

A Global Analysis of Precision Electroweak Data

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

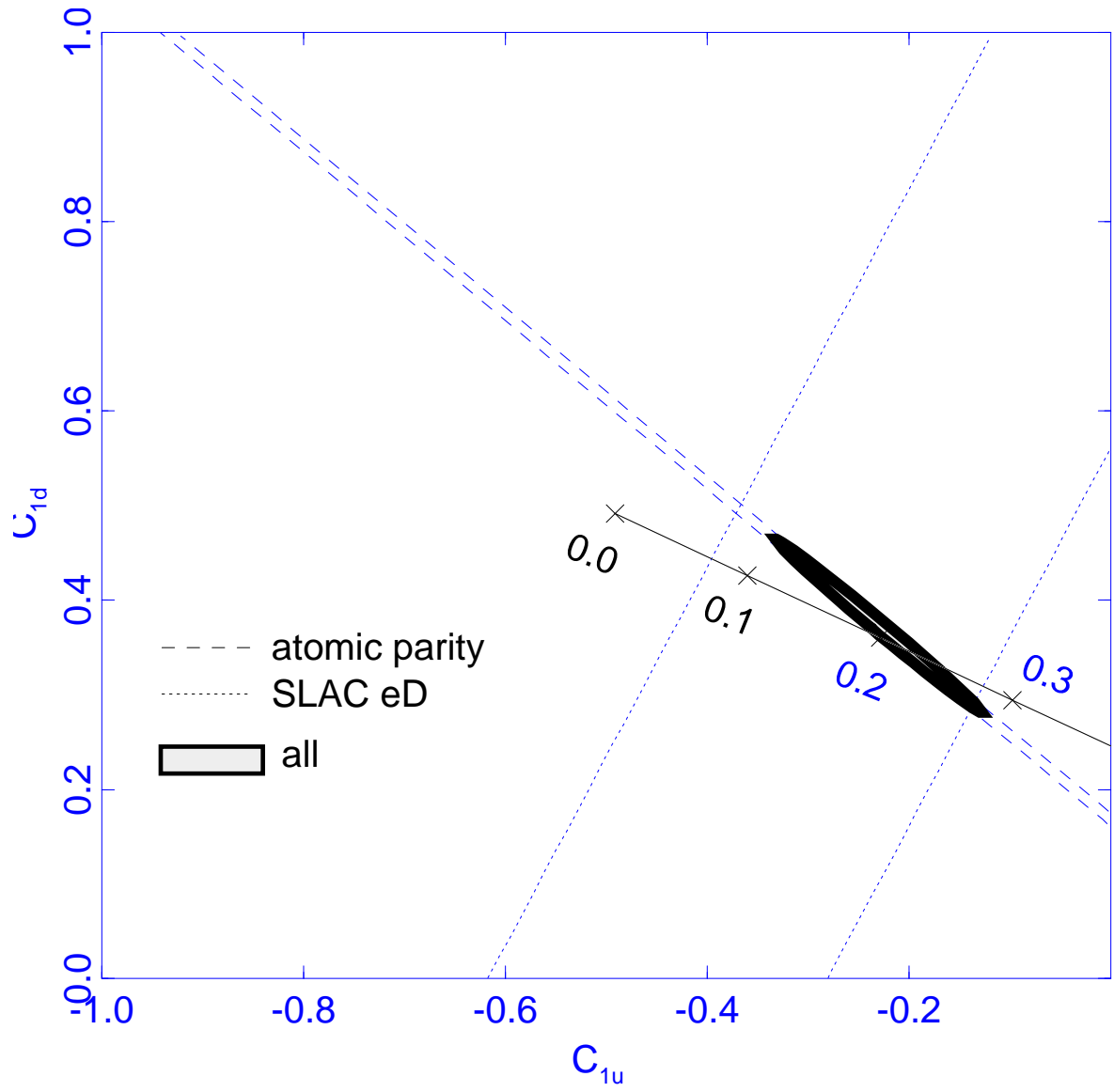
P. Langacker
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12/01/2001

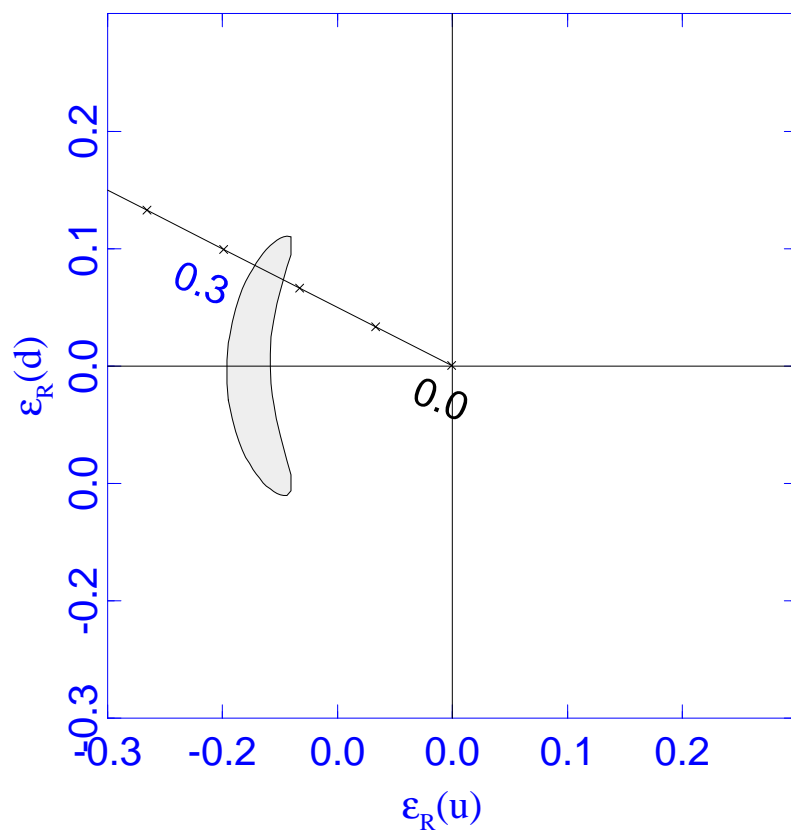
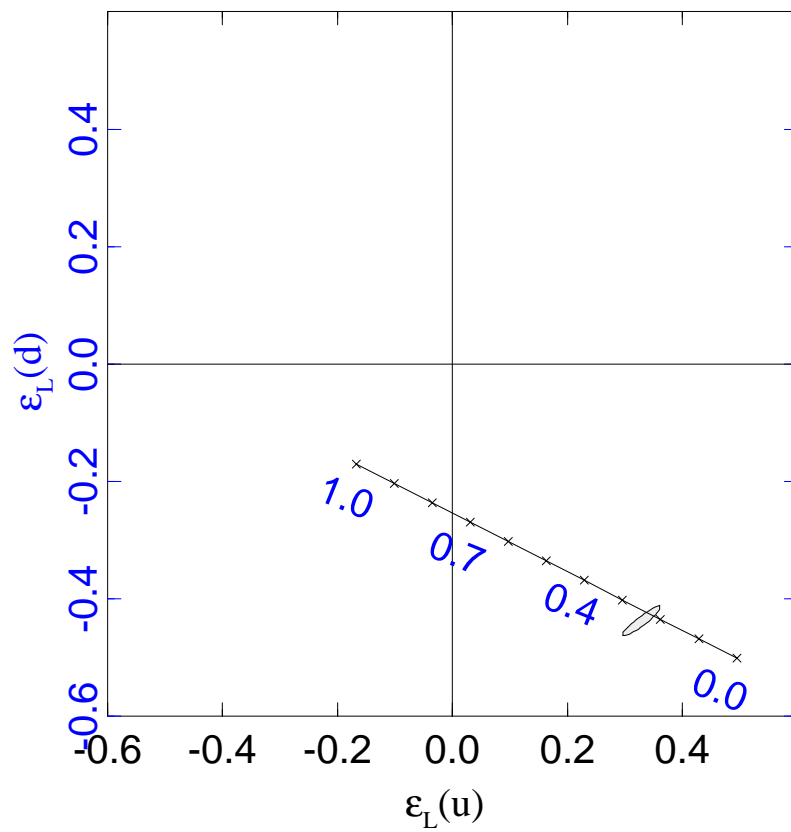
The Z , the W , and the Weak Neutral Current

