# Low energy tests of the Standard Model

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# Introduction

- Historically: low energy tests decisive to establish SM → Prescott (SLAC) experiment in polarized eD-DIS.
- Today: complex array of observables testing the SM and looking for and setting limits on extensions.
- Prospects: some fields on the verge of a revolution

- Collider complementarity (diagnostics)
- Discovery potential
- Examples include:
  - scattering: ν-e, ν-N DIS, polarized Møller, elastic e-p, QE e-N, DIS e-N or μ-N
  - β-decays: μ (Michel parameters), N, n, π, K (CKM first row unitarity)
  - "single #" measurements: g−2 (e or μ), APV
  - rare and SM forbidden processes: FCNC, EDM, LFV, p-decay, n-oscillations, ν-oscillations, 0νββ-decay

# Status of the Standard Model

# Parameters

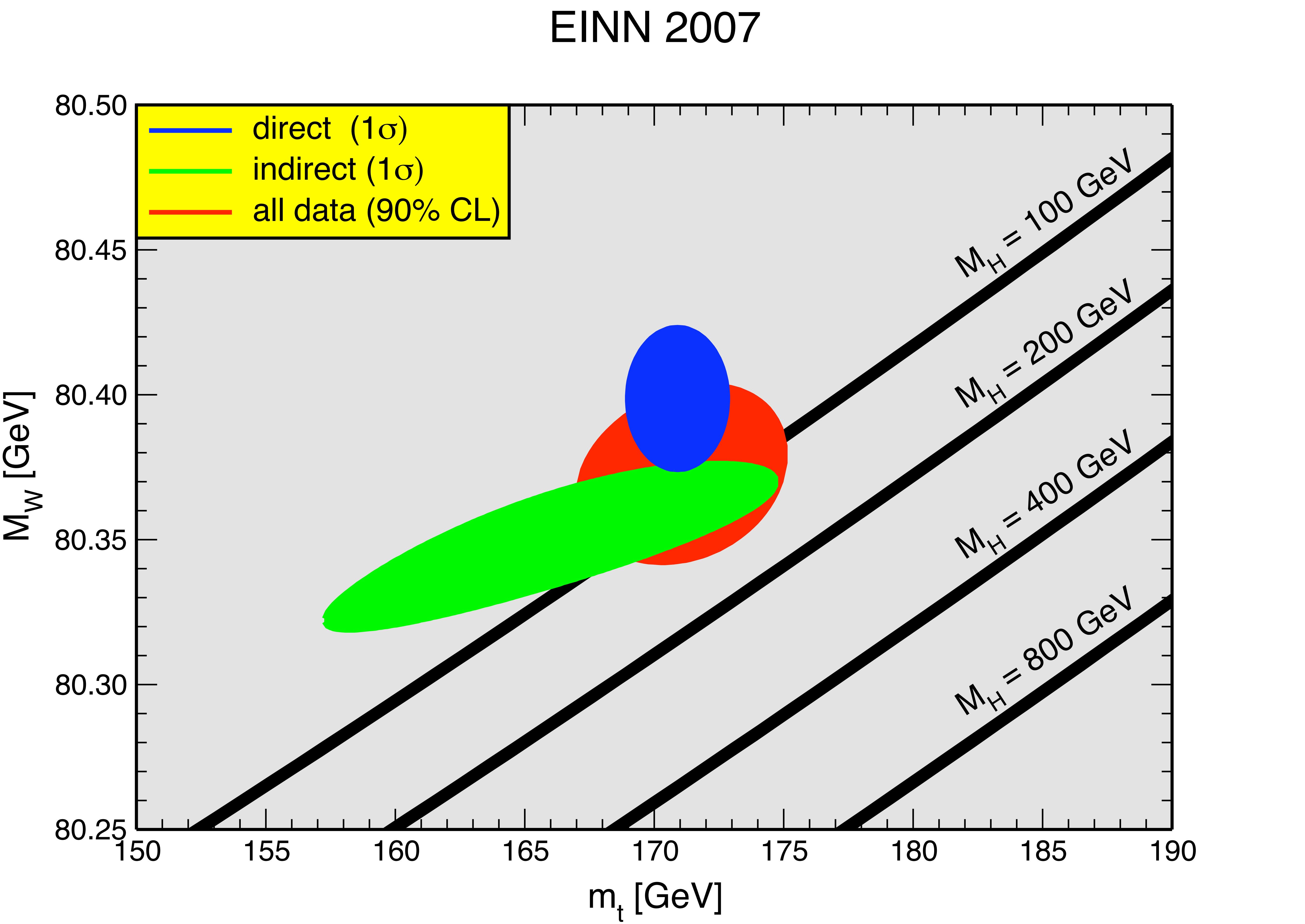
- Yukawa sector: fermion masses, Cabibbo mixing, Kobayashi-Maskawa CP-violation
- Gauge couplings: $\alpha, \hat{\alpha}_s(M_Z),$

