SUSY scenarios we’re not looking for* but should be

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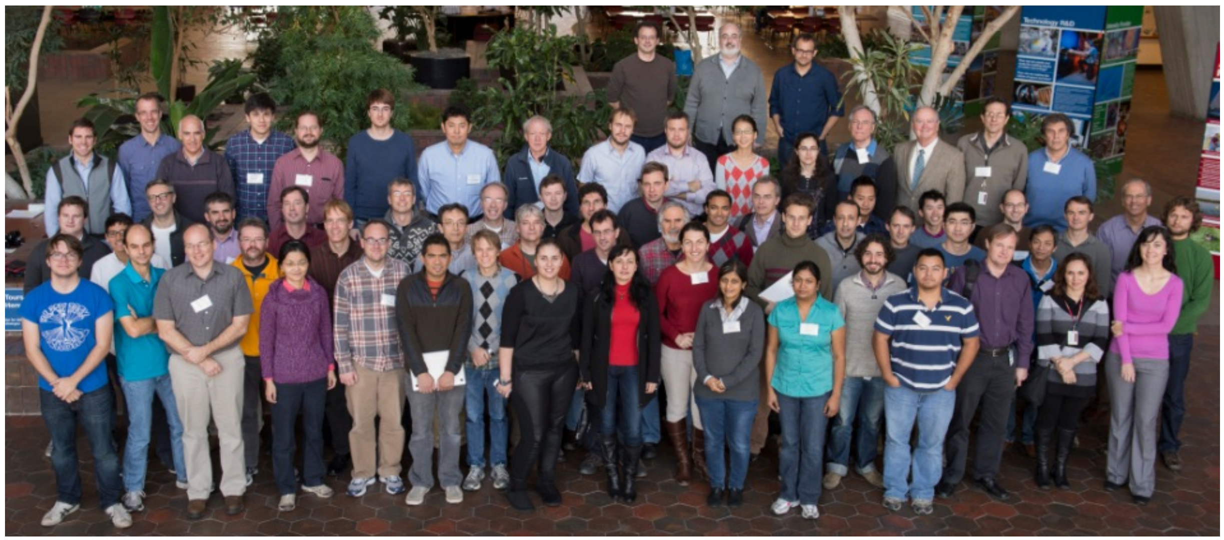
SUSY at the Near Energy Frontier



11-13 November 2013
Fermi National Accelerator Laboratory

Disclaimer

Many important “loopholes” are covered in existing or planned searches

- RPV
- Reduced MET

  compressed spectra, “stealth” SUSY,...
- Long decay chains
- NLSP → gravitino + X

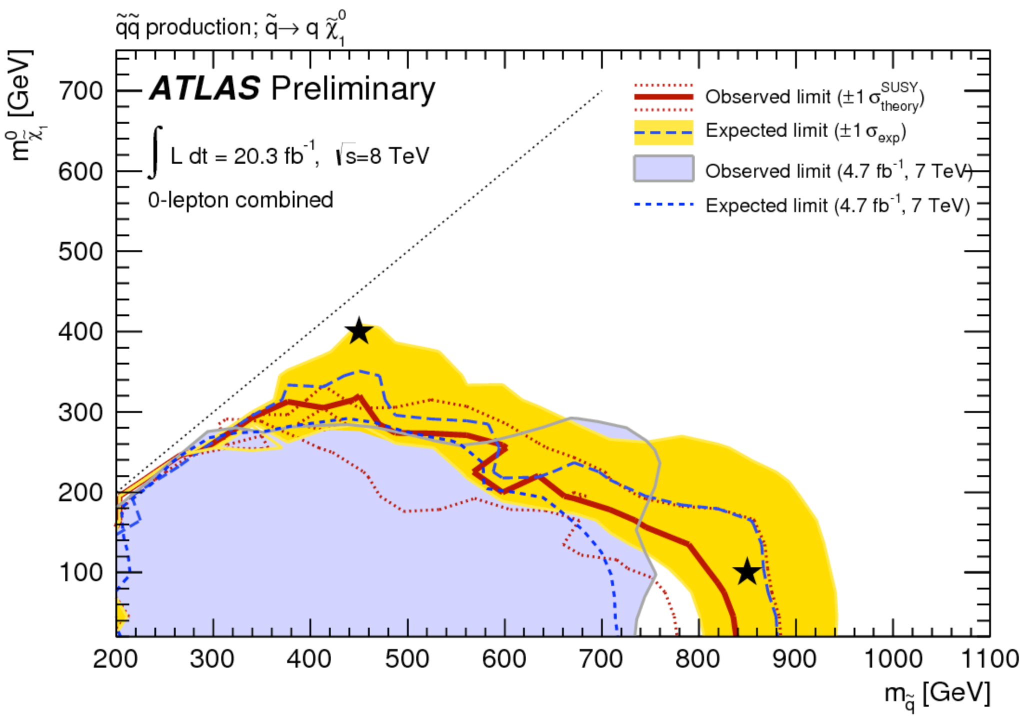
  ⋮

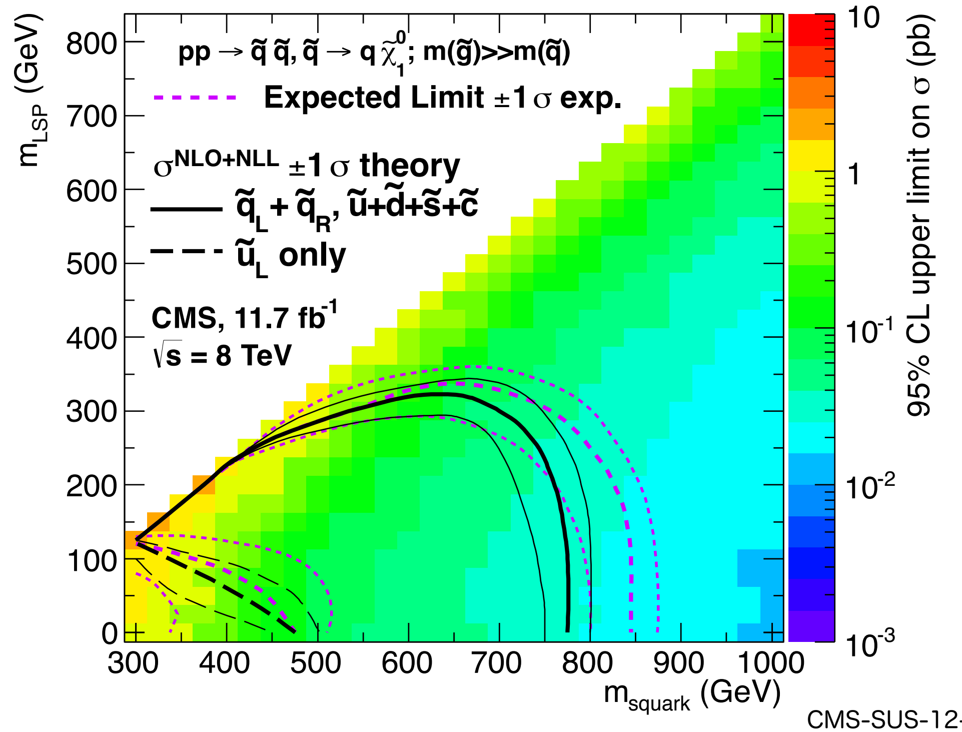
This talk will discuss a few areas that may benefit from more attention

