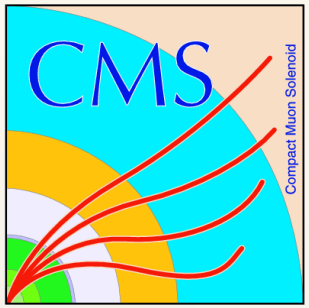
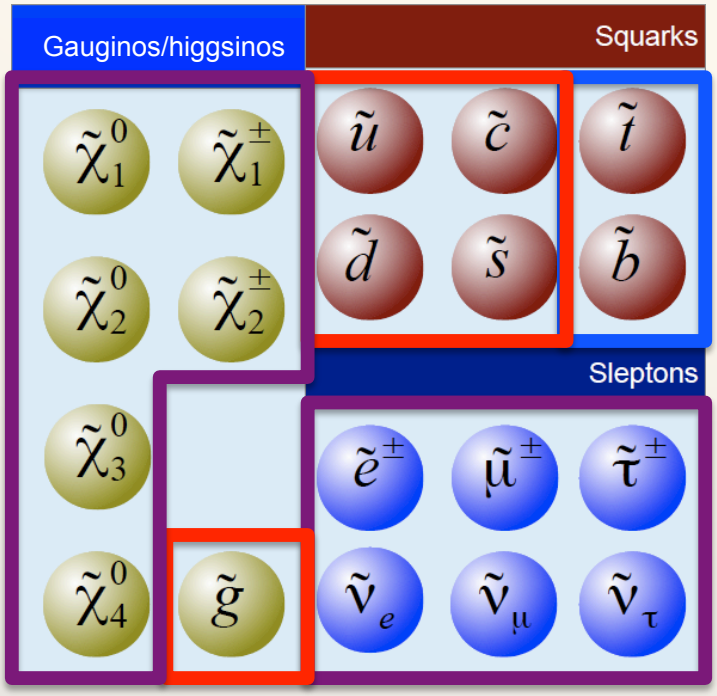


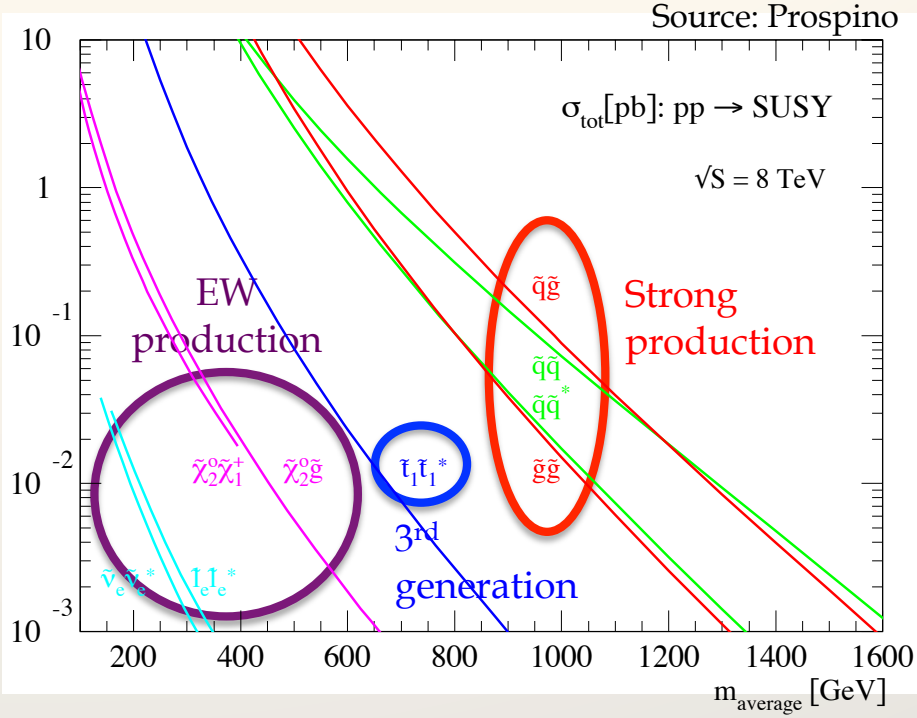
EW SUSY production searches at ATLAS and CMS

XLIX Rencontres de Moriond
Electroweak interactions and unified theories
21st March 2014

Mike Flowerdew (MPI für Physik)
On behalf of the ATLAS and CMS collaborations

Why EW SUSY?





- Weak-scale supersymmetry (SUSY) eagerly anticipated but not yet observed
  - Postulates partners to SM particles, different by $\Delta s = ½$
  - Solves electroweak hierarchy problem
  - Points to gauge coupling unification
  - Often assume R-parity conservation (RPC)
    - Lightest SUSY particle (LSP) stable
    - Dark matter candidate ($\tilde{\chi}_1^0$)
  - Potential mechanisms for neutrino masses (with R-parity violation , RPV)

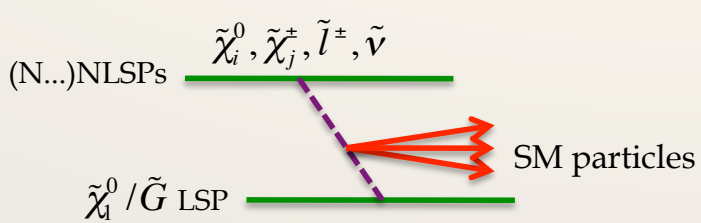
- Squark & gluino production (incl. 3rd gen) now highly constrained
  - See presentation by P Bargassa

- **Electroweak (EW) SUSY** covers direct production of sleptons, neutralinos and charginos
  - Ensure full search coverage
  - Small cross-sections → challenging!

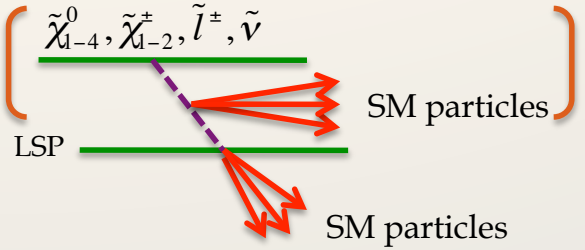
EW SUSY phenomenology

- Observable signatures in pp collisions depends on EWKino and slepton properties
  - With some assumptions, 9 relevant parameters: $M_1, M_2, \mu, \tan\beta, m^2_{\tilde{e}_L}, m^2_{\tilde{e}_R}, m^2_{\tilde{\tau}_L}, m^2_{\tilde{\tau}_R}, \theta_{\tilde{\tau}}$
  - Gauge-mediated SUSY breaking (GMSB) or general gauge mediation (GGM): $+ c\tau_{\text{NLSP}}$

- Typical scenario: EW SUSY production, followed by cascade to LSP



RPC, incl. GMSB/GGM



RPV

Many possible SM particles in SUSY cascades: **fermions**, **W**, **Z**, **h**, dependent on **bino**/**wino**/**higgsino** mixing

$\tilde{\chi}^0_{1-4}$

$$\begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix}$$

Bino
Wino
Higgsino
Higgsino

Neutralino Mass matrix

$\tilde{\chi}^\pm_{1-2}$

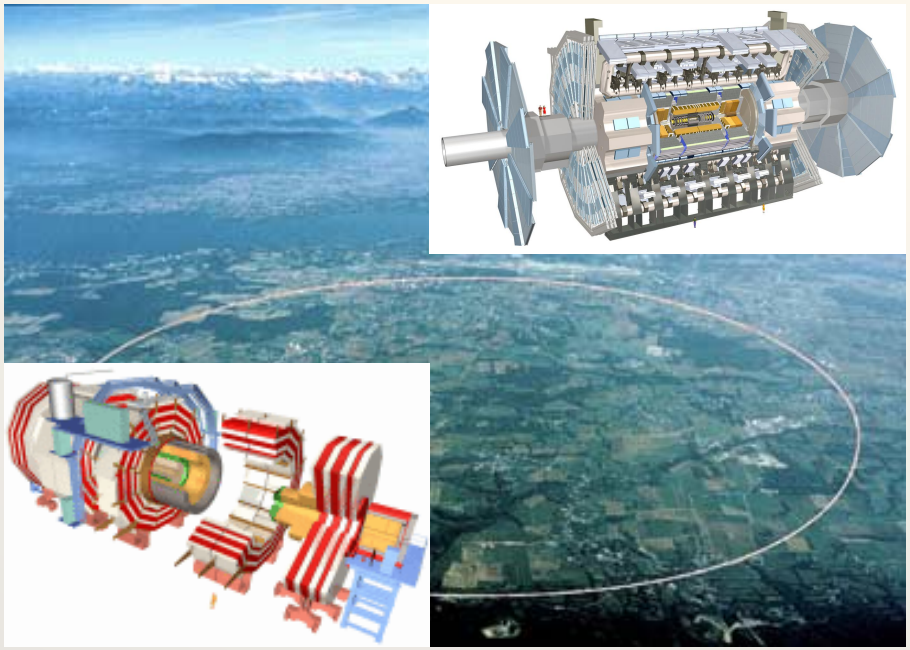
$$\begin{pmatrix} M_2 & \sqrt{2} s_\beta m_W \\ \sqrt{2} c_\beta m_W & \mu \end{pmatrix}$$

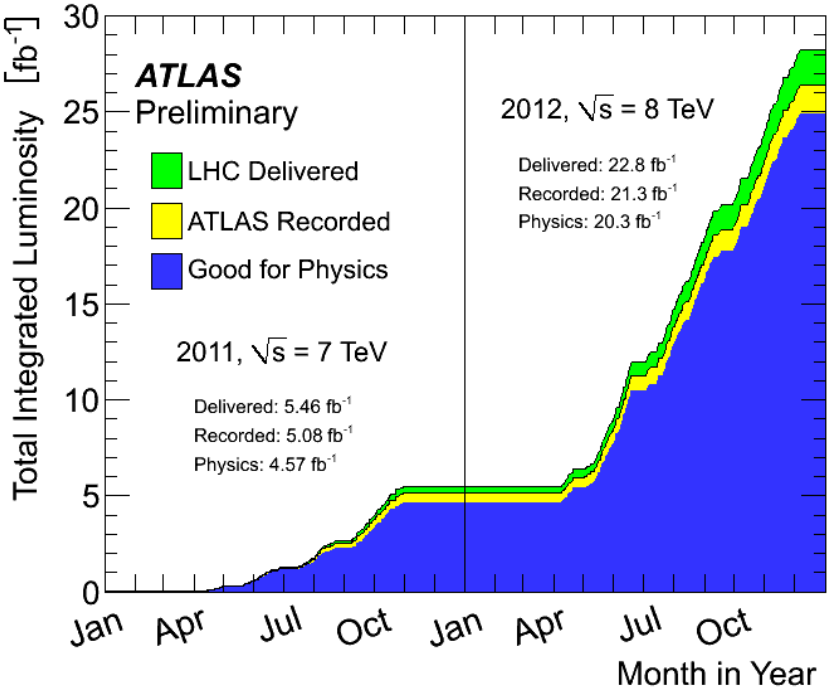
Wino
Higgsino

Chargino Mass matrix

NB: generally only **minimal** models are considered

LHC data-taking: 2011-12





- **Analyses use pp collision data collected in 2011 and 2012**
  - Many thanks to the LHC for delivery of so much data!

