

Beyond the Standard Model in the LHC Era

Riccardo Barbieri
High Precision for Hard Processes at the LHC
GGI, Florence, Sept 14-17, 2010

Particle Physics in one page

$$\mathcal{L}_{\sim SM} = -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + i\bar{\Psi} \not{D}\Psi \quad \text{The gauge sector} \quad (3)$$

$$+ |D_\mu h|^2 - V(h) \quad \text{The EWSB sector} \quad (4)$$

$$+ \Psi_i \lambda_{ij} \Psi_j h + h.c. \quad \text{The flavor sector} \quad (2)$$

$$+ N_i M_{ij} N_j \quad \text{The } \nu\text{-mass sector} \quad (1)$$

(if Majorana)

The quadrant of nature whose laws can be summarized in one page with absolute precision and empirical adequacy

Particle physics as “synthetic” physics

Can the SM be the end of the story?

But...

Dark Matter ← "direct" ←
 LHC ←
 "indirect" ←

Origin of Matter (B-asymmetry)

Dark Energy

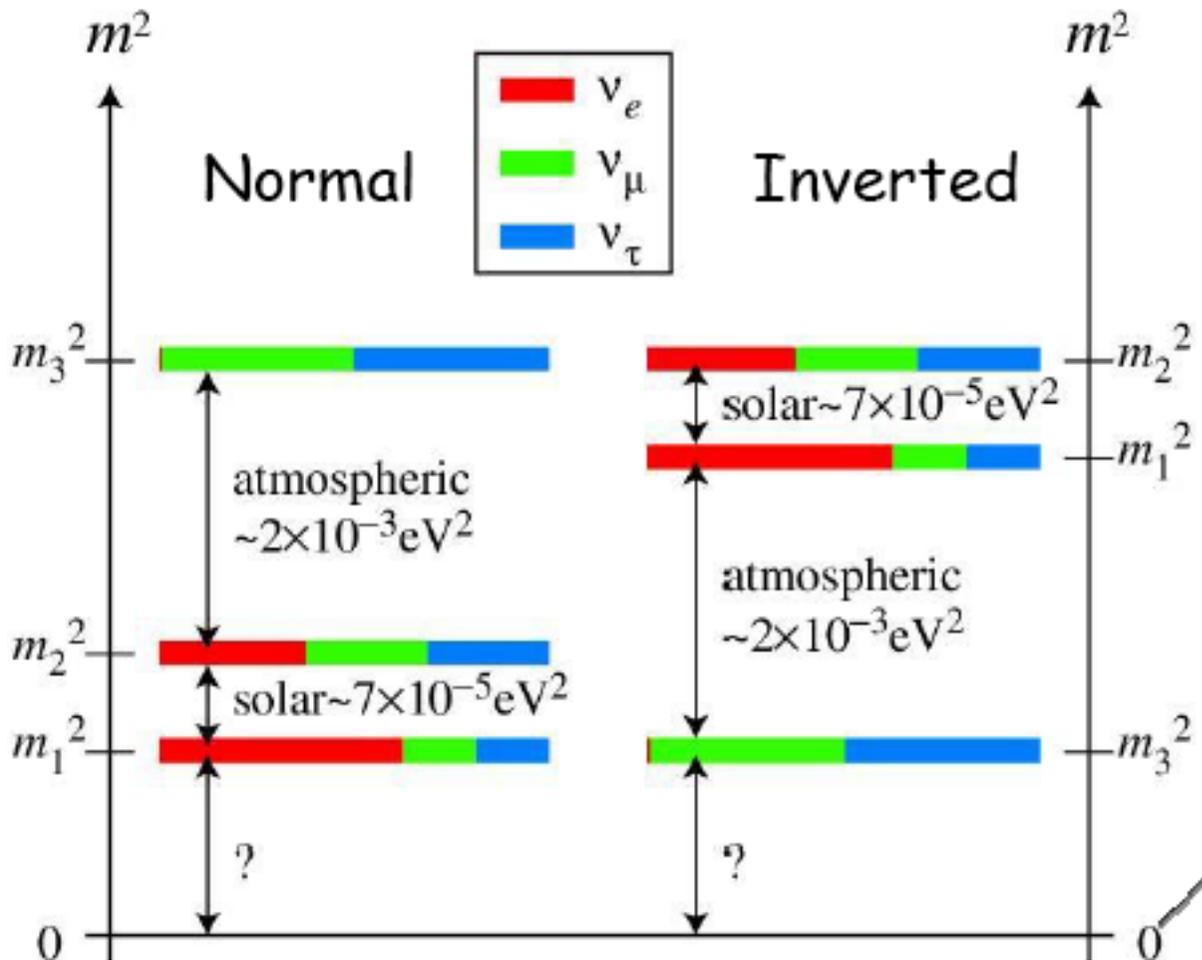
quite a number of 2÷3 sigma anomalies

• • • • •

(not touched in this talk)

Current knowledge (2010) and open problems in ν -physics

in the 3-neutrino picture



$$|\nu_i\rangle = V_{i\alpha} |\nu_\alpha\rangle$$

$$\alpha = e, \mu, \tau$$

$$\langle m^2 \rangle = ?$$

$$V_{3e} = ?$$

Normal or Inverted?

CP violated?

3 neutrinos only?

Majorana or Dirac?

The Flavour Sector

- 1 - We know the SM works quantitatively in the full quark sector (A major change in the 2000's)
- 2 - If there are other degrees of freedom at the Fermi scale carrying flavour (e.g. the s-fermions), unlikely that there be no extra flavour phenomena observable at some level
- 3 - We know all the 10 parameters in the quark sector (6+3+1) and 7 (3+2+2) out of the 10/12 (6 +3 +1/3) in the lepton sector (but no hard theory for them)

My own favorite test of Flavour Physics

$$\mu \rightarrow e + \gamma$$

Current limit $BR(\mu \rightarrow e + \gamma) < 1.2 \cdot 10^{-11}$

An experiment, MEG, under way at PSI aiming at a factor of 100 better sensitivity

Current sensitivity $6.1 \cdot 10^{-12}$
with some borderline events

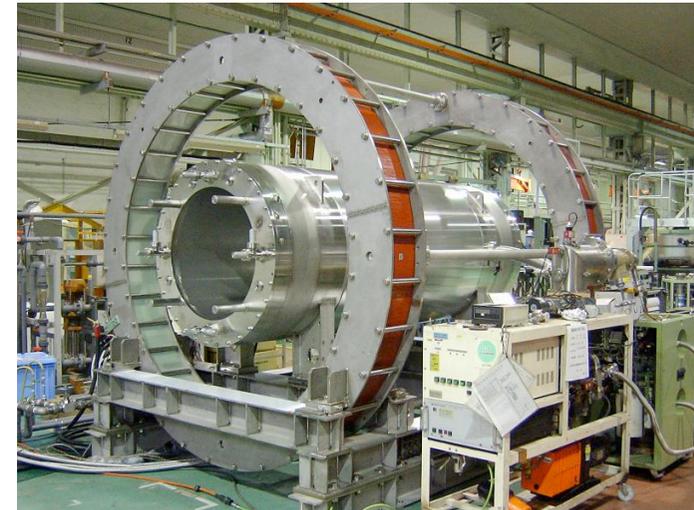
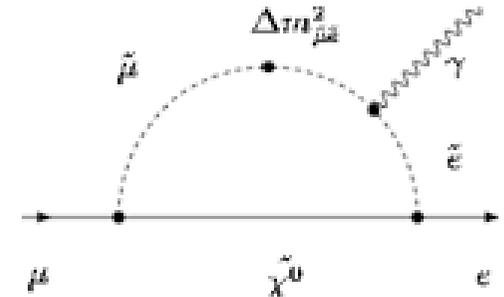
Wait and see

In suitable minimal unification

$$BR(\mu \rightarrow e + \gamma) \approx \delta \cdot 10^{-13}$$

$$\delta \approx 1 \text{ in SUGRA + SU(5)}$$

$$\delta \approx 50 \text{ in SUGRA + SO(10)}$$



(not only the LHC)

