Napoli, 15 October '04

Concluding Talk

G. Altarelli
CERN

Not a “Summary”: too many talks, too few days
also I am not competent on many technical aspects.

Not a “Conclusion”: a gigantic work in progress.

Rather a status of the physics LHC is going to address

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

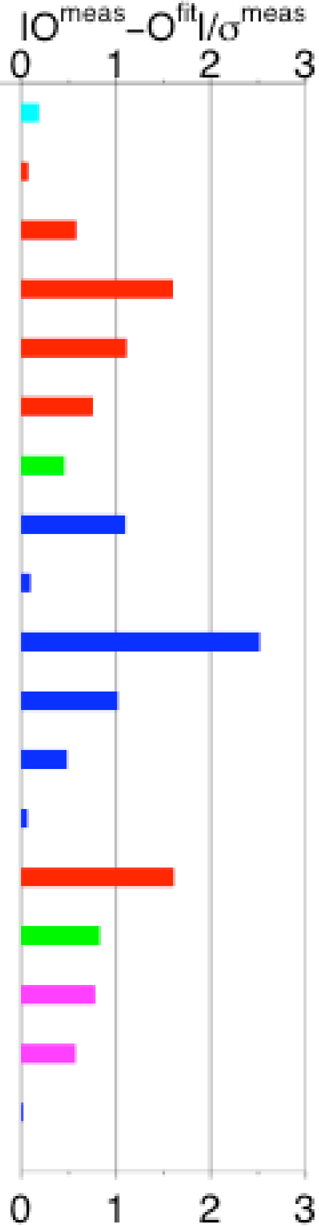
The χ^2 is reasonable:

χ^2/ndof~16/13 (~23%)

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

Winter 2004

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	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]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1



Recent!! → m_W [GeV]

New!! → m_t [GeV]

G. Altarelli

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

ICHEP'04: 0.2330±0.0015

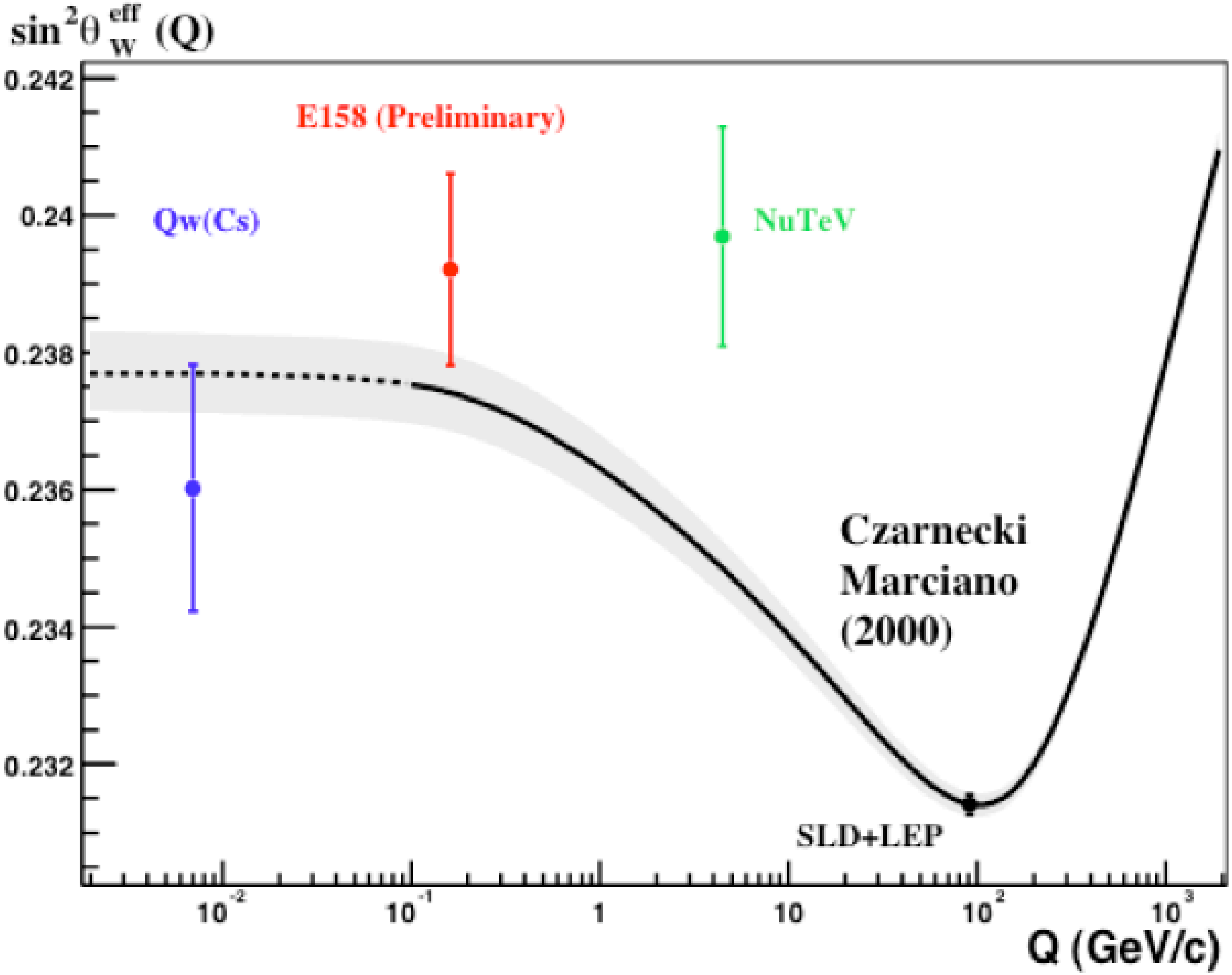
New!!

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

recall for comparison:
present WA
$\sin^2\theta_{eff}$=0.23148±0.00017

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

G. Altarelli



sin²θ W eff (Q)
0.242
0.24
0.238
0.236
0.234
0.232
E158 (Preliminary)
Qw(Cs)
NuTeV
Czarnecki
Marciano
(2000)
SLD+LEP
10⁻²
10⁻¹
1
10
10²
10³
Q (GeV/c)

G

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

G. Altarelli

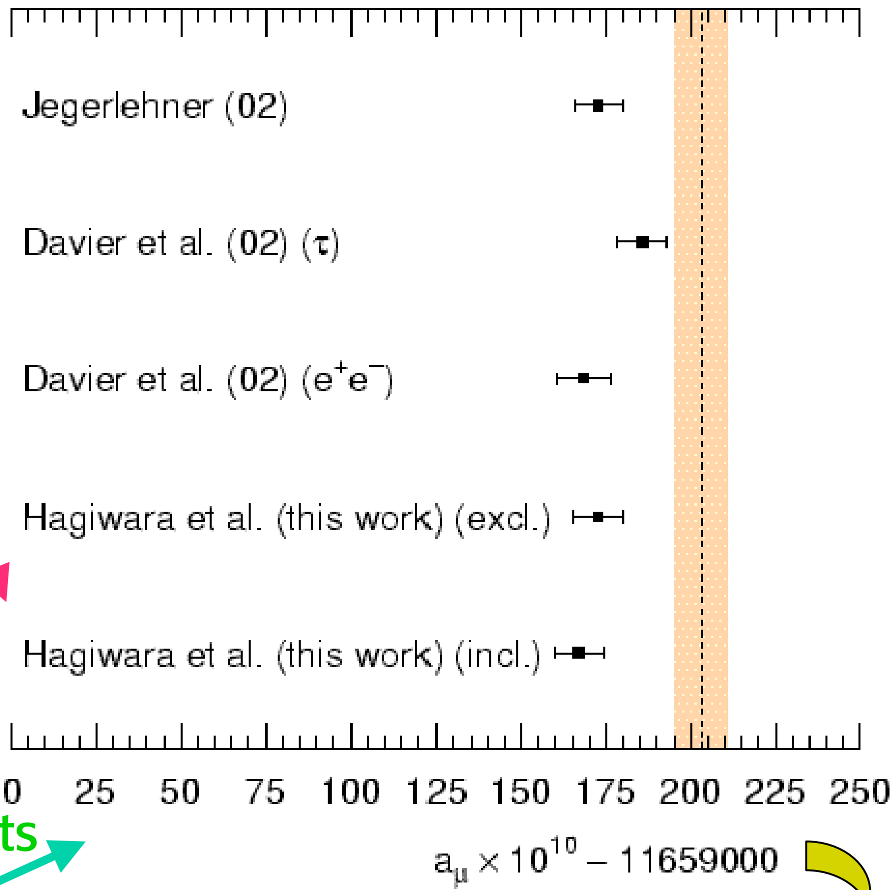
$(g-2)_\mu$ ~3σ discrepancy shown by the BNL'02 data

In 2002:

(Numbers in units 10^{-10})

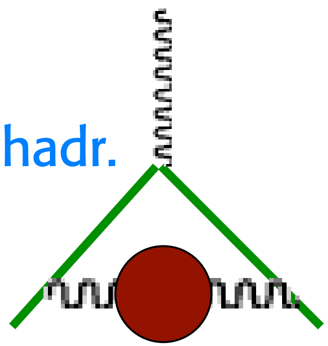
LO hadr.	688.8 ± 6.2	HMNT, 'excl.'
	$683.1 \pm 5.9 \pm 2.0_{rad}$	HMNT, 'incl.'
full a_μ	11659172.6 ± 7.7	'excl.'
	11659166.9 ± 7.4	'incl.'
BNL E821	11659203 ± 8	new world av.
		(0.7 ppm!)
EXP–TH	30.4 ± 11.1	$\sim 2.7\sigma$, 'excl.'
	36.1 ± 10.9	$\sim 3.3\sigma$, 'incl.'

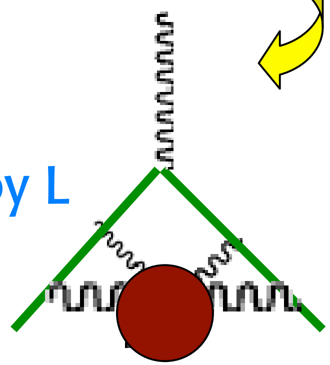
Th. and Exp. accuracy comparable!



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

The discrepancy is less: 2-2.5 σ

(new measurements of σ_{had})

2003

The spectral function from e^+e^-

Tau data below 1.8GeV

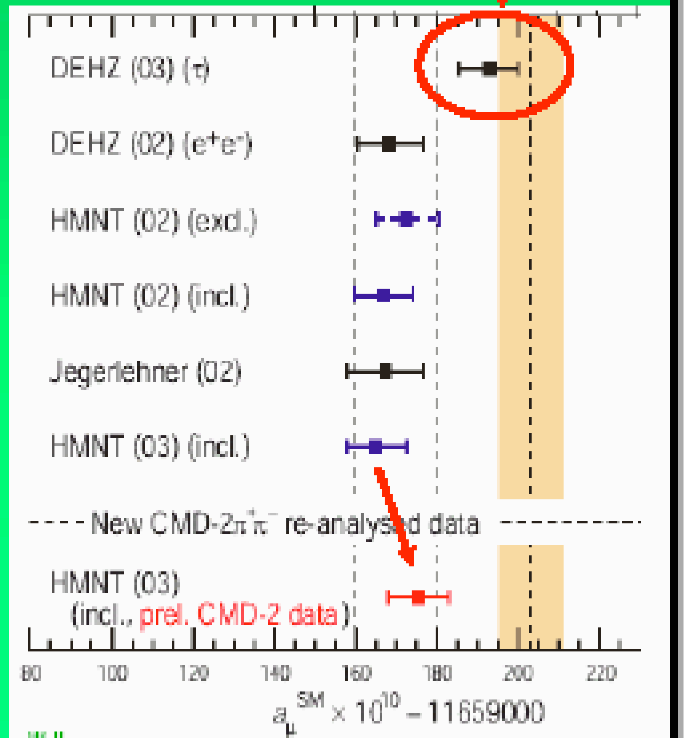
Final CMD-2 $\pi\pi$ data (2002) 0.6% syst error!
CMD-2 have recently reanalyzed their data

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

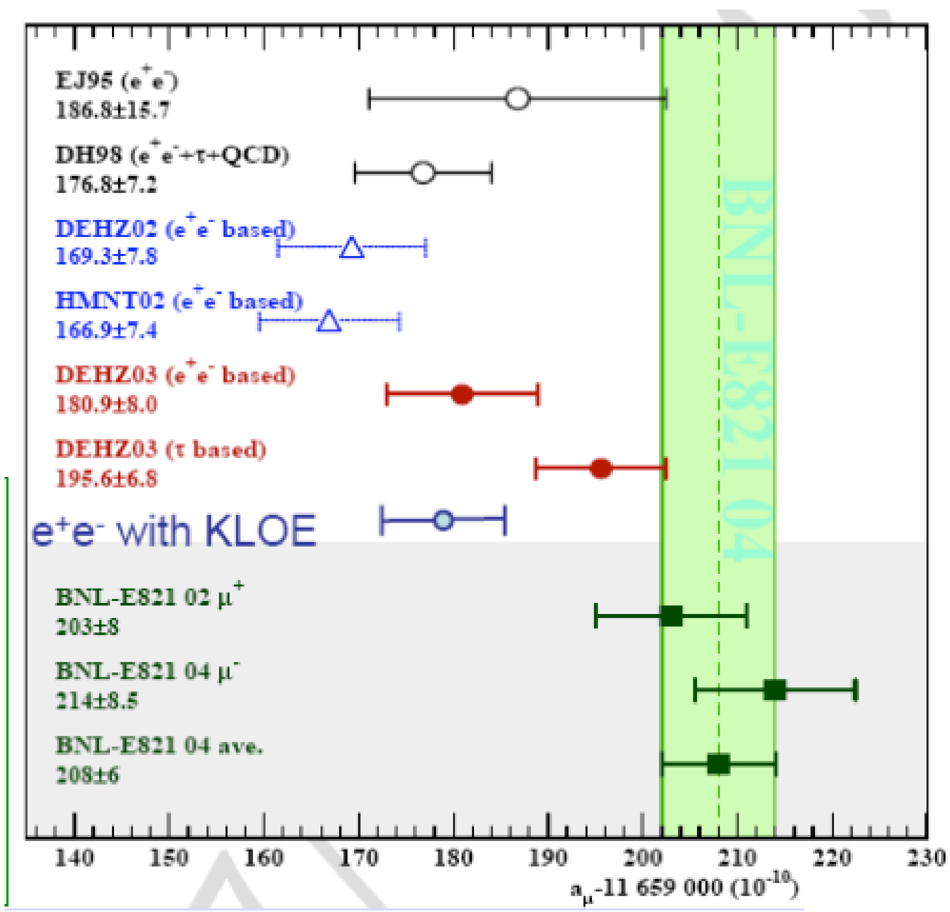
Good agreement between Aleph, CLEO, Opal τ data

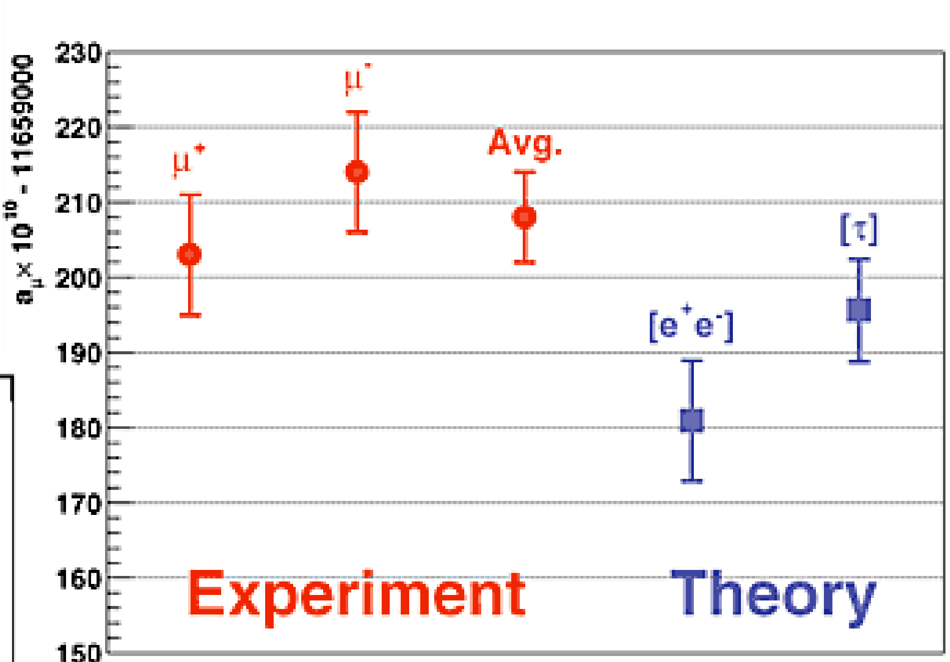


The τ data indicate no discrepancy!

