Orsay, 9-12 January '07

Beyond the Standard Model

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By "Beyond the SM" I actually mean "Beyond what we know"
in particle physics.

Since most we know is extremely well described by the SM
this is mostly "Beyond the SM"

But we must not forget that a main part of the SM,
the Higgs sector, is essentially not tested and its
explicit form and substance is so far just a mere conjecture

Plan of the lectures

- Experimental Status of the SM
- Problems of the SM (conceptual and empirical)
- Overview of Physics Beyond the SM
    - Supersymmetry
    - Little Higgs Models
    - Extra Dimensions
    - Composite Higgs
- The most accepted BSM: GUT's
- The most established BSM: Neutrino masses

My purpose: give basic facts, describe the most interesting ideas, expand on the most realistic avenues (proceed from real to imaginary)

The first collisions at the LHC are expected at the end of '07.
The physics run at 14 TeV will start in spring '08.

Physics top priorities at the LHC (ATLAS&CMS):

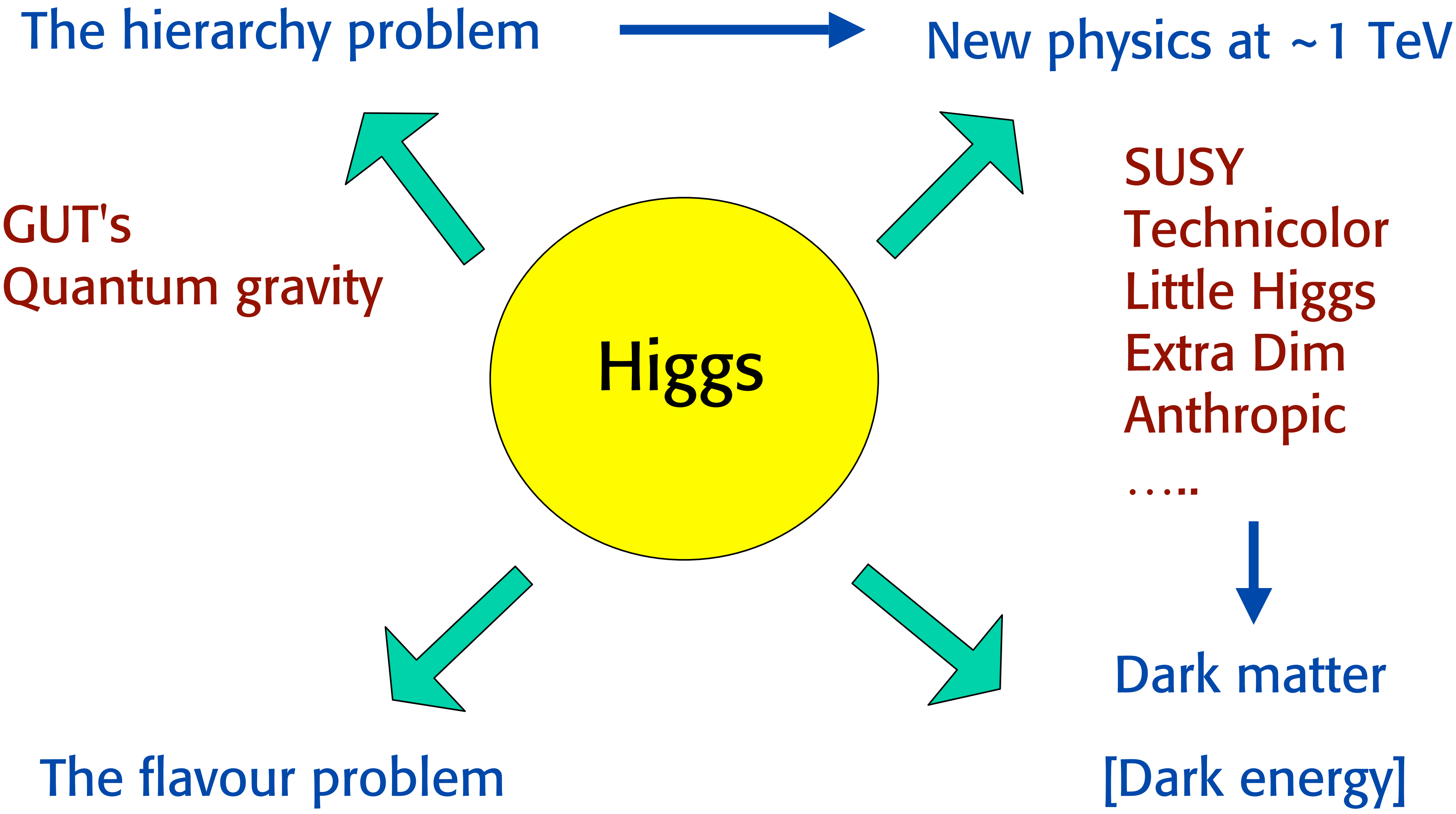
- Clarify the Higgs sector
- Search for new physics at the TeV scale
- Identify the particle(s) that make the Dark Matter in the Universe

Also:

- LHCb: precision B physics (CKM matrix and CP violation)
- ALICE: Heavy ion collisions & QCD phase diagram

At this point fresh input from experiment is badly needed

The Higgs problem is central in particle physics today



The hierarchy problem → New physics at ~1 TeV

GUT's
Quantum gravity

Higgs

SUSY
Technicolor
Little Higgs
Extra Dim
Anthropic
…..

Dark matter

[Dark energy]

The flavour problem

The Standard EW theory: $\mathcal{L} = \mathcal{L}_{\text{symm}} + \mathcal{L}_{\text{Higgs}}$

$$\mathcal{L}_{symm} = -\frac{1}{4}[\partial_\mu W^A_\nu - \partial_\nu W^A_\mu - ig\varepsilon_{ABC} W^A_\mu W^B_\nu]^2 +$$

$$-\frac{1}{4}[\partial_\mu B_\nu - \partial_\nu B_\mu]^2 +$$

$$+\bar{\psi}\gamma^\mu[i\partial_\mu + gW^A_\mu t^A + g' B_\mu \frac{Y}{2}]\psi$$

$$\mathcal{L}_{Higgs} = |[\partial_\mu - igW^A_\mu t^A - ig' B_\mu \frac{Y}{2}]\phi|^2 +$$

$$+ \; V[\phi^\dagger\phi] + \bar{\psi}\Gamma\psi\phi + \text{h.c}$$

with $V[\phi^\dagger\phi] = \mu^2(\phi^\dagger\phi)^2 + \lambda(\phi^\dagger\phi)^4$

$\mathcal{L}_{\text{symm}}$: well tested (LEP, SLC, Tevatron…), $\mathcal{L}_{\text{Higgs}}$: ~ untested

All we know from experiment about the SM Higgs:

Rad. corr's -> $m_H < 199$ GeV (95%cl, incl. direct search bound)
but no Higgs seen -> $m_H > 114.4$ GeV (95%cl);

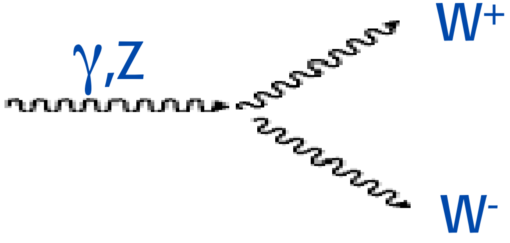
Only hint $m_W = m_Z \cos\theta_W \longrightarrow$ doublet Higgs

Experiments prove that all couplings are symmetric

Basic tree level relations: (accuracy few per mil)

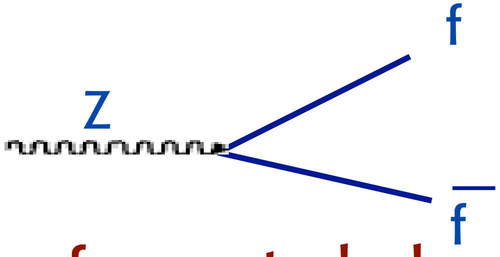
[All corrected by small, computable f(m_t^2,logm_H) radiative effects]

- $g\sin\theta_W = e;$
- $g'/g = tg\theta_W;$
- $\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2}$;
- $\frac{g_{WW\gamma}}{g_{WWZ}} = tg\theta_W$



- $\frac{g}{2\cos\theta_W}\bar{\psi}\gamma_\mu(g_V^f - g_A^f\gamma_5)\psi Z^\mu$

$$\begin{cases} g_A^f = \pm\frac{1}{2} \\ g_V^f/g_A^f = 1-4|Q^f|\sin^2\theta_W \end{cases}$$



f = u,c,t, d,s,b, e,μ, τ, ν's

Yet the symmetry is badly broken in the mass spectrum!

Gauge symmetry predicts $\left.\begin{array}{l}\text{All gauge bosons}\\ \text{All fermions}\end{array}\right\}$ Massless

But $m_W, m_Z >> 0$

$m_Z \sim M_{\substack{\text{molybdenum}\\ \text{atom}}} \sim$ 97 nucleons

In spectrum:
no remnant of even
global SU(2) symmetry!

Also, for example, $\overset{171}{m_t} \neq \overset{4.5\text{ GeV}}{m_b} \neq 0$

Spontaneous symmetry breaking

Currents, charges symmetric. Spectrum totally non symmetric

SSB in gauge theories → Higgs mechanism

That some sort of Higgs mechanism is at work has already been established

The questions are about the nature of the Higgs particle(s)

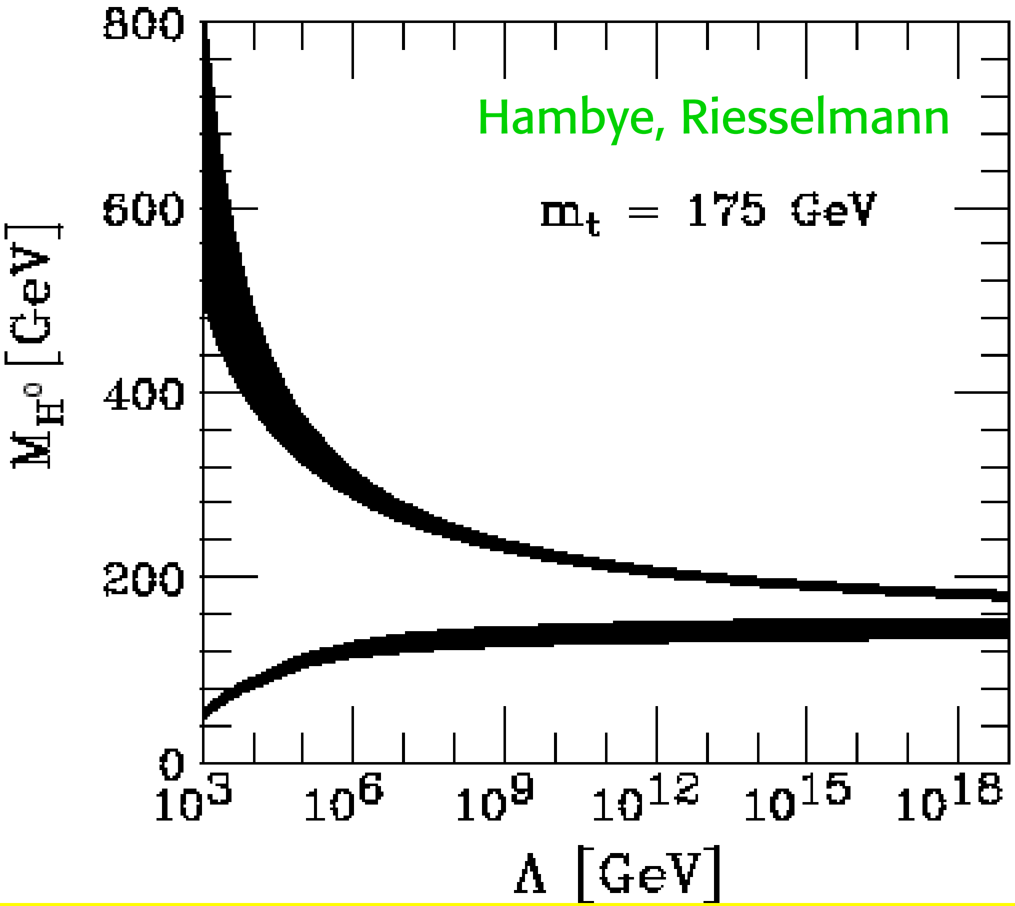
- One doublet, more doublets, additional singlets?
- SM Higgs or SUSY Higgses
- Fundamental or composite (of fermions, of WW....)
- Pseudo-Goldstone boson of an enlarged symmetry
- A manifestation of extra dimensions (fifth comp. of a gauge boson, an effect of orbifolding or of boundary conditions....)
- Some combination of the above

Theoretical bounds on the SM Higgs mass

Λ: scale of new physics beyond the SM

Upper limit: No Landau pole up to Λ
Lower limit: Vacuum (meta)stability

The LHC was designed to cover the whole range



If the SM would be valid up to M_{GUT}, M_{Pl} then m_H would be limited in a small range

Higgs potential

“Wrong” sign

Classic: $V[\phi] = -\mu^2\phi^2 + \lambda\phi^4$ $\mu^2>0, \lambda>0$

$$\phi \Rightarrow v + \frac{H}{\sqrt{2}} \Longrightarrow v^2 = \frac{\mu^2}{2\lambda} = \frac{m_H^2}{4\lambda}$$

Quantum loops: $\lambda\phi^4 \Rightarrow \lambda\phi^4\left(1 + \gamma\ln\frac{\phi^2}{\Lambda^2} + \dots\right) \xrightarrow{RG} \lambda(\Lambda)\phi'^4(\Lambda)$

(Ren. group improved pert. th)

$$\phi' = [\exp\int\gamma(t)dt]\phi$$

Running coupling

$t=\ln\Lambda/v$ h_t=top Yukawa

$$\frac{d\lambda(t)}{dt} = \beta_\lambda(t) = const[\lambda^2 + 3\lambda h_t^2 - 9h_t^4 + small]$$

Initial conditions (at $\Lambda=v$) $\lambda_0 = \frac{m_H^2}{4v^2}$ and $h_{0t} = \frac{m_t}{v}$

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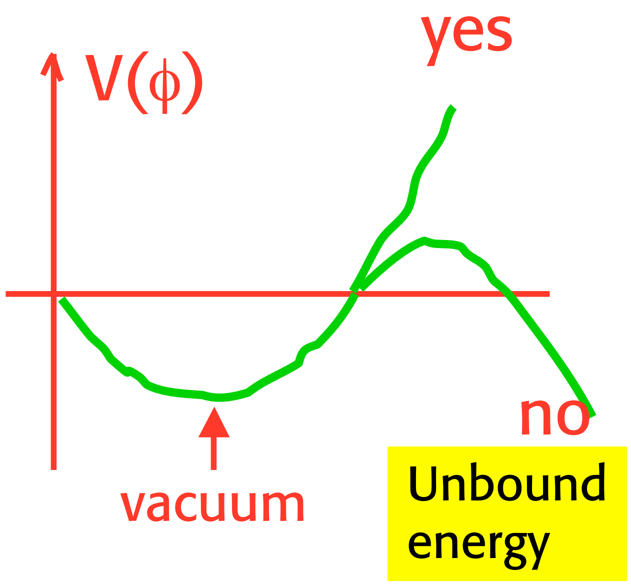
Too small m_H? h_t wins, $\lambda(t)$ decreases.
But $\lambda(t)$ must be >0 below Λ for the vacuum to be stable

⇒ $m_H \geq \sim 130$ GeV if $\Lambda \sim M_{GUT}$

(or at least metastable with lifetime $\tau > \tau_{Universe}$)

Cabibbo et al, Sher, Altarelli, Isidori

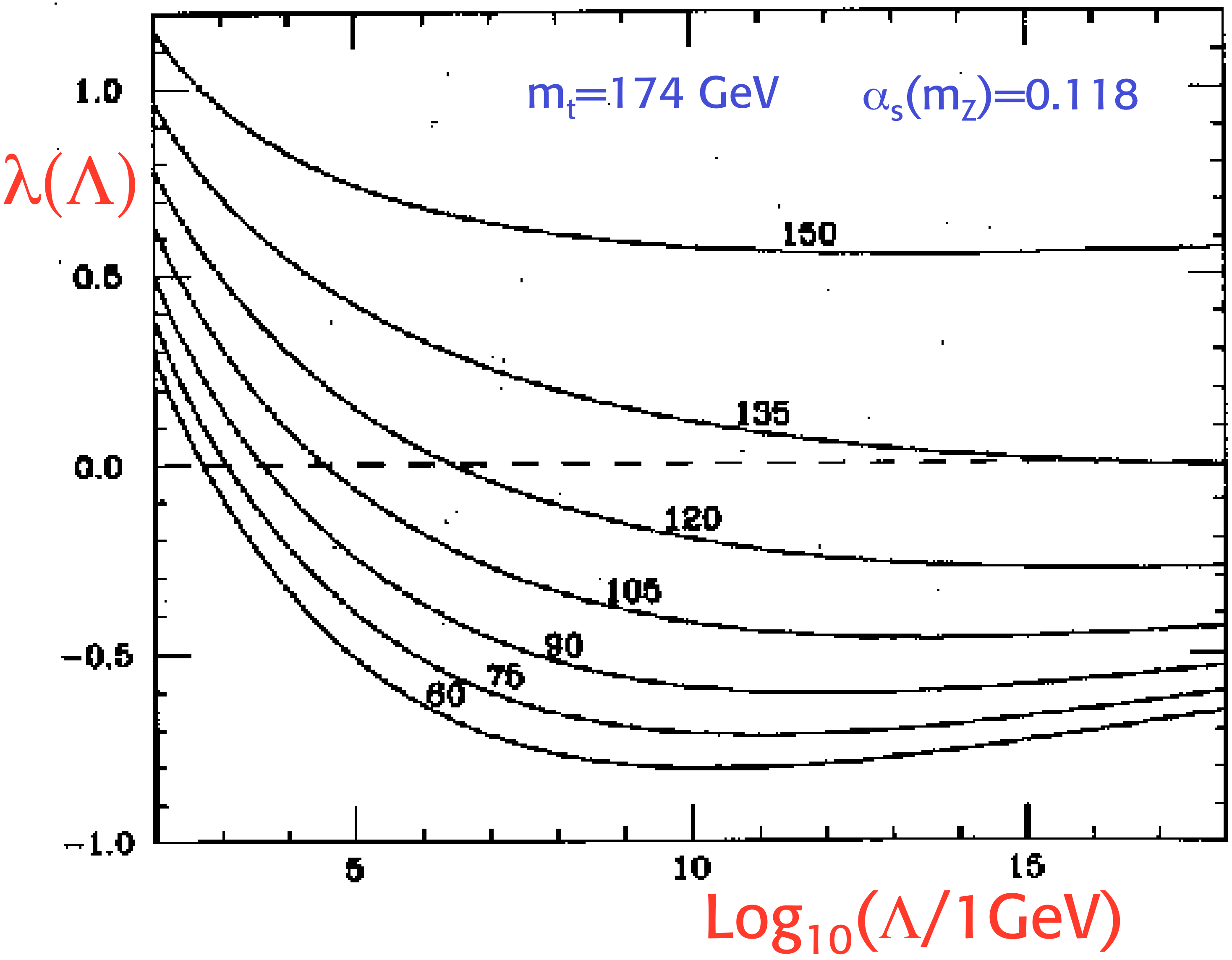


stability $$m_H > 129.5 + 2.1\,[m_t - 171.4] - 4.5\,\frac{\alpha_s(m_Z) - 0.118}{0.006}$$

metastability $$m_H(\mathrm{GeV}) > 117 + 2.9\,[m_t(\mathrm{GeV}) - (175 \pm 2)] - 2.5\left[\frac{\alpha_s(m_Z) - 0.118}{0.002}\right]$$

Isidori, Ridolfi, Strumia

Altarelli,Isidori



Running coupling $t = \ln\Lambda/v$ h_t=top Yukawa

$$\frac{d\lambda(t)}{dt} = \beta_\lambda(t) = \underset{b}{const}[\lambda^2 + 3\lambda h_t^2 - 9h_t^4 + small]$$

Initial conditions (at Λ=v) $\lambda_0 = \frac{m_H^2}{4v^2}$ and $h_{0t} = \frac{m_t}{v}$

Too large m_H? λ^2 wins, $\lambda(t)$ increases.

$$\lambda(t) \sim \frac{\lambda_0}{1 - b\lambda_0 t}$$

Landau pole

The upper limit on m_H is obtained by requiring that no Landau pole occurs below Λ

$m_H \leq$ ~180 GeV if $\Lambda \sim M_{GUT}$
~ 600-800 GeV if $\Lambda \sim$ o(TeV)

Rather than a bound says where non pert effects are important

Caution: near the pole pert. theory inadequate.
Simulations on the lattice appear to confirm the bound

Kuti et al, Hasenfratz et al, Heller et al

Precision Tests of SM

The only recent development in this domain is the decrease of the experimental value of m_t from CDF& D0 Run II

The error went also much down!

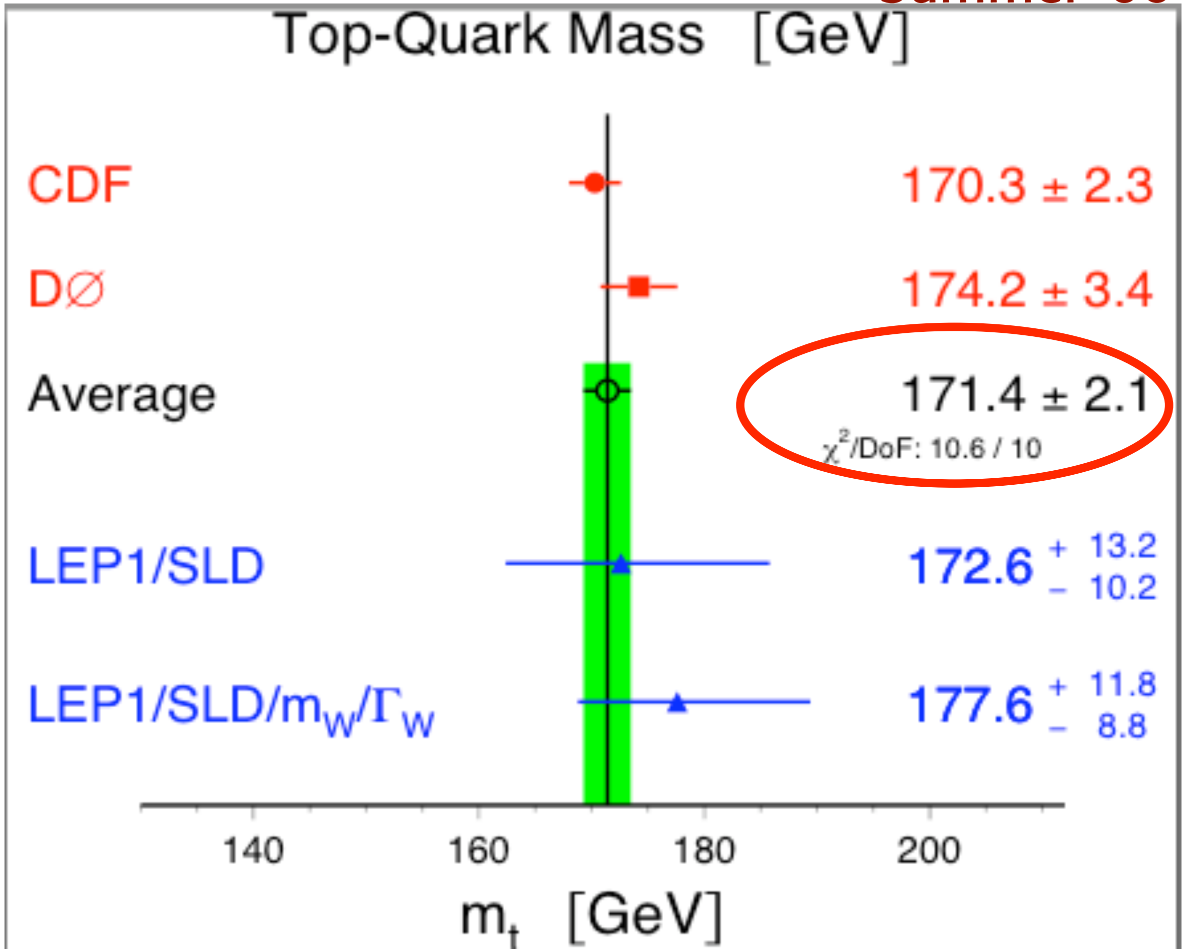
(Run I value: 178.0±4.3

This has a small effect on the quality of the SM fit and on the m_H bounds

m_t ↓ : m_H ↓

quality ↓

Summer ‘06



Overall the EW precision tests support the SM and a light Higgs.

The χ^2 is reasonable:

χ^2/ndof~17.8/13 (~16.6%)

Note: does not include NuTeV, APV, Moeller and $(g\text{-}2)_\mu$

a_μ ~3.3σ deviation?

Summer '06

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^{0} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7

Low Energy Experiments

~3σ away!?

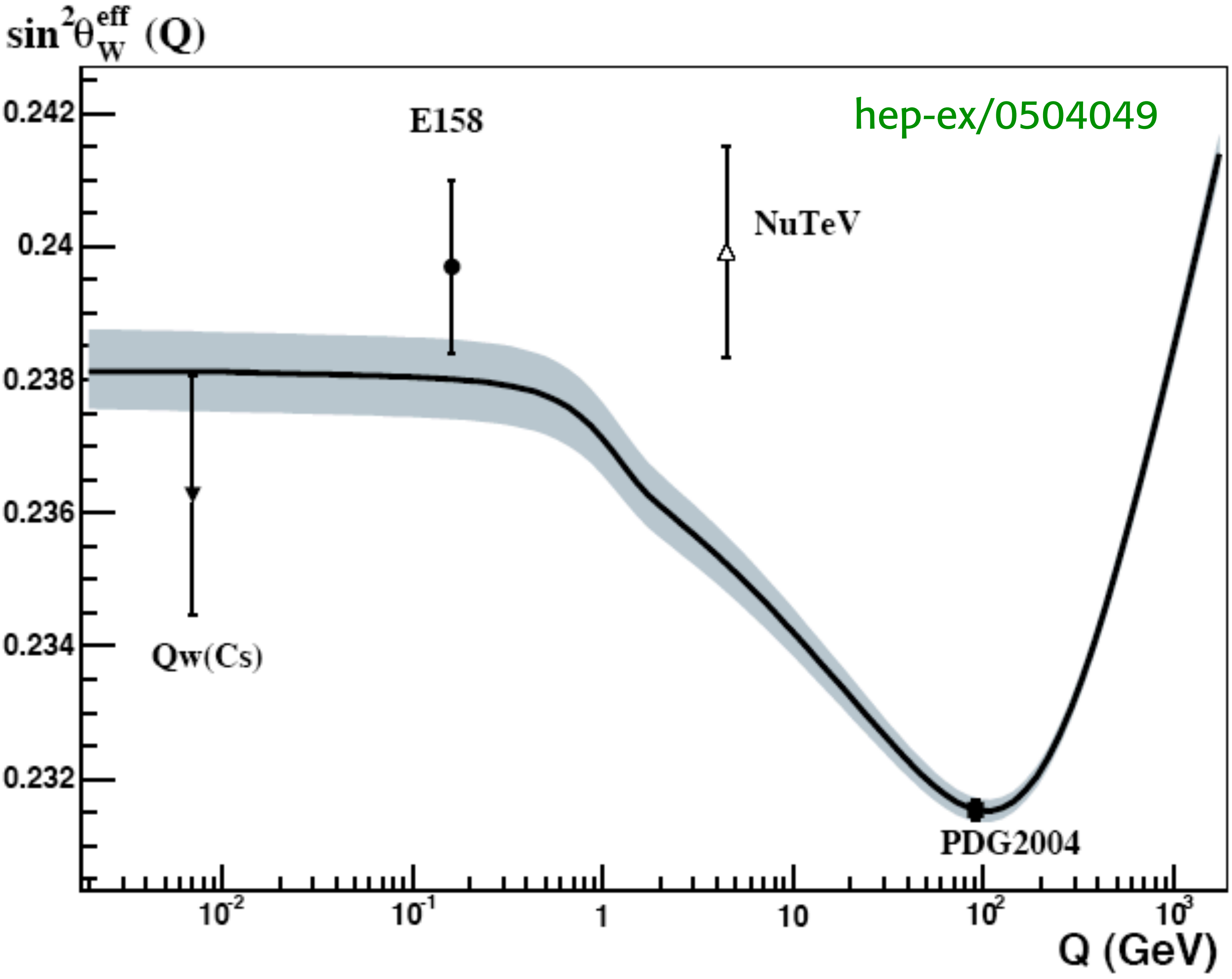
	Observable	Measurement	SM fit
NuTeV	$\sin^2\theta_W$ (νN [10])	0.2277 ± 0.0016	0.2226
APV	$Q_W(\mathrm{Cs})$ (APV [11])	-72.84 ± 0.49	-72.91
Moeller	$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ (e^-e^- [12])	~~0.2296 ± 0.0023~~	0.2314

hep-ex/0504049: 0.2330±0.0015

$$\boxed{A_{PV} = \frac{(\sigma_R - \sigma_L)}{(\sigma_R + \sigma_L)}}$$

recall for comparison:
present WA
$\sin^2\theta_{\mathrm{eff}}$=0.23153 ± 0.00016

(g-2) not included here
[no m_H implications]



hep-ex/0504049

The NuTeV anomaly probably simply arises from a large underestimation of the theoretical error (QCD analysis)

- The QCD LO parton analysis is too crude to match the required accuracy

- A small asymmetry in the momentum carried by s-sbar could have a large effect
NuTeV claims to have measured this asymmetry from dimuons. But a LO analysis of s-sbar makes no sense and cannot be directly transplanted here
(α_s*valence corrections are large and process dependent)
A recent CTEQ fit of s-sbar goes in the right direction.

- A tiny violation of isospin symmetry in parton distrib's can also be important.

