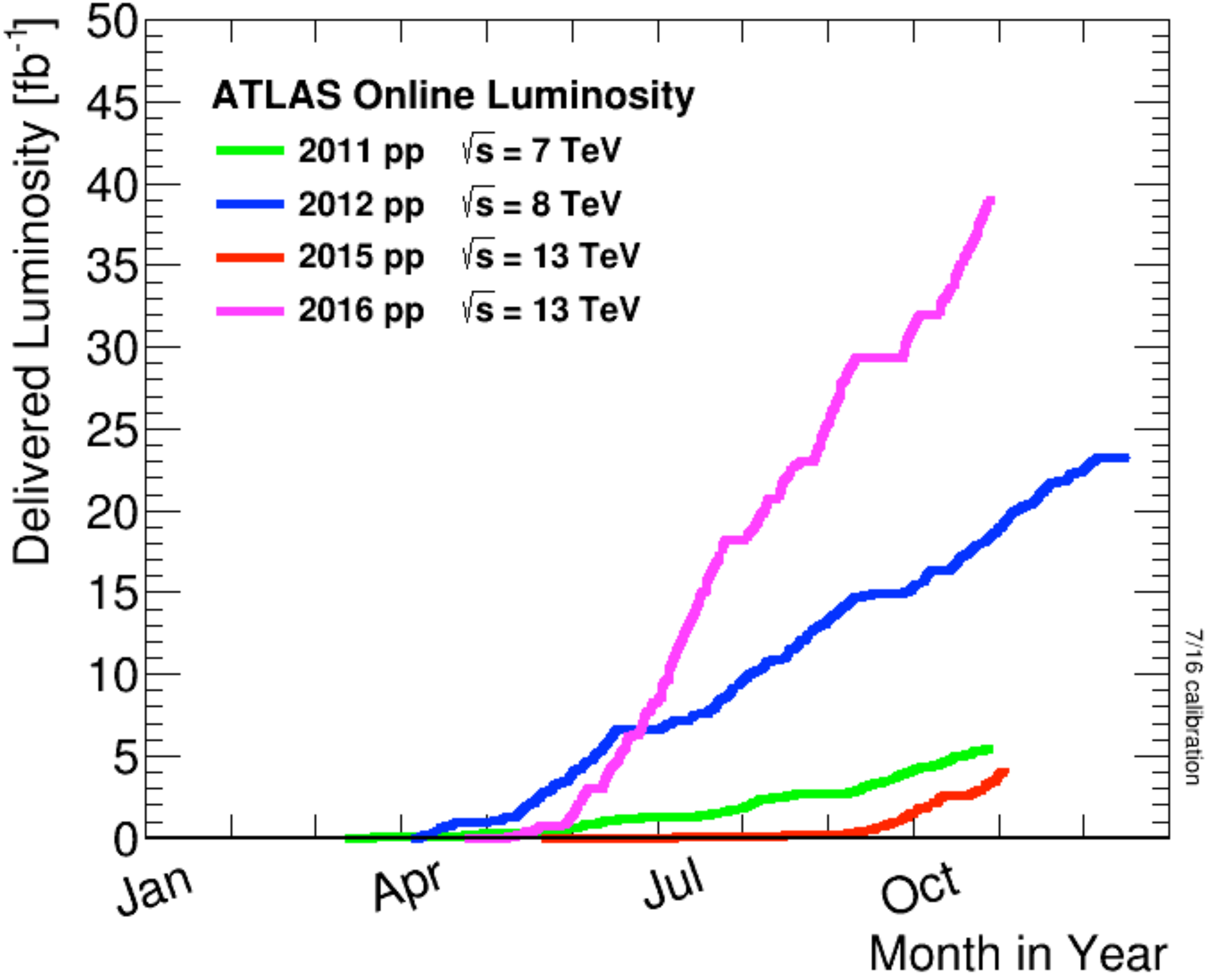
Cornering Natural SUSY at the LHC

David Shih
NHETC, Rutgers University

Pitt PACC workshop
“Digging Deeper at LHC Run II”
February 23, 2017

with Matt Buckley, Anthony diFranzo, David Feld,
Sebastian Macaluso & Angelo Monteux

Since 2010, the LHC has been performing spectacularly.



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

38TH INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

ICHEP

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ABSTRACT SUBMISSION THROUGH FEB. 7, 2016

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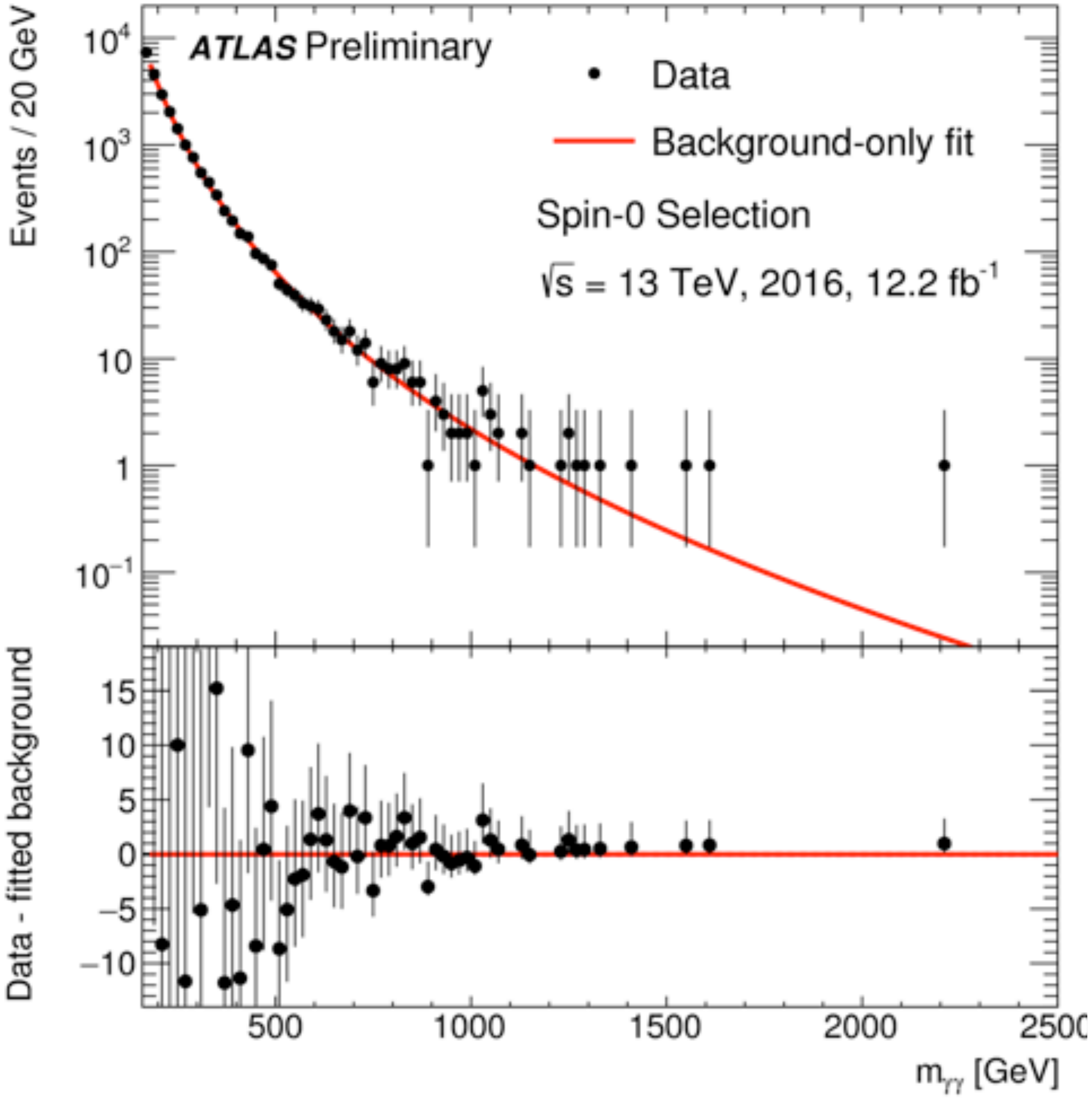
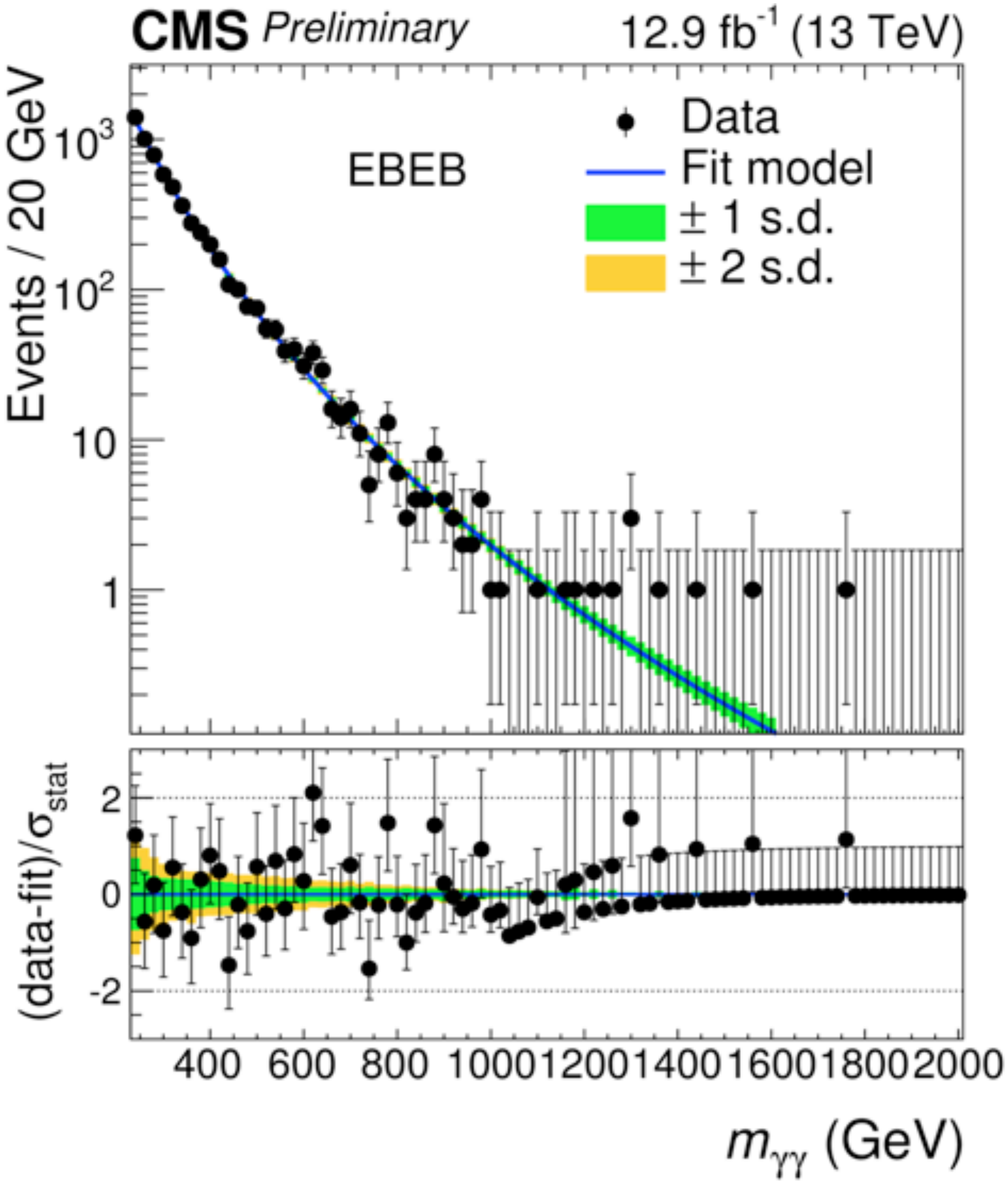
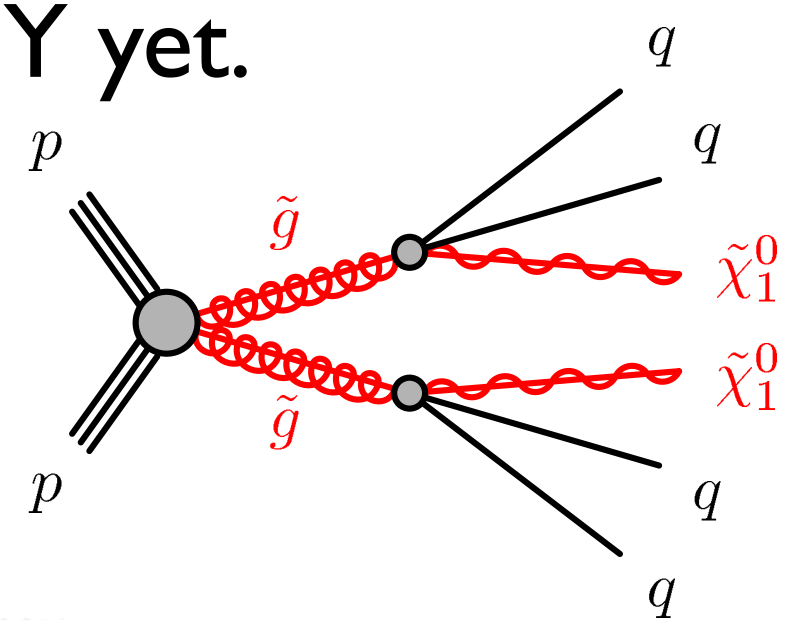
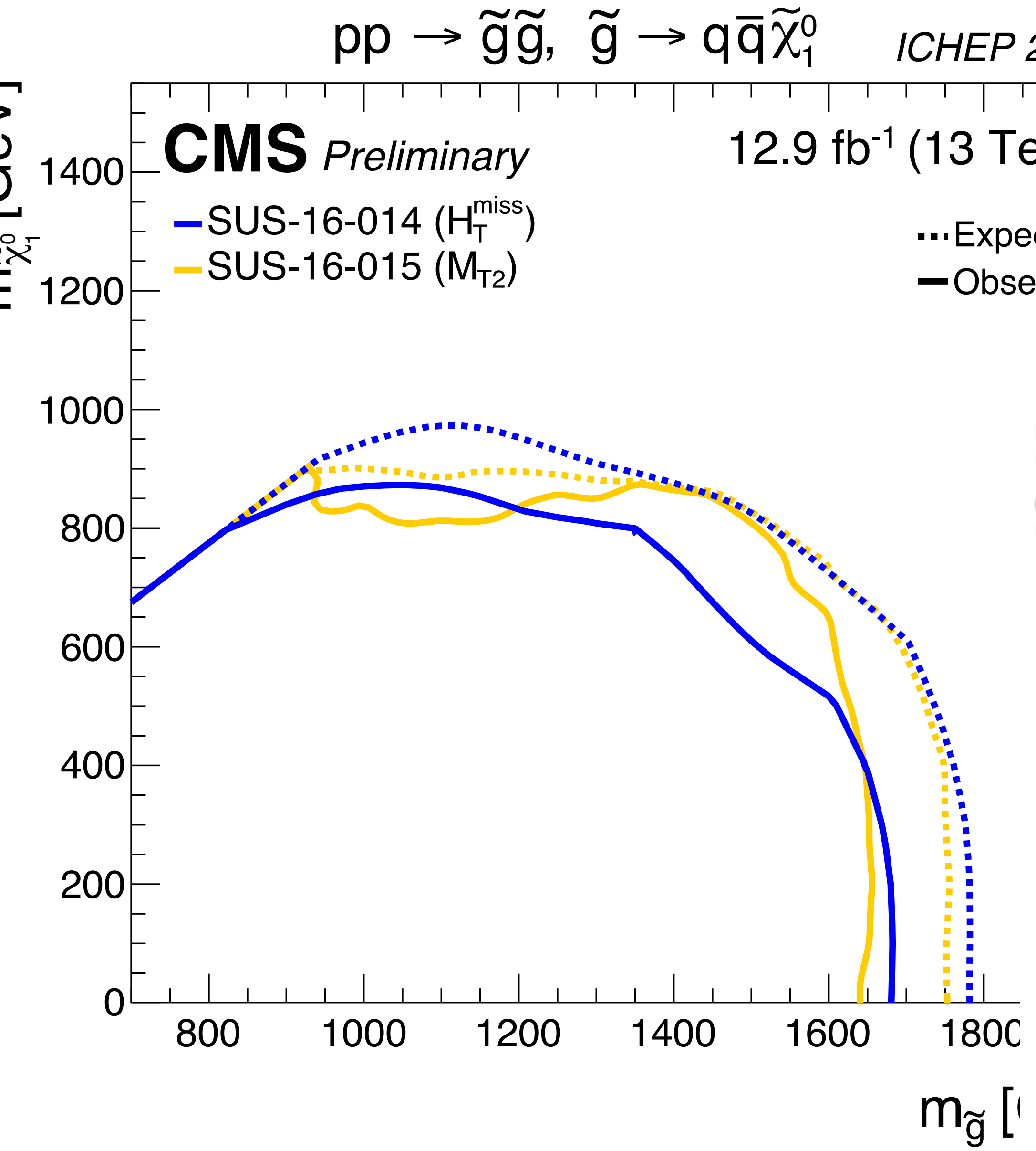
The 750 diphoton resonance is disappearing...

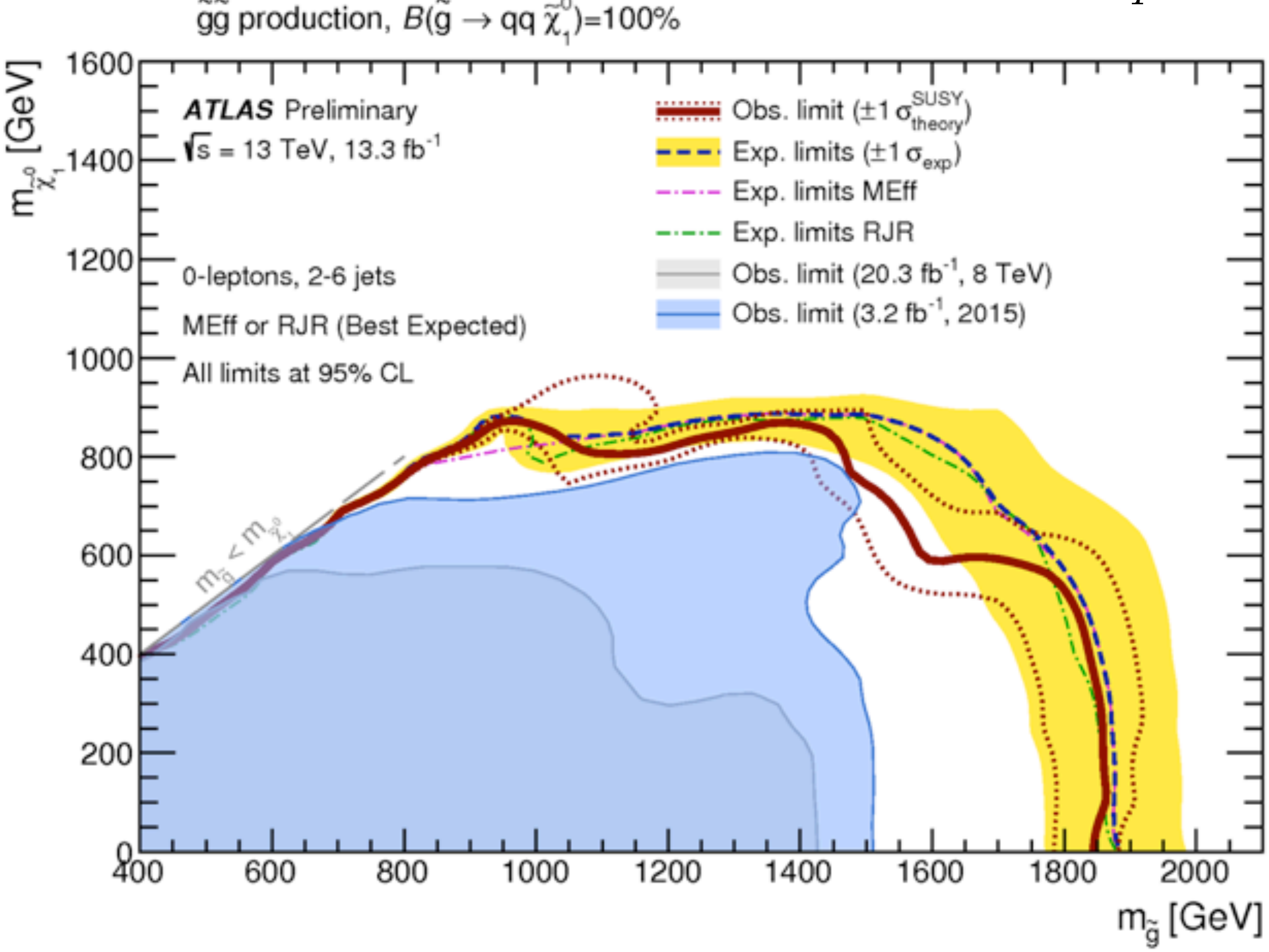




...and still no discovery of SUSY yet.







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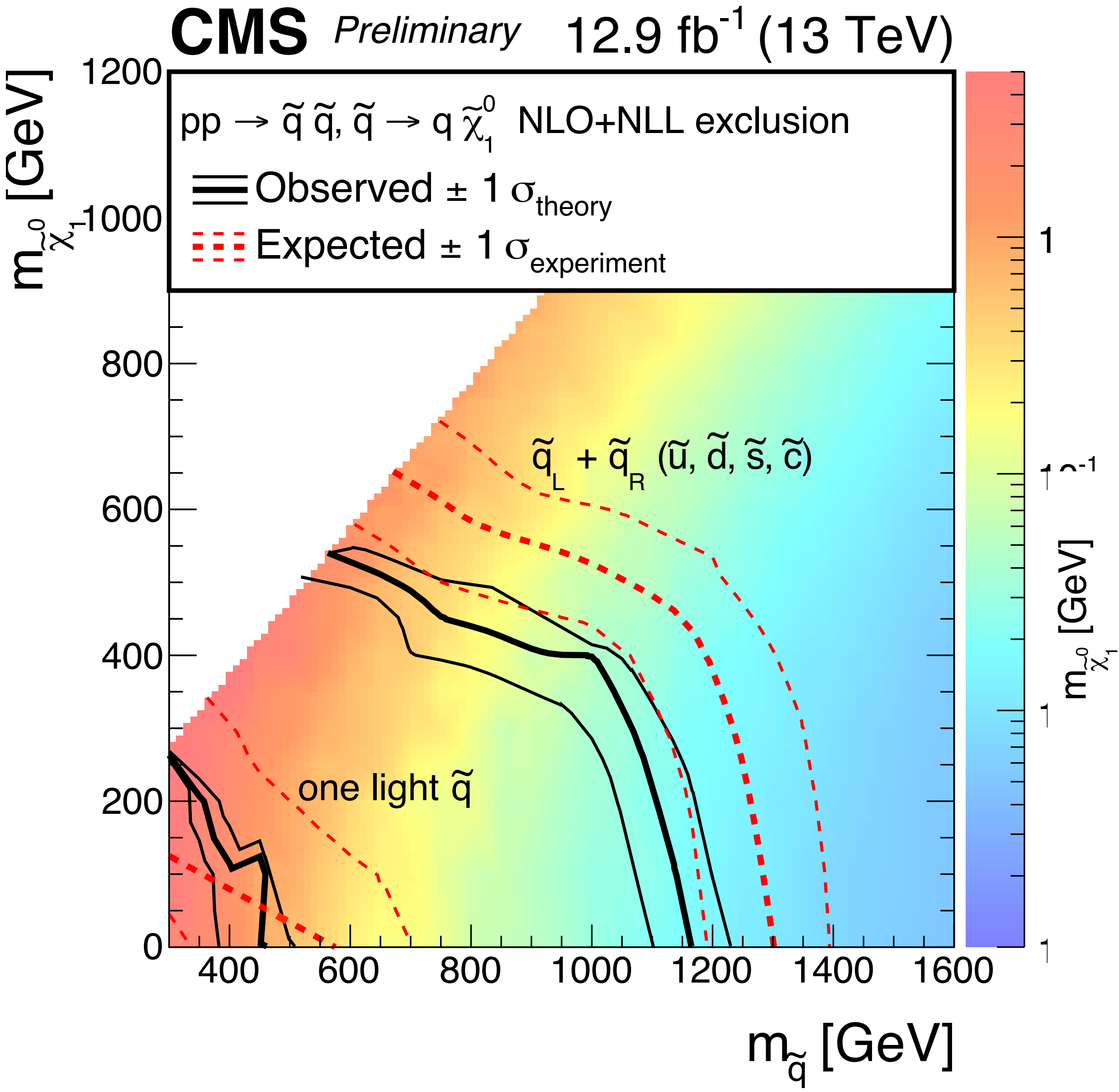
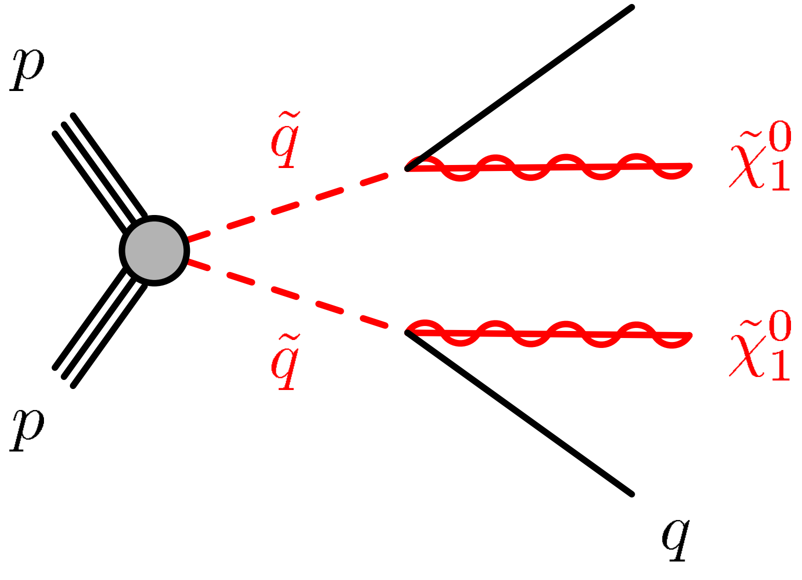
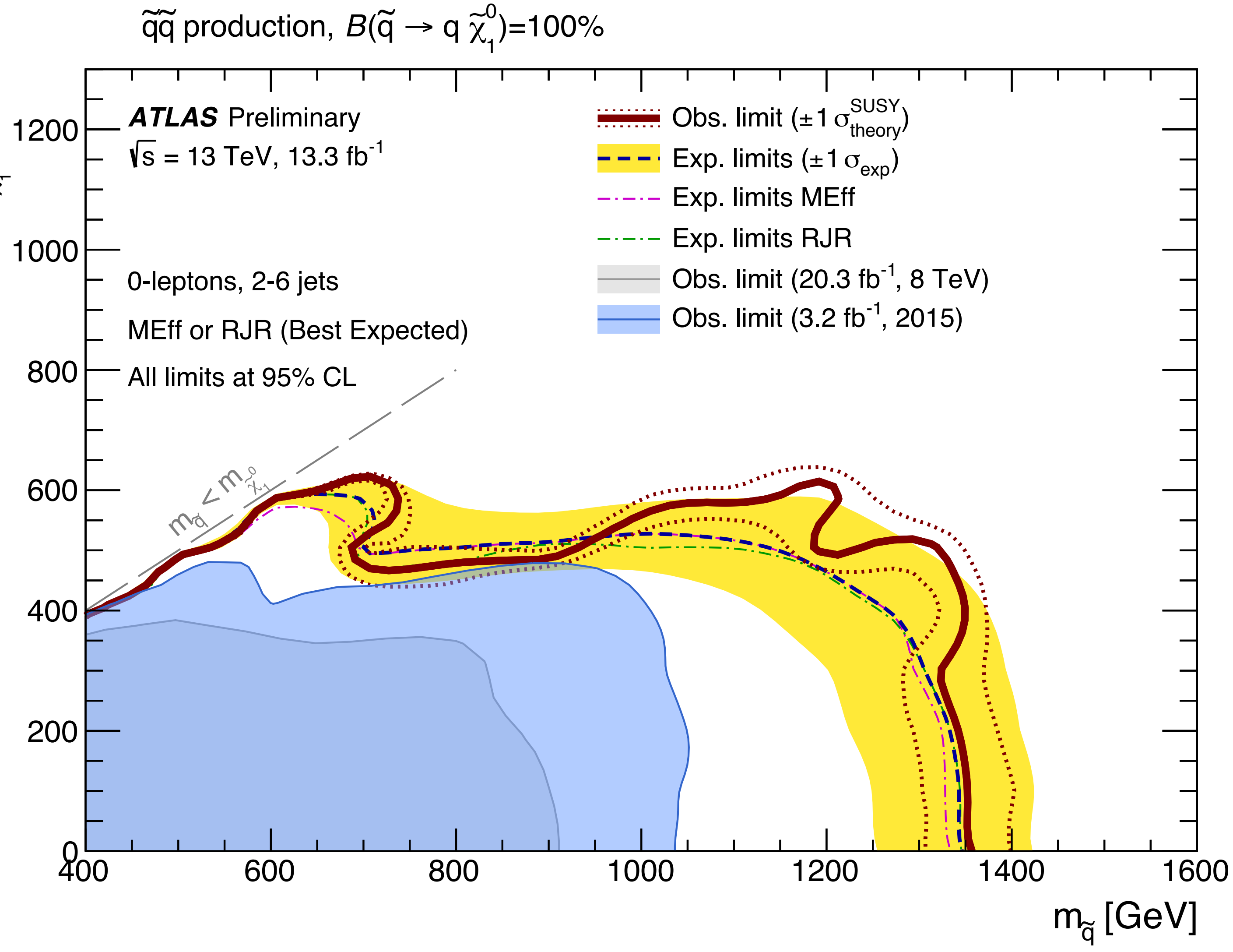
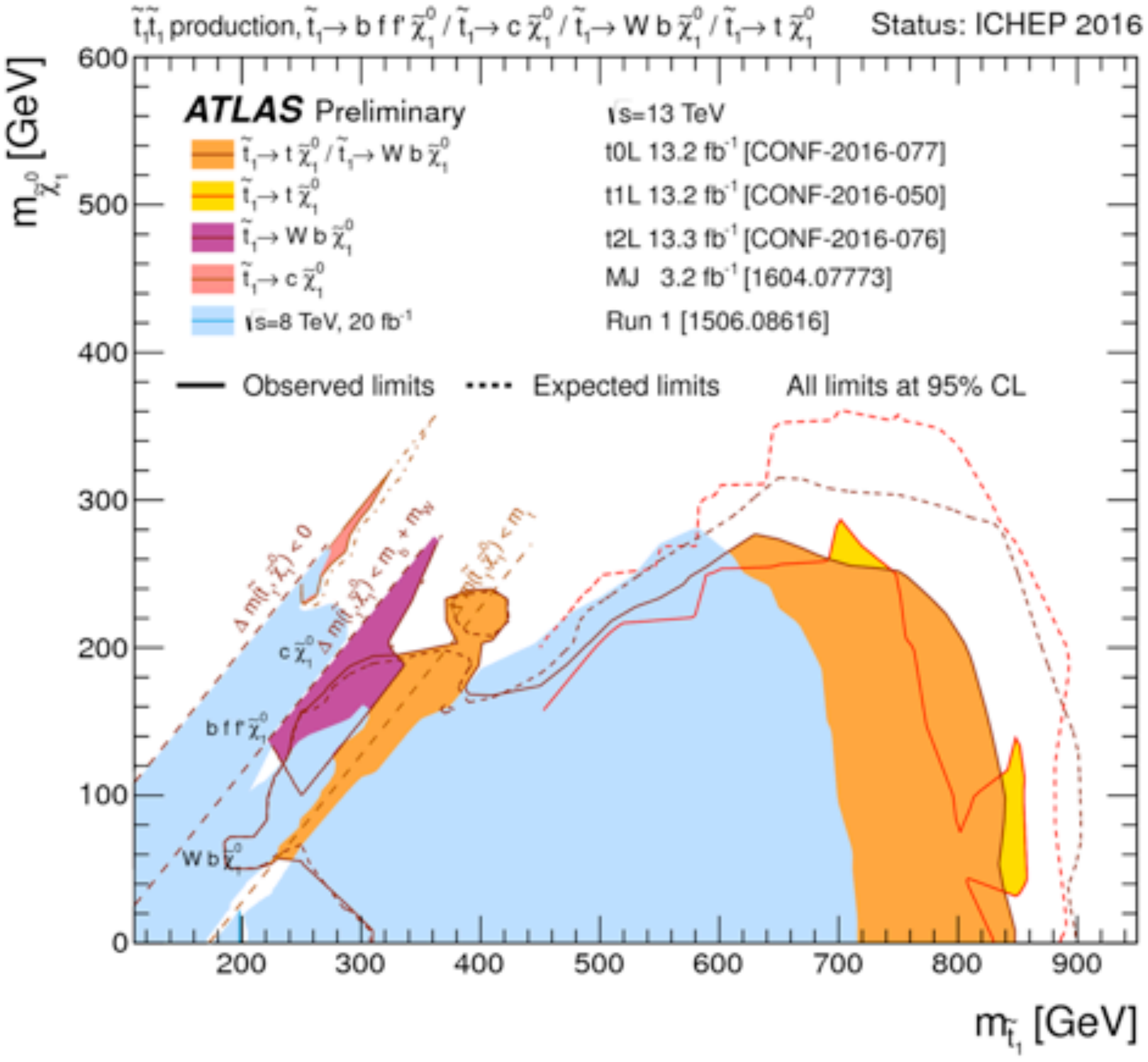


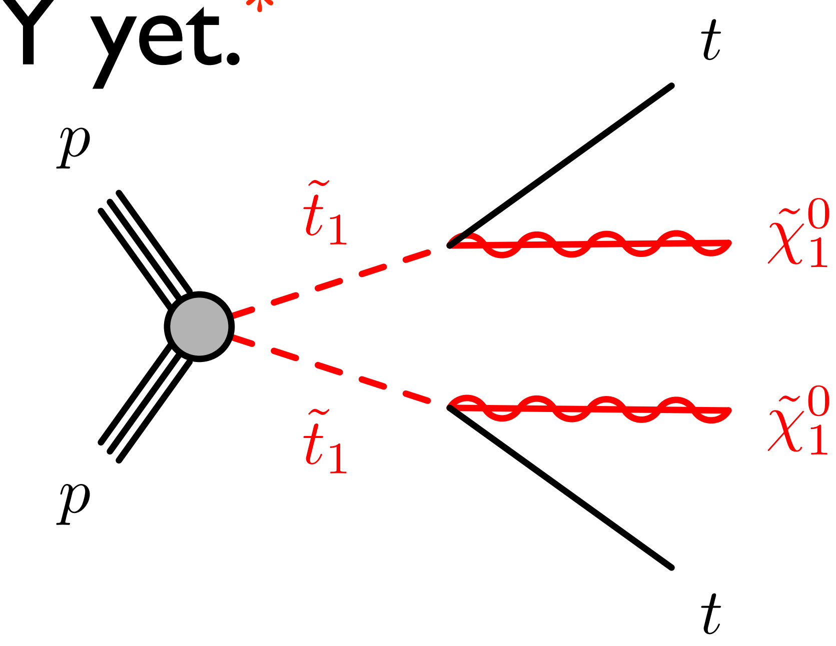


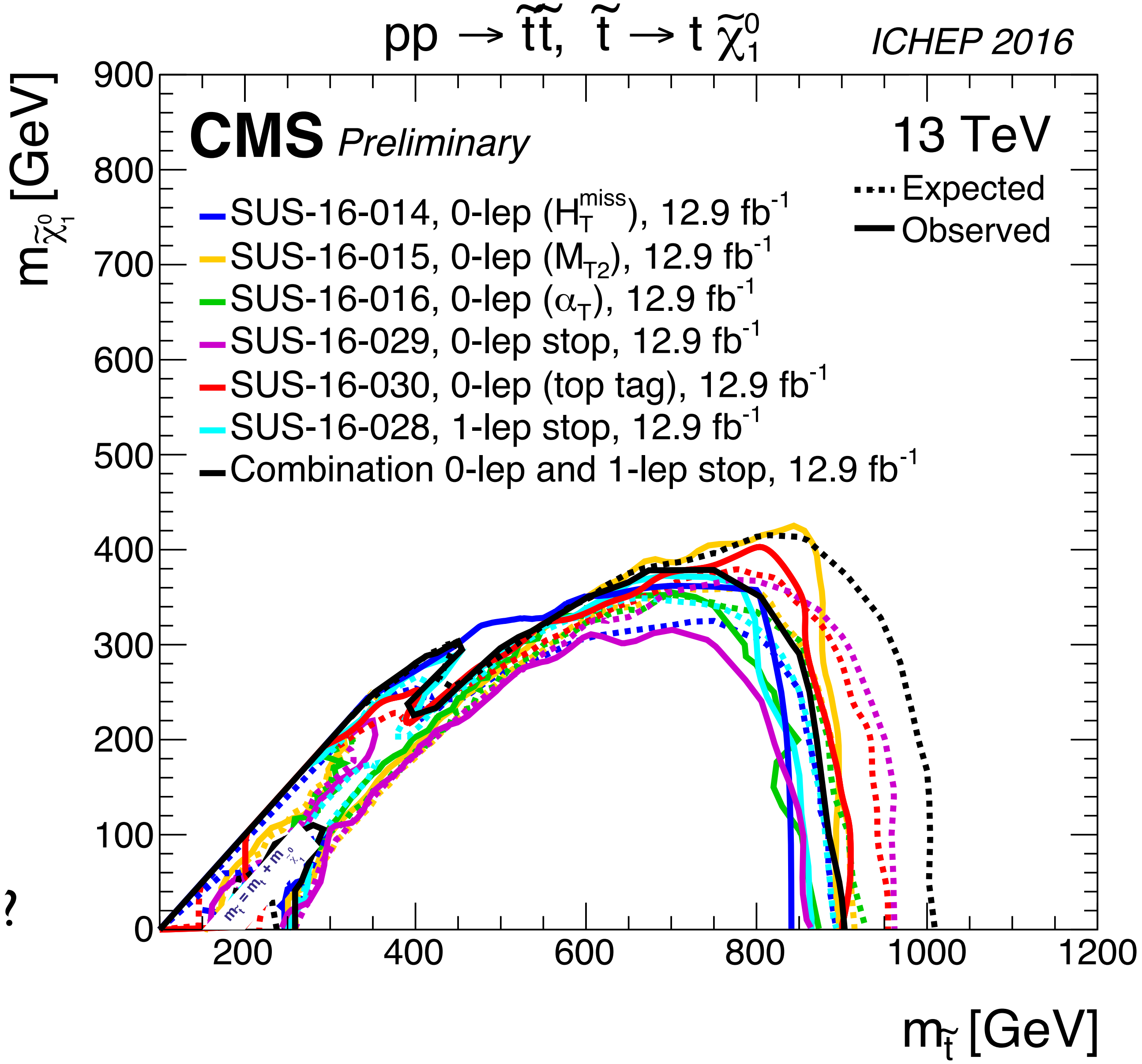


(Key assumption:
decoupled gluinos!)

