Dark Matter, New Electroweak Particles, and LHC Searches

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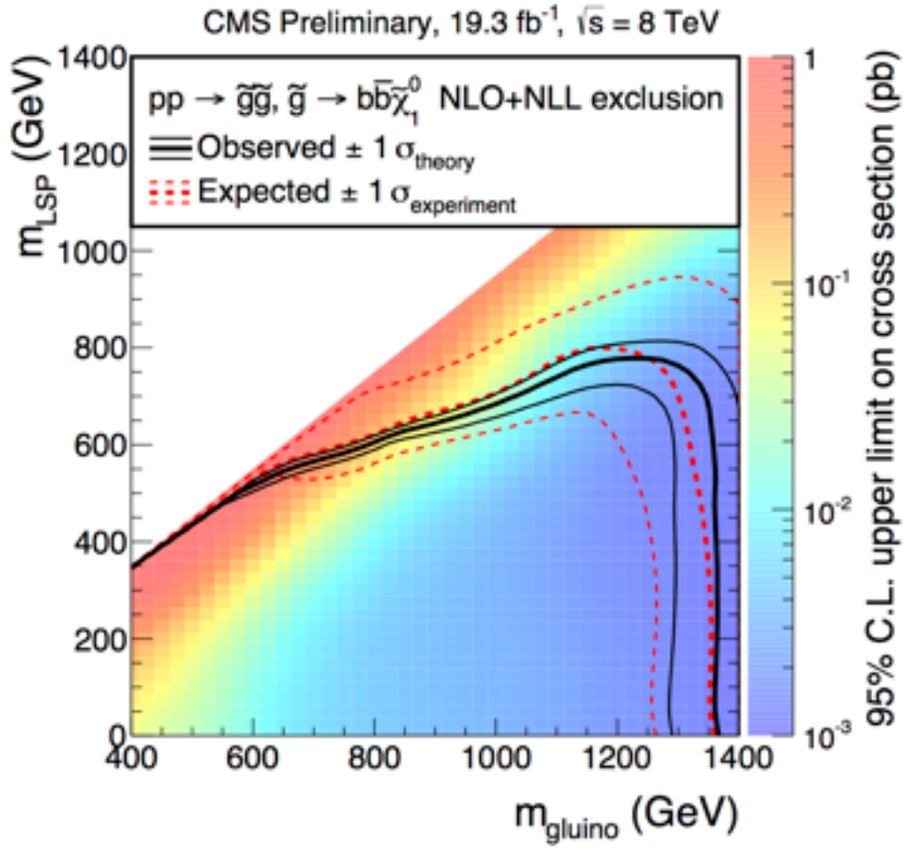
with D. Hooper, J. Kumar, H. Lippencott, J. Lykken, C. Rogan, and M. Spiropulu

Rutgers and Fermilab

What didn't we find at the LHC?

- No squarks/gluinos decaying into jets+$\not{E}_T$ with masses $\lesssim 1\ \mathrm{TeV}$
- No evidence of non-SM Higgs physics.



- Things we were looking for were motivated by "simple" supersymmetry or were "easy" to find.
- Interesting things can still be lurked at or below a TeV:
  - 3rd generation partners
  - Degenerate mass spectrum
  - Direct electroweak production (sleptons, charginos, *etc.*)

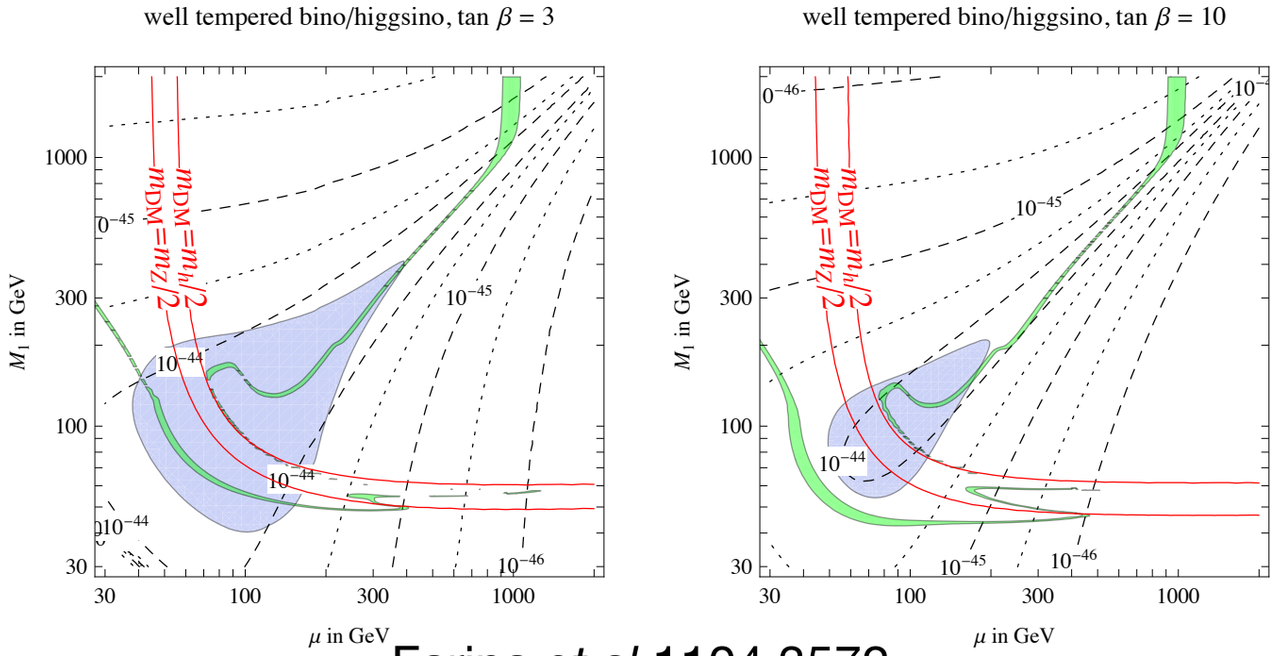
Where should we look next?

- Evidence of Beyond the Standard Model Physics:
  - Neutrino Masses
  - Dark Matter

- Two general ways to look for dark matter-related physics at the LHC:
  - Look for the decay matter “directly” via large missing energy signatures.
  - Look for additional new particles that the accompany the dark matter.

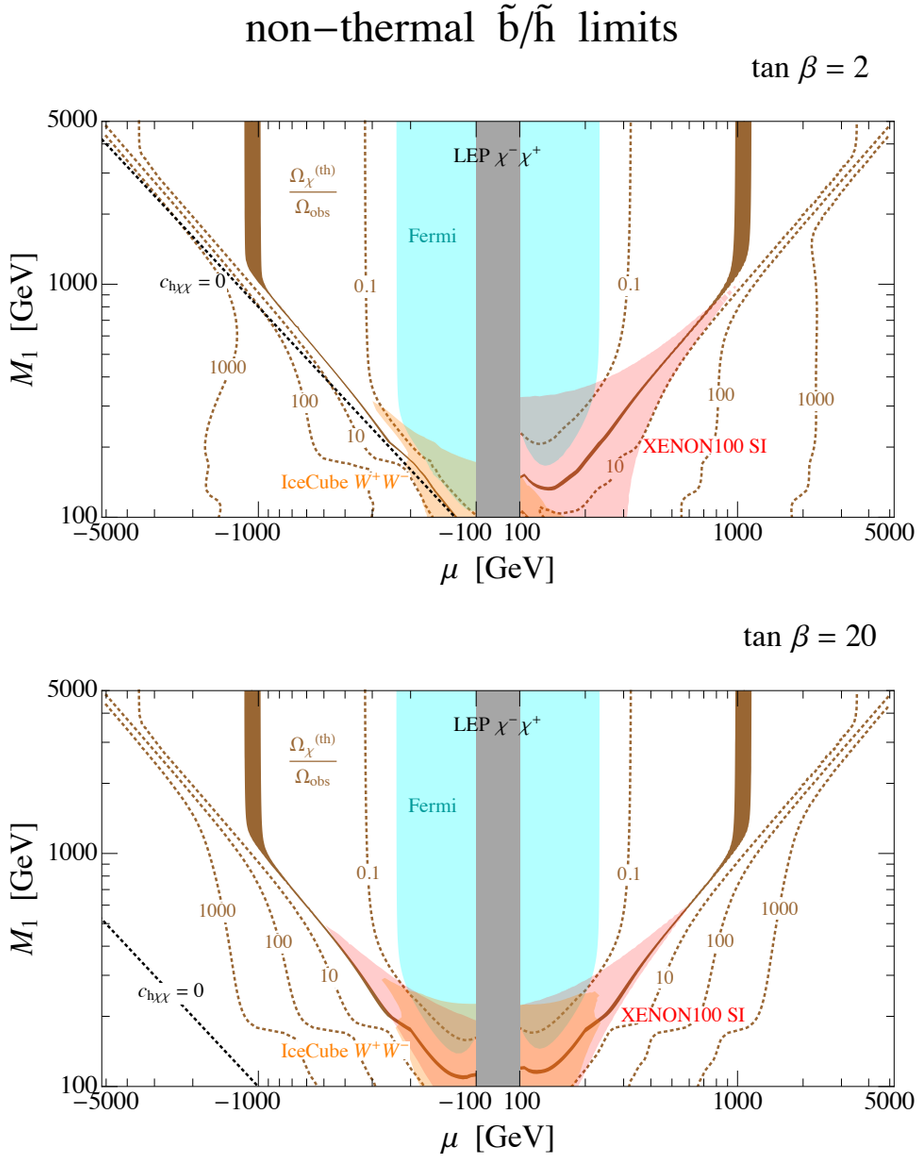
Supersymmetric Dark Matter

- Pure higgsino or wino thermal dark matter would have masses of $\mathcal{O}(1-3\ \mathrm{TeV})$
- "Well-tempered" bino-higgsino constrained



