CONACYT
Consejo Nacional de Ciencia y Tecnología

A SEARCH FOR NEW PHYSICS
Qweak

Low Energy Tests of the Standard Model with Spin Degrees of Freedom

SPIN 2006
Kyoto, October 3, 2006

Jens Erler (IF-UNAM)

INSTITUTO de FÍSICA
UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

Outline

- Introduction
- Polarized electron scattering and the weak neutral current
- Muon decay
- g-2
- Electric Dipole Moments (advertisement)
- Conclusions

Introduction

- SU(3) X SU(2) X U(1) SM is well tested (0.1% level).
- New Physics: small deviation and of decoupling type.
- Motivation (theory): instability of EW scale, gravity.
- Motivation (observation): dark matter and energy, and matter anti-matter asymmetry in the universe.
- Strategies: high energy or high precision.
- 2 general types of precision test: SM allowed (PV scattering) or SM forbidden/highly suppressed (EDMs).

The Standard Model

$$\mathcal{L}_F = \sum \bar{\Psi}_f \left(i \not{\partial} - m_f - \frac{\lambda_f}{\sqrt{2}} \right) \psi_f$$

$$-\frac{g}{2\sqrt{2}} \sum \bar{\Psi}_f \gamma^\mu (1-\gamma_5)(T^+ W_\mu^+ + T^- W_\mu^-)\psi_f$$

$$-e \sum Q_f \bar{\Psi}_f \gamma^\mu \psi_f A_\mu$$

$$-\frac{\sqrt{g^2+g'^2}}{2} \sum \bar{\Psi} \gamma^\mu (v_f - a_f \gamma_5) \psi Z_\mu^0$$

$$v_f \equiv T_3^f - 2Q_f \sin^2\theta_W \qquad a_f \equiv T_3^f$$

Weak Mixing Angle

$$Z_\mu^0 = \cos\theta_W W_\mu^3 - \sin\theta_W B_\mu$$
$$\mathrm{A}_\mu = \sin\theta_W W_\mu^3 + \cos\theta_W B_\mu$$

$$\sin^2\theta_W = \frac{g'^2}{g^2 + g'^2} = 1 - \frac{M_W^2}{M_Z^2}$$

$$e = g\sin\theta_W = g'\cos\theta_W$$

SM parameters

- Besides Yukawa sector, SM described by

  3 gauge couplings $(\alpha, \sin^2\theta_W, \alpha_s)$

  2 parameters from Higgs potential (G_F, M_H)
- α, G_F, M_Z known with negligible uncertainty

  α_s, M_H (or alternatively $\sin^2\theta_W$) from precision EW data

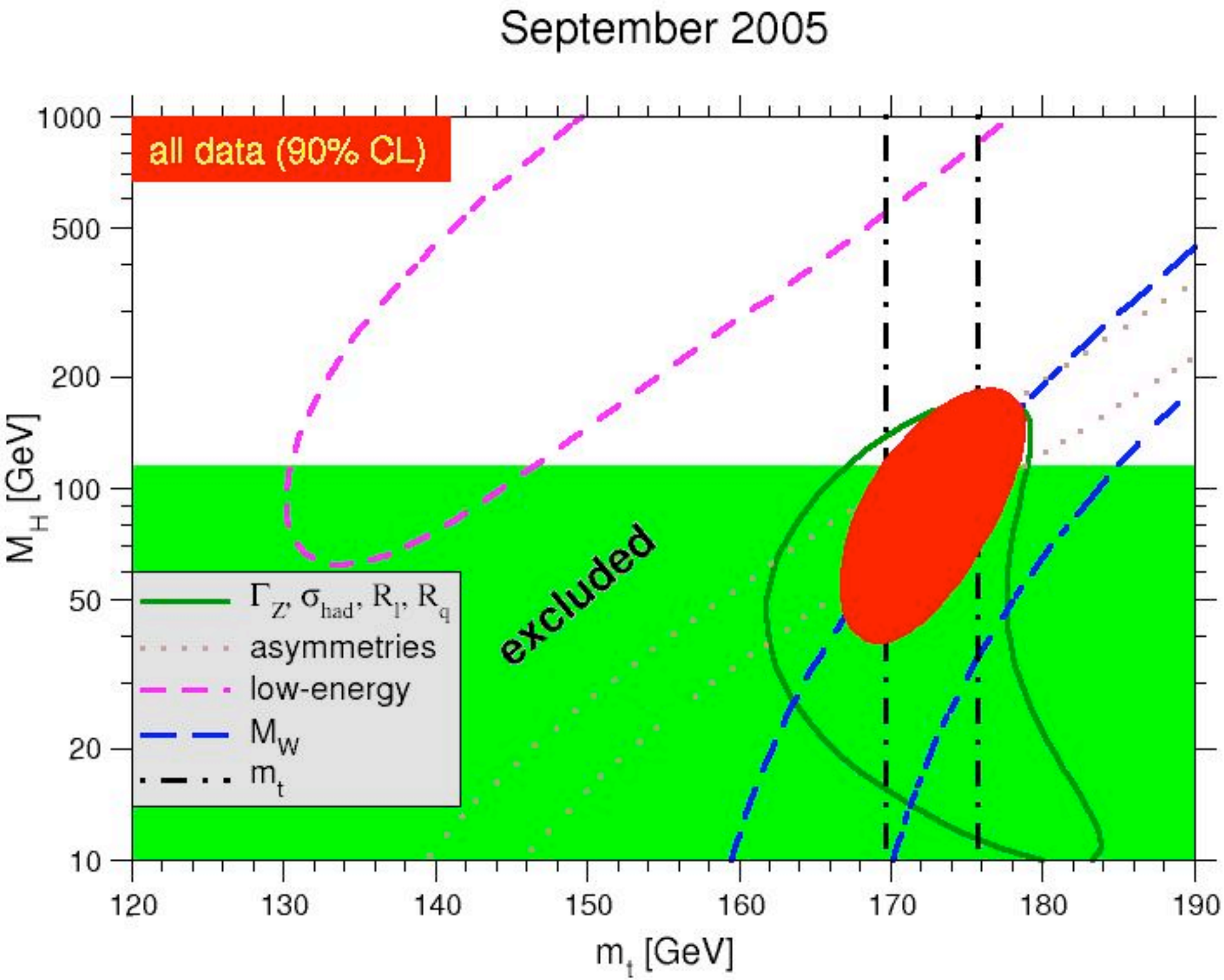
Some Background

$$\sin^2\hat{\theta}_W(M_Z) \equiv \hat{s}^2 = \frac{A^2}{M_W^2(1-\Delta\hat{r}_W)}$$

$$\hat{s}^2\hat{c}^2 = \frac{A^2}{M_Z^2(1-\hat{\Delta}r_Z)}$$

$$A = \left[\frac{\pi\alpha}{\sqrt{2}G_F}\right]^{1/2} = 37.2805(2)\ \text{GeV}$$

$\hat{\Delta}r_W, \hat{\Delta}r_Z$ collect radiative corrections...


September 2005
all data (90% CL)
excluded
Γ_Z, σ_{had}, R_l, R_q
asymmetries
low-energy
M_W
m_t
M_H [GeV]
m_t [GeV]
1000
500
200
100
50
20
10
120
130
140
150
160
170
180
190

