GGI- Florence, 20 September '05

Status of the EW Theory in the SM and beyond

G. Altarelli

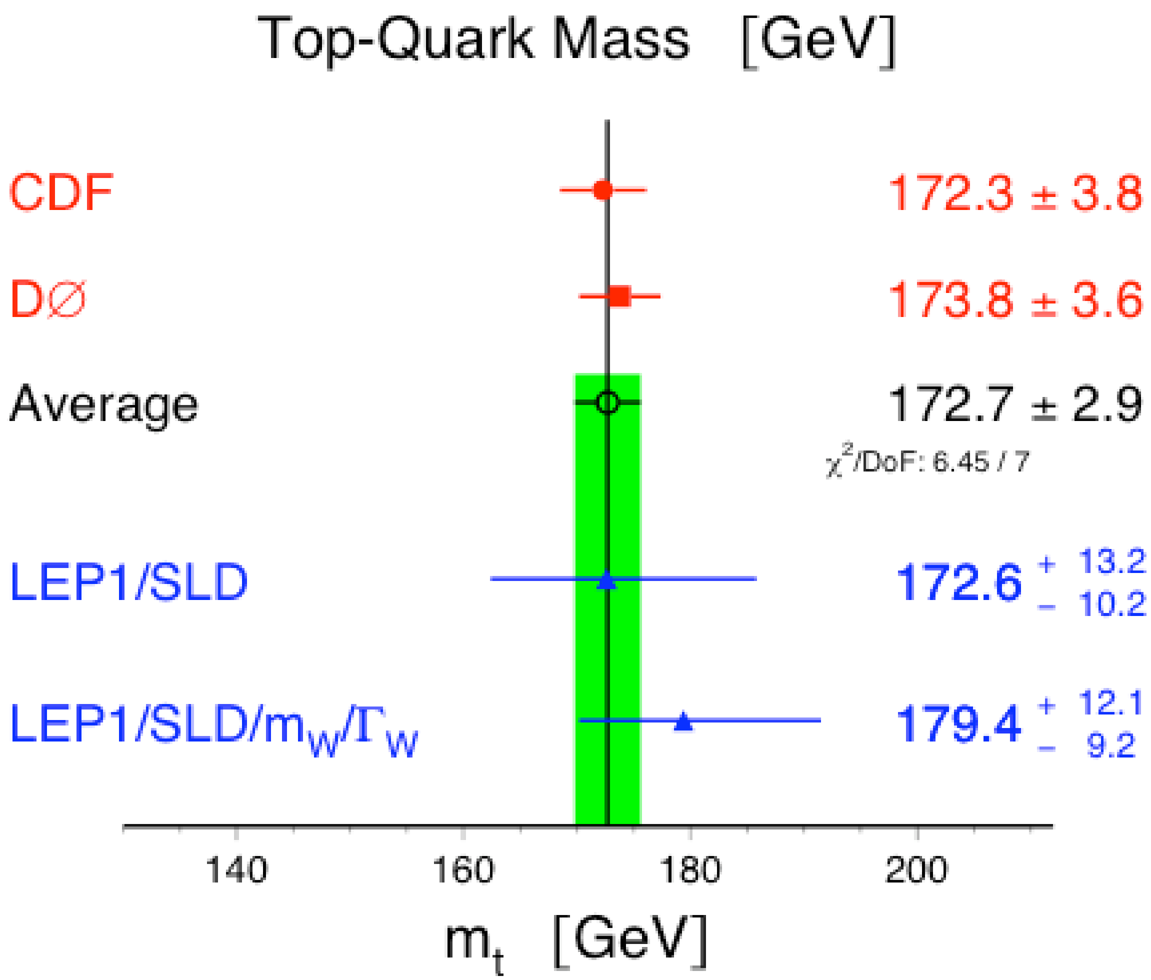
CERN/Roma Tre

Precision Tests

The only appreciable development in this domain is the decrease of the experimental value of m_t from CDF& D0 Run II
(Run I value: 178.0±4.3 GeV)

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

m_t ⇓ m_H ⇓



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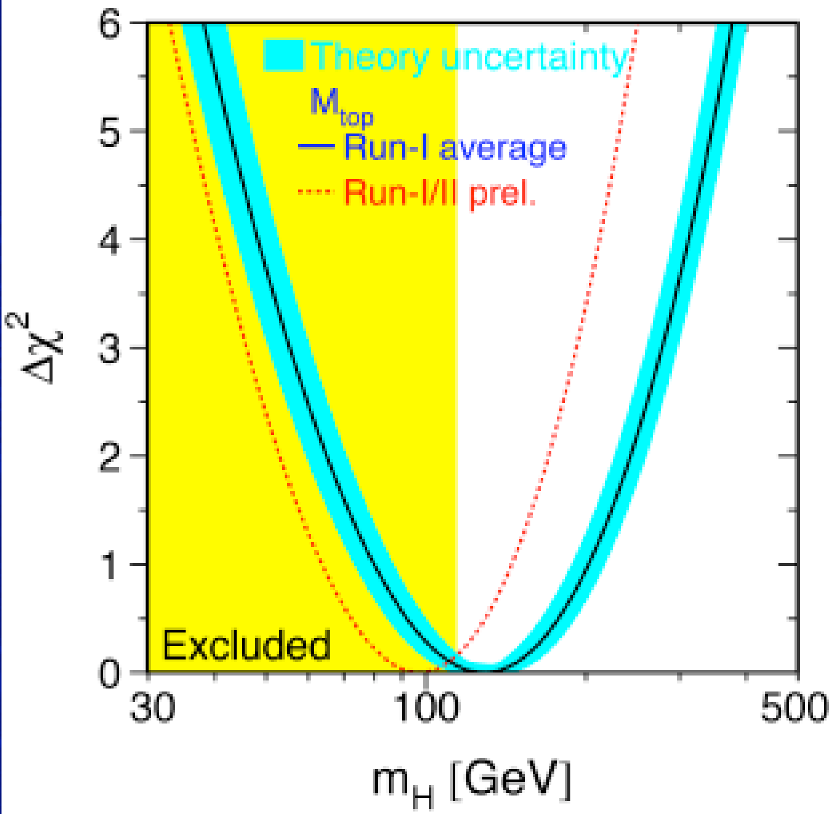
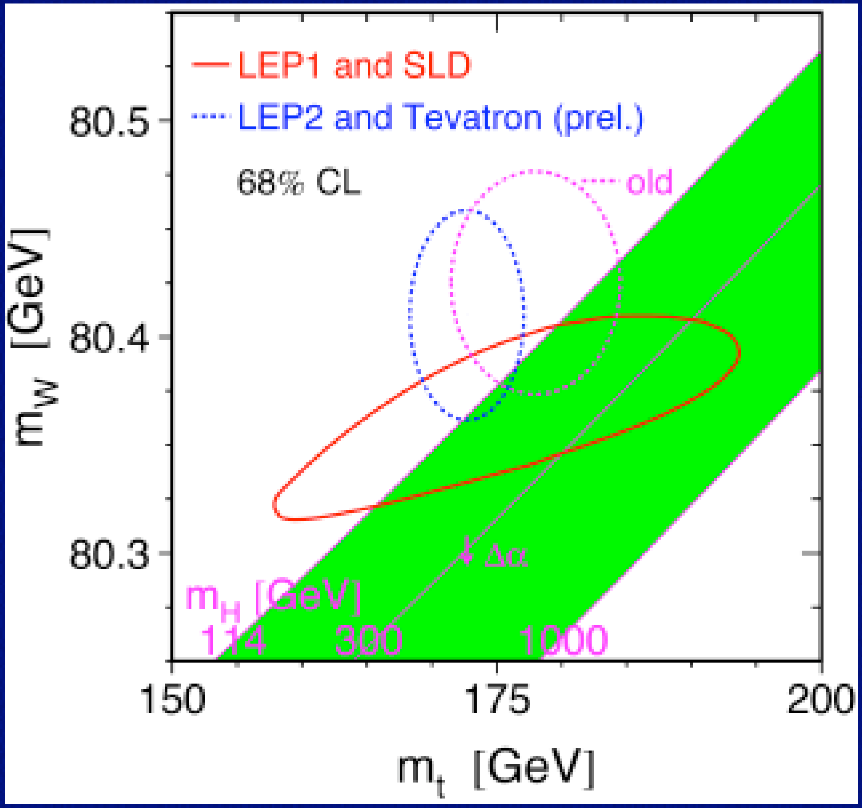
de Jong-Lisbon Conf. July'05

Consistency:





One sided limit:

(LEP-1/2+SLD+Tevatron): m_H< 186 GeV @95% CL.

Renormalising to m_H>114 GeV:

(LEP-1/2+SLD+Tevatron): m_H< 219 GeV @95% CL.

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

The χ^2 is reasonable:

χ^2/ndof~18.6/13 (~14%)

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

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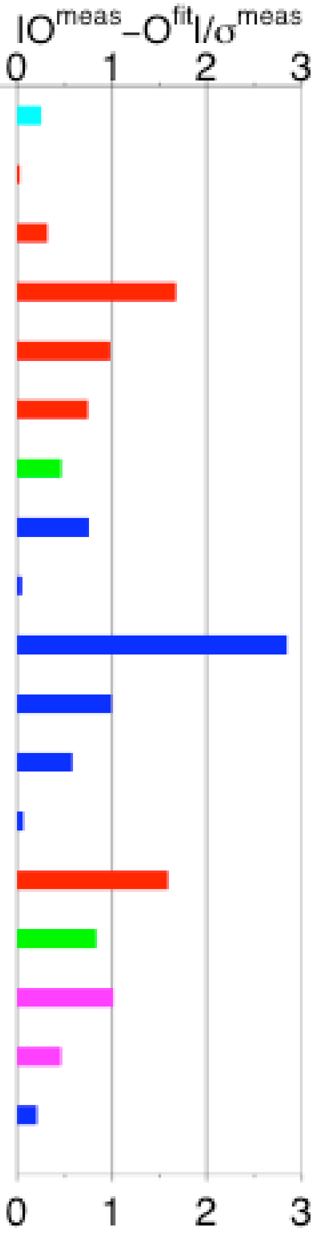
Summer 2005

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.410 ± 0.032	80.377
Γ_W [GeV]	2.123 ± 0.067	2.092
m_t [GeV]	172.7 ± 2.9	173.3



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

New!!

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

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

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

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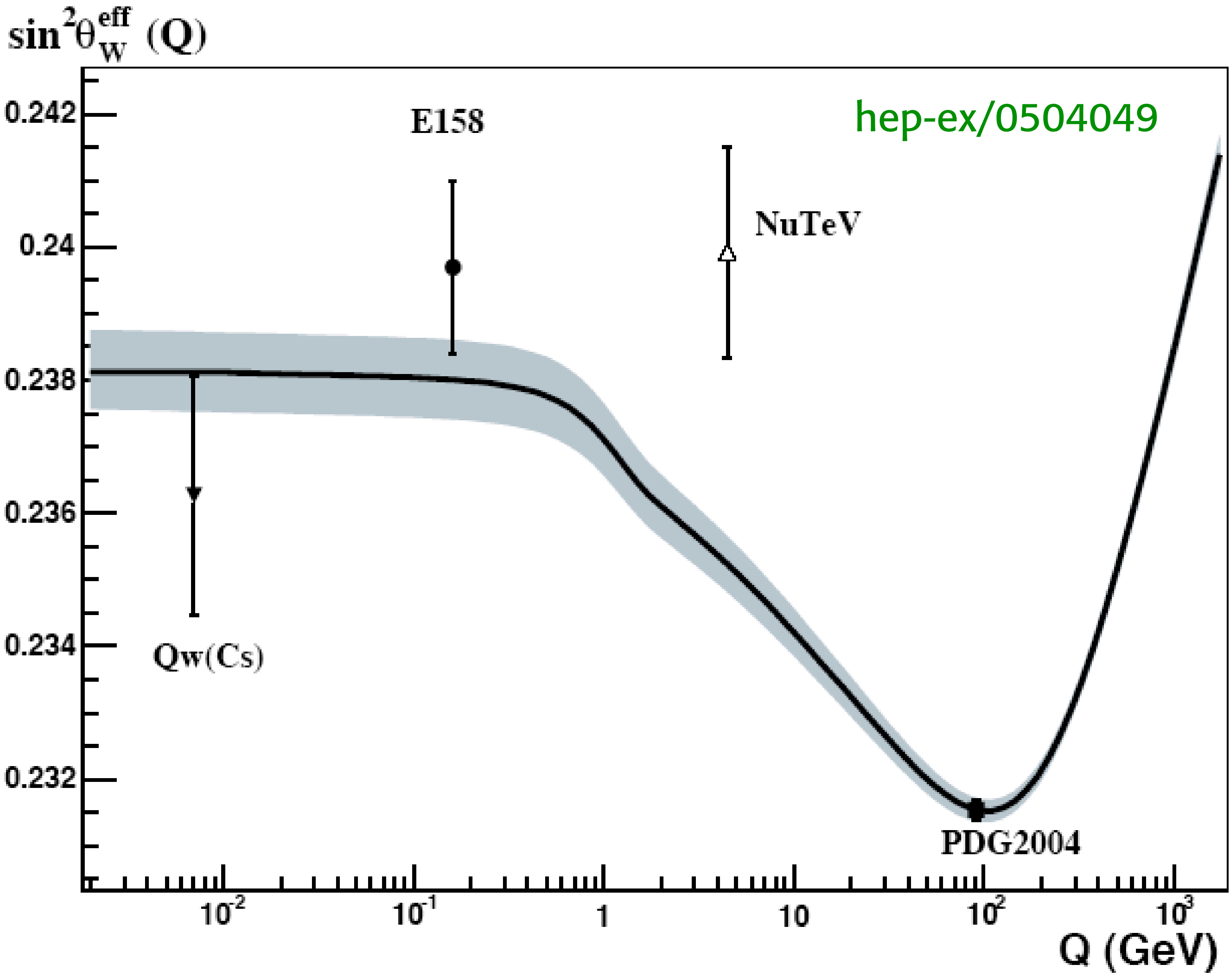

$\sin^2\theta_W^{eff}$ (Q)
hep-ex/0504049
E158
NuTeV
Qw(Cs)
PDG2004
0.242
0.24
0.238
0.236
0.234
0.232
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
Q (GeV)

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

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.

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

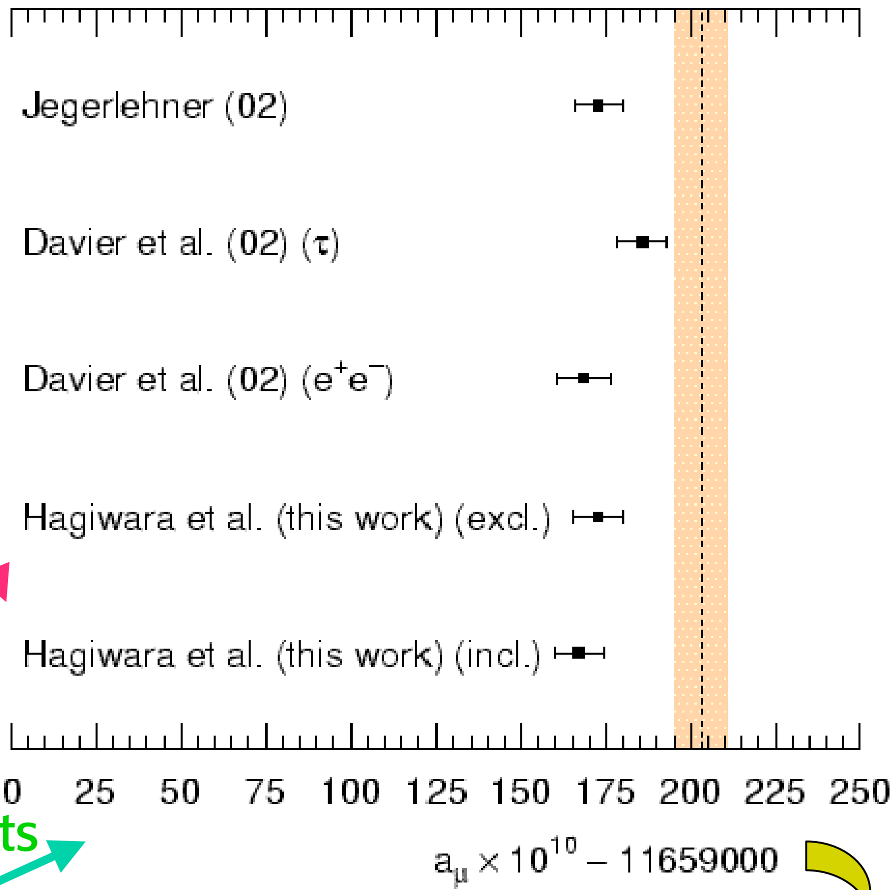
$(g\text{-}2)_\mu$ ~3σ discrepancy shown by the BNL'02 data

In 2002:

(Numbers in units 10^{-10})

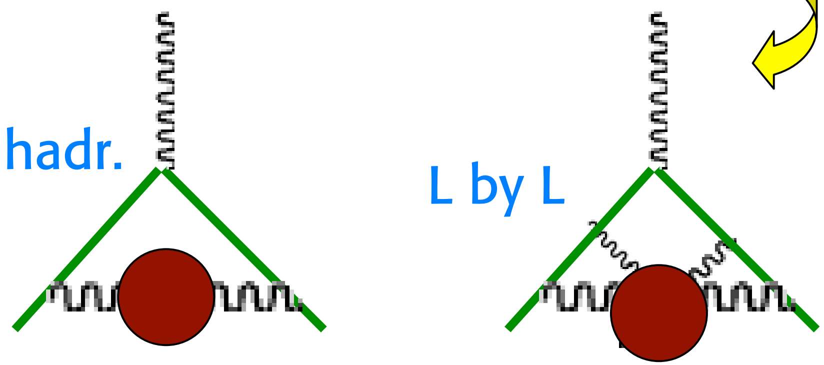
LO hadr.	688.8 ± 6.2	HMNT, 'excl.'
	$683.1 \pm 5.9 \pm 2.0_{rad}$	HMNT, 'incl.'
full a_μ	11659172.6 ± 7.7	'excl.'
	11659166.9 ± 7.4	'incl.'
BNL E821	11659203 ± 8	new world av.
		(0.7 ppm!)
EXP–TH	30.4 ± 11.1	$\sim 2.7\sigma$, 'excl.'
	36.1 ± 10.9	$\sim 3.3\sigma$, 'incl.'

