Islamabad, March '04

Electroweak Interactions in the SM and Beyond

G. Altarelli
CERN

A short course on the EW Theory

We start from the basic principles and formalism
(a fast recall).
Then we go to present status and challenges

Content

- Formalism of gauge theories
- The SU(2)xU(1) symmetric lagrangian
- The symmetry breaking sector
- Beyond tree level
- Precision tests
- Problems of the SM
- Beyond the SM

G. Altarelli

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

The χ^2 is not great:

χ^2/ndof=25.5/15 (4.4%)

Note: includes NuTeV and APV [not $(g\text{-}2)_\mu$]

Without NuTeV:
(th. error questionable)

χ^2/ndof=16.7/14 (27.3%)

Much better!

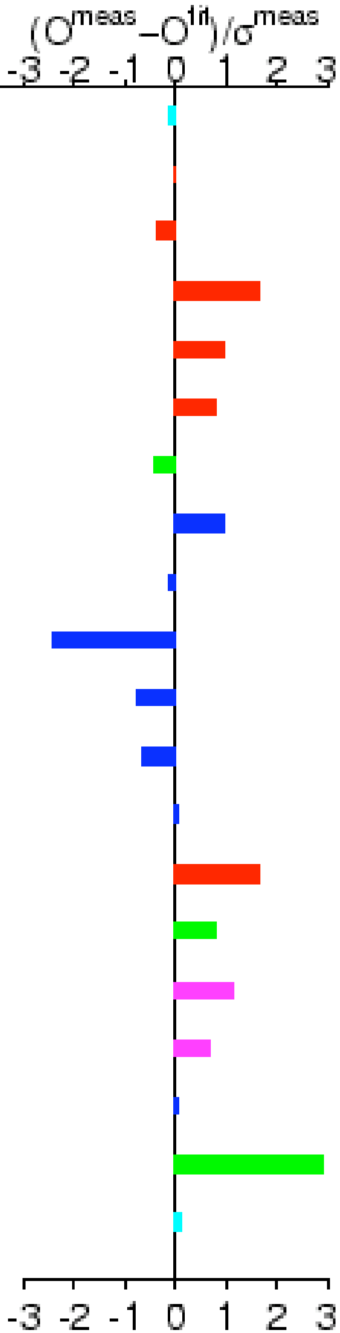
NuTeV →

APV →

G. Altarelli

Winter 2003

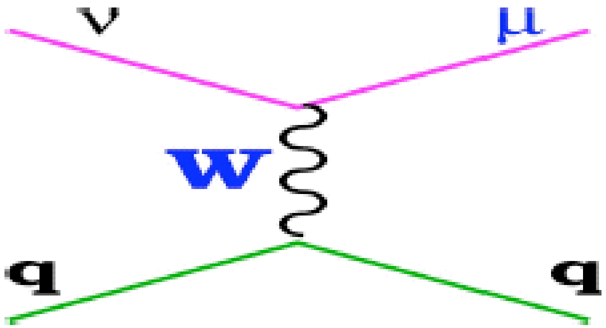
	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.16
m_Z [GeV]	91.1875 ± 0.0021	0.02
Γ_Z [GeV]	2.4952 ± 0.0023	-0.36
σ^0_{had} [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.79
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.42
R_b	0.21644 ± 0.00065	0.99
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.43
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.78
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.07
A_l(SLD)	0.1513 ± 0.0021	1.67
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.82
m_W [GeV]	80.426 ± 0.034	1.17
Γ_W [GeV]	2.139 ± 0.069	0.67
m_t [GeV]	174.3 ± 5.1	0.05
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	2.94
Q_W(Cs)	-72.83 ± 0.49	0.12



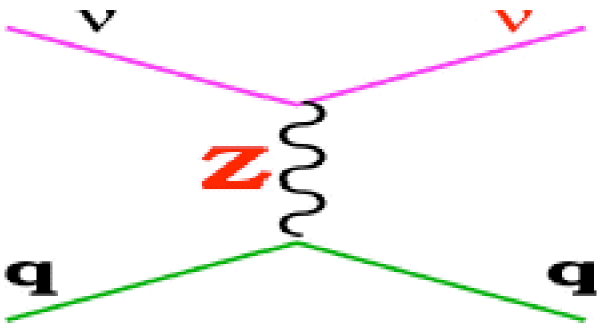
NuTeV Neutrino-Nucleon Scattering

Muon-(anti-)neutrino quark scattering:

charged current (CC)



neutral current (NC)



Paschos-Wolfenstein relation (iso-scalar target):

$$R_- = \frac{\sigma_{NC}(\nu)-\sigma_{NC}(\overline{\nu})}{\sigma_{CC}(\nu)-\sigma_{CC}(\overline{\nu})} = 4g^2_{L\nu}\sum_{q_V}\left[g^2_{Lq}-g^2_{Rq}\right] = \rho_\nu\rho_{ud}\left[\frac{1}{2}-\sin^2\theta_W^{(on-shell)}\right]$$

+ electroweak radiative corrections

Insensitive to sea quarks

Charm effects only through d_V quarks (CKM suppressed)

Need neutrino and anti-neutrino beam!

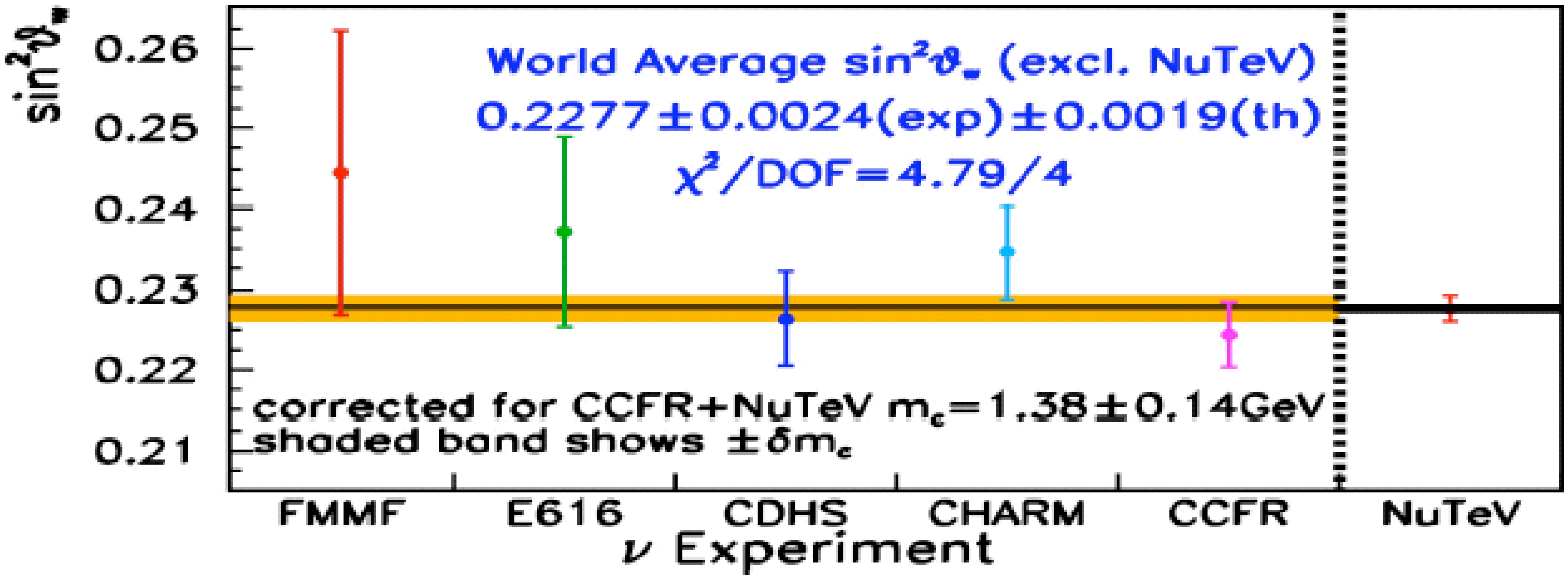
G. Altarelli [copied from Grunewald, Amsterdam '02 talk]

NuTeV's Result

$$\sin^2\theta_W^{(on-shell)} = 1 - \frac{M_W^2}{M_Z^2} = 0.2277 \pm 0.0013(stat.) \pm 0.0009(syst.)$$

$$- \; 0.00022 \frac{M_{top}^2 - (175\,GeV)^2}{(50\,GeV)^2} + 0.00032 \ln \frac{M_{Higgs}}{150\,GeV} \qquad [\rho = \rho_{SM}]$$

Factor two more precise than previous νN world average



Global SM analysis predicts: 0.2227(4) Difference of 3.0 σ!

G. Altarelli [copied from Grunewald, Amsterdam '02 talk]

The NuTeV anomaly probably simply arises from a large underestimation of the theoretical error

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

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

Gambino, LP'03

$s^- = \int dx\, x\, [s(x)-\mathrm{sbar}(x)]$

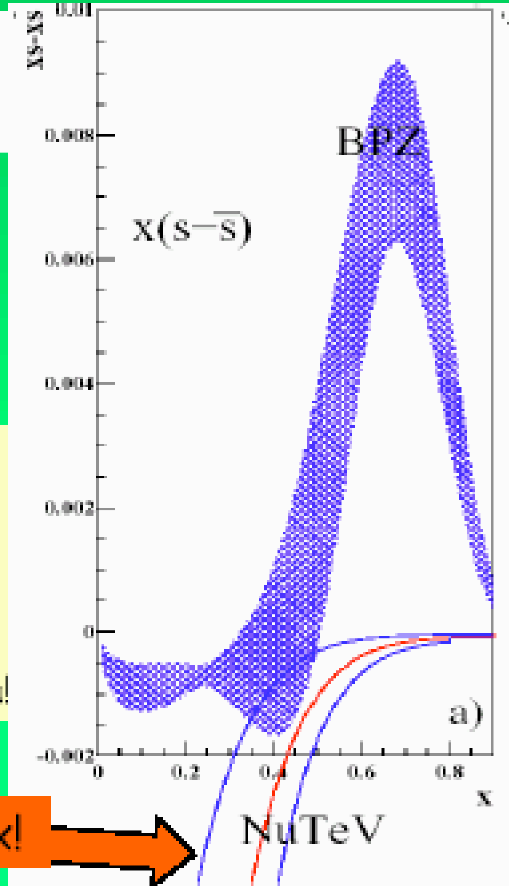
Such a strange asymmetry…(I)

$$R_{PW} = \frac{1}{2} - s_W^2 + \frac{\tilde{g}^2}{Q^-}\left[u^- - d^- + c^- - s^-\right]\{1 + O(\alpha_s)\}$$

Strange quark asymmetry
Non-perturbatively induced by p <-> KΛ
A positive s^- reduces the anomaly

Only ν-induced processes are sensitive to $s^-(x)$

<u>Inclusive ν-DIS</u>
Barone et al (BPZ99) found s^-=0.002
Recently updated (Portheault et al) couldn't access dimuon data!