S. Davidson, S. Forte, P. Gambino, N. Rius, A. Strumia '02

Electron g-2: A new measurement

Odom, Hanneke,
D'Urso, Gabrielse '06

$a_e = (g\text{-}2)/2 = 11596521808.5(7.6)\ 10^{-13}$

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + \ldots$$

$$+ a_{\mu\tau} + a_{\text{hadronic}} + \cancel{a_{\text{weak}}},$$

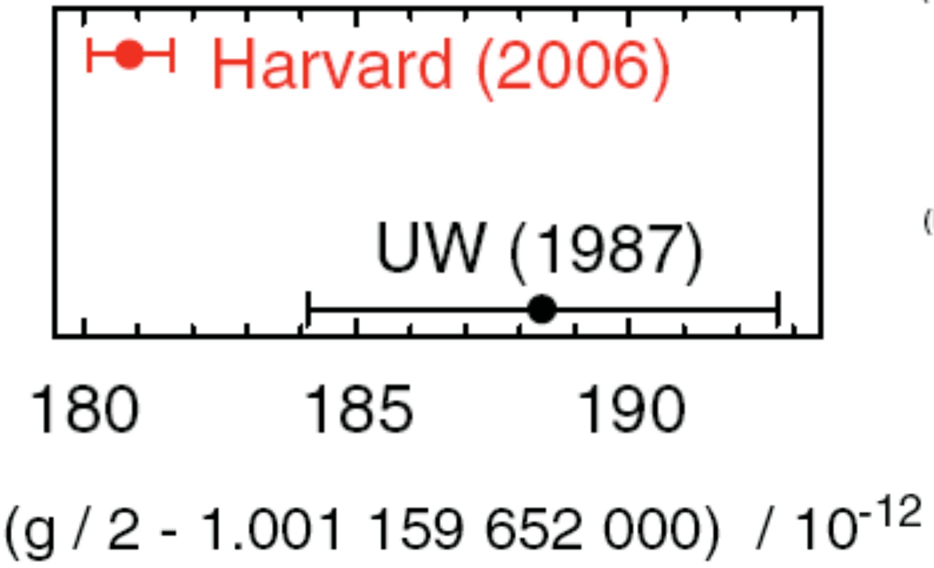
δa_h small

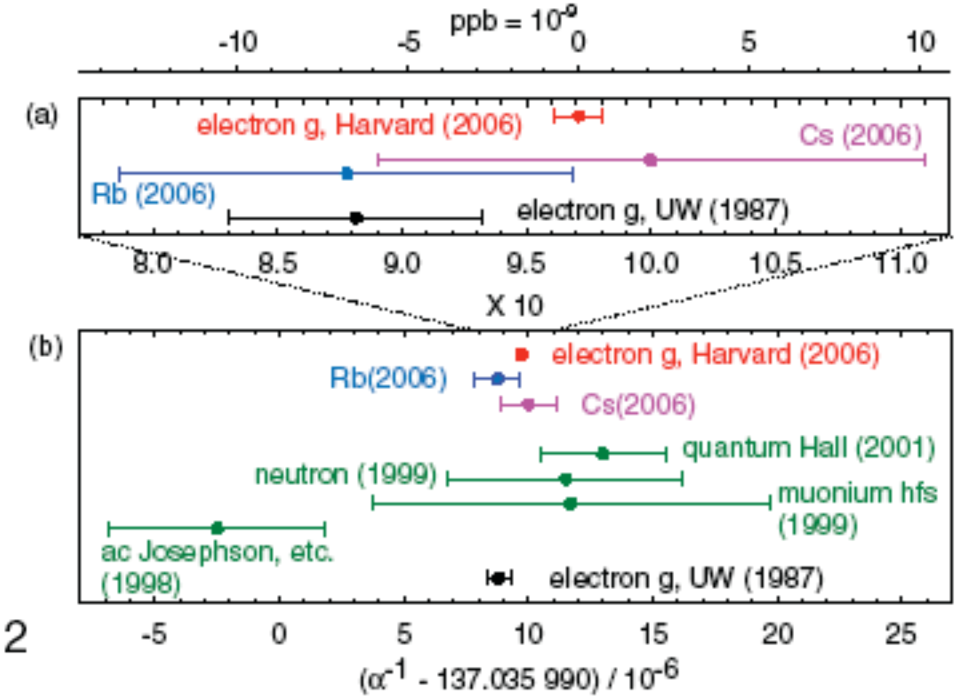
Best determination of α_{QED}

$\alpha^{-1} = 137.035999710(96)$

$$a(\text{hadron}) = 1.671\,(19) \times 10^{-12}$$

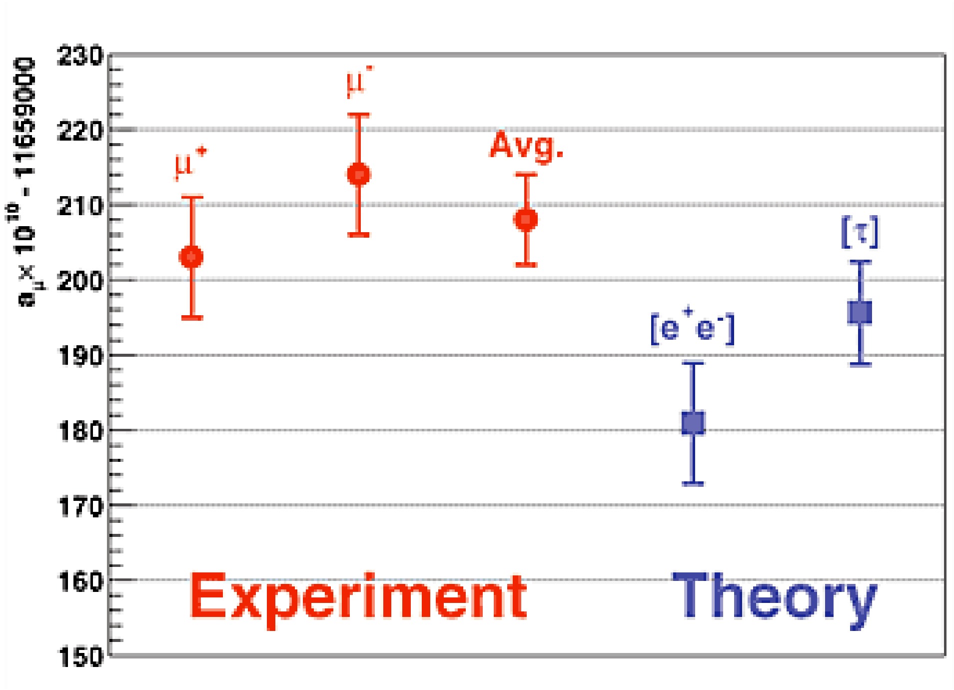
$$a(\text{weak}) = 0.030\,(01) \times 10^{-12}$$



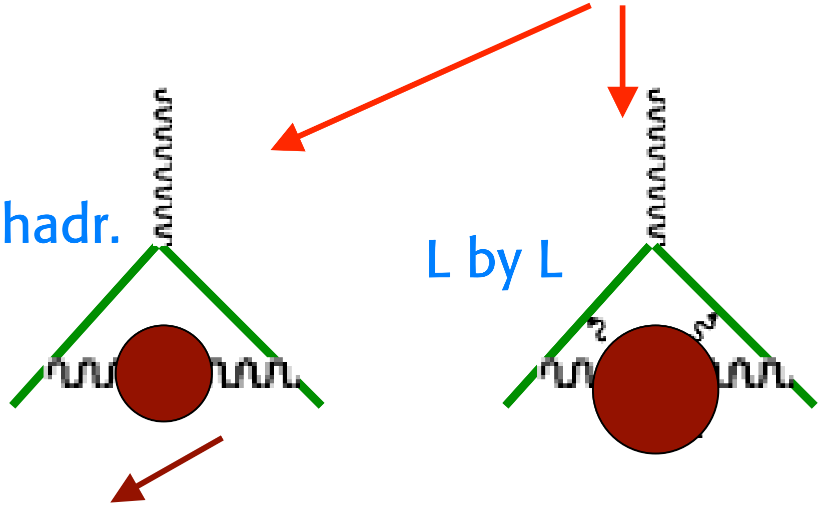


Muon g-2: more sensitive to new physics by $(m_\mu/m_e)^2 \sim 2\ 10^4$

BNL '04-'06: $a_\mu = (11659208.0 \pm 6.3)\ 10^{-10}$



$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm had}$$



$$a_\mu^{\rm had,LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds\, \frac{R(s)\, K(s)}{s^2},$$

$$R(s) = \frac{\sigma(e^+e^- \to {\rm hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)},$$

From the latest value of a_e (G. Gabrielse et al., 2006):

$$\alpha^{-1} = 137.035999710(96),$$

$$a_\mu^{\mathrm{QED}} = (116584718.09 \pm 0.14 \pm 0.08) \cdot 10^{-11}.$$

Eidelmann, ICHEP'06

Contribution	$a_\mu, 10^{-10}$
Experiment	11659208.0 ± 6.3
QED	11658471.94 ± 0.14
Electroweak	$15.4 \pm 0.1 \pm 0.2$
Hadronic	693.1 ± 5.6
Theory	11659180.5 ± 5.6
Exp.–Theory	27.5 ± 8.4 (3.3σ)

Mostly VP-LO
VP-NLO = -9.8±0.1
LbyL = 12.0±3.5

Knecht, Nyffeler'02
Melnikov, Veinshtein'04
Davier, Marciano '04

New e^+e^- Data Based Calculation of $a_\mu^{\mathrm{had,LO}}$

$\sqrt{s}$, GeV	$a_\mu^{\mathrm{had,LO}}, 10^{-10}$	$\delta a_\mu^{\mathrm{had,LO}}$, %
2π	$504.6 \pm 3.1 \pm 1.0$	73.0
ω	$38.0 \pm 1.0 \pm 0.3$	5.5
ϕ	$35.7 \pm 0.8 \pm 0.2$	5.2
$0.6 - 1.8$	$54.2 \pm 1.9 \pm 0.4$	7.8
$1.8 - 5.0$	$41.1 \pm 0.6 \pm 0.0$	6.0
$J/\psi, \psi'$	$7.4 \pm 0.4 \pm 0.0$	1.1
> 5.0	$9.9 \pm 0.2 \pm 0.0$	1.4
Total	$690.9 \pm 3.9_{\mathrm{exp}} \pm 1.9_{\mathrm{rad}} \pm 0.7_{\mathrm{QCD}}$	100.0

Higher accuracy of e^+e^- data: the $a_\mu^{\mathrm{had,LO}}$ error is 4.4 (0.63%) compared to 15.3 of EJ, 1995 and 7.2 of DEHZ, 2003!

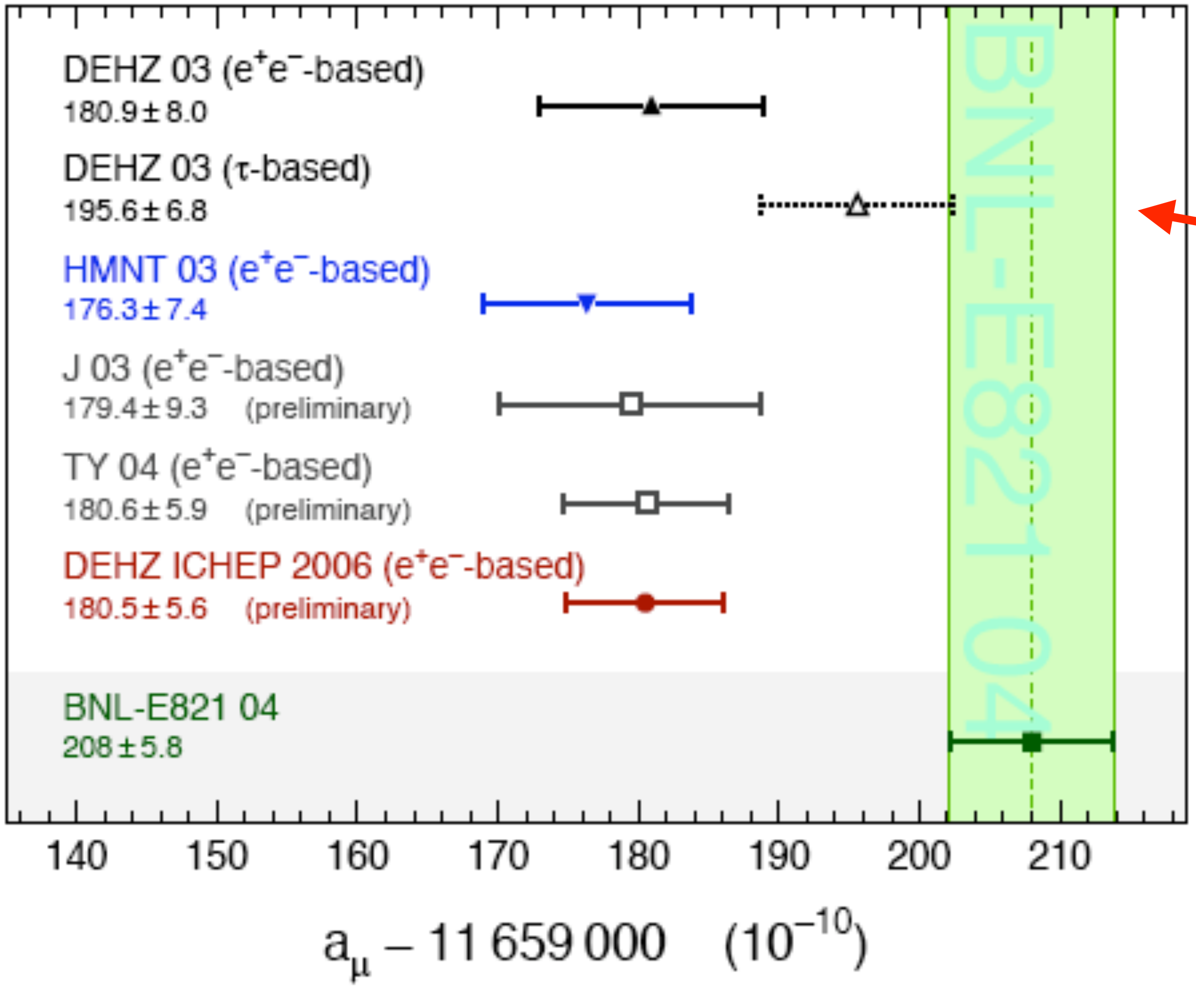
From e+e- data: ~3.3 σ

Observed Difference with Experiment:

$$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (27.5 \pm 8.4) \times 10^{-10}$$

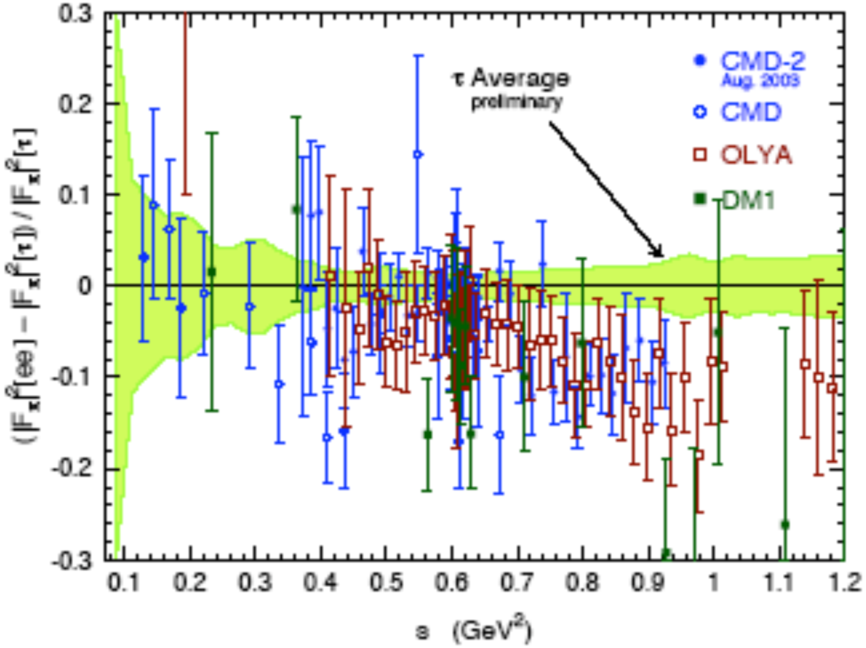
➡ 3.3 ”standard deviations“

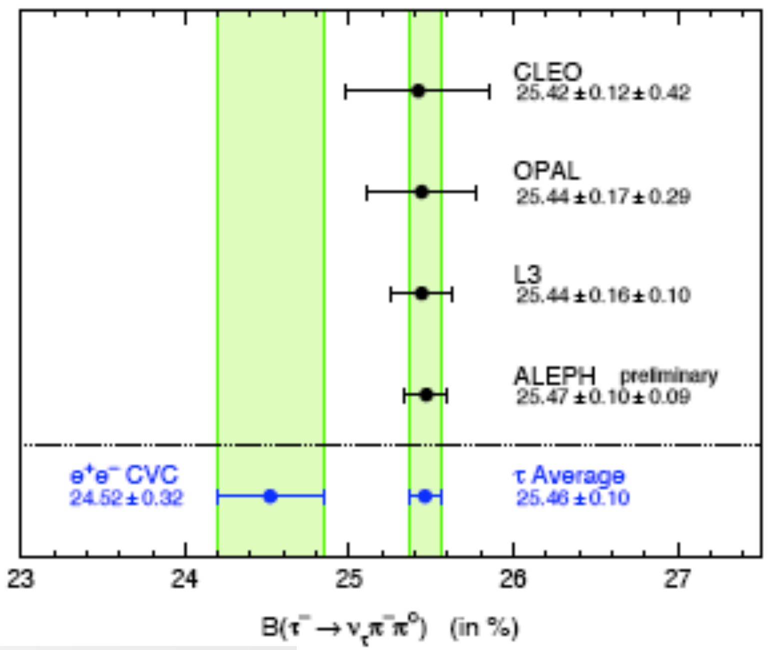
Davier/Hocker



Hadronic contr.
from data.
τ vs e+e-
discrepancy

CVC in the 2π Channel. e^+e^- vs. τ

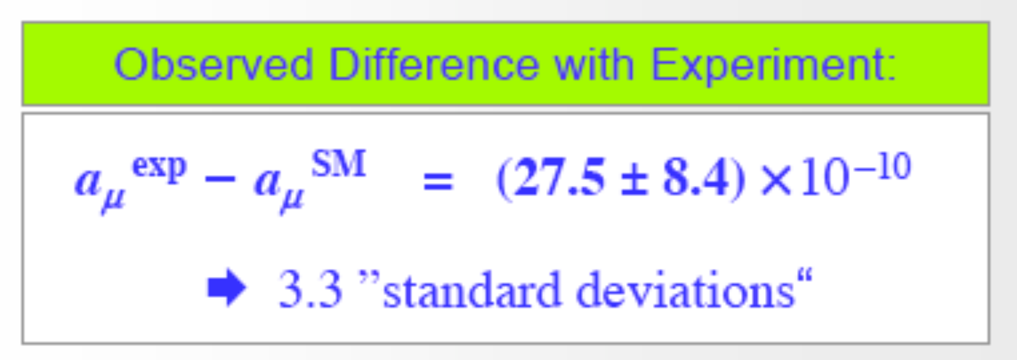




Difference: BR[τ] – BR[e^+e^- (CVC)]:

Mode	$\Delta(\tau - e^+e^-)$	"Sigma"
$\tau^- \to \pi^- \pi^0 \nu_\tau$	$+0.92 \pm 0.21$	4.5
$\tau^- \to \pi^- 3\pi^0 \nu_\tau$	-0.08 ± 0.11	0.7
$\tau^- \to 2\pi^- \pi^+ \pi^0 \nu_\tau$	$+0.91 \pm 0.25$	3.6

e^+e^- data on $\pi^- \pi^+ \pi^0 \pi^0$ not satisfactory



Observed Difference with Experiment:

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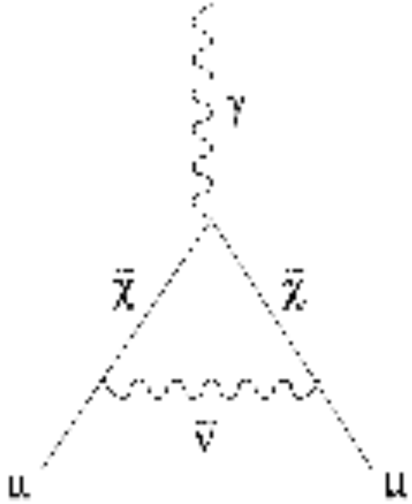
➡ 3.3 ”standard deviations“

Could be new physics
eg light SUSY

$$\delta a_\mu = 13 \cdot 10^{-10} \left(\frac{100GeV}{M_{SUSY}}\right)^2 tg\beta$$



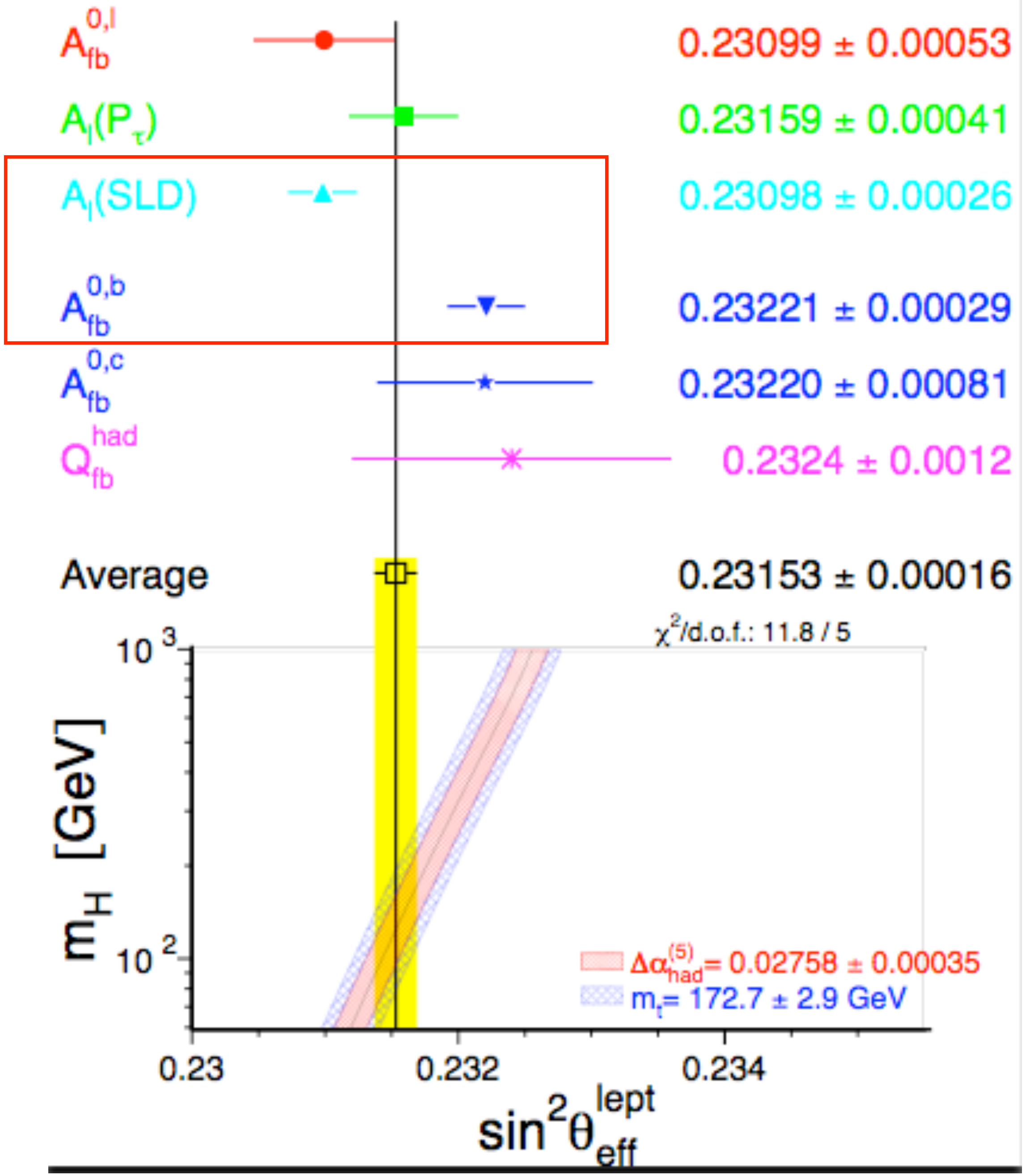
a_μ is a plausible
location for a
new physics signal!!

But the e-τ discrepancy is not understood:
theoretical errors underestimated?

$\sin^2\theta_W$

The two most precise measurements
do not really match!

This unfortunate fact makes the interpretation of precision tests less sharp.

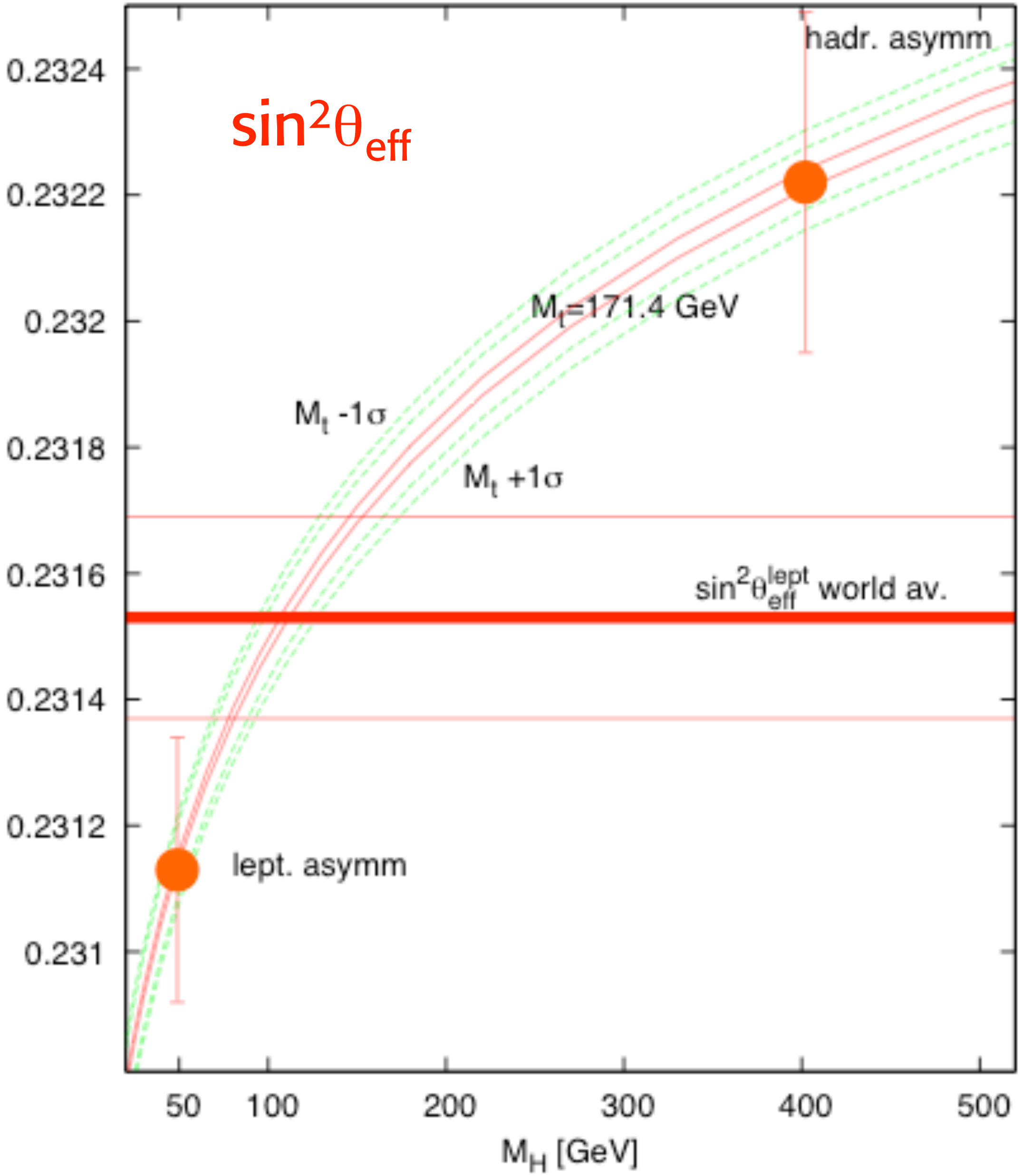


Plot $\sin^2\theta_{eff}$ vs m_H

P. Gambino

Exp. values are plotted at the m_H point that better fits given m_{texp}

Clearly leptonic and hadronic asymm.s push m_H towards different values



A^b_{FB} vs $[\sin^2\theta]_{lept}$: New physics in Zbb vertex?

Must be somewhat special!! (but not impossible->)

$$A^b_{FB} = \frac{3}{4} A_e A_b \qquad A_f = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}$$

For b:

$$g_L = g_V - g_A = -1 + \frac{2}{3} s^2 = -0.846$$

$$g_R = g_V + g_A = \frac{2}{3} s^2 = 0.154$$

$$g_L^2 \approx 0.72 >> g_R^2 \approx 0.02 \qquad (A_b)_{SM} \approx 0.936$$

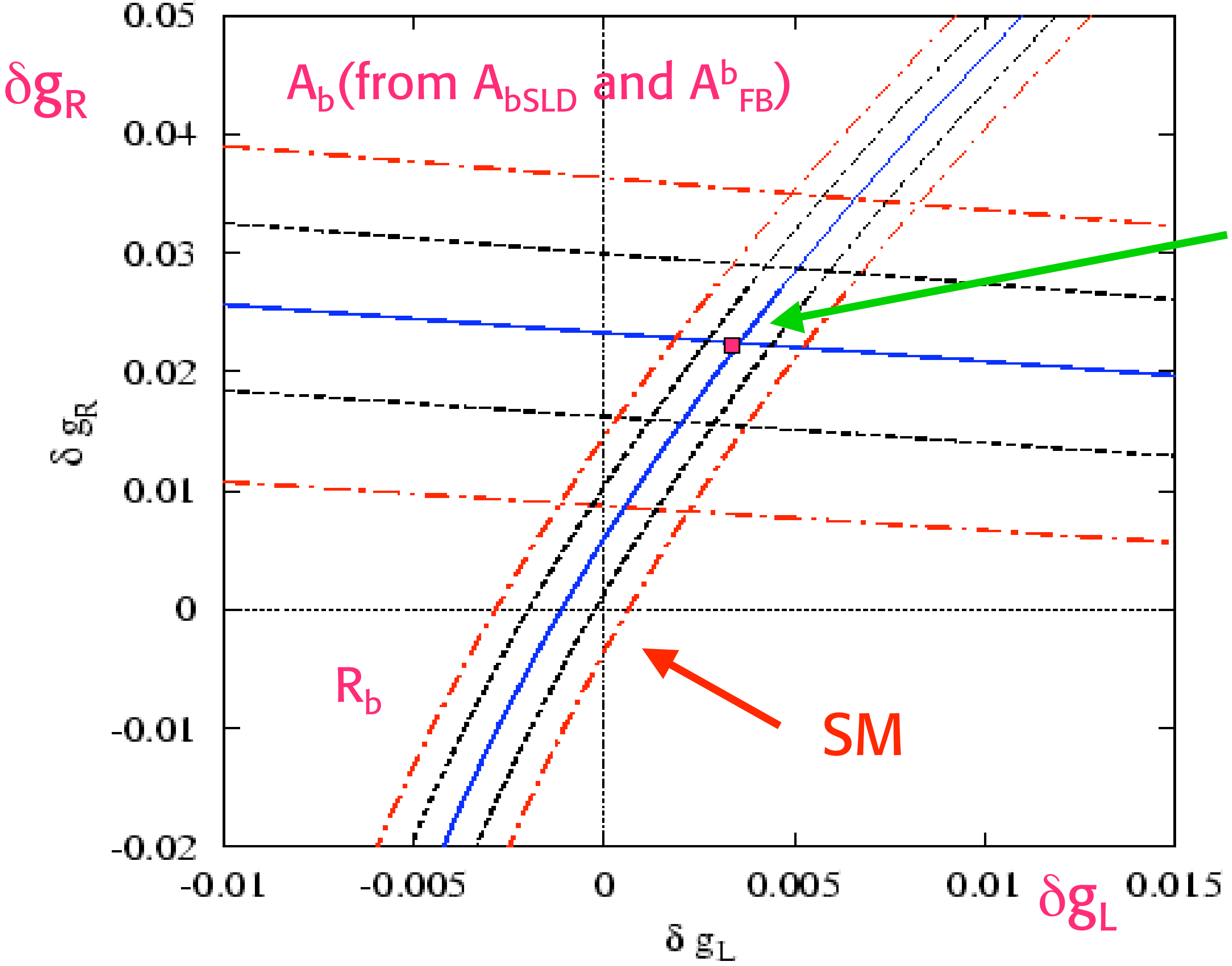
From A^b_{FB}=0.0992±0.0016, using $[\sin^2\theta]_{lept}$ =0.23113±0.00021 one obtains A_b=0.881±0.017

$(A_b)_{SM} - A_b = 0.055 \pm 0.018$ -> ~3 σ

A large δg_R needed (by about 30%!)