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



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Gambino, LP'03

The discrepancy is less: 2-2.5 σ

2003

(new measurements of σ_{had})

The spectral function from e^+e^-

Tau data below 1.8GeV

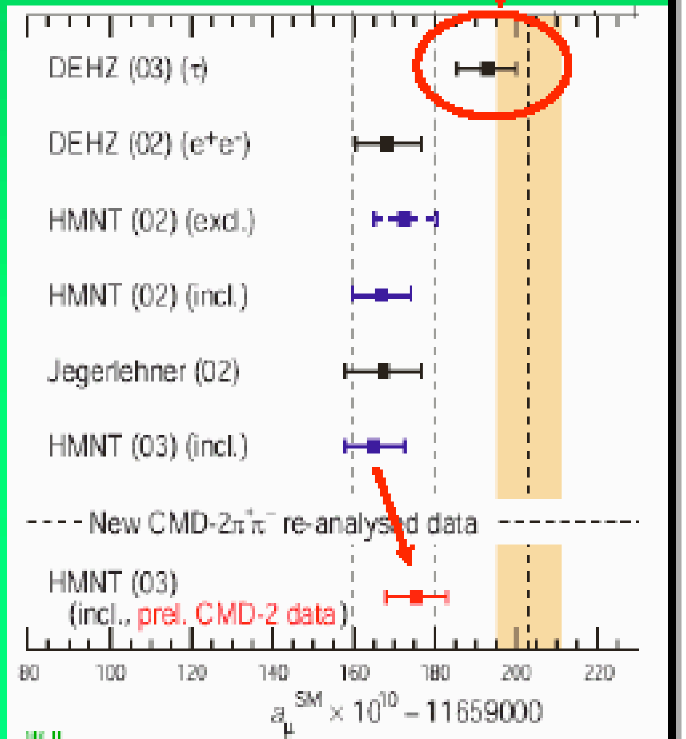
Final CMD-2 π π data (2002) 0.6% syst error!
CMD-2 have recently reanalyzed their data

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)
$a_\mu^{had,LO}=709.0\pm5.1_{exp}\pm1.2_{r.c}\pm2.8_{SU(2)}$

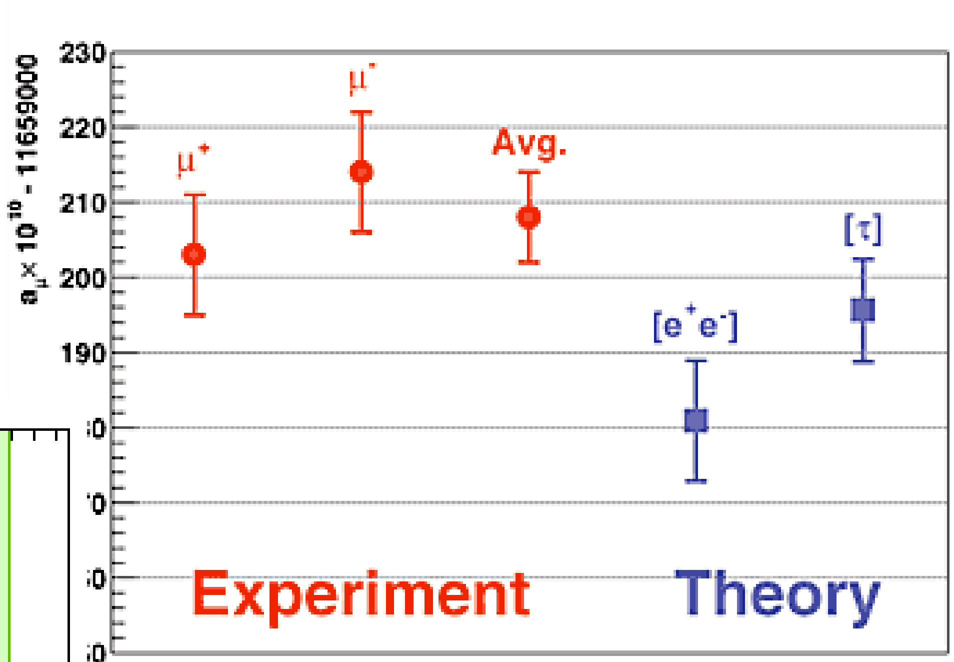
Good agreement between Aleph, CLEO, Opal τ data

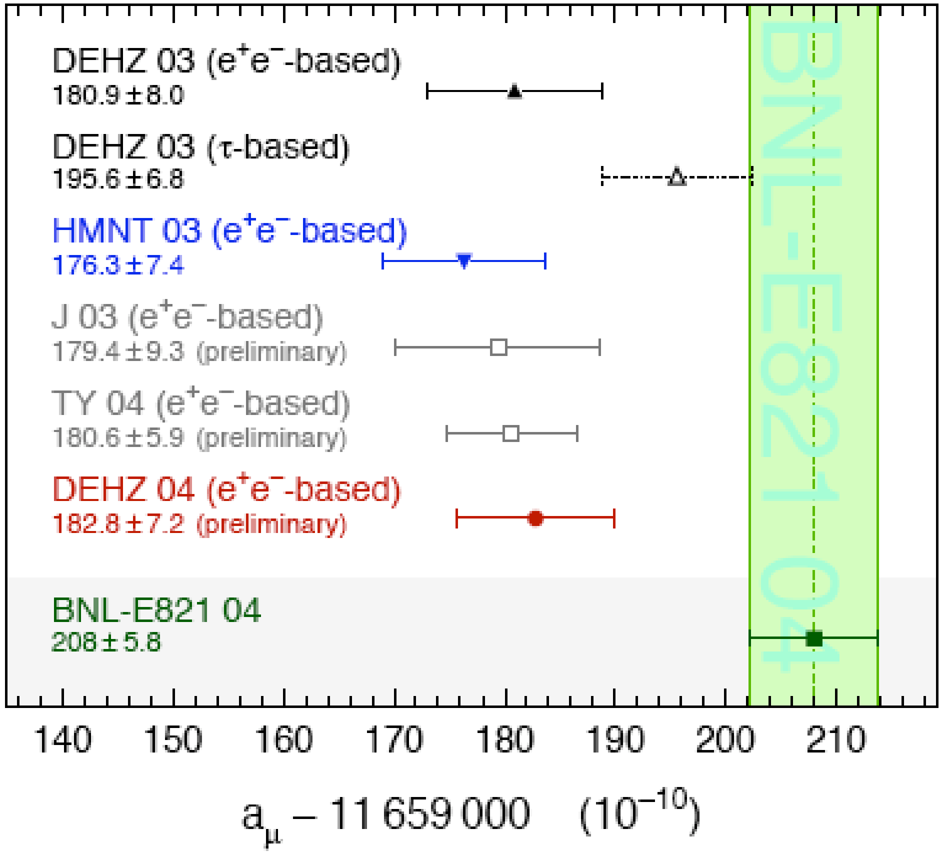


The τ data indicate no discrepancy!

2004 New results from BNL

- μ^- measured
  (was μ^+)
- discrepancy up again
  to 2.7σ (e^+e^-)

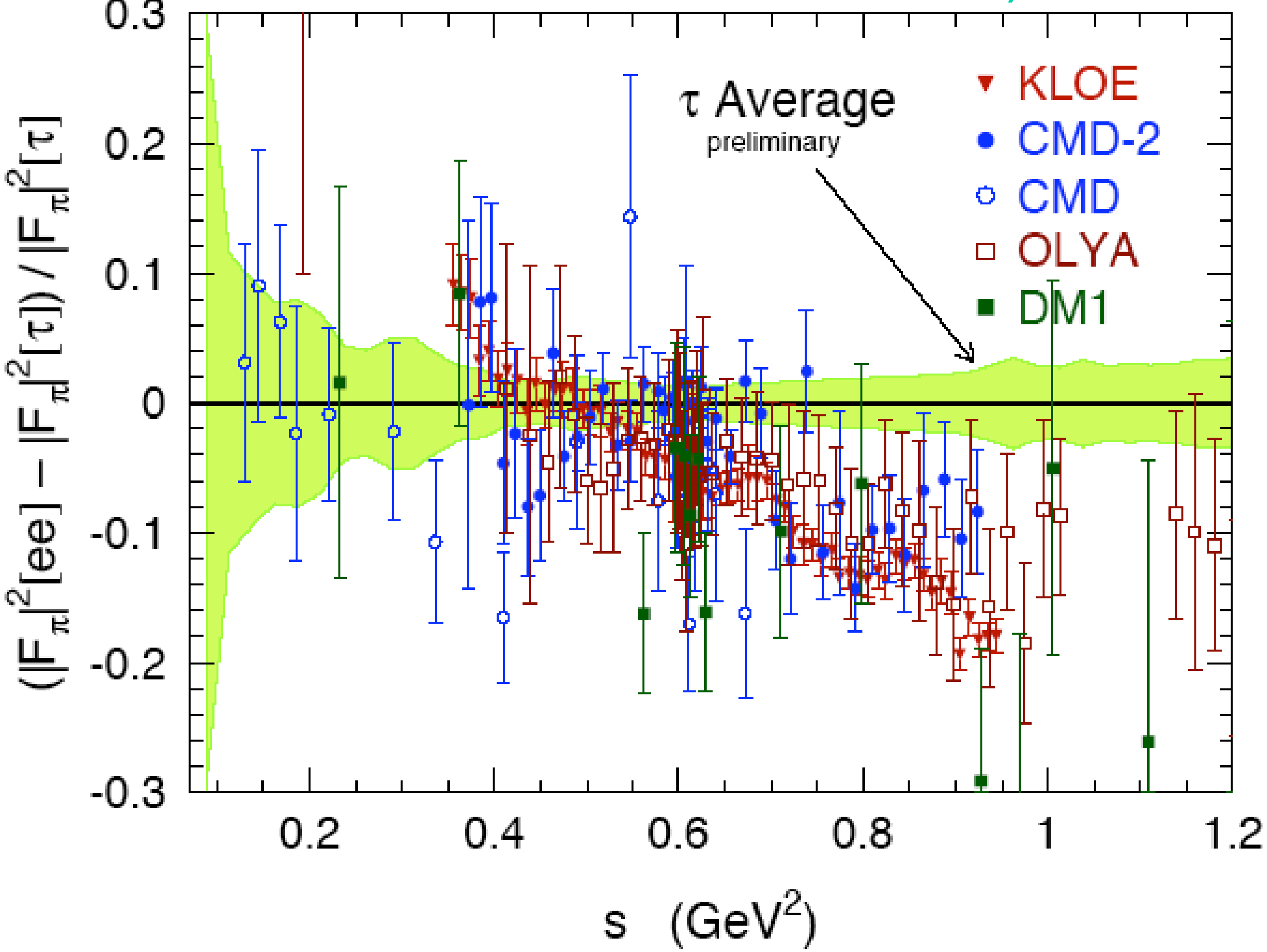




ICHEP'04

There is a persistent discrepancy between the τ and e+e- data (after correcting for V-A vs V, isospin rotation...)

Hocker, ICHEP'04



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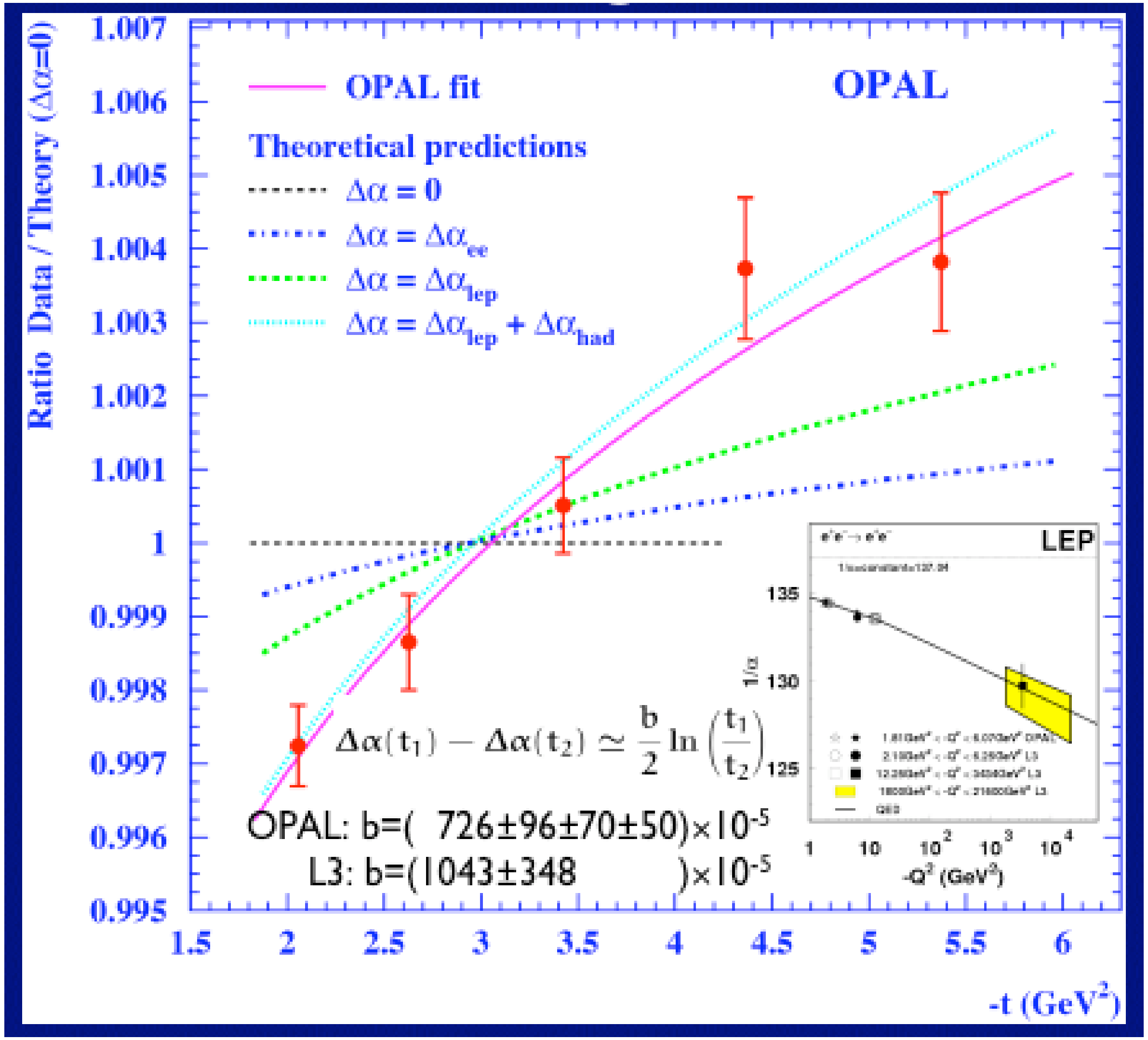
τ decay would indicate no significant deviation, while e+e- -> 2.7 σ (more direct)

Note in passing:

The running of α_{QED} has been clearly detected at LEP by OPAL and L3



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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 ~3σ away
- The measured value of m_W is a bit high

  (now worse because m_t went down)

- The central value of m_H (m_H = 91+45-32 GeV) from the fit is close to the direct lower limit (m_H>114.4 GeV at 95%) [more so if $\sin^2\theta_{eff}$ is close to that from leptonic (A_{LR}) asymm. m_H = 56+34-22 GeV] (worse now than in the past)

A well known issue:

2001: Chanowitz;
GA, F. Caravaglios, G. Giudice, P. Gambino, G. Ridolfi

Status of $\sin^2\theta_{eff}$

Combined lept. asymm.:

$[\sin^2\theta]_{lept}=0.23113(21)$

Combined hadr. asymm.:

$[\sin^2\theta]_{hadr}=0.23222(27)$

diff = 3.2 σ

Essentially the discrepancy is between A_l(SLC) & A_{fb}^{0b}

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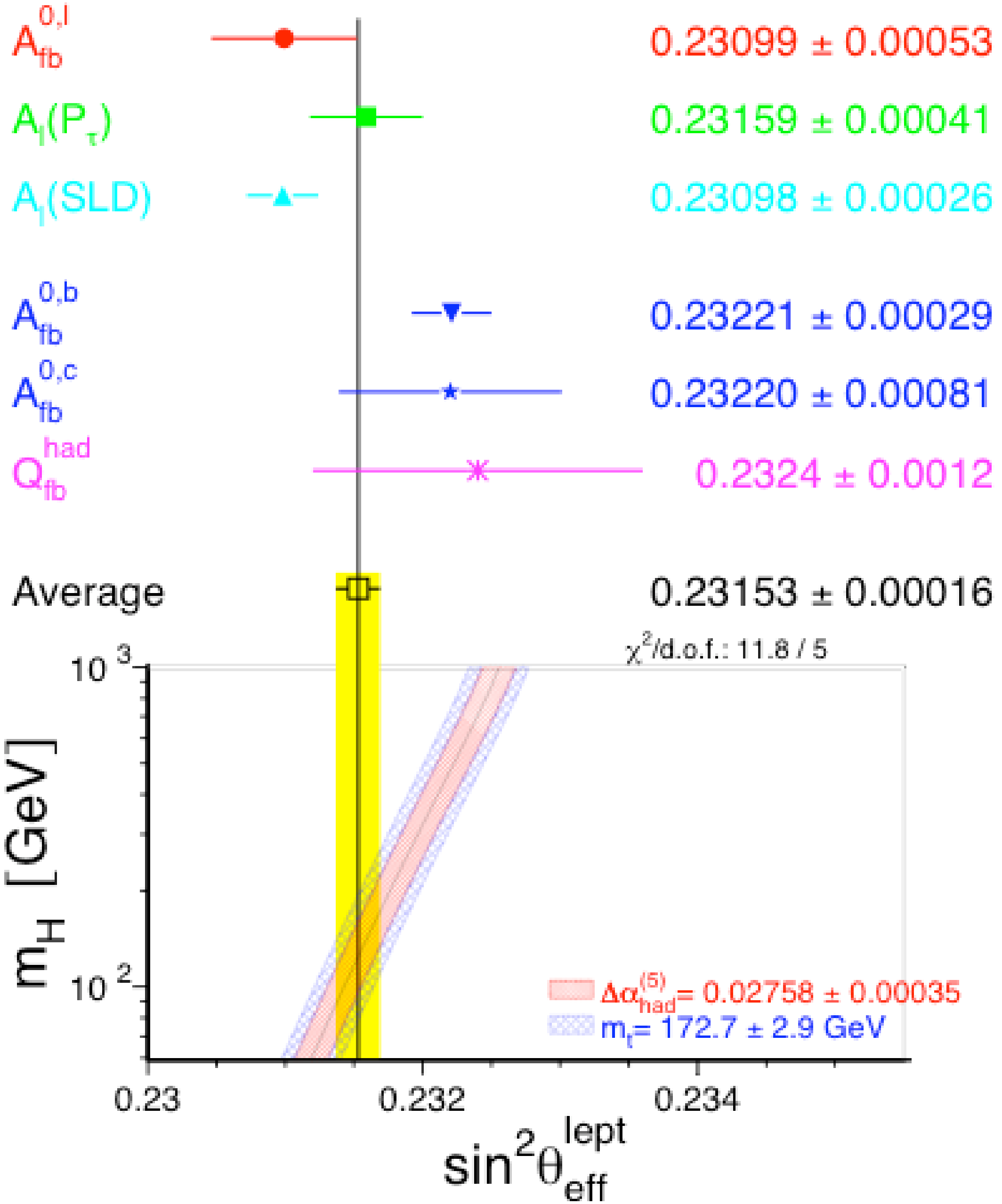


Recently the combined value of A^b_{FB} has moved a bit in the wrong direction

Cause: Discovery of omission in ZFITTER of a small 2- loop term for b-quarks

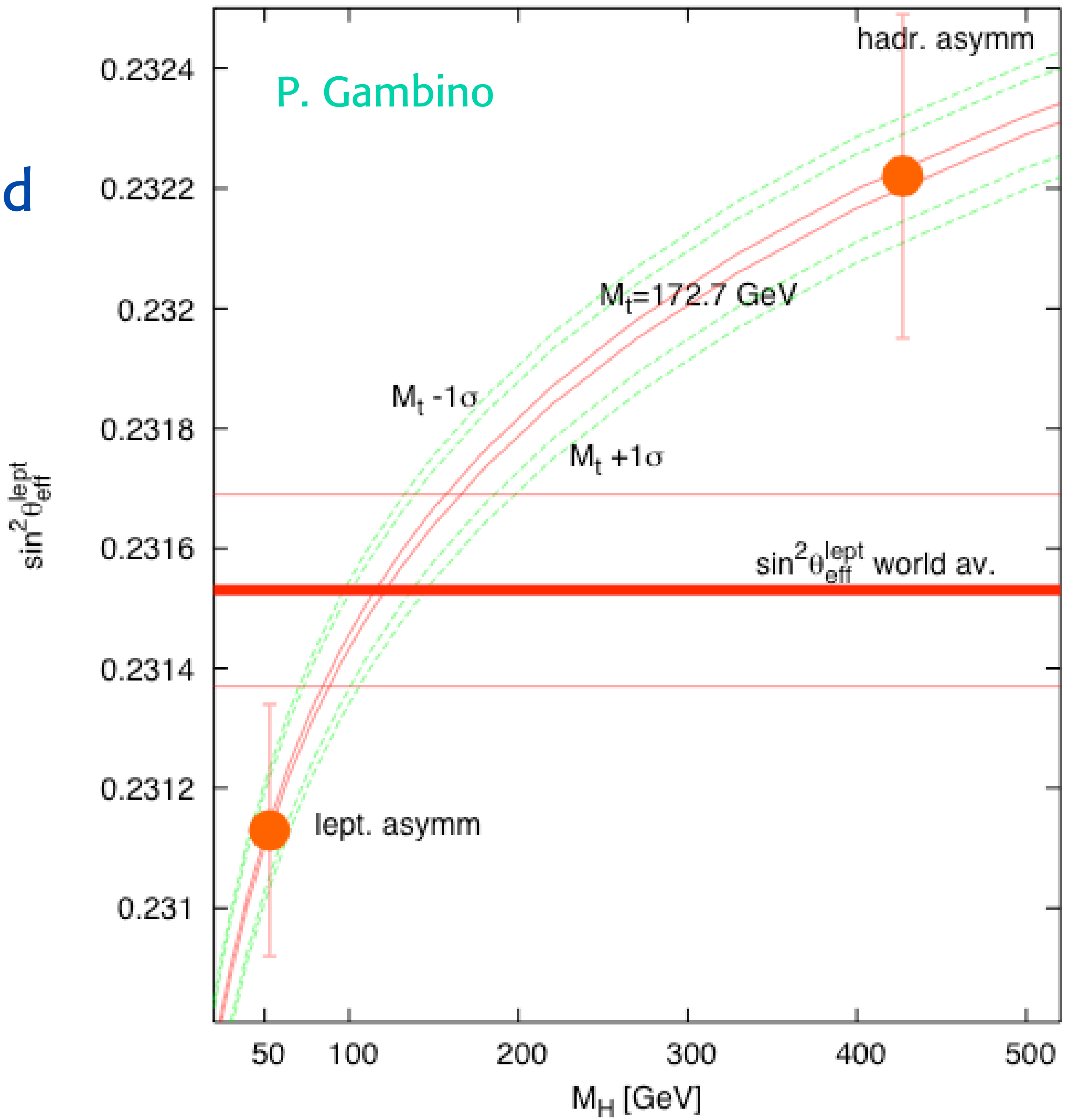
Effect: $A^b_{FB} = 0.0998 \pm 0.0017$ becomes 0.0992 ± 0.0016

The discrepancy $[\sin^2\theta]_{hadr}$-$[\sin^2\theta]_{lept}$ goes from 2.8 to 3.2σ

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

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



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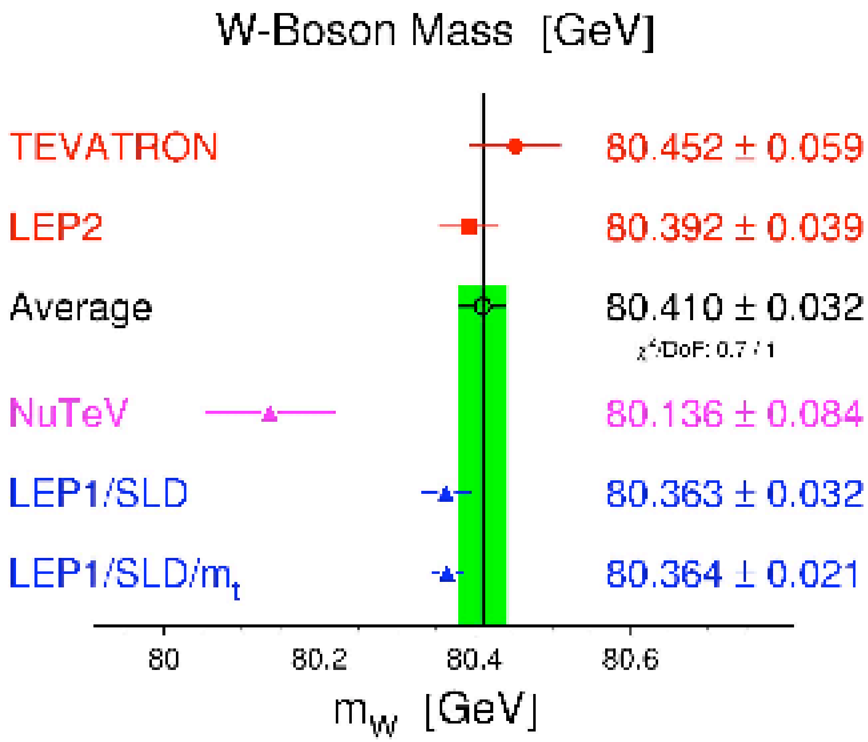

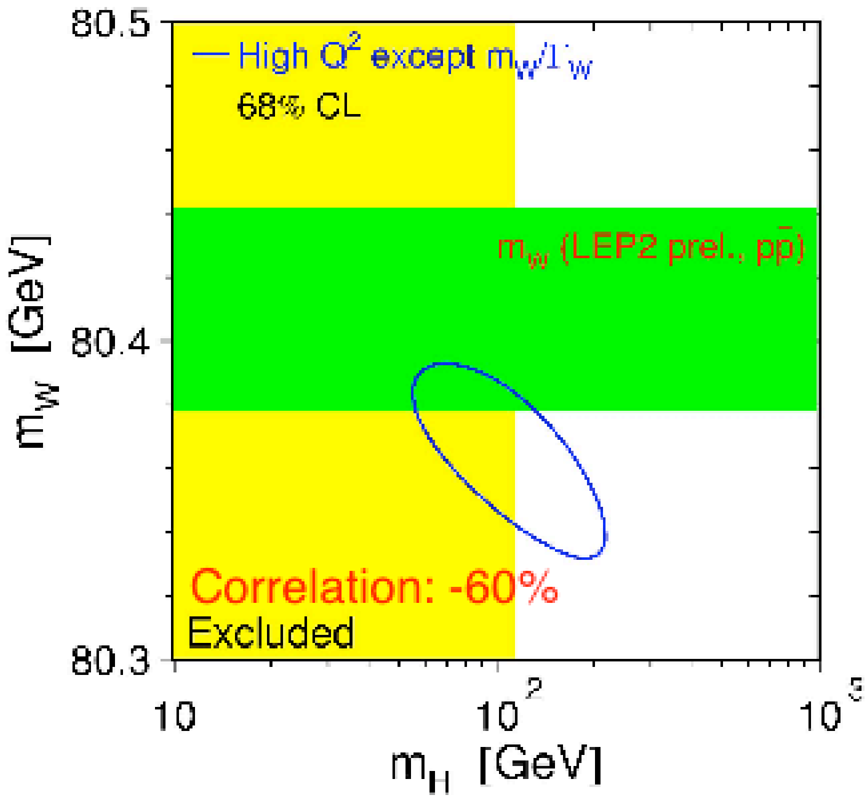

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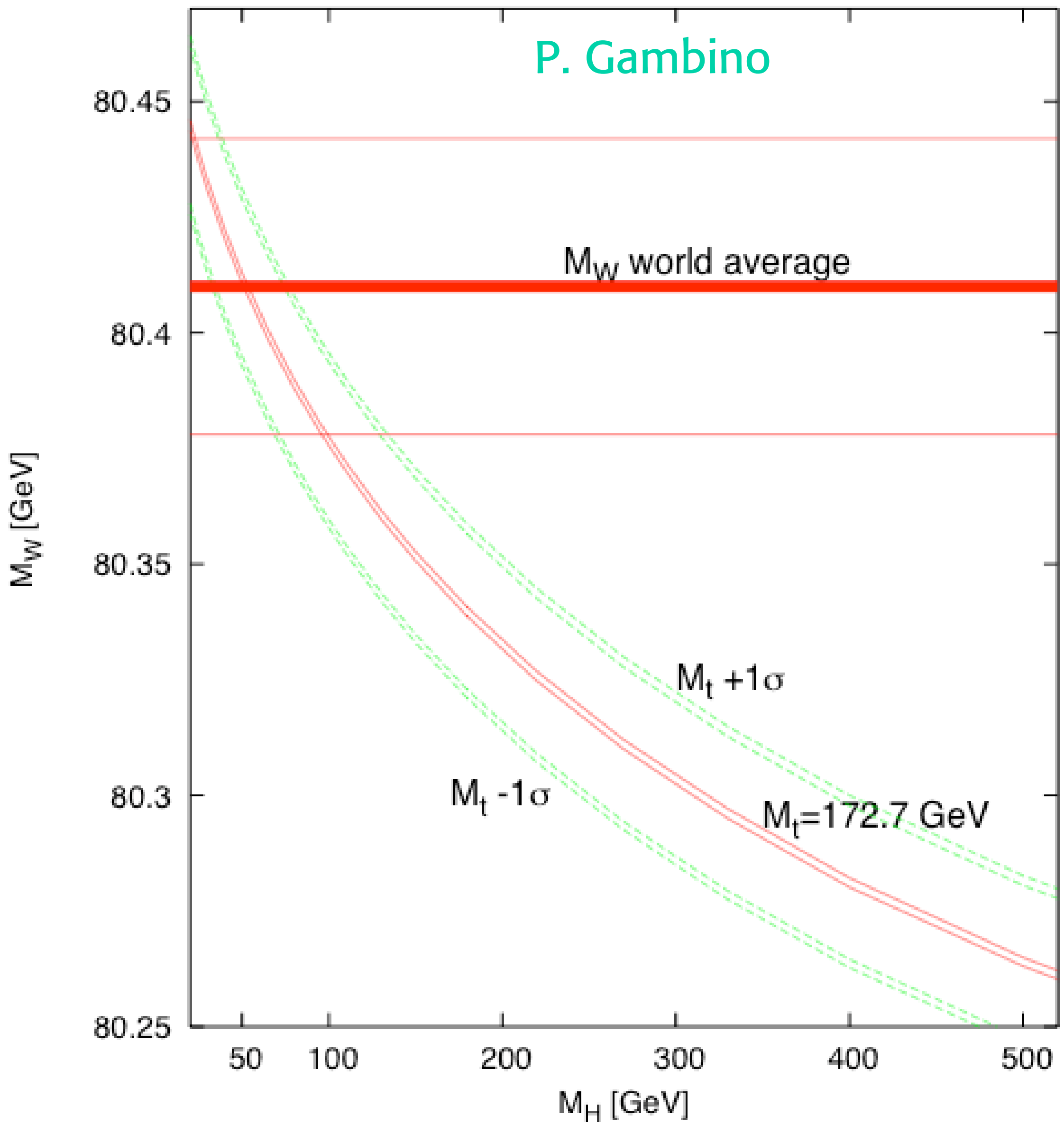
Plot m_W vs m_H

m_W points to a light Higgs!

