S. Barbara, 12 January '04

Status of the SM and Beyond

G. Altarelli
CERN

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

The χ^2 is not great:

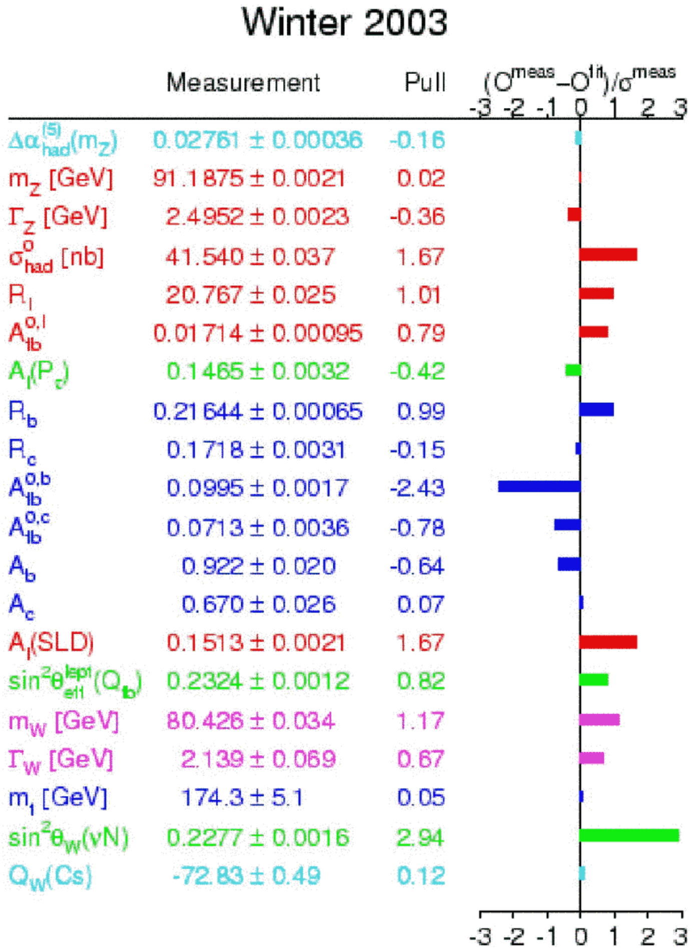
χ^2/ndof=25.5/15 (4.4%)

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

Without NuTeV:
(th. error questionable)

χ^2/ndof=16.7/14 (27.3%)

Much better!



	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^o_{had} [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A^{o,l}_{fb}$	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
$A^{o,b}_{fb}$	0.0995 ± 0.0017	-2.43
$A^{o,c}_{fb}$	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

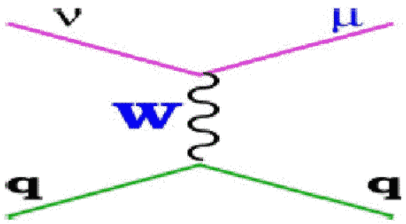
NuTe
V_{APV}

G. Altarelli

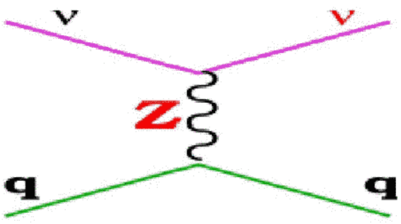
NuTeV Neutrino-Nucleon Scattering

Muon-(anti-)neutrino quark scattering:

charged current (CC)



neutral current (NC)



Paschos-Wolfenstein relation (iso-scalar target):

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

+ electroweak radiative corrections

Insensitive to sea quarks

Charm effects only through d_V quarks (CKM suppressed)

Need neutrino and anti-neutrino beam!

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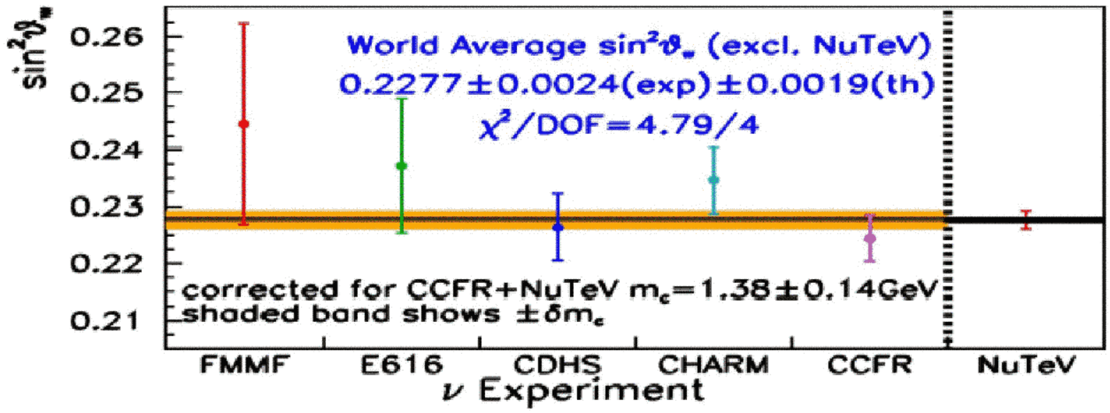
NuTeV's Result

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

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

Factor two more precise than previous νN world average



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

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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

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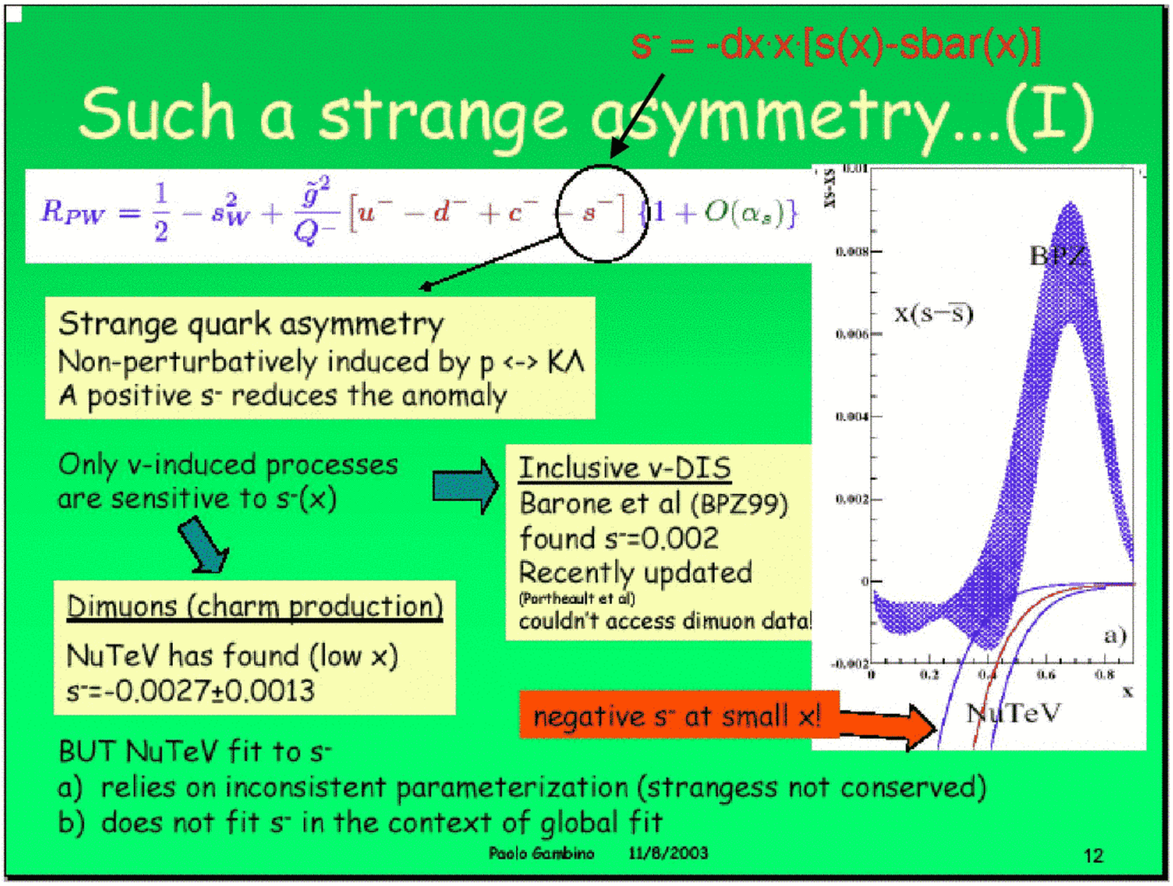
Gambino, LP'03



s⁻ = -dx·x·[s(x)-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)