Farina *et al* 1104.3572

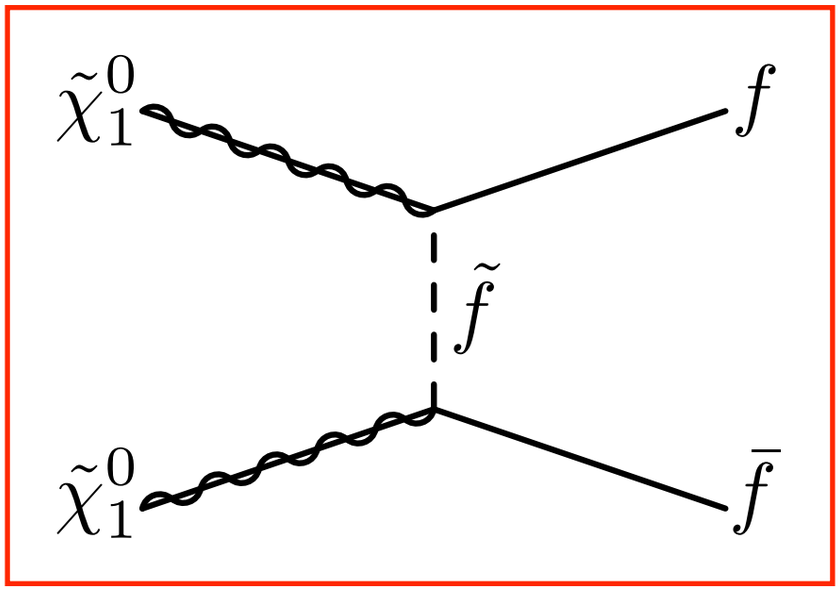
- What about pure bino dark matter?



Cheung *et al* 1211.4873

Pure Binos

- What about neutralinos that are 100% bino?
- No annihilation channels on their own
  - So they require something else around to annihilate with.



- Squarks known to be too heavy to give a large enough cross section for a thermal relic.

‘Light’ Sleptons

- Bino dark matter implies something like sleptons

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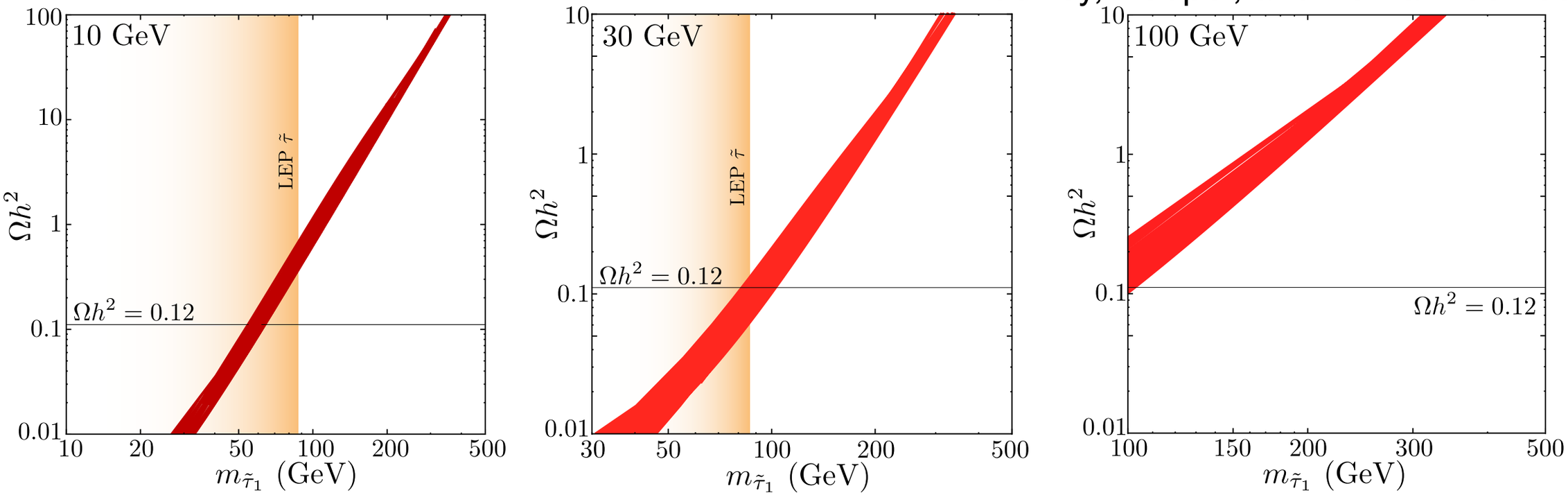
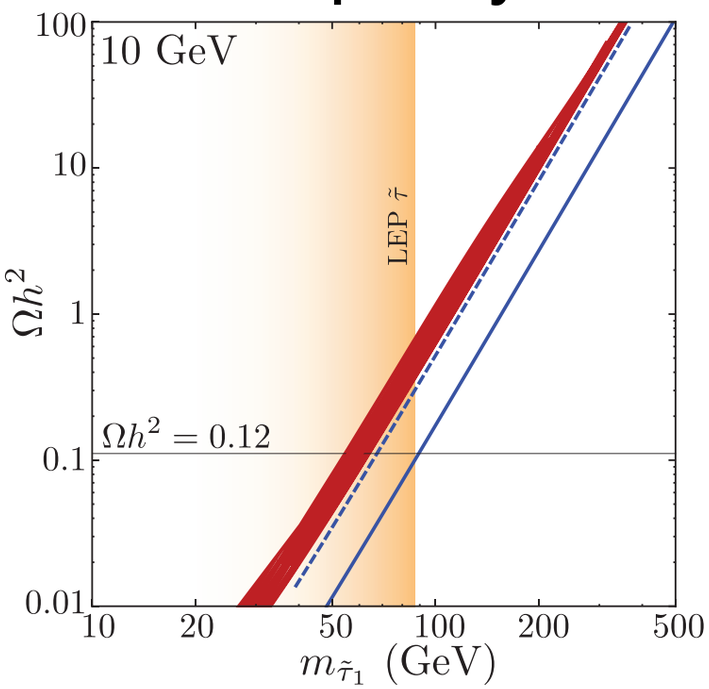
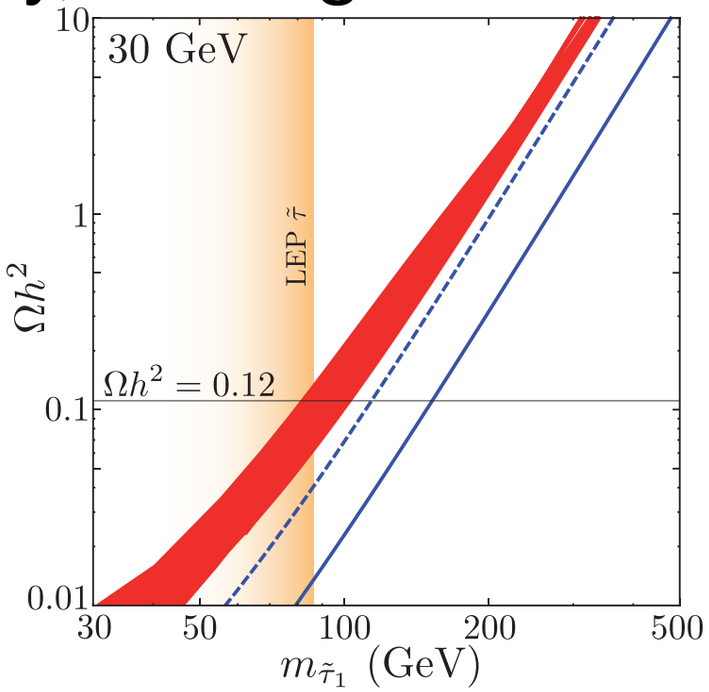


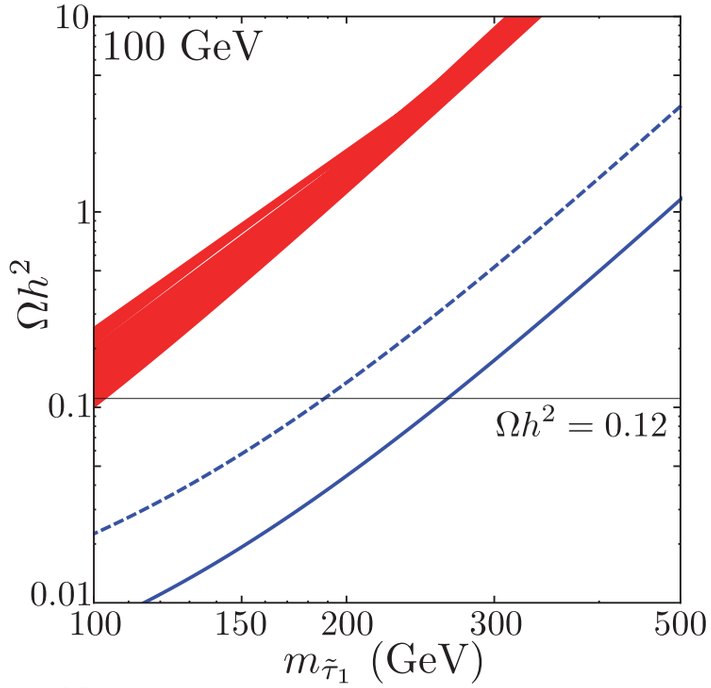
- Interestingly, there is a maximum slepton mass that will allow a dark matter solution

