Standard Model and Beyond in the LHC Era

Riccardo Barbieri

The 4th UniverseNet School
Lecce, Sept 13-18, 2010

Particle Physics in one page

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

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

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

$$+N_i M_{ij} N_j$$ The ν-mass sector (if Majorana) (1)

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 $\Leftarrow$ "direct" $\Leftarrow$ LHC $\Leftarrow$ "indirect"

Origin of Matter (B-asymmetry)

Dark Energy

quite a number of 2÷3 sigma anomalies

. . . . .

(not touched in this talk)

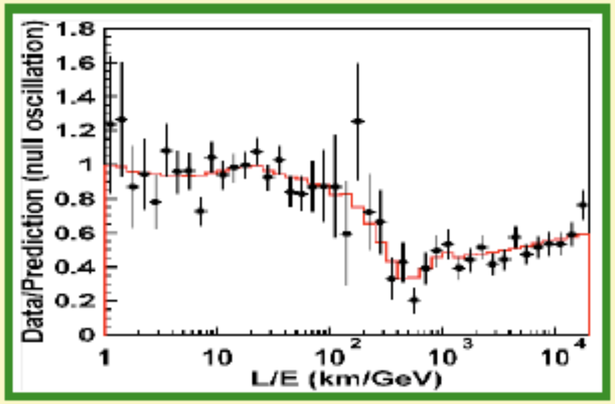
Neutrinos

$\sigma(\delta m^2)$ ~ 2.5%
$\sigma(\Delta m^2)$ ~ 5%
but sign(Δm^2) unknown

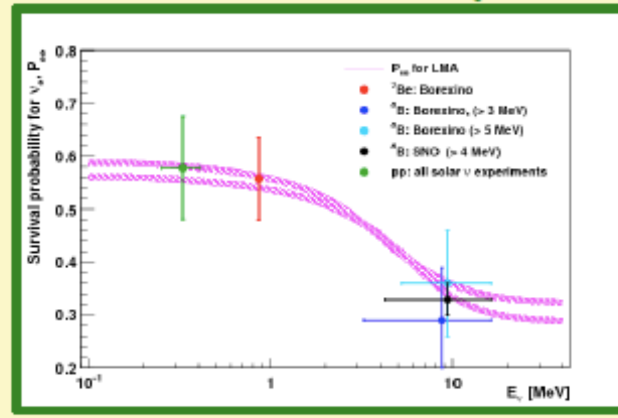
$\sigma(\sin^2\theta_{12})$ ~ 6%
$\sigma(\sin^2\theta_{23})$ ~ 11%

$\sigma(\sin^2\theta_{13})$ ~0.01
focus of attention!

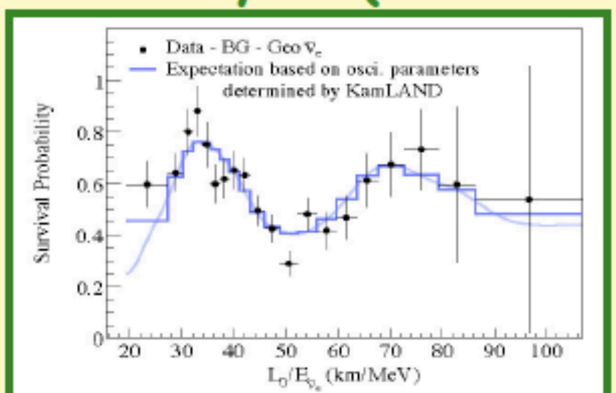
½ oscillation cycle (SK)



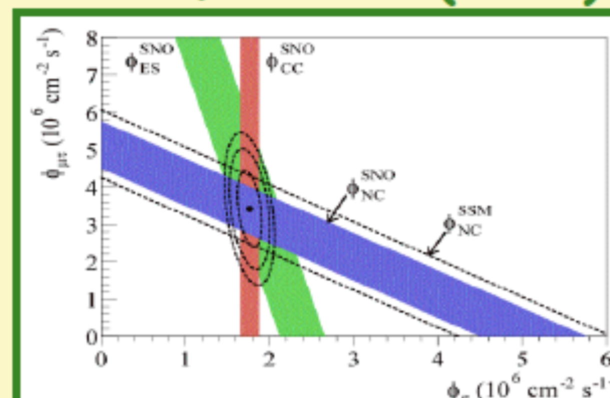
MSW in the Sun (Borex.)



1 oscill.cycle (KamLAND)

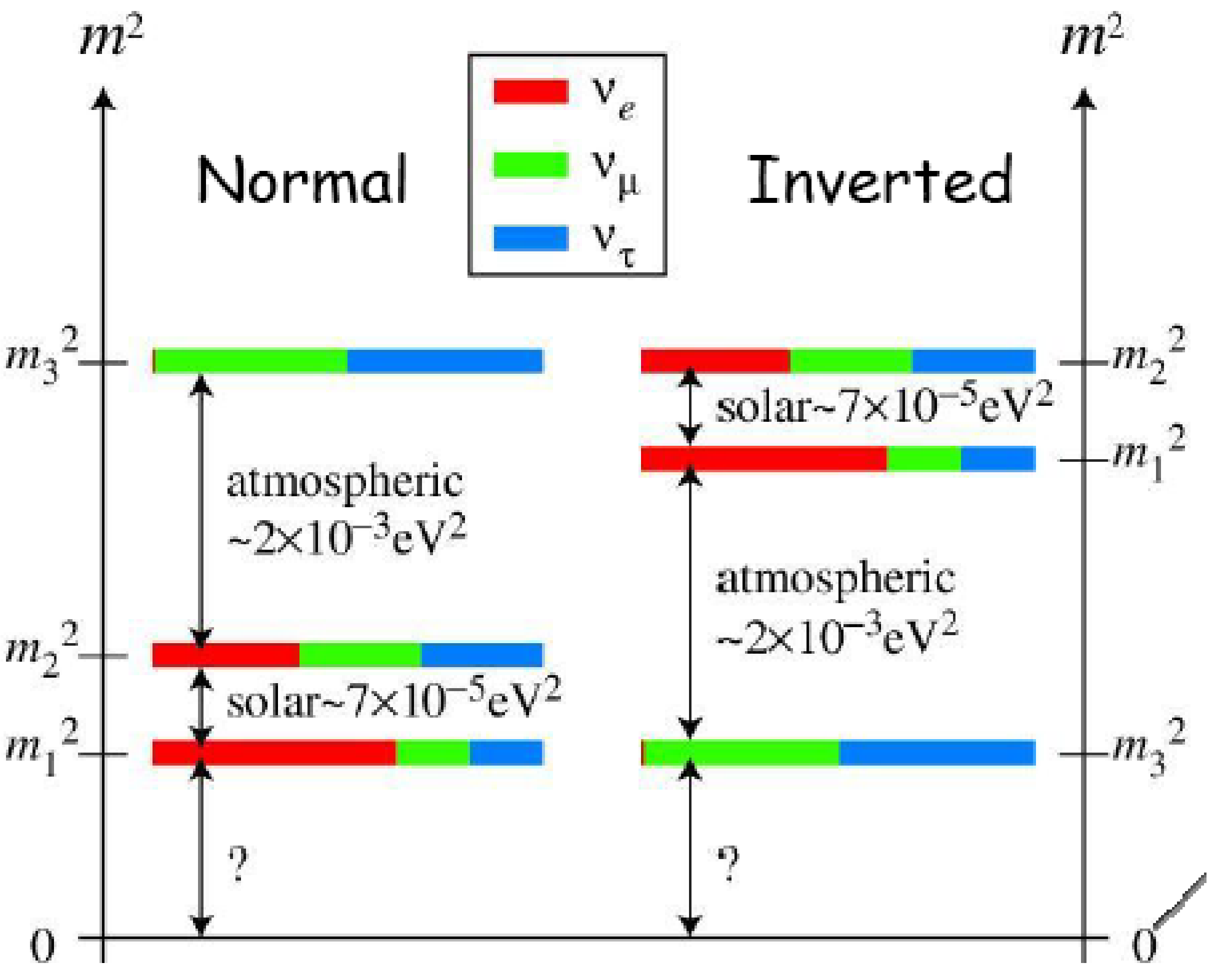


^{8}B flux, CC/NC (SNO)



A beautiful example of "empirical adequacy"

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



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

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

$$<m^2> = ?$$

$$V_{3e} = ?$$

Normal or Inverted?

CP violated ?

3 neutrinos only ?

Majorana or Dirac?

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

1- beta-decay endpoint

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

2- neutrino-less ββ-decay

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

3 - cosmology (large scale structure)

