Signatures for SUSY with light higgsinos: from here to HL- and HE-LHC

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theory still

(natural) SUSY

in collaboration with V. Barger,
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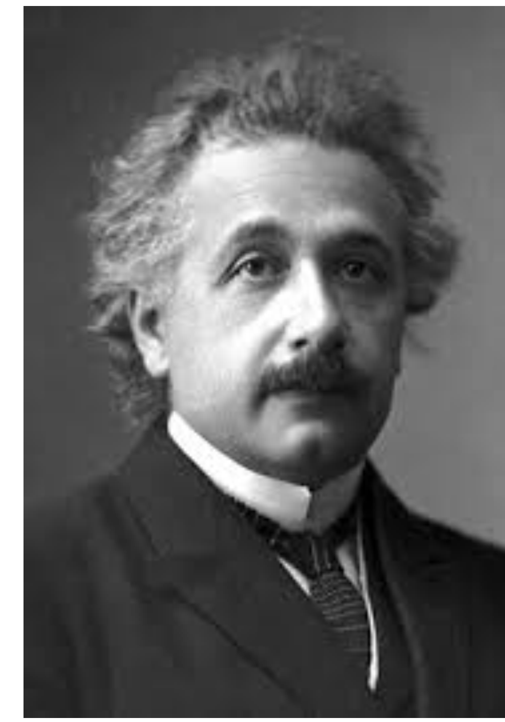
In memory of Frank Paige, author of ISAJET, 1944-2017

twin pillars of guidance:
naturalness & simplicity

``The appearance of fine-tuning in a scientific theory is like a cry of distress from nature, complaining that something needs to be better explained"

S. Weinberg



``Everything should be made as simple as possible, but not simpler"

A. Einstein

SUSY solves the gauge hierarchy problem
and thus can accommodate fundamental scalars such as
the h(125) discovered at CERN in 2012

SUSY virtual effects consistent with

- gauge couplings measurements at LEP
- m(t)~173 GeV measurement (Tevatron)
- m(h)~125 GeV measurement (LHC)

Lately: is there a Little Hierarchy problem?
Why are m(W,Z,h)~100 GeV whilst m(SUSY)>1-2 TeV?

The Naturalness question

m(weak)~100 GeV meets the SUSY Lagrangian:
minimization of scalar potential to determine Higgs vevs

Simplest, most conservative measure: Δ_{EW}

Working only at the weak scale, minimize scalar potential: calculate m(Z) or m(h)

No large uncorrelated cancellations in m(Z) or m(h)

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \quad \sim -m_{H_u}^2 - \Sigma_u^u - \mu^2$$

$\Delta_{EW} \equiv max_i \left|C_i\right| / (m_Z^2/2)$ with $C_{H_u} = -m_{H_u}^2 \tan^2\beta/(\tan^2\beta - 1)$ etc.

simple, direct, unambiguous interpretation:

- $|\mu| \sim m_Z \sim 100 - 200$ GeV (Chan, Chatto...,Nath)
- $m_{H_u}^2$ should be driven to small negative values such that $-m_{H_u}^2 \sim 100 - 200$ GeV at the weak scale and
- that the radiative corrections are not too large: $\Sigma_u^u \lesssim 100 - 200$ GeV

CETUP*-12/002, FTPI-MINN-12/22, UMN-TH-3109/12, UH-511-1195-12

Radiative natural SUSY with a 125 GeV Higgs boson

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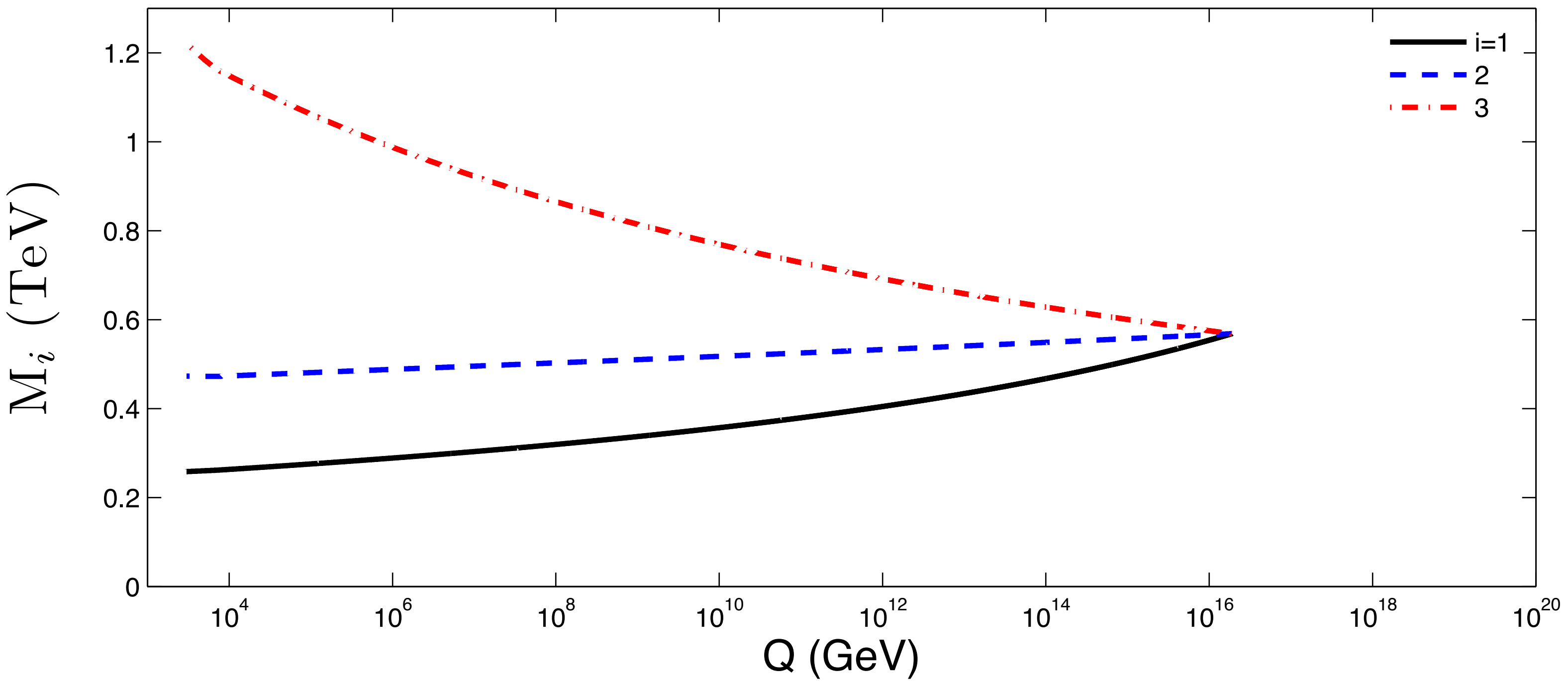
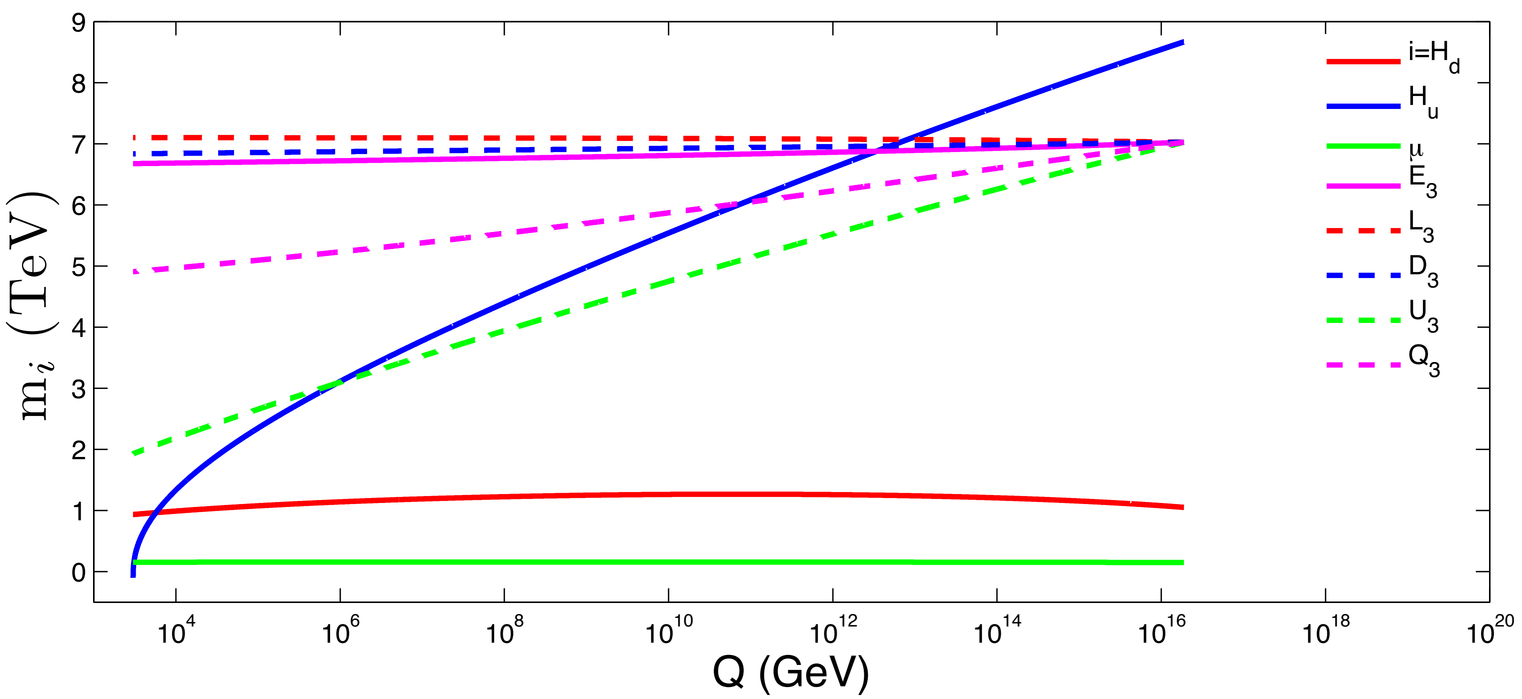
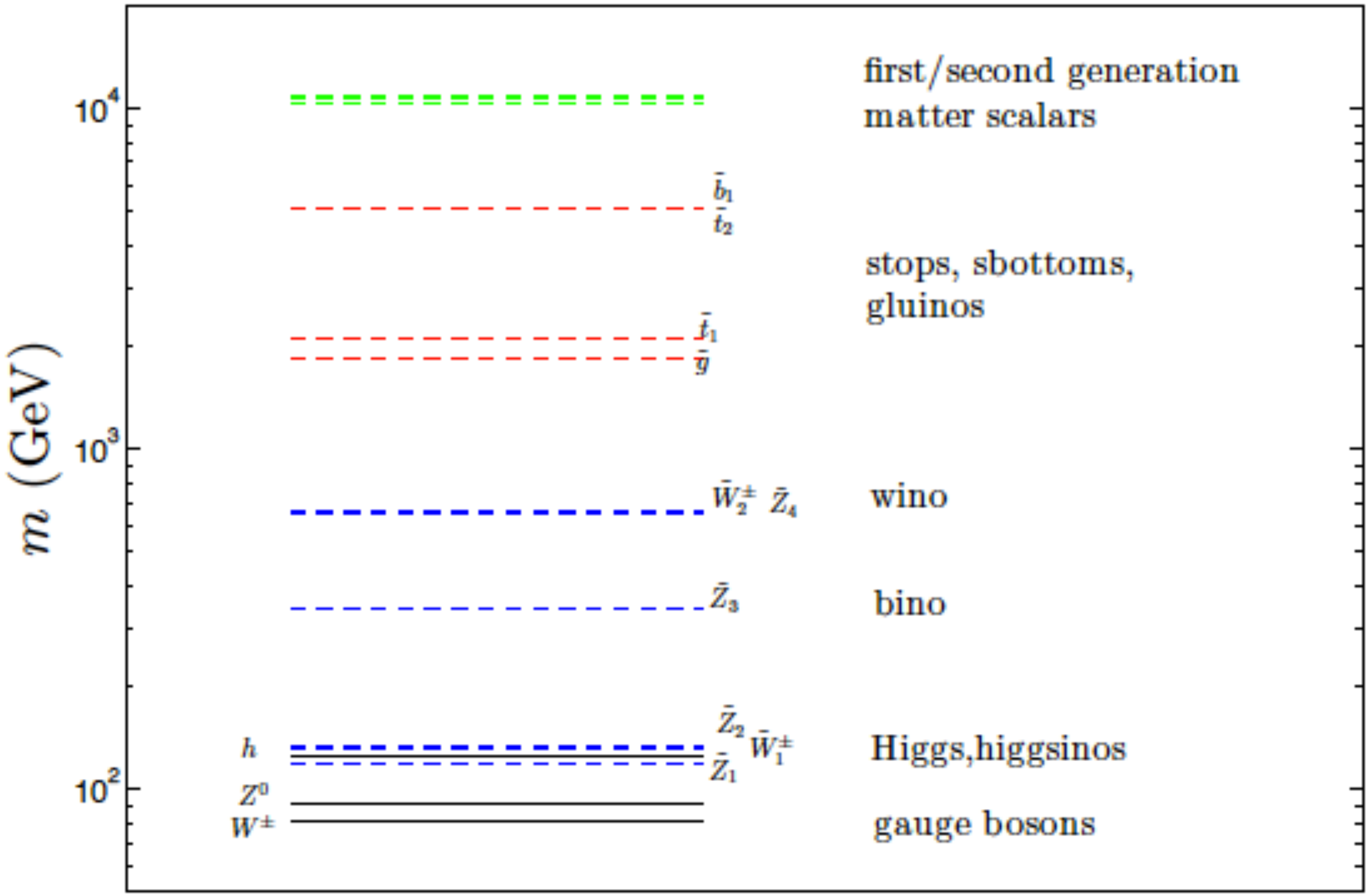