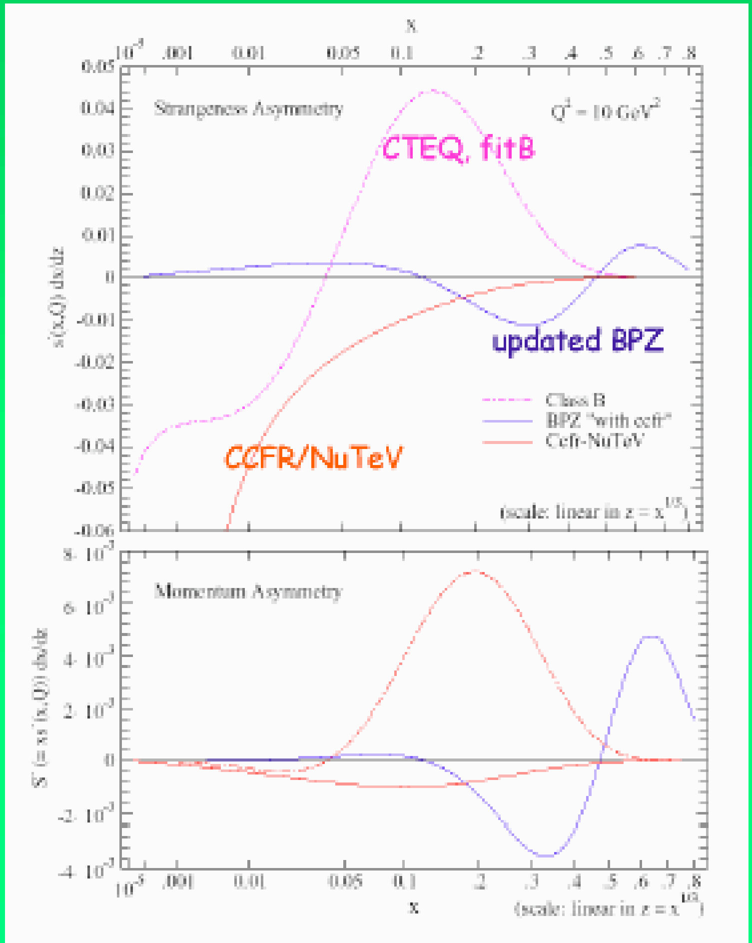
<u>Dimuons (charm production)</u>

NuTeV has found (low x)
s^-=-0.0027±0.0013

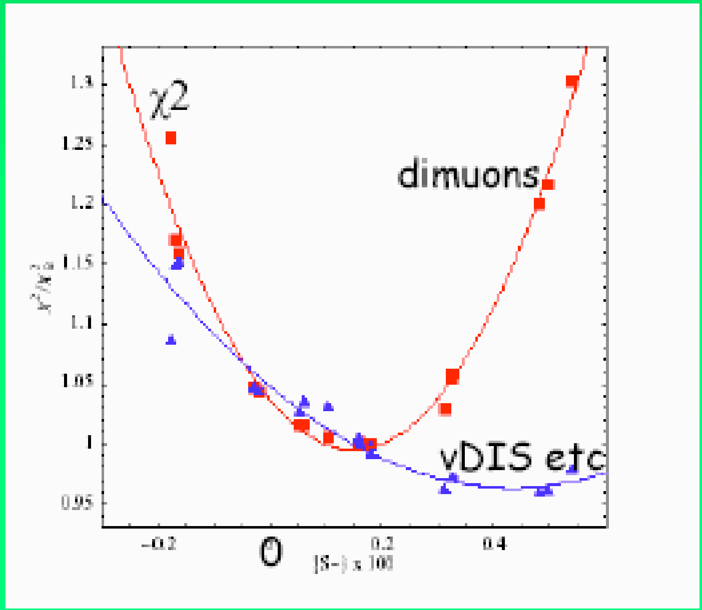
negative s^- at small x!

BUT NuTeV fit to s^-
a) relies on inconsistent parameterization (strangess not conserved)
b) does not fit s^- in the context of global fit

The new CTEQ fit



- includes all available data
- explores full range of parametrns with $S_N=0$
- fits s,sbar together with other pdfs



Most reasonable range 0.001< s- <0.003

Kretzer, Olness, Pumplin, Stump, Tung et al.

A strange end?

- Negative s^- strongly disfavoured, acceptable fits have
  $0.001 < s^- < 0.0031$,
  depending on low-x behavior
  Possible new info from W+charmed jet, lattice

fit	$[S^-] \times 100$	χ^2_{dimuon}	$\chi^2_{inclusive}$	δR^-
B^+	0.540	**1.30**	0.98	-0.0065
A	0.312	1.02	0.97	-0.0037
B	0.160	*1.00*	*1.00*	-0.0019
C	0.103	1.01	1.03	-0.0012
B^-	-0.177	**1.26**	**1.09**	0.0023

Kretzer et al

- Impact on R_{PW} in NuTeV setup estimated wrt to CTEQ s=sbar fit: $0.0012 < \delta s^2_w < 0.0037$
  very likely to carry on to NuTeV analysis

NuTeV error ±0.0016

- NuTeV : a few minor issues open. In my opinion, large sea uncertainties and shift from s^- reduce discrepancy below 2σ

Given present understanding of hadron structure, R_{PW} is no good place for high precision physics

Atomic Parity Violation (APV)

- Q_W is an idealised pseudo-observable corresponding to the naïve value for a N neutron-Z proton nucleus

- The theoretical "best fit" value from ZFITTER is

$$(Q_W)_{th} = -72.880 \pm 0.003$$

- The "experimental" value contains a variety of QED and nuclear effects that keep changing all the time:

Since the 2002 LEP EWWG fit (showing a 1.52σ deviation) a new evaluation of the QED corrections led to

$$(Q_W)_{exp} = -72.83 \pm 0.49$$

Kuchiev, Flambaum '02
Milstein et al '02

So in this very moment (winter '04) APV is OK!

G. Altarelli

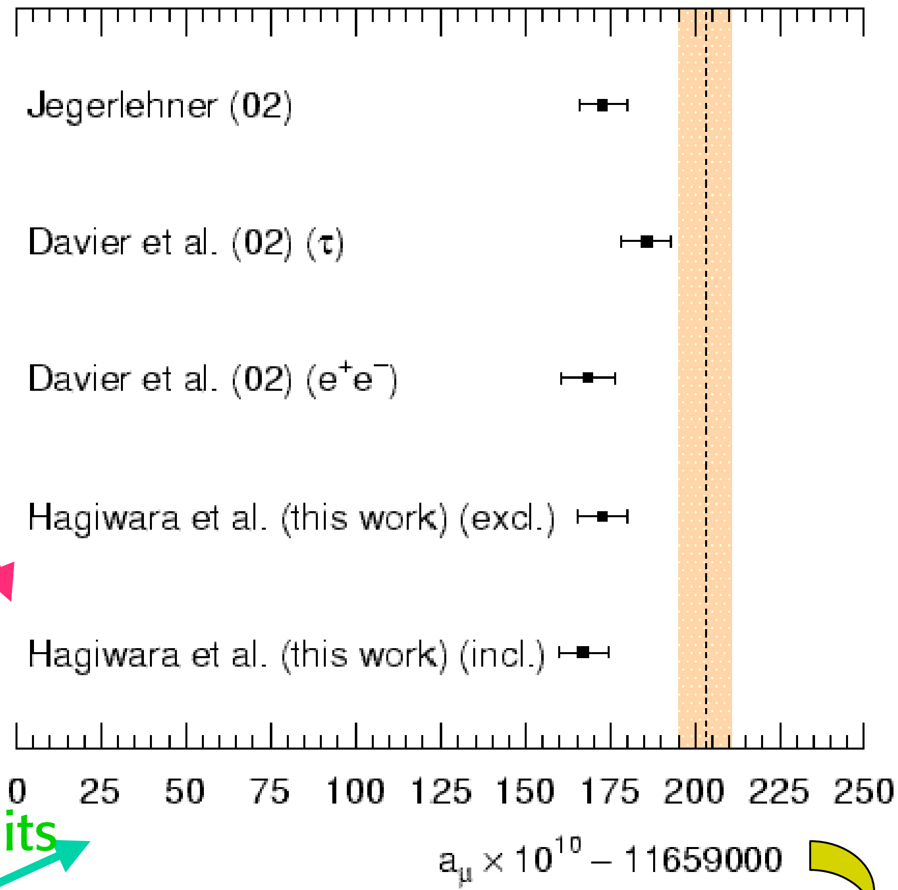
$(g\text{-}2)_\mu$ ~3σ discrepancy shown by the BNL'02 data

In 2002:

(Numbers in units 10^{-10})

LO hadr.	688.8 ± 6.2	HMNT, 'excl.'
	$683.1 \pm 5.9 \pm 2.0_{rad}$	HMNT, 'incl.'
full a_μ	11659172.6 ± 7.7	'excl.'
	11659166.9 ± 7.4	'incl.'
BNL E821	11659203 ± 8	new world av.
		(0.7 ppm!)
EXP–TH	30.4 ± 11.1	$\sim 2.7\sigma$, 'excl.'
	36.1 ± 10.9	$\sim 3.3\sigma$, 'incl.'

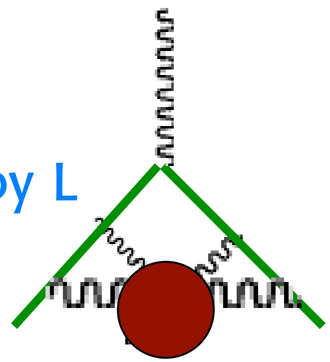
Th. and Exp. accuracy comparable!

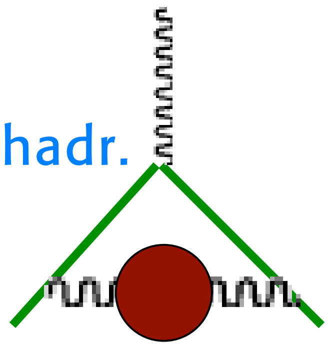


EW ~ 15.2±0.4
LO hadr ~ 683.1±6.2
NLO hadr ~ -10±0.6
Light-by-Light ~ 8±4
(was ~ -8.5±2.5)

These units

G. Altarelli





Gambino, LP'03

In '03 the deviation went down (new X-section measurements)

The spectral function from e^+e^-

Tau data below 1.8GeV

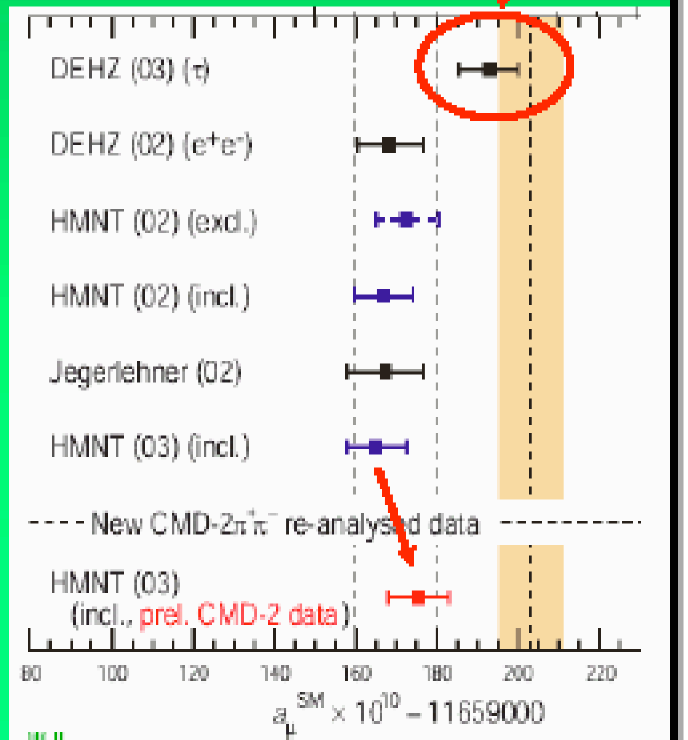
Final CMD-2 π π data (2002) 0.6% syst error!
CMD-2 have recently reanalyzed their data