Global Fit

September 2005 + new top quark and W boson masses as of October 2006

$$M_H = 84^{+32}_{-25}\ \mathrm{GeV}$$

$$m_t = 171.4 \pm 2.1\ \mathrm{GeV}$$

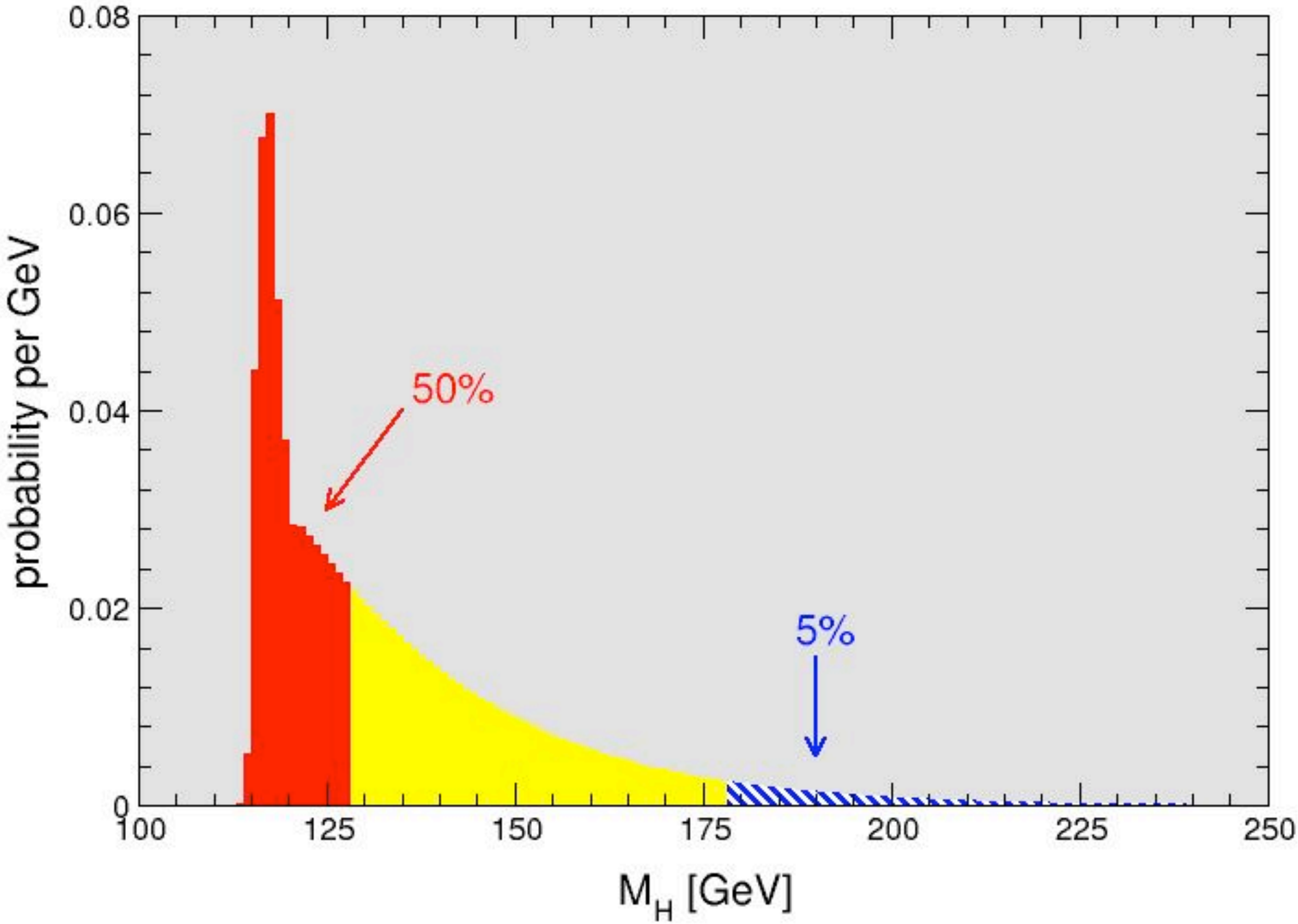
$$\alpha_s(M_Z) = 0.1216 \pm 0.0017$$

$$\chi^2/\mathrm{d.o.f.} = 47.3/42\,(27\%)$$

indirect only:

$$m_t = 171.0^{+9.5}_{-7.1}\ \mathrm{GeV}$$

October 2006



Physics Beyond the SM

- Supersymmetry stabilizes Higgs potential,
$$V(\phi) = m_\phi^2 \phi^\dagger \phi + \frac{\lambda^2}{2} (\phi^\dagger \phi)^2,$$
by virtue of non-renormalization theorems.
- Dynamical symmetry breaking (e.g. technicolor) avoids fundamental scalar.
- Large extra dimensions relate gauge hierarchy to geometry of higher dimensional space-time.
- Little Higgs: Higgs as pseudo-Goldstone boson → postpone quadratic divergences.

Weak Neutral Current

- The effective Lagrangian
- Parity violating DIS
- Polarized electron-proton scattering
- Polarized Møller scattering
- Parity violation in atoms
- Neutrino scattering
- The running weak mixing angle

effective lepton-hadron Lagrangian

$$\mathcal{L}_{\rm NC}^{\ell h} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{1q} \bar{\ell} \gamma^\mu \gamma_5 \ell \bar{q} \gamma_\mu q + \right.$$

$$\left. C_{2q} \bar{\ell} \gamma^\mu \ell \bar{q} \gamma_\mu \gamma_5 q + C_{3q} \bar{\ell} \gamma^\mu \gamma_5 \ell \bar{q} \gamma_\mu \gamma_5 q \right]$$

$$C_{1q} = -T_3^q + 2Q_q \sin^2\theta_W ,$$

$$C_{2u} = -C_{2d} = -\frac{1}{2} + 2\sin^2\theta_W ,$$

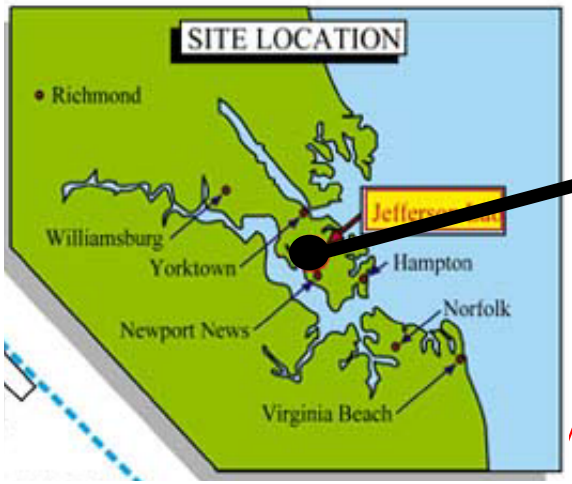
$$C_{3u} = -C_{3d} = \frac{1}{2} .$$

PV-DIS

$$A_{RL} = \frac{3G_F Q^2}{10\sqrt{2}\pi\alpha}[(2C_{1u} - C_{1d}) + g(y)(2C_{2u} - C_{2d})]$$

- eD-DIS experiment by Prescott et al. (SLAC) crucial to establish SM (before W/Z discovery!)
- Situation from APV confused at the time.
- CERN-NA-004: μ-↑ μ+↓
- JLab @ 6 GeV (approved) and 12 GeV will improve on SLAC and world average by factors of 54 and 17.
- Issues: higher twist and CSV; functions of Q^2 and x.
- Limited by polarization and Q^2 measurements (0.5%).

CEBAF at Jefferson Lab



Qweak in Hall C

Larry Lee

Qweak

Similar $Q^2 = 0.03\ \mathrm{GeV}^2$ as E-158 but E = 1.165 GeV.

P = 0.85 ± 0.01

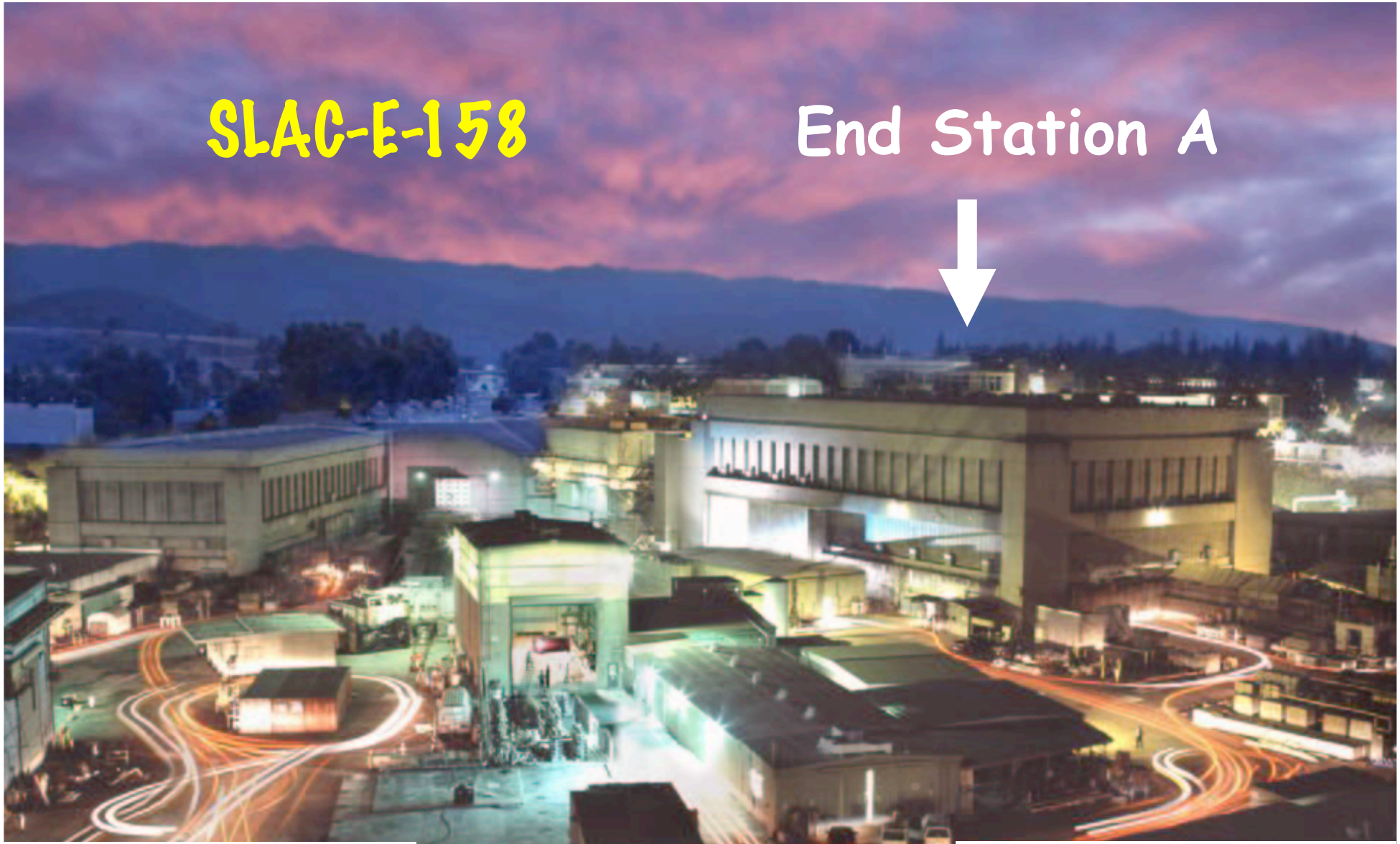
$$A_{PV} = (-2.68 \pm 0.05 \pm 0.04) \times 10^{-7}$$

