SUSY Today

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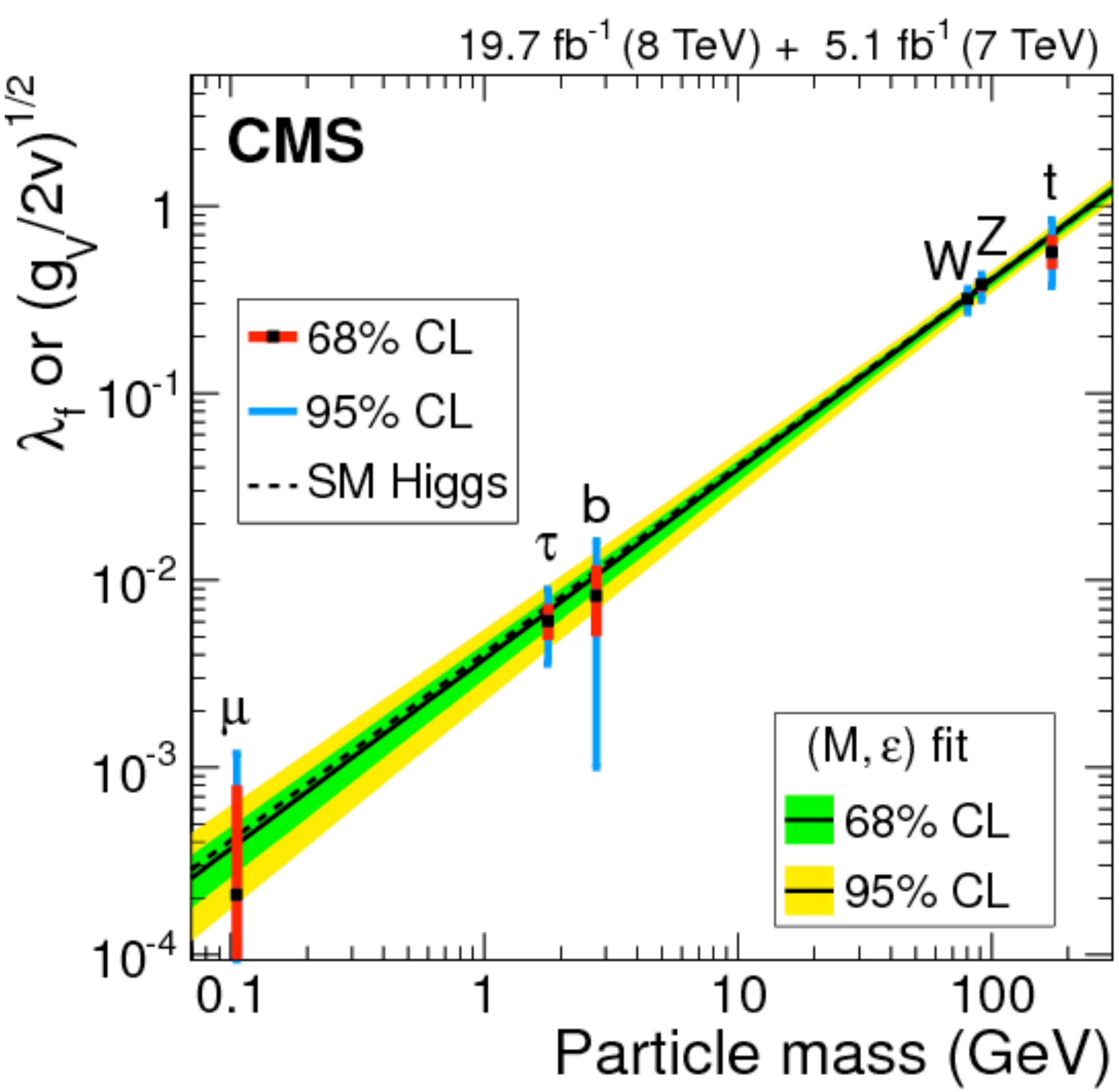
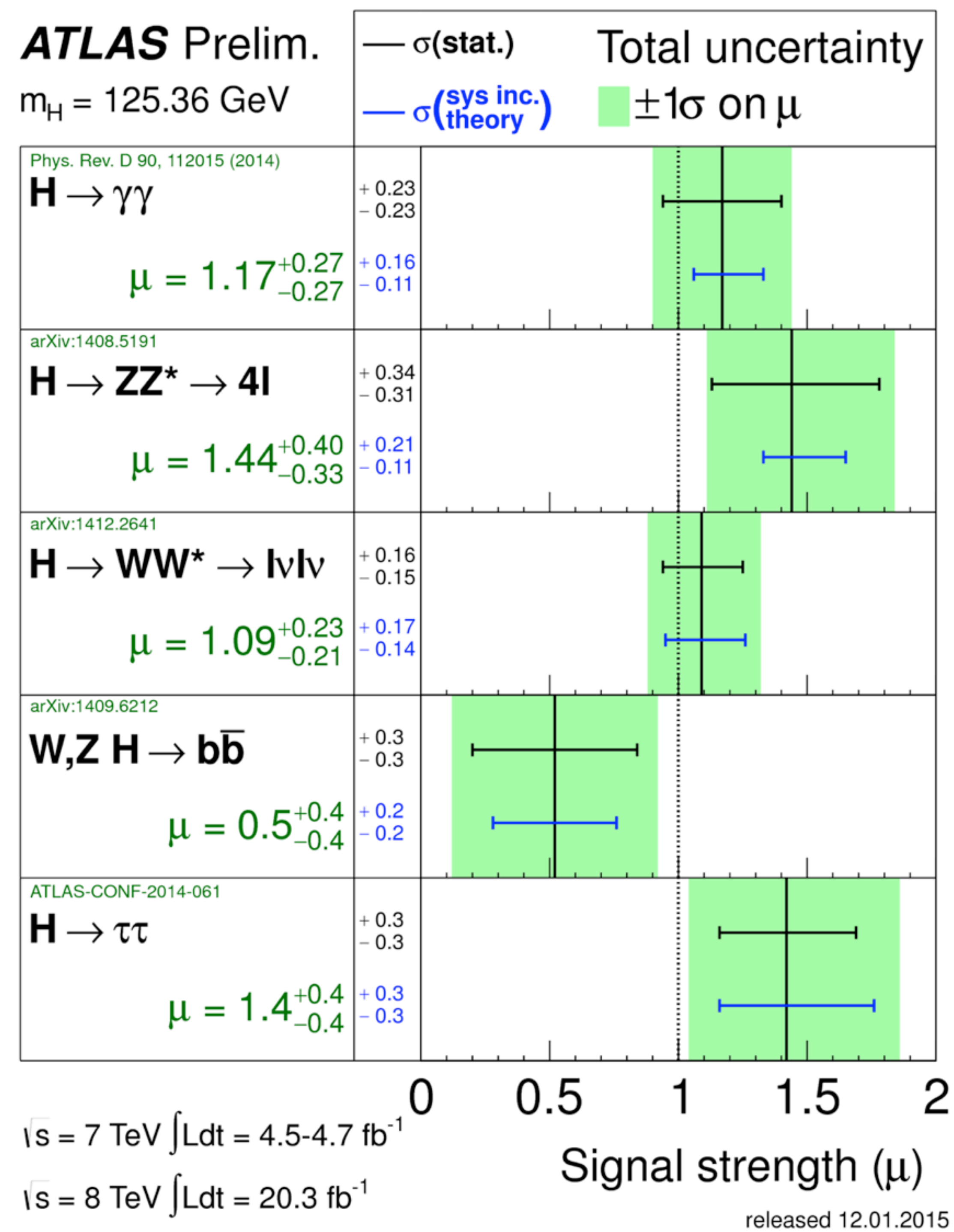
LHCP 2015
St. Petersburg, Russia
August 31-September 5

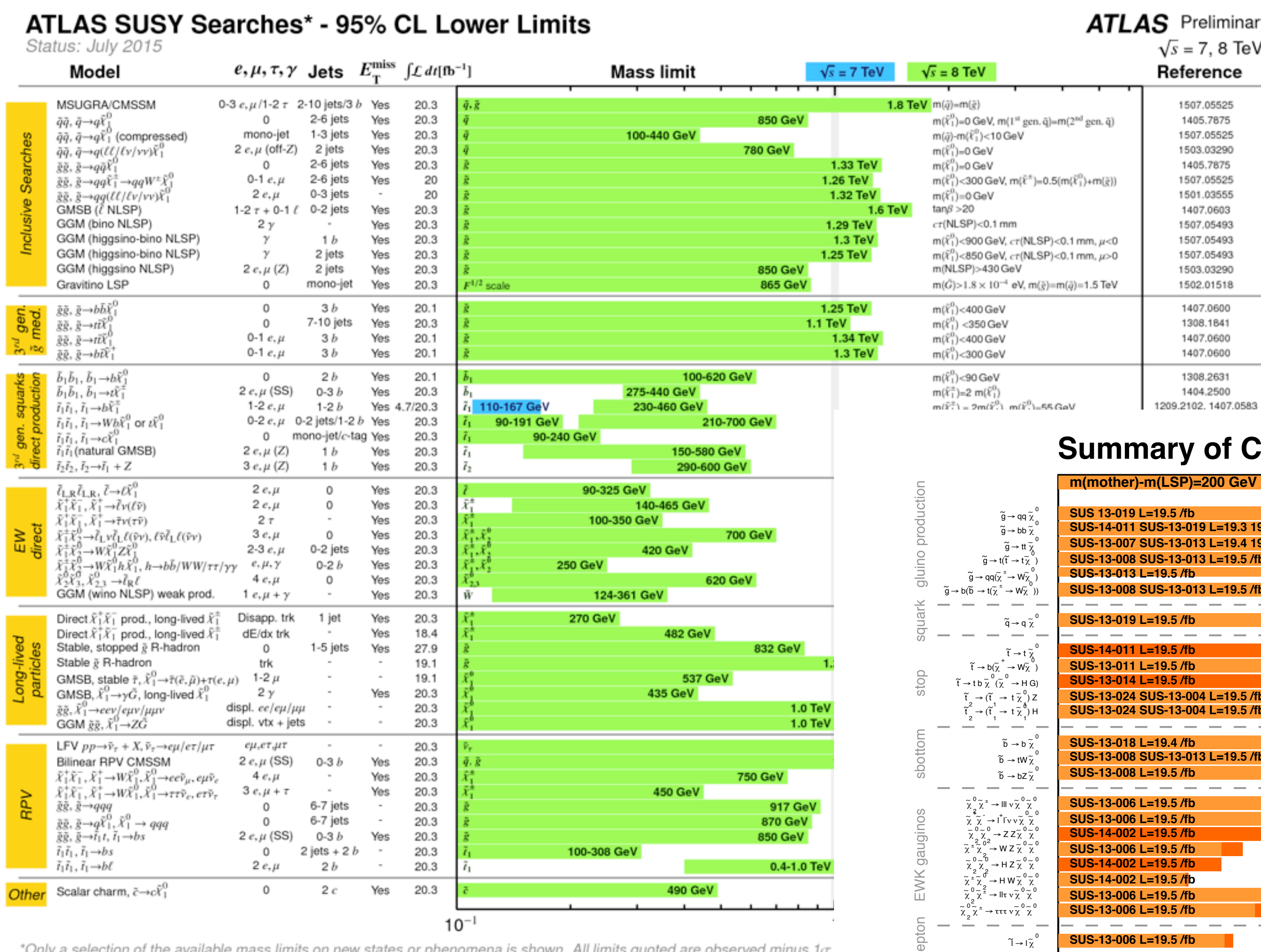
The LHC has already well-explored the TeV scale at Run I.

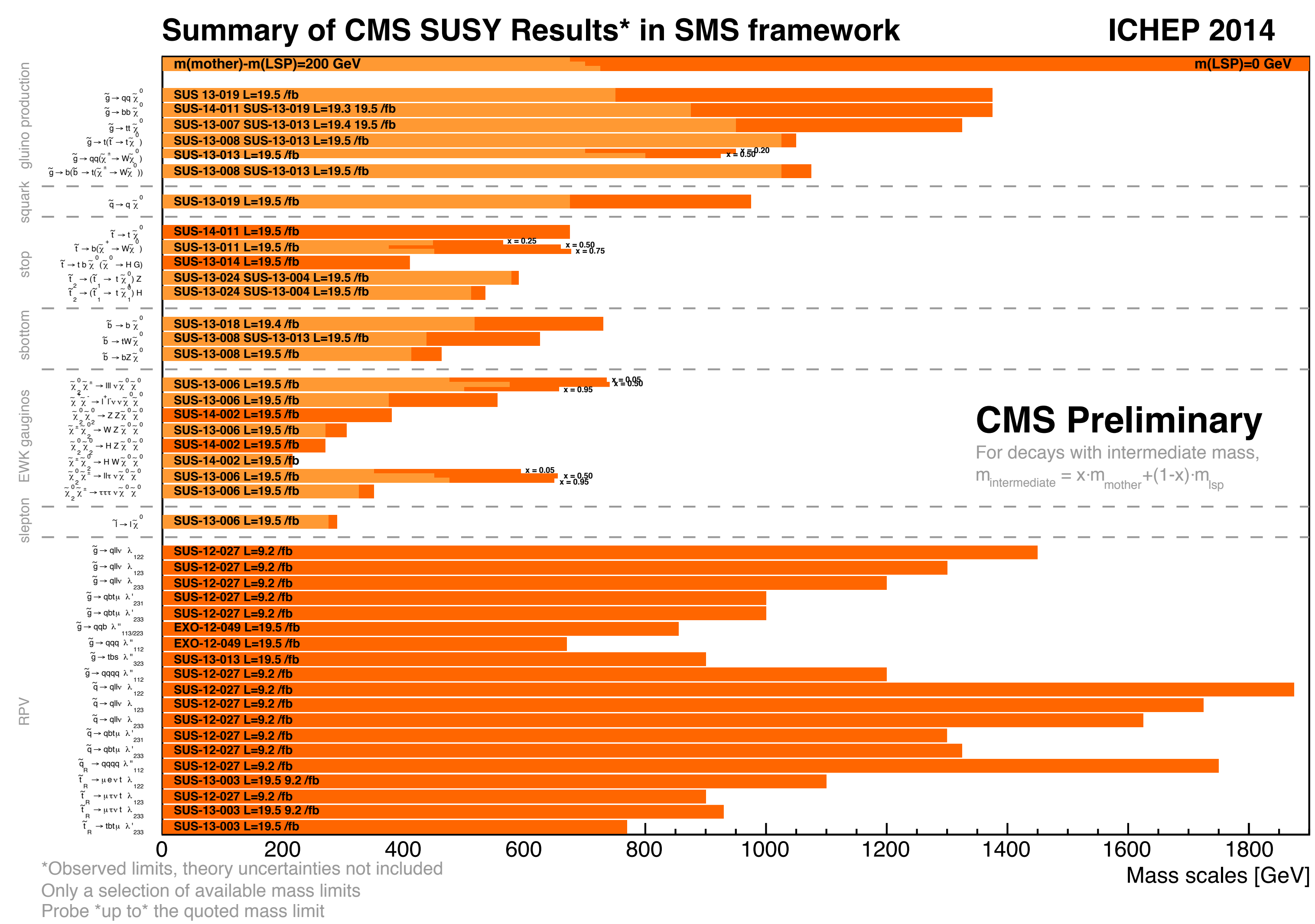
We now know there is a Standard-Model-like Higgs at 125 GeV...



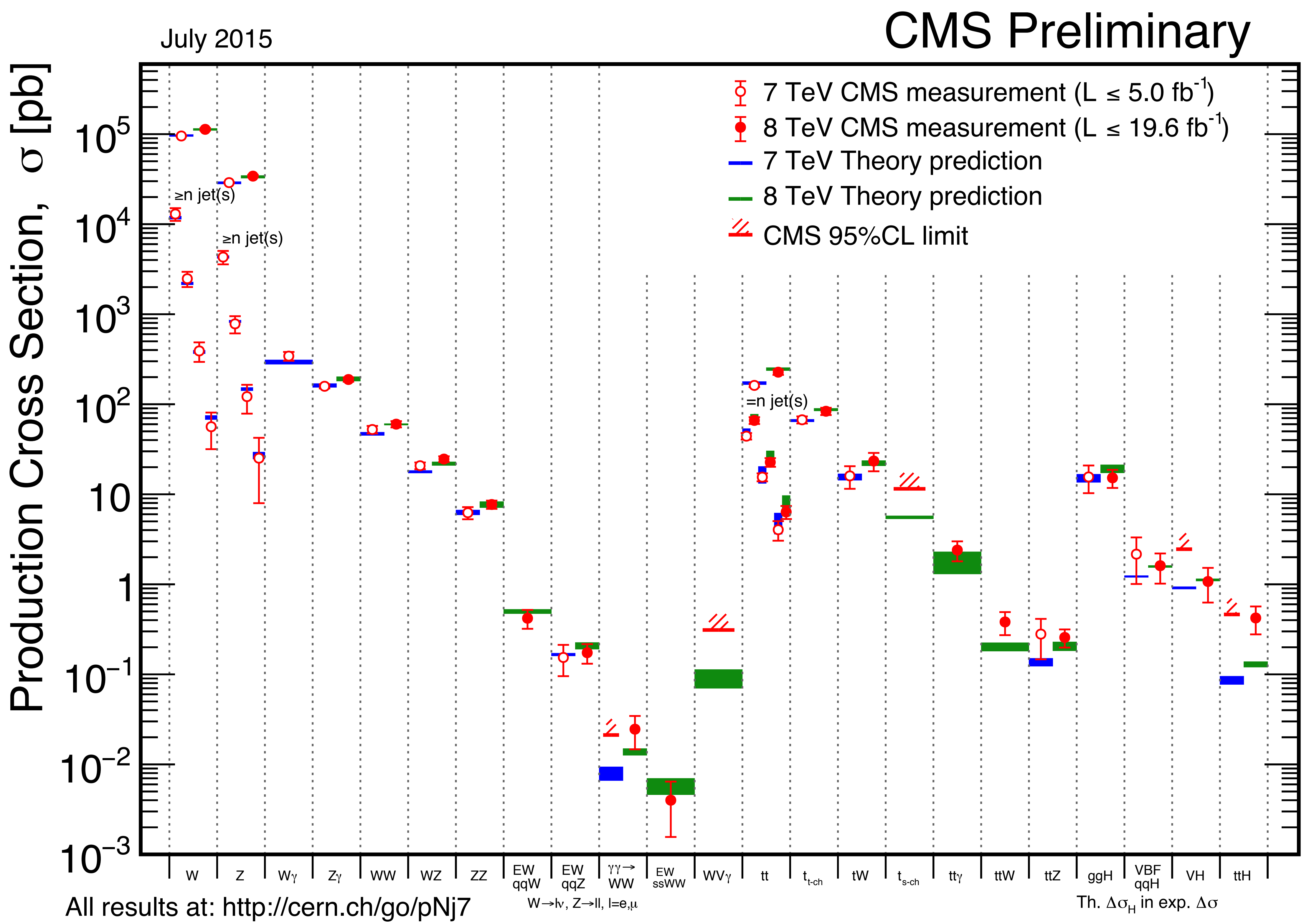


… and no definitive signal yet of new physics.



