Natural SUSY at the 13 TeV LHC: limits, naturalness and the bumps

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+ work in progress

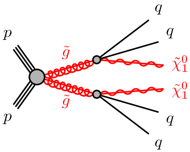
New High Energy Theory Center
Rutgers University

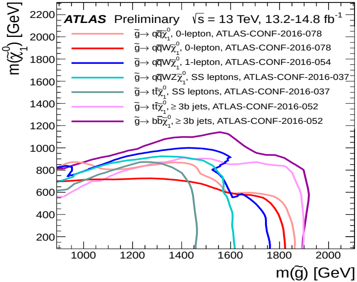
IBS CTPU Focus Workshop, Dec 7th 2016

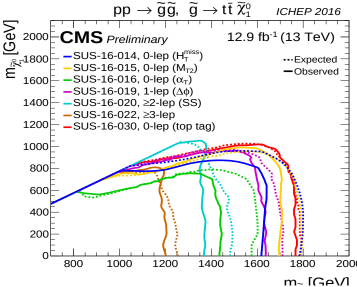
Prelude

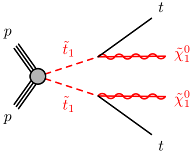
- The LHC back on after 2 years upgrade: highest energy (and luminosity) collider we ever had!
  With 15–20 fb^{-1} of public data shown at ICHEP, better reach than 8 TeV. At present time, $\mathcal{L}_{int.} \sim 35\ \text{fb}^{-1}$!
- Perfect time to look beyond simplified topologies considered by ATLAS and CMS - *comprehensive re-interpretation (recasting)*
- Are there overlooked SUSY signatures?
- Will show limits on natural SUSY spectra (10% fine-tuned or better). Many fully-natural scenarios are still viable - although prefer low messenger scales.

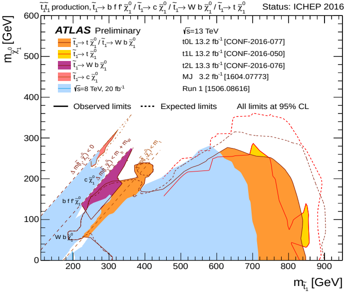
No clear signals of new physics in ∼100 searches at 13 TeV (RIP $\gamma\gamma$).
Limits on colored new physics are strong.

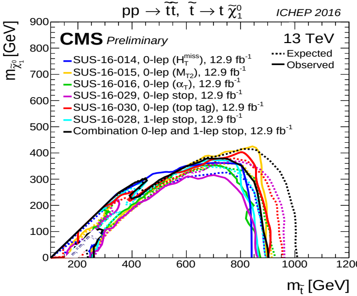












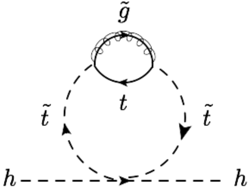
– some interesting excesses in stop searches? 1 TeV stop? . . . will mention later. . .

Natural SUSY

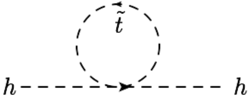
Main reason for weak scale SUSY is *naturalness of Higgs potential*.
Not all sparticles created equal! Most relevant are higgsinos, stops and gluinos.
[Dimopoulos,Giudice '95; Cohen,Kaplan,Nelson '96; Papucci,Ruderman,Weiler '10]

SUSY breaking parameters are set at the messenger scale Λ, evolve via RGE to the weak scale. $\rightarrow$ upper bound on masses

$$\Delta_M = \frac{\partial \log m_h^2}{\partial \log M_{UV}^2}$$



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



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

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

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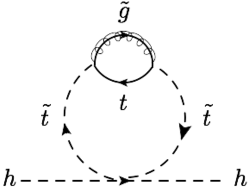

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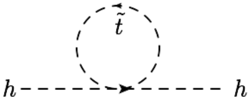
light gluinos



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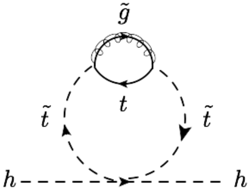

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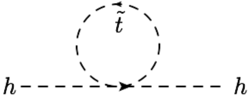

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light stops

Leading log formulas: full calculations give $\approx$ similar conclusions

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

light higgsinos

Recasting

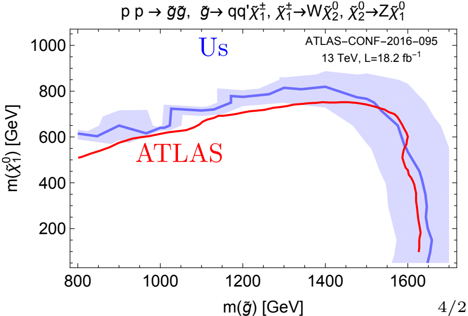
Search	Data (fb^{-1})	Reference
ATLAS 2-6 jets + MET	13.3	ATLAS-CONF-2016-078
ATLAS 8-10 jets + MET	18.2	ATLAS-CONF-2016-095
ATLAS b-jets+MET	14.8	ATLAS-CONF-2016-052
CMS jets + MET (H_T^{miss})	12.9	CMS-PAS-SUS-16-014
ATLAS SSL/3L	13.2	ATLAS-CONF-2016-037
ATLAS 1L+jets+MET	14.8	ATLAS-CONF-2016-054
ATLAS multi-jets (RPV)	14.8	ATLAS-CONF-2016-057
ATLAS lepton+many jets	14.8	ATLAS-CONF-2016-094

Our pipeline:

- Madgraph5_AMC@NLO 2.3.3
- Pythia 8.219
- Delphes 3.3.2
- ROOT 5.34

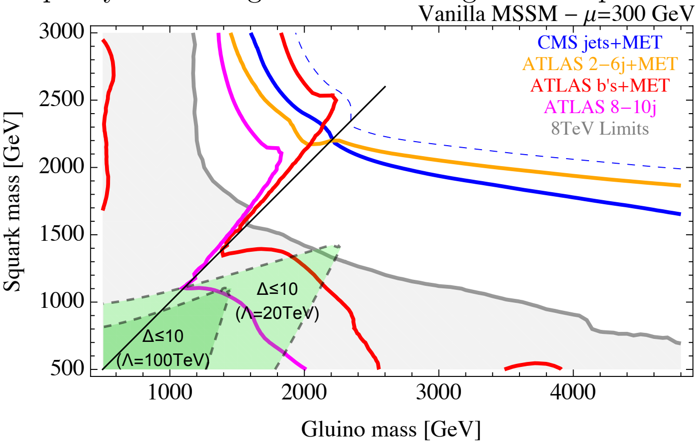
validated against official plots ⟶

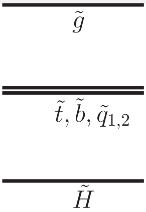
– include 50% "recast uncertainty"



Results: vanilla SUSY

R-parity conserving MSSM with degenerate squarks.





Green: better-than-10% fine-tuned regions.
Large cross sections, large MET: Vanilla SUSY is $\lesssim$ 2-5% fine-tuned.
(8 TeV limits with SIM framework.)

