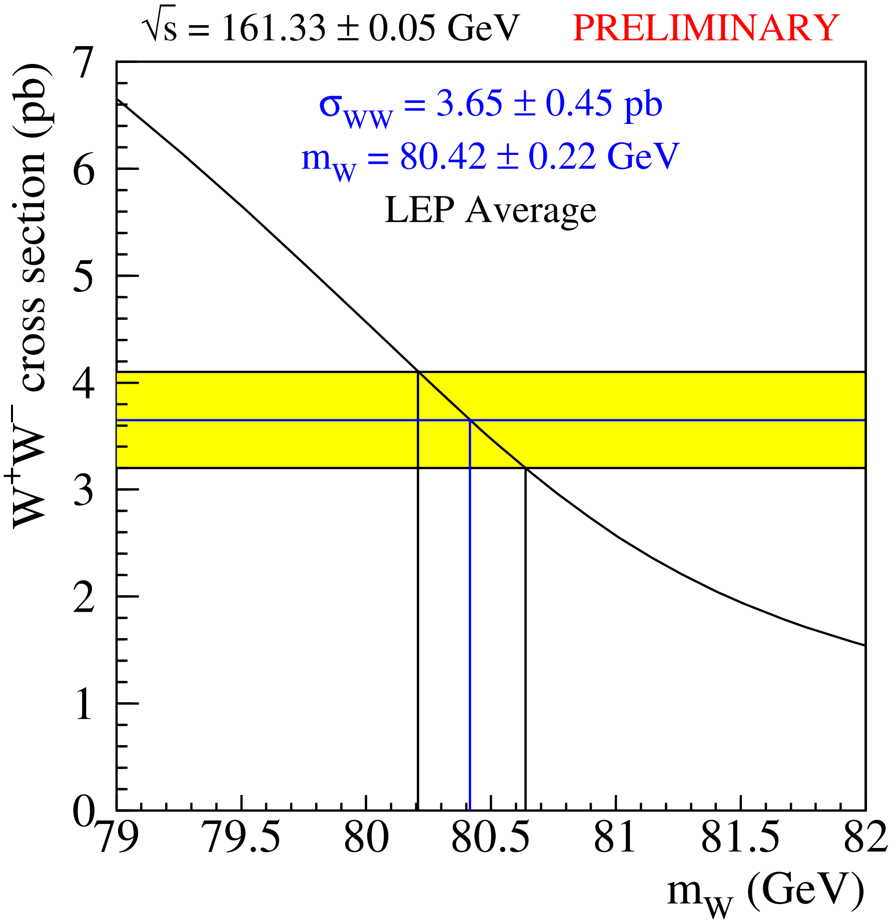


Optimal statistical sensitivity:

$\sqrt{s} = 2m_W + 0.5\ \text{GeV} = 161\ \text{GeV}$

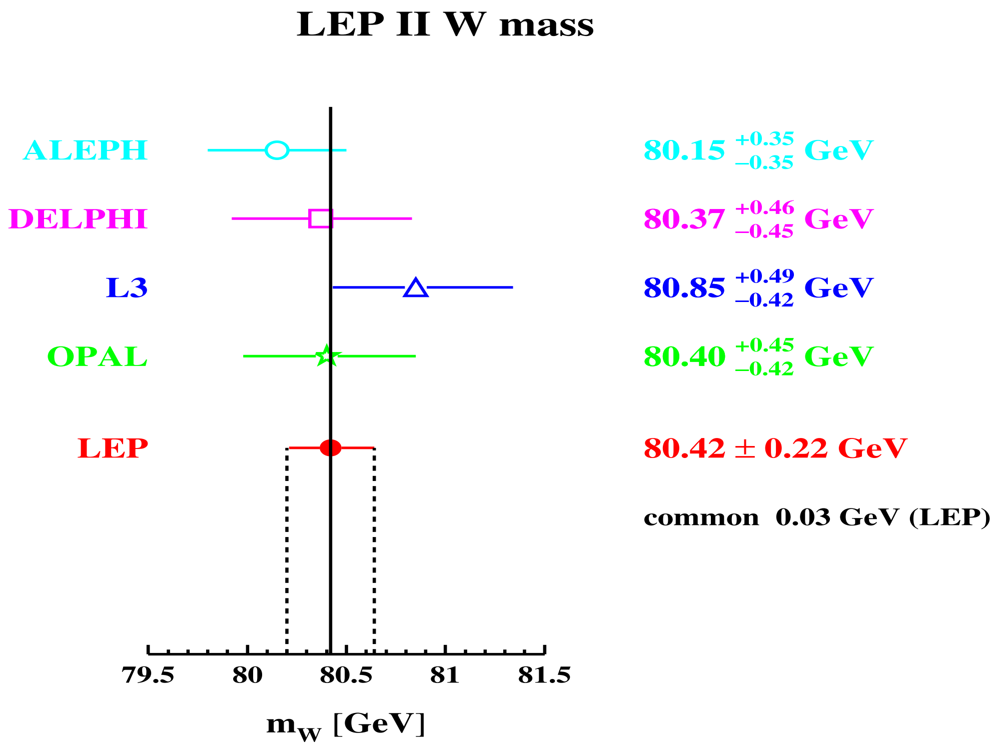
Threshold Method



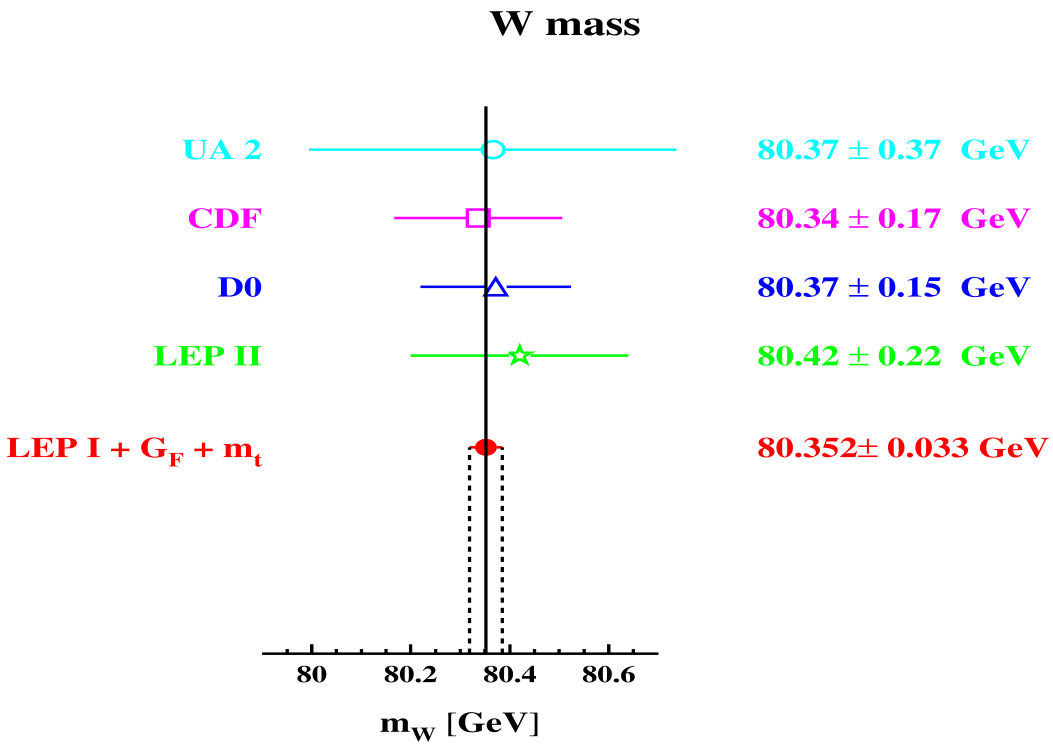


W Mass Comparisons

Among the LEP experiments:



LEP *vs* the rest:



Direct Reconstruction

Invariant mass of the W decay products

$e^+e^- \rightarrow W^+W^- \rightarrow f_1\overline{f}_2f_3\overline{f}_4$

Reconstruction of the 4 fermions (E, θ, ϕ)

$m_W = M_{inv}(W \rightarrow f\overline{f}')$

Kinematic fit for better resolution:

Energy and momentum conservation

Equal mass constraint:

$M_{inv}(1, 2) \; = \; M_{inv}(3, 4) \; \pm \; \Gamma_W$

Semileptonic $W^+W^- \rightarrow q\overline{q}'\ell\nu$ **events:**

Neutrino is given by the missing momentum

Hadronic $W^+W^- \rightarrow q\overline{q}'q\overline{q}'$ **events:**

Three possible jet-pair combinations:

$(1, 2)(3, 4) \quad (1, 3)(2, 4) \quad (1, 4)(2, 3)$

Kinematic Fit

Measurements:

E, θ, ϕ of the visible fermions

Improving the resolution:

Energy-momemtum consevation:

$$\left.\begin{aligned} \sum_i E_i &= \sqrt{s} \\ \sum_i E_i \vec{n}(\theta_i, \phi_i) &= \vec{0} \end{aligned}\right\} \quad \text{4 Constraints}$$

Additional constraints:

$$m_{ij} = m_{kl} \ (\pm\Gamma_W) \quad \Bigg| \quad \begin{aligned} m_{ij} &= m_W \ (\pm\Gamma_W) \\ m_{kl} &= m_W \ (\pm\Gamma_W) \end{aligned}$$

Ambiguities in hadronic WW events:

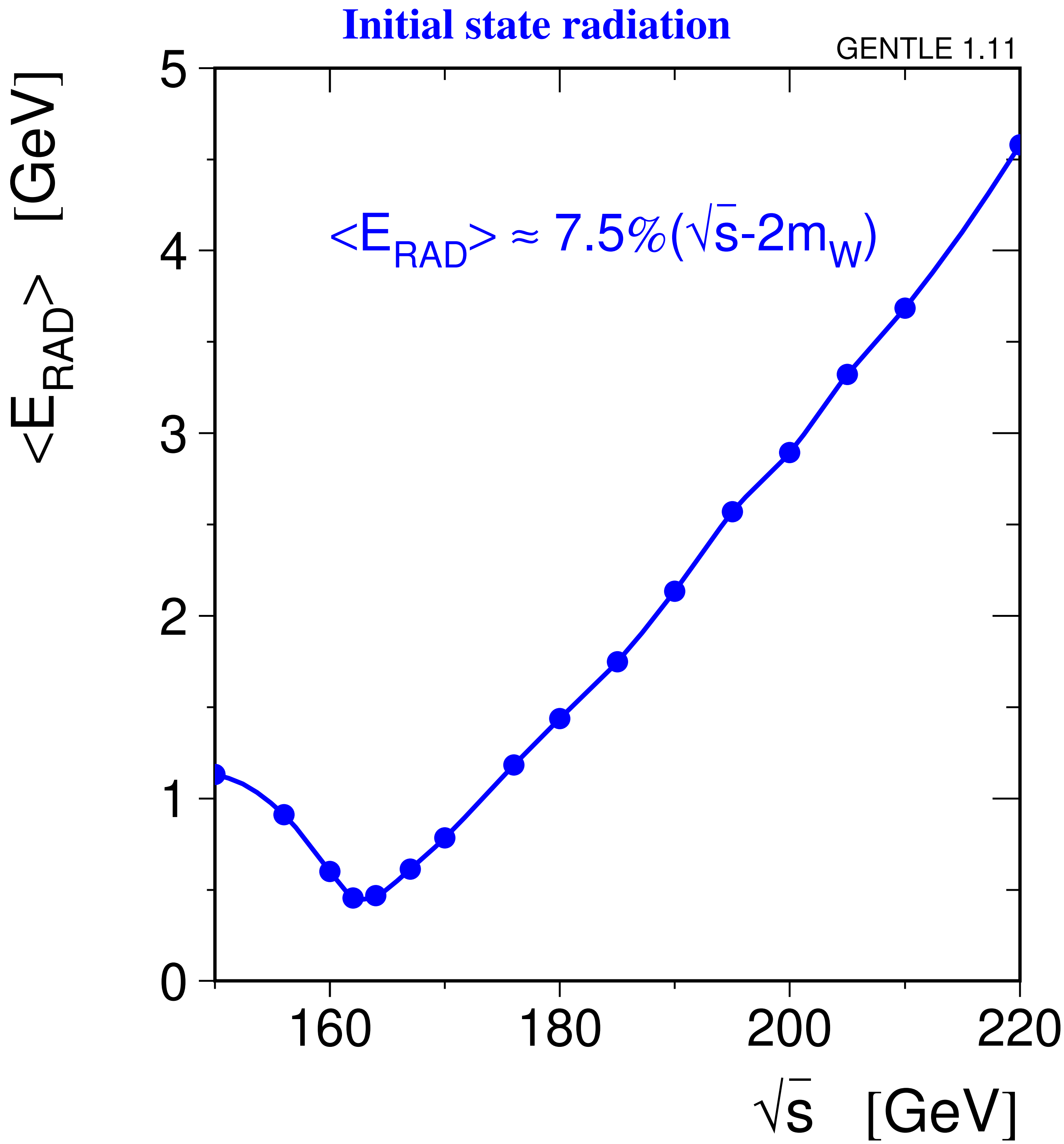
choose the jet-pairing with the best χ^2_{Fit}

