Defending a Non Standard Supersymmetric Spectrum

A bottom-up viewpoint

Riccardo Barbieri

Workshop on Heavy Particles at the LHC
Pauli Center, ETH, January 5 - 7, 2011

B, Bertuzzo, Farina, Lodone, Pappadopulo, Zhuridov

(Quite a change relative to most of yesterday's talks.
A healthy blending, I suppose, hopefully soon driven by data)

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

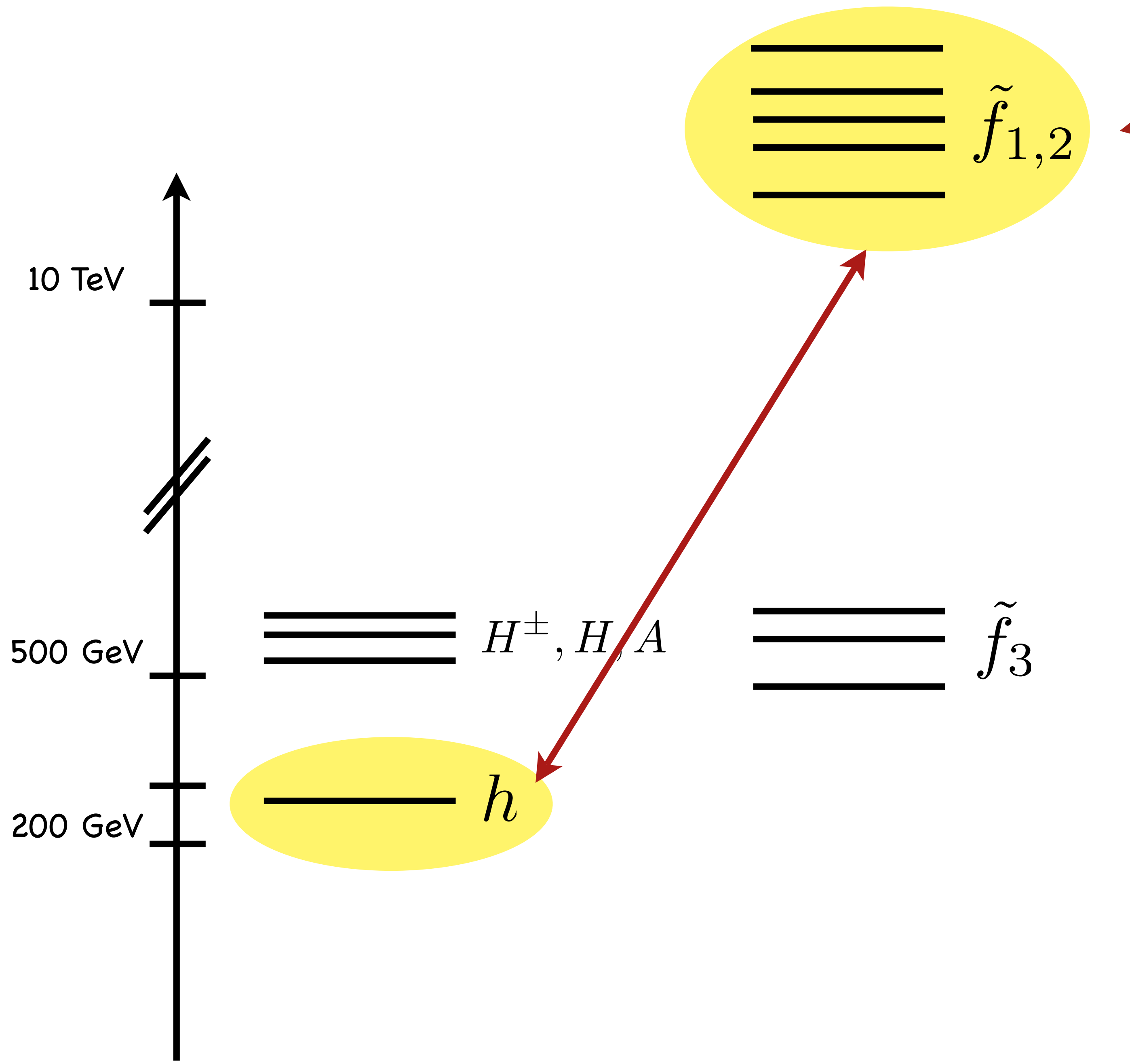
Flavour and CP (The SM works in a quantitative way)

The MSSM as the only paradigm?

Claim $\Leftrightarrow$ All problems of fine Tuning

(It could be right and we might never know)

A non-standard Supersymmetric Spectrum
Motivated? Possible at all?