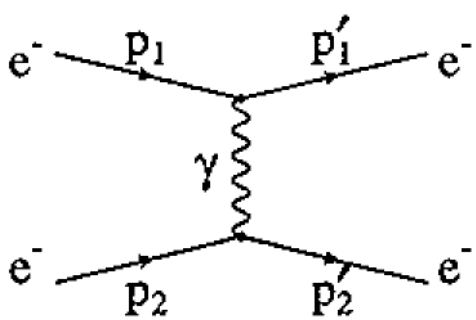
$$A_{PV} = 9 \times 10^{-5}\mathrm{GeV}(Q^2 Q_W^p + Q^4 B)$$
$$\Rightarrow \Delta \mathrm{Q}_W^p = \pm 0.003$$
$$\Rightarrow \Delta \sin^2\theta_W = \pm 0.0007$$

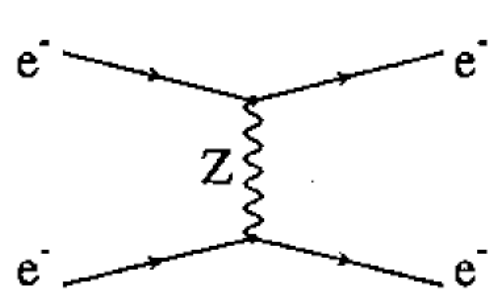
don't miss plenary talk by Bob Michaels!

SLAC-E-158

End Station A







The Møller Asymmetry

$Q^2 = 0.026\ \mathrm{GeV}^2$ (E = 45 and 48 GeV), P = 0.89 ± 0.04

Very high rates: 660 M pulses, 500 G electrons per pulse

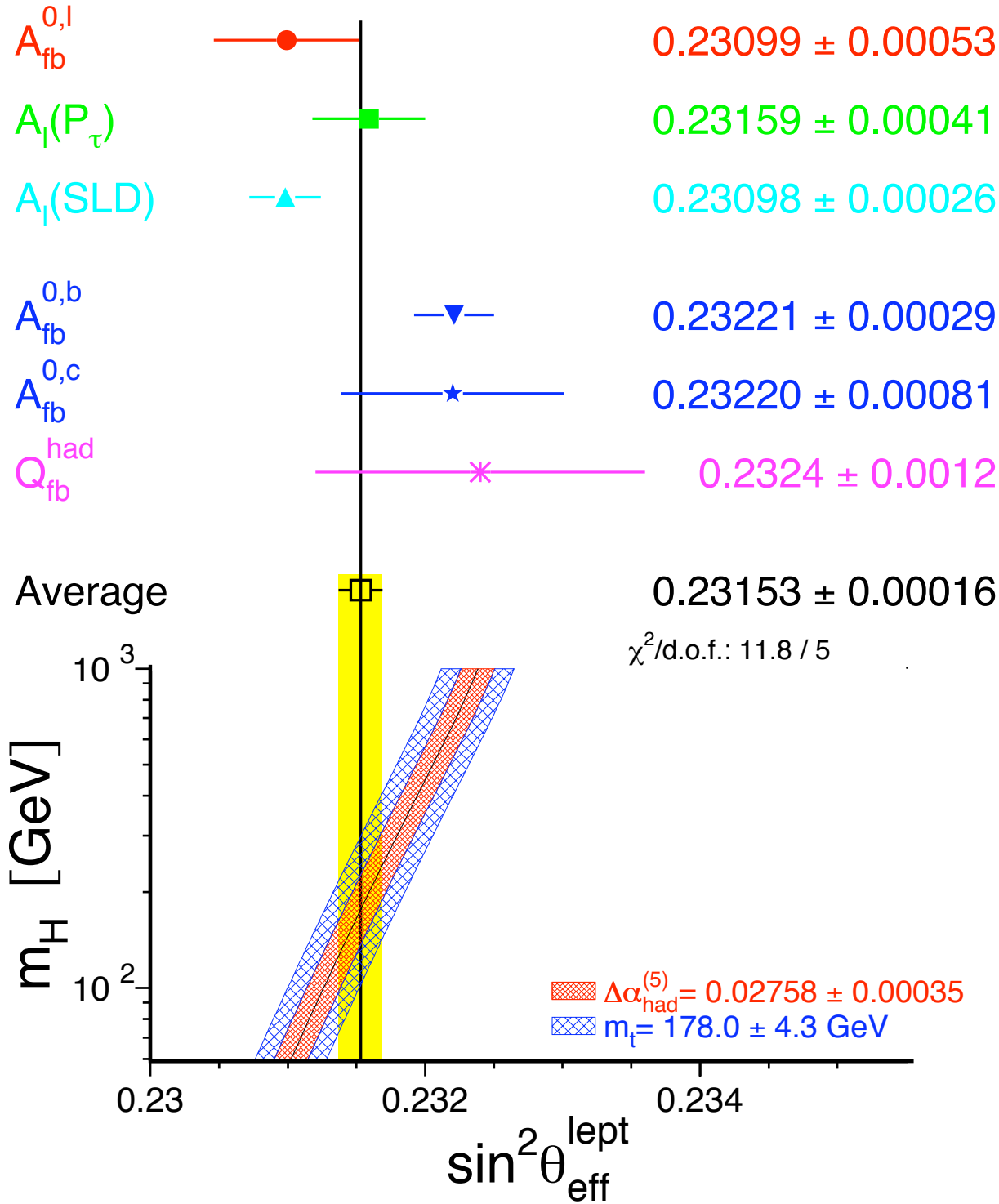
$$A_{PV} = (-1.31 \pm 0.14 \pm 0.10) \times 10^{-7}$$

