

Lessons learnt from Run 1: SUSY perspective

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Canada's National laboratory for particle and nuclear physics

on behalf of the **ATLAS** and **CMS** Collaborations

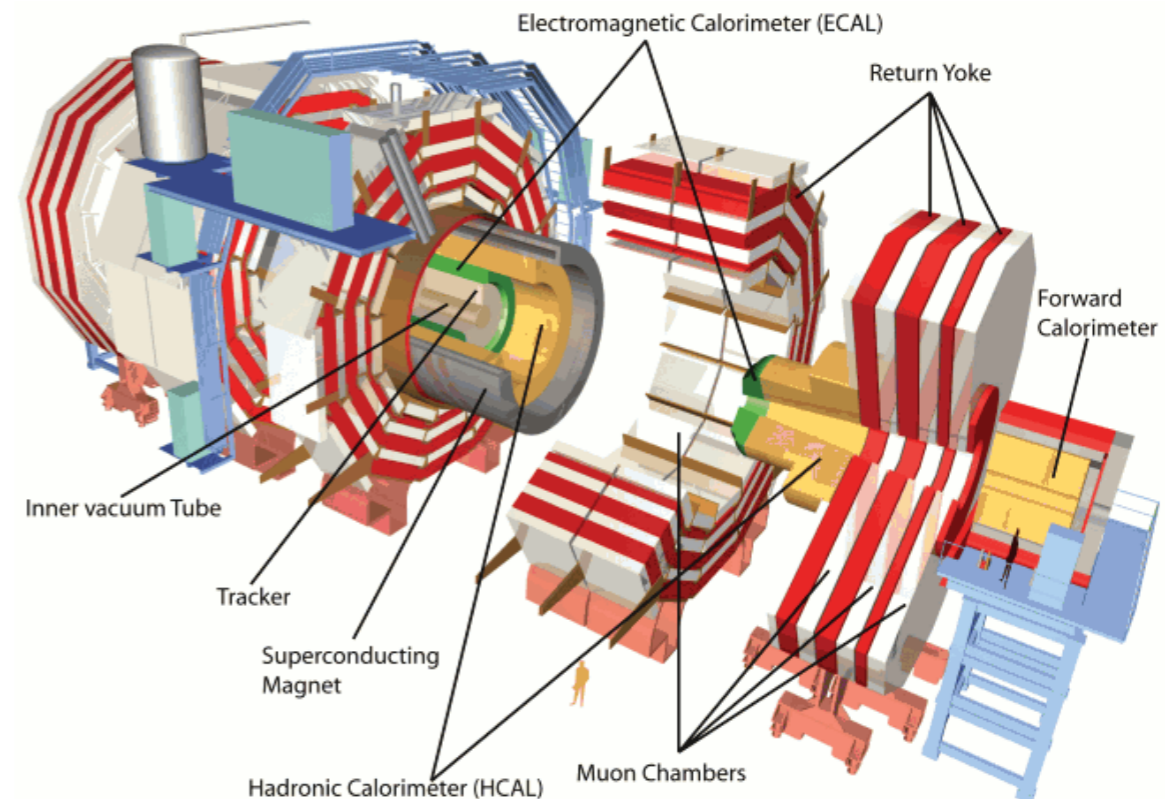
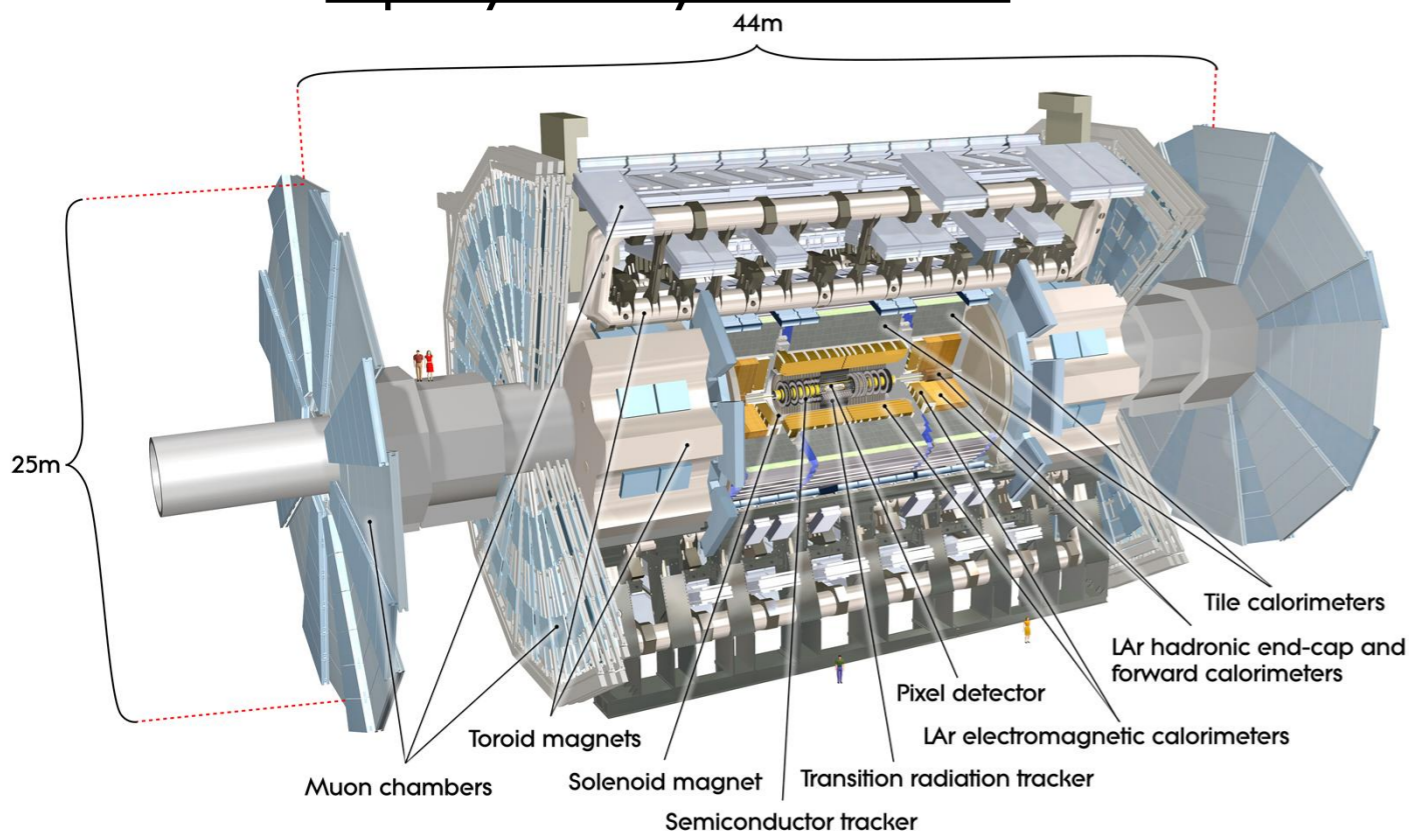
Rencontres du Vietnam 2014

Physics at LHC and beyond

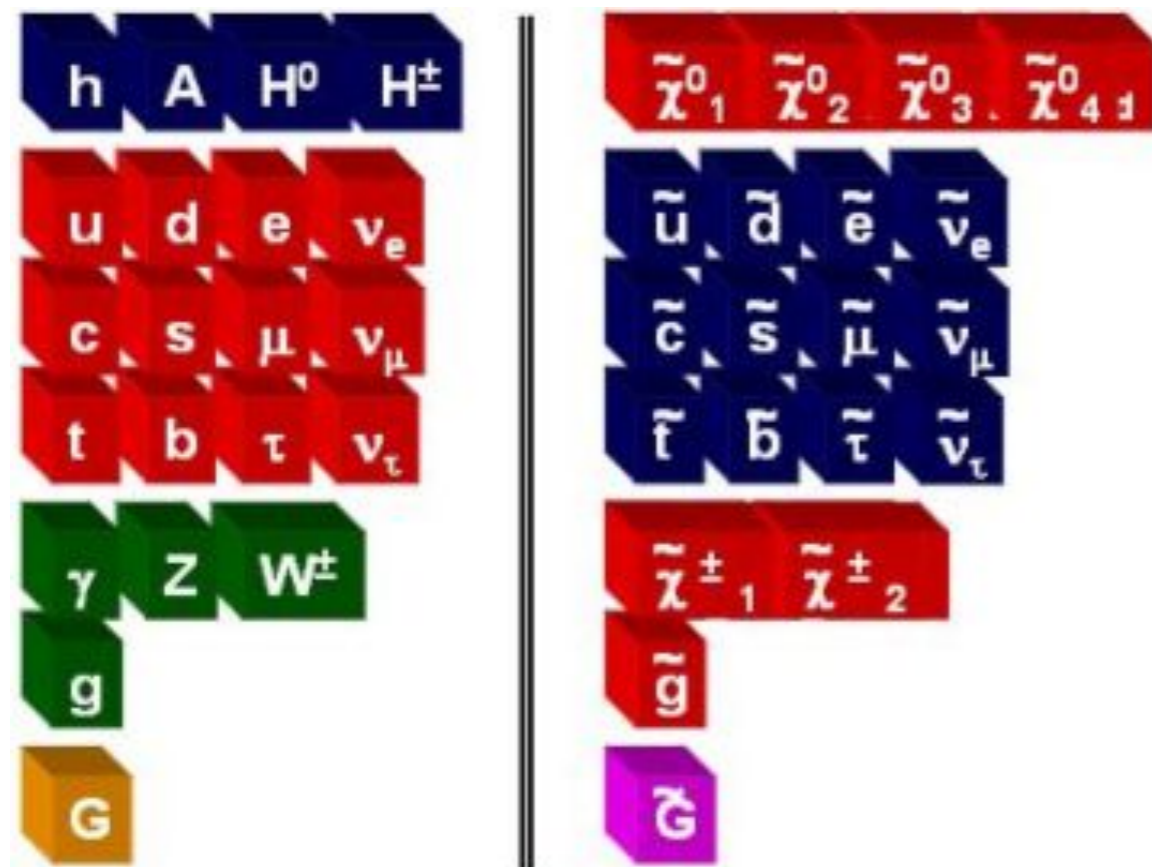
August 10-17th - 2014

Disclaimer!

- Personal choice of results to give a broad overview of the Search for SUSY at ATLAS and CMS
 - Focus on some representative results
 - No justice can be made to the *excellent* programs developed by the experiments!
 - Please, visit our public pages for more information
 - <https://twiki.cern.ch/twiki/pub/CMSPublic> and <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults>



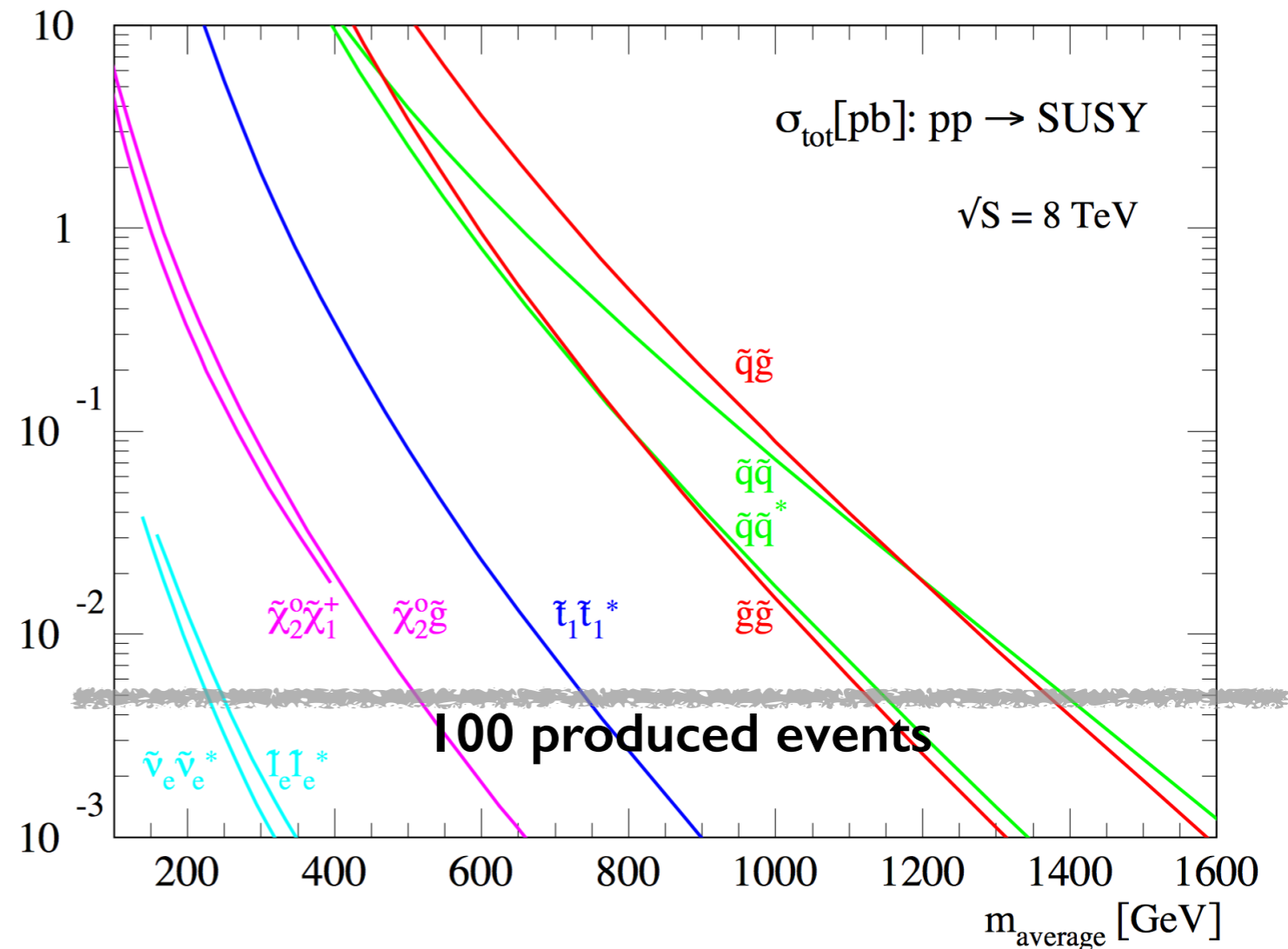
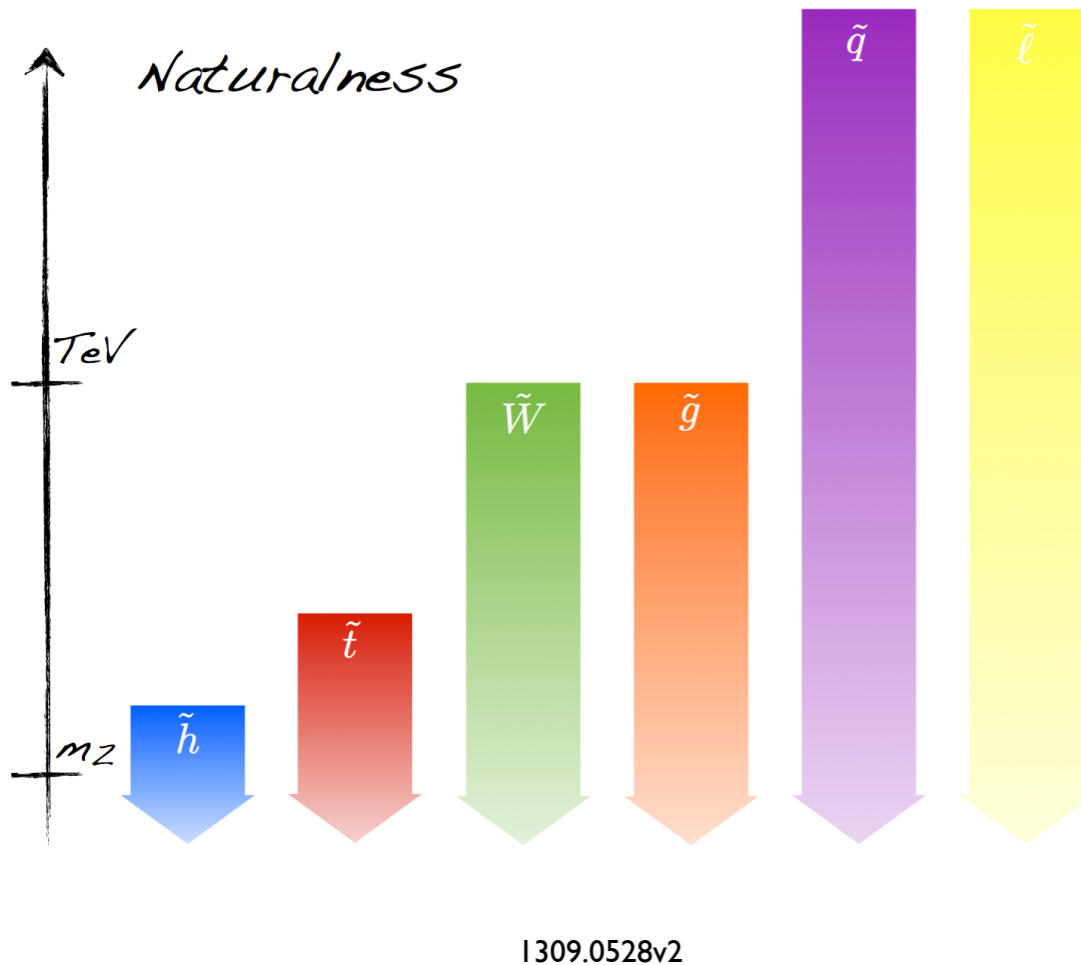
Why SUSY?



- Novel symmetry
 - Discovered in the late '60 to early '70
- Theoretically and experimentally motivated
 - extension of Poincare group, natural grand unified theory, UV complete, can incorporate gravity, **provides solution to the hierarchy problem**
 - leads to unification of gauge couplings, predicts a low mass Higgs boson, **can provide candidate for cold DM (if new parity R-parity is conserved)**
- MSSM developed in the early '80 and starting point for searches ever since

What did we expect before the LHC Run I?

<http://www.thphys.uni-heidelberg.de/~plehn/>



EWK-inos
 expected
 sensitivity up
 to 0.5 TeV

Stop
 expected
 sensitivity up
 to 0.7 TeV

Squarks-
 gluino
 sensitivity up
 expected up
 to 1.2 TeV

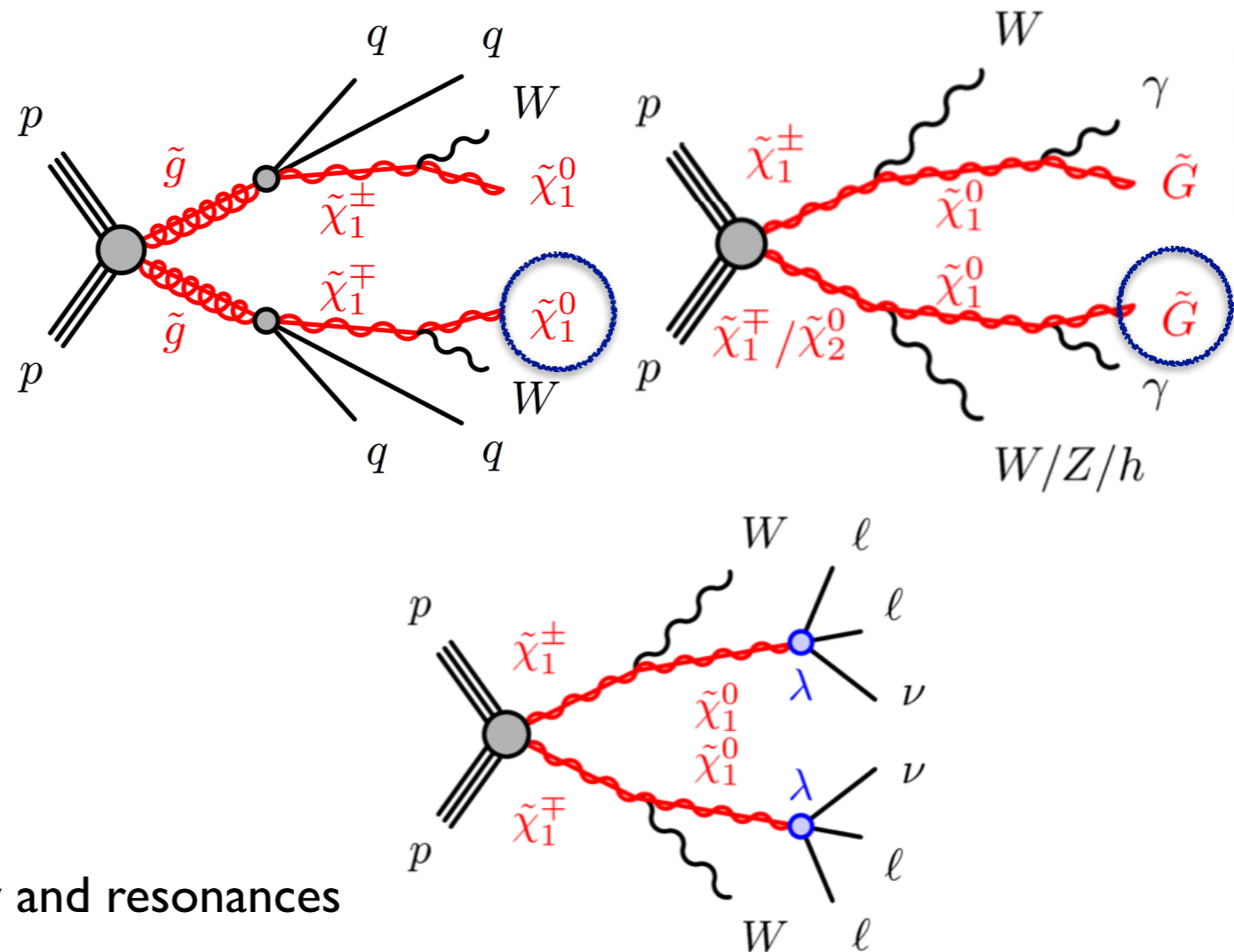
Phenomenology of SUSY

- **R-parity conserved (RPC)**

- SUSY particles created in pairs
- Stable lightest SUSY particle (LSP)
- Expect large MET from escaping LSPs

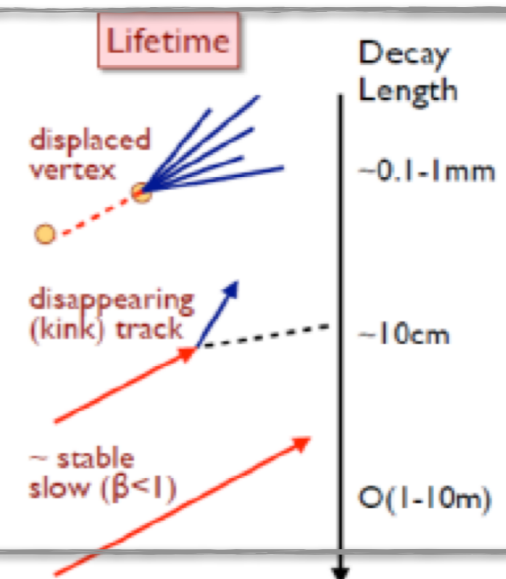
- **R-parity violated (RPV)**

- RPC pair-production, but decaying LSP
- Loss of MET, but large object multiplicity and resonances



- **Long Lived (LL) particles (in both RPC and RPV)**

- Meta-stable LSP due to small RPV coupling
- Compressed spectra
- Metastable / collider stable sparticles

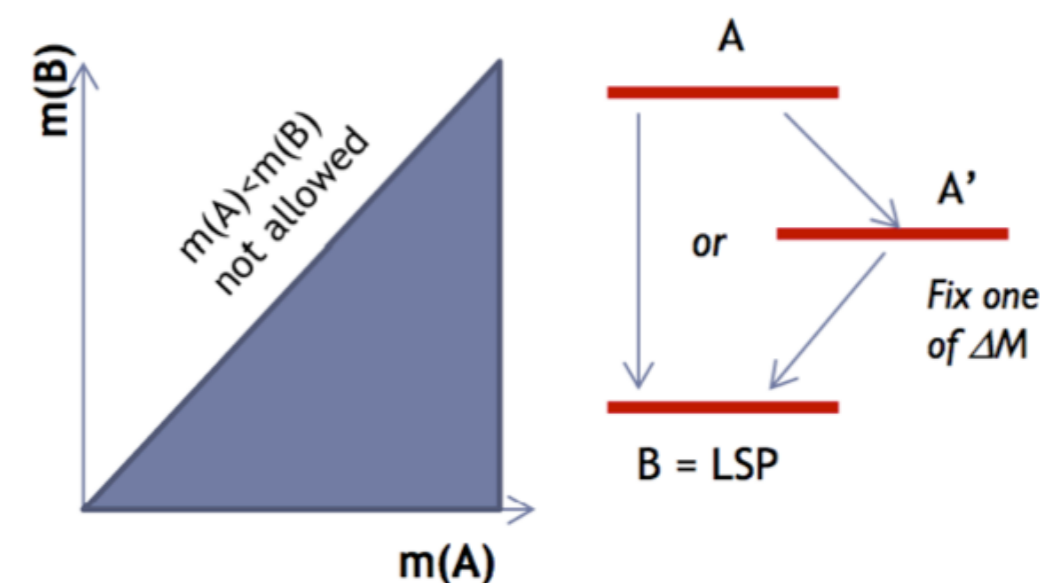
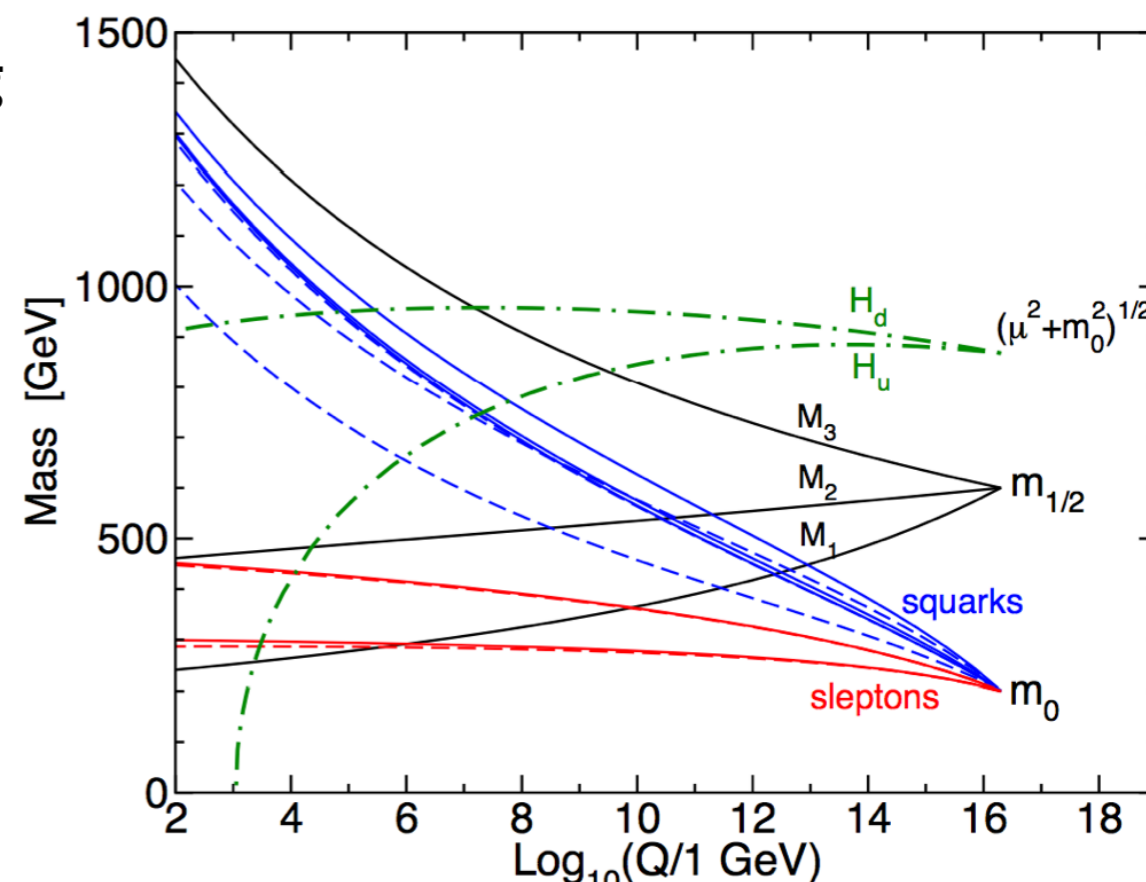