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

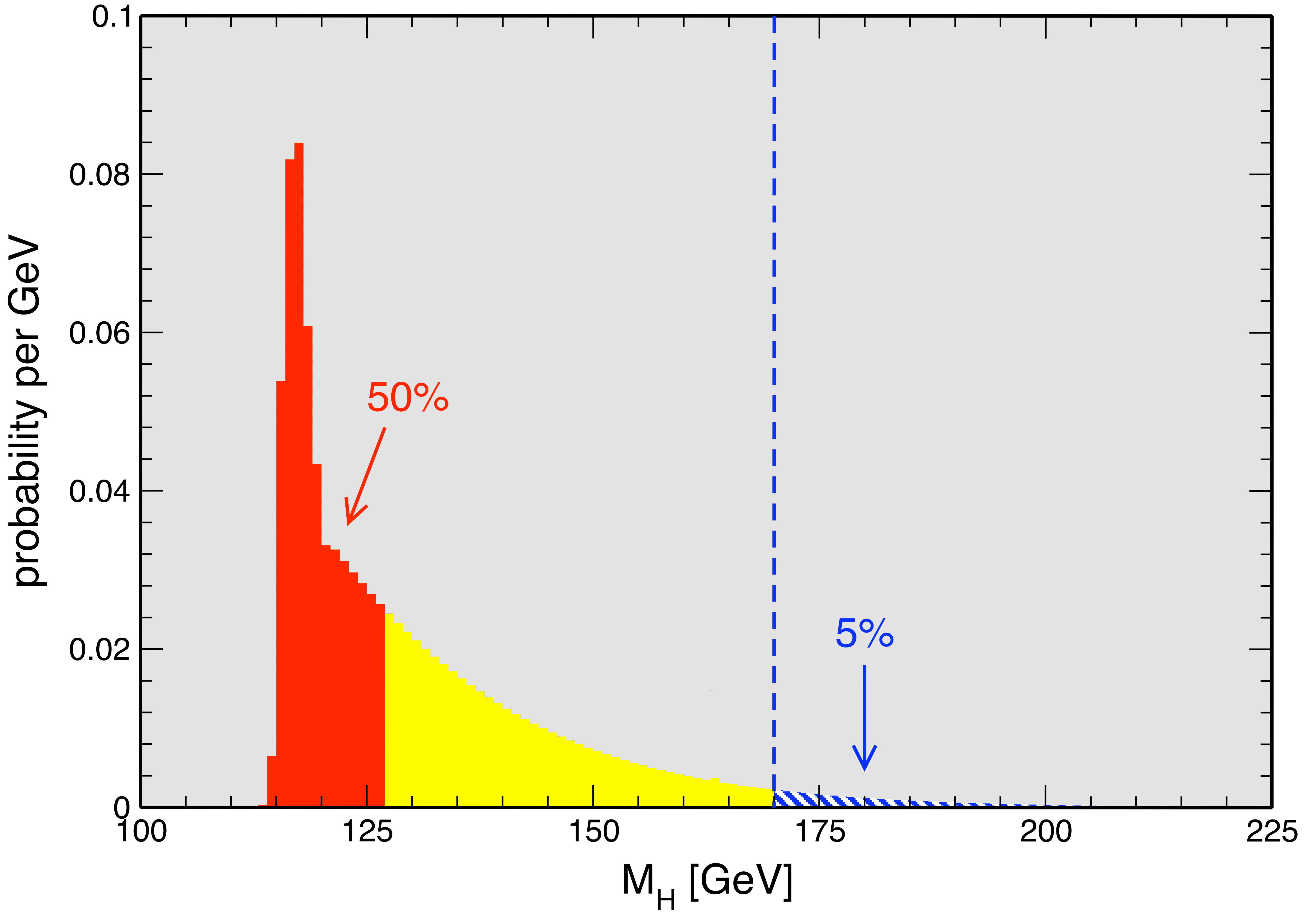
- Higgs potential: $G_F, M_H$

$$\Delta\alpha, \Delta G_F, \Delta M_Z \approx 0$$

- $\alpha_s, M_H, m_t$ : electroweak precision data
- $m_b, m_c$ : QCD sum rules or lattice