2004 New New results from BNL

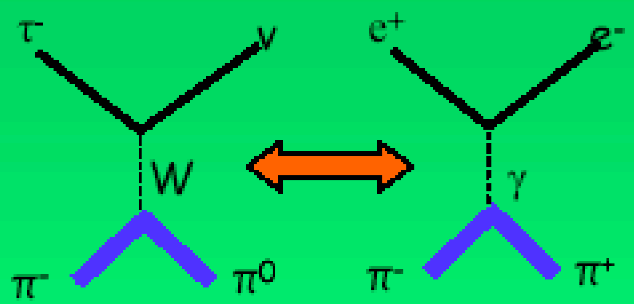
- μ^- measured
  (was μ^+)
- discrepancy up again
  to 2.7σ (e^+e^-)





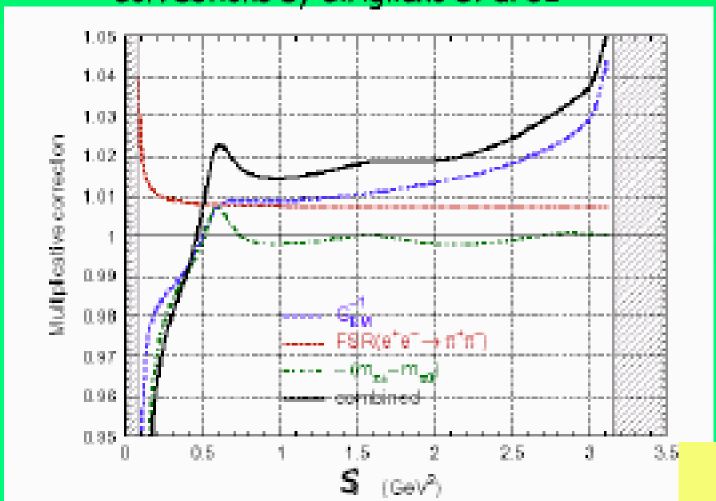
ICHEP'04

The spectral function from τ decays



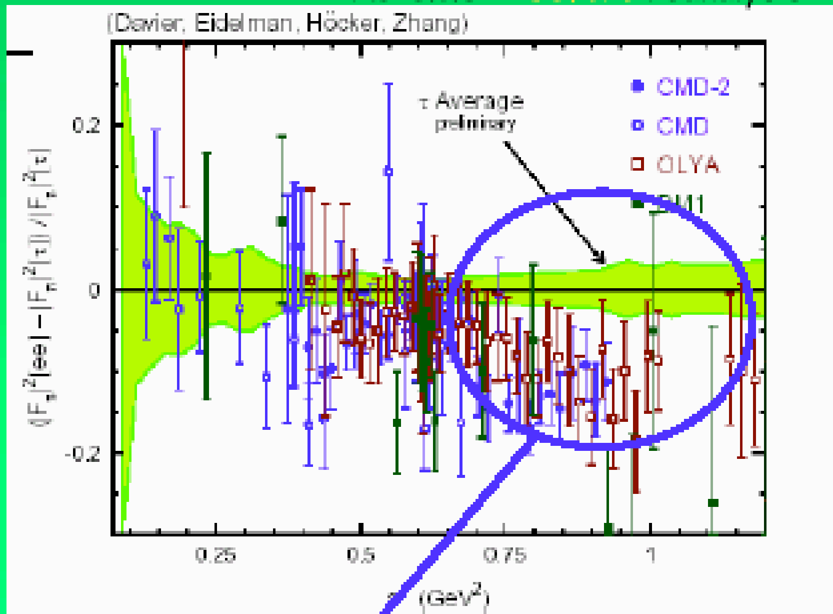
CVC + isospin symmetry

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)

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 better because m_t went up)

- The central value of m_H (m_H = 113+62-42 GeV) from the fit is at 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 = 70+49-31 GeV] (also much better now)

Used to be an issue:

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

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

Combined lept. asymm.:

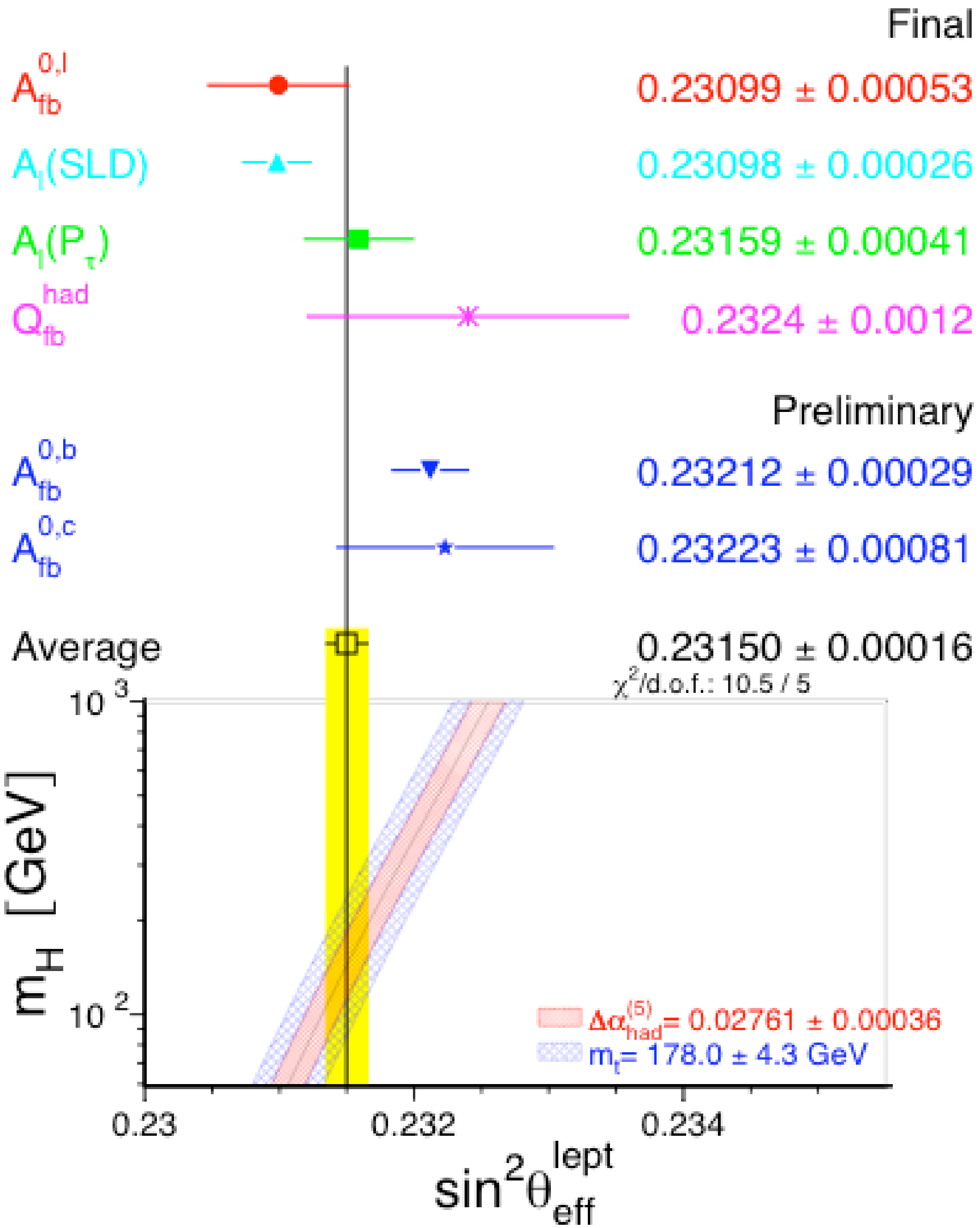
$[\sin^2\theta]_{lept}$=0.23117(20)

Combined hadr. asymm.:

$[\sin^2\theta]_{hadr}$=0.23213(27)

diff = 2.8 σ

G. Altarelli

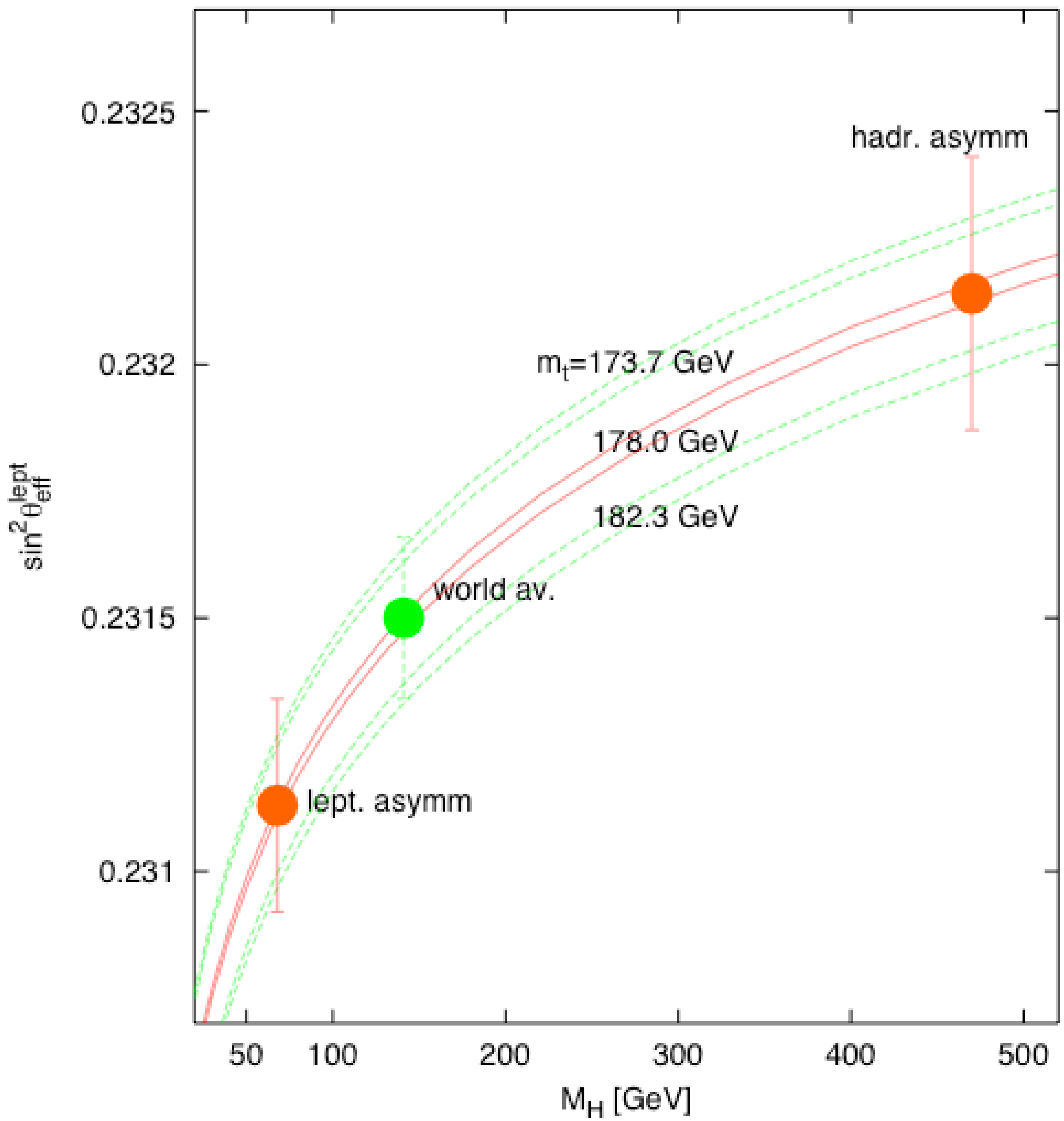


P. Gambino

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



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 a bit high

  (now better because m_t went up)

- The central value of m_H (m_H = 113+62-42 GeV) from the fit is at 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 = 70+49-31 GeV] (also much better now)

Used to be an issue:

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

Plot m_W vs m_H

m_W points to a light Higgs

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

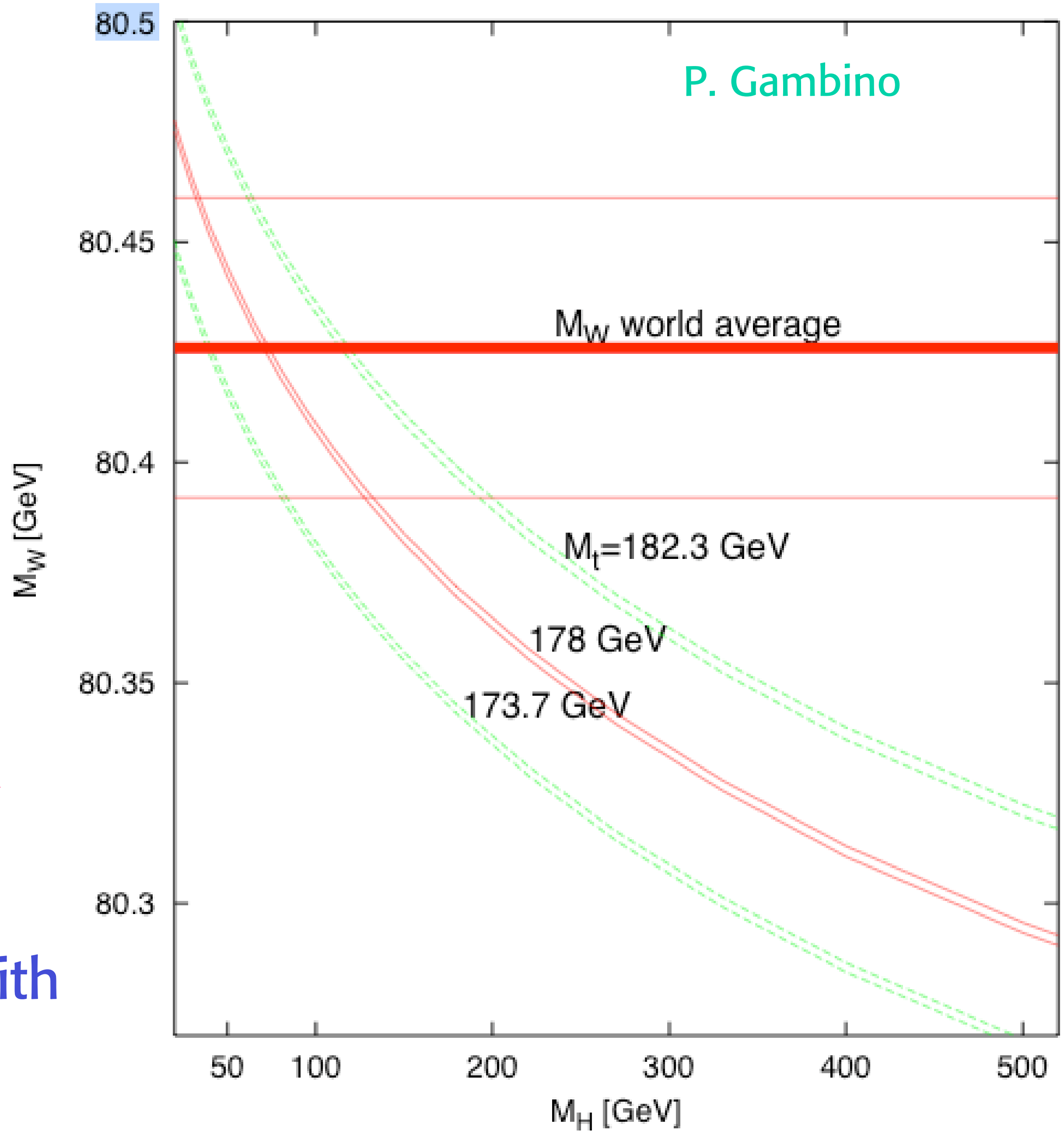
Recently:

m_W ↓ Aleph

m_t ↑ D0

Better agreement with $m_H > 114$ GeV

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 a bit high ⇨

  (now better because m_t went up)

- The central value of m_H (m_H = 113+62-42 GeV) from the fit is at 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 = 70+49-31 GeV] (also much better now)

Used to be an issue:

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

Status of the SM Higgs fit

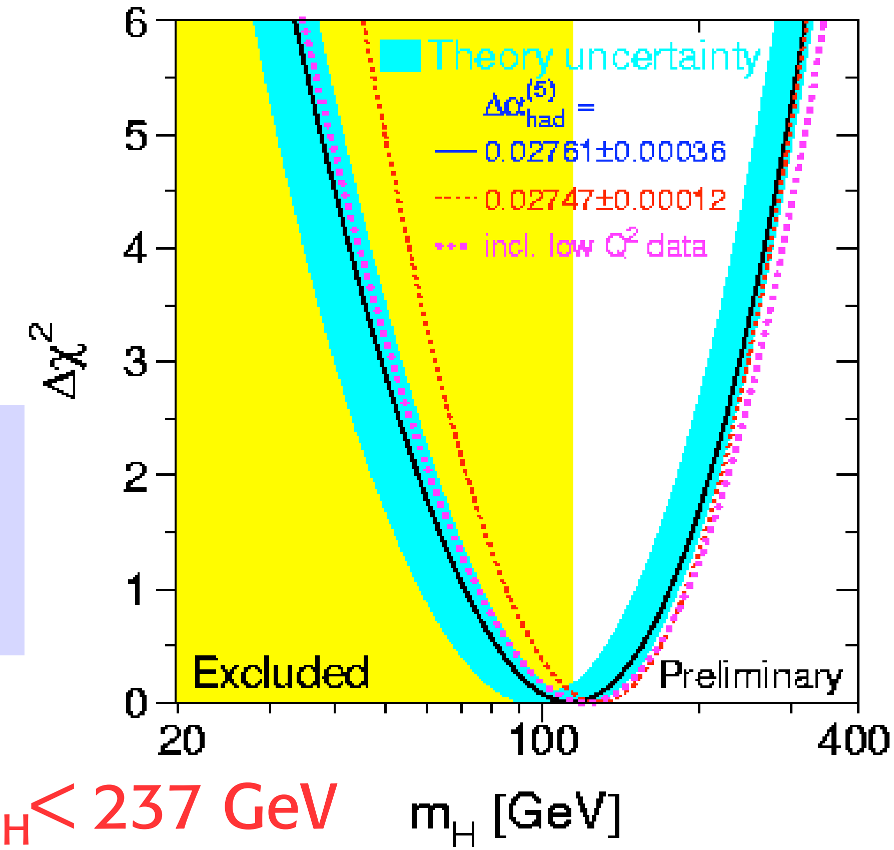
Winter '04

Sensitive to log m_H

Rad Corr.s ->

$\log_{10} m_H(\text{GeV}) = 2.05 \pm 0.20$

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

$m_H < 237$ GeV

Measurements	m_W, Γ_W	m_t	m_t, m_W, Γ_W
m_t (GeV)	$178.5^{+11.0}_{-8.5}$	177.2 ± 4.1	178.1 ± 3.9
m_H (GeV)	117^{+162}_{-62}	129^{+76}_{-50}	113^{+62}_{-42}
$\log[m_H(\text{GeV})]$	$2.07^{+0.38}_{-0.33}$	2.11 ± 0.21	2.05 ± 0.20
$\alpha_s(m_Z)$	0.1187 ± 0.0027	0.1190 ± 0.0027	0.1186 ± 0.0027
χ^2/dof	$16.3/12$	$15.0/11$	$16.3/13$

G. A

$\log_{10} m_H \sim 2$ 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 $f_{1,2}$)

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 below 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

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

EW DATA and New Physics

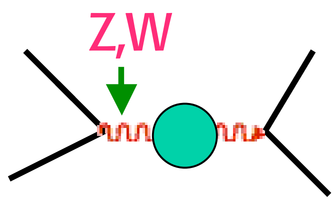
For an analysis of the data beyond the SM we use the ε formalism GA, R.Barbieri, F.Caravaglios, S. Jadach

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

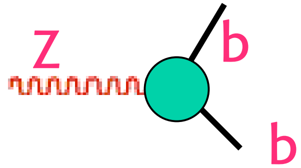
- Focus on pure weak rad. correct's, i.e. vanish in limit of tree level SM + pure QED and/or QCD correct's [a good first approximation to the data]

- 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 →

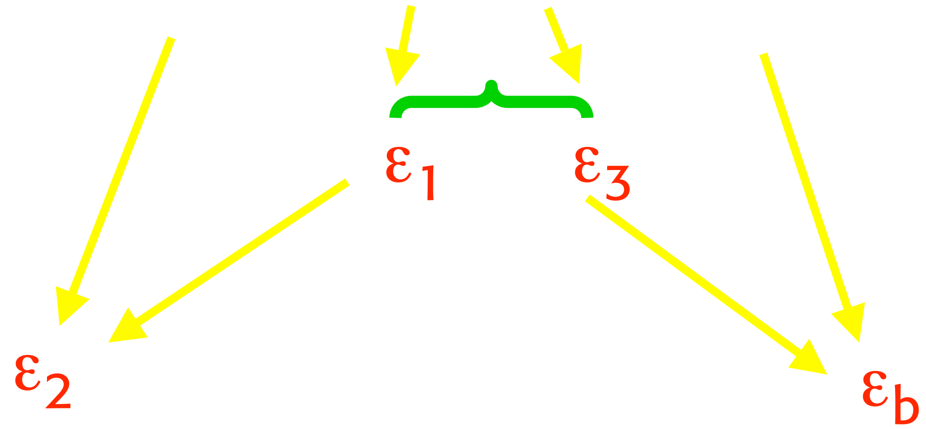


- Can be measured from the data with no reference to m_t and m_H (as opposed to S, T, U -> ε_3, ε_1, ε_2)

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}

G. Altarelli

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

The EWWG gives (winter '04):

$\varepsilon_1 = 5.4 \pm 1.0 \; 10^{-3}$
$\varepsilon_2 = -\,8.9 \pm 1.2 \; 10^{-3}$
$\varepsilon_3 = 5.25 \pm 0.95 \; 10^{-3}$
$\varepsilon_b = -\,4.7 \pm 1.6 \; 10^{-3}$

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!)

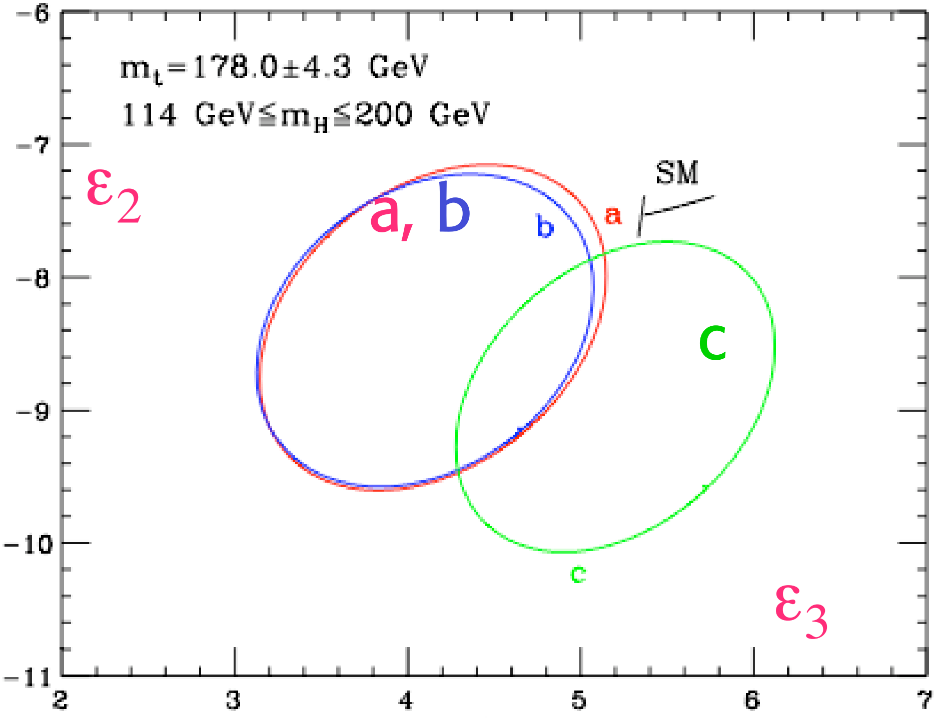
G. Altarelli

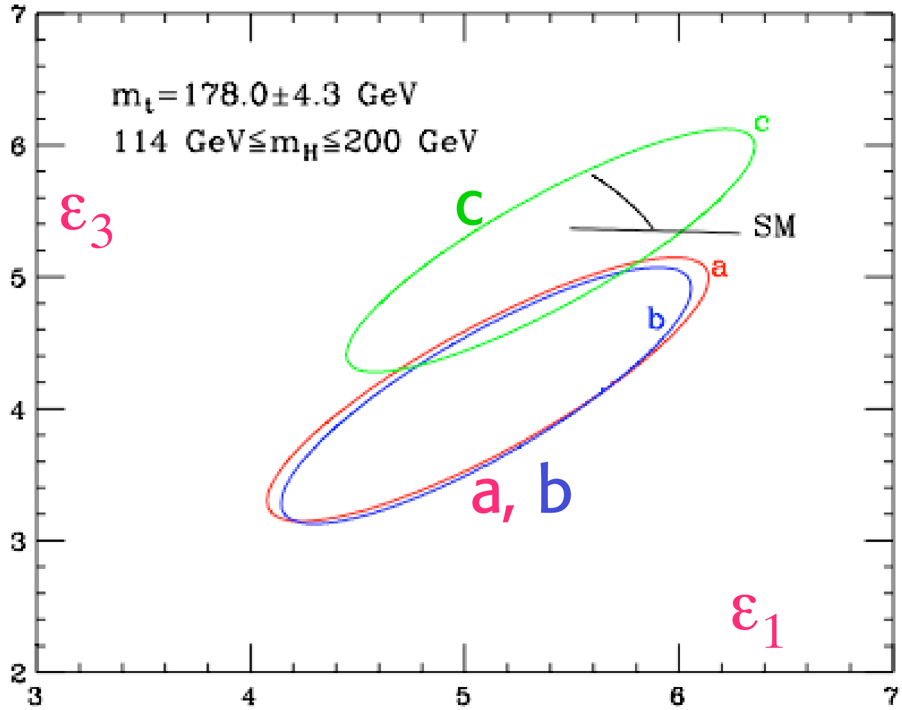
GA, F. Caravaglios, G. Giudice, P. Gambino, G. Ridolfi
(updated 2004)