B, Hall, Strumia

Strumia, Romanino

The gauge sector

Getting closer to specific LHC issues

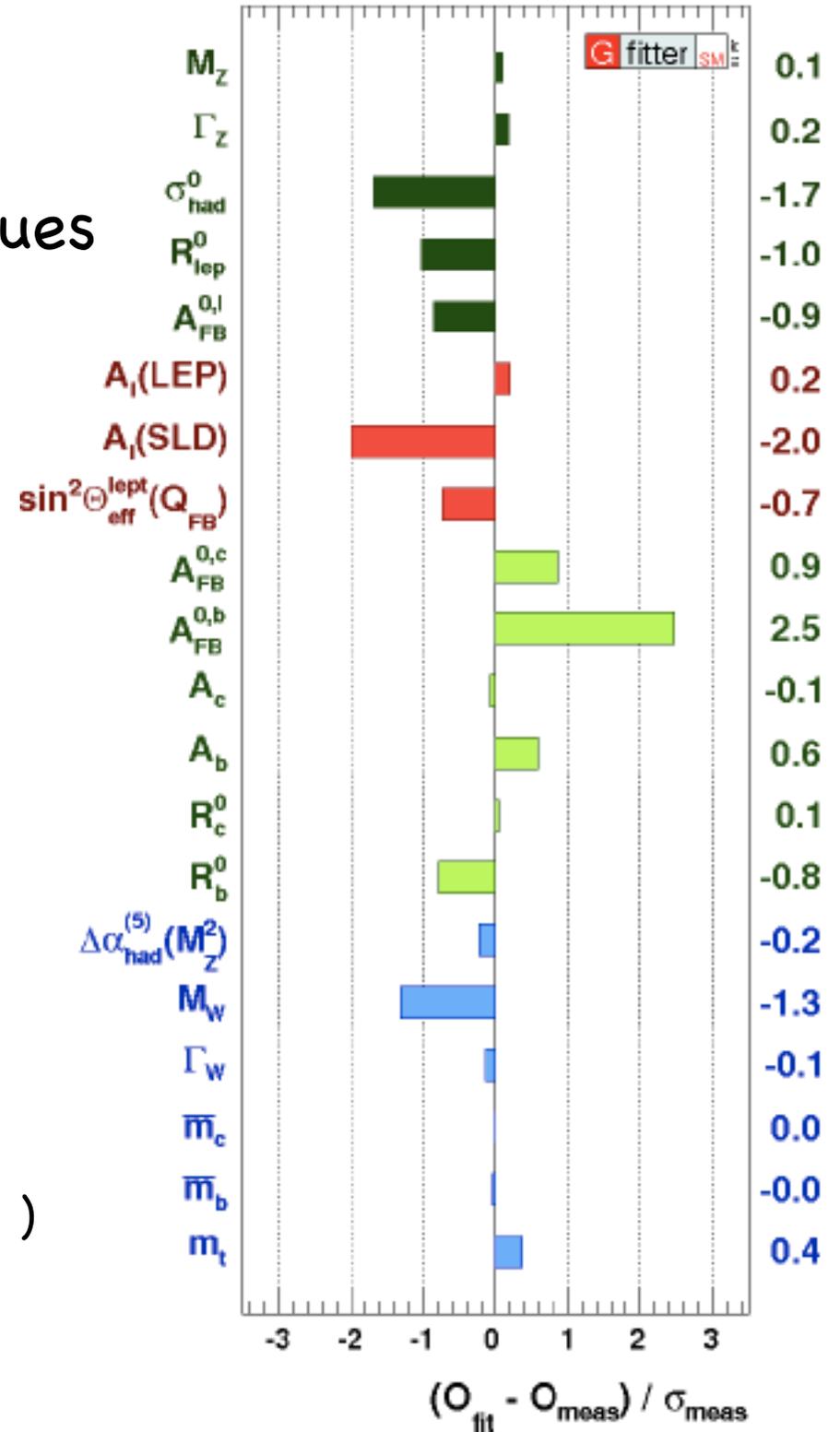
CERN-Fermilab-Stanford mostly

precision often better than 10^{-3}

In fact:
 from $l_{max} \approx 10^{-8} \text{ cm}$ (APV)
 to $l_{min} \approx 10^{-16} \div 10^{-17} \text{ cm}$

$\approx 20\%$ χ^2 probability

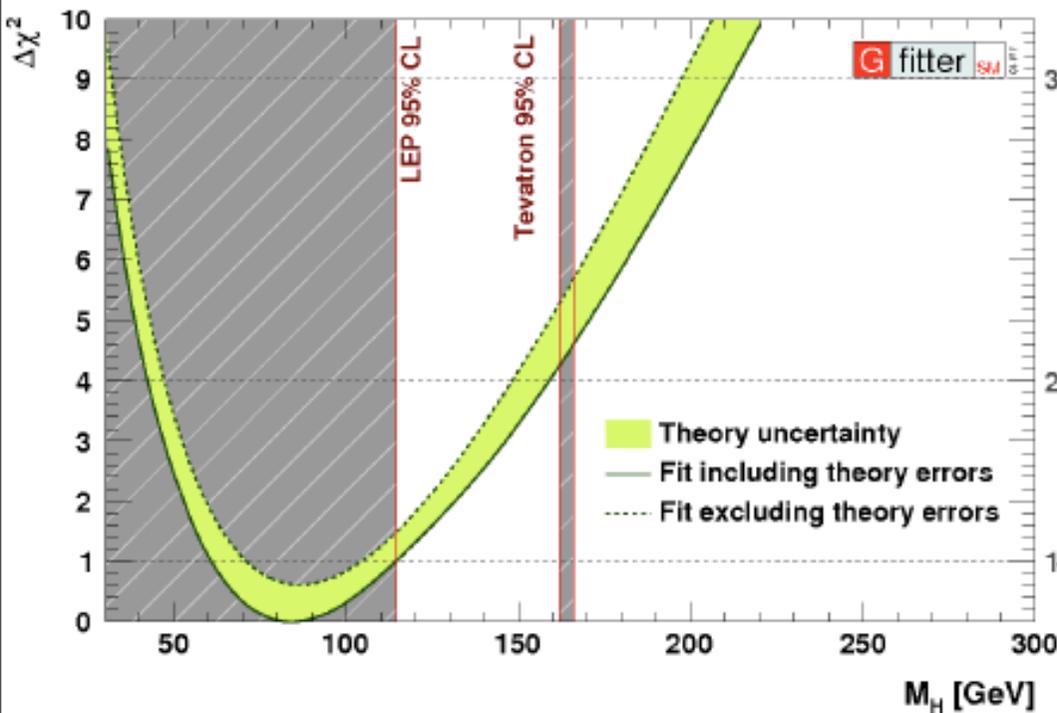
(latest top mass: $m_t = 173.3 \pm 1.1 \text{ GeV}$)



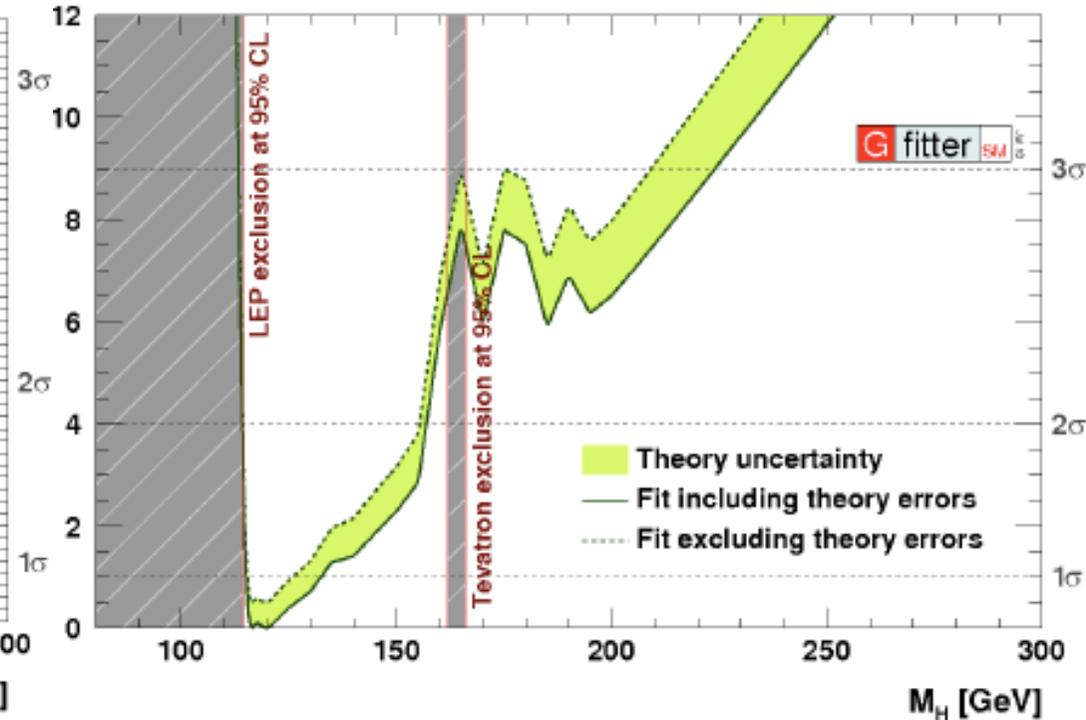
The Higgs boson mass in the SM

- value at minimum $\pm 1\sigma$:
 $M_H = 83_{-23}^{+30}$ GeV
- 2σ interval: [42, 159] GeV

- value at minimum $\pm 1\sigma$:
 $M_H = 119.1_{-4.0}^{+13.5}$ GeV
- 2σ interval: [114, 157] GeV