$$A_{PV} = -\mathcal{A}(Q^2, y)\, Q_W^e \Rightarrow Q_W^e = -0.0403 \pm 0.0053$$

$$\Rightarrow \sin^2 \hat{\theta}_W(M_Z) = 0.2330 \pm 0.0014$$

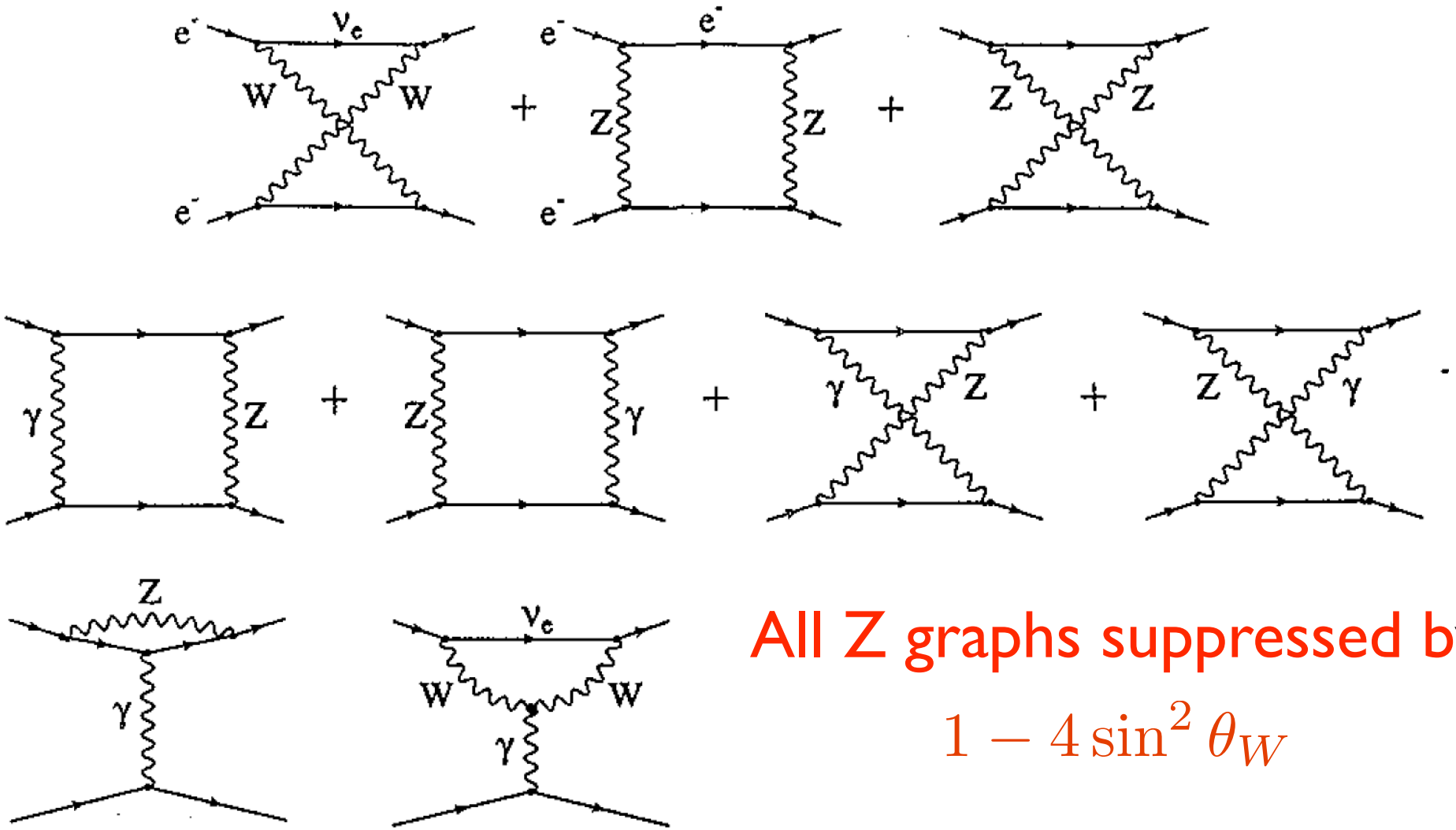
SLD: ± 0.00029, best LEP: ± 0.00028

With a factor of 5 improvement would become world's best measurement


$A_{fb}^{0,l}$
0.23099 ± 0.00053
$A_l(P_\tau)$
0.23159 ± 0.00041
A_l(SLD)
0.23098 ± 0.00026
$A_{fb}^{0,b}$
0.23221 ± 0.00029
$A_{fb}^{0,c}$
0.23220 ± 0.00081
Q_{fb}^{had}
0.2324 ± 0.0012
Average
0.23153 ± 0.00016
χ^2/d.o.f.: 11.8 / 5
m_H [GeV]
10^3
10^2
$\Delta\alpha_{had}^{(5)}$= 0.02758 ± 0.00035
m_t= 178.0 ± 4.3 GeV
0.23
0.232
0.234
$\sin^2\theta_{eff}^{lept}$

Radiative Corrections to Q_W^e

Czarnecki & Marciano



All Z graphs suppressed by

$$1 - 4\sin^2\theta_W$$

Radiative Corrections to Q_W^p

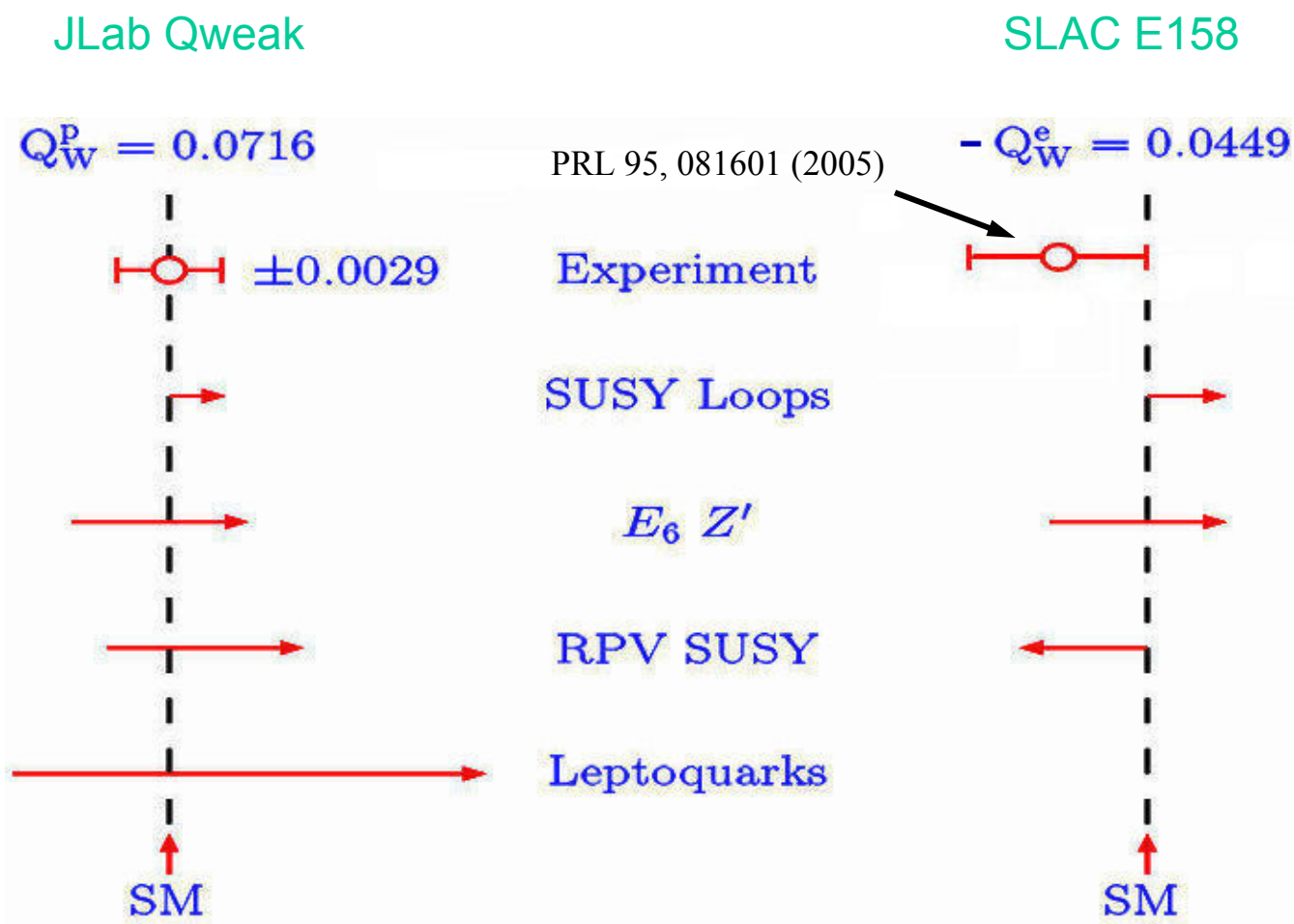
Marciano & Sirlin, Ramsey-Musolf & JE

$$Q_W^p = [\rho_{NC} + \Delta_e][1 - 4\sin^2\hat{\theta}_W(0) + \Delta_e'] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

- Similar structure as for Møller scattering.
- γZ box: long-distance QCD, suppressed by 1 - 4 $\sin^2\theta$.
- WW-box has factor 7 over Møller ⇒ 26% effect!
- ⇒ need 2-loop mixed electroweak-QCD corrections.

$$\Box_{WW} = \frac{\hat{\alpha}}{4\pi\sin^2\hat{\theta}_W}\left[2 + 5\left(1 - \frac{\alpha_s(M_W^2)}{\pi}\right)\right]$$

Proton and Electron Measurements Are Needed



$$\left(\frac{\Lambda}{g}\right)_{\text{new}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W^p|}} \approx 4.6\text{TeV}$$

Atomic Parity Violation

- Need to understand atomic structure below %-level.
- Most precise: $Q_W(\mathrm{Cs}) = -72.62 \pm 0.46$

  $Q_W(\mathrm{Tl}) = -116.4 \pm 3.64$

  Wood et al., Bouchiat et al.
  Edwards et al., Vetter et al.

