Beyond the Standard Model Theory

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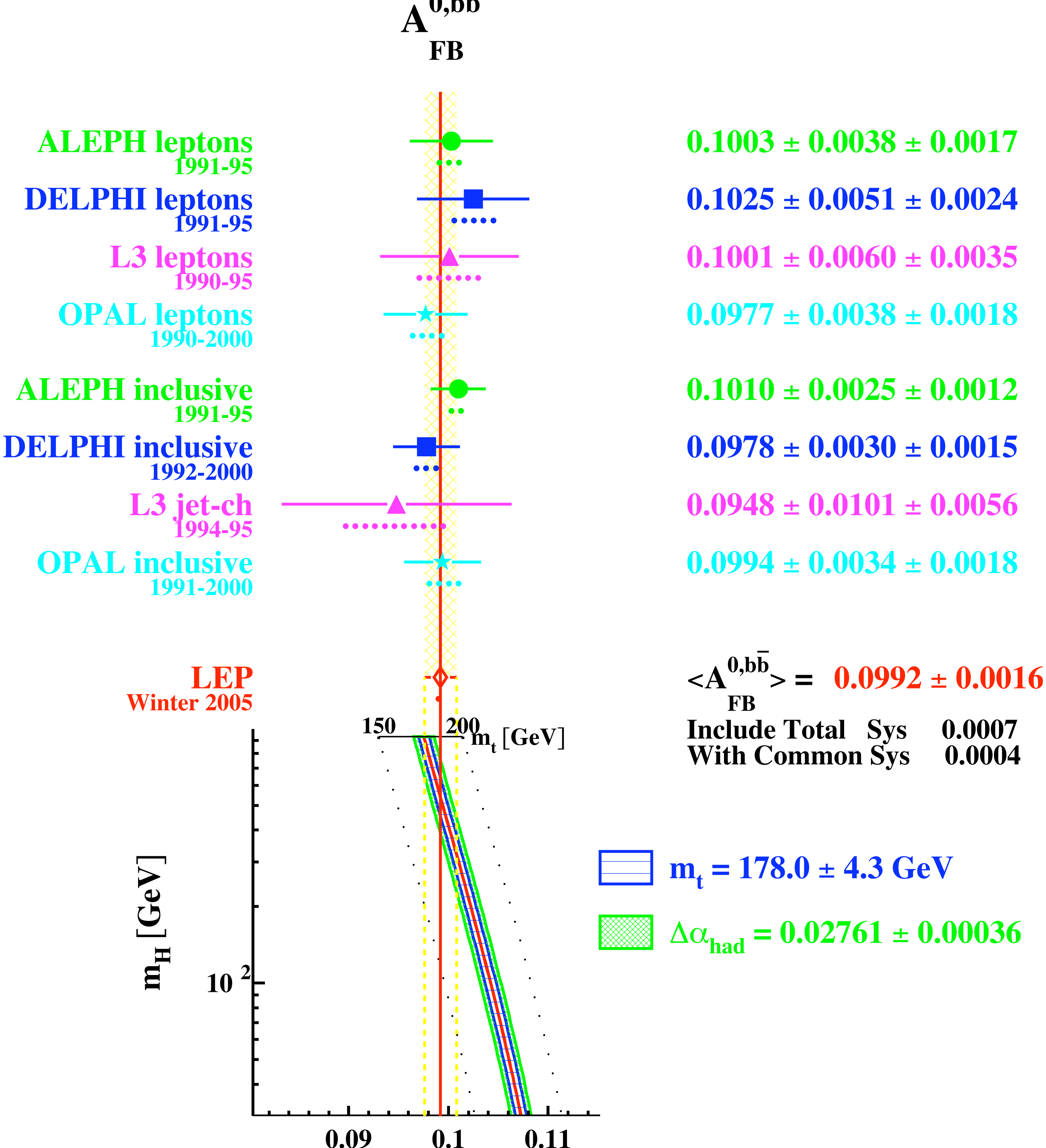
Outline

- Latest news from LEP, SLC, and Tevatron
- Implications for the Standard Model
- Low Energy Tests
- Implications for New Physics