EINN 2007
direct (1σ)
indirect (1σ)
all data (90% CL)
M_H = 100 GeV
M_H = 200 GeV
M_H = 400 GeV
M_H = 800 GeV
80.50
80.45
80.40
80.35
80.30
80.25
150
155
160
165
170
175
180
185
190
M_W [GeV]
m_t [GeV]

# EINN 2007



0.1
0.08
0.06
0.04
0.02
0
probability per GeV
50%
5%
100
125
150
175
200
225
M_H [GeV]

# Strong coupling

$$\alpha_s(M_Z)(\tau_\tau) = 0.1225^{+0.0025}_{-0.0022}$$

$$\alpha_s(M_Z)(\text{all other}) = 0.1202 \pm 0.0027$$

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$$\alpha_s(M_Z)(\text{all}) = 0.1216 \pm 0.0017$$

- slightly more precise than PDG world average
- less precise than lattice (ϒ spectroscopy): 2.2 σ disagreement
- hep-ph/0507078: 1% error for τ decay value

# Polarized lepton scattering

→ Session on Parity Violation Friday afternoon

# Effective lepton-hadron Lagrangian

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

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

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

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

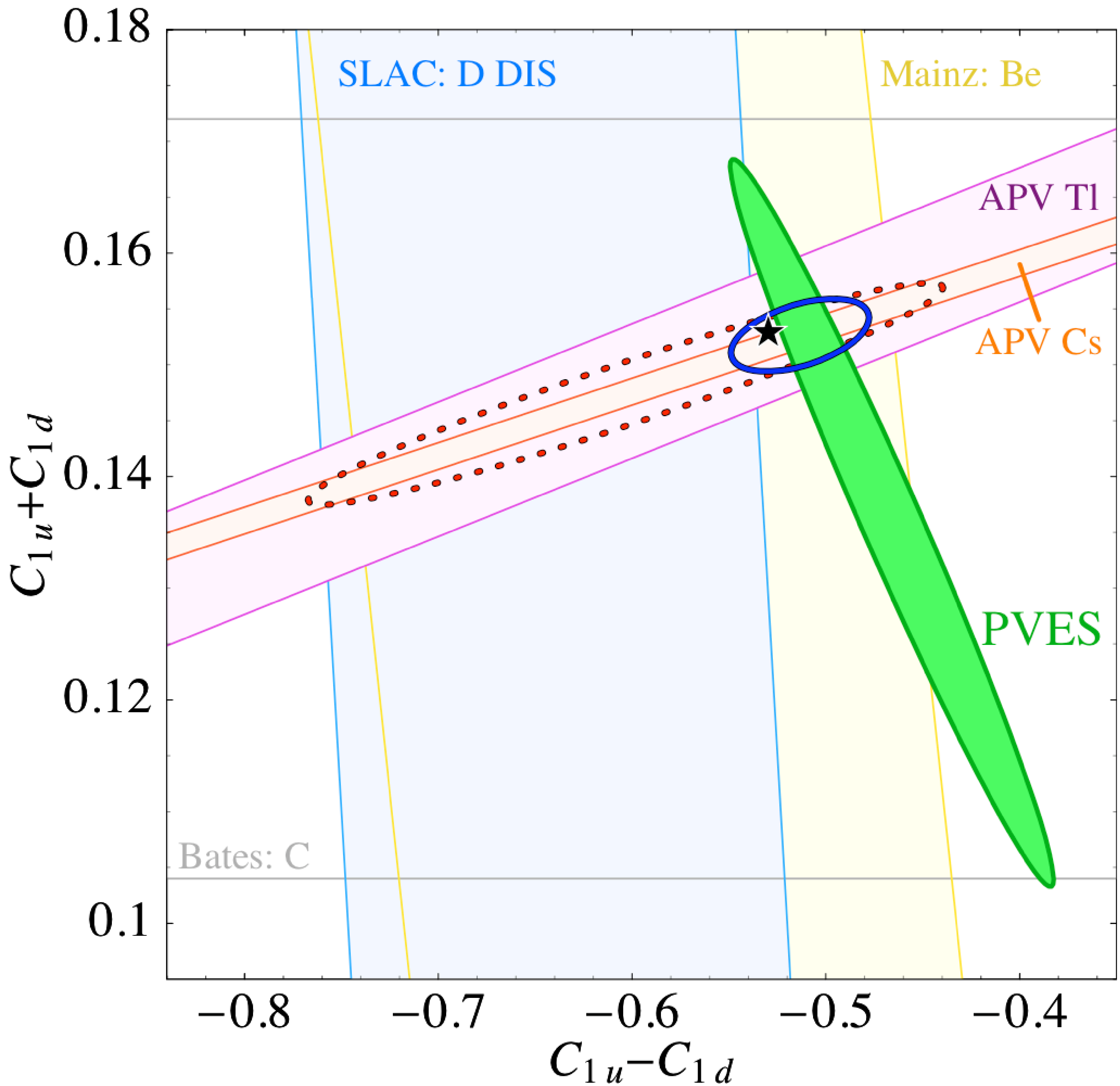
$$C_{3u} = -C_{3d} = \frac{1}{2} .$$

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

# 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 were seen
- CERN-NA-004: μ-↑ μ+↓
- JLab @ 6 GeV & 12 GeV will improve SLAC and world average by factors of 54 and 17.
- Issues: higher twist / CSV; functions of $Q^2$ / x.
- Limited by polarization and $Q^2$-scale (0.5%).




Young
Carlini
Thomas
Roche

arXiv:
0704.2618
[hep-ph]

# Møller asymmetry (E-158)

$Q^2 = 0.026$ GeV$^2$ (E = 45 & 48 GeV) P = 89 ± 4 %

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

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

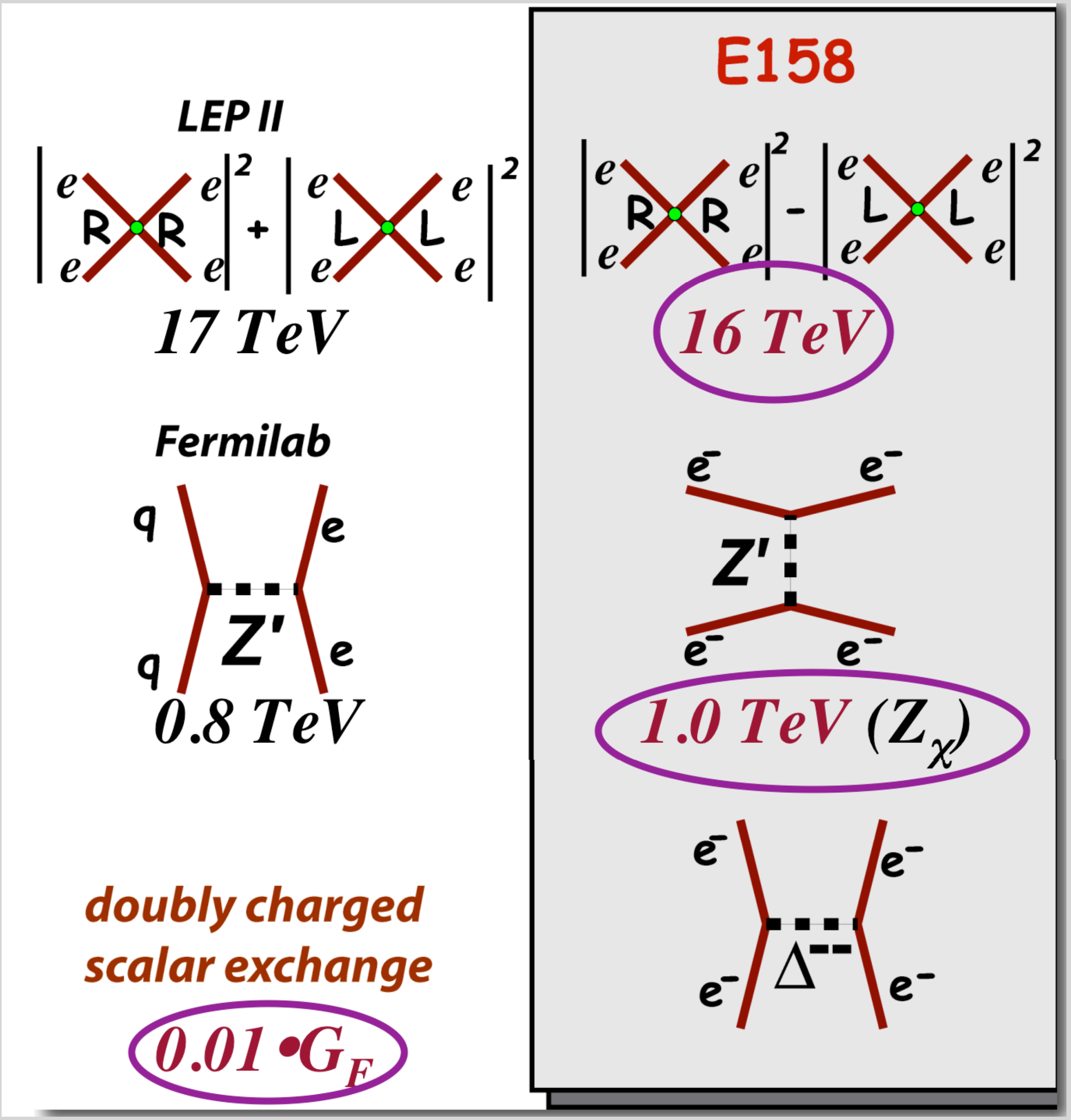
SM prediction: Czarnecki and Marciano

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

compare: SLD: ± 0.00029, best LEP: ± 0.00028

With a future factor of 5 improvement (at JLab) would become world's best measurement

# Møller asymmetry




Krishna Kumar
DPF 2006

fixed target Møller @ ILC: $\Delta \sin^2 \theta_W \sim 6 - 8 \times 10^{-5}$

# Qweak

Similar $Q^2 = 0.03$ GeV² as E-158 but E = 1.165 GeV.

