The Current State of SUSY and Ways Forward

Matt Reece
Harvard University
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Part One: The Big Picture

Part Two: A Sampling of Details

The Basics

(Broken) supersymmetry pairs *bosons* with *fermions* such that their couplings are (approximately) related.

This is what we want to discover.

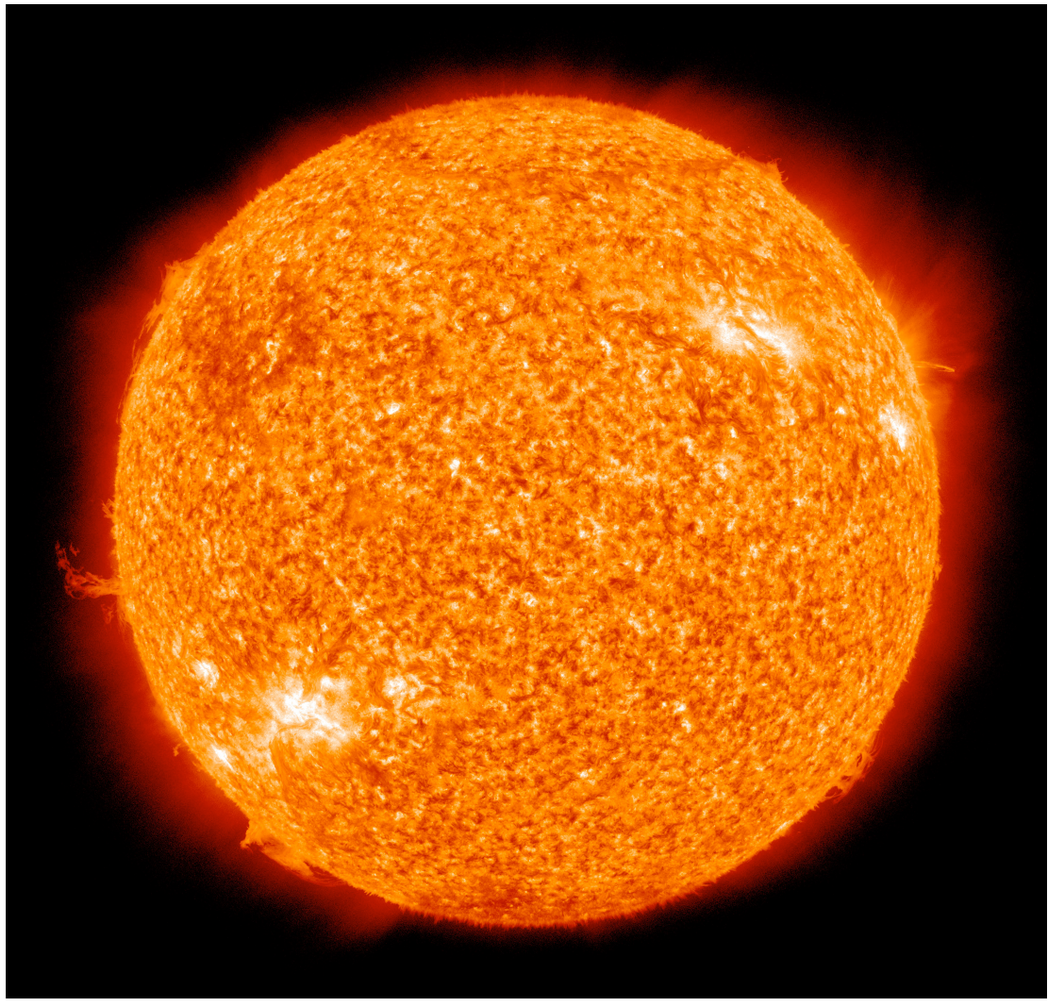
Why?

One of the rare known consistent possibilities for a **fundamental new spacetime symmetry of nature**.

Also, it may help to explain **the electroweak hierarchy.**

Hierarchies

$$M_{\rm Pl} \sim 2 \times 10^{18}\,{\rm GeV}$$



$$M_\odot \approx 2 \times 10^{30}\ {\rm kg}$$

$$\approx 1.1 \times 10^{57}\ {\rm GeV}$$

$$\approx 0.6 \left(\frac{M_{\rm Pl,unred}}{m_{\rm proton}} \right)^3 m_{\rm proton}$$

$$v_{\rm EW} \approx 246\,{\rm GeV}$$

$$\Lambda_{\rm QCD} \sim 300\,{\rm MeV}$$

[Details: V. Weisskopf, *Science* **187**(4177):605–612 (1975); Burrows and Ostriker, *PNAS* 111 (7):2409-2416 (2014).]

Hierarchies

$M_{\rm Pl} \sim 2 \times 10^{18}\,{\rm GeV}$

Flat measure on $\mathscr{L}$ parameters:

$P(\text{EW hierarchy}|\ \text{SM}) \sim \left(\frac{v_{\rm EW}}{M_{\rm Pl}}\right)^2$

$\sim 10^{-32}$

$v_{\rm EW} \approx 246\,{\rm GeV}$

$\Lambda_{\rm QCD} \sim 300\,{\rm MeV}$

Hierarchies

$M_{\rm Pl} \sim 2 \times 10^{18}\,{\rm GeV}$

Flat measure on $\mathscr{L}$ parameters:

$$P(\text{QCD hierarchy}|\ \text{SM}) \sim \frac{1}{\log(M_{\rm Pl}/\Lambda_{\rm QCD})}$$

$$\sim 10^{-2}$$

$v_{\rm EW} \approx 246\,{\rm GeV}$

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Hierarchies

$M_{\rm Pl} \sim 2 \times 10^{18}\,{\rm GeV}$

$P(\text{QCD hierarchy}|\ \text{SM}) \sim \dfrac{1}{\log(M_{\rm Pl}/\Lambda_{\rm QCD})}$

$\sim 10^{-2}$

The magic of running couplings:

$$\Lambda_{\rm QCD} \sim \Lambda_{\rm UV} e^{-8\pi^2/(bg^2)}$$

$v_{\rm EW} \approx 246\,{\rm GeV}$

$\Lambda_{\rm QCD} \sim 300\,{\rm MeV}$

The SUSY Paradigm

$M_{\rm Pl} \sim 2 \times 10^{18}\,{\rm GeV}$

Dynamical SUSY breaking

$$P(\text{EW hierarchy}|\ \text{SUSY}) \sim \frac{1}{\log(M_{\rm Pl}/M_{\rm SUSY})}$$

$$\sim 10^{-2}$$

$M_{\rm SUSY} \sim v_{\rm EW} \approx 246\,{\rm GeV}$

$\Lambda_{\rm QCD} \sim 300\,{\rm MeV}$

(Witten, 1981)

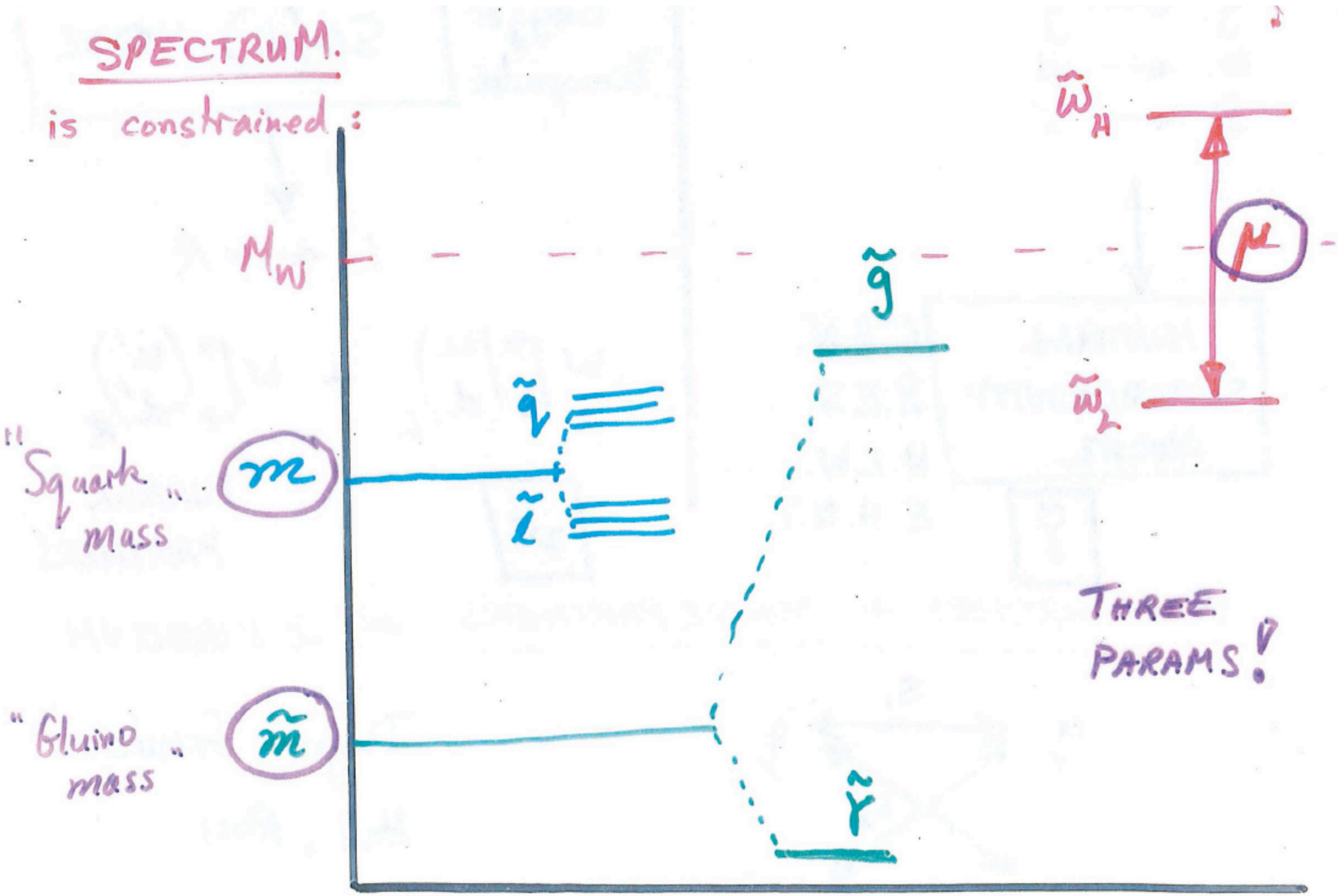
Naturalness as Bayesian Guesswork

$$P(\text{EW hierarchy}|\ \text{SM}) \sim \left(\frac{v_{\rm EW}}{M_{\rm Pl}}\right)^2 \sim 10^{-32}$$

$$P(\text{EW hierarchy}|\ \text{SUSY}) \sim \frac{1}{\log(M_{\rm Pl}/M_{\rm SUSY})} \sim 10^{-2}$$

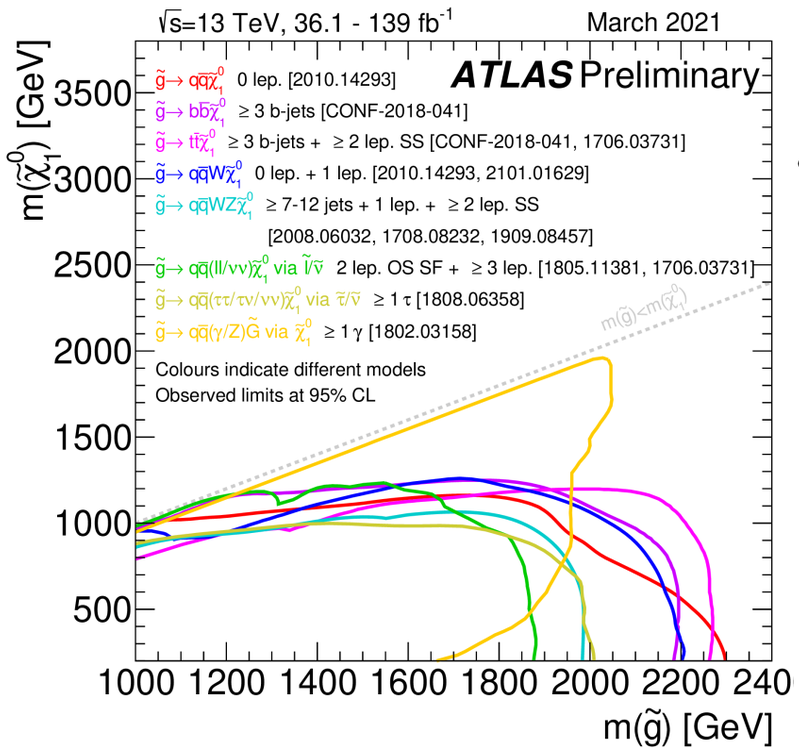
If you have no strong preconception about which theory is right, then the ***data*** that we live in a universe with a **vast hierarchy** suggests that we take ***weak-scale*** SUSY very seriously.

