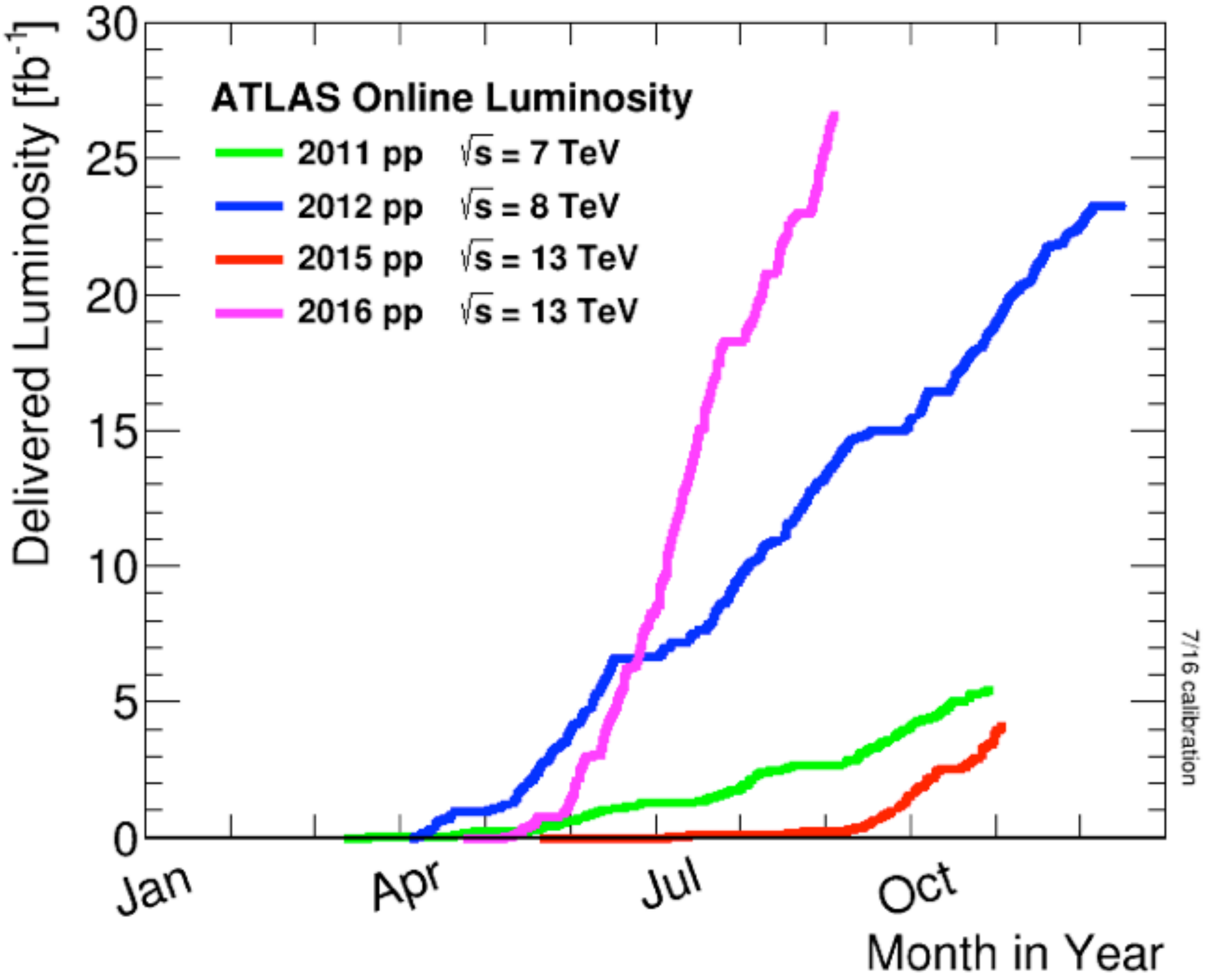
Natural SUSY
vs.
The LHC

David Shih
NHETC, Rutgers University

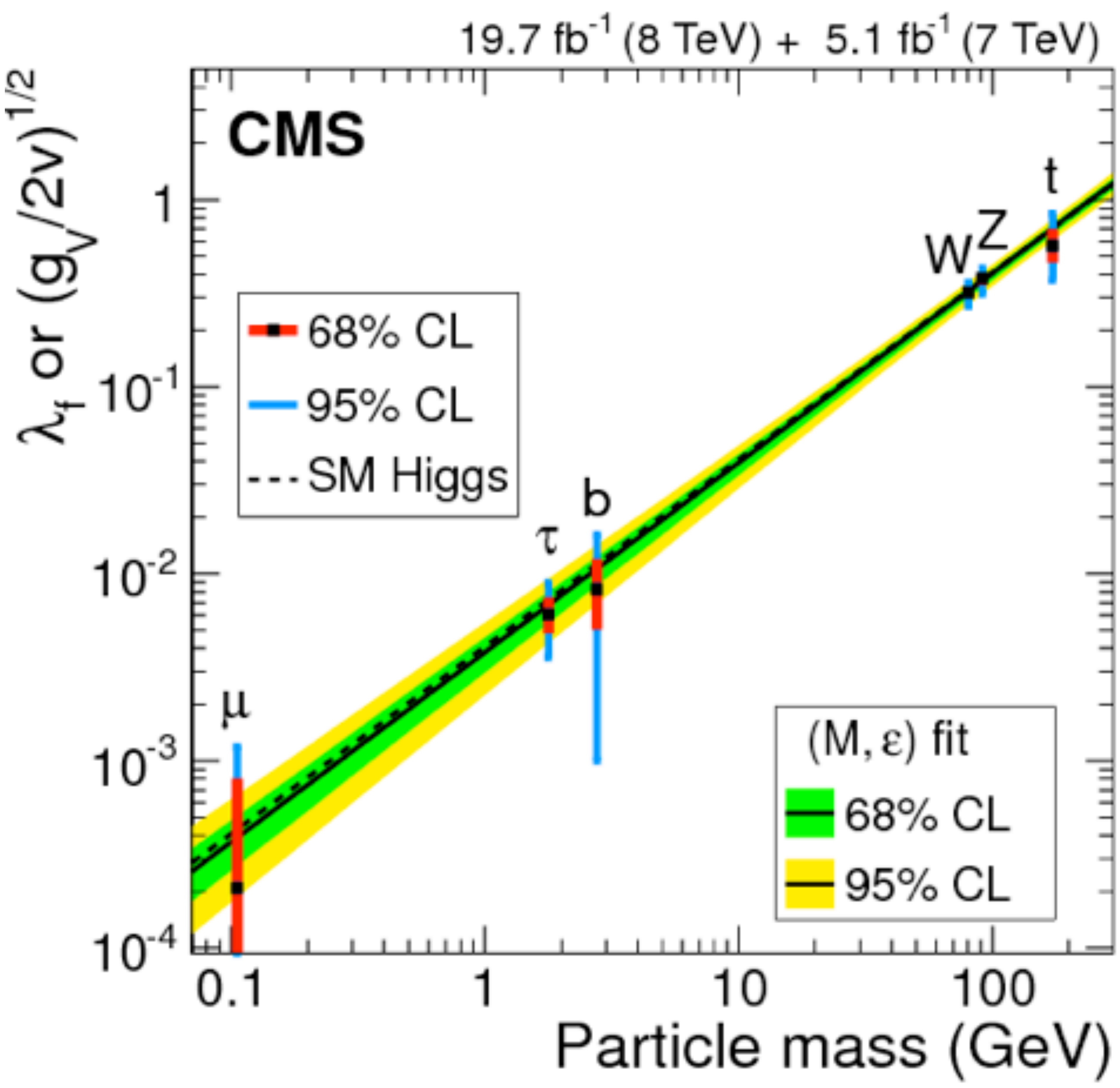
"Is SUSY Alive and Well" IFT Madrid
September 28-30, 2016

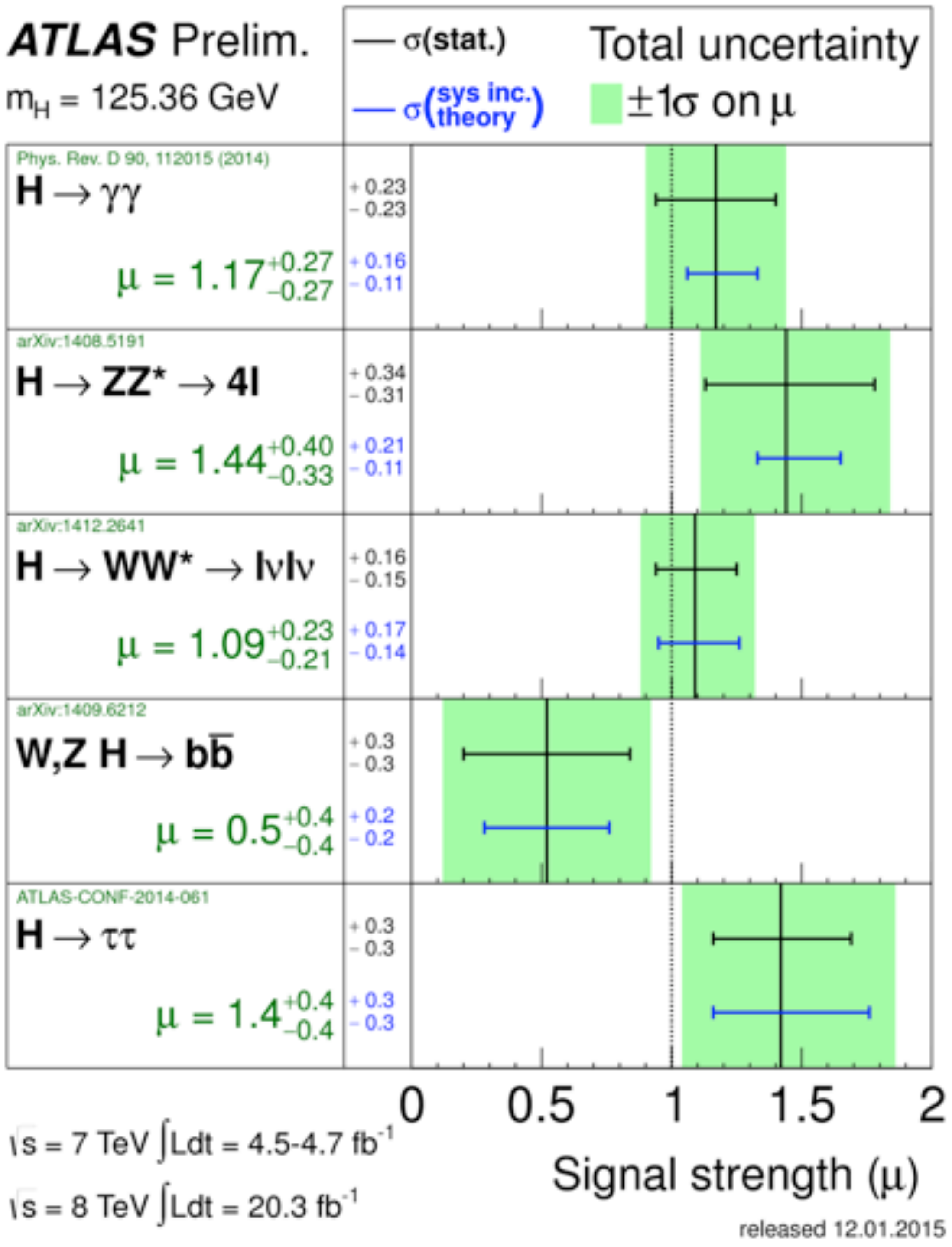
Work in progress with Matt Buckley, David Feld,
Sebastian Macaluso & Angelo Monteux

Since 2010, the LHC has been performing spectacularly.

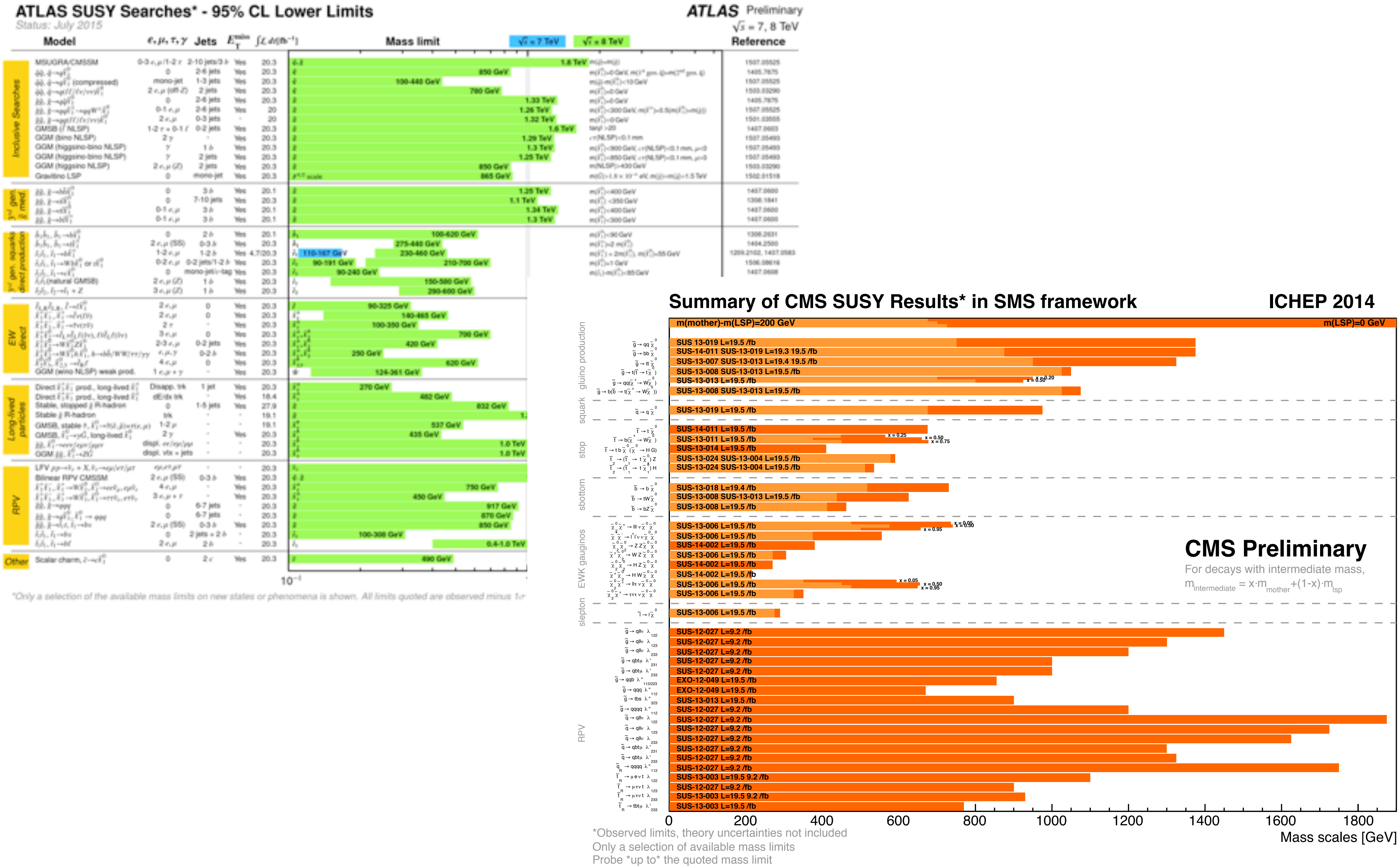


At Run I, we discovered a SM-like Higgs at 125 GeV...





… but we did not see any definitive sign of new physics.



Just recently, we reached an important milestone:
~10/fb at 13 TeV

38TH INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

ICHEP

2016CHICAGO

AUGUST 3-10, 2016

AT SHERATON GRAND CHICAGO

ICHEP2016.ORG

ABSTRACT SUBMISSION THROUGH FEB. 7, 2016

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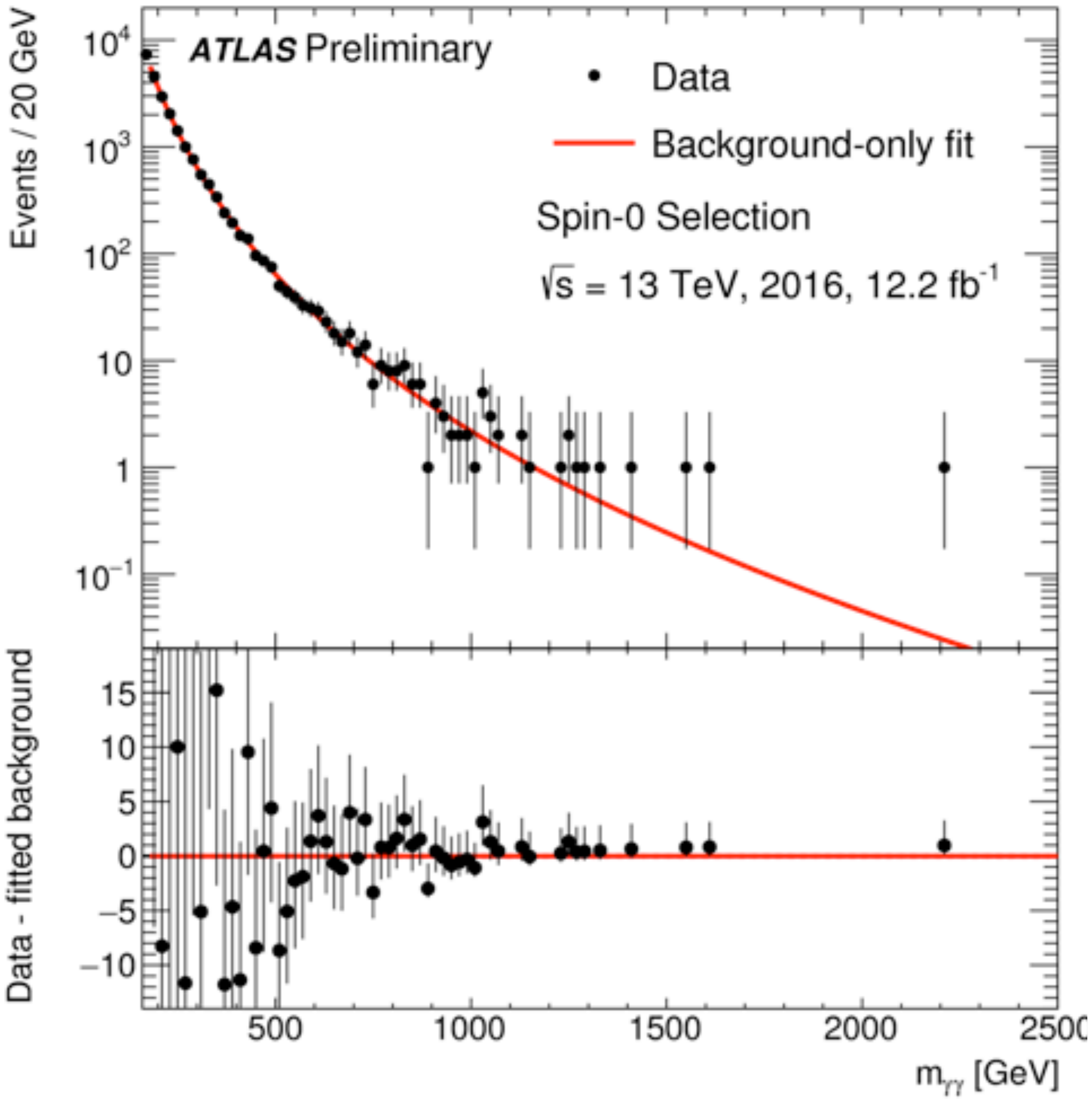
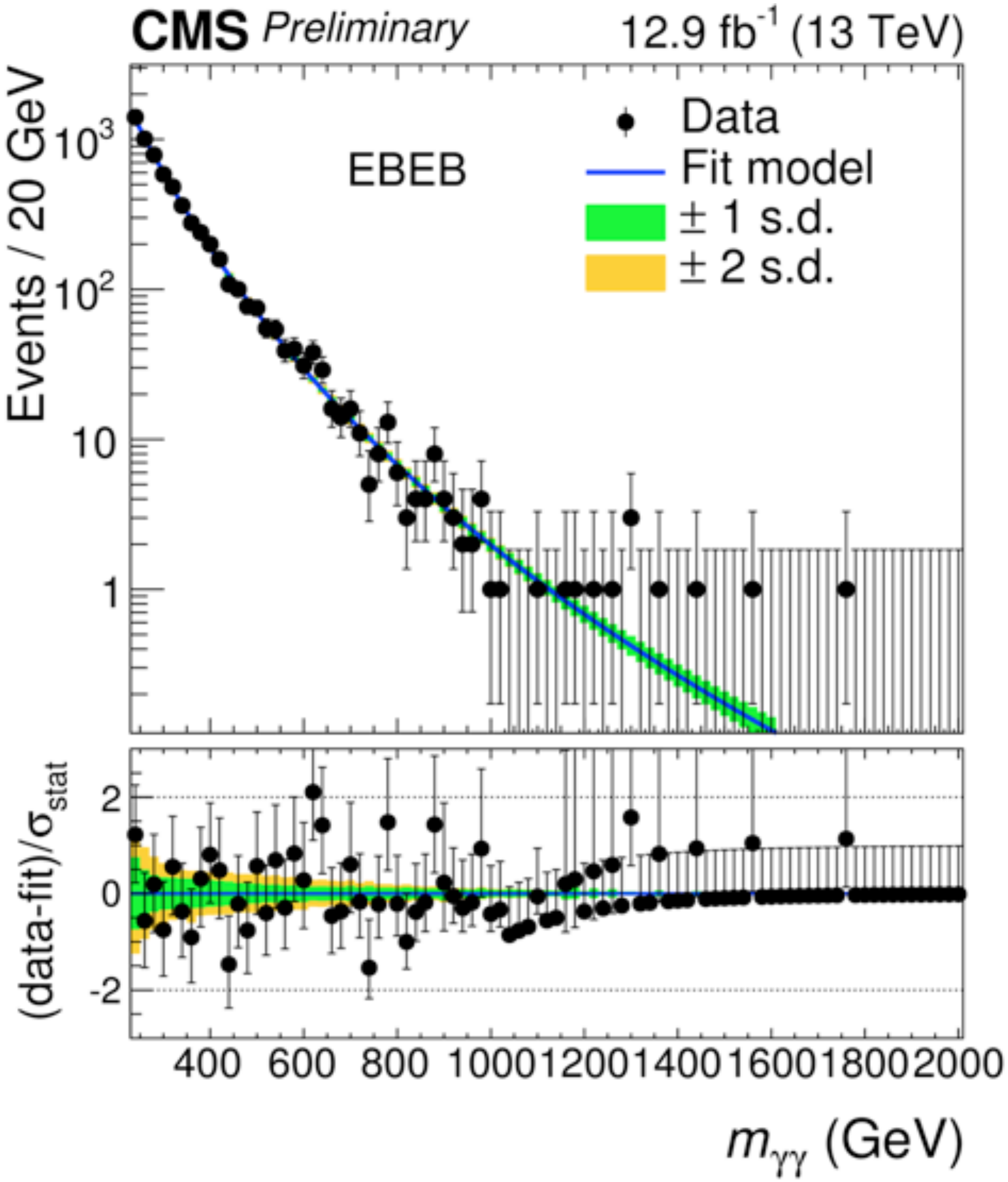
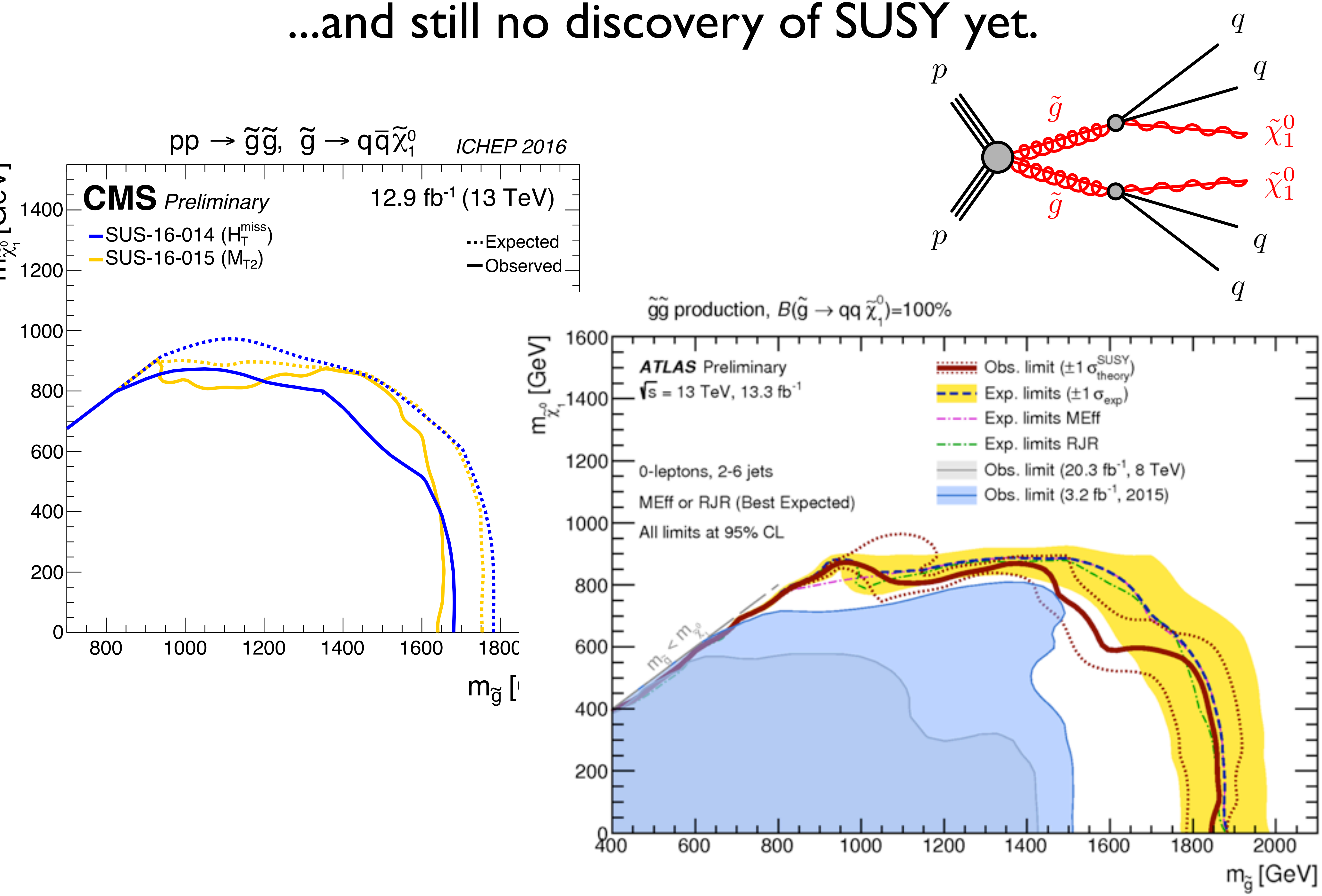
The 750 diphoton resonance is disappearing...





...and still no discovery of SUSY yet.



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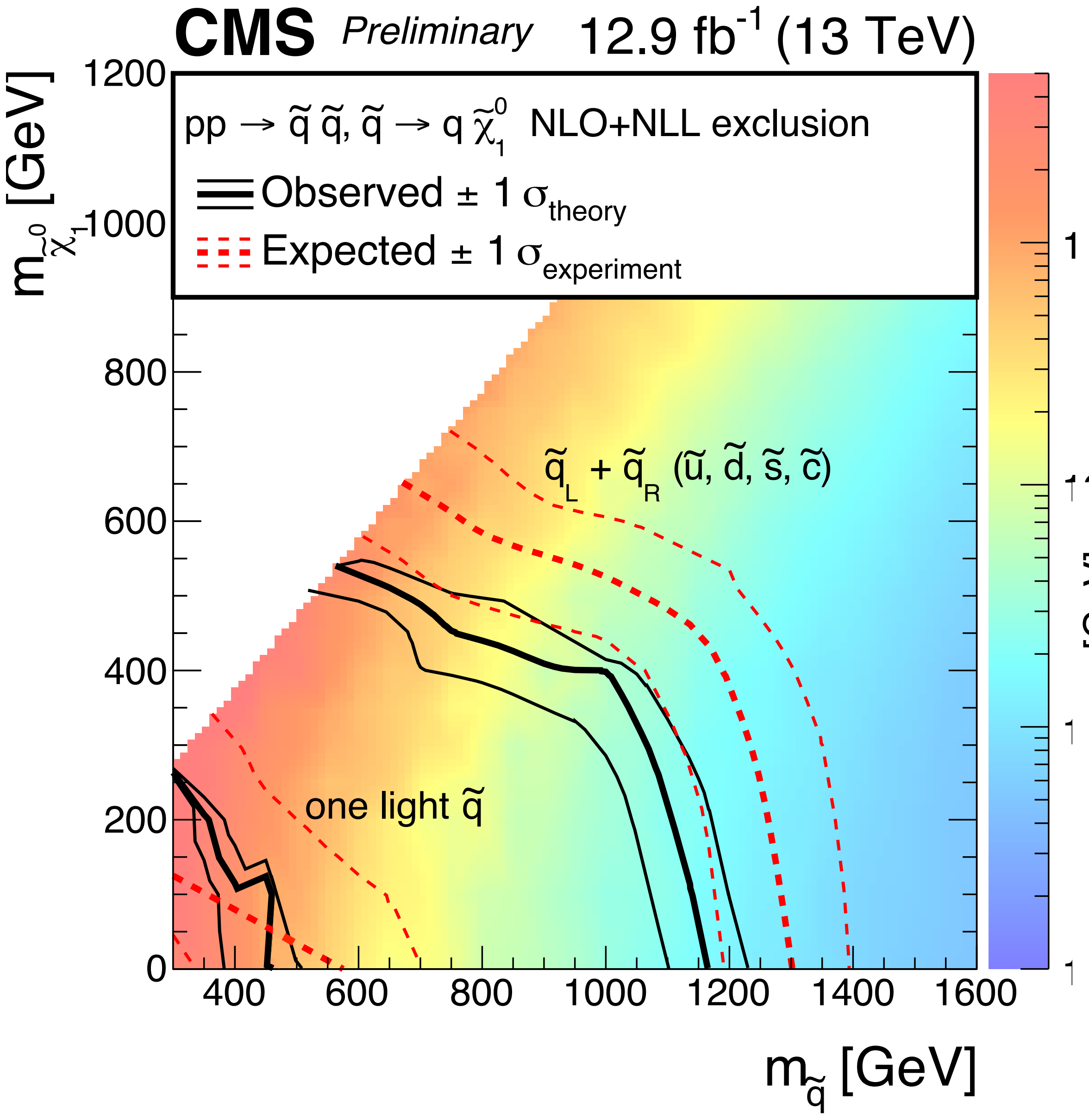
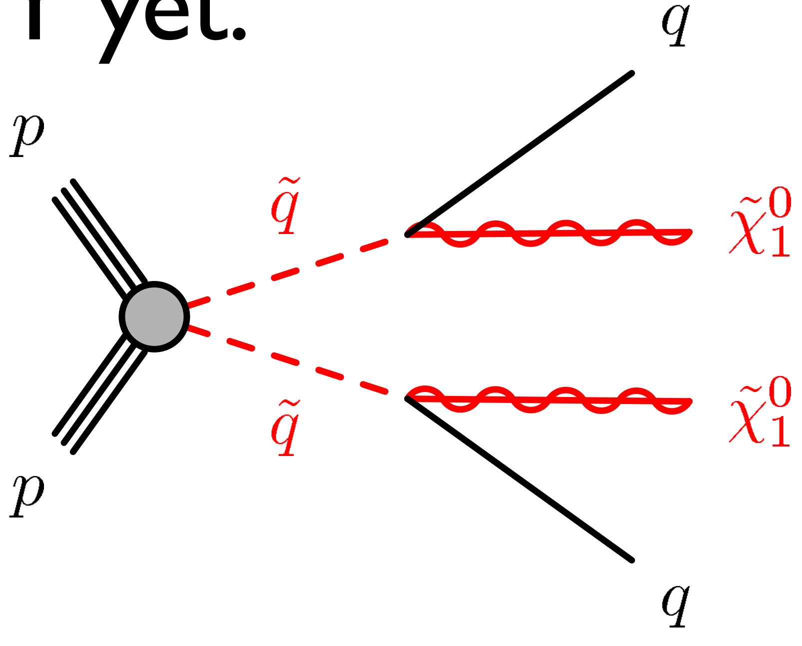
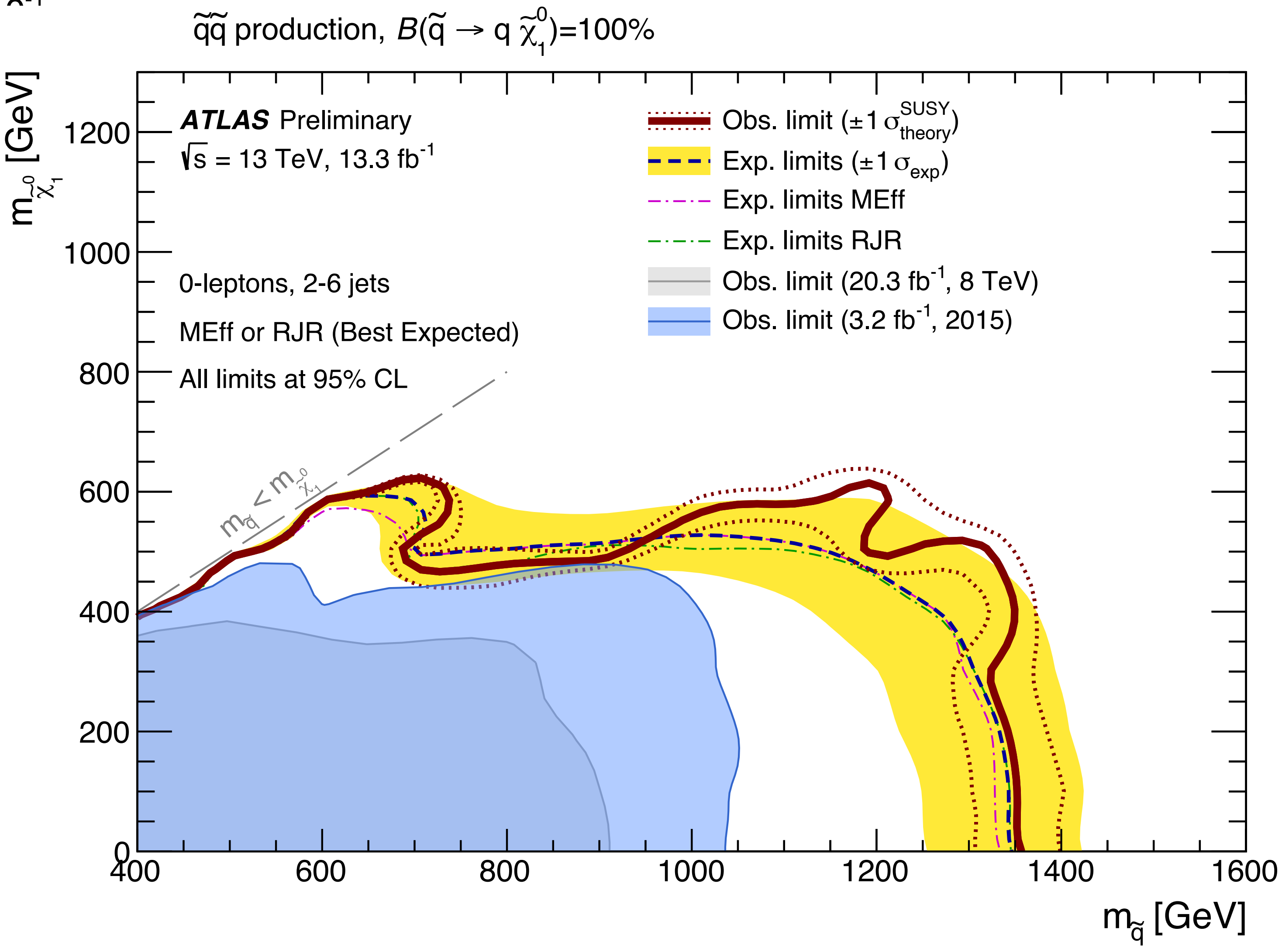
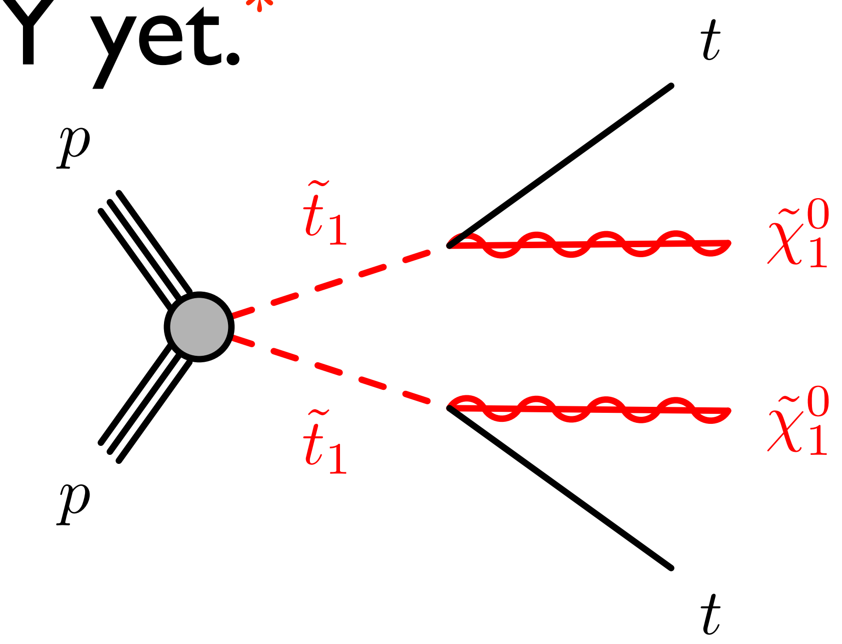