Search for SUSY at ATLAS and CMS at Run I

- Complementary approach by ATLAS and CMS
 - CMS, focus on broad signature-based searches
 - ATLAS, focus on searches for highly motivated processes

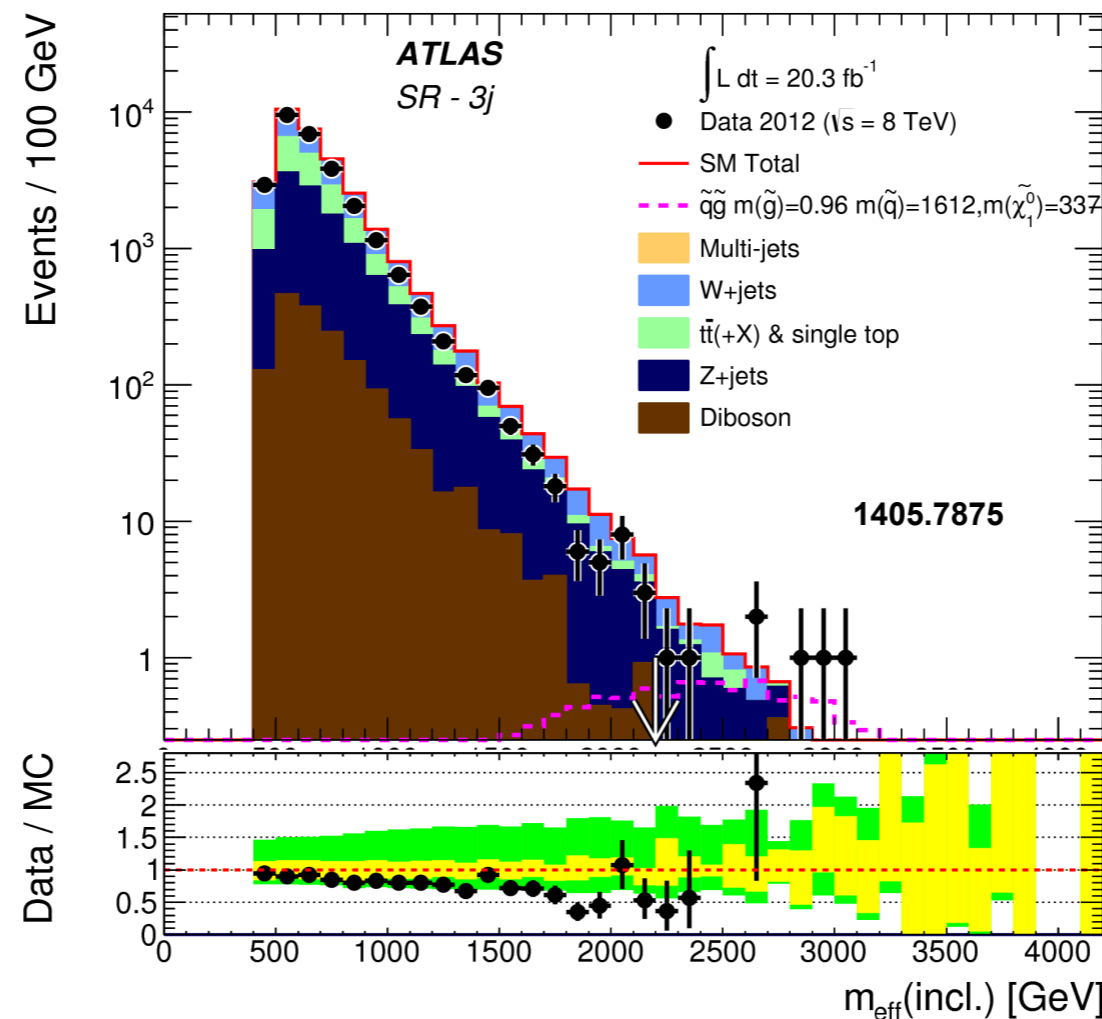
Models for Search Optimization/Interpretation

- **Complete SUSY Models with a SUSY breaking mechanism:**
 - Parameters defined at the SUSY breaking scale
 - mSUGRA/CMSSM, AMSB, GMSB, ...
- **Phenomenological Models:**
 - Parameters defined directly at the electro-weak scale
 - GGM, pMSSM: 19 parameters (+ gravitino mass)
- **Simplified Models:**
 - Parameters directly define the physical masses of selected SUSY particles
 - branching fractions 100% and particles are in pure states (no mixing)



Some of the Discriminating Observables (I)

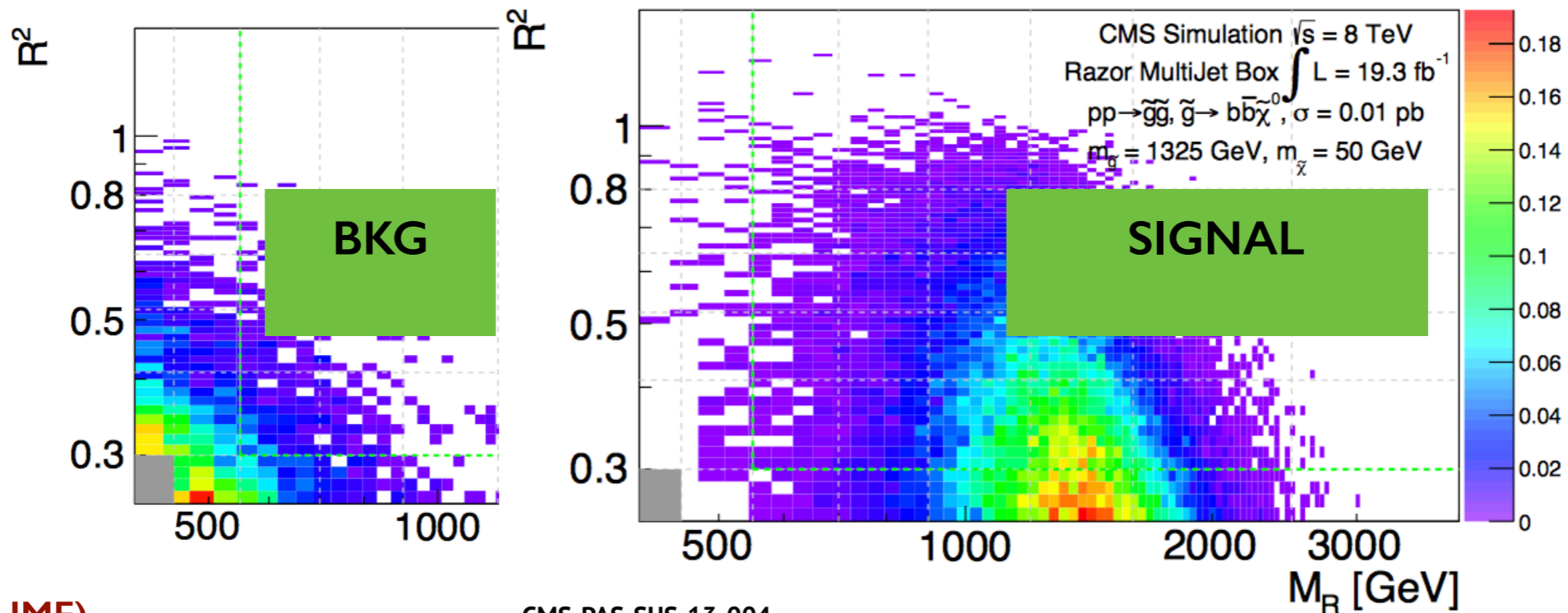
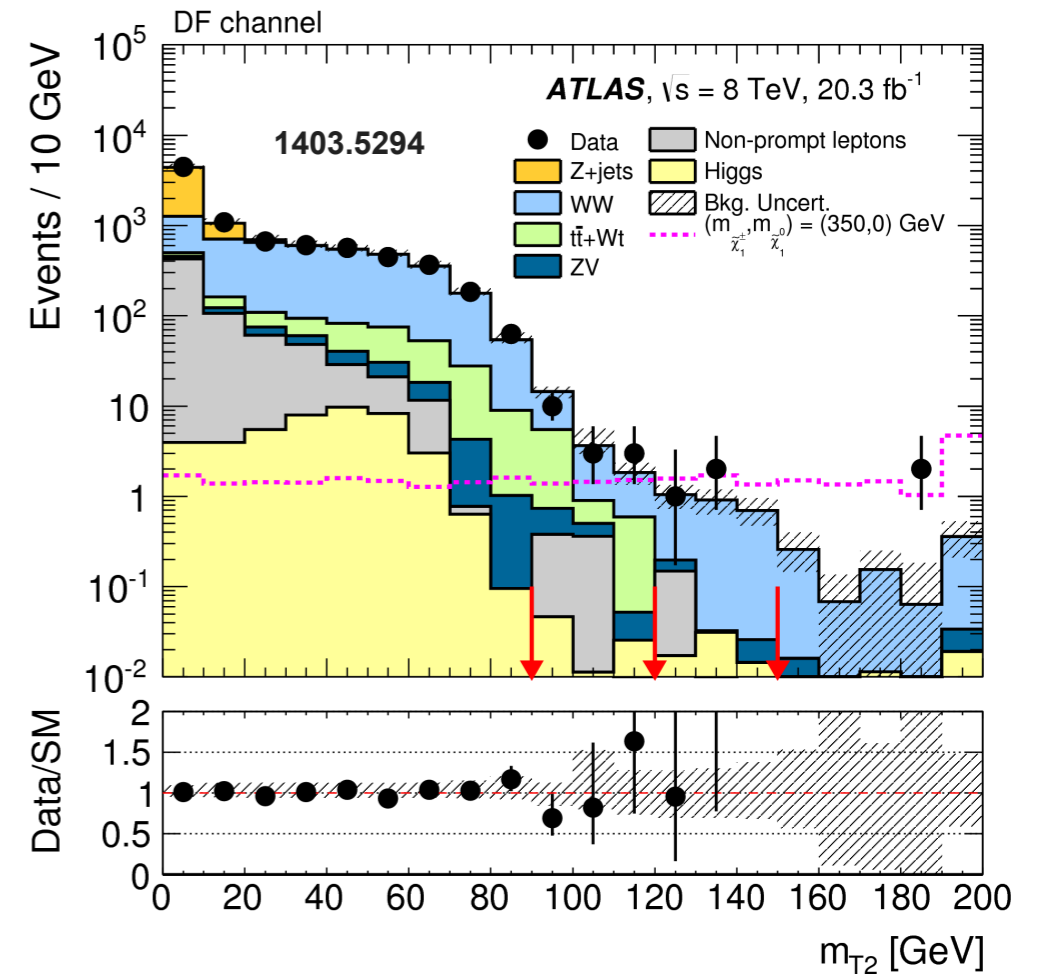
- MET from LSPs most powerful discriminant for RPC SUSY
- **Strong SUSY** discriminated from background using observables
 - related to the sparticle mass scale, e.g. $m_{\text{eff}} = \text{MET} + \sum_{\text{jet}} p_T$
 - suppressing backgrounds with jets with mis-measured energy, e.g. MET significance = $\text{MET} / \sqrt{\sum_{\text{jet}} p_T}$



Some of the Discriminating Observables (II)

- Transverse mass or MT2 (generalization of the transverse mass)
- to suppress backgrounds with Ws in searches for **stops and electroweakinos, but strong SUSY too**
- Topological observables, e.g. alphaT, razor:

$$R \equiv \frac{M_T^R}{M_R} \quad \begin{aligned} M_R &\equiv \sqrt{(p_{j1} + p_{j2})^2 - (p_z^{j1} + p_z^{j2})^2} \\ M_T^R &\equiv \sqrt{\frac{E_T^{miss}(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})}{2}} \end{aligned}$$

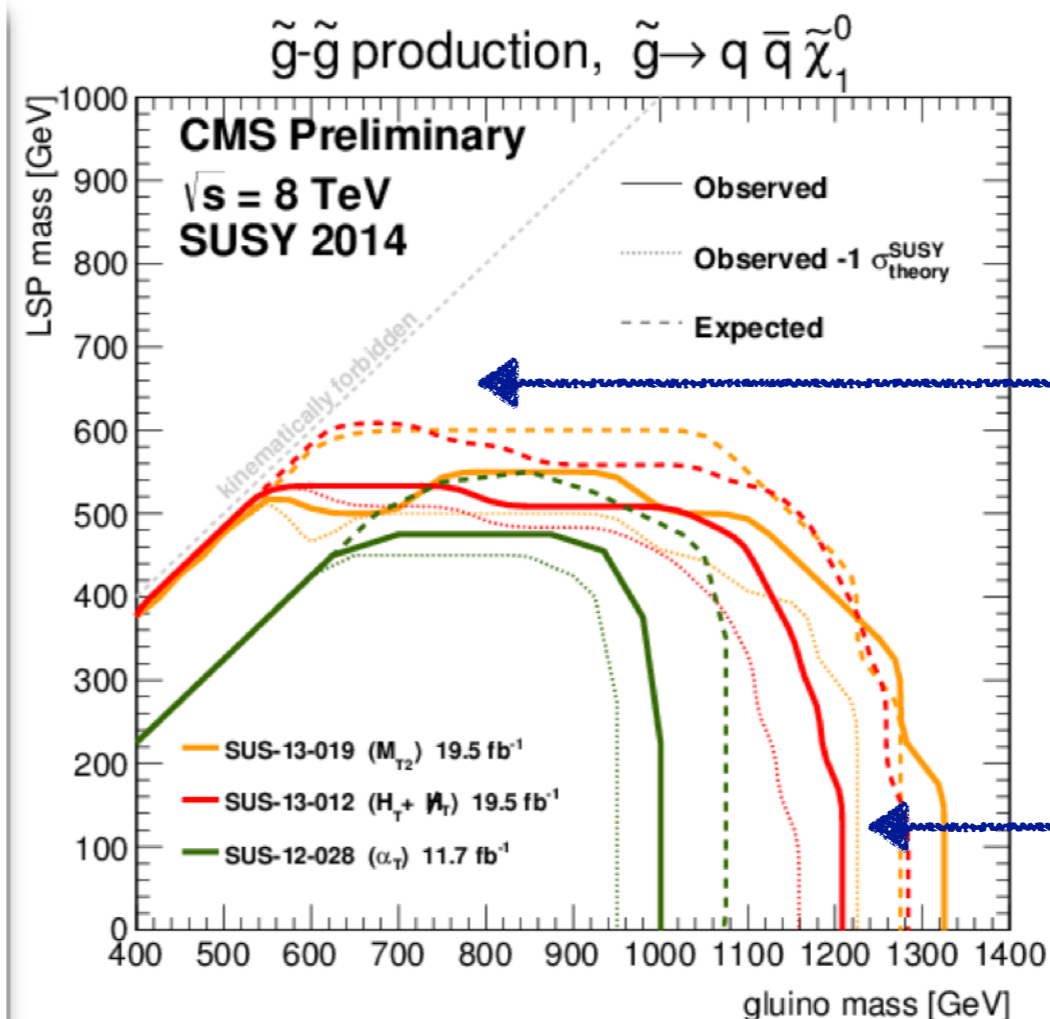
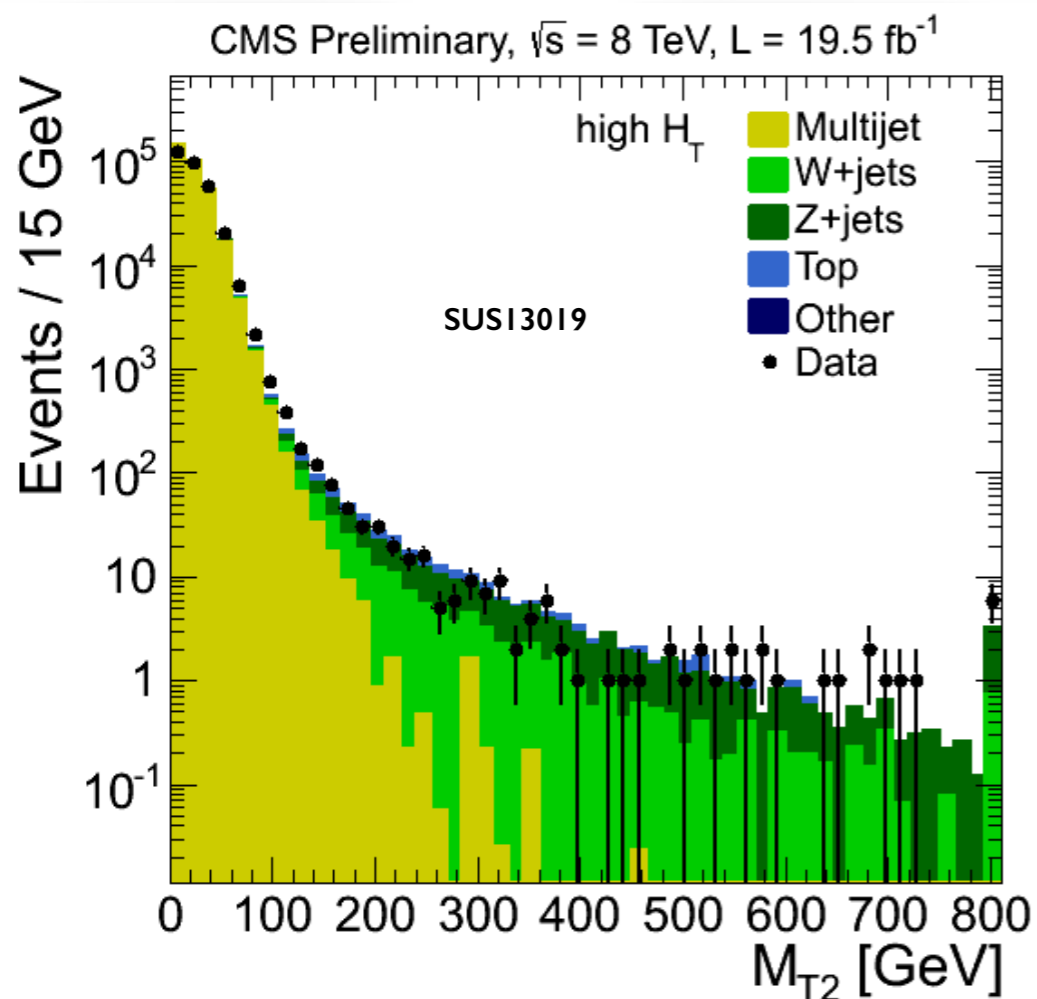
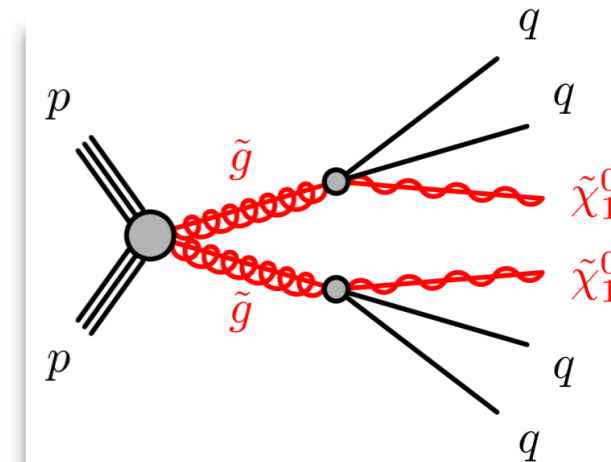


Searches for Gluinos decaying into LF quarks (I)

- One of the driving forces given the large cross-section
- Searches in signal regions with no leptons, jets, and MET

@ ATLAS: m_{eff} , MET significance

@ CMS: best sensitivity using bins of $HT = \sum_{\text{jet}} p_T$, number of b-jets, and MT_2

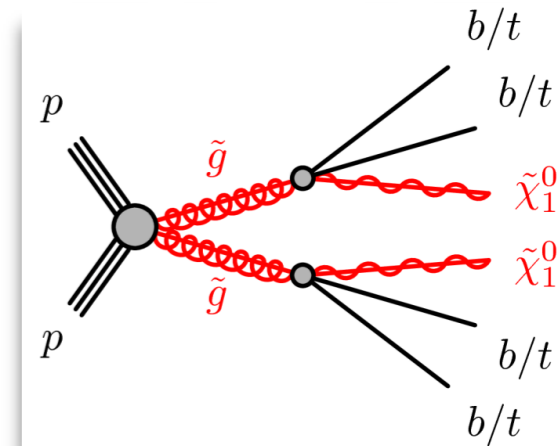


Mono-jet like signatures needed for 'compressed' spectra

Boosted objects ('fat jets') for heavy gluinos; acoplanarity

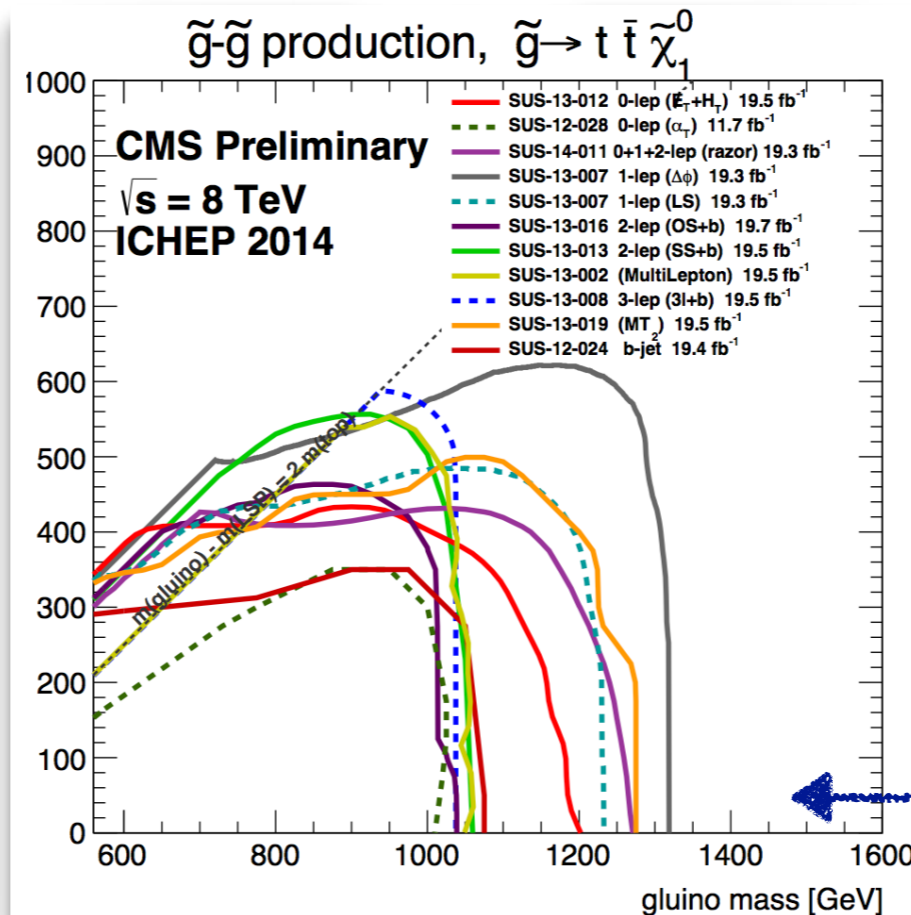
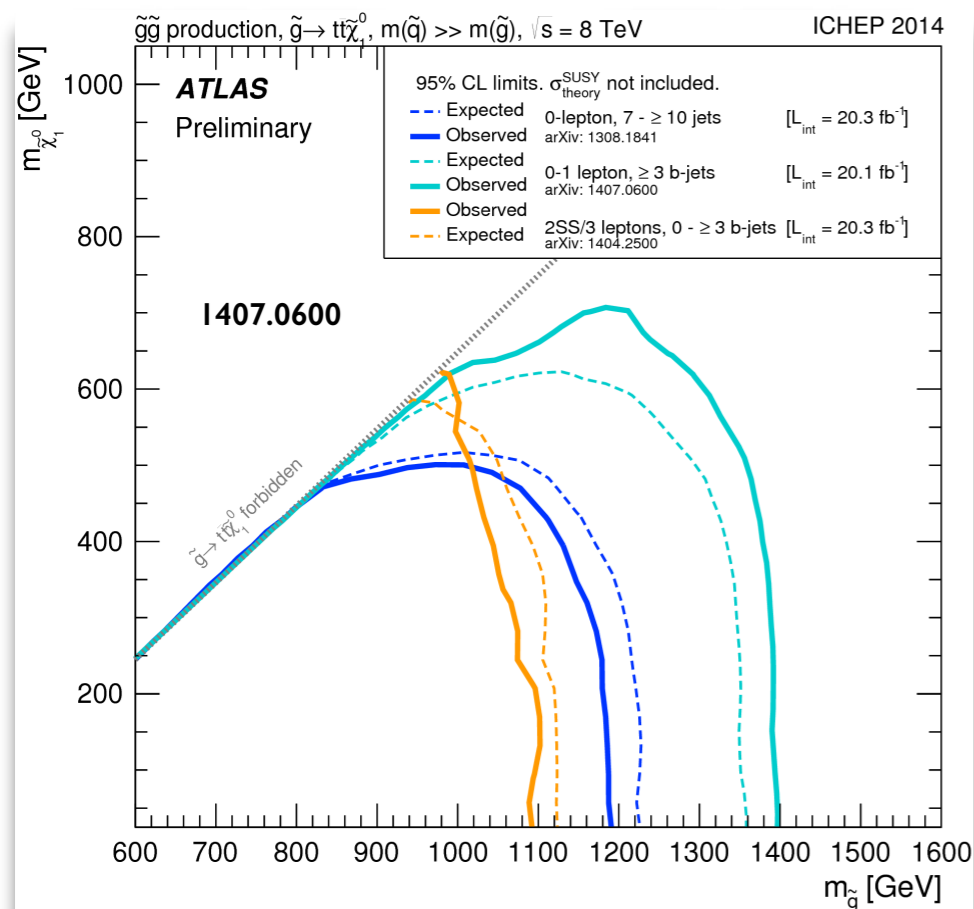
Searches for Gluinos decaying into top (II)