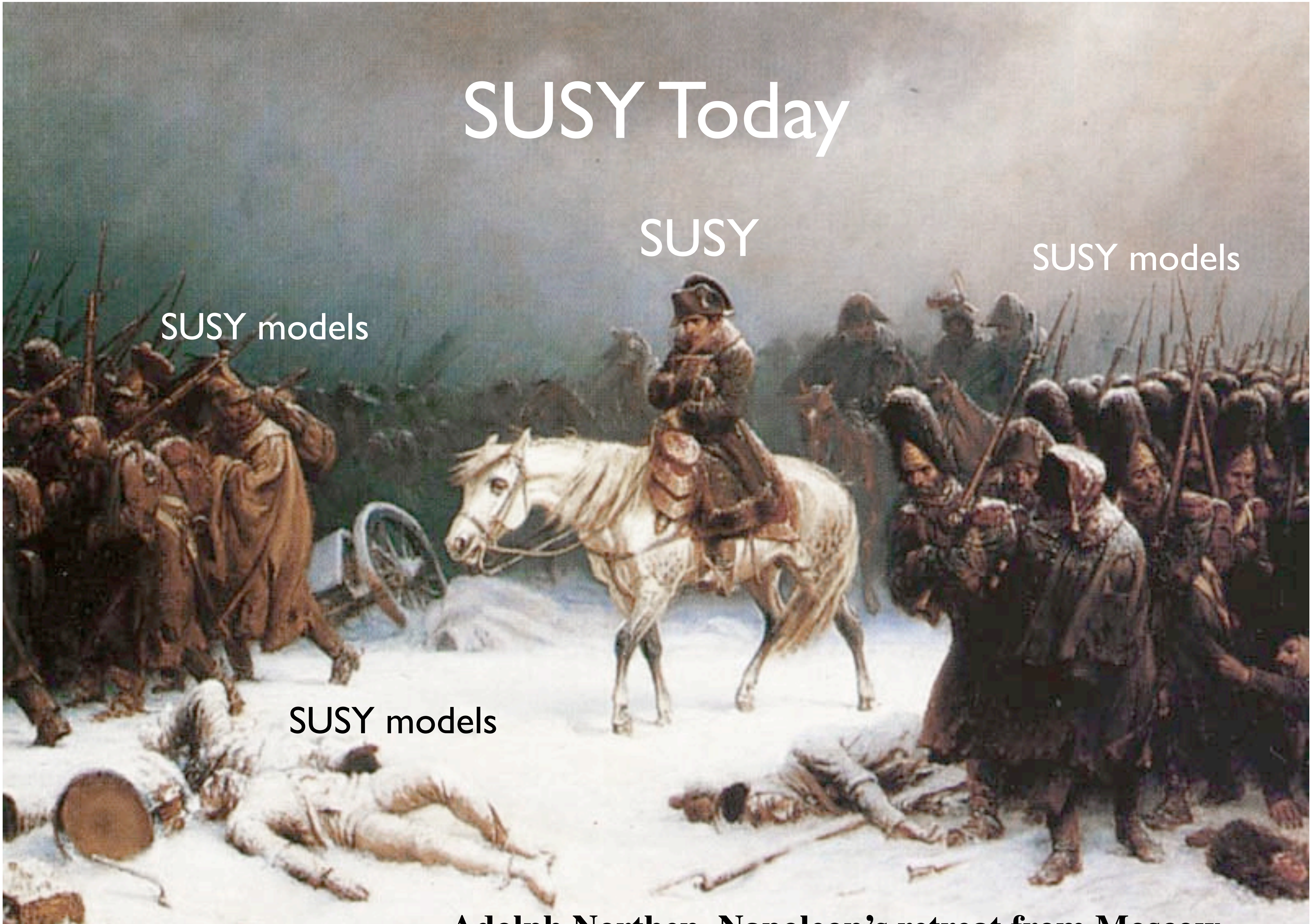


The Standard Model is looking pretty good!



SUSY Yesterday

SUSY Today



Adolph Northen, Napoleon's retreat from Moscow

SUSY Tomorrow?

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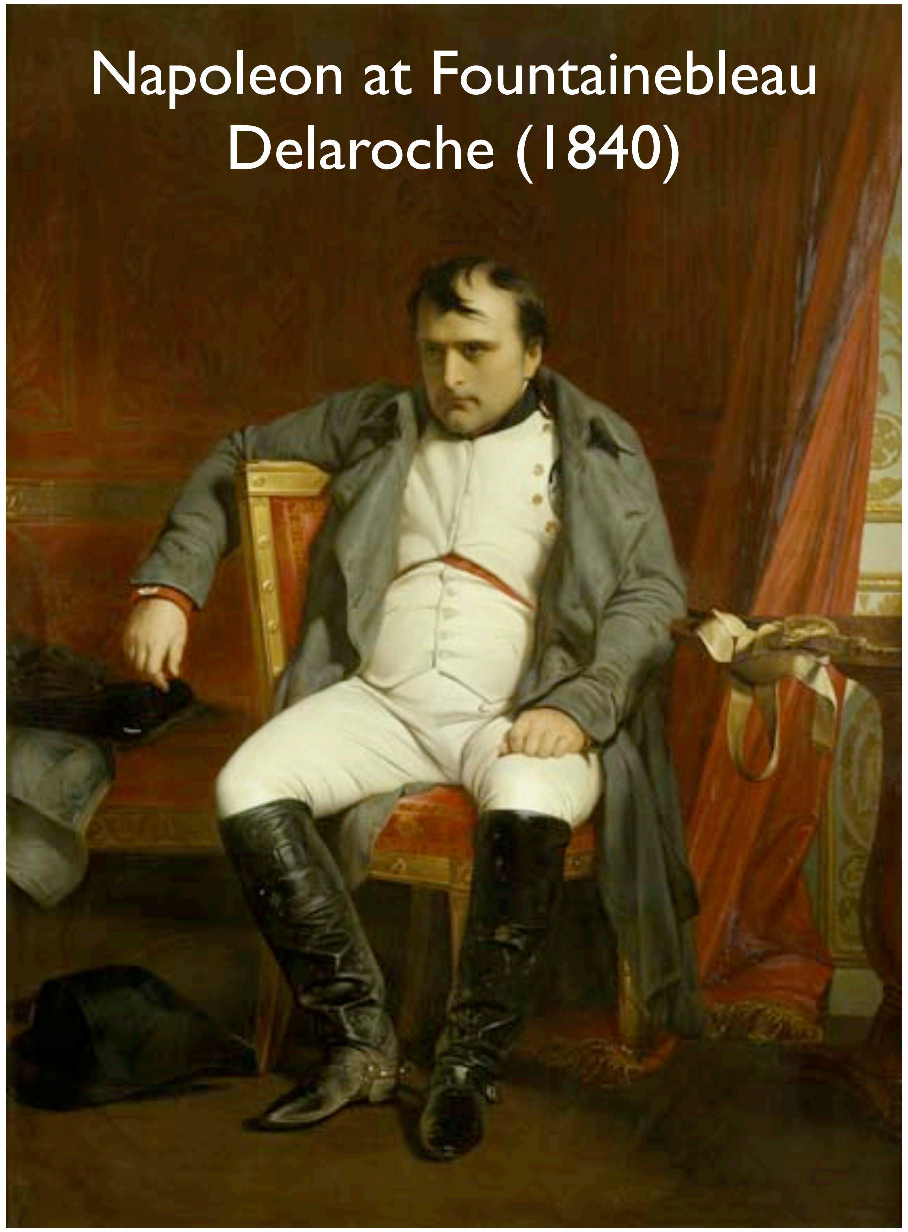
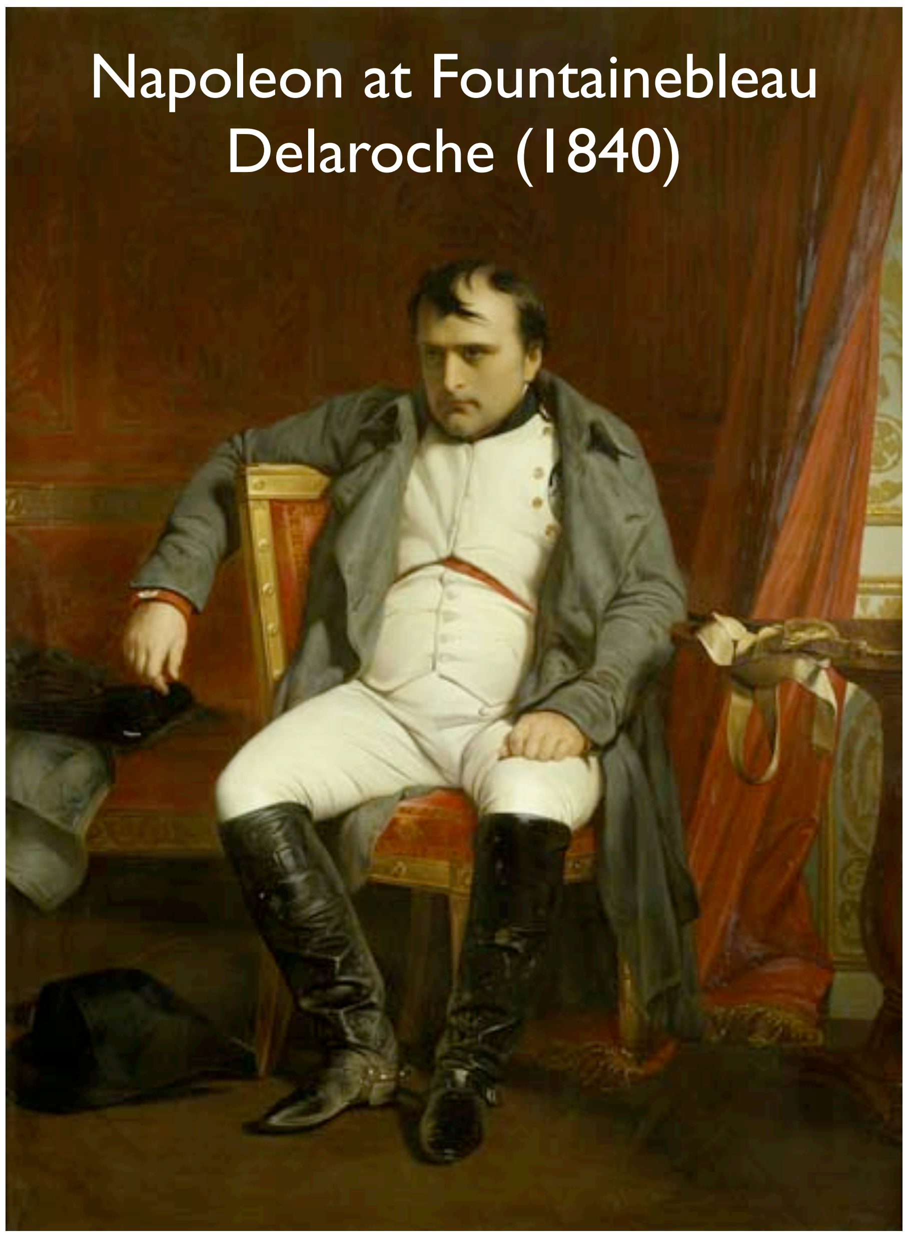

Napoleon at Fountainebleau
Delaroche (1840)

SUSY Tomorrow?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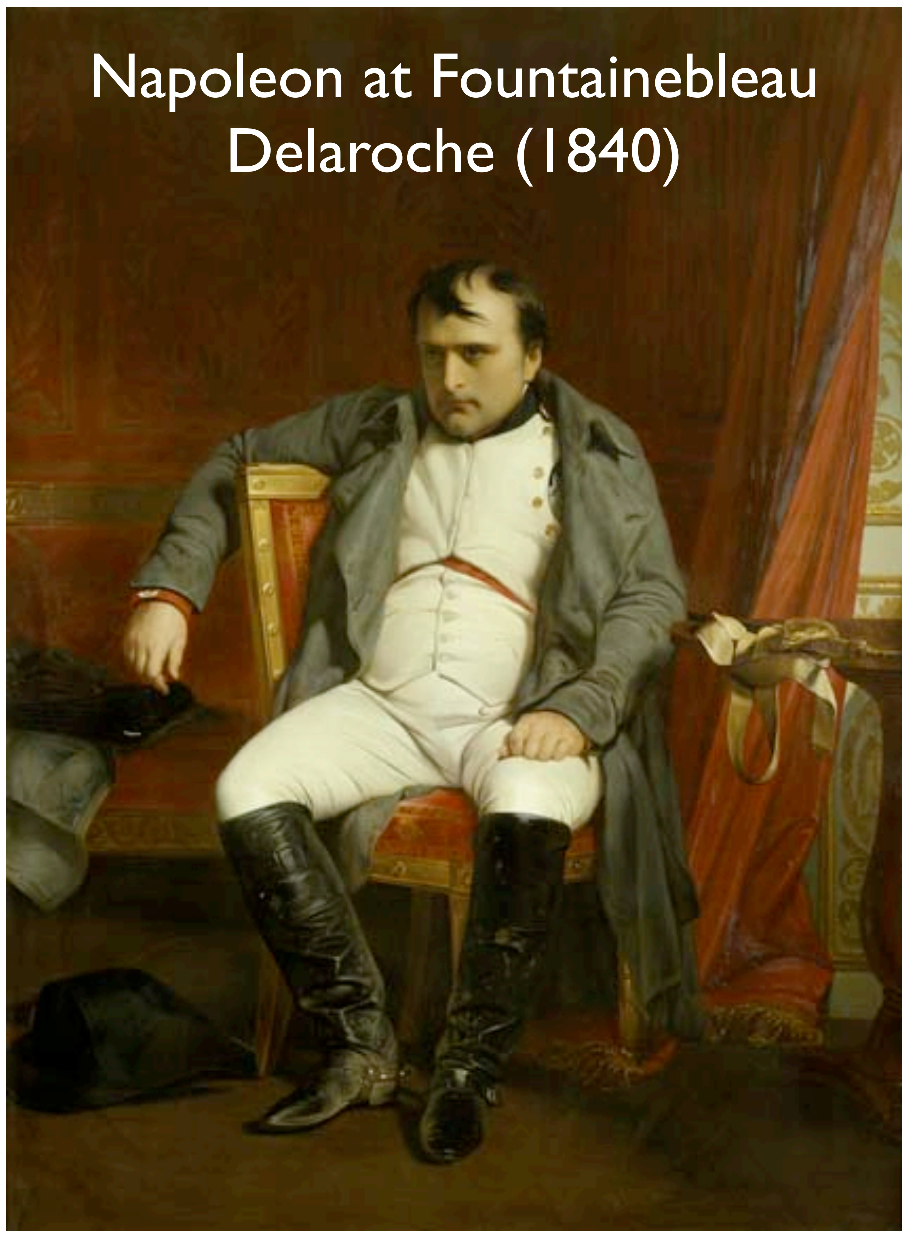
OR

SUSY Tomorrow?


Napoleon at Fountainebleau
Delaroche (1840)

OR

It all depends on what happens at Run II!!

Plan of the talk

1. Review: Naturalness and SUSY

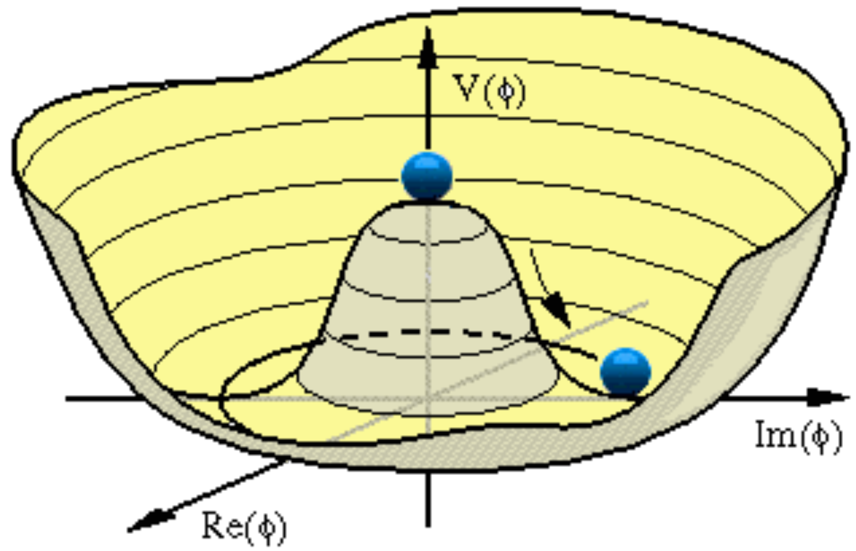
2. Vanilla SUSY: MSSM+R-parity+flavor universality

3. Beyond vanilla SUSY

Review

Run I, naturalness and SUSY

Naturalness motivates the TeV scale



$$V(H) = m_H^2|H|^2 + \frac{1}{2}\lambda_H|H|^4$$

$$v^2 = -\frac{m_H^2}{\lambda_H} = (246\ \mathrm{GeV})^2$$

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

Quantum corrections: $\delta m_H^2 \sim \Lambda^2$

$$m_H^2 = (m_H^2)_0 + \delta m_H^2 \qquad \Delta \equiv \frac{2|\delta m_H^2|}{m_h^2}$$

Λ — BSM

M_{weak} — SM

Naturalness: no enormous cancellations (if $\Lambda = M_{pl}$, need cancellation at 10^{-32} level!)

- Expect new particles at (or below) the TeV scale
- And some new mechanism (e.g. symmetry) to shield the theory from even higher scales

Supersymmetry

SUSY solves the hierarchy problem by extending chiral symmetry to the Higgs. Quadratic divergences cancelled by superpartners.

In minimal realizations of SUSY, a special role is played by the Higgsino, stops, and gluinos, which couple strongest to the Higgs.