‘Light’ Sleptons

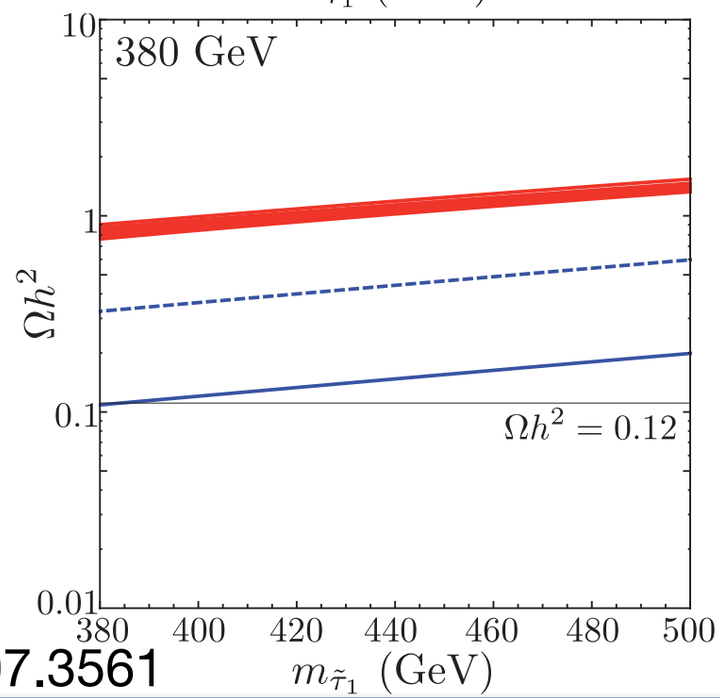
- Going beyond the MSSM, can look at R-symmetric supersymmetry, leading to Dirac neutralinos







- Allows heavier slepton solutions, but still a maximum that is $m_{\tilde{\ell}} \lesssim 380$ GeV



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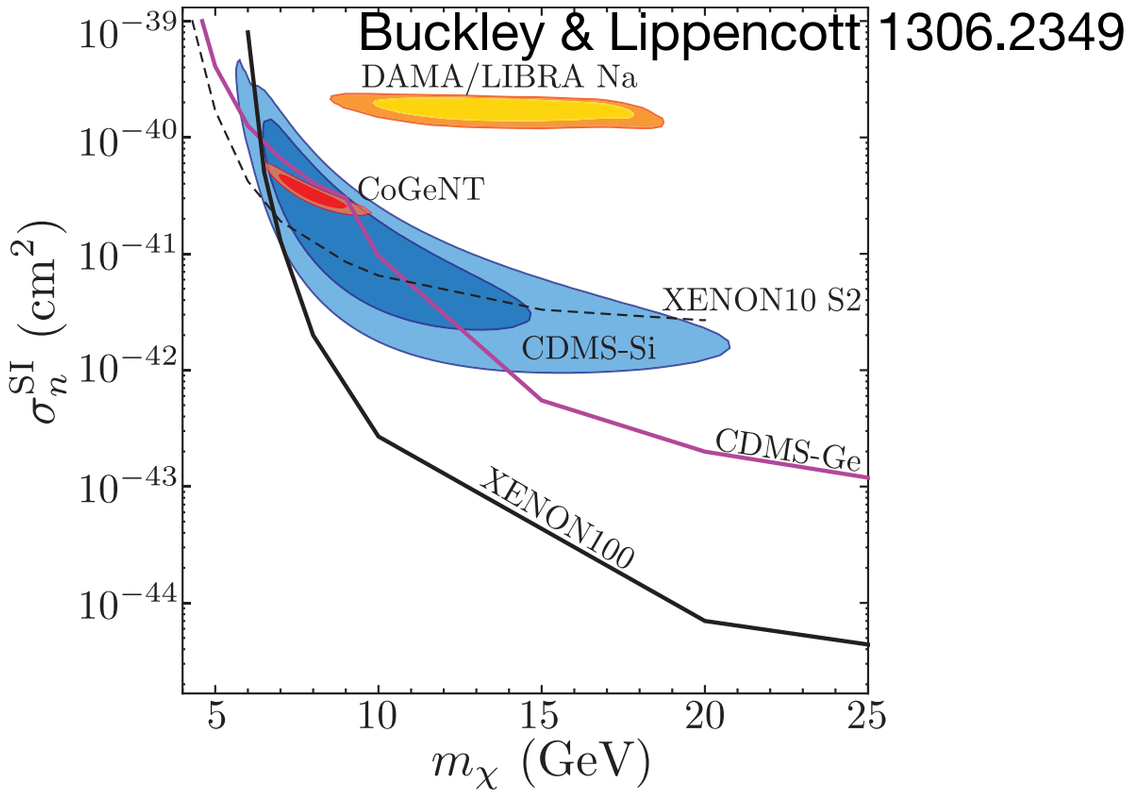
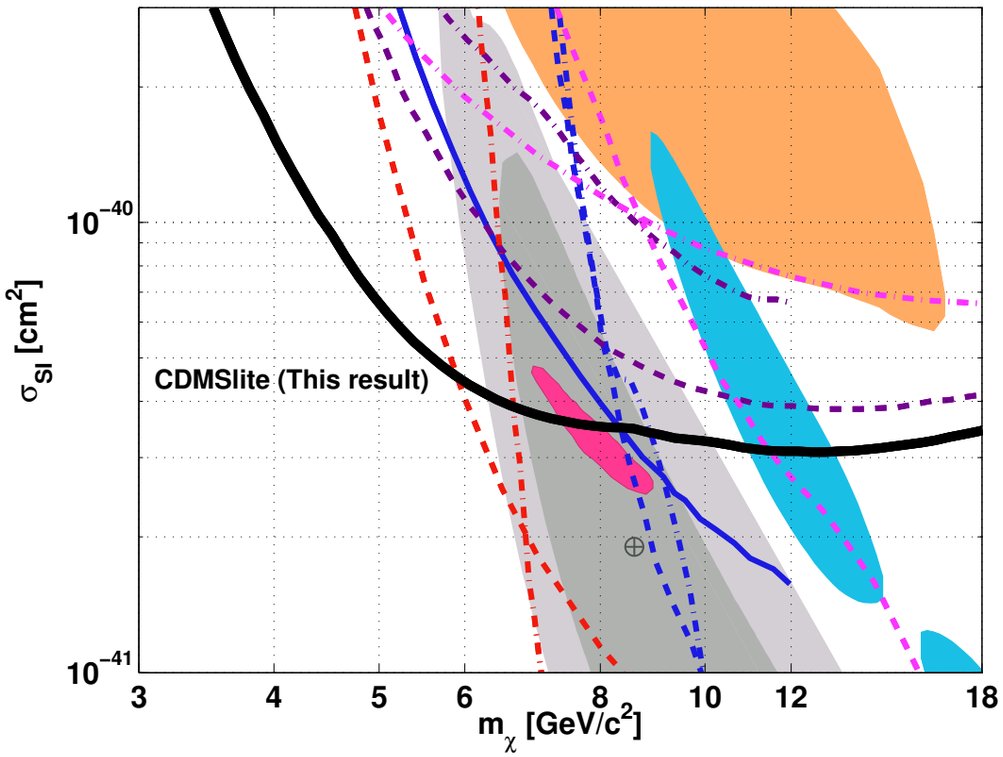
‘Light’ Dark Matter

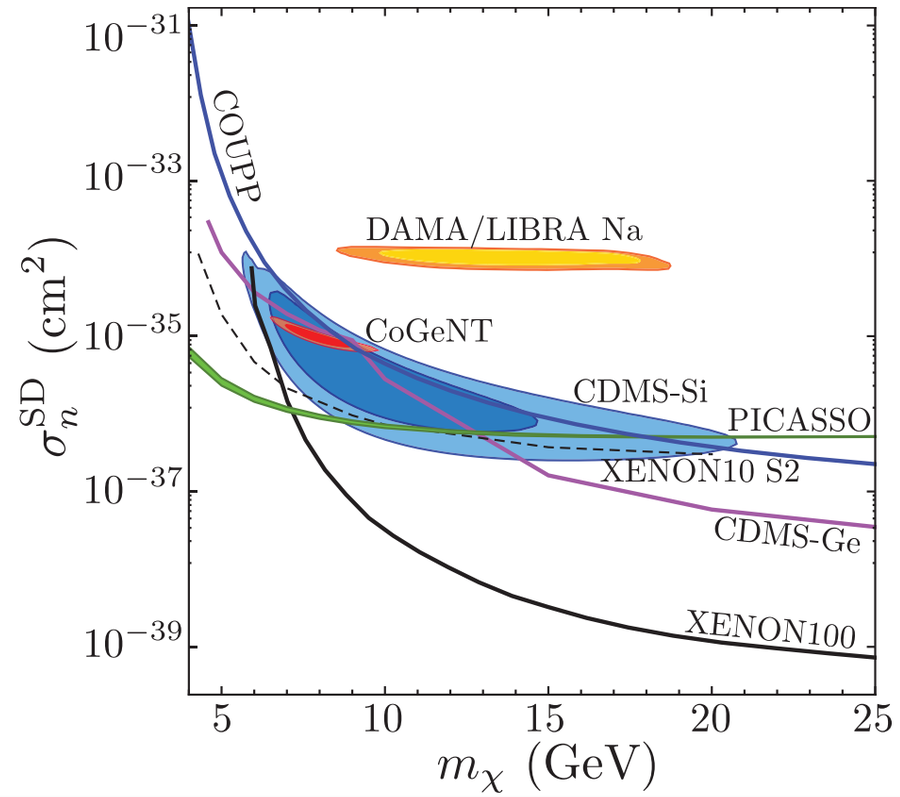
- Some possible signals of dark matter with mass $\mathcal{O}(10\ \mathrm{GeV})$

- What might this imply for LHC searches?