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







*Although some interesting deviations in stop searches?
(see B. Hooberman's talk)

IS SUSY ALIVE AND WELL?

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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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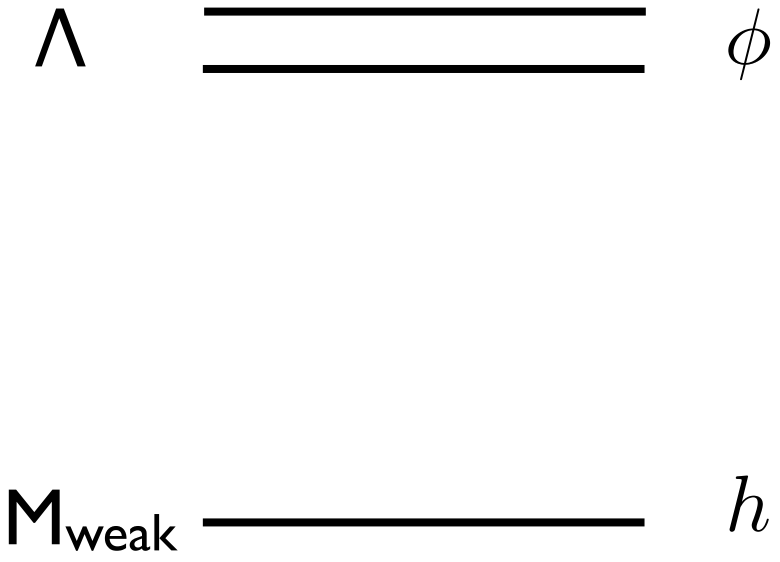
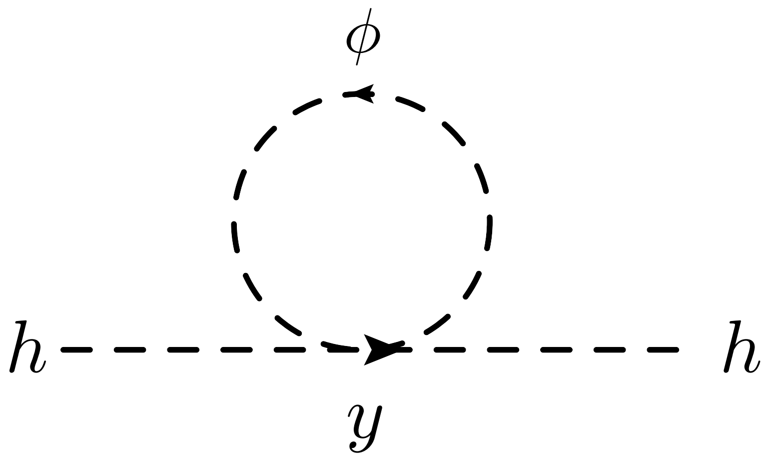
Naturalness motivates the TeV scale

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





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

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!)

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

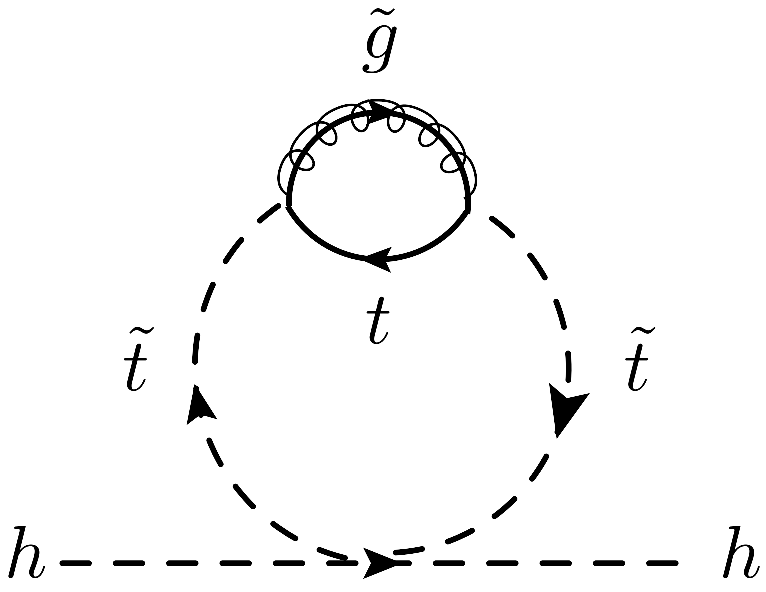
Naturalness: no enormous cancellations between different corrections.

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

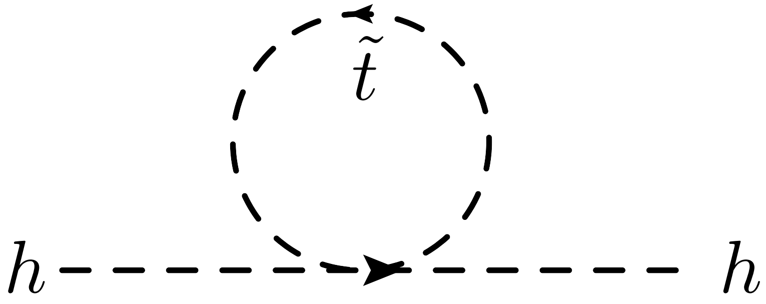
In conventional realizations of SUSY, a special role is played by the Higgsinos, stops, and gluinos, as these couple strongest to the Higgs.

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

(leading log approximation!)



$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{g_3^2}{4\pi^2}M_3^2\left(\log\frac{\Lambda}{Q}\right)^2$$



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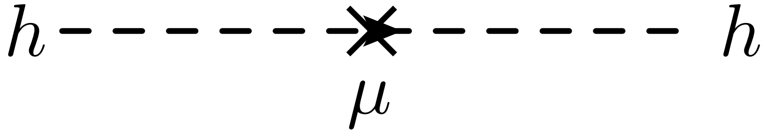
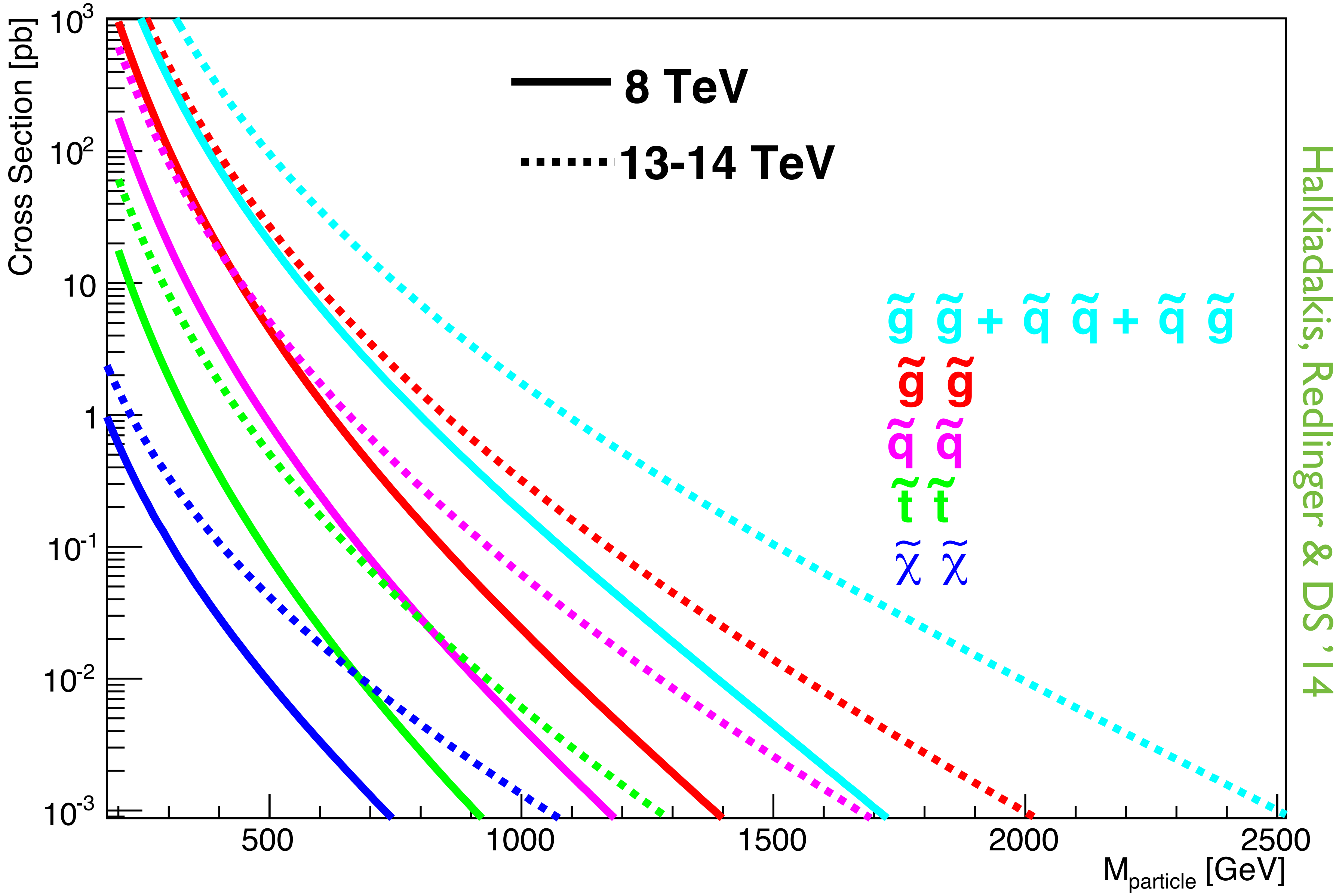


$$\delta m_H^2 \sim |\mu|^2$$

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

Q = some IR scale appropriate to the process



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

Stop cross sections are several orders of magnitude smaller but are also not negligible.

Higgsino cross sections are an order of magnitude smaller yet.

For Higgsinos, quantum corrections are small.

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

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

Expect light Higgsinos!

Unfortunately, very difficult to detect at LHC due to low cross section and high background. Currently limits do not exceed LEP.

For gluinos and squarks, the LL approximation is conventionally used...

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

$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{g_3^2}{4\pi^2}M_3^2\left(\log\frac{\Lambda}{Q}\right)^2 \qquad M_3 \lesssim \sqrt{m_h^2\Delta\left(\frac{y_t^2}{\pi^2}\frac{g_3^2}{2\pi^2}\left(\log\frac{\Lambda}{Q}\right)^2\right)^{-1}}$$

$$\delta m_H^2 \sim -\frac{3}{8\pi^2}y_t^2(m_{Q_3}^2 + m_{U_3}^2)\log\frac{\Lambda}{Q} \qquad m_{Q_3},\ m_{U_3} \lesssim \sqrt{m_h^2\Delta\left(\frac{3y_t^2}{4\pi^2}\log\frac{\Lambda}{Q}\right)^{-1}}$$

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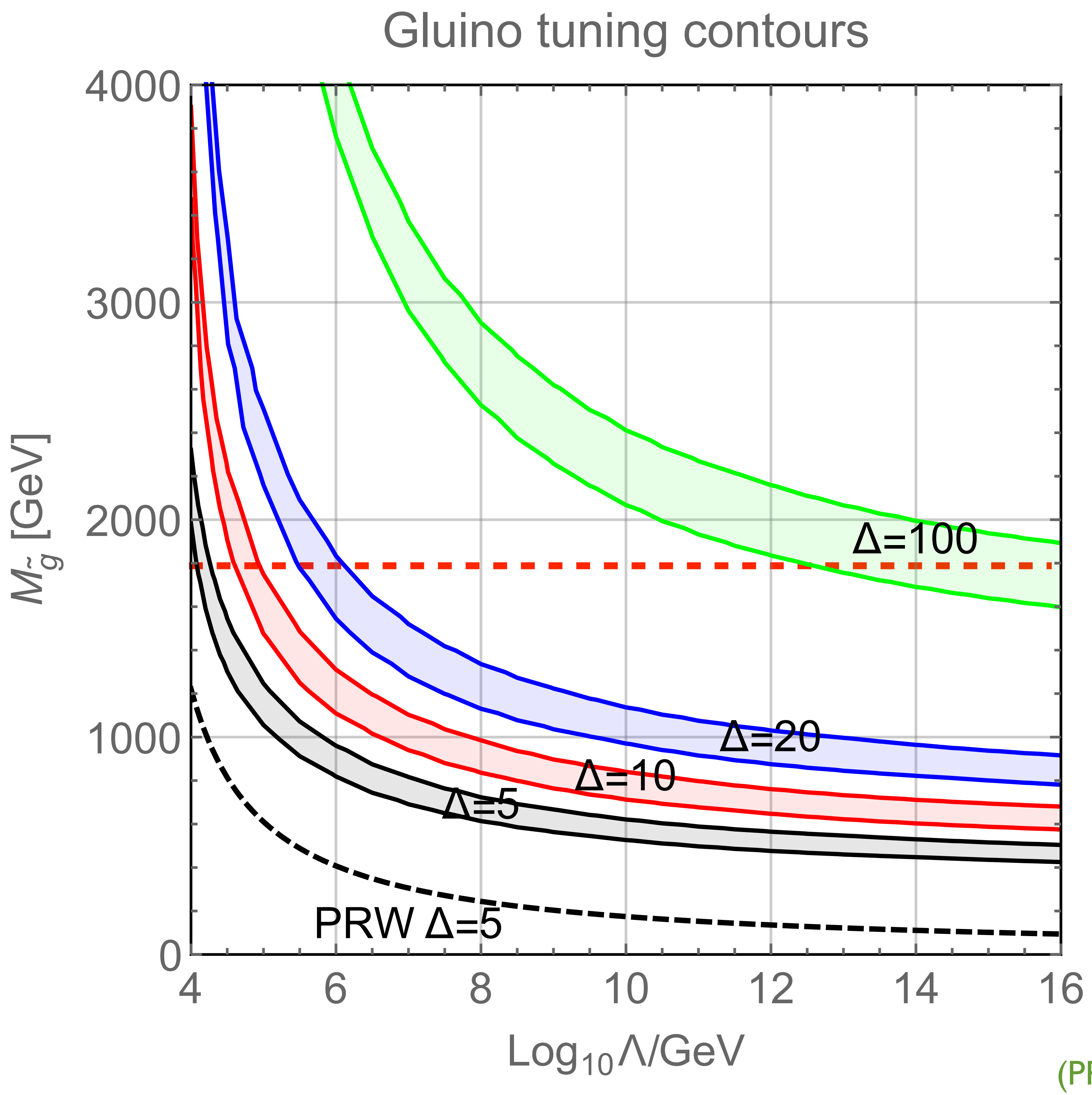
Tuning constrains UV parameters.
LHC constrains IR parameters.

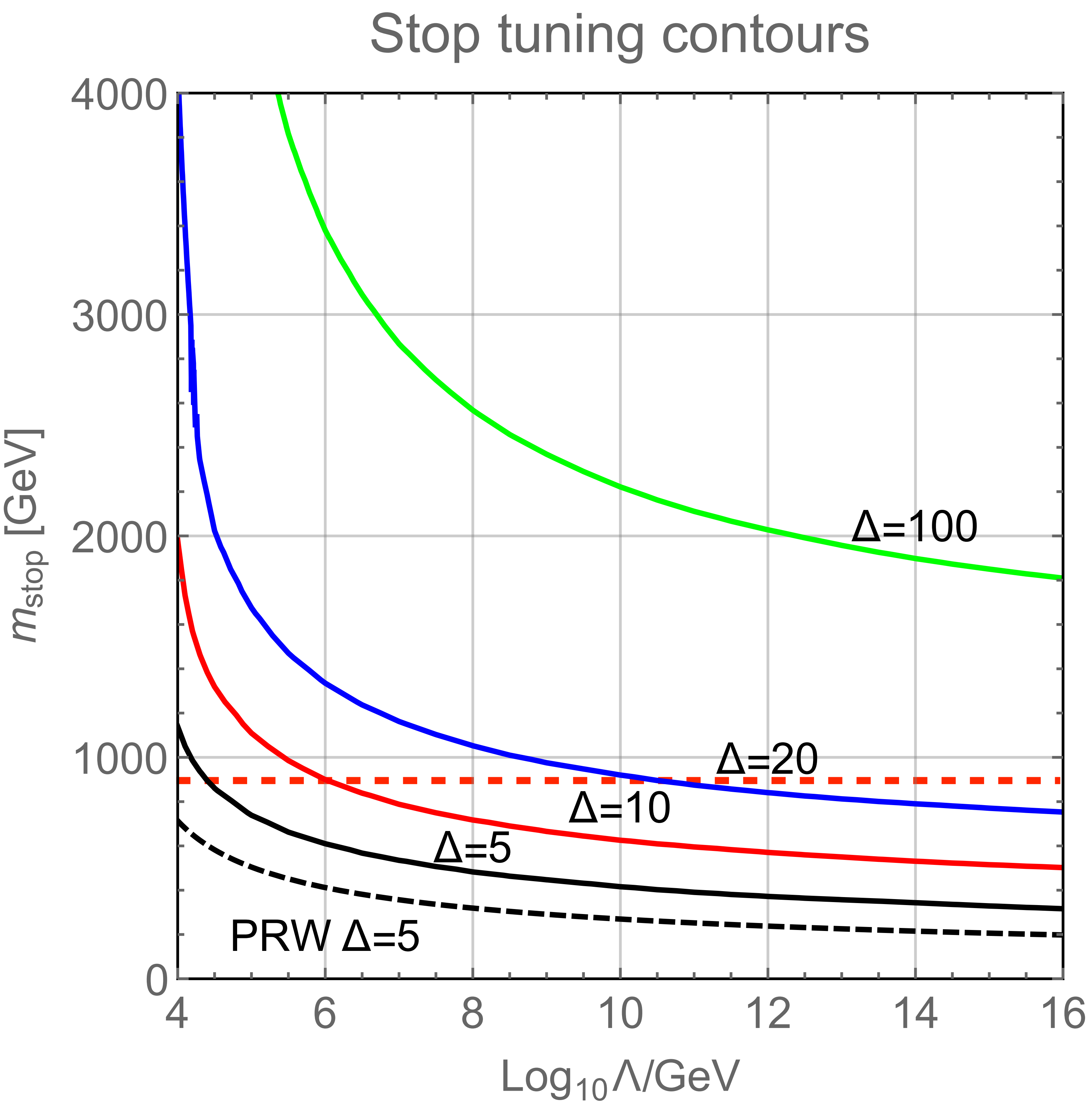


Overall, accounting for these higher-order effects significantly relaxes the gluino bounds!

Buckley, Monteux, DS 1611.05873

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

(PRW = Papucci, Ruderman & Weiler 1110.6926)



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

Buckley, Monteux, DS 1611.05873

Recasting overview

Buckley, Feld, Macaluso, Monteux & DS 1610.08059

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

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

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Buckley, Feld, Macaluso, Monteux & DS 1610.08059

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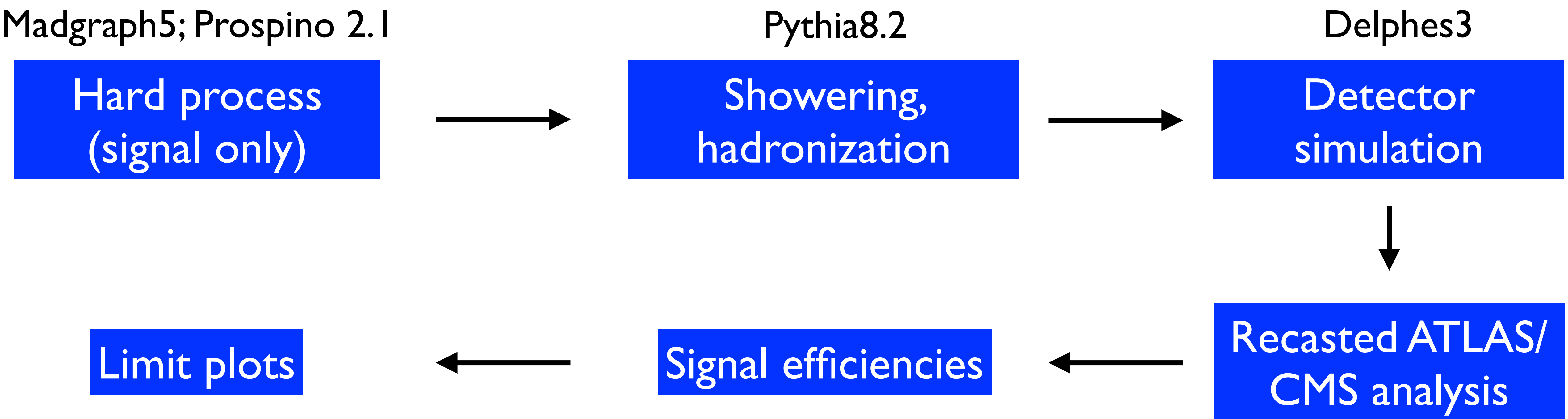


Madgraph5; Prospino 2.1

Hard process (signal only)

Pythia8.2

Showering, hadronization

Delphes3

Detector simulation

Recasted ATLAS/ CMS analysis

Signal efficiencies

Limit plots

List of recasted searches

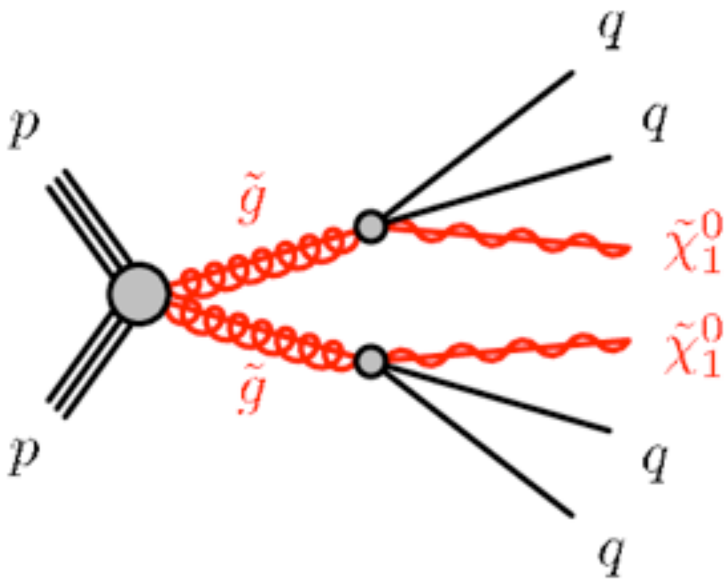
ATLAS 2-6 jets + MET	13.3/fb	CONF-2016-078
ATLAS b-jets + MET	14.8/fb	CONF-2016-052
CMS jets+MET (HT)	12.9/fb	SUS-16-014
ATLAS 7-10 jets+MET	3.2/fb	1602.06194
ATLAS 8-10 jets+MET	18.2/fb	CONF-2016-095
ATLAS 1L + jets +MET	14.8/fb	CONF-2016-054
ATLAS SS dileptons	13.2/fb	CONF-2016-037
ATLAS multijets (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

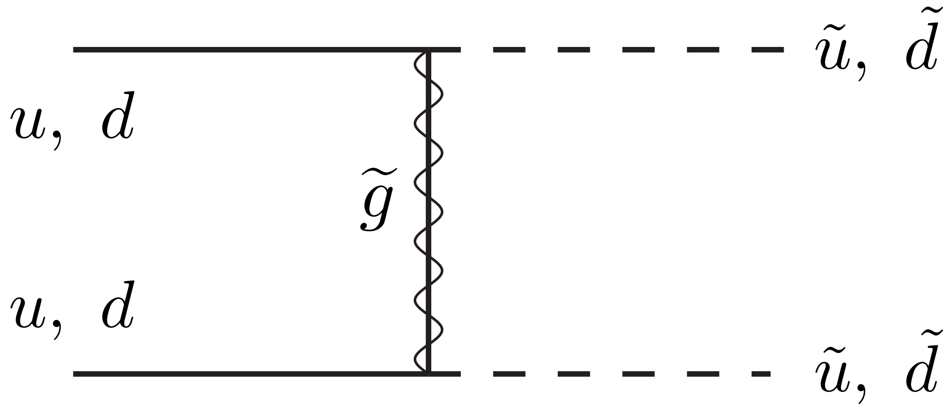
Natural SUSY scenario #1

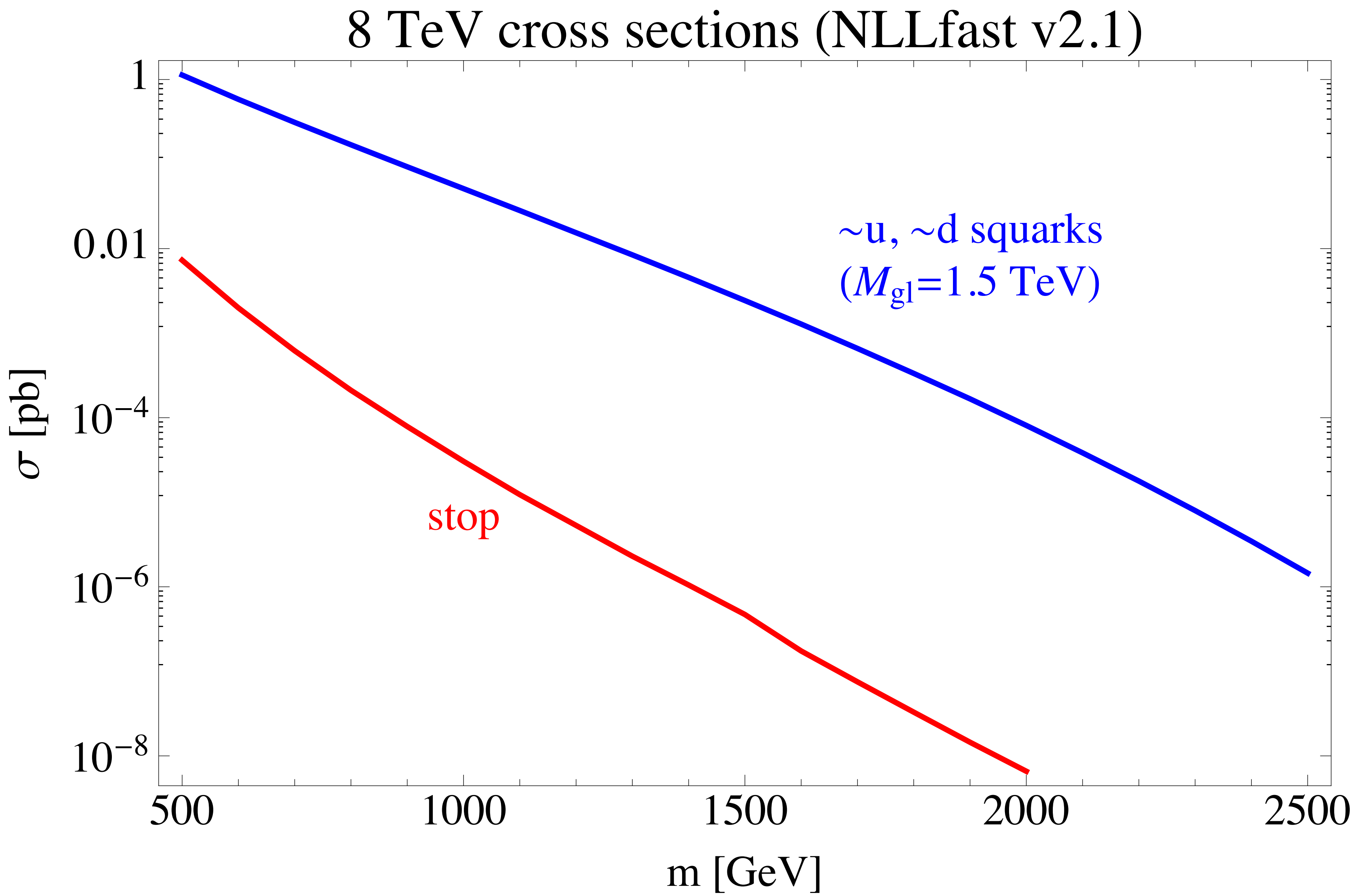
"Vanilla SUSY": MSSM + R-parity + flavor-degenerate sfermions

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

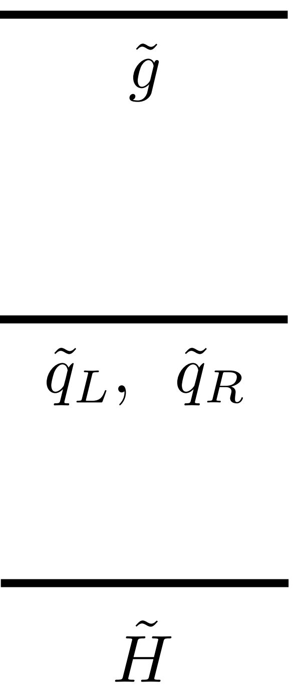
- With R-parity, LSP is stable. Light higgsinos generally lead to large missing ET.
- With flavor-universality, light stops imply light u and d squarks. Valence squark cross section is enormous!

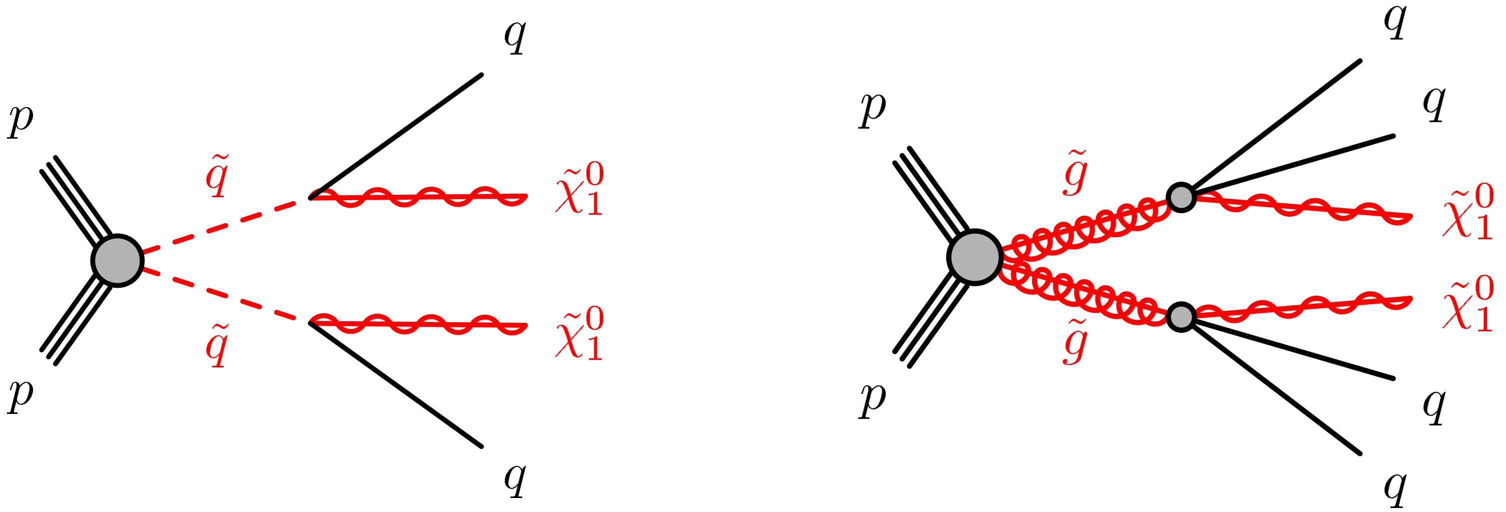




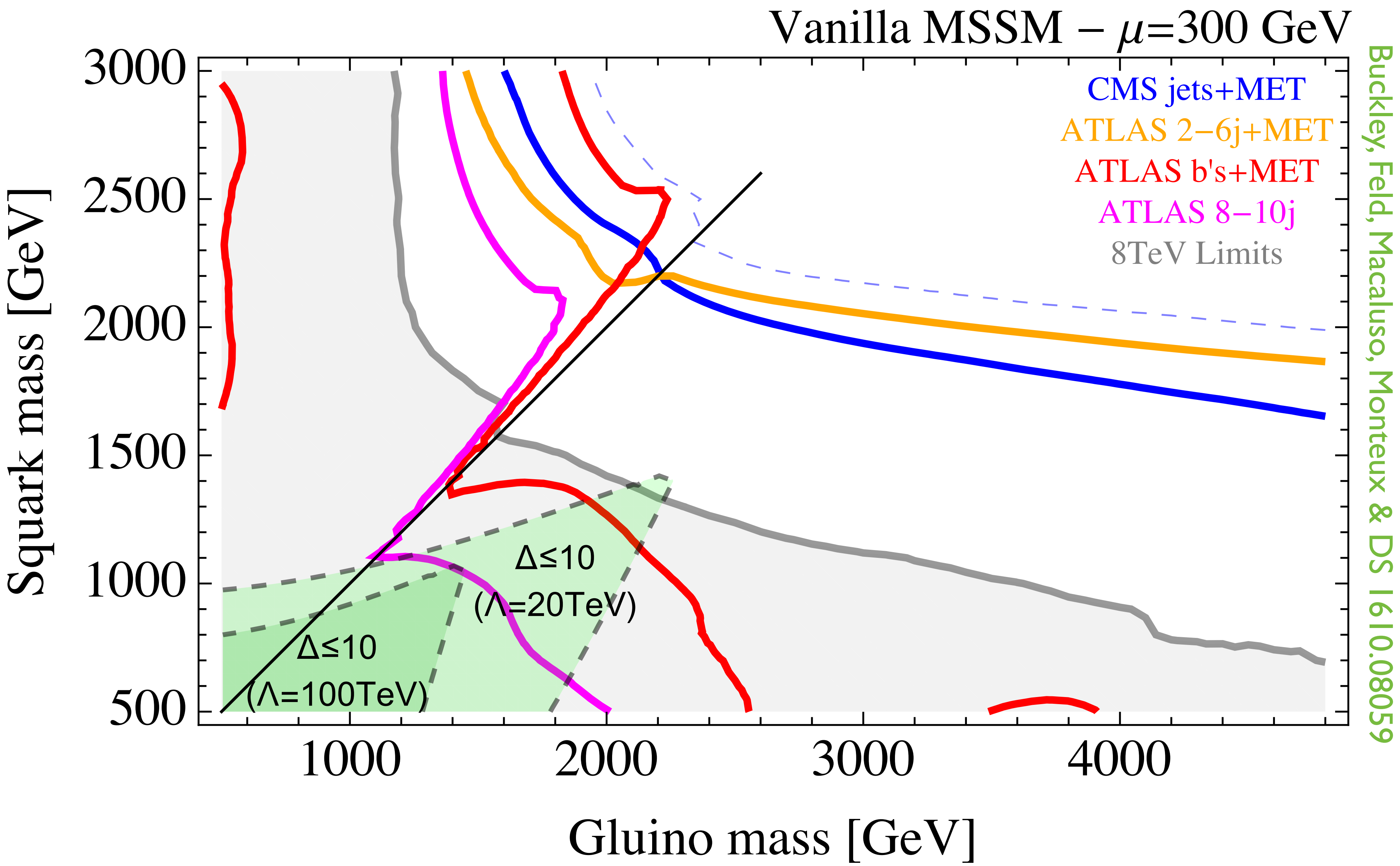


Valence squark cross section can be ~ 5 orders of magnitude larger than stop cross section!