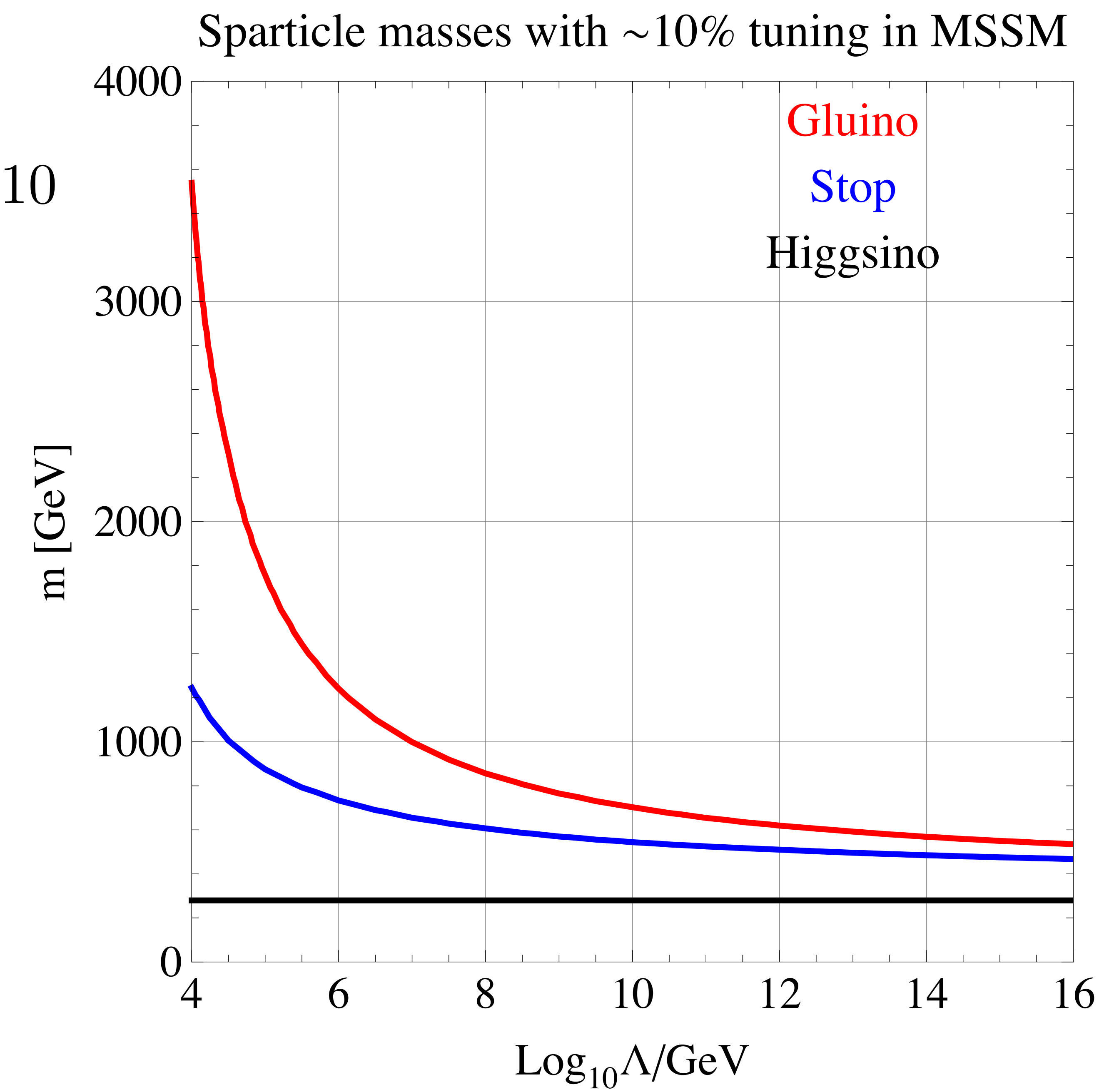
$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi} m_{gluino}^2 \left(\log \frac{\Lambda}{m_{gluino}}\right)^2$$ two-loops

$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m_{stop}^2 \log \frac{\Lambda}{m_{stop}}$$ one-loop

$$\delta m_H^2 \sim |\mu|^2$$ tree

Naturalness still bounds superpartner masses and UV scale Λ where they are generated ("messenger scale").

$$\Delta = \frac{2|\delta m_H^2|}{m_h^2} \leq 10$$



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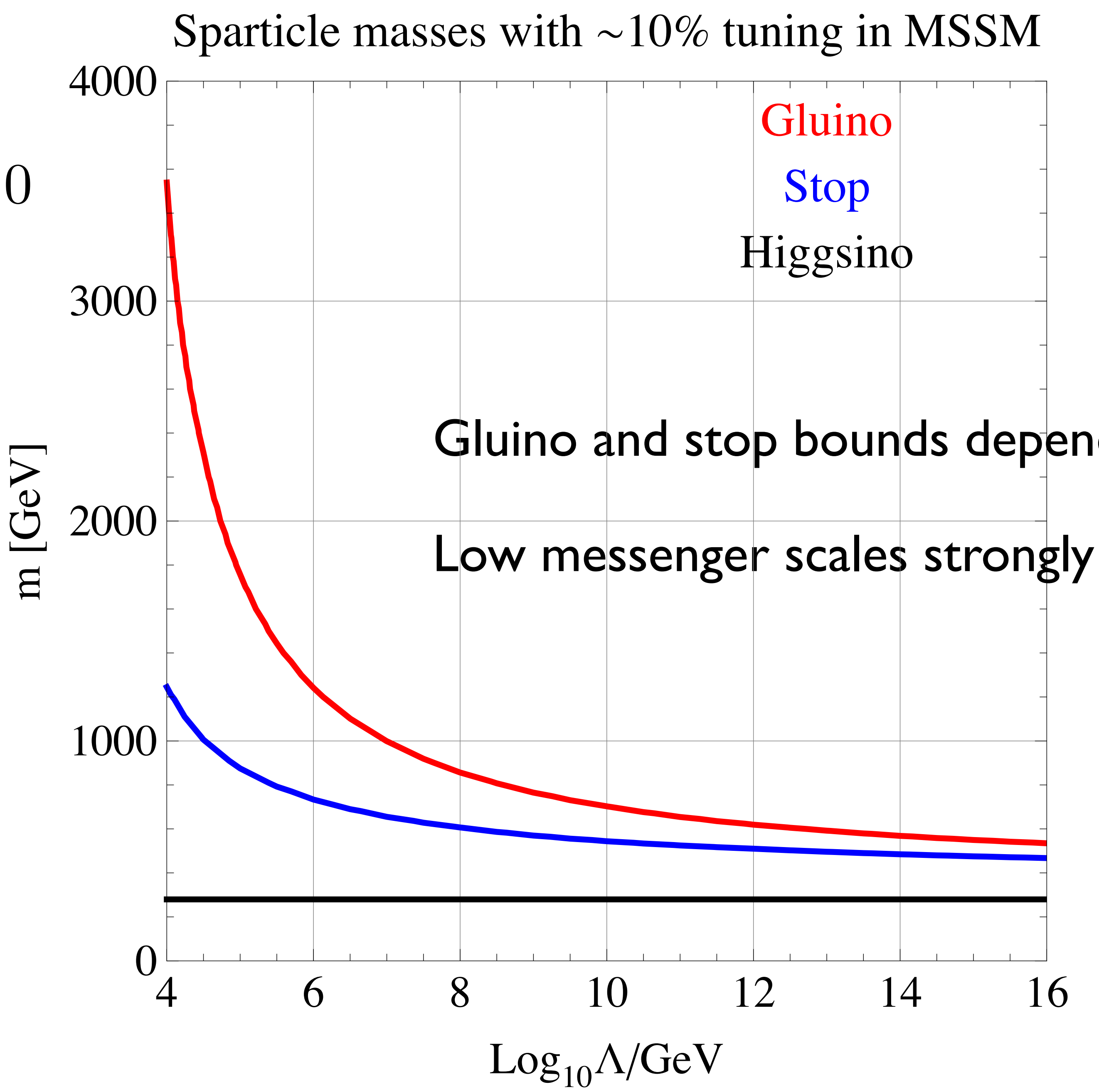

Gluino and stop bounds depend on messenger scale Λ.

Low messenger scales strongly preferred.

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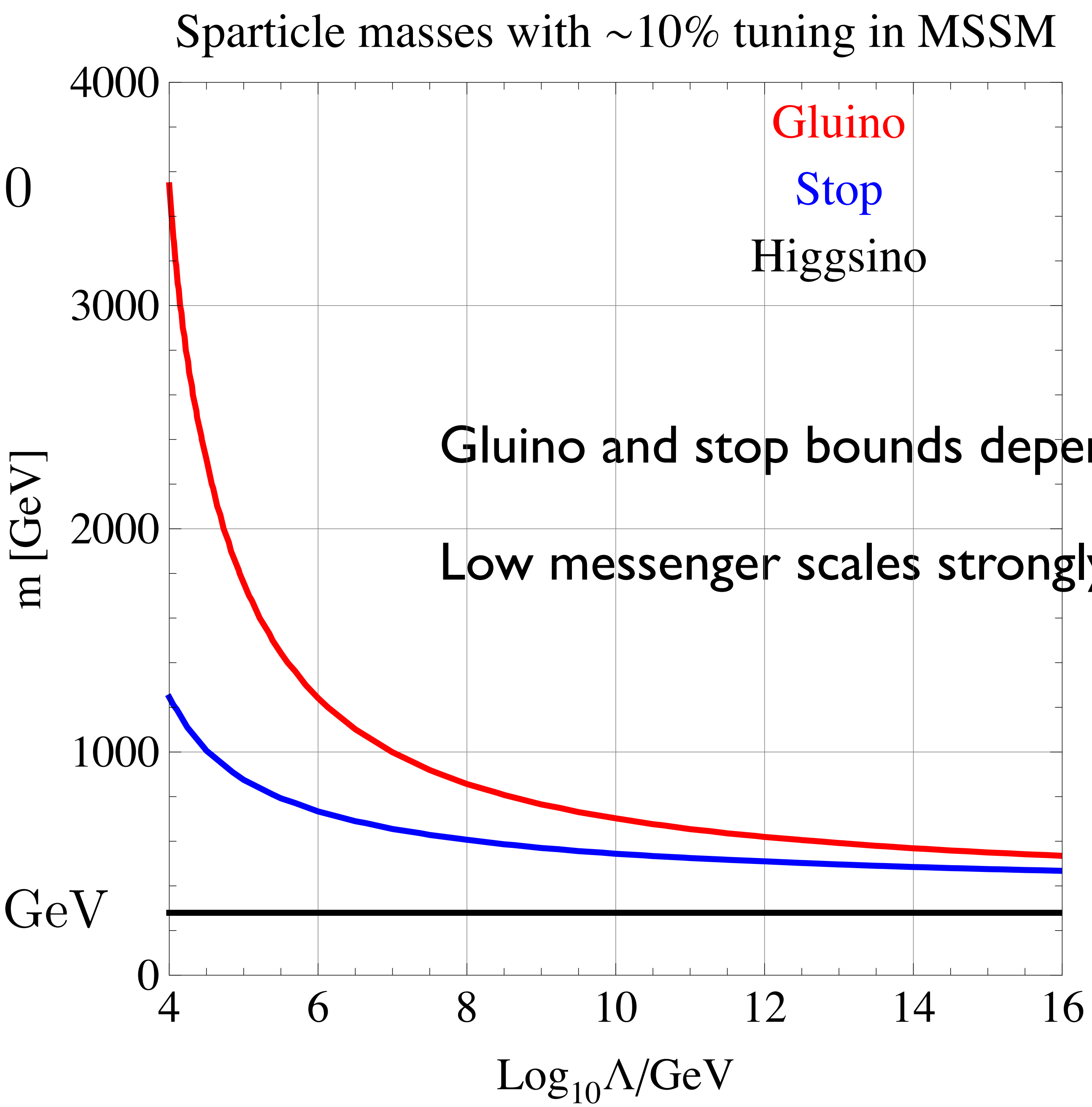

$\mu \lesssim 300$ GeV

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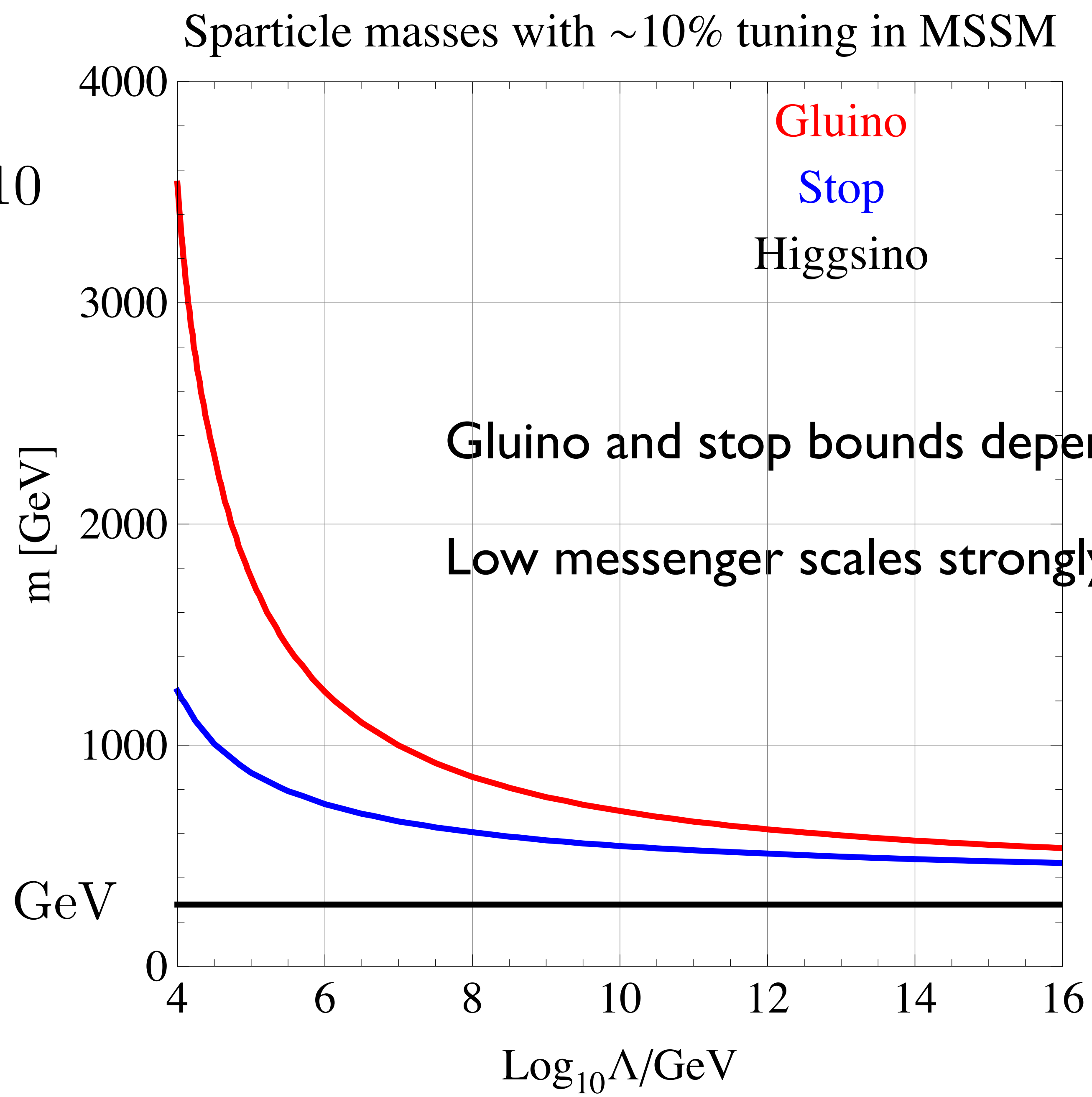

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What does the LHC say about fine-tuning?

“Vanilla SUSY”

MSSM + R-parity + flavor-universality

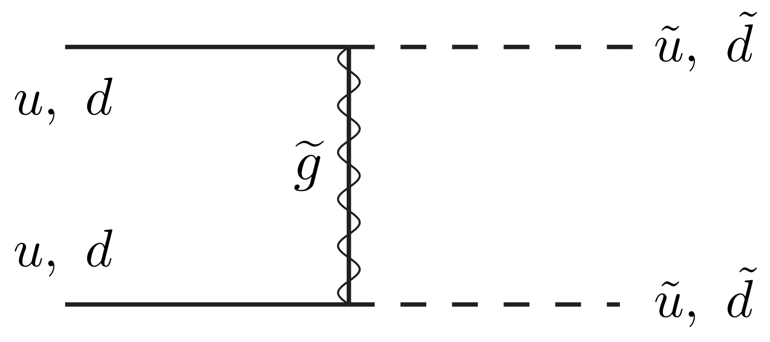
MSSM+R-parity+flavor universality

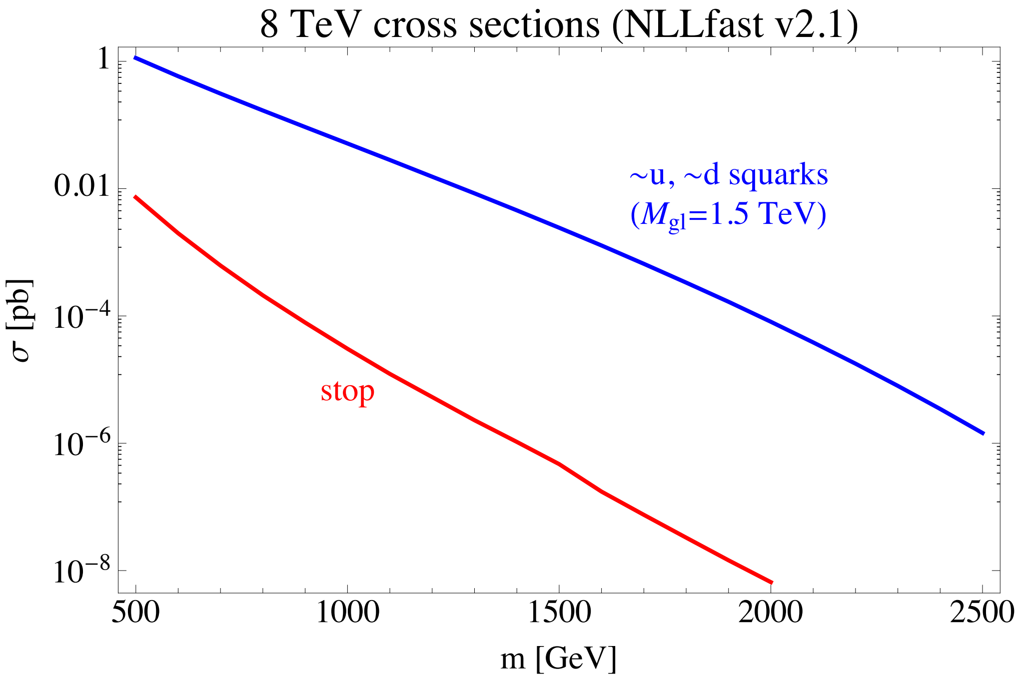
Motivations: simplest, most minimal, automatically consistent with unification, easy to embed in top-down models such as gauge mediation.

Essential baseline model!