A personal selection, no attempt at completeness

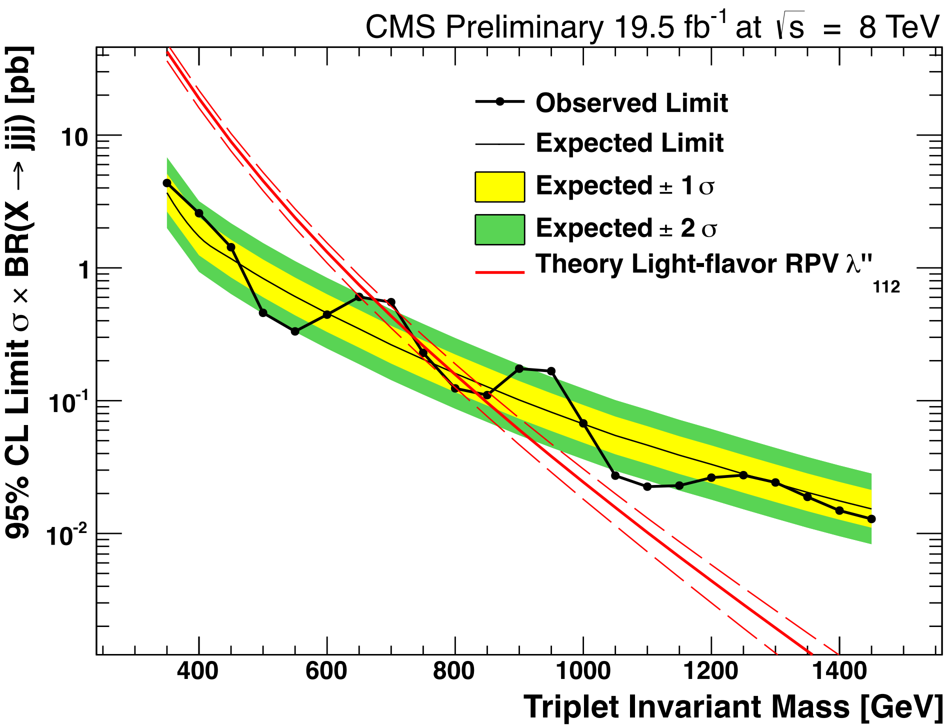
Existing SUSY Searches

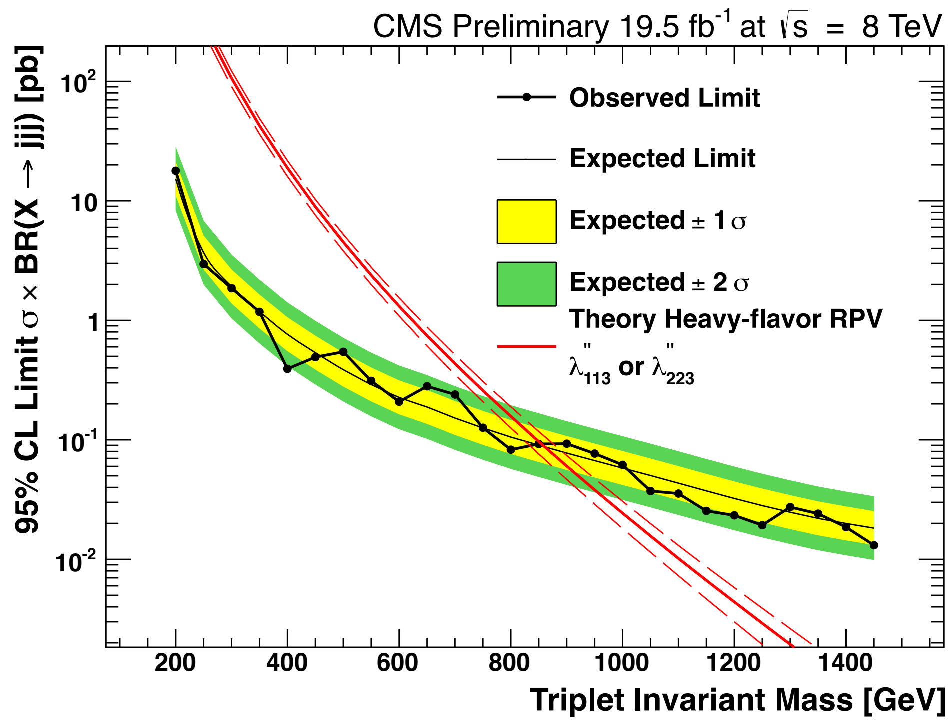
Compressed Spectra

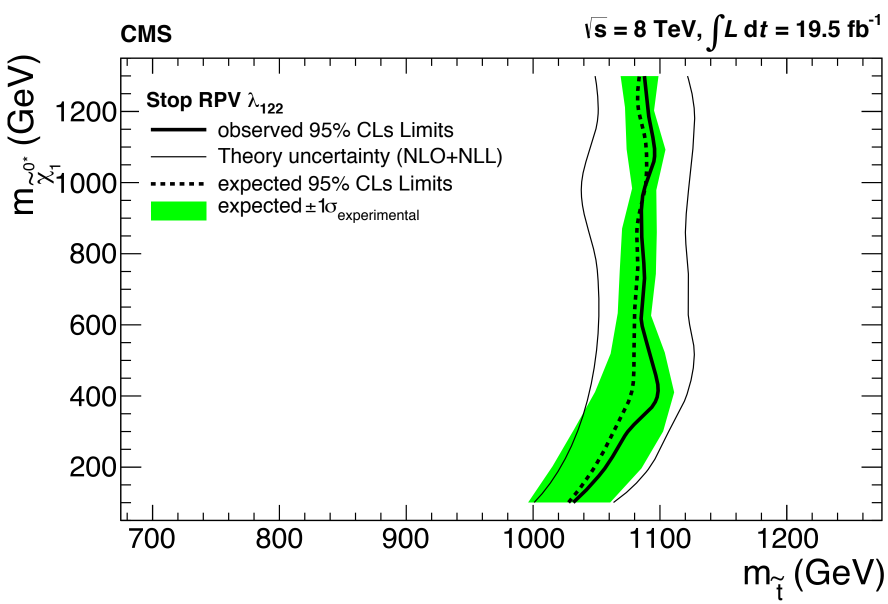


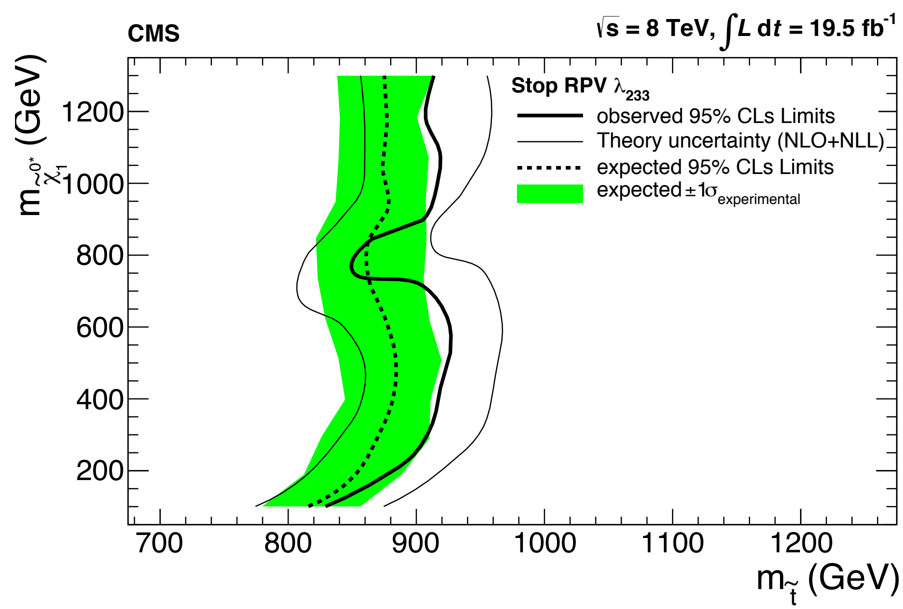


R-Parity Violation



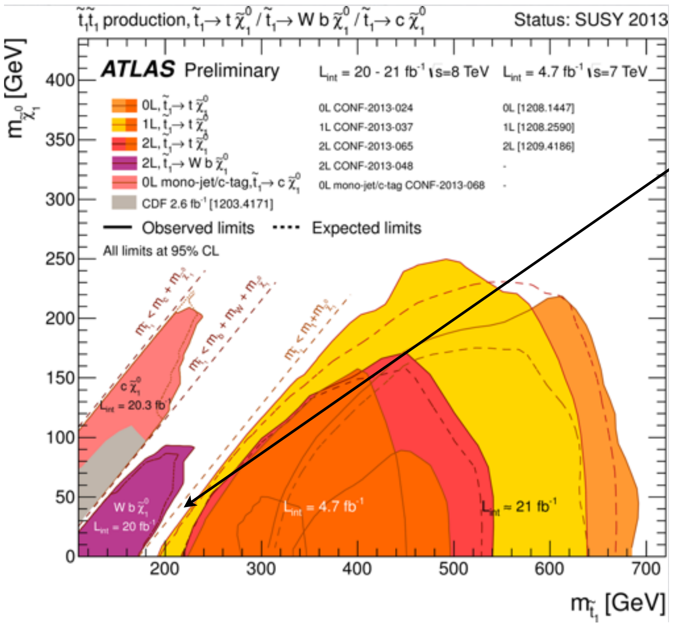


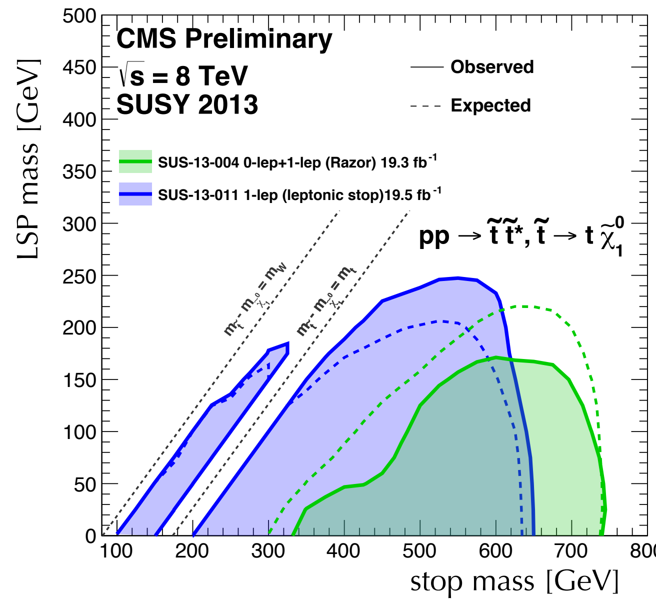