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



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- The central value of m_H (m_H = 91+45-32 GeV) from the fit is close to the direct lower limit (m_H>114.4 GeV at 95%) [more so if $\sin^2\theta_{eff}$ is close to that from leptonic (A_{LR}) asymm. m_H = 56+34-22 GeV] (worse now than in the past)

A well known issue:

2001: Chanowitz;
GA, F. Caravaglios, G. Giudice, P. Gambino, G. Ridolfi

Not a significant indication of a problem

However, since new physics at the EW scale could well be around, one looks with interest at every possible hint

Status of the SM Higgs fit

Summer '05

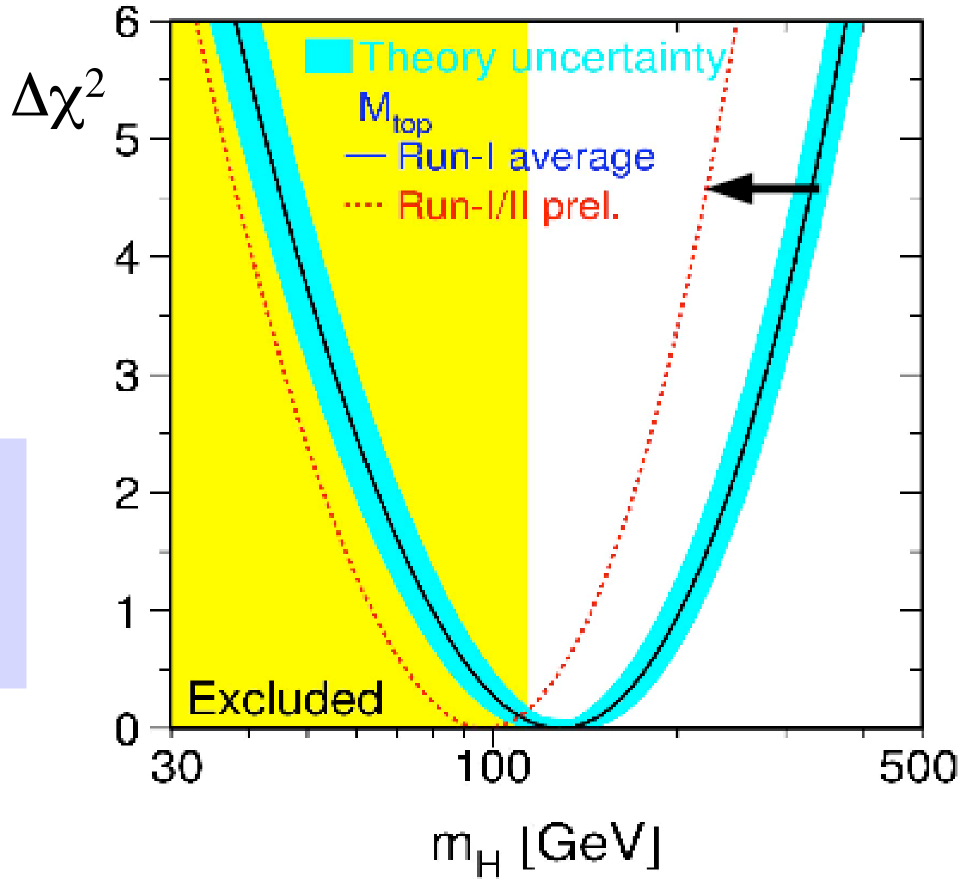
Sensitive to log m_H

Rad Corr.s ->

$\log_{10} m_H(\text{GeV}) = 1.96 \pm 0.18$

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

Direct search: $m_H > 114$ GeV



At 95% cl

$m_H < 186$ GeV (rad corr.'s)

$m_H < 219$ GeV (incl. direct search bound)

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Fit results

Summer '05

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

	m_W	m_t	m_W, m_t
m_t(GeV)	179.4±10.6	172.7±2.8	173.3±2.7
m_H(GeV)	148+248-83	112+62-41	91+45-32
log[m_H(GeV)]	2.17±0.39	2.05 ± 0.20	1.96± 0.18
$\alpha_s(m_Z)$	0.1190(28)	0.1190 (27)	0.1186 (27)
χ^2/dof	17.3/12	16.0/11	17.8/13
m_W(MeV)	80387(22)	80364(21)	80390(18)

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WA: m_W=80425(34)

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

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

$\log m_H \to \log\Lambda$ + const

Any alternative mechanism amounts to change the prediction of finite terms.

The most sensitive quantities to $\log m_H$ are $\varepsilon_1 \sim \Delta\rho$ and ε_3:

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

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

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

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

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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)?

- Possibly 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 below direct limit

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:

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

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

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

From A^b_{FB}=0.0992±0.0016, using $[\sin^2\theta]_{lept}$=0.23113±0.00021 one obtains A_b=0.881±0.014

$$(A_b)_{SM} - A_b = 0.055 \pm 0.016 \rightarrow 3.4\ \sigma$$

A large δg_R needed (by about 30%!)

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

But note: $(A_b)_{SLD}$ = 0.922±0.020,
also R_b=0.21638±0.00066 (R_{bSM}~0.2157)

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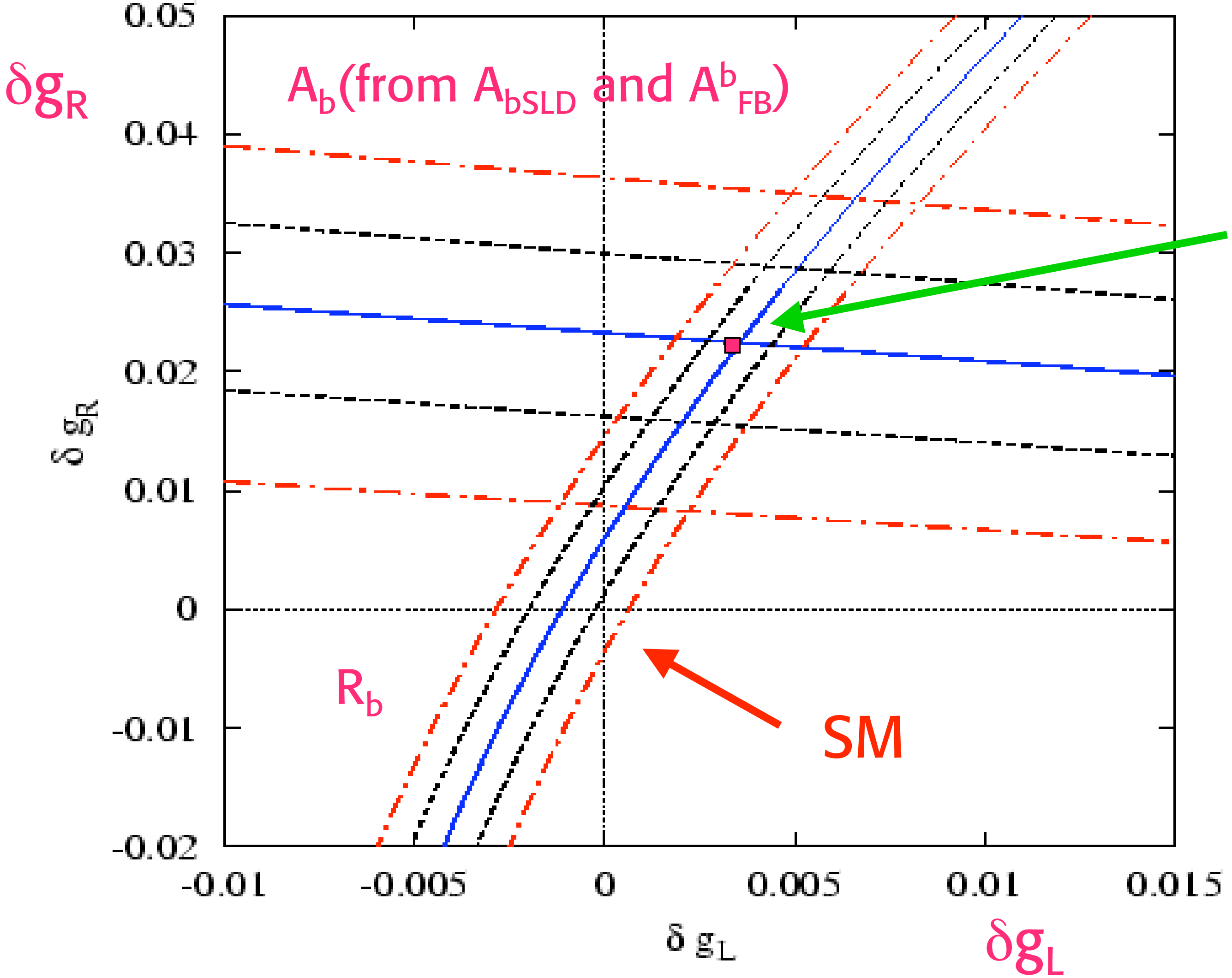

Choudhury, Tait, Wagner

$0.992\, g_L(SM)$, $1.26\, g_R(SM)$

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

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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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
- •••••

If you take all these clues I think that SUSY is the best known solution (vacuum energy is unsolved by all)

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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 hierarchy problem

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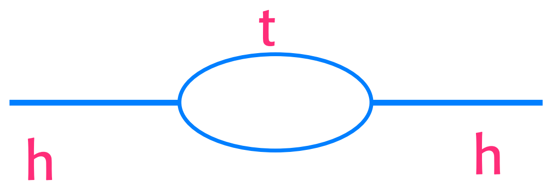
Not only it looks very unlikely, but the new physics must be near the weak scale!

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

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

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



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

This hierarchy problem demands new physics near the weak scale

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

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 are not directly visible

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Examples:

SUSY

- Supersymmetry: boson-fermion symm.

  exact (unrealistic): cancellation of $\delta\mu^2$

  approximate (possible): $\Lambda \sim m_{SUSY}\text{-}m_{ord}$ → top loop $\Lambda \sim m_{stop}$

  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

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

  "Little Higgs" models. Problems with EW precision tests

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

  Exciting. Many facets. Rich potentiality. No baseline model emerged

  --> Pomarol

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
Good Dark Matter candidates

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

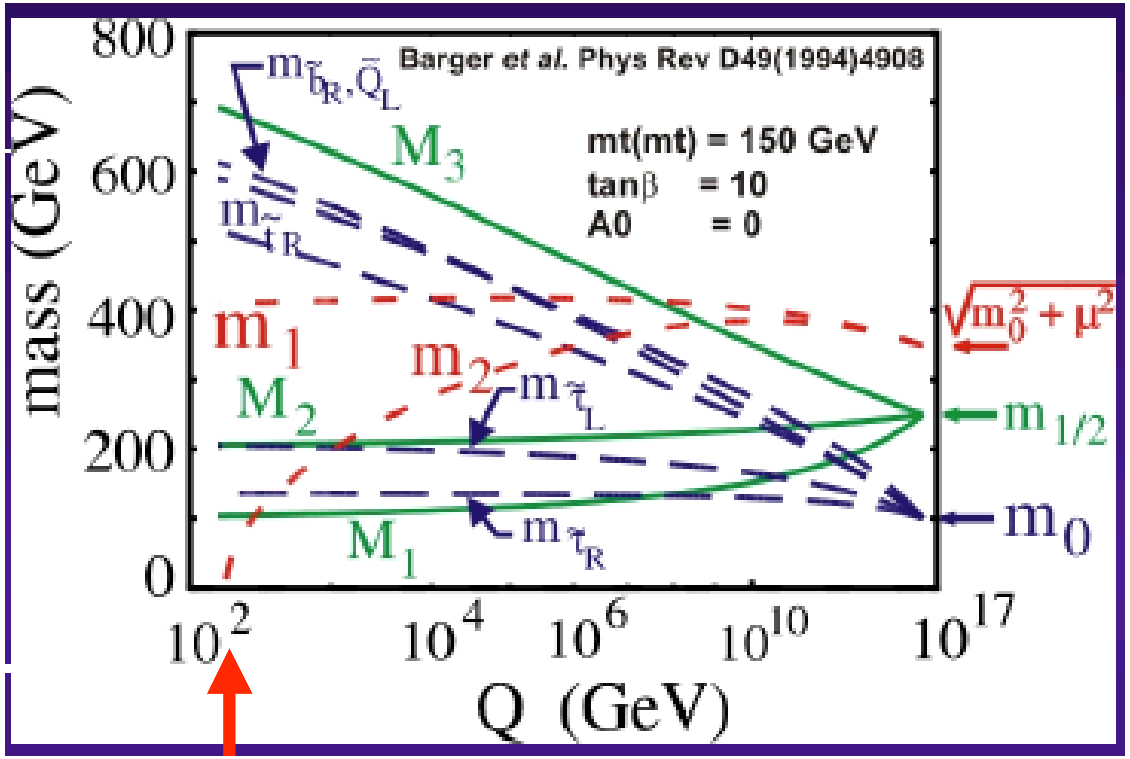
m_{stop} large tends to clash with $\delta m_h^2 \sim m_{stop}^2$

- 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

$$m_Z^2 \approx c_{1/2} m_{1/2}^2 + c_0 m_0^2 + c_t A_t^2 + c_\mu \mu^2$$

$c_a = c_a(m_t, \alpha_i, \ldots)$

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

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

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

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

Residual FT could be alleviated by going to a non minimal model e.g adding an extra Higgs singlet (NMSSM)

SUSY fits with GUT's

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

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

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

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}

- 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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EW DATA and New Physics

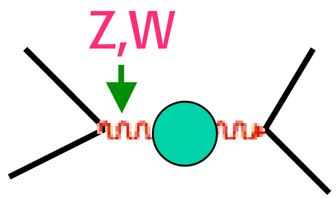
For an analysis of the LEP data beyond the SM we use the ε formalism GA, R.Barbieri, F.Caravaglios, S. Jadach

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

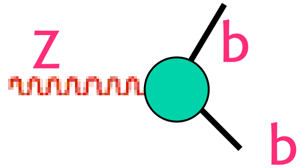
- Focus on pure weak rad. correct's, i.e. vanish in limit of tree level SM + pure QED and/or QCD correct's [a good first approximation to the data]

- 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 →

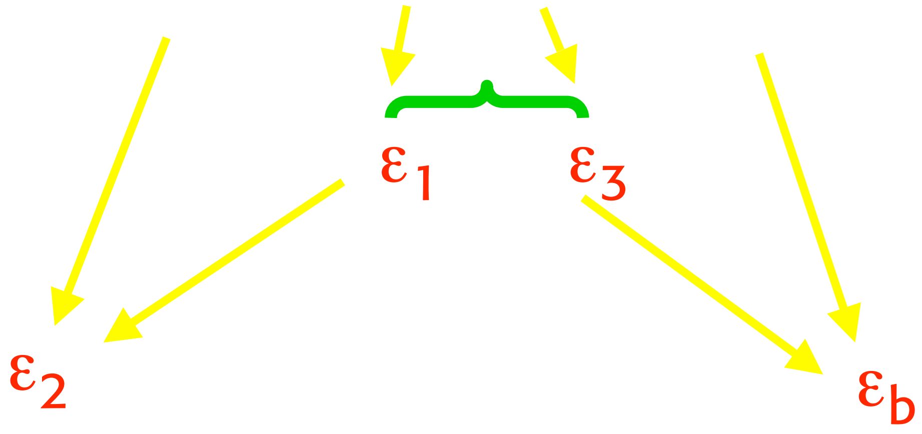


- Can be measured from the data with no reference to m_t and m_H (as opposed to S, T, U -> ε_3, ε_1, ε_2)

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.

The EWWG gives (summer '05):

$\varepsilon_1 = 5.4 \pm 1.0\ 10^{-3}$
$\varepsilon_2 = -\ 8.5 \pm 1.2\ 10^{-3}$
$\varepsilon_3 = 5.34 \pm 0.94\ 10^{-3}$
$\varepsilon_b = -\ 5.0 \pm 1.6\ 10^{-3}$

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!)