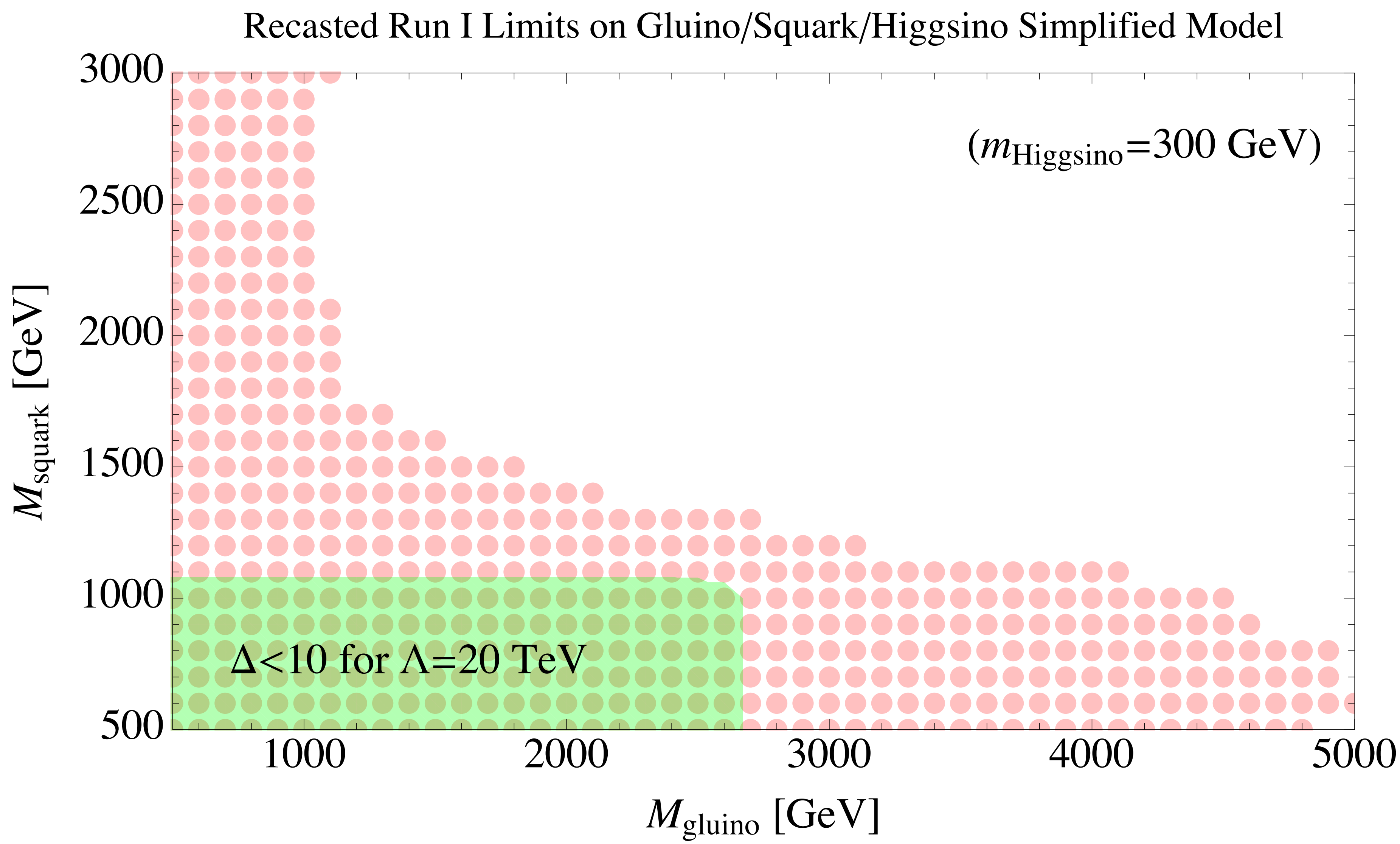
With R-parity, LSP is stable. Light higgsinos make missing ET unavoidable.

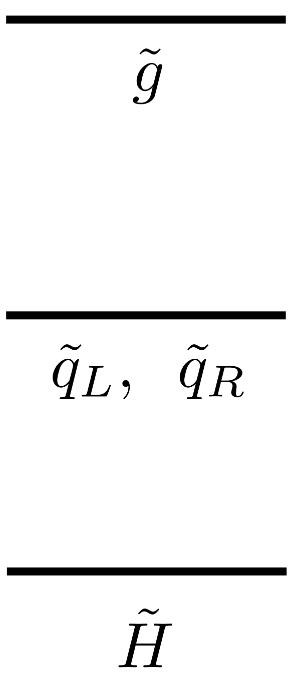
With flavor-universality, light stops imply light u and d squarks. Valence squark production xsec is enormous!





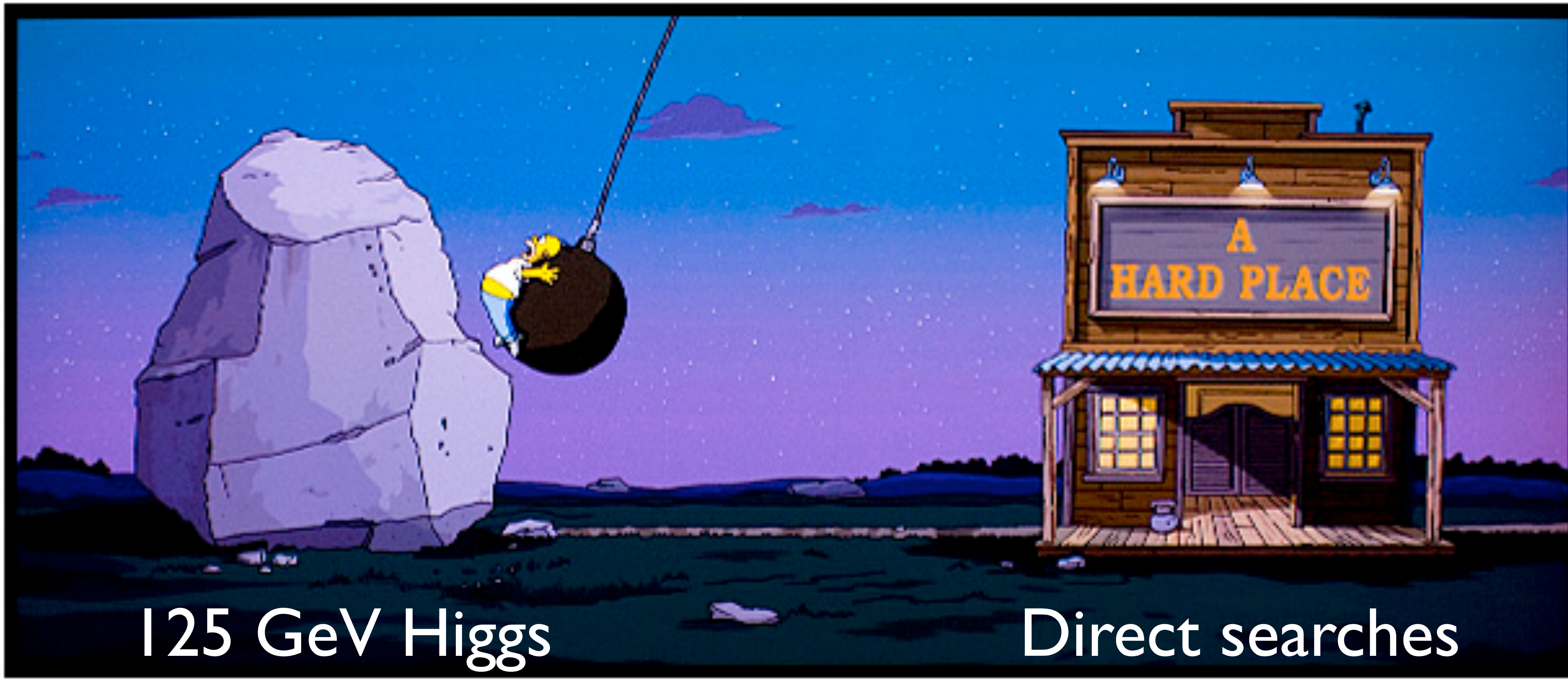
Very strong limits on squark/gluino production





Using analysis framework developed by
Jared Evans and Yevgeny Kats

Vanilla SUSY is more than 10% tuned even under extremely optimistic assumptions (ultra low messenger scale).



Then there's also the Higgs mass...

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Famous bound $(m_h)_{tree} < m_Z$. Need loop corrections from stops to raise it to 125 GeV.

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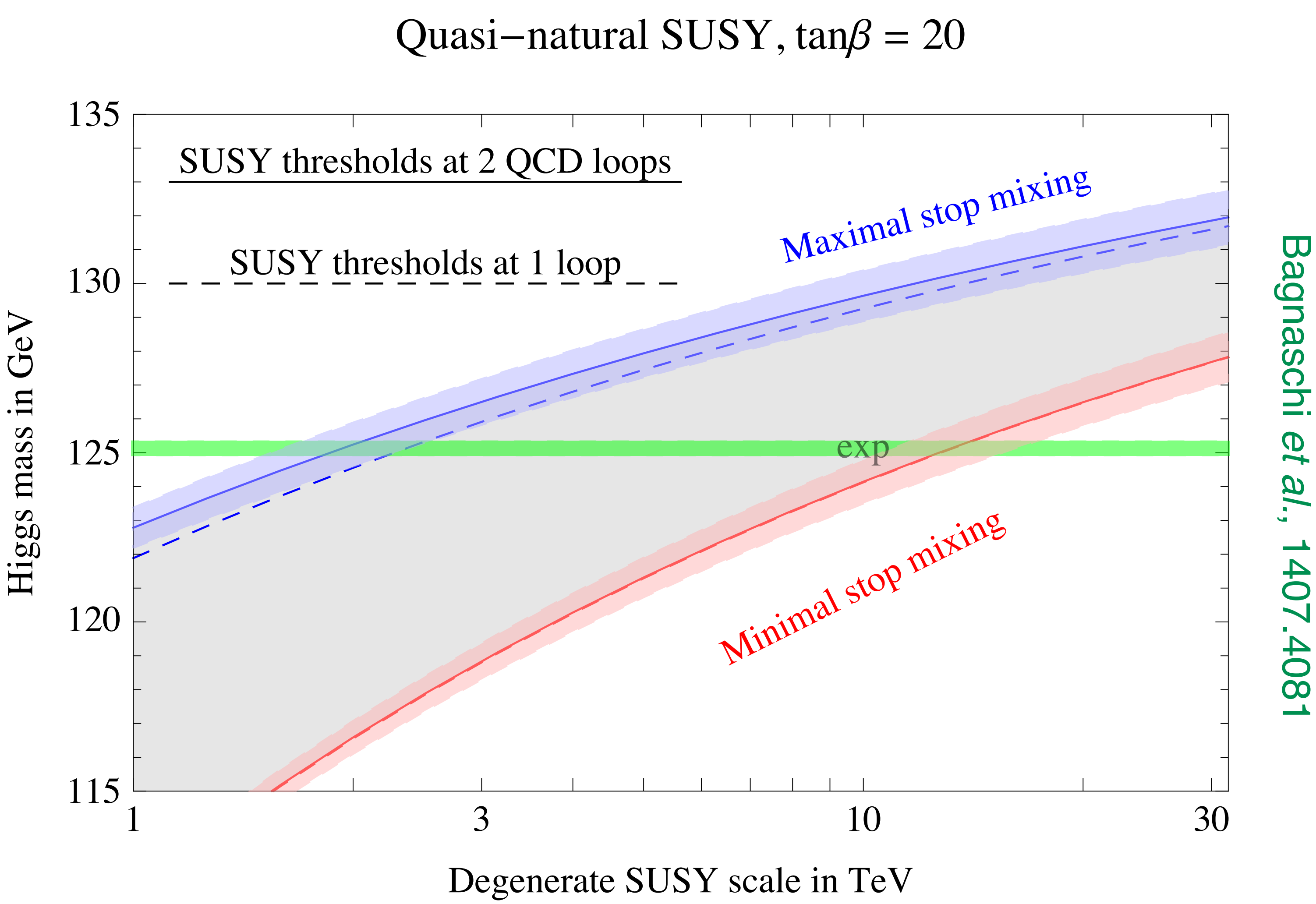

125 GeV in the MSSM requires either 10 TeV stops (0.01-0.1% tuning)...

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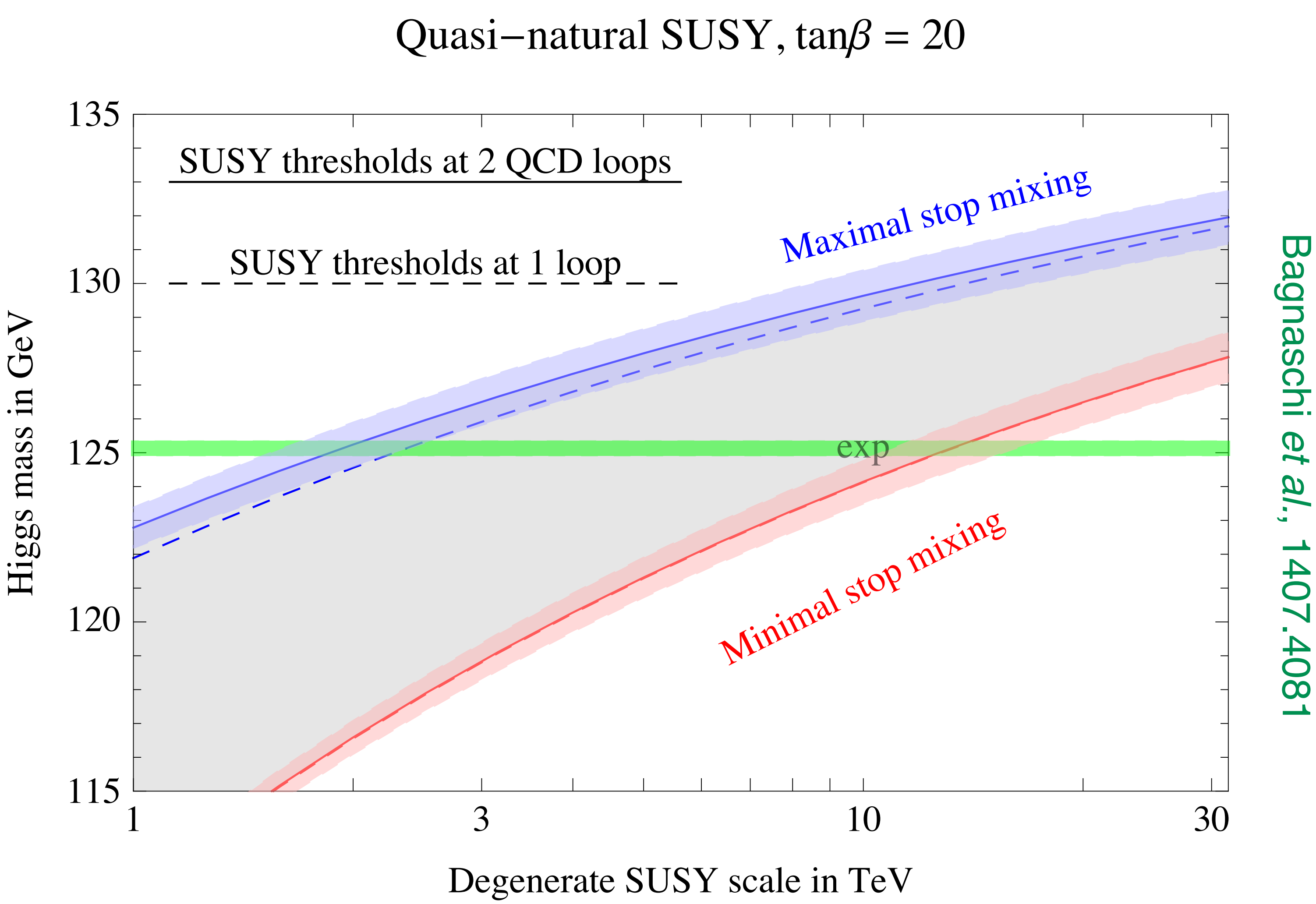

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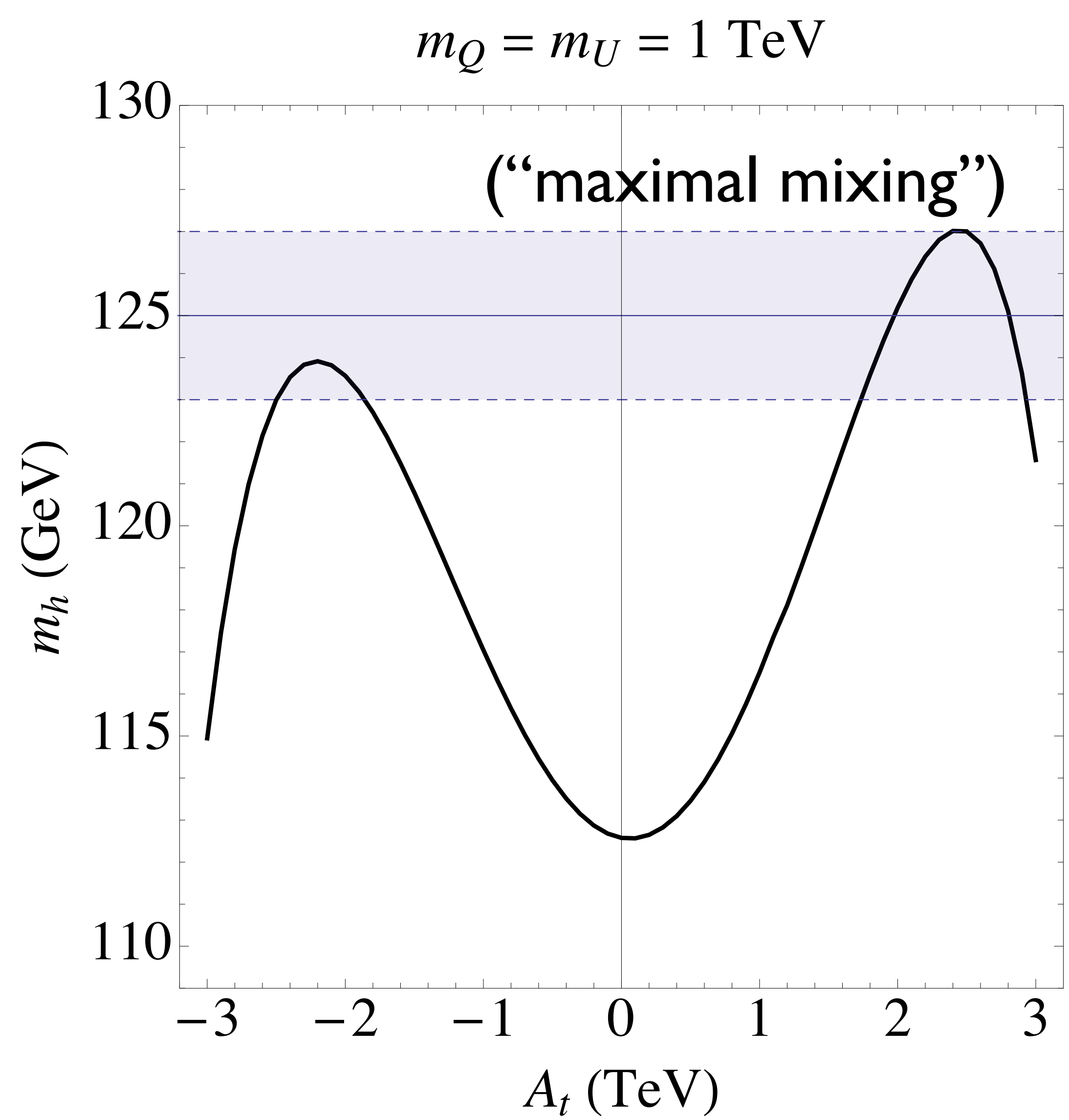


...or TeV stops with multi-TeV A-terms (1% tuning)

Vanilla SUSY does not seem 100% natural anymore.

Both direct searches and Higgs are independently pointing at heavier-than-expected superpartners and percent-level tuning.

Maybe we got unlucky and that's the way things are!