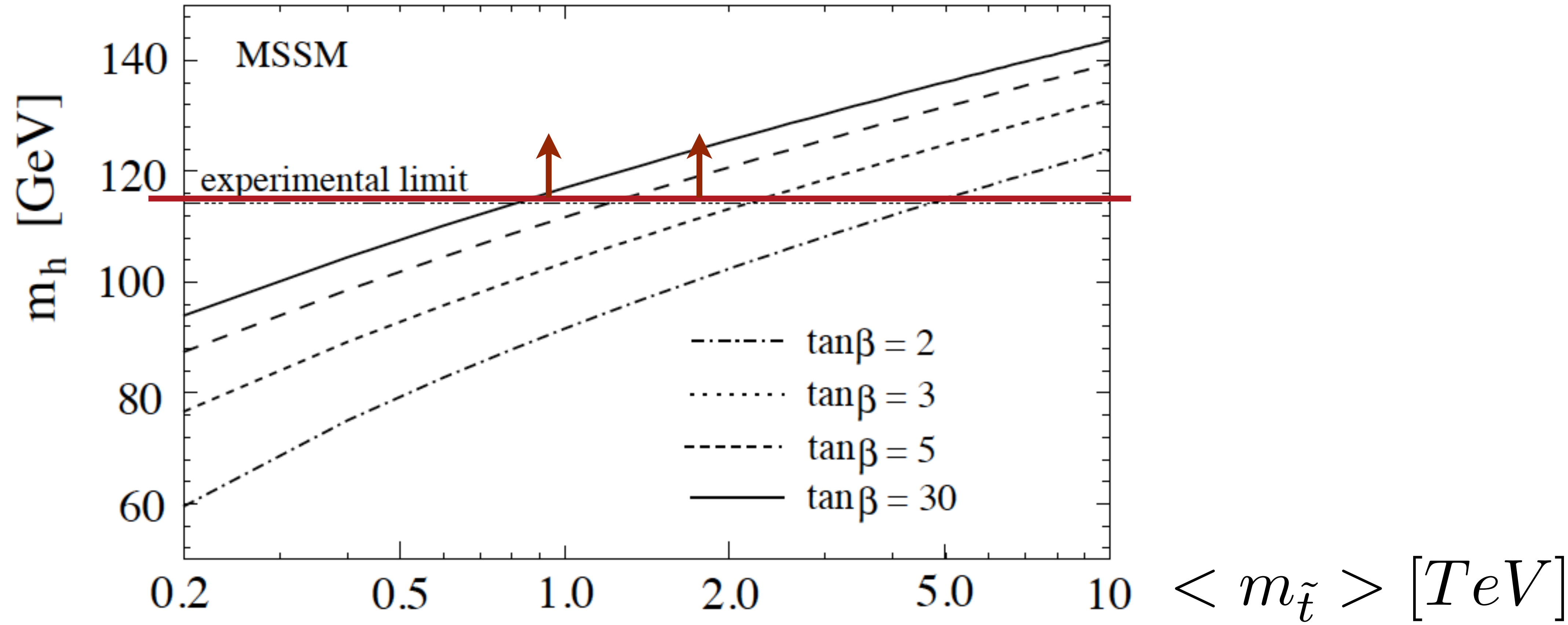


Dine, Kagan, Samuel
Pomarol, Tommasini
Cohen, Kaplan, Nelson
Dimopoulos, Giudice

⇒ the Higgs boson mass problem
⇒ the flavour problem

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

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

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

Harnik, Kribs, Larson, Murayama

B, Hall, Nomura, Rychkov

⇒ h not standard and not even light

ElectroWeak Precision Tests in λSUSY

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

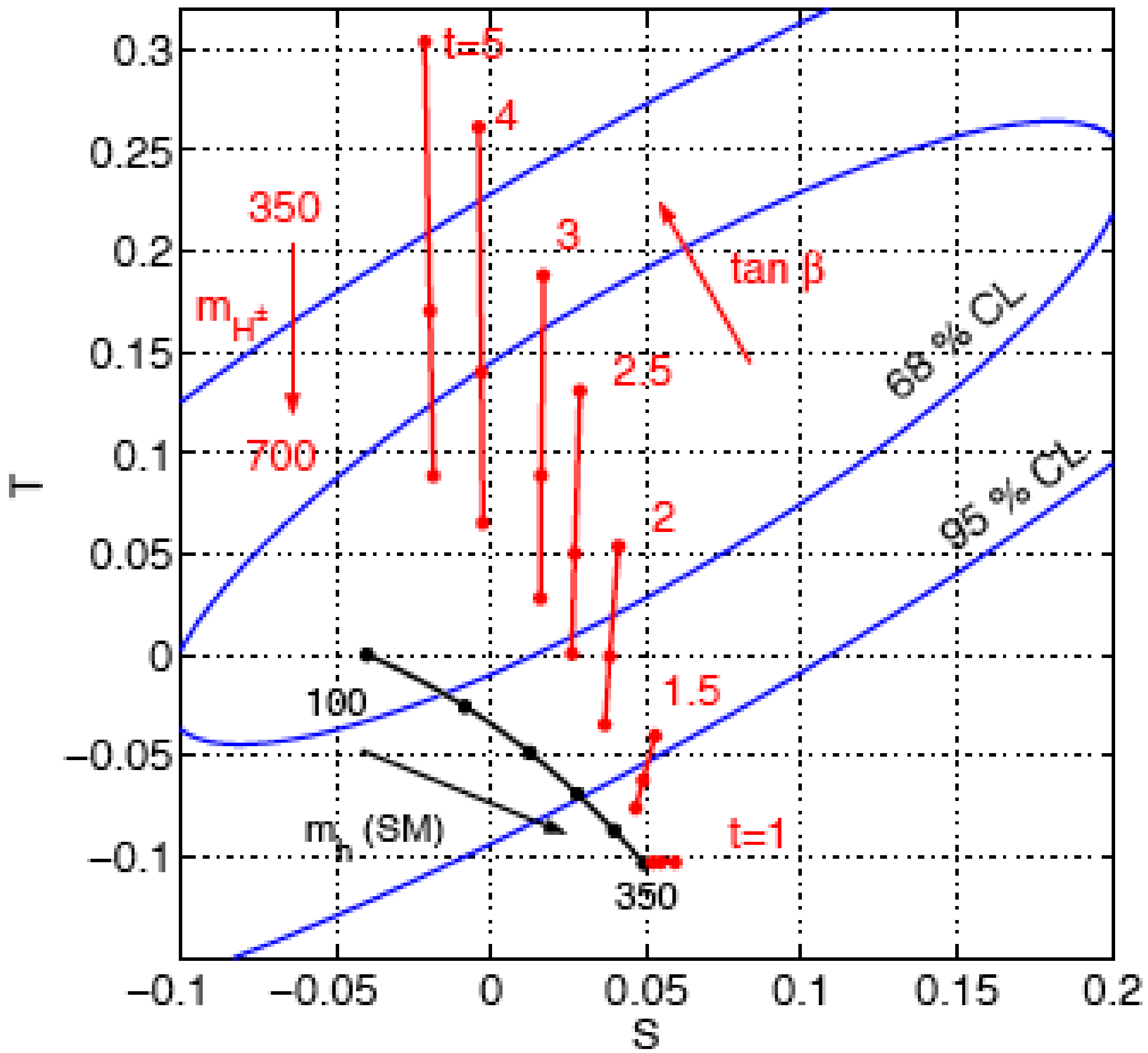
S and T from Higgs's

one loop effects but

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

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

compensated by $\Delta T \uparrow$

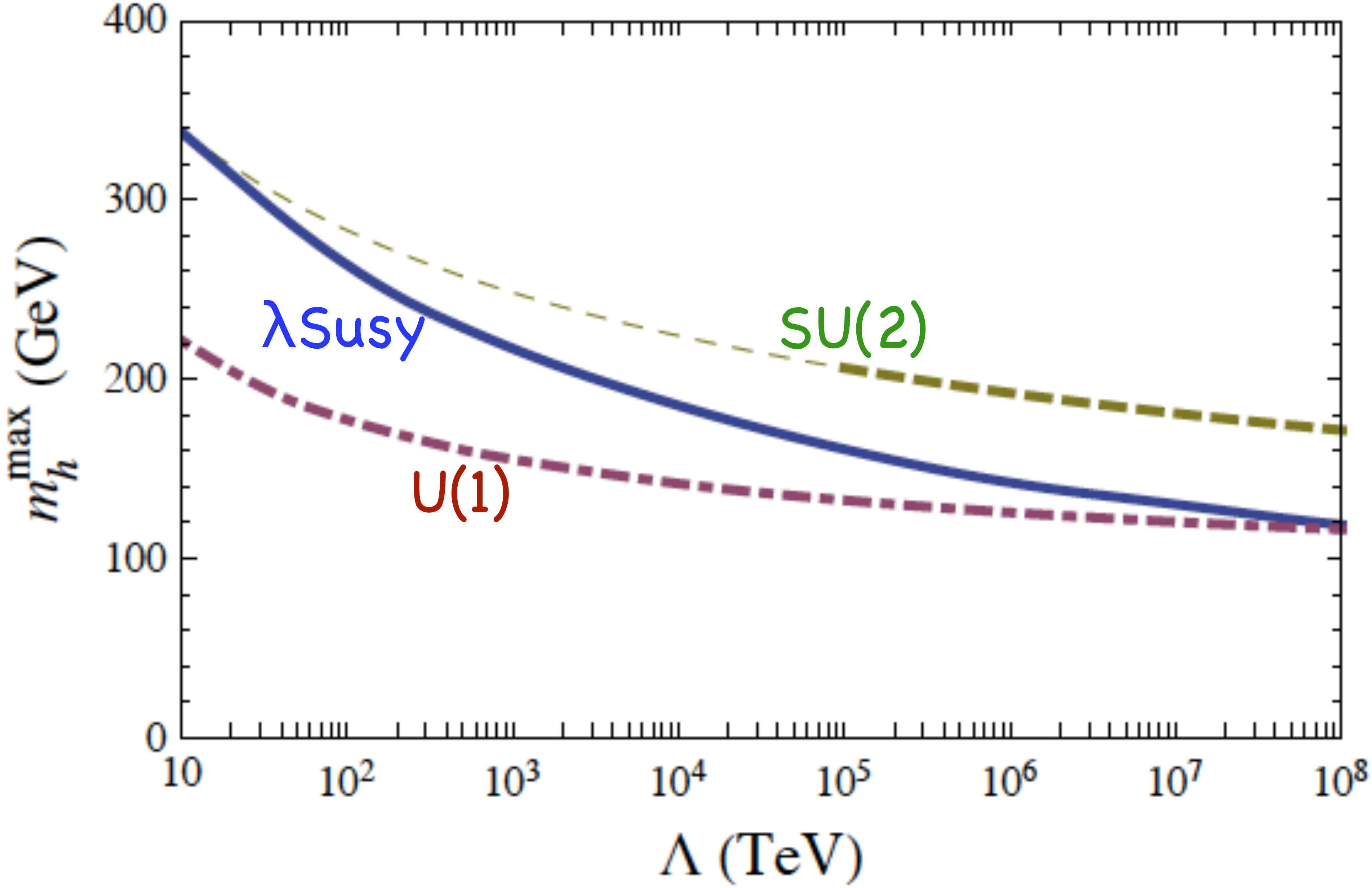


B, Hall, Nomura, Rychkov

The price to pay

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

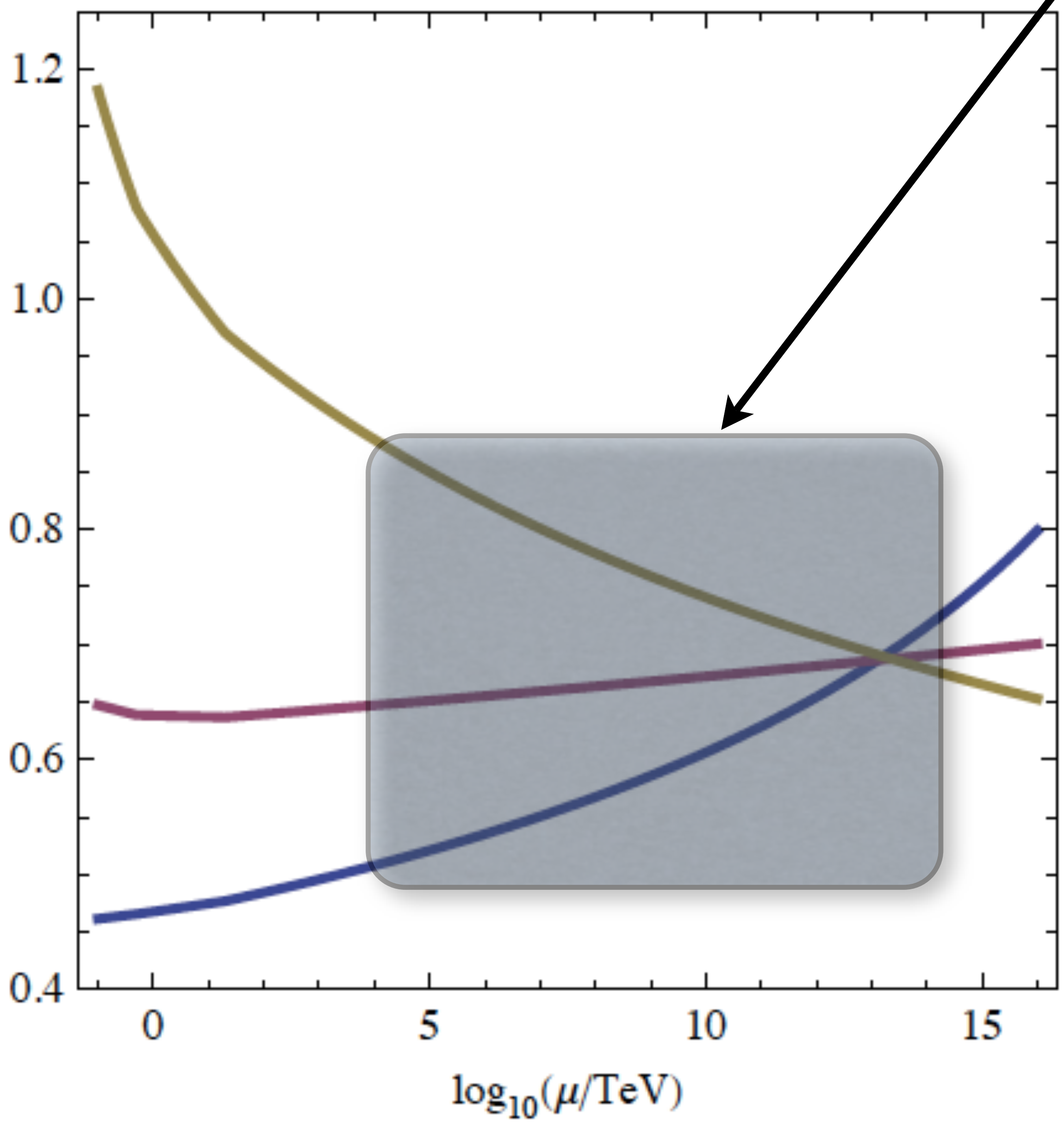
At a scale Λ some coupling starts blowing



unless some change of regime occurs before

What about gauge-coupling unification, then?

a grey box



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?!

Flavour and CP violation

2000÷2010: The CKM picture quantitatively successful

⇒ Generic BSM physics highly constrained

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Bounds on Λ in TeV ($c_{ij}=1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	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}

Isidori, Nir, Perez
2010

especially with new degrees of freedom
carrying flavour at the Fermi scale

What about supersymmetry?