Final LEP/SLC Heavy Flavor Results

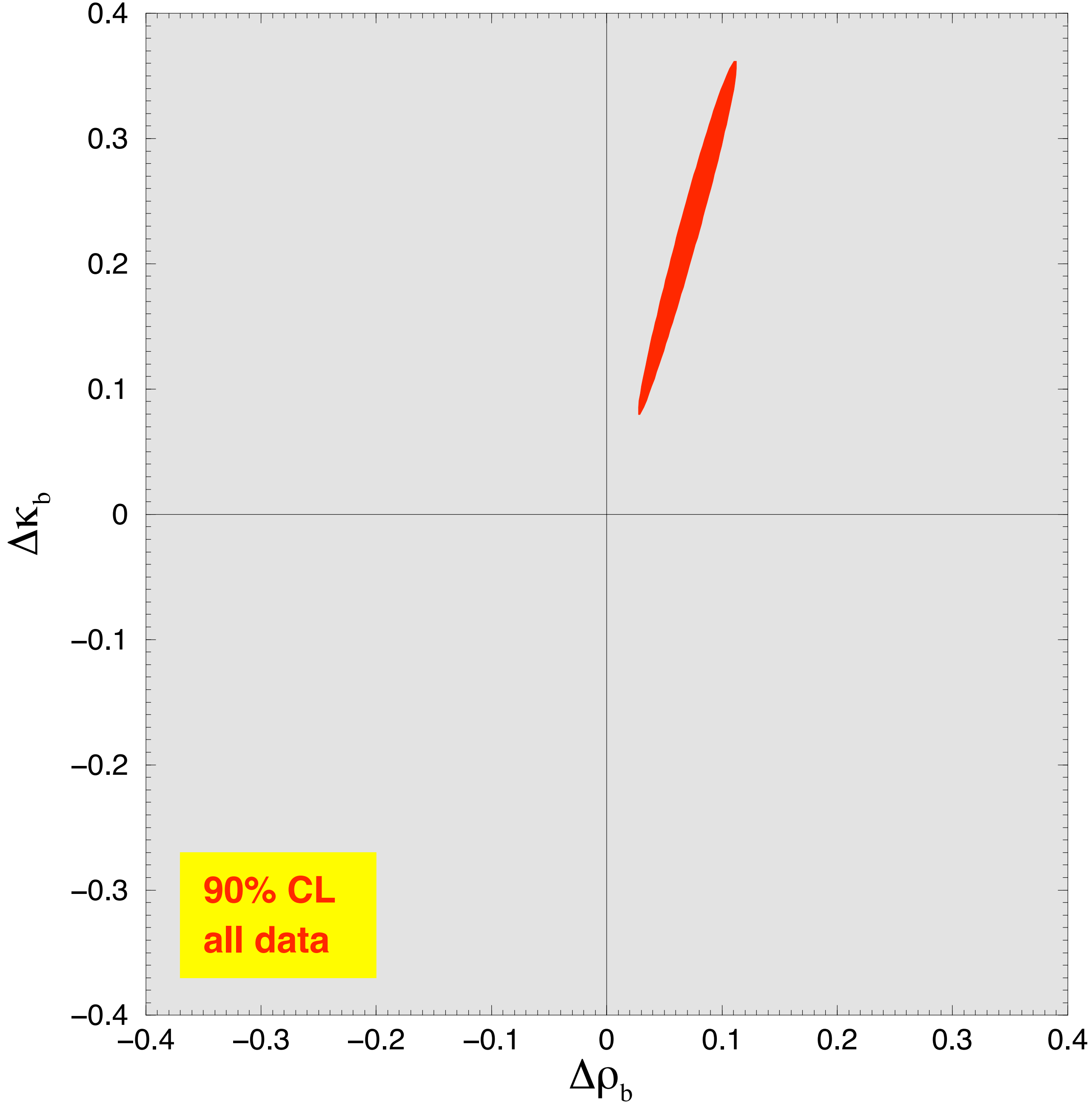
	value	error	SM	pull
R_b	0.21629	0.00066	0.21578	0.8
R_c	0.1721	0.0030	0.1723	-0.1
A_{FB}^b	0.0992	0.0016	0.1031	-2.4
A_{FB}^c	0.0707	0.0035	0.0737	-0.8
A_b	0.923	0.020	0.9347	-0.6
A_c	0.670	0.027	0.6678	0.1

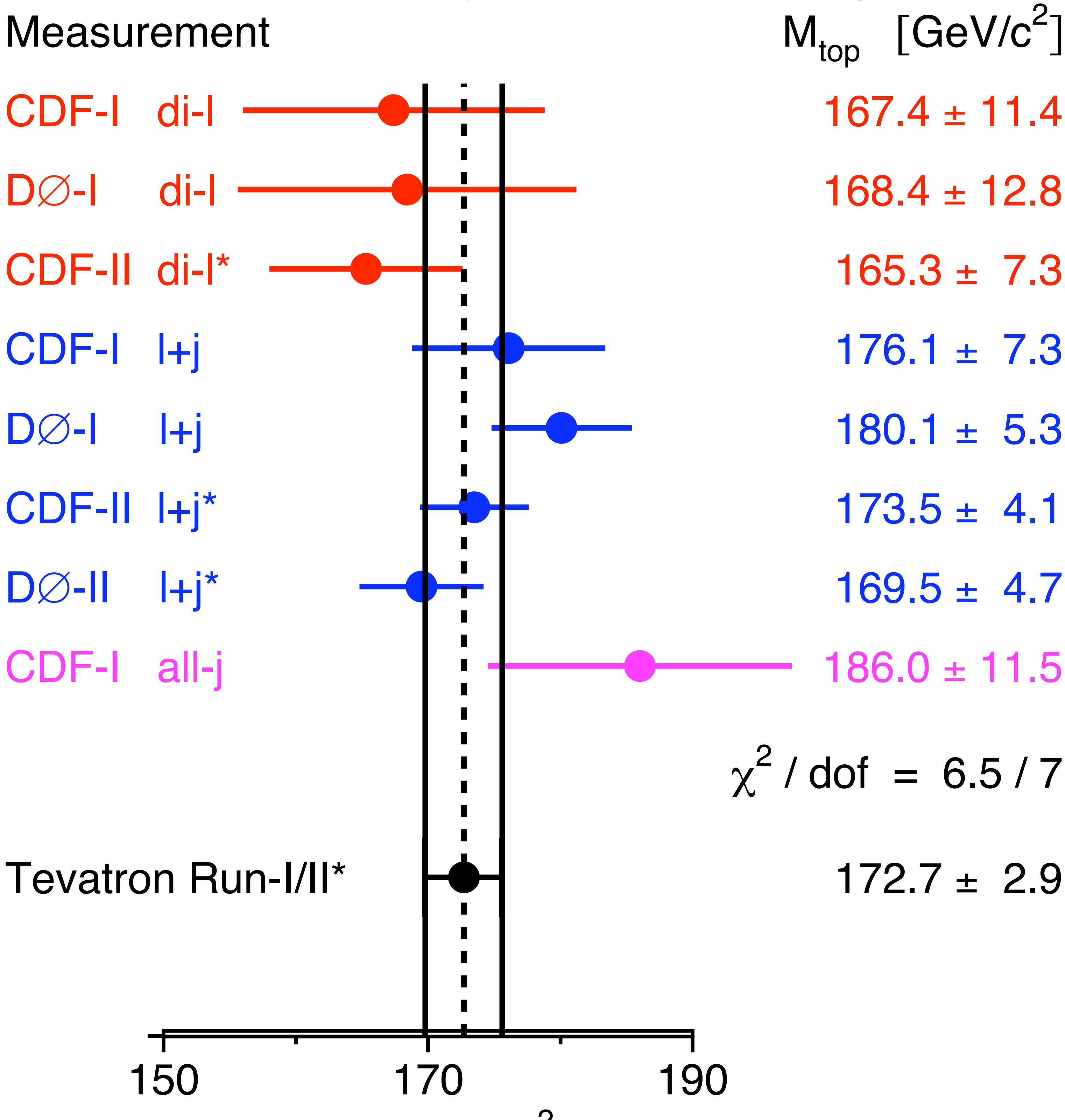
LEP 2: R_b 2.1σ low, A_{FB}^b 1.6σ low.