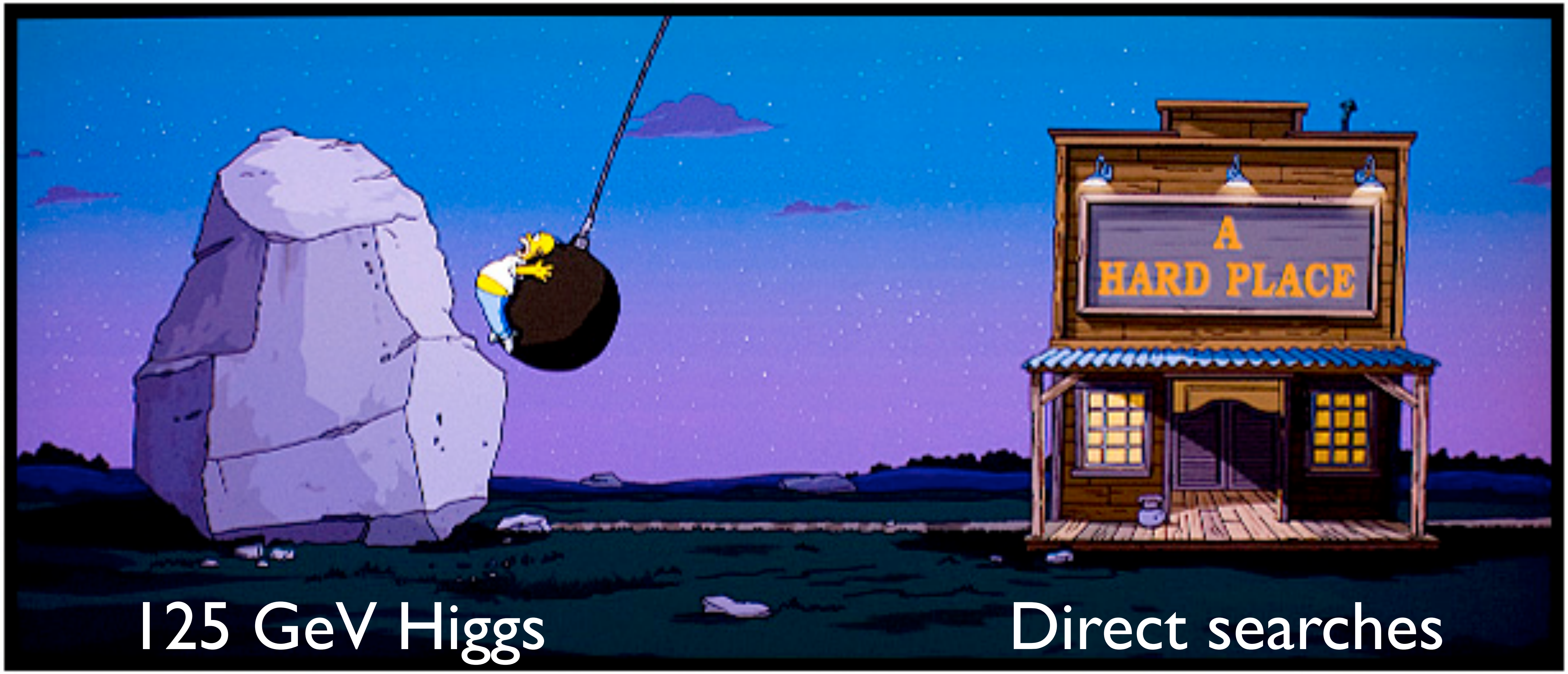


Run I recasted limits obtained using analysis framework developed by J. Evans & Y. Kats



Buckley, Feld, Macaluso, Monteux & DS 1610.08059

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.

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

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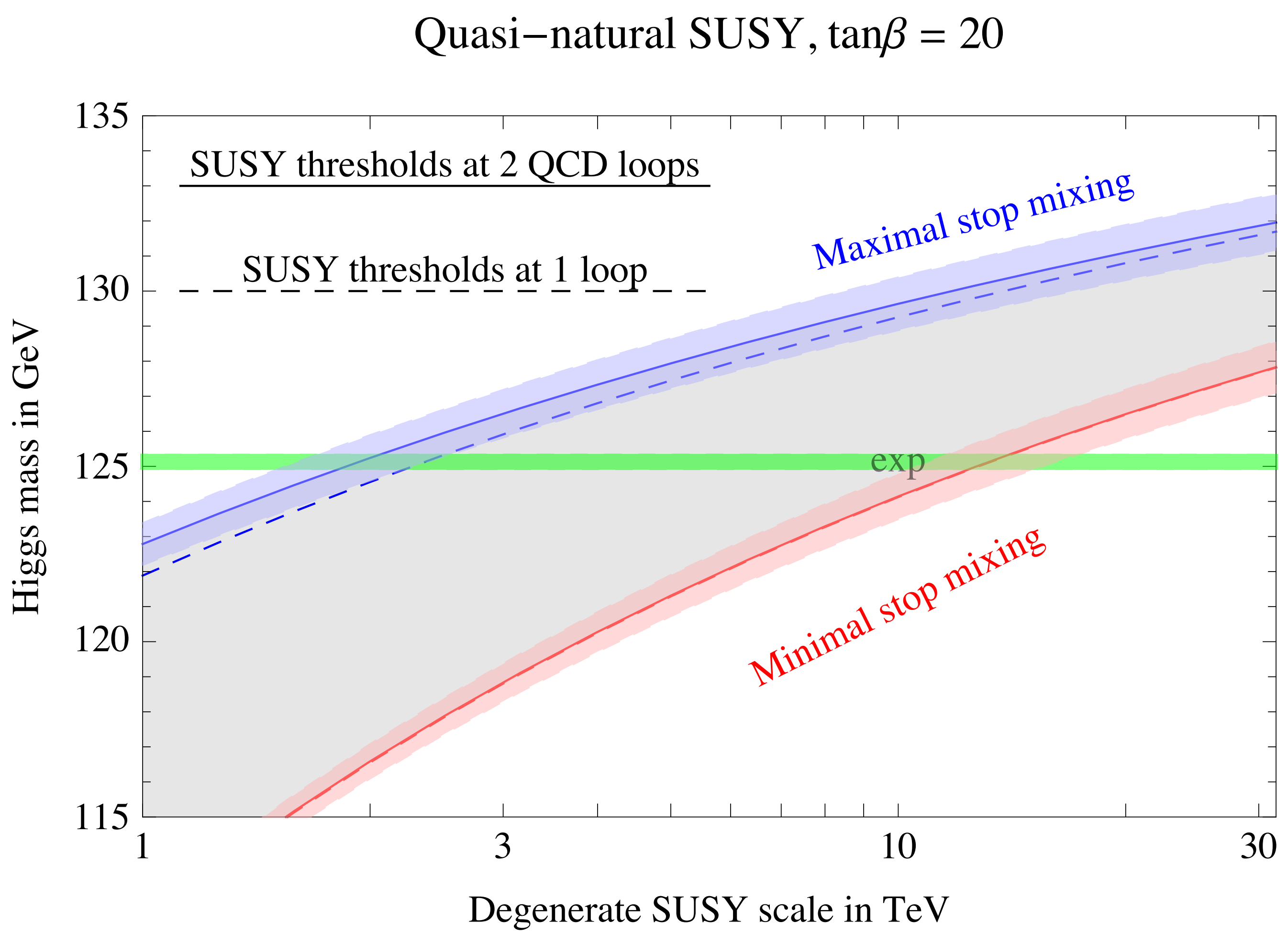

Bagnaschi *et al.*, 1407.4081

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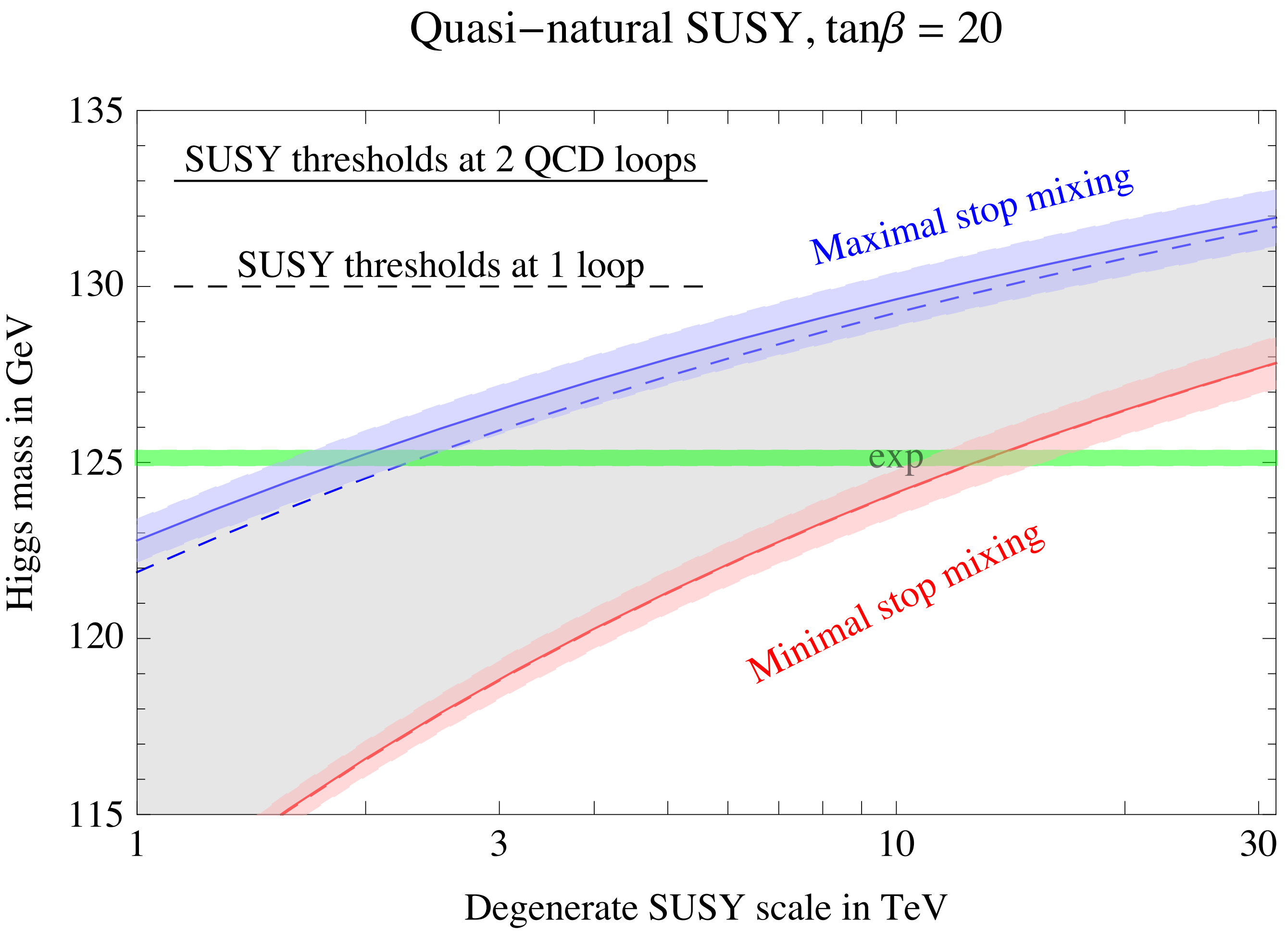

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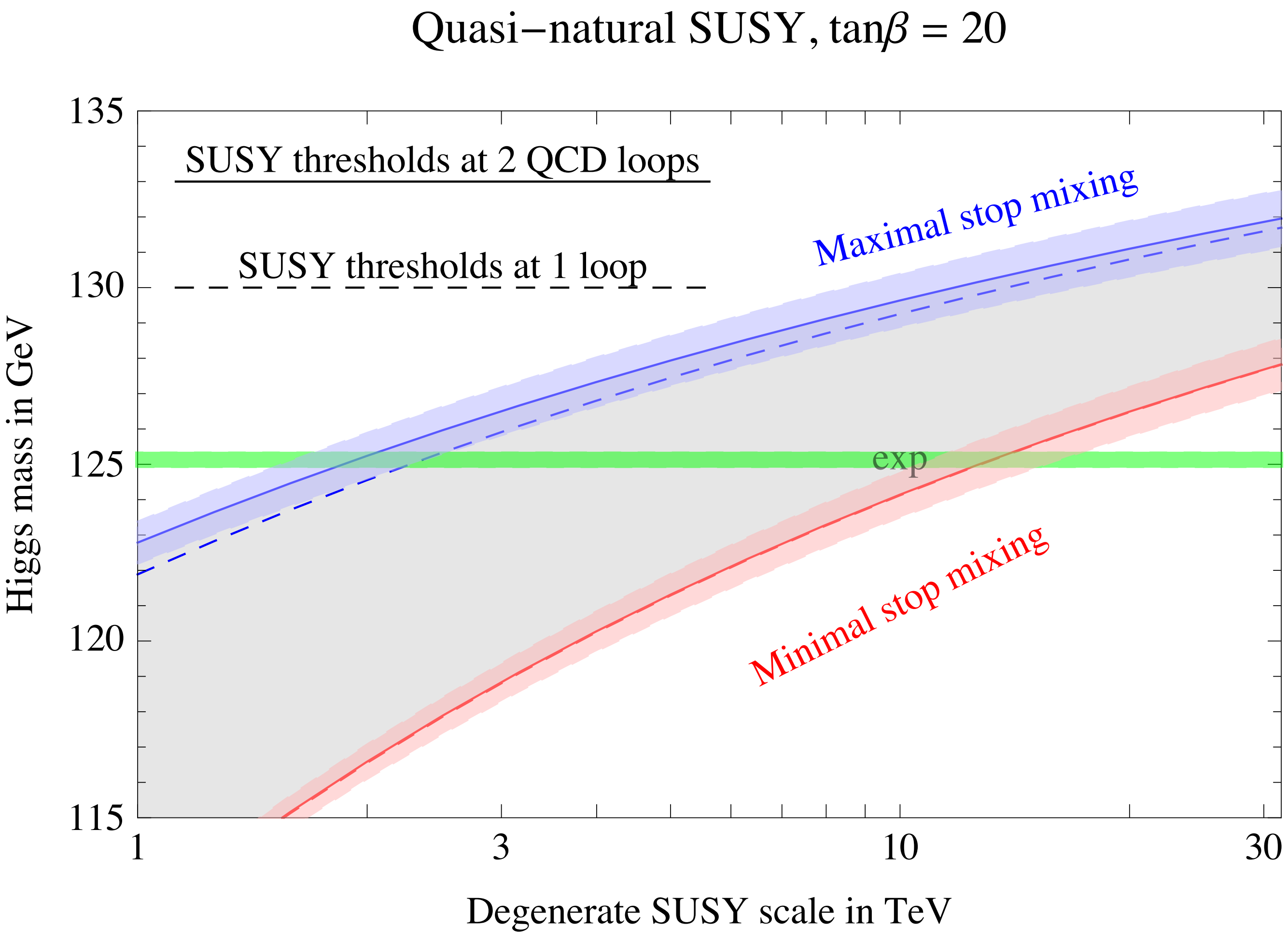
Need loop corrections from heavy stops to raise it to 125 GeV.

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



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

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

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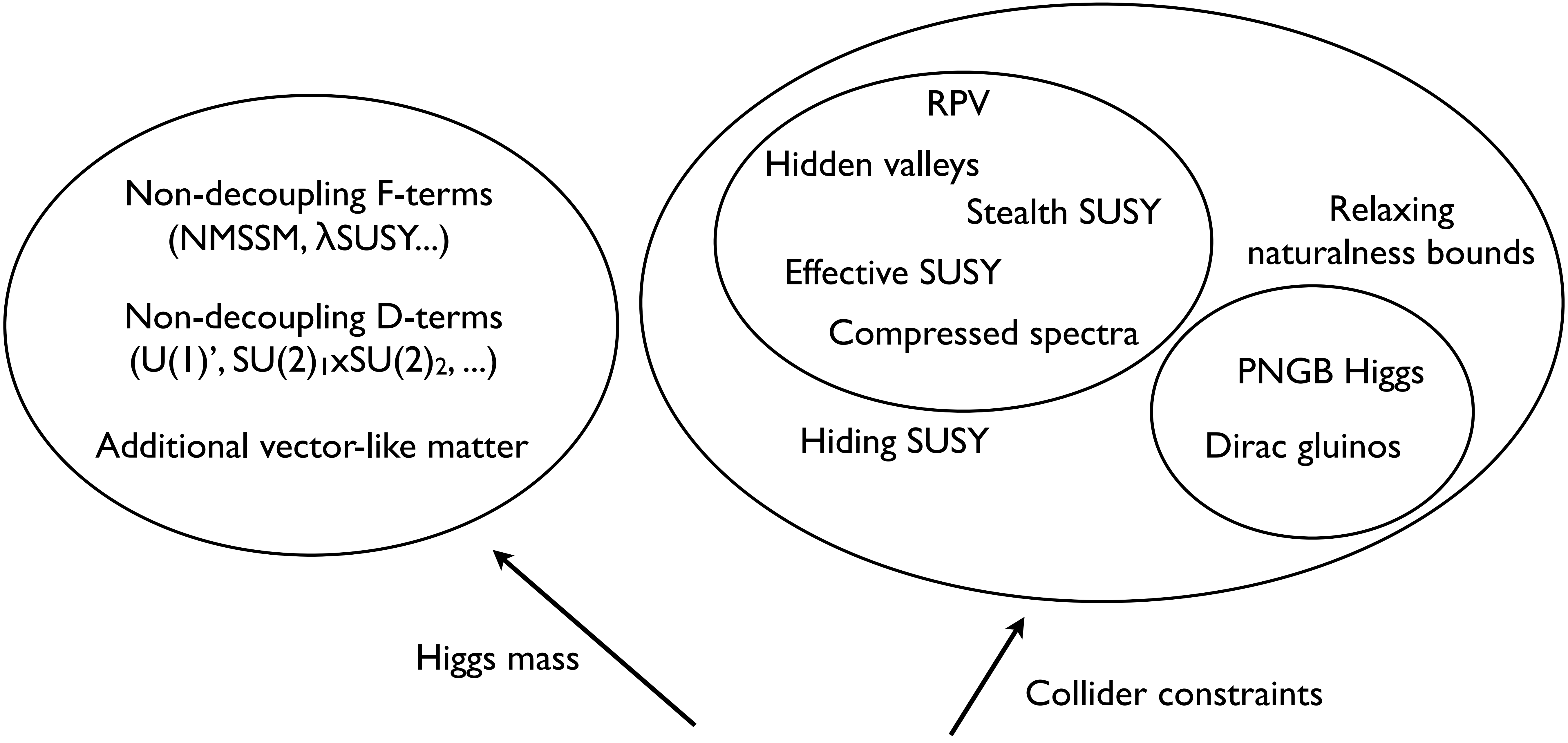
Or maybe it's not vanilla SUSY...

Going beyond vanilla SUSY



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

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

Additional vector-like matter

RPV

Hidden valleys

Stealth SUSY

Effective SUSY

Compressed spectra

Hiding SUSY

Relaxing
naturalness bounds

PNGB Higgs

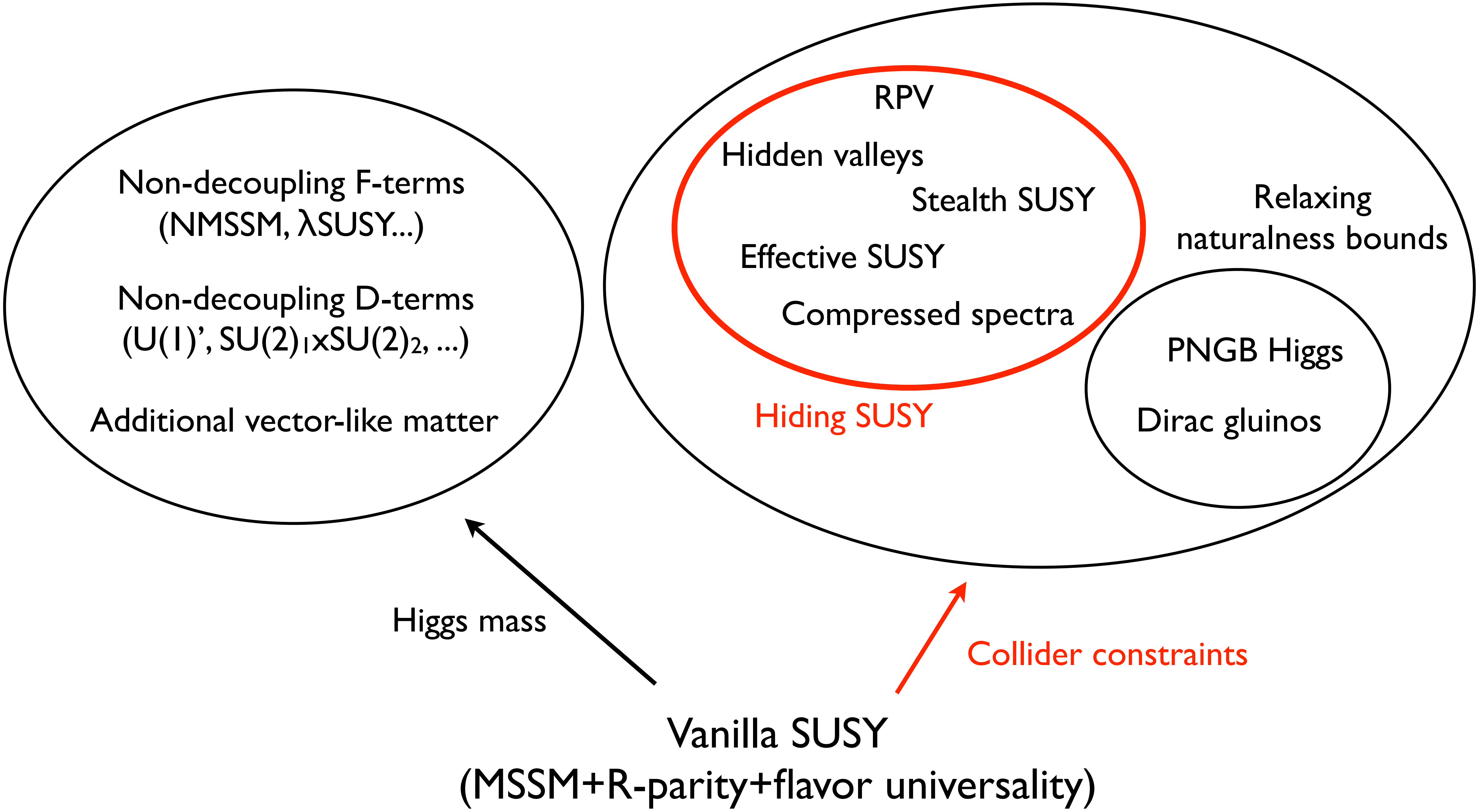
Dirac gluinos

Higgs mass

Collider constraints

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

Going beyond vanilla SUSY



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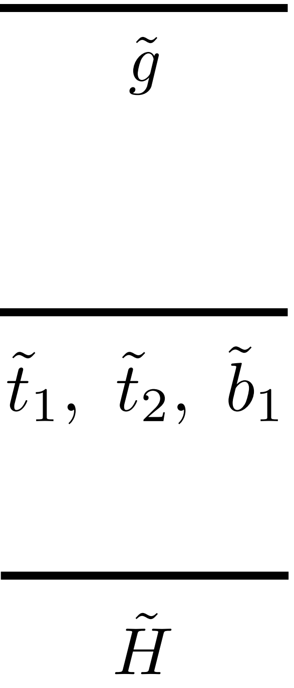
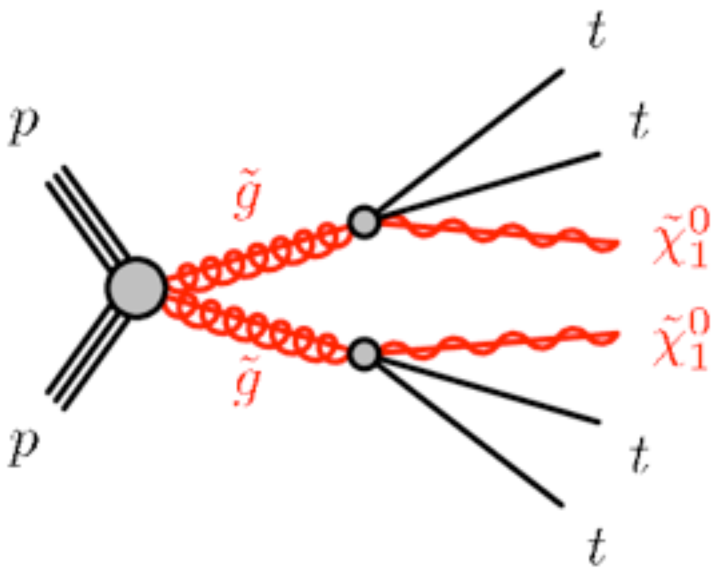


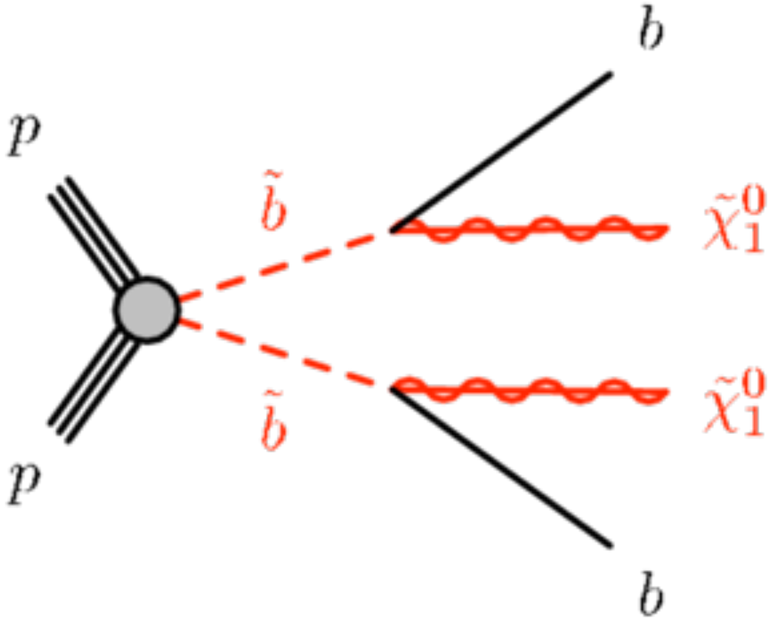
Natural SUSY scenario #2

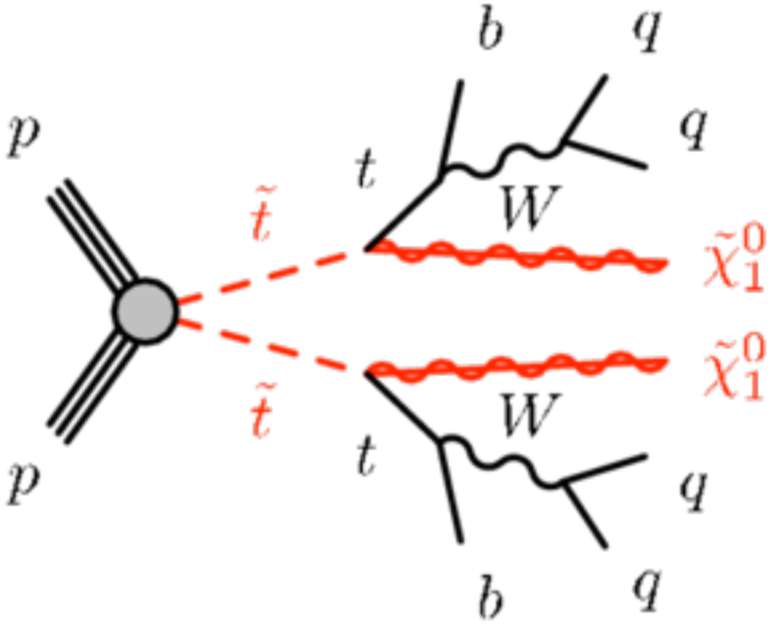
“Effective SUSY”: decoupled 1st/2nd gen. squarks

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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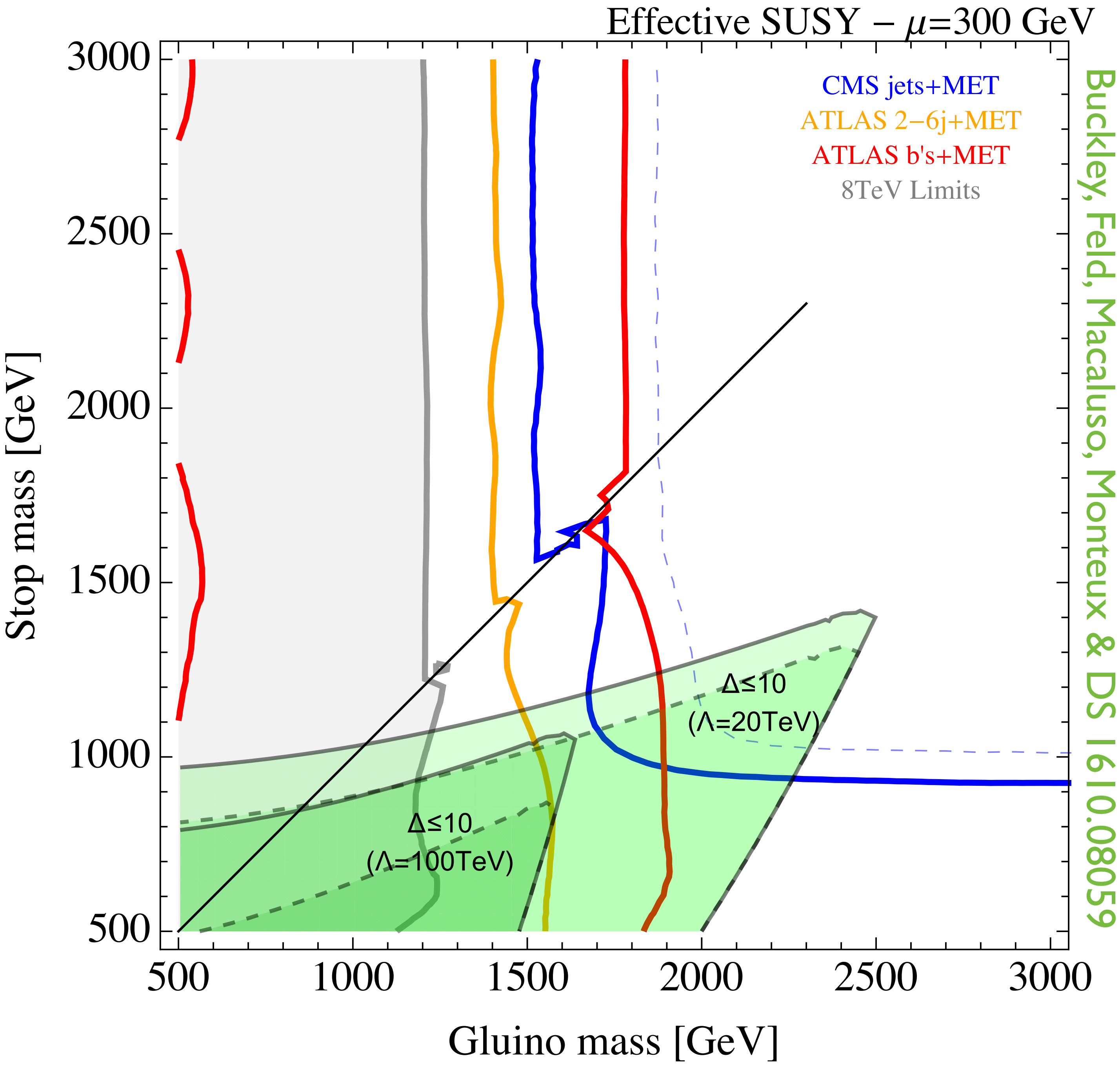


Effective SUSY – μ=300 GeV

Buckley, Feld, Macaluso, Monteux & DS 1610.08059

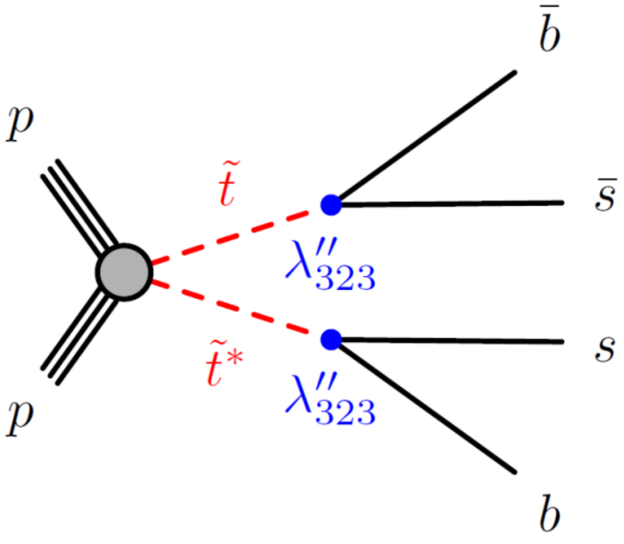
Natural SUSY scenario #3:

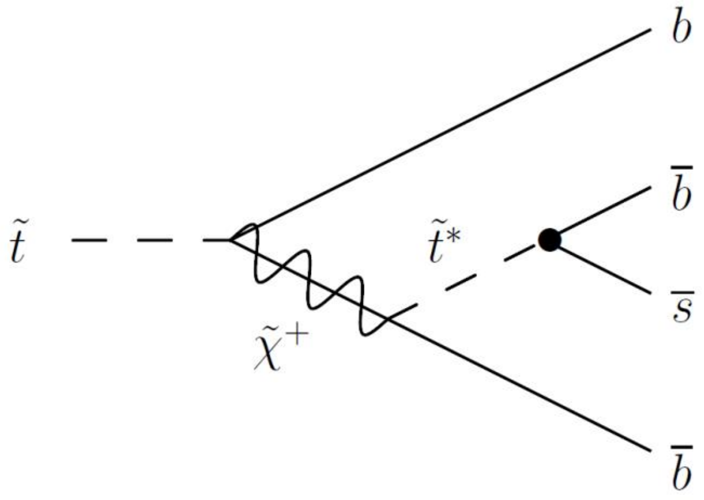
“no-MET SUSY”: R-parity violation (for example)

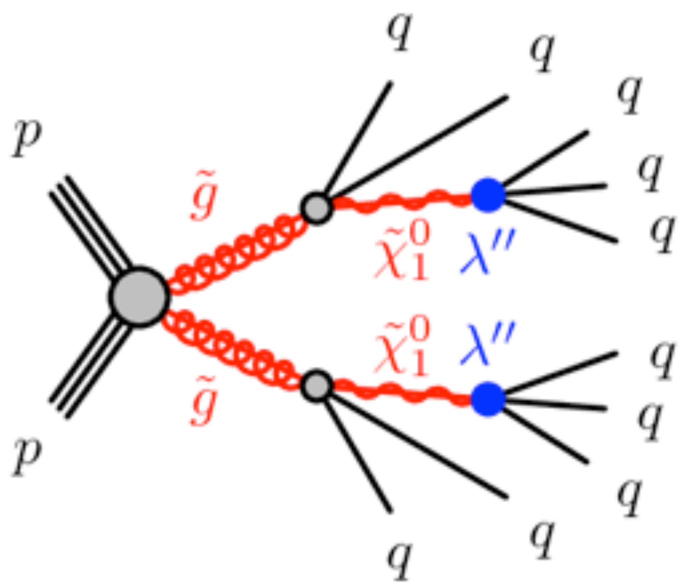
$$W_{RPV} = \frac{1}{2}\lambda_{ijk}L_iL_jE_k + \lambda'_{ijk}L_iQ_jD_k + \frac{1}{2}\lambda''_{ijk}U_iD_jD_k$$

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.