A - The prevailing answer:

$U(3)_{\hat{Q}} \times U(3)_{\hat{u}} \times U(3)_{\hat{d}}$ only broken by $Y = (3, \bar{3})$

$\Rightarrow \quad m^2_{\tilde{q}} = m^2(\mathbf{1} + aY^+Y), \quad A = A_0 Y$

Goes a long way in addressing the flavour problem:

Under mild further hypotheses:

V_{CKM} as the only mixing matrix in $d_L \rightarrow V_{CKM} d_L$ and

$\mathcal{A}^{\Delta F=2,1}_{\alpha\beta} = \mathcal{A}^{\Delta F=2,1}_{\alpha\beta}|_{SM}(1 + \epsilon^{\Delta F=2,1})$ with $\alpha, \beta = d, s, b$

(often called "Minimal Flavour Violation")

but for flavour-blind CP-phases

$$d_e \;\Rightarrow\; m_{\tilde{l}_1} \gtrsim 4\ TeV (\sin\phi_\mu \tan\beta)^{1/2}$$

$d_n \;\Rightarrow\; m_{\tilde{q}_1} \gtrsim 3\ TeV (\sin\phi_\mu \tan\beta)^{1/2}$ or $3\ TeV (\sin\phi_A \frac{A_0}{m_{\tilde{q}}})^{1/2}$

B - Our proposal:

1 - Only squarks coupled to H by Y_{top} light: $\tilde{t}_L, \tilde{t}_R, \tilde{b}_L$

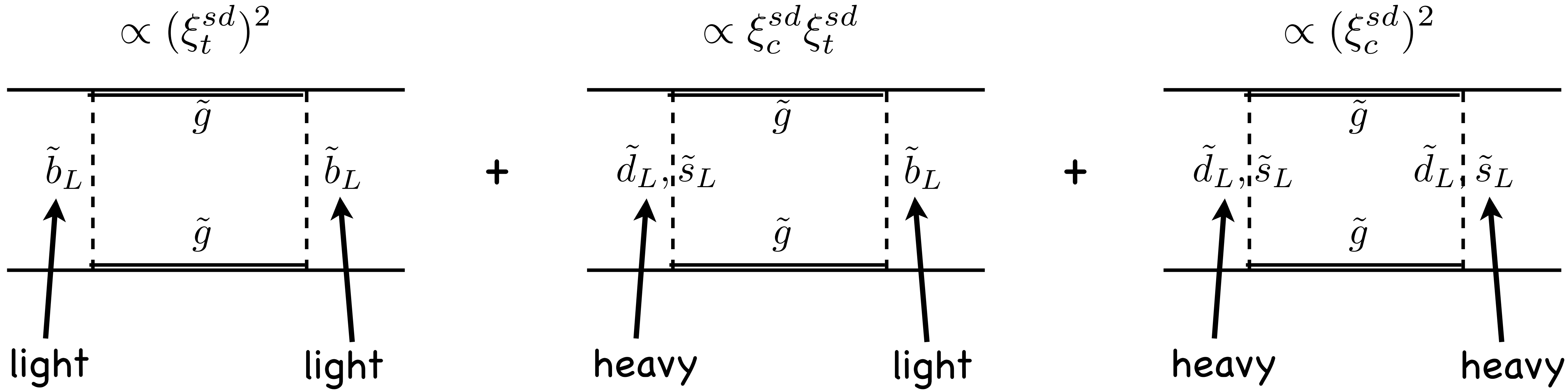
2 - With Y_u switched on, but not Y_d, individual flavours conserved

$$U(1)_{\tilde{B}_1} \times U(1)_{\tilde{B}_2} \times U(1)_{\tilde{B}_3} \times U(3)_{d_R} \quad \text{only broken by} \quad Y_{d_i} = (\mathbf{1}_{B_i}, \ \mathbf{3})$$

⇒ As in A, V_{CKM} still the only mixing matrix from $d_L \to V_{CKM} d_L$, without degenerate $\tilde{Q}_i, \tilde{u}_i$

general structure of susy effects, e.g., in ΔS=2:

$\xi_i^{sd} = V_{is} V_{id}^*, \ i = u, c, t$

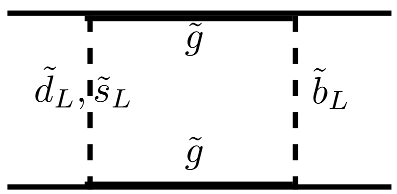


⇒ Effective Minimal Flavour Violation, if "lh" and "hh" negligible

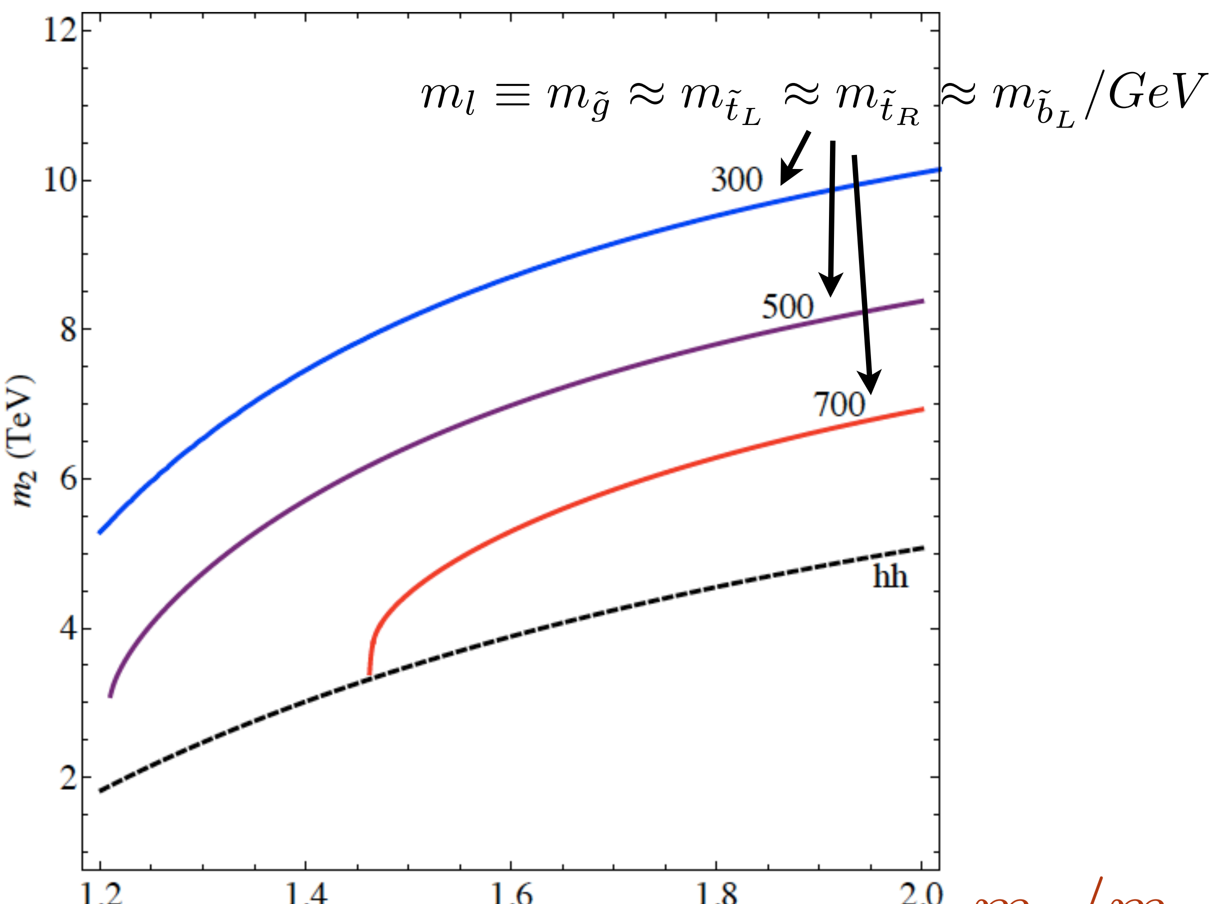
Rigorous (lower) bounds on $m_{\tilde{f}_{1,2}}$

Dominant effects:

Im(ΔS=2) from lh exchange



$m_2 (TeV)$

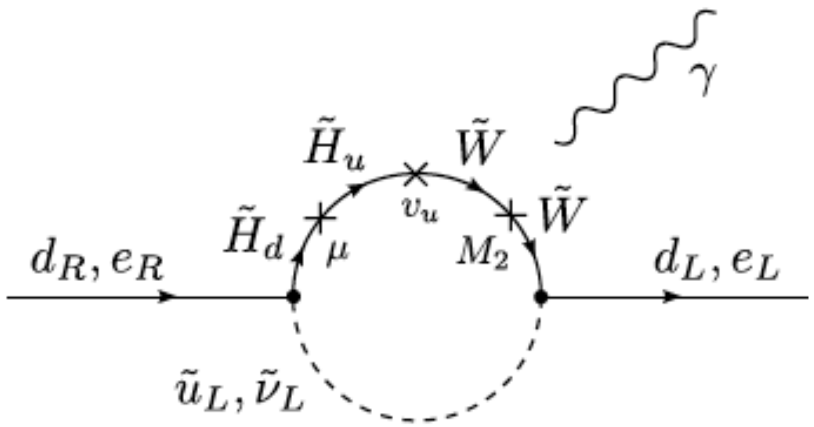


m_2/m_1

$$m_i \equiv m_{\tilde{u}_{R_i}} \approx m_{\tilde{u}_{L_i}} \approx m_{\tilde{d}_{L_i}}, \quad i = 1, 2$$

EDM's

only one diagram not suppressed by high powers of m_h or small angles



$$d_e \;\Rightarrow\; m_{\tilde{l}_1} \gtrsim 4\, TeV (\sin\phi_\mu \tan\beta)^{1/2}$$