[Evans, Kats]

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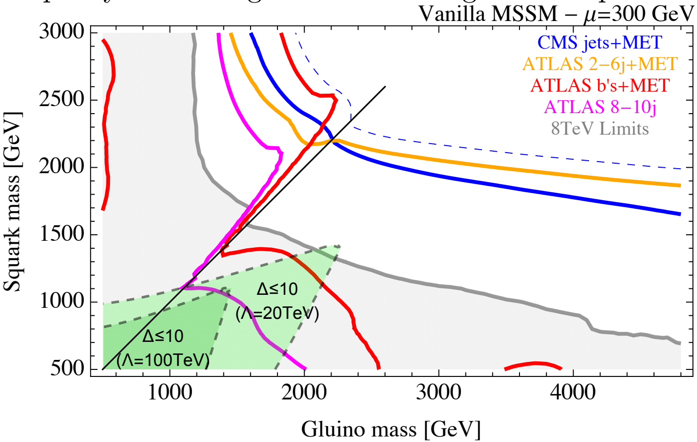

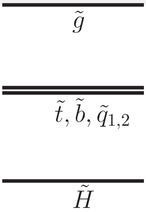

Simplest, most boring SUSY flavor excluded

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(8 TeV limits with SIM framework.)

[Evans, Kats]

SUSY beyond Vanilla

Nature did not like Vanilla, but more flavors of SUSY than you can count!

Two ways to reduce the limits:

- reduce the cross sections:
- make the final states harder to see:

SUSY beyond Vanilla I

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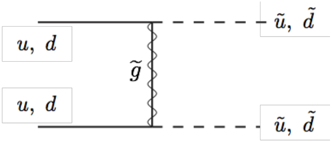
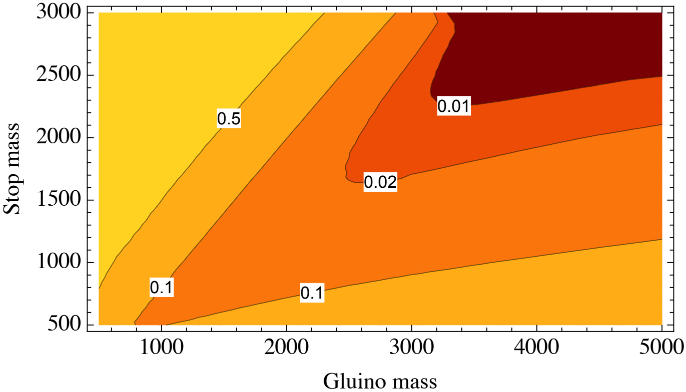
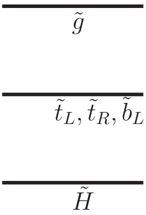
- reduce the cross sections



Valence squark production is enhanced by t-channel gluino. If only stops/sbottoms, cross sections are greatly reduced.





$\leftarrow \dfrac{\sigma(\tilde{g}, \tilde{t}_L, \tilde{t}_R, \tilde{b}_L)}{\Sigma_i \sigma(\tilde{g}, \tilde{q}_i)}$

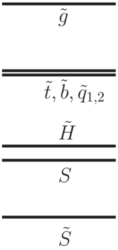
SUSY beyond Vanilla II

Two ways to reduce the limits:

- reduce the cross sections
- make the final states harder to see:
  - R-parity violation: with SM field content, B, L violated at tree-level

$$W_{RPV} \sim \mu'_i L_i H_u + \lambda_{ijk} L_i L_j \ell^c_k + \lambda'_{ijk} L_i Q_j d^c_k + \lambda''_{ijk} u^c_i d^c_j d^c_k$$

    proton decay $\to |\lambda' \lambda''| \lesssim 10^{-25}$.
    Ad hoc assumption: $R_p = (-1)^{2S+3B+L} \to$ Bonus: stability of LSP.
    Most effective RPV channel: baryonic RPV: $\tilde{H} \to u_i d_j d_k$
  - Hidden Valley / Stealth SUSY: many possibilities, but in general a singlet superfield S, e.g.



$$W = S H_u H_d + S G^a_{\mu\nu} G^{\mu\nu a} \implies \tilde{H} \to S\tilde{S} \to gg\tilde{S}$$

If mass spectrum compressed, $m_{\tilde{H}} \sim m_{\tilde{S}} + m_S$, the singlino is soft (little MET)

Additional models considered:

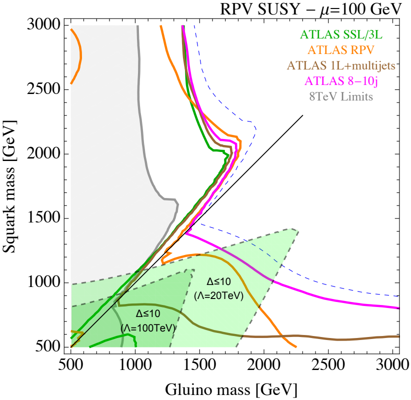
Bottom-up approach (no top-down model-building), what are the models most likely to hide SUSY?

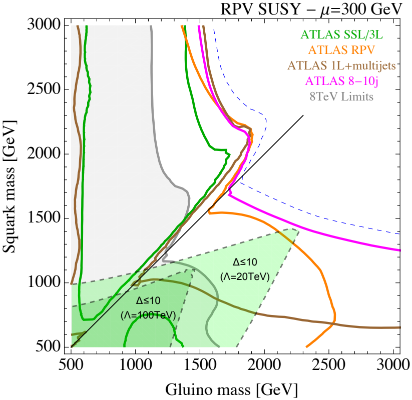
1. Effective SUSY: decouple 1st/2nd generations to 5 TeV. Light squarks: $\tilde{t}_L, \tilde{b}_L, \tilde{t}_R$ – greatly reduced cross sections.
2. RPV SUSY: unstable higgsino with baryonic decays, $\tilde{H} \to uds$. No MET, enhanced hadronic activity.
3. Stealth/Hidden Valley SUSY: unstable higgsino to nearly mass degenerate hidden sector: $\tilde{H} \to \tilde{S}S \to \tilde{S}gg$, with $m_{\tilde{H}} \sim m_{\tilde{S}} + m_S$. Reduced MET.
4. Effective RPV: decouple 1st/2nd generations, with unstable neutralino, $\tilde{H} \to uds$.

For each model, we take higgsino LSP at either 100 GeV (just above LEP) or 300 GeV (naturalness bound). We generate all possible combinations of squark/gluino pairs, and exclude a mass point if it is excluded by (at least) one signal region of the searches considered.

Results: RPV SUSY

LSP decays remove the MET signature: $\tilde{H} \to uds$



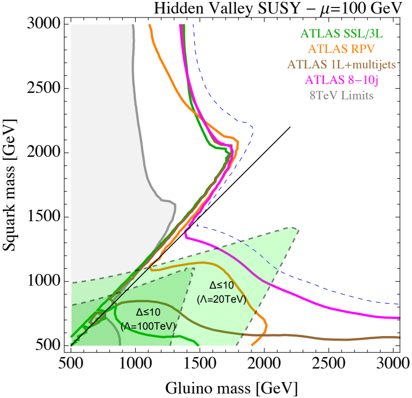


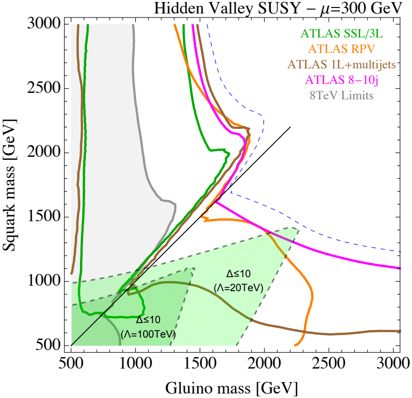
Decays with heavier higgsinos more effectively captured: lighter higgsinos decays are more boosted, resulting in merged jets.

Some fully-natural parameter space survives, but only at low messenger scales.