- Experiments performed well, operating with high efficiency
  - Challenging trigger and pile-up conditions (<μ>~10-35 in 2012)
  - Huge efforts in data quality, detector calibration, Grid computing etc – all essential for the final results

EW SUSY searches

ATLAS & CMS searches with EW SUSY interpretations

Lepton-based searches

CMS	2-4e/μ/τ	SUS-13-006
ATLAS	2τ	CONF-2013-028
ATLAS	2e/μ	CERN-PH-EP-2014-037
ATLAS	3e/μ/τ	arXiv:1402.7029 [hep-ex]
ATLAS	4e/μ/τ	CONF-2013-036*
CMS	3e/μ/τ	SUS-13-002*
CMS	$\mu^{\pm}\mu^{\pm}$	SUS-13-005
ATLAS (7 TeV)	eμ/eτ/μτ resonance	PLB 723 (2013) 15
ATLAS (7 TeV)	eμ/eτ/μτ	EPJC 72 (2012) 2040

Searches utilising $h \rightarrow b\bar{b}$

CMS	4b	SUS-13-022
CMS	WH	SUS-13-017
ATLAS	ebb/μbb	CONF-2013-093

Photon-based searches

ATLAS	γγ	CONF-2014-001*
ATLAS (7 TeV)	γ+b	PLB 719 (2013) 261*
ATLAS (7 TeV)	γ+l	CONF-2012-144*

(Meta)stable particle searches

ATLAS	Disappearing track	PRD 88 112006 (2013)
CMS	Long-lived particle	JHEP 07 (2013) 122* + EXO-13-006
ATLAS	Long-lived particle	CONF-2013-058
ATLAS (7 TeV)	Non-pointing γ	PRD 88 012001 (2013)

Not covered here: Mono-X searches
(X = jet, photon, W, Z, ...)
See presentation by Philippe Calfayan

* Production of squarks/ gluinos also considered

EW SUSY searches

ATLAS & CMS searches with EW SUSY interpretations

Primary interpretation: RPC EWKino/slepton, GMSB/GGM, RPV

Lepton-based searches

CMS	2-4e/μ/τ	SUS-13-006
ATLAS	2τ	CONF-2013-028
ATLAS	2e/μ	CERN-PH-EP-2014-037
ATLAS	3e/μ/τ	arXiv:1402.7029 [hep-ex]
ATLAS	4e/μ/τ	CONF-2013-036*
CMS	3e/μ/τ	SUS-13-002*
CMS	$\mu^{\pm}\mu^{\pm}$	SUS-13-005
ATLAS (7 TeV)	eμ/eτ/μτ resonance	PLB 723 (2013) 15
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Photon-based searches

ATLAS	γγ	CONF-2014-001*
ATLAS (7 TeV)	γ+b	PLB 719 (2013) 261*
ATLAS (7 TeV)	γ+l	CONF-2012-144*

Many results, not enough time...
Will focus on the most recent results

Not covered here: Mono-X searches
(X = jet, photon, W, Z, ...)
See presentation by Philippe Calfayan

(Meta)stable particle searches

ATLAS	Disappearing track	PRD 88 112006 (2013)
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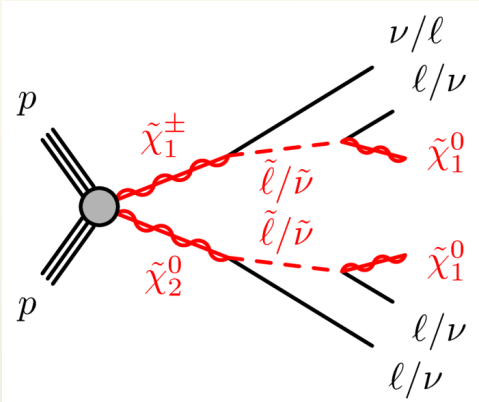
ATLAS (7 TeV)	Non-pointing γ	PRD 88 012001 (2013)

* Production of squarks/ gluinos also considered

Lepton-based wino/slepton searches

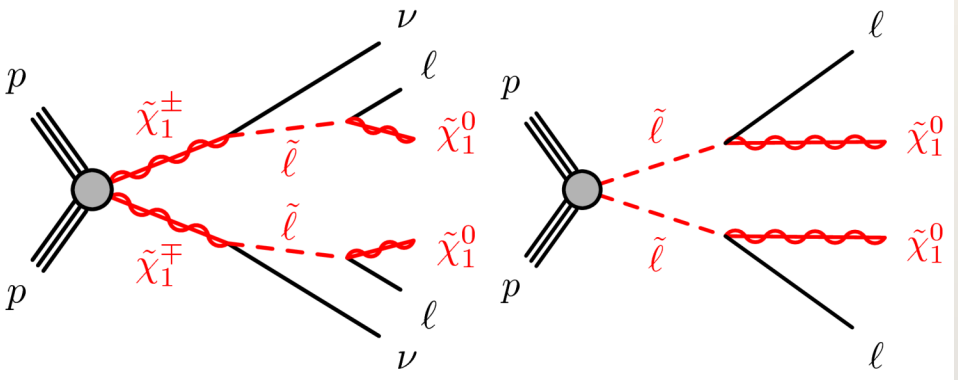
Searches rely on detection of multiple charged leptons (including τ)

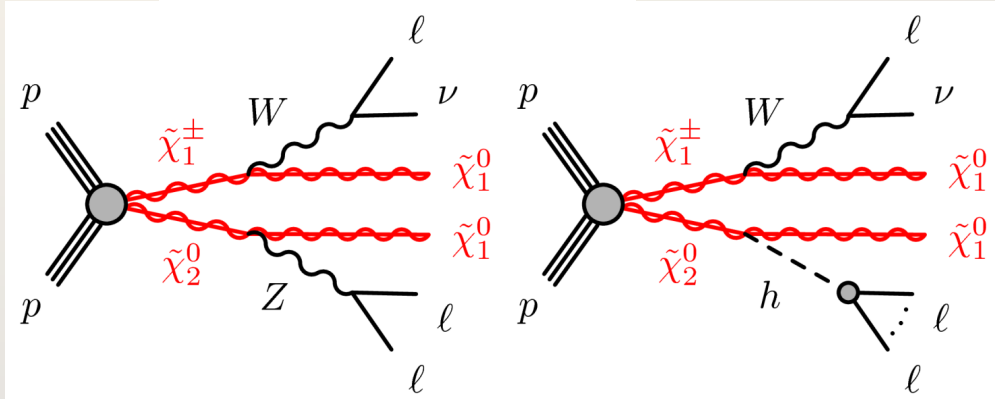
CMS	2-4e/μ/τ	SUS-13-006
ATLAS	2τ	CONF-2013-028
ATLAS	2e/μ	CERN-PH-EP-2014-037
ATLAS	3e/μ/τ	arXiv:1402.7029 [hep-ex]
ATLAS	4e/μ/τ	CONF-2013-036



Three-lepton signatures

Two-lepton signatures





Interpretations:

Simplified Models usually pure states, decays fixed to 100%

Phenomenological MSSM (pMSSM) 19 parameter specialisation of minimal SUSY models

GMSB/GGM specific model of SUSY breaking

NEW

ATLAS 2-lepton search

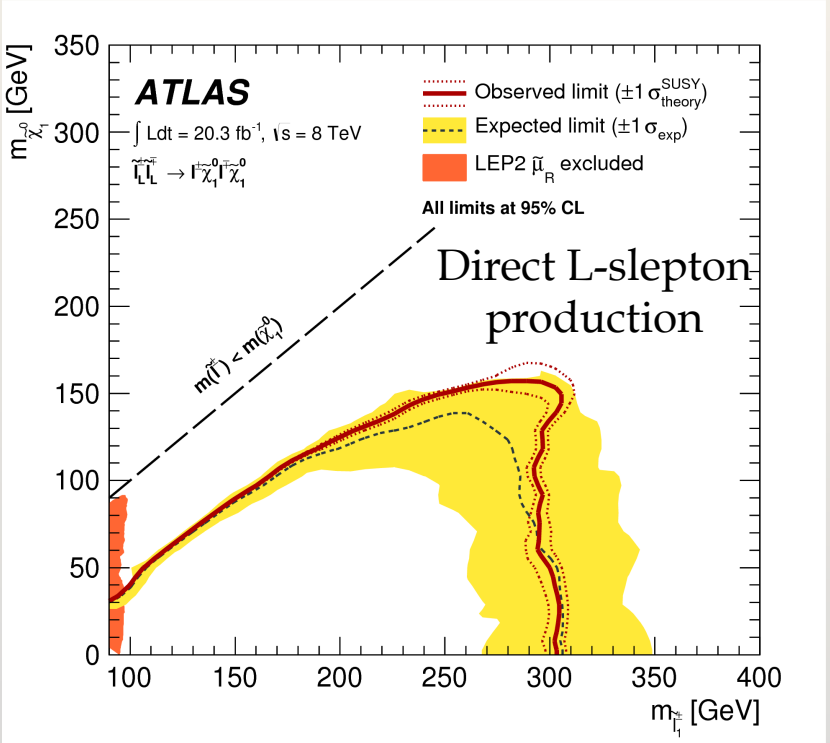
CERN-PH-EP-2014-037, to be submitted to JHEP