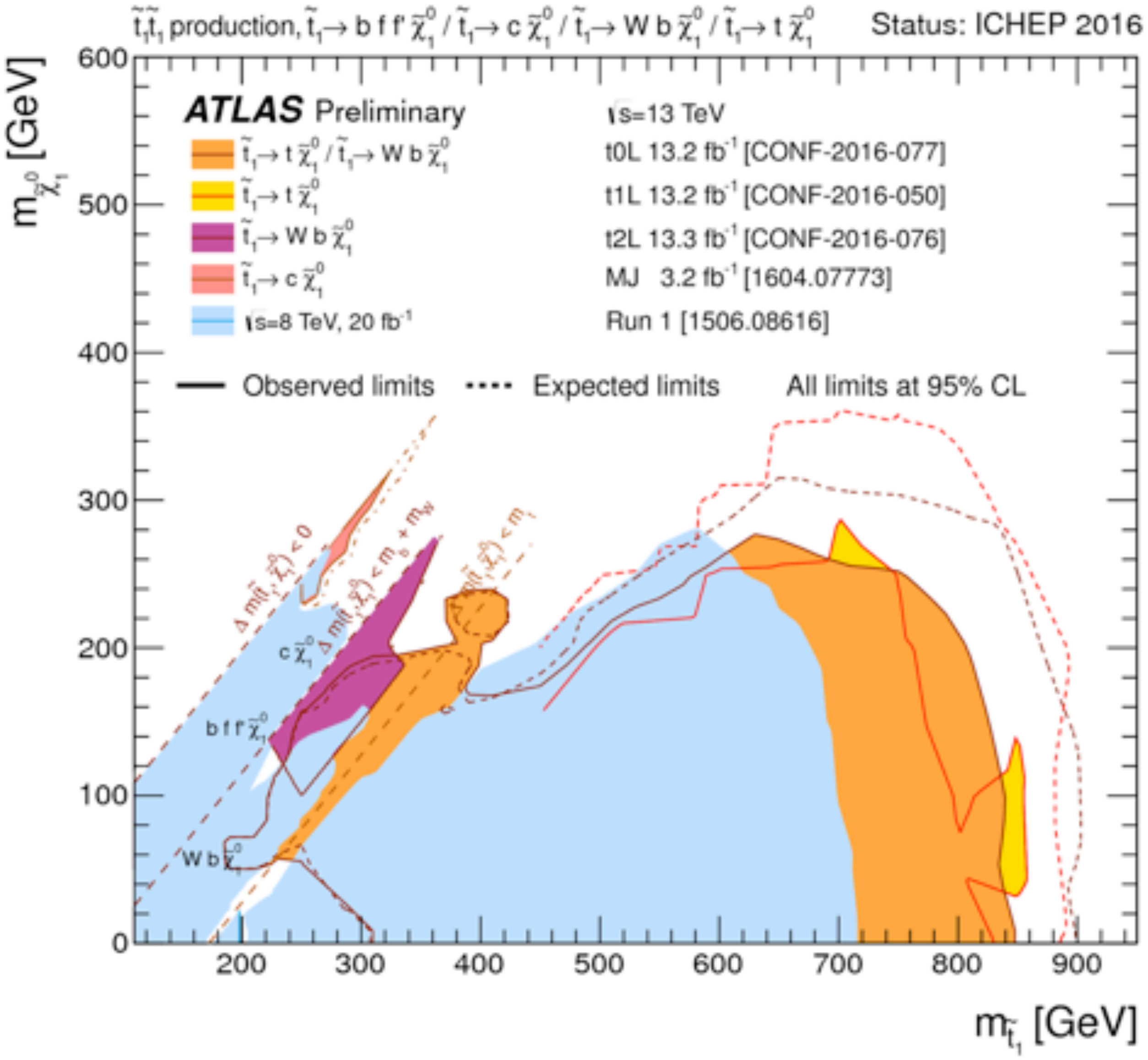


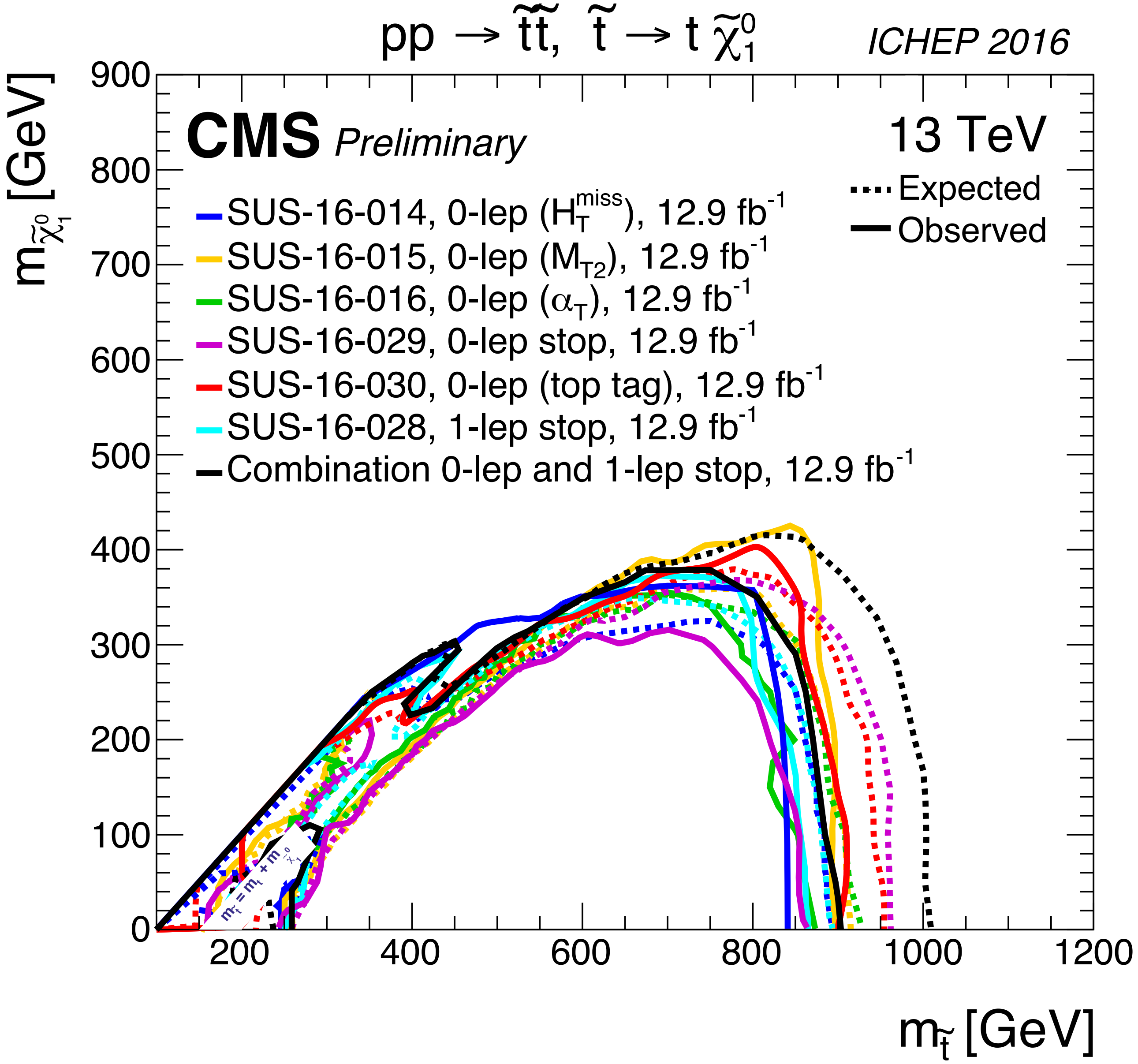


(Key assumption:
decoupled gluinos!)

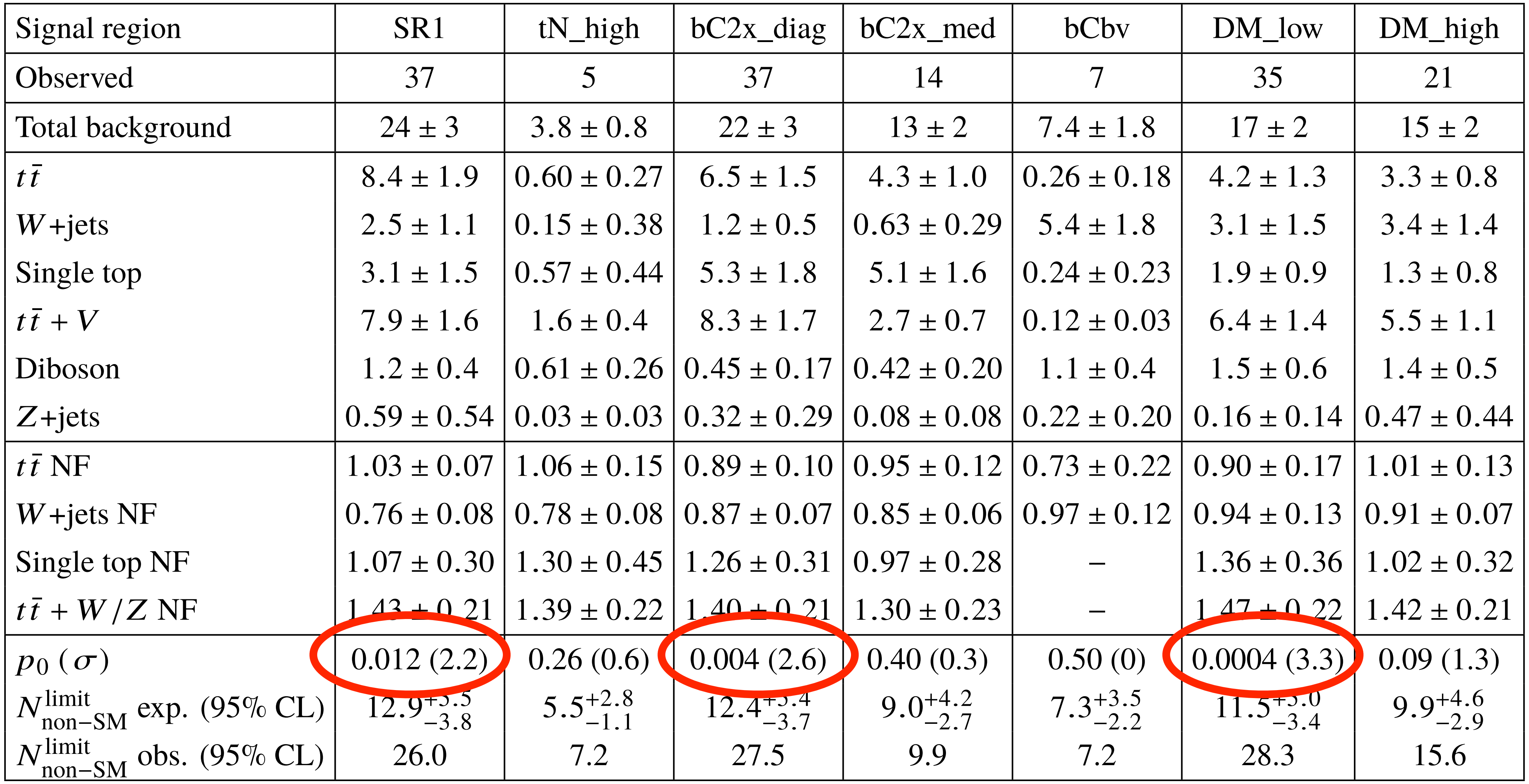
...and still no discovery of SUSY yet.*







- Although some interesting deviations in stop searches?



Signal region	SR1	tN_high	bC2x_diag	bC2x_med	bCbv	DM_low	DM_high
Observed	37	5	37	14	7	35	21
Total background	24 ± 3	3.8 ± 0.8	22 ± 3	13 ± 2	7.4 ± 1.8	17 ± 2	15 ± 2
$t\bar{t}$	8.4 ± 1.9	0.60 ± 0.27	6.5 ± 1.5	4.3 ± 1.0	0.26 ± 0.18	4.2 ± 1.3	3.3 ± 0.8
W+jets	2.5 ± 1.1	0.15 ± 0.38	1.2 ± 0.5	0.63 ± 0.29	5.4 ± 1.8	3.1 ± 1.5	3.4 ± 1.4
Single top	3.1 ± 1.5	0.57 ± 0.44	5.3 ± 1.8	5.1 ± 1.6	0.24 ± 0.23	1.9 ± 0.9	1.3 ± 0.8
$t\bar{t}+V$	7.9 ± 1.6	1.6 ± 0.4	8.3 ± 1.7	2.7 ± 0.7	0.12 ± 0.03	6.4 ± 1.4	5.5 ± 1.1
Diboson	1.2 ± 0.4	0.61 ± 0.26	0.45 ± 0.17	0.42 ± 0.20	1.1 ± 0.4	1.5 ± 0.6	1.4 ± 0.5
Z+jets	0.59 ± 0.54	0.03 ± 0.03	0.32 ± 0.29	0.08 ± 0.08	0.22 ± 0.20	0.16 ± 0.14	0.47 ± 0.44
$t\bar{t}$ NF	1.03 ± 0.07	1.06 ± 0.15	0.89 ± 0.10	0.95 ± 0.12	0.73 ± 0.22	0.90 ± 0.17	1.01 ± 0.13
W+jets NF	0.76 ± 0.08	0.78 ± 0.08	0.87 ± 0.07	0.85 ± 0.06	0.97 ± 0.12	0.94 ± 0.13	0.91 ± 0.07
Single top NF	1.07 ± 0.30	1.30 ± 0.45	1.26 ± 0.31	0.97 ± 0.28	–	1.36 ± 0.36	1.02 ± 0.32
$t\bar{t}+W/Z$ NF	1.43 ± 0.21	1.39 ± 0.22	1.40 ± 0.21	1.30 ± 0.23	–	1.47 ± 0.22	1.42 ± 0.21
p_0 (σ)	0.012 (2.2)	0.26 (0.6)	0.004 (2.6)	0.40 (0.3)	0.50 (0)	0.0004 (3.3)	0.09 (1.3)
$N^{\mathrm{limit}}_{\mathrm{non-SM}}$ exp. (95% CL)	$12.9^{+3.5}_{-3.8}$	$5.5^{+2.8}_{-1.1}$	$12.4^{+3.4}_{-3.7}$	$9.0^{+4.2}_{-2.7}$	$7.3^{+3.5}_{-2.2}$	$11.5^{+5.0}_{-3.4}$	$9.9^{+4.6}_{-2.9}$
$N^{\mathrm{limit}}_{\mathrm{non-SM}}$ obs. (95% CL)	26.0	7.2	27.5	9.9	7.2	28.3	15.6

ATLAS-CONF-2016-050

IS SUSY ALIVE AND WELL?

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Instituto de Física Teórica UAM-CSIC
Madrid, 28-30 September 2016
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G. Bélanger (LAPTH-Annecy)
O. Buchmüller (Imperial Coll.)
M. Carena (Fermilab)
M. Cicoli (ICTP & Bologna U.)
A. Djouadi (LPT-Orsay)
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DISCUSSION CONVENER: X. Tata (Hawaii U.)

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Burning questions

- Can SUSY still be natural?
- How much discovery potential for SUSY remains at the LHC?
- ……
- Should we be concerned??

IS SUSY ALIVE AND WELL?

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Naturalness motivates the TeV scale

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

$$v^2 = -\frac{m_H^2}{\lambda} = (246 \text{ GeV})^2, \qquad m_h^2 = -2m_H^2 = 2\lambda v^2 = (125 \text{ GeV})^2$$

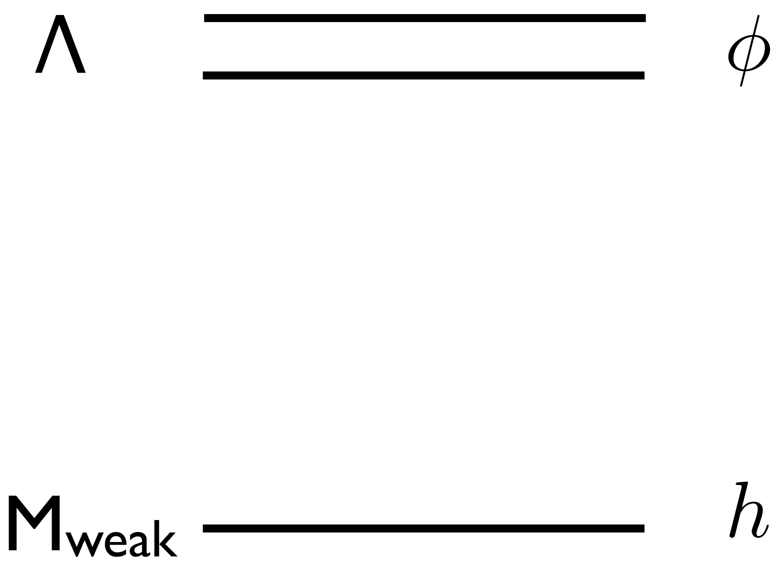
m_H^2 is the only dimensionful parameter in the SM!

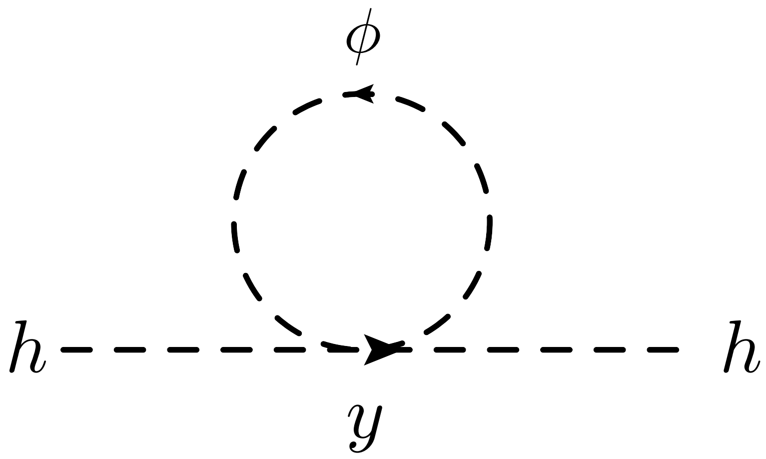
Finally, we have measured it.

What sets its scale??

Naturalness motivates the TeV scale

$$m_H^2 = (m_H^2)_0 + \delta m_H^2$$





$$\delta m_H^2 \sim \frac{y^2}{16\pi^2}\Lambda^2$$

m_H^2 is quadratically sensitive to new physics at higher scales.

Naturalness motivates the TeV scale

A measure of fine tuning:
(Barbieri & Giudice; Kitano & Nomura)

$$\boxed{\Delta \equiv \frac{2|\delta m_H^2|}{m_h^2}}$$

(Measure is arbitrary,
but still useful!)

$$m_H^2 = (m_H^2)_0 + \delta m_H^2 \qquad\qquad \delta m_H^2 \sim \frac{y^2}{16\pi^2}\Lambda^2$$

Naturalness: no enormous cancellations between different corrections.

- Want Δ ≲ 10 => expect Λ ~ TeV. New particles at the TeV scale!
- And some new mechanism to shield the theory from even higher scales

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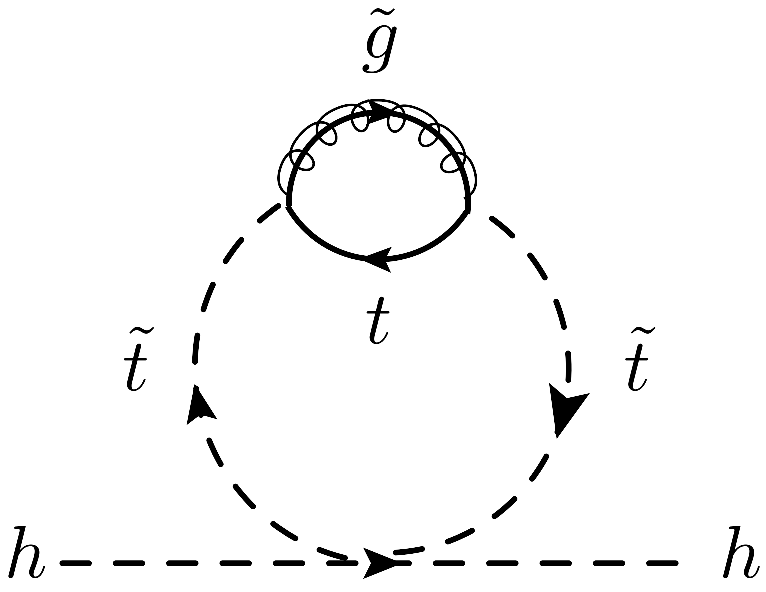
Naturalness: no enormous cancellations between different corrections.

- Want $\Delta \lesssim 10$ => expect $\Lambda \sim$ TeV. New particles at the TeV scale!
- And some new mechanism to shield the theory from even higher scales

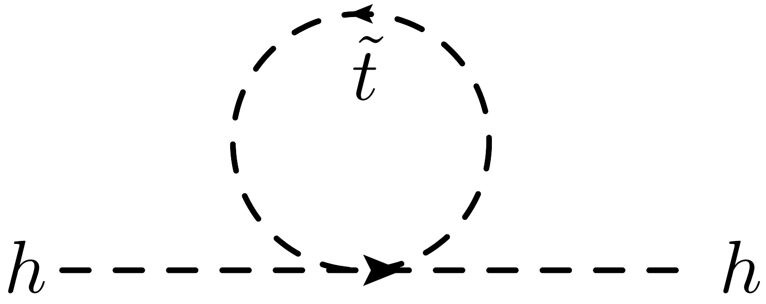
=> SUSY at the weak scale

In conventional realizations of SUSY, a special role is played by the Higgsinos, stops, and gluinos, as these couple strongest to the Higgs.

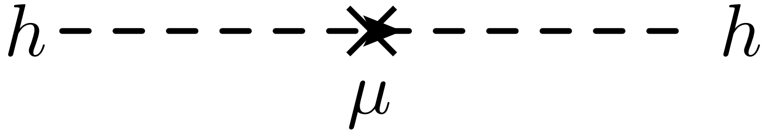
(Dimopoulos & Giudice ’95; Cohen, Kaplan & Nelson ’96 ......)



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

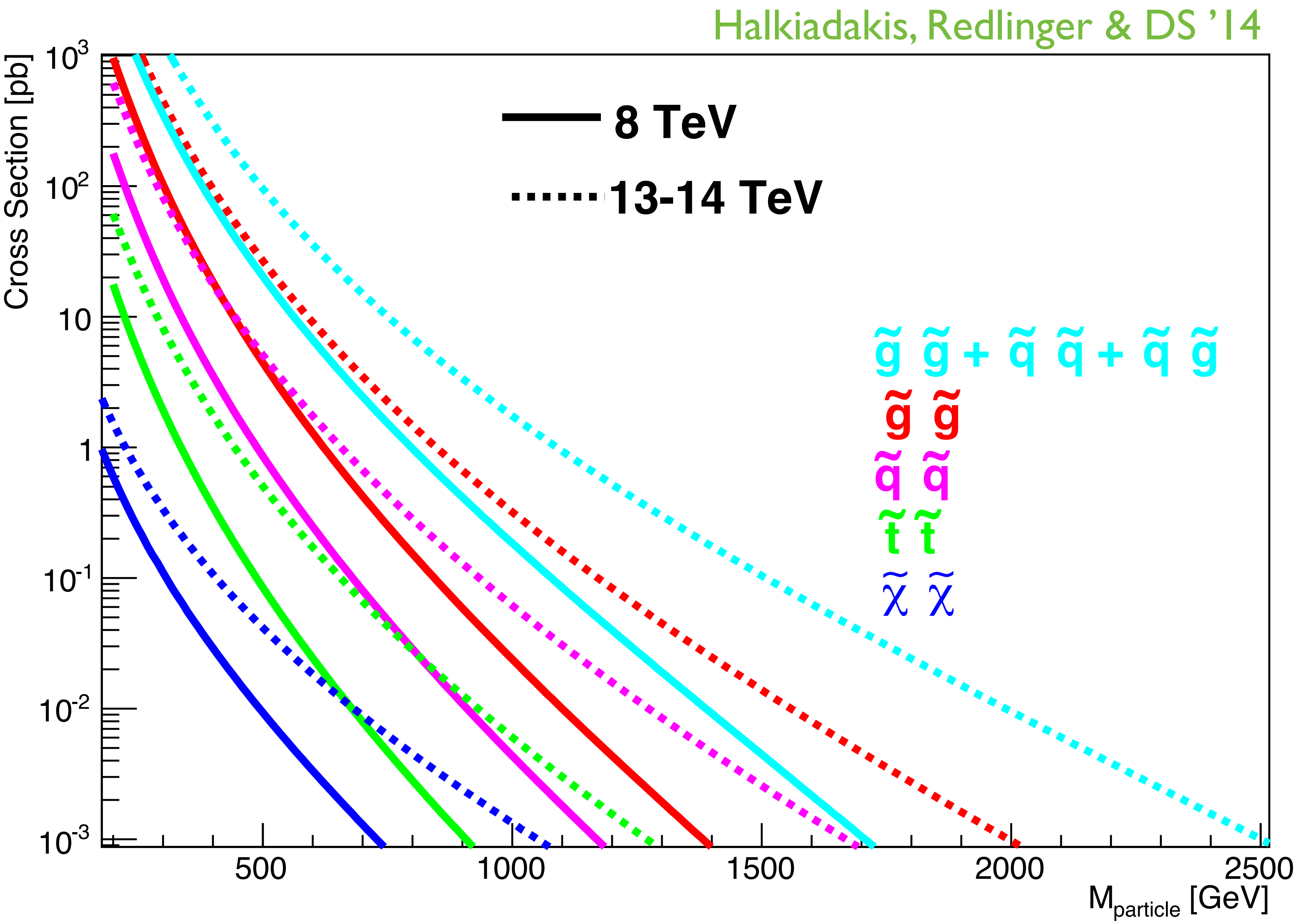


$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m_{stop}^2 \log \frac{\Lambda}{m_{stop}}$$



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

Λ = “messenger scale,” a UV scale where the soft masses are generated



Halkiadakis, Redlinger & DS ’14

Largest cross sections at LHC come from gluino and valence squark pairs.

Stop cross sections are several orders of magnitude smaller, and Higgsino cross sections are yet smaller.

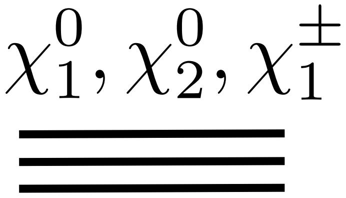
Naturalness sets a direct and simple bound on the Higgsino mass.

$$\mu \leq (300\ \mathrm{GeV}) \times \left(\frac{\Delta}{10}\right)^{1/2}$$

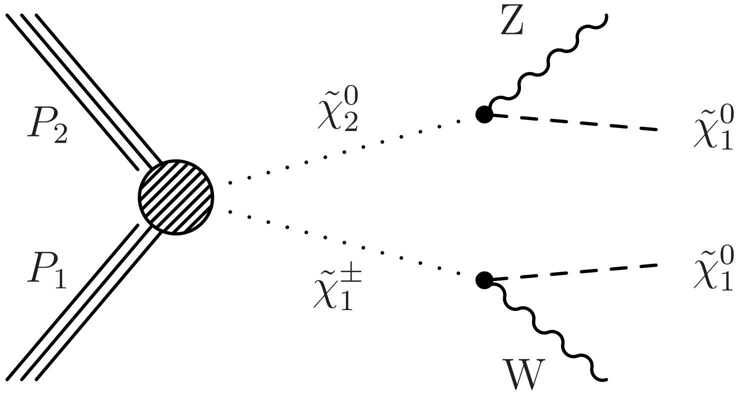
Expect light Higgsinos!

Unfortunately, very difficult to detect at LHC due to low cross section and high background.

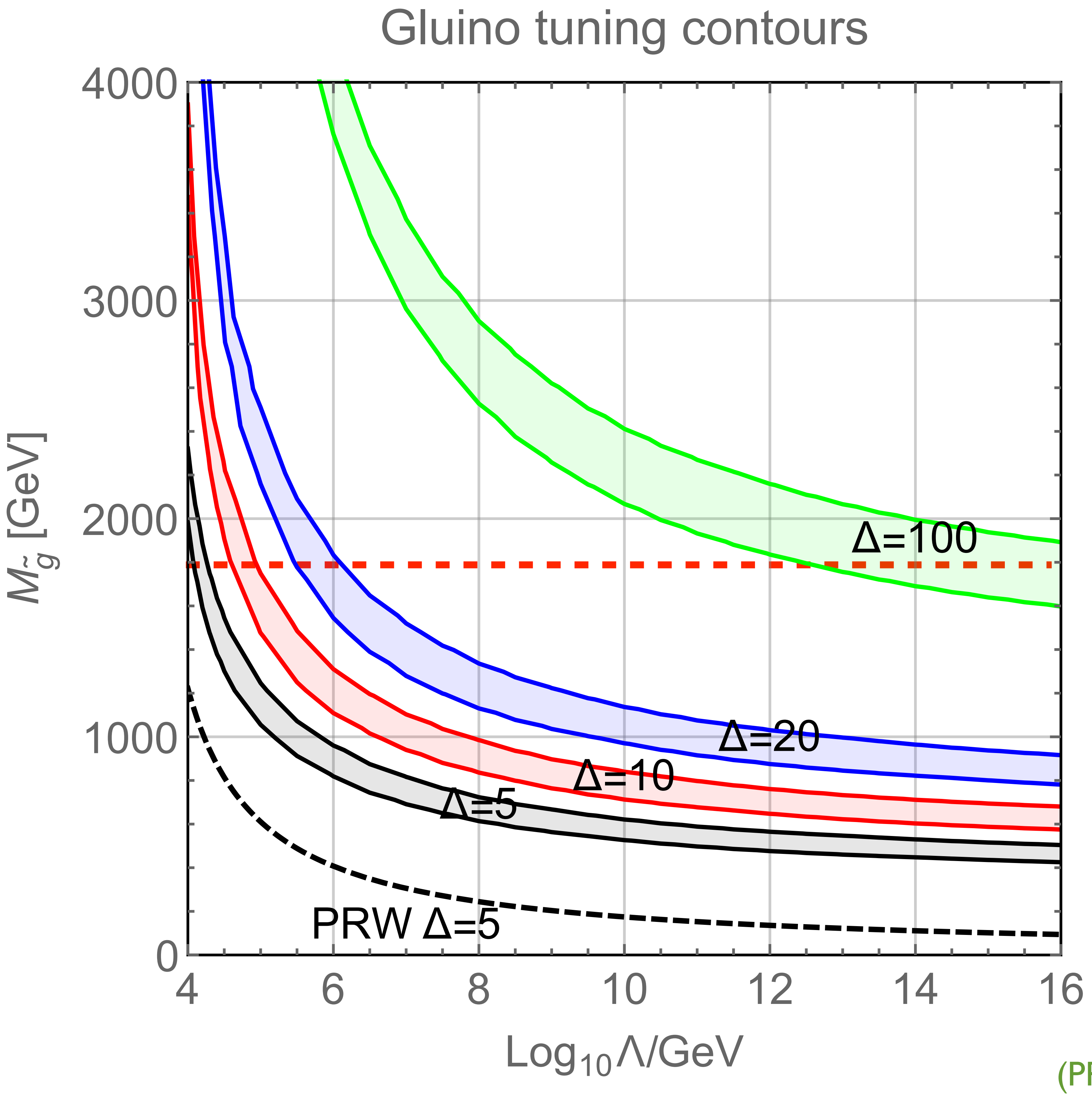
Currently, limits do not surpass LEP.



$\chi_1^0, \chi_2^0, \chi_1^\pm$



Naturalness bounds the gluino mass as a function of the messenger scale Λ.



Technical aside: accounting for several higher-order effects greatly relaxes the gluino bounds!

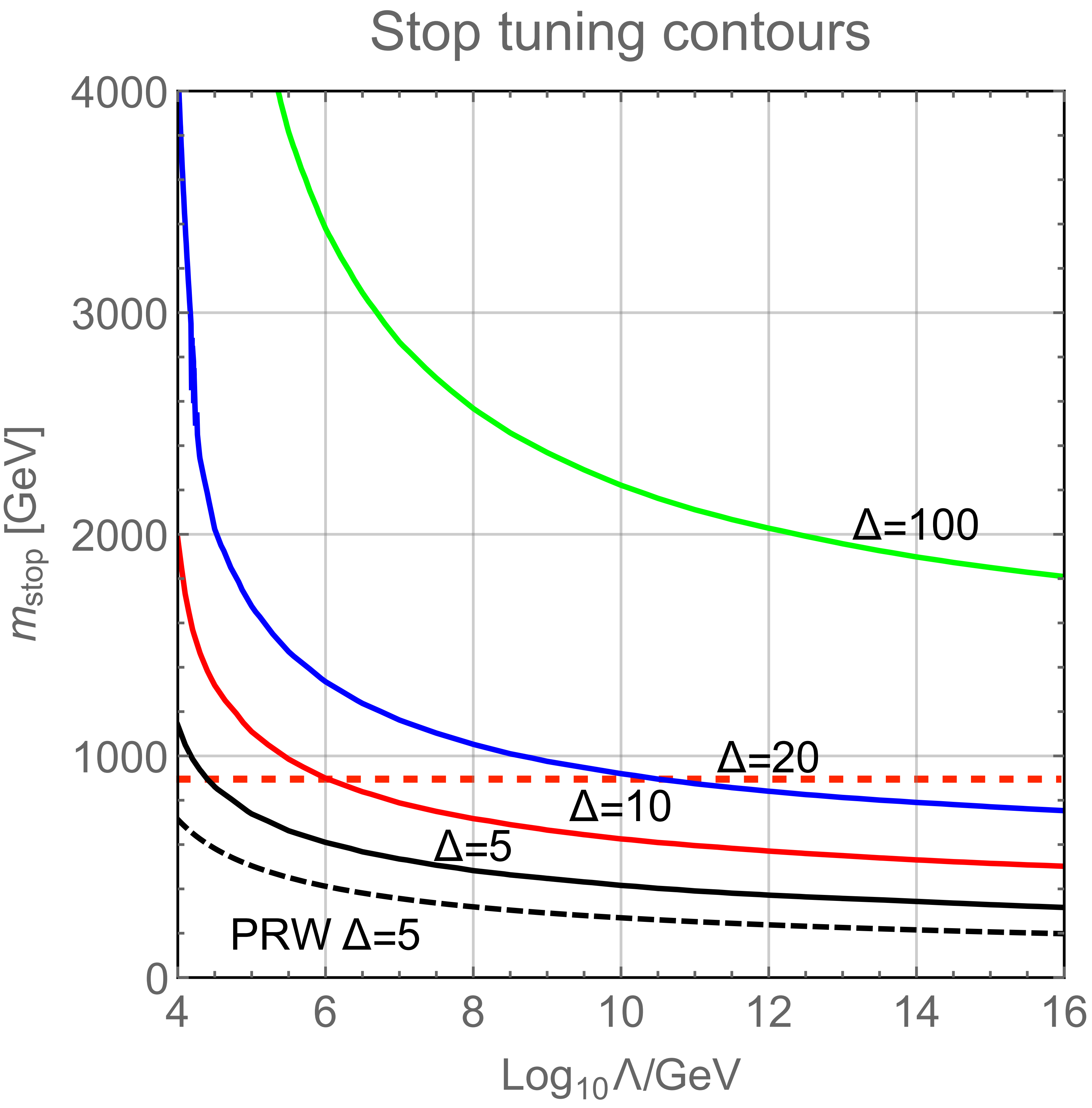
Casas, Moreno, Robles, Robiecki & Zaldivar 1407.6966

Buckley, Feld, Macaluso, Monteux, DS 1610.NNNNN

- Factor of 2 error
- UV vs. IR mass
- IR mass vs. pole mass
- 2-loop RGEs
- LL vs. resummed RGEs
- finite threshold corrections

(PRW = Papucci, Ruderman & Weiler 1110.6926)

Naturalness bounds the stop mass as a function of the messenger scale Λ.