$A_{FB}^{0,b\bar{b}}$
ALEPH leptons 1991-95
0.1003 ± 0.0038 ± 0.0017
DELPHI leptons 1991-95
0.1025 ± 0.0051 ± 0.0024
L3 leptons 1990-95
0.1001 ± 0.0060 ± 0.0035
OPAL leptons 1990-2000
0.0977 ± 0.0038 ± 0.0018
ALEPH inclusive 1991-95
0.1010 ± 0.0025 ± 0.0012
DELPHI inclusive 1992-2000
0.0978 ± 0.0030 ± 0.0015
L3 jet-ch 1994-95
0.0948 ± 0.0101 ± 0.0056
OPAL inclusive 1991-2000
0.0994 ± 0.0034 ± 0.0018
LEP Winter 2005
$\langle A_{FB}^{0,b\bar{b}} \rangle$ = 0.0992 ± 0.0016
Include Total Sys 0.0007
With Common Sys 0.0004
150
200
m_t [GeV]
m_H [GeV]
10^2
m_t = 178.0 ± 4.3 GeV
$\Delta\alpha_{had}$ = 0.02761 ± 0.00036
0.09
0.1
0.11

Zbb form factors





Measurement
M_{top} [GeV/c^2]
CDF-I di-l
167.4 ± 11.4
DØ-I di-l
168.4 ± 12.8
CDF-II di-l*
165.3 ± 7.3
CDF-I l+j
176.1 ± 7.3
DØ-I l+j
180.1 ± 5.3
CDF-II l+j*
173.5 ± 4.1
DØ-II l+j*
169.5 ± 4.7
CDF-I all-j
186.0 ± 11.5
χ^2 / dof = 6.5 / 7
Tevatron Run-I/II*
172.7 ± 2.9
150
170
190

Global Fit

$$m_t = 172.6 \pm 2.8 \text{ GeV}$$

$$M_H = 89^{+38}_{-28} \text{ GeV}$$

$$\alpha_s = 0.1216 \pm 0.0017$$

$$\chi^2/d.o.f = 47.6/42$$

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last year: $M_H = 113^{+56}_{-40} \text{ GeV}$

upper error: -12 GeV (top mass central value)
- 6 GeV (top mass uncertainty)

excl. low energy: - 5 GeV

excl. E-158: - 3 GeV

M_H

46 GeV < M_H < 155 GeV (90% range)

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incl. direct searches @ LEP:

M_H < 189 GeV (95% C.L.)