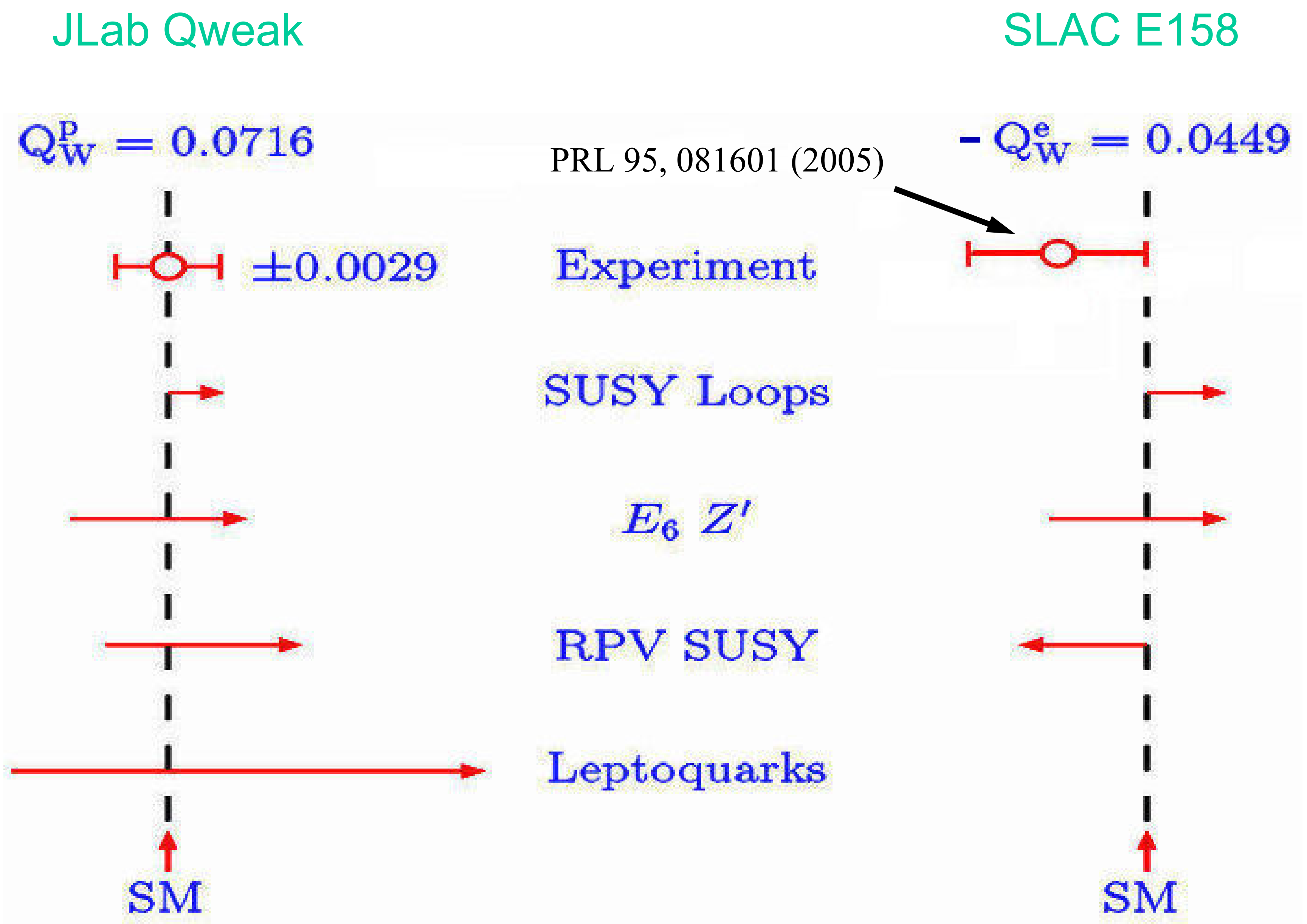
P = 85 ± 1 %

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

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

SM prediction: Marciano & Sirlin, Ramsey-Musolf & JE