Results: Stealth SUSY / Hidden Valley

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

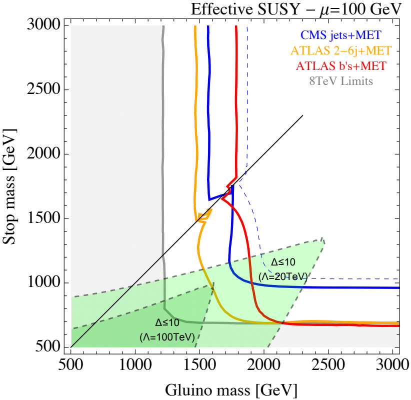


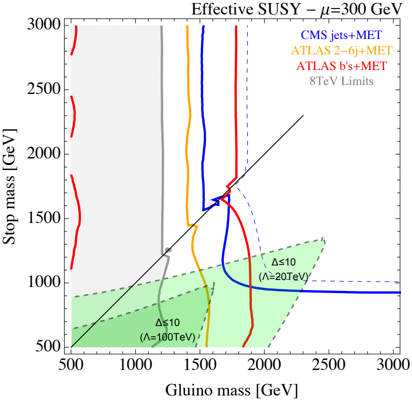


Very similar to RPV exclusions – great power of multijet searches.

Results: Effective SUSY

Set 1st/2nd generation squarks at 5 TeV: x sec lowered by O(10-100)



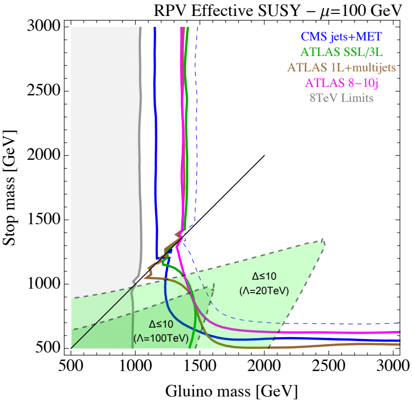


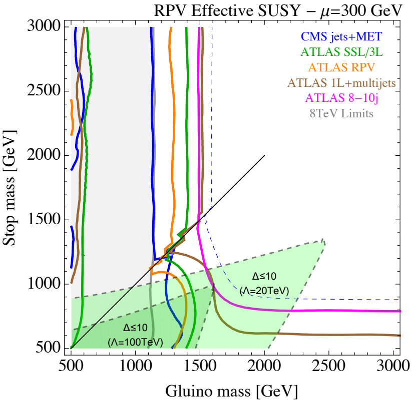
Limits greatly relaxed. Our stop limits comparable to dedicated stop searches.

Even with lower cross sections, most of 10% natural parameter space is excluded (only extremely low messenger scales allowed)

Results: Effective SUSY with RPV

Each strategy partially successful, but implying (uncomfortably?) low messenger scales. Combining them helps:

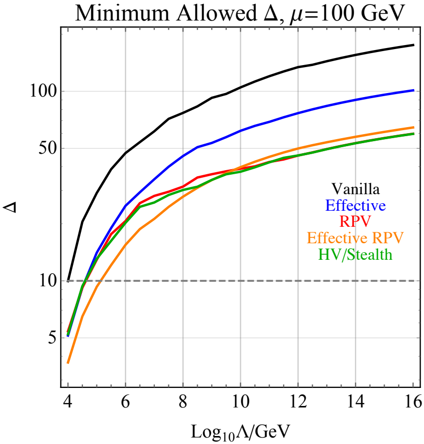


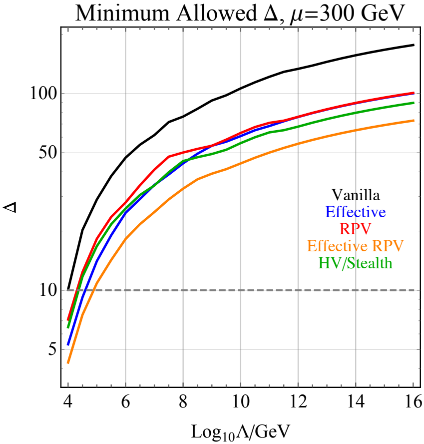


Now, a *fairly standard* 100 TeV messenger scale can be fully natural.

Naturalness: Tuning vs. Messenger Scale Λ

Maybe requiring 10% tuning is too optimistic.
Given the experimental limits, what is the *minimum amount* of fine-tuning for SUSY?

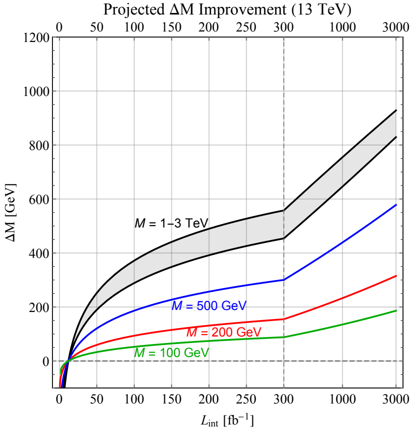


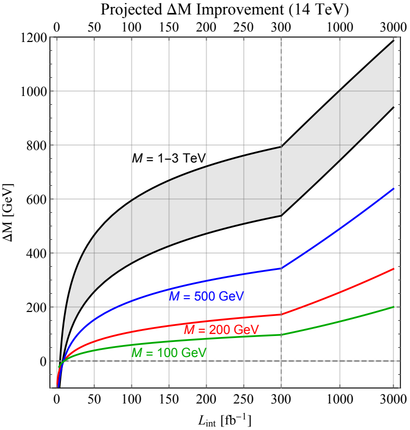


Λ = Messenger scale

Future LHC reach

Our analysis based on $\sim 15\ \mathrm{fb}^{-1}$. ATLAS and CMS now have $\sim 40\ \mathrm{fb}^{-1}$, and will collect *much* more in the next years. [Salam,Weiler]





All the 10% natural regions can be fully probed by the end of HL-LHC. Possible to probe electroweak higgsino production up to ~ 300 GeV.

Enough with limits!

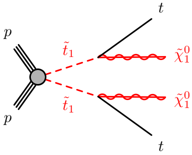
In the searches and for the spectra/models we studied, there are no significant excesses (or if there are in one search, they are excluded by a different search - what you would expect from statistical fluctuations).

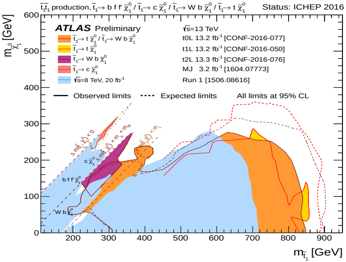
Is there any interesting (*correlated*) excess?

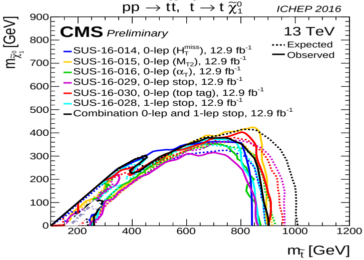
[work in progress w/ B.Allanach,M.Buckley,A.Di Franzo,D.Shih]

Greener pastures: excesses in stop searches?