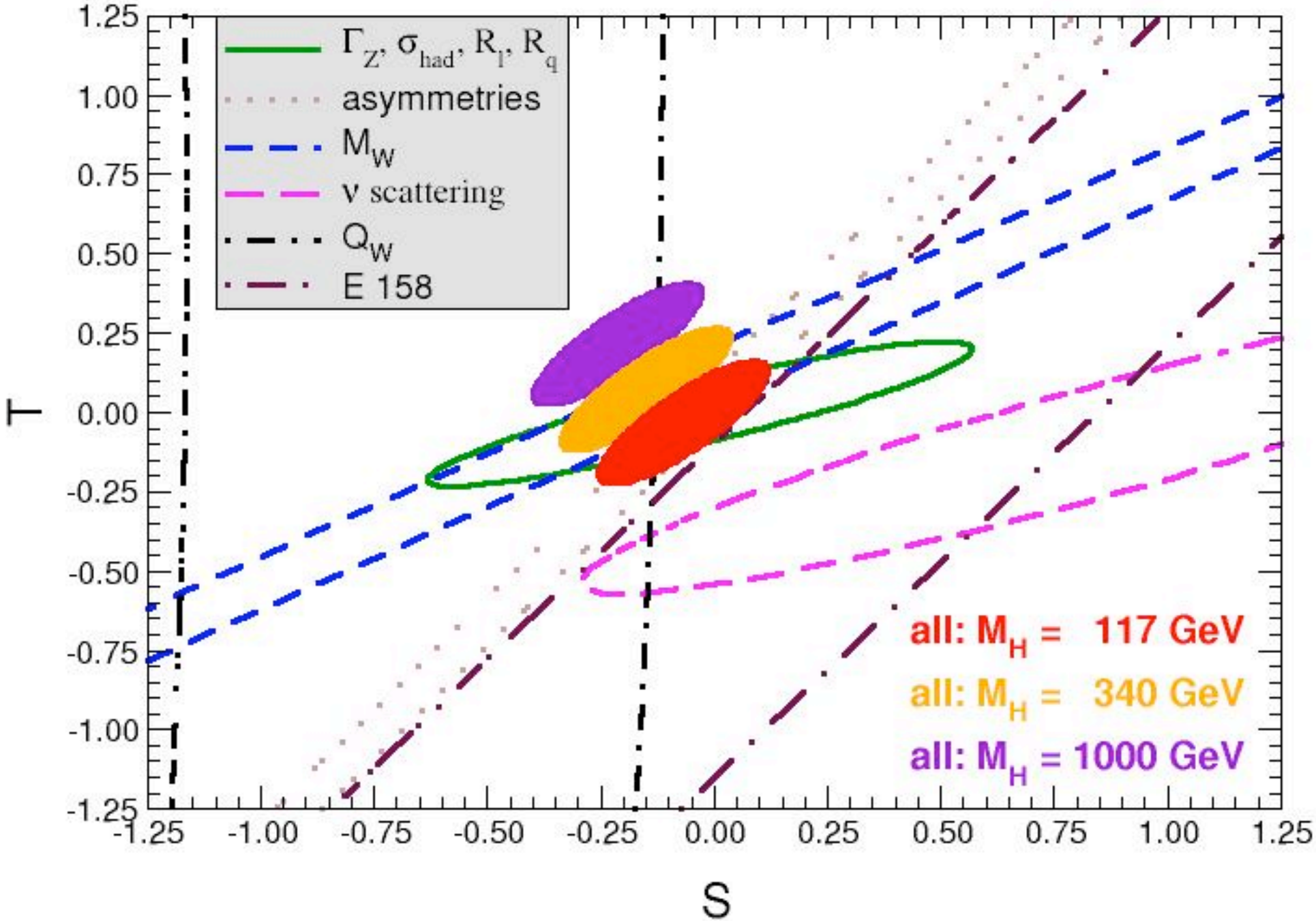
- Bi: ±1% experiment, Meekhof et al., but ±15% theory.
- Fr: ±1% theory but ±10% experiment (atom trap), Orozco et al.

talk by Victor Flambaum after this

APV (contd.)

- future directions: Ba+ (Cs-like) ion trap: ±0.35% Fortson et al.
- Yb isotope ratios: ±0.1% (mostly sensitive to Q_W^p). DeMille, Kimball, Stalnaker et al.
- Finite nuclear size effects dominated by neutron distribution (0.15%) → problem for isotope chains.
- APV = nuclear spin independent + spin dependent terms: nuclear anapole moment dominates (A>20).
- Improve experiment and theory on neutron density. Or use APV to study nuclear structure.

