SUSY: Blind spots @ Run1, perspectives at Run2 and beyond

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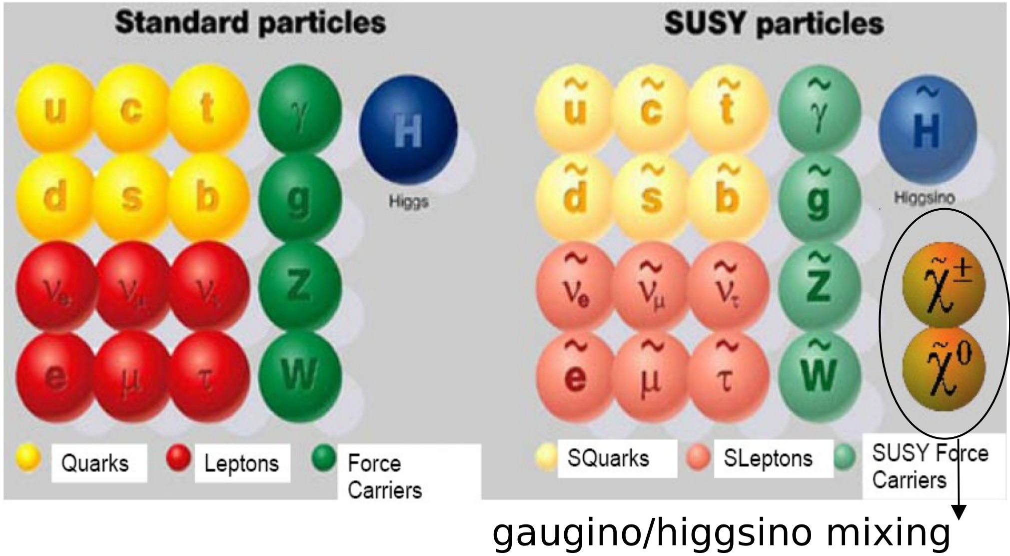
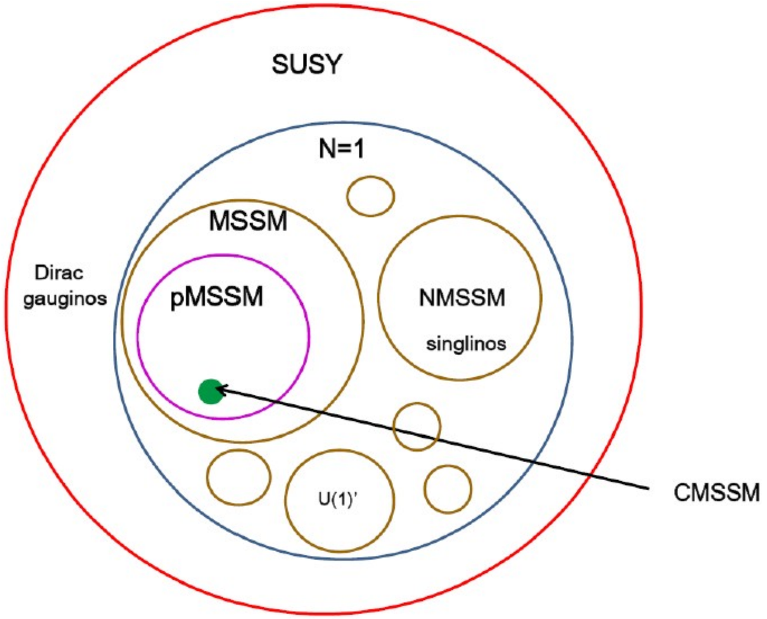
Looking for SUSY

Task of the LHC general purpose experiments: verify in the most general way the SUSY idea by direct searches of production and decay of SUSY particles





Sparticle masses from SUSY breaking not fixed by theory: large parameter space to saturate

Limiting to MSSM:

MSSM: ~109 parameters

pMSSM: 19 parameters

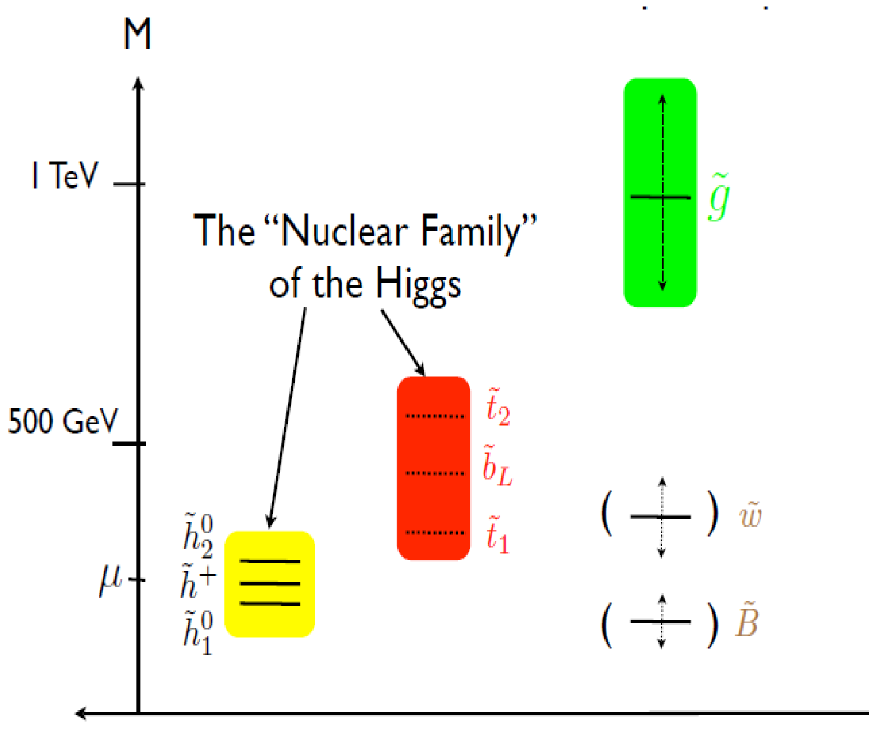
CMSSM: 4 parameters (+1 sign)

Restricting the field

- The aim: saturate parameter space of as many SUSY implementations as possible, where at least one sparticle is within kinematic reach of the machine: ~3.5 TeV for pair-produced sparticles at 14 TeV
- Two main lines of exploration:
  - R-parity conservation:
    - Main handle against SM is Missing Transverse Energy (MET) from undetected Lightest Supersymmetric Particle (LSP), assumed to be the lightest neutralino (chi01) in this talk
    - "Open" kinematics: two invisible particles in each event and no constraint on longitudinal boost of sparticle-sparticle system
  - R-parity violation:
    - No guaranteed MET
    - SUSY can appear as purely hadronic multi-jet events: difficult, but wonderful hunting ground for modern jet reconstruction techniques
- Focus on "holes" in LHC-8 coverage for R-parity conserving models

Guidance from naturalness

Approximate upper limit on sparticle masses from the requirement of “small” fine-tuning of the Higgs mass.



Plot by L. Hall

Because of their radiative contribution to higgs mass, approximate upper limit:

Gluino ~ a few TeV
Stop ~ 1 TeV
Higgsino ~2-300 GeV

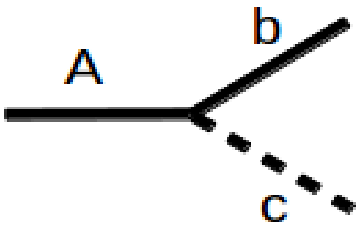
Large effort from ATLAS and CMS addressing direct production of each of the three particles with simplified models

Today: illustrate “difficult” topologies (better than blind) which prevent us from claiming we have ruled out this hierarchy at Run I

Why undetected?

- Sparticle were within kinematic reach, but:
  - Low couplings: not enough luminosity for production
  - Low BR for channels which can be separated from backgrounds
- Sparticles were abundantly produced, but:
  - Little visible energy or long-lived decays
  - Kinematics very similar to a major background
  - Complex decays: high multiplicity in decays makes objects "soft" and topology difficult to trigger on and/or cuts inefficient

Kinematics



- 2-body decay A $\rightarrow$ bc, c invisible
- m(A)~m(b)+m(c)
- A ~ at rest:
  - b and c produced at rest
  - c invisible no MET from c, process looks like production of b
- A boosted
  - b and c share the boost of A
  - If m(c)<<m(b):
    - all of the boost goes to b: no MET
  - If m(b)<<m(c)
    - all of the boost to invisible c: decay is invisible
  - If m(c) ~ m(b) boost is shared
    - Observe b and MET from c

Examples:

A = stop b = top c= LSP
m(stop)=m(top)+m(LSP)
If stop at rest: LSP does not carry MET: stop pair production mimics SM ttbar production

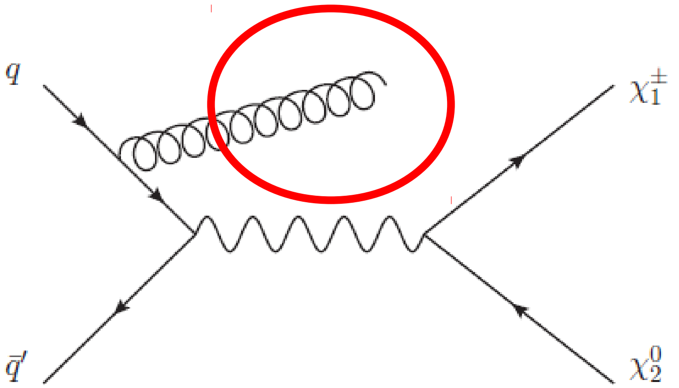
If stop boosted:
If m(LSP)<<m(top)
stop pair production mimics SM ttbar production
If m(LSP)~=m(top)
top boosted, MET from LSP detectable

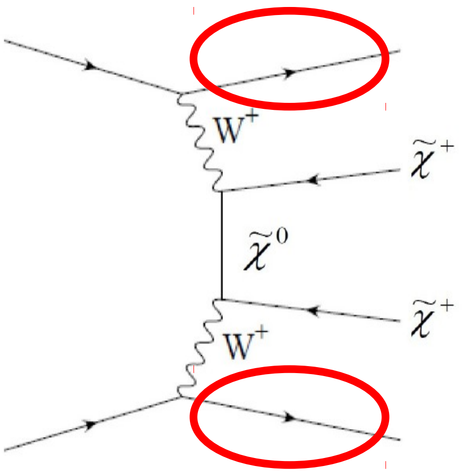
A stop b=charm c=LSP
m(stop)=m(c)+m(LSP)
Stop decay invisible both with and without boost

Generic approach for compressed kinematics

- Generic idea: try to boost the signal to raise MET or momentum of decay particles
  - Mono-X: recoil of signal against particle radiated upstream of signal
  - VBF: signal produced in fusion of EW bosons radiated by quarks, and recoiling against two forward jets.

    Forward jets can help with trigger and background reduction

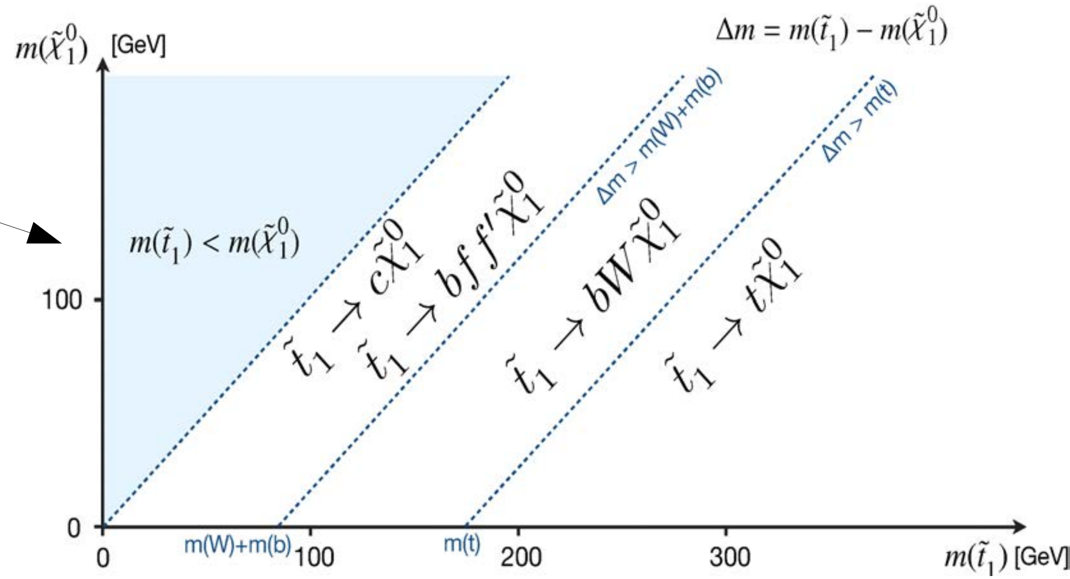


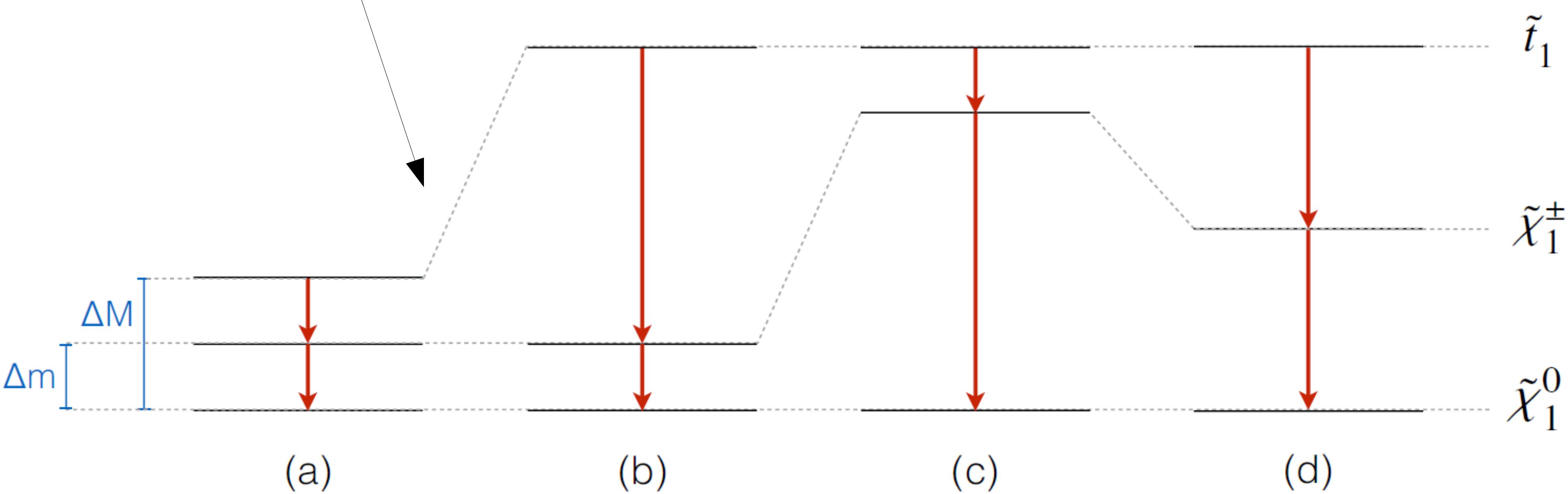


If invisible particle carries away all of the momentum:
High pT Jet(s) + invisible (MET)
If momentum shared among decay products:
High pT jet, MET and some soft particles from the decay