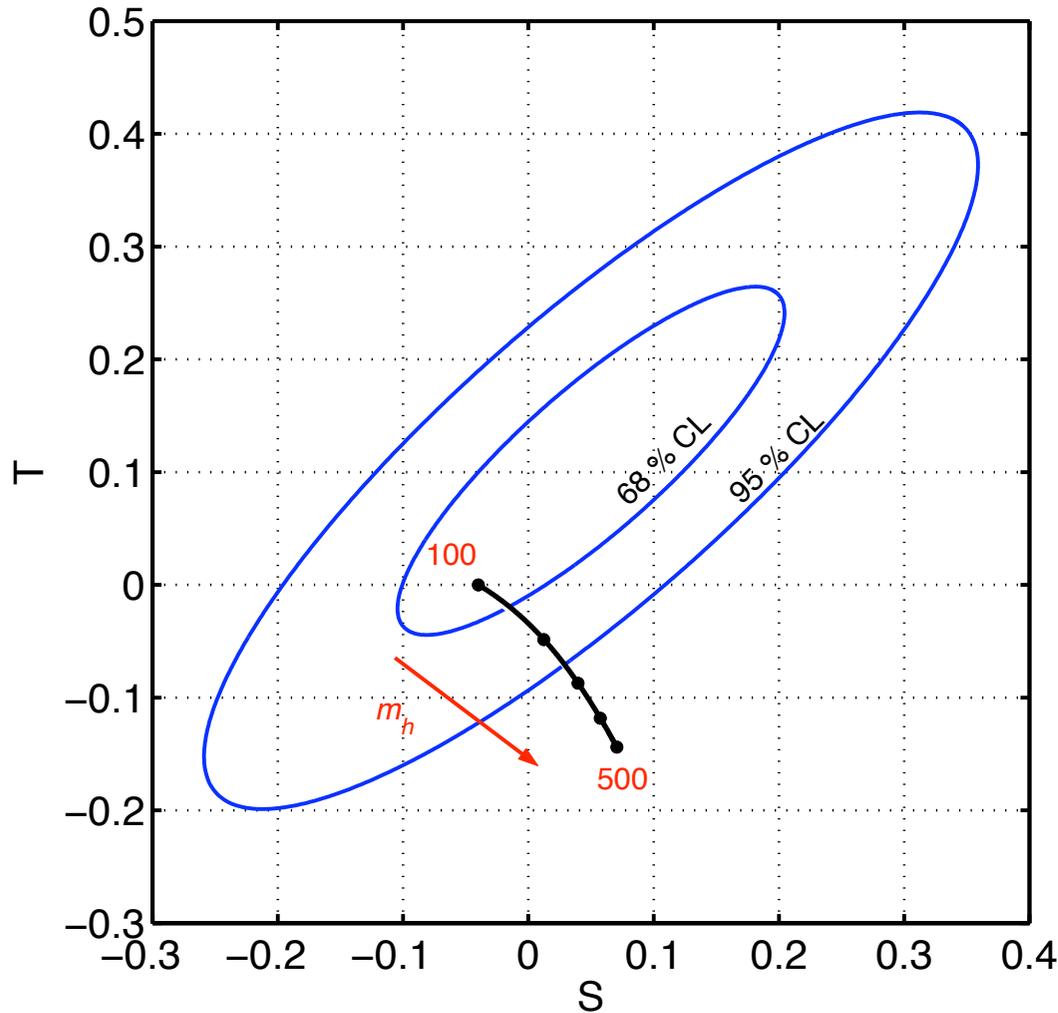
direct (negative) searches not included



direct (negative) searches included

The guidance of the EWPT

(in principle also beyond the SM)



$$T \sim \text{[diagram of } W^+ W^+ \text{ and } W^3 W^3 \text{ loops]}$$

$$S \sim \frac{d}{dp^2} \text{ [diagram of } B \text{ and } W^3 \text{ loops]}$$

More useful to constrain new theories than to prove their superiority to the SM (which is hard to beat)

[b-asymm, g-2(μ)]

ElectroWeak Symmetry Breaking

My "bias" declared:

The lack so far of a thorough exploration of the energy scales at and well above $G_F^{-1/2}$ suggests a cautious attitude about LHC expectations on EWSB

$$\Lambda_{QCD}, \textcircled{G_F^{-1/2}}$$

No comparable situation at the SppS or at the TEVATRON

1984: W, Z

1994: top

201?: the Higgs boson of the SM

A far more open case at the LHC

Which indirect information?

1999: "the LEP Paradox" (with Strumia)

2001: "the little hierarchy" problem

While all indirect tests (EWPT, flavour) indicate no new scale below several TeV's, the Higgs boson mass is apparently around the corner and is normally sensitive to any such scale

$$\Lambda_{NP} \gtrsim 5 \div 10 \text{ TeV} \quad m_h \approx 115 \text{ GeV} \left(\frac{\Lambda_{cutoff}}{400 \text{ GeV}} \right)$$
$$\Lambda_{NP} \stackrel{?}{\approx} \Lambda_{cutoff}$$

2010: the problem still there, more than ever

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_{eff}^{NP}$$

$$\mathcal{L}_{eff}^{NP} = \sum_i \frac{c_i}{\Lambda_{NP}^2} \mathcal{O}_i$$

Taking $c_i = \pm 1$ and considering one operator at a time

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{O}/\Lambda^2$$

	operator \mathcal{O}	affects	constraint on Λ
	$\frac{1}{2}(\bar{L}\gamma_\mu\tau^a L)^2$	μ -decay	10 TeV
	$\frac{1}{2}(\bar{L}\gamma_\mu L)^2$	LEP 2	5 TeV
T→	$ H^\dagger D_\mu H ^2$	θ_W in M_W/M_Z	5 TeV
S→	$(H^\dagger\tau^a H)W_{\mu\nu}^a B_{\mu\nu}$	θ_W in Z couplings	8 TeV
	$i(H^\dagger D_\mu\tau^a H)(\bar{L}\gamma_\mu\tau^a L)$	Z couplings	10 TeV
	$i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	Z couplings	8 TeV
⇒	$H^\dagger(\bar{D}\lambda_D\lambda_U\lambda_U^\dagger\gamma_{\mu\nu}Q)F^{\mu\nu}$	$b \rightarrow s\gamma$	10 TeV
⇒	$\frac{1}{2}(\bar{Q}\lambda_U\lambda_U^\dagger\gamma_\mu Q)^2$	B mixing	10 TeV

1 σ -bounds \oplus a light Higgs

More conservatively: $\Lambda > \sim 5$ TeV

EWSB: "weak" or "strong"?

"weak"

a relatively light Higgs boson exists
perturbativity extended \rightarrow high E (M_{GUT}, M_{Pl})
perhaps (probably) embedded in susy
gauge couplings unify

"strong"

EWSB related to new forces, new degrees of freedom
or even new dimensions opening up in the TeVs
perturbativity lost in the multi-TeV range
high E extrapolation highly uncertain

The “weak coupling” way

Favoured by indirect-data

EWPT, unification (susy), ν -masses (?)

Which problems, if susy?

No Higgs boson so far (hidden in LEP data? See below)

No s -particle

Flavour? (follow $\mu \rightarrow e\gamma$ at PSI)

Tuning? (It could be right and we might never know)

The MSSM as the only paradigm?

The “strong coupling” way

Disfavoured by indirect-data

EWPT: mostly $\Delta S > 0$, but don't forget the $S \leftrightarrow T$ correlation

Models not fully convincing

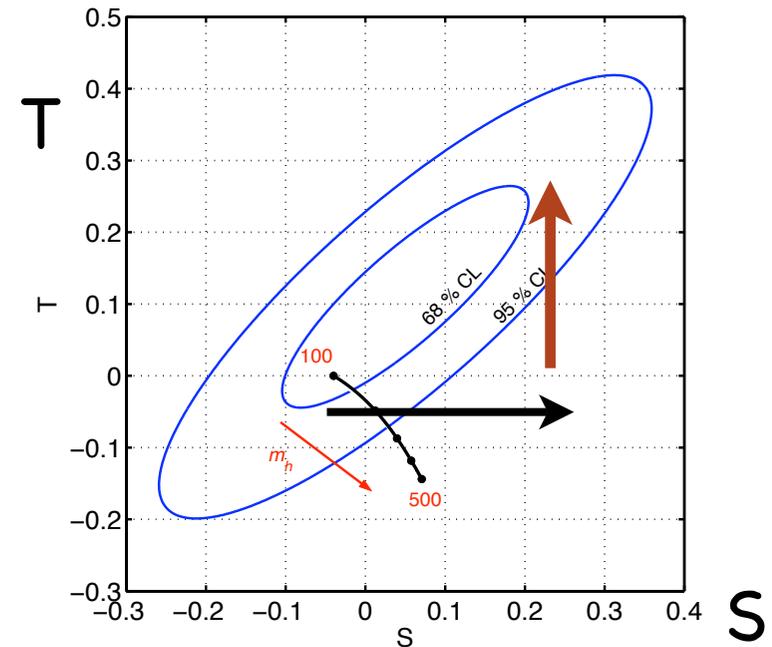
(although enlarged by $5D \leftrightarrow 4D$ holography)

Flavour problematic?

(yes, but what about the SM λ_{ij}^Y ?)

“Higgs” or “Higgs-less”?

(a real question, although with a most likely answer)



Valid questions about the Higgs boson

- ⇒ Can one make without it?
- ⇒ Can it be a “composite” object?
- ⇒ Can it have escaped detection?
- ⇒ Can it be significantly heavier than expected?
- ⇒ Where is the supersymmetric Higgs boson?