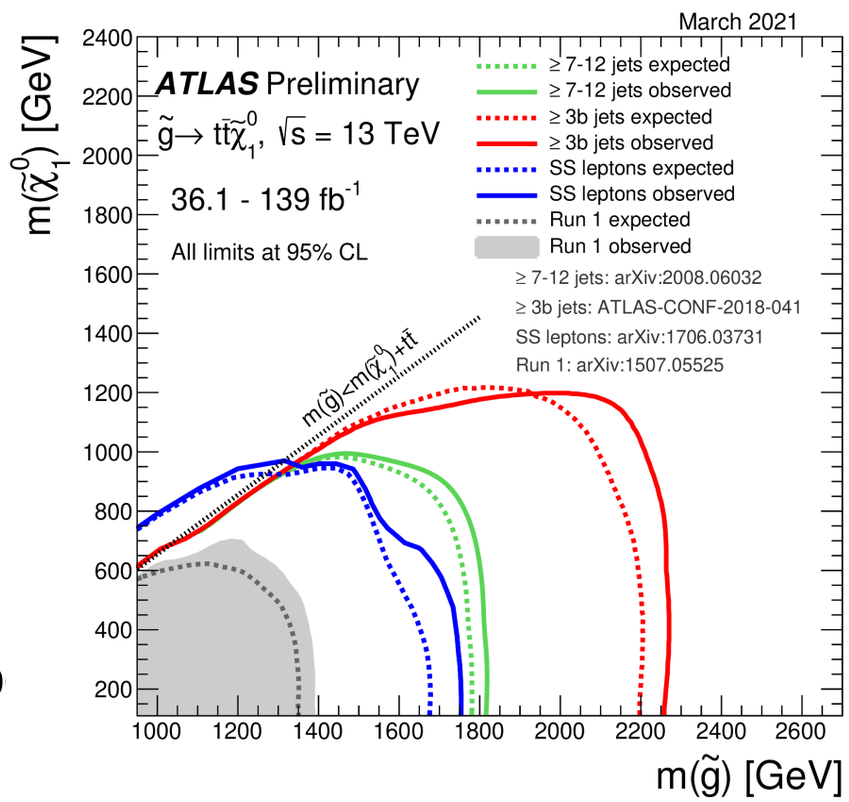
Weak-Scale SUSY: View from 1984

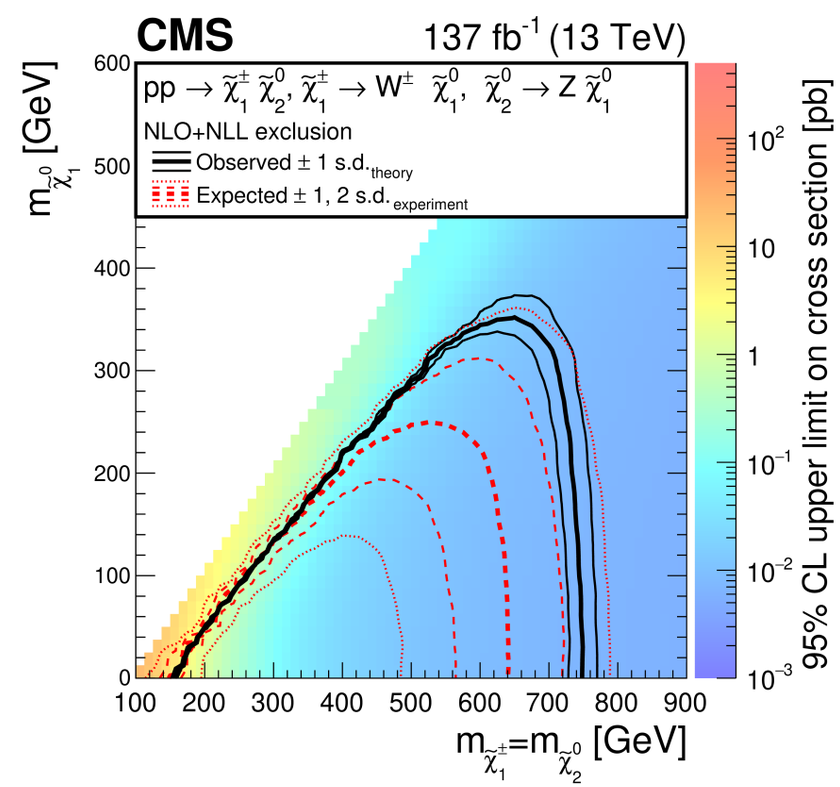


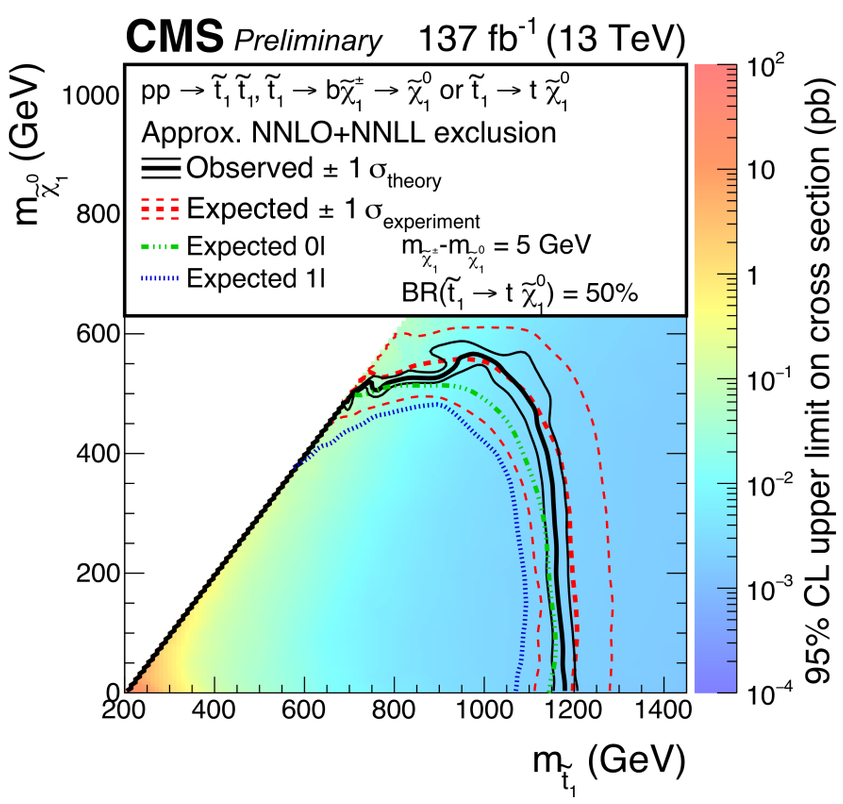
(1984 slide, resurfaced in Lawrence Hall's talk at Savasfest, 2012).

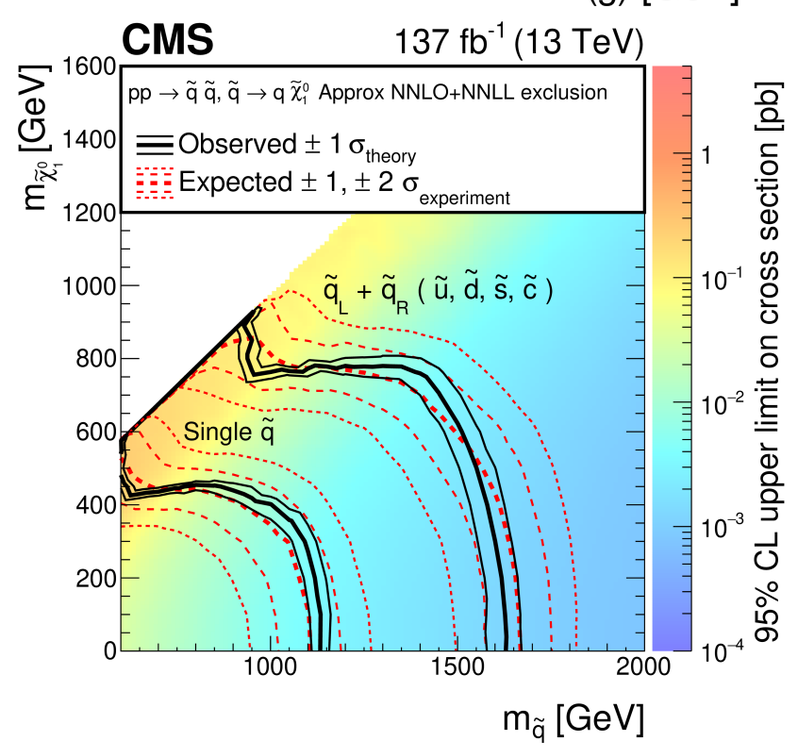
The View from 2021

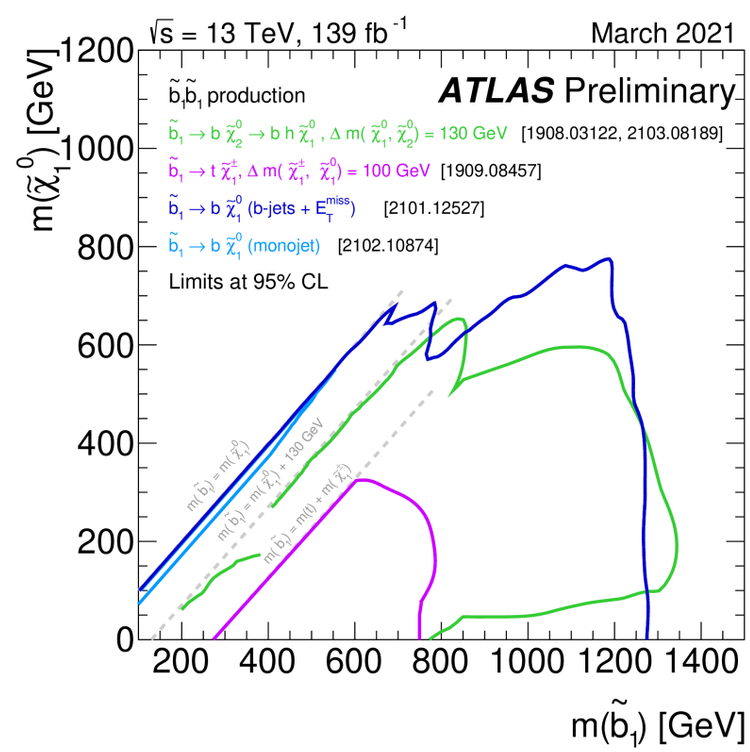






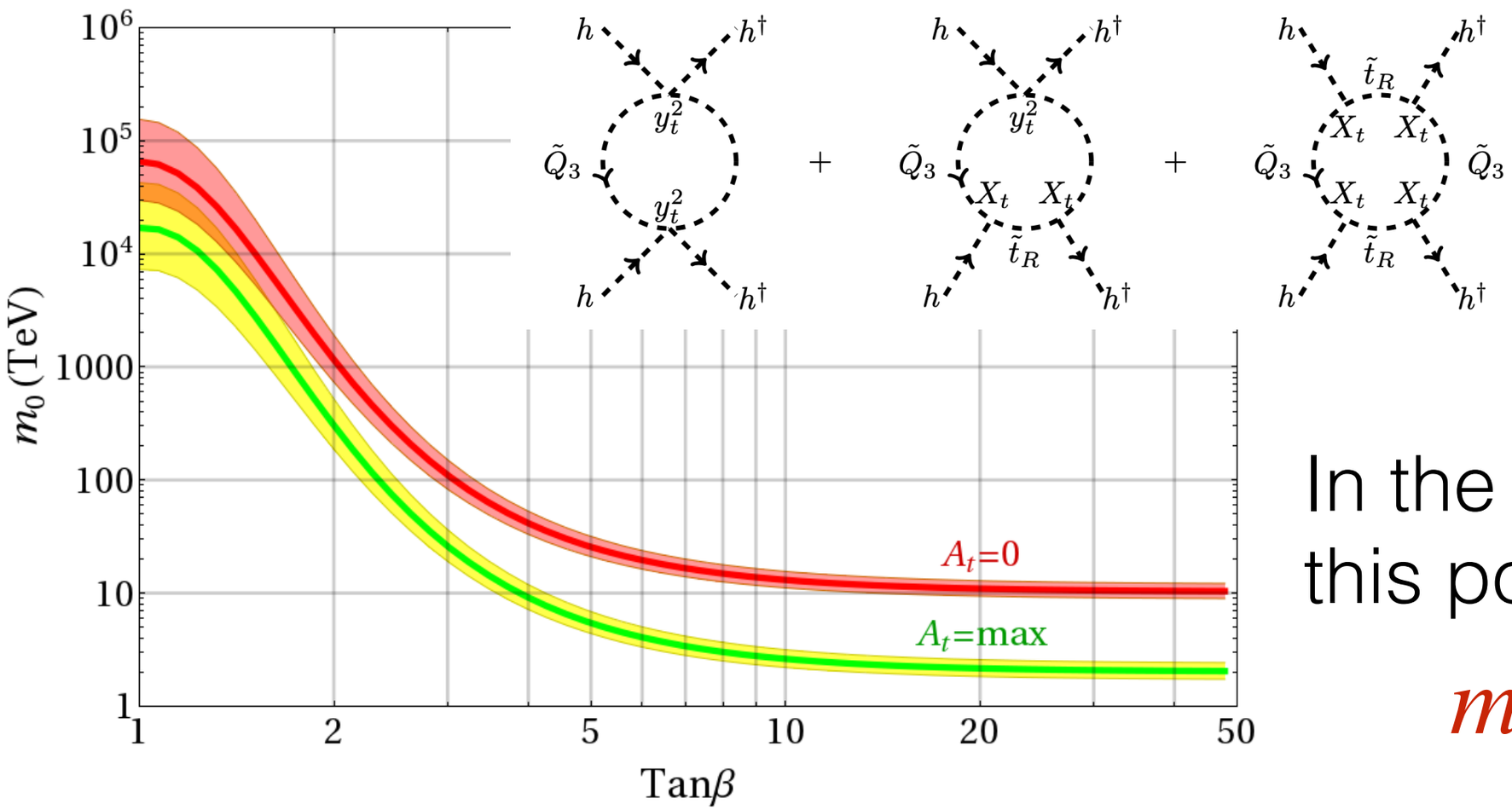






The Importance of 125 GeV

Perhaps more important than any direct search is the measured value of the Higgs boson mass.



Arvanitaki, Craig, Dimopoulos, Villadoro
1210.0555

In the simplest models, this points to

$$m_{\tilde{t}} \gtrsim 10\,\mathrm{TeV}$$

"Mini-Split" SUSY!