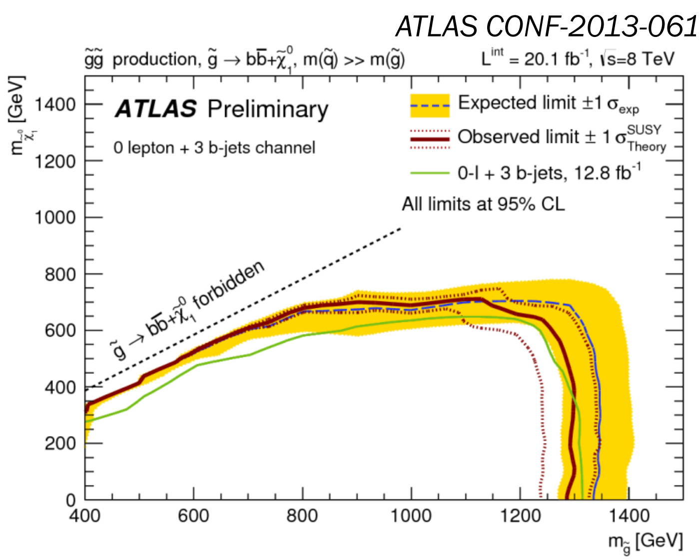
Natural SUSY

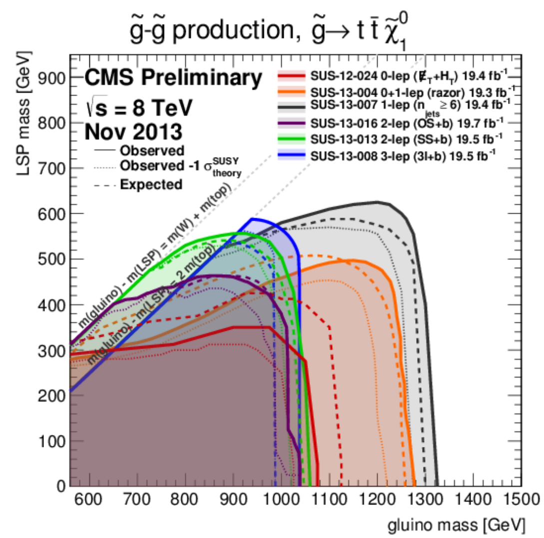
Stops



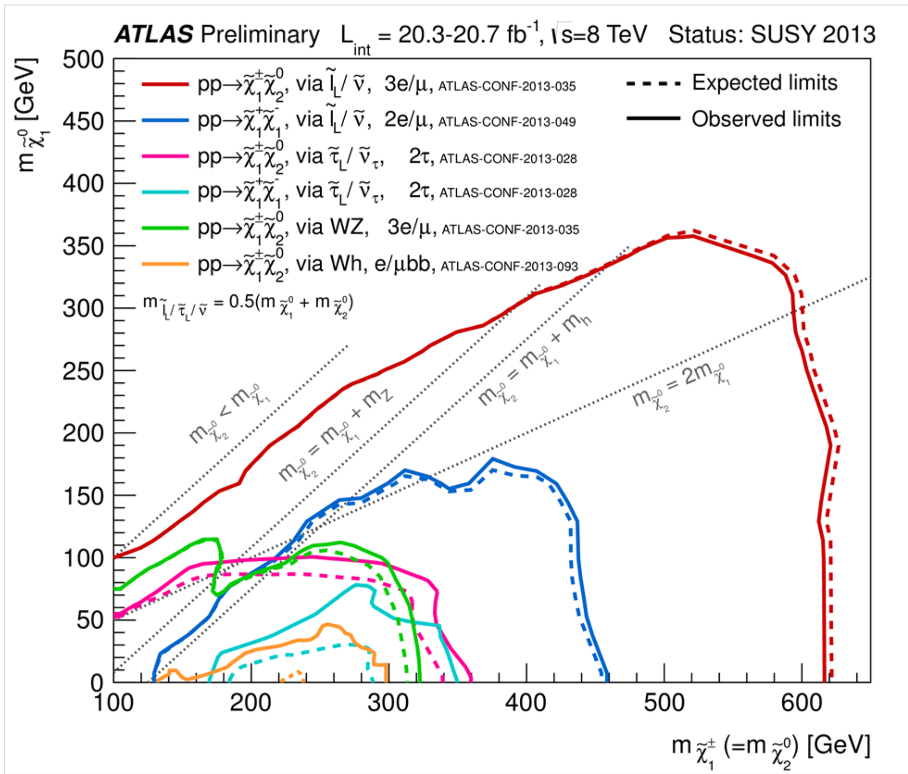


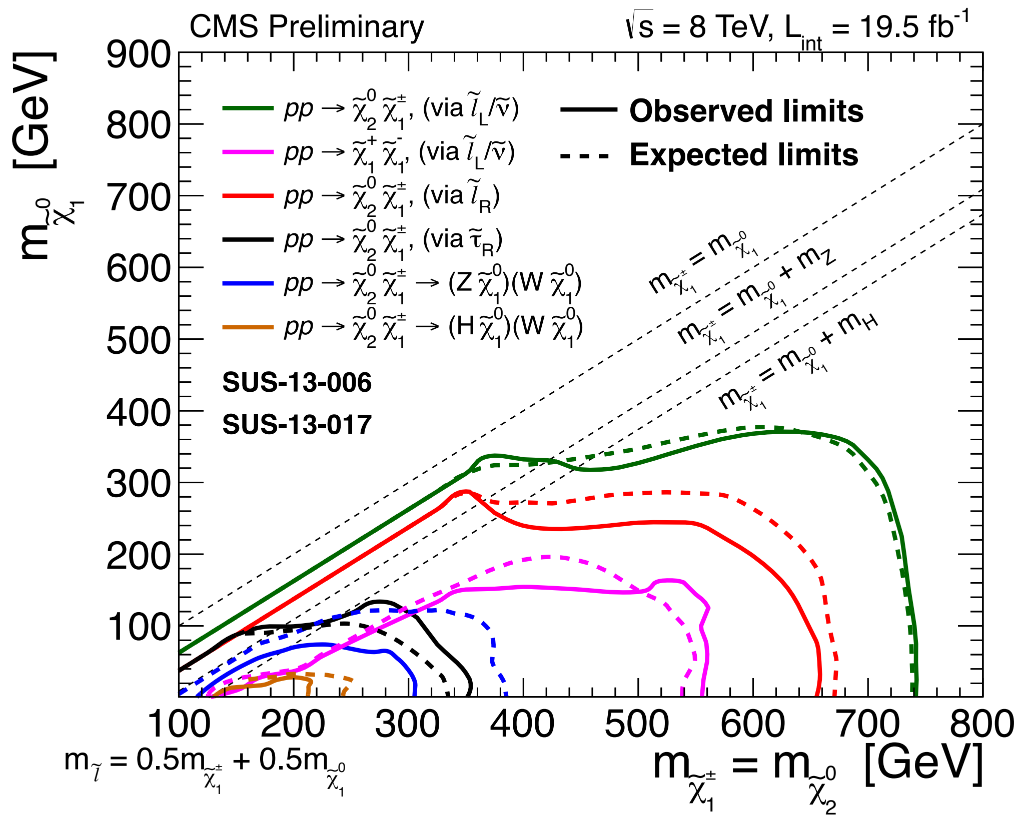
Gluinos:





Electroweakinos





The Big Picture

125 GeV Higgs
SM-like couplings

SUSY

Composite Higgs

We don’t know what we’re doing

Simplicity vs. Naturalness

SM is the perfect effective theory...