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}



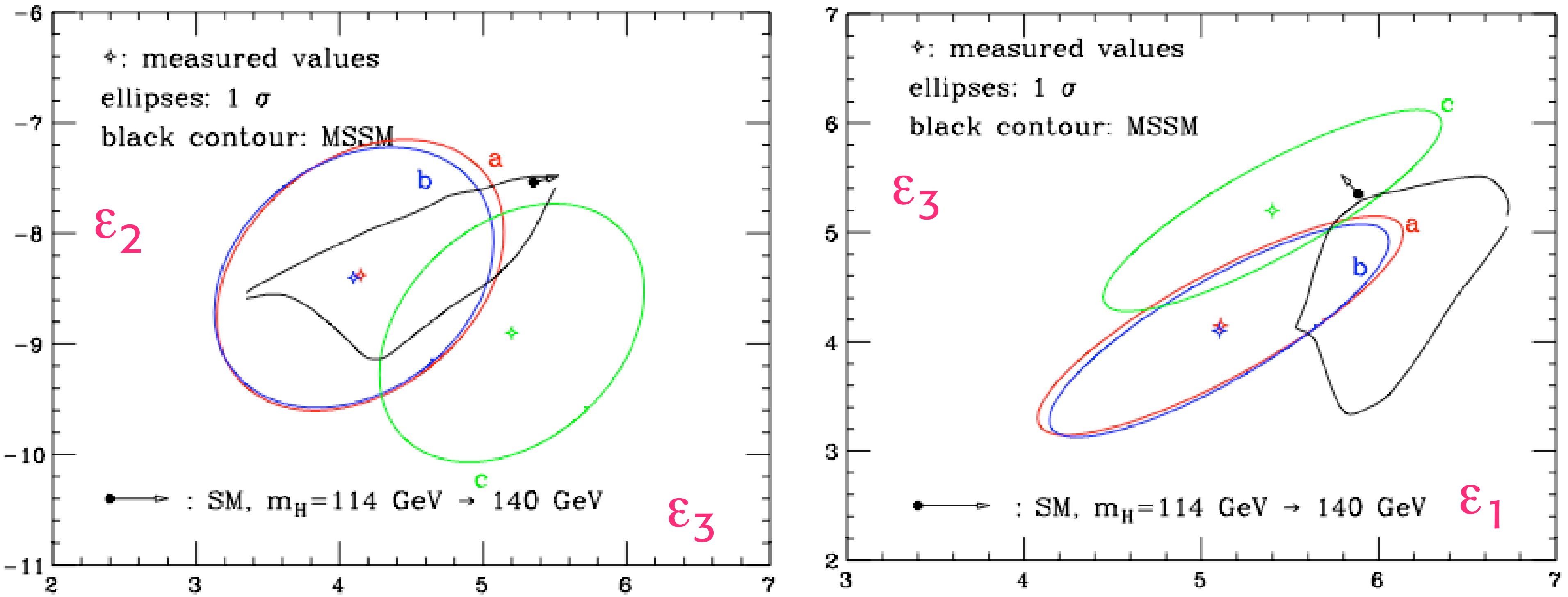


G. Altarelli

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)

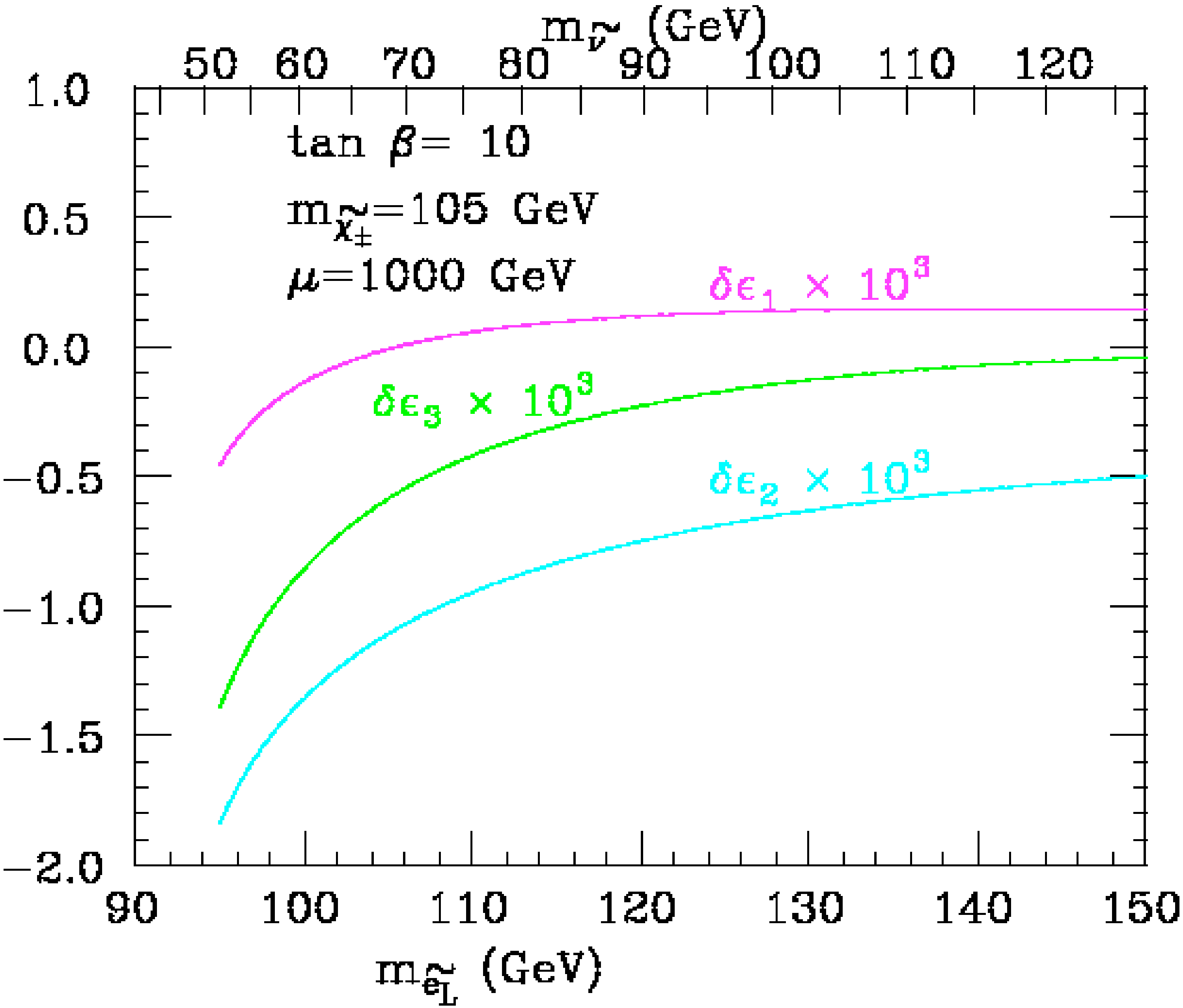
MSSM: $m_{\tilde{e}L} = 96\text{-}300$ GeV, $m_{\chi^-} = 105\text{-}300$ GeV,
$\mu = (-1)\text{-}(+1)$ TeV, $tg\beta = 10$, $m_h = 114$ GeV,
$m_A = m_{\tilde{e}R} = m_{\tilde{q}} = 1$ TeV

Units: 10^{-3}



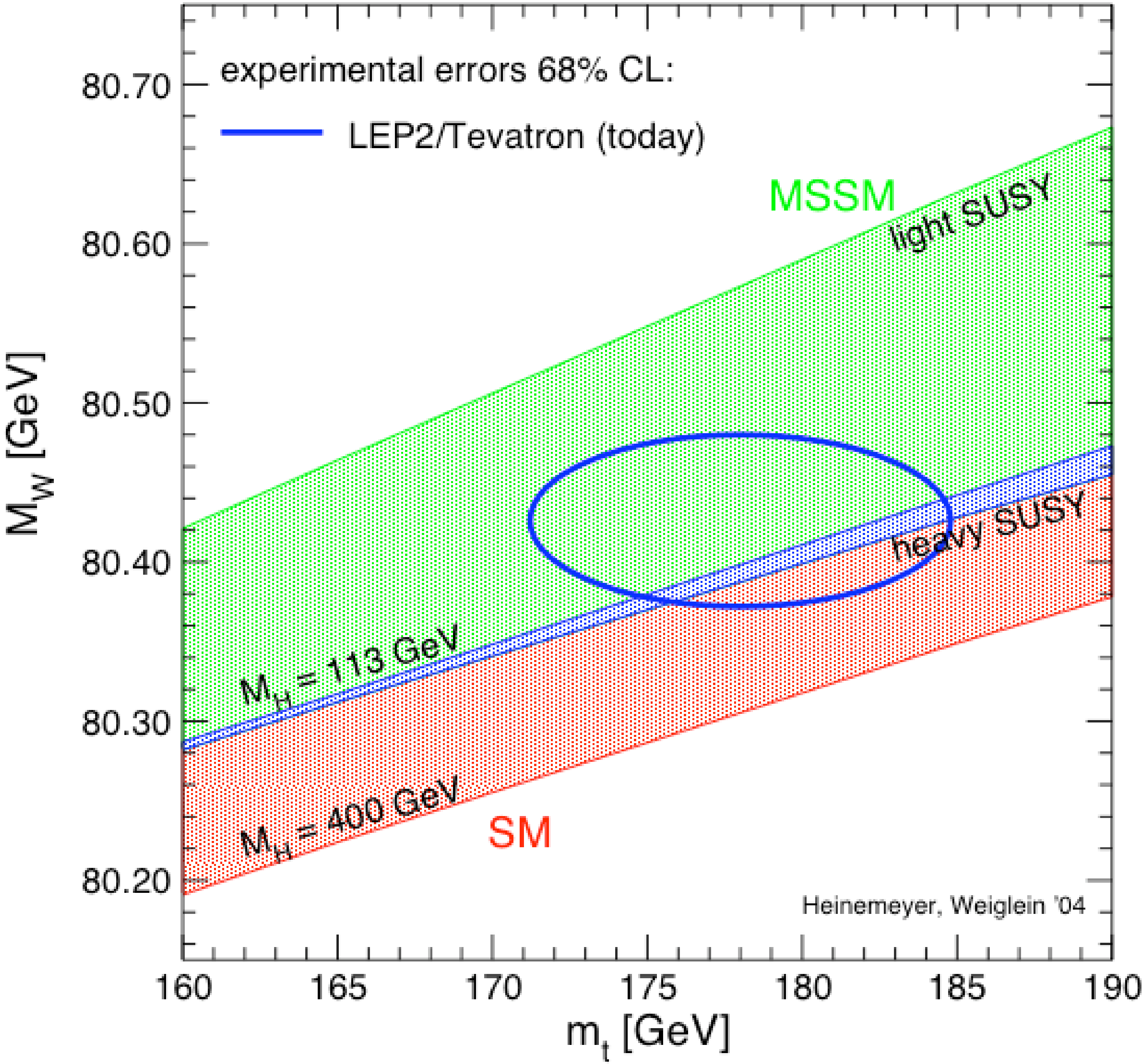
G. Altarelli

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

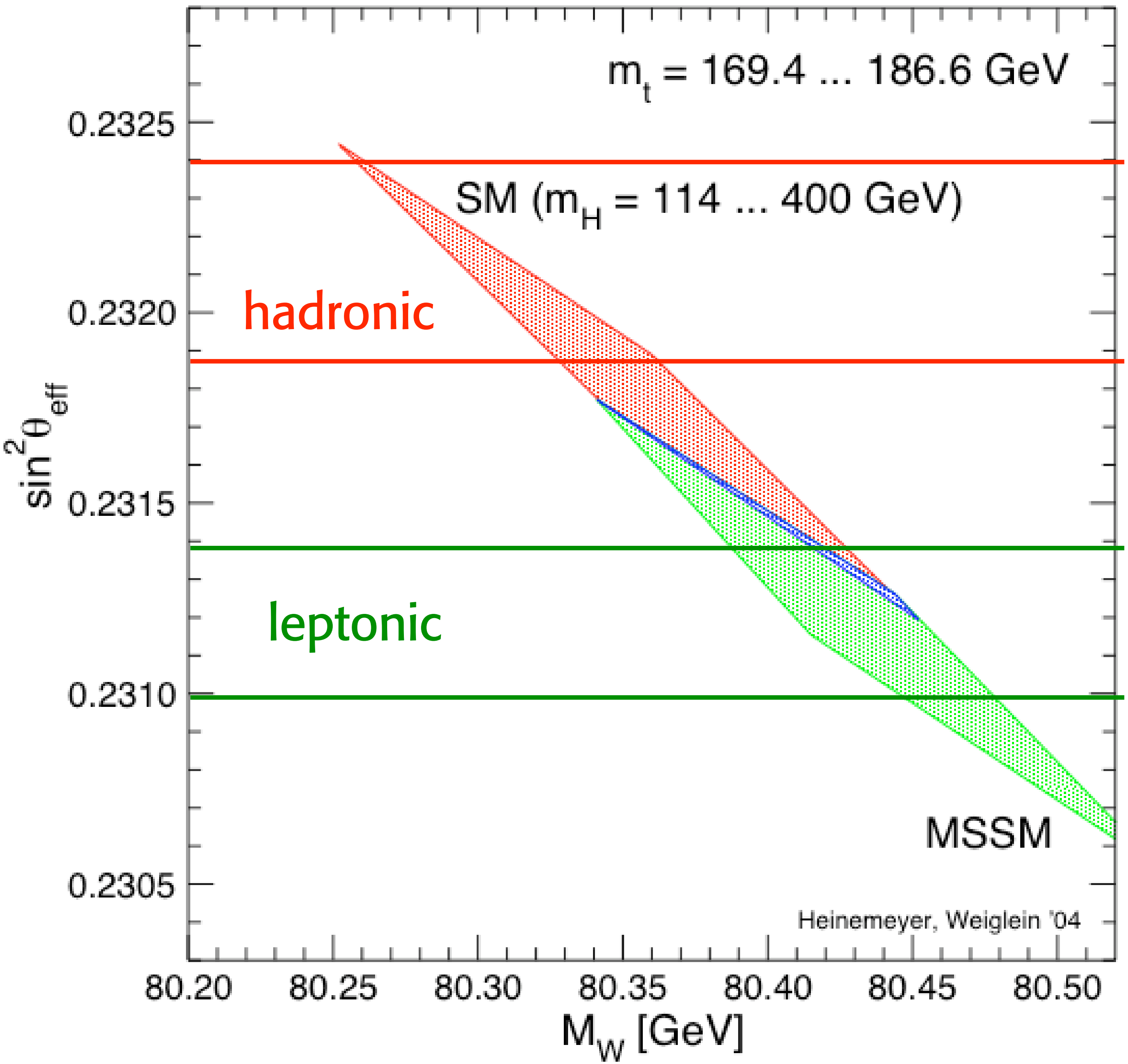


G. Altarelli

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



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]



m_t = 169.4 ... 186.6 GeV
SM (m_H = 114 ... 400 GeV)
hadronic
leptonic
MSSM
Heinemeyer, Weiglein '04
sin²θ_eff
0.2325
0.2320
0.2315
0.2310
0.2305
80.20
80.25
80.30
80.35
80.40
80.45
80.50
M_W [GeV]

G. Altarelli

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, $m_{\chi+}$~ m ~140 GeV

Light s-leptons and gauginos predict a deviation!

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
- •••••

G. Altarelli

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

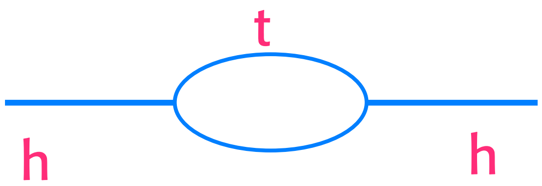
Not only it looks very unlikely, but the new physics must be near the weak scale!