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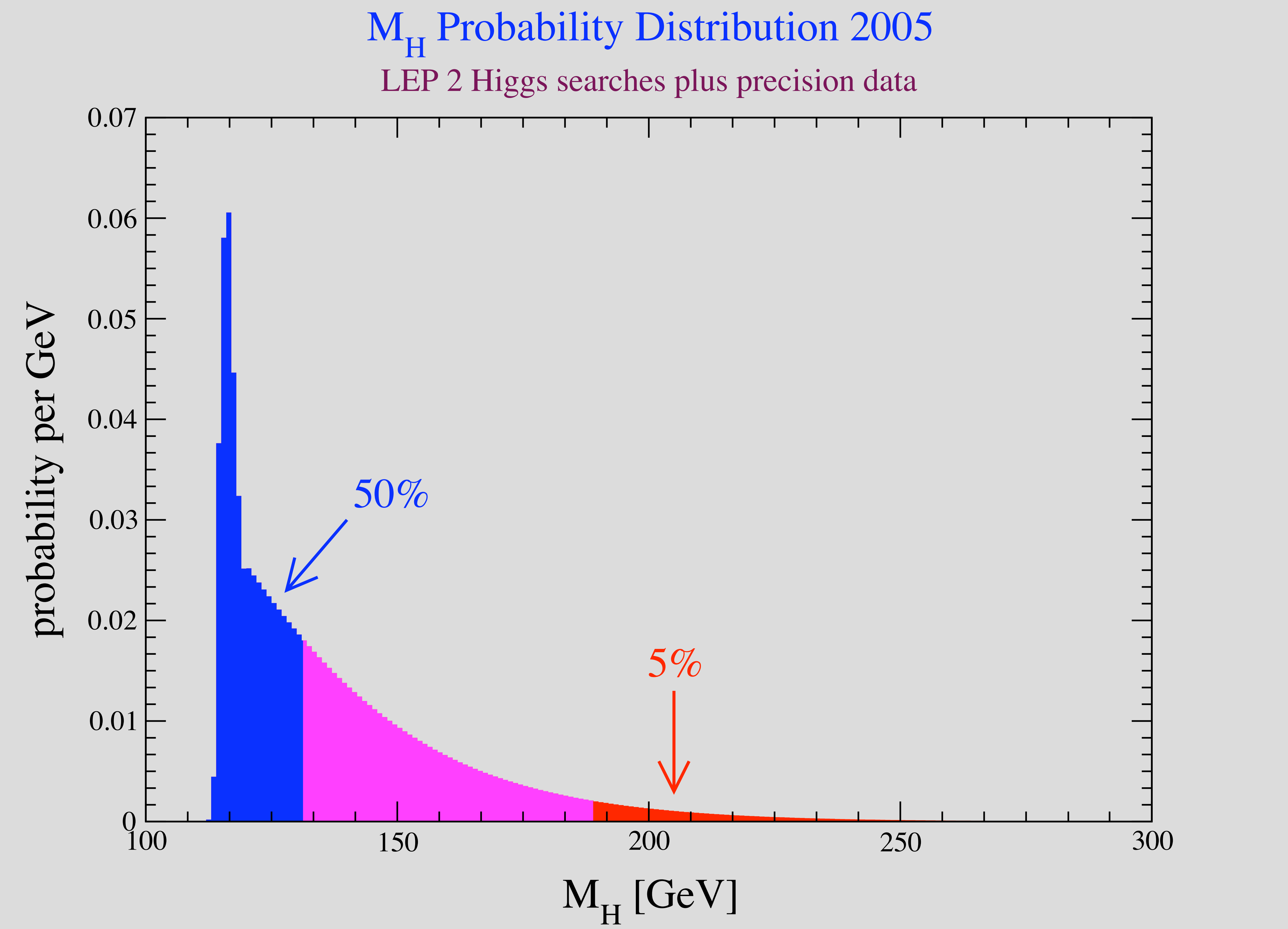
lower direct limit (LEP 2):

M_H > 114.4 GeV (95% C.L.)



M_H Probability Distribution 2005
LEP 2 Higgs searches plus precision data
probability per GeV
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
100
150
200
250
300
50%
5%
M_H [GeV]