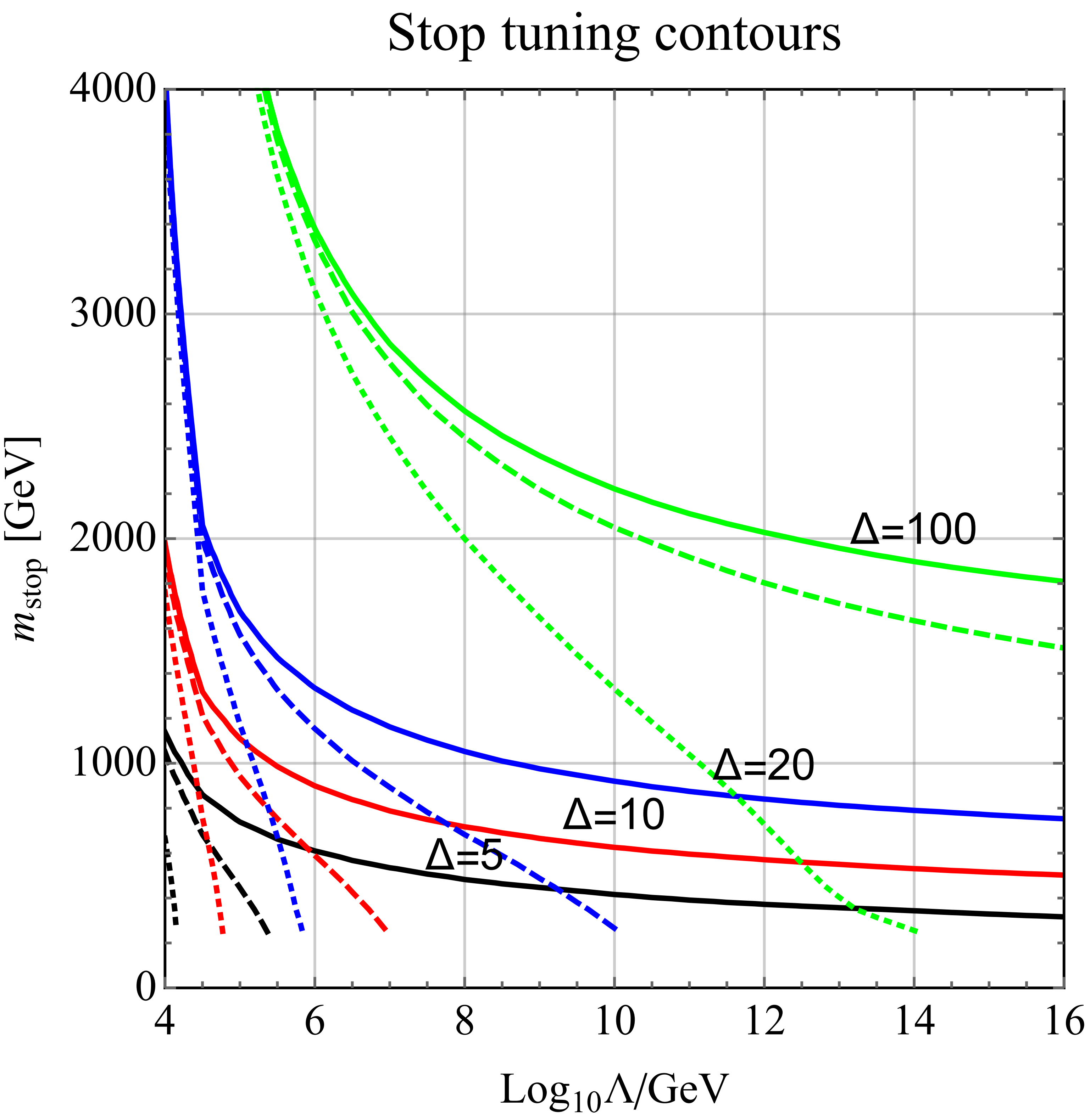


Higher-order effects (primarily UV vs IR mass) also significantly relax the stop bounds!

Casas, Moreno, Robles, Robiecki & Zaldivar 1407.6966

Buckley, Feld, Macaluso, Monteux, DS 1610.NNNNN

Naturalness bounds the stop mass as a function of the messenger scale Λ.



Decoupling 1st/2nd generation squarks can *decrease* stop masses through 2-loop RGEs.

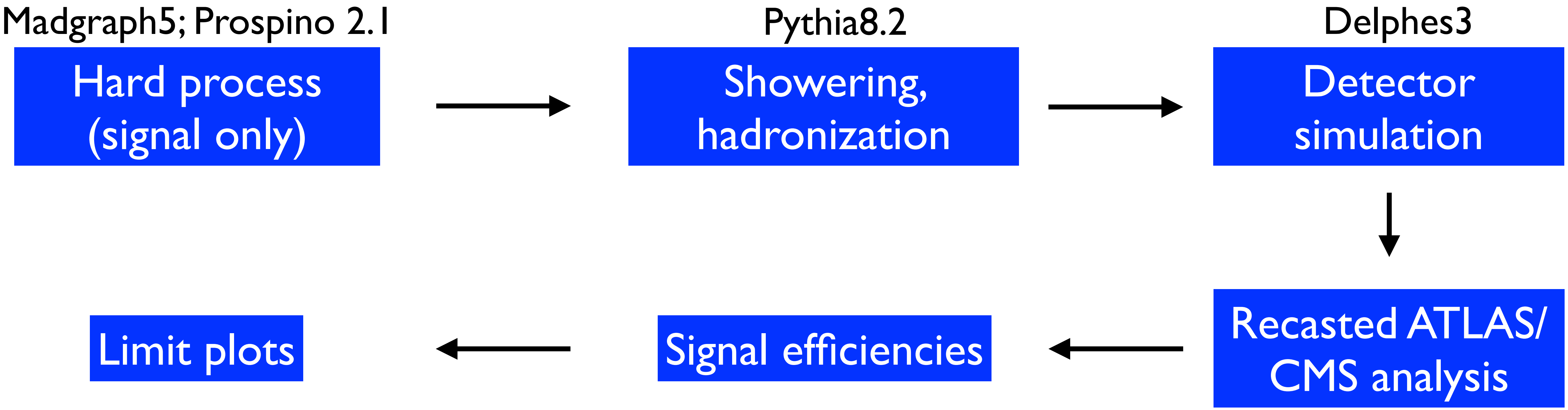
This problem might be fixable in extensions of the MSSM. (e.g. Hisano, Kurosawa & Nomura, 0002286)

Recasting overview

What are the implications of the latest ICHEP results for natural SUSY?

There are many natural SUSY scenarios, whereas the official ATLAS and CMS analyses set limits on just a handful of specific simplified models.

Applying the official limits to natural SUSY scenarios is usually not straightforward. Generally requires a detailed reinterpretation ("recasting") of the official results.



Madgraph5; Prospino 2.1

Hard process (signal only)

Pythia8.2

Showering, hadronization

Delphes3

Detector simulation

Recasted ATLAS/ CMS analysis

Signal efficiencies

Limit plots

List of recasted searches

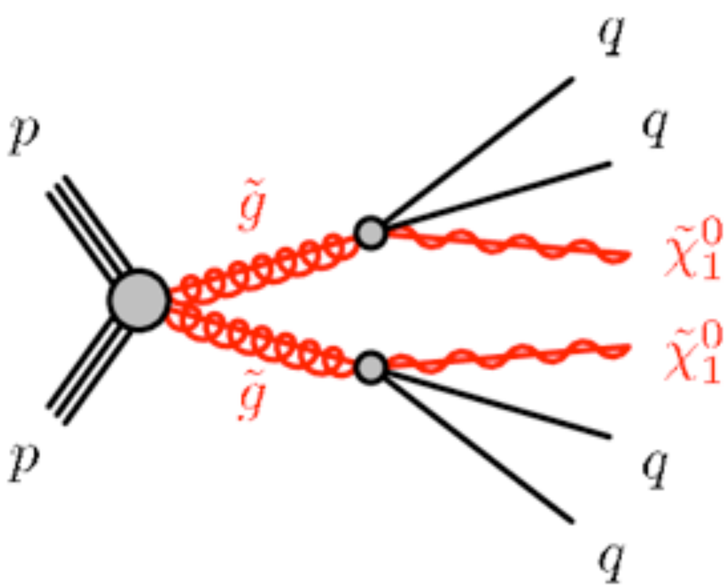
ATLAS 2-6 jets + MET	13.3/fb	CONF-2016-078
ATLAS b-jets + MET	14.8/fb	CONF-2016-052
CMS jets+MET (HT)	12.9/fb	SUS-16-014
ATLAS 7-10 jets+MET	3.2/fb	1602.06194
ATLAS 8-10 jets+MET	18.2/fb	CONF-2016-095
ATLAS 1L + jets +MET	14.8/fb	CONF-2016-054
ATLAS SS dileptons	13.2/fb	CONF-2016-037
ATLAS multijets (RPV gluinos)	14.8/fb	CONF-2016-057
CMS BH (many jets)	2.2/fb	EXO-15-007
ATLAS 1L + many jets	14.8/fb	CONF-2016-094

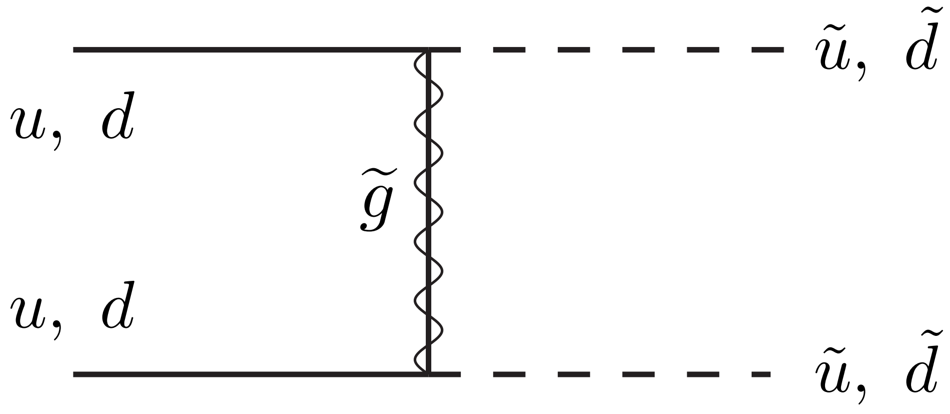
Natural SUSY scenario #1

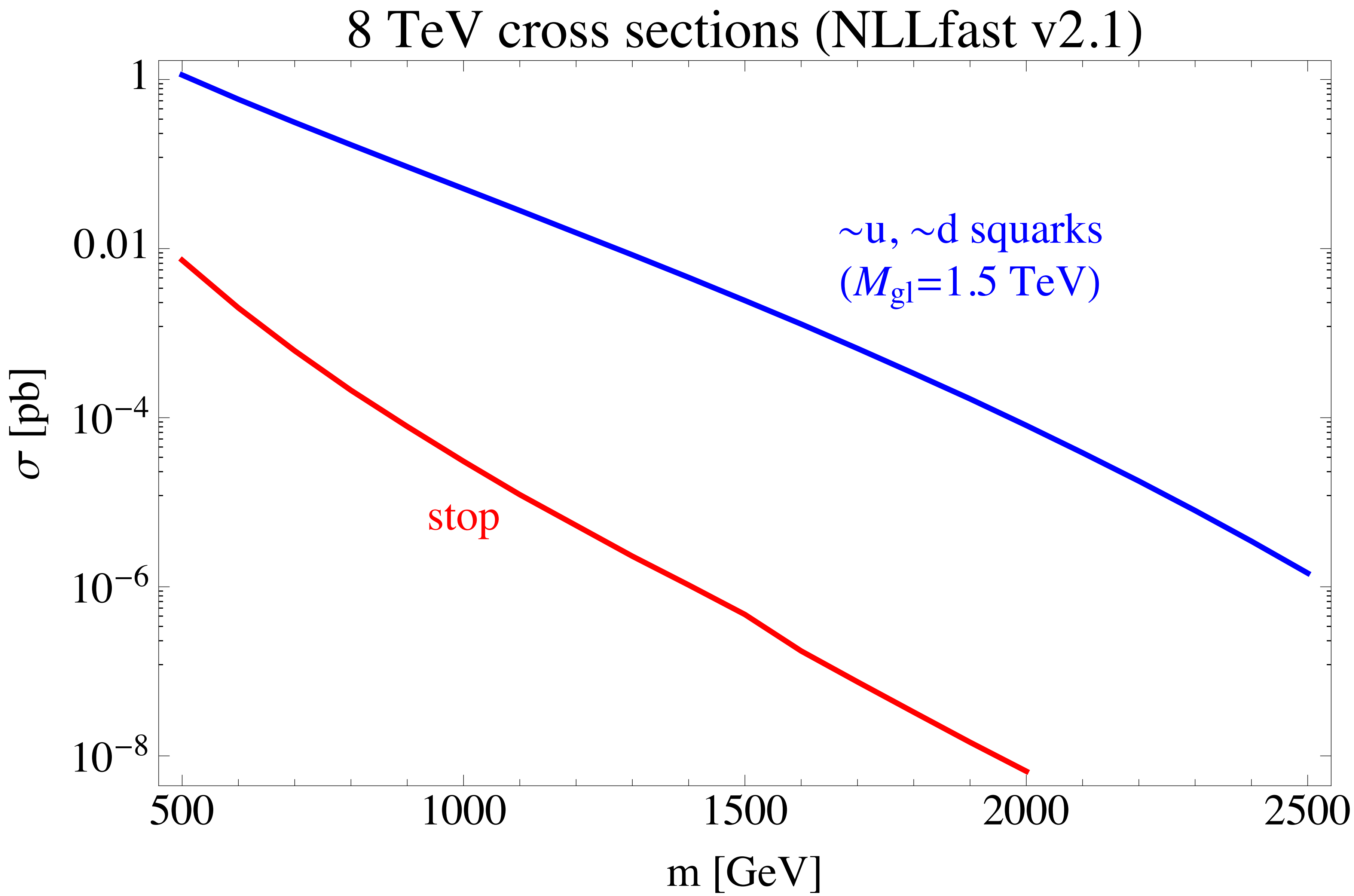
“Vanilla SUSY”: MSSM + R-parity + flavor-degenerate sfermions

Simplest, most minimal, consistent with unification, precision flavor and CP.
Essential baseline model!

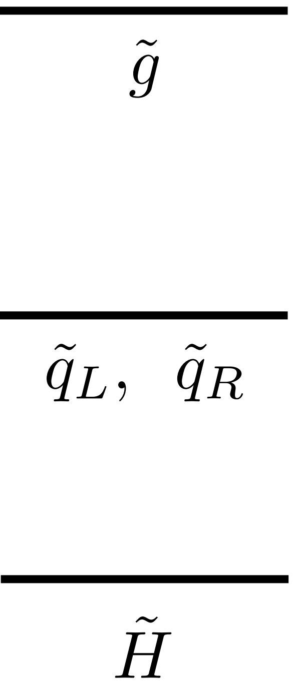
- With R-parity, LSP is stable. Light higgsinos generally lead to large missing ET.
- With flavor-universality, light stops imply light u and d squarks.
  Valence squark cross section is enormous!

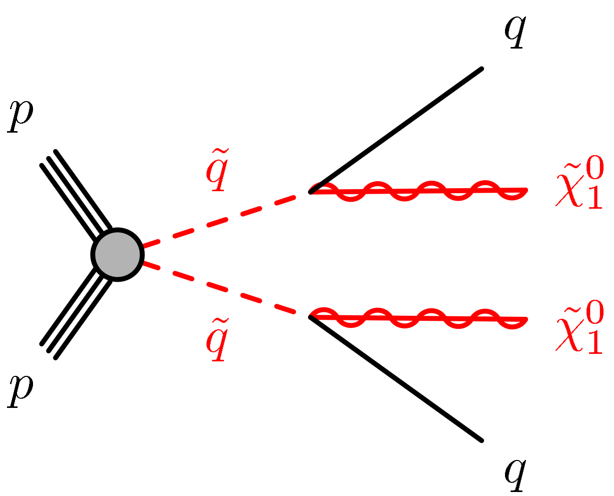


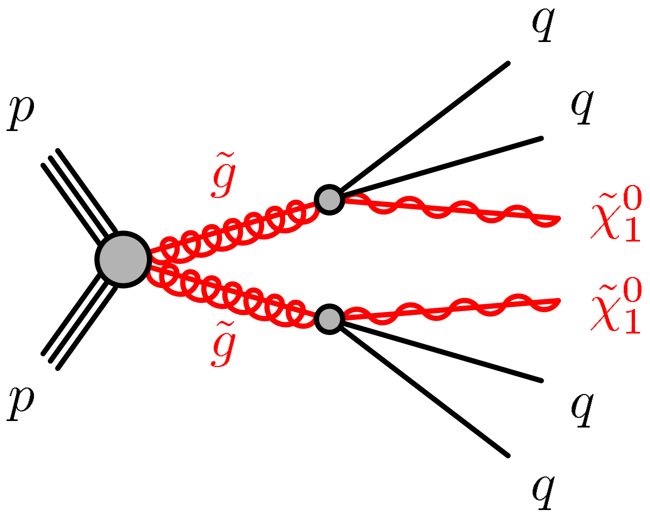




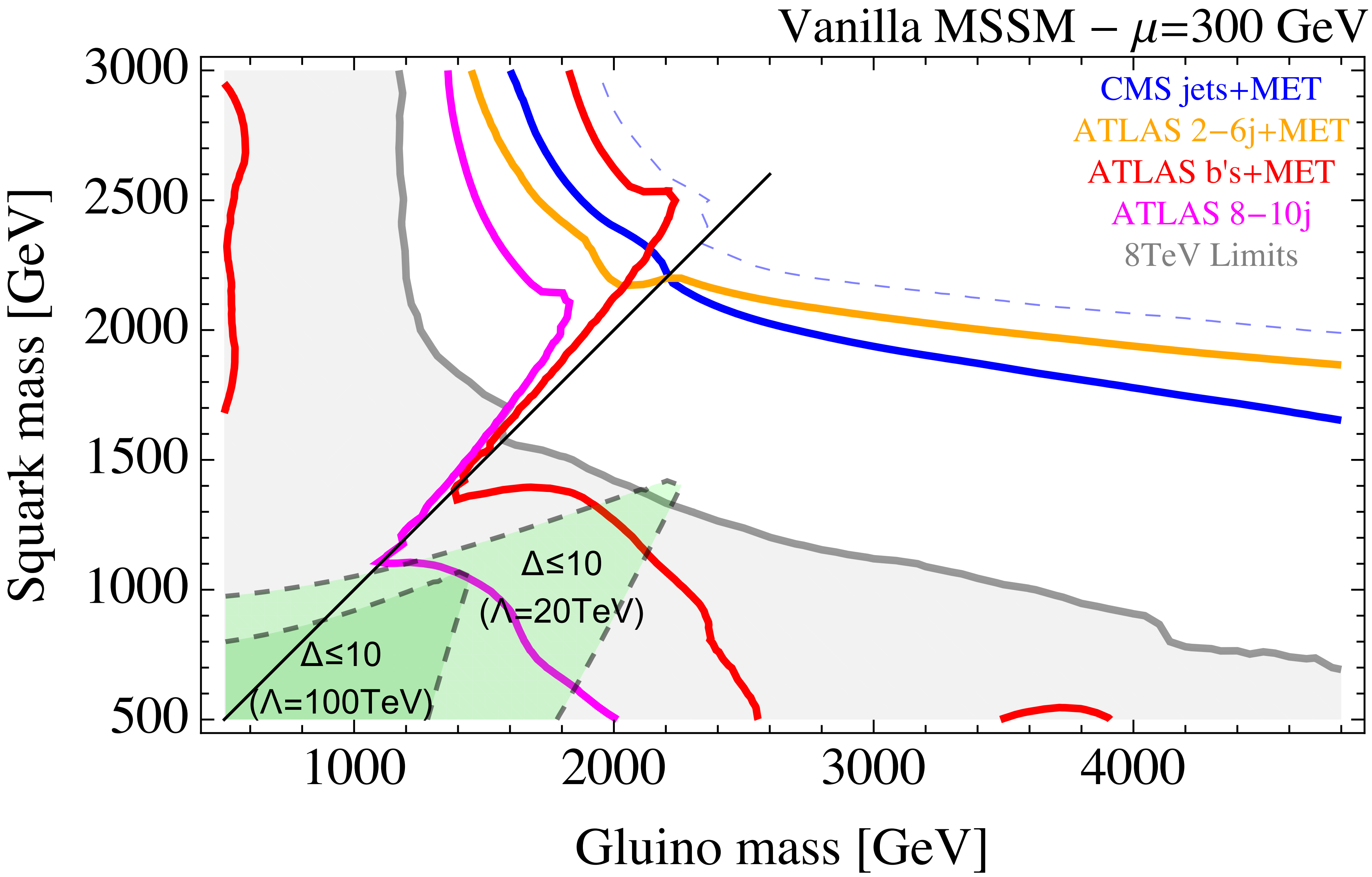
Valence squark cross section can be ~ 5 orders of magnitude larger than stop cross section!



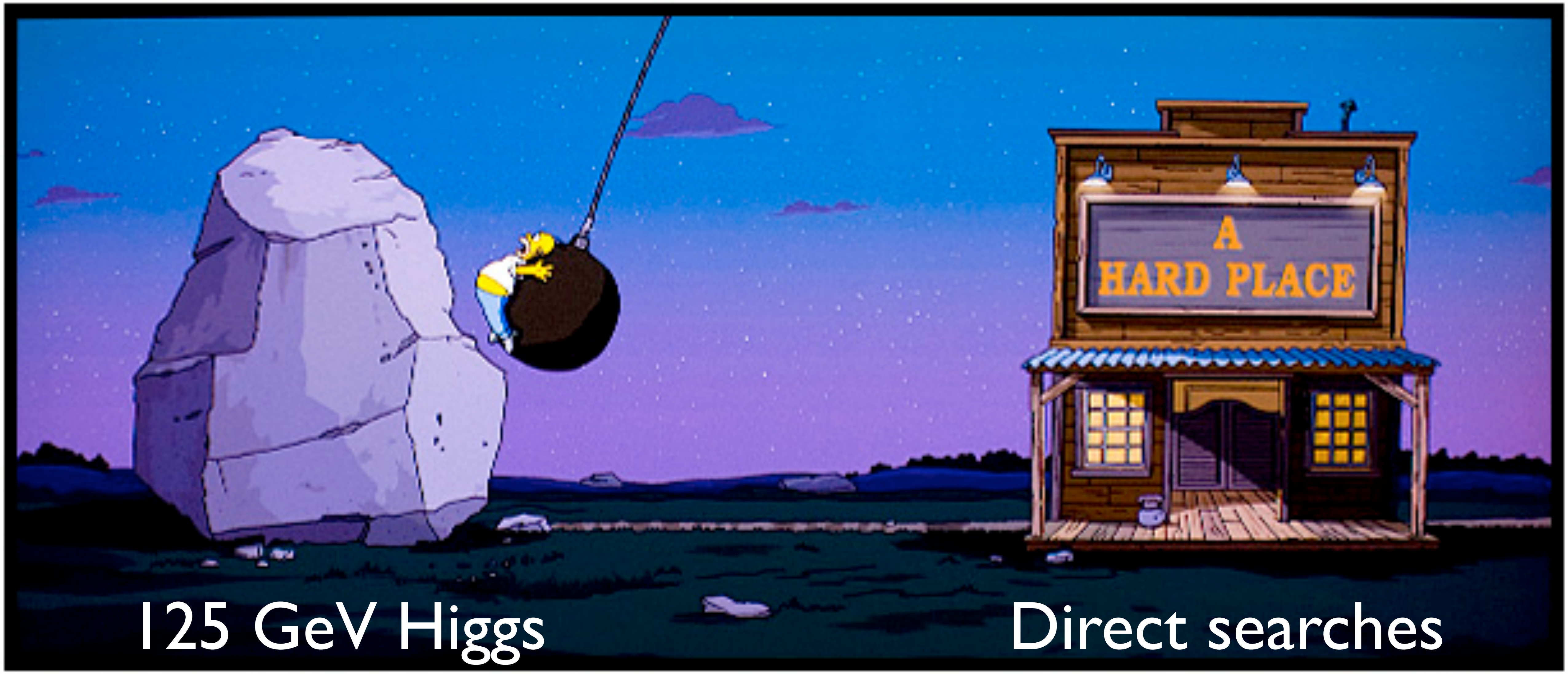




Run I recasted limits obtained using analysis framework developed by J. Evans & Y. Kats



Vanilla SUSY was more than 10% tuned even at Run I.



Then there’s also the Higgs mass...

m_h=125 GeV is independently pushing up the SUSY-scale in the MSSM.

$$m_h^2 = m_Z^2 \cos^2(2\beta) + \frac{3v^2}{4\pi^2}\left(|y_t|^4 \log\left(\frac{M_S^2}{m_t^2}\right) + \frac{A_t^2}{M_S^2}\left(|y_t|^2 - \frac{A_t^2}{12M_S^2}\right)\right) + \dots$$

m_h=125 GeV is independently pushing up the SUSY-scale in the MSSM.

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Famous bound $(m_h)_{\text{tree}}<m_Z$.

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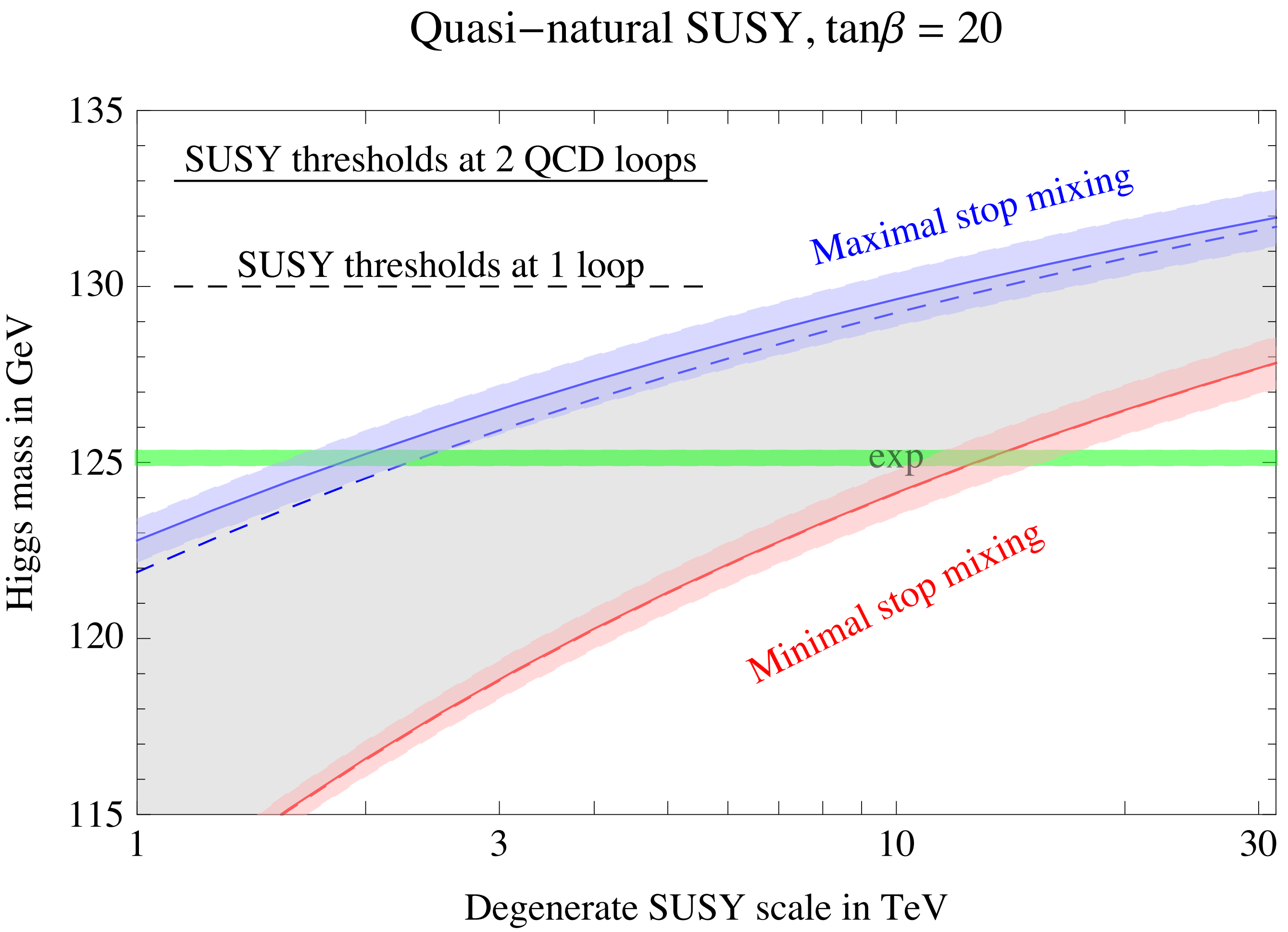
Quasi−natural SUSY, tanβ = 20

Bagnaschi *et al.*, 1407.4081

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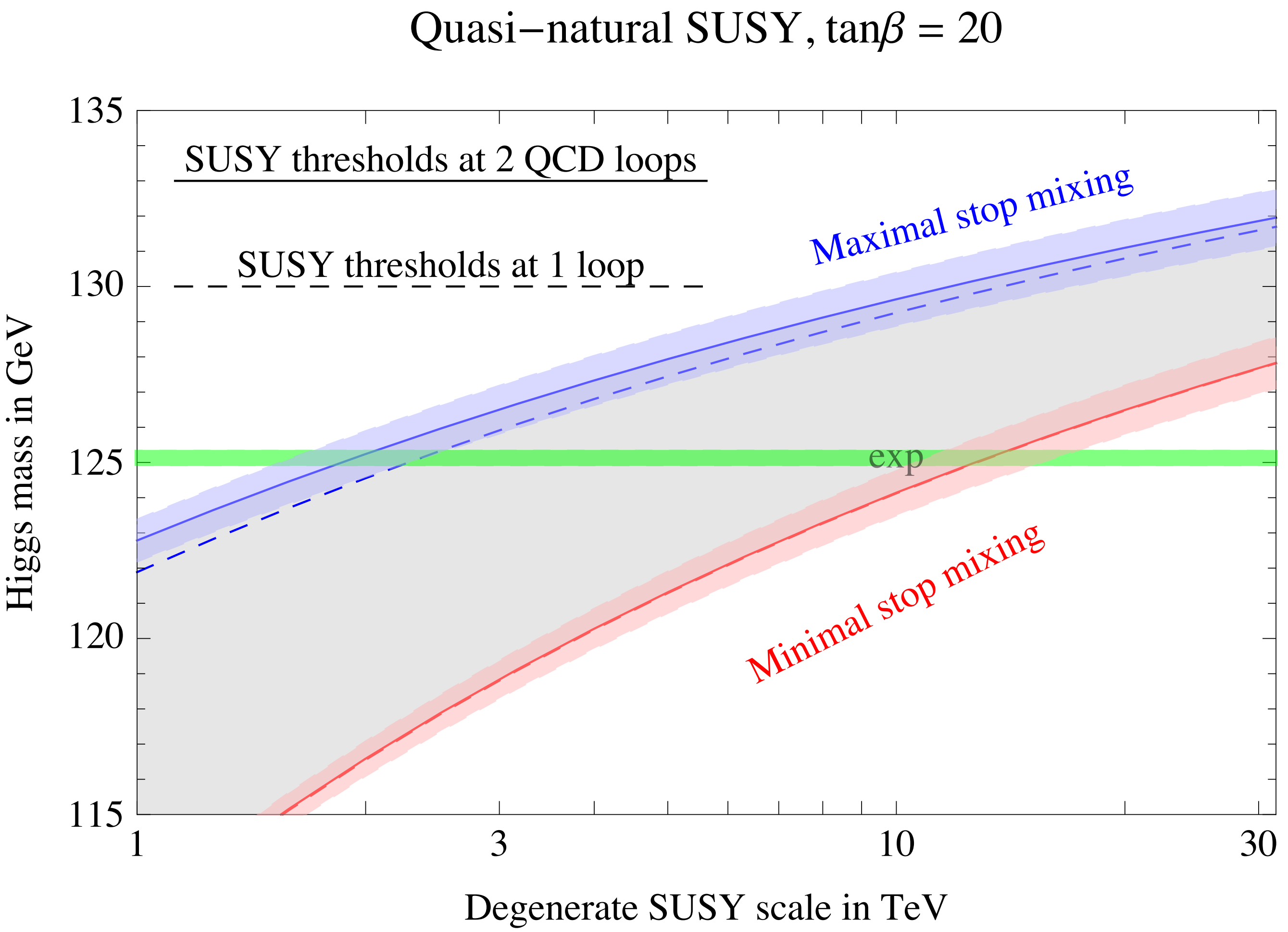

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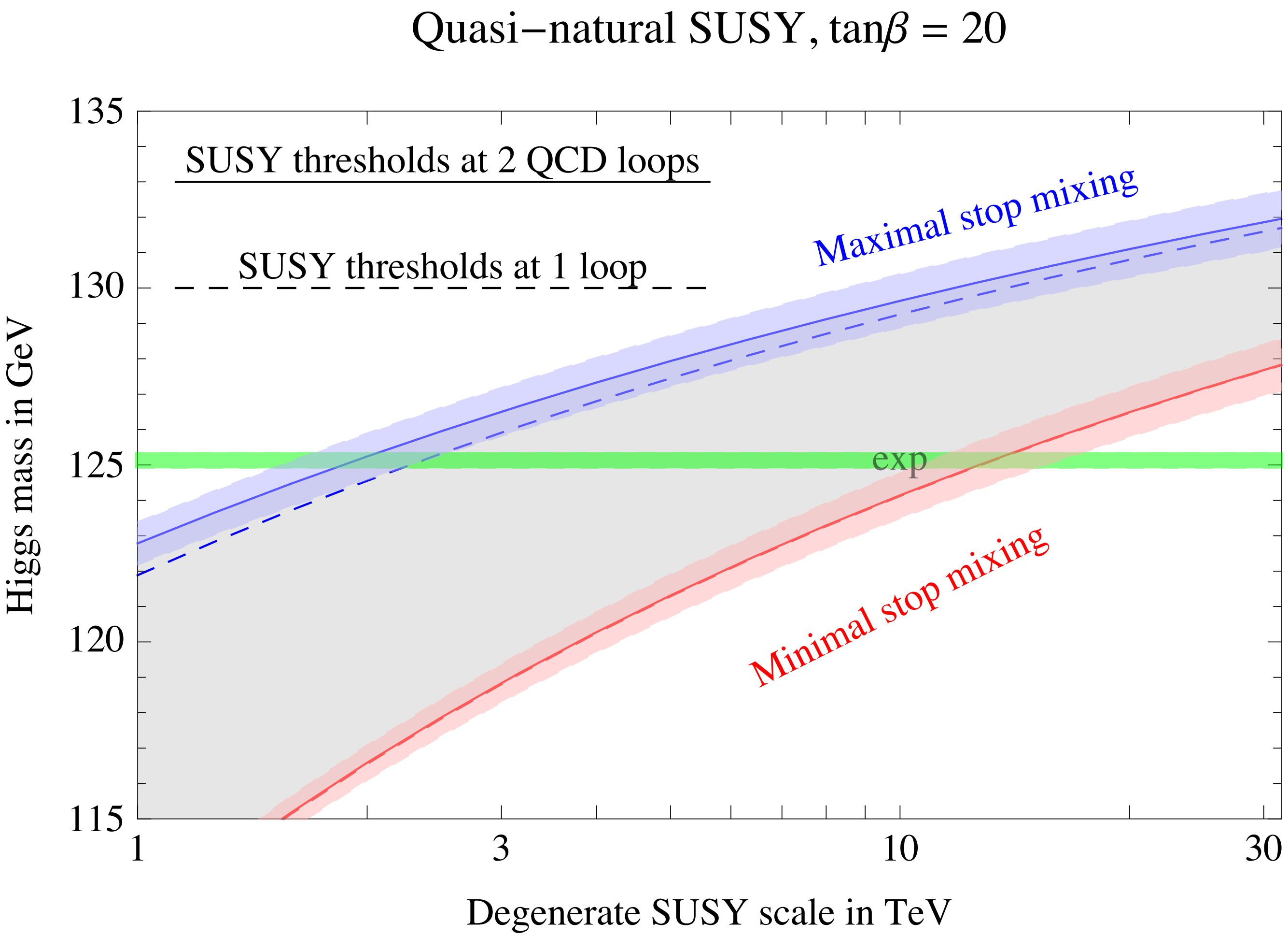

Bagnaschi *et al.*, 1407.4081

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

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

Vanilla SUSY cannot be 100% natural anymore.

Both direct searches and the 125 GeV Higgs are separately pointing at heavier-than-expected superpartners and percent-level tuning.

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.

Vanilla SUSY cannot be 100% natural anymore.

Both direct searches and the 125 GeV Higgs are separately pointing at heavier-than-expected superpartners and percent-level tuning.

Maybe we got unlucky and that’s the way things are?

