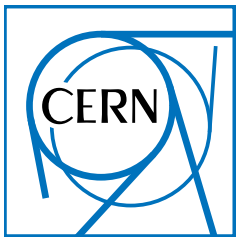
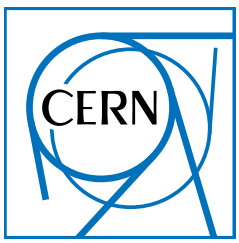
Ws at CERN

World
Wide
Web

made in 

Ws at CERN

We
Want
Ws

made in 

We Want Ws — Why?

Latest step in a century-old investigation of the weak interaction.

1896 H. Becquerel: Discovery of Radioactivity:

- α radiation (He^4 nuclei):
  - Nucleus ejects a group of particles
  - Strong interaction

- β radiation (Electrons e):
  - A constituent of the nucleus changes into a different particle (n $\rightarrow$ p)
  - Weak interaction

- γ radiation (Photons γ):
  - Excited nucleus drops to lower E-level
  - Electromagnetic interaction (QED)

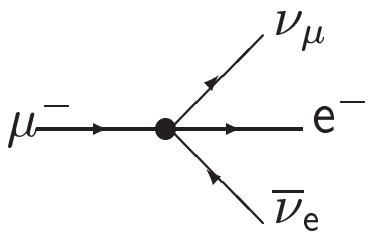
Historical Highlights of the Weak Interaction

1930 Pauli: neutrino hypothesis

to explain apparent E non-conservation in β-decay

- $m_\nu = 0$
- ν has only weak interactions (practically undetectable)

1934 Fermi: 4-fermion theory (point coupling)



$$\mathcal{M} = G_F \cdot \left(\bar{\Psi}_{\nu_\mu} \mathcal{O} \Psi_\mu\right) \cdot \left(\bar{\Psi}_e \mathcal{O} \Psi_{\nu_e}\right)$$

Fermi Coupling $G_F \approx 10^{-5}\ \text{GeV}^2$

As in E-M, $\mathcal{O} = \gamma^\mu$ – a vector operator

1957 Wu: parity not conserved in Co^{60} β-decay

$\Longrightarrow$ $\mathcal{O}$ not vector

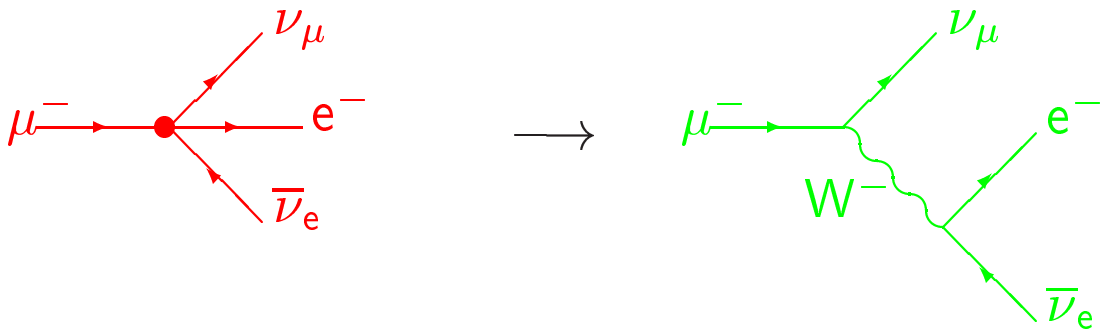
Weak Historical Highlights, cont.

1957-8 Marshak and Sudarshan, Gell-Mann and Feynman, Sakurai: $V-A$ theory: $\mathcal{O}=\gamma^{\mu}\left(V-A\gamma^{5}\right)$
with $V=A$ for maximal parity violation
or equivalently, in terms of helicity of fermions:
- left-handed fermions have coupling $V+A\neq 0$
- right-handed fermions have coupling $V-A=0$

$\Longrightarrow$ only left-handed fermions
(right-handed anti-fermions) have weak interactions

1959 Reines and Cowan: discovery of ν

1967-8 Weinberg, Salam: W-S model



new gauge bosons Z, $W^{\pm}$
- exchanged like γ in QED, but massive

1971 't Hooft: W-S model renormalizable

1973 CERN: discovery of "neutral currents" (Z-exchange)

1983 CERN: discovery of Z, W
with masses consistent with W-S

Electroweak Standard Model

Glashow, Salam, Weinberg:

Gauge theory generalizing QED to include weak interactions "backwards compatible"

- Matter consists of fermions (spin $\frac{1}{2}$):
  Left-handed Doublets ("weak isospin" $T = \frac{1}{2}$)
  under the weak interaction

1	2	3	q_f	T_f^3
$\begin{pmatrix} \nu_{\mathrm{e}} \\ \mathrm{e} \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$	0 -1	$+1/2$ $-1/2$
$\begin{pmatrix} \mathrm{u} \\ \mathrm{d}' \end{pmatrix}$	$\begin{pmatrix} \mathrm{c} \\ \mathrm{s}' \end{pmatrix}$	$\begin{pmatrix} \mathrm{t} \\ \mathrm{b}' \end{pmatrix}$	$+2/3$ $-1/3$	$+1/2$ $-1/2$

- Gauge particles are Bosons (spin 1):

  γ Z W^+ W^-

- Non-Abelian gauge theory

  $\Longrightarrow$ Self-coupling of gauge bosons

Electroweak Standard Model

Massless gauge bosons B^0,$\mathrm{W}^{+,0,-}$
acquire mass via Higgs mechanism:

B^0 and W^0 mix to become
γ and Z such that $m_\gamma = 0$:

$$\begin{pmatrix} \gamma \\ \mathrm{Z} \end{pmatrix} = \begin{pmatrix} \cos\theta_\mathrm{W} & \sin\theta_\mathrm{W} \\ -\sin\theta_\mathrm{W} & \cos\theta_\mathrm{W} \end{pmatrix} \cdot \begin{pmatrix} \mathrm{B} \\ \mathrm{W}^0 \end{pmatrix}$$

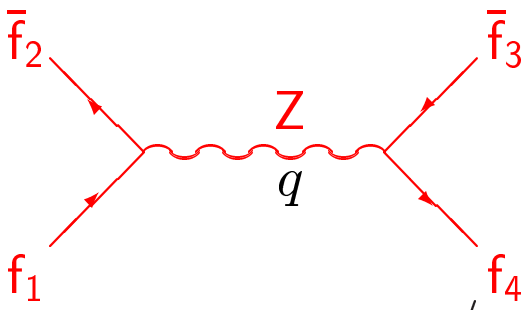
with $\cos\theta_\mathrm{W} = \frac{m_\mathrm{W}}{m_\mathrm{Z}}$

Higgs mechanism
$\Longrightarrow$ spin-0 Higgs particle must exist
(So far we have not seen it.)

Electroweak Standard Model

Feynman diagrams – same rules as in QED

Example:



$$\mathcal{M} = \left[\bar{\Psi}_2 \mathcal{O}_1^\nu \Psi_1\right] \cdot \frac{g_{\nu\sigma} - q_\nu q_\sigma / m_\mathsf{Z}^2}{q^2 - m_\mathsf{Z}^2} \cdot \left[\bar{\Psi}_3 \mathcal{O}_2^\sigma \Psi_4\right]$$

where operators $\mathcal{O}$ are

vertex	$\mathcal{O}^\mu$	coupling
$\gamma f \bar{f}$	$-\imath q_f g_\mathsf{e} \gamma^\mu$	$g_\mathsf{e} = e = \sqrt{4\pi\alpha}$
$\mathsf{Z} f \bar{f}$	$\frac{\imath}{2} q_f g_\mathsf{Z} \gamma^\mu \left(g_{\mathsf{V}f} - g_{\mathsf{A}f}\gamma^5\right)$ $g_{\mathsf{V}f} = T_f^3 - 2q_f \sin^2\theta_\mathsf{W}$ $g_{\mathsf{A}f} = T_f^3$	$g_\mathsf{Z} = \frac{g_\mathsf{e}}{\sin\theta_\mathsf{W}\cos\theta_\mathsf{W}}$
$\mathsf{W} f \bar{f}$	$\frac{\imath}{2\sqrt{2}} q_f g_\mathsf{W} \gamma^\mu \left(1 - \gamma^5\right)$	$g_\mathsf{W} = \frac{g_\mathsf{e}}{\sin\theta_\mathsf{W}}$

Note: α and θ_W determine all couplings.

Apart from fermion and Higgs masses, only 3 parameters, *e.g.*, α, m_Z, m_W

LEP

LEP (Large Electron Positron) collider at CERN built primarily to study Electroweak interaction, $i.e.$, to test Electroweak Standard Model

Phase 1 (1989–1995): $E_{\mathrm{cms}} \approx 91$ GeV $\approx m_{\mathrm{Z}}$

$$\mathrm{e}^+\mathrm{e}^- \to \gamma/\mathrm{Z} \to f\bar{f}$$

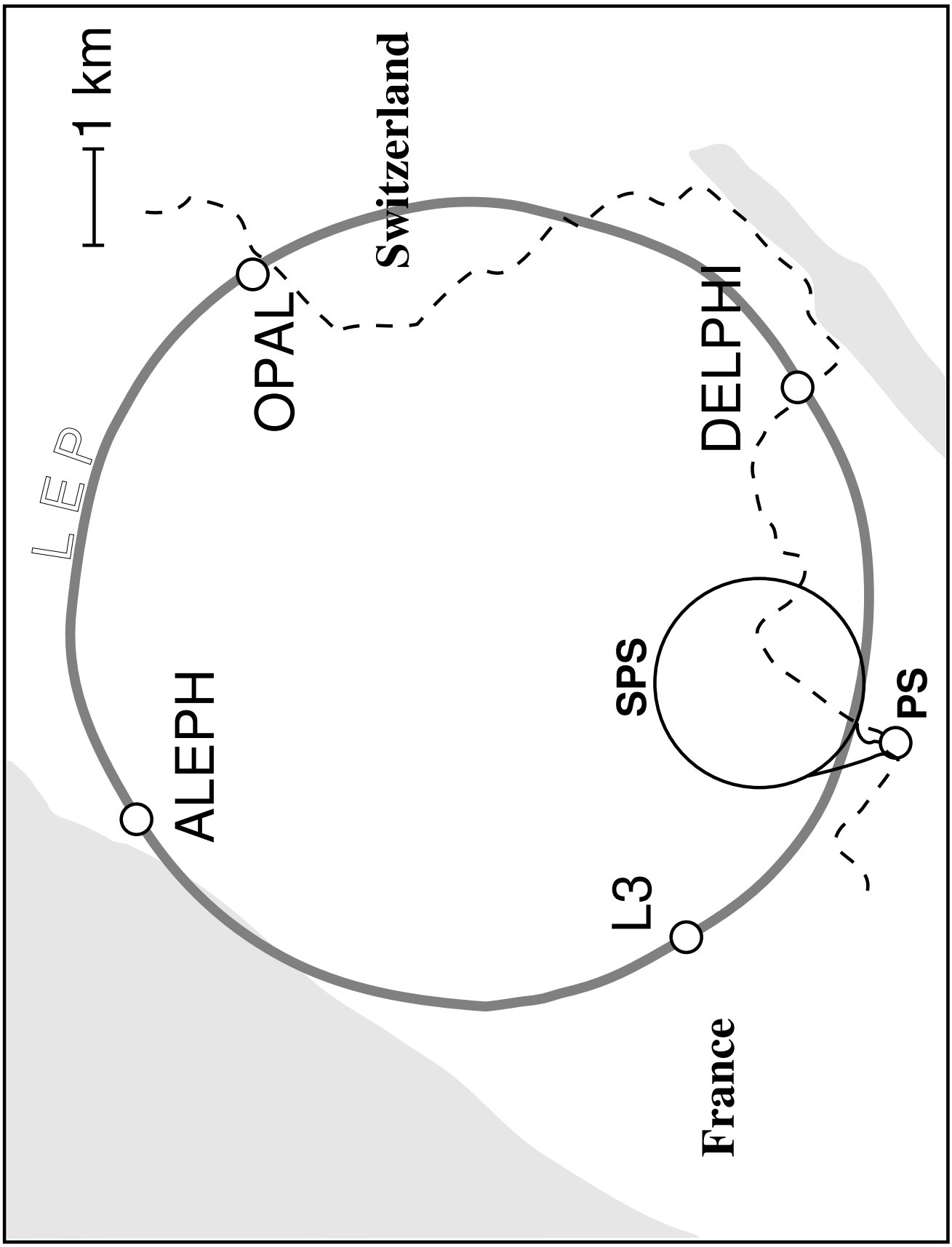
Production of all Fermions except t quark

3.6 M	hadronic	events per expt.
0.4 M	leptonic	

At LEP-1:

- Measure properties of Z (m, Γ, Γ_f)
- Measure couplings of fermions to Z, $g_{\mathrm{V}f}$, $g_{\mathrm{A}f}$
- Test S.M. relations between these quantities

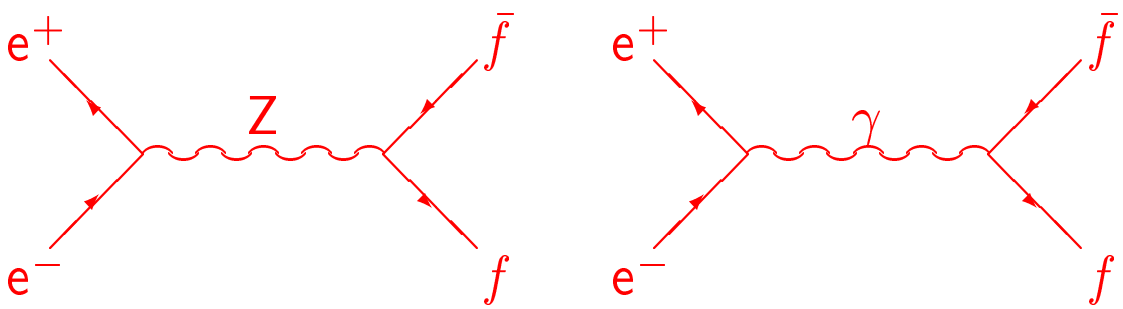
LEP



The Z Resonance

Feynman Graphs in lowest order:

$$e^+e^- \to f\bar{f}$$



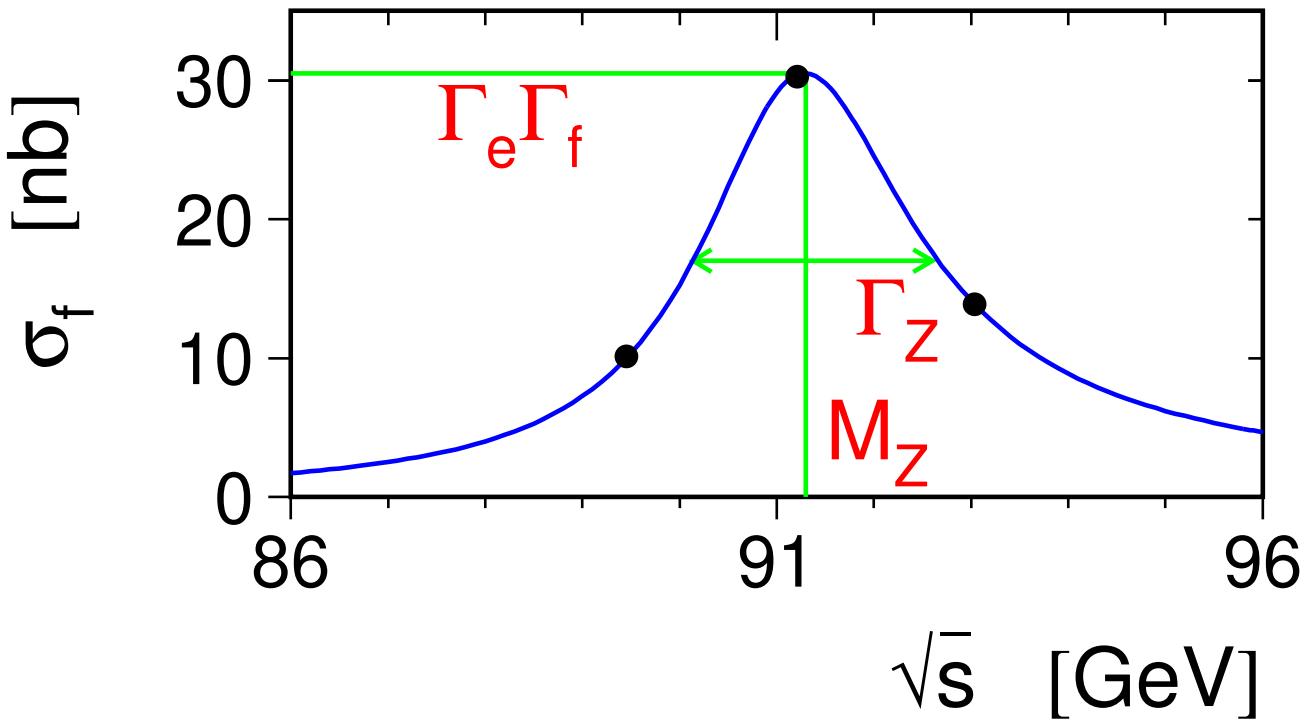
Three contributions to cross section:

$$\sigma^\circ = \sigma^\circ_Z + \sigma^\circ_\gamma + \sigma^\circ_{\text{int}}$$