CDMSlite Agnese *et al.*



Effective Operator Interpretation

- Assume that effective operators describe the new physics in direct & indirect detection, as well as colliders.
- Laundry list of operators:

Name	Operator	Coefficient	DD
D1	$[\bar{\chi}\chi][ff]$	$m_f\Lambda^{-3}$	SI
D2	$[\bar{\chi}\gamma^5\chi][ff]$	$im_f\Lambda^{-3}$	–
D3	$[\bar{\chi}\chi][f\gamma^5 f]$	$im_f\Lambda^{-3}$	–
D4	$[\bar{\chi}\gamma^5\chi][f\gamma^5 f]$	$m_f\Lambda^{-3}$	–
D5	$[\bar{\chi}\gamma^\mu\chi][\bar{f}\gamma_\mu f]$	Λ^{-2}	SI
D6	$[\bar{\chi}\gamma^\mu\gamma^5\chi][f\gamma_\mu f]$	Λ^{-2}	–
D7	$[\bar{\chi}\gamma^\mu\chi][f\gamma_\mu\gamma^5 f]$	Λ^{-2}	–
D8	$[\bar{\chi}\gamma^\mu\gamma^5\chi][f\gamma_\mu\gamma^5 f]$	Λ^{-2}	SD
D9	$[\bar{\chi}\sigma^{\mu\nu}\chi][f\sigma_{\mu\nu}f]$	Λ^{-2}	SD
D10	$[\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi][f\sigma_{\mu\nu}f]$	$i\Lambda^{-2}$	–
D11	$[\bar{\chi}\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	SI
D12	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}G^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D13	$[\bar{\chi}\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D14	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	–

Name	Operator	Coefficient	DD
C1	$[\chi^*\chi][ff]$	$m_f\Lambda^{-2}$	SI
C2	$[\chi^*\chi][f\gamma^5 f]$	$im_f\Lambda^{-2}$	–
C3	$[\chi^*\partial_\mu\chi][f\gamma^\mu f]$	Λ^{-2}	SI
C4	$[\chi^*\partial_\mu\chi][f\gamma^\mu\gamma^5 f]$	Λ^{-2}	–
C5	$[\chi^*\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S\Lambda^{-2}$	SI
C6	$[\chi^*\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S\Lambda^{-2}$	–
R1	$[\chi\chi][ff]$	$m_f\Lambda^{-2}$	SI
R2	$[\chi\chi][f\gamma^5 f]$	$im_f\Lambda^{-2}$	–
R3	$[\chi\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S\Lambda^{-2}$	SI
R4	$[\chi\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S\Lambda^{-2}$	–

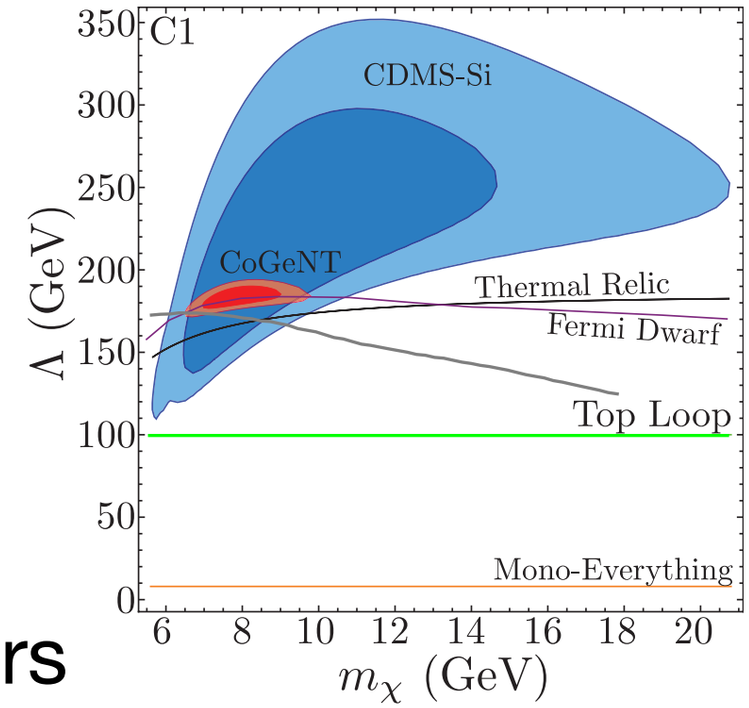
- Some of which can induce SI/SD direct detection

Effective Operator Interpretation

- Require a SI/SD operator to give CoGeNT/CDMS-Si without violating collider, indirect detection bounds
  - Only one set can do so and have a large enough cross section to give a thermal relic:

$$m_f \Lambda^{-2} [\chi \chi^{(*)}][\bar{f} f]$$

  - (and it's constrained by CDMSlite now)
- All other SI/SD operators have Λ needed for thermal relics ruled out.
  - Adding additional operators doesn't work because the values of Λ needed for those operators also ruled out.

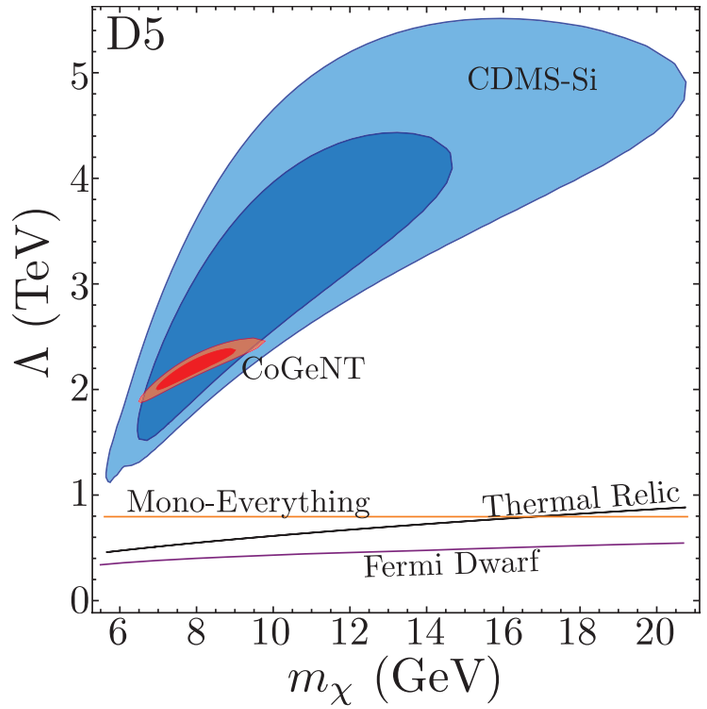


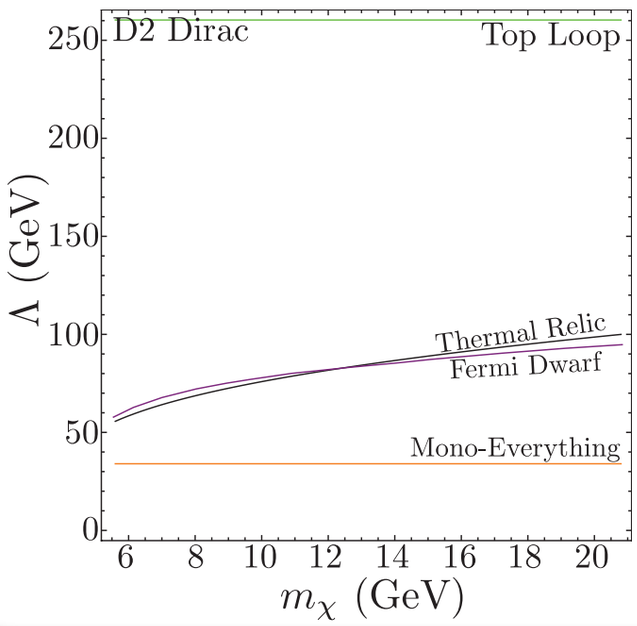
Effective Operator Interpretation

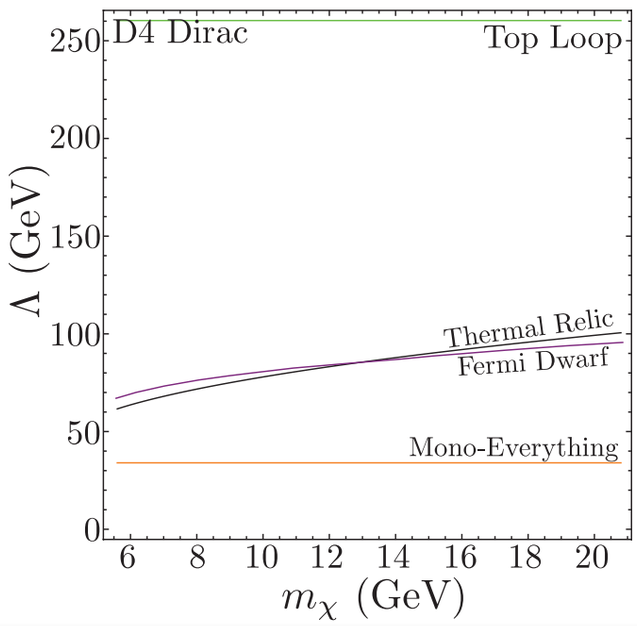
- Example: fermionic dark matter giving CoGeNT/ CDMS-Si through $\Lambda^{-2}[\bar{\chi}\gamma^{\mu}\chi][\bar{f}\gamma_{\mu}f]$ (D5) operator:

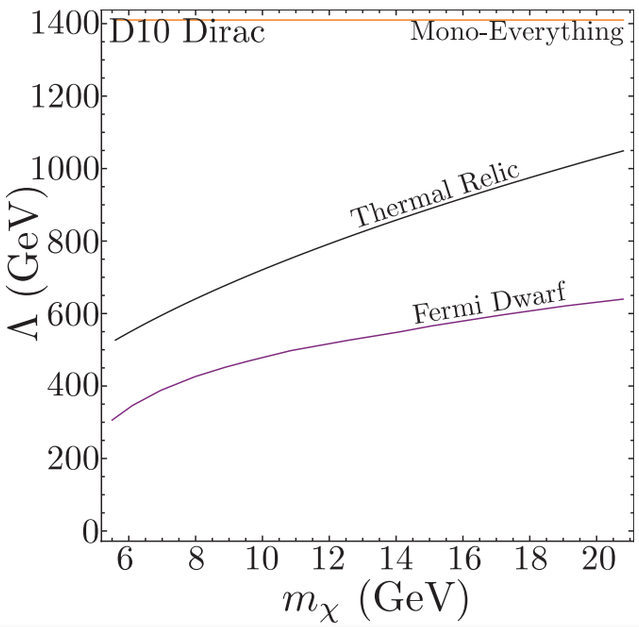
- Thermal cross section too small, so boost it via additional eff. operators to quarks and/or gluons

- But those are excluded too









Implications for the LHC

- Assuming CoGeNT/CDMS-Si anomaly is dark matter, what does this effective operator analysis tell us?
- Barring the single operator C1/R1, either:
  - Effective formalism not applicable (new light particles coupling to DM at the LHC)
  - Flavor violation in the DM couplings
  - Additional annihilation channels to non-strongly interacting states

- At least one option leads us to suspect interesting couplings to leptons/electroweak sector
- So, how do we look for them?