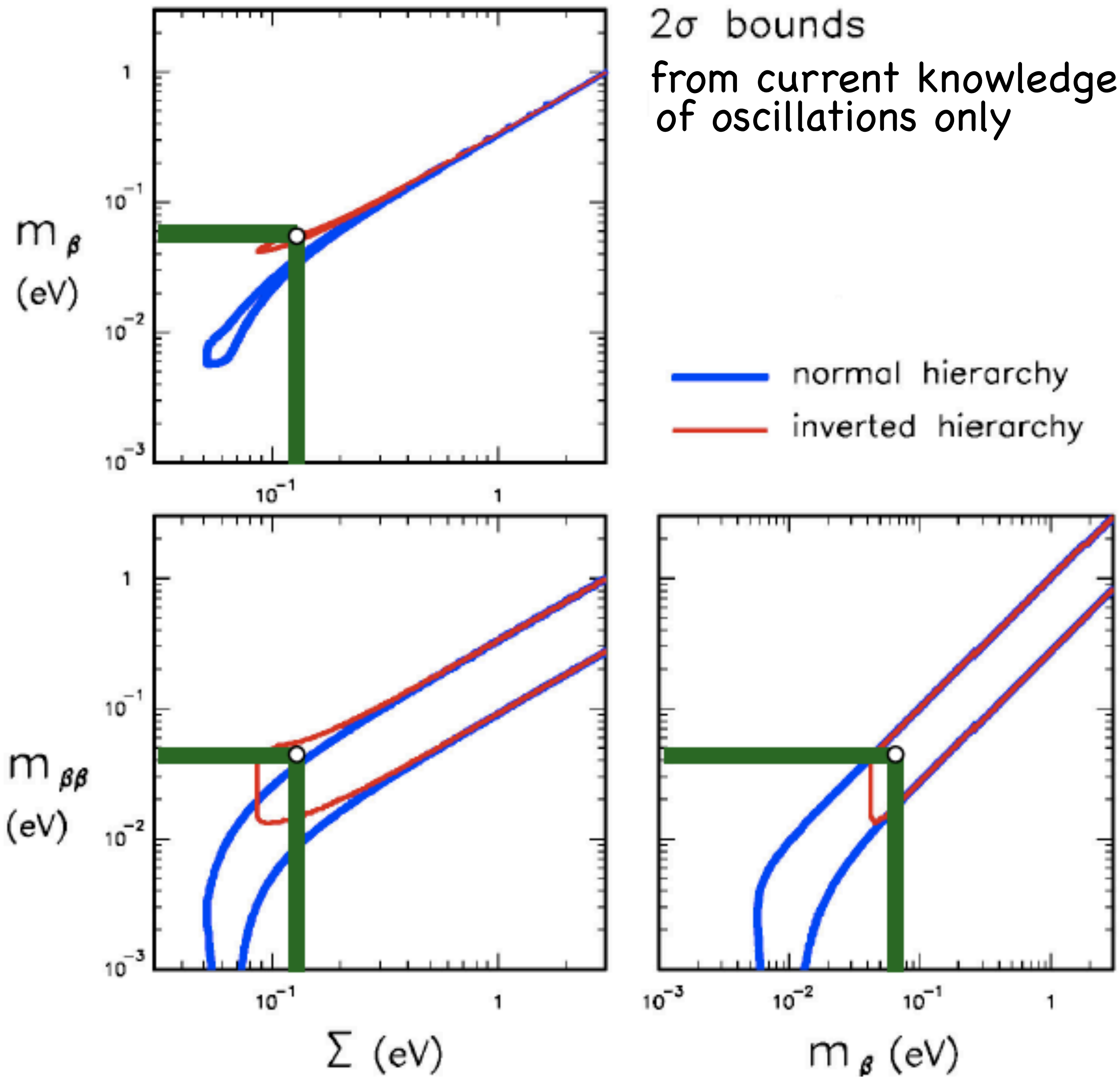
$$\Sigma = m_1 + m_2 + m_3$$

The "3 neutrino concordance" (Lisi)

Suppose that at some point:

⇒ most (all) questions answered

or, maybe, a clash!



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)

The impact of the newest data (in part)

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

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}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	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: $\mathrm{SU}(3)_Q \times \mathrm{SU}(3)_U \times \mathrm{SU}(3)_D$
in the SM only broken by $Y_U,\ Y_D$

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

Operator	Bound on Λ	Observables
$H^\dagger \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right) (eF_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}
$H_D^\dagger \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right) (g_s G^a_{\mu\nu})$	3.4 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) \left(\overline{E}_R \gamma_\mu E_R\right)$	2.7 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$i\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) H_U^\dagger D_\mu H_U$	2.3 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) \left(\overline{L}_L \gamma_\mu L_L\right)$	1.7 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) (eD_\mu F_{\mu\nu})$	1.5 TeV	$B \to X_s\ell^+\ell^-$

$\Rightarrow$ If some suitable "MFV" operative,
the scale of flavour can still be nearby

If strictly MFV

$$\mathcal{A}(d^i \to d^j)_{\rm MFV} = (V_{ti}^* V_{tj}) \; \mathcal{A}_{\rm SM}^{(\Delta F=1)} \left[1 + a_1 \frac{16\pi^2 M_W^2}{\Lambda^2}\right]$$

$$\mathcal{A}(M_{ij} - \overline{M}_{ij})_{\rm MFV} = (V_{ti}^* V_{tj})^2 \mathcal{A}_{\rm SM}^{(\Delta F=2)} \left[1 + a_2 \frac{16\pi^2 M_W^2}{\Lambda^2}\right]$$

still room for surprises. E.g.:

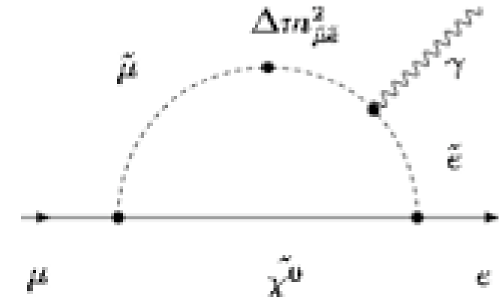
Observable	Experiment	MFV prediction	SM prediction
β_s from $\mathcal{A}_{\rm CP}(B_s \to \psi\phi)$	[0.10, 1.44] @ 95% CL	$0.04(5)^*$	0.04(2)
$\mathcal{A}_{\rm CP}(B \to X_s\gamma)$	$< 6\%$ @ 95% CL	$< 0.02^*$	< 0.01
$\mathcal{B}(B_d \to \mu^+\mu^-)$	$< 1.8 \times 10^{-8}$	$< 1.2 \times 10^{-9}$	$1.3(3) \times 10^{-10}$
$\mathcal{B}(B \to X_s\tau^+\tau^-)$	–	$< 5 \times 10^{-7}$	$1.6(5) \times 10^{-7}$
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	$< 2.6 \times 10^{-8}$ @ 90% CL	$< 2.9 \times 10^{-10}$	$2.9(5) \times 10^{-11}$

Isidori, Nir, Perez

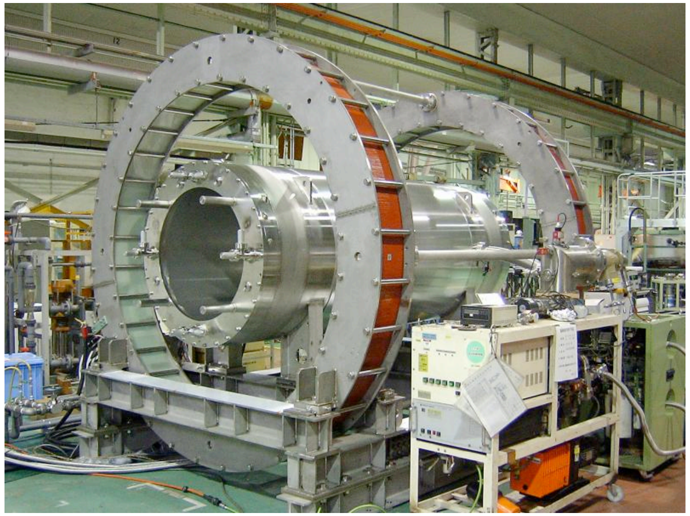
and MFV itself unlikely to be exact

My own favorite test of Flavour Physics

$$\mu \to e + \gamma$$



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



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

(not only the LHC)

In suitable minimal unification

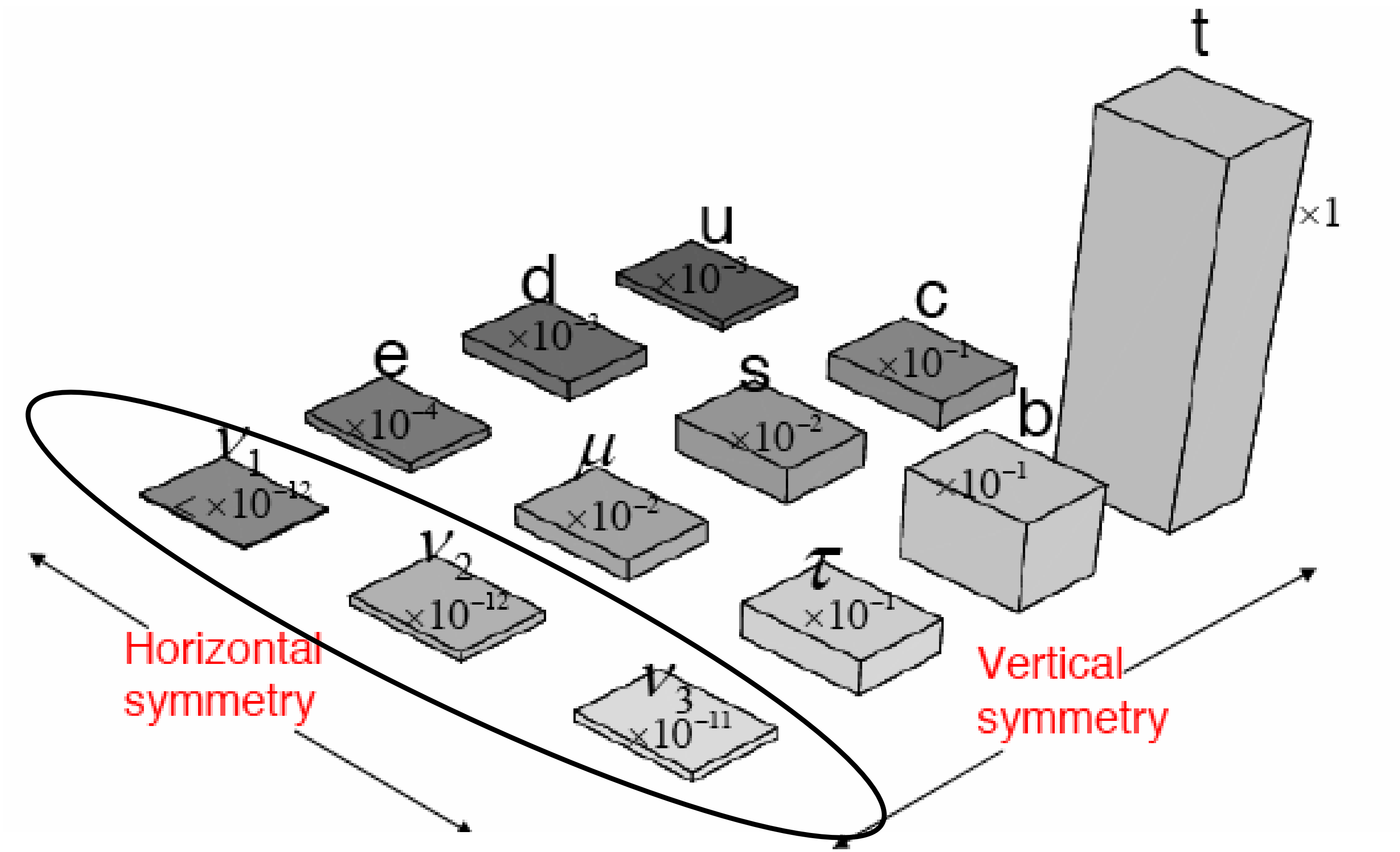
$$BR(\mu \to e + \gamma) \approx \delta \cdot 10^{-13}$$