RNS: Radiative corrections
drive m(Hu)^2 to
natural value ~m(Z) at weak scale

mu hardly evolves

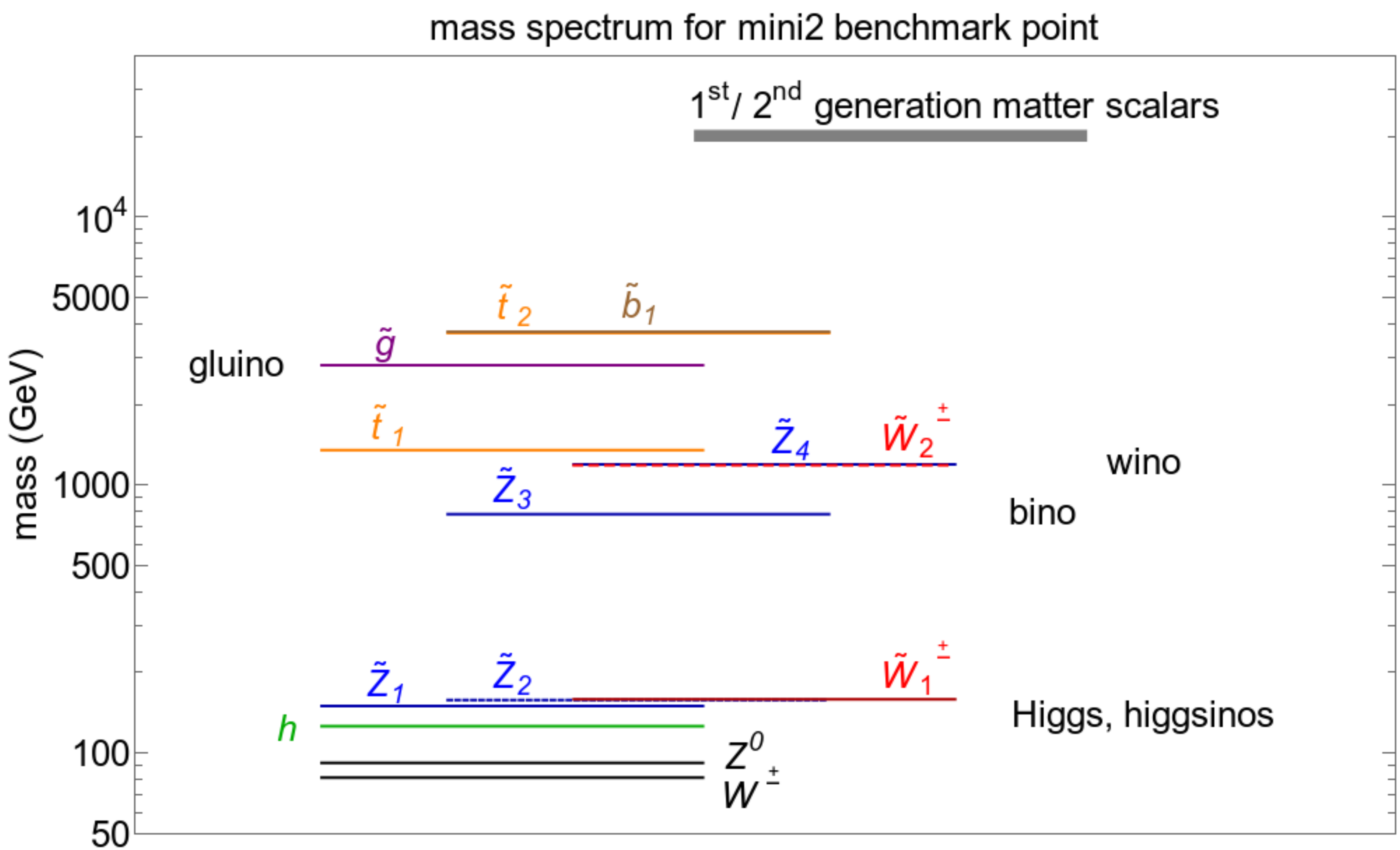
Typical spectrum for low Δ_{EW} models



There is a Little Hierarchy, but it is no problem

$$\mu \ll m_{3/2}$$

m(higgsinos)~100-200 GeV; m(gluino)<5 TeV; m(t1)<3 TeV; m(wino)~M3/3.5 (ino-unification)



For string motivated mirage mediation scenarios,
then m(bino)~m(wino)~M3 with mirage ino-unification

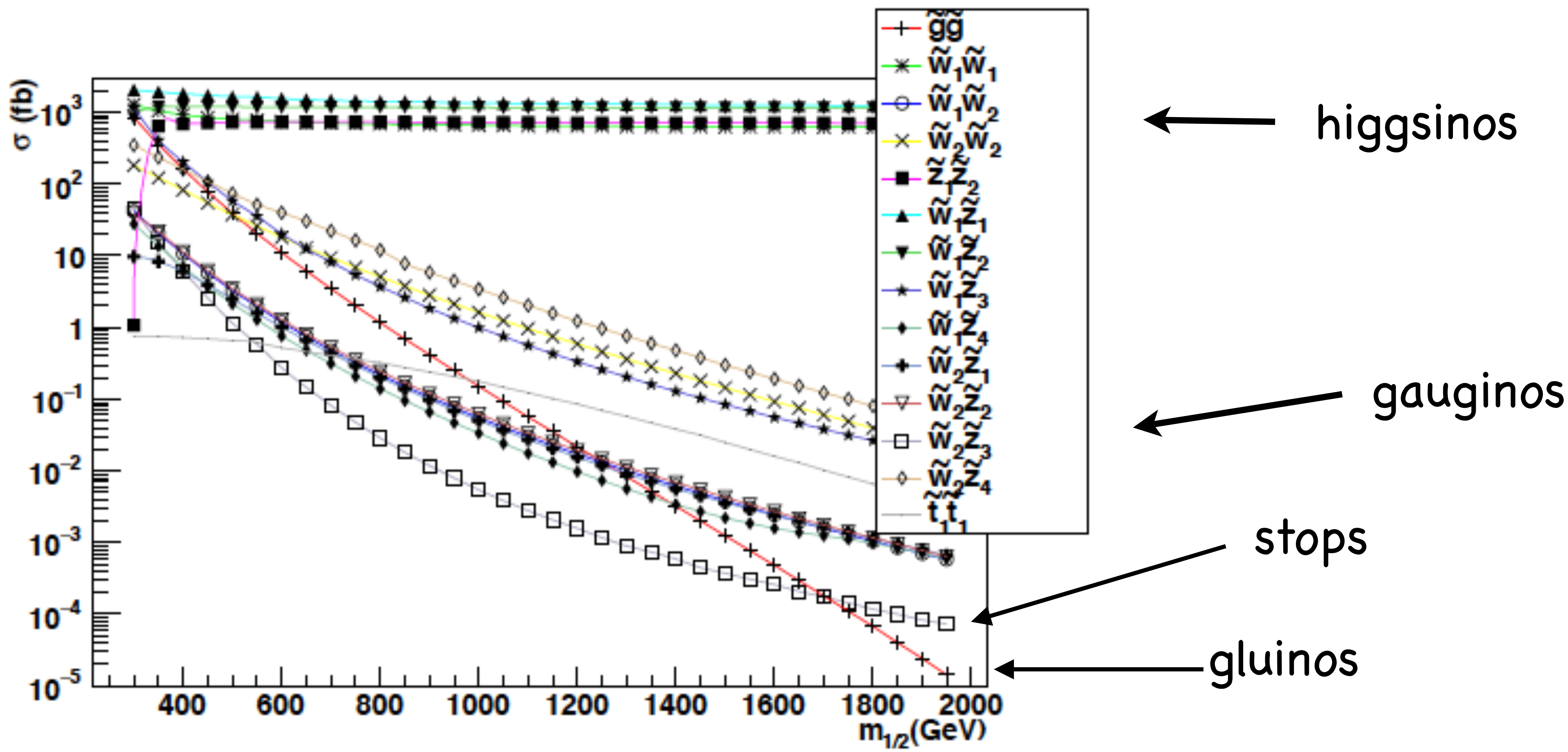
masses depend on location of fields within compact dimensions

Prospects for SUSY at LHC:

new signature list:

- $\tilde{g}\tilde{g}$
- $\tilde{t}_1\tilde{t}_1^*$
- $\tilde{Z}_1\tilde{Z}_2$ (higgsino pair production)
- $\tilde{W}_2^{\pm}\tilde{Z}_4$ (wino pair production)

Sparticle prod'n along RNS model-line at LHC14:



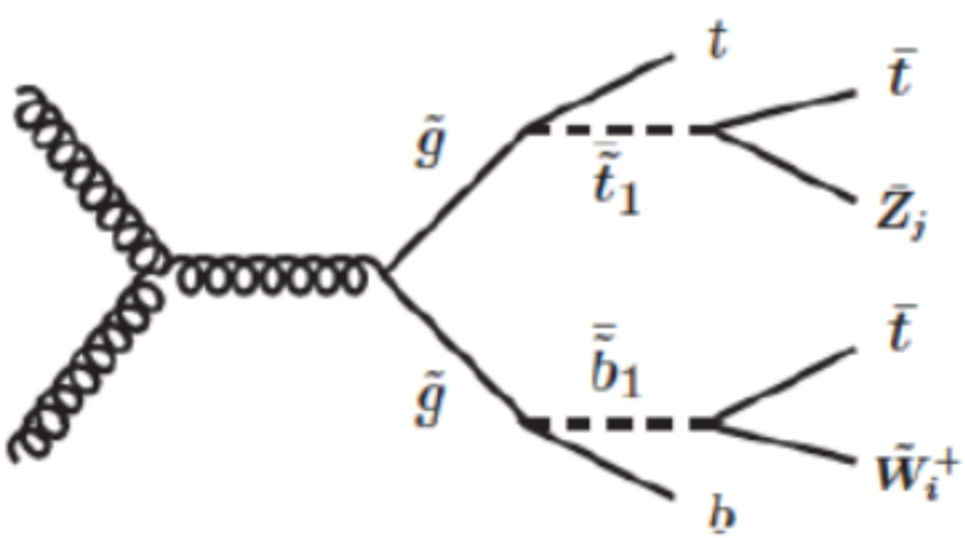
higgsino pair production dominant-but only soft visible energy release from higgsino decays