Hagiwara et al (HMNT) NEW result:
$a_\mu^{had,LO}=691.7\pm5.8_{exp}\pm2.0_{r.c.}$

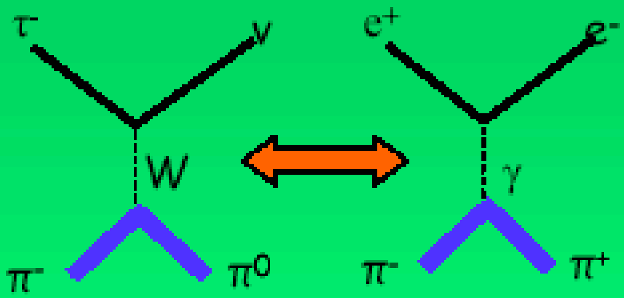
This translates in a ~2-2.5σ discrepancy depending on which e^+e^- analysis

Using τ data below 1.8 GeV Davier at al (DEHZ)
$a_\mu^{had,LO}=709.0\pm5.1_{exp}\pm1.2_{r.c}\pm2.8_{SU(2)}$

Good agreement between Aleph, CLEO, Opal τ data

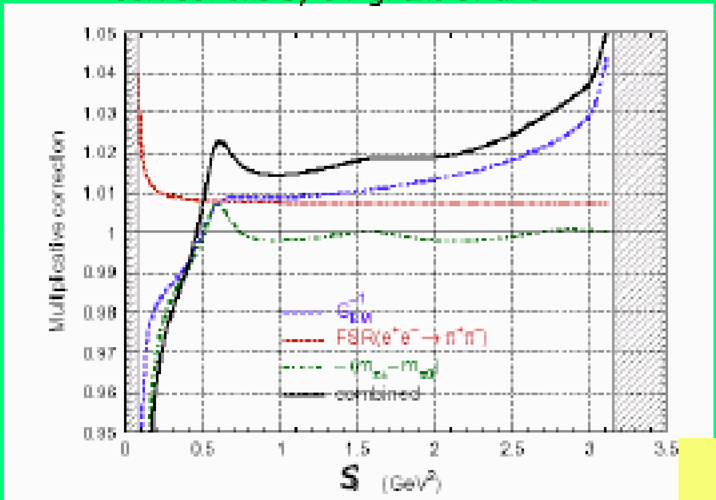


The spectral function from τ decays



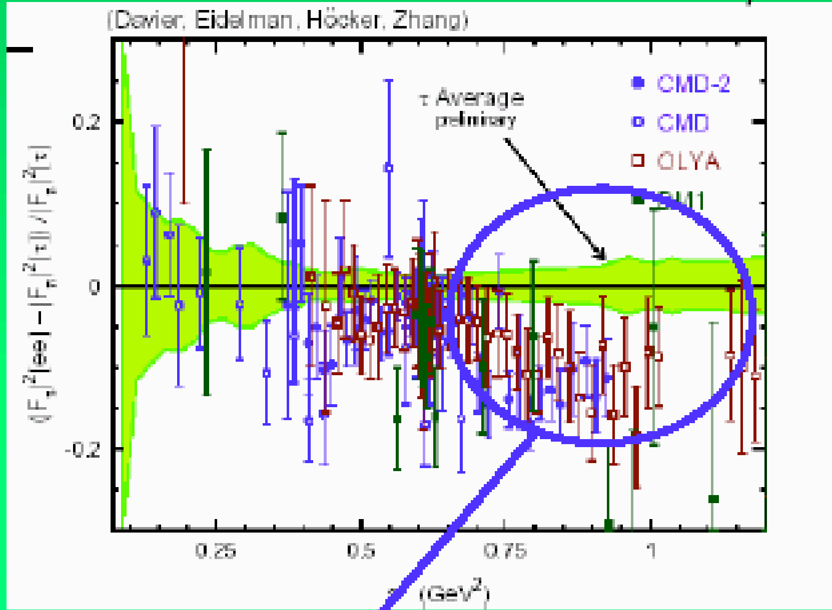
CVC + isospin symmetry

Corrections by Cirigliano et al 02



Corrections applied to τ data

NB *CMD-2* before reanalysis



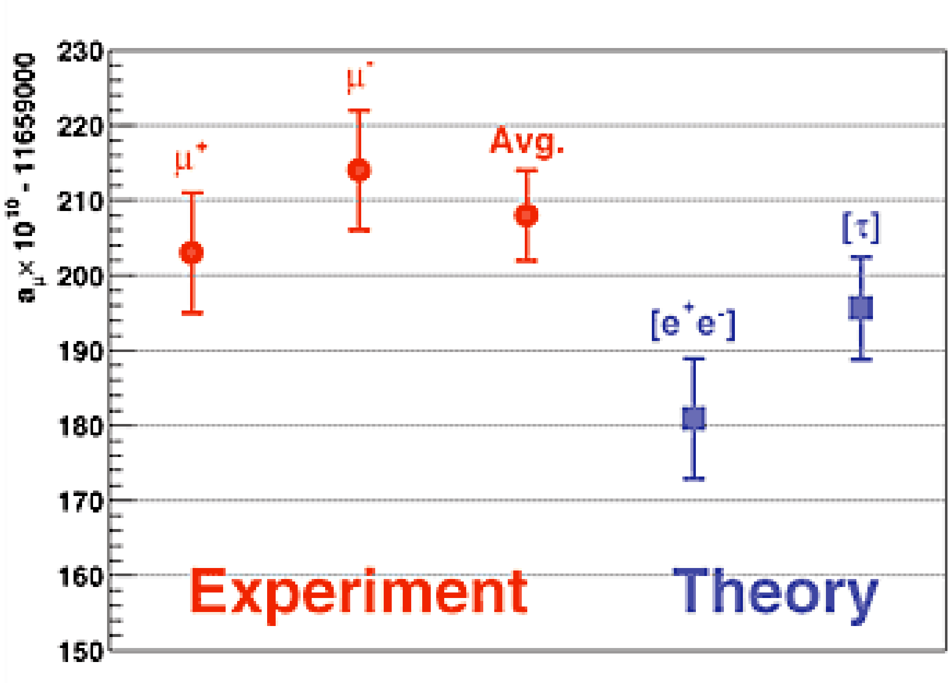
Relative difference between π form f. from τ and e^+e^-

>5% difference! cannot be isospin breaking. Needs further study. Data?

After new CMD-2 for $\Delta_{\pi\pi}$=(11-13±7) 10^{-10}(was 21)

2004 New   New results from BNL

- μ^- measured (was μ^+)
- discrepancy up again to ~3σ



It looks to me peculiar that one cannot find ~5M$ to continue this experiment

G. Altarelli

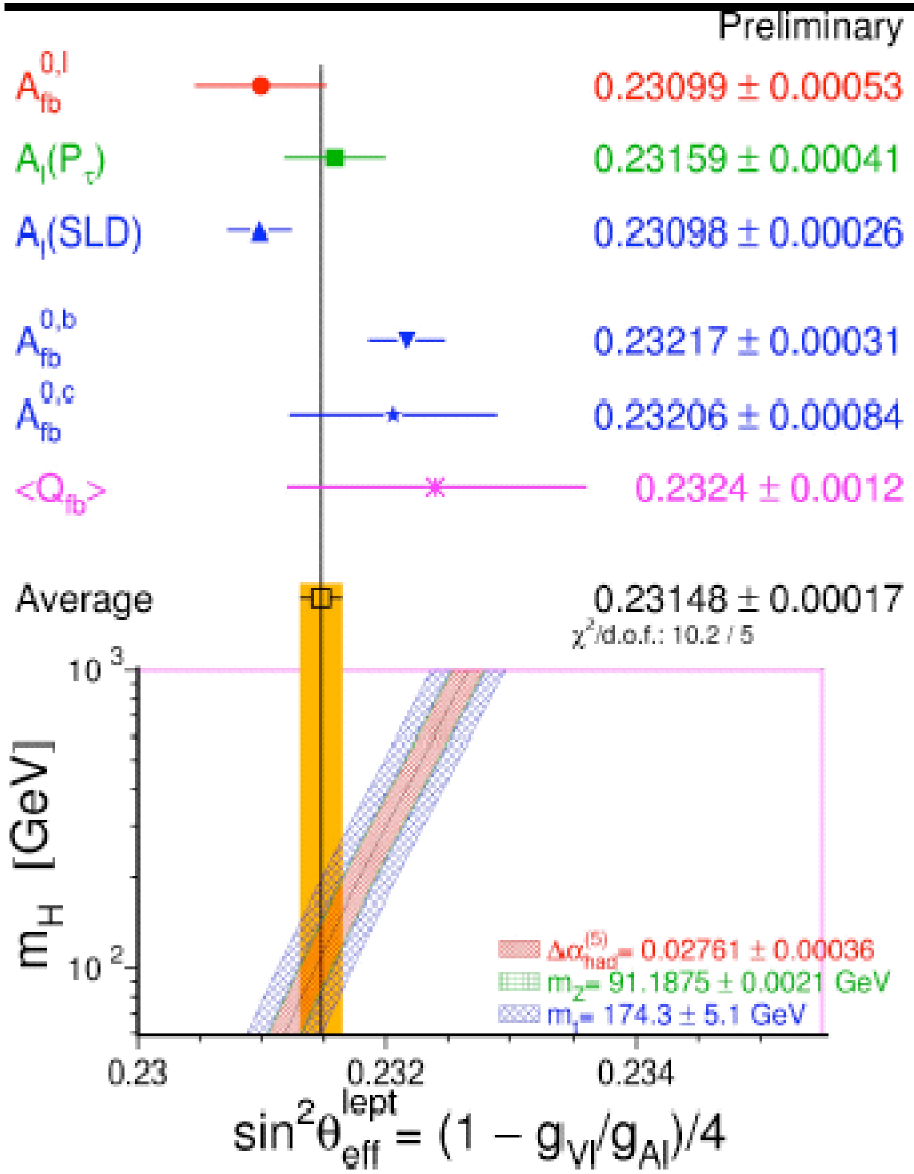
Question Marks on EW Precision Tests

- The measured values of $\sin^2\theta_{eff}$ from leptonic (A_{LR}) and from hadronic (A^b_{FB}) asymmetries are ~3σ away
- The measured value of m_W is somewhat high
- The central value of m_H (m_H=83+50-33 GeV) from the fit is below the direct lower limit (m_H114.4 GeV at 95%)
  [more so if $\sin^2\theta_{eff}$ is close to that from leptonic (A_{LR}) asymm. m_H < ~110 GeV]

Chanowitz;
GA, F. Caravaglios, G. Giudice, P. Gambino, G. Ridolfi

Hints of new physics effects??