...if one parameter is tuned

$m^2_{H,\mathrm{eff}} =$ function of more fundamental parameters

versus

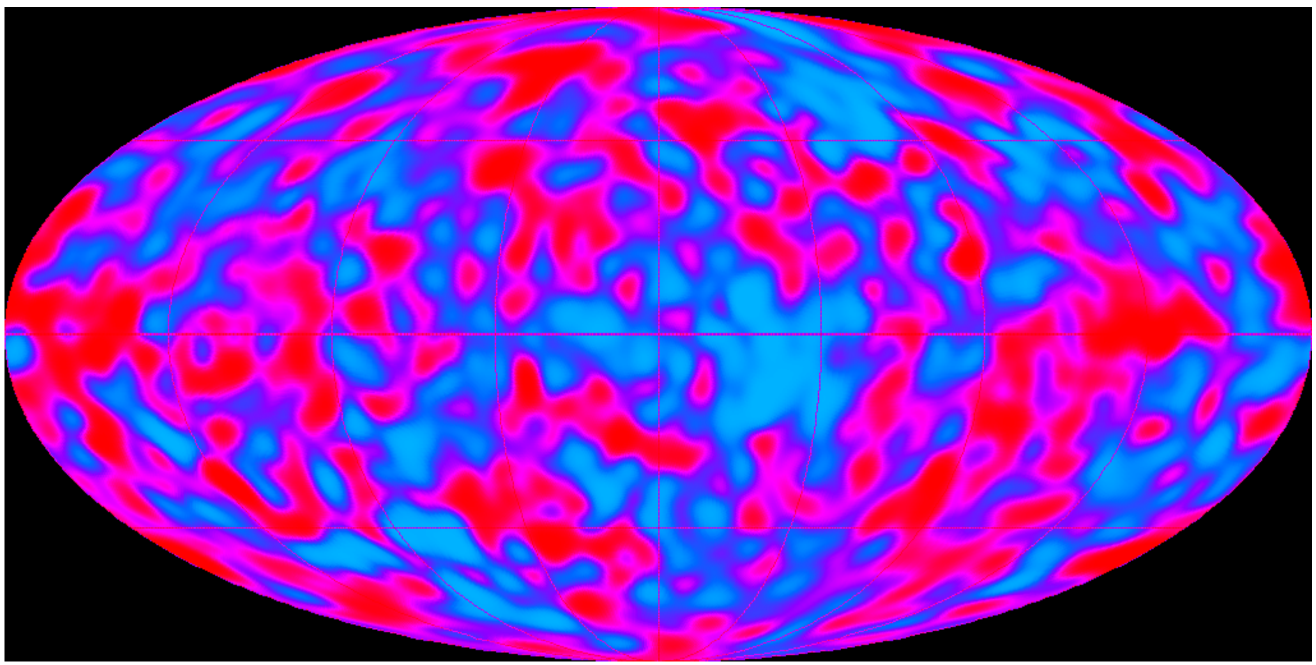
Naturalness = no tuning of parameters

Simplicity = minimality of structure & assumptions

An Unnatural Story

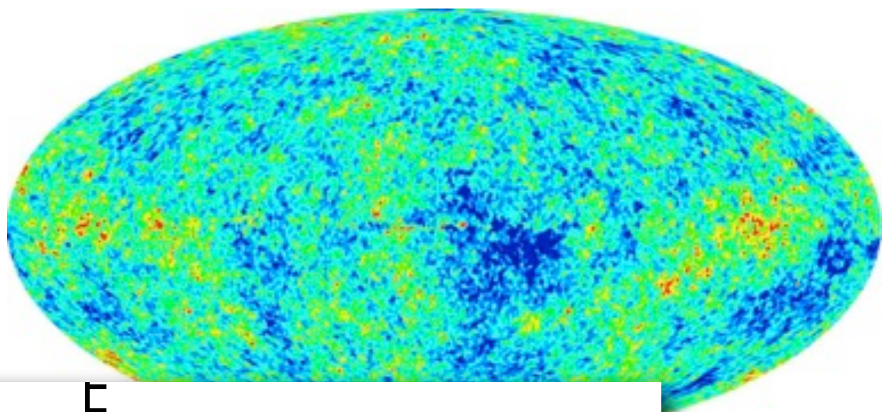
In the early 1990s limits on the CMB quadrupole were pushing the limits of cold dark matter cosmology...