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

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

B, Hall, Strumia
Strumia, Romanino

The persistent flavour puzzle



Unlikely to be solved without

"beyond the SM" flavour signals

The gauge sector

Getting closer to specific LHC issues

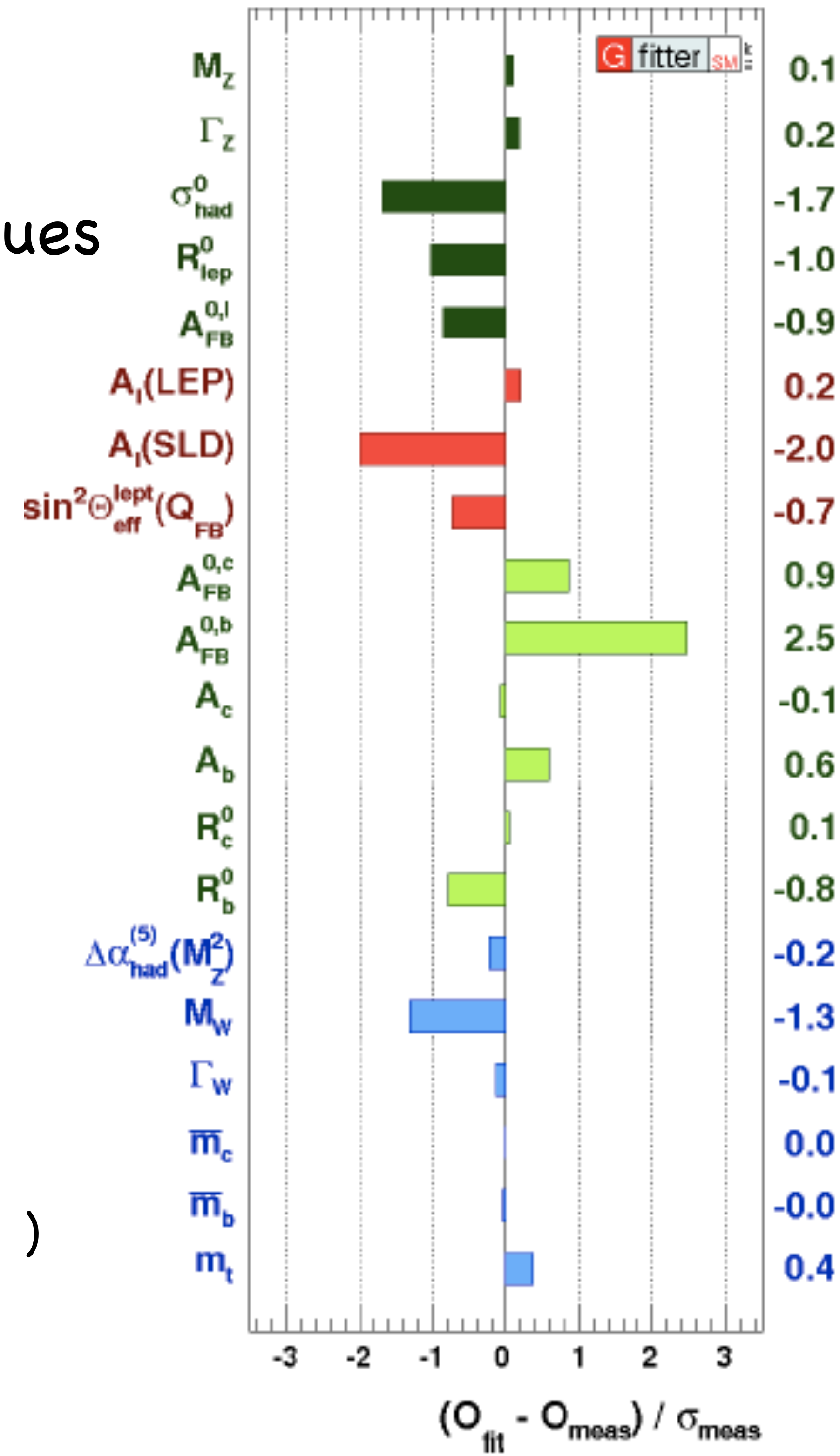
CERN-Fermilab-Stanford mostly

precision often better than 10^{-3}

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

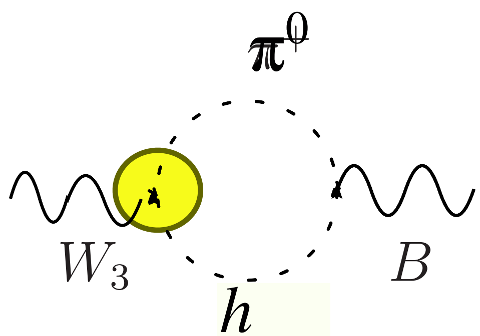
≈ 20% χ^2 probability

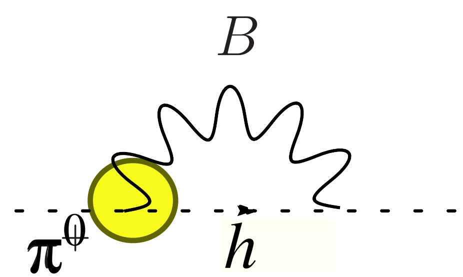
(latest top mass: m_t =173.3±1.1 GeV)



The main Standard Model effects

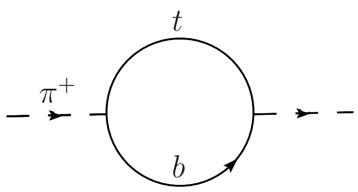
$$\hat{S} = \frac{g}{g'}\Pi'_{30}(0) \qquad \hat{T} = \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{m_W^2}$$

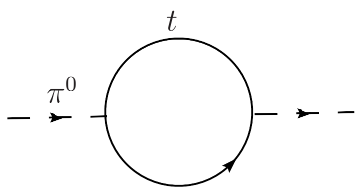




$$\hat{S} \approx \frac{G_F m_W^2}{12\sqrt{2}\pi^2}\log m_h \qquad \hat{T} \approx -\frac{3G_F m_W^2}{4\sqrt{2}\pi^2}\tan^2\theta \log m_h$$

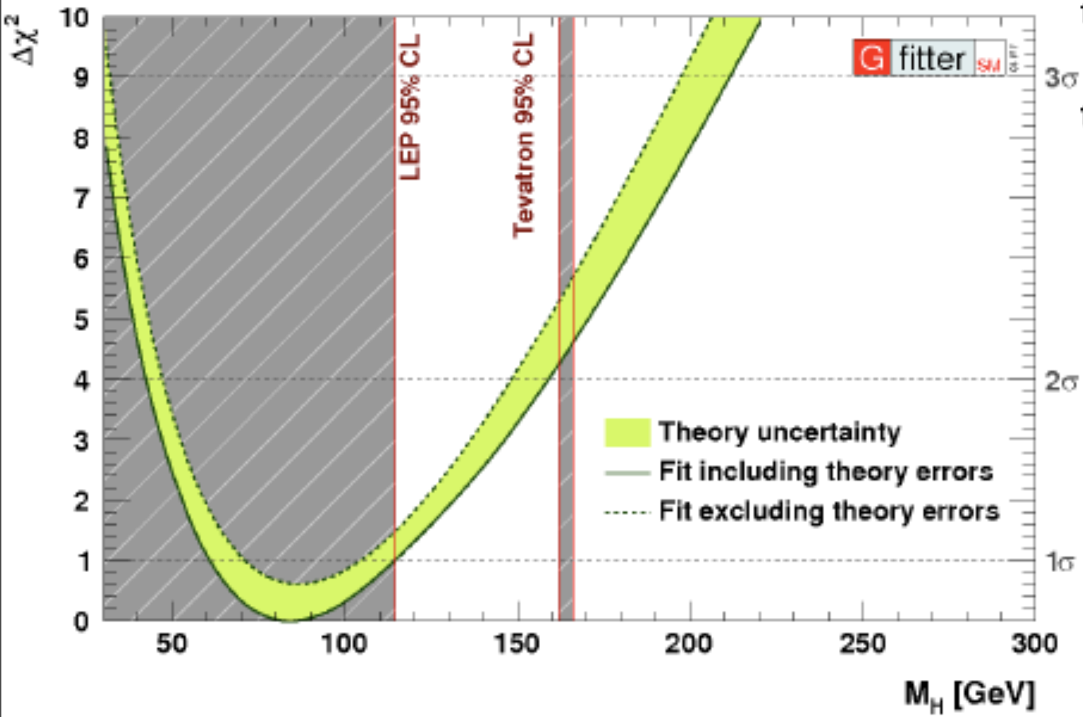
$$\rho - 1 = \hat{T} = 1 + \frac{3G_F m_t^2}{8\sqrt{2}\pi^2}$$



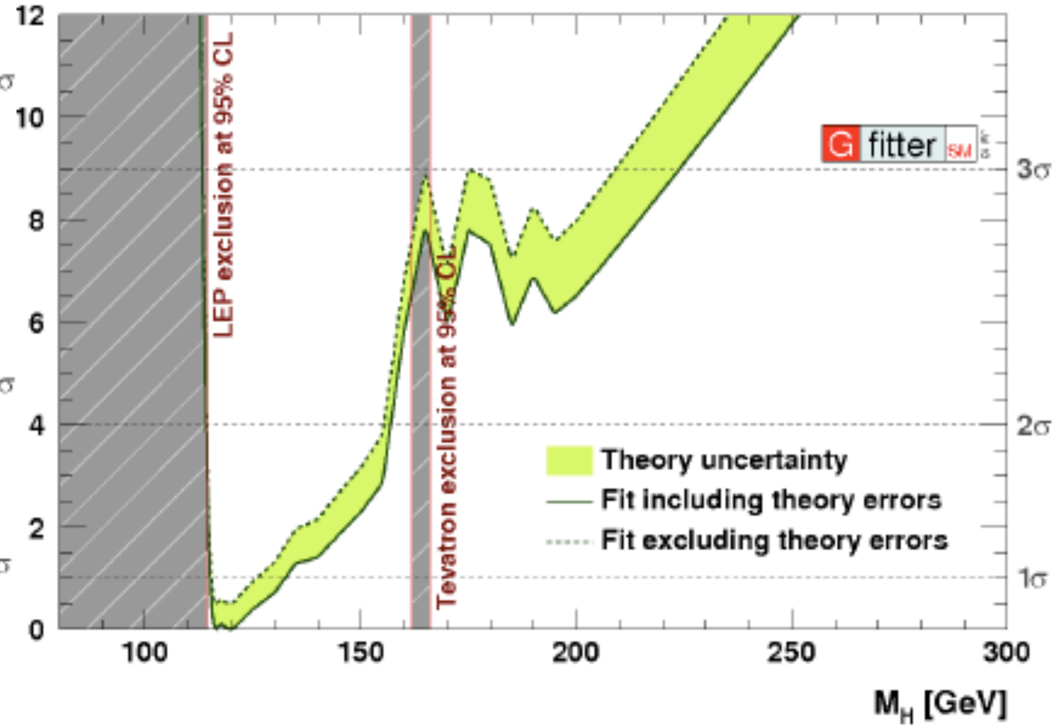


The Higgs boson mass in the SM

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



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

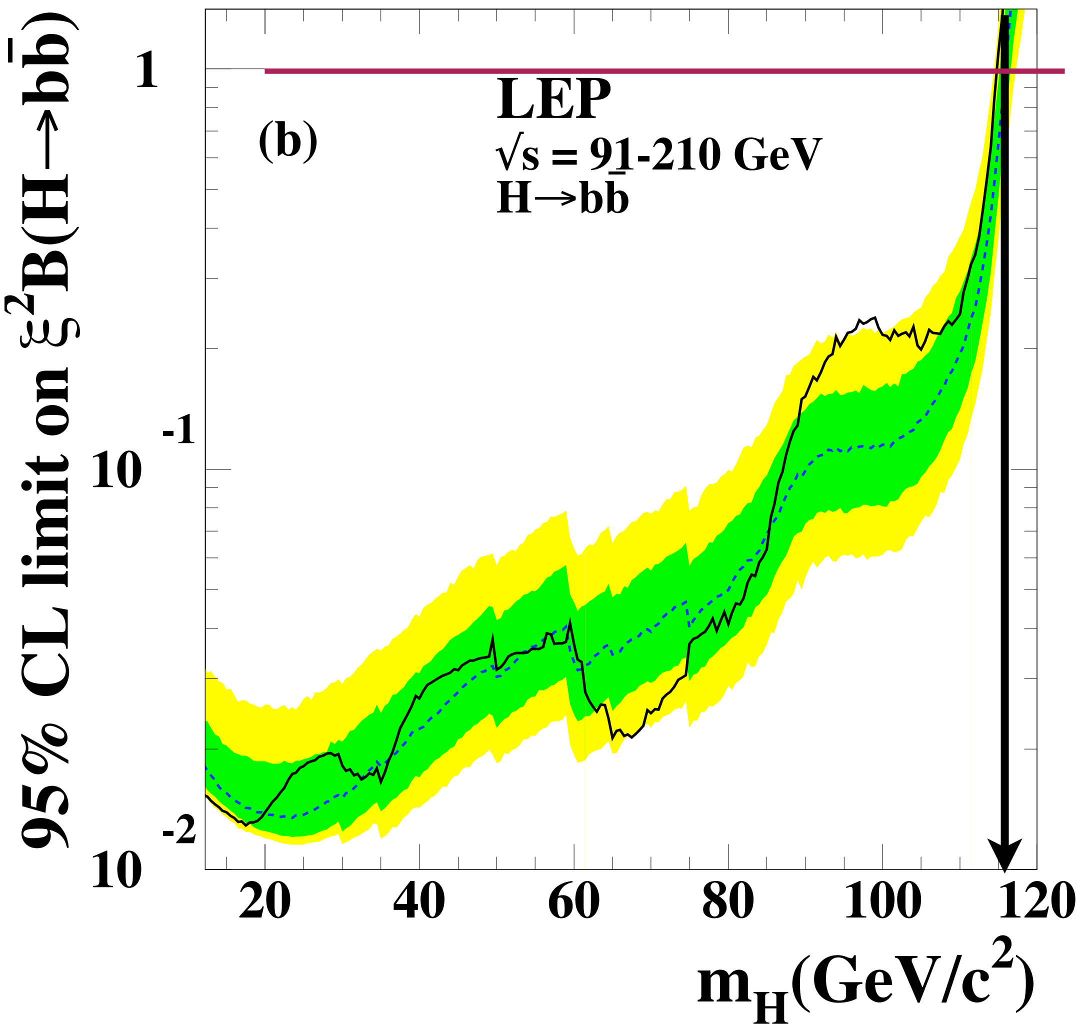


Dörthe Ludwig

The current direct limit

$$e^+e^- \to Z\,h$$
$$\hookrightarrow b\,\bar{b} \quad \tau\,\bar{\tau}$$

$$\xi_{h_1 ZZ} = \left(\frac{g_{h_1 ZZ}}{g_{hZZ}}\right)^2$$



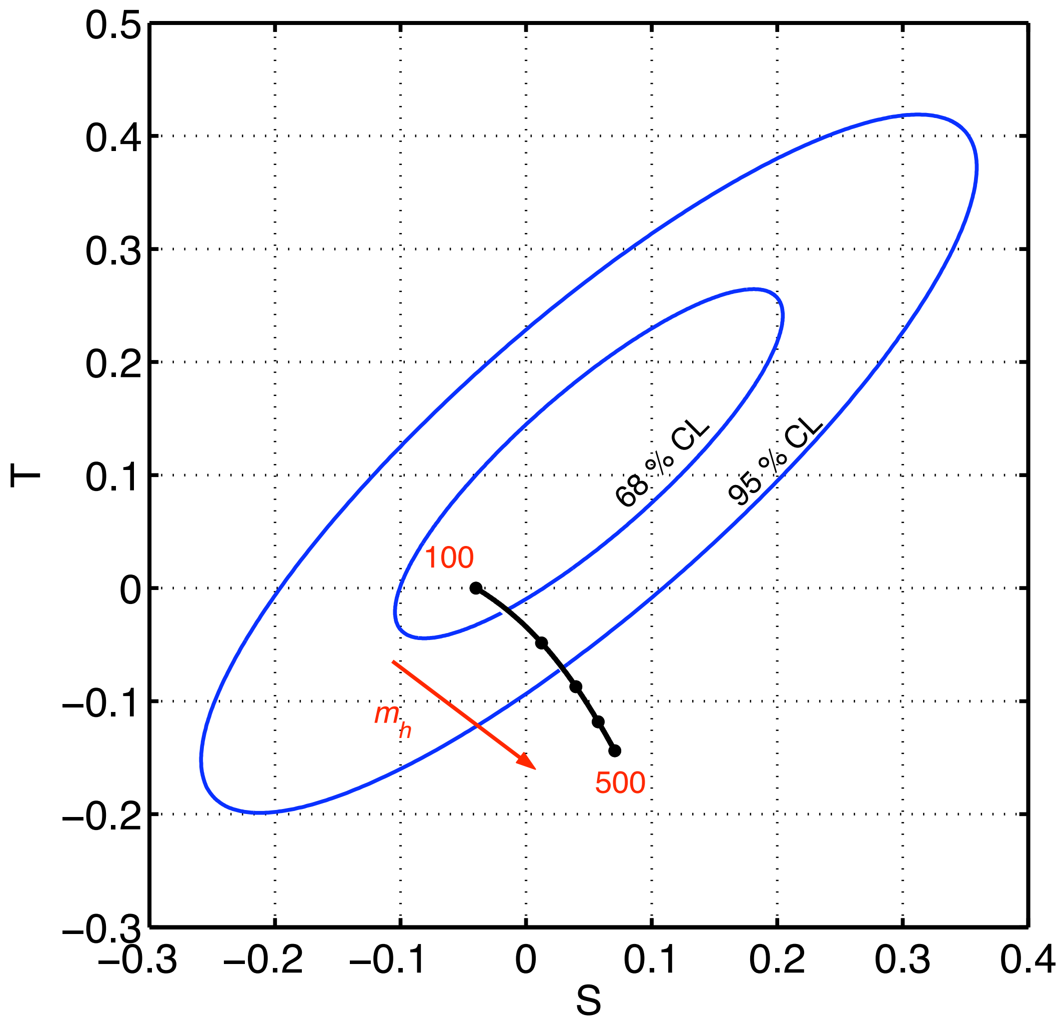
If standard,

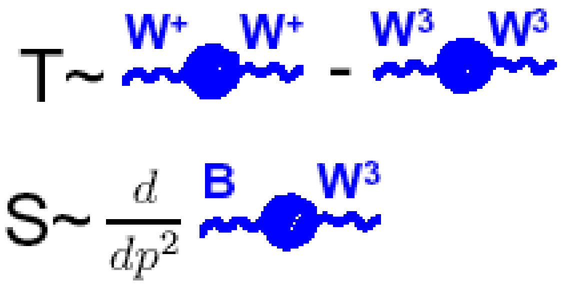
$m_h \geq 115\ GeV$

LEPHWG

(but more later)

The guidance of the EWPT
(in principle also beyond the SM)





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

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

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

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

$$\Lambda_{NP} \overset{?}{\approx} \Lambda_{cutoff}$$

2010: the problem still there, more than ever

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

$$\mathcal{L}_{eff}^{NP} = \Sigma_i \frac{c_i}{\Lambda_{NP}^2} O_i$$

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

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

	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→	$\lvert H^\dagger D_\mu H\rvert^2$	θ_W in M_W/M_Z	5 TeV
S→	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	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
⇒	$H^\dagger(\bar{D}\lambda_D \lambda_U \lambda_U^\dagger \gamma_{\mu\nu} Q) F^{\mu\nu}$	$b \to s\gamma$	10 TeV
⇒	$\frac{1}{2}(\bar{Q}\lambda_U \lambda_U^\dagger \gamma_\mu Q)^2$	B mixing	10 TeV

1σ-bounds ⊕ a light Higgs

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

EWSB: "weak" or "strong"?

