Dirac NMSSM

Santa Fe 2014 "LHC After the Higgs"
July 3rd

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2nd Year Anniversary Tomorrow!

Outline

- Introduction: LHC results, naturalness
- Tensions in Supersymmetry
- Beyond MSSM
  - NMSSM and Dirac NMSSM
- Phenomenology of Dirac NMSSM
- Conclusion

Introduction

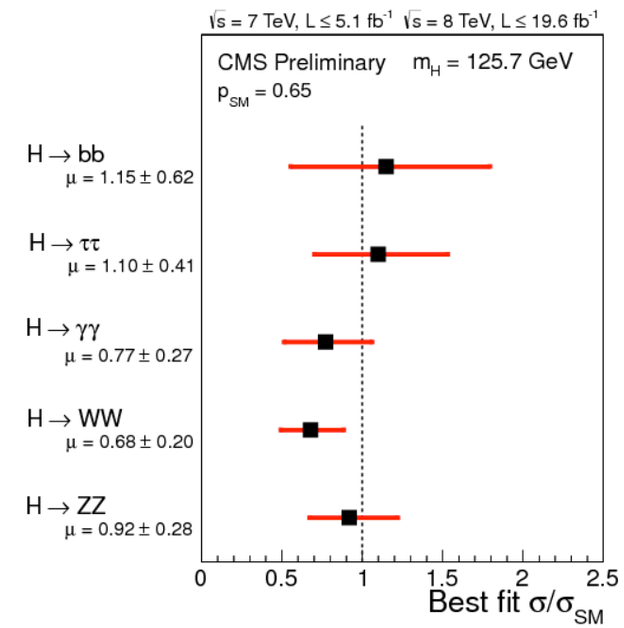
Results: Discovery and Non-discovery

- Higgs Boson

  Standard Model like (spin and coupling

$$m_H^2 = 125.4 \pm 0.37(stat) \pm 0.18(syst)\text{GeV} \quad \text{(ATLAS)}$$

$$m_H^2 = 125.7 \pm 0.3(stat) \pm 0.3(syst)\text{GeV} \quad \text{(CMS)}$$



- No discovery/evidence of physics beyond the Standard Model (BSM)

  - constraint simple supersymmetry models

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.6 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ 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	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta$ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	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	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	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	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3rd 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	20.7	$\tilde{b}_1$ 275-430 GeV	$m(\tilde{\chi}_1^\pm)=2\ m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-200 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 271-520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
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	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
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	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (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	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	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	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e, μ (SS)	1 b	Yes	14.3	sgluon 800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

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

$\sqrt{s}$ = 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.

End of LHC Revolution?

- Naturalness problem

$$V = \mu_H^2 \mid H \mid^2 + \frac{\lambda_H}{4} \mid H \mid^4$$

$$< H >= v = 174\,\mathrm{GeV}$$

$$m_H^2 = -2\mu_H^2 = \lambda_H v^2 \approx (125\mathrm{GeV})^2$$

No Symmetry for mass term

$$\mu_H{}^2 = \mu_{H_0}{}^2 + \sum \frac{g^2}{16\pi^2}\Lambda^2 \sim -\frac{m_H^2}{2}\ ?$$

For $\Lambda = M_{Pl}$, 10^{30} fine-tuning $\quad \Delta = \frac{\delta m_H^2}{m_H^2} = \frac{-2\delta\mu_H^2}{m_H^2}$

Naturalness in electron mass and Higgs mass

Murayama('94)

Electron mass

Classical E&M

$$\delta m_e \simeq \frac{\alpha}{\pi}\Lambda$$

+positron →

10^3 tuning ($\Lambda^{-1}=10^{-3}$fm)

Chiral Symmetry (softly-broken by m_e)

$$\delta m_e \simeq \frac{3\alpha}{2\pi} m_e \log\frac{\Lambda}{m_e}$$

Higgs mass

Fermion ↔ Boson

SM

$$\delta\mu_H{}^2 \simeq \frac{g^2}{16\pi^2}\Lambda^2$$

+SUSY particle →

SUSY (softly-broken by M_{SUSY})

$$\delta\mu_H{}^2 \simeq \frac{g^2}{16\pi^2} M_{\rm SUSY}^2 \log\frac{\Lambda^2}{M^2}$$

M_{SUSY} is not too far from weak-scale⇒Expect TeV SUSY!

8min

Two Tensions in SUSY

Tension 1: Naturalness VS m_h=125 GeV

$m_h^2 = \lambda_H v^2$ Quartic coupling→Higgs mass

- Tree-level upper bound in the minimal model: MSSM

$$m_h \simeq m_z \cos 2\beta \lesssim 91\text{GeV} \qquad \lambda_H \leq \frac{g_1^2 + g_2^2}{8}$$

$$\tan\beta \equiv \frac{v_u}{v_d}$$

- Need large radiative corrections

$$\Delta m_h^2 \simeq \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

need large m_{stop}

$$X_t \equiv A_t - \mu\cot\beta$$

Effective quartics

Okada, Yamaguchi, Yanagida (1991)/Ellis, Ridolfi, Zwirner(1991)/Haber, Hempfling(1991)

Tension 1: Naturalness VS m_h=125 GeV

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need large m_{stop}

$$X_t \equiv A_t - \mu\cot\beta$$

Large m_{stop} drastically changes Higgs mass parameters

fine-tuning of <1%

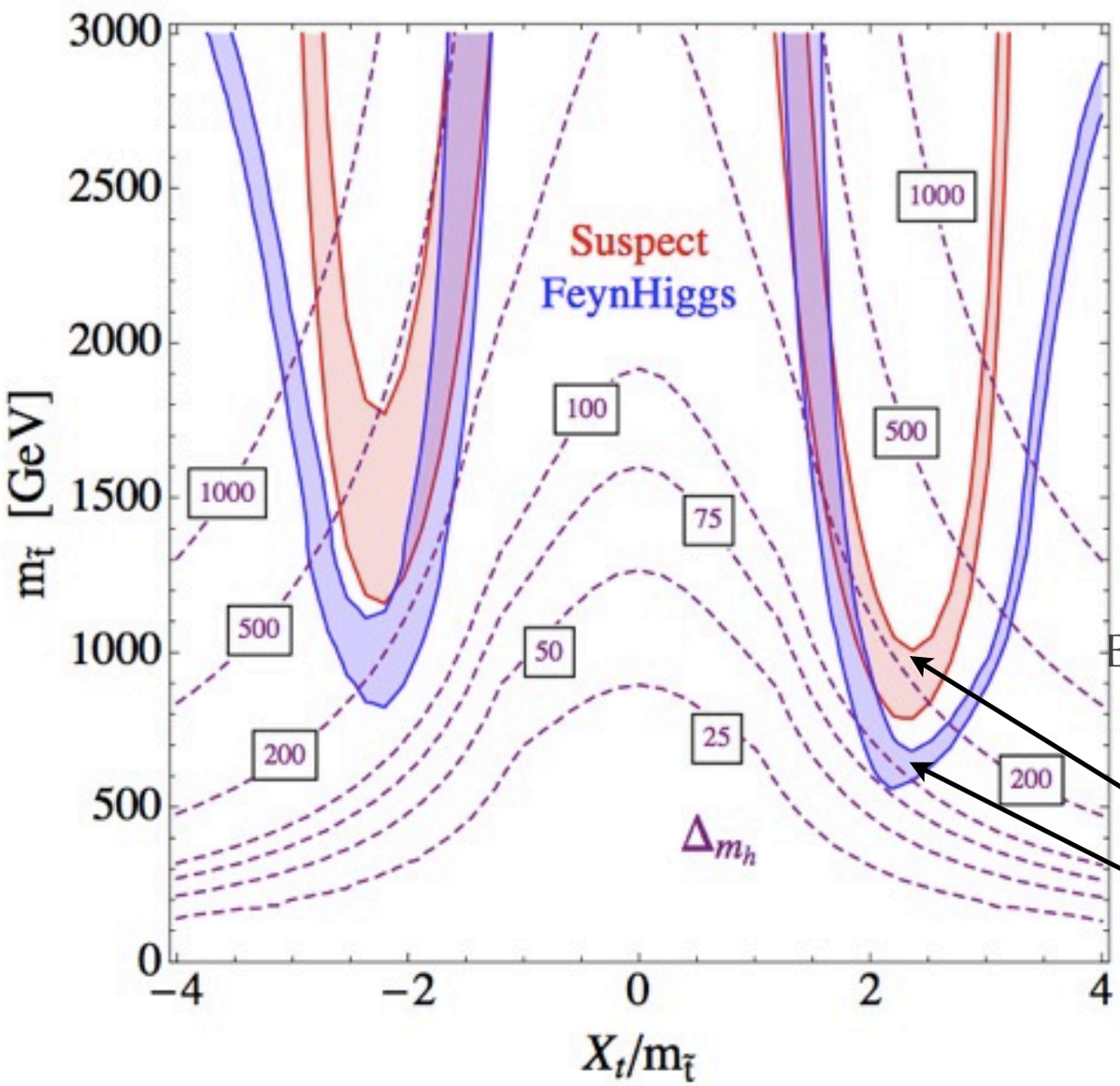
$$\mu\frac{d}{d\mu}m_{H_u}^2 \sim \frac{3y_t^2}{8\pi^2}(2m_{\tilde{t}}^2 + |A_t|^2)$$

Fine-tuning and stop mass

できれば12分

$$\Delta_{m_h} = \frac{\delta m_h^2}{m_h^2} \left(= \frac{-2\delta\mu_H^2}{m_h^2} \right) \quad (\Lambda_{med} = 10\,\mathrm{TeV})$$

Hall, Pinner, Ruderman('12)



At best ~1%
(low-scale mediation)

For CMSSM, at best
~0.1%

Baer, Barger, Huang, Mickelson, Mustafayez, Tata('12)

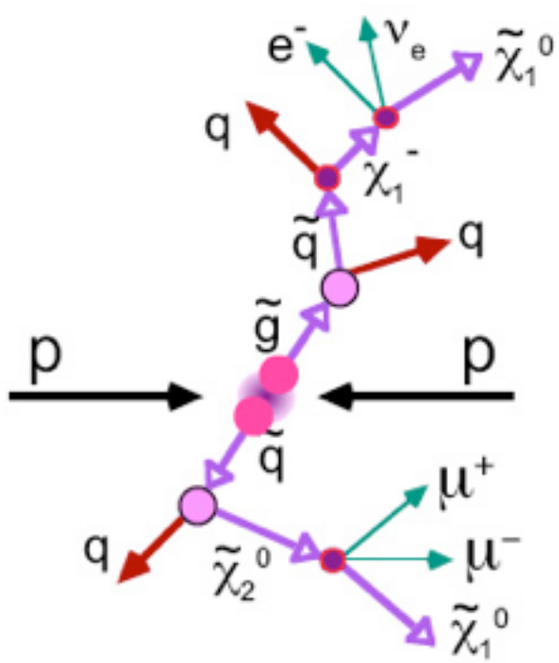
Suspect m_h=125GeV

FeynHiggs m_h=125GeV

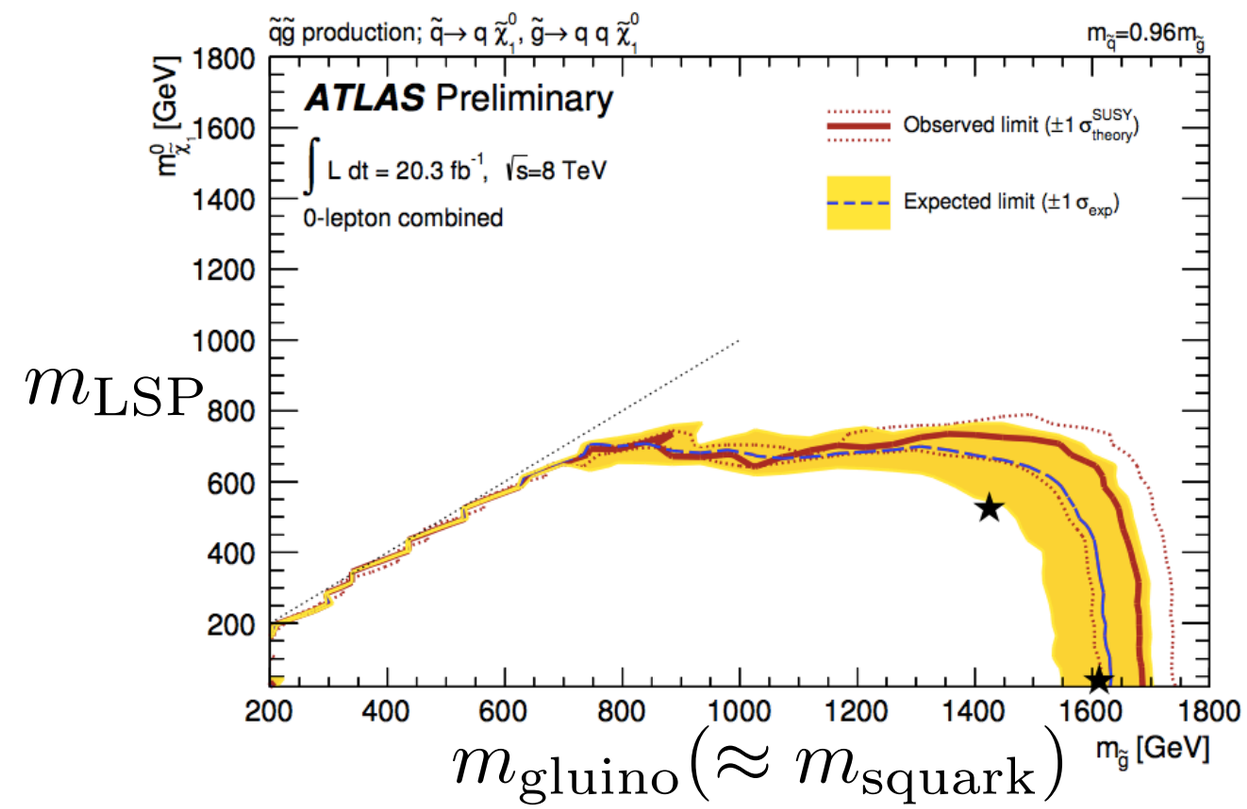
Tension II: No SUSY signal in direct search

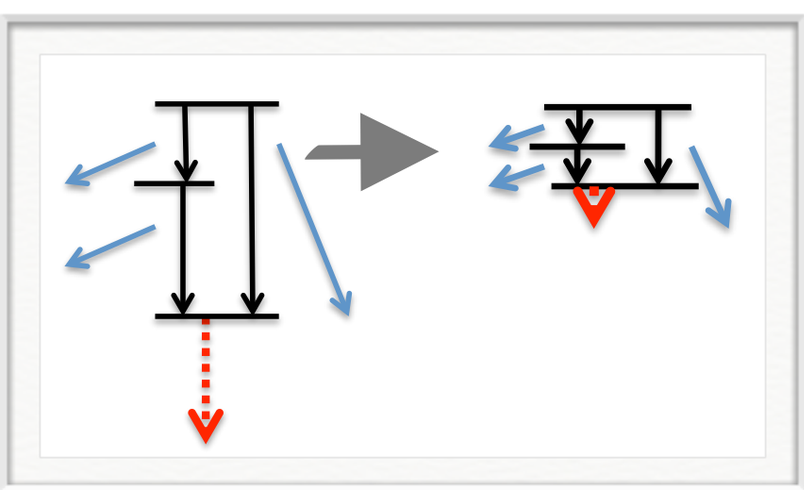
- E_T^{miss} searches constraint simple models like CMSSM

SUSY Event at LHC



Limit ATLAS multijet 20fb^{-1}, 8TeV



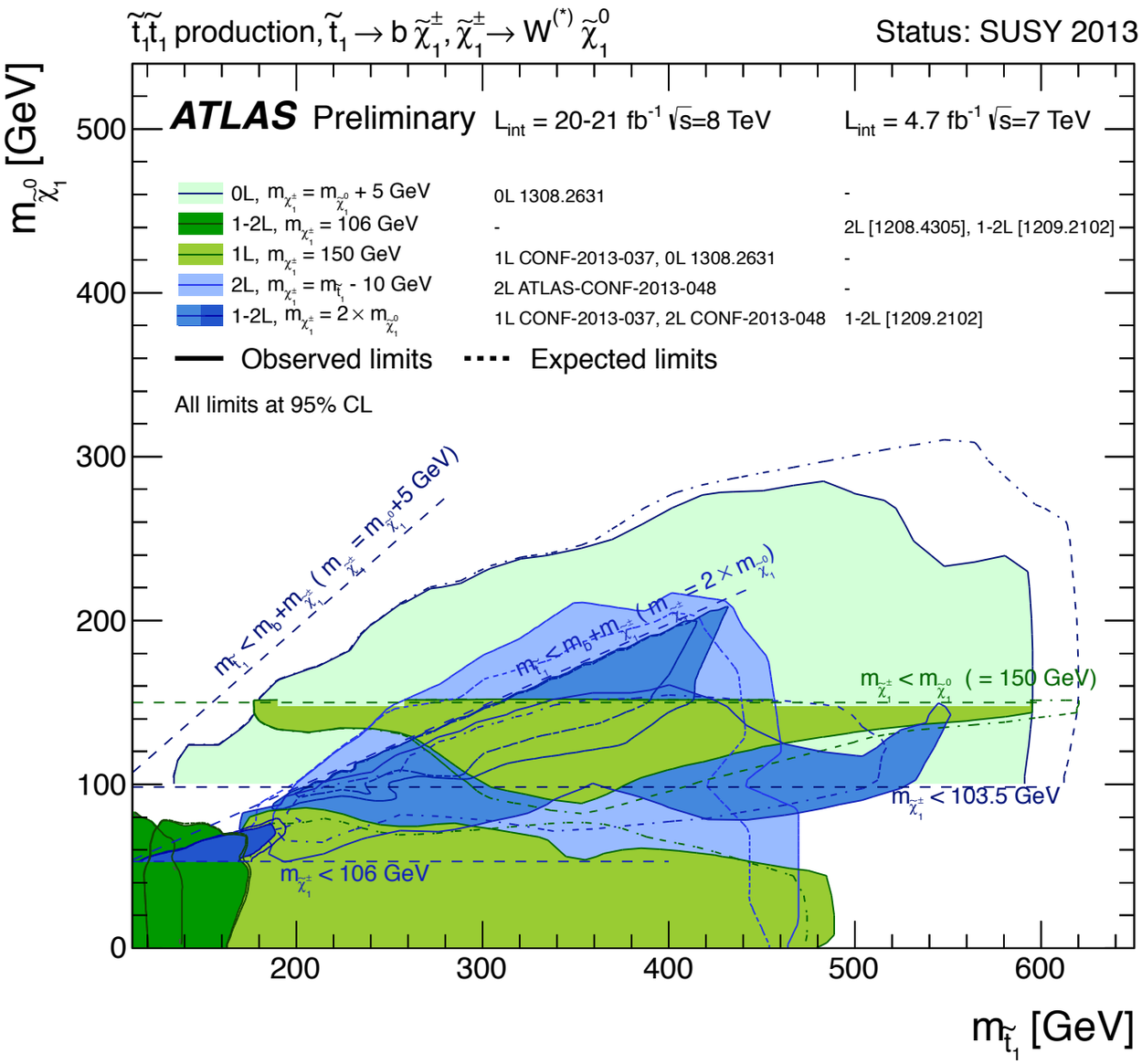


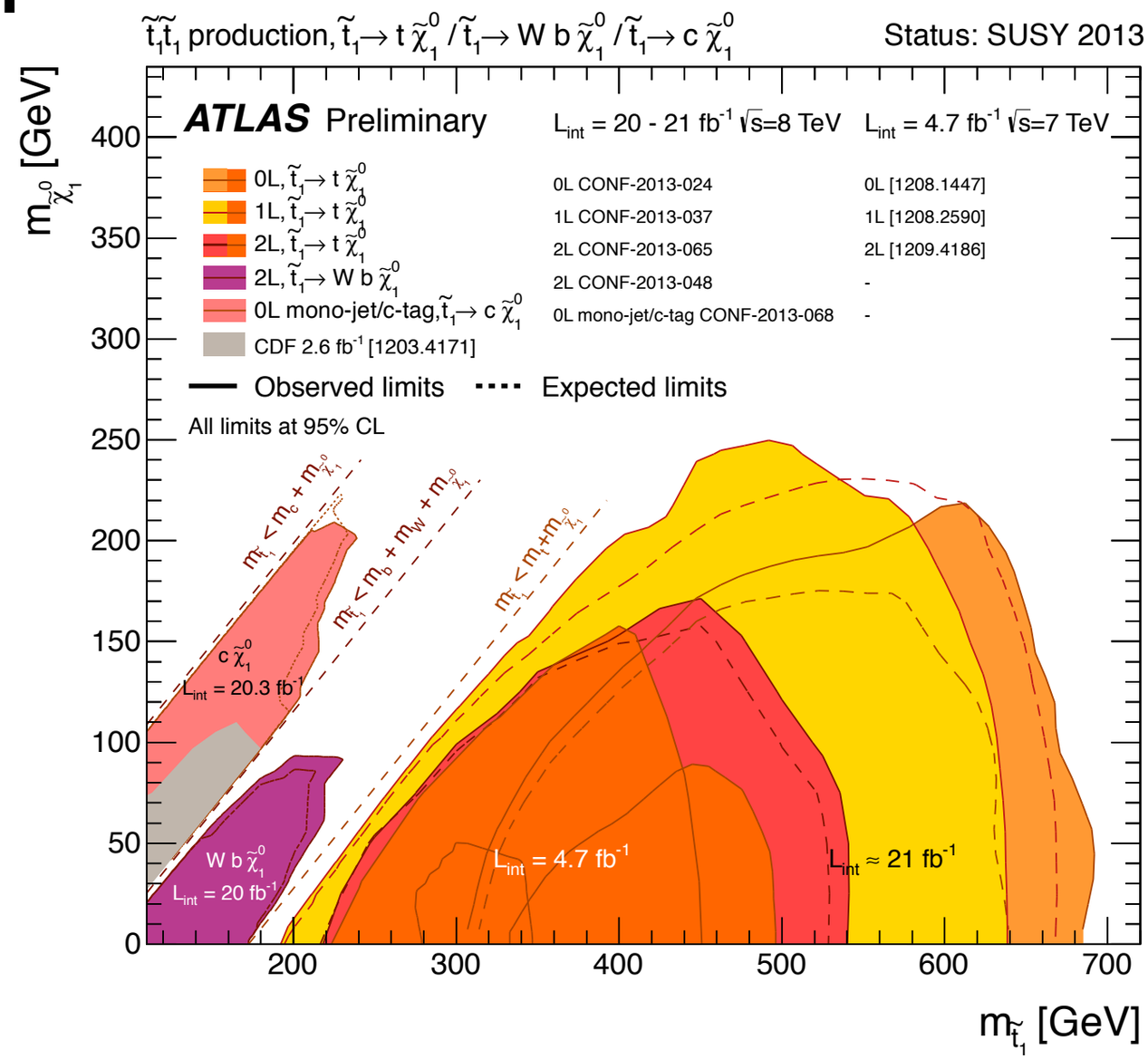
$$m_{\tilde{g}} \simeq m_{\tilde{q}} \gtrsim 1.7 \text{ TeV} \rightarrow 1\,\text{TeV} \;\; (\Delta m \lesssim 300\,\text{GeV})$$

weaker limit for compressed spectrum

Scherk-Schwarz breaking Murayama, Nomura, Shirai, KT ('12)

Tension II: No SUSY signal in direct search stop limit





Focus

Naturalness

Higgs Mass of 125 GeV

Missing Sparticles

Experimental loopholes?
e.g.) RPV, Compressed ..

13 min

Focus

Naturalness

Higgs Mass of 125 GeV

Missing Sparticles

Experimental loopholes?
e.g.) RPV, Compressed ..

Natural Higgs sector beyond MSSM

Beyond MSSM

Beyond MSSM

Attempts beyond MSSM to accommodate Higgs mass.

e.g.

- New gauge group non-decoupling D-term
- New field (iso-triplet, singlet) non-decoupling F-term

  - Two singlets (Dirac NMSSM)

Usually, new states should be at a few 100 GeV due to naturalness, but in Dirac NMSSM a new state relevant to non-decoupling effect is not necessarily light.
Large SUSY breaking and naturalness are compatible.

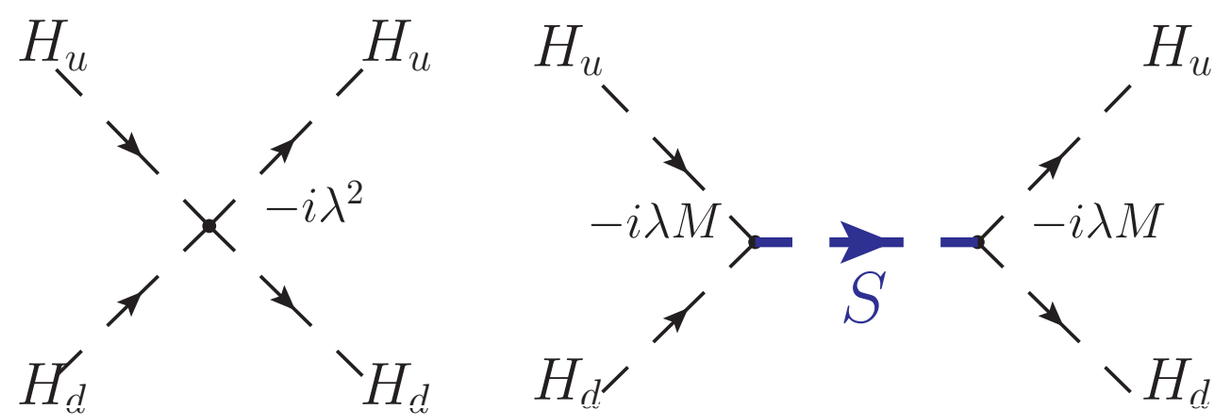
M is at weak scale
簡単に！

Non-decoupling effect in NMSSM

$$W \supset \lambda S H_u H_d + M S^2/2 + \mu H_u H_d$$

Nomura, Poland, Tweedie ('05)
Dine, Seiberg, Thomas('07)

$$\Rightarrow \; V \supset |F_S|^2 = |\lambda H_u H_d + MS|^2$$



New quartic

$$\lambda^2 \left(1 - \frac{M^2}{M^2 + m_S^2}\right) |H_u H_d|^2$$

Non-decoupling: SUSY breaking m_S needed

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \lambda^2 \left(\frac{m_S^2}{M^2 + m_S^2}\right) \sin^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

Fine-tuning

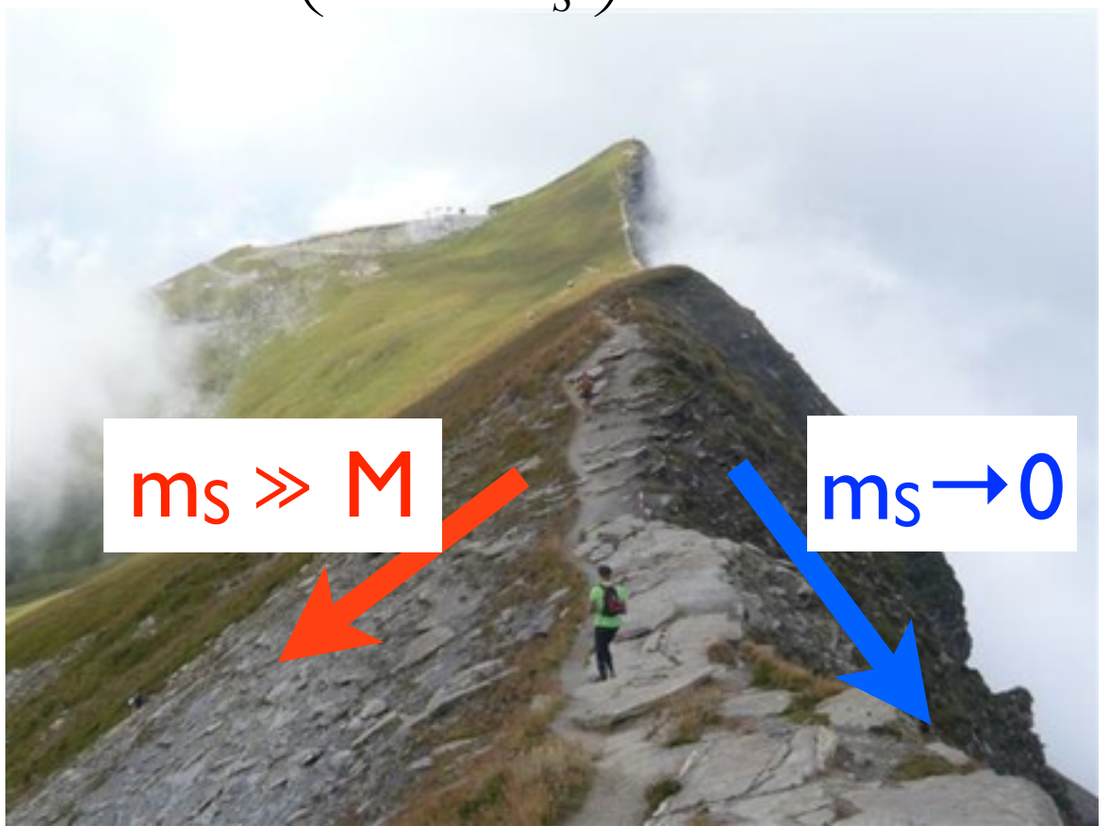
$$\mu \frac{d}{d\mu} m_{H_u}^2 \sim \frac{\lambda^2}{8\pi^2} m_S^2 + \frac{3 y_t^2}{8\pi^2} (2 m_{\tilde{t}}^2 + |A_t|^2)$$

Large m_S is unnatural!

簡単に！
右から左へ

Tension in NMSSM

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \lambda^2 \left(\frac{m_S^2}{M^2 + m_S^2} \right) \sin^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$



Non-decoupling
Singlet feedback
fine-tuning

MSSM limit
Small Higgs mass at tree
Need large stop mass
fine-tuning

$$\mu \frac{d}{d\mu} m_{H_u}^2 \sim \frac{\lambda^2}{8\pi^2} m_S^2 + \frac{3y_t^2}{8\pi^2} (2m_{\tilde{t}}^2 + |A_t|^2)$$

Dirac NMSSM

Lu, Murayama, Ruderman, KT

$$W \supset \lambda S H_u H_d + M S^2/2 + \mu H_u H_d$$

$$W \supset \lambda S H_u H_d + \boxed{M S\bar{S}} + \mu H_u H_d$$

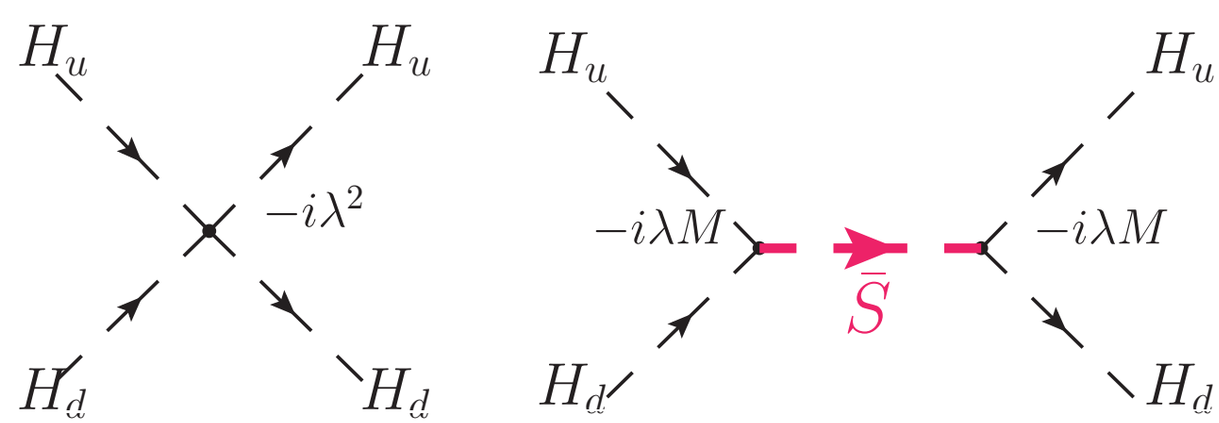
18 min

Dirac mass of singlets

Non-decoupling effect in Dirac NMSSM

$$W \supset \lambda S H_u H_d + M S\bar{S} + \mu H_u H_d$$

$$\Rightarrow \; V \supset |F_S|^2 = |\lambda H_u H_d + M\bar{S}|^2$$



New quartic

$$\lambda^2 \left(1 - \frac{M^2}{M^2 + m_{\bar{S}}^2}\right) |H_u H_d|^2$$

Non-decoupling: SUSY breaking m_{Sbar} needed

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \lambda^2 \left(\frac{m_{\bar{S}}^2}{M^2 + m_{\bar{S}}^2}\right) \sin^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

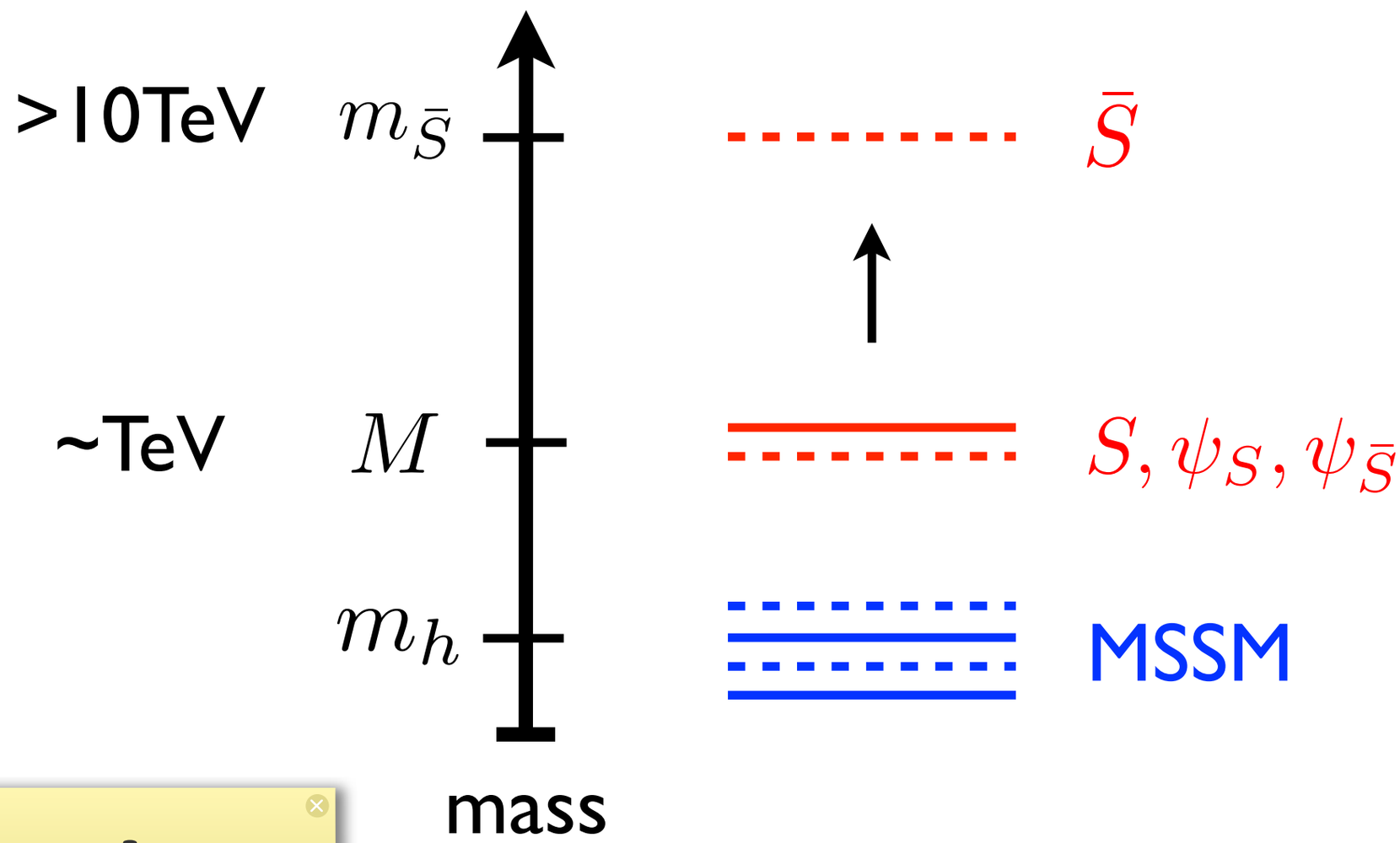
Fine-tuning

$$\mu \frac{d}{d\mu} m_{H_u}^2 \sim \frac{\lambda^2}{8\pi^2} m_S^2 + \frac{3y_t^2}{8\pi^2}(2m_{\tilde{t}}^2 + |A_t|^2)$$

Large m_{Sbar} is OK

compatible

Naturalness ↔ Non-decoupling



20 min

あっさりと！
とにかく正当化出来ると言う

Symmetry

$$W \supset \lambda S H_u H_d + M S\bar{S} + \mu H_u H_d$$

	Matter	H_u	H_d	S	$\bar{S}$	μ	M	ϵ_μ	ϵ_M
$U(1)_{PQ}$	$-1/2$	1	1	-2	-2	-2	4	-2	4
$U(1)_{\bar{S}}$	0	0	0	0	1	0	-1	0	-1

$$\epsilon_{\mu,M} \sim \frac{\mu, M}{M_{pl}} \ll 1$$

Forbidden $\quad S, S^2, S^3, S^2\bar{S}$

Suppressed $\quad (\epsilon_M \epsilon_\mu)^2 M_{pl} \bar{S}^2, (\epsilon_M \epsilon_\mu)^3 \bar{S}^3, \epsilon_M^2 \epsilon_\mu S \bar{S}^2$

Adequate $\quad (\epsilon_M \epsilon_\mu) M_{pl}^2 \bar{S} \qquad W \supset c_{\bar{S}} \mu M \bar{S}$

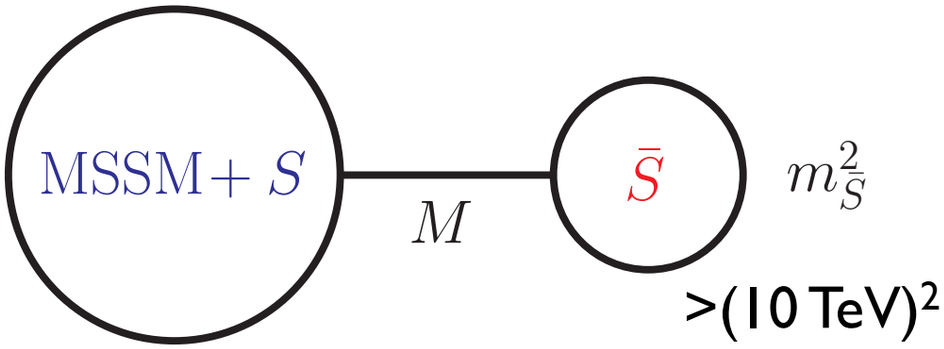
$$V_{\rm Dirac}^{soft} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + m_{\bar{S}}^2 |\bar{S}|^2$$
$$+ \lambda A_\lambda S H_u H_d + M B_S S \bar{S} + \mu B H_u H_d + t_{\bar{S}} \bar{S} + t_S S + c.c.$$

ゆっくり！！Whether higher order radiative corrections is really OK for naturalness?? 2min!!

Naturalness vs radiative corrections

$$W \supset \lambda S H_u H_d + M S\bar{S} + \mu H_u H_d$$

In $M \to 0$ limit
effects of $\bar{S}$ must decouple



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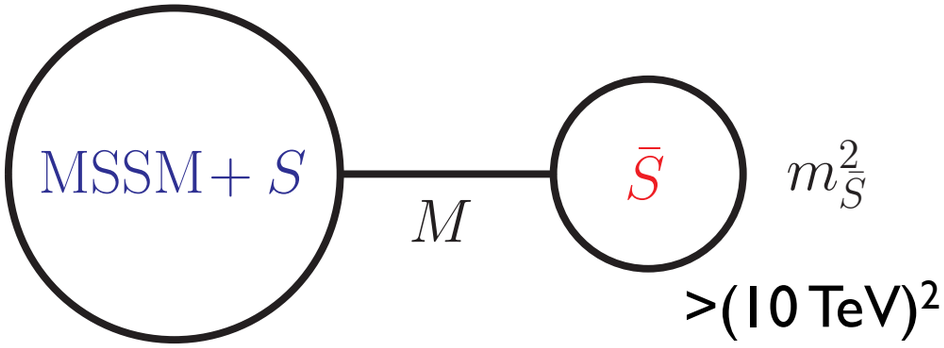

RGEs

Higgs parameters are independent of $m_{\bar{S}}^2$ at all orders

too high dimension

D≧4 $m_{\bar{S}}^2 M^2$ ✗→ D=2 $m_{H_u}^2$, $m_{H_d}^2$, b

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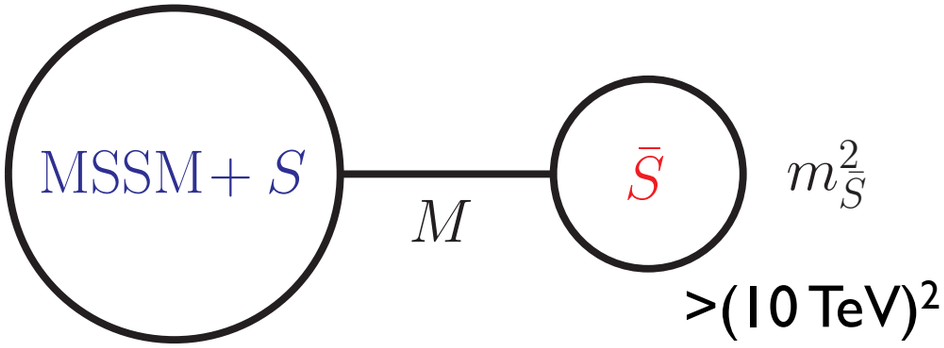


RGEs

Higgs parameters are independent of $m_{\bar{S}}^2$ at all orders

too high dimension

D≧4 $m_{\bar{S}}^2 M^2$ → D=2 $m_{H_u}^2,\ m_{H_d}^2,\ b$

Threshold correction $E < m_{\bar{S}}^2$

$$\delta m_{H_{u,d}}^2 = \frac{\lambda^2}{16\pi^2} M^2 \log\left(\frac{M^2 + m_{\bar{S}}^2}{M^2}\right)$$

log-dependence

Not analytic in m_{IR}

$$\delta m_{H_u}^2 \propto \frac{M^2 m_{\bar{S}}^2}{m_{IR}^2}$$

safe at all orders

23 min

Secretly Soft-breaking

$S, \bar{S}, \psi_S, \psi_{\bar{S}}$

$$W \supset \lambda S H_u H_d + M S \bar{S} + c_{\bar{S}} \mu M \bar{S}$$

$$L \supset -|\lambda H_u H_d + M\bar{S}|^2 - |MS + c_{\bar{S}}\mu M|^2 - M\psi_S \psi_{\bar{S}} + h.c.$$

$m_{\bar{S}} \to \infty$

$S, \psi_S, \psi_{\bar{S}}$

Lack of $\bar{S}$

$$L \supset -|\lambda H_u H_d|^2 - |MS + c_{\bar{S}}\mu M|^2 - M\psi_S \psi_{\bar{S}} + h.c.$$

Even in presence of large SUSY breaking...

EFT ~ softly-broken SUSY!

Reintroduce superfield

$$\bar{S}' = \phi_{\bar{S}'} + \theta \psi_{\bar{S}} + \theta^2 F_{\bar{S}'}$$

$$\mathcal{K}_{eff} = \bar{S}'^\dagger \bar{S}' - \theta^2 \bar{\theta}^2 \left(M^2 |S + c_{\bar{S}}\mu|^2\right) \ ,$$

$$W_{eff} = \lambda S H_u H_d - \theta^2 \left(M \mathcal{D}^\alpha S \, \mathcal{D}_\alpha \bar{S}'\right)$$

"Semi-soft breaking"

Higgs mass

- Potential

$$V \simeq |\lambda H_u H_d|^2 \frac{m_{\bar{S}}^2}{M^2 + m_{\bar{S}}^2} - \frac{\lambda^2}{M^2 + m_S^2} \left| A_\lambda H_u H_d + \mu^* (|H_u|^2 + |H_d|^2) \right|^2$$

- SM-like Higgs mass

$$m_h^2 \simeq m_{h,MSSM}^2(m_{\tilde{t}}) + \lambda^2 v^2 \left\{ \sin^2 2\beta \frac{m_{\bar{S}}^2}{M^2 + m_{\bar{S}}^2} - \frac{|A_\lambda \sin 2\beta - 2\mu_{\rm eff}^\dagger|^2}{M^2 + m_S^2} \right\}$$

Radiative corrections: RG-Improved 1-loop (A_t=0)

>>Cosistent with FeynHiggs, within Δm_h=1GeV for MSSM

$$y_t \to y_t \left(1 + (\beta_t + \beta_s) \log \frac{Q}{m_t} \right)$$

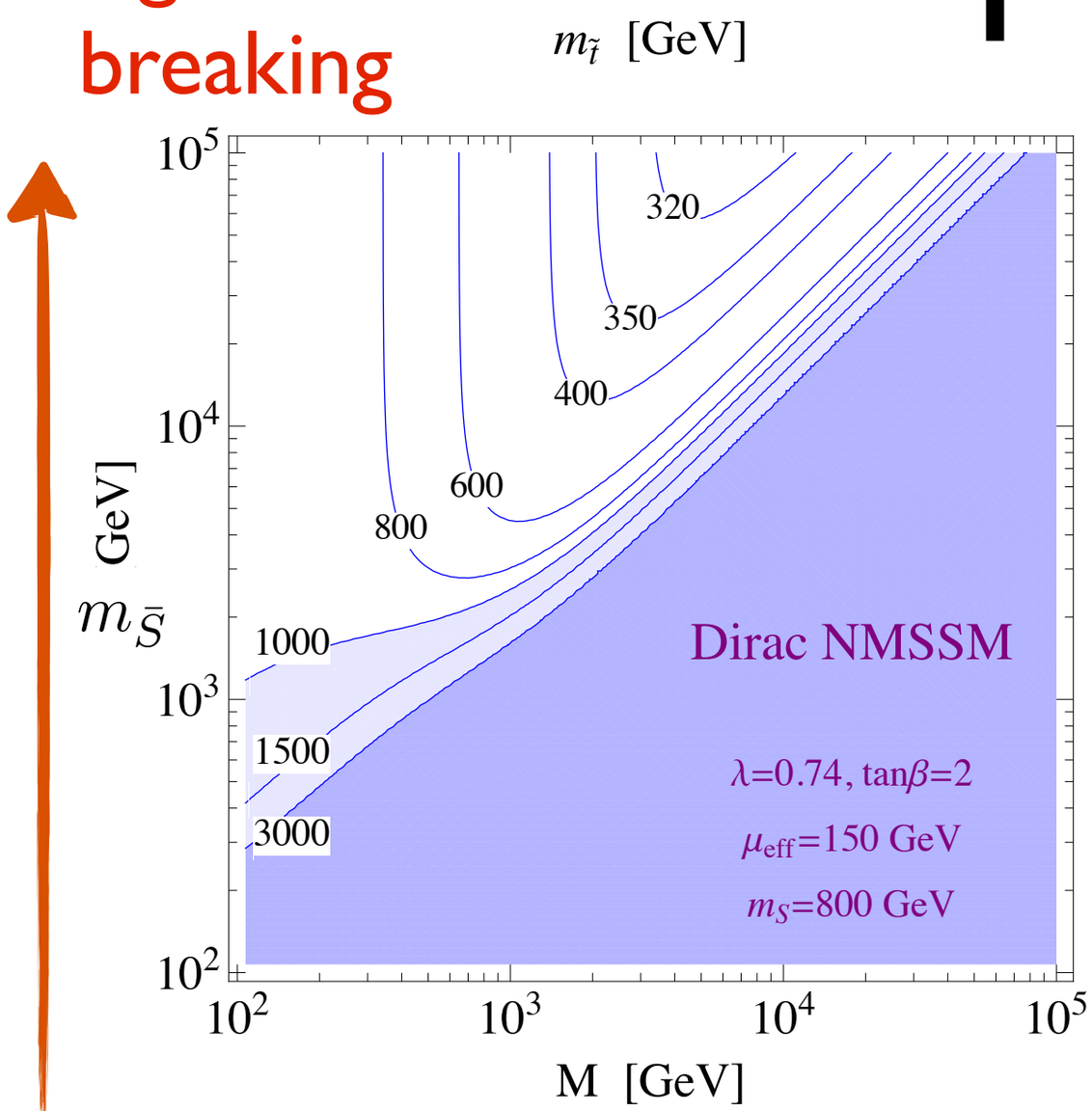
$$Q = c_{y_t} \sqrt{m_t (m_{\tilde{t}}^2 + m_t^2)^{1/2}}$$

$$\lambda = 0.74,\ \tan\beta = 2,\ \mu_{\rm eff} = 150\,{\rm GeV},$$
$$M = 1\,{\rm TeV},\ m_{\bar{S}} = 10\,{\rm TeV},\ m_S = 800\,{\rm GeV},$$
$$B_S = 100\,{\rm GeV},\ A_\lambda = 0$$

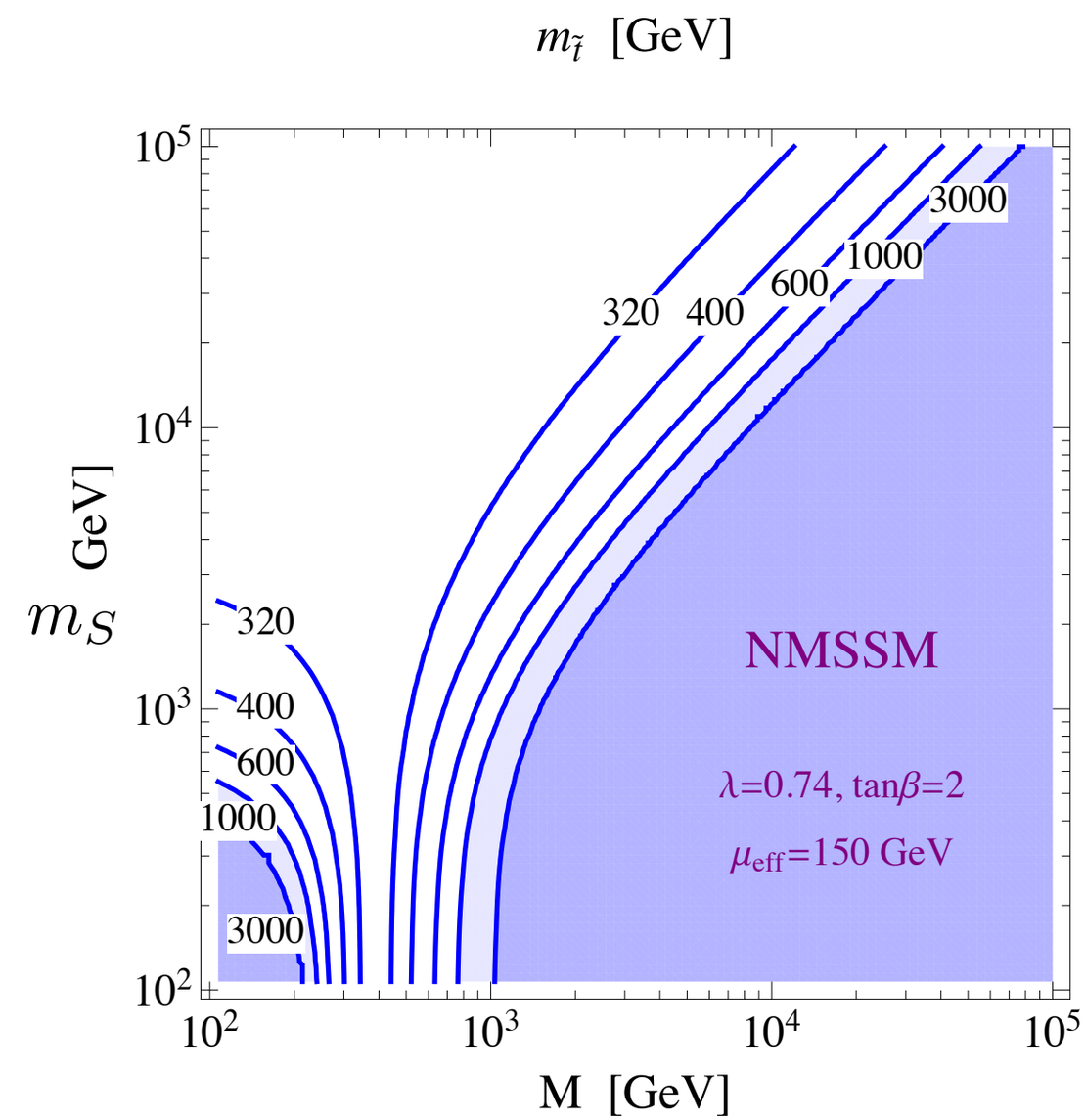
25 min

Stop mass

Large SUSY breaking



Dirac NMSSM



NMSSM

$$m_h^2 \simeq m_{h,MSSM}^2(m_{\tilde{t}}) + \lambda^2 v^2 \left\{ \sin^2 2\beta \frac{m_{\bar{S}}^2}{M^2 + m_{\bar{S}}^2} - \frac{|A_\lambda \sin 2\beta - 2\mu_{\rm eff}^\dagger|^2}{M^2 + m_S^2} \right\}$$

Choose stop mass so that m_h=125 GeV

Tuning level

Tuning measure (bottom-up)

Kitano, Nomura('06)

$$\Delta \equiv \frac{\delta m_h^2}{m_h^2} \Rightarrow \Delta = \frac{2}{m_h^2}\max\left(m_{H_u}^2, m_{H_d}^2, \frac{dm_{H_u}^2}{d\ln\mu}L, \frac{dm_{H_d}^2}{d\ln\mu}L, \delta m_H^2, b_{eff}\right)$$

$$L = \ln\frac{\Lambda}{v} = 6,\ 30$$

$$\frac{dm_{H_u}^2}{d\ln\mu} = \frac{1}{8\pi^2}\left(3y_t^2(m_{\widetilde{Q}_3}^2 + m_{\widetilde{t_R}}^2) + \lambda^2 m_S^2\right) \ \ldots$$

Gluino contribution is not included

$$\delta m_H^2 = \frac{\lambda^2}{16\pi^2} M^2 \log\left(\frac{M^2 + m_{\widetilde{S}}^2}{M^2}\right)$$

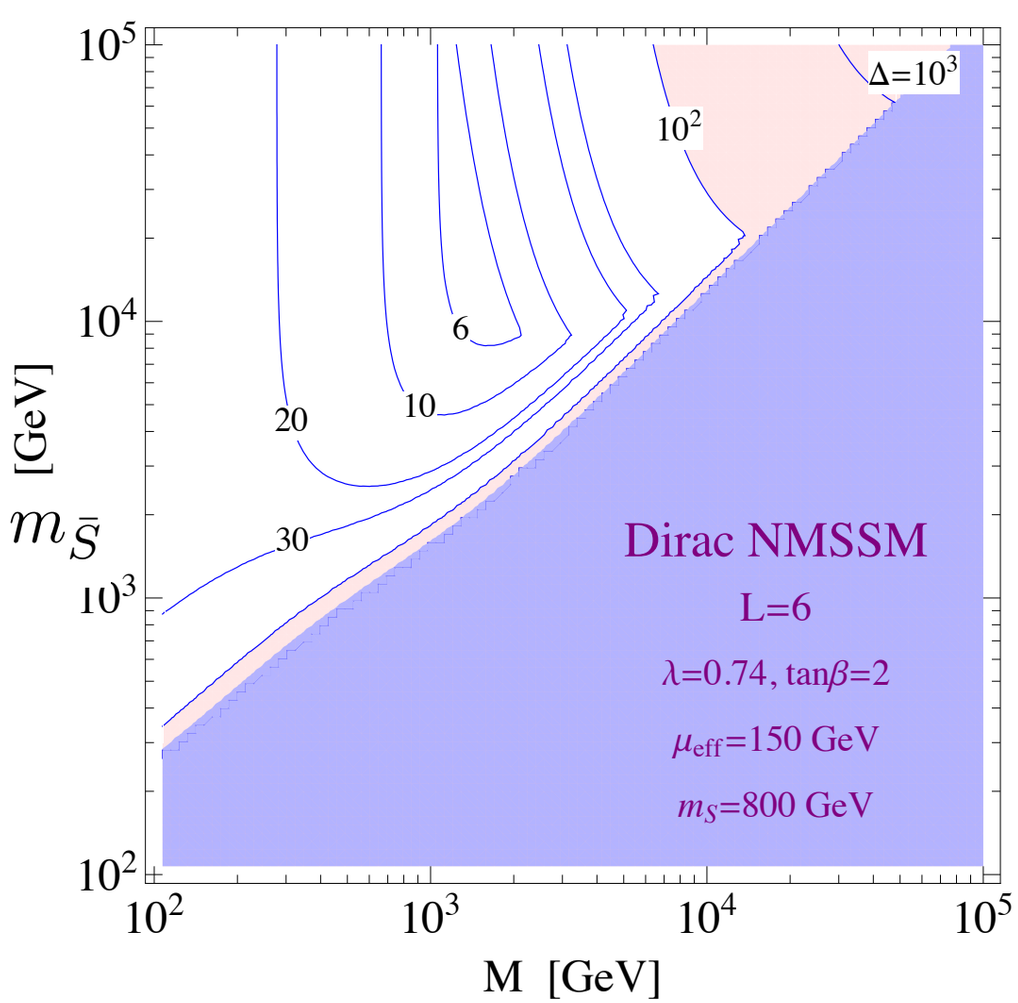
Tuning level

Large SUSY breaking

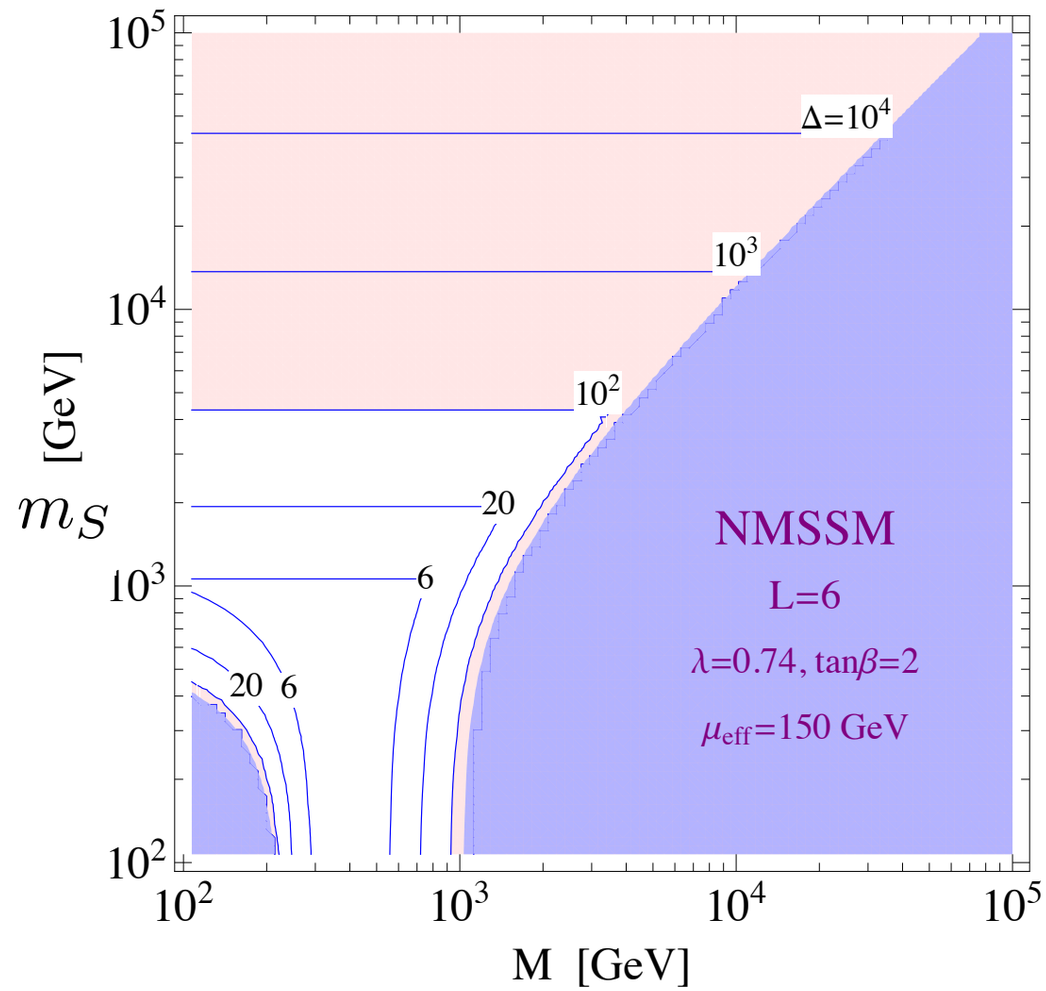
Low-scale mediation

L=6

Dirac NMSSM



NMSSM



$$m_h^2 \simeq m_{h,MSSM}^2(m_{\tilde{t}}) + \lambda^2 v^2 \left\{ \sin^2 2\beta \frac{m_{\bar{S}}^2}{M^2 + m_{\bar{S}}^2} - \frac{|A_\lambda \sin 2\beta - 2\mu_{\rm eff}^\dagger|^2}{M^2 + m_S^2} \right\}$$

$$\Delta = \frac{2}{m_h^2} \max\left(m_{H_u}^2, m_{H_d}^2, \frac{dm_{H_u}^2}{d\ln\mu} L, \frac{dm_{H_d}^2}{d\ln\mu} L, \delta m_H^2, b_{eff} \right)$$

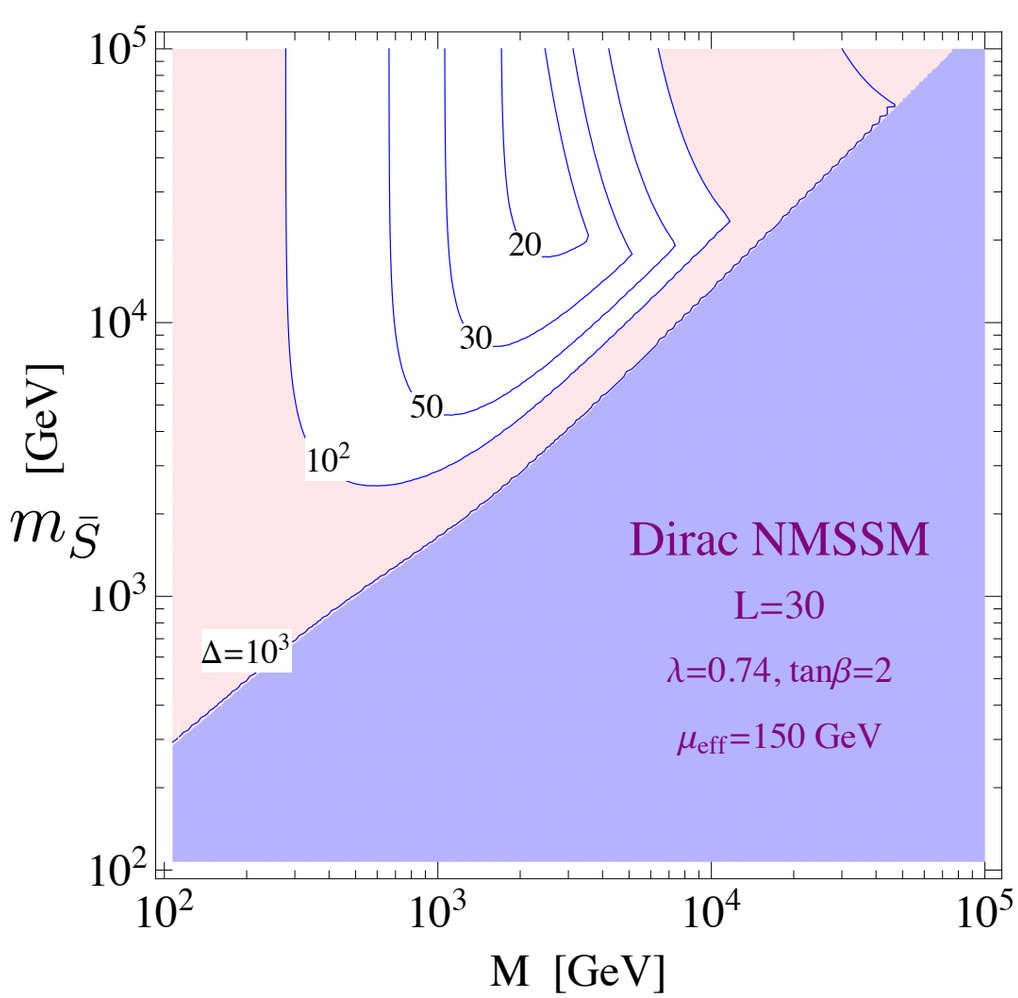
Dirac NMSSM: natural region largely spreads in large SUSY breaking

Tuning level

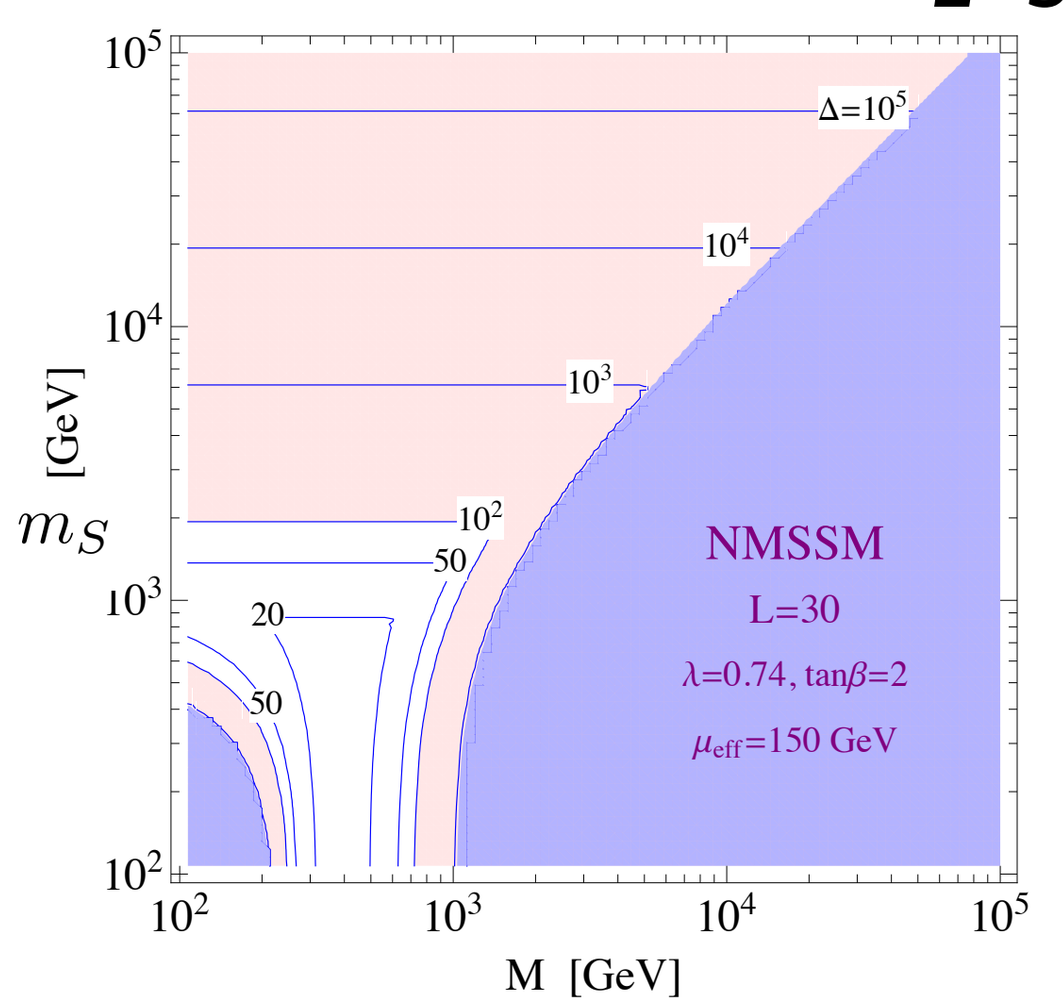
Large SUSY breaking

High-scale mediation *L=30*

Dirac NMSSM



NMSSM



$$m_h^2 \simeq m_{h,MSSM}^2(m_{\tilde{t}}) + \lambda^2 v^2 \left\{ \sin^2 2\beta \frac{m_{\bar{S}}^2}{M^2 + m_{\bar{S}}^2} - \frac{|A_\lambda \sin 2\beta - 2\mu_{\rm eff}^\dagger|^2}{M^2 + m_S^2} \right\}$$

$$\Delta = \frac{2}{m_h^2} \max\left(m_{H_u}^2, m_{H_d}^2, \frac{dm_{H_u}^2}{d\ln\mu} L, \frac{dm_{H_d}^2}{d\ln\mu} L, \delta m_H^2, b_{eff} \right)$$

Dirac NMSSM: natural region largely spreads in large SUSY breaking

30 min max35 min

Phenomenology

Phenomenology

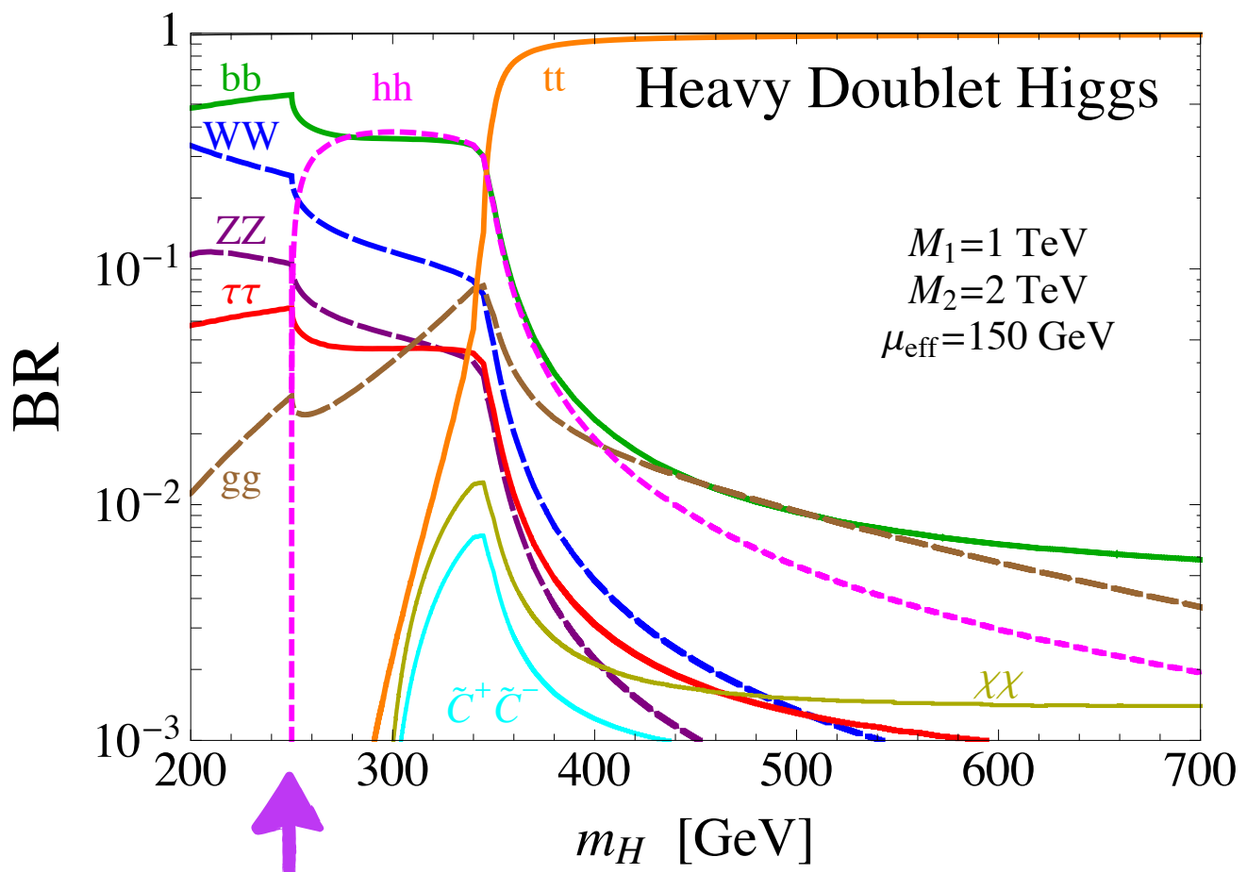
- Singlets themselves are hard to probe (heavy and gauge-singlet) ⇒2HDM with low tanβ

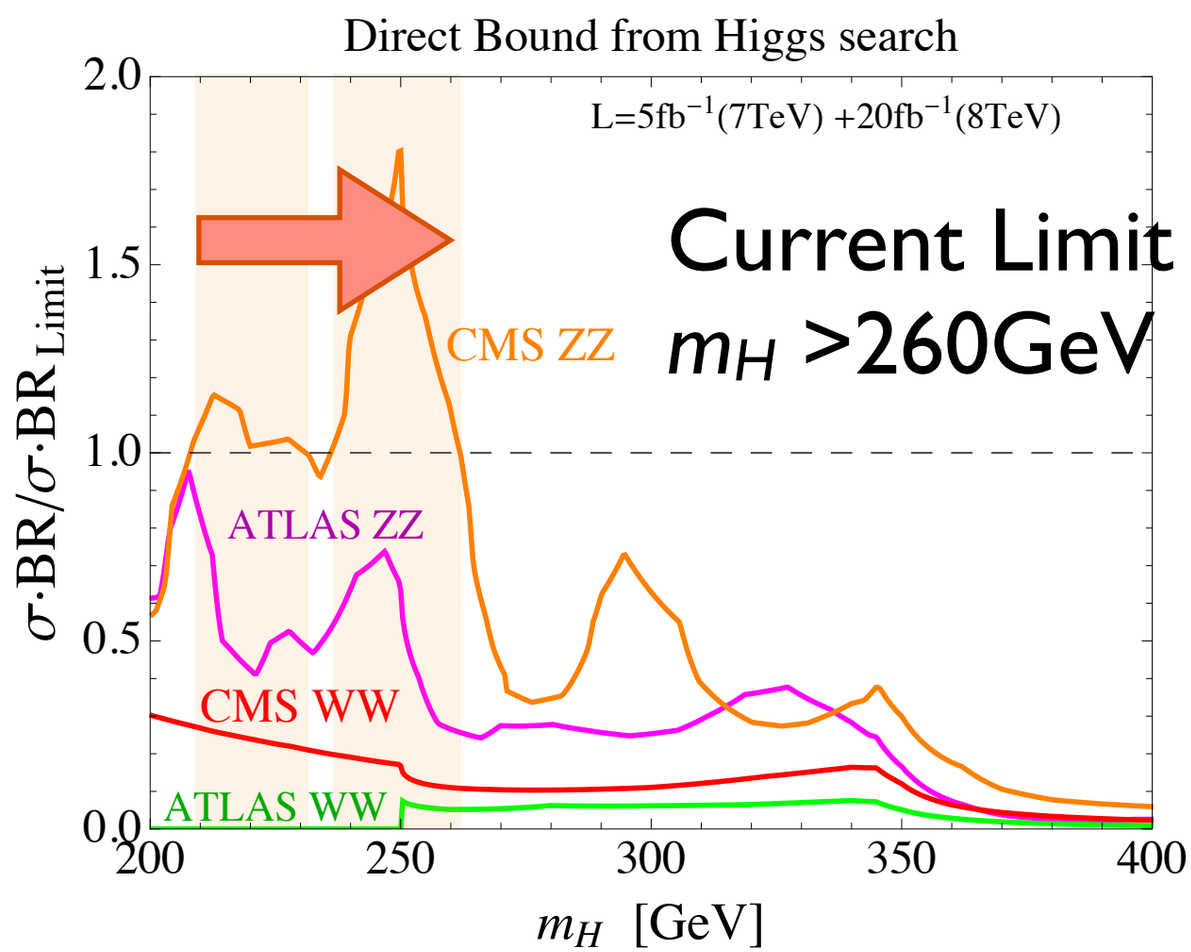
$$\begin{pmatrix} \bar{m}_A^2 s_\beta^2 + m_Z^2 c_\beta^2 & & & \\ -(\bar{m}_A^2 + m_Z^2 - 2\lambda^2 v^2) s_\beta c_\beta & \bar{m}_A^2 c_\beta^2 + m_Z^2 s_\beta^2 & & \\ \lambda v(2\mu_{eff} c_\beta - A_\lambda s_\beta) & \lambda v(2\mu_{eff} c_\beta - A_\lambda s_\beta) & M^2 + m_S^2 + \lambda^2 v^2 & \\ -\lambda v M s_\beta & -\lambda v M c_\beta & M B_S & M^2 + m_{\bar{S}}^2 \end{pmatrix} \begin{pmatrix} H_d \\ H_u \\ S \\ \bar{S} \end{pmatrix}$$

- Precision of SM-like Higgs, h, and direct search for heavy doublet-like Higgs, H

$$\lambda = 0.74,\ \tan\beta = 2,\ \mu_{\rm eff} = 150\,{\rm GeV},$$
$$M = 1\,{\rm TeV},\ m_{\bar{S}} = 10\,{\rm TeV},\ m_S = 800\,{\rm GeV},$$
$$B_S = 100\,{\rm GeV},\ A_\lambda = 0$$

H direct search



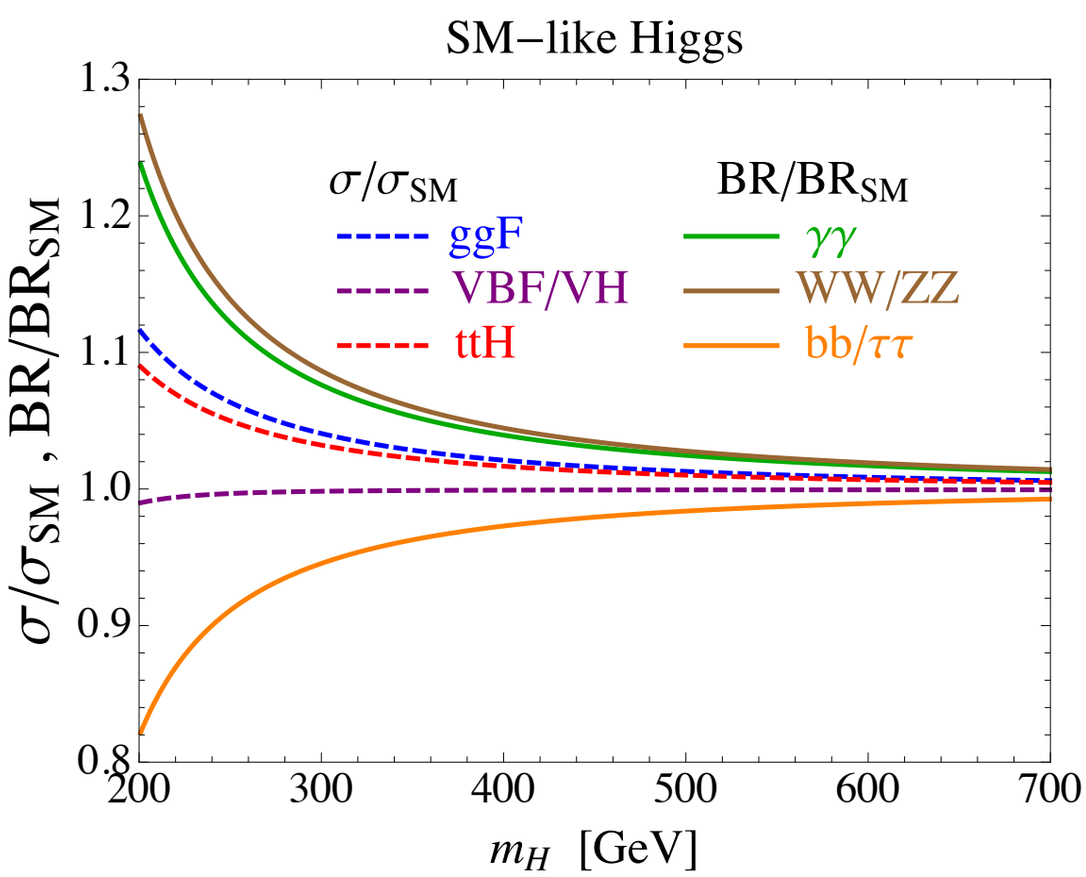


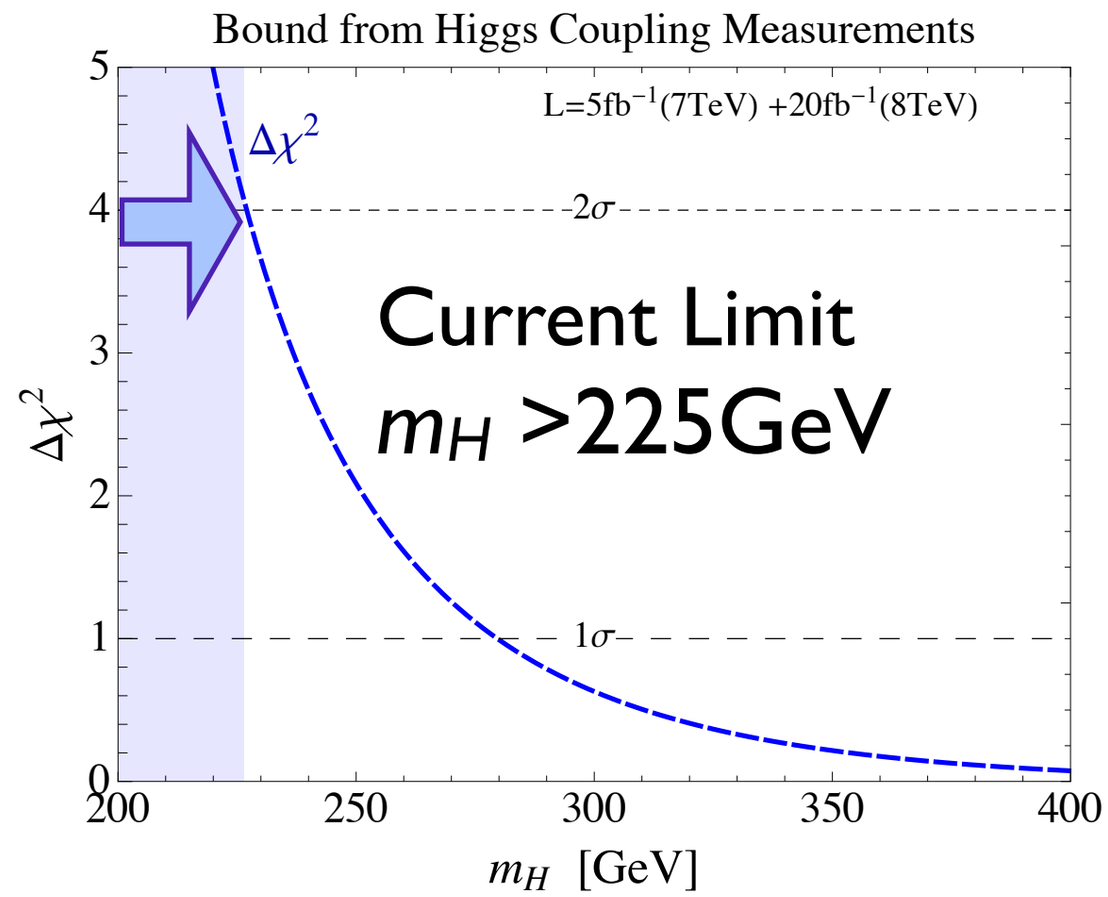
$\lambda^2 |H_u H_d|^2$

Higgs self-coupling & low tanβ

lead to H→hh decay, m_H >250GeV

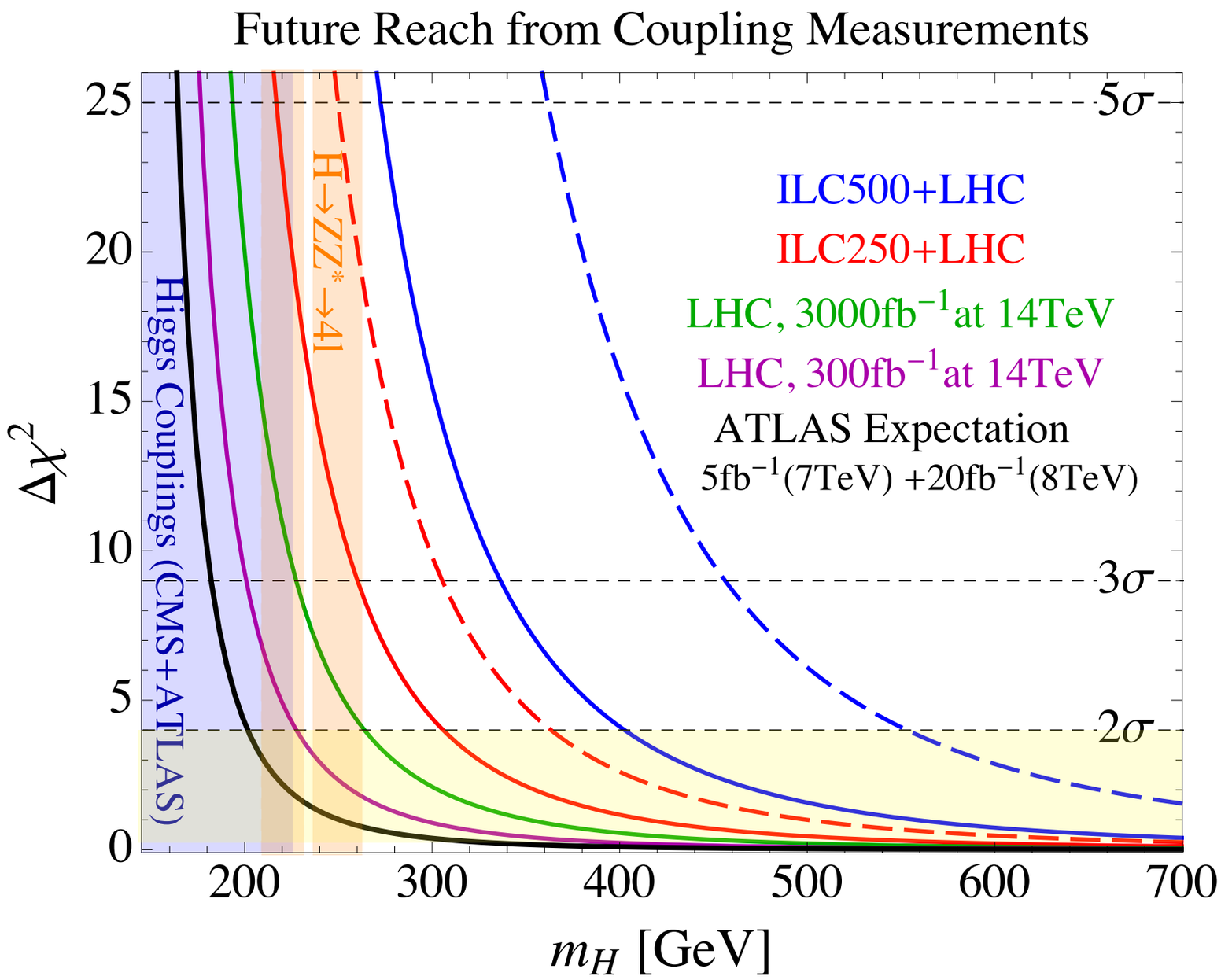
h production and decay



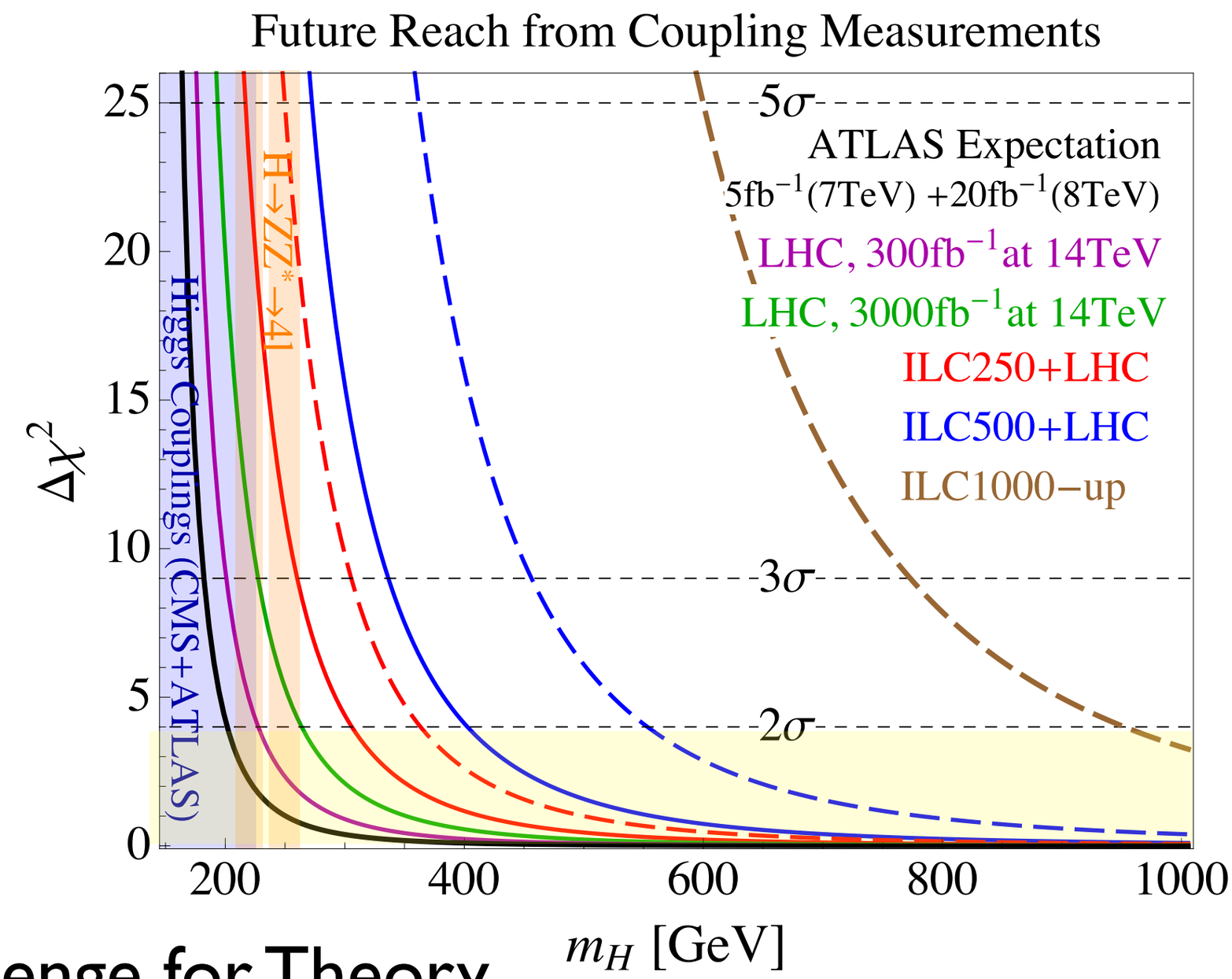


Due to the mixing, *h* couplings with *bb*/ττ are lowered compared to SM Higgs

Reach in HL-LHC and ILC



HL-ILC (Snowmass)



Challenge for Theory

$$\Delta\kappa_b^{\exp} = 0.31\%$$

(at HL-LHC 4~7%)

40 min

Conclusion

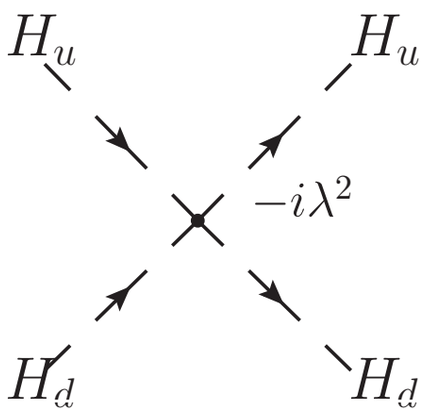
- After Higgs discovery at m_{higgs}=125GeV, naturalness implies new states beyond MSSM
- Higgs couples to Singlets with Dirac mass, Dirac NMSSM
- Dirac NMSSM presents a possibility that extremely large SUSY breaking boosts the lightest Higgs mass while maintaining the naturalness
- Precise Higgs coupling measuremts in HL-LHC and ILC can probe this scenario

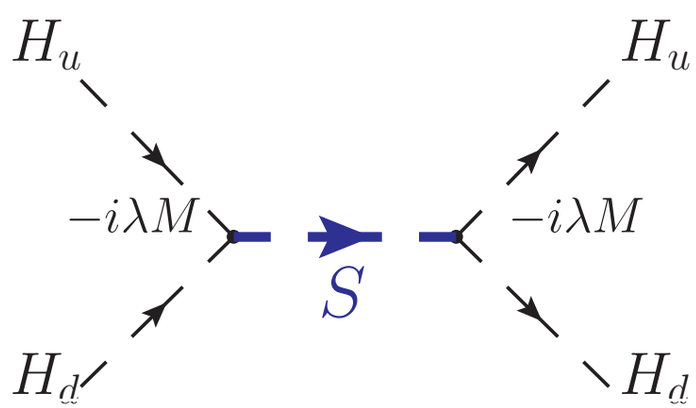
Thank you for your attention!

BACKUP

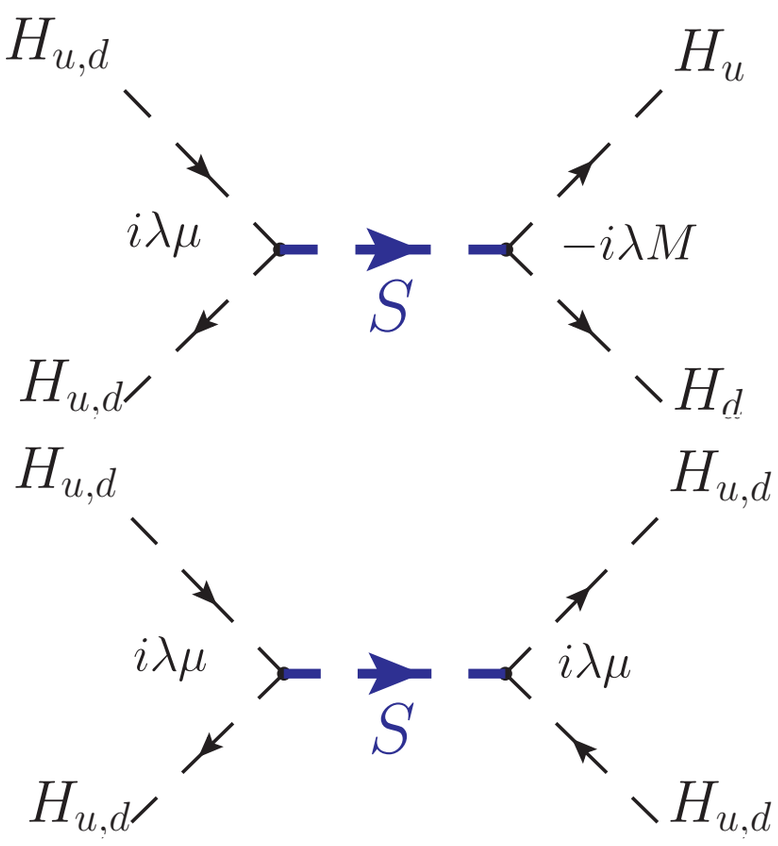
Backup

NMSSM in SUSY limit





=0 (in SUSY limit)



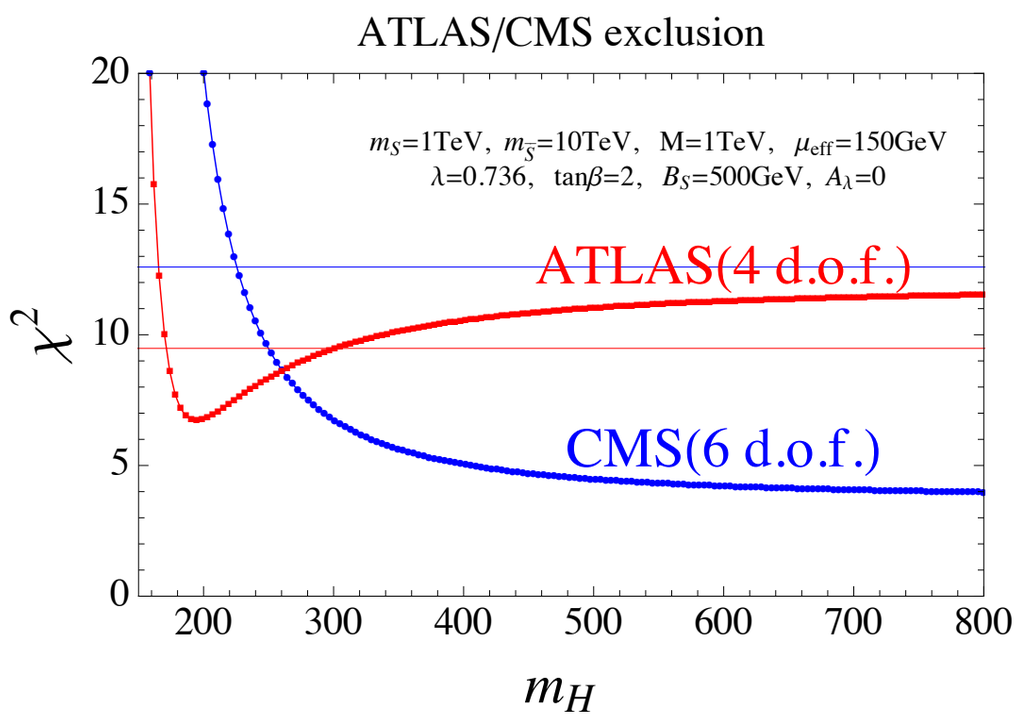
$$W \supset \lambda S H_u H_d + \frac{M}{2} S^2 + \mu H_u H_d$$

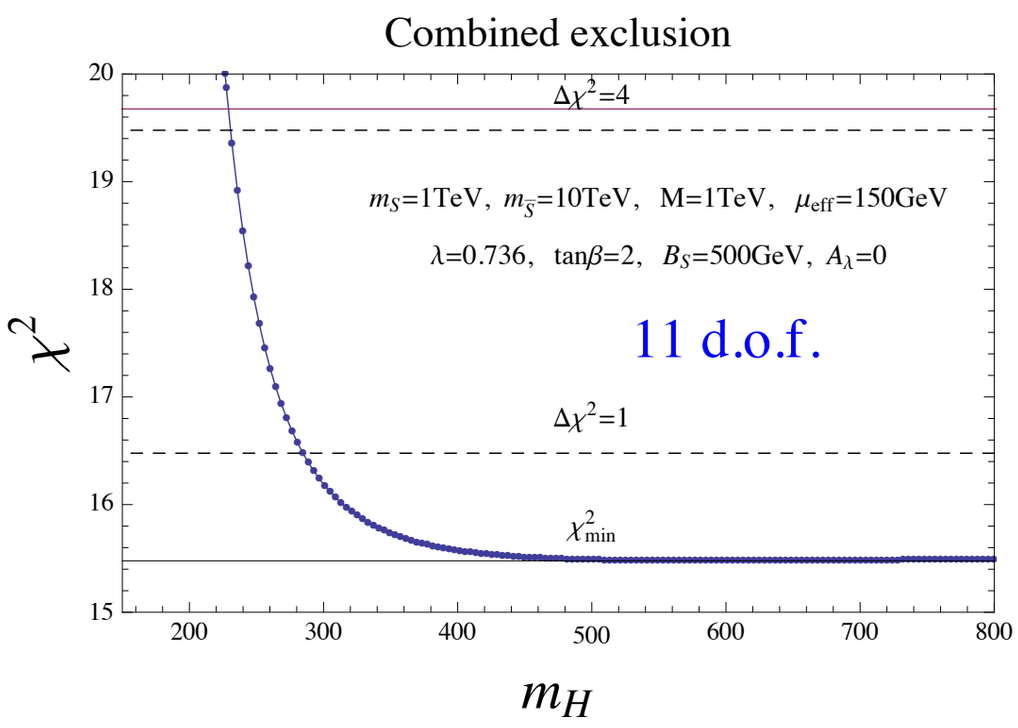
$$\delta m_h^2 = 4\lambda^2 v^2 \left(\frac{\mu}{M} \sin 2\beta - \frac{\mu^2}{M^2} \right)$$

Nomura, Poland, Tweedie 0509244

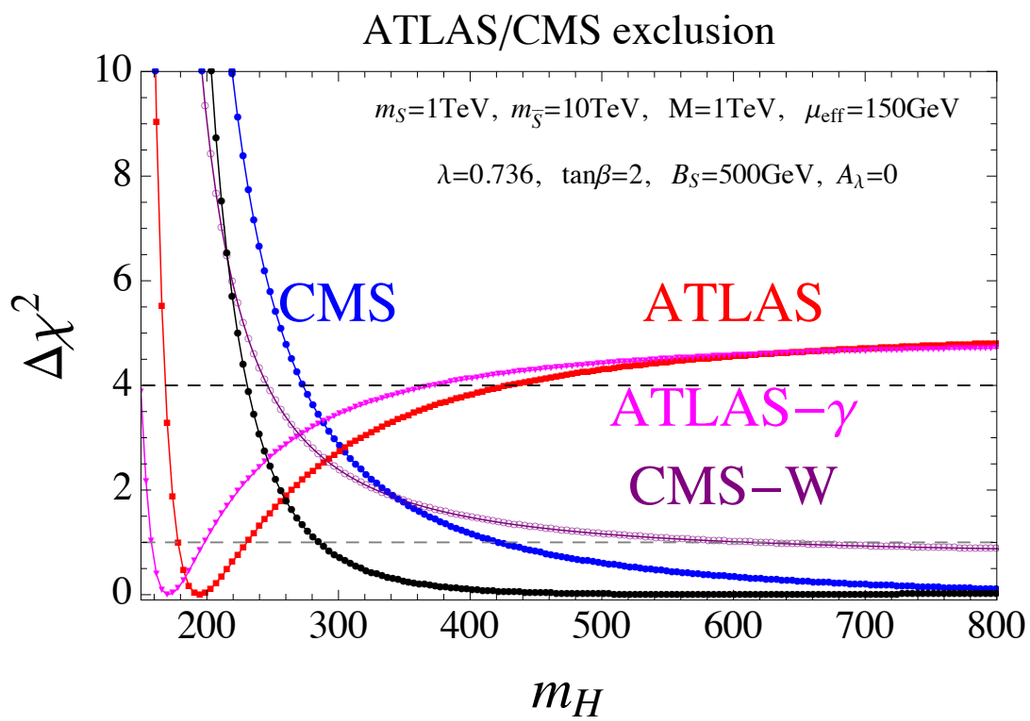
Backup chi-squared dist. and delta-chi-squared dist.