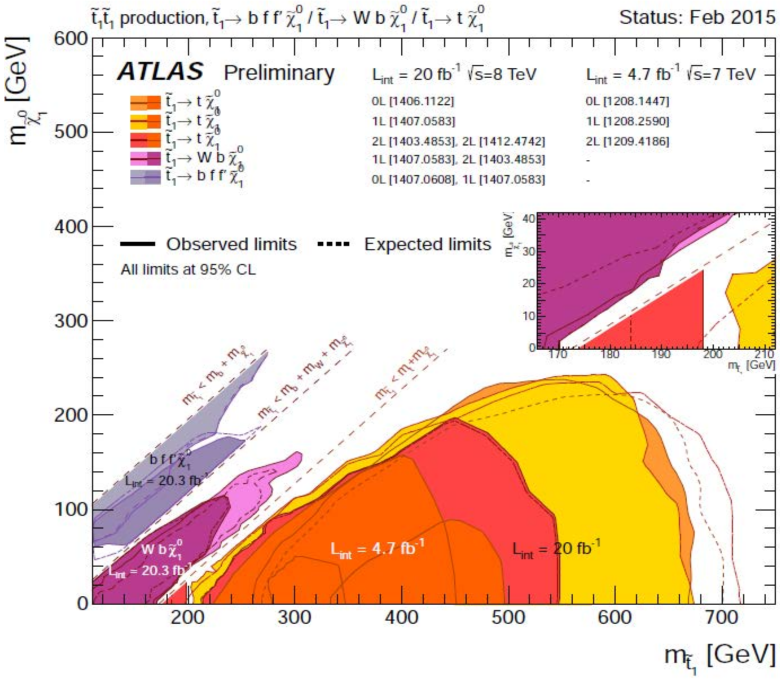
Stop searches

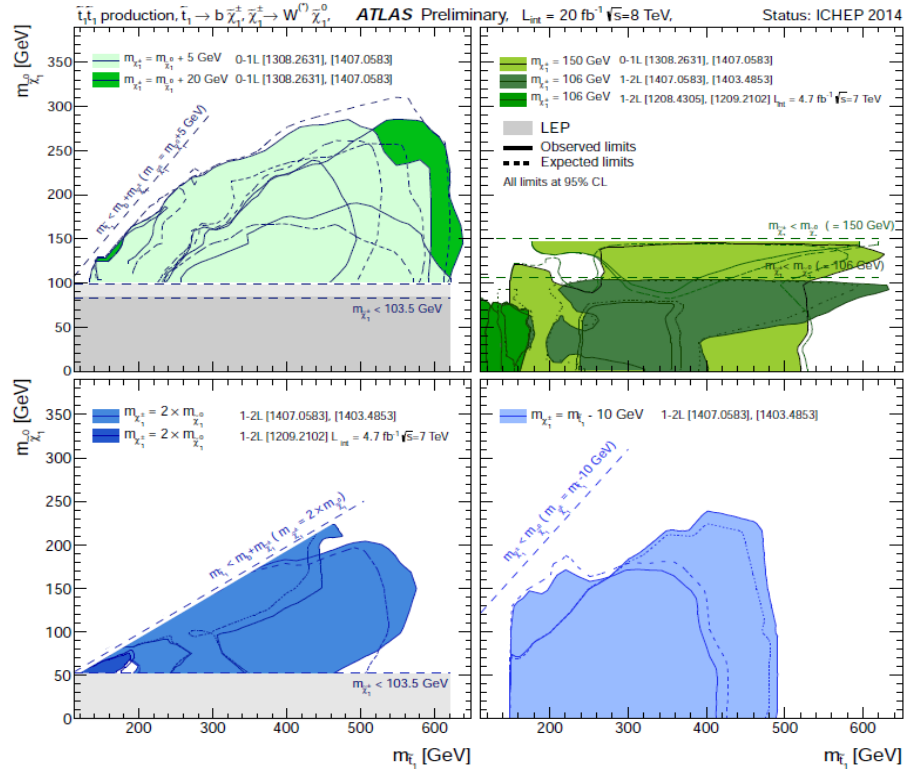
- Two main configurations:
  - Stop NLSP: 2-4 bodies, two-parameter space
  - m(chargino)<m(stop): cascade of two 2-body decays , 3-parameter space

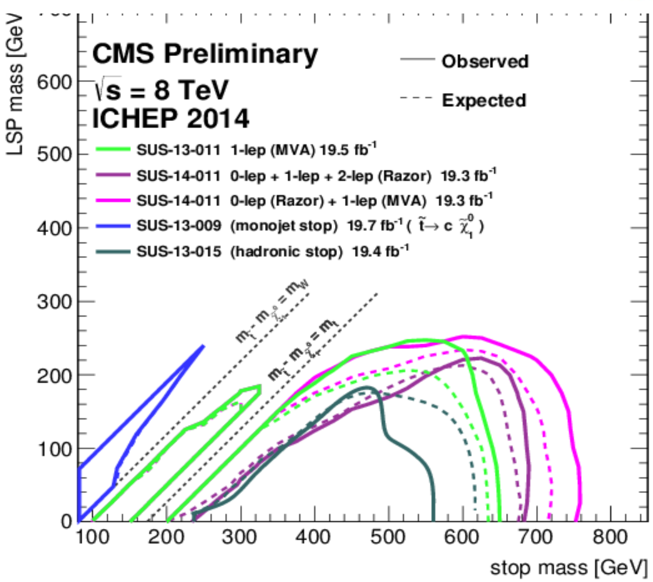




Official summaries







Stop NLSP (left) and stop to chargino (right) shown separately with 100% BR assumption

Combinations assuming different BR's and dedicated analysis with one leg decaying to top and the other to chargino available or underway

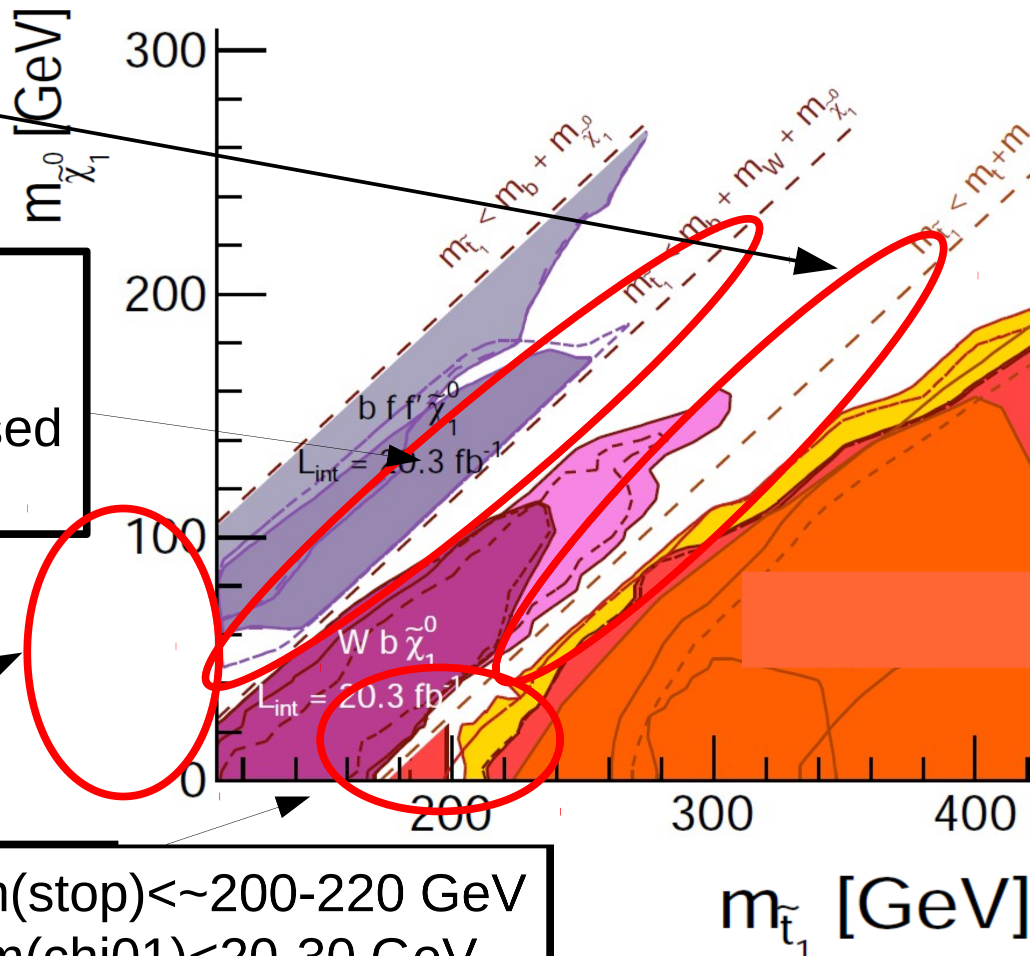
Stop NLSP: difficult regions

Stop to charm (not shown) covers completely relevant region up to 200 GeV stop mass. Work in progress to verify whether stop excluded for any BR combination of stop → c chi01 and stop → bff'chi01

m(stop)>~250 GeV,
m(stop)-m(chi01)~m(t)

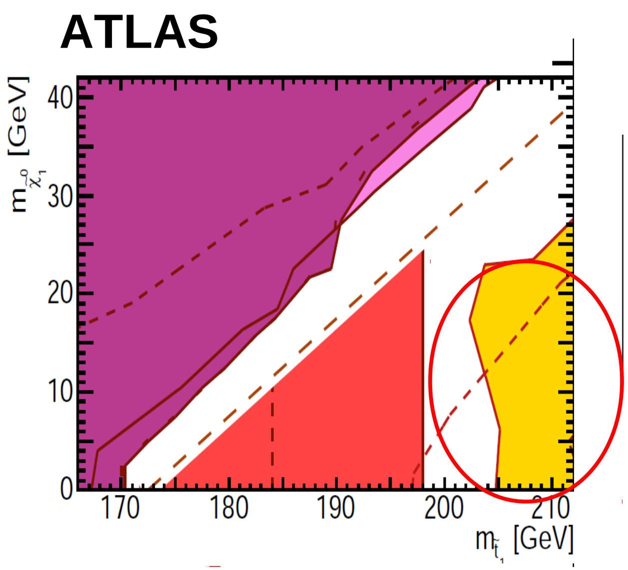
m(stop)-m(chi01)~m(W)
May be covered already with Run I data and dedicated MT2-based selection in 2-lepton channel?

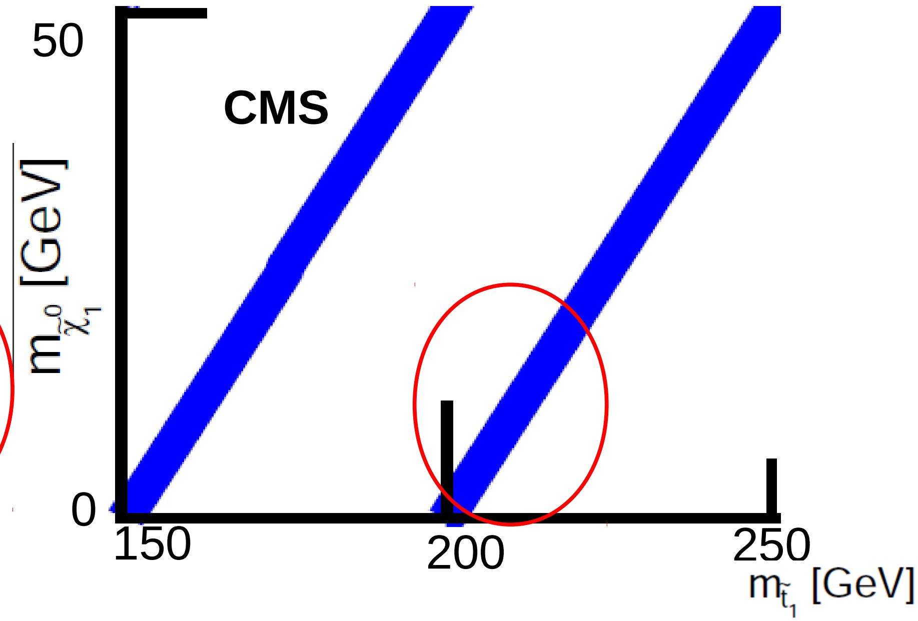
m(stop)<100 GeV
Most likely OK,
Need to match LEP/Tevatron exclusions



m(stop)<~200-220 GeV
m(chi01)<20-30 GeV

Stop mass around top mass (1)