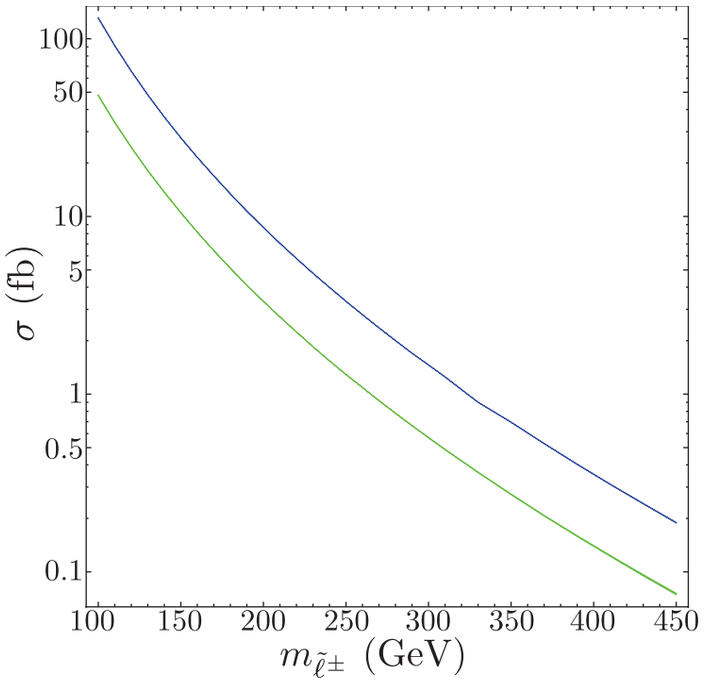
Sleptons and Charginos

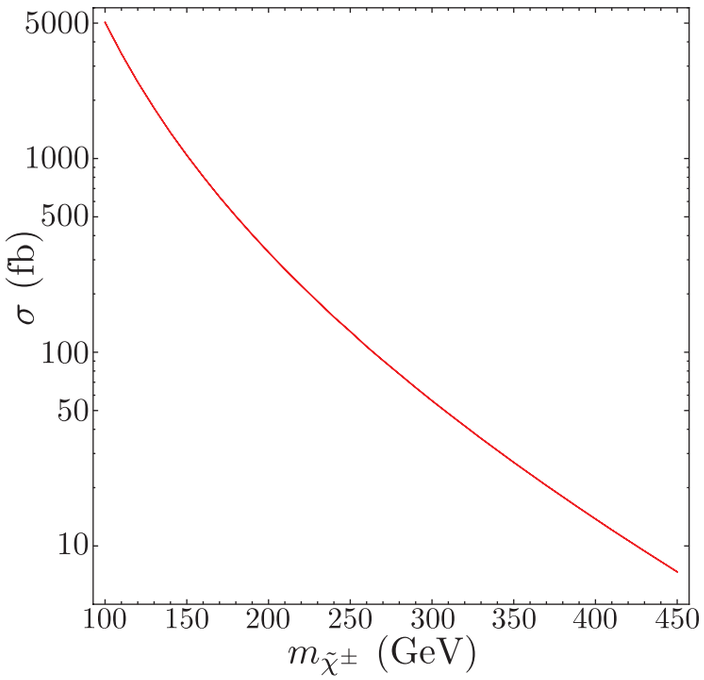
- Very difficult signatures at the LHC

$$pp \to \tilde{\ell}^-_{L/R}\tilde{\ell}^+_{L/R} \to (\ell^-\tilde{\chi}^0_1)(\ell^+\tilde{\chi}^0_1)$$

$$pp \to \tilde{\chi}^+_1\tilde{\chi}^-_1 \to (W^+\tilde{\chi}^0_1)(W^-\tilde{\chi}^0_1) \to (\ell^+\nu\tilde{\chi}^0_1)(\ell^-\bar{\nu}\tilde{\chi}^0_1)$$

  - Small cross sections





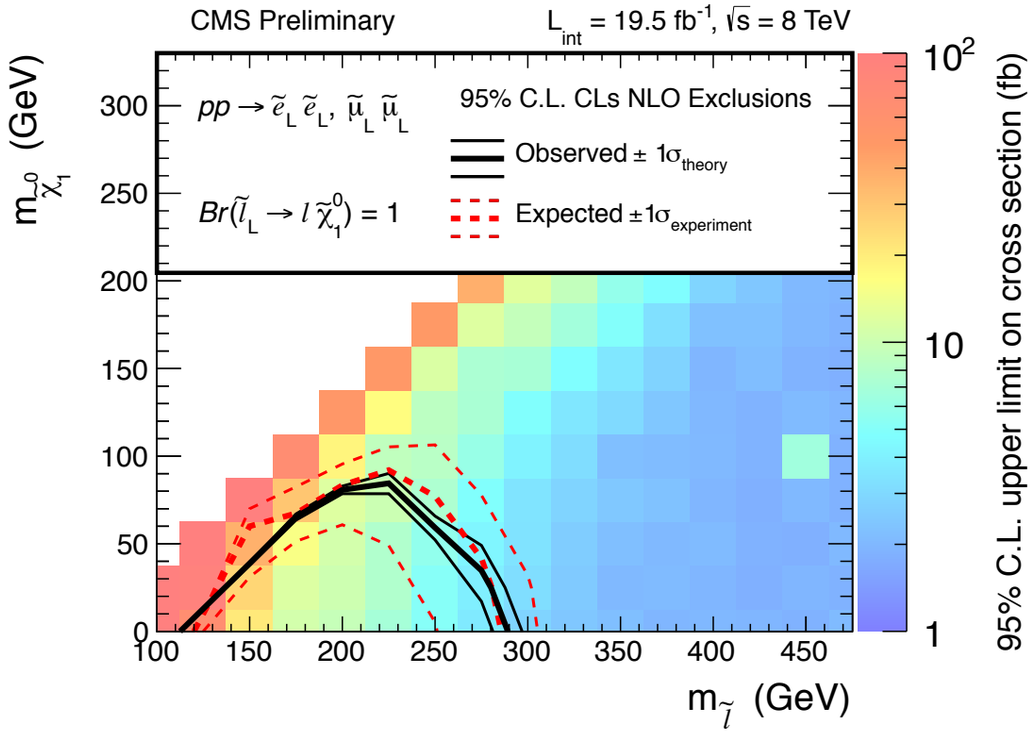
  - Large backgrounds (W^-W^+ and Drell-Yan)

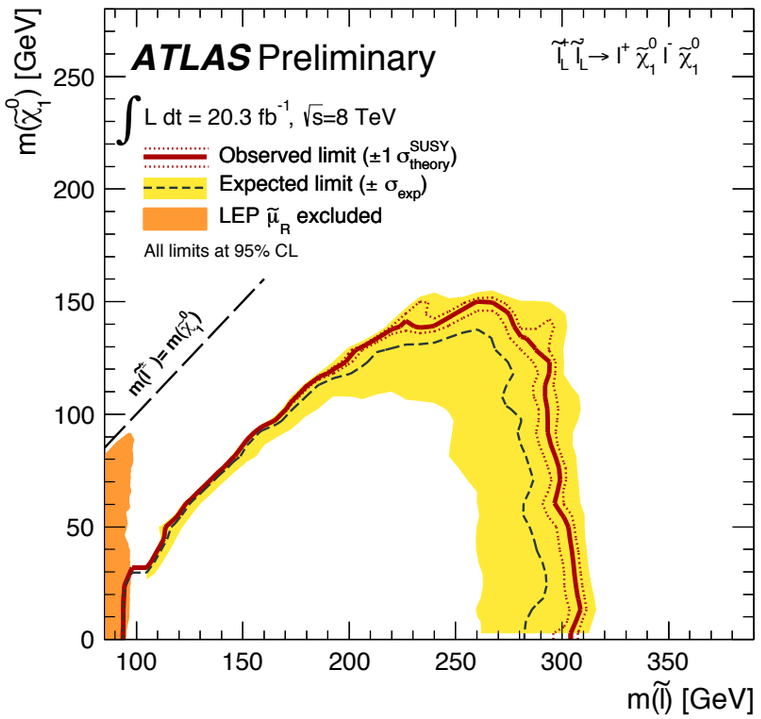
Current Bounds

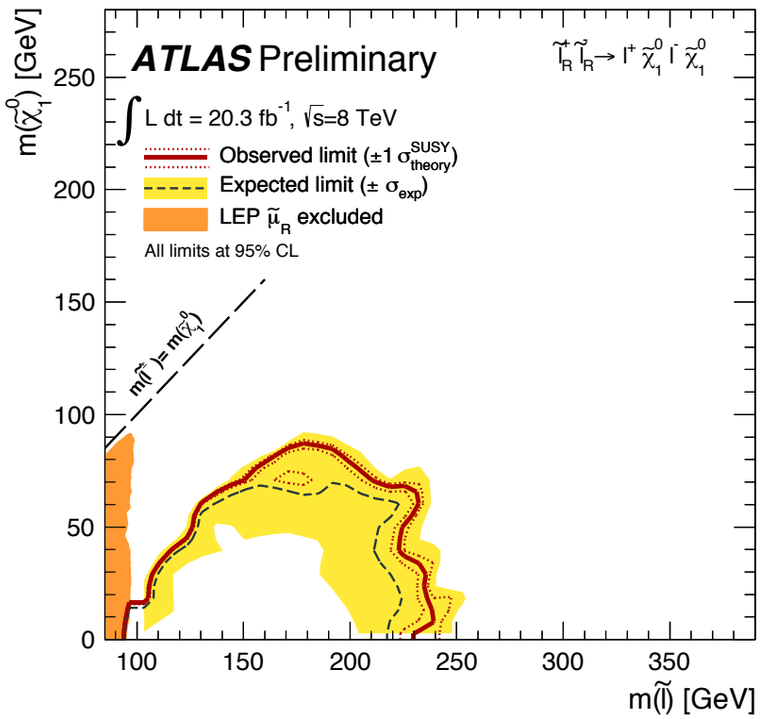
- Existing ATLAS and CMS searches in the slepton channels. Sensitive to

$$M_\Delta = (m^2_{\tilde{\ell}/\tilde{\chi}^\pm} - m^2_{\tilde{\chi}^0})/m_{\tilde{\ell}/\tilde{\chi}^\pm}$$