Comparison of all Z-Pole Asymmetries



Effective electroweak mixing angle:

$\sin^2\Theta_{eff}$ = 0.23148 (17)

χ^2/ndof = 10.2/5 [7.0%]

A-posteriori observation:

0.23113 (21) leptons
0.23217 (29) hadrons

But is really:

A_l(SLD) vs. A_{fb}b(LEP)

Both:

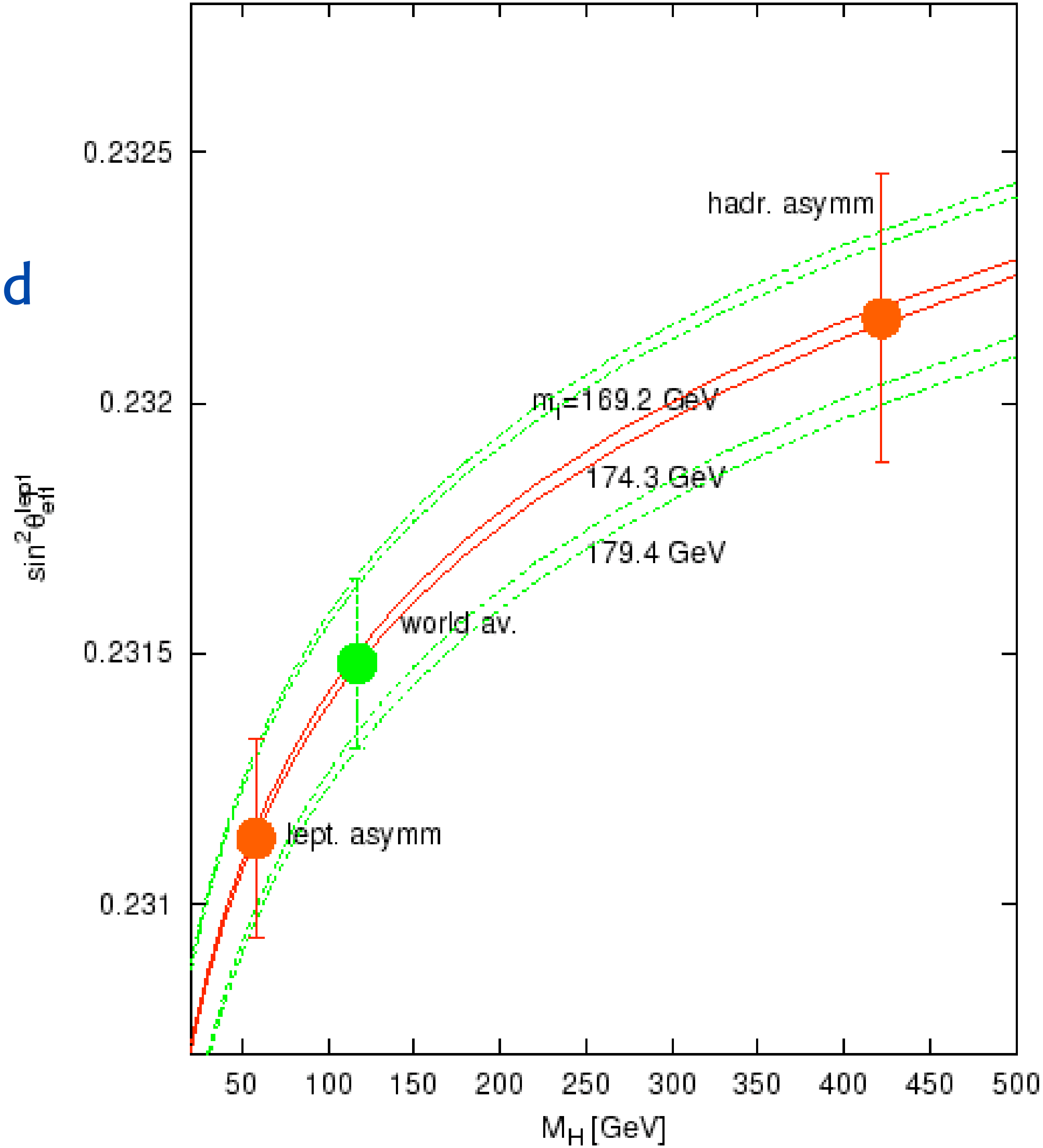
2.9 σ difference

G. Altarelli

[copied from Grunewald, Amsterdam '02 talk]

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

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



G. Altarelli

Question Marks on EW Precision Tests

- The measured values of $\sin^2\theta_{eff}$ from leptonic (A_{LR}) and from hadronic (A^b_{FB}) asymmetries are $\sim 3\sigma$ away
- The measured value of m_W is somewhat high
- The central value of m_H (m_H=83+50-33 GeV) from the fit is below the direct lower limit (m_H114.4 GeV at 95%)
[more so if $\sin^2\theta_{eff}$ is close to that from leptonic (A_{LR}) asymm. $m_H < \sim 110$ GeV]

Chanowitz;
GA, F. Caravaglios, G. Giudice, P. Gambino, G. Ridolfi

Hints of new physics effects??

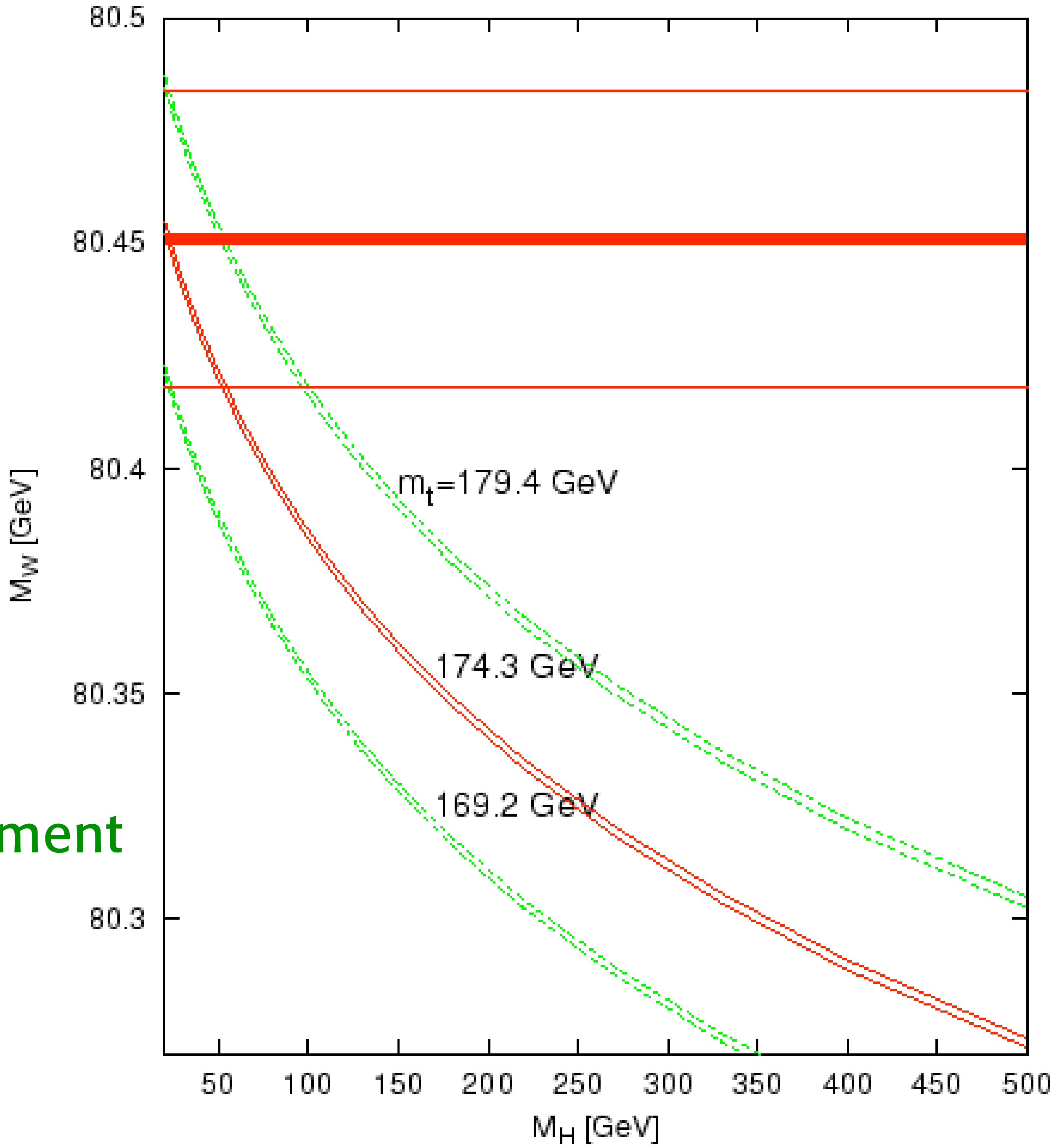
G. Altarelli

Plot m_W vs m_H

m_W points to a light Higgs

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

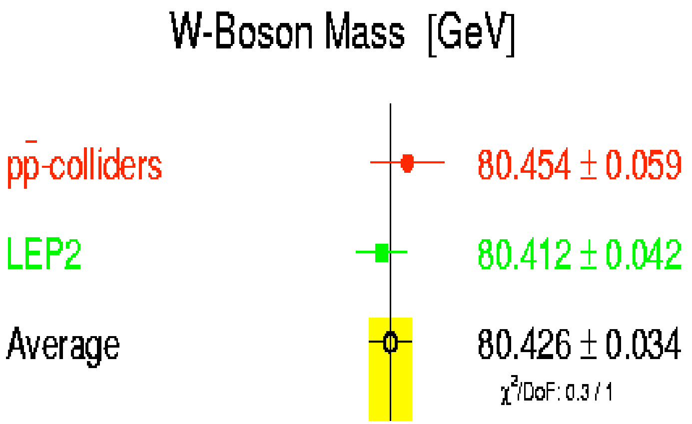
Note that if m_t is larger m_H increases → better agreement with bound m_H>114 GeV