$R_b \sim g_L^2 + g_R^2$

But note: $(A_b)_{SLD}$ = 0.923±0.020,
also R_b=0.21629±0.00066 (R_{bSM}~0.2157)



Choudhury,
Tait, Wagner '01

0.992 g_L(SM),
1.26 g_R(SM)

Too large for
a loop effect.
Needs a ad hoc
tree level effect

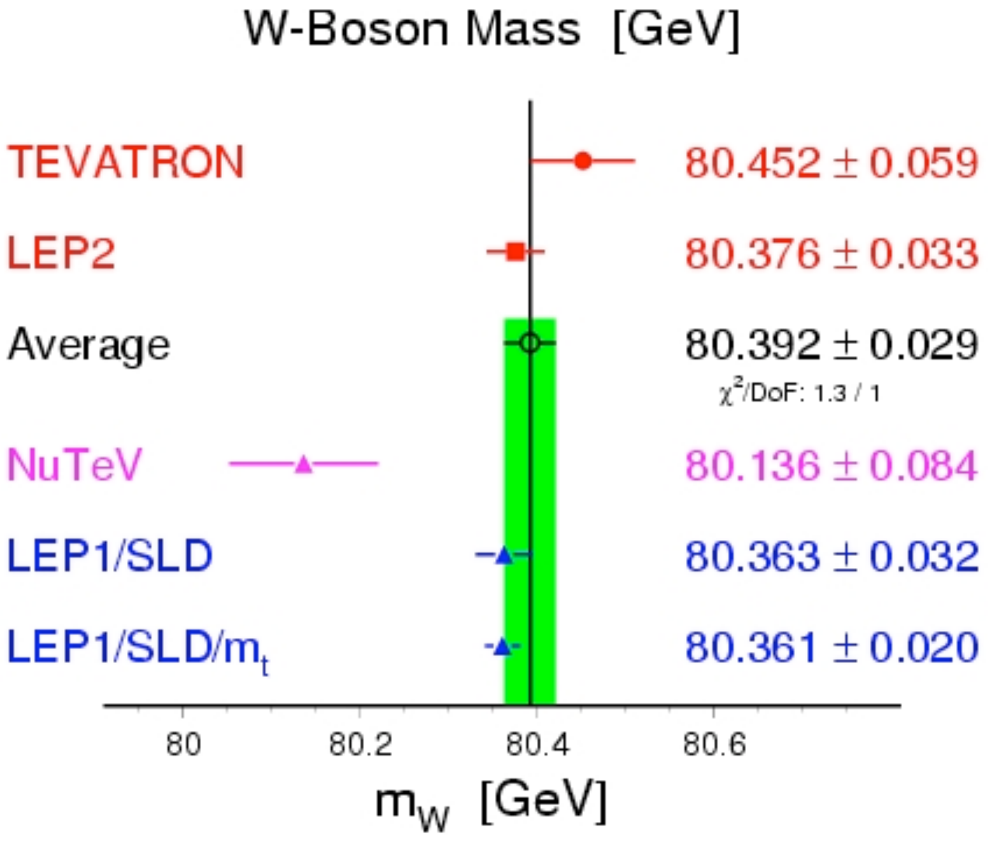
Mixing of the b quark with a vectorlike doublet (ω,χ) with charges (2/3, -1/3) or (-1/3, -4/3)? CTW'01
Or mixing of Z with Z' and KK recurrences in extra dim models?

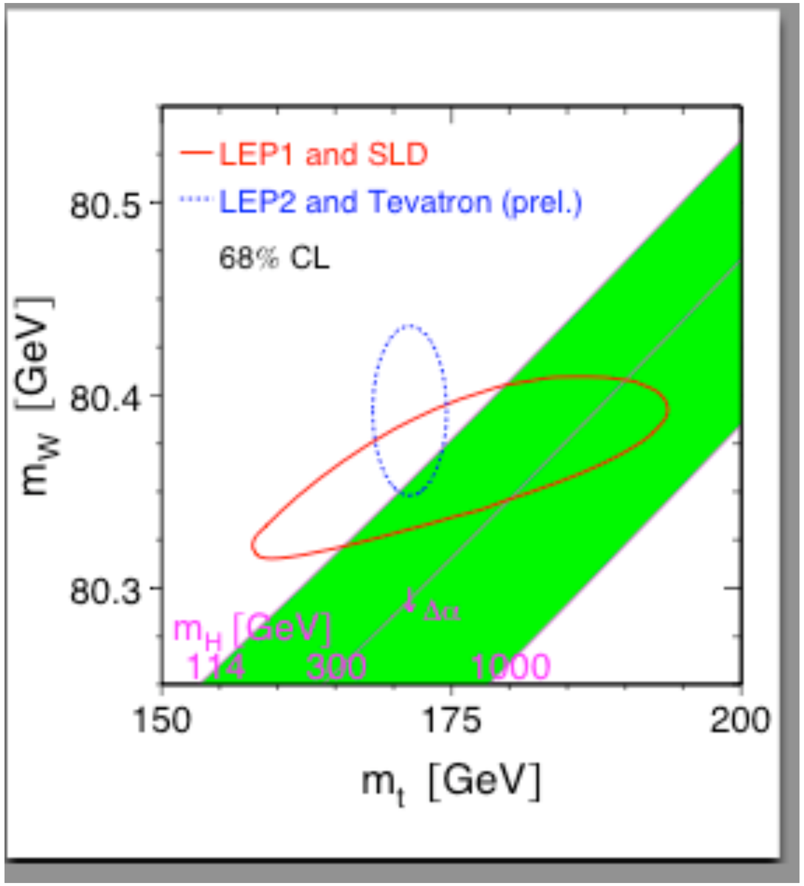
Agashe, Contino, Pomarol '06; Djouadi, Moreau, Richard '06

- The measured value of m_W is a bit high (given m_t)

(now came a little bit down from 80.420 -> 80.392)

Summer 2006



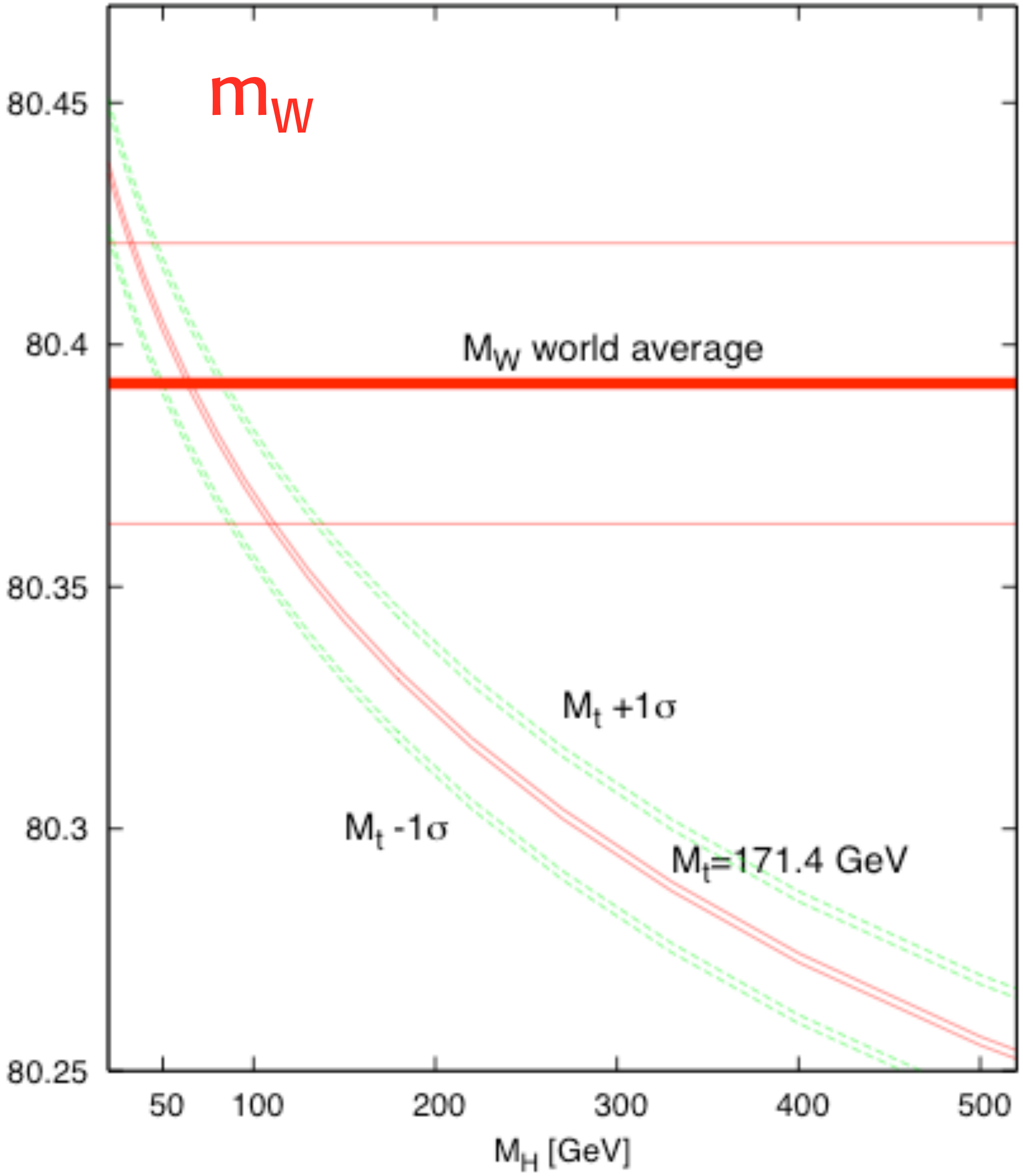


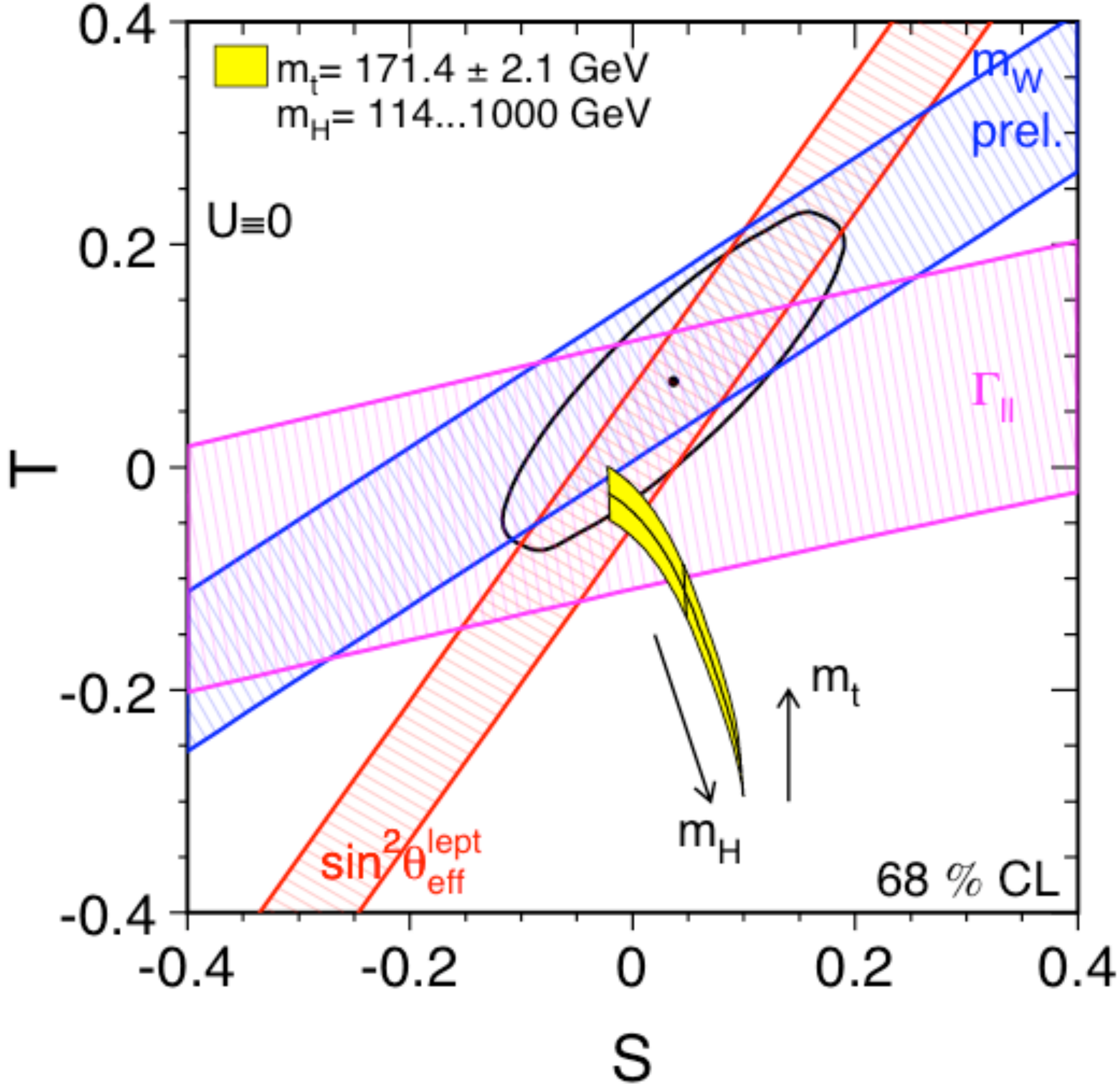
Plot m_W vs m_H

P. Gambino

m_W points to a light Higgs!

Like $[\sin^2\theta_{eff}]_l$




🟨 m_t= 171.4 ± 2.1 GeV
m_H= 114...1000 GeV
U≡0
m_W
prel.
Γ_{ll}
$\sin^2\theta_{eff}^{lept}$
m_t
m_H
68 % CL
T
S
0.4
0.2
0
-0.2
-0.4
-0.4
-0.2
0
0.2
0.4

Fit results

Here only m_W and not m_t is used:
shows m_t from rad. corr.s

Summer ‘06

	m_W	m_t	m_W, m_t
m_t(GeV)	177.6+12-9	171.4±2.1	171.7±2.0
m_H(GeV)	137+228-76	103+54-37	85+39-28
log[m_H(GeV)]	2.14±0.39	2.01 ± 0.19	1.93± 0.17
$\alpha_s(m_Z)$	0.1190(28)	0.1190 (27)	0.1186 (26)
χ^2/dof	17.4/12	16.0/11	17.8/13
m_W(MeV)	80380(21)	80361(20)	80371(16)

WA: m_W=80392(29)

Rad. corr.’s predict m_t and m_W very well. May be also m_H!