Problems:

initial state radiation

hard gluon radiation leading to additional jets

Direct Reconstruction

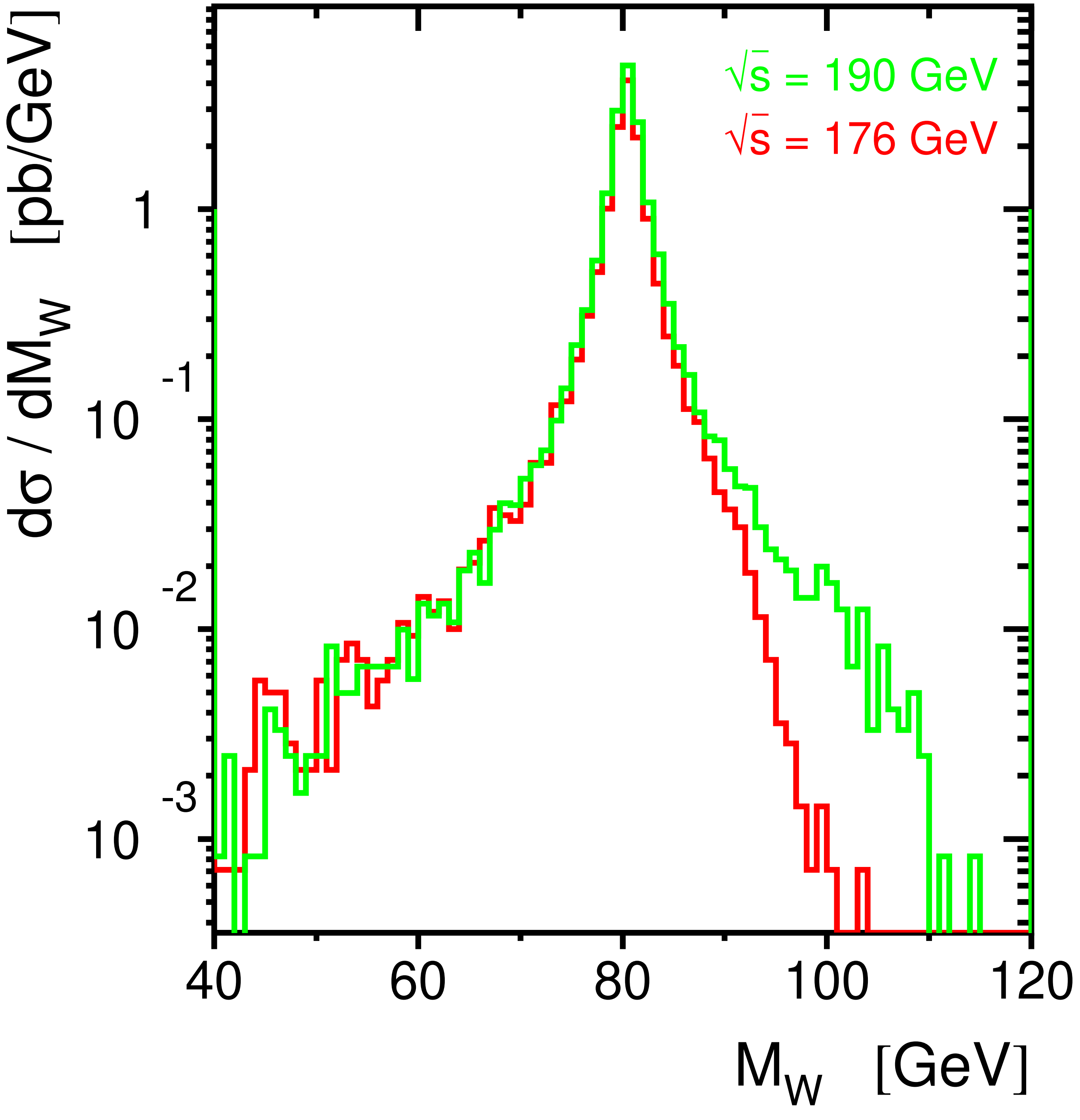


Bias in reconstructed mass:

$$\Delta M_{inv} \simeq \frac{M_{inv}}{\sqrt{s}} < E_{rad} >$$

W Mass Distribution

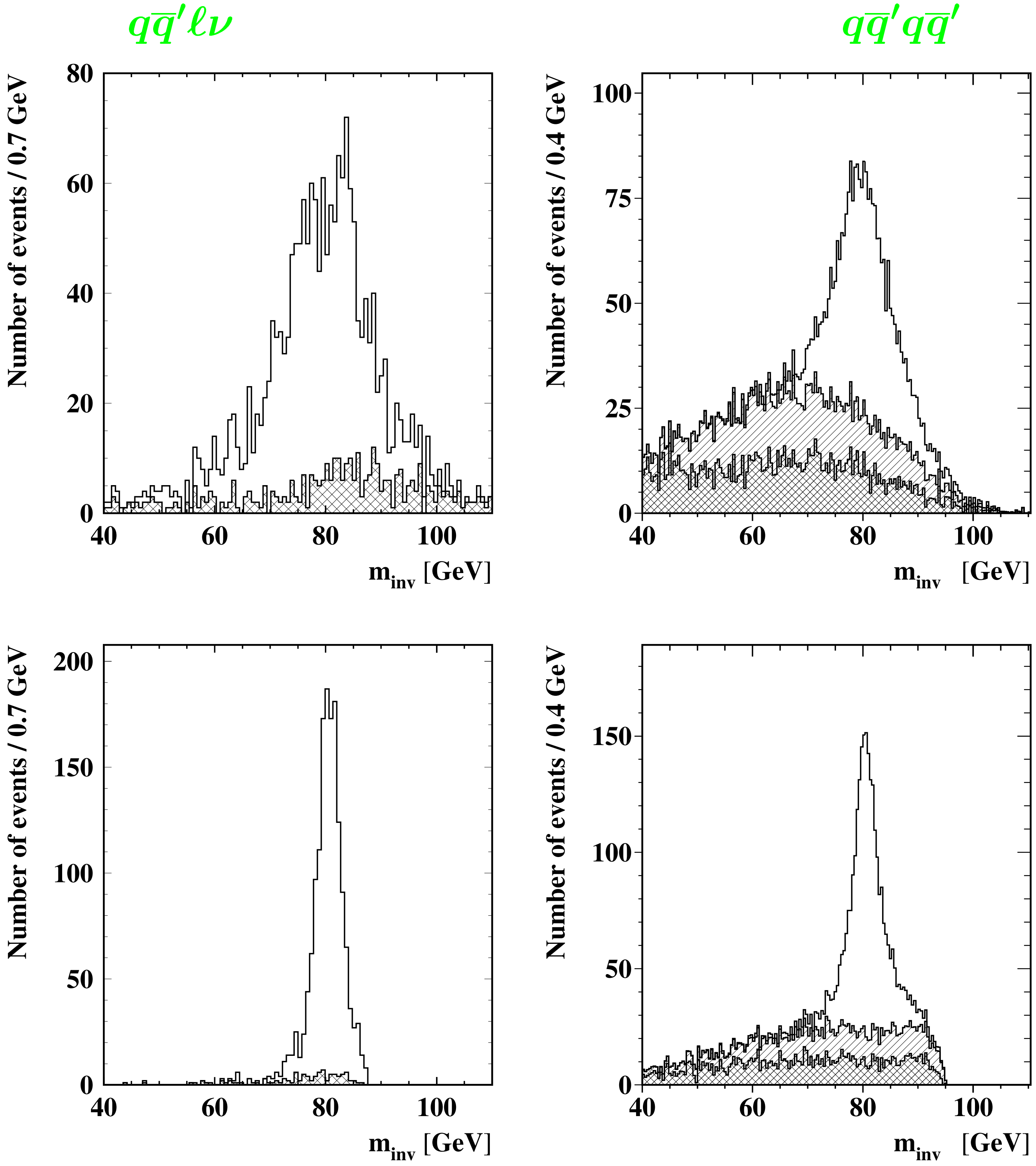