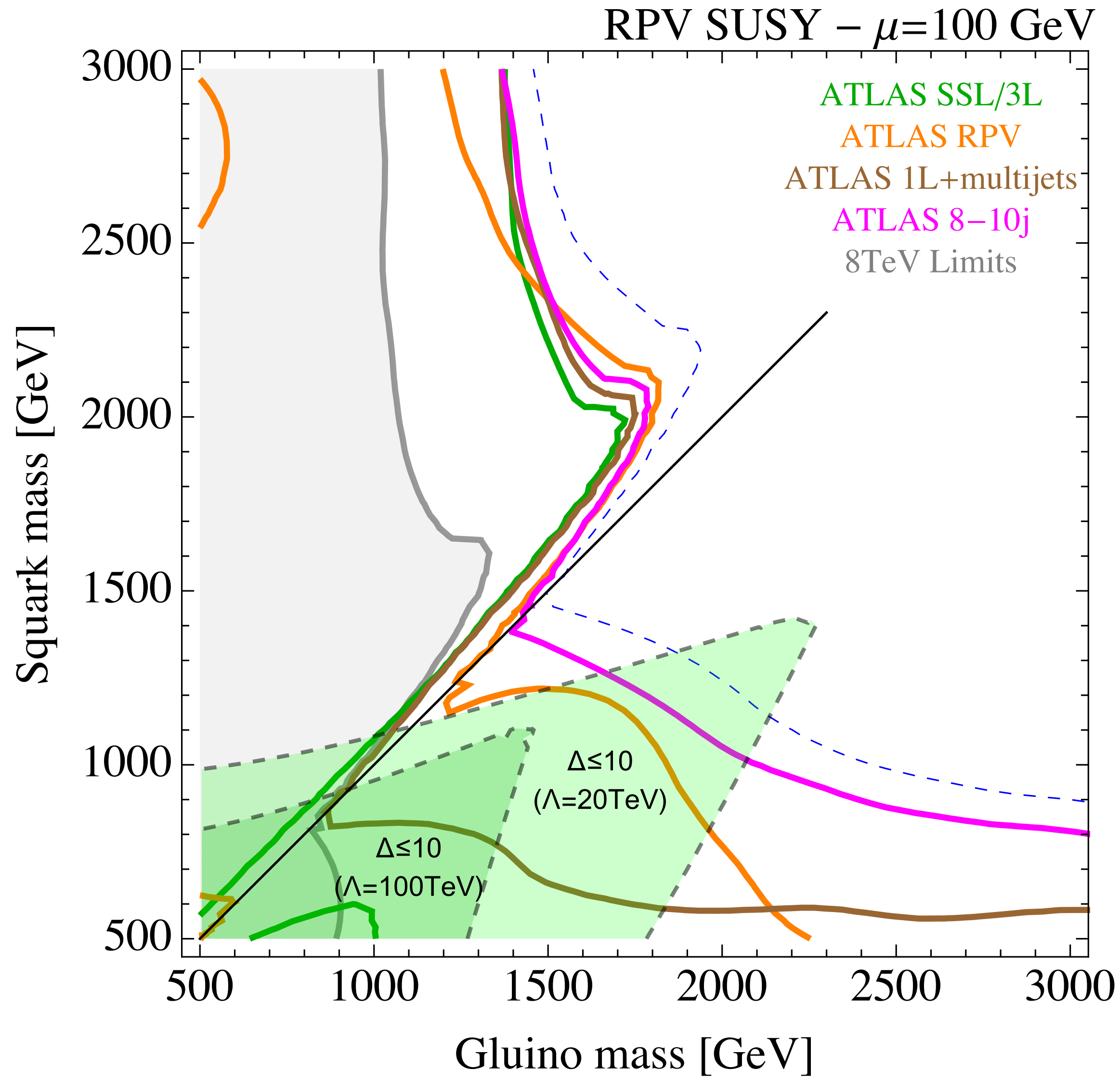
(See Jared’s talk for many more examples and counterexamples!)

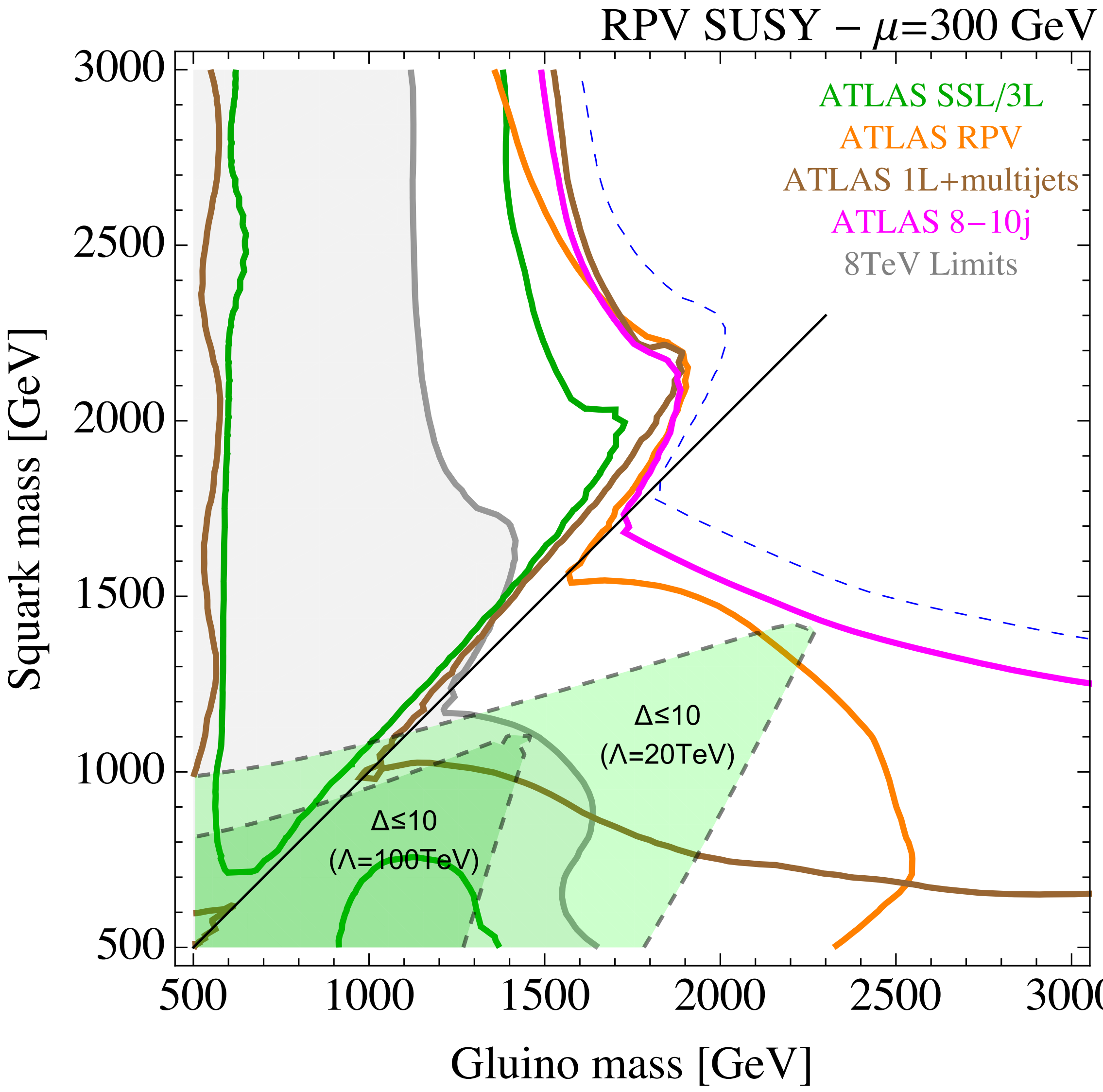






RPV + flavor universal squarks





Buckley, Feld, Macaluso, Monteux & DS 1610.08059

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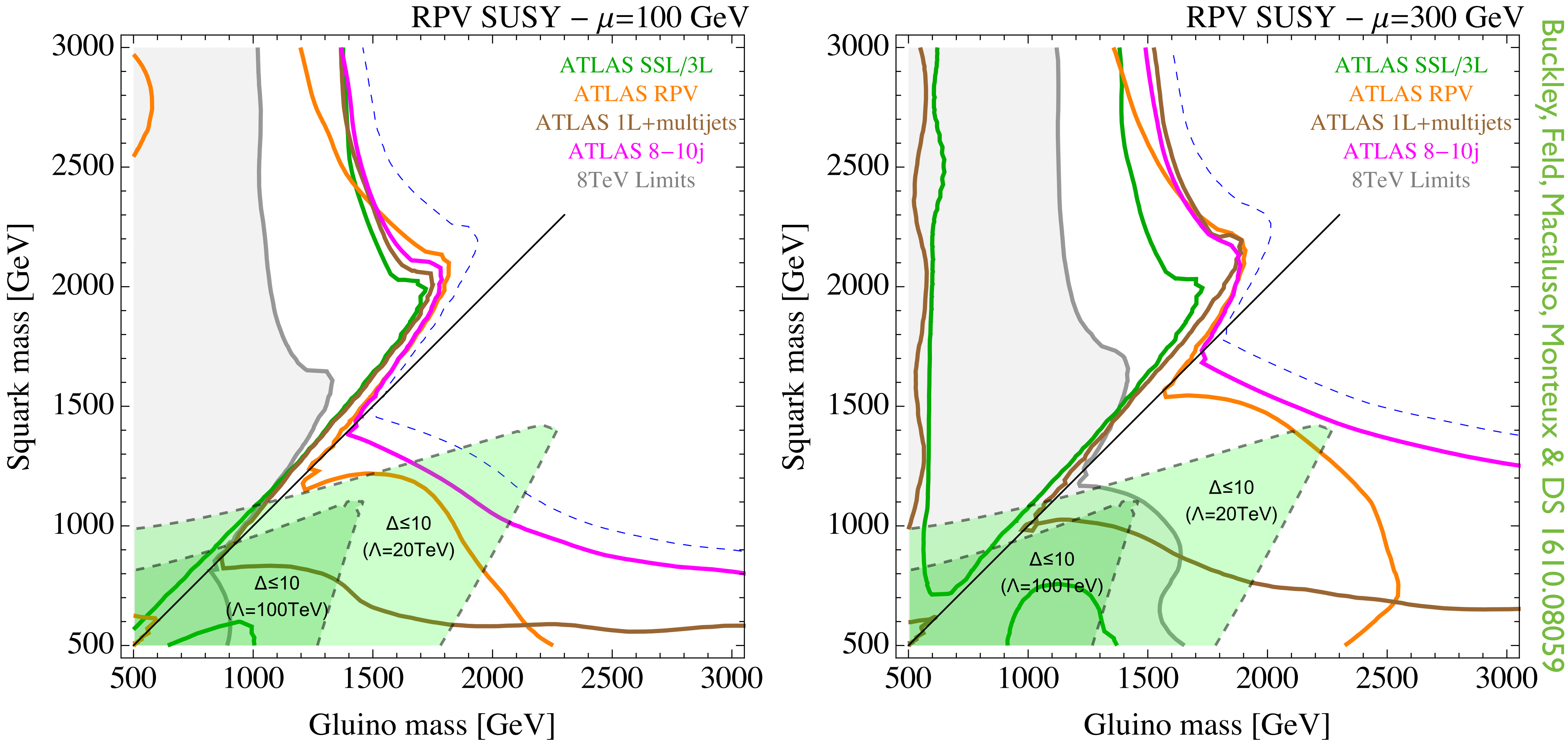
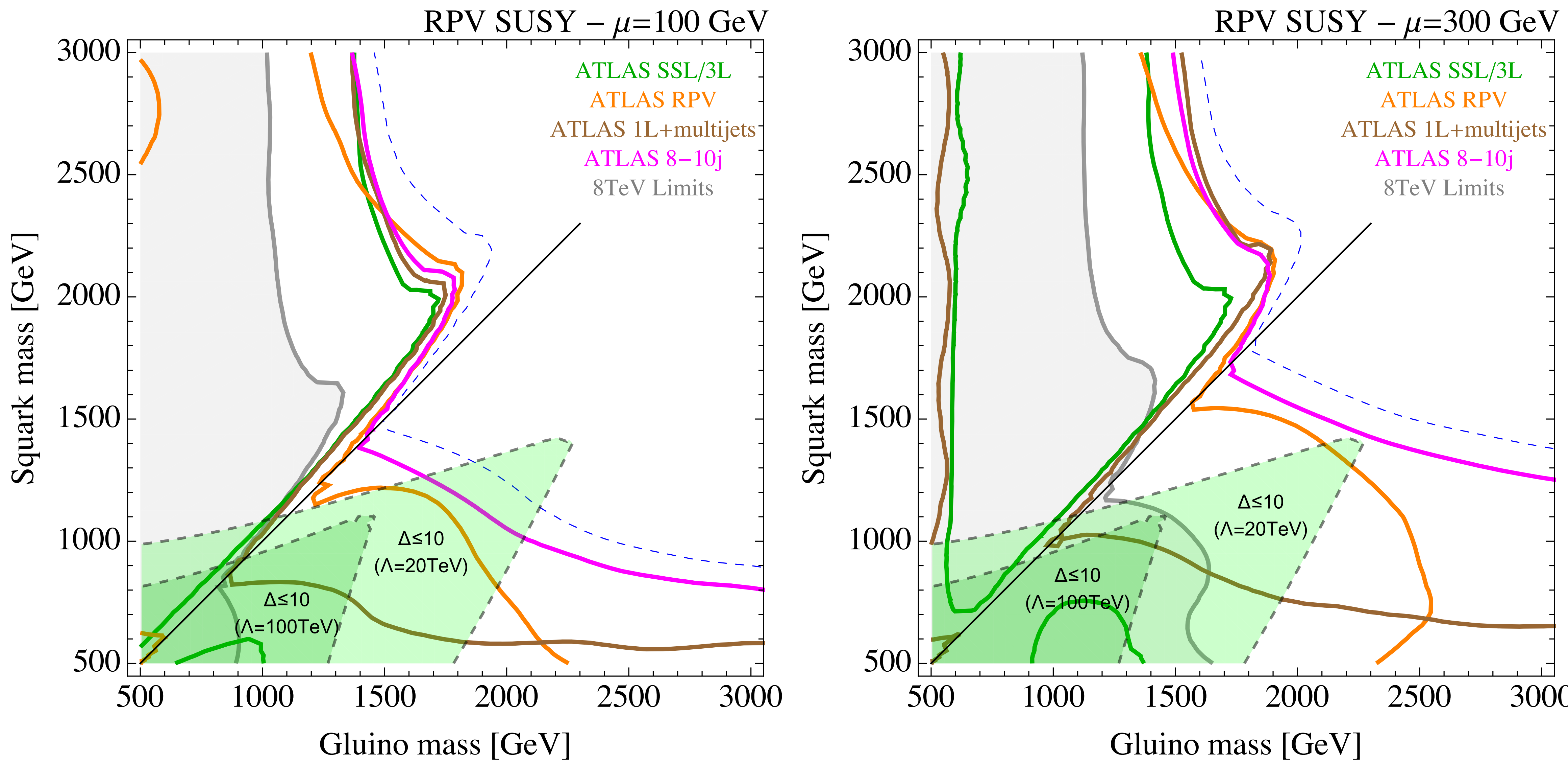


Buckley, Feld, Macaluso, Monteux & DS 1610.08059

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

RPV + flavor universal squarks



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

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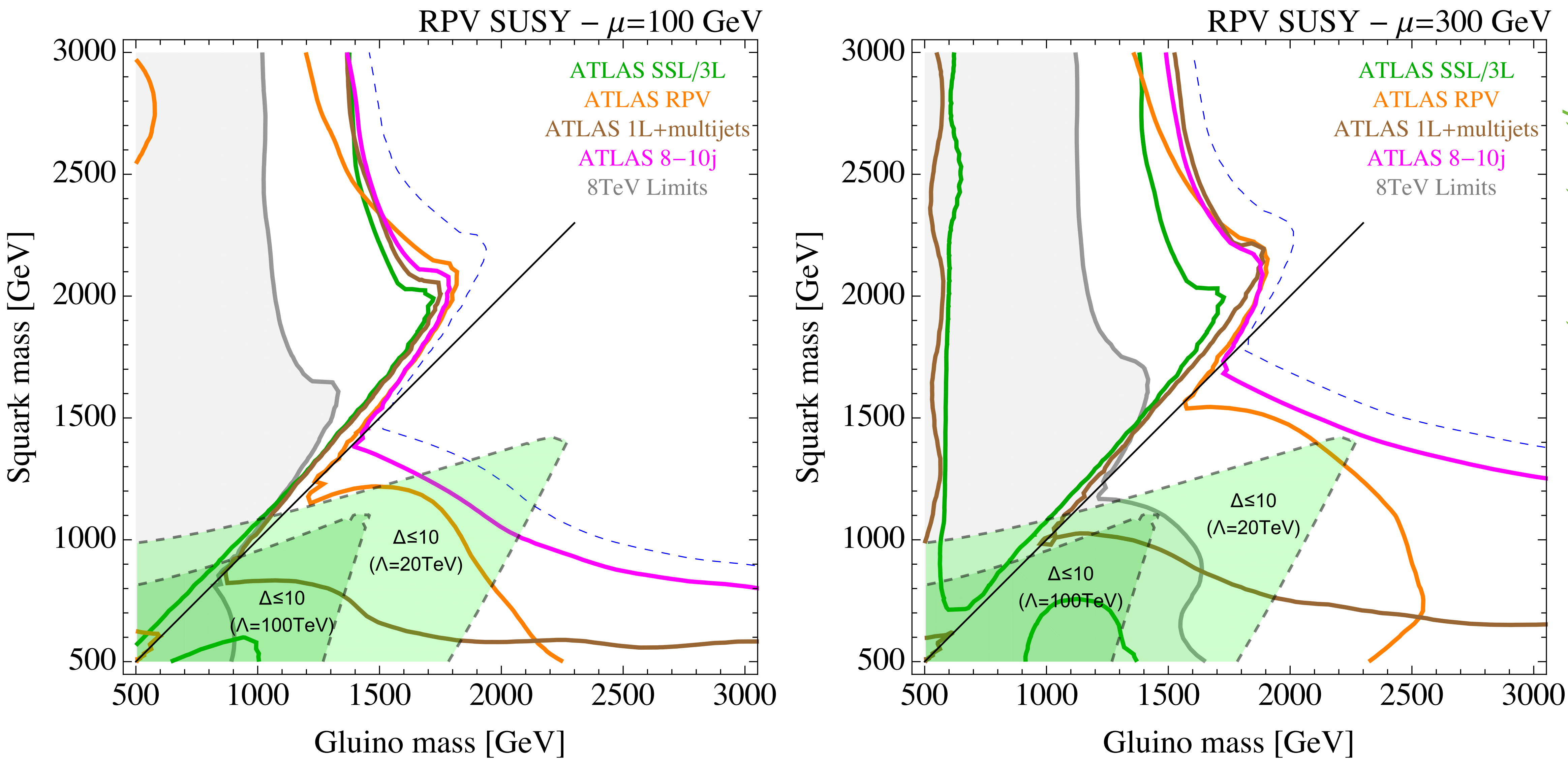

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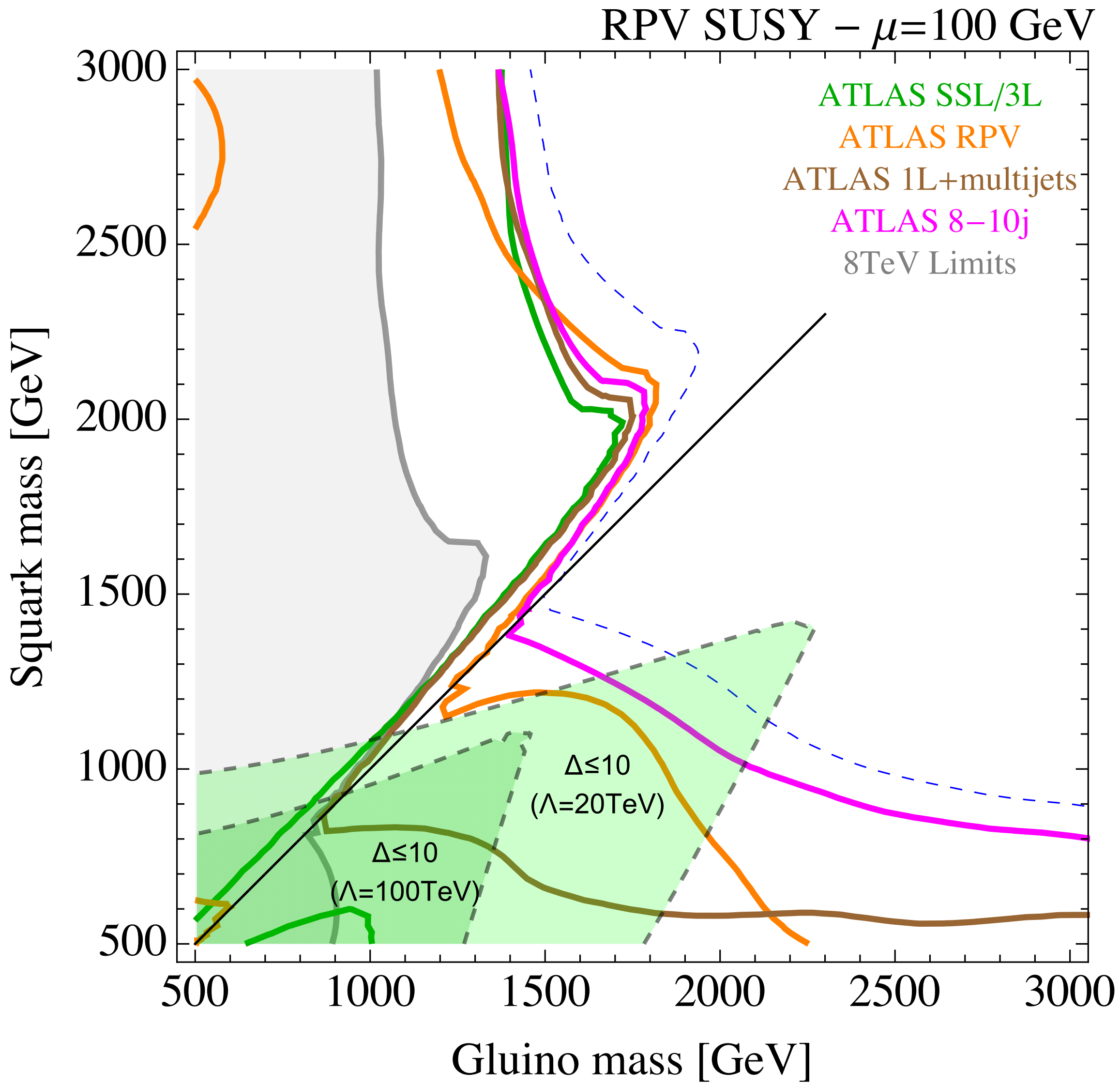
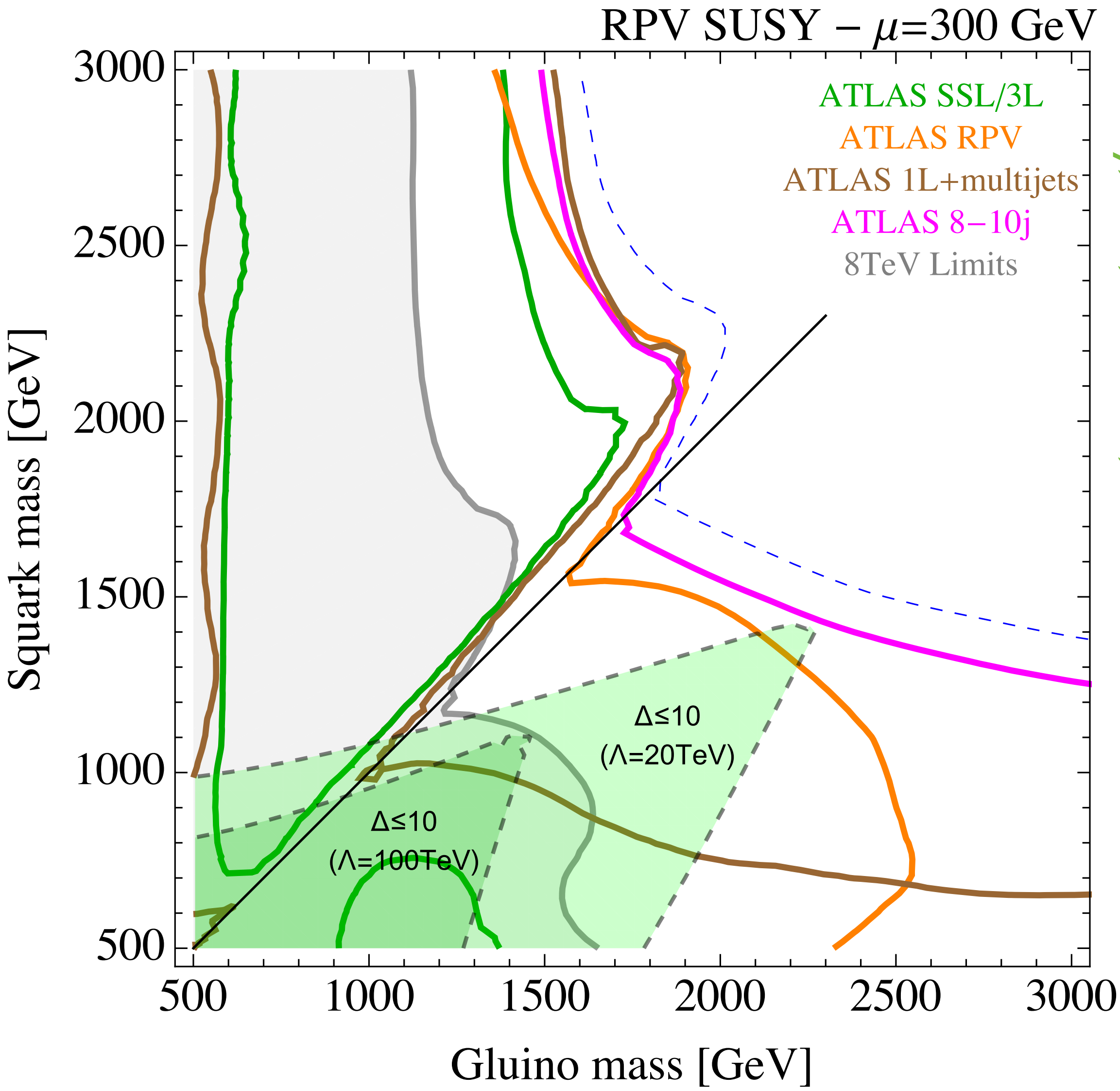
RPV + flavor universal squarks

(Interesting dependence on Higgsino mass!)





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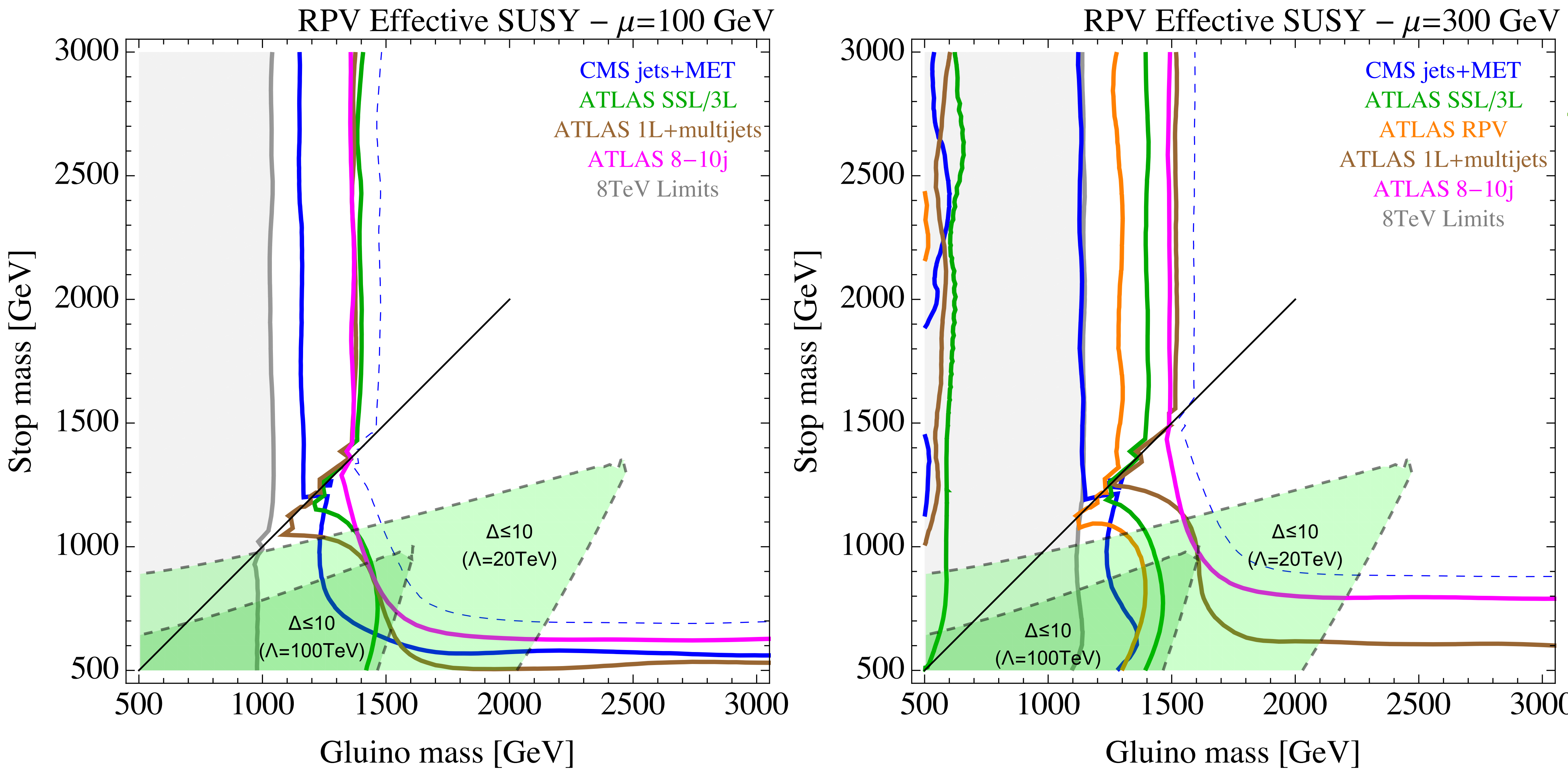
RPV + effective SUSY

limits on RPV stops as low as 600 GeV still??

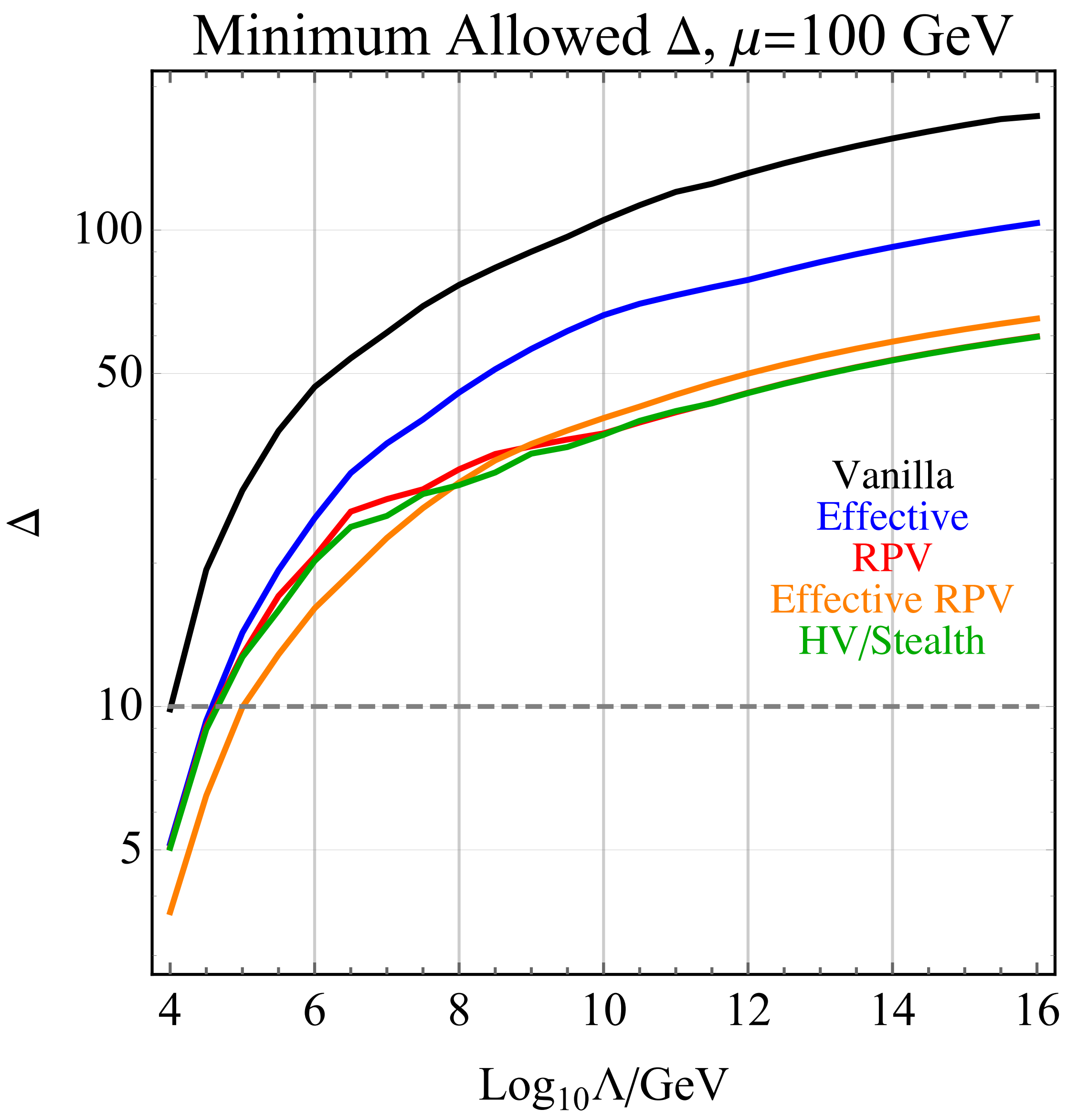


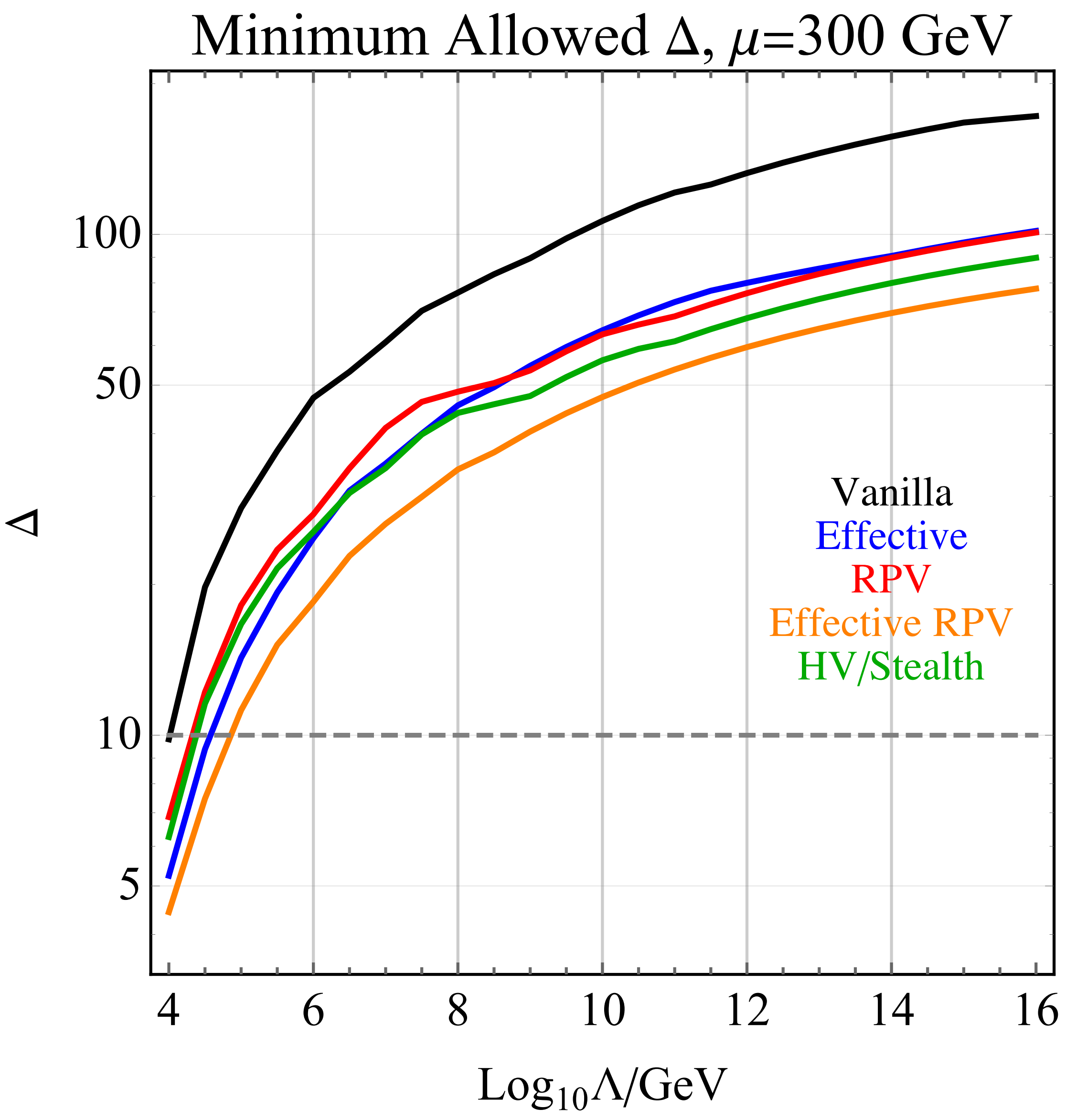
Buckley, Feld, Macaluso, Monteux & DS 1610.08059

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


Minimum Allowed Δ, μ=100 GeV


Minimum Allowed Δ, μ=300 GeV

Even in best case scenario, need $\Lambda<100$ TeV for $\Delta < 10$!

IS SUSY ALIVE AND WELL?

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Madrid, 28-30 September 2016
https://workshops.ift.uam-csic.es/susyaaw

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G. Bélanger (LAPTH-Annecy)
O. Buchmüller (Imperial Coll.)
M. Carena (Fermilab)
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EXCELENCIA SEVERO OCHOA
European Research Council SPLE Advanced Grant

Burning questions

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

Burning questions

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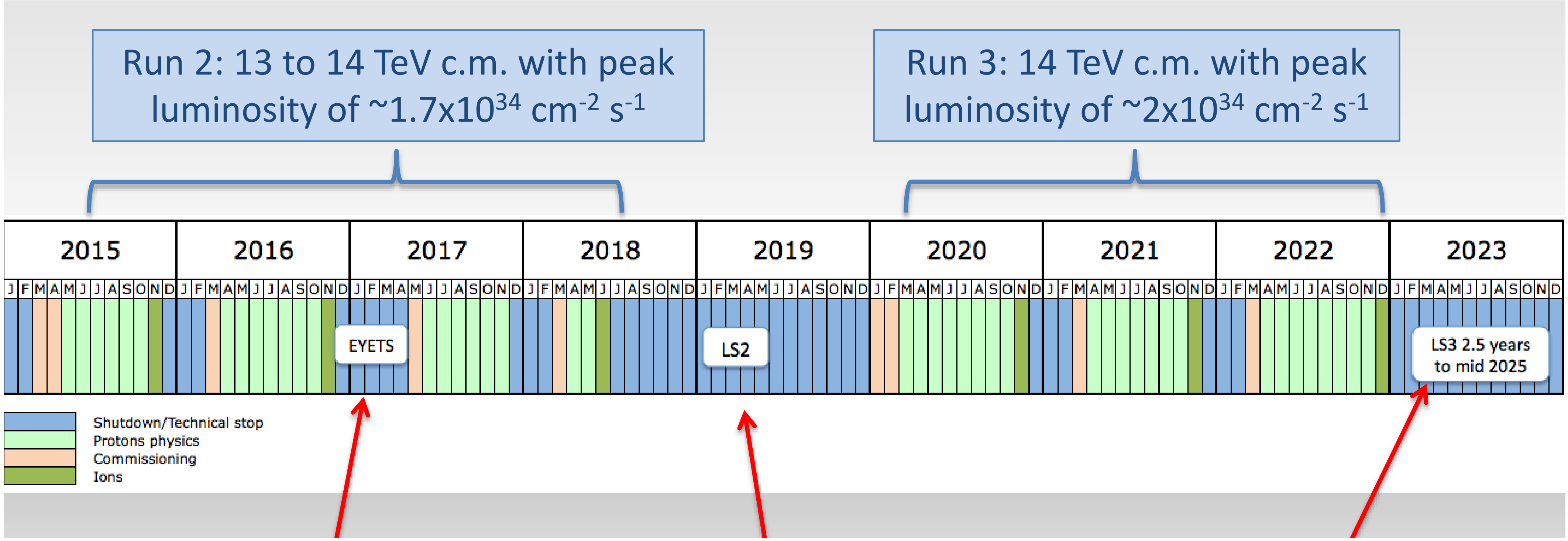
We are entering the slow phase...

	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

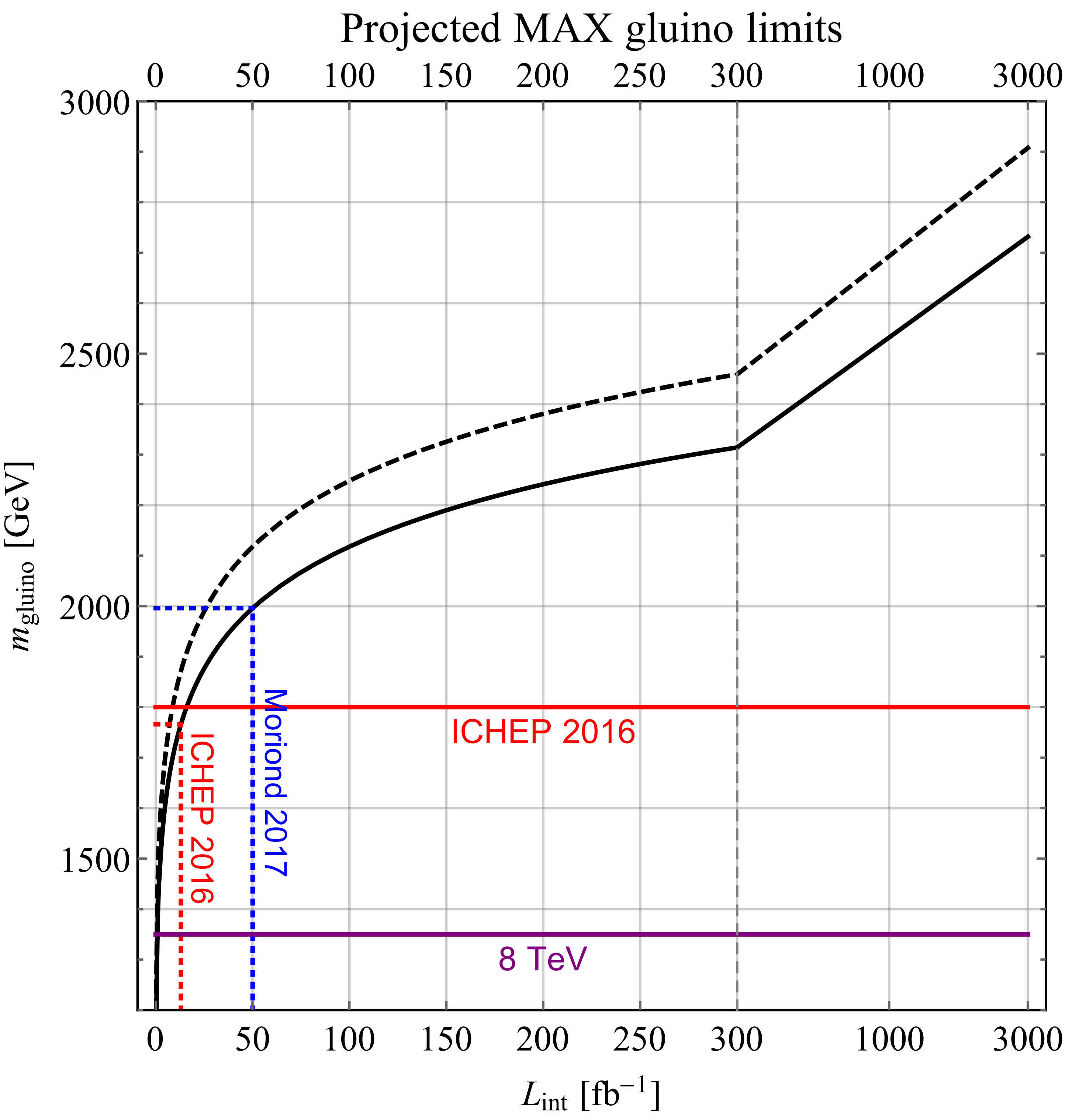
(M. Lamont, Moriond 2015)



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

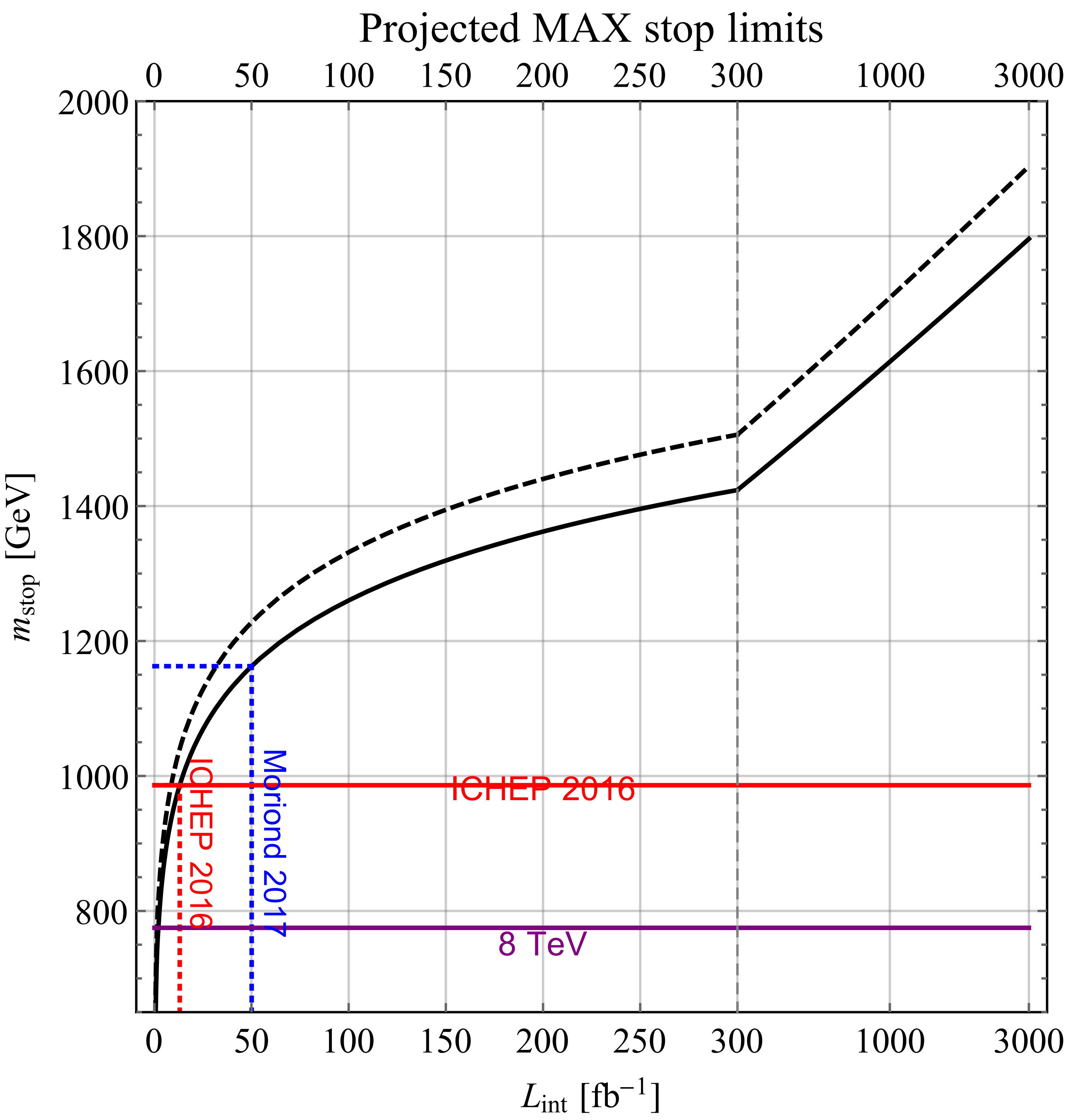
Run 3: 14 TeV c.m. with peak luminosity of ~2x10^{34} cm^{-2} s^{-1}

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...



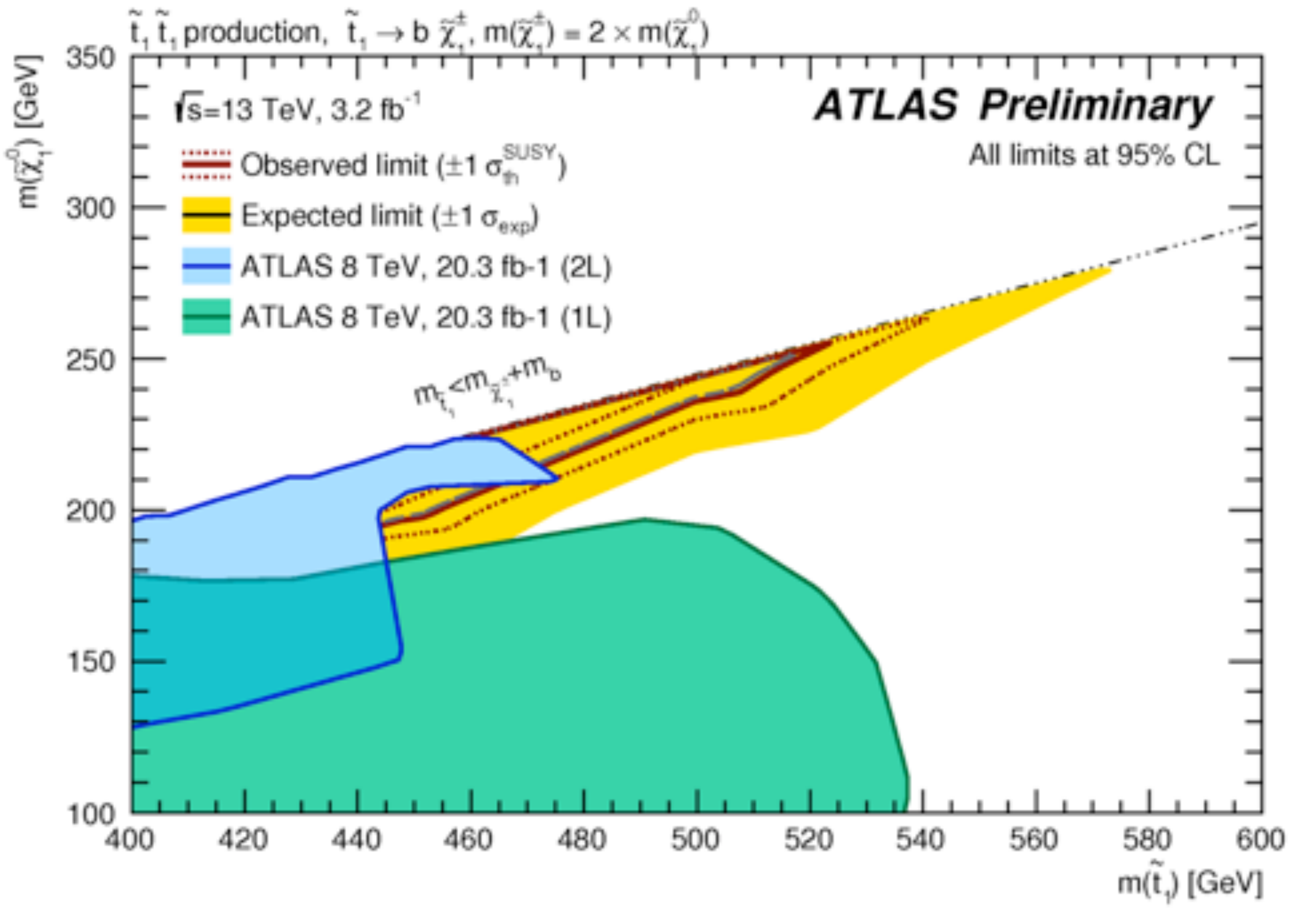
(parton luminosity ~ $e^{-a\,m}$ => reach Δm ~ 1000 GeV across a wide range of m!)

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 lower xsecs or difficult kinematic configurations.

More data and better analysis techniques could still have a dramatic impact here.



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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 - theory

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 - experiment

- Keep up the good work!
- Consider setting limits and optimizing searches for natural SUSY simplified models
  - light Higgsinos (more complex stop BRs)
  - stopL, stopR, sbottomR
- Degraded sensitivity to
  - RPV stop->higgsino (600 GeV)
    - many jets + bjets + lepton without mT cut?
  - RPV with light higgsino LSP
    - 3-jet substructure with variable mass?

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

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

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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.

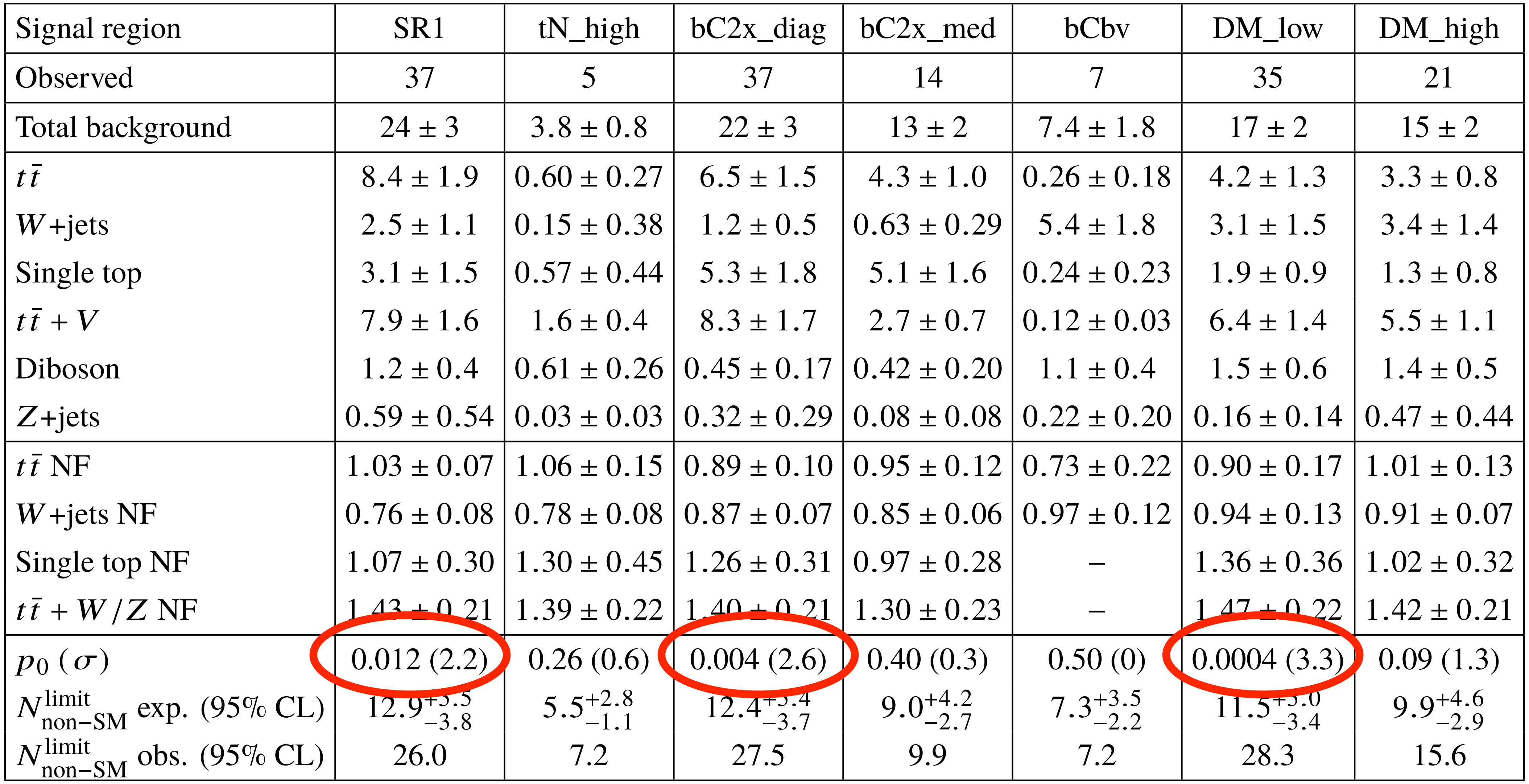
Also, there exist many, more challenging signatures that will require more data and improved analysis techniques.

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!

*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)
$N^{\text{limit}}_{\text{non-SM}}$ exp. (95% CL)	$12.9^{+3.5}_{-3.8}$	$5.5^{+2.8}_{-1.1}$	$12.4^{+3.4}_{-3.7}$	$9.0^{+4.2}_{-2.7}$	$7.3^{+3.5}_{-2.2}$	$11.5^{+3.0}_{-3.4}$	$9.9^{+4.6}_{-2.9}$
$N^{\text{limit}}_{\text{non-SM}}$ obs. (95% CL)	26.0	7.2	27.5	9.9	7.2	28.3	15.6

ATLAS-CONF-2016-050

M. Buckley, A. DiFranzo, A. Monteux & DS

ATLAS 2016-050 (stop 1L)

Variable	DM_low
≥4 jets with $p_T >$ [GeV]	(60 60 40 25)
E_T^{miss} [GeV]	> 300
$H_{T,sig}^{miss}$	> 14
m_T [GeV]	> 120
am_{T2} [GeV]	> 140
$\min(\Delta\phi(p_T^{miss}, \text{jet}_i))(i \in \{1-4\})$	> 1.4
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	> 0.8
$\Delta R(b_1, b_2)$	–
Number of b-tags	≥ 1

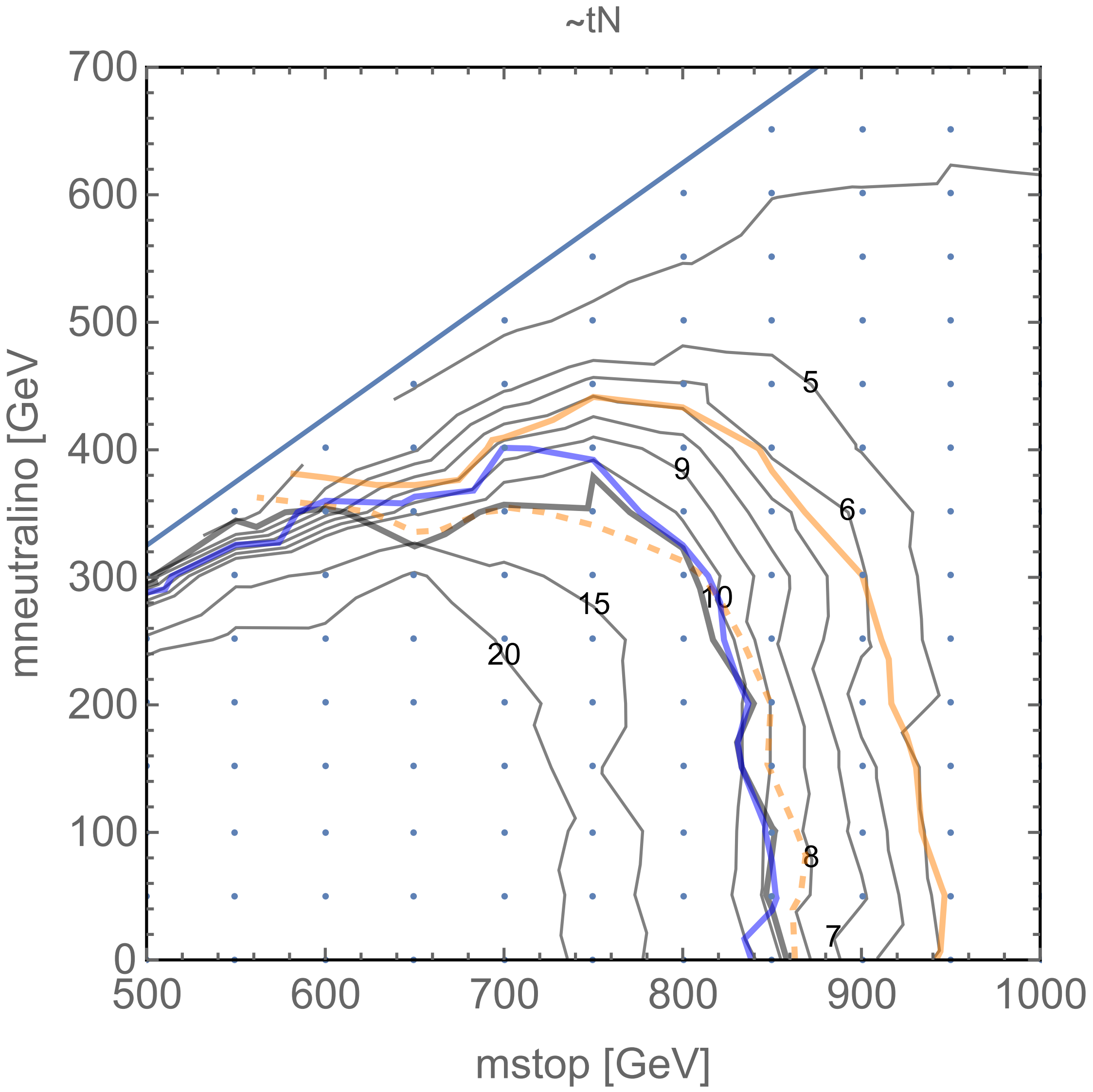
17 ± 2 exp
35 obs

CMS 16-028 (stop 1L)

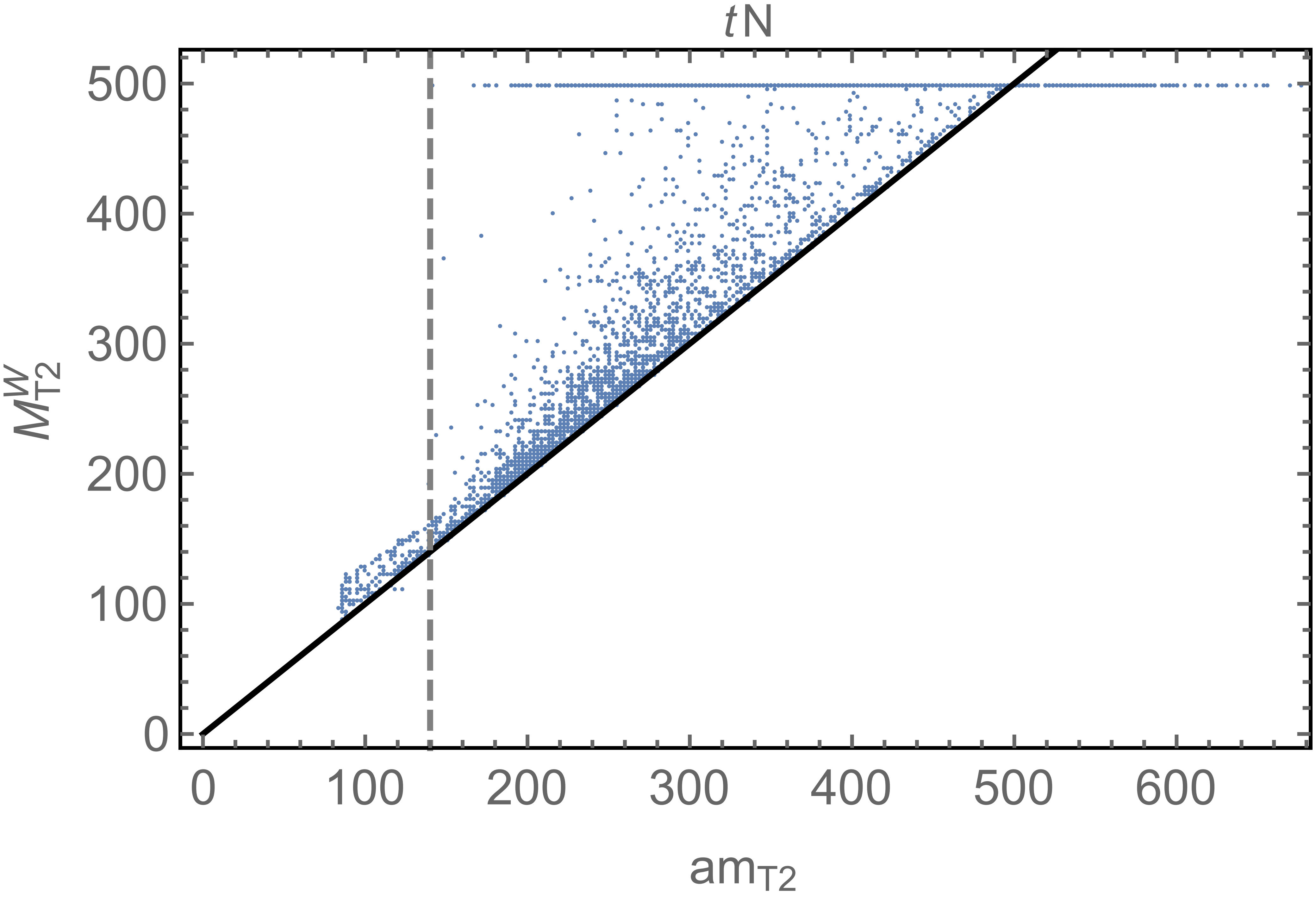
E_T^{miss} [GeV]	Lost Lepton	1ℓ (not from top)	$t\bar{t} \to 1\ell$	$Z \to \nu\bar{\nu}$	Total background	Data
	≥ 4 jets, $M_{T2}^W > 200$ GeV					
250 – 350	29.3 ± 4.2	7.6 ± 3.3	2.8 ± 2.8	3.6 ± 1.4	43.3 ± 6.2	44
350 – 450	7.8 ± 1.8	3.3 ± 1.3	0.97 ± 0.97	2.2 ± 0.8	14.2 ± 2.5	11
450 – 550	3.5 ± 1.1	0.34 ± 0.25	0.04 ± 0.04	0.86 ± 0.43	4.8 ± 1.3	5
550 – 650	1.0 ± 0.5	0.48 ± 0.31	—	0.19 ± 0.10	1.7 ± 0.6	1
> 650	0.37 ± 0.20	0.23 ± 0.19	0.11 ± 0.11	0.21 ± 0.13	0.92 ± 0.33	3

21.62 ± 2.90 exp
20 obs

- M_{T2}^W and am_{T2} are highly correlated (Bai et al 1203.4813)
- Max # events in DMlow consistent with CMS16-028: ~ 10
- Naive combination: ~3.3σ→ ~2.3σ



M. Buckley, A. DiFranzo, A. Monteux & DS



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:

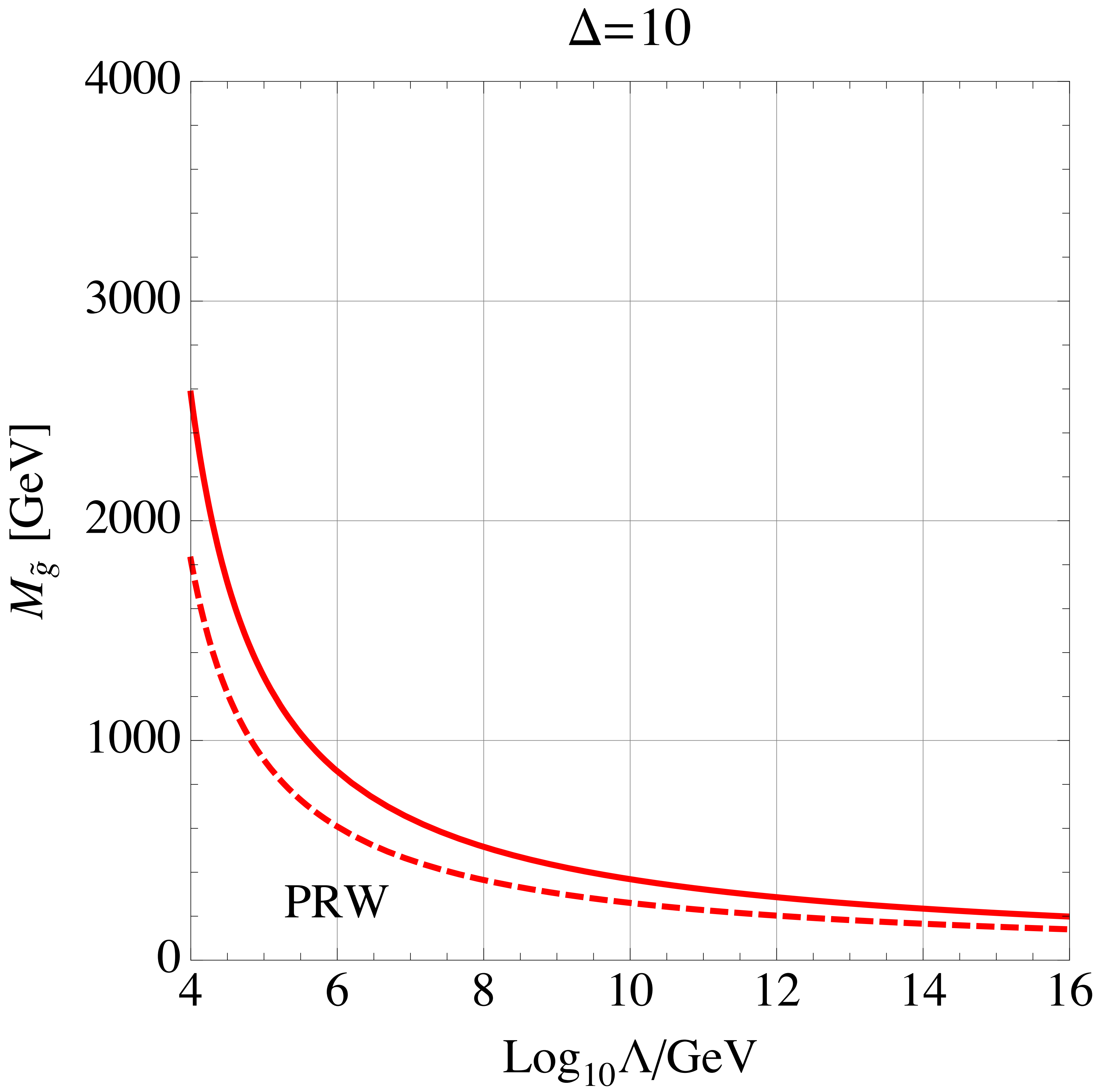
- Not easy to break tree-level connection between Higgsinos and tuning.
- One interesting idea: Higgsino mass from hard SUSY breaking (Brust, Katz, Lawrence & Sundrum ’11; Nelson & Roy ’15; Martin ’15)

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

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

- 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.