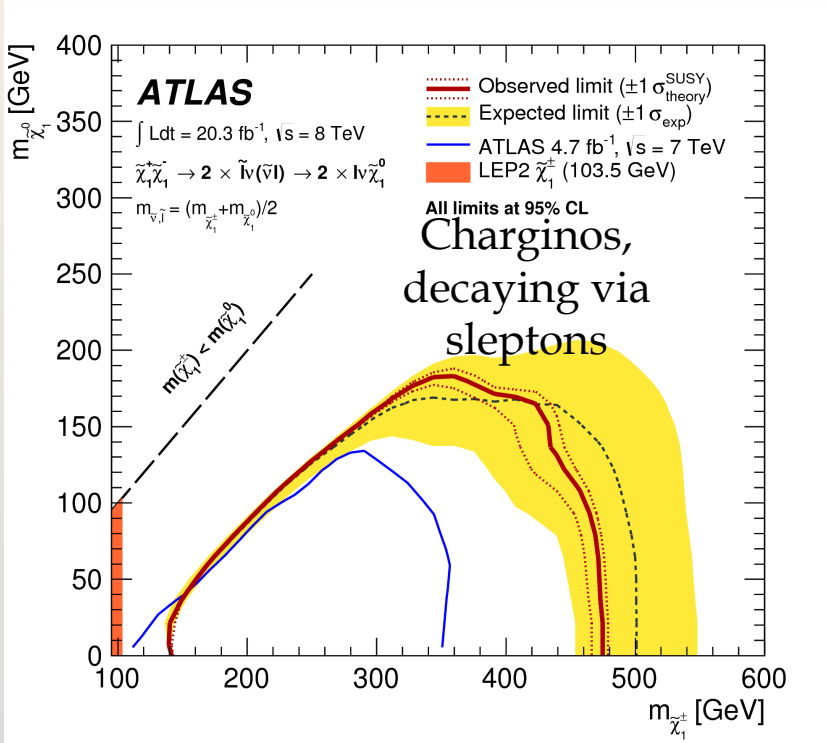
- Two leptons selected (ee, eμ, μμ) with opposite charges
- Signal regions targeting specific two-lepton signatures:
  - Slepton/chargino-like and WW-like regions
    - Rely on m_{T2} variable to reject WW and top background using kinematic edge at m_W

$$m_{T2} = \min_{\mathbf{q}_T}\left[\max\left(m_T\left(\mathbf{p}_T^{\ell 1},\mathbf{q}_T\right),m_T\left(\mathbf{p}_T^{\ell 2},\mathbf{p}_T^{\text{miss}}-\mathbf{q}_T\right)\right)\right]$$

    - Main background sources normalised with data in control regions
  - Z+jets-like region
    - Uses jet smearing in well-measured Z+jets events to reduce QCD modelling uncertainty

No significant excess seen ⇒ several models constrained





ATLAS 3-lepton search

NEW in 2014

arXiv:1402.7029 [hep-ex], submitted to JHEP

- Search for EW production of charginos & neutralinos
  - **3 leptons, up to 2 taus**
  - Different charge/flavor combinations explored in 5 signal regions
  - b-jet veto rejects ttbar

Signal region	SR0τa	SR0τb	SR1τ	SR2τa	SR2τb
Flavour/sign	$\ell^+\ell^-\ell$, $\ell^+\ell^-\ell'$	$\ell^\pm\ell^\pm\ell'^\mp$	$\tau^\pm\ell^\mp\ell^\mp$, $\tau^\pm\ell^\mp\ell'^\mp$	$\tau\tau\ell$	$\tau^+\tau^-\ell$
b-tagged jet	veto	veto	veto	veto	veto
$E_{\mathrm{T}}^{\mathrm{miss}}$	binned	> 50	> 50	> 50	> 60
Other	m_{SFOS} binned m_{T} binned (20 bins)	$p_{\mathrm{T}}^{3^{\mathrm{rd}}\ell} > 20$ $\Delta\phi_{\ell\ell'}^{\mathrm{min}} \leq 1.0$	$p_{\mathrm{T}}^{2^{\mathrm{nd}}\ell} > 30$ $\sum p_{\mathrm{T}}^{\ell} > 70$ $m_{\ell\tau} < 120$ m_{ee} Z veto	$m_{\mathrm{T2}}^{\mathrm{max}} > 100$	$\sum p_{\mathrm{T}}^{\tau} > 110$ $70 < m_{\tau\tau} < 120$
Target model	$\tilde{\ell}$ WZ-mediated	Wh-mediated	Wh-mediated	$\tilde{\tau}_L$-mediated	Wh-mediated

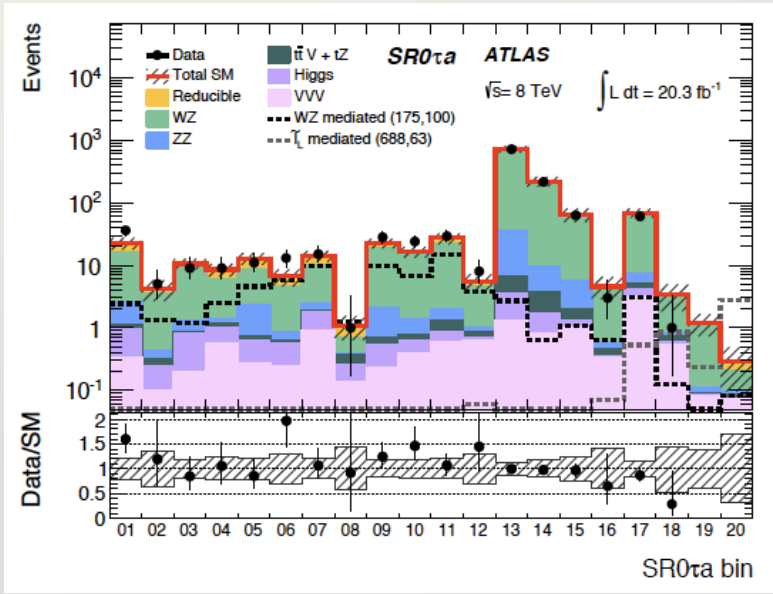
Enhanced sensitivity to compressed mass spectra

Charge/flavor requirement rejects WZ

Coverage of hadronic τ decays

- Background estimation
  - ttbar, Z+jets, W+jets estimated from data
    - Control regions invert lepton ID/ isolation on up to two leptons
    - Matrix method model
  - WZ, ZZ, ttV, tZ, VVV, higgs (≥3 isolated leptons) estimated using simulation
    - Checked in multiple validation regions

SR0τa observations



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    - Control regions invert lepton ID/ isolation on up to two leptons
    - Matrix method model
  - WZ, ZZ, ttV, tZ, VVV, higgs (≥3 isolated leptons) estimated using simulation
    - Checked in multiple validation regions
- No significant excess observed ⇒ limits set in benchmark models

Other signal region observations

	SR0τb	SR1τ	SR2τa	SR2τb
Total SM	3.8 ± 1.2	10.3 ± 1.2	6.9 ± 0.8	$7.2^{+0.7}_{-0.8}$
Data	3	13	6	5
p_0 (σ)	0.50	0.19 (0.86)	0.50	0.50
N_{exp}^{95}	$5.6^{+2.2}_{-1.4}$	$8.1^{+3.2}_{-2.2}$	$6.8^{+2.7}_{-1.9}$	$6.7^{+2.8}_{-1.8}$
N_{obs}^{95}	5.4	10.9	6.0	5.2

ATLAS 3-lepton search results

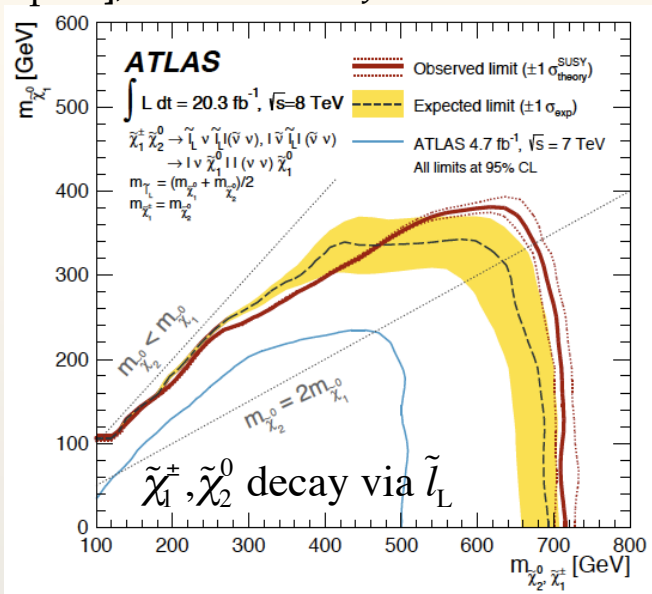
arXiv:1402.7029 [hep-ex], submitted to JHEP

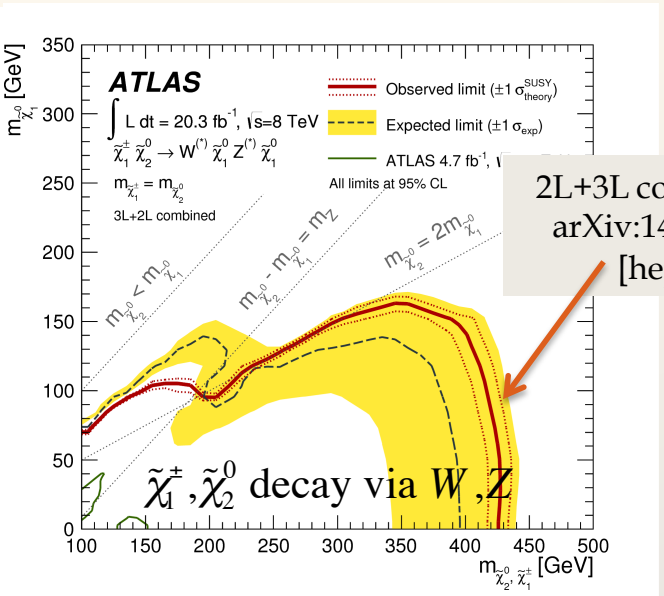
Strong constraints on many decay channels

Simplified models assume wino-like $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$