- Chargino searches usually assume 100% BR into $\ell + \not{E}_T$



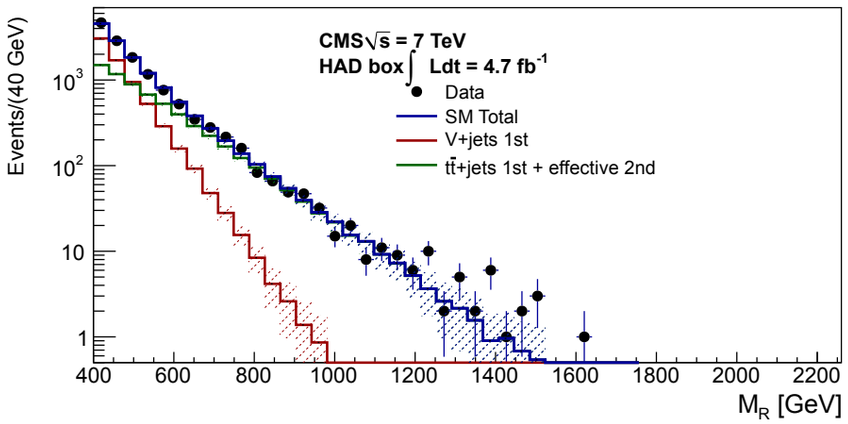


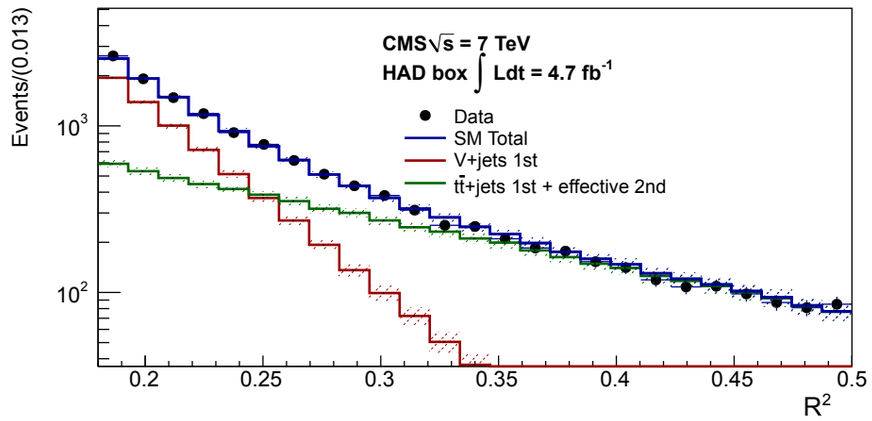


The Razor

- How can we do better?

- Original razor: make longitudinal boost to a frame that we expect to approximate pair-production frame.
  - Originally developed for gluino/squark searches
  - Hadronic events with MET





- What if there were particles that are clearly not part of the new physics? (*i.e.* jets in EW searches)

The Super-Razor

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Everything, We're Doing Five Blades

COMMENTARY · Opinion · Business · ISSUE 40·07 · Feb 18, 2004

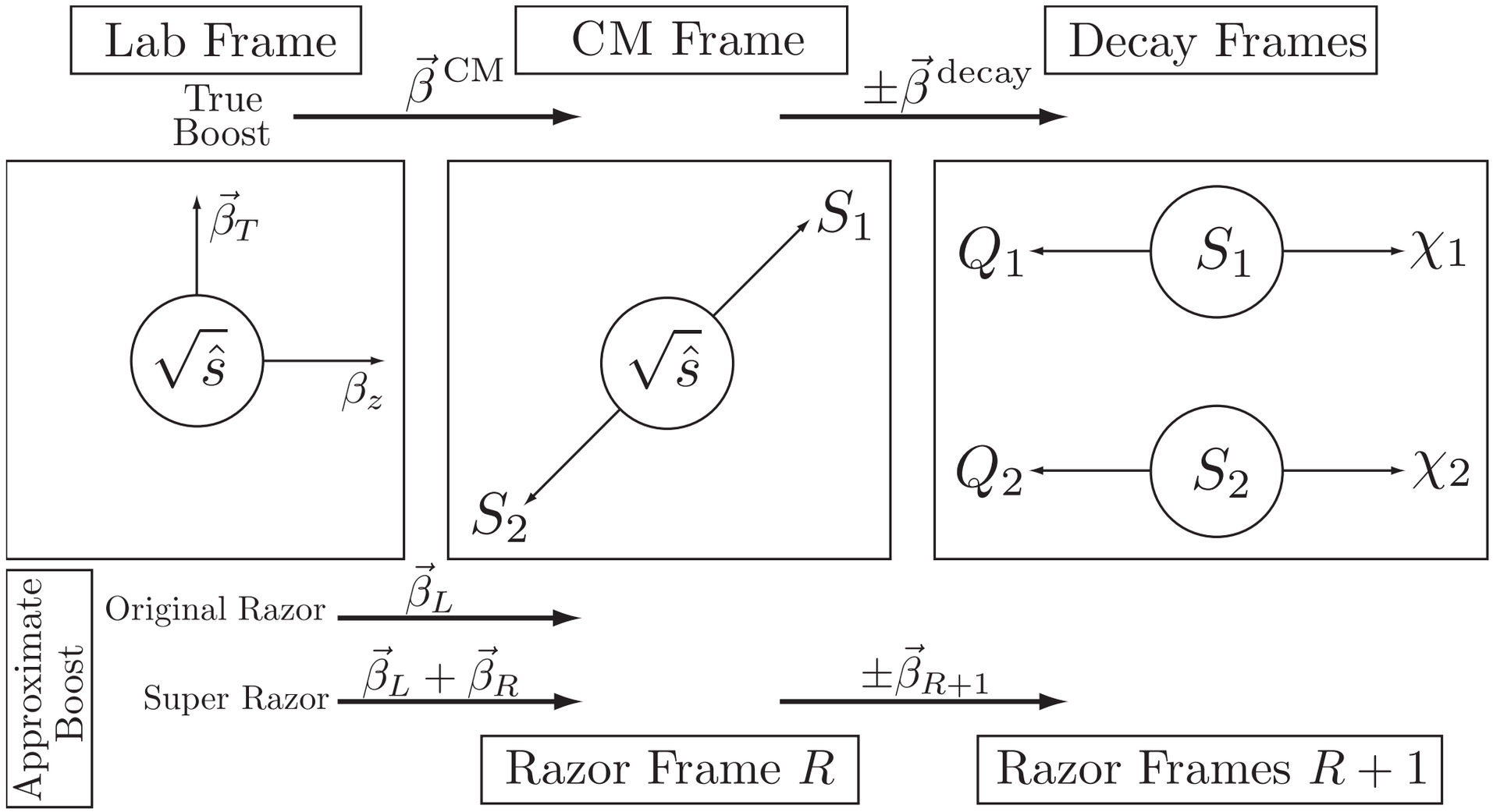
**By James M. Kilts, CEO And President,
The Gillette Company**

James M. Kilts

Would someone tell me how this happened? We were the vanguard of shaving in this country. The Gillette Mach3 was *the* razor to own. Then the other guy came out with a three-blade razor. Were we scared? Hell, no. Because we hit back with a little thing called the Mach3Turbo. That's three blades *and* an aloe strip. For moisture. But you know what happened next? Shut up, I'm telling you what happened—the bastards went to four blades. Now we're standing around with our

The Super-Razor

- Estimate boosts to both the production and decay frames. Have to assume invisible system invariant mass equivalent to that of the visible.