- Highly motivated scenario in Natural SUSY models!
- Rich phenomenology with 4Ws and 4bs addressed by variety of searches
- Events with large number of (b-)jets, MET, and 0-1-3 leptons, SS leptons



@ ATLAS: MET, HT, METsignificance; best sensitivity with 1L+3b

@ CMS: alphaT, MT2 and razor, angular selection; best sensitivity with 1L using $\Delta\phi(W, l)$



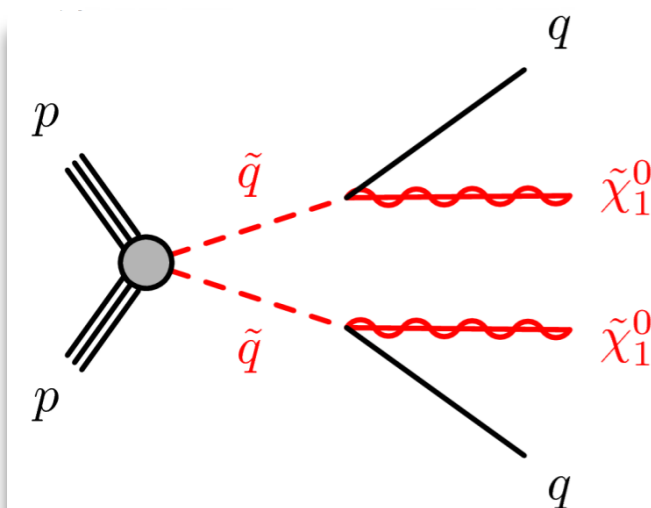
Gluino mass

> 1.3-1.4 TeV

for most of the decays
via virtual stop and
sbottom

“Top” Tagging for
heavy gluinos

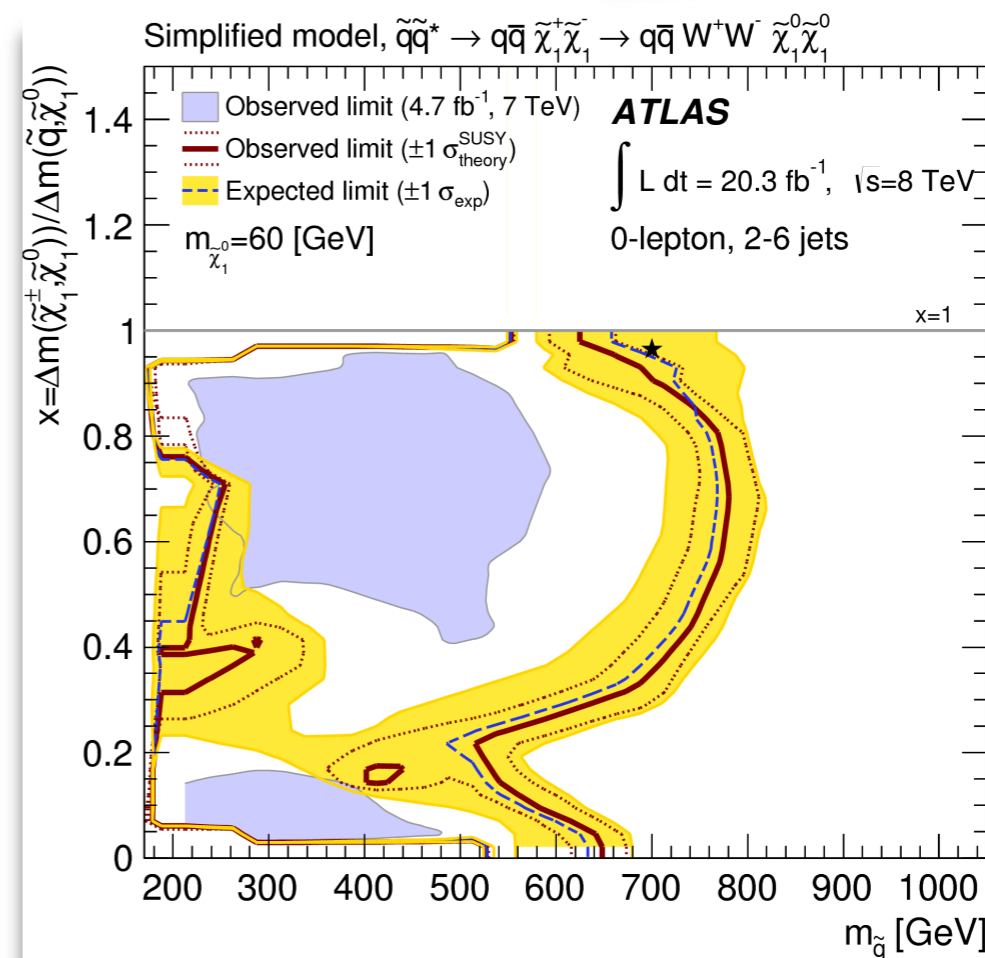
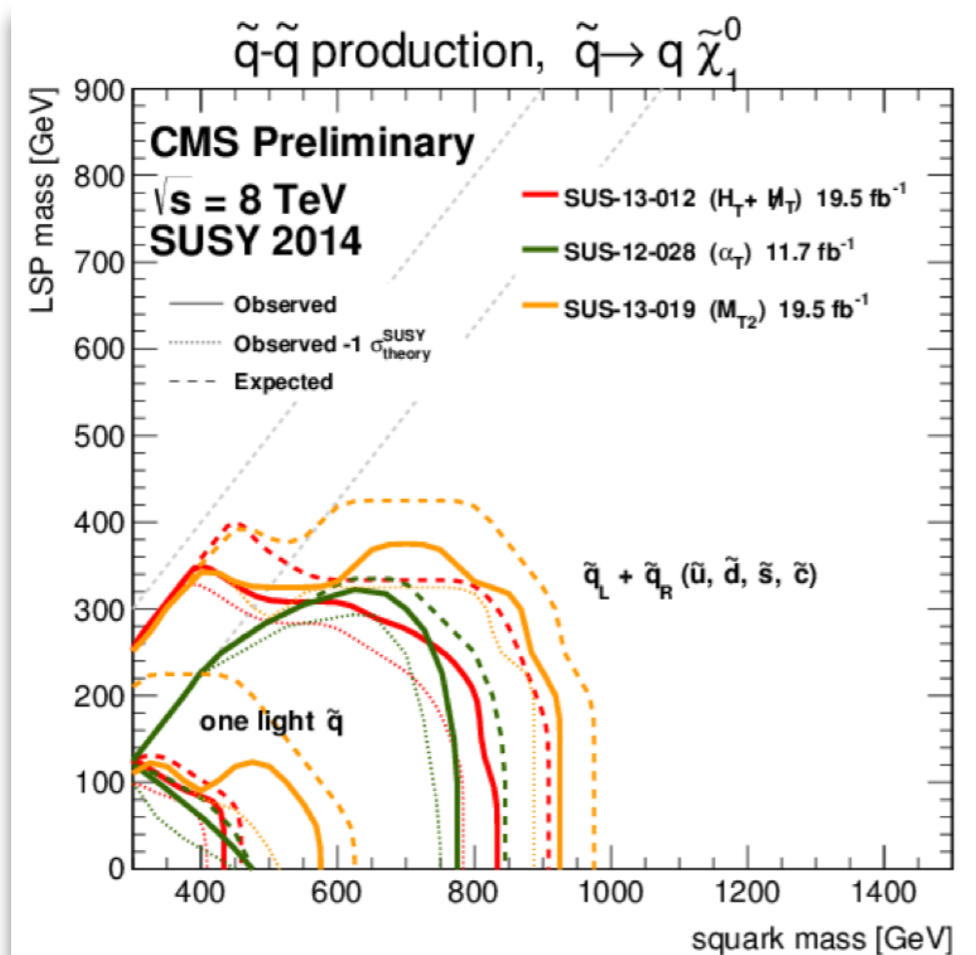
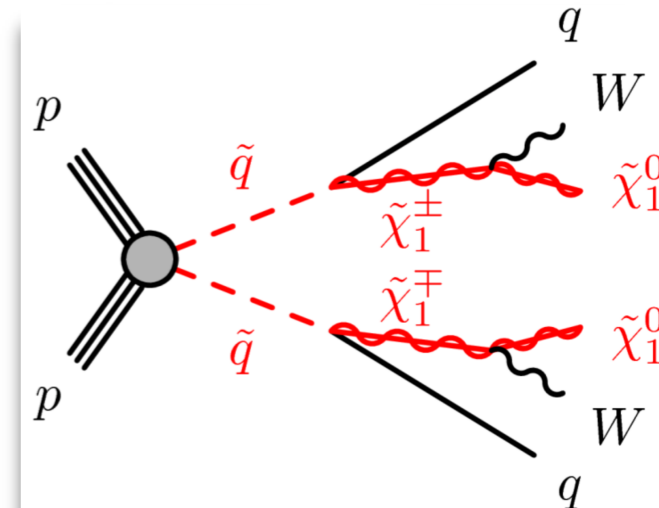
Search for Light Flavor Squarks



- Challenging final states with low number of jets and low M_{eff} !

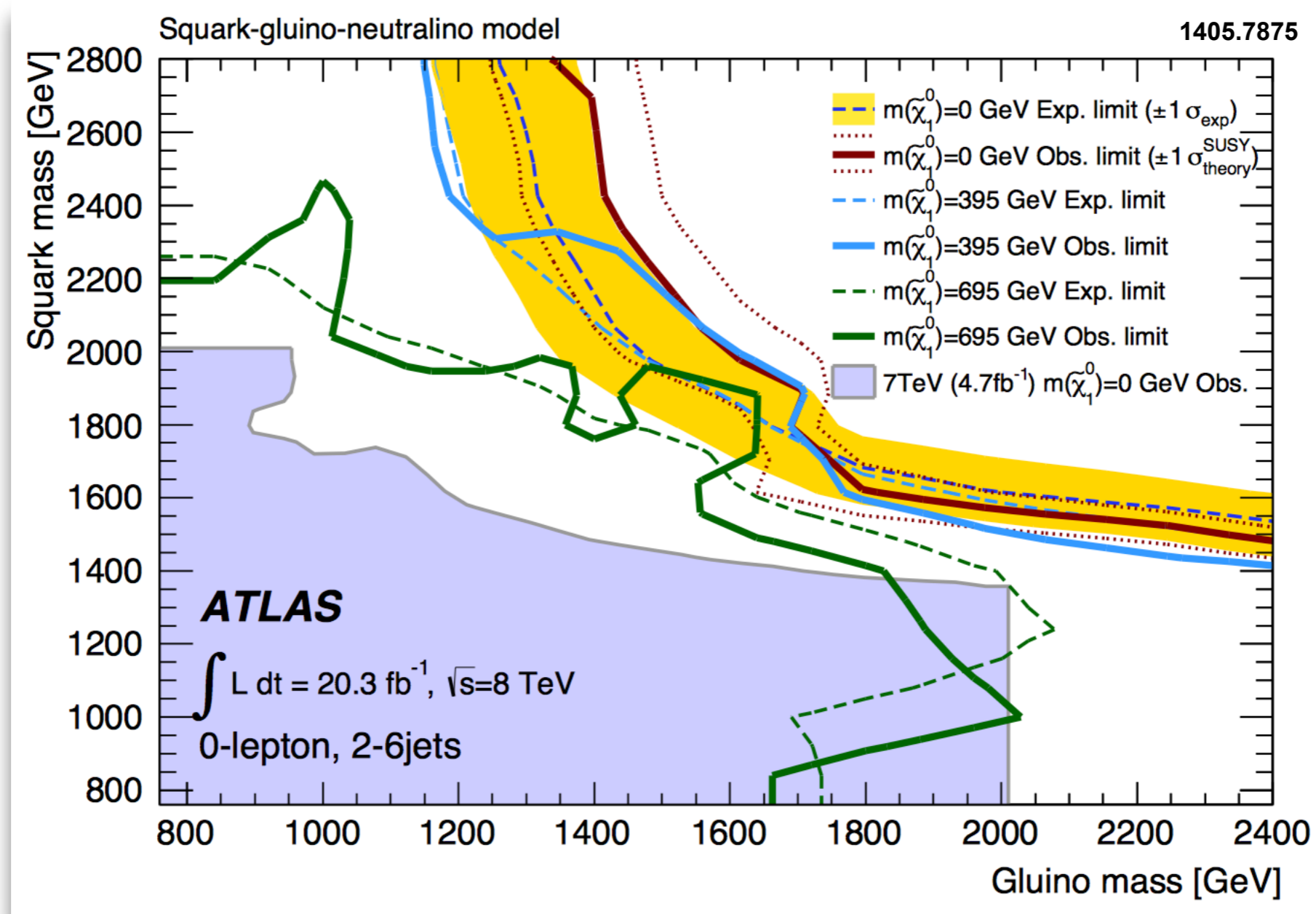
@ ATLAS: MET and MET-significance; 0 and 1L

@ CMS: alphaT; best sensitivity with MT2



Sensitivity up to $\sim 900 \text{ GeV}$ squark,
but 400 GeV if one squark only is light

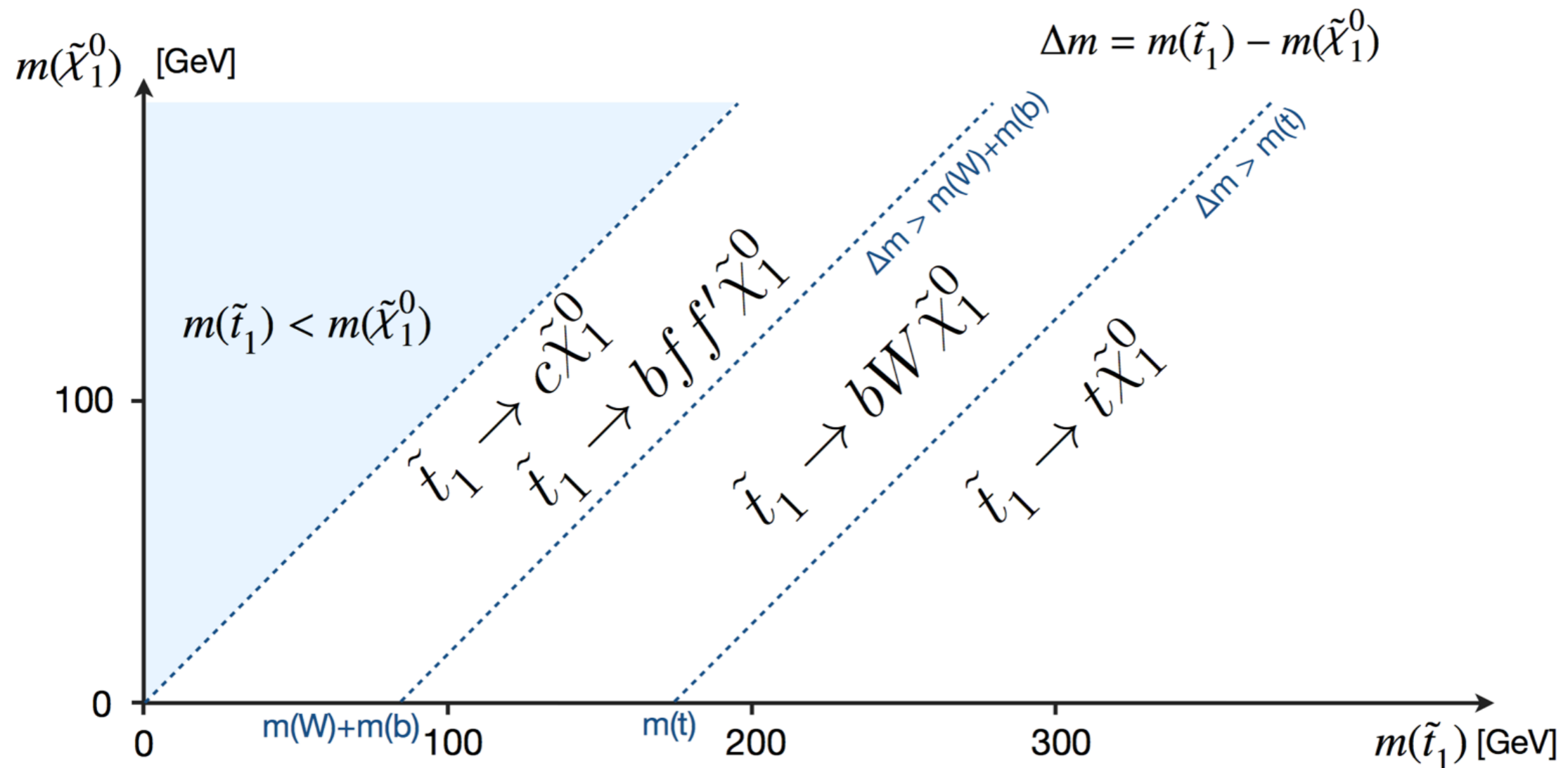
Phenomenological model with squarks and gluinos



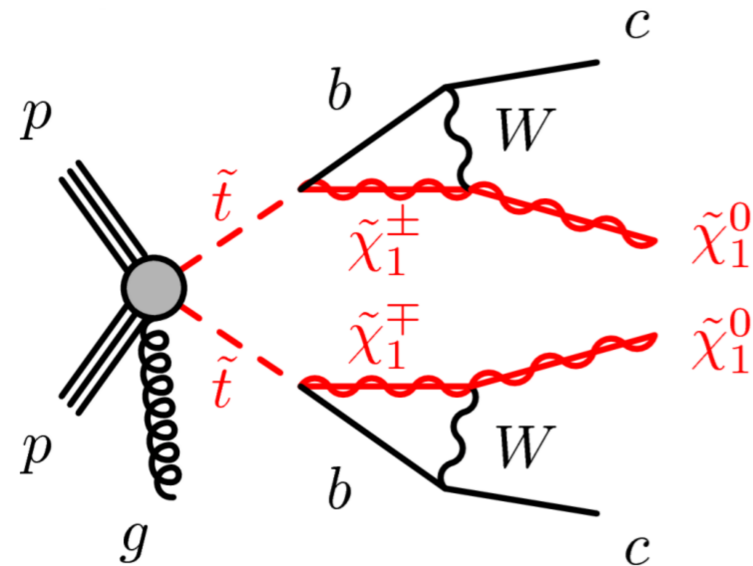
Enhanced sensitivity to squarks due to pair production of squarks and gluinos and gluino mediated processes

Search for Stop

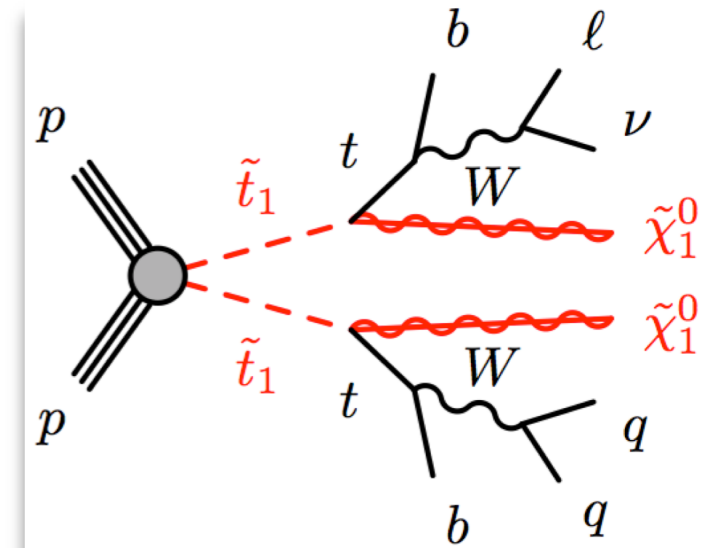
- **Key to naturalness but challenging!**
 - cross section is suppressed, 10pb to 1fb from 200 to 900 GeV stops
 - sensitivity highly dependent on the decay mode, the mass hierarchy of “sparticles” participating (and to some extent on the stop “handedness”)



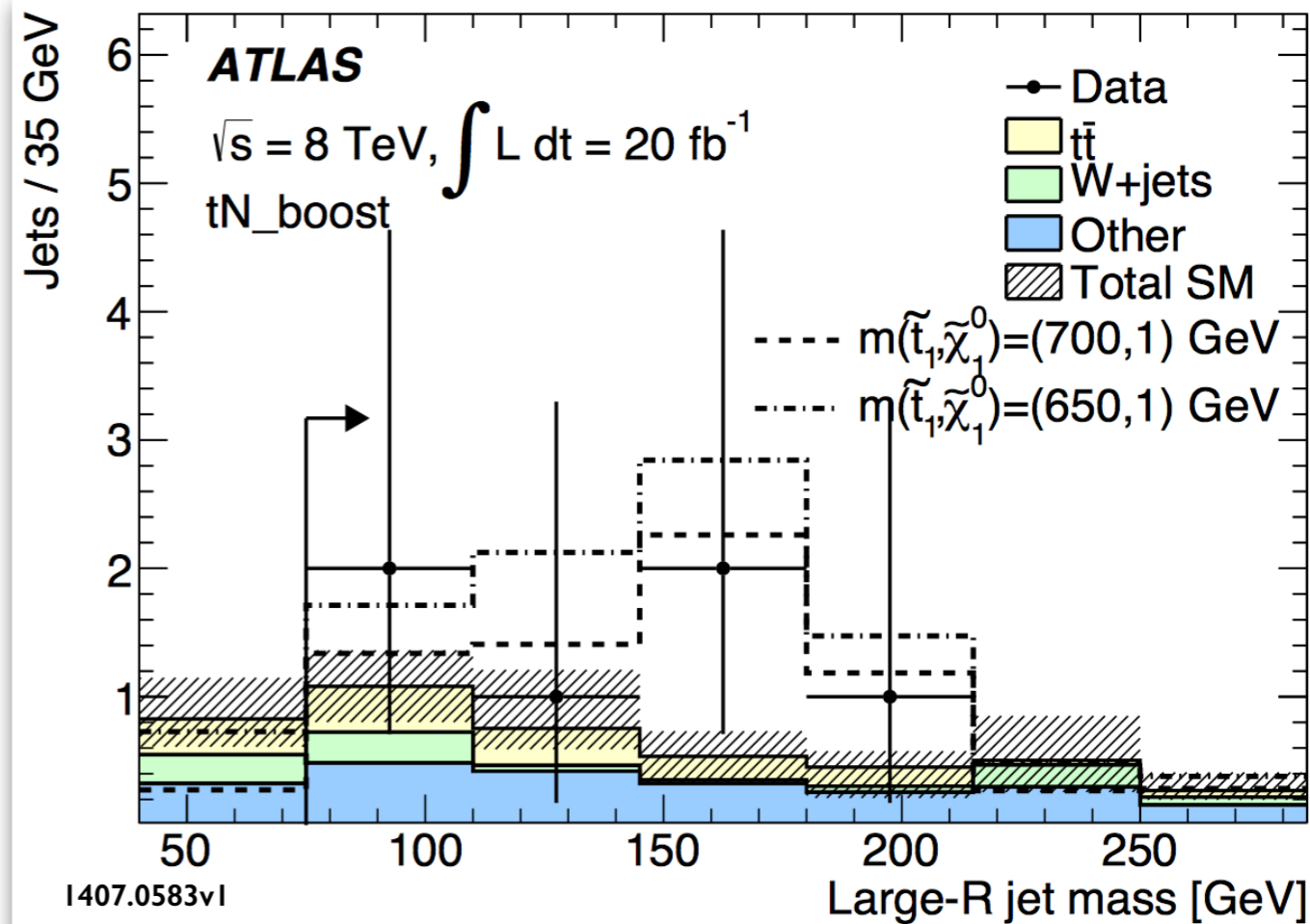
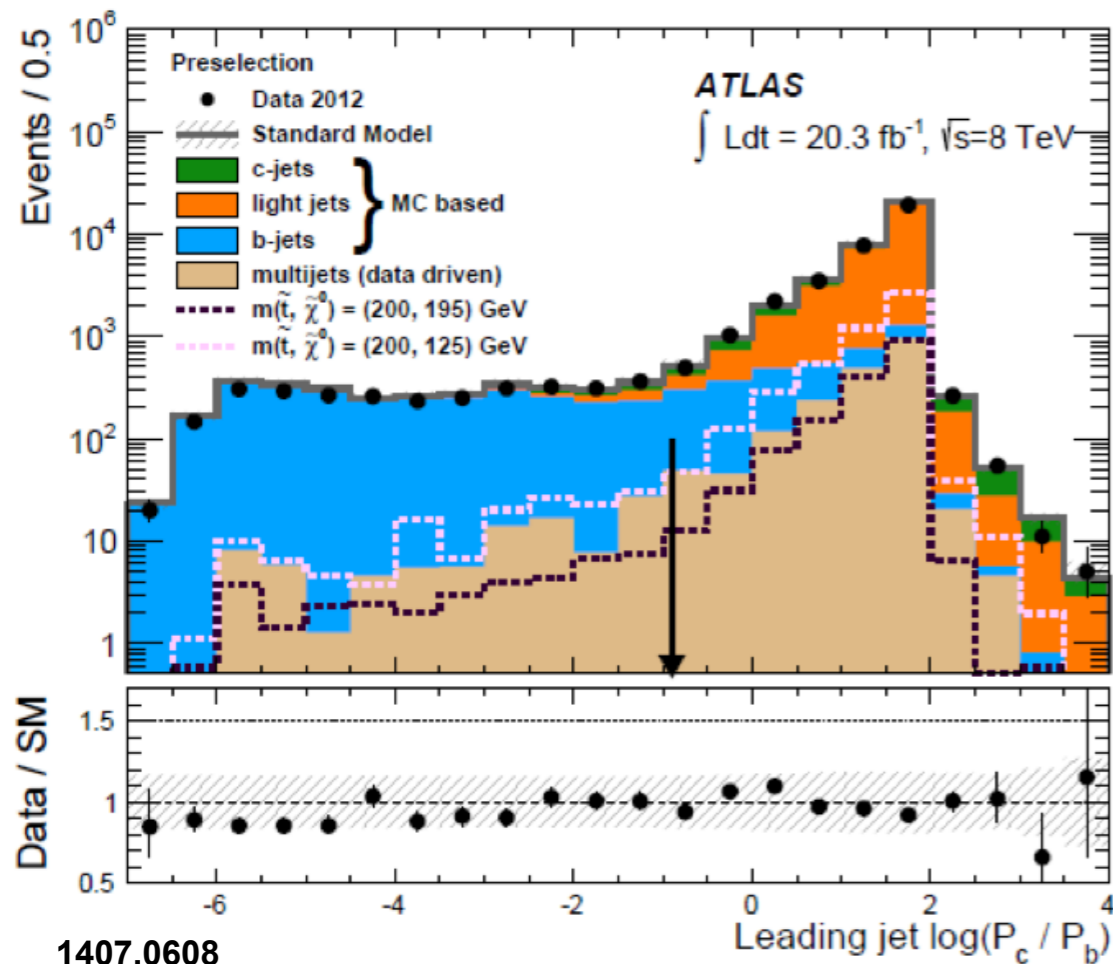
Recent Highlights