The Z Resonance

Dominant for $E_{cms} = \sqrt{s}$ near m_Z:

$$\sigma_Z^\circ = \frac{12\pi}{m_Z^2}\frac{\Gamma_e}{\Gamma_Z}\frac{\Gamma_f}{\Gamma_Z} \cdot \frac{s\Gamma_Z^2}{(s-m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$$



Resonance curve determines Z parameters:

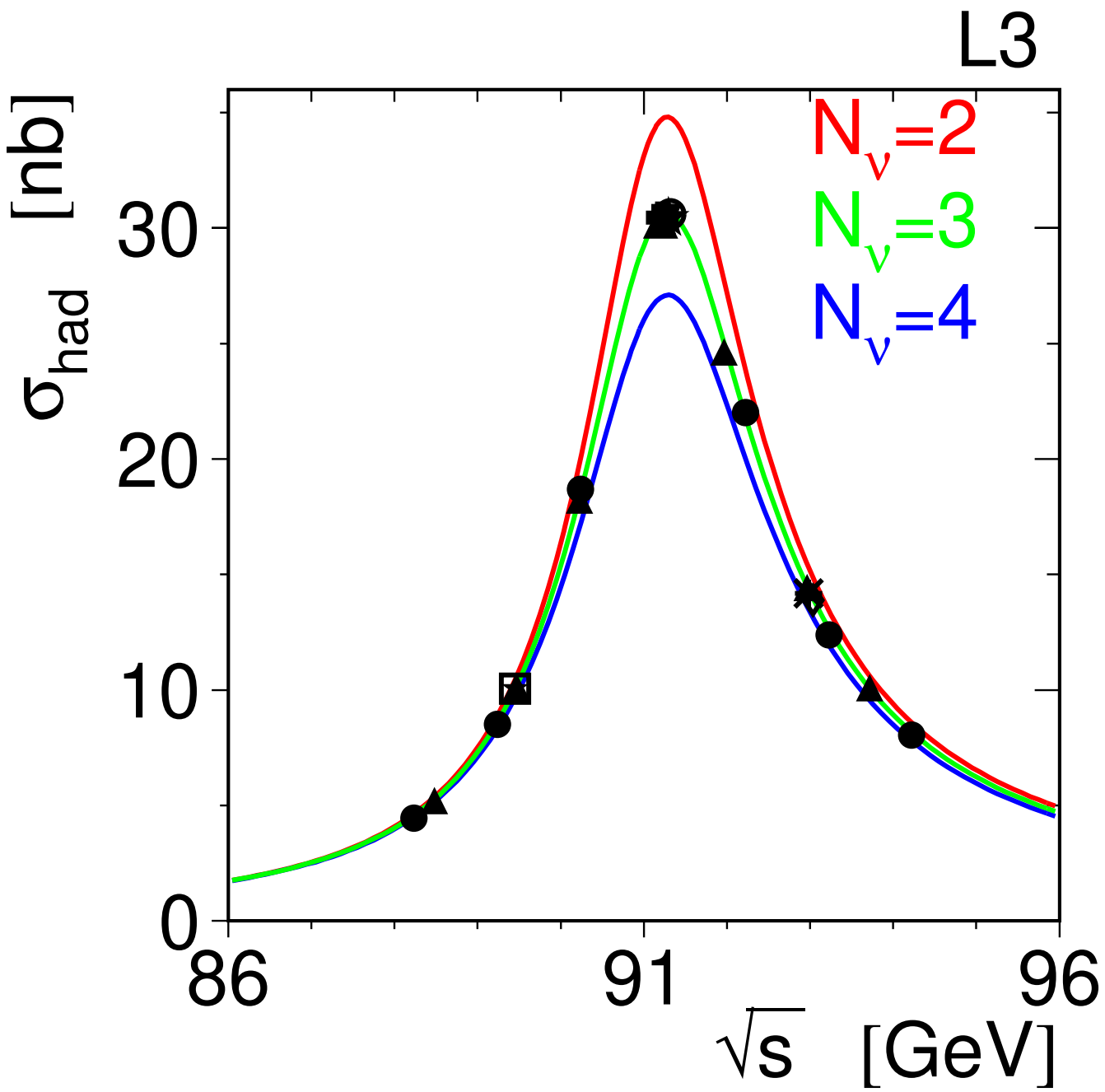
Position: m_Z

Width: $\Gamma_Z = \Gamma_{had} + \Gamma_e + \Gamma_\mu + \Gamma_\tau + N_\nu\Gamma_\nu$

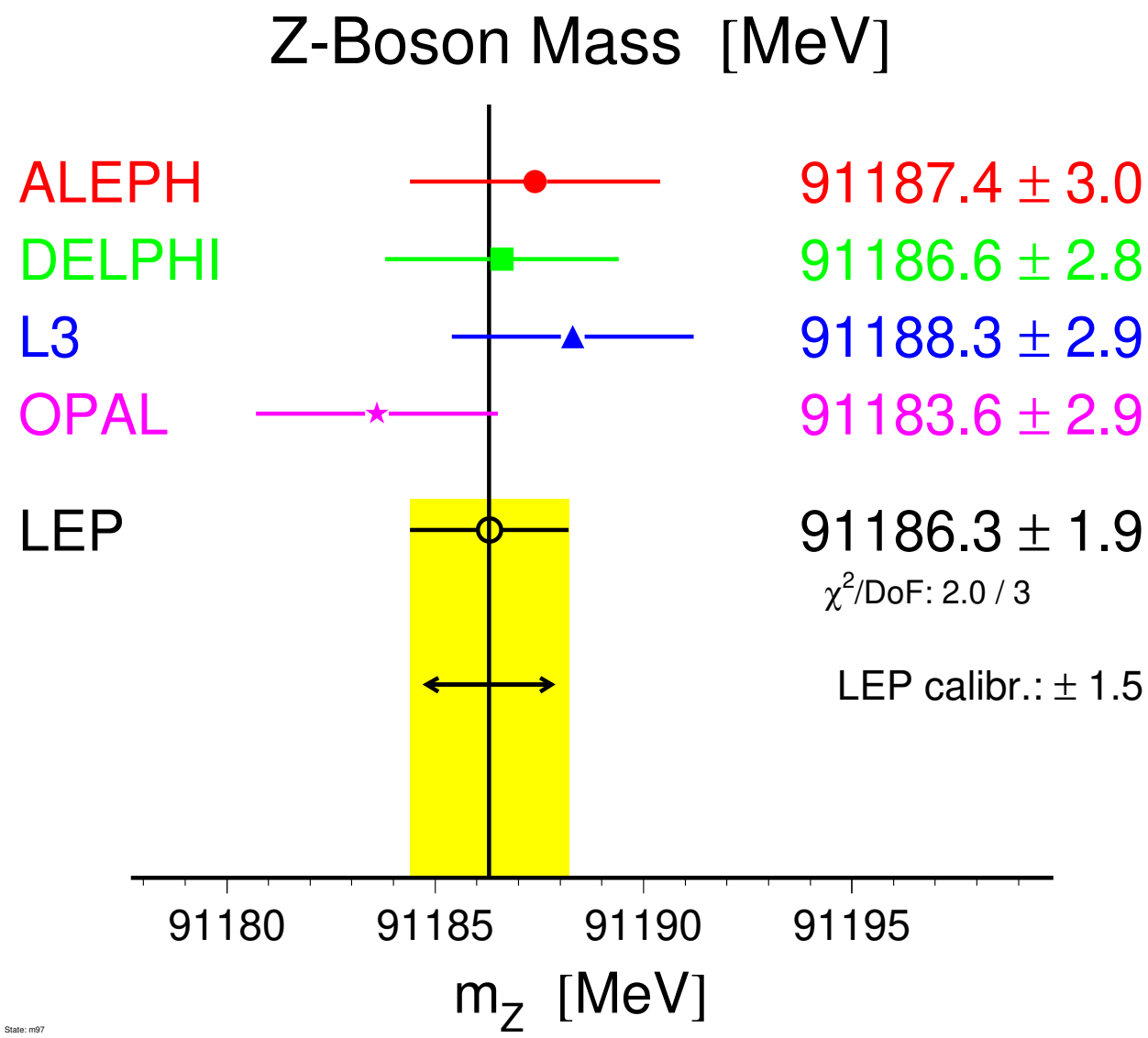
Height: $\sigma_f \propto \frac{\Gamma_e}{\Gamma_Z}\frac{\Gamma_f}{\Gamma_Z}$

The Z Resonance $e^+e^- \rightarrow$ Hadrons

Resonance curve of Z:



m_Z


Z-Boson Mass [MeV]
ALEPH
DELPHI
L3
OPAL
LEP
91187.4 ± 3.0
91186.6 ± 2.8
91188.3 ± 2.9
91183.6 ± 2.9
91186.3 ± 1.9
χ²/DoF: 2.0 / 3
LEP calibr.: ± 1.5
91180
91185
91190
91195
m_Z [MeV]
State: m97

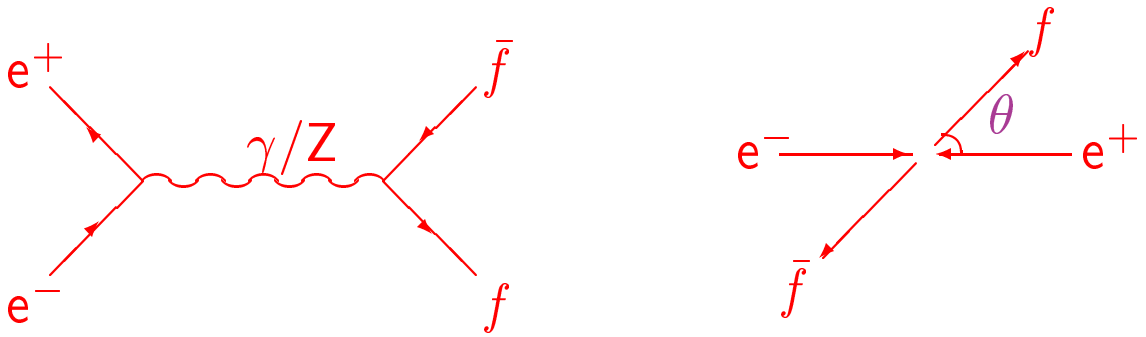
Properties of the Z

High precision results:

$$
\begin{aligned}
m_{\mathsf{Z}} &= 91186.3 \pm 1.9 \text{ MeV} \\
\Gamma_{\mathsf{Z}} &= 2494.6 \pm 2.7 \text{ MeV} \\
\Gamma_{\mathsf{had}} &= 1743.6 \pm 2.5 \text{ MeV} \\
\Gamma_{\ell} &= 83.91 \pm 0.11 \text{ MeV}
\end{aligned}
$$

Forward-Backward Asymmetry

Differential cross section: $\frac{d\sigma}{d\cos\theta}$



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

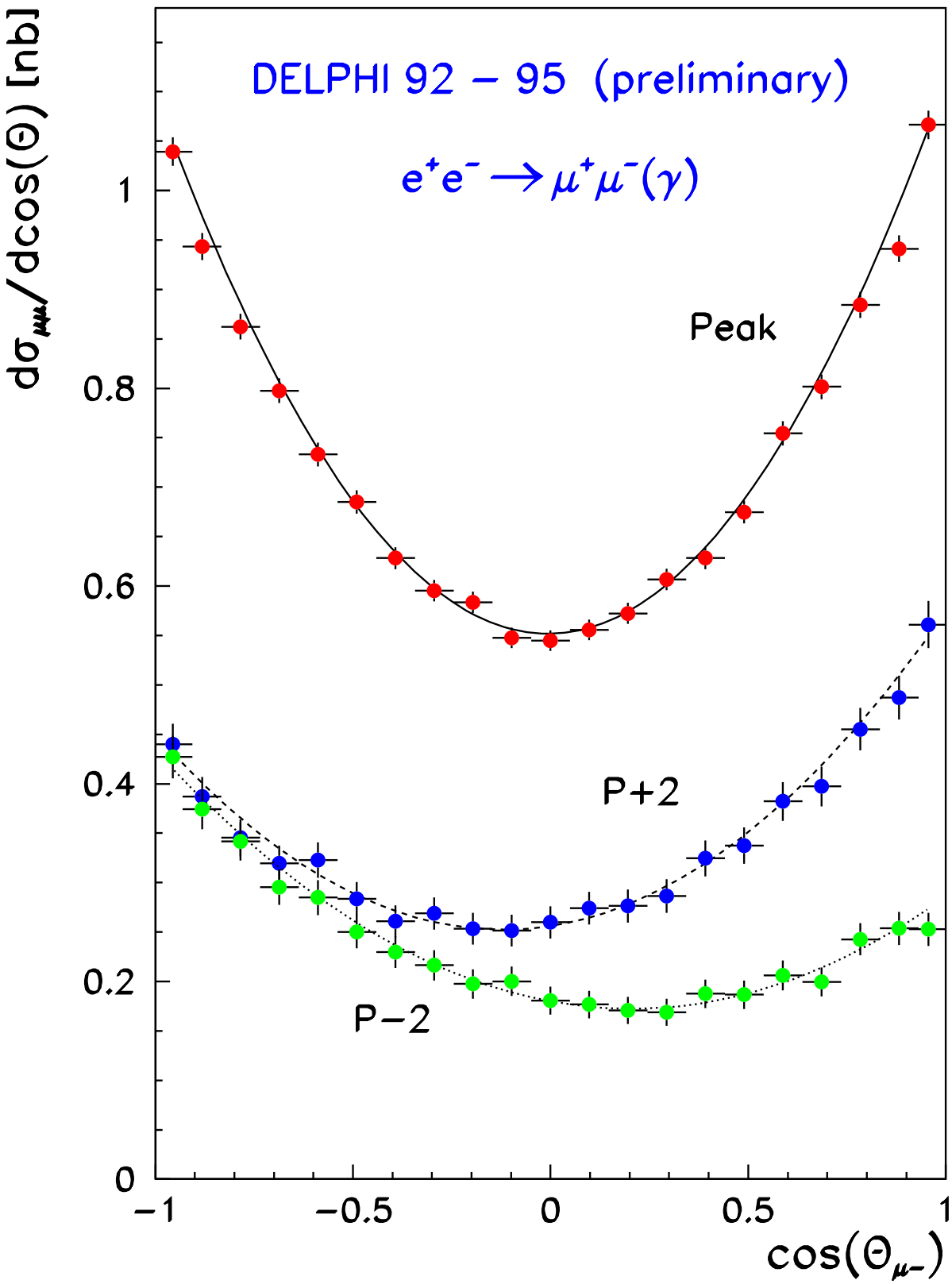
$$A_{FB}(s) = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)}$$

Asymmetry depends on couplings:

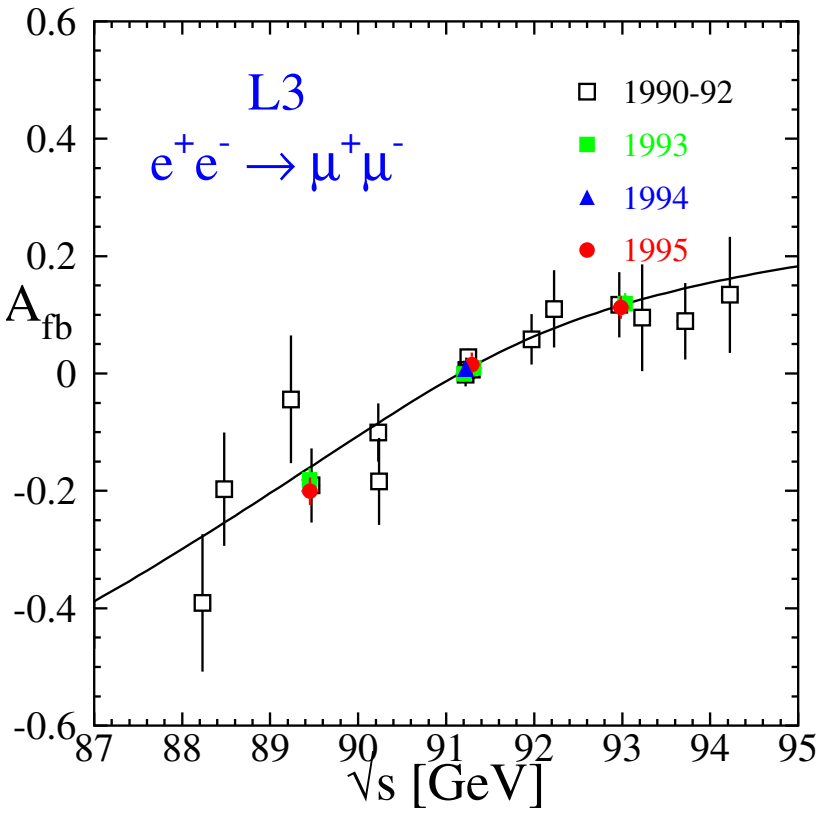
$$A_{FB}^{\circ,f} = \frac{3}{4} A_e A_f$$

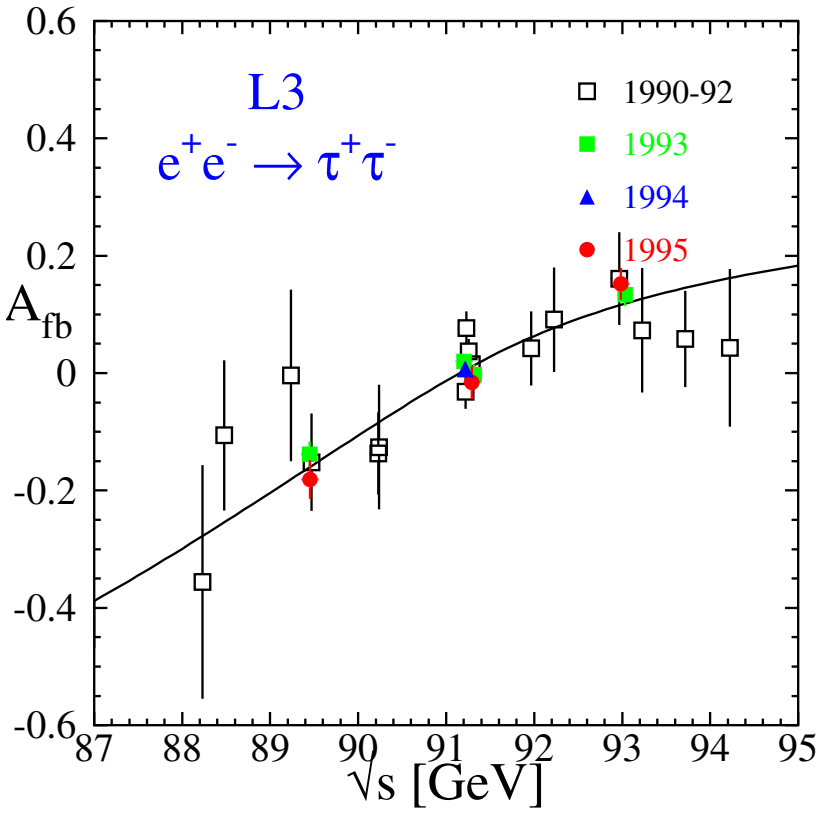
$$A_f = 2\frac{g_{Vf}/g_{Af}}{1 + (g_{Vf}/g_{Af})^2}$$

Forward-Backward Asymmetry



Forward-Backward Asymmetry





Higher Orders

Experimental Results: from asymmetries, partial widths,

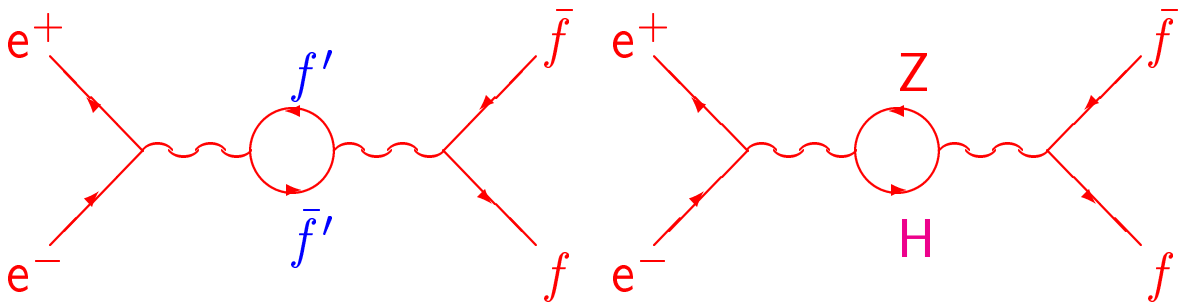
$$g_{V\ell} = -0.03776 \pm 0.00062$$

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

Why is $g_{A\ell} \neq T_\ell^3 = -\frac{1}{2}$? $(\ell = e^-, \mu^-, \tau^-)$

$-\frac{1}{2}$ is only the lowest-order prediction.

Higher-order loop diagrams (radiative corrections):

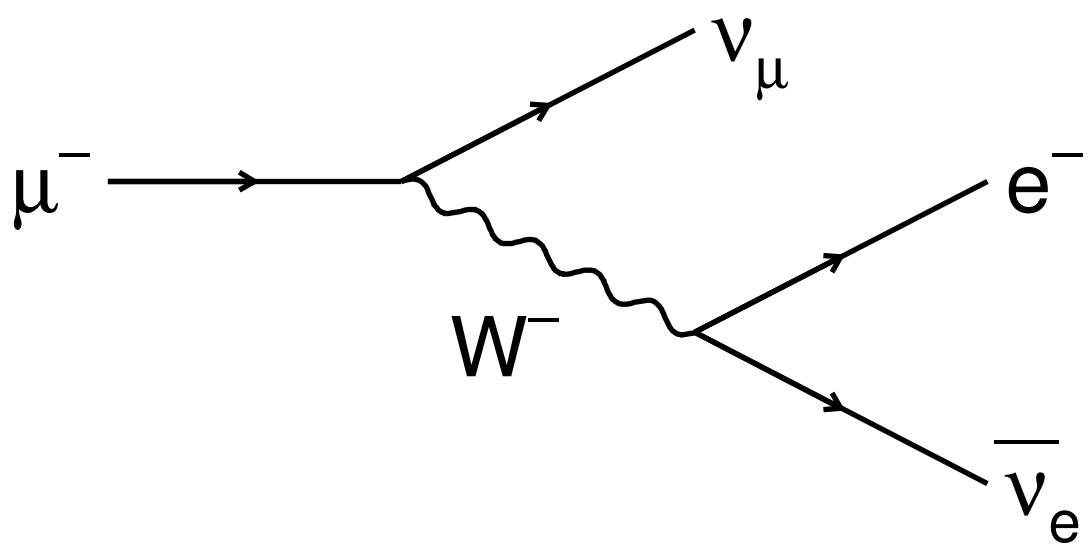


Corrections depend on $m_{f'}^2$ and $\log m_H$

- sensitive to top quark mass m_t
- sensitive to Higgs mass m_H

Higher Orders, continued

Recall, α, m_Z, m_W determine couplings of S. M.
m_W is poorly measured.
But can measure it indirectly from μ decay



μ lifetime gives Fermi constant:

$$G_F = (1.16639 \pm 0.00002) \cdot 10^{-5} \text{ GeV}^{-2}$$

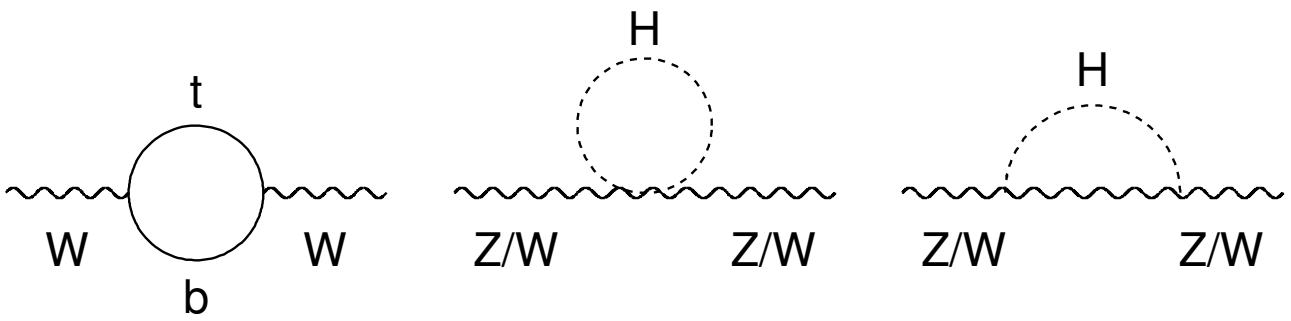
$$G_F = \frac{\pi\alpha(0)}{\sqrt{2}} \cdot \frac{m_Z^2}{m_W^2(m_Z^2 - m_W^2)} \cdot \frac{1}{1 - \Delta r}$$

G_F much better known than m_W
So use α, m_Z, G_F as input for calculations

Δr depends on loop corrections:

Higher Orders

Δr depends on loop corrections:

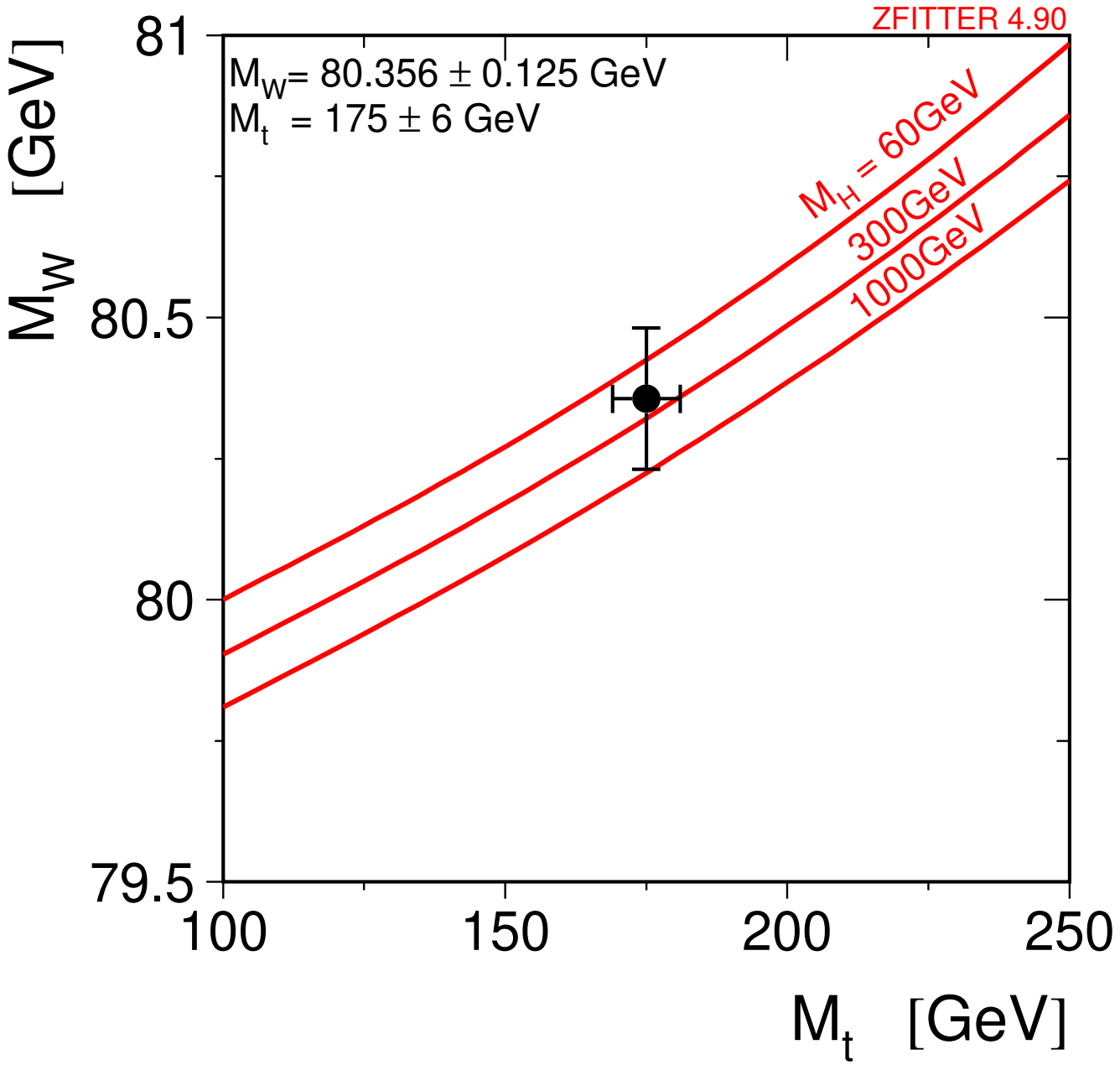


$\Delta r(m_{\mathsf{t}}, m_{\mathsf{H}}) = -a\, m_{\mathsf{t}}^2 - b \log m_{\mathsf{t}} + c \log m_{\mathsf{H}} + \text{h.o.}$
a, b, c positive coefficients
m_{H} and m_{t} enter G_{F} only as radiative corrections

Fit S. M. using all data except m_{W}, m_{t}
and calculate m_{W}, m_{t}, for different values of m_{H}:

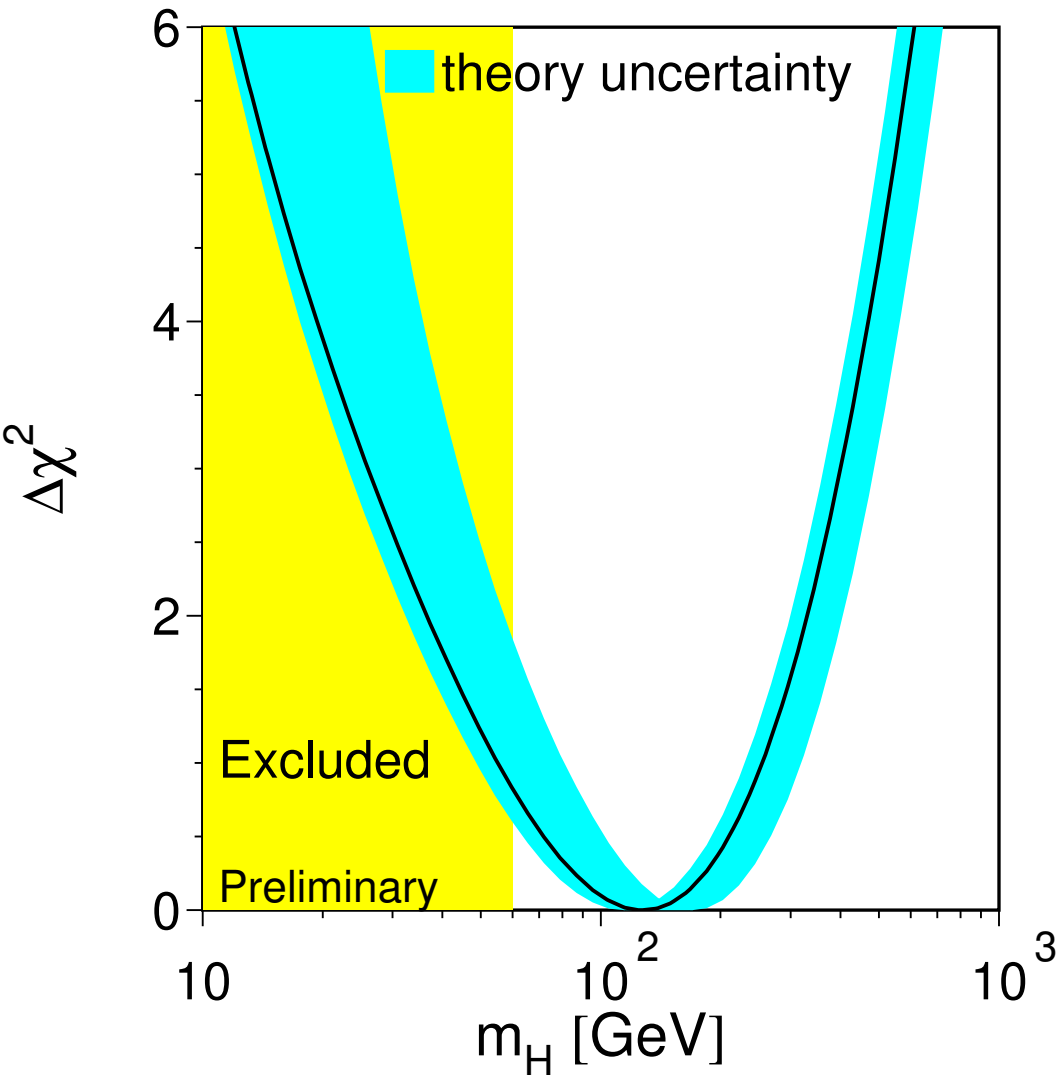
Masses from Higher Orders

Compare S-M loop calculations with
measurements from TeVatron ($p\overline{p}$, $E_{\text{cms}} = 1.8$ TeV)



Mass of the Higgs

Using m_{t}, m_{W} from TeVatron



$\Longrightarrow m_{\mathrm{H}} \approx 149^{+148}_{-82}$ GeV

Experimentally, $m_{\mathrm{H}} \gtrsim 69$ GeV since not yet found at LEP

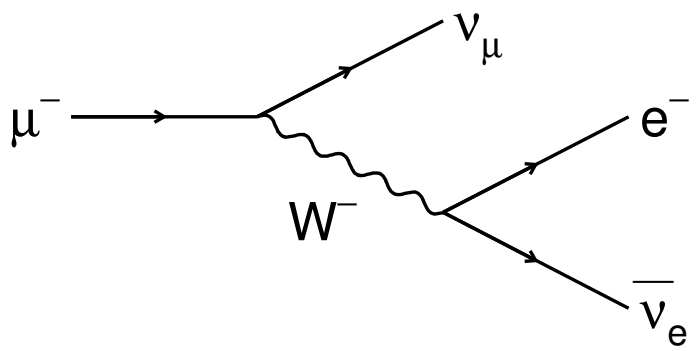
We Want Ws — Why?