# Proton and Electron Measurements Are Needed




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

# Atomic Parity Violation

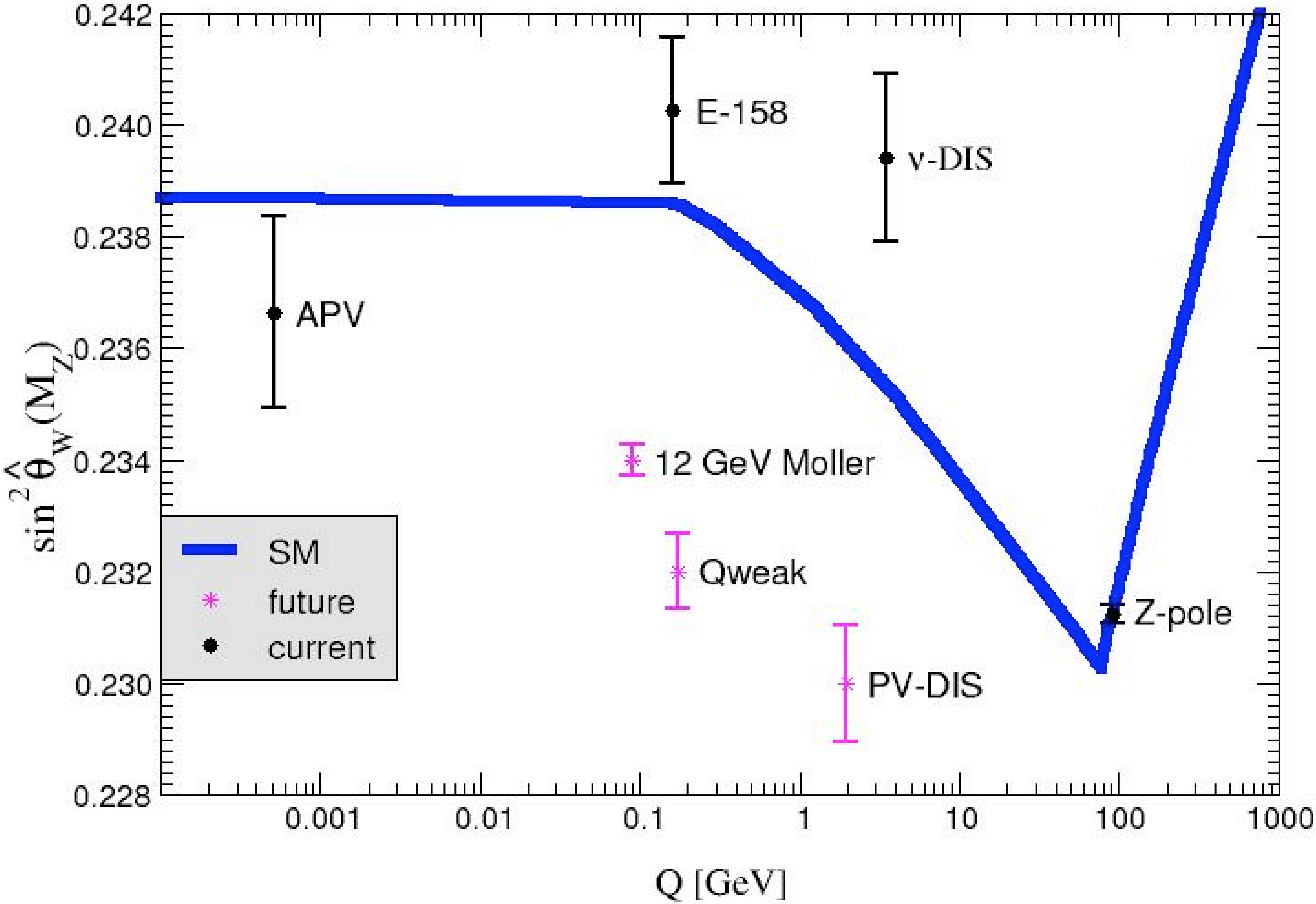
- Need to understand atomic structure below %-level.
- Most precise: $Q_W(Cs) = -72.62 \pm 0.46$