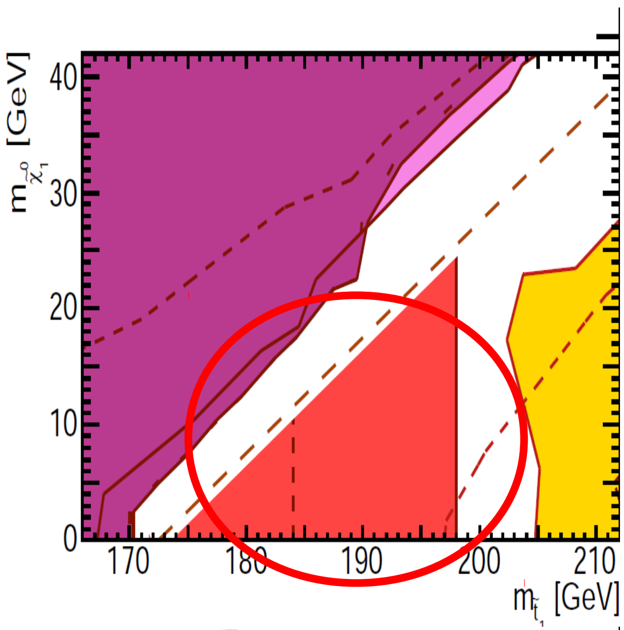


Standard semi-leptonic analysis, ATLAS cut-based shape fit, CMS BDT

Stop mass (GeV)	175	190	200	225
ATLAS 95% excluded XS (pb)		60	23	2.3
CMS 95% excluded XS (pb)	48.1		22.7	10.3
Production XS (pb)	36.8	24	18.5	10

Exclusions for m(LSP)=0
200 GeV excluded at 89% by ATLAS
(200,25) excluded at 95%

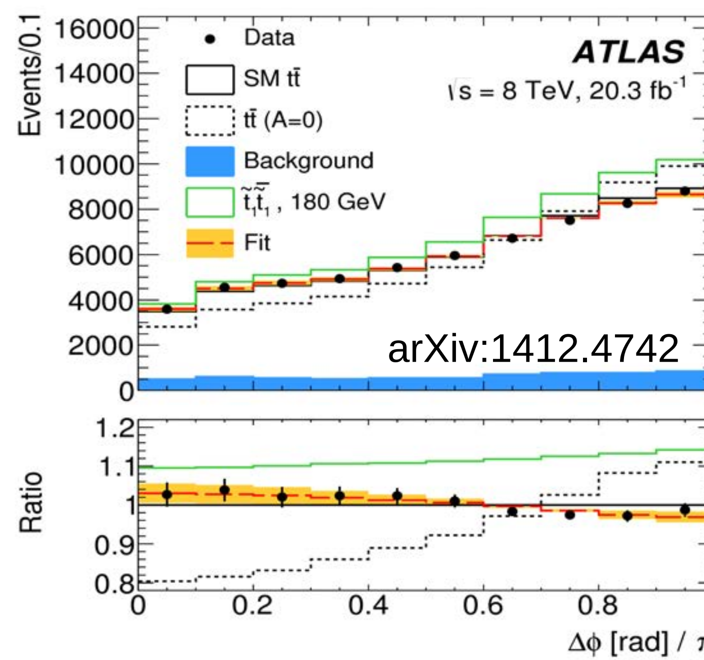
Stop mass around top mass (2)



Below ~200 GeV: proposals in literature based on distortion in SM ttbar measurements

- Stop X-section ~10% of top cross-section
- Could be observed as an increase of measured top cross-section wrt (wonderfully precise) theory
- For di-leptonic decay could distort azimuthal angle which measures top spin polarization
- Main issue is uncertainty on theory X-section and angular distribution due to PDF uncertainties

ATLAS result based on both likelihood fit to $\Delta\phi$ shape, and comparison of normalisation with theoretical expectation

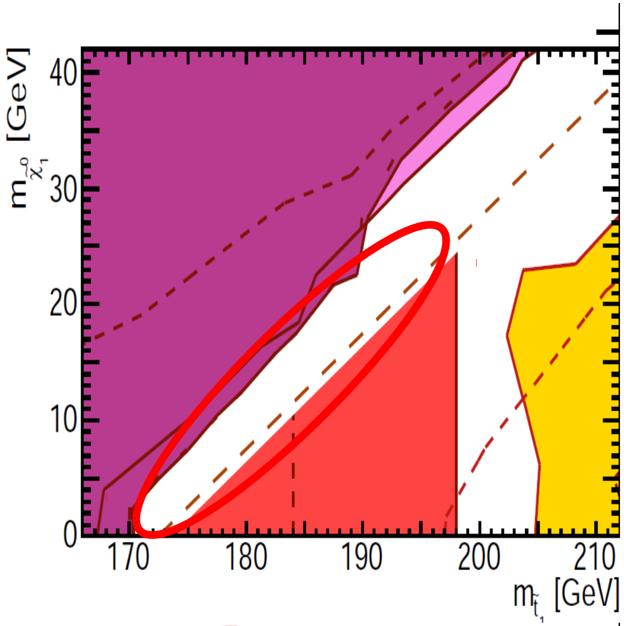


Run II Outlook:

Theoretical uncertainty dominant in measurement

With higher statistics one can select special kinematic regions where polarisation effect is enhanced and impact of systematics reduced (arXiv 1310.0356)

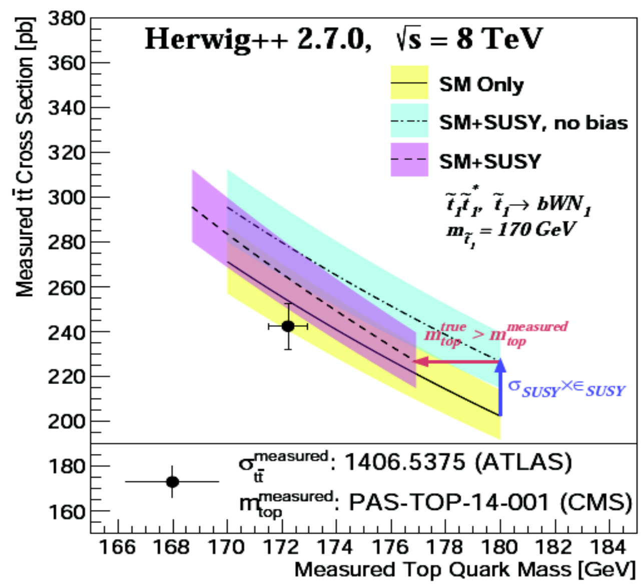
Stop mass around top mass (3)



Analysis based on top cross-section normalization and comparison of observed $\Delta\phi_{ll}$ with expectation from ttbar should also cover 3-body (stop → Wb chi01) region for 170 <~ m(stop) <~ 200 GeV, but two caveats requiring dedicated study:

- In the relevant area, decay kinematics has a significant dependence on the left-right admixture of stop

- A contamination of the three-body decay of stop in the SM top sample might bias the top mass measurement, thus affecting the theoretical prediction of the SM ttbar cross-section (arXiv 1410.7025)



Compressed stop

Large amount of work in literature on tagging of boosted tops from non-compressed stop decay

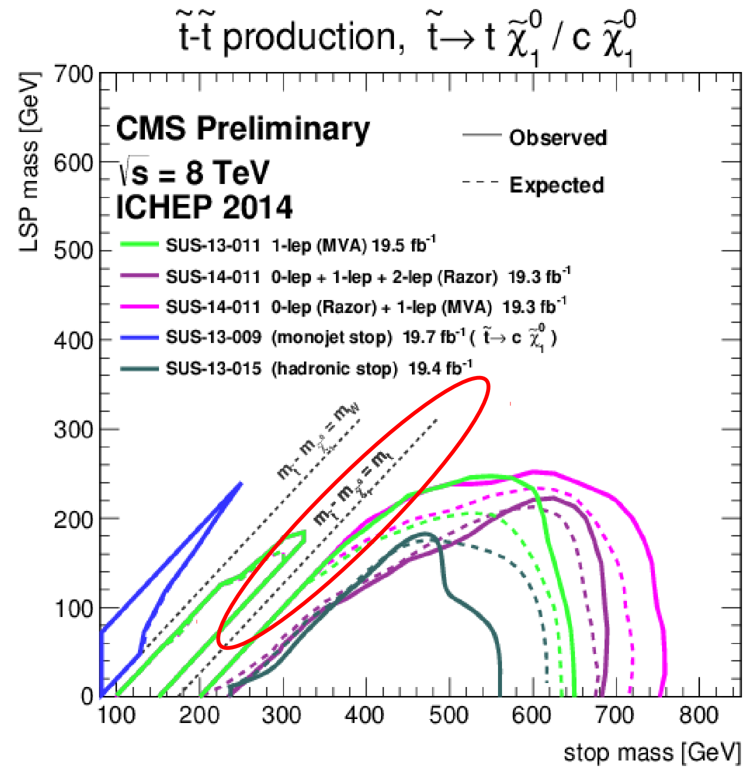
Similar techniques can be used for compressed spectra recoiling against ISR

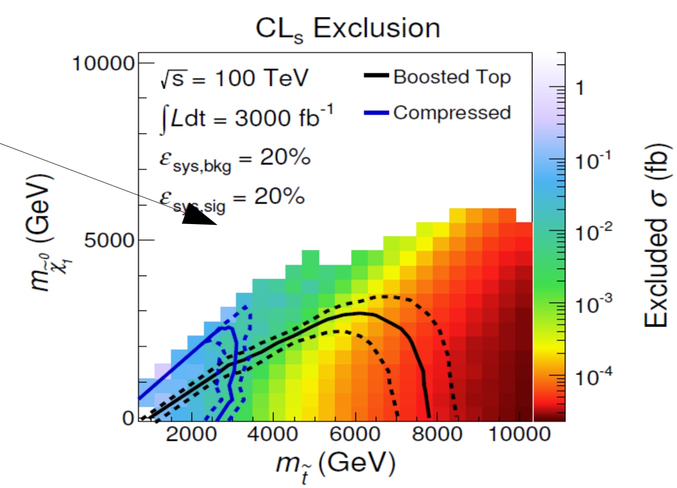
For m(stop)>~300 GeV neutralino carries away half of the boost

Signature would be one or two tagged tops, one additional hard jet and MET

Exercise for 100 TeV Collider (arXiv 1406.4512) looks promising, similar 14 TeV exercise for compressed region needed

Alternative method applied in ATLAS and CMS is search for stop_2 decay into Z/h stop_1



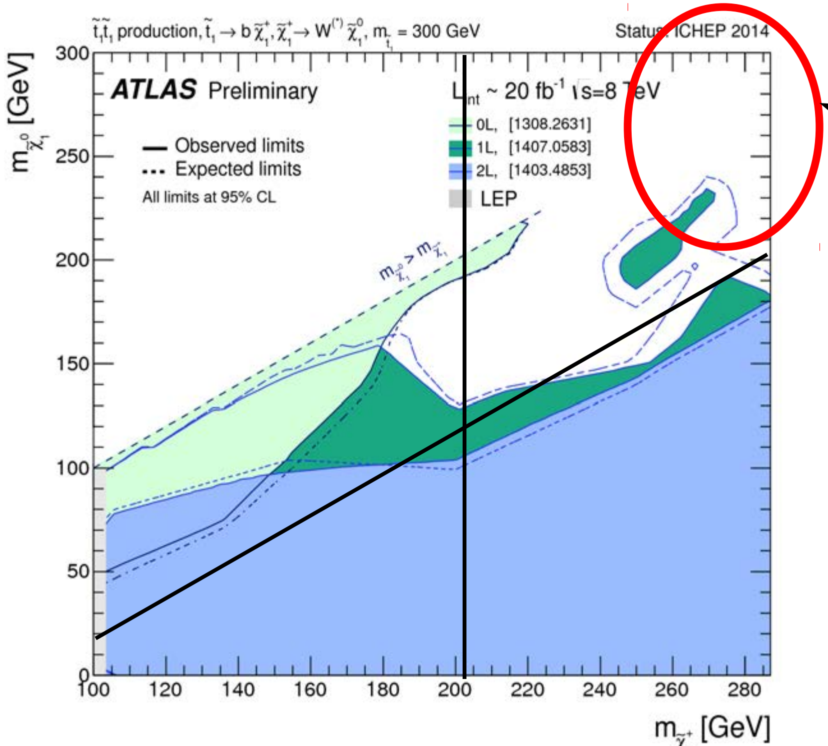


Stop to chargino: difficult regions for m(stop)=300 GeV

It becomes difficult when both mass gaps become smaller than the equivalent ones for top

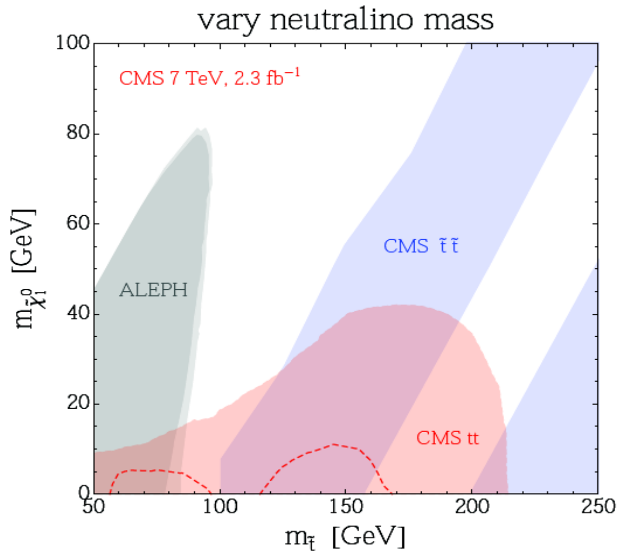
m(chip)-m(chi01)<m(W)
m(stop)-m(chip)<m(top)-m(W)

Similar situation as for compressed stop NLSP, but with softer visible particles
Need to develop special signal region based on boosted topologies for Run 2



Compressed spectrum:
m(stop)~m(chip)~m(chi01)
Will be excluded in run 2 by monojet searches, in run 1 m(stop) up to ~250 GeV

Very low stop mass



Examples in literature :