Still Guessing

$M_{\rm Pl} \sim 2 \times 10^{18}\,{\rm GeV}$

$M_{\rm SUSY} \sim 10\,{\rm TeV}$

$v_{\rm EW} \approx 246\,{\rm GeV}$

$\Lambda_{\rm QCD} \sim 300\,{\rm MeV}$

The cost of 125 GeV?

$P(\text{EW hierarchy}|\ \text{Mini-Split})$

$$\sim \frac{1}{\log(M_{\rm Pl}/M_{\rm SUSY})}\left(\frac{v_{\rm EW}}{M_{\rm SUSY}}\right)^2$$

$$\sim 10^{-6}$$

Paths Forward

Constraints from Data

Simple, somewhat tuned
e.g., “Mini-Split SUSY”

Complicate model to hide signals
e.g., Stealth SUSY, variants of neutral naturalness

Qualitatively new paradigm
e.g., cosmological dynamics, UV/IR connections

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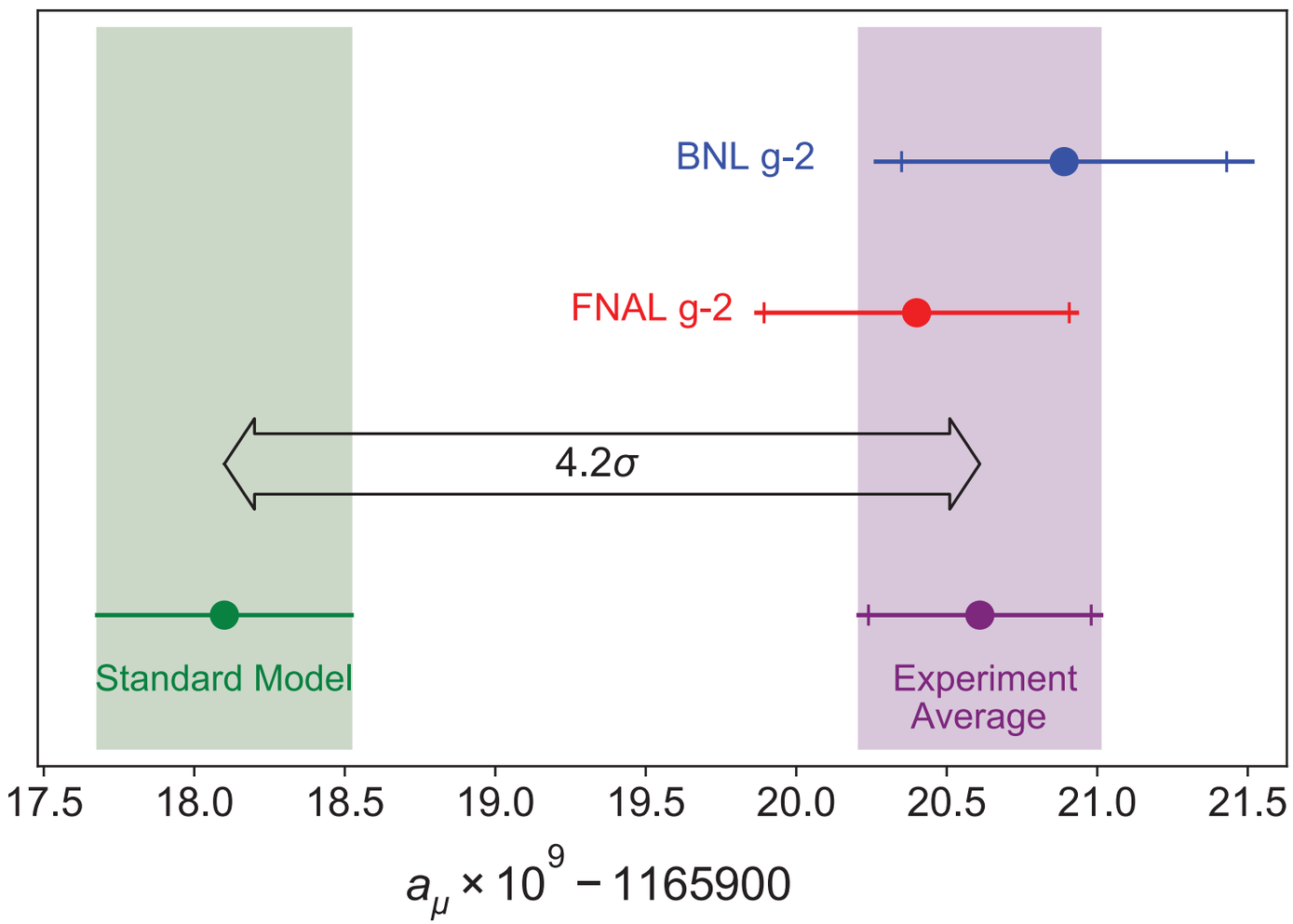
The Electroweak Target

Electroweak SUSY is a good target for LHC Run 3!

Importance highlighted by muon $g-2$.

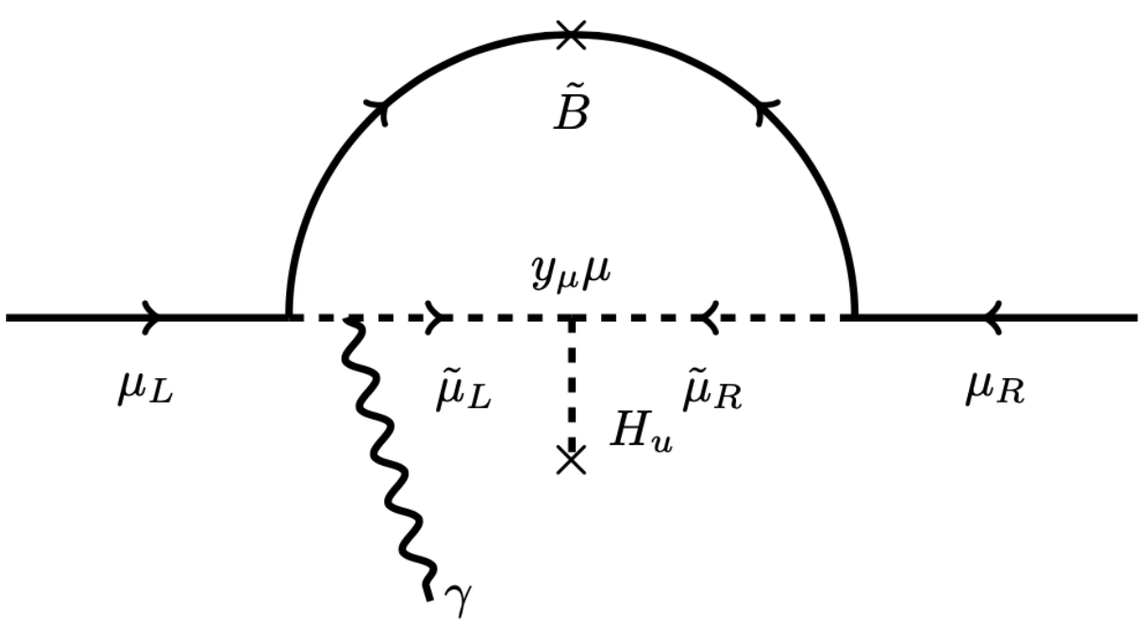


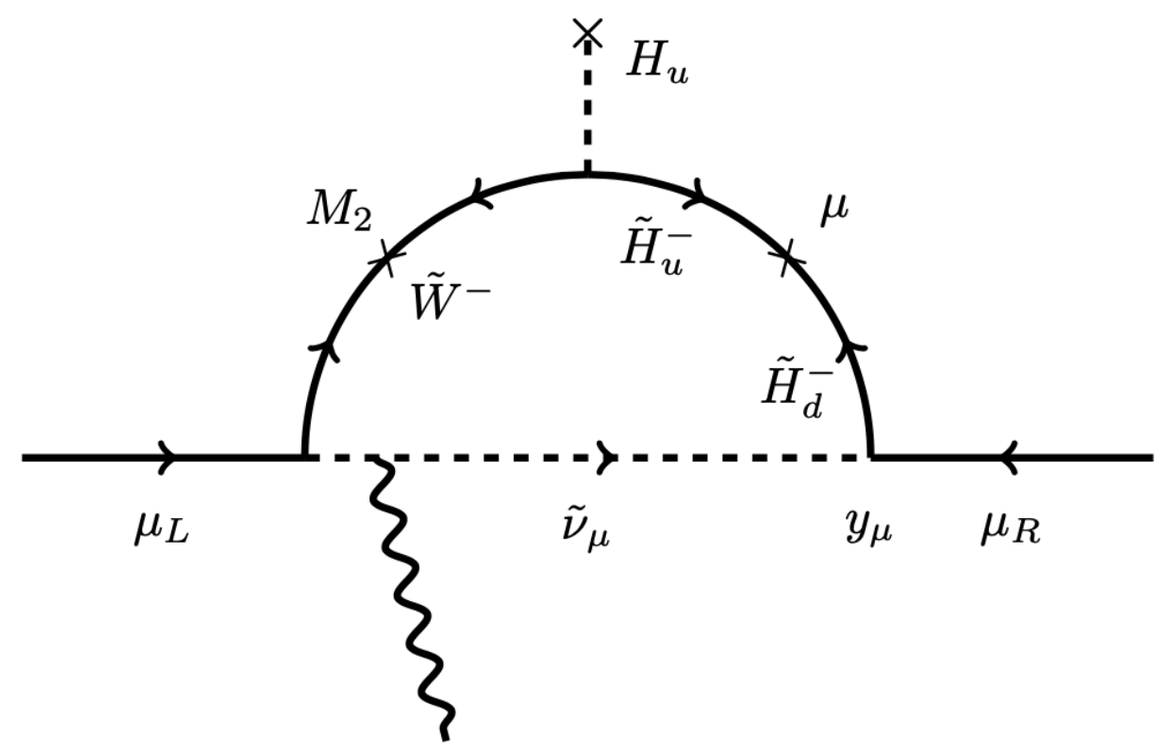
Muon $g-2$ and SUSY

Basic dimensional analysis: new physics around weak scale!

$$\Delta a_\mu \sim \left(\frac{g^2}{8\pi^2}\right)\left(\frac{m_\mu}{M_{\rm BSM}}\right)^2 \sim 2.5\times 10^{-9} \Rightarrow M_{\rm BSM} \sim 150\ {\rm GeV}$$

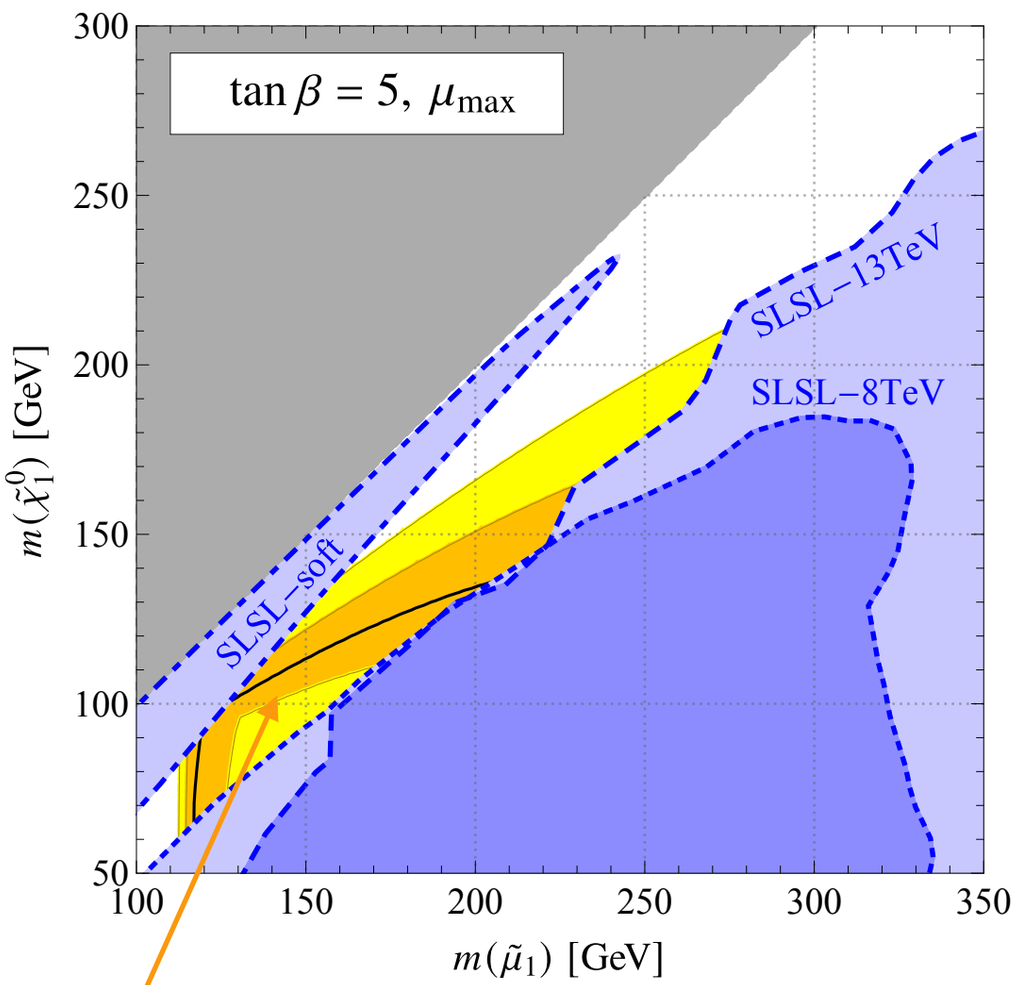
e.g., from smuon/bino or sneutrino/chargino loops:





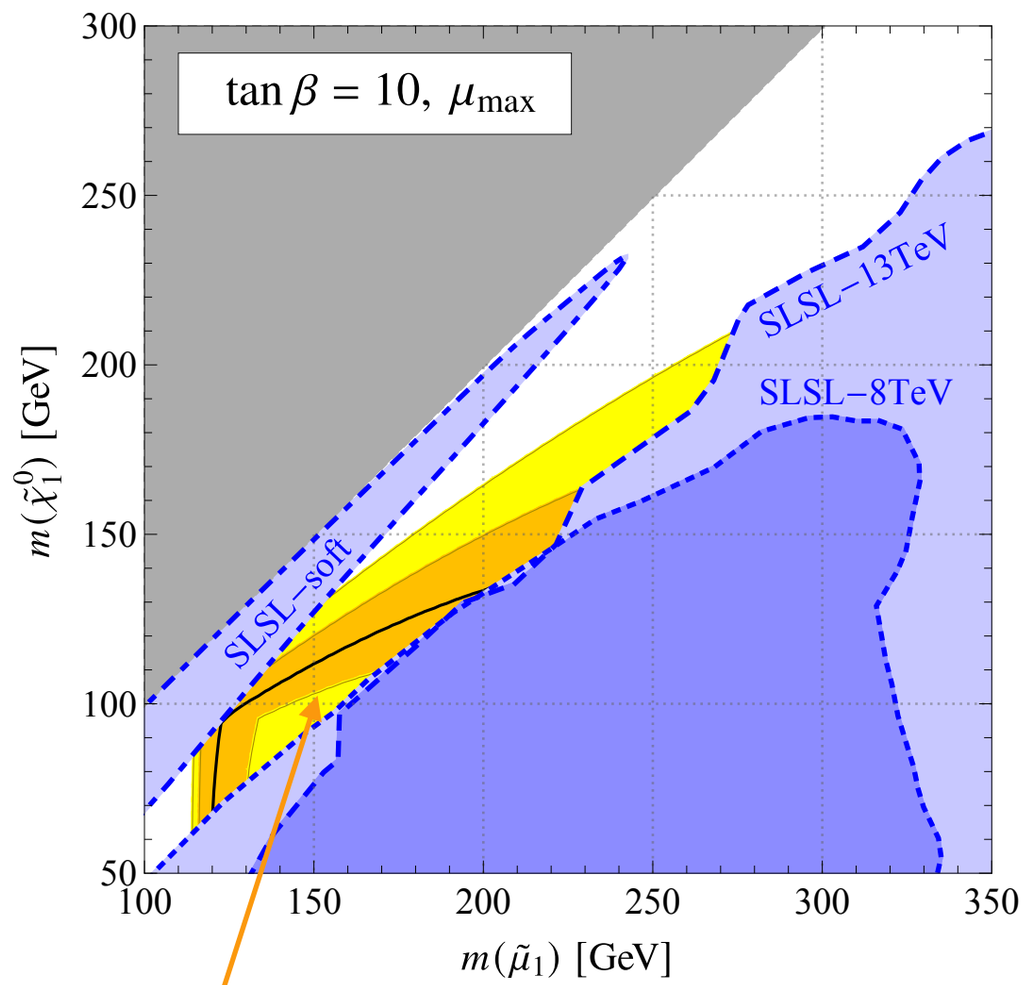
Example: bino dominated loop $\propto \frac{\alpha_Y}{4\pi} \frac{m_\mu^2 M_1 \mu}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2} \tan\beta$

smuons, bino



g-2

(A) $\tan\beta = 5$

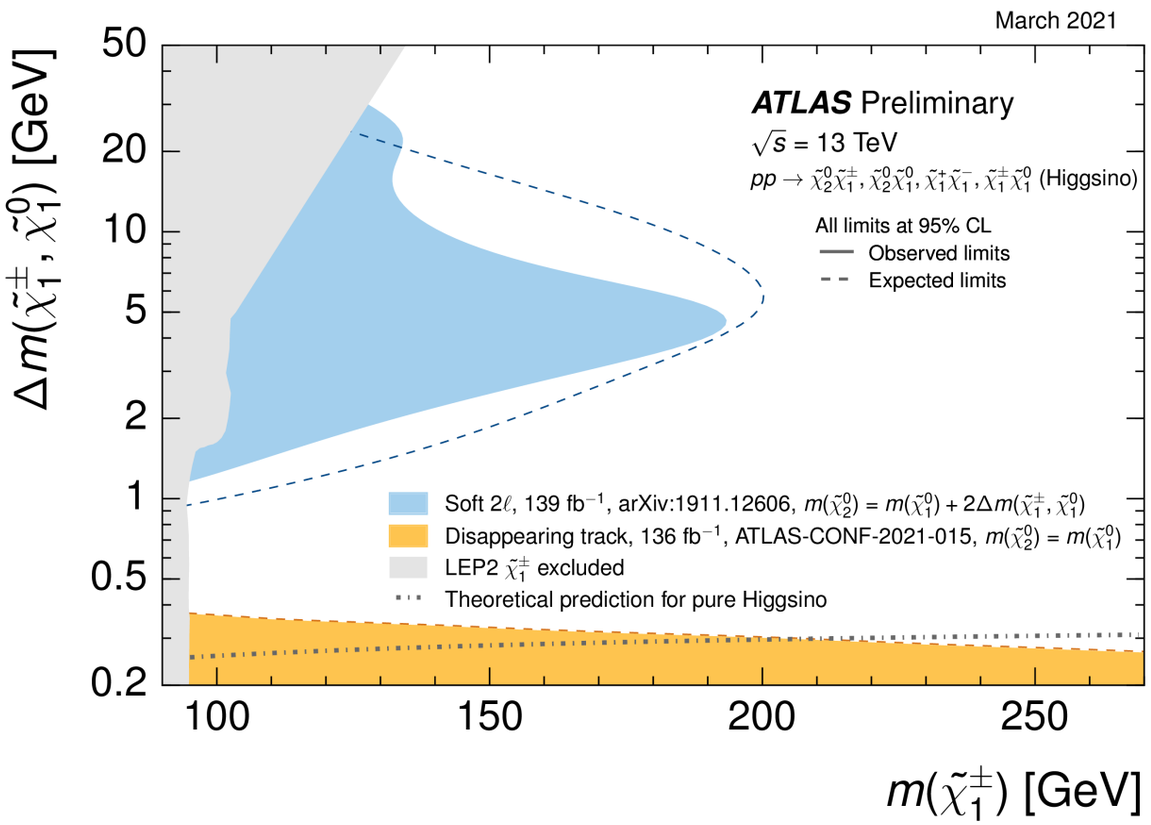


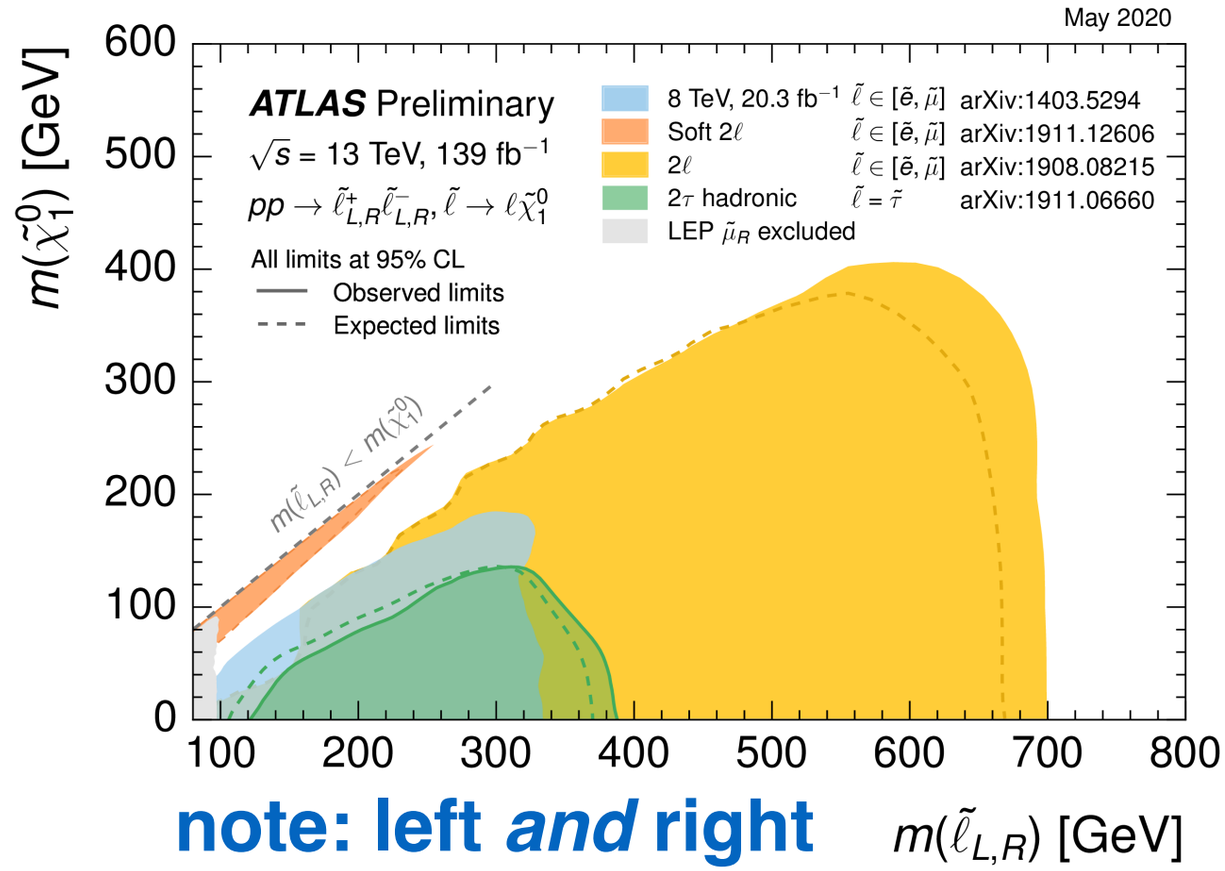
g-2

(B) $\tan\beta = 10$

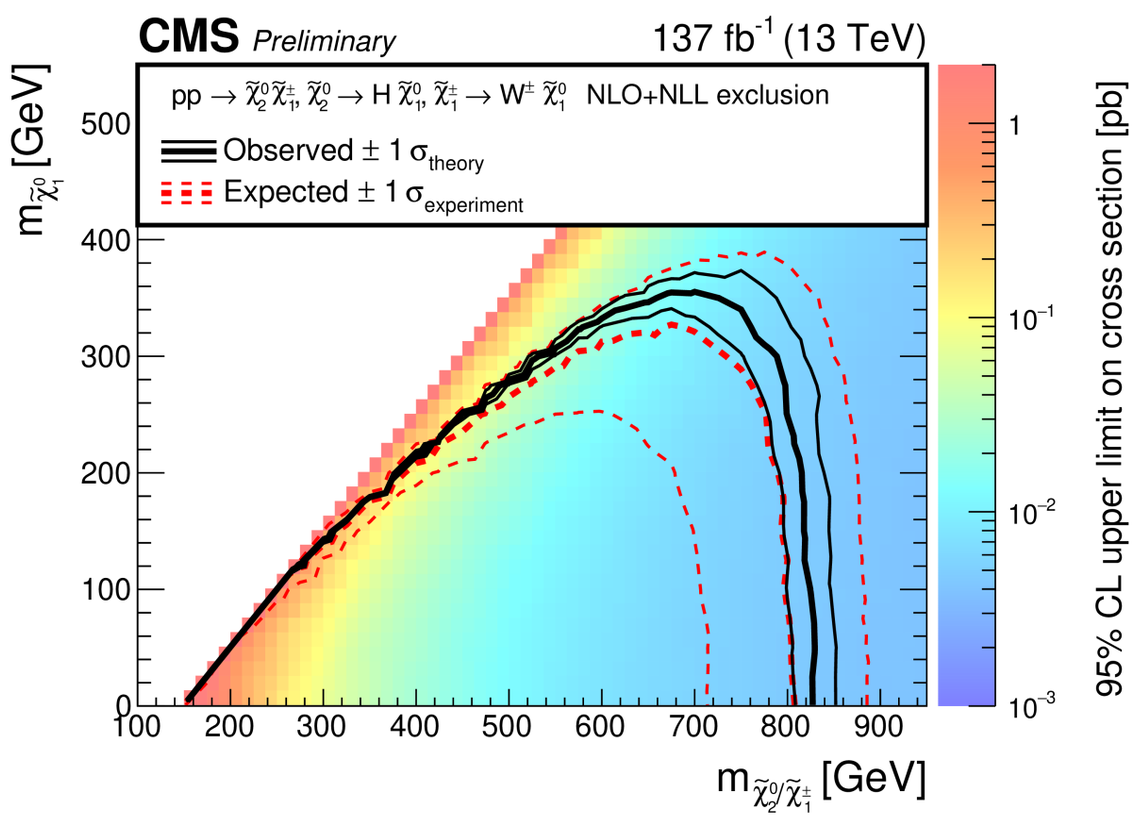
Endo, Hamaguchi, Iwamoto, Kitahara 2104.03217