Small Deviations

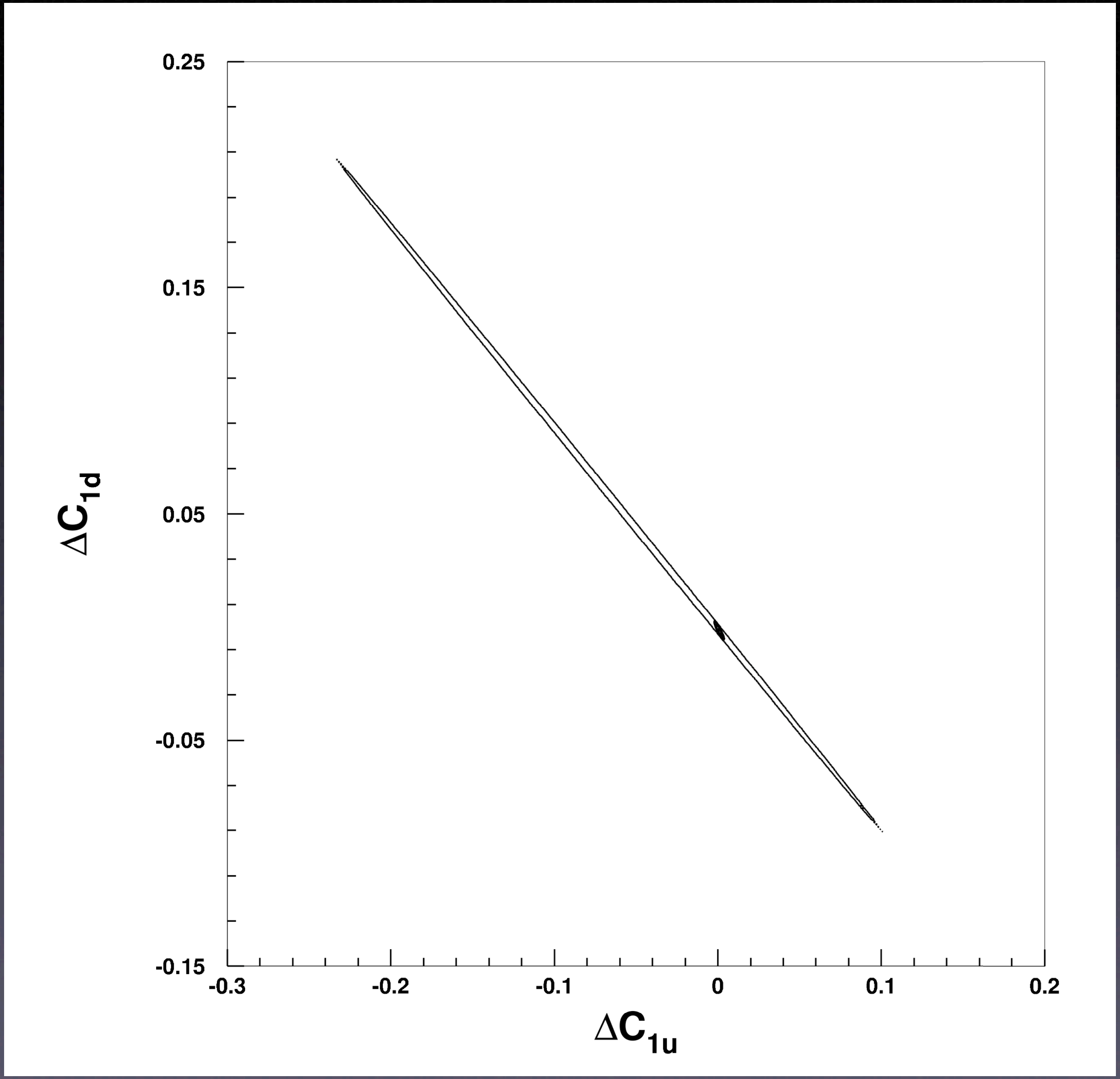
	value	error	SM	pull
$\sigma^0_{\rm had}$[nb]	41.541	0.037	41.467	2.0
R_τ(LEP)	0.0188	0.0017	0.0162	1.5
A_{LR}(SLD)	0.1514	0.0022	0.1471	2.0
$10^9 \frac{g-2-\frac{\alpha}{\pi}}{2}$	4511.07	0.82	4509.82	1.5
g_L^2(NuTeV)	0.3001	0.0014	0.3038	2.7
$Q_W(Cs)$	-72.56	0.48	-73.17	1.3
$10^7 A_{LR}$(E158)	-1.31	0.17	-1.53	1.3
$\sin^2\theta_W^{\rm eff.}$(FNAL)	0.2238	0.0050	0.2315	-1.5

New Physics

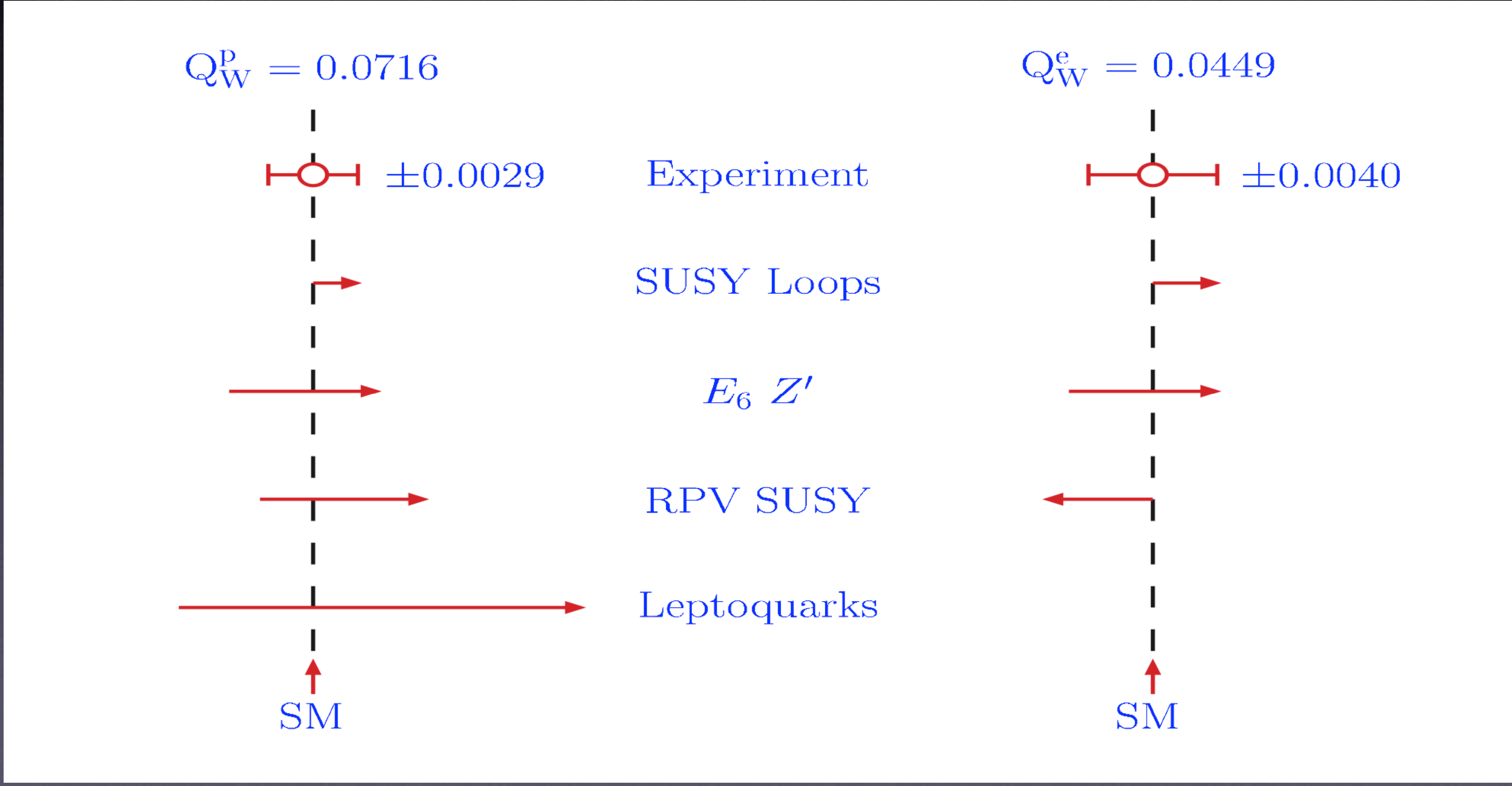
- Z-pole: Z-couplings; new physics indirect
- LEP 2 + Tevatron: oblique parameters (S,T,U)
- LEP 2: high energies, low statistics
- Low energy: interference; new physics direct