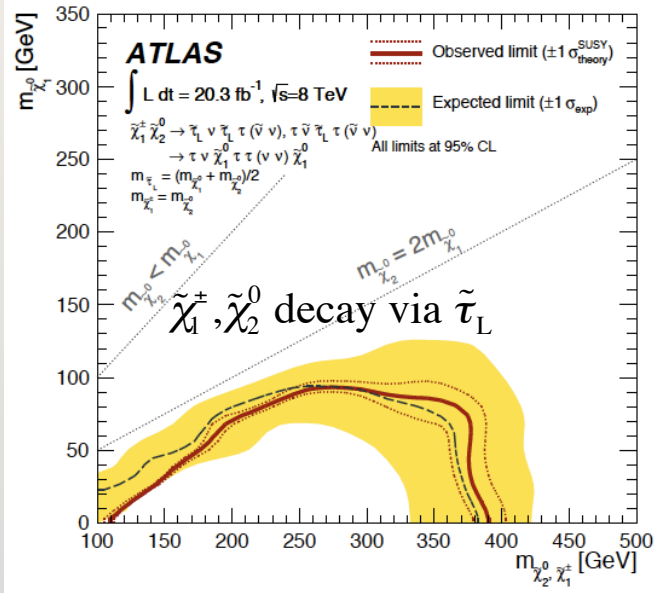
Reach up to m=700 GeV in the best cases

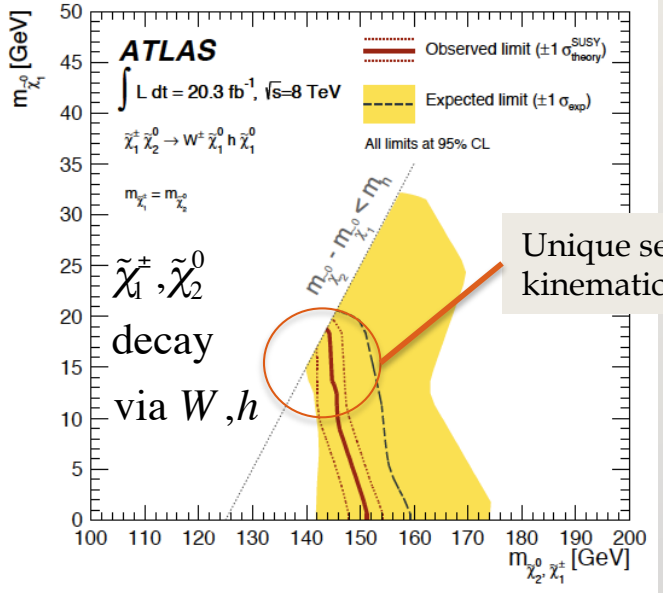
Constraints also in pMSSM models (M_2-μ planes for a set of M_1 values) with and without decays via intermediate sleptons





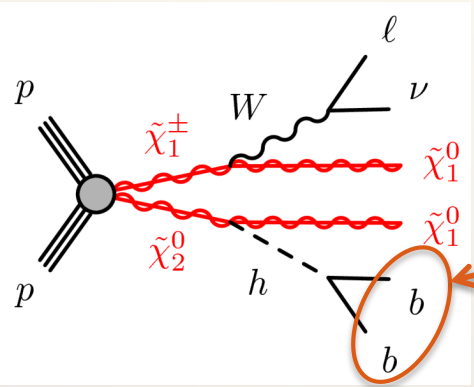
2L+3L combination arXiv:1403.XXXX [hep-ex]



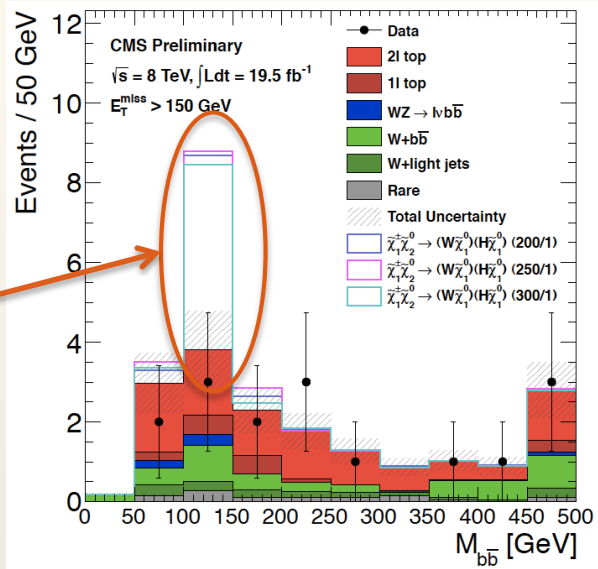


Unique sensitivity at kinematic limit

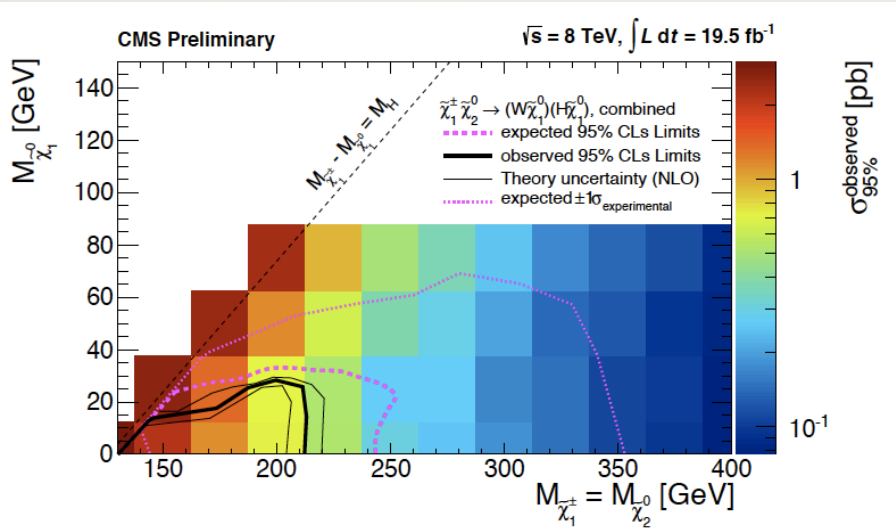
Further exploitation of higgs signatures



+ other W & h decay modes



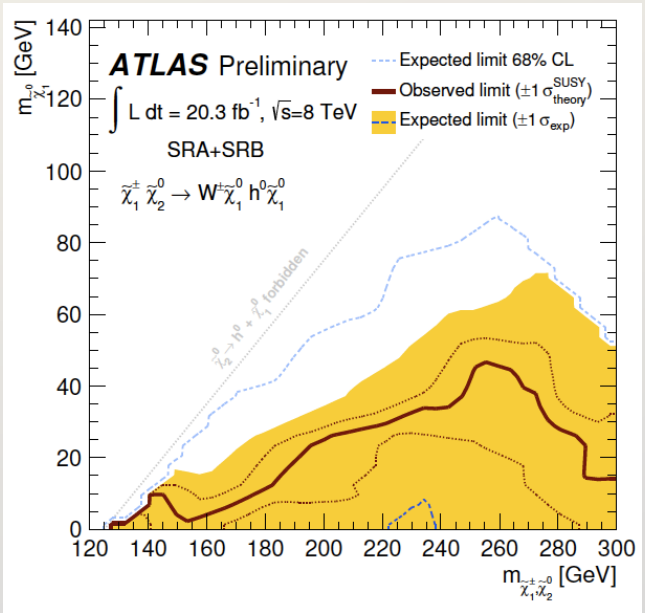
CMS PAS SUS-13-017



Only discovered in 2012, SUSY searches are already exploiting higgs boson reconstruction

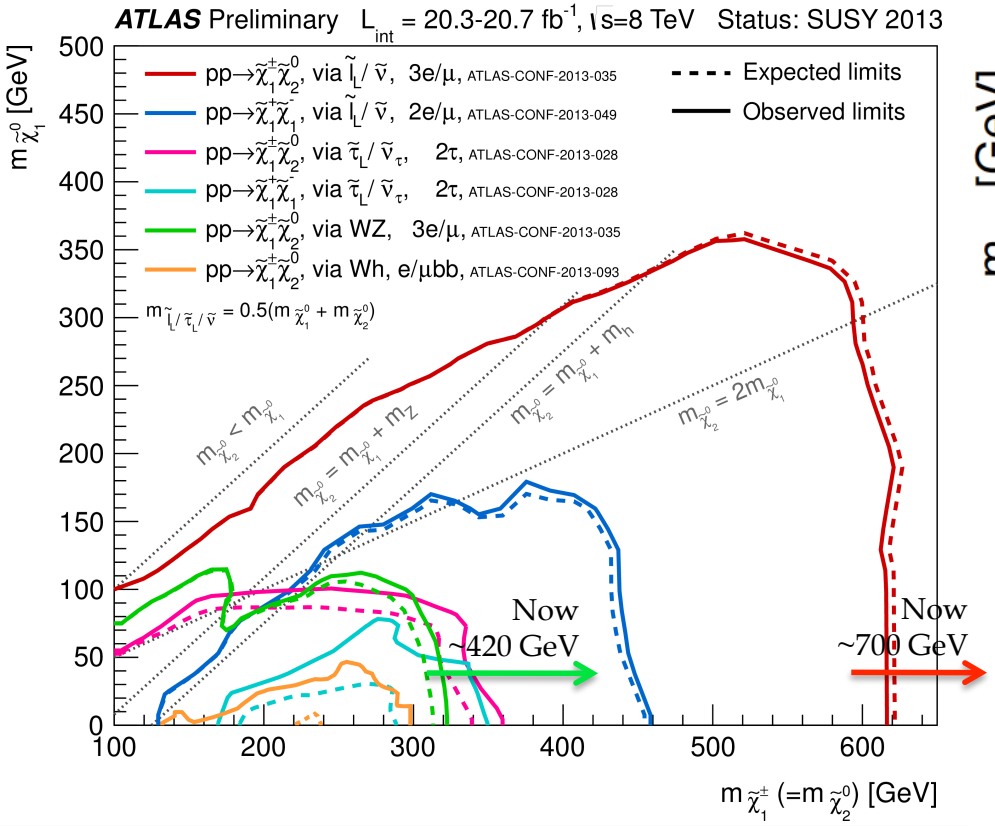
Constraints complementary to those from other EW SUSY signatures