{ heretic, yet
meaningful

Concentrate on this



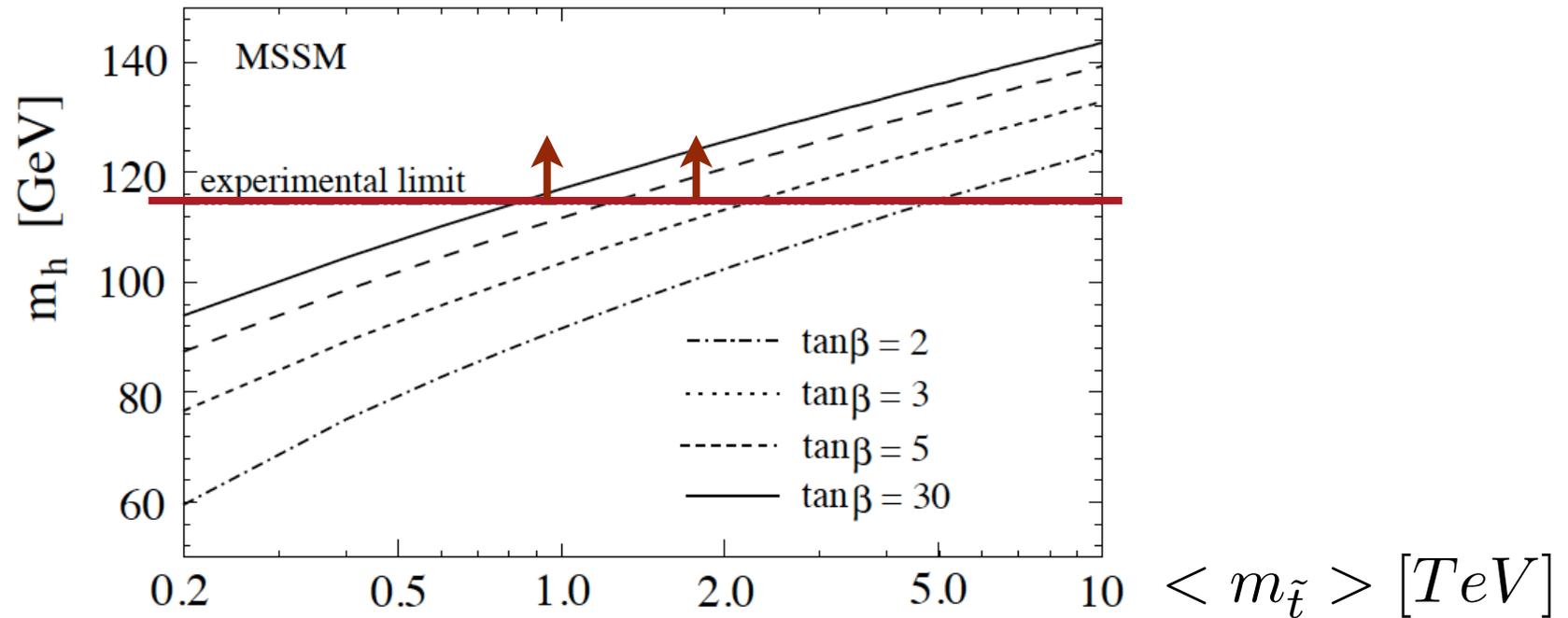
True Higgs bounds (channel-dependent)

Decay channel	Limit (GeV)
$h \rightarrow b\bar{b}, \tau\bar{\tau}$	115
$h \rightarrow jj$	113
$h \rightarrow \gamma\gamma$	117
$h \rightarrow WW^*, ZZ^*$	110
$h \rightarrow$ invisible	115
$h \rightarrow \eta\eta \rightarrow 4b$	110
$h \rightarrow \eta\eta \rightarrow 4\tau, 4c, 4g$	86
model indep.	82

moved to ~ 110 GeV for 4τ
by LEP resuscitation
Spagnolo et al, ALEPH Coll

Where is the supersymmetric Higgs boson?

MSSM



⇒ Take large $\tan\beta$ (muon anomaly?) and large stop mass but swallow, e.g. in SUGRA, a large contribution to M_Z , to be fine-tuned away

$$\Delta M_Z^2 \approx (2 \div 3) m_{\tilde{t}}^2 \geq 100 M_Z^2$$

⇒ *h just around the corner and quasi-standard*

Supersymmetry without a light Higgs boson

Want to keep the success of the EWPT
⇒ Effective theories not enough

★ MSSM $m_h^2 \leq m_Z^2 \cos^2 2\beta$ + rad. corr.

★ Extra U(1) $m_h^2 \leq \left(m_Z^2 + \frac{g_x^2 v^2}{2\left(1 + \frac{M_X^2}{2M_\phi^2}\right)} \right) \cos^2 2\beta$ Batra, Delgado, Kaplan, Tait

★ Extra SU(2) $m_h^2 \leq m_Z^2 \frac{g'^2 + \Delta g^2}{g'^2 + g^2} \cos^2 2\beta$ $\Delta = \frac{1 + \frac{M_\Sigma^2}{M_X^2} \frac{g_I^2}{g^2}}{1 + \frac{M_\Sigma^2}{M_X^2}}$

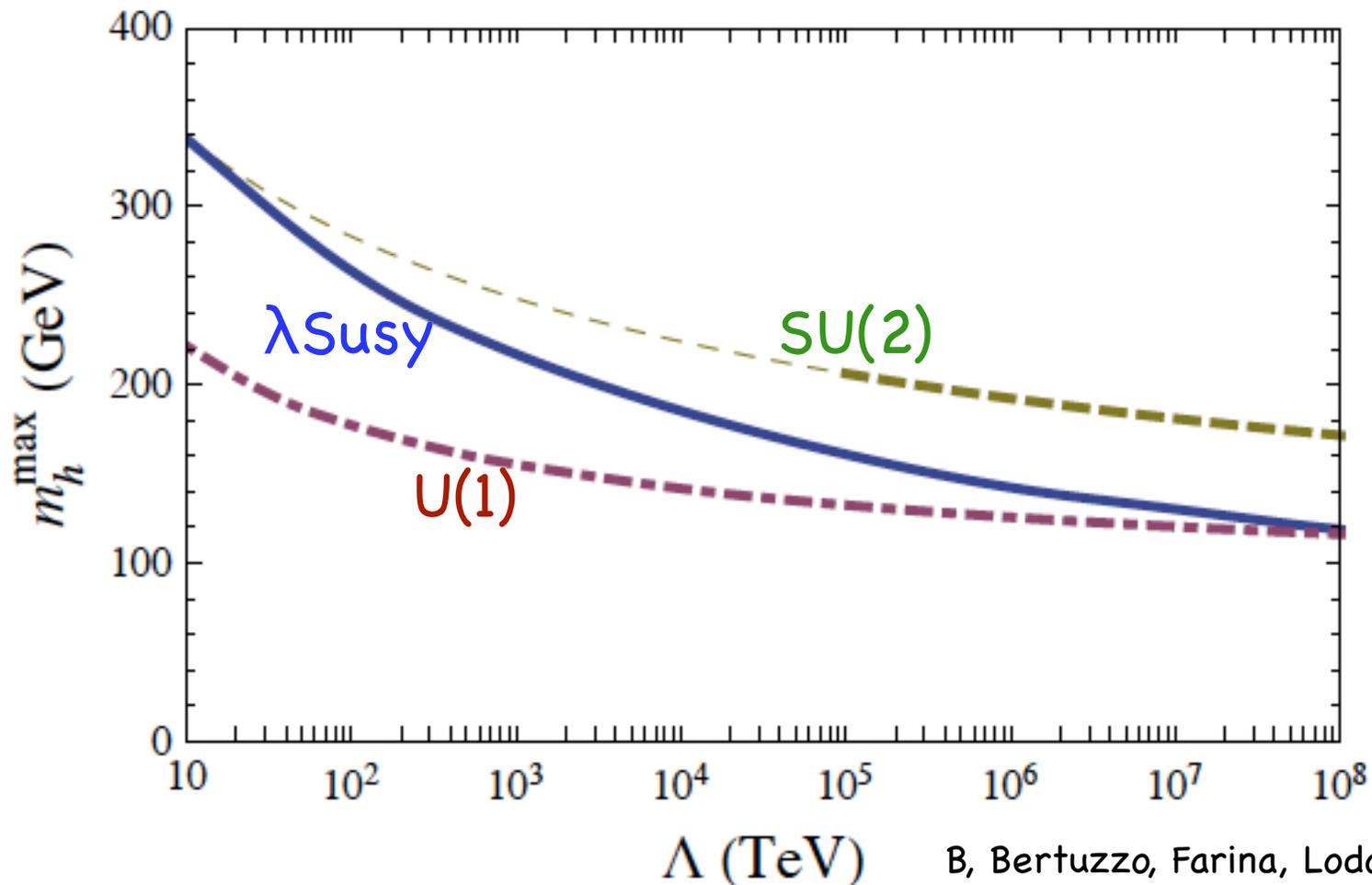
★ $\Delta f = \lambda S H_1 H_2$ $m_h^2 \leq m_Z^2 \left(\cos^2 2\beta + \frac{2\lambda^2}{g^2 + g'^2} \sin^2 2\beta \right)$
(NMSSM ⇒ λ susy) Harnik, Kribs, Larson, Murayama
B, Hall, Nomura, Rychkov