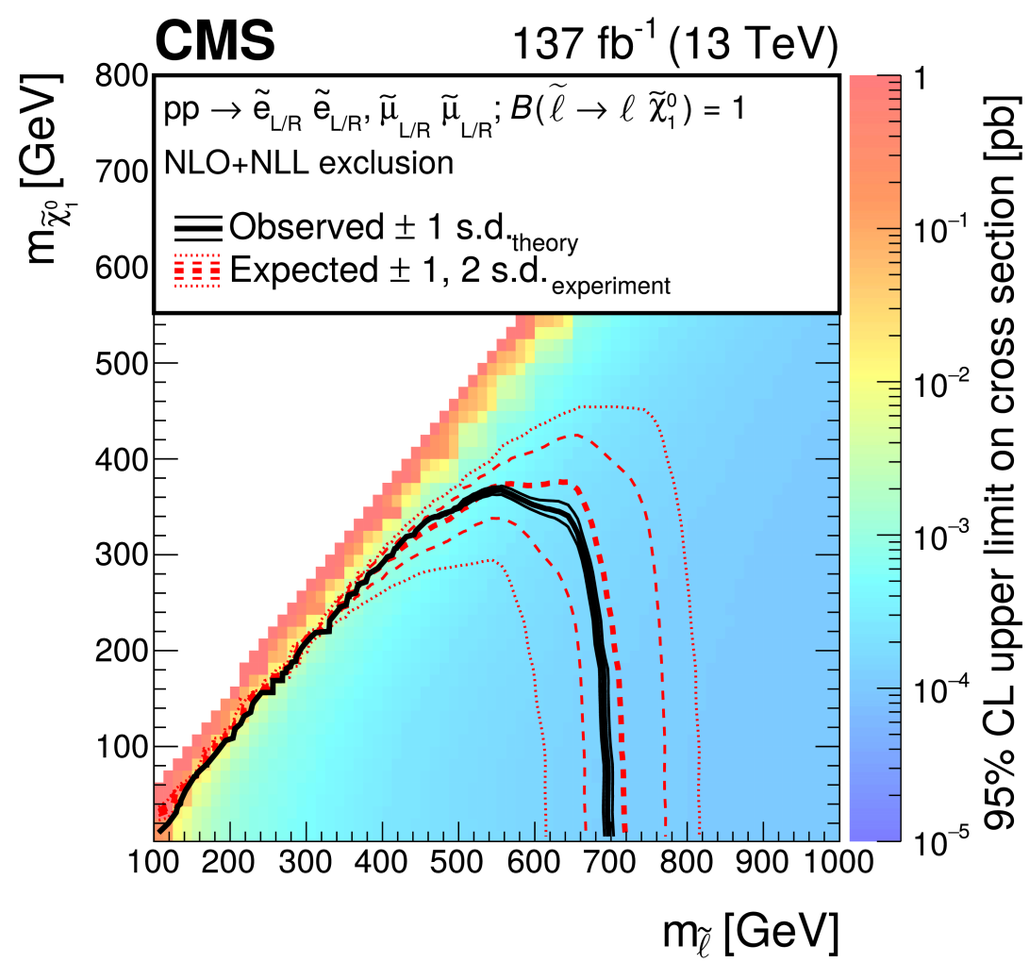
Mind the Gaps



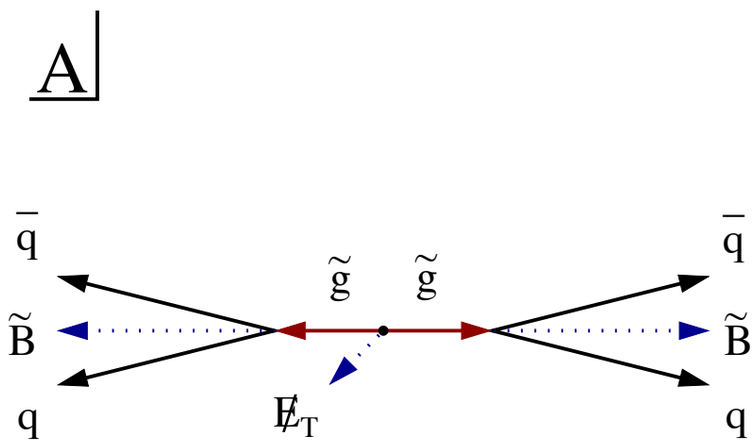


note: left *and* right

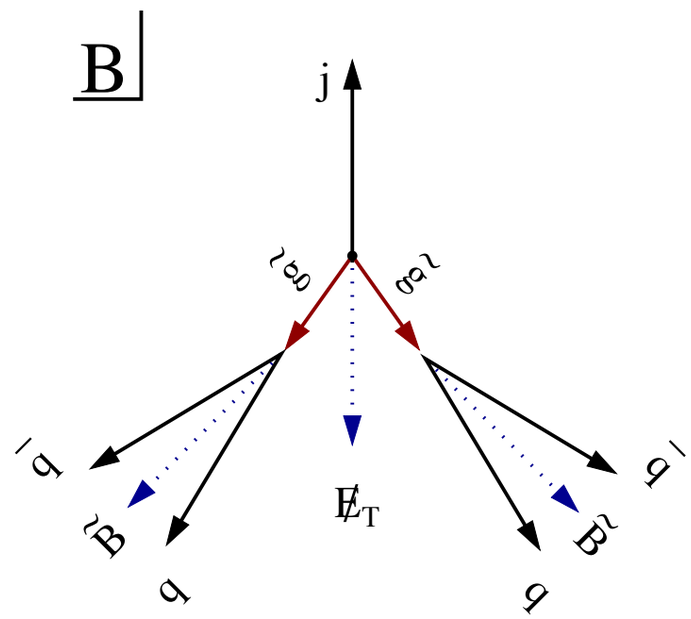




Squeezing the Signals

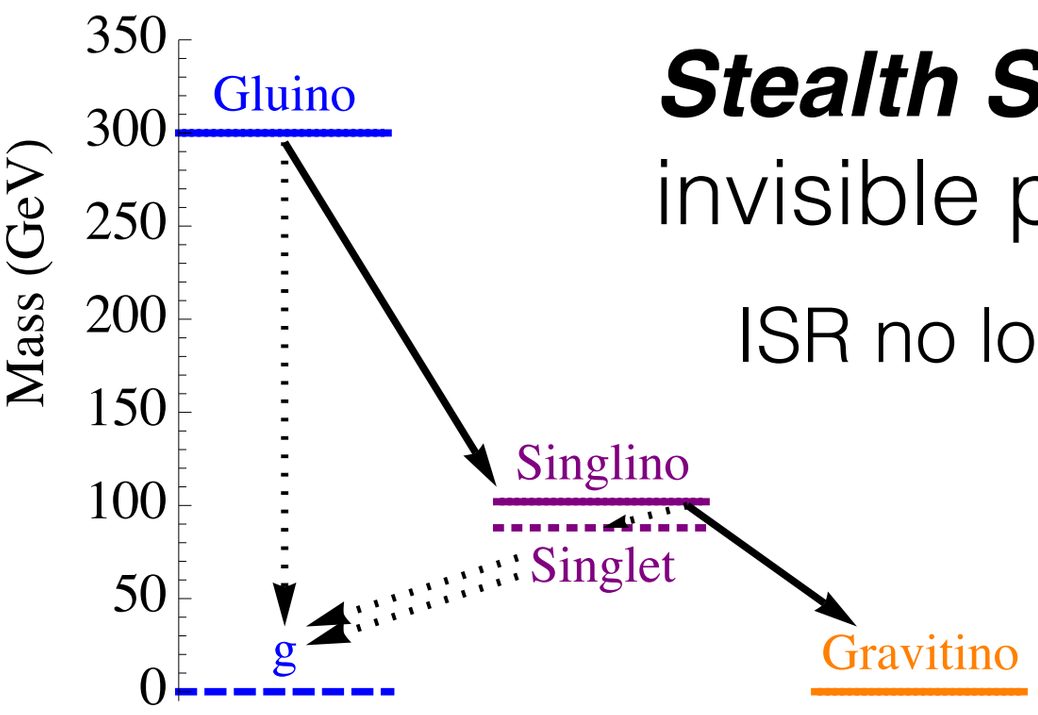


heavy invisible particle



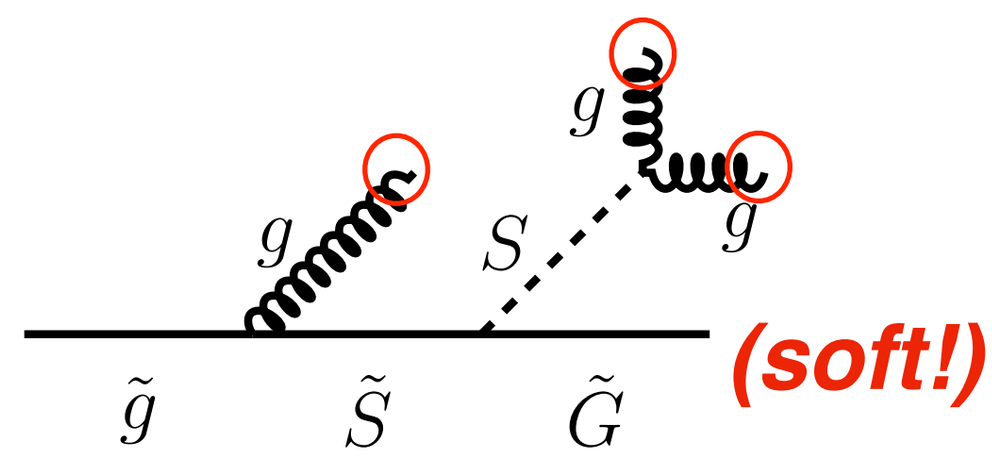
Compressed SUSY: softer visible particles from smaller mass differences

Missing momentum if ISR recoil ("monojet"-like): Alwall, Le, Lisanti, Wacker 0803.0019



Stealth SUSY: light invisible particle

ISR no longer helps

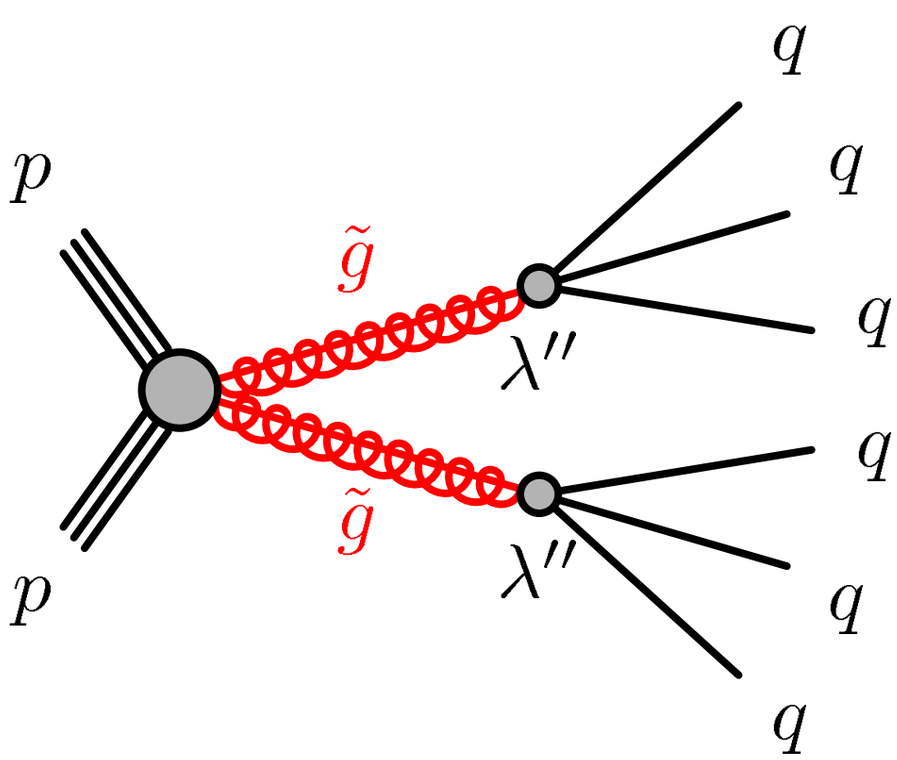


Fan, Reece, Ruderman 1105.5135

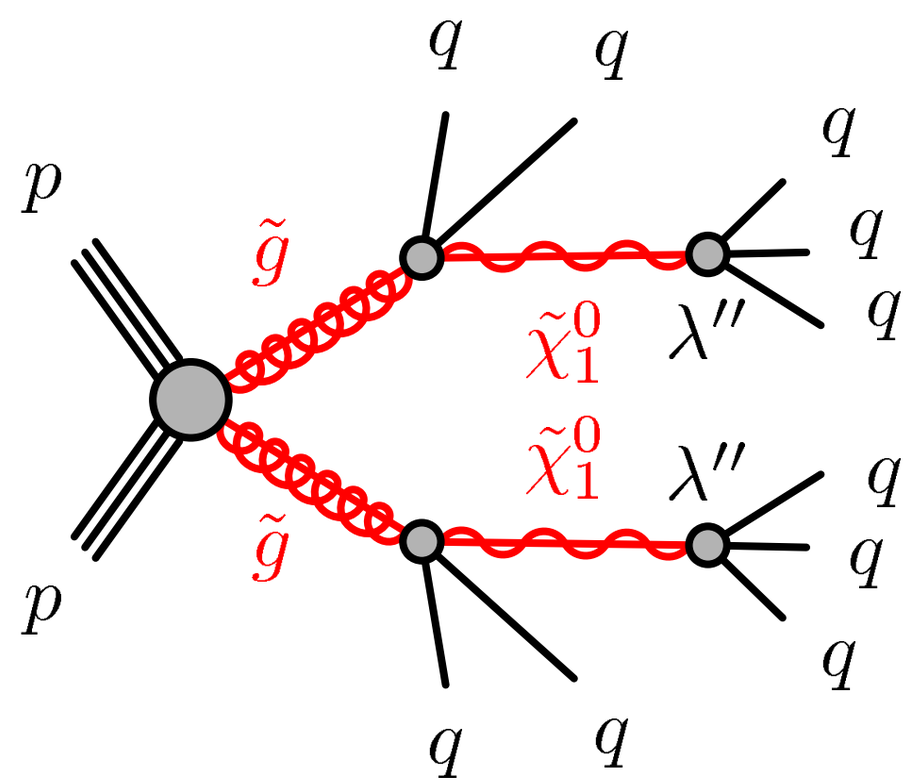
R-Parity or Not?

Motivated by proton stability, but neither necessary nor sufficient to solve that problem.

Trilinear RPV terms: **QLD, LLE, UDD**
UDD only: compatible with Minimal Flavor Violation (Csaki, Grossman, Heidenreich ’11)

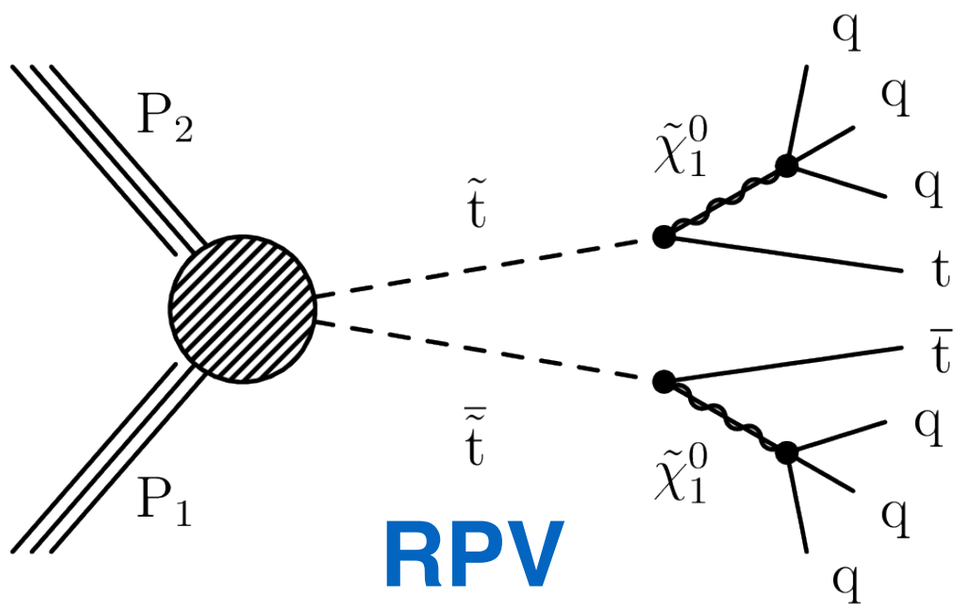


(a) 6-quark model

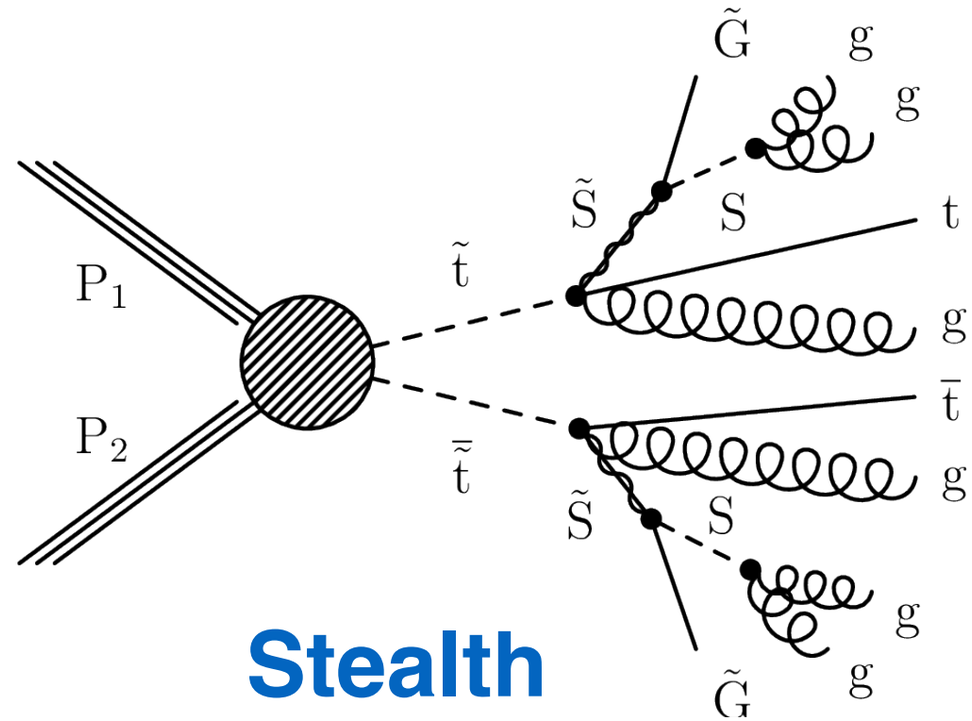


(b) 10-quark model

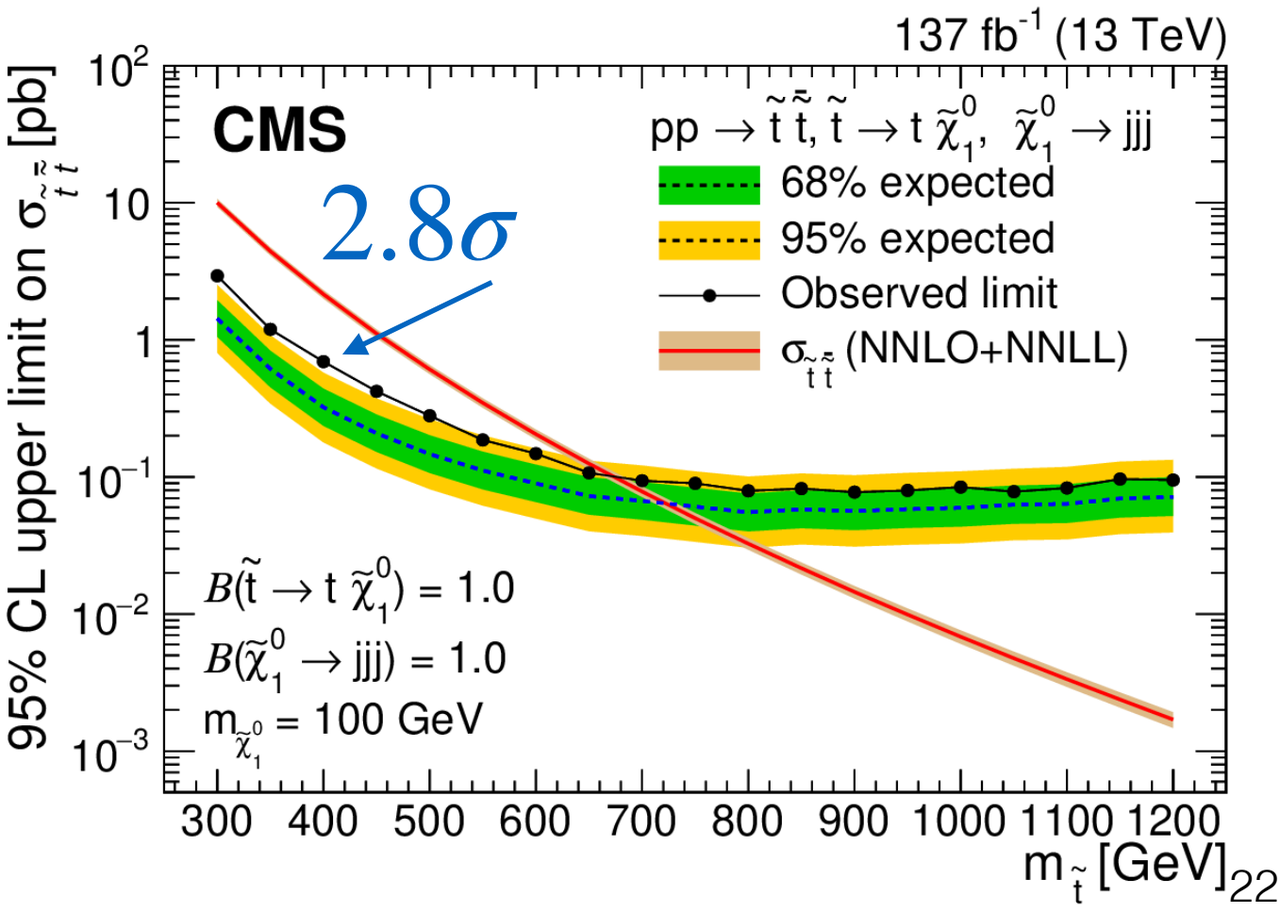
CMS RPV/Stealth Stop Search

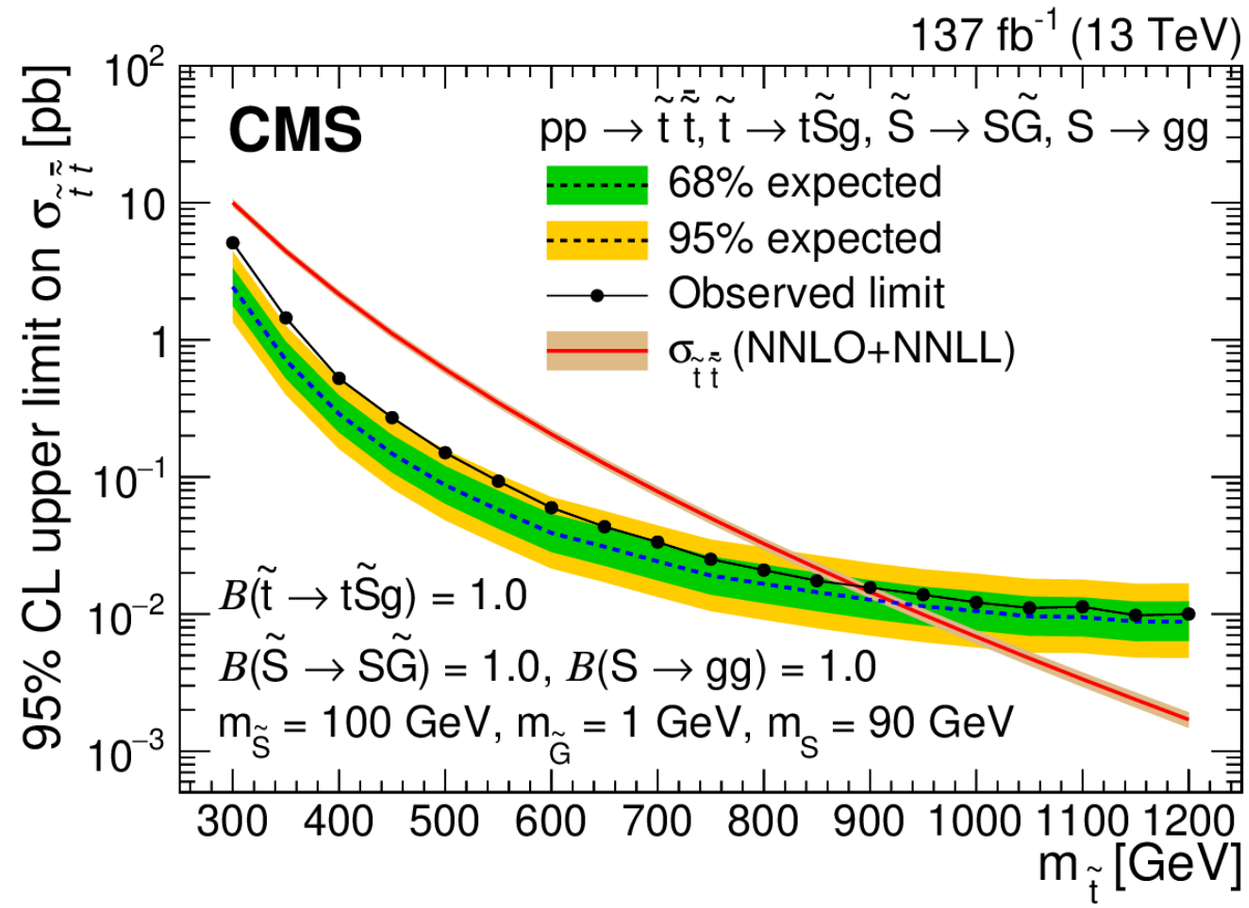


RPV



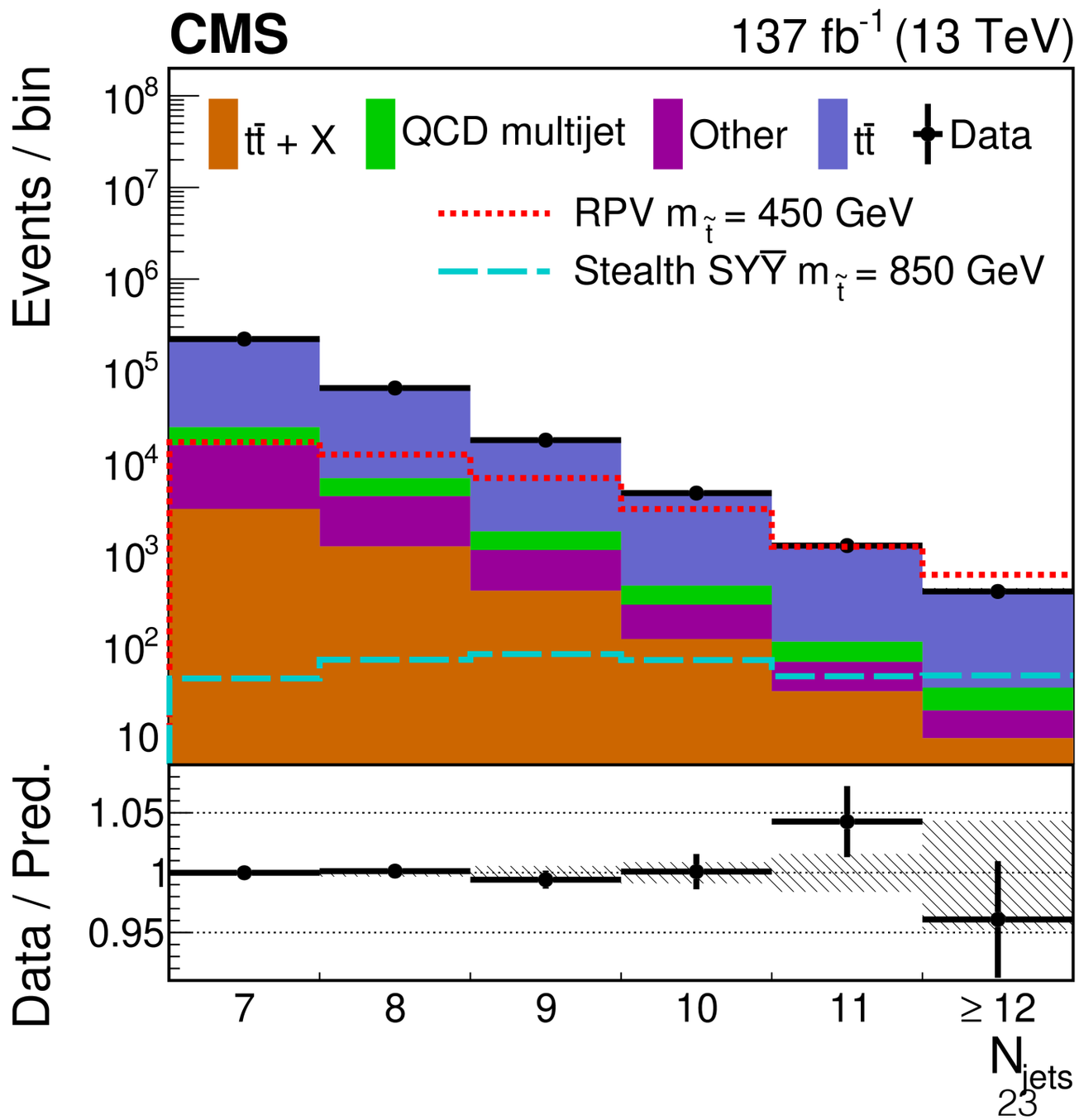
Stealth

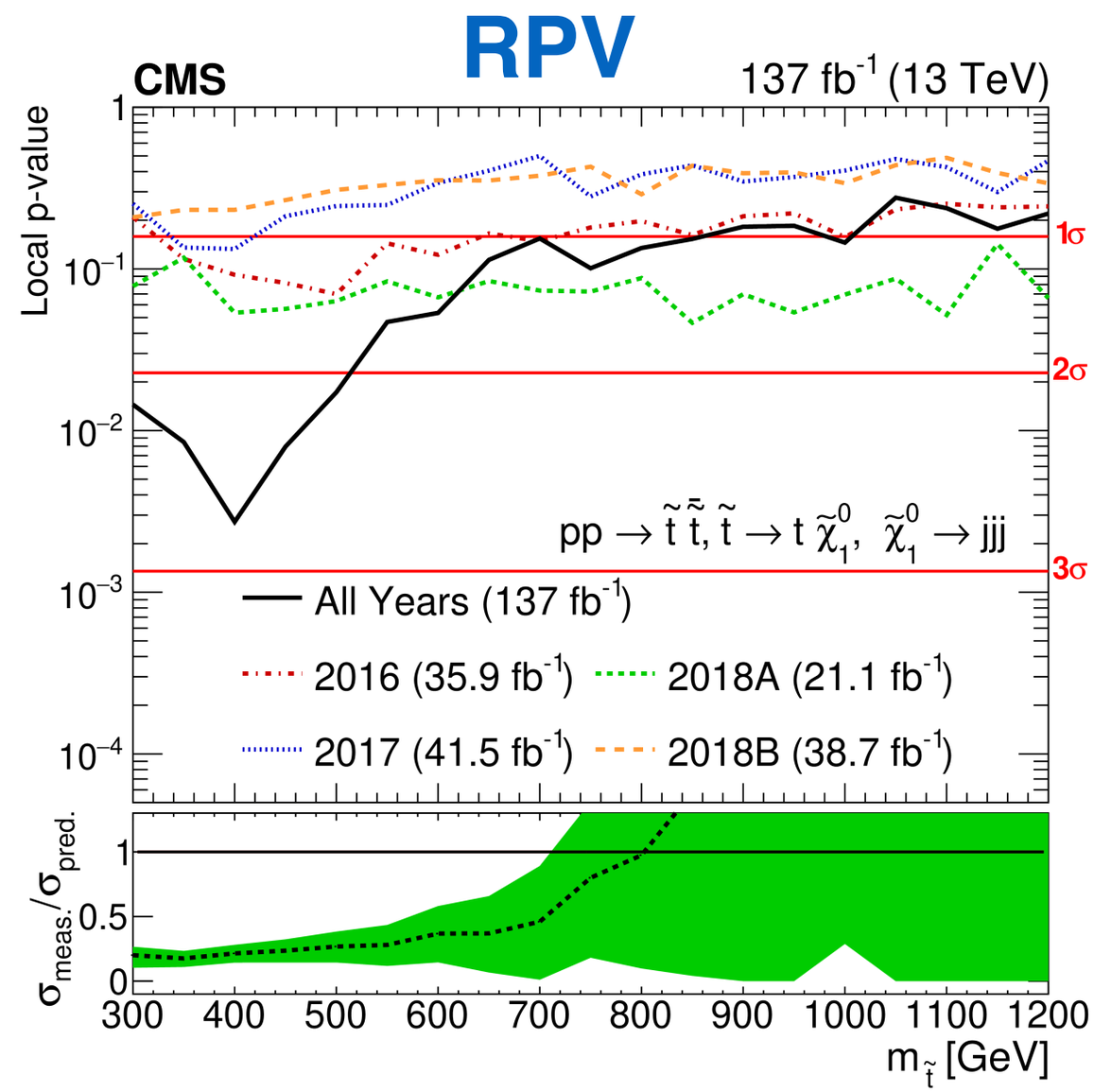




CMS RPV/Stealth Stop Search

Looked at many-jet events

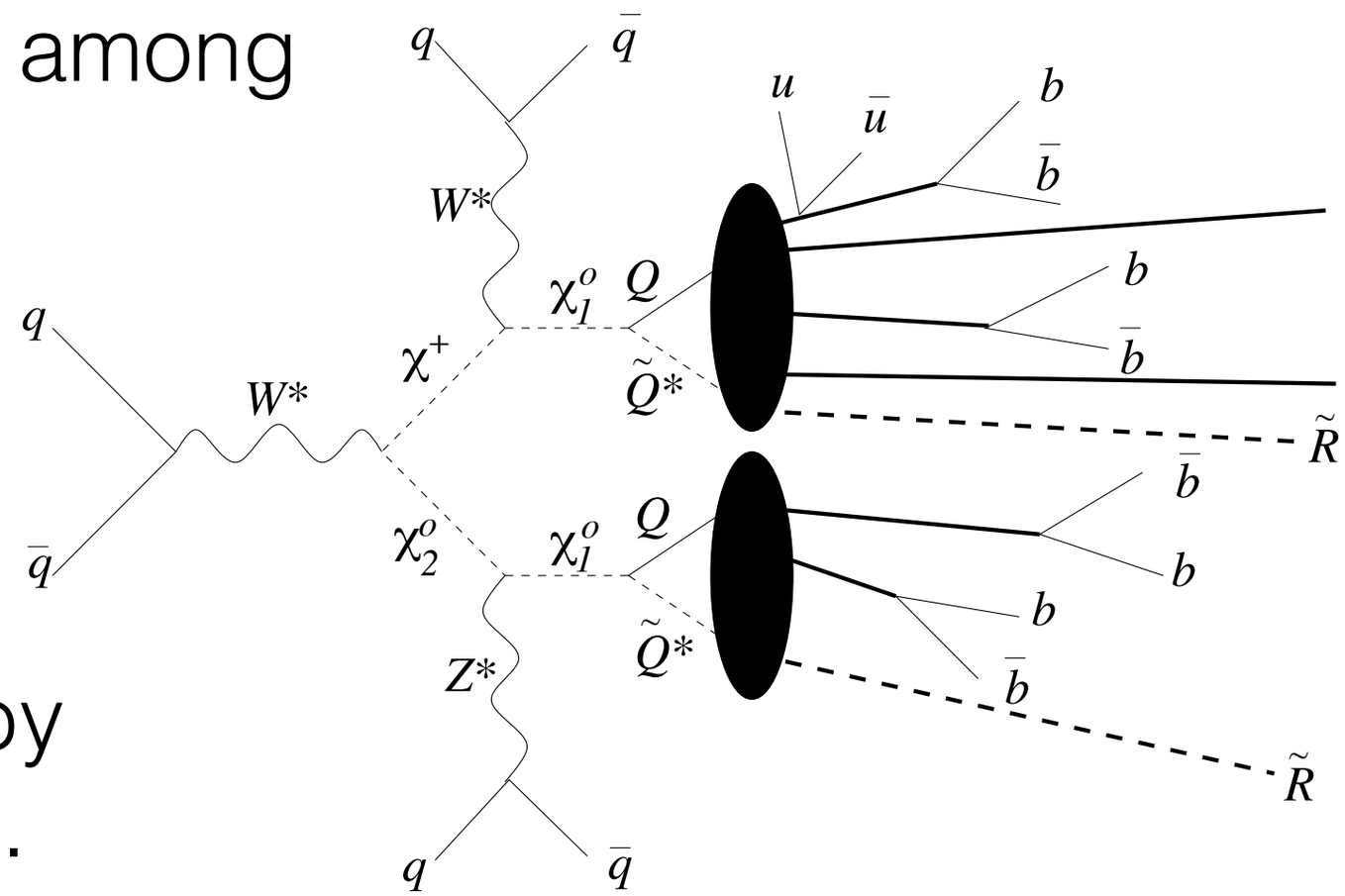