Parts of Standard Model NOT yet (precisely) tested:

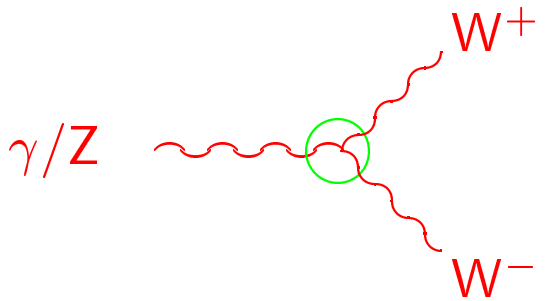
- m_{Z} is well measured, but m_{W} is not

$$m_{\mathrm{Z}} = 91186.3 \pm 2.0 \text{ MeV}$$
$$m_{\mathrm{W}} = 80356 \pm 125 \text{ MeV } (\mathrm{p\overline{p}})$$

- W$f\bar{f}$ only measured at low energy, $e.g.$, μ decay



- Triple-Boson vertices NOT yet tested



Ws at CERN

We
Want
Ws

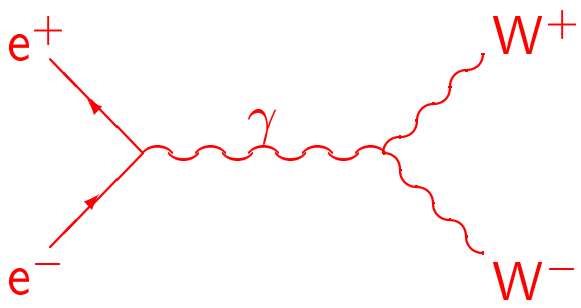
and we are getting them!

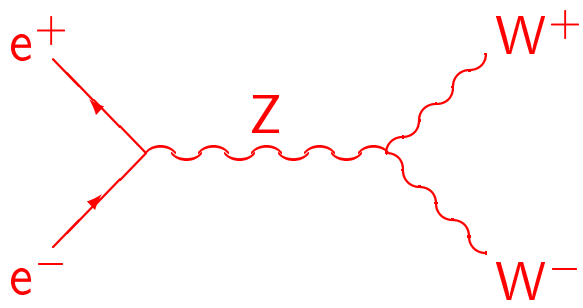
LEP Phase 2		E_{cms} (GeV)	luminosity (pb^{-1}/expt.)
Summer	1996	161	11
Fall	1996	172	10
Expect	1997	~ 183	100–150
	1998	~ 188	
	1999	~ 192	

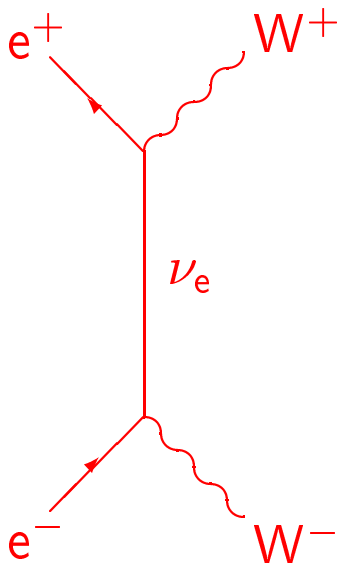
By 2000 expect ~ 500 pb^{-1}/expt.
~ 8000 W^+W^- events/expt.

W-pair Production at LEP 2

$E_{\mathrm{cms}} \gtrsim 2m_{\mathrm{W}}$: pair production of $\mathrm{W}^+\mathrm{W}^-$ bosons







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

$\mathrm{e}^+\mathrm{e}^- \to \mathrm{W}^+\mathrm{W}^- \to \mathrm{f}_1\bar{\mathrm{f}}_2\mathrm{f}_3\bar{\mathrm{f}}_4$

Decay of W Bosons

Produced W bosons decay:

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

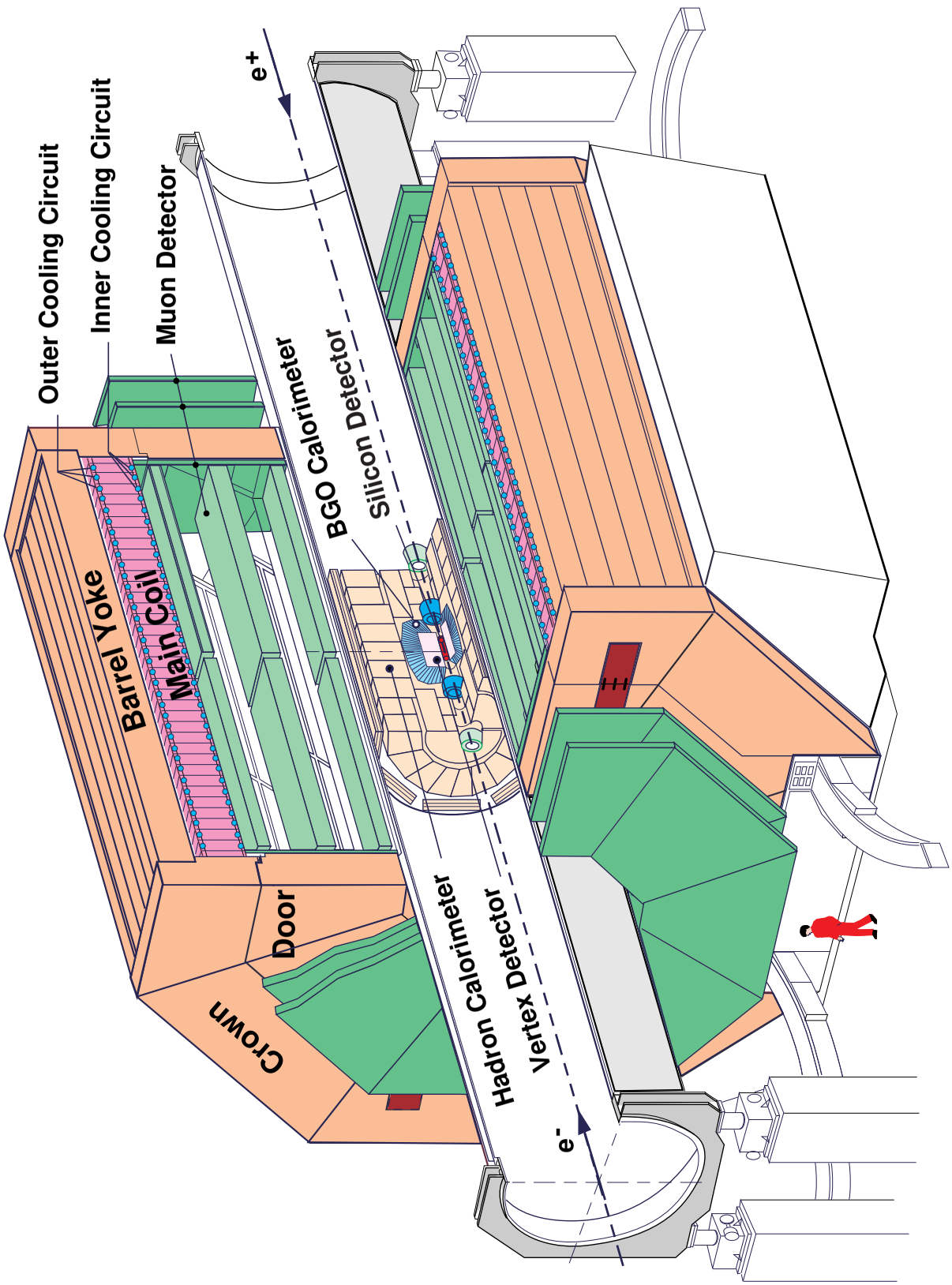
$$B(W \to \text{leptons}) \approx 1/3$$

$$B(W \to \text{hadrons}) \approx 2/3$$

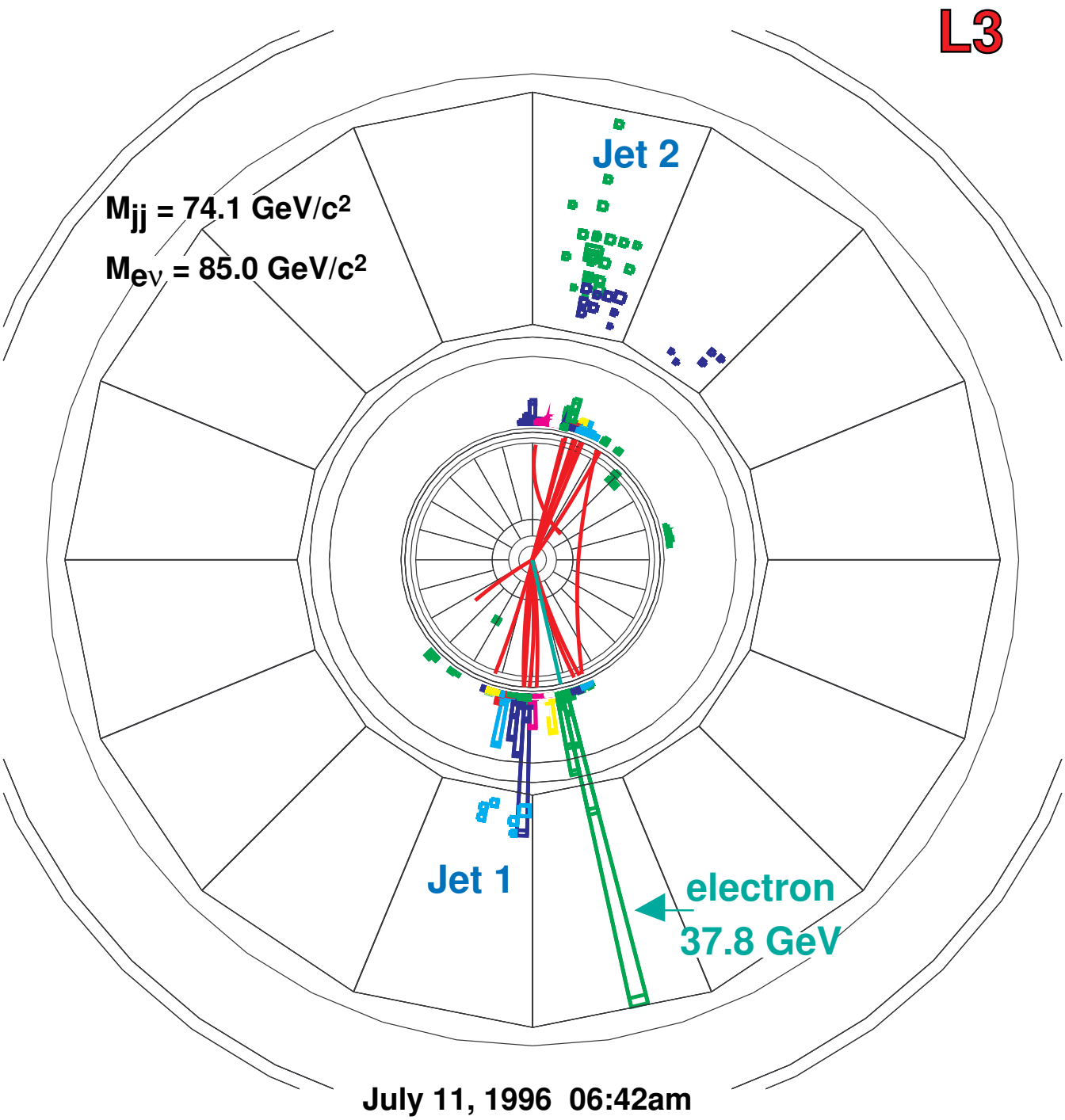
Event signatures:

$e^+e^- \to W^+W^-$	type	fraction
$\to q\bar{q}'q\bar{q}' \to$ 4 jets	hadronic	46%
$\to q\bar{q}'\ell\nu \to$ 2 jets $\ell\nu$	semileptonic	44%
$\to \ell^+\nu\ell^-\nu$	leptonic	10%

LEP Experiment L3



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



First W pair event observed by the L3 Experiment at LEP 2.

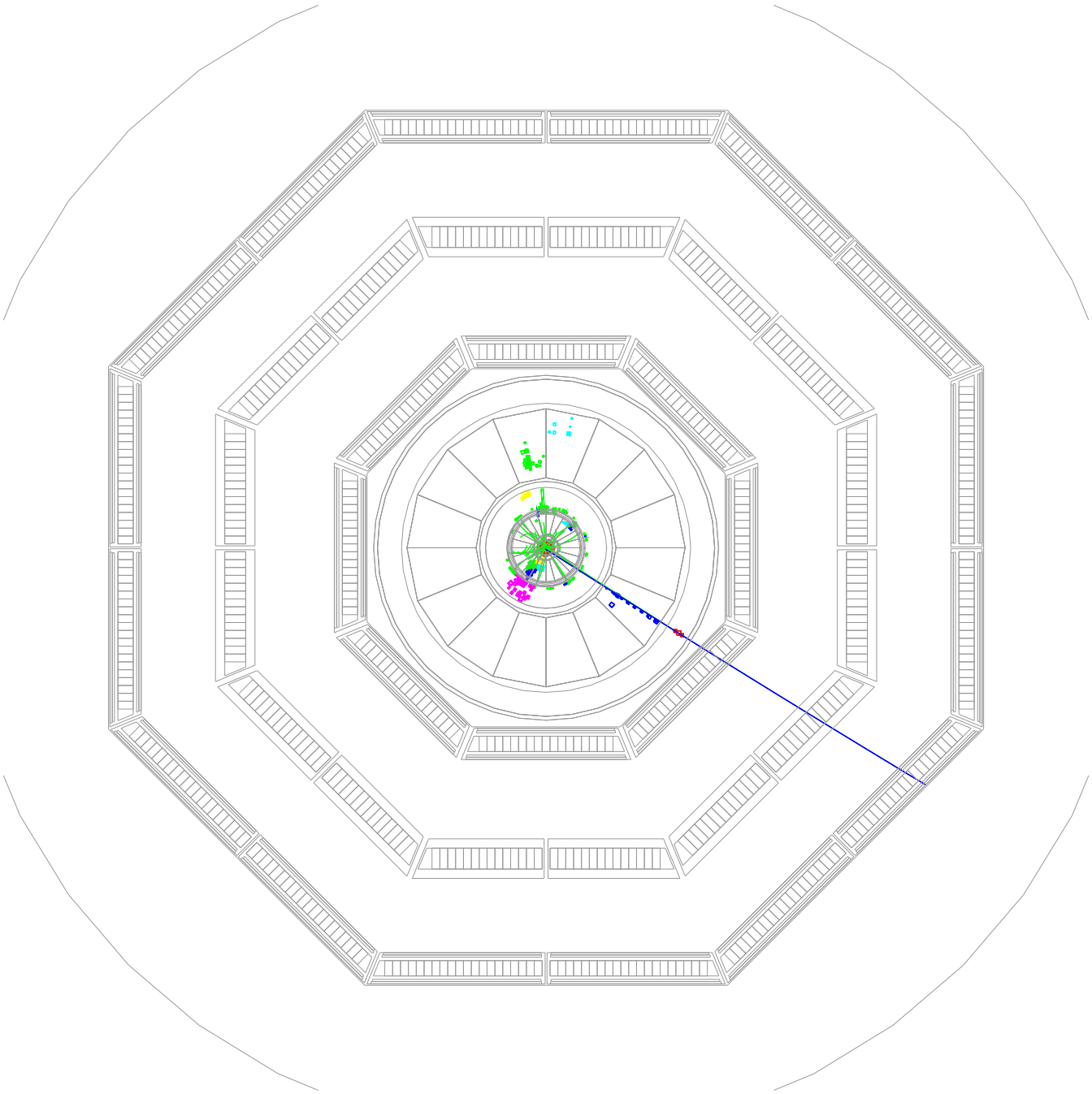
$e^+ e^- \to W^+ W^-$

$W^- \to e^- \bar{\nu}$

$W^+ \to$ jet + jet

$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}'\mu\nu \rightarrow 2$ Jets $+ \mu$