"weak"

a relatively light Higgs boson exists

perturbativity extended → 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

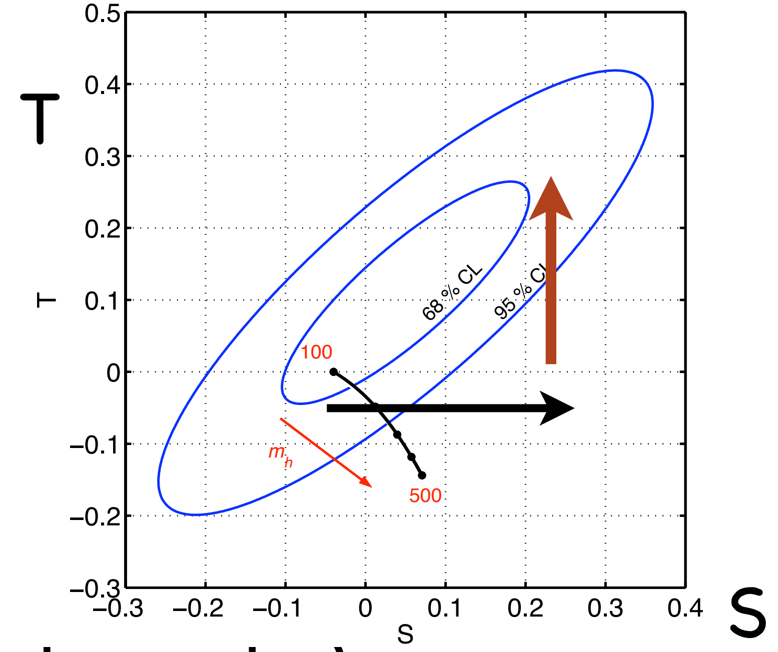
Flavour? (follow $\mu \to e\gamma$ at PSI)

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 ΔS>0, but don't forget the S↔T correlation

Models not fully convincing

(although enlarged by 5D↔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?

} heretic, yet meaningful

⇒ Can it have escaped detection?

⇒ Can it be significantly heavier than expected?

⇒ Where is the supersymmetric Higgs boson?

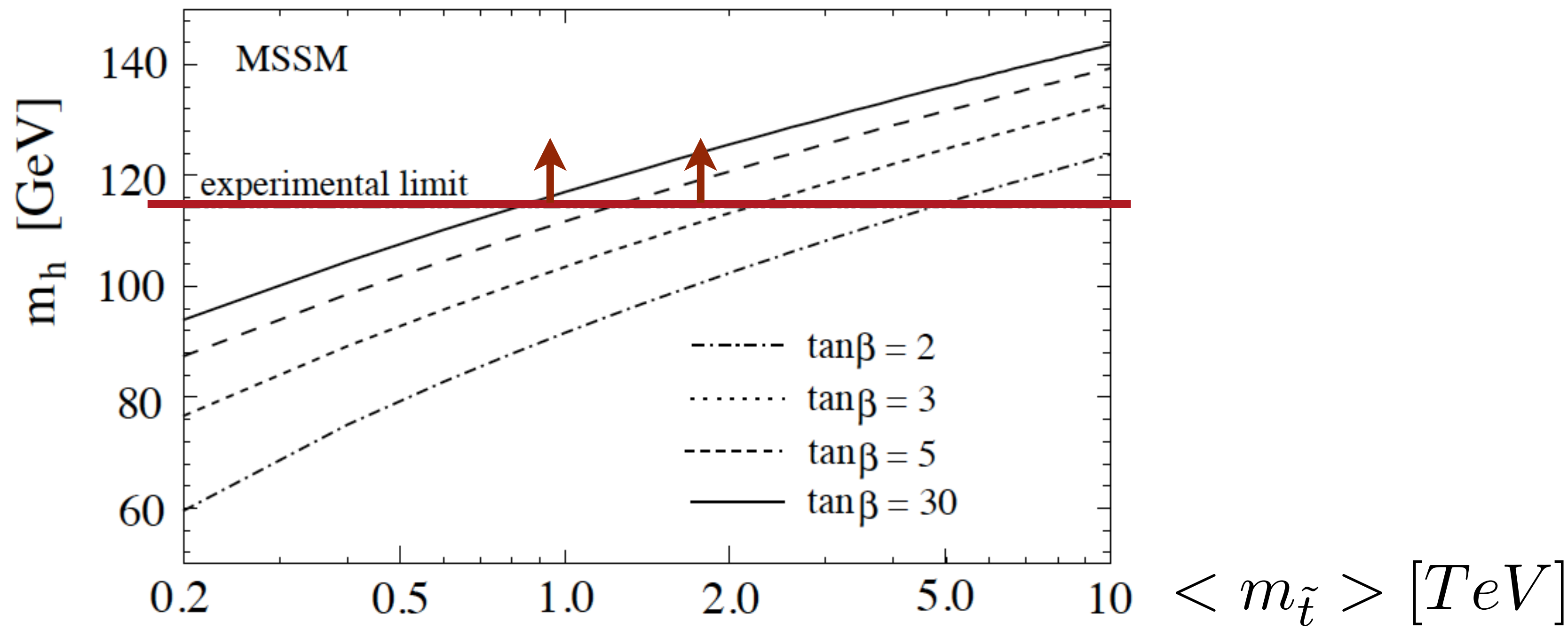
True Higgs bounds (channel-dependent)

Decay channel	Limit (GeV)
$h \to b\bar{b}, \tau\bar{\tau}$	115
$h \to jj$	113
$h \to \gamma\gamma$	117
$h \to WW^*, ZZ^*$	110
$h \to$ invisible	115
$h \to \eta\eta \to 4b$	110
$h \to \eta\eta \to 4\tau, 4c, 4g$	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 tanβ (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 $$m_h^2 \le m_Z^2 \cos^2 2\beta$$

- ⋆ Extra U(1) $$m_h^2 \le (m_Z^2 + \frac{g_x^2 v^2}{2(1+\frac{M_X^2}{2M_\phi^2})}) \cos^2 2\beta$$

  Batra, Delgado, Kaplan, Tait

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

- ⋆ $\Delta f = \lambda S H_1 H_2$ (NMSSM ⇒ λsusy) $$m_h^2 \le m_Z^2 (\cos^2 2\beta + \frac{2\lambda^2}{g^2 + g'^2} \sin^2 2\beta)$$