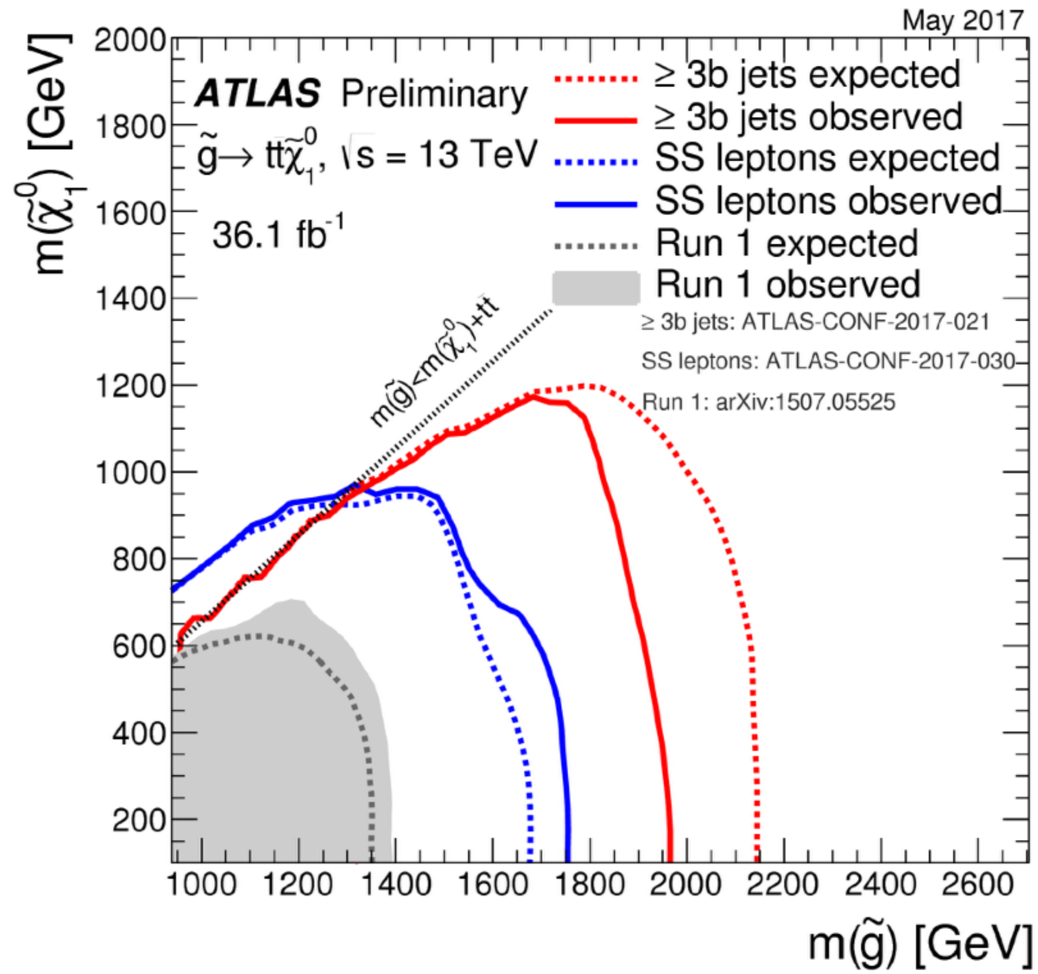
largest visible cross section: wino pairs

gluino pairs sharply dropping

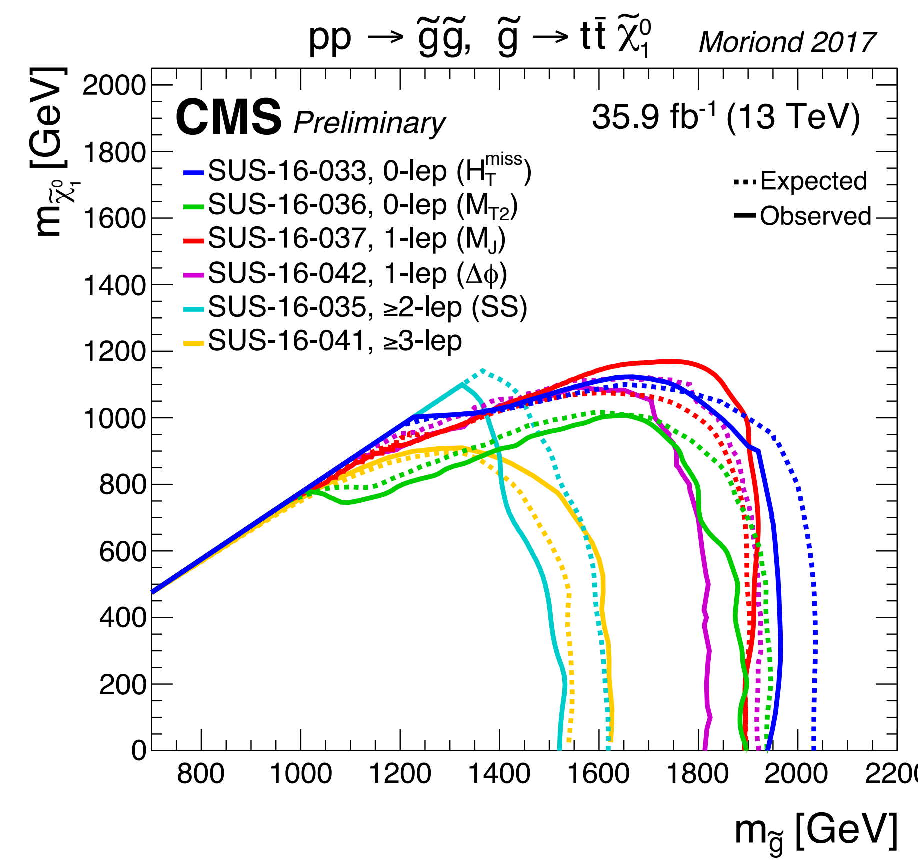
stops at bottom

gluino pair cascade decay signatures

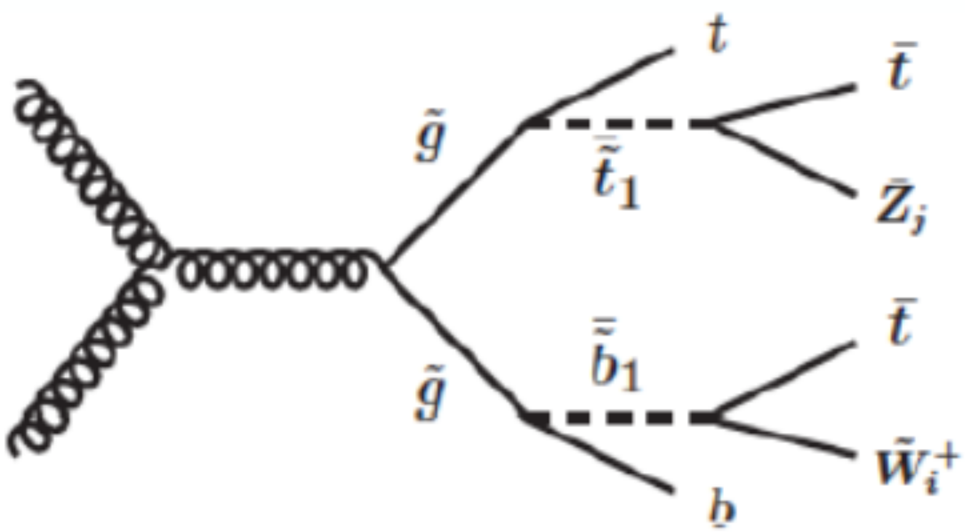




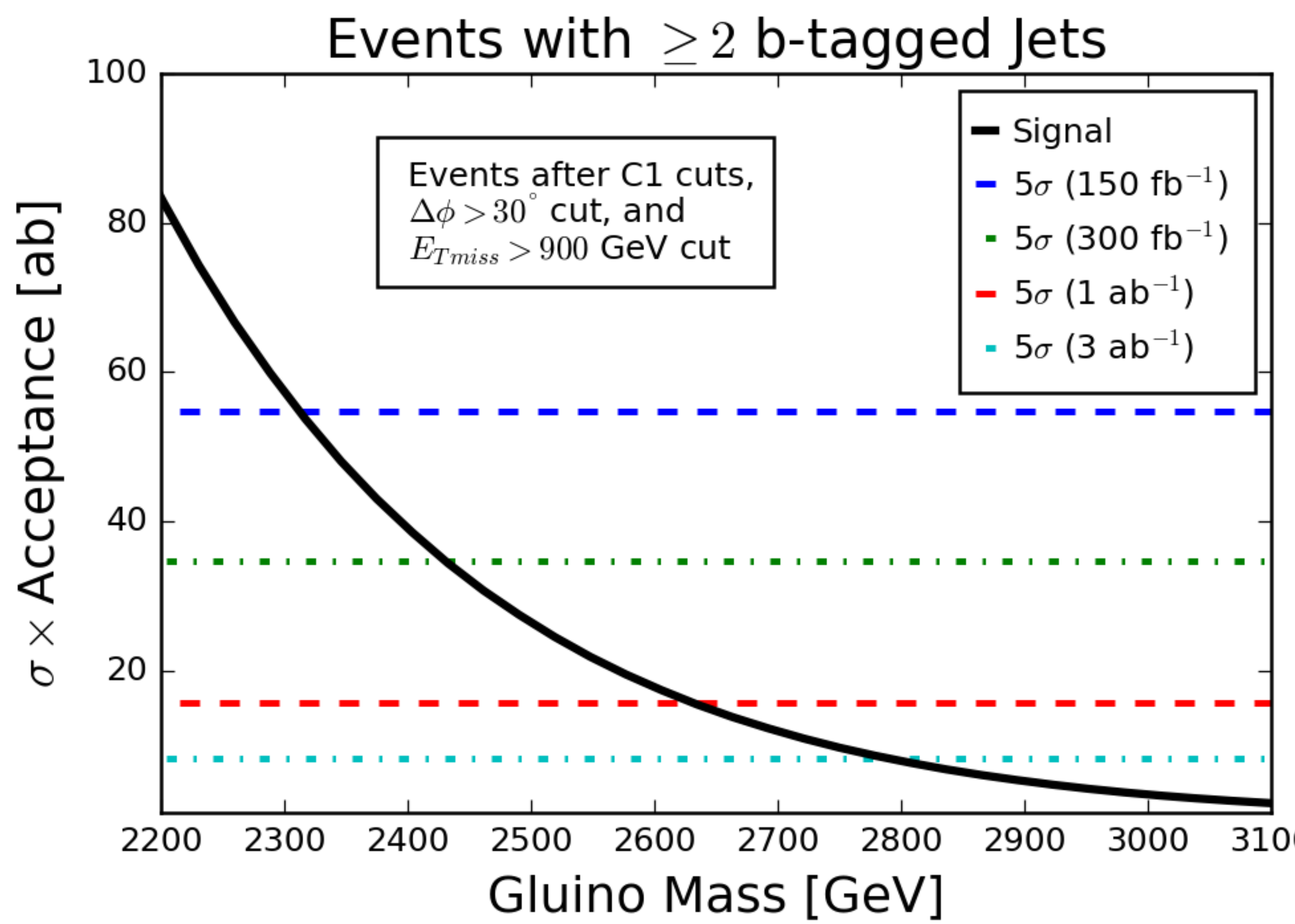
Current limits for m(Z1)~150 GeV:
m(glno)>~2 TeV