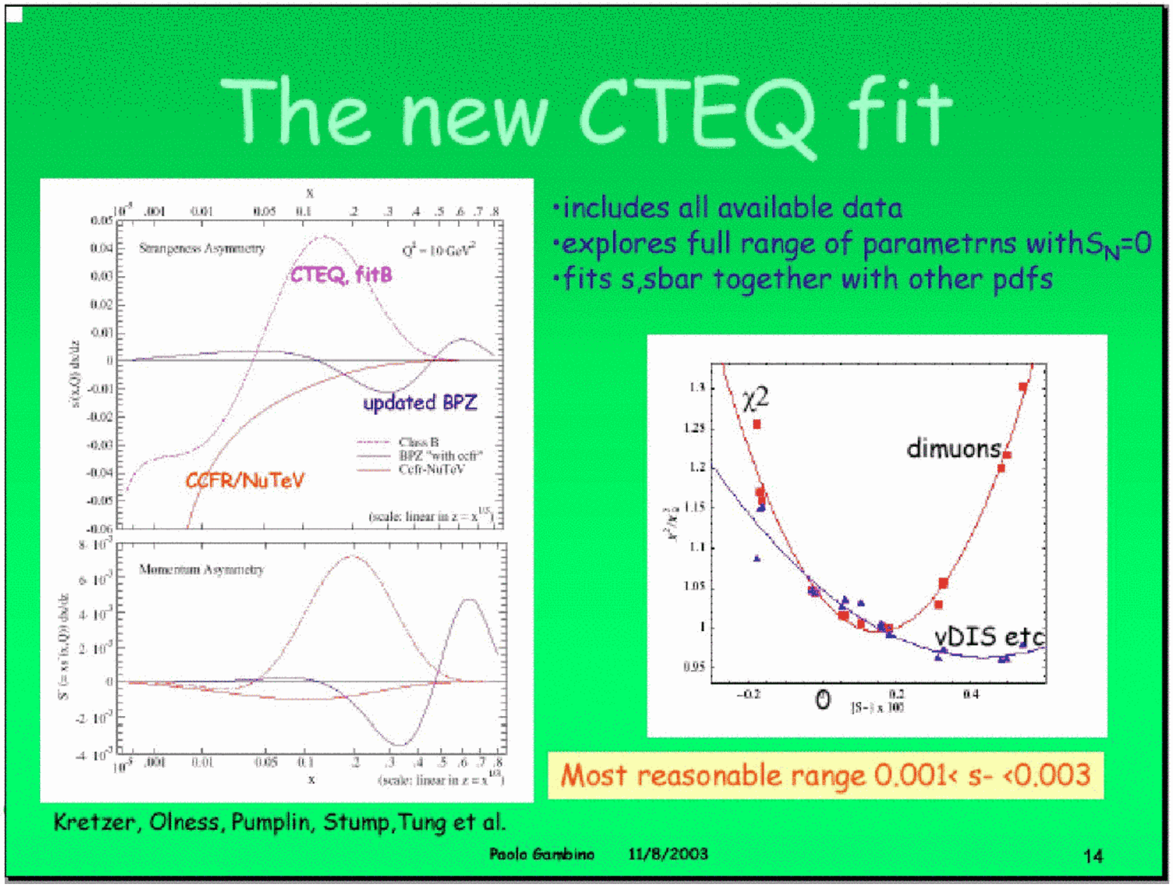
Inclusive ν-DIS
Barone et al (BPZ99) found s⁻=0.002
Recently updated (Portheault et al) couldn't access dimuon data!

Dimuons (charm production)
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 (strangeness not conserved)
b) does not fit s⁻ in the context of global fit

Paolo Gambino 11/8/2003 12

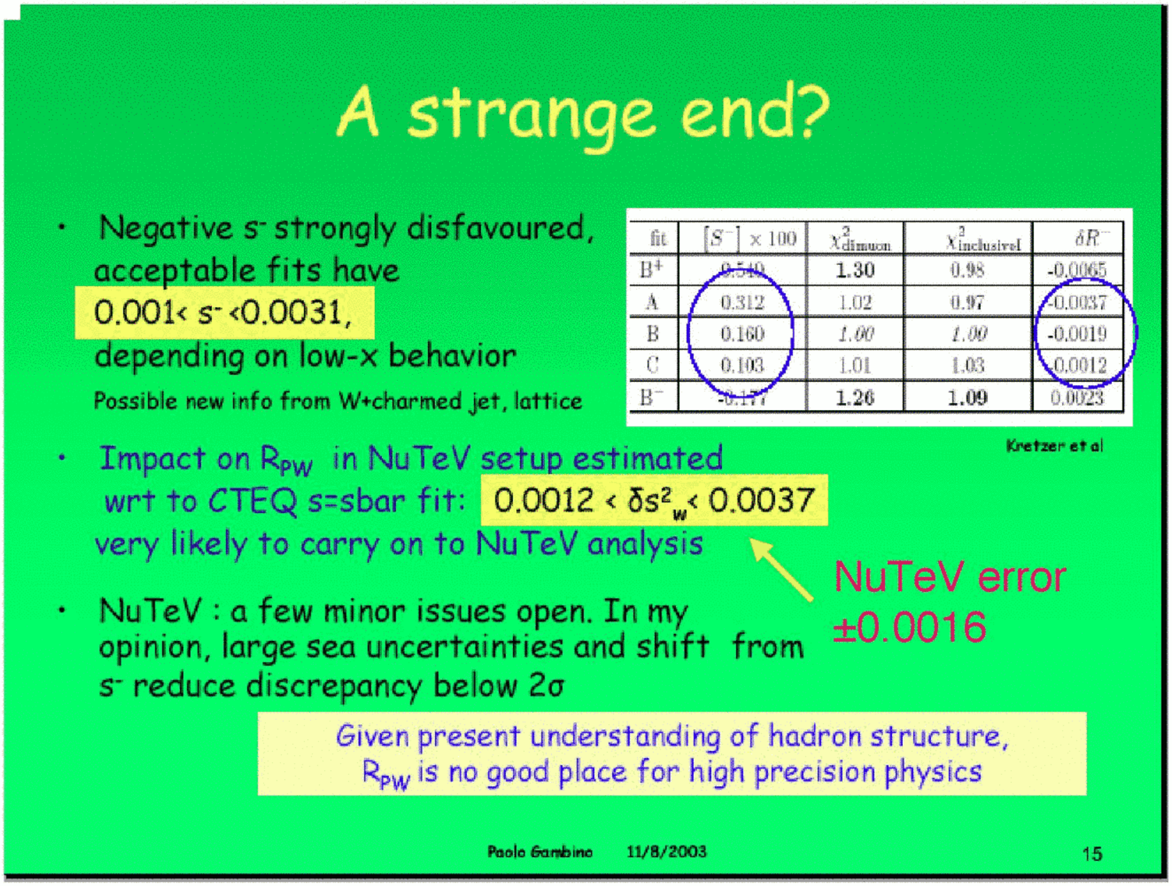


The new CTEQ fit

- 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 < δs^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!

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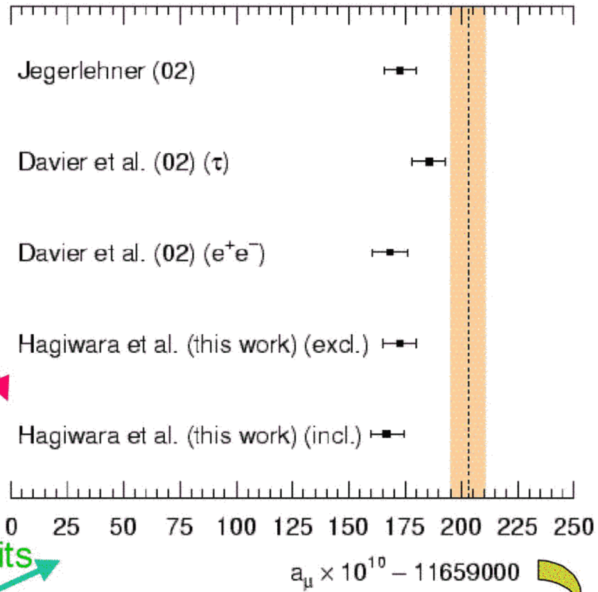
$(g-2)_\mu$ ~3σ discrepancy shown by the BNL'02 data

In 2002:

(Numbers in units 10^{-10})

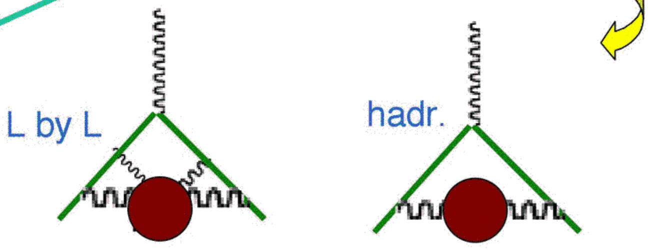
LO hadr.	688.8 ± 6.2	HMNT, 'excl.'
	$683.1 \pm 5.9 \pm 2.0_{rad}$	HMNT, 'incl.'
full a_μ	11659172.6 ± 7.7	'excl.'
	11659166.9 ± 7.4	'incl.'
BNL E821	11659203 ± 8	new world av. (0.7 ppm!)
EXP−TH	30.4 ± 11.1	$\sim 2.7\sigma$, 'excl.'
	36.1 ± 10.9	$\sim 3.3\sigma$, 'incl.'

Th. and Exp. accuracy comparable!



These units

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)



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Gambino, LP'03

Now the discrepancy is less: 2-2.5 σ

2003

(new measurements of σ_{had})

The spectral function from e^+e^-

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

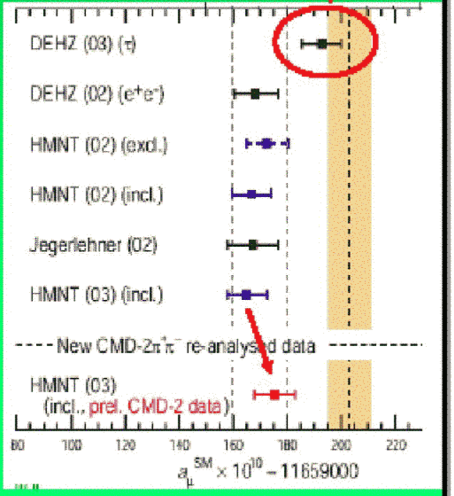
Hagiwara et al (HMNT) NEW result:
$a_\mu^{had,LO}=691.7\pm5.8_{exp}\pm2.0_{r.c.}$

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

Tau data below 1.8GeV



The τ data indicate no discrepancy!

