New Physics in the LHC1 Era

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La Thuile, March 2011

⇒ Which physical origin for the Fermi scale?

Which physics behind the quark and lepton spectrum?
(Why the SM so successful in flavour physics?)

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"

2001: "the little hierarchy" problem

B, Strumia

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

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

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

2011: 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

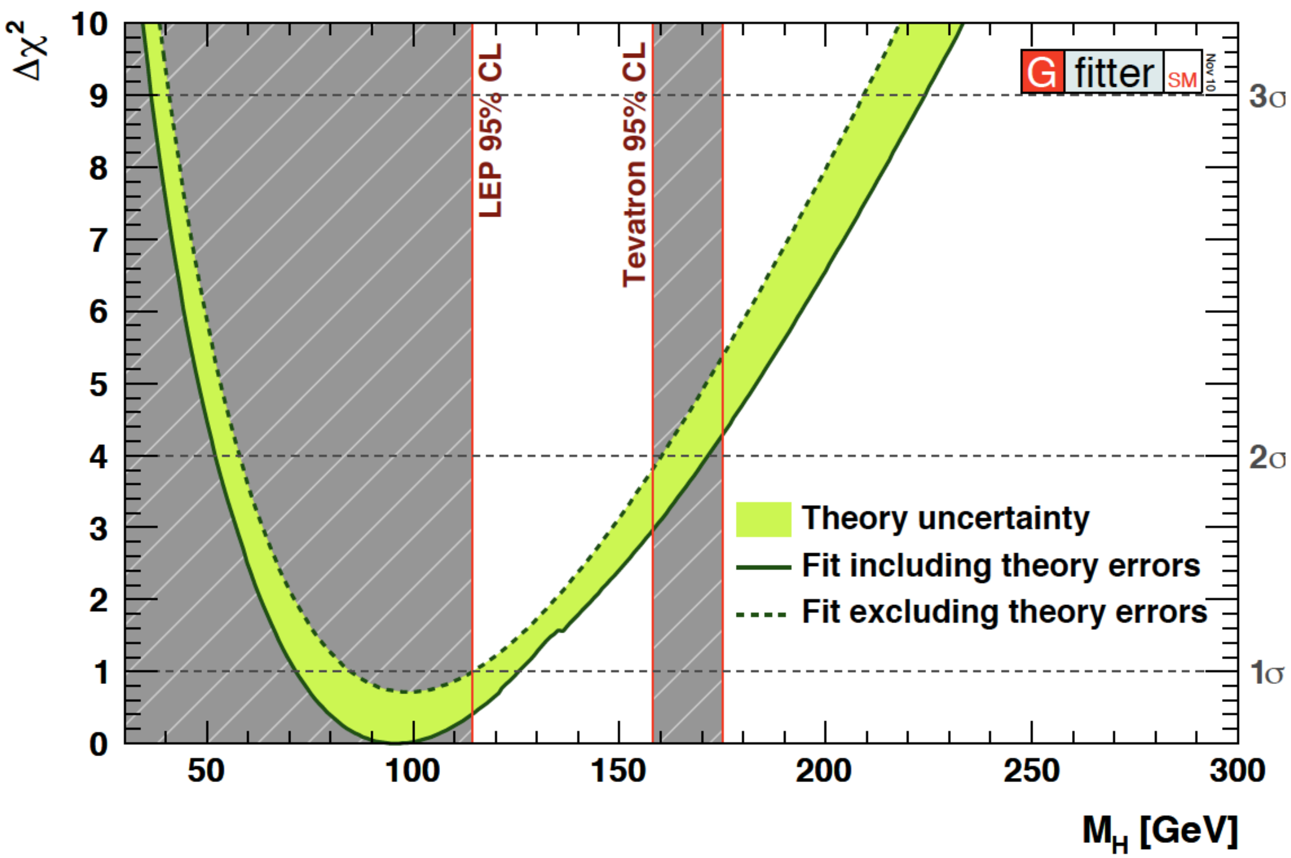
$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \mathcal{O}/\Lambda^2$$