G. Altarelli

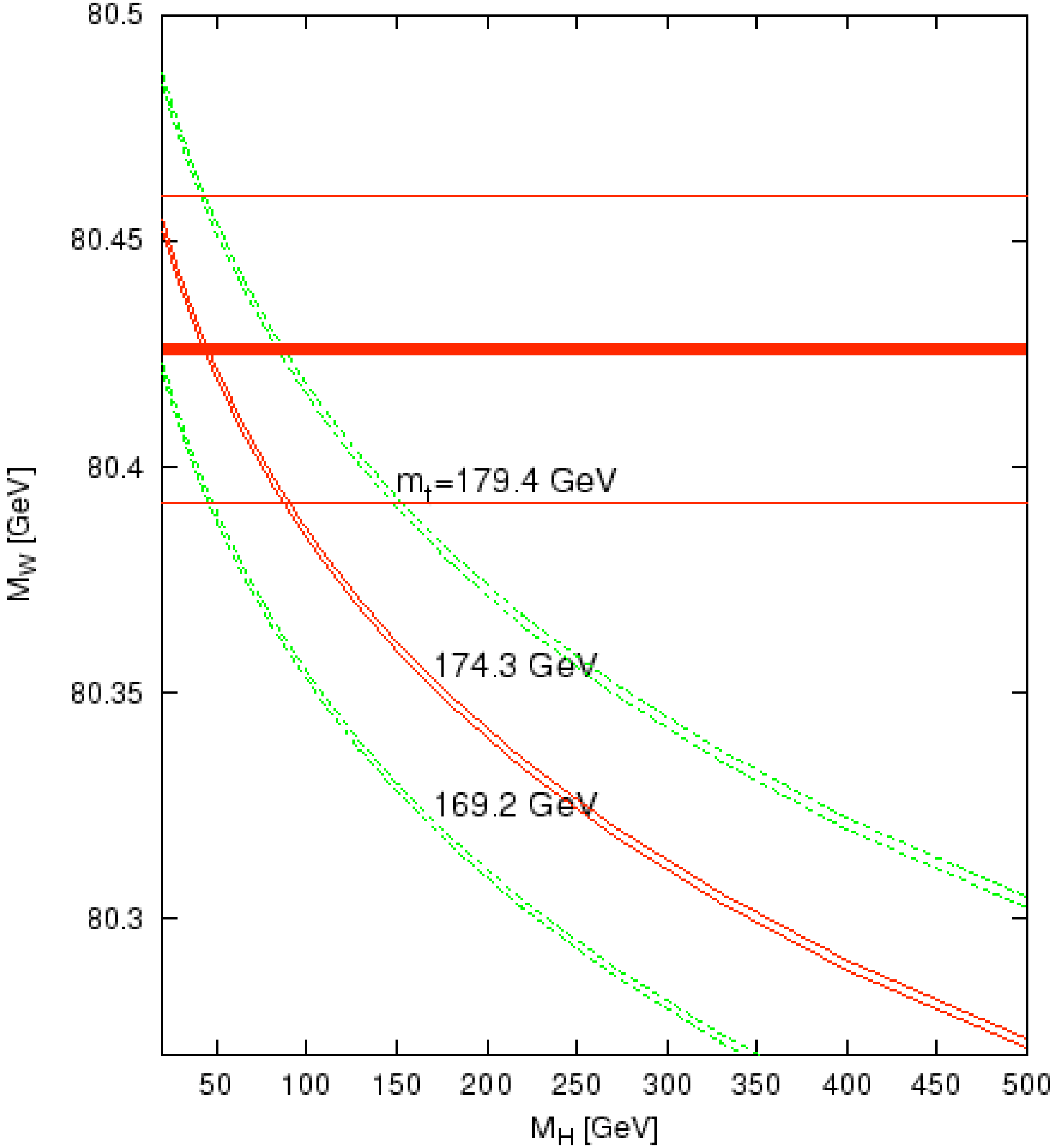
New developments (winter '03)

m_W went down
(ALEPH: -79 MeV).
Still the central value points to m_H~50 GeV



Now: 80.426±0.034
Was: 80.449±0.034

G. Altarelli



Question Marks on EW Precision Tests

- The measured values of $\sin^2\theta_{eff}$ from leptonic (A_{LR}) and from hadronic (A^b_{FB}) asymmetries are ~3σ away
- The measured value of m_W is somewhat high
- The central value of m_H (m_H=83+50-33 GeV) from the fit is below the direct lower limit (m_H114.4 GeV at 95%) [more so if $\sin^2\theta_{eff}$ is close to that from leptonic (A_{LR}) asymm. m_H < ~110 GeV]

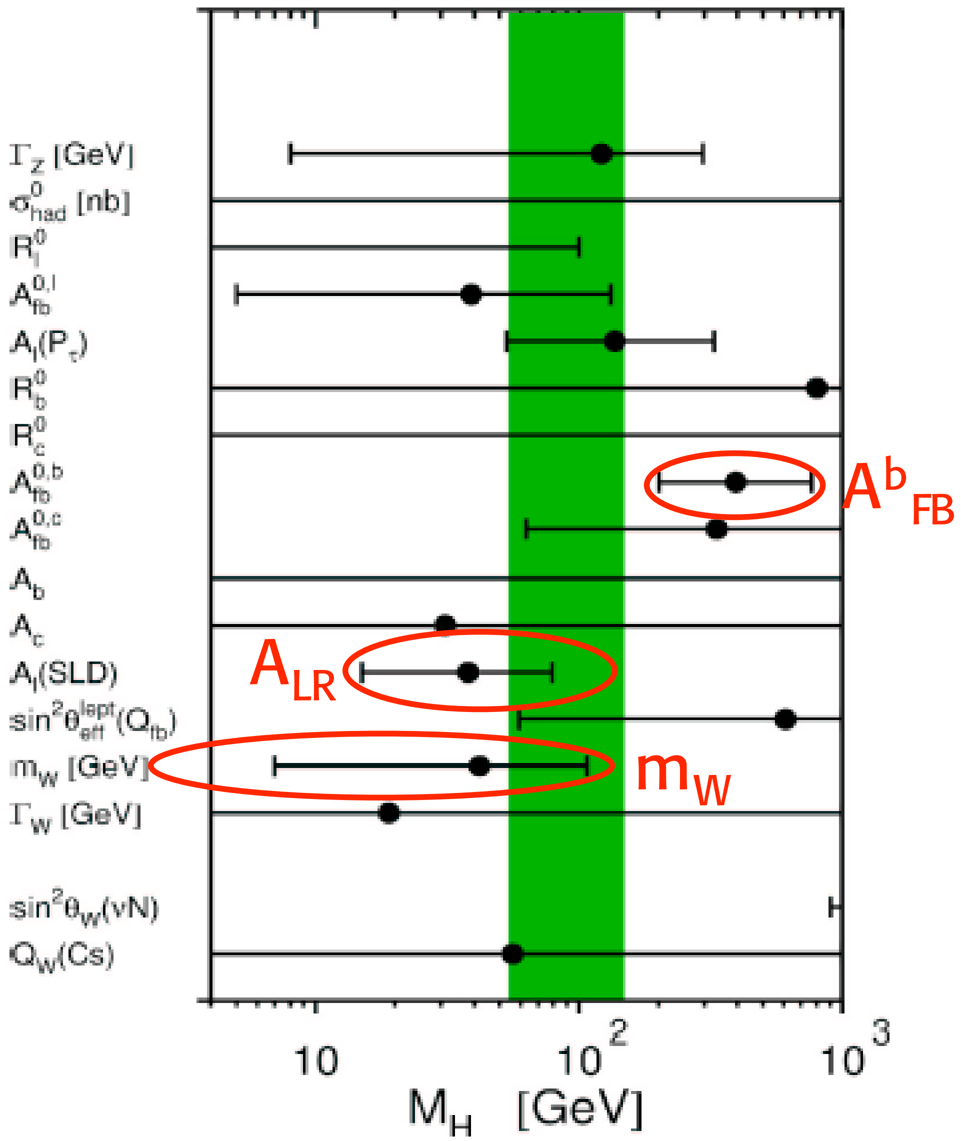
Chanowitz;
GA, F. Caravaglios, G. Giudice, P. Gambino, G. Ridolfi

Hints of new physics effects??

Sensitivities to m_H

The central value of m_H would be even lower if not for A^b_{FB}

One problem helpes the other:
A^b_{FB} vs A_{LR} confusion is somewhat hiding the problem of A_{LR}, m_W clashing with m_H>114.4 GeV



G. Altarelli

Some indicative fits

Note: here 2001 data

Most important observables:
m_t, m_W, Γ_l, R_b, $\alpha_s(m_Z)$, α_{QED}, $\sin^2\theta_{eff}$

Taking $\sin^2\theta_{eff}$ from leptonic or hadronic asymmetries as separate inputs, $[\sin^2\theta_{eff}]_l$ and $[\sin^2\theta_{eff}]_h$, with α^{-1}_{QED}=128.936±0.049 (BP'01) we obtain:

χ^2/ndof=18.4/4, CL=0.001; $m_{Hcentral}$=100 GeV,
m_H< 212 GeV at 95%

Taking $\sin^2\theta_{eff}$ from only hadronic asymm. $[\sin^2\theta_{eff}]_h$

χ^2/ndof=15.3/3, CL=0.0016;

Taking $\sin^2\theta_{eff}$ from only leptonic asymm. $[\sin^2\theta_{eff}]_l$

χ^2/ndof=2.5/3, CL=0.33; $m_{Hcentral}$=42 GeV,
m_H< 109 GeV at 95%

Much better χ^2 but clash with direct limit!

G. Altarelli

- It is not simple to explain the difference $[\sin^2\theta]_l$ vs $[\sin^2\theta]_h$ in terms of new physics.
A modification of the Z->bb vertex (but R_b and A_b(SLD) look ~normal)? →

- Probably it arises from an experimental problem

- Then it is very unfortunate because $[\sin^2\theta]_l$ vs $[\sin^2\theta]_h$ makes the interpretation of precision tests ambigous

Choose $[\sin^2\theta]_h$: bad χ^2 (clashes with m_W, …)
Choose $[\sin^2\theta]_l$: good χ^2, but m_H clashes with direct limit

- In the last case, SUSY effects from light s-leptons, charginos and neutralinos, with moderately large $\tan\beta$ can solve the m_H problem and lead to a better fit of the data

GA, F. Caravaglios, G. Giudice, P. Gambino, G. Ridolfi

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

Unlikely!! (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:

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

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

$$g_L^2 \approx 0.72 >> g_R^2 \approx 0.02$$

$$(A_b)_{SM} \approx 0.936$$

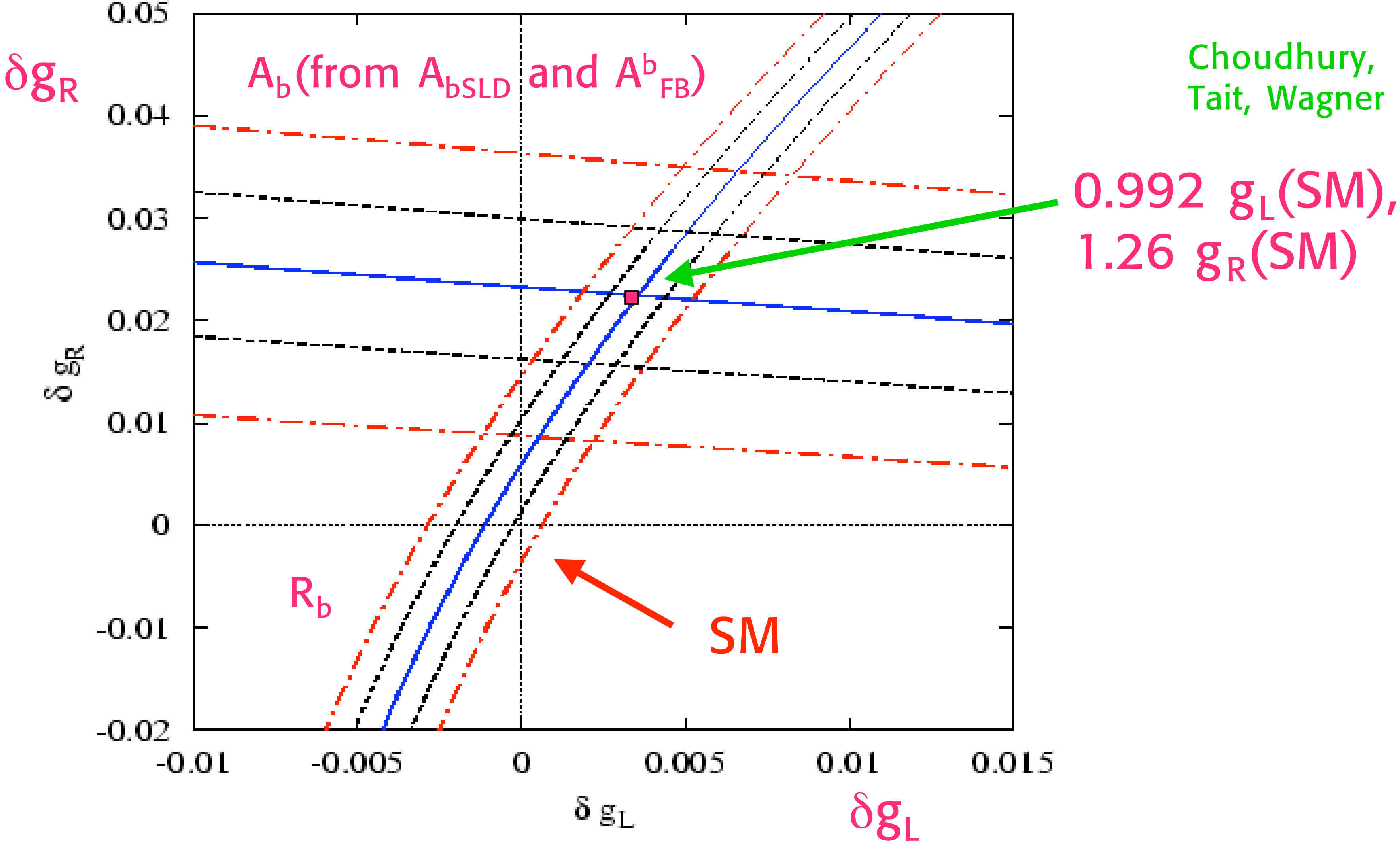
From A^b_{FB}=0.0995±0.0017, using $[\sin^2\theta]_{lept}$ =0.23113±0.00020 or A_e=0.1501±0.0016, one obtains A_b=0.884±0.018

$(A_b)_{SM} - A_b$ = 0.052 ± 0.018 -> 2.9 σ

A large δg_R needed (by about 30%!)

G. Altarelli

But note: $(A_b)_{SLD}$ = 0.922±0.020, R_b=0.21644±0.00065 (R_{bSM}~0.2157)



A possible model involves mixing of the b quark with a vectorlike doublet (ω,χ) with charges (-1/3, -4/3)

G. Altarelli

- It is not simple to explain the difference $[\sin^2\theta]_l$ vs $[\sin^2\theta]_h$ in terms of new physics.

A modification of the Z->bb vertex (but R_b and A_b(SLD) look ~normal)?

- Probably it arises from an experimental problem

- Then it is very unfortunate because $[\sin^2\theta]_l$ vs $[\sin^2\theta]_h$ makes the interpretation of precision tests ambigous

Choose $[\sin^2\theta]_h$: bad χ^2 (clashes with m_W, …)
Choose $[\sin^2\theta]_l$: good χ^2, but m_H clashes with direct limit

- In the last case, SUSY effects from light s-leptons, charginos and neutralinos, with moderately large $\tan\beta$ can solve the m_H problem and lead to a better fit of the data

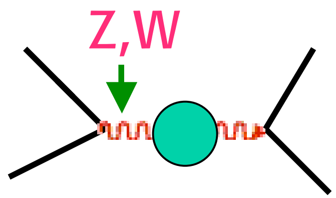
GA, F. Caravaglios, G. Giudice, P. Gambino, G. Ridolfi

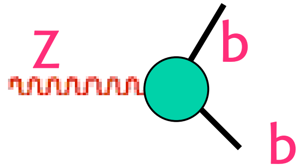
EW DATA and New Physics

For an analysis of the data beyond the SM we use the ε formalism GA, R.Barbieri, F.Caravaglios, S. Jadach

One introduces ε_1, ε_2, ε_3, ε_b such that:

- Focus on pure weak rad. correct's, i.e. vanish in limit of tree level SM + pure QED and/or QCD correct's
[a good first approximation to the data]

- Are sensitive to vacuum pol. ε_1, ε_2, ε_3 →


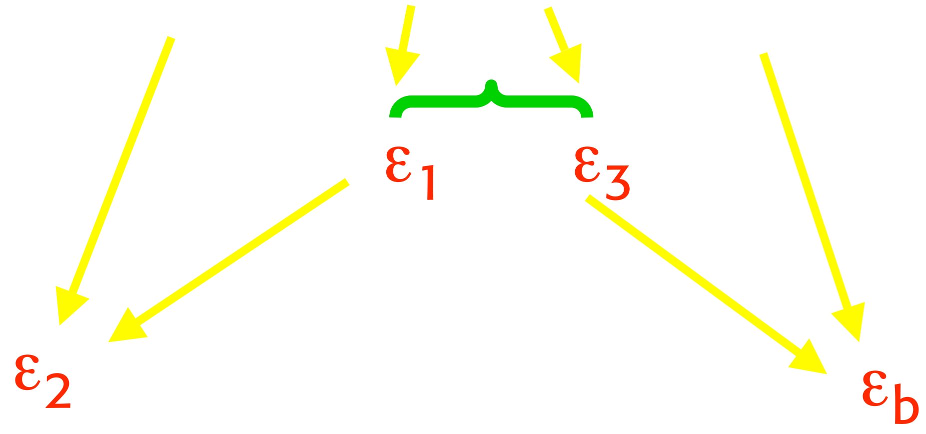
and Z->bb vertex corr.s
(but also include non oblique terms) ε_b →


- Can be measured from the data with no reference to m_t and m_H (as opposed to S, T, U -> ε_3, ε_1, ε_2)

G. Altarelli

One starts from a set of defining observables:

$$O_i = m_W/m_Z, \quad \Gamma_\mu, \quad A^\mu_{FB}, \quad R_b$$



$$O_i[\varepsilon_k] = O_i^{\text{"Born"}}[1 + A_{ik}\,\varepsilon_k + \ldots]$$

$O_i^{\text{"Born"}}$ includes pure QED and/or QCD corr's.

A_{ik} is independent of m_t and m_H

Assuming lepton universality: Γ_μ, A^μ_{FB} --> Γ_l, A^l_{FB}

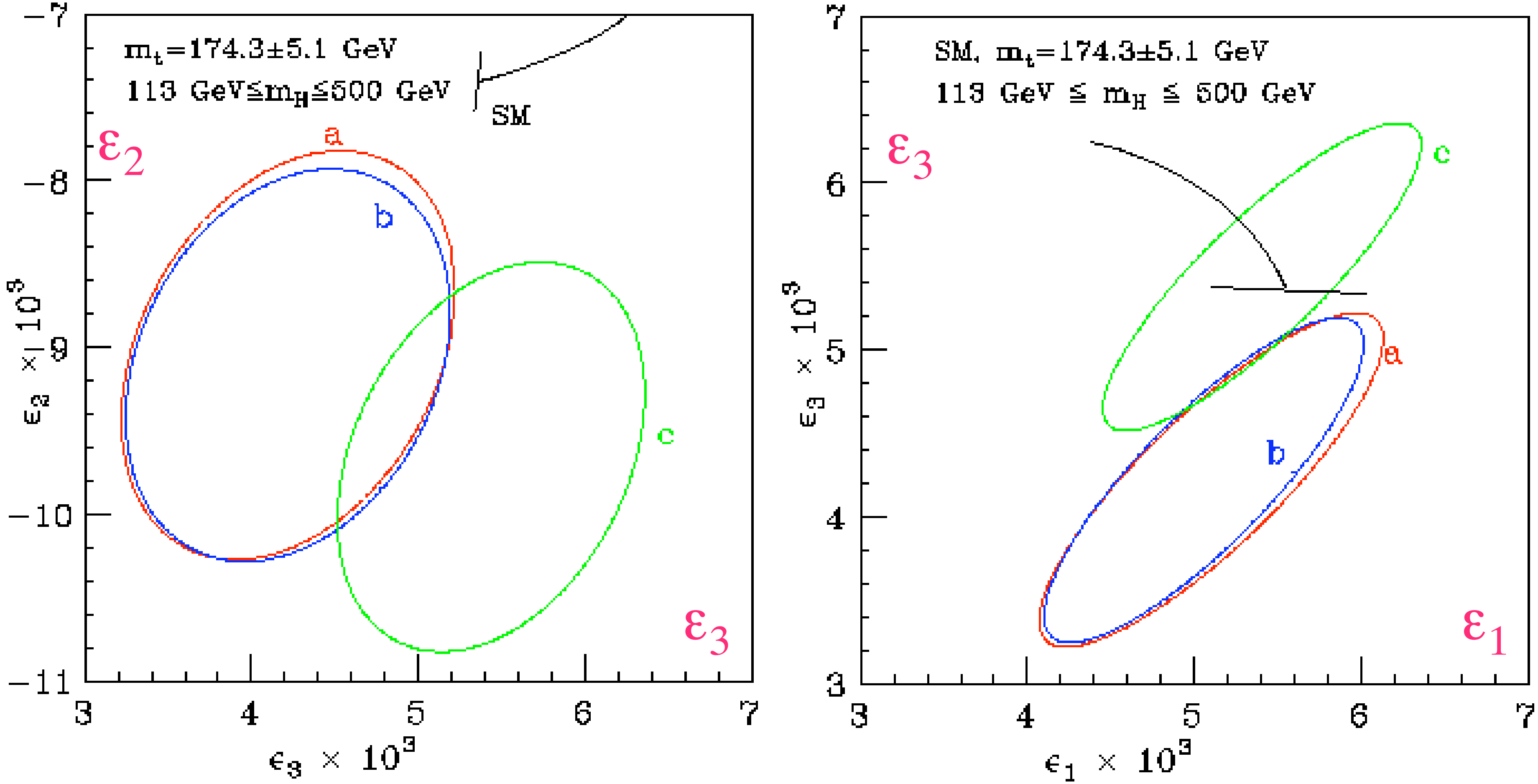
To test lepton-hadron universality one can add Γ_Z, σ_h, R_l to Γ_l etc.

a: m_W, Γ_l, R_b, $[\sin^2\theta]_l$

b: m_W, Γ_l, R_b, Γ_Z, σ_h, R_l, $[\sin^2\theta]_l$

c: m_W, Γ_l, R_b, Γ_Z, σ_h, R_l, $[\sin^2\theta]_l+[\sin^2\theta]_h$

Note:
1σ ellipses (39% cl)



G. Altarelli

ε_1 is OK, ε_2 is low (m_W),
ε_3 depends on $\sin^2\theta$: low for $[\sin^2\theta]_l$ (m_H)

The EWWG gives (summer '03):

$\varepsilon_1 = 5.4 \pm 1.0 \ 10^{-3}$

$\varepsilon_2 = -\ 9.7 \pm 1.2 \ 10^{-3}$

$\varepsilon_3 = 5.25 \pm 0.95 \ 10^{-3}$

$\varepsilon_b = -\ 4.7 \pm 1.6 \ 10^{-3}$

Non-degenerate
much larger shift of ε_1

For comparison:
a mass degenerate fermion multiplet gives

$$\Delta\varepsilon_3 = N_C \frac{G_F m_W^2}{8\pi^2\sqrt{2}} \cdot \frac{4}{3}[T_{3L} - T_{3R}]^2$$