- Search for stop into charm
 - @ both ATLAS and CMS: ISR approach
 - @ ATLAS: also charm-tagged search
- Search medium-heavy stop



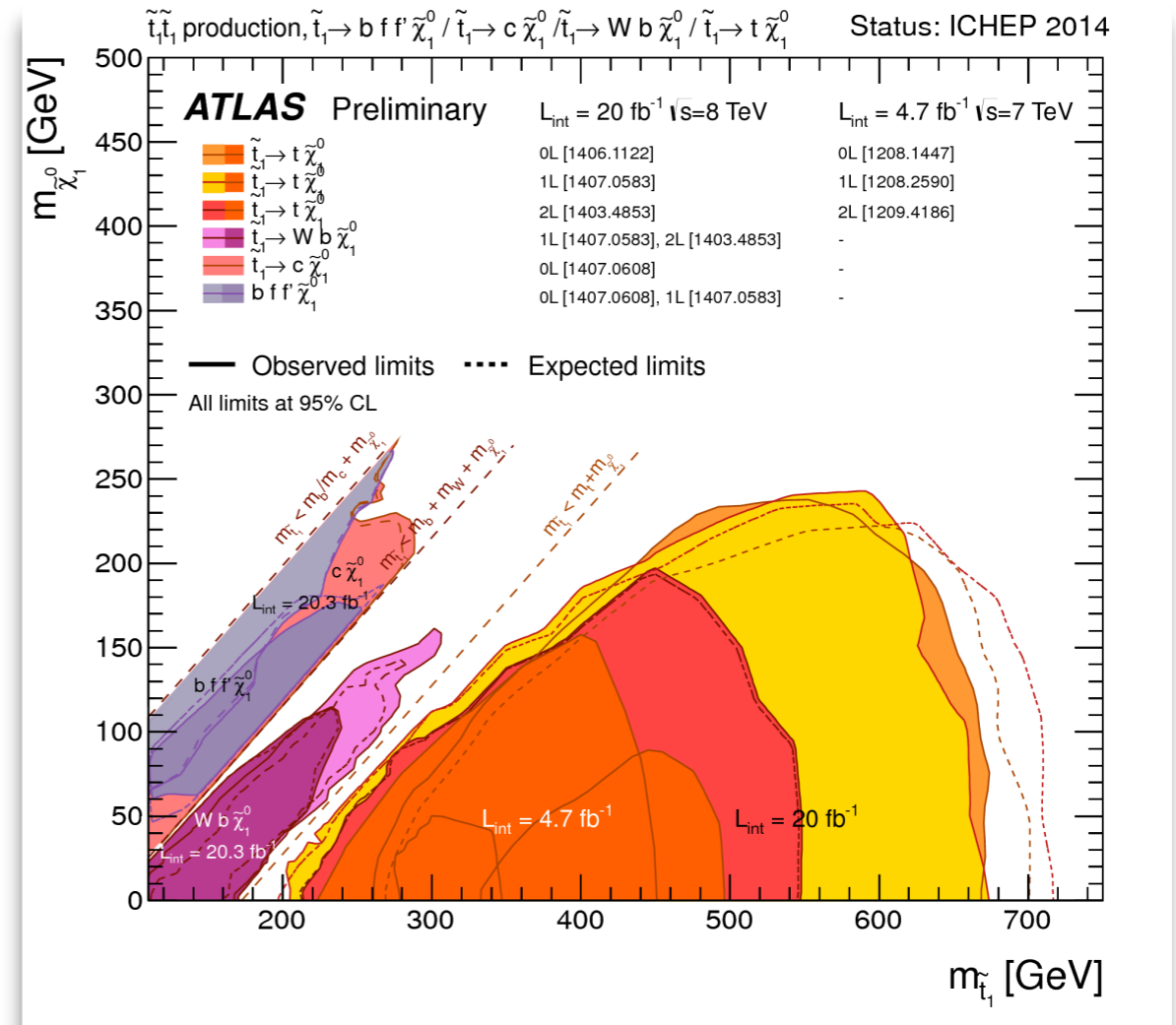
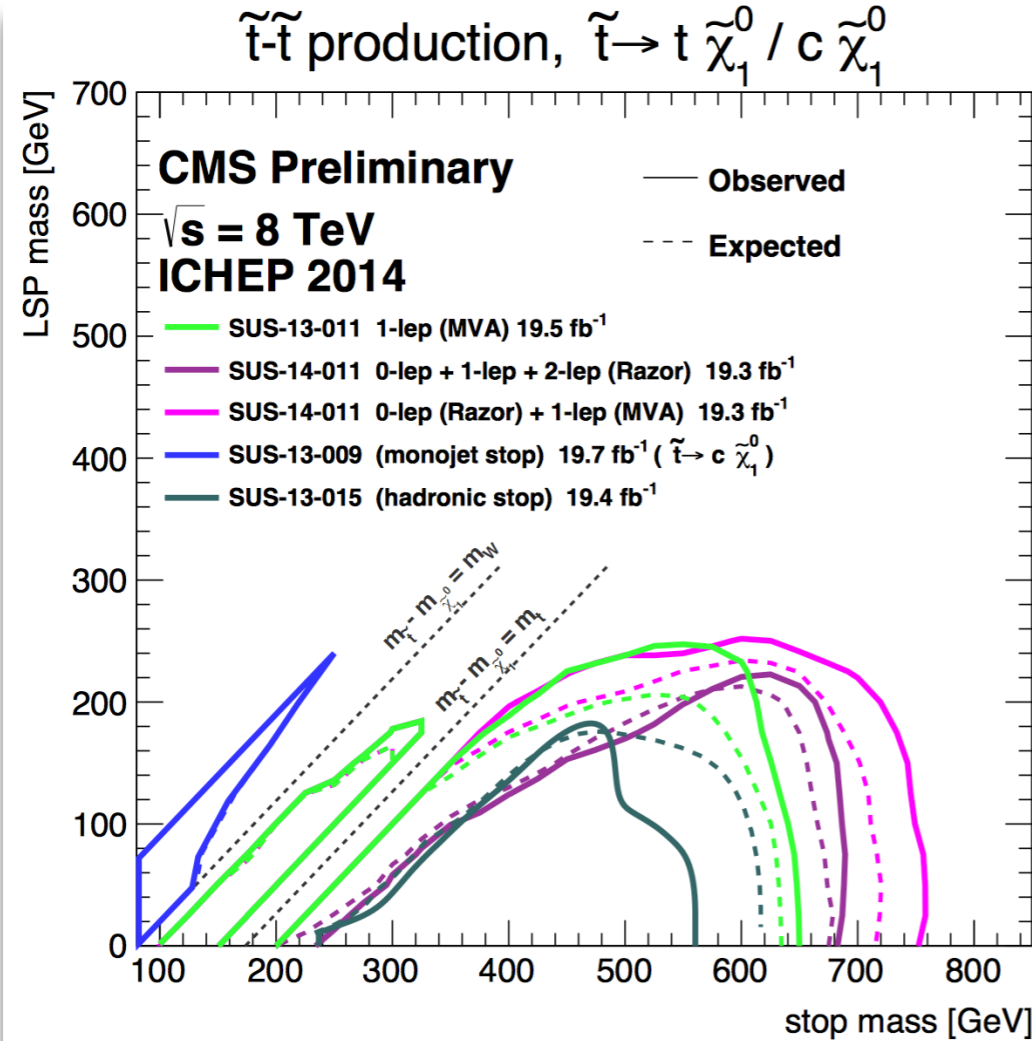
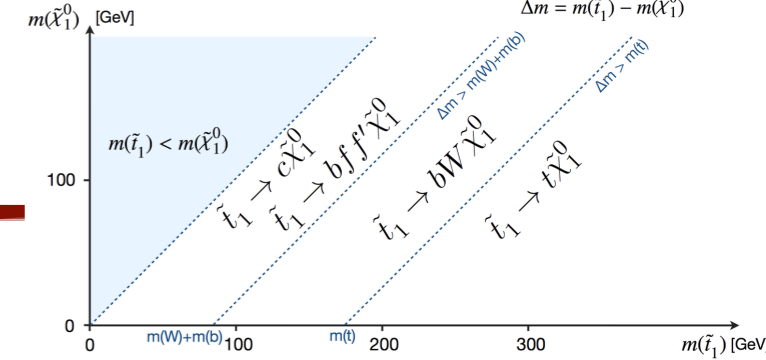
@ ATLAS: SRs with 1 lepton and requests on asymmetric MT2 (aMT2), 'topness', top mass, HT, MET and MET significance



Searches for Stops

- Complementarity of searches

- not shown here results from searches addressing low mass stops decaying into $b\tilde{C}l$, bW^*

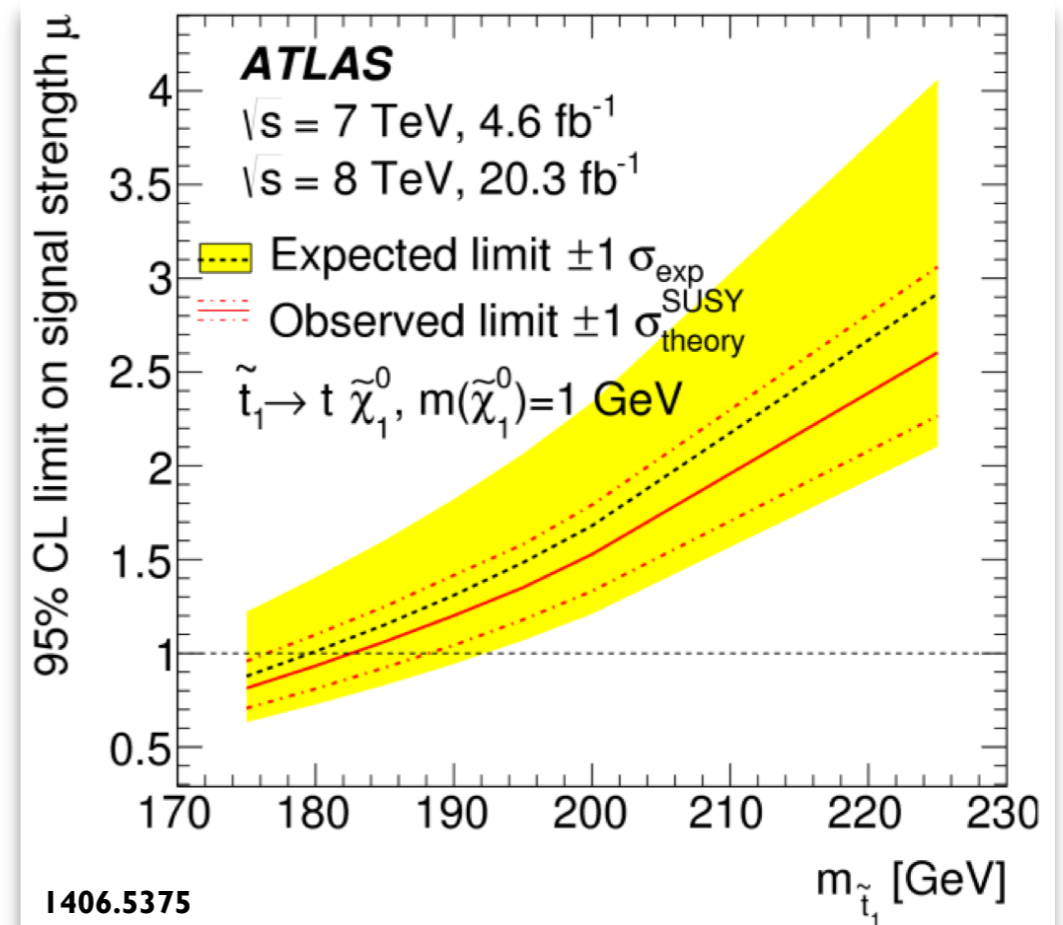
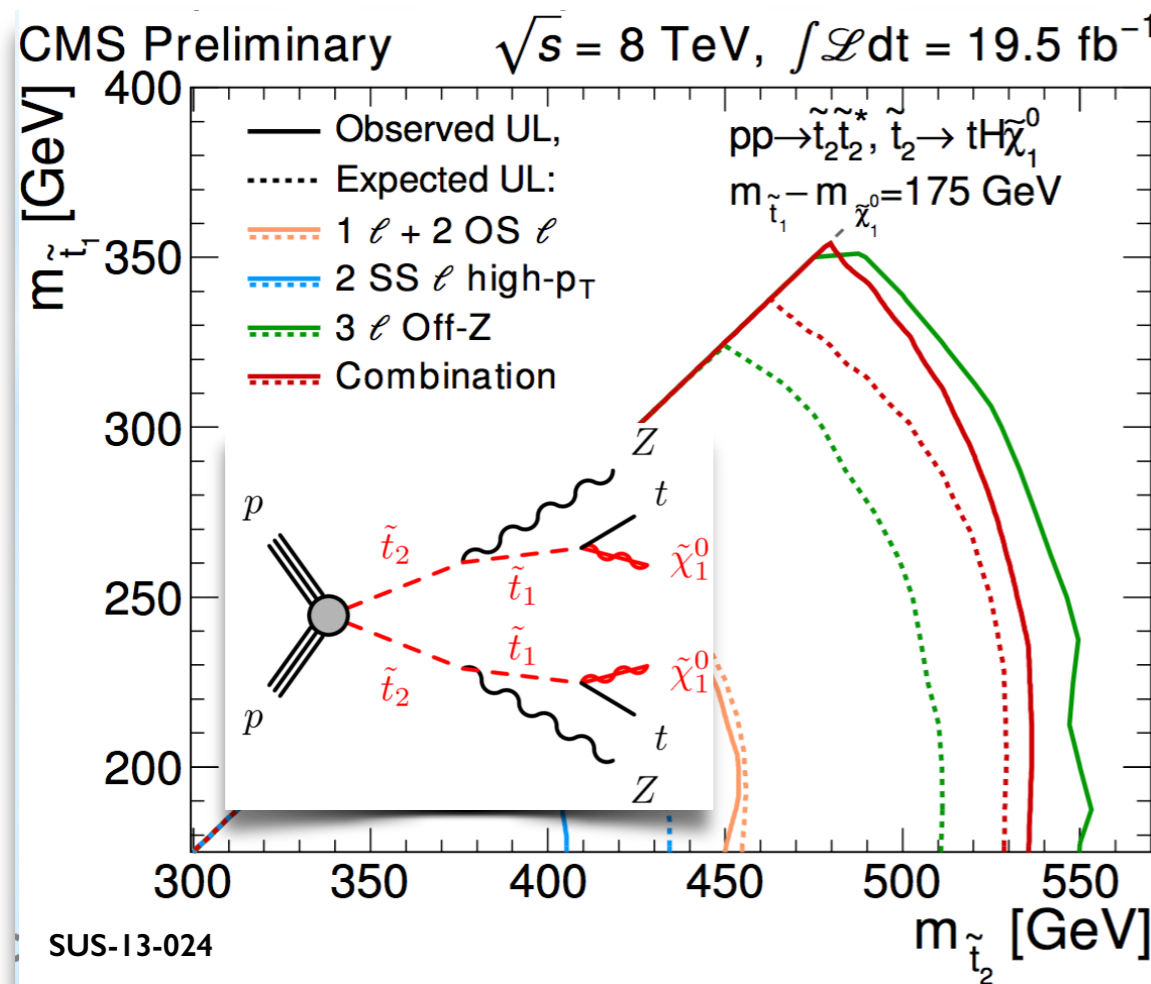
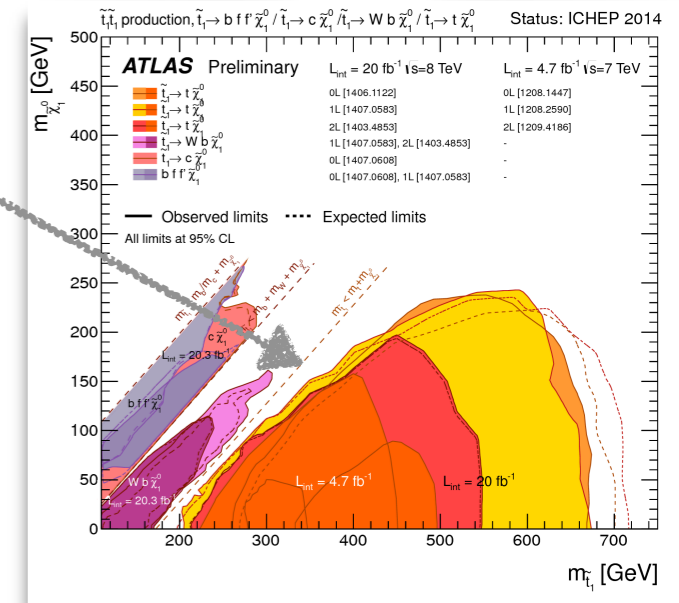


Stop mass > 700 GeV

Sensitivity exceeds that for light flavor squarks thanks to the richer signature originating from stop decays (better signal to background discrimination)

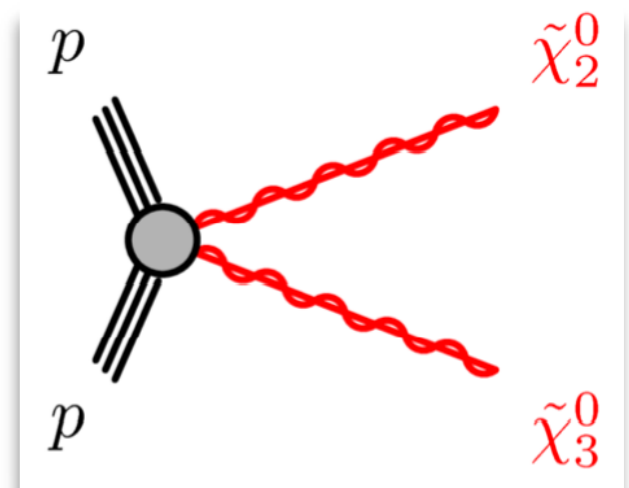
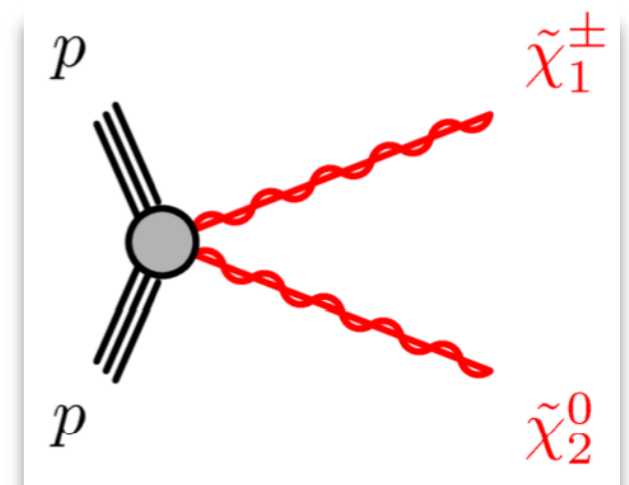
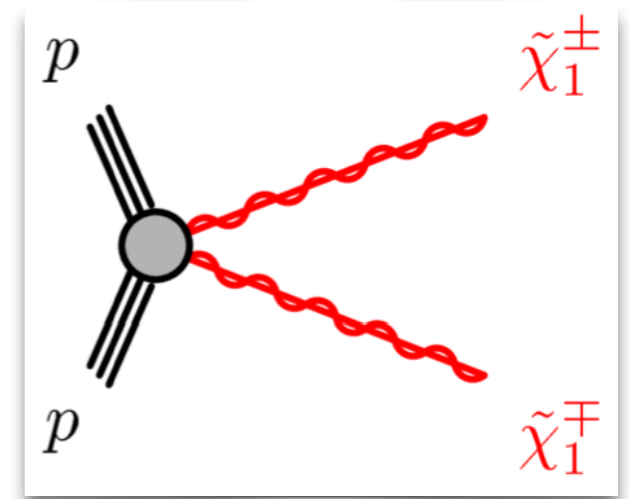
Sensitivity to Stops when $m_{\text{Stop}} \sim m_{\text{Top}} + m_{\text{NL}}$

- Challenging region as the light stop signal is indistinguishable from the SM top production
- Searches for stop2 in decays via Z and H (H in into bb, WW, ZZ)
 - in events with 1, 2, 3 leptons and b-jets
- Constraints from the SM top-pair production cross-section



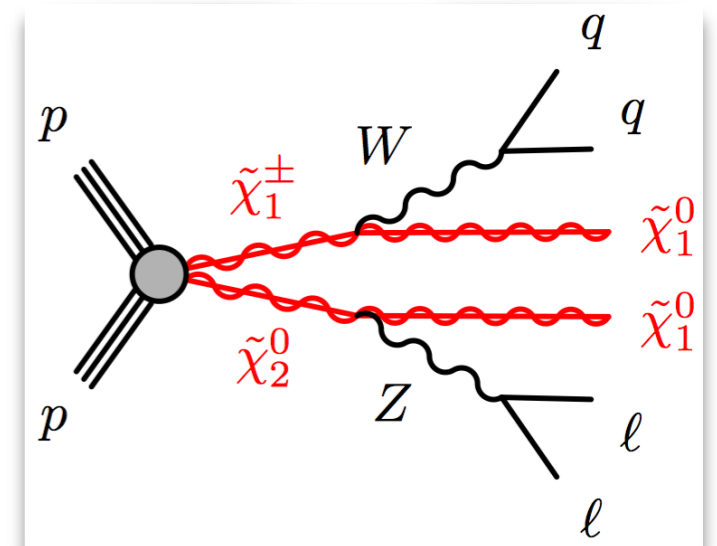
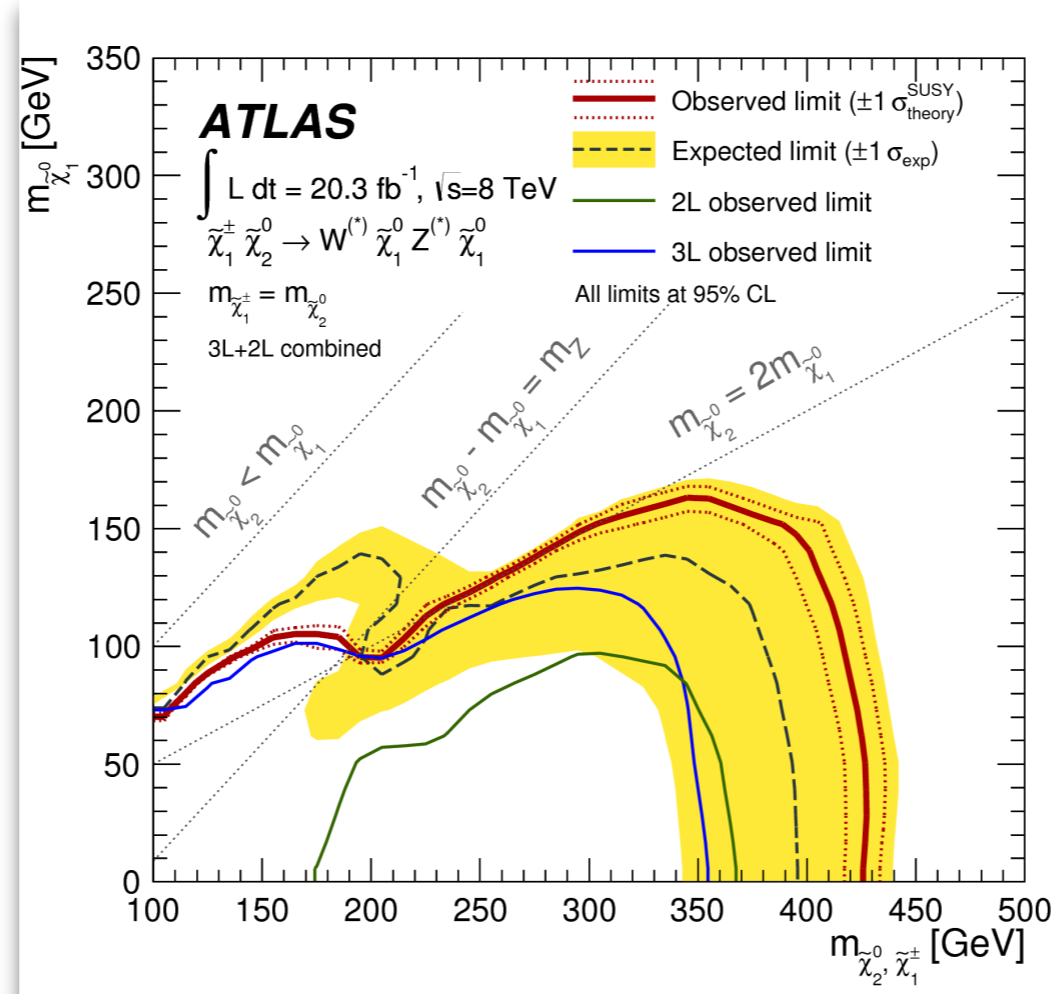
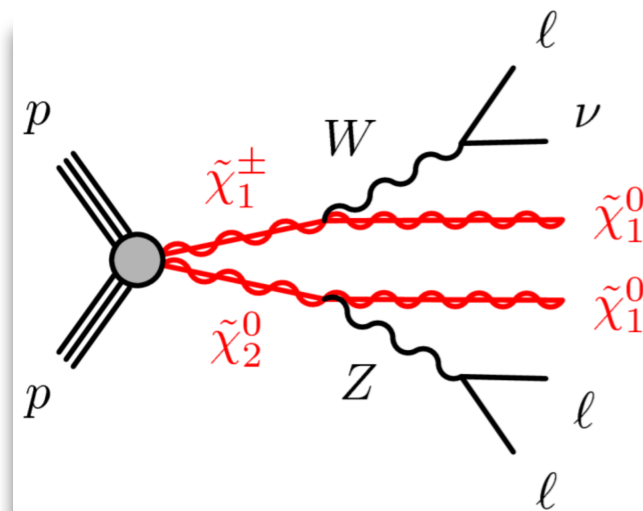
Search for Electroweakinos