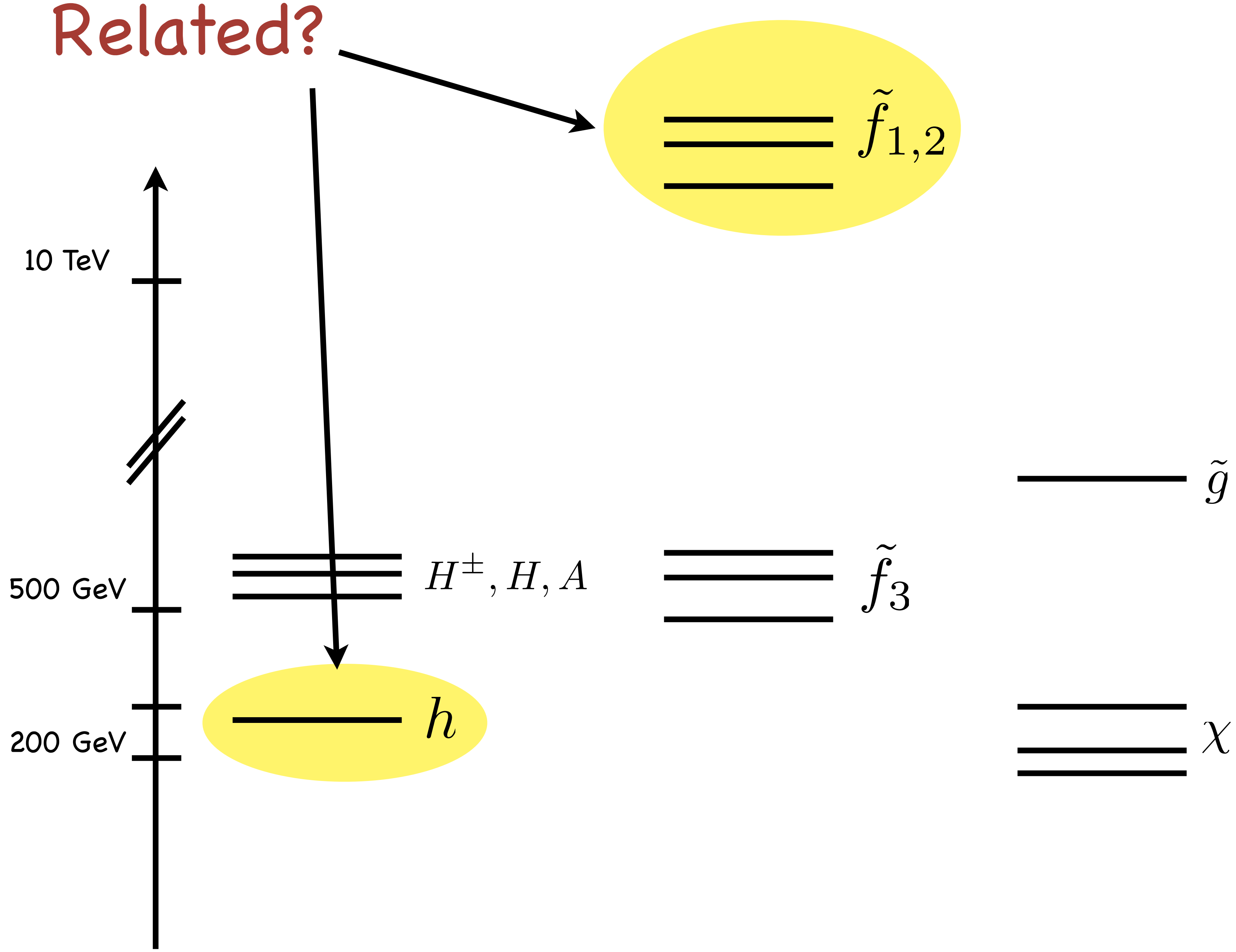
$$d_n \;\Rightarrow\; m_{\tilde{q}_1} \gtrsim 3\, TeV (\sin\phi_\mu \tan\beta)^{1/2}$$

⇒ Need $m_{\tilde{f}_{1,2}} \gtrsim 10\, TeV$ to be on the safe side

A non-standard Supersymmetric Spectrum

Motivated? Yes

Related?



⇒ the Higgs boson mass problem

⇒ the flavour problem

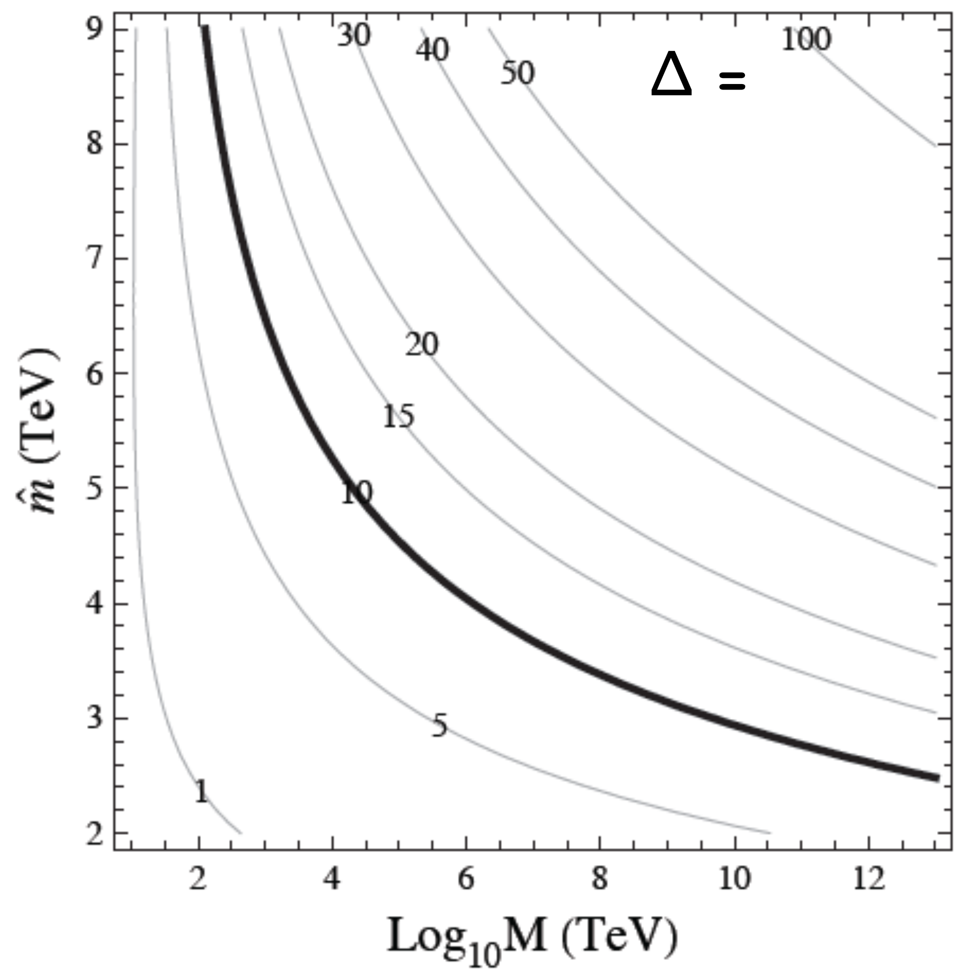
A matter of naturalness, once again

the Higgs mass problem $\Leftrightarrow$ $\frac{m_{\tilde{t}}^2}{m_h^2} \frac{\delta m_h^2}{\delta m_{\tilde{t}^2}}$

the flavour problem $\Leftrightarrow$ $\frac{m_{\tilde{f}_{1,2}}^2}{m_h^2} \frac{\delta m_h^2}{\delta m_{\tilde{f}_{1,2}}^2}$

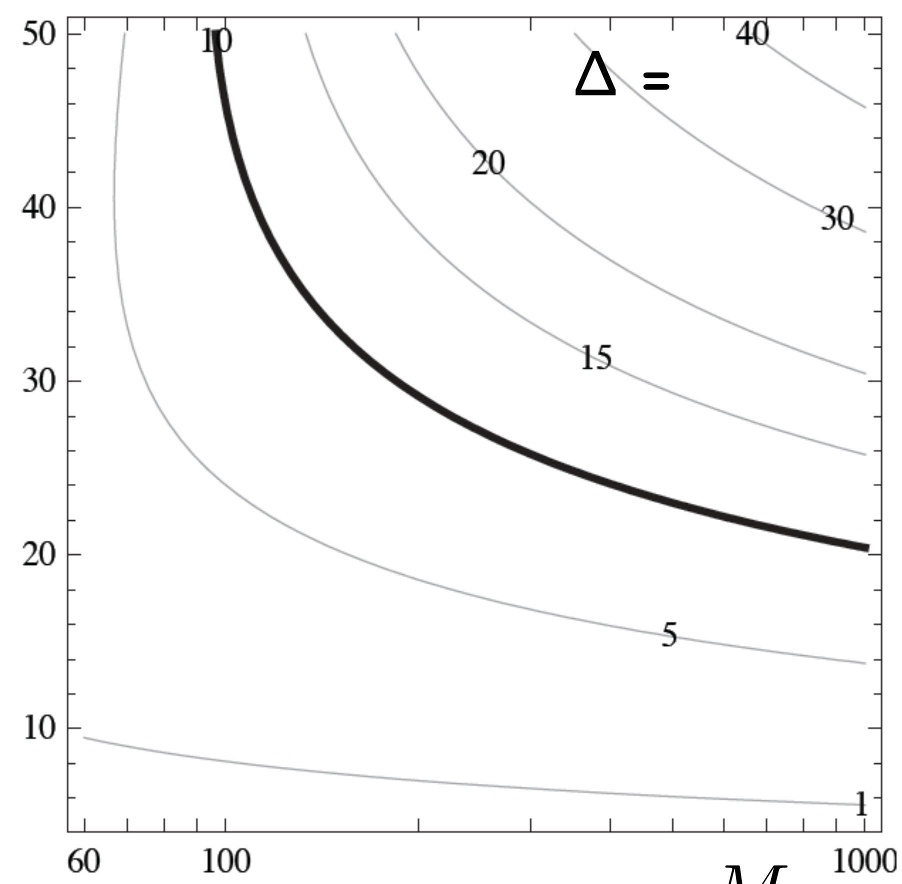
Both problems ameliorated by a heavier m_h