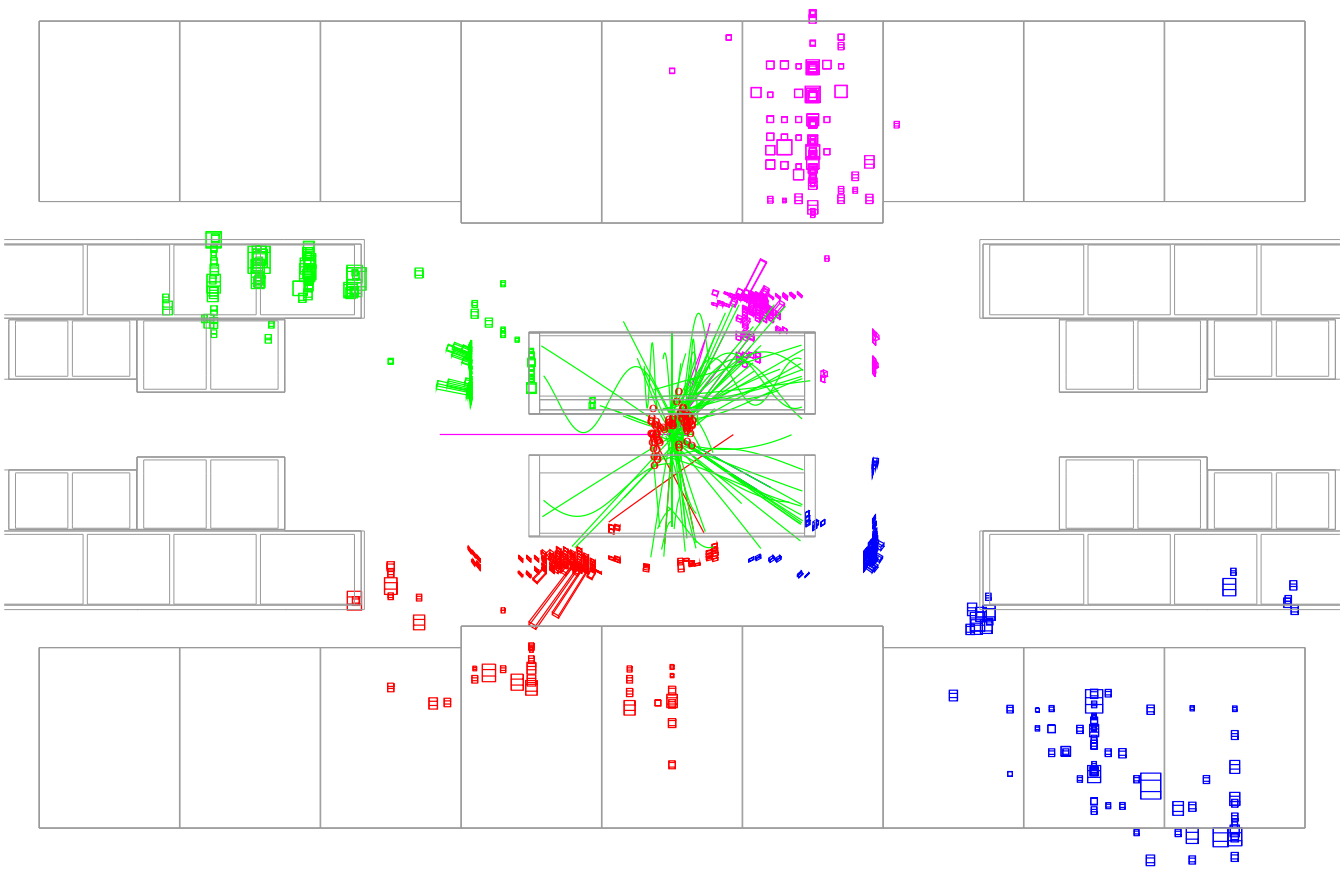
Run # 658011 Event # 1231 Total Energy : 122.50 GeV



Transverse Imbalance : .2201		**Longitudinal Imbalance :** -.3240
Thrust : .8833	**Major :** .3870	**Minor :** .0891
Event DAQ Time : *960717 112140*		

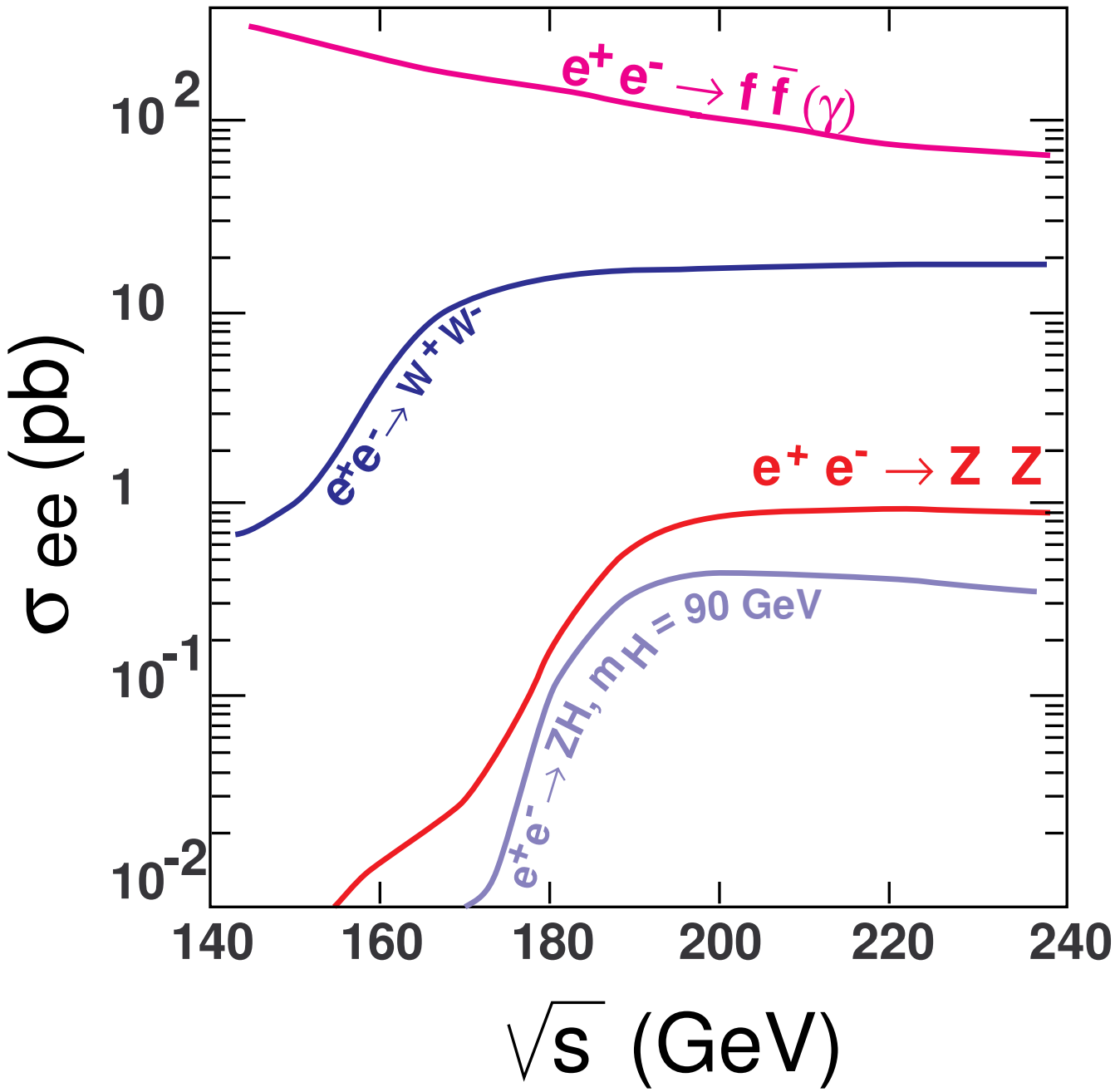
$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}'q\bar{q}' \rightarrow 4$ Jets

Run # 658704 Event # 3418 Total Energy : 166.00 GeV



Transverse Imbalance : .0337		**Longitudinal Imbalance :** .0655
Thrust : .6895	**Major :** .5806	**Minor :** .2150
Event DAQ Time : *960721 132534*		

Cross Sections at LEP 2

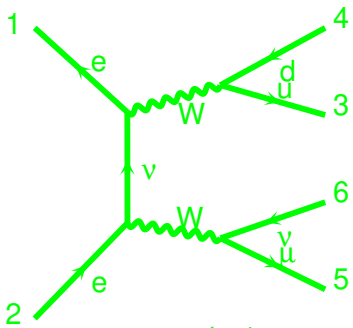


Backgrounds:

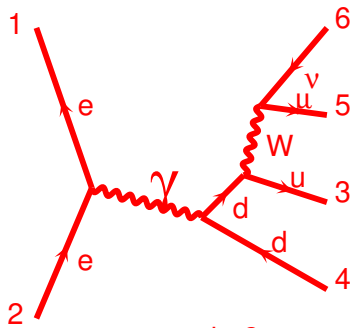
1. $e^+e^- \to f\bar{f}$
2. $e^+e^- \to f\bar{f}f\bar{f}$, non-$W^+W^-$

Four-Fermion Production

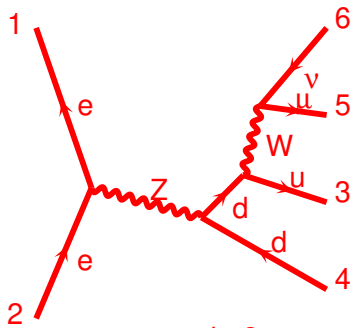
Diagrams by MadGraph



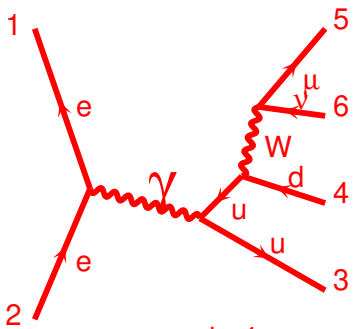
graph 1



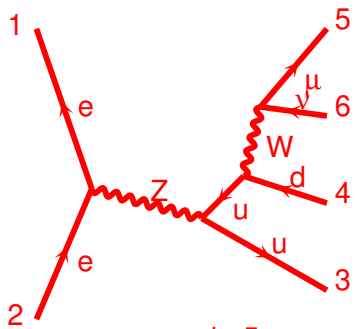
graph 2



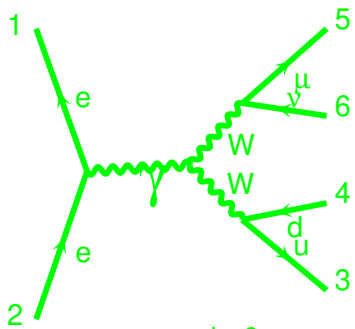
graph 3



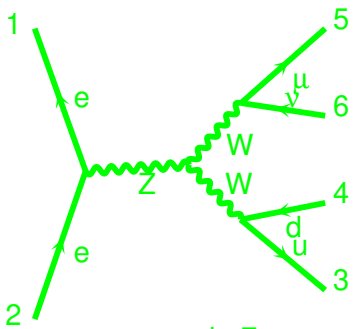
graph 4



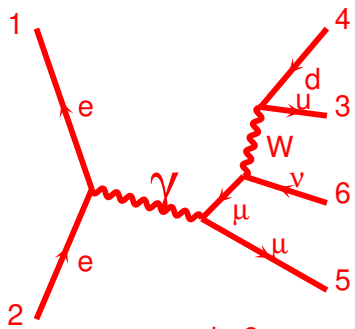
graph 5



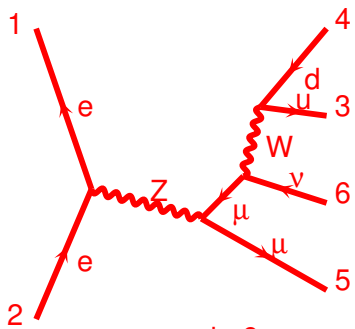
graph 6



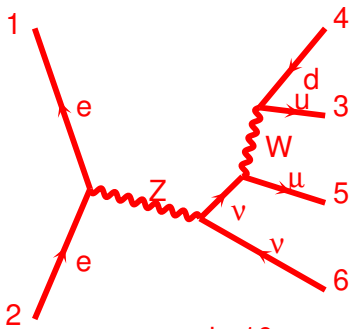
graph 7



graph 8



graph 9



graph 10

$e^+e^- \to u\bar{d}\mu^-\nu_\mu$

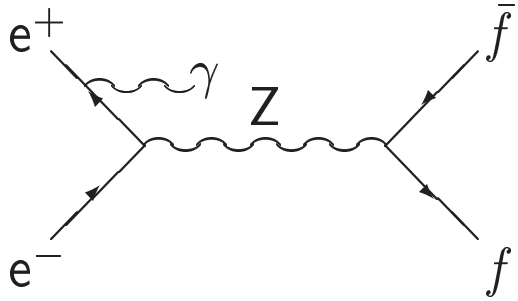
Non-resonant background: small

reduced by M_{inv} cuts

$e^+e^- \to W^+W^- \to q\bar{q}'q\bar{q}'$ Selection

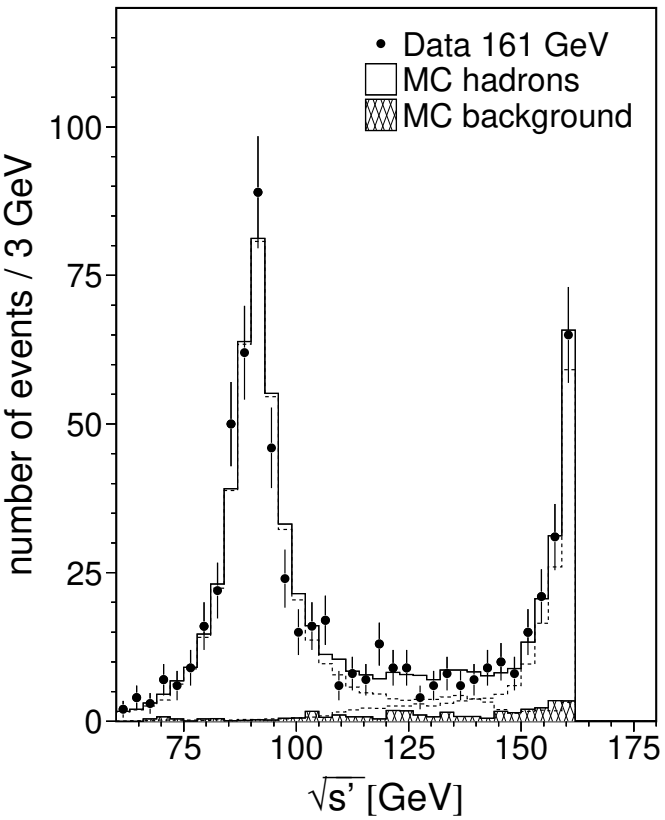
$e^+e^- \to \gamma/Z \to f\bar{f}(\gamma)$, $s = E_{cms} \gg m_Z^2$:

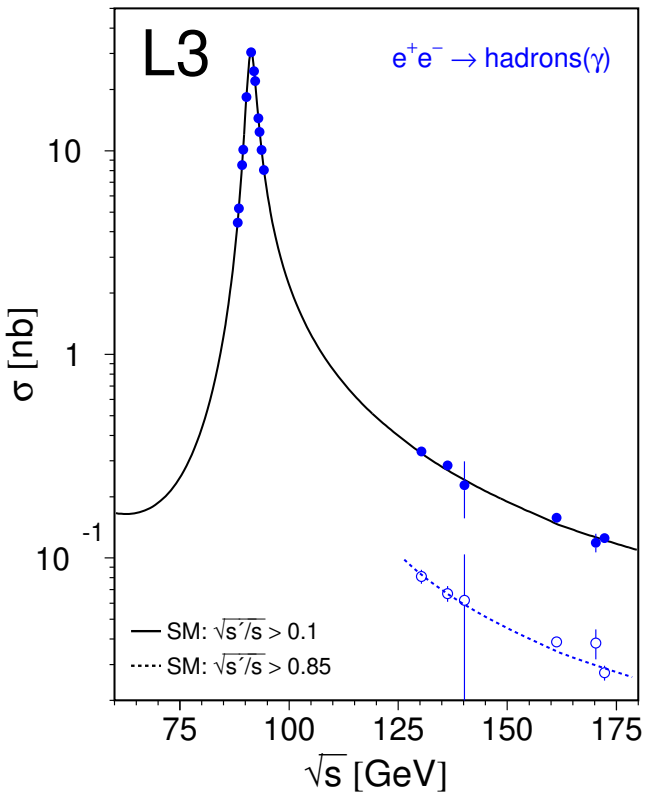
Photon radiated from initial e^- or e^+ (ISR)



Large fraction of $e^+e^- \to f\bar{f}(\gamma)$ is radiative return to Z:

Mass $m_{f\bar{f}} = \sqrt{s'}$ of $f\bar{f}$ System: $s' = s - 2E_\gamma\sqrt{s} \approx m_Z^2$





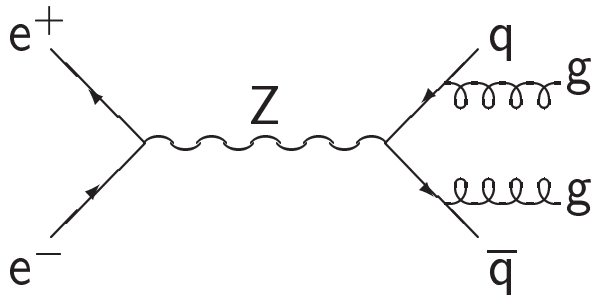
$\sim 15\%$ of time, ISR photon is in detector:

Reject events if photon with $E_\gamma > 30$ GeV

Reject events if large "Missing Energy" along beam

$e^+e^- \to W^+W^- \to q\bar{q}'q\bar{q}'$ Selection

Most $e^+e^- \to \gamma/Z \to q\bar{q}$ events look like 2 jets
But quarks can radiate high-energy gluons
leading to additional jets, *e.g.*,