Don’t Assume the MSSM

Example:
“**Hidden Valley**” (Strassler/ Zurek): divide energy among many particles

figure from M. Strassler, hep-ph/0607160



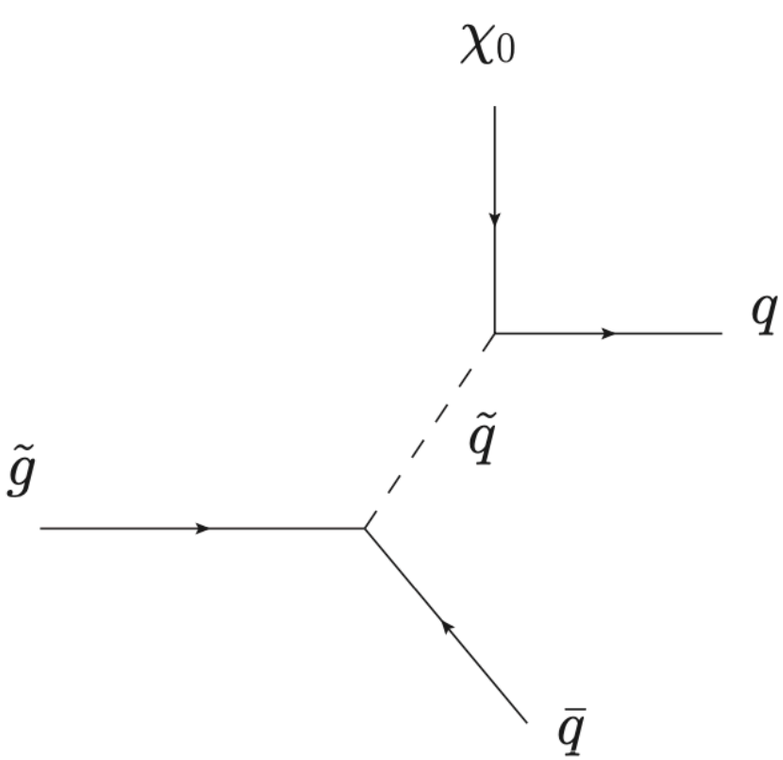
Roughly divide MET by #(final state particles). See also lepton jets, etc.

Novel observables might help: see C. Cesarotti talk yesterday on ***event isotropy***

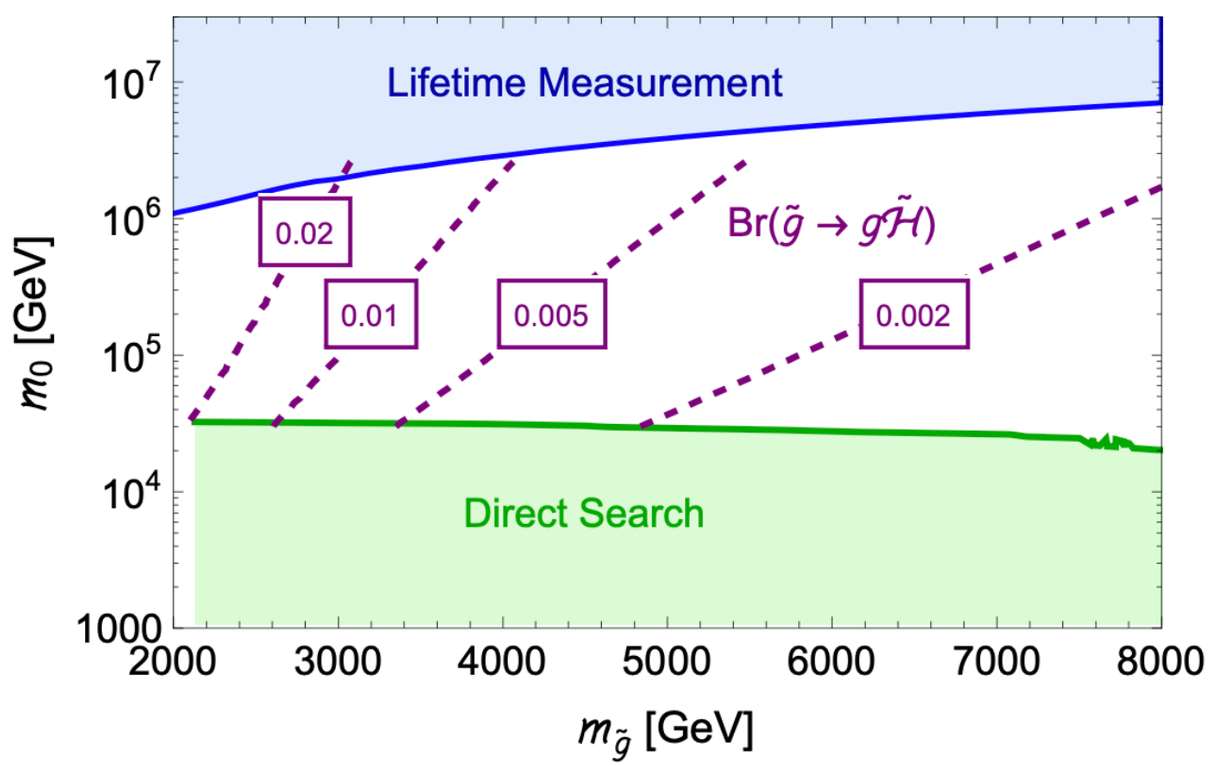
Don’t Assume Promptness

SUSY events can have ***mildly displaced*** decays, e.g., hundred micron ~ millimeters. Predicted for gluinos in “Mini-Split” or “Simply Unnatural” scenario.