Status of the SM Higgs fit

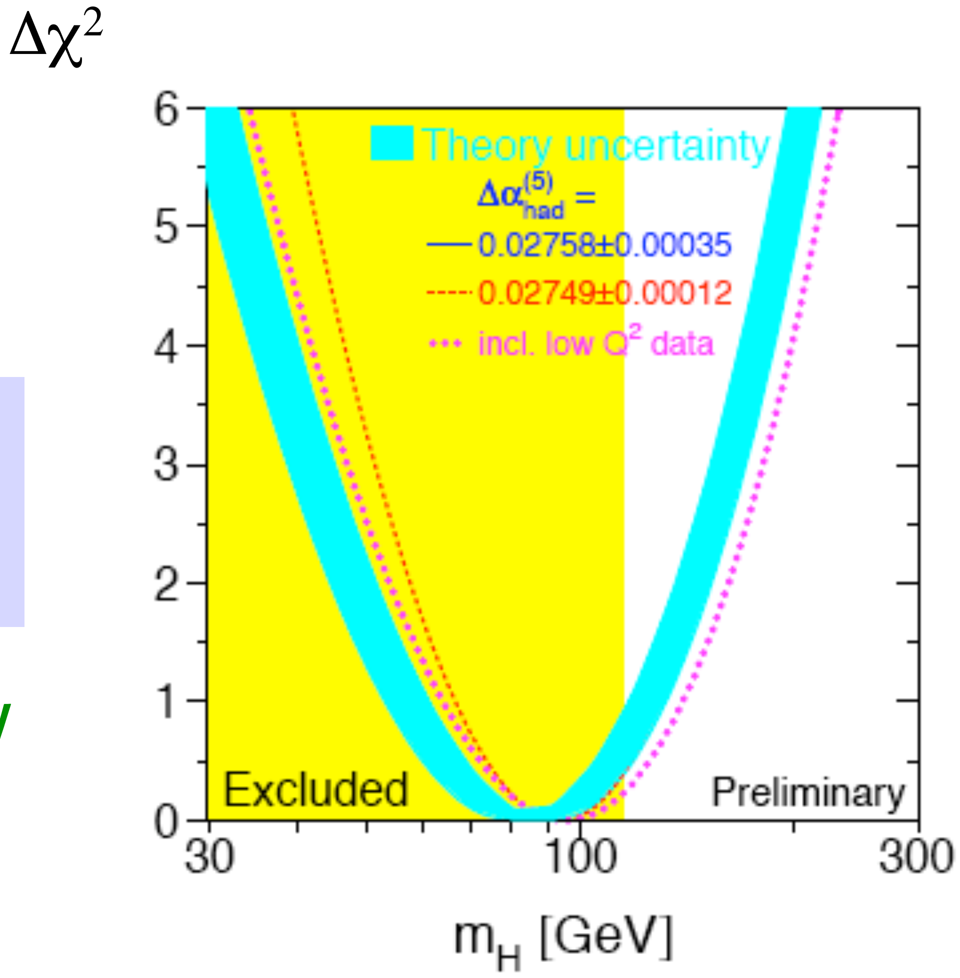
Summer ‘06

Sensitive to log m_H

Rad Corr.s ->
$\log_{10} m_H(\mathrm{GeV}) = 1.93 \pm 0.17$

This is a great triumph for the SM: right in the narrow allowed window $\log_{10} m_H \sim 2$ - 3

Direct search: $m_H > 114.4$ GeV



At 95% cl
$m_H < 166$ GeV (rad corr.’s)
$m_H < 199$ GeV (incl. direct search bound)

$\log_{10} m_H$ ~2 is a very important result!!

Drop H from SM -> renorm. lost -> divergences -> cut-off Λ

$$\log m_H \rightarrow \log\Lambda + \text{const}$$

Any alternative mechanism amounts to identify the physics of Λ and the prediction of finite terms.

The most sensitive to $\log m_H$ are $\varepsilon_1 \sim \Delta\rho$ and ε_3 (or T&S):

$\log_{10} m_H$ ~2 means that
$f_{1,3}$ are compatible with
the SM prediction

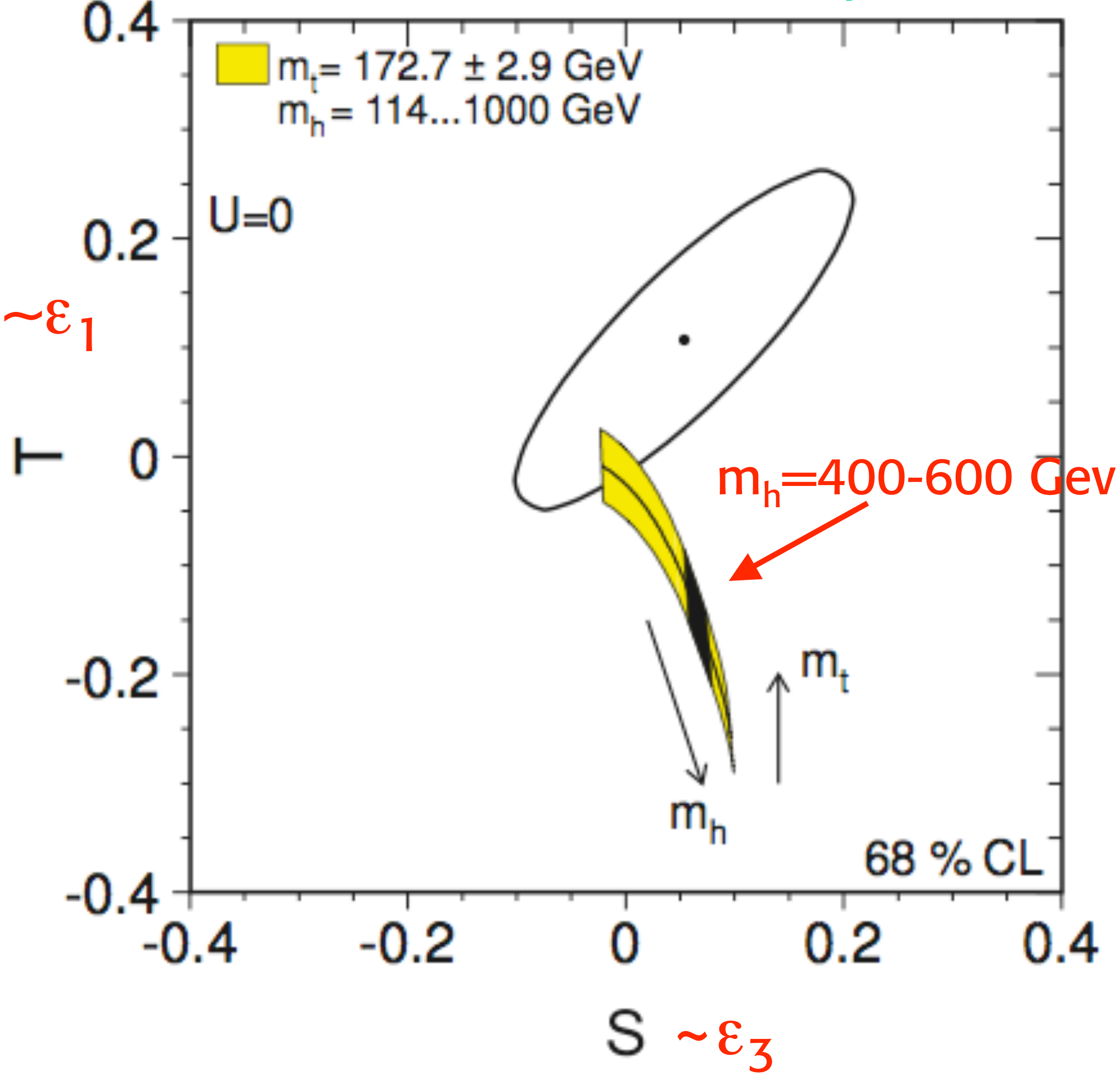
$$\varepsilon_1 = \underbrace{-\frac{3 G_F m_W^2}{4\pi^2\sqrt{2}}\mathrm{tg}^2\theta_W}_{-1.2\ 10^{-3}}\left[\log\frac{m_H}{m_Z} + f_1\right]$$

New physics can change the bound on m_H (different $f_{1,2}$): well possible!

$$\varepsilon_3 = \underbrace{\frac{G_F m_W^2}{12\pi^2\sqrt{2}}}_{0.45\ 10^{-3}}\left[\log\frac{m_H}{m_Z} + f_3\right]$$

Some conspiracy is needed to simulate a light Higgs

We see that to shift m_h up we need a new physics effect that mainly pushes T up



Barbieri, Hall, Rychkov

$\sim\varepsilon_1$

m_h=400-600 Gev

$\sim\varepsilon_3$

Is it possible that the Higgs is not found at the LHC?

Looks pretty unlikely!!

The LHC range is large enough:
$m_H < \sim 1$ TeV
the Higgs should be really heavy!

Rad. corr's indicate a light Higgs (whatever its nature)

Such a heavy Higgs would make perturbation theory to collapse nearby (violations of unitarity for $m_H > 0.8$ TeV)

e.g. strongly interacting WW or WZ scattering

Such nearby collapse of pert. th. is very difficult to reconcile with EW precision tests plus simulating a light Higgs

The SM perfect agreement with the data favours forms of new physics that keep at least some Higgs light

The Standard Model works very well

So, why not find the Higgs and declare particle physics solved?

First, you have to find it!

→ LHC

Because of both:

Conceptual problems

- Quantum gravity
- The hierarchy problem
- •••••

and experimental clues:

- Coupling unification
- Neutrino masses
- Baryogenesis
- Dark matter
- Vacuum energy
- •••••

Some of these problems
point at new physics
at the weak scale: eg
Hierarchy
Dark matter

Conceptual problems of the SM

Most clearly:

- No quantum gravity (M_{Pl} ~ 10^{19} GeV)
- But a direct extrapolation of the SM leads directly to GUT's (M_{GUT} ~ 10^{16} GeV)

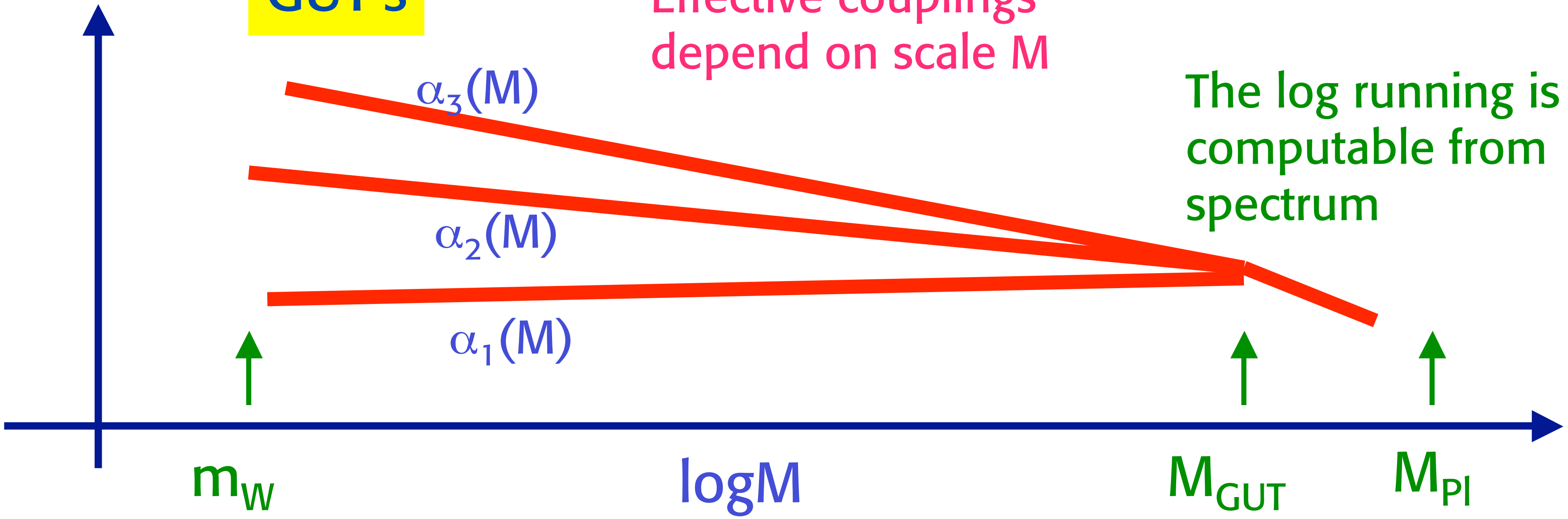
M_{GUT} close to M_{Pl}

- suggests unification with gravity as in superstring theories
- poses the problem of the relation m_W vs M_{GUT}- M_{Pl}

Can the SM be valid up to M_{GUT}- M_{Pl}?? ← The “big” hierarchy problem

Not only it looks very unlikely, but the new physics must be near the weak scale!

GUT's



Effective couplings depend on scale M

The log running is computable from spectrum

The large scale structure of particle physics:

- SU(3) $\otimes$ SU(2) $\otimes$ U(1) unify at M_{GUT}
- at M_{Pl}: quantum gravity

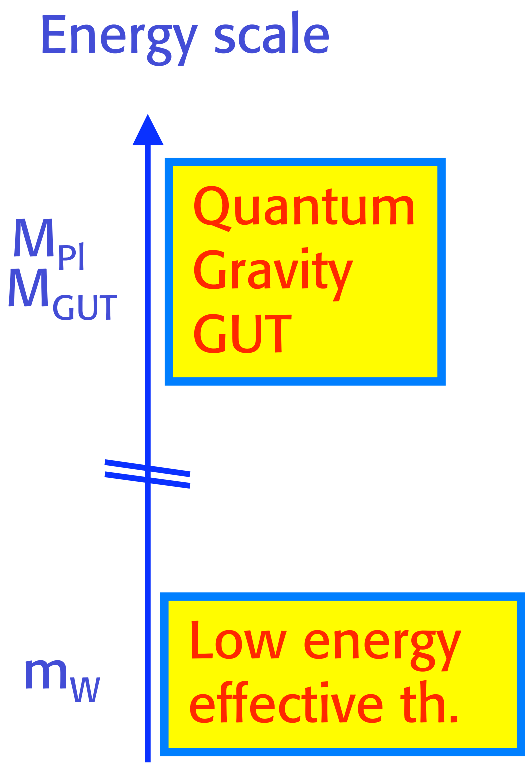
$$G_{Newton} = \frac{\hbar c}{M_{Pl}^2}$$

$r \sim 10^{-33}$ cm

Superstring theory:
a 10-dimensional non-local, unified theory of all interact's

The really fundamental level

The hierarchy problem



Energy scale

M_{Pl}
M_{GUT}

Quantum
Gravity
GUT

m_W

Low energy
effective th.

Assume:

- A TOE at $\Lambda \sim M_{GUT} \sim M_{Pl}$
- A low en. th at o(TeV)
- A "desert" in between

The low en. th must be renormalisable as a necessary condition for insensitivity to physics at Λ.

[the cutoff can be seen as a parametrisation of our ignorance of physics at Λ]

But, as Λ is so large, in addition the dep. of ren. masses and couplings on Λ must be reasonable:

e.g. a mass of order m_W cannot be linear in Λ if $\Lambda \sim M_{GUT}$, M_{Pl}.