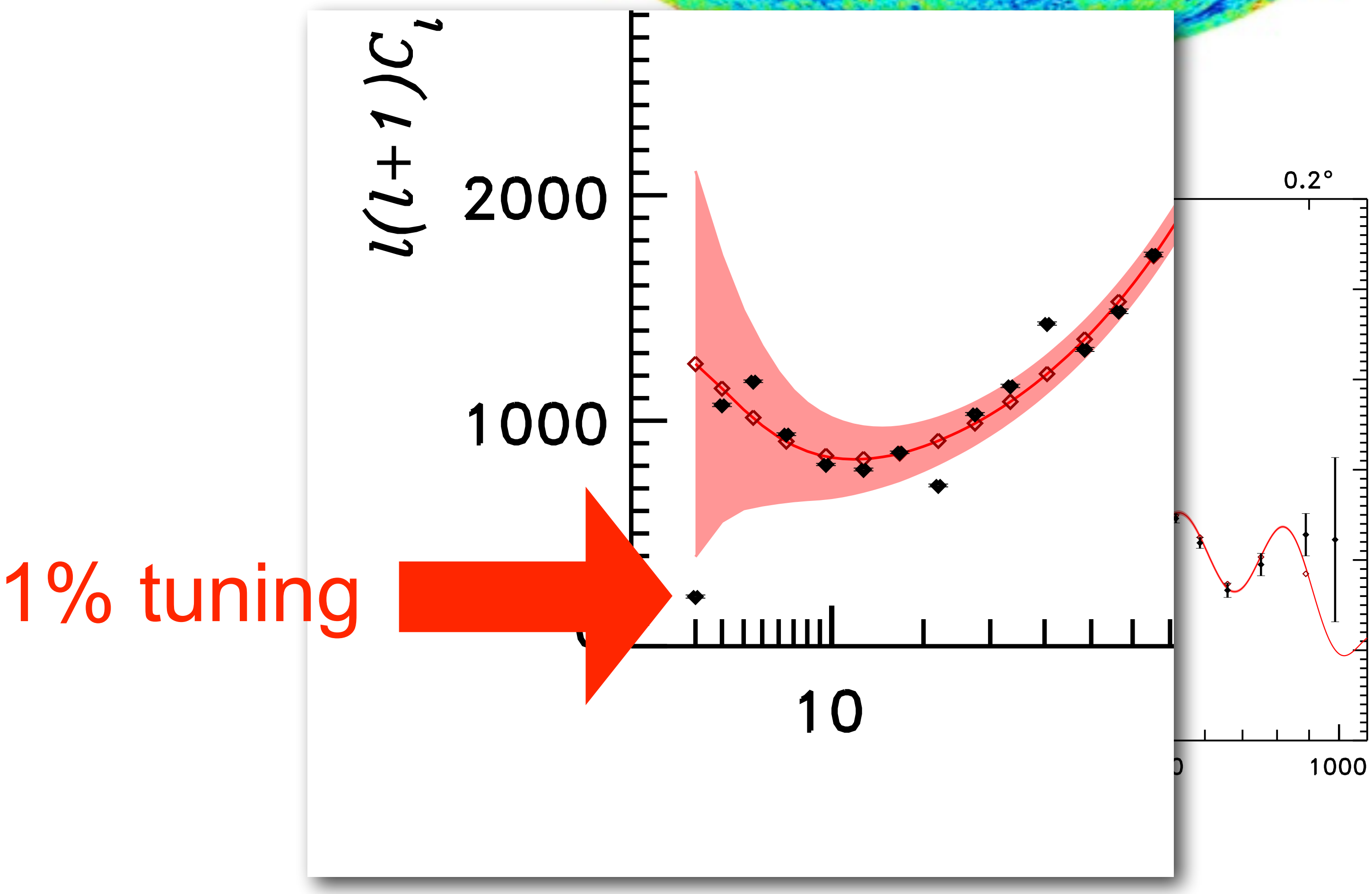
...and then came COBE



So what about the quadrupole?

Tuning!





Outline

- Tuned SUSY
- Natural SUSY
  - BMSSM Higgs
  - Displaced vertices
    - R-parity violation
    - Hidden sector dark matter

Tuned SUSY

Occam's razor:

"Entities must not be multiplied beyond necessity"

MSSM with one tuning is arguably the <u>simplest</u> explanation of particle physics data

Implications:

- SUSY most likely "just around the corner"
- Keep looking for standard SUSY signals

Natural SUSY

Crucial to test...

Requirements:

$$\mu \lesssim 200 \text{ GeV}$$
$$m_{\tilde{t}} \lesssim 500 \text{ GeV} \quad \longleftrightarrow$$
$$m_{\tilde{g}} \lesssim 1.5 \text{ TeV}$$

EWino searches,
stop, sbottom searches

But also: Higgs sector beyond MSSM

BMSSM Higgs

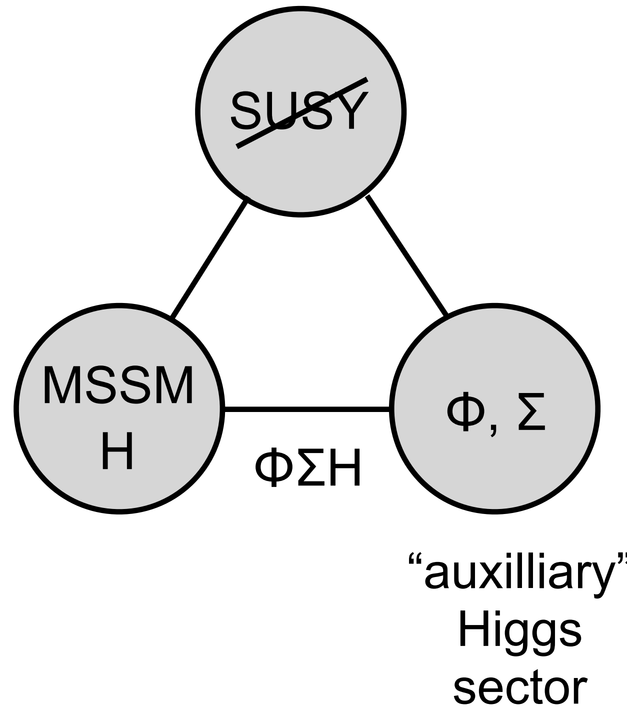
$$V_{\rm eff} = m_H^2|H|^2 + \lambda|H|^4 \qquad \Rightarrow (126 \text{ GeV})^2 = 2\lambda v^2$$