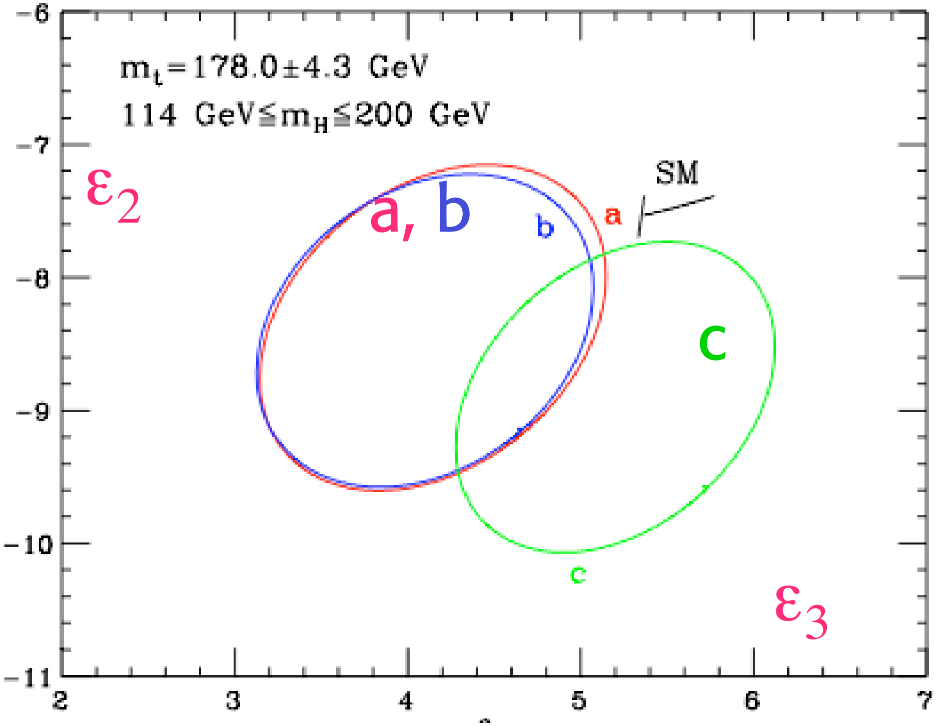
G. Altarelli

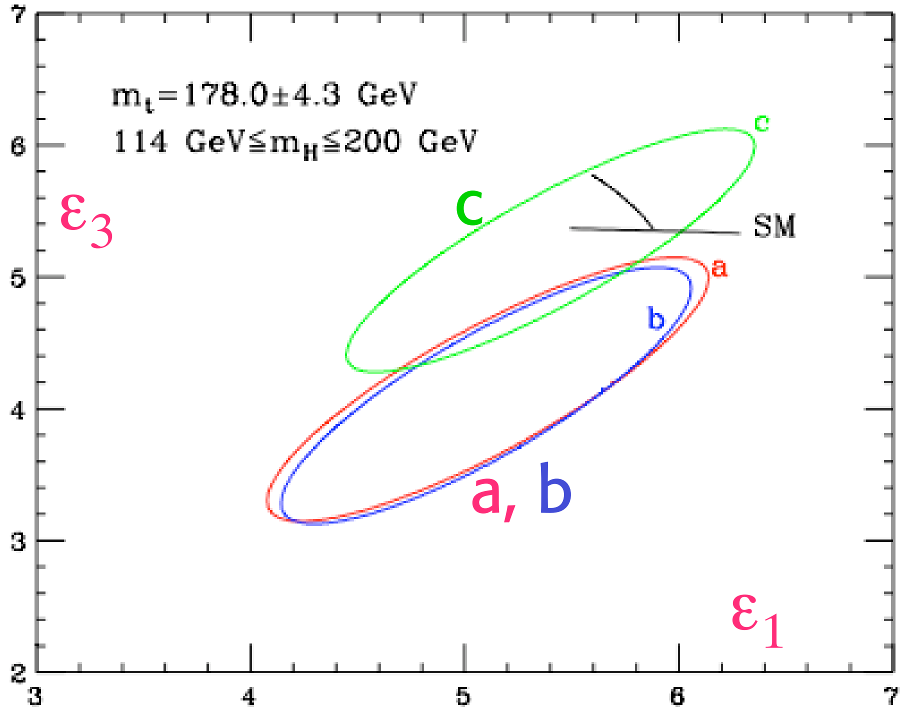
GA, F. Caravaglios, G. Giudice, P. Gambino, G. Ridolfi
(updated 2004)

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)

Units: 10^{-3}





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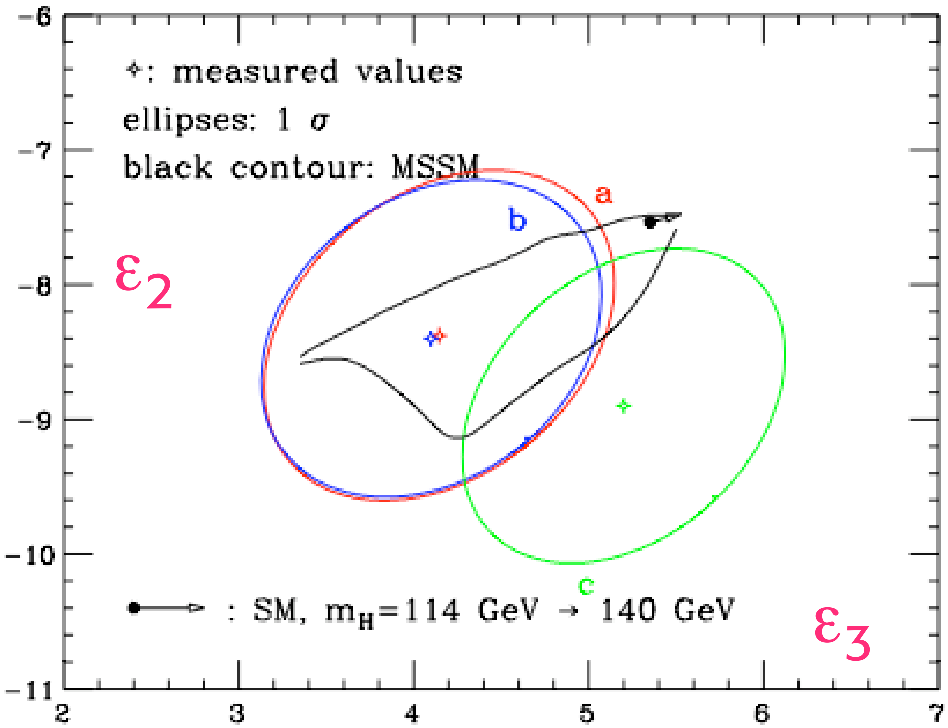
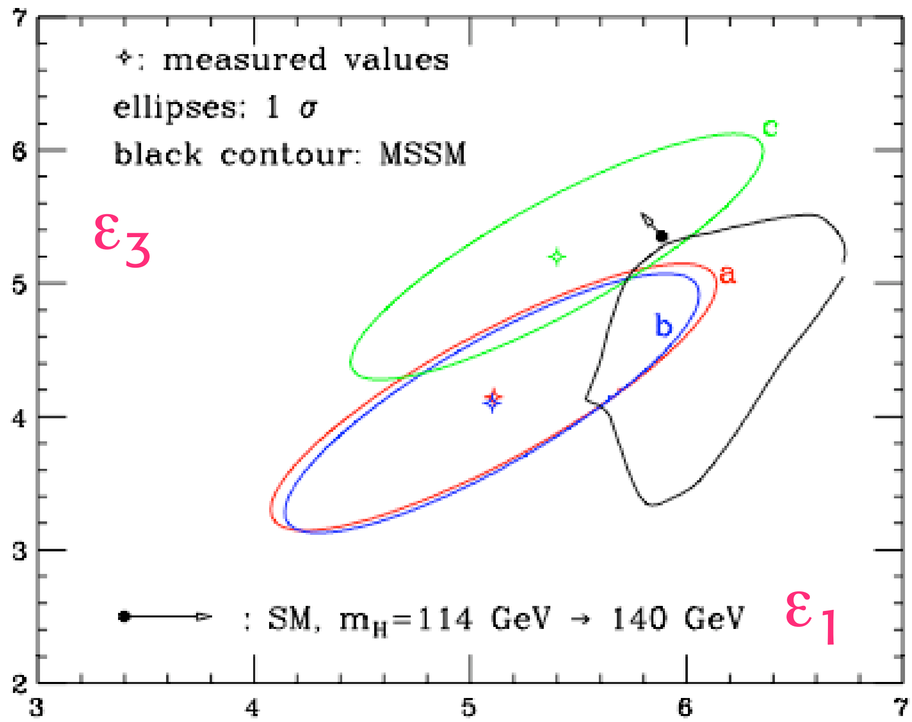
ε_1 is ~OK (on the low side), ε_2 is a bit low (m_W),
ε_3 depends on $\sin^2\theta$: low for $[\sin^2\theta]_l$ (m_H)

MSSM: $m_{\tilde{e}L}$ = 96-300 GeV, m_{χ^-} = 105-300 GeV,
μ = (-1)-(+1) TeV, tgβ = 10, m_h = 114 GeV,
$m_A = m_{\tilde{e}R} = m_{\tilde{q}}$ =1 TeV

Units: 10^{-3}





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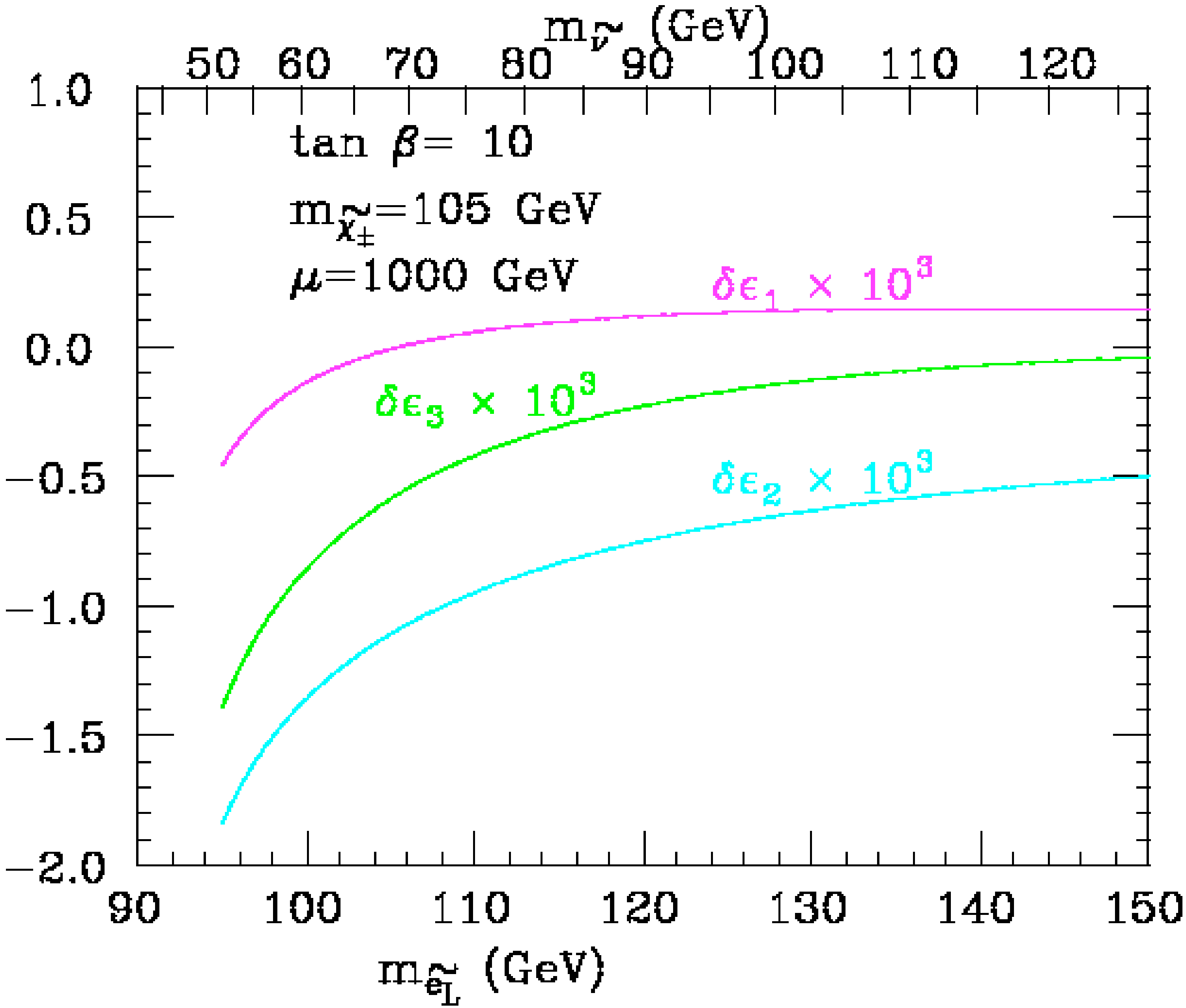
to get large (ie ~1σ) effects s-leptons <u>and</u> s-ν's plus gauginos must be as light as possible given the present exp. bounds!



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

Light SUSY is compatible with $(g\text{-}2)_\mu$

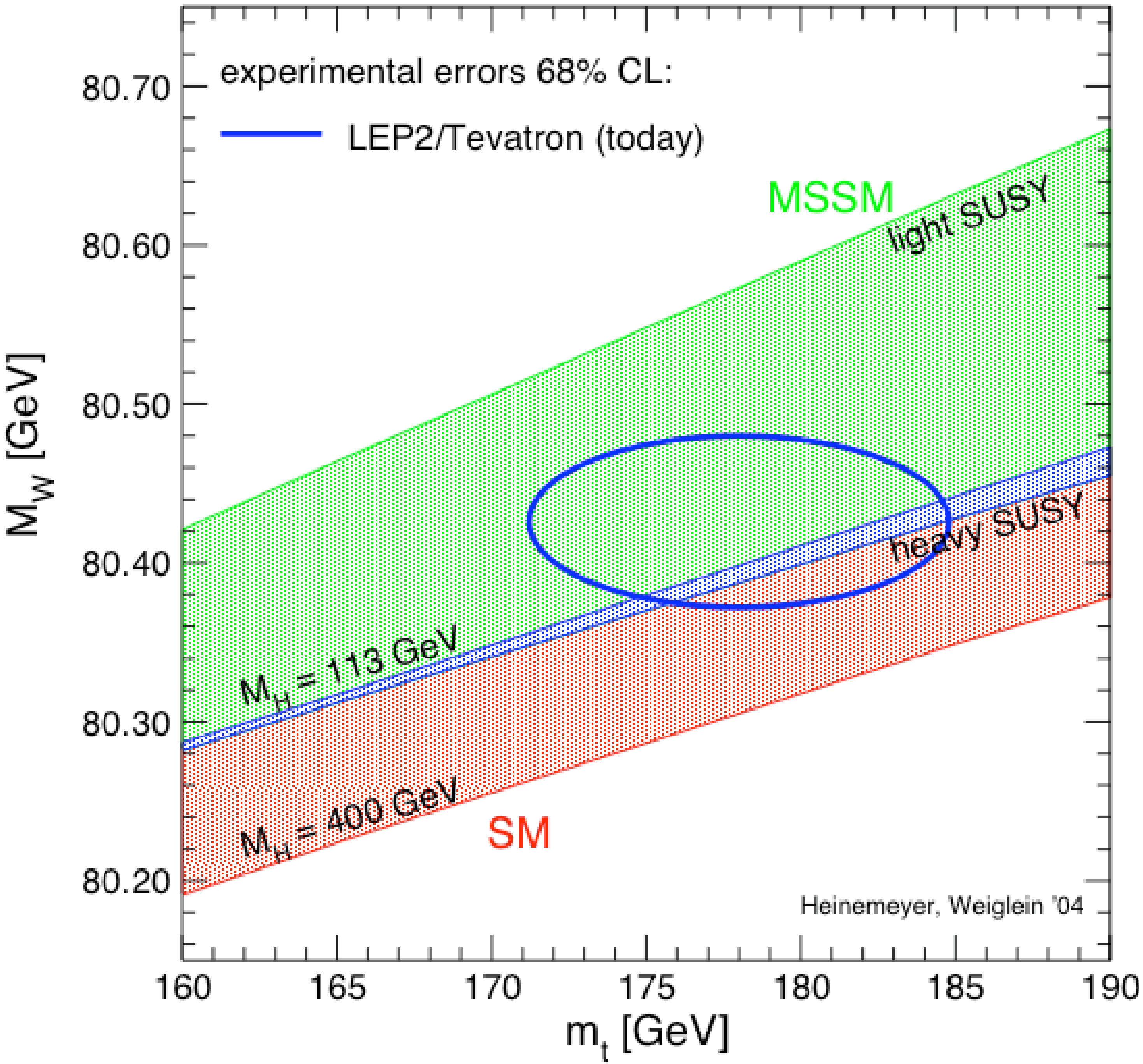
Typically at large tgβ:

Exp. ~250

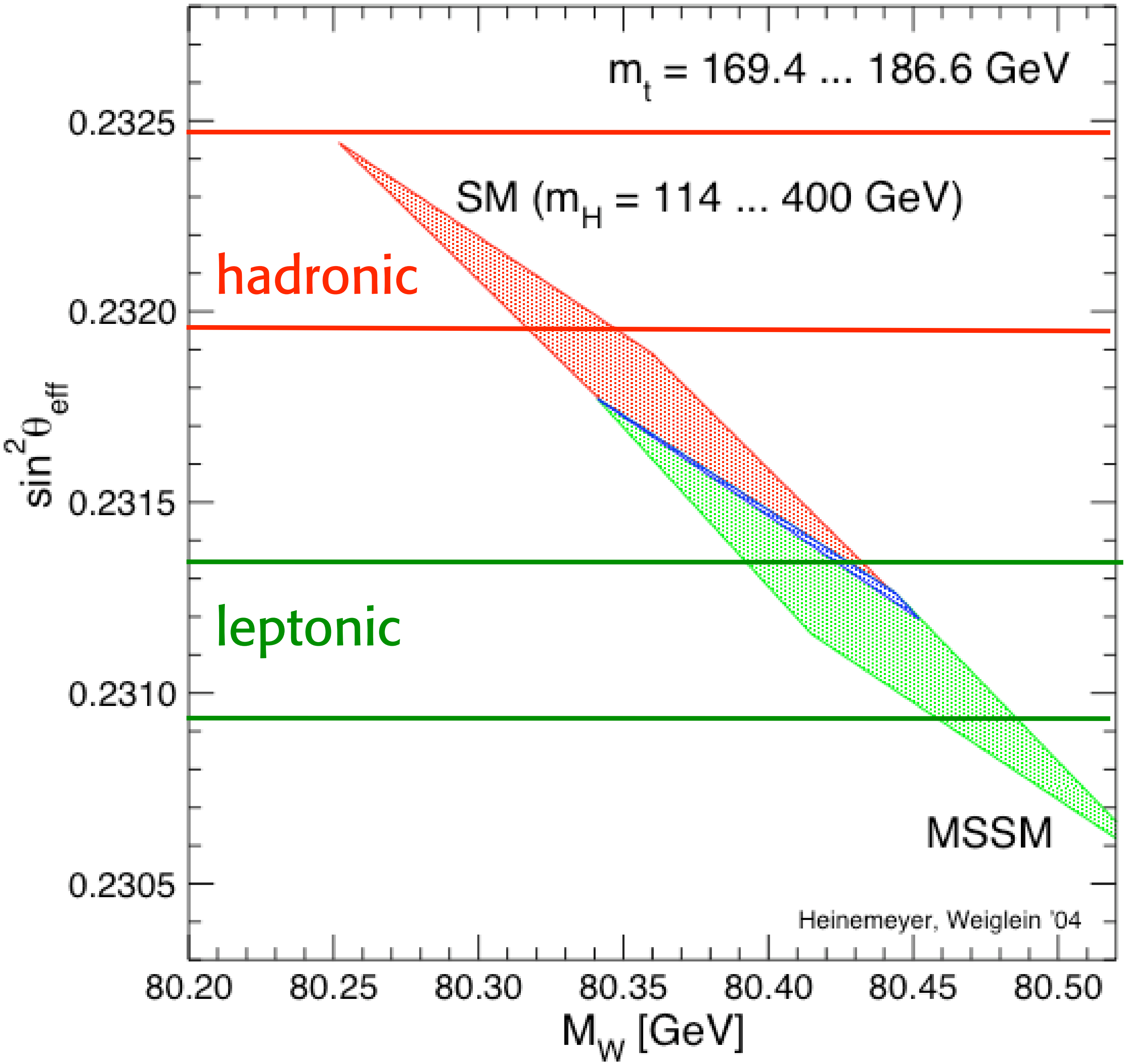
$$\delta a_\mu \sim 150\ 10^{-11}(100\ \mathrm{GeV}/m)^2\ \mathrm{tg}\beta$$

OK for e.g. tanβ~4, $m_{\chi^+} \sim m \sim 140$ GeV

Light s-leptons and gauginos predict a deviation!


experimental errors 68% CL:
LEP2/Tevatron (today)
MSSM
light SUSY
heavy SUSY
M_H = 113 GeV
M_H = 400 GeV
SM
Heinemeyer, Weiglein '04
80.70
80.60
80.50
80.40
80.30
80.20
M_W [GeV]
160
165
170
175
180
185
190
m_t [GeV]

G. Altarelli



m_t = 169.4 ... 186.6 GeV
SM (m_H = 114 ... 400 GeV)
hadronic
leptonic
MSSM
Heinemeyer, Weiglein '04
0.2325
0.2320
0.2315
0.2310
0.2305
$\sin^2\theta_{eff}$
80.20
80.25
80.30
80.35
80.40
80.45
80.50
M_W [GeV]

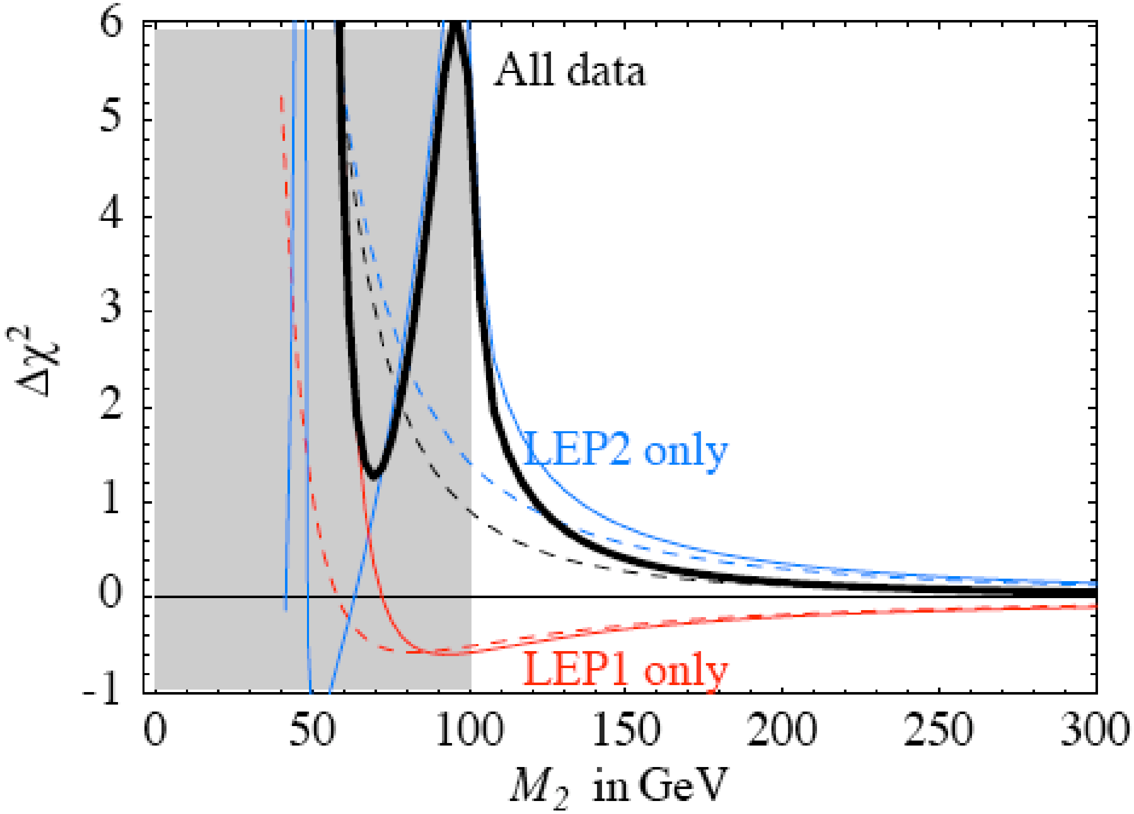
G. Altar

Recent:

However, LEP2 data do not support the virtual effects of light SUSY Marandella, Shappacher, Strumia

When including LEP2: ε1, ε2, ε3 --> $\hat{S}, \hat{T}, W, Y$

Barbieri, Pomarol, Rattazzi, Strumia



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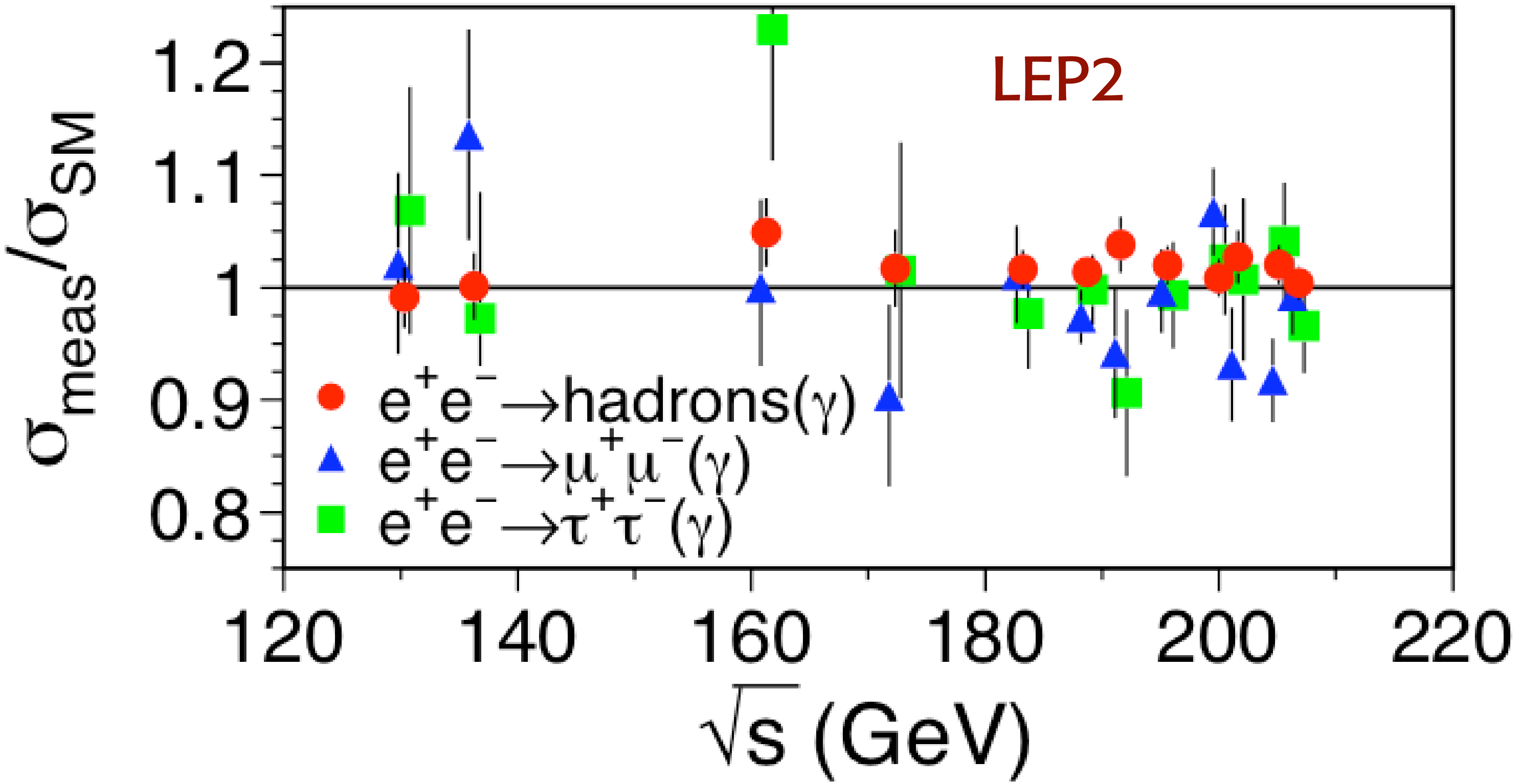
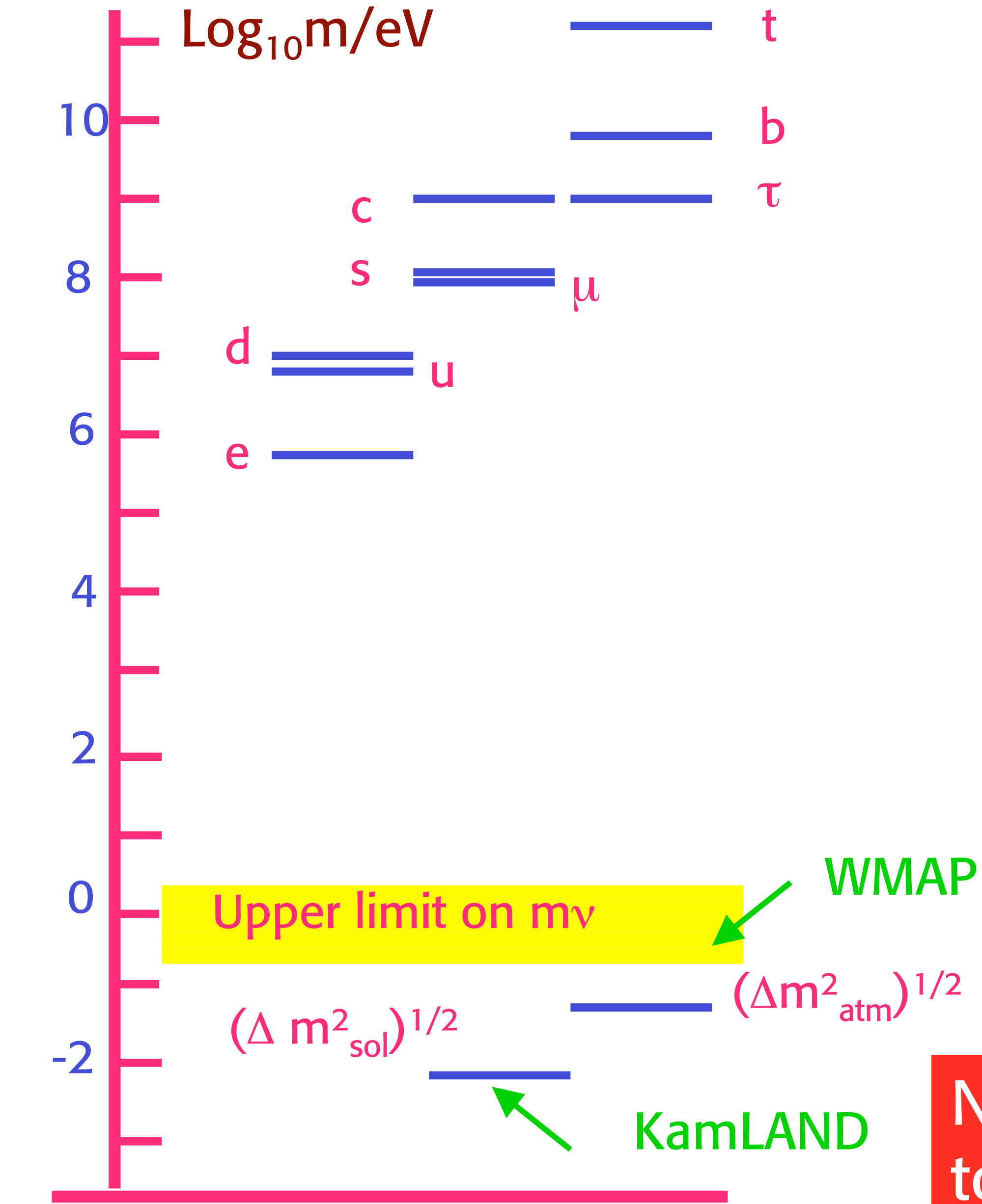
A 1.7σ excess in the hadronic cross-section at LEP2



Virtual light SUSY effects would go in the opposite direction.
But this effect looks too large to be a virtual SUSY effect
(a 2% effect is like increasing α_s by a factor 1.5)



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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 $M \sim M_{GUT}$

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

$m \sim m_t \sim v \sim 200$ 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} !

G. Altarelli

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

indeed add considerable support to this idea.

Technicolor, Little Higgs, Extra dim....:
nearby cut-off. Problem of suppressing

$$O_5 = \nu_L^T \frac{\lambda}{M} \nu_L HH$$

Another big plus of neutrinos is the elegant picture of baryogenesis thru leptogenesis

(after LEP has disfavoured BG at the weak scale)

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 Δ(B-L)is not zero
(otherwise is washed out at T_{ew} by instantons)

Main candidate: decay of lightest ν_R ($M \sim 10^{12}$ 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 for hierarchy $m_i < 10^{-1}$ eV

Buchmuller, Di Bari, Plumacher; Giudice et al; Pilaftsis et al; Hambye et al

Can be relaxed for degenerate neutrinos
So fully compatible with oscill'n data!!

Dark Matter

WMAP

Most of the Universe is not made up of atoms: $\Omega_{tot}\sim 1$, $\Omega_b\sim 0.044$, $\Omega_m\sim 0.27$
Most is Dark Matter and Dark Energy

Most Dark Matter is Cold (non relativistic at freeze out)
Significant Hot Dark matter is disfavoured
Neutrinos are not much cosmo-relevant: $\Omega_\nu<0.015$ (WMAP)

SUSY has excellent DM candidates: Neutralinos (--> LHC)
Also Axions are still viable
(in a mass window around m $\sim 10^{-4}$ eV and $f_a \sim 10^{11}$ GeV
but these values are simply a-posteriori)

Identification of Dark Matter is a task of enormous importance for particle physics and cosmology

LHC?

