SUSY search highlights from CMS

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on behalf of the CMS collaboration

CIPANP 2018
May 30, 2018

Summary in advance

- LHC provides **incredible sensitivity to bulk of natural SUSY parameter space**:
  - **Initial searches are relatively general** to rapidly take advantage of increasing pp collision energies.

- Analysis effort continues to increase on less general, targeted searches for both:
  - **alternate SUSY models**
  - **challenging corners of natural SUSY parameter space**

- **Aim of this talk**
  - **NOT** to indicate the vast breadth of our search program
  - **explain status and give a few examples** of expanding focus on specific/ targeted searches

Supersymmetry (SUSY)

Spacetime symmetry that turns bosonic states into fermionic states and vice versa:

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \qquad Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

SM particles

SM fermions	u	d	e	ν_e
	c	s	μ	ν_μ
	t	b	τ	ν_τ
SM bosons	h	A	H^0	$H^\pm$
	γ	Z^0	$W^\pm$	g

SUSY partners

$\tilde{u}$	$\tilde{d}$	$\tilde{e}$	$\tilde{\nu}_e$
$\tilde{c}$	$\tilde{s}$	$\tilde{\mu}$	$\tilde{\nu}_\mu$
$\tilde{t}$	$\tilde{b}$	$\tilde{\tau}$	$\tilde{\nu}_\tau$
$\tilde{\chi}^0_1$	$\tilde{\chi}^0_2$	$\tilde{\chi}^0_3$	$\tilde{\chi}^0_4$
$\tilde{\chi}^\pm_1$	$\tilde{\chi}^\pm_2$		$\tilde{g}$

Why SUSY?

- Explains dark matter
- Explains hierarchy problem
- Unifies forces

Special particles

- gluino ($\tilde{\mathbf{g}}$)
- top squark or stop ($\tilde{\mathbf{t}}$)
- neutralino or LSP ($\tilde{\chi}^0_1$)
- higgsinos ($\tilde{\mathbf{h}}$; $\tilde{\chi}^0_2$, $\tilde{\chi}^\pm_1$, $\tilde{\chi}^0_1$)

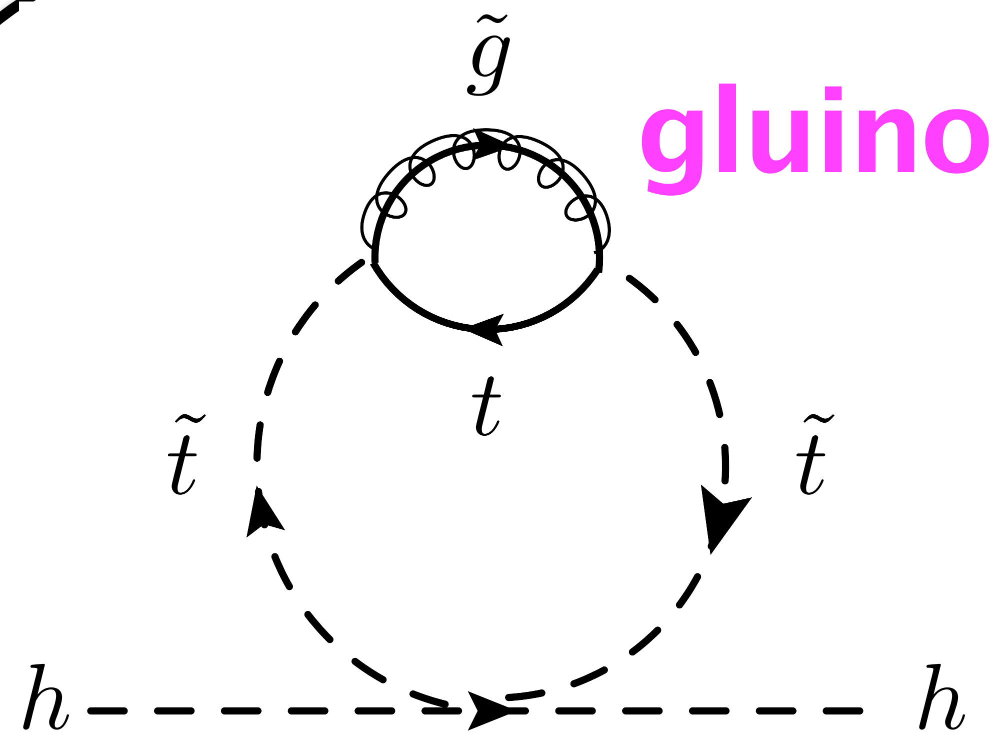
“Natural” SUSY spectrum

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

- We measure $|m_H^2| \sim |100\ \mathrm{GeV}|^2$.
- In standard model (SM), $\delta m_H^2 \sim 10^{30}$ GeV.
- In SUSY, δm_H^2 can be small, but depends on sparticle masses.
- Define “natural” spectrum as giving δm_H^2 not $\gg m_H^2$.
- Traditional metric: $\Delta \equiv \frac{2|\delta m_H^2|}{m_h^2}$

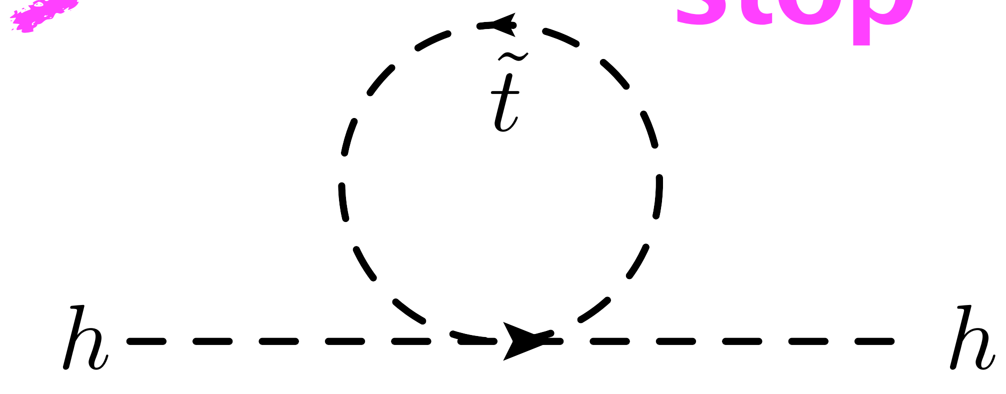
D. Shih

gluino



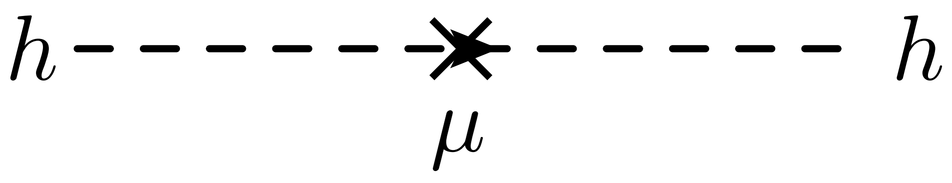
$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{g_3^2}{4\pi^2}M_3^2\left(\log\frac{\Lambda}{Q}\right)^2$$

stop



$$\delta m_H^2 \sim -\frac{3}{8\pi^2}y_t^2(m_{Q_3}^2 + m_{U_3}^2)\log\frac{\Lambda}{Q}$$

higgsino



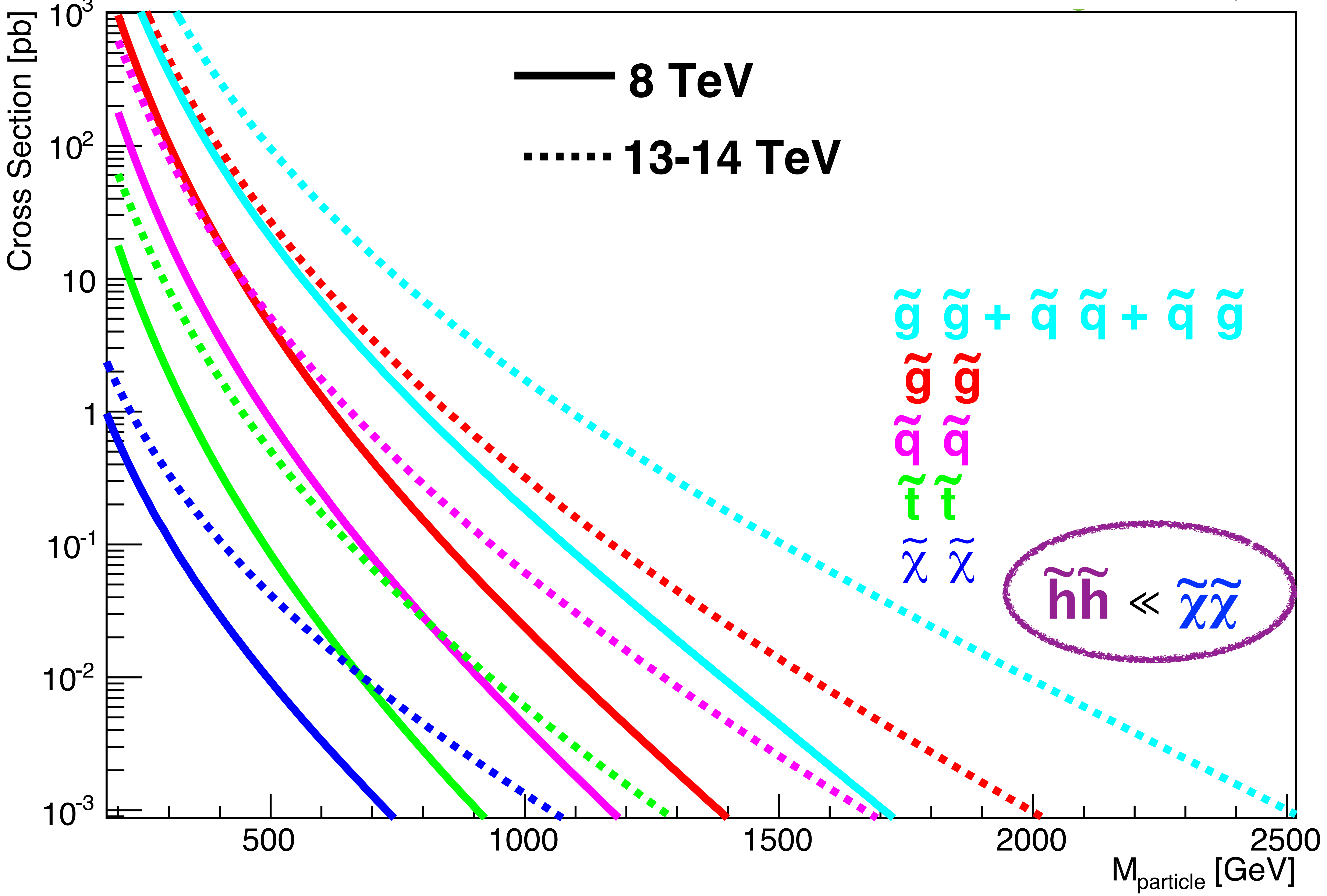
$$\delta m_H^2 \sim |\mu|^2$$

Λ = UV cutoff scale
Q = IR scale appropriate to process

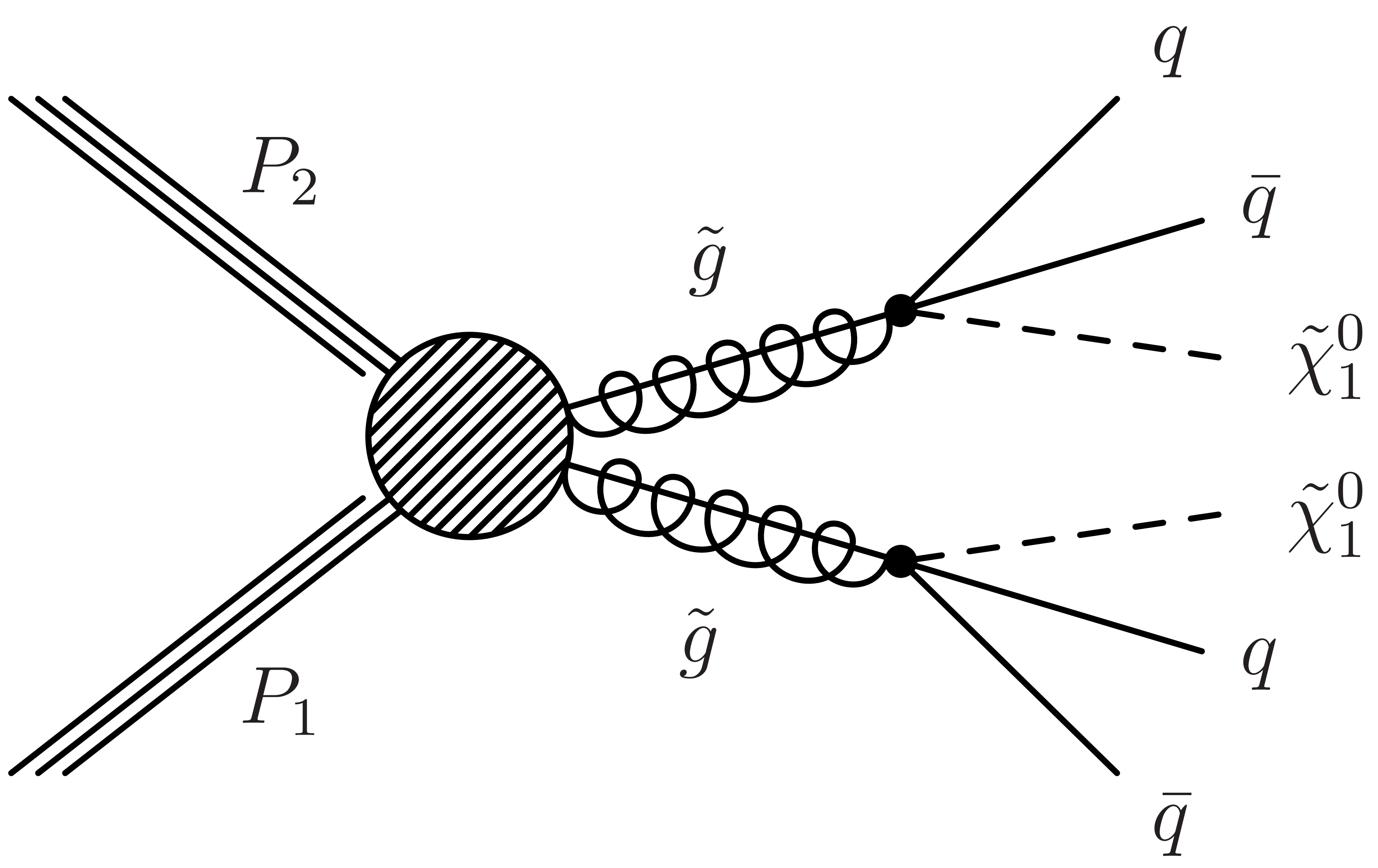
Papucci, Ruderman, Weiler, arXiv:1110.6926
Barbieri, Giudice (1988)
Martin arXiv:hep-ph/9709356