G. Altarel

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

G. Altarelli

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

- 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. Technically could work

G. Altarelli

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

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
$\alpha_s(m_Z)=0.130\pm0.010$

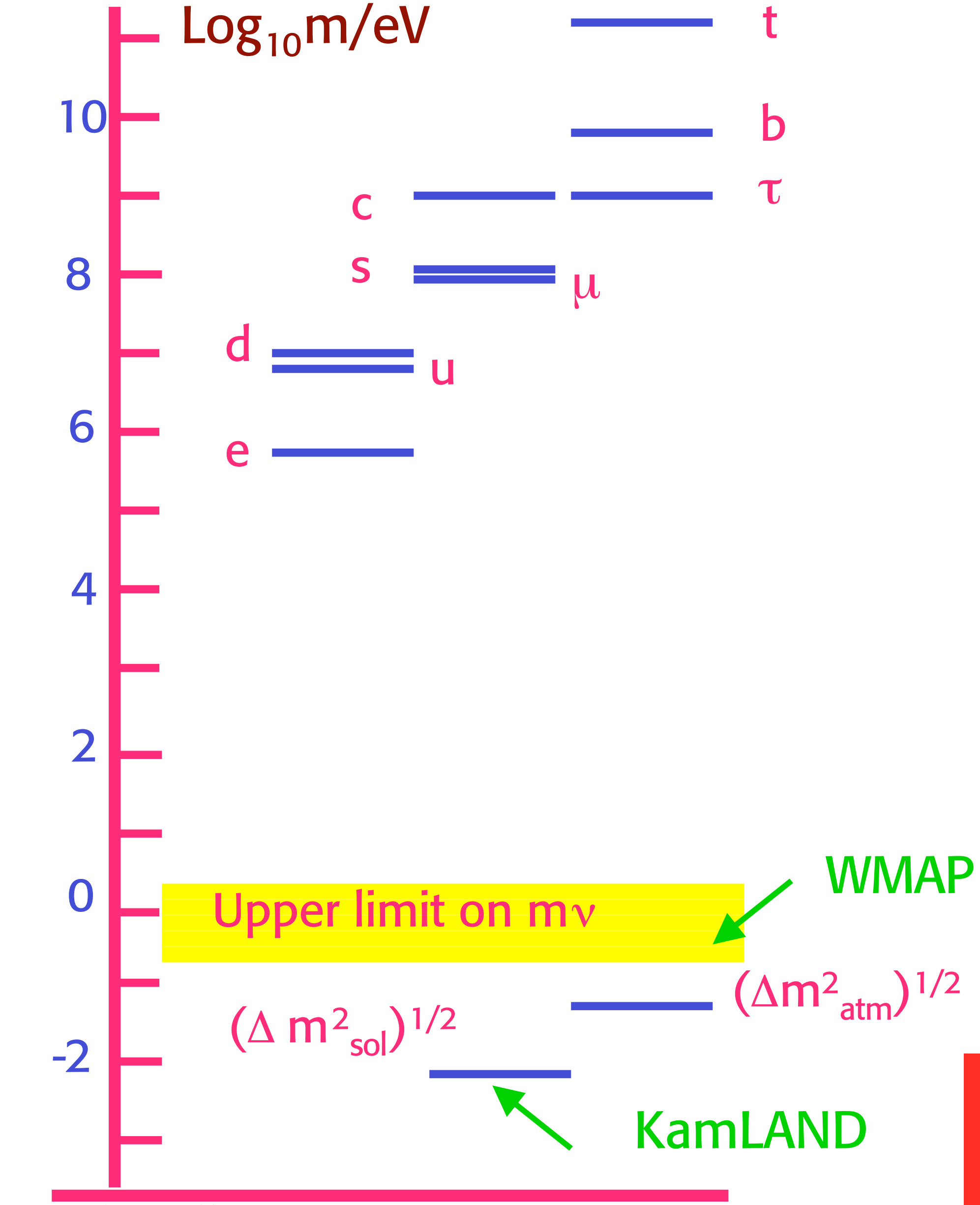
Langacker, Polonski

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

G. Altarelli



G. Altarelli

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} !

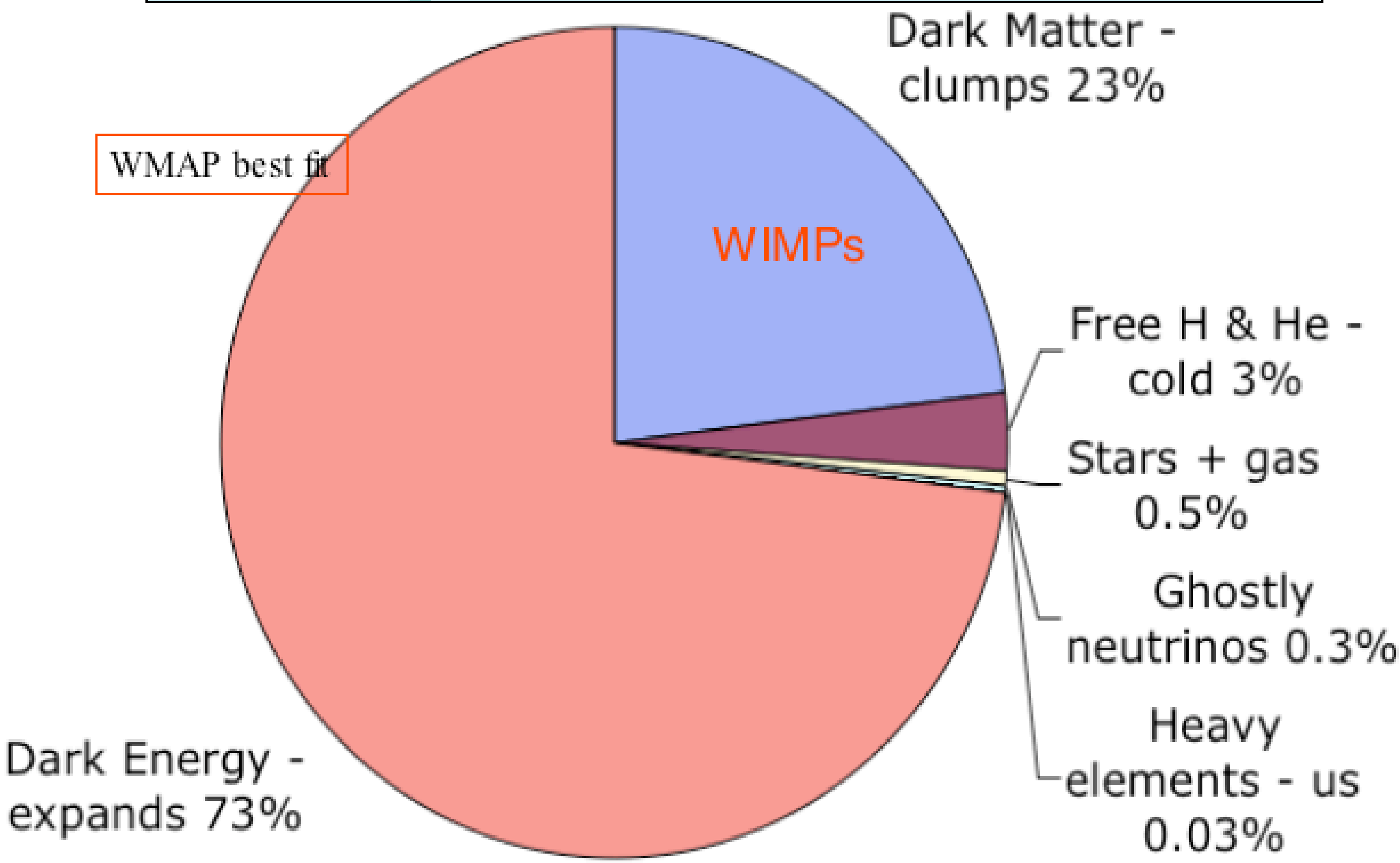
At the end of the XIX century J. J. Thompson proved the necessity of new physics (beyond em and gravity) proving that the energy from the sun and the stars cannot be obtained from chemistry

Today the clearest evidence for new physics comes from dark matter and dark energy

[More and more unity of particle physics and cosmology]

Dark matter could be accessible to present particle physics: a most important mission

Composition of the Cosmos



Binetruy

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?

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

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

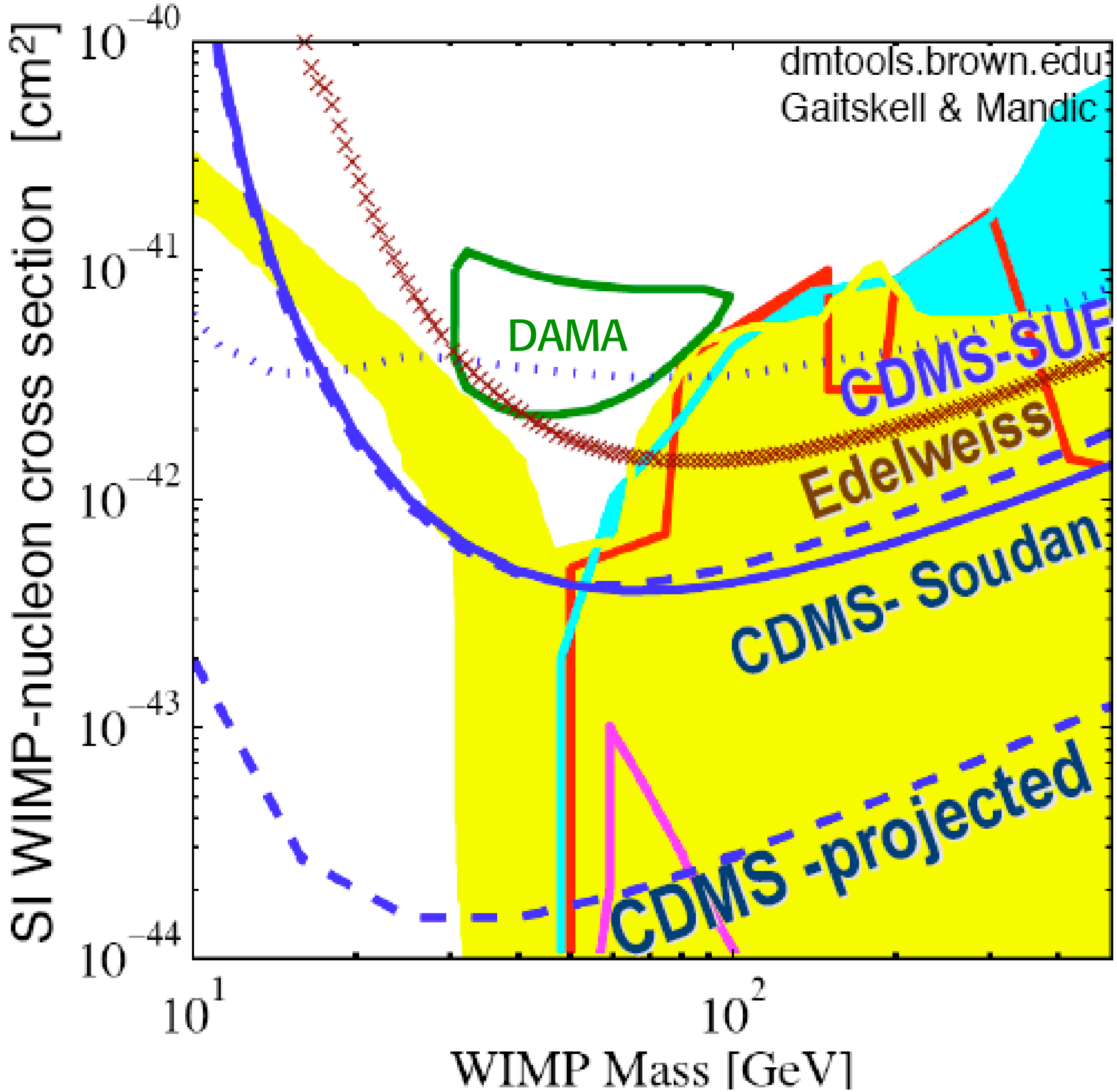
For WIMP's in thermal equilibrium after inflation the density is:

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

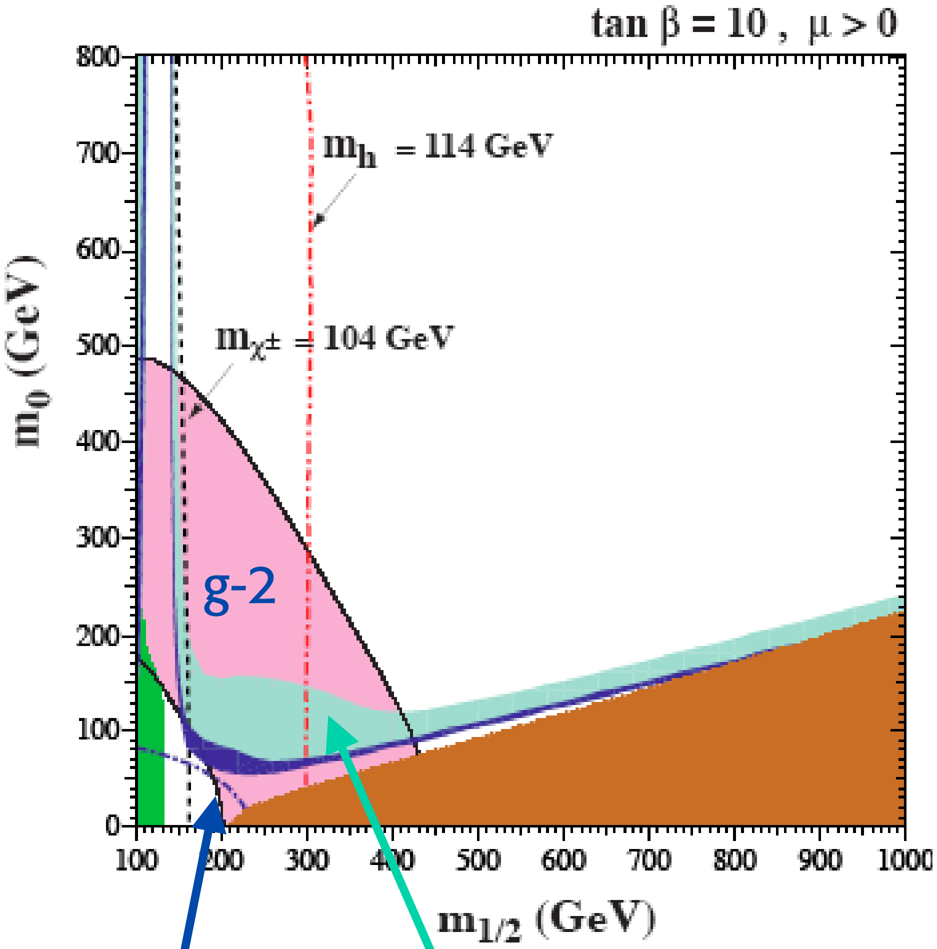
can work for typical weak cross-sections!!!