MSSM $m_h^{max} = 91\ GeV$



$m_{\tilde{f}_{1,2}}/TeV$

λSusy $m_h^{max} = 250\ GeV$



M_{susy}/TeV

Phenomenological consequences

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

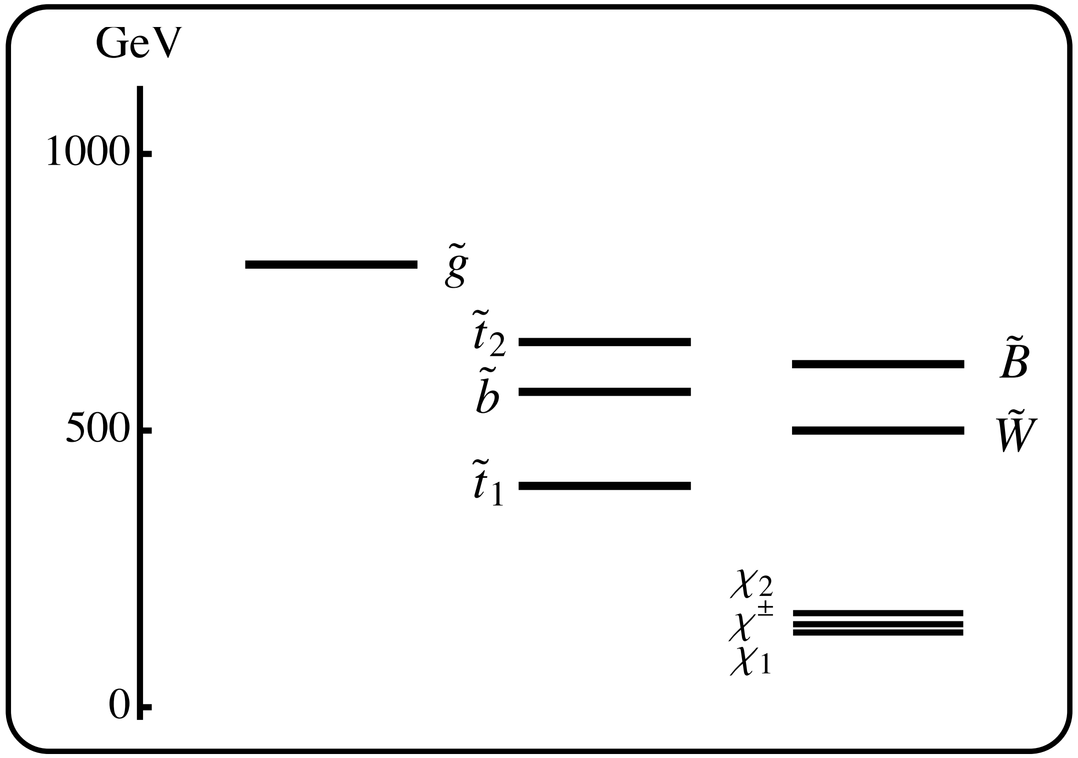
- ✶ a largely unconventional Higgs sector
  (non MSSM-like)

- ✶ Dark Matter: relic abundance and detection
  affected

- ✶ Flavour signals in EDM's and
  direct CP violation in b-physics (at low $\tan\beta$)

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

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

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

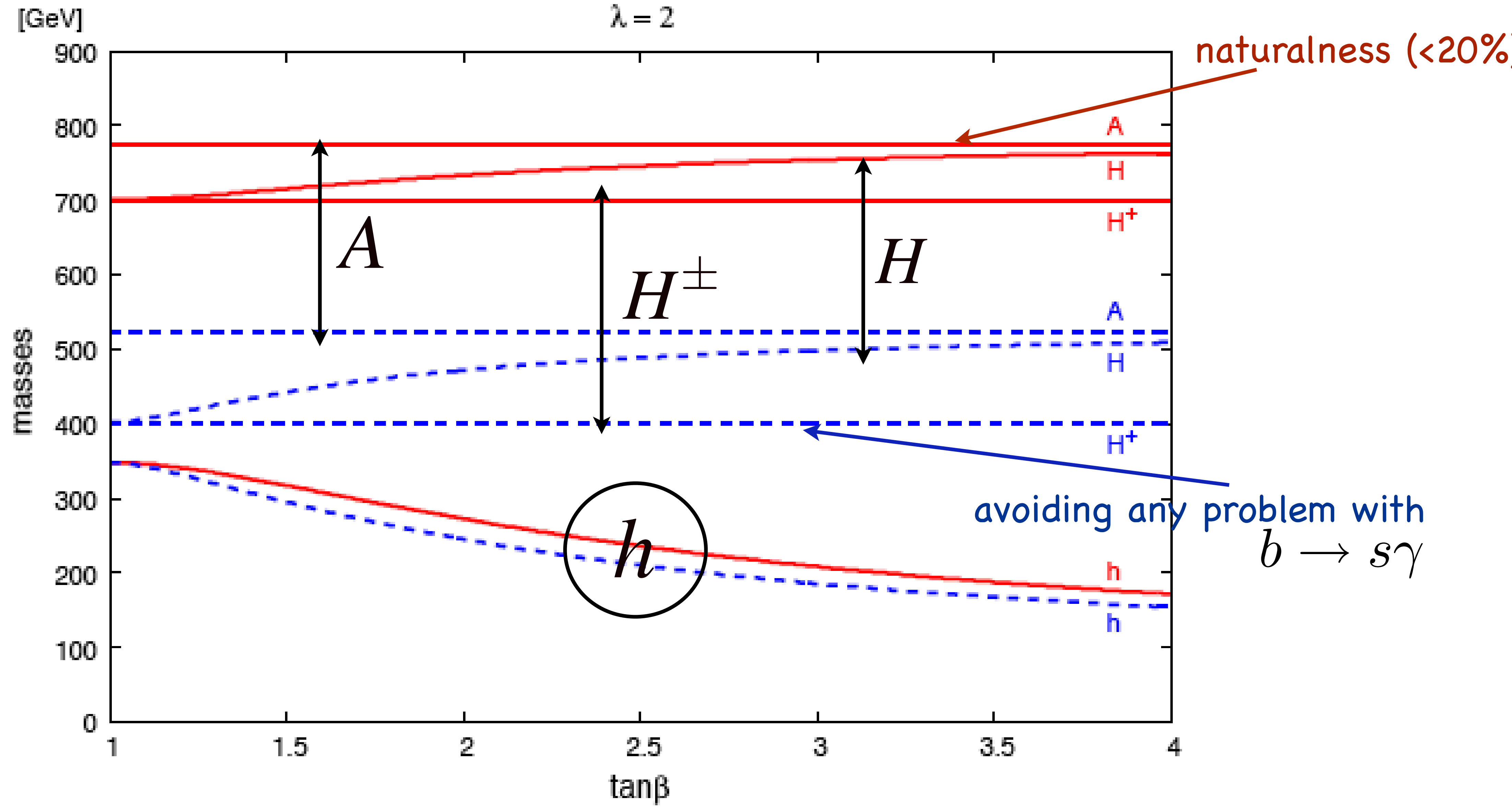
$$\tilde{g} \to b\bar{b}\chi$$

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

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

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

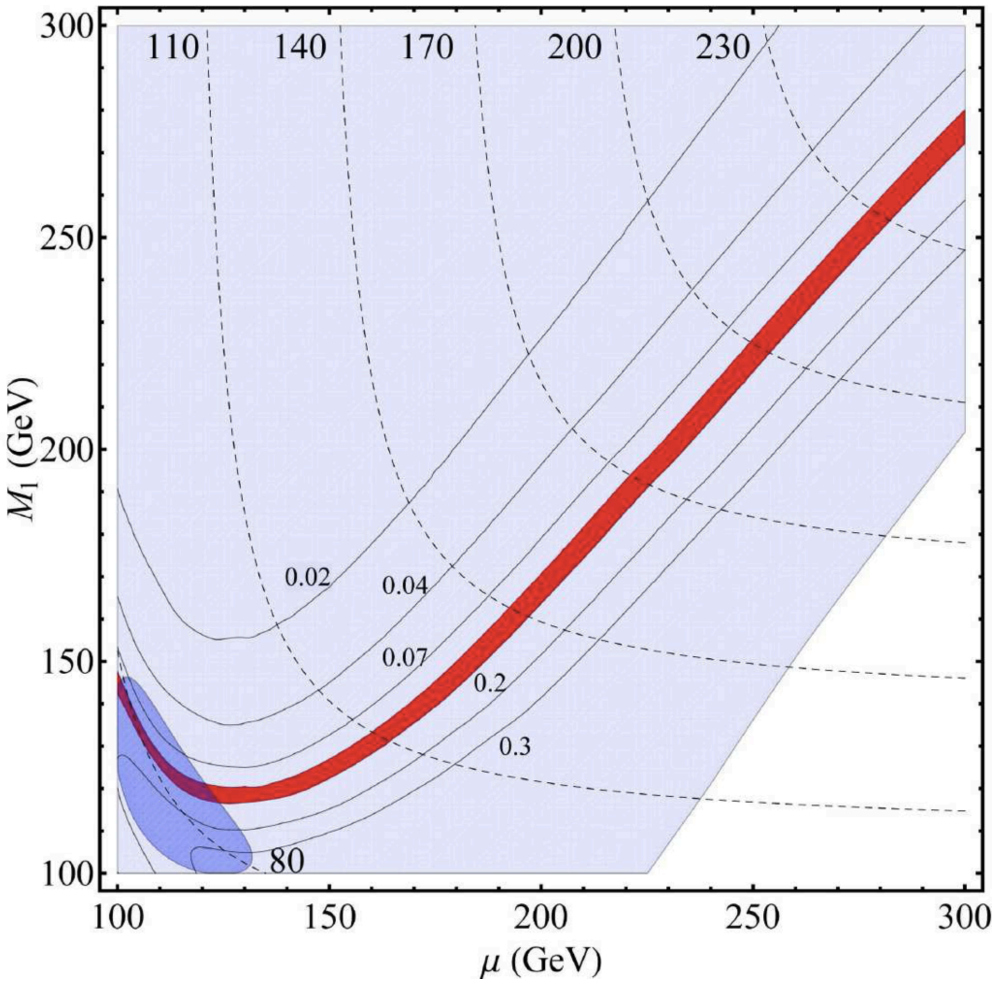
4.3 Dark Matter: relic abundance and detection