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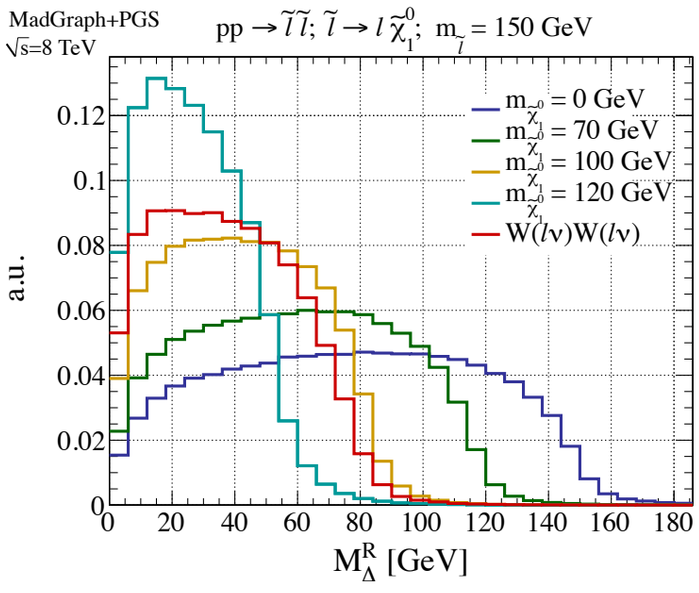
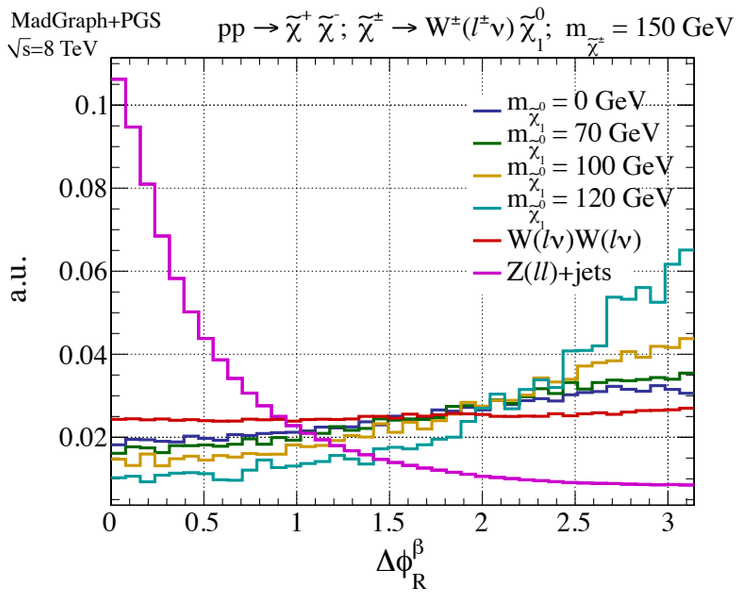
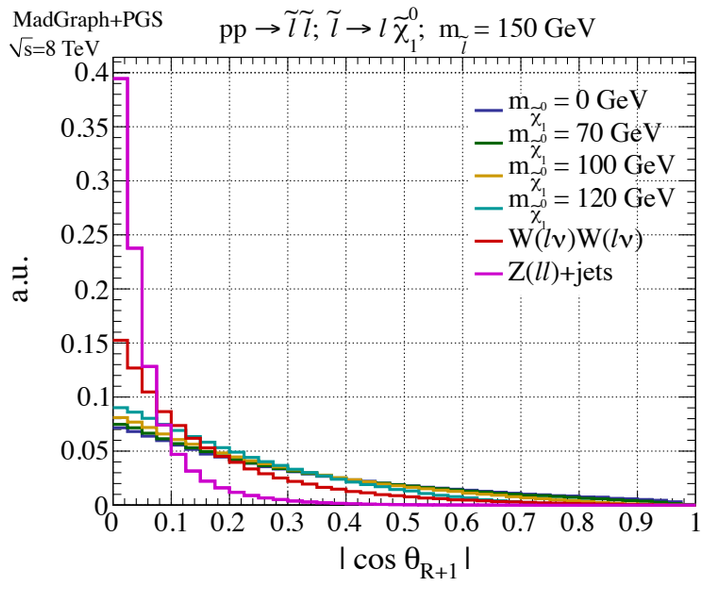
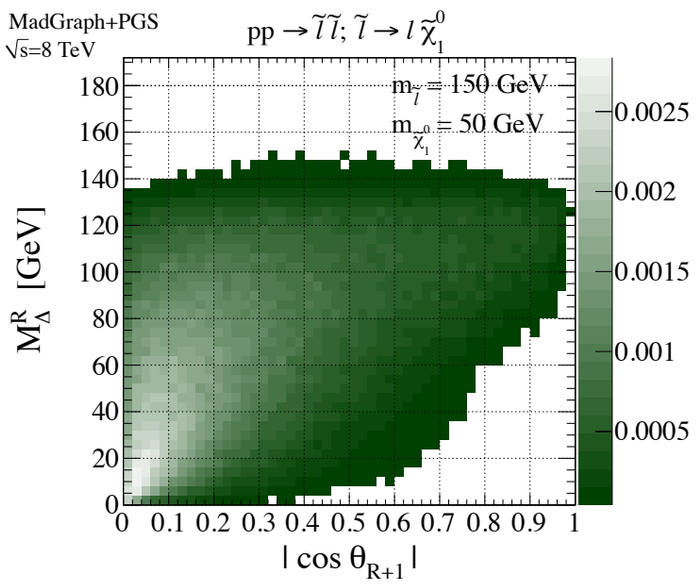
Super-Razor Variables

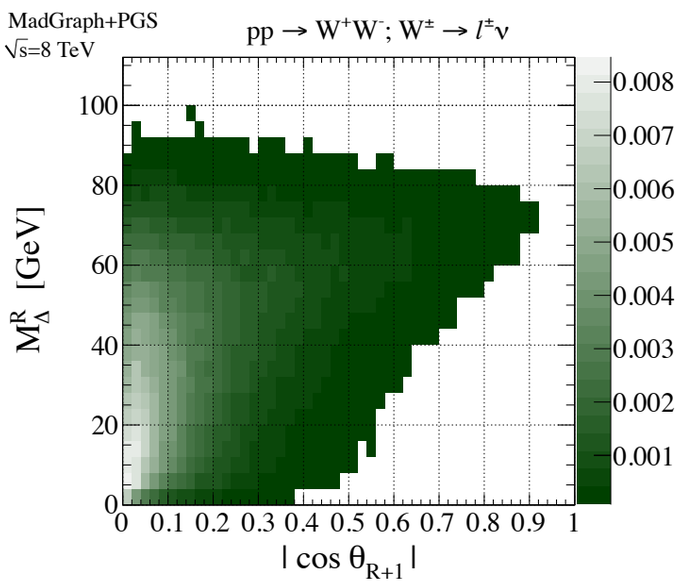
- Chris Rogan has discussed the set of variables constructed in these razor frames.

