SUMMING UP THE LEP RESULTS

(Marc WINTER – IReS/Strasbourg)

Outline

- Historical perspective
- The LEP machine
- Brief overview of theoretical context
- Precision measurements at LEP-1
- Precision measurements at LEP-2
- Standard Higgs search
- Non standard particle search
- ▸ Summary & Conclusion

Historical Perspective

1967/71 : Electroweak theory, with symmetry breaking via Higgs mechanism

1973 : Discovery of Neutral Currents ($\nu_\mu e \rightarrow \nu_\mu e$)

1974 : "Completion" of S. Model formulation

1976 : Start of LEP design ($M_W \sim 65\,GeV$, $M_Z \sim 80\,GeV$)

1979 : Les Houches Summer Study:

→ machine considered as buildable

→ "it would be both arrogant and unhistorical to believe that our naive extrapolation from physics at 2 GeV to physics at 200 GeV is likely to be correct in detail ..." S. Glashow summary

1983 :
- W & Z discovery
- LEP construction starts

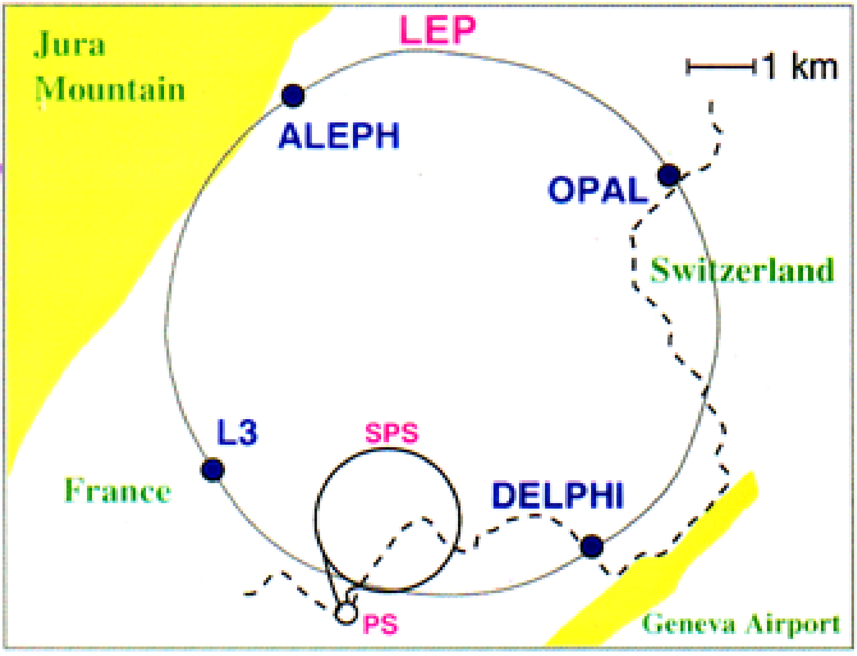
1989 : First collisions at LEP-1

1995/96 : First collisions at LEP-2

2000 : END OF LEP

The LEP Machine

- 26.7 km long quasi-circular ring ~100-200m underground between Jura mountains and Geneva Lake

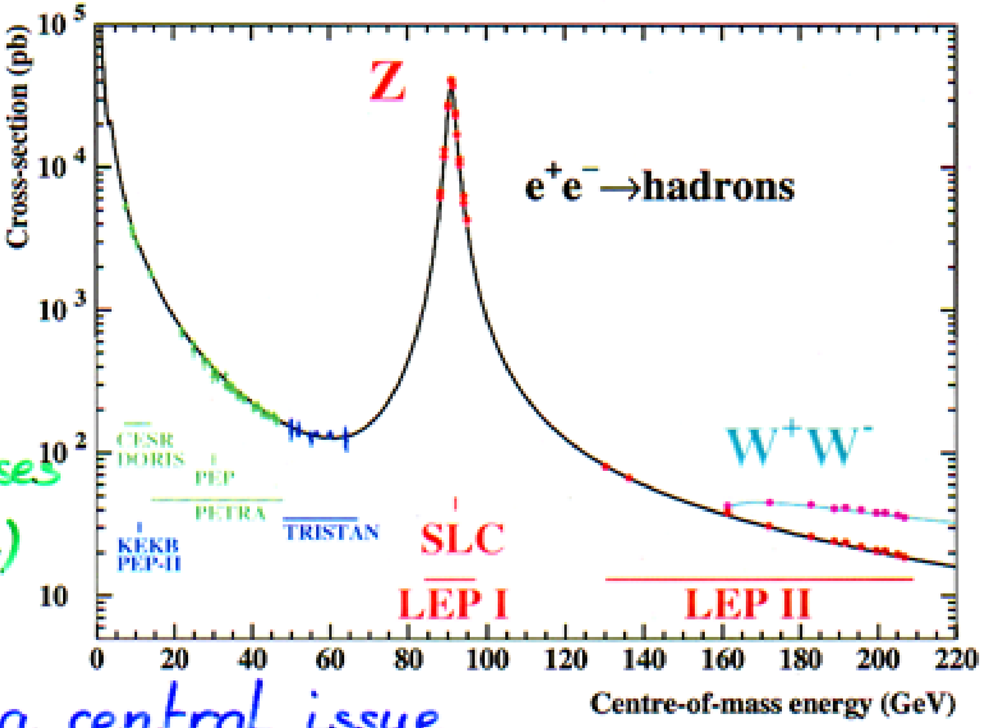


$\xrightarrow{T}$

- {E,L} driven by the study of Z^0 & $W^\pm$ bosons

$\Downarrow$

2 operation phases (5-6 years each)



- Precision was a central issue for measurements and for searches
  - → knowledge of E_{beam} $\xrightarrow{T}$
  - → knowledge of integrated luminosity $\xrightarrow{T}$
  - → ~4π sophisticated experiments $\xrightarrow{T}$

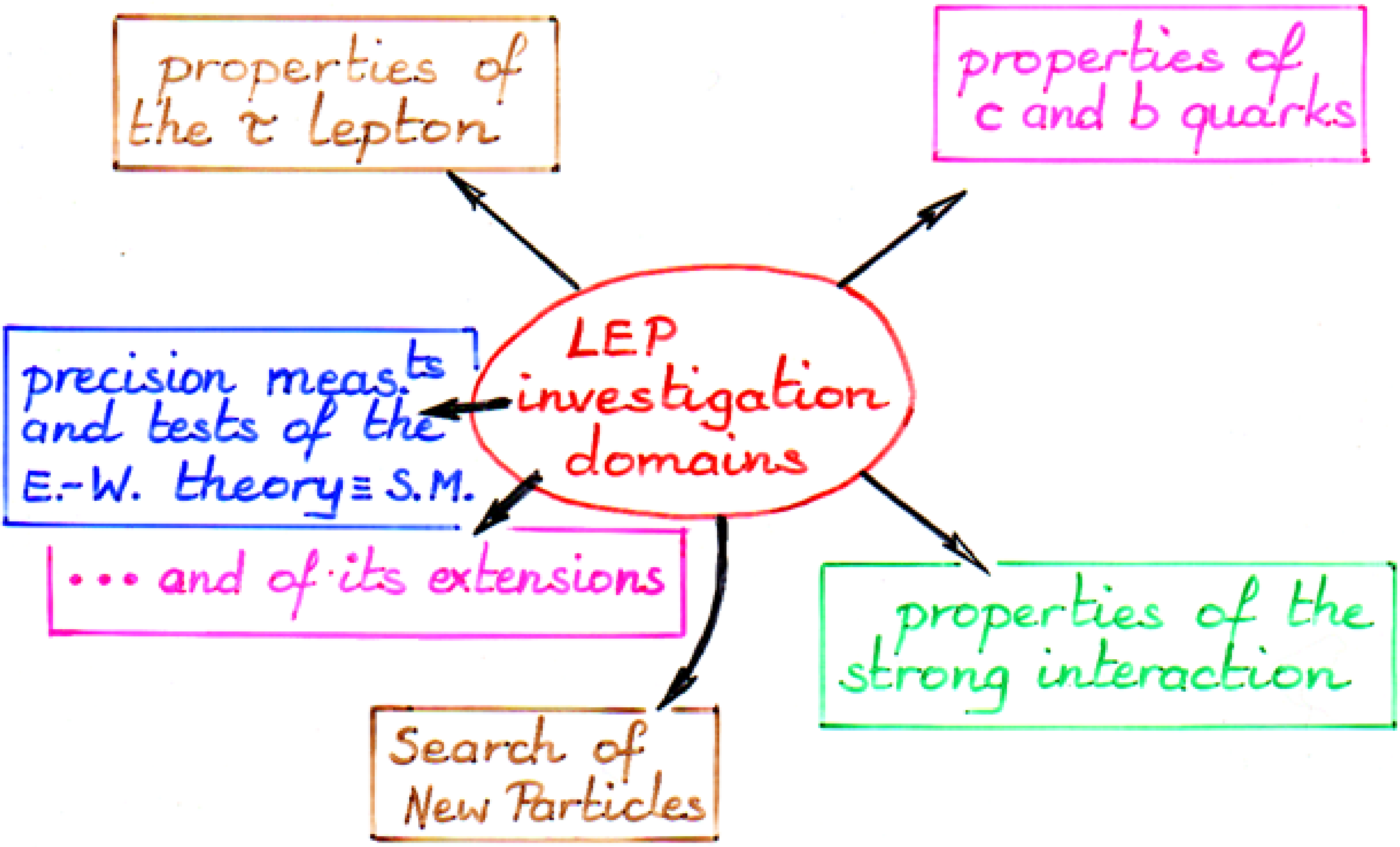
↑x-check essential

LEP goals

1- Determine the (unpredictable) value of fundamental parameters of the theory

2- Investigate the consistency of the Standard Model (expecting it would not hold ...)

3- Look (directly and indirectly) for non-standard physics



LEP investigation domains

properties of the τ lepton

properties of c and b quarks

precision meas.ts and tests of the E.-W. theory ≡ S.M.

... and of its extensions

Search of New Particles

properties of the strong interaction

■ LEP energy calibration

How to measure $\int B dl$ with $\sim 10^{-5}$ accuracy?

▶ Multi-step procedure :

advantages

- resonant depolarisation → exploits small e^- spin asymmetry induced by synchrotron radiation :

  $\Delta E_b = \pm 0.2$ MeV (single beam only !)

  very accurate

- NMR probes measuring the field of 1+2 dipoles :

  $\Delta E_b \sim$ MeV but ~1‰ of $\int B.dl$ seen

  during physics

- Flux Loopes embeded in each dipole to measure its field (during cycling):

  $\Delta E_b \gg$ MeV

  96.5% of $\int B.dl$

⇒ NMR probes and Flux Loops were calibrated with resonant depolarisation :

$$\Delta M_Z = \pm 1.7 \text{ MeV} \qquad \Delta \Gamma_Z = \pm 1.2 \text{ MeV}$$

▶ LEP-2 : Res. Depol. works up to $E_b \sim 60$ GeV

- NMR probes (and Flux Loops) were calibrated with resonant depolarisation over the range $E_b = 41, \ldots, 60$ GeV and extrapolated to LEP2 working energies :

$$\Delta M_W \approx \pm 20 \text{ MeV}$$

Luminosity per beam crossing:

$$\mathcal{L} = f_{rev} n_b \frac{N^+ N^-}{4\pi \sigma_x \sigma_y}$$

$f_{rev} \simeq 11$ kHz = LEP revolution frequency

$n_b = 8$ = number of bunches per beam

N^+ = number of e^+ per bunch $\sim 10^{11}$

N^- = number of e^- per bunch $\sim 10^{11}$

σ_x = horizontal beam spread

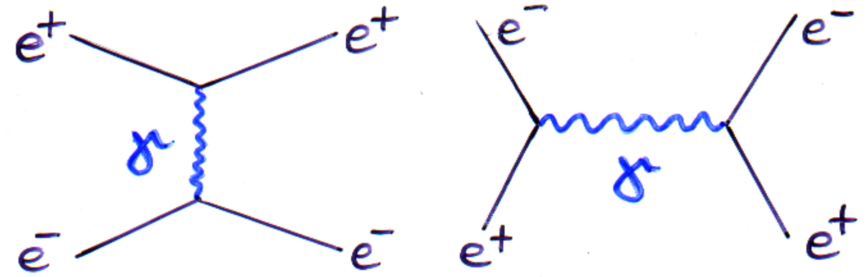
σ_y = vertical beam spread

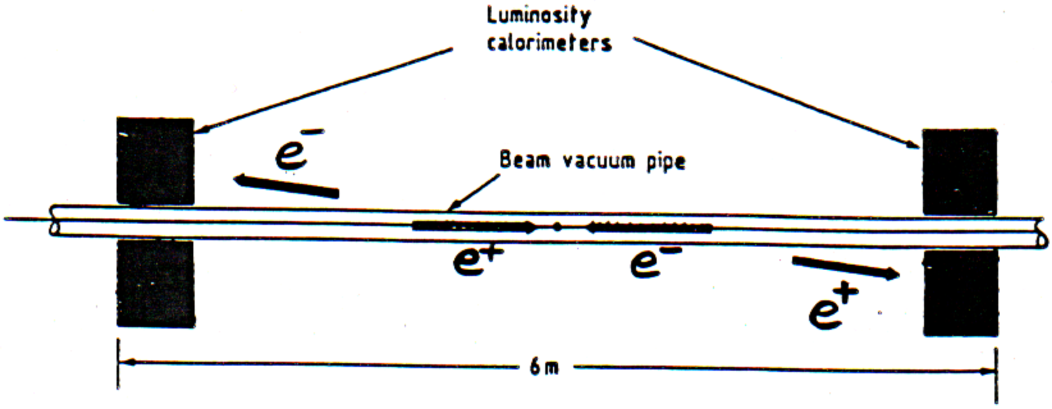
$$L_{Fill} = \int_{start}^{end} \mathcal{L}\, dt$$ not very accurate ($\gtrsim 5\%$)

$\Longrightarrow$ > 10 times better accuracy needed!

LUMINOSITY MEASUREMENT

- reference reaction : Bhabha scattering at small angle (20 – 130 mrad)





- $L(\sqrt{s}) = \dfrac{N_{Bb}(\sqrt{s})}{\varepsilon_{Bb}\cdot\sigma_{vis}^{Bb}(\sqrt{s})}$

number of Bhabha events observed

$\sim 100\%$

$$= \int_{\theta_{min}}^{\theta_{max}} \frac{d\sigma_{th}^{Bb}}{d\theta}\, d\theta \simeq \frac{16\pi\alpha^2}{s}\left(\frac{1}{\theta_{min}^2}-\frac{1}{\theta_{max}^2}\right)$$

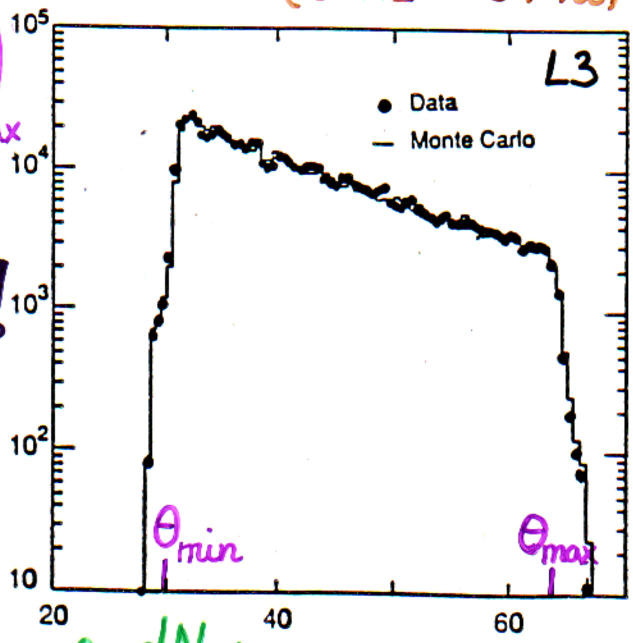
theoretical precision = 0.61‰

(OPAL : 0.54‰)

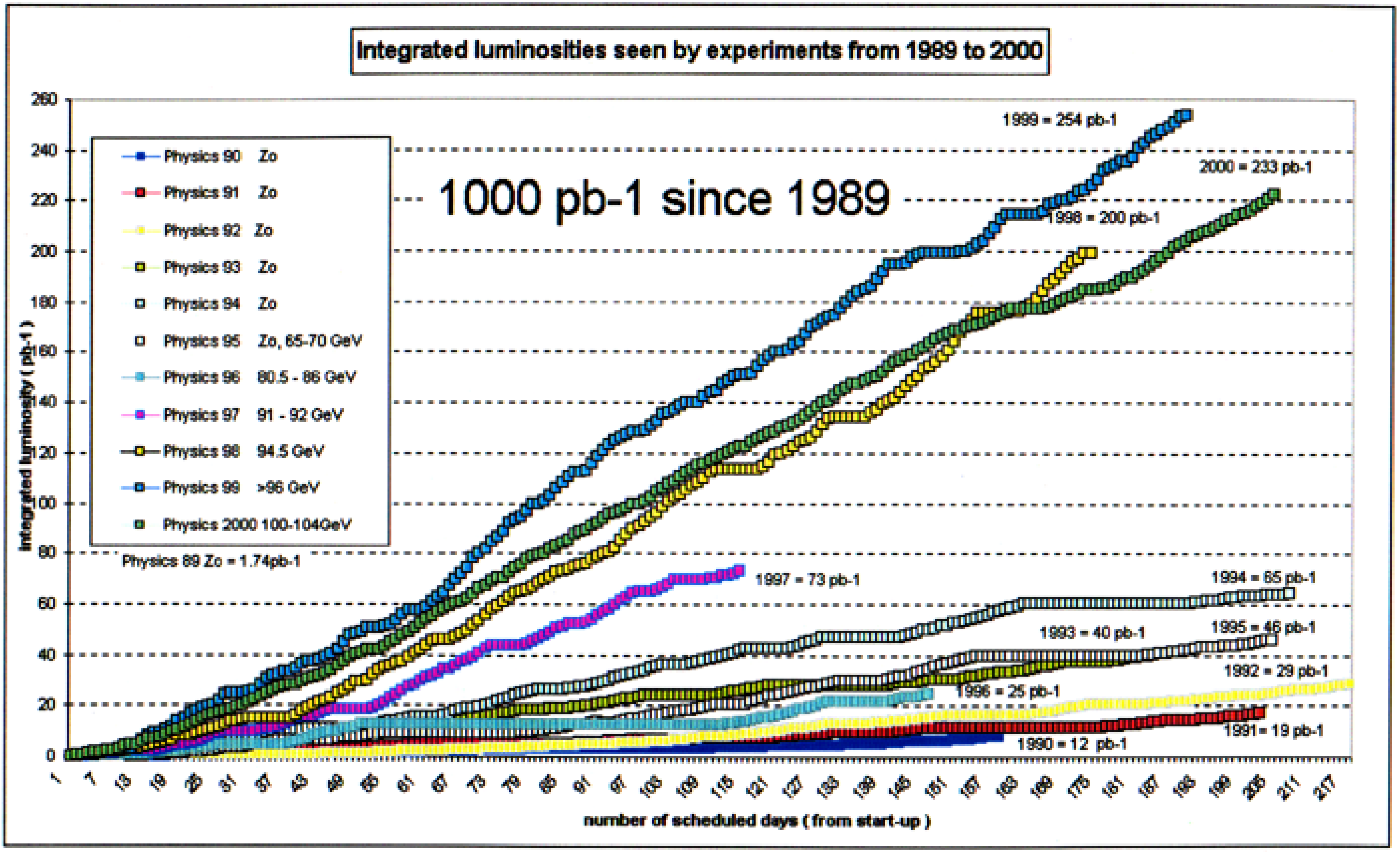
$$\simeq \frac{32\pi\alpha^2}{s}\cdot\frac{1}{\theta^3}$$

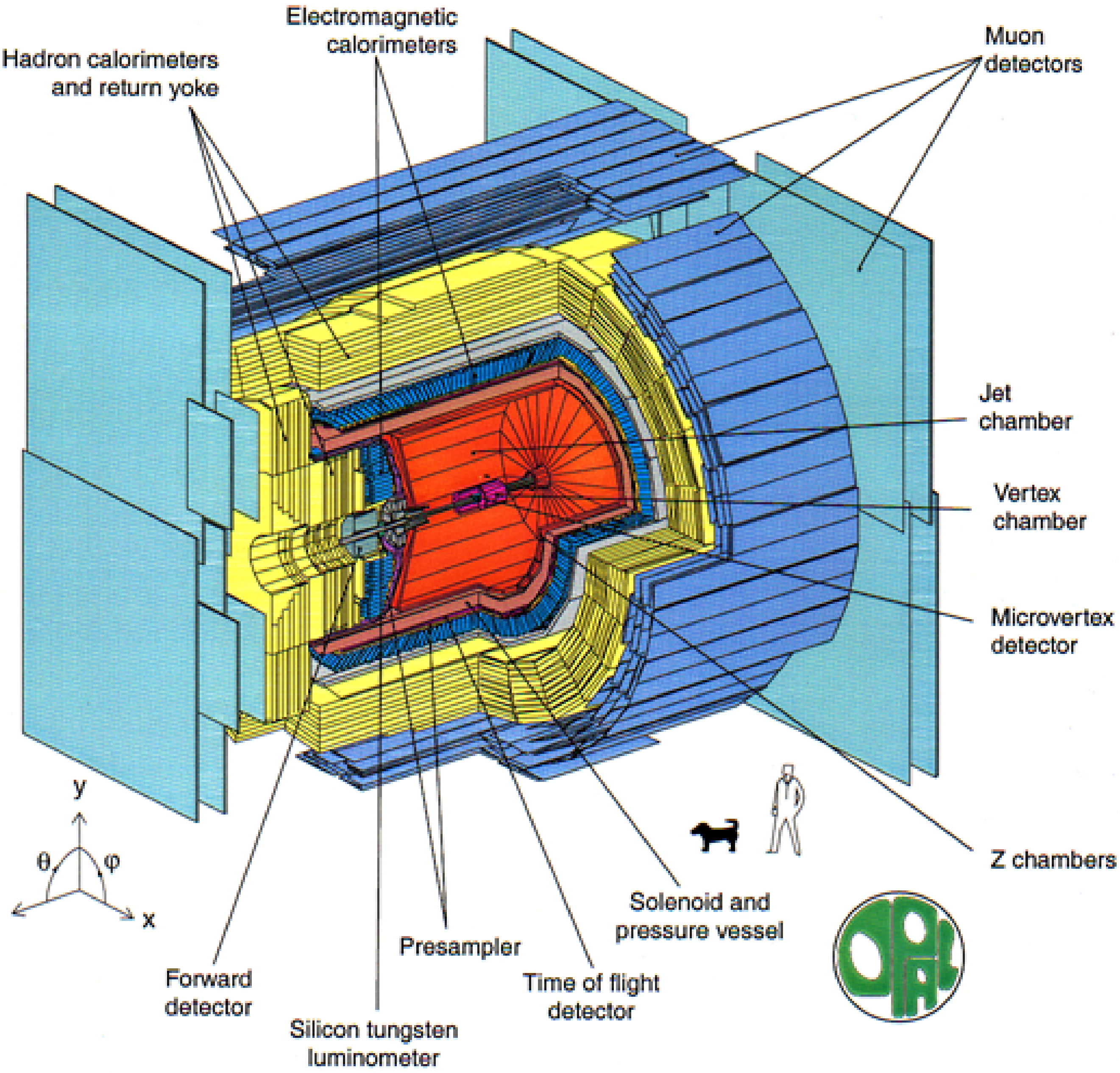
$$\frac{\Delta L}{L} < 10^{-3}\,!$$

θ_{min} has to be known very accurately



$\ln \dfrac{dN_{Bb}}{d\theta}$ vs θ [mrad]


Integrated luminosities seen by experiments from 1989 to 2000
1000 pb-1 since 1989
Physics 90 Zo
Physics 91 Zo
Physics 92 Zo
Physics 93 Zo
Physics 94 Zo
Physics 95 Zo, 65-70 GeV
Physics 96 80.5 - 86 GeV
Physics 97 91 - 92 GeV
Physics 98 94.5 GeV
Physics 99 >96 GeV
Physics 2000 100-104GeV
Physics 89 Zo = 1.74pb-1
1999 = 254 pb-1
2000 = 233 pb-1
1998 = 200 pb-1
1997 = 73 pb-1
1994 = 65 pb-1
1993 = 40 pb-1
1995 = 46 pb-1
1992 = 29 pb-1
1996 = 25 pb-1
1991 = 19 pb-1
1990 = 12 pb-1
integrated luminosity (pb-1)
260
240
220
200
180
160
140
120
100
80
60
40
20
0
1
7
13
19
25
31
37
43
49
55
61
67
73
79
85
91
97
103
109
115
121
127
133
139
145
151
157
163
169
175
181
187
193
199
205
211
217
number of scheduled days (from start-up)


Electromagnetic calorimeters
Hadron calorimeters and return yoke
Muon detectors
Jet chamber
Vertex chamber
Microvertex detector
Z chambers
y
θ
φ
x
Solenoid and pressure vessel
Presampler
Time of flight detector
Forward detector
Silicon tungsten luminometer

Profile of the Standard Model (1/2)

- description of subnuclear world in terms of MATTER and FORCES

- MATTER → point-like spin-$\frac{1}{2}$ fermions

$$\text{Leptons} \quad \begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L \quad \begin{pmatrix}\overset{?}{\boxed{\nu_\tau}}\\ \tau^-\end{pmatrix}_L \quad \left.\begin{matrix}+1/2\\ -1/2\end{matrix}\right\} T_3$$

$$\text{Quarks} \quad \begin{pmatrix}u\\ d\end{pmatrix}_L \quad \begin{pmatrix}c\\ s\end{pmatrix}_L \quad \begin{pmatrix}\overset{?}{\boxed{t}}\\ b\end{pmatrix}_L \quad \left.\begin{matrix}+1/2\\ -1/2\end{matrix}\right\} T_3$$

how many generations? (≤ 4?)

+ (R) singlets

- FORCES → 3 interactions mediated by 12 Gauge Bosons and described by Gauge Symmetry Groups

- Gauge Theories work smoothly in absence of masses : $M_\gamma = M_Z = M_W = 0$ ($= m_{g_{x\varphi}}$)

  Experimental evidence for $M_W \sim 80$ GeV, $M_Z \sim 91$ GeV (UA1/2) calls for the introduction of E.W. Spontaneous Symmetry Breaking via the Higgs Mechanism :

  → translates in the existence of H. boson (scalar!)

  → generates boson and fermion masses

Profile of the Standard Model (2/2)

- renormalisable theory $\xrightarrow{\text{€}}$ predictions based on free input parameters

fermion masses	$9 + 3$
flavour mixing matrix ele^{ts}	$4 + 4$
M_H	1
v (from V_{Higgs})	1
coupling constants	3
	$18 + 7$

$18 \to$ 24 in E.W. sector

$7 \searrow$ 22 "in" Higgs sector

- at high energy, 3 parameters dominate E.W. sector:

$\{g_{em}, g_W, v\} \longleftrightarrow$ observables

$$\begin{tikzcd}
& \left\{\begin{array}{ll} \alpha_{em.} & (10^{-8}) \\ G_F & (10^{-5}) \\ \sin^2\theta_W & \end{array}\right. \arrow[dl, leftrightarrow] \arrow[dr, leftrightarrow] & \\
\begin{array}{c} \{\alpha_{em}, G_F, M_Z^2\} \\ (5\,10^{-3}) \end{array} \arrow[rr, leftrightarrow] & & \begin{array}{c} \{\alpha_{em}, G_F, M_W^2\} \\ (5\,10^{-3}) \end{array}
\end{tikzcd}$$

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} = \frac{\sqrt{2}\,\pi\,\alpha_{em}\,G_F}{M_Z}$$

Fundamental - Higgs driven - Relations

- charges : $e = g_W \sin\theta_W = \sqrt{4\pi\alpha_{em}}$

- boson masses :

$$M_W = M_Z \cos\theta_W = \frac{g_W}{2}\cdot v$$

$$M_Z = \frac{\sqrt{g_W^2 + g_{em}^2}}{2}\cdot v$$

- H·B$_V$ couplings :

$$g_{WWH} \sim -ie\frac{M_W}{\sin\theta_W}$$

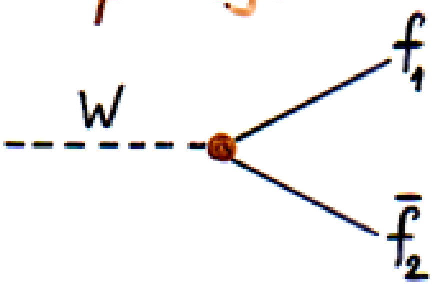
$$g_{ZZH} \sim -ie\frac{M_Z}{\sin\theta_W \cos\theta_W}$$

$$g_{\gamma\gamma H} = 0 \, !$$

- H·f couplings : introduce "Yukawa-like" potential

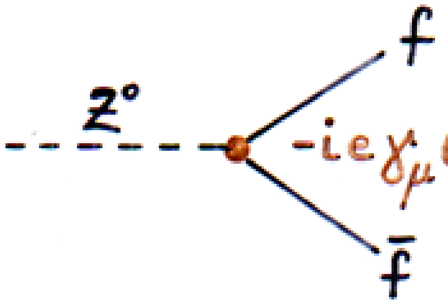
$\Rightarrow$ fermions get massive : $m_f = g_{ffH}\cdot\frac{v}{\sqrt{2}}$

- B$_V$·f couplings :



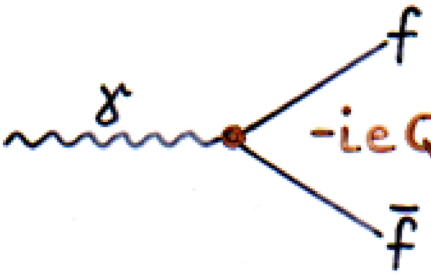
f_L only

$$-ie\gamma_\mu(1-\gamma_5)\frac{1}{2\sqrt{2}\,\sin\theta_W}\,V_{12}$$



$$-ie\gamma_\mu(v_f - a_f\gamma_5)$$

no flavour mixing



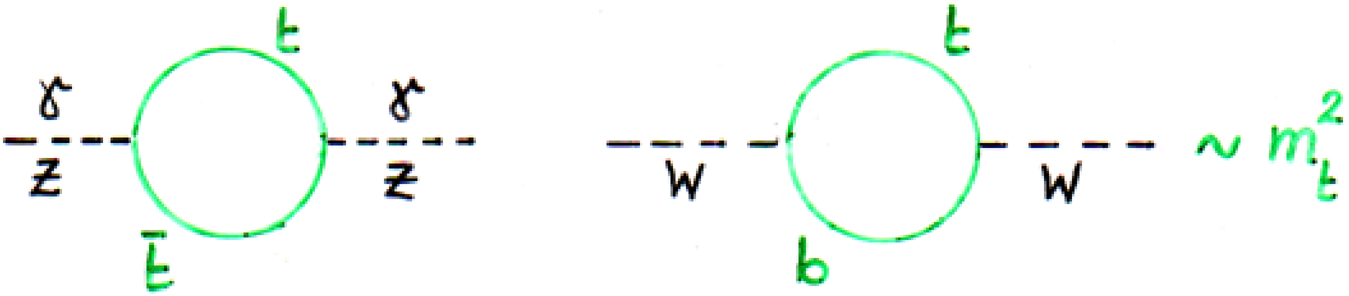
$$-ieQ_f\gamma_\mu$$

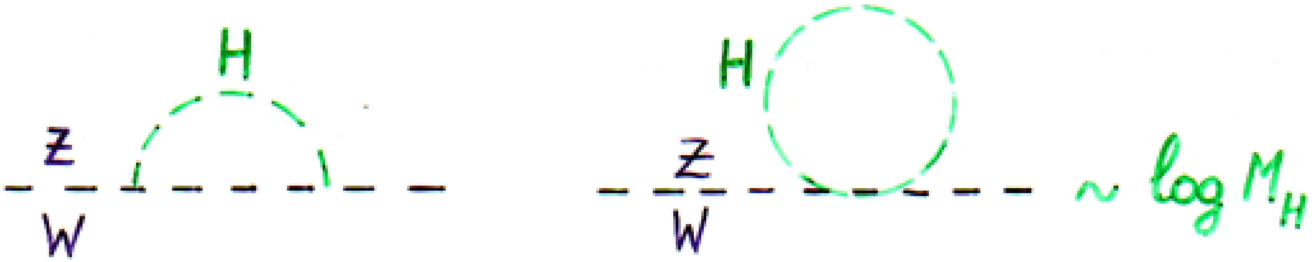
E.W. Corrections (1/2)

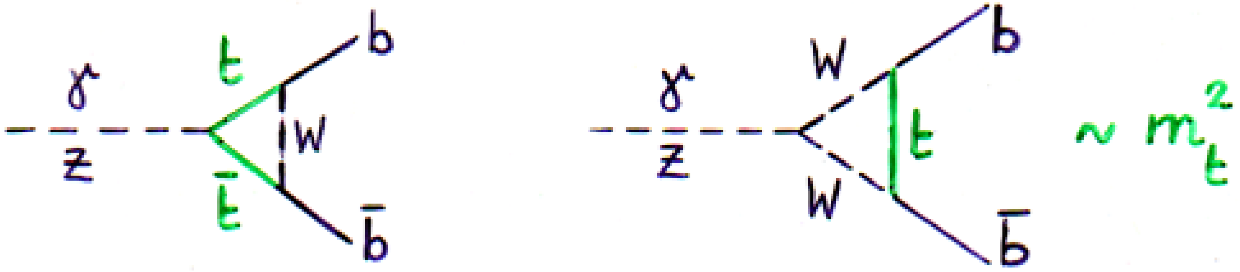
- physical vacuum is "active" ($\Delta E \cdot \Delta t \lesssim \hbar/2$)

→ csq on : - coupling "constants"
- fermion and boson masses
  } they "run"
- couplings between B_V and f
- etc.