- Challenging searches due to very small production cross-section and significant irreducible background from diboson
 - **but highly motivated as electro-weakinos expected to be light mass!**
- Comprehensive search program covering pair production of charginos, neutralinos, chargino-neutralino and decays via sleptons, staus, W, Z, Higgs bosons
- Events with 1, 2, 3, 4 leptons (including hadronic taus), with mild selection on MET, MT, and MT2
 - binned SRs to enhance sensitivity over large area of parameter space
 - requests of b-jets when searching for Higgs



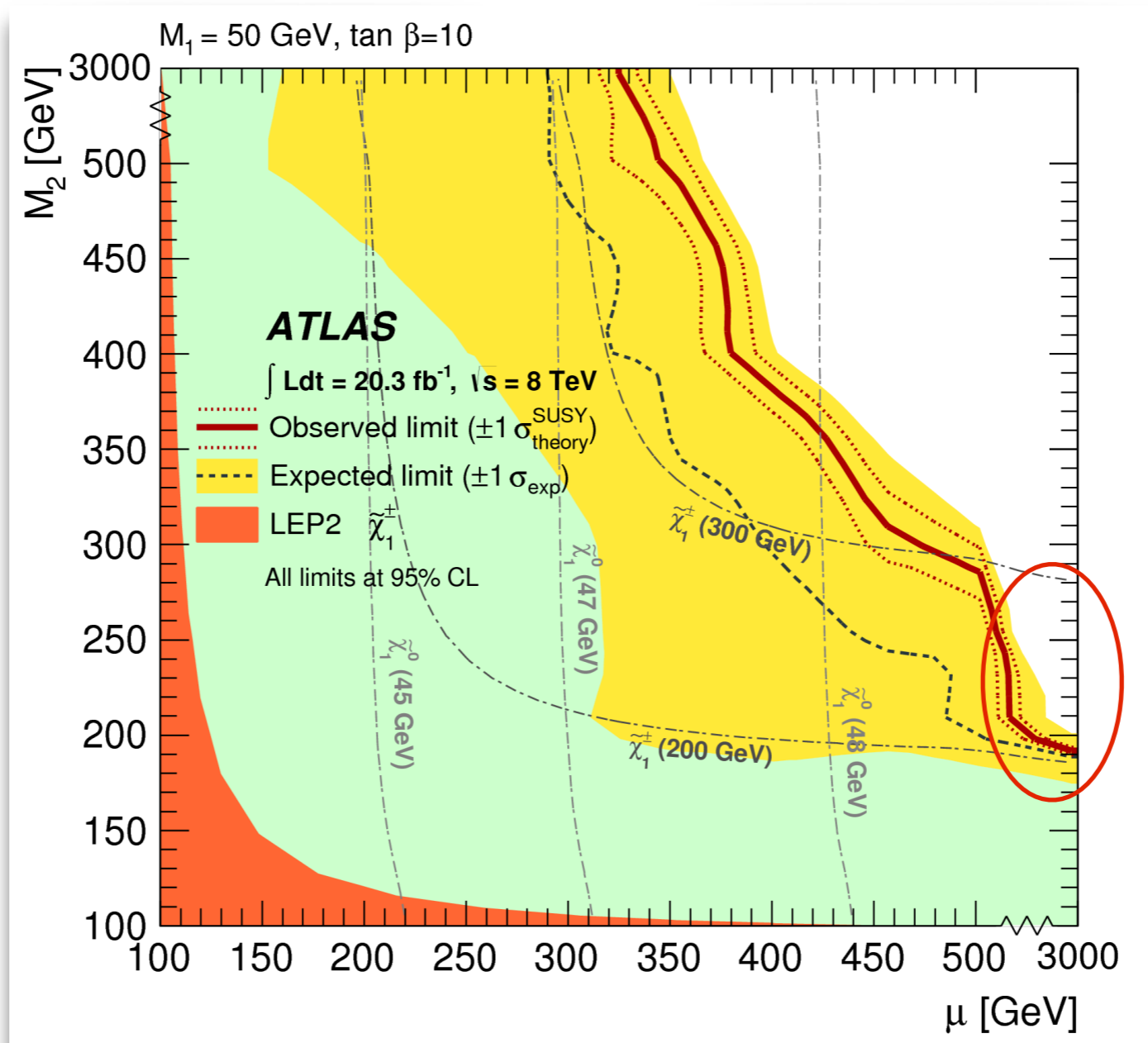
Scenarios with Heavy Sleptons

- Natural scenarios
- Sensitivity up to **~450 GeV** charginos and heavy neutralinos
 - **exceed the LEP limit!**
- 2L+j covers scenarios with large mass charginos, while 3L has sensitivity for most of the parameter space



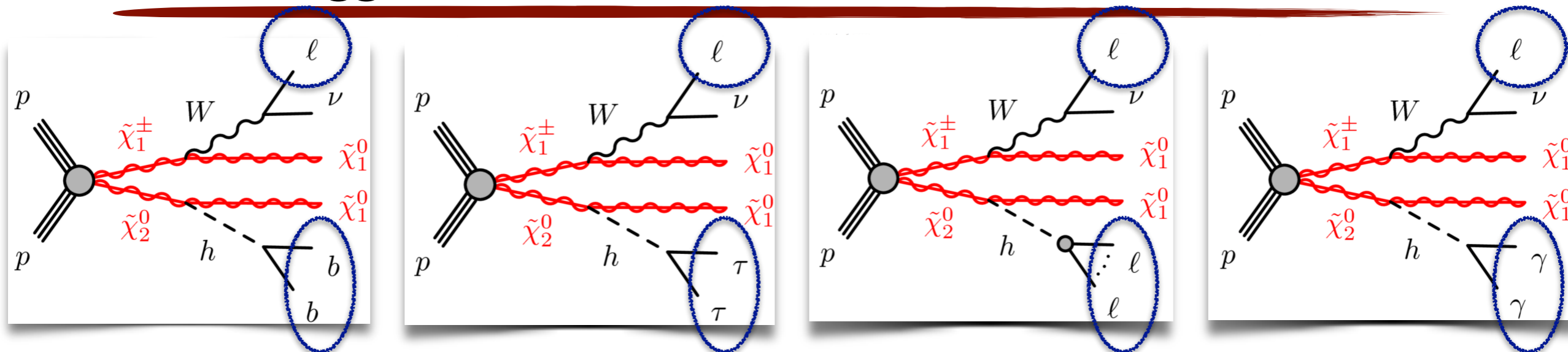
Phenomenological MSSM for EWK SUSY

- The electro-weakino sector is parametrized by only 4 parameters:
- M_1 (bino), M_2 (wino), μ (higgsino) and $\tan\beta$
- Sensitivity up to $\sim 200\text{-}350$ GeV charginos and heavy neutralinos depending on the nature of the electroweakinos (higgsino dominated, wino dominated)

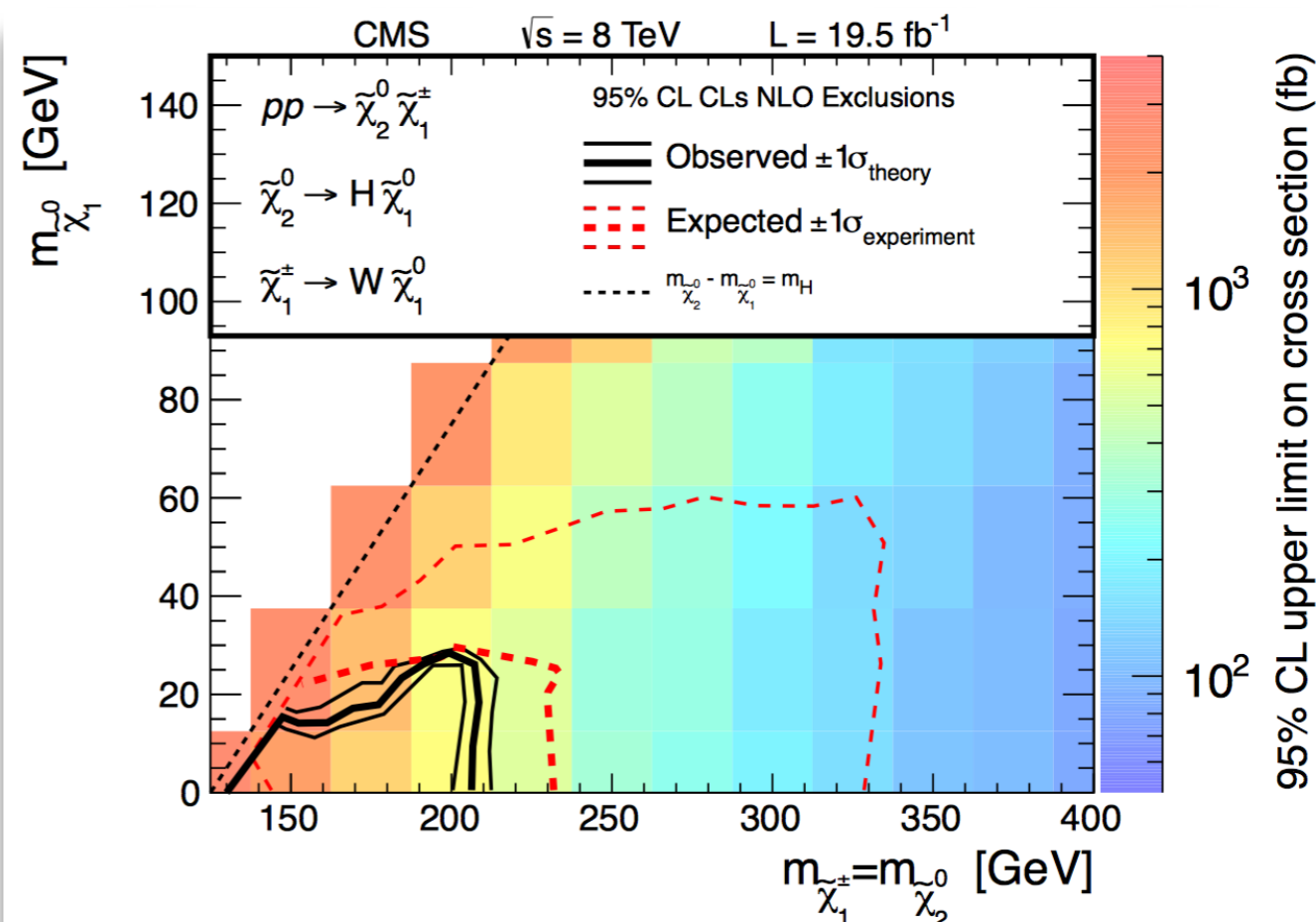
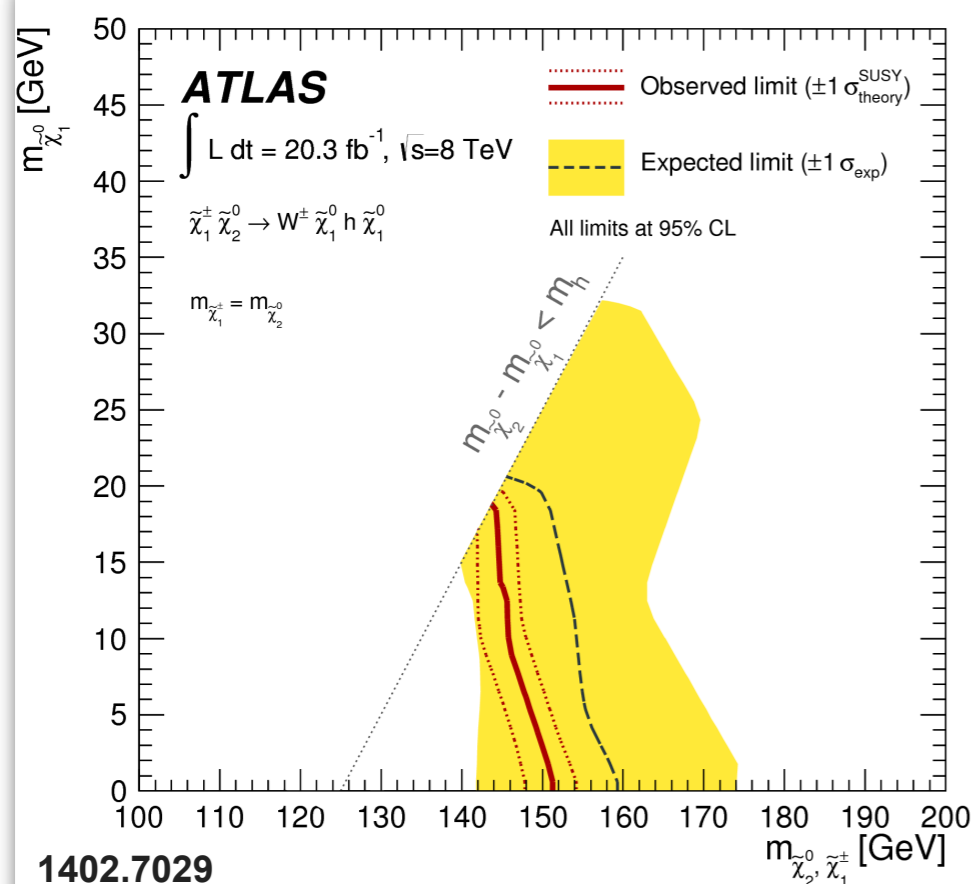


Higgs in decays

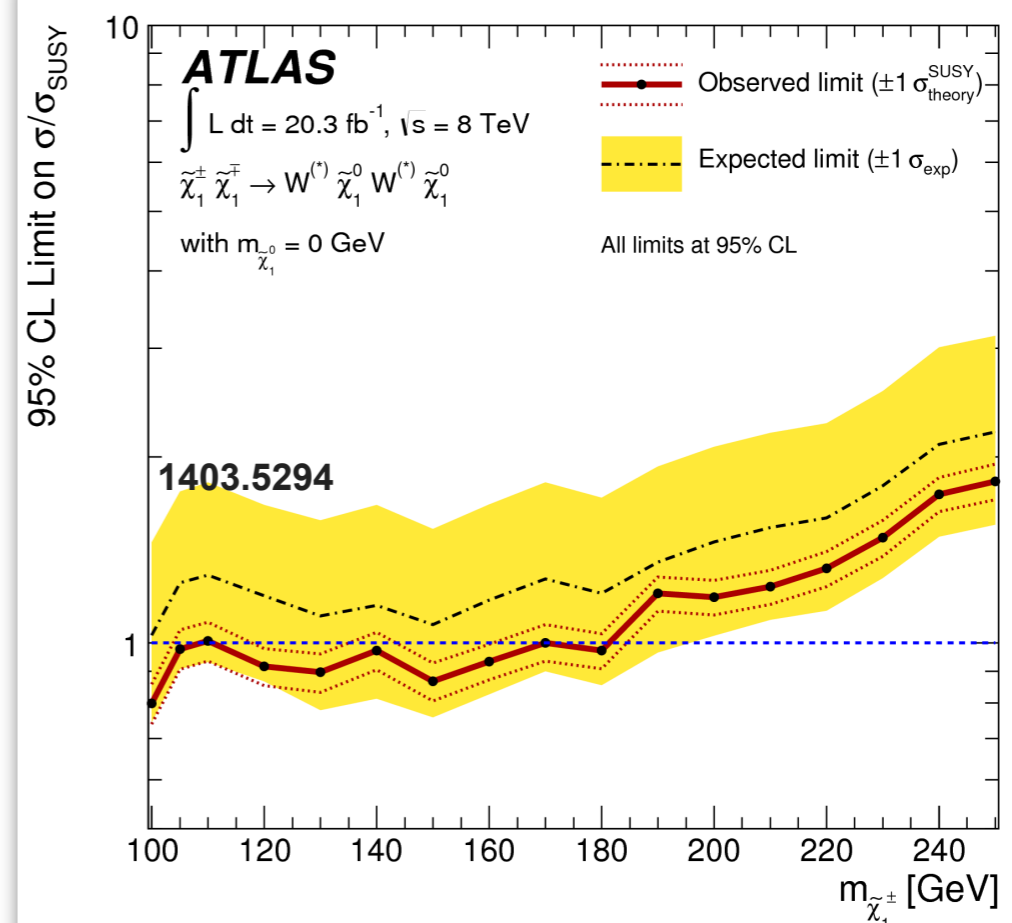
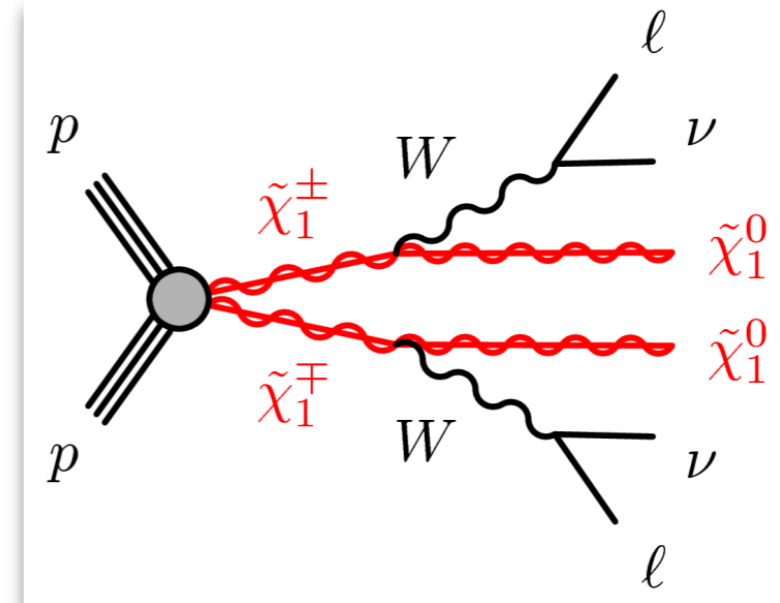
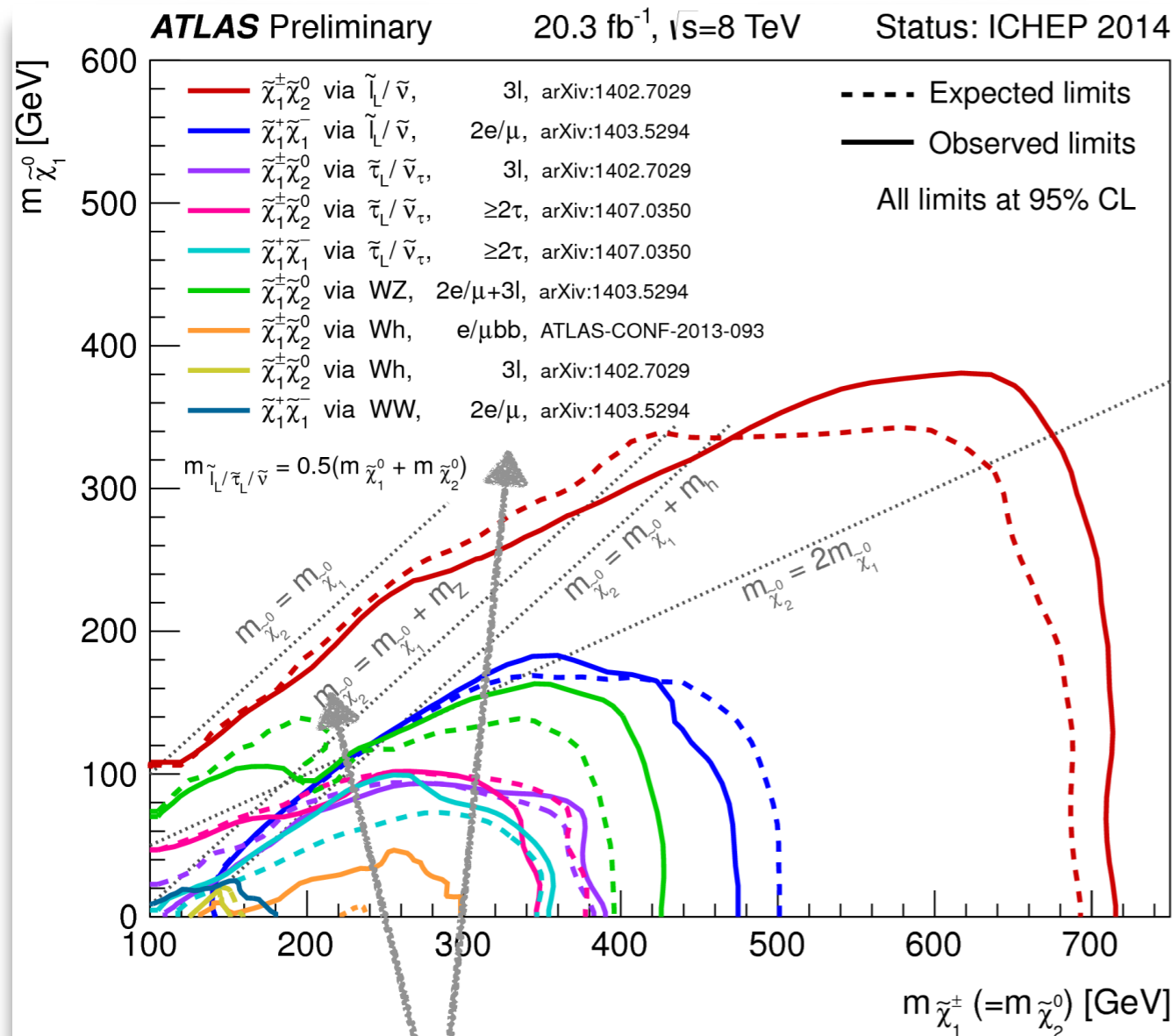
Higgs Bosons as Probes for EWSB SUSY



- Very challenging due to low BR of the Higgs into di-photon and lepton final states, and high background when Higgs decays into b-quarks



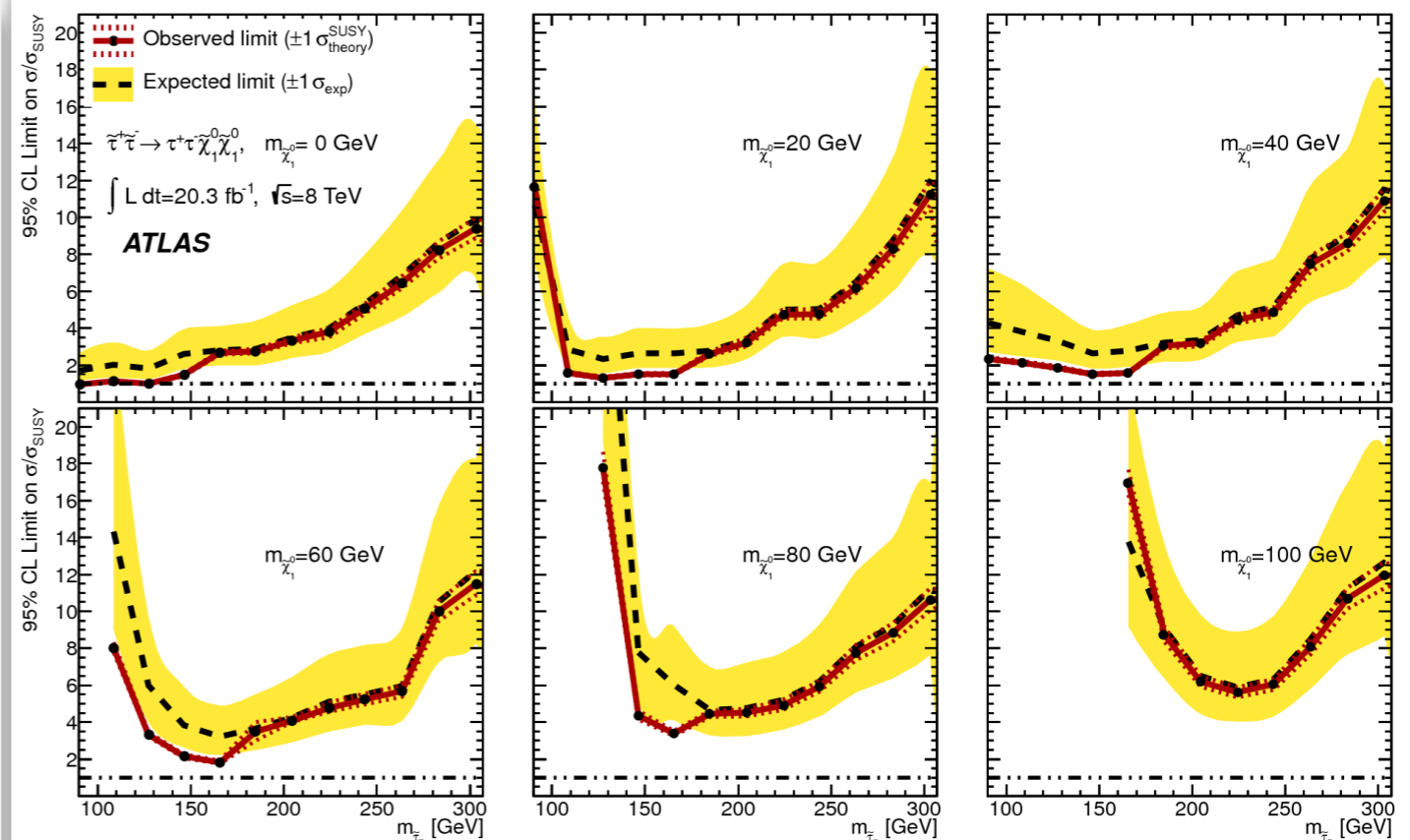
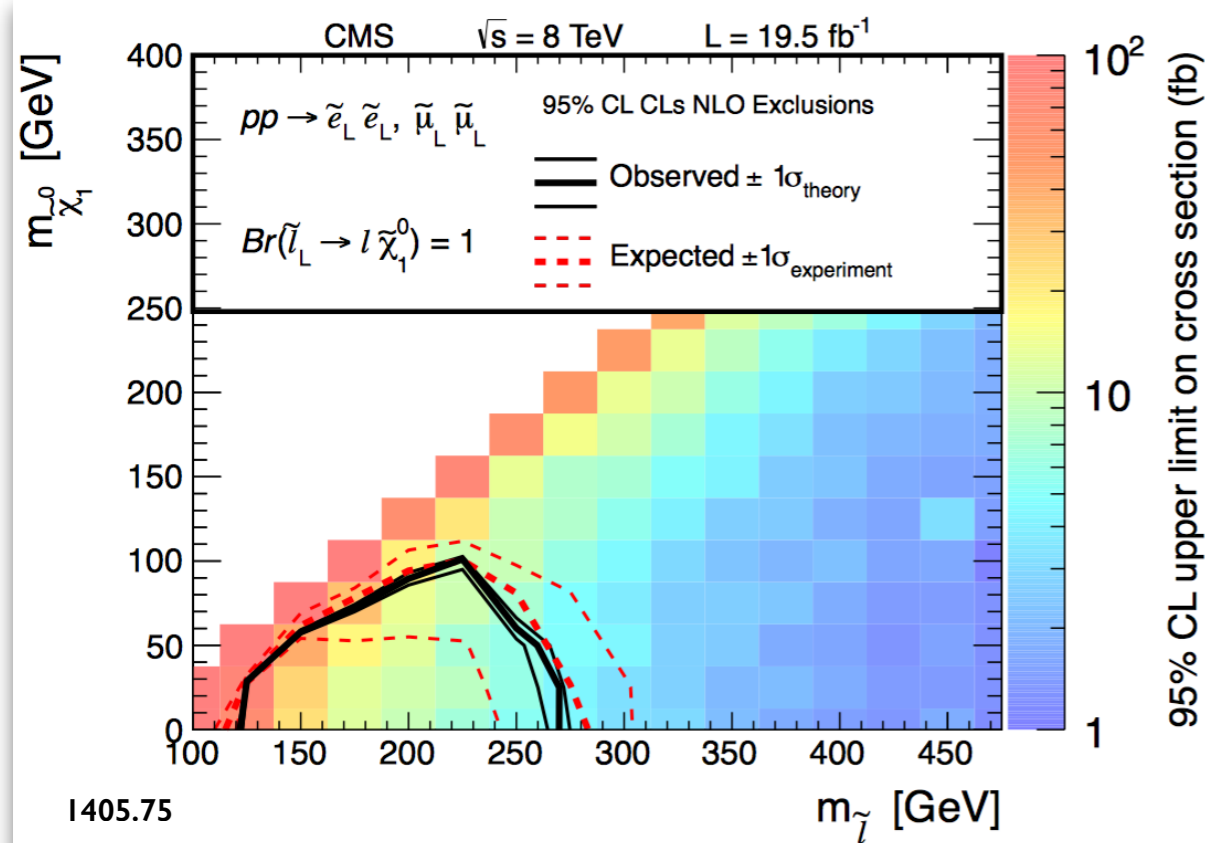
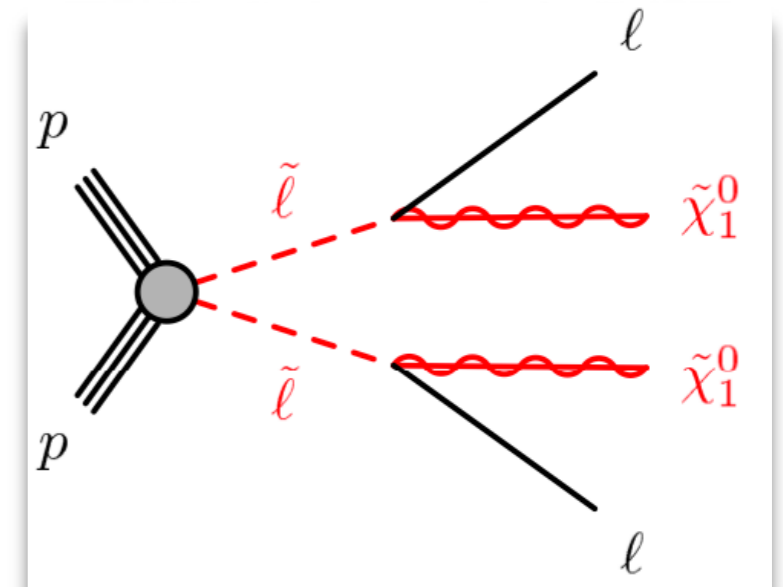
Overview of the Search for Electro-Weakinos