gluino pair cascade decay signatures



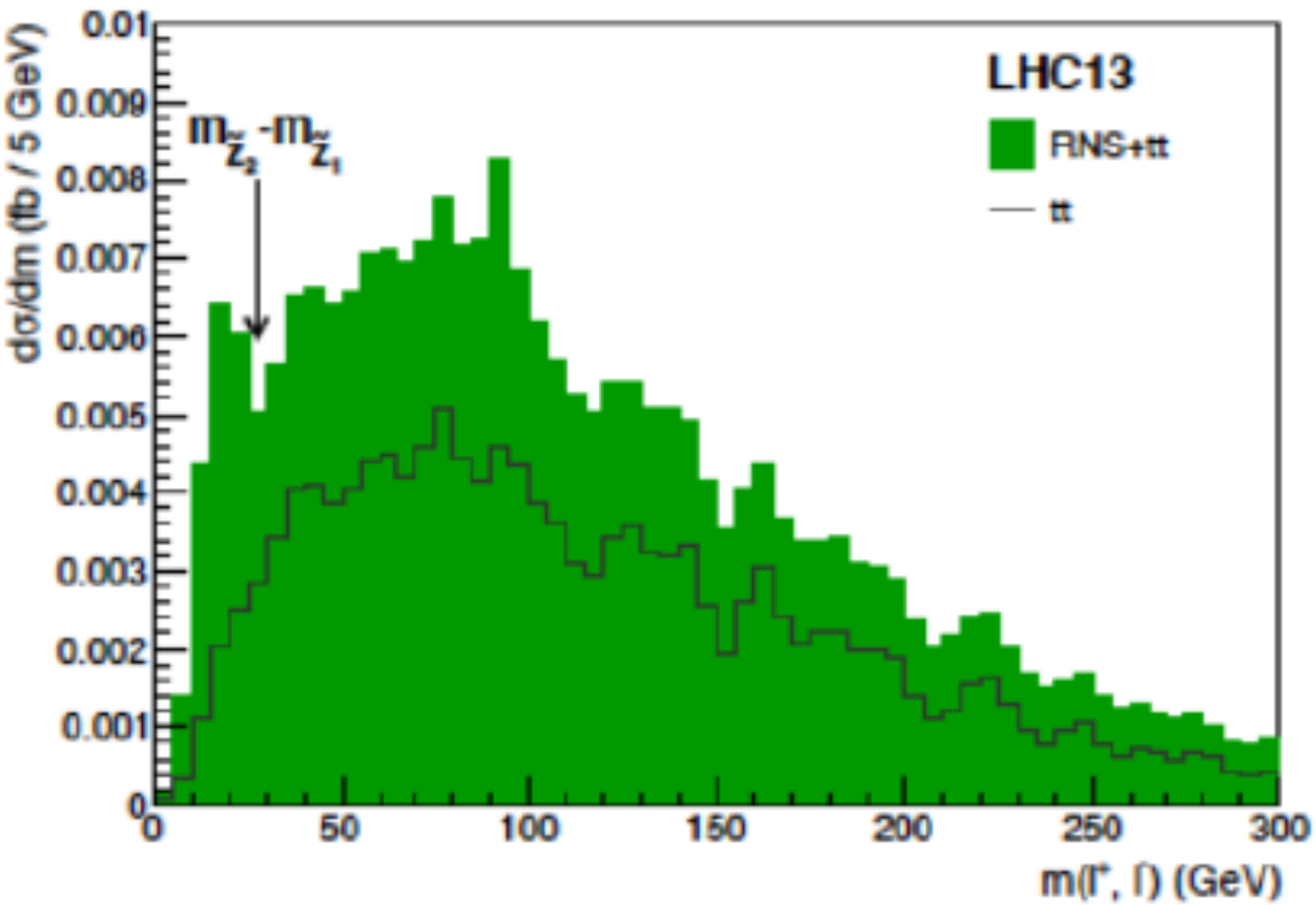
Estimated HL-LHC reach for gluinos



HL-LHC reach to
m(glno)~2.8 TeV;
RNS: m(glno)<~5 TeV

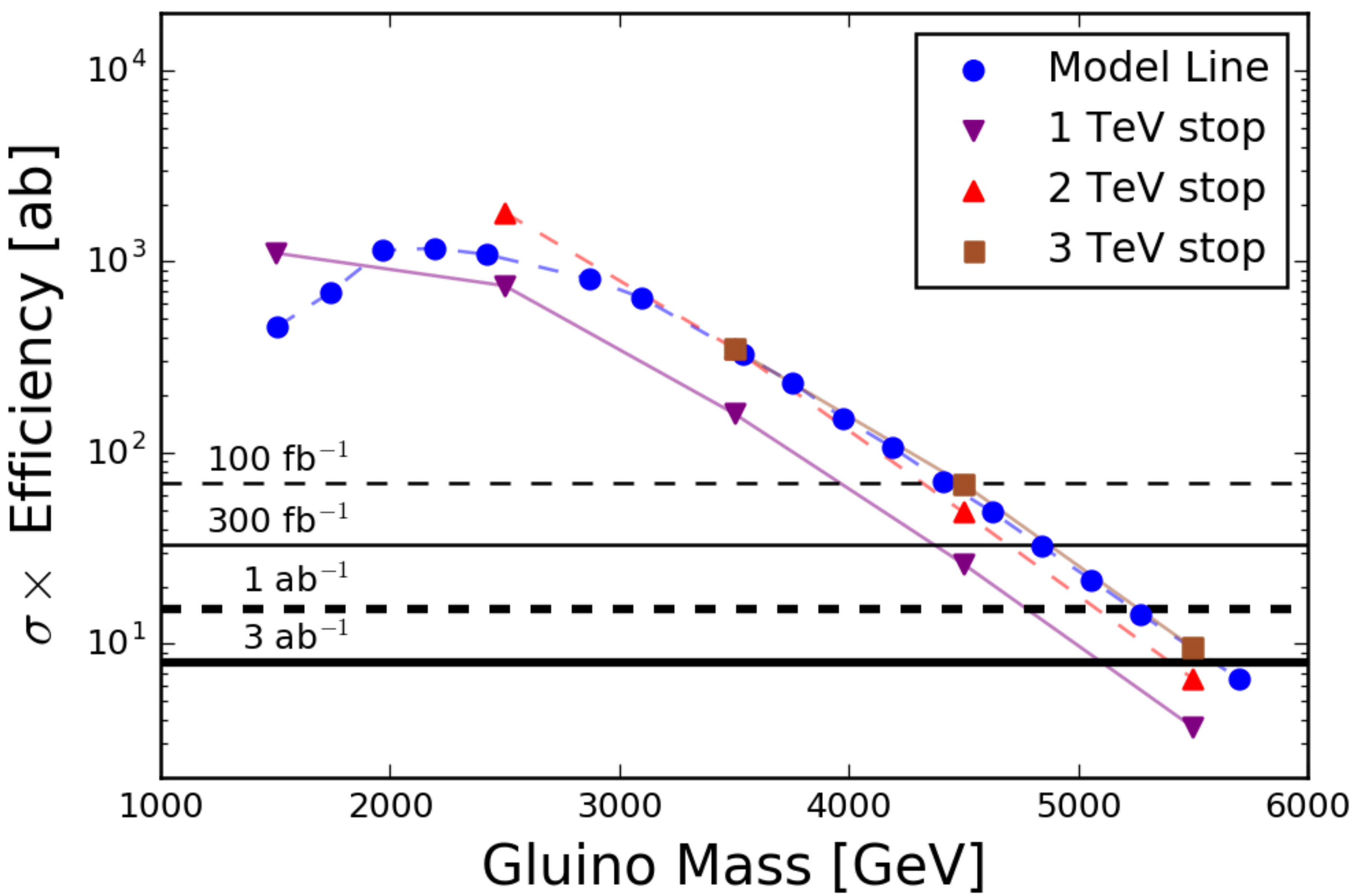
HB, Barger, Huang, Gainer, Savoy, Sengupta, Tata

LHC14 has some reach for gluino pair production in RNS; if a signal is seen, should be distinctive



OS/SF dilepton mass edge apparent from cascade decays with z2->z1+l+lbar

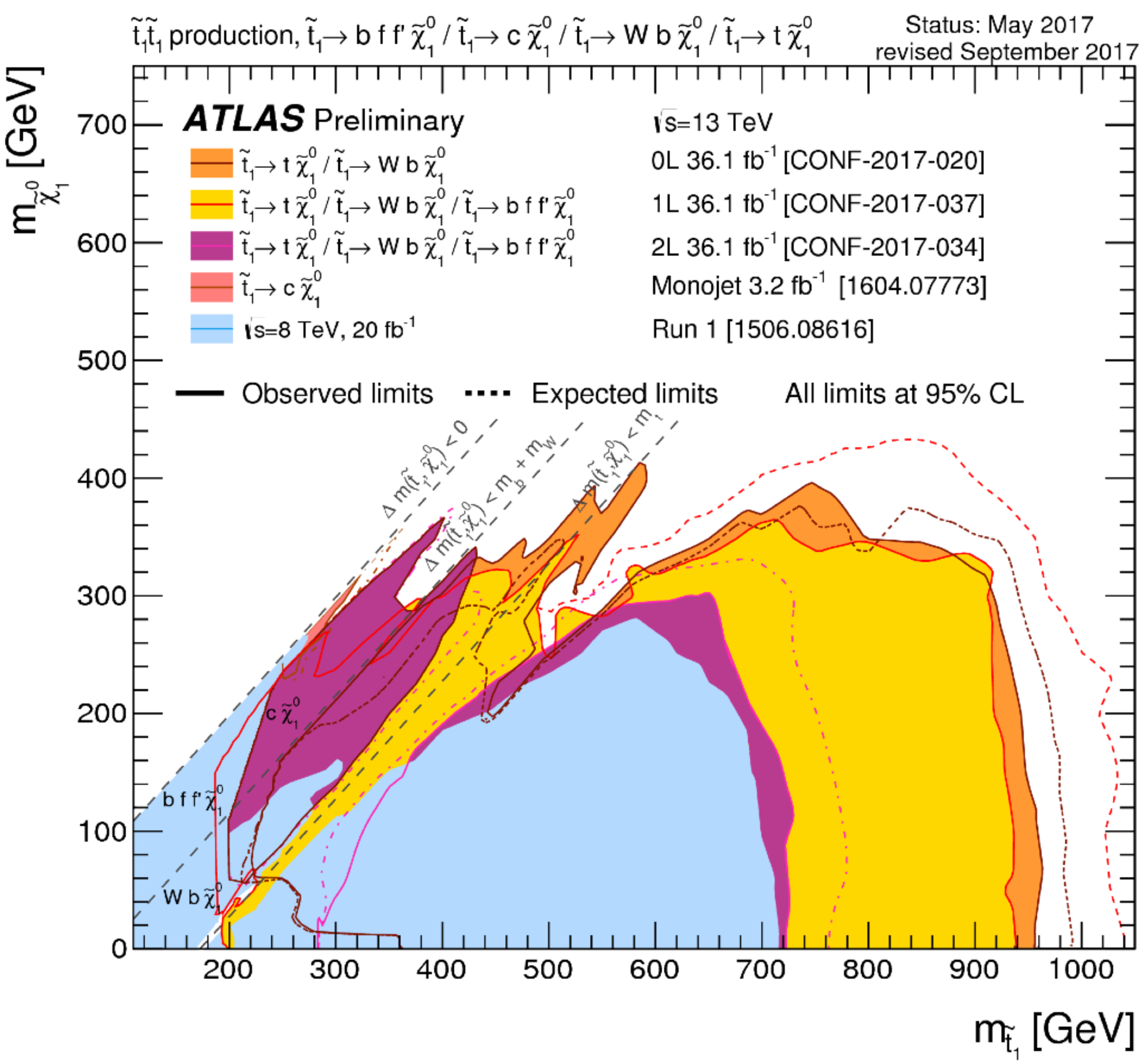
Gluino reach at LHC33: to about m(glno)~5 TeV