	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

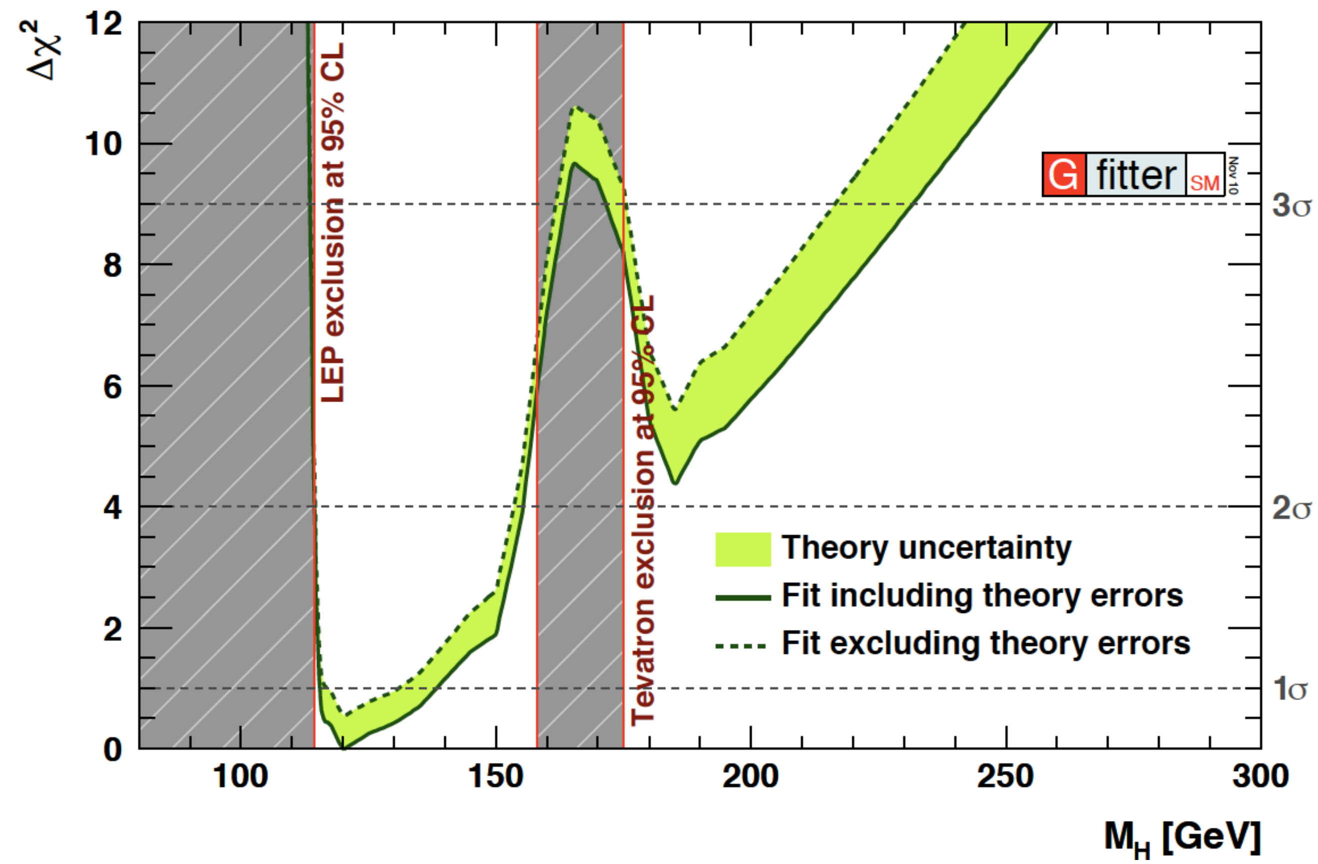
1σ-bounds ⊕ a light Higgs

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

The Higgs boson mass in the SM



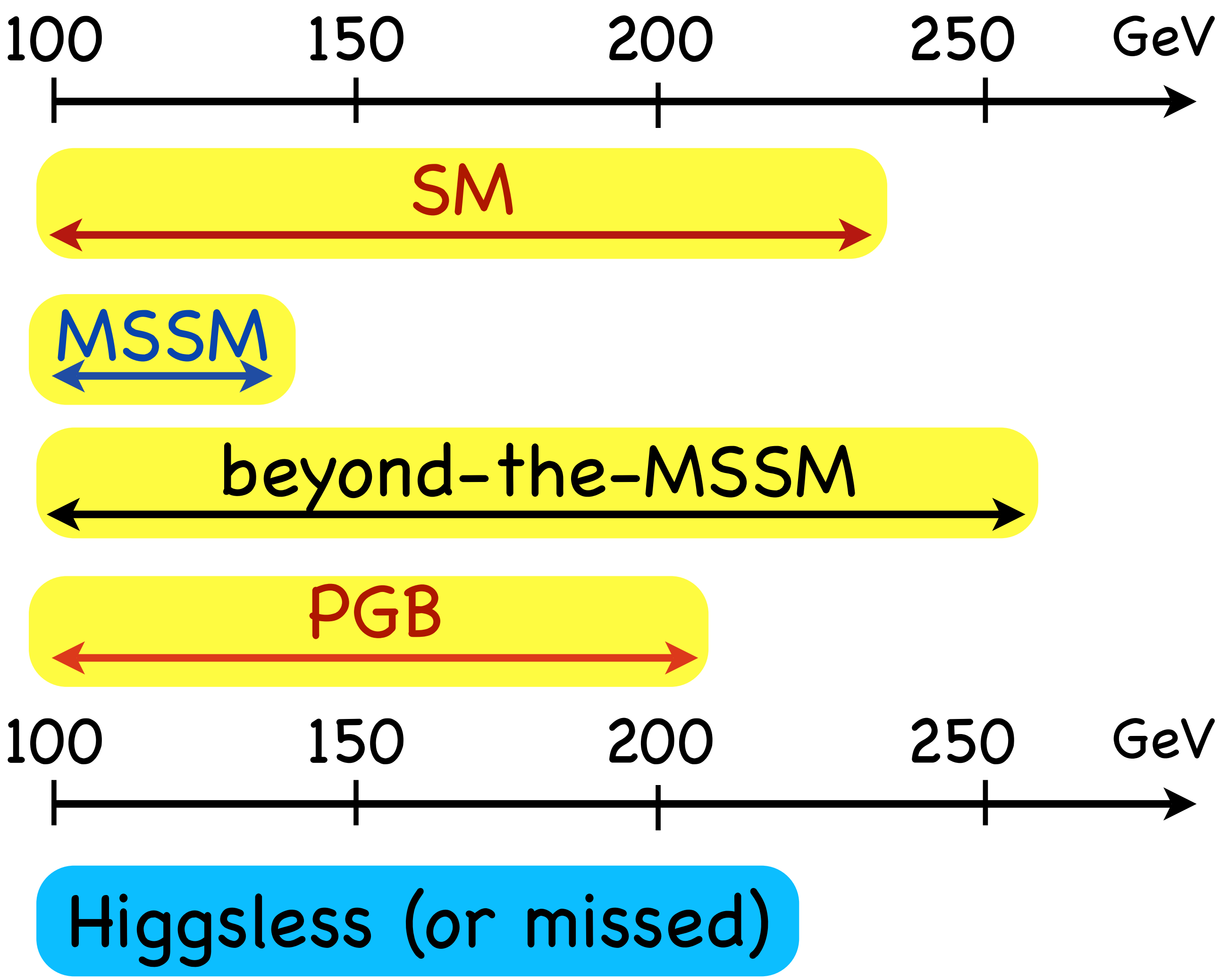
direct (negative) searches not included

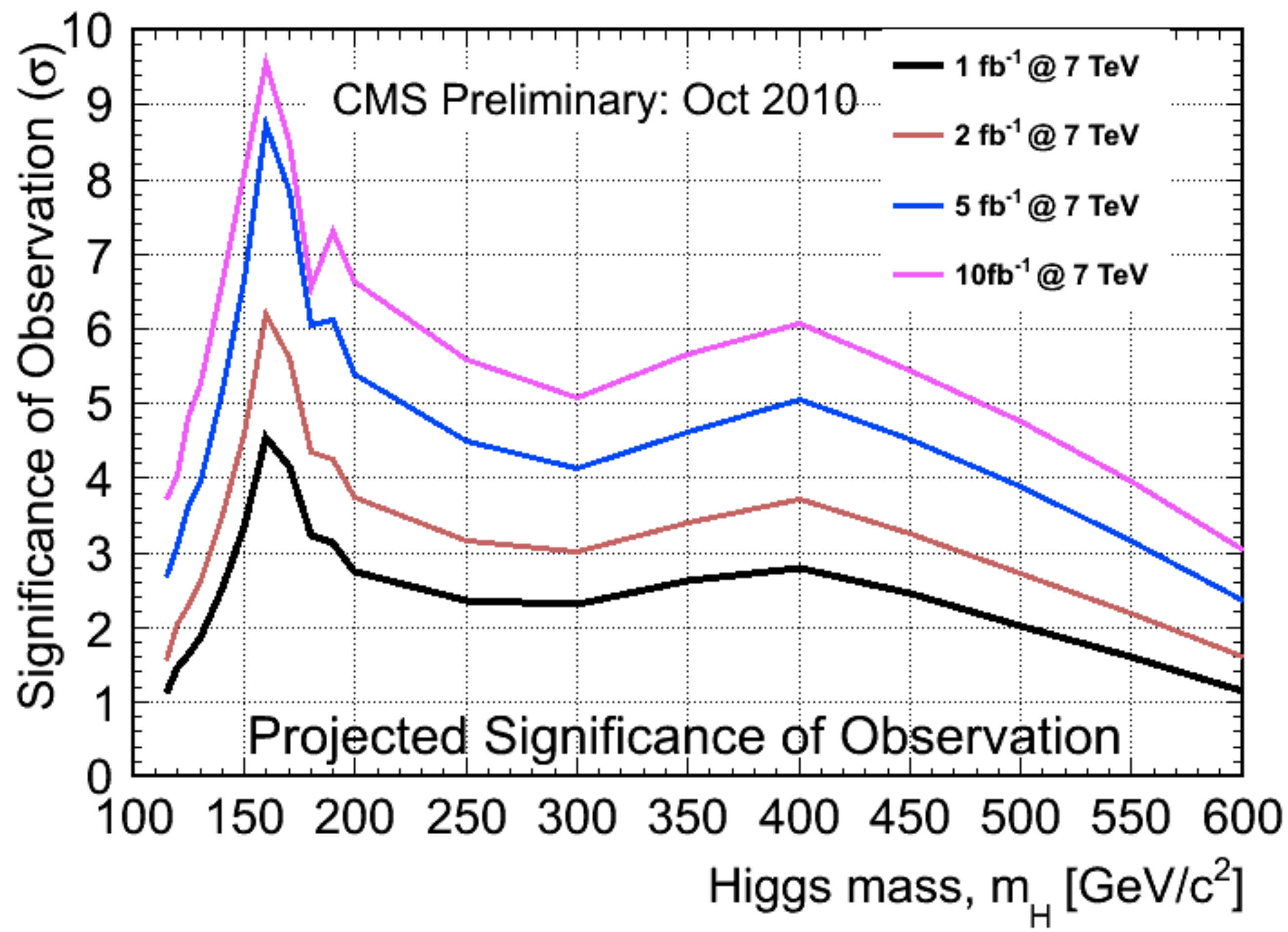


direct (negative) searches included

$m_h \lesssim 230\ GeV$, not difficult to evade (in too many ways)

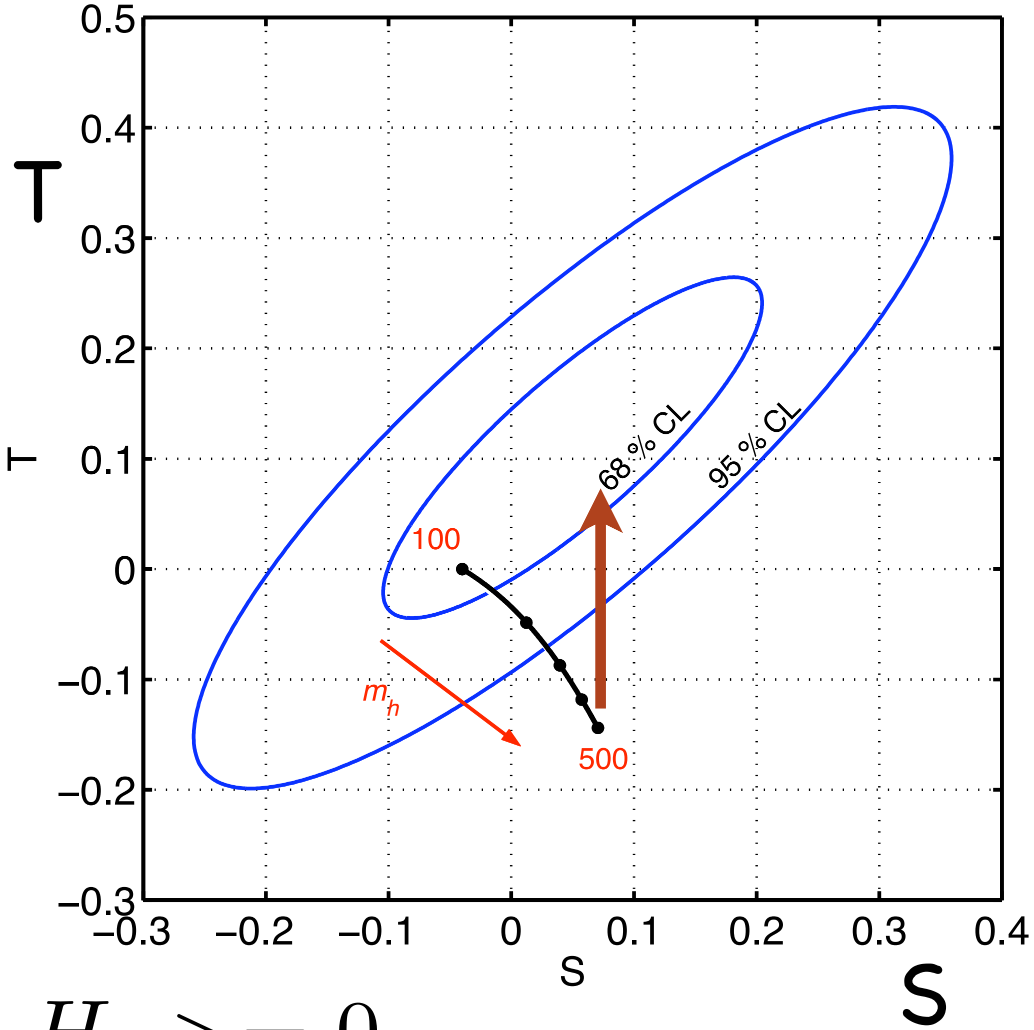
Everything around the Higgs boson





Fortunately (hopefully) not

Evading the indirect bound of the SM on m_h



A heavier Higgs boson requires a small positive ΔT (0.1-0.2)

A minimal (motivated) example:

$$V = -\mu_1^2 H_1^+ H_1 + \mu_2^2 H_2^+ H_2$$ + quartics

with only H_1 coupled to matter and $< H_2 >= 0$

H_2 a "inert" doublet, whose lightest neutral component can make the DM

$$H_2 = \begin{pmatrix} H^+ \\ (S+iA)/\sqrt{2} \end{pmatrix}$$

B, Hall, Rychkov

ΔS negligible $\quad \Delta T \approx \frac{1}{24\pi^2 \alpha v^2}(m_H - m_A)(m_H - m_S) \approx G_F \Delta_{HA}\Delta_{HS}$

$q\bar{q}' \to H^{\pm} A(S) \qquad H^{\pm} \to S W^{\pm(*)} \qquad S \to A Z^{(*)}$ (not for LHC1)

The "weak coupling" way to EWSB

Favoured by indirect-data

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

Which problems, if susy?