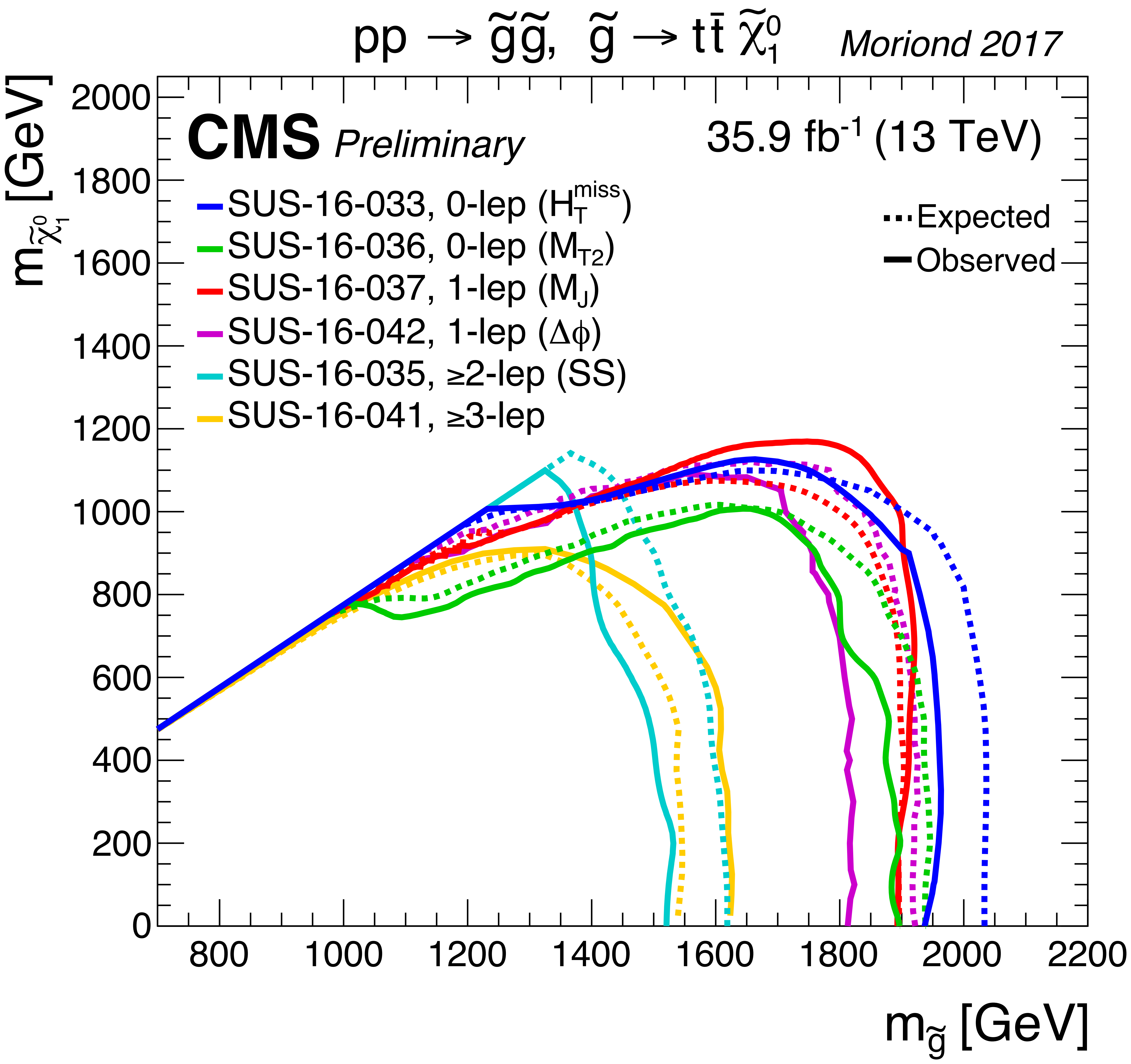
SUSY production cross sections

Halkiadakis, Redlinger, Shih (2014)



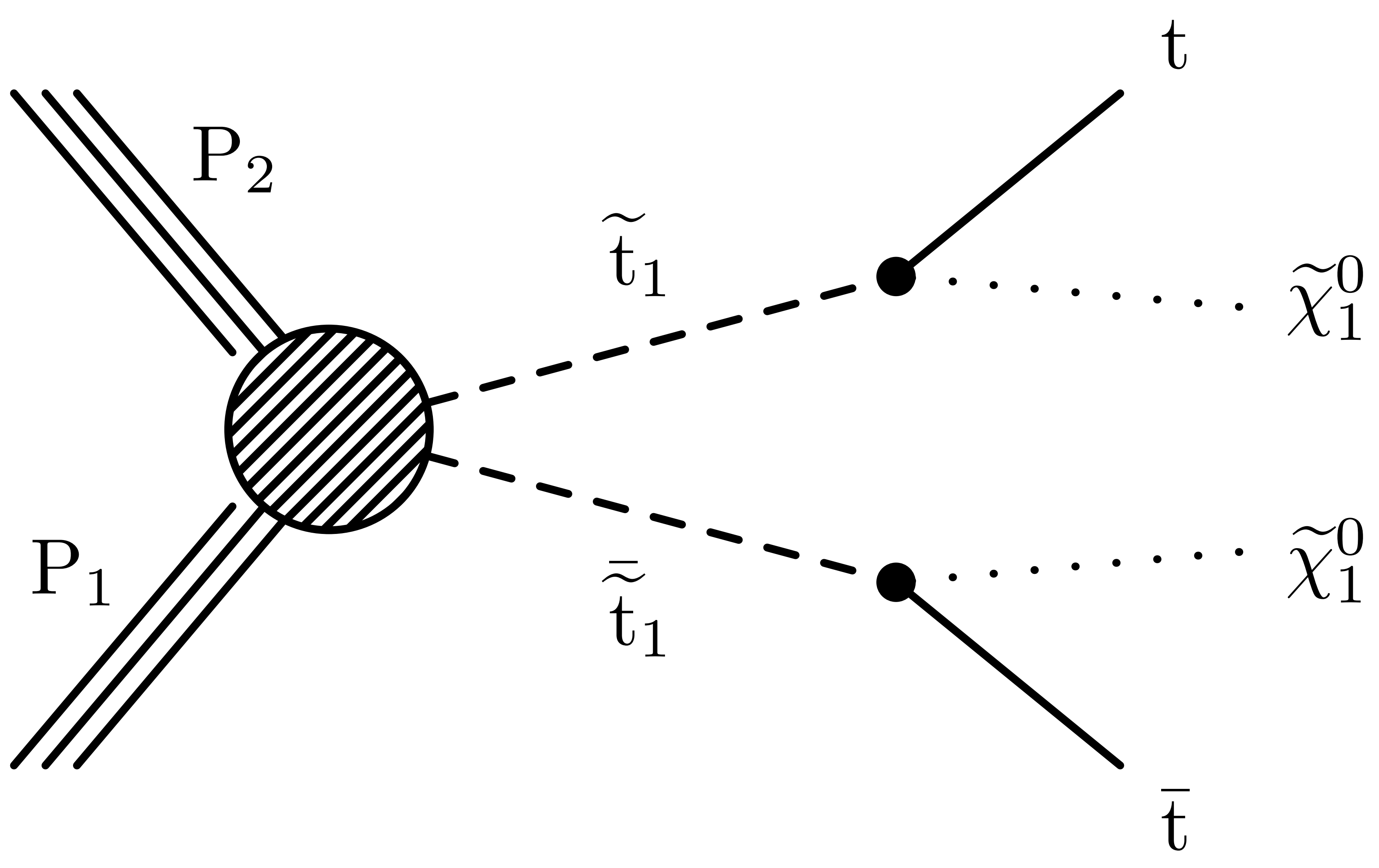
Gluino exclusions



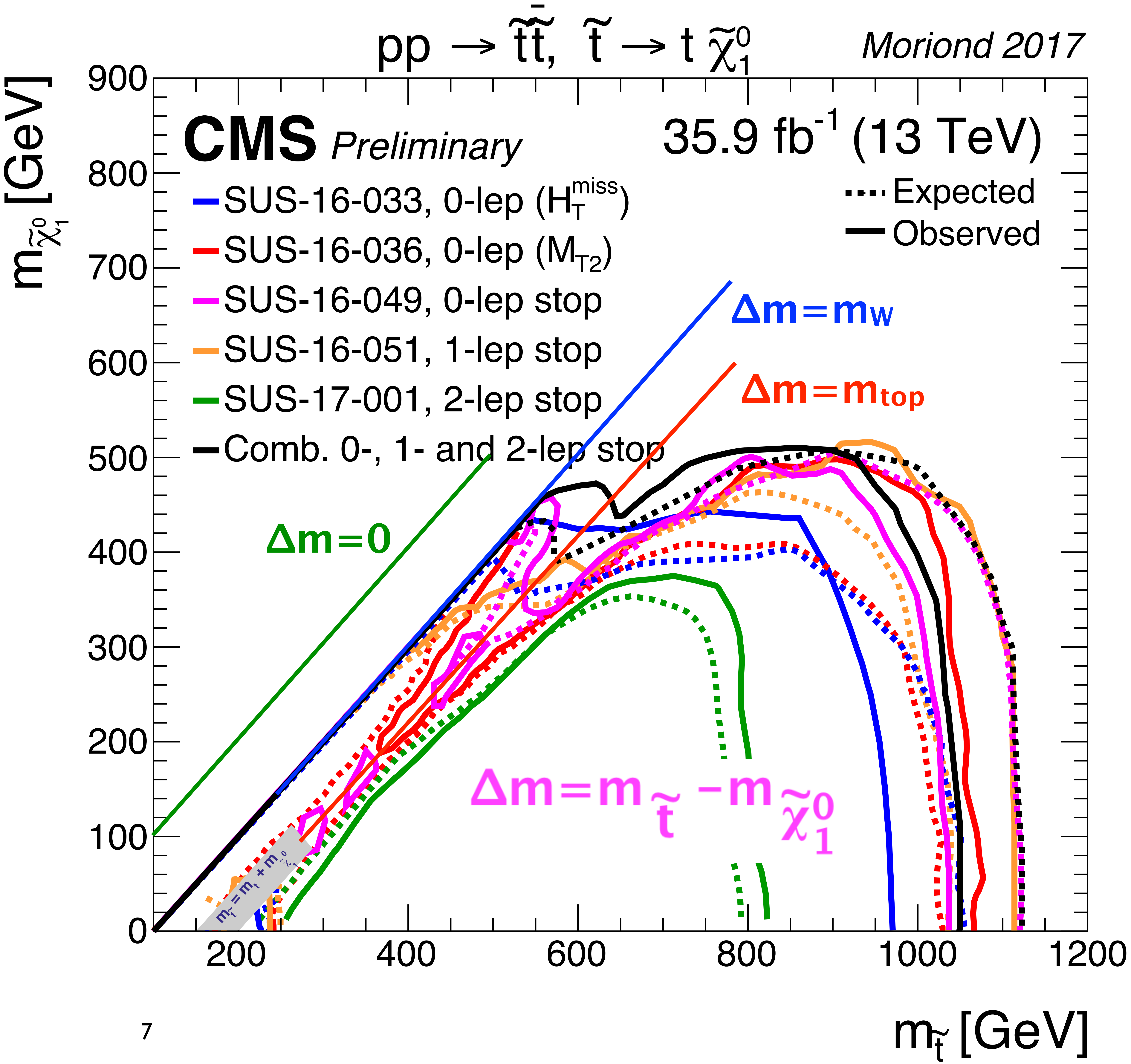


- Attack high cross section gluino with **general, inclusive search** for events with
  - large **missing transverse energy (MET)**
  - large **total event energy (H_T)**
  - many **jets**
  - many **b-tagged jets**