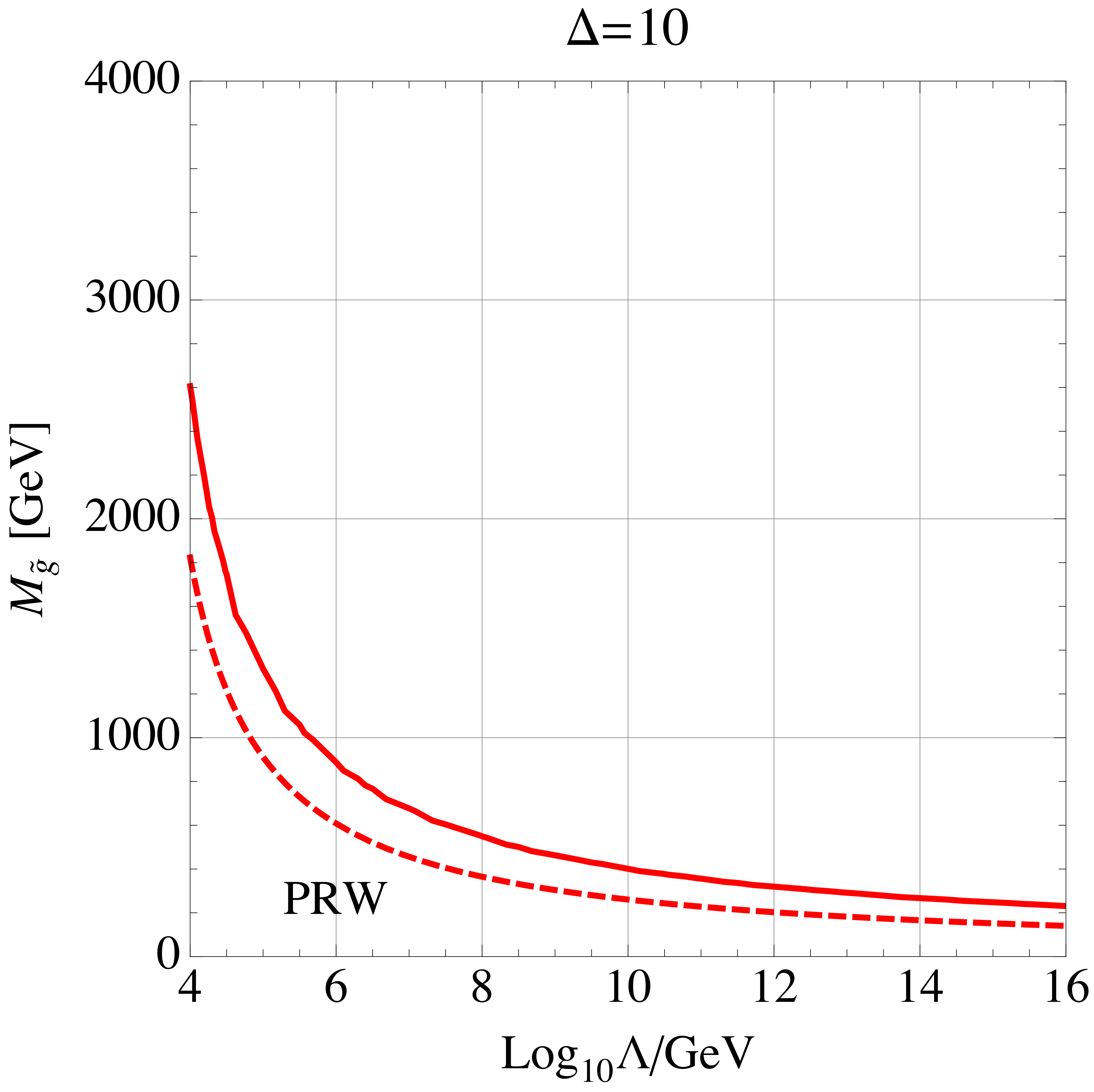


In calculating the gluino tuning bound, it is important to do a careful treatment of the quantum corrections

- Factor of 2 error

cf Casas et al 1407.6966

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

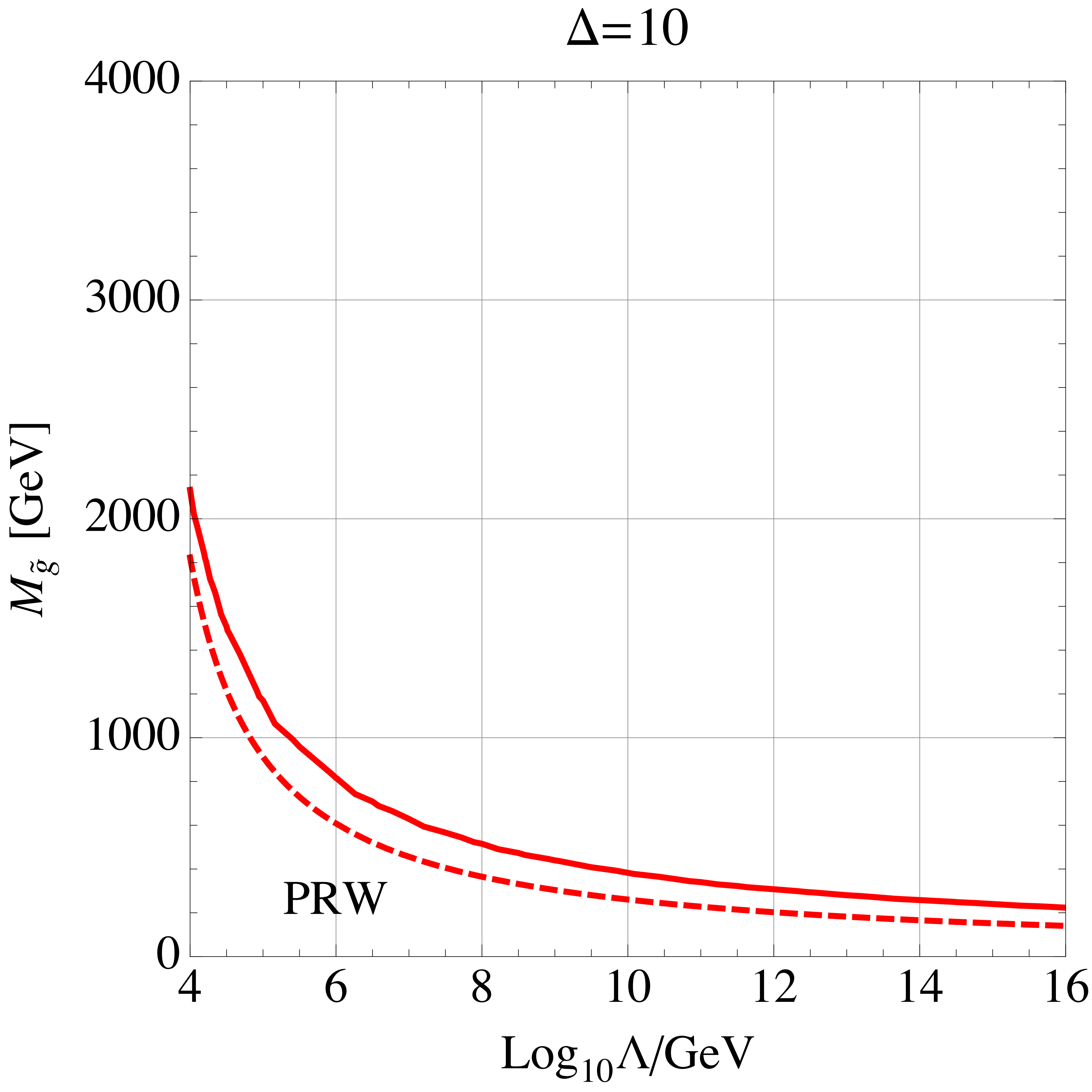


In calculating the gluino tuning bound, it is important to do a careful treatment of the quantum corrections

- Factor of 2 error
- LL vs. resummed RGEs

cf Casas et al 1407.6966

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

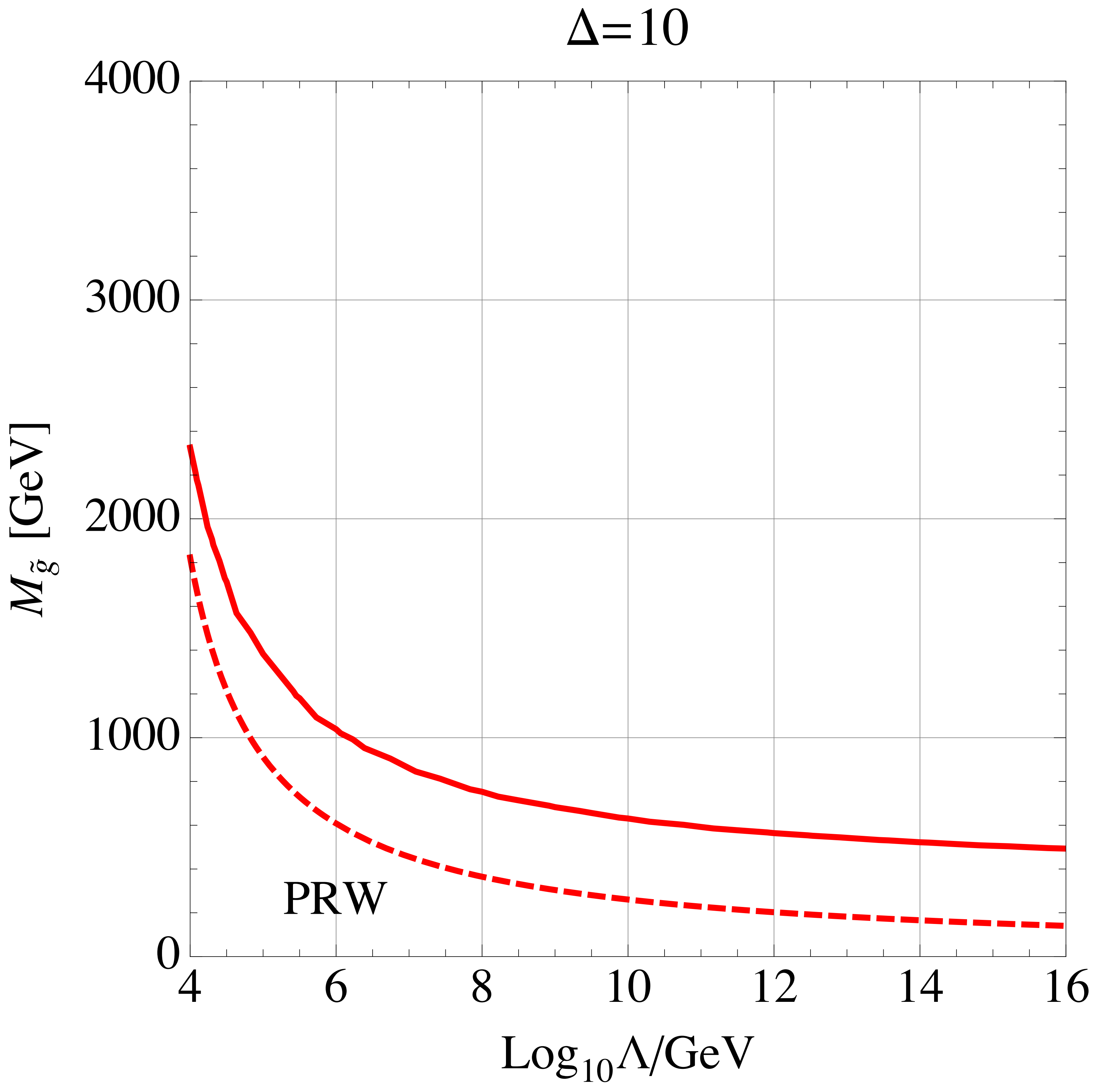


In calculating the gluino tuning bound, it is important to do a careful treatment of the quantum corrections

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

cf Casas et al 1407.6966

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

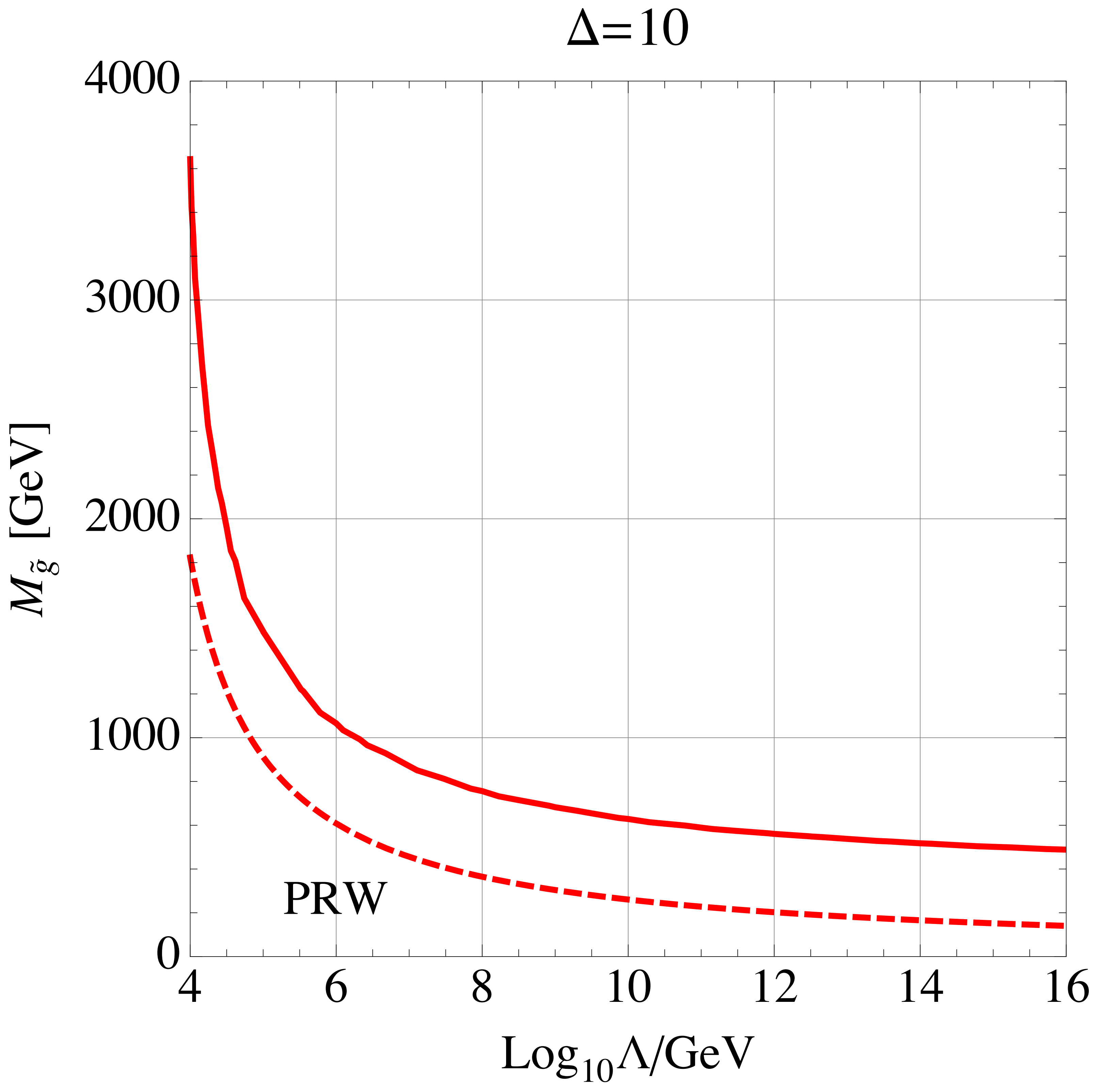


In calculating the gluino tuning bound, it is important to do a careful treatment of the quantum corrections

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

cf Casas et al 1407.6966

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

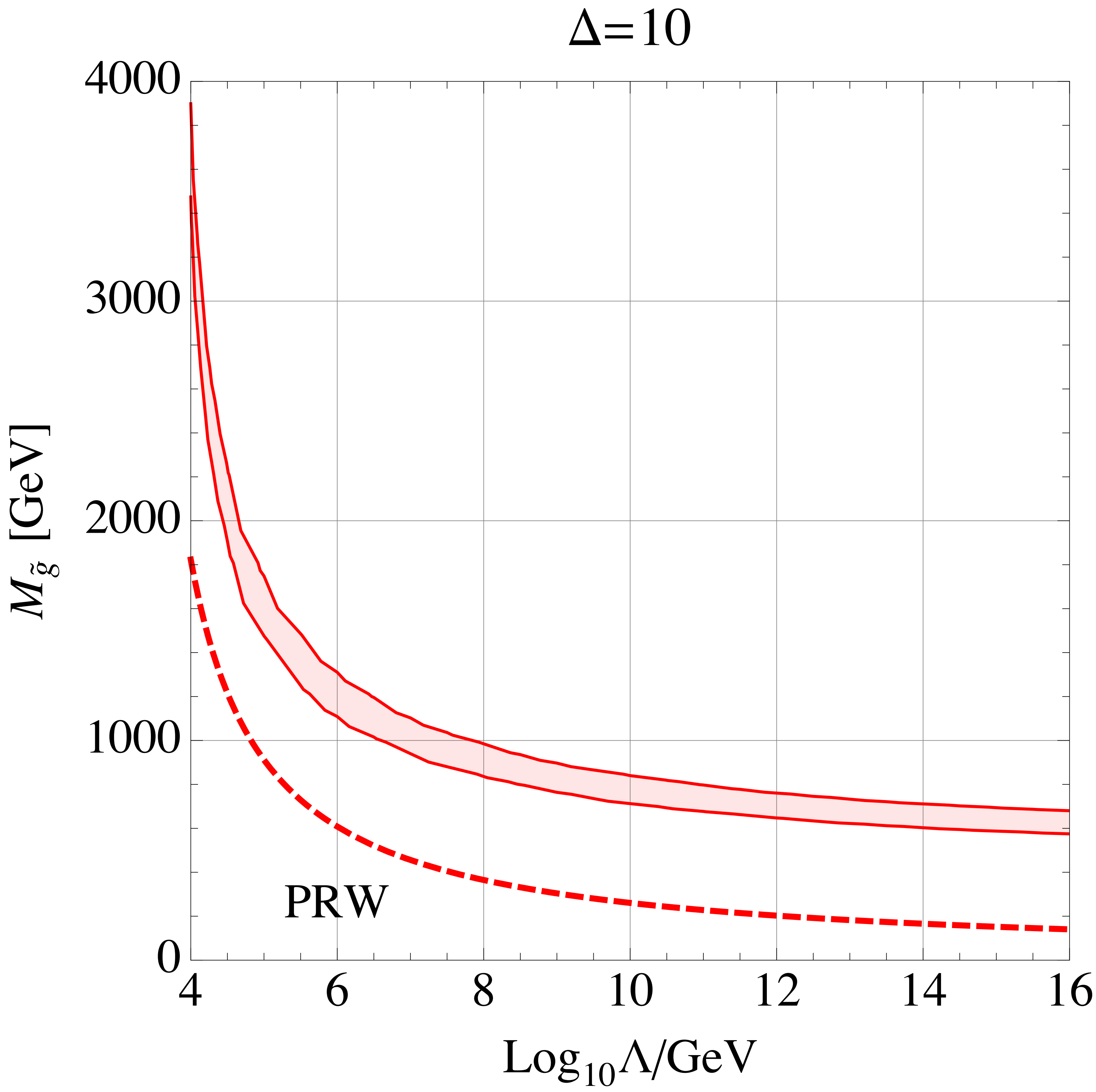


In calculating the gluino tuning bound, it is important to do a careful treatment of the quantum corrections

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

cf Casas et al 1407.6966

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

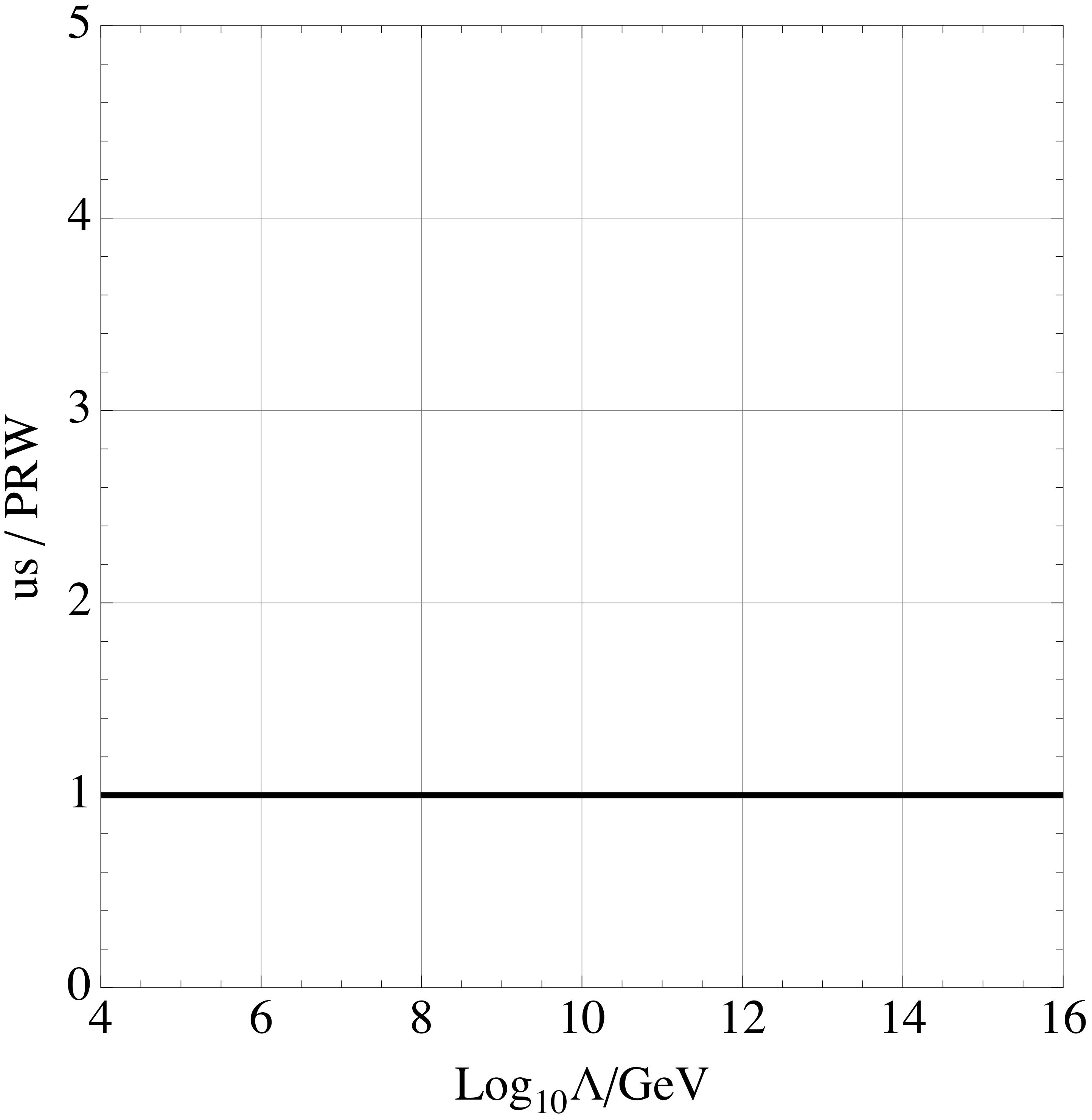
- Factor of 2 error
- LL vs. resummed RGEs
- 2-loop RGEs
- UV vs. IR mass
- finite threshold corrections
- IR mass vs. pole mass

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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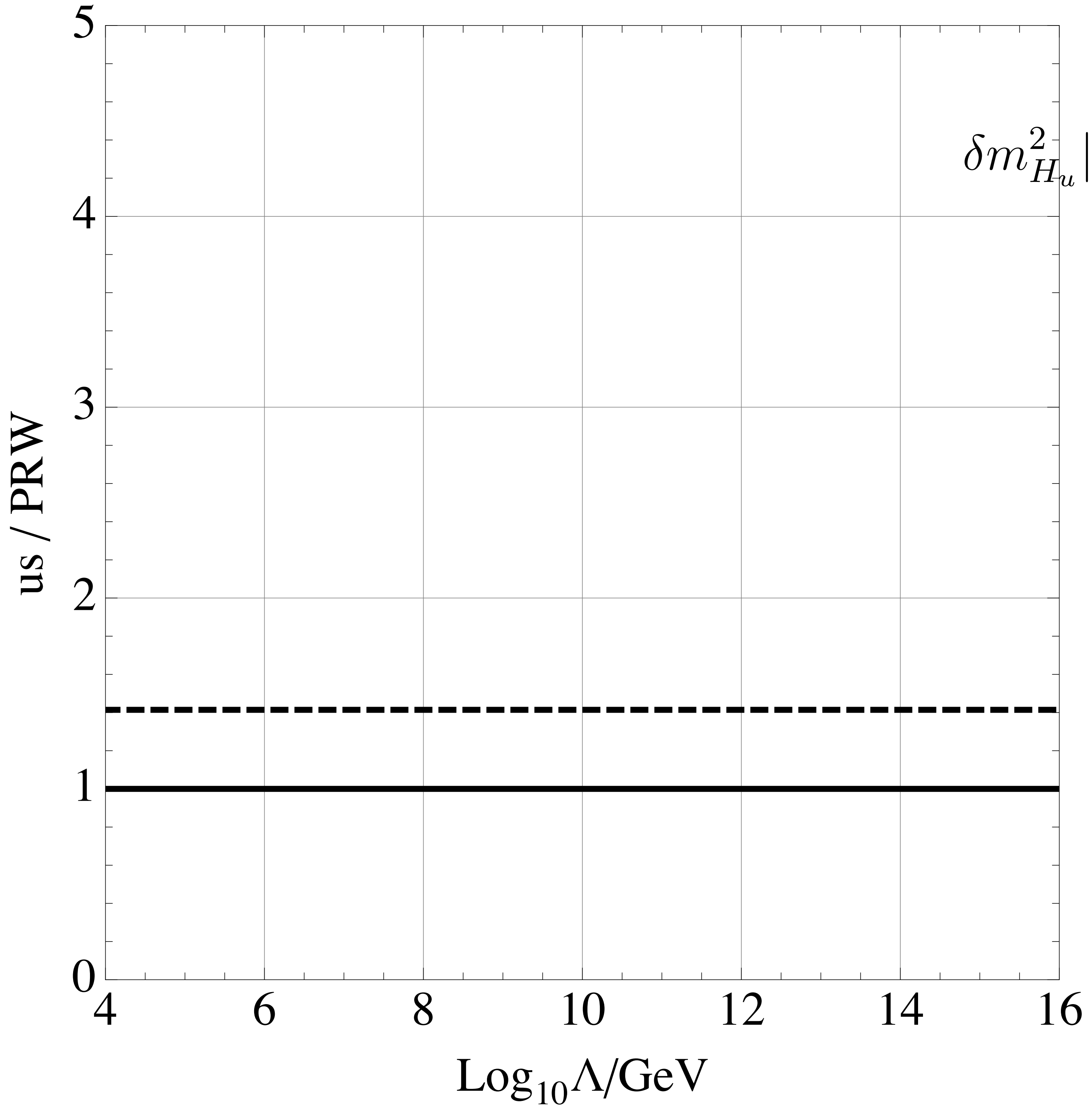
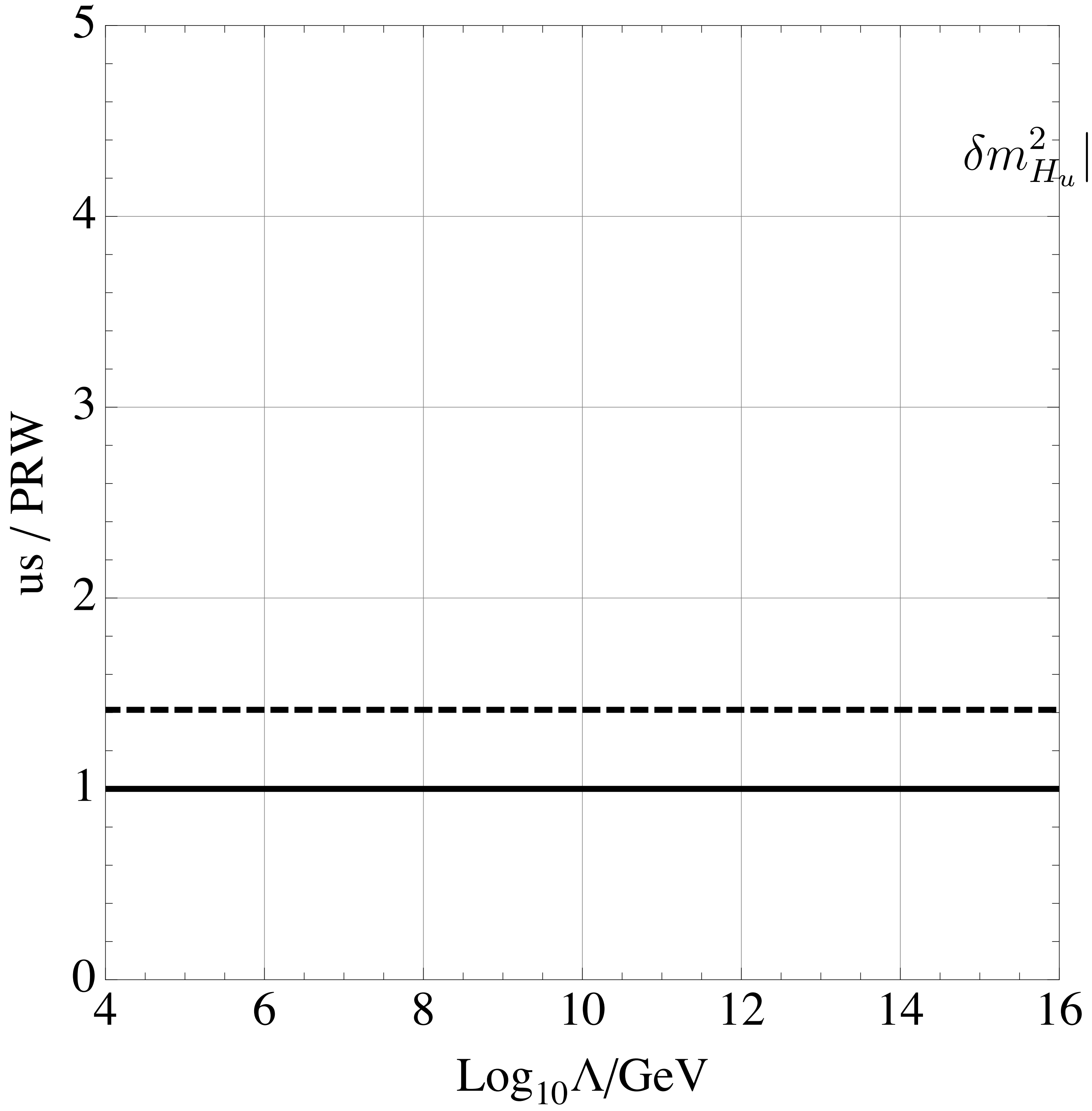


- Factor of 2 error

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

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

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



- Factor of 2 error

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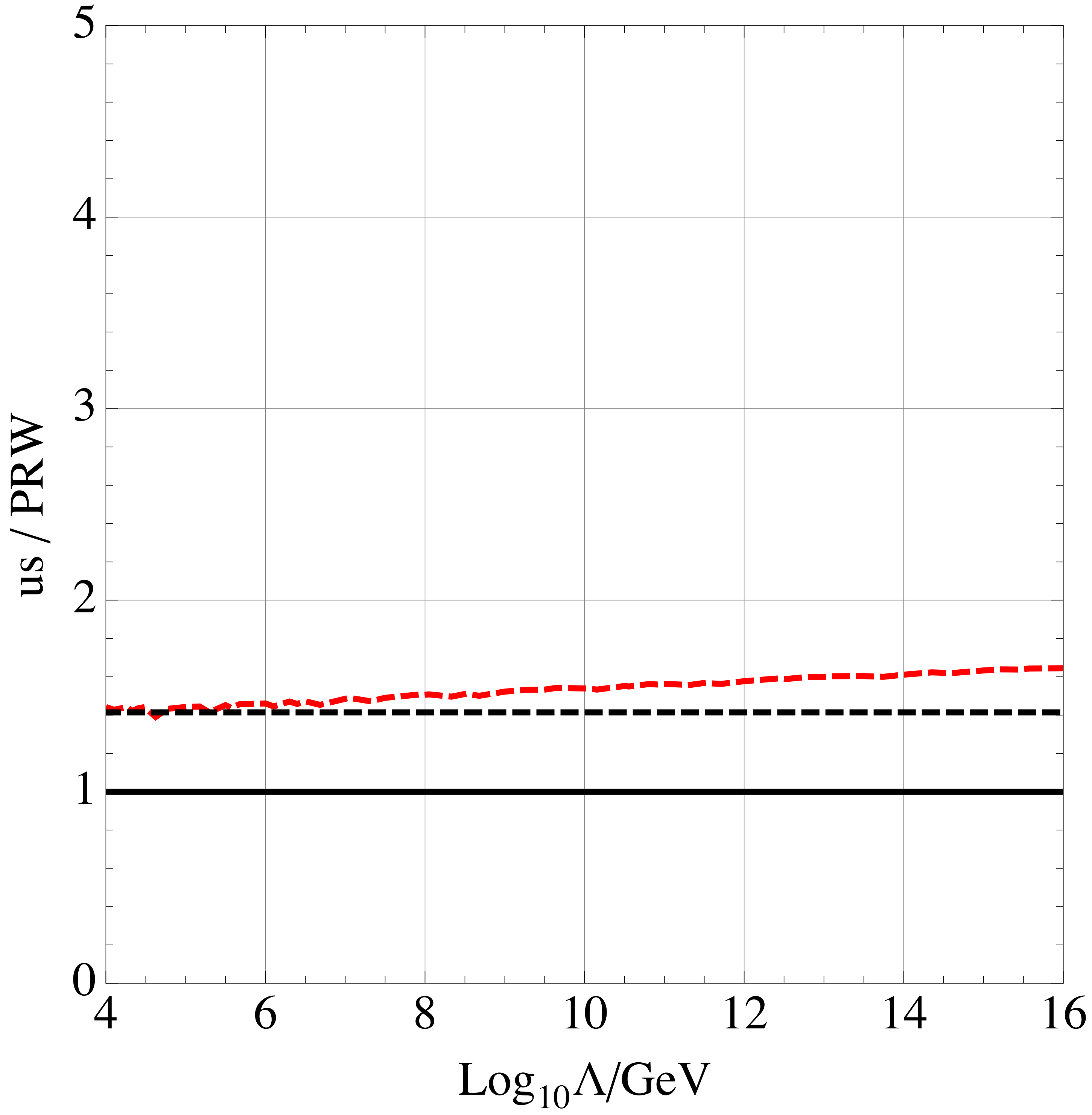