No Higgs boson so far

No s-particle yet

Flavour and CP (The SM works in a quantitative way)

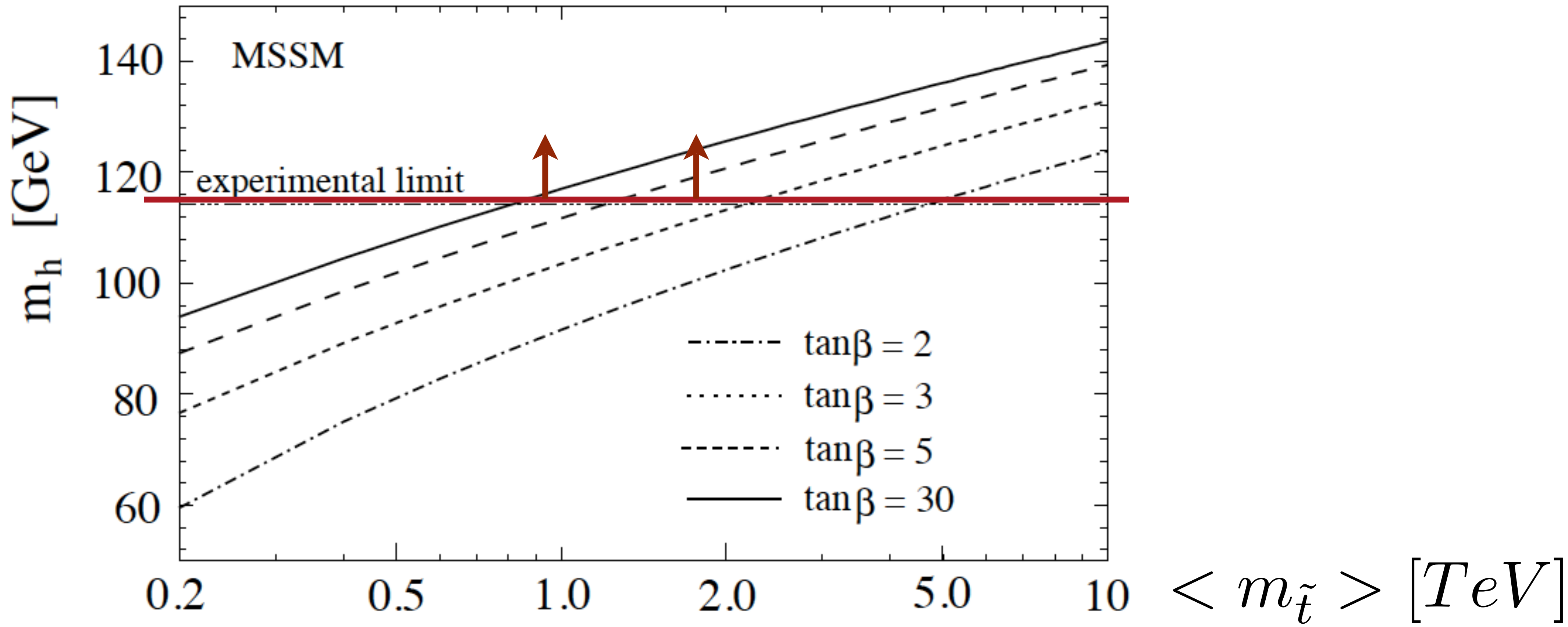
⇒ SUSY signals just around the corner?

⇒ SUSY irrelevant at the Fermi scale?

The MSSM as the only paradigm?

Where is the supersymmetric Higgs boson?

MSSM

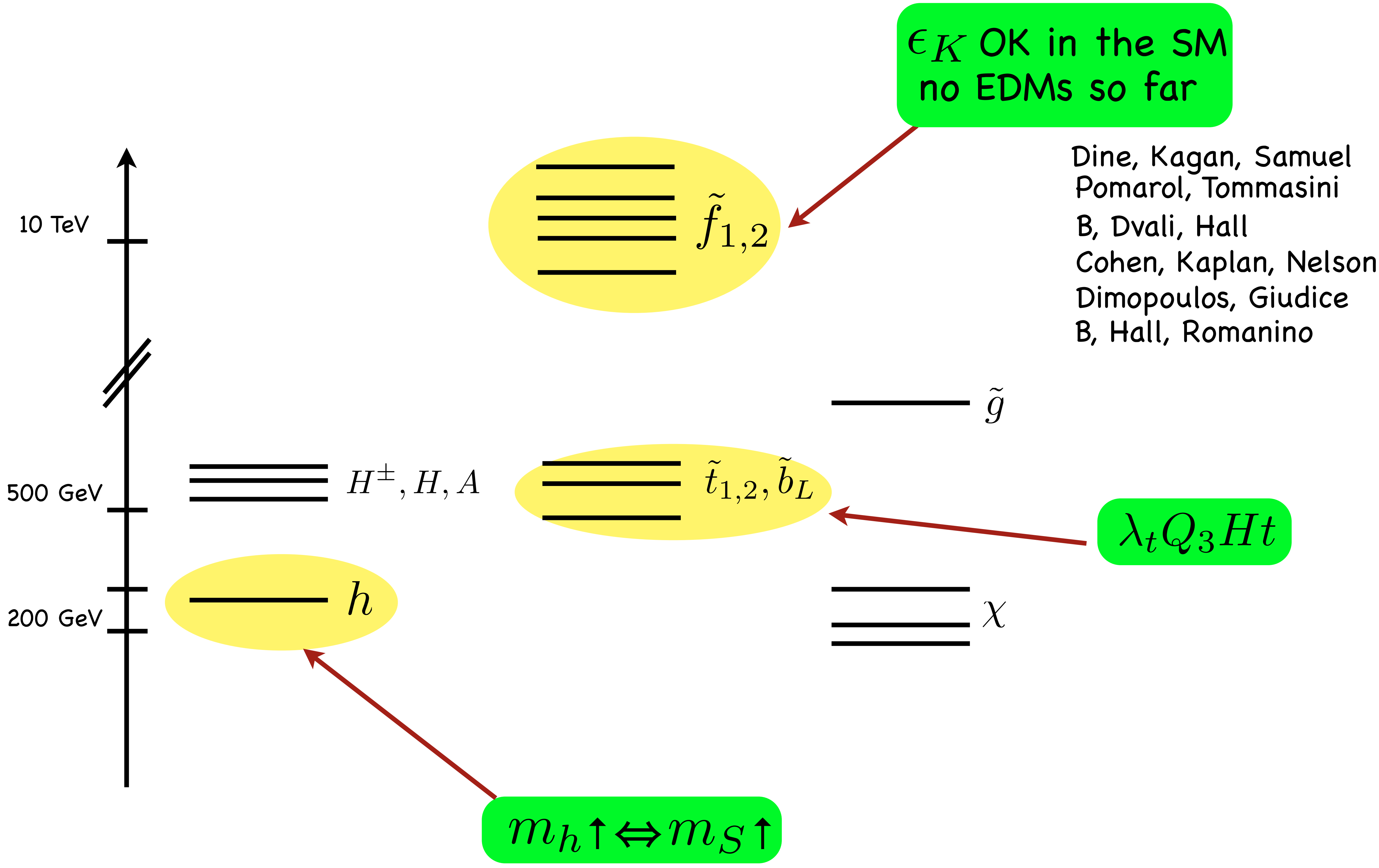


⇒ Take large tanβ (muon anomaly?) and large stop mass
but swallow, e.g. in SUGRA, a large contribution to M_Z
to be fine-tuned away

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

⇒ h just around the corner and quasi-standard

Beyond the MSSM



Supersymmetry without a light Higgs boson

Want to keep the success of the EWPT
$\Rightarrow$ Effective theories not enough

★ MSSM $$m_h^2 \leq m_Z^2 \cos^2 2\beta$$

+ rad. corr.

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

Batra, Delgado, Kaplan, Tait

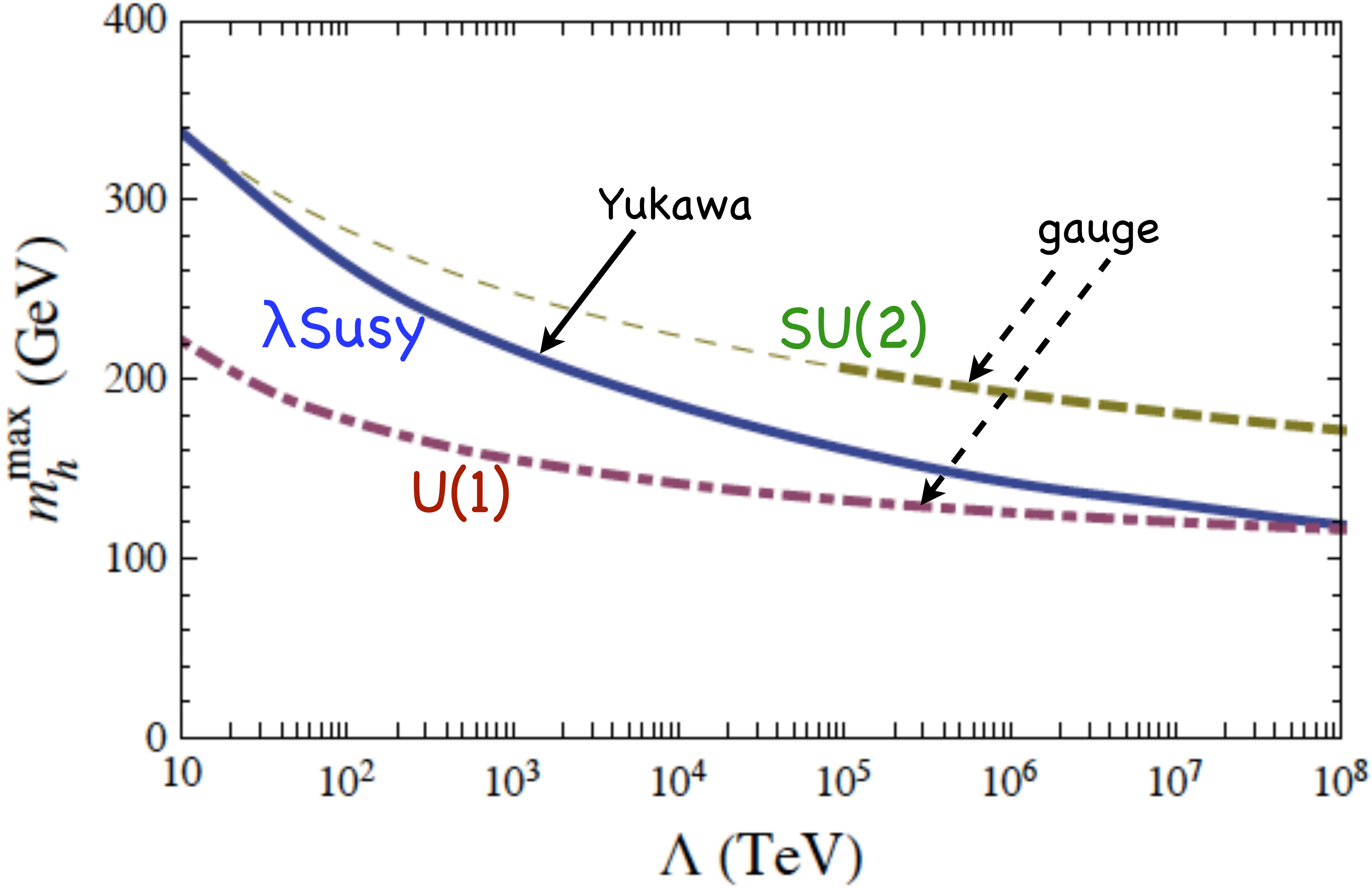
★ Extra SU(2) $$m_h^2 \leq m_Z^2 \frac{g'^2 + \Delta g^2}{g'^2 + g^2} \cos^2 2\beta \qquad \Delta = \frac{1 + \frac{M_\Sigma^2}{M_X^2}\frac{g_I^2}{g^2}}{1 + \frac{M_\Sigma^2}{M_X^2}}$$