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

Search for neutralinos



SUSY Dark Matter: we hope it is the neutralino

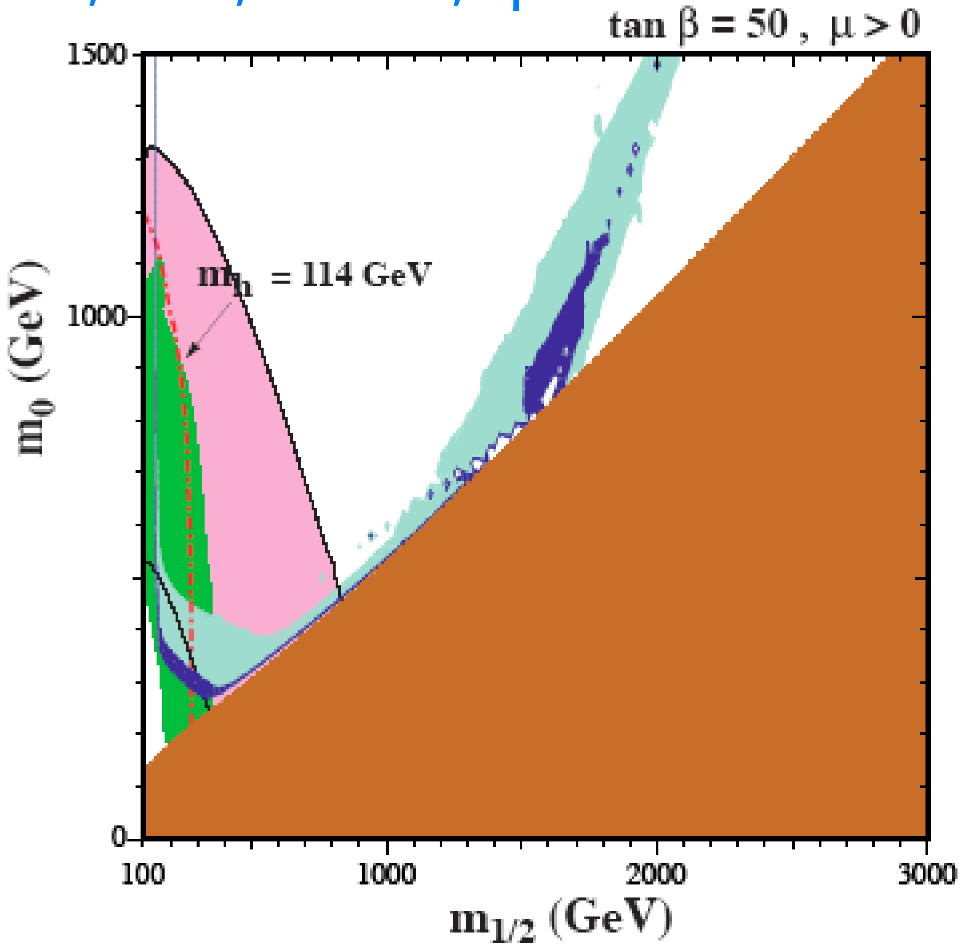


WMAP

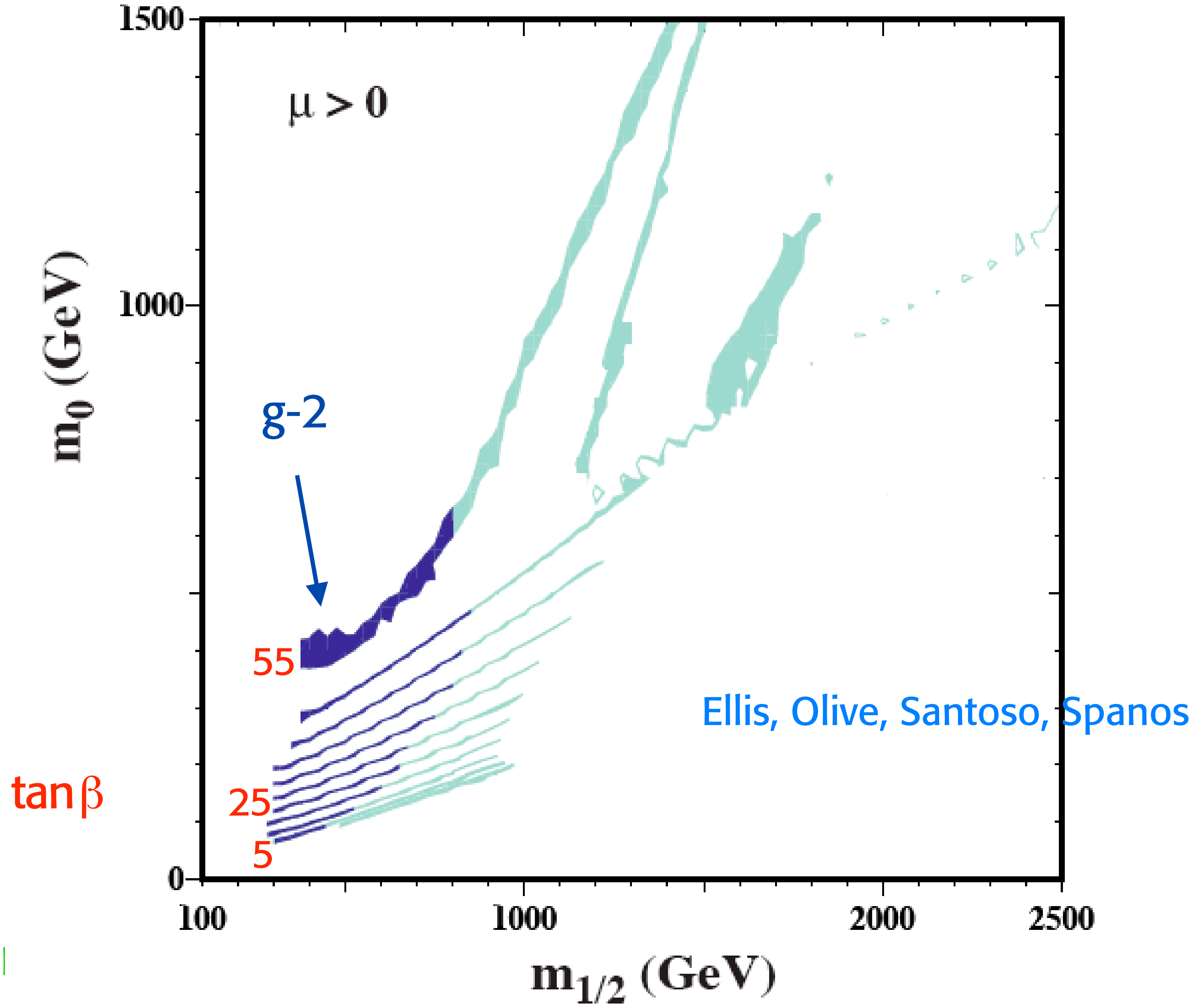
G. Altarelli

$0.1<\Omega h^2<0.3$

Ellis, Olive, Santoso, Spanos



This is for the CMSSM
With less constraints more space



1500
1000
0
100
1000
2000
2500
m_0 (GeV)
$m_{1/2}$ (GeV)
μ > 0
g-2
55
25
5
tan β
Ellis, Olive, Santoso, Spanos

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!!

The scale of the cosmological constant is a big mystery.

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

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

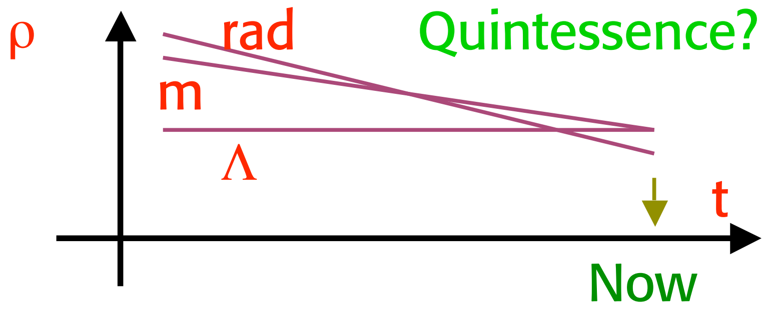
If $\Lambda_{cutoff} \sim M_{Pl}$ → $\rho_\Lambda \sim 10^{123}\ \rho_{obs}$

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?



G. Altarelli

The scale of vacuum energy poses a large naturalness problem!

So far no clear way out:

- A modification of gravity at 0.1mm? (large extra dim.)
- Leak of vac. energy to other universes (wormholes)?

- Anthropic principle: just right for galaxy formation

(Weinberg)

Perhaps naturality irrelevant also for Higgs: Arkani-Hamed, Dimopoulos; Giudice, Romanino '04

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

Or simply a two-scale non-SUSY GUT with axions as DM

But: Lack of SUSY signals at LEP + lower limit on m_H

→ problems for minimal SUSY

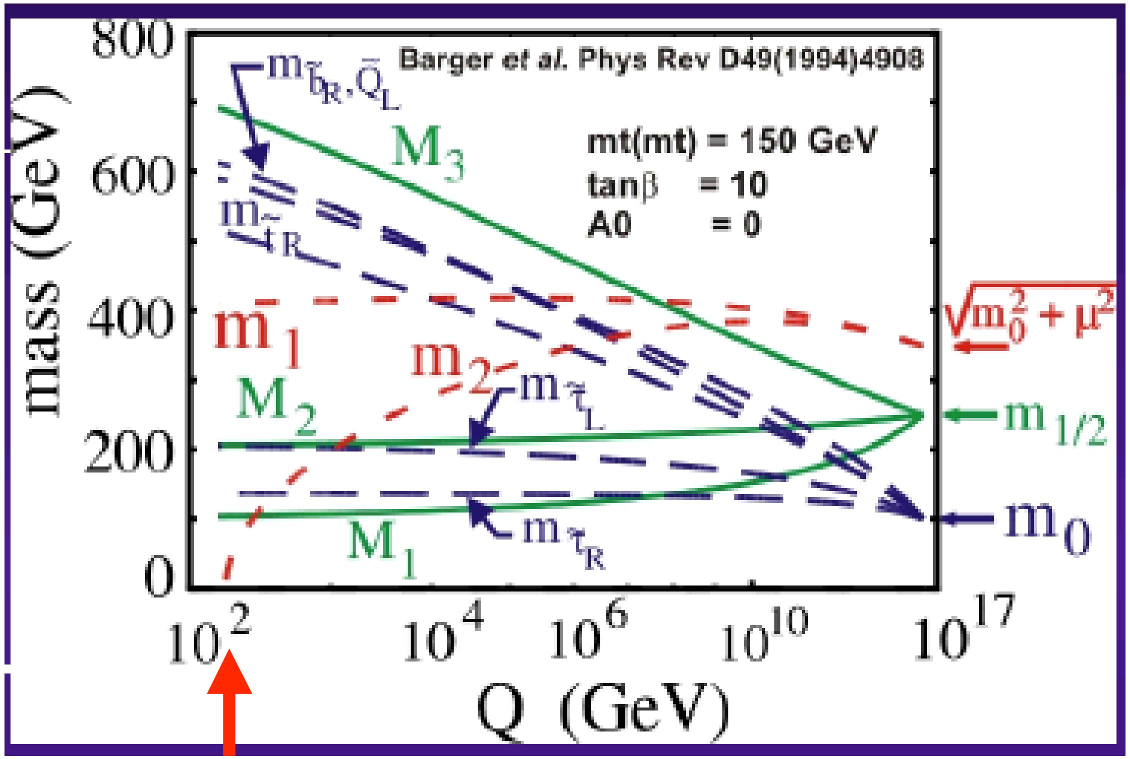
m_{stop} large tends to clash with $\delta m_h^2 \sim m_{stop}^2$

- 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 →



G. Altarelli

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

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

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

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

G. Altarelli

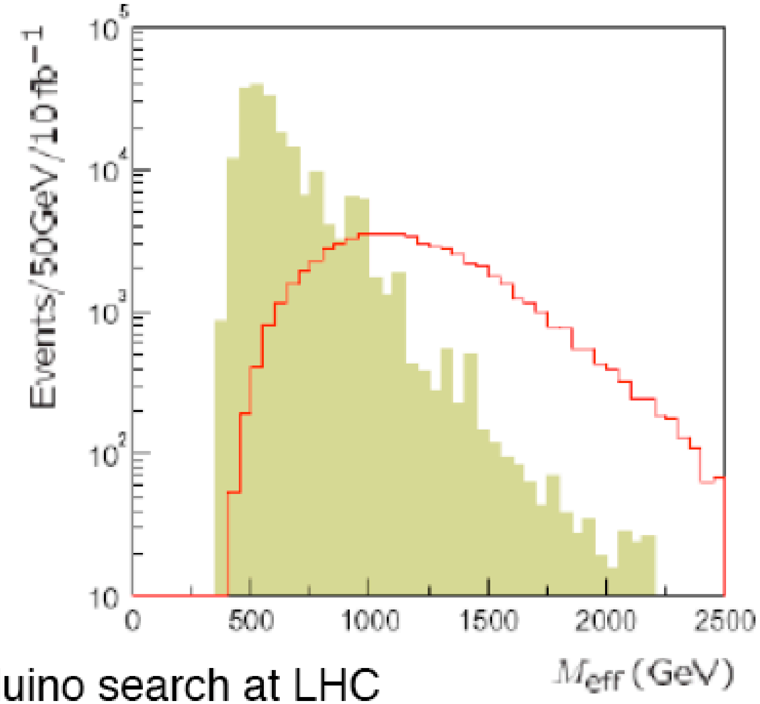
Supersymmetry: the reactions to the "problem"