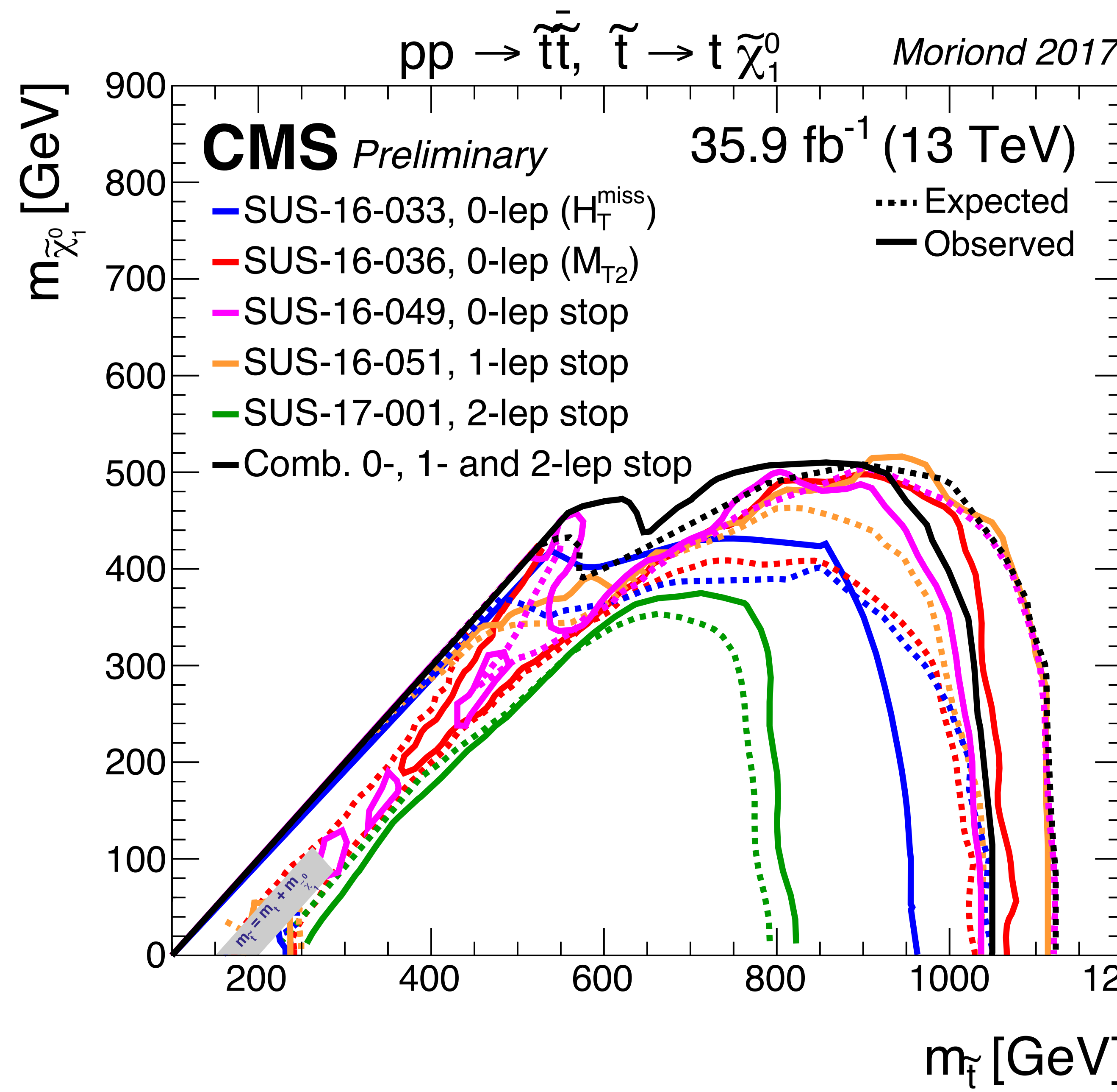


>=4 jets; >=2-b-jets;MET>1500 GeV

HB,Barger, Gainer,Huang, Savoy, Serce, Tata

Present limits on top squarks from LHC

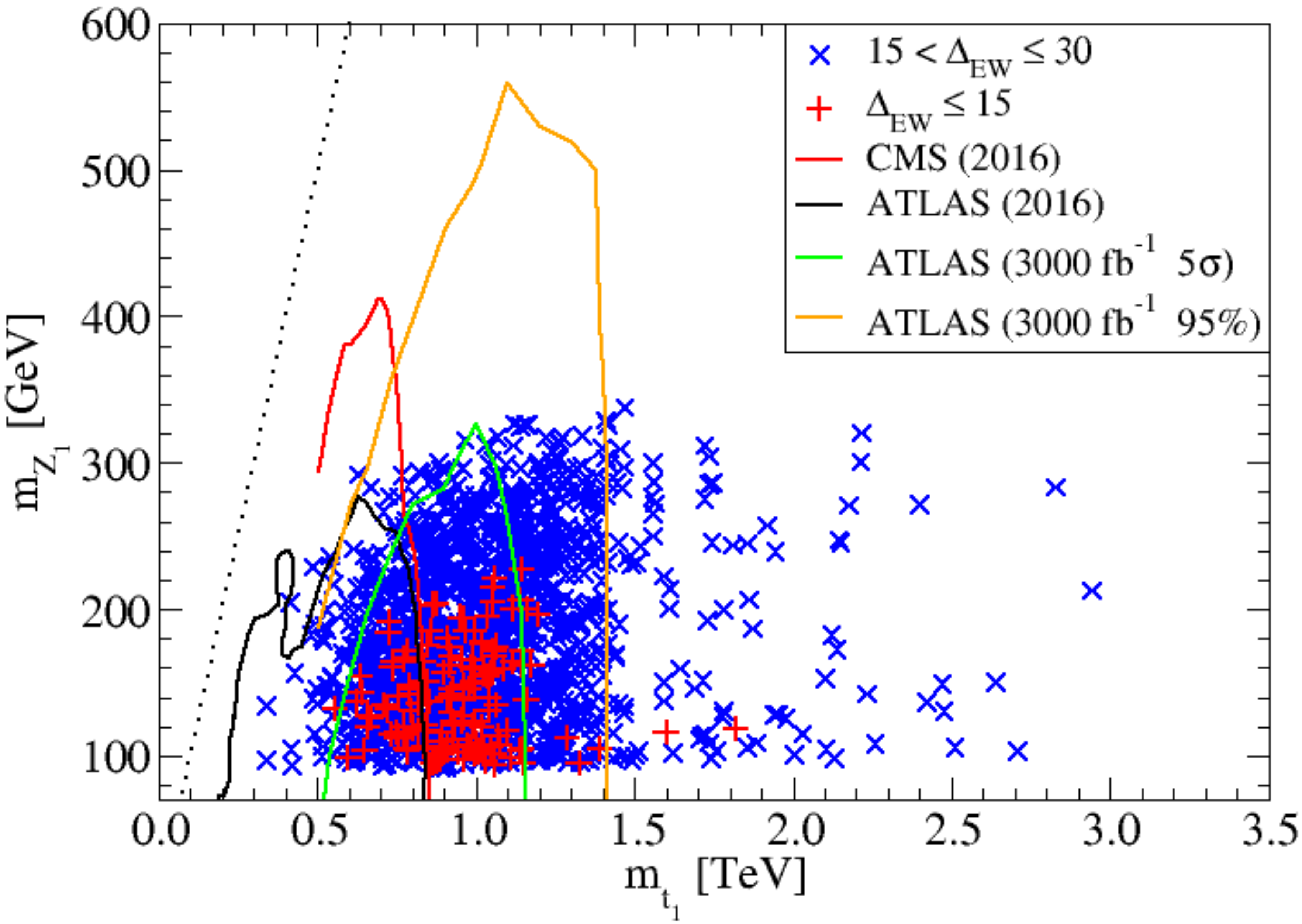




Evidently m(t1)>~1 TeV for m(LSP)~150 GeV

* TeV-scale top squark needed for m(h)~125 GeV
* Also needed for b-> s gamma

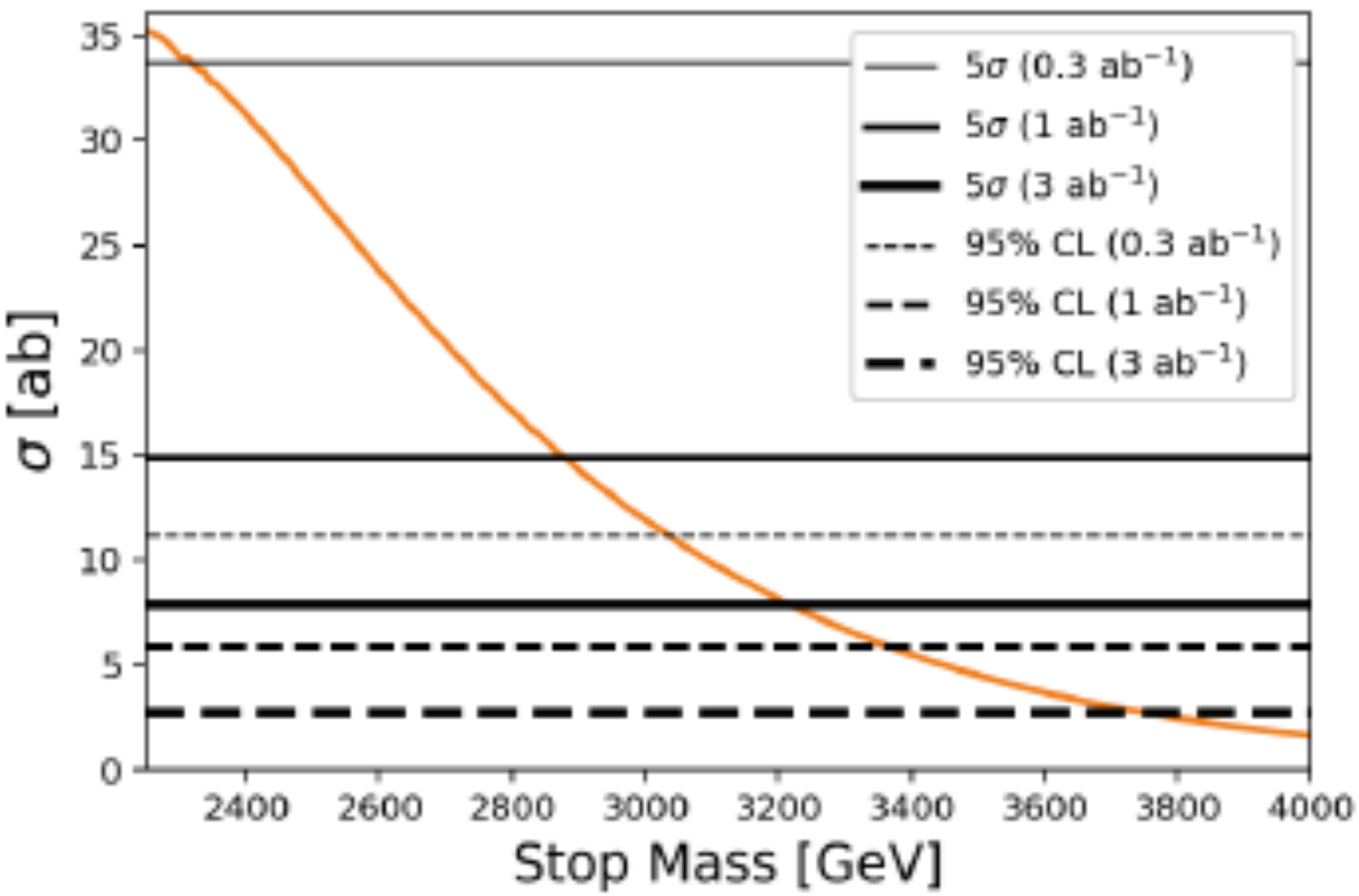
Prospects for top squarks in natural SUSY



m(t1) can range up to 3 TeV with little cost to naturalness;
the hunt for stops has only begun!

HL-LHC reach extends to m(t1)~1.2-1.4 TeV

Reach of LHC33 for top squarks



- $\tilde{t}_1 \to b\tilde{W}_1; \sim 50\%$
- $\tilde{t}_1 \to t\tilde{Z}_1; \sim 25\%$
- $\tilde{t}_1 \to t\tilde{Z}_2; \sim 25\%$

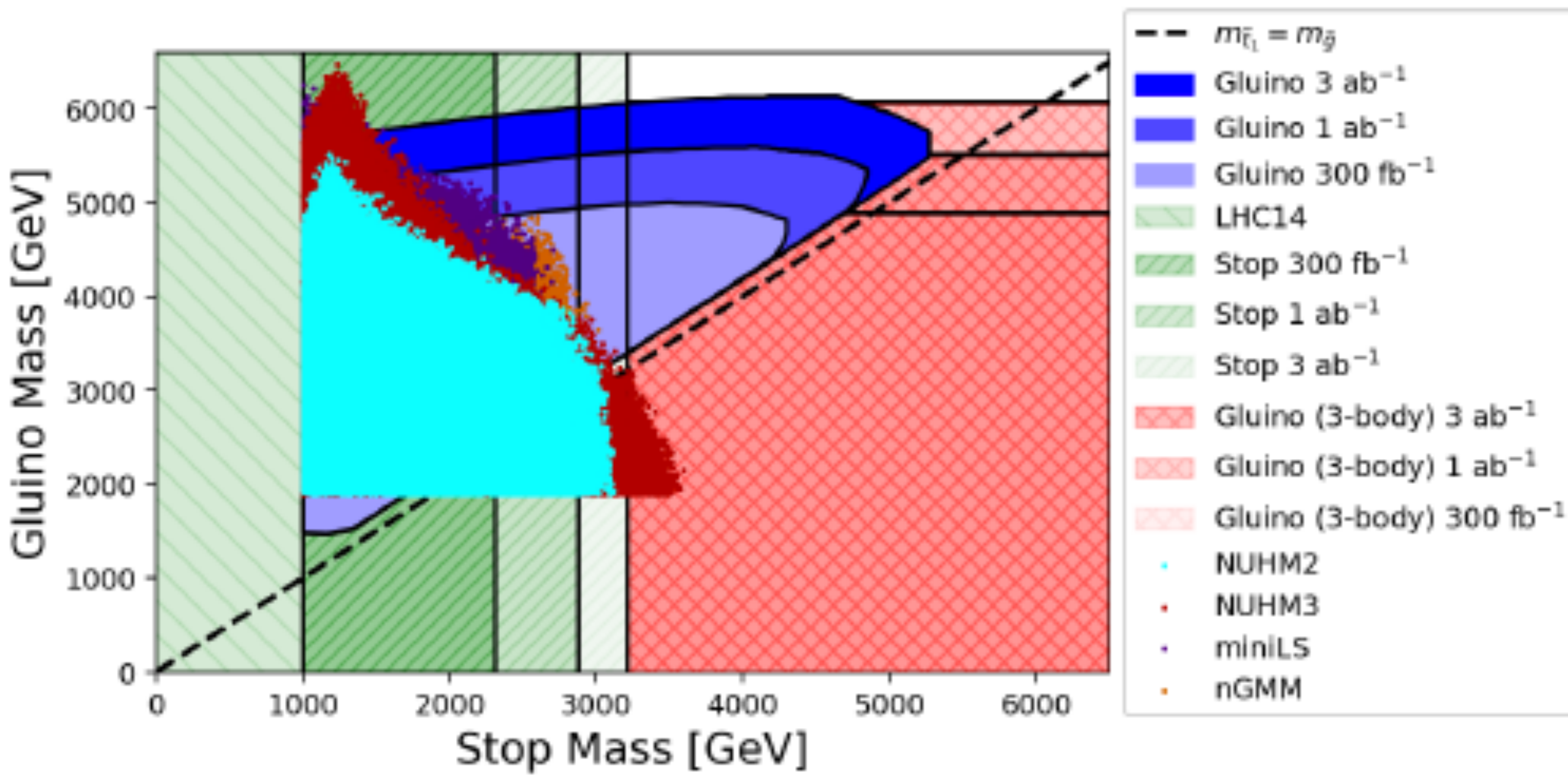
- A. $\tilde{t}_1\tilde{t}_1^* \to b\bar{b} + E_T^{\rm miss}$ $\sim 25\%$,
- B. $\tilde{t}_1\tilde{t}_1^* \to b\bar{t},\ \bar{b}t + E_T^{\rm miss}$ $\sim 50\%$,
- C. $\tilde{t}_1\tilde{t}_1^* \to t\bar{t} + E_T^{\rm miss}$ $\sim 25\%$.