★ $\Delta f = \lambda S H_1 H_2$ $$m_h^2 \leq m_Z^2 (\cos^2 2\beta + \frac{2\lambda^2}{g^2 + g'^2} \sin^2 2\beta)$$
(NMSSM $\Rightarrow$ λsusy)

Harnik, Kribs, Larson, Murayama
B, Hall, Nomura, Rychkov

The price to pay
(big, according to standard wisdom, but...)

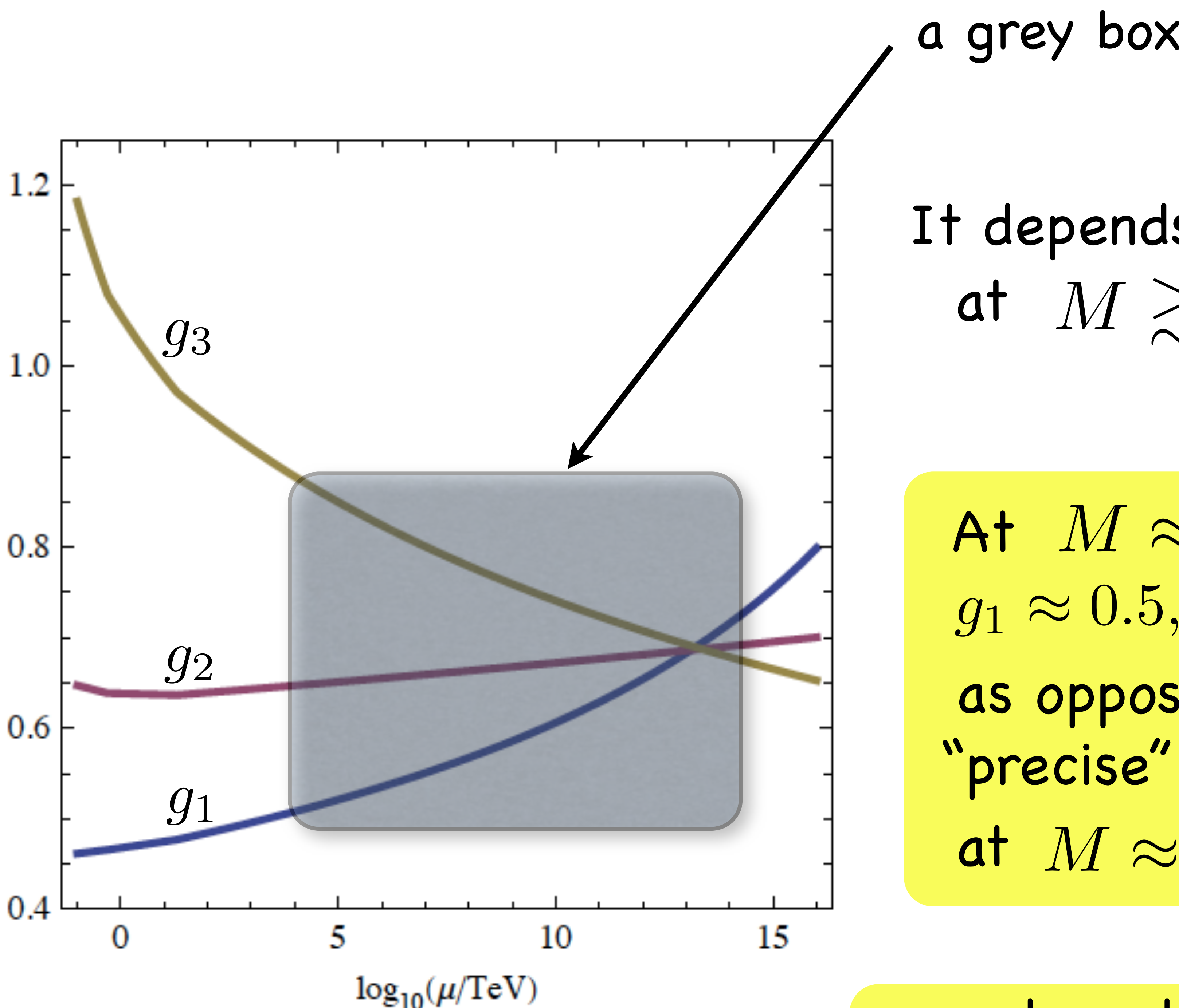
At a scale Λ some coupling starts blowing



$$\lambda^2(\Lambda) = 4\pi$$
$$g^2(\Lambda) = 4\pi$$

unless some change of regime occurs before

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 $M \approx 10^{13} \; TeV$

an unbearable step backward?!

NOT IN MY VIEW

Phenomenological consequences
(non MSSM-like)

- ✶ gluino pair production and decays into top/bottom-rich final states

- ✶ a largely unconventional Higgs sector

  $h \to VV$ (with reduced rate by $h \to \chi\chi$)

  → $h \to aa \to (b\bar{b},\ \tau\bar{\tau},\ c\bar{c})^2$ ←

- ✶ Dark Matter: relic abundance and detection affected

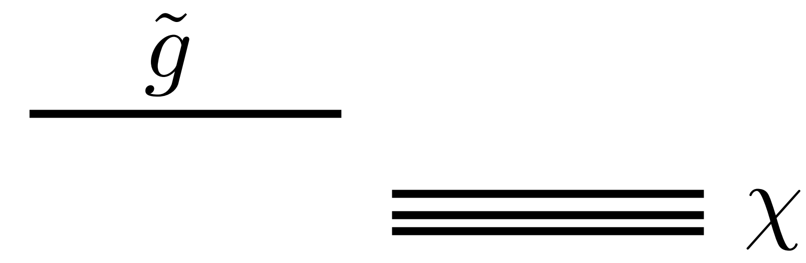
- ✶ Flavour signals in EDM's and direct CP violation in b-physics (at low tanβ)

Cavicchia, Franceschini, Rychkov
B, Bertuzzo, Farina, Lodone, Pappadopulo
B, Lodone, Straub

The signals from gluino production

1. $pp \to \tilde{g}\tilde{g} \to E_{Tmiss} + jets$

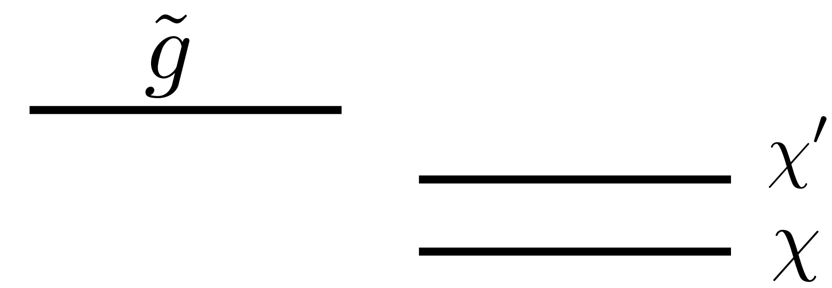
   $\tilde{g} \to q\bar{q} + \chi$



2. $pp \to \tilde{g}\tilde{g} \to E_{Tmiss} + jets + l's$

   $\tilde{g} \to q\bar{q} + \chi', \;\; \chi' \to V + \chi$

   $\chi' \to l\bar{l} + \chi$



3. as 1,2 above but, specifically, $q\bar{q} = t\bar{t} \; or \; t\bar{b} \; or \; b\bar{b}$ (since $\tilde{q}_{1,2}$ heavy)

4. as 1,2,3 above + 2 γ's

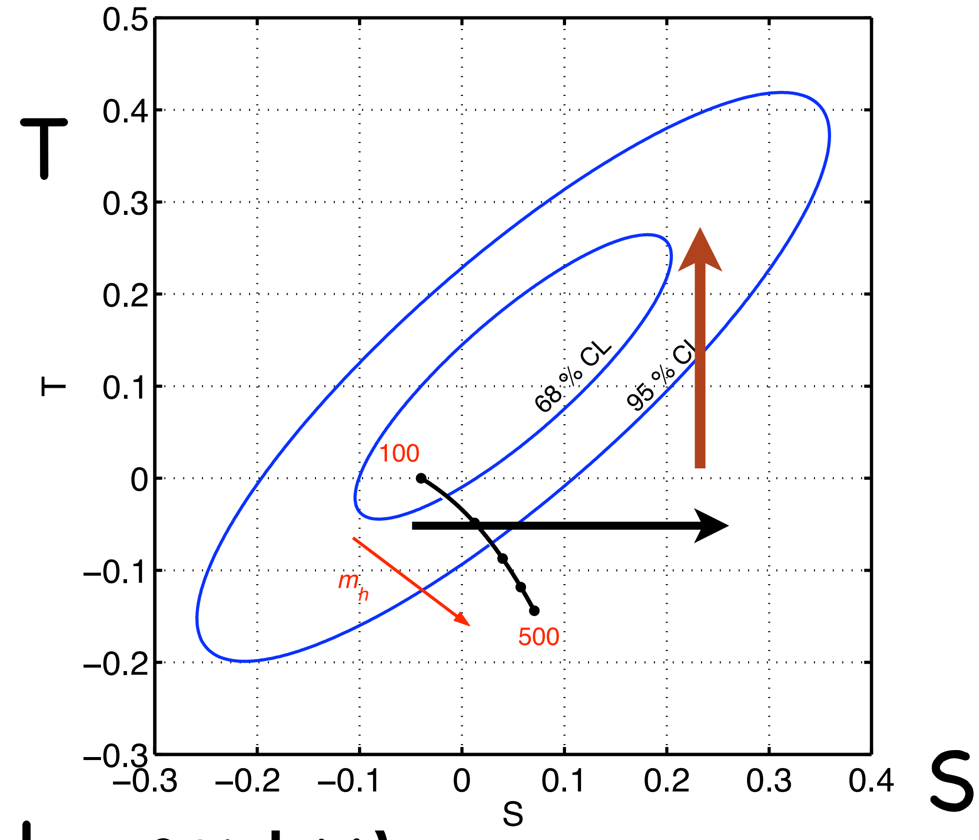
   from $\chi \to gravitino + \gamma$

5. $pp \to \tilde{g}\tilde{g} \to 2 \; stable \; hadrons$

all of which deserving attention (in the MSSM and beyond) and characterizable in terms of few physical variables

The "strong coupling" way to EWSB

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?

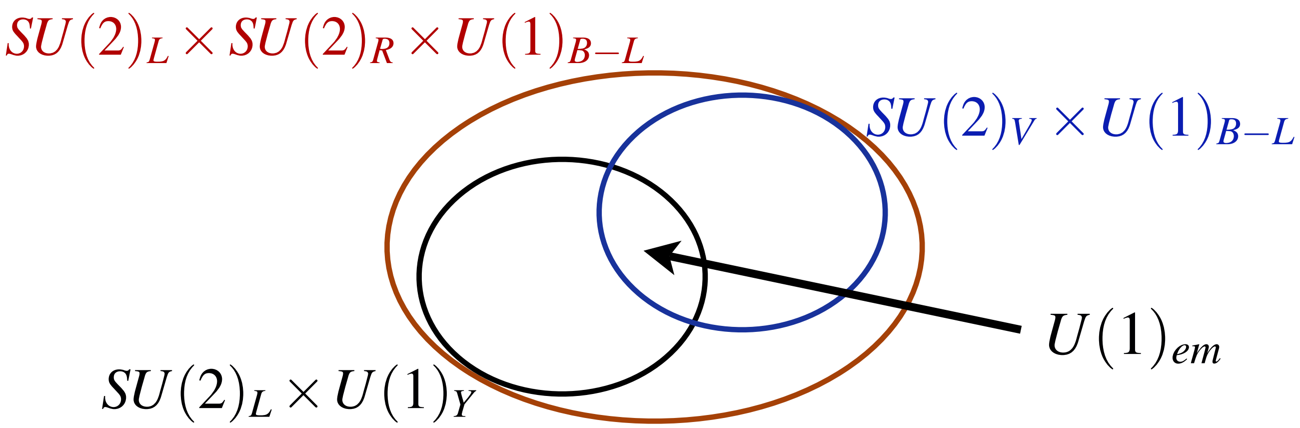
(yes, but what about the SM λ^Y_{ij}?)

"Higgs" or "Higgs-less"?

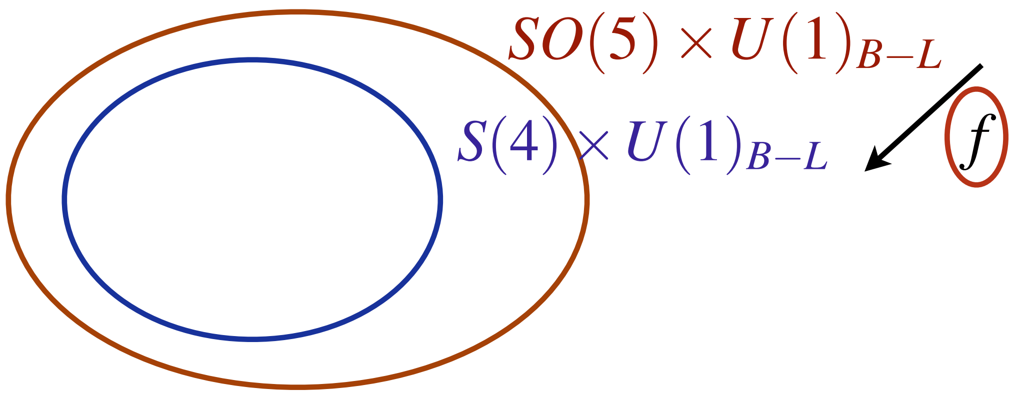
(a real question, although with a most likely answer)

The Higgs boson as a pseudo-Goldstone boson

Georgi, Kaplan
Agashe, Pomarol, Contino



inside



(not without problems with EWPT and flavour)

Relevant features for LHC1:

$\lambda H\bar{t}t$ not quite a PGB coupling; need to extend to other Q's

$pp \to Q\bar{Q}$ $\quad Q \equiv (T^{2/3}, B^{-1/3}, X^{5/3})$ $\quad Q \to tV,\ th$

(t or b, depending on the charge)

Unitarity in WW scattering only partially restored

$h \to WW$ down, BR($h \to \gamma\gamma$) up?

"Higgs-less"

("technicolour, BESS, ...)

1. Keep SU(2)xU(1) gauge invariance but leave out the Higgs boson, while insisting on $SU(2)_L \times SU(2)_R \to SU(2)_{L+R}$

$$\mathcal{L} = \mathcal{L}^{SM}_{gauge} + \frac{v^2}{4} < (D_\mu U)^+ (D_\mu U) > + \frac{v}{\sqrt{2}} \bar{Q}_{Li} U Q_{Ri}$$

$$U(x) = e^{i\hat{\pi}(x)/v}, \qquad \hat{\pi}(x) = \tau^a \pi^a \qquad Q_{Ri} = \begin{pmatrix} \lambda^u_{ij} u_{Rj} \\ \lambda^d_{ij} d_{Rj} \end{pmatrix}$$

"π"= W,Z longitudinal

Consistent with all data so far, including flavour, except the EWPT (although ρ≈1) and reliable only up to Λ≈4πv≈1÷3 TeV

2. Introduce new "composite" particles of mass < Λ consistently with 1 and see what happens:

scalars(e.g. 0^{++}), fermions, vectors(e.g. 1^{--})

V production and decays

V_a^μ = a $SU(2)_{L+R}$- triplet (ρ-like, but not too much)

$$\mathcal{L}_{1V} = -\frac{i g_V}{2\sqrt{2}} \left\langle \hat{V}^{\mu\nu}[u_\mu, u_\nu] \right\rangle - \frac{f_V}{2\sqrt{2}} \left\langle \hat{V}^{\mu\nu}(u W^{\mu\nu} u^\dagger + u^\dagger B^{\mu\nu} u) \right\rangle$$

Single V-production by VBF (g_V)

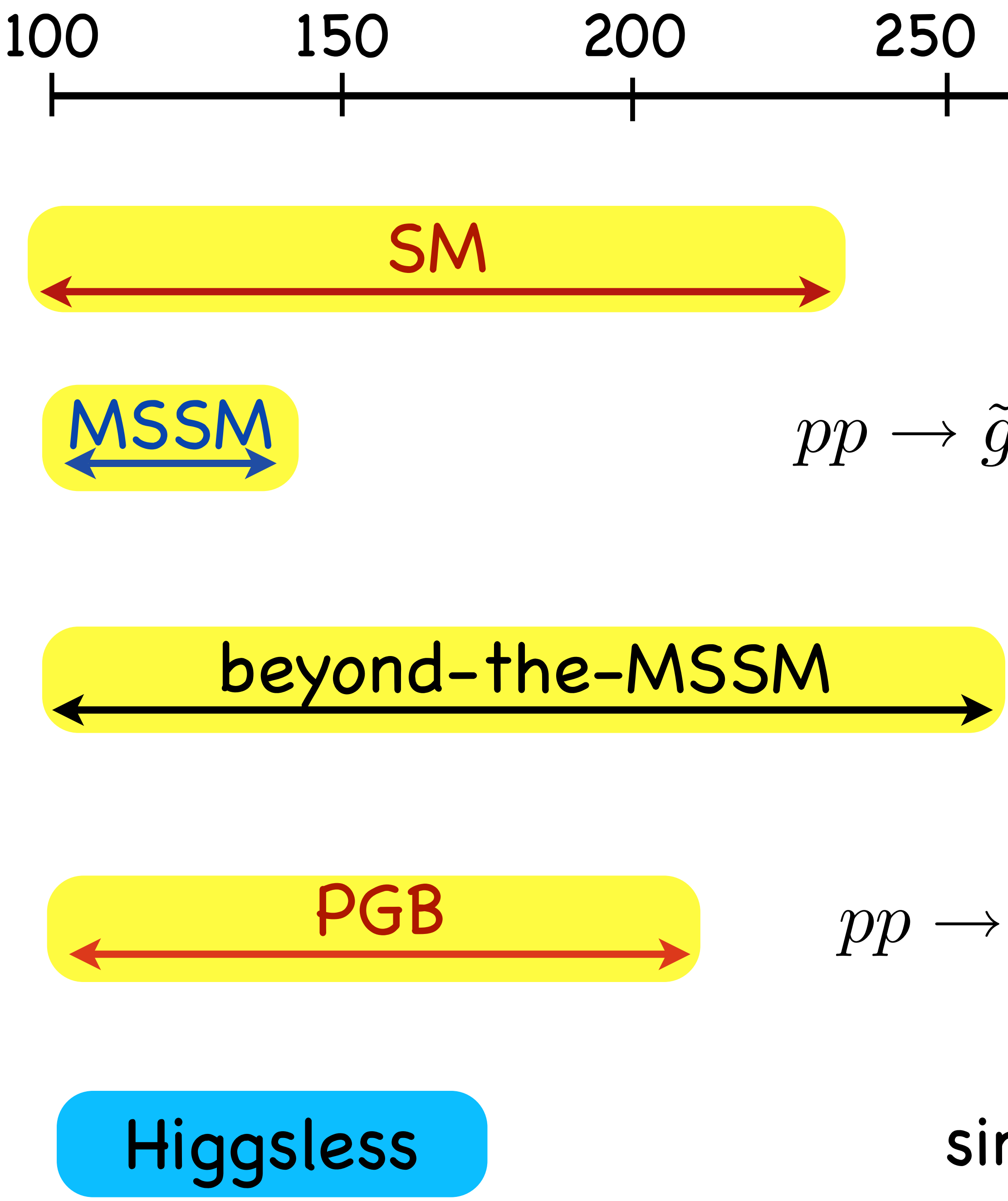
Single V or associated V W/Z production by DY (f_V)