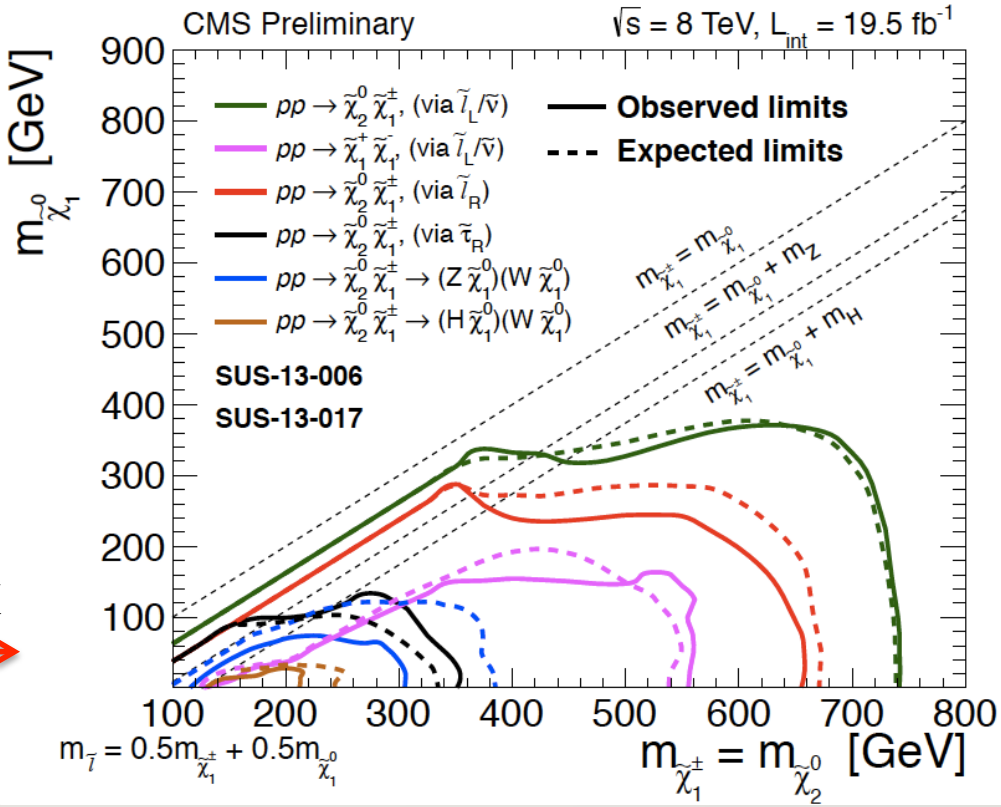
ATLAS-CONF-2013-093



Chargino/neutralino summary

Note: ATLAS plot does not yet include new 2L/3L results.
The new version will soon appear on the public twiki.





- Constraints highly dependent on available decay channel(s)
  - Strongest for decays via sleptons, weakest for decays producing higgs bosons
  - Compressed scenarios challenging

RPV searches

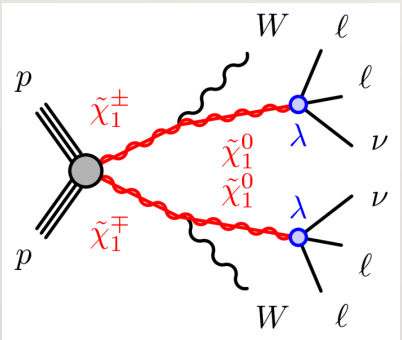
R-parity violation allows the LSP to decay via one or more RPV interactions

$$W_{LNV+BNV} = \epsilon_{ab}\left[\underbrace{\frac{1}{2}\lambda_{ijk}L_i^a L_j^b \bar{E}_k}_{LLE\ \text{term}} + \underbrace{\lambda'_{ijk}L_i^a Q_j^{xb}\bar{D}_{kx}}_{LQD\ \text{term}}\right] - \underbrace{\epsilon_{ab}\kappa^i L_i^a H_u^b}_{LH\ \text{term}} + \underbrace{\frac{1}{2}\epsilon_{xyz}\lambda''_{ijk}\bar{U}_i^x\bar{D}_j^y\bar{D}_k^z}_{UDD\ \text{term}}$$

Main focus for EW-rate production

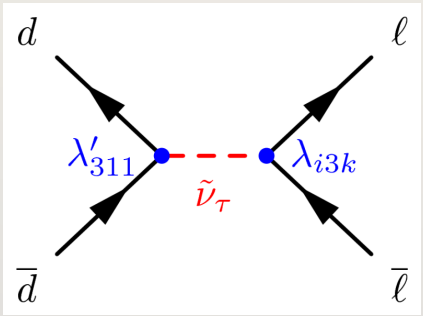
a)	ATLAS	4e/μ/τ	CONF-2013-036
b)	CMS	$\mu^{\pm}\mu^{\pm}$	SUS-13-005
c)	ATLAS (7 TeV)	eμ/eτ/μτ resonance	PLB 723 (2013) 15
d)	ATLAS (7 TeV)	eμ/eτ/μτ	EPJC 72 (2012) 2040

a)



Wino masses constrained up to 750 GeV

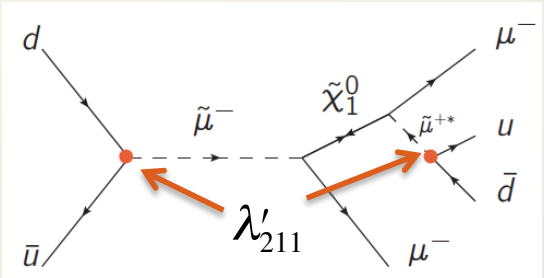
c)

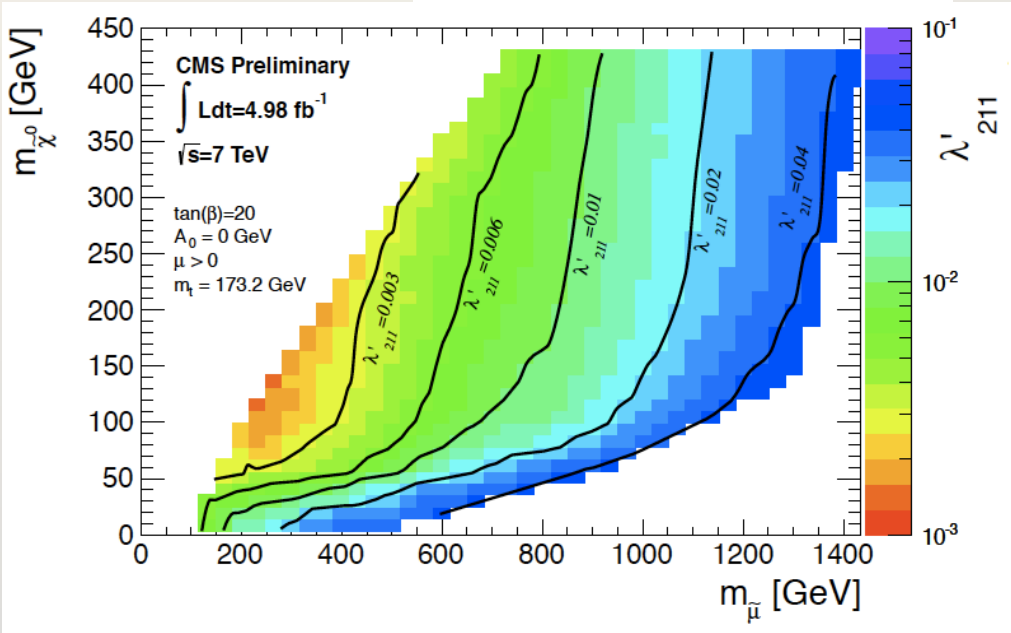


Sneutrino masses constrained up to 1610 GeV (λ'_{311}=0.10, λ_{132}=0.05)

b)

Single production of SUSY particles possible





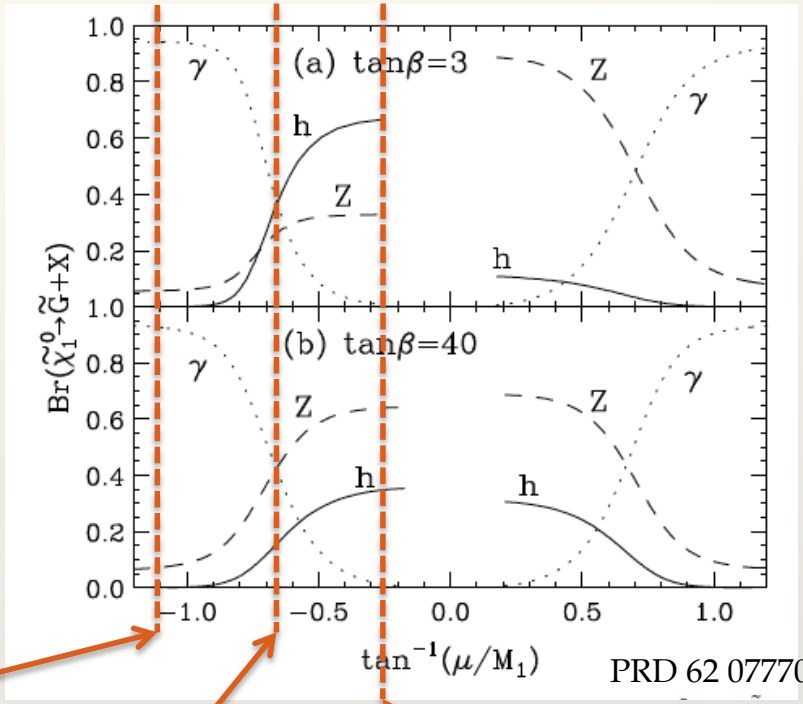
GMSB/GGM models

GMSB signatures are largely determined by the nature of the NLSP
⇒ decay to (very light) gravitino

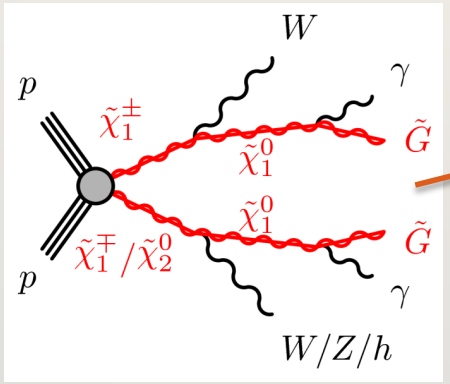
ATLAS	γγ	CONF-2014-001
CMS	3e/μ/τ	SUS-13-002*
CMS	4b	SUS-13-022
ATLAS (7 TeV)	γ+b	PLB 719 (2013) 261
ATLAS (7 TeV)	γ+l	CONF-2012-144