  Harnik, Kribs, Larson, Murayama

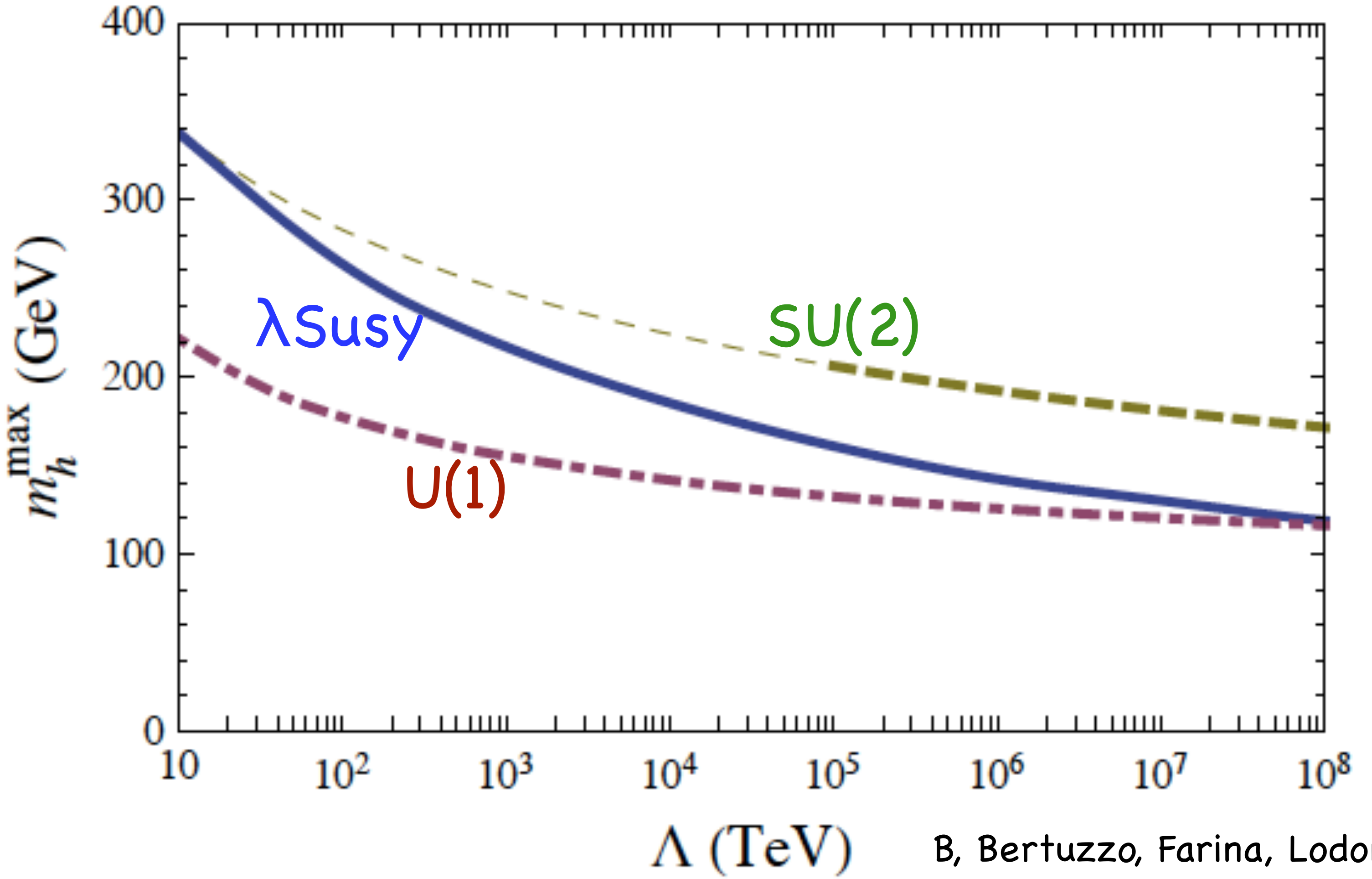
  B, Hall, Nomura, Rychkov

⇒ h not standard and not even light

The price to pay

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

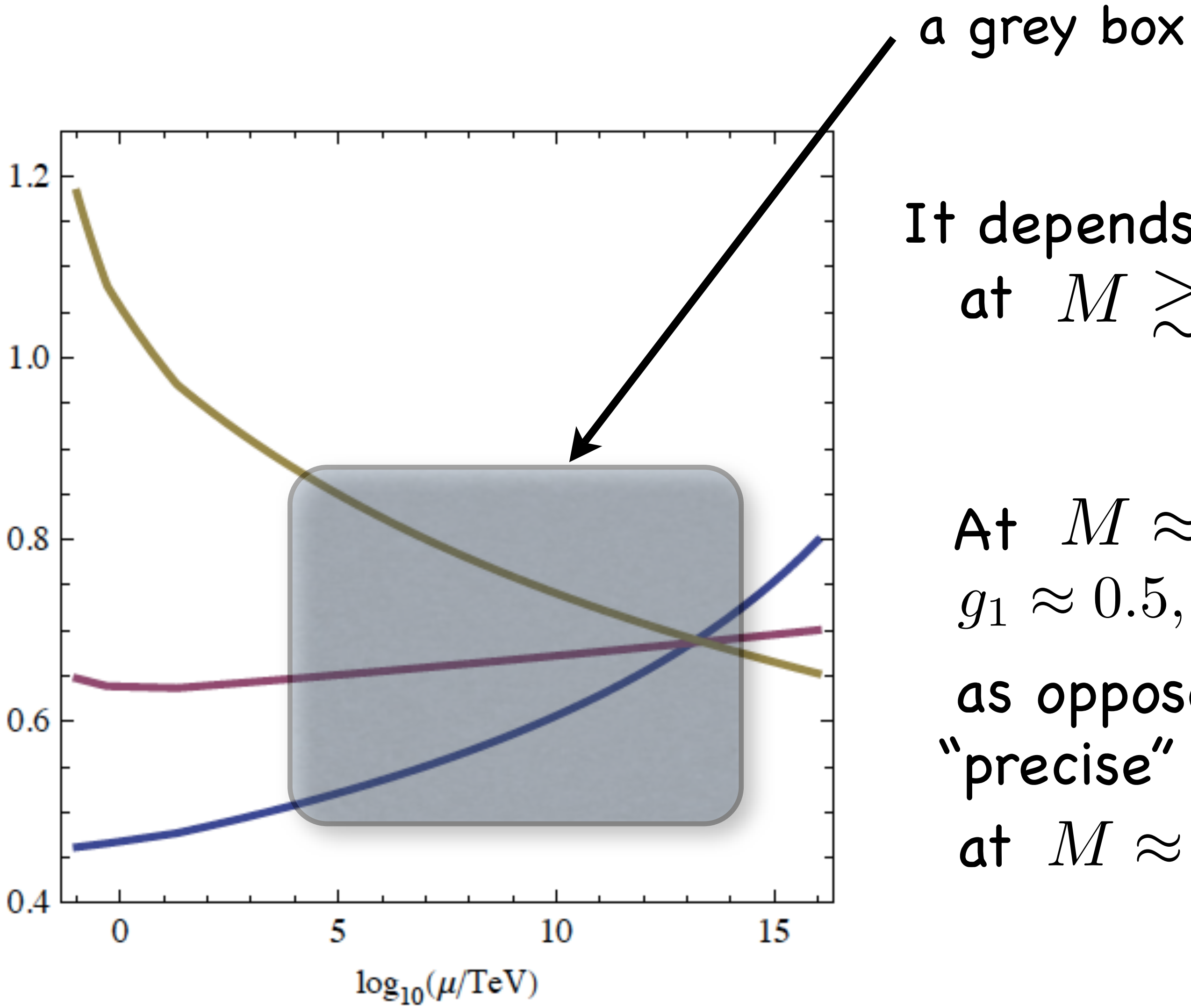
At a scale Λ some coupling starts blowing



B, Bertuzzo, Farina, Lodone, Pappadopulo

unless some change of regime occurs there

What about gauge-coupling unification, then?



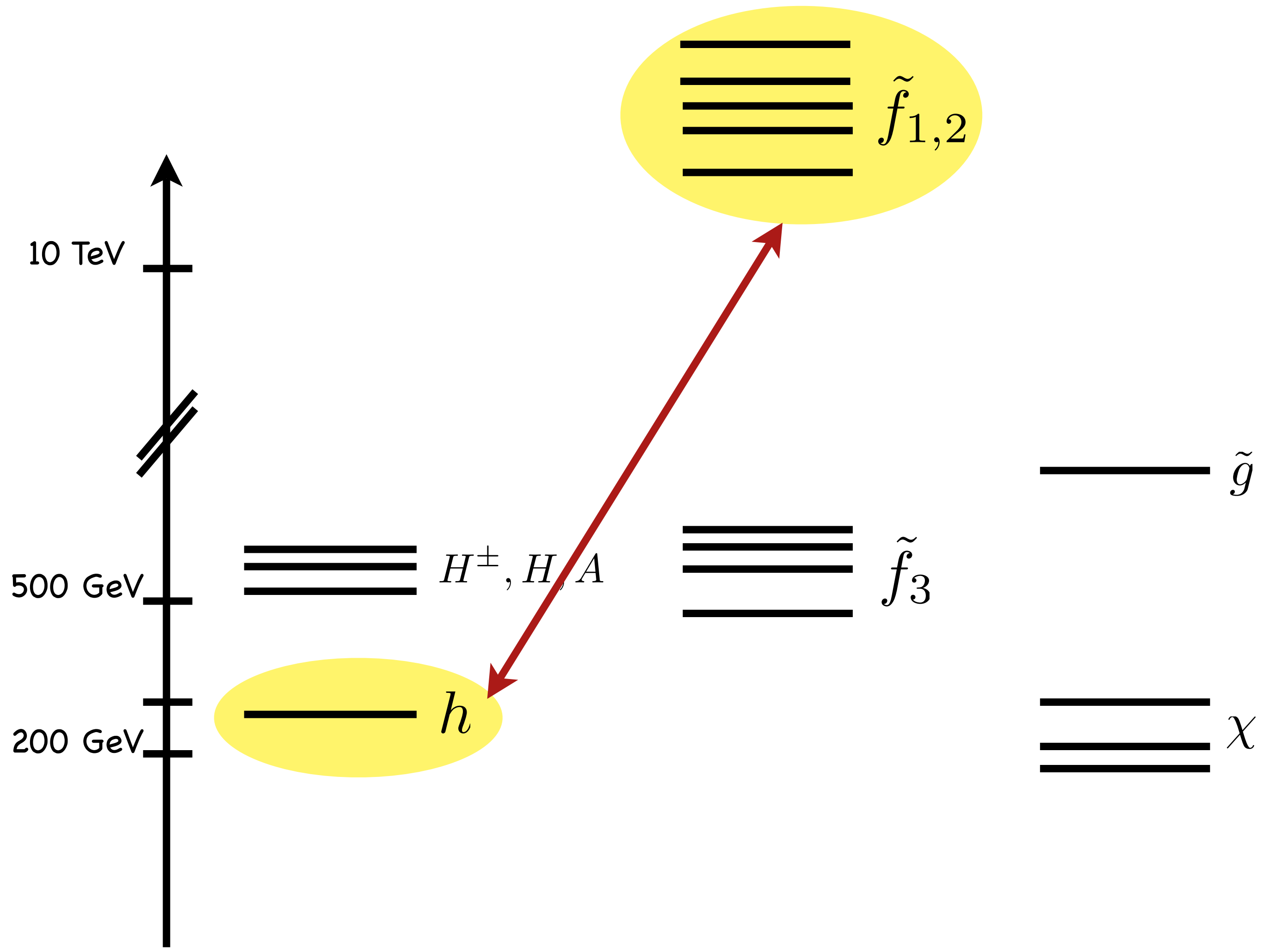
It depends on what happens at $M \gtrsim 10^4 TeV$

At $M \approx 10^4\ TeV$:

$g_1 \approx 0.5,\ g_2 \approx 0.7,\ g_3 \approx 0.85$

as opposed to "precise" unification at $M \approx 10^{13}\ TeV$

A non-standard but motivated Supersymmetric Spectrum



B, Bertuzzo, Farina, Lodone, Pappadopulo

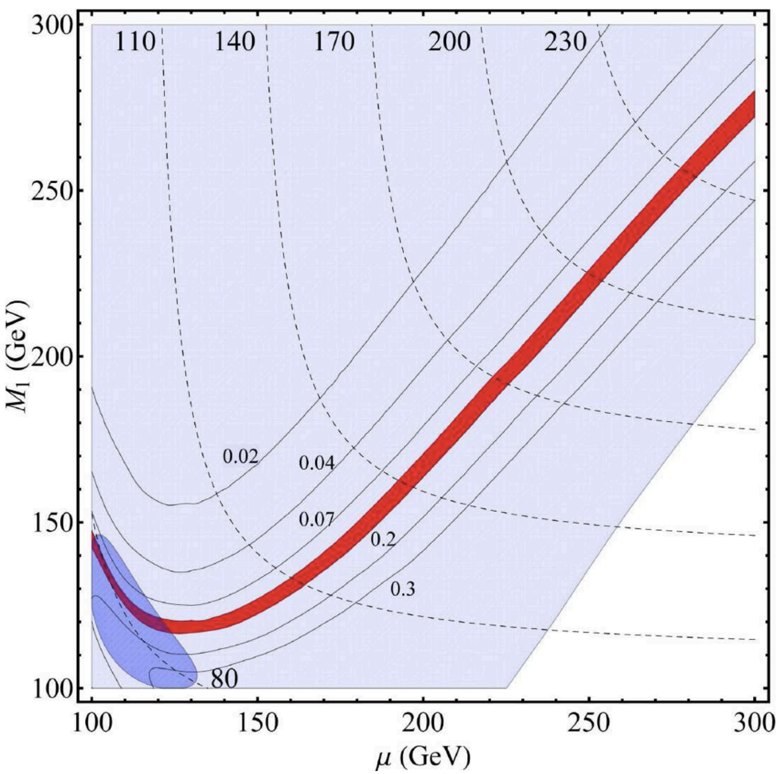
Dark Matter: relic abundance and detection

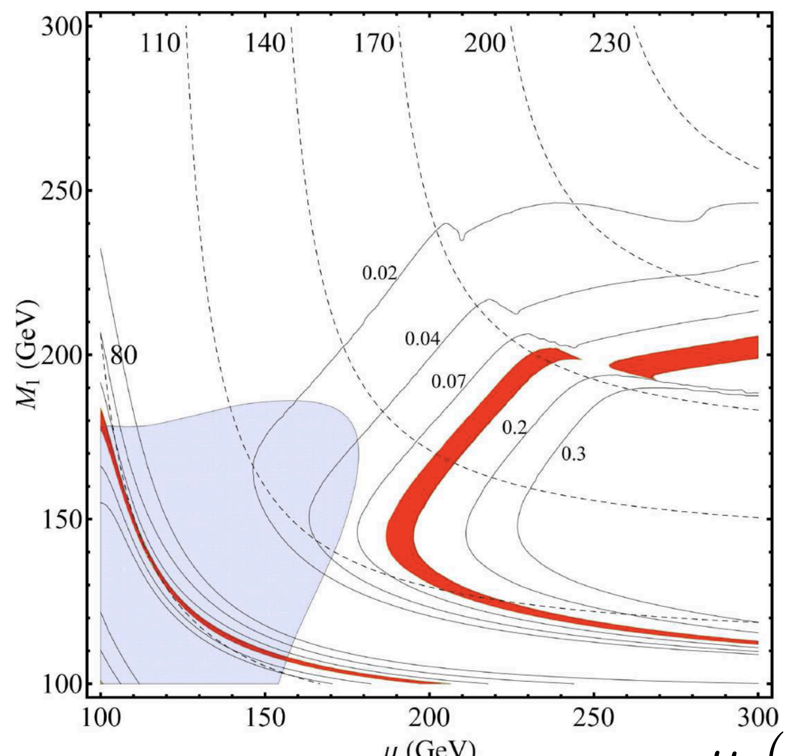
Relic abundance:

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

M_2 large

$M_1 (GeV)$





$\mu \ (GeV)$

MSSM $m_h = 120 \ GeV$

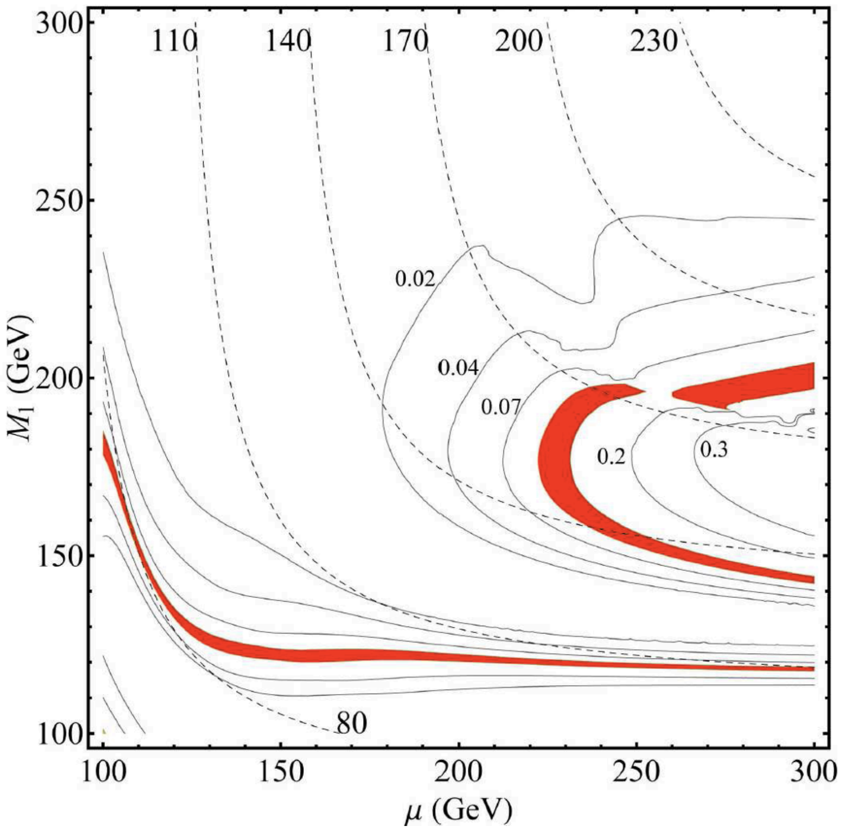
λSusy: $m_h = 200 \ GeV$

dark blu: CDMS now
light blu: "XENON100"

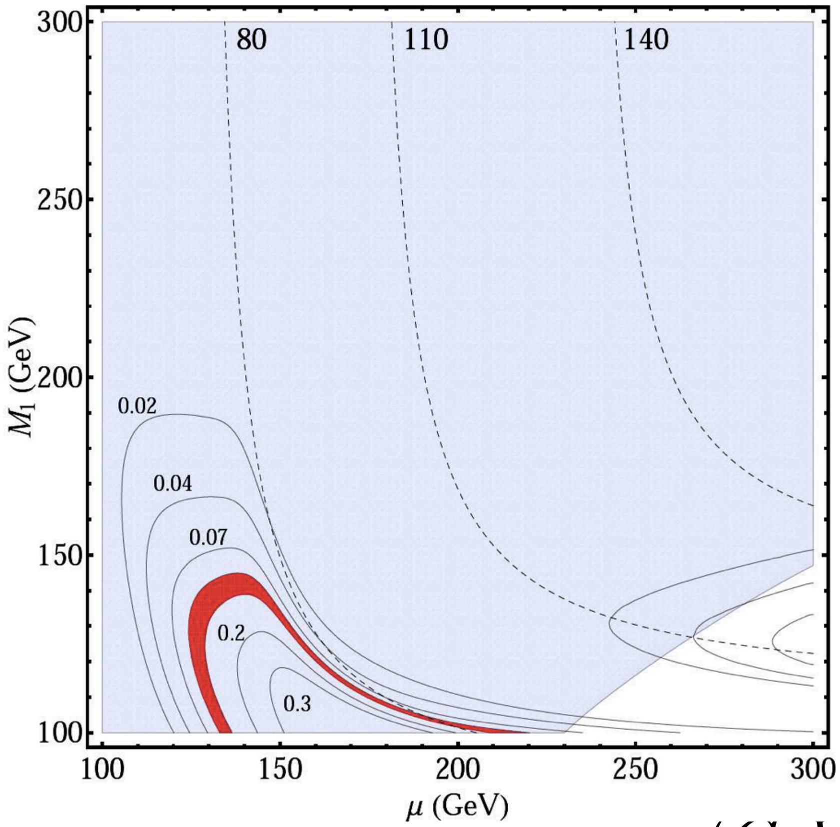
Direct detection affected by $\sigma \propto \frac{1}{m_h^4}$ and different mixing

Dark Matter: relic abundance and detection

$M_1 (GeV)$ M_2 large



$M_2 = 200\ GeV$



$\mu\ (GeV)$

λSusy: $m_h = 250\ GeV$

dark blu: CDMS now
light blu: "XENON100"

Conclusion

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

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

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

$$+N_i M_{ij} N_j$$ The ν-mass sector (1)
(if Majorana)

⇒ Beyond the SM:

Progress in "synthetic" physics requires and justifies a patient and brave attitude