Need additional contributions to quartic

- NMSSM
- Non-decoupling D-terms

...or additional sources of EWSB

- “Induced” EWSB



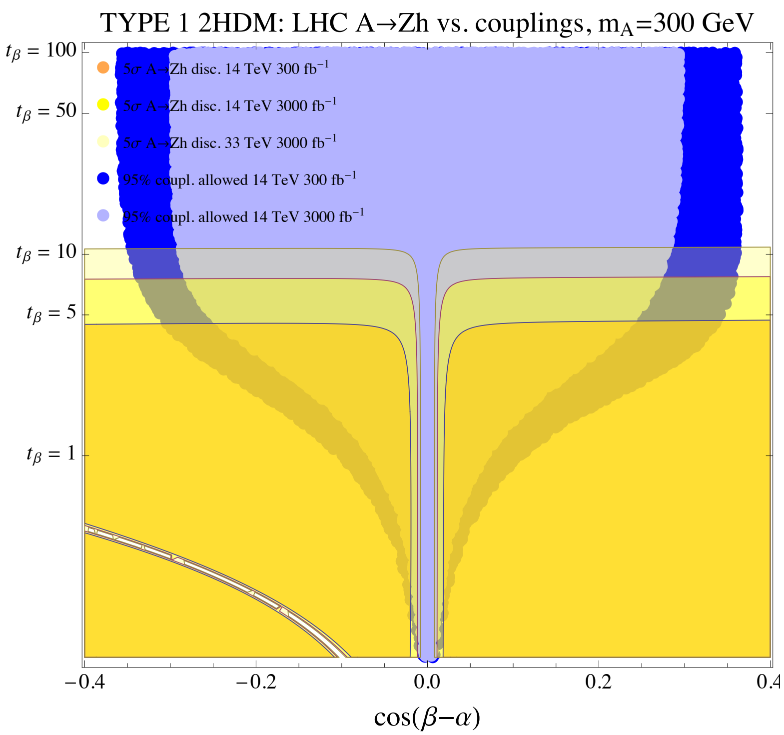
Motivate searches for additional Higgs bosons with significant mixing to 126 GeV state

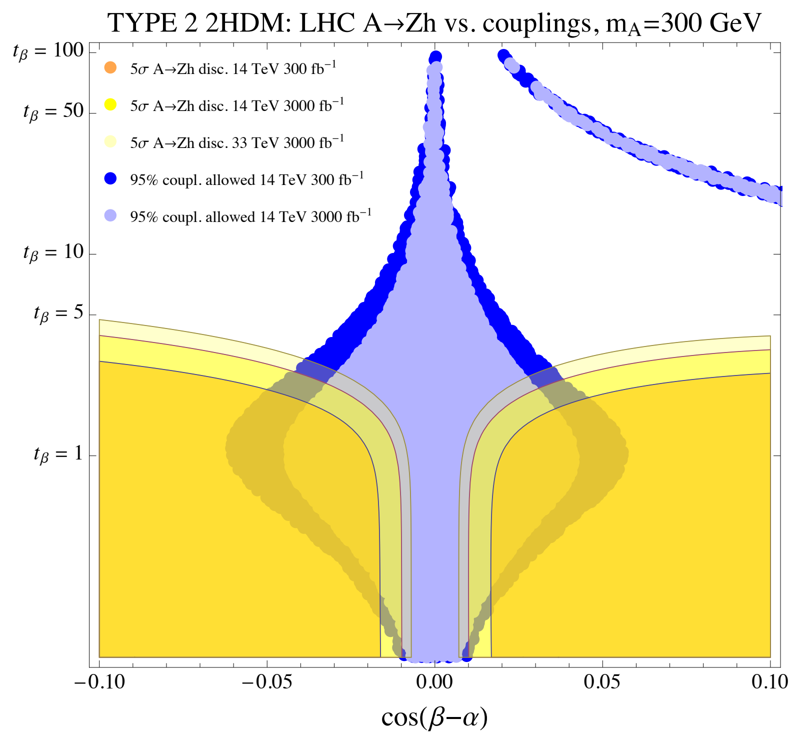
BMSSM Higgs Signals

Models have many parameters, but signals described by simplified models with few parameters

Novel feature: heavy Higgs fields can be far from decoupling limit

Example: A → Zh → (ll)(bb) or (ττ)

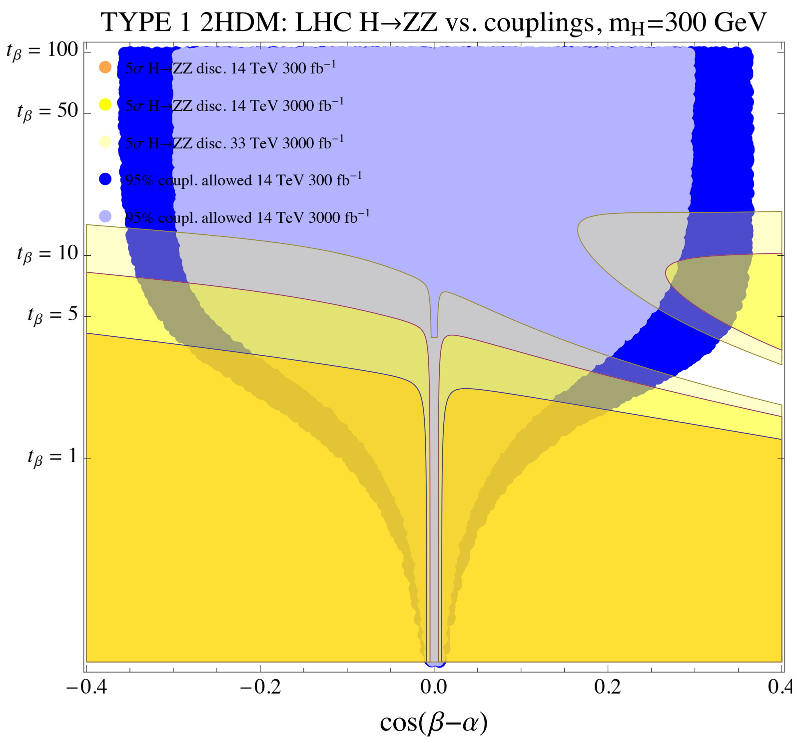


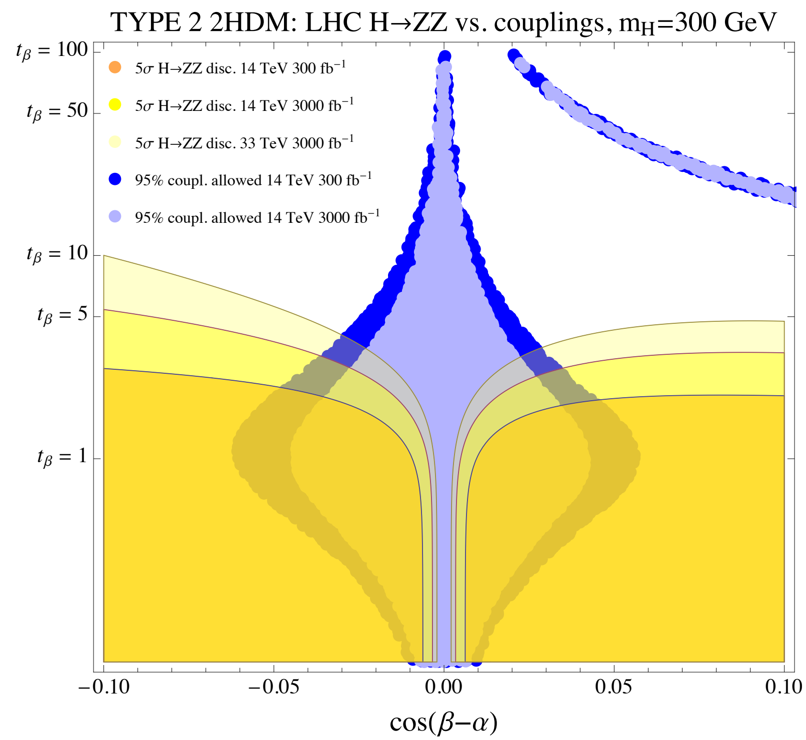


Brownson, Kukartsev, Narain, Heintz, Stupak, Craig Snowmass 2013

BMSSM Higgs Signals

Also: H → ZZ → (ll)(ll)





Other examples deserving further study:

H/A → tt, bb, ττ   H → hh

H → A Z → ZZh

R-Parity Violation

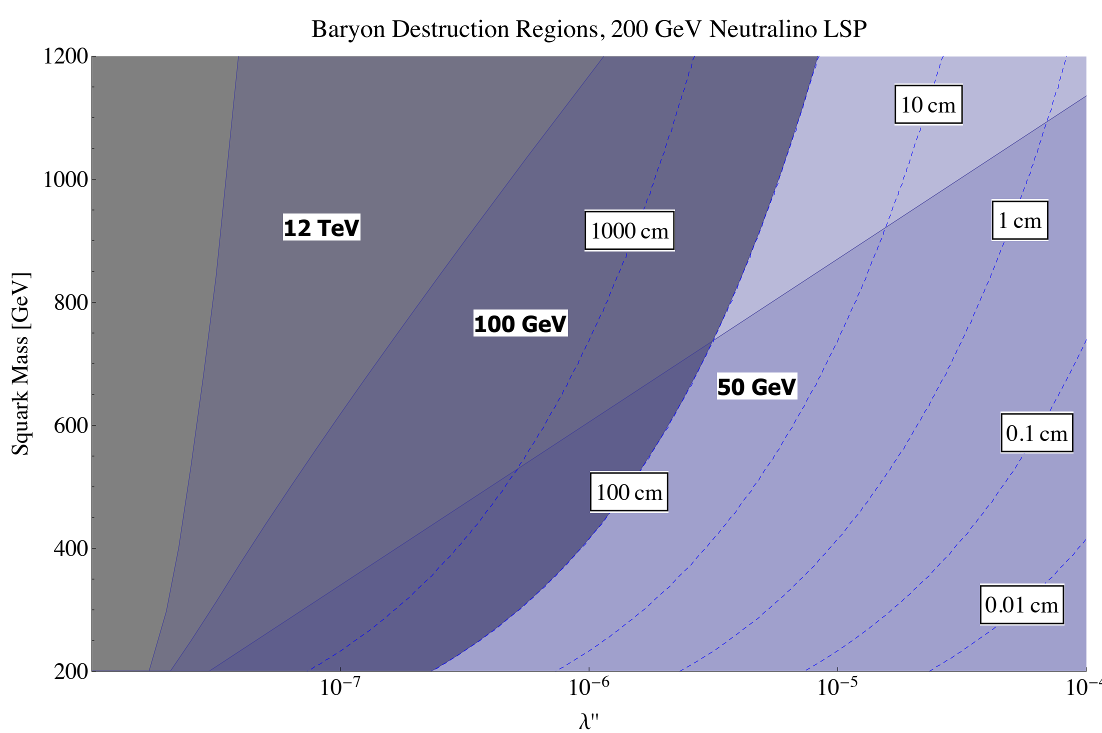
UDD R-parity violation is often considered as a way to “hide” natural SUSY

Cosmology motivates displaced vertices

Barry, Graham, Rajendran arXiv:1310.3853

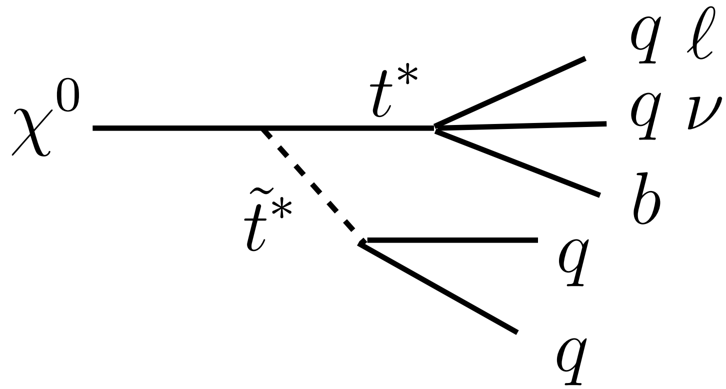
UDD destroys baryon asymmetry in early universe

⇒ requires low scale baryogenesis

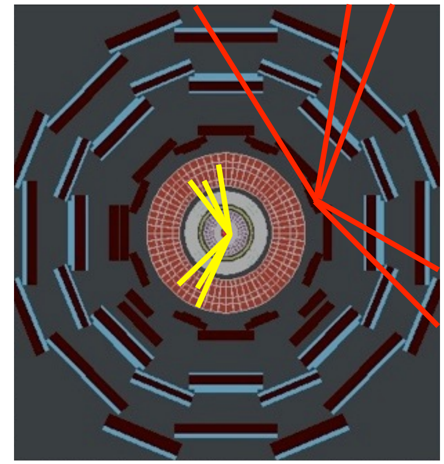


Displaced RPV

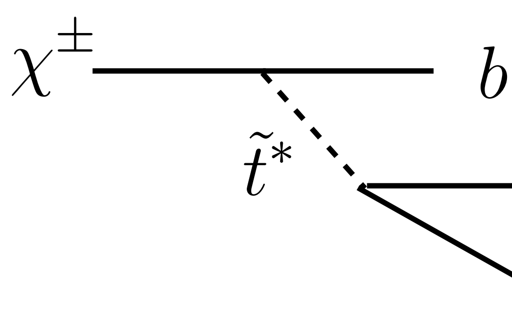
NLSP = neutralino



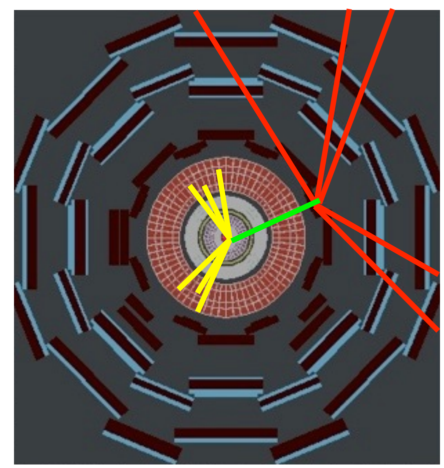
⇒ displaced vertex



NLSP = chargino



⇒ exploding track



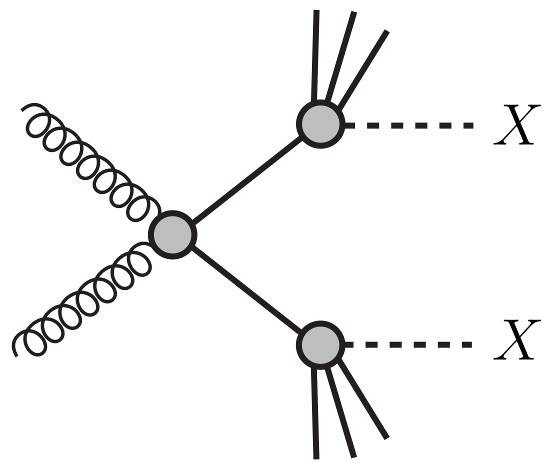
BMSSM Dark Matter

Dark matter exists

It requires physics beyond the standard model

But can we learn it's identity?

SUSY WIMP:



In the absence of signals in direct detection and collider searches, look at plausible mechanisms beyond WIMPs

⇒ new signals?

Hidden Sector Dark Matter

$$\Delta\mathcal{L} = \epsilon \mathcal{O}_{\rm vis} \mathcal{O}_{\rm hidden}$$

LSP in hidden sector ⇒ may be dark matter

LOSP (lightest ordinary supersymmetric particle)
decays to dark matter, may be long-lived

- SuperWIMP (Feng, Rajaraman, Takayama 2003)

LOSP dominates universe, then decays

$$\Omega_X = \frac{m_X}{m_{\rm LOSP}} \Omega_{\rm LOSP}$$

X = gravitino or ...