September 2005

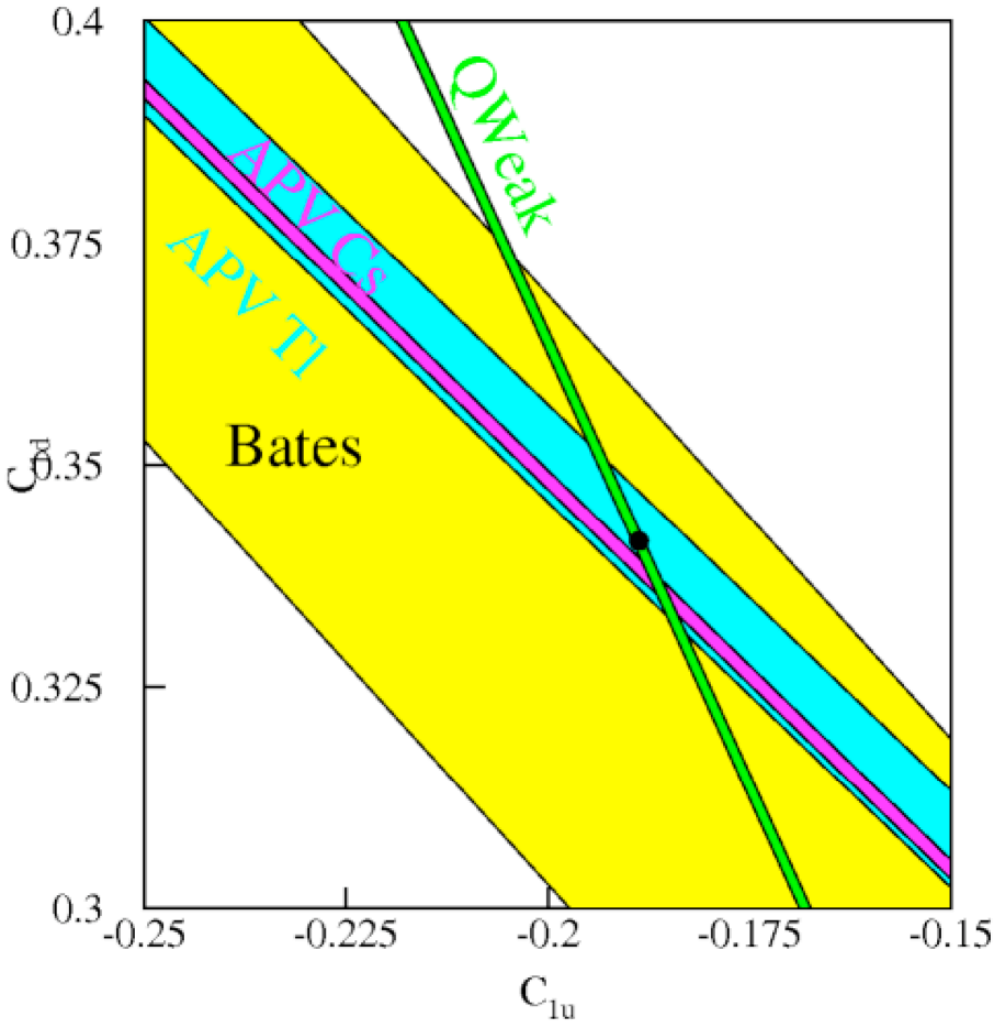


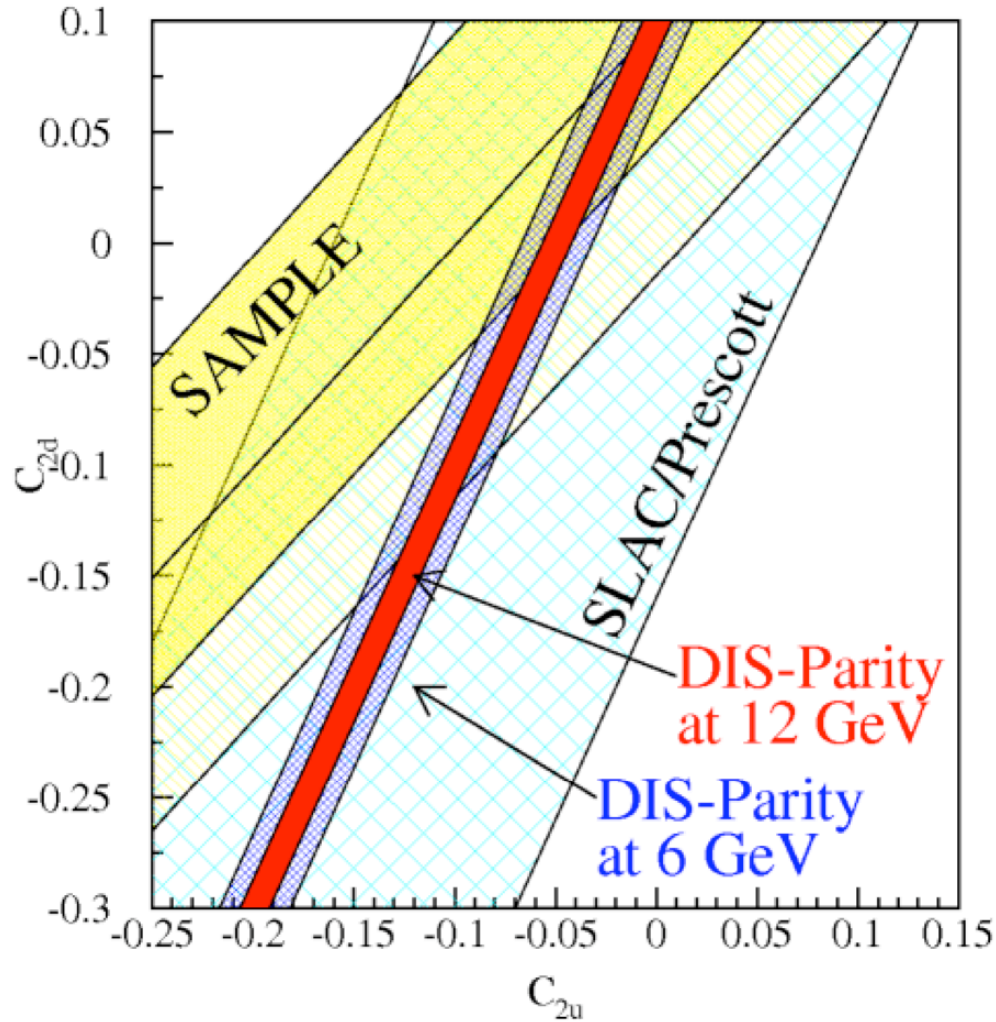
LEPTON-HADRON COUPLINGS

beam	Process	$\overline{Q^2}$ [GeV^2]	Combination	Result/Status	SM
SLAC	e^--D DIS	1.39	$2C_{1u} - C_{1d}$	-0.90 ± 0.17	-0.7181
SLAC	e^--D DIS	1.39	$2C_{2u} - C_{2d}$	$+0.62 \pm 0.81$	-0.0979
CERN	$\mu^\pm$-C DIS	34	$0.66(2C_{2u} - C_{2d})$ $+2C_{3u} - C_{3d}$	$+1.80 \pm 0.83$	$+1.4354$
CERN	$\mu^\pm$-C DIS	66	$0.81(2C_{2u} - C_{2d})$ $+2C_{3u} - C_{3d}$	$+1.53 \pm 0.45$	$+1.4207$
Mainz	e^--Be QE	0.20	$2.68C_{1u} - 0.64C_{1d}$ $+2.16C_{2u} - 2.00C_{2d}$	-0.94 ± 0.21	-0.8532
Bates	e^--C elastic	0.0225	$C_{1u} + C_{1d}$	$+0.138 \pm 0.034$	$+0.1528$
Bates	e^--D QE	0.1	$C_{2u} - C_{2d}$	-0.042 ± 0.057	-0.0621
Bates	e^--D QE	0.04	$C_{2u} - C_{2d}$	-0.12 ± 0.074	-0.0621
JLab	e^--p elastic	0.03	$2C_{1u} + C_{1d}$	approved	-0.0356
JLab	e^--D DIS	1.1 & 1.9	$2C_{2u} - C_{2d}$	approved	-0.0979
JLab	e^--D DIS	3.3	$2C_{2u} - C_{2d}$	letter of intent	-0.0979
—	^{133}Cs APV	0	$-376C_{1u} - 422C_{1d}$	-72.69 ± 0.48	-73.17
—	^{205}Tl APV	0	$-572C_{1u} - 658C_{1d}$	-116.6 ± 3.7	-116.8

Fit to effective couplings

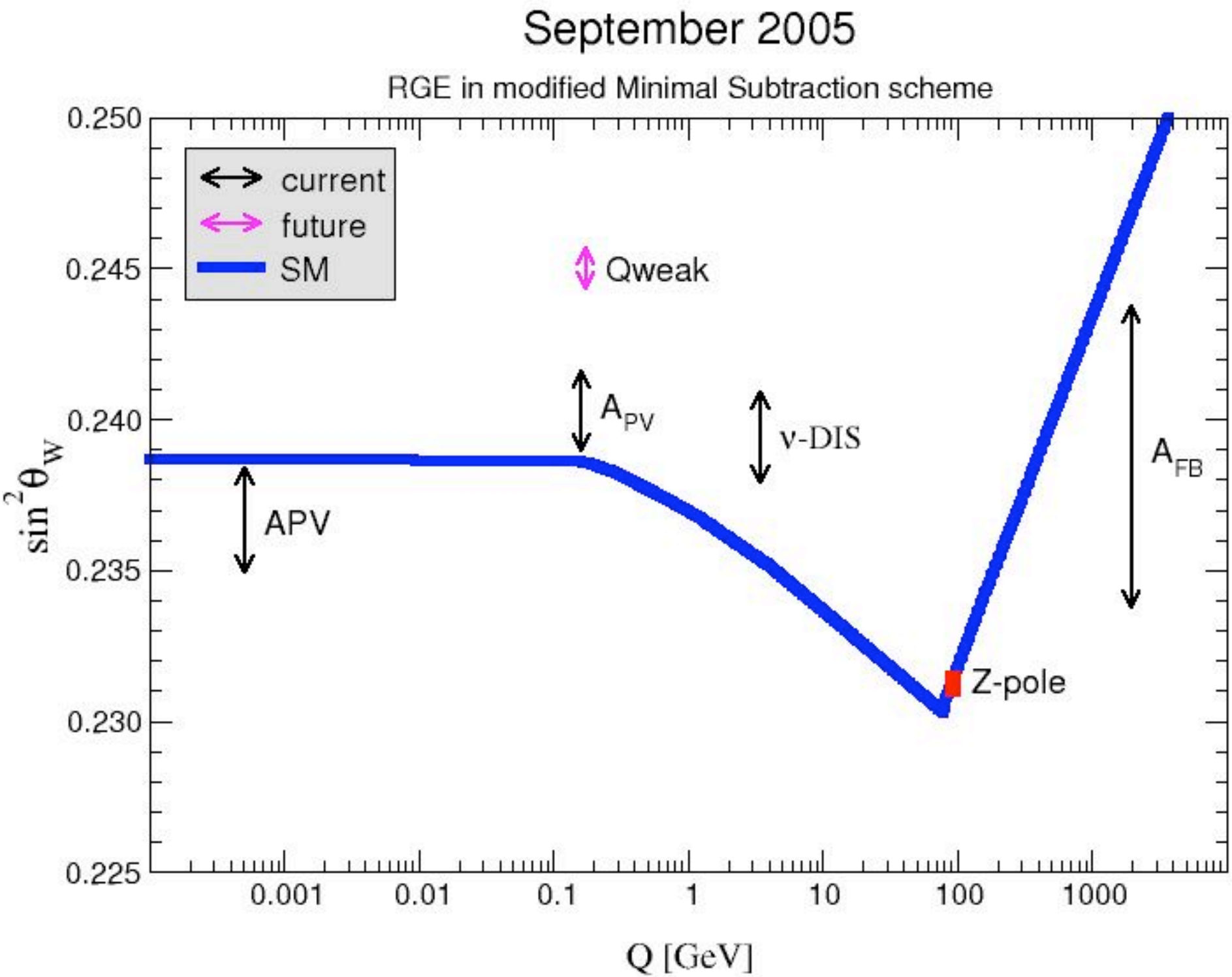
	value	error	SM	Correlation		
$C_{1u} + C_{1d}$	0.147	±0.004	0.1529(1)	0.95	-0.75	-0.10
$C_{1u} - C_{1d}$	-0.604	±0.066	-0.5297(4)		-0.79	-0.10
$C_{2u} + C_{2d}$	0.72	±0.89	-0.0095			-0.11
$C_{2u} - C_{2d}$	-0.071	±0.044	-0.0621(6)			


0.4
0.375
0.35
0.325
0.3
-0.25
-0.225
-0.2
-0.175
-0.15
C_{1d}
C_{1u}
QWeak
APVCs
APV Tl
Bates


0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.25
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
C_{2d}
C_{2u}
SAMPLE
SLAC/Prescott
DIS-Parity
at 12 GeV
DIS-Parity
at 6 GeV