- Factor of 2 error
- LL vs. resummed RGEs

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

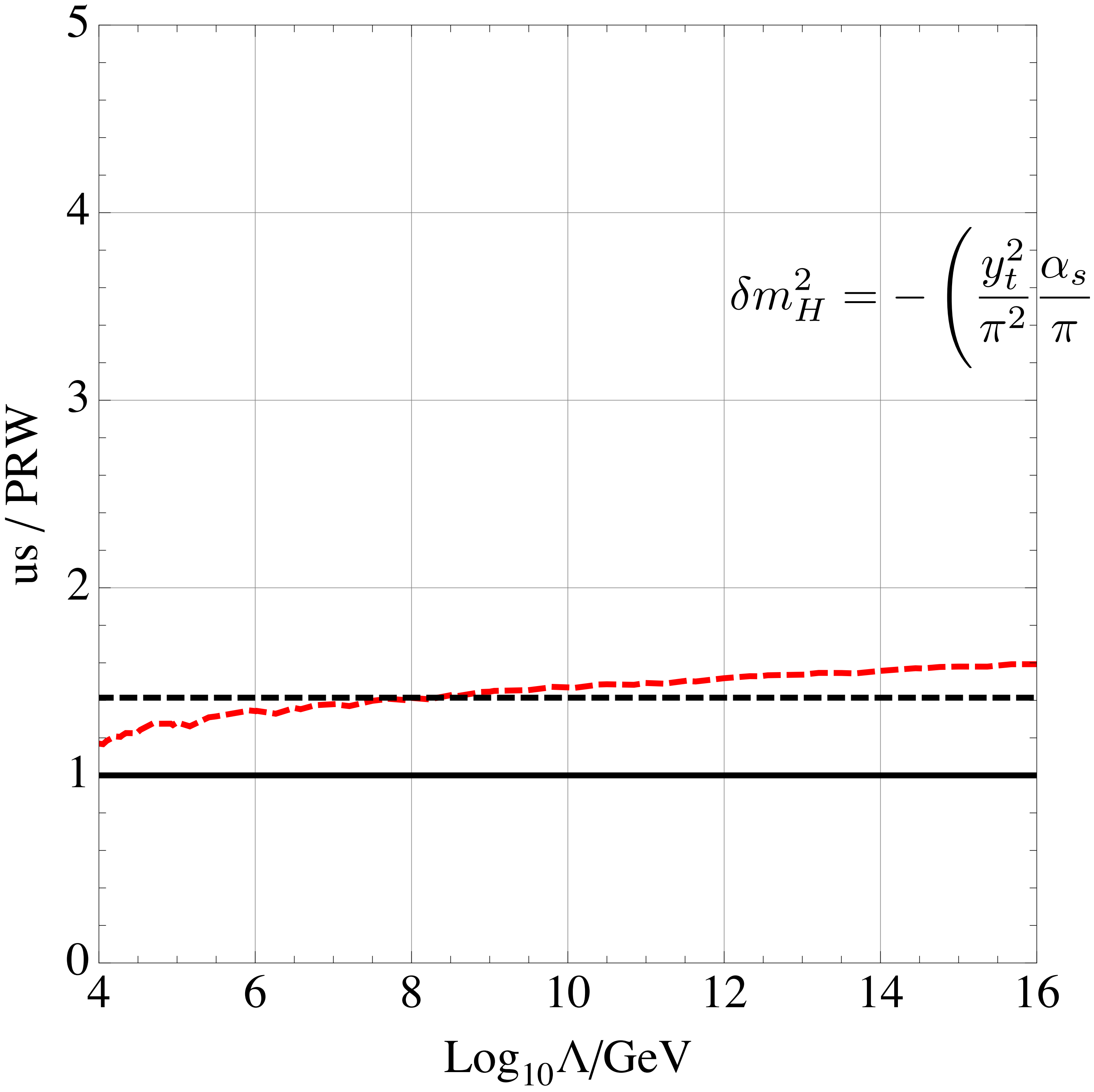
$$\downarrow$$

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

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)

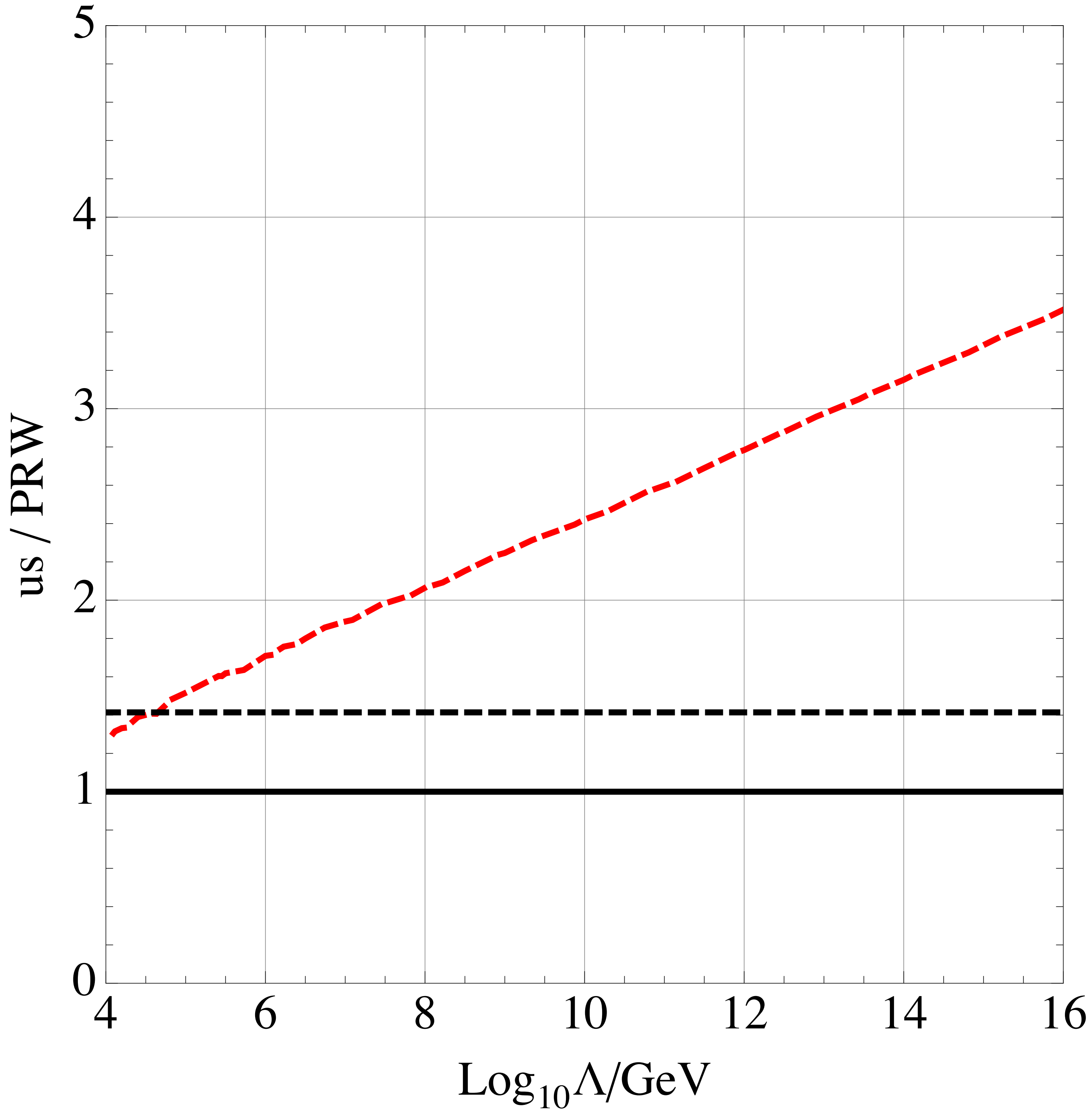


- Factor of 2 error
- LL vs. resummed RGEs
- 2-loop RGEs

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

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)

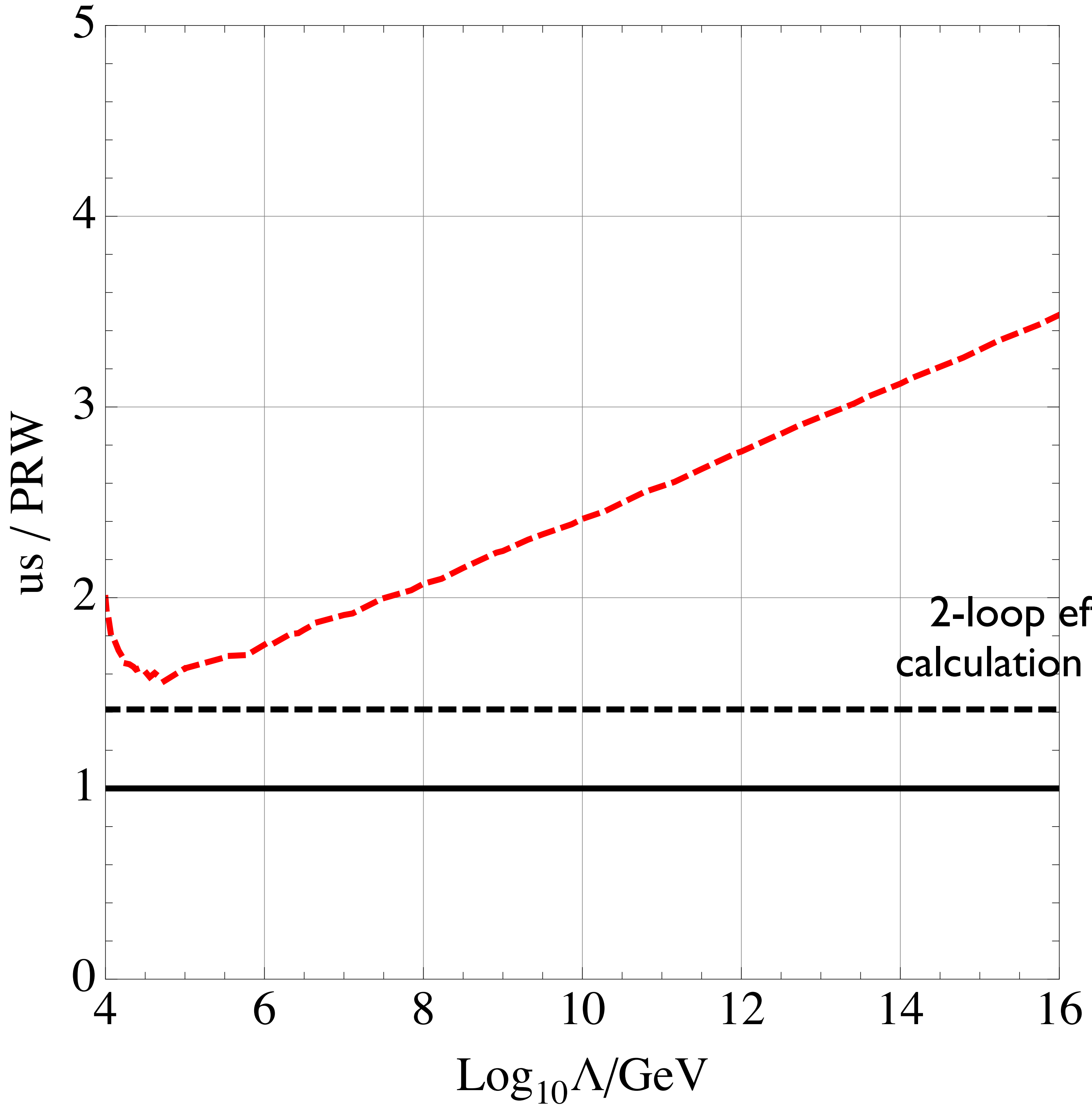


- Factor of 2 error
- LL vs. resummed RGEs
- 2-loop RGEs
- UV vs. IR mass

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

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

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



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

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

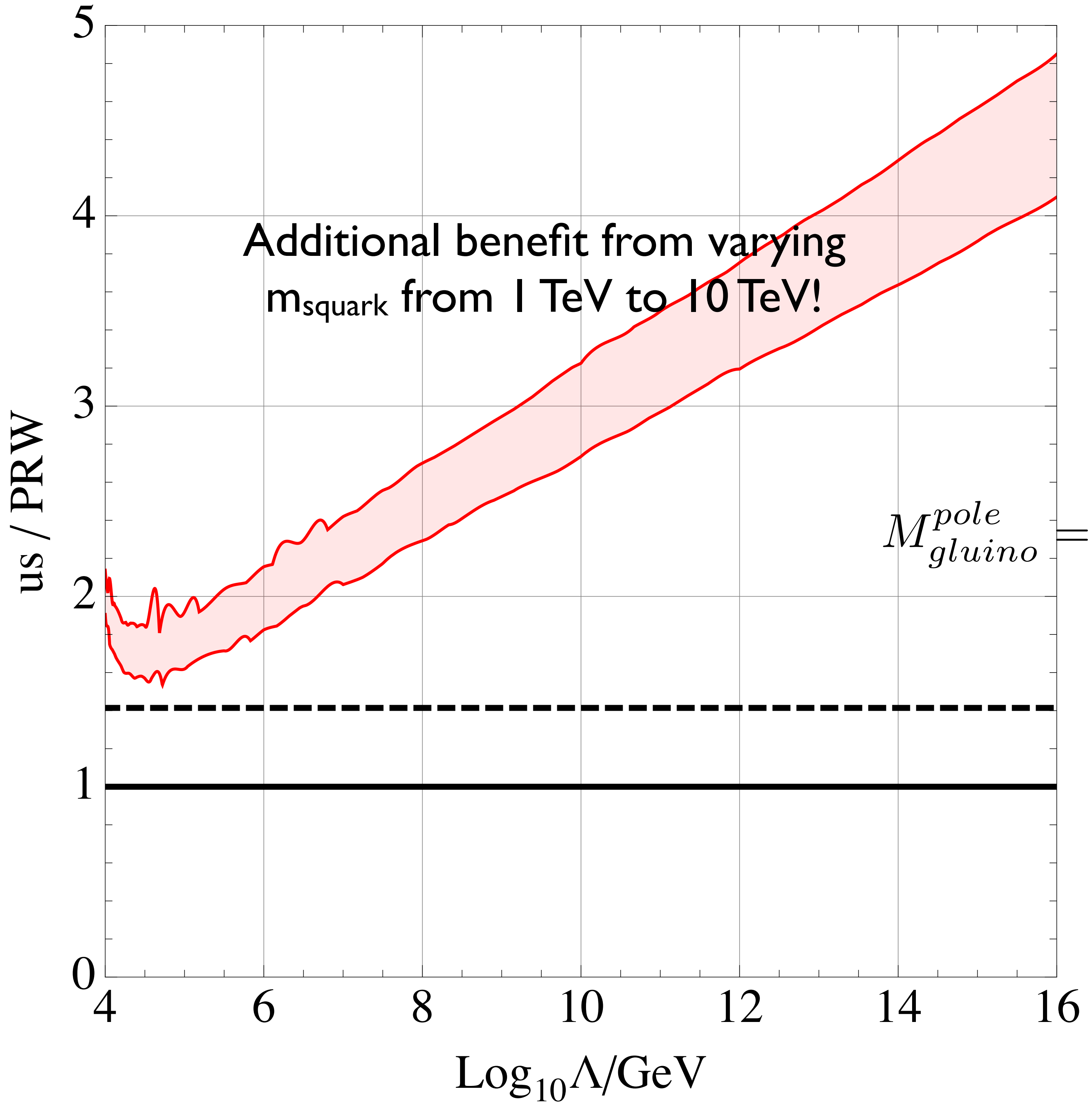
$$\Big\downarrow$$

2-loop effective potential calculation (Martin 0206136)

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

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!

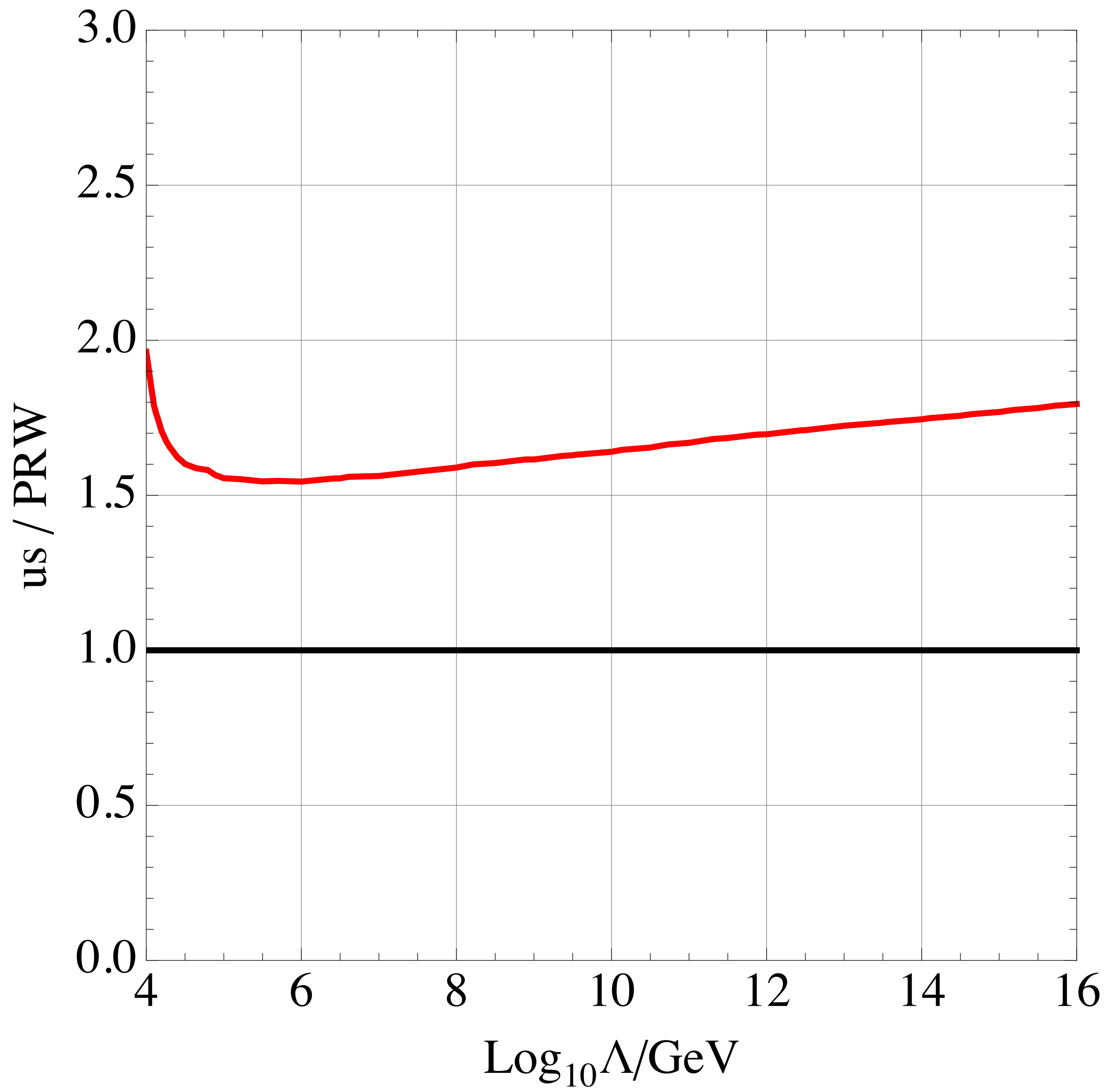
- Factor of 2 error
- LL vs. resummed RGEs
- 2-loop RGEs
- UV vs. IR mass
- finite threshold corrections
- IR mass vs. pole mass

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

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:

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

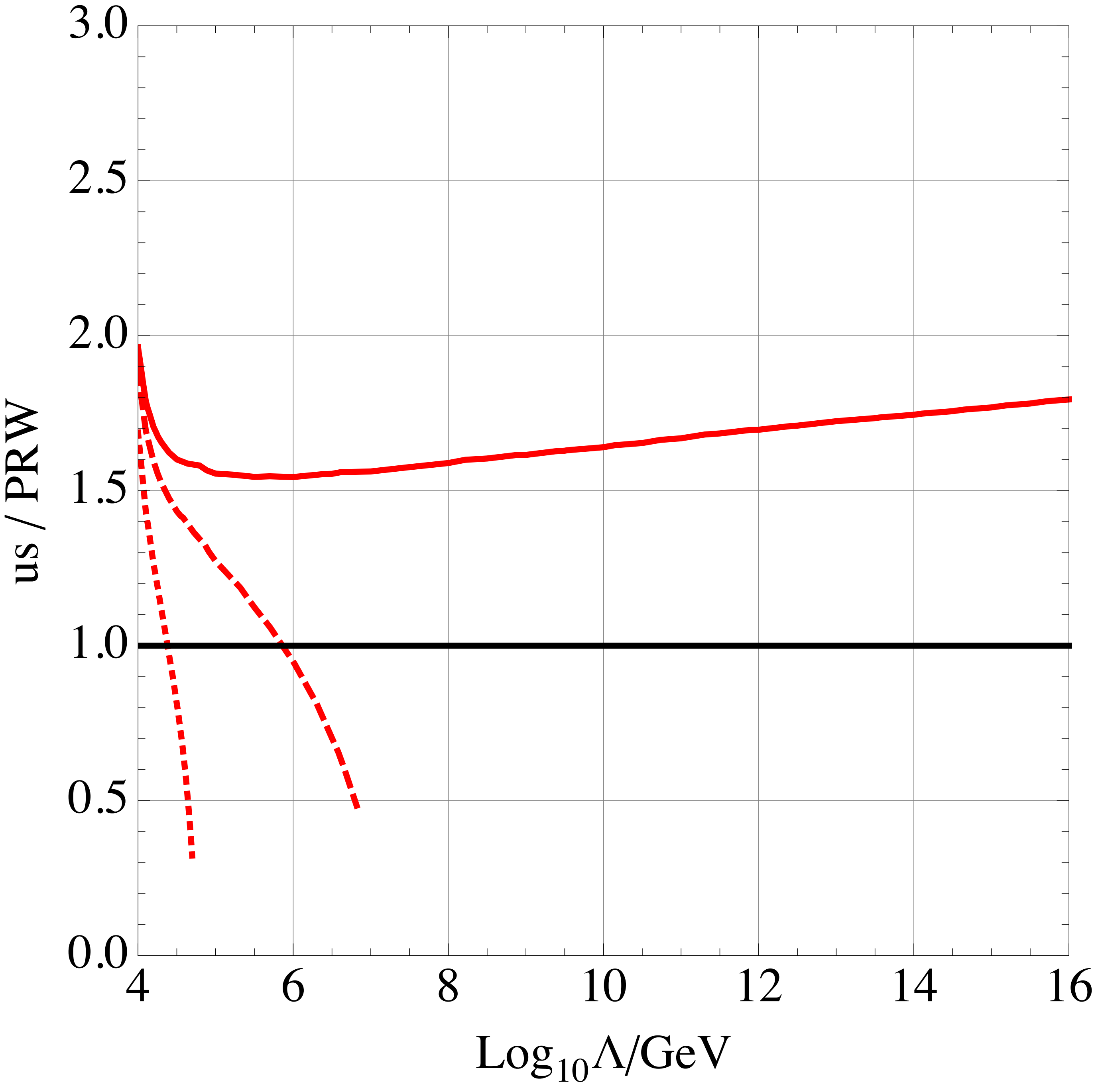
$$\delta m^2_{H_u}(Q) = -a(Q;\Lambda)m^2_{Q_3}(\Lambda)$$

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

Heavier gluino can result in more naturally heavier stops!

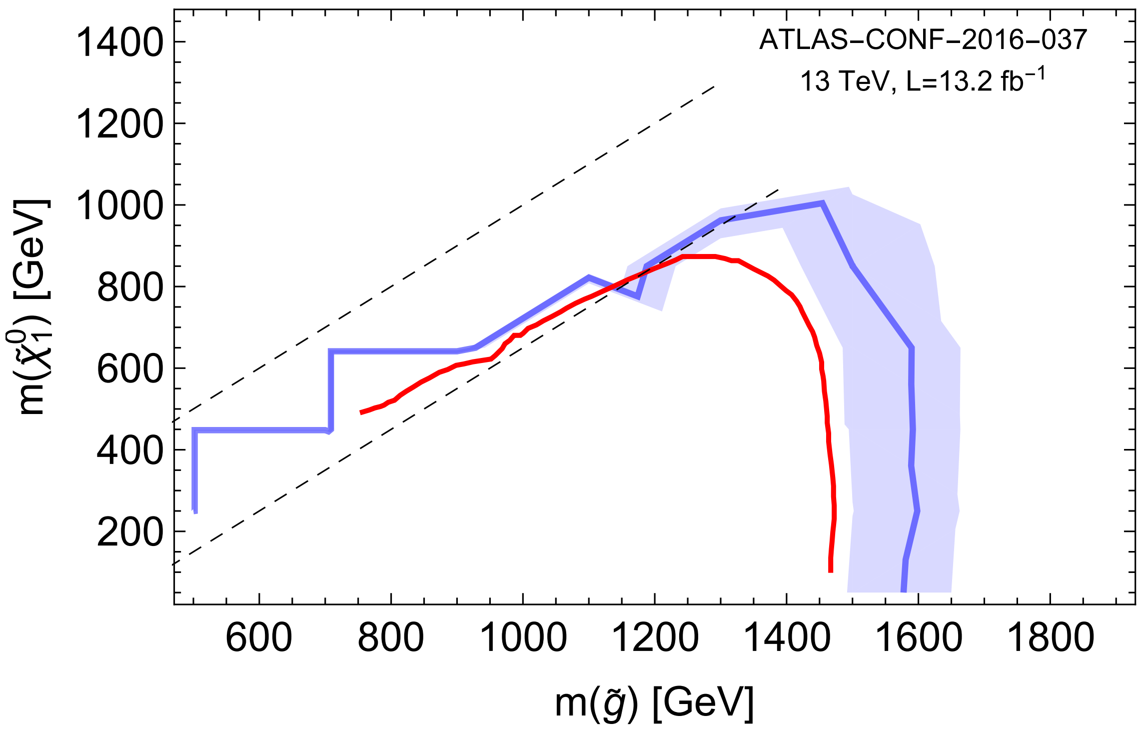
In calculating the stop tuning bound, it is important to treat the quantum corrections carefully.

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

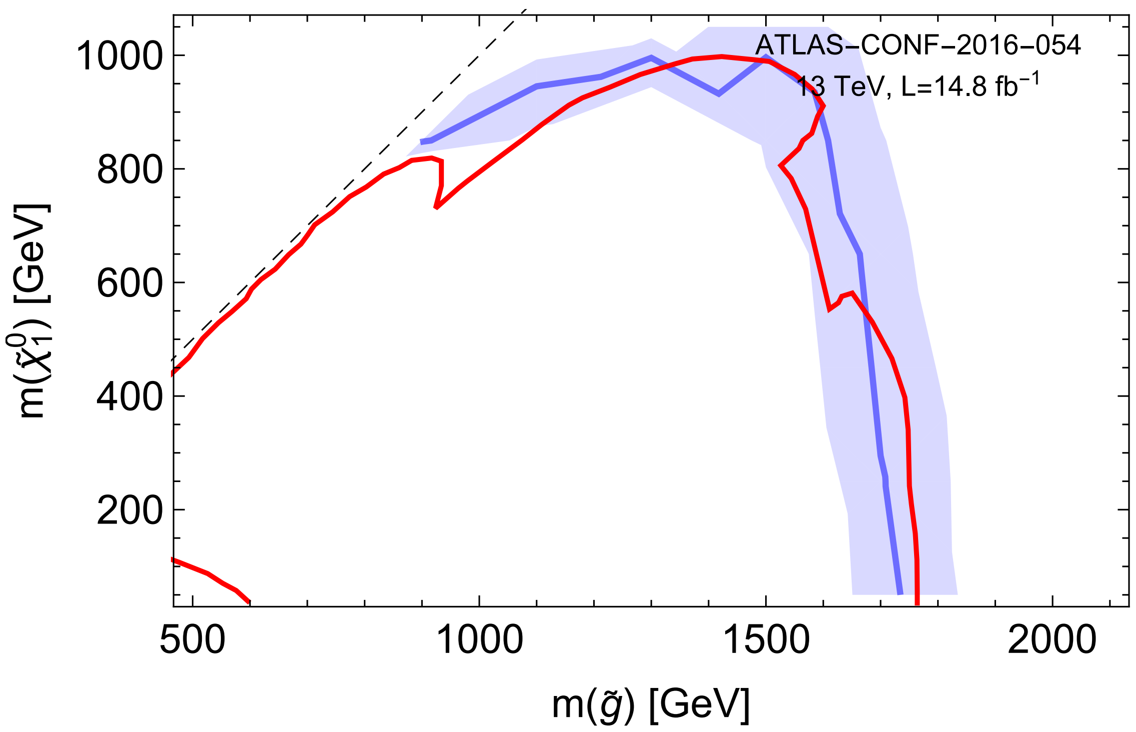


Validation plots

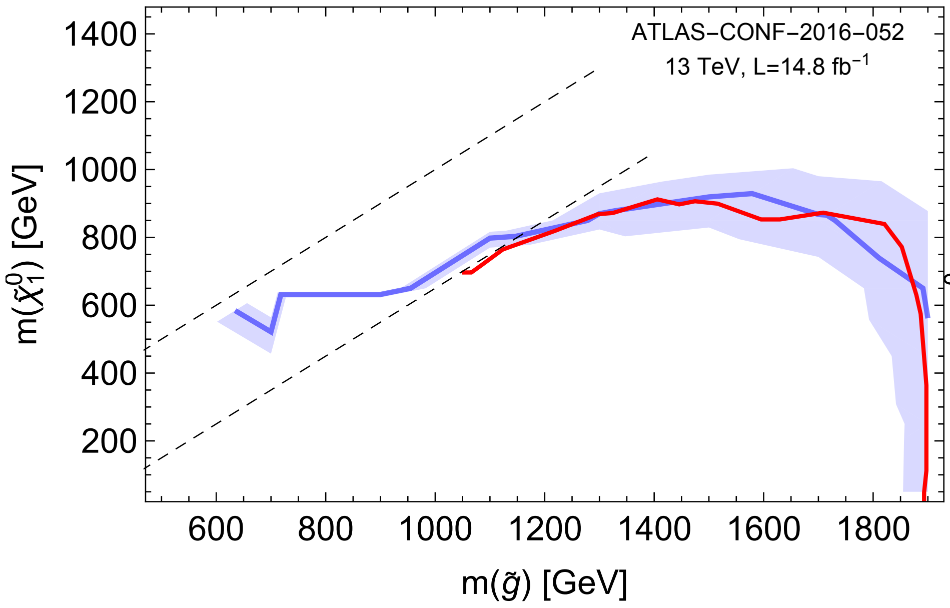
$p\,p \to \tilde{g}\tilde{g},\ \ \tilde{g}\to t t \tilde{\chi}_1^0$



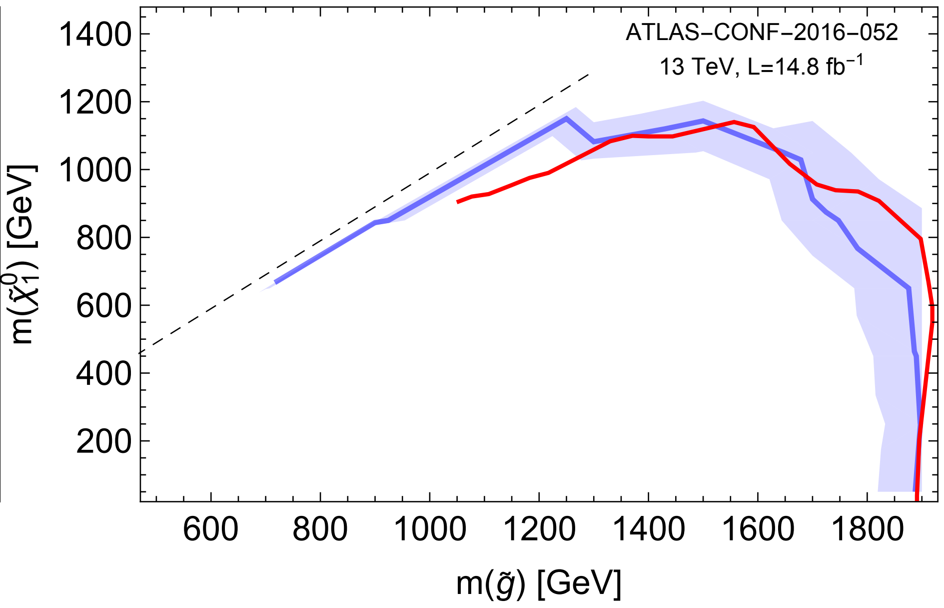
$p\,p \to \tilde{g}\tilde{g},\ \ \tilde{g}\to q q' \tilde{\chi}_1^{\pm},\ \tilde{\chi}_1^{\pm}\to W\tilde{\chi}_1^0$



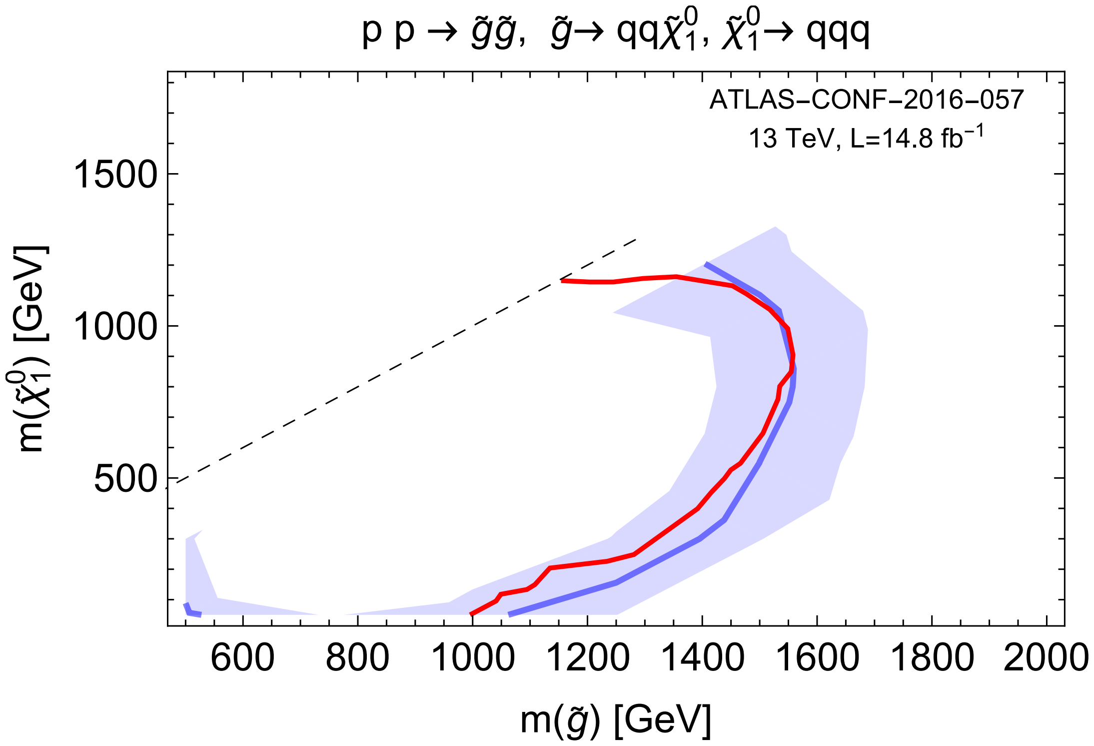
$p\,p \to \tilde{g}\tilde{g},\ \ \tilde{g}\to t t \tilde{\chi}_1^0$



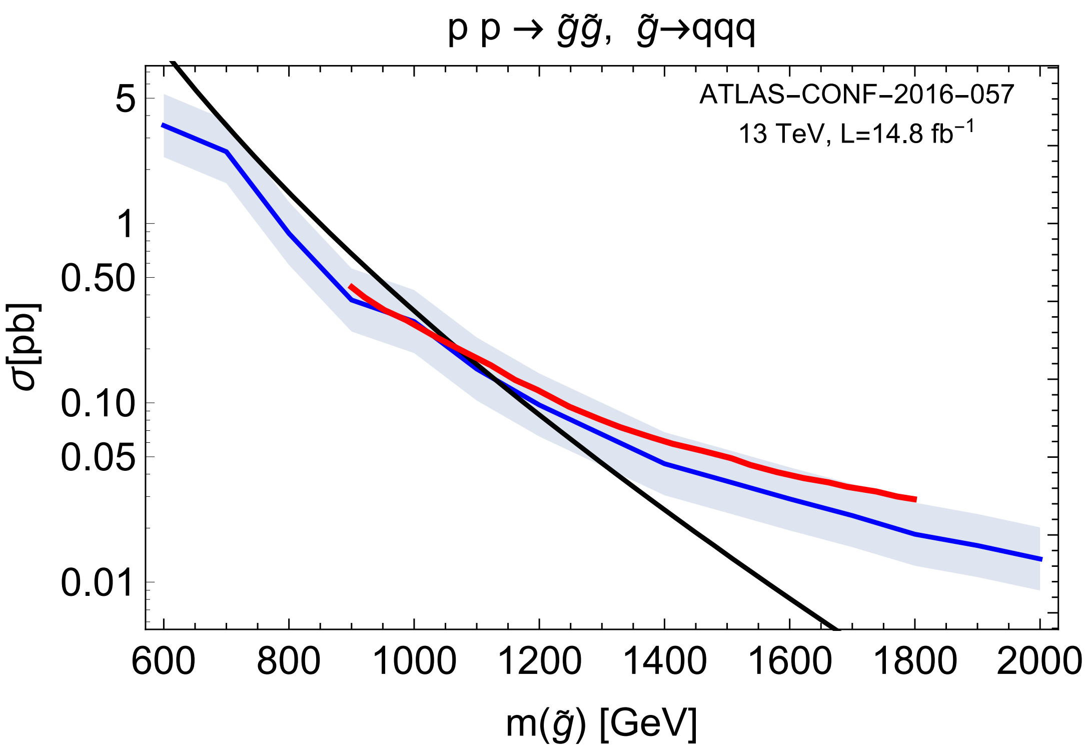
$p\,p \to \tilde{g}\tilde{g},\ \ \tilde{g}\to b b \tilde{\chi}_1^0$