⇒ *h not standard and not even light*

The price to pay

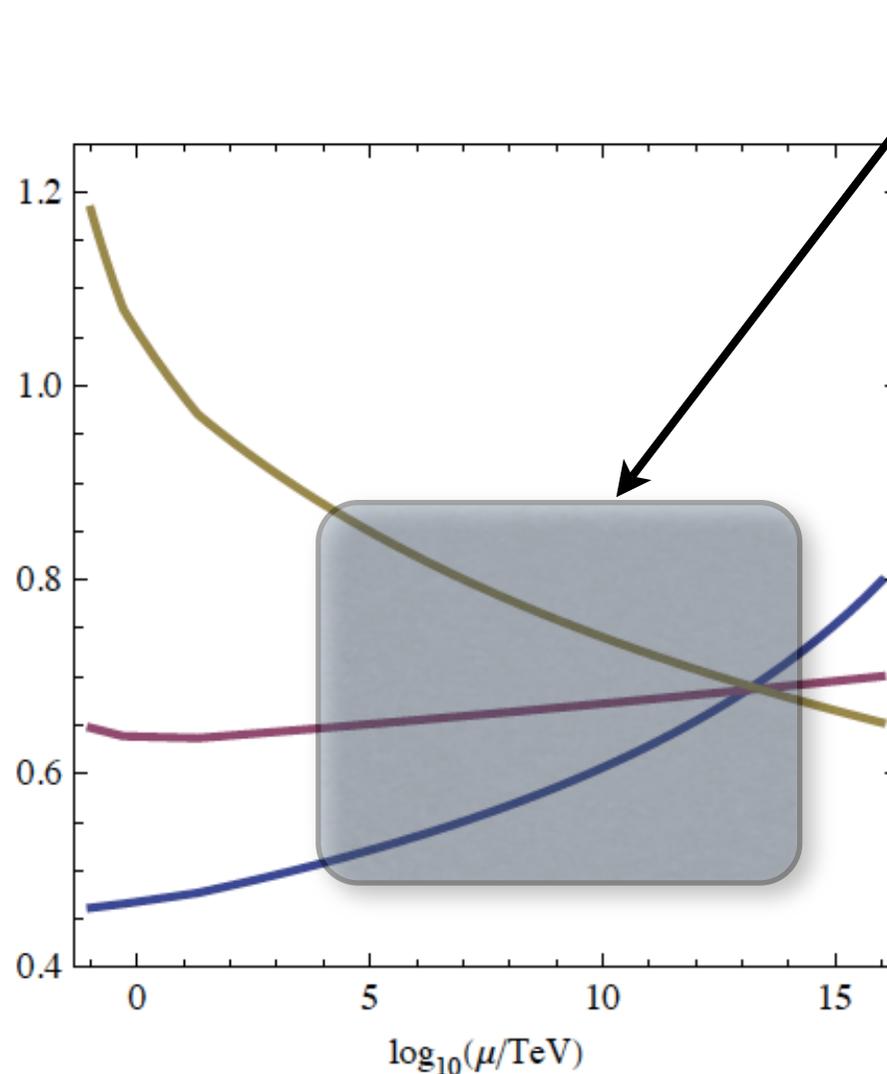
(big, according to standard wisdom, but...)

At a scale Λ some coupling starts blowing



unless some change of regime occurs there

What about gauge-coupling unification, then?



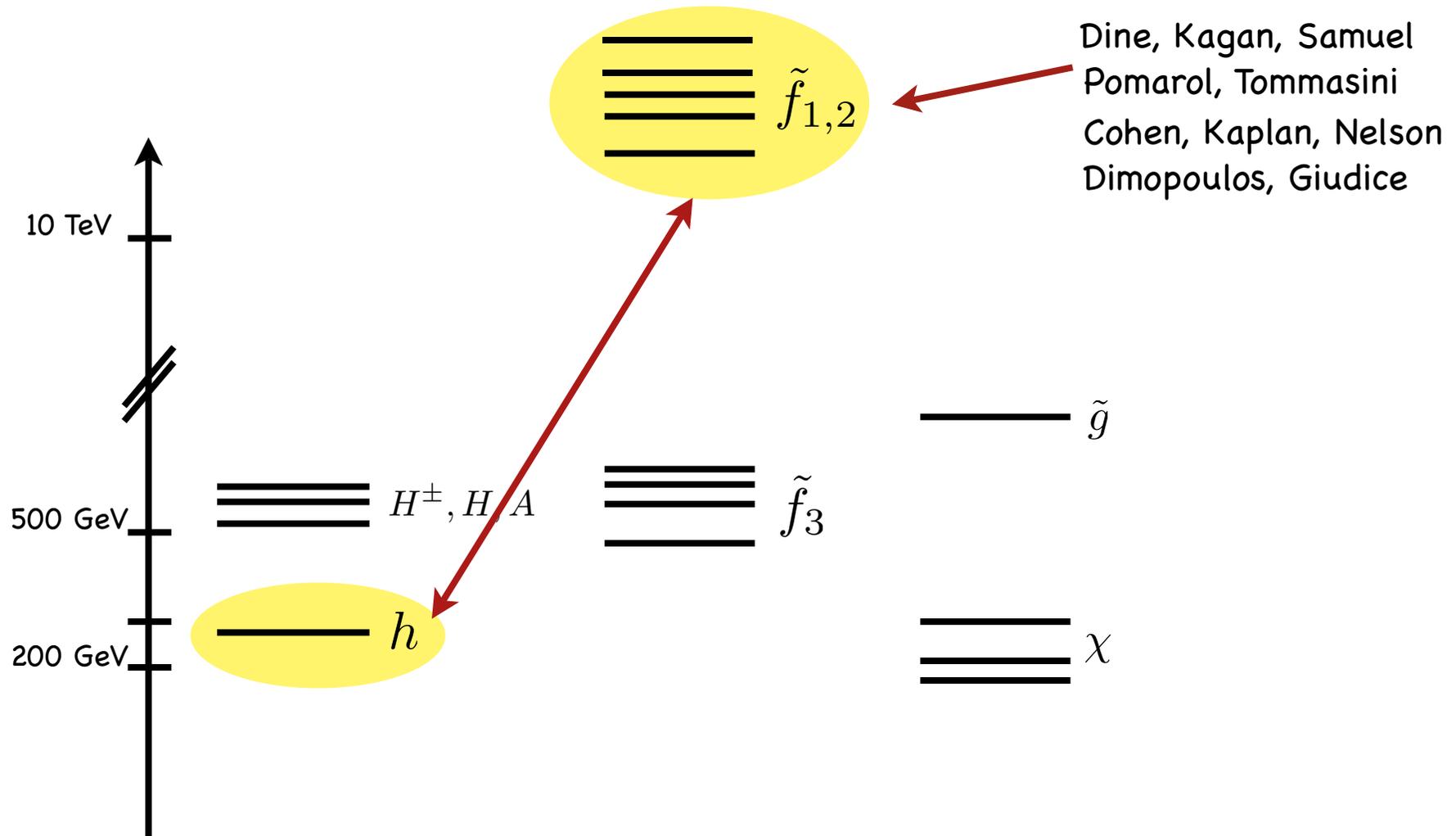
a grey box

It depends on what happens
at $M \gtrsim 10^4 \text{ TeV}$

At $M \approx 10^4 \text{ TeV}$:
 $g_1 \approx 0.5$, $g_2 \approx 0.7$, $g_3 \approx 0.85$
as opposed to
"precise" unification
at $M \approx 10^{13} \text{ TeV}$

an unbearable step backward?!

A non-standard but motivated Supersymmetric Spectrum



⇒ the Higgs boson mass problem
⇒ the flavour problem

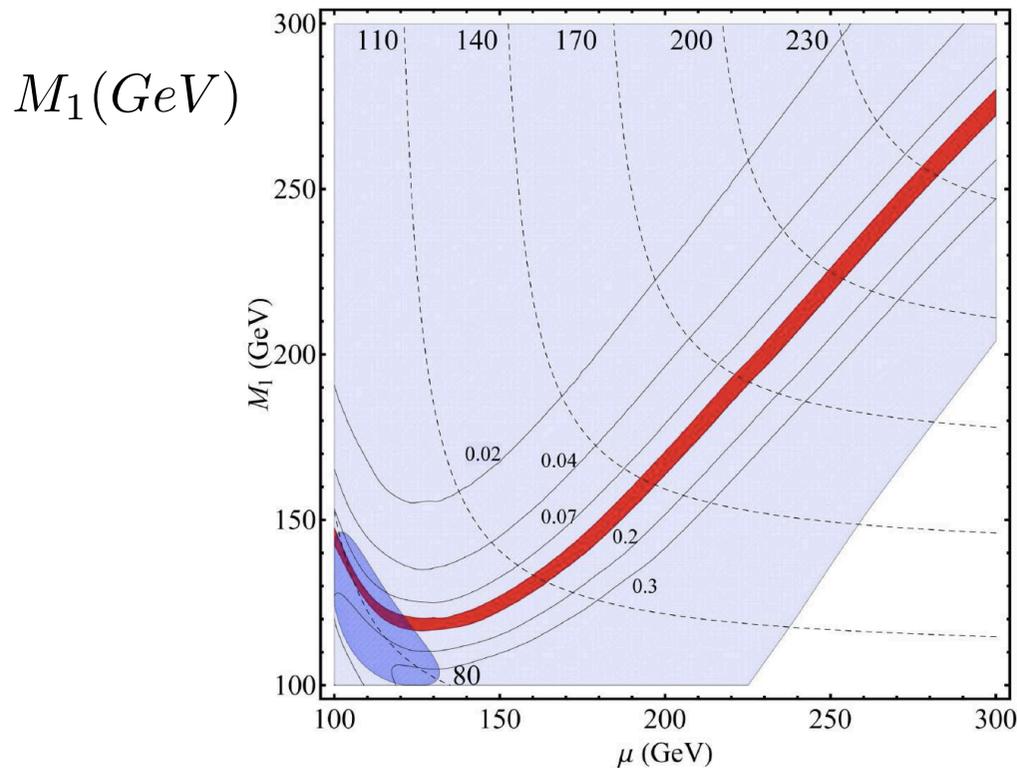
B, Bertuzzo, Farina, Lodone, Pappadopulo

