SUSY and the Higgs

or "A SM Higgs Guide to Find SUSY"

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in collaboration with:
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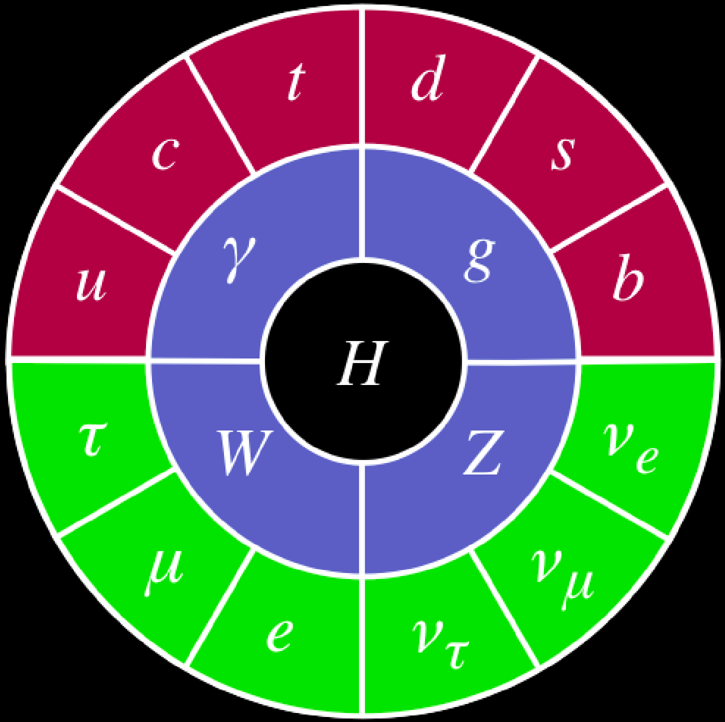

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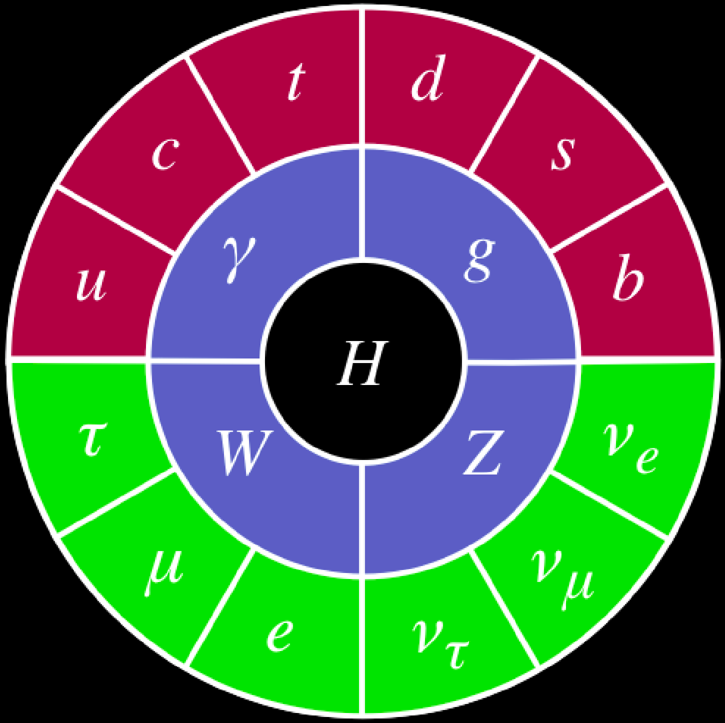

$$\mathcal{L}_{\mathrm{SM}} = -\frac{1}{4}F^2 + i\bar{\psi}\not{D}\,\psi + H\psi Y\psi + h.c. + |D_\mu H|^2 + m^2|H|^2 - \lambda|H|^4 - \Lambda$$

the Standard ~~Model~~ EFT

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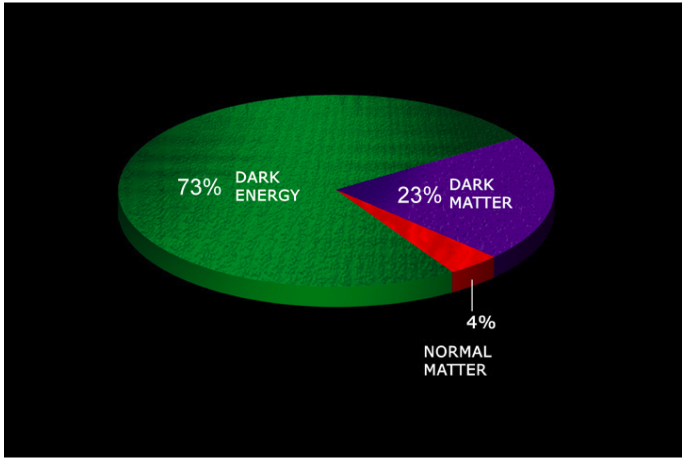

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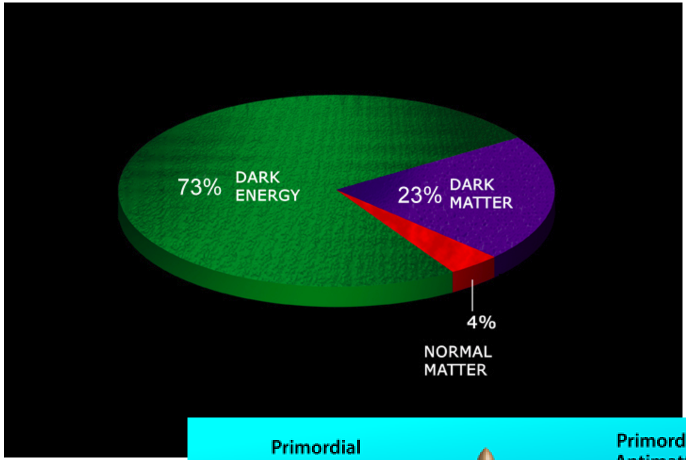

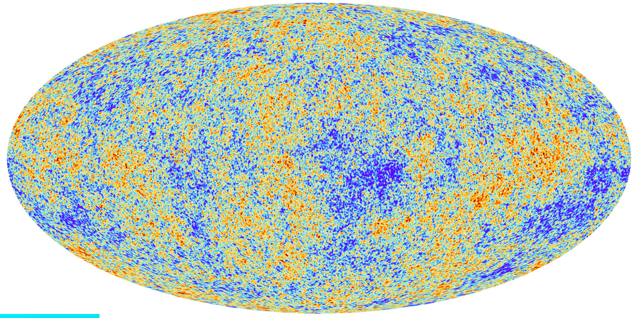

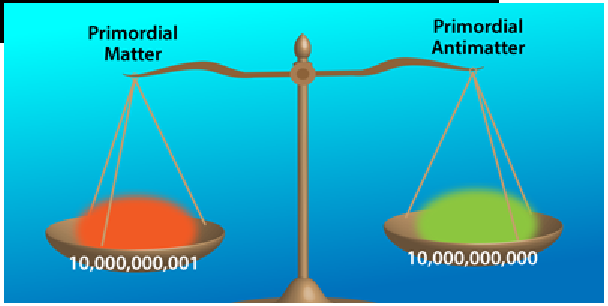

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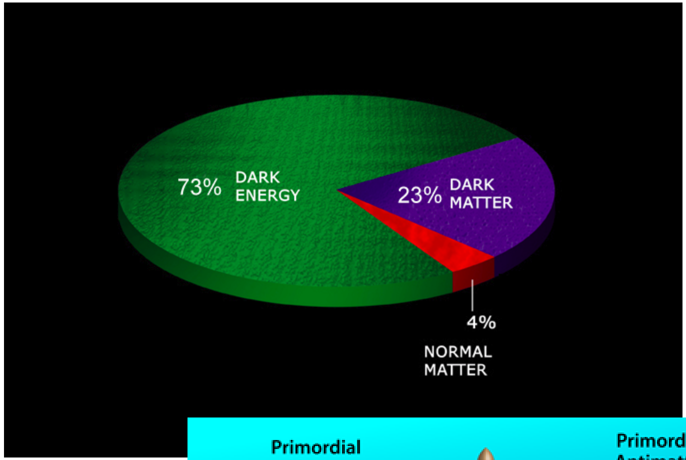

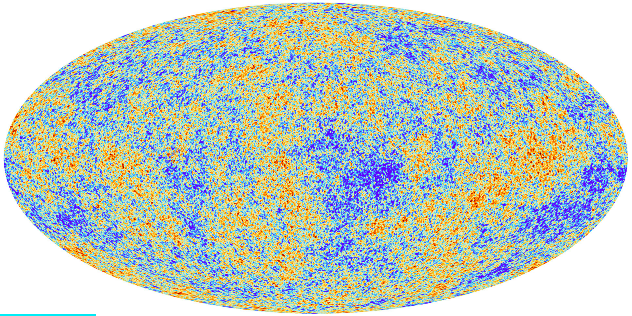

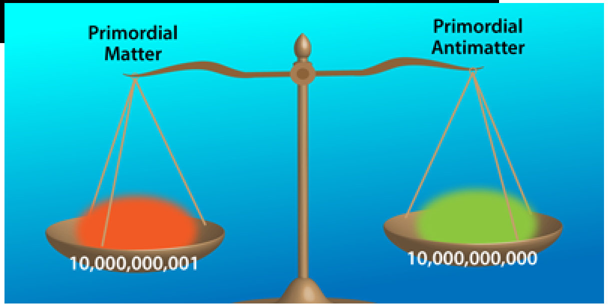

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naturally:

small FCNC:

$$\frac{\psi g \not{F} \psi}{M_{\rm NP}} + \dots$$

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large M_{NP}

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light EW scale: $\boxed{m^2 = M_{\rm NP}^2}$

The CC problem:

$$\overset{10^{-47}\ \text{GeV}^4}{\Lambda} = \overset{10^{-3}\ \text{GeV}^4}{-m_K^2 f_K^2} - \overset{10^{8}\ \text{GeV}^4}{\frac{1}{2} m_h^2 v^2} + \cdots + M_{\rm NP}^4$$

10^{-47} GeV^4 10^{-3} GeV^4 10^{8} GeV^4

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only known solution: SUSY – $\Lambda = m_{\mathrm{SUSY}}^4$

Λ prefers m_{SUSY} as low as possible!

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The EW hierarchy problem: $m^2 = M_{\rm NP}^2$

possible solutions: SUSY, composite models, extra-dimensions...

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt = (1.0 - 20.3)$ fb^{-1} $\sqrt{s}$ = 7, 8 TeV

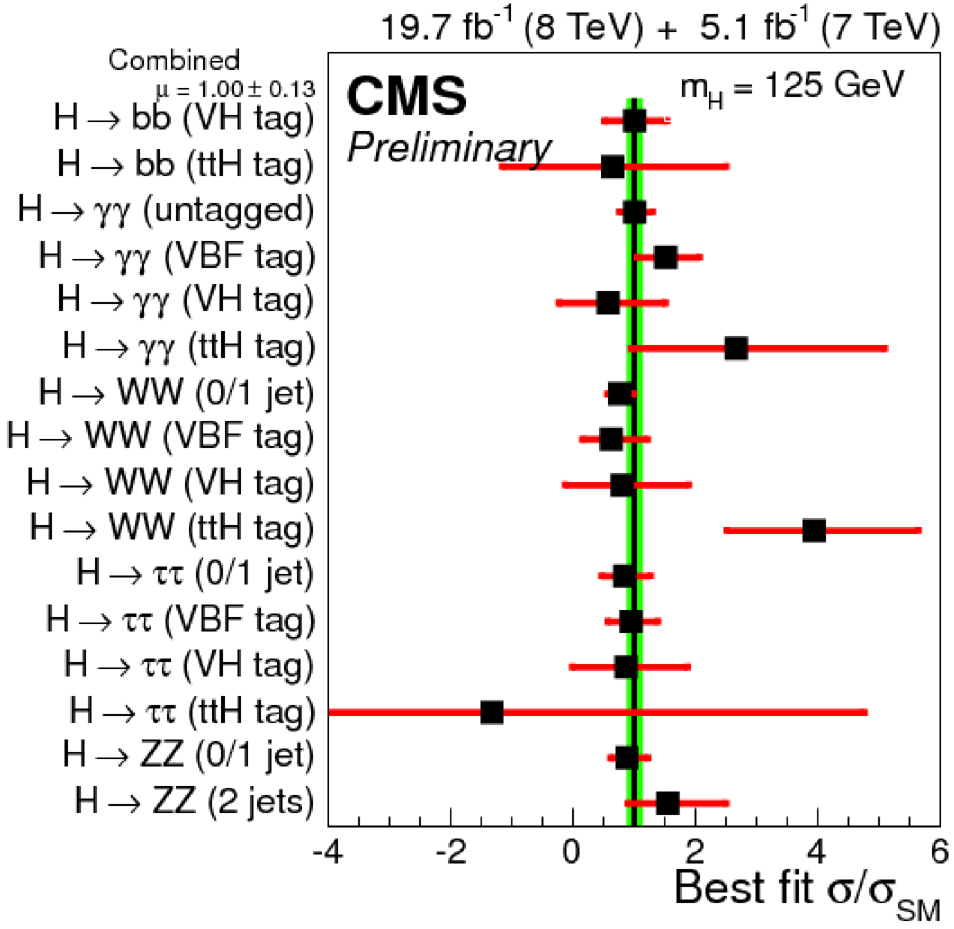
	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	M_S 5.2 TeV	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	2 e, μ	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to ZZ \to \ell\ell qq$	2 e, μ	2 j / 1 J	–	20.3	G_{KK} mass 730 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	2 e, μ	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	2 γ	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\, \ell'\ell'$	3 e, μ	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	W' mass 1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R \to t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
	LRSM $W'_R \to t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.77 TeV		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	2 e, μ	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	0 e, μ	1-2 j	Yes	10.5	M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	0 e, μ	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	1 e, μ, 1 τ	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	T mass 735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		to be submitted to PLB
	LRSM Majorana ν	2 e, μ	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	2 e, μ	–	–	5.8	$N^{\pm}$ mass 245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2 e, μ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g \rvert = 1 g_D$	1207.6411

$\sqrt{s}$ = 7 TeV $\sqrt{s}$ = 8 TeV

10^{-1} 1 10 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown.

the "SM" Higgs:



19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
Preliminary
mH = 125 GeV
Combined
μ = 1.00 ± 0.13
H → bb (VH tag)
H → bb (ttH tag)
H → γγ (untagged)
H → γγ (VBF tag)
H → γγ (VH tag)
H → γγ (ttH tag)
H → WW (0/1 jet)
H → WW (VBF tag)
H → WW (VH tag)
H → WW (ttH tag)
H → ττ (0/1 jet)
H → ττ (VBF tag)
H → ττ (VH tag)
H → ττ (ttH tag)
H → ZZ (0/1 jet)
H → ZZ (2 jets)
-4
-2
0
2
4
6
Best fit σ/σSM

Compatible/Expected from indirect searches:

Flavor:	$\gtrsim$ **10^5 TeV**
EDMs:	$\gtrsim$ **100 TeV**
LEP2:	$\gtrsim$ **20 TeV**
EWPT:	$\gtrsim$ **few TeV**

(*assuming O(1) couplings*)

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EDMs:	$\gtrsim 100$ TeV
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(*assuming O(1) couplings*)

What about SUSY?