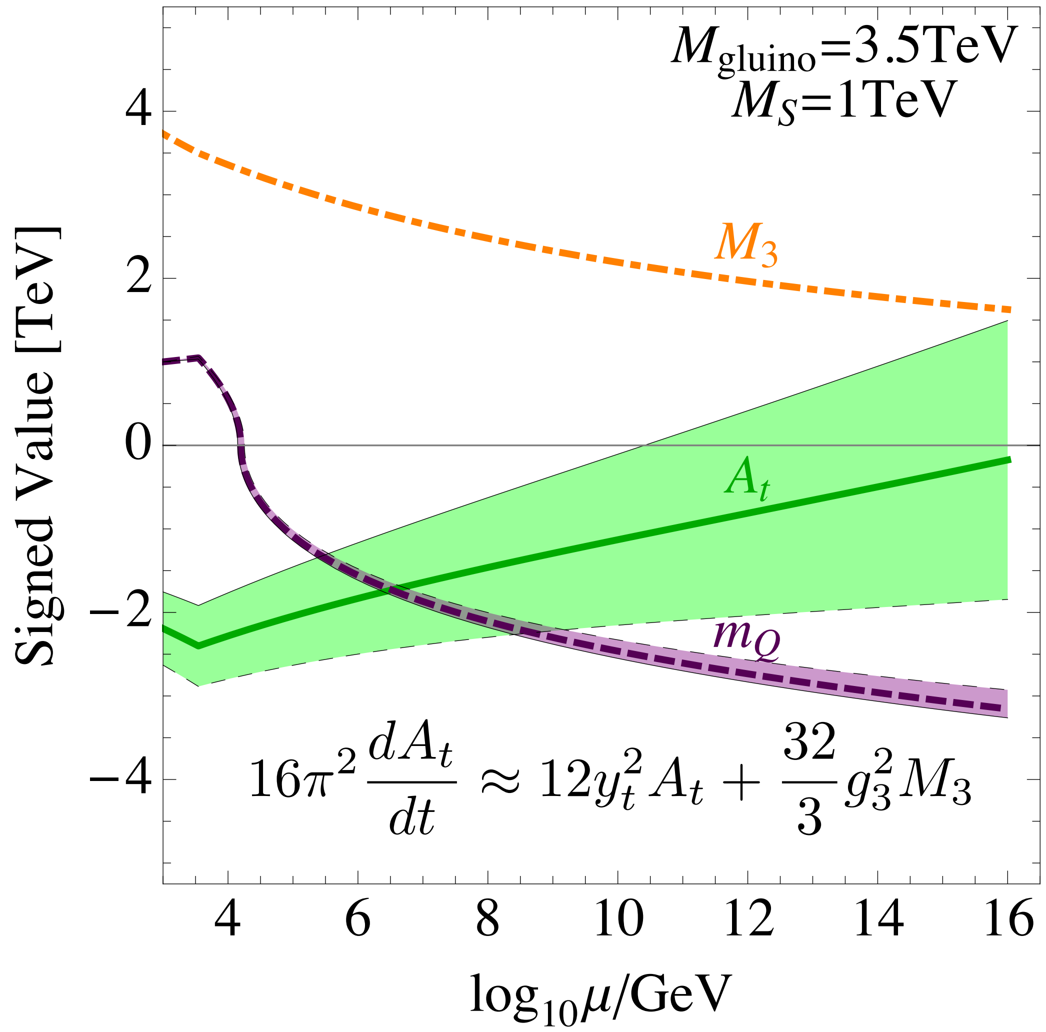
VANILLA REDUCED FAT ICE CREAM:

Ingredients: Milk, Sugar, Cream, Nonfat Milk Solids, Corn Syrup Solids, Mono- and Diglycerides, Guar Gum, Dextrose, Sodium Citrate, Artificial Vanilla Flavor, Sodium Phosphate, Carrageenan, Disodium Phosphate, Cellulose Gum, Vitamin A Palmitate.

Models for A-terms

Models for A-terms were not well-explored prior to the Higgs discovery. Interesting theoretical challenge!

- A-terms not generated at messenger scale in well-motivated models such as GGM.
- Can use RG; parameter space very constrained by Higgs mass (Draper, Meade, Reece & DS '11, Knapen, Redigolo & DS '15)
  - Colored superpartners largely out of reach even at Run II.
  - Light EW-inos are generic and within reach.



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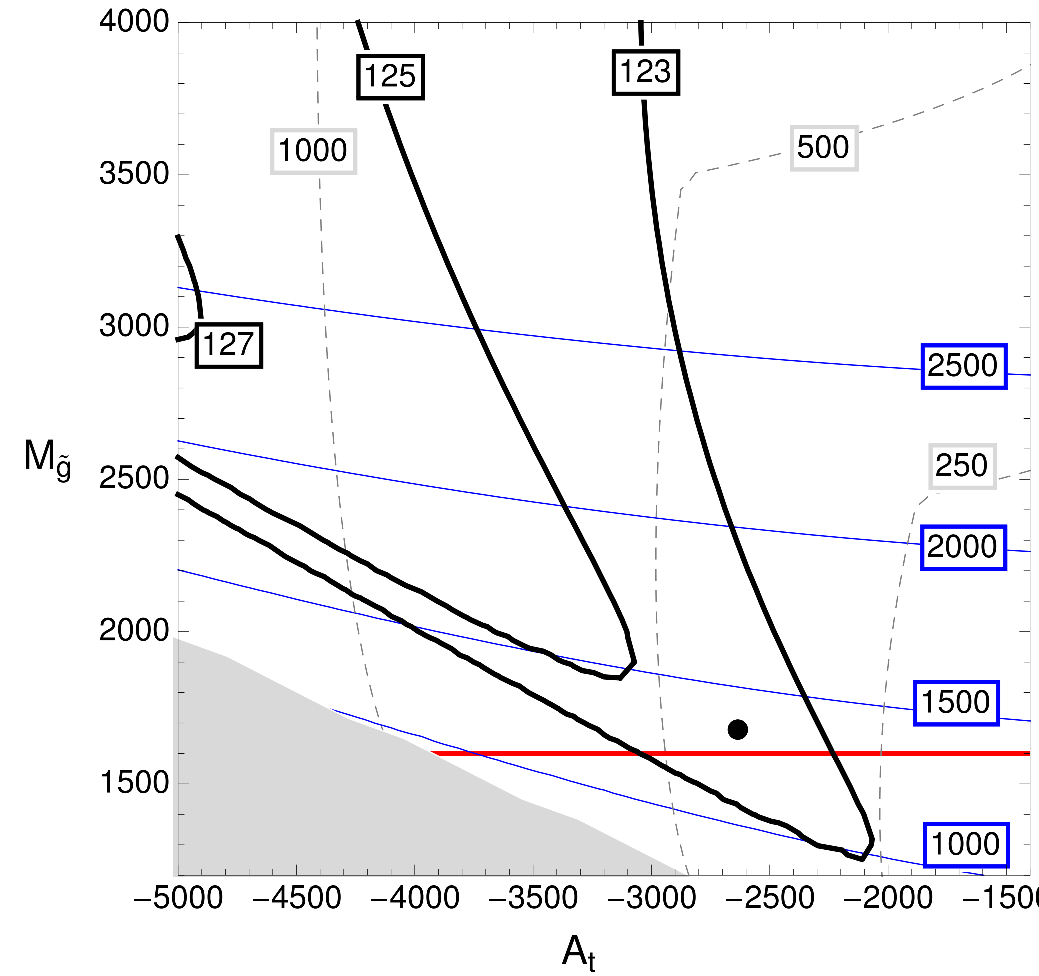
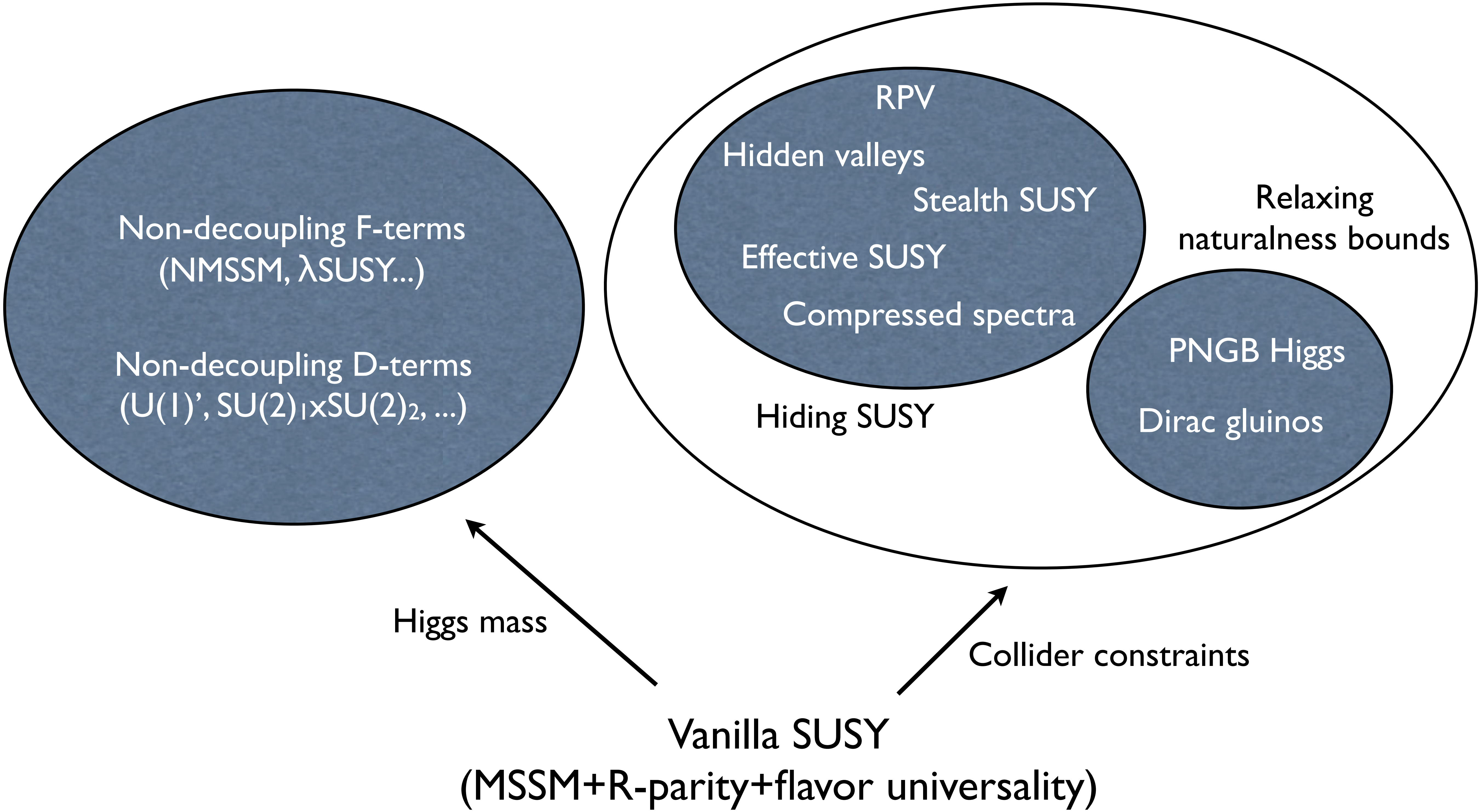
- Alternatively, can generate A-terms at messenger scale, using direct messenger-MSSM couplings.
- Very active area since the Higgs discovery!
- Can achieve best-possible tuning in MSSM (Evans & DS '13; Basirnia, Egana, Knapen & DS '15).
- Interesting flavor signatures. (Abdullah et al '12; Jay Perez et al '12; Calibbi et al '13; Evans, DS & Thalapillil '15)



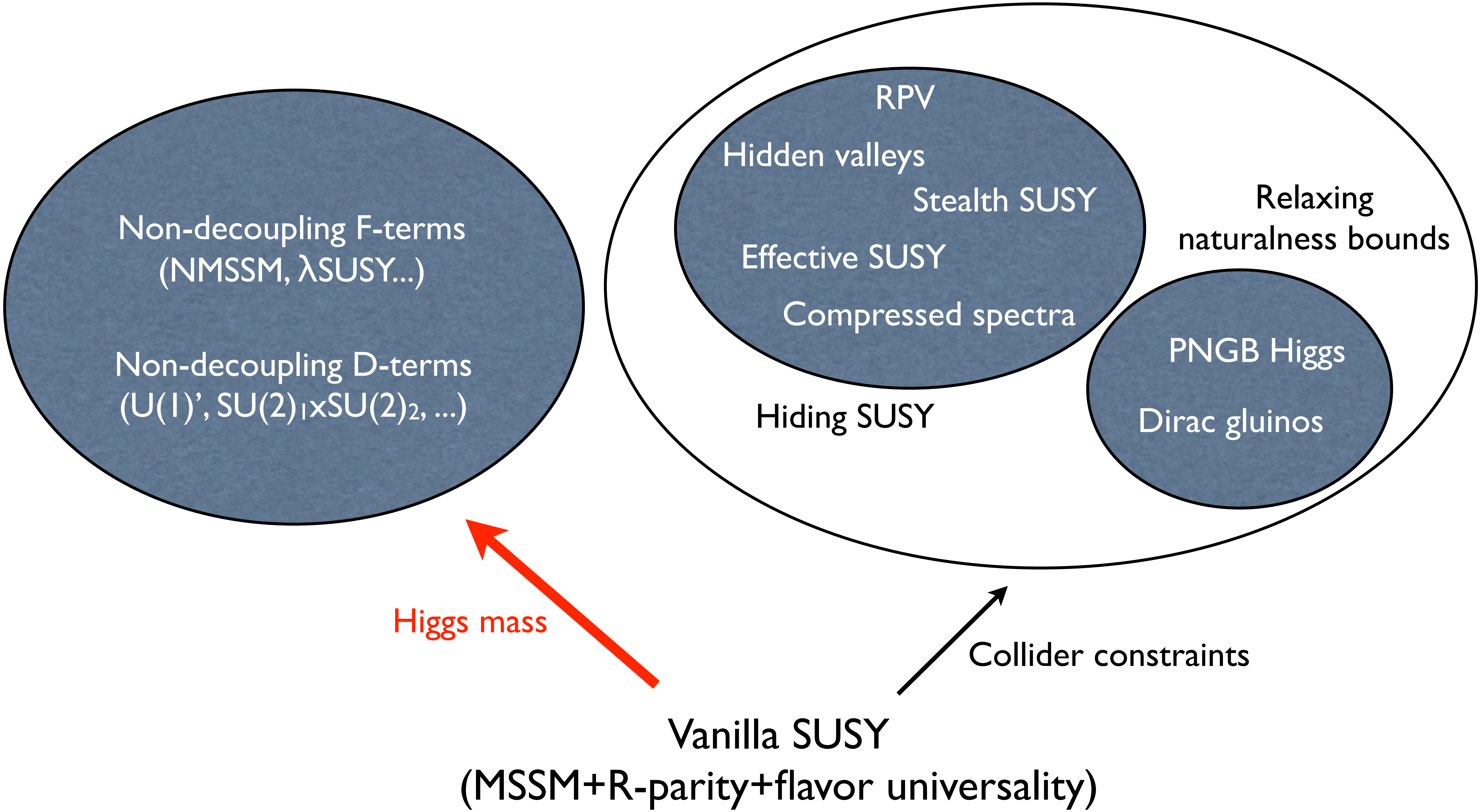
Basirnia, Egana, Knapen & DS '15

Or maybe it's not vanilla SUSY...



Must modify (at least) one of the starting points.

Must address BOTH challenges facing vanilla SUSY.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(NMSSM, λSUSY...)
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Dirac gluinos
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Collider constraints
Vanilla SUSY
(MSSM+R-parity+flavor universality)

Raising the Higgs mass

$$V(H) = m_H^2|H|^2 + \frac{1}{2}\lambda_H|H|^4$$

$$v^2 = -\frac{m_H^2}{\lambda_H} = (246\ \mathrm{GeV})^2$$

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

$$\lambda_H = \frac{1}{2}(g^2 + g'^2) + \delta\lambda_H$$

In the MSSM, tree-level Higgs quartic related to gauge couplings by SUSY.

Idea: extend MSSM with extra states that interact with the Higgs. Augment Higgs quartic at tree-level, can raise m_h and restore naturalness.

Two options: Quartic from F-terms (extended matter sector) or D-terms (extended gauge sector).

Non-decoupling F-terms

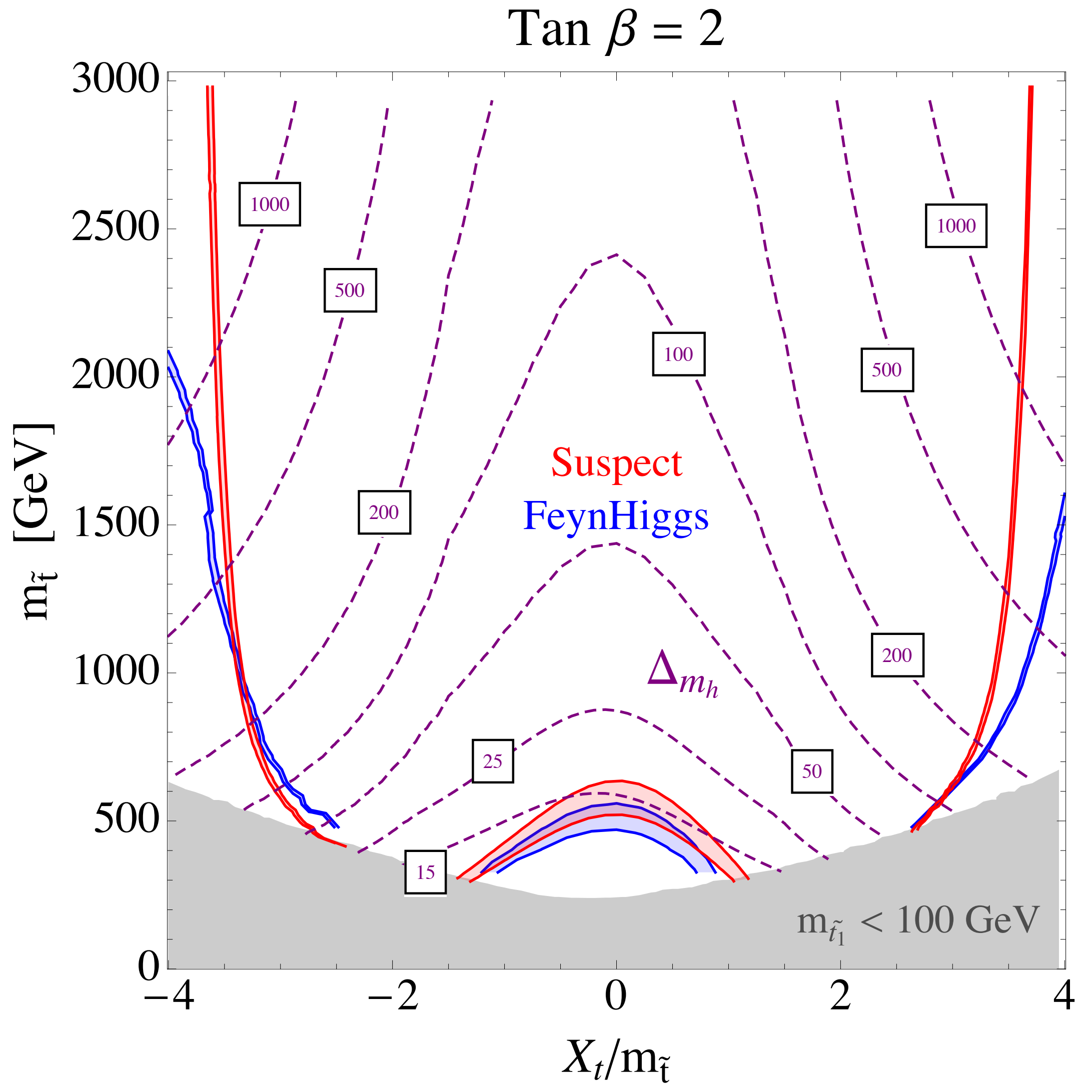
Integrating out extra singlets can give add'l contributions to Higgs quartic.

$$W \supset \lambda S H_u H_d$$

$$V_F \supset \left| \frac{\partial W}{\partial S} \right|^2 = \lambda^2 |H_u H_d|^2$$

Naturalness: expect light (sub-TeV) singlet/singlino and modified Higgs couplings.