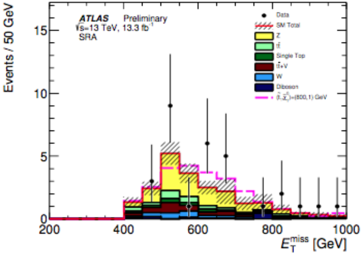
Several excesses in top-specific searches: $pp \to t\bar{t} + \not{E}_T$

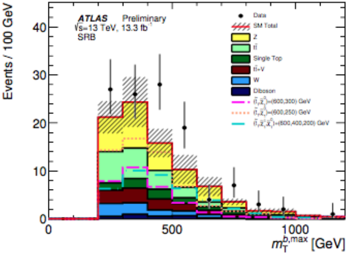






Correlated excesses would be expected if real signal...





stop 0L

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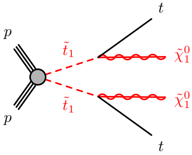

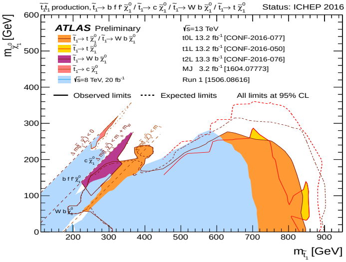

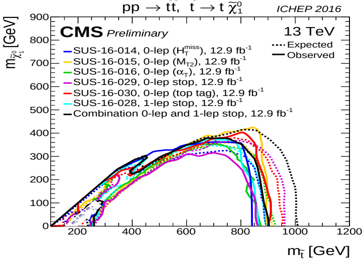

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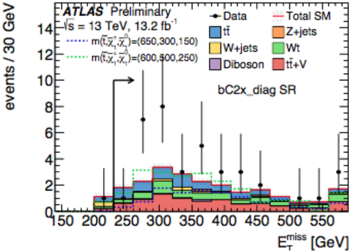
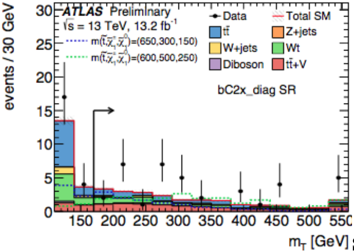




stop 1L

Bumps $\to$ interpretation?

Interpreting these excesses and combining different searches (bumps vs. signals) is a non-trivial step:

- Limits shown earlier are shown by "best observed SR": out of all $O(100)$ signal region, pick the one with best exclusion power.
- *Naive expectation:* if N searches $\to \sqrt{N}$ stronger limits.
- In a perfect world, diluting the signal into N final states diminishes the power of each search, but the N small deviations can be combined

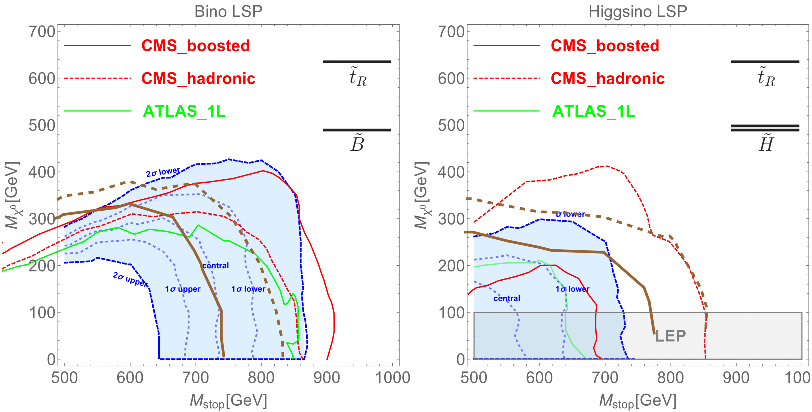
  [e.g. CMS, w/ 100-1000 SRs]
- In the real world, this is harder: *the backgrounds are correlated* - one cannot add up the likelihoods for the similar SRs as if they were independent (e.g. cannot do it for overlapping SRs). To be precise, we need correlation matrices from experiments.

As theorists, we can still try. Obviously the LHC always has the final word.

Excesses in stop searches? Interpretation

Which model explains the excess? Is it excluded by other searches? Depends on the spectrum.

[Han,Nojiri,Takeuchi,Yanagida, `1609.09303`]



Shaded blue = explain excess. Red/Green lines: exclusions by stop searches. Solid (dashed) Brown: our (non) conservative exclusions from *CMS jets + MET*

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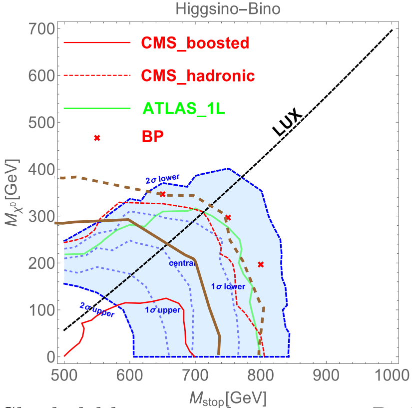

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Any blind spot?

For collider signatures, we have assumed the standard lore:

- *vanilla* SUSY production modes (mostly QCD production).
- *vanilla* cascade decays ending in higgsino LSP ($\tilde{g} \to \bar{q}\,\tilde{q} \to \bar{q}q\tilde{\chi}_1^0$)

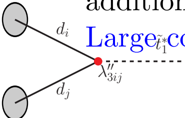
With this we find:

$$\Delta \geq 10 \implies \Lambda \lesssim 100 \text{ TeV},$$

$$m_{\tilde{g}} \gtrsim 1.4 - 1.8 \text{ TeV}, \qquad m_{\tilde{q}} \gtrsim 0.7 - 1.9 \text{ TeV}, \qquad m_{\tilde{t}} \gtrsim 600 - 900 \text{ GeV}$$

Other possibilities?

- other neutralinos? Longer decay chains, limits should be stronger (checked for specific mass points, should be general)
- light gravitino? Again, longer decay chains, $\tilde{H} \to \psi_{3/2} h/\gamma/Z$
- Displaced decays? Usually more constrained than prompt decays [Csaki,Kuflik,Lombardo,Slone,Volansky '15] [Liu,Tweedie '15]
- only possiblity: direct decays into RPV or hidden valleys if additional $O(1)$ couplings: e.g. $\tilde{g} \to tbs$ or $\tilde{t} \to bs$.



Large couplings → new SUSY production modes

Resonant RPV production!

[AM, 1601.03737]

Conclusions

I have shown recasted limits on a representative set of natural SUSY models, and some new signatures.

SUSY with 10% fine-tuning endures. All models can be completely covered by end of HL-LHC. *(no need to wait 100 TeV collider!)*

Very low messenger / SUSY breaking scale. Will require careful model-building, especially if tied to flavor.

e.g. [Aharony, Hochberg et al., 1001.0637] [Craig et al, 1103.3708]

Open questions: Light gravitino cosmology? Weaken experimental bounds and raise Higgs mass at same time? Also get dark matter?

Amusing to compare to other similarly-untuned solutions of the hierarchy problem (e.g. Twin Higgs), which also have UV-completion scales in the multi-TeV range.

Thanks for listening!