ISR- and soft leptons based searches for scenarios with compressed mass spectrum (higgsino-like low mass states)

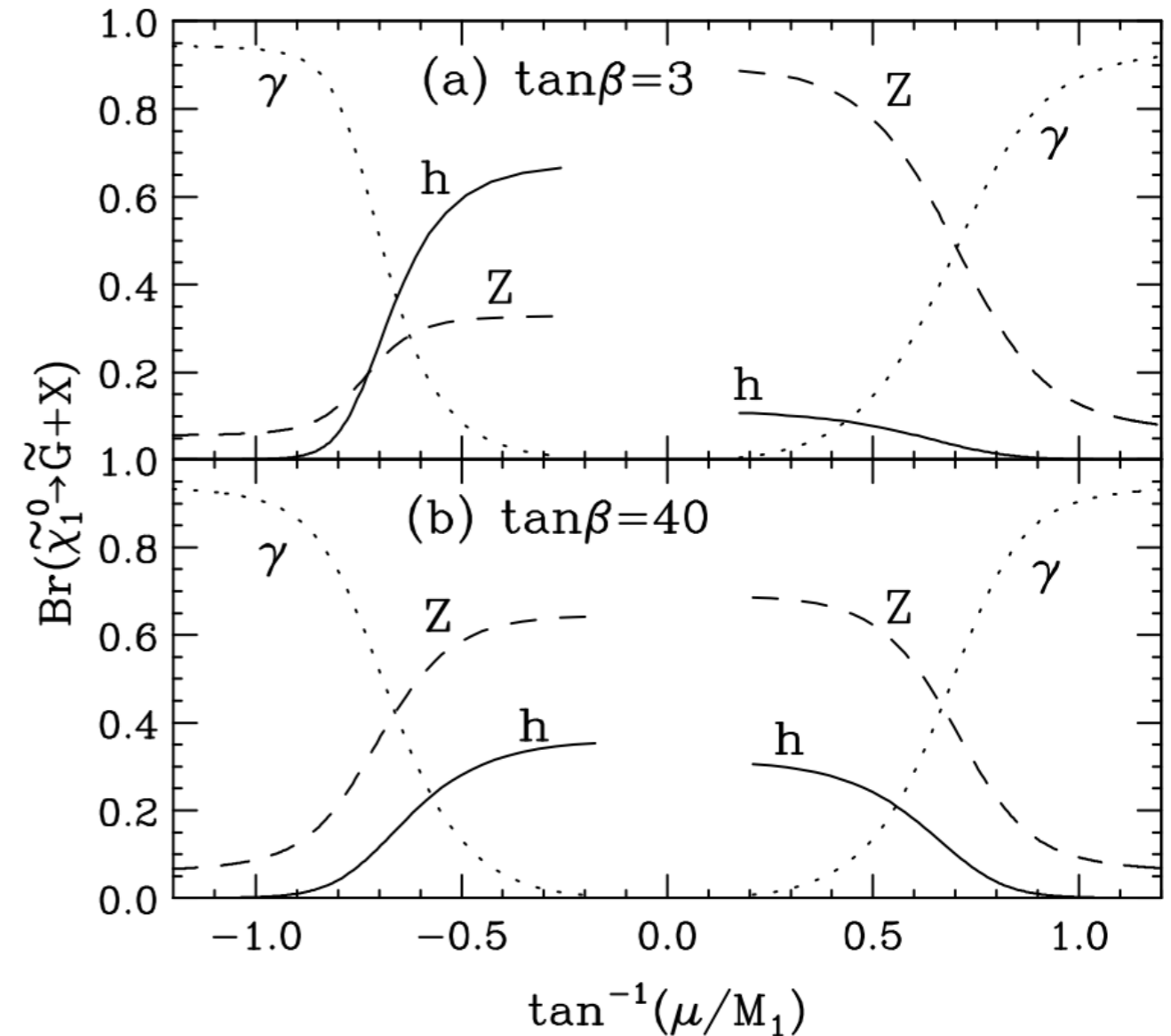
Search for Sleptons and Staus

- Light flavor slepton mass $> 250\text{-}300\text{ GeV}$
- LHC sensitive to the purely EWK production of sleptons, exceeding the LEP limits!
- Interplay between the search for electroweakinos decaying via sleptons and the direct search for slepton being explored

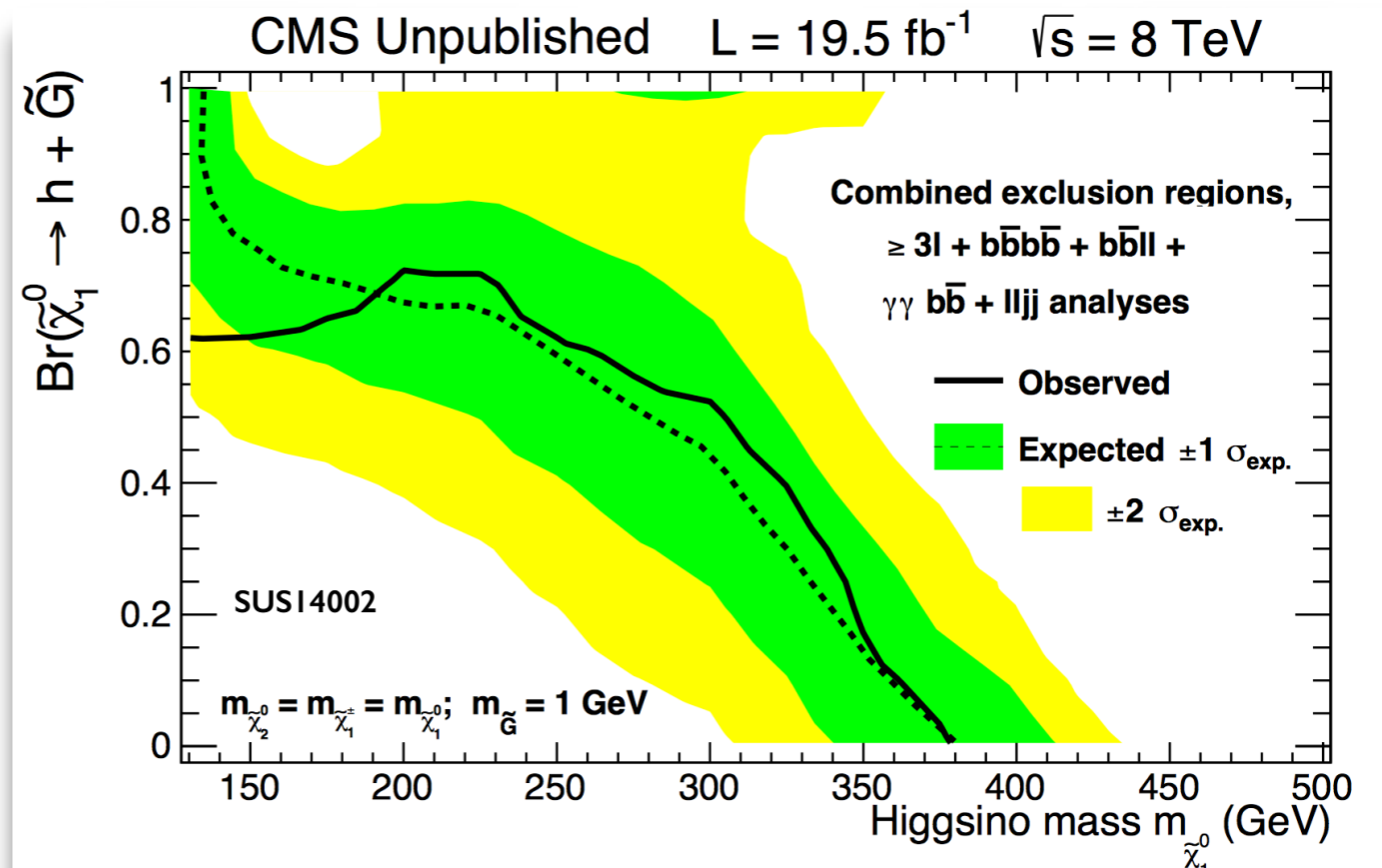
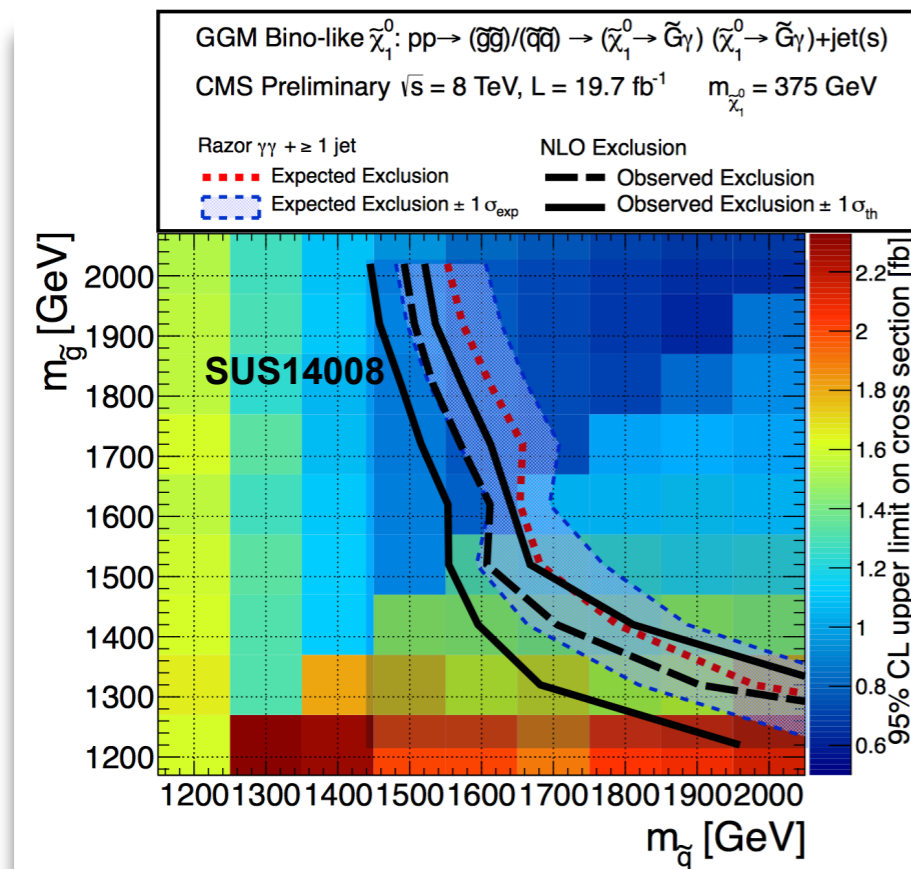
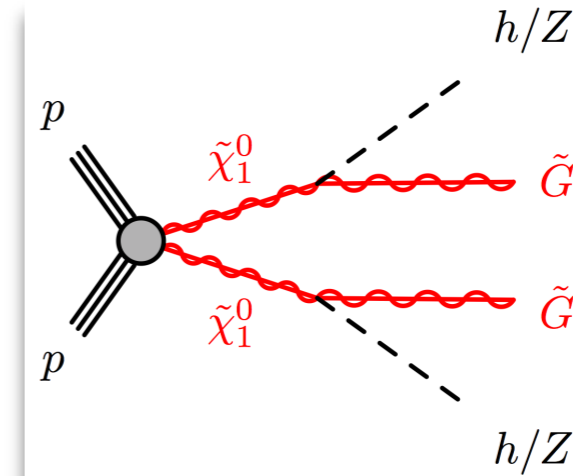
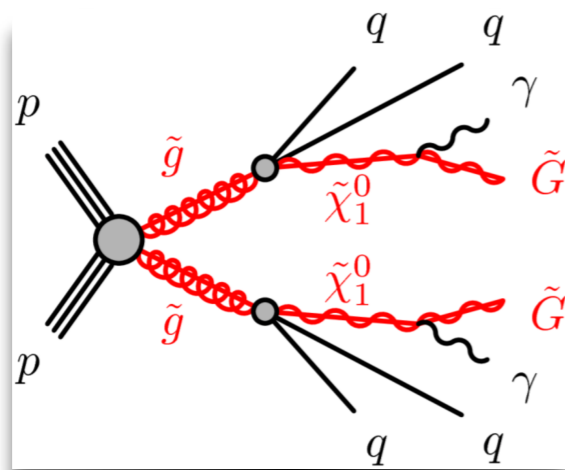


Gauge Mediated SUSY Models

- Gravitino LSP
- Phenomenology driven by the nature of the NLSP
 - typically $\tilde{N}1$
 - but also sleptons, squarks, gluinos,...
- Can have photons in the final state!
- Search program organized according to production process
 - Gluinos/squarks, stop/sbottom, EWK-inos



Searches for GMSB (inspired) SUSY

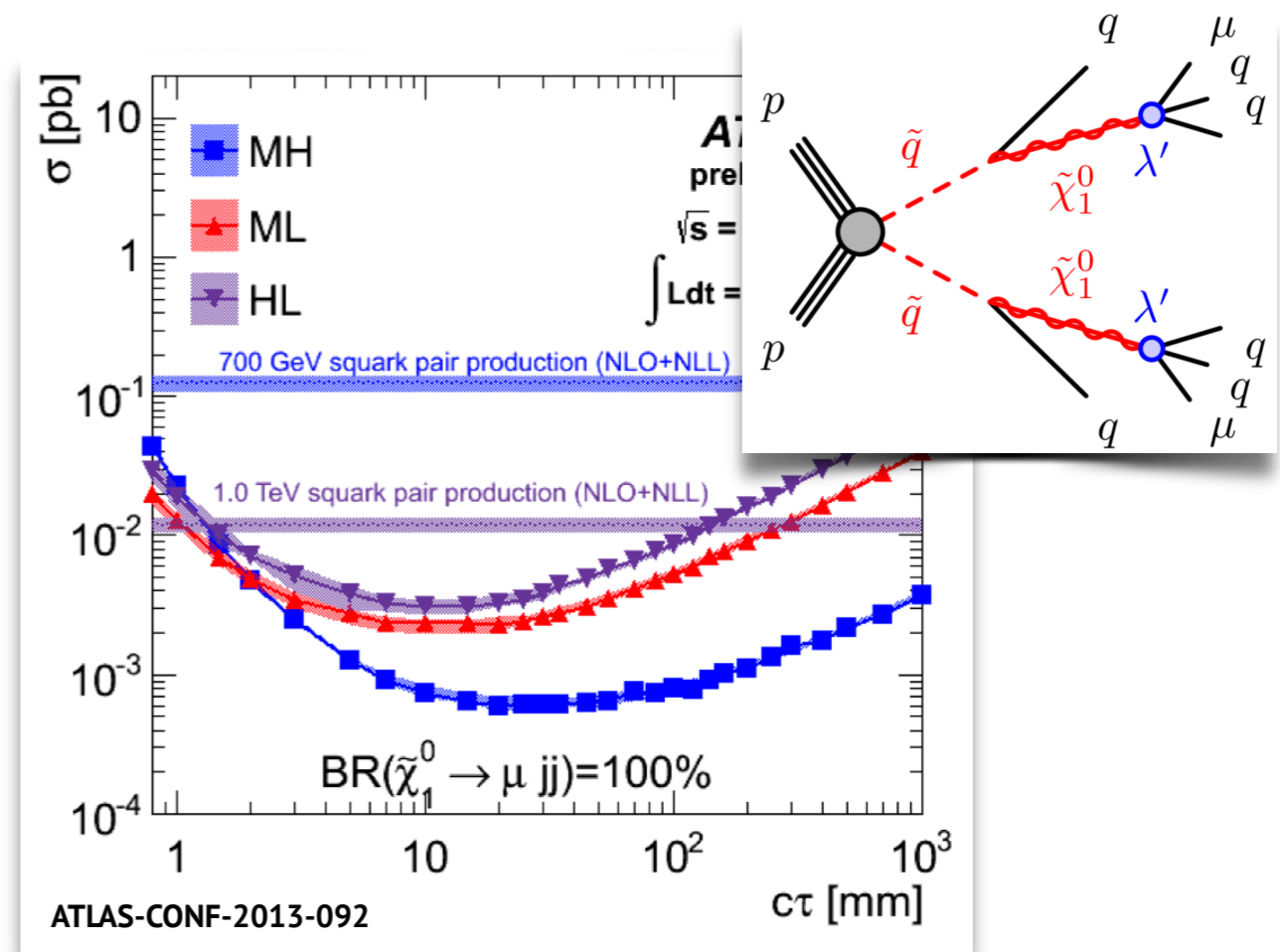
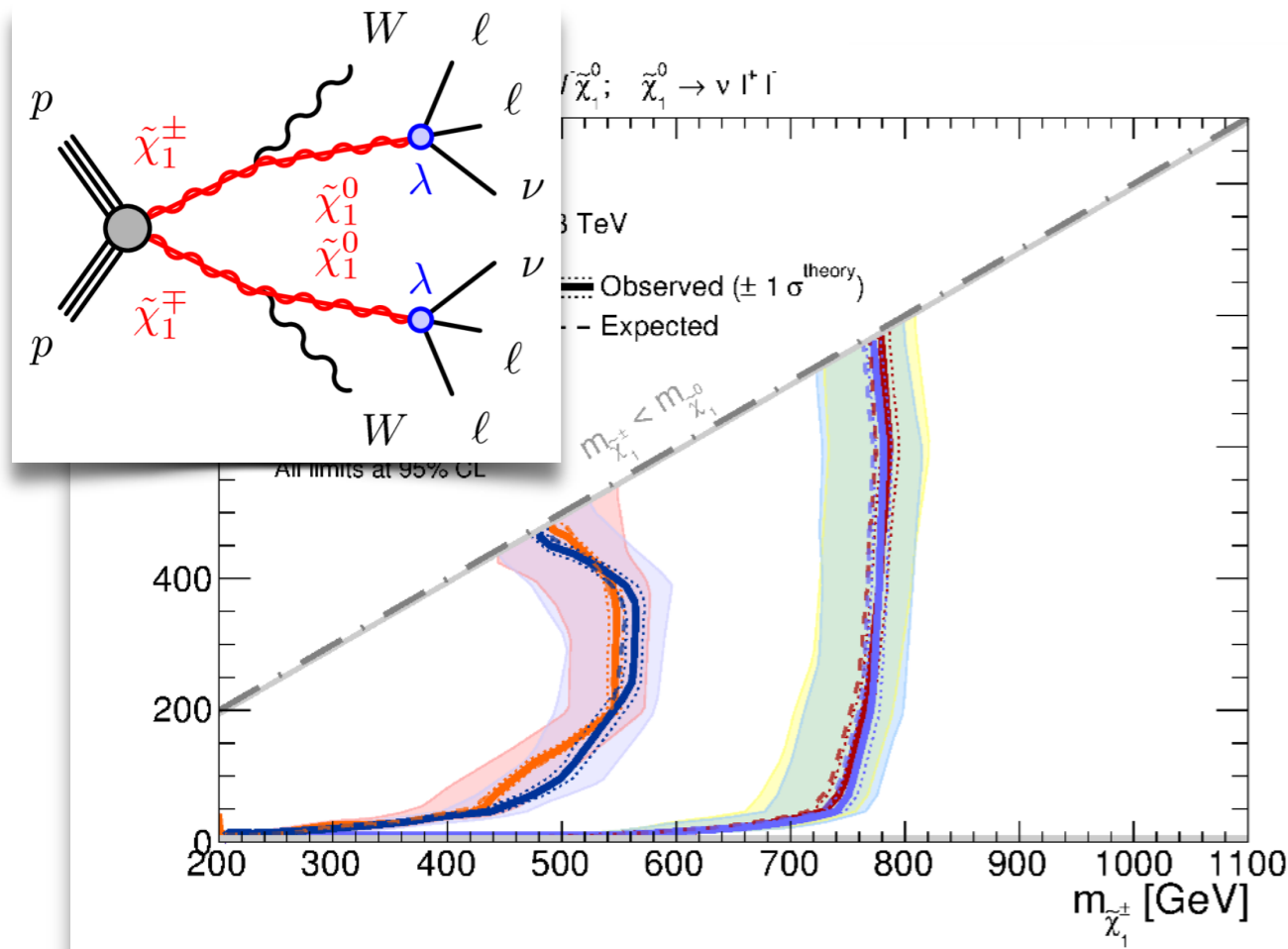


Sensitivity to GMSB/GGM models is comparable to that of models with NI LSP!
 Comprehensive program being developed

R-parity Violation

- Phenomenology driven by R-parity violating couplings:
 - lepton-number violating decays of LSP probed with search using 4 leptons and MET/Meff and baryon number violating decays with a search for displaced vertices.