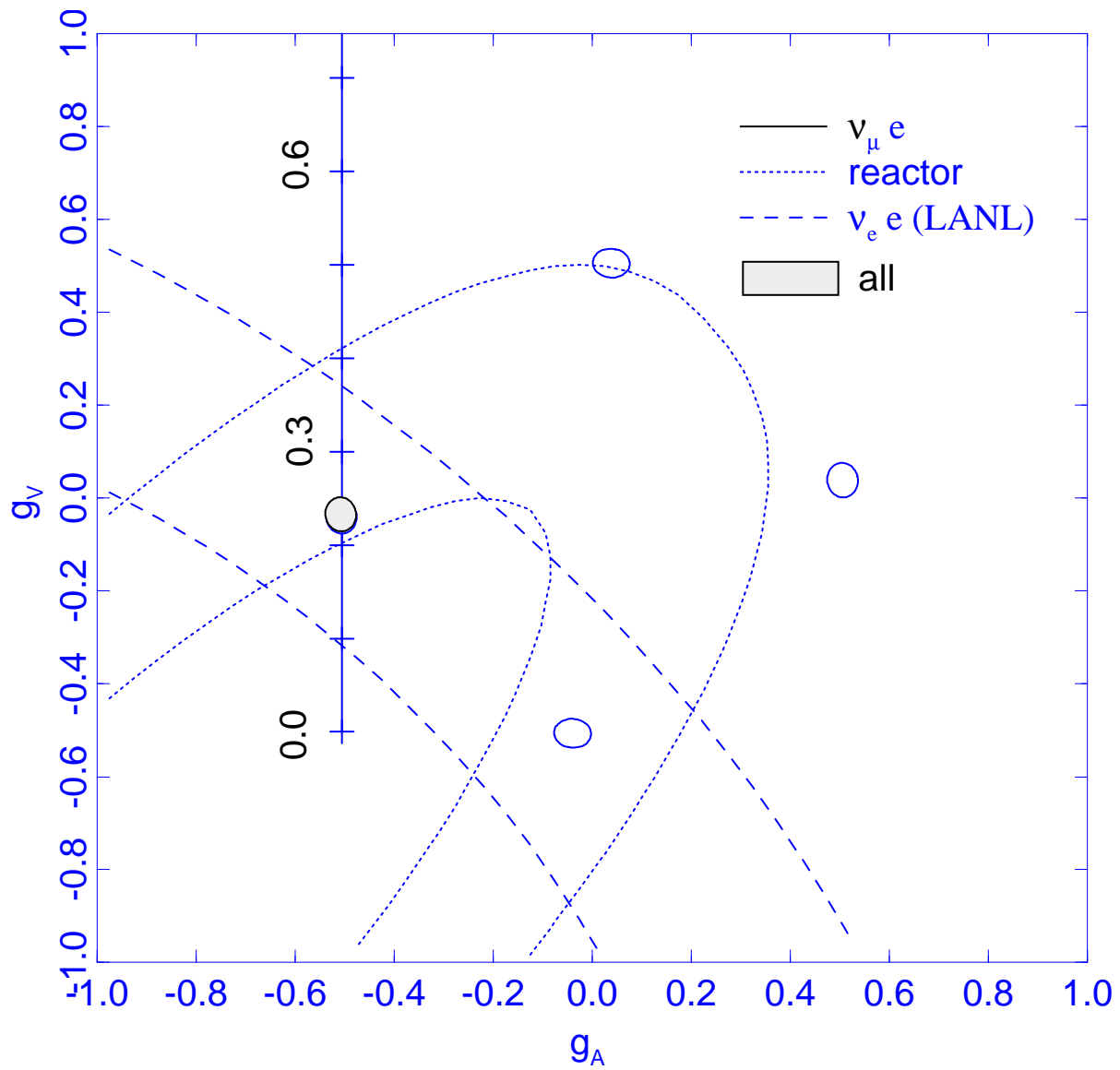
- Primary prediction and test of electroweak unification
- WNC discovered 1973 (Gargamelle, HPW)
- 70's, 80's: weak neutral current experiments (few %)
 - Pure weak: νN , νe scattering
 - Weak-elm interference in eD , e^+e^- , atomic parity violation
- W , Z discovered directly 1983 (UA1, UA2)
- 90's: 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 , α_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 νq , νe , 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 ν_τ 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), 5×10^5 , $P_{e^-} \sim 75\%$
- Z pole observables
 - lineshape: M_Z, Γ_Z, σ
 - 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_τ , mixed
 - lepton family universality
- LEP 2
 - M_W, Γ_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)

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

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

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

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

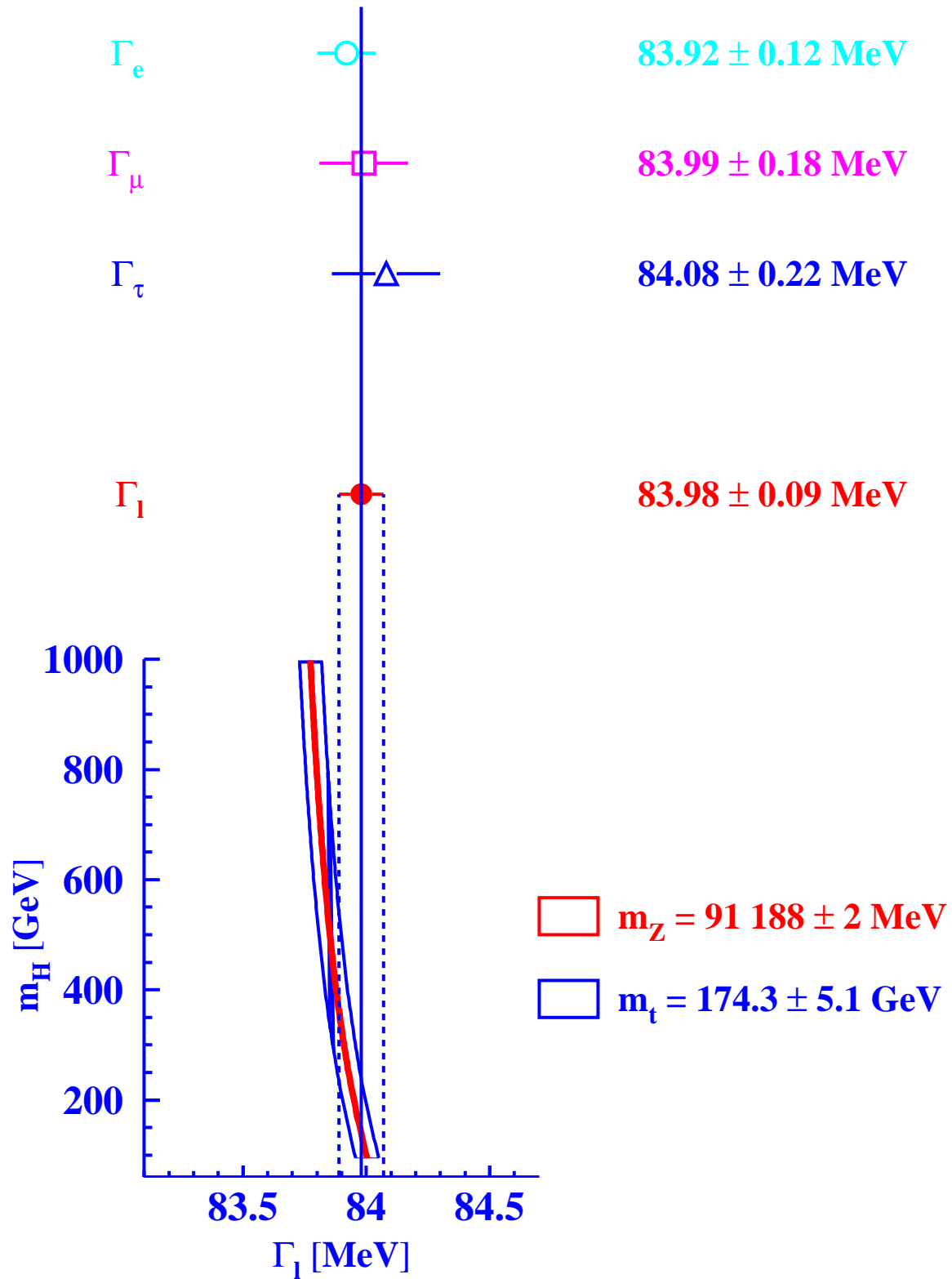
($R_e = R_\mu = R_\tau \equiv R_\ell \rightarrow$ lepton universality)