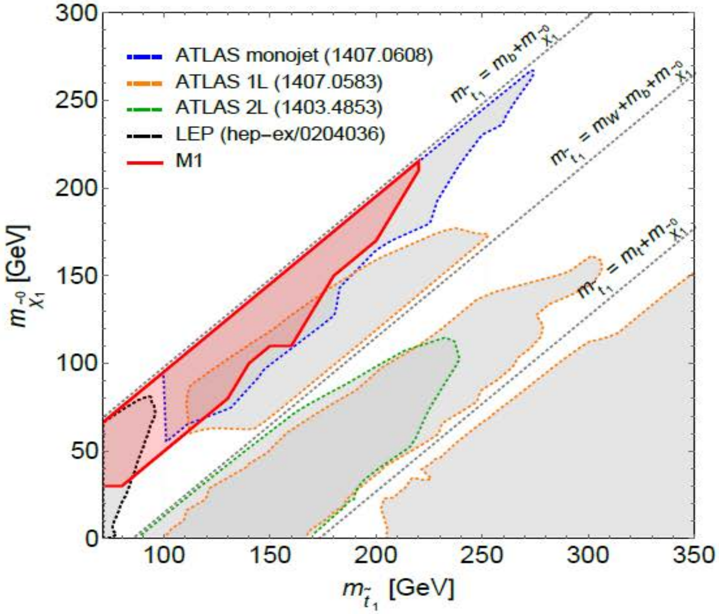
Left: arXiv:1407.1043

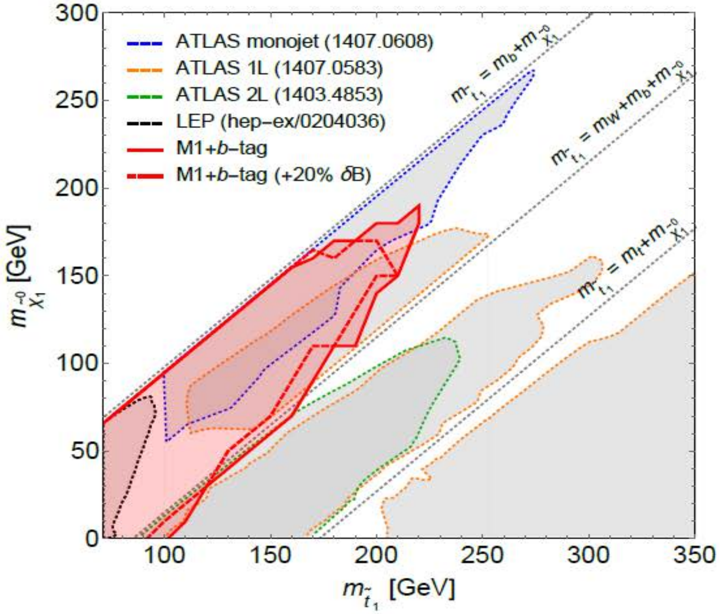
Based on precision ttbar cross-section measurement

Below: arXiv:1502.01721

Left: Extending to low mass ATLAS monojet analysis (Ptj1>280 GeV, MET>220 GeV)

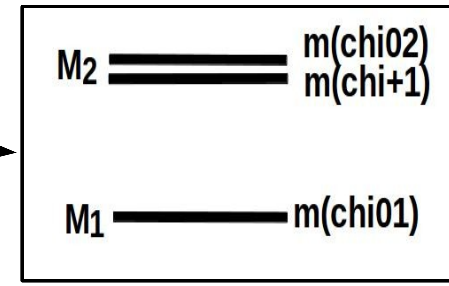
Right: adding b-tag to the same selection

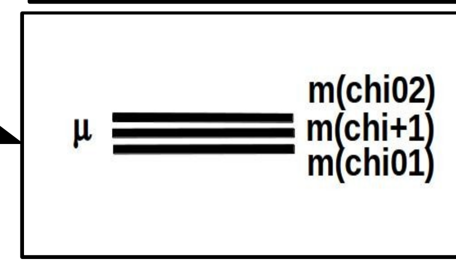


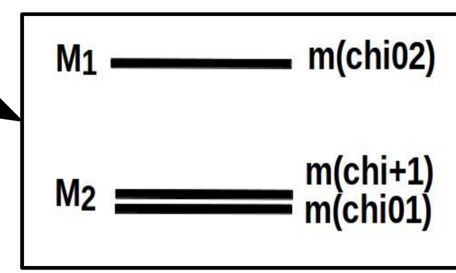


Ewkino phenomenology

- Ewkino are a mix of higgsinos, binos and Winos
- Hierarchy defined by neutralino and chargino mixing matrices
- 4 parameters: higgsino mass μ, bino mass M_1, Wino mass M_2, $\tan\beta$
- Hierarchies with unmixed ewkino states:
  - M1 < M2 << μ: LSP is bino, chi02, chi+1 Wino
    - chi02, chi+1 ~ mass degenerate.
  - μ << M1, M2: LSP, chi02, chi+1 higgsinos
    - LSP, chi+1, chi02 ~ mass degenerate
  - M2 < M1 << μ: LSP is Wino, chi02 bino, chi+1 Wino
    - LSP and chi+1 ~ mass degenerate
- For Ewkinos mass degeneracy is not an accidental feature, but a consequence of the mixing
- Pure higgsino and Wino LSP good dark matter candidates

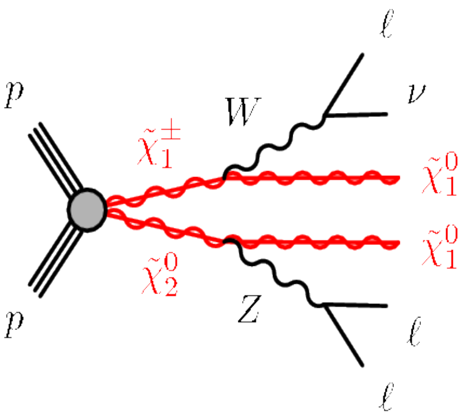






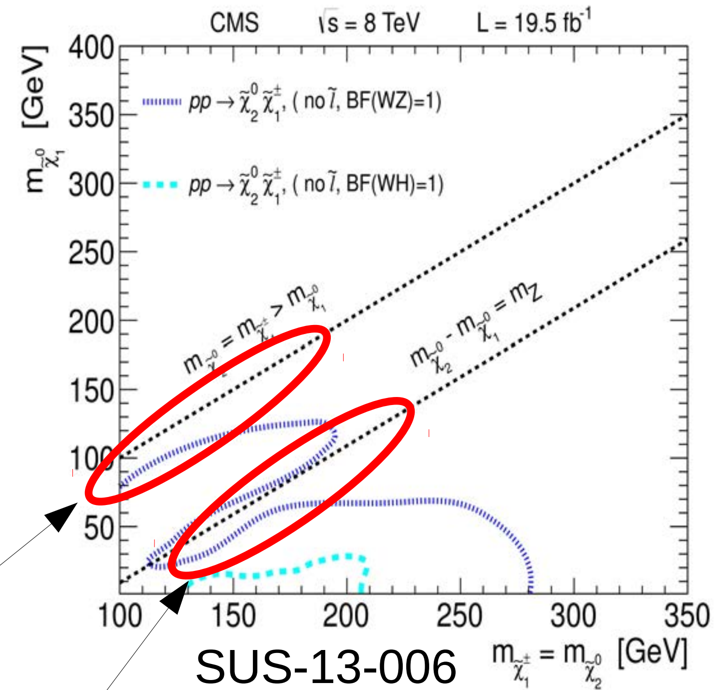
Ewkino: difficult regions

Case with heavy sleptons more difficult,
as decay into vector bosons imply large
Loss in statistics for multi-lepton channels



Results for low masses dominated by searches for chi02 chi+ decaying into 3 leptons + MET

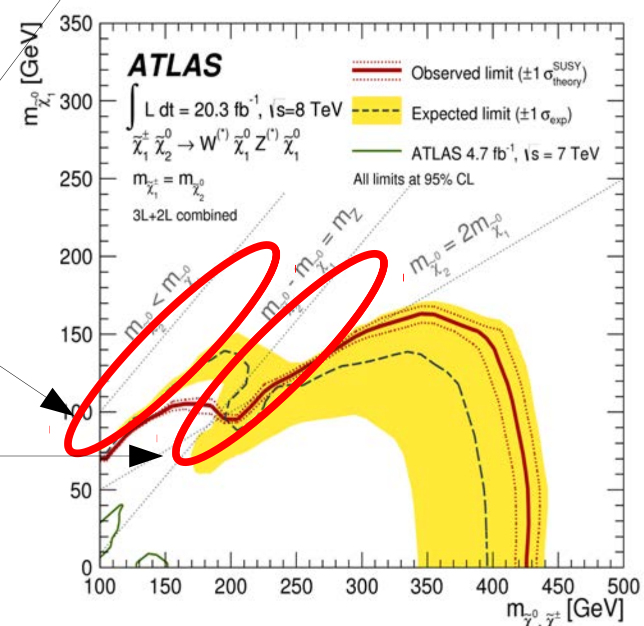
Decay of neutralino into higgs explored as well



SUS-13-006

m(chi02)~m(chiplus)~m(chi01)
Maps the cases with chi01 pure Higgsino

m(chi02)=m(chiplus)=m(chi01)+m(Z)
Kinematics identical to SM WZ



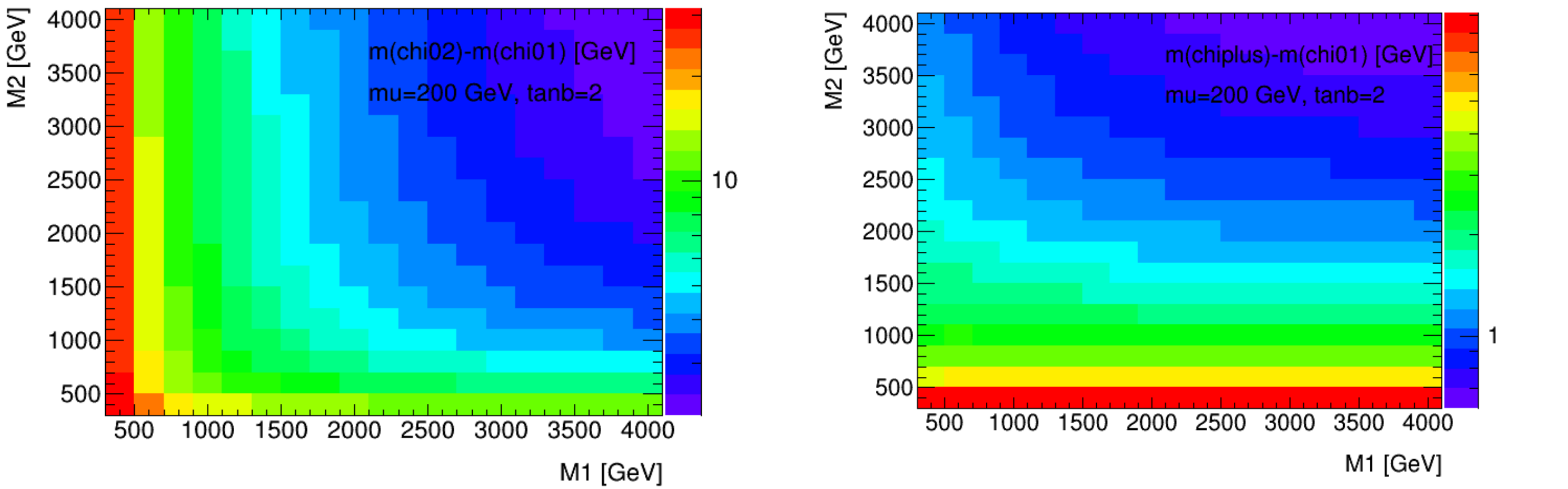
arXiv:1403.5294

In the following: concentrate on pure higgsino case which has lowest X-section and most difficult kinematics

Higgsino perspectives at 14 TeV

Experimental detectability of higgsino crucially depends on

Δm = m(chi02)-m(chi01) ~ m(chiplus)-m(chi01)



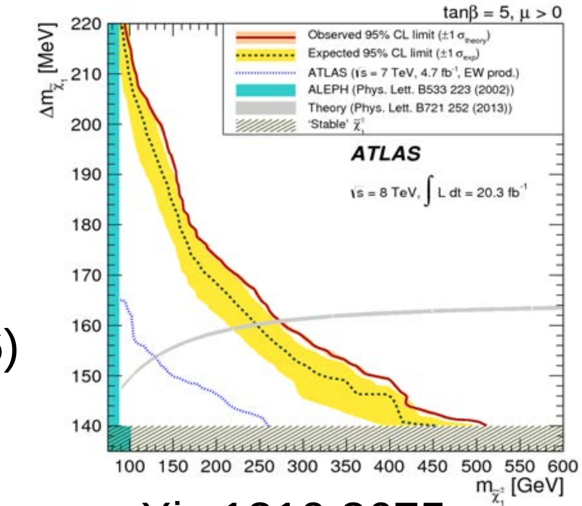
Δm for an higgsino of 200 GeV, calculated with SUSYHIT, with all of the sfermions at 3 TeV.

With M1,M2 in the several tens of TeV region, higgsino completely pure, and mass difference in the few hundred MeV area because of radiative corrections.

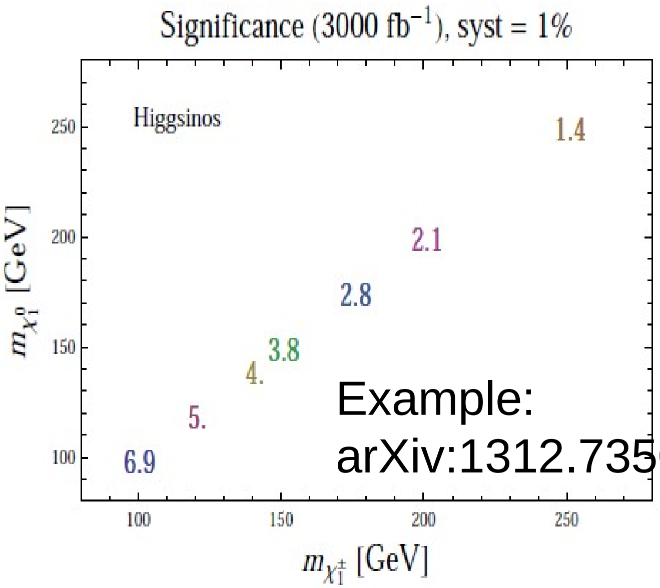
Depending on model parameters mass differences vary between ~10-20 GeV and few hundred MeV.

Run 1 analyses sensitive down to Δm~30 GeV, evaluation of 14 TeV reach need to take into account several possible possible experimental approaches depending on Δm

Δm a few hundred MeV: non-prompt higgsino decay:
May consider extending disappearing track analysis
Which has been used in Run 1 for the more degenerate
Wino case (Δm in the 100 MeV region)
(see also ATLAS long-lived talk, and CMS: arXiv:1411.6006)



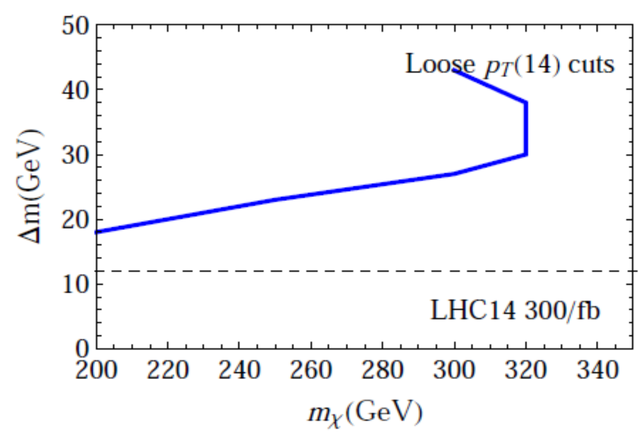
arXiv:1310.3675



Example:
arXiv:1312.7350

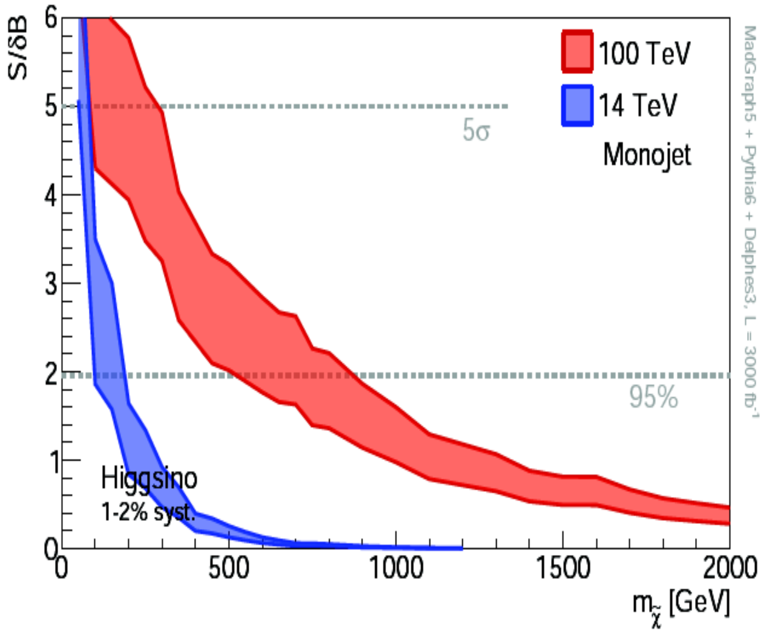
Δm~ a few GeV: prompt decay,
final state products ~invisible:
Monojet + Etmiss or VBF+ Etmiss analysis.
Generic conclusion for monojets:
S/B ~ 2 (1)% for μ= 100 (200) GeV
Run 1 systematics on monojet background ~3 to 5%

Δm from a few GeV to 10-20 GeV: may be able to
Add the request of soft leptons to the ISR jet,
thus achieving background reduction



Example: arXiv:1307.5952 3-lepton analysis

Theoretical projections for higgsino at 100 TeV

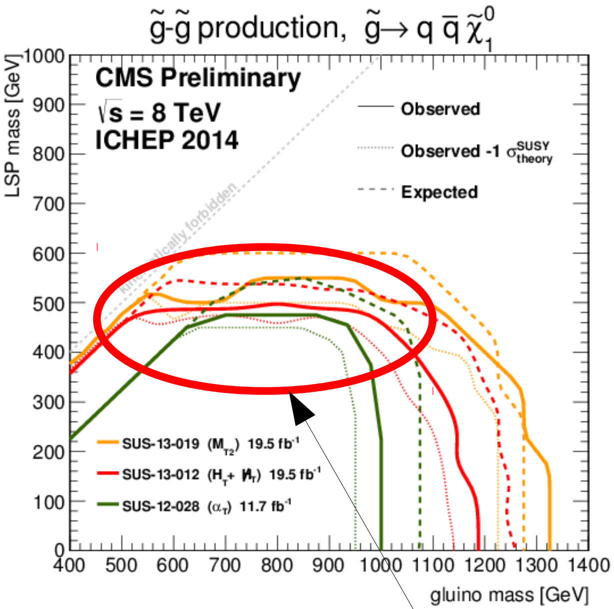


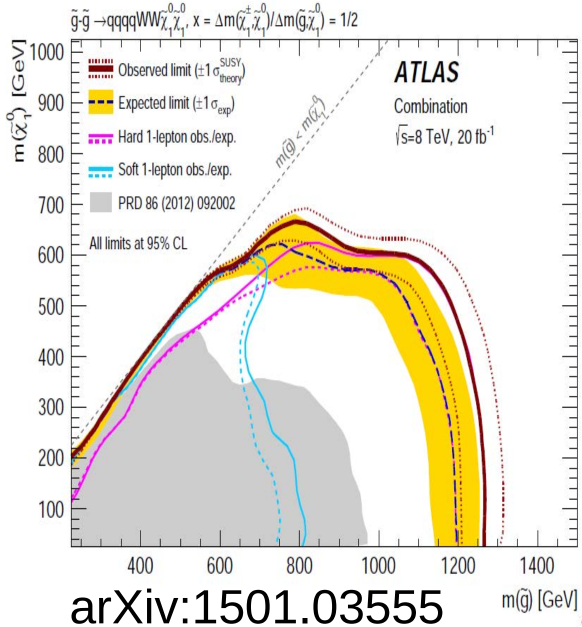
Example: arXiv:1404.0682
Monojet analysis:
Assumed luminosity is 3000 fb-1
Bands: varying systematics between 1 and 2%
Exclusion up to 500-800 GeV, ~no discovery unless systematics down to 1%
Comparable result for disappearing tracks with 20% background systematics

A systematic control of backgrounds in monojet searches at the level of 1% seems mandatory for a discovery, even with a 100 TeV proton-proton collider

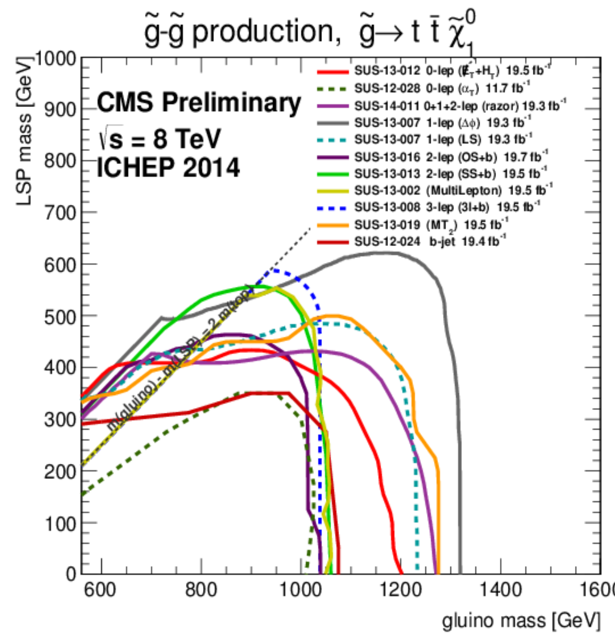
For higgsinos in the 100-200 GeV mass range and Δm ~ GeV best option for proper observation seems to be an e+e- collider

Gluino searches





arXiv:1501.03555



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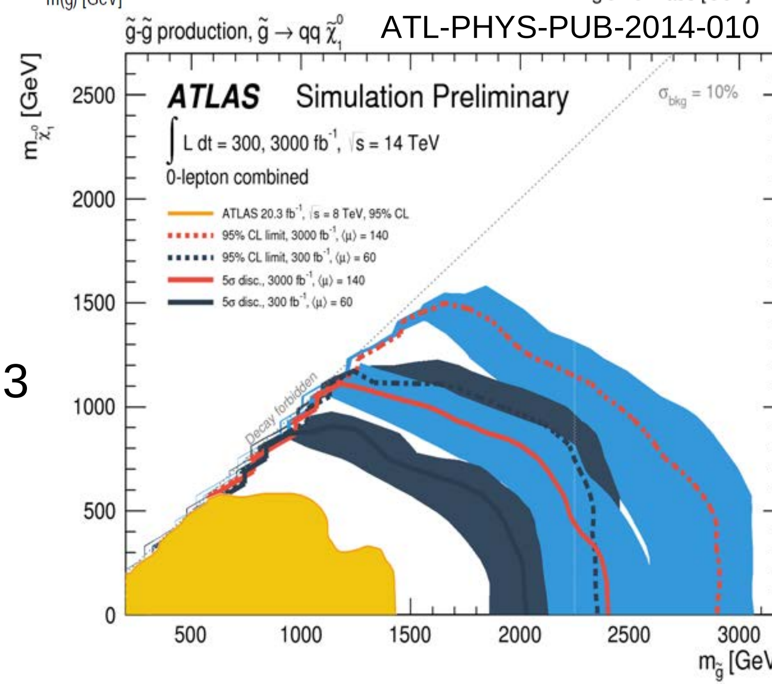


Gluino fully excluded only for m(gluino)<~600 GeV
For higher masses only if m(chi01)<~500 GeV

Gluino fully excluded up to ~1200 GeV with Run 2+3

Analyses rely on additional jets in the event

Equivalent results frm CMS (CMS-SUS-14-012)

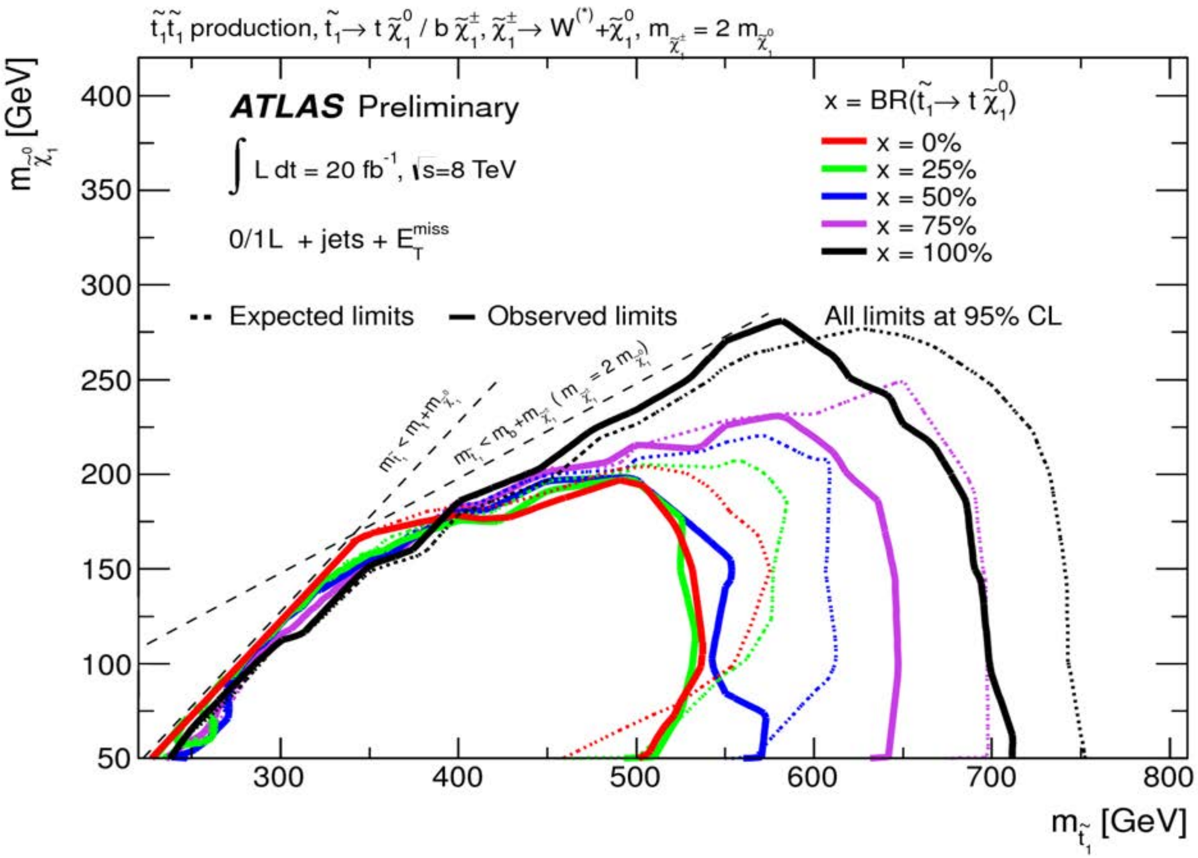
Conclusions

- Discussed possible difficult spots for RPC natural SUSY at the LHC
- Three case studies examined:
  - Stop: it should be possible to cover all the relevant space at the LHC for m(stop)<~1TeV, although difficult areas exist, and further work on boosted tops at 14 TeV is needed
  - Higgsino: very difficult at the LHC, different handles depending on how compressed the spectrum is, but typically low S/B, need to achieve excellent background control
  - Gluino: already with Run 2-3 should cover above the TeV
- Many other examples possible, which could not fit into a single talk, a few notable example:
  - Fully hadronic RPV, it seems we have some nice handles
  - A large zoo of models with long-lived sparticles
  - Models with diluted MET because of long decay chains (nMSSM)
  - pMSSM scan approach to identify uncovered regions

Backup

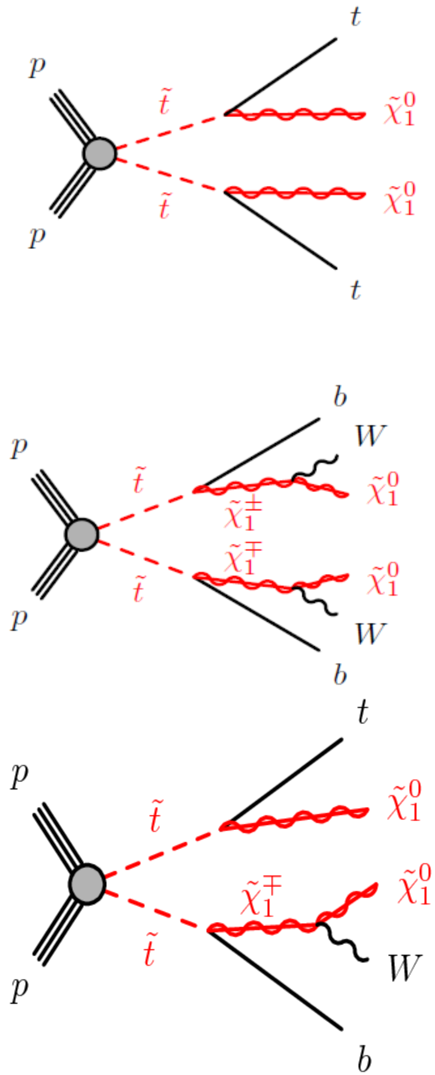
BR-dependent stop limits

Combination of 0 and 1-lepton analyses



NEW from ATLAS CONF-SUSY-2015-01

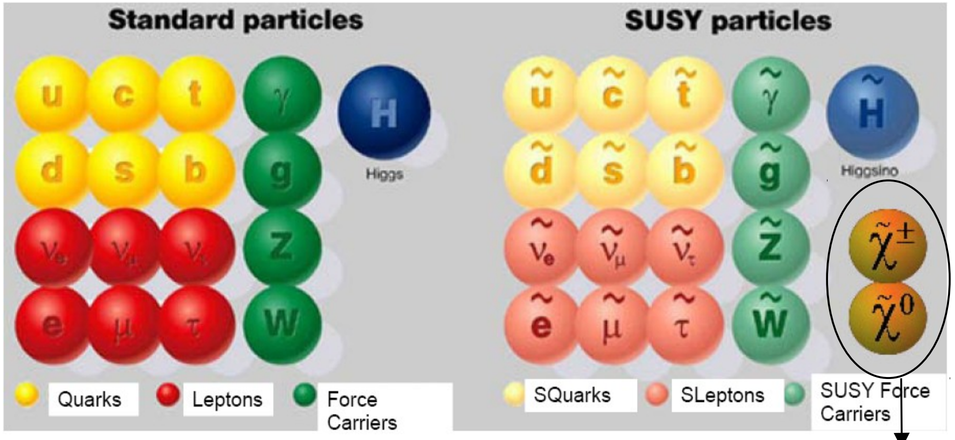
Final state topologies:



Minimal Supersymmetric Standard Model (MSSM)

Minimal particle content:

- A superpartner for each SM particle
- Two Higgs doublets and spartners:
  5 Higgs bosons: h,H,A,H+,H-



gaugino/higgsino mixing

- Insert in Lagrangian all soft breaking terms: 105 parameters.
- If we assume that flavour matrices are aligned with SM ones
  (minimal flavour violation): 19 parameters

Additional ingredient: R-parity conservation: $R=(-1)^{3(B-L)+2S}$

- Sparticles are produced in pairs
- The Lightest SUSY particle (LSP) is stable, neutral weakly interacting
  - Excellent dark matter candidate
  - It will escape collider detectors providing Etmiss signature

Models with R-parity violating terms are also studied: no E_T^{miss} signature, but often 'easier' kinematic signatures

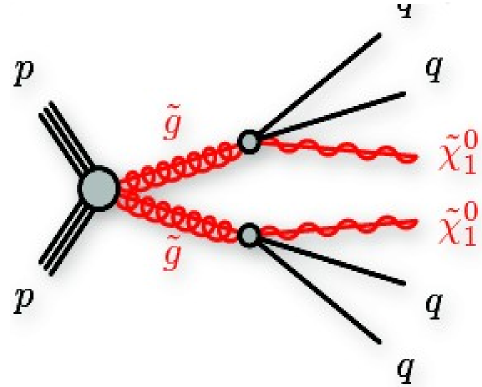
pMSSM interpretation

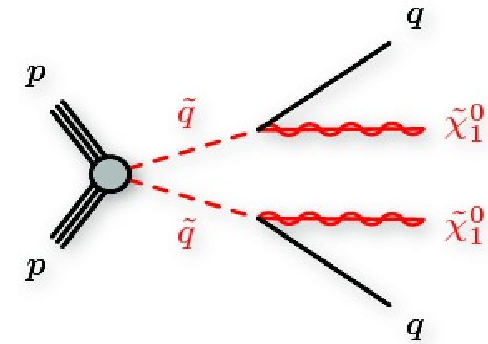
pMSSM: slice: fix all but two parameters, and choose Signature where reach mostly determined by free parameters

Example: 1-step decays of squark and gluinos: 0 lepton signature

All other sparticles decoupled

Except LSP: only two decays allowed

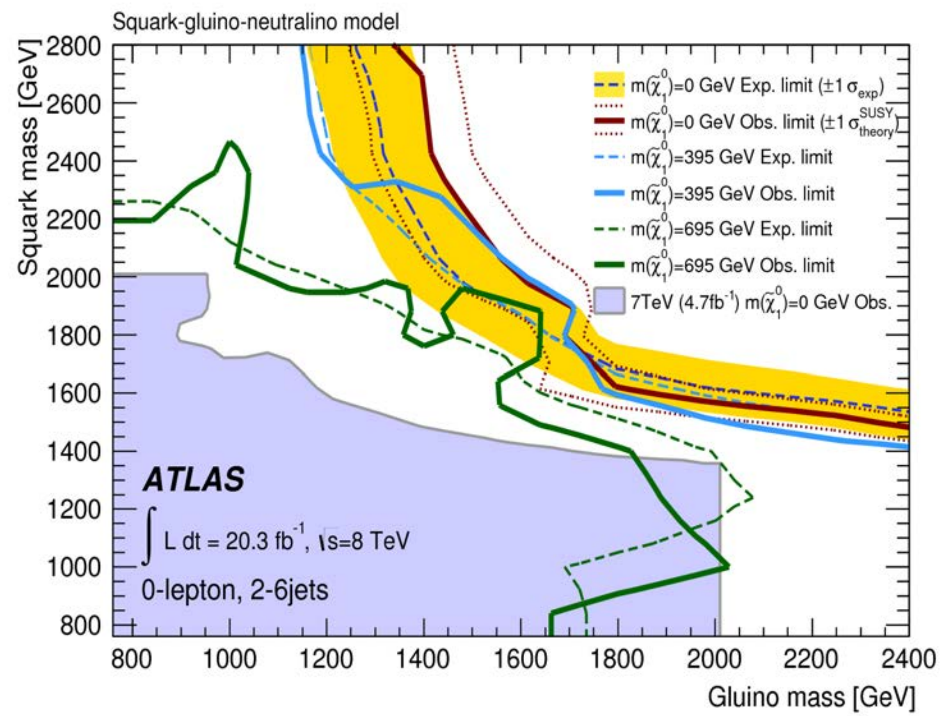




Squark-gluino excluded up to ~1.5 TeV

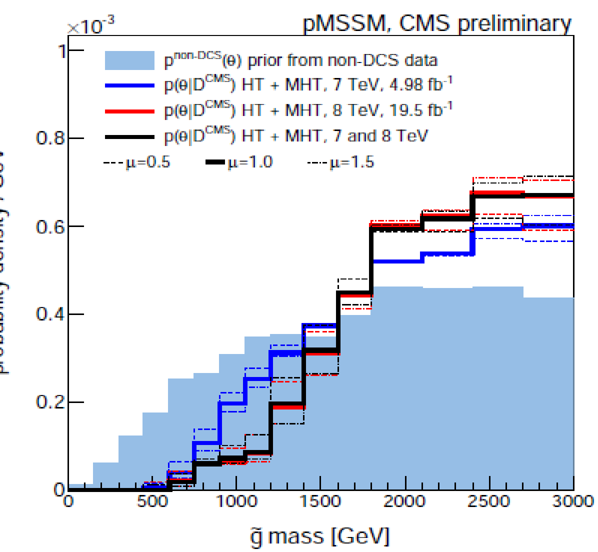
BUT

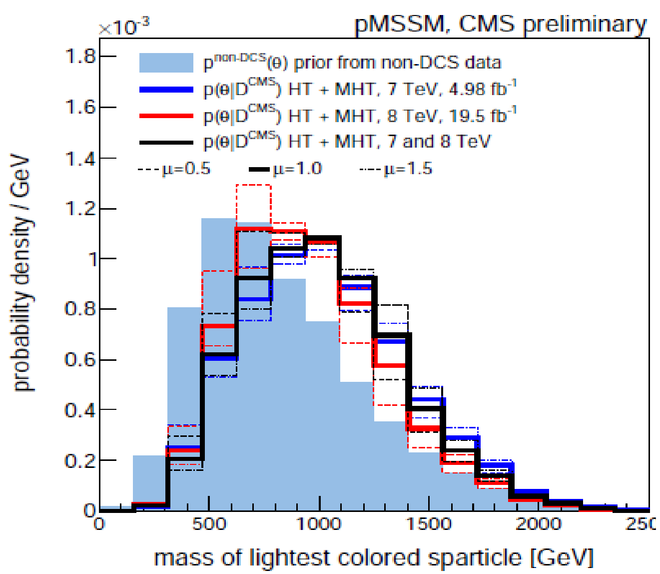
Dependence on neutralino mass

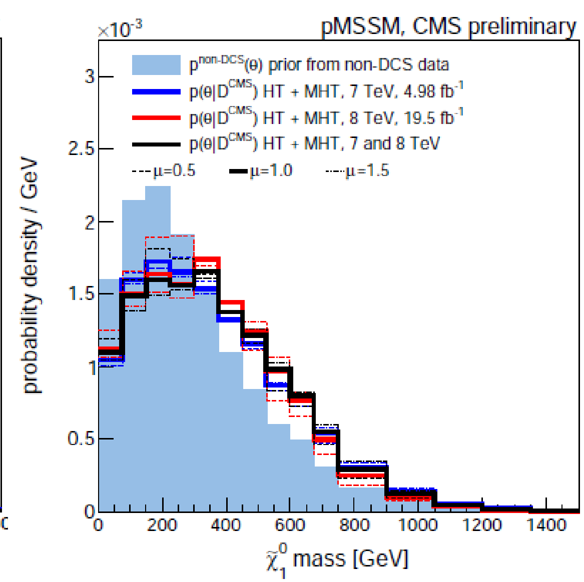


pMSSM interpretation (CMS)

- Select large grid of points in 19-parameters space compatible with LEP and flavour constraints, neutralino LSP and sparticles lighter than 3 TeV
- Build likelihood with results of CMS EW and inclusive Ht + Etmiss (+b-jets) searches
- Show marginalized distributions for sparticle masses
  - Blue are prior distributions
  - Lines are posteriors from CMS searches



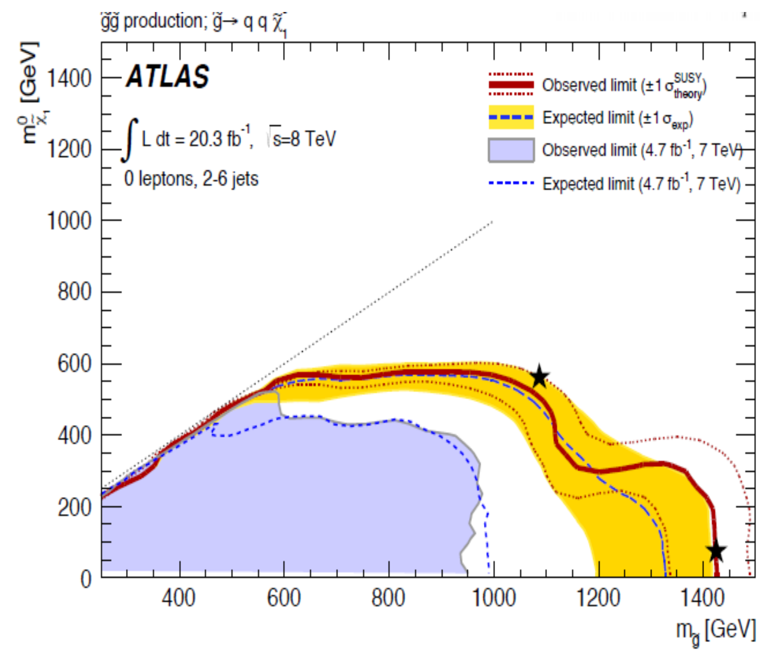


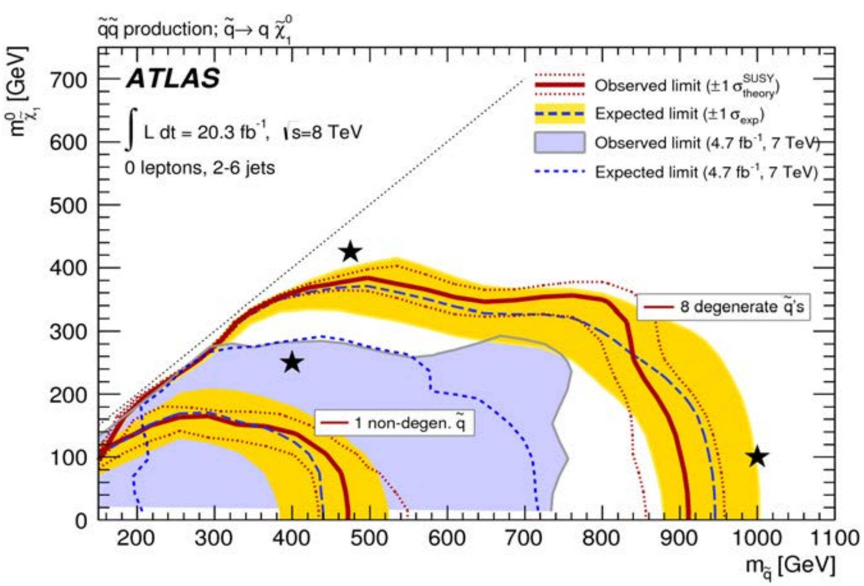


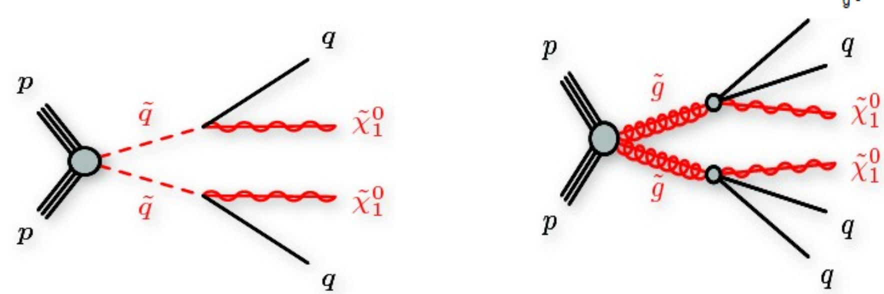
“simplified model” interpretation

Simplified models as a tool for analysis optimisation and display:

- Generate events with given decay chain on both legs
- Assume 100% BR in both legs and the SUSY production cross-section
- Express reach in 2d mass plane
- No statement on theory but very clear Representation of our potential for a specific kinematics



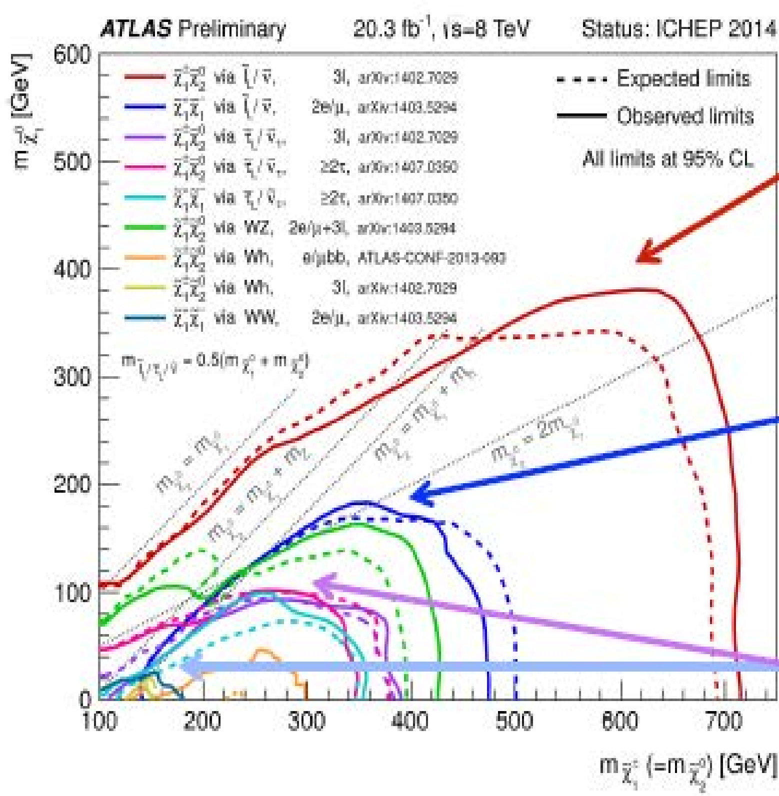


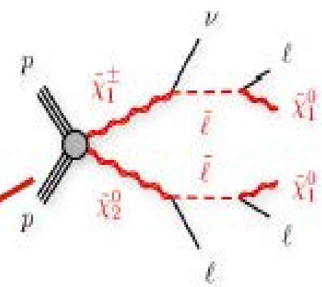


For low LSP mass, exclude gluinos with mass below ~1.4 TeV
And squarks with mass below ~900 GeV

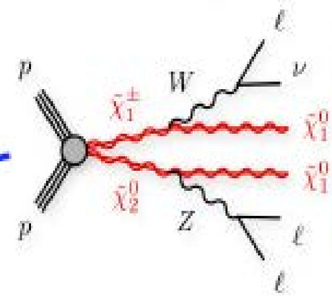
Electroweak SUSY production

- Clean signature: multi leptons, depending on slepton masses and gauge mixture.
- Many possible models are covered by several comprehensive analyses.

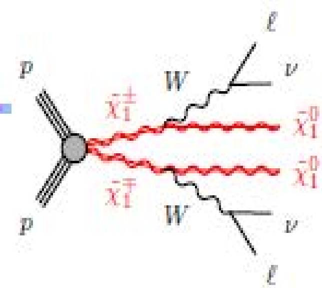




Large cross-section.
3 lepton final states if light sleptons:
exclusion up to m_{LSP}<~380 GeV.



If heavy slepton, smaller cross-section to lepton WZ/h with 3/2 leptons:
up to m_{LSP}<~180 GeV



Tiny cross-section of chargino pair production via WW with 2 leptons.
Sensitivity increased if light stau.

Interpretation of EW production in pMSSM

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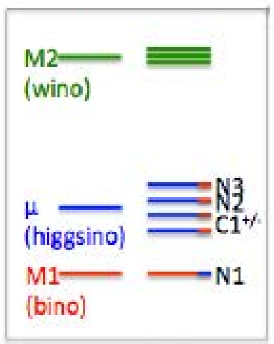
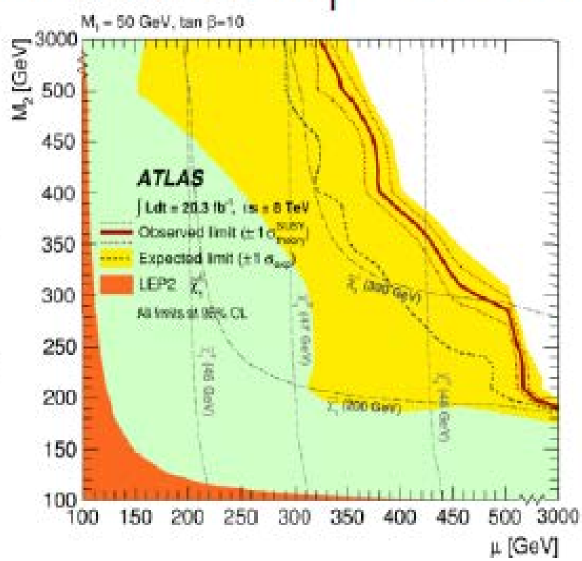
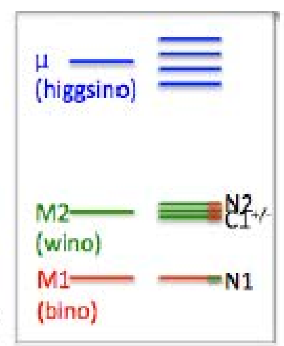
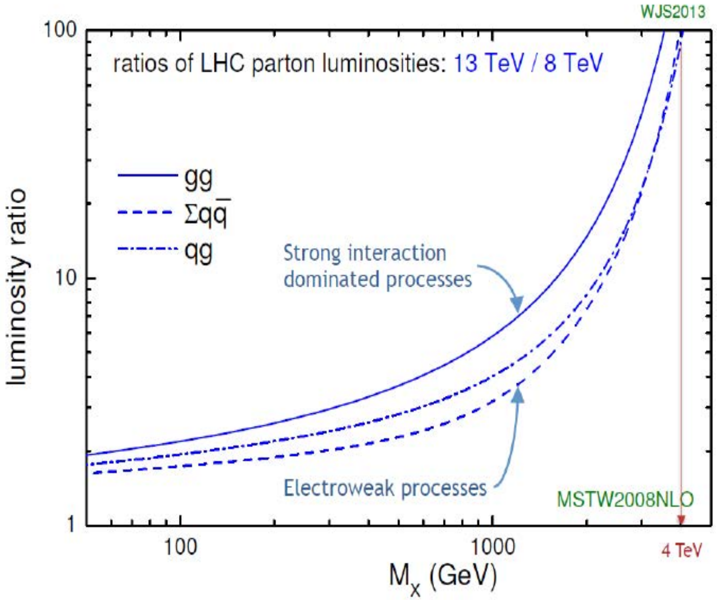
- Phenomenological MSSM (pMSSM) can put generic constraints on most of the phenomenological features of the RPC MSSM.
- Interpretation of 2-lepton+3-lepton analyses in pMSSM:
  - on higgsino μ- wino M_2 mass-plane also with very large slepton masses.
  - Assumption is bino mass M_1 = 50GeV and $\tan\beta$ = 10.