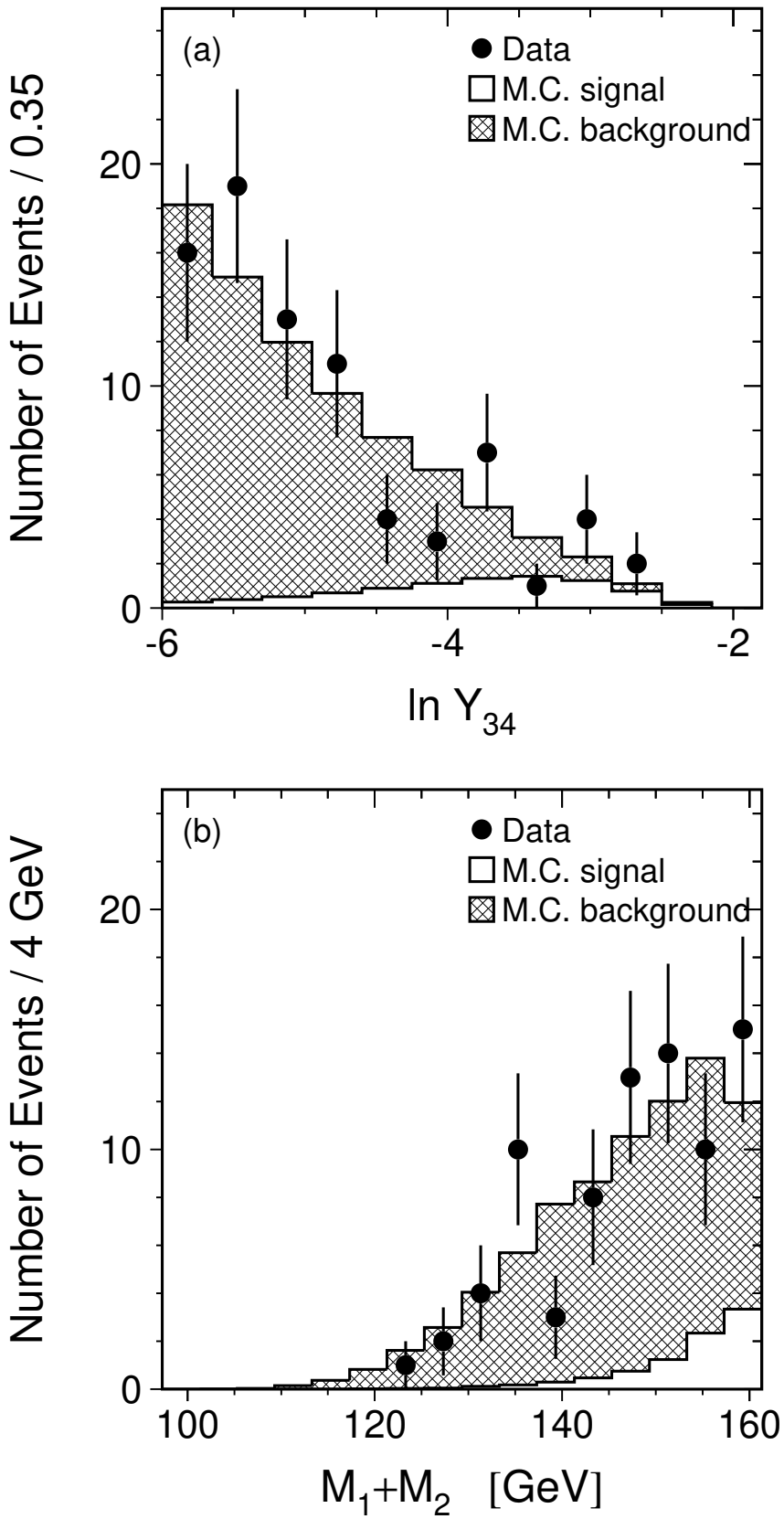


We need to reject these.

Identify 12 variables sensitive to difference between

e^+e^-	$\to$	γ/Z	$\to$	$q\bar{q}$ gg	$\to$ 4 jets
e^+e^-	$\to$	W^+W^-	$\to$	$q\bar{q}'q\bar{q}'$	$\to$ 4 Jets

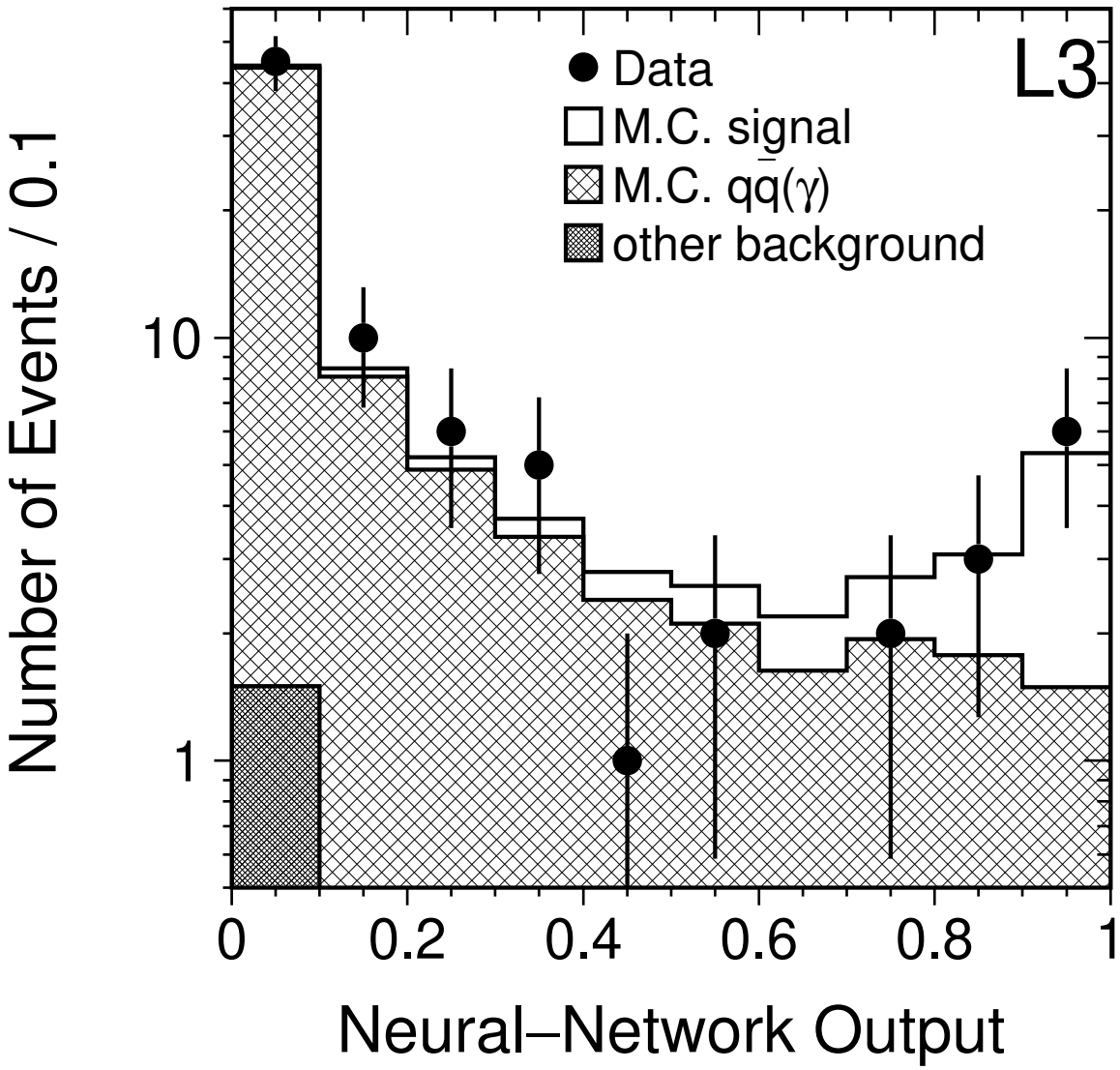
$e^+e^- \to W^+W^- \to q\bar{q}'q\bar{q}' \to 4$ Jets



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

Use 12 such variables as input to Neural Net
trained to give 1 for W^+W^-, 0 for $q\bar{q}$ background.
Fit NN of data to sum of W^+W^-, $q\bar{q}$ background
to find number of W^+W^- events

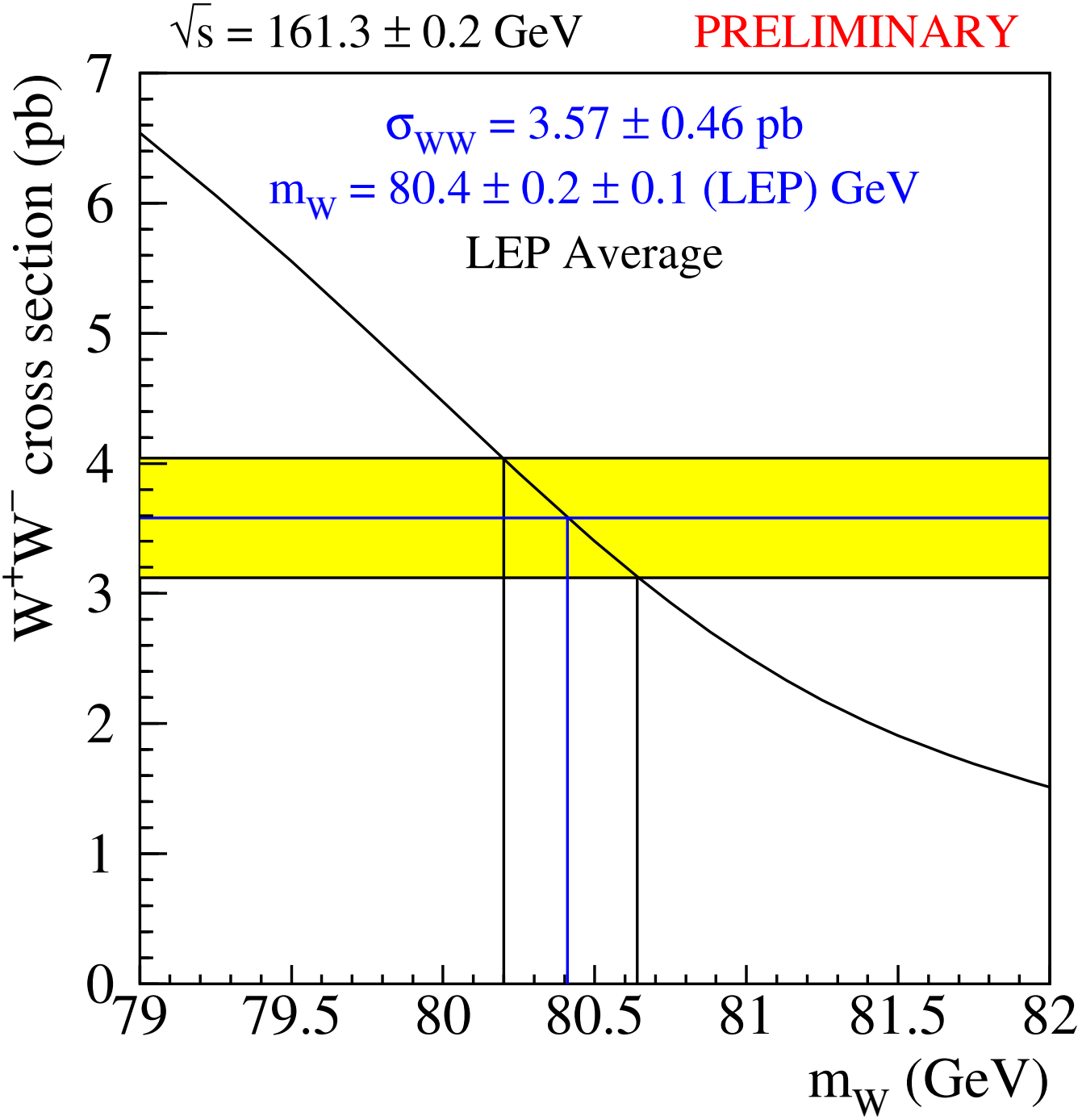
$$\Longrightarrow \qquad \sigma(e^+e^- \to W^+W^-)$$



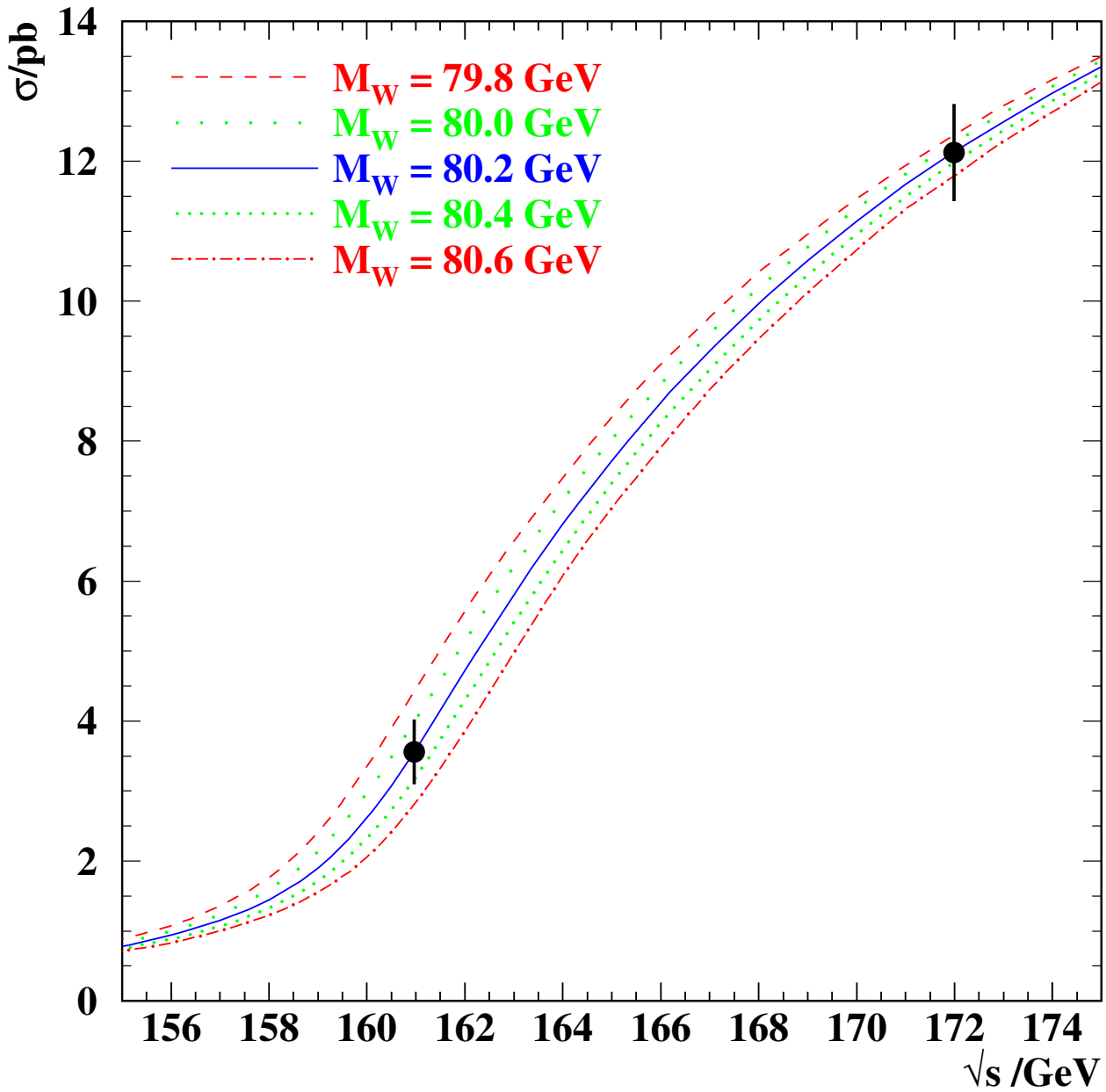
or select sample of W^+W^- events by cut on NN output