With new physics at Λ the low en. th. is only an effective theory.
After integration of the heavy d.o.f.:

$\mathcal{L}_i$: operator of dim i

$$\mathcal{L} = \underbrace{o(\Lambda^2)\mathcal{L}_2 + o(\Lambda)\mathcal{L}_3 + o(1)\mathcal{L}_4}_{\text{Renorm.ble part}} \quad \underbrace{+\, o(1/\Lambda)\mathcal{L}_5 + o(1/\Lambda^2)\mathcal{L}_6 + \ldots}_{\text{Non renorm.ble part}}$$

In absence of special symmetries or selection rules,
by dimensions $c_i\mathcal{L}_i \sim o(\Lambda^{4-i})\mathcal{L}_i$

$\mathcal{L}_2$: Boson masses ϕ^2. In the SM the mass in the Higgs potential is unprotected: $c_2 \sim o(\Lambda^2)$
$\mathcal{L}_3$: Fermion masses $\bar{\psi}\psi$. Protected by chiral symmetry and SU(2)xU(1): $\Lambda \to m\log\Lambda$
$\mathcal{L}_4$: Renorm.ble interactions, e.g. $\bar{\psi}\gamma^\mu\psi A_\mu$
$\mathcal{L}_{i>4}$: Non renorm.ble: suppressed by $1/\Lambda^{i-4}$ e.g. $1/\Lambda^2\bar{\psi}\gamma^\mu\psi\bar{\psi}\gamma^\mu\psi$

B and L conservation in SM:

"Accidental" symmetries: in SM there is no dim.$\leq$4 gauge invariant operator that violates B and/or L (if no ν_R, otherwise M $\nu^T_R\,\nu_R$ is dim-3 $|\Delta L|=2$)

The same is true in SUSY with R-parity cons.

e. g. for the $\Delta B=\Delta L=-1$ transition $u + u \to e^+ + \overline{d}$

all good quantum numbers are conserved:

e.g. colour $u\sim 3$, $\overline{d}\sim\overline{3}$ and $3\times3 = 6+\overline{3}$ but

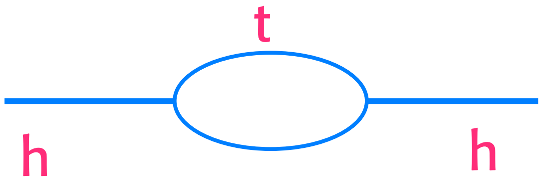
$$\frac{\lambda}{M^2}\,\overline{d}^c\Gamma u\ \overline{e}^c\Gamma u \longrightarrow \text{dim-6}$$

SU(5): $p \to e^+\pi^0$

For the low energy theory: the “little hierarchy” problem:

e.g. the top loop (the most pressing):

$m_h^2 = m^2_{bare} + \delta m_h^2$



$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$

$\Lambda \sim o(1\text{TeV})$

This hierarchy problem demands new physics near the weak scale

Λ: scale of new physics beyond the SM

- $\Lambda >> m_Z$: the SM is so good at LEP
- $\Lambda \sim$ few times $G_F^{-1/2} \sim o(1\text{TeV})$ for a natural explanation of m_h or m_W

Barbieri, Strumia

The LEP Paradox: m_h light, new physics must be so close but its effects were not visible at LEP

And also are not visible in flavour physics

Precision Flavour Physics

Another area where the SM is good, too good.....

- Light Higgs -> New physics at ~ few TeV
- But all effective non rinorm. vertices for FCNC have bounds above a few TeV

Apparently the SM suppression of FCNC and the CKM mechanism for CP violation is only mildly modified by new physics:
an intriguing mystery and a major challenge for models of new physics

New CDF&D0 results on Δm_s

B^0/B_s^0 mix through box diagram:

$$\Delta m_q \propto m_{B_q} \hat{B}_{B_q} f_{B_q}^2 \left| V_{tb} V_{tq}^* \right|^2$$

$$q = s, d$$

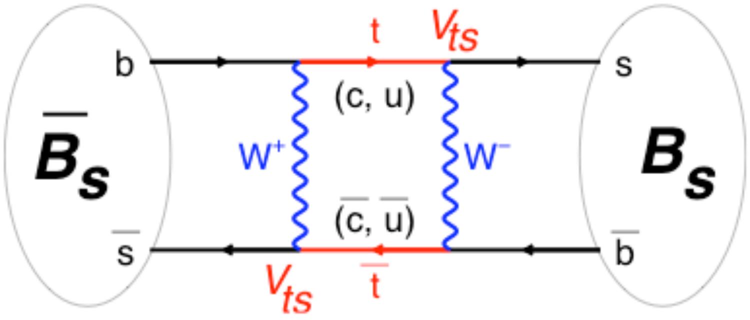
Uncertainties cancel in ratio:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

with $\xi = 1.21 \, {}^{+0.047}_{-0.035}$

(Okamoto, Lattice 2005)

Gomez-Ceballos



D0: $\Delta m_s = 17\text{-}21 \text{ ps}^{-1}$ at 90%

A. Abulencia *et al.*, PRL **97** 242003 (2006)

Observation of B_s Oscillations and precise measurement of Δm_s

$$\Delta m_s = 17.77 \pm 0.10\,(\text{stat.}) \pm 0.07\,(\text{syst.})\ \text{ps}^{-1}$$

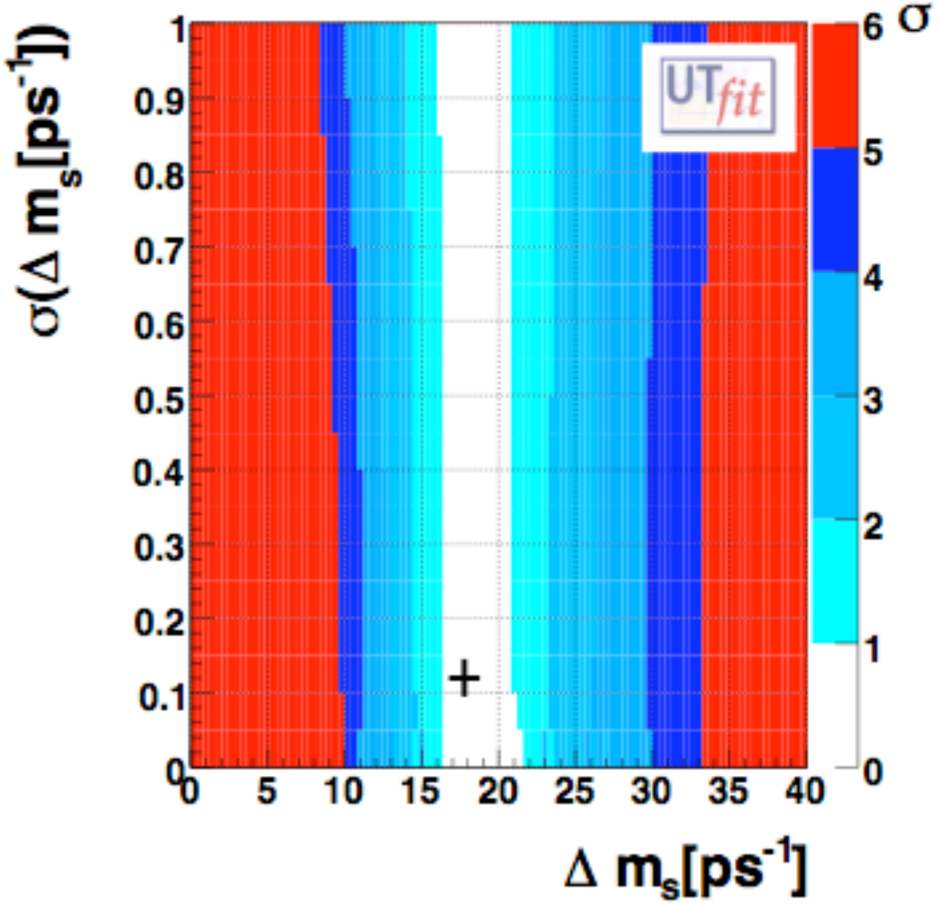
Kroll

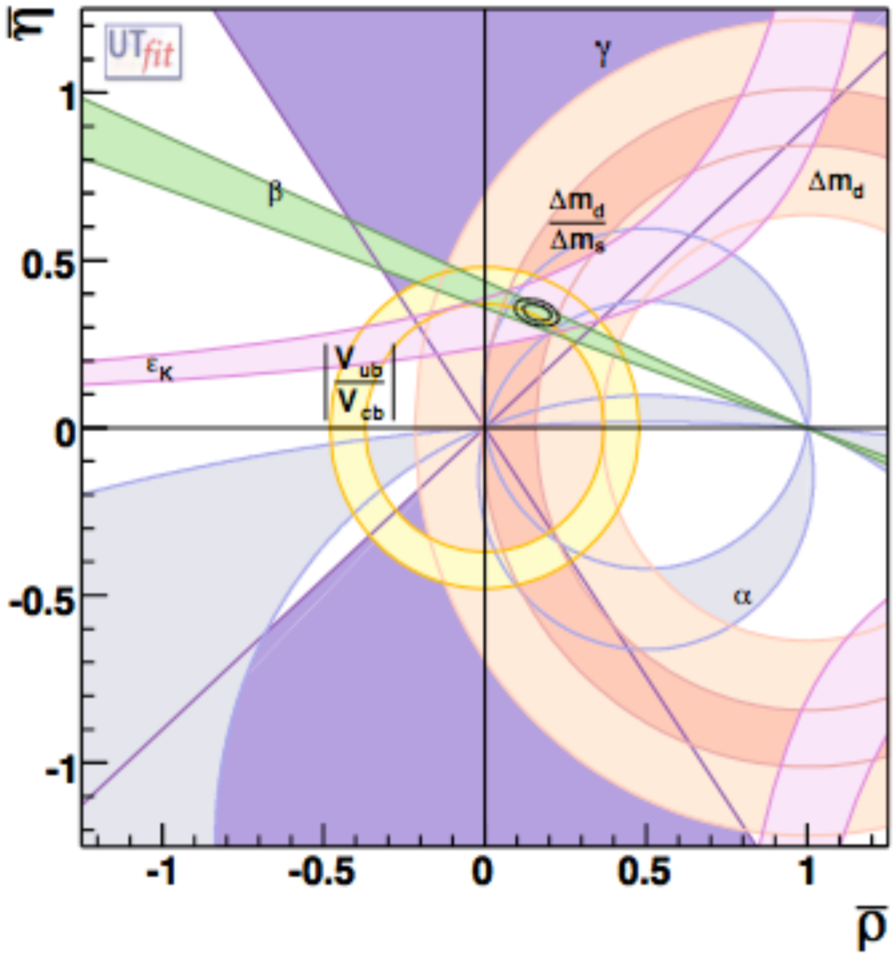
Most precise measurement of $|V_{td}/V_{ts}|$

$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.2060 \pm 0.0007\,(\Delta m_s)^{+0.0081}_{-0.0060}\,(\Delta m_d + \xi)$$

$$\left|V_{td}/V_{ts}\right| = \lambda\sqrt{(1-\bar{\rho})^2+\bar{\eta}^2}$$

(recall: $V_{ts} = -A\lambda^2$)





$$\Delta m_s = 18.4 \pm 2.4\, ps^{-1} \qquad INDIRECT$$

$$\Delta m_s = 17.77 \pm 0.12\, ps^{-1} \qquad DIRECT$$

ρ = 0.163 ± 0.028

η = 0.344 ± 0.016

A new result (also OK with SM)

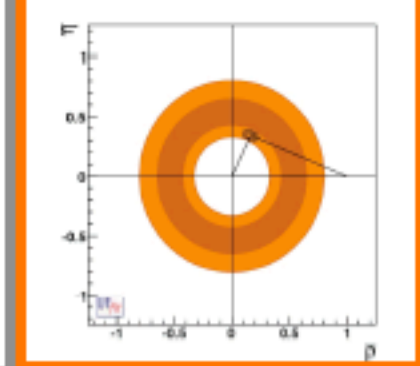
Martinelli

$B \rightarrow \tau\nu_\tau$

BaBar: $(0.88\,^{+0.68}_{-0.67} \pm 0.11) \times 10^{-4}$

Belle: $(1.79\,^{+0.56}_{-0.49}\,^{+0.39}_{-0.46}) \times 10^{-4}$

Average: $(1.31 \pm 0.48) \times 10^{-4}$



Potentially large NP contributions (i.e. MSSM at large tanβ, Isidori & Paradisi)

f_B= (190 ± 14) MeV [UTA]
V_{ub} = (36.7 ± 1.5) 10^{-4} [UTA]

$BR(B \rightarrow \tau\nu_\tau) = (0.89 \pm 0.16) \times 10^{-4}$
(Best SM prediction)

f_B= (189 ± 27) MeV [LQCD]
V_{ub} = (35.0 ± 4.0) 10^{-4} [Exclusive]

$BR(B \rightarrow \tau\nu_\tau) = (0.84 \pm 0.30) \times 10^{-4}$

(Independent from other NP effects)

f_B= (189 ± 27) MeV [LQCD]
V_{ub} = (44.9 ± 3.3) 10^{-4} [Inclusive]

$BR(B \rightarrow \tau\nu_\tau) = (1.39 \pm 0.44) \times 10^{-4}$

From BR($B \rightarrow \tau\nu_\tau$) and V_{ub}(UTA): $f_B = (237 \pm 37)$ MeV

Adding effective operators to SM generally leads to very large Λ

$$M(B_d\text{-}\bar{B}_d) \sim \; c_{SM}\frac{(y_t\, V_{tb}{}^{*} V_{td})^2}{16\,\pi^2 M_W{}^2} + c_{new}\frac{1}{\Lambda^2}$$

If $c_{new} \sim c_{SM} \sim 1$

Isidori

$\Lambda > 10^4$ TeV for $O^{(6)} \sim (\bar{s}\,d)^2$

$[\,K^0\text{-}\bar{K}^0$ mixing $]$

$\Lambda > 10^3$ TeV for $O^{(6)} \sim (\bar{b}\,d)^2$

$[\,B^0\text{-}\bar{B}^0$ mixing $]$

But the hierarchy problem demands Λ in the few TeV range

only assuming $c_{NP} \sim (y_t\, V_{tb}{}^{*} V_{td})^2$ (or anyway small)

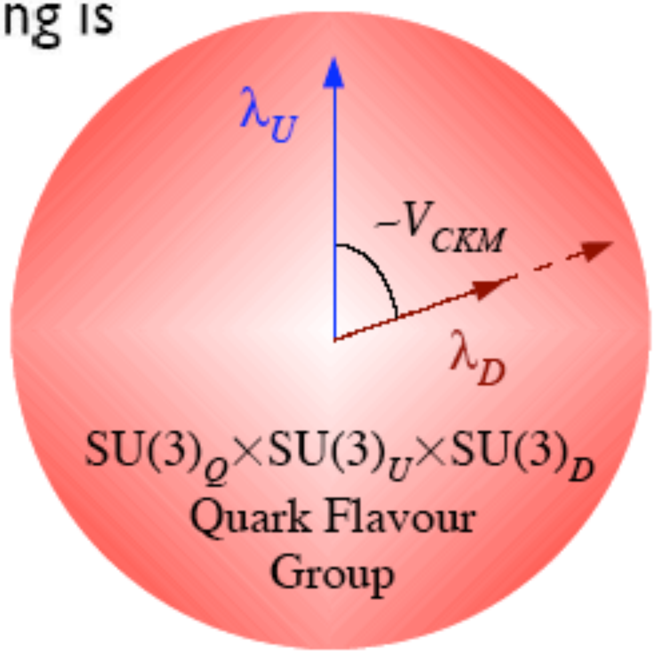
we get a bound on Λ in the TeV range

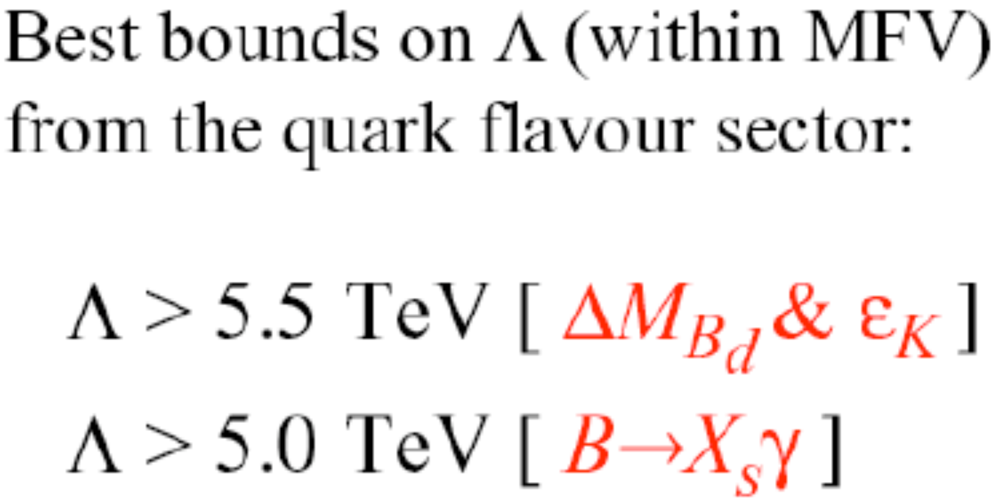
eg in Minimal Flavour Violation (MFV) models

D'Ambrosio, Giudice, Isidori, Strumia'02

Minimal Flavor Violation (MFV)