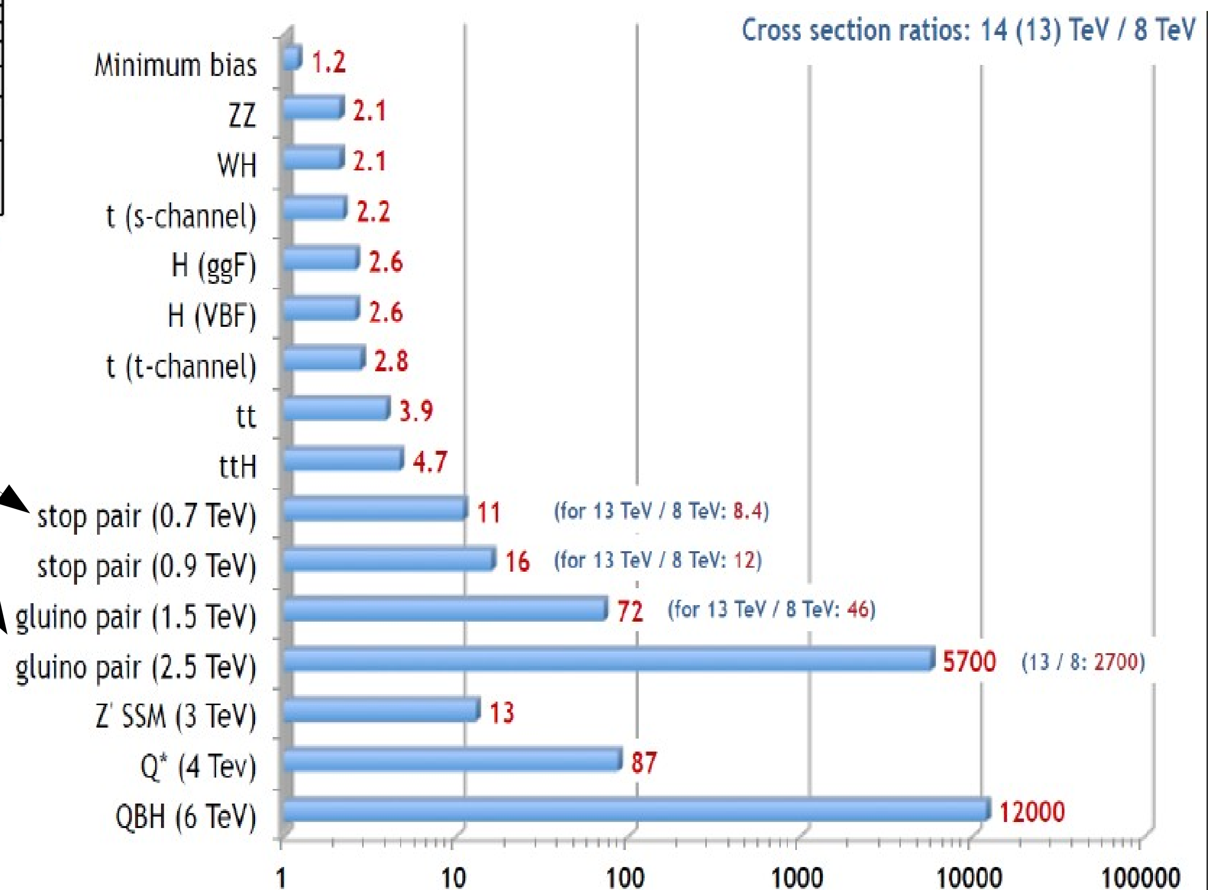




Prospects for SUSY in Run2



Ingredient number 1: CMS Energy

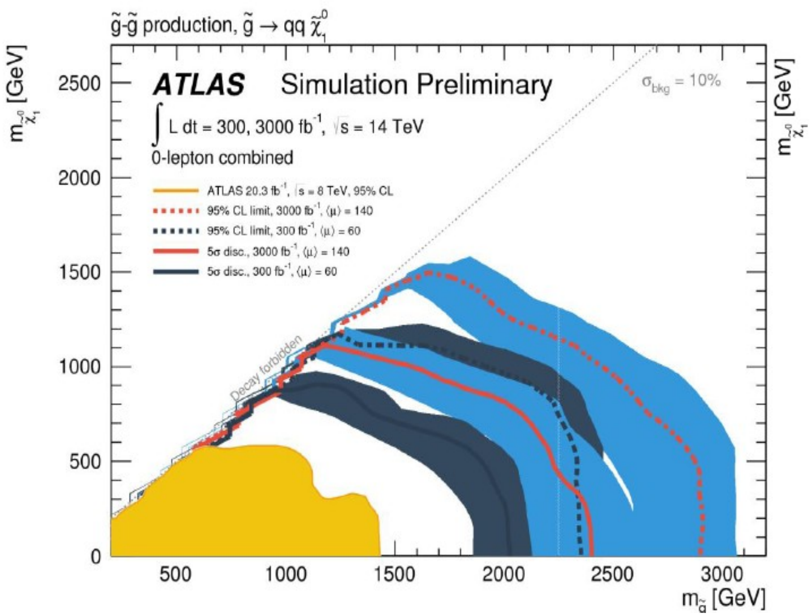


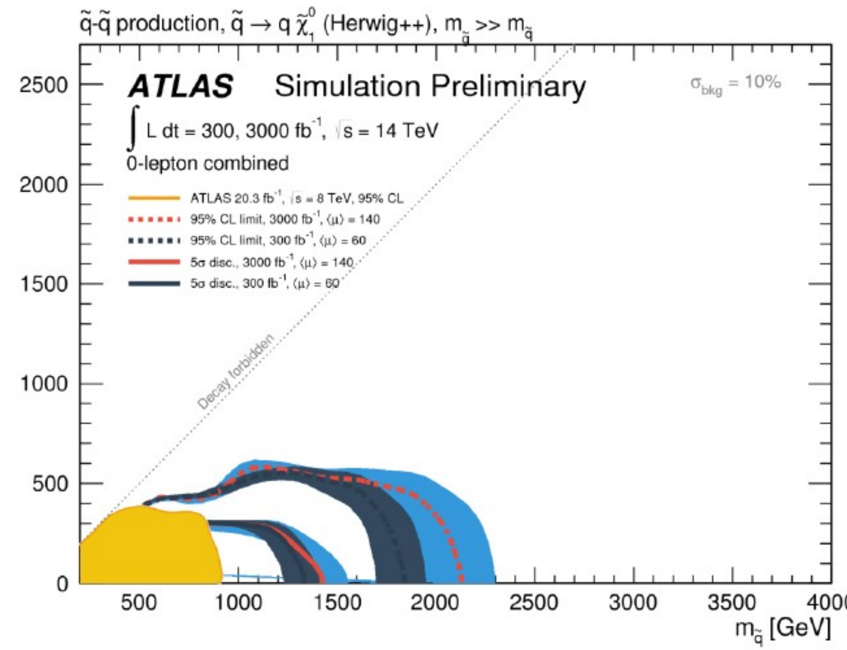
~Reach we had with 8 TeV 20 fb-1

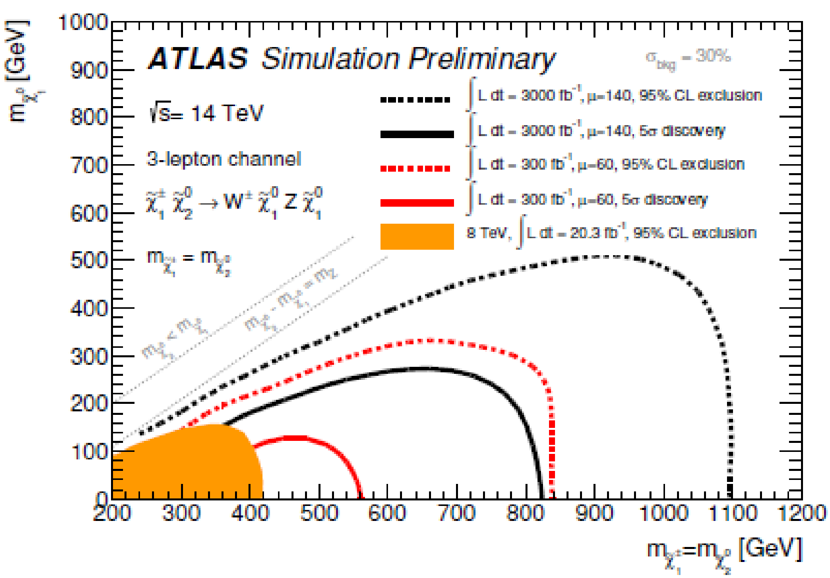
With 1 fb-1 we will produce ~twice as many gluino pairs at 1.5 TeV as in full Run 1

With 5 fb-1 we will produce ~twice as many stop pairs at 0.7 TeV as in full Run 1

Longer term perspective





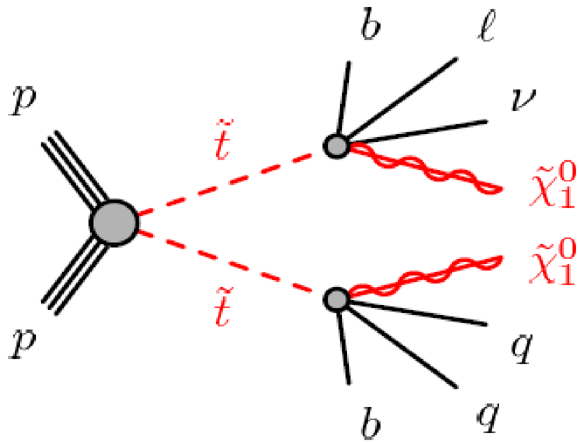


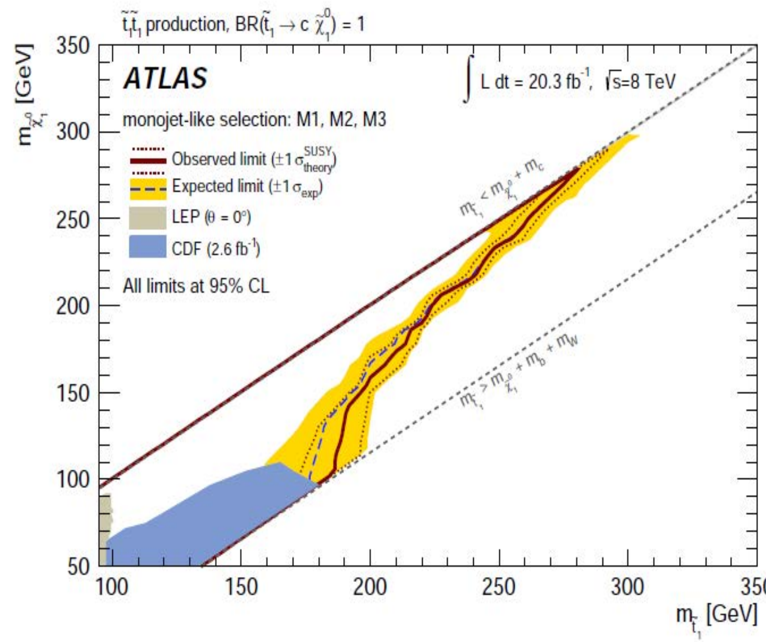
For high luminosity running need
To take into account large pileup
Which will smear Etmiss.
Simulation done in two scenarios:
<μ>=60 for 300 fb^{-1}
<μ>=140 for 3000 fb^{-1}

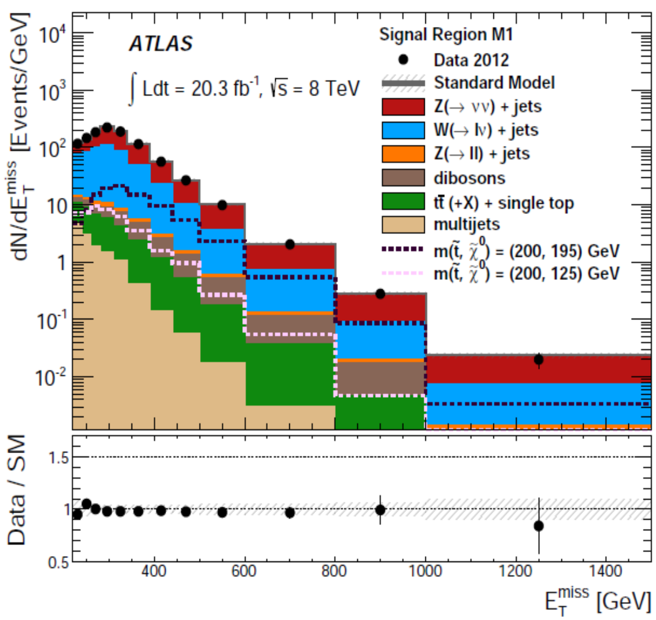
The mono-x analyses

- Select events with a high pt object (jet, photon, lepton hadronically decaying W/Z) and large MET
- Veto events in which:
  - A lepton is identified: *remove electroweak background*
  - There are more than 2 jets: *remove top or multijets*
  - MET is pointing along an jet: *remove fake MET from mismeasured jets*
- Estimate from data main backgrounds:
  - $(Z \to \nu\nu)$+ X (irreducible)
  - $(W \to l\nu)$+X, $(Z \to ll)$+X, with lost lepton
  - Multi-jets, γ+jets with fake MET
  - Non-collision events
- Estimate from MC smaller backgrounds: top, diboson

Interpretation: stop







Search for 4-body decay of stop

Require:

One high pT jet and MET,

No more than 3 jets with pt>30 GeV

Lepton Veto

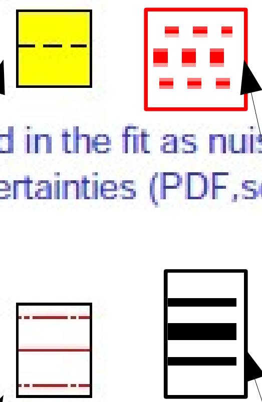
$\Delta\phi$(jets, MET)>0.4

M1: Ptj>280 GeV, Etmiss>220 GeV

Interlude: what are all those lines on limit plots?

❑ Exclusion limits : a new standard ATLAS/CMS procedure (>June 2012)

- Ease the life of theorist by separating the signal theoritical and experimental systematics



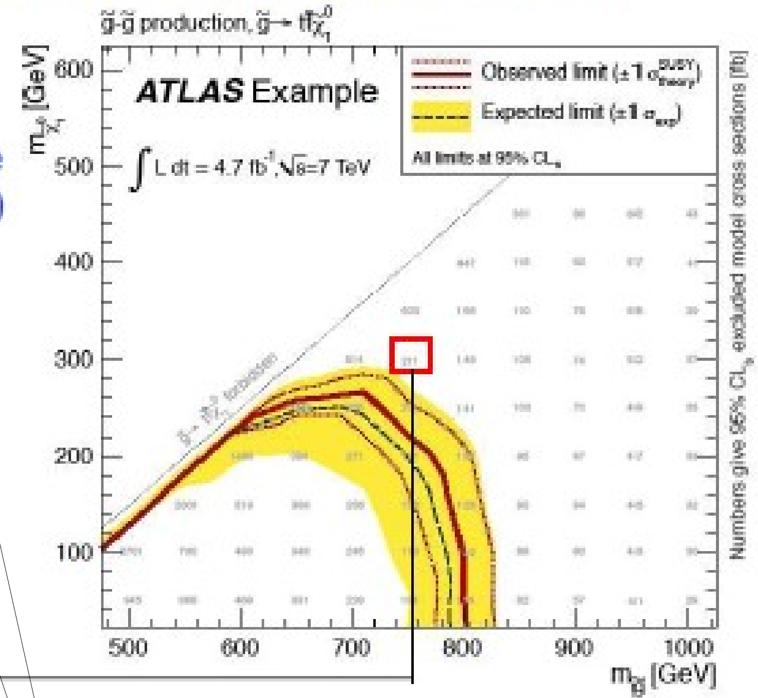
Expected limit:

- **Central value:** all uncertainties included in the fit as nuisance parameters, except theoretical signal uncertainties (PDF,scales)
- **±1σ band** : ±1σ results of the fit

Observed limit:

- **Central value**: Idem as for expected limit
- **±1σ band** : re-run and increase/decrease the signal cross section by the theoretical signal uncertainties (PDF, scales)

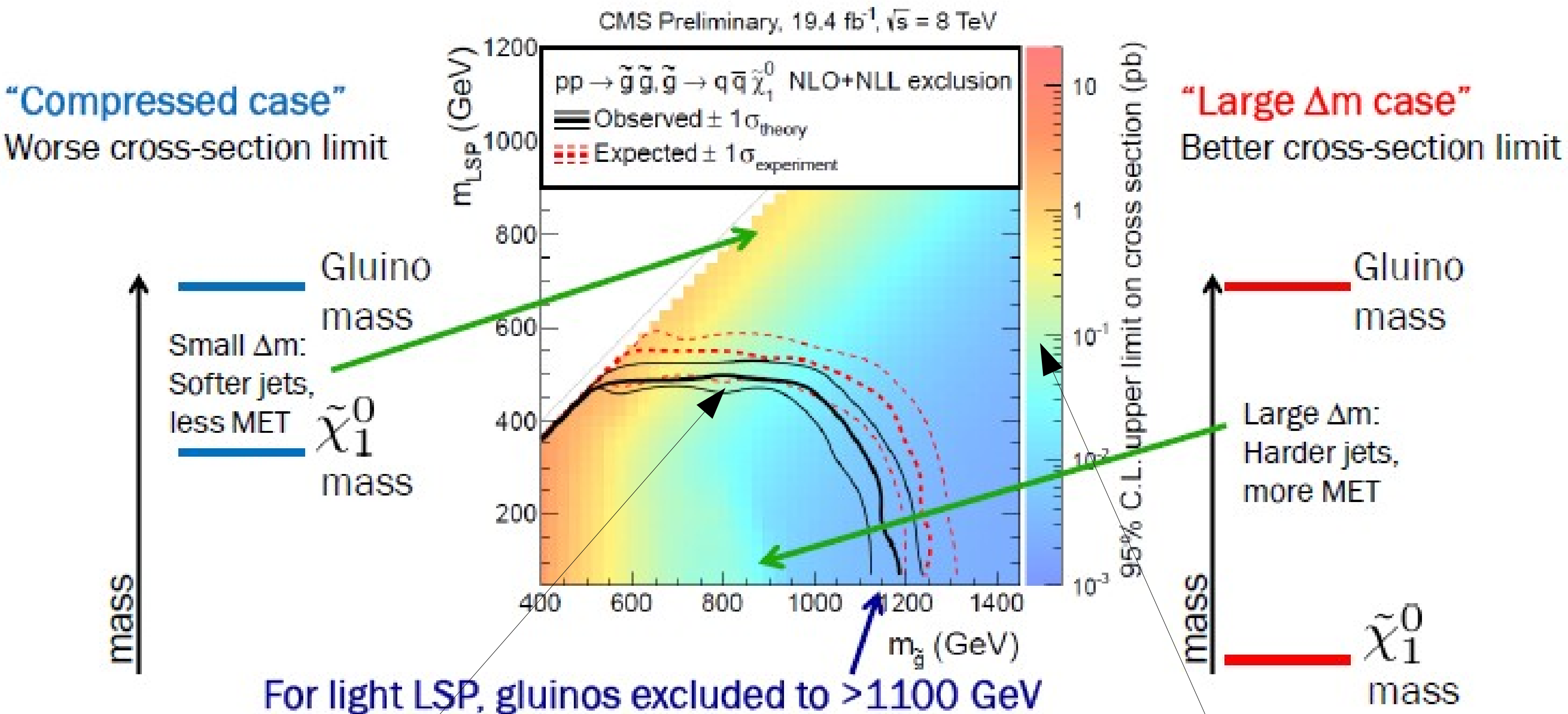
Excluded Model Cross section (SMS)



➔ Number quoted in paper correspond to observed -1 σ observed (conservative)

ATLAS CMS

How to read a simplified model plot



Lines are model dependent, assume
- Production cross-section for initial state
- Branching fraction for decay

Color of plot is important:
It gives excluded cross section
In model-indipendent way,
Can be used to exclude different
Model with same topology