- some major contributions :

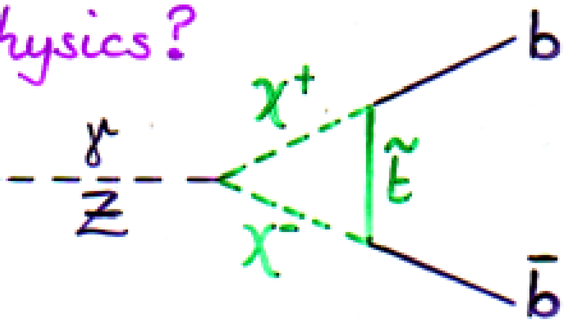






- . . . from New Physics?

e.g. SUSY



E.W. Corrections (2/2)

- $\rho = \frac{M_W^2}{M_Z^2\cos^2\theta_W} \longrightarrow \bar{\rho} = 1 + \Delta\rho \; (+\Delta\rho_b)$

  where $\Delta\rho = \frac{3G_F m_t^2}{8\pi^2\sqrt{2}} - \frac{3G_F M_W^2}{8\pi^2\sqrt{2}}\, tg^2\theta_W \left(\log\frac{M_H^2}{M_W^2} - \frac{5}{6}\right) + \dots$

  $\Delta\rho_b = -\frac{G_F m_t^2}{2\sqrt{2}\pi^2} + \dots$

- $\sin^2\theta_W \longrightarrow \sin^2\theta_{eff} = \left[1 + \Delta\kappa \; (+\Delta\kappa_b)\right] \sin^2\theta_W$

  where $\Delta\kappa = \frac{3G_F m_t^2}{8\pi^2\sqrt{2}} \cdot cotg^2\theta_W - \frac{11}{3}\frac{G_F M_W^2}{8\pi^2\sqrt{2}} \left(\log\frac{M_H^2}{M_W^2} - \frac{5}{6}\right) + \dots$

  $\Delta\kappa_b = -\frac{1}{2}\Delta\rho_b = \frac{G_F m_t^2}{4\sqrt{2}\pi^2} + \dots$

- $M_W^2 \longrightarrow \frac{\pi\alpha}{\sqrt{2}\, G_F \sin^2\theta_W} \cdot \frac{1}{1 - (\Delta r_W + \Delta\alpha)}$

  where $\Delta r_W = -\, cotg^2\theta_W\, \Delta\rho(m_t, \log M_H) + \dots$

  $\Delta\alpha = \Delta\alpha_{e\mu\tau}^{(s)} + \Delta\alpha_{top}^{(s)} + \Delta\alpha_{udscb}^{(s)}$

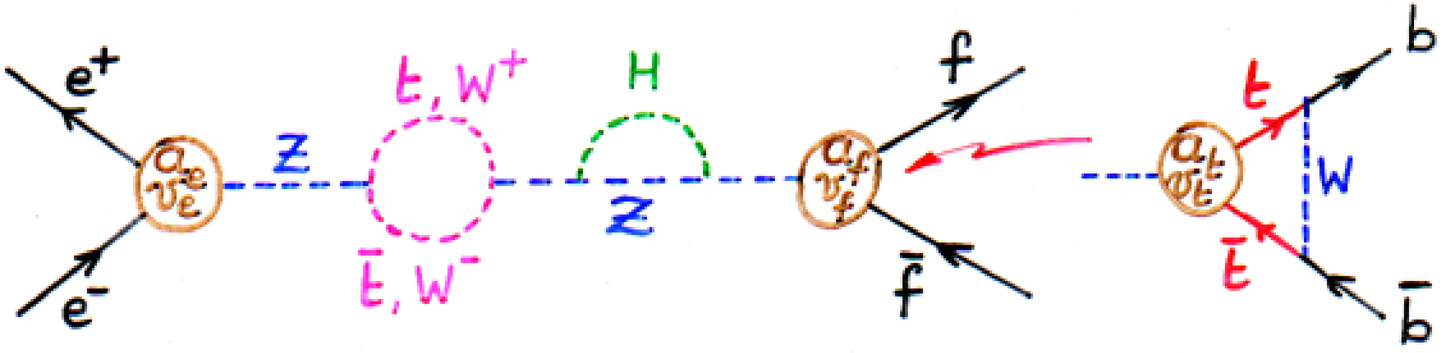
  $\uparrow$ exp^{al} determination

  $\Longrightarrow$ uncertainty!

$\longrightarrow$ compare $O_{exp}(m_t, M_H)$ to $O_{SM}(m_t, M_H)$ in order to predict m_t and M_H or to infirm the S.M. $\longrightarrow$ New Physics

LEP-1 Observables (1/2)

mainly fermion-pair production $e^+e^- \longrightarrow Z \longrightarrow f\bar{f}\ (\equiv q\bar{q},\ \ell^+\ell^-,\ \nu_\ell\bar{\nu}_\ell)$



- Measure at various $\sqrt{s}$: $\sigma(e^+e^- \longrightarrow f\bar{f}) = \dfrac{N_{sel} - \bar{B}_{MC.}}{\varepsilon_f \cdot L}$

$$\frac{d\sigma}{d\cos\theta_f}(e^+e^- \longrightarrow f\bar{f}) \sim 1 + \cos^2\theta_f + \frac{8}{3} A^f_{FB} \cos\theta_f \longrightarrow A^f_{FB}$$

τ polarisation $(\tau \longrightarrow \pi\nu_\tau,\ \rho\nu_\tau,\ A_1\nu_\tau,\ l\nu_l\nu_\tau)$

- Determine : $M_Z,\ \Gamma_Z,\ N_{\nu_l},\ \alpha_s,\ a_f, v_f\ (\sin^2\theta_{eff}), \ldots$

↪ extract EW corrections :

$\exists$? m_t? M_H? New Physics?

LEP-1 Observables (2/2)

S.M. predictions:

- $$\sigma_{f\bar{f}} = \underbrace{\frac{12\pi}{M_Z^2} \cdot \frac{\Gamma_e \Gamma_f}{\Gamma_Z^2}}_{\sigma_0^f} \cdot \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + \frac{s^2\Gamma_Z^2}{M_Z^2}} + \gamma Z \text{ int.} + \gamma \text{ exch.}$$

where $\Gamma_f \approx N_c^f \cdot \frac{G_F M_Z^3}{6\sqrt{2}\pi} \cdot (a_f^2 + v_f^2)\sqrt{1 - 4\frac{m_f^2}{M_Z^2}}$

couplings : $a_f = \sqrt{\bar{\rho}}\, T_3$

$v_f = \sqrt{\bar{\rho}}\,(T_3 - 2Q_f \sin^2\theta_W)$

- $A_{FB}^f \approx 3\,\frac{a_e v_e}{a_e^2 + v_e^2} \cdot \frac{a_f v_f}{a_f^2 + v_f^2}$ on Z-resonance peak

- $\bar{P}_\tau \approx -2\,\frac{a_\tau v_\tau}{a_\tau^2 + v_\tau^2} + \dots$

- $A_{FB}^{pol}(\tau) \approx -\frac{3}{4} \cdot \frac{2\,a_e v_e}{a_e^2 + v_e^2} + \dots$

Accuracies expected at LEP

- Situation in Summer 1989:

$M_Z = 91.12 \pm 0.16$ GeV $M_W = 80.0 \pm 0.36$ GeV

$\Gamma_Z = 3.8 \pm 1.5$ GeV $\sin^2\theta_W = 0.227 \pm 0.006$

$N_\nu = 3.0 \pm 0.9$

- LEP expectations :

M_Z $\pm 50-20$ MeV

Γ_Z $\pm 20-10$ MeV

M_W ± 100 MeV

N_ν ± 0.3

A_{FB}^μ ± 0.0035

A_{FB}^b ± 0.0050

A_τ ± 0.011

■ Z^0 Line - Shape Fits

	'90/91	'92	'93	'94	'95	Total
hadrons	$1.7\ 10^6$	$2.7\ 10^6$	$2.6\ 10^6$	$5.9\ 10^6$	$2.6\ 10^6$	$15.5\ 10^6$
leptons	$0.2\ 10^6$	$0.3\ 10^6$	$0.3\ 10^6$	$0.7\ 10^6$	$0.3\ 10^6$	$1.7\ 10^6$

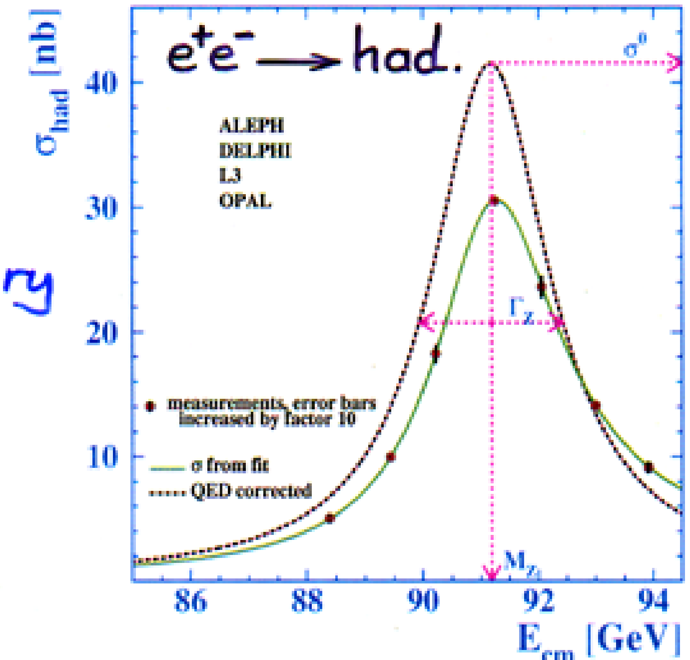
all : $\sim 17\ 10^6\ Z^0$

Fits to $\sigma_{exp}(s)$ and $A^{\ell^-}_{FB}(s)$ for $e^+e^- \longrightarrow$ had., $\mu^+\mu^-, \tau^+\tau^-, e^+e^-$

$$\sigma^f_{th}(s) = \int_{\frac{4m_f^2}{s}}^{1} dz\, \mathcal{H}^{tot}_{QED}(z,s)\, \sigma^f_{EW}(s)$$

initial ⊕ final state photon radiation $O(\alpha^2 - \alpha^3)$

elementary process



9 and 5 parameter fits:

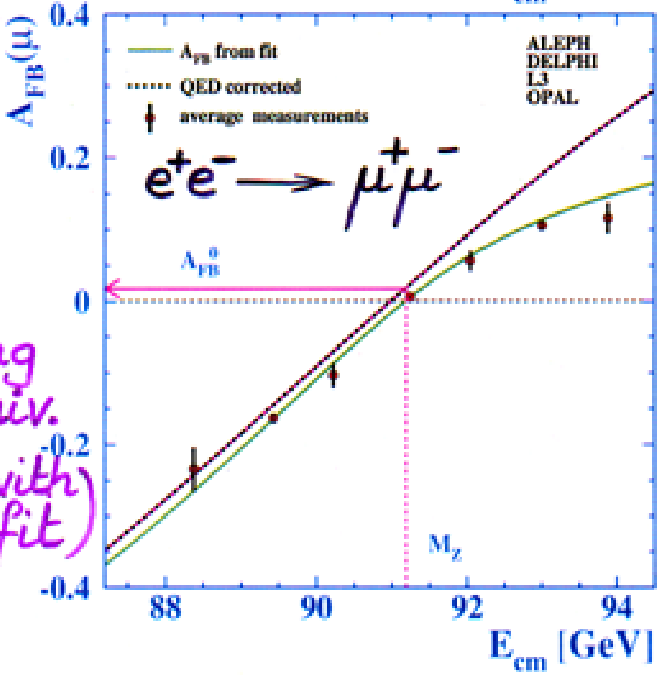
$M_Z = 91.1875 \pm 0.0021\ \text{GeV}/c^2$

$\Gamma_Z = 2.4952 \pm 0.0023\ \text{GeV}$

$\sigma^h_0 = 41.540 \pm 0.037\ \text{nb}$

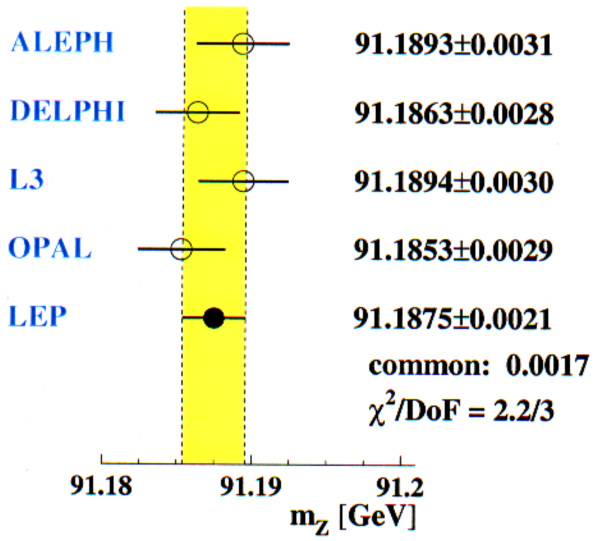
$\left.\begin{array}{l} R^0_\ell = 20.767 \pm 0.025 \\ A^\ell_{FB} = 0.0171 \pm 0.0010 \end{array}\right\}$ assuming lepton univ. (checked with 9-param. fit)

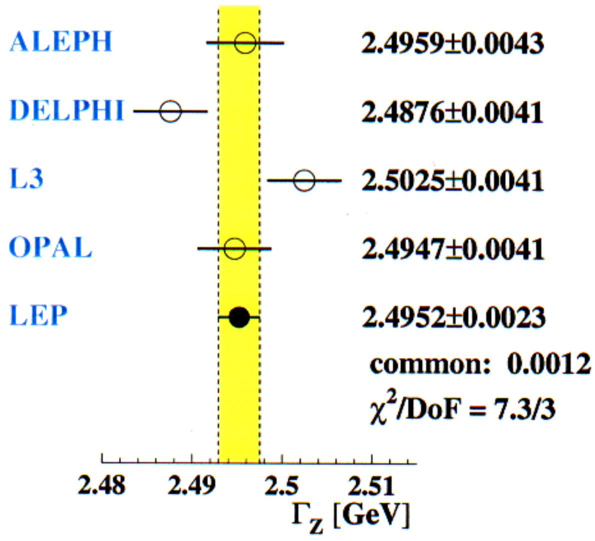
$\chi^2/_{d.o.f.} = 36.5/31$

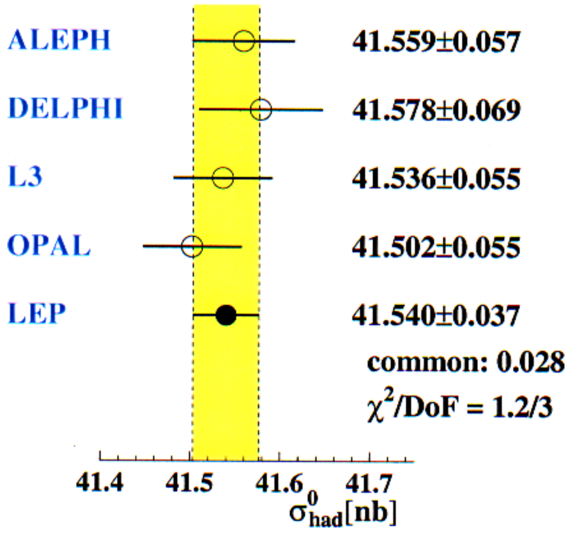


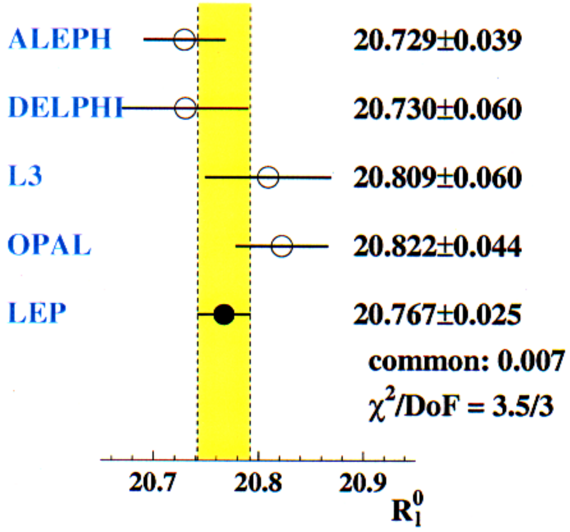
$R^0_\ell = \frac{\Gamma_{had}}{\Gamma_\ell}$

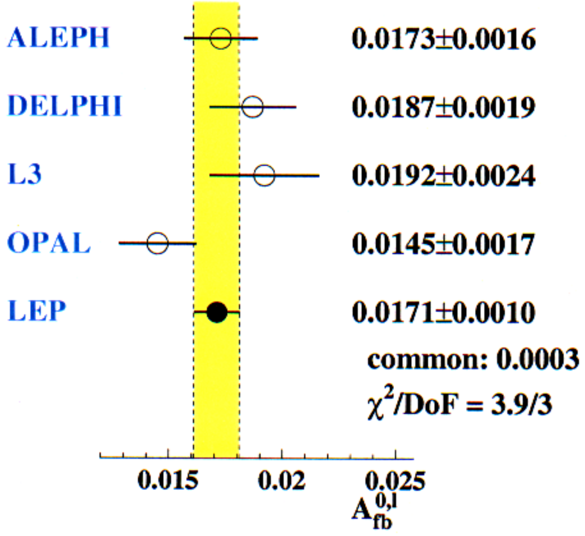
Comparison between 5-param. Fit results











Excellent agreement
between the 4 experiments
for all 5 parameters

▪ Check Universality of a_l, v_l

$$A_{FB}^{l} \approx 3 \frac{a_e v_e}{a_e^2+v_e^2} \cdot \frac{a_l v_l}{a_l^2+v_l^2}$$

$$R_l^0 \approx \frac{\sum_q (a_q^2+v_q^2)}{a_l^2+v_l^2}$$

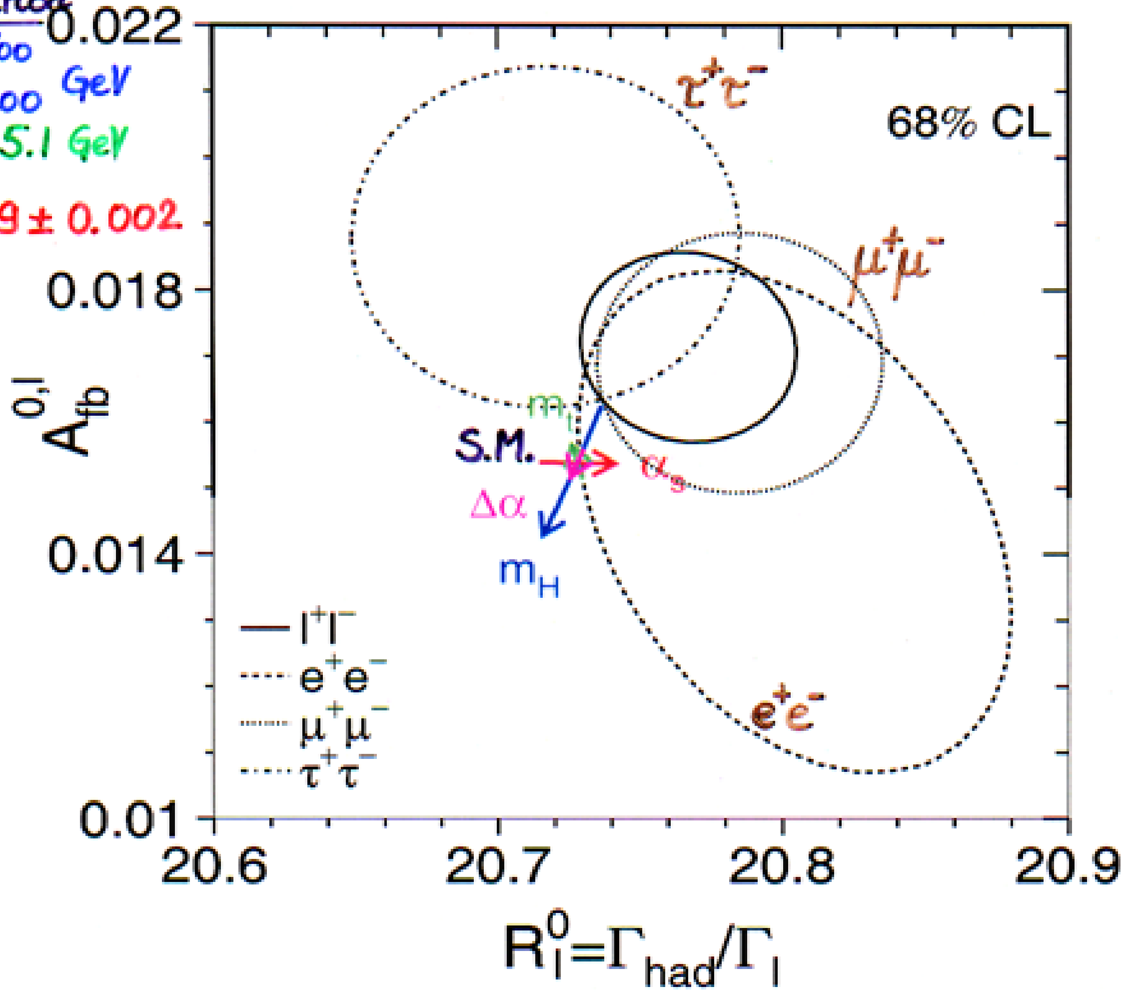
where $a_l = -\frac{1}{2}\sqrt{\bar{e}}$, $v_l = \sqrt{\bar{e}}\left(-\frac{1}{2} + \sin^2\theta_{eff}^{l}\right)$

S.M. prediction

$M_H = 300^{+700}_{-200}$ GeV

$m_t = 174.3 \pm 5.1$ GeV

$\alpha_s(M_Z^2) = 0.119 \pm 0.002$



good agreement with S.M. expectation

↳ best for low Higgs mass

Effective Leptonic Coupling Constants

All leptonic measurements combined (LEP-1+SLD)

$v_l = -\ 0.03783 \pm 0.00041$

$a_l = -\ 0.50123 \pm 0.00026$ $\neq a_l^{Born}$ by 4.7 st. dev.

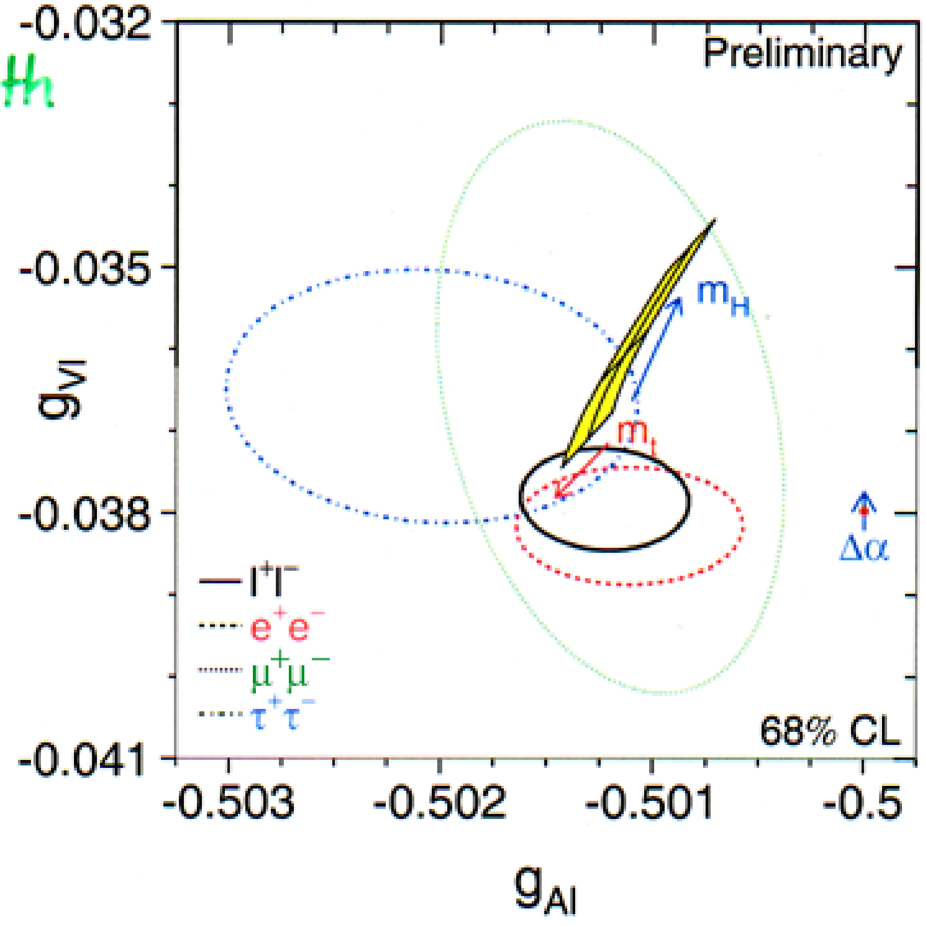
$\rho_l = 1.0049 \pm 0.0010 \Longrightarrow$ EW corrections exist!

$\sin^2\theta_{eff}^{l} = 0.23113 \pm 0.00021 \Longrightarrow$ accuracy $< 10^{-3}$!

comparison with S.M. prediction

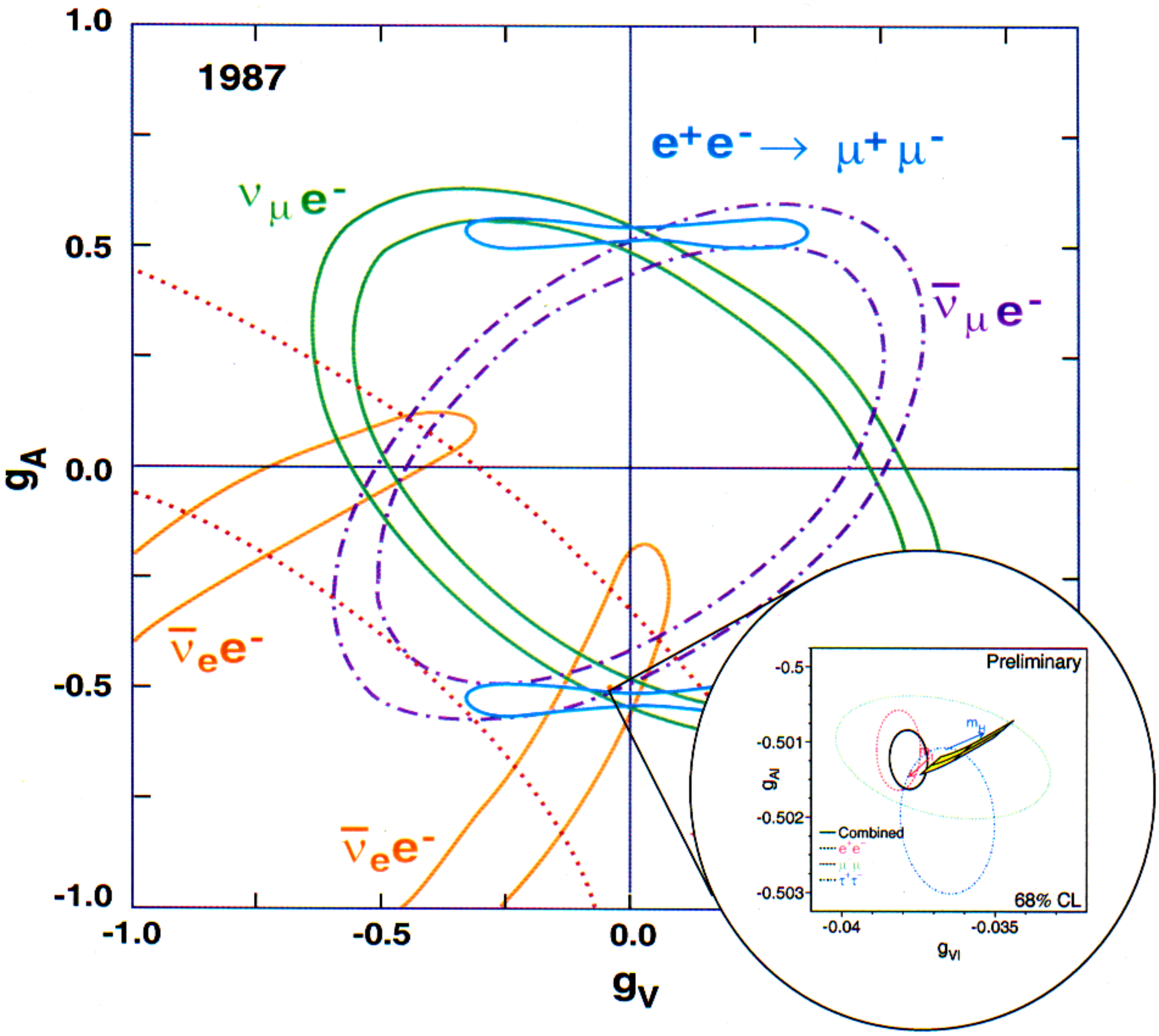
↓

agreement best for light Higgs



LEP : The breakthrough in precision

$\{a_l, v_l\}$ from $Z^0 \rightarrow l^+l^-$ (LEP) and A_{LR} (SLD)



Number of light (left handed) ν species

- extract $\frac{\Gamma_{inv}}{\Gamma_l} = \frac{\Gamma_Z - (\Gamma_{l^\pm}^{tot} + \Gamma_{had})}{\Gamma_l} = \sqrt{\frac{12\pi R_l^0}{\sigma_h^0 M_Z^2}} - R_l^0 - 3$

  from the 5-param. fit: $\frac{\Gamma_{inv}}{\Gamma_l} = 5.942 \pm 0.016$

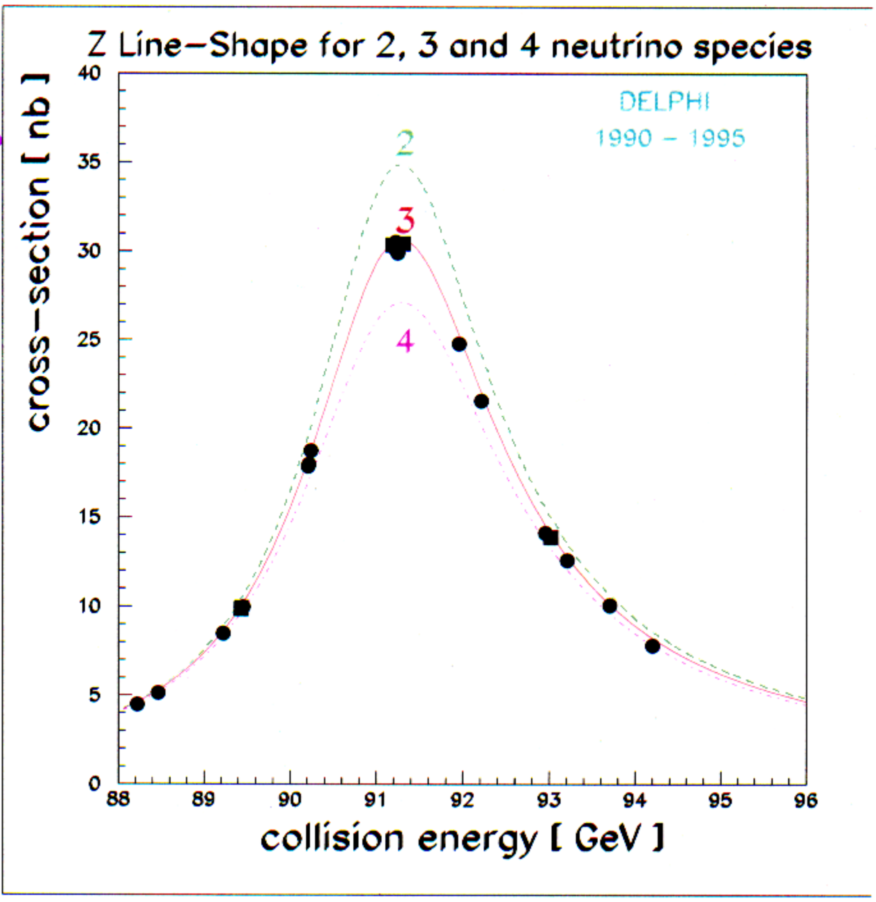
- take $\frac{\Gamma_\nu}{\Gamma_l}$ from the S.M. (precise prediction): $\rightarrow 1.9912 \pm 0.0012$

- $N_\nu = \frac{\Gamma_{inv}/\Gamma_l}{\Gamma_\nu/\Gamma_l} = 2.9841 \pm 0.0083$

  within 2 st. deviations from 3 !?

  ↓

  ~24% He in Universe agrees with direct obs.



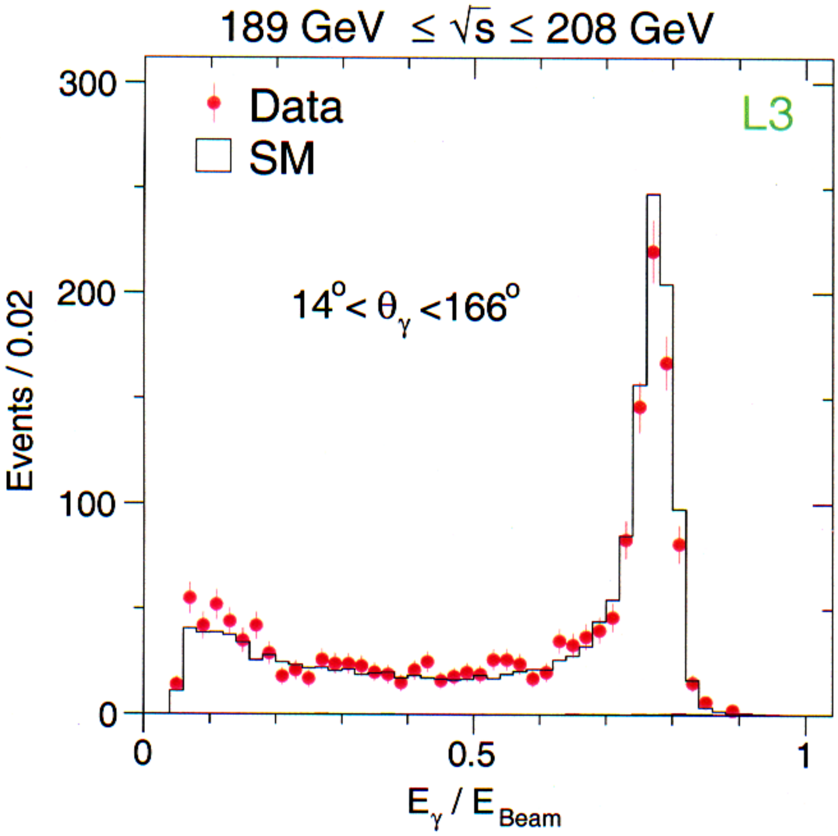
- $\delta\Gamma_{inv}^{new} = \Gamma_{inv}^{exp} - \Gamma_{inv}^{SM}$

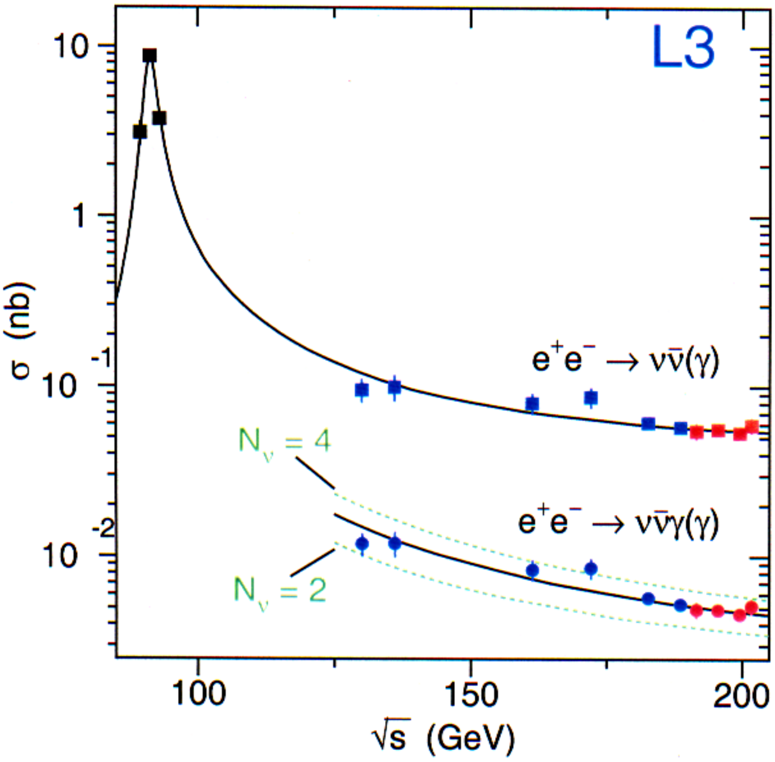
  $= -2.7 \pm 1.6$ MeV

  ⇓

  extra contribution to Γ_{inv} due to New Physics is < 1 MeV with 99% C.L.

$e^+e^- \to \nu\bar{\nu}\gamma$





From single photon:

$N_\nu = 2.86 \pm 0.13$ (LEP 2)

$N_\nu = 2.98 \pm 0.10$ (LEP 1)

From Z width:

$N_\nu = 2.978 \pm 0.014$

Search for $e^+e^- \to \tilde{G}\tilde{\chi}^0_1 \to \tilde{G}\tilde{G}\gamma$ No signal observed

τ Polarisation

$$\mathcal{P}_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$\mathcal{P}_\tau(\cos\theta_\tau) = -\frac{A_\tau(1+\cos^2\theta_\tau) + 2A_e\cos\theta_\tau}{1+\cos^2\theta_\tau + \frac{8}{3}A^\tau_{FB}\cos\theta_\tau}$$

$$\hookrightarrow \overline{\mathcal{P}}_\tau = -A_\tau \quad \text{and} \quad A^{pol}_{FB} = -\frac{3}{4}A_e$$

$$\left(\text{with } A_l = \frac{2a_l v_l}{a_l^2 + v_l^2}\right)$$

Results

$A_\tau = 0.1439 \pm 0.0043$

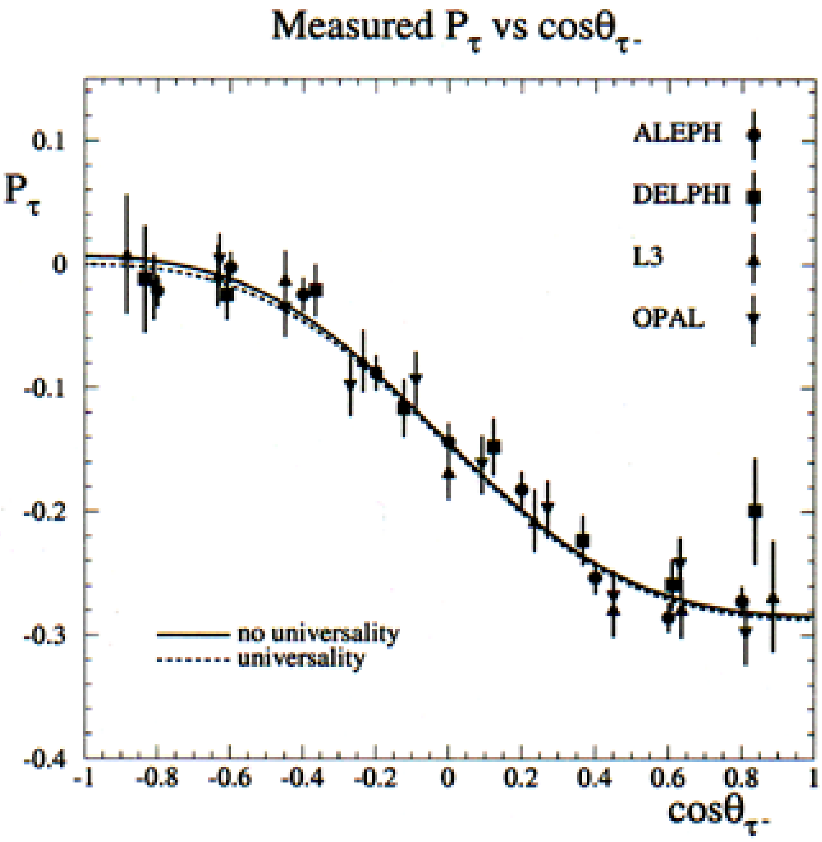
$A_e = 0.1498 \pm 0.0049$

$\downarrow$ assuming universality

$A_l = 0.1465 \pm 0.0033$

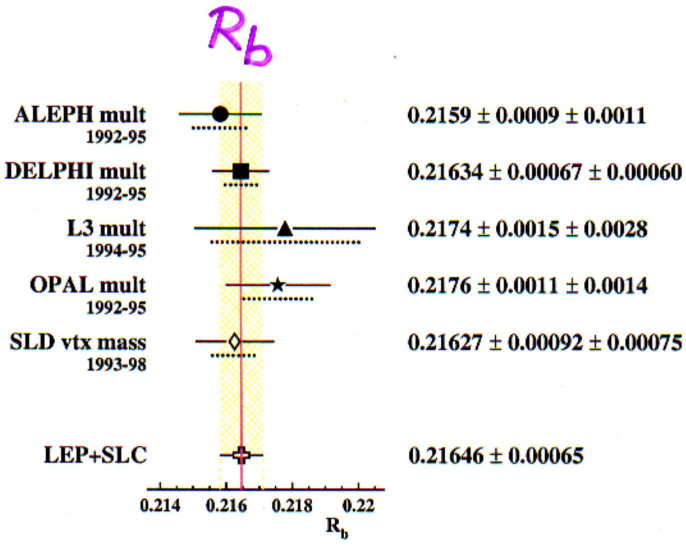
(SLD : 0.1513 ± 0.0021)

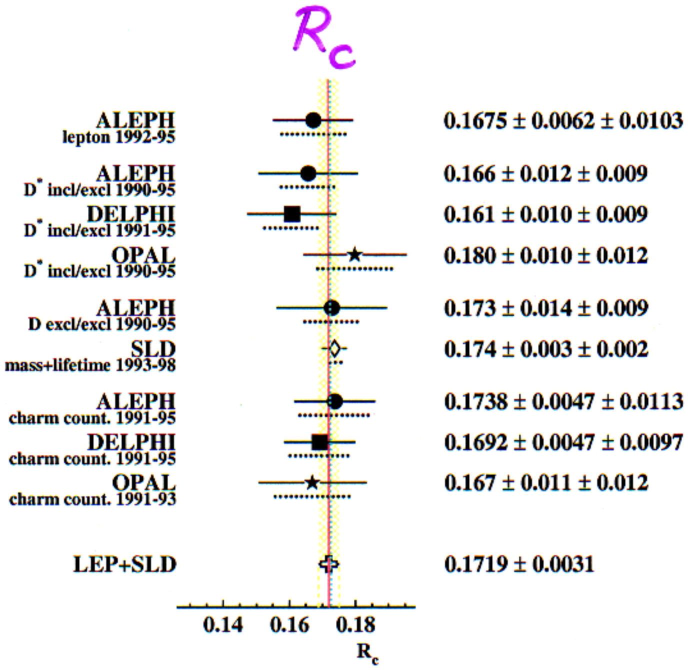
$\sin^2\theta^l_{eff} = 0.23159 \pm 0.00041$

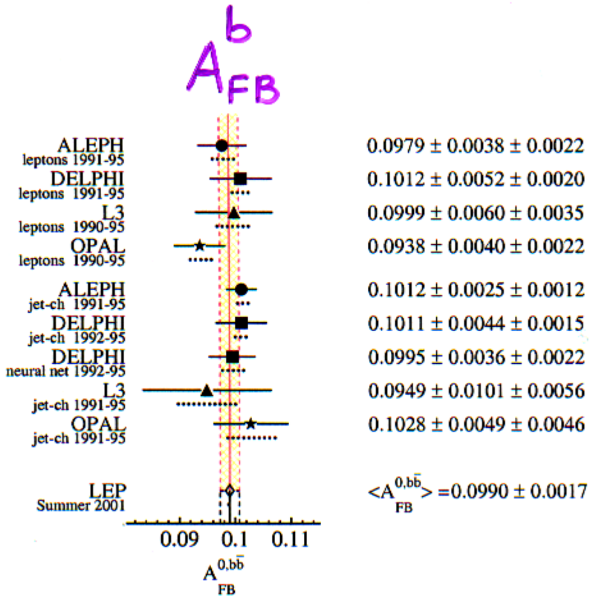

Measured P_τ vs $\cos\theta_{\tau^-}$

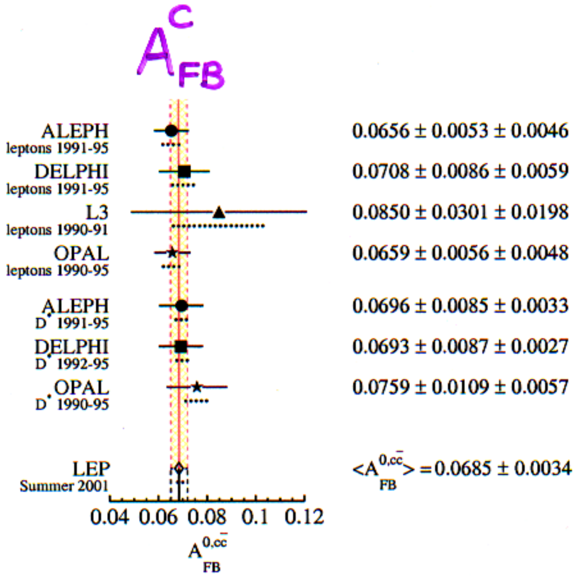
■ b and c quark results (1/3)

- ► tagging based on:
  - lifetime (+ vertex charge)
  - prompt lepton
  - charmed hadron decays
- ► determine $R_{b,c} = \frac{\Gamma_{b,c}}{\Gamma_{had}}$ and $A_{FB}^{b,c}$


R_b

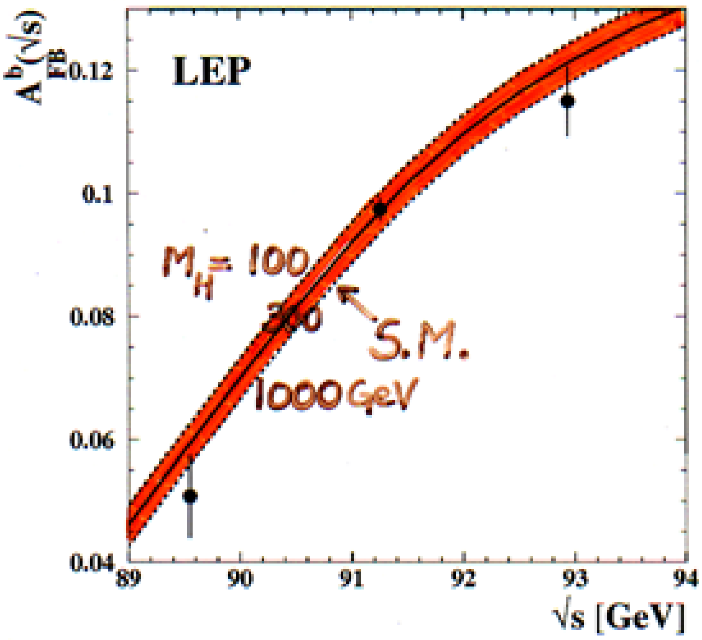

R_c

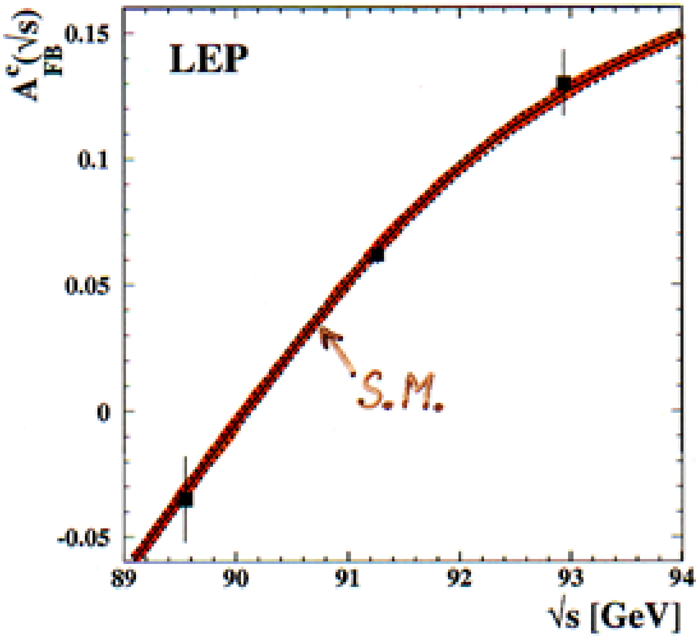

A_{FB}^b


A_{FB}^c

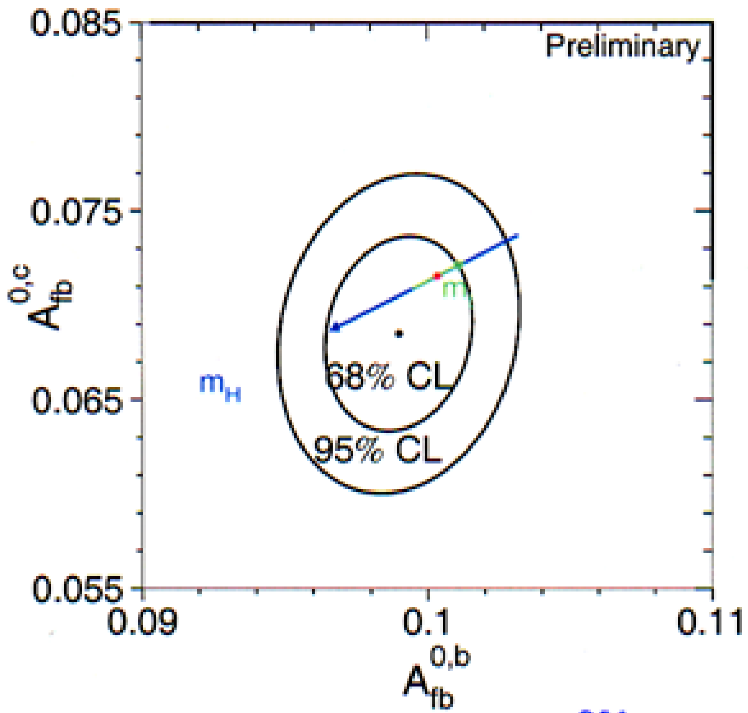
b and c quark results (2/3)

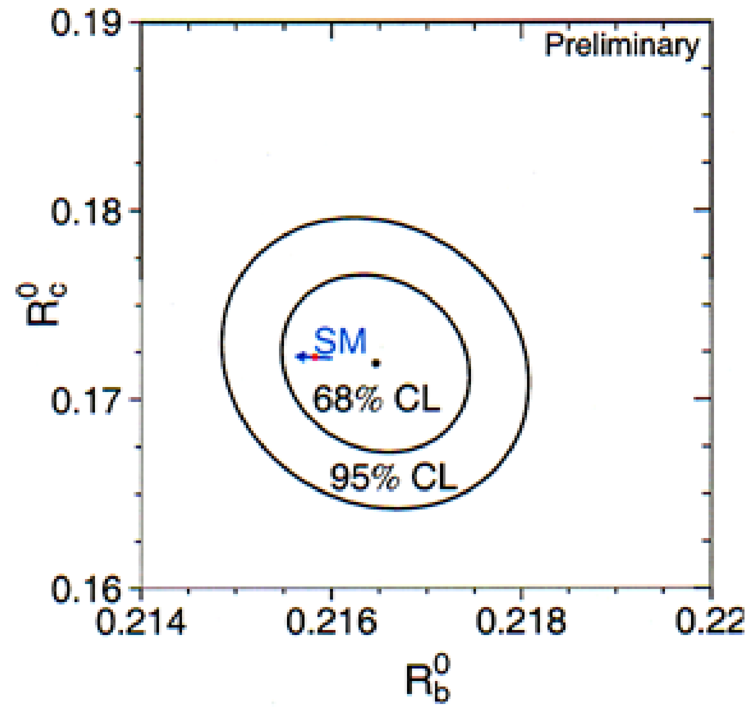
▶ $\sqrt{s}$ dependence of asymmetries





▶ test of S.M. consistency





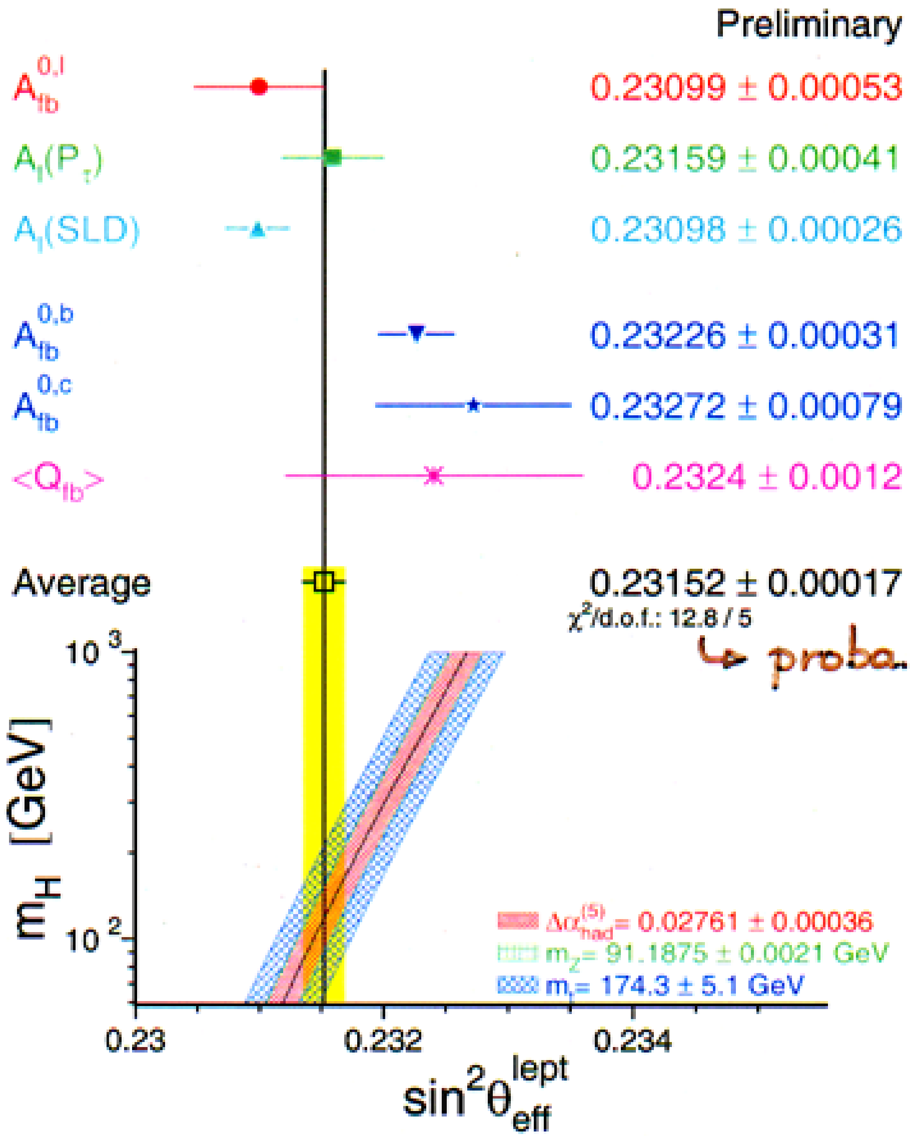
R_b^{exp} agrees with R_b^{SM} $\Rightarrow$ no evidence for New Physics!

$\Downarrow$

$m_t \approx 150 \pm 25$ GeV

■ Value of $\sin^2\theta_{eff}^{l}$ from A_{FB}^{f}

Compatibility of various determinations?



leptons {

quarks {

↳ proba. ~ 2.5%

χ^2/d.o.f.

$Z^0 \longrightarrow l^+l^-$: $\sin^2\theta_{eff}^{l} = 0.23113 \pm 0.00021$ 1.6/2

$Z^0 \longrightarrow q\bar{q}$: $\sin^2\theta_{eff}^{l} = 0.23230 \pm 0.00029$ 0.3/2

difference ~ 3.3 st. dev.

→ stat. fluctuation or sign of New Physics?
(or unknown source of systematics?)

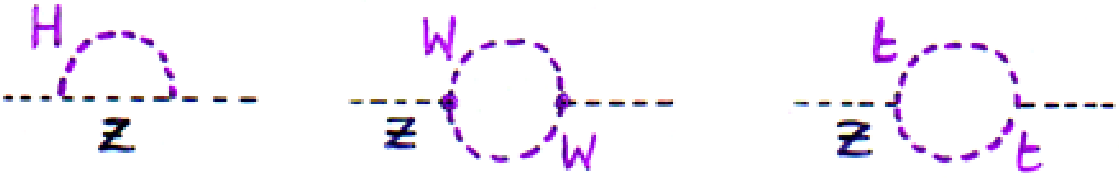
▪ Derivation of EW corrections

▶ LEP1 + SLC : S.M. (Born + QED)

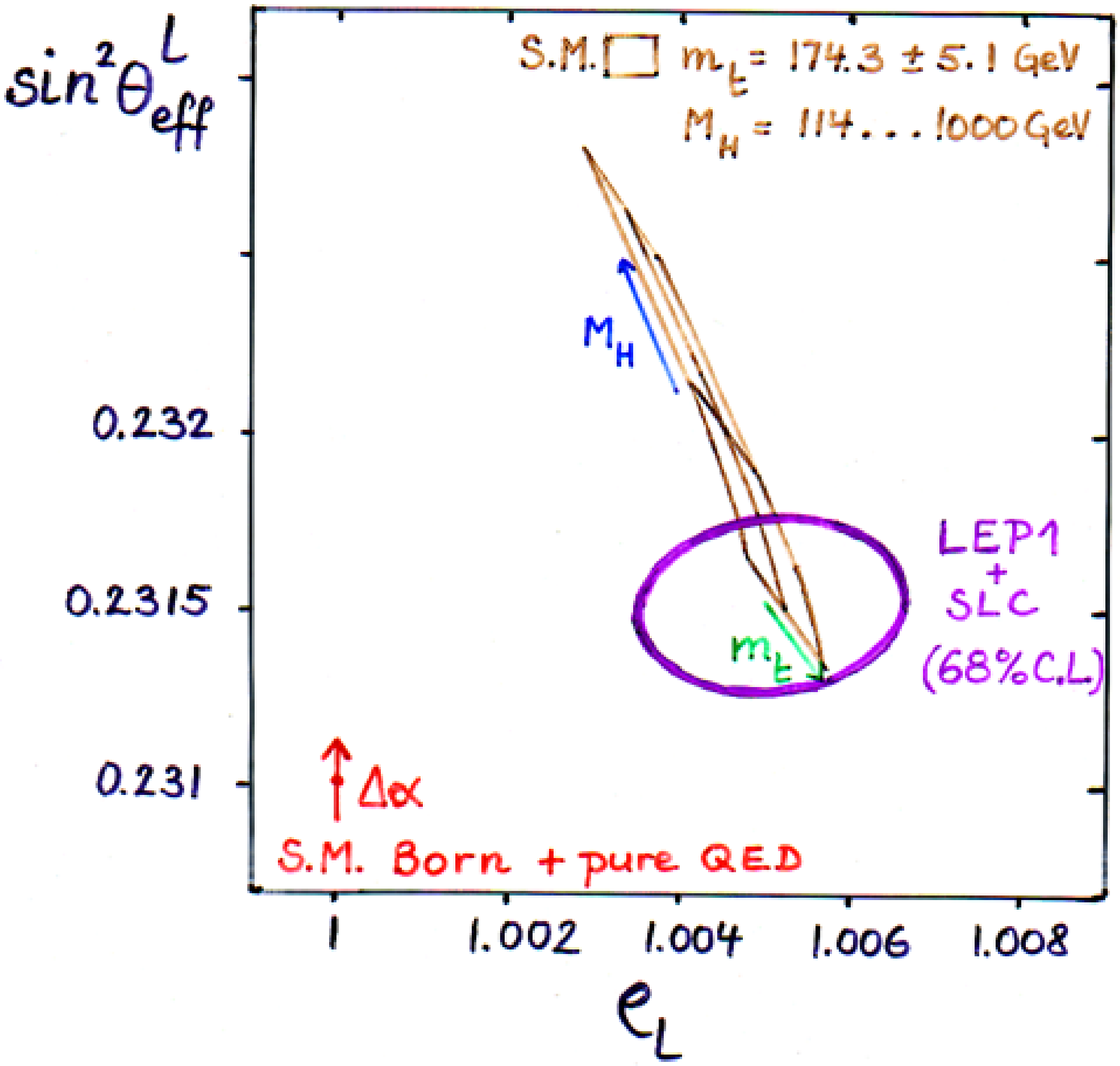
$\sin^2\theta_{eff}^{l} = 0.23150 \pm 0.0016$ 0.23101 ± 0.00012

$\rho = 1.0050 \pm 0.0010$ 1

⇒ evidence for (non-pure QED) EW corrections!



→ determine m_t, M_H



■ Global Fit : m_t, M_H, α_s, $\sin^2\theta_W$, M_W

with SLD, NuTeV(νN), APV, $\Delta\alpha_{had}$ results

$m_t = 169^{+12}_{-9}$ GeV (Tevatron : 174.3 ± 5.1 GeV)

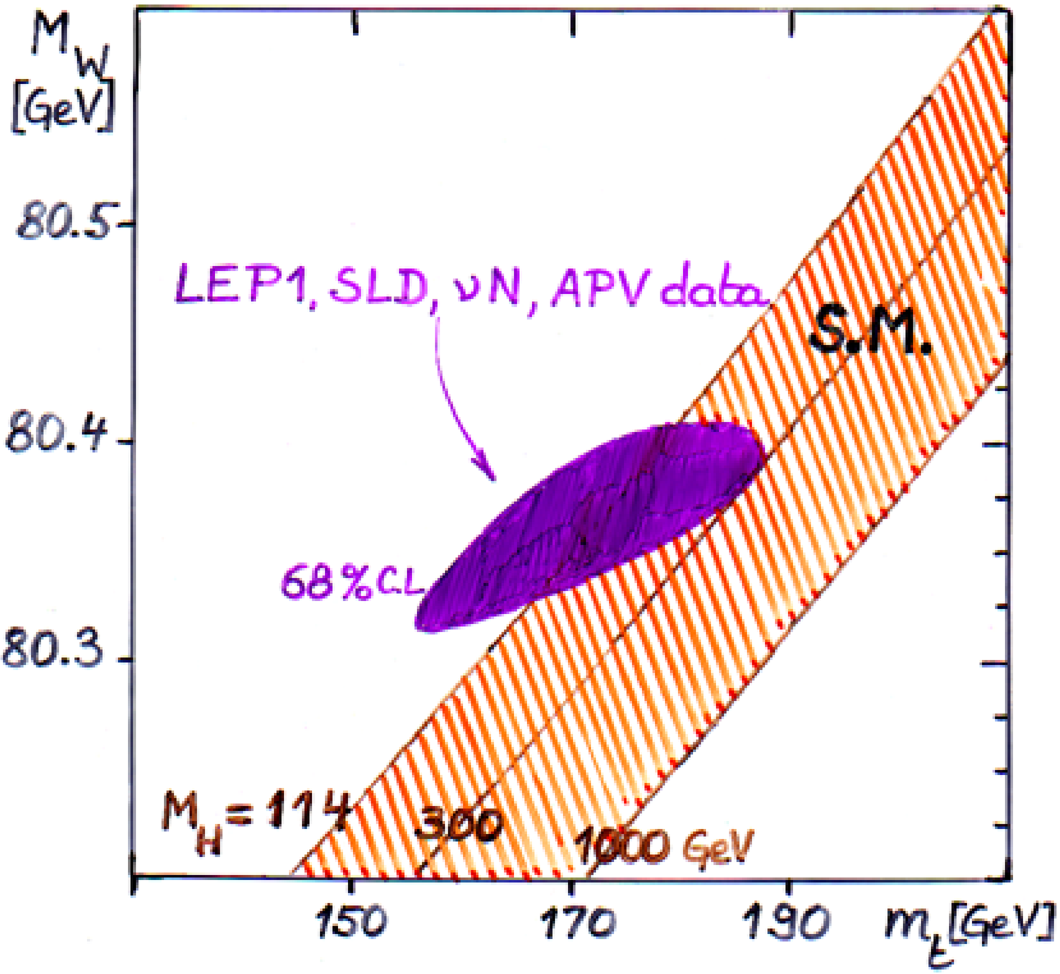
$M_H = 81^{+109}_{-40}$ GeV $\longrightarrow$ $M_H \lesssim 330$ GeV (95% C.L.)

$\alpha_s(M_Z^2) = 0.1187 \pm 0.0027$

$\chi^2/_{d.o.f.} = 18.9/_{12}$ (proba. ~ 7%)

$\sin^2\theta^{L}_{eff} = 0.23150 \pm 0.00016$ (precision 0.7‰)

$M_W = 80.363 \pm 0.032$ GeV (Tevatron : 80.454 ± 0.060)



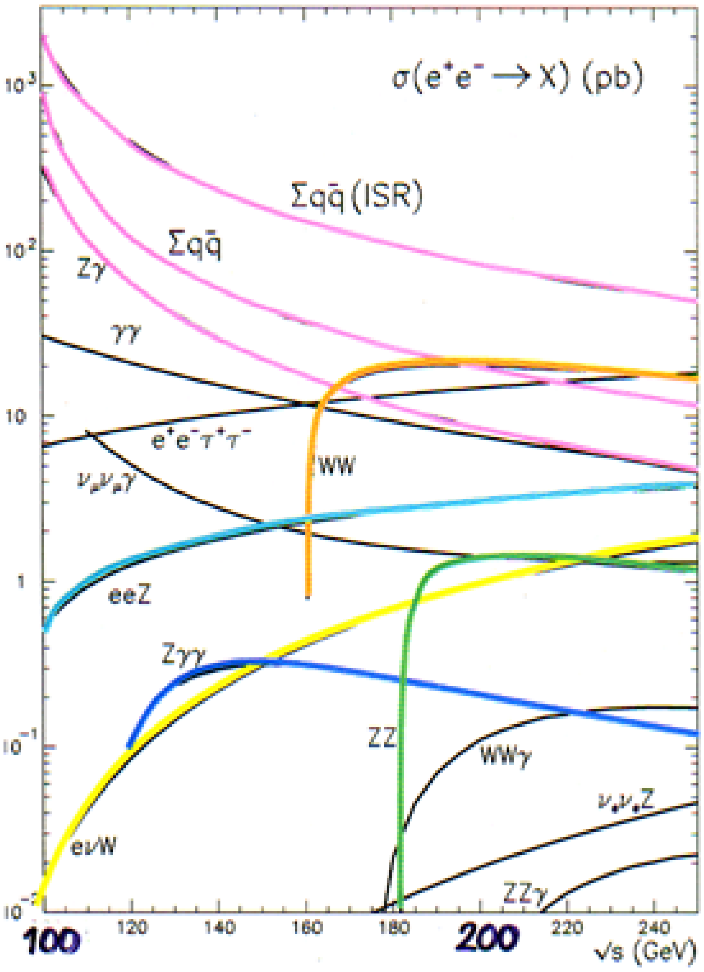
LEP2 Measurements

- When starting LEP2 (1996), new processes (4f!) were predicted by the S.M. → experiments should check whether they occur as predicted or not...

$$\left.\begin{array}{l} e^+e^- \longrightarrow W^+W^- : M_W,\ \Gamma_W,\ TGC \\ \\ e^+e^- \longrightarrow We\nu_e : TGC \end{array}\right\} \begin{array}{l}\text{W properties} \\ \text{(incl. Br's)}\end{array}$$

$$e^+e^- \longrightarrow ZZ : TGC$$

Born cross-sections



$$\sigma^W_{LEP2} \sim 10^{-3} \sigma^Z_{LEP1}$$

$$\downarrow$$

$\sim 10^4$ W^+W^- pairs/$_{exp^t}$

exp.$^{\underline{tal}}$ conditions more difficult than at LEP1

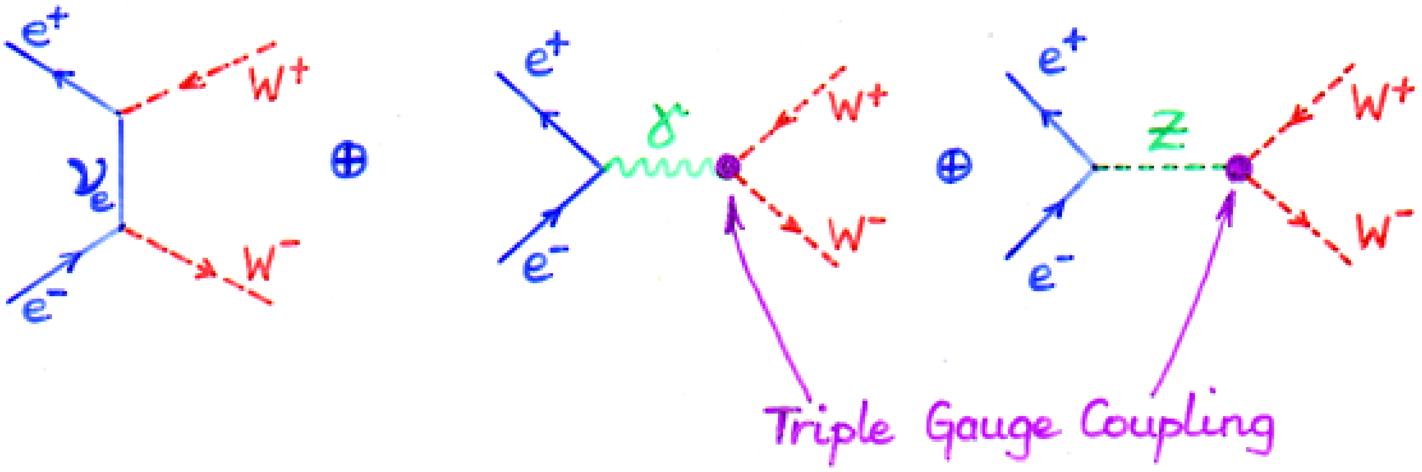
☹ Resonant depolarisation not operational for $E_{beam} \gtrsim 60$ GeV ⟹ $\sqrt{s}$ less well known than at LEP1

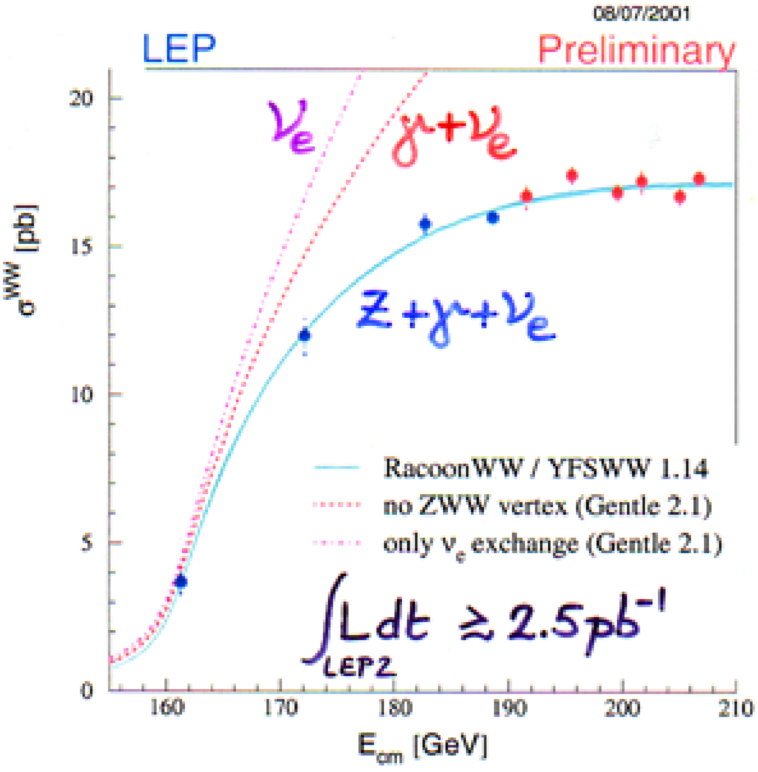
($\Delta E_b \sim \pm 20$ MeV) ($\Delta E_b \sim \pm 1$ MeV)

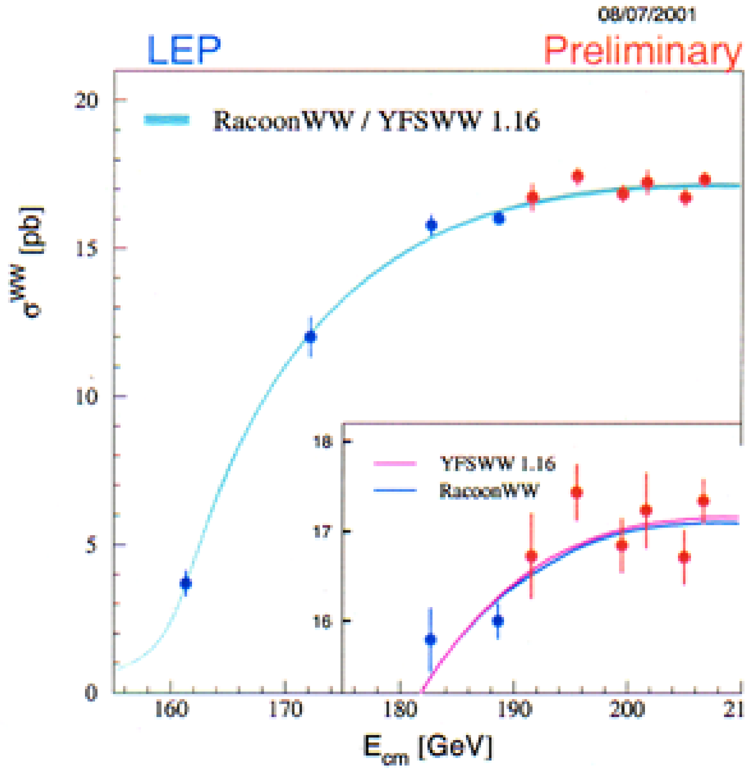
W^+W^- pair production

- reflects the gauge structure of the S.M.:

3 competing diagrams





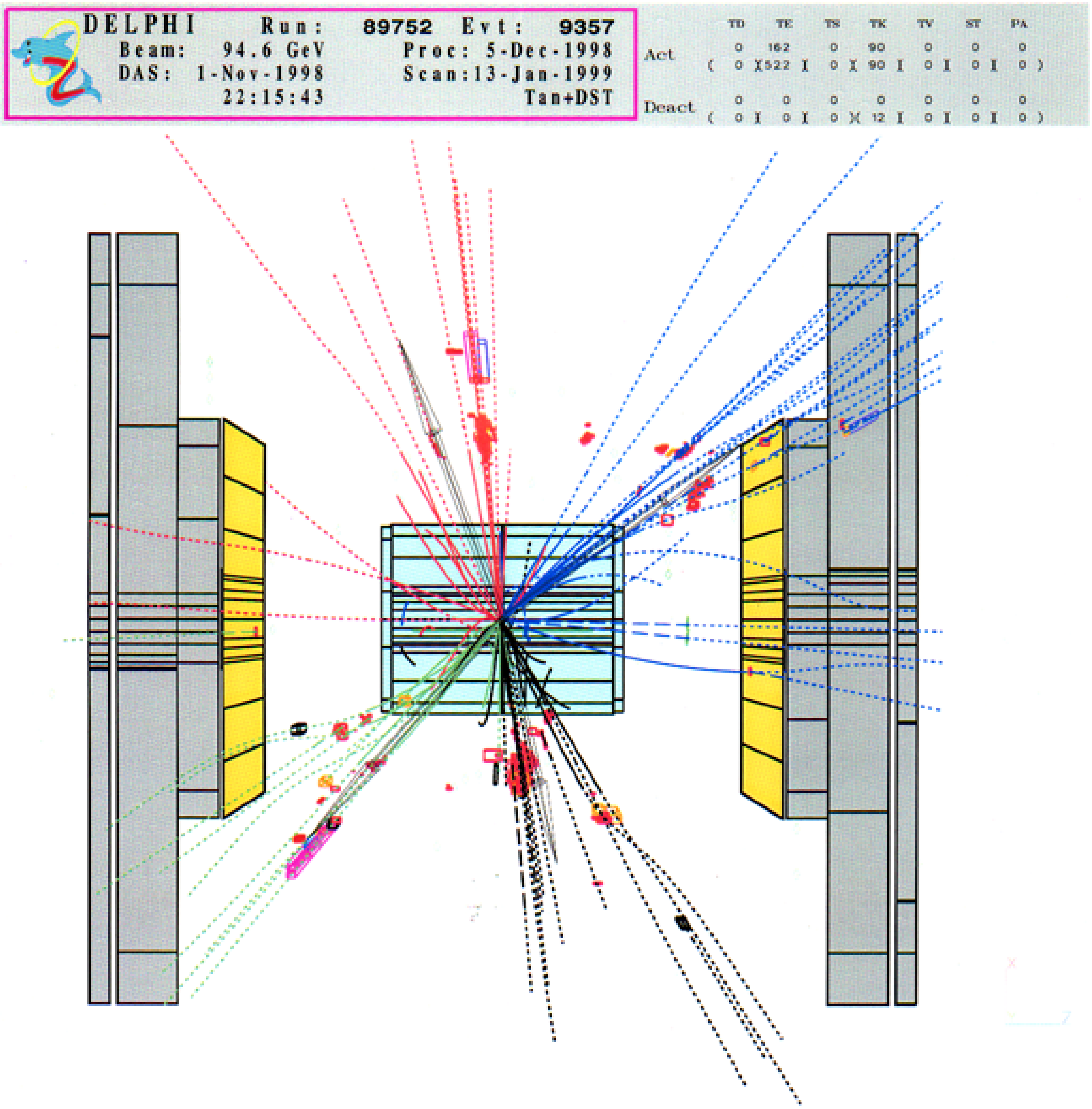


excellent agreement with (improved!) full $O(\alpha)$ theoretical predictions

↳ fit to threshold line-shape:

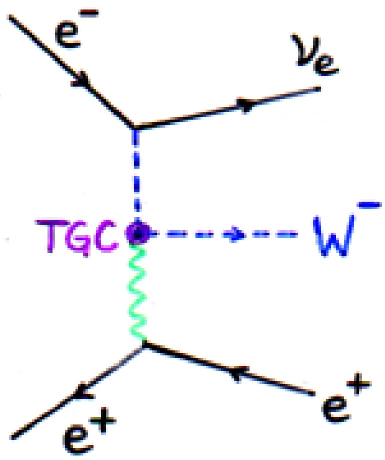
$$M_W = 80.40 \pm 0.21 \text{ GeV}$$

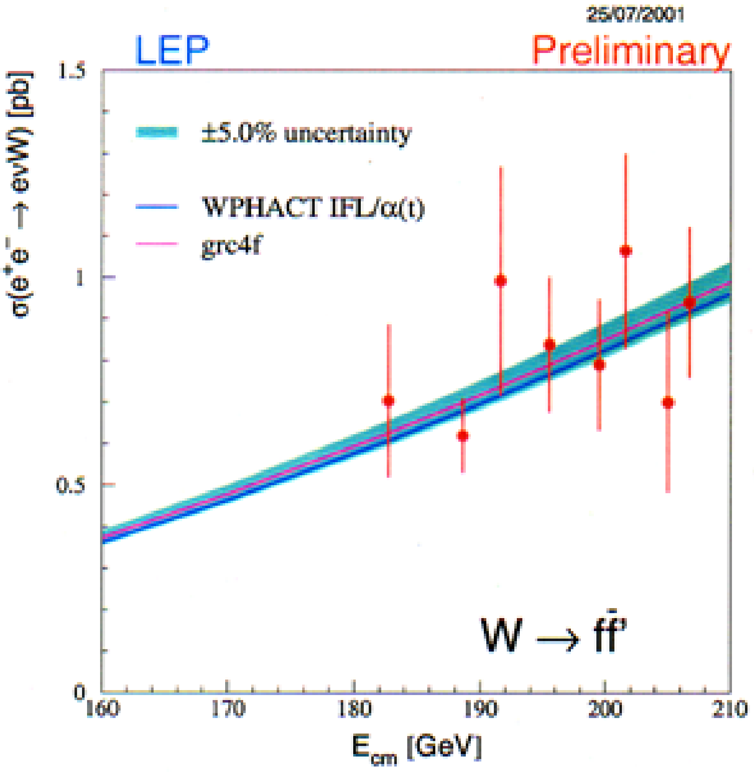
$e^+e^- \longrightarrow W^+W^- \longrightarrow$ 4 jets at $\sqrt{s} = 189$ GeV



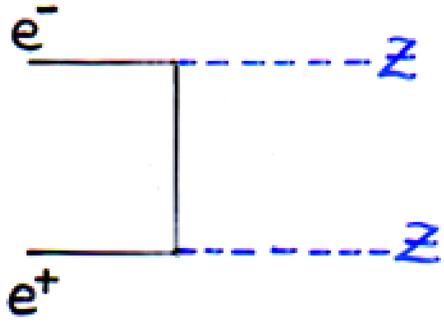
■ $e\nu_e W$ and ZZ production

▶ $e^+e^- \longrightarrow e\nu W$

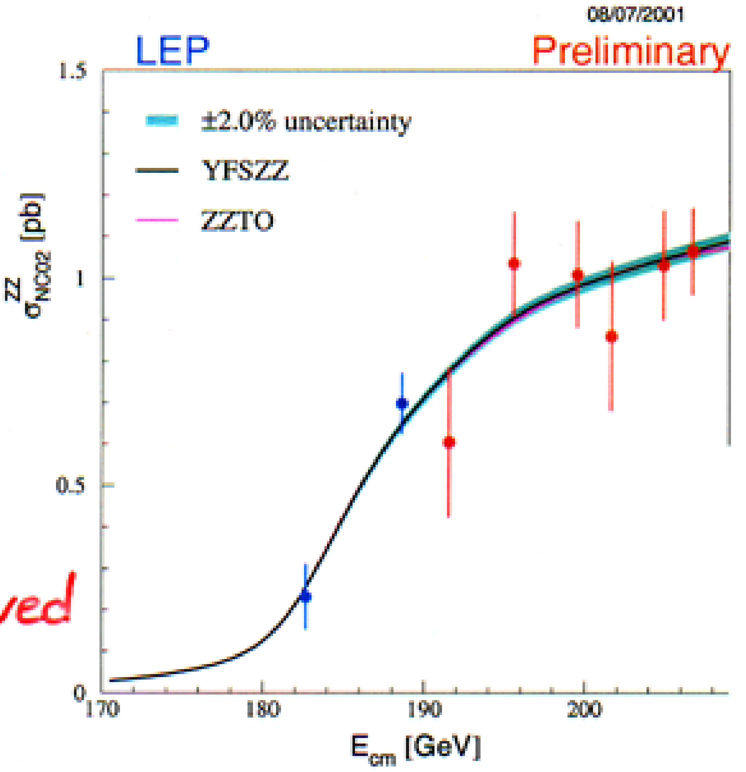




▶ $e^+e^- \longrightarrow ZZ$



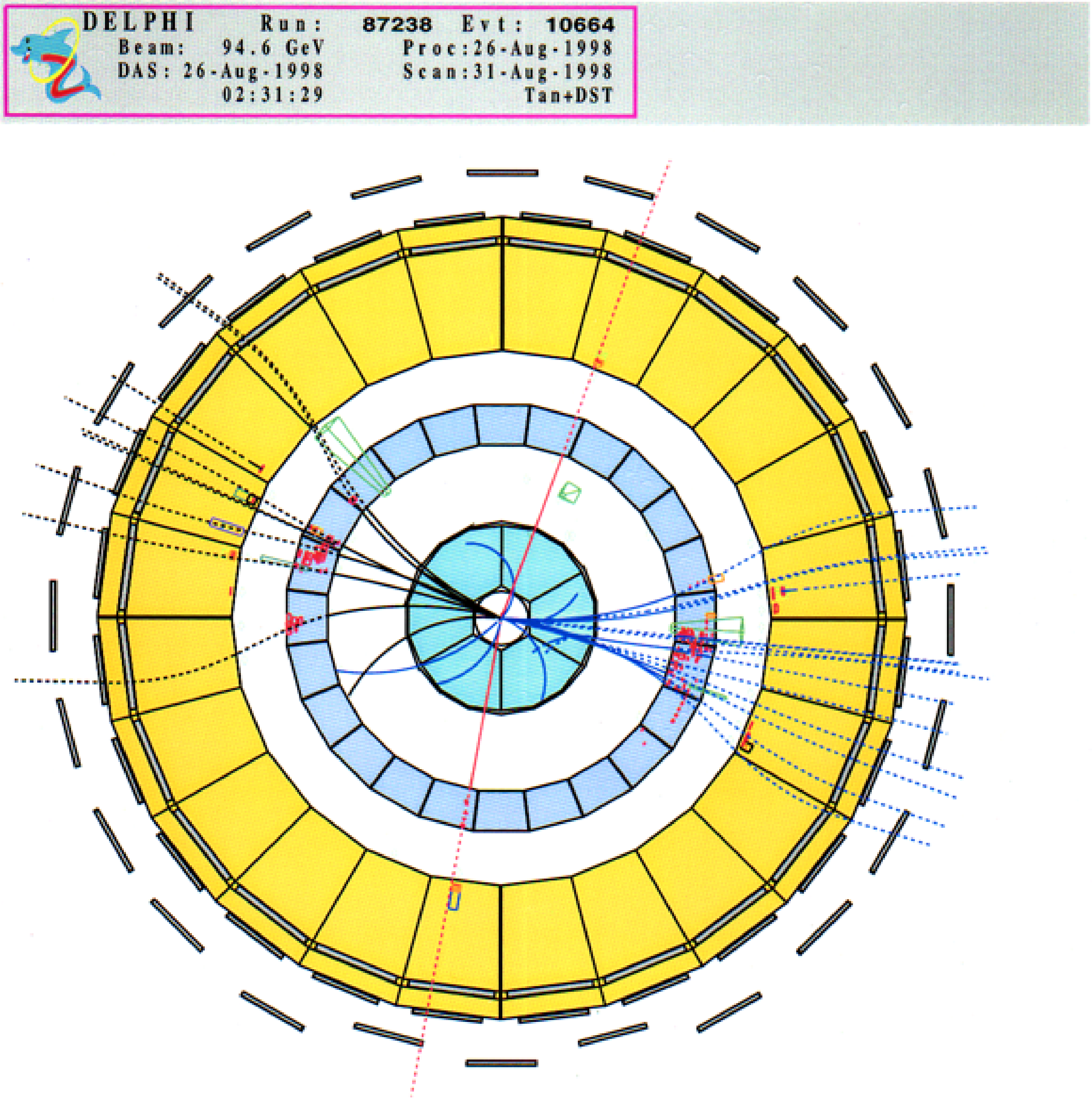
no gauge coupling



- both phenomena observed as predicted by the S.M.

$e^+e^- \longrightarrow Z^0Z^0 \longrightarrow (q\bar{q})\,(\mu^+\mu^-)$ at $\sqrt{s} = 189$ GeV

2 jets

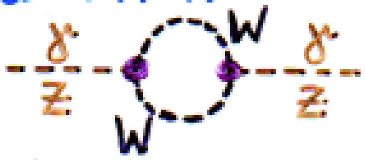


Triple Gauge Couplings (½)

- LEP2: <u>direct</u> observation of the couplings of 3 gauge bosons: ZWW, γWW from $e^+e^- \longrightarrow W^+W^-, e\nu W, \nu\nu\gamma$

- $C(ZWW)$ and $C(\gamma WW)$ defined by "Yang-Mills" ($\equiv$ non-abelian) structure of gauge sector in S.M.

- several forms of couplings beyond the S.M. constrained by LEP1 and SLC because of:
  - relations between $Vf\bar{f}$ and VW^+W^-
  - bosonic loop corrections



$\Rightarrow$ LEP2 useful mainly when $C(Vf\bar{f})$ poorly related to $C(VWW)$, e.g. new SU(2) group

- most general Lorentz invariant form: 7 independent terms for each (γ, Z) coupling:

CP conserving	CP violating
$g_{VWW}, \kappa_V, \lambda_V, z_V$ $(\not{C}, \not{P})$	$\kappa'_V, \lambda'_V, \kappa''_V$

$$\mathcal{L}^{VWW}_{SM} \text{ conserves CP} \Rightarrow \begin{cases} g_{ZWW} = g_1^Z = 1 \\ \kappa_\gamma = \kappa_Z = 1 \\ \lambda = \lambda' = \kappa' = \kappa'' = 0 \end{cases}$$

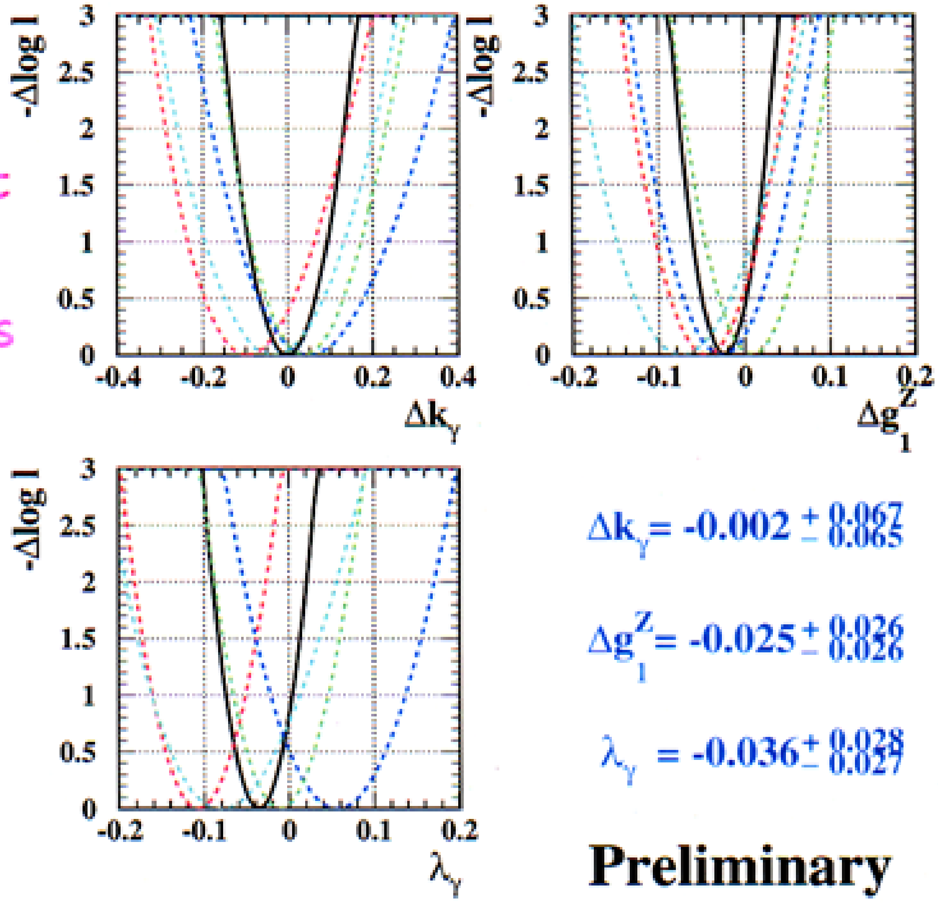
TGC : LEP results on γW^+W^- and $Z W^+W^-$

Fit $\Delta g_1^Z, \Delta\kappa_\gamma, \lambda_\gamma$ to $\frac{d\sigma^{exp}}{d\Omega_W \cdot d\Omega_f} \longrightarrow$ deviations from 0?

▶ 1- param. fits

ALEPH + DELPHI + L3 + OPAL

good agreement between the 4 LEP experiments



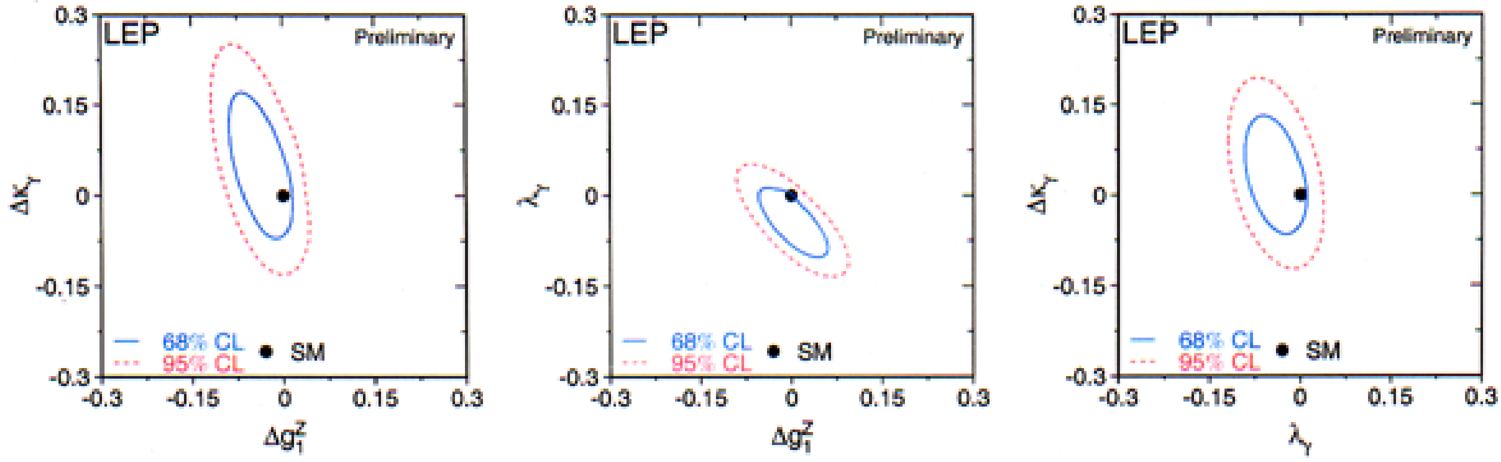
$\Delta k_\gamma = -0.002^{+0.067}_{-0.065}$

$\Delta g_1^Z = -0.025^{+0.026}_{-0.026}$

$\lambda_\gamma = -0.036^{+0.028}_{-0.027}$

Preliminary

▶ 2- param. fits :



⇒ All results well reproduced by the S.M.

Triple Gauge Couplings (2/2)

- Neutral TGC ($\nexists$ in S.M.)

  investigate $\underbrace{Z\gamma\gamma^*, Z\gamma Z^*}_{h^\gamma_{1,\dots,4},\ h^Z_{1,\dots,4}}$, $\underbrace{ZZ\gamma^*, ZZZ^*}_{f^\gamma_{4,5},\ f^Z_{4,5}}$ couplings

  2 classes of Lorentz invar. structures

  no departure from S.M. observed

- Quartic Gauge Couplings (QGC)

  investigate $WW\gamma\gamma$ and $ZZ\gamma\gamma$ vertices

  no departure from S.M. observed

▪ W Properties

▶ Branching ratios:

$\underrightarrow{T}$

	S.M.
$Br(W \to \ell\nu) = 10.69 \pm 0.09\,\%$	10.83 %
$Br(W \to q_1\bar{q}_2) = 67.92 \pm 0.27\,\%$	67.51 %

▶ CKM matrix element:

$$\frac{1}{Br(W \to \ell\nu)} = 3\left\{1 + \left[1 + \frac{\alpha_s(M_W^2)}{\pi}\right] \sum_{\substack{i=u,c \\ j=d,s,b}} |V_{ij}|^2 \right\}$$

↳ $|V_{cs}| = 0.996 \pm 0.012$ (LEP2) $\pm\, 0.004$ (external)

▶ Mass and Width:

$\underrightarrow{T}$

$M_W^{LEP} = 80.450 \pm 0.039$ GeV (preliminary)

$\downarrow$ ± 0.035 GeV expected

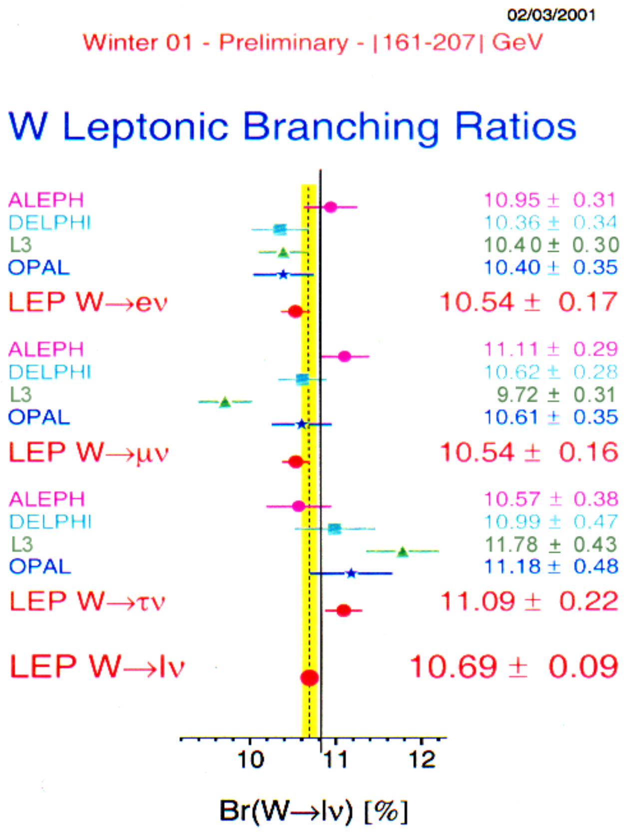
$\Gamma_W^{all} = 2.134 \pm 0.069$ GeV (S.M. : 2.095 GeV)

↳ LEP : 2.150 ± 0.091 GeV (prelim.)

FNAL : 2.11 ± 0.11 GeV (prelim.)

W Branching Ratios

- $W^{\pm} \to l^{\pm}\nu$



02/03/2001

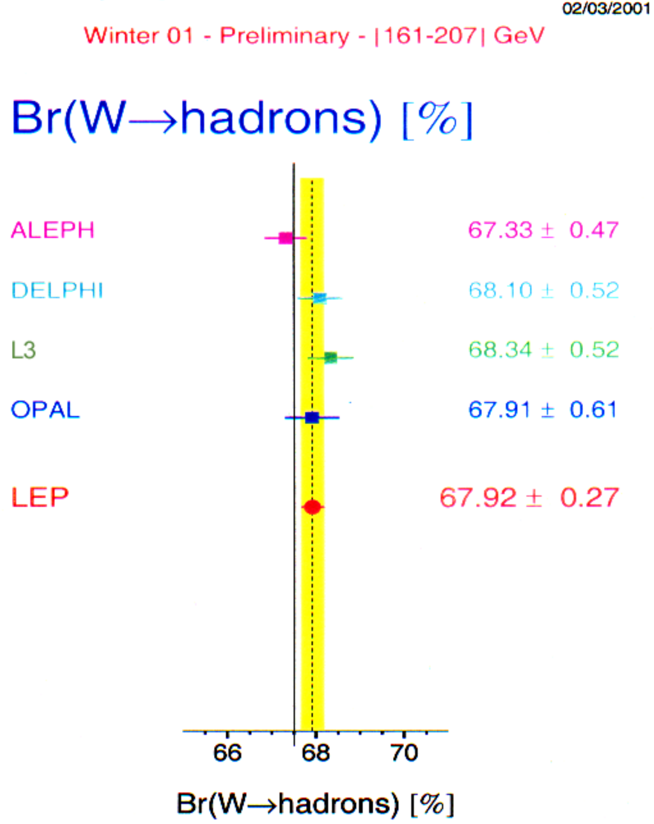
Winter 01 - Preliminary - |161-207| GeV

W Leptonic Branching Ratios

ALEPH	10.95 ± 0.31
DELPHI	10.36 ± 0.34
L3	10.40 ± 0.30
OPAL	10.40 ± 0.35
LEP W→eν	10.54 ± 0.17
ALEPH	11.11 ± 0.29
DELPHI	10.62 ± 0.28
L3	9.72 ± 0.31
OPAL	10.61 ± 0.35
LEP W→μν	10.54 ± 0.16
ALEPH	10.57 ± 0.38
DELPHI	10.99 ± 0.47
L3	11.78 ± 0.43
OPAL	11.18 ± 0.48
LEP W→τν	11.09 ± 0.22
LEP W→lν	10.69 ± 0.09

lepton universality verified at a few % level

- $W \to q_1\bar{q}_2$



02/03/2001

Winter 01 - Preliminary - |161-207| GeV

Br(W→hadrons) [%]

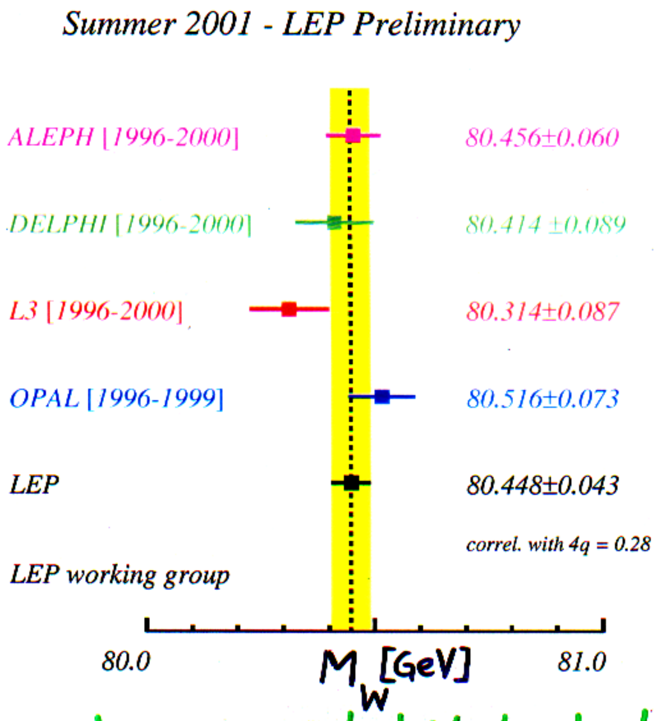
ALEPH	67.33 ± 0.47
DELPHI	68.10 ± 0.52
L3	68.34 ± 0.52
OPAL	67.91 ± 0.61
LEP	67.92 ± 0.27

← 0.4% precision

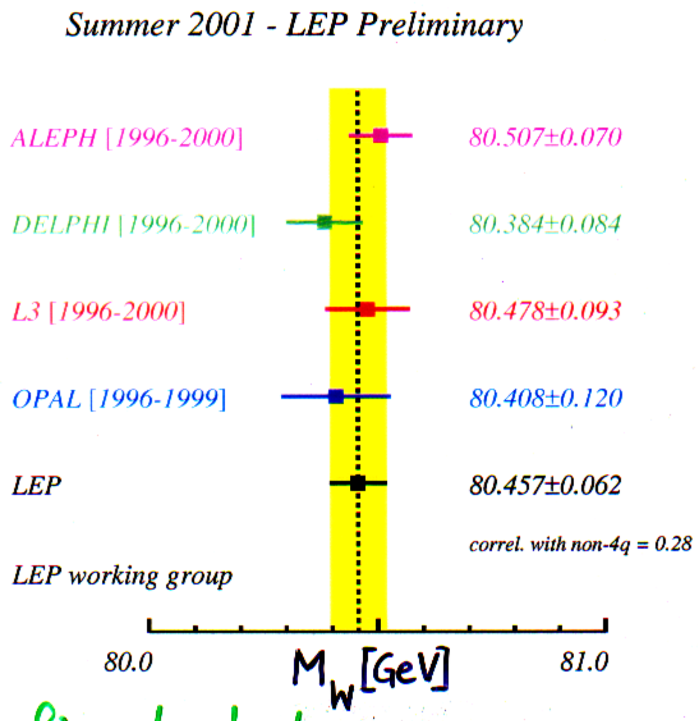
W Mass (½)

Measurements based on reconstructed dijet $M_{inv.}(q_1 q_2, l\nu)$ with $\{E, \vec{p}\}$ conservation constraints (E_{beam}!)

- $WW \longrightarrow q_1\bar{q}_2 l\nu, l_1\nu_1 l_2\nu_2$

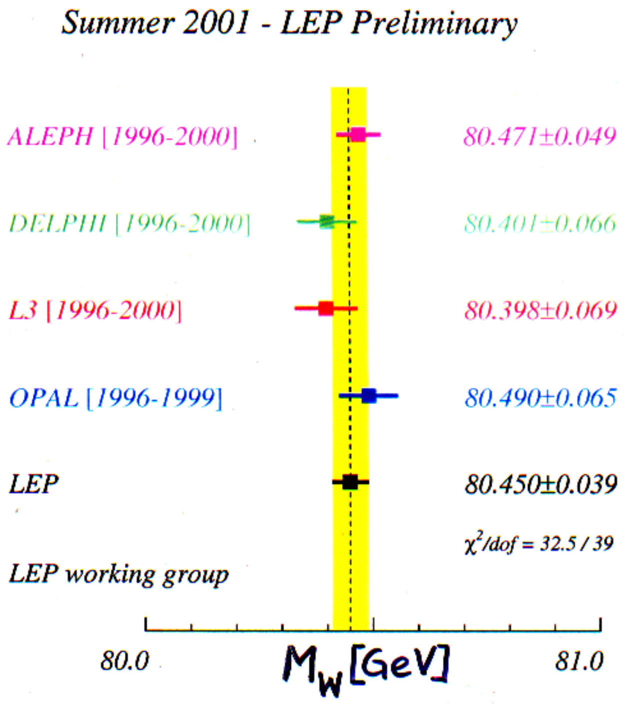


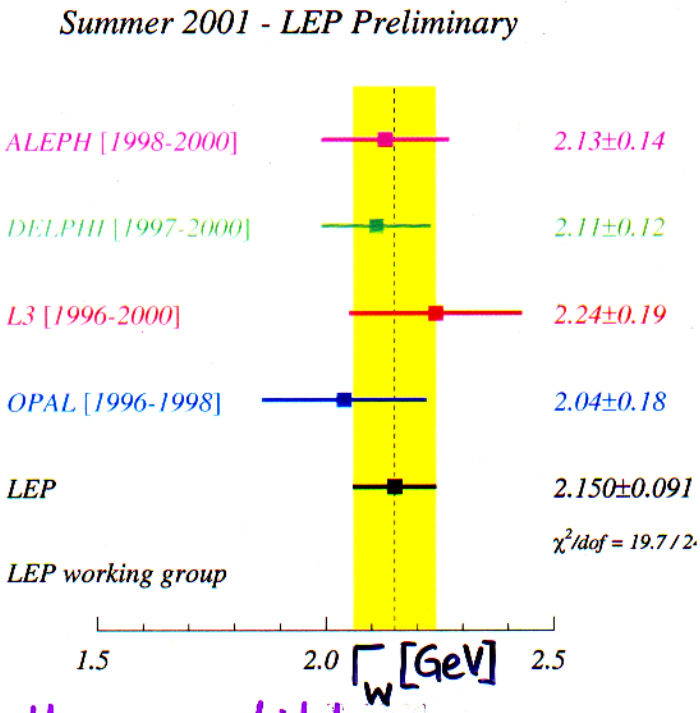
$WW \longrightarrow q_1\bar{q}_2 q_3\bar{q}_4$



Good compatibility between final states:

$\Delta M_W = 9 \pm 46$ MeV ⟶ no sign of F. State Interactions

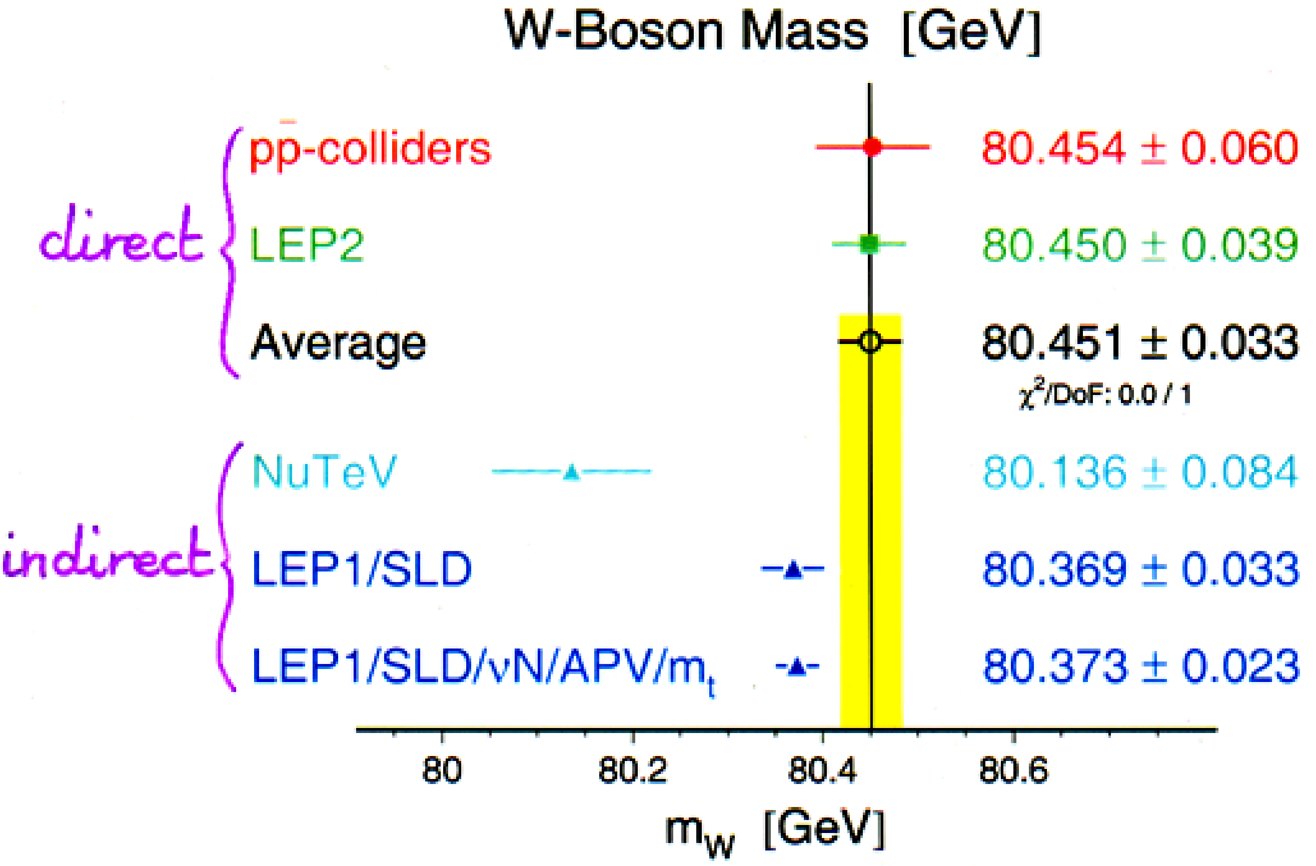
- 



Results of the 4 LEP exp$^{\underline{ts}}$ well compatible

W Mass (2/2)

comparison with other determinations of M_W



- direct measurements agree well

- indirect determinations differ by ~ 2 st. dev. from direct measurements

Accuracies expected at LEP

- Situation in Summer 1989:

$M_Z = 91.12 \pm 0.16$ GeV

$M_W = 80.0 \pm 0.36$ GeV

$\Gamma_Z = 3.8 \pm 1.5$ GeV

$\sin^2\theta_W = 0.227 \pm 0.006$

$N_\nu = 3.0 \pm 0.9$

- LEP expectations :	LEP achievments :
$M_Z \pm 50-20$ MeV	± 2.1 MeV
$\Gamma_Z \pm 20-10$ MeV	± 2.3 MeV
$M_W \pm 100$ MeV	± 39 MeV ···> 35
$N_\nu \pm 0.3$	± 0.008
$A_{FB}^{\mu} \pm 0.0035$	± 0.0013
$A_{FB}^{b} \pm 0.0050$	± 0.0017
$A_\tau \pm 0.011$	± 0.0043

up to factor of ~10
better than expected

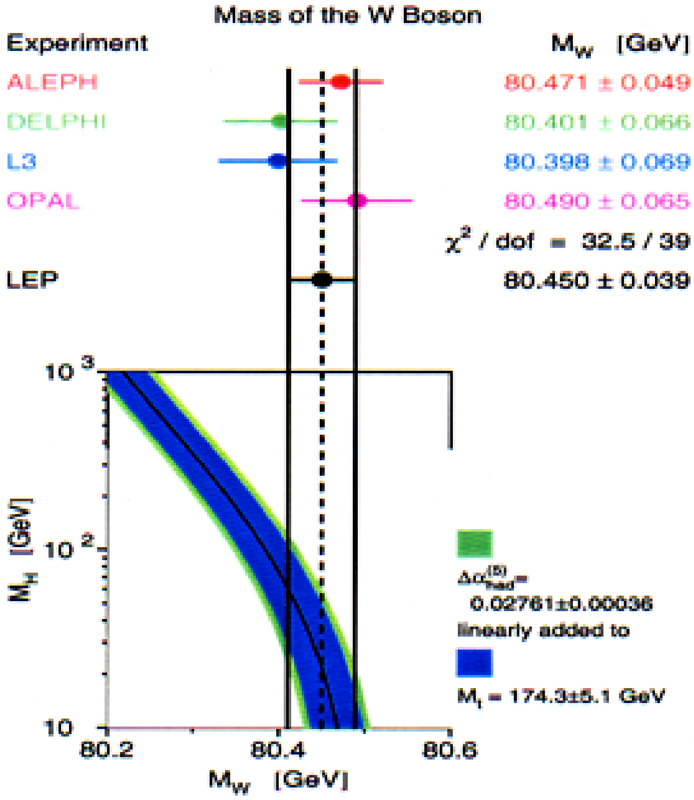
■ M_H from M_W

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}\,G_F \sin^2\theta_W} \cdot \frac{1}{1-(\Delta r_W + \Delta\alpha)}$$

$$\Delta r_W \approx -\cot g^2\theta_W \cdot \Delta\rho\,(m_t^2, \log M_H)$$

↓

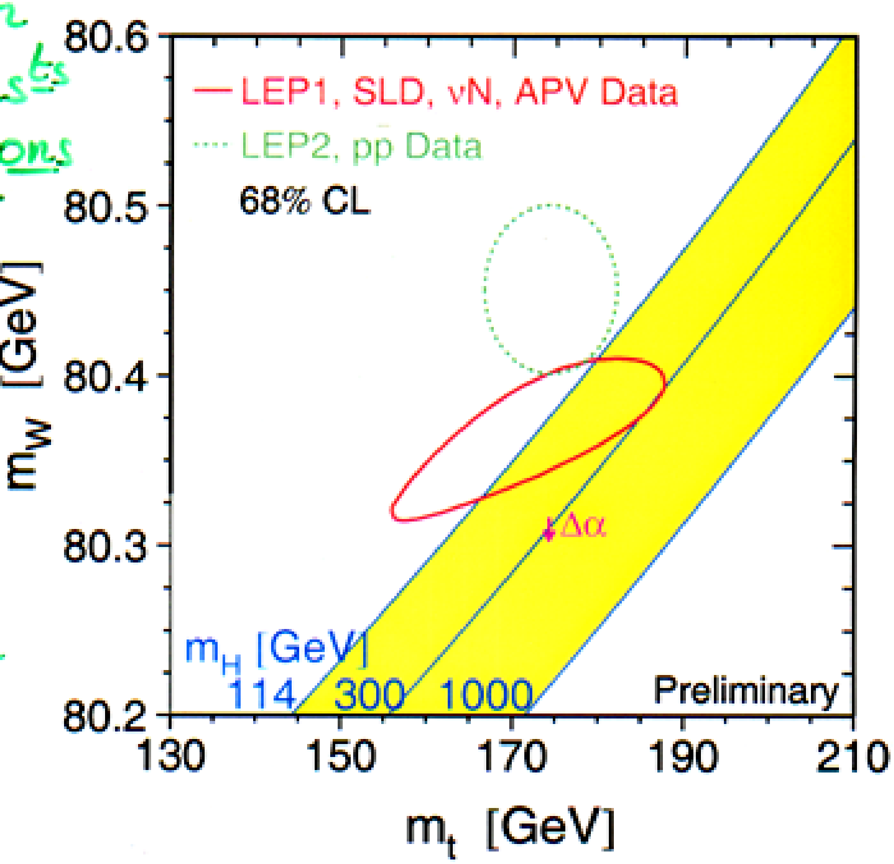
LEP2 data favour a light Higgs



Comparison between
- direct $\{M_W, m_t\}$ meas^{ts}
- indirect determin.$^{\underline{ons}}$ of $\{M_W, m_t\}$

↓

constraints on M_H : light Higgs favoured by both sets of results



Global Fit

- using LEP1, LEP2, SLC, Tevatron, APV data and constraint on $\Delta\alpha_{udscb} = \Delta\alpha^{(5)}_{had}$ (2 options)

	LEP including LEP-2 M_W	all data except M_W and m_t	all data except M_W	all data except m_t	all data
m_t (GeV)	186^{+13}_{-11}	169^{+12}_{-9}	$173.3^{+4.7}_{-4.6}$	181^{+11}_{-9}	$175.8^{+4.4}_{-4.3}$
M_H (GeV)	260^{+404}_{-155}	81^{+109}_{40}	108^{+70}_{-44}	126^{+182}_{-69}	88^{+53}_{-35}
$\log(M_H$ /GeV)	$2.42^{+0.41}_{-0.39}$	$1.91^{+0.37}_{0.29}$	$2.03^{+0.22}_{-0.23}$	$2.10^{+0.39}_{-0.34}$	$1.94^{+0.21}_{-0.22}$
χ^2/d.o.f.	15.5/8	18.9/12	19.1/13	22.6/14	22.9/15 (9%)
$\sin^2\theta^{lept}_{eff}$	0.23162	0.23150	0.23151	0.23139	0.23136
	± 0.00018	± 0.00016	± 0.00016	± 0.00015	± 0.00014
$\sin^2\theta_W$	0.22282	0.22333	0.22313	0.22248	0.22263
	± 0.00051	± 0.00063	± 0.00045	± 0.00045	± 0.00036
M_W (GeV)	80.389 ± 0.026	80.363 ± 0.032	80.373 ± 0.023	80.406 ± 0.023	80.398 ± 0.019

all data : $\kappa = 1.0371 \pm 0.0027$

$\rho_L = 1.00501 \pm 0.00075$ → 6.5 st.dev. evidence for genuine EW corr.

$\Delta r_W = -0.0246 \pm 0.0022$

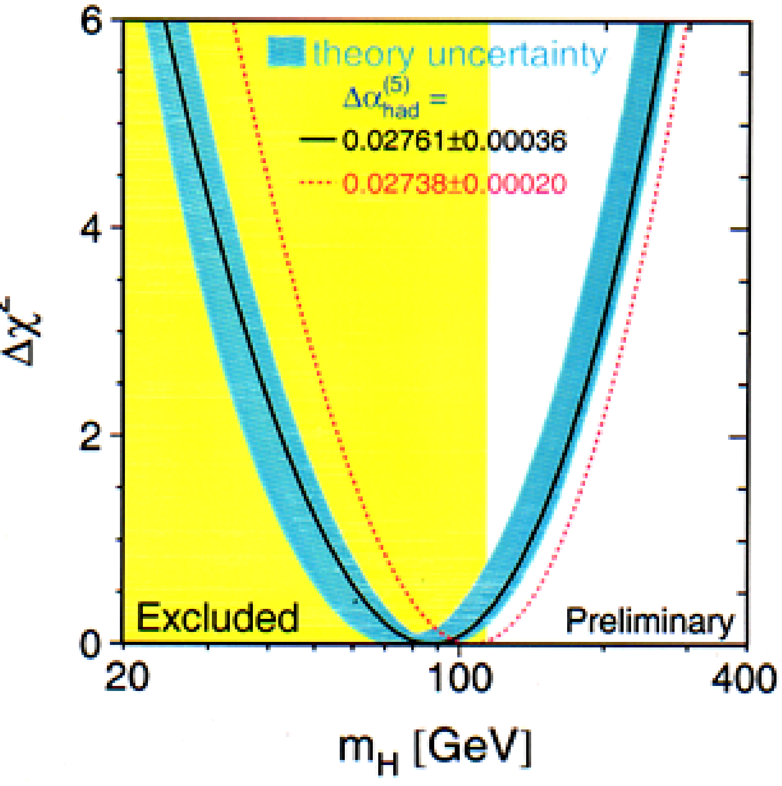
$\Delta r = 0.0360 \pm 0.0020$

Higgs mass:

$M_H = 88^{+53}_{-35}$ GeV

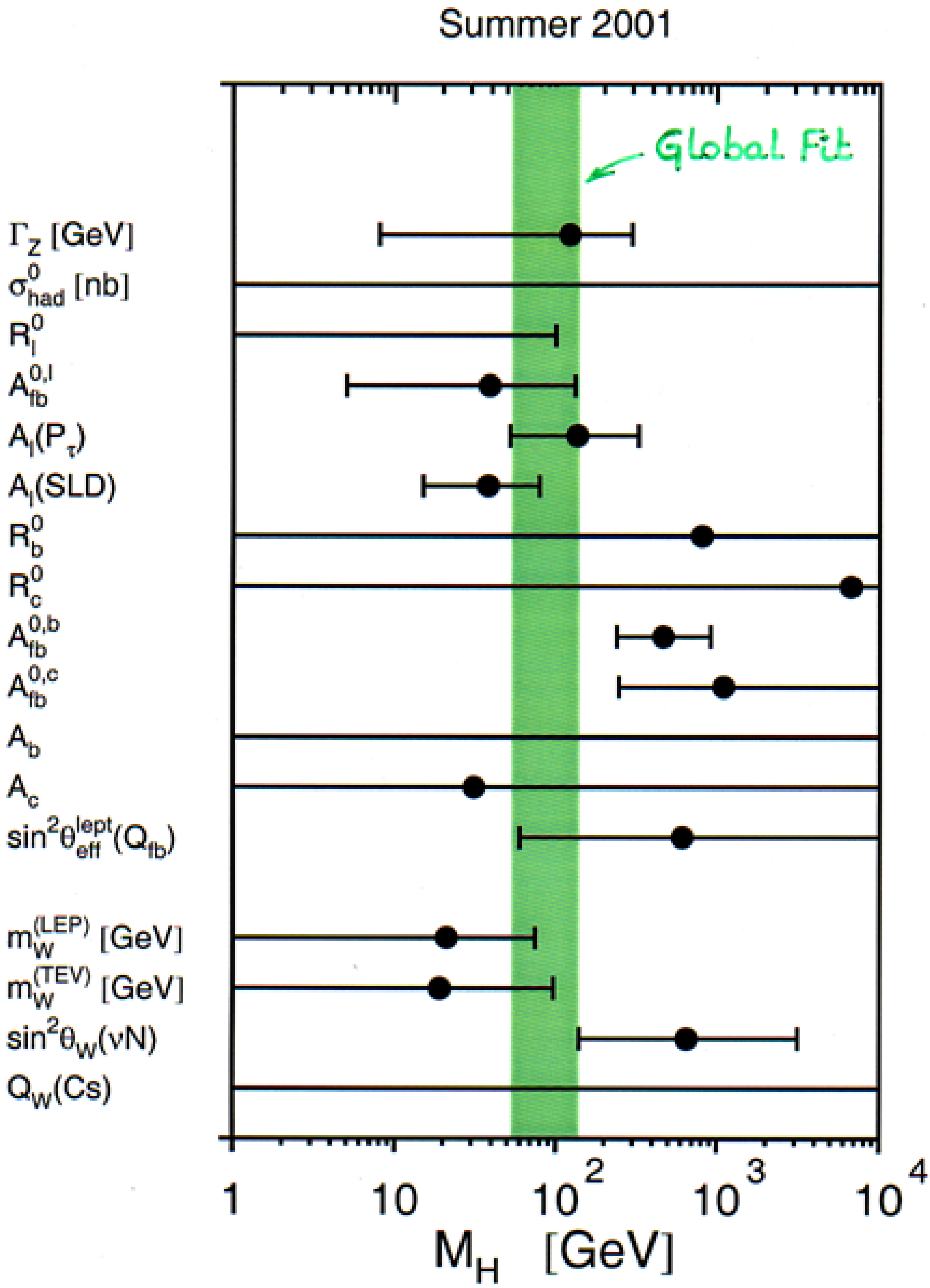
$M_H < 196-222$ GeV (95% C.L.)

$M_H < 270$ GeV (99% C.L.)



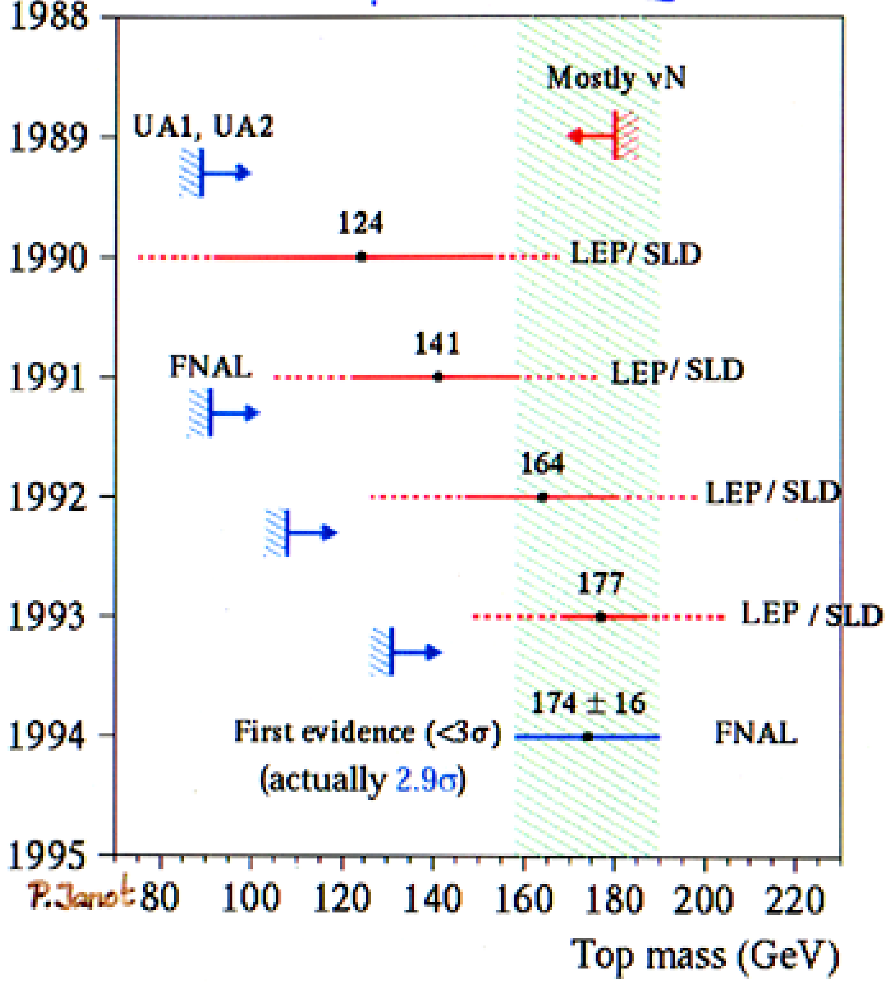
- Higgs Mass

constraints on M_H (68% C.L.) from each observable



Prediction of top mass

until top discovery



March '94 : $m_t^{LEP} \simeq 177 \pm 10 \pm 20(M_H)$ GeV

April '94 : $m_t^{FNAL} = 174 \pm 16$ GeV

Today

R_b : $m_t \simeq 150 \pm 25$ GeV

Γ_Z : $m_t \simeq 165 \pm 25$ GeV

LEP1 + SLD + νN + APV : $m_t = 169^{+12}_{-9}$ GeV

with M_W : $m_t = 180.5 \pm 10.0$ GeV

$m_t^{FNAL} = 174.3 \pm 5.1$ GeV

excellent agreement

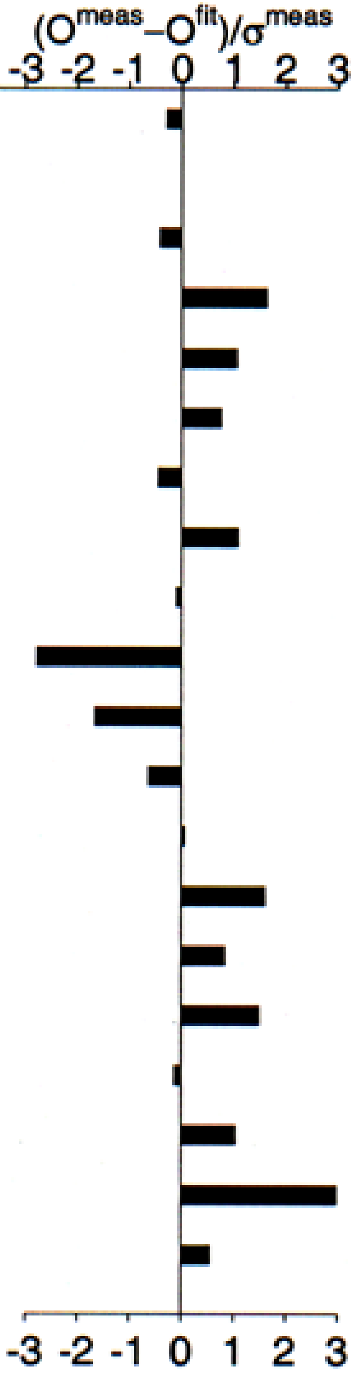
illustration of the predictive power of EW corrections

Test of the S.M. Consistency

Comparison of all EW meas.^{ts} to S.M. predictions

Fall 2001

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.30
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.41
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.06
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.76
$A_l(P_\tau)$	0.1465 ± 0.0033	-.45
R_b	0.21646 ± 0.00065	1.08
R_c	0.1719 ± 0.0031	-.12
$A^{0,b}_{fb}$	0.0990 ± 0.0017	-2.78
$A^{0,c}_{fb}$	0.0685 ± 0.0034	-1.67
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.07
A_l(SLD)	0.1513 ± 0.0021	1.61
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.83
$m_W^{(LEP)}$ [GeV]	80.450 ± 0.039	1.50
m_t [GeV]	174.3 ± 5.1	-.14
$m_W^{(TEV)}$ [GeV]	80.454 ± 0.060	1.04
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	2.98
$Q_W(Cs)$	-72.50 ± 0.70	.56



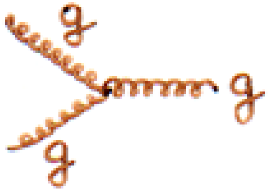
→ $\chi^2/\text{dof} \sim \frac{30.6}{15}$ (~1%)

- largest deviations : A^b_{FB} and new $\sin^2\theta_W(\nu N)$ → more understand.^{g} needed
- overall agreement quite good

Determination of α_s

- test the running of $\alpha_s = \frac{g_s^2}{4\pi}$ with Q^2

QCD: $\frac{d\alpha_s}{d\ln Q^2} < 0$ due to non-abelian structure of the strong interaction



gluon self-coupling

- LEP results:

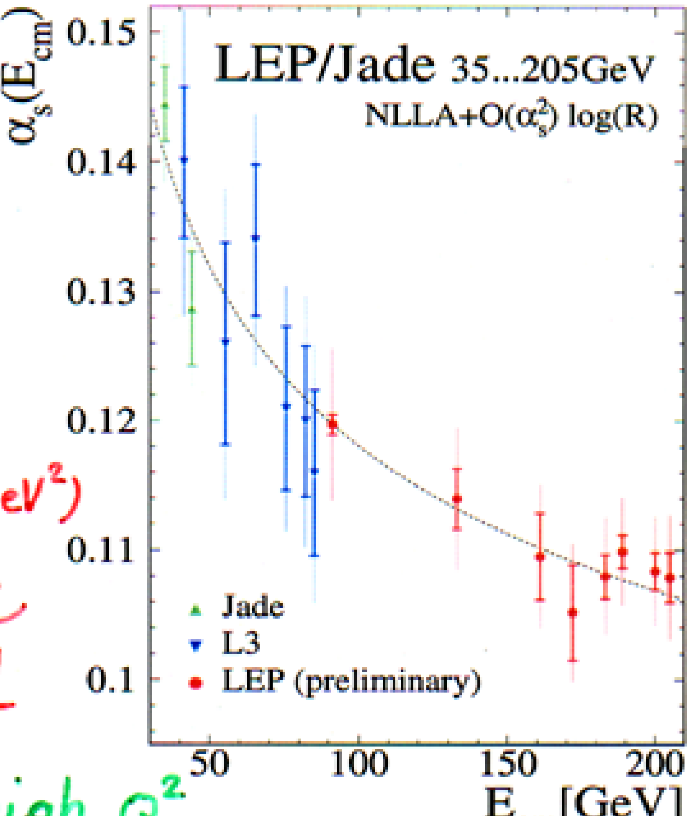
$R_l^0 \longrightarrow \alpha_s(M_Z^2) = 0.1224 \pm 0.0038$

$\sigma_L^0 \longrightarrow \alpha_s(M_Z^2) = 0.1180 \pm 0.0030$

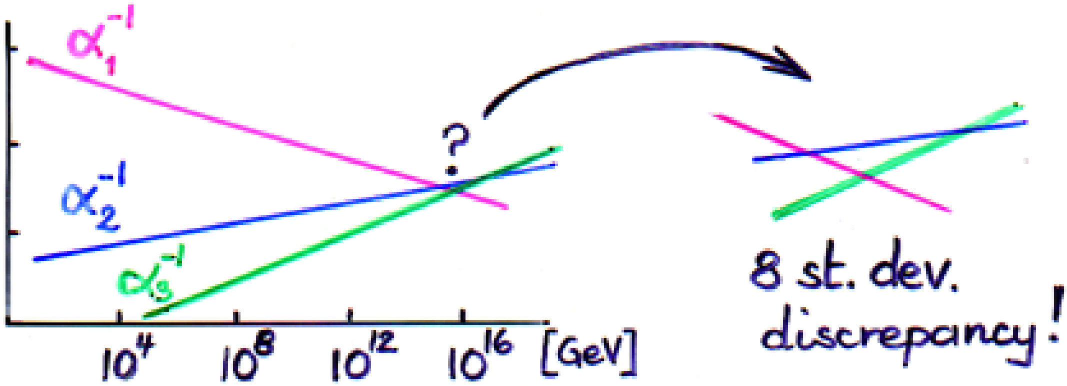
global fit $\longrightarrow \alpha_s(M_Z^2) = 0.1183 \pm 0.0027$

event shape variables $\longrightarrow \alpha_s(40^2 \to 205^2\,\mathrm{GeV}^2)$

$$\underbrace{\alpha_s(M_Z^2) = 0.1178 \pm 0.0033}_{\text{running established}}$$

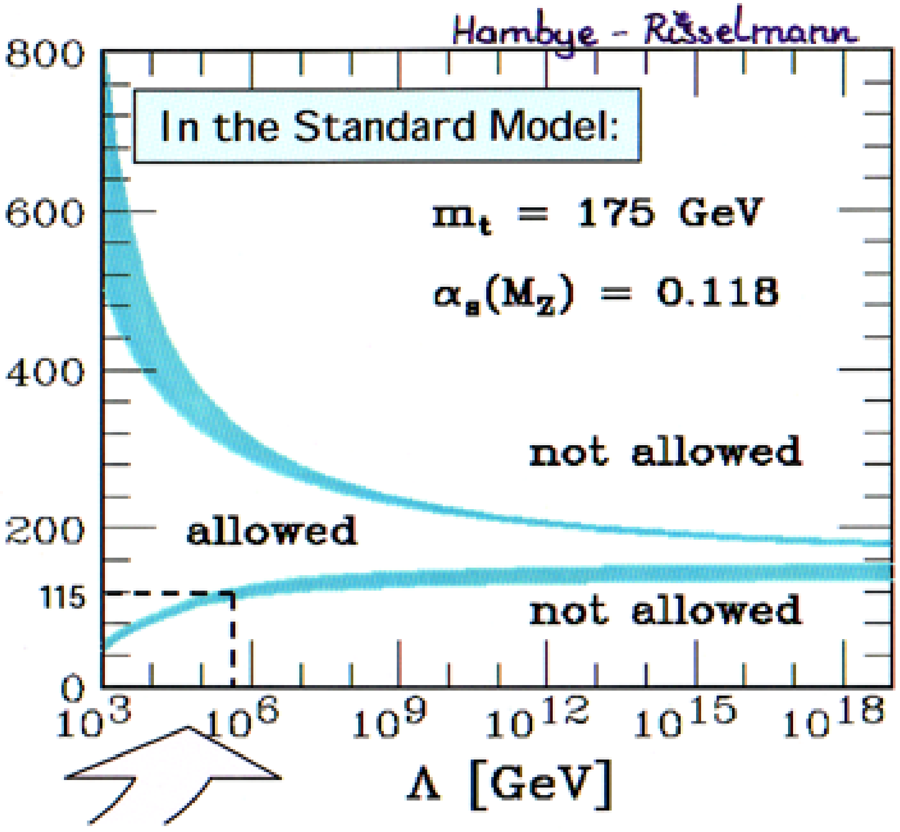


- extrapolation to very high Q^2 tests Gran Unification



8 st. dev. discrepancy!

Standard Higgs Search (1)



- Higgs potential ⟶ M_H

$$V(\phi) = \frac{\lambda}{3}\left[\phi\bar{\phi} - \frac{v^2}{2}\right] \quad (v \sim 246 \text{ GeV})$$

$$= \frac{1}{2}\frac{\lambda v^2}{3} H^2 + \frac{\lambda v}{3!} H^3 + \frac{\lambda}{4!} H^4 \quad \text{near minimum}$$

$$M_H = v\sqrt{\frac{\lambda}{3}} \longleftarrow \text{"running" constant}$$

window towards
very large values of Λ

Theoretical constraints on M_H:

$$\underset{\text{vacuum stability}}{0} \leqslant \lambda(\Lambda) < \underset{\text{triviality}}{\infty}$$

Λ: energy scale where S.M. stops being valid

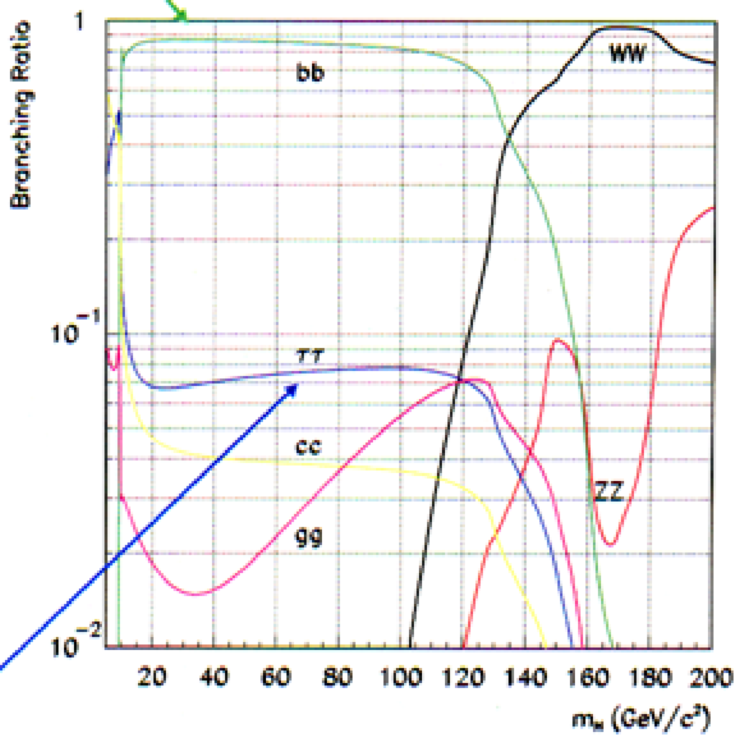
Standard Higgs search (2)

▶ Higgs decay branching ratios determined by M_H:

- $M_H < 2m_e$: large lifetime $\rightarrow \beta c\gamma\tau_H \sim 6.3\left(\frac{40}{M_H[\mathrm{MeV}]}\right)^2 \mathrm{m}$
- $M_H < 2m_\mu$: mainly $H \rightarrow e^+e^-$
- $M_H < 2m_\pi$: mainly $H \rightarrow \mu^+\mu^-$
- $M_H < 3\text{-}4$ GeV : mainly $H \rightarrow gg$ $(\pi\pi, KK, \eta\eta, \dots)$
- $M_H < 2m_b$: mainly $H \rightarrow \tau^+\tau^-$ and $c\bar{c}$
- $M_H > 2m_b$

$Br(H \rightarrow b\bar{b}) \sim 85\%$

LEP allowed to cover all 6 cases



$Br(H \rightarrow \tau^+\tau^-) \sim 8\%$

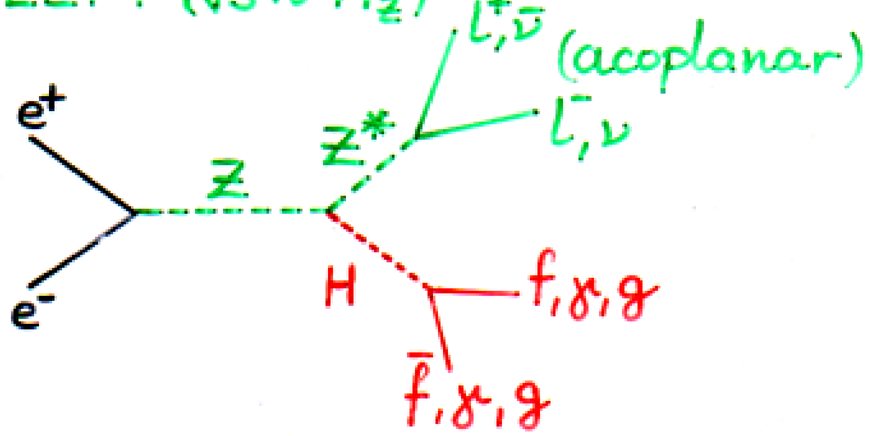
Standard Higgs search (3)

Davier, Nguyen-Ngoc
P.L.B. 229 ('89) 150

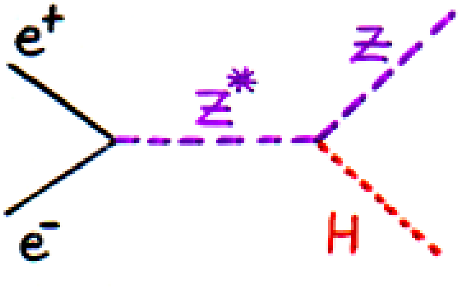
- the situation before LEP:
  $1.2\ \mathrm{MeV} < M_H < 52\ \mathrm{MeV}$ excluded with 90% c.L.
  other limits existed as well, but very model dependent
  (NP-QCD)

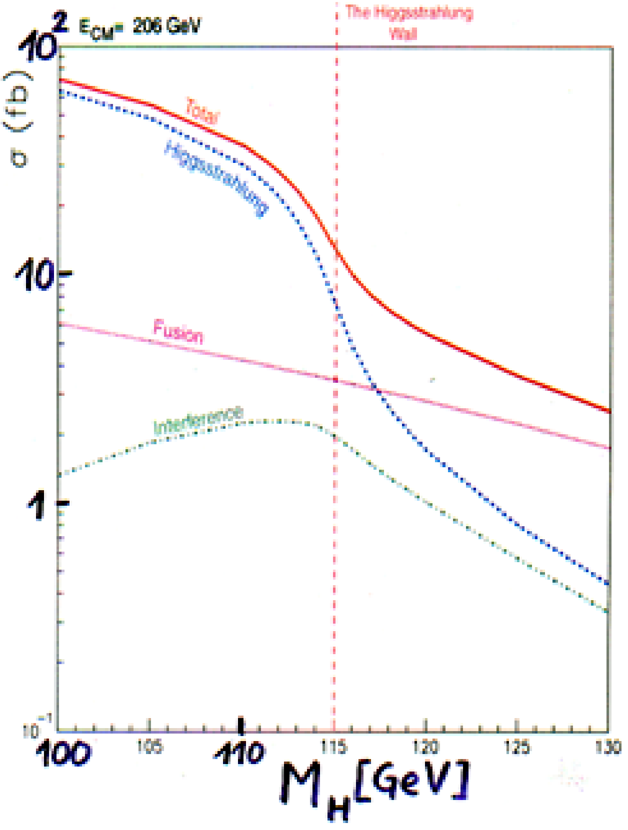
- main Higgs production mode at LEP: Higgsstrahlung

  - LEP1 ($\sqrt{s} \sim M_Z$)

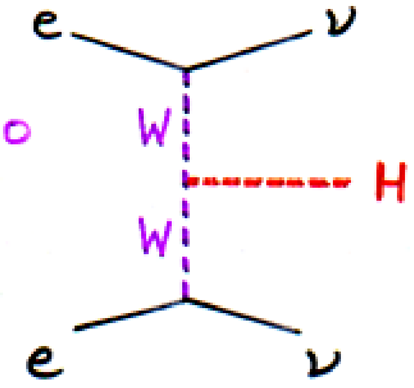


  - LEP2 ($\sqrt{s} \geq M_Z + M_H$)





also



but $\sigma(H\nu\nu) \ll \sigma(ZH)$

Standard Higgs search (4)

- very low mass domain:
  Higgs decays outside of detector
  ⇒ look for acoplanar l^+l^- pairs from recoil Z

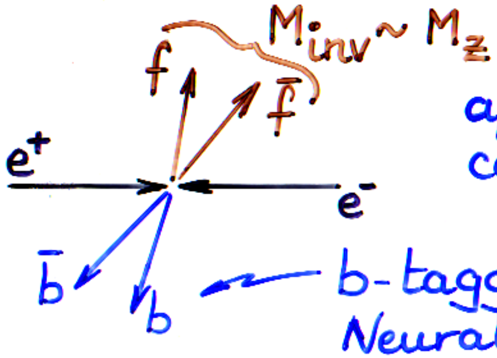
- $M_H < 2m_\mu$:
  Higgs decays inside detector ($\lambda_H \sim 1\,m$ for $M_H = 100MeV$)
  ⇒ look for V_0's : $$\begin{tikzcd} & e^+ \\ H \arrow[ur] \arrow[dr] & \\ & e^- \end{tikzcd}$$

- $M_H > 2m_\mu$:
  look for acoplanar l^+l^- and jet-pairs (b-tagged!)