+ searches for metastable particles (coming up)

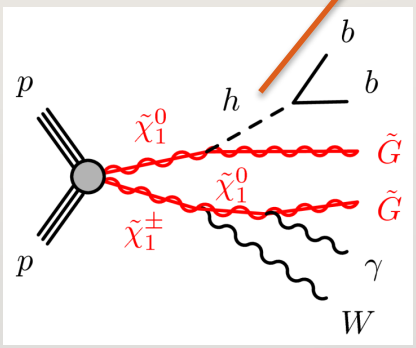
Eg neutralino decays can produce high p_T photons and/or higgs bosons



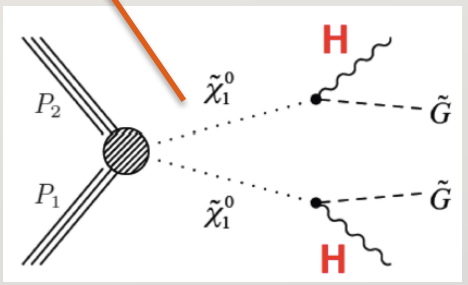
PRD 62 077702 (2000)



Bino-like NLSP



Mixed NLSP



Higgsino-like NLSP

ATLAS diphoton search

NEW in 2014

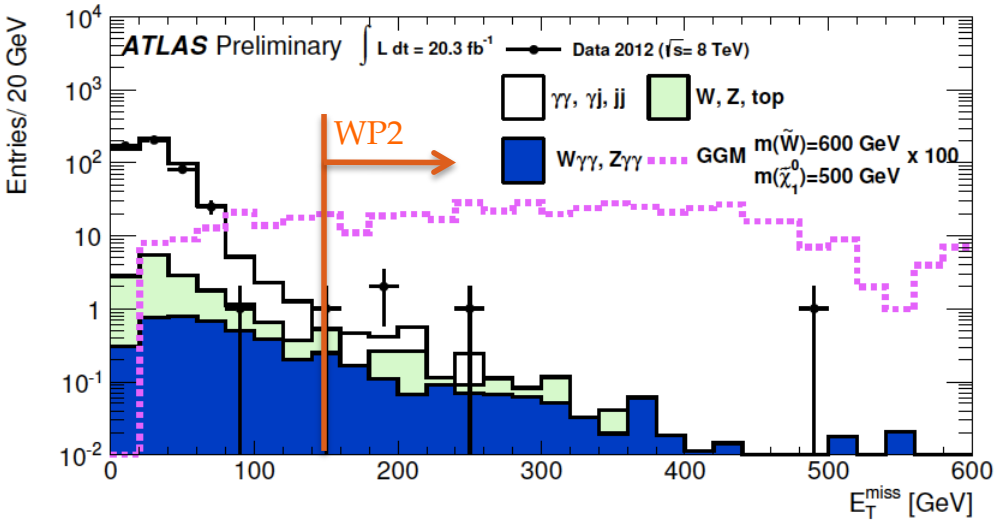
ATLAS-CONF-2014-001

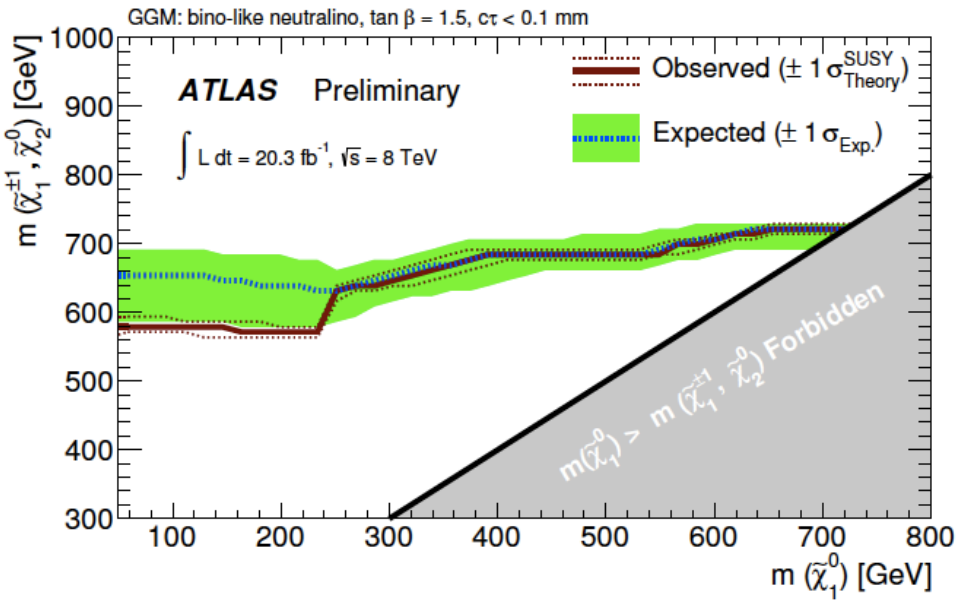
- Diphoton search, sensitive to bino-like NLSP (GGM)
  - No explicit requirements/vetoes on additional leptons or jets
  - Two EW production signal regions
    WP1: E_T^{miss} > 200 GeV and H_T > 400 GeV
    WP2: E_T^{miss} > 150 GeV and H_T > 600 GeV
    - + requirements on angles between E_T^{miss} and jets/photons

- Background estimation
  - QCD background estimated by inverting identification criteria on one photon
    - Normalised in E_T^{miss} < 60 GeV region
  - Electroweak background (W, Z, top) from e+γ control region
  - Irreducible (W/Z+γγ) from MC
    - W+γγ normalised in lγγ+E_T^{miss} control region

Interpretation in terms of wino production
(and gluino production, not shown here)

E_T^{miss} in WP2 region



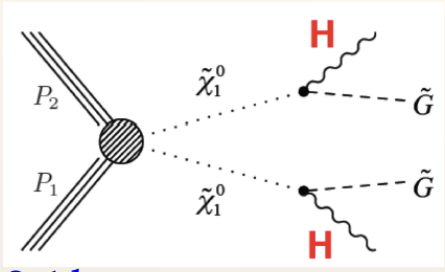


CMS 4b search

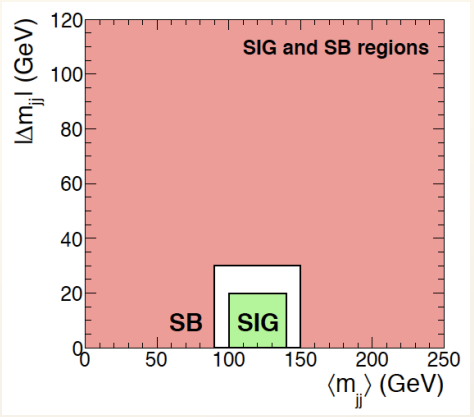
NEW in 2014

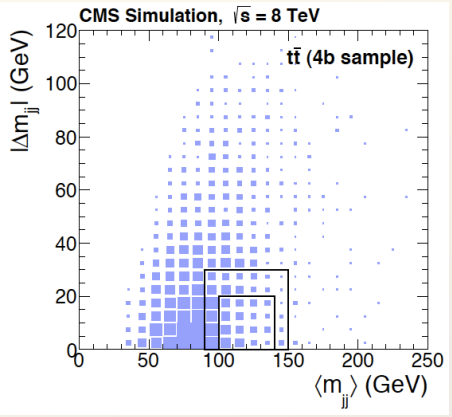
CMS PAS SUS-13-022

- GMSB-inspired search for two higgs bosons + E_T^{miss}

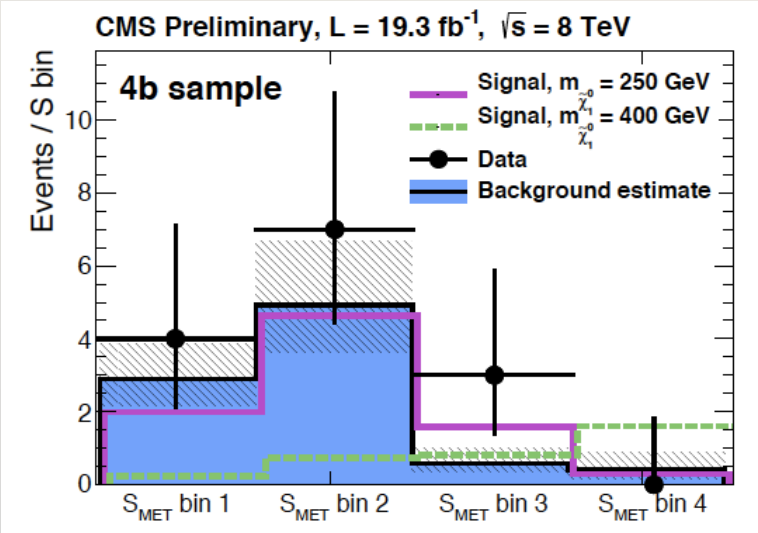


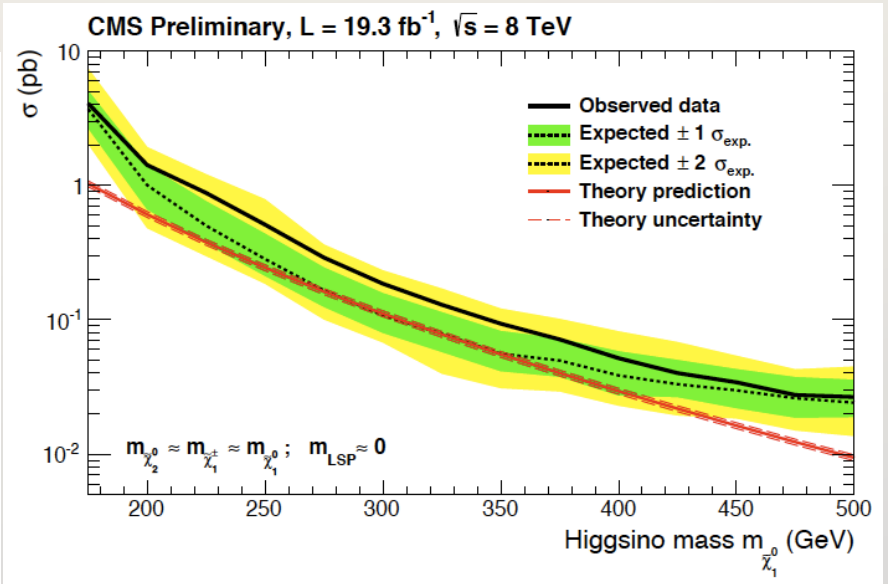
- Selection:
  - 4-5 jets, at least 2-4 b-tags
  - Binned E_T^{miss} significance (S_{MET})
  - Higgs reconstruction uses 4 most b-like jets, in pairs with the smallest $|\Delta m_{jj}|$
  - $100\ \text{GeV} < \langle m_{jj} \rangle = \frac{1}{2}\left(m_{jj,1} + m_{jj,2}\right) < 140\ \text{GeV}$