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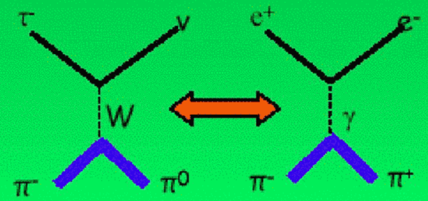
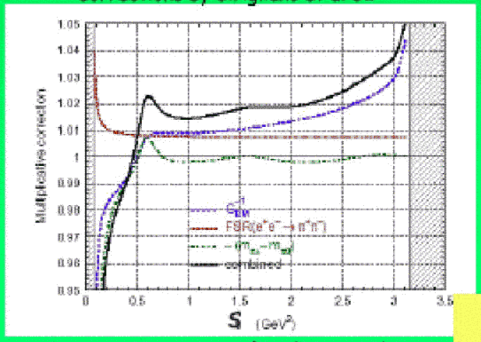
The spectral function from τ decays

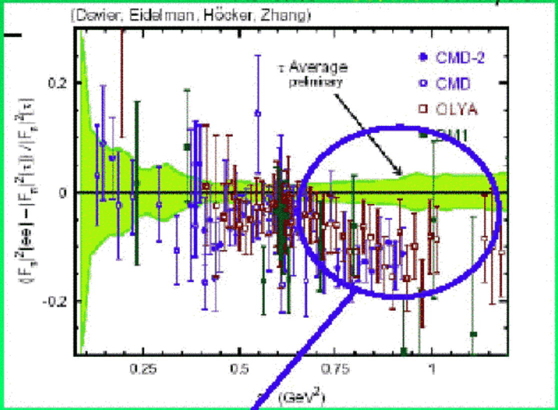


CVC + isospin symmetry
Corrections by Cirigliano et al 02



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)

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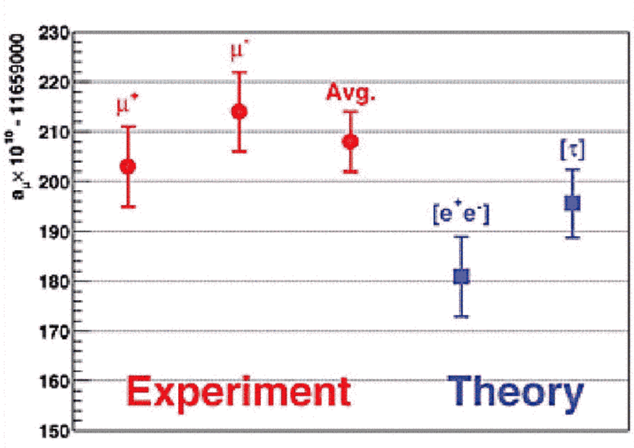
2004 New New results from BNL

- μ^- measured (was μ^+)
- discrepancy up again to $\sim 3\sigma$



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

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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 ($m_H \geq 114.4$ 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??

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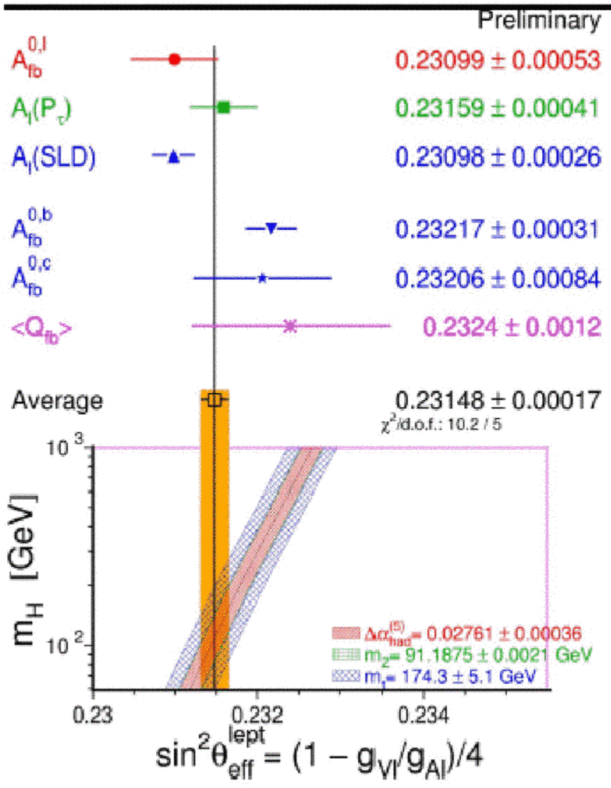
Comparison of all Z-Pole Asymmetries



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

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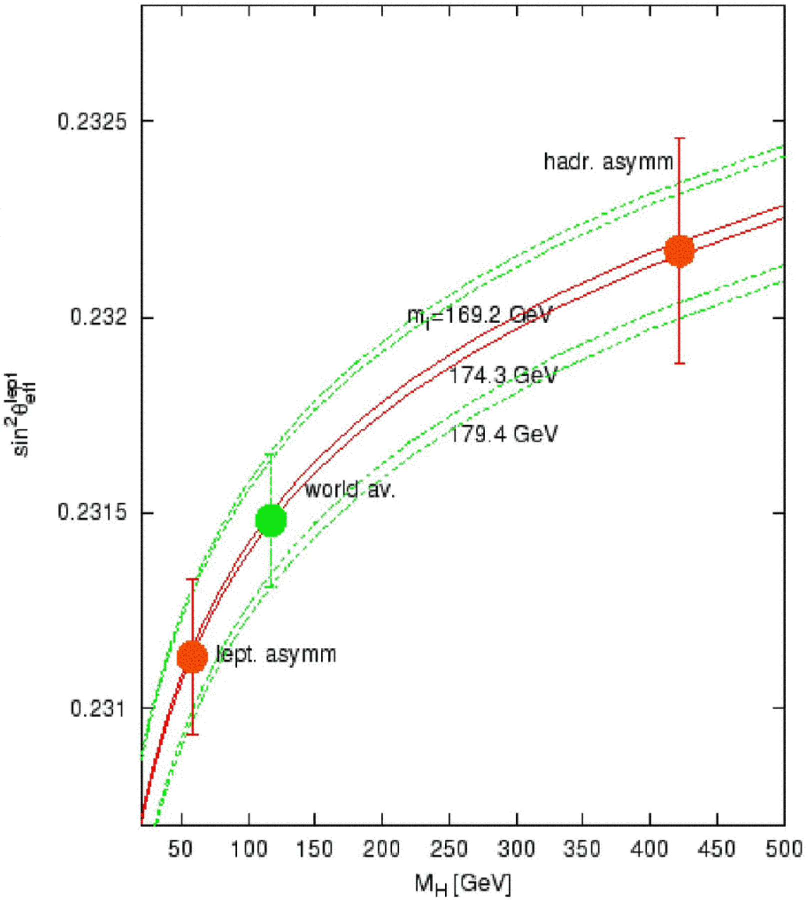
[copied from Grunewald, Amsterdam ‘02 talk]

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

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



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Hints of new physics effects??

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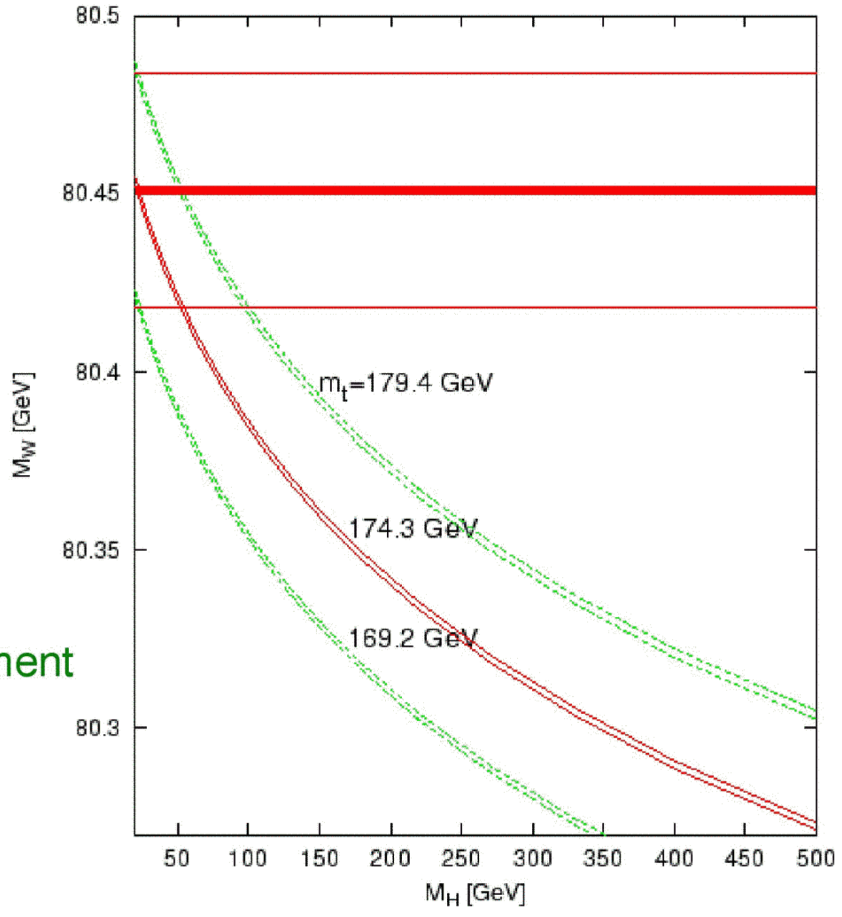
Plot m_W vs m_H