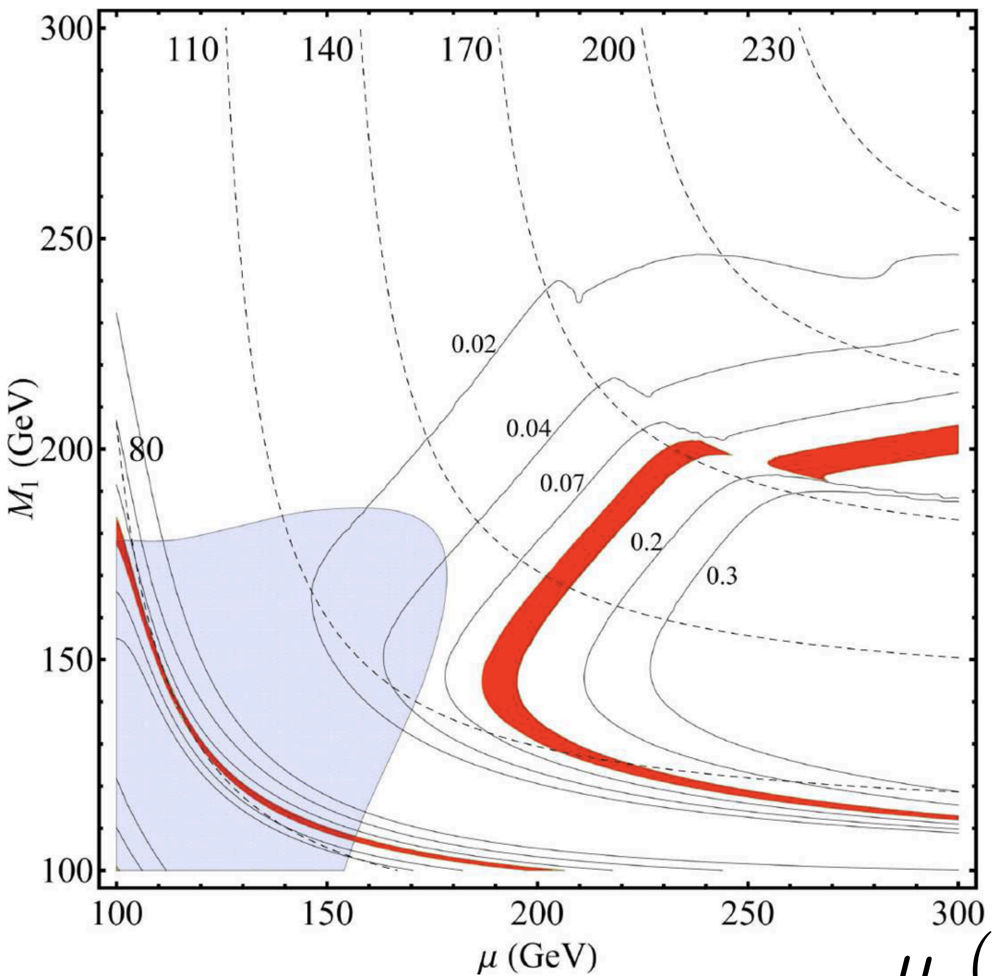
Relic abundance:

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

Conclusions

✶ The elusiveness of supersymmetry so far suggests giving consideration to a Non Standard Supersymmetric Spectrum where:

$$m_h = 200 \div 250 \; GeV$$
$$m_{\tilde{f}_{1,2}} \gtrsim 10 \; TeV >> m_{\tilde{f}_3}$$

✶ Naturally possible at least in λSusy
(although with canonical unification under threat)

✶ Phenomenology (non MSSM-like):

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

⇒ $h \to ZZ, \; aa; \quad H \to hh, \; hhh$

⇒ DM: no "well-temperation"
Direct Detection affected

⇒ CP-violation signals in EDM's and b-physics

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

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

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

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

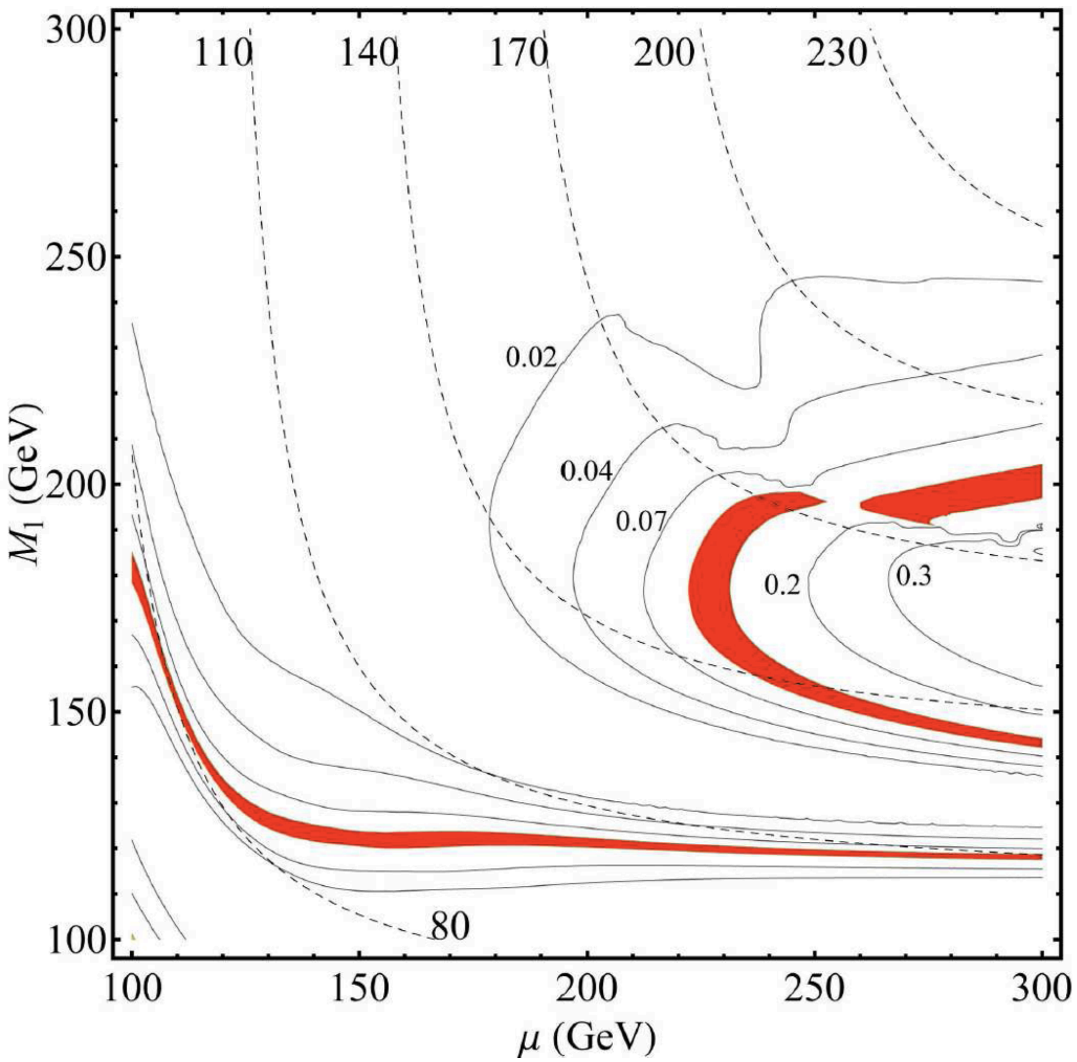
	operator $\mathcal{O}$	affects	constraint on Λ
	$\frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	μ-decay	10 TeV
	$\frac{1}{2}(\bar{L}\gamma_\mu L)^2$	LEP 2	5 TeV
T→	$\lvert H^\dagger D_\mu H \rvert^2$	θ_{W} in M_W/M_Z	5 TeV
S→	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	θ_{W} in Z couplings	8 TeV
	$i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L)$	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

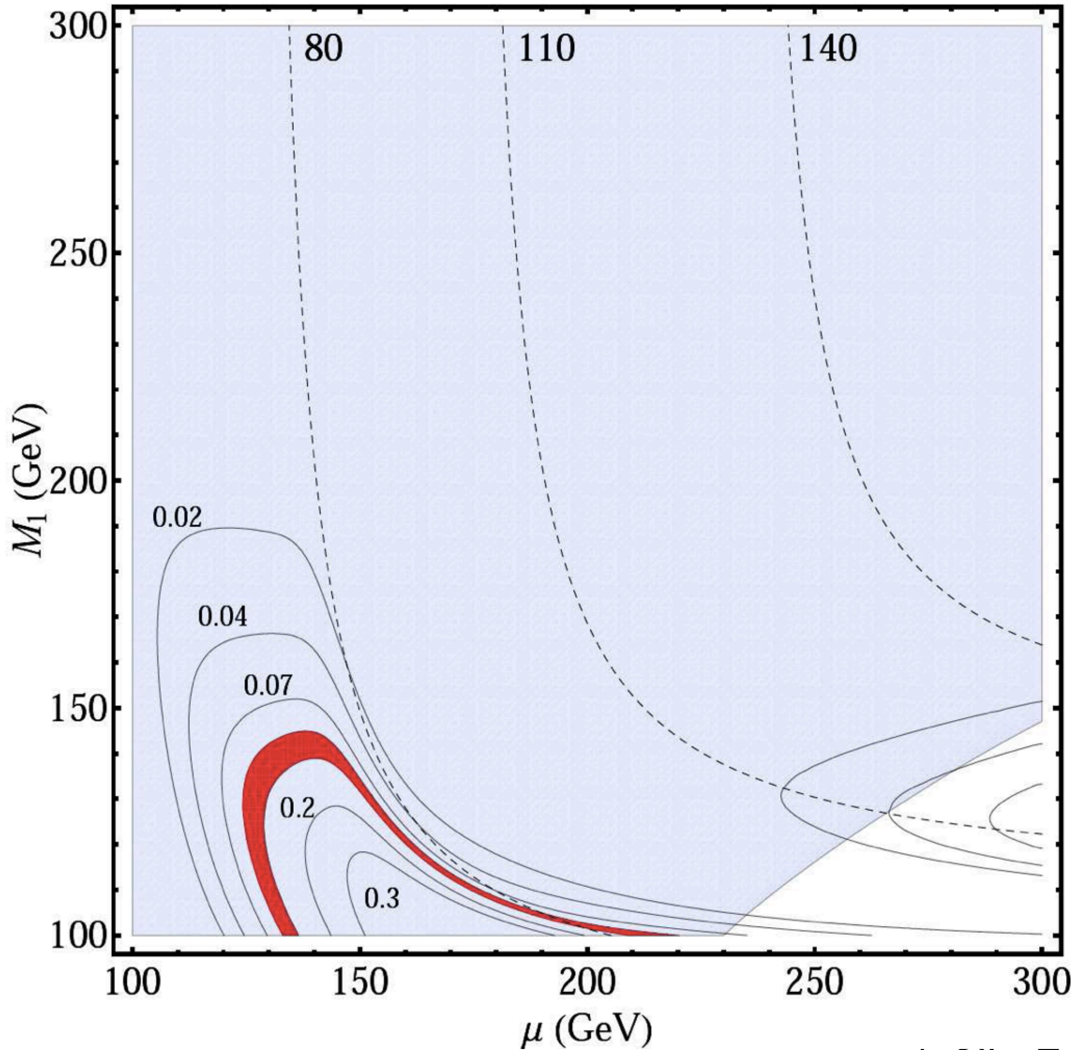
More conservatively: $\Lambda > \sim 5$ TeV