- Main background: semileptonic ttbar
  - Estimated using (nearly) inverted $|\Delta m_{jj}|$, $\langle m_{jj} \rangle$ selection in ABCD-like method
- Likelihood fit in 6 selections * 4 S_{MET} bins



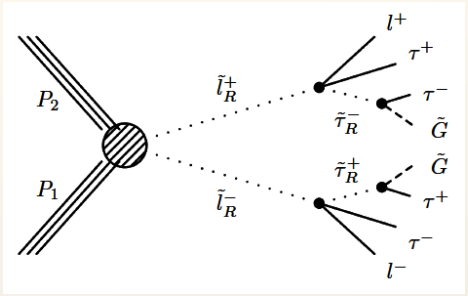


No exclusion of any higgsino mass due to slight data excess

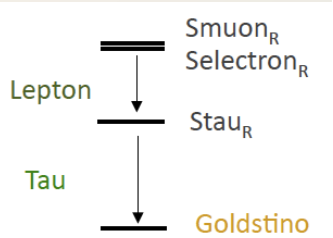
CMS 3-lepton search

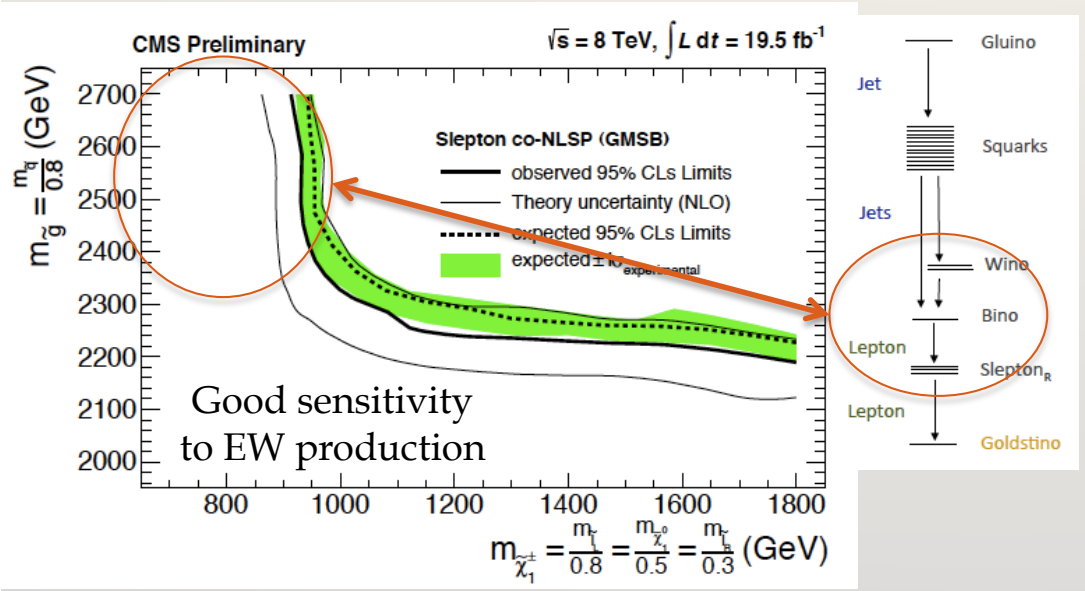
CMS PAS SUS-13-002

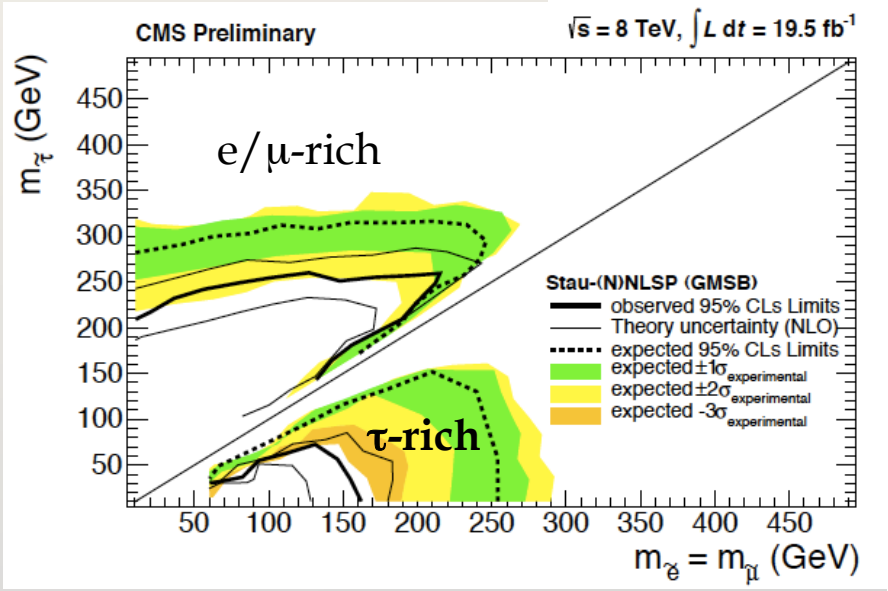
- Selection: **≥3 leptons, max 1 τ**, data split into exclusive channels, based on
  - Number of opposite-sign same-flavor pairs (0-2)
  - Presence/absence of $Z \rightarrow l^+l^-$ candidate
  - # b-jet (0, >0) and τ (0,1) candidates
  - H_T from jets (< or > 200 GeV), E_T^{miss} (binned)



- Background estimation
  - Drell-Yan & internal photon conversions estimated from data control regions:
    - 2 leptons + isolated track, "loose" tau or photon
  - Other background sources estimated using MC
    - Top and WZ: sophisticated corrections to data for E_T^{miss}, lepton isolation, N_{jets}







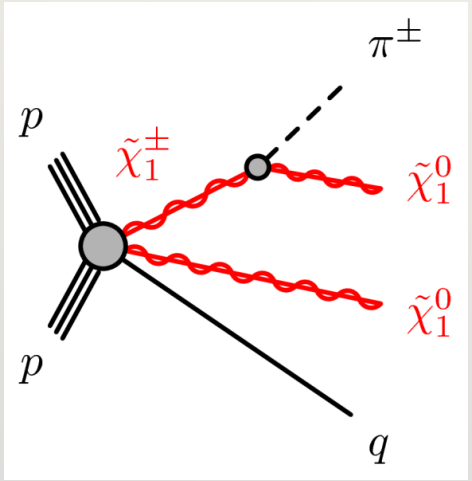
Metastable/long-lived searches

- SUSY particles may travel significant distances before they decay
  - Extremely degenerate spectra (eg anomaly mediated symmetry breaking, AMSB)
  - Weak coupling to gravitino LSP in GMSB/GGM models
  - Small RPV couplings (so far explored only for strong production)

a)	ATLAS	Disappearing track	PRD 88 112006 (2013)
b)	CMS	Long-lived particle	JHEP 07 (2013) 122 + EXO-13-006
c)	ATLAS	Long-lived particle	CONF-2013-058
d)	ATLAS (7 TeV)	Non-pointing γ	PRD 88 012001 (2013)

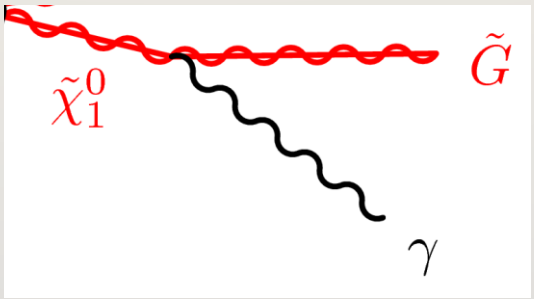
- Challenging, unusual signatures
  - Anomalously high charge deposition (dE/dx)
  - Delayed/out-of-time signals
  - Momentum misaligned wrt primary vertex (non-pointing)
  - High-mass secondary vertices, etc

a)



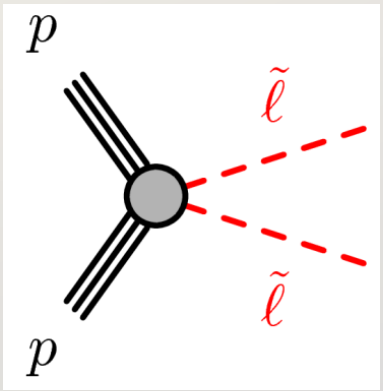
AMSB,
wino-like co-LSPs

d)



GMSB, bino-like LSP

b)
c)



GMSB,
slepton NLSP

CMS HSCP search

JHEP 07 (2013) 122

Heavy Stable Charged Particle

GMSB mass limits

Direct production only: $m_{\tilde{\tau}} > 339$ GeV

Direct+indirect: $m_{\tilde{\tau}} > 500$ GeV

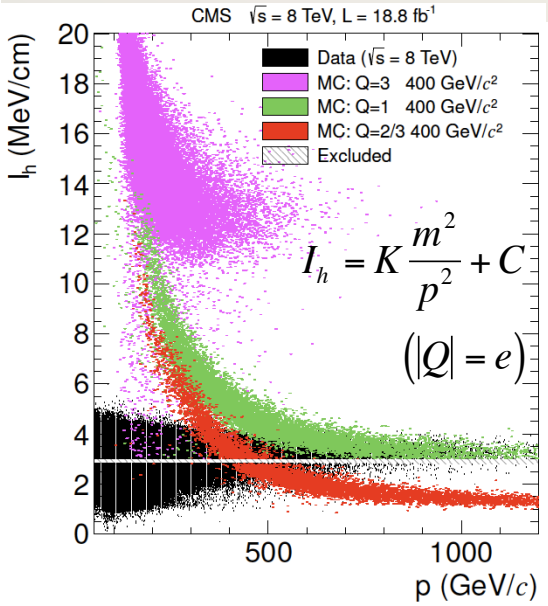
- GMSB predicts that **slepton NLSPs** may be detector-stable
- **5 strategies** for reconstructing HSCPs
  - Best results for sleptons combine inner tracker & muon detector information
- Three principal discriminating variables
  - **Track p_T** > 70 GeV
  - **1/β** > 1.225, from time of flight in muon system
  - I_h > 0.125, measure of ionisation in inner tracker