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

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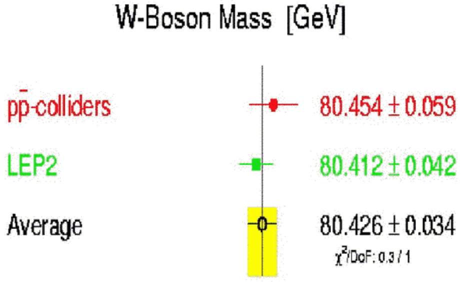
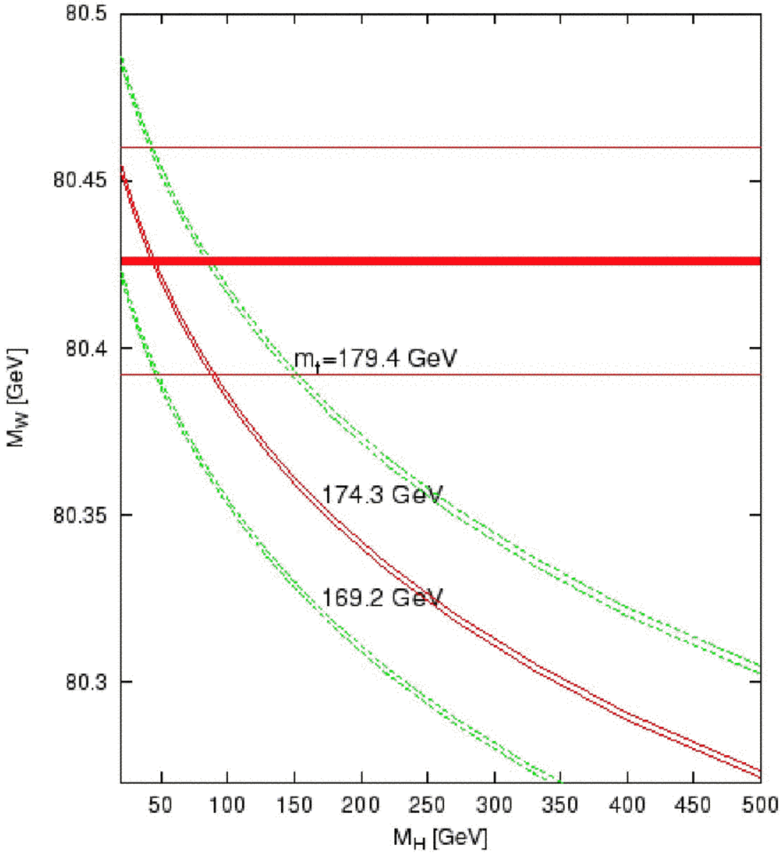
New developments (winter ‘03)

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

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Question Marks on EW Precision Tests

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[more so if $\sin^2\theta_{eff}$ is close to that from leptonic (A_{LR}) asymm.
m_H < ~110 GeV]

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Hints of new physics effects??

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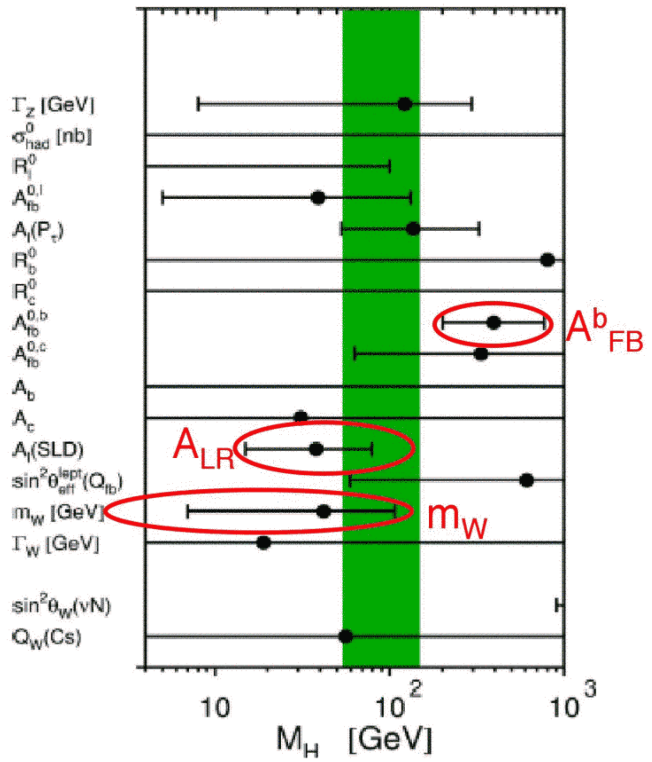
Sensitivities to m_H

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

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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 $\alpha^{-1}{}_{QED}$=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!

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- 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 tanβ can solve the m_H problem and lead to a better fit of the data

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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

$$(A_b)_{SM} - A_b = 0.052 \pm 0.018 \rightarrow 2.9\ \sigma$$

A large δg_R needed (by about 30%!)

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

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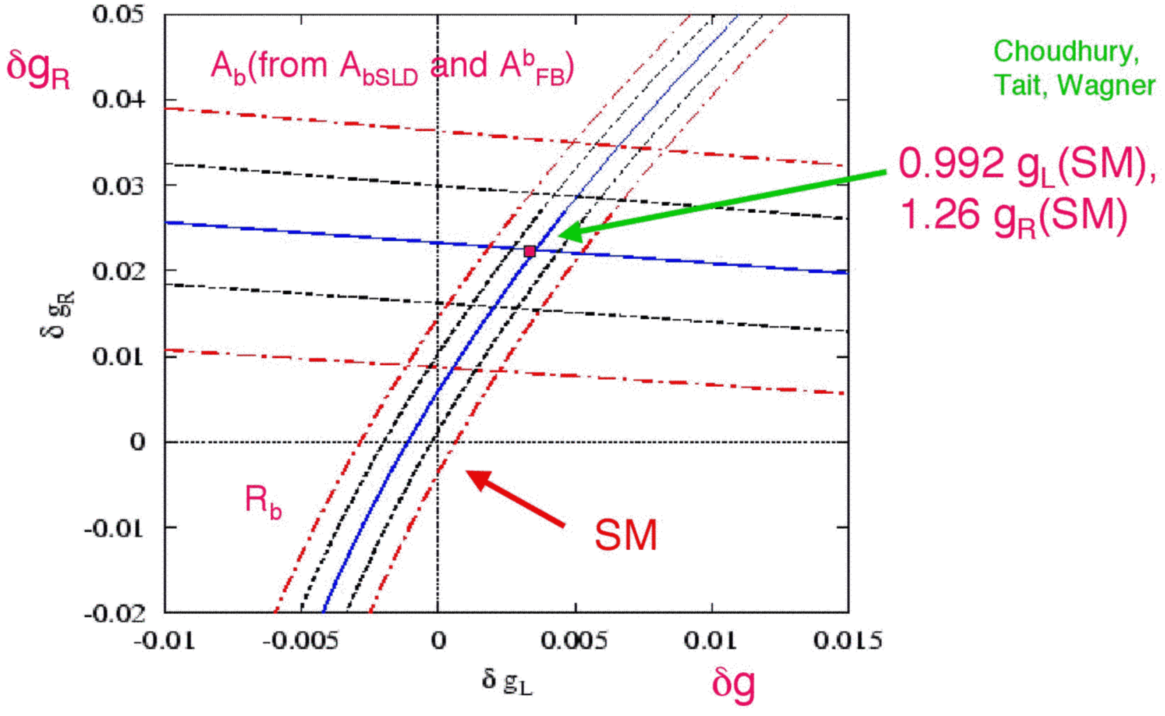

A possible model involves mixing of the b quark with a vectorlike doublet (ω,χ) with charges (-1/3, -4/3)

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

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EW DATA and New Physics

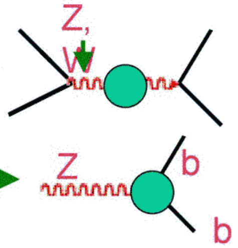
For an analysis of the data beyond the SM we use the ε formalism GA, R.Barbieri, F.Caravaglios, S. Jadach

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

ε_1, ε_2, ε_3 →

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)

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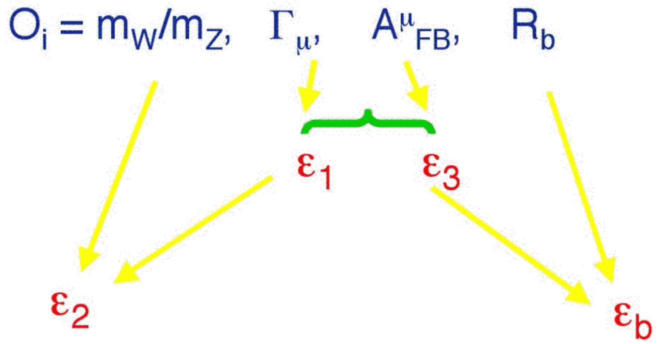
One starts from a set of defining observables:



$O_i = m_W/m_Z$, Γ_μ, $A^\mu{}_{FB}$, R_b

ε_1 ε_3

ε_2 ε_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, $A^\mu{}_{FB}$ --> Γ_l, $A^l{}_{FB}$

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

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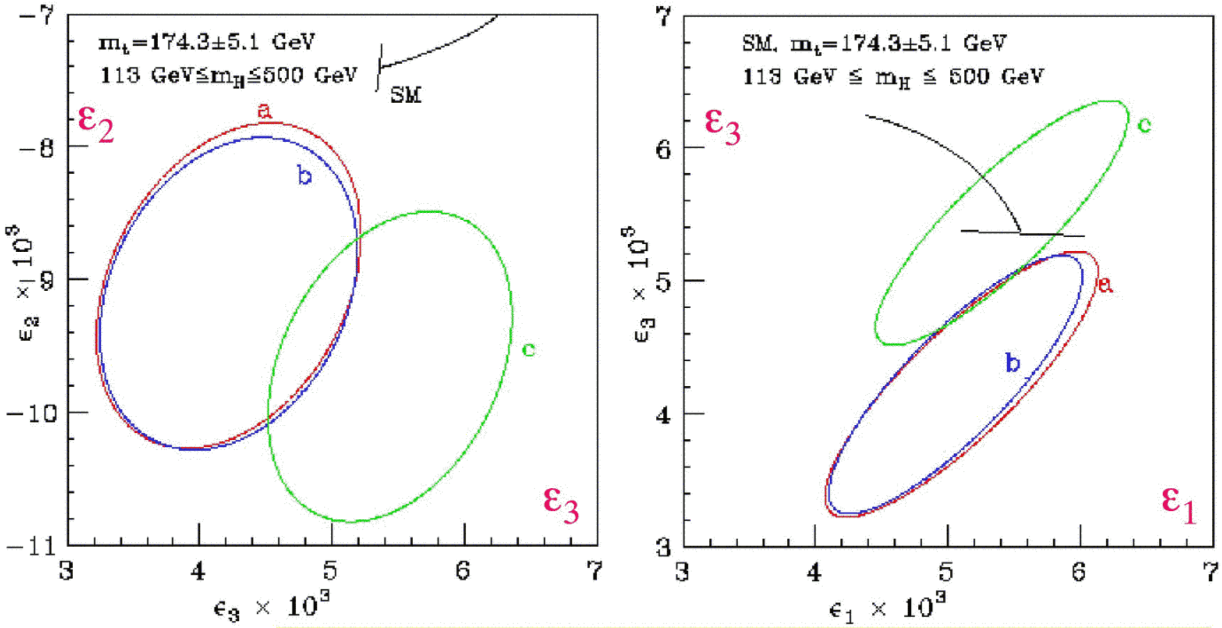
a: m_W, Γ_l, R_b, $[\sin^2\theta]_l$

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)



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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!)