$$\frac{\Lambda_{\mathrm{NEW}}}{g} \approx \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W|}} \approx \left\{ \begin{array}{l} 4.6\ \mathrm{TeV}(Q_W^p) \\ 3.2\ \mathrm{TeV}(Q_W^e) \end{array} \right.$$

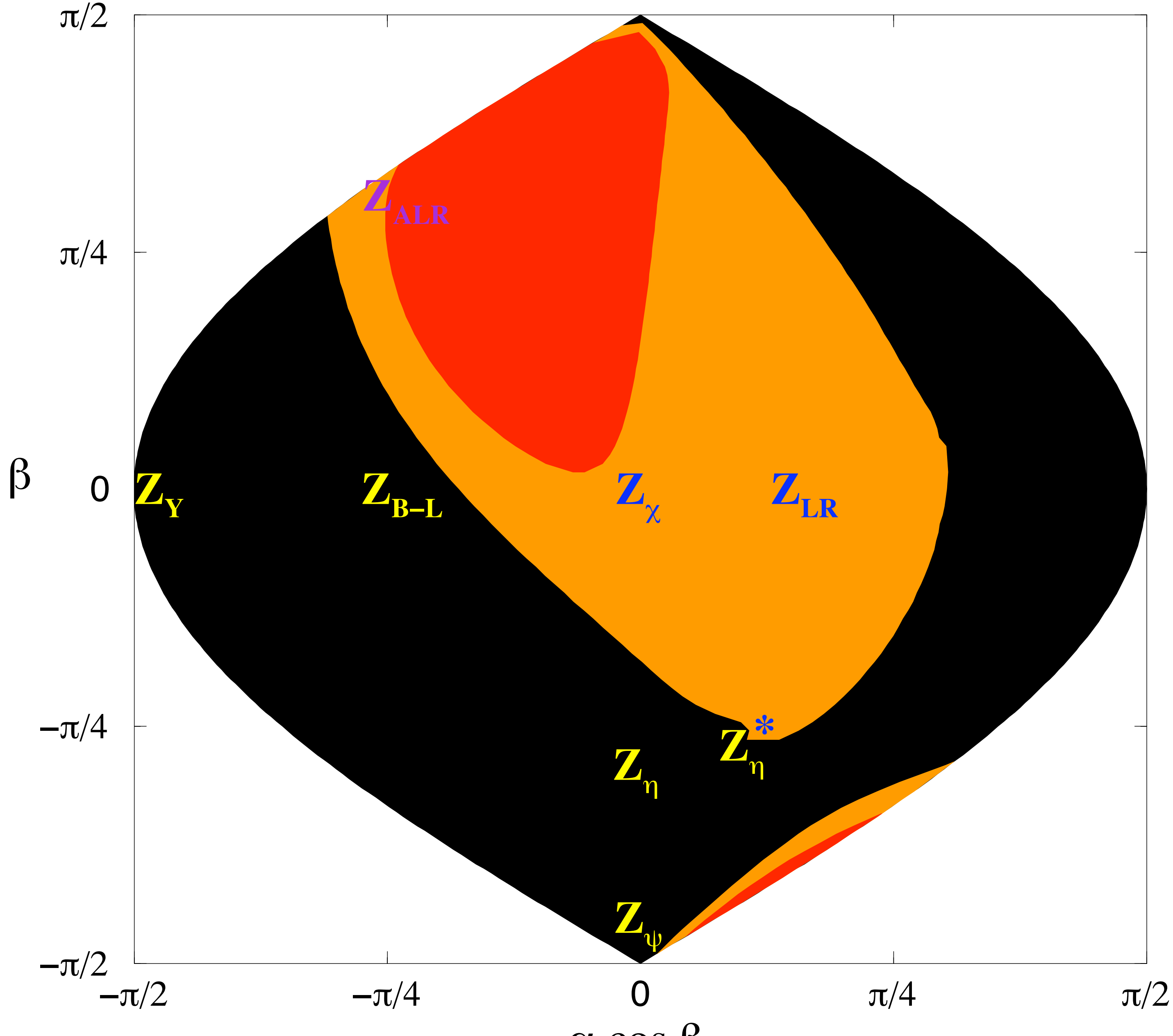
$v_q a_e$ 4-Fermi couplings



Low Energy Complementarity

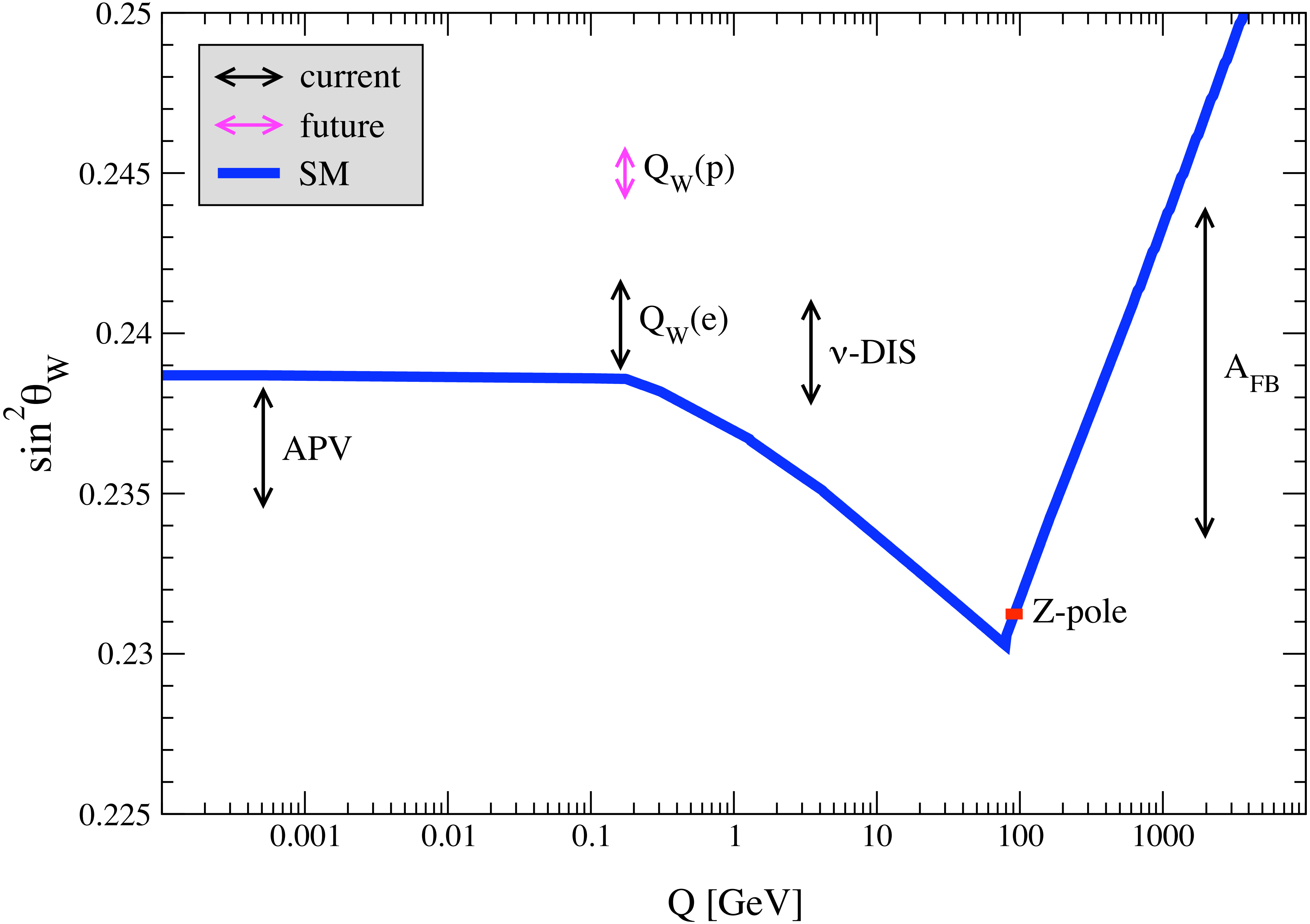


Z' bosons from E_6



Weak Mixing Angle

Scale dependence in $\overline{\text{MS}}$ scheme including higher orders



$$\hat{s}^2(\mu) = \frac{\hat{\alpha}(\mu)}{\hat{\alpha}(\mu_0)}\hat{s}^2(\mu_0) + \lambda_1\left[1 - \frac{\hat{\alpha}(\mu)}{\hat{\alpha}(\mu_0)}\right] +$$

$$\hat{\alpha}(\mu)\left[\frac{\lambda_2}{3}\ln\frac{\mu^2}{\mu_0^2} + \frac{3\lambda_3}{4}\ln\frac{\hat{\alpha}(\mu)}{\hat{\alpha}(\mu_0)} + \tilde{\sigma}(\mu_0) - \tilde{\sigma}(\mu)\right].$$