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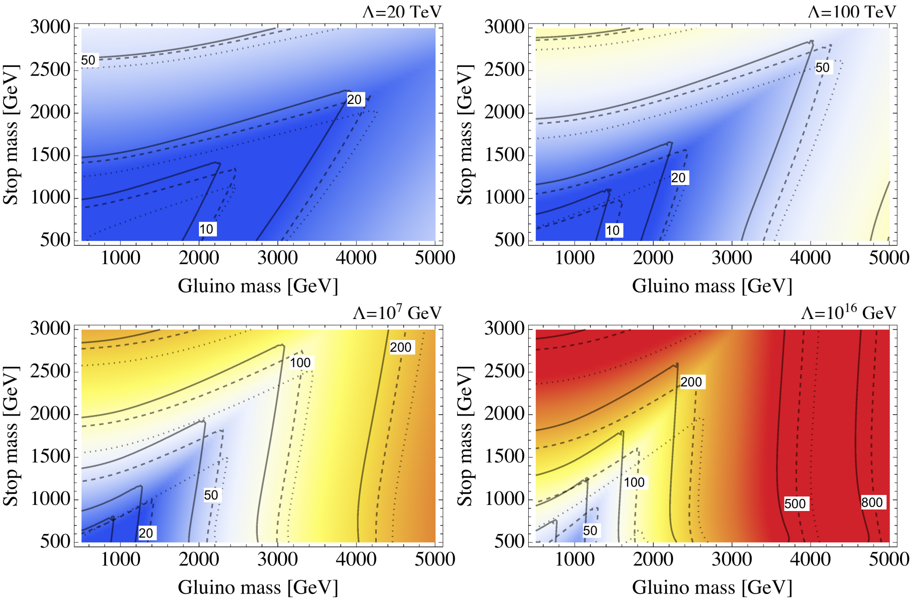
Thanks for listening!

Extra slides

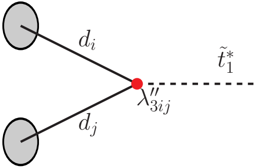
Arbitrary tuning plots



Resonant Stop production

Focus on stop couplings, (will take $\tilde{t}_R$ only)

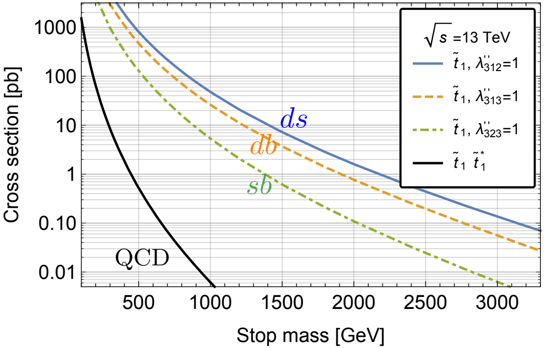
$$\mathcal{L} \supset \lambda''_{3ij} \tilde{t}^* d_i d_j + h.c., ij = 12, 13, 23$$



$$\hat{\sigma} = \frac{8\pi}{3} \frac{|\lambda''_{ijk}|^2}{m_{\tilde{t}}^2} \sin^2 \theta_{\tilde{t}} \, \delta(\hat{s} - m_{\tilde{t}}^2)$$

For $\lambda'' \gtrsim 10^{-2} - 10^{-3}$, cross section can be larger than stop pair-production (even from non-valence quarks bs).

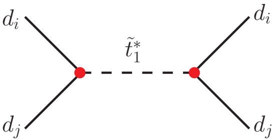
NLO cross sections [Plehn,hep-ph/0006182]



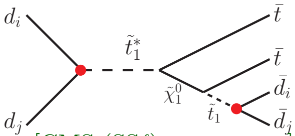
Disclaimer: somewhat old idea.[Dreiner,Ross,1991] Tevatron [Berger,Harris,Sullivan,1999], pre-LHC [Choudhury,Datta,Maity,2011], CMS and ATLAS: resonant $\tilde{\nu}$ search (LRPV).

Signatures:

- dijet resonances:



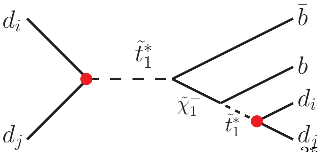
- same-sign tops + jets



[CMS (SSℓ), 1311.6736]
[ATLAS-CONF-2016-037, 13.2fb^{-1}@13TeV]

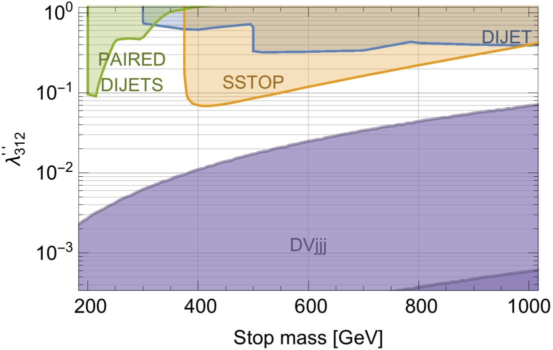
- four-jet resonances

  (dominates over SStops b/c phase space)



Resonant Results - higgsino LSP

In this case limits from available 8&13 TeV searches are much weaker:



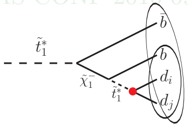
(here $m_{\tilde\chi_1^0} = 200$ GeV)

Chargino decay mode dominates ($\tilde t \to 4j$) $\to$ no limits at 8 TeV

In brown, our 13 TeV limits for pair-produced stops $\to 8j$

[ATLAS-CONF-2016-095]

In dashed gray, reach for single four-jet resonance.



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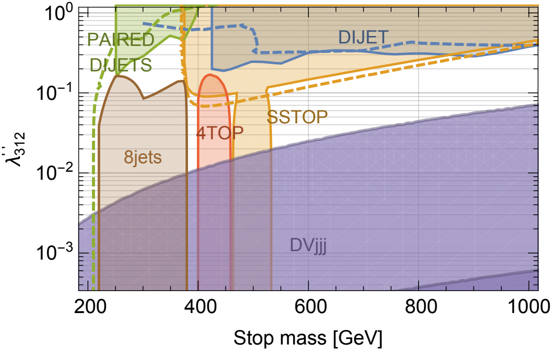

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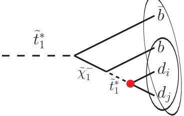

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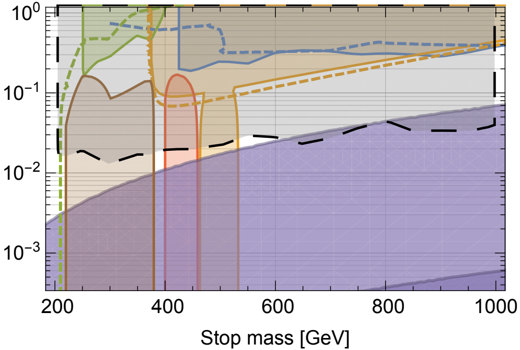

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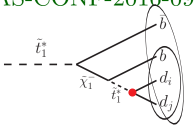
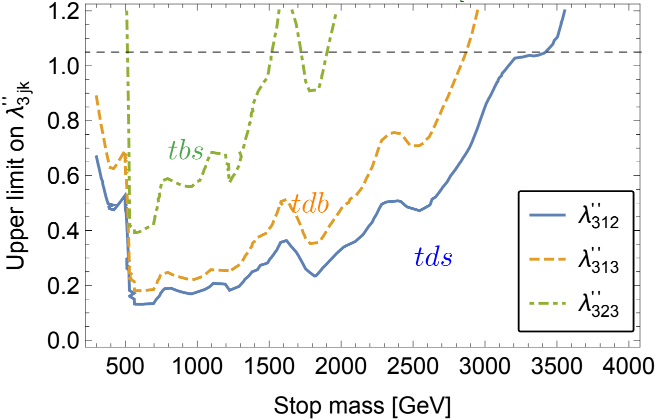


Resonant Signatures I: stop LSP

[ATLAS-1407.1376, 20.3fb^{-1}@8TeV]
[CMS-1501.04198, 19.7fb^{-1}@8TeV]
[CMS-PAS-EXO-14-005, 19.7fb^{-1}@8TeV]
[ATLAS-CONF-2016-069, 15.7fb^{-1}@13TeV]
[CMS-PAS-EXO-16-032, 12.9fb^{-1}@13TeV]



8 TeV limits

Below 1 TeV, best limits from *scouting / trigger level analysis*.