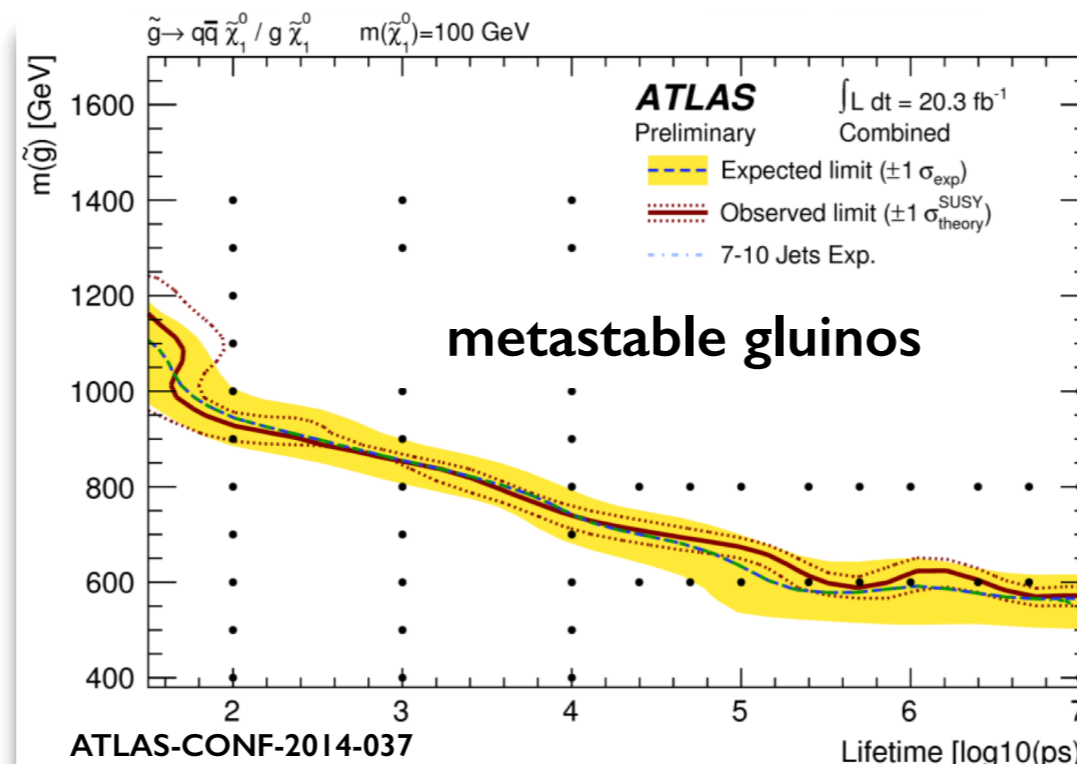
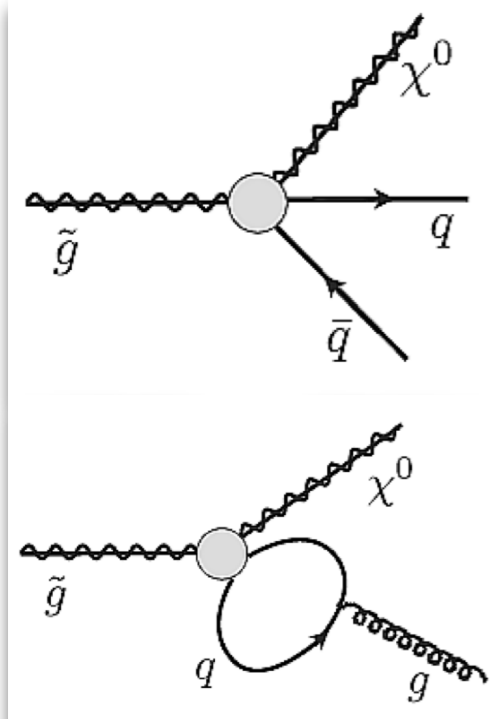
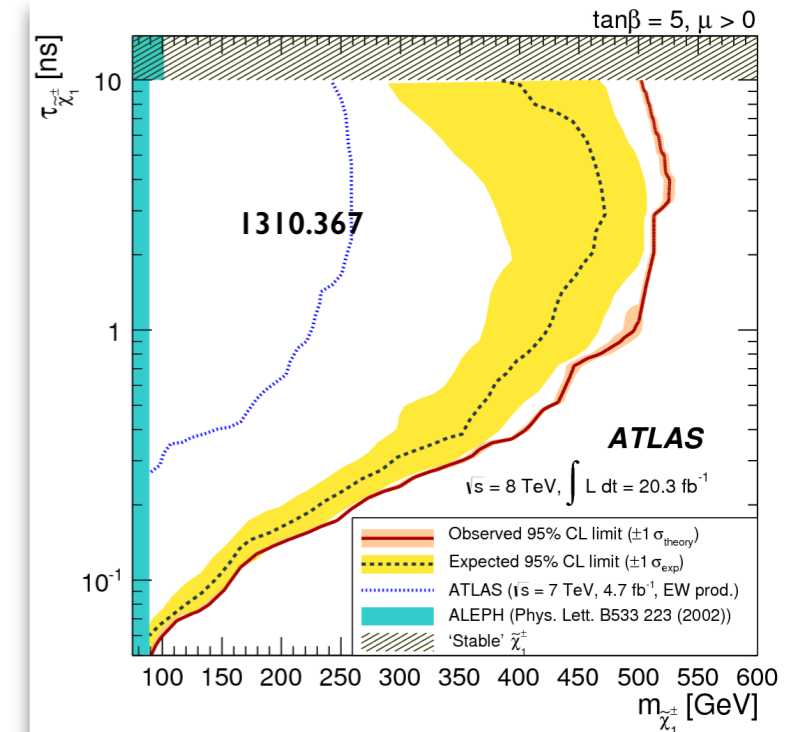
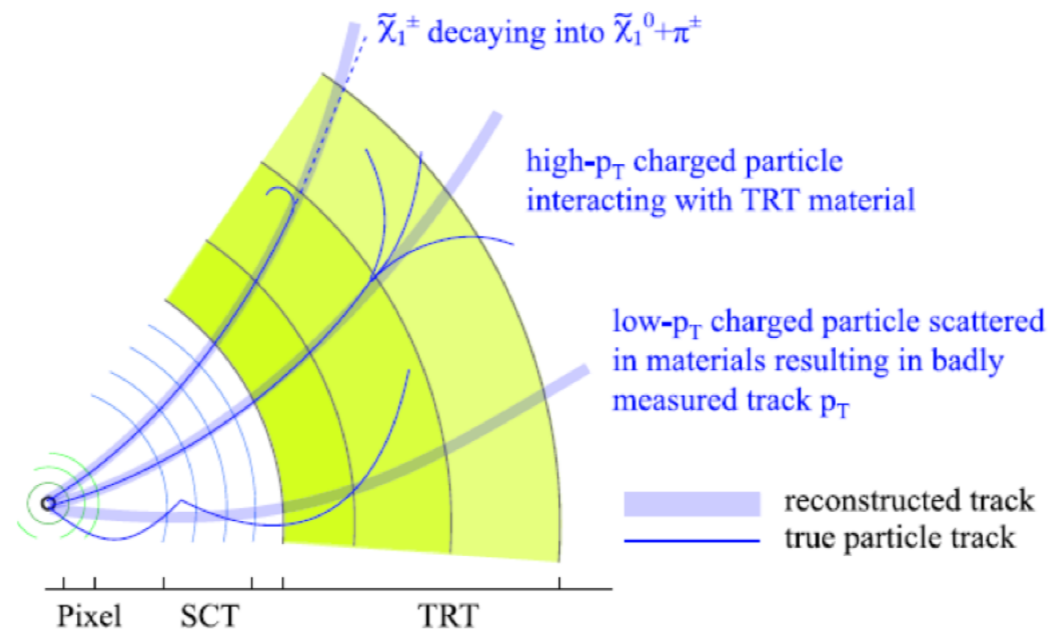
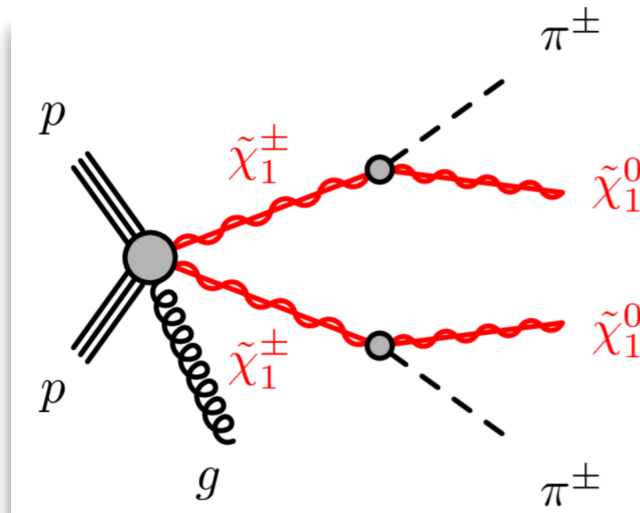
$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$$



Excellent sensitivity and good coverage, but region of parameter space yet to explore!

Long Lived SUSY

- Long lived SUSY due to small RPV couplings, very compressed spectra, or e.g. Split SUSY



Experimentally
challenging searches

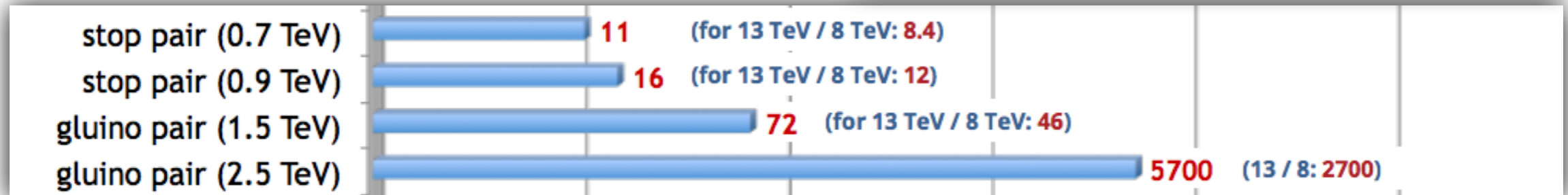
(dedicated trigger,
reconstruction,
calibration...)

More results in the near
future

Looking Ahead

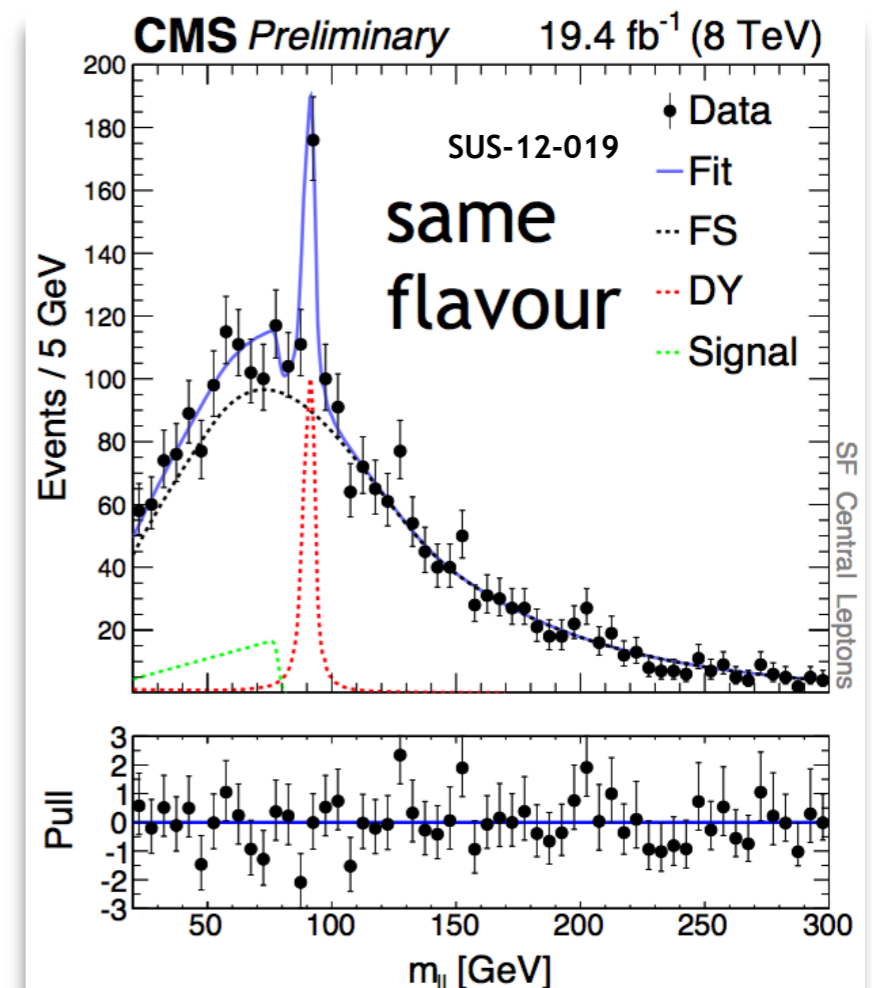
- Explore the new energy scale as the LHC turns on in Spring 2015, SUSY may indeed be just around the corner!

Cross section ratios: 14 (13) TeV / 8 TeV



- Relax the pre-LHC expectations, i.e. naturalness and parsimony, and strengthen the program looking for

- very compressed SUSY
- RPV**
- Long Lived**
- non Minimal SUSY
- ... exploit further kinematic variables

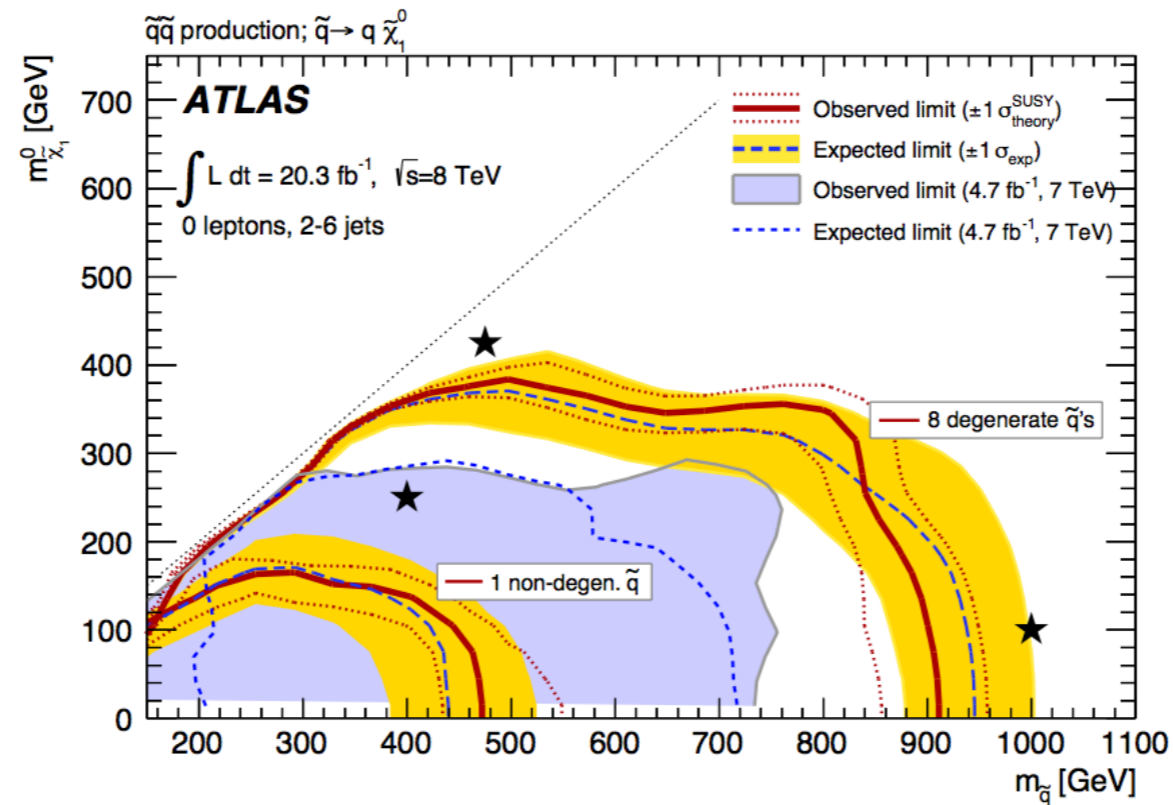
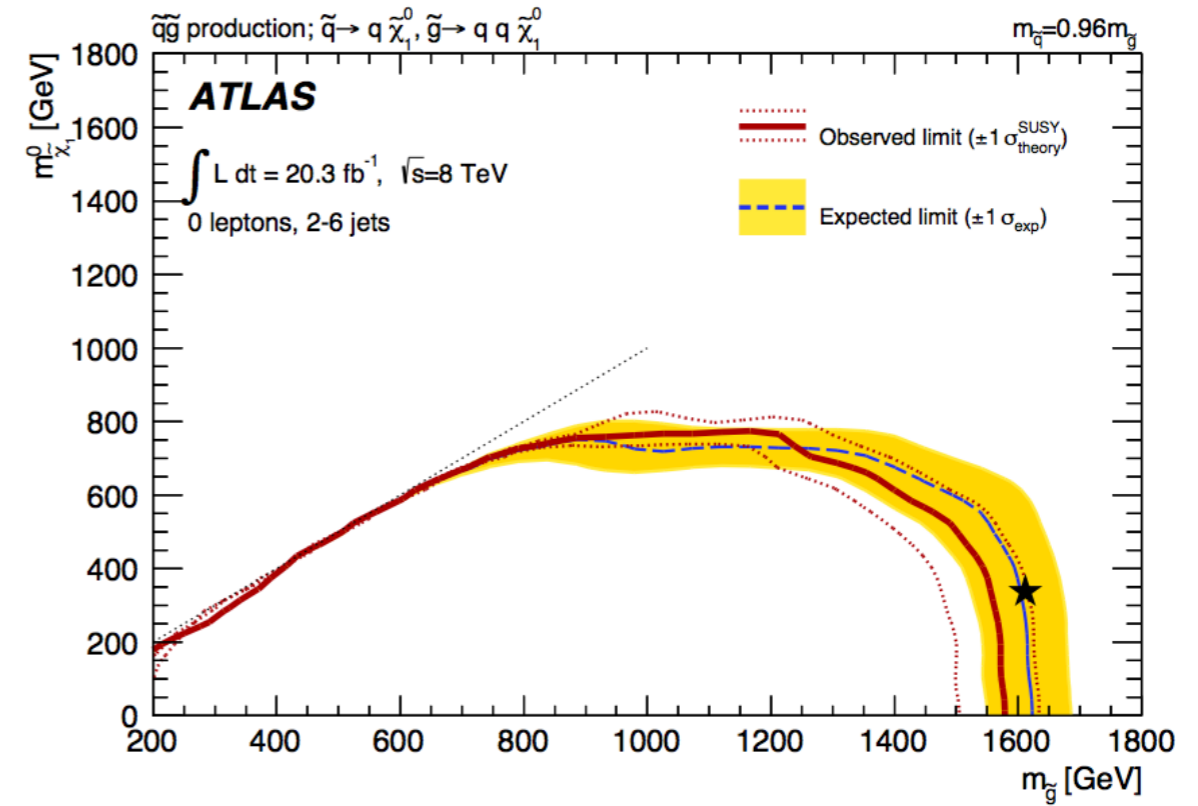
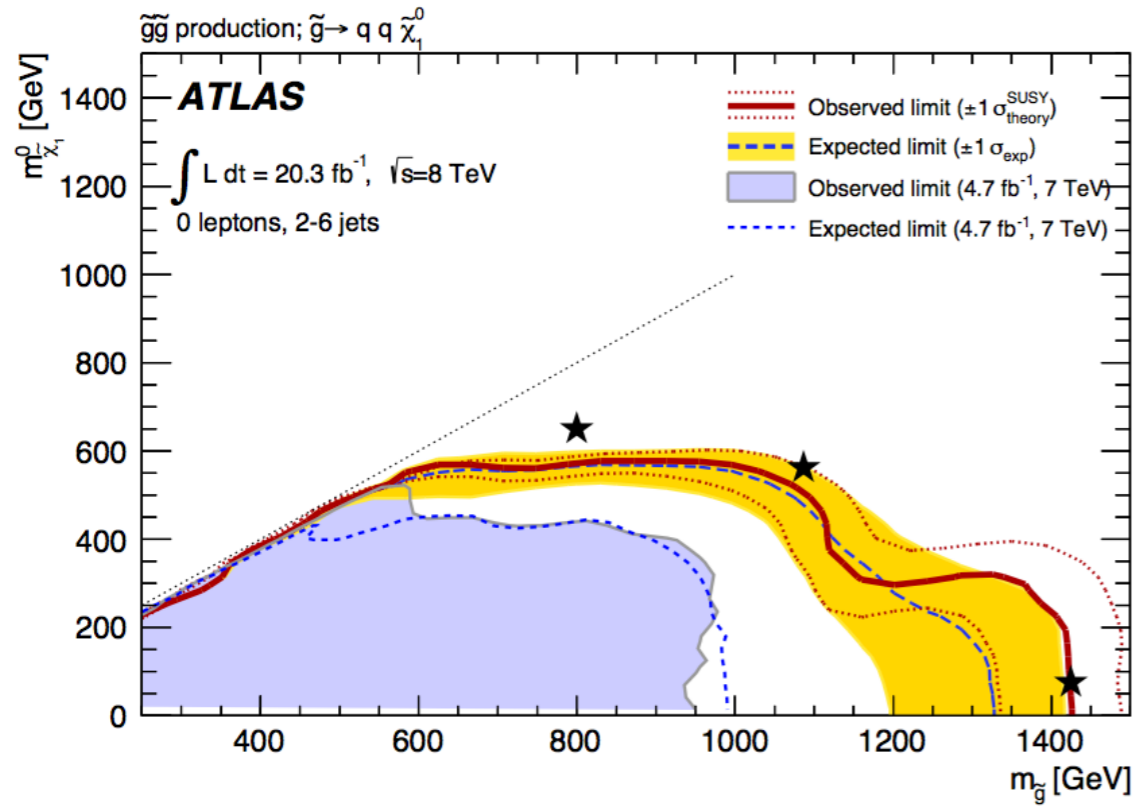


Looking Forward to an exciting Run 2!

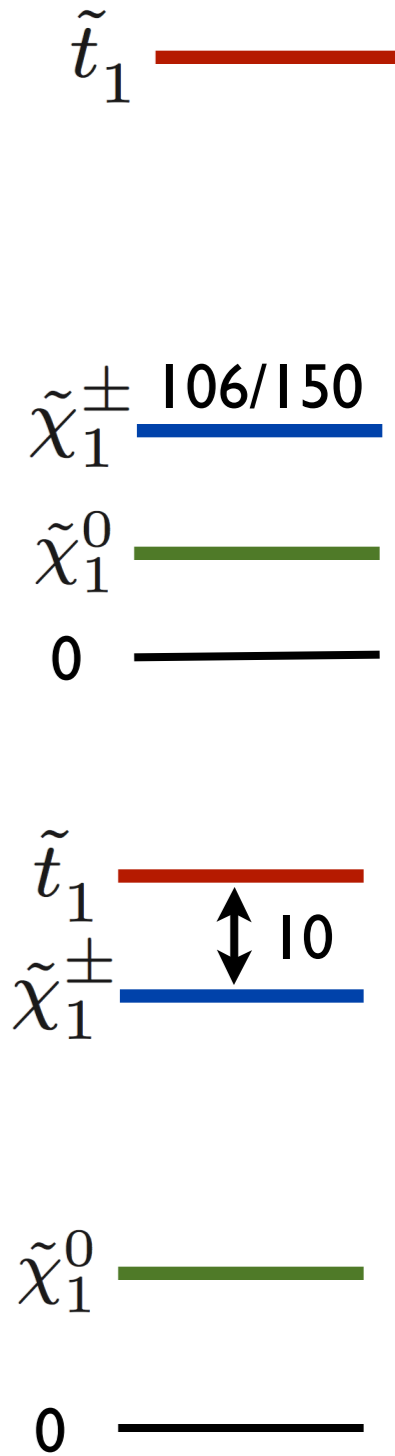
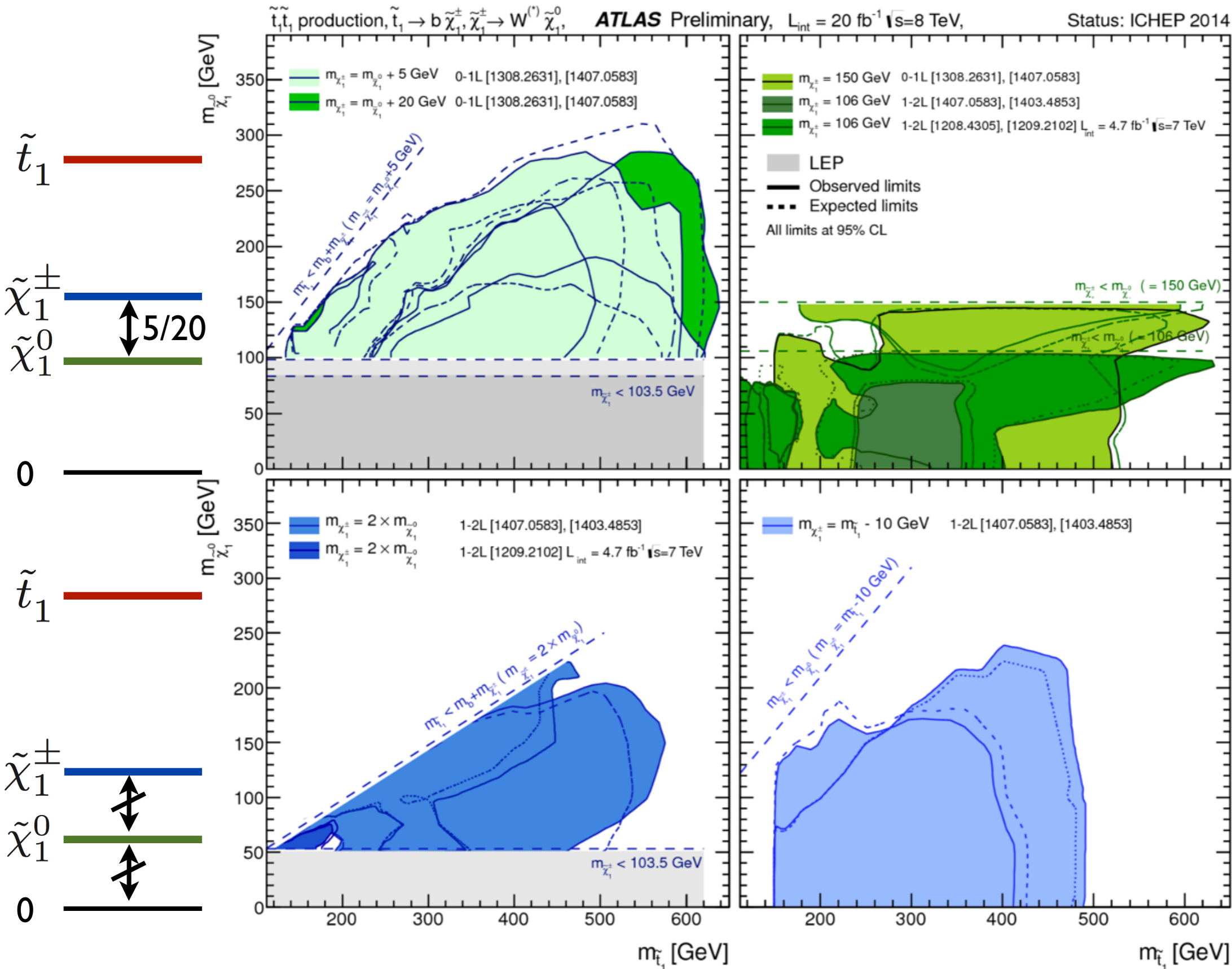