4.3 Dark Matter: relic abundance and detection

$M_1 (GeV)$ $\qquad$ M_2 large



$M_2 = 200\ GeV$

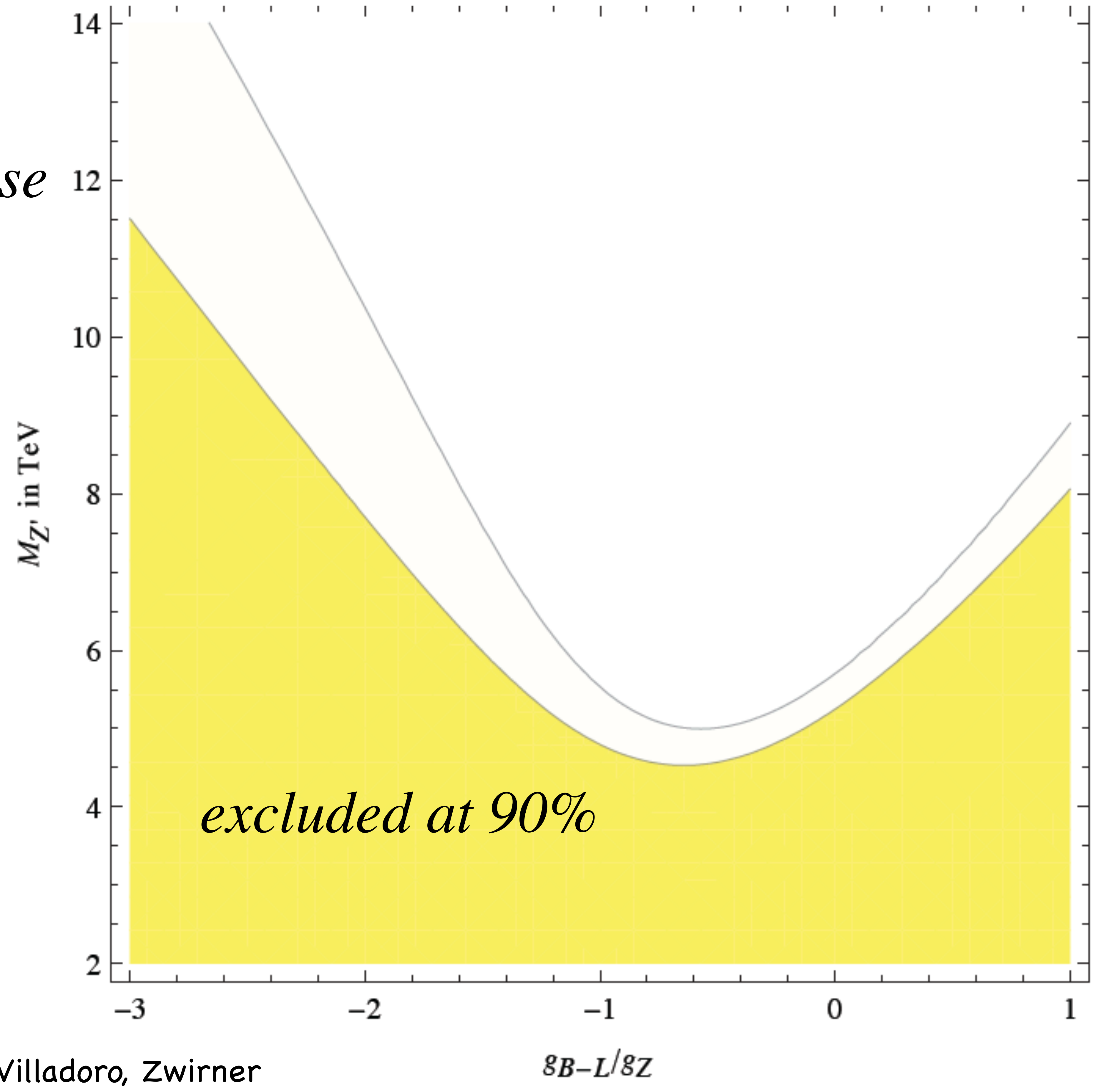


$\mu\ (GeV)$

λSusy: $m_h = 250\ GeV$

dark blu: CDMS now
light blu: "XENON100"

extra U(1) case



Salvioni, Strumia, Villadoro, Zwirner

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"

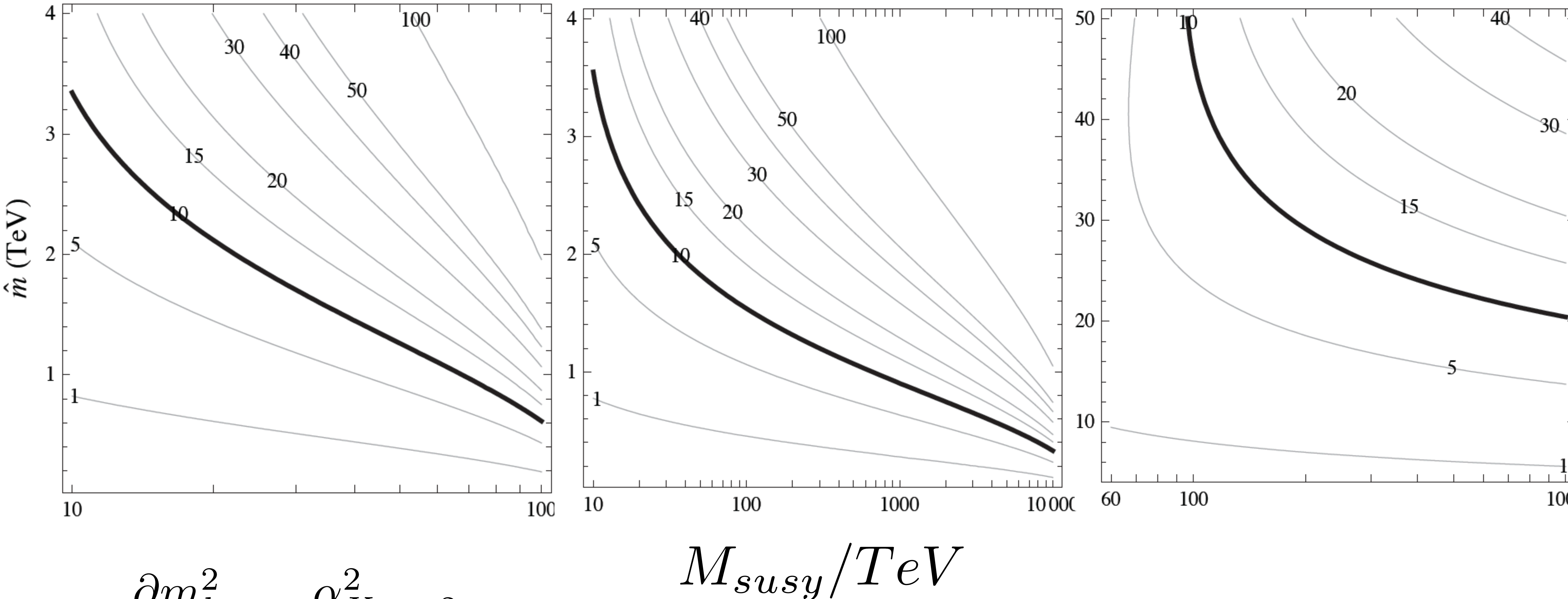
EWSB related to new forces, new degrees of freedom or even new dimensions opening up in the TeVs

perturbativity lost in the multi-TeV range

high E extrapolation highly uncertain

Naturalness bounds

U(1) $m_h^{max} = 180\ GeV$ SU(2) $m_h^{max} = 250\ GeV$ λSusy $m_h^{max} = 250\ GeV$



$$\frac{\partial m_h^2}{\partial t} \approx \frac{\alpha_X^2}{16\pi^2}\tilde{m}_{1,2}^2$$

$\hat{m}$ is $m_{\tilde{f}_{1,2}}$ with vertical degeneracy among $\tilde{f}$'s at M_{susy}