New techniques: recoil off of hard ISR γ/jet

[Shimmin,Whiteson, 1602.07727]
[ATLAS-CONF-2016-070, 15.7fb^{-1}@13TeV]

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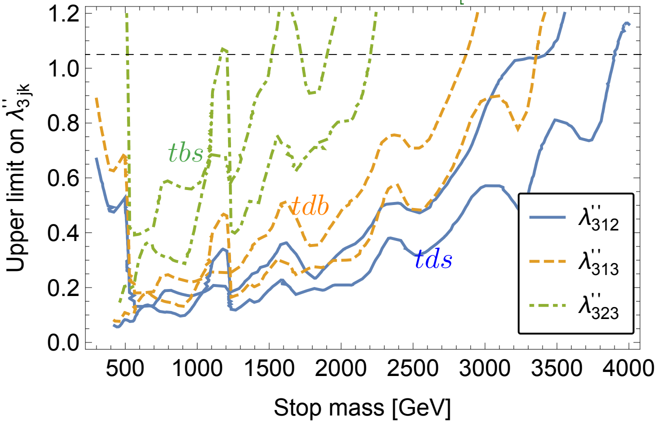


New ICHEP limits

Below 1 TeV, best limits from *scouting / trigger level analysis*.

New techniques: recoil off of hard ISR γ/jet

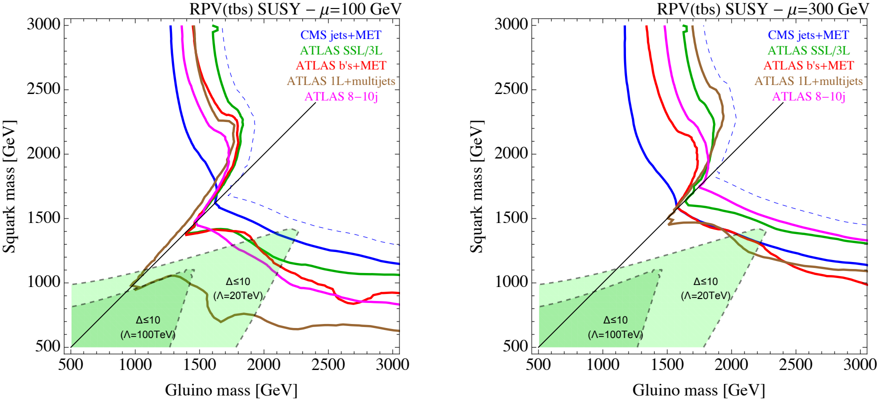
[Shimmin,Whiteson, 1602.07727]
[ATLAS-CONF-2016-070, 15.7fb^{-1}@13TeV]

Aside: hierarchical RPV

If RPV couplings are hierarchical, e.g. set by flavor symmetries, the higgsino dominantly decays to final states with tops: $\tilde{H} \to tbs$

[Csaki,Grossman,Heidenreich '11]

$\to$ SS leptons, re-introduce some MET.



Limits significantly stronger with respect to decays to light quarks.

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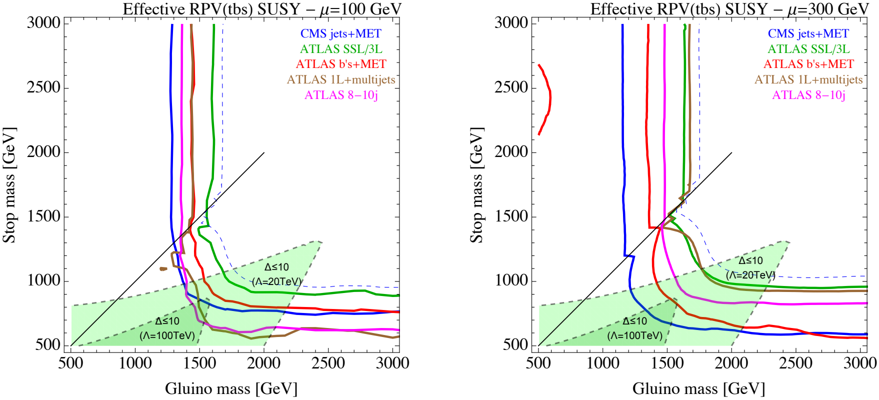

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Flavor and RPV

Flavor physics constraints ($K-\bar{K}$, $\Delta B = 2$ transitions, e.g. $n-\bar{n}$):

$$n-\bar{n}: \quad |\lambda''_{11k}| \lesssim 10^{-7}\left(\frac{\tilde{m}}{100\text{ GeV}}\right)^{5/2}, \; |\lambda''_{312,313}| \lesssim 10^{-2}\left(\frac{\tilde{m}}{200\text{ GeV}}\right)^{5/2}$$

$$K-\bar{K}: \quad |\lambda''^{*}_{323}\lambda''_{313}| \lesssim 10^{-3}\left(\frac{m_{\tilde{u}_i}}{100\text{ GeV}}\right)$$

[Barbier et al., hep-ph/0406039]

[Calibbi,Ferretti,Milstead,Petersson, 1602.04821]

Flavor models also favor hierarchies with large 3^{rd} generation couplings.

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix}_{horiz.U(1)} = \lambda''_{323}\begin{pmatrix} 3\times10^{-5} & 3\times10^{-3} & 0.05 \\ 10^{-4} & 10^{-2} & 0.2 \\ 6\times10^{-4} & 0.05 & 1 \end{pmatrix}$$

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RPV involving the stop is much less constrained, and also more relevant in terms of naturalness. Large couplings are still possible.

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But those are only leading-log expressions, and don't differentiate between IR and UV parameters, or runnning of couplings.

Series of corrections, from UV to IR:

- UV masses set by SUSY breaking dynamics, RGE'd to IR masses. Large corrections, give rise to non-trivial correlations.
- threshold corrections to IR masses: running IR mass to pole mass, which are the experimentally accessible quantitites.

  [Pierce,Bagger,Matchev,Zhang '96] [Agashe,Graesser '98]
- threshold corrections to $m_{H_u}^2$: Higgs effective potential [Martin '02]

All of those tend to *weaken the naturalness bounds*, i.e. allow heavier natural sparticles than LL considerations.

$$RGEs: \quad M_3(Q_{IR}) = C^{M_3}_{M_3} M_3(\Lambda) + \ldots$$

$$m^2_{Q_3}(Q_{IR}) = A^{m^2_{Q_3}}_{m^2_{Q_3}}\ m^2_{Q_3}(\Lambda) + A^{m^2_{\tilde{q}_{1,2}}}_{m^2_{Q_3}}\ m^2_{\tilde{q}_{1,2}}(\Lambda) + B^{M_3\,M_3}_{m^2_{Q_3}}\ |M_3(\Lambda)|^2 + \ldots$$