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

(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

LEP averages of leptonic widths



Z-Pole Asymmetries

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

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

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

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

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

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

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

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

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

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

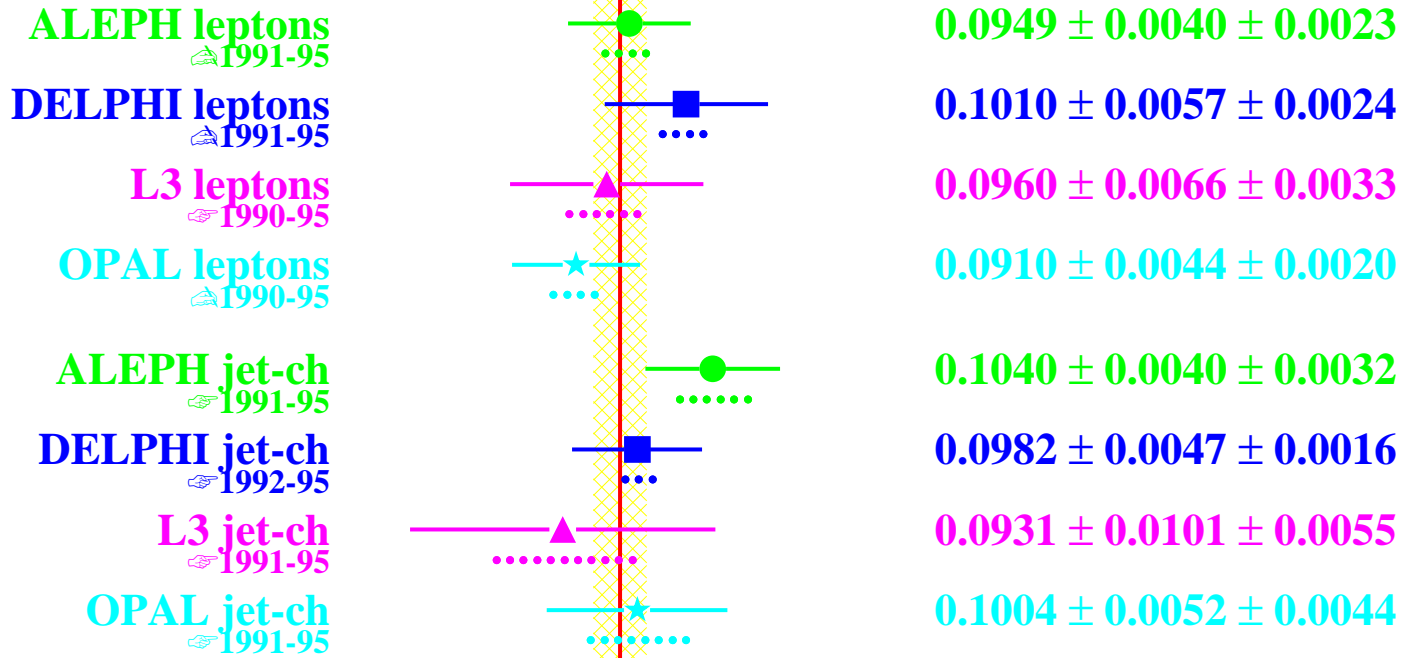
where \bar{s}_f^2 the effective weak angle,

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

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

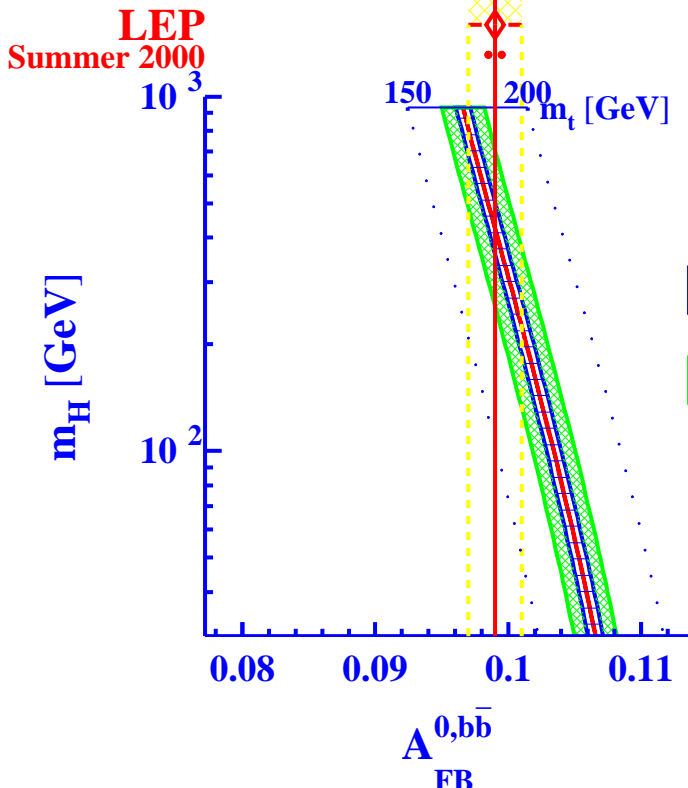
ρ_f, κ_f , and $\hat{\kappa}_f$ are electroweak corrections, $q_f =$ electric charge, $t_{3f} =$ weak isospin

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



0.0990 ± 0.0020

Include Total Sys 0.0009
With Common Sys 0.0006



$m_t = 174.3 \pm 5.1$ GeV

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

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

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

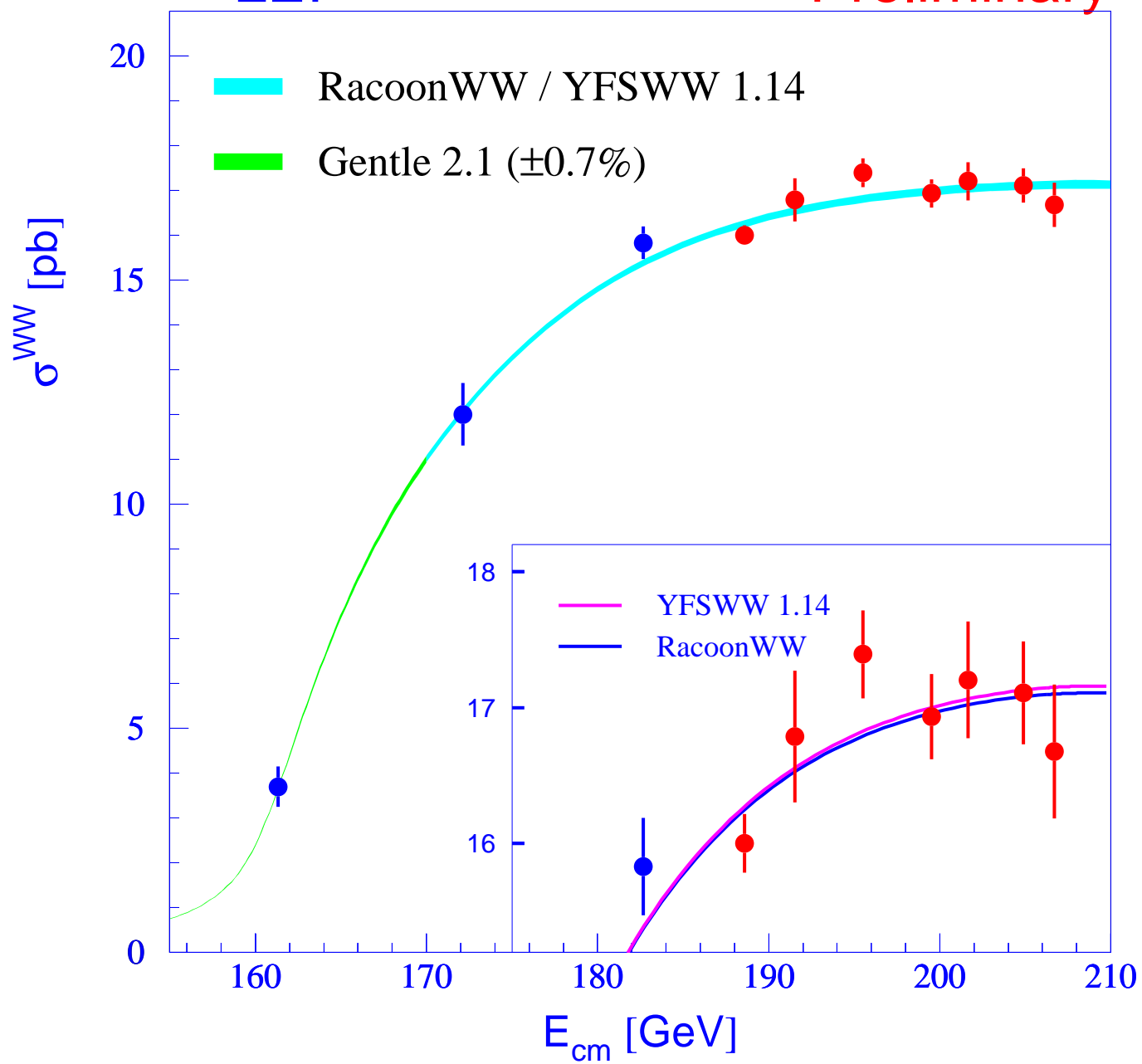
Non- Z Pole Precision Observables: Tevatron, LEP 2, νN , APV (7/01)

Quantity	Group(s)	Value	Standard Model	pull
m_t [GeV]	Tevatron	174.3 ± 5.1	175.3 ± 4.4	-0.2
M_W [GeV]	LEP	80.446 ± 0.040	80.391 ± 0.019	1.4
M_W [GeV]	Tevatron,UA2	80.451 ± 0.061		1.0
R^-	NuTeV	$0.2277 \pm 0.0021 \pm 0.0007$	0.2300 ± 0.0002	-1.1
κ^ν	CCFR	$0.5820 \pm 0.0027 \pm 0.0031$	0.5833 ± 0.0004	-0.3
R^ν	CDHS	$0.3096 \pm 0.0033 \pm 0.0028$	0.3093 ± 0.0002	0.1
R^ν	CHARM	$0.3021 \pm 0.0031 \pm 0.0026$		-1.7
$R^{\bar{\nu}}$	CDHS	$0.384 \pm 0.016 \pm 0.007$	0.3862 ± 0.0002	-0.1
$R^{\bar{\nu}}$	CHARM	$0.403 \pm 0.014 \pm 0.007$		1.0
$R^{\bar{\nu}}$	CDHS 1979	$0.365 \pm 0.015 \pm 0.007$	0.3817 ± 0.0002	-1.0
$g_V^{\nu e}$	CHARM II	-0.035 ± 0.017	-0.0398 ± 0.0003	—
$g_V^{\nu e}$	all	-0.040 ± 0.015		-0.1
$g_A^{\nu e}$	CHARM II	-0.503 ± 0.017	-0.5065 ± 0.0001	—
$g_A^{\nu e}$	all	-0.507 ± 0.014		0.0
$Q_W(\text{Cs})$	Boulder	$-72.65 \pm 0.28 \pm 0.34$	-73.10 ± 0.03	1.0
$Q_W(\text{Tl})$	Oxford,Seattle	$-114.8 \pm 1.2 \pm 3.4$	-116.67 ± 0.05	0.5
$\frac{\Gamma(b \rightarrow s\gamma)}{\Gamma(b \rightarrow ce\nu)}$	CLEO	$3.26_{-0.68}^{+0.75} \times 10^{-3}$	$3.14_{-0.16}^{+0.17} \times 10^{-3}$	0.2
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	E821	$4510.55 \pm 1.51 \pm 0.51$	4506.55 ± 0.36	2.5