Challenges: Landau poles, μ problems



Hall, Pinner, Ruderman '11

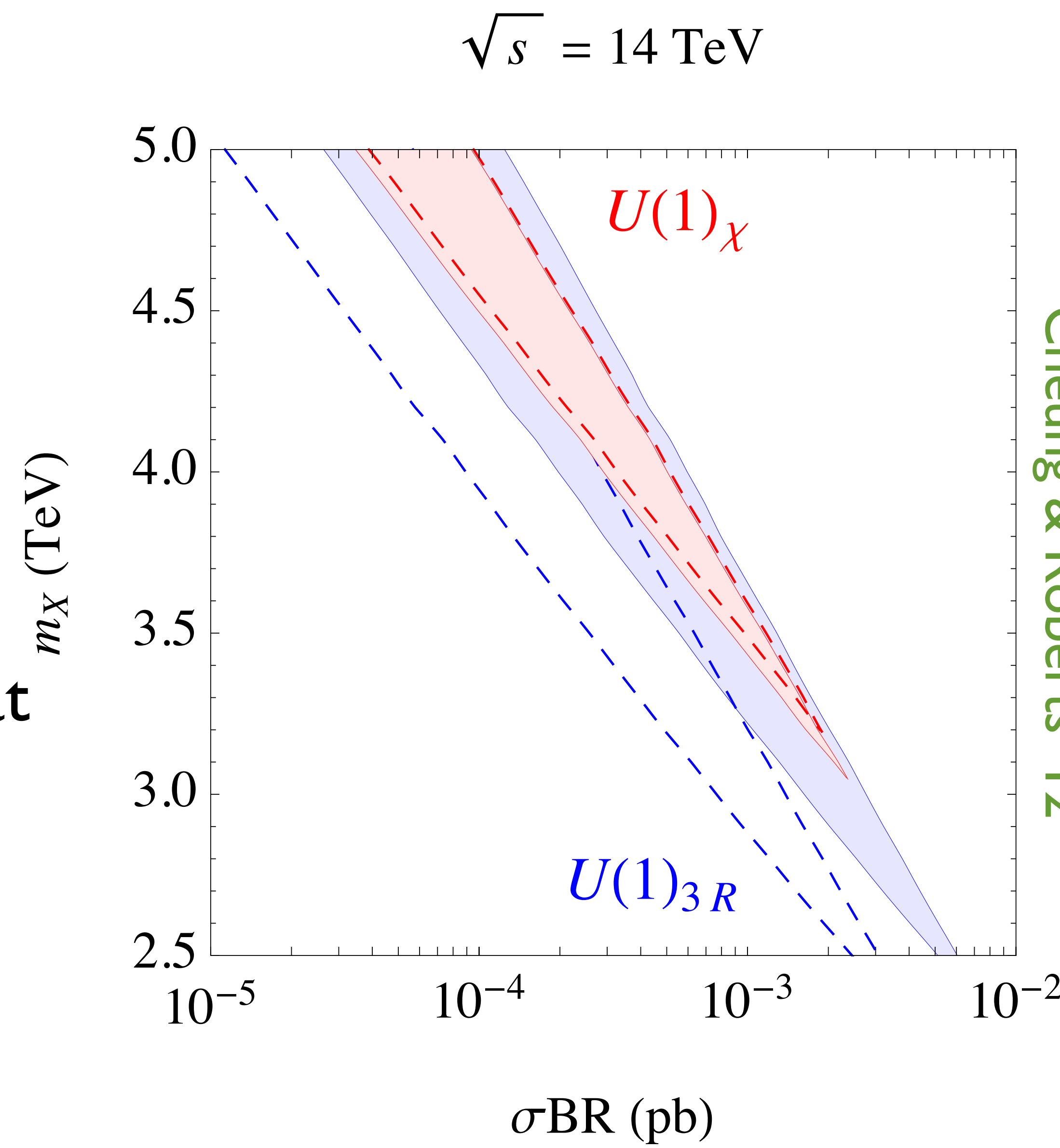
Non-decoupling D-terms

Charging the Higgs under additional gauge interactions (e.g. U(1)') can lift Higgs mass through D-terms (Batra et al '03)

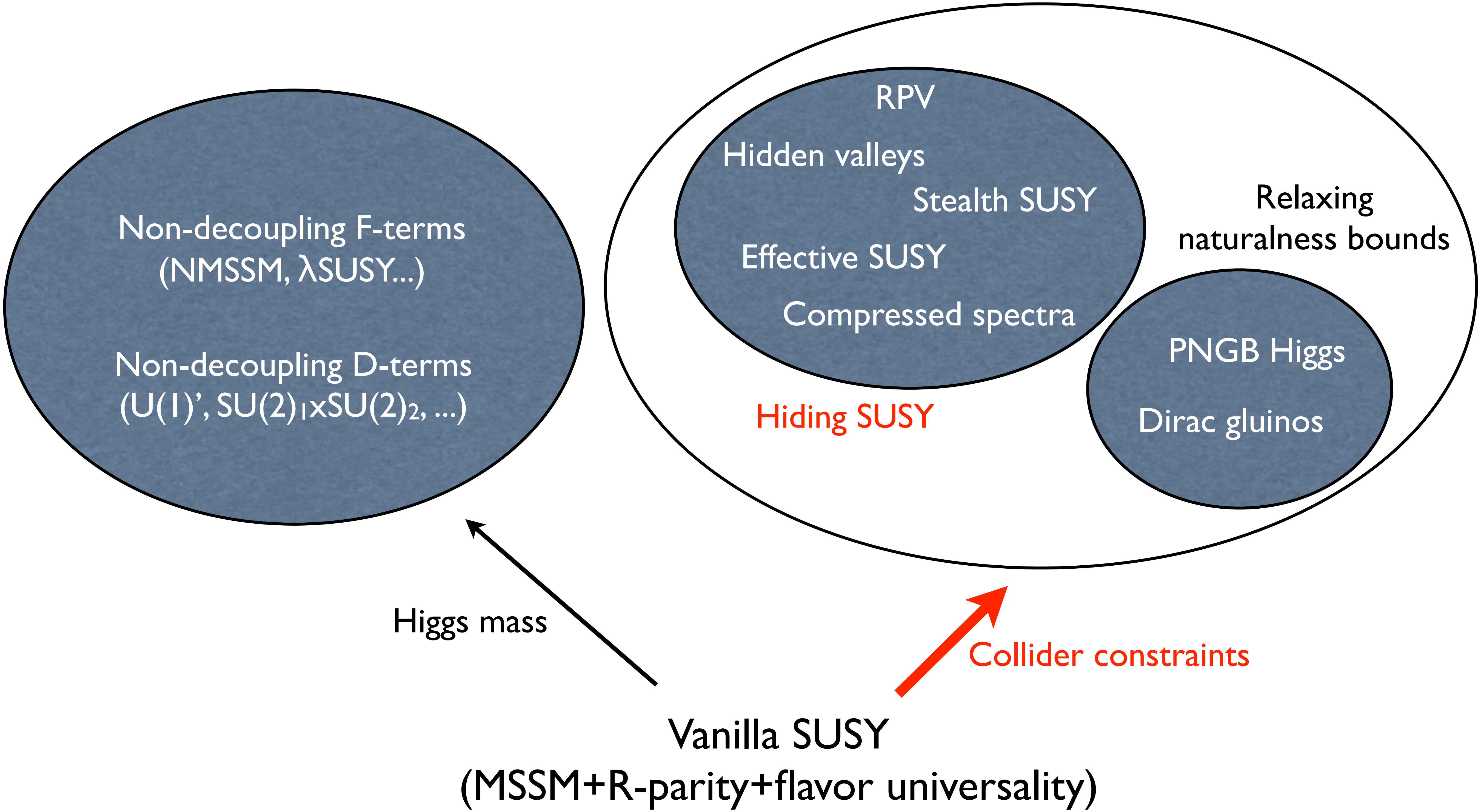
$$V_D \supset (q_u|H_u|^2 + q_d|H_d|^2 + \dots)^2$$

Naturalness: expect Z' resonances accessible at Run II! (Cheung & Roberts '12; Bertuzzo & Frigiuele '14)

Challenges: Landau pole, unification, EWPT.



Cheung & Roberts '12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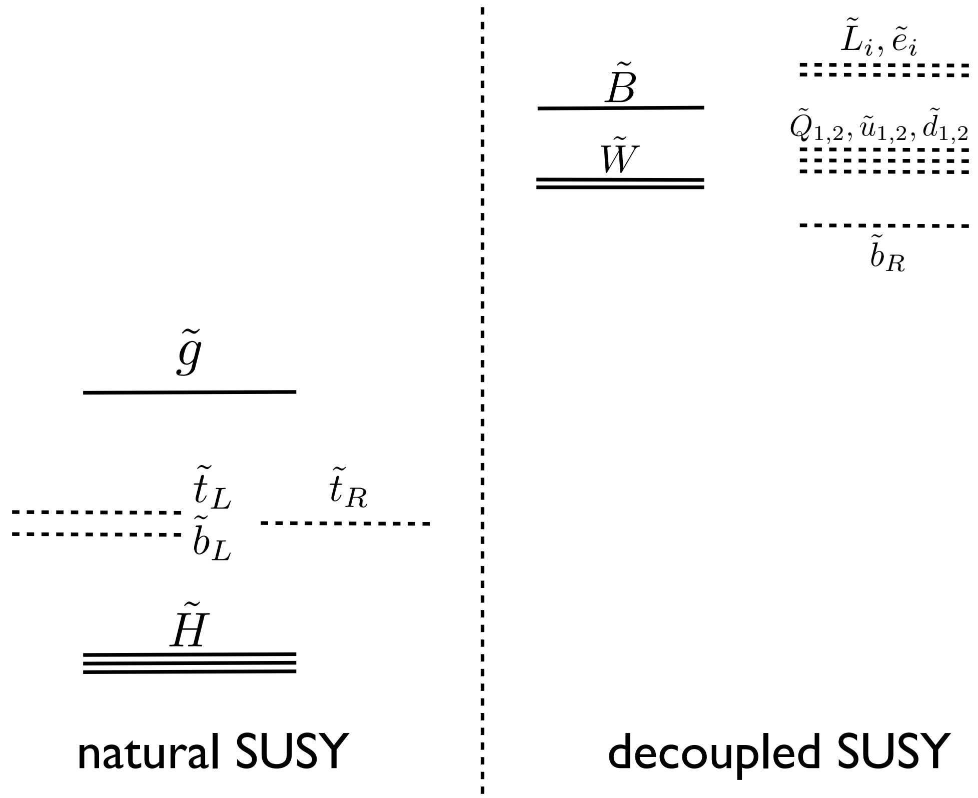
Effective SUSY

Light 1st/2nd generation squarks not required for naturalness.

(Dine, Leigh & Kagan '93; Dimopoulos & Giudice '95; Cohen, Kaplan & Nelson '96)



Papucci, Ruderman, Weiler '11

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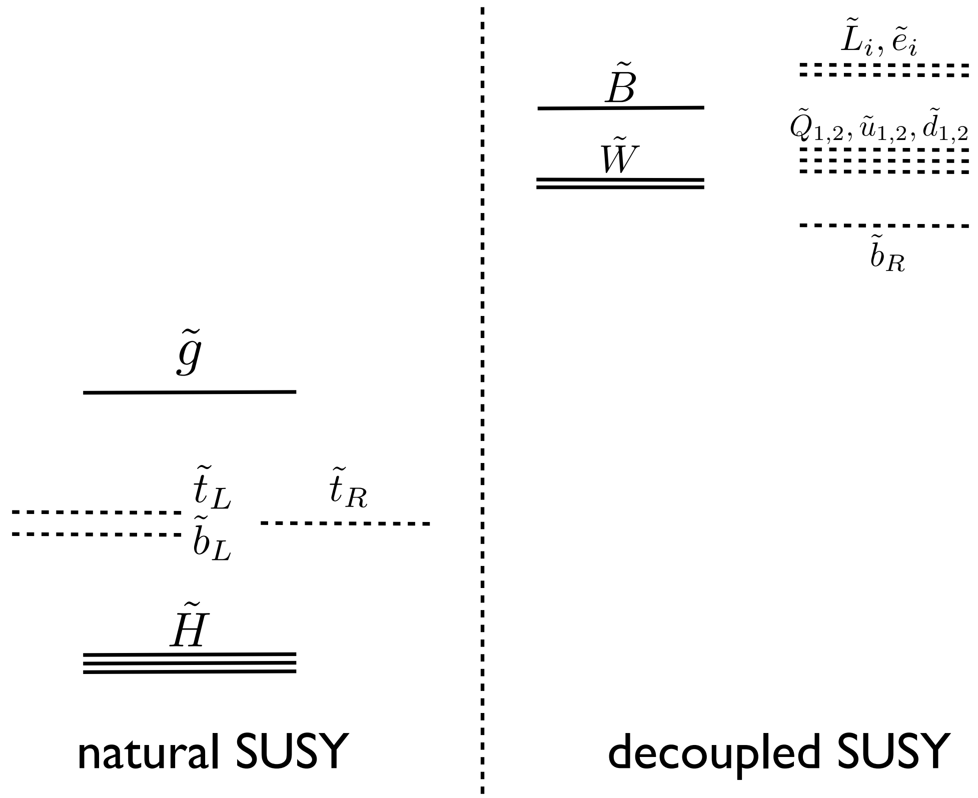

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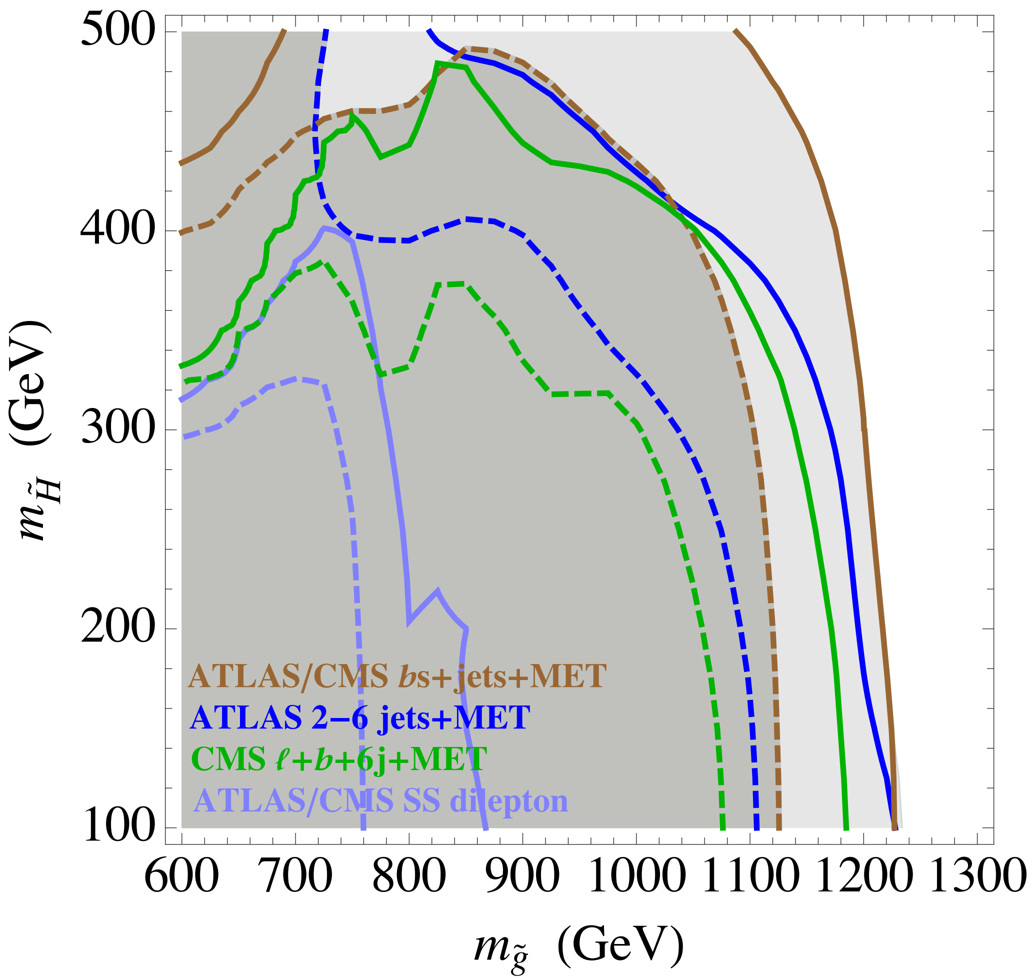
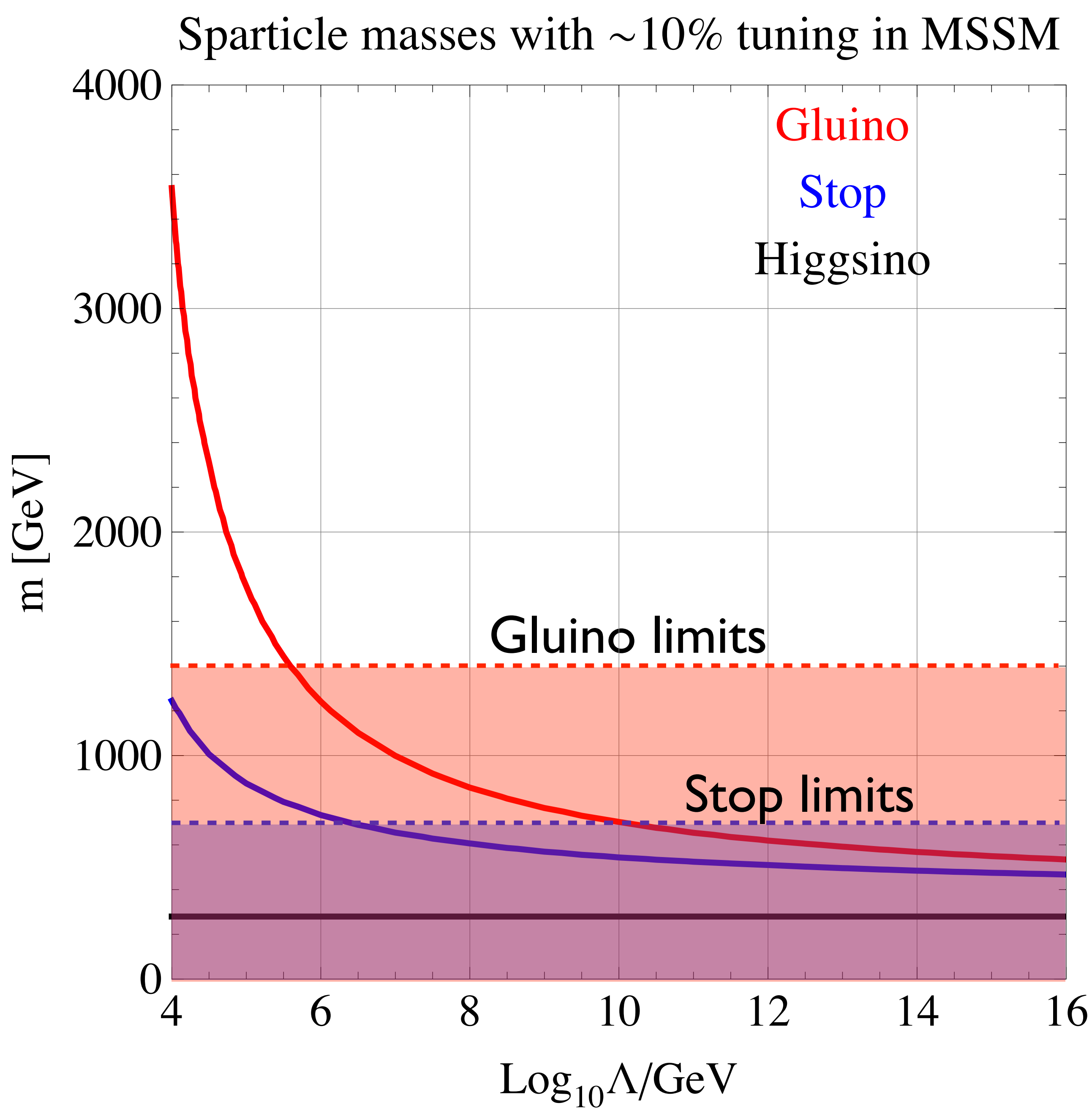
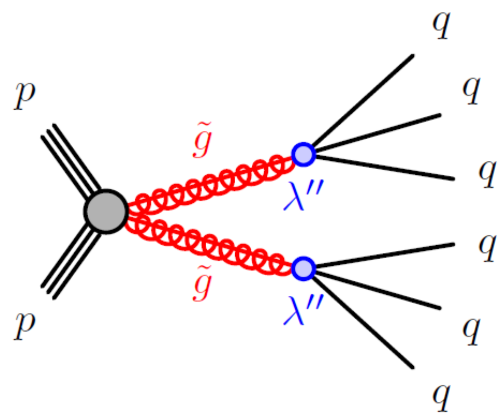
Decoupling them relaxes collider limits, but not completely