Narrow ($\Gamma \propto M_V^3$< 40 GeV at M < 1 TeV) and dominated by V→W W/Z ($l\bar{l}$ small but≠0 because of VZ kin. mixing)

Perhaps visible at LHC1 if light enough

Belyaev et al
Cata, Isidori, Kamenik

Summary



SM: If $m_h \gtrsim 230$ GeV the SM incomplete

MSSM: $pp \to \tilde{g}\tilde{g},\ \tilde{g}\tilde{q},\ \tilde{q}\tilde{q} \Rightarrow jets + E_{T miss} (+l's)$

beyond-the-MSSM:

$pp \to \tilde{g}\tilde{g} \Rightarrow$ multi top/bottom events

$h \to VV$ (with reduced rate by $h \to \chi\chi$)

$h \to aa \to (b\bar{b},\ \tau\bar{\tau},\ c\bar{c})^2$

PGB: $pp \to Q\bar{Q}$ $\quad Q \equiv (T^{2/3}, B^{-1/3}, X^{5/3})$ $\quad Q \to tV,\ th$

Higgsless: single vector production by VBF or DY

$V^0 \to W^+W^- \qquad V^\pm \to W^\pm Z$

Most of these signals available for LHC1

Physics in its normal mode of operation

2HDM in an alternative phase

B, Hall, Rychkov

IDM

$$V = -\mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 + \text{ quartics}$$

For natural flavor conservation impose

$H_2 \to -H_2$

Only H_1 couples to matter

$$H_2 = \begin{pmatrix} H^+ \\ H + iA \end{pmatrix}$$

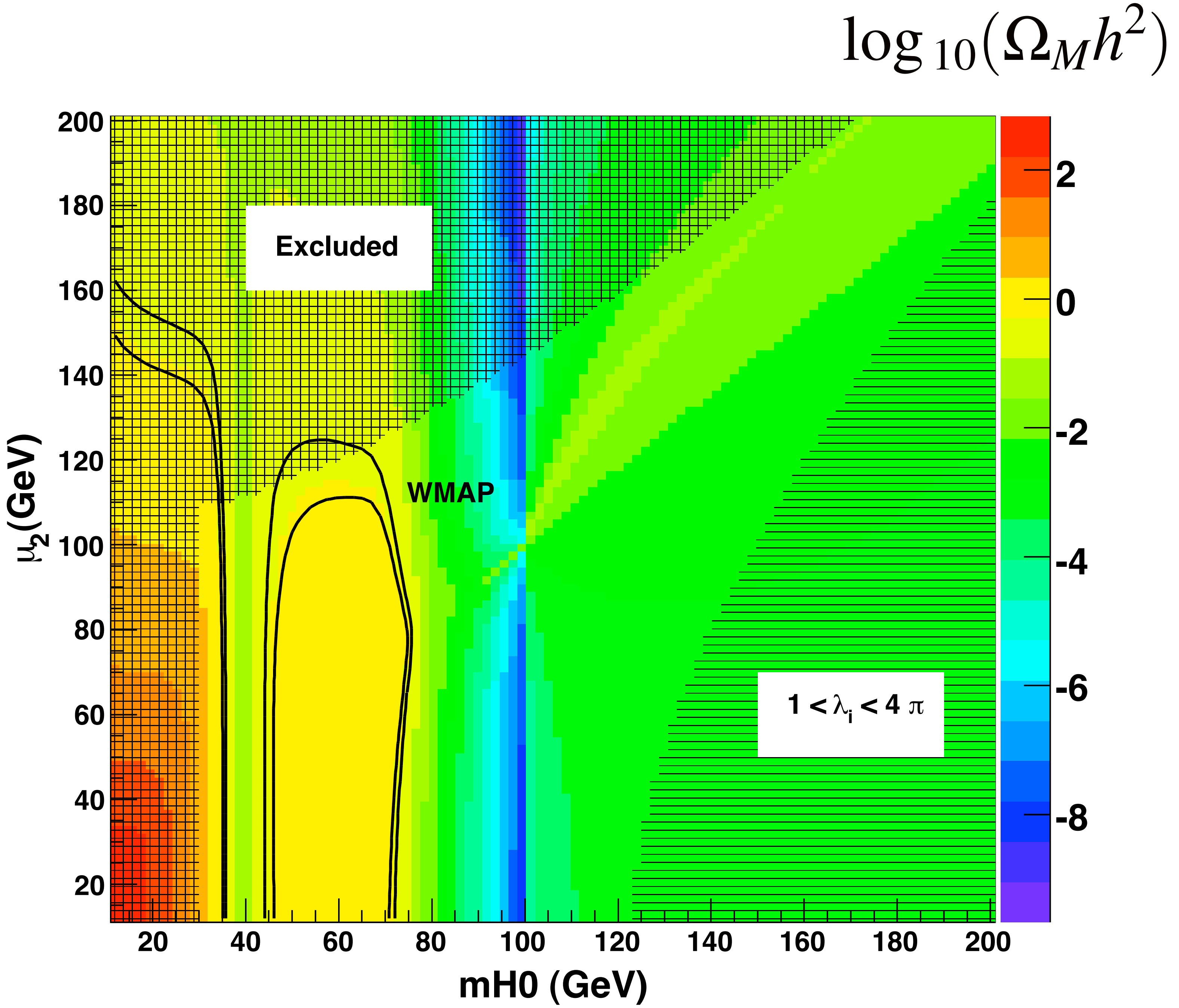
is "inert"

$v_2 = 0$

This is not the usual phase in the fine-tuned limit of $v_2 \ll v_1$

1. $H_1 = \begin{pmatrix} 0 \\ v + h \end{pmatrix}$ similar to SM Higgs
2. H_2 mass splittings lead to $\Delta T > 0$ *controlled by approximate* $SU(2)_V$
3. $H_2 \to -H_2$ is exact, and not spontaneously broken

Lightest Inert Particle (LIP) is stable and could be Dark Matter



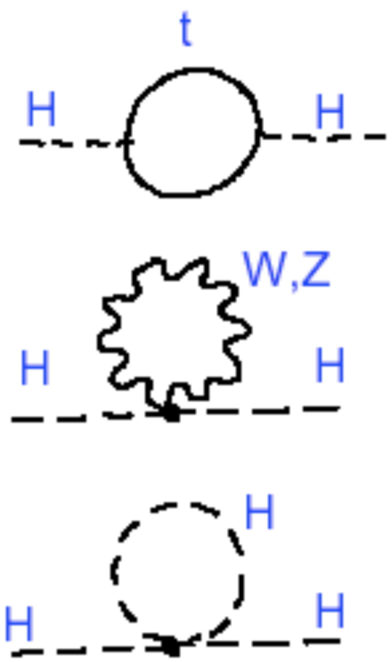
log 10(ΩMh2)
Excluded
WMAP
1 < λi < 4 π
μ2(GeV)
mH0 (GeV)
200
180
160
140
120
100
80
60
40
20
20
40
60
80
100
120
140
160
180
200
2
0
-2
-4
-6
-8

Tytgat et al

1. the Higgs boson mass and the fine-tuning continued

(It could be right and we might never know)

$$V = -\mu^2 H^2 + \lambda H^4 \qquad m_h^2 = 2\mu^2 = \frac{\lambda}{2\sqrt{2}} G_F^{-1}$$