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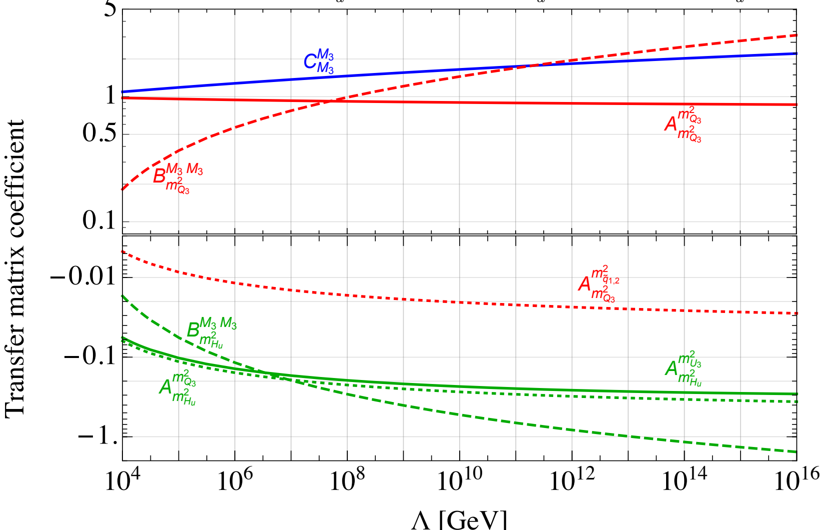

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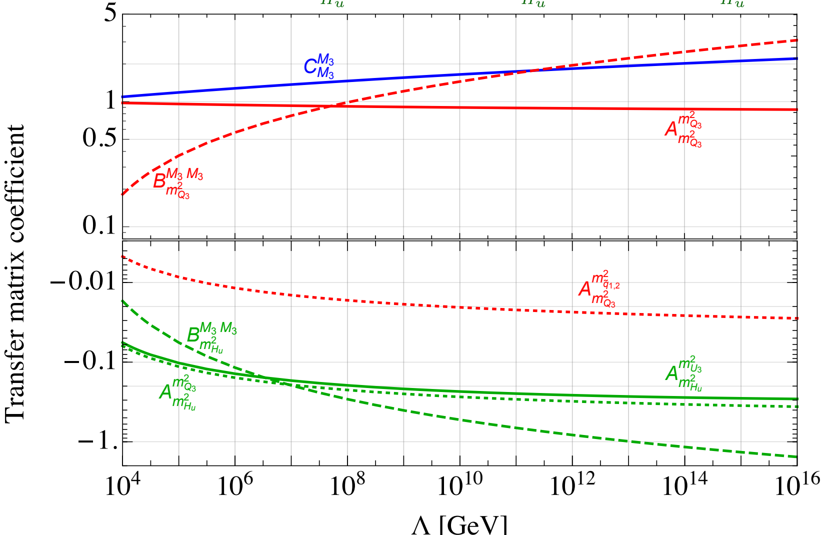

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All of those tend to *relax the naturalness bounds*, i.e. allow heavier natural sparticles than LL considerations.

On the other hand, decoupled 1st/2nd gen squarks push IR stops tachyonic - does not come without a cost

[Arkani-Hamed,Murayama '97] [Agashe,Graesser '98]

Some of these effect were taken into account previously, but not as comprehensively, and not focused on LHC reach.

[Casas,Moreno,Robles,Rolbiecki,Zaldivar '14]

Aside: SS leptons excesses

Some excesses in 8 TeV SS lepton searches (2σ level): $2t + 2b + \not{E}_T$
Also, the ttH cross section is slightly high (does not need to be a H):

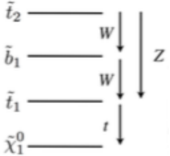
$$ttH : \qquad \mu = 5.3^{+2.1}_{-1.8} \text{ (ATLAS)}, \; 2.8^{+2.1}_{-1.9} \text{ (CMS)}$$

[Huang,Ismail,Low,Wagner, 1507.01601]

Can be interpreted as

$$\tilde{t}_R \to t + \tilde{B} \to t + W + \tilde{W} \to t + W + \tilde{\chi}^0_1 + soft$$

with $m_{\tilde{t}} = 550$ GeV, $m_{\tilde{B}} = 340$ GeV, $m_{\tilde{W}} = 260$ GeV.

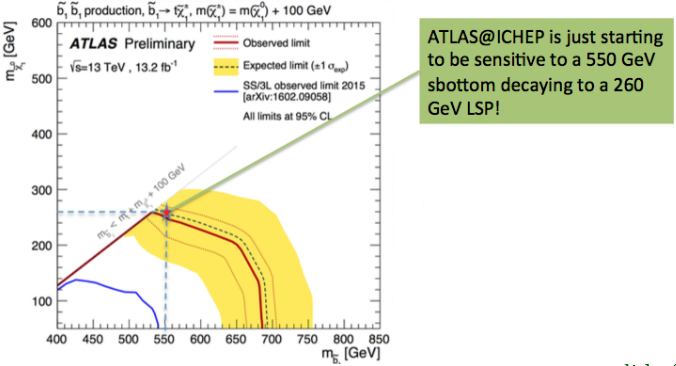


Other option: $\tilde{t}_2 \to \tilde{b}_1 + W \to \tilde{t}_1 + W + W \to \tilde{\chi}^0_1 + t + W + W$
with $m_{\tilde{t}_2} = 750$ GeV, $m_{\tilde{b}_1} = 525$ GeV, $m_{\tilde{t}_1} = 410$ GeV.

[Cheng,Li,Qin, 1607.06547]

Aside: SS leptons excesses

Same 13 TeV searches are getting close to excluding those benchmark points, but not yet:



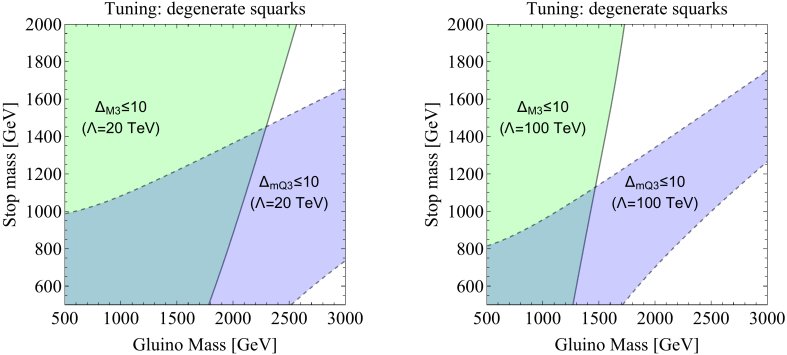
slide from Ian Low, @ICTP

If real, it would show up elsewhere: $t, W's \to$ jets

We find: CMS jets + MET excludes all benchmark points explaining the excesses (SLHA files provided by Ian Low, Hsin-Chia Cheng).

Natural SUSY redux

With light higgsino, the natural (10% fine-tuned or less) regions in the stop-gluino mass plane look like this (for $\Lambda = 20,\ 100$ TeV):



Stop and gluino masses correlated. When multiple sources of tuning, we take the max $\rightarrow$ intersection wedge.