m_{W} from Cross Section

Assuming S.M., calculate $\sigma(\mathrm{W^+W^-})$ as fct. of m_{W}

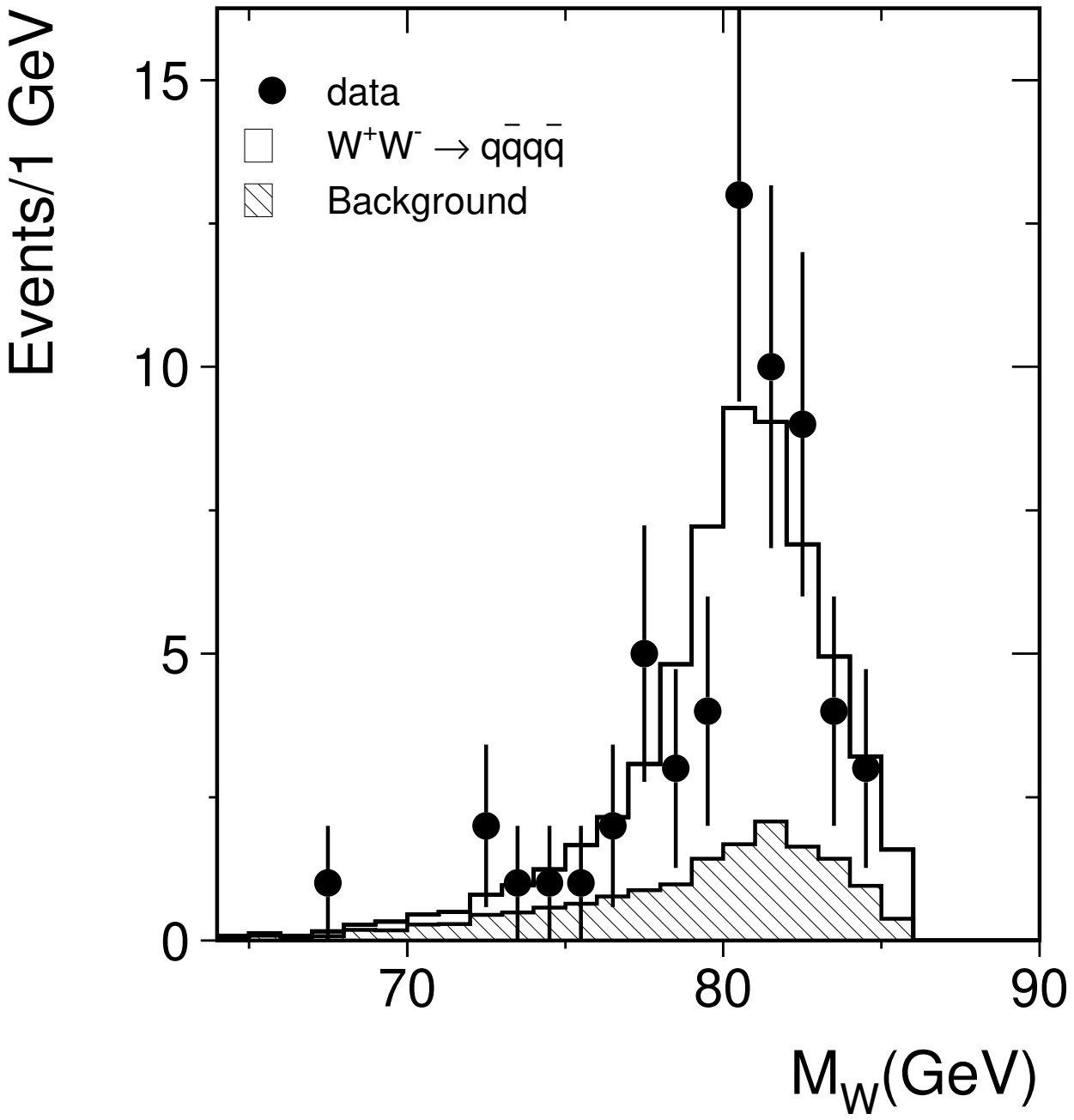


m_W from Cross Section



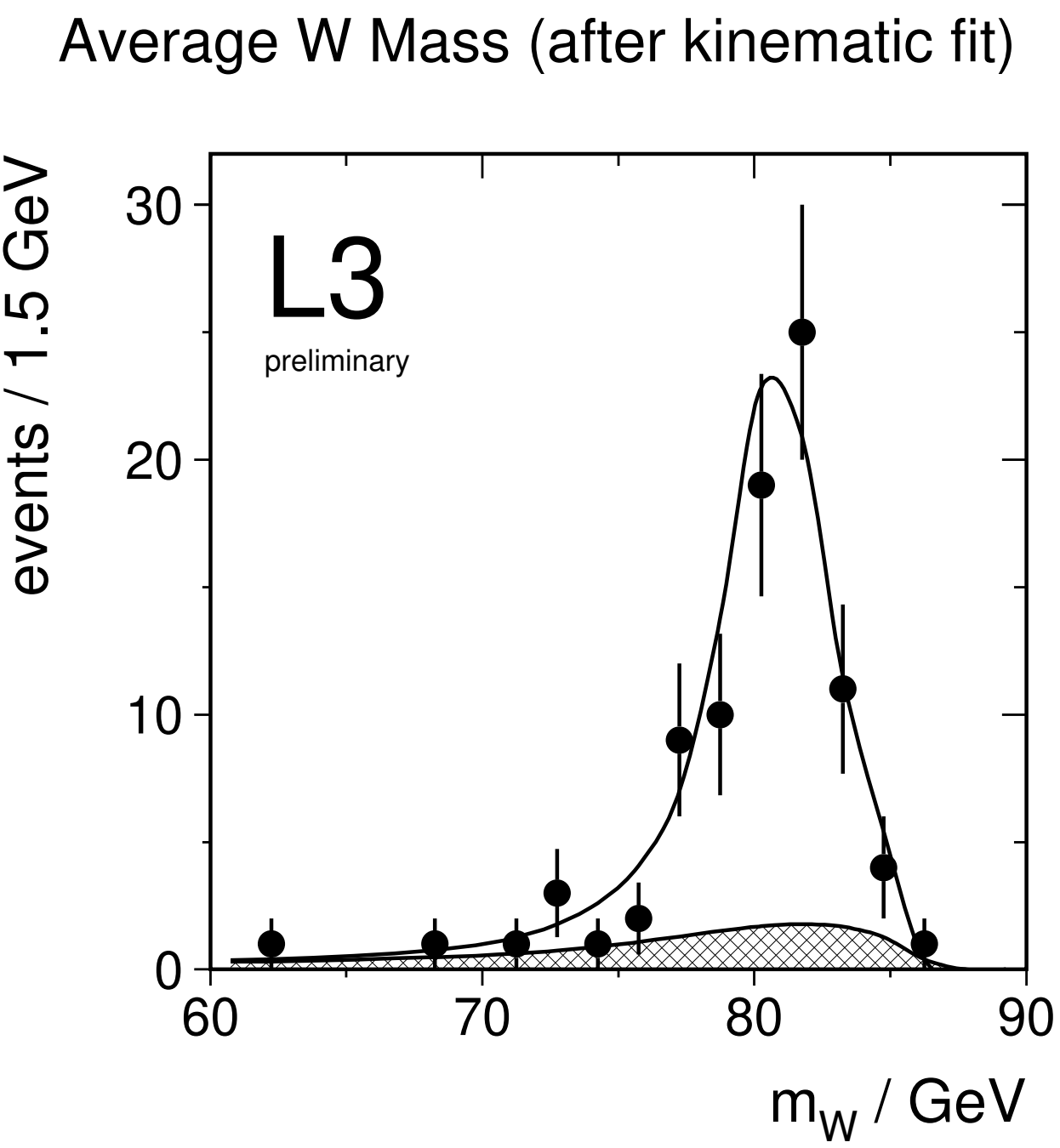
m_{W} from Direct Reconstruction

Select sample of $\mathrm{W}^+\mathrm{W}^-$ events by cut on NN output
Calculate mass of 2-jet combinations:



m_{W} from Direct Reconstruction

Combining $\mathrm{q\bar{q}q\bar{q}}$ and $\mathrm{q\bar{q}}\ell\nu$ events,



$m_{\mathrm{W}} = 80.70 \pm 0.38$ (stat) GeV

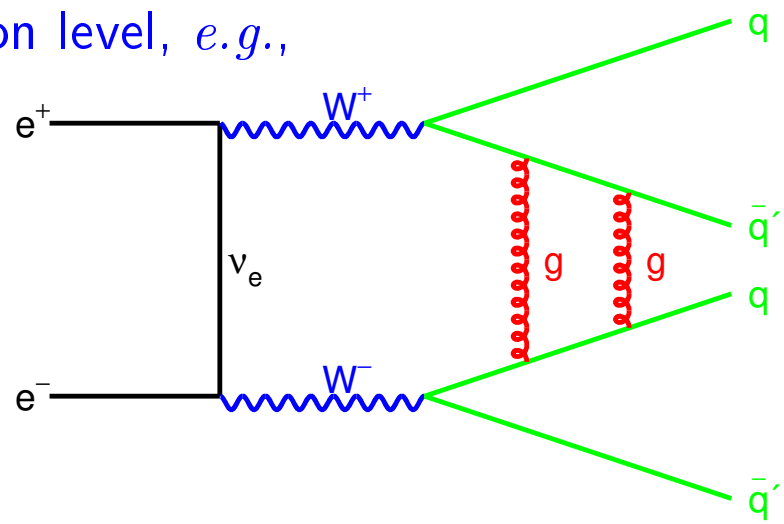
systematic errors under study

Complications in Direct Reconstruction from 4 Jets

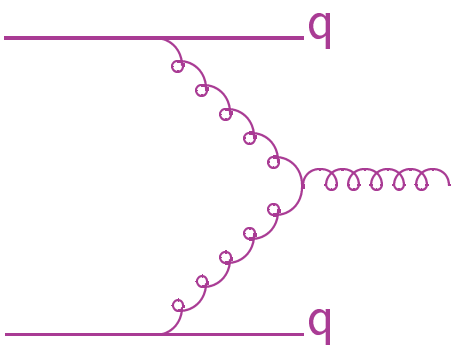
The quarks from different Ws "talk" to each other, distorting the shape of the Jet-Jet Mass distribution

- At the parton level, *e.g.*,

gluon exchange



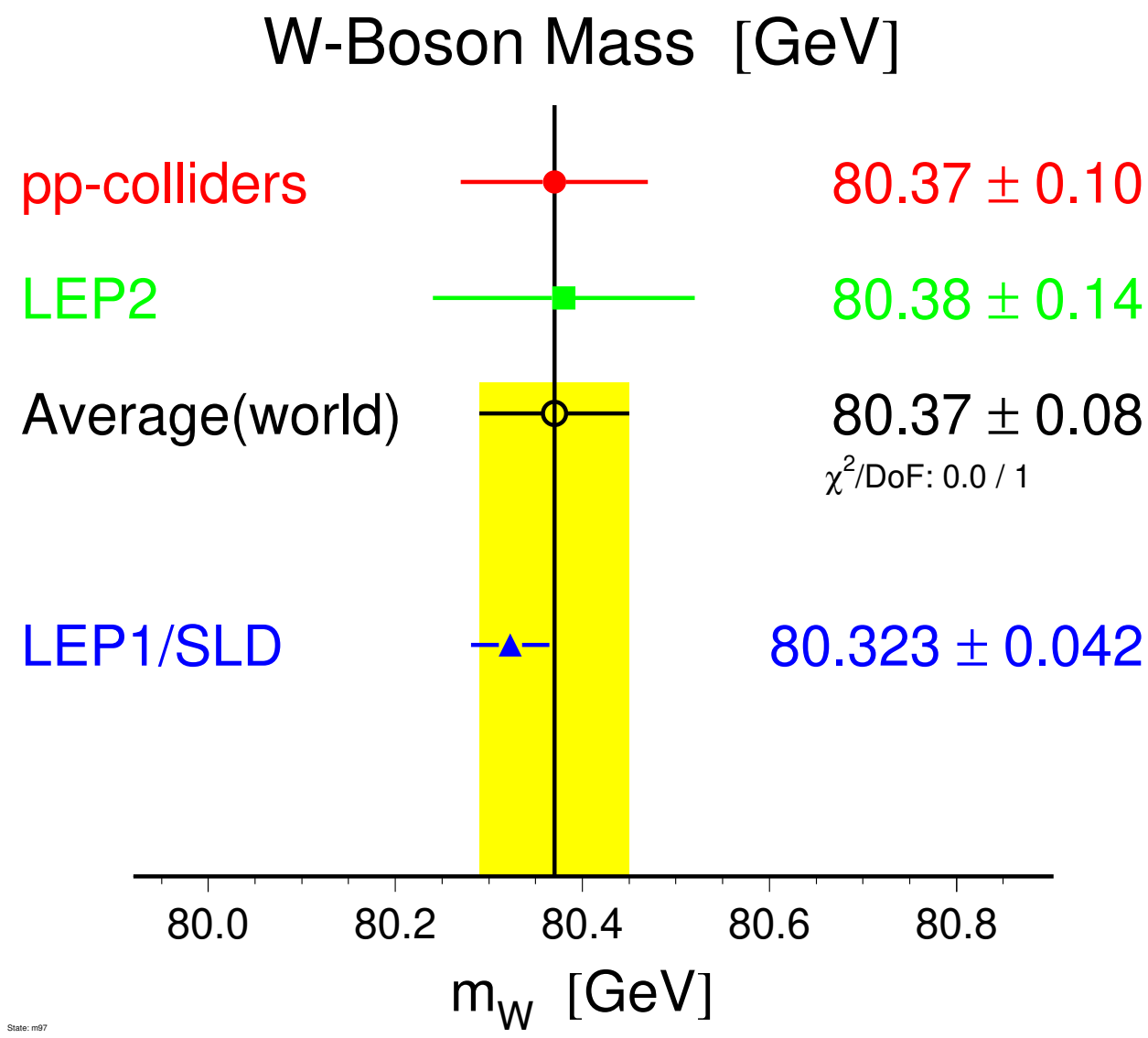
Color reconnection of gluons from different Ws



- At the hadronic level:
  - Strong final-state interactions among hadrons
  - Bose-Einstein correlations among identical bosons (πs)

Poorly understood at present
Systematic errors $\Delta m_{\mathrm{W}} \approx 40 - 100$ MeV

m_W



Expect at end of LEP-2 to have measured m_W to ± 40 MeV

$e^+e^- \to W^+W^-$ Cross Sections - 172 GeV

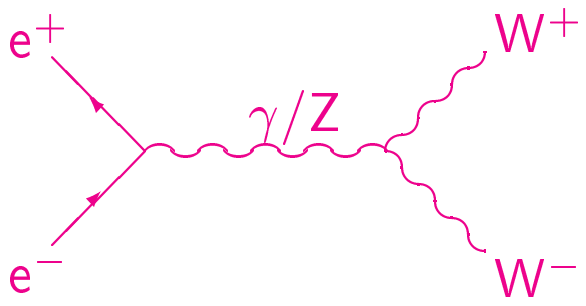
Using m_W, calculate cross sections for each channel and compare to data:

Final State	σ (pb)	σ_{SM} (pb)	Difference
$q\bar{q}e\nu$	$2.37^{+0.63}_{-0.54}$	1.81	$+1.0\sigma$
$q\bar{q}\mu\nu$	$1.14^{+0.44}_{-0.35}$	1.81	-1.5σ
$q\bar{q}\tau\nu$	$2.14^{+0.91}_{-0.77}$	1.81	$+0.4\sigma$
$l\nu l\nu$	$2.30^{+0.82}_{-0.67}$	1.32	$+1.5\sigma$
$q\bar{q}q\bar{q}$	$5.51^{+1.03}_{-0.94}$	5.66	-0.1σ
			$\chi^2 = 5.7/5$ DoF

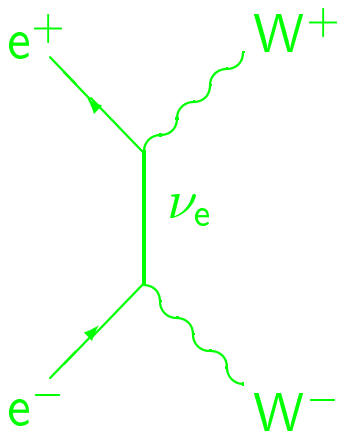
Triple Gauge Boson Couplings

W-sector involves new Three-Boson Vertices:
γW^+W^-, ZW^+W^-

New Vertices



Known Vertices



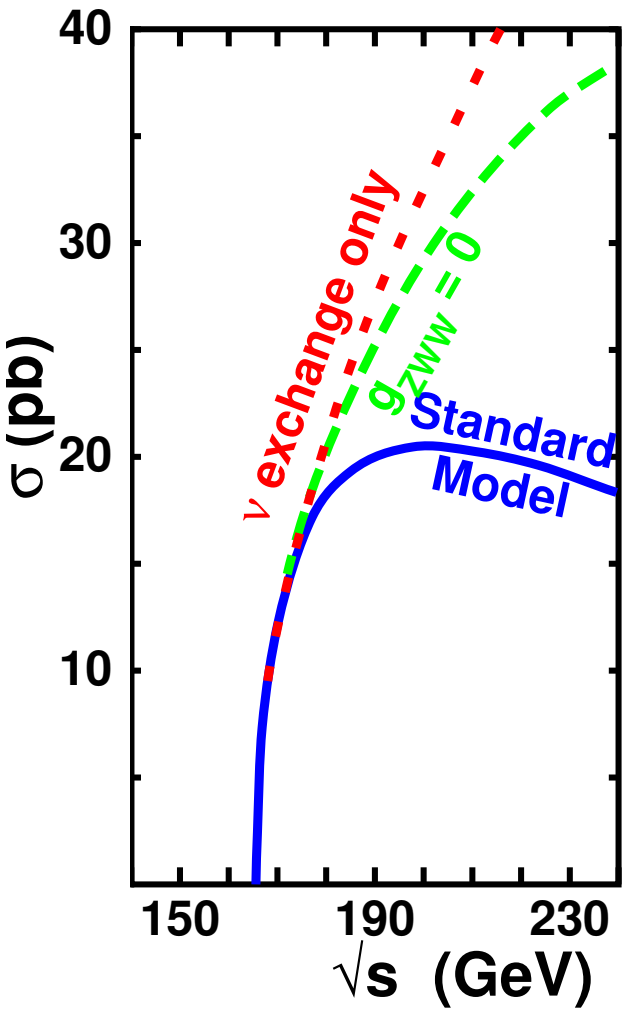
Triple Gauge Boson Couplings in S.M.:

γW^+W^- coupling: $g_{\gamma W^+W^-} = 1$

ZW^+W^- coupling: $g_{ZW^+W^-} = \cot\theta_W$

Triple Gauge Boson Couplings

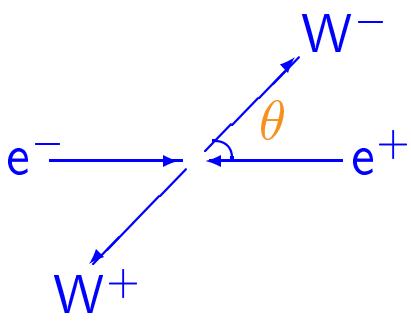
Departure from S.M. affects σ, $\cos\theta$