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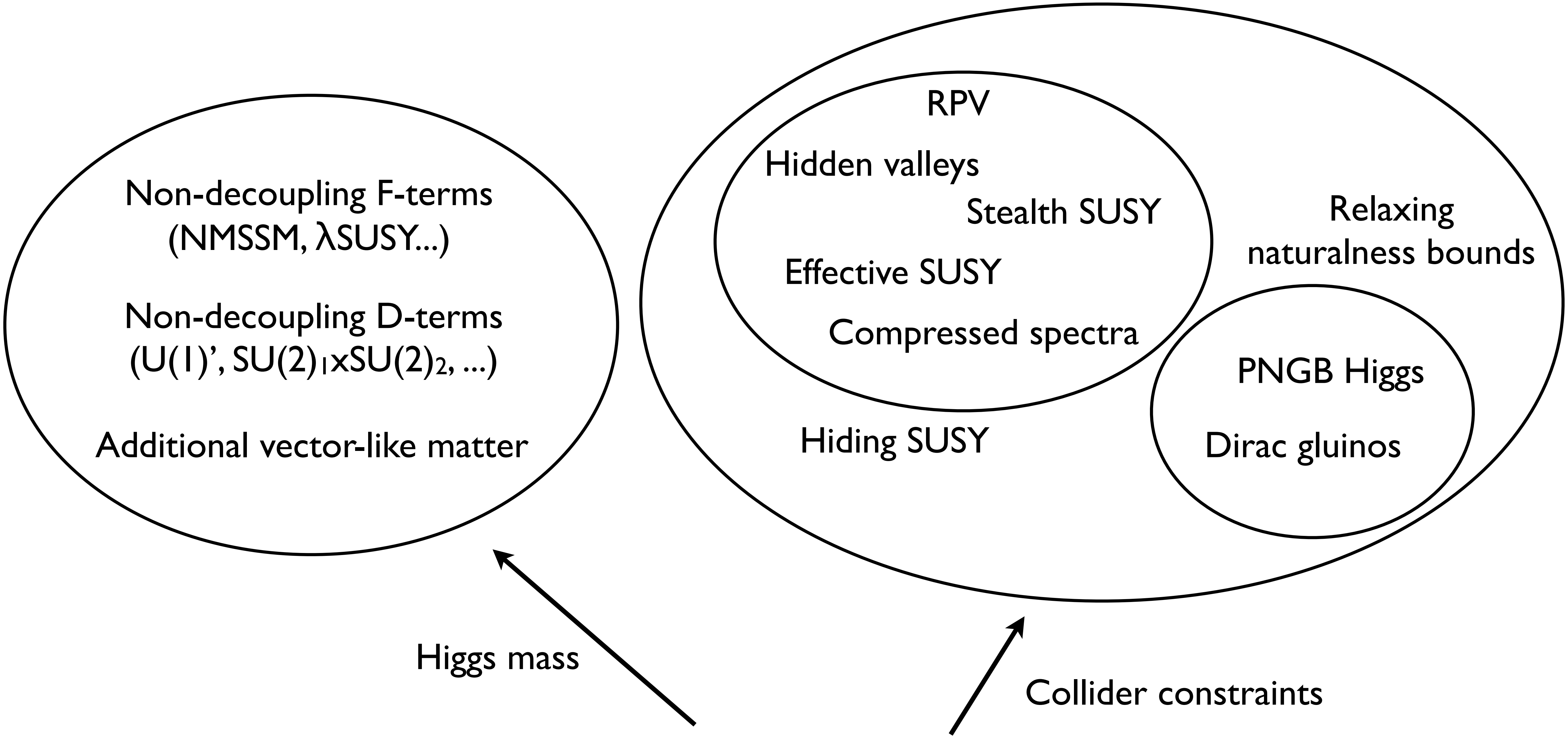
Or maybe it’s not vanilla SUSY...

Going beyond vanilla SUSY



Non-decoupling F-terms
(NMSSM, λSUSY...)

Non-decoupling D-terms
(U(1)’, SU(2)$_1$xSU(2)$_2$, ...)

Additional vector-like matter

RPV

Hidden valleys

Stealth SUSY

Effective SUSY

Compressed spectra

Hiding SUSY

Relaxing
naturalness bounds

PNGB Higgs

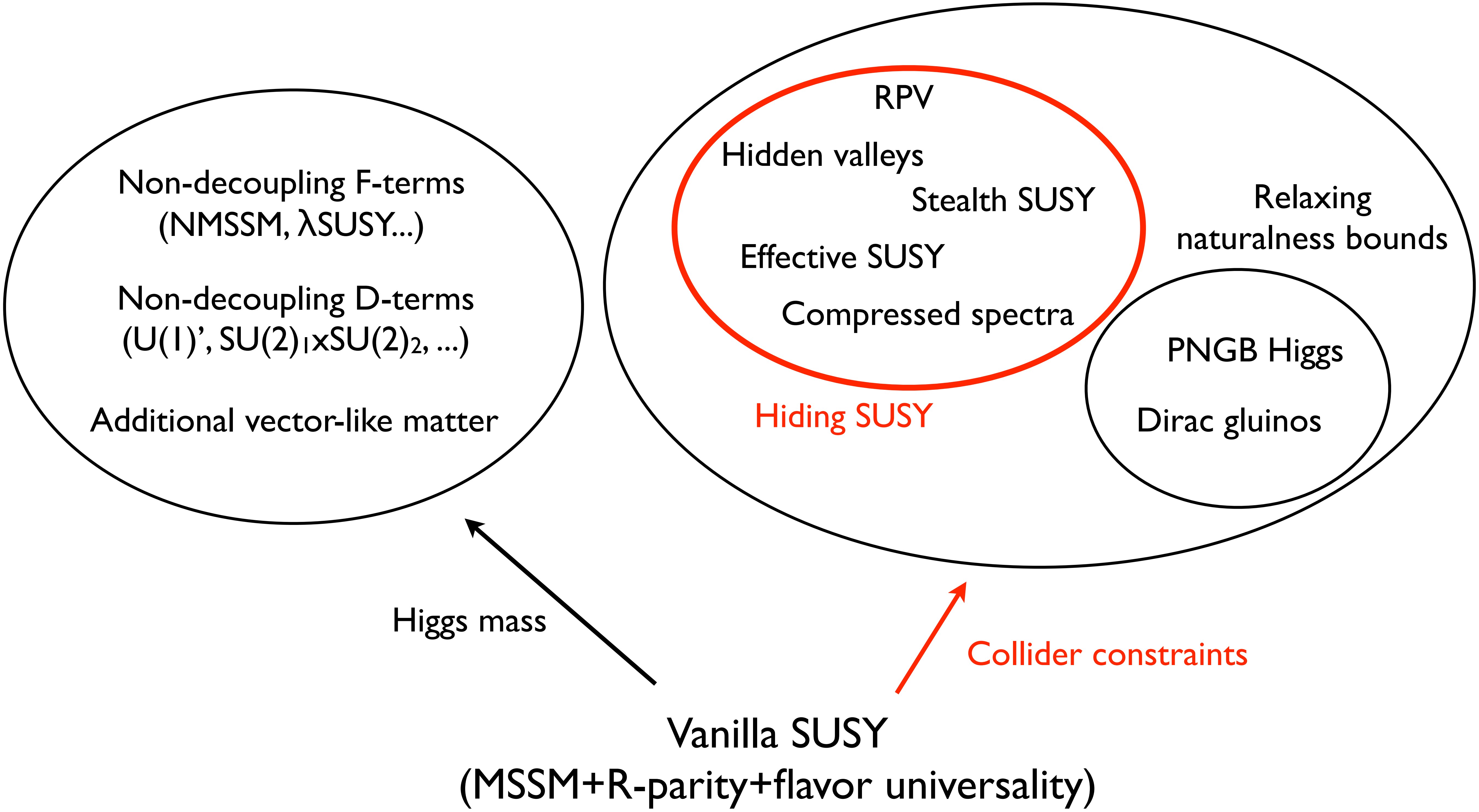
Dirac gluinos

Higgs mass

Collider constraints

Vanilla SUSY
(MSSM+R-parity+flavor universality)

Going beyond vanilla SUSY



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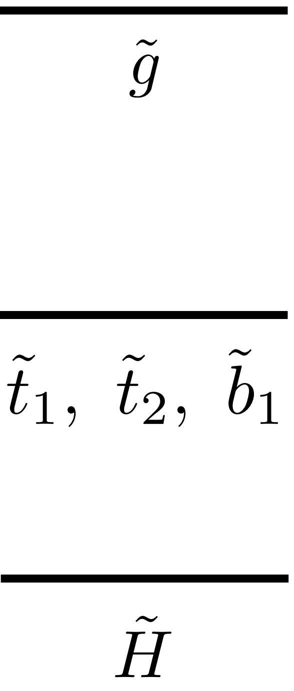
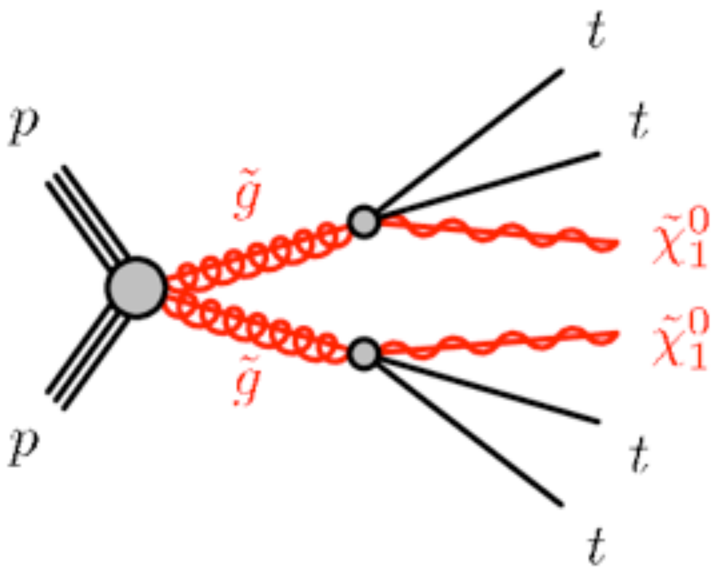


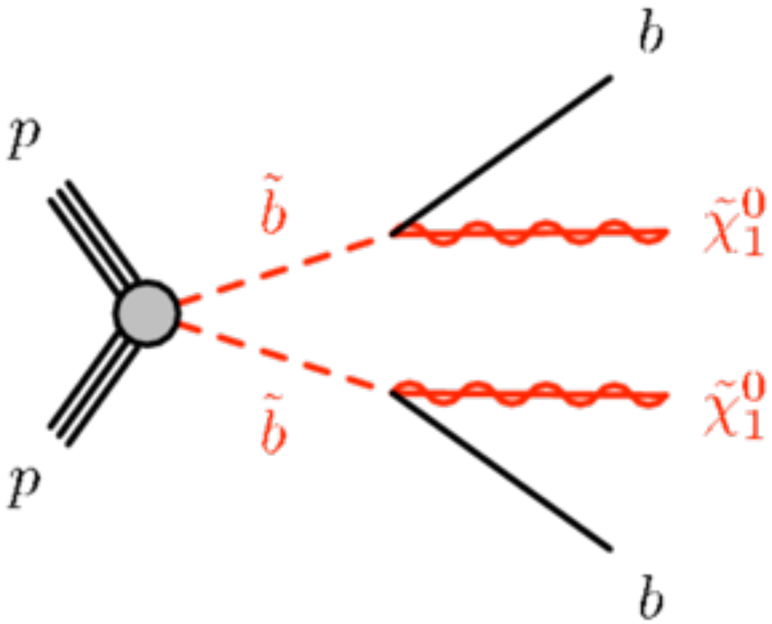
Natural SUSY scenario #2

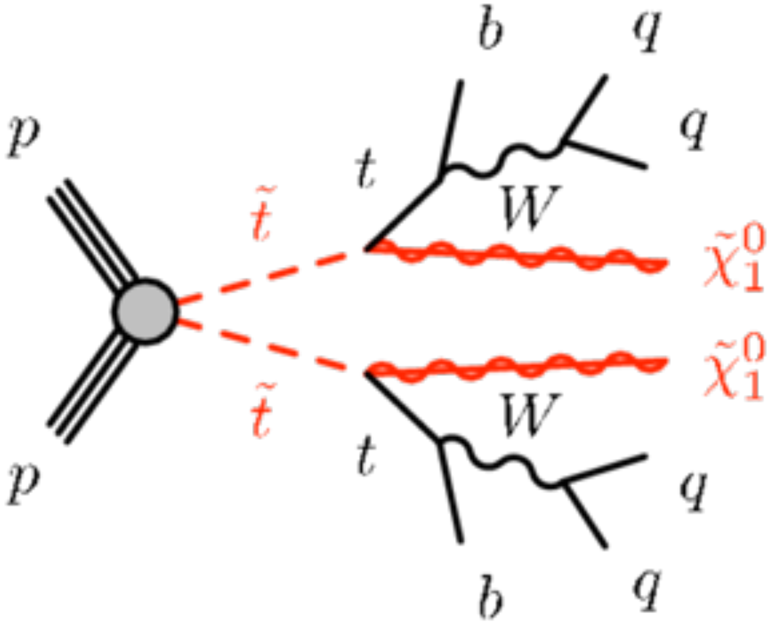
“Effective SUSY”: decoupled 1st/2nd gen. squarks

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

Decoupling them relaxes collider limits by decreasing SUSY xsec, but not completely.







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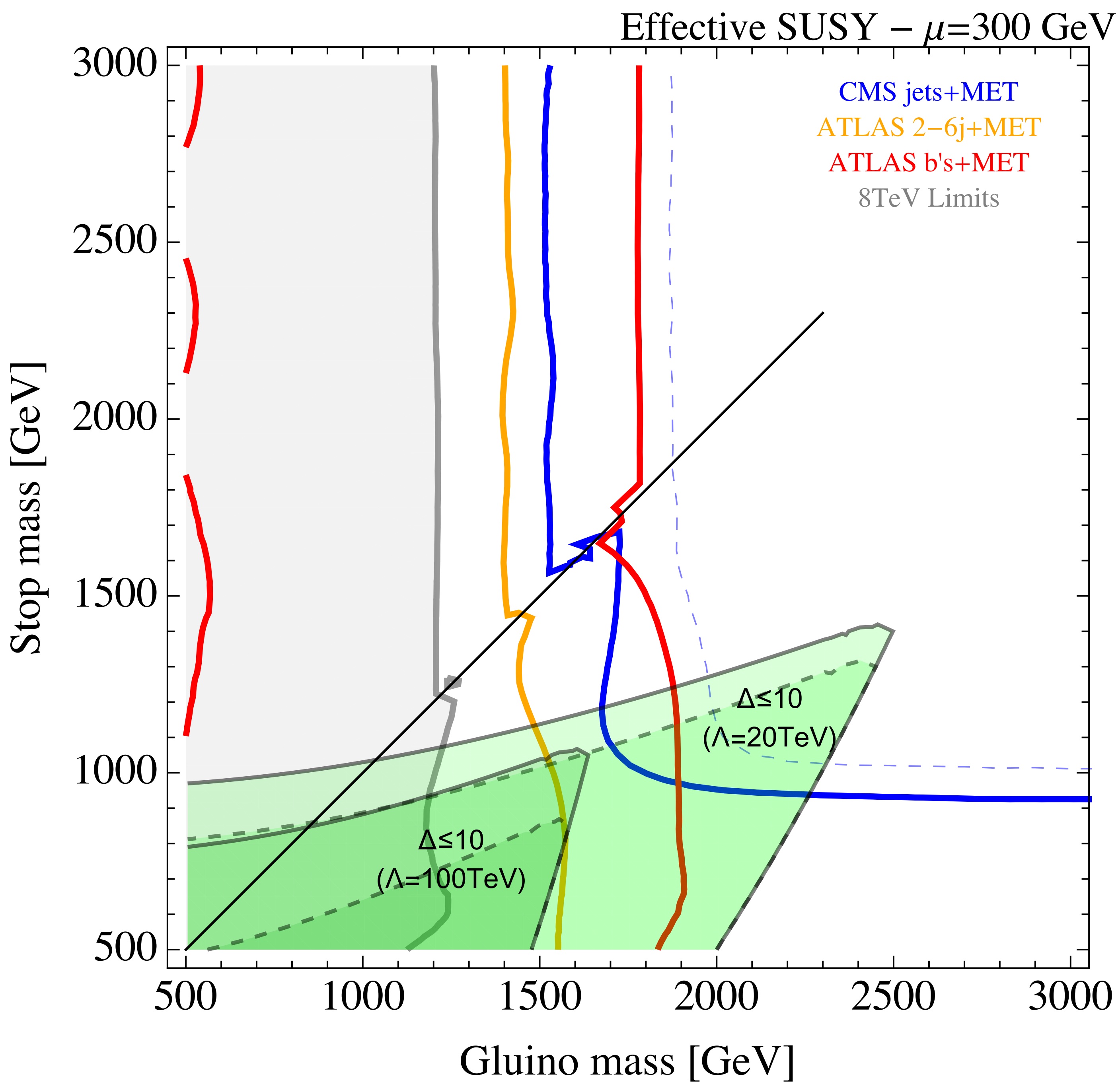
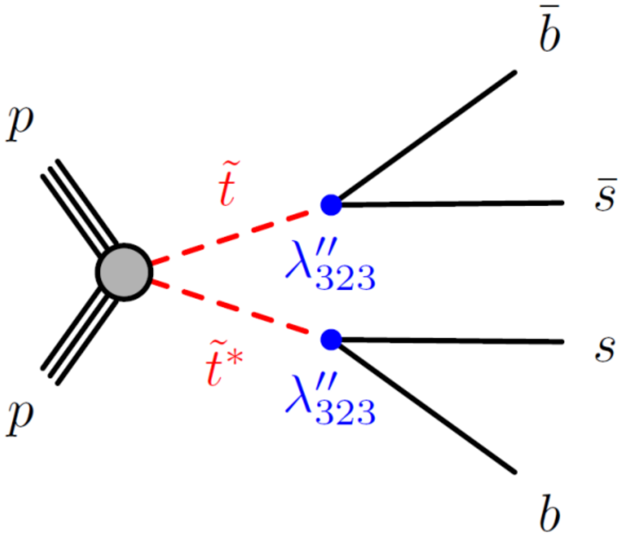


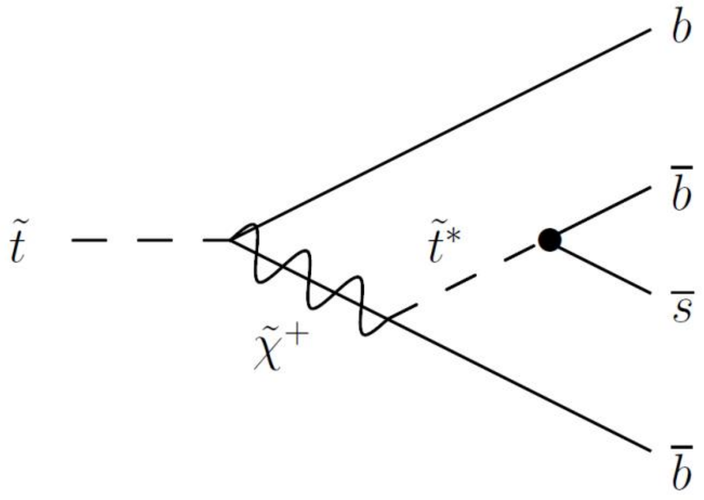
Natural SUSY scenario #3:

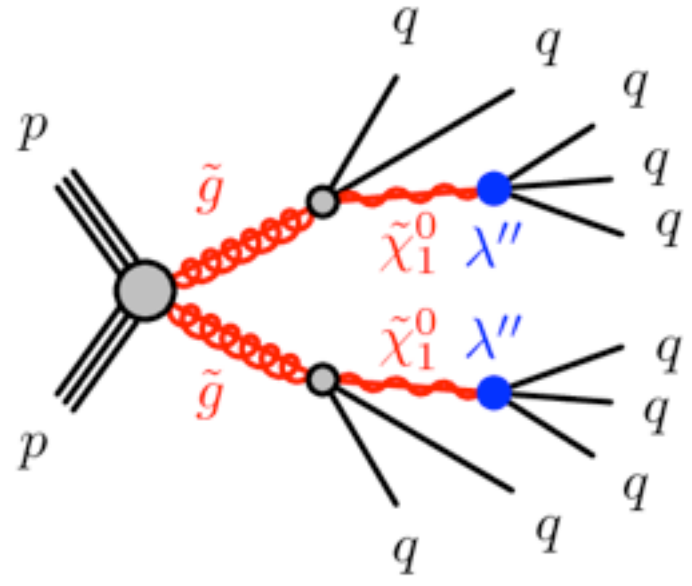
“no-MET SUSY”: R-parity violation (for example)

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

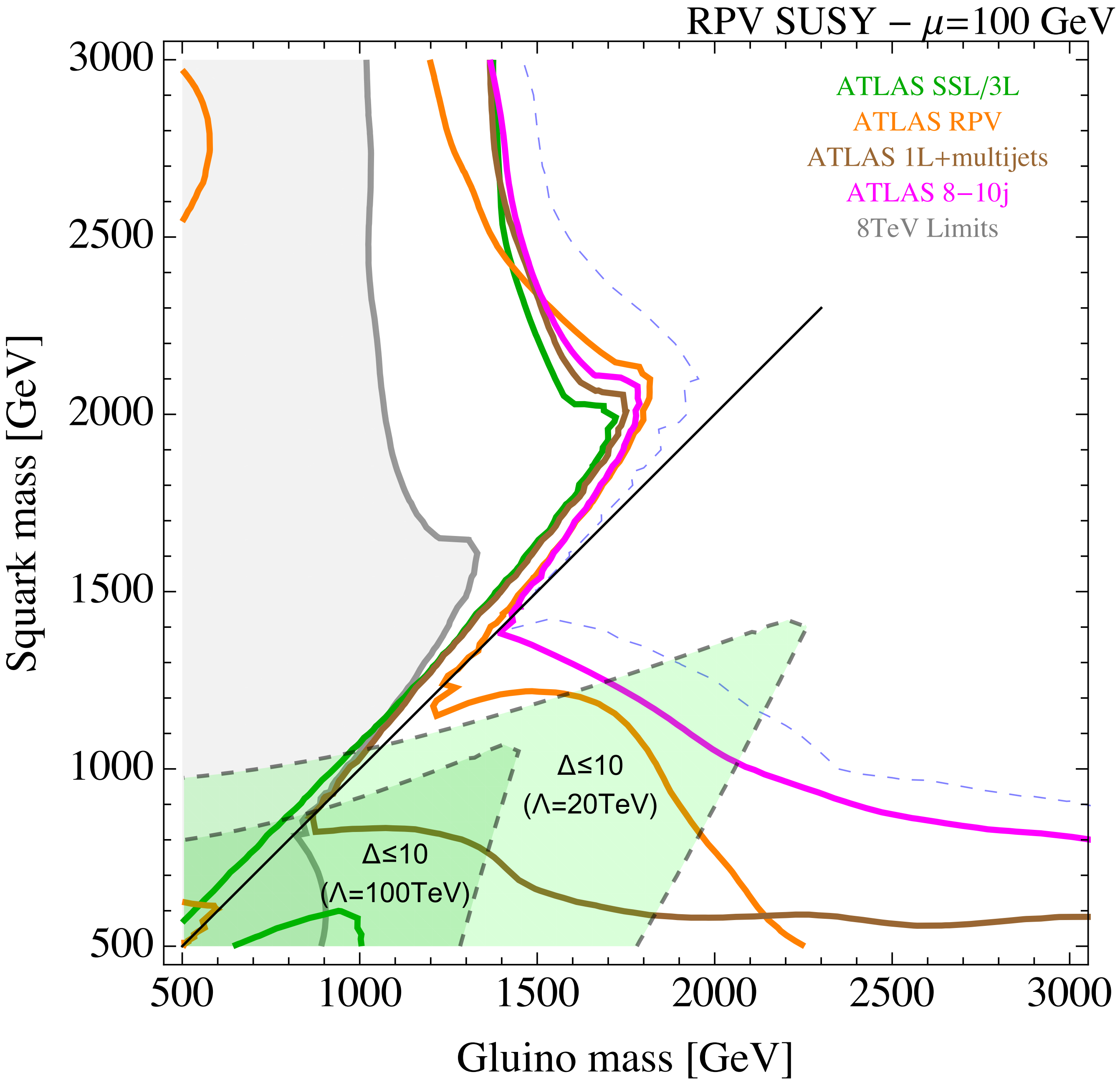
Turning on R-parity violation allows the LSP to decay to SM particles. Trading the MET from the LSP for jets generally weakens the limits.

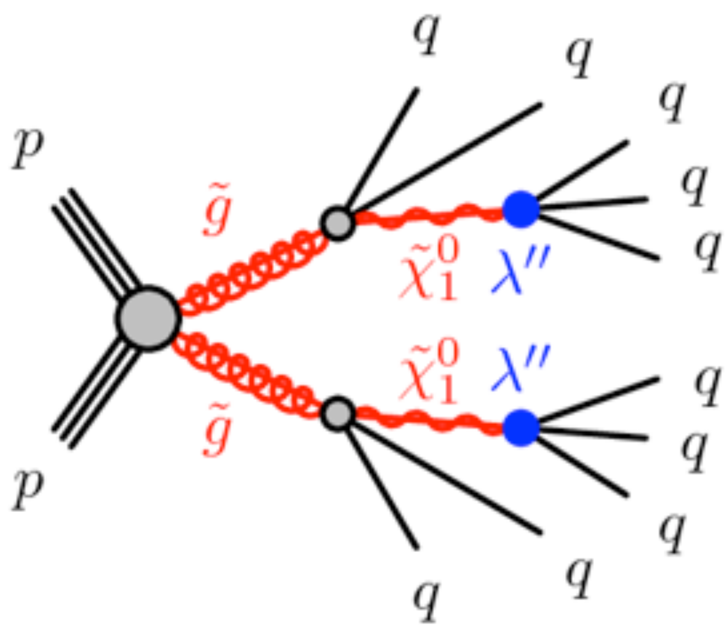






RPV + flavor universal squarks





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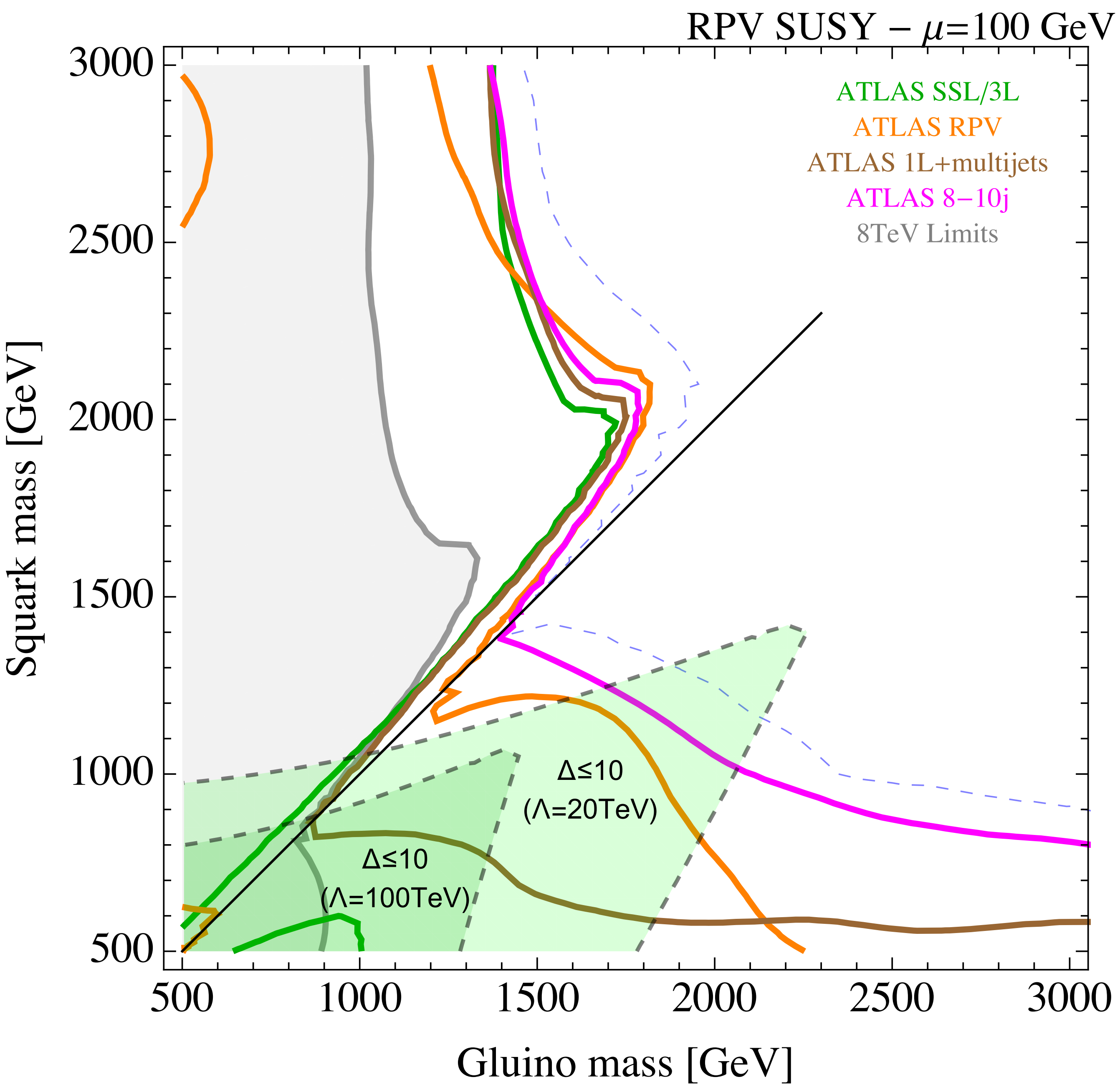
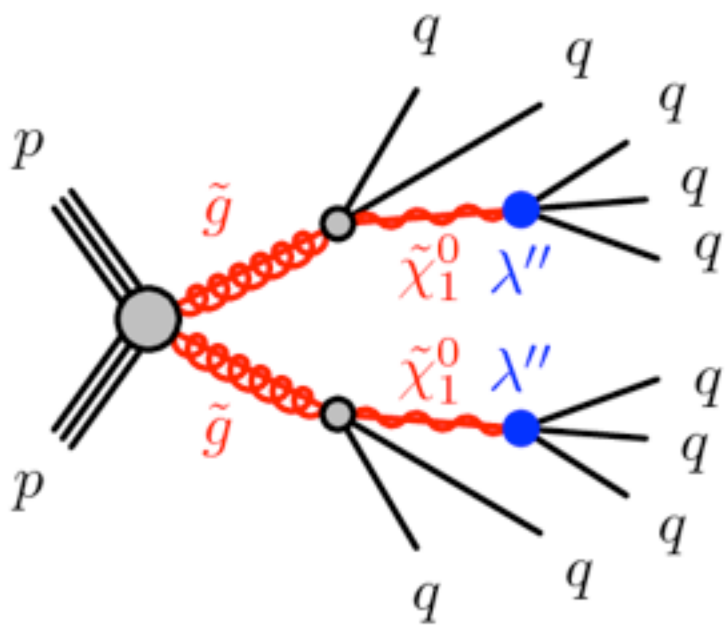
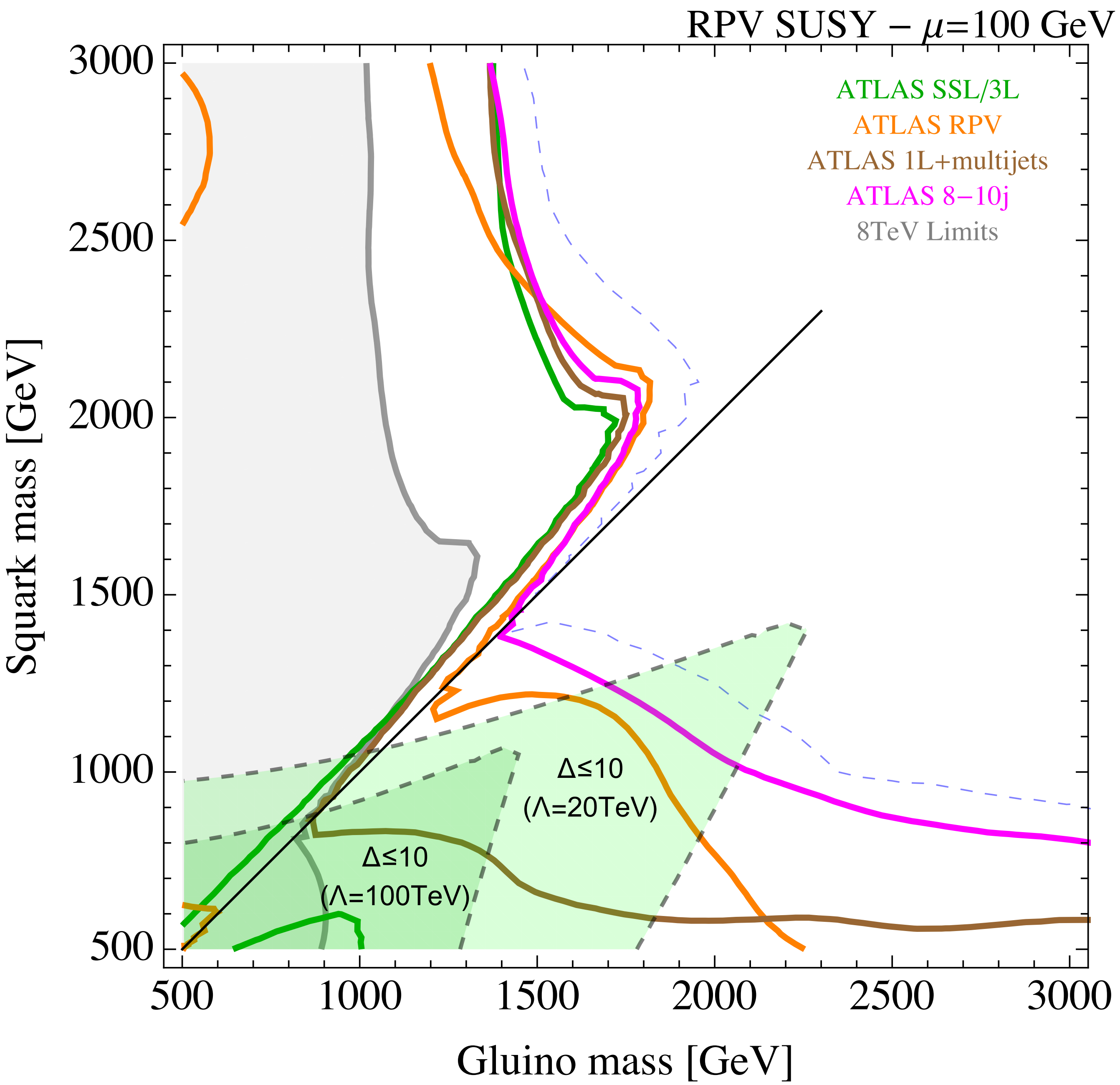


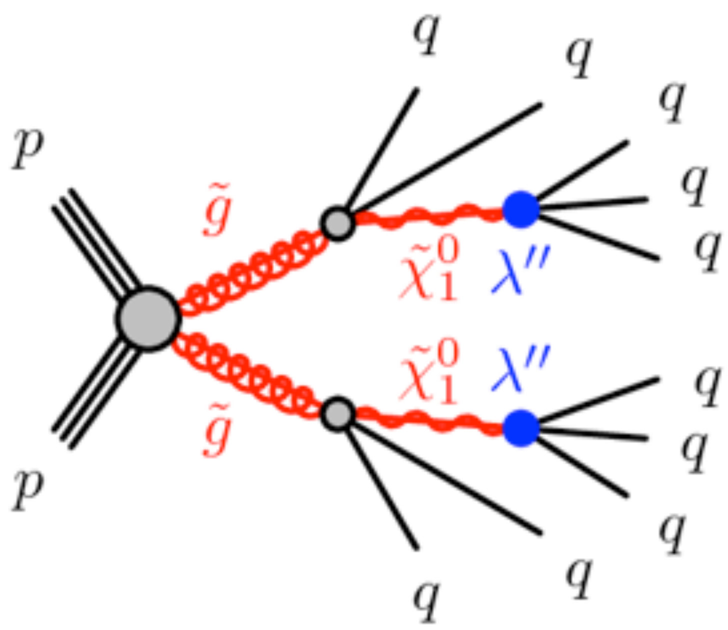


RPV can relax bounds on flavor-universal squarks.