- Quark sector in SM, in absence of masses has large flavor (global) symmetry: $\boxed{G_F = SU(3)^3 \times U(1)^2}$
- Symmetry is only broken by Yukawa interactions, parametrized by couplings λ_U and λ_D
- MFV: all breaking of G_F must transform as these
- When going to mass eigenstate basis, all mixing is parametrized by CKM and GIM is automatic
  - Adding more Higgs doublets we can change the relative normalization of λ_U & λ_D (controlled by tanβ)
  - Adding more *spurions* (new sources of flavour symmetry breaking) ⇒ next-to-MFV…

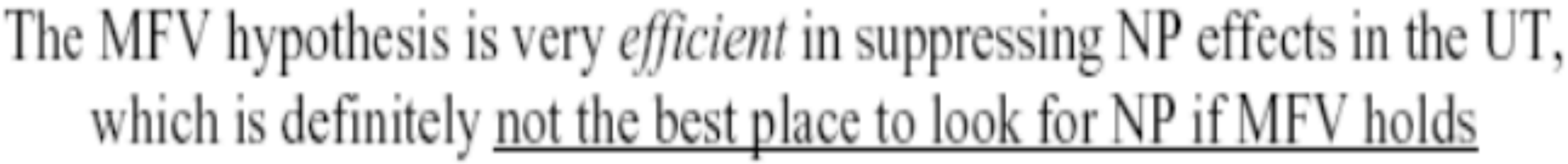




Best bounds on Λ (within MFV)
from the quark flavour sector:

$$\Lambda > 5.5 \text{ TeV } [\ \Delta M_{B_d} \& \ \varepsilon_K\ ]$$

$$\Lambda > 5.0 \text{ TeV } [\ B \to X_s \gamma\ ]$$



The MFV hypothesis is very *efficient* in suppressing NP effects in the UT, which is definitely not the best place to look for NP if MFV holds

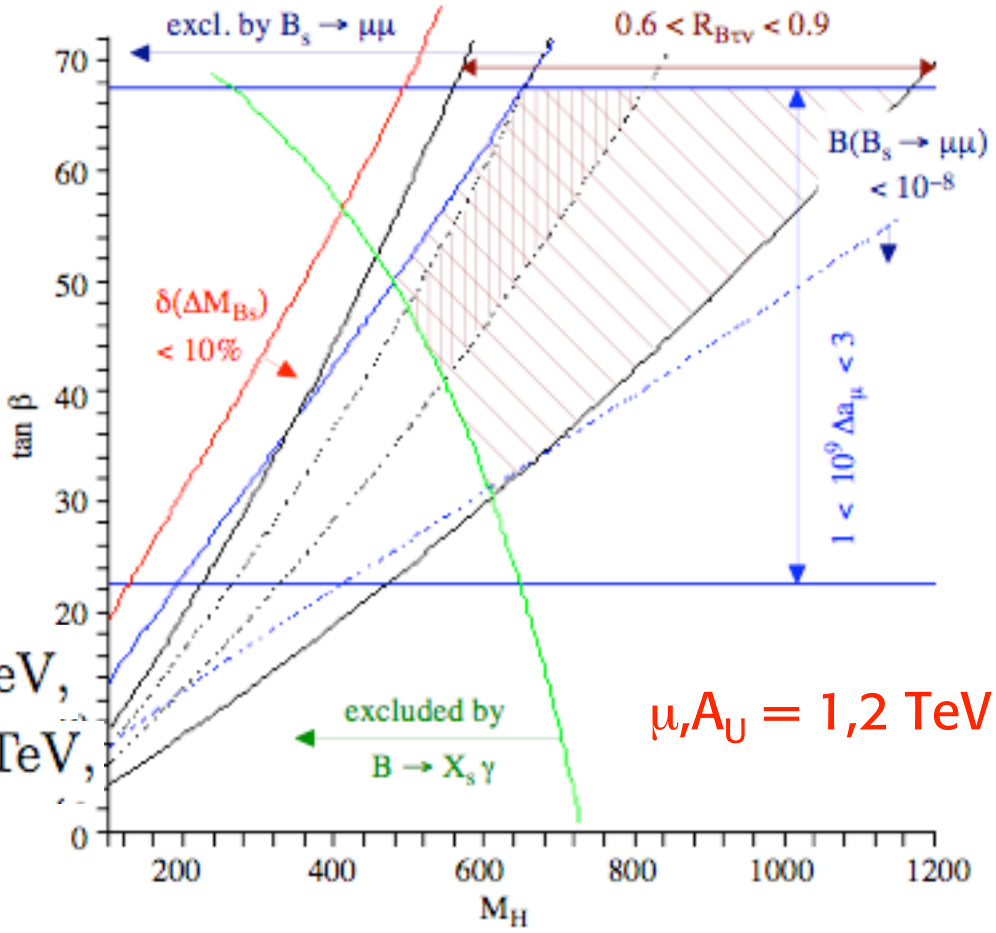
Isidori

Isidori, Paradisi'06

MSSM with MFV and large tanβ

Can fix $(g-2)_\mu$ compatible with $b \to s\gamma$

$B \to \tau\nu$,...



$$M_{\tilde{q}} = 1 \text{ TeV},$$
$$M_{\tilde{\ell}} = 0.5 \text{ TeV},$$

$\mu, A_U = 1,2$ TeV

$B(B \to X_s\gamma)_{exp} = (3.55 \pm 0.26)\ 10^{-4}$ $(E_\gamma > 1.6 \text{ GeV})$

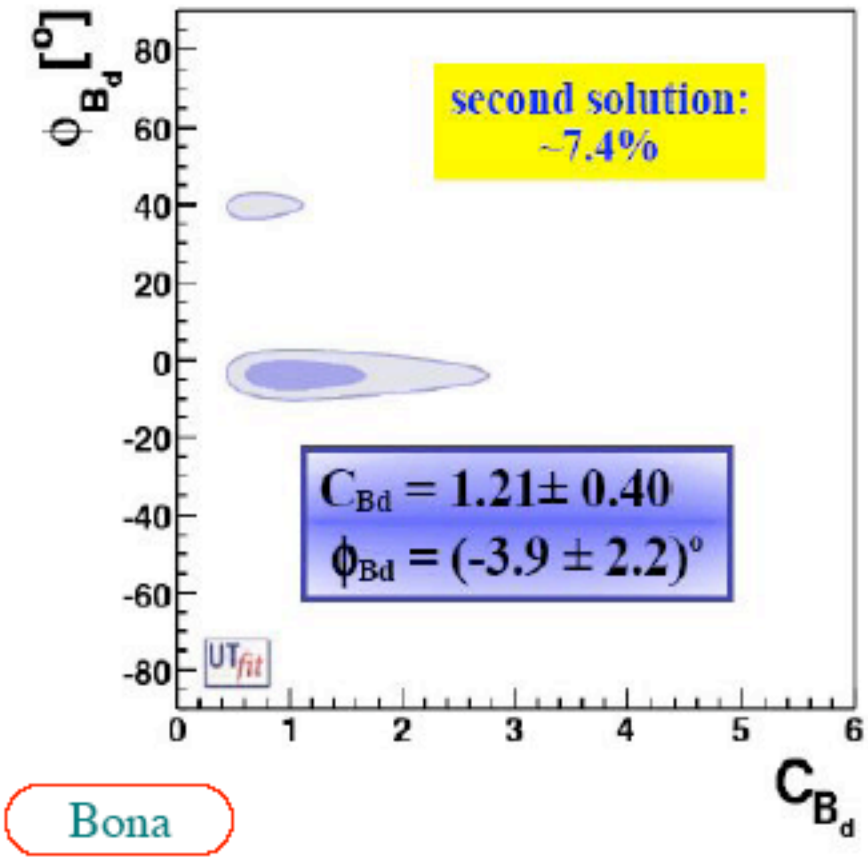
$B(B \to X_s\gamma)_{SM} = (3.15 \pm 0.23)\ 10^{-4}$ $(E_\gamma > 1.6 \text{ GeV})$

Misiak et al '06

Examples of Model-independent fits:

$$C_{B_q} e^{2i\phi_{B_q}} = r_q^2 e^{2i\theta_q} = \frac{\langle \bar{B}_q^0 | M_{12}^{SM+NP} | B_q^0 \rangle}{\langle \bar{B}_q^0 | M_{12}^{SM} | B_q^0 \rangle}$$

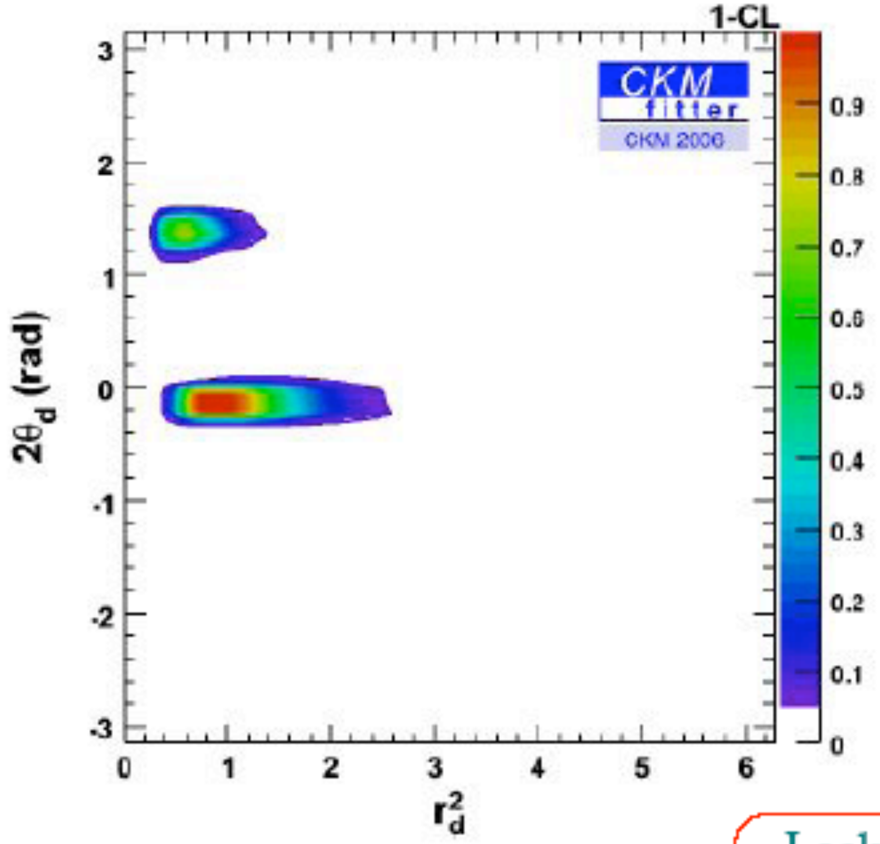
New physics in ΔF=2
and negligible NP contributions in
tree-level observables
(used to determine the CKM matrix)



second solution: ~7.4%

C_{Bd} = 1.21± 0.40
ϕ_{Bd} = (-3.9 ± 2.2)°

Bona



Lacker

Masiero

What to make of this triumph of the CKM pattern in flavor tests?

New Physics at the Elw. Scale is Flavor Blind
CKM exhausts the flavor changing pattern at the elw. Scale →

MINIMAL FLAVOR VIOLATION

MFV : Flavor originates only from the SM Yukawa coupl.

New Physics introduces

NEW FLAVOR SOURCES in addition to the CKM pattern. They give rise to contributions which are <20% in the "flavor observables" which have already been observed!

B-factories, CDF, D0..... have severely tested the CKM picture
(in the particularly dangerous 3rd generation sector).

The CKM picture is confirmed as the main source of CPV

$H_{NP} < 20\% \, H_{SM}$

$H_{NP} \sim$ loops?
$H_{NP} \sim$ MFV?

This poses strong constraints for models BSM

Not only one needs small NP contributions at the weak scale.
But also to control feedback from high scales thru RGE

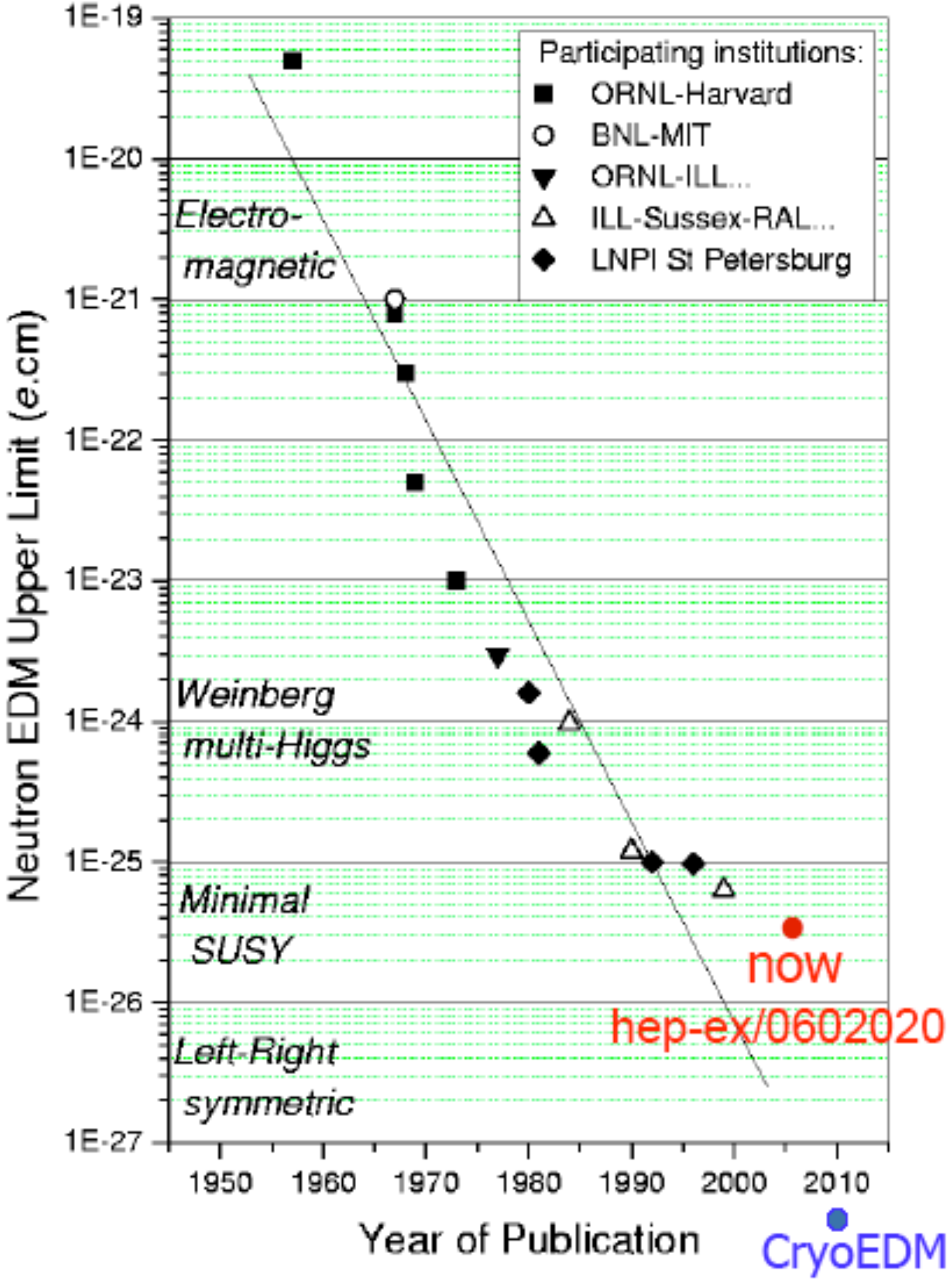
In particular additional constraints on SUSY models.

CPV in FC channels is dominated by CKM

What in flavour conserv. channels?

New limit on nEDM from Grenoble

$|d_n| < 3\ 10^{-26}$ e cm (90%cl)



now

hep-ex/0602020

CryoEDM