WANTED

~~DEAD~~ OR ALIVE

SUSY

REWARD $ 1,000,000

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

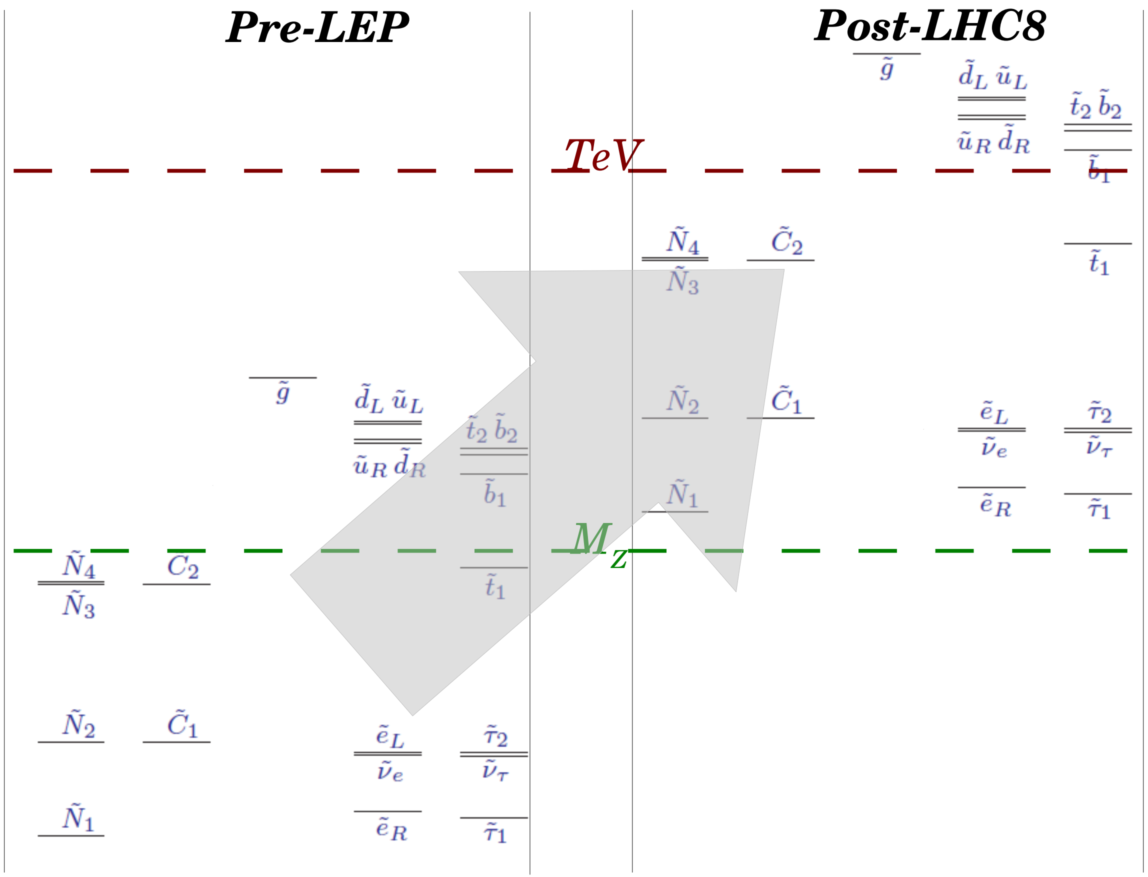
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(1^{st}$ gen. $\tilde{q})=m(2^{nd}$ gen. $\tilde{q})$	1405.7875
	$\tilde{q}\tilde{q}\gamma, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0) = m(c)$	1411.1559
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	1501.03555
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^\pm)=2\,m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV, 230-460 GeV	$m(\tilde{\chi}_1^\pm) = 2m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 90-191 GeV, 215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	1-2 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1407.0583,1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 250 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	1310.3675
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 $\mu s<\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e + \mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu) + \tau$	1 $e,\mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 750 GeV	$m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^\pm)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^\pm)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

Mass scale [TeV] (10^{-1} – 1)

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

SUSY is tuned!

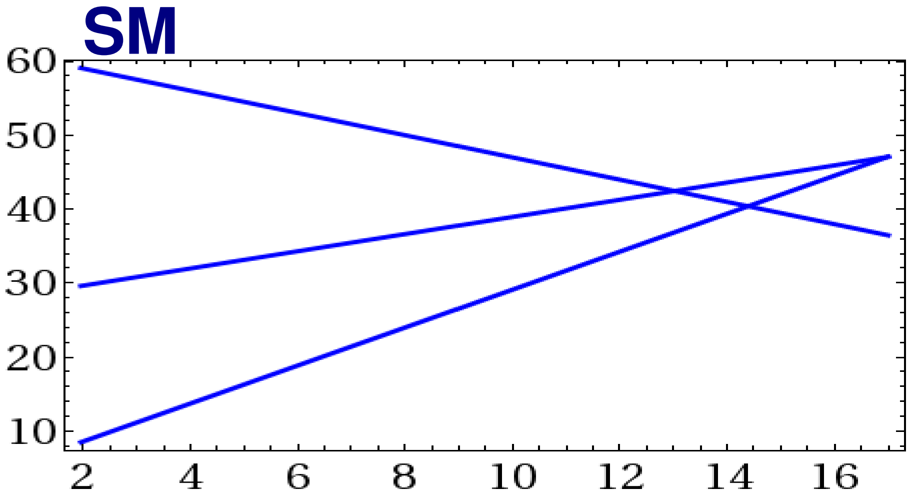


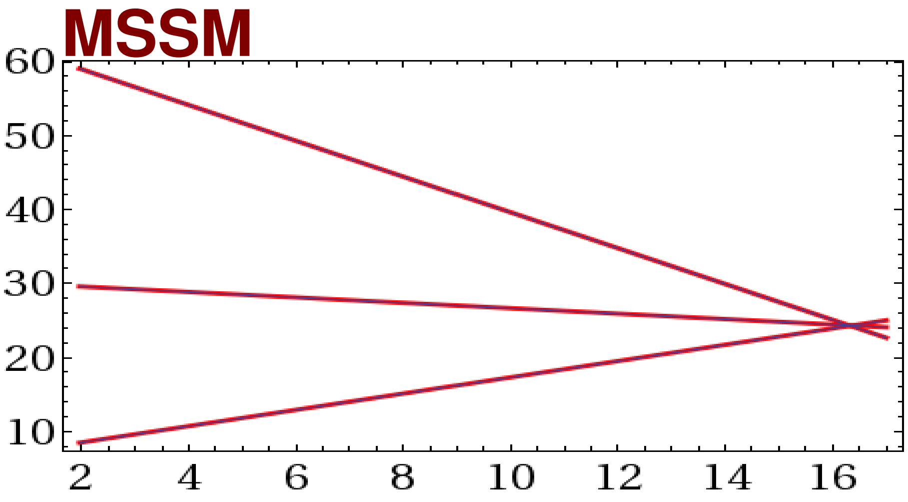
Keep trying with "clever" model building

Accept that naturalness is not a good criterion for BSM

Weaker hint:

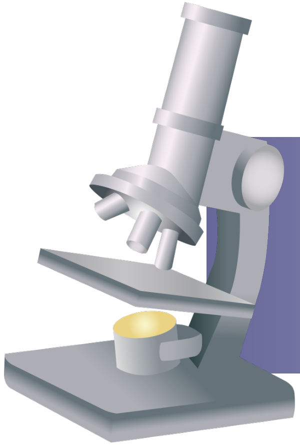
Gauge Coupling Unification





$$\boxed{m_{\mathrm{SUSY}} \lesssim \mathrm{few} \cdot 10\ \mathrm{TeV}}$$

SUSY breaking scale?



Back to Experiments

Use Precision Data

In SUSY the Higgs mass is calculable:

ATLAS + CMS $m_h^{\mathrm{exp}} = 125.09 \pm 0.24\ \mathrm{GeV}$

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$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3}{\pi^2}\frac{m_t^4 \sin^4\beta}{v^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \tilde{X}_t^2\left(1 - \frac{\tilde{X}_t^2}{12}\right)\right] + \ldots$$

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only *log*-dependence on new physics scale

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only *log*-dependence on new physics scale

⇒ high precision to get reliable constraints

In SUSY the Higgs mass is calculable:

ATLAS + CMS $m_h^{\text{exp}} = 125.09 \pm 0.24 \text{ GeV}$

$$\underbrace{m_h^2}_{125^2} \simeq \underbrace{m_Z^2 \cos^2 2\beta}_{90^2} + \underbrace{\frac{3}{\pi^2} \frac{m_t^4 \sin^4 \beta}{v^2} \left[\log \frac{m_{\tilde{t}}^2}{m_t^2} + \tilde{X}_t^2 \left(1 - \frac{\tilde{X}_t^2}{12} \right) \right] + \ldots}_{90^2}$$

$125^2 \approx$ 90^2 + 90^2

$$\Rightarrow \delta m_h \sim \delta m_t$$

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$125^2 \approx 90^2 + 90^2$

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$$m_t^{\overline{\rm MS}}(M_t) = 173.34 - 8.00 - 1.90 - 0.59 - 0.21~\text{GeV}$$

1 *loop* 2 *loop* 3 *loop* 4 *loop*

Exploiting the Hierarchy Problem:

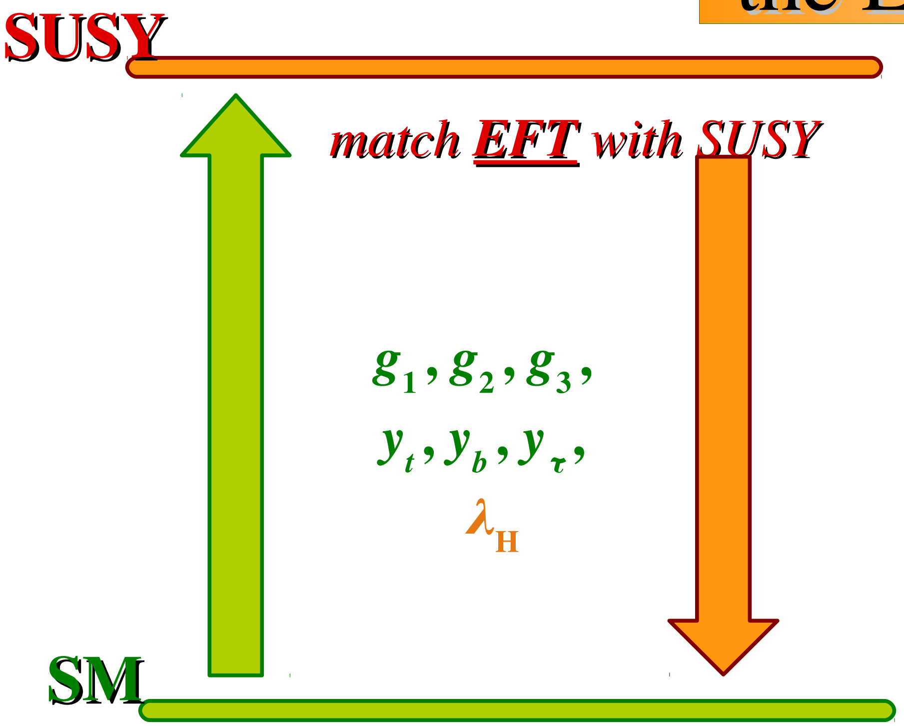
the EFT technique

SUSY

SM

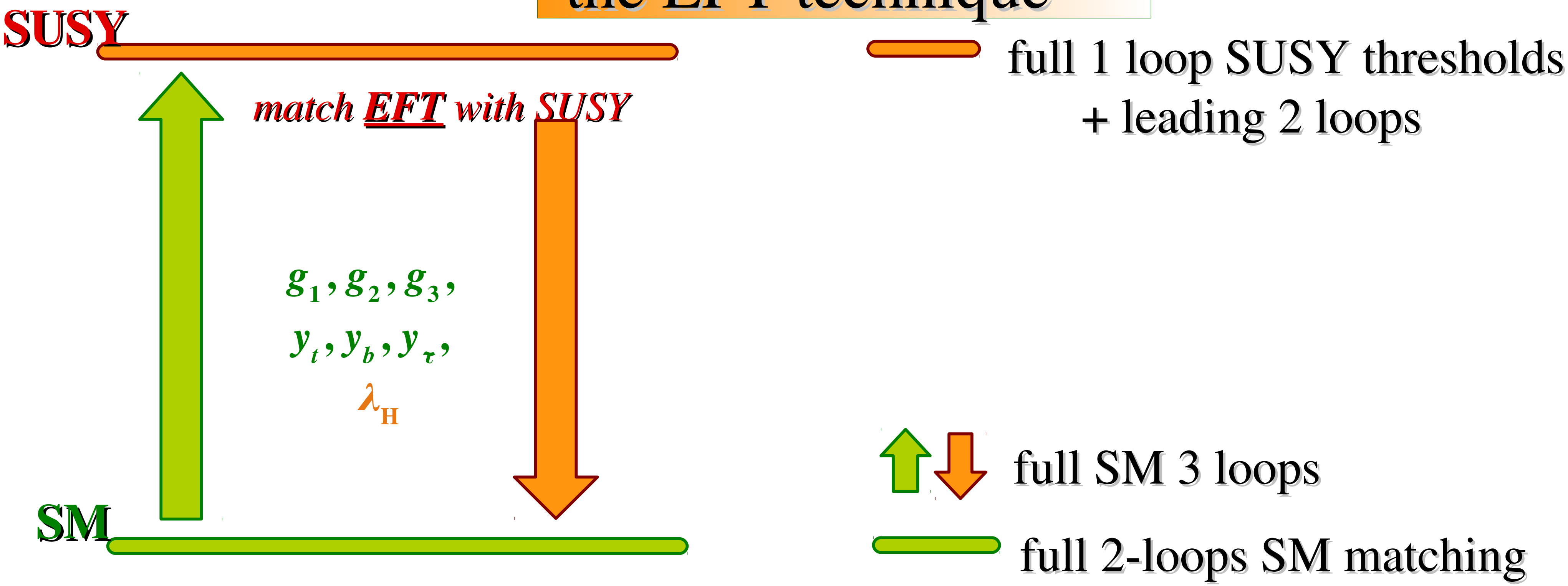
Exploiting the Hierarchy Problem:

the EFT technique



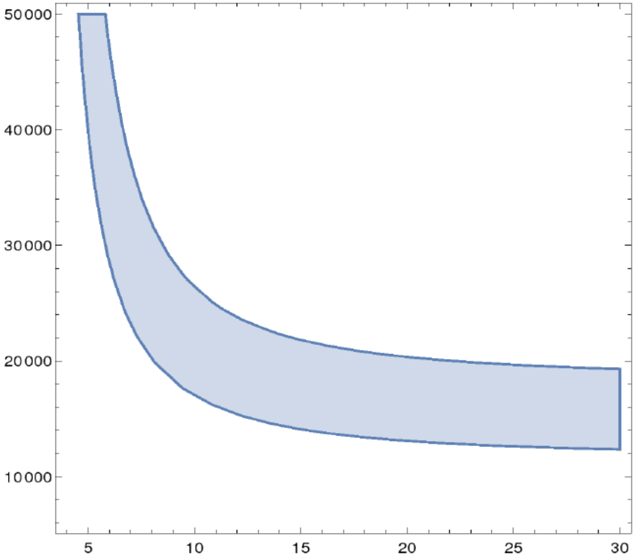
Exploiting the Hierarchy Problem:

the EFT technique

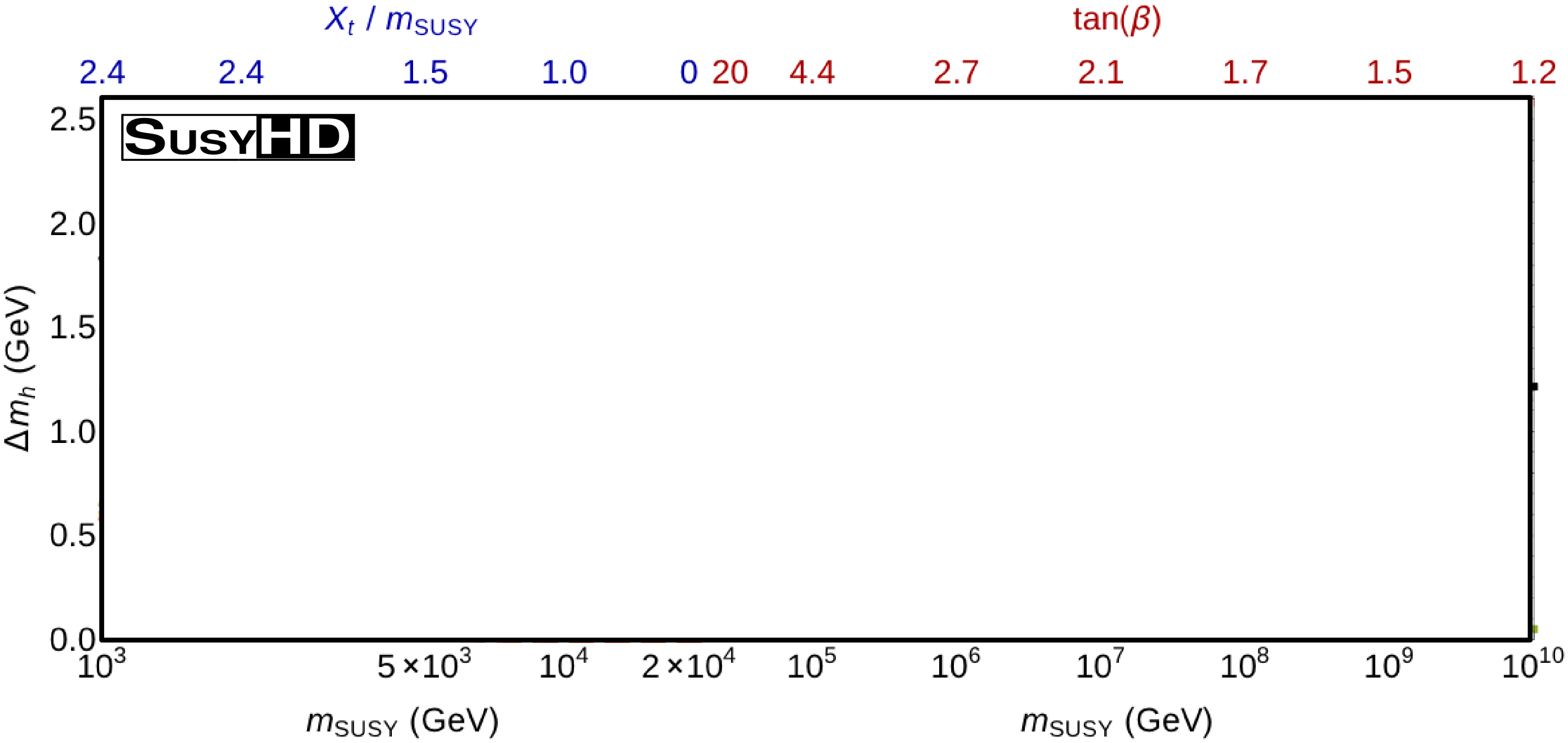


www.ictp.it/~susyhd

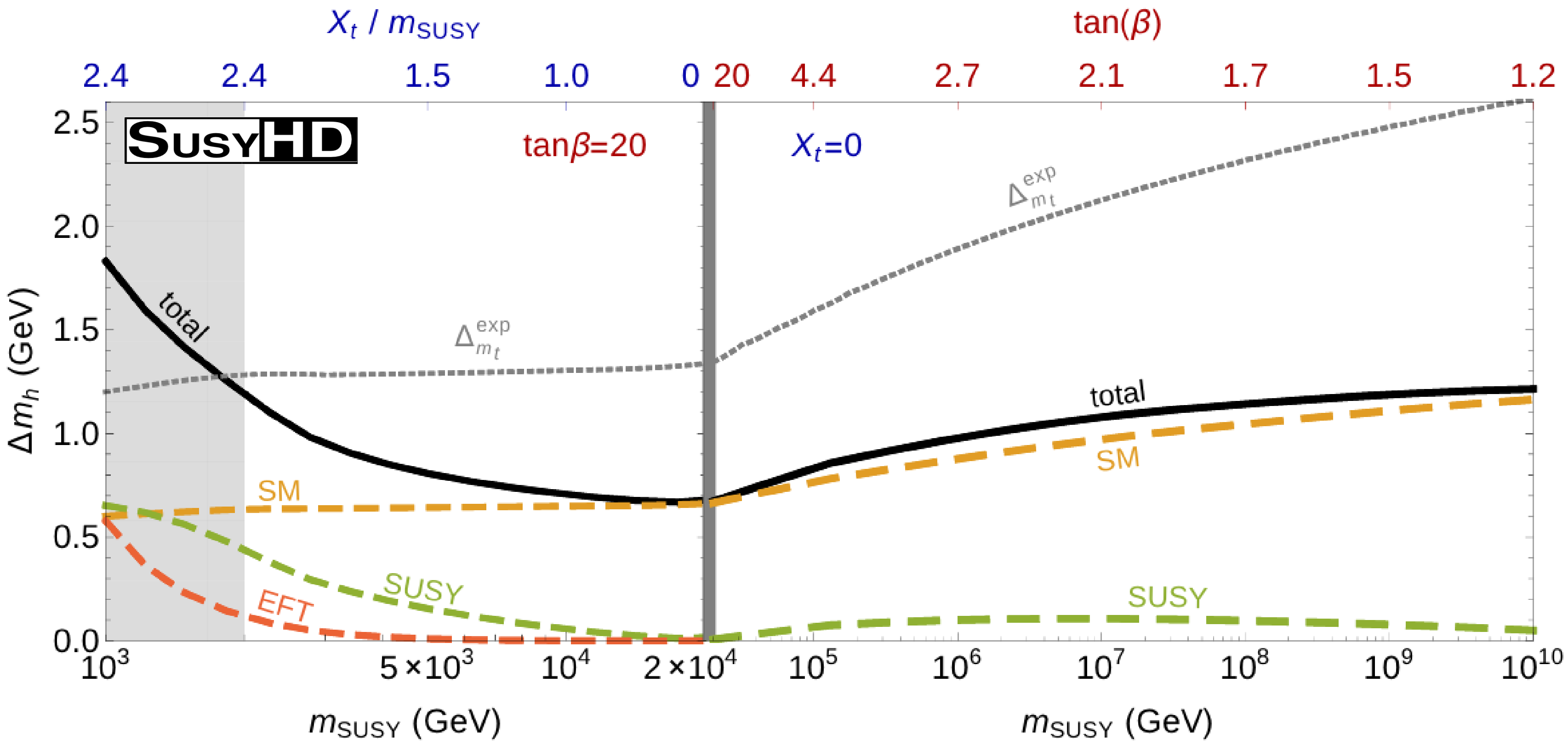
```
In[1]:= << SUSYHD`

In[2]:= mh := MHiggs[{tb, m0, At}]
        Δmh := ΔMHiggs[{tb, m0, At}]

In[4]:= tb := 20;
        m0 := 2000;
        At := 5000;
        mh // Timing
        Δmh // Timing

Out[7]= {0.006999, 125.033}

Out[8]= {0.039994, 1.30843}

In[9]:= RegionPlot[125 - Δmh < mh < 125 + Δmh, {tb, 4, 30}, {m0, 6000, 50 000}]

Out[9]=
```



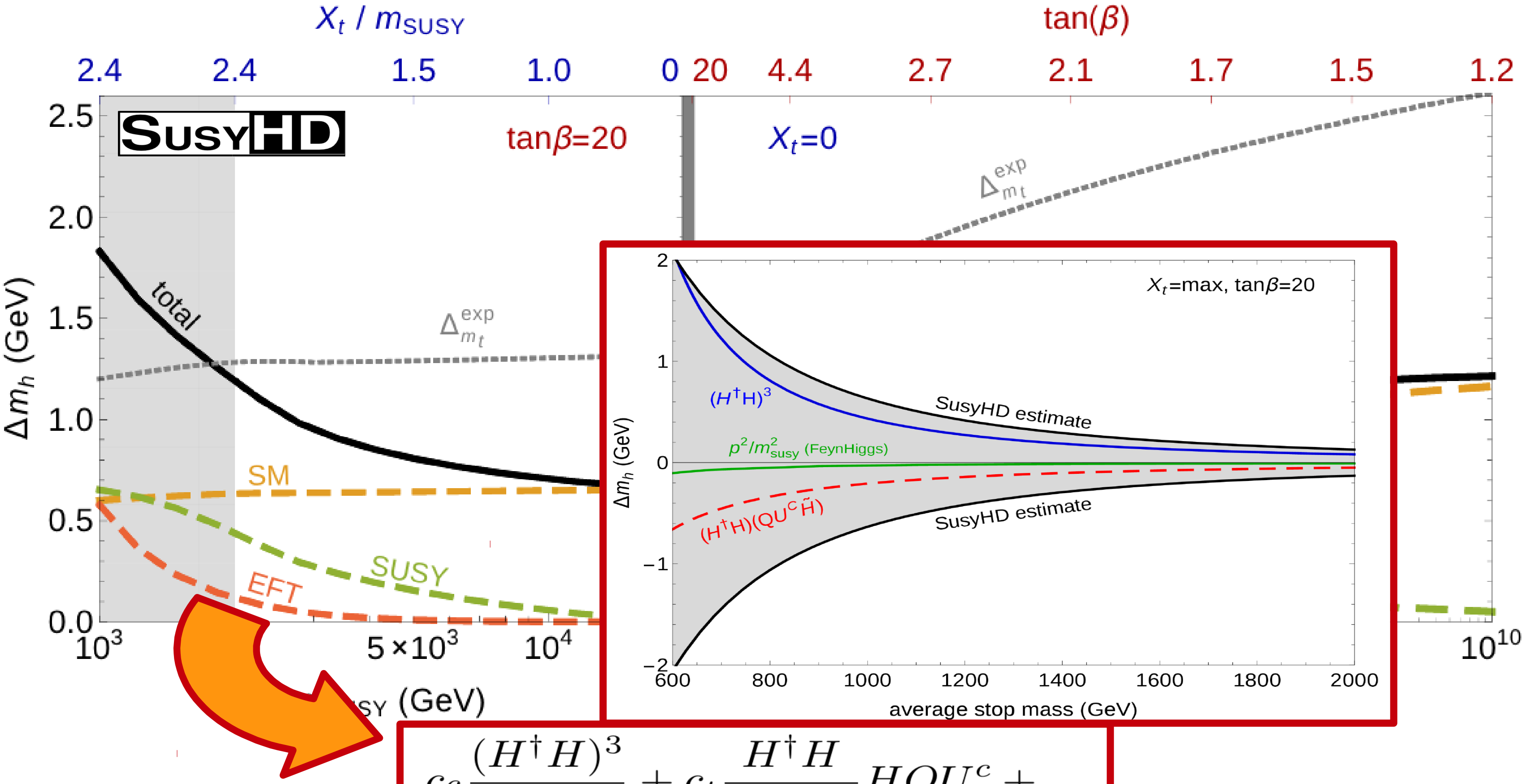
Estimate of the Uncertainties:



Estimate of the Uncertainties:

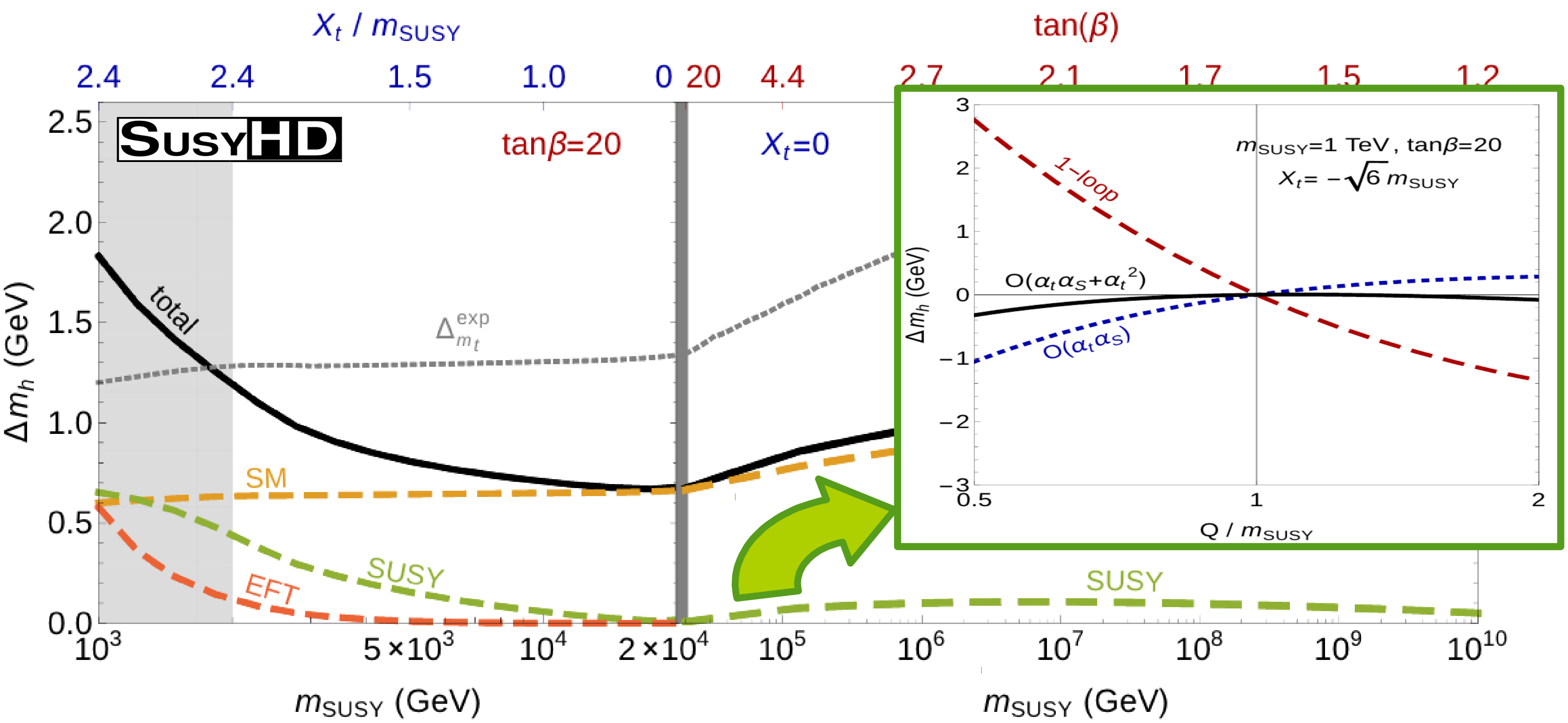


Estimate of the Uncertainties:

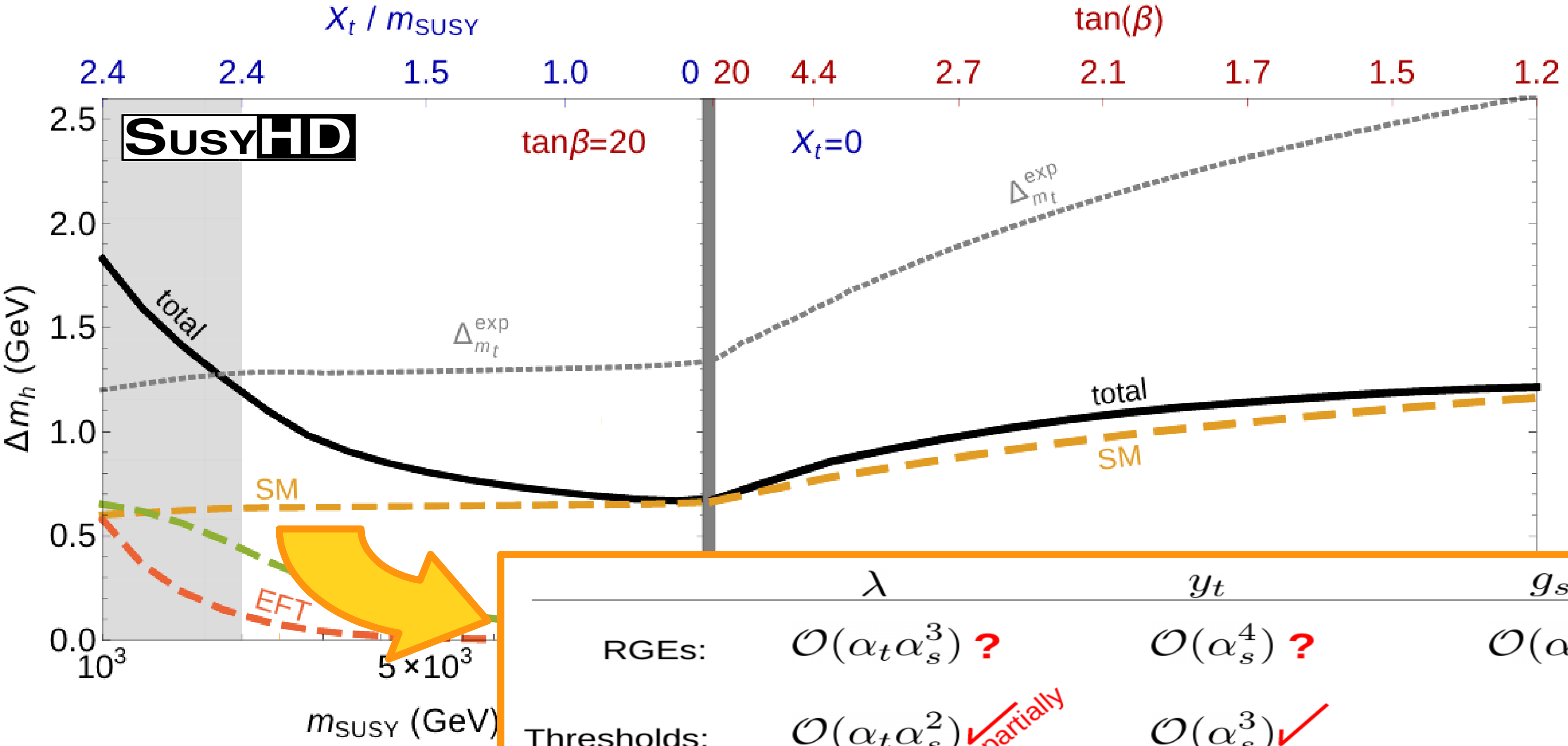


$$c_6 \frac{(H^\dagger H)^3}{m^2_{\rm SUSY}} + c_t \frac{H^\dagger H}{m^2_{\rm SUSY}} HQU^c + \ldots$$

Estimate of the Uncertainties:



Estimate of the Uncertainties:



	λ	y_t	g_s
RGEs:	$\mathcal{O}(\alpha_t\alpha_s^3)$?	$\mathcal{O}(\alpha_s^4)$?	$\mathcal{O}(\alpha_s^4)$ ✓
Thresholds:	$\mathcal{O}(\alpha_t\alpha_s^2)$ ✓ partially	$\mathcal{O}(\alpha_s^3)$ ✓	

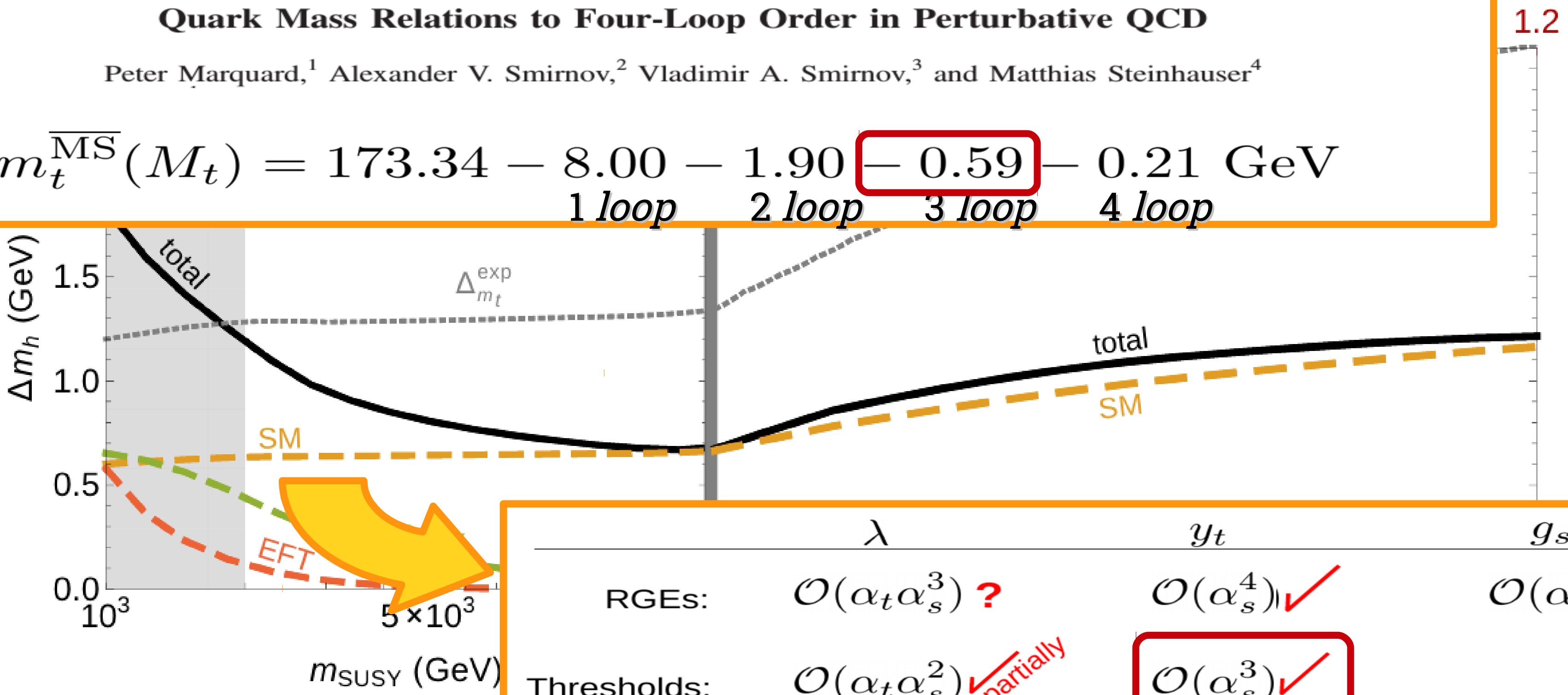
Estimate of the Uncertainties:

PRL **114**, 142002 (2015) PHYSICAL REVIEW LETTERS week ending 10 APRIL 2015

Quark Mass Relations to Four-Loop Order in Perturbative QCD

Peter Marquard,[1] Alexander V. Smirnov,[2] Vladimir A. Smirnov,[3] and Matthias Steinhauser[4]

$$m_t^{\overline{\mathrm{MS}}}(M_t) = 173.34 - \underbrace{8.00}_{1\ loop} - \underbrace{1.90}_{2\ loop} \boxed{- \underbrace{0.59}_{3\ loop}} - \underbrace{0.21}_{4\ loop}\ \mathrm{GeV}$$



	λ	y_t	g_s
RGEs:	$\mathcal{O}(\alpha_t\alpha_s^3)$?	$\mathcal{O}(\alpha_s^4)$ ✓	$\mathcal{O}(\alpha_s^4)$ ✓
Thresholds:	$\mathcal{O}(\alpha_t\alpha_s^2)$ ✓ partially	$\boxed{\mathcal{O}(\alpha_s^3)}$ ✓	

Estimate of the Uncertainties:

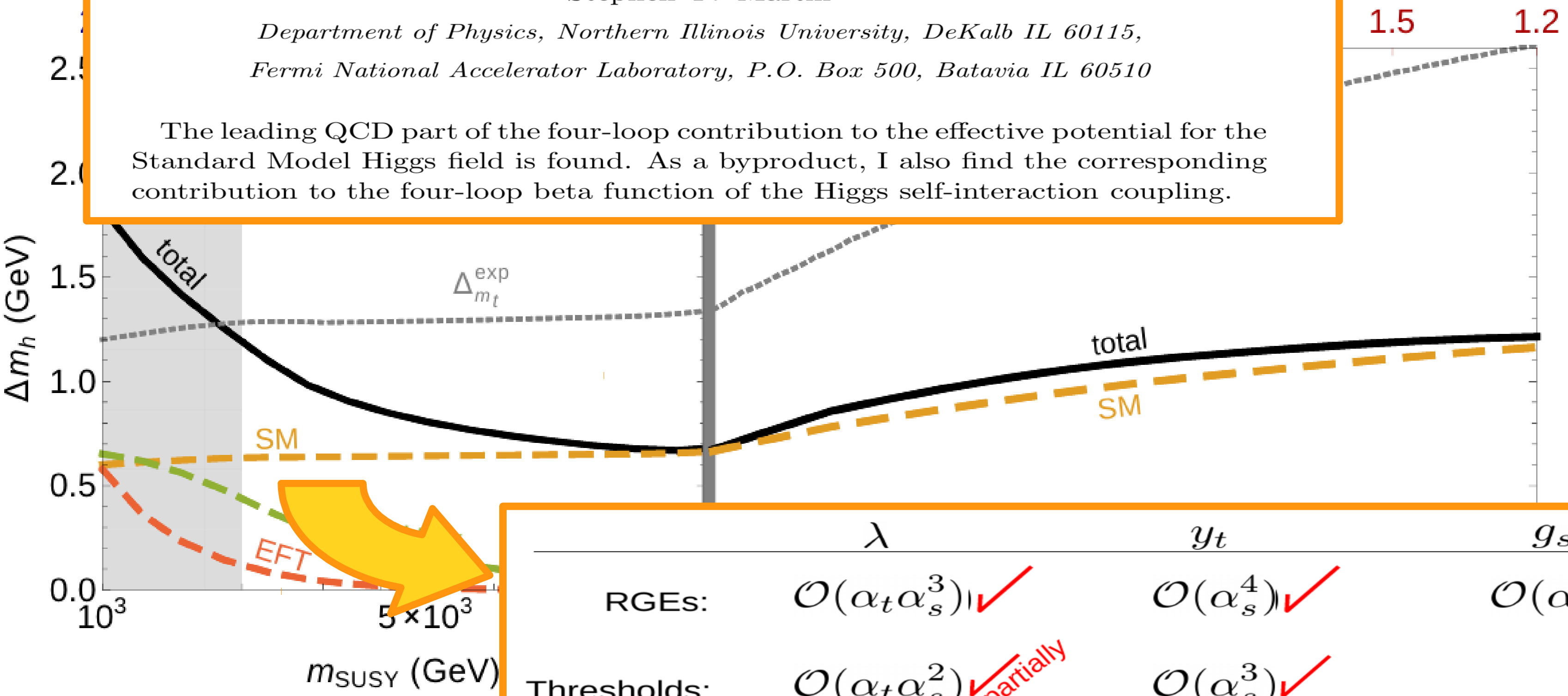
Four-loop Standard Model effective potential at leading order in QCD

Stephen P. Martin

Department of Physics, Northern Illinois University, DeKalb IL 60115,

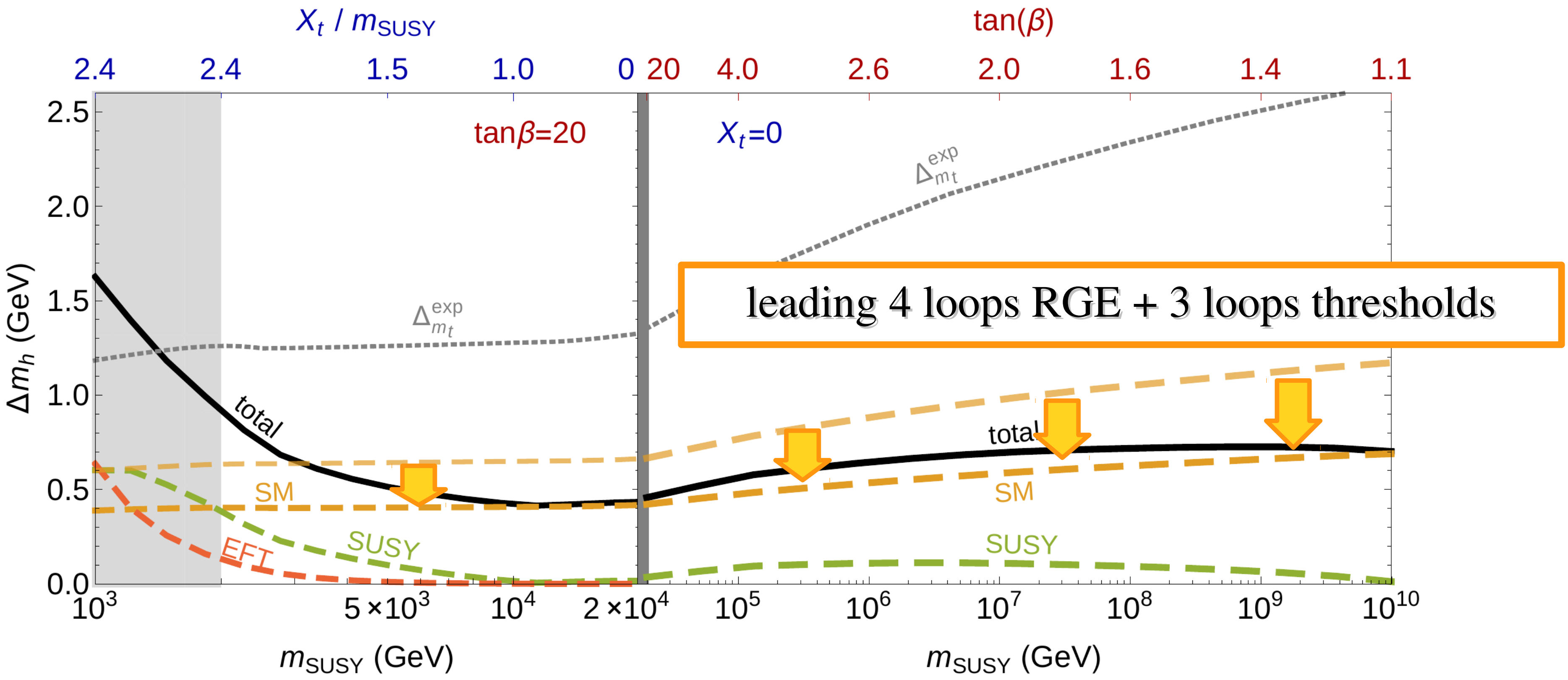
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia IL 60510

The leading QCD part of the four-loop contribution to the effective potential for the Standard Model Higgs field is found. As a byproduct, I also find the corresponding contribution to the four-loop beta function of the Higgs self-interaction coupling.



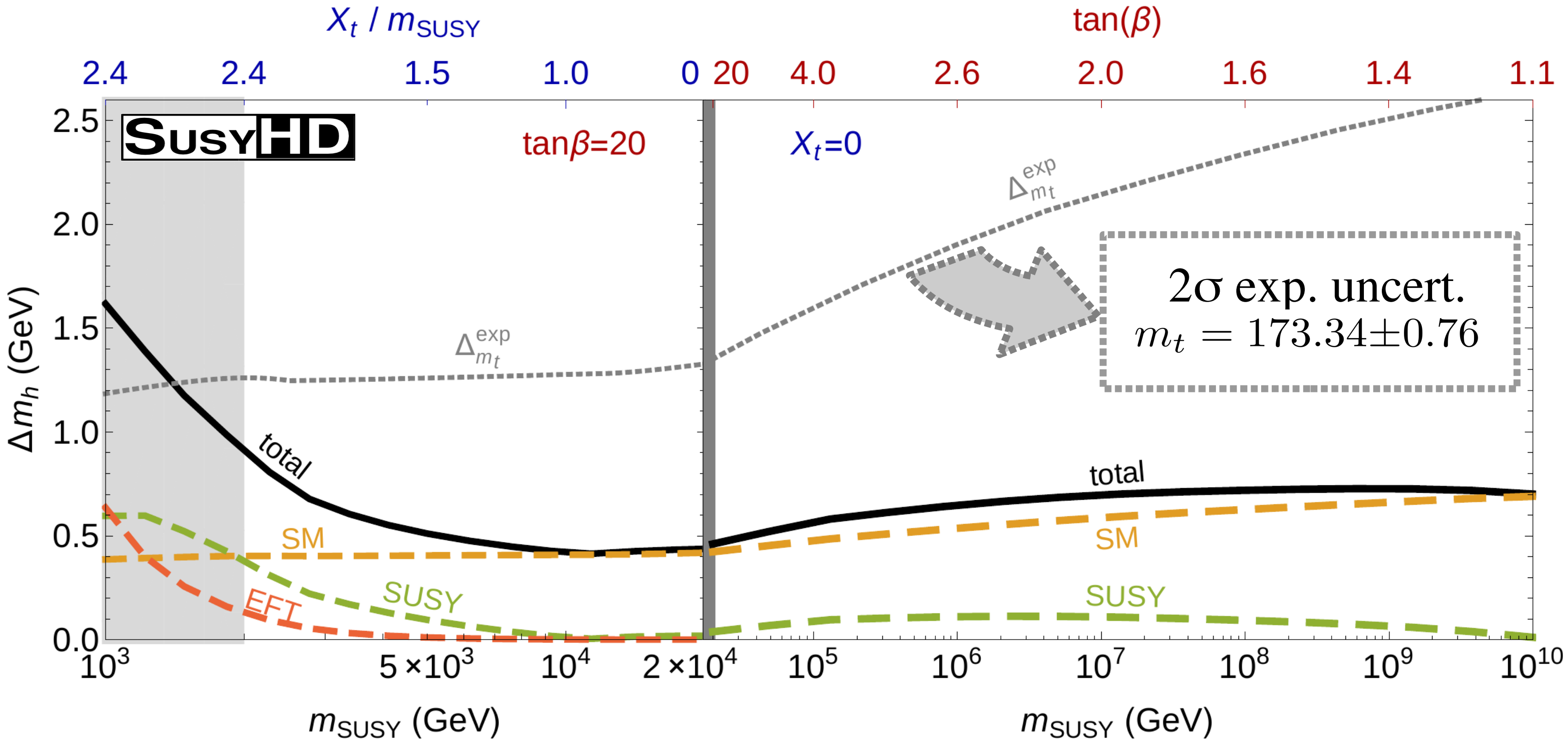
	λ	y_t	g_s
RGEs:	$\mathcal{O}(\alpha_t\alpha_s^3)$ ✓	$\mathcal{O}(\alpha_s^4)$ ✓	$\mathcal{O}(\alpha_s^4)$ ✓
Thresholds:	$\mathcal{O}(\alpha_t\alpha_s^2)$ ✓ partially	$\mathcal{O}(\alpha_s^3)$ ✓	

Estimate of the Uncertainties:



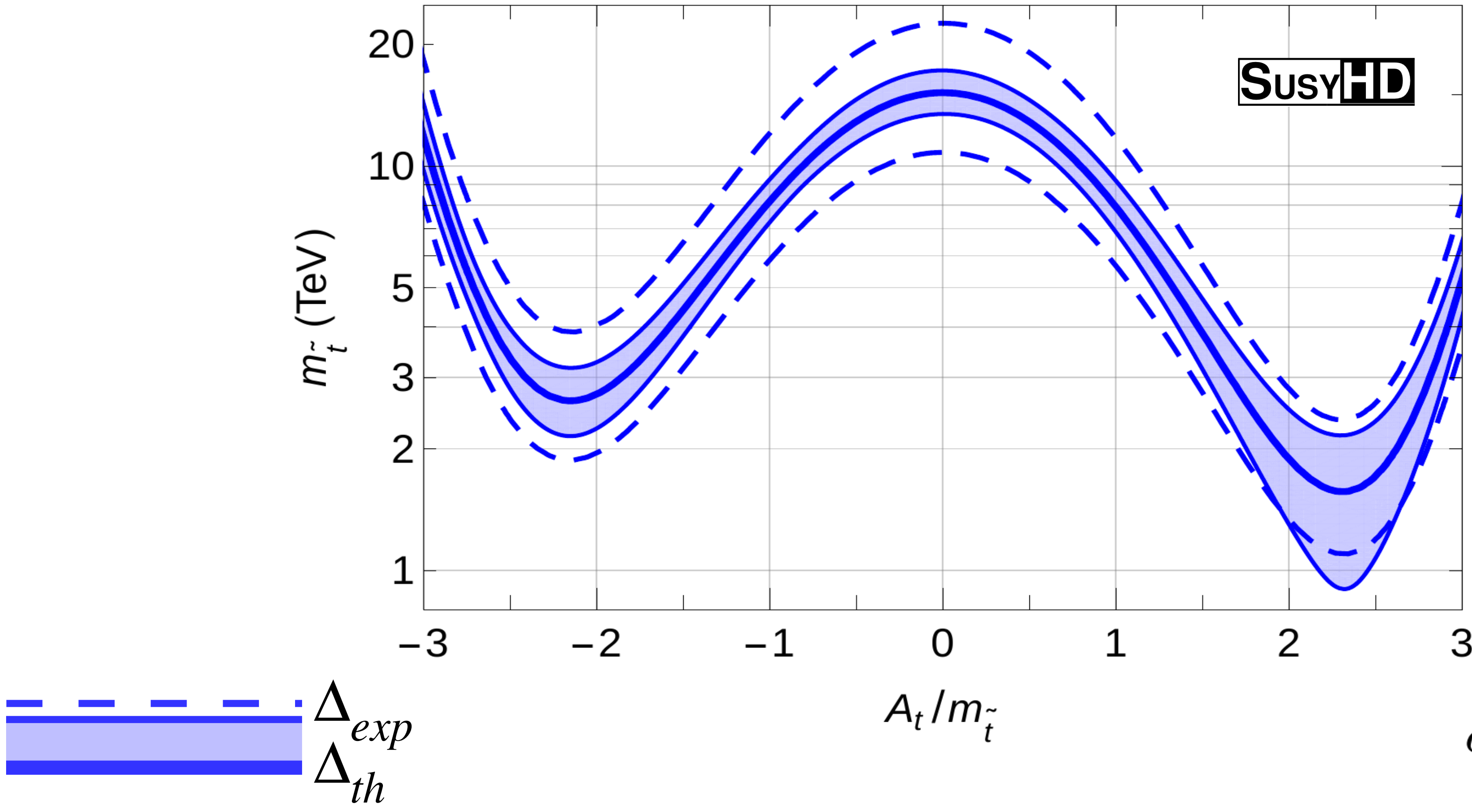
soon in SusyHD v1.1

Estimate of the Uncertainties:



Where is SUSY ?

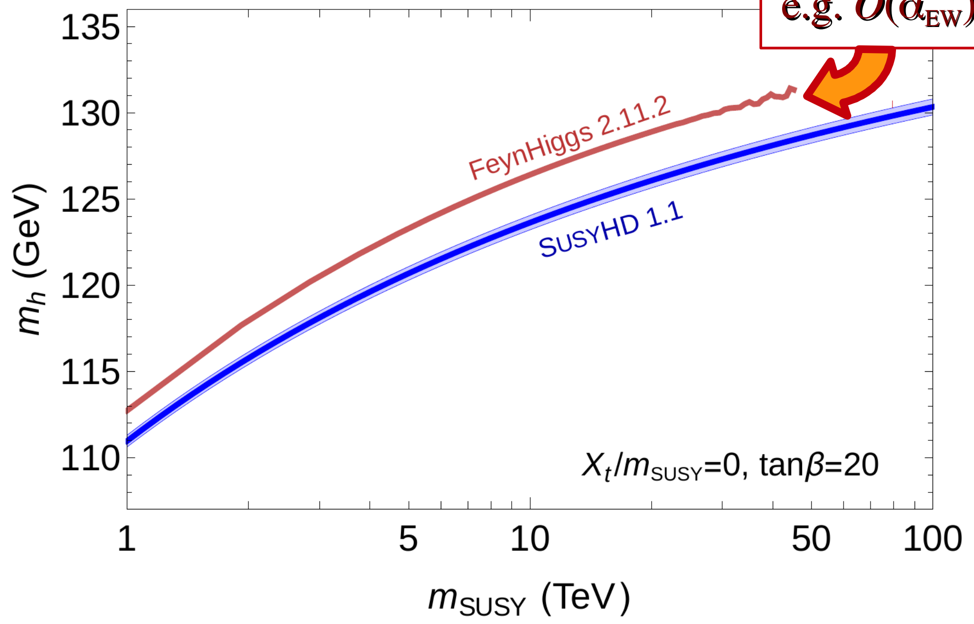
@ $\tan\beta = 20$,   w/ degenerate spectrum $m_{SUSY} = m_{stop}$

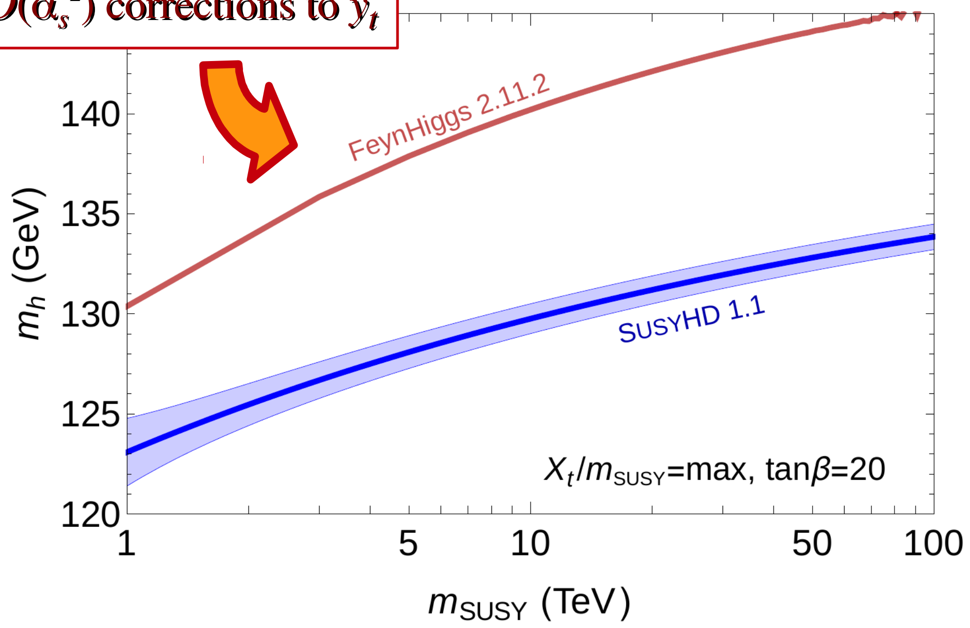


$\partial A_t/\partial\mu > 0$

Comparison with fixed order comp.: FeynHiggs

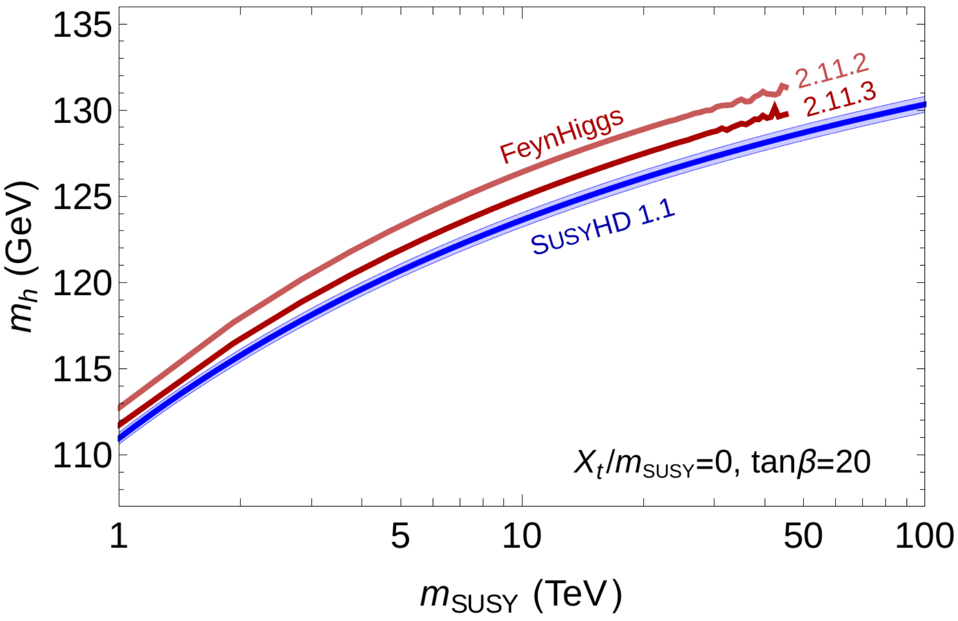
no EFT approx.
but missing corrections:
e.g. $O(\alpha_{EW}) + O(\alpha_s^2)$ corrections to y_t

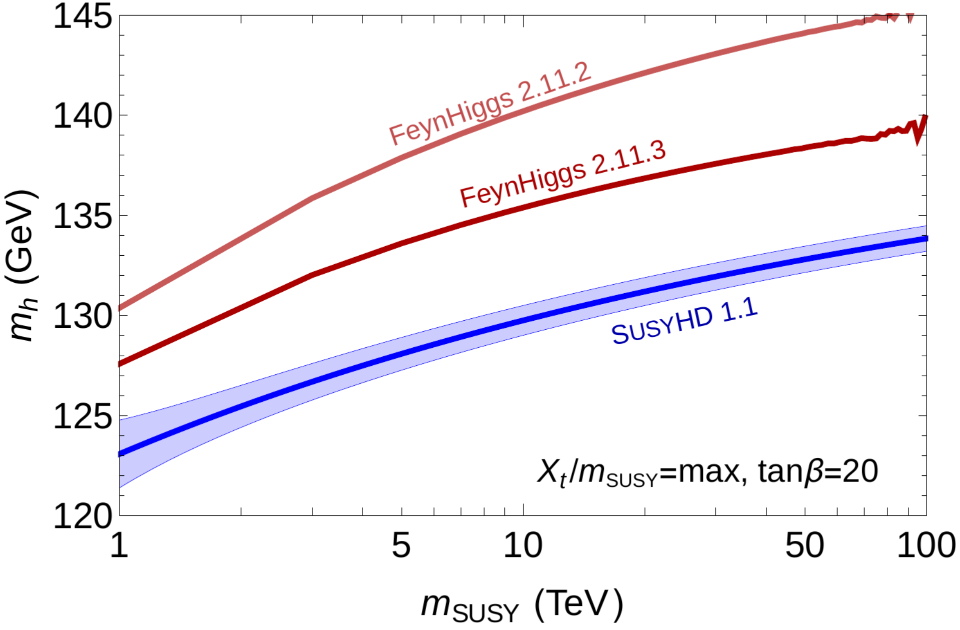




Comparison with fixed order comp.: FeynHiggs

FH 2.11.3 now includes $O(\alpha_s^2)$ corrections to y_t

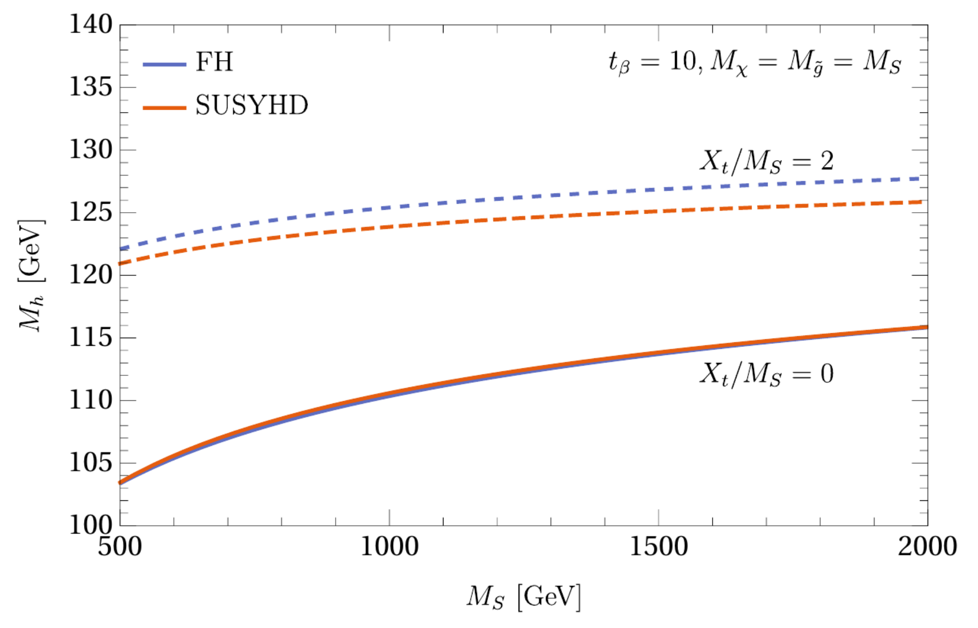


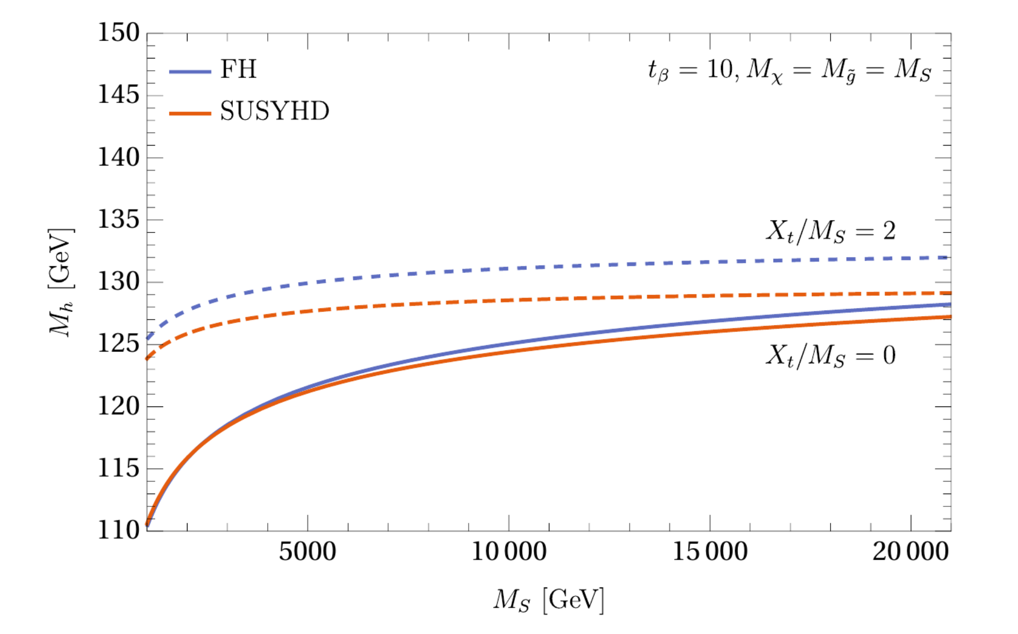


Comparison with fixed order comp.: FeynHiggs

towards implementing all higher order corrections in FH...

from **Henning Bahl** talk @ KUTS'16 - 21/01/2016





Where is the Simplest SUSY?

The Simplest SUSY

(m_h, λ)

SM

The Simplest SUSY

(m_h, λ)

$$\underbrace{\text{SM} \quad + \quad \text{SUSY}}_{\text{MSSM} \ (\mu)}$$

The Simplest SUSY

$$(m_h, \lambda)$$

$$\underbrace{\text{SM} \quad + \quad \text{SUSY}}_{\text{MSSM} \ (\mu)} \quad + \quad \underset{(F)}{\cancel{\text{SUSY}}}$$

The Simplest SUSY

(m_h, λ)

$$\underbrace{\text{SM} \quad + \quad \text{SUSY}}_{\text{MSSM}\ (\mu)} \quad + \quad \underbrace{\cancel{\text{SUSY}}}_{(F)} \quad + \quad \underbrace{\text{Mess.}}_{(M)}$$

The Simplest SUSY

(m_h, λ)

$$\underbrace{\text{SM} \quad + \quad \text{SUSY}}_{\text{MSSM} \ (\mu)} \quad + \quad \underset{(F)}{\cancel{\text{SUSY}}} \quad + \quad \underset{(M)}{\text{Mess.}}$$

μ , $\Lambda = F/M$ fixed by m_Z , m_h

weak dependence on log(M)

Minimal Gauge Mediation

Dine, Nir, Shirman
Rattazzi, Sarid '96

spectrum mostly fixed by usual GM relations

gauginos $M_j = N \frac{\alpha_j}{4\pi} \Lambda$ **scalars** $m_i = 2\sqrt{N} C_{ij} \frac{\alpha_j}{4\pi} \Lambda$ **higgsinos** μ

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$\Downarrow$

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$A_t \leq m_0 \quad \rightarrow$ *no maximal mixing*

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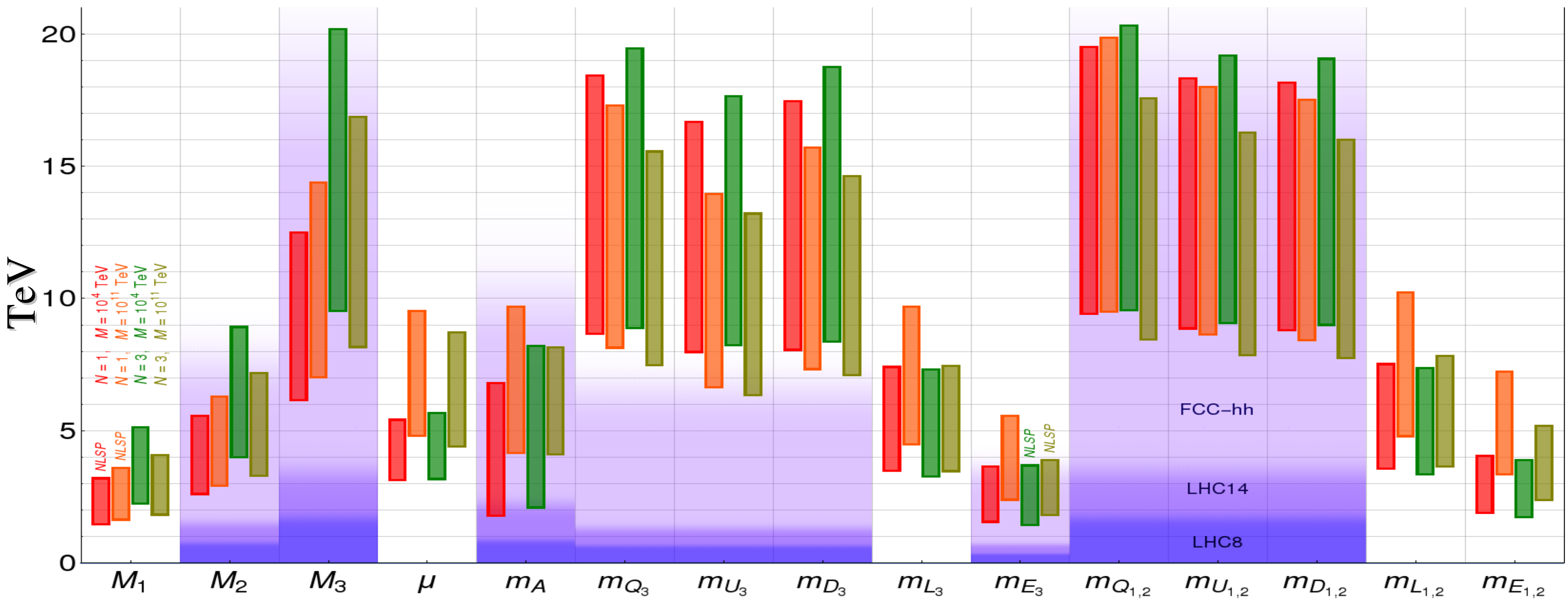
$A_t \leq m_0 \quad \rightarrow$ *no maximal mixing*

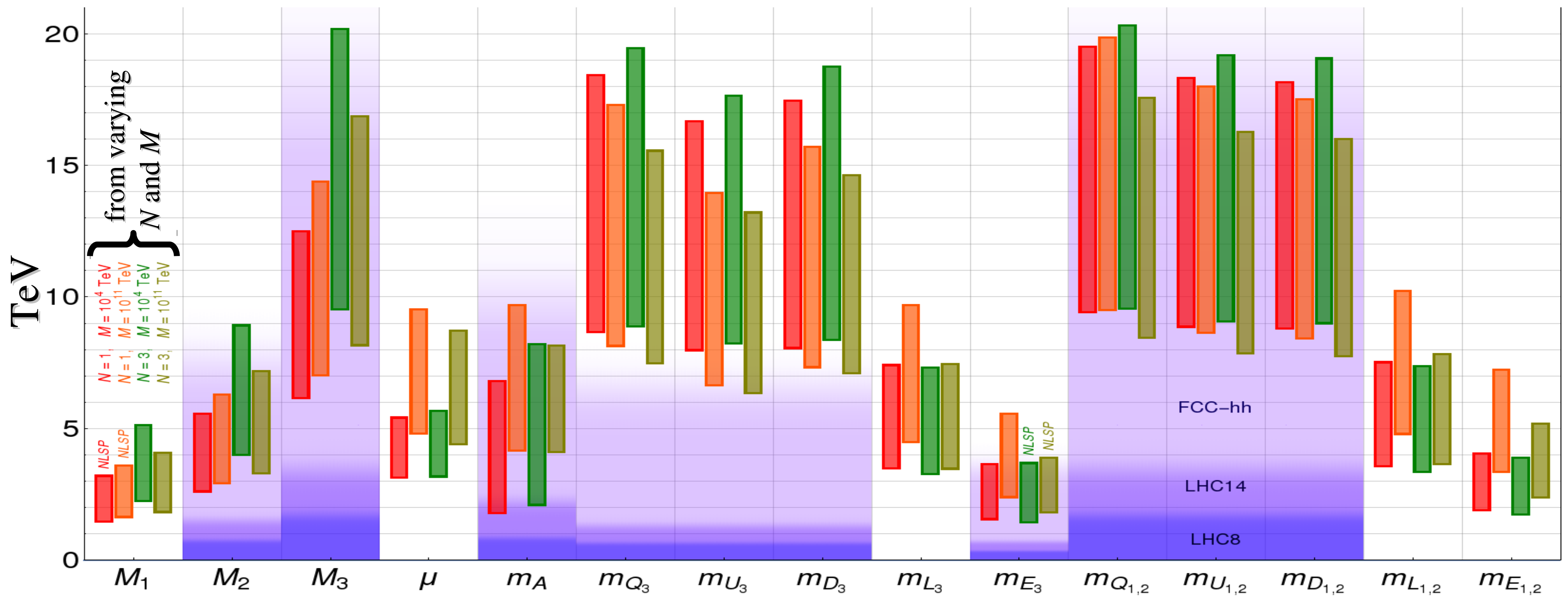
$B_\mu \ll m_0^2 \quad \rightarrow \quad \tan(\beta) \sim 30 - 60$

no CP phases $\rightarrow$ *no EDMs*

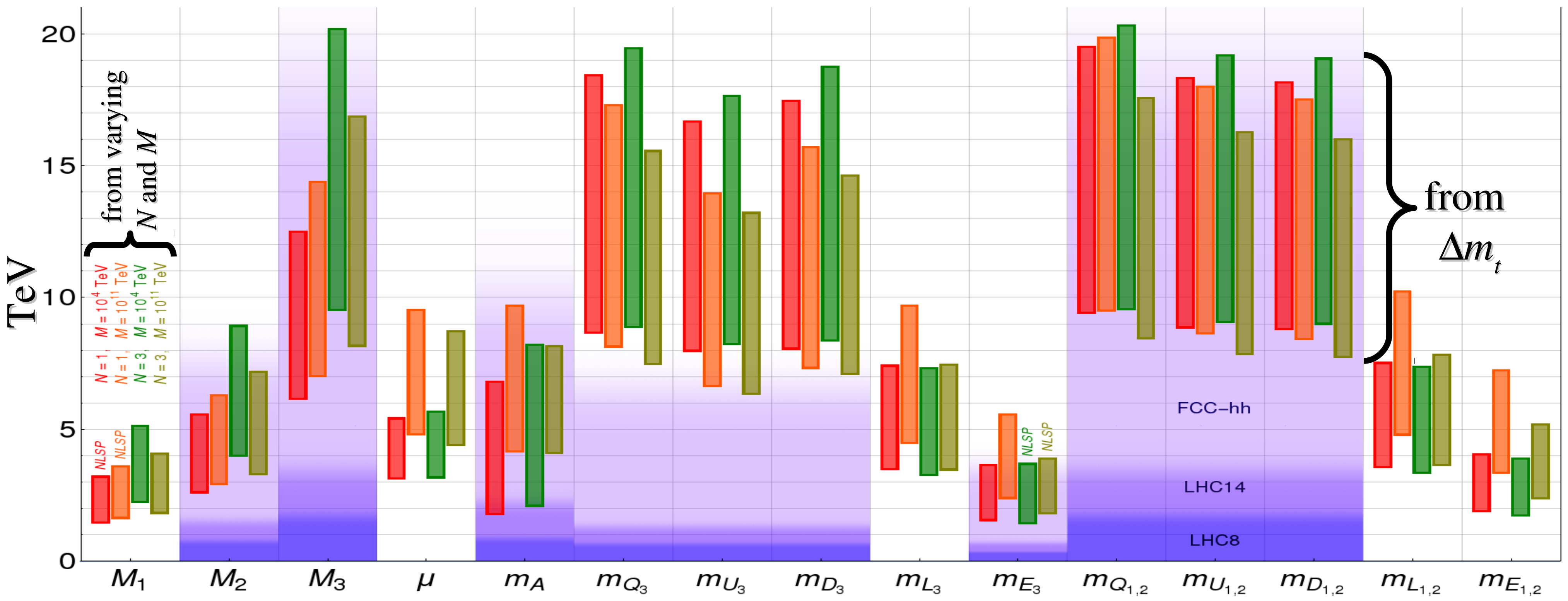
Predicting the MGM spectrum



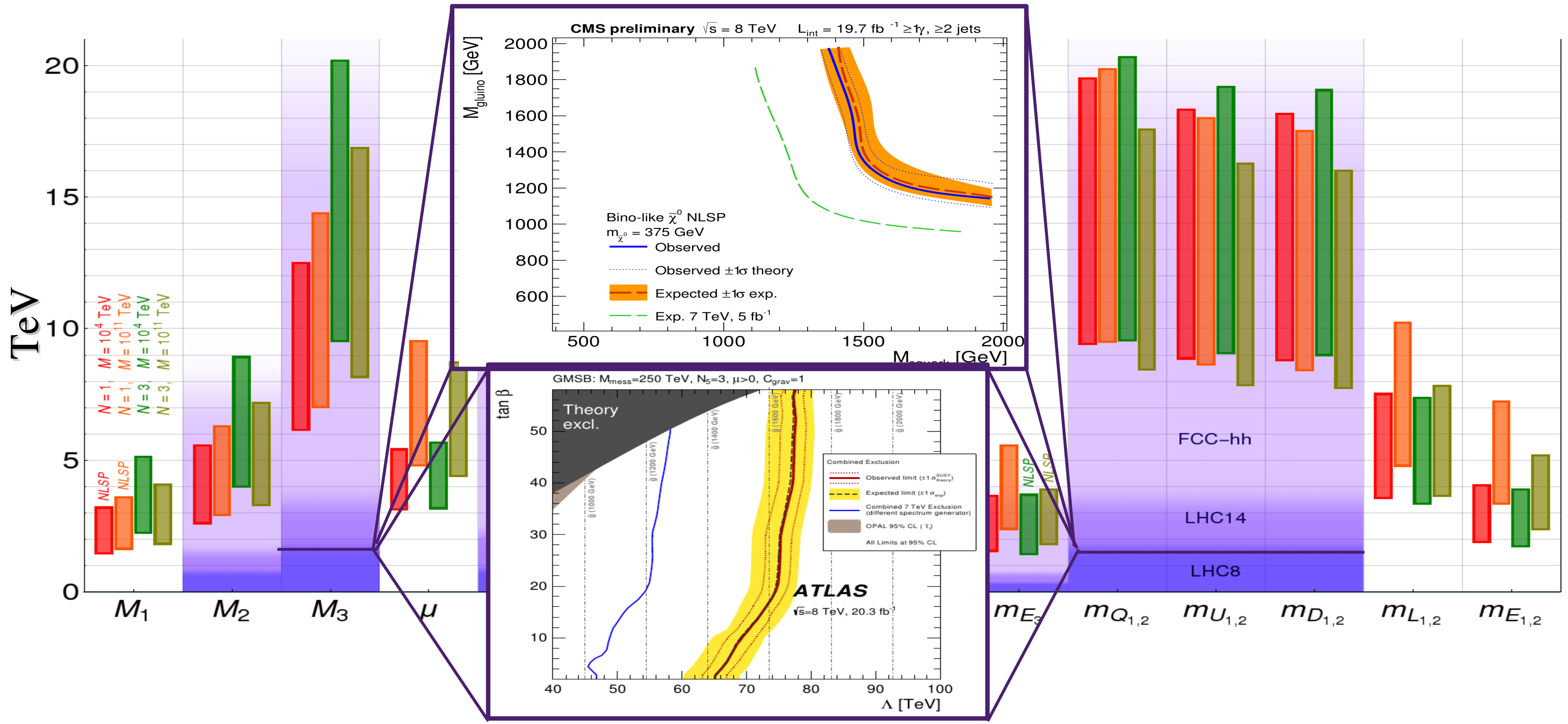
Predicting the MGM spectrum



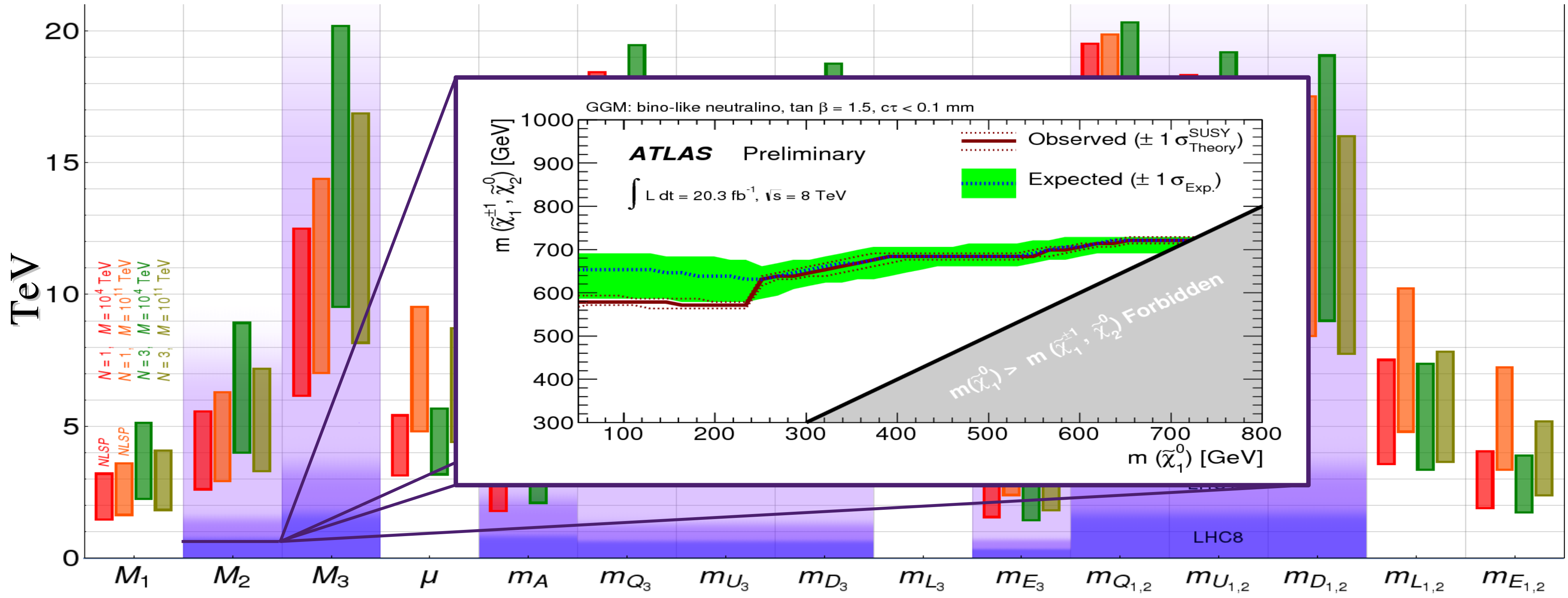
Predicting the MGM spectrum



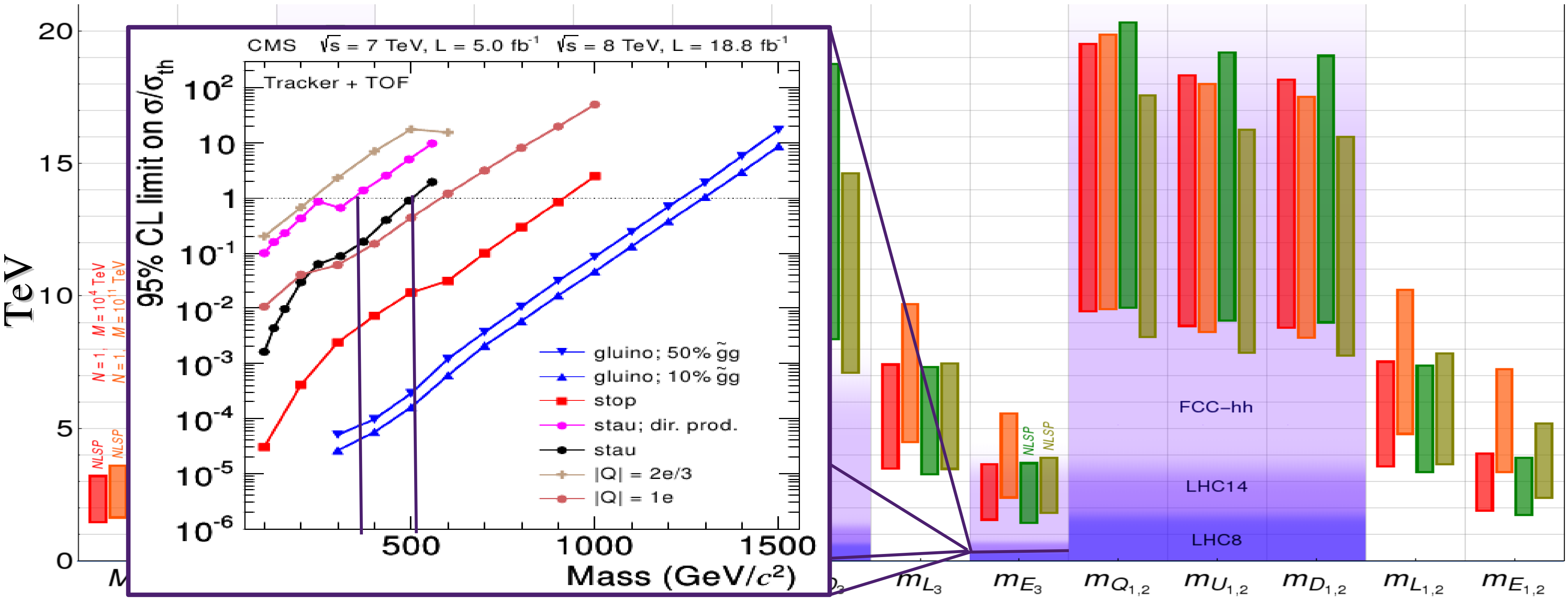
Predicting the MGM spectrum



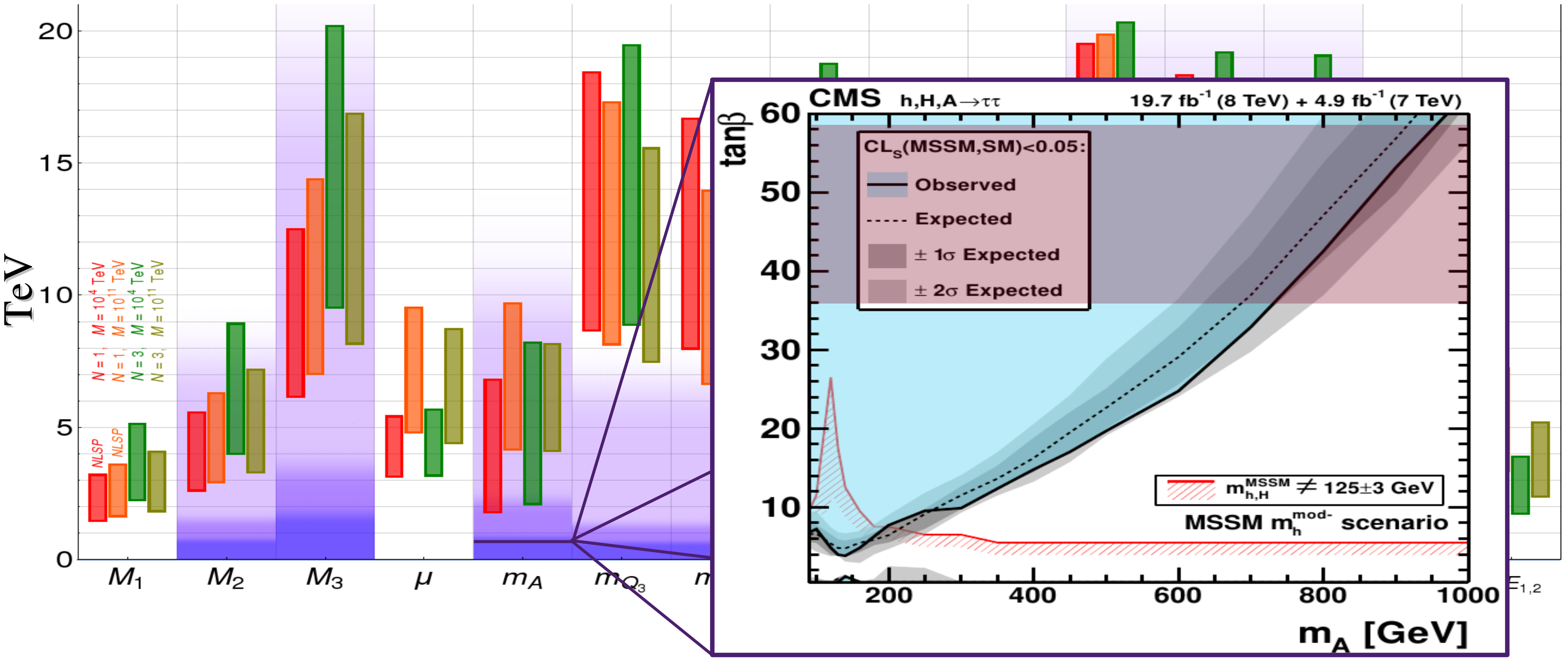
Predicting the MGM spectrum



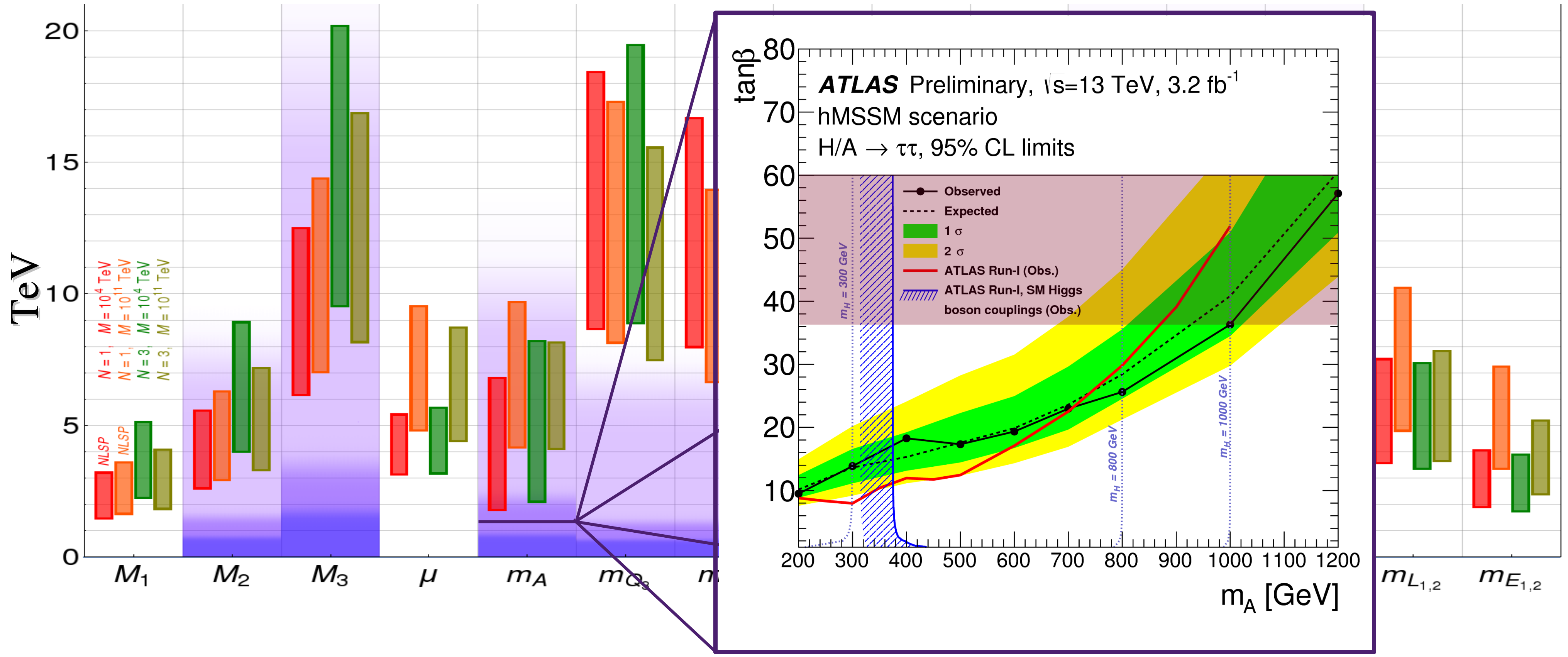
Predicting the MGM spectrum



Predicting the MGM spectrum



Predicting the MGM spectrum



MGM:

minimal and most predictive implementation of SUSY

it explains:

- absense of deviation in flavor
- absence of EDMs
- absence of DM in WIMP searches
- gauge coupling unification
- absence of sparticles at the LHC!