Validation plots

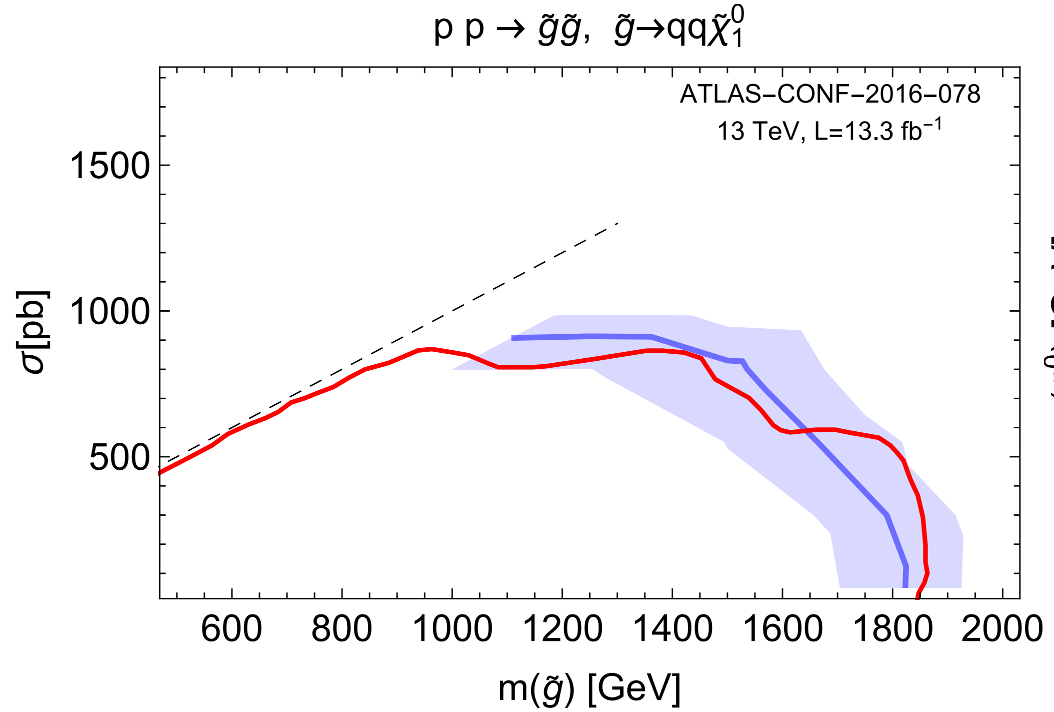


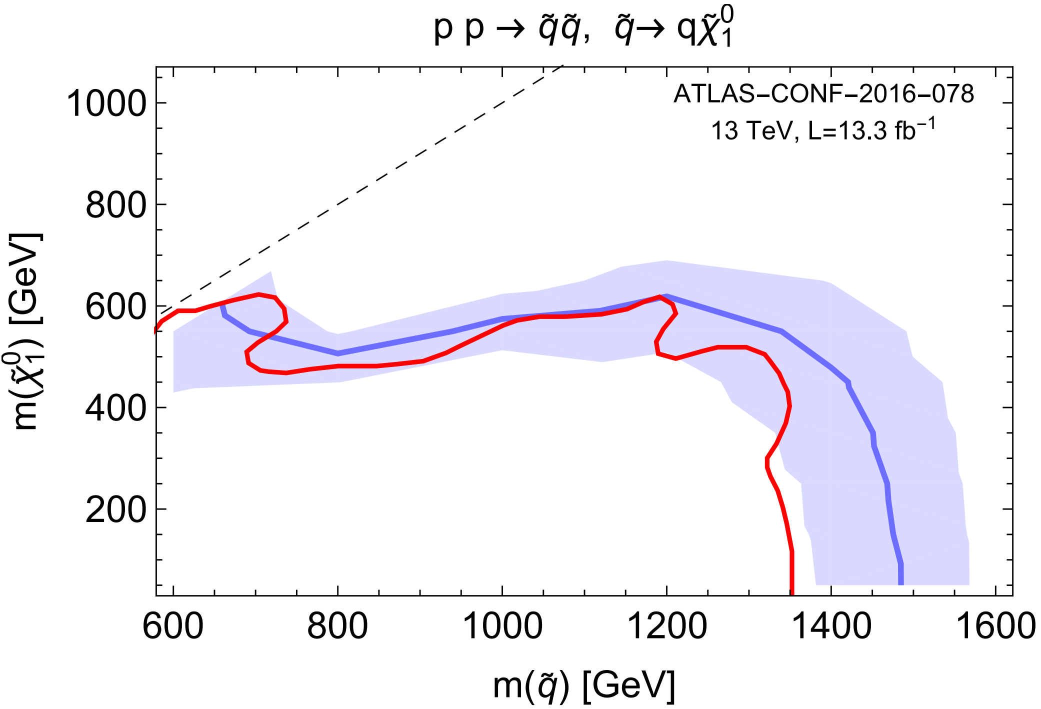
$p\, p \to \tilde{g}\tilde{g},\ \ \tilde{g} \to qq\tilde{\chi}_1^0,\ \tilde{\chi}_1^0 \to qqq$

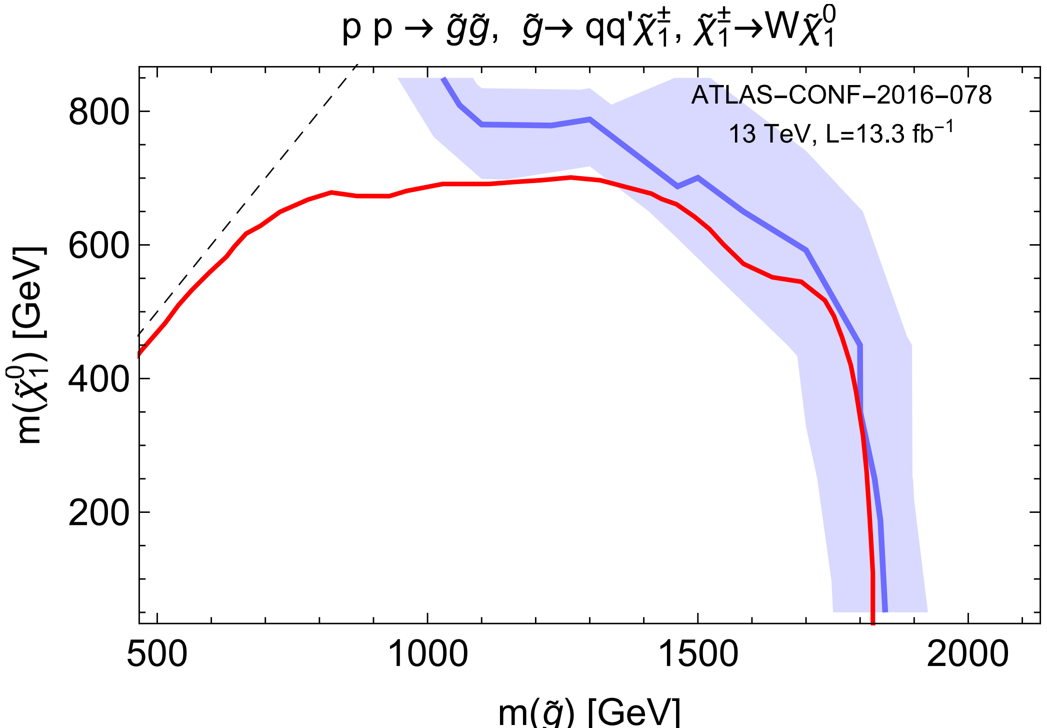


$p\, p \to \tilde{g}\tilde{g},\ \ \tilde{g} \to qqq$

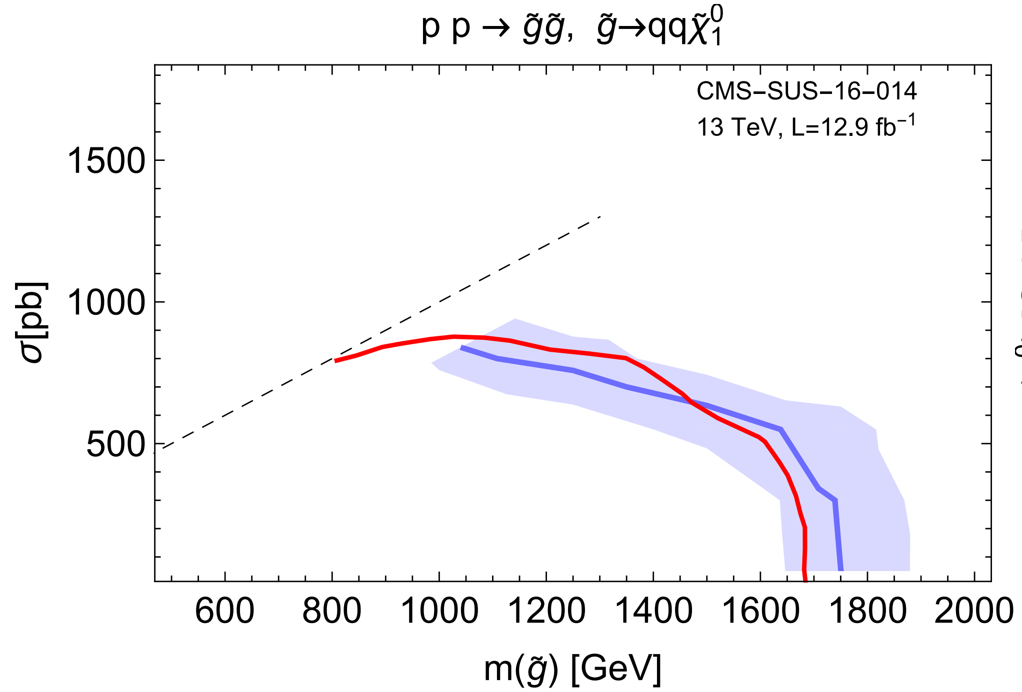
Validation plots



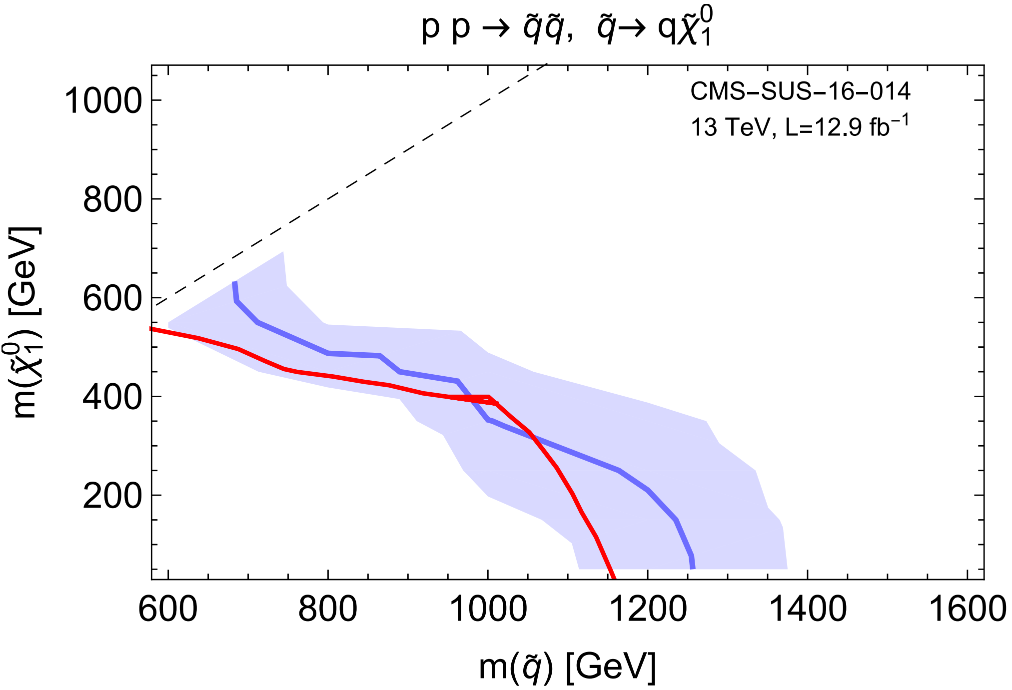




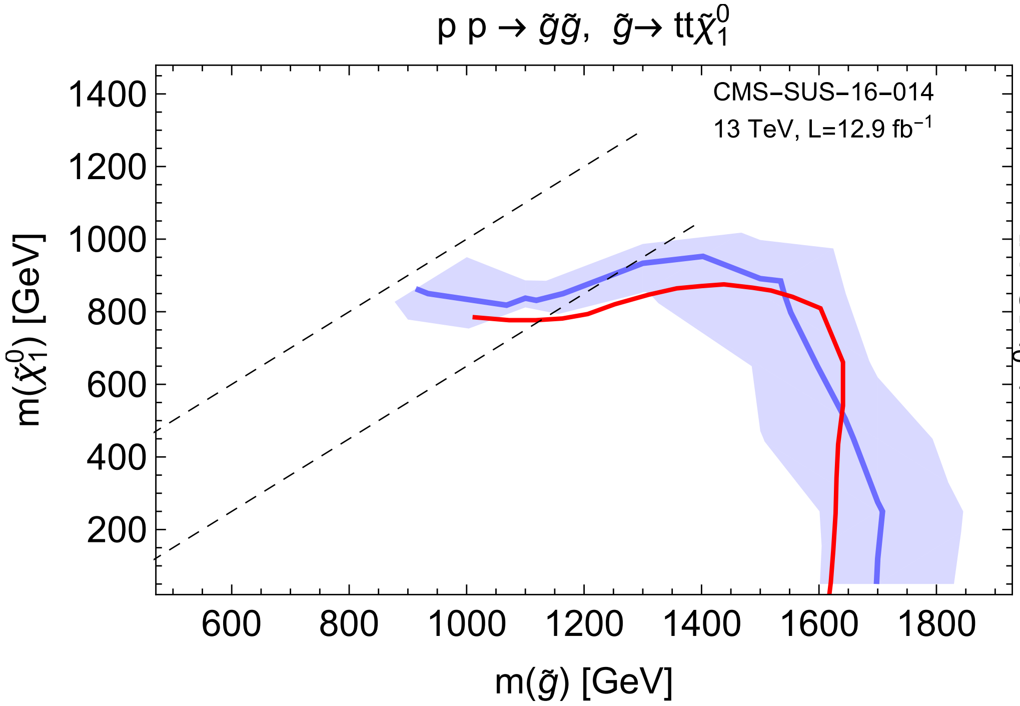
Validation plots



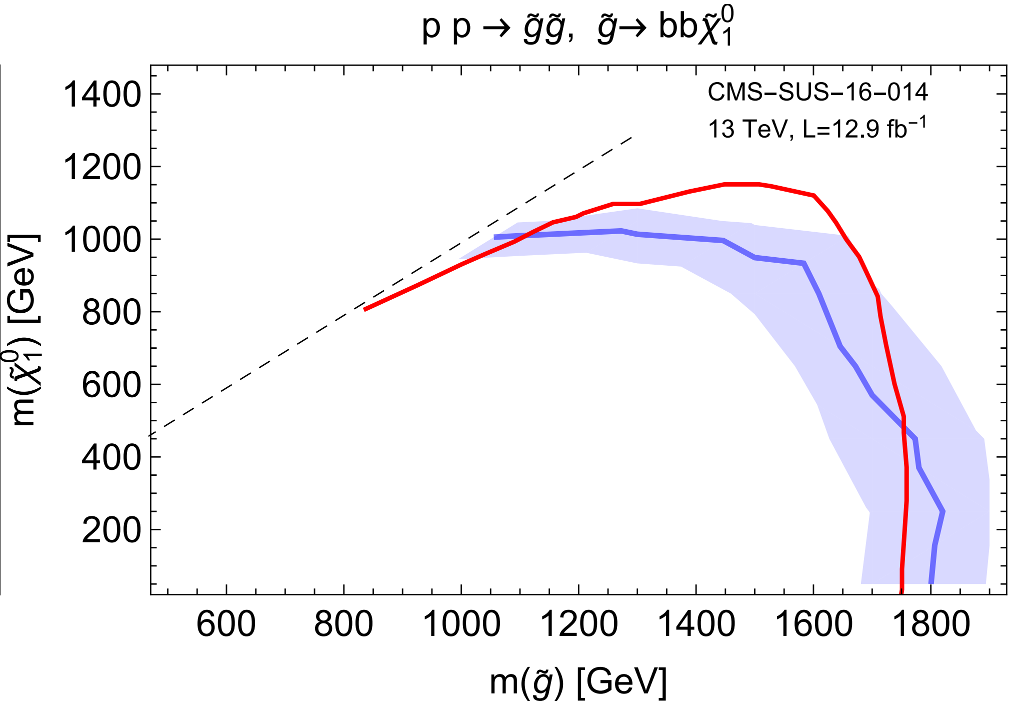
$p\,p \to \tilde{g}\tilde{g},\ \tilde{g}\to qq\tilde{\chi}_1^0$



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



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



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

A better approach...

A better approach...

- Resum RGEs (called "transfer matrix" in Knapen, Redigolo & DS 1507.04364)

$$
\begin{aligned}
m_{H_u}^2(Q) &= -C_{H_u}^{M_3}(Q;\Lambda)M_3(\Lambda)^2 - C_{H_u}^{Q_3}(Q;\Lambda)m_{Q_3}^2(\Lambda) - C_{H_u}^{U_3}(Q;\Lambda)m_{U_3}^2(\Lambda) + \ldots \\
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- Resum RGEs (called "transfer matrix" in Knapen, Redigolo & DS 1507.04364)

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- Add threshold corrections to remove Q dependence and transform to physical pole masses

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&m_{H_u}^2(Q) \to (m_{H_u}^2)_{eff} \\
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Given naturalness bounds on UV soft parameters, corresponding bounds on IR parameters could be quite different due to RG and thresholds!

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“gluino sucks effect”

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gaugino unification

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"gluino sucks effect"

tachyons from effective SUSY

gaugino unification

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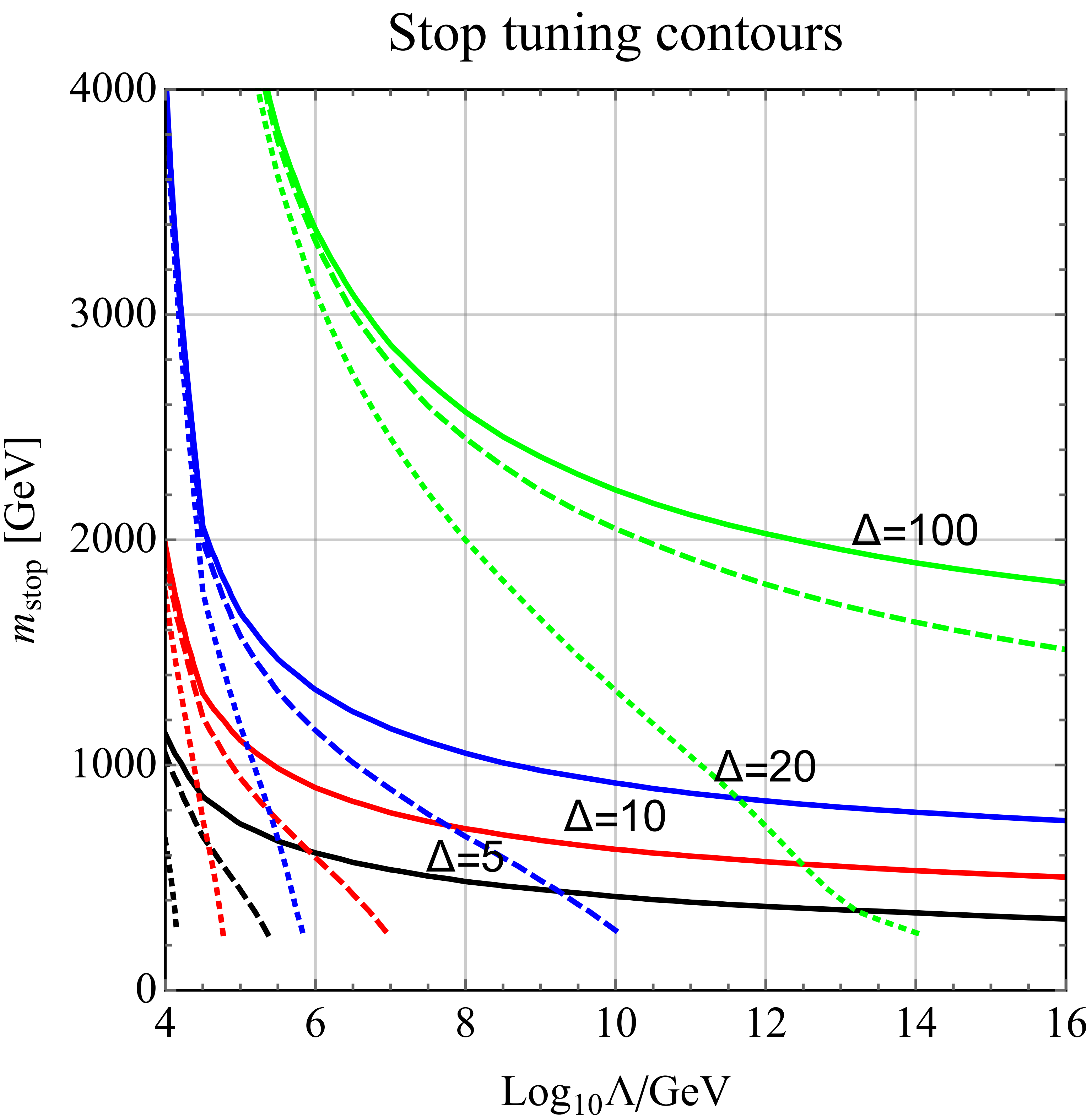
Naturalness bounds the stop mass as a function of the messenger scale Λ.



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

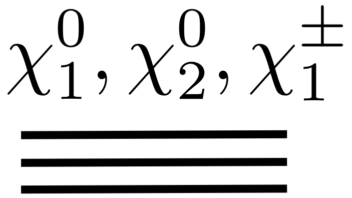
(Murayama & Arkani-Hamed; Agashe & Graesser)

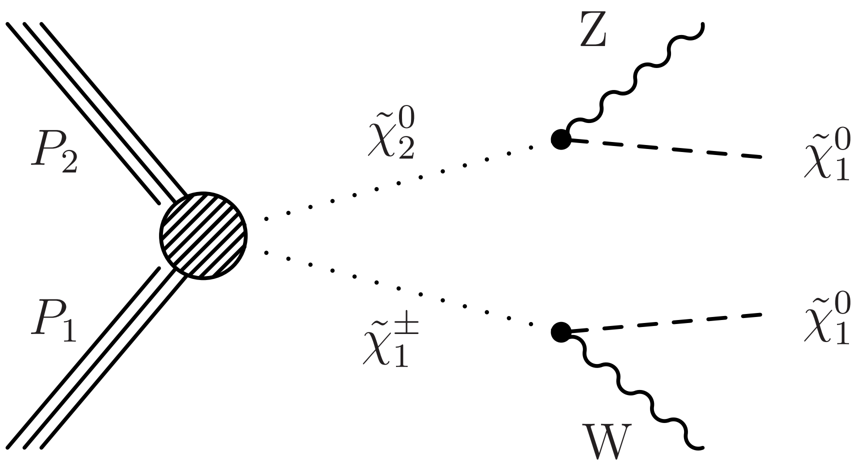
$$(16\pi^2)^2 \frac{d}{dt} m_{Q_3}^2 = \frac{128}{3} g_3^4 m_{12}^2 + \ldots$$

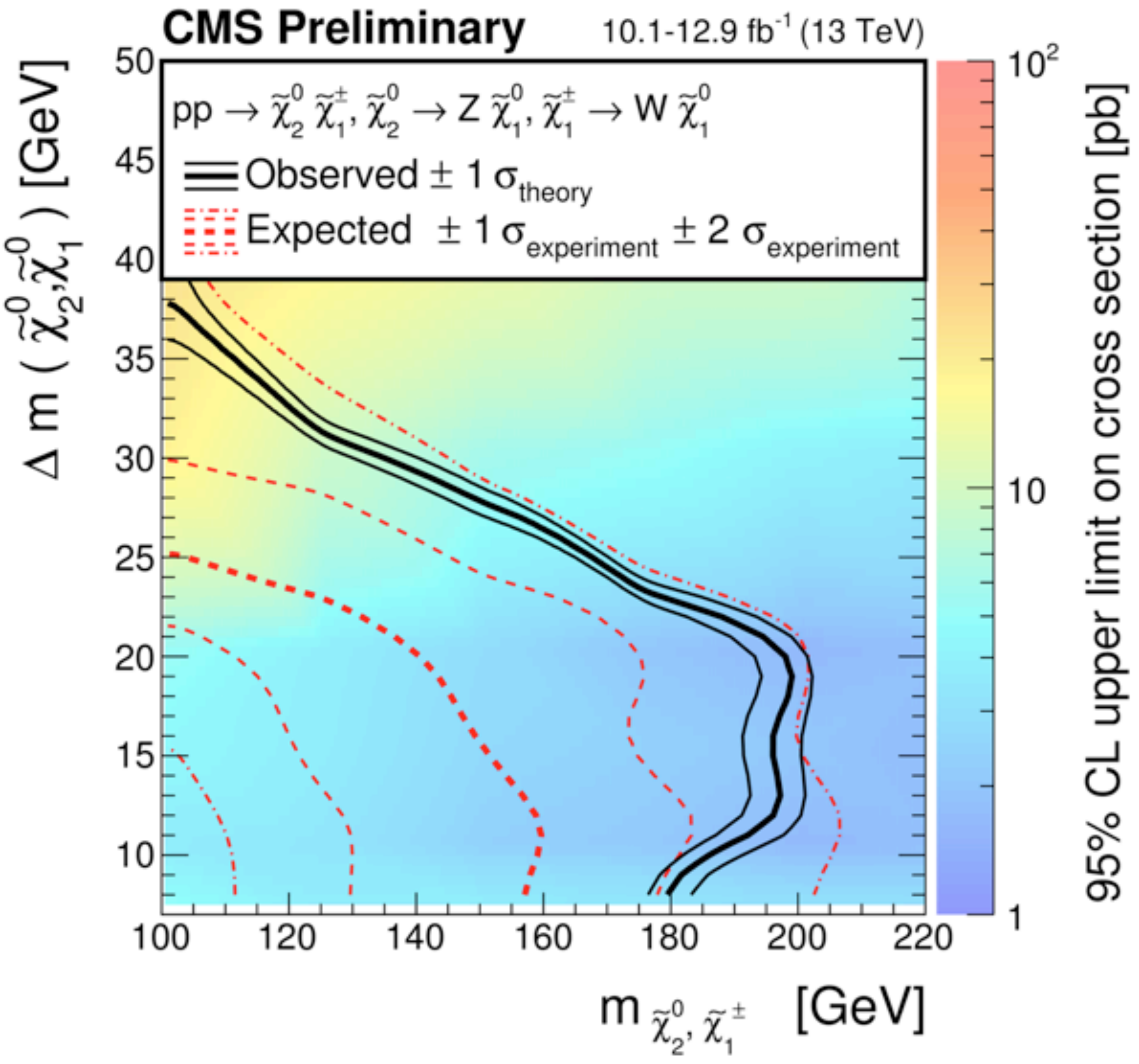
Important limitation of effective SUSY!

This problem might be fixable in certain extensions of the MSSM.

(e.g. Hisano, Kurosawa & Nomura, 0002286)







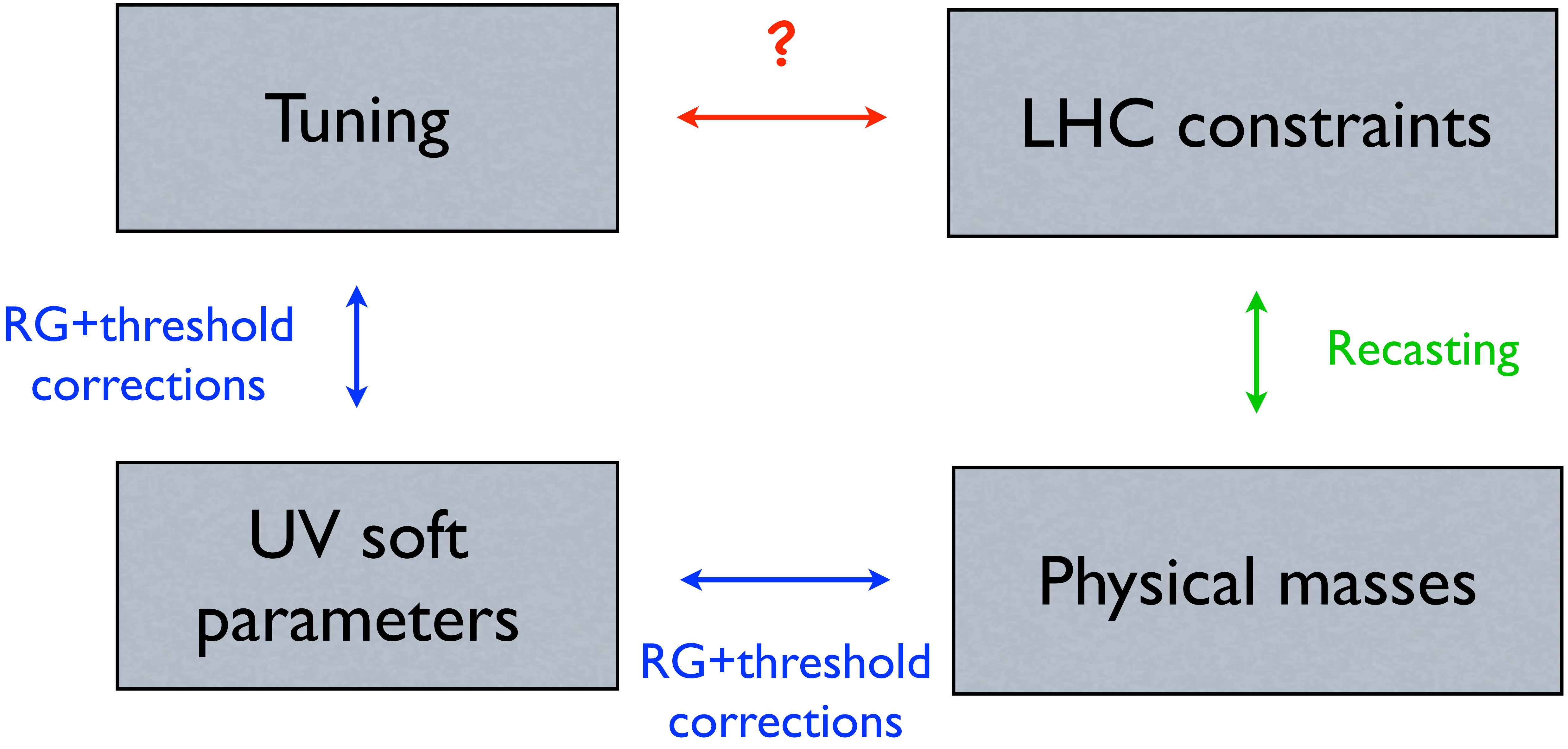
Very interesting recent CMS result on direct EWino production with (moderately) small splittings.

Unfortunately, limits are for Wino production.

Higgsino xsecs are smaller and currently limit does not yet exceed LEP.

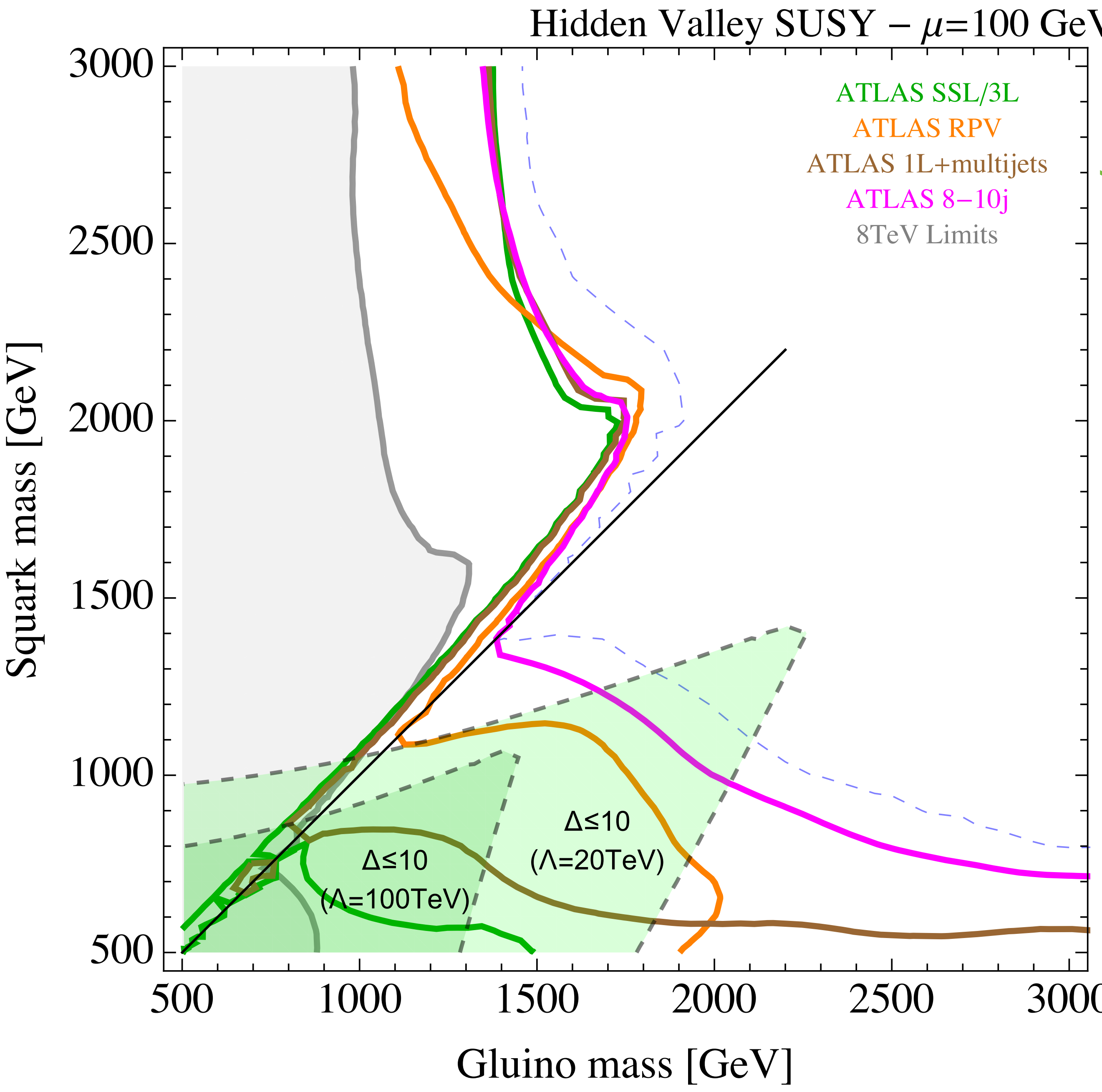
Something to keep an eye on. Will have direct implications for naturalness!

What do the current LHC limits imply for naturalness in SUSY?



Tuning constrains UV parameters.
LHC constrains IR parameters.

Alternative to RPV: HV/Stealth



Buckley, Feld, Macaluso, Monteux & DS 1610.08059

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

For example:

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

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

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