LHC33 reach extends to m(t1)~3-3.8 TeV

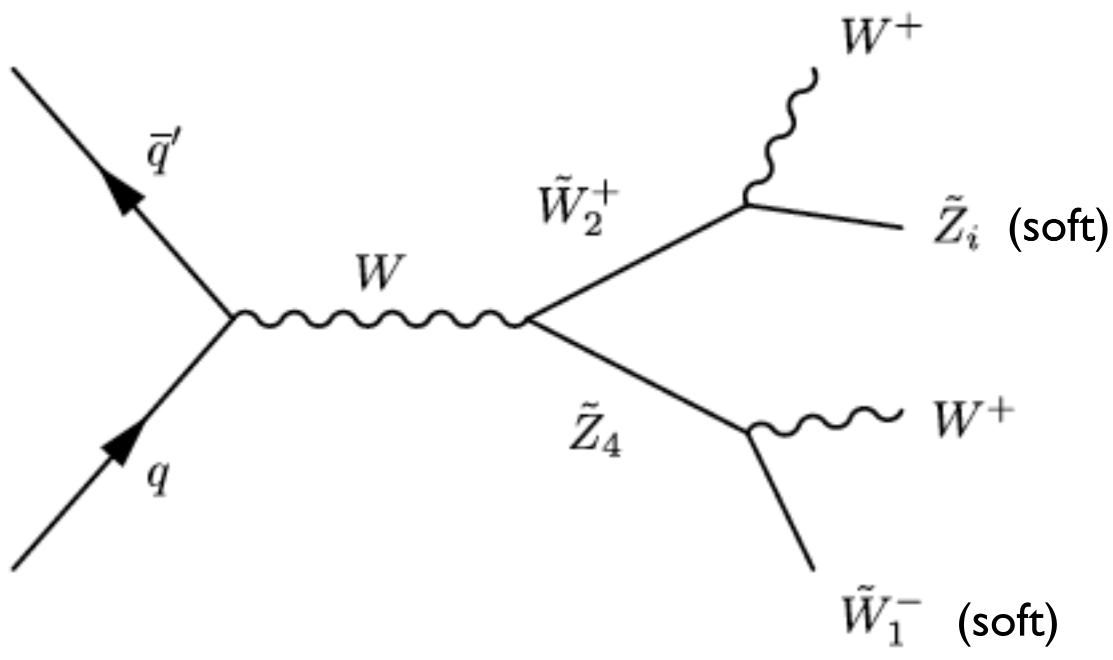
n(b-jets)>=2; MET>750 GeV

HB, Barger, Gainer, Serce, Tata

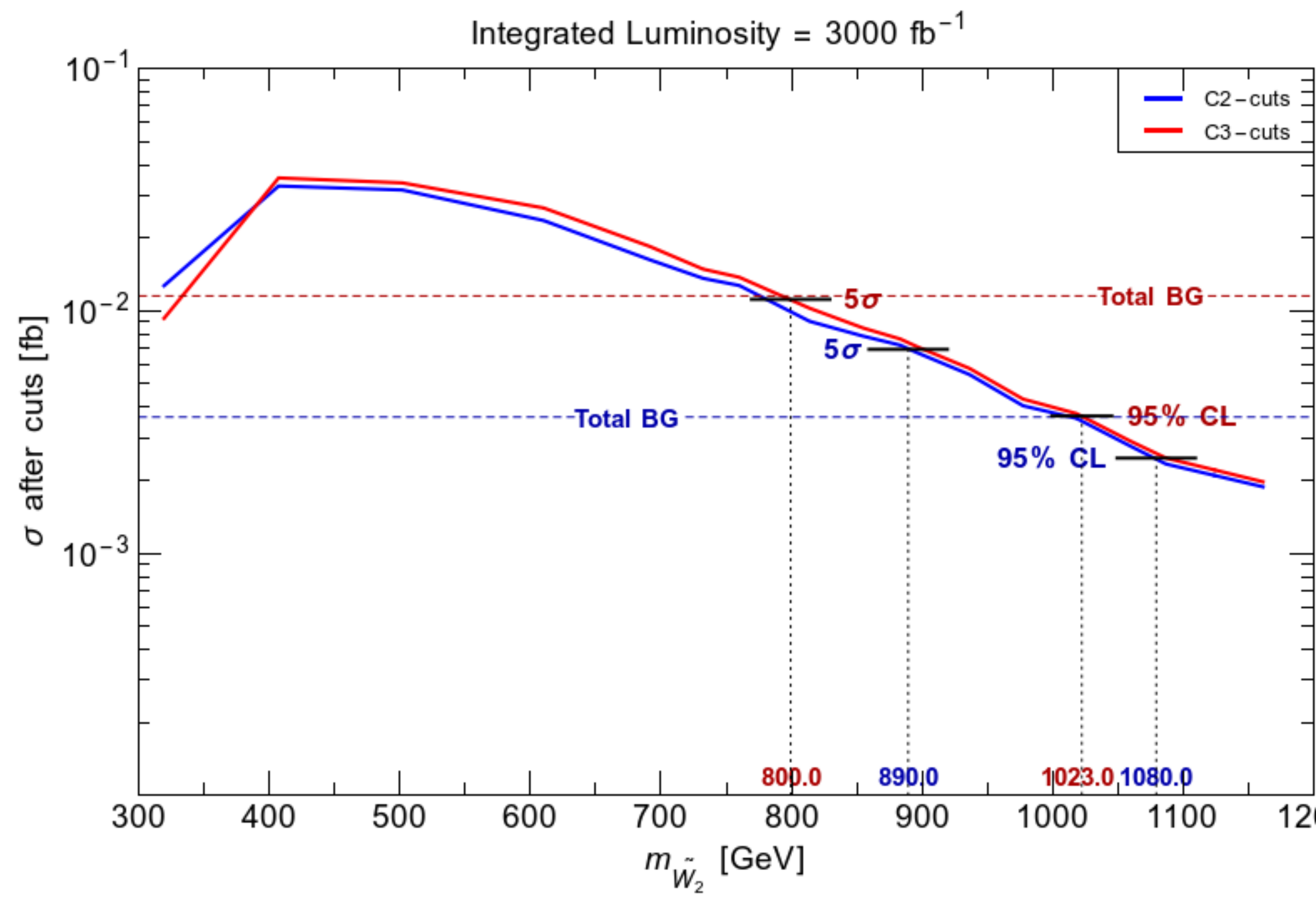
Combined LHC33 reach for t1 and glno covers all natural SUSY p-space!



Distinctive same-sign diboson (SSdB) signature from SUSY models with light higgsinos!



wino pair production

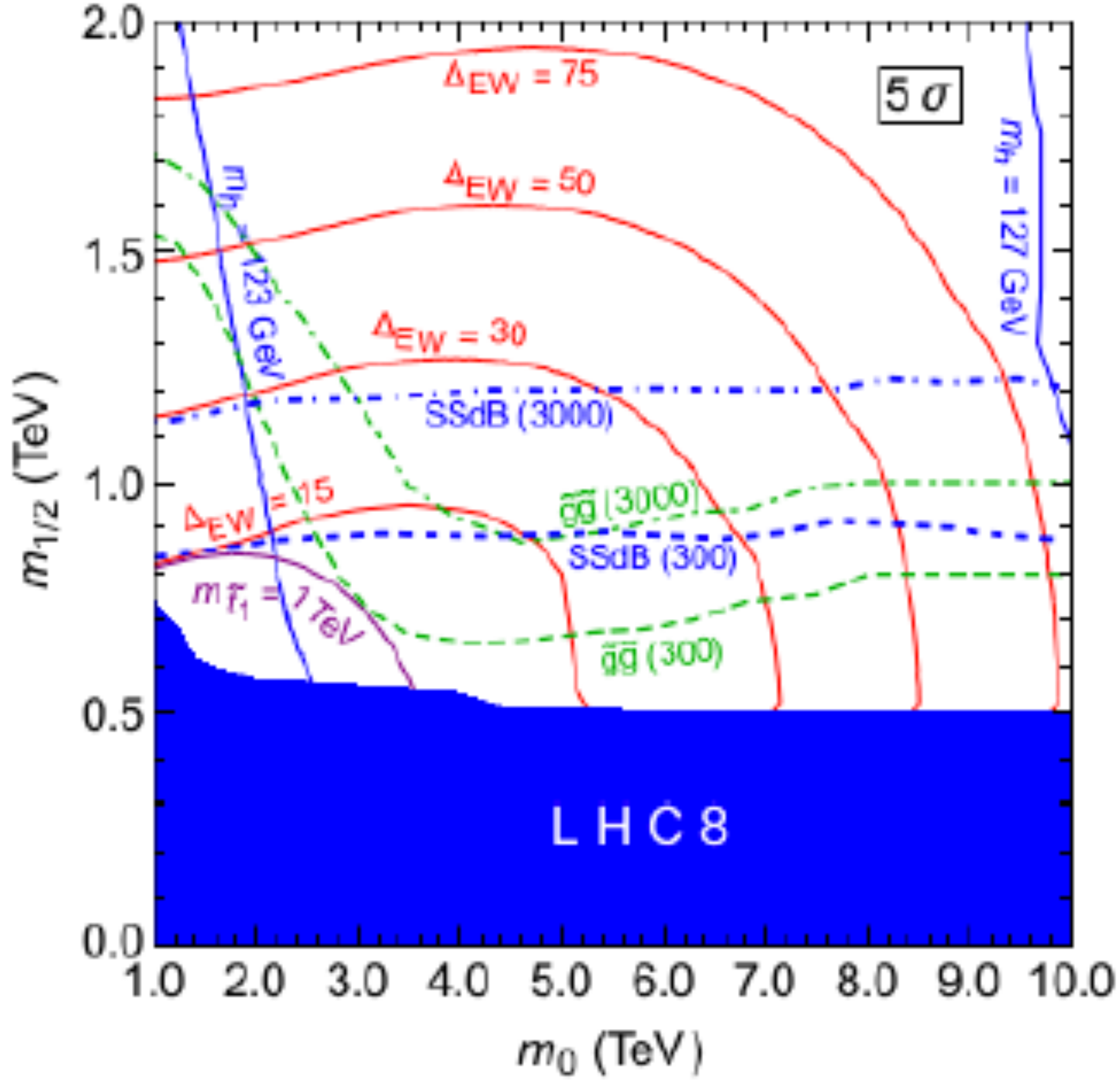


This channel offers good reach of LHC14 for RNS; it is also indicative of wino-pair prod'n followed by decay to higgsinos

H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev, W. Sreethawong and X. Tata, *Phys. Rev. Lett.* **110** (2013) 151801.