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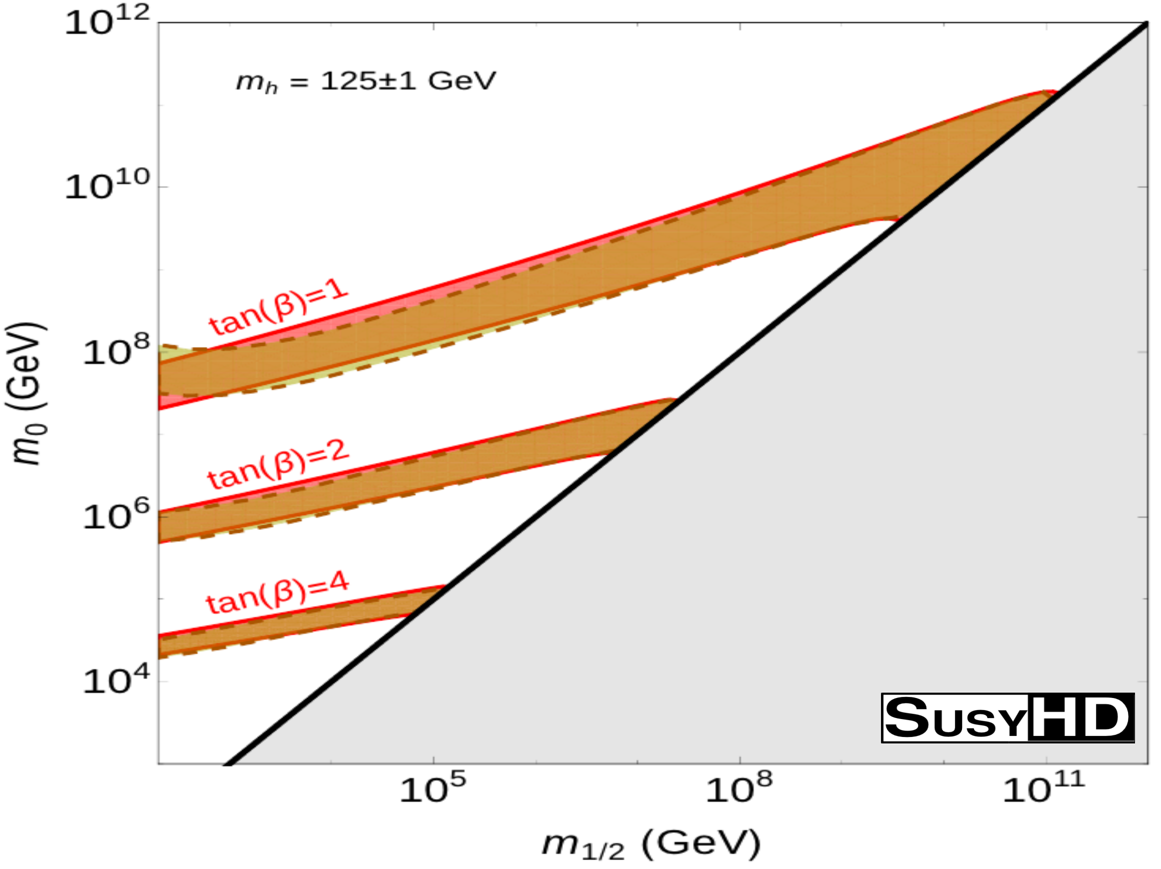
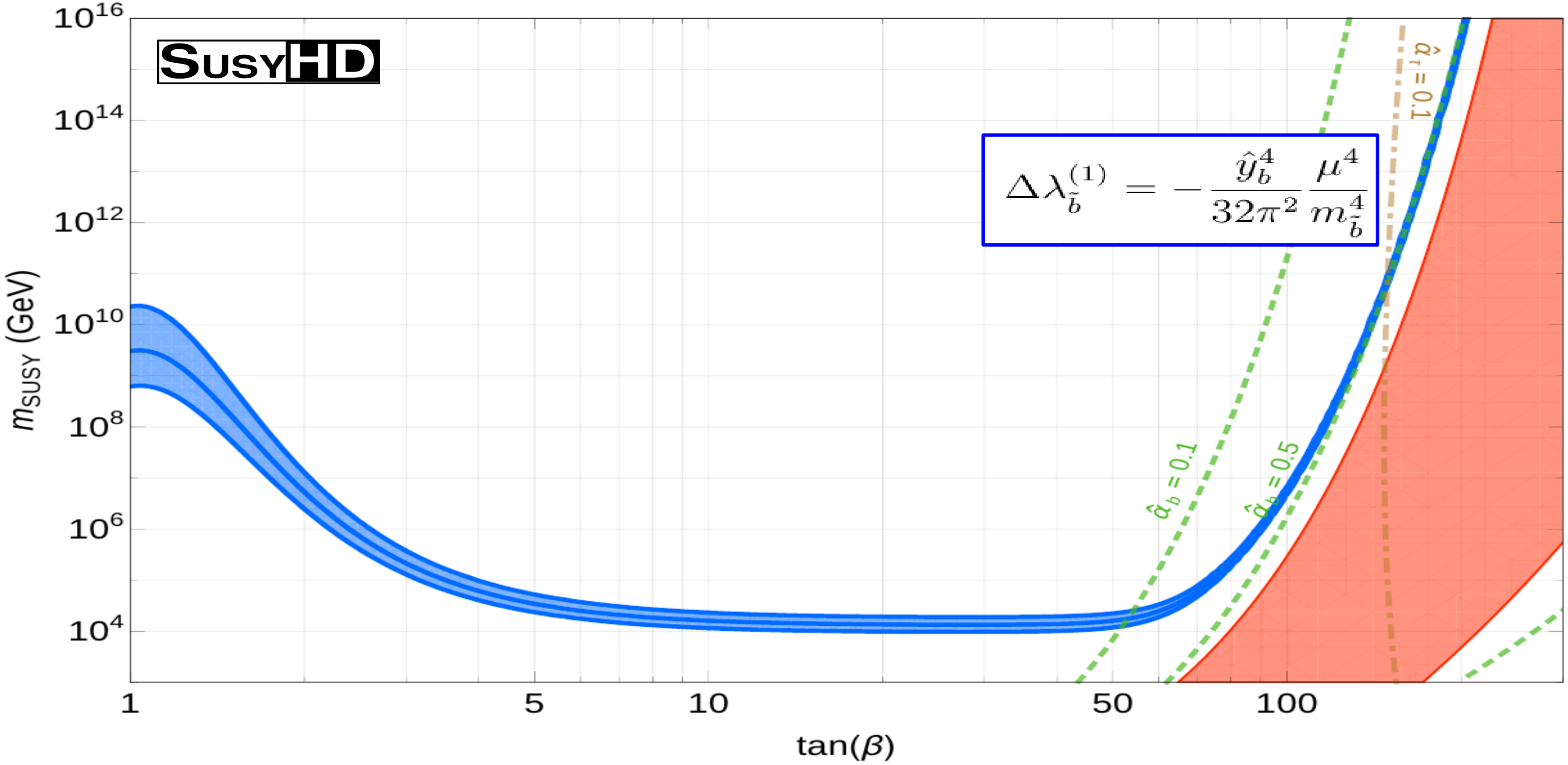
Perfect target for an 100 TeV collider?

Improvement on *top* mass **required**!

Backup

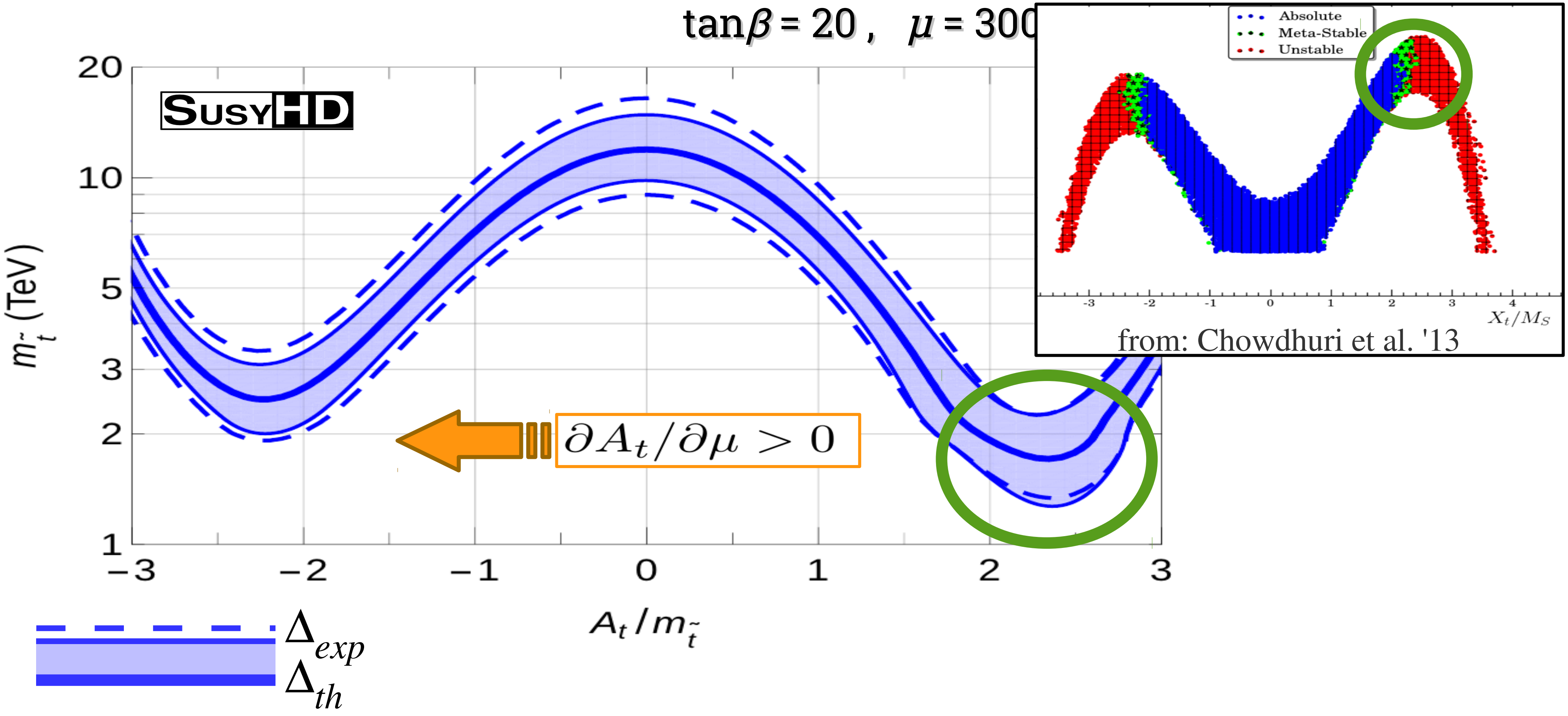
Effects from splitting fermions





SusyHD
$\Delta\lambda^{(1)}_{\tilde{b}} = -\frac{\hat{y}_b^4}{32\pi^2}\frac{\mu^4}{m_{\tilde{b}}^4}$
$\hat{\alpha}_b = 0.1$
$\hat{\alpha}_b = 0.5$
$\hat{\alpha}_\tau = 0.1$
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
m_{SUSY} (GeV)
1
5
10
50
100
$\tan(\beta)$

A “natural” SUSY-like spectrum:



No naturalness → no μ problem:

SUSY term

$\boldsymbol{\mu}$

No naturalness → no μ problem:

μ

no EWSB

m_0, $M_{1/2}$

No naturalness → no μ problem:

EWSB ~ m_0

No naturalness → no μ problem:

μ

m_0, $M_{1/2}$

$$|\mu|^2 \simeq -m_{H_u}^2 + \ldots$$

m_Z

EWSB « m_0

No naturalness → no μ problem:

μ

m_0, $M_{1/2}$

$$|\mu|^2 \simeq -m^2_{H_u} + \ldots$$

m_Z

EWSB « m_0

$B_\mu, A = 0$ at the scale M

generated radiatively

No naturalness → no μ problem:

μ

m_0, $M_{1/2}$

$|\mu|^2 \simeq -m^2_{H_u} + \ldots$

m_Z

EWSB « m_0

$B_\mu, A = 0$ at the scale M

generated radiatively

$A_t \lesssim m_0$ *no maximal mixing*

No naturalness → no μ problem:

μ

m_0, $M_{1/2}$

$$|\mu|^2 \simeq -m_{H_u}^2 + \ldots$$

m_Z

EWSB « m_0

$\boxed{B_\mu, A = 0 \quad \text{at the scale } M}$

<u>generated radiatively</u>

$A_t \lesssim m_0$ *no maximal mixing*

$B_\mu \ll m_0^2$ $\tan(\beta) \sim 30\text{-}60$

No naturalness → no μ problem:

μ

m_0, $M_{1/2}$

$|\mu|^2 \simeq -m^2_{H_u} + \ldots$

m_Z

EWSB « m_0

$B_\mu, A = 0$ at the scale M

generated radiatively

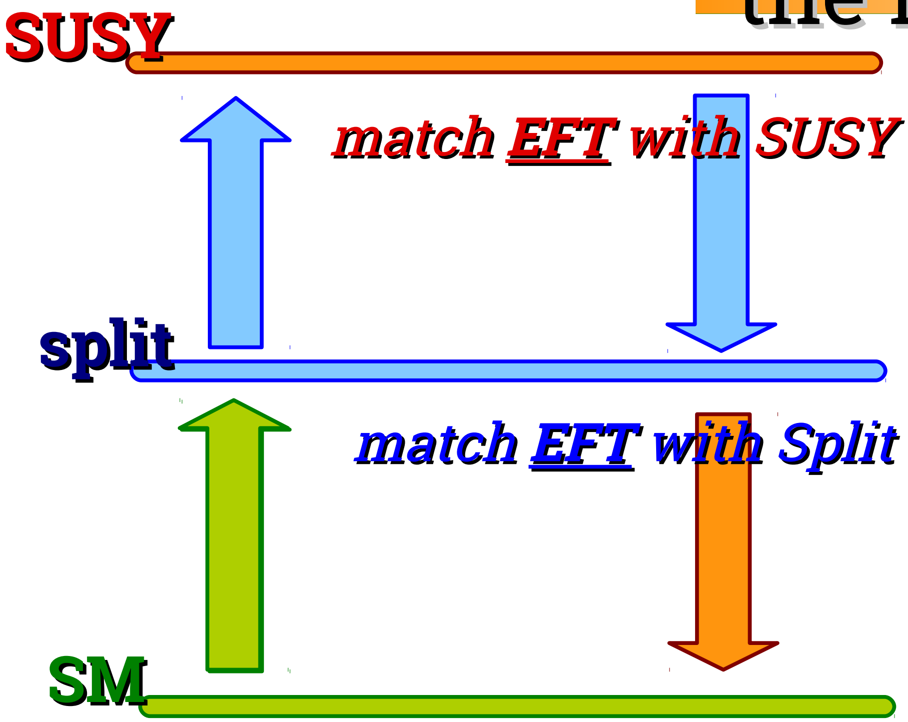
$A_t \lesssim m_0$ — *no maximal mixing*

$B_\mu \ll m_0^2$ — tan(β) ~ 30-60

no CP phases → *no EDMs*

Exploiting the Hierarchy Problem:

the EFT technique



full 1 loop SUSY thresholds
+ leading 2 loops

2 loop split RGE
+ 1 loop thresholds

full SM 3 loops

full 2-loops SM matching

Small improvement w.r.t. to a longstanding effort

Pokorski, Rosiek, Dabelstein, Zhang, Espinosa, Quiros, Hempfling, Hoang, Heinemeyer, Hollik, Weiglein, Brignole, Slavich, Zwirner, Degrassi, Martin, Giudice, Strumia, Wagner … many many others

apologies to the missing ones

Our contribution: (mostly w.r.t. Bagnaschi *et al.* '14)

- Recomputation of $O(\alpha_s\alpha_t)$ corrections
- Computation of $O(\alpha_t^2)$ with scale dependence
- Inclusion bottom/tau corrections (w/ resummation of tanβ enhanced corr.)
- Computation both in DRbar and OS schemes
- Study of the uncertainties and comparison with existing computations
- A "fast" Mathematica® package: SusyHD