From loops: $\delta\mu^2 \propto (\lambda_t^2, g^2) m_s^2$

which sets the naturalness upper bounds on m_s^2

for fixed Higgs boson mass, or fixed λ

IF $\lambda \rightarrow a^2 \lambda$ then $m_h \rightarrow a m_h$

$m_s^{max} \rightarrow a m_s^{max}$

$$\frac{1}{\Delta} \rightarrow a^2 \frac{1}{\Delta}$$

ElectroWeak Precision Tests in λSUSY

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

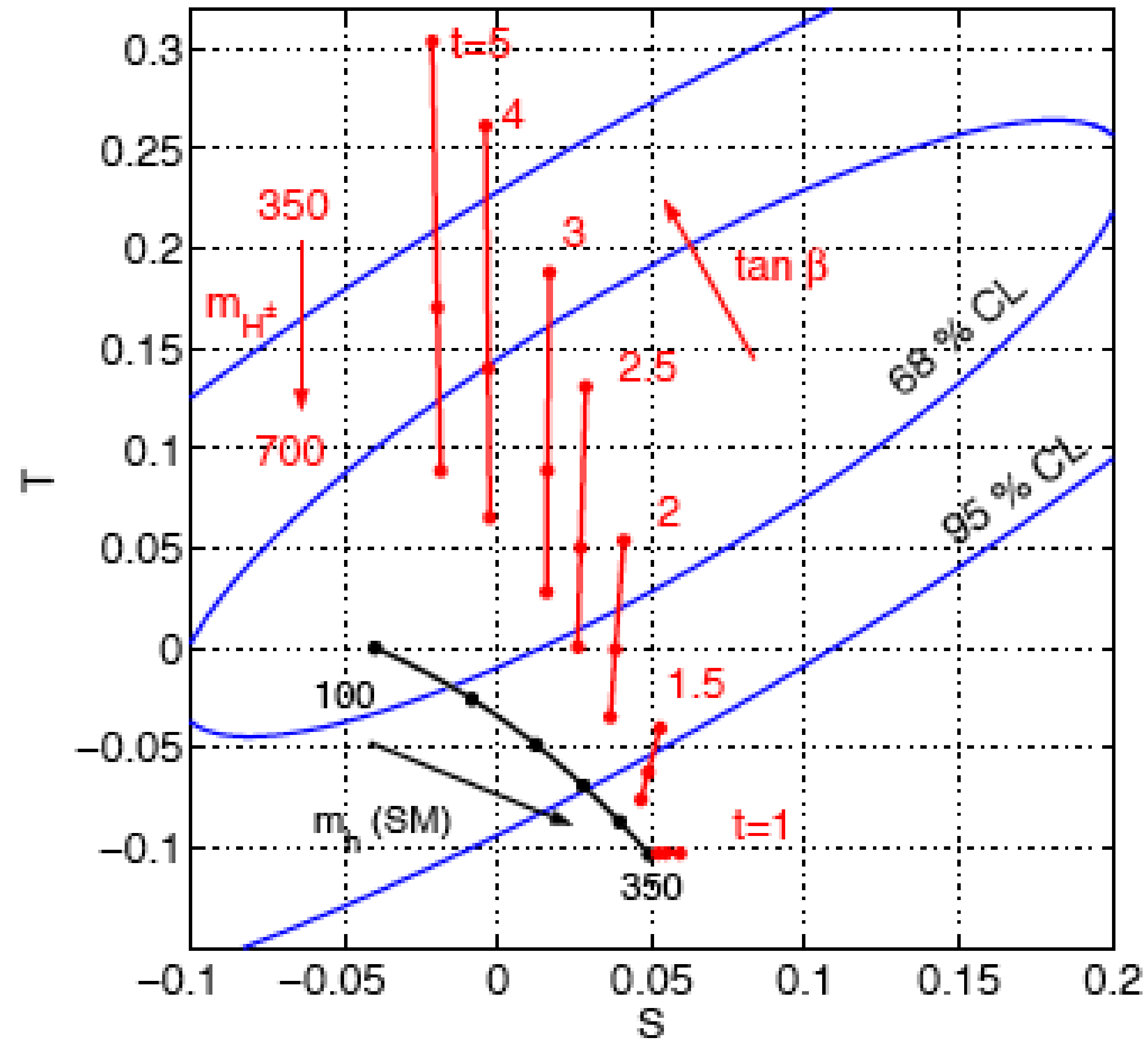
S and T from Higgs's

one loop effects but

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

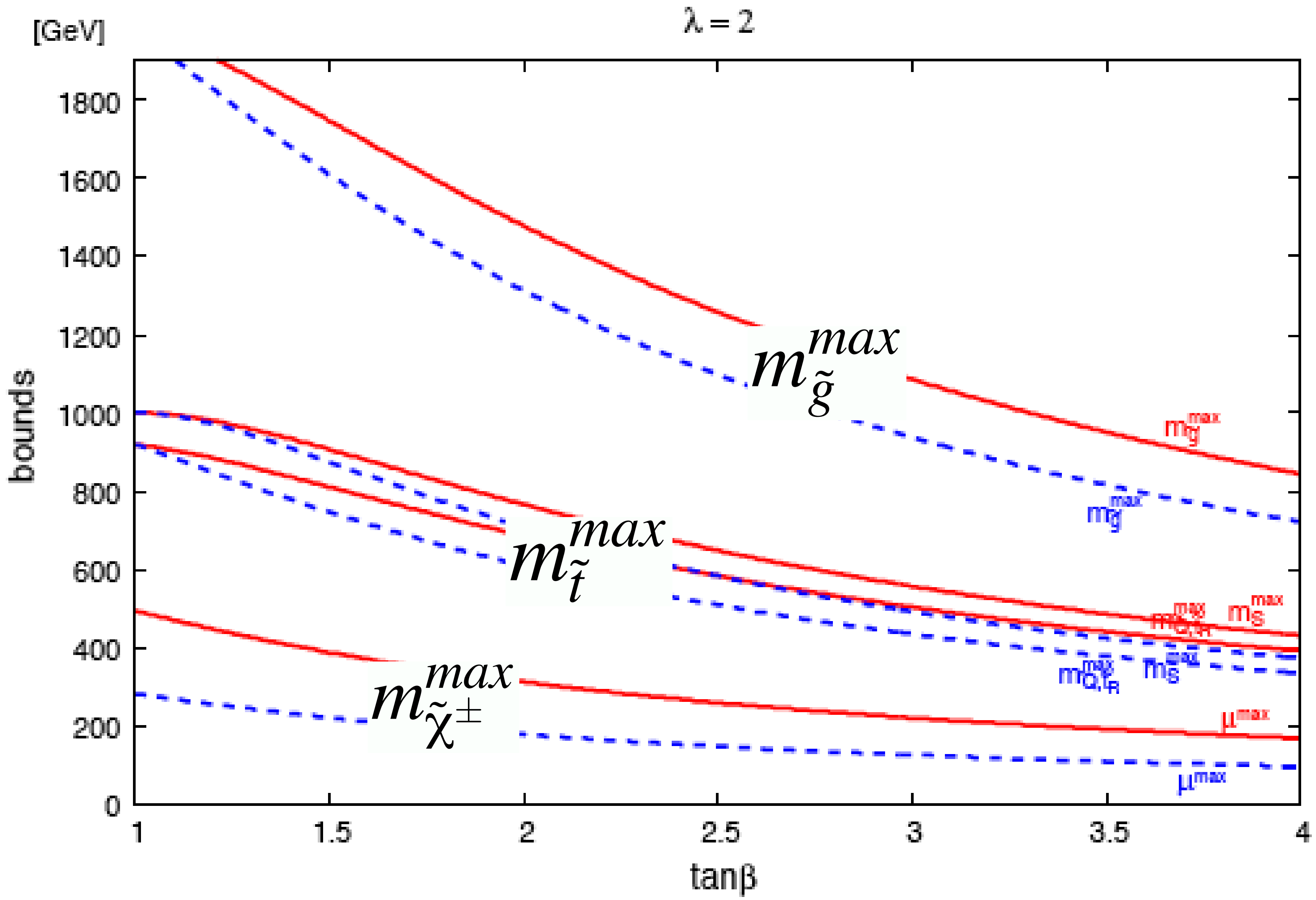
$$\lambda \uparrow \Rightarrow m_h \uparrow$$

compensated by $\Delta T \uparrow$



B, Hall, Nomura, Rychkov

Particle spectrum (naturalness bounds)



$\lambda = 2$

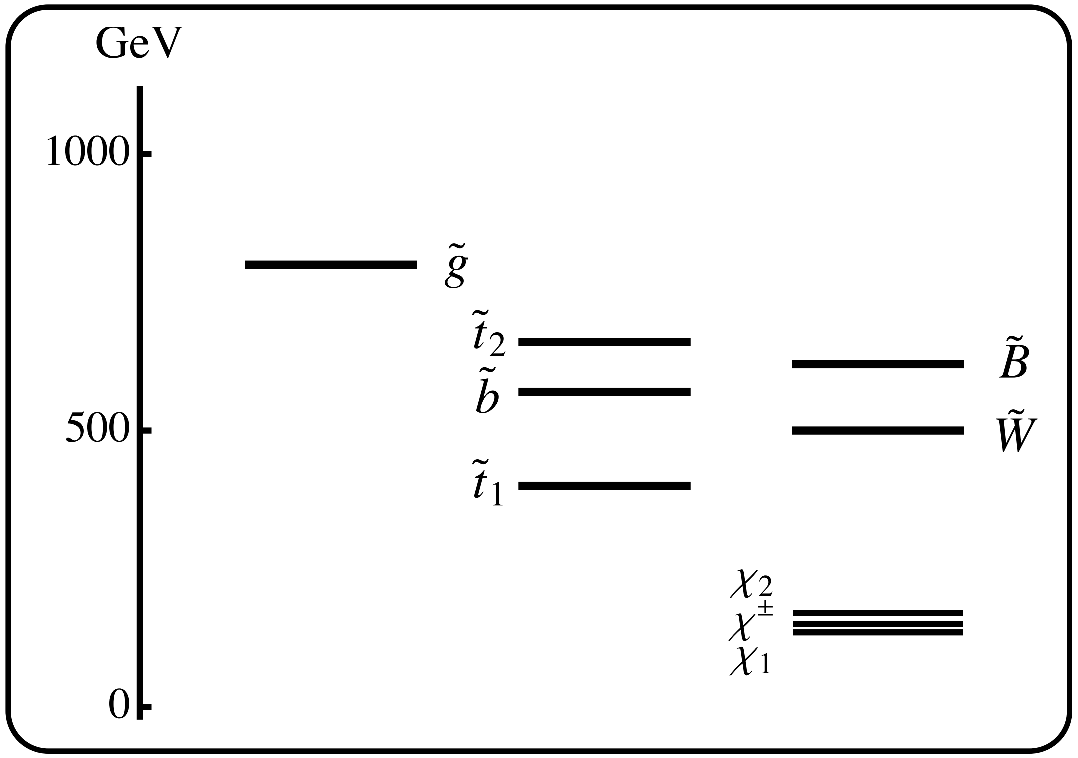
with up to 20% tuning $(m^{max} \propto \sqrt{\Delta/5})$

$\Lambda_{mess} = 100\ TeV$

Always a light neutralino in the spectrum $m_{\chi_1} < m_{\tilde{\chi}^\pm}$

4.1 Gluino pair production and decays

A typical configuration



More in general

$$m_{\tilde{g}} = 400 \div 1800\ GeV$$

$$m_{\tilde{t}_1} < m_{\tilde{t}_2} < 800\ GeV \quad \theta_t = 0 \div \pi/2$$

$$\mu = 100 \div 400\ GeV$$

$$M_1,\ M_2 = 100 \div 500\ GeV$$

(s-lepton masses almost always unimportant)