ABCD-like background estimation

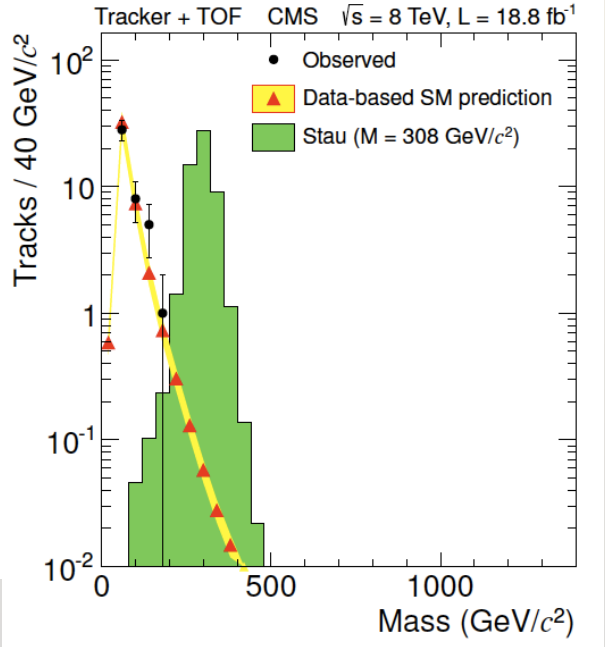
$$N_{\text{bkg}}(m) = \frac{N_{\text{pass } p_T} N_{\text{pass } 1/\beta} N_{\text{pass } I_h}}{N^2_{\text{fail all three}}}$$

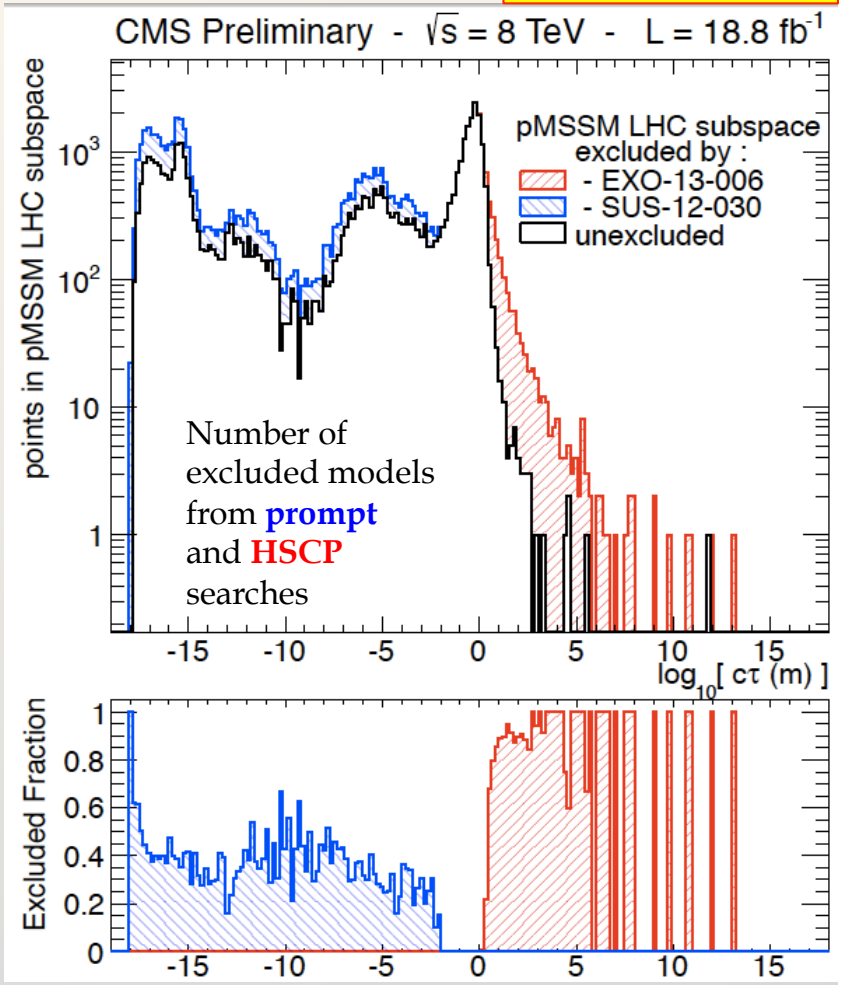
Meta-stable chargino reinterpretation in **CMS PAS EXO-13-006**

NEW in 2014



I_h in data & various signal models

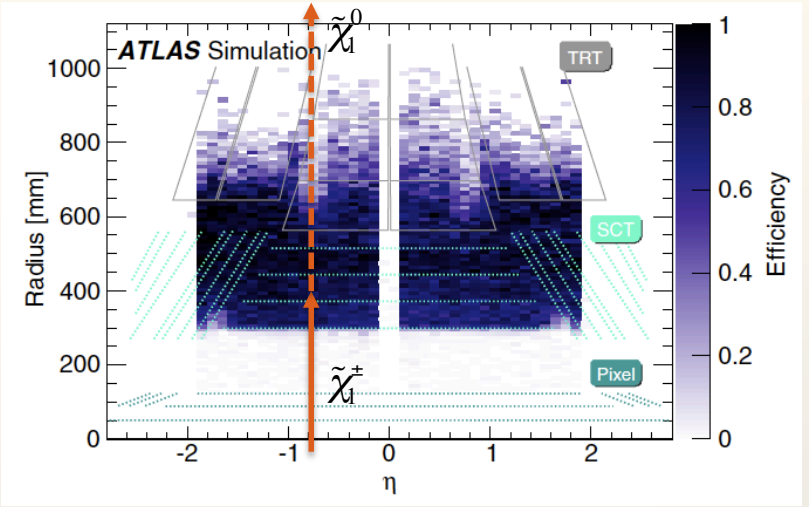




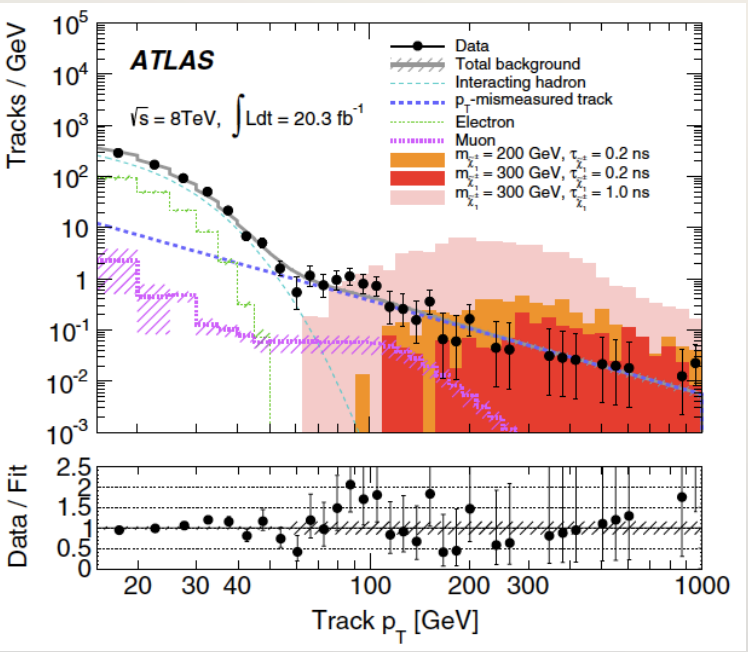
ATLAS disappearing track search

PRD 88 112006 (2013)

- In AMSB, LSP is nearly pure wino neutralino
  - Chargino has $\tau \sim O(\text{ns})$ due to small (~160 MeV) chargino/neutralino mass splitting
  - $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 \pi^{\pm}$ soft pion not reconstructed ⇒ track "disappears"
- Trigger on jet from initial state radiation
  - $+E_T^{miss}$ requirement



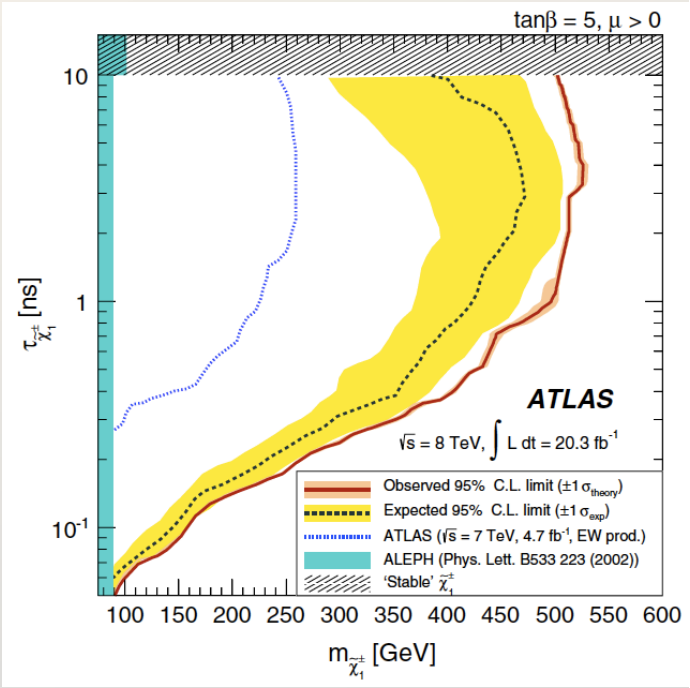
Signal efficiency vs η and r



Background

- **p_T-mismeasured tracks** dominant at high p_T Estimated using high-impact-parameter tracks
- **Interacting hadrons** and unidentified **lepton tracks** also estimated using data

Limits placed on LSP properties in mass-lifetime and mass-Δm planes



Conclusion

- Coverage of EW production and decay of SUSY particles in ATLAS & CMS searches is extensive
  - **Wino, higgsino** production with bino-like LSP
  - **GMSB/GGM** scenarios
  - **R-parity violation** and **long-lived particles**

- Significant constraints on EW SUSY sector, many loopholes being closed

- For more information on these and further SUSY searches, see

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults