

# Electroweak Physics

- Precision Experiments: Historical Perspective
- LEP/SLD Physics
- Probing the Standard Model
- Beyond the Standard Model

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## The $Z$ , the $W$ , and the Weak Neutral Current

- Primary prediction and test of electroweak unification
- WNC discovered 1973 (Gargamelle, HPW)
- 70's, 80's: weak neutral current experiments (few %)
  - Pure weak:  $\nu N$ ,  $\nu e$  scattering
  - Weak-elm interference in  $eD$ ,  $e^+e^-$ , atomic parity violation
- $W$ ,  $Z$  discovered directly 1983 (UA1, UA2)
- 90's:  $Z$  pole (LEP, SLD), 0.1%; lineshape, modes, asymmetries
- LEP 2:  $M_W$ , Higgs, gauge self-interactions
- Tevatron:  $m_t$ ,  $M_W$
- Implications
  - SM correct and unique to zeroth approx. (gauge principle, group, representations)
  - SM correct at loop level (renorm gauge theory;  $m_t$ ,  $\alpha_s$ ,  $M_H$ )
  - TeV physics severely constrained (unification vs compositeness)
  - Precise gauge couplings (gauge unification)

## Results before the LEP/SLD era

- Global Analysis
  - more information than individual experiments
  - caveat: exp./theor. systematics, correlations
- model-independent fits
  - Unique  $\nu q$ ,  $\nu e$ ,  $eq$ 
    - \* SM correct to first approximation
    - \* Contrived imitators out
- QCD evolved structure functions
- Radiative corrections necessary ( $\sin^2 \theta_W$  defns)
- $\sin^2 \theta_W = .230 \pm 0.007$ ,  $m_t < 200$  GeV
- Unique fermion reps. (wnc + wcc)
- $t$  and  $\nu_\tau$  exist
- Grand unification
  - Ordinary  $SU_5$  excluded; “consistent with SUSY GUTS and perhaps even the first harbinger of supersymmetry”
- Stringent limits on new physics
- $Z'$ , exotic fermions, exotic Higgs, leptoquarks, 4-F operators

## The LEP/SLD Era

- $Z$  Pole:  $e^+e^- \rightarrow Z \rightarrow \ell^+\ell^-, q\bar{q}, \nu\bar{\nu}$ 
  - LEP (CERN),  $2 \times 10^7 Z$ 's, unpolarized;  
SLC (SLAC),  $5 \times 10^5$ ,  $P_{e^-} \sim 75\%$
- $Z$  pole observables
  - lineshape:  $M_Z, \Gamma_Z, \sigma$
  - branching ratios
    - \*  $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$
    - \*  $q\bar{q}, c\bar{c}, b\bar{b}, s\bar{s}$
    - \*  $\nu\bar{\nu} \Rightarrow N_\nu = 2.985 \pm 0.008$  if  $m_\nu < M_Z/2$
  - asymmetries: FB, polarization,  $P_\tau$ , mixed
  - lepton family universality
- LEP 2
  - $M_W, \Gamma_W, B$  (also hadron colliders)
  - $M_H$  limits (hint?)
  - $WW$  production (triple gauge vertex)
  - quartic vertex
  - SUSY/exotics searches
- Other: atomic parity (Boulder);  $\nu e; \nu N$  (NuTeV);  
 $M_W, m_t$  (Tevatron)

## The Z Lineshape

- $e^+e^- \rightarrow f\bar{f}$  ( $f = e, \mu, \tau, s, b, c, \text{hadrons}$ );  
 $s = E_{CM}^2$

$$\sigma_f(s) \sim \sigma_f \frac{s\Gamma_Z^2}{(s - M_Z^2)^2 + \frac{s^2\Gamma_Z^2}{M_Z^2}}$$

(plus initial state rad. corrections)

$$\sigma_f = \frac{12\pi}{M_Z^2} \frac{\Gamma(e^+e^-)\Gamma(f\bar{f})}{\Gamma_Z^2}$$

$$\begin{aligned} \Gamma(\text{inv}) &= \Gamma_Z - \Gamma(\text{had}) - \sum_i \Gamma(\ell_i\bar{\ell}_i) \\ &\equiv N_\nu\Gamma(\nu\bar{\nu}) \end{aligned}$$

$$R_{q_i} \equiv \frac{\Gamma(q_i\bar{q}_i)}{\Gamma(\text{had})}, \quad q_i = b, c, s$$

$$R_{\ell_i} \equiv \frac{\Gamma(\text{had})}{\Gamma(\ell_i\bar{\ell}_i)}, \quad \ell_i = e, \mu, \tau$$

( $R_e = R_\mu = R_\tau \equiv R_\ell \rightarrow$  lepton universality)

$$\Gamma(f\bar{f}) \sim \frac{C_f G_F M_Z^3}{6\sqrt{2}\pi} [|\bar{g}_{Vf}|^2 + |\bar{g}_{Af}|^2]$$

(plus mass, QED, QCD corrections;  $C_\ell = 1$ ,  $C_q = 3$ ;  $\bar{g}_{V,Af}$  = effective coupling (includes ew))

- $M_Z, \Gamma_Z, \sigma_{\text{had}}, R_\ell, R_b, R_c$  mainly weakly correlated

## Z-Pole Asymmetries

- $A^0 =$  Born asymmetry, after removing  $\gamma$ , off-pole, box (small),  $P_{e^-}$

$$\text{forward} - \text{backward} : A_{FB}^{0f} \simeq \frac{3}{4} A_e A_f$$

$$(A_{FB}^{0e} = A_{FB}^{0\mu} = A_{FB}^{0\tau} \equiv A_{FB}^{0\ell} \rightarrow \text{universality})$$

$$\tau \text{ polarization} : P_{\tau}^0 = -\frac{A_{\tau} + A_e \frac{2z}{1+z^2}}{1 + A_{\tau} A_e \frac{2z}{1+z^2}}$$

$$(z = \cos \theta, \quad \theta = \text{scattering angle})$$

$$e^- \text{ polarization (SLD)} : A_{LR}^0 = A_e$$

$$\text{mixed (SLD)} : A_{LR}^{0FB} = \frac{3}{4} A_f$$

$$A_f \equiv \frac{2\bar{g}_{VF}\bar{g}_{Af}}{\bar{g}_{VF}^2 + \bar{g}_{AF}^2}$$

$$\bar{g}_{Af} = \sqrt{\rho_f} t_{3f}$$

$$\bar{g}_{Vf} = \sqrt{\rho_f} [t_{3f} - 2\bar{s}_f^2 q_f]$$

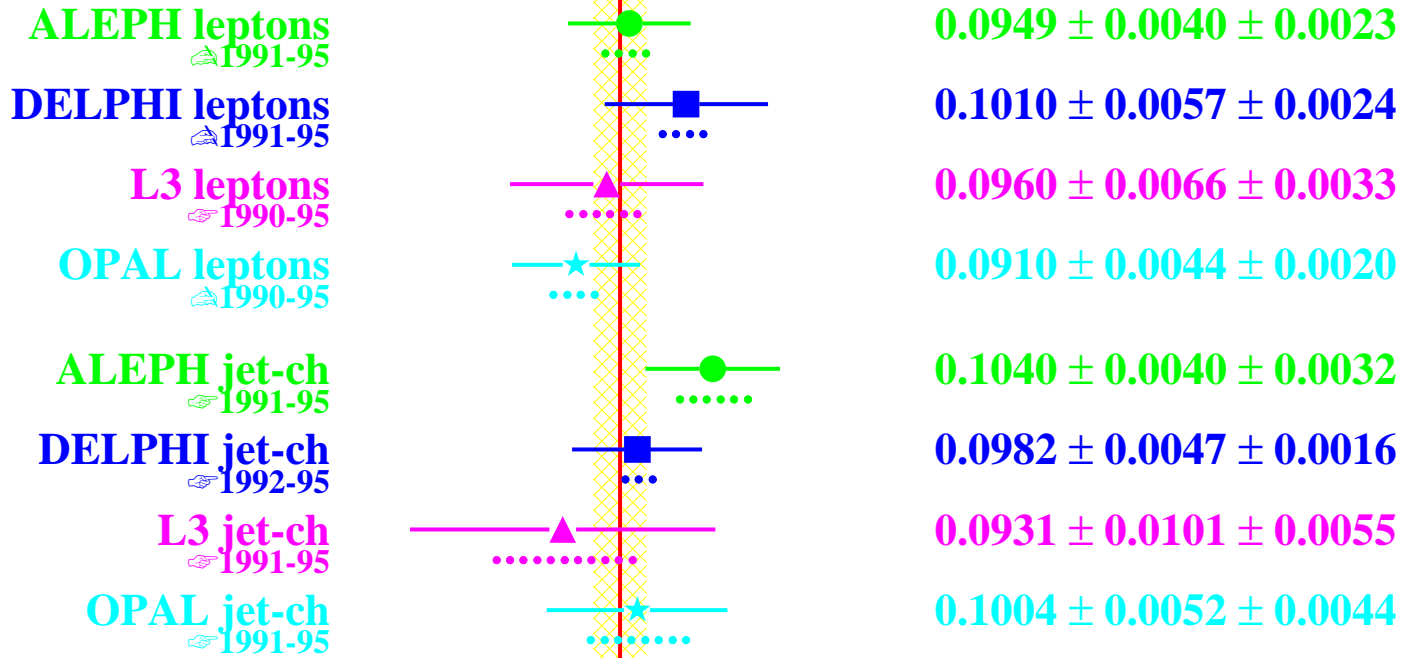
where  $\bar{s}_f^2$  the effective weak angle,

$$\bar{s}_f^2 = \kappa_f s_W^2 \quad (\text{on-shell})$$

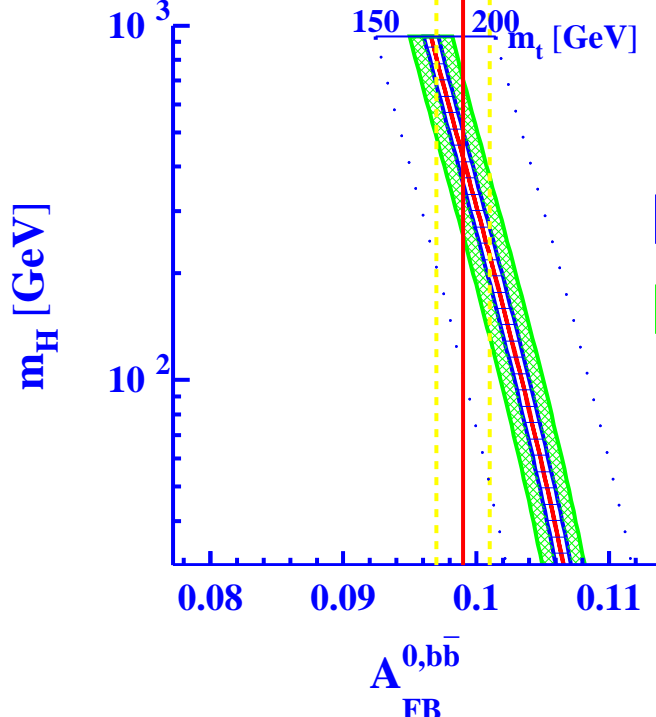
$$= \hat{\kappa}_f \hat{s}_Z^2 \sim \hat{s}_Z^2 + 0.00029 \quad (f = e) \quad (\overline{\text{MS}}),$$

$\rho_f, \kappa_f$ , and  $\hat{\kappa}_f$  are electroweak corrections,  $q_f =$  electric charge,  $t_{3f} =$  weak isospin

$$A_{\text{FB}}^{b\bar{b}} \text{ at } \sqrt{s} \approx m_Z$$



LEP Summer 2000



$0.0990 \pm 0.0020$

Include Total Sys 0.0009  
With Common Sys 0.0006

$m_t = 174.3 \pm 5.1 \text{ GeV}$

$\Delta\alpha_{\text{had}} = 0.02804 \pm 0.00065$

## The Z Pole Observables: LEP and SLC (7/01)

Quantity	Group(s)	Value	Standard Model	pull
$M_Z$ [GeV]	LEP	$91.1876 \pm 0.0021$	$91.1874 \pm 0.0021$	0.1
$\Gamma_Z$ [GeV]	LEP	$2.4952 \pm 0.0023$	$2.4966 \pm 0.0016$	-0.6
$\Gamma(\text{had})$ [GeV]	LEP	$1.7444 \pm 0.0020$	$1.7429 \pm 0.0015$	—
$\Gamma(\text{inv})$ [MeV]	LEP	$499.0 \pm 1.5$	$501.76 \pm 0.14$	—
$\Gamma(\ell^+\ell^-)$ [MeV]	LEP	$83.984 \pm 0.086$	$84.019 \pm 0.027$	—
$\sigma_{\text{had}}$ [nb]	LEP	$41.541 \pm 0.037$	$41.477 \pm 0.014$	1.7
$R_e$	LEP	$20.804 \pm 0.050$	$20.744 \pm 0.018$	1.2
$R_\mu$	LEP	$20.785 \pm 0.033$	$20.744 \pm 0.018$	1.2
$R_\tau$	LEP	$20.764 \pm 0.045$	$20.790 \pm 0.018$	-0.6
$A_{FB}(e)$	LEP	$0.0145 \pm 0.0025$	$0.01637 \pm 0.00026$	-0.8
$A_{FB}(\mu)$	LEP	$0.0169 \pm 0.0013$		0.4
$A_{FB}(\tau)$	LEP	$0.0188 \pm 0.0017$		1.4
$R_b$	LEP + SLD	$0.21664 \pm 0.00068$	$0.21569 \pm 0.00016$	1.4
$R_c$	LEP + SLD	$0.1729 \pm 0.0032$	$0.17230 \pm 0.00007$	0.2
$A_{FB}(b)$	LEP	$0.0982 \pm 0.0017$	$0.1036 \pm 0.0008$	-3.2
$A_{FB}(c)$	LEP	$0.0689 \pm 0.0035$	$0.0740 \pm 0.0006$	-1.5
$A_{FB}(s)$	DELPHI,OPAL	$0.0976 \pm 0.0114$	$0.1037 \pm 0.0008$	-0.5
$A_b$	SLD	$0.921 \pm 0.020$	$0.9347 \pm 0.0001$	-0.7
$A_c$	SLD	$0.667 \pm 0.026$	$0.6681 \pm 0.0005$	0.0
$A_s$	SLD	$0.895 \pm 0.091$	$0.9357 \pm 0.0001$	-0.4
$A_{LR}$ (hadrons)	SLD	$0.15138 \pm 0.00216$	$0.1478 \pm 0.0012$	1.7
$A_{LR}$ (leptons)	SLD	$0.1544 \pm 0.0060$		1.1
$A_\mu$	SLD	$0.142 \pm 0.015$		-0.4
$A_\tau$	SLD	$0.136 \pm 0.015$		-0.8
$A_\tau(\mathcal{P}_\tau)$	LEP	$0.1439 \pm 0.0041$		-0.9
$A_e(\mathcal{P}_\tau)$	LEP	$0.1498 \pm 0.0048$		0.4
$\bar{s}_\ell^2(Q_{FB})$	LEP	$0.2322 \pm 0.0010$	$0.23143 \pm 0.00015$	0.8

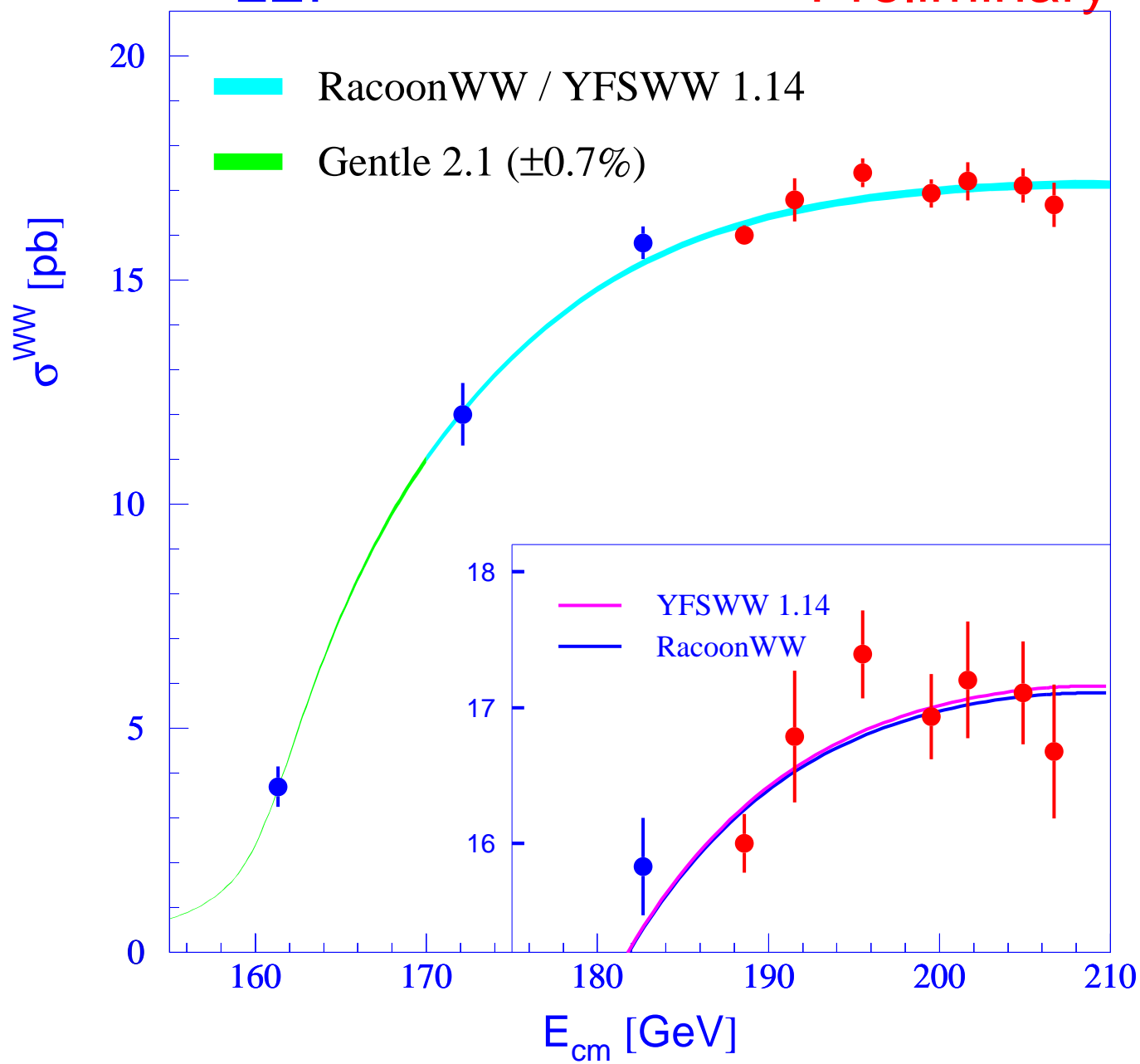
## Non-Z Pole Precision Observables: Tevatron, LEP 2, $\nu N$ , APV (7/01)

Quantity	Group(s)	Value	Standard Model	pull
$\sigma_{\text{had}}^e[\text{nb}]$	Tevatron	$174.3 \pm 5.1$	$175.3 \pm 4.4$	-0.2
$\sigma_{\text{had}}^e[\text{nb}]$	LEP	$80.446 \pm 0.040$	$80.391 \pm 0.019$	1.4
$\sigma_{\text{had}}^e[\text{nb}]$	Tevatron,UA2	$80.451 \pm 0.061$		1.0
	NuTeV	$0.2277 \pm 0.0021 \pm 0.0007$	$0.2300 \pm 0.0002$	-1.1
	CCFR	$0.5820 \pm 0.0027 \pm 0.0031$	$0.5833 \pm 0.0004$	-0.3
	CDHS	$0.3096 \pm 0.0033 \pm 0.0028$	$0.3093 \pm 0.0002$	0.1
	CHARM	$0.3021 \pm 0.0031 \pm 0.0026$		-1.7
	CDHS	$0.384 \pm 0.016 \pm 0.007$	$0.3862 \pm 0.0002$	-0.1
	CHARM	$0.403 \pm 0.014 \pm 0.007$		1.0
	CDHS 1979	$0.365 \pm 0.015 \pm 0.007$	$0.3817 \pm 0.0002$	-1.0
	CHARM II	$-0.035 \pm 0.017$	$-0.0398 \pm 0.0003$	—
	all	$-0.040 \pm 0.015$		-0.1
	CHARM II	$-0.503 \pm 0.017$	$-0.5065 \pm 0.0001$	—
	all	$-0.507 \pm 0.014$		0.0
$\sigma_{\text{had}}^e[\text{nb}]$	Boulder	$-72.65 \pm 0.28 \pm 0.34$	$-73.10 \pm 0.03$	1.0
$\sigma_{\text{had}}^e[\text{nb}]$	Oxford,Seattle	$-114.8 \pm 1.2 \pm 3.4$	$-116.67 \pm 0.05$	0.5
$\sigma_{\text{had}}^e[\text{nb}]$	CLEO	$3.26_{-0.68}^{+0.75} \times 10^{-3}$	$3.14_{-0.16}^{+0.17} \times 10^{-3}$	0.2
$\sigma_{\text{had}}^e[\text{nb}]$	E821	$4510.55 \pm 1.51 \pm 0.51$	$4506.55 \pm 0.36$	2.5

21/07/2000

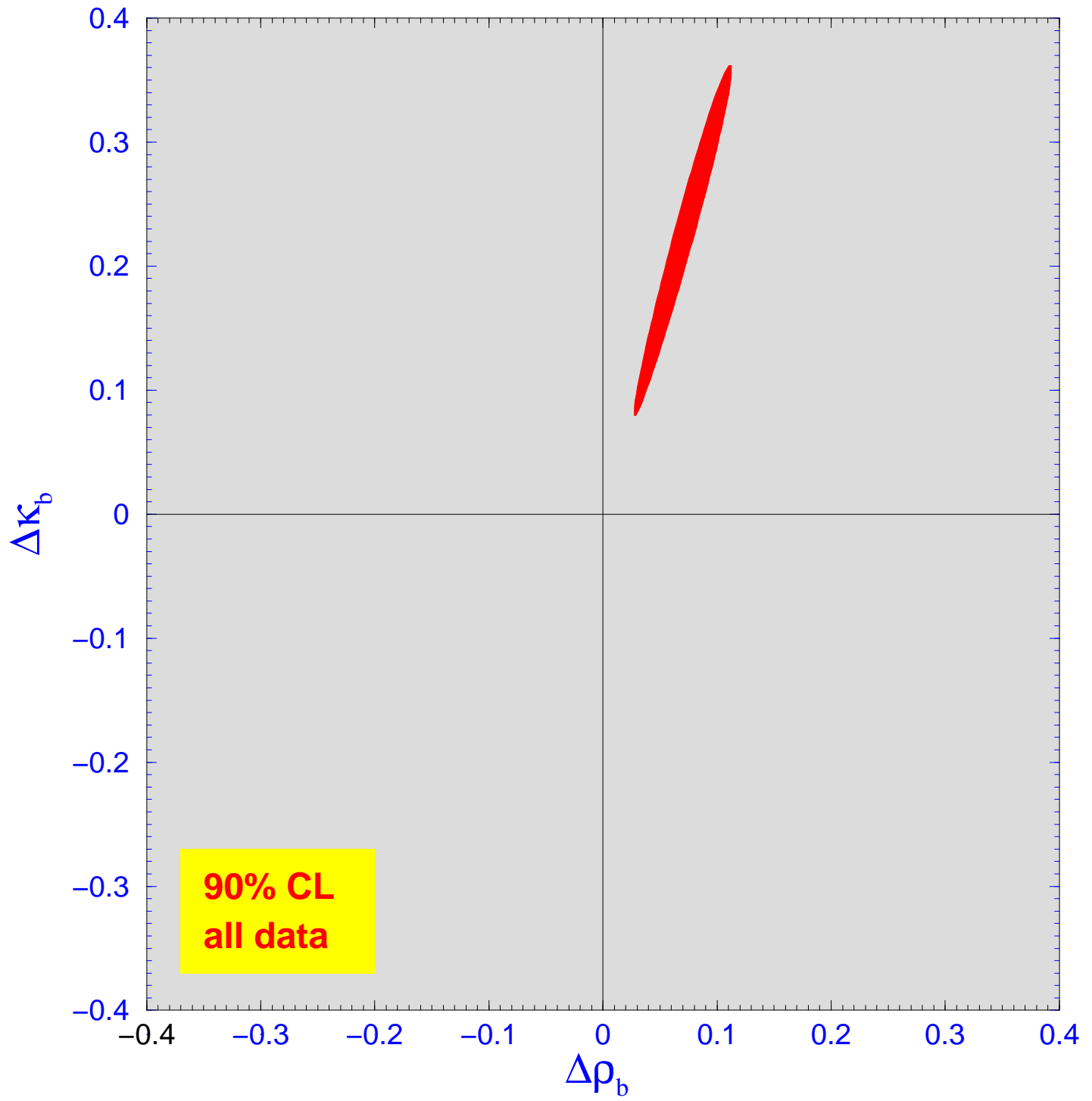
LEP

Preliminary



## $A_{FB}(b)$

- $A_{FB}(b) = 0.0994 \pm 0.0017$  (SM:  $0.1038 \pm 0.0008$ ,  $-2.6\sigma$ )
  - $R_b = 0.21664 \pm 0.00068$  (SM:  $0.21569 \pm 0.00016$ , agrees at  $1.4\sigma$ )
  - $A_b = 0.921 \pm 0.020$  (SM:  $0.93474 \pm 0.00011$  agrees at  $-0.7\sigma$ )
- 5% effect, but  $\sim 25\%$  in  $\kappa \rightarrow$  probably tree level affecting third family
- Compensation of  $L$  and  $R$  couplings ( $R_b$ )
- $M_H$  correlations, whether new physics or systematics



- LEP/SLD remarkably successful (beyond anticipation)
  - Machine
  - Detectors: ALEPH, DELPHI, L3, OPAL (LEP); SLD (SLC)
  - Analysis: tides, water table/lake, trains
  - LEPEWWG critical
  - Theoretical inputs
    - \* precise QED, EW, QCD, mixed radiative corrections
    - \*  $\sin^2 \theta_W$  definitions
    - \*  $\alpha_{\text{had}}$  (running  $\alpha$ )
    - \* Packages: ZFITTER, TOPAZ0, ALIBABA, BHLUMI, GAPP, (LEP2)
    - \* new physics parametrizations
  - Global analyses: LEPEWWG, PDG, ...
  - Polarization: SLC advantage; (Blondel scheme)
- Future: GigaZ ?

# The Anomalous Magnetic Moment of the Muon

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{Had}} + a_\mu^{\text{EW}} = 11659177(7) \times 10^{-10}$$

$$\begin{aligned} a_\mu^{\text{QED}} &= \frac{\alpha}{2\pi} + 0.765857376(27) \left(\frac{\alpha}{\pi}\right)^2 \\ &\quad + 24.05050898(44) \left(\frac{\alpha}{\pi}\right)^3 + 126.07(41) \left(\frac{\alpha}{\pi}\right)^4 \\ &\quad + 930(170) \left(\frac{\alpha}{\pi}\right)^5 = 11658470.57(0.29) \times 10^{-10} \end{aligned}$$

$$\begin{aligned} a_\mu^{\text{Had}} &= a_\mu^{\text{Had}}(\text{vp})_{1+2} + a_\mu^{\text{Had}}(\text{ll}) \\ &= (692(6) - 10.0(0.6) + 8.6(3.2)) \times 10^{-10} \end{aligned}$$

$$a_\mu^{\text{EW}}(2 \text{ loop}) = 15.1(0.4) \times 10^{-10}$$

- BNL (2002) + other:  $a_\mu^{\text{exp}} = 11659203(8) \times 10^{-10}$

- $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (26 \pm 11) \times 10^{-10} \quad (2.6\sigma)$

- Statistics? (will improve);  $a_\mu^{\text{Had}}$  ?

- New physics? Supersymmetry:  
( $\tilde{m} \sim 55 \text{ GeV} \sqrt{\tan \beta}$ )

## Radiative Corrections

- Dominant two-loop electroweak ( $\alpha^2 m_t^4$ ,  $\alpha^2 m_t^2$ )
- Dominant 3 loop QCD (4 loop estimate)
- Dominant 3 loop mixed QCD-EW ( $\alpha\alpha_s$  vertex)
- Definitions of renormalized  $\sin^2 \theta_W$

– On shell:  $s_W^2 \equiv 1 - \frac{M_W^2}{M_Z^2}$

– Z mass:  $s_{M_Z}^2 \left(1 - s_{M_Z}^2\right) \equiv \frac{\pi\alpha(M_Z)}{\sqrt{2}G_F M_Z^2}$

–  $\overline{\text{MS}}$  :  $\hat{s}_Z^2 \equiv \frac{\hat{g}'^2(M_Z)}{\hat{g}'^2(M_Z) + \hat{g}^2(M_Z)}$

– Effective (Z-pole):  $\bar{s}_f^2 \equiv \frac{1}{4} \left(1 - \frac{\bar{g}_{Vf}}{\bar{g}_{Af}}\right)$

$$M_W^2 = \frac{(\pi\alpha/\sqrt{2}G_F)}{s_W^2(1 - \Delta r)} = \frac{(\pi\alpha/\sqrt{2}G_F)}{\hat{s}_Z^2(1 - \Delta \hat{r}_W)}$$

$$M_Z^2 = \frac{M_W^2}{c_W^2} = \frac{M_W^2}{\hat{\rho}\hat{c}_Z^2}$$

$$\bar{s}_f^2 = \kappa_f s_W^2 = \hat{\kappa}_f \hat{s}_Z^2$$

$$\bar{s}_e^2 \sim \hat{s}_Z^2 + 0.00029$$

( $\kappa_f, \hat{\kappa}_f$  depend on  $m_t, M_H$ )

$$\hat{\rho} \sim 1 + \frac{3G_F \hat{m}_t^2}{8\sqrt{2}\pi^2} + \dots$$

$$\Delta \hat{r}_W \sim \Delta\alpha + \dots \sim 0.066 + \dots$$

## Definitions of $\sin^2 \theta_W$

On-shell : $s_W^2 = 1 - \frac{M_W^2}{M_Z^2} = 0.22278$ (36)
<ul style="list-style-type: none"> <li>+ most familiar</li> <li>+ simple conceptually</li> <li>– large <math>m_t</math>, <math>M_H</math> dependence from <math>Z</math>-pole observables</li> <li>– depends on SSB mechanism – awkward for new physics</li> </ul>
Z-mass : $s_{M_Z}^2 = 0.23105$ (8)
<ul style="list-style-type: none"> <li>+ most precise (no <math>m_t</math>, <math>M_H</math> dependence)</li> <li>+ simple conceptually</li> <li>– <math>m_t</math>, <math>M_H</math> reenter when predicting other observables</li> <li>– depends on SSB mechanism – awkward for new physics</li> </ul>
$\overline{MS}$ : $\hat{s}_Z^2 = 0.23113$ (15)
<ul style="list-style-type: none"> <li>+ based on coupling constants</li> <li>+ convenient for GUTs</li> <li>+ usually insensitive to new physics</li> <li>+ <math>Z</math> asymmetries <math>\sim</math> independent of <math>m_t</math>, <math>M_H</math></li> <li>– theorists definition; not simple conceptually</li> <li>– usually determined by global fit</li> <li>– some sensitivity to <math>m_t</math>, <math>M_H</math></li> <li>– variant forms (<math>m_t</math> cannot be decoupled in all processes; <math>\hat{s}_{ND}^2</math> larger by 0.0001 – 0.0002)</li> </ul>
effective : $\bar{s}_\ell^2 = 0.23143$ (15)
<ul style="list-style-type: none"> <li>+ simple</li> <li>+ <math>Z</math> asymmetry independent of <math>m_t</math></li> <li>+ <math>Z</math> widths: <math>m_t</math> in <math>\rho_f</math> only</li> <li>– phenomenological; exact definition in computer code</li> <li>– different for each <math>f</math></li> <li>– hard to relate to non <math>Z</math>-pole observables</li> </ul>

## Running of $\alpha$

- Largest theory uncertainty in  $M_Z - \hat{s}_Z^2$  (cf.  $a_\mu^{\text{had}}$ )

$$\alpha(M_Z^2) = \frac{\alpha}{1 - \Delta\alpha}$$

$$\begin{aligned} \Delta\alpha &= \Delta\alpha_\ell + \Delta\alpha_t + \Delta\alpha_{\text{had}}^{(5)} \\ &\sim 0.031497 - 0.000070 + \Delta\alpha_{\text{had}}^{(5)} \end{aligned}$$

$$\alpha^{-1} \sim 137.036$$

$$\alpha^{-1}(M_Z) \sim \hat{\alpha}^{-1}(M_Z) + 0.99 \sim 129$$

$$M_Z^2 = \frac{(\pi\alpha/\sqrt{2}G_F)}{\hat{\rho}\hat{c}_Z^2\hat{s}_Z^2(1 - \Delta\hat{r}_W)}$$

$$\hat{\rho} \sim 1 + \frac{3G_F\hat{m}_t^2}{8\sqrt{2}\pi^2} + \dots$$

$$\Delta\hat{r}_W \sim \Delta\alpha + \dots$$

- Calculation of  $\Delta\alpha_{\text{had}}^{(5)}$ 
  - Data driven:  $R_{\text{had}}$  up to  $\sim 40$  GeV; PQCD above
  - Theory driven: PQCD + NPQCD (OPE, sum rules) above  $\sim 2$  GeV  $\rightarrow$  smaller uncertainties
  - New BES-II data  $\rightarrow$  convergence
- Measurements of running  $\alpha$ : TOPAZ ( $e^+e^-\mu^+\mu^-$ ); VENUS, L3 (Bhabha), OPAL (high  $Q^2$ )

## Recent evaluations of on-shell $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$

(Adjusted to fixed  $\alpha_s(M_Z) = 0.120$ )

Author(s)	Result	Comment
Martin & Zeppenfeld	$0.02744 \pm 0.00036$	PQCD for $\sqrt{s} > 3$ GeV
<b>Eidelman &amp; Jegerlehner</b>	<b><math>0.02803 \pm 0.00065</math></b>	PQCD for $\sqrt{s} > 40$ GeV
Geshkenbein & Morgunov	$0.02780 \pm 0.00006$	$\mathcal{O}(\alpha_s)$ resonance model
Burkhardt & Pietrzyk	$0.0280 \pm 0.0007$	PQCD for $\sqrt{s} > 40$ GeV
Swartz	$0.02754 \pm 0.00046$	use of fitting function
Aleman, Davier, Höcker	$0.02816 \pm 0.00062$	includes $\tau$ decay data
Krasnikov & Rodenberg	$0.02737 \pm 0.00039$	PQCD for $\sqrt{s} > 2.3$ GeV
Davier & Höcker	$0.02784 \pm 0.00022$	PQCD for $\sqrt{s} > 1.8$ GeV
Kühn & Steinhauser	$0.02778 \pm 0.00016$	complete $\mathcal{O}(\alpha_s^2)$
<b>Erlar</b>	<b><math>0.02779 \pm 0.00020</math></b>	converted from $\overline{\text{MS}}$ scheme
Davier & Höcker	$0.02770 \pm 0.00015$	use of QCD sum rules
Groote <i>et al.</i>	$0.02787 \pm 0.00032$	use of QCD sum rules
Jegerlehner	$0.02778 \pm 0.00024$	converted from MOM
Martin, Outhwaite, Ryskin	$0.02741 \pm 0.00019$	includes new BES data
<b>Pietrzyk</b>	<b><math>0.02755 \pm 0.00046</math></b>	details not published
<b>Trocóniz, Ynduráin</b>	<b><math>0.02747 \pm 0.00012</math></b>	BES, $\alpha_s = 0.117(3)$

- $Z$  pole + LEP 2 + WNC + Tevatron
  - SM tested at 0.1% level, including EW loops (gauge principle, group, representations, renorm. field theory)
  - $\sin^2 \theta_W$ ;  $m_t$ ,  $\alpha_s$  (loops; agree with direct) determined;  $\alpha_{had}$ ,  $M_H$  constrained
  - $M_H \lesssim 205$  GeV (direct:  $M_H > 112$  GeV)  $\leftrightarrow$  SUSY
  - however, sensitive to  $A_{FB}(b)$
  - severe constraint on TeV physics
    - \* unification (decoupling): expect 0.1%
    - \* TeV compositeness: expect several %
  - precise gauge coupling constants (unification)

## Global Electroweak Fits

- much more information than individual experiments
- caveat: experimental/theoretical systematics, correlations
- PDG '00 review + spring 01 (J. Erler and PL)
- Complete  $Z$ -pole and WNC (important beyond SM)
- New radiative correction program (Erler)
  - GAPP: Global Analysis of Particle Properties
  - Fully  $\overline{\text{MS}}$  (ZFITTER on-shell)
- New  $\Delta\alpha_{had}$ , correlated with  $\alpha_s$
- Good agreement with LEPWWG up to well-understood effects (WNC, HOT,  $\Delta\alpha_{had}$ ) despite different renormalization schemes
- [www.physics.upenn.edu/~erler/electroweak/](http://www.physics.upenn.edu/~erler/electroweak/)

## Fit Results (06/02) (Erler, PL)

$$\begin{aligned}M_H &= 86_{-32}^{+49} \text{ GeV}, \\m_t &= 174.2 \pm 4.4 \text{ GeV}, \\\alpha_s &= 0.1210 \pm 0.0018, \\\hat{\alpha}(M_Z)^{-1} &= 127.922 \pm 0.020 \\\hat{s}_Z^2 &= 0.23110 \pm 0.00015, \\\bar{s}_\ell^2 &= 0.23139 \pm 0.00015, \\s_W^2 &= 0.22277 \pm 0.00035 \\s_{M_Z}^2 &= 0.23105 \pm 0.00008 \\\chi^2/\text{d.o.f.} &= 49.0/40(15\%)\end{aligned}$$

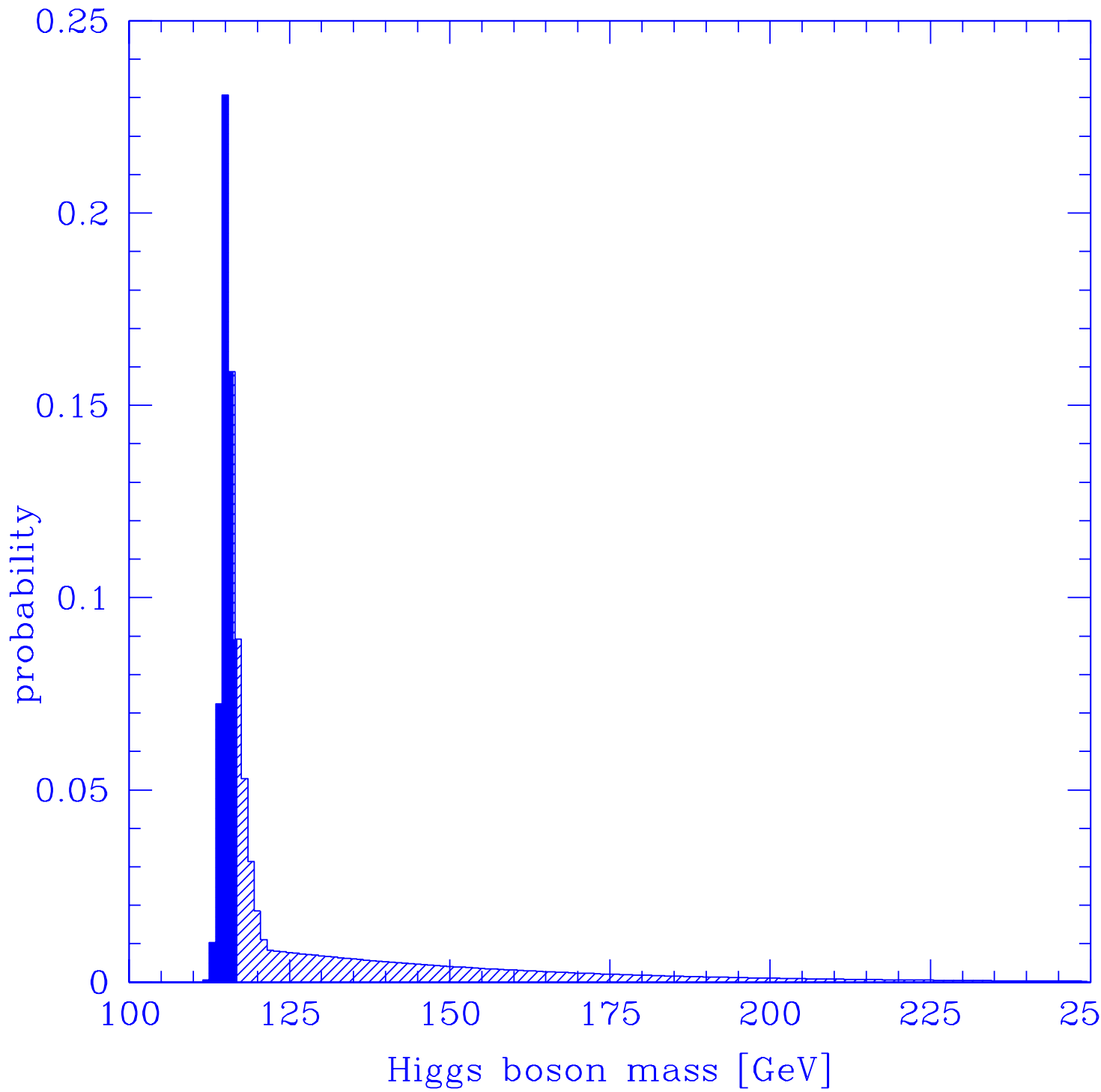
- LEPEWWG (on-shell, data set, H.O.T.,  $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$ ) (05/02)

- $M_H = 85_{-34}^{+54} \text{ GeV}$
- $\alpha_s = 0.1183 \pm 0.0027$
- $m_t = 174.7_{-4.3}^{+4.5} \text{ GeV}$
- $\bar{s}_\ell^2 = 0.23137 \pm 0.00015$
- $s_W^2 = 0.22272 \pm 0.00036$

- $m_t = 174.2 \pm 4.4 \text{ GeV}$

- $174.0_{-7.4}^{+9.9} \text{ GeV}$  from indirect (loops) only (direct:  $174.3 \pm 5.1$ )

- $\alpha_s = 0.1210 \pm 0.0018$ 
  - Higher than world average  $\alpha_s = 0.1172(20)$  (Hinchliffe (PDG) 2001), because of  $\tau$  lifetime
  - insensitive to oblique new physics
  - very sensitive to non-universal new physics (e.g.,  $Zb\bar{b}$  vertex)
- Higgs mass  $M_H = 86_{-32}^{+49}$  GeV
  - direct limit (LEP 2):  $M_H \gtrsim 114.4(95\%)$  GeV
  - SM:  $115$  (vac. stab.)  $\lesssim M_H \lesssim 750$  (triviality)
  - MSSM:  $M_H \lesssim 130$  GeV (150 in extensions)
  - indirect:  $\ln M_H$  but significant
    - \* fairly robust to new physics (except  $S < 0$ ,  $T > 0$ )
    - \* however, strong  $A_{FB}(b)$  effect
    - \*  $M_H < 215$  GeV at 95%, including direct



## Skeletons in the Closet

Standard model ( $SU_3 \times SU_2 \times U_1$  + general relativity) correct to  $10^{-16}$  cm, *but* 21 free parameters ( $\geq 28$  with  $m_\nu \neq 0$ ).

- Gauge Problem

- complicated gauge group with 3 couplings
- charge quantization ( $|q_e| = |q_p|$ ) unexplained

- Fermion problem

- Fermion masses, mixings, families unexplained

- Higgs/hierarchy problem

- Expect  $M_H^2 = O(M_W^2)$
- higher order corrections:  $\delta M_H^2 / M_W^2 \sim 10^{34}$

- Strong CP problem

- Can add  $\frac{\theta}{32\pi^2} g_s^2 F \tilde{F}$  to QCD (breaks, P, T, CP)
- $d_N \Rightarrow \theta < 10^{-9}$
- but  $\delta\theta|_{\text{weak}} \sim 10^{-3}$

- Graviton problem

- gravity not unified
- quantum gravity not renormalizable
- cosmological constant:  $\Lambda_{\text{SSB}} = 8\pi G_N \langle V \rangle > 10^{50} \Lambda_{\text{obs}}$

## The Two Paths: Unification or Compositeness

### ● The Bang

- unification of interactions
- grand desert to unification (GUT) or Planck scale
- elementary Higgs, supersymmetry (SUSY), GUTs, strings
- possibility of probing to  $M_P$  and very early universe
- hint from coupling constant unification
- tests
  - \* light ( $< 110 - 130$  GeV) Higgs (LEP 2, TeV, LHC)
  - \* *absence of deviations in precision tests* (usually)
  - \* supersymmetry (LHC)
  - \* possible:  $m_b$ , proton decay,  $\nu$  mass, rare decays
  - \* SUSY-safe:  $Z'$ ; seq/mirror/exotic fermions; singlets

### ● The Whimper

- onion-like layers
- composite fermions, scalars (dynamical sym. breaking)
- *not* like to atom  $\rightarrow$  nucleus  $+ e^- \rightarrow p + n \rightarrow$  quark
- at most one more layer accessible (LHC)
- *rare decays* (e.g.,  $K \rightarrow \mu e$ )
  - \* severe problem
  - \* no realistic models
- *effects* (typically, few %) expected at LEP & other precision observables (4-f ops;  $Zb\bar{b}$ ;  $\rho_0$ ;  $S, T, U$ )
- *anomalous  $VVV$* , new particles, future  $WW \rightarrow WW$

## Beyond the standard model

- $\rho_0$ ;  $S, T, U$ : Higgs triplets, nondegenerate fermions or scalars; chiral families (ETC)

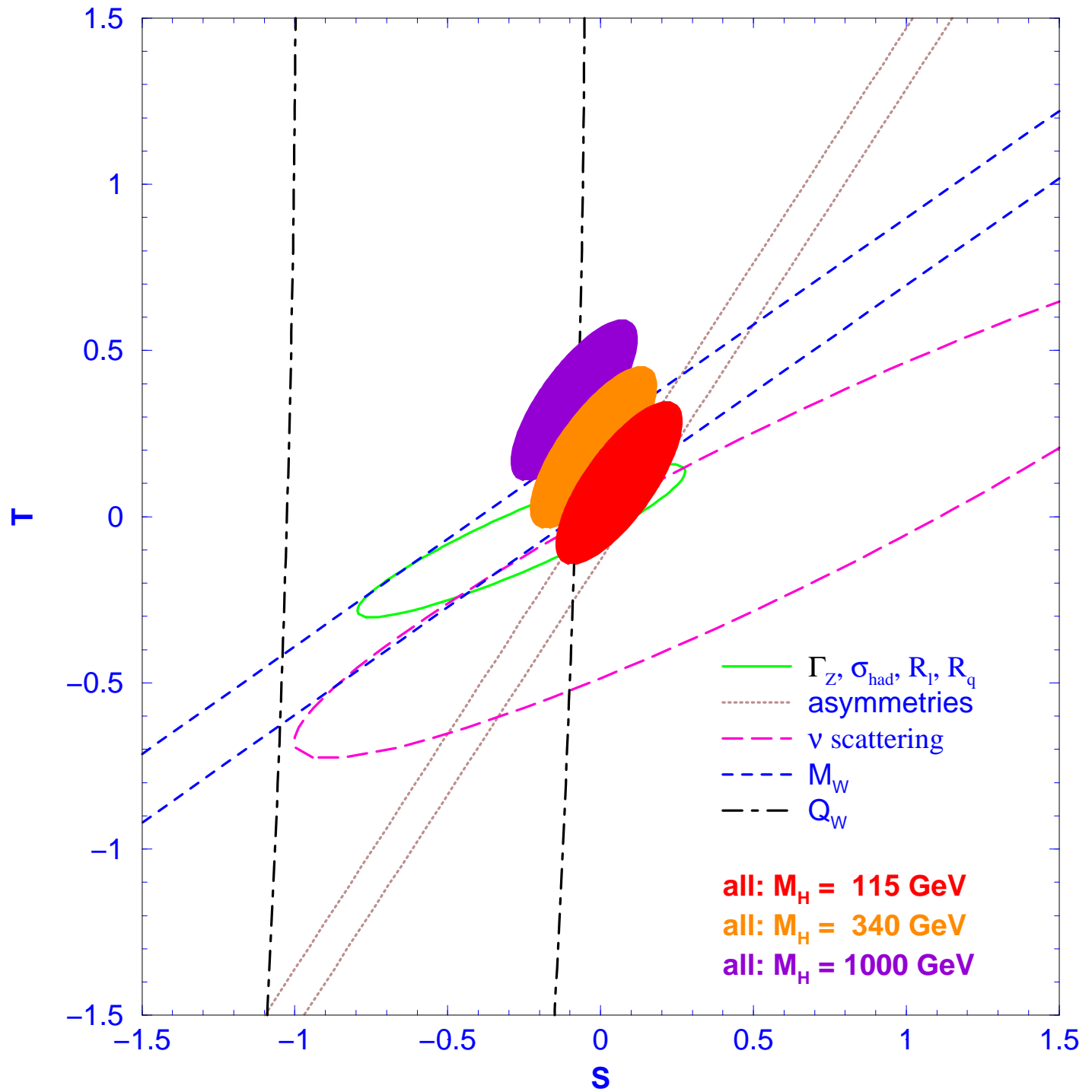
$$S = -0.14 \pm 0.10(-0.08)$$

$$T = -0.15 \pm 0.12(+0.09)$$

$$U = 0.32 \pm 0.12(+0.01) \quad (2.6\sigma)$$

for  $M_H = 115.6$  (300) GeV

- $\rho_0 \approx 1 + \alpha T = 0.9997^{+0.0011}_{-0.0008}$   
( $M_H = 73^{+106}_{-34}$  GeV) for  $S = U = 0$
- For  $T = U = 0$ :  $S = 0.10^{+0.12}_{-0.30}$ ,  $M_H < 570$  GeV at 95%;  $N_{\text{fam}} = 2.81 \pm 0.29$  (cf. lineshape:  $N_\nu = 2.986 \pm 0.007$ )
- $N_{\text{fam}} = 2.79 \pm 0.43$  for  $T = -0.01 \pm 0.11$



- Supersymmetry

- decoupling limit ( $M_{new} \gtrsim 200 - 300 \text{ GeV}$ ): only precision effect is light SM-like Higgs
- little improvement on SM fit
- SUSY parameters constrained

- Heavy  $Z'$ : GUTs, string theories

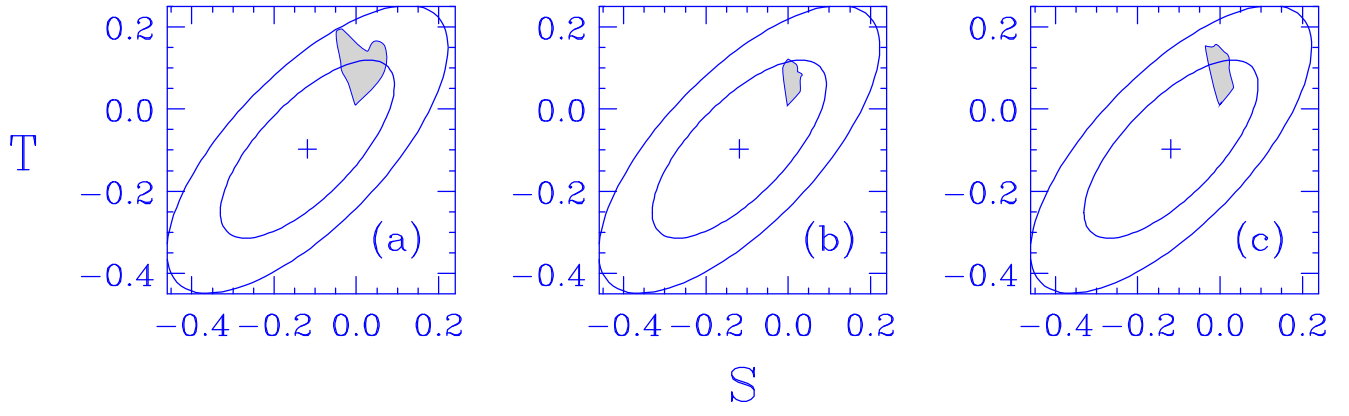
- Typically  $M_{Z'} > 500 - 800 \text{ GeV}$  (Tevatron, LEP 2, WNC),  $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$  ( $Z$ -pole)

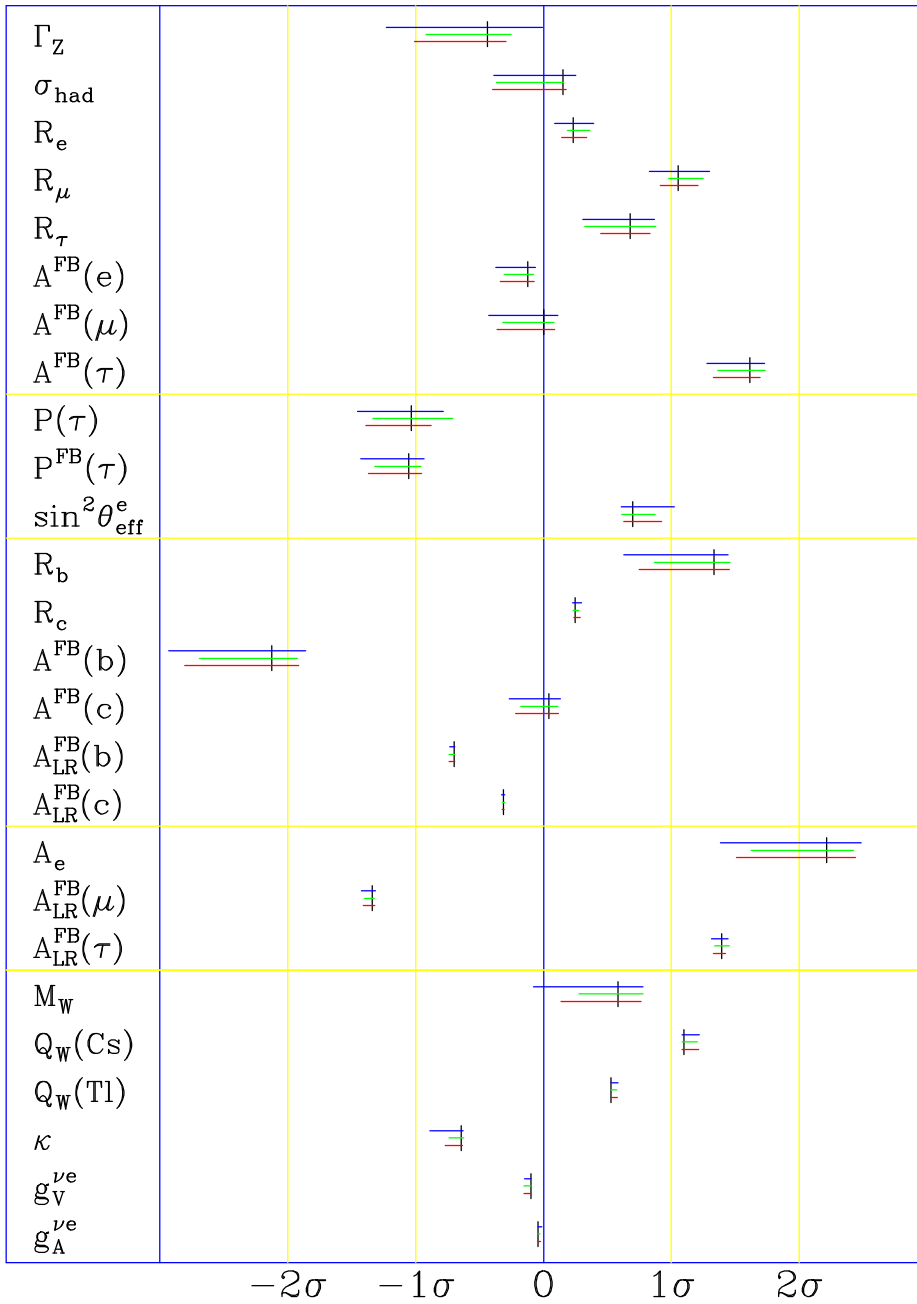
- Other

- Exotic fermion mixings
- Large extra dimensions
- New Four-fermi operators
- Leptoquark bosons

- Gauge unification: GUTs, string theories

- $\alpha + \hat{s}_Z^2 \rightarrow \alpha_s = 0.130 \pm 0.010$
- $M_G \sim 3 \times 10^{16} \text{ GeV}$
- Perturbative string:  $\sim 5 \times 10^{17} \text{ GeV}$  (10% in  $\ln M_G$ ). Exotics:  $O(1)$  corrections.





## A Heavy $Z'$ ?

- Expected in many grand unified theories
- Expected in many string constructions
  - Typically,  $M_{Z'} \lesssim 1 \text{ TeV}$
  - Often family non-universal (FCNC)
- Natural solution to  $\mu$  problem
- Nonstandard superpartner spectrum
- Typically  $M_{Z'} > 500 - 800 \text{ GeV}$  (Tevatron, LEP 2, WNC),  $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$  ( $Z$ -pole)

- Possible hints of  $Z'$

- Atomic parity violation (controversial)

- \* SM:  $Q_W(\text{Cs}) = -73.09 \pm 0.03$

- \* experiment: value has fluctuated depending on Breit correction (large), vac. pol. (large), and electron line (?) corrections. Recent:  $Q_W = -72.12(28)(34) (2.2\sigma)$  (Johnson et al, 2001);  $-72.18(29)(36) (2\sigma)$  (Dzuba et al, 2002);  $-72.83(29)(39)$  (Kuchiev, 2002)

- \* Theory error?