HB, Barger, Gainer, Sengupta, Tata

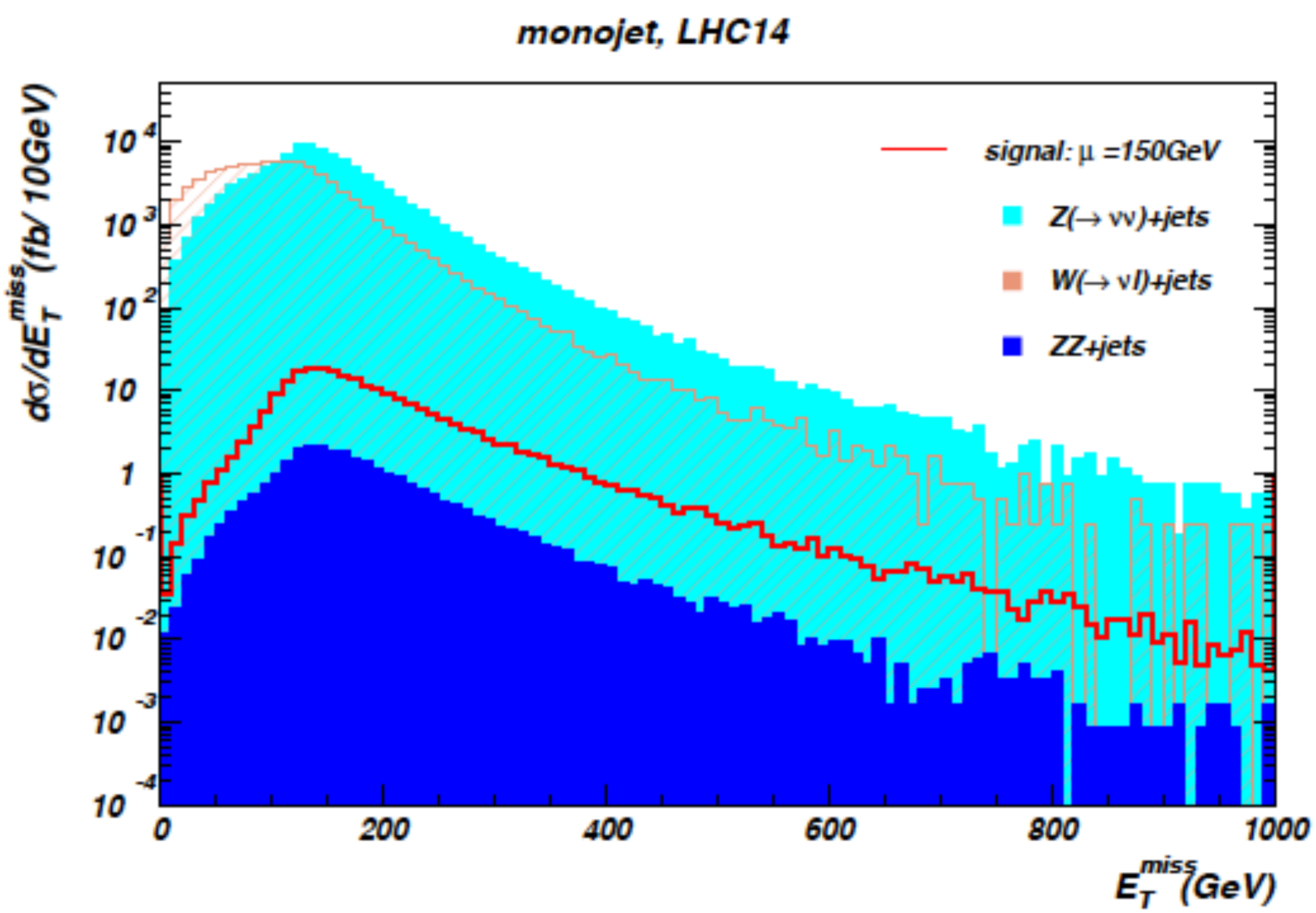
Good old m0 vs. mhf plane still viable, but needs mu~100-200 GeV as possible in NUHM2 instead of CMSSM/mSUGRA



For models with ino mass unif'n, reach via SSdB may exceed glno pairs for high luminosity

HB,Barger,Savoy, Tata; arXiv:1604.07438

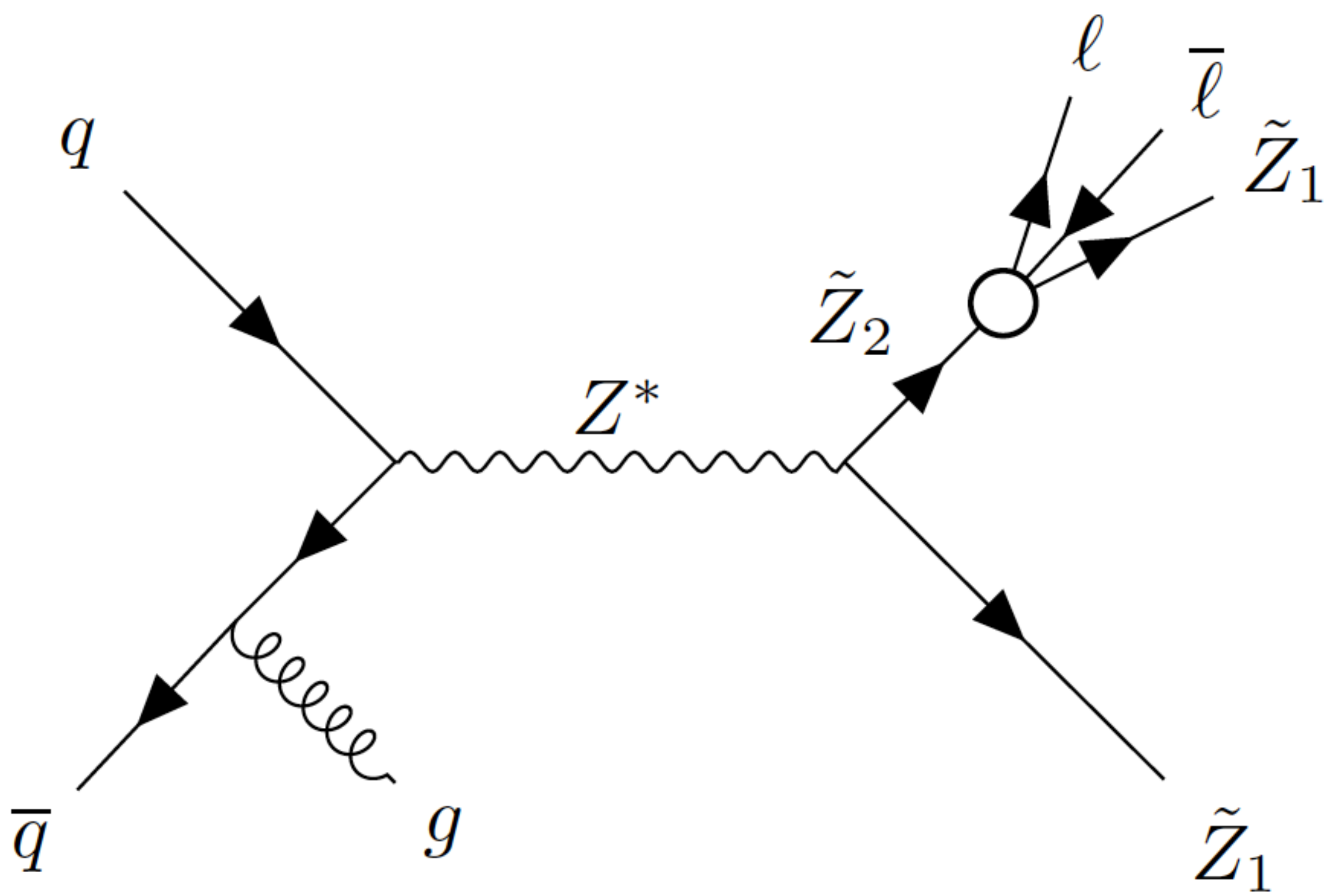
See direct higgsino pair production recoiling from ISR (monojet signal)?

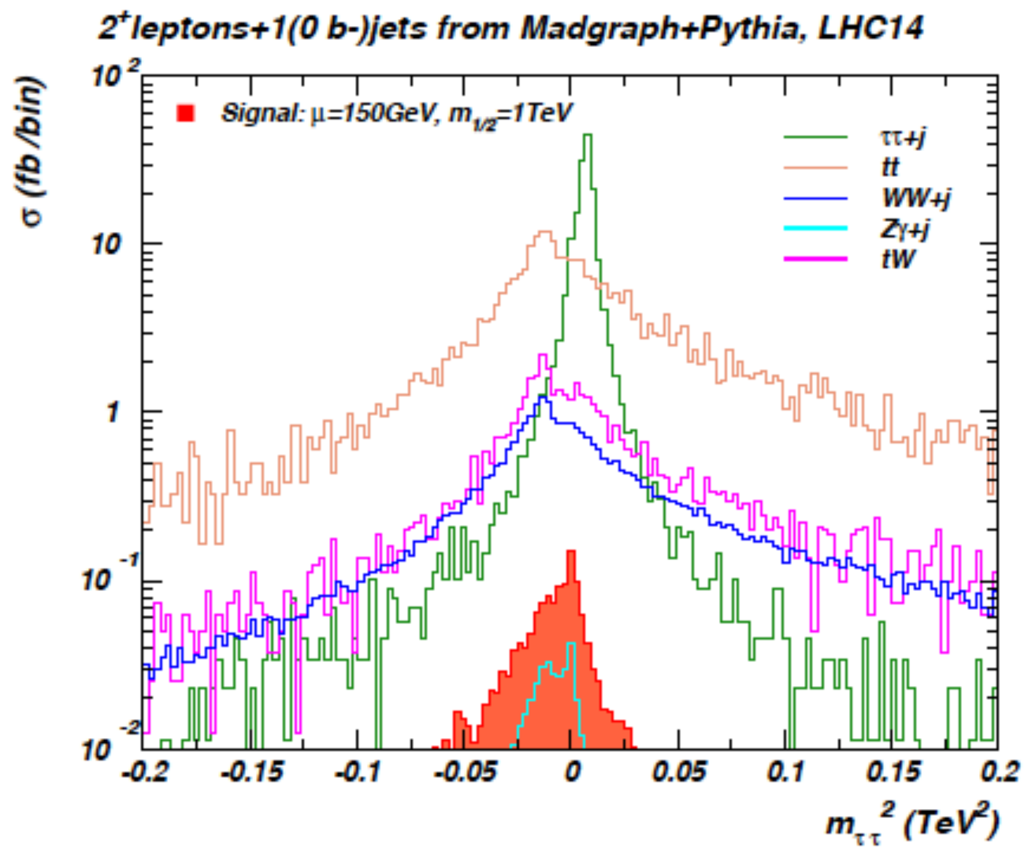


typically 1% S/BG after cuts:
very tough to do!

What about $pp \to \tilde{Z}_1\tilde{Z}_2 j$ with $\tilde{Z}_2 \to \tilde{Z}_1\ell^+\ell^-$?