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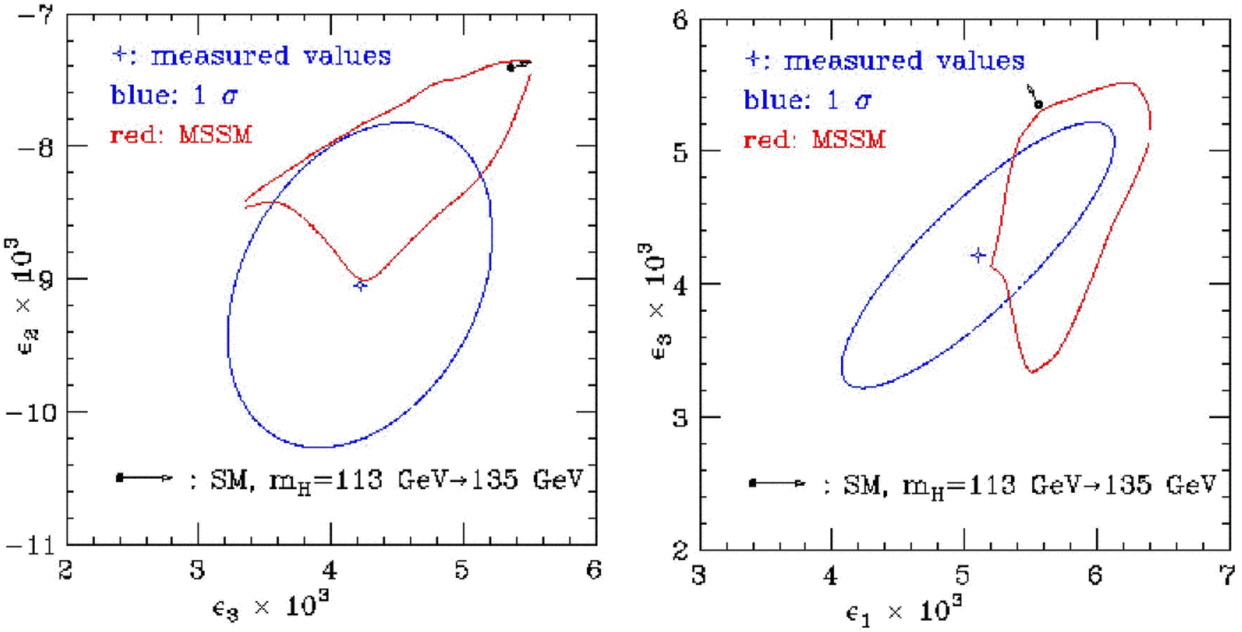
MSSM: $m_{\tilde{e}L}$ = 96-300 GeV, m_{χ^-} = 105-300 GeV,
μ = (-1)-(+1) TeV, tgβ = 10, m_h = 113 GeV,
$m_A = m_{\tilde{e}R} = m_{\tilde{q}}$ = 1 TeV



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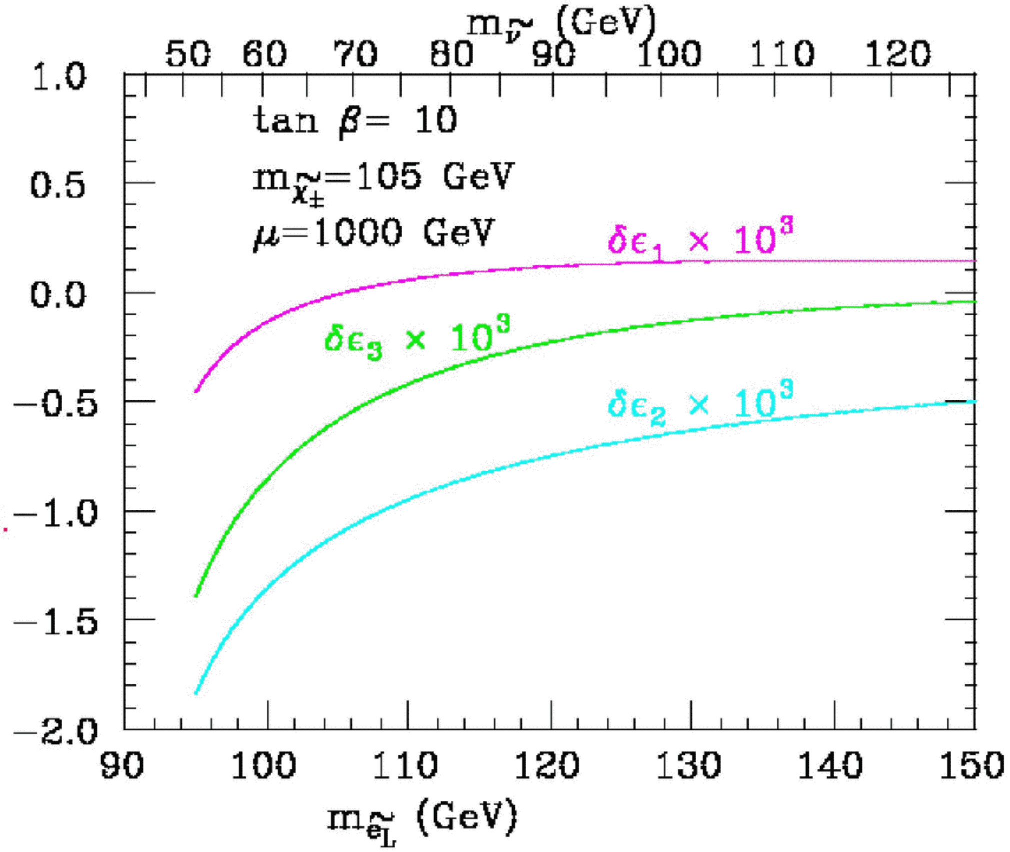
s-leptons
<u>and</u> s-ν's
plus
gauginos
must be
as light as
possible
given the
present exp.
bounds!



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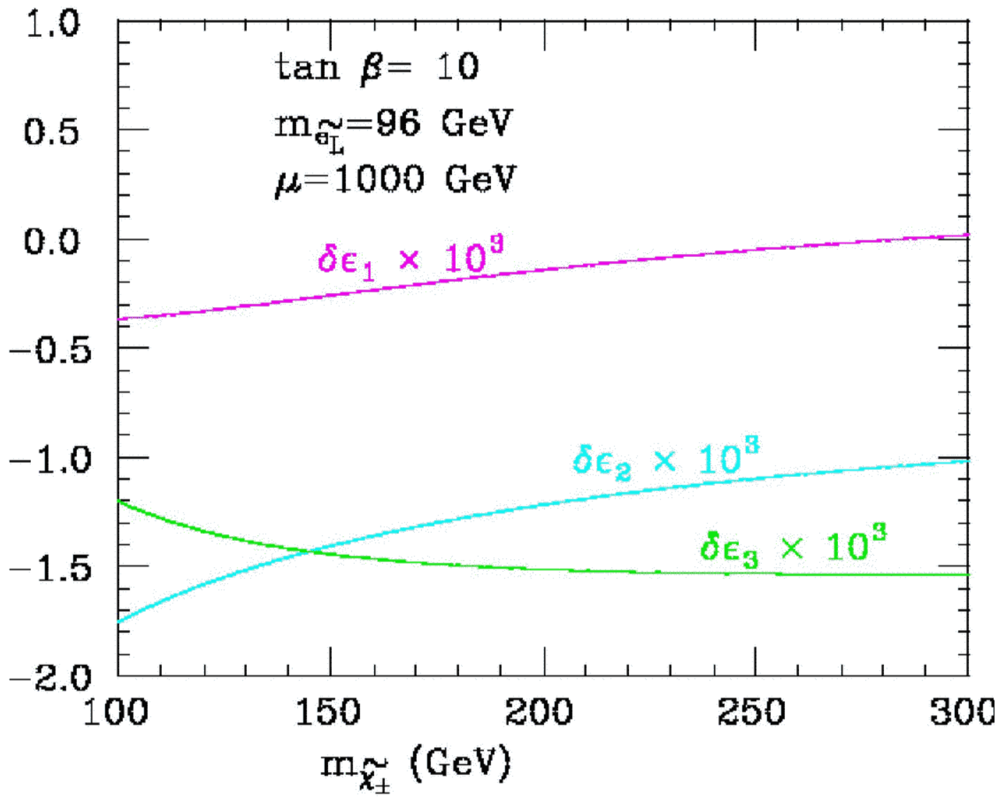
In general in MSSM: $m^2_{\tilde{e}^-} = m^2_{\tilde{\nu}} + m^2_W |\cos 2\beta|$