- New NuTeV results ( $\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu N$ )

- \*  $\sin^2 \theta_W = 0.2277(13)(9)(3.0\sigma)$  (SM:  $0.2228(4)$ )

- $Z$  lineshape ( $\sigma_{\text{had}}$ )

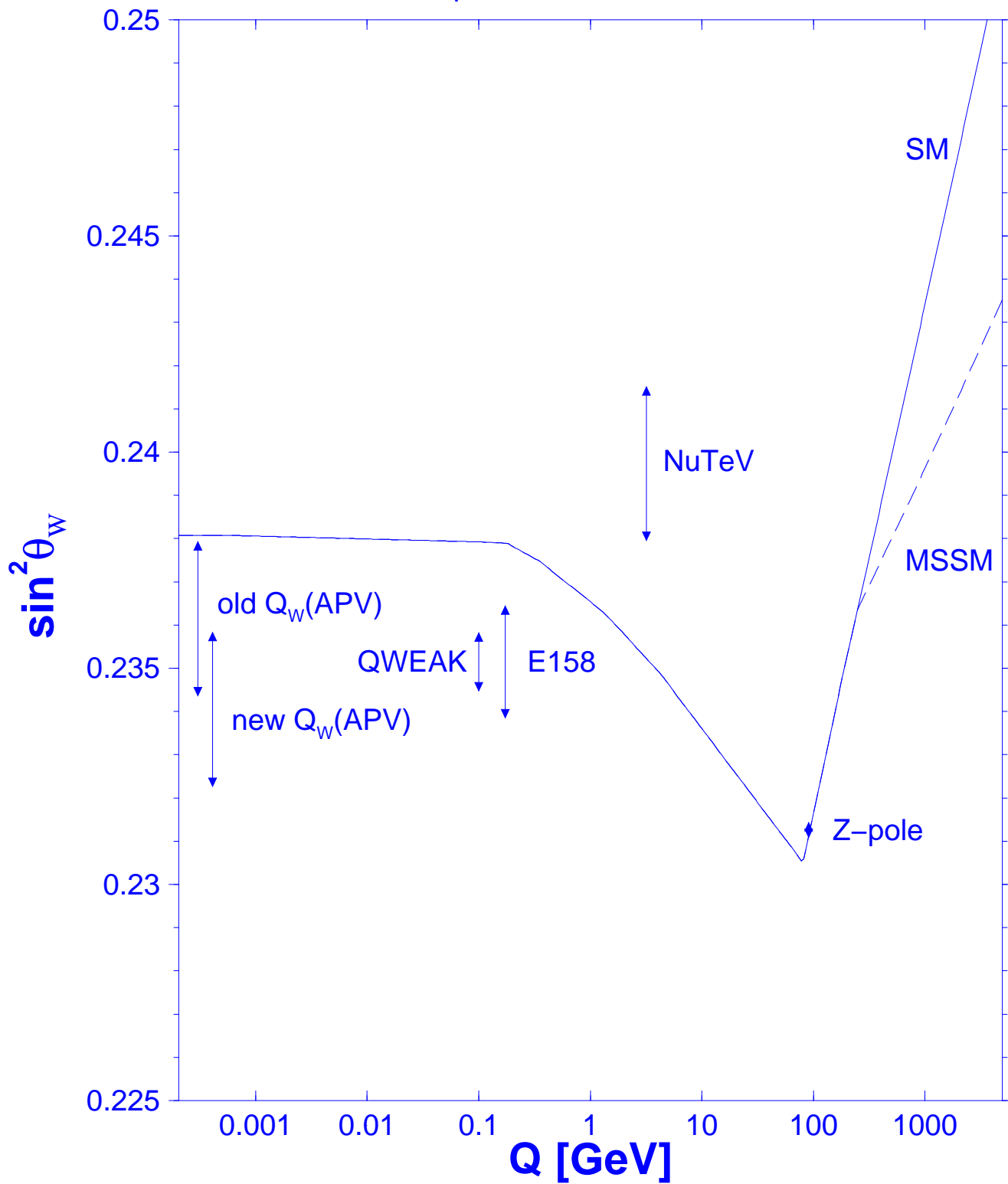
- $A_{FB}(b)$  (if non-universal couplings)

- Should be observable at Tevatron if present

- Detailed studies of couplings at LHC and LC

# weak mixing angle

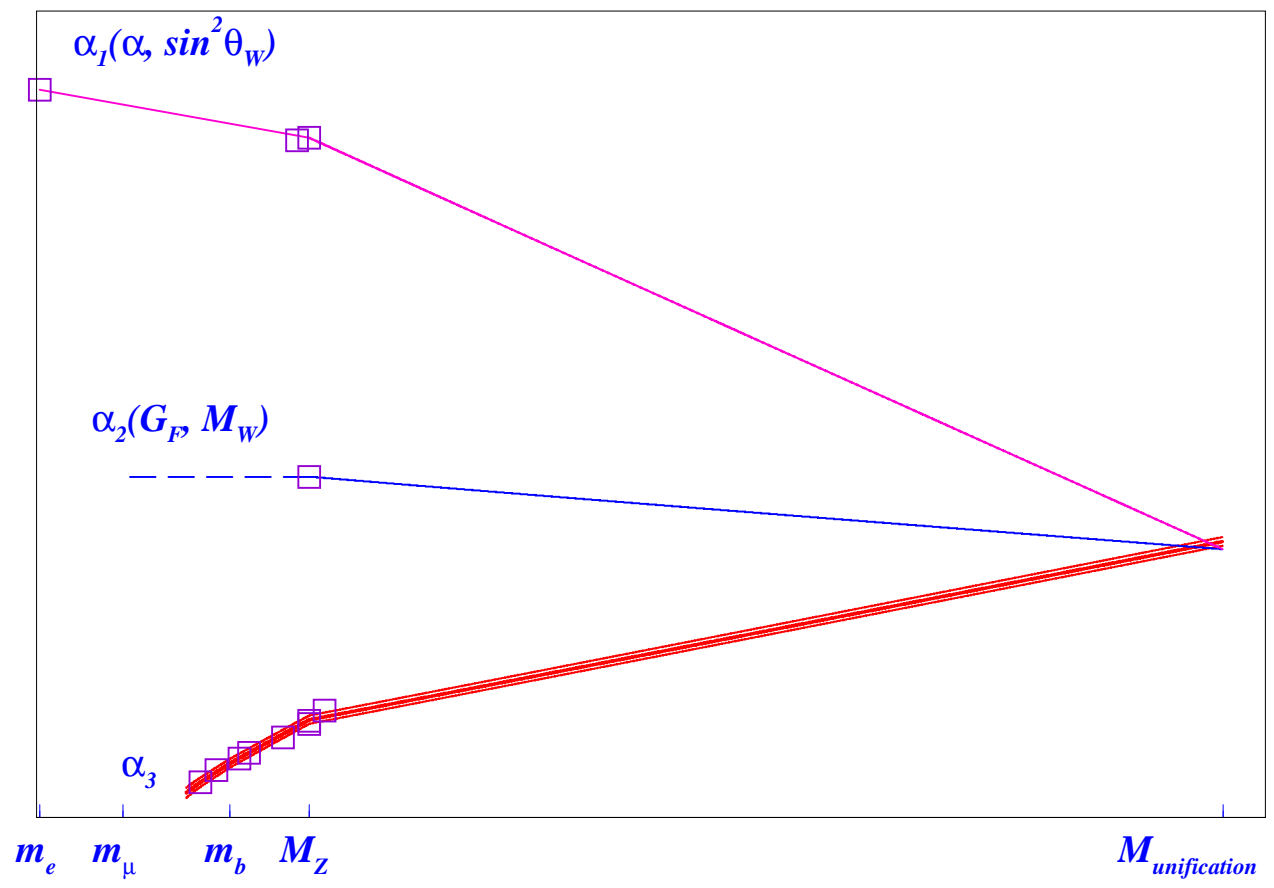
scale dependence in  $\overline{MS}$  scheme





## Discovery of Pluto

- 1781 Uranus observed by  
(Sir William Herschel)
- 1846 Uranus orbit anomalies  
→ Neptune predicted  
(John Adams, Jean Leverrier)
- 1846 Neptune observed in  
predicted location
- 1900's Further Uranus anomalies  
→ Pluto predicted by “computers”  
(several possible locations)
- 1930 Pluto discovered in one of predicted  
locations (Clyde Tombaugh)
- 1978 Charon discovered →  $m_{\text{Pluto}}$  too  
small to affect Uranus orbit



## Conclusions

- WNC,  $Z$ ,  $W$  are primary predictions and test of electroweak unification
- SM correct and unique to first approx. (gauge principle, group, representations)
- SM correct at loop level (renorm gauge theory;  $m_t$ ,  $\alpha_s$ ,  $M_H$ )
- Watershed: TeV physics severely constrained (unification vs compositeness)  $\Rightarrow$  implications for Tevatron (Run II) and LHC
- Precise gauge couplings (gauge unification)
- Future
  - Direct production of new particles at hadron colliders
  - CP violation in  $B$  system
  - New precision era in future linear collider
  - Polarized Møller, polarized  $ep$ , APV