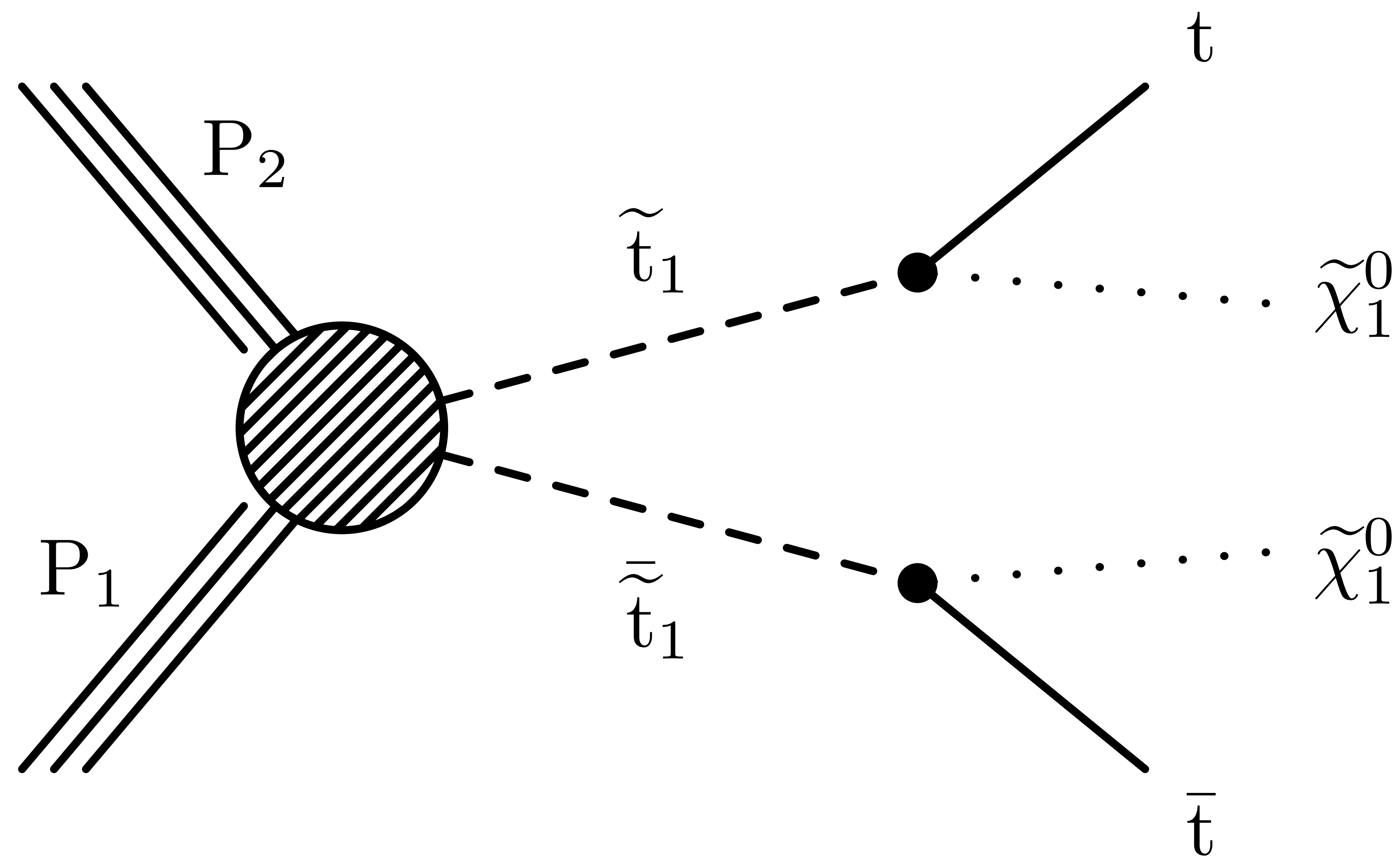
Top squark exclusions



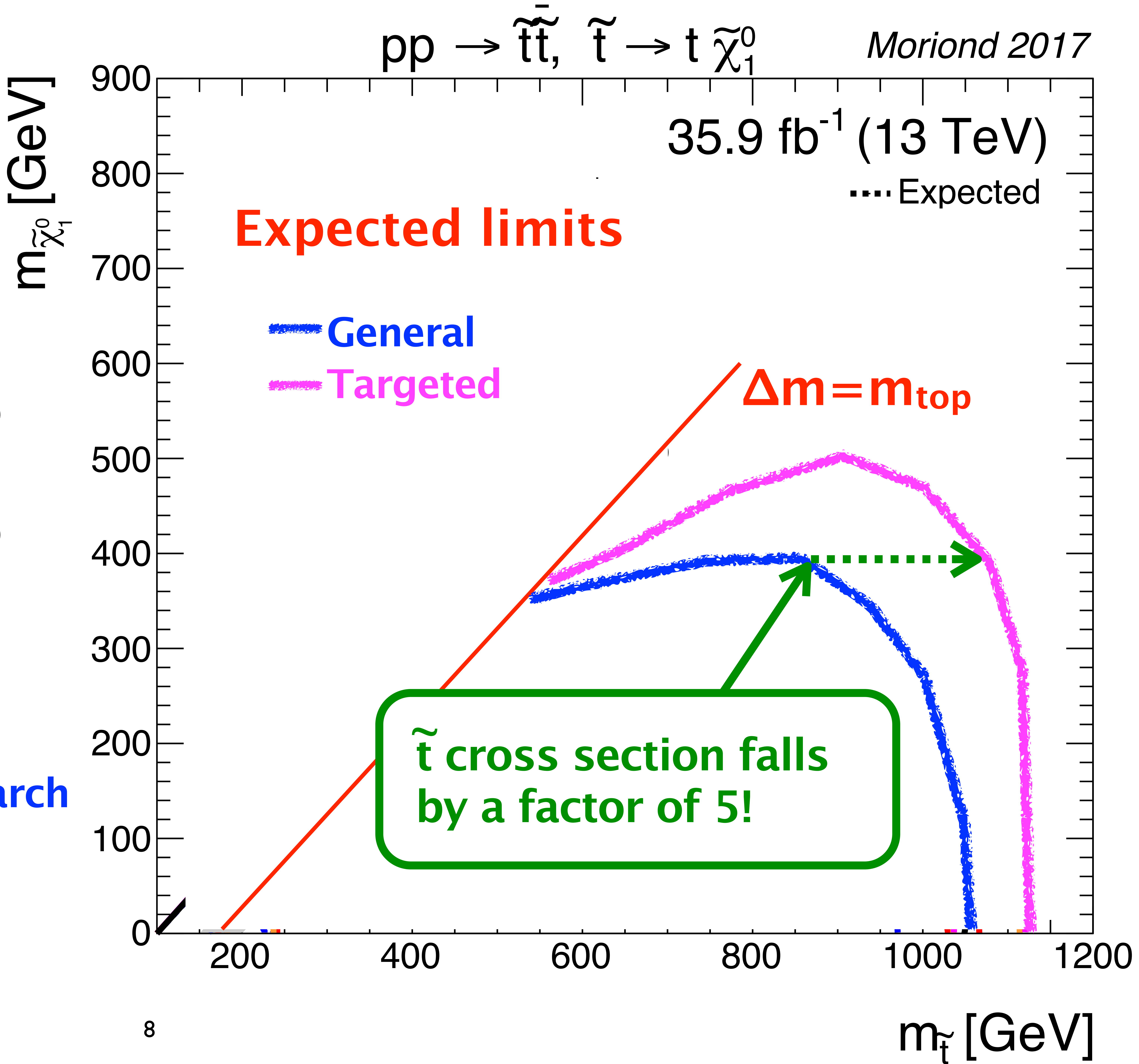
- Good sensitivity to 1 TeV stop for low mass LSP.
- **Gap in sensitivity** when $\Delta m \approx m_{top}$ or $\Delta m < m_W$
- **Later show search for $\Delta m < m_W$**



Top squark exclusions



- Primary example of **benefits of targeted search over general search**
- Targeted searches uses:
  - MVA-based top ID algorithms
  - Top quark decay kinematics



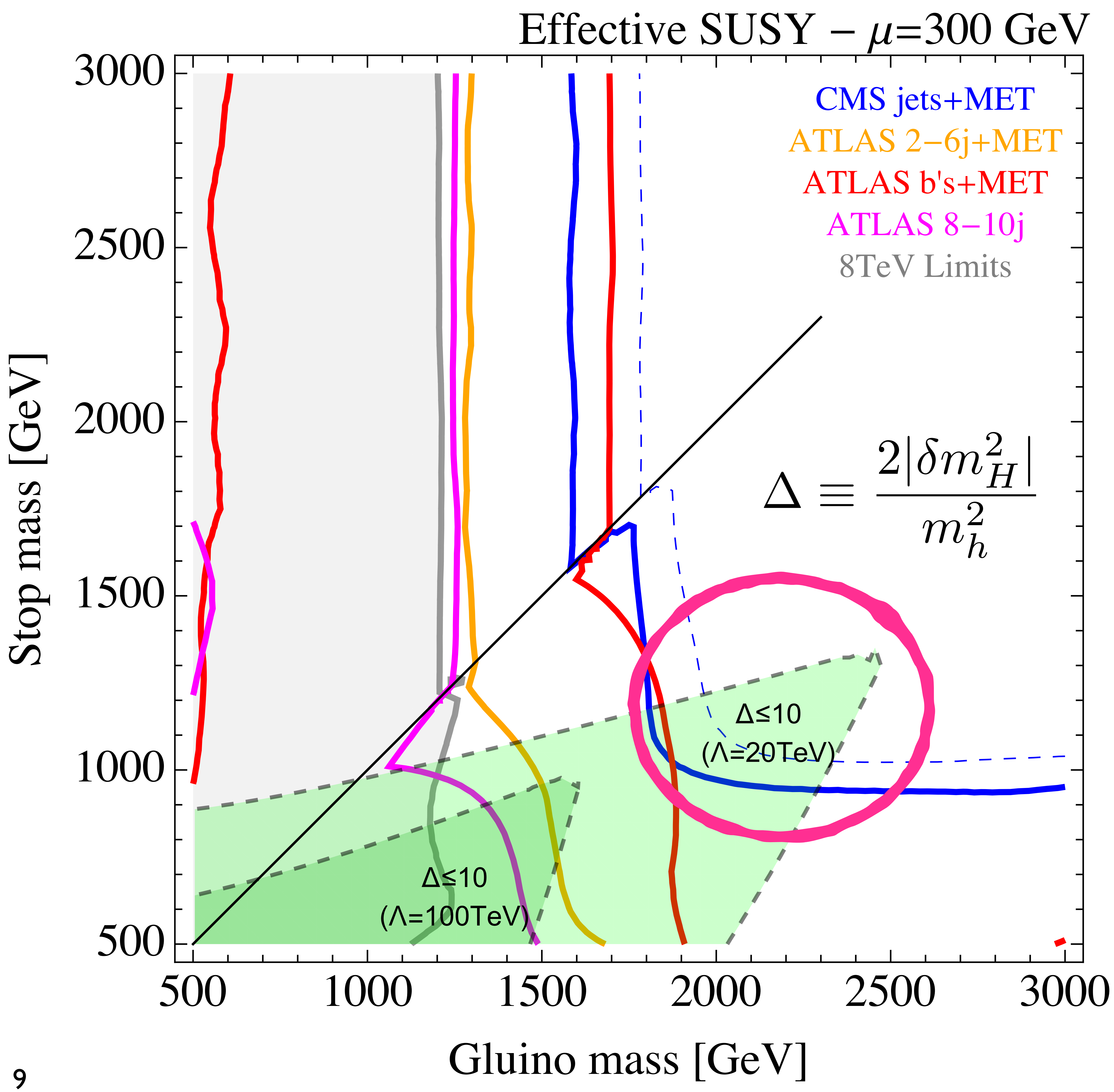
State of natural SUSY

[1] Buckley, Feld, Macaluso, Monteux, Shih; arXiv:1610.08059

- Allowed phase space for **10% fine tuning with low Λ=20TeV**.
- Λ=GUT scale implies 0.5% fine tuning.

Options:

- **Denial:** new naturalness metric?
  H.Baer et al. arXiv:1611.08511
- **Guilt/anger:** Are missing we are looking in the right places?
- **Depression:** Naturalness mechanism without accessible particles? Twin Higgs?
- **Acceptance:** 0.1% tuning better than 10^{-30}
- **Hope:** a few more places to look …



Recent search highlights

Give up solving hierarchy problem?

Look for **long-lived gluino** in "split" SUSY model.

- ☑ Explains dark matter
- ☒ Explains hierarchy problem
- ☑ Unifies forces

Give up dark matter candidate?

Look for **MET-less gluino resonances** in R-parity violating SUSY.

- ☒ Explains dark matter
- ☑ Explains hierarchy problem
- ☑ Unifies forces

- **Challenging corners of parameter space** for natural SUSY?
  - **low p_T decay products** for **top squark** mass degenerate with neutralino LSP.
  - **low cross sections** and **low p_T decay products** for mass degenerate **higgsinos**.

Alternate models

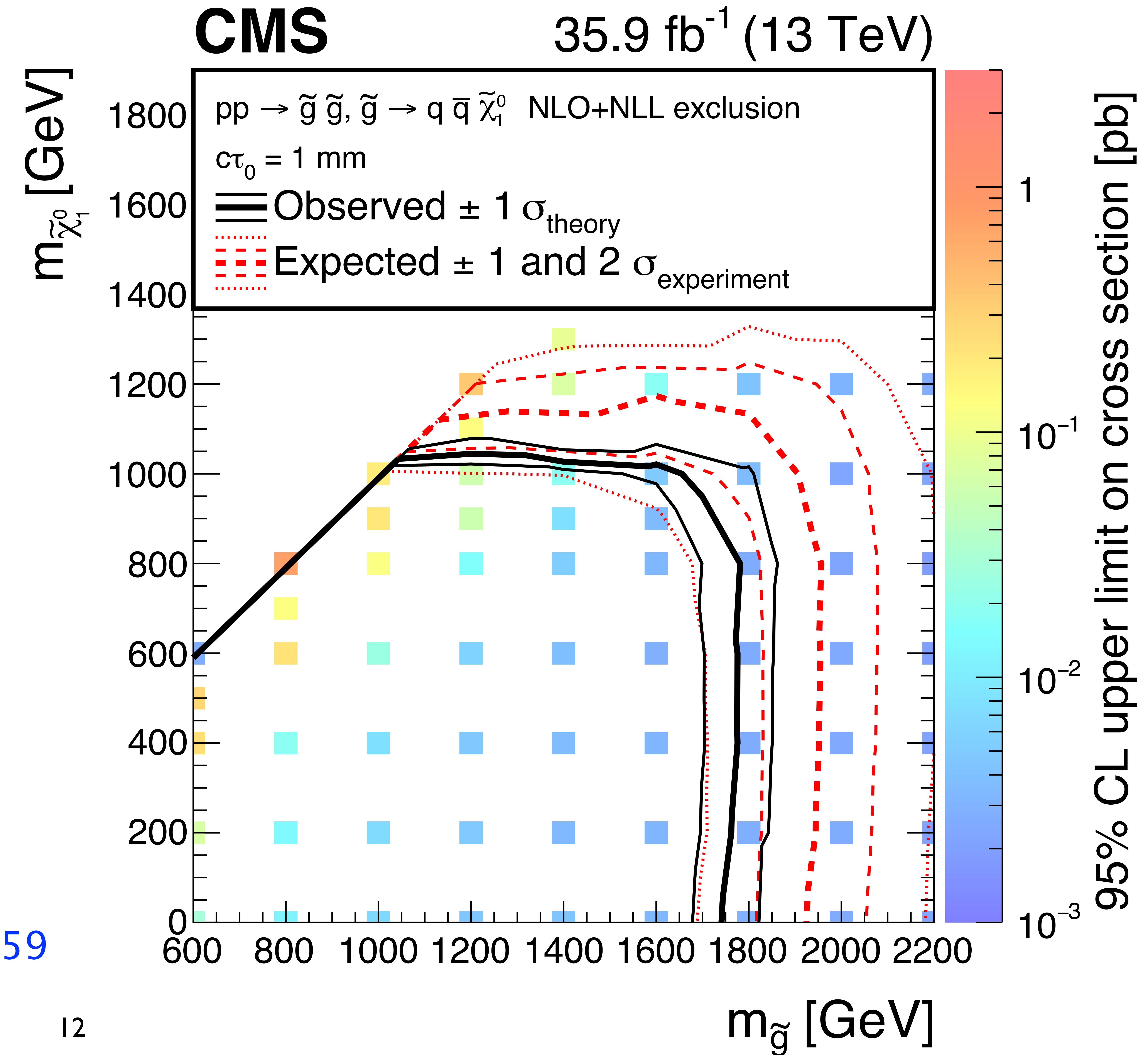
- long-lived particles in split SUSY
- R-parity violation

Long-lived gluino in split SUSY SUS-16-038

Split SUSY [1,2]:

- bosonic sparticles have very high mass
- **gluino is long-lived** from suppressed decay through highly off-shell squark

- **Inclusive search**
  - uses only standard prompt jets and missing energy
  - makes **no assumption about interaction of gluino** with detector – only decay products.



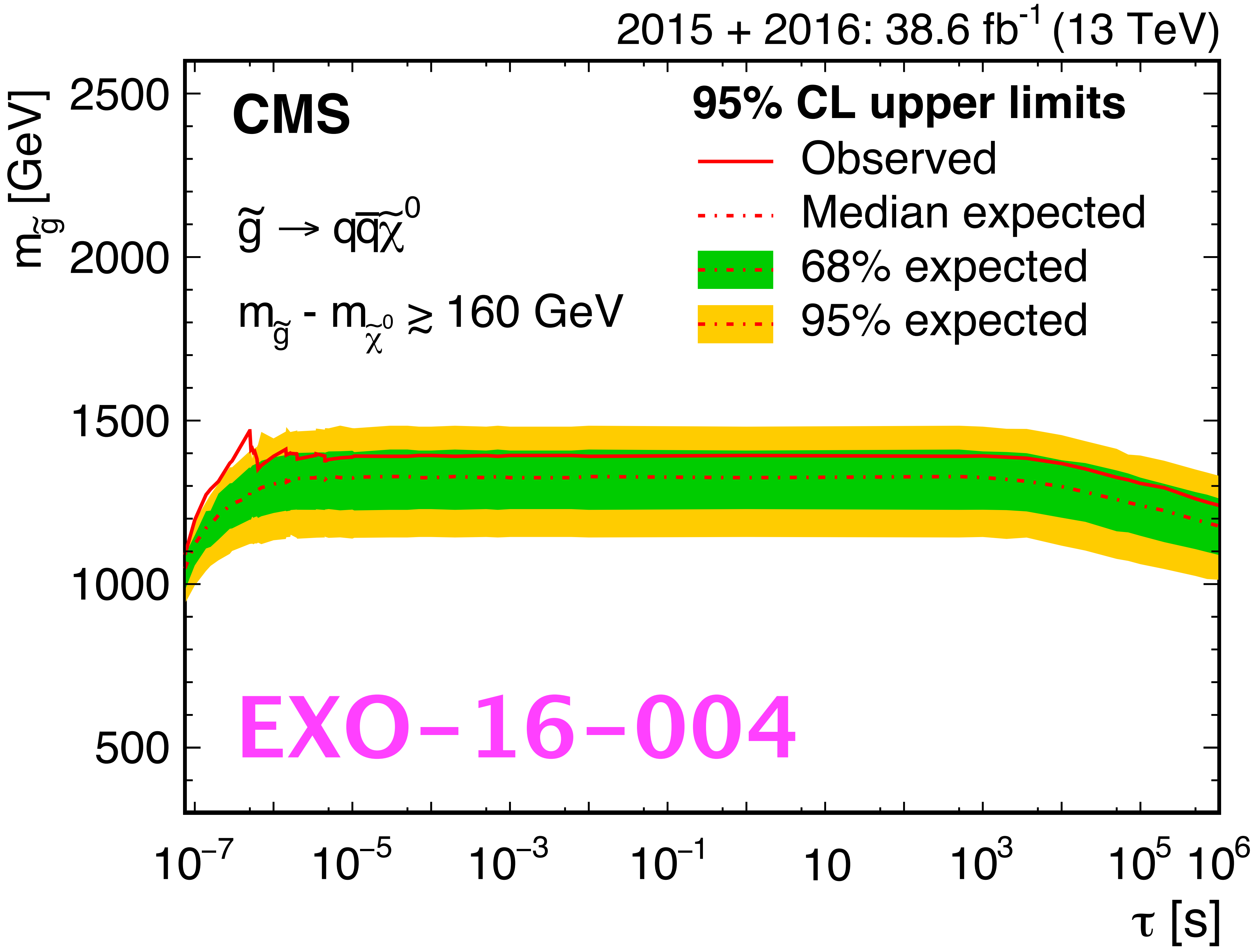
[1] Arkani-Hamed, Dimopolous; arXiv:hep-th/0405159