⇒ $0.0 < M_H < 65.6$ GeV
excluded with 95% C.L.
at LEP1

Standard Higgs search (5)

LEP2 :



apply $\{E, \vec{p}\}$ conservation

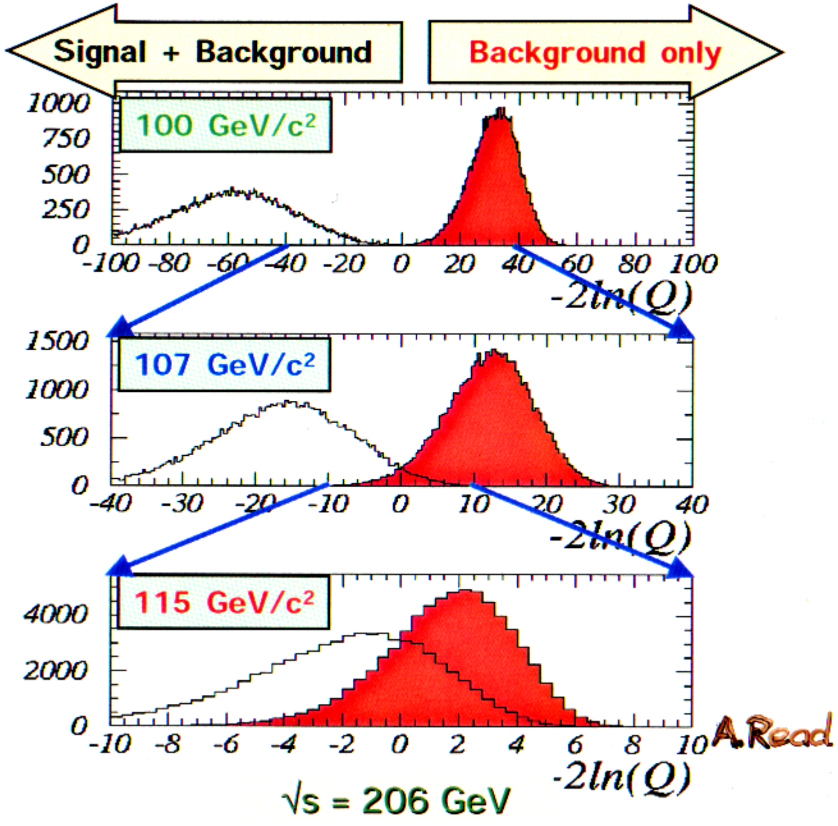
T→

b-tagging with Neural Networks

NN attributes to each event a probability to originate from the signal (s_i) or from any background (b_i) :

event weight $w_i = \frac{s_i}{b_i}$

→ Likelihood $Q = \prod_{i=1}^{N} \frac{s_i + b_i}{b_i}$

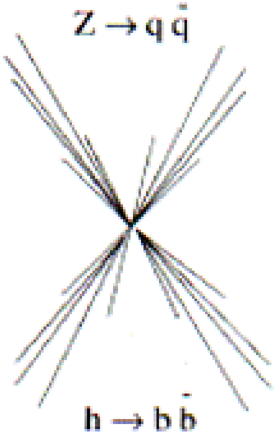


Discriminating power of ln(Q) as a function of M_H at $\sqrt{s} = 206$ GeV

Standard Higgs search

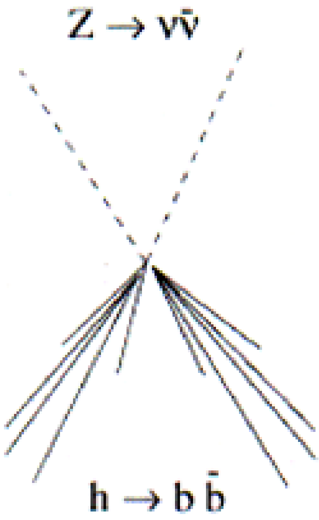
The different topologies

4 jets



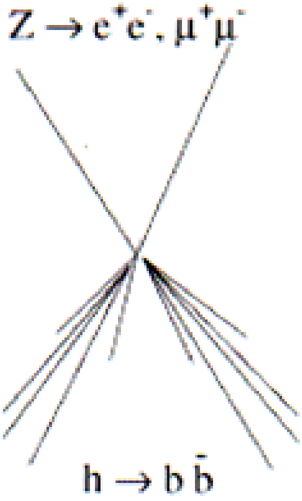
60%

2 jets & missing energy



19%

2 jet & 2 lepton



6%

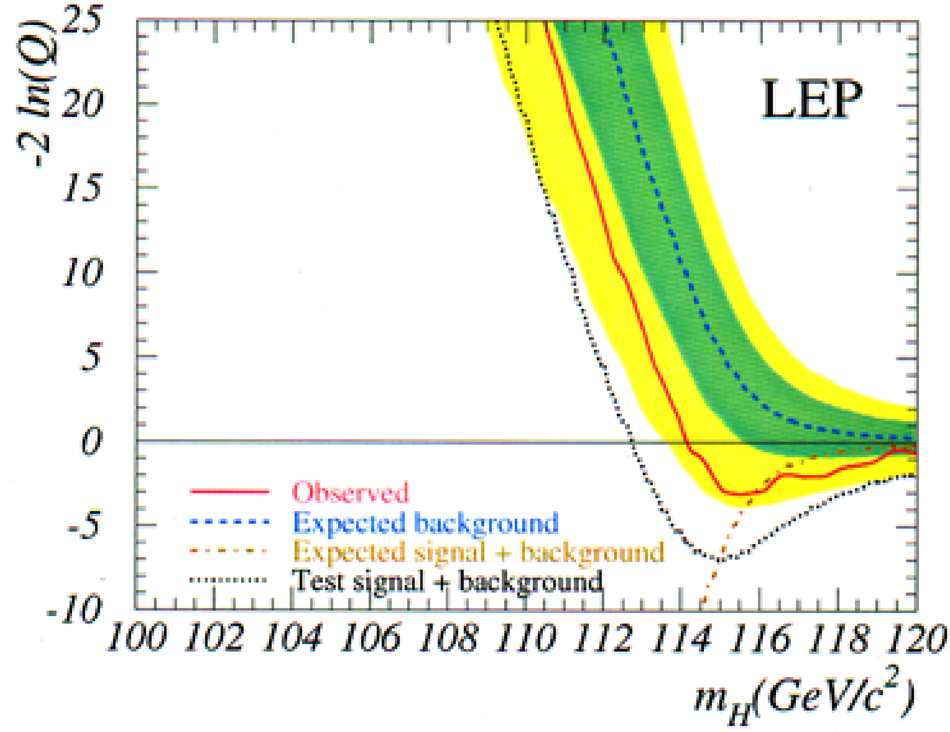
Or a τ
instead of the b

C. Mariotti

Standard Higgs search (5)

- 1 event ($q\overset{?}{\bar{q}}H$) was found by ALEPH with $w_i = 4.7$ (and another with $w_i = 2.3$), but ADLO did not find convincing evidence for Higgs production.

- likelihood result :



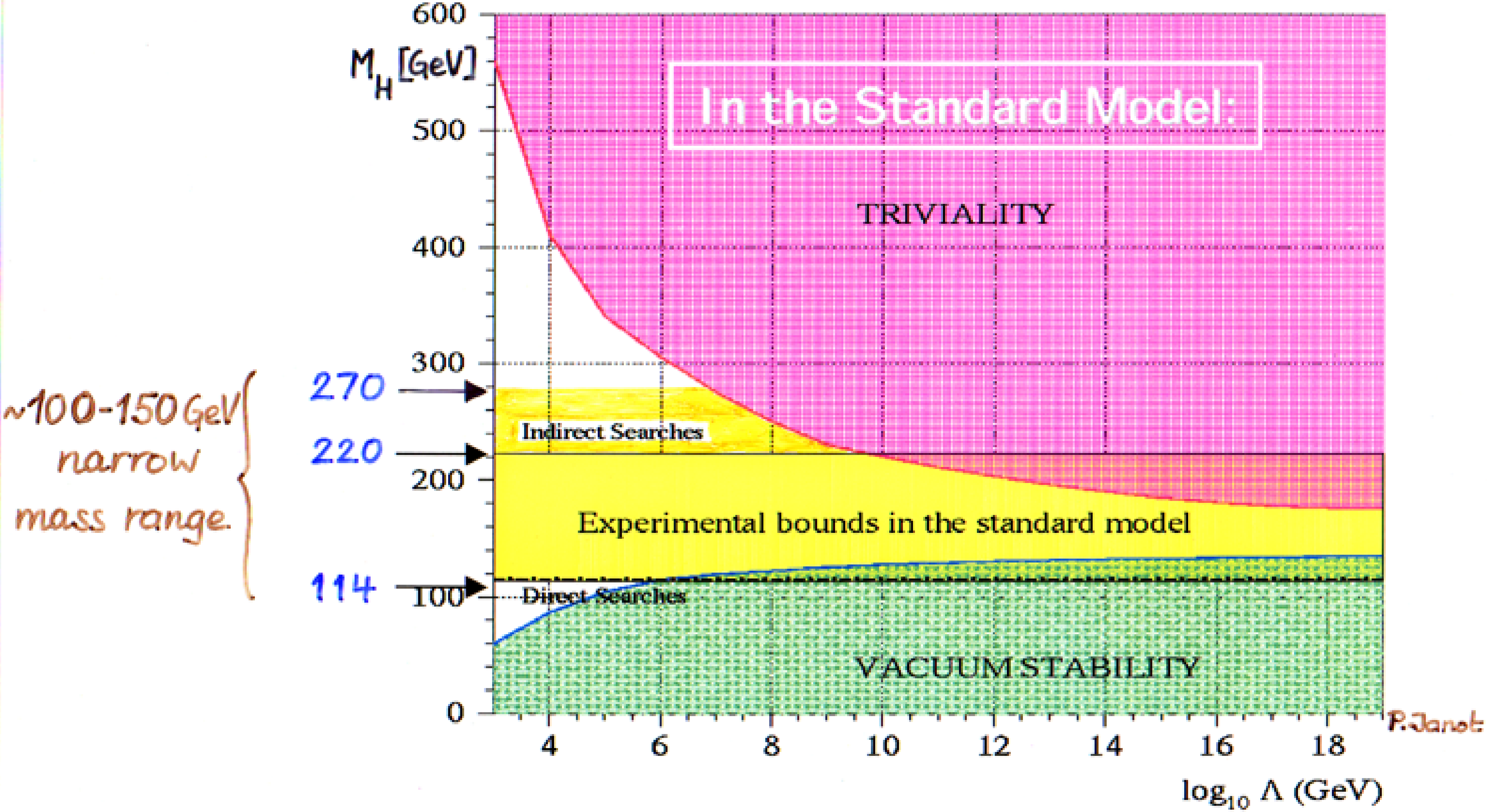
Probability that a bg fluctuation was observed: 3.5%

Probability of a 115.6 ± 0.8 GeV Higgs : 41 %

↳ $M_H \gtrsim 114$ GeV (95% C.L.)

- Summary of constraints on M_H^{SM}

$114 < M_H < 220-270$ GeV



Beyond the S.M.

- the S.M. is incomplete:
  - 25 free input parameters
  - gravitation not included
  - excess of matter over antimatter not explained
  - why is $M_{W,Z} \ll M_{Pl}$? ("hierarchy" pb)
  - etc.

- what could be beyond the S.M., modifying its predictions by $\lesssim O(10^{-3})$ at LEP energies?

?

more symmetries
(e.g. Supersymmetry)

?

more elementary constituent
(e.g. composite models)

- investigation of New Physics based on:
  - direct searches
  - deviations from S.M. predictions

signs of SUSY, Technicolour, Leptoquarks,
excited fermions, Extra dimensions,
additionnal gauge interactions,
genuine contact interactions, ...

▪ Constraints on New Physics from precision meas.^{t}

▶ Parametrize room left for virtual corrections due to New Physics with 4 parameters:

$$\varepsilon_1 = \Delta\rho \quad ; \quad \varepsilon_2 = c_0^2 \Delta\rho + \frac{s_0^2}{c_0^2 - s_0^2} \Delta r_W - 2 s_0^2 \Delta\kappa'$$

$$\varepsilon_3 = c_0^2 \Delta\rho + (c_0^2 - s_0^2) \Delta\kappa' \quad ; \quad \varepsilon_b = \frac{1}{2} \Delta\rho_b$$

where : $s_0^2 = \sin^2\theta^l_{SM}(\text{Born} + \text{QED} + \text{QCD})$; $c_0^2 = 1 - s_0^2$

$$\sin^2\theta^l_{eff} = (1 + \Delta\kappa') s_0^2$$

$\varepsilon_i = 0$ for S.M. tree level with pure QED and QCD correctio

$\Longrightarrow$ ε_i measure the purely weak loop corrections

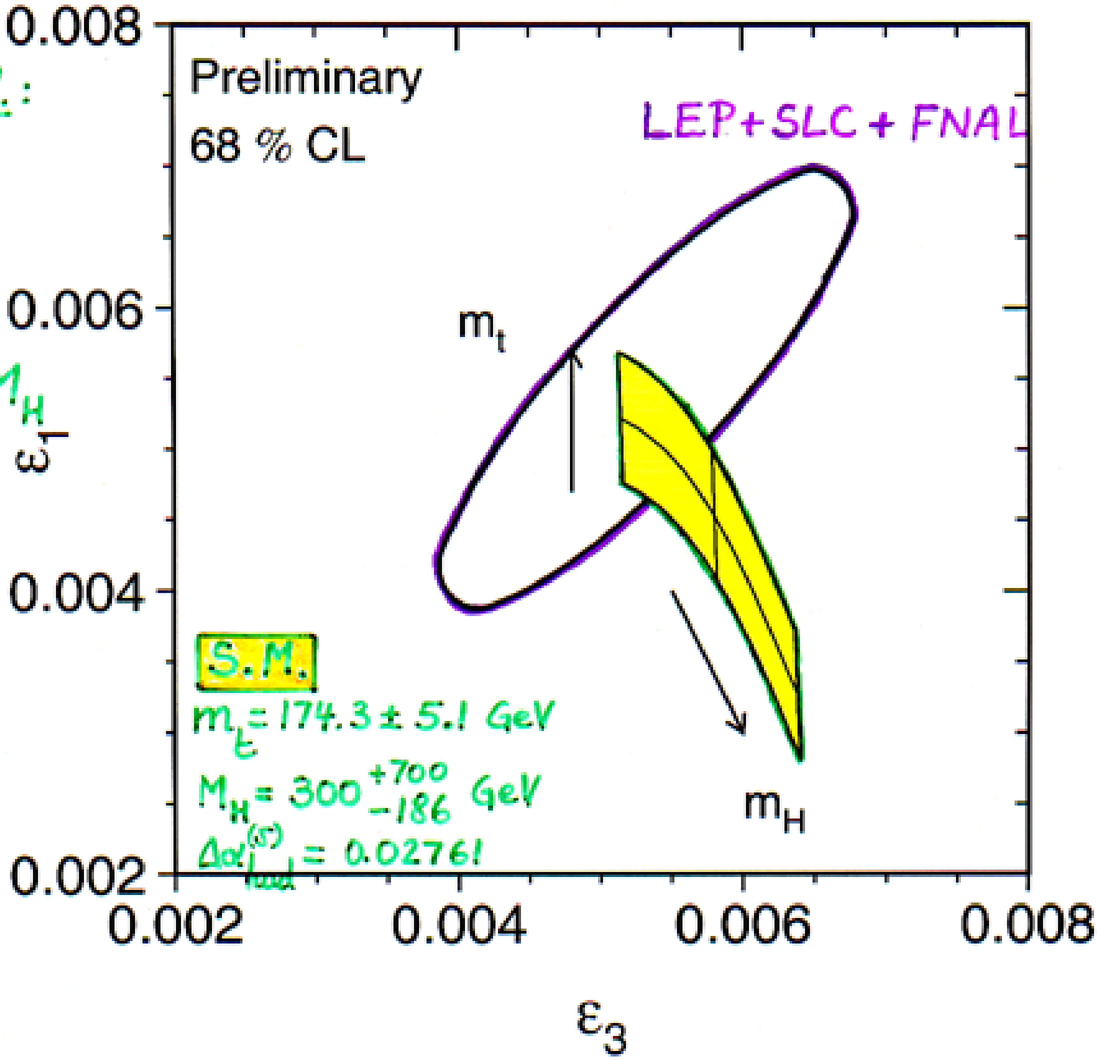
in the S.M.:

$\varepsilon_1 \sim m_t^2$

$\varepsilon_2 \sim M_W^2$

$\varepsilon_3 \sim M_W^2 \ln M_H$

$\varepsilon_b \sim m_t^2$



$m_t = 174.3 \pm 5.1$ GeV

$M_H = 300^{+700}_{-186}$ GeV

$\Delta\alpha^{(5)}_{had} = 0.02761$

Constraints on New Physics from precision meas.^{ts}

any model going beyond the S.M. has to cope with the experimental values of ε_i.

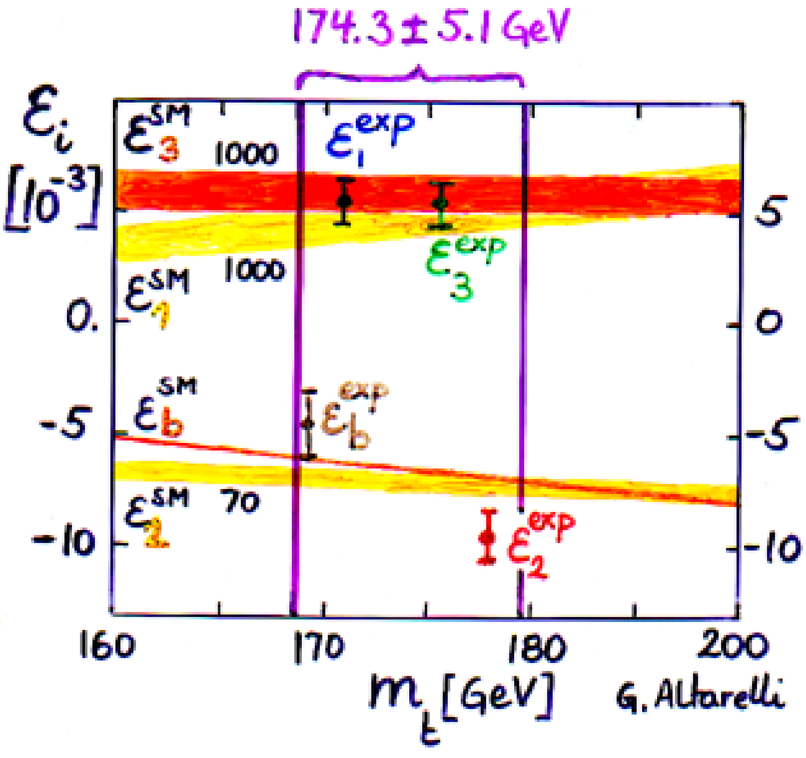
"LEP + SLC legacy"

(still preliminary)

$$\left.\begin{array}{l} \varepsilon_1 = +0.0054 \pm 0.0010 \\ \varepsilon_2 = -0.0096 \pm 0.0012 \\ \varepsilon_3 = +0.0053 \pm 0.0010 \\ \varepsilon_b = -0.0045 \pm 0.0016 \end{array}\right\}$$

provide > 10 st. dev. evidence for genuine E.W corrections

comparison with S.M. expectation



G. Altarelli

bands are due to M_H intervalle (70 – 1000 GeV)

small room (10^{-3} level) for New Physics . . .

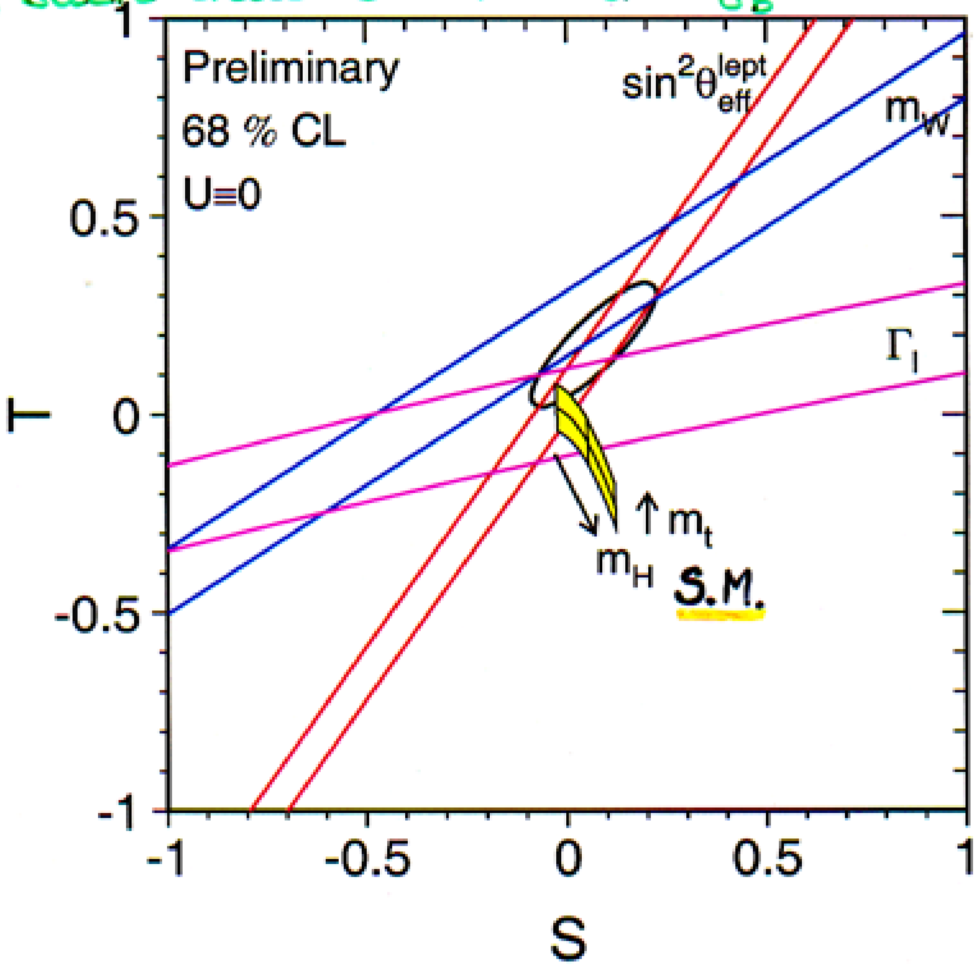
Constraints on New Physics from precision meas.$^{\underline{ts}}$

- another way to parametrize EW corrections
  → S, T, U, γ_b parametrize the departure from S.M.:

- $S \simeq \varepsilon_3 \frac{4s_0^2}{\alpha(M_Z^2)} - C_S^{SM}$
- $U \simeq -\varepsilon_2 \frac{4s_0^2}{\alpha(M_Z^2)} - C_U^{SM}$
- $T \simeq \varepsilon_1 \frac{1}{\alpha(M_Z^2)} - C_T^{SM}$
- $\gamma_b \simeq 2\varepsilon_b - C_b^{SM}$

$C^{SM}_{S,U,T,b}$ = SM full prediction for given values of $m_t, M_H, \Delta\alpha, M_W, M_Z$, such that $S^{SM} = T^{SM} = U^{SM} = \gamma_b^{SM} = 0$

S.M. predictions for:
$\alpha_s(M_Z^2) = 0.118$
$m_t = 175$ GeV
$M_H = 150$ GeV
$M_Z = 91.1875$ GeV
$\Delta\alpha^{(5)}_{had} = 0.02761$



- LEP + SLC legacy:

$S = +0.07 \pm 0.10$; $T = +0.17 \pm 0.10$; $\gamma_b = +0.0028 \pm 0.0034$
when U fixed to 0 (very few N.P. models affect U)

↳ simple TechniColour in bad shape, but TC still alive...

Supersymmetry: an appealing hypothesis

- introduces a symmetry between fermions & bosons:
  each S.M. fermion has a spin-0 superpartner
  each S.M. boson has a spin-½ superpartner

	Particles	Spin	Sparticles	Spin	
Matter	$\ell^\pm_{L,R}$		$\tilde{\ell}^\pm_L$ $\tilde{\ell}^\pm_R$		$\ell^\pm$ $\tilde{\ell}^\pm$
	ν_L	½	$\tilde{\nu}_L$	0	ν $\tilde{\nu}$
	$q_{L,R}$		$\tilde{q}_L$ $\tilde{q}_R$		q $\tilde{q}$
Radiation	g		$\tilde{g}$		g $\tilde{g}$
	γ	1	$\tilde{\gamma}$		γ Z^0
					▷ neutralinos
	Z^0		$\tilde{Z}^0$		χ^0_1 χ^0_2 χ^0_3 χ^0_4
	$H^0_{1,2,3}$	0	$\tilde{H}^0_1$, $\tilde{H}^0_2$	½	H^0_1 H^0_2 H^0_3
					▷ charginos
	$H^\pm$		$\tilde{H}^\pm$		$\chi^\pm_1$ $\chi^\pm_2$
	$W^\pm$	1	$\tilde{W}^\pm$		$W^\pm$
Gravity	G	2	$\tilde{G}$	3/2	G $\tilde{G}$

- consequences of particle spectrum enrichment
  - compensates high q^2 divergences of S.M.

$\delta M_H^2 \sim$  $+$ 

$$= -\frac{g_f^2}{16\pi^2}(\Lambda^2 + m_f^2) + \frac{g_{\tilde{f}}^2}{16\pi^2}(\Lambda^2 + m_{\tilde{f}}^2)$$

$$= O\left(\frac{\alpha}{\pi}\right) \underbrace{|m_{\tilde{f}}^2 - m_f^2|}_{\substack{\text{naturally small} \\ \text{if } |m_{\tilde{f}}^2 - m_f^2| \lesssim 1\,\text{TeV}^2}} \text{ if } \begin{cases} nb(\tilde{f}) = nb(f) \\ g_{\tilde{f}}^2 \approx g_f^2 \end{cases}$$

  - allows $g_{em} = g_W = g_s$ at $\Lambda \gtrsim 10^{16}$ GeV if $10^2 \lesssim M_{\tilde{f},\chi,H} < 10^4$ GeV
    (Renorm. Gr. Equ.)

$\underrightarrow{T}$

- consequences on Higgs sector:
  $\gtrsim 2$ Higgs doublets $\Longrightarrow$ $\gtrsim 5$ Higgs bosons $\begin{cases} H^+, H^- \\ h^0, A, H^0 \end{cases}$
  $\leftarrow M_{h^0} \lesssim 130\text{-}205\,\text{GeV}$

- new quantum number: $R_p = (-1)^{3B+L+2S}$
  R_p may be conserved or not $\longrightarrow$ all sparticles unstable
  (but one? $\rightarrow$ LSP)

- SUSY modifies S.M. predictions at LEP1 energies (e.g. A_{FB}, $\sin^2\theta_{eff}^{L}$, ρ) only slightly if $m_{\tilde{p}} \gtrsim \frac{\sqrt{s}}{2}$

- other features (e.g. Super Gravity)

■ SUSY breaking

▶ SUSY cannot be exact since $m_{\tilde{f}} \neq m_f$

$\Longrightarrow$ it is broken at some energy scale M_{SUSY}

↳ ~ 124 new input parameters!

▶ SUSY breaking reduces this number to a handful:

- Gravity Mediated SUSY Breaking (SUGRA)
- Gauge Mediated " " (GMSB)
- Anomaly Mediated " " (AMSB)
- etc.

→ determine production rates, mass spectrum, decay channels of the sparticles

ex: minimal SUGRA (χ_1^0 or $\tilde{\nu}$ LSP, $\in$ D.M.?)

$tg\beta = \frac{v_1}{v_2}$ (v.e.v. of H doublets)

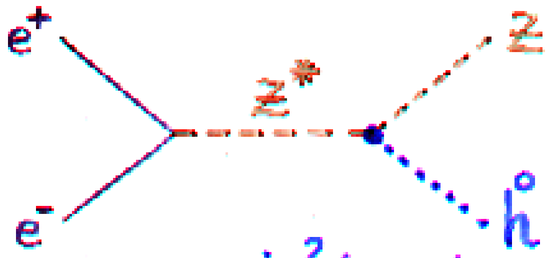
sign(μ) ($\mu \equiv$ Higgs mixing param.)

m_0 ($\equiv m_{\tilde{f}}$) $m_{1/2}$ ($\equiv M_{\chi,\tilde{g}}$)

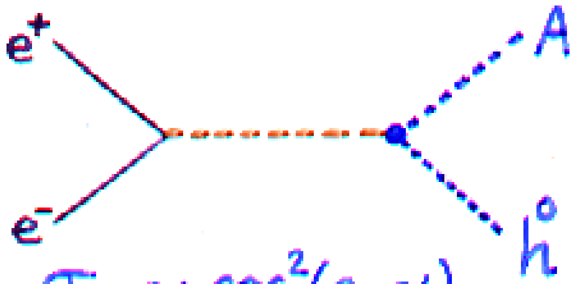
A_0 ($\equiv \tilde{f}$ mixing param.)

• Manifestations of SUSY

▶ Higgs boson production at LEP2



$\sigma_{Zh} \sim \sin^2(\beta-\alpha)$

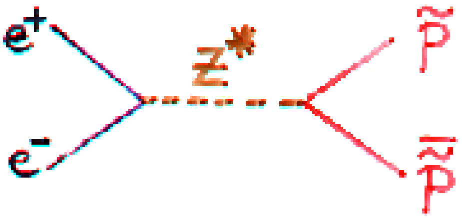


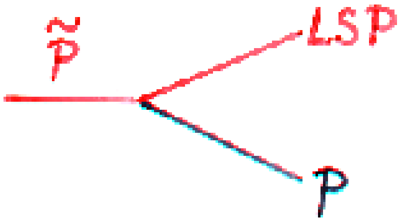
$\sigma_{Ah} \sim \cos^2(\beta-\alpha)$

→ combine both searches

▶ Sparticle production

- R_p conserved (e.g. mSUGRA):





weakly interacting neutral, colourless D.M. candidate

→ look for acoplanar $\{p, \bar{p}\}$ and E_{miss} (except if $\tilde{g} \equiv$ LSP)

* experimental sensitivity depends on m_{LSP}

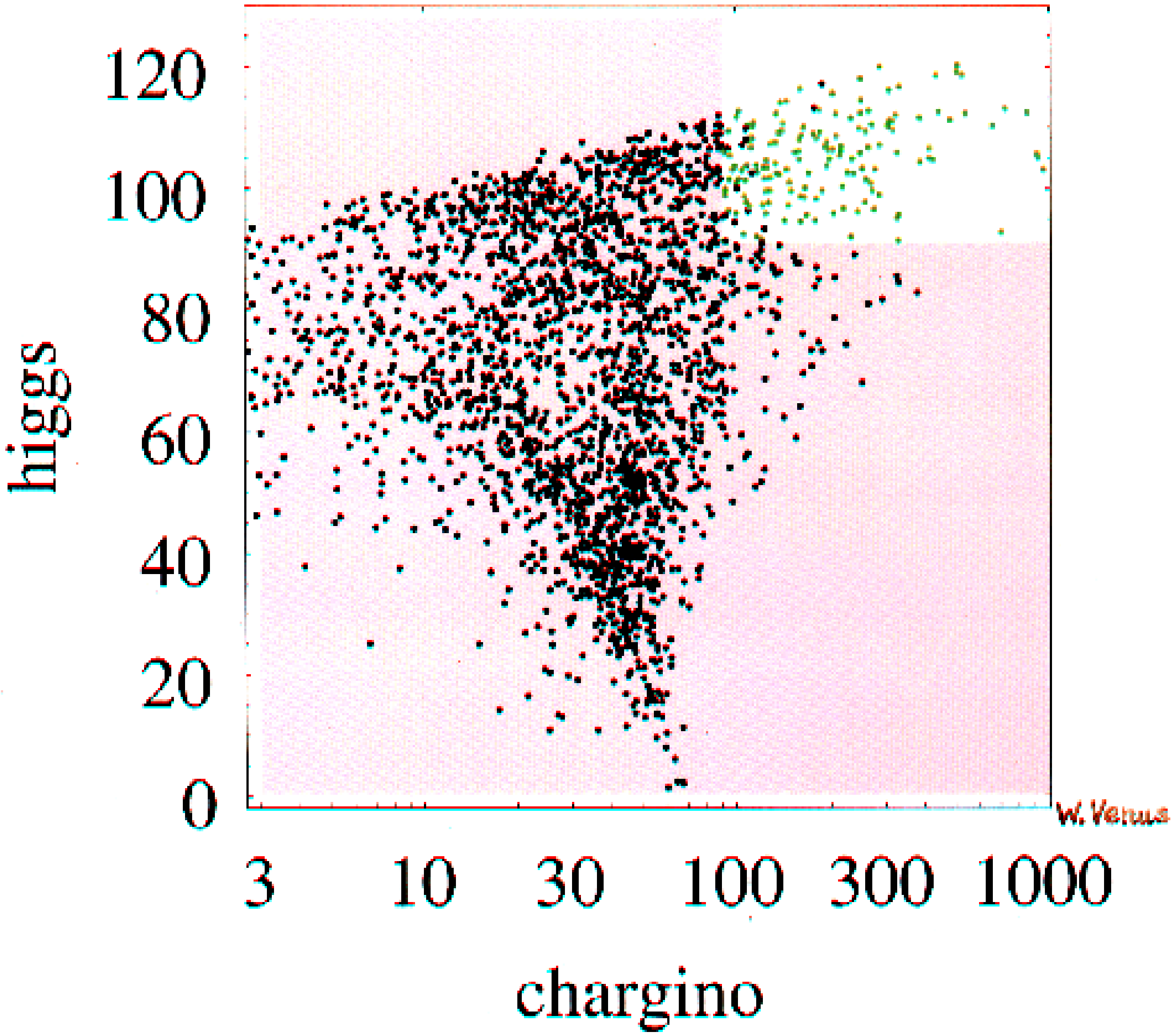
- R_p not conserved :

all $\tilde{p}$ decay into particles (including LSP, which is not any more a D.M. candidate)

→ look for multi-jet or multi-$\ell^{\pm}$ final states (with or without E_{miss})

the remaining mSUGRA corner...