(Graham, Rajendran & Saraswat '14)

RPV + flavor universal squarks

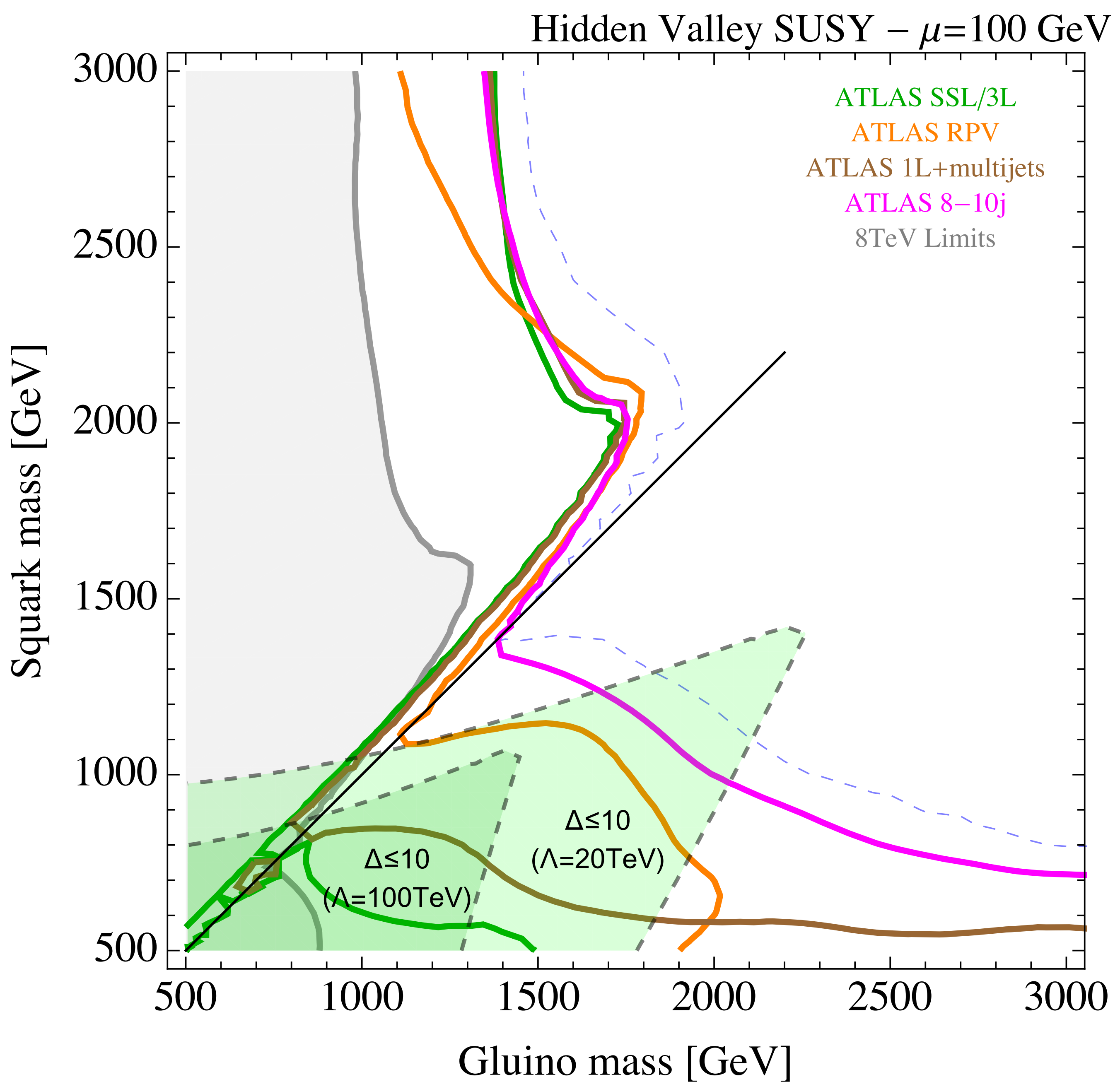




RPV can relax bounds on flavor-universal squarks.
(Graham, Rajendran & Saraswat '14)

But after the ICHEP results, the fully natural part of parameter space is shrinking...

Alternative to RPV: HV/Stealth



Can also preserve R-parity while trading MET for jets, using hidden valleys/Stealth SUSY.
(Strassler & Zurek;
Fan, Reece & Ruderman)

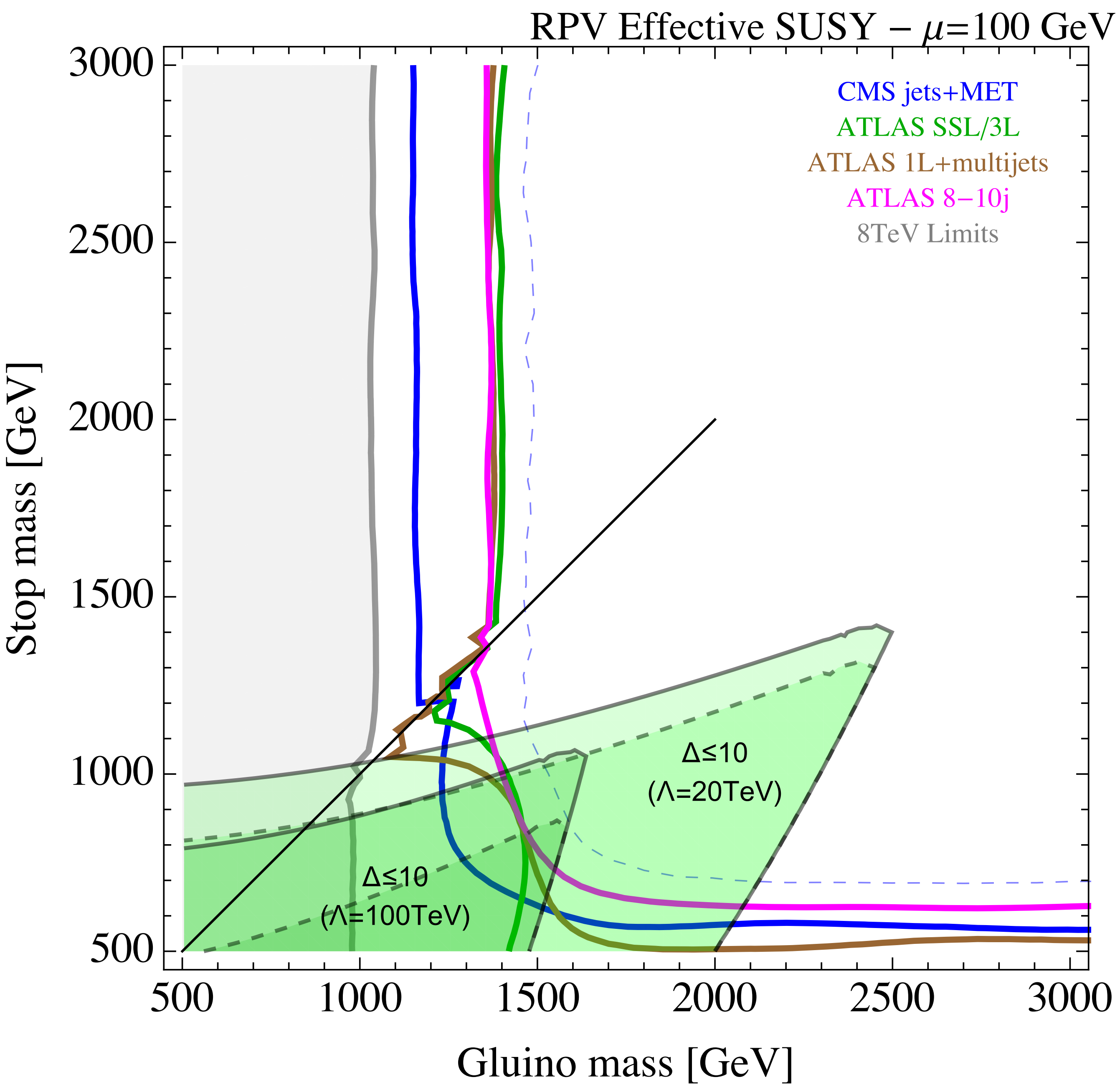
For example:

$$\tilde{H} \to S\tilde{S}, \quad S \to gg$$

$$m_S + m_{\tilde{S}} \approx m_{\tilde{H}}$$

$$m_{\tilde{S}} \approx 0$$

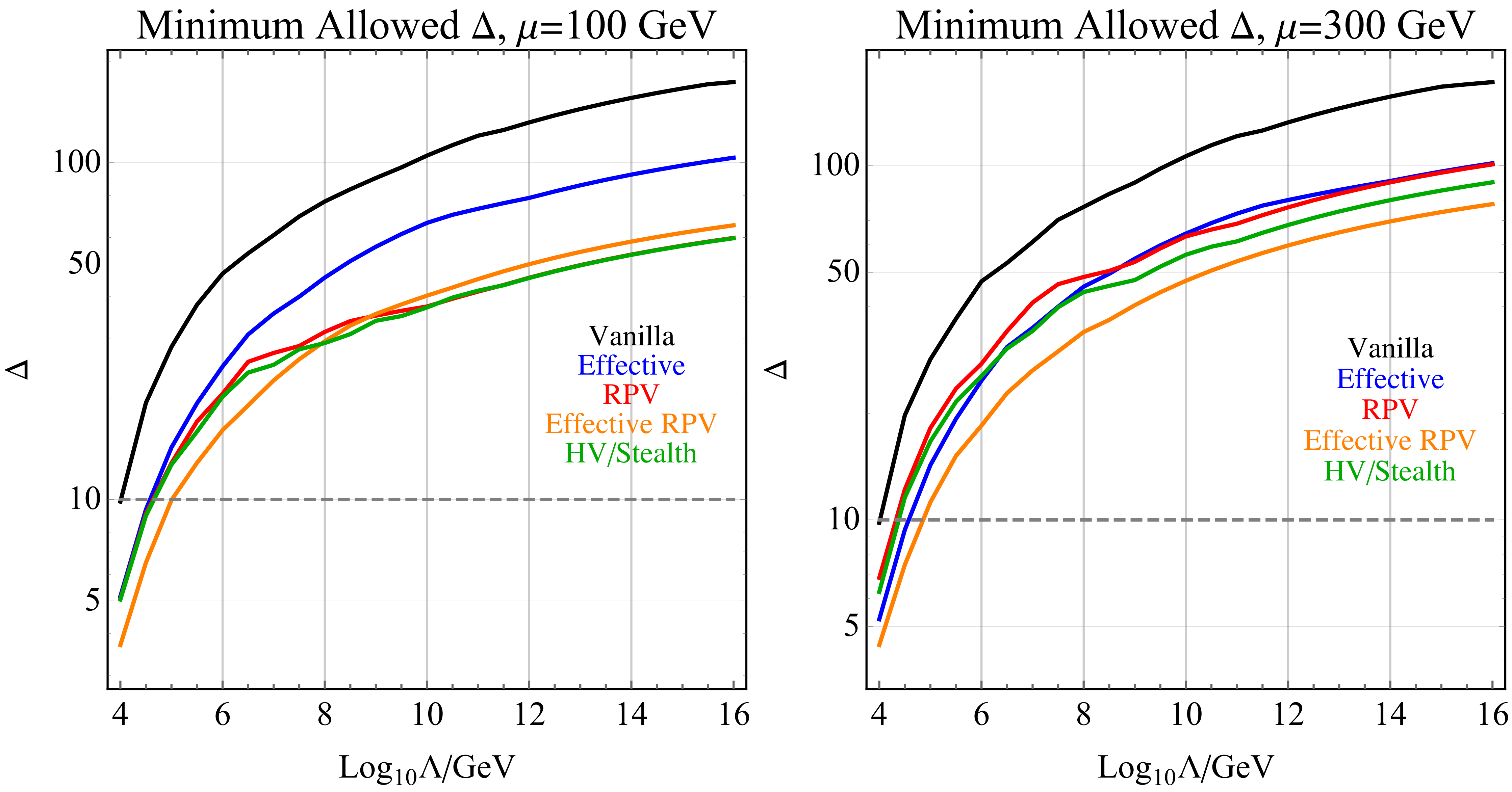
RPV + effective SUSY



Trading MET for jets and decoupling 1st/2nd generation squarks opens up the most parameter space for natural SUSY.

But still only at extremely low messenger scales...

Tuning vs. Messenger Scale



Even in best case scenario, need Λ<100 TeV for Δ < 10!

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DISCUSSION CONVENER: X. Tata (Hawaii U.)

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Burning questions

- Can SUSY still be natural?
- How much discovery potential for SUSY remains at the LHC?
- ……
- Should we be concerned??

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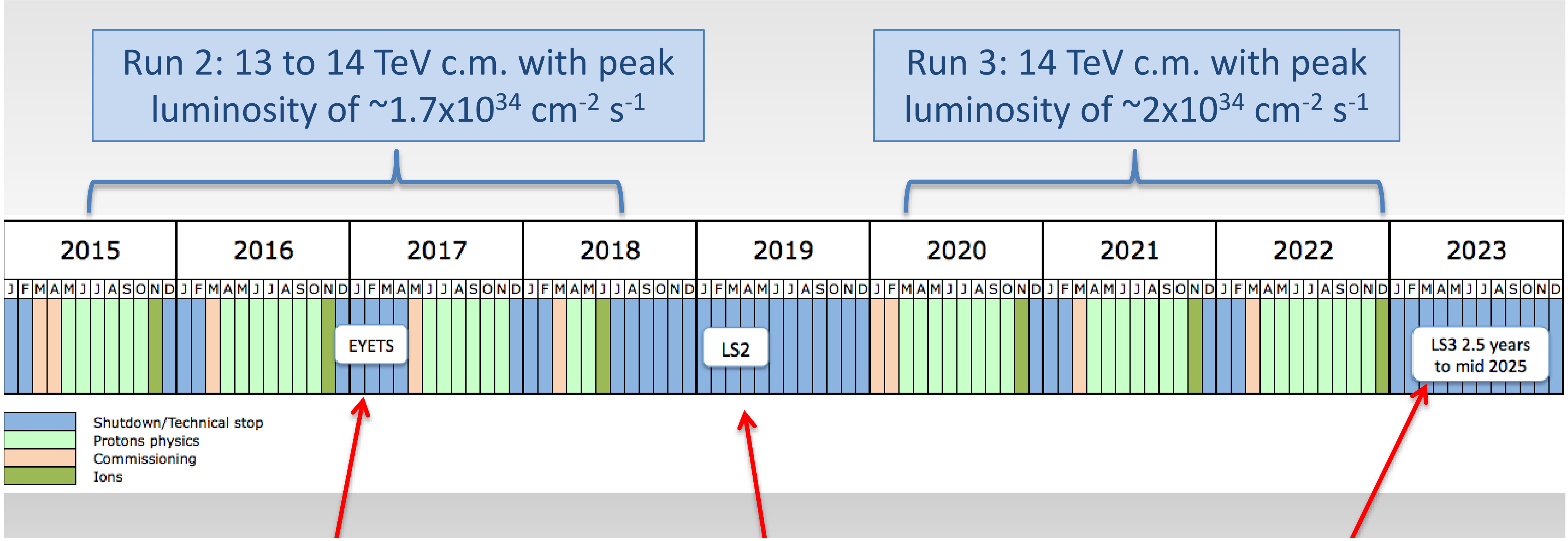
We are entering the slow phase…

	Peak lumi E34 $cm^{-2}s^{-1}$	Days proton physics	Approx. int lumi [fb^{-1}]
2015	1.3	100	10
2016	1.5	160	35
2017	1.7	160	45
2018	1.7	40	10

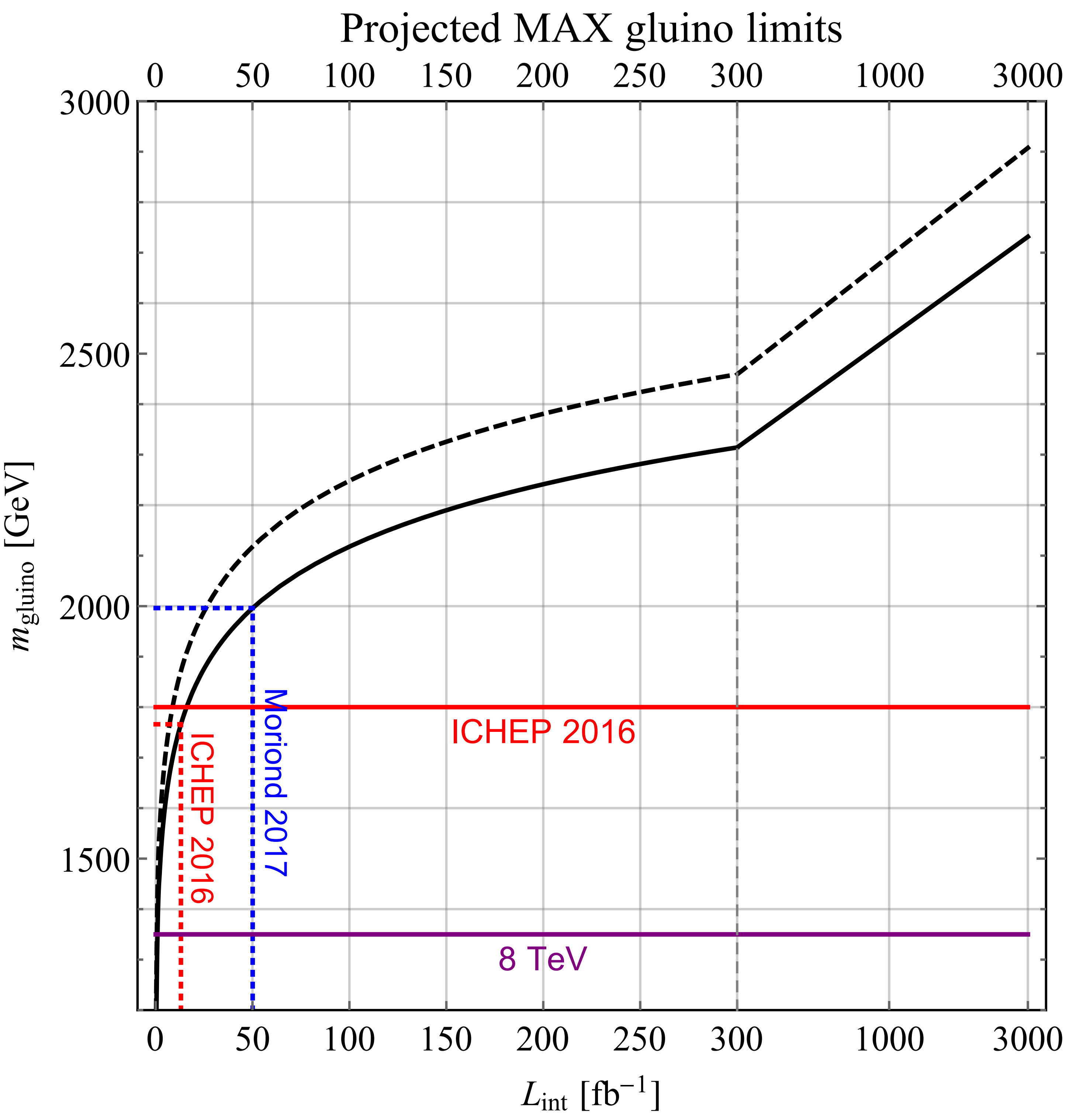
(M. Lamont, Moriond 2015)



Run 2: 13 to 14 TeV c.m. with peak luminosity of ~1.7x10^{34} cm^{-2} s^{-1}

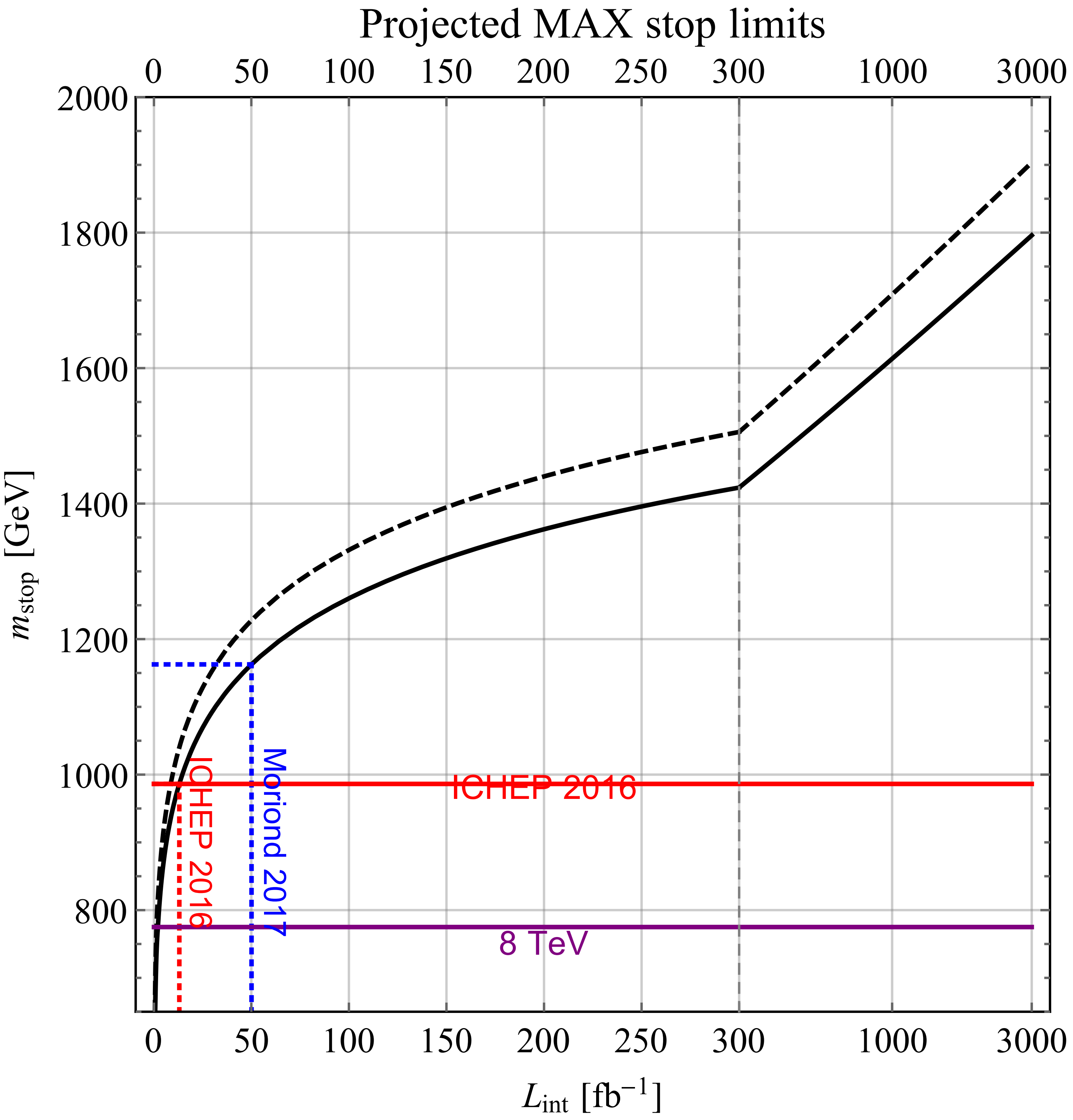
Run 3: 14 TeV c.m. with peak luminosity of ~2x10^{34} cm^{-2} s^{-1}

Relative to previous 8 TeV limits, we've probed only a third of the eventual gluino reach, although future progress will be slower.



Assumptions: background, signal efficiencies unchanged, cross section controlled by parton luminosity divided by m^2. (cf. Salam & Weiler http://collider-reach.web.cern.ch/collider-reach/)

More potential for rapid progress in max stop reach...



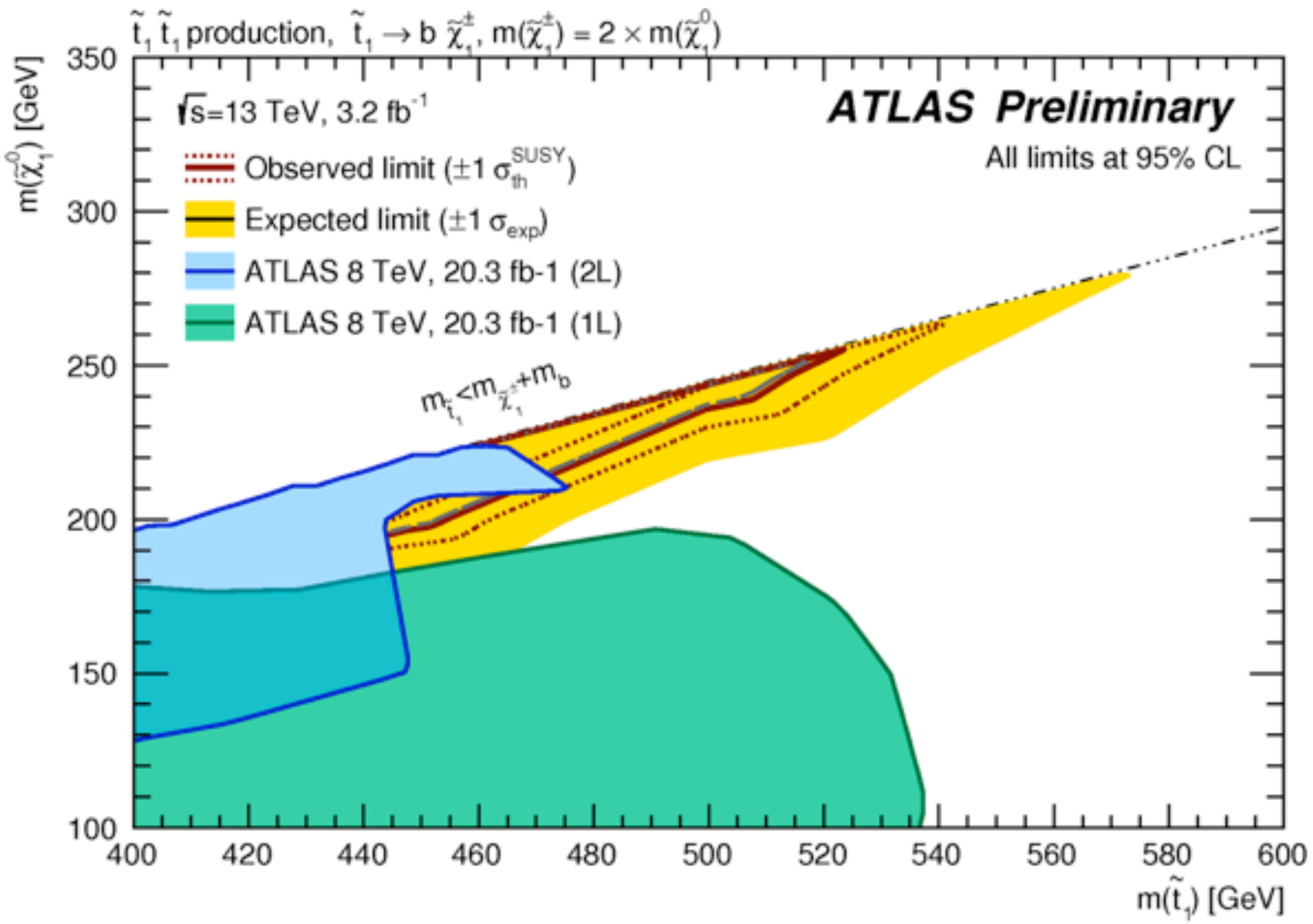
(parton luminosity ~ $e^{-a\,m}$ => reach Δm ~ 1000 GeV across a wide range of m!)

Important Caveat

These are just the maximum possible limits (“kinematic limits”).
They assume low background and optimal signal efficiencies.

There is still much parameter space at lower masses that involves more difficult kinematic configurations.

We still need more data to probe these regions.



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Summary

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

- The vanilla scenario is at least percent-level tuned.
- But many other flavors of natural SUSY are still viable, even after ICHEP.
- For instance, decoupling 1st/2nd generation squarks and trading MET for jets both allow for natural SUSY to evade current searches.
- Fully natural SUSY must have a very low messenger scale $\Lambda < 100$ TeV to be compatible with all the bounds.

If SUSY exists and is fully natural, it's almost certainly not what most people envisioned before the LHC turned on.

Outlook

Opportunities for model building:

- Effective SUSY with such a low mediation scale? Is it really possible? Existing models?
- Hidden valley / Stealth SUSY -- ad hoc or good for anything else (dark matter, Higgs mass...)
- Dirac gluinos?
- Models where Higgsino mass comes from SUSY breaking instead of mu-term?

Outlook

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Natural SUSY (and new physics more generally) could still be around the corner.

We've looked in most of the obvious places and haven't found anything yet, but there is still time for a fluctuation to grow into a discovery.

Also, there exist many, more challenging signatures that will require more data and improved analysis techniques.

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With only a few percent of the data collected so far, much discovery potential still remains...

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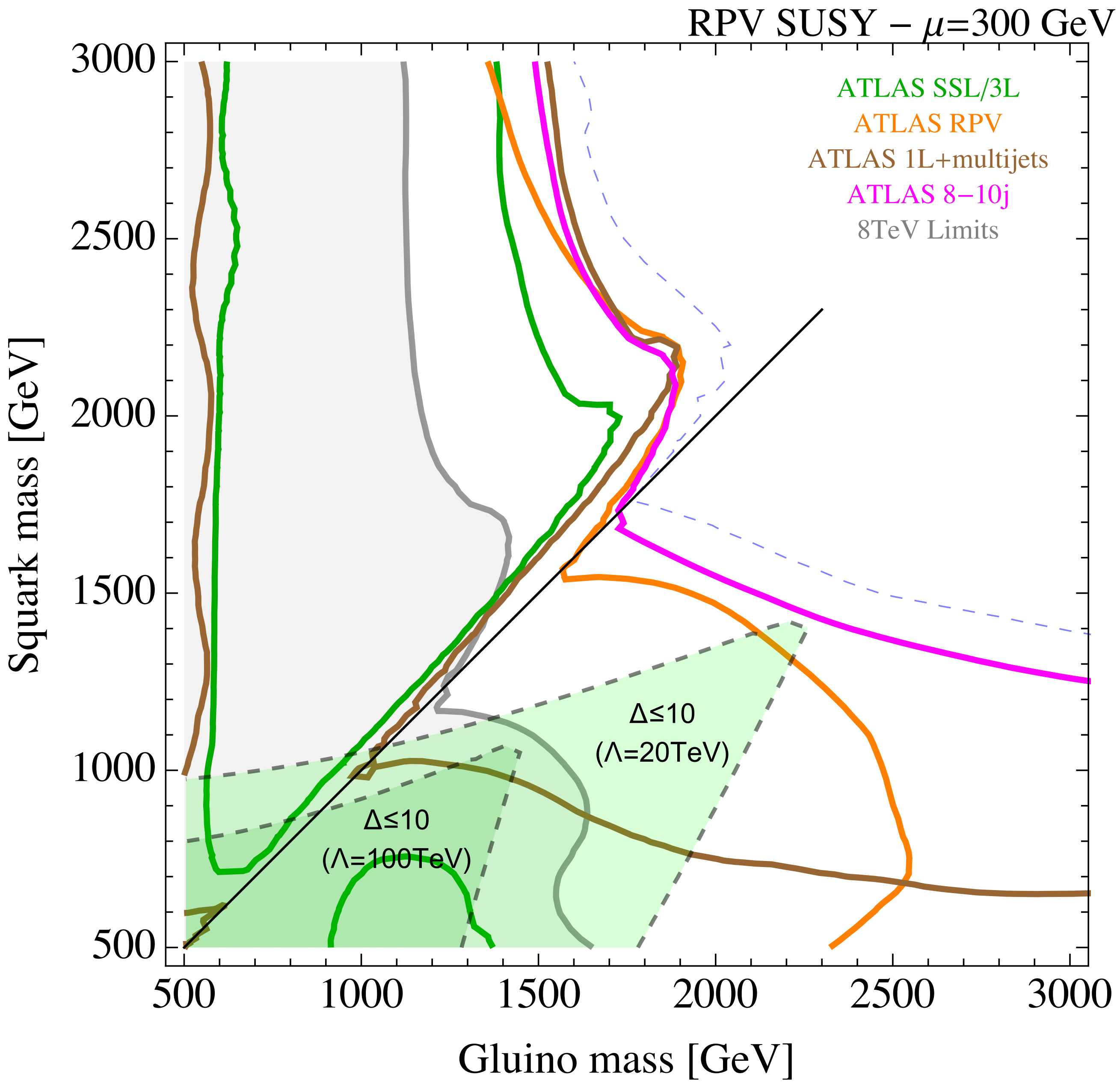
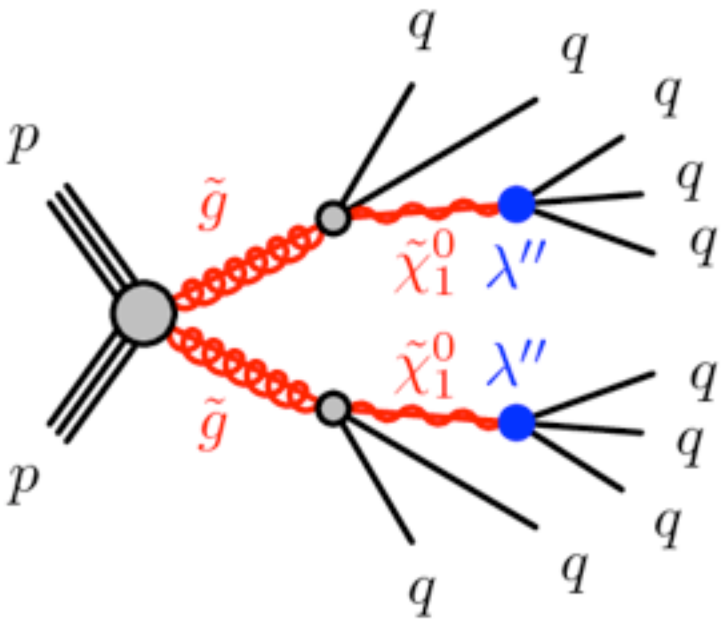
With only a few percent of the data collected so far, much discovery potential still remains...

...but we may need to be patient.

Thanks for your attention!