  $Q_W(Tl) = -116.4 \pm 3.64$

  Wood et al., Bouchiat et al.
  Edwards et al., Vetter et al.
- Bi: ±1% experiment, Meekhof et al., but ±15% theory.
- Fr: ±1% theory, Orozaco et al., but ±10% experiment (atom trap).

# APV: 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. (also Dy from solid state exp. Sushkov et al.)
- Problem: finite nuclear size effects (±0.1% from dominant neutron distributions) → improve experiment and theory on these — or use APV to study nuclear structure.
- H, D slow meta-stable beams (from FELs?): ±0.3% in $C_{1D}$ (≈Qweak) & other $C_{ij}$, Dunford, Holt, arXiv:0706.2407 [hep-ph]




(uncertainty not $Q^2$-independent)

# SM tests with μ & ν(μ)

# νN-DIS (NuTeV)

- NuTeV: 2.7 σ (2nd largest deviation) in left coupling
- new QED radiative corrections (Diener, Dittmaier, Hollik) not yet included by NuTeV
- Valence parton Charge Symmetry Violation from "quark model" and "QED splitting" effects each predict removal of 1/3 of anomaly; phenomenological parton CSV PDFs can remove or double the effect (MRST)
- s-quark asymmetry: $\int dx\, x\, (S - \bar{S})$ = 0.0020 ± 0.0014 → 30 ± 20% of effect (NuTeV now agrees with CTEQ)
- nuclear effects: different for NC and CC; about ± 20% of effect, both signs possible (Brodsky, Schmidt, Yang)

# Muon anomalous magnetic moment

- 3.3 $\sigma$ (?) deviation from SM (supersymmetry?)
- for 2-loop vacuum polarization contribution need optical theorem and same data as for running $\alpha$ and running weak mixing angle.
- inconsistencies between $\tau$ and e+ e- data: if from CVC violation need enhancement factor
- inconsistencies among e+ e- annihilation data
- 3-loop light-by-light contribution

# Muon decay

$$\tau_\mu = 2.197034\ (18)\ \mu s$$

(MuLan: ±24 μs, FAST: ±35 μs, previous: ±40 μs)

$$\Rightarrow G_F = 1.166367\ (5) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

| Michel parameters | SM | TWIST |
|---|---|---|
| ρ (spectral shape) | 3/4 | 0.7508(10) |
| δ (asymmetry shape) | 3/4 | 0.7496(13) |
| P(μ)ξ (asymmetry) | 1 | 1.0003(38) |
| η e-mass suppressed | 0 | −0.0036(69) |

global fit to all 9 (w/o ν-detection) parameters

Gagliardi, Tribble & Williams (hep-ph/0509069)

# CKM first row

$$|V_{ud}| = 0.97372\ (10)_{\rm uncorr.}\ (15)_{\rm Coulomb}\ (19)_{\rm SD}$$

$$= 0.97372 \pm 0.00026$$ (nuclear β-decays)

Marciano & Sirlin, hep-ph/0510099 & KAON 07

| | theory | reference | V(us) |
|---|---|---|---|
| K/π→μν | lattice | HP/UKQCD | 0.2262(4)(13) |
| K→πlν | lattice | RBC/ " | 0.2255(5)(12) |
| τ | sum rules | Gámiz et al. | 0.2165(26)(5) |
| all | | | 0.2248(9) |
| V(ud) | unitarity | CKM | 0.2277(11) |