$e^+e^- \rightarrow W^+W^-$ (Generator)



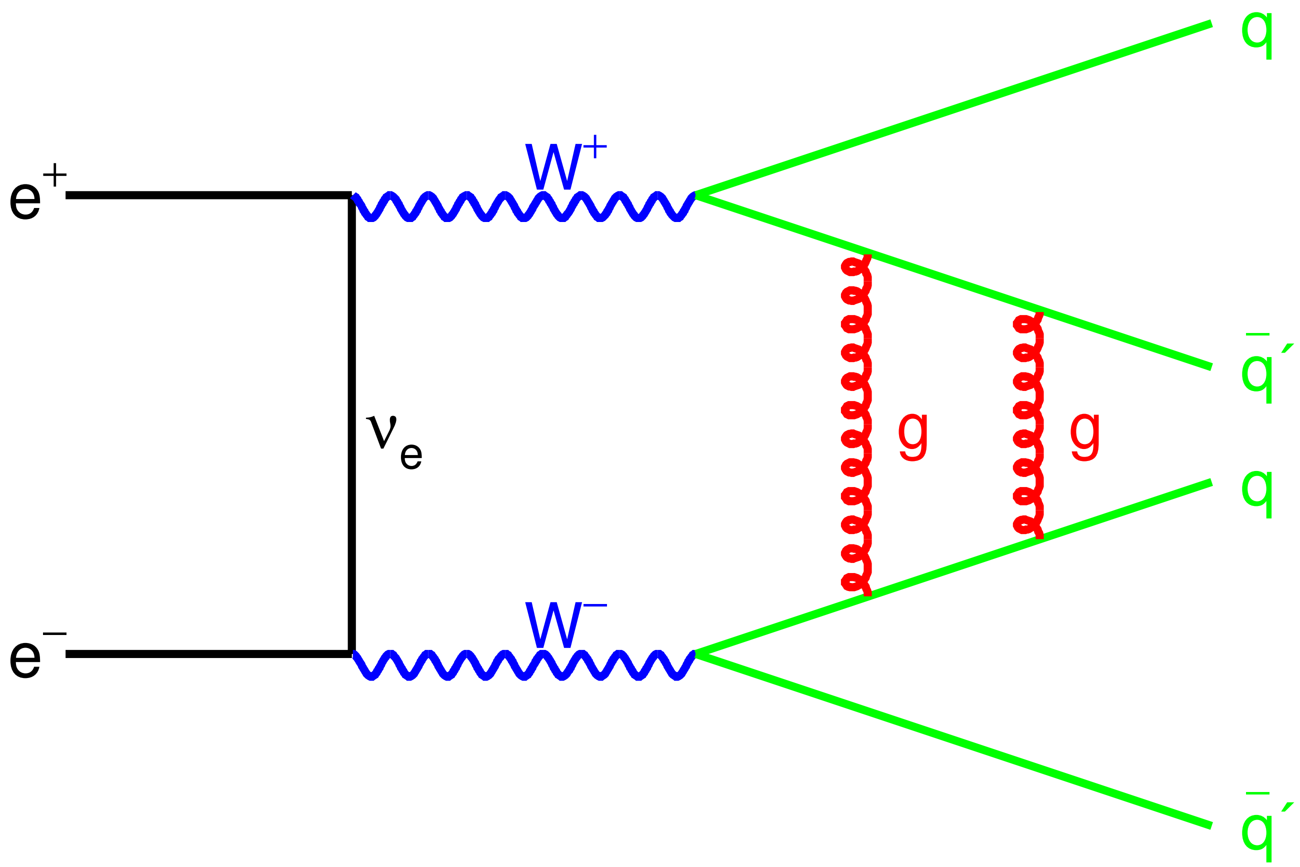
Breit-Wigner Resonance modified by phase space