For each member of the multiplet

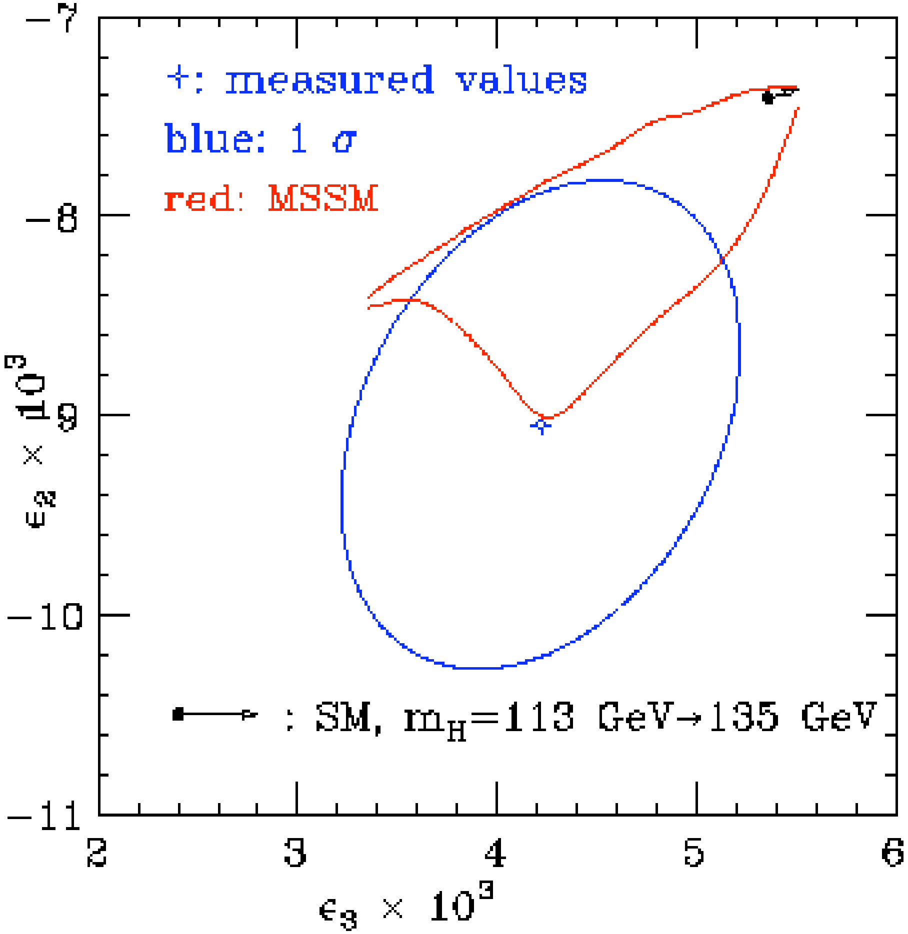
One chiral quark doublet (either L or R):

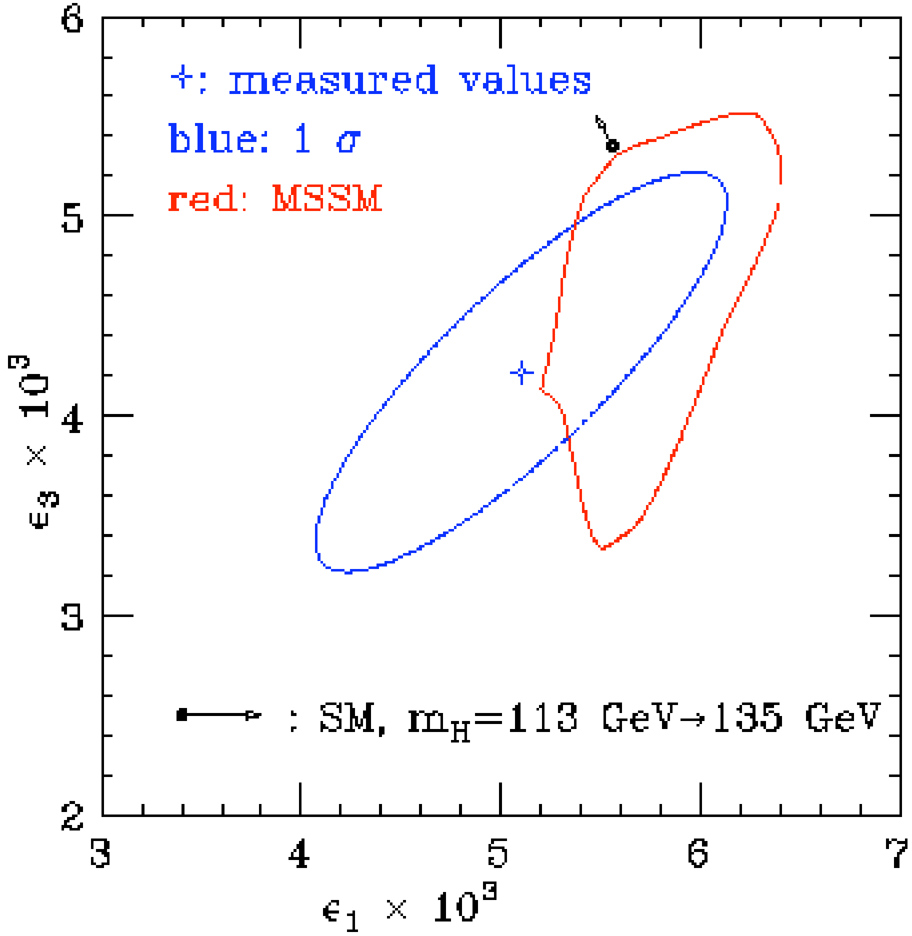
$$\Delta\varepsilon_3 = +\ 1.4 \ 10^{-3}$$

(Note that ε_3 if anything is low!)

G. Altarelli

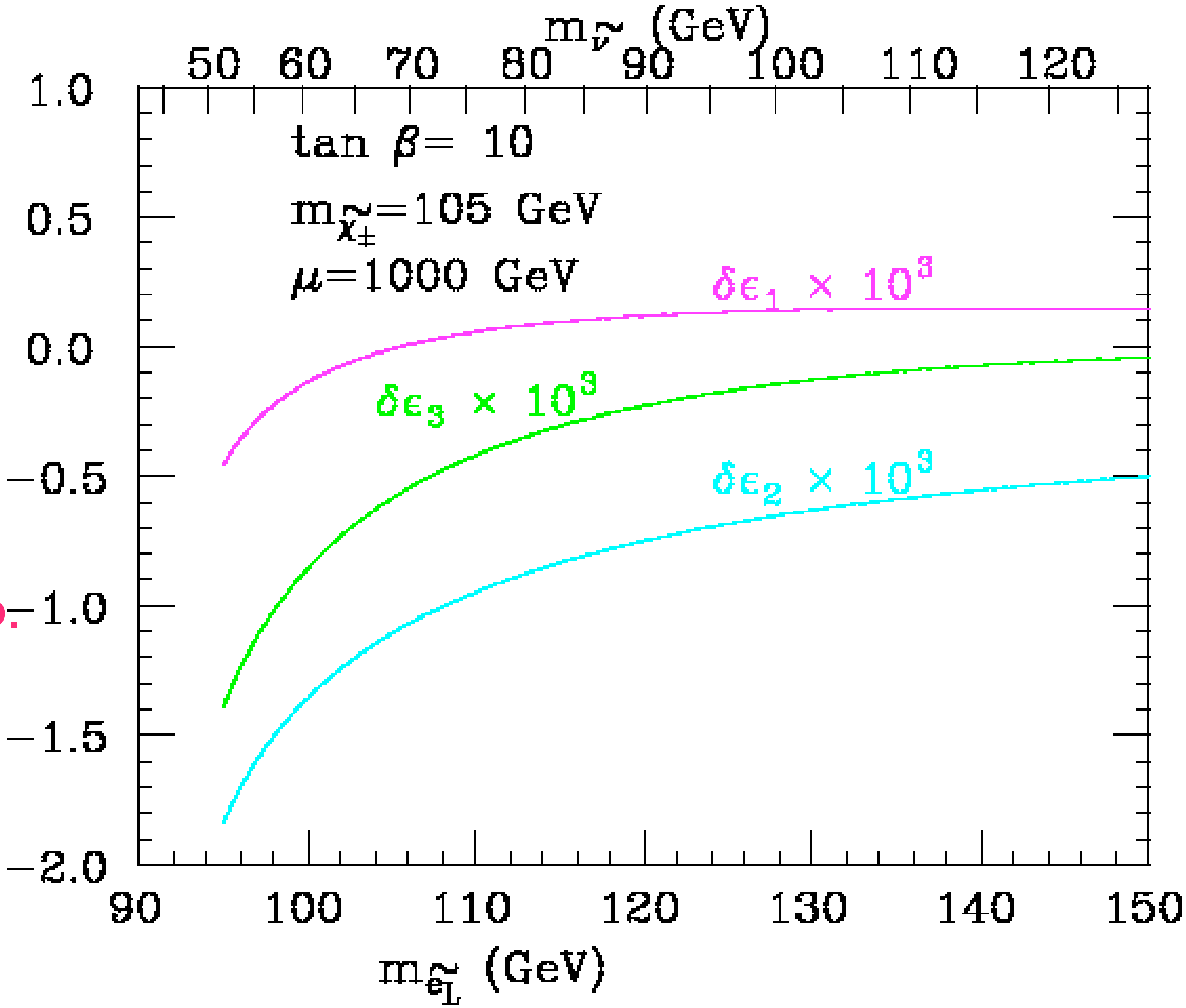
MSSM: $m_{\tilde{e}L} = 96\text{-}300$ GeV, $m_{\chi^-} = 105\text{-}300$ GeV,
$\mu = (-1)\text{-}(+1)$ TeV, $tg\beta = 10$, $m_h = 113$ GeV,
$m_A = m_{\tilde{e}R} = m_{\tilde{q}} = 1$ TeV