⇒ $m_{\tilde{f}_{1,2}} \gtrsim 20\ TeV$ OK in λSusy at M = 100÷1000 TeV

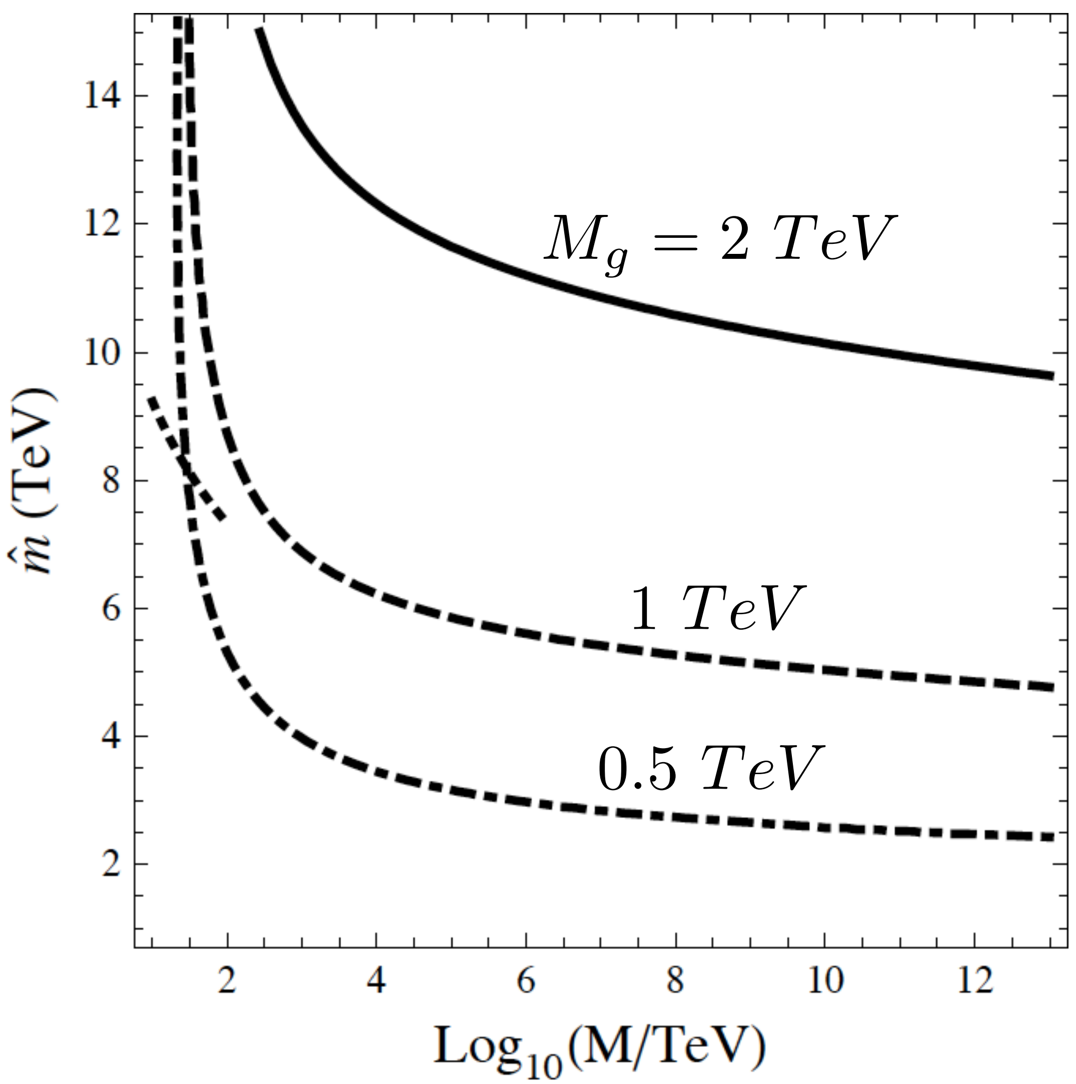
Colour/em conservation

Arkani-Hamed, Murayama

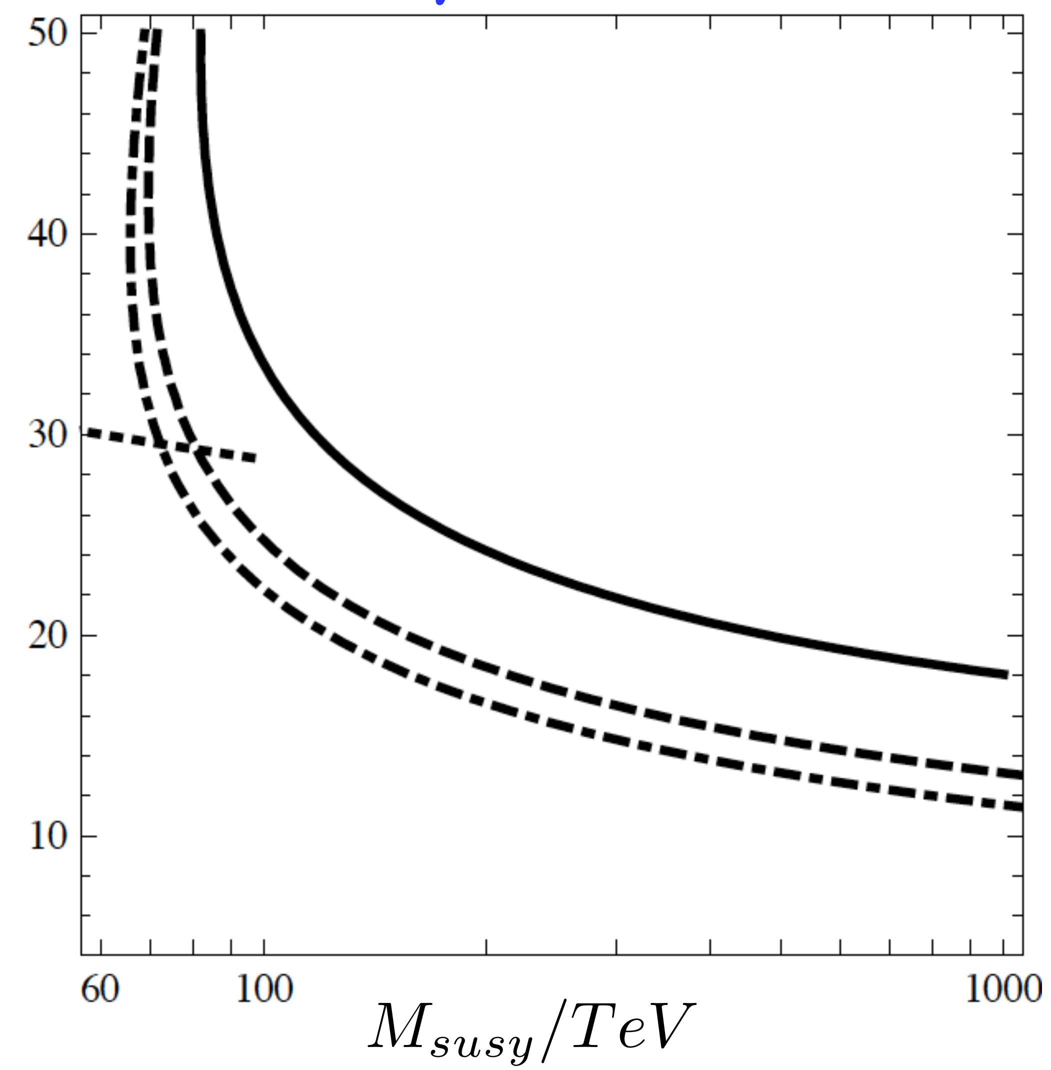
$$\frac{dm^2_{\tilde{Q}_3}}{d\log\mu} \approx -\frac{\alpha_S}{4\pi}M_g^2 + \frac{\alpha_S^2}{16\pi^2}\hat{m}^2_{1,2}$$

Require $m^2_{\tilde{Q}_3} > 0$ for natural $m^2_{\tilde{Q}_3}(M)$

MSSM $m_h^{max} = 90\ GeV$



λSusy $m_h^{max} = 250\ GeV$

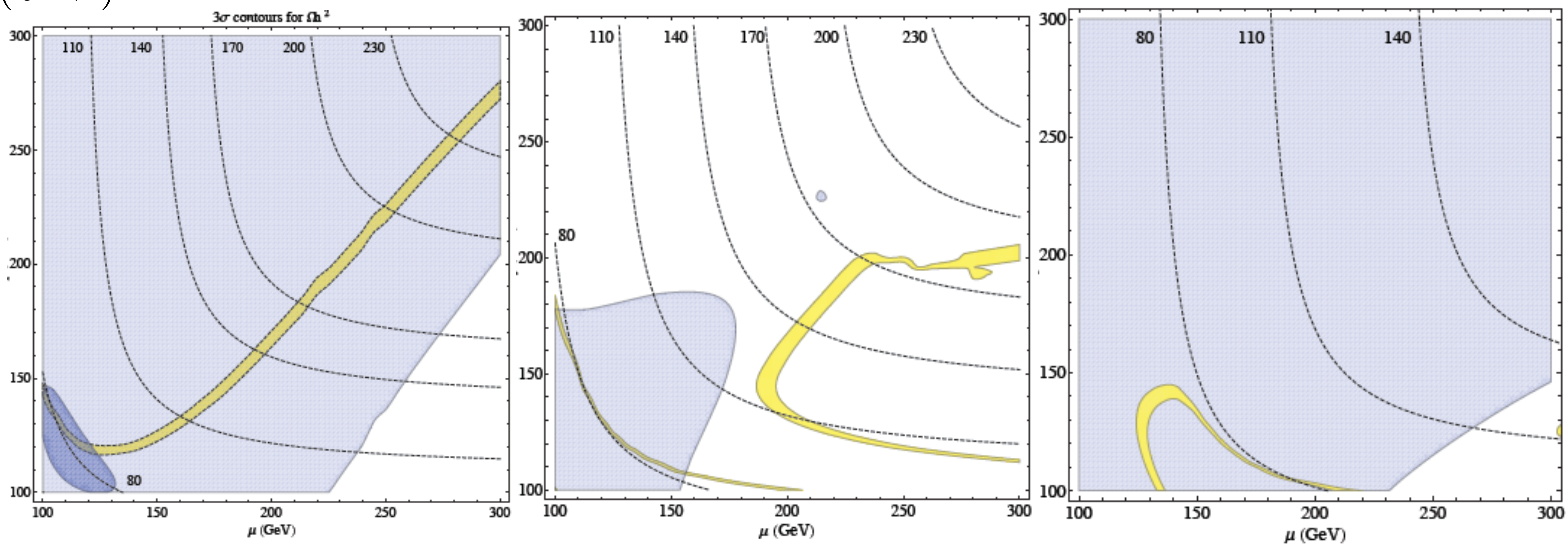


4.3 Dark Matter: relic abundance and detection

Relic abundance:

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

$M_1(GeV)$ M_2 large M_2 large $M_2 = 200\ GeV$



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