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

ElectroWeak Precision Tests in λSUSY

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

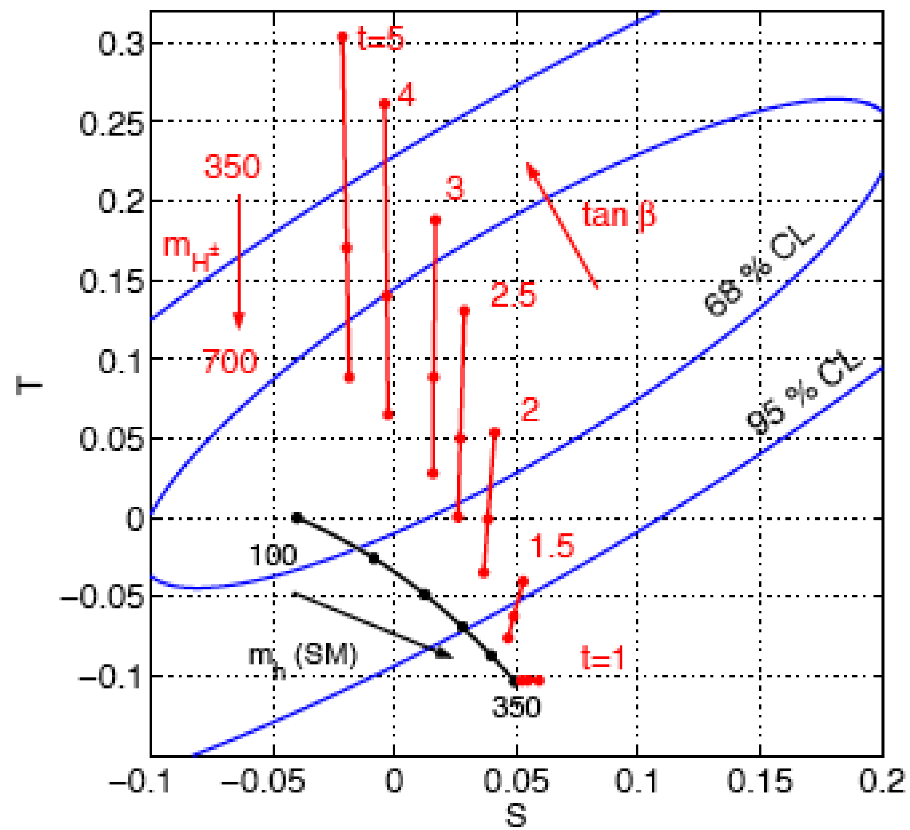
S and T from Higgs's

one loop effects but

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

$$\lambda \uparrow \Rightarrow m_h \uparrow$$

compensated by $\Delta T \uparrow$



B, Hall, Nomura, Rychkov

A simple concrete possibility

(others have been considered)

NMSSM

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

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

(2x4 + 2)- (2+1) = 7 = 2 + 3 + 2

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

Out of the 3 CP even states,

take the only one coupled to ZZ, WW

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

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

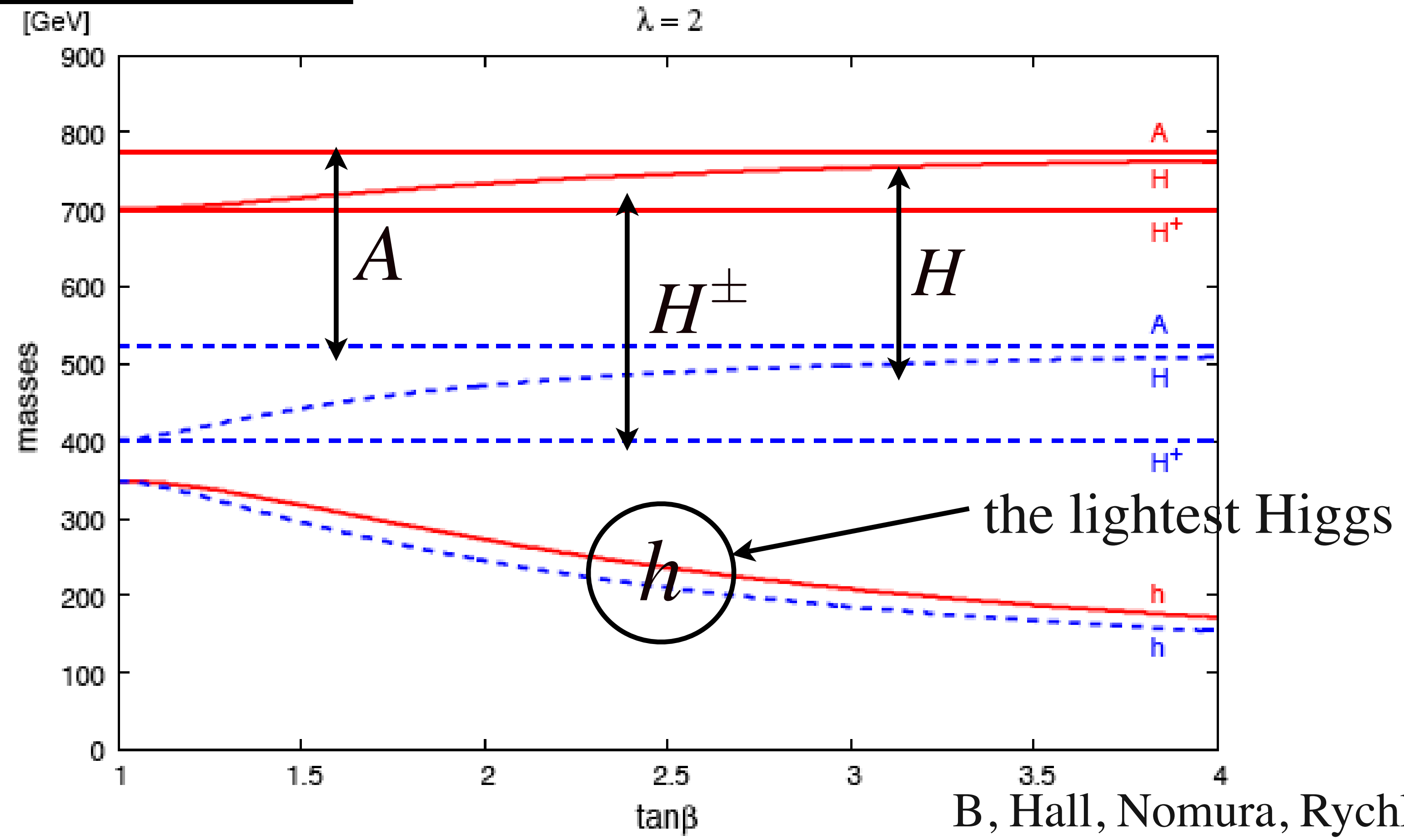
To respect the EWPT (unification?)

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

To maintain manifest perturbative unification

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

The Higgs boson spectrum



B, Hall, Nomura, Rychkov

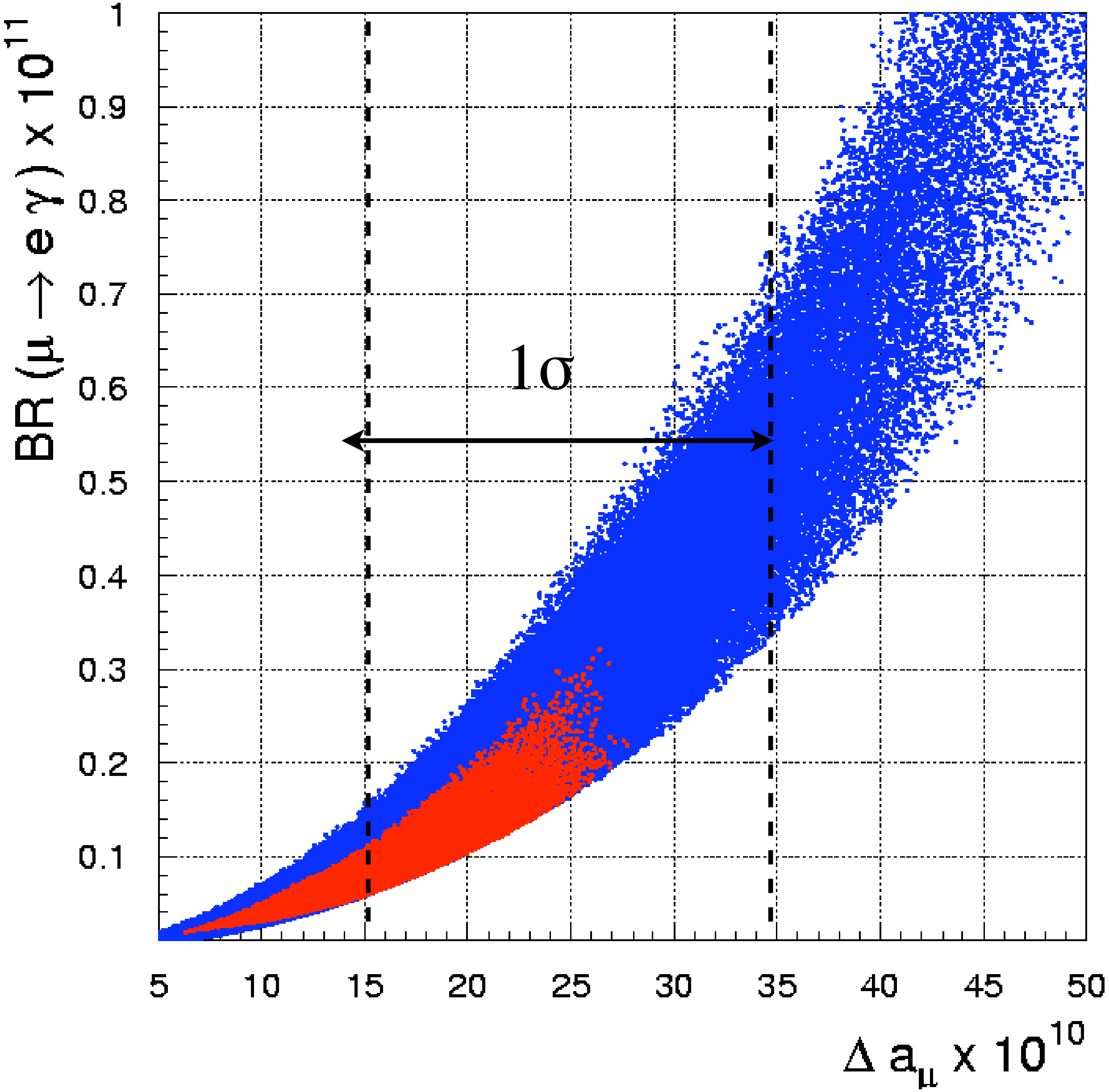
$h \to ZZ \to l^+l^- \; l^+l^-$ easy, but very much NON-susy

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

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

possible with $100\; fb^{-1}$

Cavicchia, Franceschini, Rychkov



Gino Isidori