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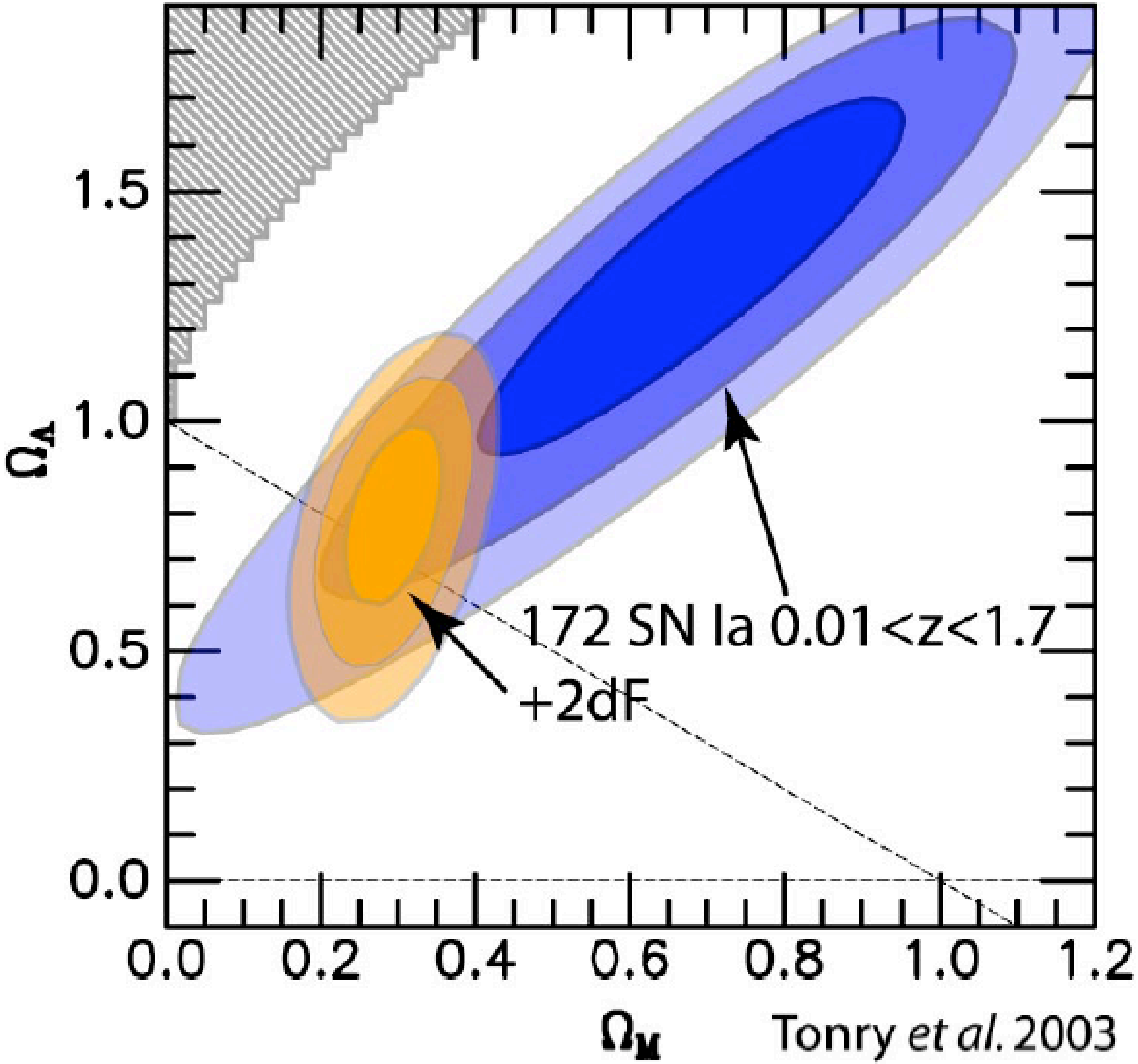
Supernova
Cosmology
Project

High-z SN
Search Team



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LHC has good chances because it can reach any kind of WIMP:

WIMP: weakly interacting particle with m ~ 10^1-10^3 GeV

For WIMP's in thermal equilibrium after inflation the density is:

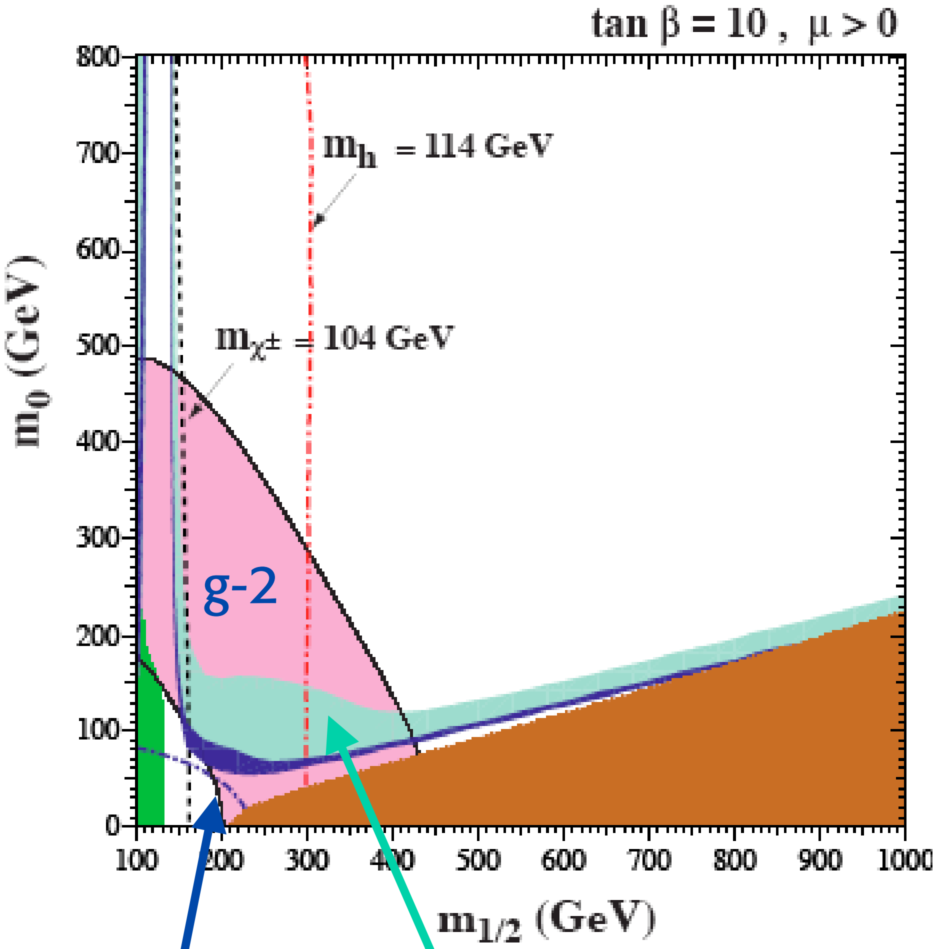
$$\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma_A v \rangle}$$

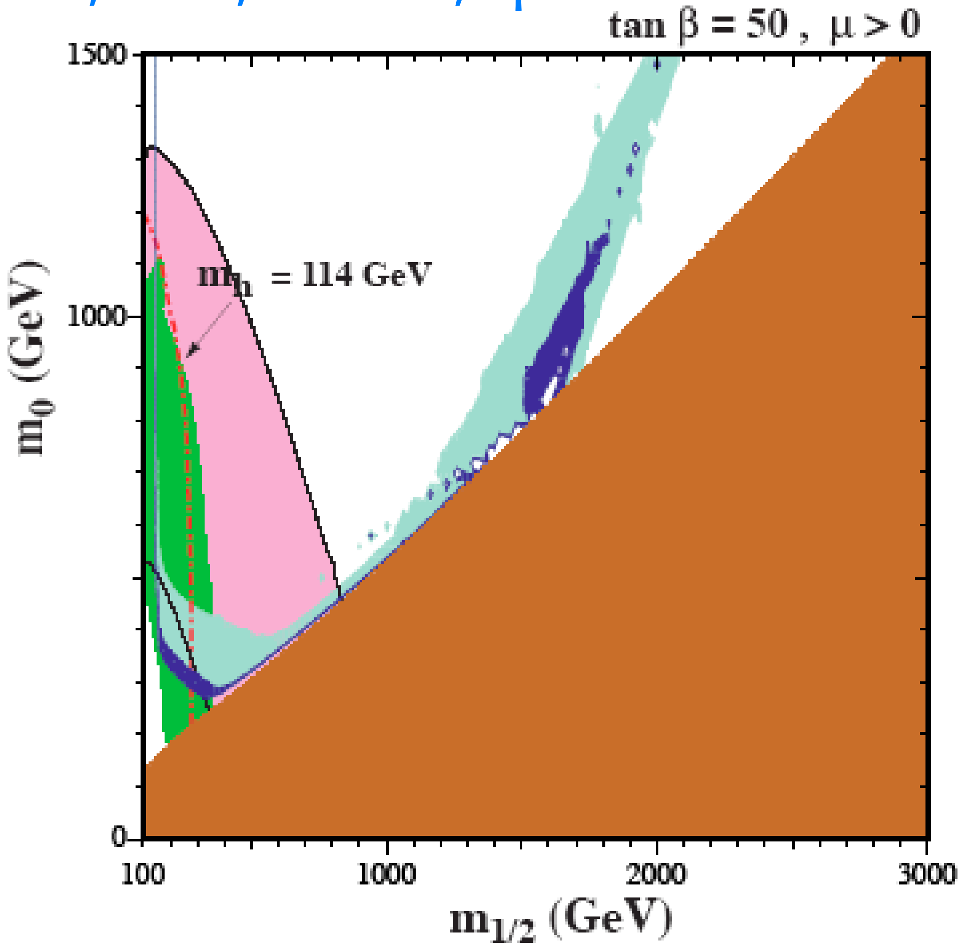
can work for typical weak cross-sections!!!

This "coincidence" is a good indication in favour of a WIMP explanation of Dark Matter

SUSY Dark Matter: we hope it is the neutralino

Ellis, Olive, Santoso, Spanos





WMAP

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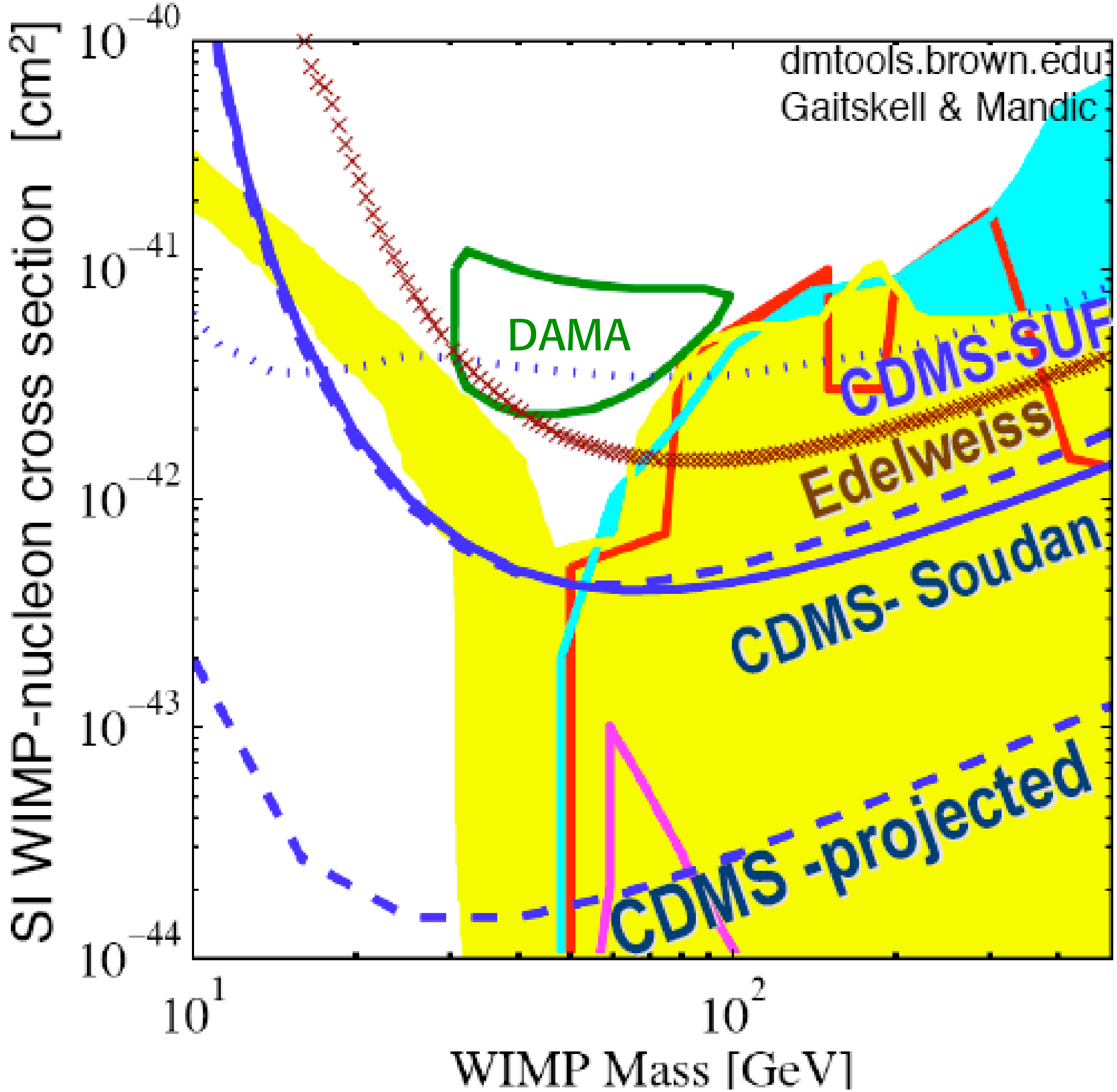
$0.1<\Omega h^2<0.3$

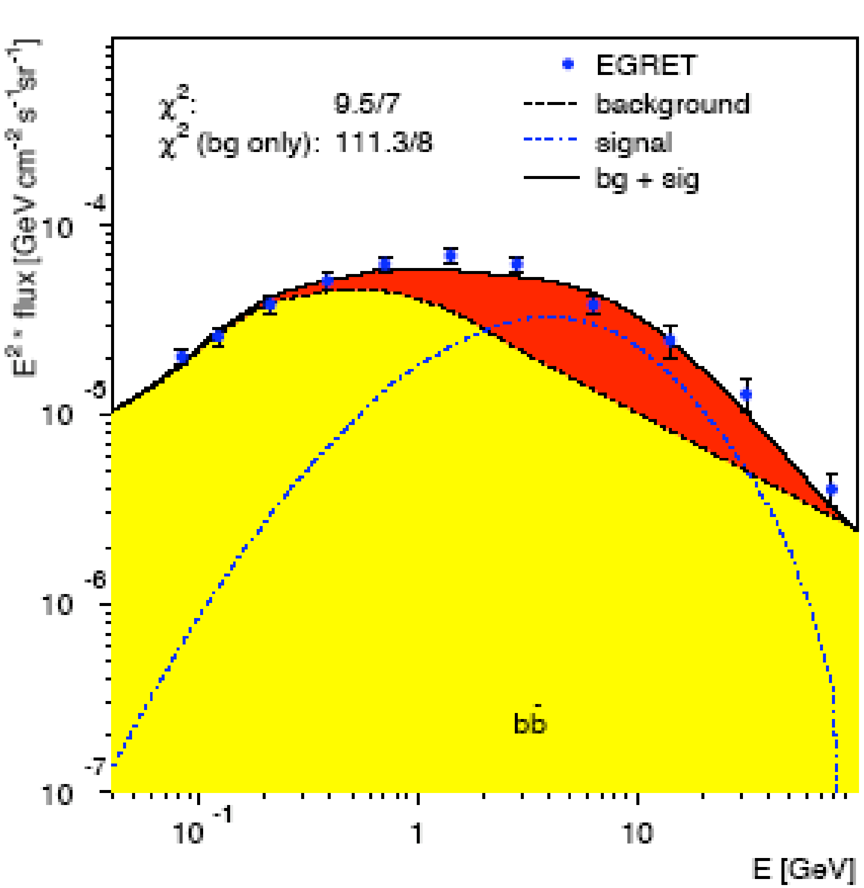
This is for the CMSSM
With less constraints more space