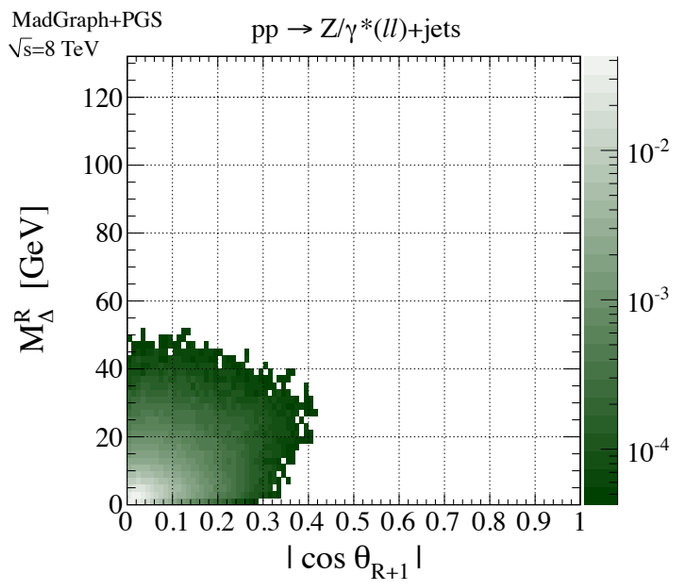




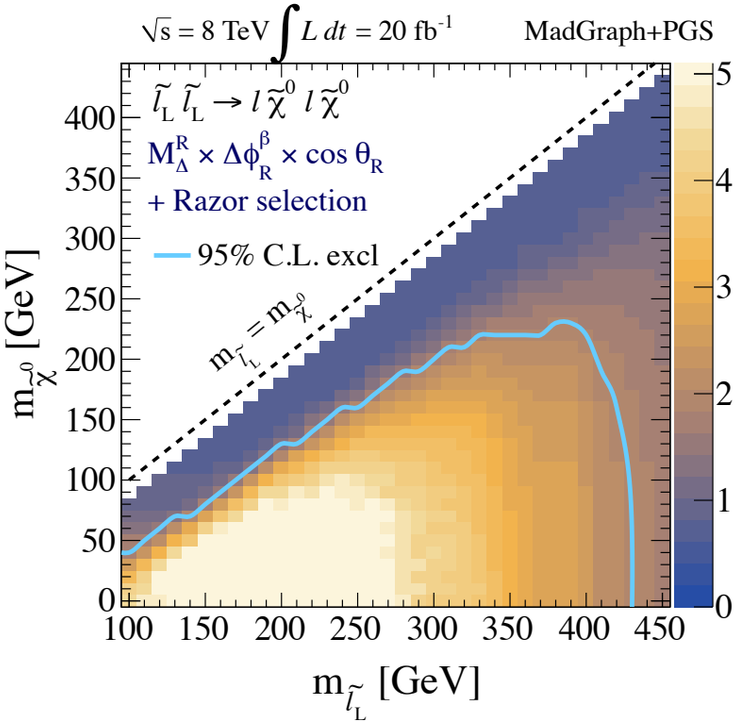


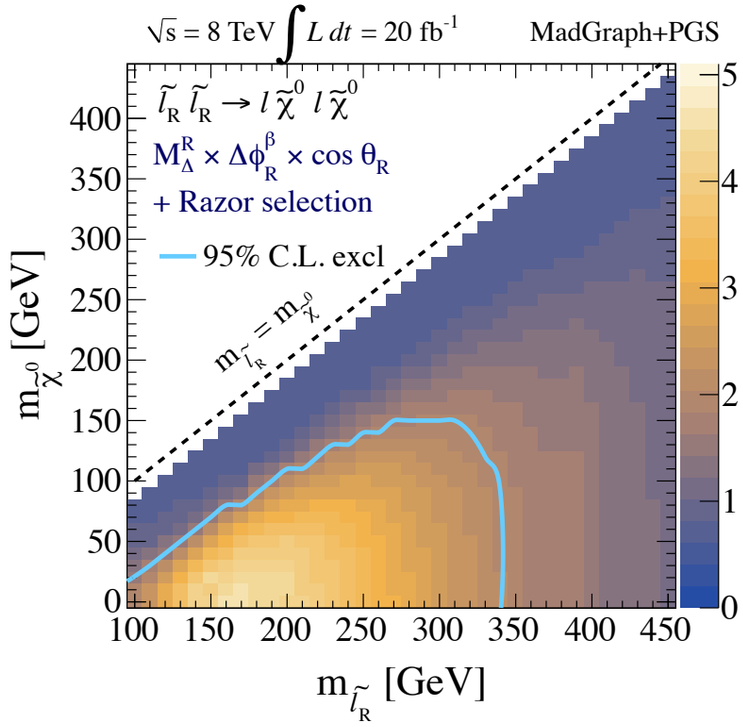


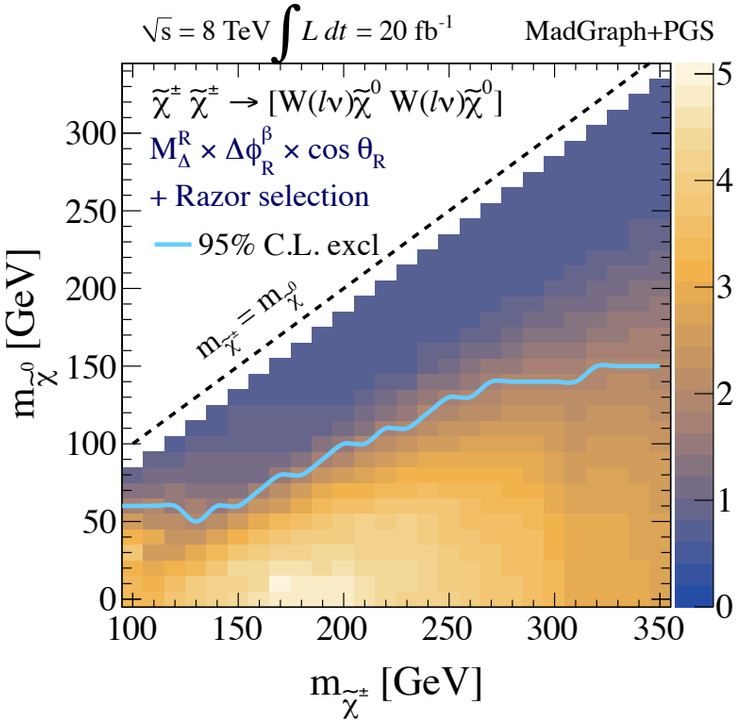


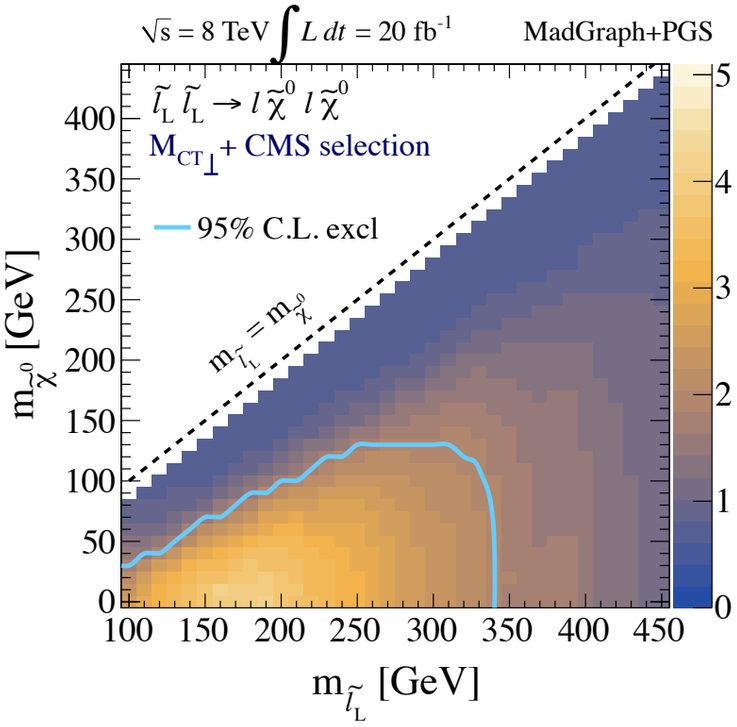


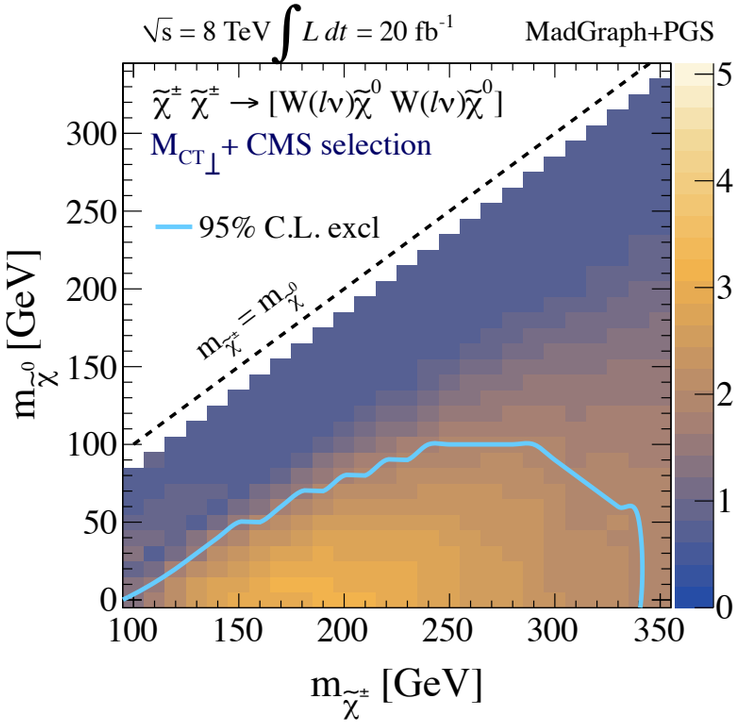
Expected Bounds











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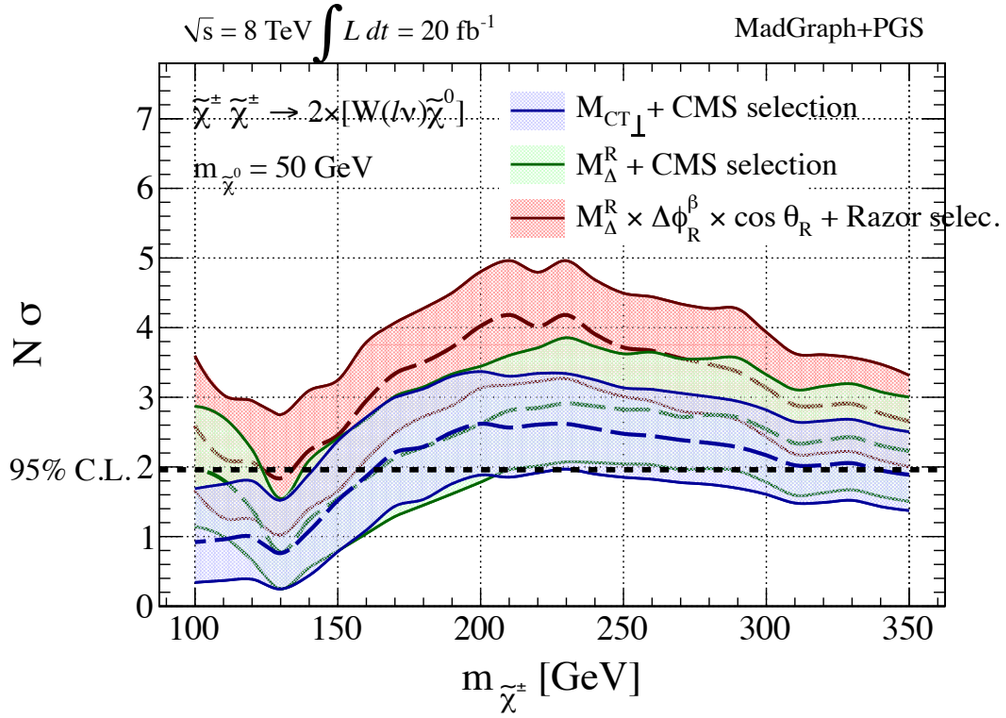
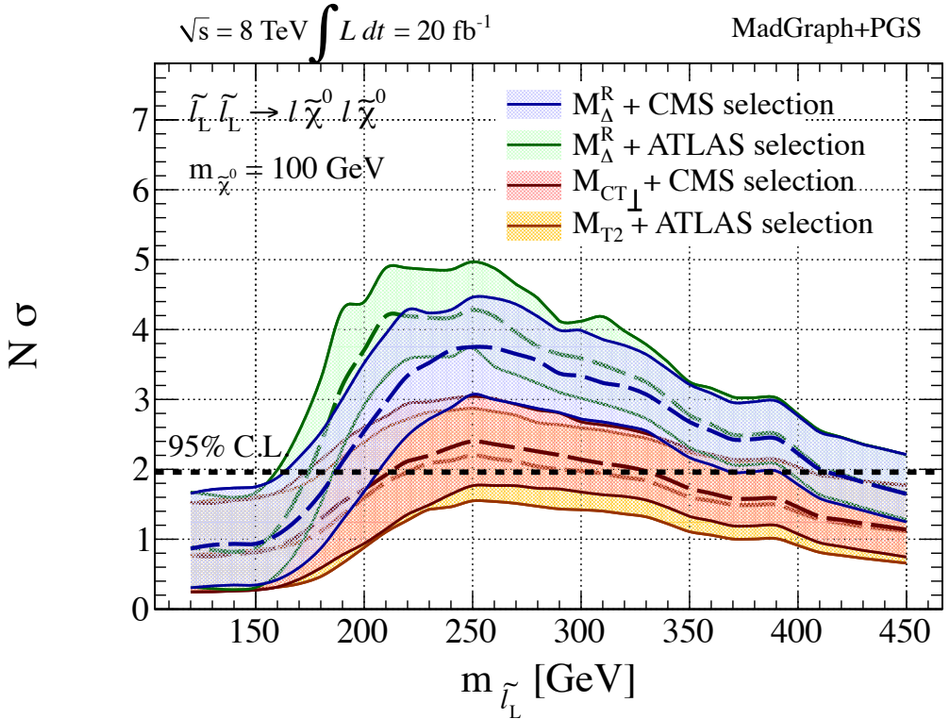
Expected Bounds

- Taking 1D slices of these exclusion regions:





- Clear improvement over existing techniques, for both high masses and degenerate spectra.

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Conclusions

- Interesting things can still lurk at the LHC
  - Even in the 8 TeV data!
  - Even supersymmetry!
  - These things might even be motivated by dark matter physics!

- Examples:
  - Sub-350(ish) GeV lepton partners for generalized bino-like thermal dark matter
  - Effective operator analysis of CoGeNT/CDMS-Si suggestive of new physics at LHC energies.
    - Non-colored states one of a limited set of options.

Conclusions

- How to look for such things?

- Constraints are weak because these channels are hard - large backgrounds, small signals, low MET
  - Need to get clever.
- Razor analysis: clever.
  - It’s a new hammer, so I’m going to go hit things with it. But it can’t be the only game in town.