Dark Matter: relic abundance and detection

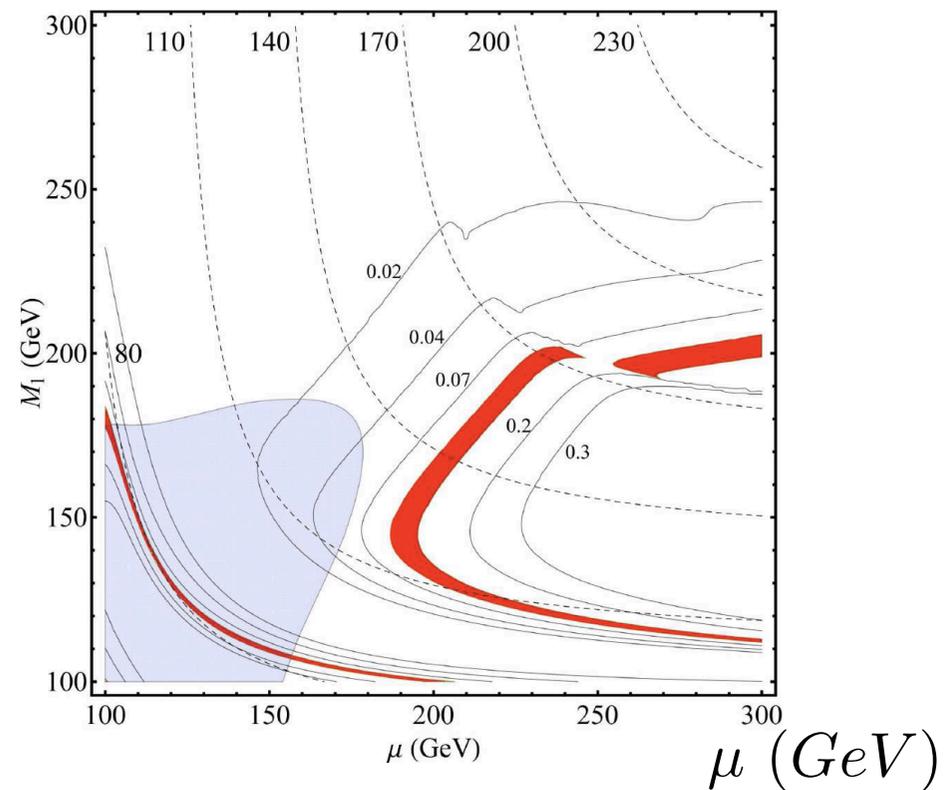
Relic abundance:

A strong effect of the s-channel heavier Higgs exchange
 No "well-temperament"

heavy singlino
 M_2 large



MSSM $m_h = 120$ GeV



λ Susy: $m_h = 200$ GeV

dark blu: CDMS now
 light blu: "XENON100"

Direct detection affected by $\sigma \propto \frac{1}{m_h^4}$ and different mixing

Conclusion

$$\mathcal{L}_{\sim SM} = -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + i\bar{\psi} \not{D}\psi \quad \text{The gauge sector} \quad (3)$$

$$+ |D_\mu h|^2 - V(h) \quad \text{The EWSB sector} \quad (4)$$

$$+ \psi_i \lambda_{ij} \psi_j h + h.c. \quad \text{The flavor sector} \quad (2)$$

$$+ N_i M_{ij} N_j \quad \text{The } \nu\text{-mass sector} \quad (1)$$

(if Majorana)

⇒ Beyond the SM:

Progress in “synthetic” physics requires and justifies a patient as a brave attitude

LHC, although not alone, likely to give a decisive kick

3 ways to be sensitive to the absolute ν -mass scale

1- beta-decay endpoint

$$m_\beta = [c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{\frac{1}{2}}$$

2- neutrino-less $\beta\beta$ -decay

$$m_{\beta\beta} = |c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

3 - cosmology (large scale structure)

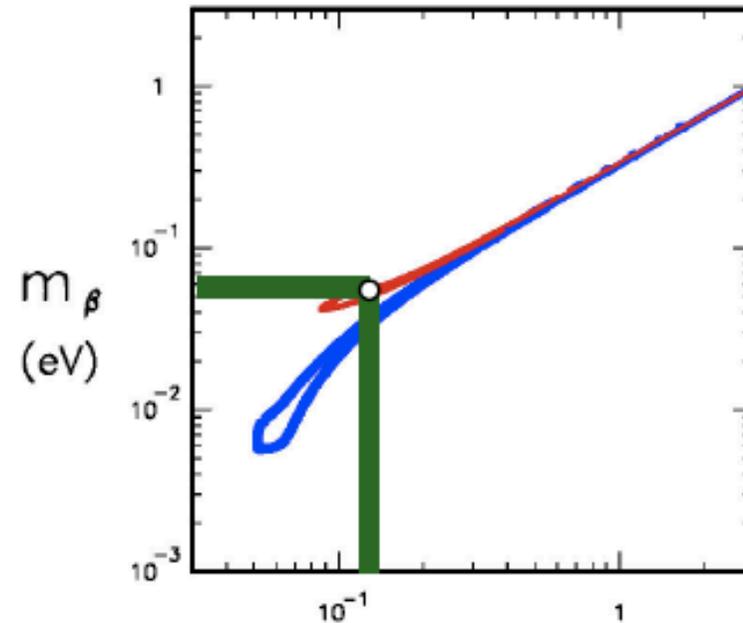
$$\Sigma = m_1 + m_2 + m_3$$

The "3 neutrino concordance" (Lisi)

Suppose that
at some point:

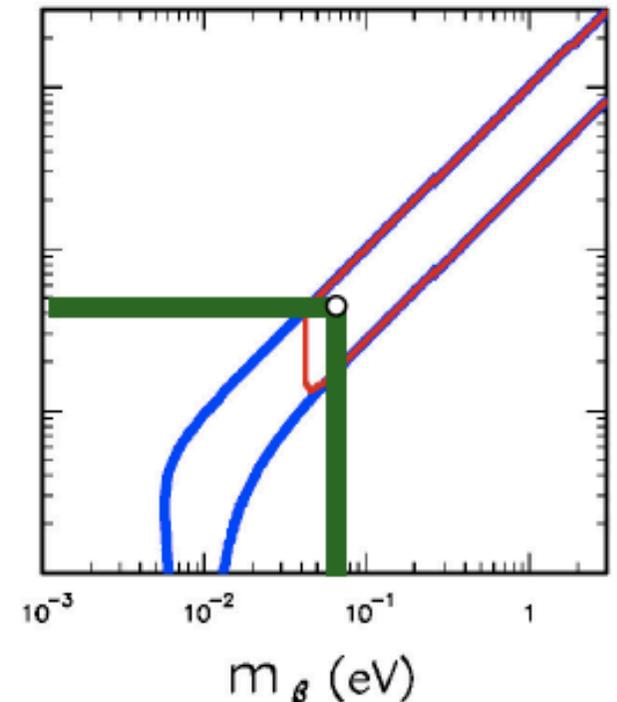
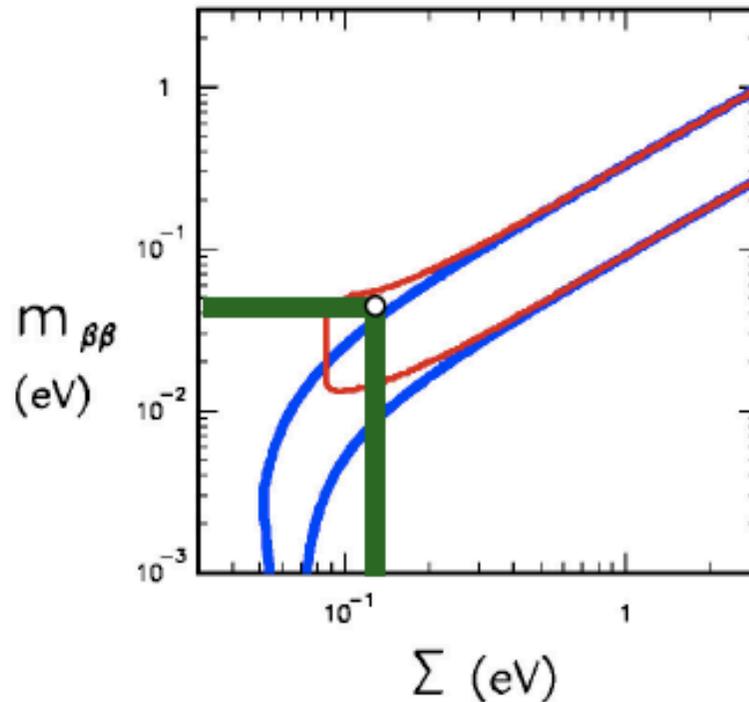
⇒ most (all)
questions
answered

or, maybe,
a clash!