RPV + flavor universal squarks





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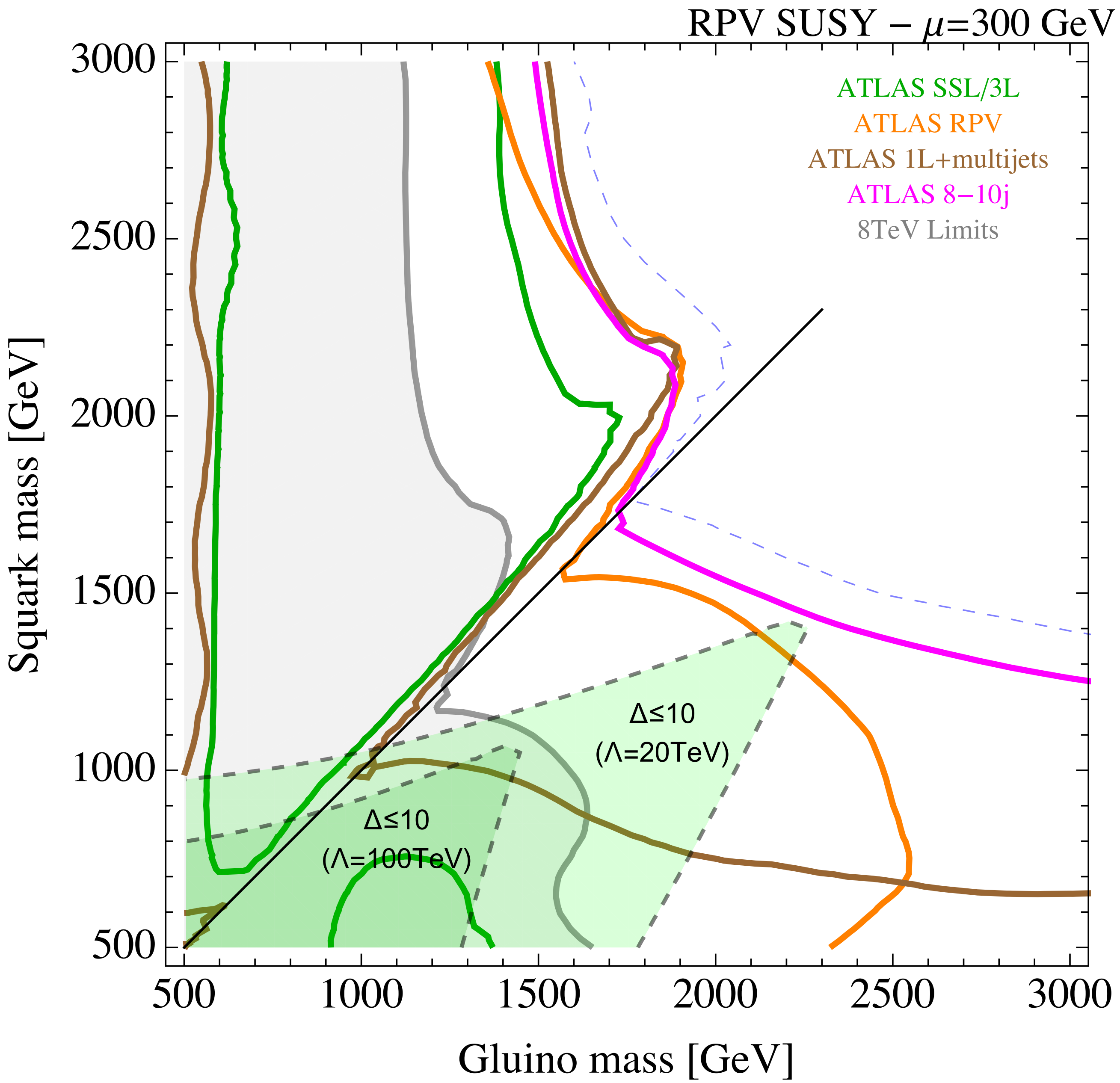
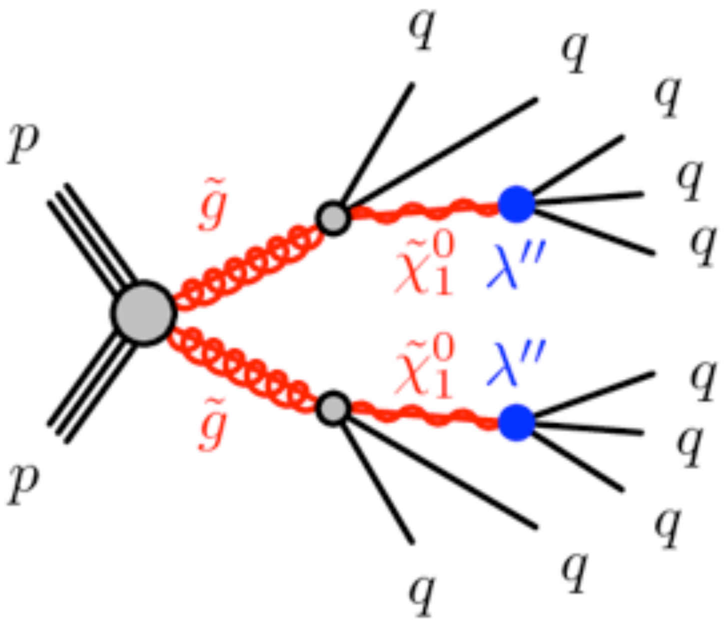
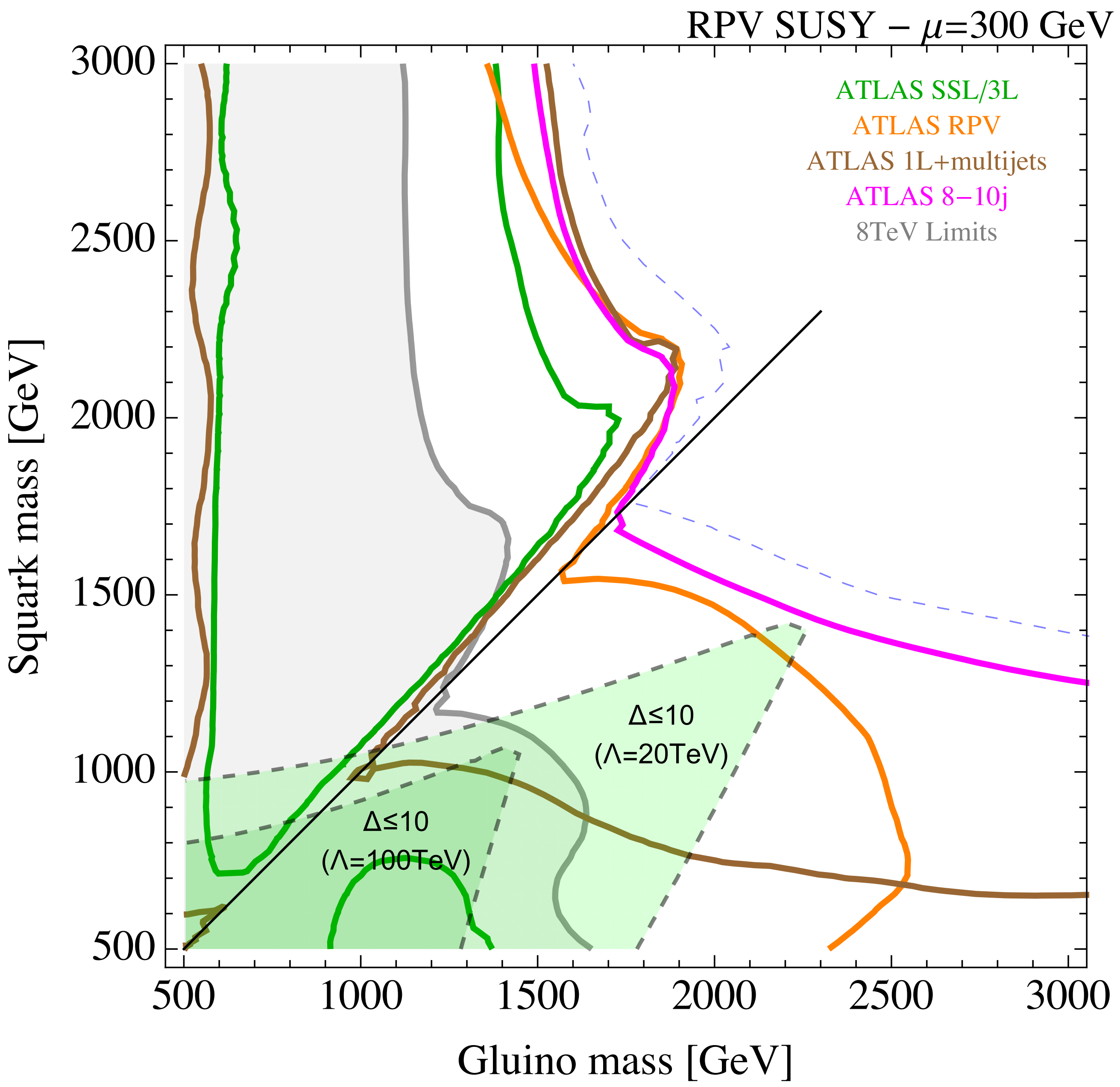
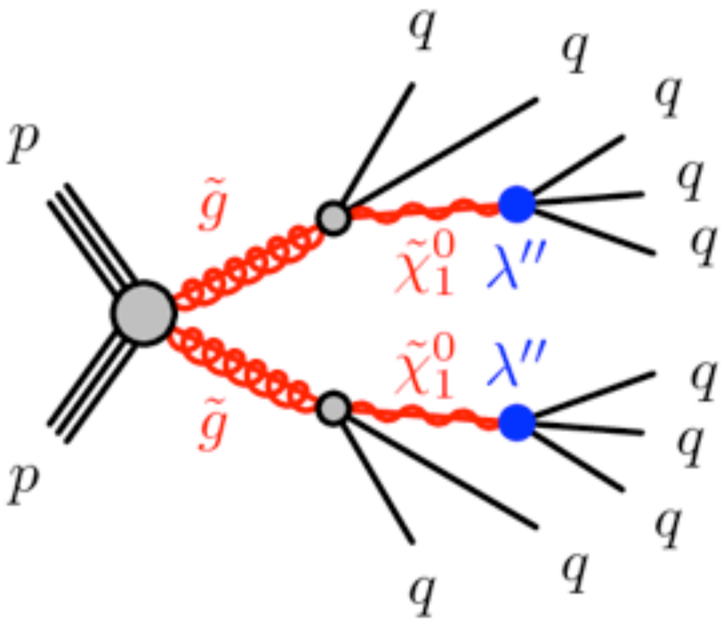




RPV can relax bounds on flavor-universal squarks (Graham, Rajendran & Saraswat '14)

RPV + flavor universal squarks





RPV can relax bounds on flavor-universal squarks (Graham, Rajendran & Saraswat ’14)

But after the ICHEP results, the fully natural part of parameter space is shrinking...

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, e.g. decreased squark cross sections at LHC (Kribs & Martin '12)
- Incompatible with simple SU(5) unification, mu/Bmu type problems, tachyons

Relaxing Naturalness Bounds

Higgsinos:

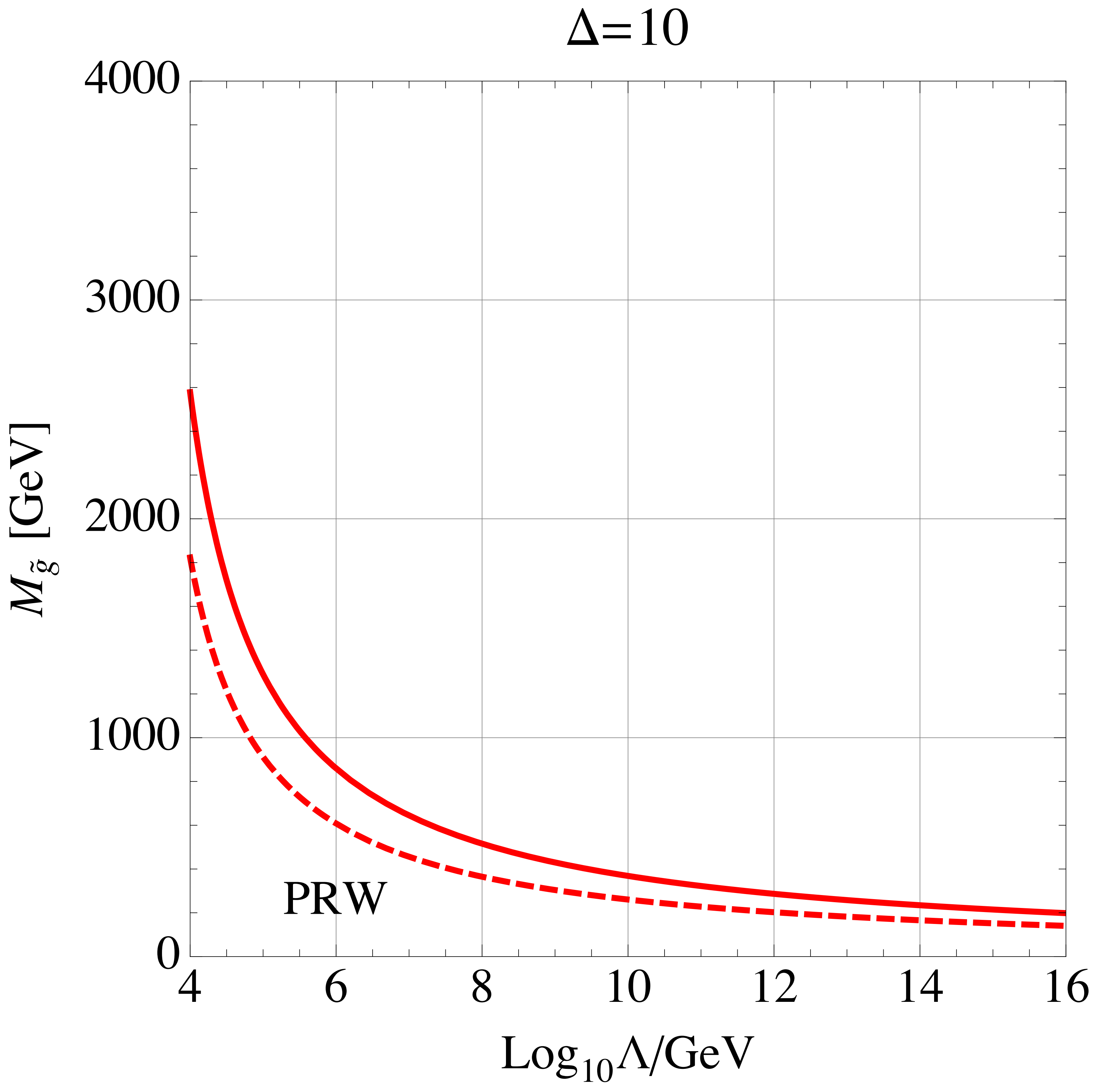
- Not easy to break tree-level connection between Higgsinos and tuning.
- One interesting idea: Higgsino mass from hard SUSY breaking
  (Brust, Katz, Lawrence & Sundrum ’11; Nelson & Roy ’15; Martin ’15)

$$\mathcal{L} = \int d^2\theta\, W'_\alpha D^\alpha H_u H_d$$

$$\mathcal{L} = \int d^4\theta\, X^\dagger X D^\alpha H_u D_\alpha H_d$$

- Can generate Higgsino mass without contributing to $m_{H_u}^2$. UV completion??
- Other ideas: Higgs as PNGB? (Cohen, Kearny & Luty ’15). Or SUSY from 5D Scherk-Schwarz compactification? (Dimopoulos, Howe & March Russell ’14)...

Naturalness bounds the gluino mass as a function of the messenger scale Λ.



In calculating the gluino tuning bound, it is important to do a careful treatment of the quantum corrections

- Factor of 2 error

cf Casas et al 1407.6966

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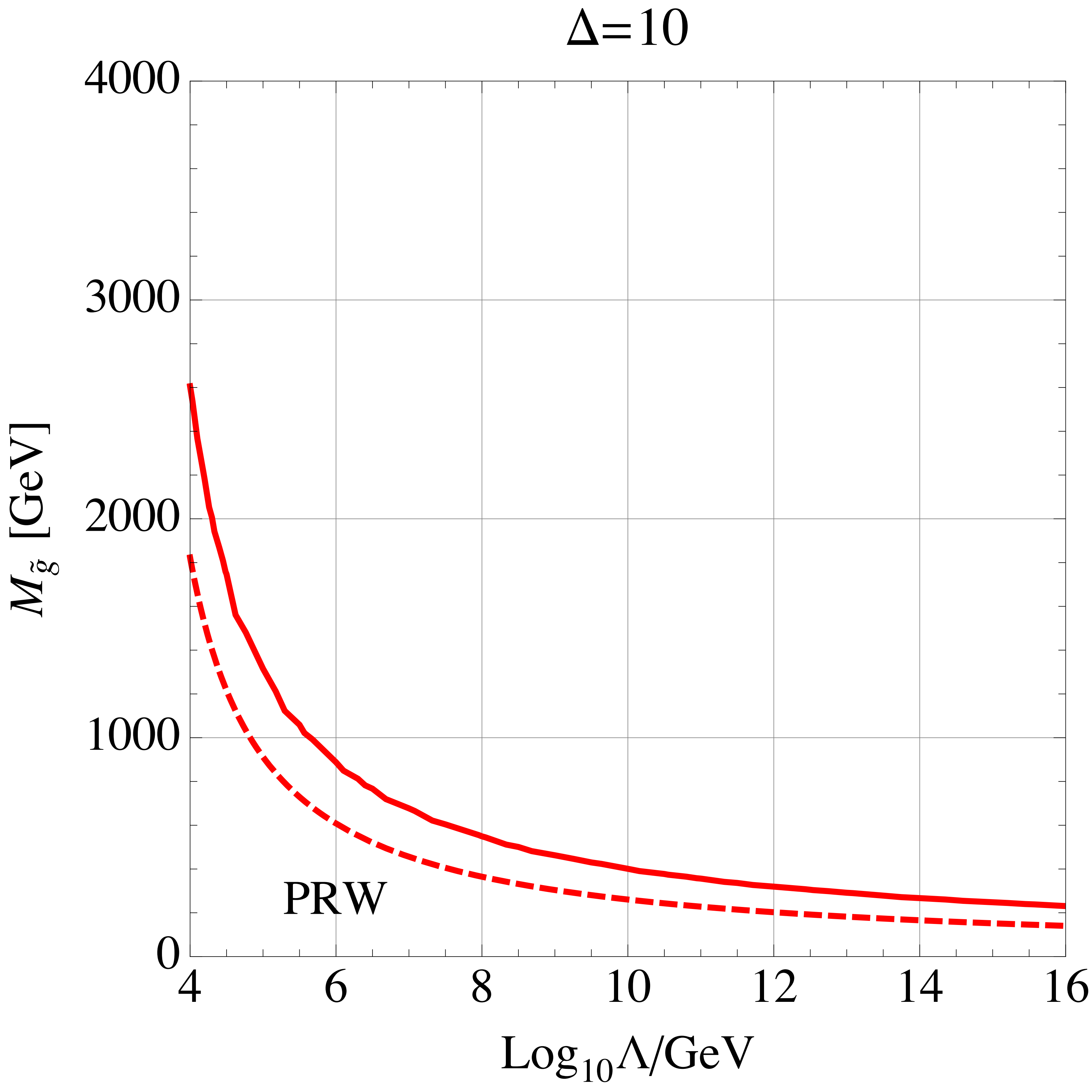

In calculating the gluino tuning bound, it is important to do a careful treatment of the quantum corrections

- Factor of 2 error
- LL vs. resummed RGEs

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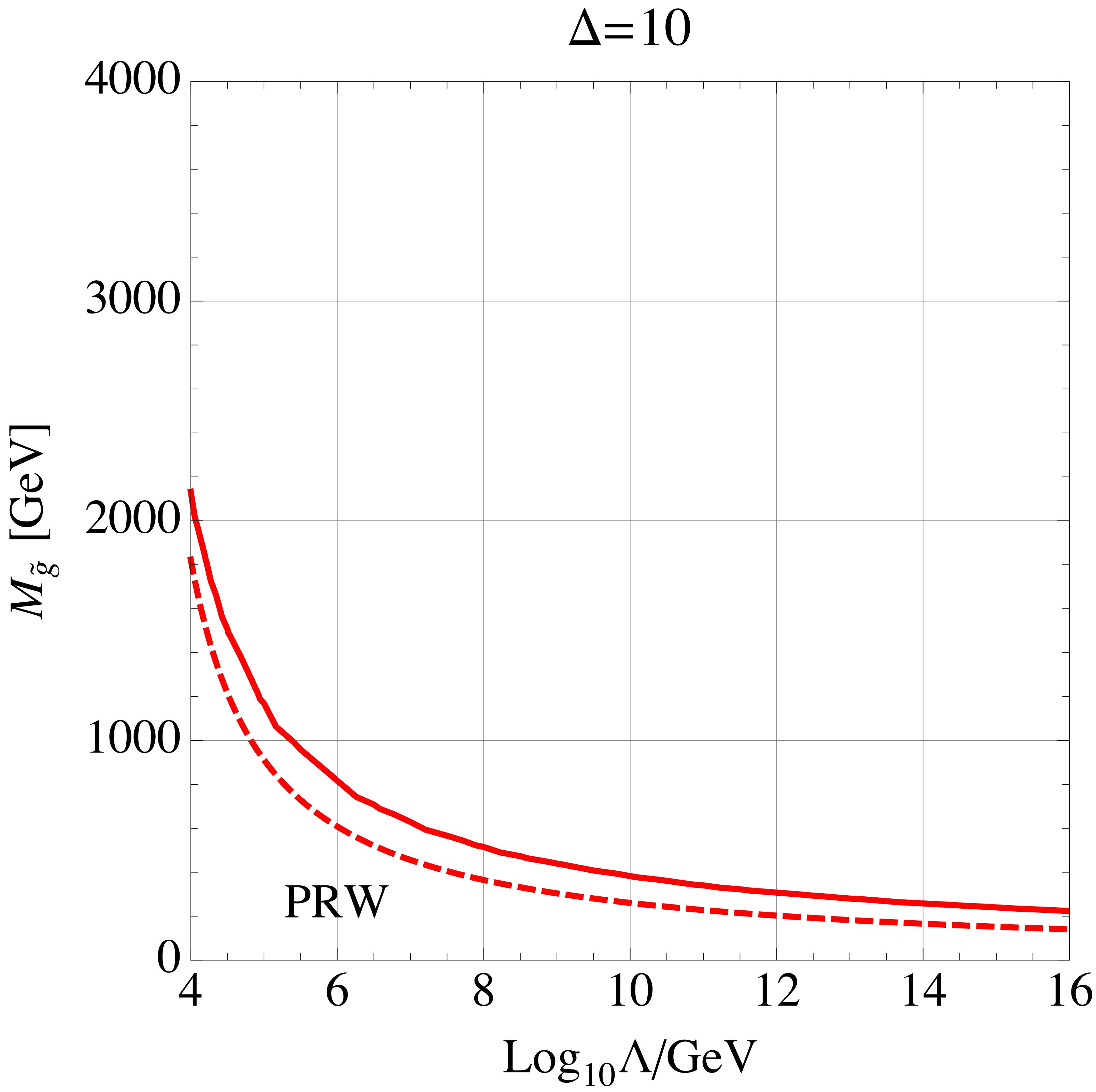

In calculating the gluino tuning bound, it is important to do a careful treatment of the quantum corrections

- Factor of 2 error
- LL vs. resummed RGEs
- 2-loop RGEs

cf Casas et al 1407.6966

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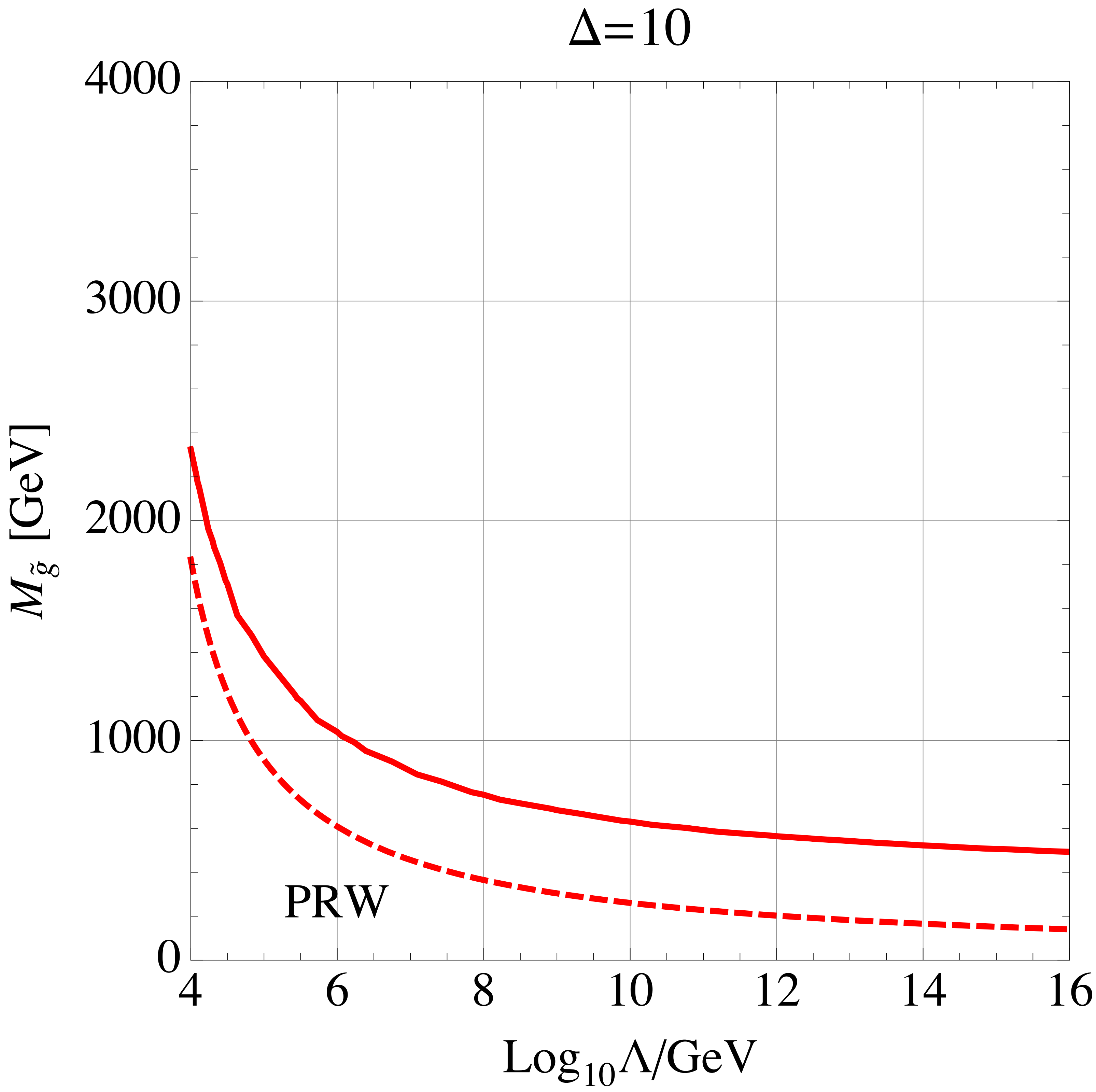

In calculating the gluino tuning bound, it is important to do a careful treatment of the quantum corrections

- Factor of 2 error
- LL vs. resummed RGEs
- 2-loop RGEs
- UV vs. IR mass

cf Casas et al 1407.6966

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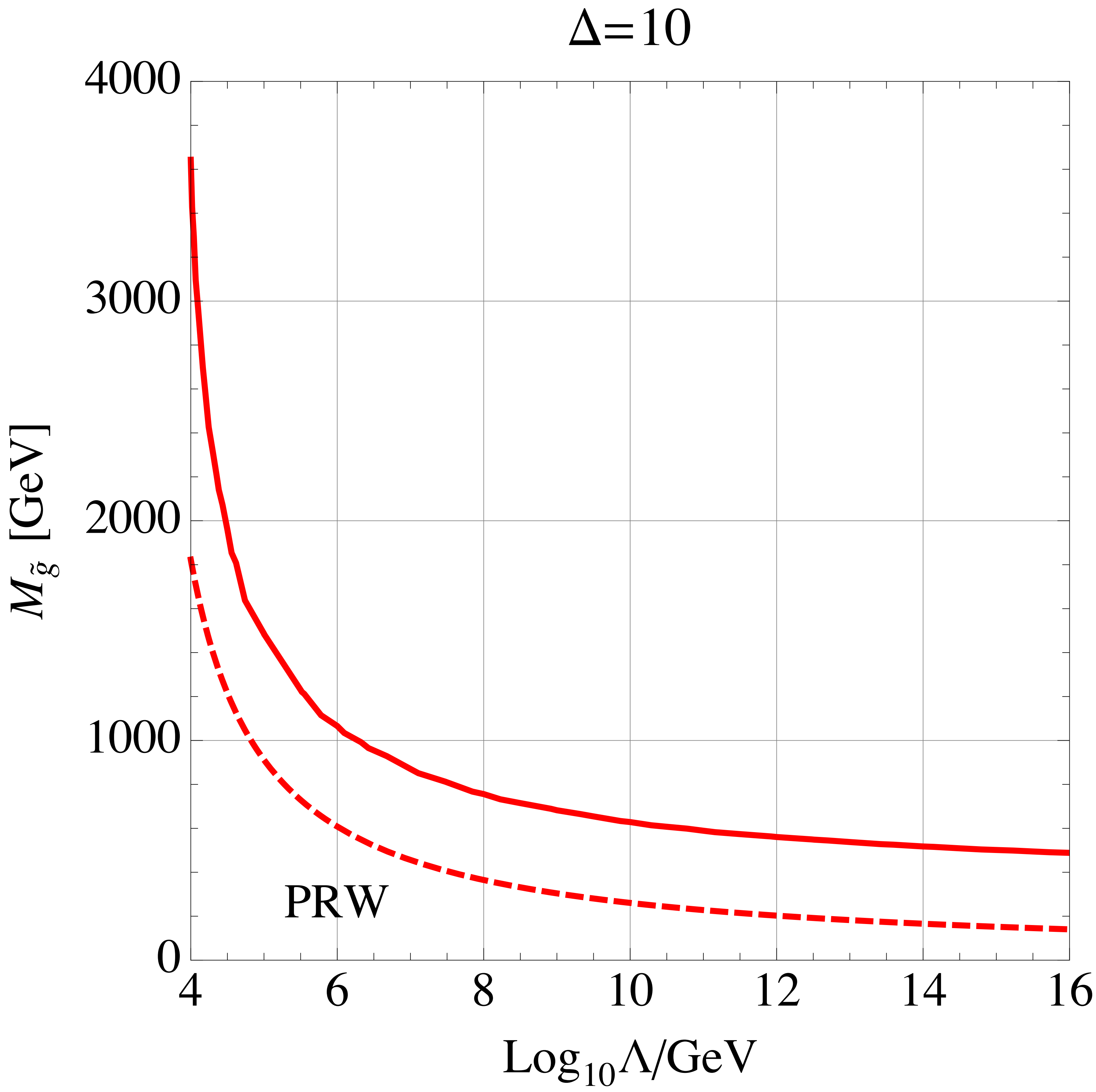

In calculating the gluino tuning bound, it is important to do a careful treatment of the quantum corrections

- Factor of 2 error
- LL vs. resummed RGEs
- 2-loop RGEs
- UV vs. IR mass
- finite threshold corrections

cf Casas et al 1407.6966

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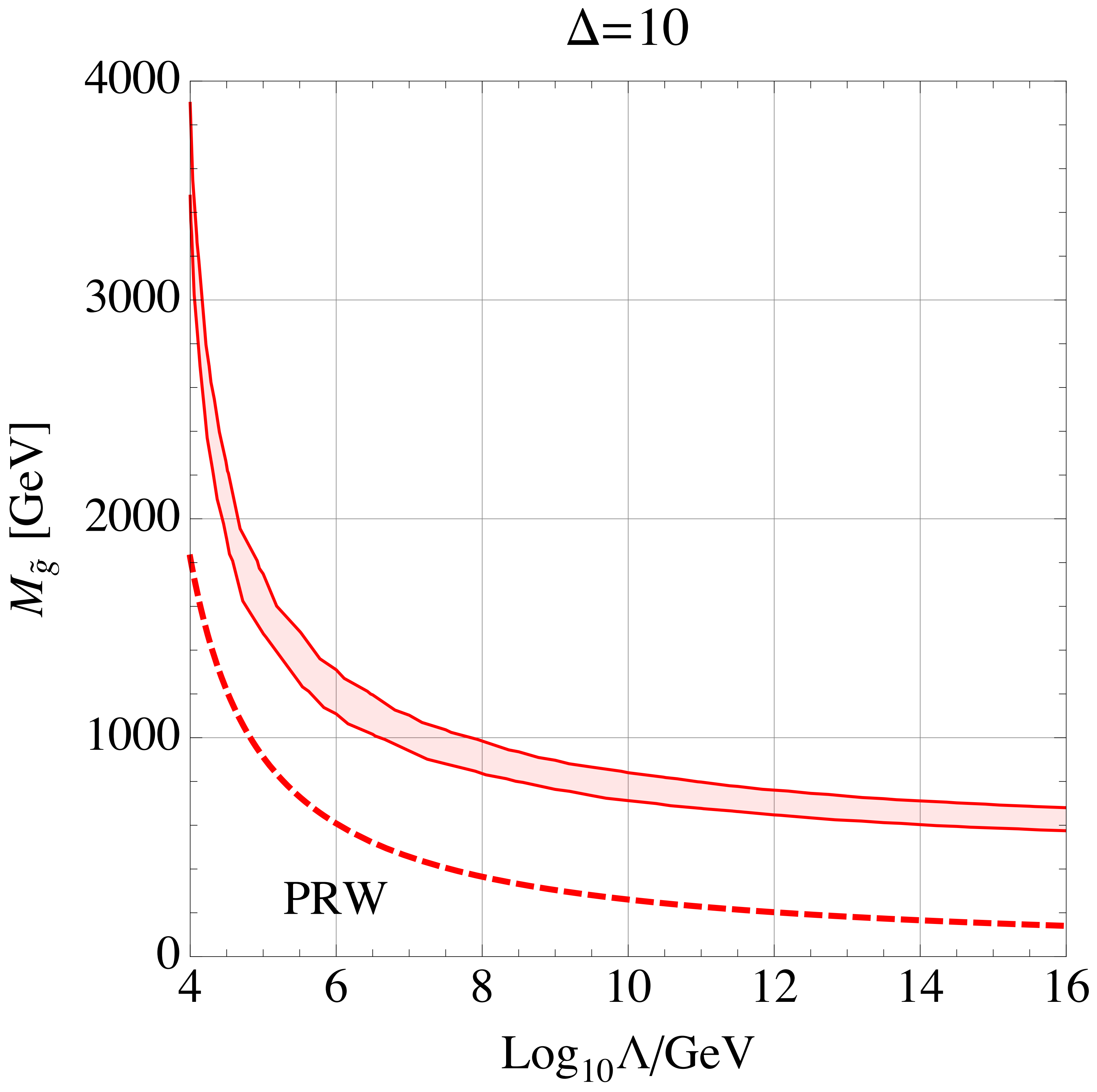


In calculating the gluino tuning bound, it is important to do a careful treatment of the quantum corrections

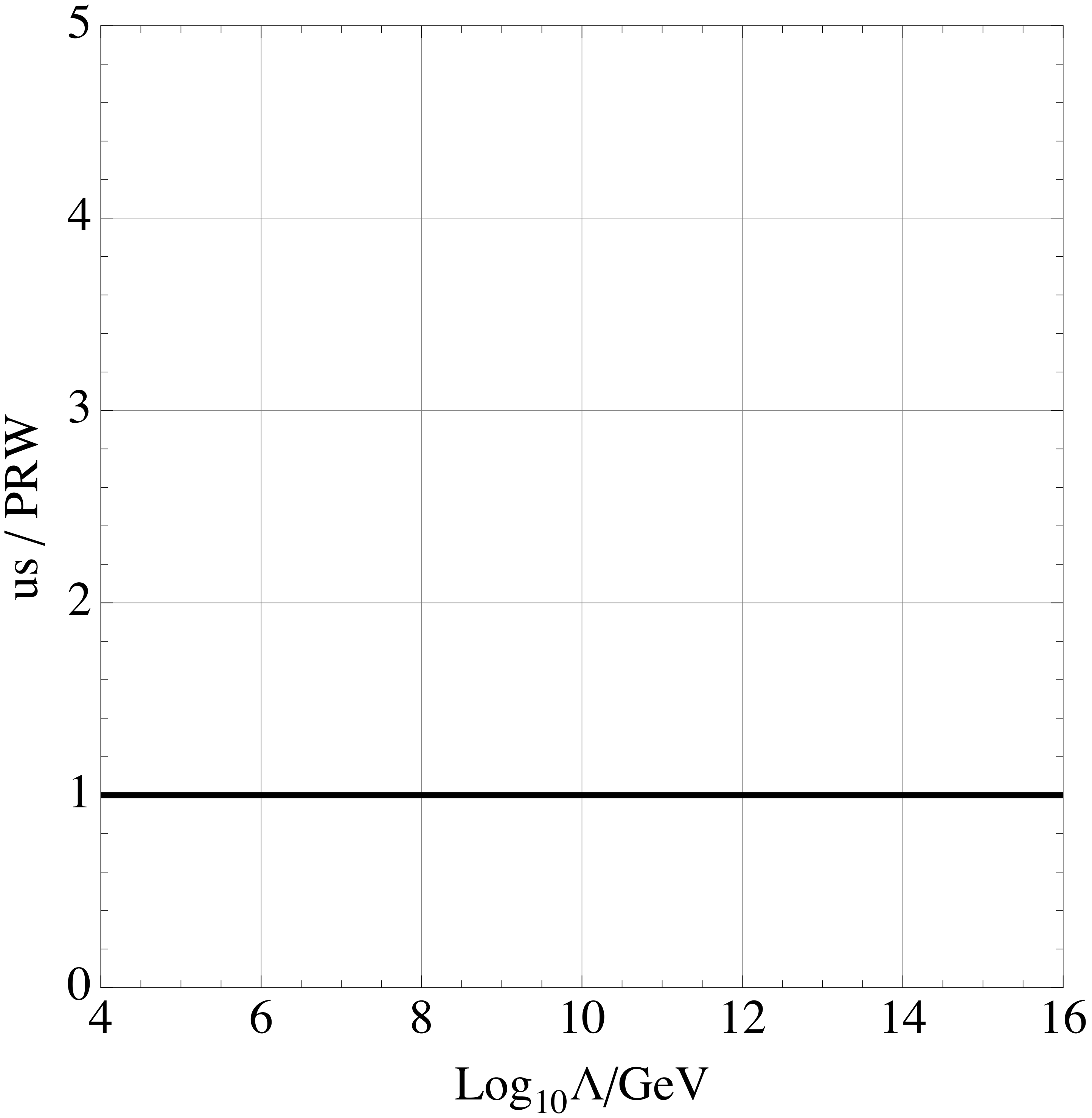
- Factor of 2 error
- LL vs. resummed RGEs
- 2-loop RGEs
- UV vs. IR mass
- finite threshold corrections
- IR mass vs. pole mass

Together, these effects relax the gluino tuning bounds by at least a factor of 2!

cf Casas et al 1407.6966

In calculating the gluino tuning bound, it is important to treat the quantum corrections carefully.