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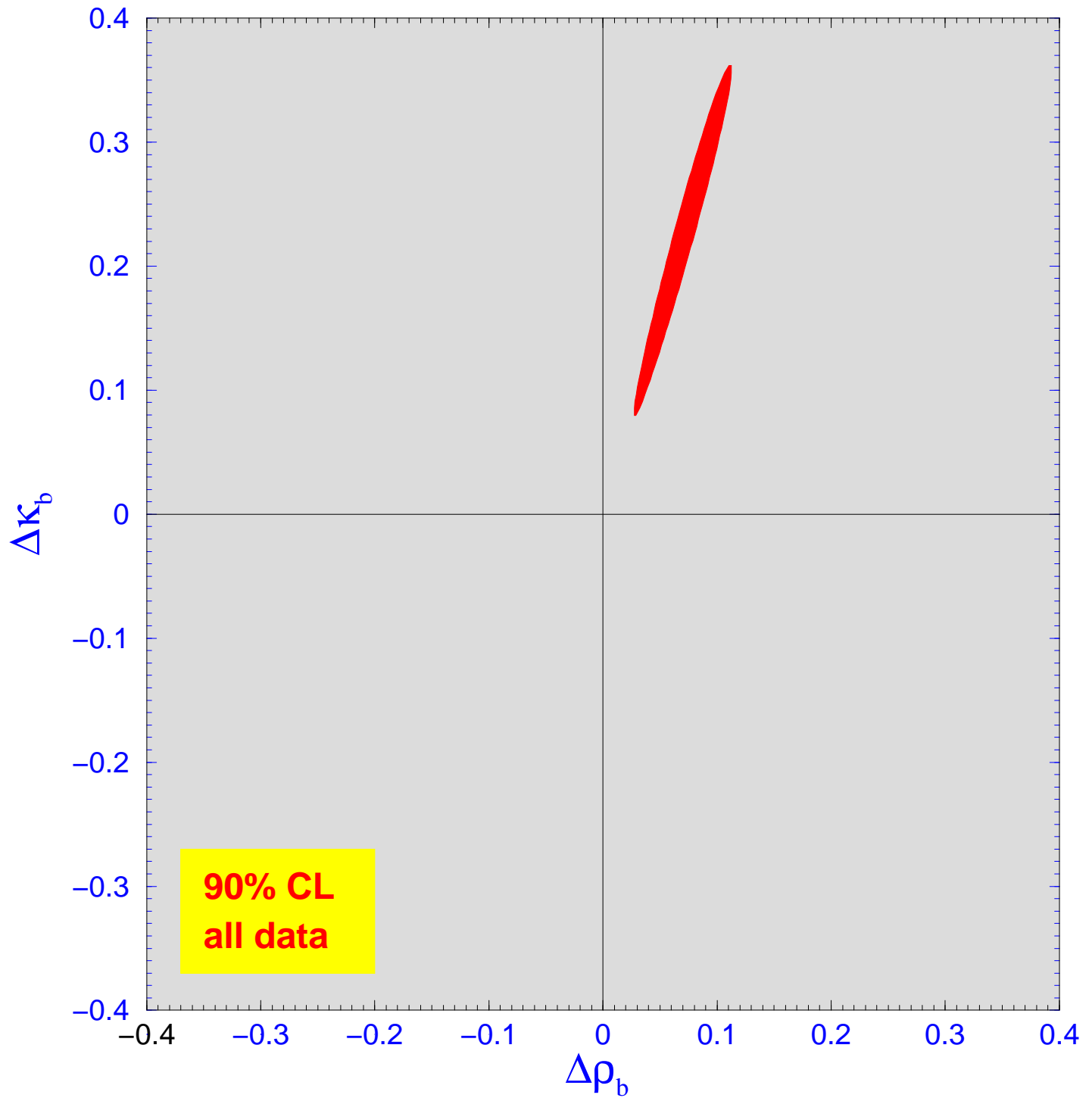
LEP

Preliminary



$A_{FB}(b)$

- $A_{FB}(b) = 0.0982 \pm 0.0017$ (SM: 0.1036 ± 0.0008 , -3.2σ)
 - $R_b = 0.21664 \pm 0.00068$ (SM: 0.21569 ± 0.00016 , agrees at 1.4σ)
 - $A_b = 0.921 \pm 0.020$ (SM: 0.93474 ± 0.00011 agrees at -0.7σ)
- 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
 - * α_{had} (running α)
 - * 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

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

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{Had}} + a_\mu^{\text{EW}} = 116591597(67) \times 10^{-11}$$

$$\begin{aligned} a_\mu^{\text{QED}} &= \frac{\alpha}{2\pi} + 0.765857376(27) \left(\frac{\alpha}{\pi}\right)^2 \\ &\quad + 24.05050898(44) \left(\frac{\alpha}{\pi}\right)^3 + 126.07(41) \left(\frac{\alpha}{\pi}\right)^4 \\ &\quad + 930(170) \left(\frac{\alpha}{\pi}\right)^5 = 116584705.7(2.9) \times 10^{-11} \end{aligned}$$

$$\begin{aligned} a_\mu^{\text{Had}} &= a_\mu^{\text{Had}}(\text{vp}) + a_\mu^{\text{Had}}(\text{ll}) \sim 6739(67) \times 10^{-11} \\ a_\mu^{\text{EW}}(2 \text{ loop}) &= 152(4) \times 10^{-11} \end{aligned}$$

- CERN (1977): $a_\mu^{\text{exp}} = 116592300(840) \times 10^{-11}$
- BNL (2001): $a_\mu^{\text{exp}} = 116592020(160) \times 10^{-11}$
- $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (426 \pm 165) \times 10^{-11} \quad (2.6\sigma)$
 - Statistics? (will improve by 3); a_μ^{Had} ?
 - Erler: $a_\mu^{\text{Had}} - \Delta\alpha_{\text{had}}^{(5)}(M_Z)$ correlation $\rightarrow M_H$ lower by 5 GeV
 - 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 $\sin^2 \theta_W$

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

Running of α

- Largest theory uncertainty in $M_Z - \hat{s}_Z^2$ (cf. a_μ^{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_{had} up to ~ 40 GeV; PQCD above
 - Theory driven: PQCD + NPQCD (OPE, sum rules) above ~ 2 GeV \rightarrow smaller uncertainties
 - New BES-II data \rightarrow convergence
- Measurements of running α : 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 ± 0.00036	PQCD for $\sqrt{s} > 3$ GeV
Eidelman & Jegerlehner	0.02803 ± 0.00065	PQCD for $\sqrt{s} > 40$ GeV
Geshkenbein & Morgunov	0.02780 ± 0.00006	$\mathcal{O}(\alpha_s)$ resonance model
Burkhardt & Pietrzyk	0.0280 ± 0.0007	PQCD for $\sqrt{s} > 40$ GeV
Swartz	0.02754 ± 0.00046	use of fitting function
Alemany, Davier, Höcker	0.02816 ± 0.00062	includes τ decay data
Krasnikov & Rodenberg	0.02737 ± 0.00039	PQCD for $\sqrt{s} > 2.3$ GeV
Davier & Höcker	0.02784 ± 0.00022	PQCD for $\sqrt{s} > 1.8$ GeV
Kühn & Steinhauser	0.02778 ± 0.00016	complete $\mathcal{O}(\alpha_s^2)$
Erler	0.02779 ± 0.00020	converted from $\overline{\text{MS}}$ scheme
Davier & Höcker	0.02770 ± 0.00015	use of QCD sum rules
Groote <i>et al.</i>	0.02787 ± 0.00032	use of QCD sum rules
Jegerlehner	0.02778 ± 0.00024	converted from MOM
Martin, Outhwaite, Ryskin	0.02741 ± 0.00019	includes new BES data
Pietrzyk	0.02755 ± 0.00046	details not published

- 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 , α_s (loops; agree with direct) determined; α_{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 α_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/

Fit Results (07/01) (Erler, PL)