Direct Reconstruction

Kinematic fit: $e^+e^- \rightarrow W^+W^- \rightarrow$



Direct Reconstruction



Hadronic $W^+W^- \rightarrow q\bar{q}'q\bar{q}'$ events:
Two overlapping hadronic systems

Strong final state interactions:
Color recombination
Bose-Einstein correlations

Individual invariant masses are not conserved:
Model calculations: $\Delta m_W \simeq 40 - 100$ MeV
Further study is needed!

Direct Reconstruction

Statistical error:

for $\mathcal{L} = 500\mathrm{pb}^{-1}$ and $\overline{\epsilon_{\mathrm{WW}}} = 70\%$:

$\delta m_{\mathrm{W}} = 70 - 90$ MeV for $\mathrm{W}^+\mathrm{W}^- \to q\overline{q}'q\overline{q}'$

$\delta m_{\mathrm{W}} = 70 - 90$ MeV for $q\overline{q}'\mathrm{e}\nu + q\overline{q}'\mu\nu$

Systematic error:

Source	δm_{W} [MeV]	
	$q\overline{q}'\ell\nu$	$q\overline{q}'q\overline{q}'$
Beam energy	12	
Photon radiation	10	
Fragmentation	16	
Background	6	12
QCD/BE Effect	—	40-100
Detector calibration	10	
MC statistics	10	
Fit procedure	10	
Jet pairing	—	5
Total	30	50-105