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



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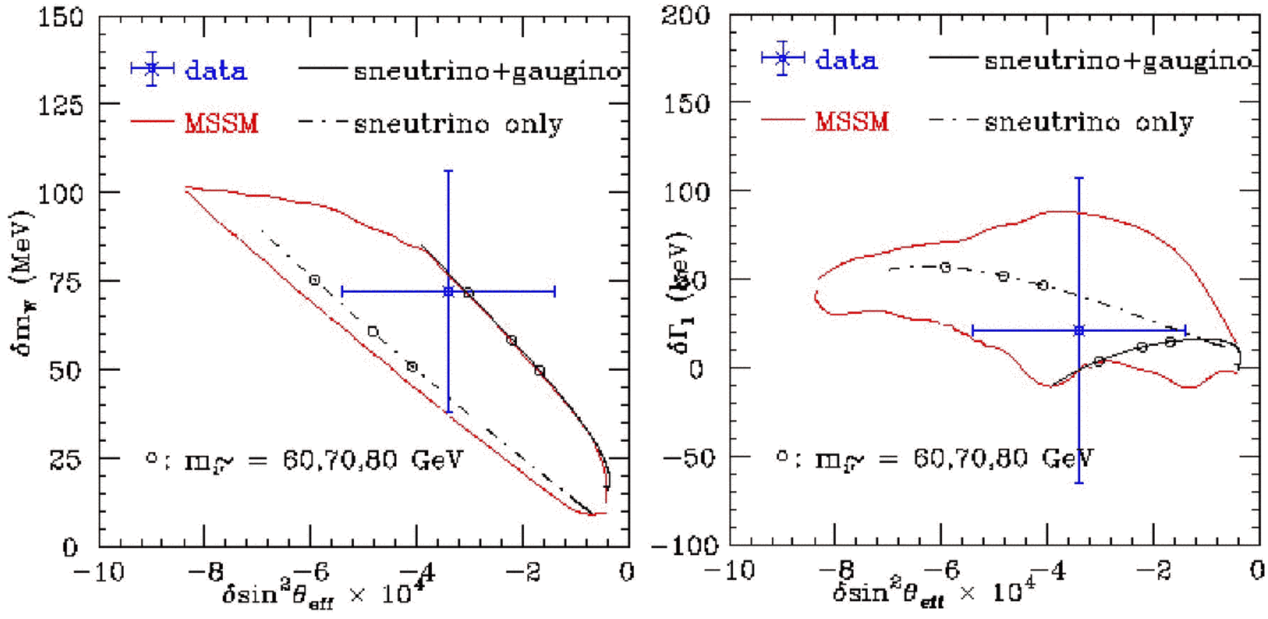

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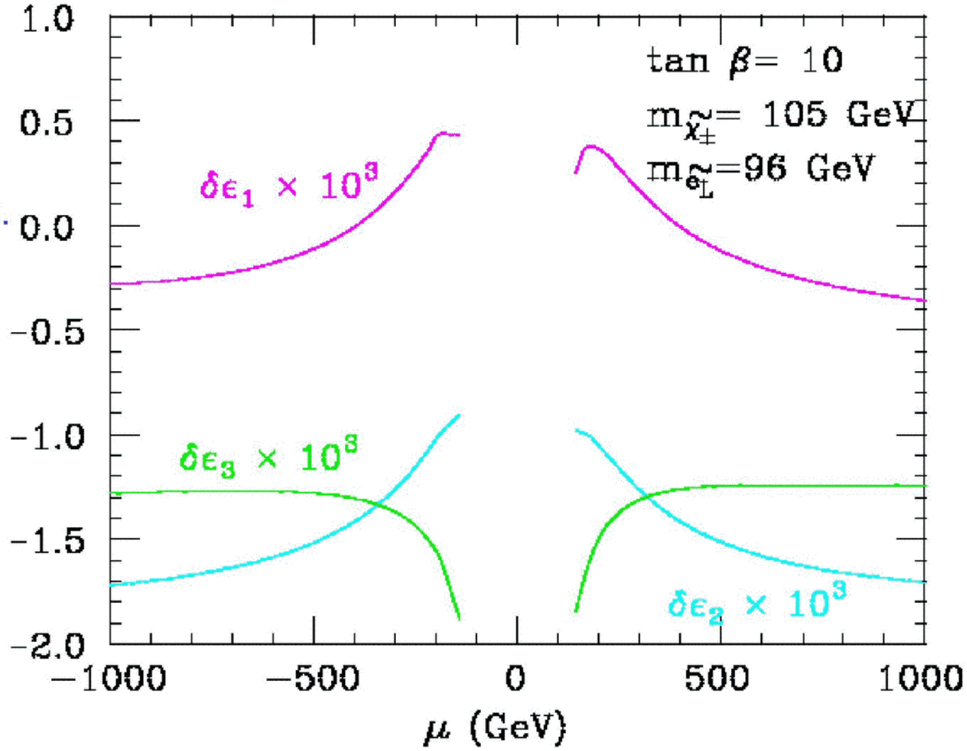
The sign of μ is irrelevant here. But crucial for $(g-2)_\mu$



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

Typically at large tgβ:

Exp. ~300

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

OK for e.g. tanβ~4, m_{χ^+}~140 GeV

The model predicts a deviation!

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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

•••••

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Conceptual problems of the SM

Most clearly:

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

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

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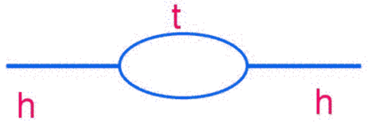
For the low energy theory: the "little hierarchy" problem:

e.g. the top loop (the most pressing): $m_h^2 = m^2_{bare} + \delta m_h^2$



$$\delta m^2_{h|top} = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim (0.3\Lambda)^2$$

$\Lambda \sim o(1TeV)$

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 $G_F^{-1/2} \sim o(1TeV)$ 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 are not directly visible

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Examples:

SUSY

- Supersymmetry: boson-fermion symm.
  exact (unrealistic): cancellation of $\delta\mu^2$
  approximate (possible): $\Lambda \sim m_{SUSY} - m_{ord}$

The most widely accepted

- The Higgs is a $\bar{\psi}\psi$ condensate. No fund. scalars. But needs new very strong binding force: $\Lambda_{new} \sim 10^3 \Lambda_{QCD}$ (technicolor).

Strongly disfavoured by LEP

- Large extra spacetime dimensions that bring M_{Pl} down to o(1TeV)

Elegant and exciting. Rich potentiality. Does it work?

- Models where extra symmetries allow m_h only at 2 loops and non pert. regime starts at $\Lambda \sim 10$ TeV

"Little Higgs" models. Does it work?

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SUSY at the Fermi scale

- Many theorists consider SUSY as established at M_{Pl} (superstring theory).
- Why not try to use it also at low energy to fix some important SM problems.
- Possible viable models exists:
  - MSSM softly broken with gravity mediation
    - or with gauge messengers
    - or with anomaly mediation
    - •••
- Maximally rewarding for theorists
  - Degrees of freedom identified
  - Hamiltonian specified
  - Theory formulated, finite and computable up to M_{Pl}

Unique!

Fully compatible with, actually supported by GUT's

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SUSY fits with GUT's

- Coupling unification: Precise matching of gauge couplings at M_{GUT} fails in SM and is well compatible in SUSY

From $\alpha_{QED}(m_Z)$, $\sin^2\theta_W$ measured at LEP predict $\alpha_s(m_Z)$ for unification (assuming desert)

Non SUSY GUT's
$\alpha_s(m_Z)=0.073\pm0.002$

SUSY GUT's
$\alpha_s(m_Z)=0.130\pm0.010$

Langacker, Polonski

Dominant error:
thresholds near M_{GUT}

EXP: $\alpha_s(m_Z)=0.119\pm0.003$
Present world average

- Proton decay: Far too fast without SUSY
- $M_{GUT} \sim 10^{15}$GeV non SUSY ->10^{16}GeV SUSY
- Dominant decay: Higgsino exchange

While GUT's and SUSY very well match,
(best phenomenological hint for SUSY!)
in technicolor , large extra dimensions,
little higgs etc., there is no ground for GUT's

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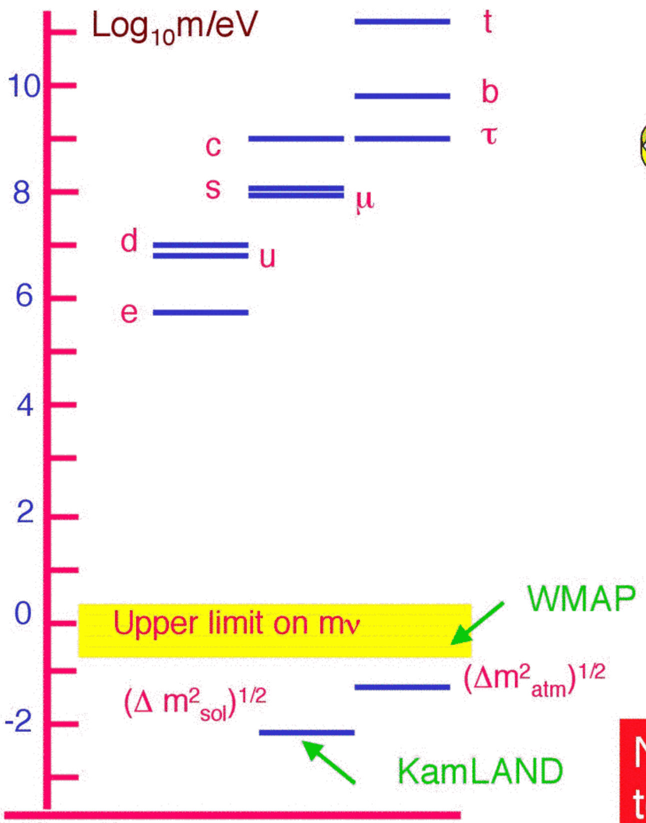

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Neutrino masses are really special!

$m_t/(\Delta m^2_{atm})^{1/2} \sim 10^{12}$

Massless ν's?

- no ν_R
- L conserved

Small ν masses?

- ν_R very heavy
- L not conserved

Neutrino masses point to M_{GUT}, well fit into the SUSY picture and in GUT's

---

A very natural and appealing explanation:

ν's are nearly massless because they are Majorana particles and get masses through L non conserving interactions suppressed by a large scale $M \sim M_{GUT}$

$$m_\nu \sim \frac{m^2}{M}$$

$m \le m_t \sim v \sim 200$ GeV
M: scale of L non cons.

Note:

$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.05$ eV
$m \sim v \sim 200$ GeV

$M \sim 10^{15}$ GeV

Neutrino masses are a probe of physics at M_{GUT} !

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Baryogenesis A most attractive possibility:

BG via Leptogenesis near the GUT scale

$T \sim 10^{12\pm3}$ GeV (after inflation)

Buchmuller, Yanagida,
Plumacher, Ellis, Lola,
Giudice et al, Fujii et al
.....