2σ bounds
from current knowledge
of oscillations only

— normal hierarchy
— inverted hierarchy



The impact of the newest data (in part)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{c_{ij}}{\Lambda^2} O_{ij}^{(6)}$$

Isidori, Nir, Perez

Operator	Bounds on Λ in TeV ($c_{ij} = 1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K; \epsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K; \epsilon_K$
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D; q/p , \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D; q/p , \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

New O(1)-sources of flavour breaking
in the multi-TeV range definitely excluded

“Minimal Flavour Violation”

However, in the quark sector: $SU(3)_Q \times SU(3)_U \times SU(3)_D$
 in the SM only broken by Y_U, Y_D

If extended beyond the SM: $Y_D \sim 3_Q \times \bar{3}_D$ $Y_U \sim 3_Q \times \bar{3}_U$

Operator	Bound on Λ	Observables
$H^\dagger (\bar{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L) (e F_{\mu\nu})$	6.1 TeV	$B \rightarrow X_s \gamma, B \rightarrow X_s \ell^+ \ell^-$
$\frac{1}{2} (\bar{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$	5.9 TeV	$\epsilon_K, \Delta m_{B_d}, \Delta m_{B_s}$
$H_D^\dagger (\bar{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L) (g_s G_{\mu\nu}^a)$	3.4 TeV	$B \rightarrow X_s \gamma, B \rightarrow X_s \ell^+ \ell^-$
$(\bar{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L) (\bar{E}_R \gamma_\mu E_R)$	2.7 TeV	$B \rightarrow X_s \ell^+ \ell^-, B_s \rightarrow \mu^+ \mu^-$
$i (\bar{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L) H_U^\dagger D_\mu H_U$	2.3 TeV	$B \rightarrow X_s \ell^+ \ell^-, B_s \rightarrow \mu^+ \mu^-$
$(\bar{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L) (\bar{L}_L \gamma_\mu L_L)$	1.7 TeV	$B \rightarrow X_s \ell^+ \ell^-, B_s \rightarrow \mu^+ \mu^-$
$(\bar{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L) (e D_\mu F_{\mu\nu})$	1.5 TeV	$B \rightarrow X_s \ell^+ \ell^-$

⇒ If some suitable “MFV” operative,
 the scale of flavour can still be nearby

ElectroWeak Precision Tests in λ SUSY

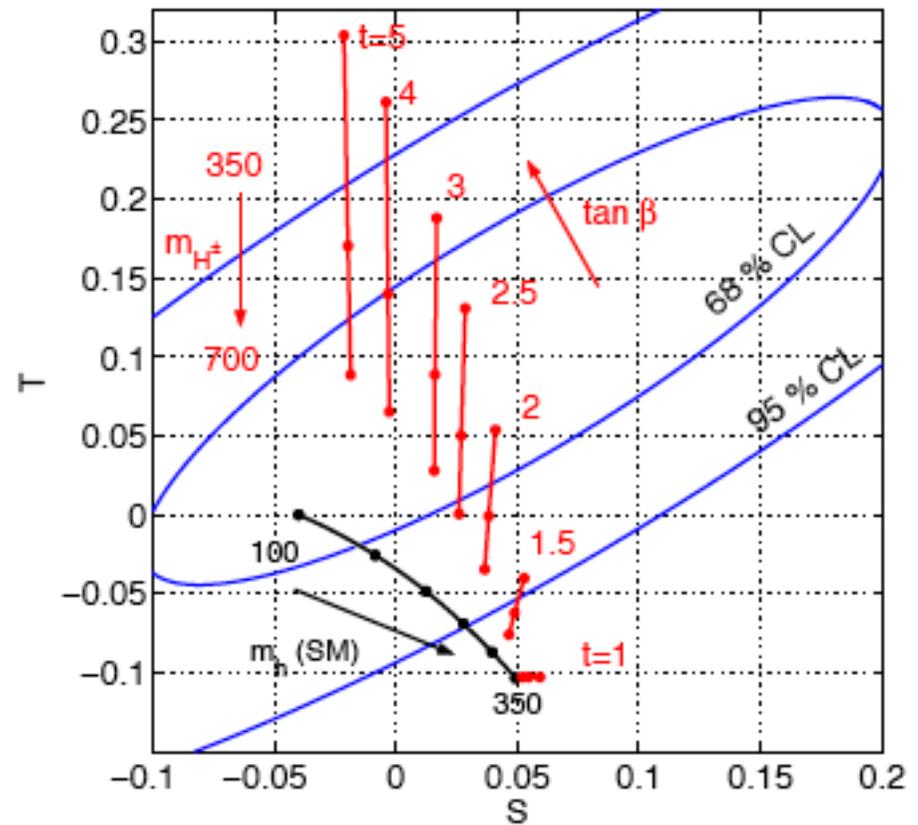
$$\lambda(G_F^{-1/2}) \approx 2$$

one loop effects but

$$\Delta T \propto \lambda^4$$

$\lambda \uparrow \Rightarrow m_h \uparrow$
compensated by $\Delta T \uparrow$

S and T from Higgs's



B, Hall, Nomura, Rychkov

A simple concrete possibility

(others have been considered)

NMSSM

$$f = \mu H_1 H_2 \Rightarrow f = \lambda S H_1 H_2$$

$$\Delta V = |f_S|^2 = \lambda^2 |H_1 H_2|^2$$

$$(2 \times 4 + 2) - (2 + 1) = 7 = 2 + 3 + 2$$

$$H^\pm \quad h_i^{CP+} \quad A_k^{CP-}$$

Out of the 3 CP even states,

take the only one coupled to ZZ, WW

$$m_h^2 = M_Z^2 \cos^2 2\beta - \lambda^2 v^2 \sin^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

before mixing with the other 2 states

1. What about λ ?
2. What about mixing effects?

$$\min[m(h_i^{CP+})] < m_h$$

What about λ ?

Two interesting alternatives:

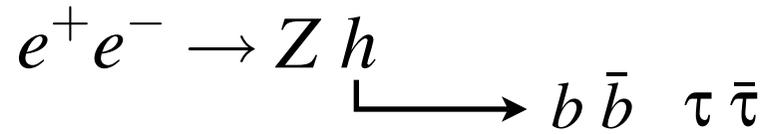
1.
$$\left(\frac{\lambda}{4\pi}\right)^2(10\text{TeV}) \leq 0.1 \quad \Rightarrow \quad \lambda(G_F^{-1/2}) \leq 2$$

To respect the EWPT (unification?)

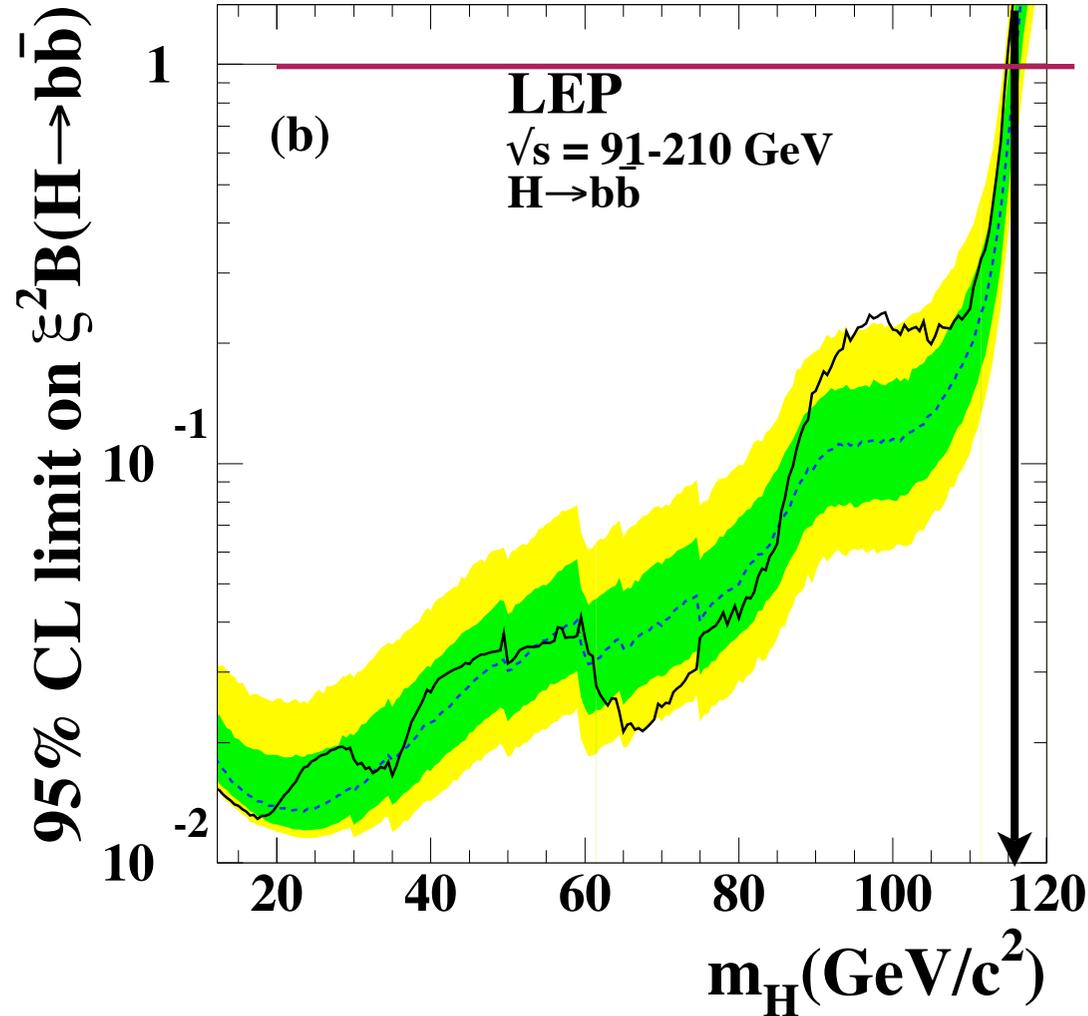
2.
$$\left(\frac{\lambda}{4\pi}\right)^2(M_{GUT}) \leq 0.1 \quad \Rightarrow \quad \text{See below}$$