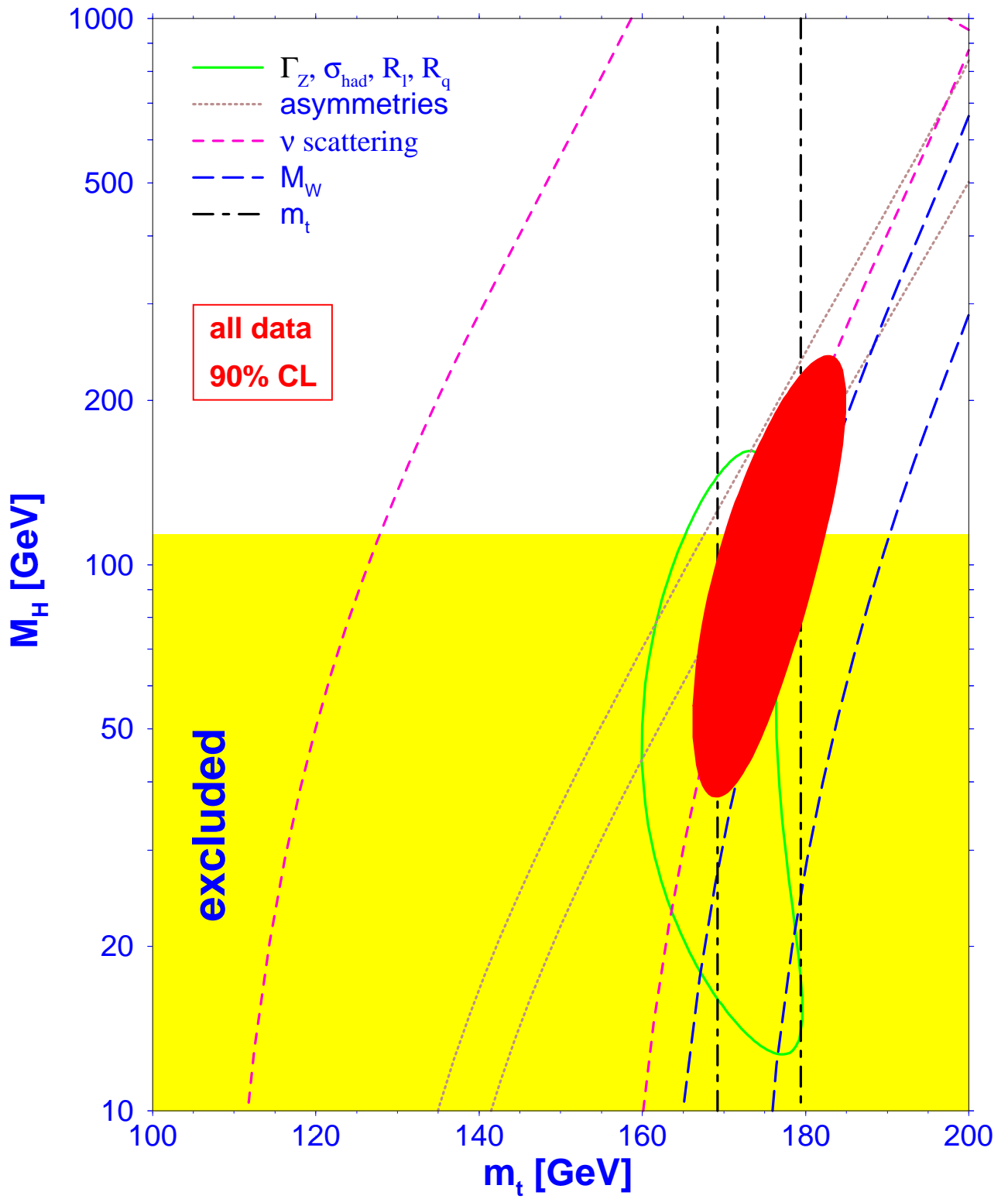
$$\begin{aligned}M_H &= 98_{-35}^{+51} \text{ GeV}, \\m_t &= 175.3 \pm 4.4 \text{ GeV}, \\\alpha_s &= 0.1200 \pm 0.0028, \\\hat{s}_Z^2 &= 0.23113 \pm 0.00015, \\\bar{s}_\ell^2 &= 0.23143 \pm 0.00015, \\s_W^2 &= 0.22278 \pm 0.00036 \\s_{M_Z}^2 &= 0.23105 \pm 0.00008 \\ \Delta\alpha_{\text{had}}^{(5)}(M_Z) &= 0.02778 \pm 0.00020\end{aligned}$$

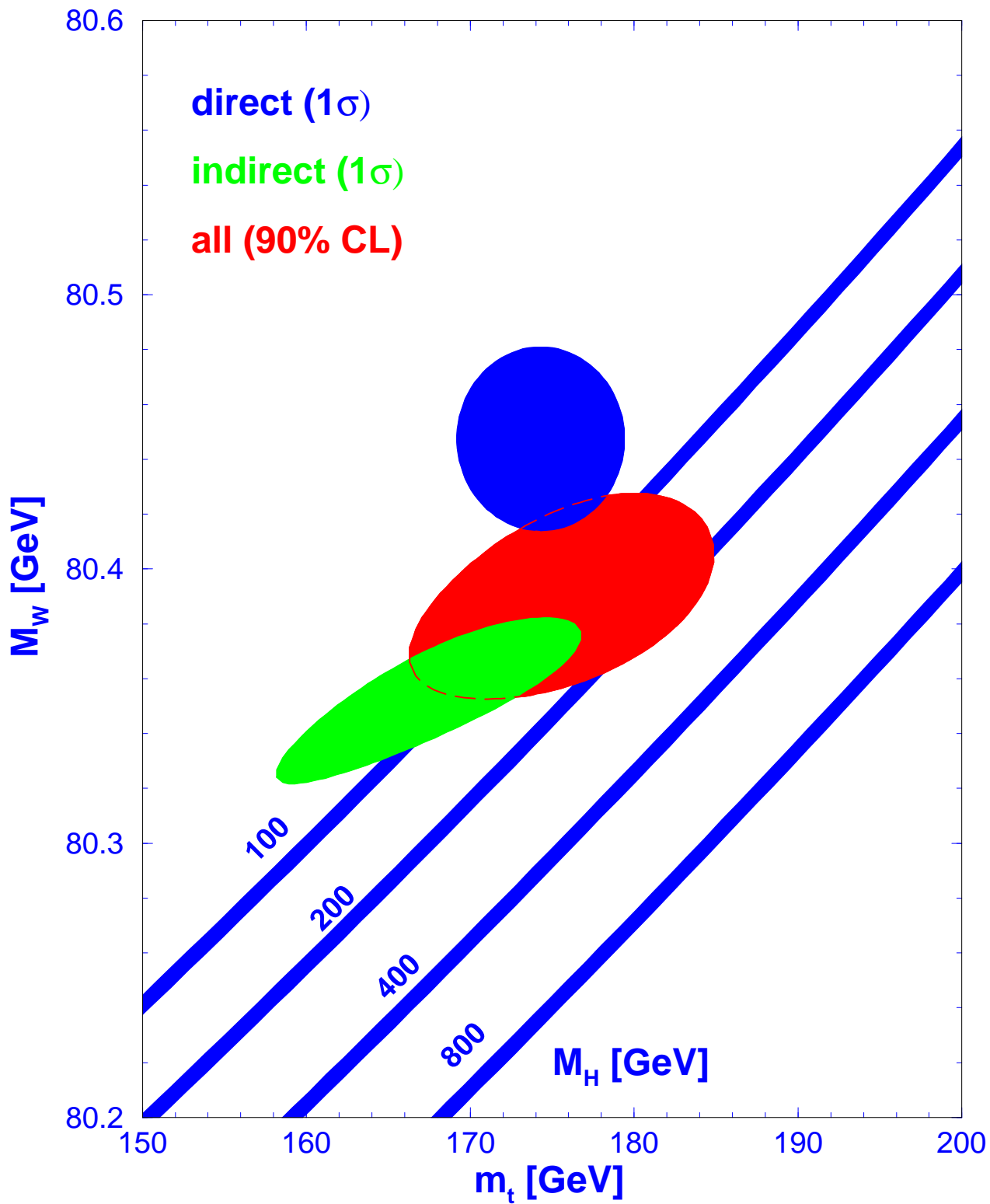
- LEPEWWG (on-shell, data set, H.O.T., $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$)
 - $M_H = 98_{-38}^{+58} \text{ GeV}$
 - $\alpha_s = 0.118 \pm 0.003$
 - $m_t = 175.7_{-4.3}^{+4.4} \text{ GeV}$
 - $\bar{s}_\ell^2 = 0.23142 \pm 0.00014$
- $m_t = 175.3 \pm 4.4 \text{ GeV}$
 - $178.1_{-8.3}^{+10.4} \text{ GeV}$ from indirect (loops) only (direct: 174.3 ± 5.1)