Looser definitions of “acceptable fine-tuning” (1%?): larger natural range

Instead of going down that rabbit hole: back to the LHC

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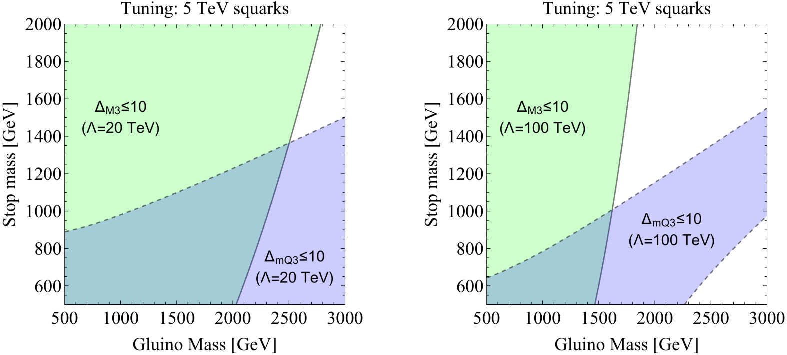

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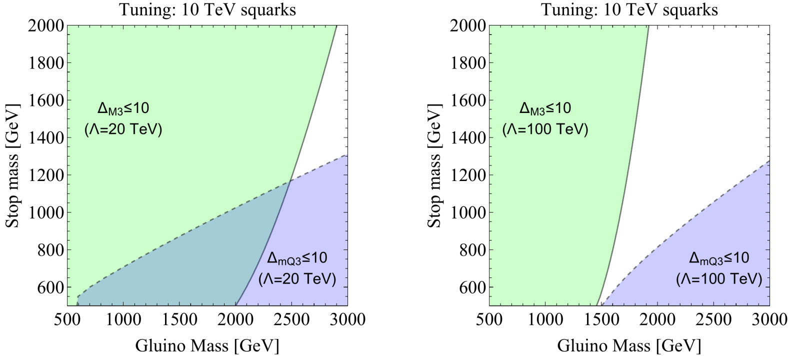

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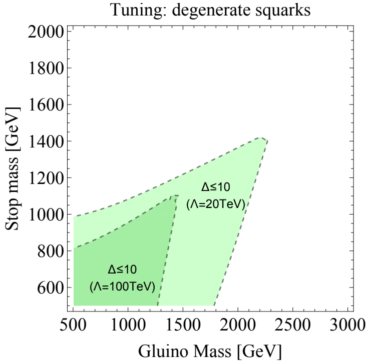

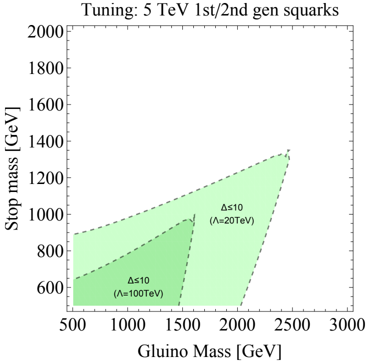

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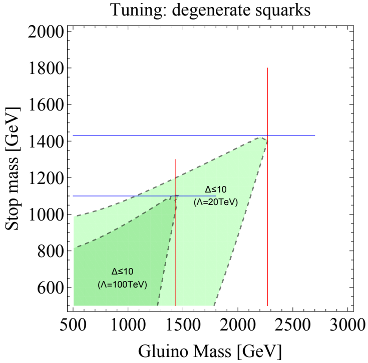

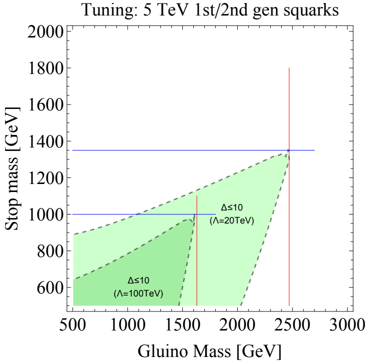

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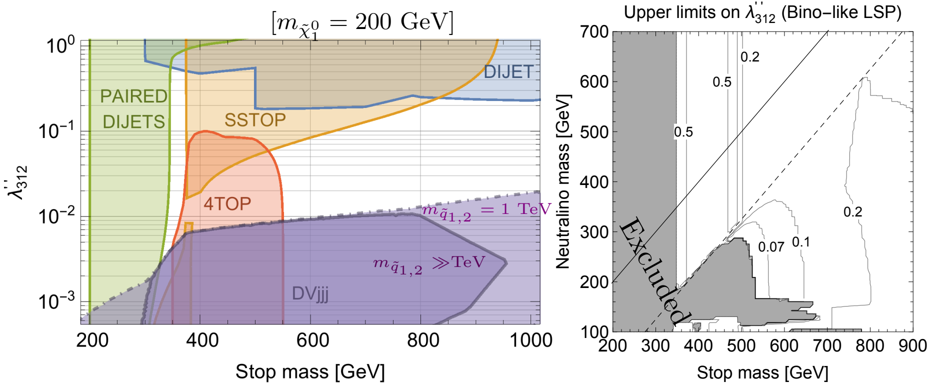
Resonant Signatures II: Bino LSP @8 TeV

Putting together all the signatures, limits from available 8 TeV searches:

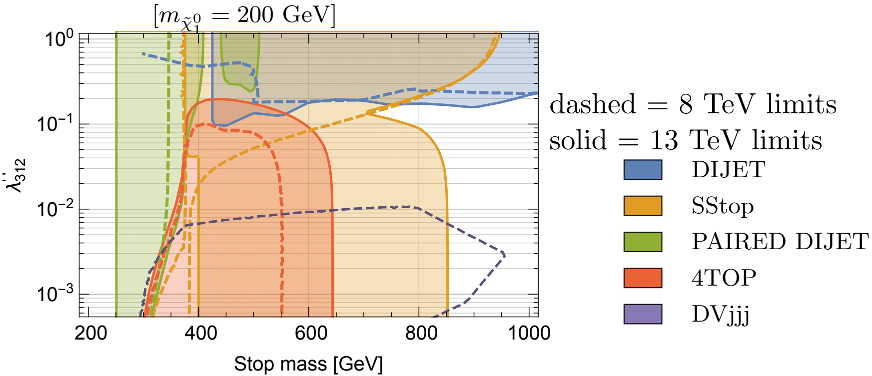


Reach stops up to 500 GeV: *comparable to RPC searches!*

Similar results for $\lambda''_{313}, \lambda''_{323}$ (weaker: resonant production penalized by non-valence quarks) (backup slides)

Resonant Signatures II: Bino LSP @13 TeV

Recasting searches presented at ICHEP, we find significant improvements over Run I:

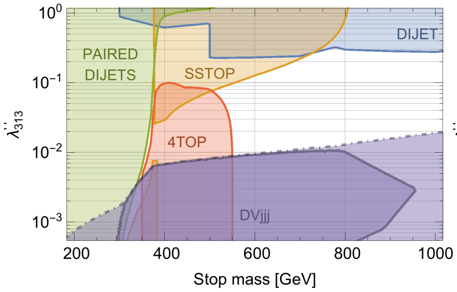


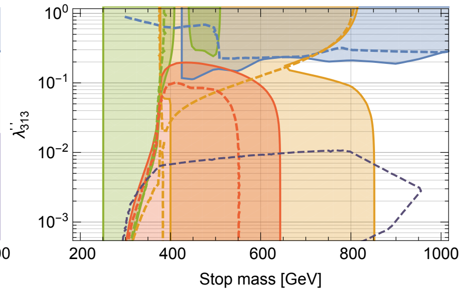
We can already reach up to 800 GeV!

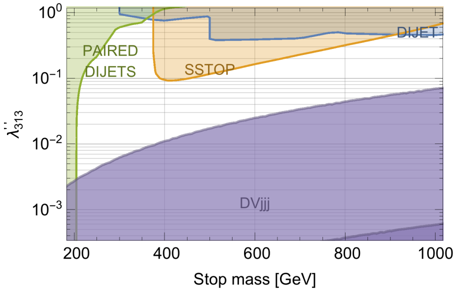
Most important searches are the multi-top searches, not currently optimized for these signatures. Extra jets (possibly b's) in final state.

Resonant $\to$ 2 SS tops + 2 jets. Pair-produced $\to$ 4 tops + 4 jets.

resonant RPV 313







resonant RPV 323