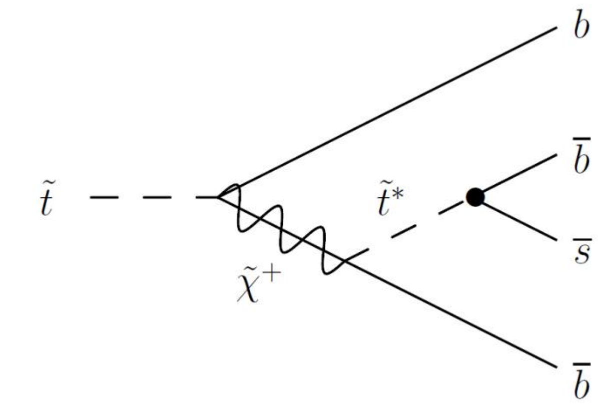
Evans, Kats, DS & Strassler '13



Without doing something more, only low messenger scales survive naturalness bound!



RPV



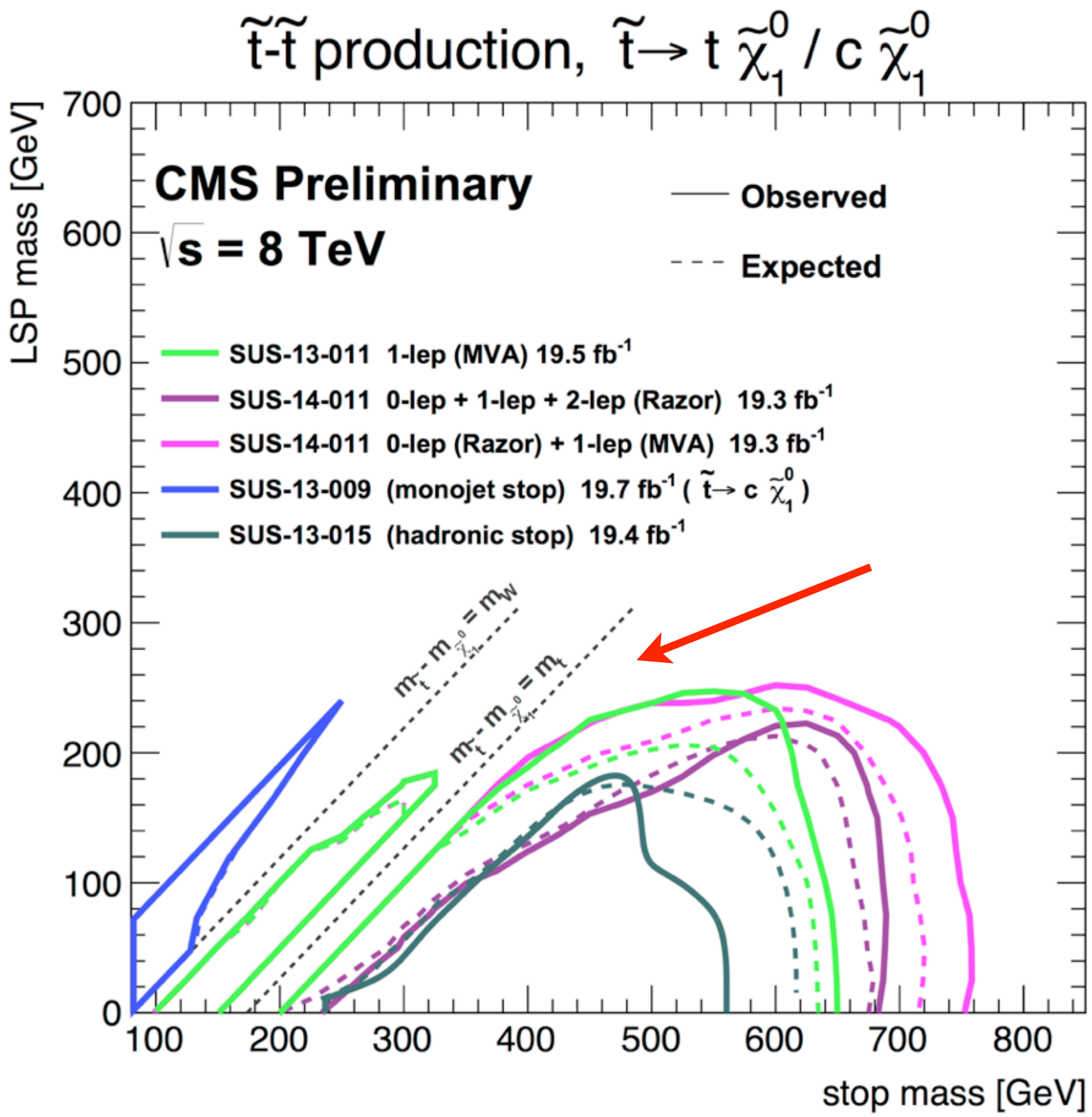
$$W_{RPV} = \frac{1}{2}\lambda_{ijk}L_iL_jE_k + \lambda'_{ijk}L_iQ_jD_k + \frac{1}{2}\lambda''_{ijk}U_iD_jD_k$$

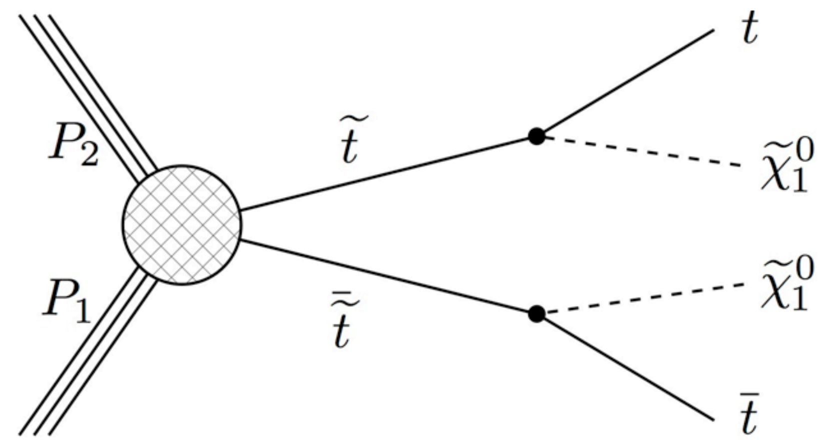
RPV and related mechanisms (hidden valleys, stealth) can hide SUSY by turning MET into jets and leptons, but the gaps are closing.

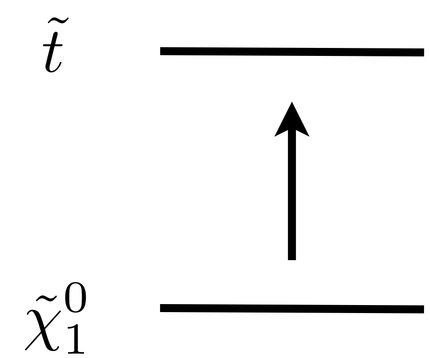
- Stops:
  - first two body limits (stop→qq) were recently obtained by ATLAS (CONF-2015-026) and CMS (1412.7706). Limits between 300-400 GeV.
  - Many-body stop decays still unconstrained! (Evans & Kats '12, '13; Evans '14)
- Gluinos: robust, model-independent lower bound ~ 1 TeV (Kats, Evans, Strassler & DS '13)
- RPV can significantly relax bounds on flavor-universal squarks (Graham et al '14)
- Gaps in displaced RPV decays largely closing (Liu & Tweedie '15; Csaki et al '15)

See Y. Kats talk in parallel session for more details!

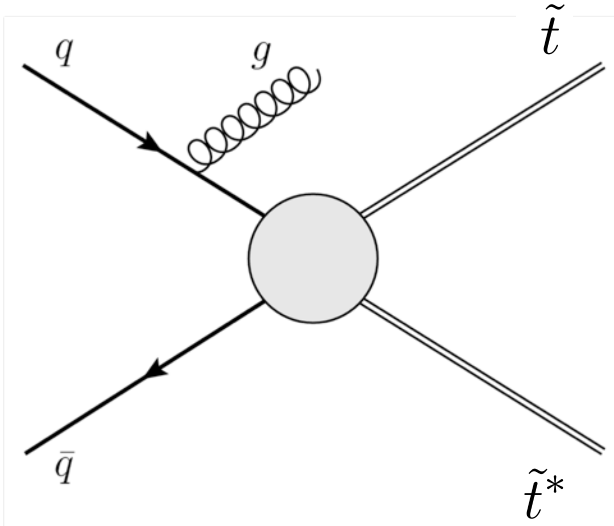
Compressed stops

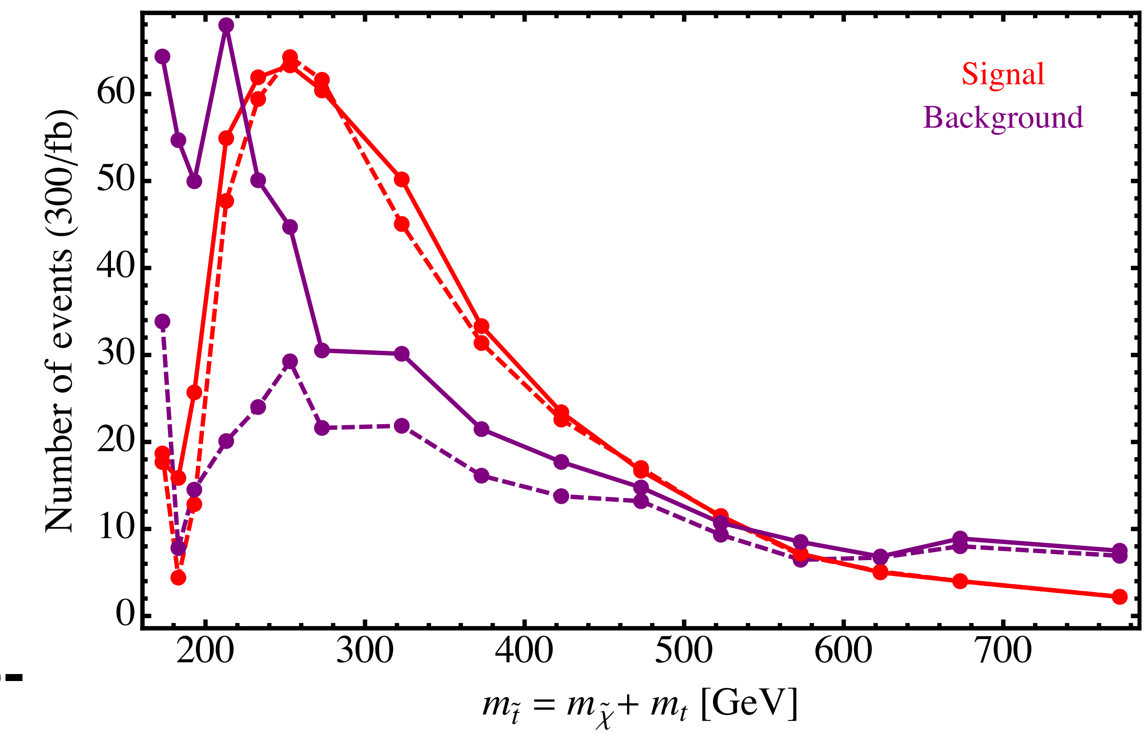






All event activity (MET, jets,...) decreased as $m_{LSP} \rightarrow m_{stop}$

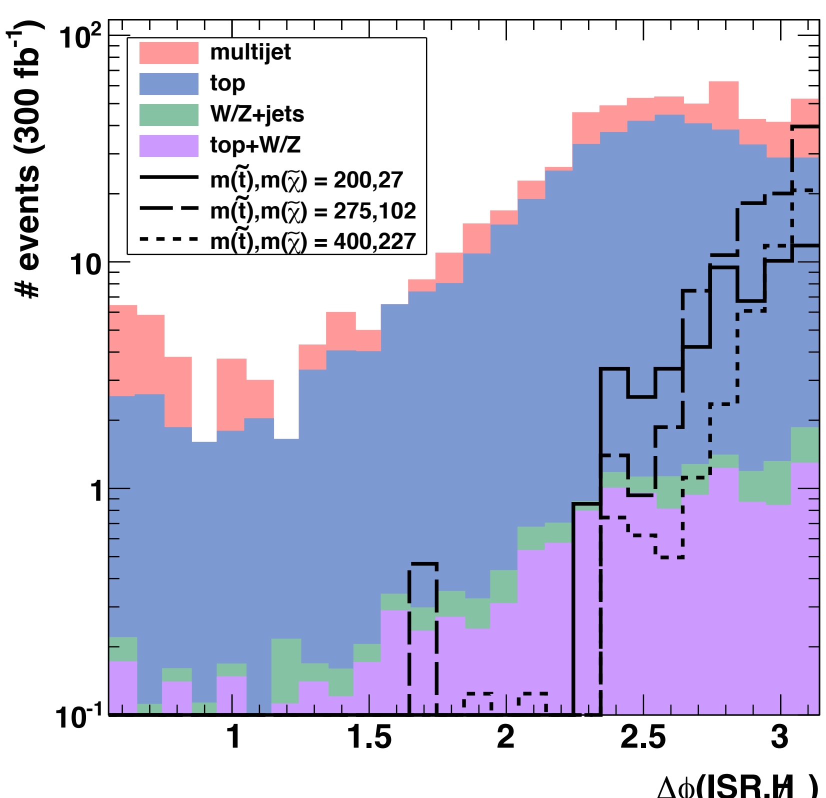


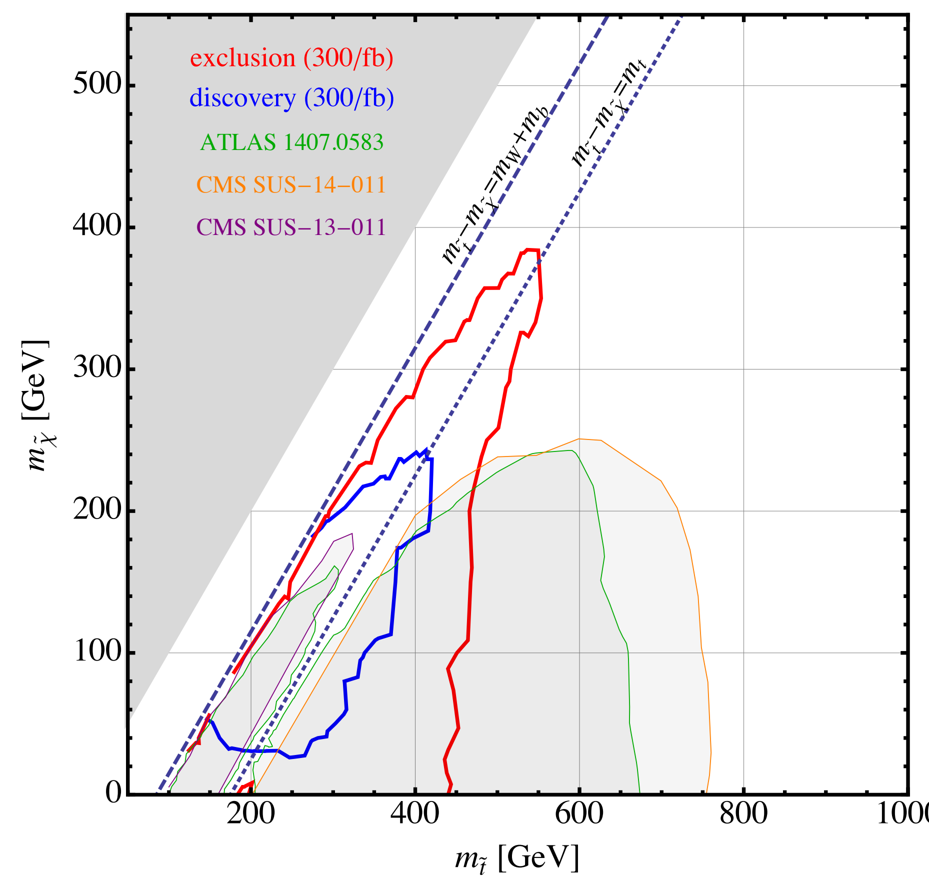


Recent idea: use recoil off hard ISR jet.