energy range	λ_1	λ_2	λ_3	λ_4
$\bar{m}_t \leq \mu$	$9/20$	$289/80$	$14/55$	$9/20$
$M_W \leq \mu < \bar{m}_t$	$21/44$	$625/176$	$6/11$	$3/22$
$\bar{m}_b \leq \mu < M_W$	$21/44$	$15/22$	$51/440$	$3/22$
$m_\tau \leq \mu < \bar{m}_b$	$9/20$	$3/5$	$2/19$	$1/5$
$\bar{m}_c \leq \mu < m_\tau$	$9/20$	$2/5$	$7/80$	$1/5$
$\bar{m}_s \leq \mu < \bar{m}_c$	$1/2$	$1/2$	$5/36$	0
$\bar{m}_d \leq \mu < \bar{m}_s$	$9/20$	$2/5$	$13/110$	$1/20$
$\bar{m}_u \leq \mu < \bar{m}_d$	$3/8$	$1/4$	$3/40$	0
$m_\mu \leq \mu < \bar{m}_u$	$1/4$	0	0	0
$m_e \leq \mu < m_\mu$	$1/4$	0	0	0
$\mu < m_e$	0	0	0	0

$$\bar{m} = \hat{m}(\hat{m}) \exp\left[-\frac{13}{24}\frac{\hat{\alpha}_s(\hat{m})}{\hat{\alpha}_s(\hat{m})+\pi} - \frac{\hat{\alpha}_s^2}{288\pi^2}\left(655\zeta(3) - \frac{3847}{6} + \frac{361}{9}n_q + \frac{295}{9}\frac{\sum_{q\neq f} Q_q^2}{Q_f^2}\right)\right].$$

$$\hat{\alpha}_s(M_Z) = 0.1214 \pm 0.0018,$$
$$\hat{m}_c(\hat{m}_c) = 1.285^{+0.040}_{-0.047}\ GeV$$
$$\hat{m}_b(\hat{m}_b) = 4.205 \pm 0.031\ GeV$$
$$\bar{m}_c = 1.176\ GeV$$
$$\bar{m}_b = 3.995\ GeV$$

$$\xi_q = 2\bar{m}_q/M_{1S}$$
$$\xi_q \to 1 \text{ for } \bar{m}_q \to \infty$$
$$\xi_q \to 0 \text{ for } \bar{m}_q \to 0$$
$$\text{Heavy quark: } \xi_q \sim 1$$
$$\text{Light quark: } \xi_q \ll 1$$
$$\bar{m}_1 < \bar{m}_2 \Longrightarrow \xi_1 < \xi_2$$
$$\xi_c = 0.759, \xi_b = 0.845$$
$$\bar{m}_s = \xi_s M_\phi/2 < \xi_c M_\phi/2 = 387\ MeV$$

Limits on the strange quark contribution

$$\Delta_s\hat{\alpha}(\bar{m}_c) = Q_s^2\frac{\alpha}{\pi}K_{\rm QCD}^s \ln\frac{\bar{m}_c^2}{\bar{m}_s^2} > Q_s^2\frac{\alpha}{\pi}K_{\rm QCD}^c \ln\frac{\bar{m}_c^2}{\bar{m}_s^2} > \frac{2\alpha}{9\pi}K_{\rm QCD}^c \ln\frac{M_{J/\Psi}}{M_\phi} = 6.9\times 10^{-4}.$$

$$K_{\rm QCD}^s > K_{\rm QCD}^c = 1 + \frac{\hat{\alpha}_s(\bar{m}_c)}{\pi} + \frac{103}{48}\frac{\hat{\alpha}_s^2(\bar{m}_c)}{\pi^2} + \frac{1979}{576}\frac{\hat{\alpha}_s^3(\bar{m}_c)}{\pi^3} = 1.209,$$

$$\Delta_s\hat{\alpha}(\bar{m}_c) < \frac{\Delta\hat{\alpha}^{(3)}(\bar{m}_c)}{6} - \frac{5}{27}\frac{\alpha}{\pi}K_{\rm QCD}^s \ln\frac{M_\phi}{M_\omega} < \frac{\Delta\hat{\alpha}^{(3)}(\bar{m}_c)}{6} - \frac{5}{27}\frac{\alpha}{\pi}K_{\rm QCD}^c \ln\frac{M_\phi}{M_\omega} = 9.9\times 10^{-4}.$$

$$\Delta\hat{\alpha}^{(3)}(\bar{m}_c) = 0.00678 \pm 0.00010,$$

$$\Delta_s\hat{\alpha}(\bar{m}_c) = (8.4\pm 1.5)\times 10^{-4}, \bar{m}_s = 305^{-65}_{+82}\ \text{MeV}.$$

Uncertainties

- Heavy flavor: parametric (α_s, m_b, m_c)
- effects fully correlated with $\alpha(M_Z)$
- SU(3) breaking effect
- Isospin violation
- OZI rule violation

Error Breakdown

Source	$\Delta \sin^2 \theta_W(0)$
$\Delta \sin^2 \theta_W(M_Z)$	1.5×10^{-4}
ΔM_Z	1.4×10^{-5}
$\Delta m_c, \Delta m_b$	4×10^{-5}
$\Delta \alpha_s$	4×10^{-5}
$\Delta^{(3)} \alpha(m_\tau)$	3×10^{-5}
SU(3) breaking	5×10^{-5}
SU(2) breaking	$< 10^{-5}$
OZI rule breaking	3×10^{-5}
TOTAL	$\pm 0.00016 \ \ (0.00007)_{\text{theory}}$

Conclusions

- Above, below, and top of the Z-pole offer complementary BSM physics opportunities.
- Polarized electron scattering at low energies is valuable diagnostic tool.
- "Discovering" new physics would require factor 4 or better improvement in precision.
- Diversification: many different observables will hedge us against error and help distinguish between competing models for physics Beyond the SM.