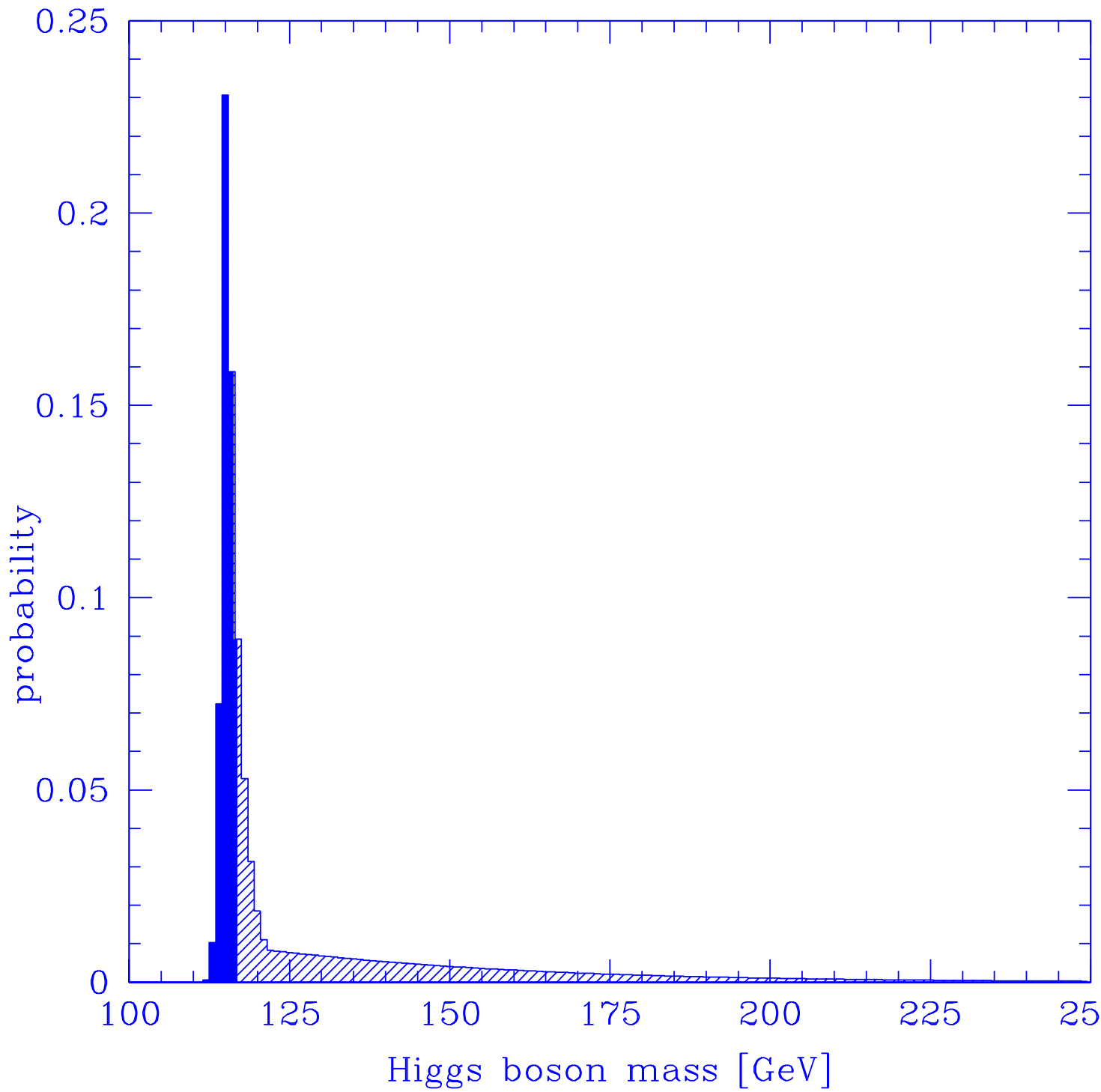
- $\Delta\alpha_{\text{had}}^{(5)}(M_Z) = 0.02778 \pm 0.00020$
 - 0.02866 ± 0.00040 from indirect only
 - * theory (Erler): 0.02779 ± 0.00020
 - * 1.9σ , mainly from $g_\mu - 2$

- $\alpha_s = 0.1200 \pm 0.0028$ consistent w. other values
 - (PDG: 0.1182 ± 0.0013 w/o lineshape;
 - QCD average (Bethke 2000): 0.1184 ± 0.0031)
 - insensitive to oblique new physics
 - very sensitive to non-universal new physics (e.g., $Zb\bar{b}$ vertex)

- Higgs mass $M_H = 98_{-35}^{+51}$ GeV
 - direct limit (LEP 2): $M_H \gtrsim 113.5$ 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
 - * a_μ (included) lowers M_H by 5 GeV (Erler)
 - * $M_H < 199$ 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 (≥ 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, ν 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; $Zb\bar{b}$; ρ_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)

$$S = -0.03 \pm 0.11(-0.08)$$

$$T = -0.02 \pm 0.13(+0.09)$$

$$U = 0.24 \pm 0.13(+0.01)$$

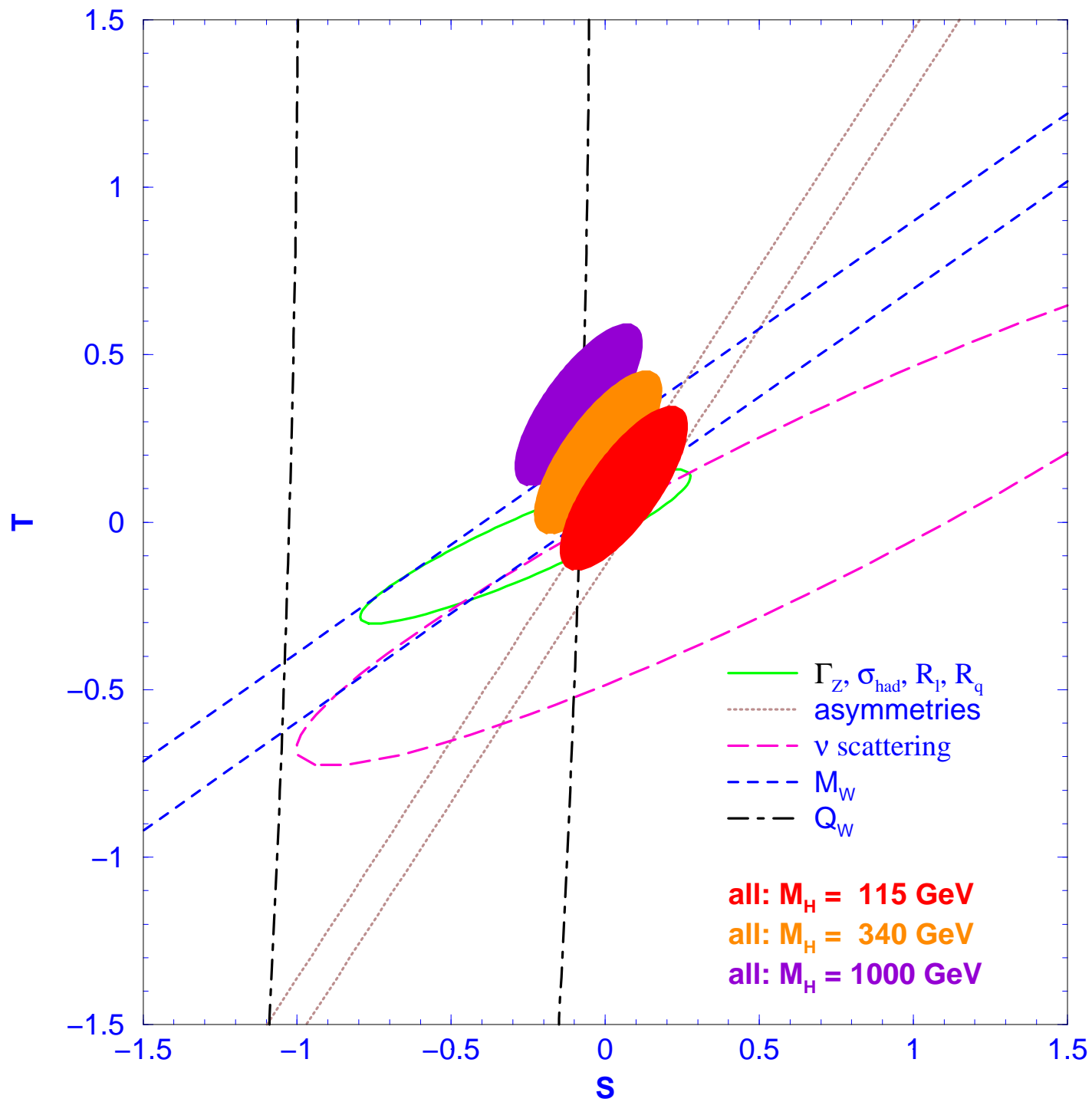
for $M_H = 115$ (340) GeV

$$- \rho_0 \approx 1 + \alpha T = 1.0012^{+0.0023}_{-0.0014}$$

$$(M_H = 211^{+814}_{-139} \text{ GeV})$$

$$- N_{\text{fam}} = 2.97 \pm 0.30 \text{ for } T = U = 0 \text{ (cf. line-shape: } N_\nu = 2.985 \pm 0.008)$$