No sensitivity
at current energy,
$\sqrt{s} = 172\,\text{GeV}$

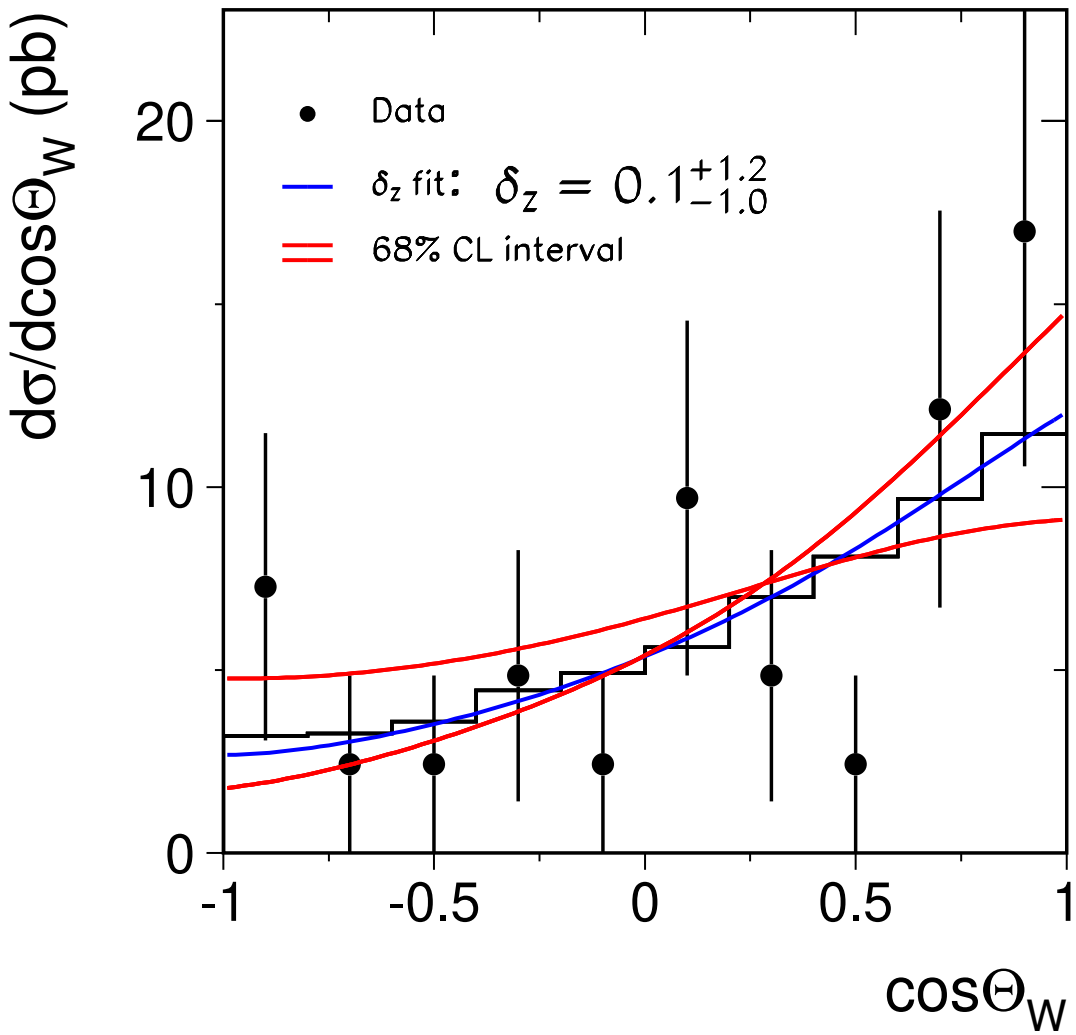
Triple Gauge Boson Couplings

To measure W couplings use
W production angle θ



$(W^+W^- \to q\bar{q}\ell\nu)$
ℓ tags W charge)

Measure $\delta_Z = g_{ZWW} - g^{SM}_{ZWW}$
with all other couplings fixed to SM values



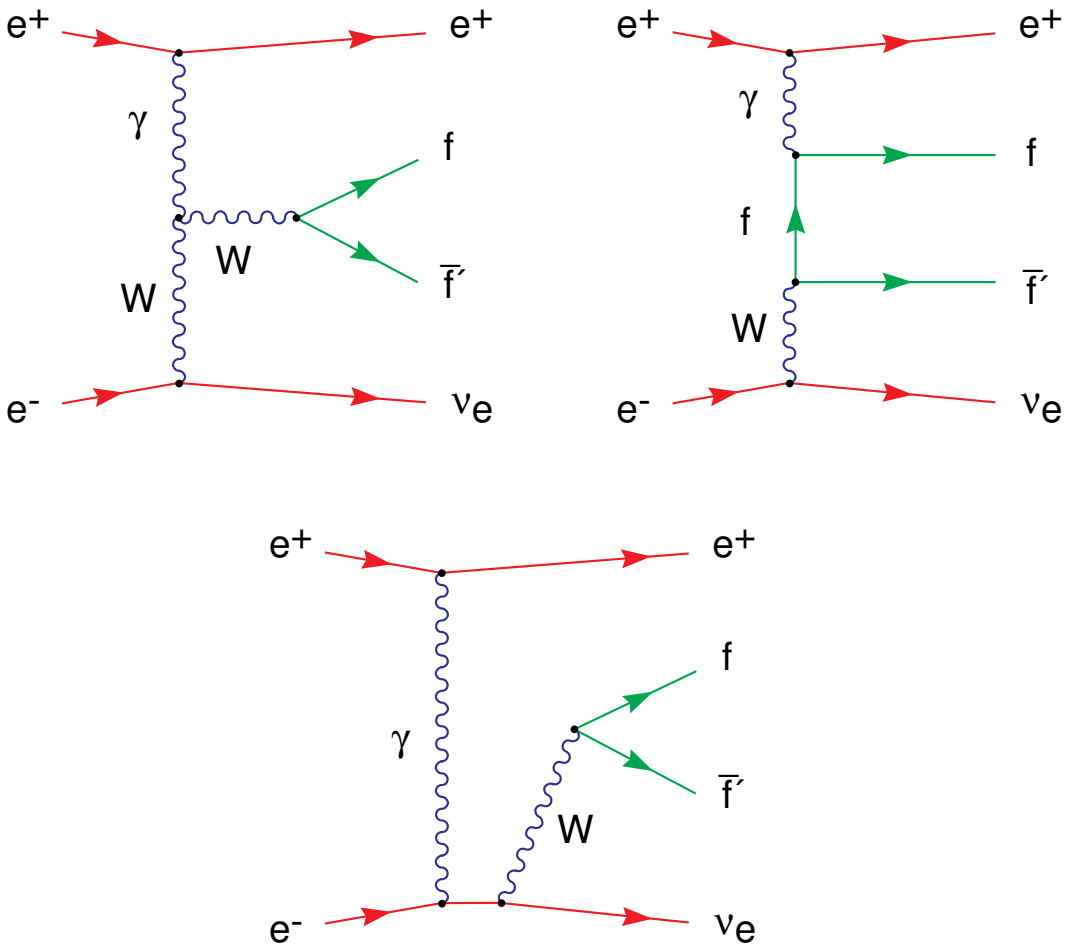
$\delta_Z = 0.1^{+1.2}_{-1.0}$

Single W Production

Disadvantage of σ, $\frac{d\sigma}{d\cos\theta}$:

Difficult to separate effects of γWW and ZWW vertices

So look at $e^+e^- \to e^+\nu_e W^-$ (or $e^-\overline{\nu}_e W^+$)



(plus same diagrams with $\gamma \leftrightarrow Z$)

$e^+e^+\gamma$ vertex favors e^+ at small angles (in beam pipe)

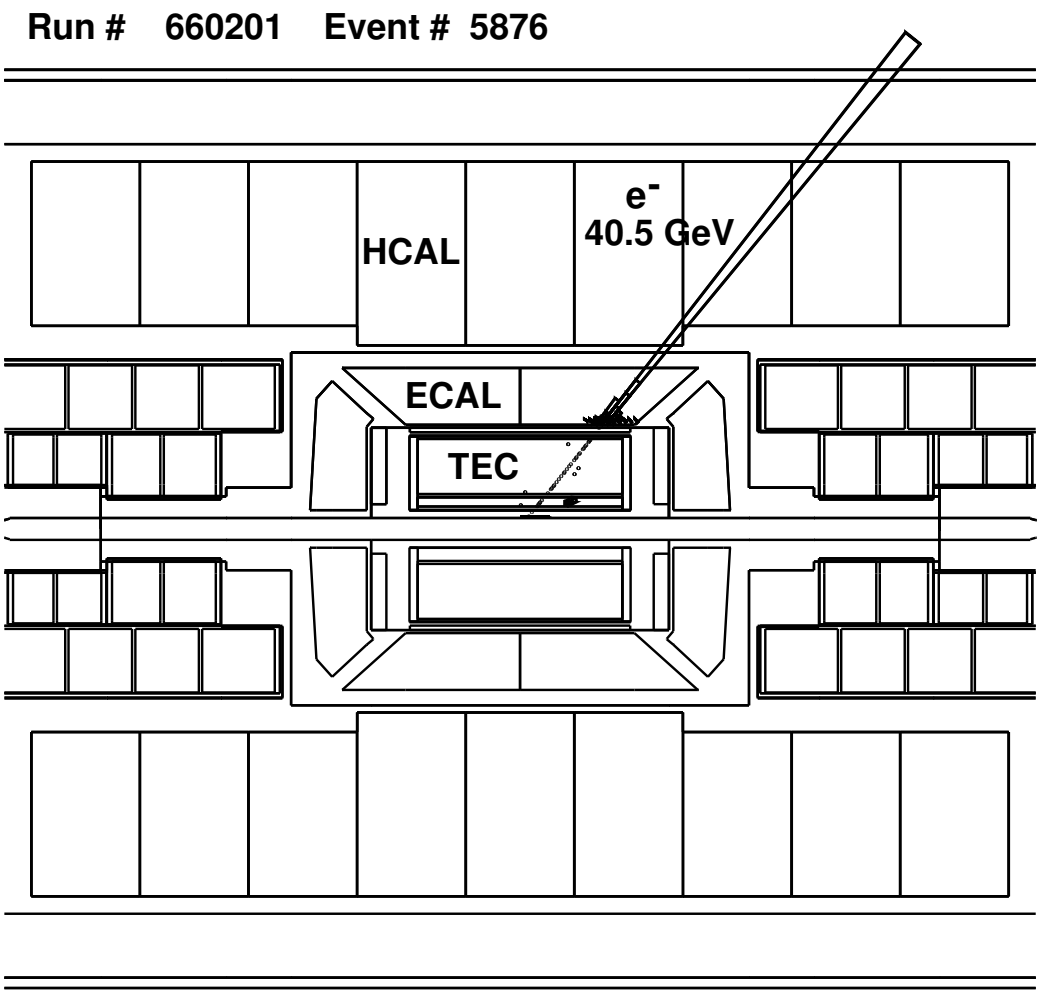
e^+e^+Z vertex favors e^+ at larger angles

At small e^+ angles, only Triple-Boson coupling is γWW

But cross section is low

Single W Production

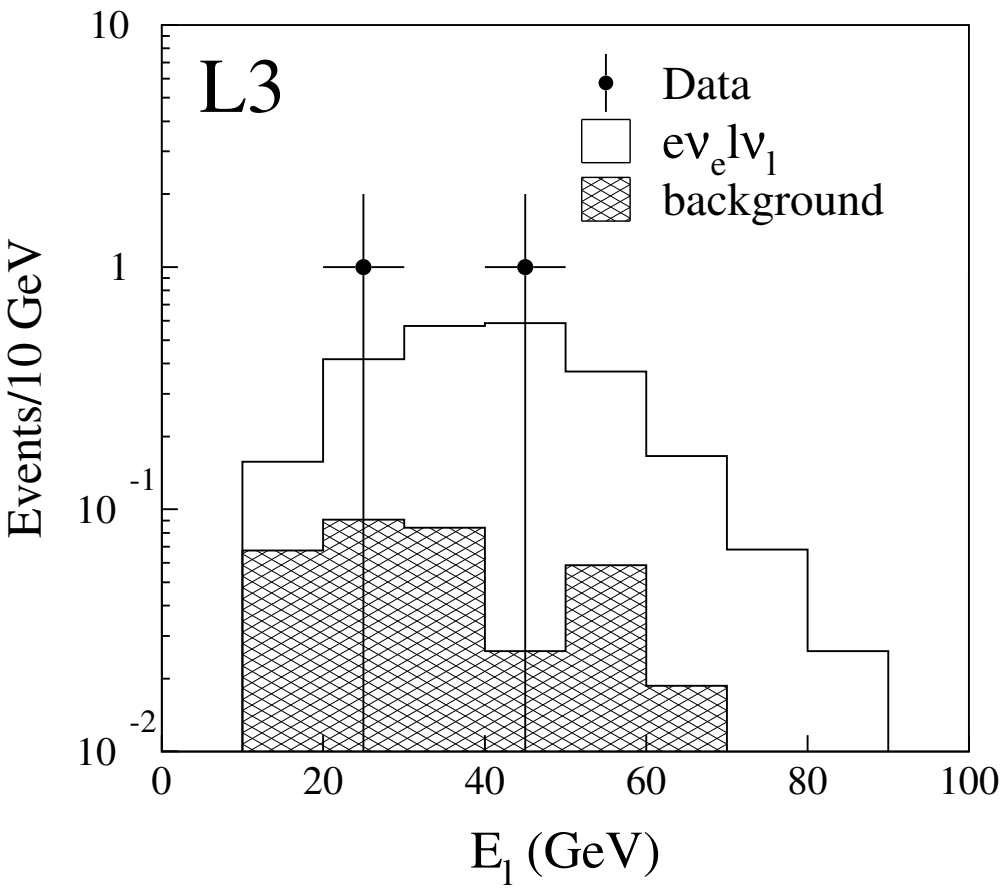
Observe 2 events compatible with $e^+e^- \to e\ell\nu\nu$ with only the ℓ detected.



Expect background of 0.5 ± 0.1 events.

Single W Production

Energy of observed 2 events is compatible with S.M.



Signal is consistant with S.M.

Conclusion

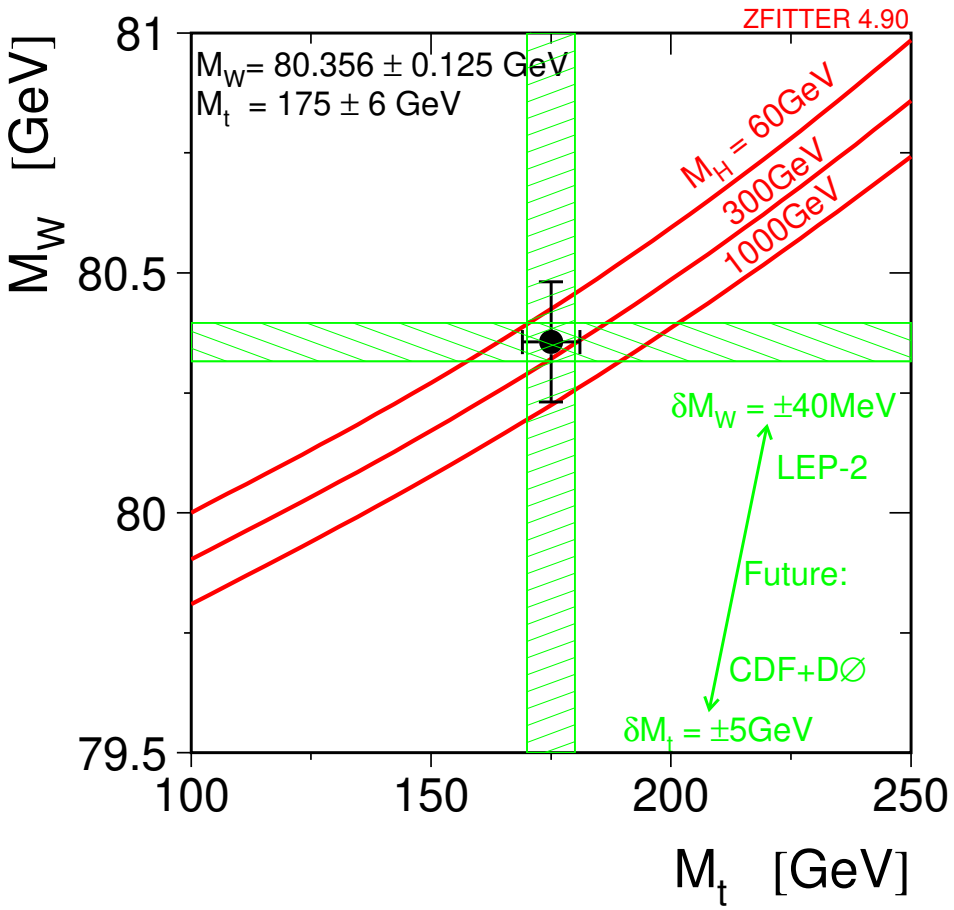
- LEP-1 has tested Z-sector of S.M. to high accuracy

- LEP-2 has begun to test W-sector

  1. W properties
  2. Triple Boson couplings

  No discrepancies with S.M. seen yet

- Tests will become more accurate in coming few years, *e.g.*,



- If Nature has been kind,
  we will discover the Higgs at LEP-2