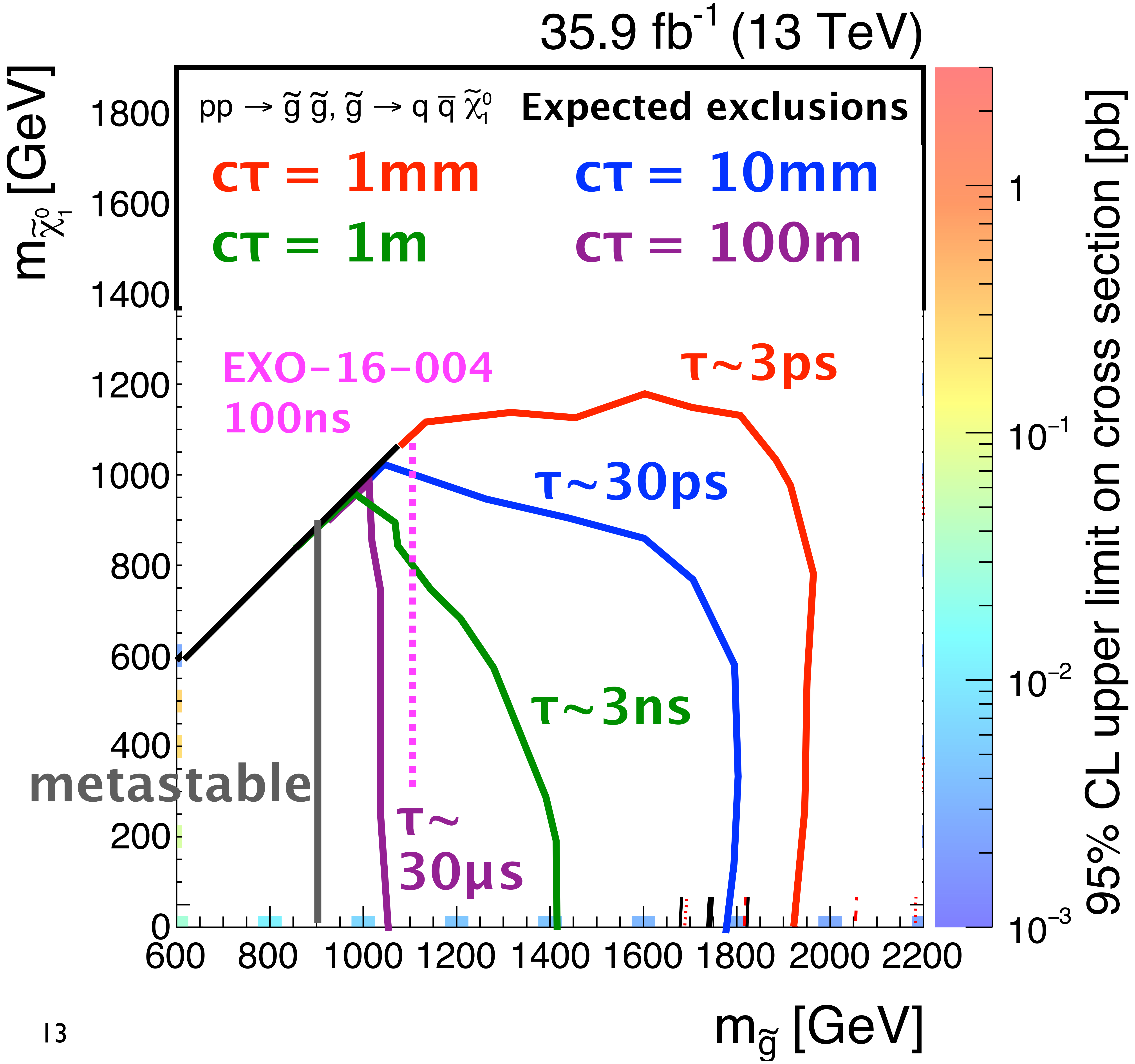
[2] Giudice, Romanino; arXiv:hep-ph/0406088

Long-lived gluino in split SUSY

SUS-16-038

- Probes 10^{-15}s < τ < metastable
- Complementary to long-lived gluino searches for out-of-time energy deposition in range $10^{-7} < \tau < 10^{6}$ s.





R-parity

- R-parity is even for SM particles and odd for SUSY particles

  $R_P = (-1)^{3(B-L)+2S}$

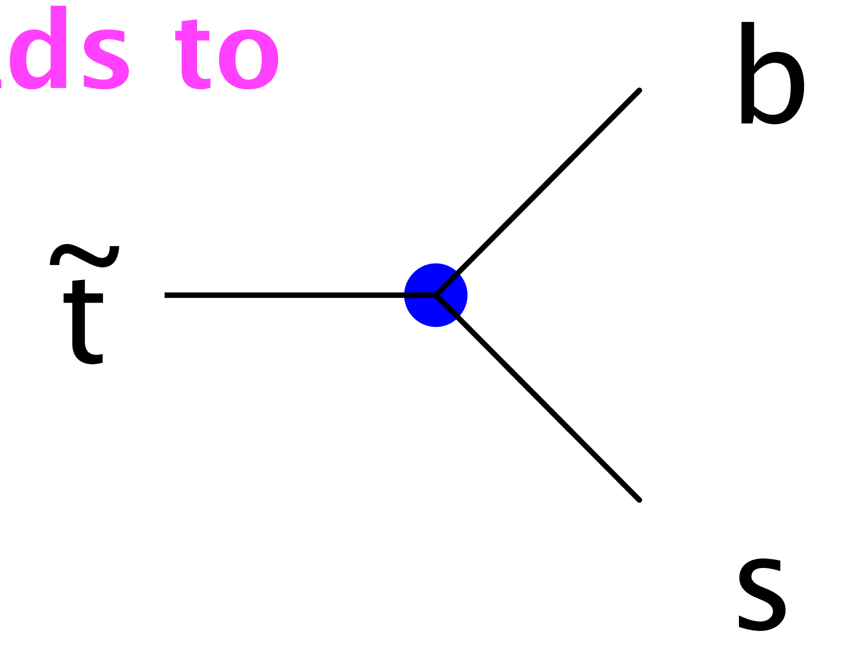
- R_P conservation ➔ SUSY does result in rapid proton decay or other unobserved processes.
- However, allowing **single** R_P violating coupling (λ, λ', λ") in the super potential would not cause problems for theory:

$$W_{\mathrm{RPV}} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

$(\Delta L, \Delta B) = (1,0)$ $\quad (\Delta L, \Delta B) = (1,0)$ $\quad (\Delta L, \Delta B) = (0,1)$

L = left-handed lepton doublet
Q = left-handed quark doublet
E = right-handed lepton singlet
U,D = right-handed quark singlet
i, j, k = generation indices
$\lambda, \lambda', \lambda''$ = RPV couplings

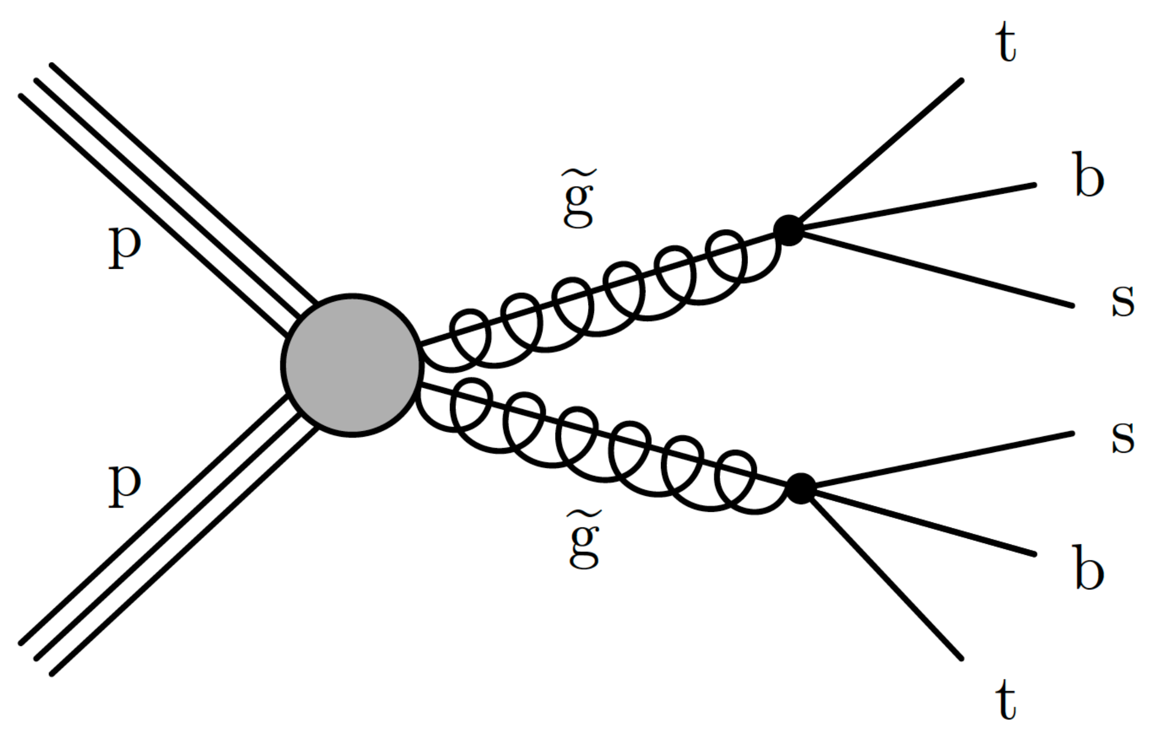
λ''_{323} > 0 leads to interaction



R-parity violating gluino decay

SUS-16-040

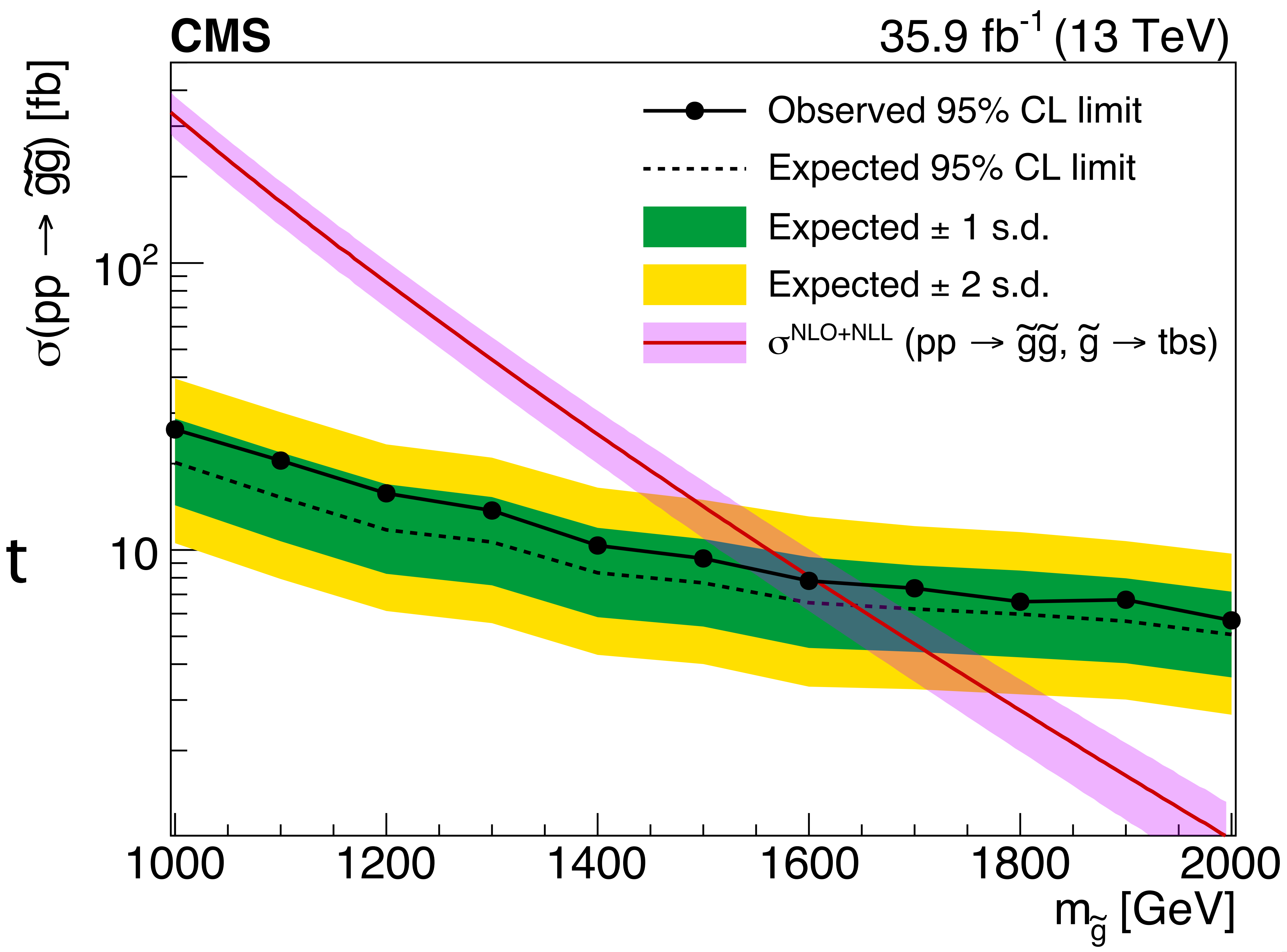
- When λ"$_{323}$>0, gluino ➔ tbs decay proceeds via virtual $\tilde{t}$.
    - Preferred decay in models with minimal flavor violation.

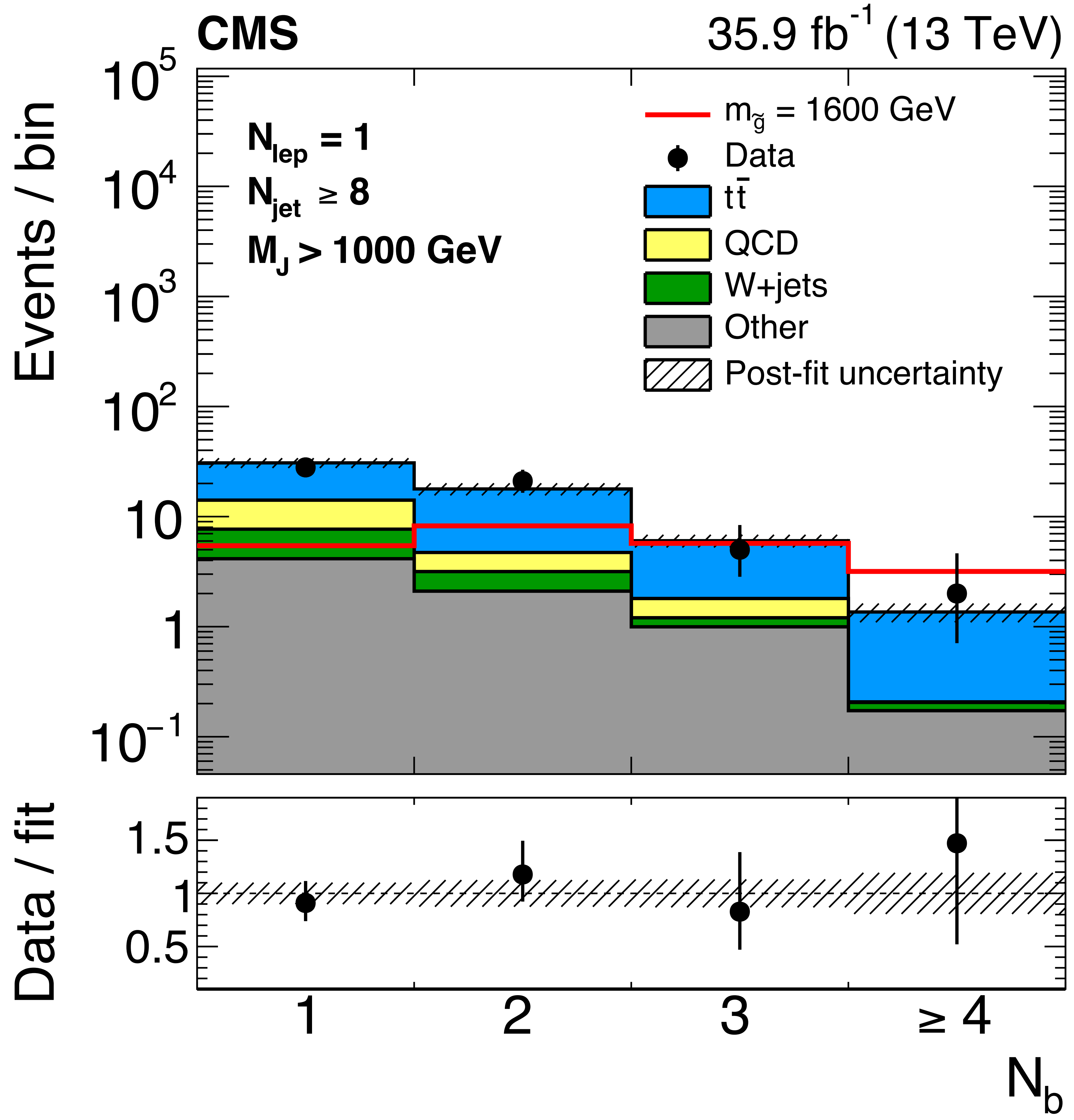


- Main sensitivity from events with 1ℓ, ≥8 jets, ≥4 b-tagged jets, and ΣM_{jets} > 1TeV.