To maintain manifest perturbative unification

The current direct limit



$$\xi_{h_1ZZ} = \left(\frac{g_{h_1ZZ}}{g_{hZZ}} \right)^2$$



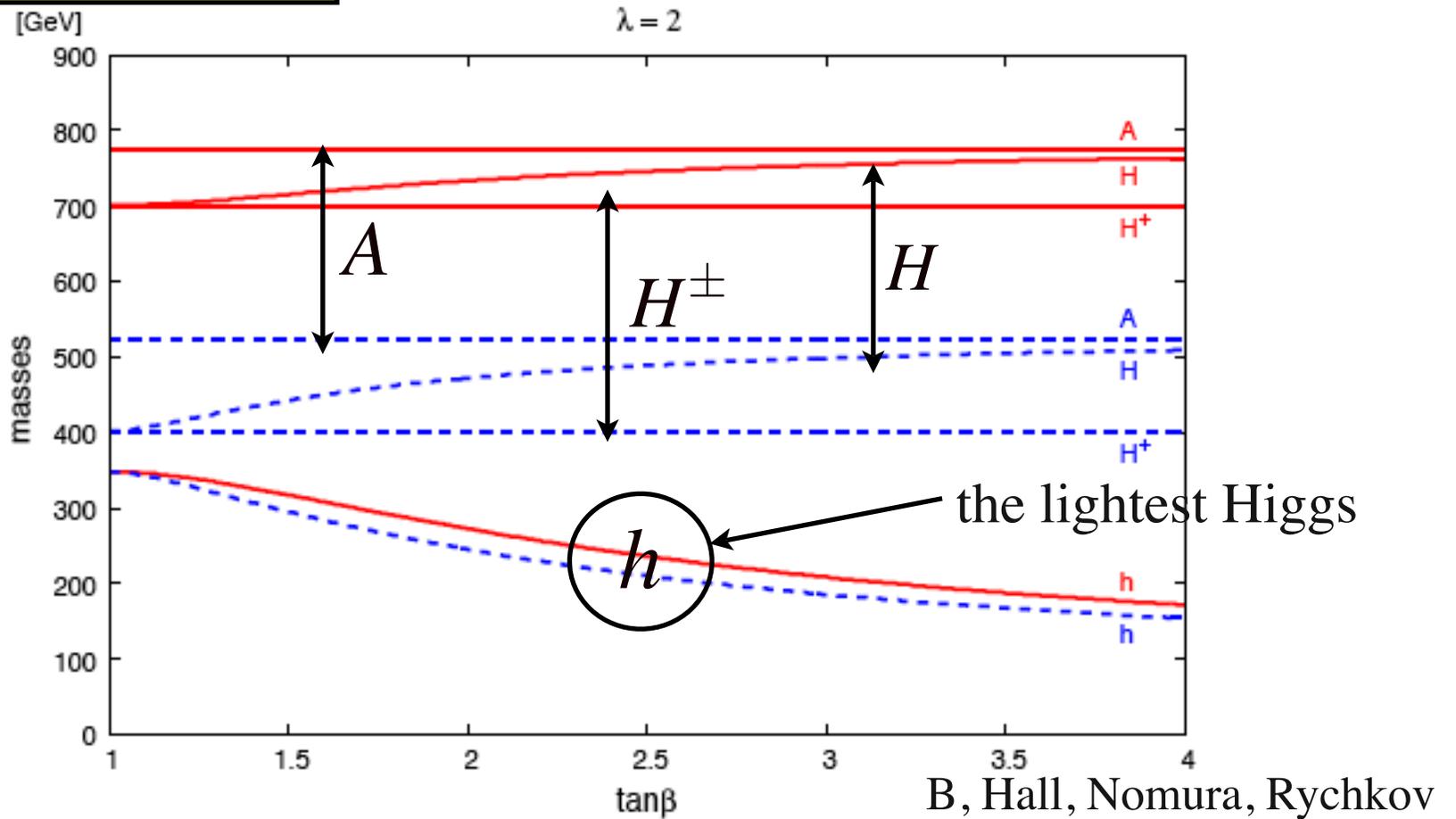
If standard,
 $m_h \geq 115 \text{ GeV}$

LEPHWG

(but more later)

$$\lambda(G_F^{-1/2}) \approx 2$$

The Higgs boson spectrum



$$h \rightarrow ZZ \rightarrow l^+l^- l^+l^-$$

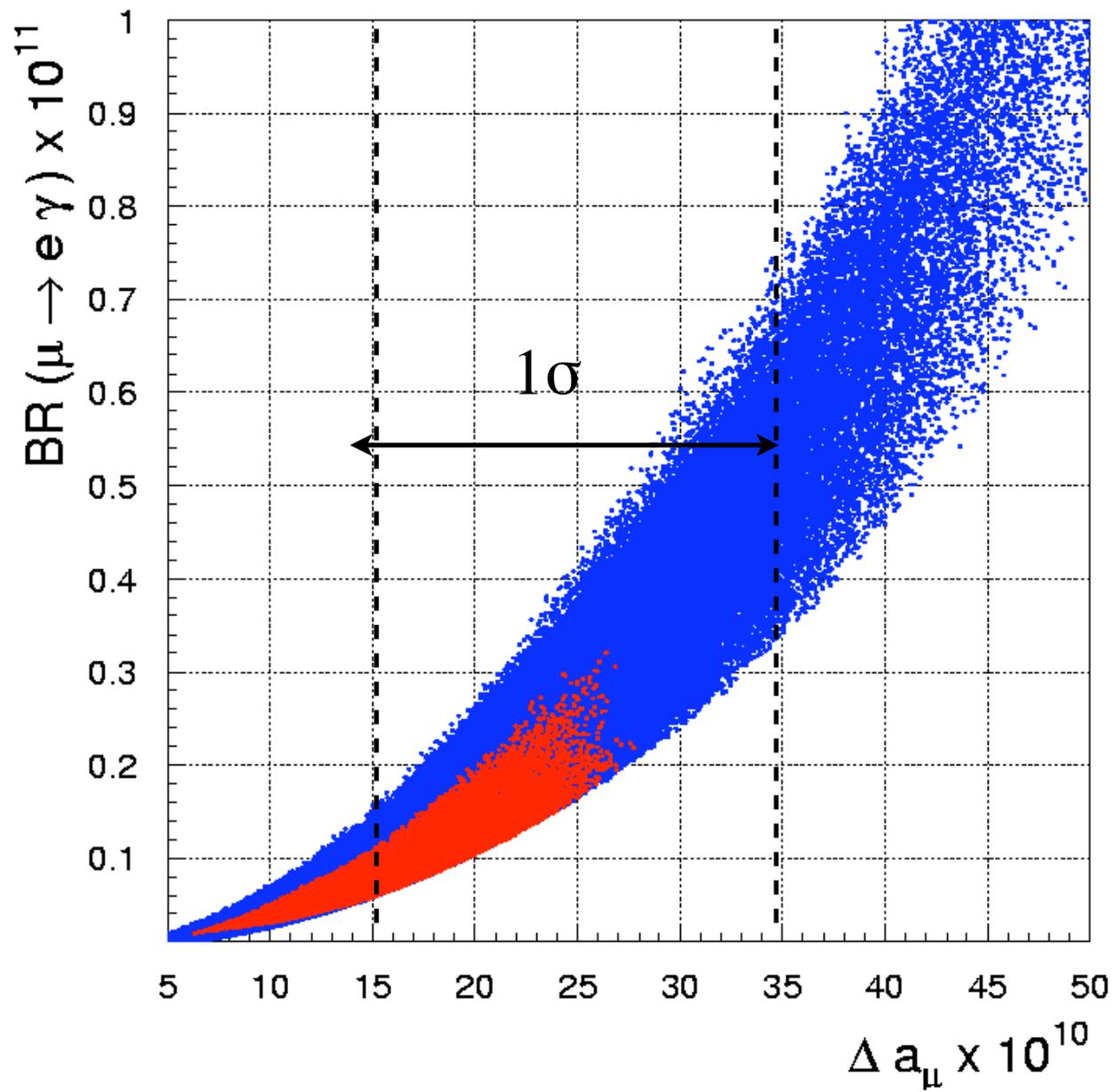
easy, but very much NON-susy

$$H \rightarrow hh \rightarrow 4V \rightarrow l^+l^- 6j$$

possible with 100 fb^{-1}

$$A \rightarrow hZ \rightarrow VV Z \rightarrow l^+l^- 4j$$

Cavicchia, Franceschini, Rychkov



Gino Isidori