$$c\tau \approx 10^{-5}\mathrm{m}\left(\frac{m_{\tilde{q}}}{\mathrm{PeV}}\right)^4\left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5 .$$



Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski ’12

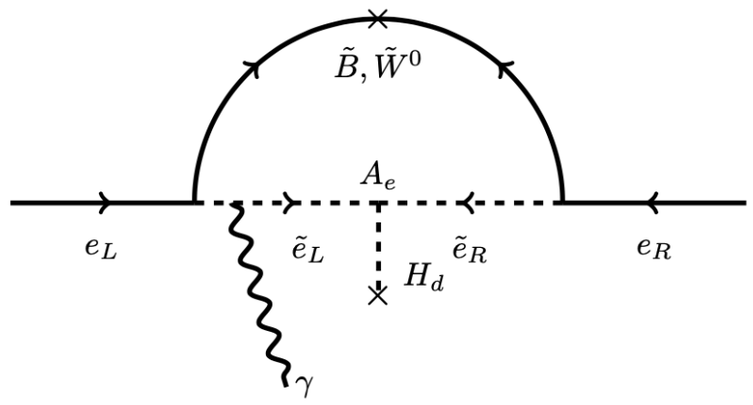


Agrawal, Fan, MR, Xue, ’17

Could CP and Flavor Lead the Way?

EDM, 1-loop

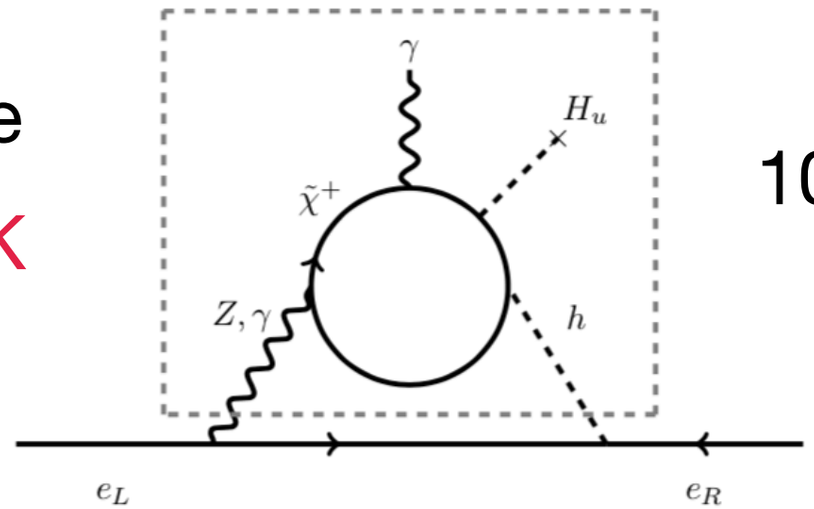
electron-flavored



10^{-32} *e* cm $\Longrightarrow$ ~ **1 PeV (!)**

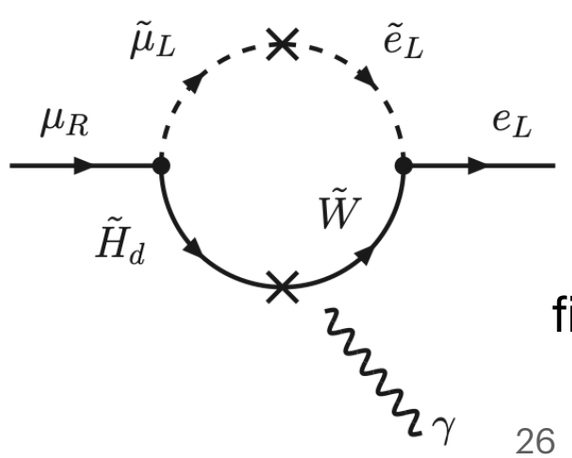
EDM, 2-loop Barr-Zee

Anything Higgs+EWK



10^{-32} *e* cm $\Longrightarrow$ ~ **50 TeV (!)**

μ→*e*, 1-loop,
flavor violating



10^{-19} on Al $\Longrightarrow$ ~ **50+ TeV (!)**

fig. from 1308.3653: Altmannshofer, Harnik, Zupan

(w/ electron Yukawa spurions on all diagrams)

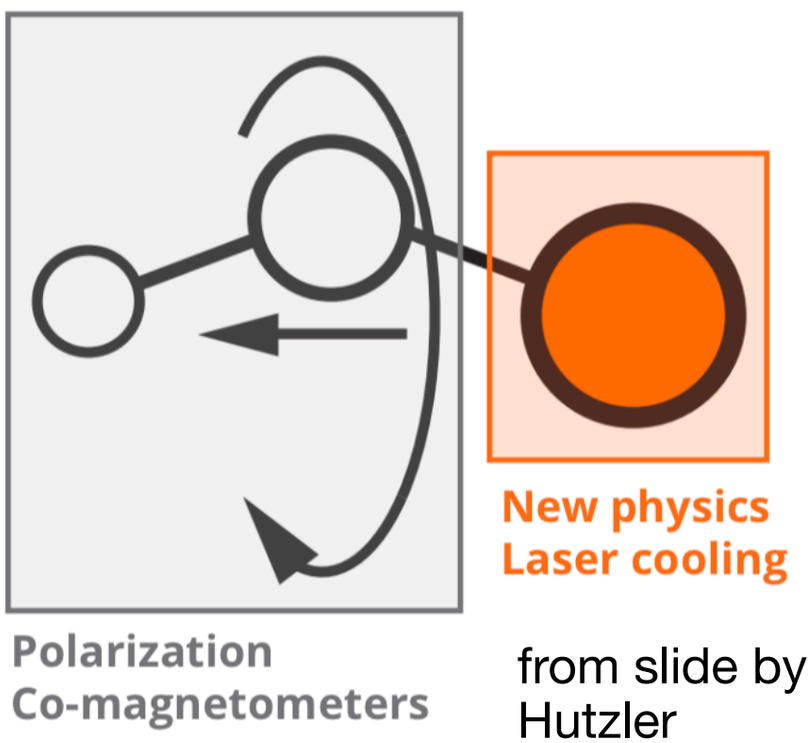
Concluding Remarks

- SUSY remains a compelling bet to solve the “big” hierarchy
- Electroweak signals (low rates) or many-jet signals (high backgrounds) need more attention
- Don’t assume leptons + missing p_T is “easy”; low cross sections need more work! **Test g-2**.
- Be careful not to miss mildly displaced vertices! **Test Higgs mass origin**.
- SUSY can have many guises. RPV, Stealth, Hidden Valleys; SUSY can mimic a wide range of signals. **Search broadly!**

EDM Precision on the Horizon

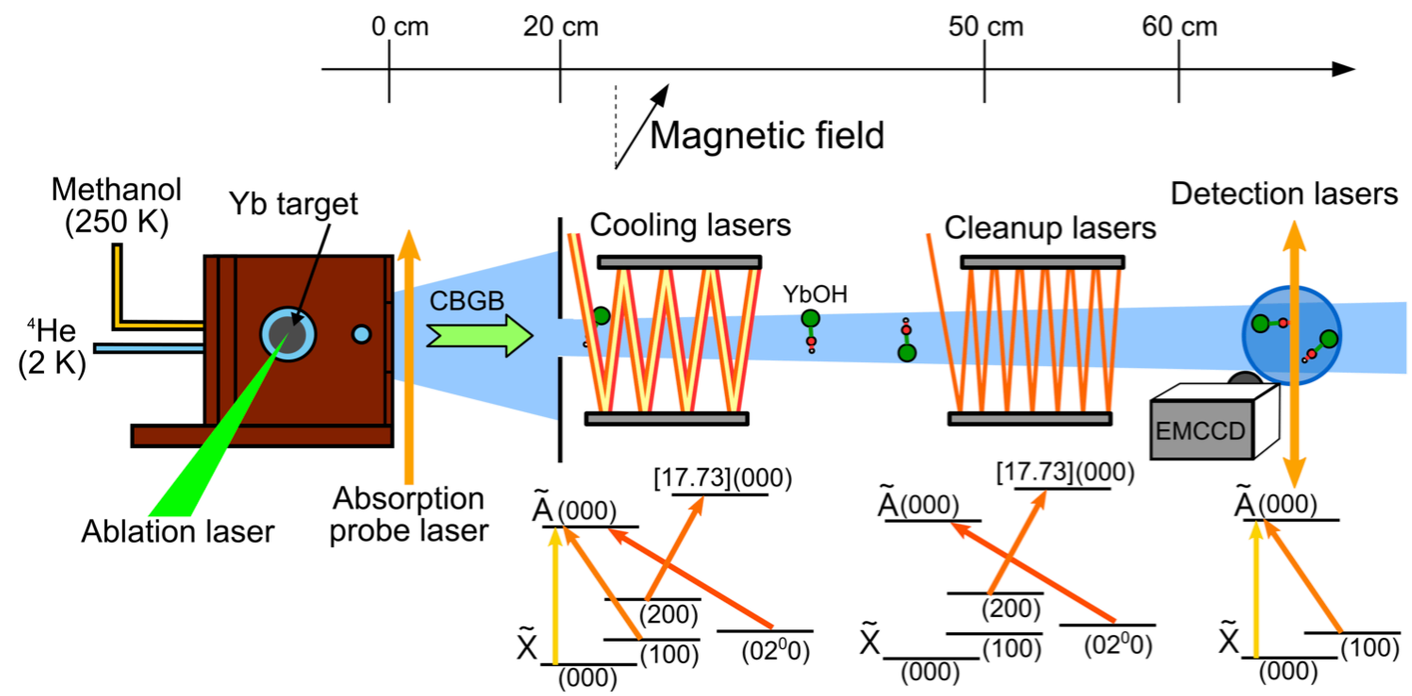
One of several parallel approaches:

Polyatomic Molecules
(e.g., YbOH)



from slide by N. Hutzler

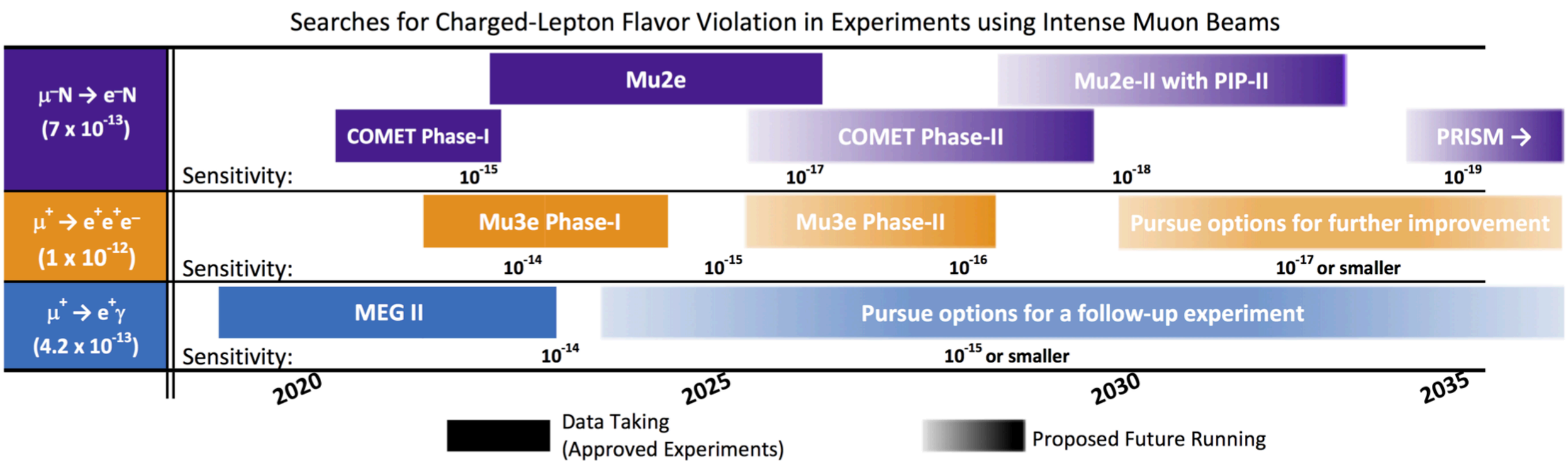
Hutzler, Kozyryev 1705.11020



Laser cooling achieved
(Augenbraun et al., 1910.11318)

Electron EDM: $10^{-29} e\,\mathrm{cm} \longrightarrow 10^{-32} e\,\mathrm{cm}$ **!**

Charged Lepton Flavor Violation



Source: Baldini et al., 1812.06540, submission to 2020 European Strategy from COMET, MEG, Mu2e and Mu3e collaborations