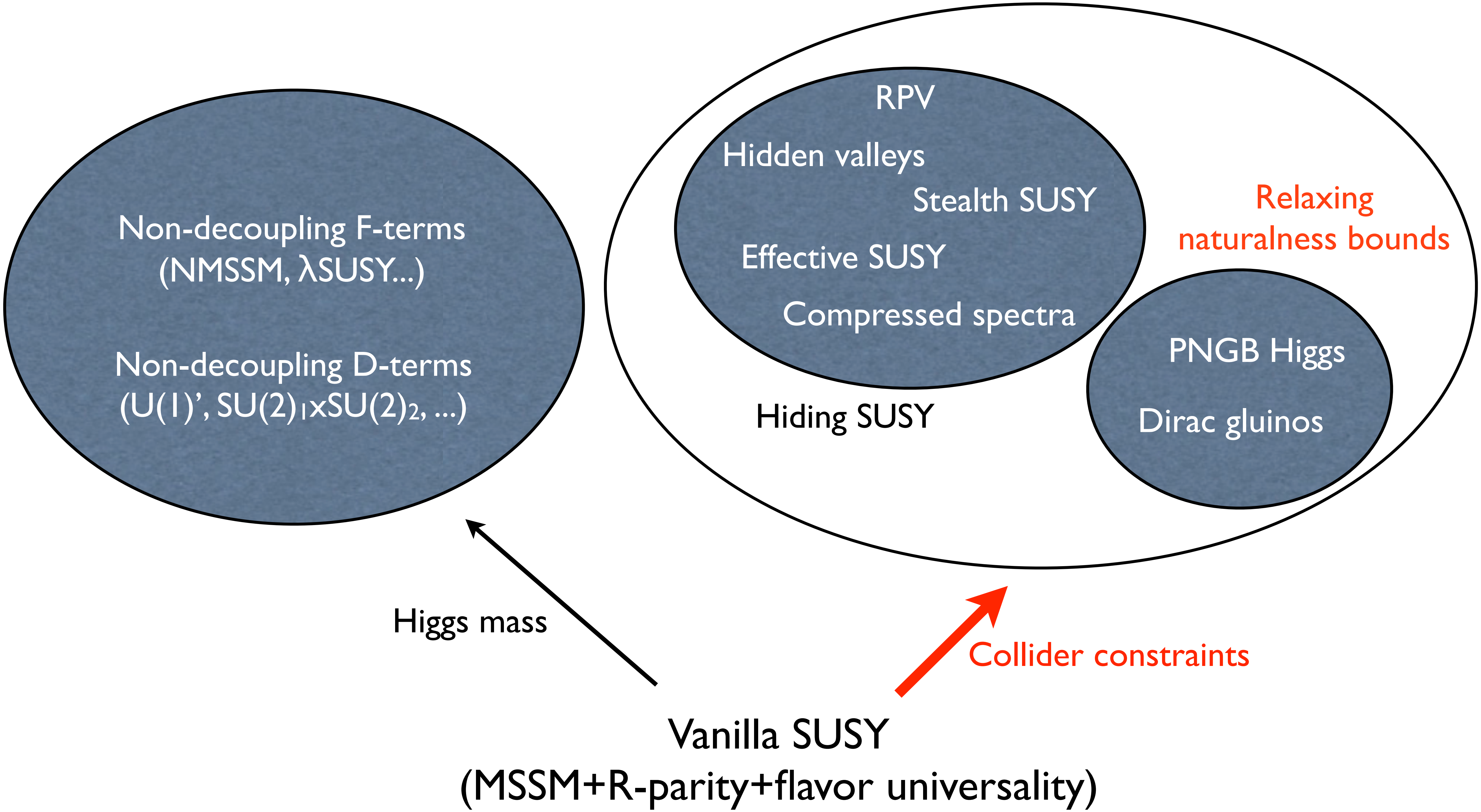
In all-hadronic channel, MET will be back-to-back with ISR jet. Not true of dominant backgrounds (QCD, ttbar)!

(Hagiwara & Yamada '13; An & Wang '15; Macaluso, Park, DS & Tweedie '15)





Can access compressed region with high S/B at Run II!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Relaxing Naturalness Bounds

Gluinos:

- Well-known solution: Dirac instead of Majorana masses for gluinos.

$$M_3 \tilde{g}\tilde{g} \quad \rightarrow \quad M_3 \tilde{g}\psi$$

ψ: new color octet

$$\delta m_{\tilde{t}}^2 \sim \alpha_3 M_3^2 \log \frac{\Lambda}{M_3} \quad \rightarrow \quad \delta m_{\tilde{t}}^2 \sim \alpha_3 M_3^2$$

Dirac mass is "supersoft"
(Fox, Nelson & Weiner '02)

$$\delta m_{H_u}^2 \sim \alpha_3 \alpha_t M_3^2 \left(\log \frac{\Lambda}{M_3}\right)^2 \quad \rightarrow \quad \delta m_{H_u}^2 \sim \alpha_3 \alpha_t M_3^2 \log \frac{\Lambda}{M_3}$$

- Allows for much heavier (multi-TeV) gluinos without spoiling naturalness.
- Many positive benefits, including decreasing valence squark cross sections at LHC (Kribs & Martin '12)
- Incompatible with simple SU(5) unification

Relaxing Naturalness Bounds

Higgsinos:

- Not easy to break tree-level connection between Higgsinos and tuning.
- One idea: Higgs as PNGB (Cohen, Kearny & Luty '15). In principle, Higgsino can be much heavier than in MSSM without sacrificing naturalness.
- But 10% tuning of v/f inevitable in all PNGB models, so total naturalness not possible here. In a more complete model, Cohen et al found ~ 3% tuning at best. Not a huge overall improvement over MSSM tuning in absolute terms.
- As with all PNGB models, needs unknown UV completion at relatively low scales. Unification likely spoiled.

Conclusions

Natural SUSY is under extreme pressure from LHC searches and m_h =125 GeV.

Models of natural SUSY must overcome both collider constraints and raise m_h to 125 GeV. Many ideas for one or the other, but very few (any?) complete models.

The vanilla scenario is at least 1% tuned.

Maybe we're unlucky and the weak scale is a bit of a numerical accident.

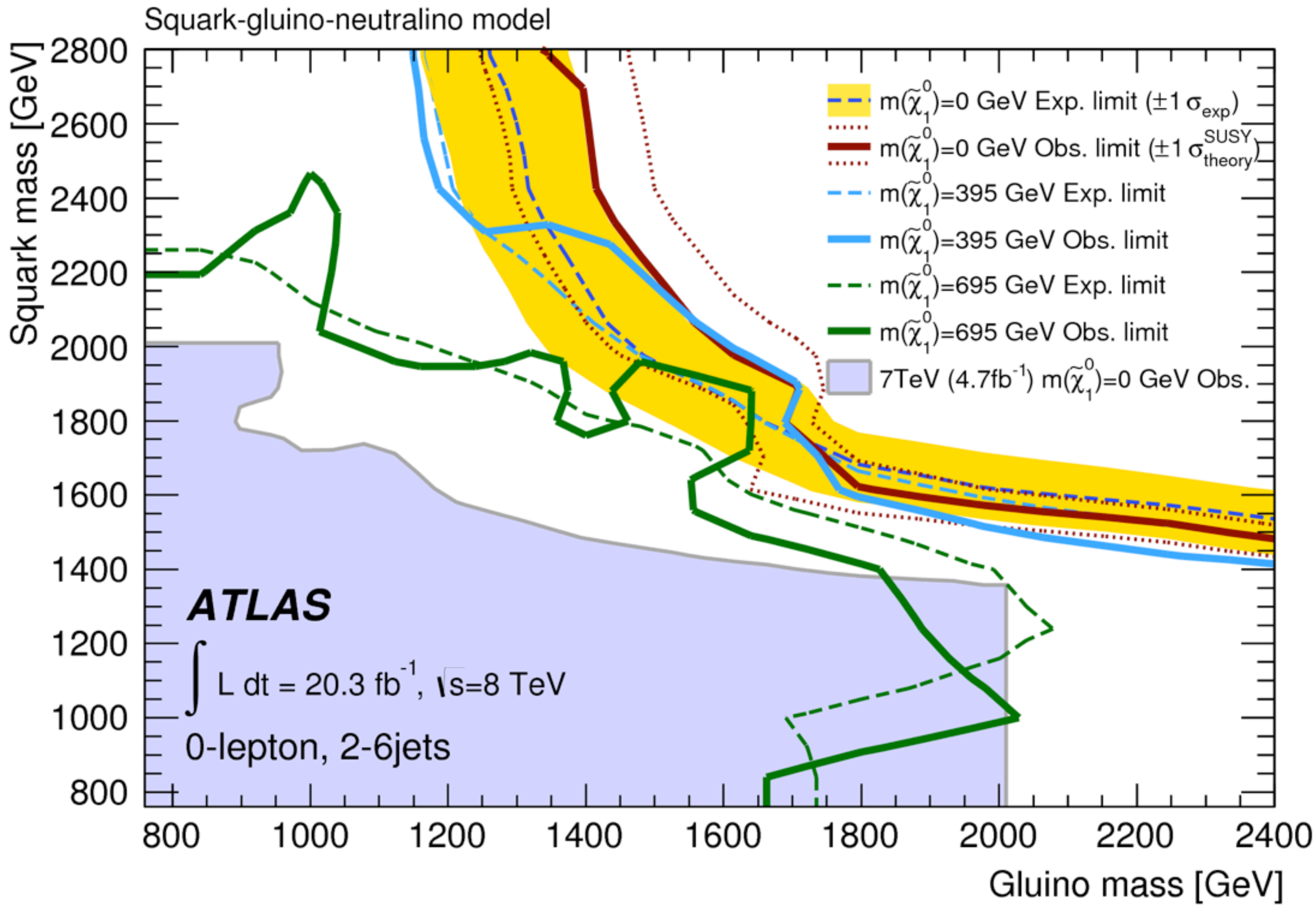
Or else Nature has given us a twist and SUSY is not completely minimal.

Many flavors of natural SUSY still remain. Are any of them realized in Nature? We need experiment to lead the way!

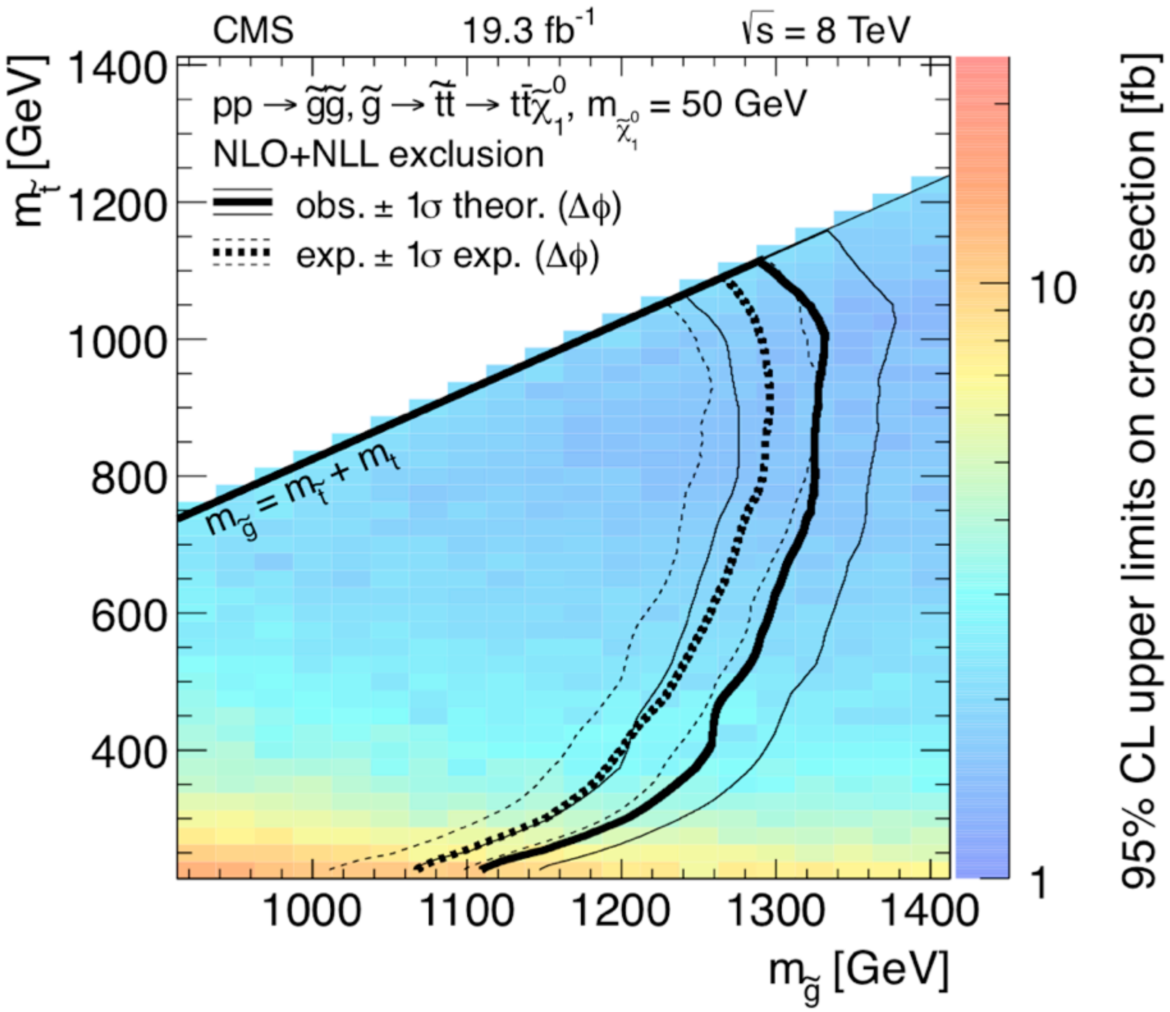
Thanks for your attention!

SUSY at a glance

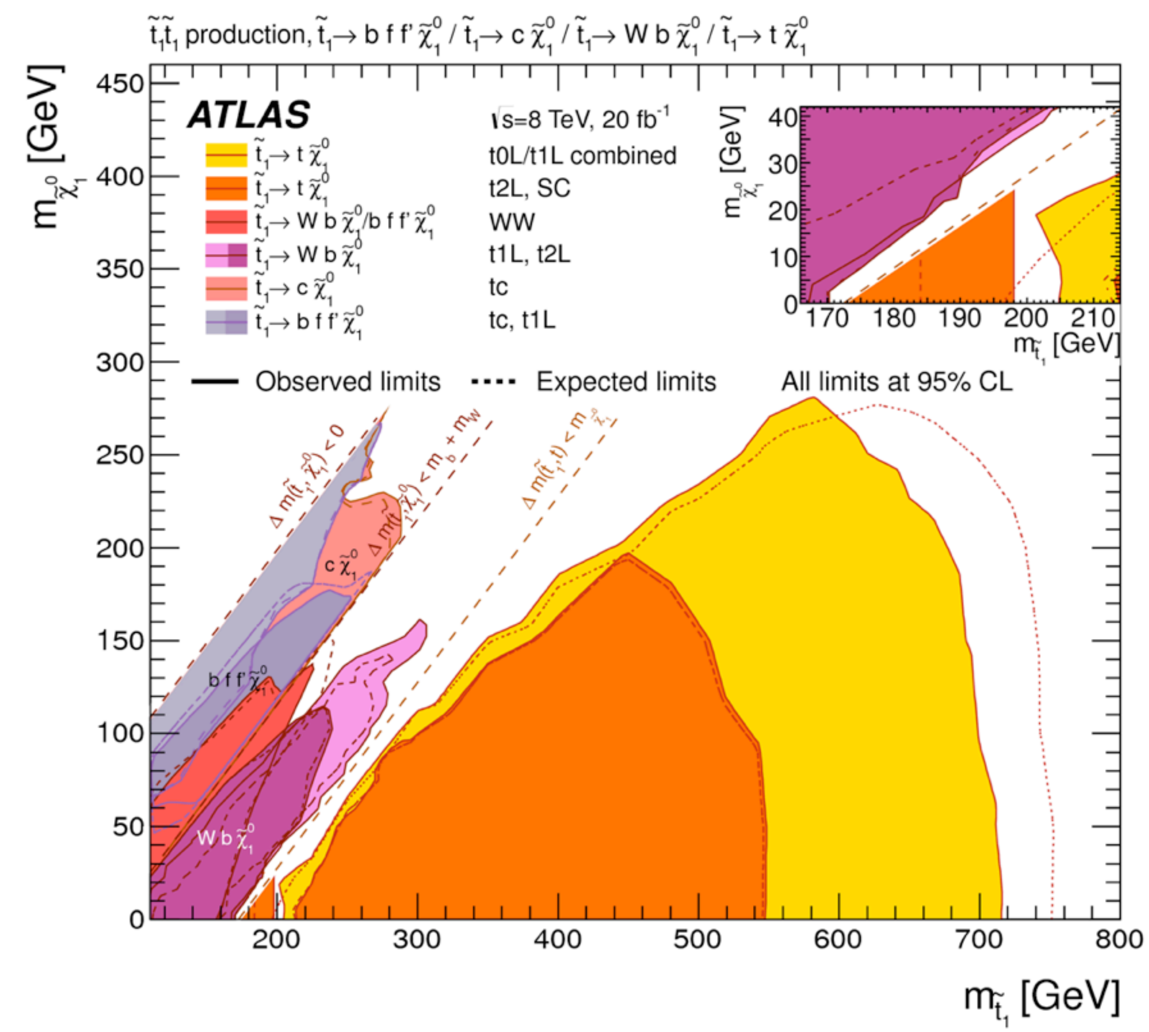
	Motivations	Challenges
IR	Naturalness Dark matter	Little hierarchy problem Missing superpartner problem Higgs mass
UV	Unification Uniqueness	Flavor and CP problems Proliferation of parameters Origin of soft terms mu problem



Squark-gluino-neutralino model
Squark mass [GeV]
Gluino mass [GeV]
$m(\tilde{\chi}_1^0)$=0 GeV Exp. limit ($\pm 1\ \sigma_{exp}$)
$m(\tilde{\chi}_1^0)$=0 GeV Obs. limit ($\pm 1\ \sigma_{theory}^{SUSY}$)
$m(\tilde{\chi}_1^0)$=395 GeV Exp. limit
$m(\tilde{\chi}_1^0)$=395 GeV Obs. limit
$m(\tilde{\chi}_1^0)$=695 GeV Exp. limit
$m(\tilde{\chi}_1^0)$=695 GeV Obs. limit
7TeV (4.7fb^{-1}) $m(\tilde{\chi}_1^0)$=0 GeV Obs.
ATLAS
$\int L\,dt$ = 20.3 fb^{-1}, $\sqrt{s}$=8 TeV
0-lepton, 2-6jets



CMS
19.3 fb⁻¹
√s = 8 TeV
pp → g̃g̃, g̃ → t̃t → tt̄χ̃⁰₁, m_χ̃⁰₁ = 50 GeV
NLO+NLL exclusion
obs. ± 1σ theor. (Δφ)
exp. ± 1σ exp. (Δφ)
m_g̃ = m_t̃ + m_t
m_t̃ [GeV]
m_g̃ [GeV]
95% CL upper limits on cross section [fb]



t̃₁t̃₁ production, t̃₁→ b f f' χ̃⁰₁ / t̃₁→ c χ̃⁰₁ / t̃₁→ W b χ̃⁰₁ / t̃₁→ t χ̃⁰₁
ATLAS
√s=8 TeV, 20 fb⁻¹
t̃₁→ t χ̃⁰₁ t0L/t1L combined
t̃₁→ t χ̃⁰₁ t2L, SC
t̃₁→ W b χ̃⁰₁/b f f' χ̃⁰₁ WW
t̃₁→ W b χ̃⁰₁ t1L, t2L
t̃₁→ c χ̃⁰₁ tc
t̃₁→ b f f' χ̃⁰₁ tc, t1L
Observed limits
Expected limits
All limits at 95% CL
m_χ̃⁰₁ [GeV]
m_t̃₁ [GeV]