Additional Material

Squarks and Gluinos



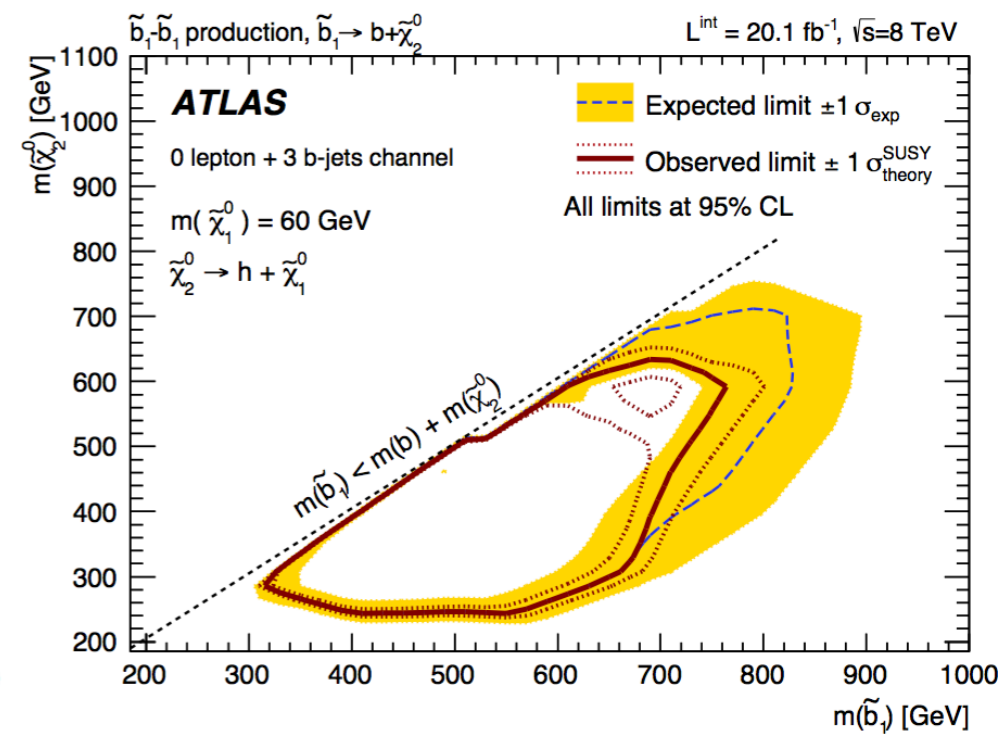
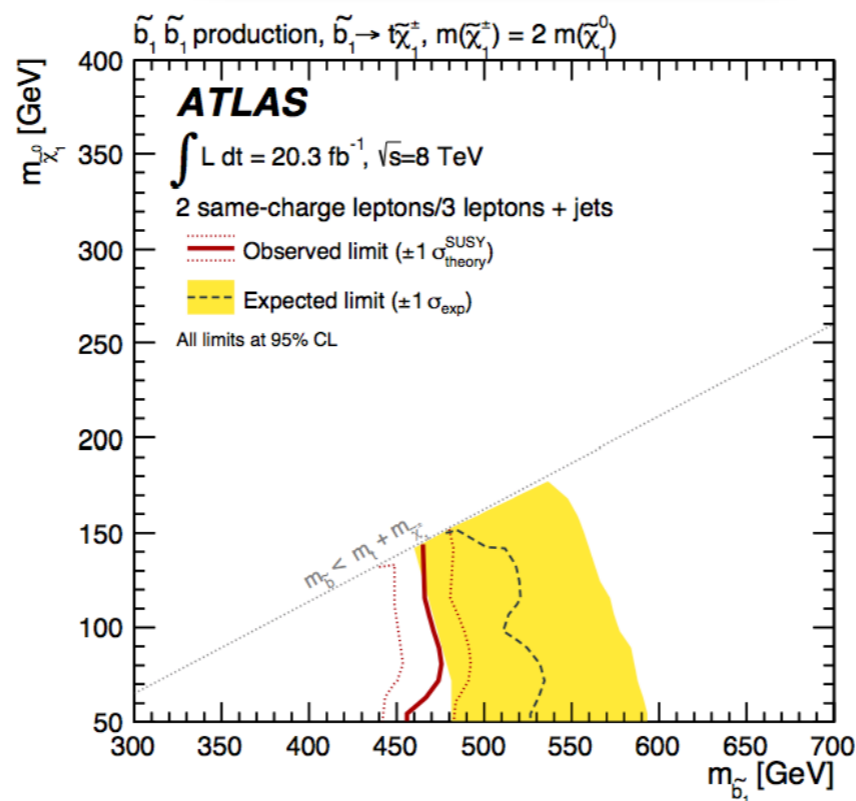
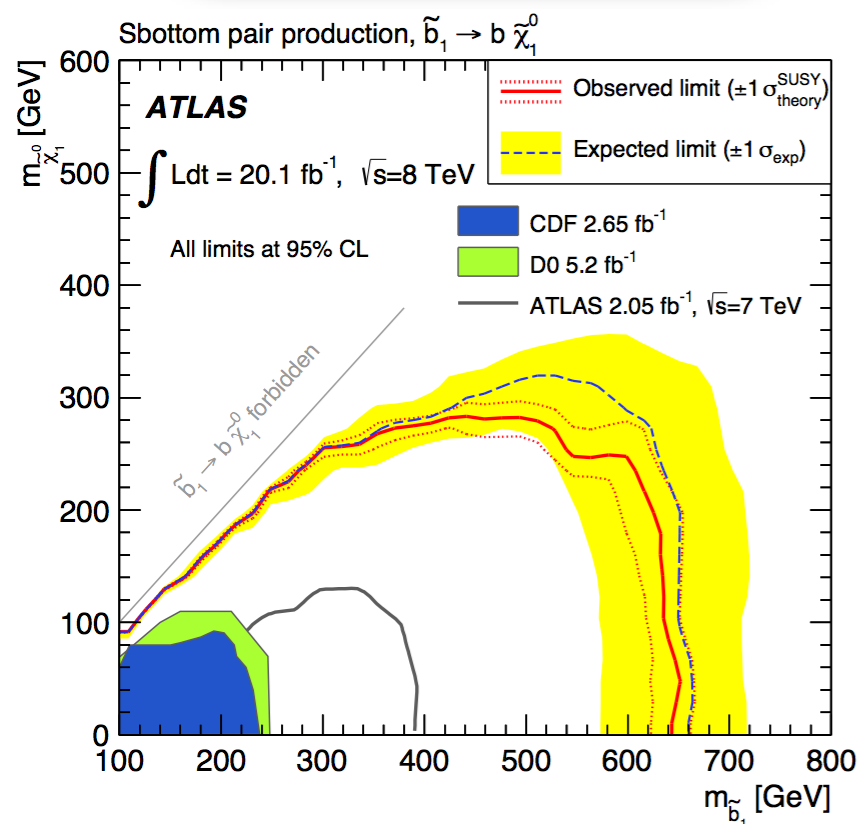
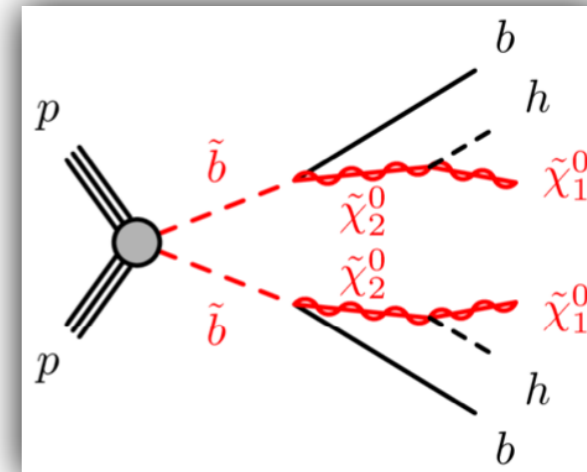
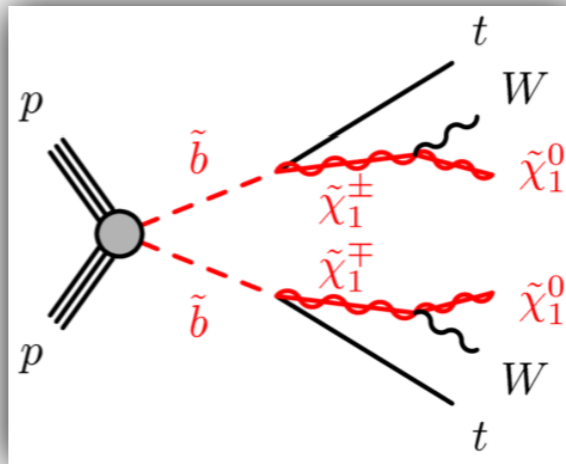
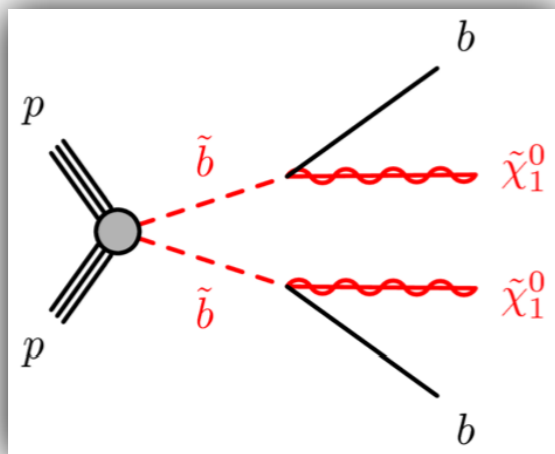
Summary of $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$



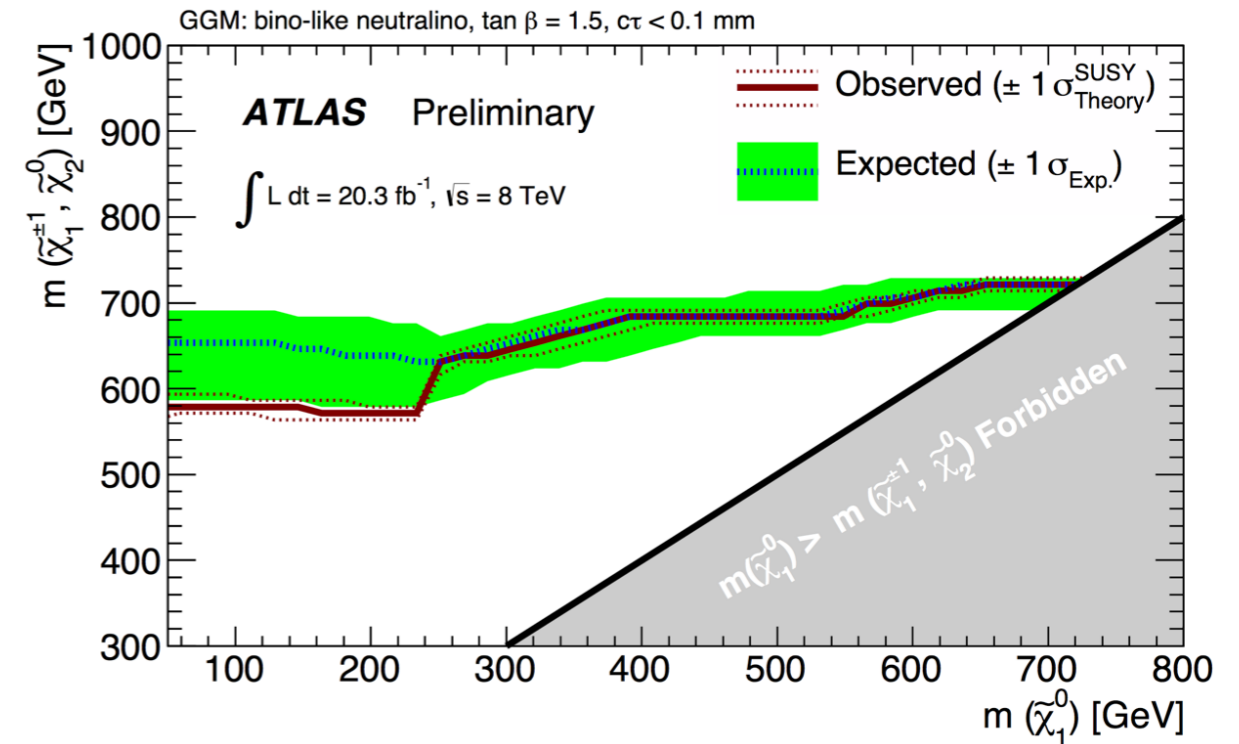
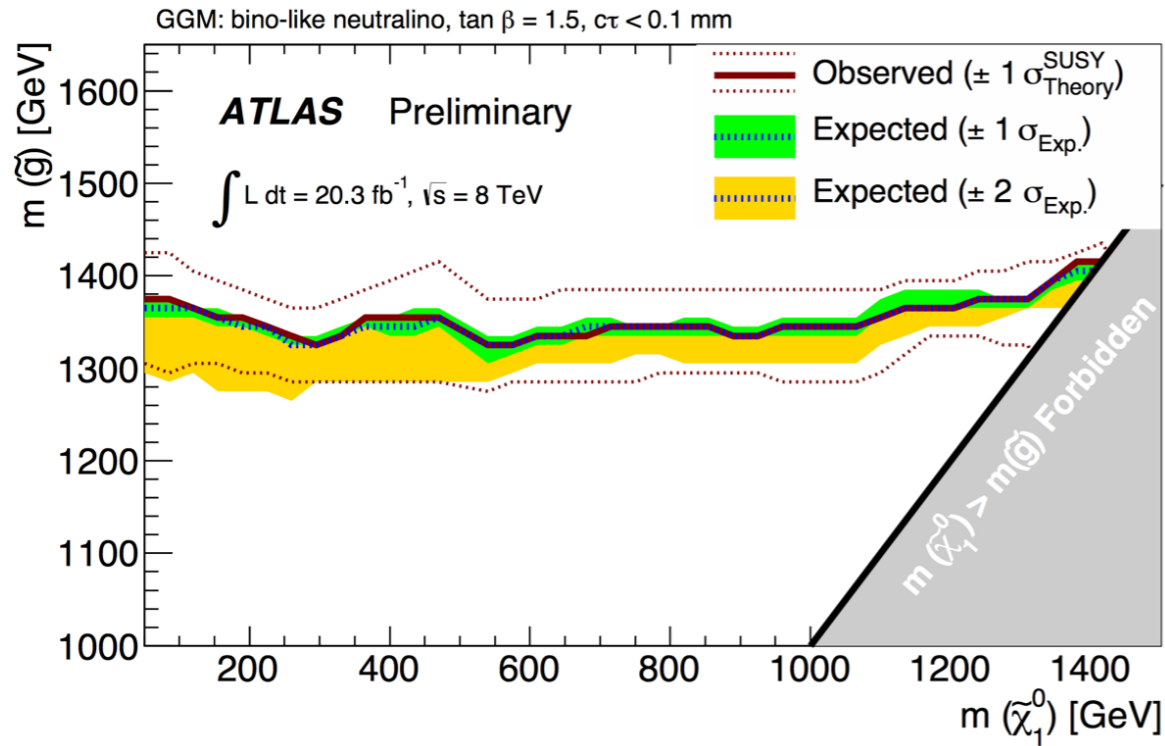
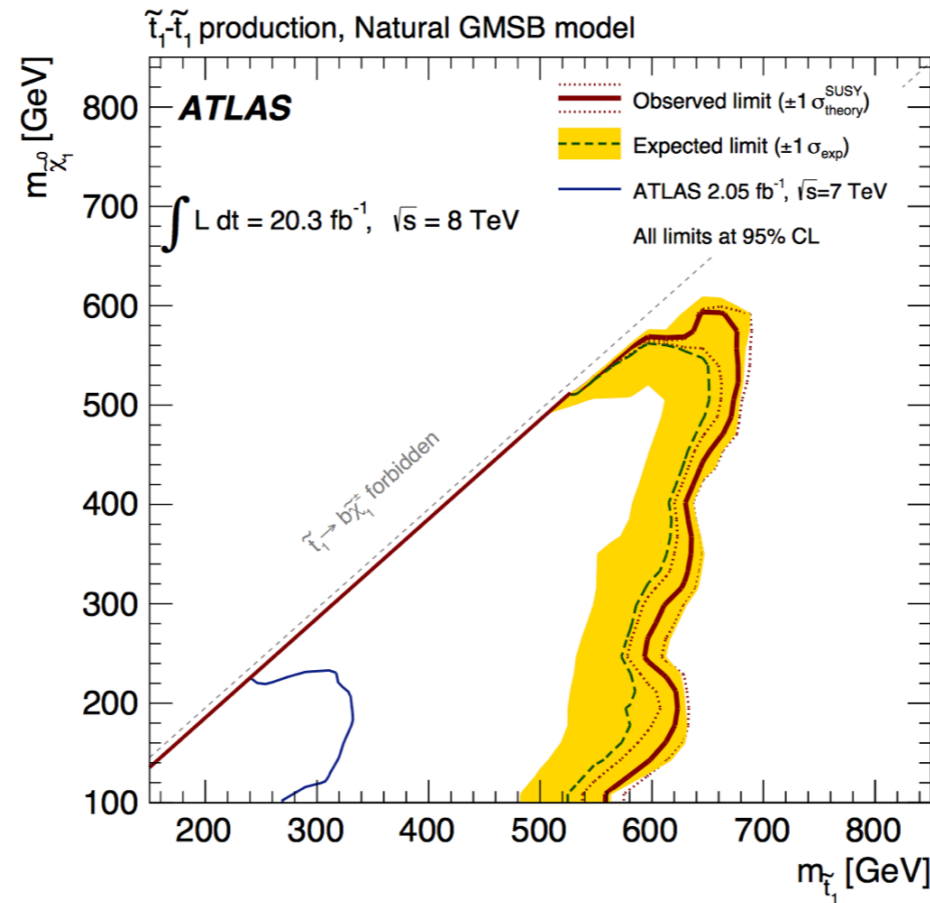
● Limits in the range of 500-600 GeV

Searches for Sbottom Production

- $2b + \text{MET}$
- Bins in MCT
- $2L(\text{SS}) + b + \text{MET} + \text{Meff}$
- $3L + \text{MET} + \text{Meff}$
- $0L + 3b + \text{MET} + \text{Meff}$
- Sensitivity limited by MET in compressed region

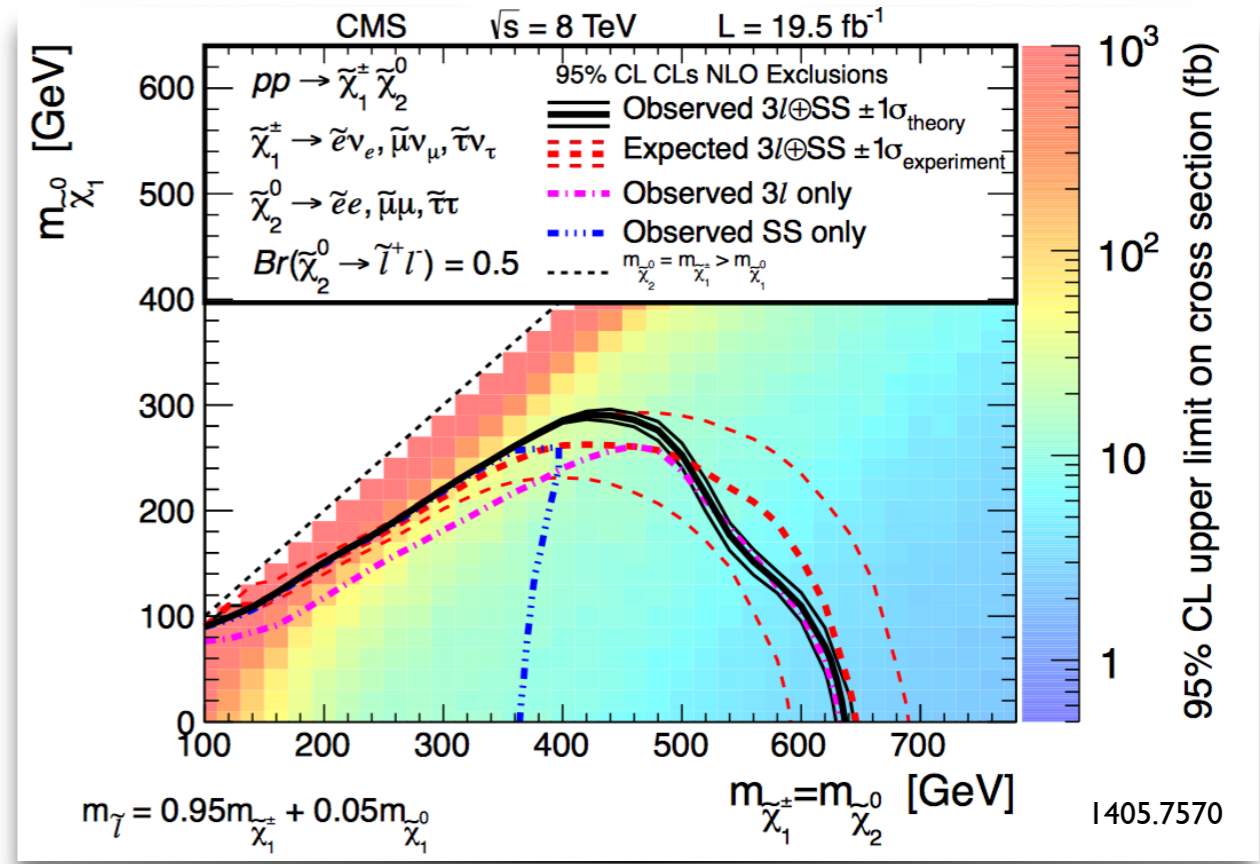
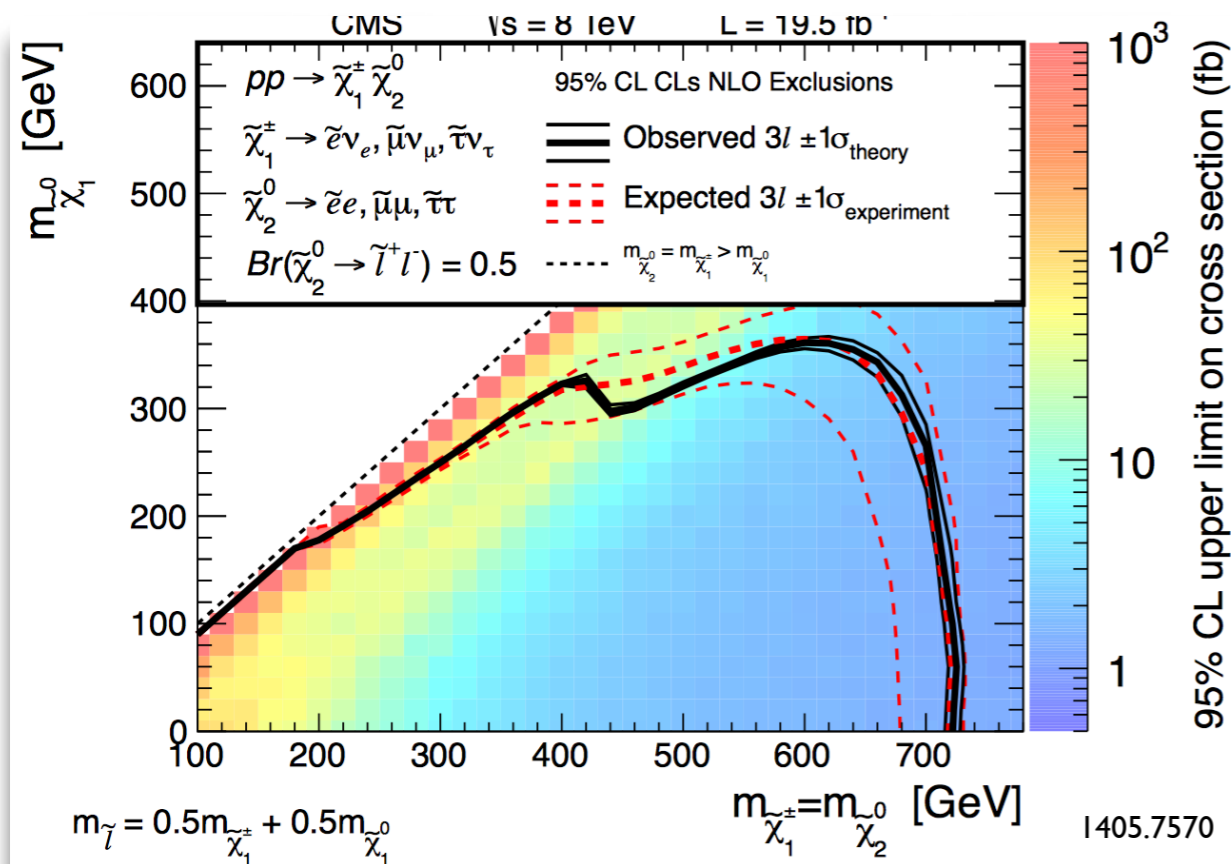
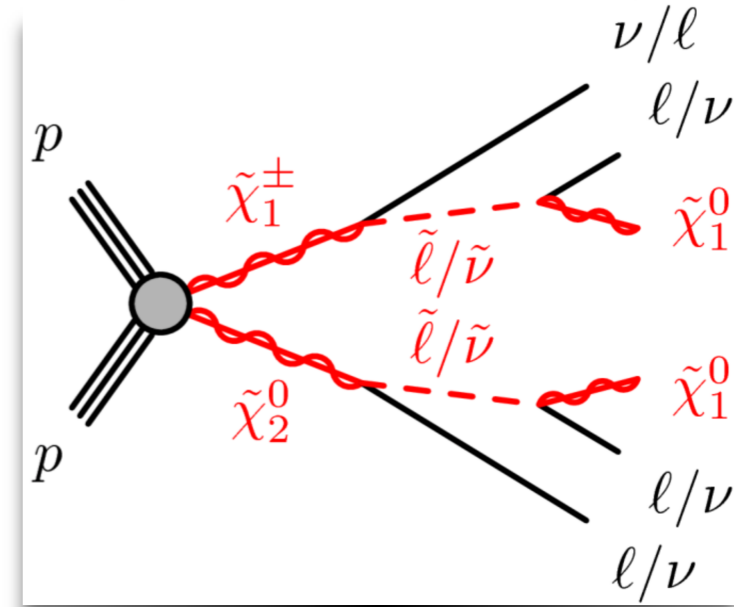


Gauge Mediated SUSY Models



Scenarios with Light Sleptons

- **Sensitivity up to ~700 GeV charginos and heavy neutralinos**
 - exceeding the LEP limit on EWK production of SUSY!
 - up to 350 GeV if stau only are light due to high background
 - reach depends on the mass difference between electro-weakinos and sleptons



MT2

$$(M_T^{(i)})^2 = (m^{\text{vis}(i)})^2 + m_{\tilde{\chi}}^2 + 2 \left(E_T^{\text{vis}(i)} E_T^{\tilde{\chi}(i)} - \vec{p}_T^{\text{vis}(i)} \cdot \vec{p}_T^{\tilde{\chi}(i)} \right)$$

$$M_{T2}(m_{\tilde{\chi}}) = \min_{\vec{p}_T^{\tilde{\chi}(1)} + \vec{p}_T^{\tilde{\chi}(2)} = \vec{p}_T^{\text{miss}}} \left[\max \left(M_T^{(1)}, M_T^{(2)} \right) \right]$$