- Exclude m<1.6 TeV without use of MET!

- Final states w/out top and bottom quarks are more challenging.

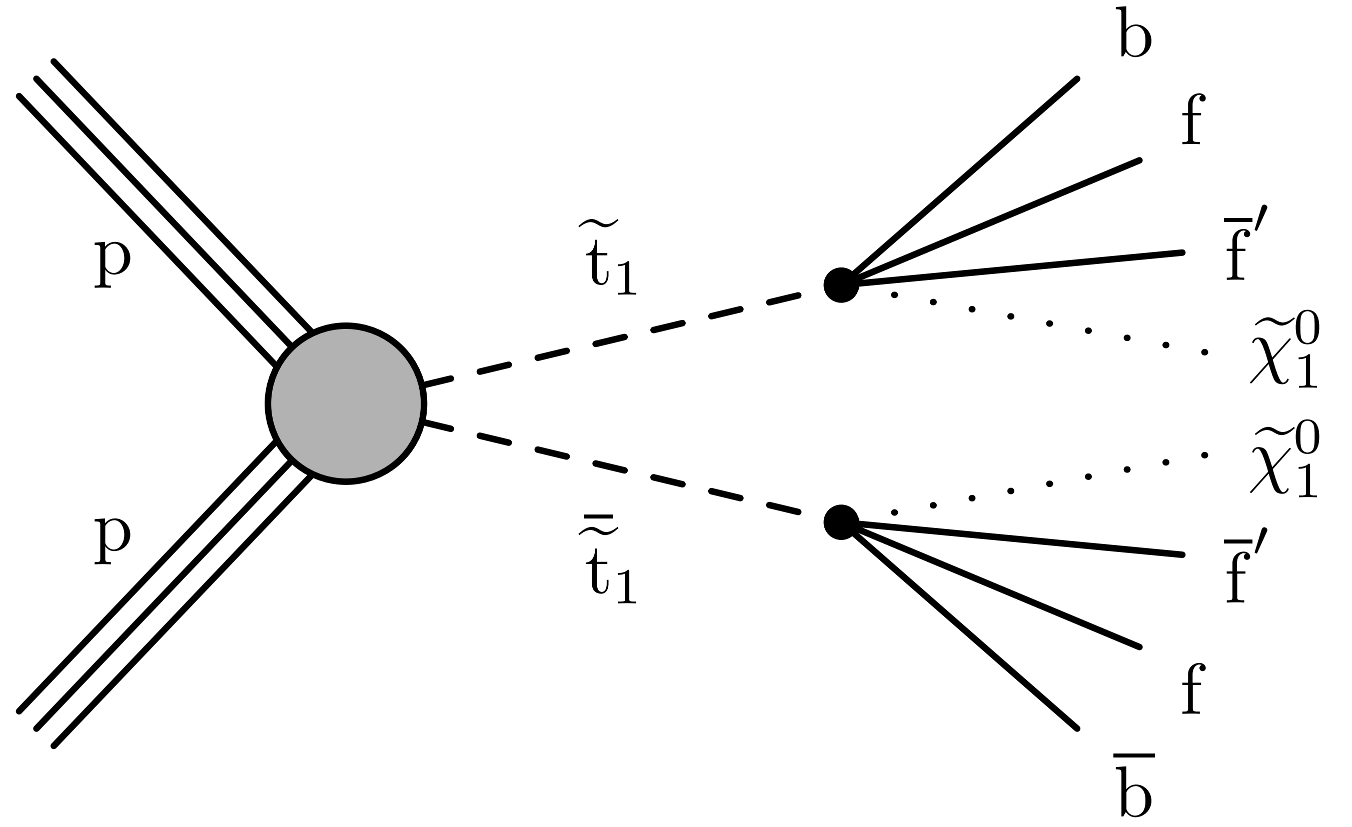




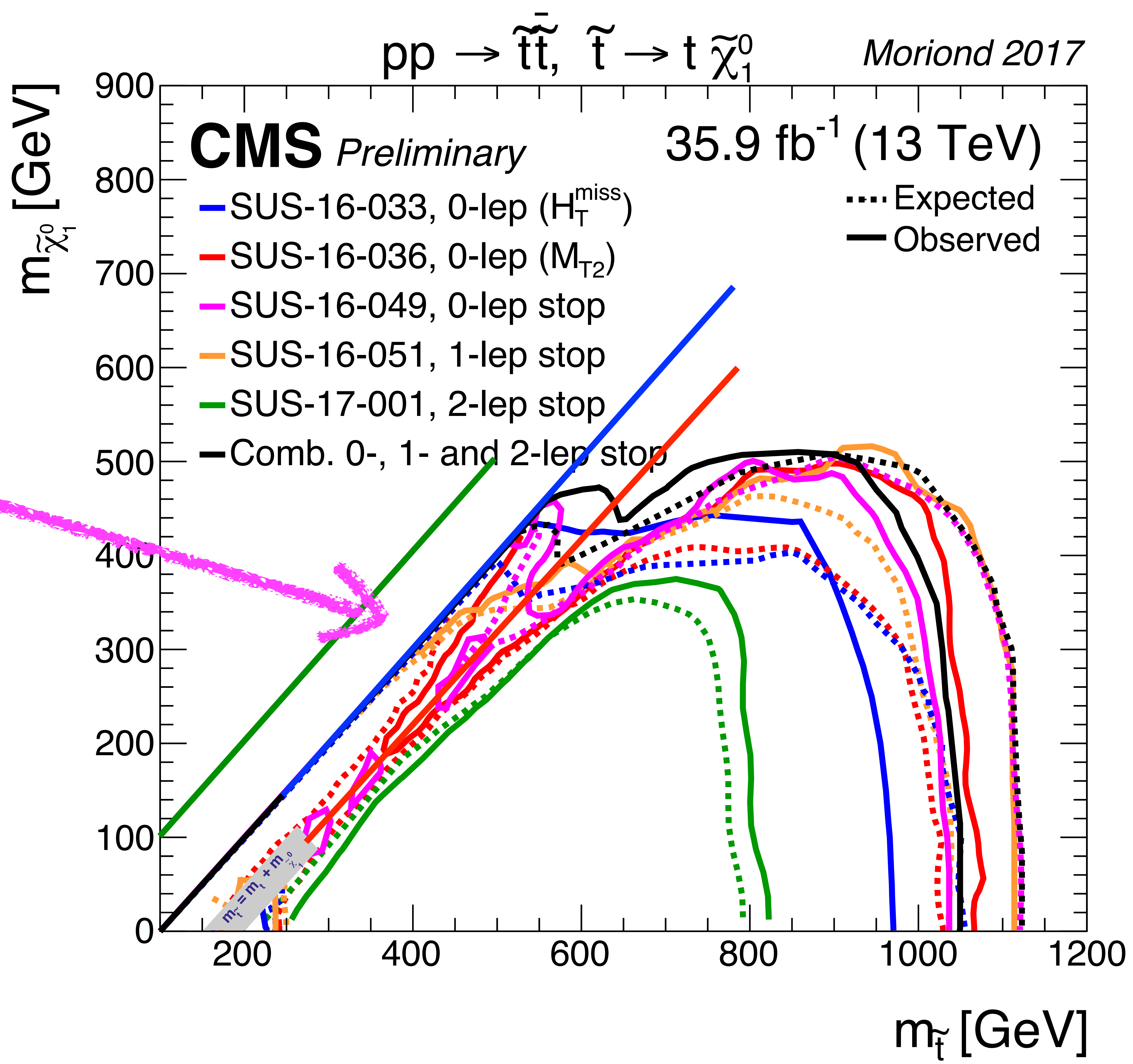
Challenging corners of natural SUSY parameter space

- mass degenerate top squark and neutralino
- mass degenerate higgsinos

Top squark in "compressed spectrum"



- One $\tilde{t}_1$ should be light since mass splitting ∝ Yukawa coupling
- CMB measurements consistent with $\tilde{\chi}_1^0$ dark matter mass degenerate with co-annihilating $\tilde{t}$ [1].
- **Challenge**: When $\Delta m(\tilde{t}, \tilde{\chi}_1^0) < m_W$, $\tilde{t}$ undergoes 4-body decay into low p_T final state particles.



How to identify this challenging signature?

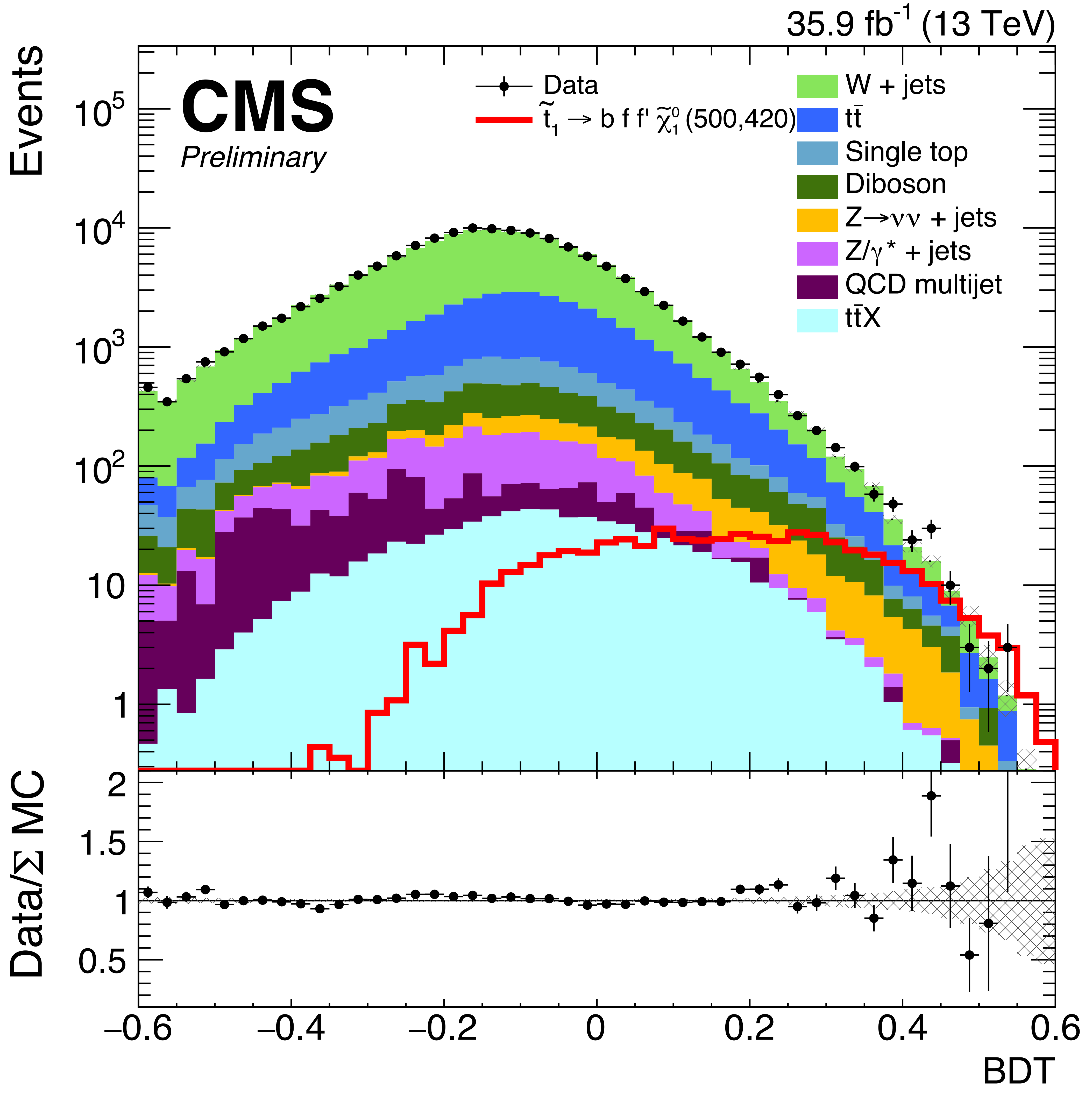
- Trigger on jet from **gluon initial state radiation** (ISR).
- **Require** ℓ with p_T > 3.5-5 GeV, MET > 200 GeV, Njets = 1 or 2.

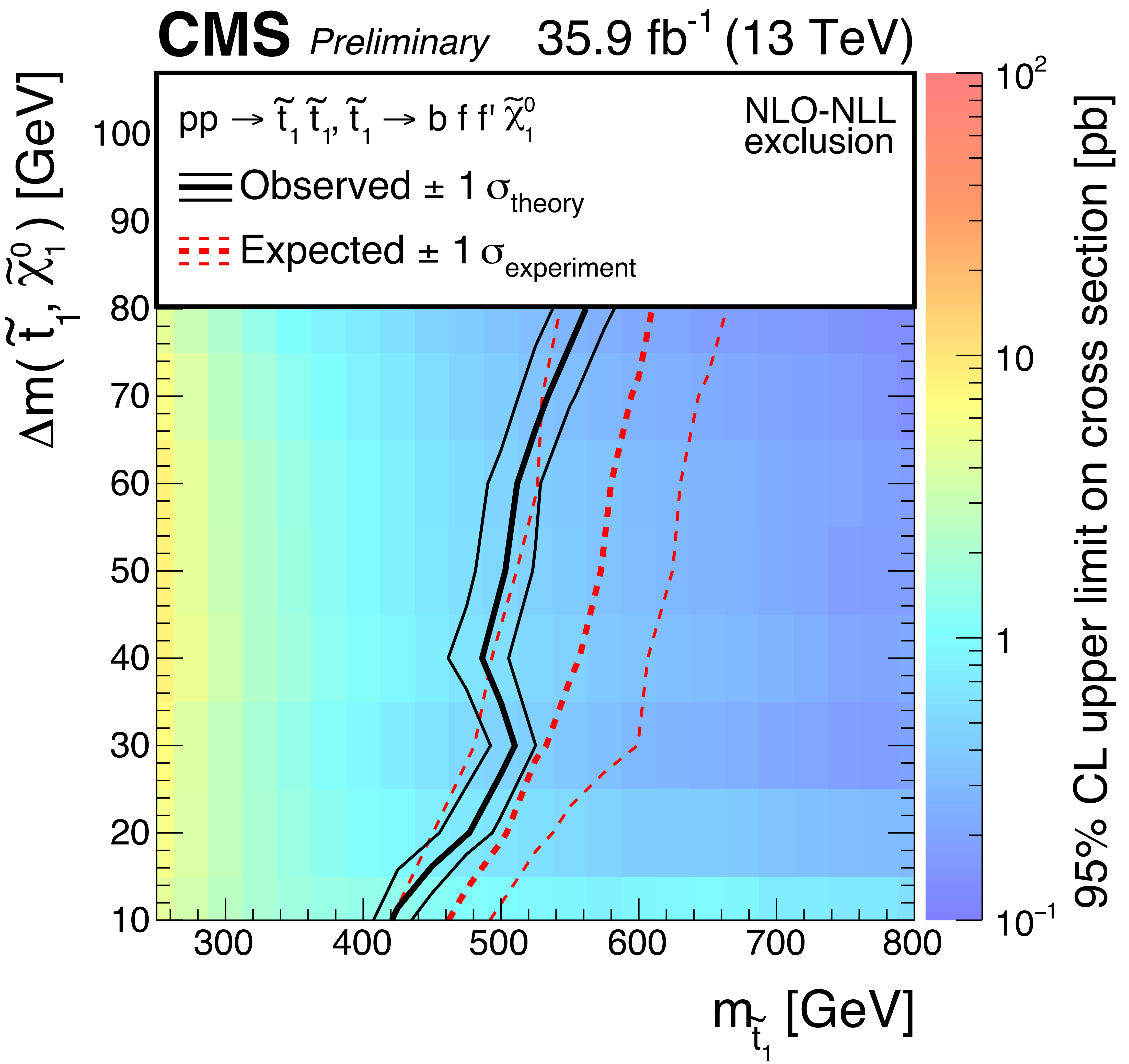
[1] Balazs, Carena, Wagner; arXiv:hep-ph/0403224

Top squark in "compressed spectrum"

- Use Boosted Decision Tree to distinguish from W and tt background.
- BDT based on final state kinematics, multiplicity, b-tagging, etc.