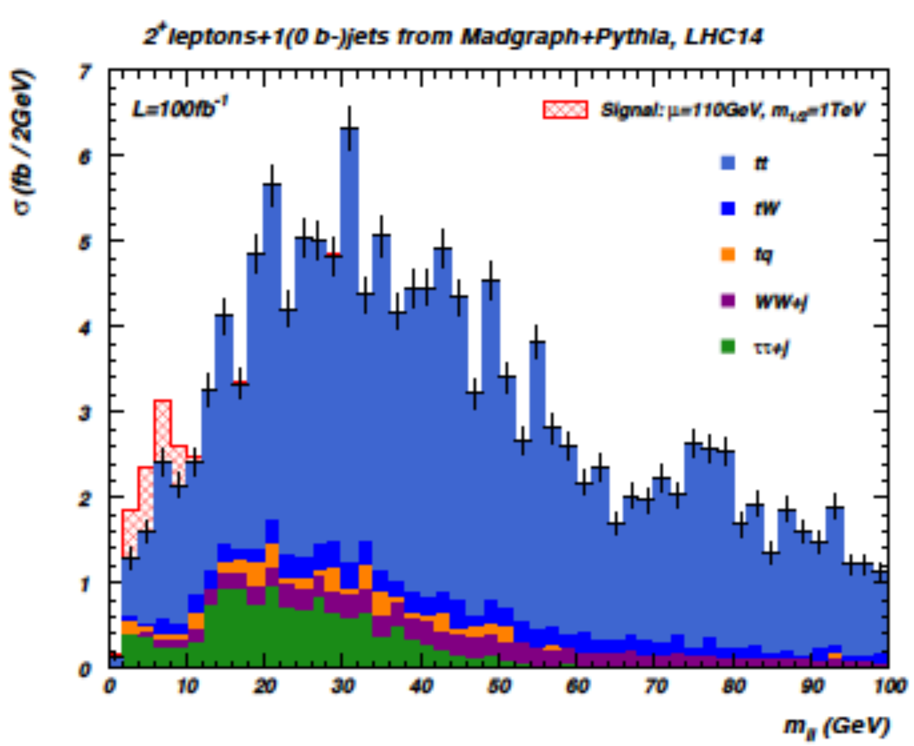
Han, Kribs, Martin, Menon, PRD89 (2014) 075007;
HB, Mustafayev, Tata, PRD90 (2014) 115007;

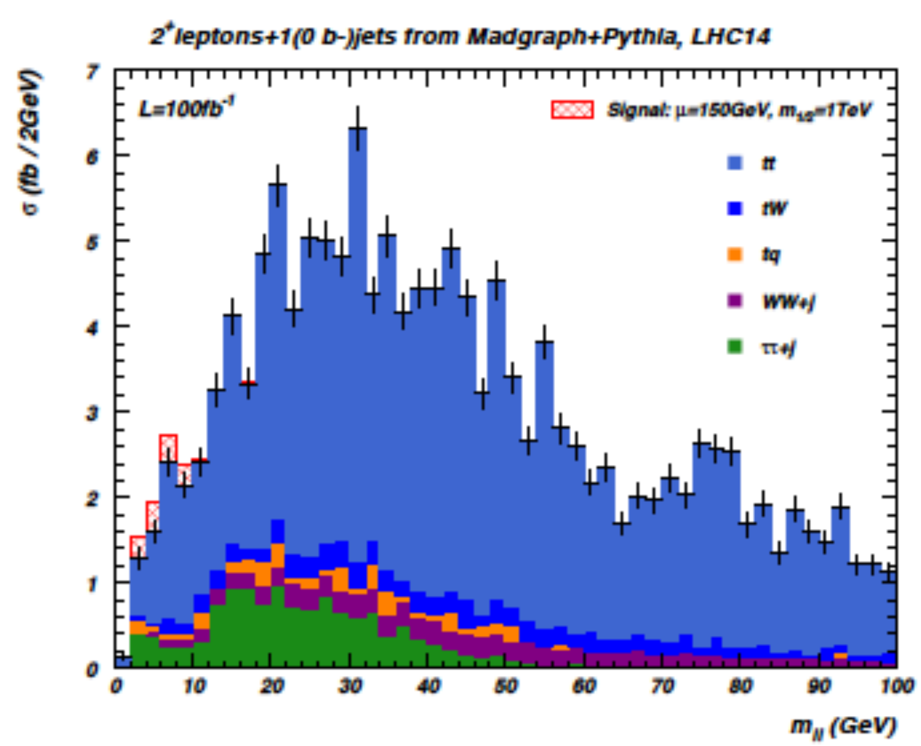




use MET to construct m^2(tau-tau)

cut m(ditau)^2<0

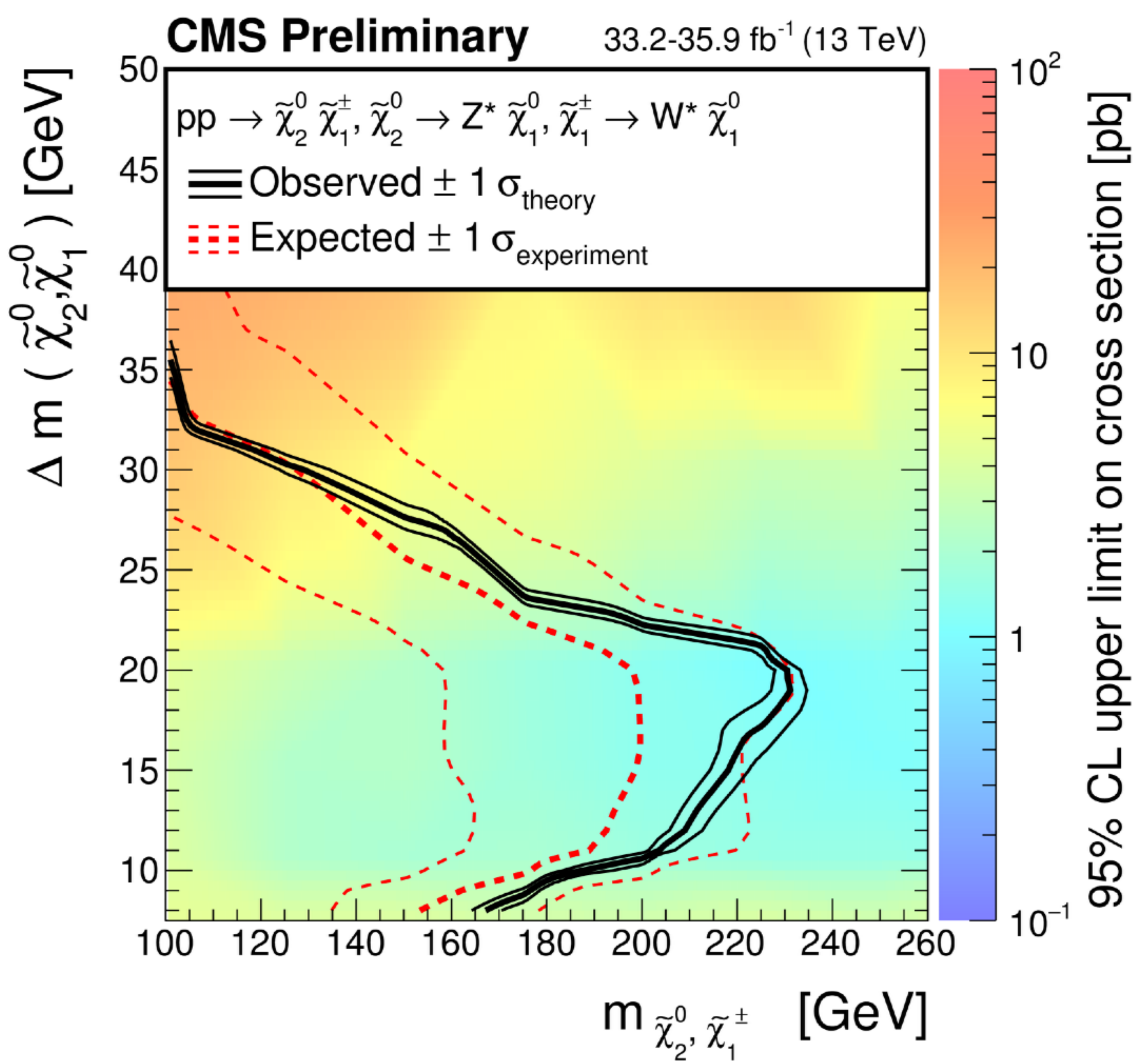




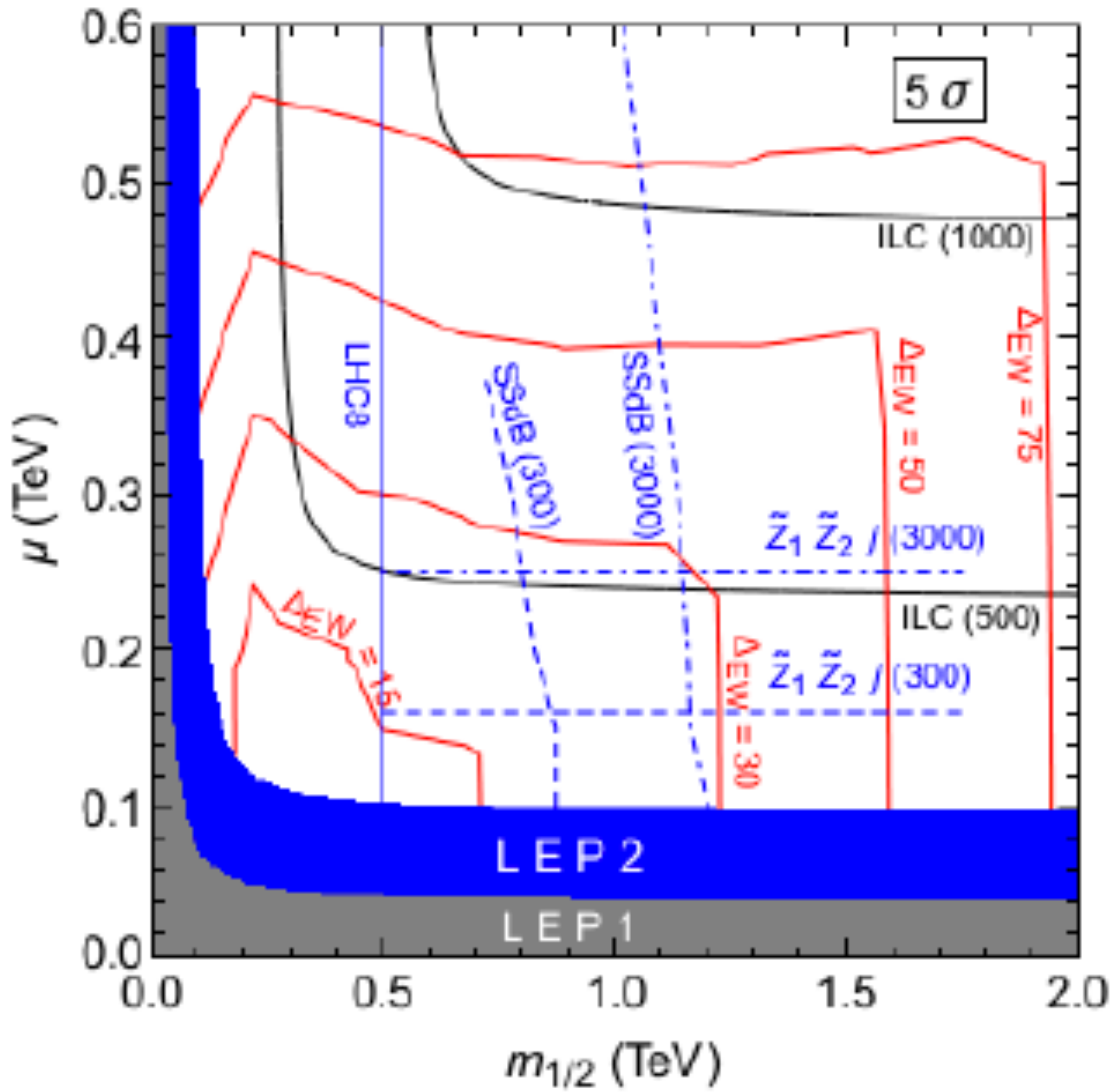
CMS analysis complete but results shown for wino pair production; higgsino pair production factor ~3.5 smaller so present CMS limit barely touches p-space

Atlas study underway- results soon?

NatSUSY z2-z1 mass gap may range down to 3 GeV so need to ID very soft leptons



panoramic view of reach of HL-LHC for natural SUSY



Combined SSdB/lljMET searches may cover all Nat SUSY p-space at HL-LHC for models with ino mass unification; in mirage scenario, z2-z1 mass gap can be reduced and M2 can be much higher than in NUHM2

Conclusions:

- In light of recent LHC bounds (m(glno)>2 TeV, m(t1)>1 TeV) and m(h) requiring TeV-scale highly mixed top squarks, concern has arisen about an emerging Little Hierarchy problem characterized by m(weak)~100 GeV<< m(SUSY)~multi-TeV rendering perhaps SUSY as ``unnatural"
- We propose an improved naturalness measure based upon scalar potential minimization condition

$$m_Z^2/2 = \frac{m_{H_d}^2+\Sigma_d^d-(m_{H_u}^2+\Sigma_u^u)\tan^2\beta}{\tan^2\beta-1} - \mu^2 \simeq -m_{H_u}^2 - \Sigma_u^u(\tilde{t}_{1,2}) - \mu^2$$

This leads to upper bounds from naturalness:

DM=WIMP/axion mix?

- m(higgsinos)~100-300 GeV (the lighter the better)
- m(t1)<~3 TeV
- m(glno)<~5 TeV

process	current	HL-LHC	HE-LHC
glno-glno	m(glno)>2 TeV	~2.8 TeV	5 TeV
t1-t1	m(t1)>1 TeV	1.3 TeV	3.5 TeV
SSdB (winos)	x	m(W2)~1 TeV	?
z1z2j->l+lb+j+MET	barely	mu~250 GeV	?

Conclusions:
1. SUSY still natural;
2. hunt for nSUSY has only begun;
3. HL-LHC handle most SUSY with ino-mass unification;
4. other (e.g. mirage) may require HE-LHC to complete search

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Sengupta,Serce