Buckley, Feld, Macaluso, Monteux, DS 1609.NNNNN
(see also Casas et al 1407.6966)



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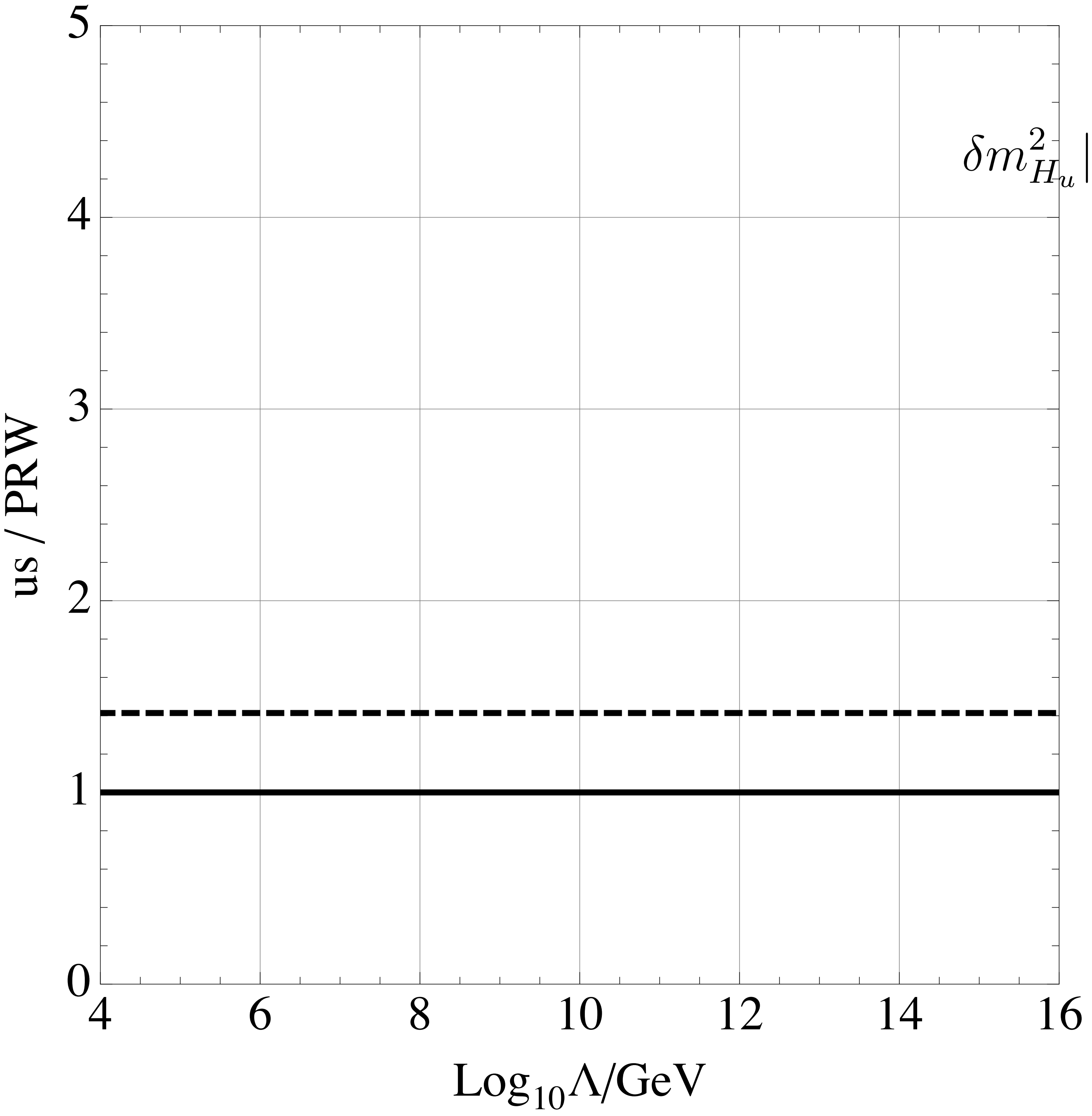

- Factor of 2 error

$$\delta m^2_{H_u}|_{gluino} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

In calculating the gluino tuning bound, it is important to treat the quantum corrections carefully.

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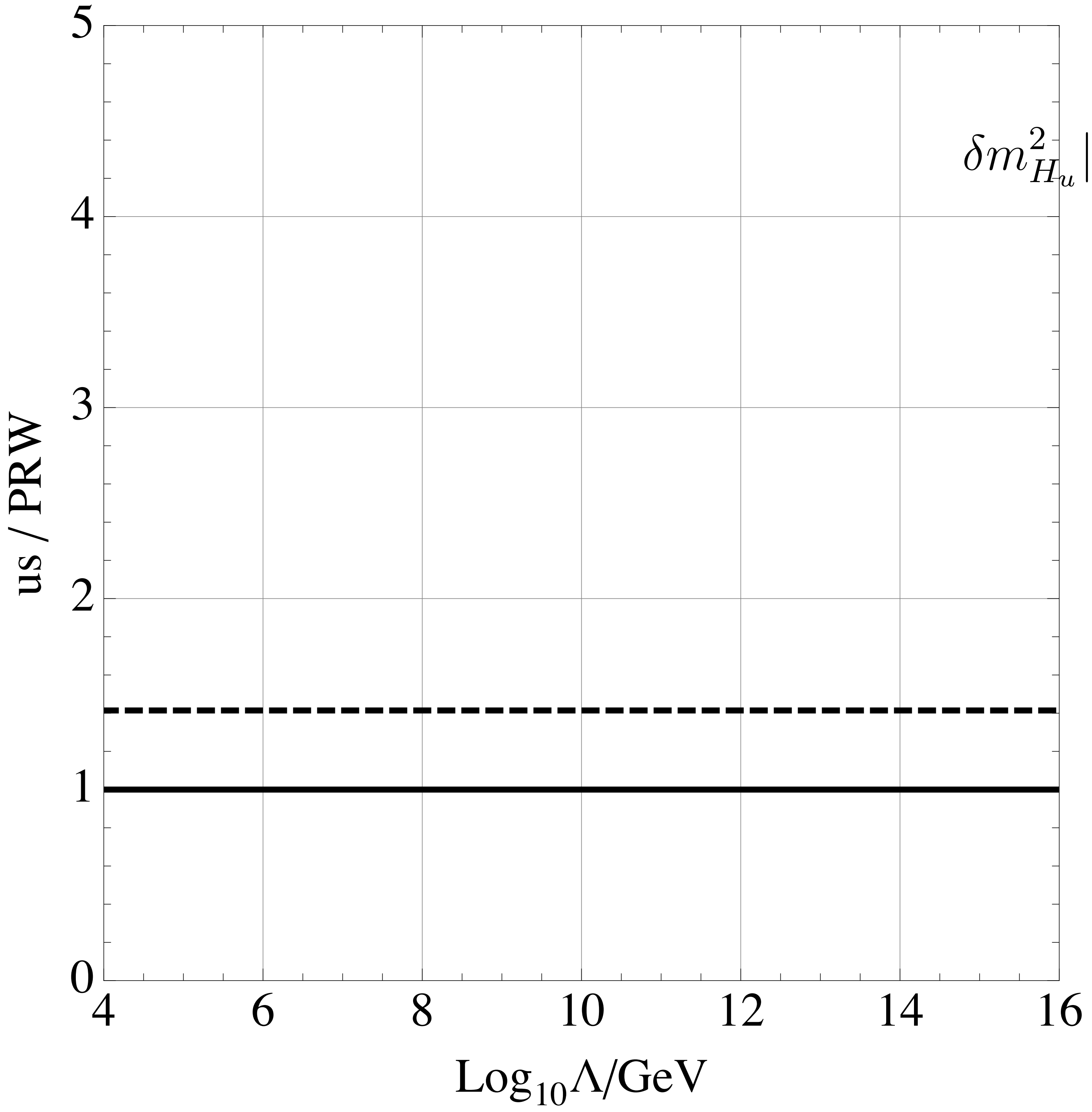

- Factor of 2 error

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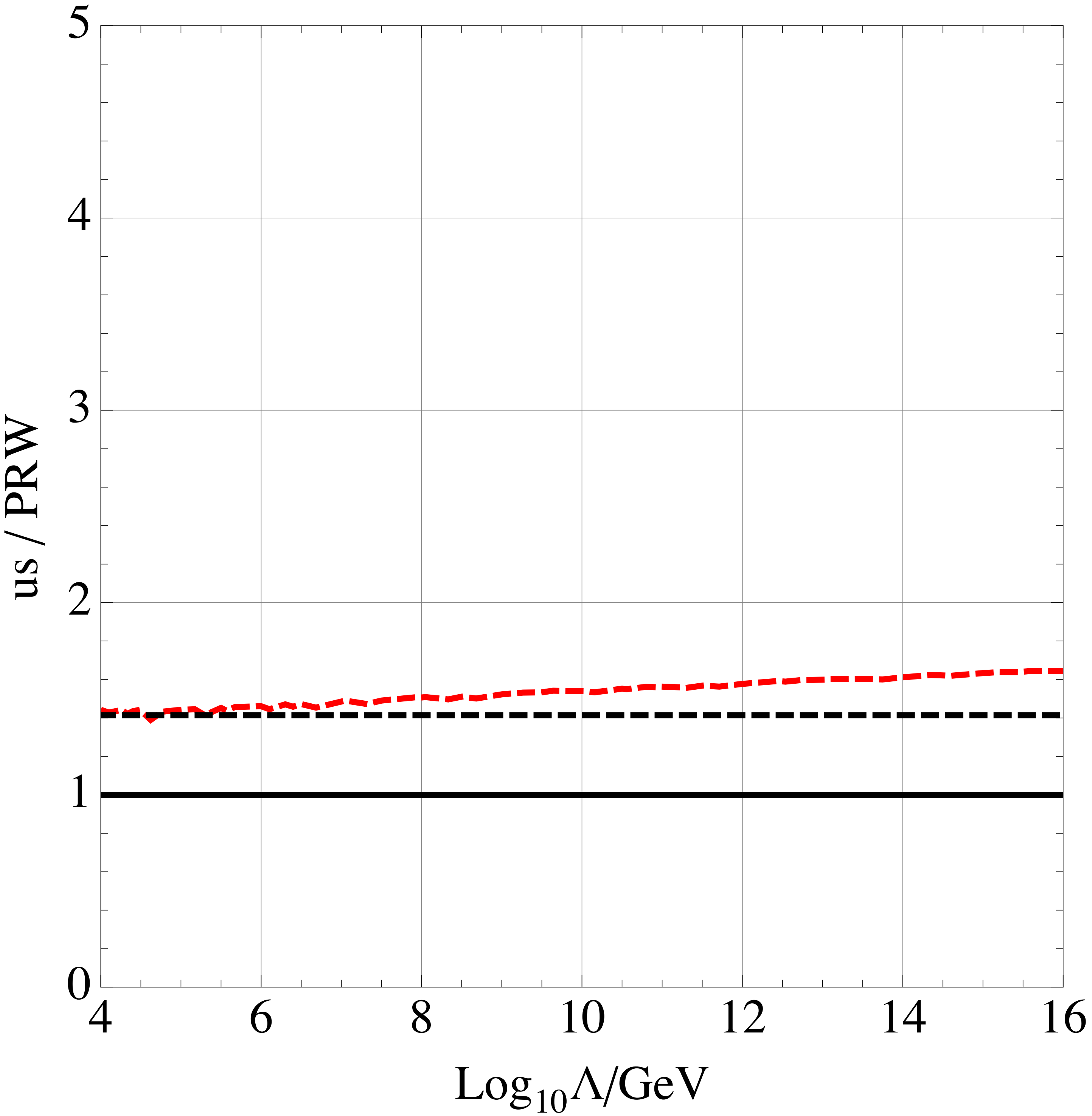


- Factor of 2 error
- LL vs. resummed RGEs

$$\delta m_H^2 = -\left(\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi}\left(\log\frac{\Lambda}{\mathrm{TeV}}\right)^2\right)M_3^2$$

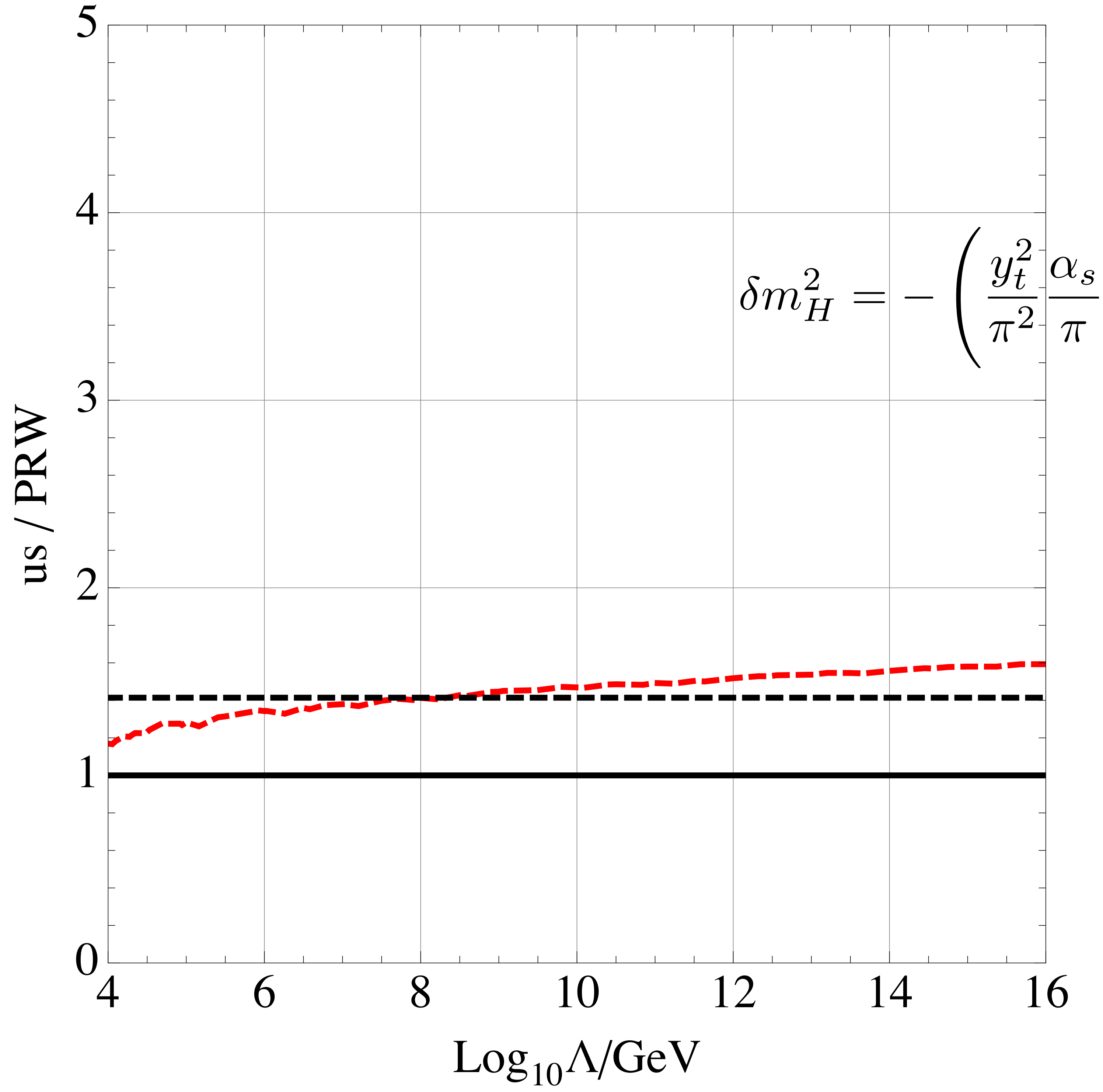
$$\downarrow$$

$$\delta m_H^2(Q) = -c(Q;\Lambda)M_3^2$$

e.g. c(Q=1 TeV; $\Lambda=10^{16}$ GeV)~1.5

In calculating the gluino tuning bound, it is important to treat the quantum corrections carefully.

Buckley, Feld, Macaluso, Monteux, DS 1609.NNNNN
(see also Casas et al 1407.6966)



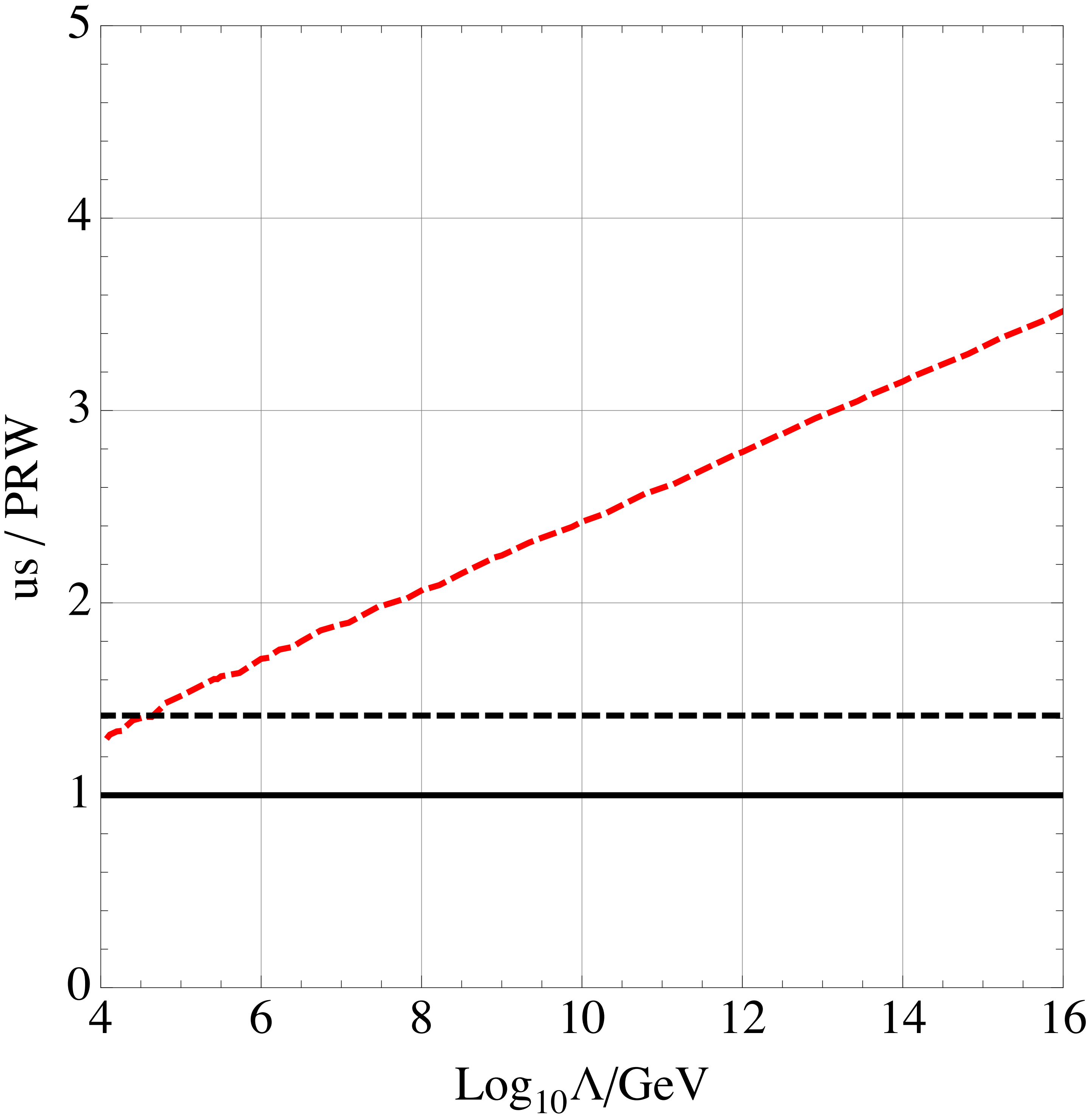
- Factor of 2 error
- LL vs. resummed RGEs
- 2-loop RGEs

$$\delta m_H^2 = -\left(\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi}\left(\log\frac{\Lambda}{\mathrm{TeV}}\right)^2 + \frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi}\left(\log\frac{\Lambda}{\mathrm{TeV}}\right)\right)M_3^2$$

In calculating the gluino tuning bound, it is important to treat the quantum corrections carefully.

Buckley, Feld, Macaluso, Monteux, DS 1609.NNNNN

(see also Casas et al 1407.6966)



- Factor of 2 error
- LL vs. resummed RGEs
- 2-loop RGEs
- UV vs. IR mass

$$M_3^{IR} = \frac{(g_3^2)^{IR}}{(g_3^2)^{UV}} M_3^{UV}$$

In calculating the gluino tuning bound, it is important to treat the quantum corrections carefully.

Buckley, Feld, Macaluso, Monteux, DS 1609.NNNNN
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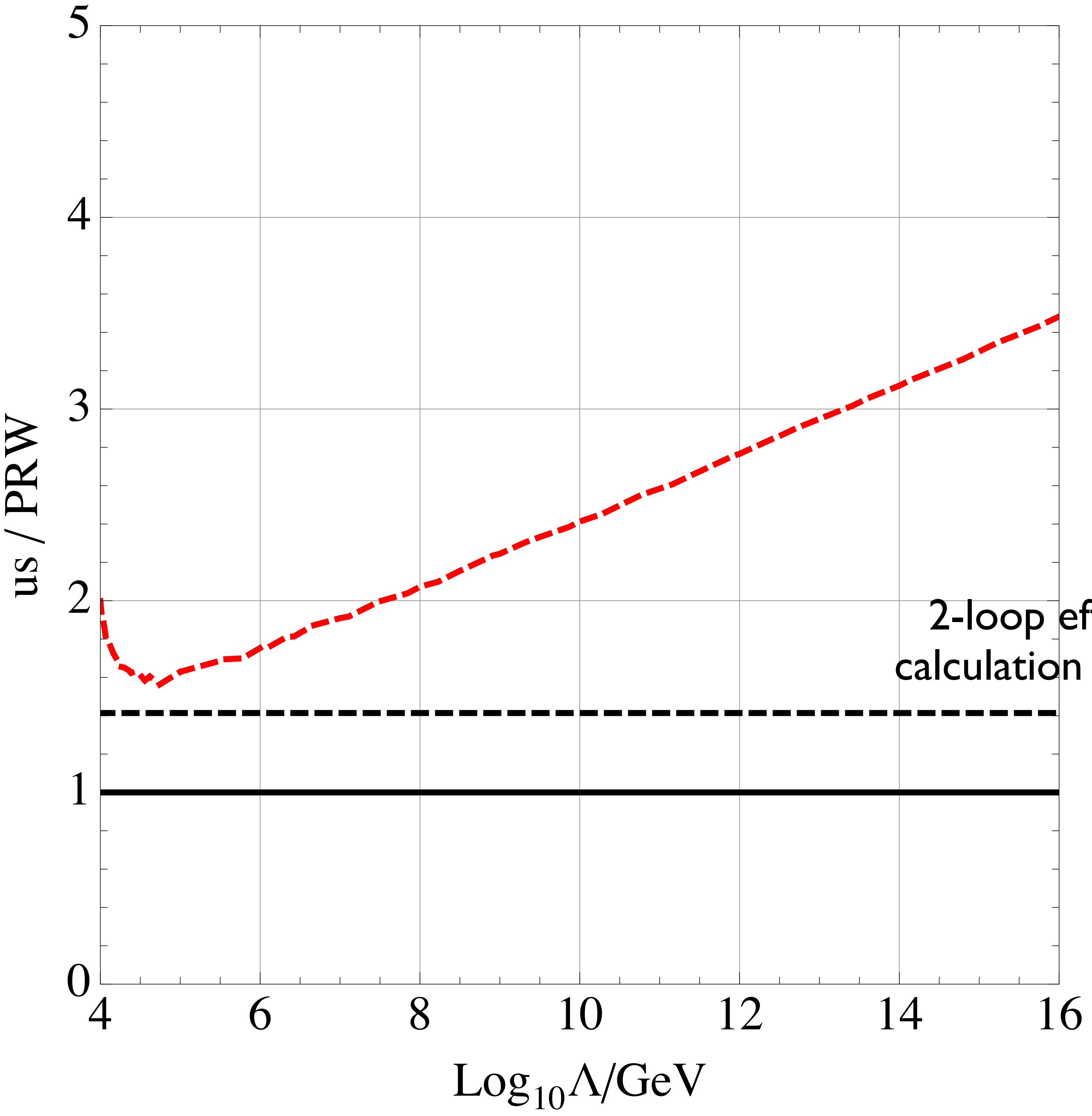


- Factor of 2 error
- LL vs. resummed RGEs
- 2-loop RGEs
- UV vs. IR mass
- finite threshold corrections

$$\delta m_H^2 = -\left(\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi}\left(\log\frac{\Lambda}{\mathrm{TeV}}\right)^2\right) M_3^2$$

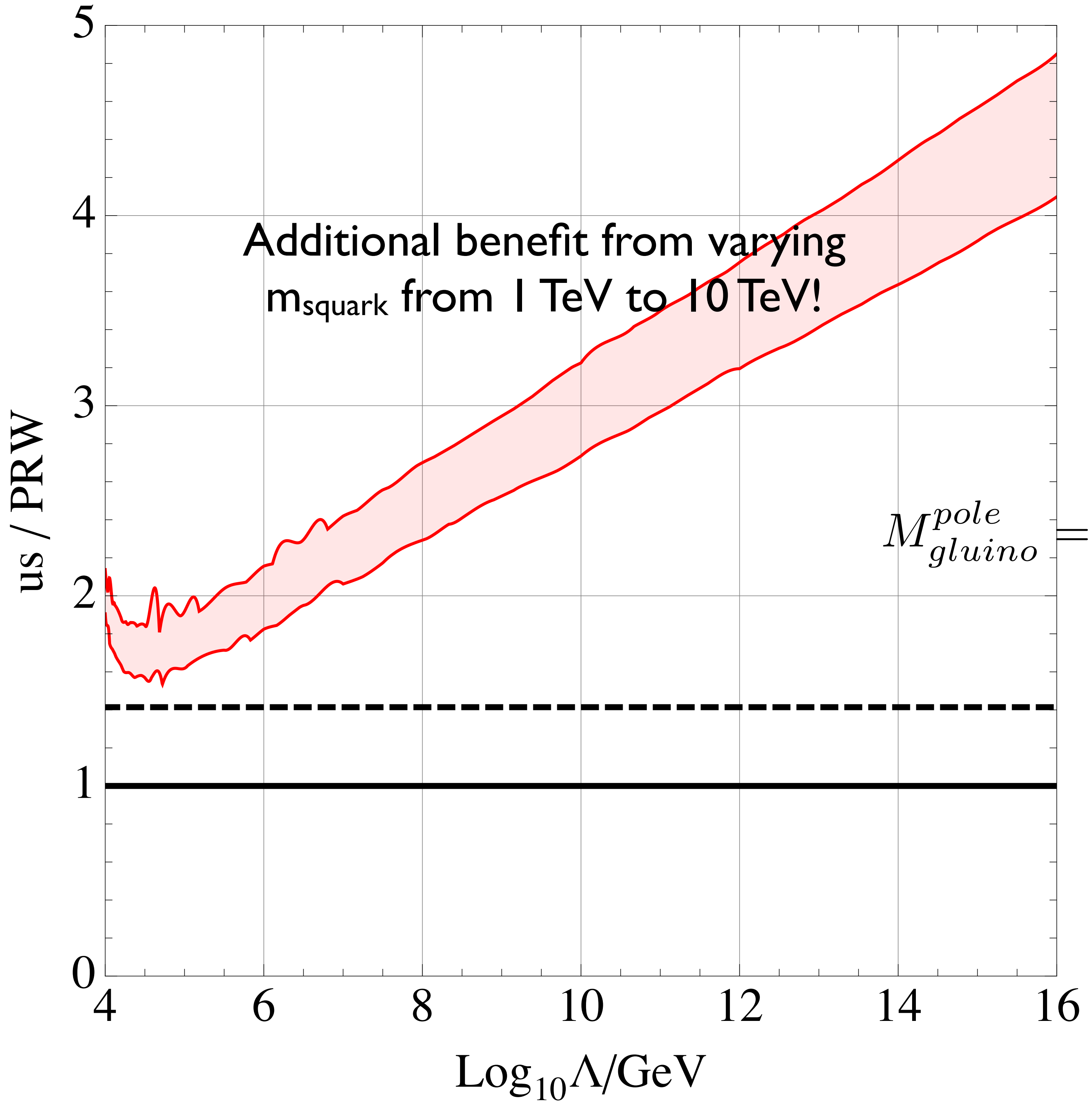
2-loop effective potential calculation (Martin 0206136)

$$\Big\downarrow$$

$$\delta m_H^2 = -\left(\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi}\left(\log\frac{\Lambda}{\mu_{\mathrm{eff}}}\right)^2\right) M_3^2$$

In calculating the gluino tuning bound, it is important to treat the quantum corrections carefully.

Buckley, Feld, Macaluso, Monteux, DS 1609.NNNNN
(see also Casas et al 1407.6966)



Additional benefit from varying m_{squark} from 1 TeV to 10 TeV!

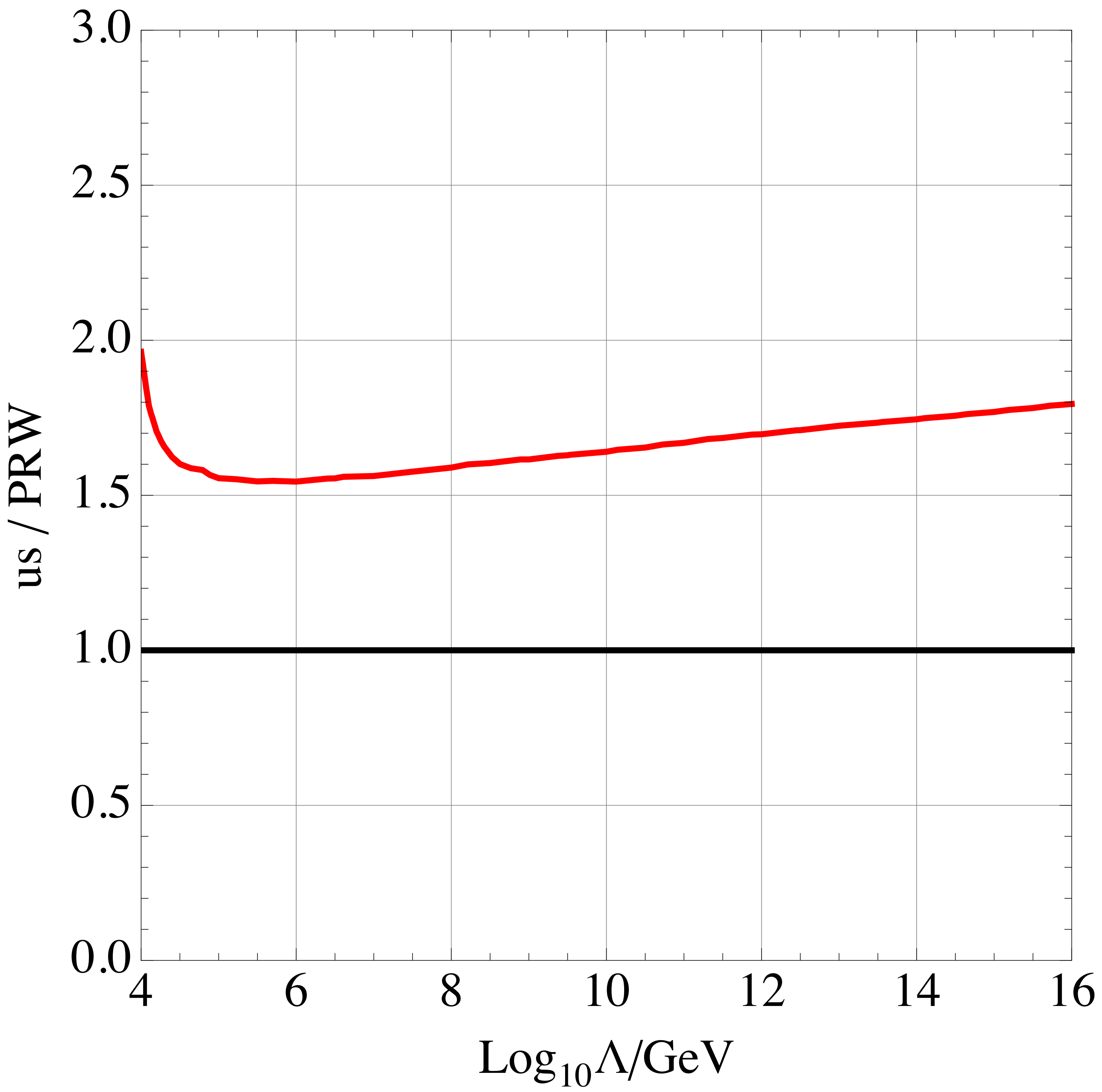
- Factor of 2 error
- LL vs. resummed RGEs
- 2-loop RGEs
- UV vs. IR mass
- finite threshold corrections
- IR mass vs. pole mass

$$M^{pole}_{gluino} = M_3(Q)\left[1-\left(\frac{\Delta M_3}{M_3}\right)^{g\tilde{g}} - \left(\frac{\Delta M_3}{M_3}\right)^{q\tilde{q}}\right]^{-1}$$

Together, these effects relax the gluino tuning bounds by a factor of 2 or more!

In calculating the stop tuning bound, it is important to treat the quantum corrections carefully.

Buckley, Feld, Macaluso, Monteux, DS 1609.NNNNN
(see also Casas et al 1407.6966)



Here the main effect is UV vs IR stop mass:

$$\delta m^2_{Q_3}(Q) = +b(Q;\Lambda)M_3(\Lambda)^2$$

$$\delta m^2_{H_u}(Q) = -a(Q;\Lambda)m^2_{Q_3}(\Lambda)$$

Tuning bounds UV stop mass, while IR stop mass is pulled up by gluinos.

Heavier gluino can result in more naturally heavier stops!

In calculating the stop tuning bound, it is important to treat the quantum corrections carefully.