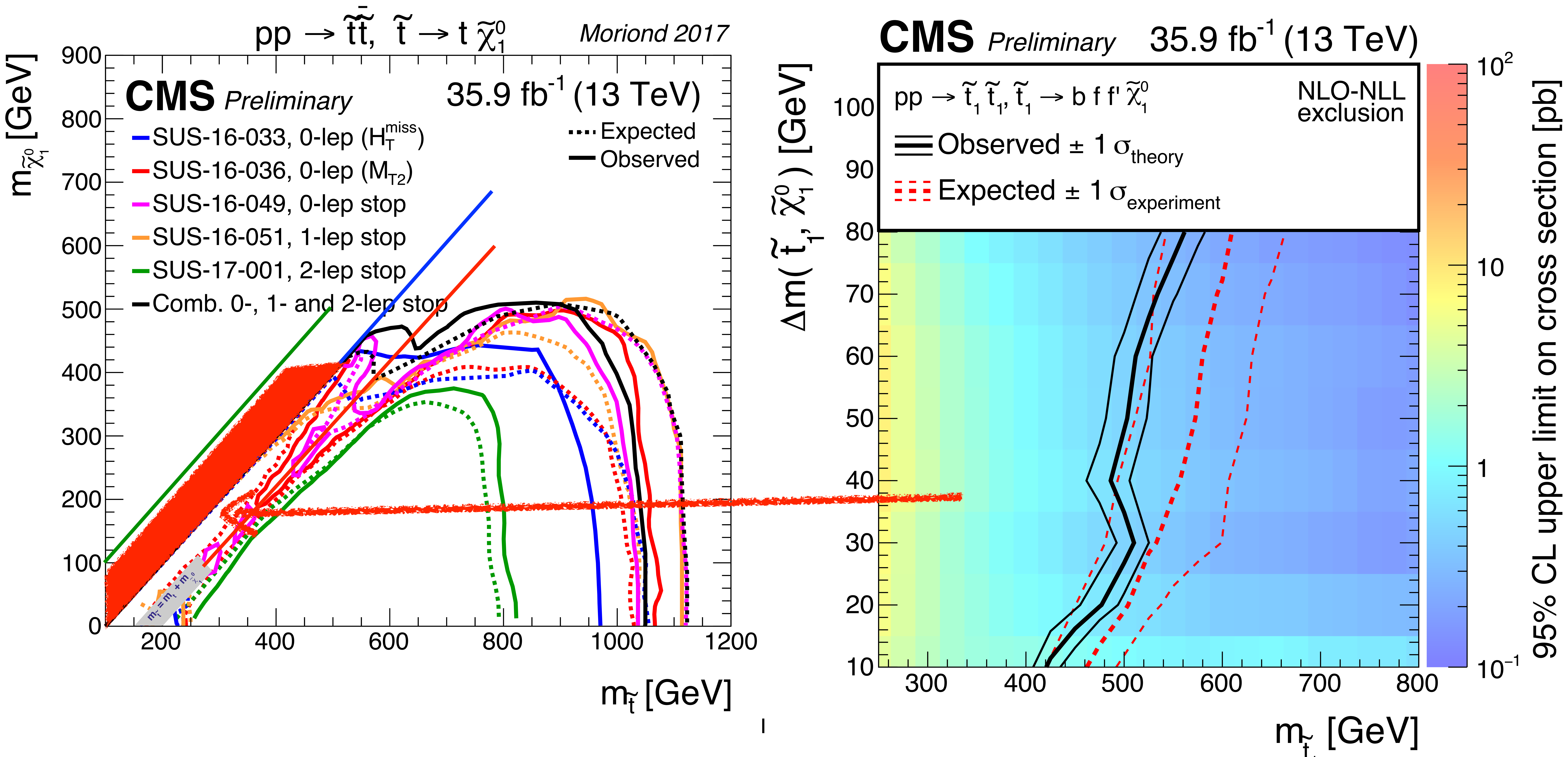
SUS-17-005



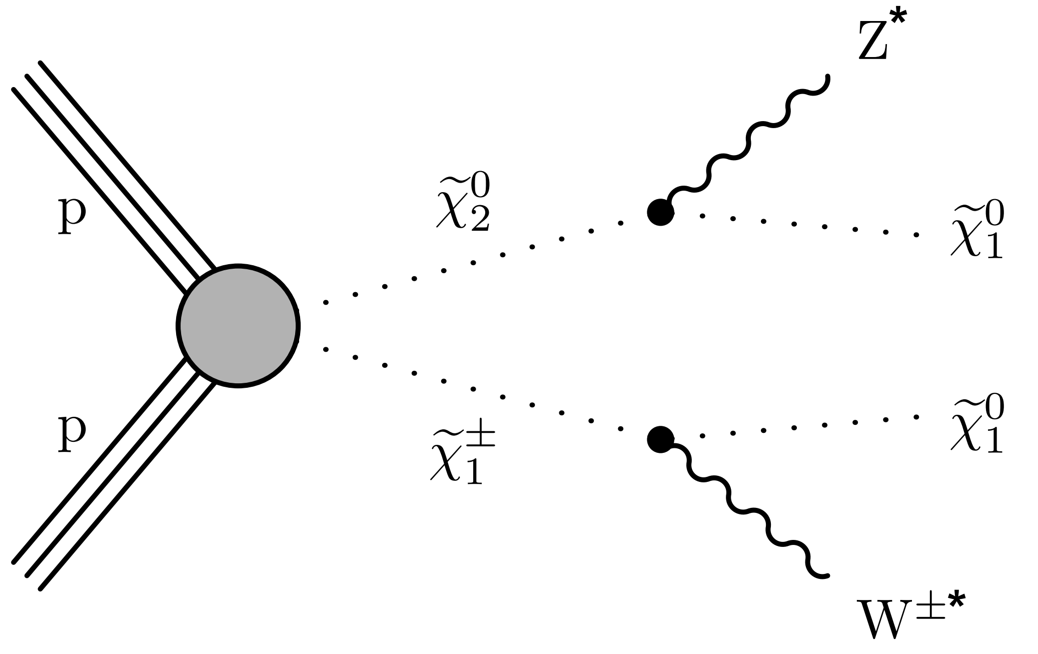


Top squark in "compressed spectrum"

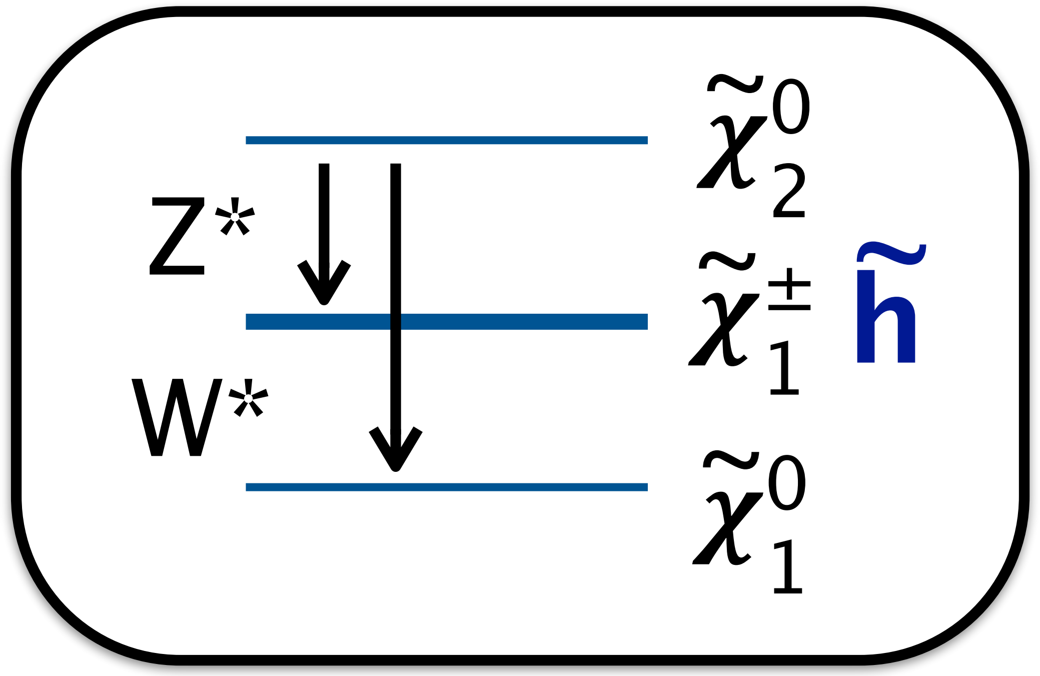
SUS-17-005



Higgsino search **SUS-16-048**



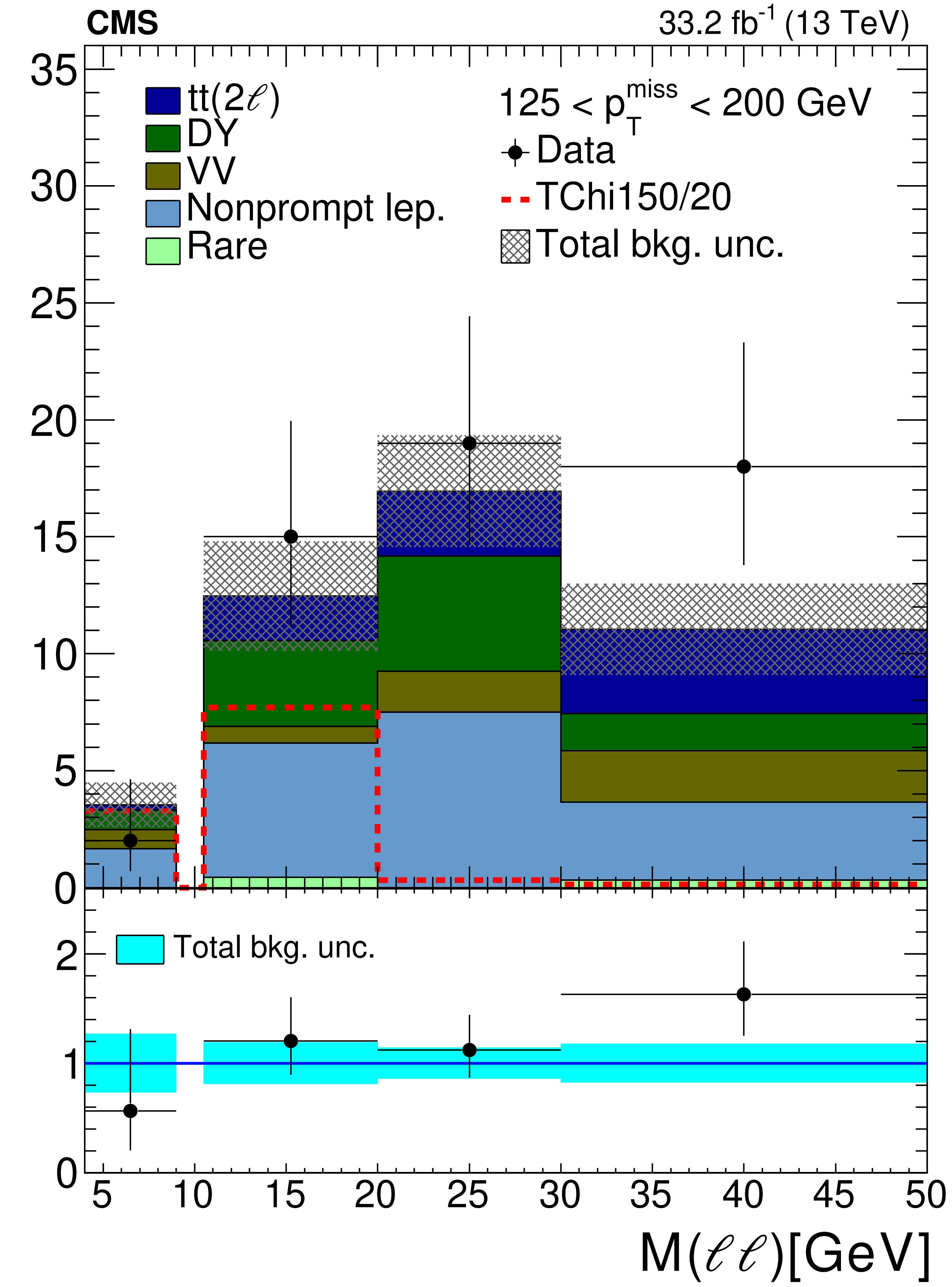
Two challenges:



- Mass splitting between $\tilde{h}$ states expected to be <10 GeV, so decay products have low pT.
- Higgsino cross section is smallest of all SUSY particles.

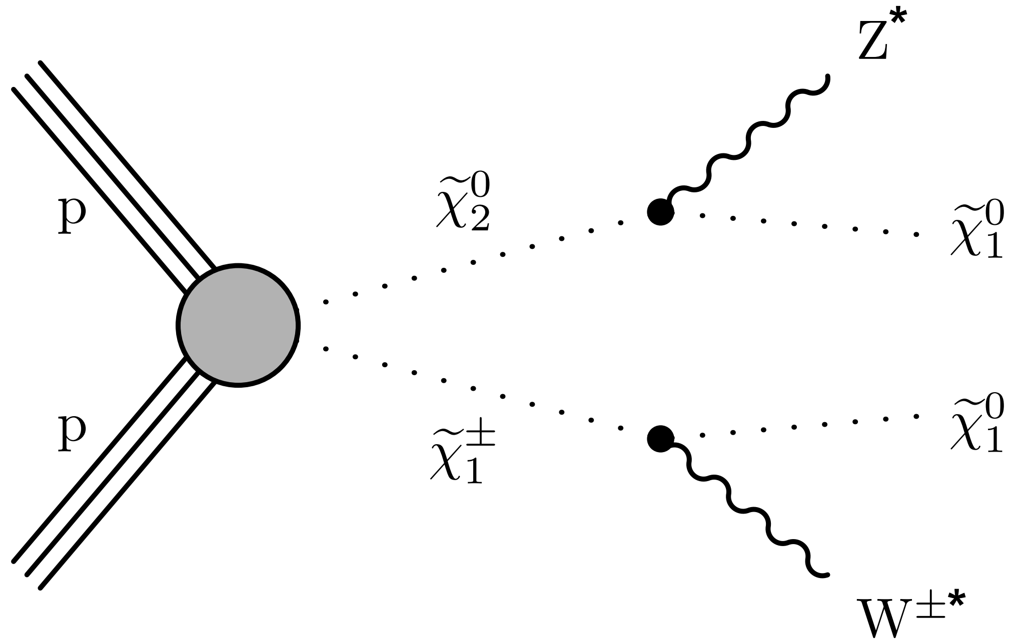
- As for top squark search, **trigger** on ISR jet.
- Search for ISR jet + missing energy and $\ell\ell$ with ℓ p_T of 3.5 – 30 GeV.