Only survives if $\Delta(B\text{-}L)\neq0$
(otherwise is washed out at T_{ew} by instantons)

Main candidate: decay of lightest ν_R ($M\sim10^{12}$ GeV)

L non conserv. in ν_R out-of-equilibrium decay:
B-L excess survives at T_{ew} and gives the obs. B asymmetry.

Quantitative studies confirm that the range of m_i from
ν oscill's is compatible with BG via (thermal) LG

In particular the bound
was derived

$m_i<10^{-1}$ eV

Close to WMAP

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Buchmuller, Di Bari, Plumacher

Dark Matter

Most of the Universe is not made up of
atoms: $\Omega_{tot}\sim1$, $\Omega_b\sim0.04$, $\Omega_m\sim0.3$

Most is non baryonic dark matter and dark energy

Cold

Non relativistic
at freeze out

Good clustering at small distances
(galaxies, …)

SUSY:

Neutralino:
Good candidate

Axions not excluded

Hot

Relativistic
at freeze out →

Relevant for large scale mass distrib'ns

Could be ν's
But:
$\Omega_\nu<0.015$ (WMAP)

Conclusion:

Most Dark Matter is Cold (Neutralinos, Axions…)
Significant Hot Dark matter is disfavoured
Neutrinos are not much cosmo-relevant.

The scale of the cosmological constant is a big mystery.

$\Omega_\Lambda \sim 0.65$ → $\rho_\Lambda \sim (2\ 10^{-3}\ \text{eV})^4 \sim (0.1\text{mm})^{-4}$ → Similar to m_ν!?

In Quantum Field Theory: $\rho_\Lambda \sim (\Lambda_{cutoff})^4$

If $\Lambda_{cutoff} \sim M_{Pl}$ → $\rho_\Lambda \sim 10^{123}\ \rho_{obs}$

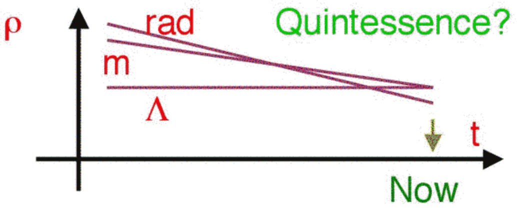
Exact SUSY would solve the problem: $\rho_\Lambda = 0$

But SUSY is broken: $\rho_\Lambda \sim (\Lambda_{SUSY})^4 < 10^{59}\ \rho_{obs}$

It is interesting that the correct order is $(\rho_\Lambda)^{1/4} \sim (\Lambda_{EW})^2/M_{Pl}$

So far no solution:
- A modification of gravity at 0.1mm?(large extra dim.)
- Leak of vac. energy to other universes (wormholes)?
- …

Other problem:
Why now?



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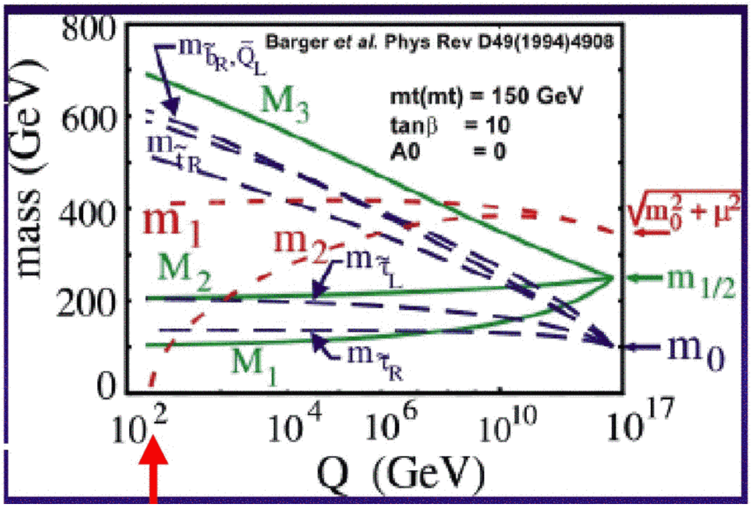
But: Lack of SUSY signals at LEP + lower limit on m_H → problems for minimal SUSY

- In MSSM: $$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3\alpha_w m_t^4}{4\pi m_W^2 \sin^2\beta} \ln\frac{\tilde{m}_t^4}{m_t^4} < \sim 130\ \text{GeV}$$

So $m_H > 114$ GeV considerably reduces available parameter space.

- In SUSY EW symm. breaking is induced by H_u running

Exact location implies constraints →



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m_Z can be expressed in terms of SUSY parameters

For example, assuming universal masses at M_{GUT} for scalars and for gauginos

$$m_Z^2 \approx c_{1/2} m_{1/2}^2 + c_0 m_0^2 + c_t A_t^2 + c_\mu \mu^2 \qquad c_a = c_a(m_t, \alpha_i, \ldots)$$

Clearly if $m_{1/2}$, m_0,… >> m_Z: Fine tuning!

LEP results (e.g. $m_{\chi+}$ >~100 GeV) exclude gaugino universality if no FT by > ~20 times is allowed

Without gaugino univ. the constraint only remains on m_{gluino} and is not incompatible

$$m_Z^2 \approx 0.7 m_{gluino}^2 + \ldots$$

[Exp. : m_{gluino} >~200GeV]

Barbieri, Giudice; de Carlos, Casas; Barbieri, Strumia; Kane, King; Kane, Lykken, Nelson, Wang......

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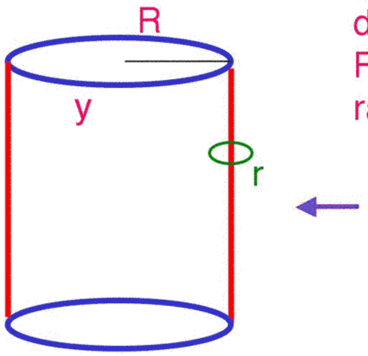
Large Extra Dimensions

Solve the hierachy problem by bringing gravity down from M_{Pl} to o(1TeV)

Arkani-Hamed, Dimopoulos/ Dvali+Antoniadis/ Randall,Sundrun…..

Inspired by string theory, one assumes:
- Large compactified extra dimensions
- SM fields are on a brane
- Gravity propagates in the whole bulk



y: extra dimension
R: compact'n radius

y=0 "our" brane (possibly with thickness r)

G_N~$1/M^2_{Pl}$: Newton const.
M_{Pl} large as G_N weak

The idea is that gravity appears weak as a lot of lines of force escape in extra dimensions

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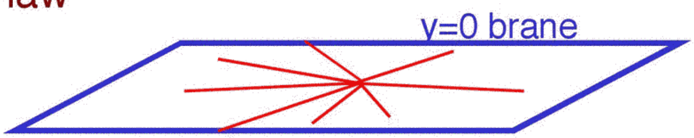
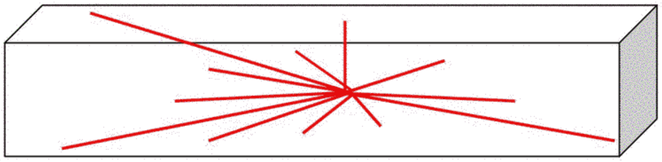
r >> R: ordinary Newton law



$$F \sim \frac{G_N}{r^2} \sim \frac{1}{M_{Pl}^2 r^2}$$

r << R: lines in all dimensions



Gauss in d dim:

r^{d-2} ρ ~m

$$F \sim \frac{1}{m^2 (mr)^{d-4} \cdot r^2}$$

By matching at r=R

$$\left(\frac{M_{Pl}}{m}\right)^2 = (Rm)^{d-4}$$

For m ~ 1 TeV, (d-4 = n)

n = 1 R~ 10^{15} cm (excluded)
n = 2 R~ 1mm (close to limits)
n = 4 R~ 10^{-9} cm
•••

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Limits on deviations from Newton law

$$V(r) = -G \frac{m_1 m_2}{r} (1 + \alpha e^{-r/\lambda})$$

Hoyle et al,
PRL 86,1418,2001

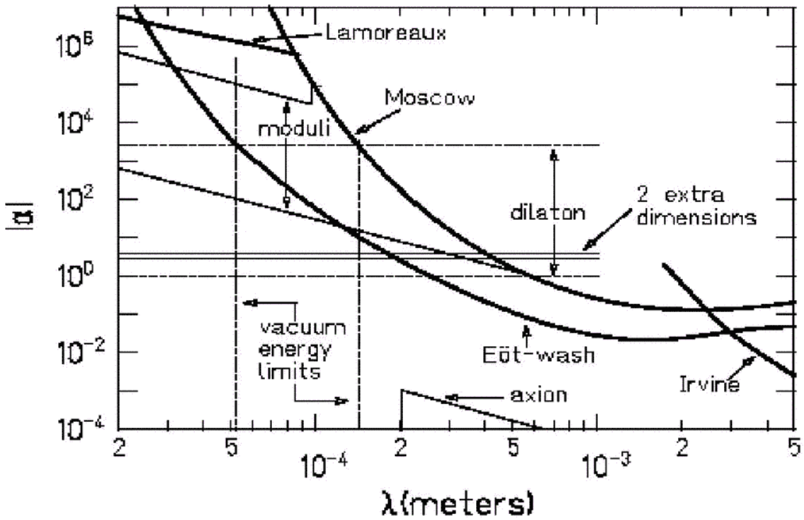

FIG. 4. 95% confidence upper limits on $1/r^2$-law violating interactions of the form given by Eq. (2). The region excluded by previous work [2,3,20] lies above the heavy lines labeled Irvine, Moscow and Lamoreaux, respectively. The data in Fig. 3 imply the constraint shown by the heavy line labeled Eöt-wash. Constraints from previous experiments and the theoretical predictions are adapted from Ref. [8], except for the dilaton prediction which is from Ref. [14].