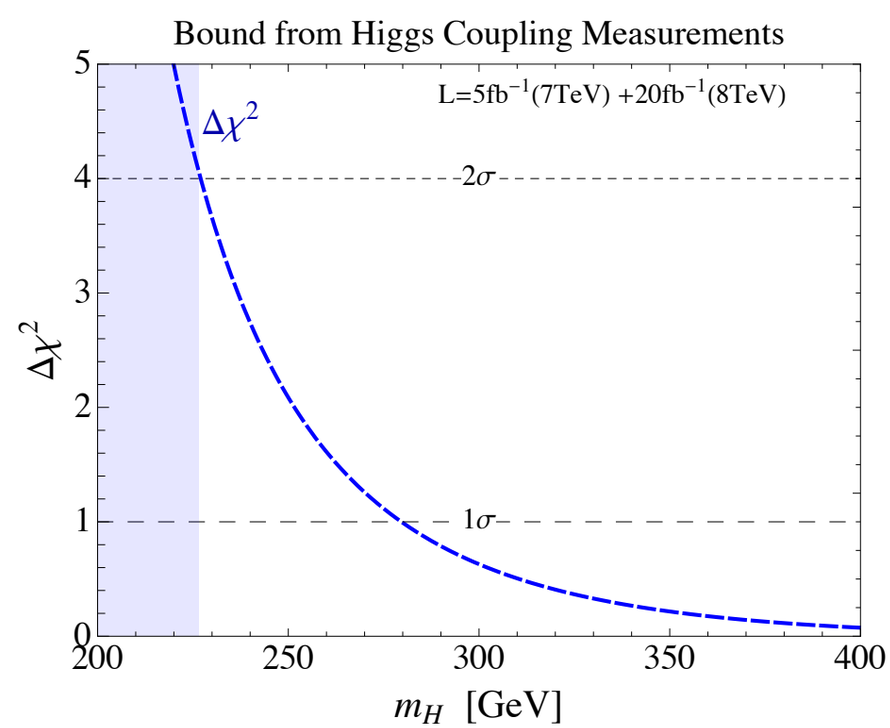
Test of Modeling





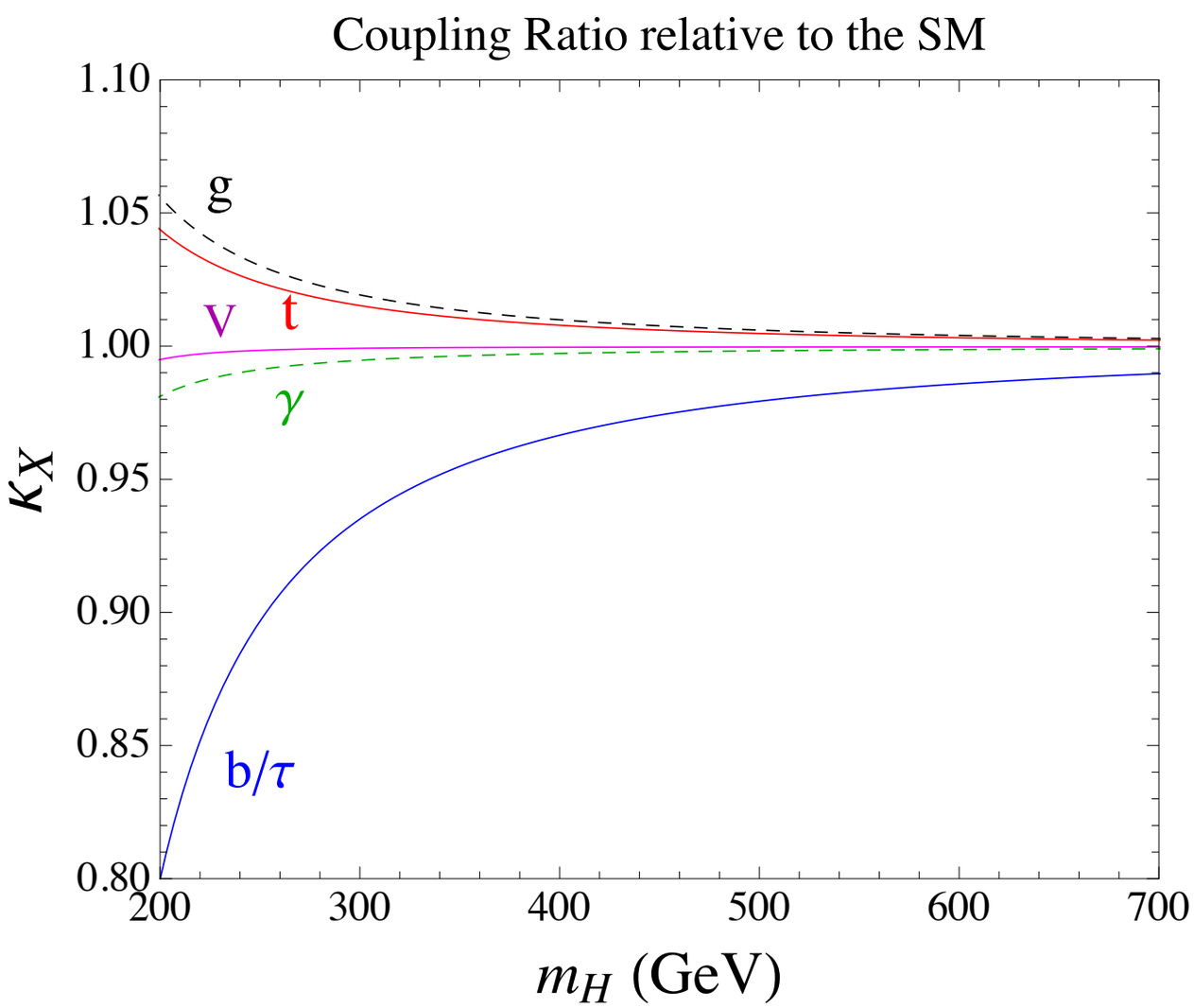
Exclude parameter

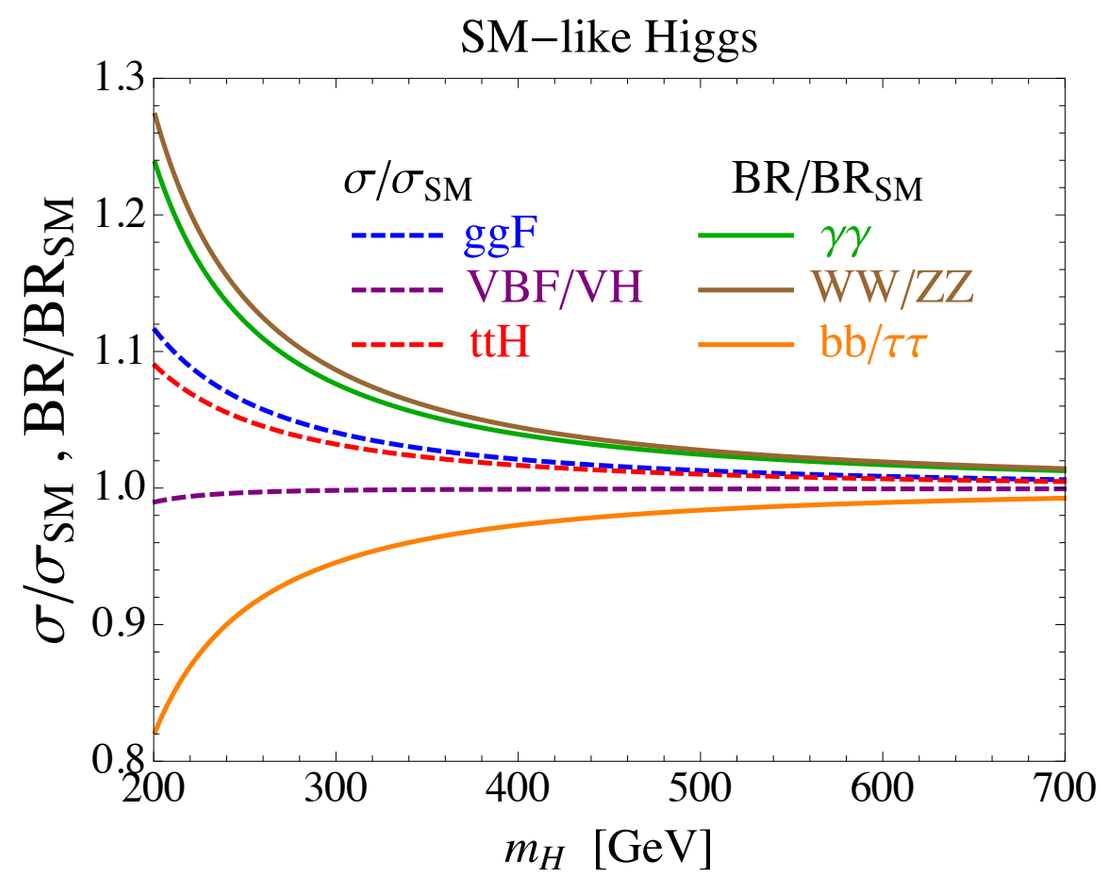




Backup

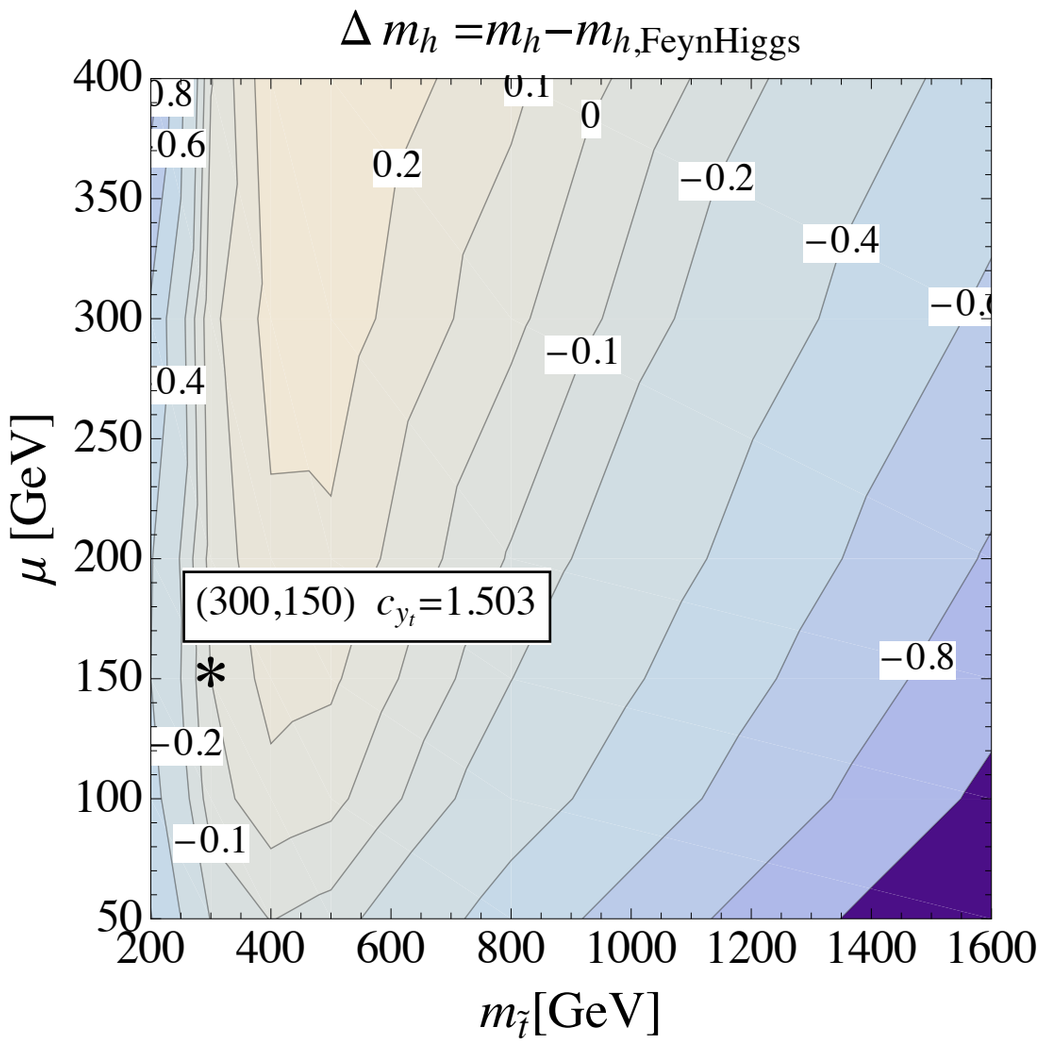
Coupling deviation





Backup

RG-improved calculation



Backup

b→sγ

$$\mathcal{H}_{\rm eff} \supset -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left(C_7 O_7 + C_8 O_8 + \tilde{C}_7 \tilde{O}_7 + \tilde{C}_8 \tilde{O}_8 \right)$$

$$O_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu} \ , \quad O_8 = \frac{g_s}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} T^A P_R b) G^A_{\mu\nu} \ .$$

$$\mathrm{BR}(B \to X_s\gamma)^{\rm SM}_{E_\gamma > 1.6{\rm GeV}} = (3.15 \pm 0.23) \times 10^{-4}$$ M. Misiak et al [hep-ph/0609232]

$$\mathrm{BR}(B \to X_s\gamma)^{\rm exp}_{E_\gamma > 1.6{\rm GeV}} = (3.52 \pm 0.25) \times 10^{-4}$$ E. Barberio et al., [0808.1297]

$$3 \times 10^{-4} \lesssim \mathrm{BR}(B \to X_s\gamma)^{\rm SM+BSM} \lesssim 4 \times 10^{-4}$$

M. Wick, W.Altmannshofer[0810.2874]

$|\Delta BR^{\rm Compact}| < 0.2 \times 10^{-4}$

$\Delta BR^{\rm DiracNMSSM(H\pm)} \sim +0.7 \times 10^{-4}$

chargino contribution

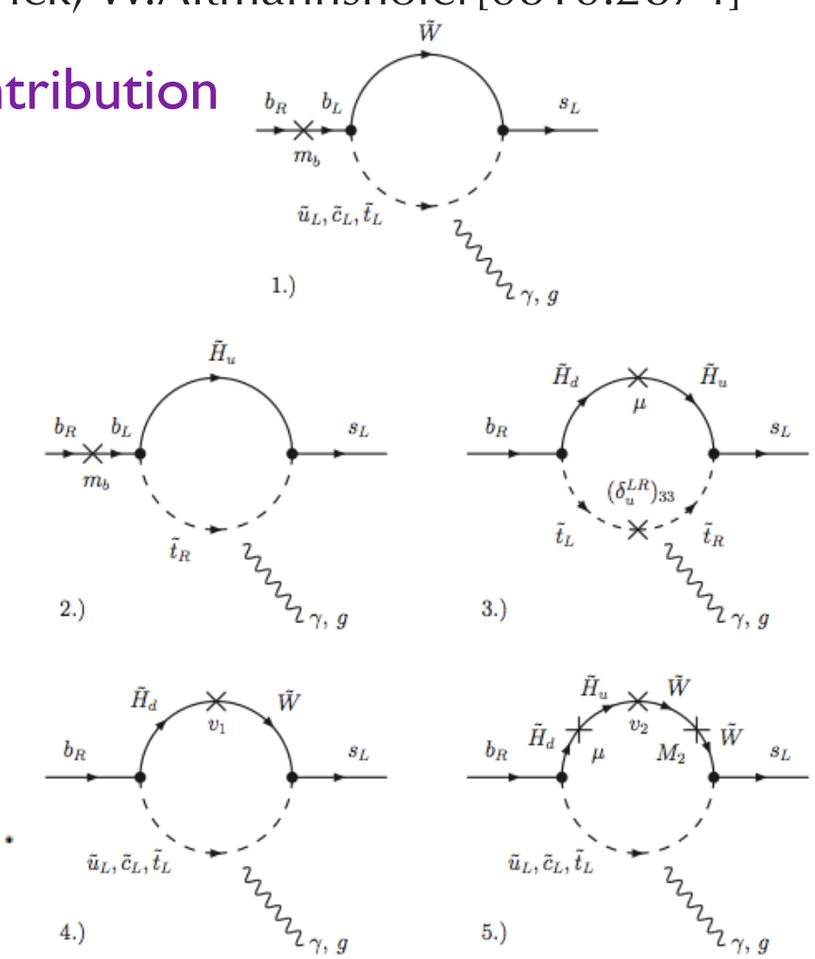
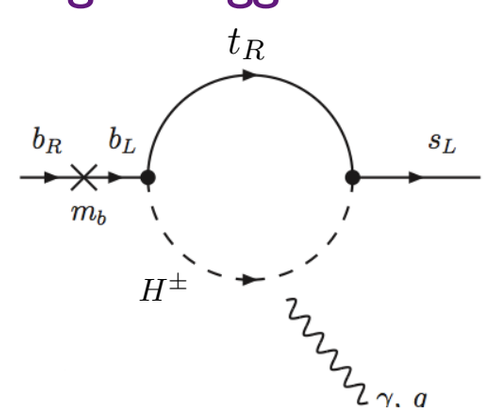


FIGURE 1. Chargino contributions to $C_{7,8}$ in the MIA. The

charged Higgs contribution



*NP contributions can be deconstructive

$$C_{7,8}^{H^\pm} \simeq \left(\frac{1 - \epsilon t_\beta}{1 + \epsilon t_\beta} \right) \frac{1}{2} h_{7,8}(y_t)$$

$$\frac{4G_F}{\sqrt{2}} C_{7,8}^{\tilde{\chi}^\pm} \simeq \frac{g_2^2}{\tilde{m}^2} \left[\frac{(\delta_u^{LL})_{32}}{V_{tb}V_{ts}^*} \frac{\mu M_2}{\tilde{m}^2} f_{7,8}^{(1)}(x_2, x_\mu) + \frac{m_t^2}{M_W^2} \frac{A_t \mu}{\tilde{m}^2} f_{7,8}^{(2)}(x_\mu) \right] \frac{t_\beta}{(1 + \epsilon t_\beta)} \ .$$

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