- **Reduce background**: tight requirements on ℓ impact parameter, small $M_T(\ell$, MET), small $M_{\ell\ell}$, no b-tagged jets

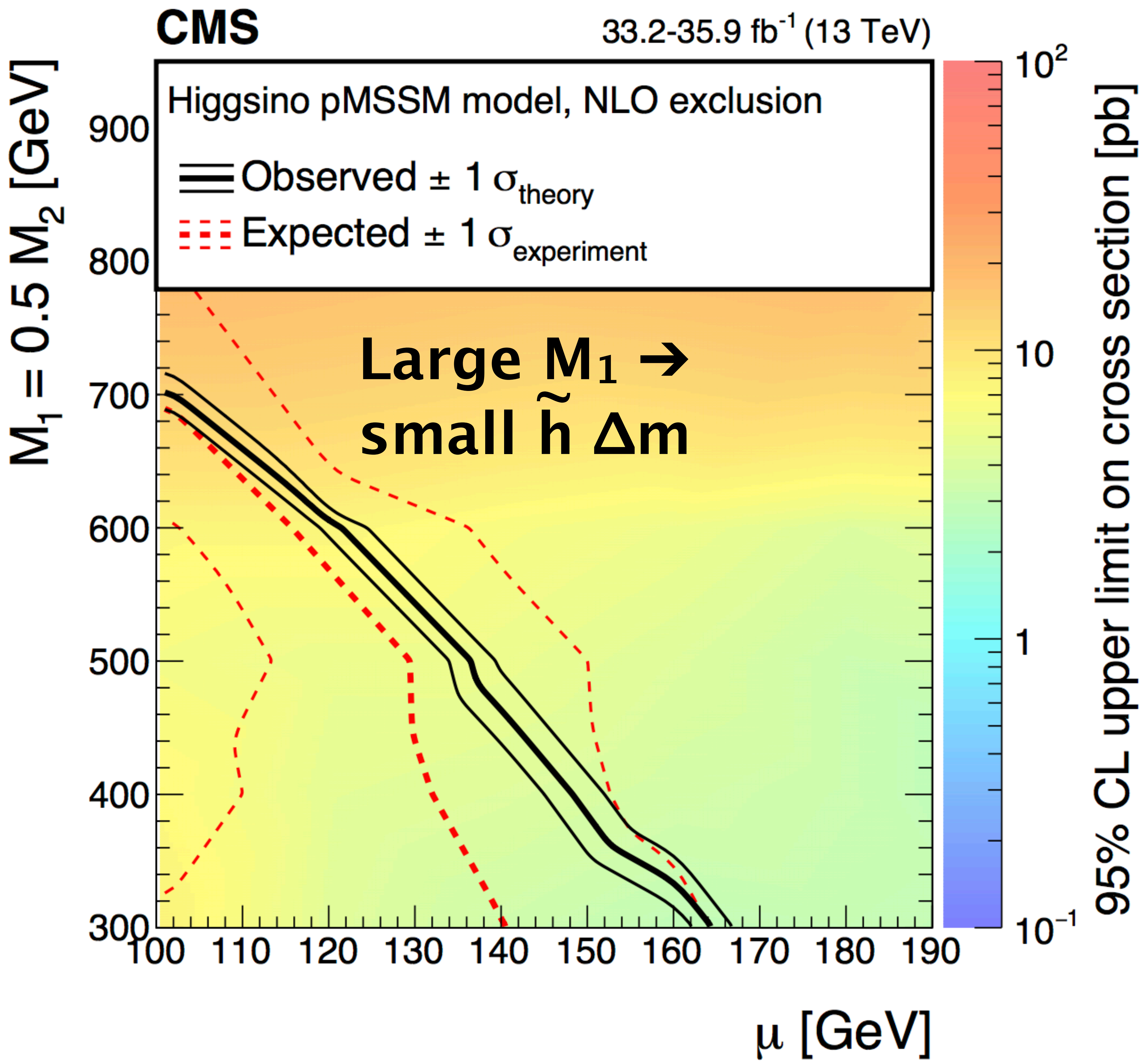


Two $\tilde{h}$ search interpretations

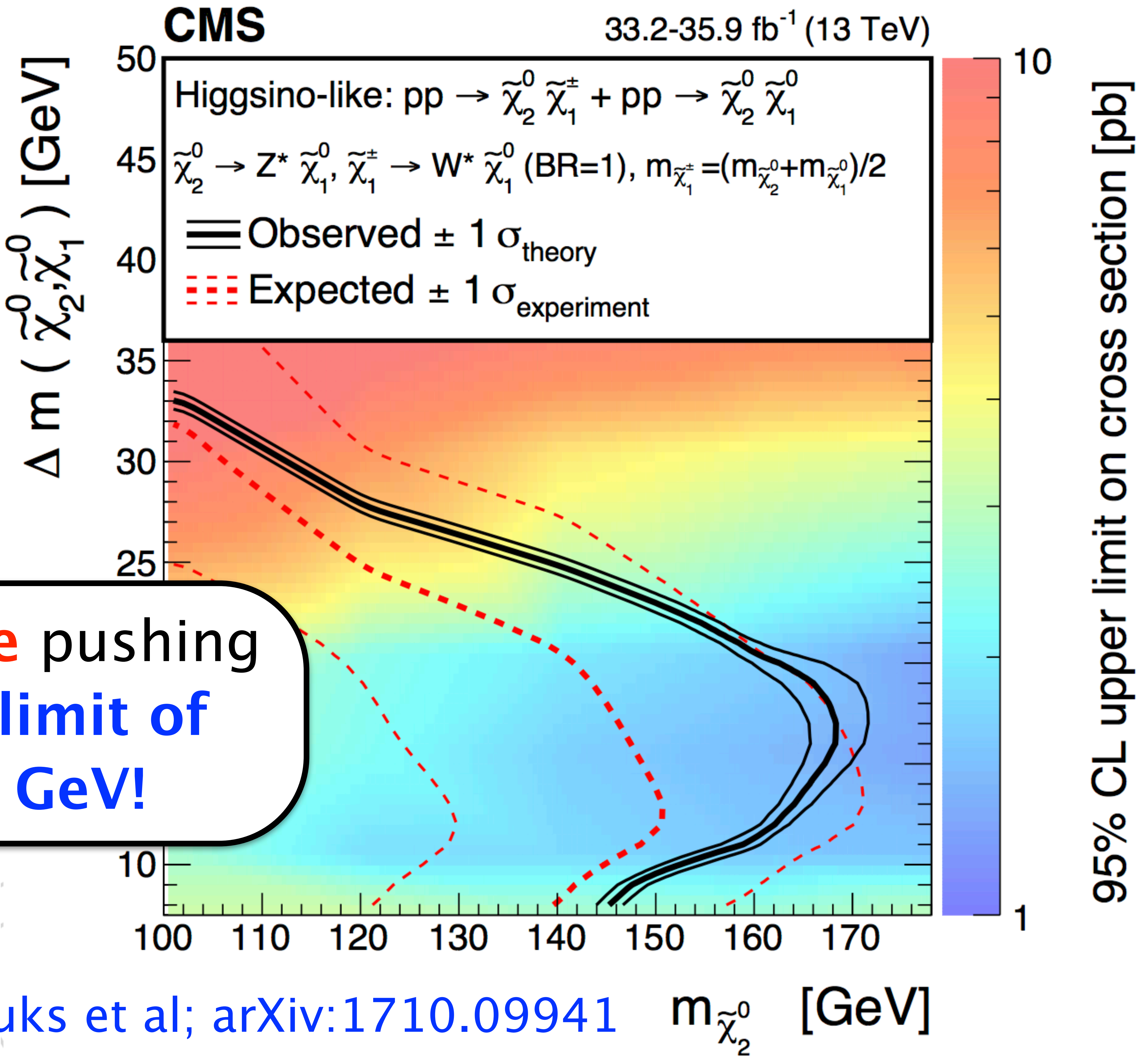
SUS-16-048



1. **pMSSM** : vary M_1 (bino) and μ (higgsino), M_2 (wino) = $2M_1$, other mass scales set high



2. **realistic simplified model [1]**



First time pushing past **LEP limit of m_h >100 GeV!**

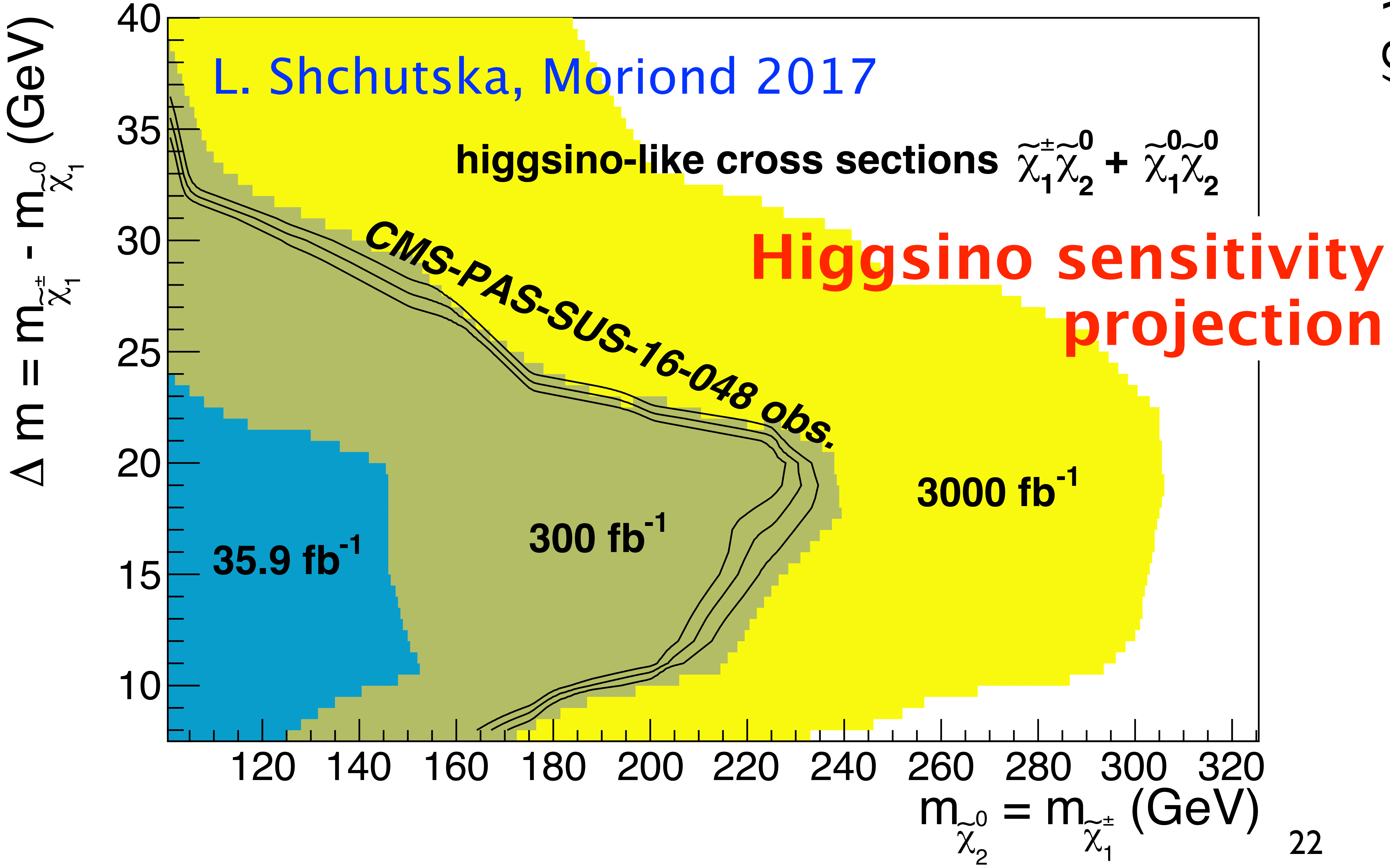
[1] Fuks et al; arXiv:1710.09941

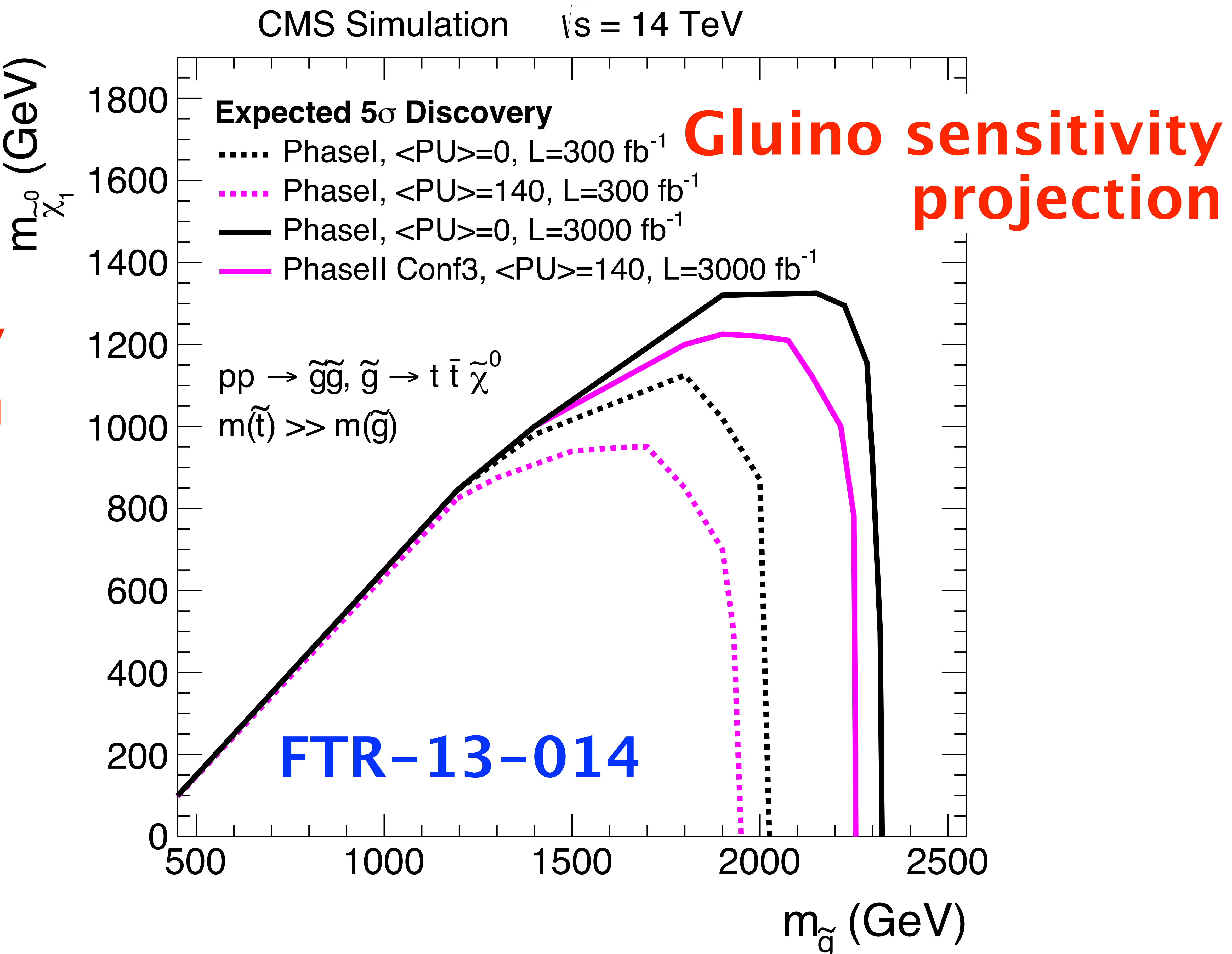
Summary and outlook

- As bulk of natural SUSY space is ruled out, **focus on targeted searches increases**.