Total error (LEP-2): $35 - 50$ MeV

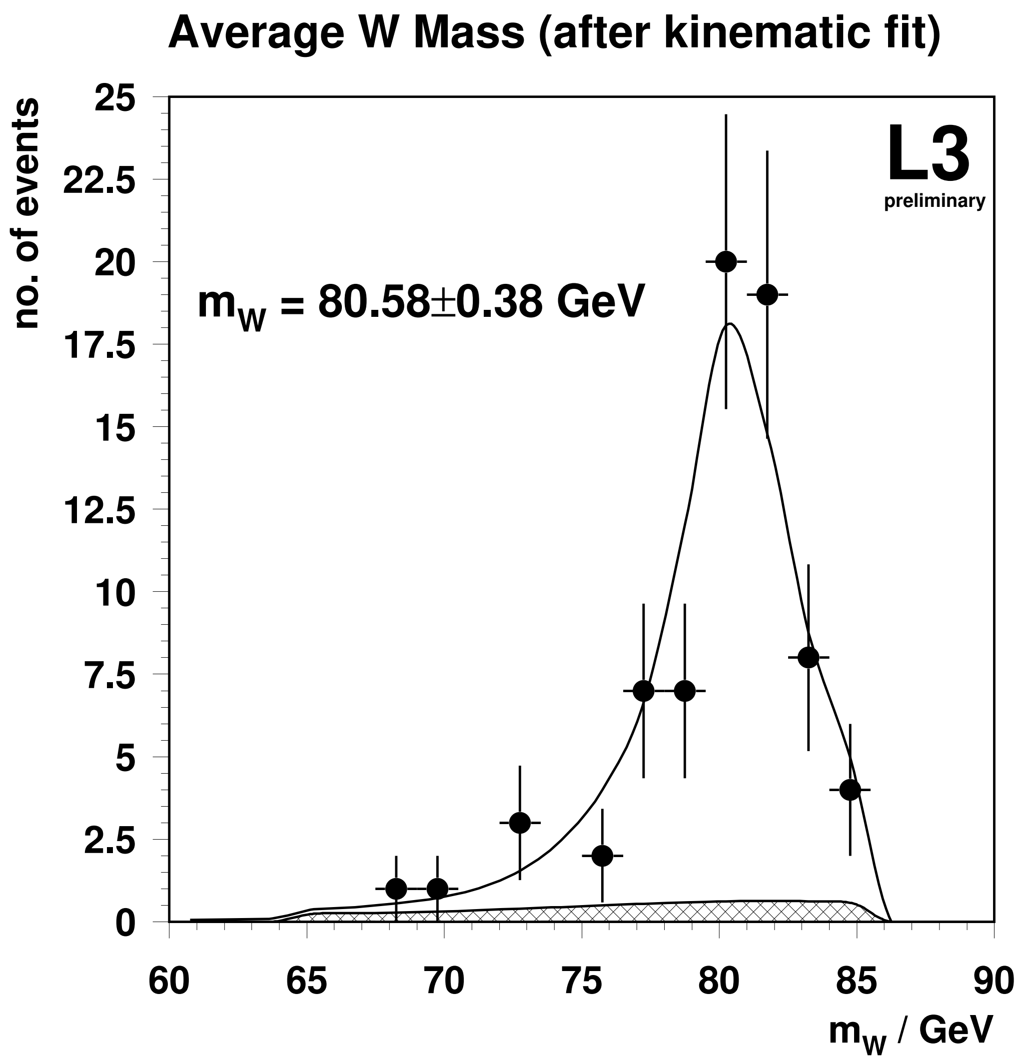
TEVATRON (100 pb^{-1}): $70 - 90$ MeV

And now for some data!

Cross-sections at 172 GeV:

Delphi	$11.38^{+1.54}_{-1.43} \pm 0.32$ pb
L3	$12.13^{+1.63}_{-1.51}$ pb
Opal	$12.3 \pm 1.3 \pm 0.3$ pb

Mass:



NOTE: statistical error only!

Conclusions

- In 1995 $R_{b\bar{b}}$ and $R_{c\bar{c}}$ ruled out the SM at the 99.9% CL.
- Now they are only about 1.7σ off.

- In 1995 only SLD caused problems with $\sin^2\theta_{\rm eff}^{\rm lept}$.
- Now $A_{b\bar{b}}$ is causing its share.

- In 1995 we didn't know about the trains yet.
- Now we know that the 1993 energies were off by about 4 MeV.

- In 1995 we started seeing hints of $m_{\rm H}$ sensitivity.
- Now it's looking somewhat more impressive (even with a lower $R_{b\bar{b}}\ldots$).

- We have now embarked on the LEP-II program, with the first results on $m_{\rm W}$.