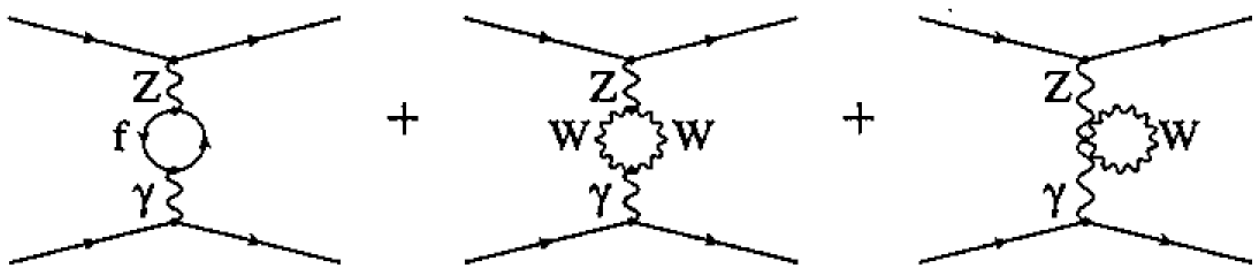
NuTeV

- 2.7 σ (largest deviation)
- new QED radiative corrections (Diener, Dittmaier, Hollik) but not yet included by NuTeV collaboration
- Charge Symmetry Violation can remove or double the effect (MRST); model dependent
- s-quark asymmetry: 25% of effect (CTEQ), wrong sign (NuTeV) based on same data
- nuclear effects: different for NC and CC; ~ 20% of effect, both signs possible (Brodsky, Schmidt, Yang)


September 2005
RGE in modified Minimal Subtraction scheme
current
future
SM
Qweak
A_{PV}
ν-DIS
A_{FB}
APV
Z-pole
$\sin^2\theta_W$
Q [GeV]
0.250
0.245
0.240
0.235
0.230
0.225
0.001
0.01
0.1
1
10
100
1000

Radiative Corrections

Marciano & Sirlin; Ramsey-Musolf & JE



- Need e+e- → hadrons and/or hadronic tau decay data for quark (hadron) contribution.
- Assume (and correct for) isospin symmetry.
- Separate strange quark contribution → study scaled heavy quark and SU(3) limits.
- Discuss singlet (QCD-annihilation) contribution (very small).
- ⇒ small theory error = ± 0.00007.

μ-decay

$$\tau_\mu \Rightarrow G_F = 1.16637 \pm 0.00001 \ (\mathrm{exp.}) \quad \rightarrow$$

2 new experiments at PSI (FAST and μLan); goal 1 ppm

Michel parameters

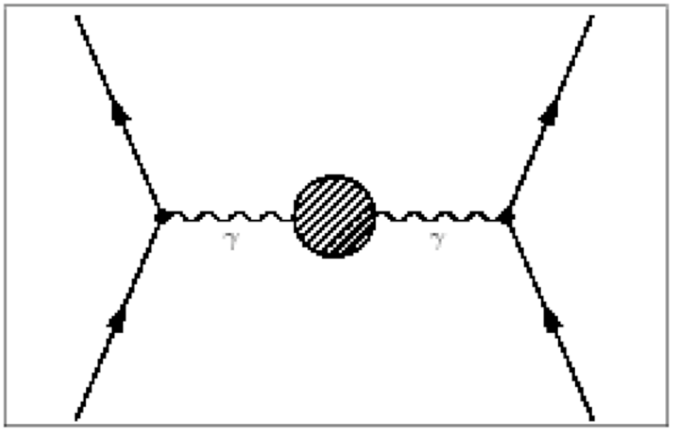
	value	error	SM	TWIST
ρ (spectral shape)	0.7518	±0.0026	3/4	±0.0001
δ (asymmetry shape)	0.7486	±0.0040	3/4	±0.00014
P(μ)ξ (asymmetry)	1.0027	±0.0085	1	±0.00013
η e-mass suppressed	-0.007	±0.013	0	±0.003

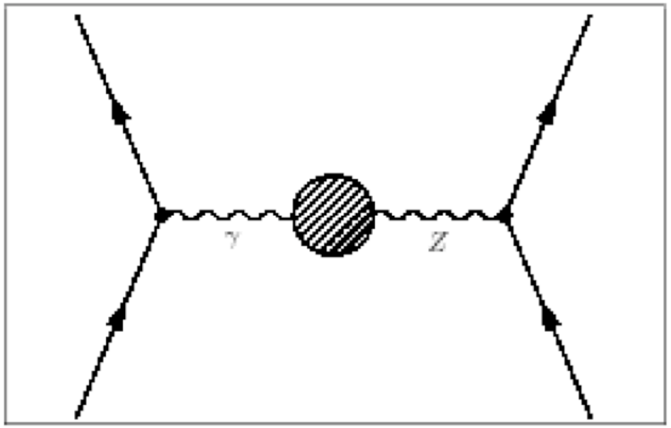
talk by Wulf Fetscher in Session 1,3 on Friday

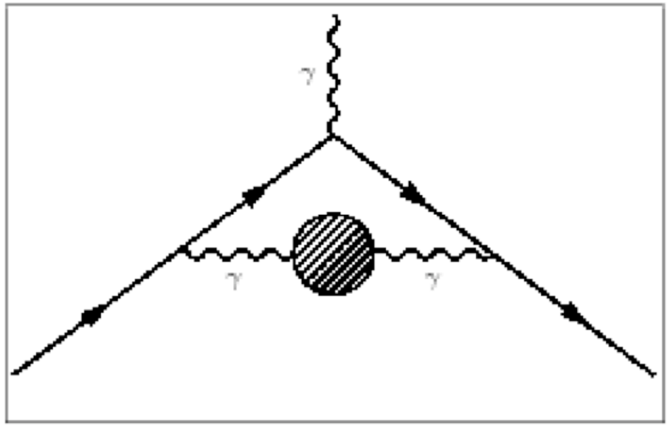
Muon g-2

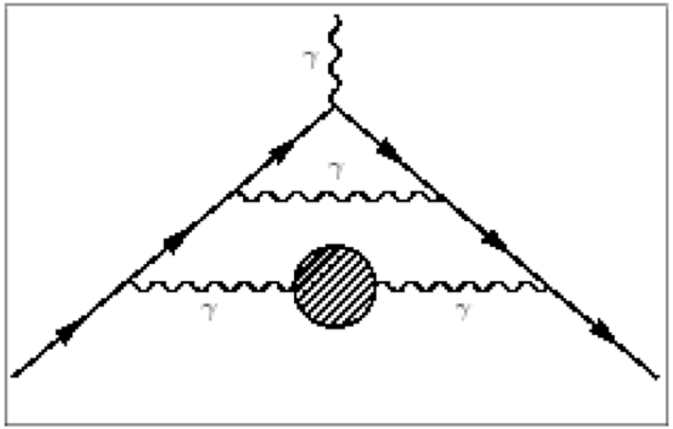
- 2 to 3 σ deviation from SM
- for 2-loop vacuum polarization contribution need optical theorem and same data as for running α and running weak mixing angle
- inconsistencies between e+ e- annihilation data
- inconsistencies between τ decay and e+ e- data
- extra trouble: 3-loop light-by-light contribution

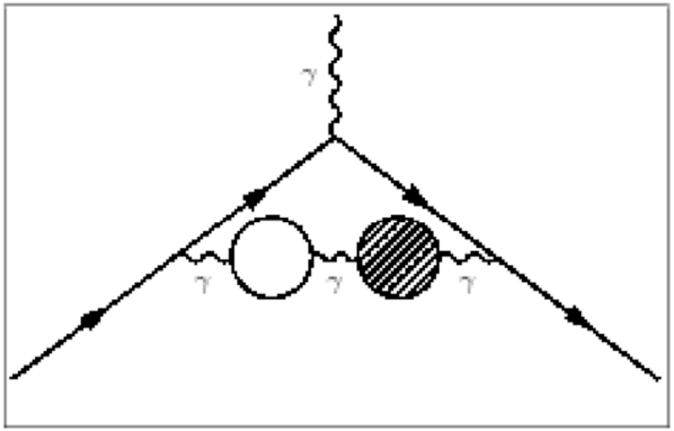
talk by Gerry Bunce in Session 1,3 on Friday