"Natural" distributions of $tg\beta$ and SUSY masses in mSUGRA proposed by Giusti, Romanino, Strumia
hep-ph/9811386



only ~ 1% of the original mSUGRA phase space still survives today!

→ is SUSY getting less natural?

Results of SUSY searches

95% C.L. limits

▶ **Higgs sector :** $\overset{T}{\rightarrow}$

$M_h \geq 91$ GeV $\quad 0.5 \leq tg\beta \leq 2.4$

(still preliminary)

▶ **Gauginos :**

$M_{\chi^0_1} \gtrsim 40-60$ GeV depending on assumption on SUSY breaking mechanism

$M_{\chi^\pm} \gtrsim 91$ GeV within C-MSSM (5 free param.)

▶ Sleptons (within C-MSSM)

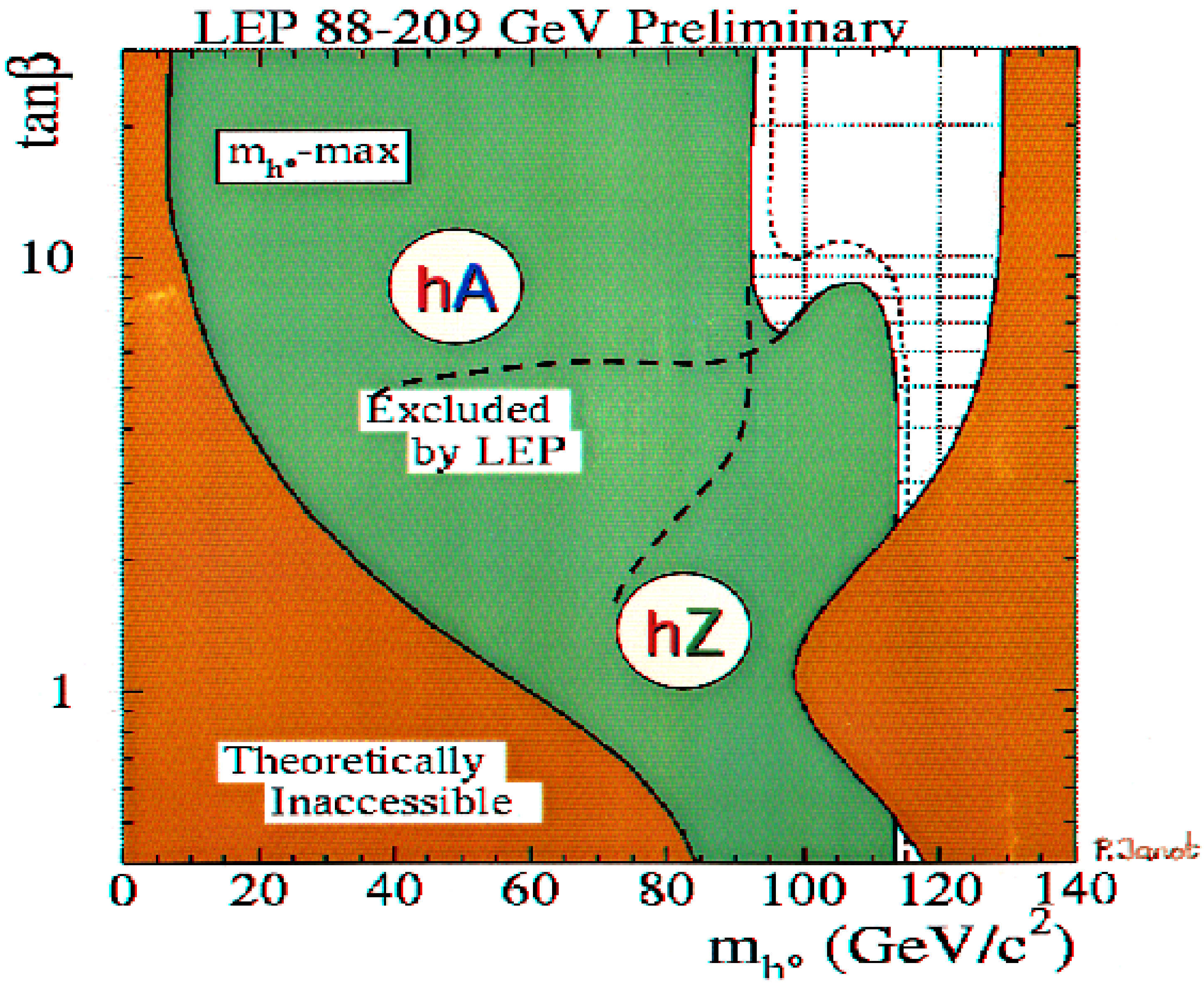
$m_{\tilde{e}} \geq 77$ GeV $\quad m_{\tilde{\mu}} \geq 83$ GeV $\quad m_{\tilde{\tau}} \geq 65$ GeV

▶ LSP : limits (when they exist) depend on various theoretical assumptions . . .
(gaugino mass unif., SUSY breaking mecha.)

⟶ mSUGRA squeezed in very small corner ! $\overset{T}{\rightarrow}$

... GMSB and AMSB even more so . . .

m_h, $m_A > 91$-92 GeV/c^2
at 95% C.L., any tanβ.



■ Search for New Physics ≠ SUSY

⚠ Much less predictive than mSUSY → limits less meaningful

- **TechniColour** : an alternative way to generate masses
  - naïve TC ruled out by EW correction measurements
  - less naïve/predictive TC : $e^+e^- \longrightarrow \rho_T^0 \longrightarrow W_L W_L, f\bar{f}(g), \pi_T^0 \gamma$.
    ↳ no ρ_T^0, π_T^0 observed ; no deviation from $\sigma_{WW}^{SM}, \sigma_{f\bar{f}}, \dots$

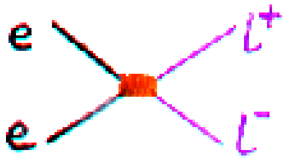
    also $\rho_T^* \to \pi_T \pi_T, W_L \pi_T \; (\pi_T \to bc)$ ... Fig →
- **Low Scale Quantum Gravity**: $M_{Pl} = M_D^{\delta+2} \cdot R^{\delta}$
  - direct search : $e^+e^- \longrightarrow G\gamma$ or $GZ \to f\bar{f}G$
  - indirect effects : $e^+e^- \longrightarrow f\bar{f}, \gamma\gamma, WW, ZZ$

    $M_S > 1$ TeV

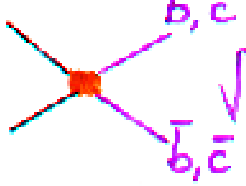
    $\delta = 2$ 4 6

    $M_D >$ 1.0-1.3 0.7-0.8 0.5 TeV (prelim.)
- **Additionnal gauge bosons (neutral)**

  $e^+e^- \longrightarrow l^+l^-$: $M_{Z'} \gtrsim 400 - 800$ GeV
- **Contact interactions**



$\sqrt{4\pi}\,\frac{\Lambda}{g} > 8.5 - 26$ TeV



$\sqrt{4\pi}\,\frac{\Lambda}{g} > 2.2 - 15$ TeV Fig → T

- **Excited leptons**

  $l^* \longrightarrow l\gamma, lZ, lW$

  $M_{l^*} > 200$ GeV

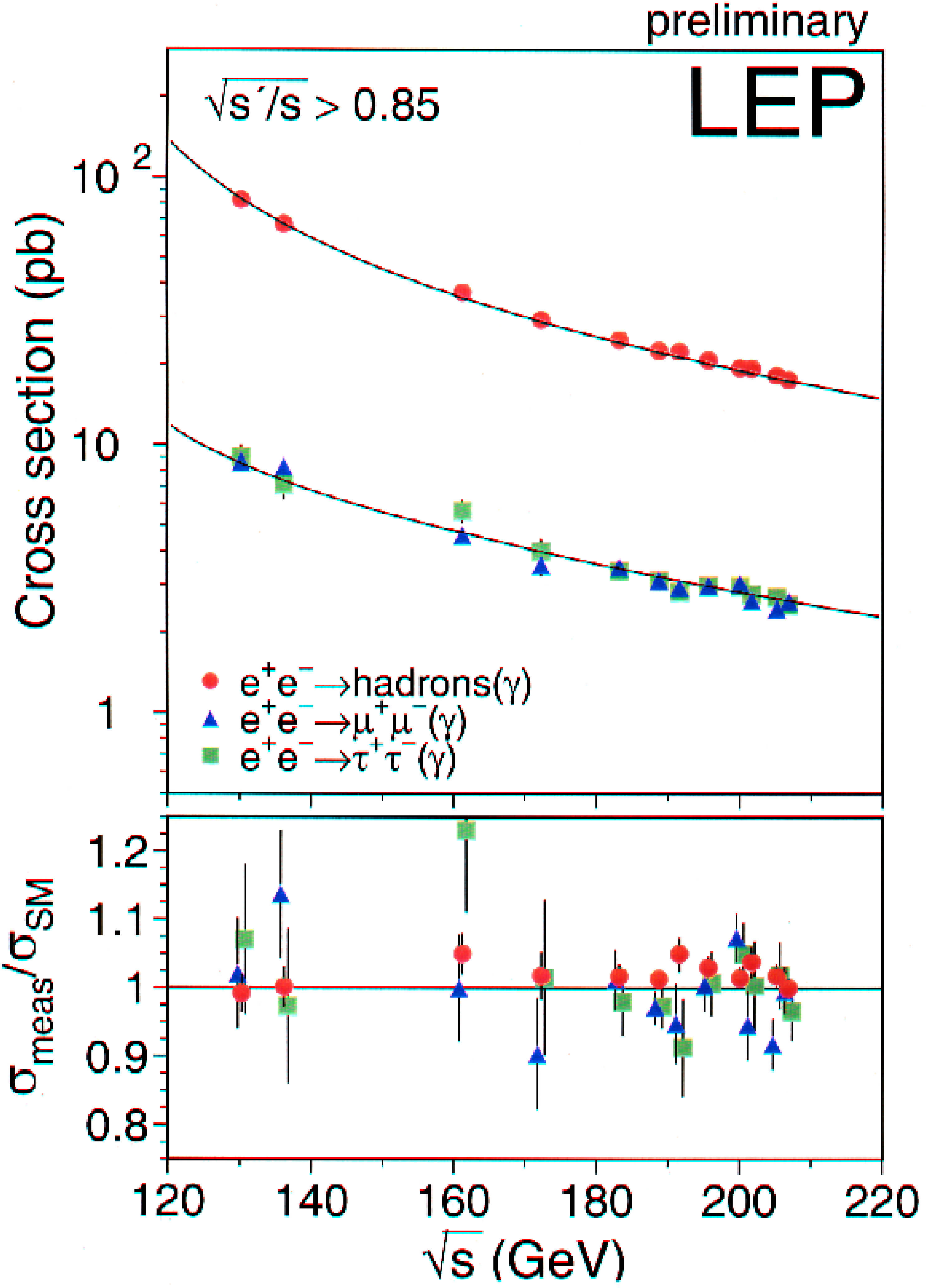
$M_{e^*} > 300$ GeV

- **LeptoQuarks** : colored objects carrying L and B, spin 0 or 1

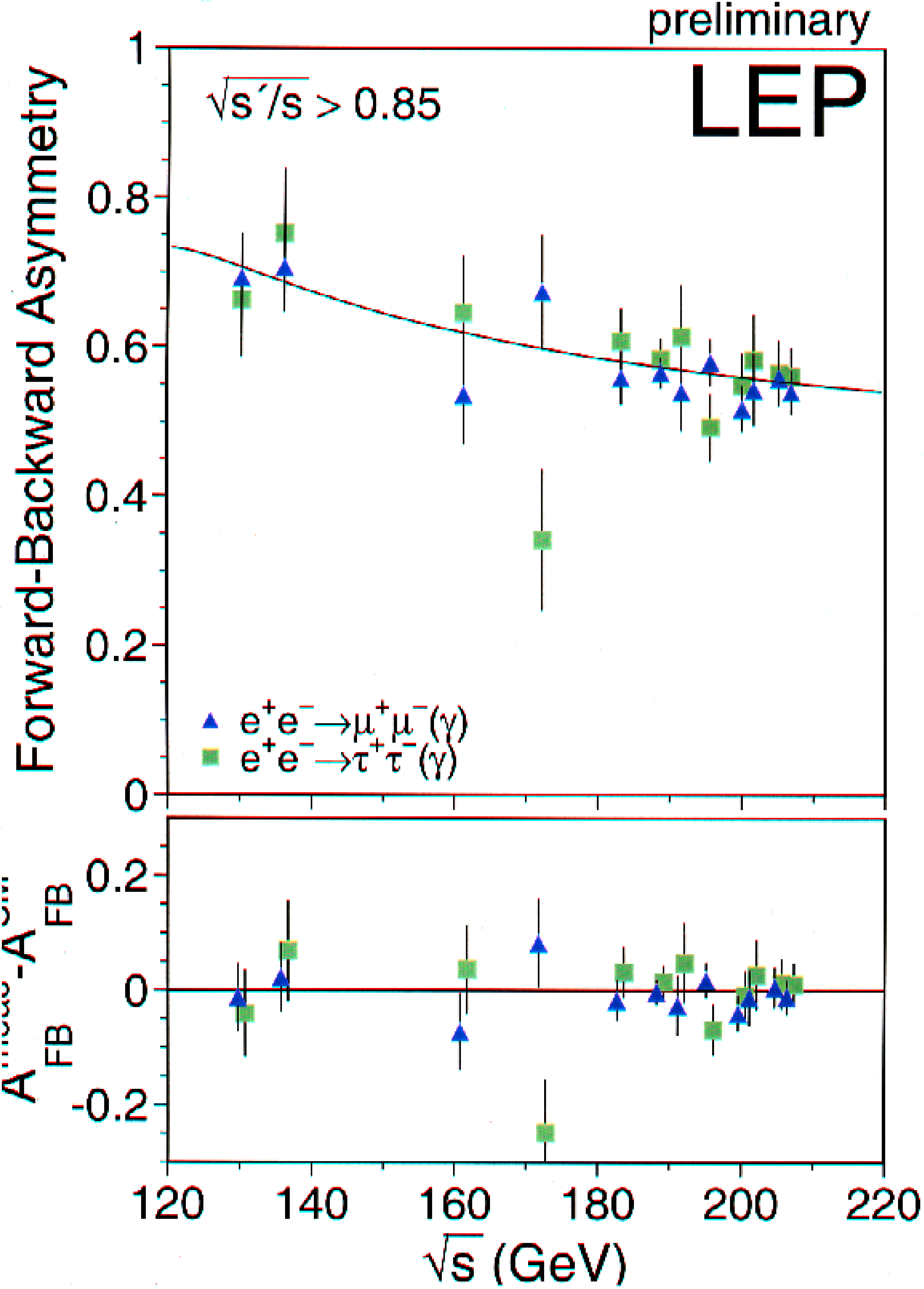
  $LQ \longrightarrow lq$: $M_{LQ} \gtrsim 50 - 400$ GeV
- **FCNC** : $e^+e^- \longrightarrow tc \longrightarrow Wbc$

  $\sigma < 90$ fb at $\sqrt{s} \simeq 194$ GeV

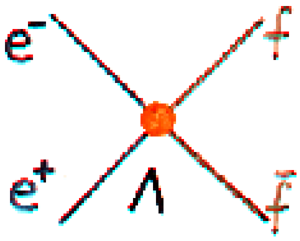
$\sigma(e^+e^- \longrightarrow f\bar{f})$



$A_{FB}(e^+e^- \longrightarrow \mu^+\mu^-, \tau^+\tau^-)$



▪ Contact interactions ($e^+e^- \to f\bar{f}$)



add to $\mathcal{L}_{SM}$:

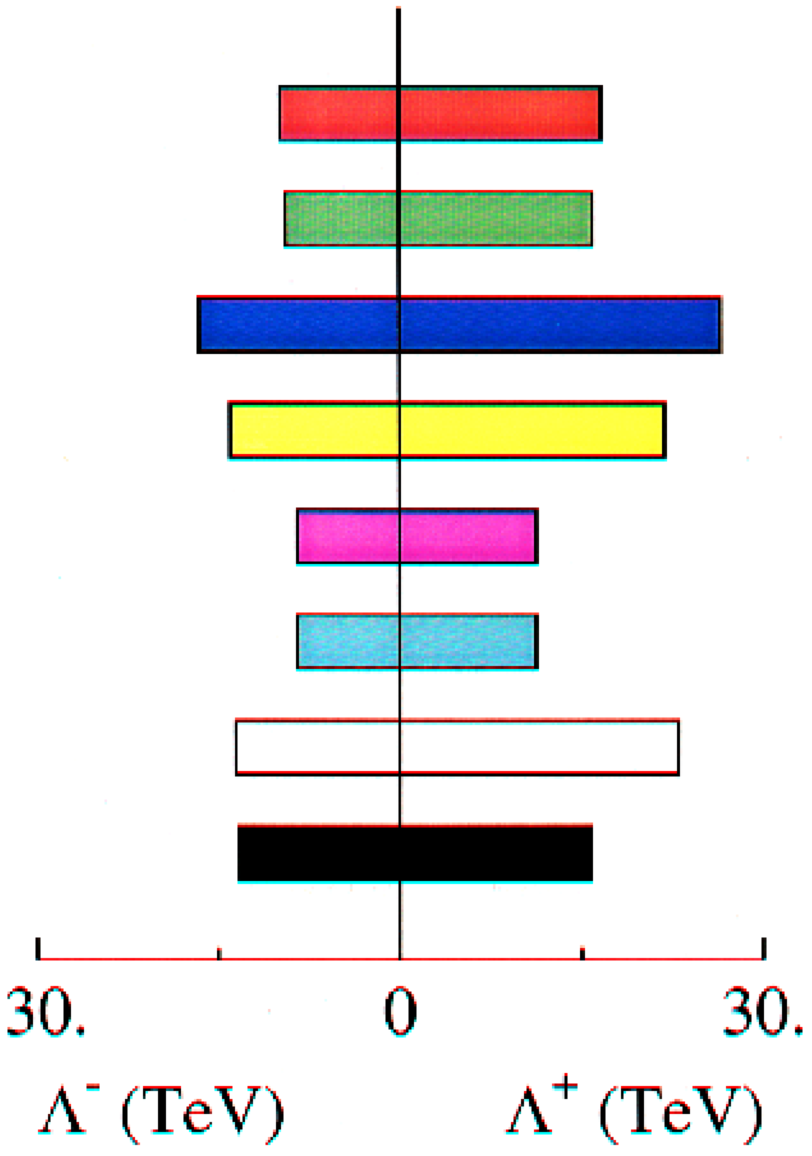
$$\mathcal{L}_{eff} = \frac{g^2}{(1+\delta)\Lambda^2}\sum_{i,j=L,R}\eta_{ij}\,\bar{e}_i\gamma_\mu e_i\,\bar{f}_j\gamma^\mu f_j$$

assuming various helicity couplings between initial and final states ⟶ constructive or destructive interference with S.M. process

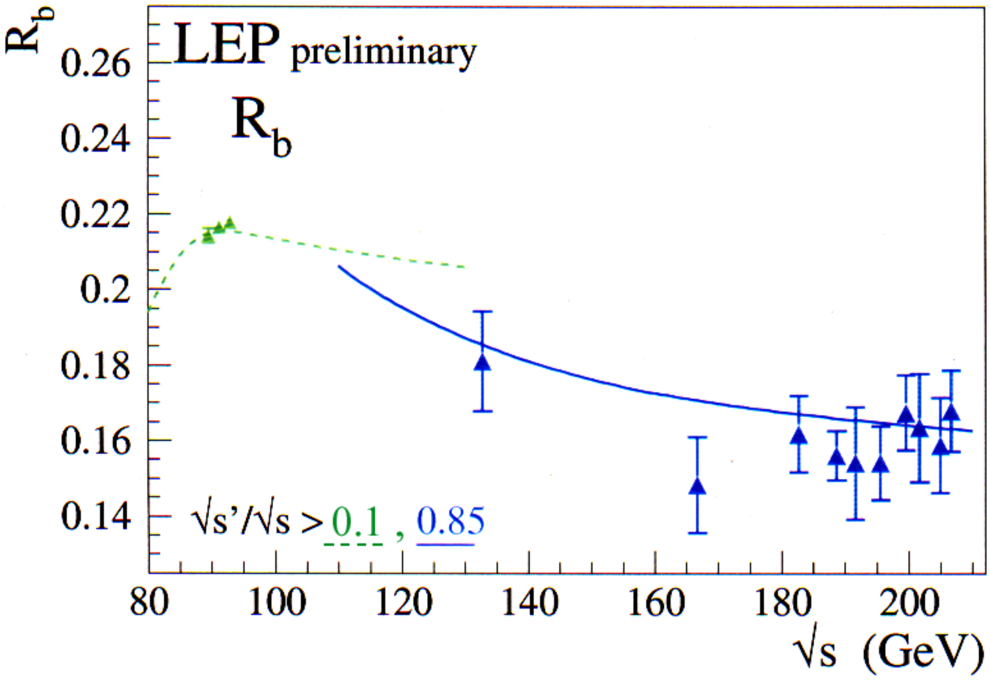
Preliminary LEP Combined

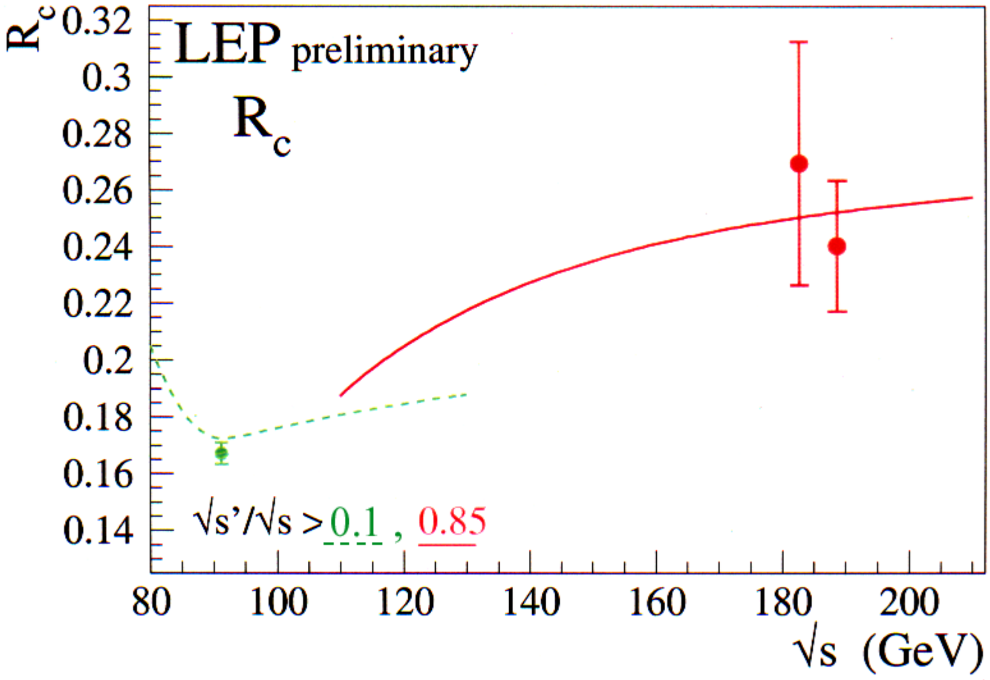
	Λ^-	Λ^+
LL	9.8	16.5
RR	9.4	15.8
VV	16.5	26.2
AA	14.0	21.7
LR	8.5	11.2
RL	8.5	11.2
V0	13.5	22.9
A0	13.2	15.6

l^+l^-

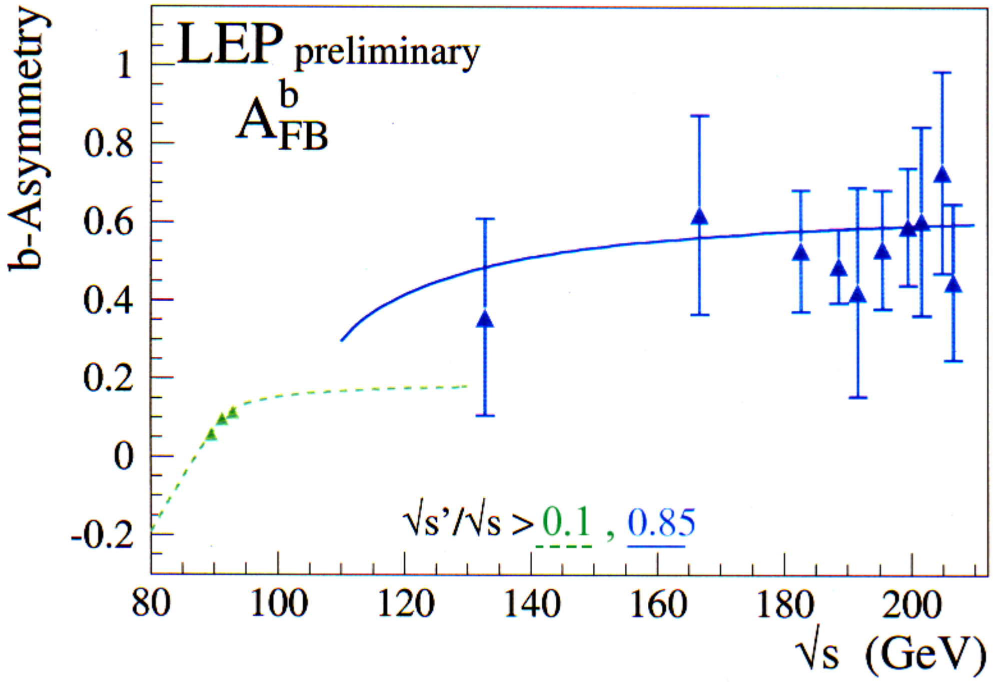


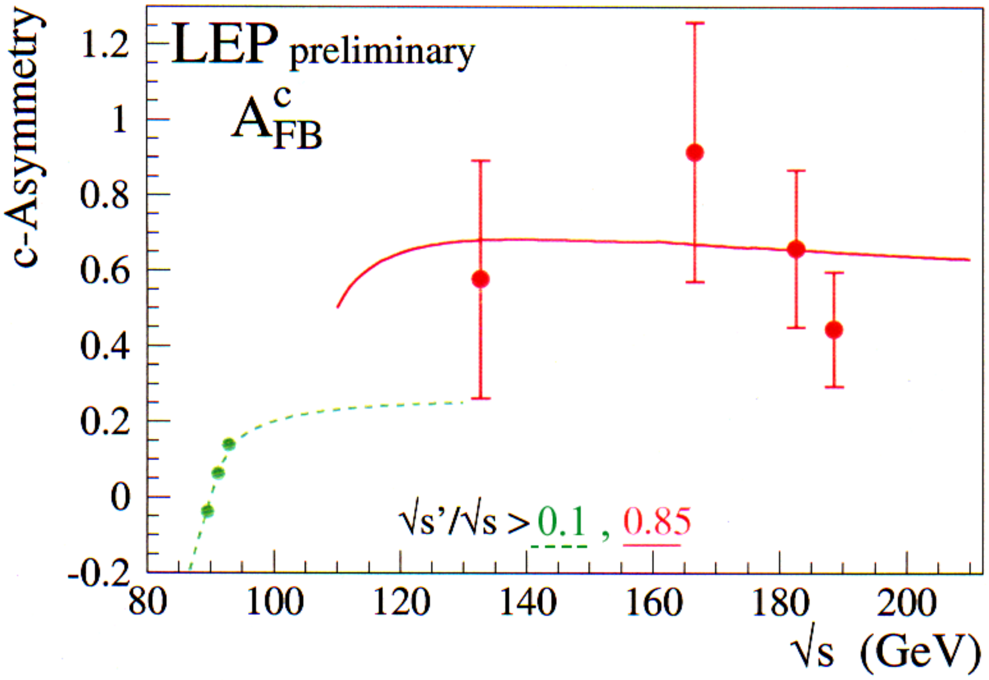
- $e^+e^- \longrightarrow b\bar{b}, c\bar{c}$: $R_b(\sqrt{s})$ and $R_c(\sqrt{s})$





- $e^+e^- \longrightarrow b\bar{b}, c\bar{c}$: $A^{b}_{FB}(\sqrt{s})$ and $A^{c}_{FB}(\sqrt{s})$





Summary

S.M. established, and tested with very high precision

- $M_Z \pm 2\,10^{-5}$, $R_b \pm 0.3\%$, $N_{\nu_L} \simeq 3 \pm 0.3\%$, $M_W \pm 4\,10^{-4}$, $\sin^2\theta^{\ell}_{eff} \pm 6\,10^{-4}$, ...
- evidence for pure EW corrections, tested at ~10% level
  - $\hookrightarrow$ prediction of m_t, and of $M_H^{SM} < 270$ GeV (99% C.L.)
- wide range of Higgs boson mass explored (primor!)
  - $\hookrightarrow$ $M_H^{SM} \gtrsim 114$ GeV (95% C.L.)
- gauge cancellation established in W^+W^- production $O(10^{-2})$
- universality of neutral (charged) EW couplings confirmed at 10^{-3} (10^{-2}) level
- running of α_s well established, as predicted by QCD
- perturbative QCD studied in much detail
- knowledge of τ properties (Br_i, τ_τ, ...) much improved
- knowledge of heavy quark properties also improved

⋮

- no sign of physics beyond the S.M. (a surprise!)
  - $\hookrightarrow$ mSUSY squeezed in very small corner! $M_h \gtrsim 90$ GeV, $tg\beta > 2.4$
  - strong constraints on various alternatives to SUSY
  - should we take modest discrepancies (A^b_{FB}, $\sin\theta_{\nu N}$, N_ν ⋮) for signs of New Physics?

Conclusion

the '90s brought big conceptual progress ...

- Relativistic Quantum Field Theory describes nature

theorists should believe in their ideas ...

- (Microscopic) forces are due to local symmetries
  → gauge fields

→ vacuum structure

- E.W theory is a real Renormalisable Q.F.T.
  → one can make predictions in gauge sector and in Higgs sector
  → one can ask accurate questions able to drive H.E. physics in coming decades (= targets)

what is behind E.W.S.B.?

how to answer questions triggered by the S.M. weaknesses?

Tevatron

LHC

Linear Collider

$\not{CP}$

τ_p

ν

$\Lambda_{cos.}$

2005

2015

something should happen!