3 relevant semi-inclusive BR's

$$\tilde{g} \to t\bar{t}\chi$$

$$\tilde{g} \to t\bar{b}\chi\ (\bar{t}b\chi)$$

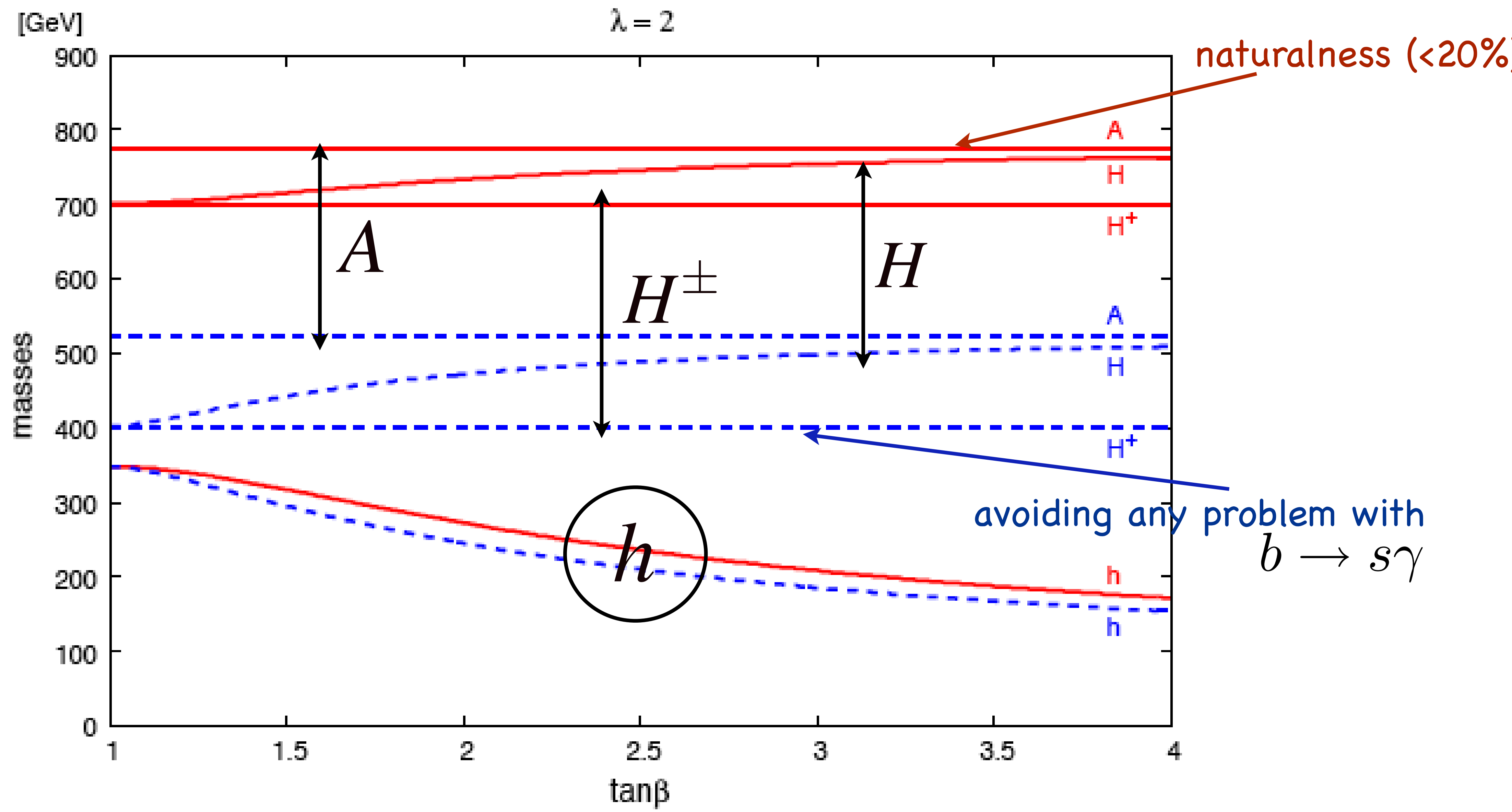
$$\tilde{g} \to b\bar{b}\chi$$

with $B_{tt} + 2B_{tb} + B_{bb} \approx 1$

and $\chi = \chi_{LSP} + W, Z's$

⇒ multi top events
⇒ spherical events
⇒ 4 b's always

4.2 A largely unconventional Higgs sector



$h \to ZZ \to l^+l^- \, l^+l^-$ or even $h \to aa \to \tau\tau \; bb$ with a large rate

$H \to hh \to 4V \to l^+l^- \, 6j$ $\quad BR \propto \lambda^2$ $\quad$ much larger than normal

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

Vectors: a "composite" ρ-like state

V^{μ}_{a} = a $SU(2)_{L+R}$- triplet   Why light? (unitarity, EWPT?)

The formalism is there since always (CCWZ):

$$u \equiv \sqrt{U} \rightarrow g_R u h^\dagger = h u g_L^\dagger$$ under $SU(2)_L \times SU(2)_R$

$$V_\mu = \frac{1}{\sqrt{2}} \tau^a V_\mu^a, \;\; V^\mu \rightarrow h V^\mu h^\dagger$$

unlike a standard gauge boson!

two more covariant vectors made of π, W, B

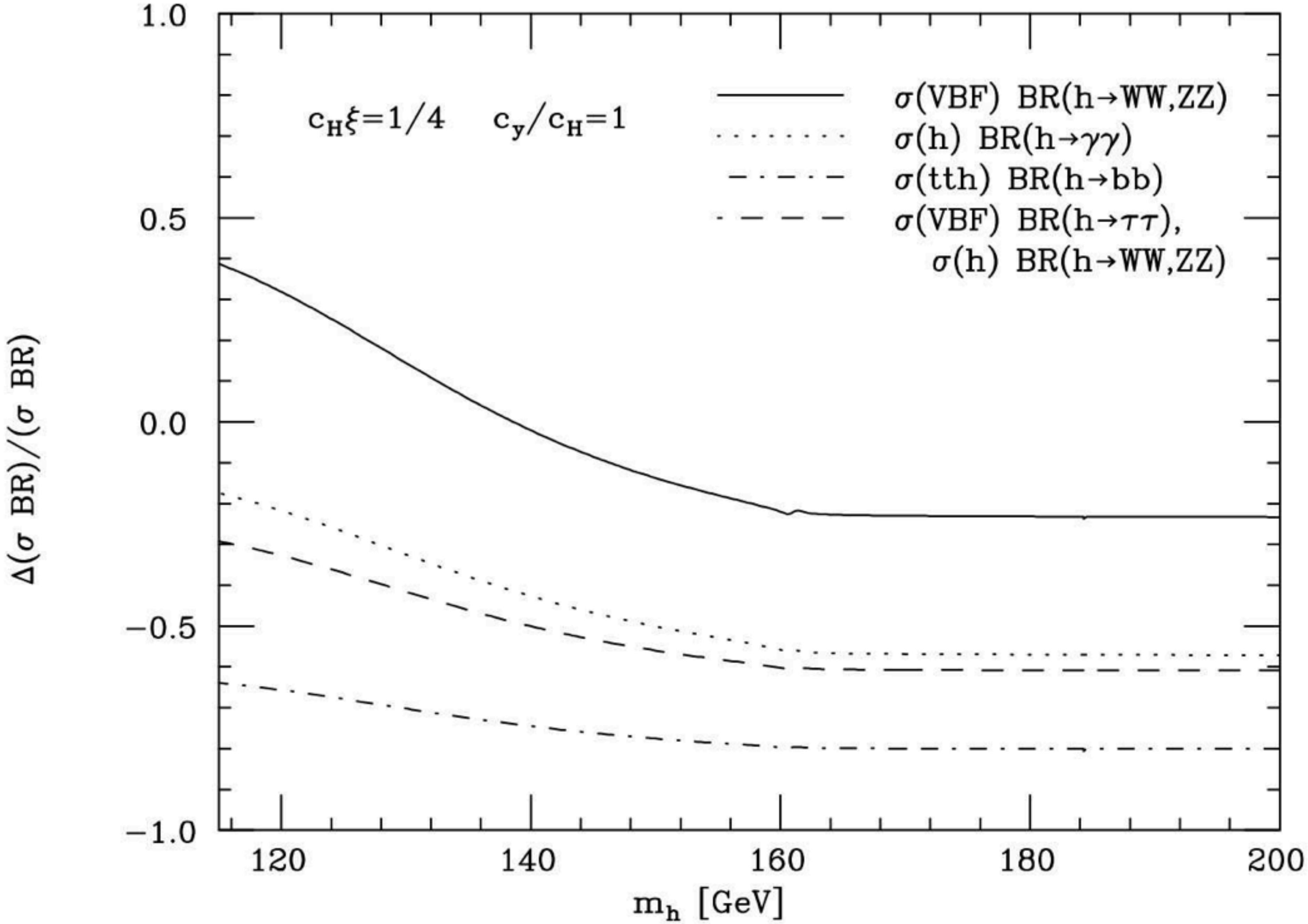
$$\Gamma_\mu = \frac{1}{2} \Big[u^\dagger \left(\partial_\mu - i B_\mu \right) u + u \left(\partial_\mu - i W_\mu \right) u^\dagger \Big]$$

$$u_\mu = u_\mu^\dagger = i u^\dagger D_\mu U u^\dagger$$

E.g.:

$$\mathcal{L}_{\mathrm{kin}}^{V} = -\frac{1}{4} \left\langle \hat{V}^{\mu\nu} \hat{V}_{\mu\nu} \right\rangle + \frac{M_V^2}{2} \left\langle V^\mu V_\mu \right\rangle \;,$$

$$\hat{V}_{\mu\nu} = \nabla_\mu V_\nu - \nabla_\mu V = \partial_\mu V + [\Gamma_\mu, V]$$



$c_H\xi=1/4$ $c_y/c_H=1$
σ(VBF) BR(h→WW,ZZ)
σ(h) BR(h→$\gamma\gamma$)
σ(tth) BR(h→bb)
σ(VBF) BR(h→$\tau\tau$),
σ(h) BR(h→WW,ZZ)
$\Delta(\sigma$ BR$)/(\sigma$ BR$)$
m_h [GeV]
1.0
0.5
0.0
−0.5
−1.0
120
140
160
180
200