Freeze-in Dark Matter

(Hall, Jedamzik, March-Russell, West 2009)

Relic density generated by LOSP decay

X never in equilibrium ⇒ no inverse decays

$$\Omega_X \simeq \frac{10^{27}}{g_*^{3/2}(m_{\mathrm{LOSP}})} \frac{m_X \Gamma(\mathrm{LOSP} \to X)}{m_{\mathrm{LOSP}}^2}$$

$$c\tau(\mathrm{LOSP} \to X) \sim 0.5 \text{ m} \left(\frac{m_X}{\mathrm{keV}}\right) \left(\frac{m_{\mathrm{LOSP}}}{100 \text{ GeV}}\right)^{-2}$$

$m_X \gtrsim \mathrm{keV}$ (structure formation)

⇒ motivates highly displaced decays

Asymmetric Dark Matter

(Kaplan, ML, Zurek 2009)

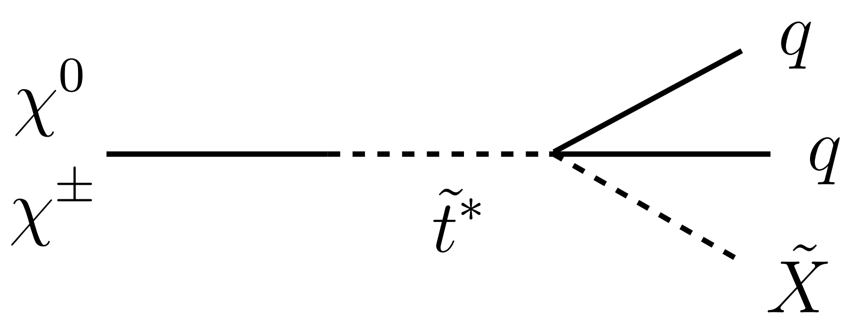
$$\Delta W = \frac{1}{M^2} \underbrace{UDD}_{\text{visible}} \underbrace{X^2}_{\text{hidden}}$$

Transfers B-L asymmetry to dark matter

Freeze out: $T_f \gtrsim m_X \;\Rightarrow\; \Omega_X \sim \frac{m_X}{m_p}\Omega_B \;\Rightarrow\; m_X = 14 \text{ GeV}$

Valid for $M \gtrsim \text{TeV}$ due to rapid decoupling for $T < m_{\tilde{q}}$

Decay:

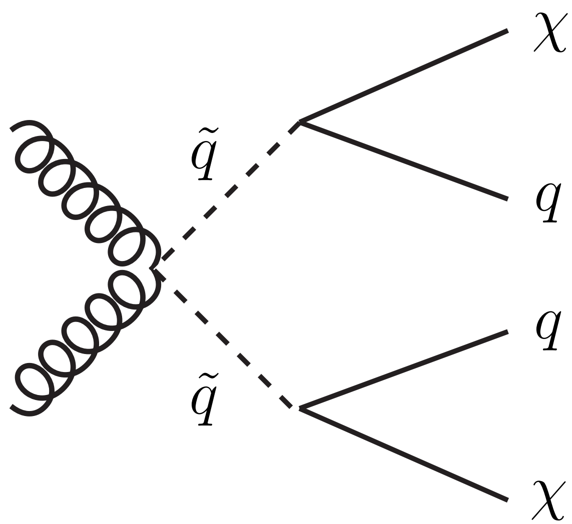


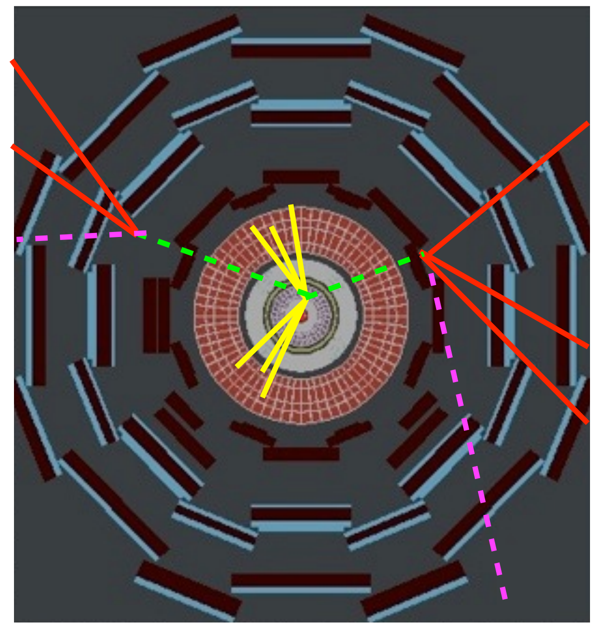
$$c\tau \sim \text{cm} \left(\frac{M}{\text{TeV}}\right)^4 \left(\frac{m_{\tilde{t}}}{500 \text{ GeV}}\right)^4 \left(\frac{m_\chi}{100 \text{ GeV}}\right)^{-9}$$

Displaced Optimism

Displaced vertices are exciting discovery mode…

…and open the possibility of fully reconstructing SUSY events





LOSP = charged: SUSY fully reconstructed

LOSP = neutral: $\vec{v}_{\mathrm{LOSP}}$ from vertex position + timing

Constraining/measuring dark matter mass possible

Conclusions

• Impressive breadth and depth of SUSY searches

• Both tuned and natural versions of SUSY are still plausible and important to test

• BMSSM Higgs and displaced vertices are important to search for

Decoupling Limit

Additional MSSM Higgs generically near decoupling limit

$$\begin{pmatrix} H \\ H_\perp \end{pmatrix} = \begin{pmatrix} \sin\beta & \cos\beta \\ \cos\beta & -\sin\beta \end{pmatrix} \begin{pmatrix} H_u \\ H_d^\dagger \end{pmatrix} \qquad \tan\beta = \frac{v_u}{v_d}$$

$$\underbrace{\langle H \rangle}_{\text{}} = \frac{v}{\sqrt{2}} \qquad \langle H_\perp \rangle = 0$$

<u>the</u> Higgs field

126 GeV mass eigenstate $\simeq H_\parallel^0$

⇒ additional Higgs fields decouple from W, Z
(but not fermions)

Simplified Models

Simplified models for BSM/BMSSM Higgs searches

For SUSY interpretation, assume decoupling

$$H = H_u \sin\beta + H_d^\dagger \cos\beta$$

$H_\perp$ decoupled

⇒ SM Higgs with one additional parameter $\tan\beta$

governs couplings of H to fermions

...now add BMSSM Higgs

Higgs + Singlet

$$V_{\rm eff} = m_H^2|H|^2 + \lambda_H|H|^4$$
$$+ \tfrac{1}{2}m_\Phi\Phi^2 + \tfrac{1}{4}\lambda_\Phi\Phi^4 + \tfrac{1}{2}\lambda_{\Phi H}S^2|\Phi|^2$$

6 parameters: $m_1, m_2, v, \tan\beta, \cos\gamma, \langle\Phi\rangle$

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\gamma & \sin\gamma \\ -\sin\gamma & \cos\gamma \end{pmatrix}$$

Model 1: $\Phi =$ CP even $m_1 = 126\ \mathrm{GeV}$

Production and decay of h_2 governed by m_2, β, γ

$$h_2 \to ZZ,\ WW,\ \bar{t}t,\ h_1h_1$$

Model 2: $\Phi =$ CP odd PNGB

$m_2 = 126\ \mathrm{GeV}$

$\langle\Phi\rangle = 0$

$$h_1 \to aa \qquad a \to \bar{b}b,\ \tau^+\tau^-$$