Barbieri, ICHEP'04

1. Never mind a few % accidental tuning

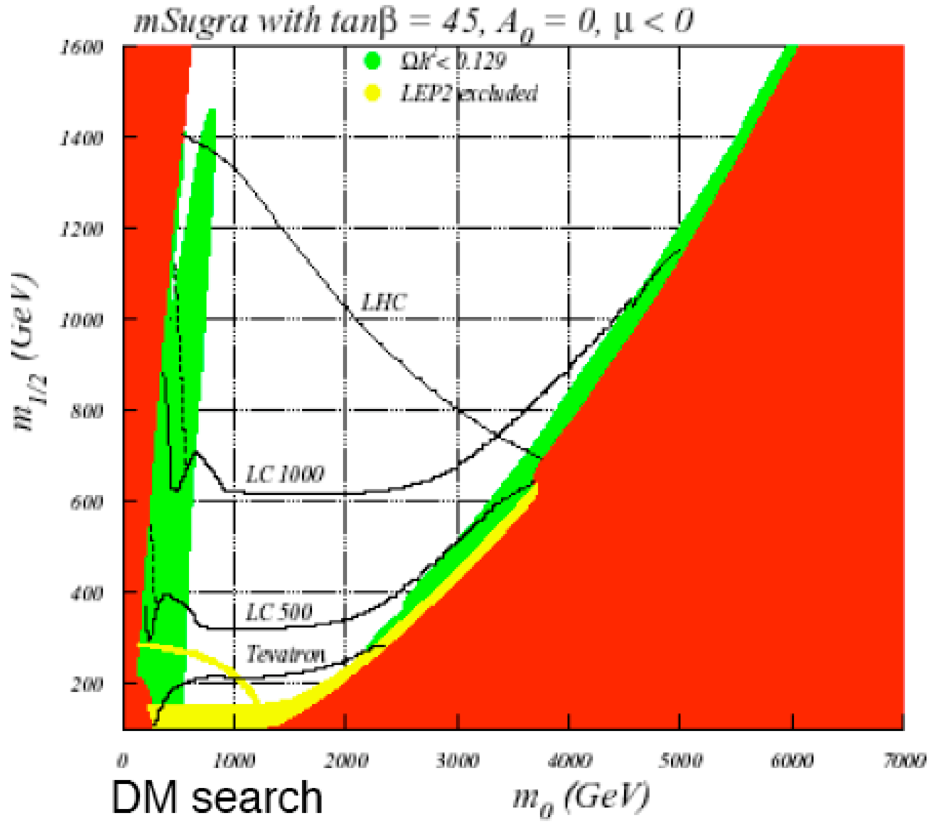
LHC ⊕ LC can systematically explore ~ all of the MSSM parameter space up to a per-mille tuning

$m_h \leq 125 \div 130 GeV$



Gluino search at LHC

ATLAS Coll



DM search

Baer et al

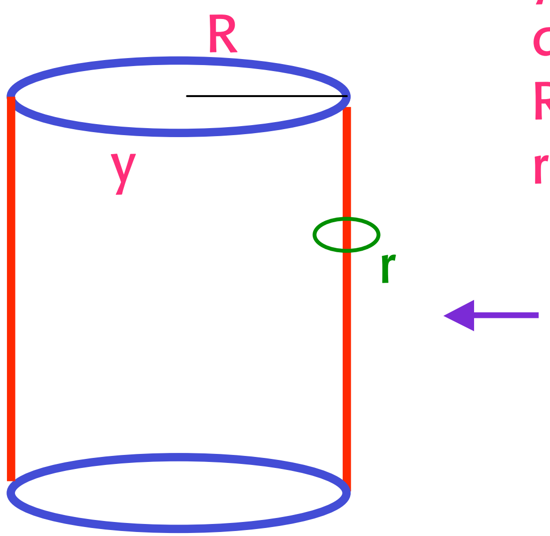
Large Extra Dimensions

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)

$G_N \sim 1/M^2_{Pl}$: Newton const.

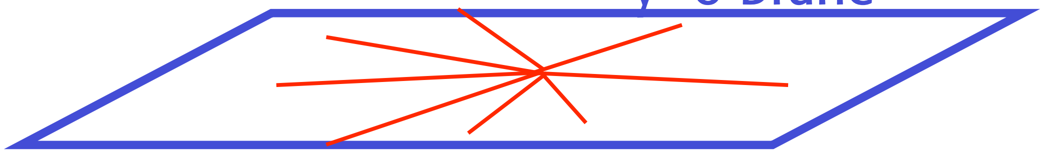
M_{Pl} large as G_N weak

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

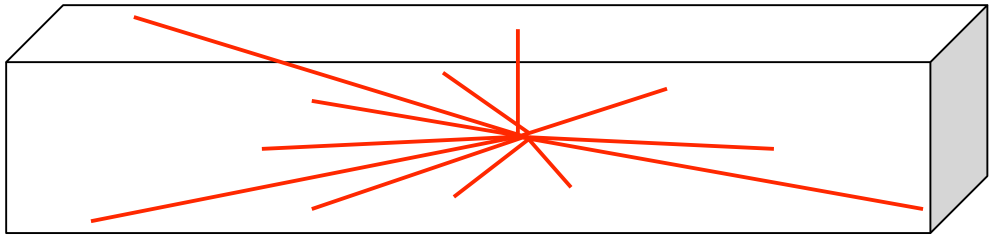
G. Altarelli

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:

$r^{d-2}\ \rho \sim m$

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

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
•••

G. Altarelli

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

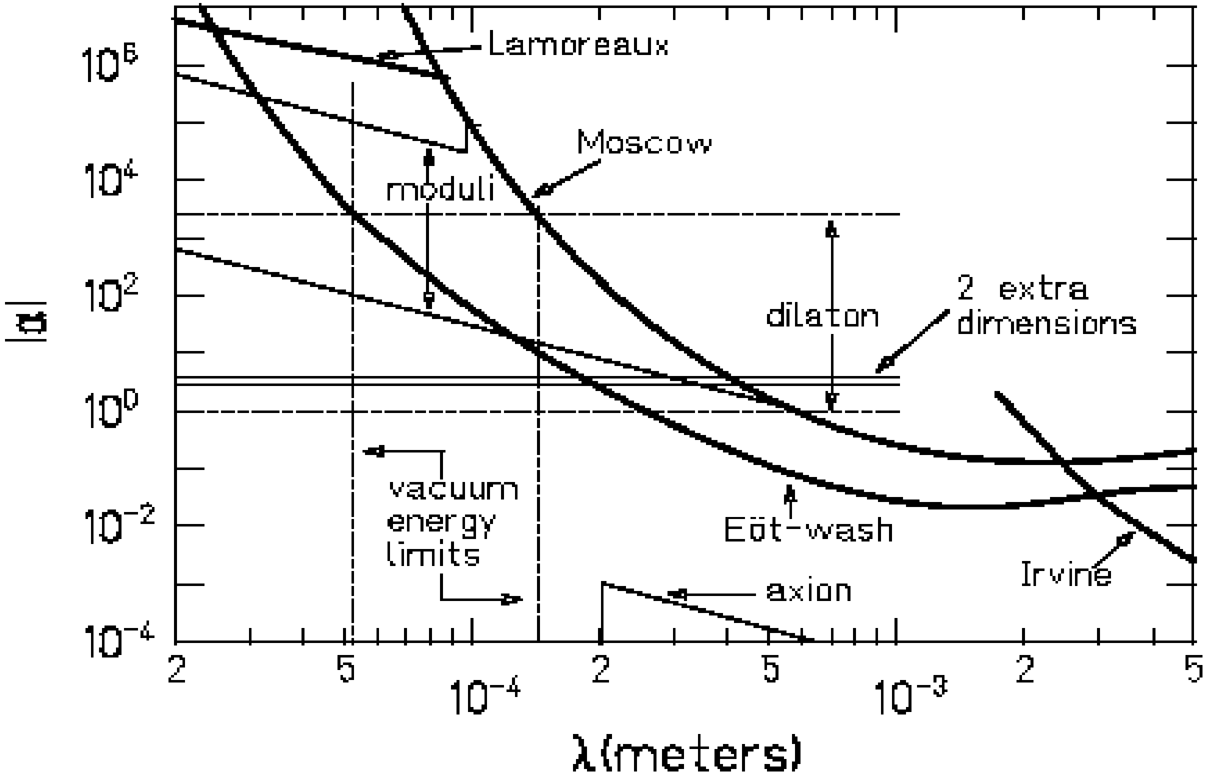


FIG. 4. 95% confidence upper limits on $1/r^2$-law violating interactions of the form given by Eq. (2). The region excluded by previous work [2,3,20] lies above the heavy lines labeled Irvine, Moscow and Lamoreaux, respectively. The data in Fig. 3 imply the constraint shown by the heavy line labeled 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

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

Many possibilities:

- SM fields on a brane

The brane can itself have a thickness r:
$1/r >\sim 1\text{TeV}$ → $r <\sim 10^{-17}$ 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:

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

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

perhaps the most promising

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

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

G. Altarelli

- 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

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

$$m = M_{Pl} exp(-2mR\pi)$$

  * $\Lambda \sim 1/R$ 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

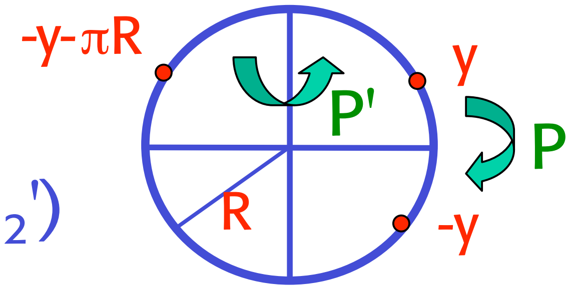
- But could be part of the truth!

- Interesting directions explored →

Symmetry breaking by orbifolding

For $1/R \sim M_{GUT}$

$S/(Z_2 x Z_2')$



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
- ...

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

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

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

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

Symmetry breaking at the weak scale

$1/R \sim o(\mathrm{TeV})$

- **SUSY Breaking** — Barbieri, Hall, Nomura.....Papucci, Marandella.

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

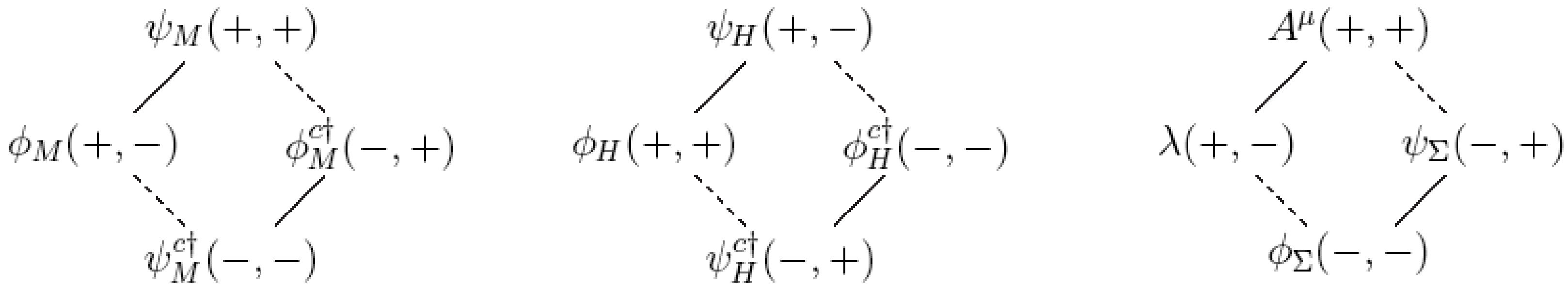
•Z breaks N=2 SUSY, Z′ N=1 SUSY (Scherk-Schwarz)

effective theory non-SUSY (SUSY recovered at d<R)

- Higgs boson mass in principle computable

no invariant Higgs mass operator in 5-dim

rather insensitive to UV $m_H \sim 110$ - 125 GeV



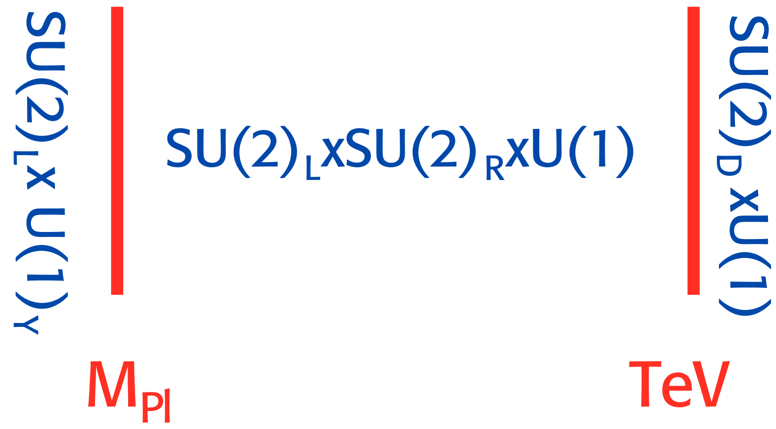
matter — Higgs (only 1!) — gauge

all are in the bulk

G. Altarelli

• Gauge Symmetry Breaking (Higgsless theories)

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



Warped R-S background

Symmetries broken by Boundary Conditions (BC) on the branes →

Altogether only $U(1)_Q$ unbroken

- Unitarity breaking (no Higgs) delayed by KK recurrences

- Dirac fermions on the bulk (L and R doublets). Only one chirality has a zero mode on the interval

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

But: serious problems with EW precision tests

e.g. Barbieri, Pomarol, Rattazzi,Strumia, Chivukula et al

y-Boundary Conditions

A scalar example

Action: $$S = \int dx \int dy \left[\frac{1}{2}(\partial_M \phi)^2 - V(\phi)\right] + \int_{y=0,\pi R} dx \left[\frac{1}{2} M^2 \phi^2\right]$$

Varying the action: $$\delta S = \int dx \int dy \left[\Box \phi + \frac{\partial V}{\partial \phi}\right]\delta\phi + \int dx \left[(\partial_y \phi - M^2 \phi)\delta\phi\right]_0^{\pi R}$$

Thus, at y=0,πR $\phi_{0,\pi R} = cte \Rightarrow 0$ or $[\partial_y \phi - M^2 \phi]_{0,\pi R} = 0$

Note: $M^2 \to 0$ $[\partial_y \phi]_{0,\pi R} = 0$ Neumann $\phi \sim \cos \frac{ny}{R}$

$M^2 \to$ infinity $\phi_{0,\pi R} = 0$ Dirichlet $\phi \sim \sin \frac{ny}{R}$

Gauge theory: $(A^a_\mu)_{0,\pi R} = 0$ or $[\partial_y A^a_\mu - V^{ab} A^b_\mu]_{0,\pi R} = 0$

$V^{ab} = v t^a t^b v$ can arise from a Higgs H localised on the brane: $D_M H D^M H$, $D_M = \ldots + t^a A_M^a$, $\langle H \rangle = v$