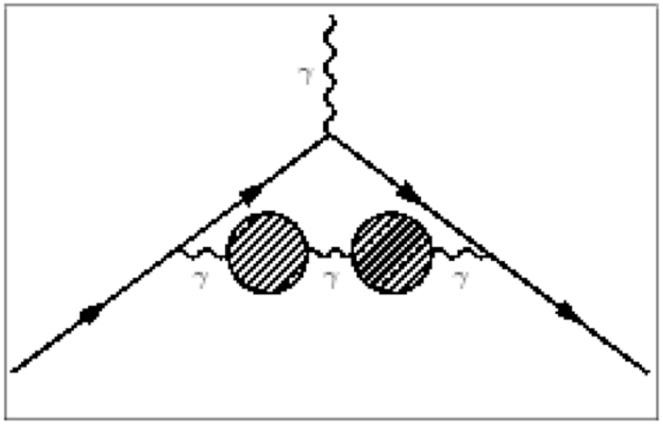

γ
γ

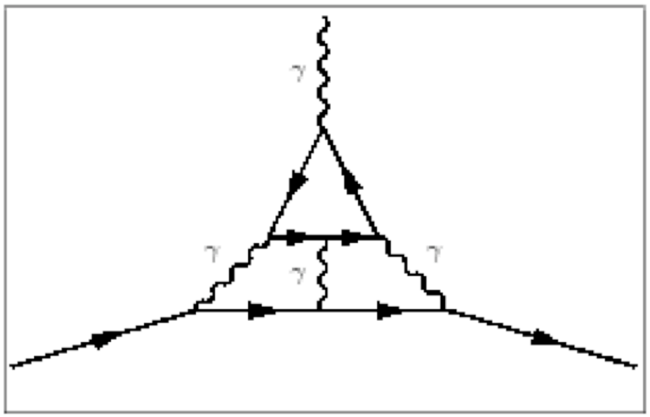

γ
Z

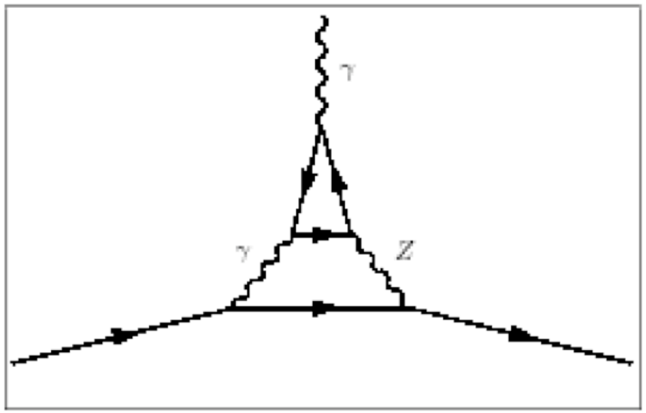

γ
γ
γ


γ
γ
γ
γ

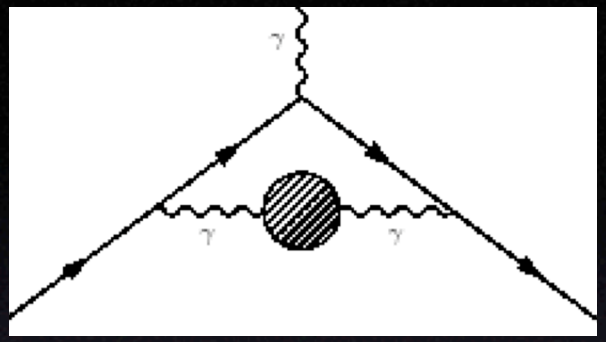

γ
γ
γ
γ


γ
γ
γ
γ


γ
γ
γ
γ

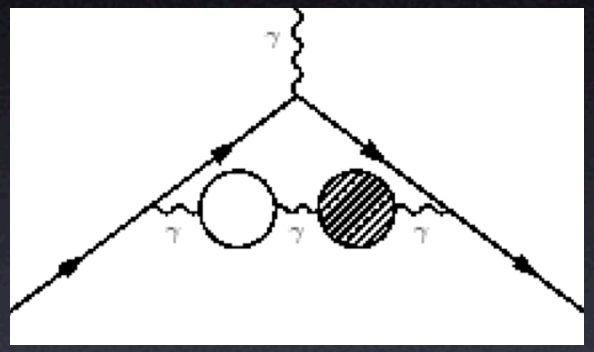

γ
γ
Z

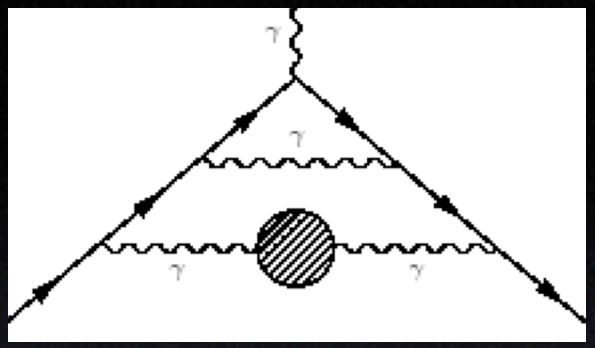
vacuum polarization effects



(1)

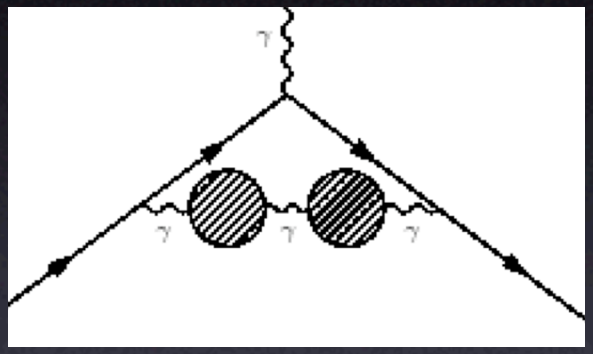
(2a)





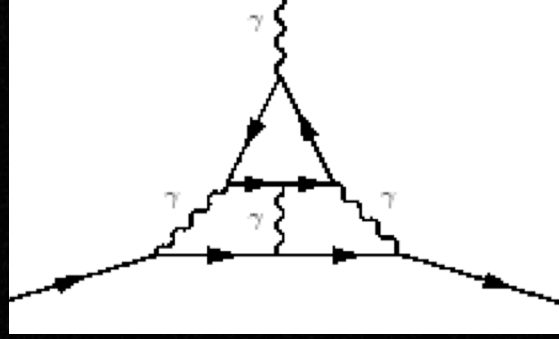
(2b)

(2c)



kernel	free quarks	data	deviation
$K^{(1)}$	+65.1	+70.3	8%
$K^{(2a)}$	-2.11	-1.82	14%
$K^{(2b)}$	+1.07	+0.99	7%
$K^{(2c)}$	+0.027	+0.028	4%

Light-by-light contribution



- free quark estimate (using quark masses for running α)
- exact for infinitely heavy quarks (short distances OK)
- overestimate in chiral limit with m_μ/m_π fixed (charged pointlike pions contribute negatively)
- VMD: $1.36 \pm 0.25 \times 10^{-9}$ (error: "rough guess"; μ ~ 0.6 GeV) Melnikov & Vainshtein, PRD70, 113006 (2004)

$$\text{free quarks} \begin{cases} 1.37^{-0.27}_{+0.15} \times 10^{-9} \\ < 1.59 \times 10^{-9} \ (95\% \ \text{CL}) \end{cases}$$

Toledo, JE

Electric Dipole Moments

- SM weak CP (CKM-phase) mixing and mass suppressed (many orders too small).
- SM strong CP (topological θ-term) limited by EDMs,

$$\mathcal{L}_\theta = \theta_{QCD} \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

- Baryon asymmetry ⇨ CP violation beyond the SM, but precise implication for EDMs unclear.

talk by Koichiro Asahi in Session 1,3 on Friday

EDM experiments

System	Present Limit (e-cm)	Group	Future	SM (CKM)
e^-	1.6×10^{-27} (90% CL)	Berkeley		$< 10^{-38}$
e^-		Yale	$\sim 10^{-29}$	
e^-		LANL	$\sim 10^{-30}$	
μ	1.05×10^{-18} (90% CL)	CERN		$< 10^{-36}$
μ		BNL	$\sim 10^{-24}$	
n	6.3×10^{-26} (90% CL)	ILL	1.5×10^{-26}	1.4×10^{-33}
n		PSI	7×10^{-28}	$\rightarrow$
n		LANL	2×10^{-28}	1.6×10^{-31}
^{199}Hg	2.1×10^{-27} (95% CL)	Seattle	5×10^{-28}	$< 10^{-33}$
^{225}Ra		Argonne	10^{-28}	
^{129} Xe		Princeton	10^{-31}	$< 10^{-34}$
D		BNL	$\sim 10^{-27}$	

I am sticking my neck out:
the next generation of EDM searches is virtually guaranteed to make a discovery.

Paul Langacker

Conclusions

- A network of high precision polarized electron scattering experiments is set to study TeV scale.
- Next generation μ-decay experiments is looking for deviations from V−A.
- Searches for permanent EDMs highly motivated with spectacular experimental developments.

Low energy measurements will remain indispensable even with loads of LHC data!