Prospect for long term discovery at HL-LHC depends on particle:

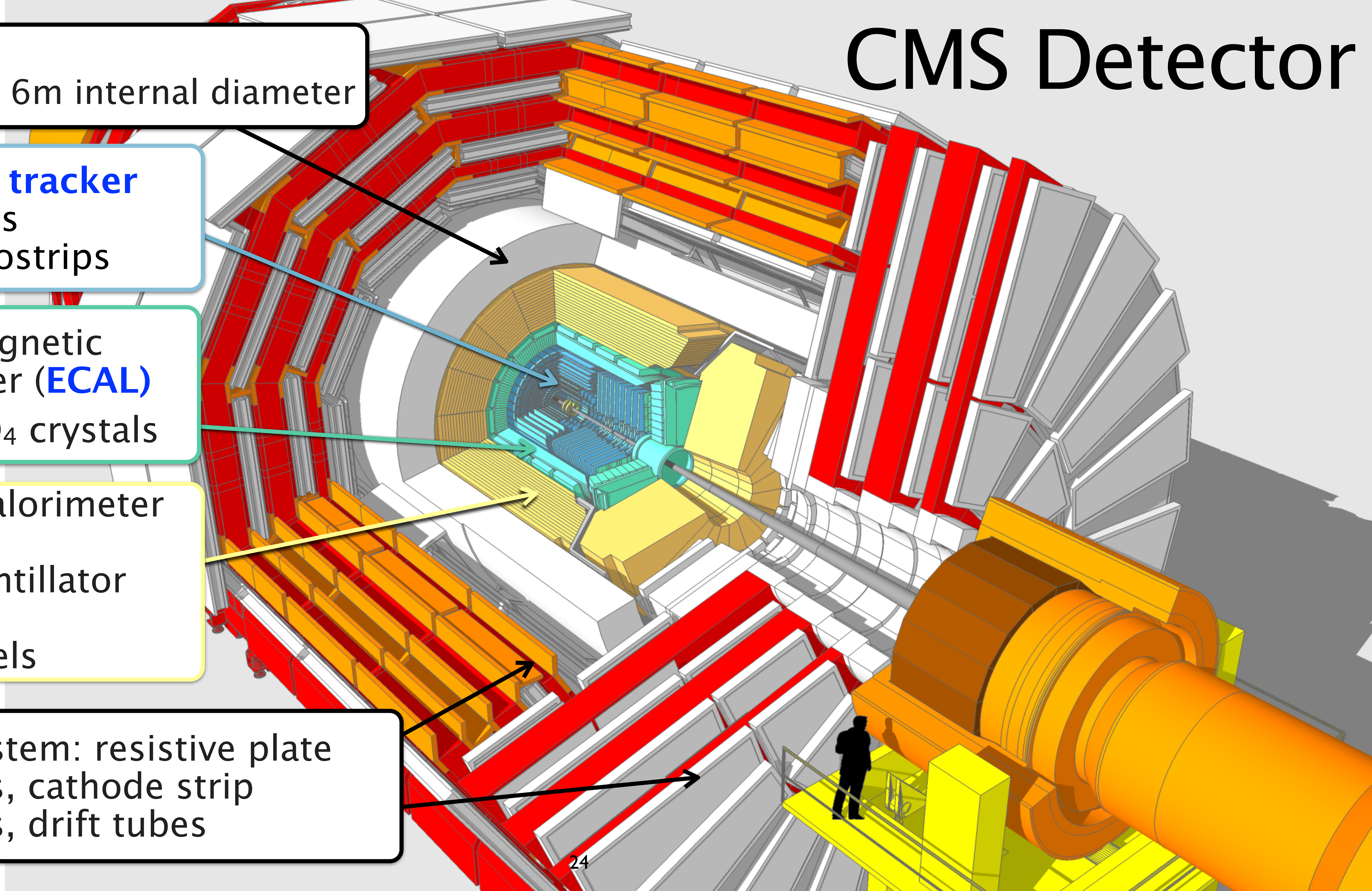
- 5σ reach for **gluinos** is ~2.3 TeV at HL-LHC; current reach is 1.9 TeV.
- 2σ reach for **higgsinos** is 300 GeV at HL-LHC; current reach is 170 GeV.



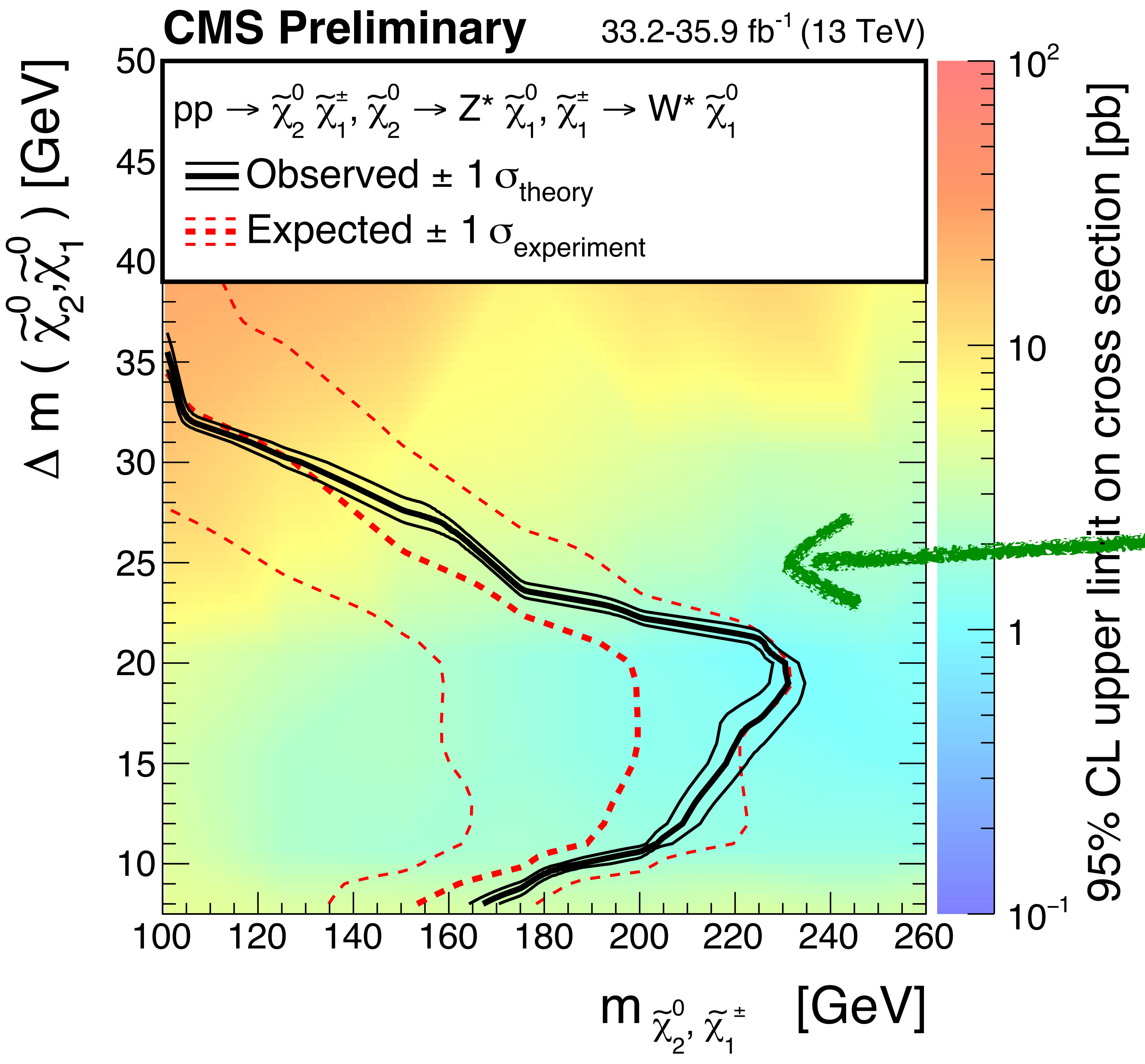


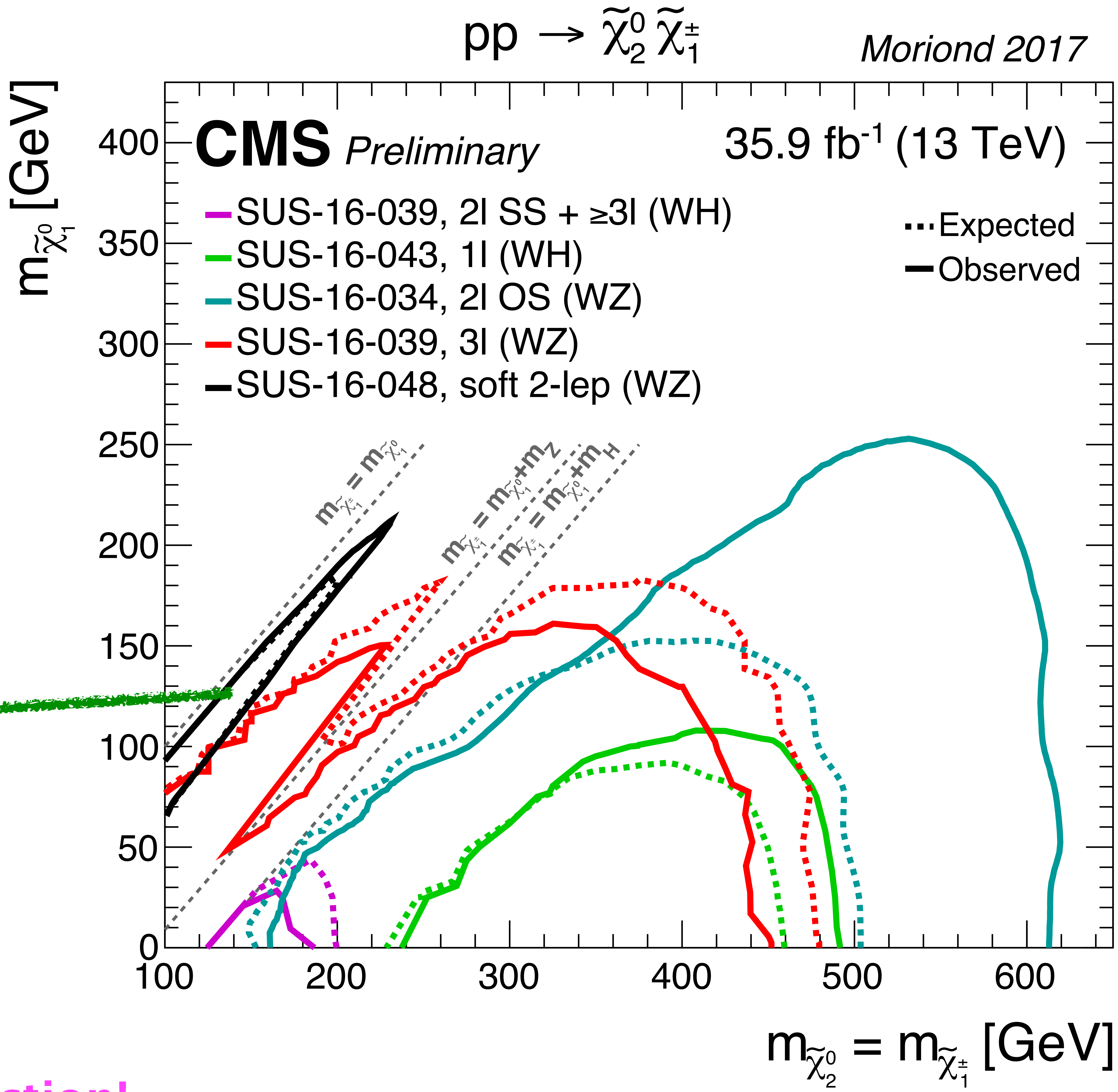
Additional Material

CMS Detector



EWKino sensitivity





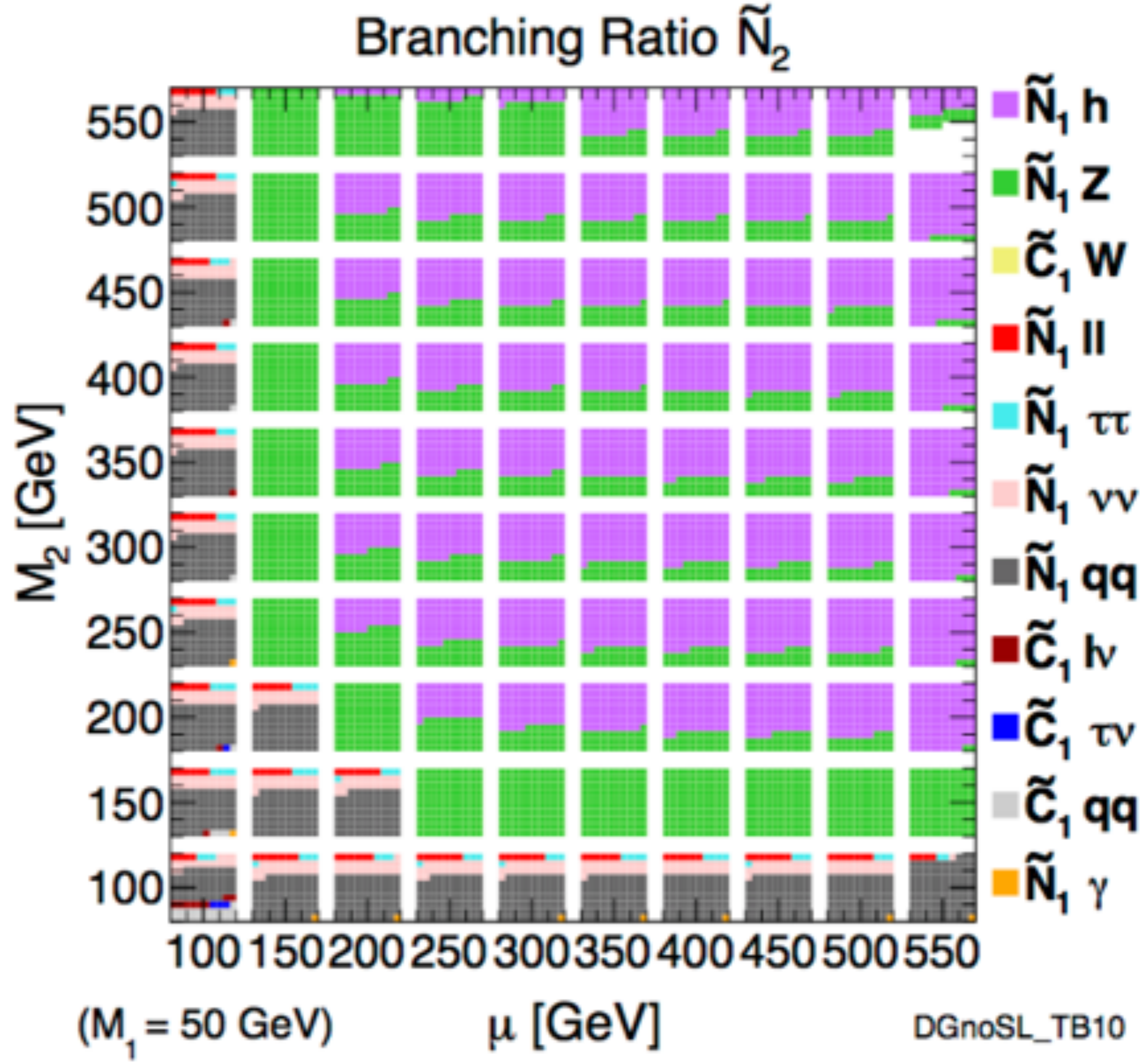
NB: assumes wino-like cross section!

EWKino branching fractions in pMSSM

- M_1 (bino) = 50 GeV
- M_2 (wino), μ (higgsino) running
- all others decoupled

SUS-16-048

- M_1, μ running
- $M_2 = 2M_1$
- tan β = 10



gaugino–higgsino simplified model

[1] Fuks et al; arXiv:1710.09941

To calculate the cross sections in this model, a scan in $|\mu|$, M_1, M_2 and tan β is carried out. All parameters are required to be real, M_2 to be positive and $\tan\beta \in [1, 100]$. The remaining SUSY particle masses are decoupled, and all trilinear couplings are discarded. The parameter space is then scanned to achieve the maximum higgsino content for χ_2^0, $\chi_1^\pm$, and χ_1^0.