Buckley, Feld, Macaluso, Monteux, DS 1609.NNNNN
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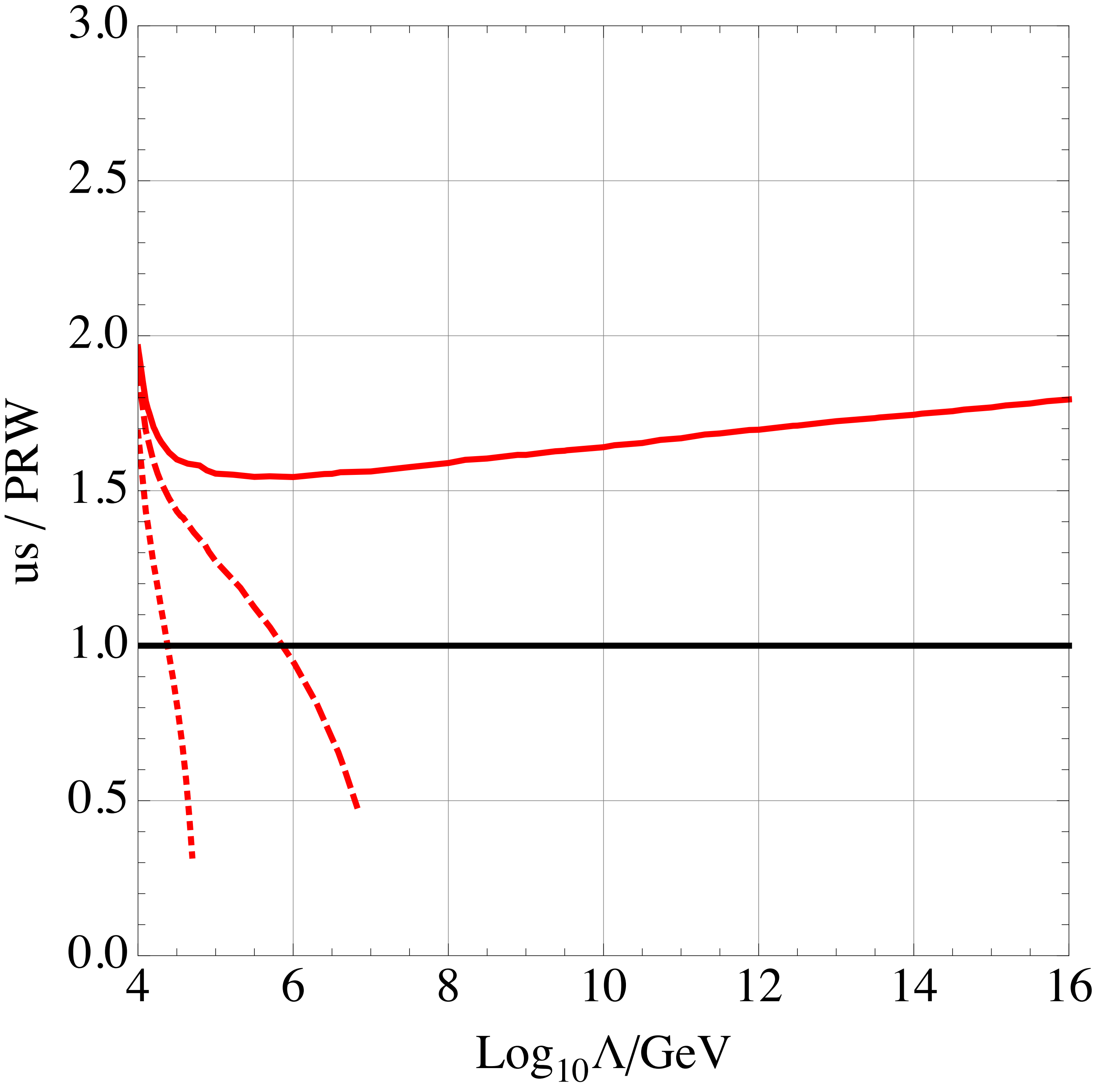
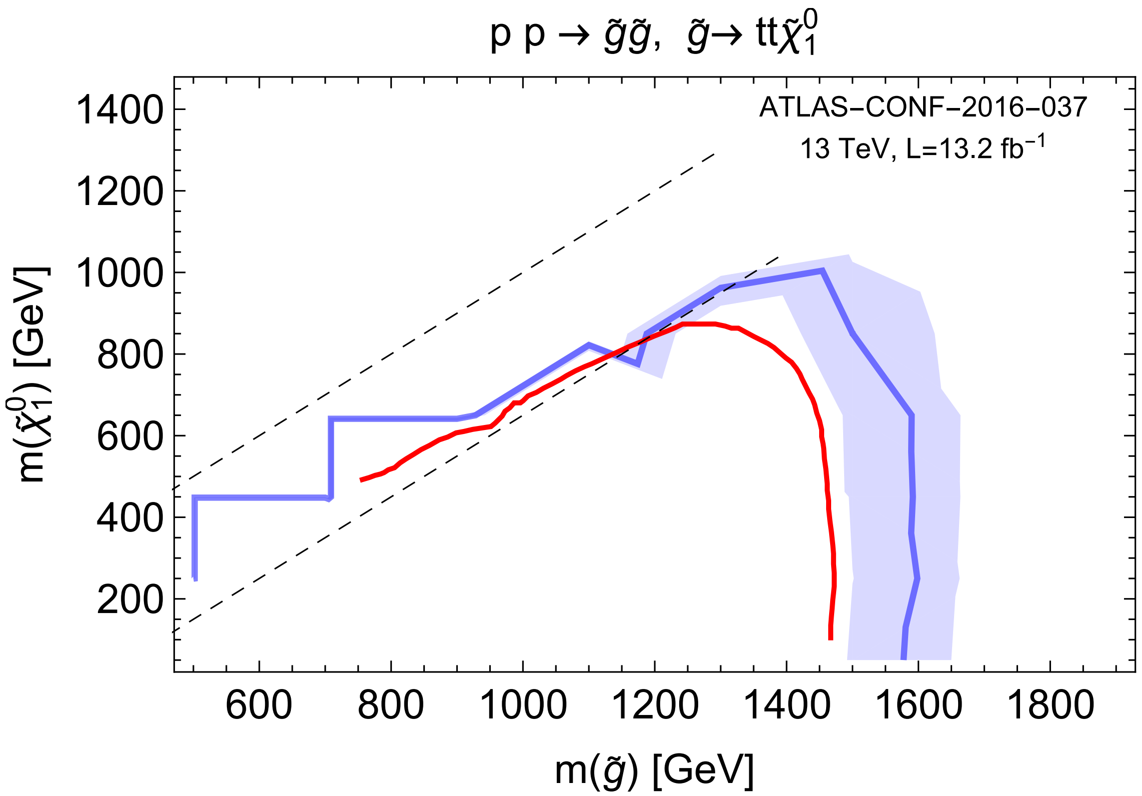
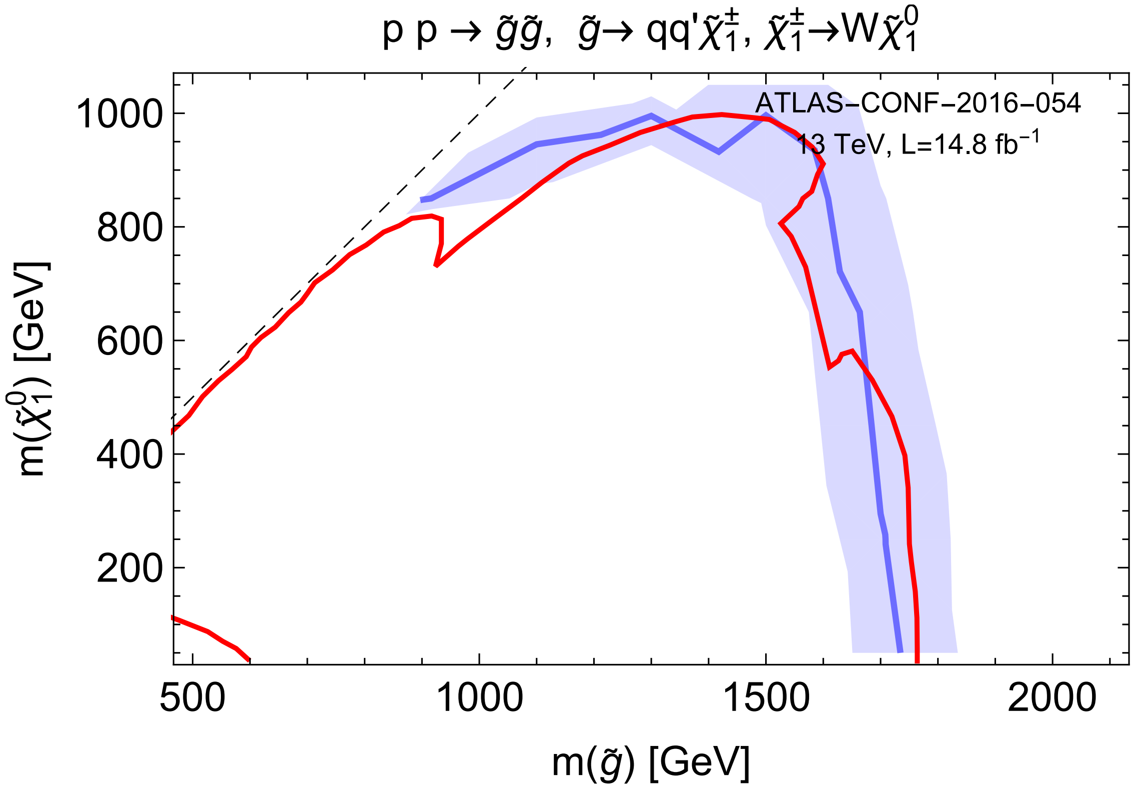
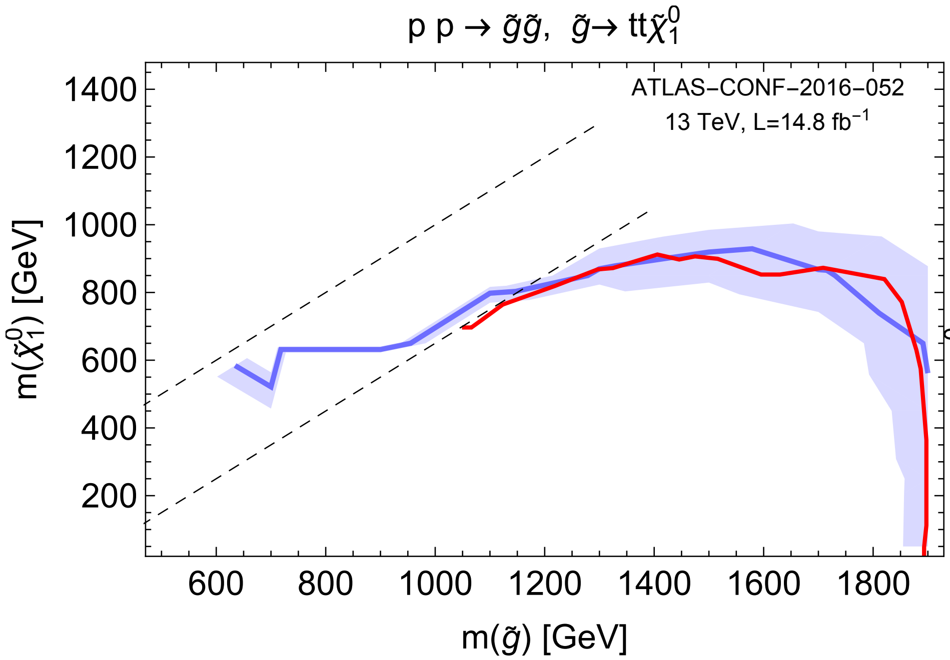
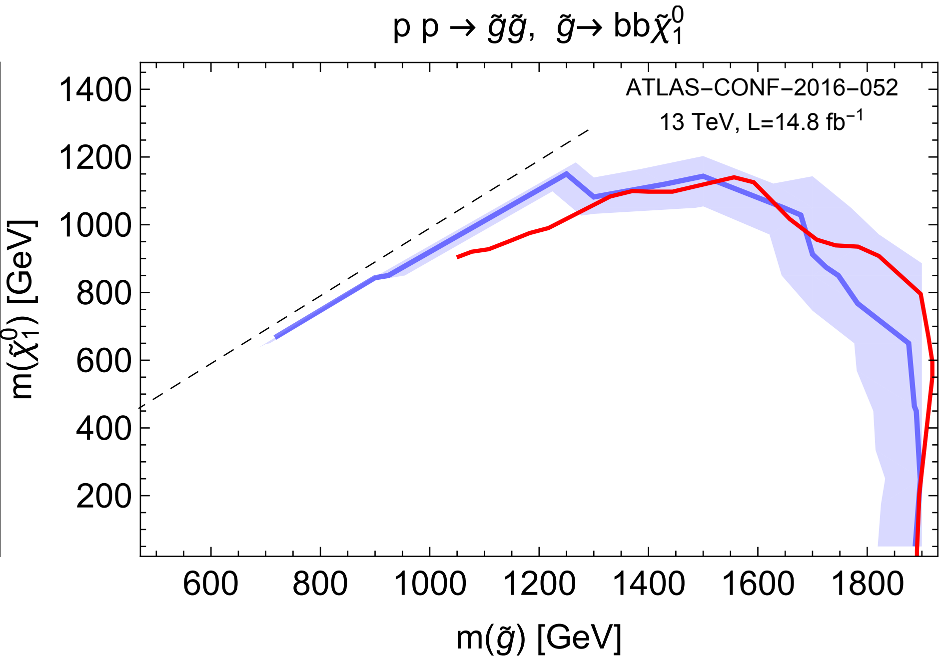


Validation plots









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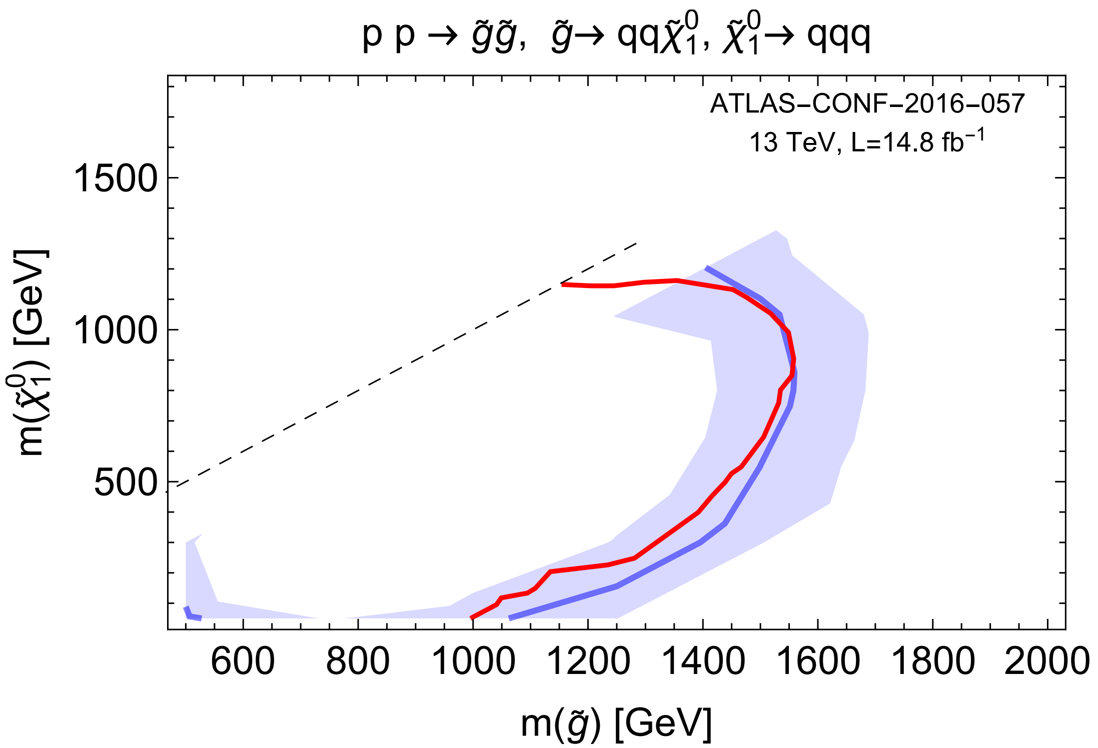
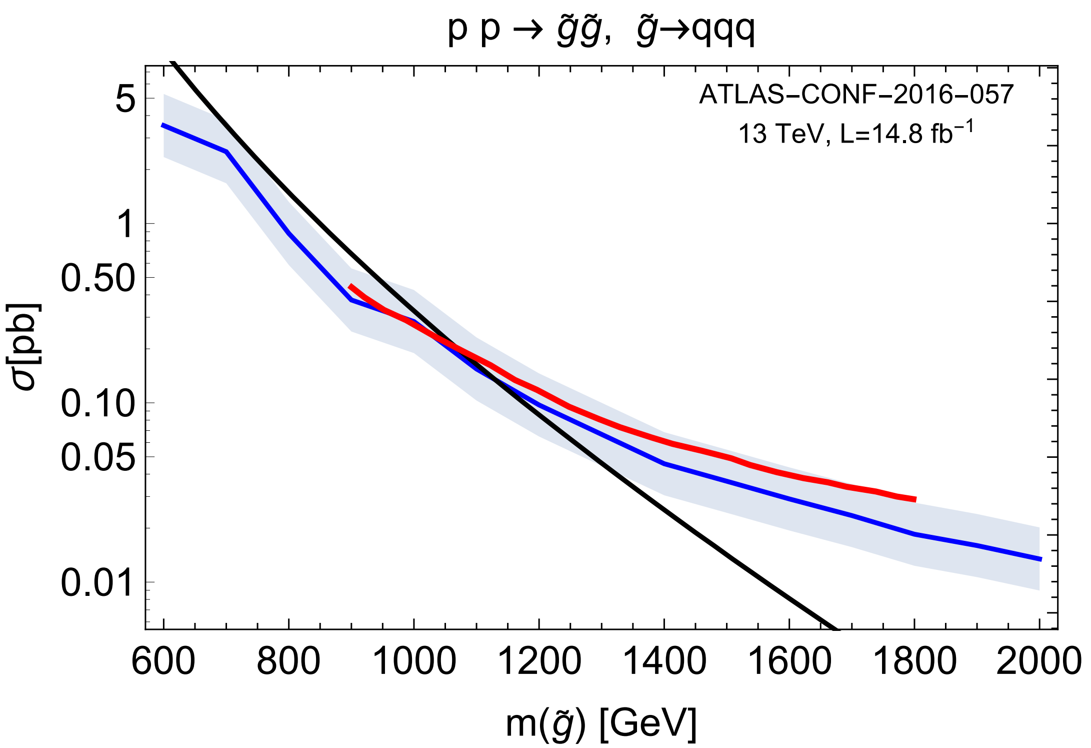
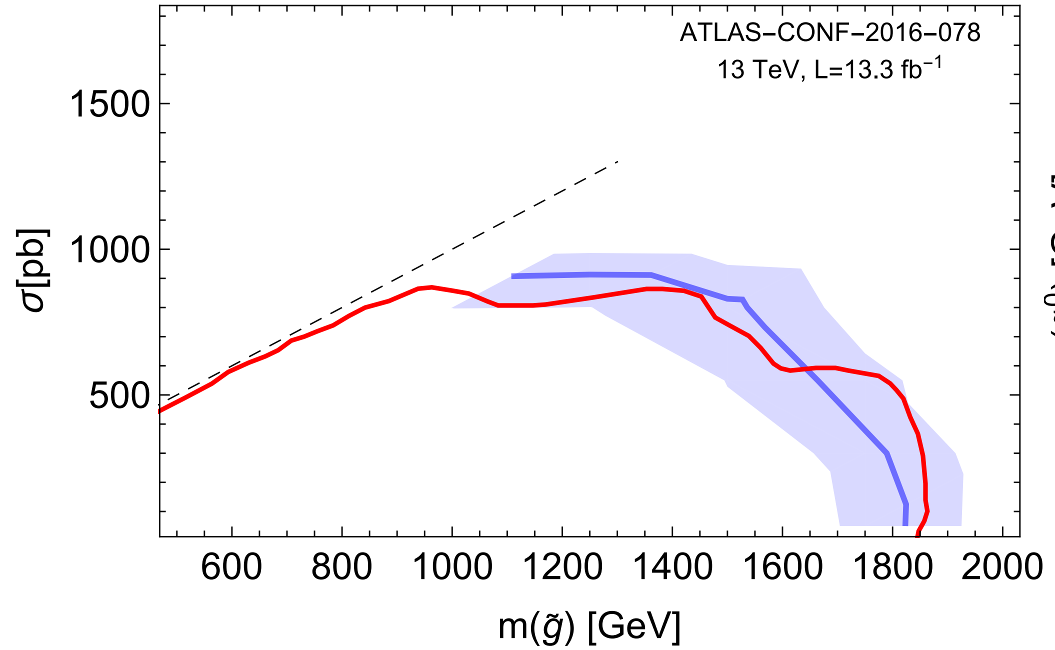


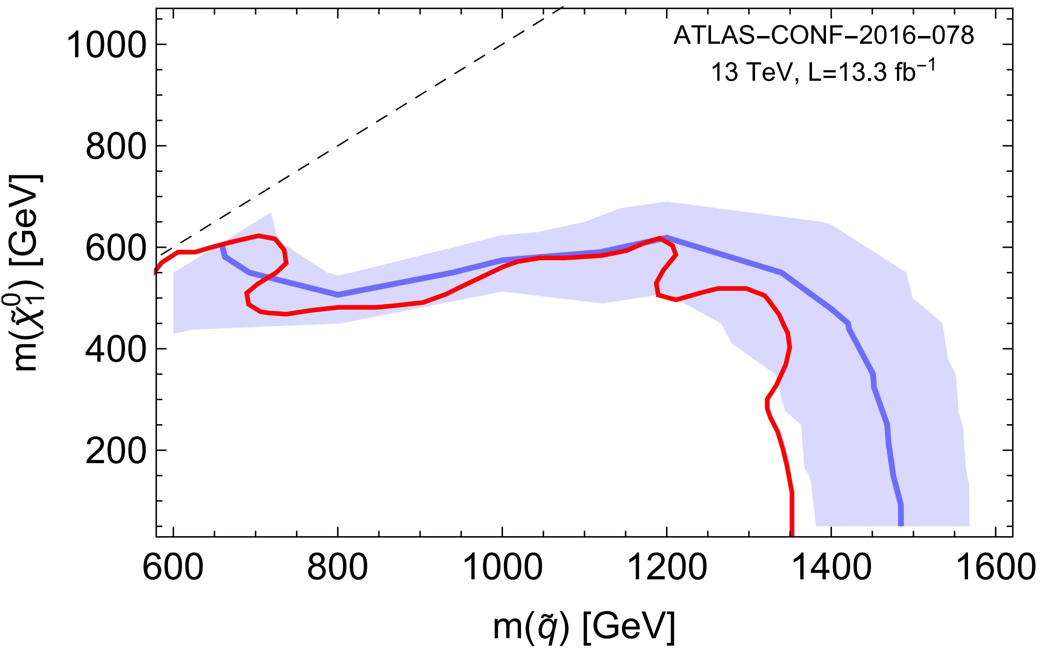


Validation plots

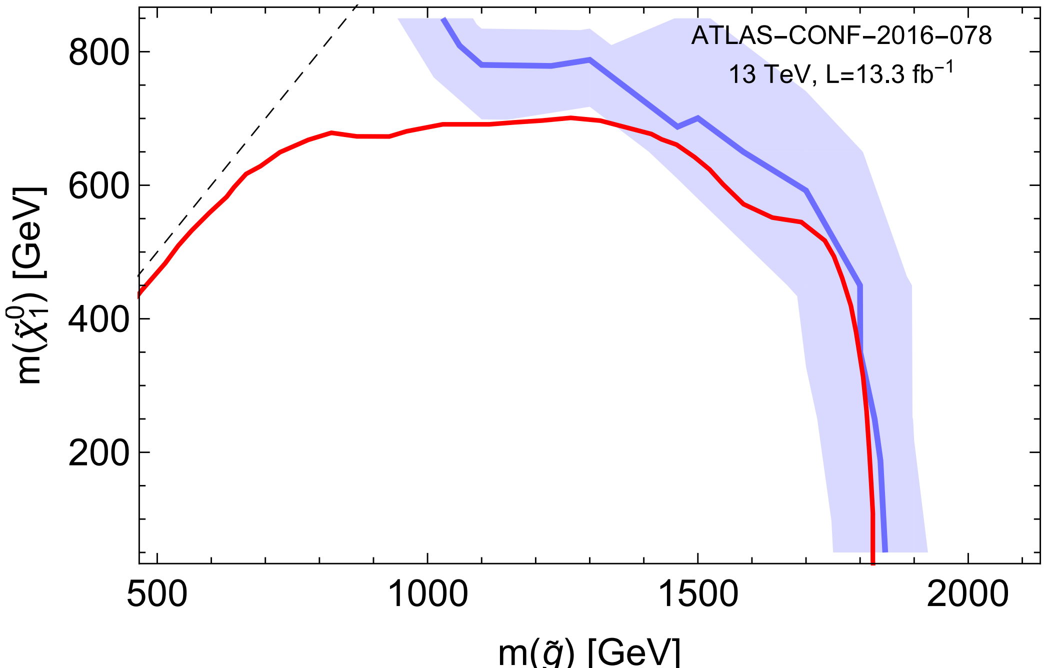
$p\,p \to \tilde{g}\tilde{g},\ \ \tilde{g}\to qq\tilde{\chi}_1^0$



$p\,p \to \tilde{q}\tilde{q},\ \ \tilde{q}\to q\tilde{\chi}_1^0$



$p\,p \to \tilde{g}\tilde{g},\ \ \tilde{g}\to qq'\tilde{\chi}_1^\pm,\ \tilde{\chi}_1^\pm\to W\tilde{\chi}_1^0$



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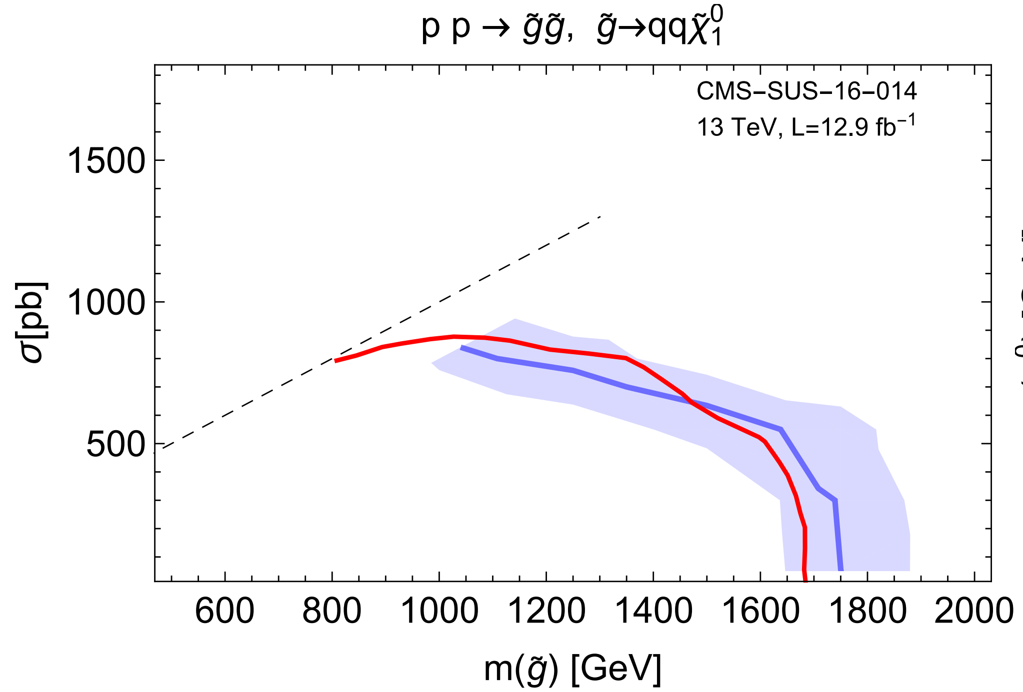
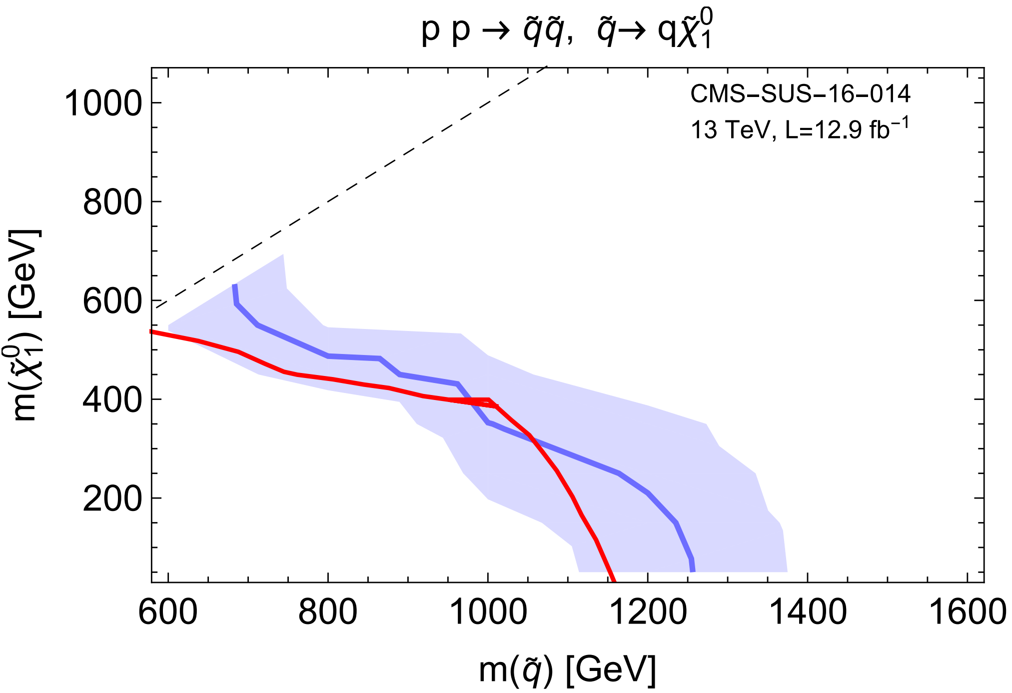
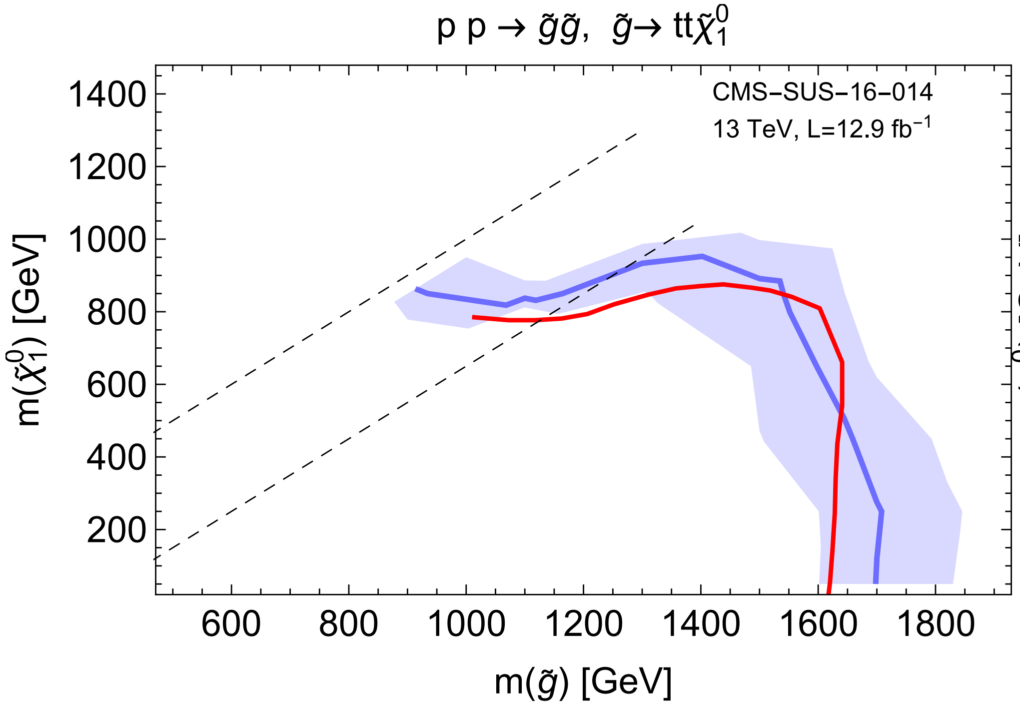
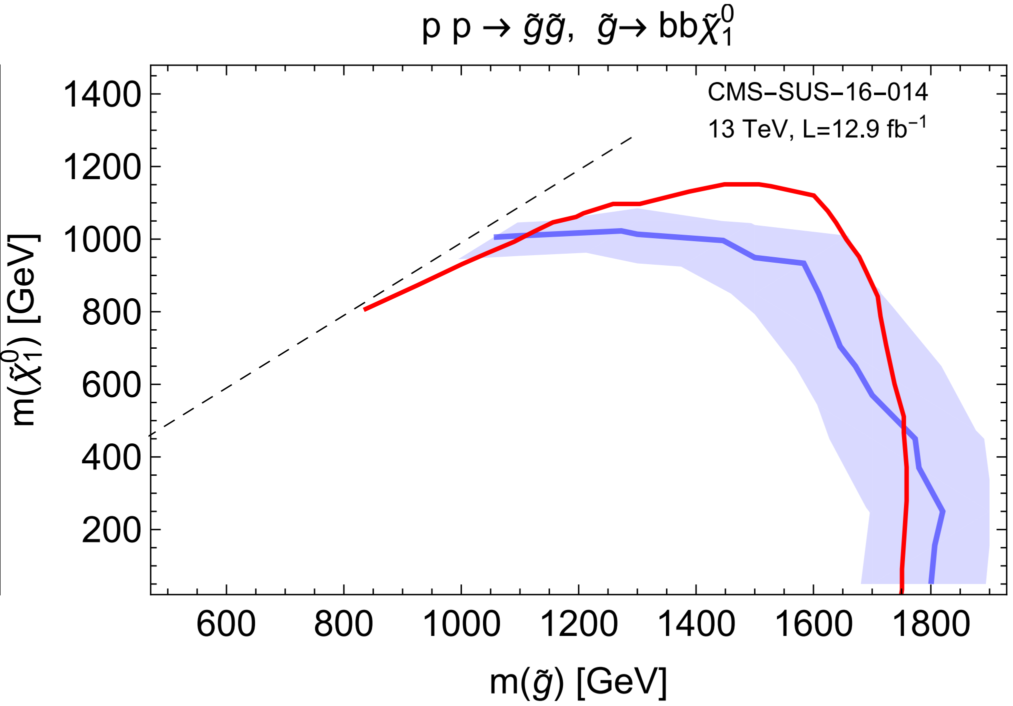
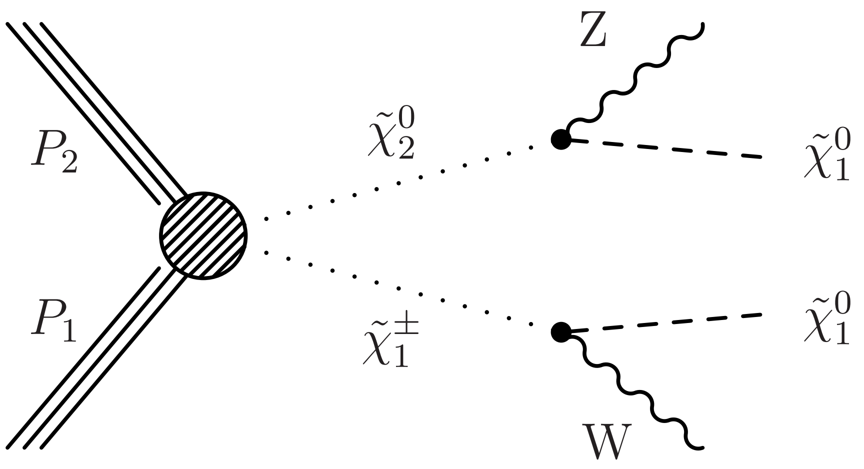
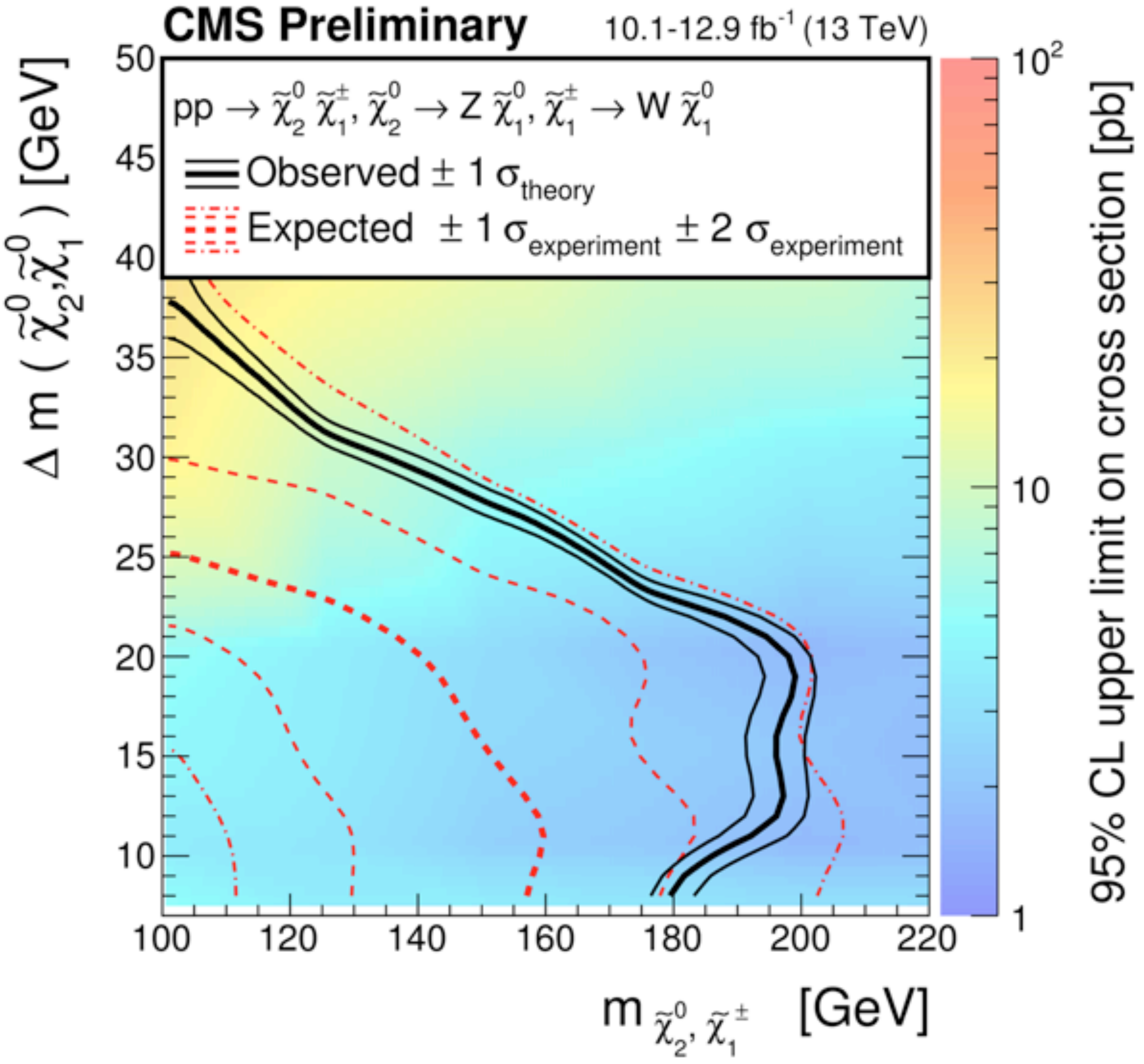








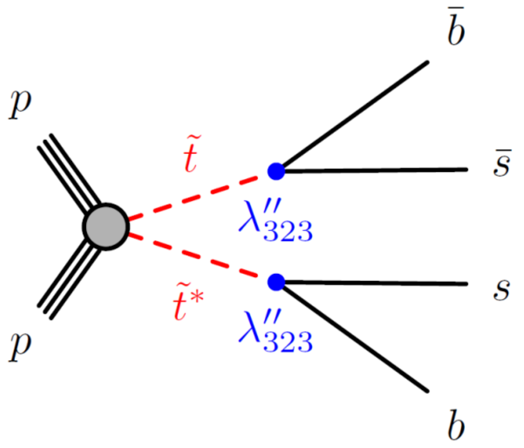




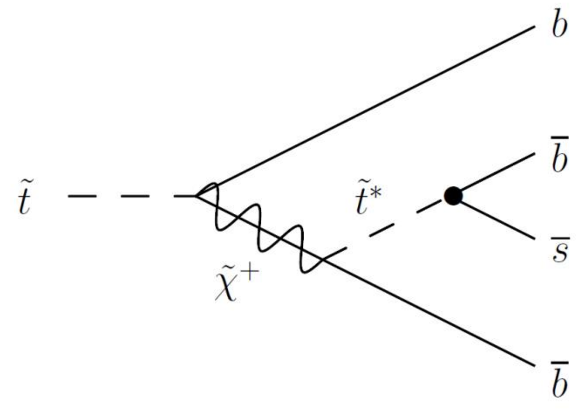
Very interesting recent CMS result on direct EWino production with (moderately) small splittings.

Unfortunately, limits are for Wino production. Higgsino xsecs are smaller and currently limit does not yet exceed LEP.

Something to keep an eye on. Will have direct implications for naturalness!



RPV: stops



For example, stops could be the LSP and decay to qq through UDD RPV.

- Until relatively recently, this scenario was completely unconstrained (Evans & Kats ’12)
- Latest searches now exclude stops below ~400 GeV. Stop LSP is in tension with Higgsino naturalness bound (μ ≲ 300 GeV)!
- Many-body stop decays still largely unconstrained?
  (Evans & Kats ’12, ’13; Evans ’14; Monteux ’16)