G. Altarelli

Suppose we want, at y=πR: $\partial_y A = VA$

We set: $A = A_0 \cos My$

Note. At y=0: $\partial_y A = 0$

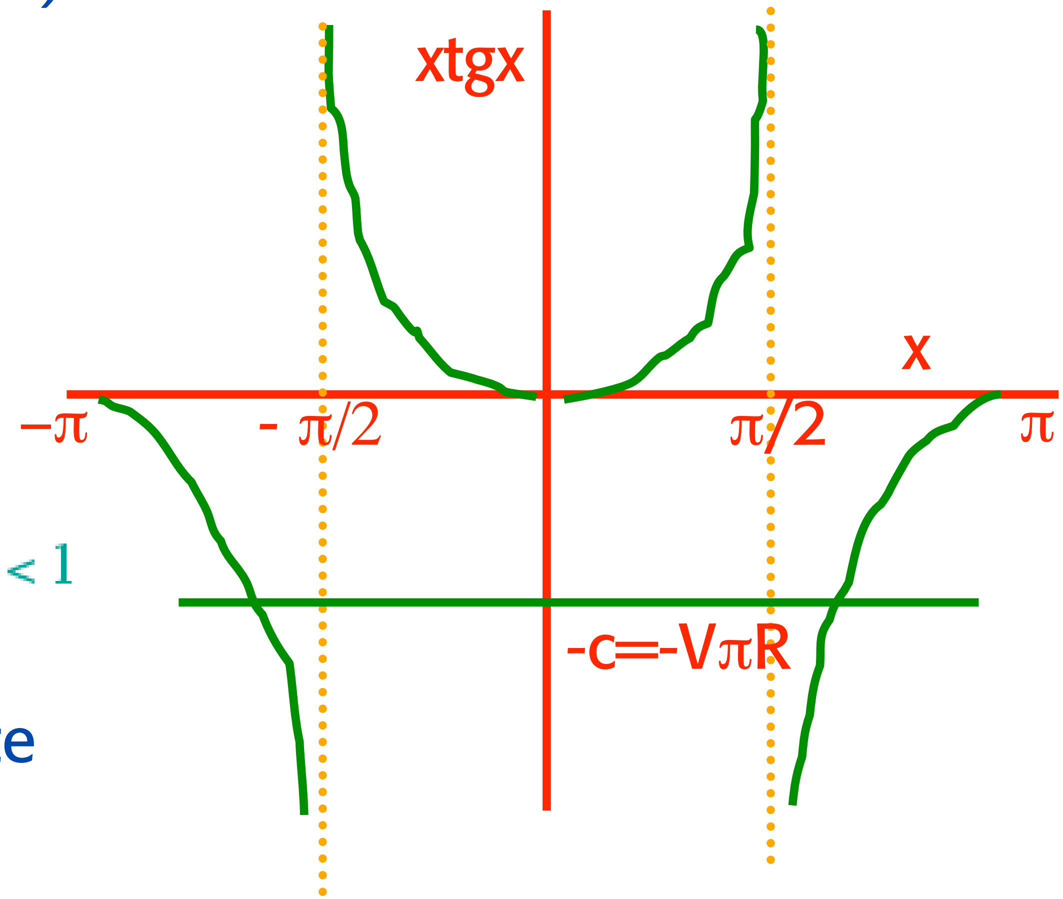
We find M (mass of boson A):

$$-M \sin M\pi R = V \cos M\pi R$$

$$-M\pi R \sin M\pi R = V\pi R \cos M\pi R$$

$$xtgx = -c$$

$$\frac{\pi}{2} < |x| < \pi \;\rightarrow\; \frac{1}{2} < |MR| < 1$$



Note that MR remains finite for V-> infinity

G. Altarelli

Boundary conditions allow a general breaking pattern
(for example, can lower the rank of the group)
equivalent to have generic Higgses on the brane

Breaking by orbifolding is more rigid
(the rank remains fixed)
corresponds to Higgs in the adjoint (A_5 the 5th A_M)

No realistic Higgsless model for EW symmetry breaking sofar emerged

However be alerted of possible signals at the LHC:
no Higgs but KK recurrences of W, Z and additional gauge bosons

Little Higgs Models

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

$$G \supset [SU(2) \otimes U(1)]^2 \supset SU(2) \otimes U(1)$$

global — gauged — SM

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:

$\delta m^2_{H\|top}$	new coloured fermion χ	~1 TeV
$\delta m^2_{H\|gauge}$	W', Z', γ'	
$\delta m^2_{H\|Higgs}$	new scalars	

2 Higgs doublets ~0.2 TeV

E-W Precision Tests? Problems

GUT's? But signatures at LHC clear

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

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

SU(3) broken spont.ly

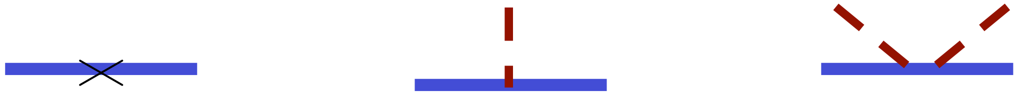
$$\varphi = \exp i \frac{\begin{bmatrix} - & h \\ h^\dagger & - \end{bmatrix}}{f} \begin{bmatrix} 0 \\ 0 \\ f \end{bmatrix}$$

Yukawa coupling:

expl. SU(3) breaking

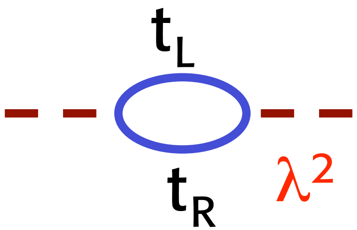
$$\lambda \begin{bmatrix} t^\dagger{}_L & b^\dagger{}_L & \chi^\dagger{}_L \end{bmatrix} \exp i \frac{\begin{bmatrix} - & h \\ h^\dagger & - \end{bmatrix}}{f} \begin{bmatrix} 0 \\ 0 \\ f \end{bmatrix} t_R + M \chi^\dagger{}_L \chi_R$$

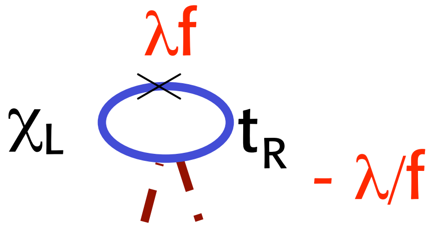
$$\lambda f \chi^\dagger{}_L t_R + i\lambda \begin{bmatrix} t^\dagger{}_L & b^\dagger{}_L \end{bmatrix} h t_R - \frac{\lambda}{2f} \chi^\dagger{}_L t_R h^\dagger h + \ldots.$$



top loop:

coeff. Λ^2





G. Altarelli

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 ~ 200 GeV
better if m_H heavier ⇒

Presumably can be fixed by complicating the model

G. Altarelli

Barbieri, ICHEP'04

Back to 4D: the little Higgs models

Keep the essence of 5D, while avoiding its constraints by suitable (somewhat *ad hoc*) tricks

$G_5 \simeq G_{gl}$ broken to H_{gl} $\quad G_{IR} \simeq H_{gl}$ $\quad G_{UV} \simeq G_{gauge}$

Problems: give the Higgs a quartic self-coupling and a top-Yukawa consistent with observations

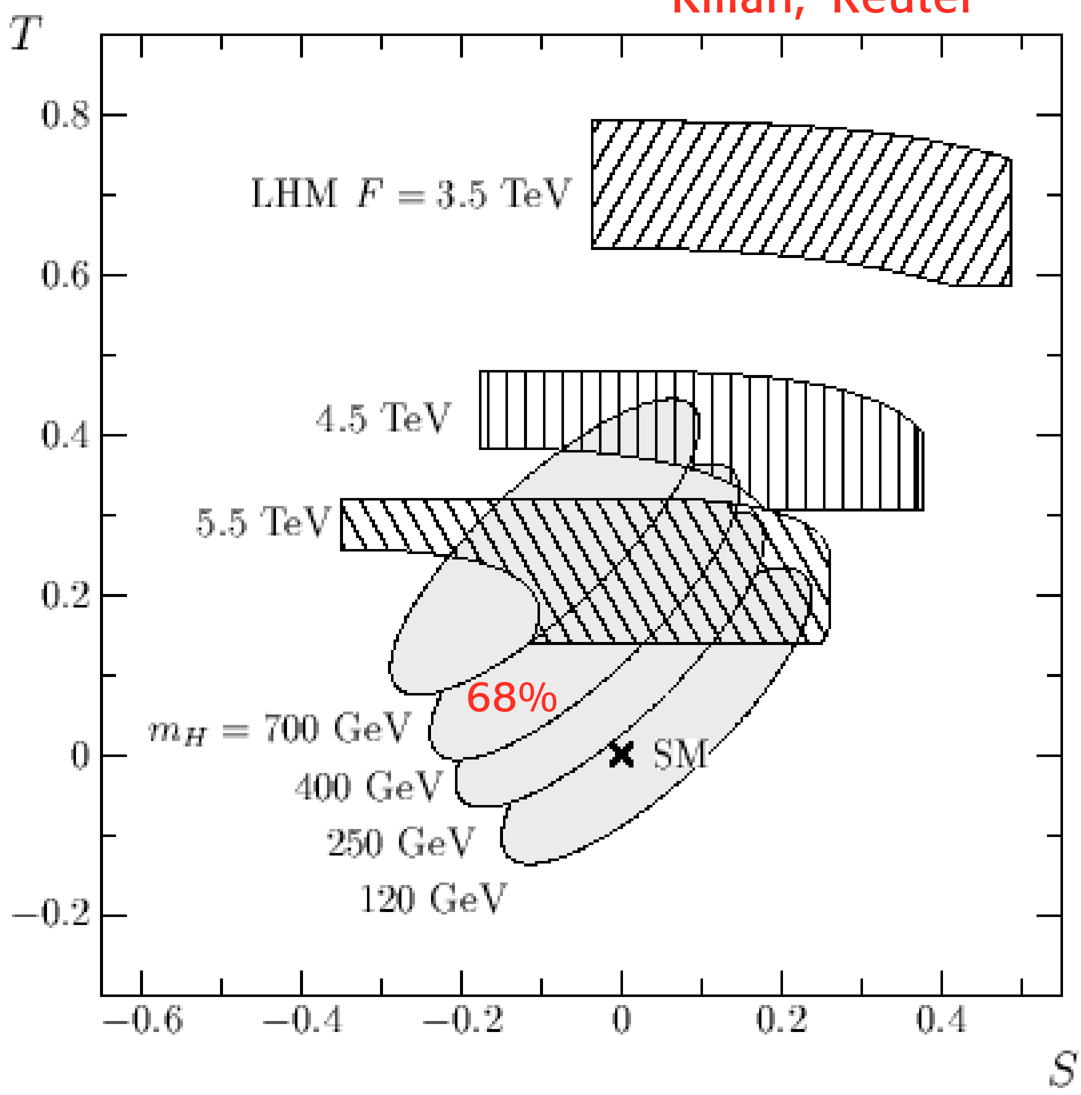
(Too) many models:

$$f = \Lambda_{LH}$$

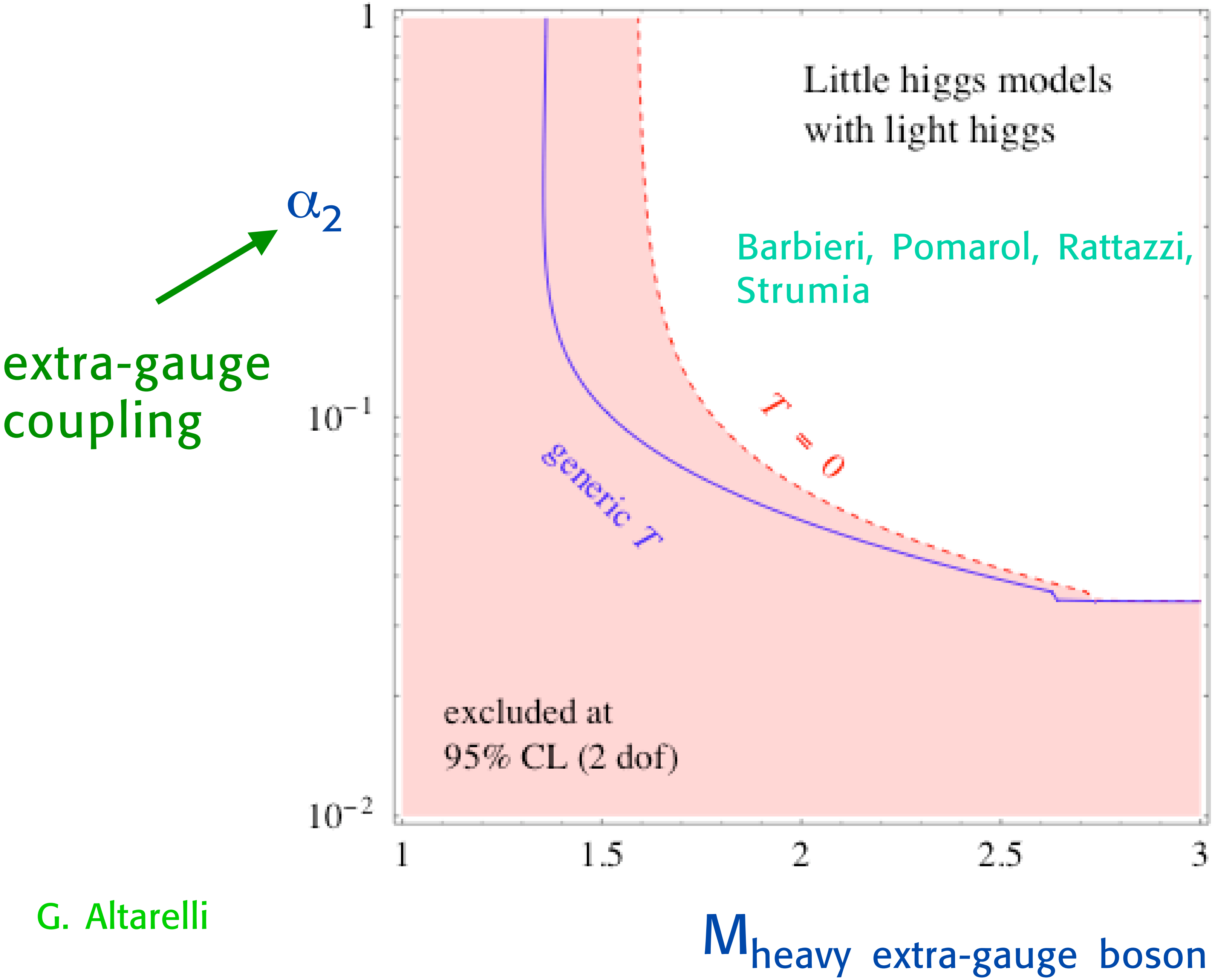
	The "littlest"	The "simplest"
Global	$SU(5) \xrightarrow{f} SO(5)$	$(SU(3)XU(1))^2 \xrightarrow{f} (SU(2)XU(1))^2$
Gauge	$(SU(2)XU(1))^2 \Longrightarrow SU(2)XU(1)$	$SU(3)XU(1) \Longrightarrow SU(2)XU(1)$
	Arkani-Hamed et al	Kaplan, Schmaltz

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

Kilian, Reuter



G. Altarelli



α_2
extra-gauge
coupling
1
10^{-1}
10^{-2}
1
1.5
2
2.5
3
Little higgs models
with light higgs
Barbieri, Pomarol, Rattazzi,
Strumia
T = 0
generic T
excluded at
95% CL (2 dof)
$M_{heavy\ extra\text{-}gauge\ boson}$

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 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)