$$- N_{\text{fam}} = 3.27 \pm 0.45 \text{ for } T = 0.10 \pm 0.11$$



- Supersymmetry

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

- Heavy Z' : GUTs, string theories

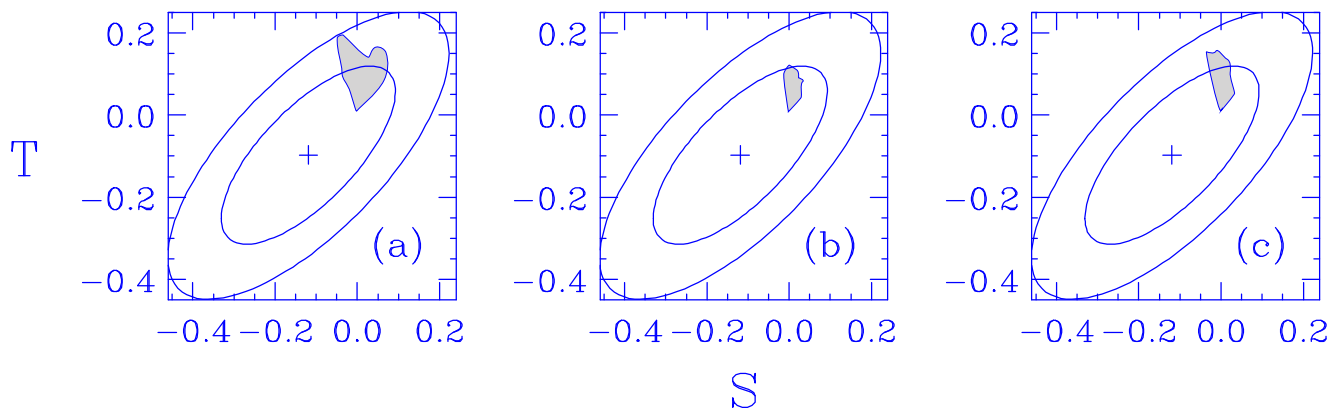
- Typically $M_{Z'} > 500 - 800$ GeV (Tevatron, LEP 2, WNC), $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ (Z-pole)

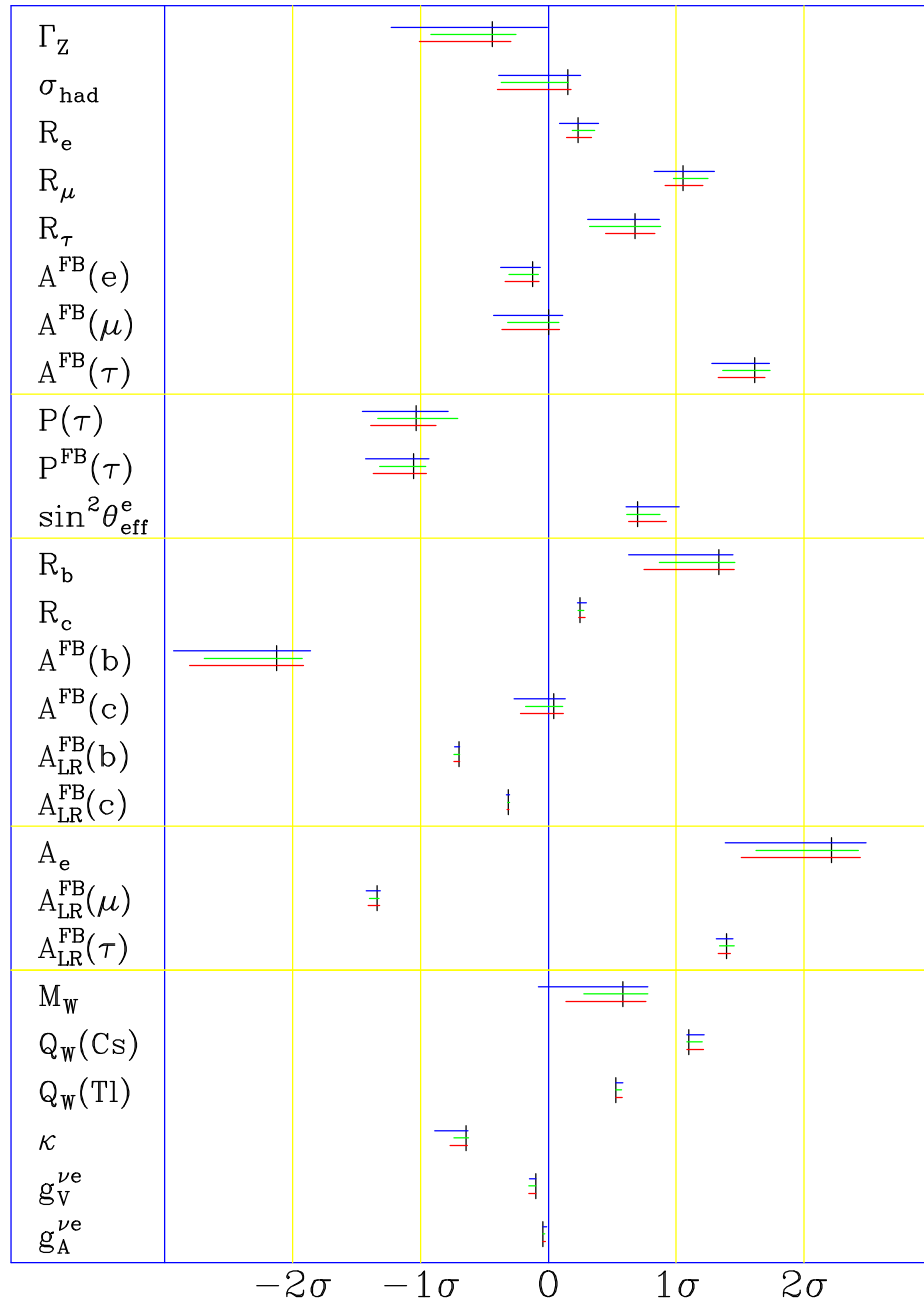
- Other

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

- Gauge unification: GUTs, string theories

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





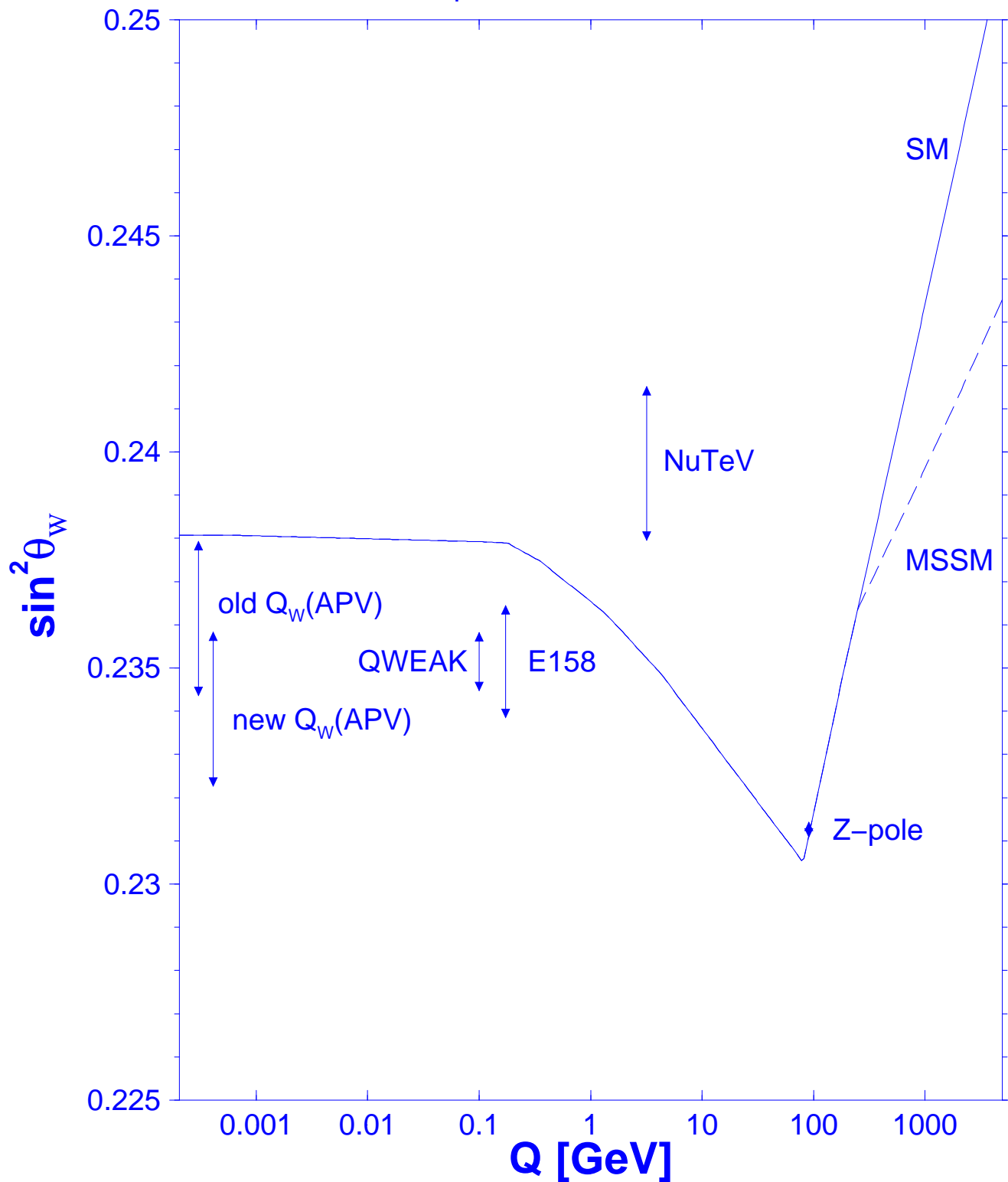
A Heavy Z' ?