Search for neutralinos

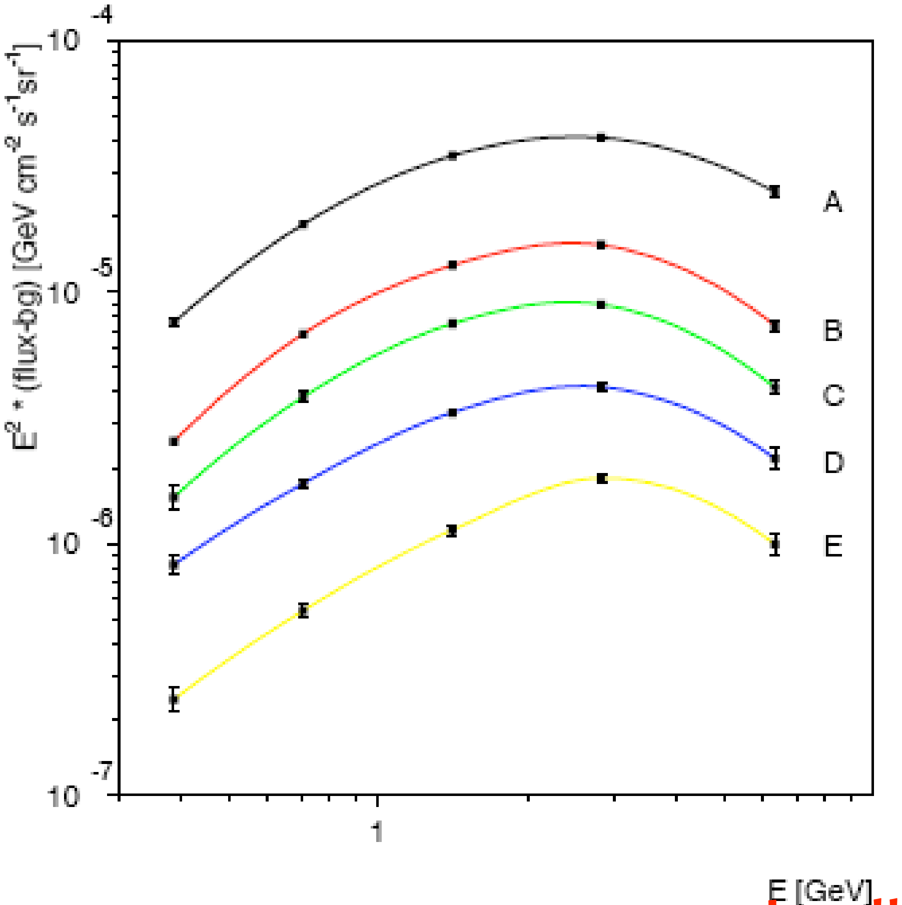


EGRET excess of diffuse gamma rays is compatible with neutralino Dark Matter

De Boer; De Boer, Herold, Sander, Zhukov



red: the DM contribution



same excess spectrum in all regions

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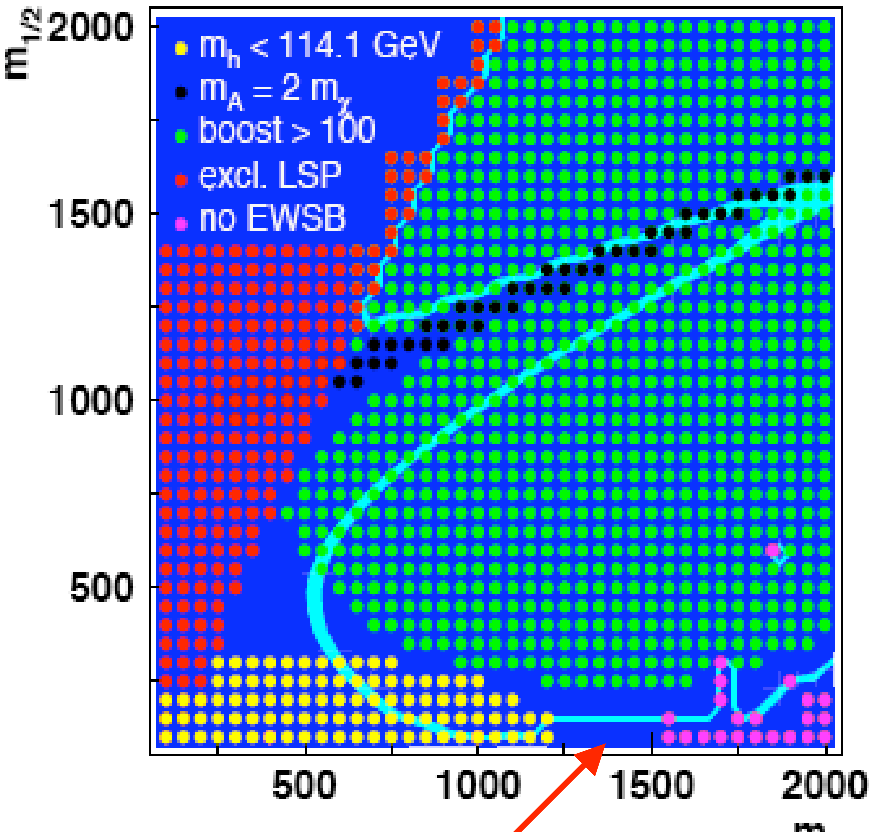
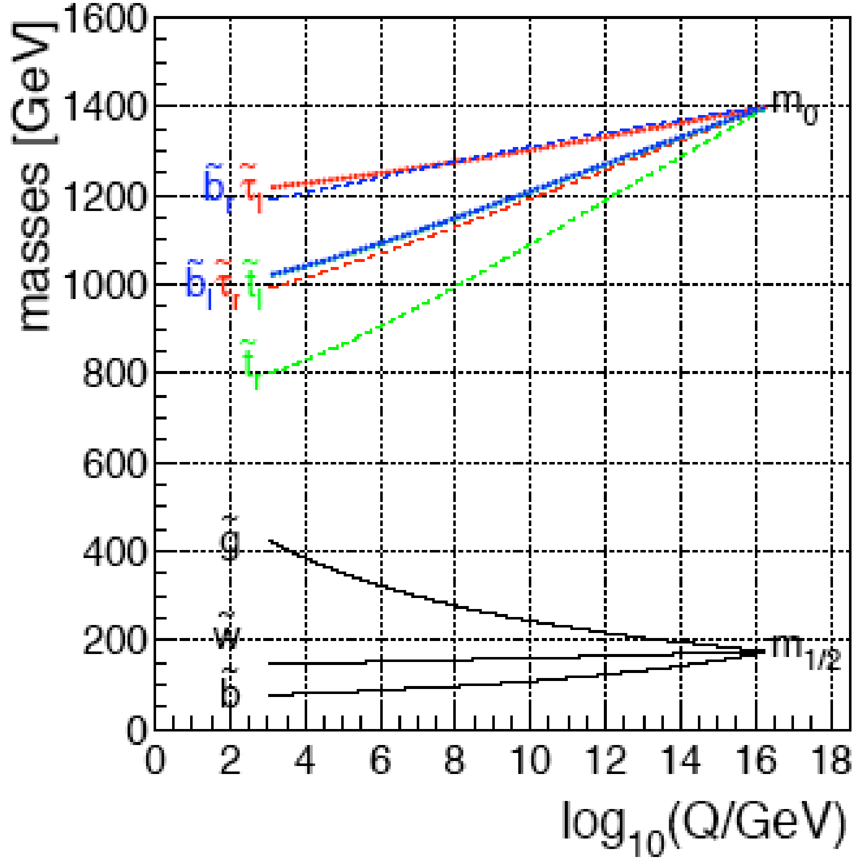
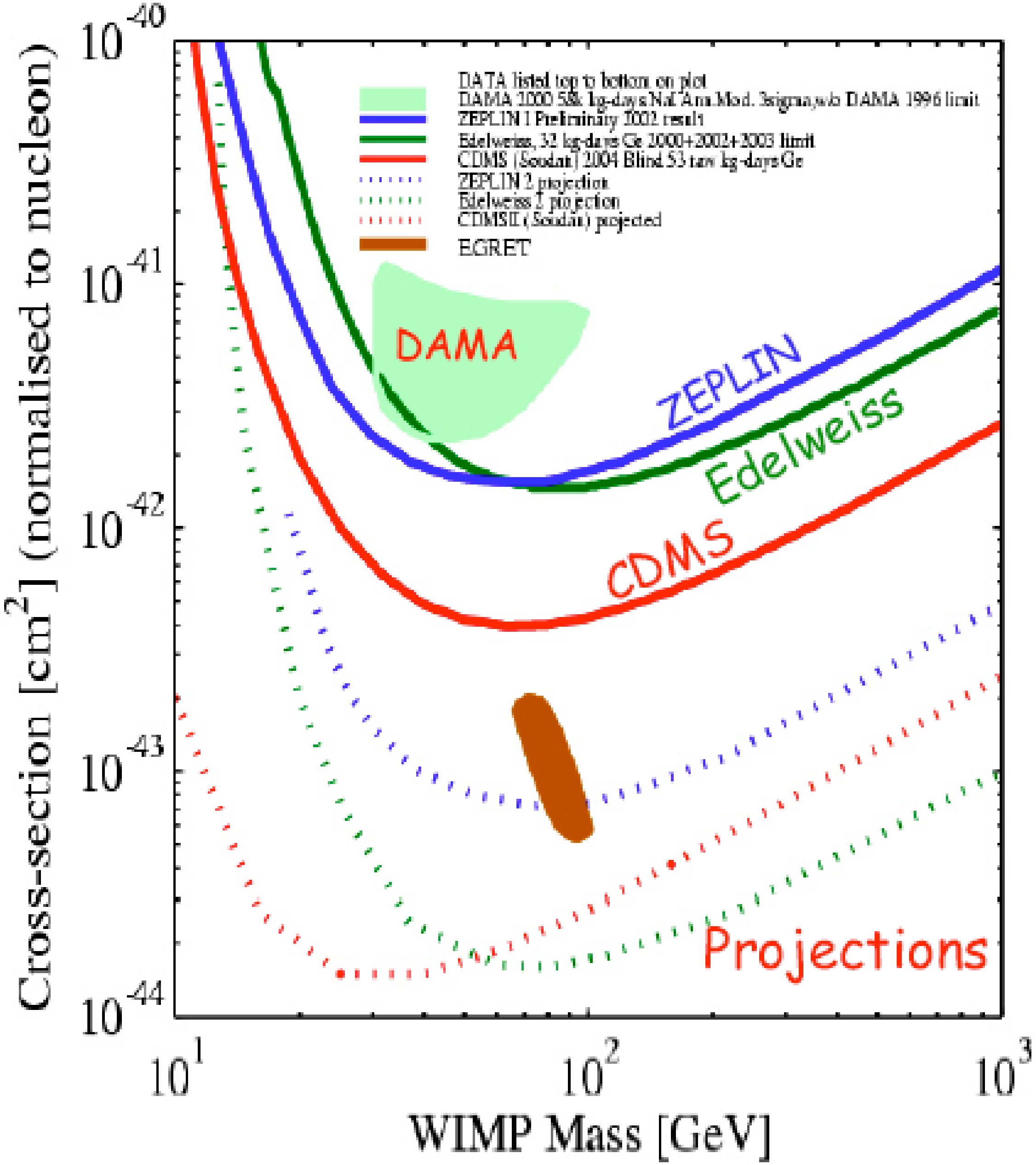
The excess is compatible with neutralinos: $m_\chi \sim$ 50-100 GeV, $m_0 \sim$ 1400 GeV, $m_{1/2} \sim$ 180 GeV, $tg\beta \sim$ 50





correct relic density (WMAP) and annihilation cross section

G.


DATA listed top to bottom on plot
DAMA 2000 58k kg-days NaI Ann.Mod. 3sigma,w/o DAMA 1996 limit
ZEPLIN I Preliminary 2002 result
Edelweiss, 32 kg-days Ge 2000+2002+2003 limit
CDMS (Soudan) 2004 Blind 53 raw kg-days Ge
ZEPLIN 2 projection
Edelweiss 2 projection
CDMSII (Soudan) projected
EGRET
DAMA
ZEPLIN
Edelweiss
CDMS
Projections
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{1}
10^{2}
10^{3}
Cross-section [cm^2] (normalised to nucleon)
WIMP Mass [GeV]

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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: $\rho_\Lambda \sim (\Lambda_{cutoff})^4$

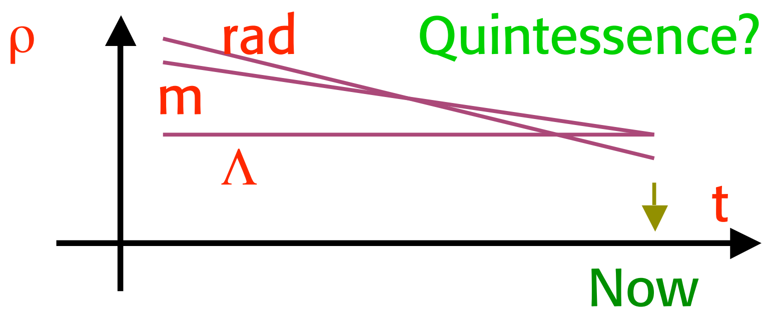
If $\Lambda_{cutoff} \sim M_{Pl}$ → $\rho_\Lambda \sim 10^{123}\ \rho_{obs}$

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

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

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

Other problem:
Why now?



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Quintessence: the cosmological "constant" is actually a vev of a scalar field ϕ which evolves towards the minimum

Could explain smallness, but not "why now?"

To have $\rho_m / \rho_\Lambda \sim o(1)$ now means
$\rho / \rho_\Lambda \sim 10^9$ at recombination

For radiation: $\rho \sim R^{-4} \sim T^4$
For matter: $\rho_m \sim R^{-3} \sim T^3$
For const. Λ : $\rho_\Lambda \sim$ constant

A coupling of ν's to Quintessence could explain "why now?"

Fardon, Nelson, Weiner; Peccei....

The Majorana mass M of ν_R could be $M(\phi)$ and the combined evolution could explain "why now?"

But: ad hoc potentials and energy scales

A new approach: introduce light ν_R's coupled to ϕ PGB.
Explain $\Lambda \sim (m_\nu)^4$, but smallness of m_ν unexplained

Barbieri, Hall, Oliver, Strumia

The scale of vacuum energy poses a large naturalness problem!

So far no clear way out:

- A modification of gravity? (extra dim.)
- Leak of vac. energy to other universes (wormholes)?
- • • • •

Perhaps naturality irrelevant

- Anthropic principle: just right for galaxy formation

(Weinberg)

Perhaps naturality irrelevant also for Higgs: Arkani-Hamed, Dimopoulos; Giudice, Romanino '04, String Th. Landascapes '05

Split SUSY: a fine tuned light Higgs + light gauginos and higgsinos. all other s-partners heavy (a new scale) preserves coupling unification and dark matter

But then also a two-scale non-SUSY GUT with axions as DM

G. Altarelli

Normal SUSY, no SUSY, split SUSY? LHC will tell

An April 1st joke?

hep-th/0503249

The SM

Supersplit Supersymmetry

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Veronica Sanz,[6] Martin Schmaltz,[4] Matthew D. Schwartz,[7] and Neal Weiner[8]

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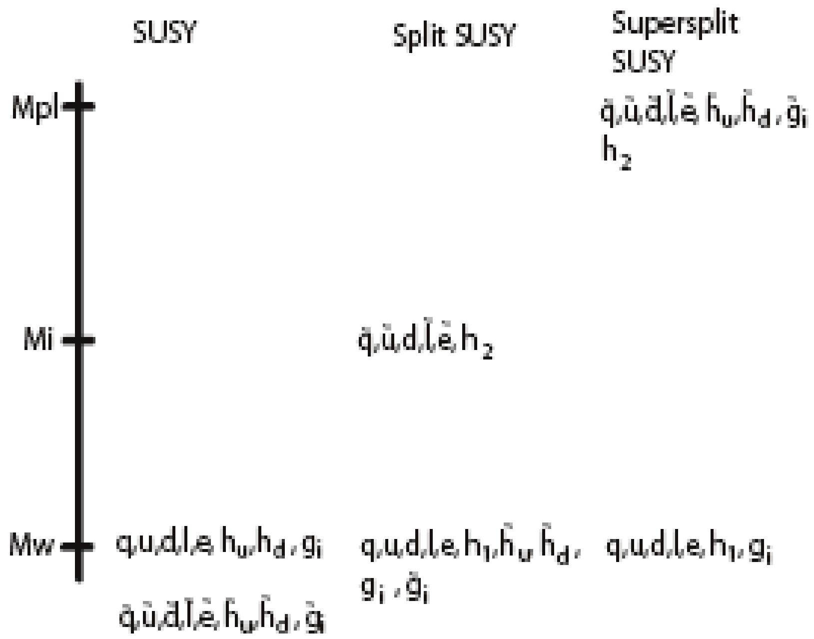
(Dated: April 1, 2005)

The possible existence of an exponentially large number of vacua in string theory behooves one to consider possibilities beyond our traditional notions of naturalness. Such an approach to electroweak physics was recently used in “Split Supersymmetry”, a model which shares some successes and cures some ills of traditional weak-scale supersymmetry by raising the masses of scalar superpartners significantly above a TeV. Here we suggest an extension - we raise, in addition to the scalars, the gaugino and higgsino masses to much higher scales. In addition to maintaining many of the successes of Split Supersymmetry - electroweak precision, flavor-changing neutral currents and CP violation, dimension-4 and 5 proton decay - the model also allows for natural Planck-scale supersymmetry breaking, solves the gluino-decay problem, and resolves the coincidence problem with respect to gaugino and Higgs masses. The lack of unification of couplings suggests a natural solution to possible problems from dimension-6 proton decay. While this model has no weak-scale dark matter candidate, a Peccei-Quinn axion or small black holes can be consistently incorporated in this framework.



Note added: While this work was being completed, we became aware of [18, 19, 20], a series of conference talks where a similar model was considered. While there are some similarities (specifically, field content and interactions), the philosophy is completely unrelated.

[18] S. Glashow, "Towards a Unified Theory - Threads in a Tapestry," Nobel Lecture, Dec 8, 1979.

[19] A. Salam, "Gauge Unification of Fundamental Forces," Nobel Lecture, Dec 8, 1979.

[20] S. Weinberg, "Conceptual Foundations of the Unified Theory of Weak and Electromagnetic Interactions," Nobel Lecture, Dec 8, 1979.

G. Altarelli

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 one expected SUSY discovery at LEP

(this is why there is a revival of alternative model building
and of anthropic conjectures: see the talk by Arkani-Hamed)

- No compelling, realistic alternative so far developed

(not an argument! But…see the talk by Pomarol)

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

(both interesting to pursue)

Get the LHC ready fast; we badly need exp input!!!