Generic feature:

compact dim. → Kaluza-Klein (KK) modes

$p=n/R$ $m^2=n^2/R^2$ (quantization in a box)

Many possibilities:

- SM fields on a brane

  The brane can itself have a thickness r:

  $1/r >\sim 1$TeV → $r <\sim 10^{-17}$ cm

→ KK recurrences of SM fields: W_n, Z_n etc

cfr: • Gravity on bulk

$1/R >\sim 10^{-3}$ eV → $R <\sim 0.1$ mm

- Factorized metric:

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu + h_{ij}(y) dy^i dy^j$$

perhaps the most promising

- Warped metric: Randall-Sundrum (R-S)

$$ds^2 = e^{-2mR|\varphi|} \eta_{\mu\nu} dx^\mu dx^\nu - R^2 \varphi^2$$

$m=M_{Pl}\exp(-2mR\pi)$ → $Rm \sim 10$

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- Large Extra Dimensions is a very exciting scenario.
- However, by itself it is difficult to see how it can solve the main problems (hierarchy, the LEP Paradox)

  * Why (Rm) not 0(1)?

  R-S better in this respect

$$\boxed{\begin{gathered}\left(\frac{M_{Pl}}{m}\right)^2 = (Rm)^{d-4} \\ m=M_{Pl}exp(-2mR\pi)\end{gathered}}$$

  * $\Lambda \sim 1/R$ must be small (m_H light)

  * But precision tests put very strong lower limits on Λ (several TeV)

In fact in typical models of this class there is no mechanism to sufficiently quench the corrections

- But could be part of the truth!

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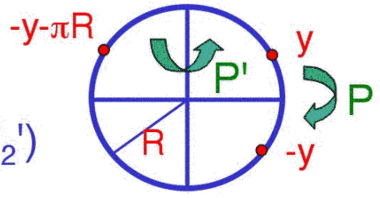
- Interesting directions explored →

Symmetry breaking by orbifolding



$S/(Z_2 x Z_2')$

For $1/R \sim M_{GUT}$
GUT's in ED: very appealing
SU(5), SO(10) in 5 or 6 dimensions

Z_2-> P: y ⟺ -y

Kawamura/GA, Feruglio/ Hall, Nomura;
Hebecker, March-Russell;
Hall, March-Russell, Okui, Smith
Asaka, Buchmuller, Covi
....

Z_2'-> P': y' ⟺ -y'
$y' = y + \pi R/2$
or y ⟺ -y- πR

- No baroque Higgs system
- Natural doublet-triplet splitting
- Coupling unification can be maintained
- • • •

$$\phi_{++}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{++}^{(2n)}(x_\mu)\cos\frac{2ny}{R}$$

$$\phi_{+-}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{+-}^{(2n+1)}(x_\mu)\cos\frac{2n+1}{R}y$$

$$\phi_{-+}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{-+}^{(2n+1)}(x_\mu)\sin\frac{2n+1}{R}y$$

$$\phi_{--}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{--}^{(2n+2)}(x_\mu)\sin\frac{2n+2}{R}y$$

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Symmetry breaking at the weak scale

- SUSY Breaking Barbieri, Hall, Nomura...

5D SUSY-SM compactified on $S/(Z_2\text{-}Z_2^{'})$

•Different SUSY breaking at each boundary (Scherk-Schwarz)

γeffective theory non-SUSY

(SUSY recovered at d<R)

- Higgs boson mass constrained (rather insensitive to UV)

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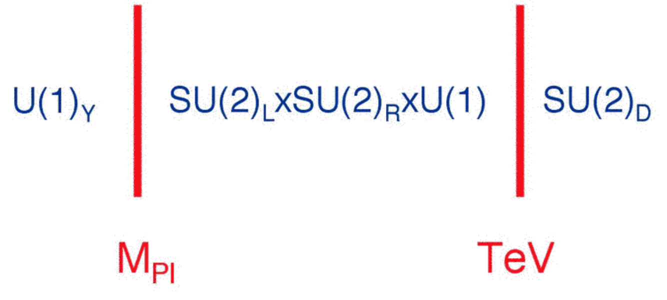
- Gauge Symmetry Breaking (Higgsless theories)

Csaki et al/Nomura/Davoudiasl et al/Barbieri, Rattazzi, Pomarol....



Symmetries broken by Boundary Conditions (BC) on the branes

Altogether only $U(1)_Q$ unbroken

Warped R-S background

Unitarity breaking (no Higgs) delayed by KK recurrences
Still problems with EW precision tests

A new way to look at walking technicolor by AdS/CDF correspondence

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Little Higgs Models

Georgi (moose)/Arkani-Hamed et al/Low, Skiba, Smith/Kaplan, Schmaltz/Chang,Wacker/Gregoire et al

$$\underset{\text{global}}{\overset{}{G}} \supset [\underset{\text{gauged}}{SU(2) \otimes} U(1)]^2 \supset SU(2) \underset{\text{SM}}{\otimes} U(1)$$

H is (pseudo)-Goldstone boson of G: takes mass only at 2-loops (needs breaking of 2 subgroups or 2 couplings)

cut off Λ ~10 TeV

Λ^2 divergences canceled by:

$$\left.\begin{array}{ll} \delta m^2_{Hltop} & \text{new coloured fermion } \chi \\ \delta m^2_{Hlgauge} & W', Z', \gamma' \\ \delta m^2_{HlHiggs} & \text{new scalars} \end{array}\right\} \sim 1 \text{ TeV}$$

2 Higgs doublets ~0.2 TeV

E-W Precision Tests? Problems
GUT's? But signatures at LHC clear

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e.g.: enlarge $SU(2)_{weak} \longrightarrow$ global SU(3)

quark doublet $\longrightarrow$ triplet $\begin{bmatrix} t_L \\ b_L \\ \chi_L \end{bmatrix}$

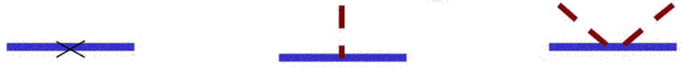
SU(3) broken spont.ly $\varphi = \exp i \dfrac{\begin{bmatrix} - & h \\ h^\dagger & - \end{bmatrix}}{f} \begin{bmatrix} 0 \\ 0 \\ f \end{bmatrix}$

Yukawa coupling:

expl. SU(3) breaking

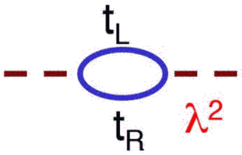
$$\lambda \left[t^\dagger_L \; b^\dagger_L \; \chi^\dagger_L \right] \exp i \frac{\begin{bmatrix} - & h \\ h^\dagger & - \end{bmatrix}}{f} \begin{bmatrix} 0 \\ 0 \\ f \end{bmatrix} t_R + M \chi^\dagger_L \chi_R$$

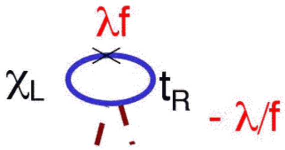
$$\lambda f \chi^\dagger_L t_R + i\lambda \left[t^\dagger_L \; b^\dagger_L \right] h t_R - \frac{\lambda}{2f} \chi^\dagger_L t_R h^\dagger h + \ldots$$



top loop:

coeff. Λ^2





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Little Higgs: Big Problems with Precision Tests

Hewett, Petriello, Rizzo/ Csaki et al/Casalbuoni, De Andrea, Oertel/ Kilian, Reuter/

Even with vectorlike new fermions large corrections arise mainly from W_i', Z' exchange.
[lack of custodial SU(2) symmetry]

A combination of LEP and Tevatron limits gives:

$$f > 4 \text{ TeV at } 95\% \; (\Lambda = 4\pi f)$$

Fine tuning > 100 needed to get $m_h \sim 200$ GeV
better if m_H heavier ⇨

Presumably can be fixed by complicating the model

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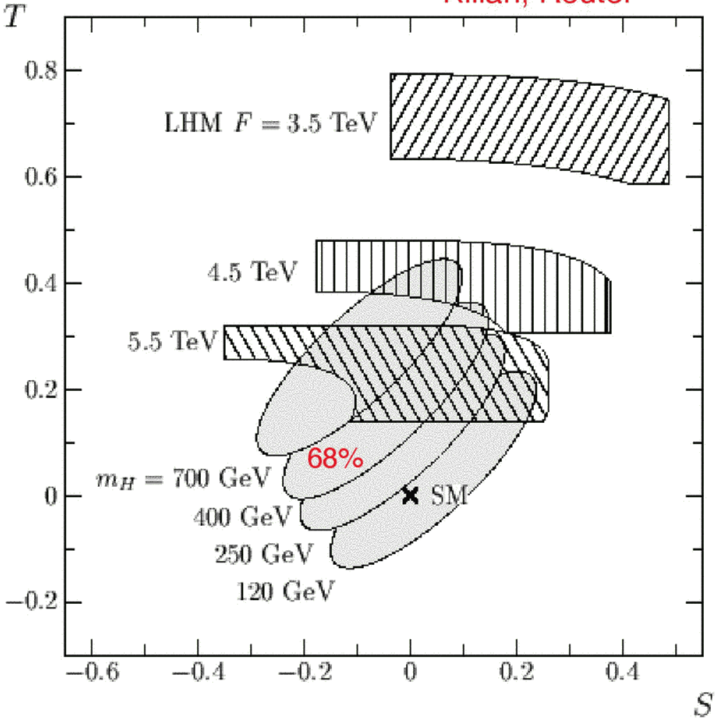
For a light Higgs F (=f) must be large.
Better if m_H increases

Kilian, Reuter



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Summarizing

- SUSY remains the Standard Way beyond the SM
- What is unique of SUSY is that it works up to GUT's .

GUT's are part of our culture!
Coupling unification, neutrino masses, dark matter, ...
give important support to SUSY

- It is true that the train of SUSY is already a bit late

(this is why there is a revival of alternative model building)

- No complete, realistic alternative so far developed

(not an argument! But…)

- Extra dim.s is a complex, rich, attractive, exciting possibility.
- Little Higgs models look as just a postponement

(both interesting to pursue)

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