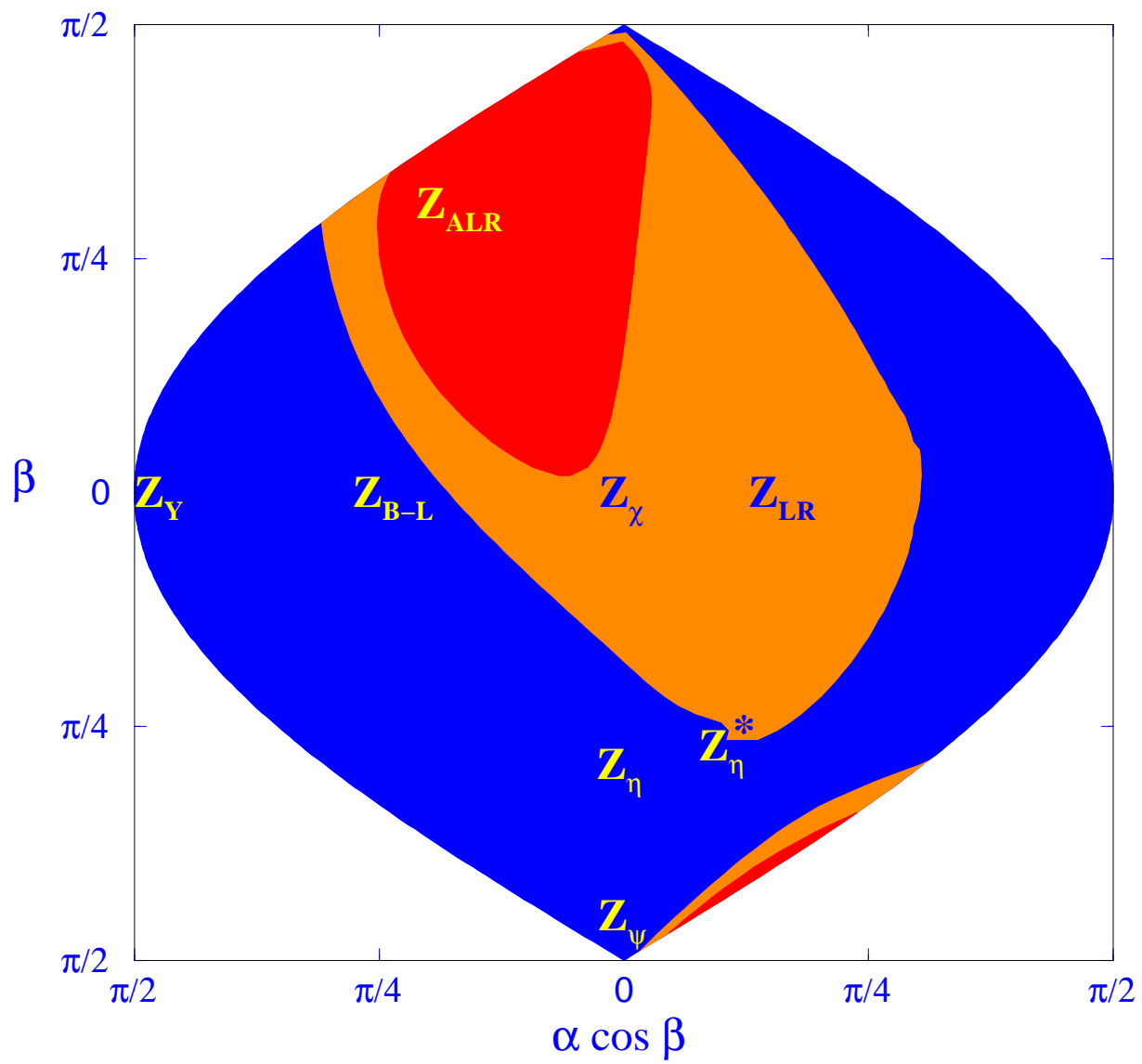
- Expected in many grand unified theories
- Expected in many string constructions
 - Typically, $M_{Z'} \lesssim 1 \text{ TeV}$
 - Often family non-universal (FCNC)
- Natural solution to μ problem
- Nonstandard superpartner spectrum
- Typically $M_{Z'} > 500 - 800 \text{ GeV}$ (Tevatron, LEP 2, WNC), $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ (Z -pole)
- Possible hints of Z'
 - Atomic parity violation (controversial)
 - * SM: $Q_W = -73.10 \pm 0.03$
 - * exp: $Q_W = -72.06 \pm 0.28 \pm 0.34(2.3\sigma) \rightarrow -72.65 \pm 0.28 \pm 0.34(1\sigma, \text{Breit}) \rightarrow -72.12 \pm 0.28 \pm 0.34(2.2\sigma, \text{vac.pol})$ or $-72.49 \pm 0.29 \pm 0.51(1.1\sigma)$
 - * 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 (σ_{had})
 - $A_{FB}(b)$ (if non-universal couplings)

- Both precise off-pole measurements of $\sin^2 \hat{\theta}_W(M_Z)$ deviate by $2 - 3\sigma$
- $\Delta\chi^2 \sim -7.9$ for 3 extra df (for $M_{Z'} = 600$ GeV)
- Should be observable at Tevatron if present
- Detailed studies of couplings at LHC

weak mixing angle

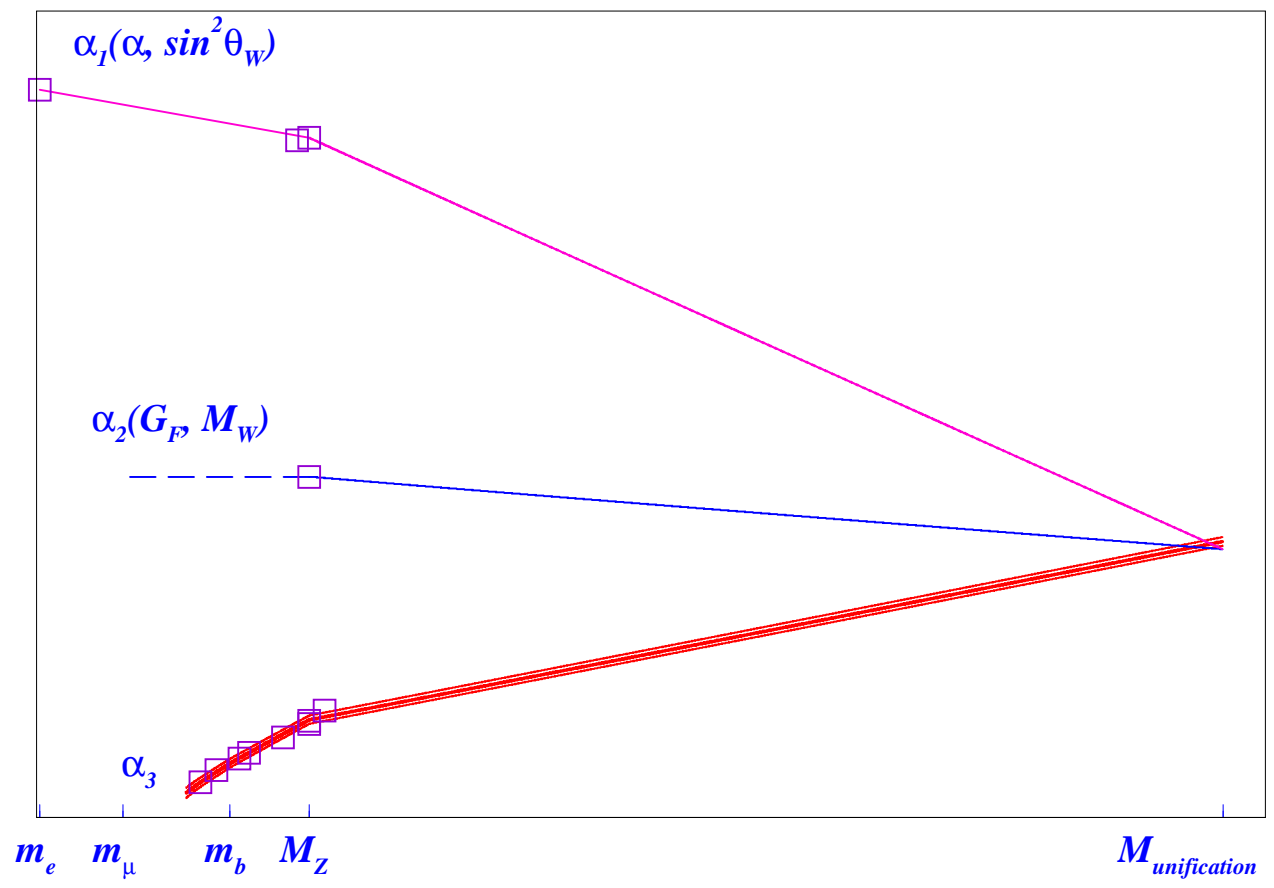
scale dependence in \overline{MS} scheme





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_{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 , α_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