G. Altarelli

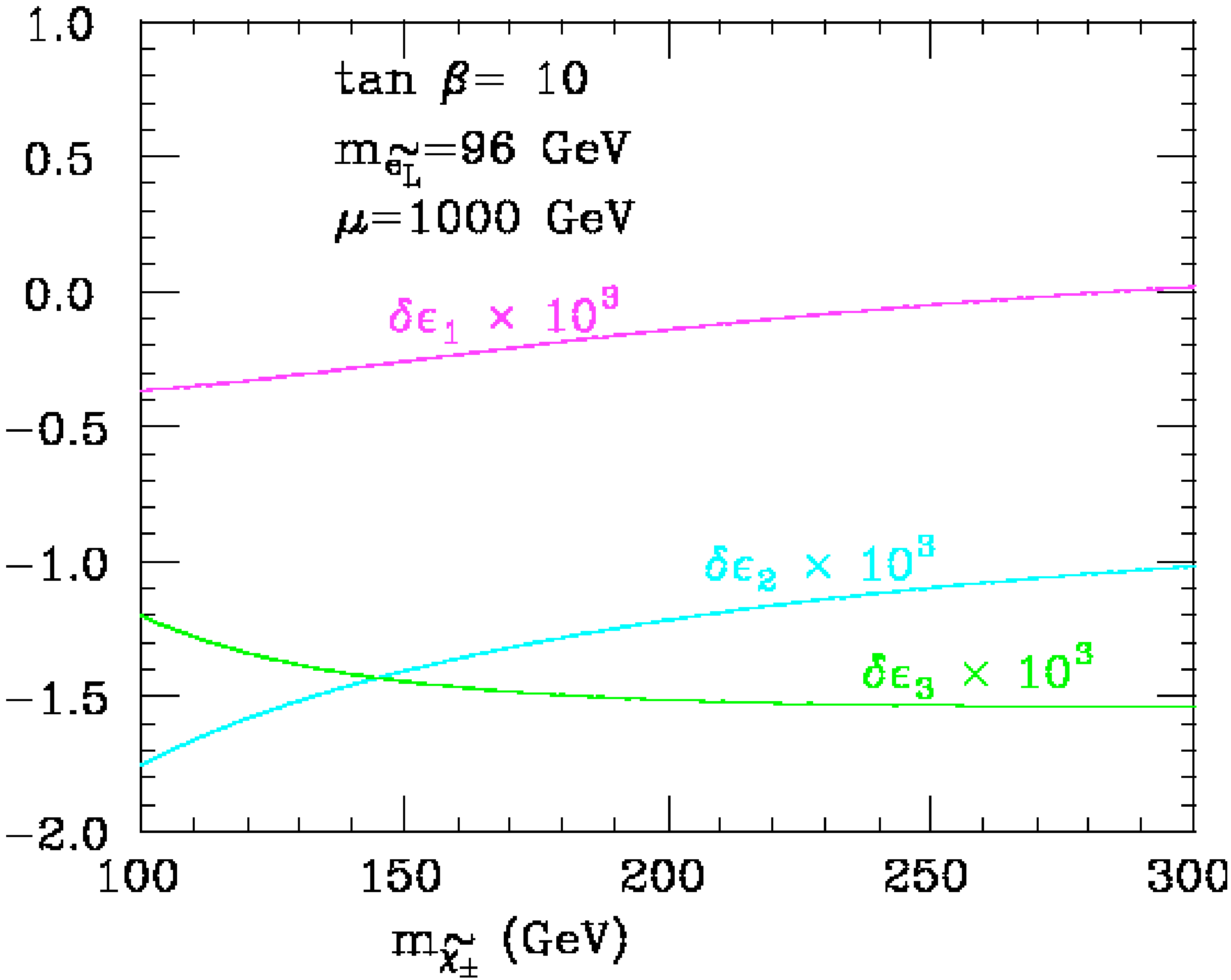
s-leptons
and s-ν's
plus
gauginos
must be
as light as
possible
given the
present exp.
bounds!

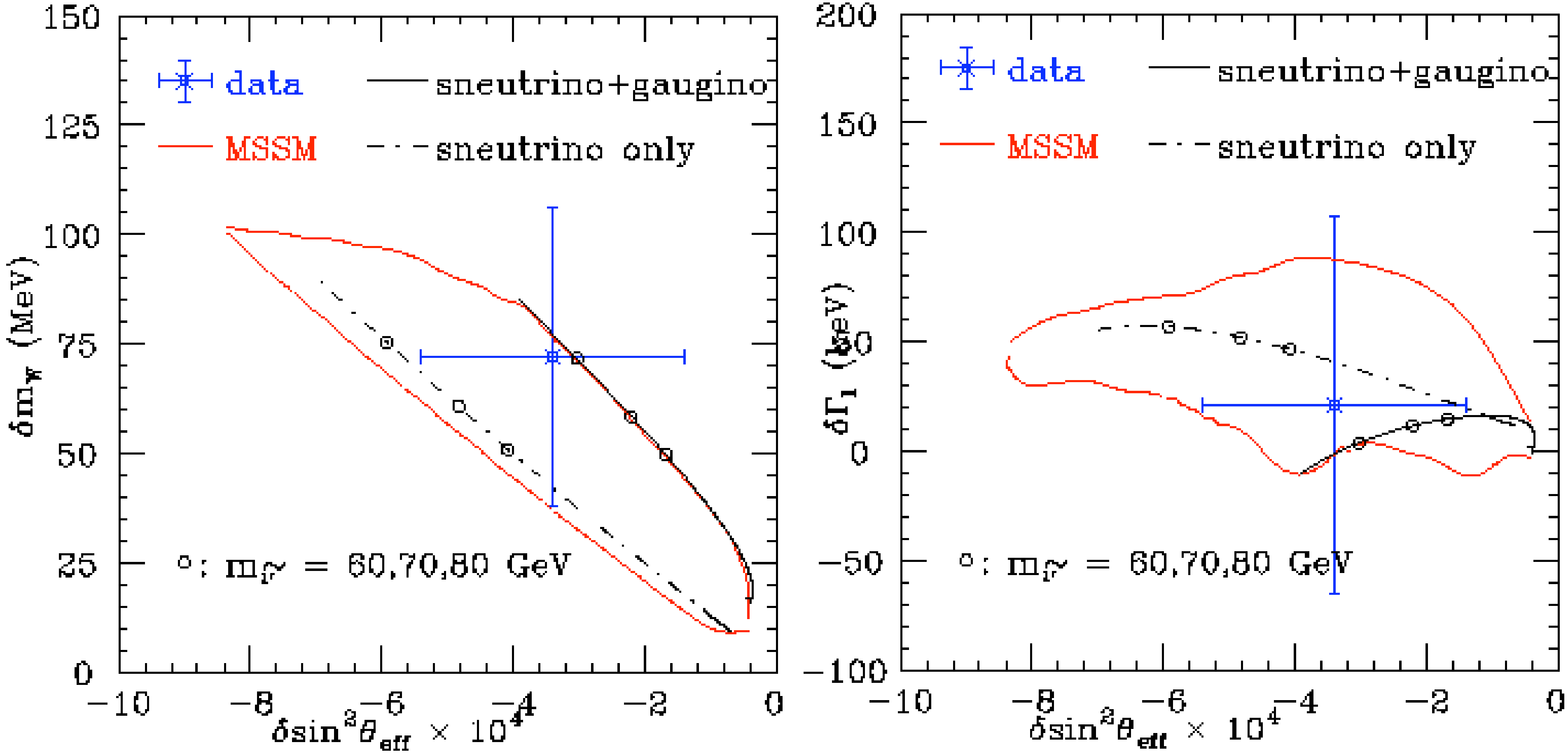


G. Altarelli

In general in MSSM: $m^2_{\tilde{e}^-} = m^2_{\tilde{\nu}} + m^2_W|\cos 2\beta|$

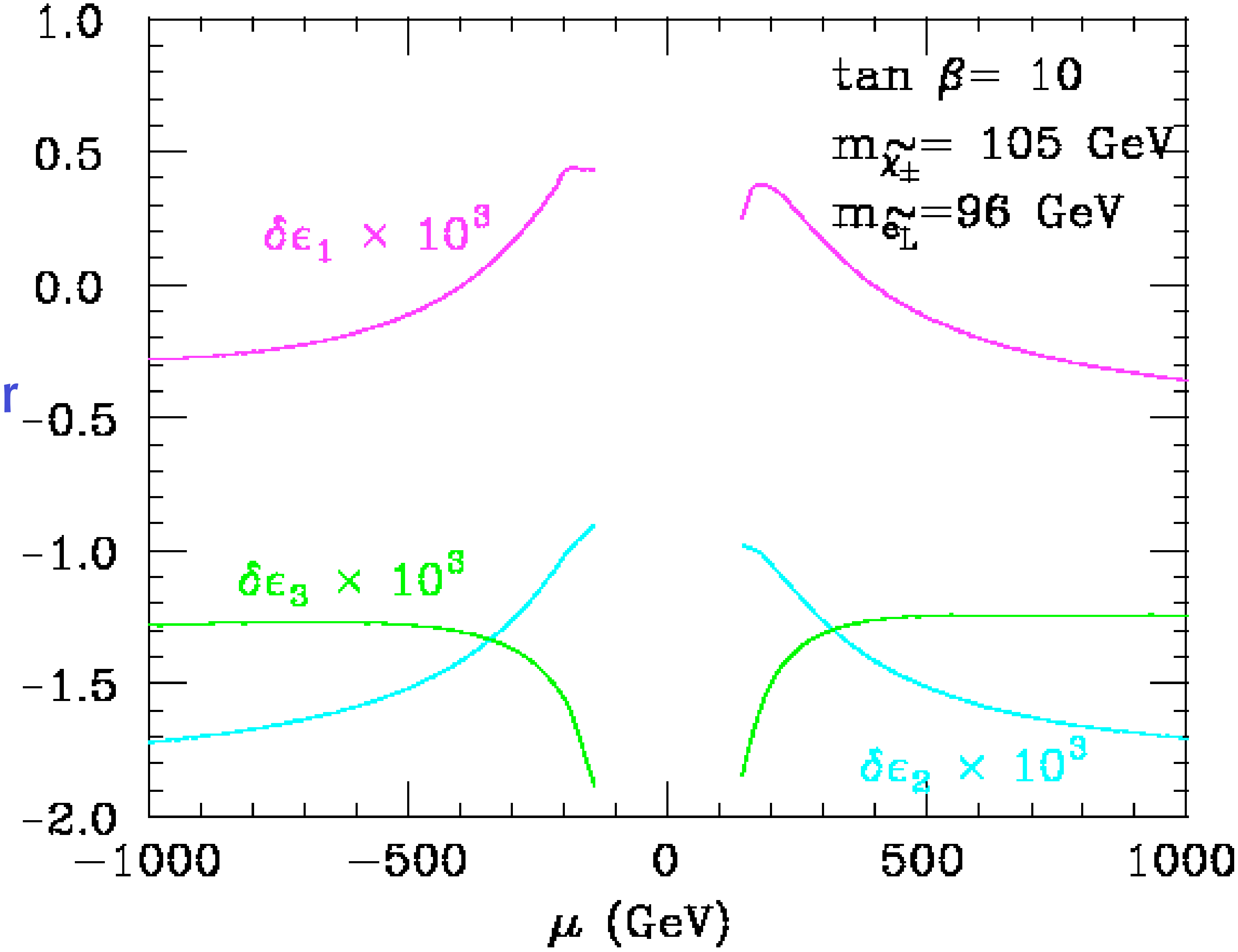
Light charginos also help by making ε_2 corr's larger than those of ε_3




data
MSSM
sneutrino+gaugino
sneutrino only
○: m_ν̃ = 60,70,80 GeV
δm_W (MeV)
δΓ_l (MeV)
δsin²θ_eff × 10⁴
150
125
100
75
50
25
0
200
150
100
50
0
−50
−100
−10
−8
−6
−4
−2
0

G. Altarelli

The sign of μ is irrelevant here.
But crucial for $(g\text{-}2)_{\mu}$



This model is compatible with $(g-2)_\mu$

Typically at large $tg\beta$:

Exp. ~300

$$\delta a_\mu \sim 150\ 10^{-11} (100\ \mathrm{GeV}/\tilde{m})^2\ tg\beta$$

OK for e.g. $\tan\beta \sim 4$, $m_{\chi^+} \sim 140$ GeV

The model predicts a deviation!