# CKM unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.00132 \pm 0.00065$$

- 2 σ "unitarity deficit"
- future of V(ud): neutron decay (many new experiments); currently exp. discrepancies
- future of V(us): lattice (form factors, m(s))
- New physics: heavy fermion mixing, Z', W* (KK), SUSY loops (but prefer excess); effect may be in μ-decay (normalization!)

$$\Lambda_{new} = \left[\sqrt{2} G_F |0.00065|\right]^{-1/2} \approx 10 \text{ TeV}$$

# Rare and forbidden processes

# 0νββ-decay (status)

- Inverted hierarchy: <m(ββ)> ~ 20−50 meV

$$\Rightarrow T_{1/2} \sim 10^{27} y \Rightarrow \text{ rate } \sim \text{ few } / t\ y$$

- Heidelberg-Moscow (best) limit: < 0.35 eV
- Klapdor-Kleingrothaus et al. claim: 0.24−0.58 eV

$$\Rightarrow T_{1/2} \sim 10^{25} y \Rightarrow \text{ rate } \sim \text{ hundreds } / t\ y$$

- nuclear matrix elements: extraction of <m(ββ)> difficult

# $0\nu\beta\beta$-decay (models)

- Majorana masses
- right-handed currents (no helicity flip)
- other lepton number violating (L#V) effects: heavy neutrinos, R-parity violating SUSY, leptoquarks, scalar bilinears
- To distinguish use other L#V observables, like $\mu \to e\gamma$ decay, or $\mu \to e$ conversion Cirigliano et al., PRL 93, 231802
- or produce corresponding particles at LHC

# $0\nu\beta\beta$-decay (prospects)

- running: NEMO-3, CUORICINO (<m(ββ)> 0.4 – 1 eV)
- under construction: EXO-200, GERDA
- prototype: CANDLES, COBRA, XMASS
- proposed: CUORE, EXO, Majorana, MOON, SNO++, SuperNEMO
- details: Avignone III, Elliott, Engel, arXiv:0708.1033 [nucl-ex]

# CP violation & EDMs

- SM (CKM phase): Electric Dipole Moments $\neq 0$, but tiny.
- QCD $\theta$-angle: constrained by neutron EDM
- Baryon Asymmetry of the Universe (BAU) requires new CP violating phases
- any CP phase should contribute to EDMs
- MSSM: EDMs large (why not seen?) unless small CP phases (but then BAU also small)

# EDMs (prospects)

- This tension EDMs ↔ BAU is quite model-independent ⇒ finding EDMs ≠ 0 in future measurements (e.g., e, μ, n, atoms) “virtually guaranteed” (Paul Langacker)
- 2-4 orders of magnitude improvements (!) in next generation experiments
- → talk by Dominique Rebreyend on neutron EDM later this morning

# Conclusions

- Next generation of (relatively) low-energy experiments will challenge the SM and explore multi-TeV scales, in many cases beyond LHC reach
- LHC may be fatal for the SM, but not for low-energy precision measurements

# Outlook

*Enjoy the conference and the island!*

# Small deviations

| | value | error | SM | pull | comment |
|---|---|---|---|---|---|
| $\frac{10^9}{2}\left(g-2-\frac{\alpha}{\pi}\right)$ | 4511.07 | 0.80 | 4508.46 | 3.3 | no τ data |
| $g_L^2$(NuTeV) | 0.3001 | 0.0014 | 0.3037 | 2.7 | QED, PDFs |
| $A_{FB}^b$(LEP) | 0.0992 | 0.0016 | 0.1032 | 2.5 | best $s^2$ at LEP |
| $\sigma_{\text{had}}^0$[nb] | 41.541 | 0.037 | 41.466 | 2.0 | # ν: 2.986(7) |
| $A_{LR}$(SLD) | 0.1514 | 0.0022 | 0.1473 | 1.9 | best $s^2$ |
| $R_\nu$(CHARM) | 0.3021 | 0.0041 | 0.3090 | 1.7 | sign of NuTeV |
| $\sin^2\theta_W^{\text{eff.}}$(FNAL) | 0.2238 | 0.0050 | 0.2315 | 1.5 | first result |
| $A_{FB}^\tau$(LEP) | 0.0188 | 0.0017 | 0.0163 | 1.5 | final result |
| $M_W(p\bar{p})$ | 80.428 | 0.037 | 80.374 | 1.5 | mostly CDF II |