SUSY searches - electroweak production

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On behalf of the ATLAS and CMS collaborations
LPNHE/CNRS

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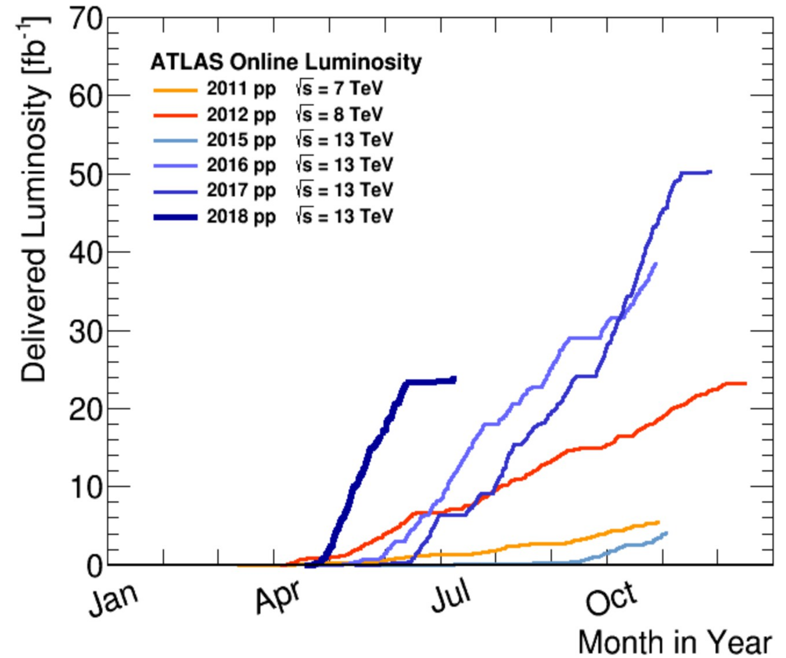
Why SUSY? Why electroweak SUSY?

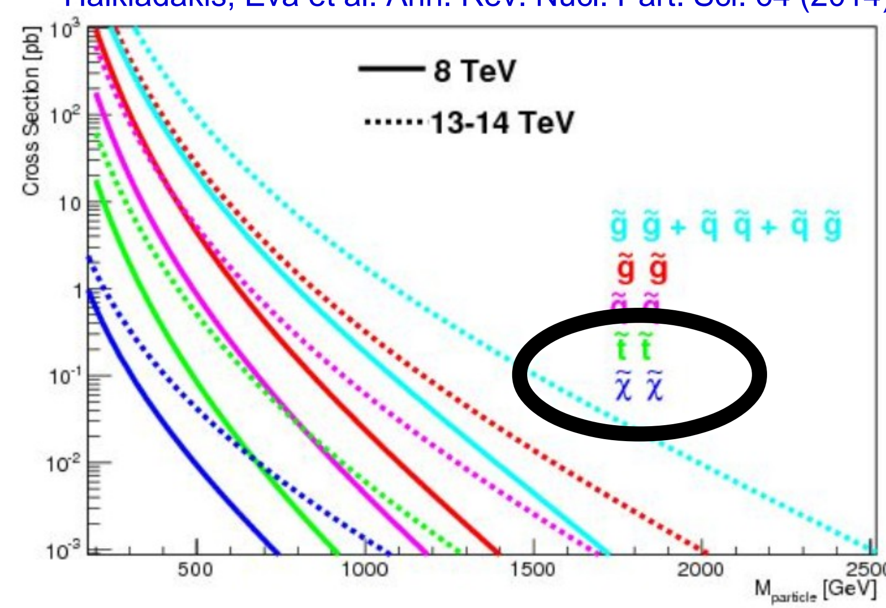
- SUSY: a framework, many realizations – not magic

- Why SUSY?
  - Provide a dark matter candidate
  - Unify the fundamental forces at high energies
  - Solves the fine-tuning problem of the Higgs mass

- So far all the inclusive/wide reach searches performed have found no SUSY
  - No more big jumps in luminosity/energy in the near future

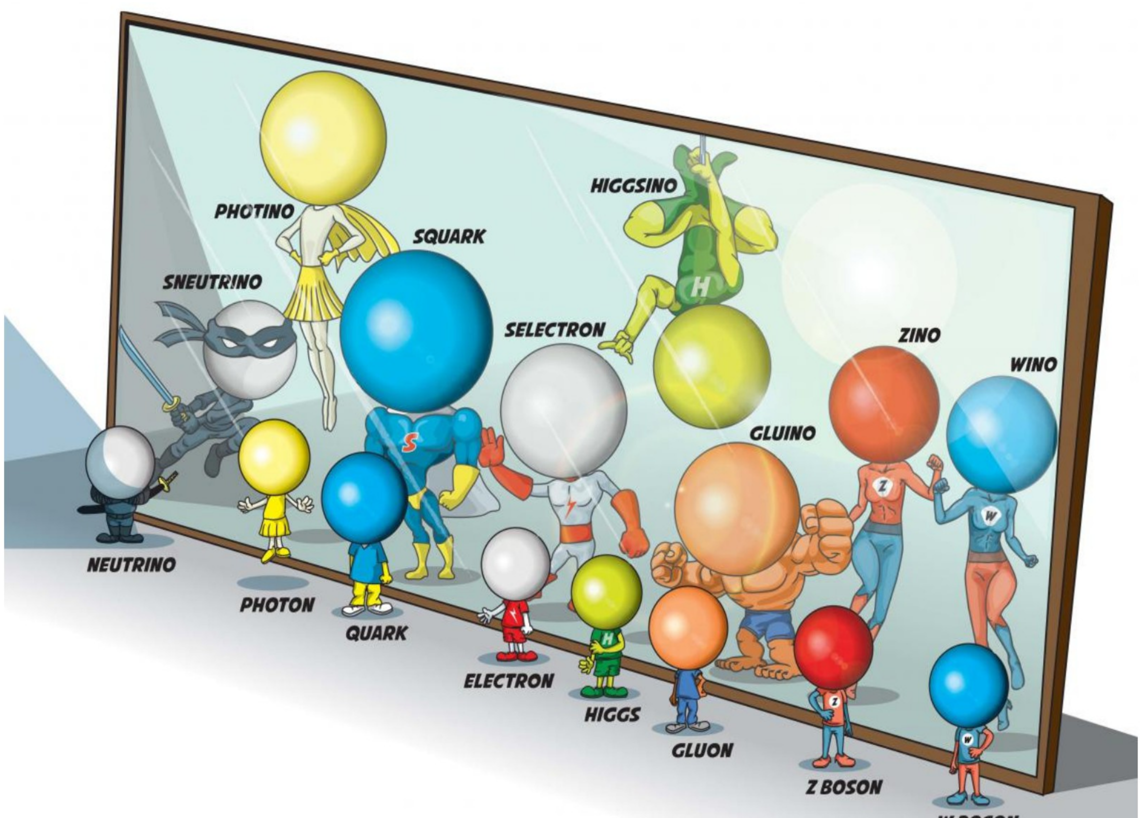


Halkiadakis, Eva et al. Ann. Rev. Nucl. Part. Sci. 64 (2014)



Why SUSY? Why electroweak SUSY?

- Do not panic: we can push the field still!
  - New/advanced performance tools
  - Look for lower cross-section processes: electroweak SUSY
    - Latest strong SUSY limits ~TeV scale, thus making electroweak production promising and important probe to search for SUSY at the LHC



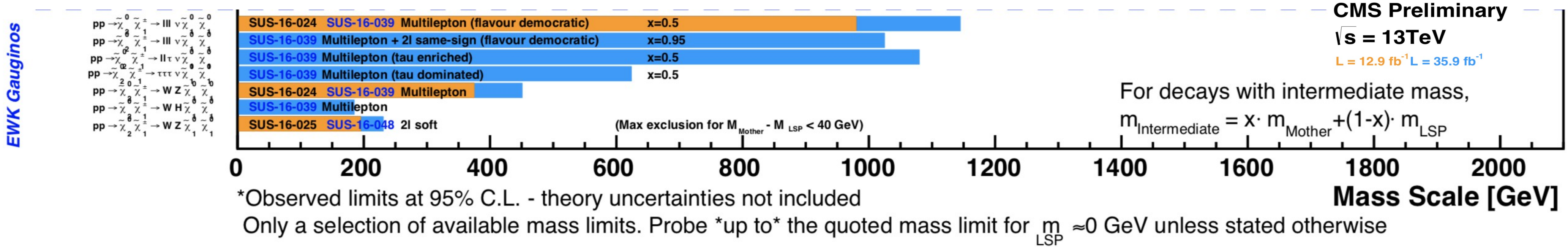
Electroweak Sector:

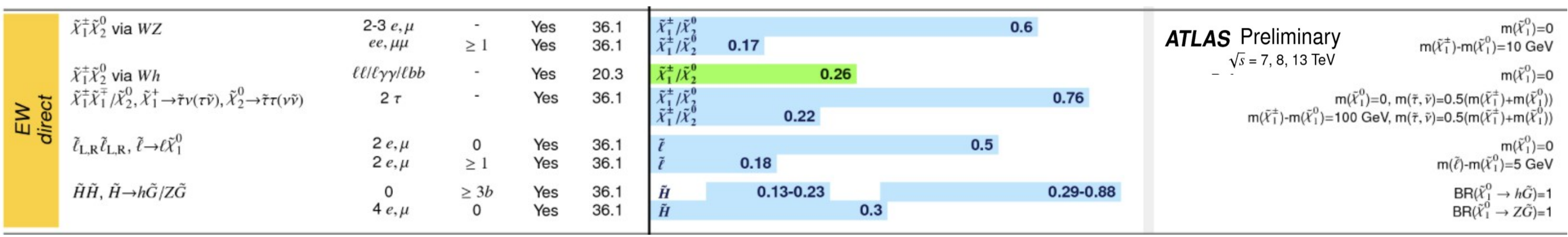
$\tilde{B}$ (bino), $\tilde{W}$ (wino), $\tilde{H}$ (higgsino)

mixing

$\tilde{\chi}_i^{\pm}$ w/ $i \in [1,2]$ (charginos)
$\tilde{\chi}_i^{0}$ w/ $i \in [1,4]$ (neutralinos)

Why SUSY? Why electroweak SUSY?





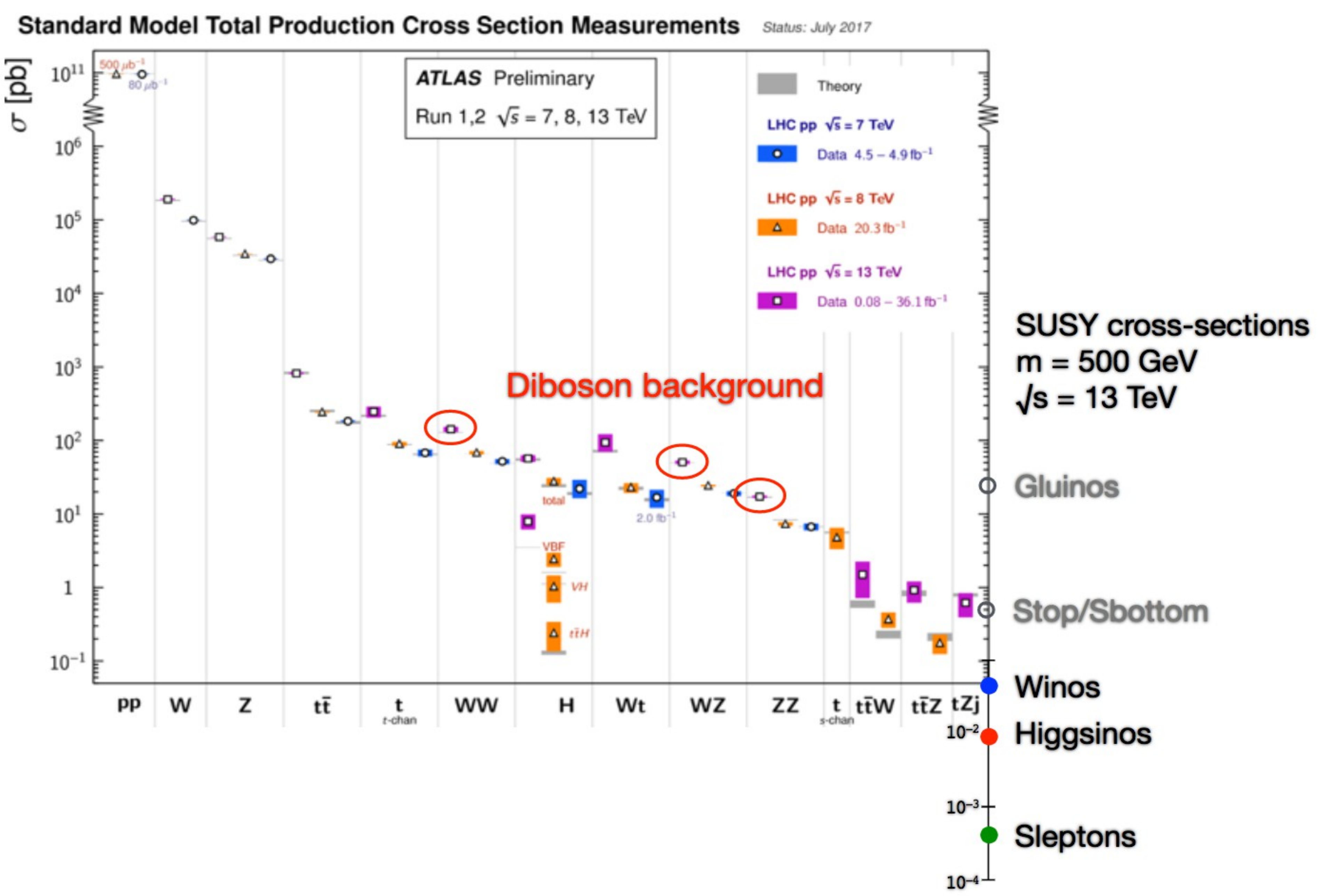
- Huge effort from both collaborations to looks at the Run-2 data for EWK SUSY
  - Reaching sensitivity to the TeV scale

- EWK SUSY gives a high number of potential signatures: essentially anything from SM + missing transverse energy

- Impossible to cover all the available results
  - I will try to give an overview of what is available: classical signatures and compressed scenarios but focus only on new results wrt SUSY2017

- More details in the parallel sessions, in particular on Tuesday afternoon

A “typical” EWK SUSY search



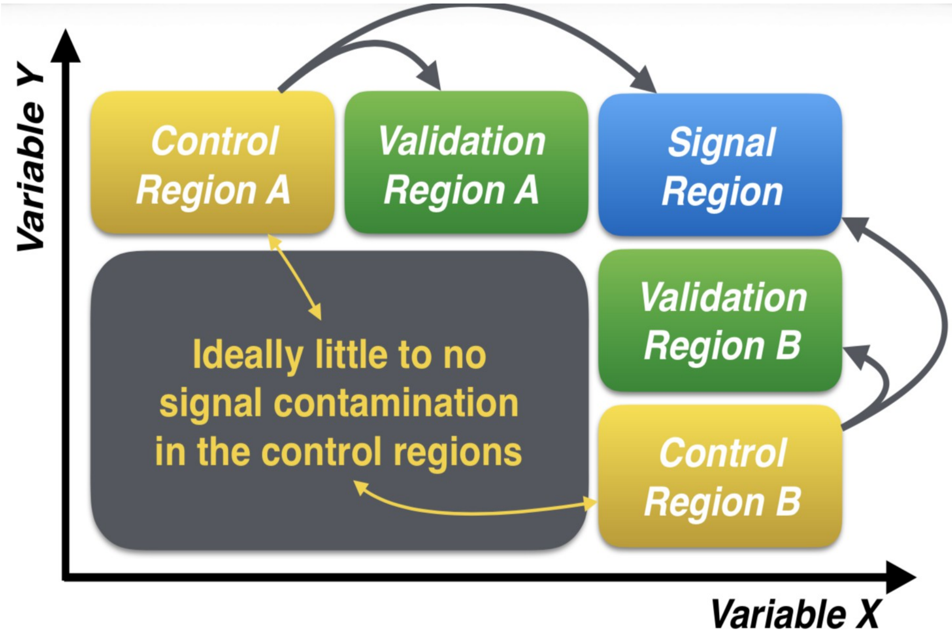
A "typical" EWK SUSY search

- Usually searches are optimized either for:
  - Discovery: inclusive cut & count signal regions (SRs)
  - Exclusion: more complex, involving shape-fits, MVAs, etc

- Typical handles on new physics

Object counting *(soft) leptons, (b-) jets, MET…*	Kinematic variables H_T, m_{eff}, m_T, m_{T2}…	Composite objets/event shapes *razor variables, JSS, recursive jigsaw reconstruction*

- Background estimation approach:
  - For each important process define a representative control region (CR)
  - Fit the background to data simultaneously in all CRs to get the scale factors (SF)
  - Validate these SFs in the validation regions (VR) then use them in the SRs



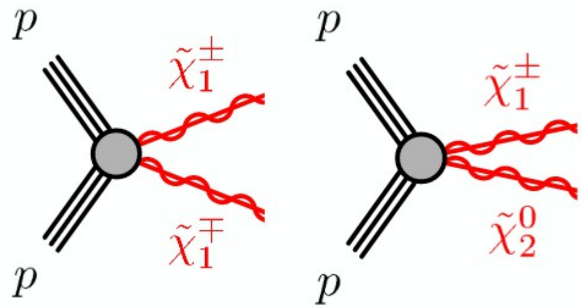
*Check Jesse Liu's talk

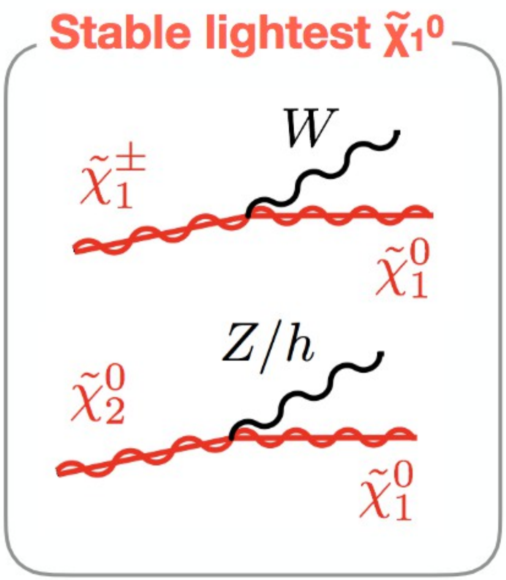
A “typical” EWK SUSY search

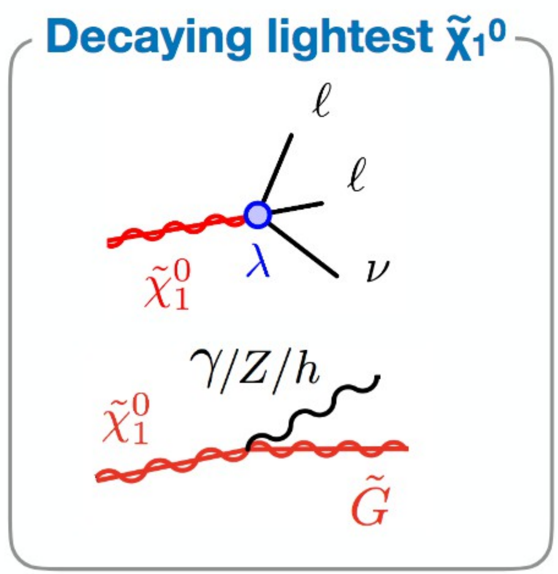
- A word regarding results and interpretations:
  - Signal models are important to interpret our results
    - Can explain a discrepancy in an existing analysis
  - Currently almost exclusively Simplified Models are used:
    - Limited number of free parameters
    - Relatively easy to present results (2-D scans in particle masses)
    - Typically assuming 100% branching ratios for the considered decay chains
    - But
      - Unrealistic situation: “Do not confuse limits in simplified models with real limits on SUSY masses” [Sven Heinemeyer, LHCP2018]

Classical SUSY EWK signals

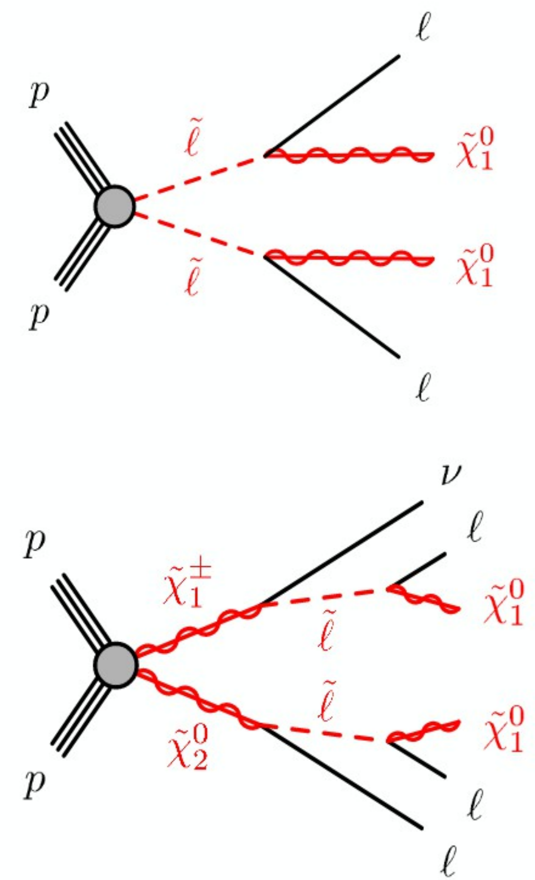
Neutralino and chargino production







slepton production



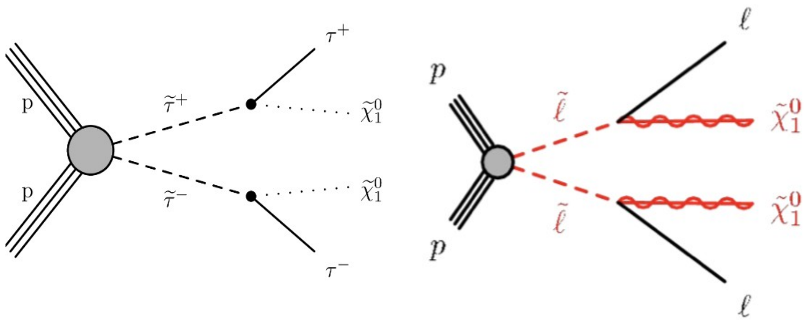
- Cleanest signatures: leptons & MET (similar to SM EWK)
- Main irreducible background: dibosons
- Jet vetos common to reduce ttbar backgrounds

- *Reminder 1: neutralinos and charginos are mixings of the Higgsinos and the electroweak boson's partners*
- *Reminder 2: Stable lightest supersymmetric particle (LSP) $\tilde{\chi}_1^0$ → Dark matter candidate*
- *Long lived particles searches will be covered by Laura Jeanty*

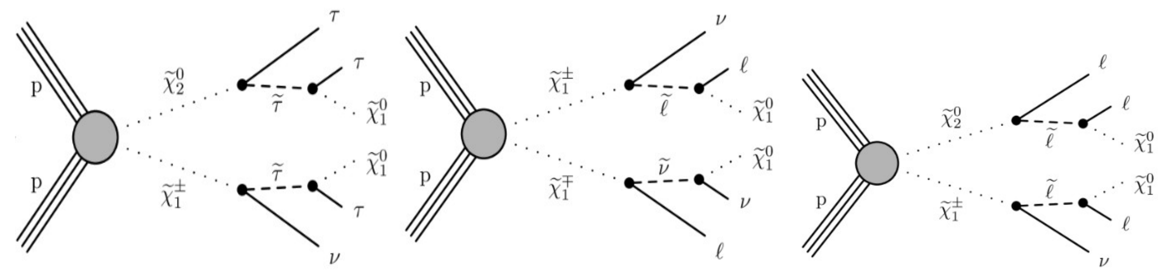
Classical SUSY EWK signals

Summary sleptons searches:

Direct slepton pair production



Slepton-mediated chargino/neutralino decay



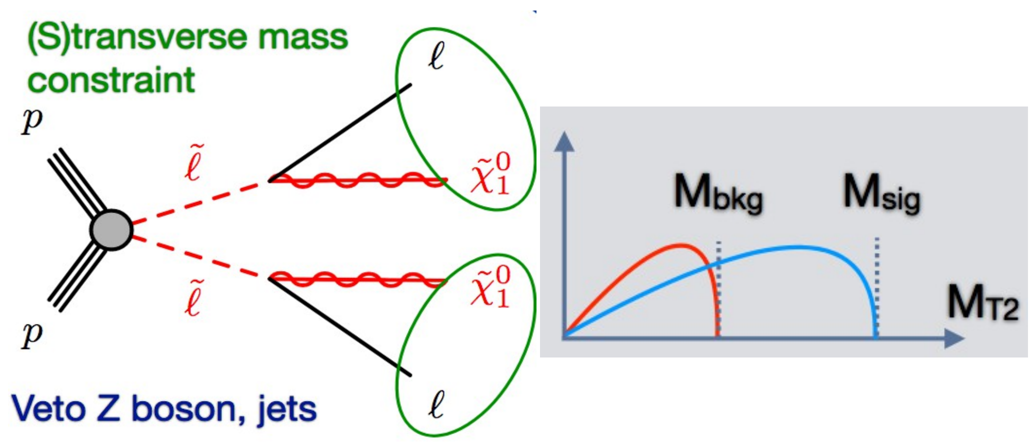
Motivated by bino co-annihilation, g-2 oriented scenario etc.

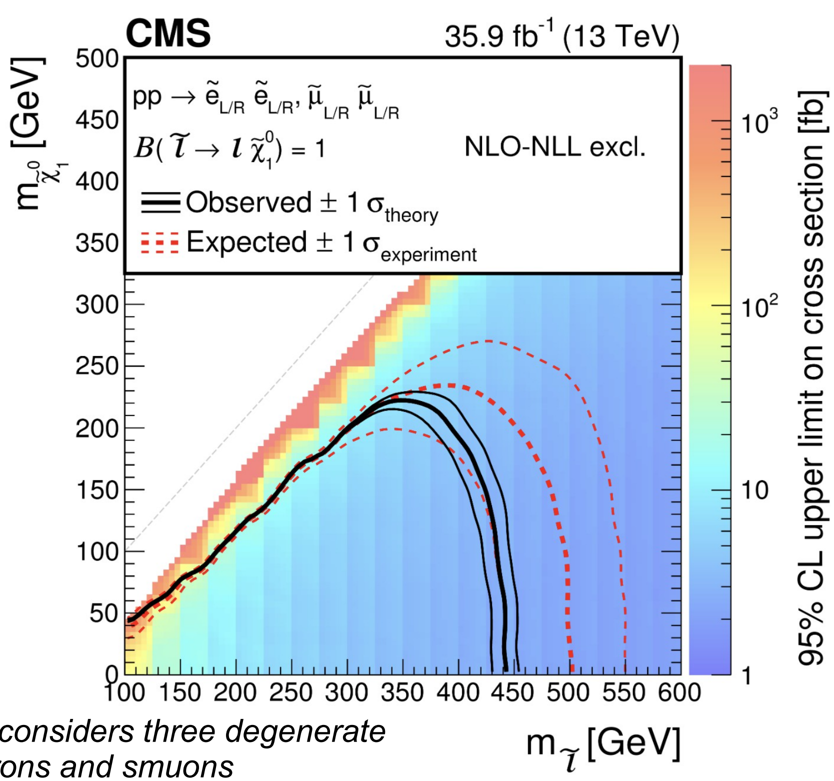
Topology	Final state	ATLAS	CMS
Direct light slepton	2L0J + MET	**1803.02762 (~500 GeV in slepton mass)**	1806.05264 (~290/400 GeV in left/right handed slepton mass) **SUS-17-008 (resonant s-lepton production)**
	2 soft leptons + MET	Phys. Rev. D 97, 052010 (2018) (~200 GeV for ΔM~10 GeV)	
Direct stau	2 taus + MET	Phys. Rev. D 93, 052002 (2016)	1807.02048 Upper limit 0.66 pb on σxBR
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm/\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via light slepton	2L0J/3L+MET	**1803.02762 (~750 GeV limit in m($\tilde{\chi}_1^\pm$,$\tilde{\chi}_2^0$))**	**1807.07799 (2L)** JHEP 03 (2018) 166 (3L+2LSS) ~800 GeV for $\tilde{\chi}_1^\pm$ and 320 GeV for $\tilde{\chi}_2^0$
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm/\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via stau	2 taus + MET	Eur. Phys. J. C 78 (2018) 154 (~1.1 TeV limit in m($\tilde{\chi}_1^\pm$,$\tilde{\chi}_2^0$)), had. taus	1807.02048 Up to 560 GeV depending on config.

Searching for light sleptons

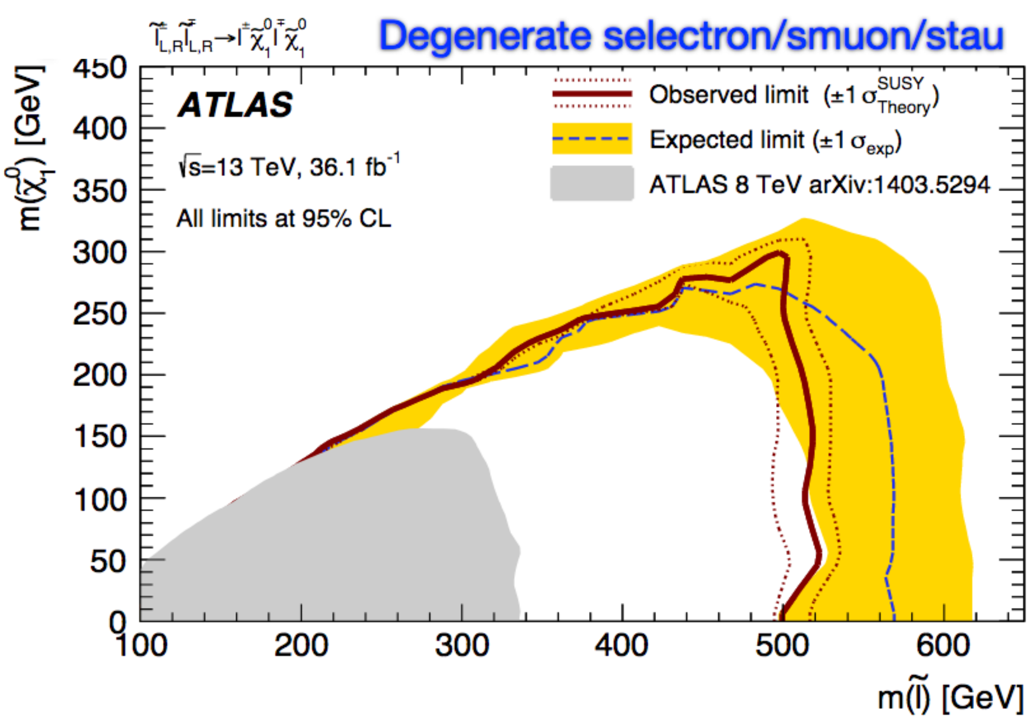
CMS: 1806.05264 ATLAS: 1803.02762

- Selected dileptons: opposite charge, same flavour
- Veto in hadronic jets and m_{T2} selection:
  - Upper bound on mass of pair-produced particles each decaying to l+LSP
  - m_{T2} > 90 GeV suppresses WW
- Search binned in MET (mll and m_{T2}) for CMS (ATLAS)
- Main backgrounds: ttbar, WW
- No excess found





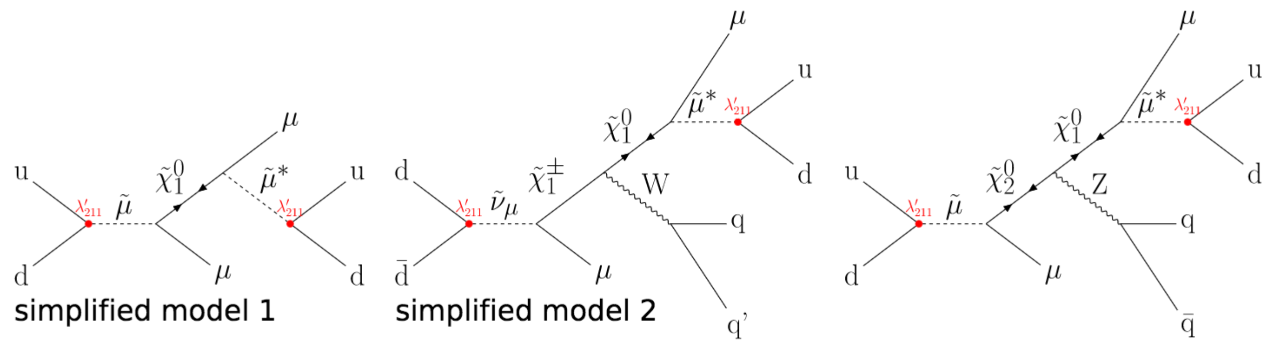
*CMS considers three degenerate selectrons and smuons



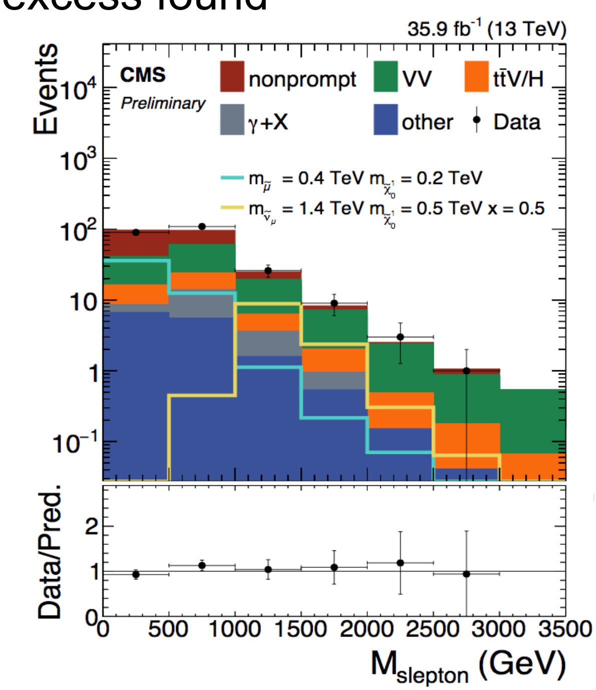
*Check Daniel Antrim and Alexis Kalogeropoulos' talks

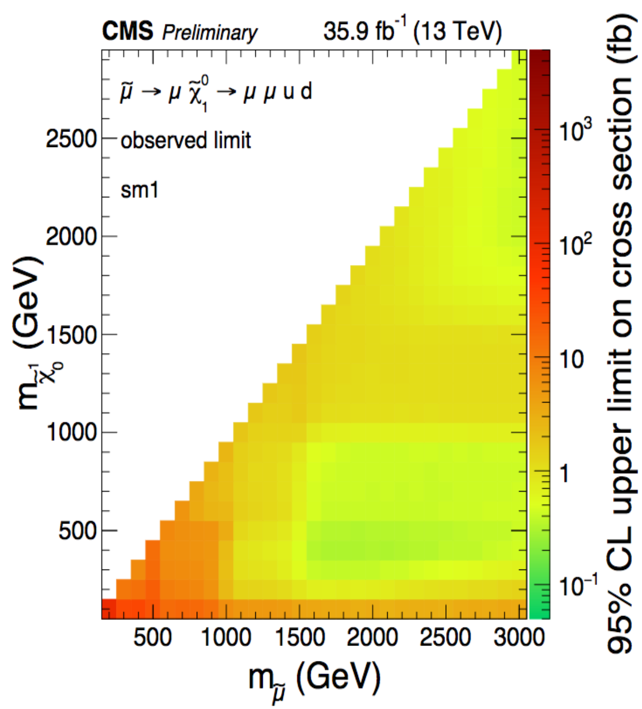
Slepton second generation production

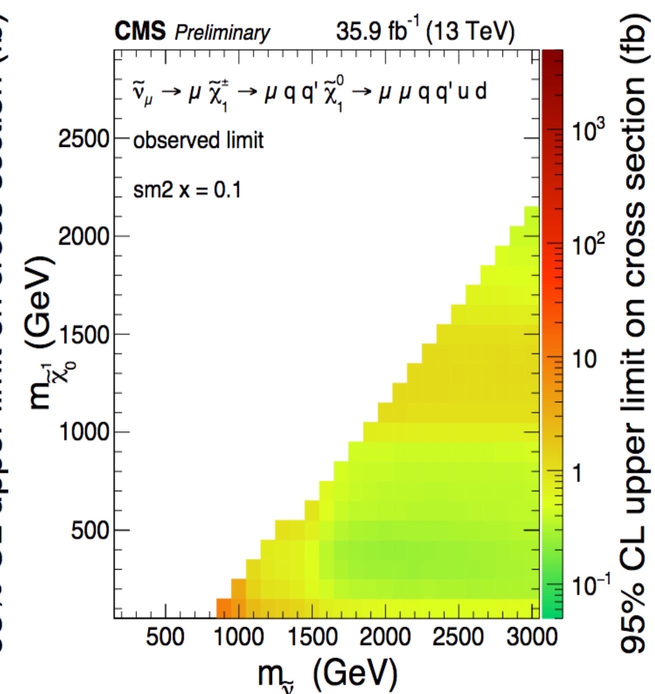
CMS: SUS-17-008



- Exactly two muons with same charge and invariant mass > 15 GeV
- At least two jets are required and the signal region is divided into bins in the Mslepton- mχ plane
  - Events from signal processes would lead to a broad peak around the slepton mass in the Mslepton plane
- Main backgrounds: non prompt muons mainly from ttbar and dibosons
- No excess found







Classical SUSY EWK signals

Summary gaugino searches: stable lightest $\tilde{\chi}_1^0$

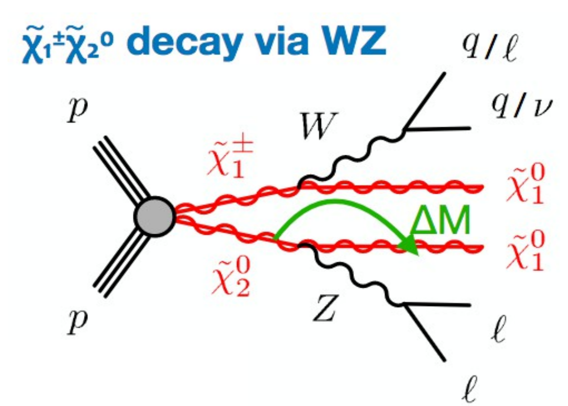
Topology	Final state	ATLAS	CMS
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ via WW	**2L0J + MET**	**ATLAS-CONF-2018-042**	**1807.07799**
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2 soft leptons + MET	Phys. Rev. D 97, 052010 (2018)	Phys. Lett. B 782 (2018) 440
	2L/3L + MET	1803.02762	JHEP 03 (2018) 166 JHEP 03 (2018) 076
	2L/3L + MET RJR	**1806.02293**	
	3L+HT		JHEP 03 (2018) 160 (specif ic treatment of the "WZ corridor")
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	Wh	Eur. Phys. J. C (2015) 75:208 (Run1)	JHEP 11 (2017) 029 Phys. Lett. B 779 (2018) 166 JHEP 03 (2018) 166
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Zh	Zh	Eur. Phys. J. C (2015) 75:208 (Run1)	JHEP 03 (2018) 076 Phys. Lett. B 779 (2018) 166 JHEP 03 (2018) 166
$\tilde{\chi}_2^0\tilde{\chi}_3^0$ via ZZ	4L	Phys. Rev. D. 90, 052001 (2014) (Run1)	JHEP 03 (2018) 076 JHEP 03 (2018) 166 Eur. Phys. J. C 74 (2014) 3036 (Run 1)
Combination			**JHEP 03 (2018) 160**

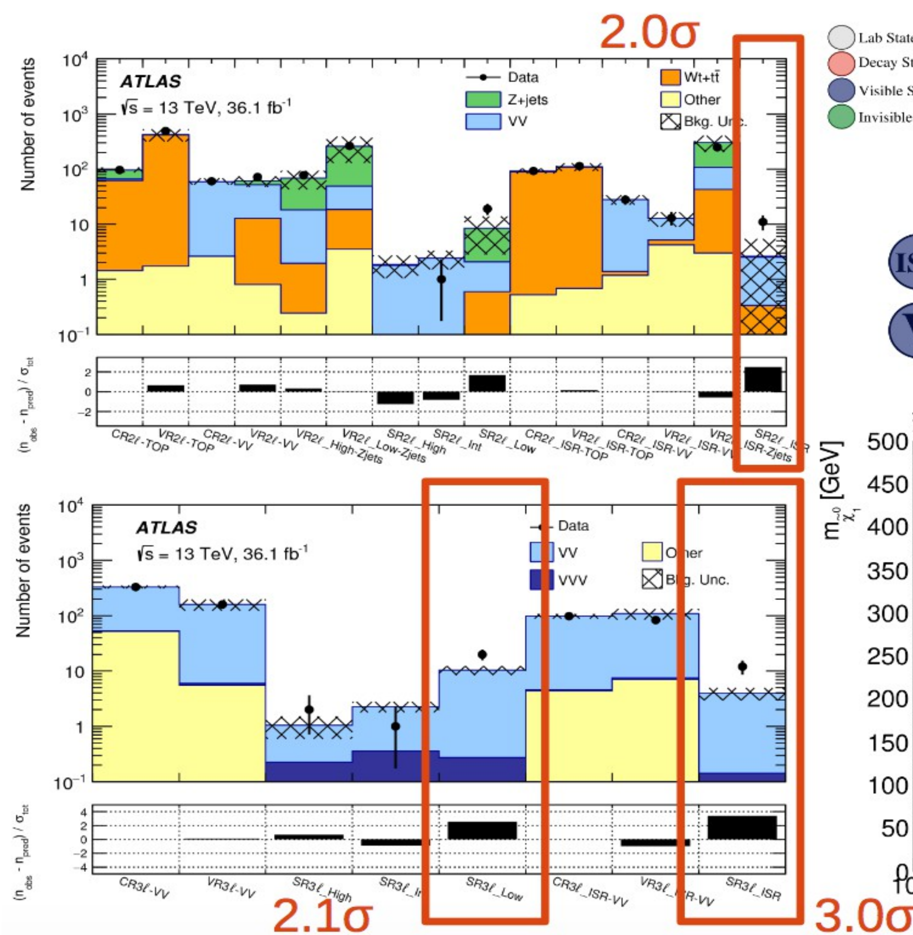
**Check Basil Schneider and Matthew Klein' talks*

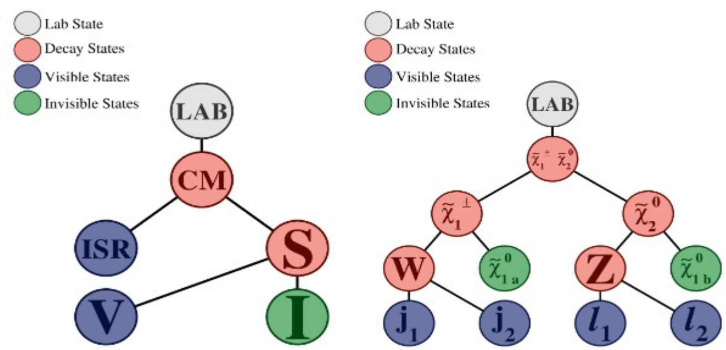
Chargino/neutralino production: 2L/3L + MET RJR

ATLAS: 1806.02293

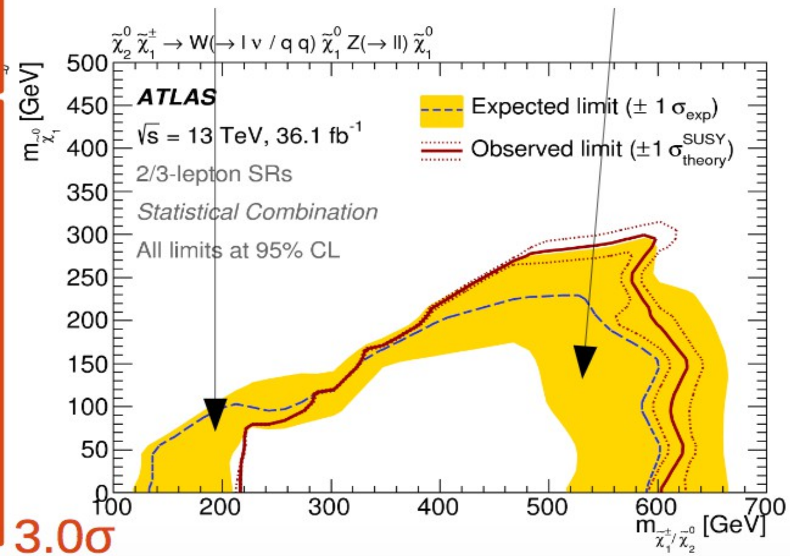
- Use recursive jigsaw reconstruction techniques (RJR)
  - Algorithm recursively reconstructing the decay chain of pair produced heavy particles
- Event selection: 8 regions targeting different ΔM
  - [2L, 3L]x[ISR, low, intermediate, high]
- 3.0 σ excess in 3 lepton ISR selection (compressed scenarios)
  - Shape not consistent with any benchmark signals or backgrounds
  - Not present in the conventional 2L/3L analysis using the same data







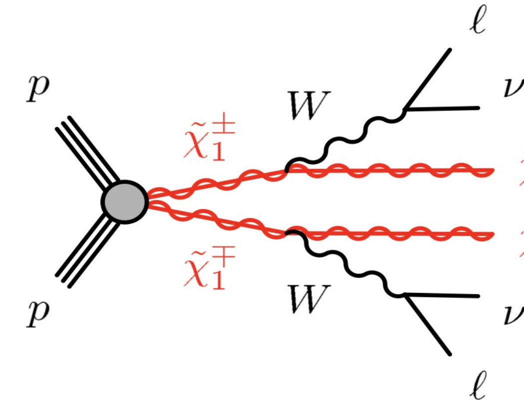
Example of RJR "tree" for compressed scenario and 2L



Chargino production: 2L0J + MET

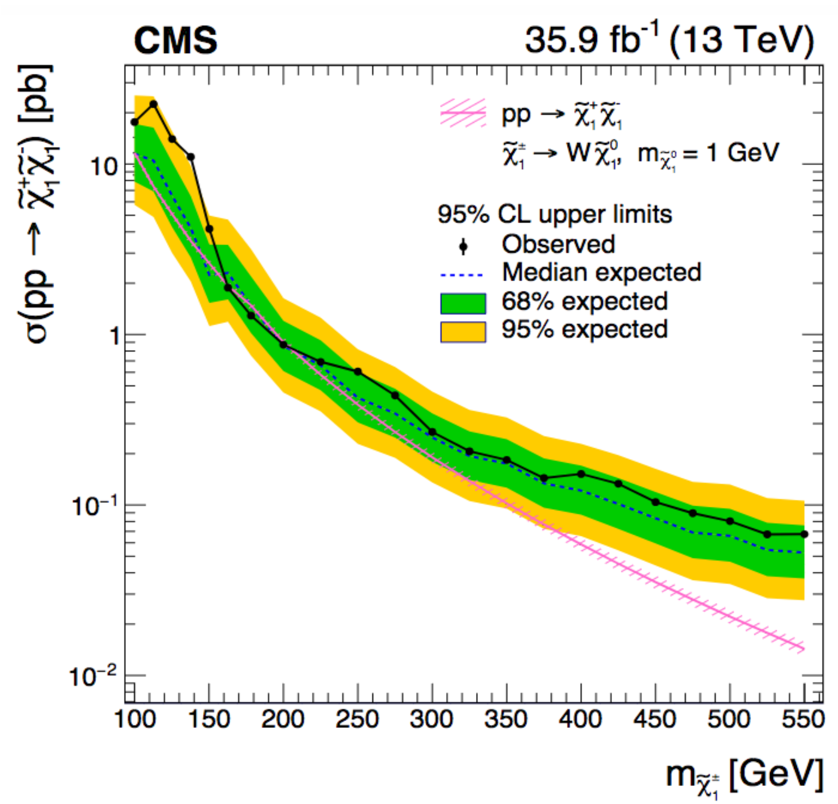
CMS: 1807.07799 ATLAS: ATLAS-CONF-2018-042

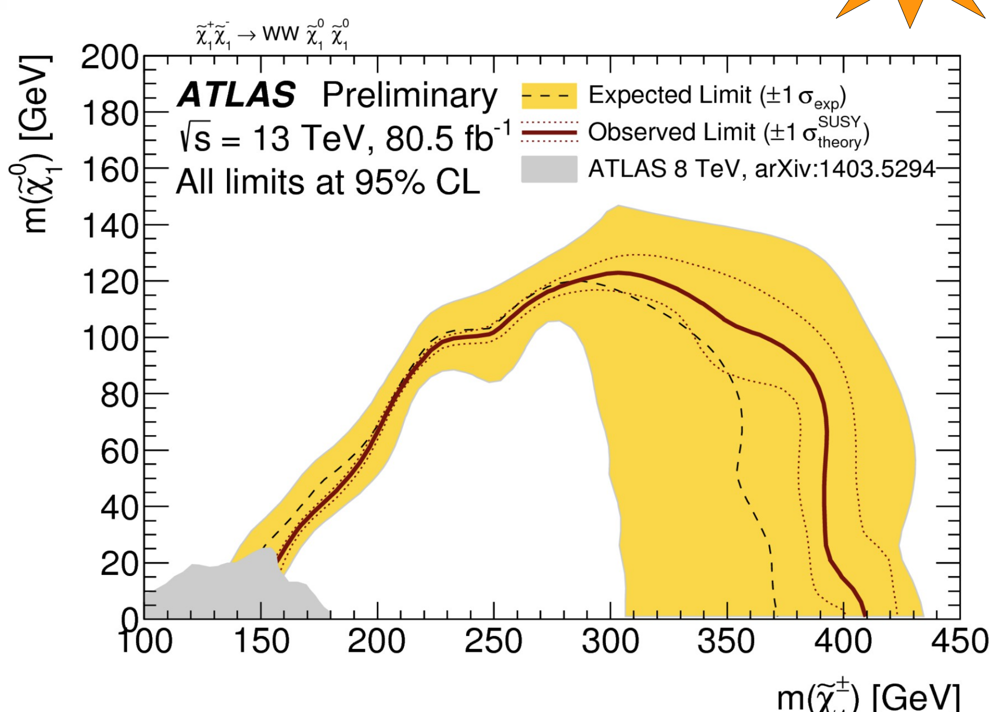
- Leptonic decay of the W considered: two isolated leptons (e,μ) with opposite charge, m_{ll}>25 (20) GeV and MET>110 (140) GeV for ATLAS (CMS)
- m_{T2} binned regions for model-dependent exclusions and inclusive SRs for model independent results



- Main background is SM WW and top production
- No deviation from SM: stronger limits wrt Run 1 limit

80/fb



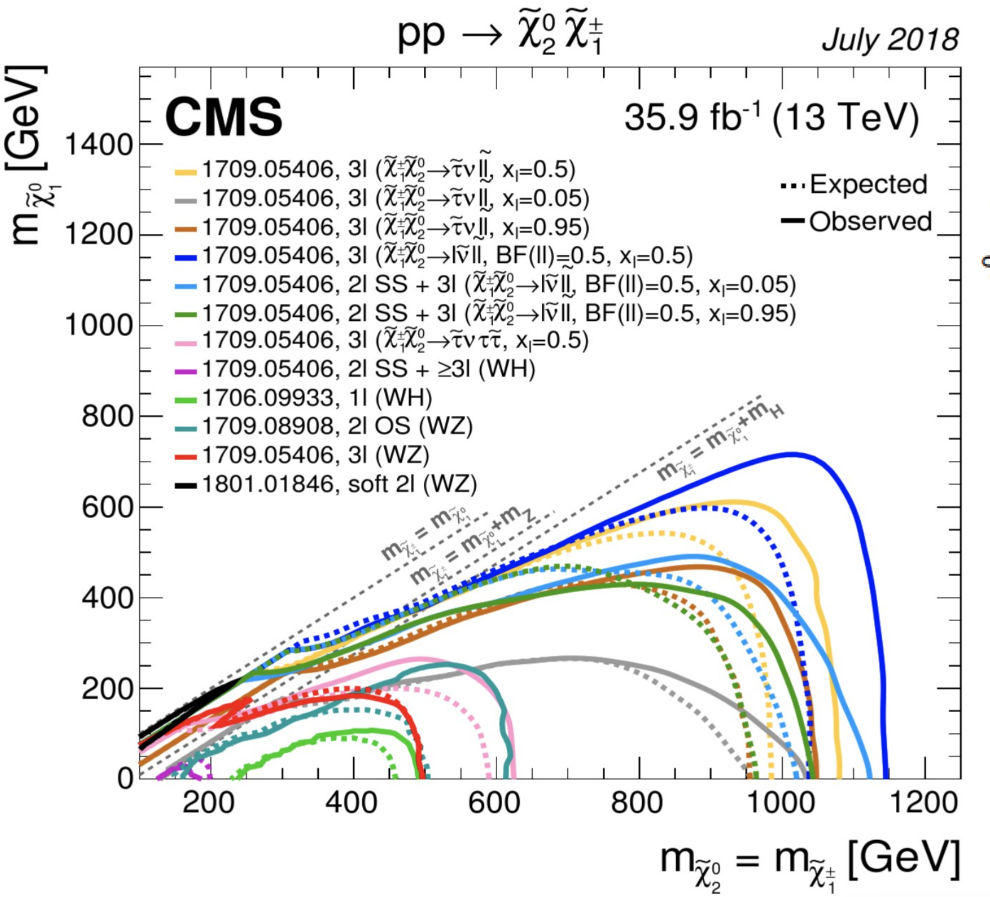


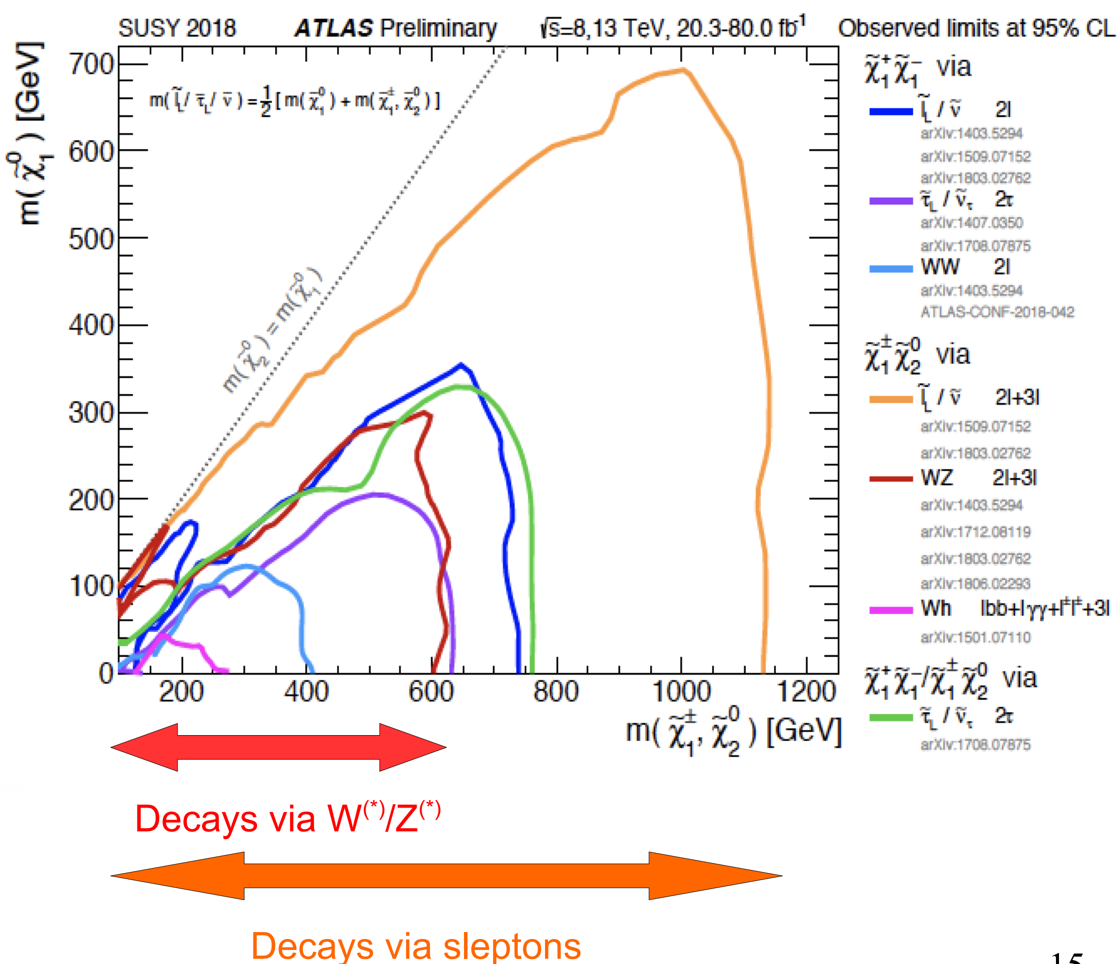
Chargino/neutralino pair production summary

SUSY CMS public

SUSY ATLAS public

- Limits on slepton-mediated charginos & neutralinos reaching beyond 1 TeV — large BR to multileptons





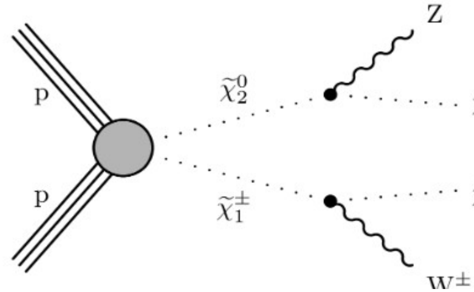
*Mass limits at 95% CL obtained in the context of simplified models

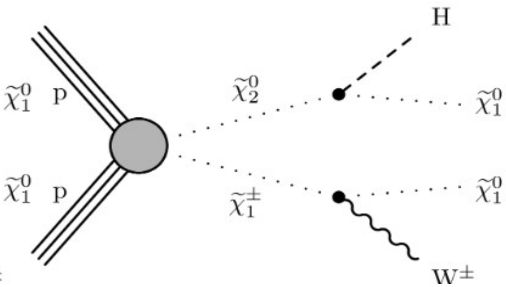
Chargino/neutralino pair production combination

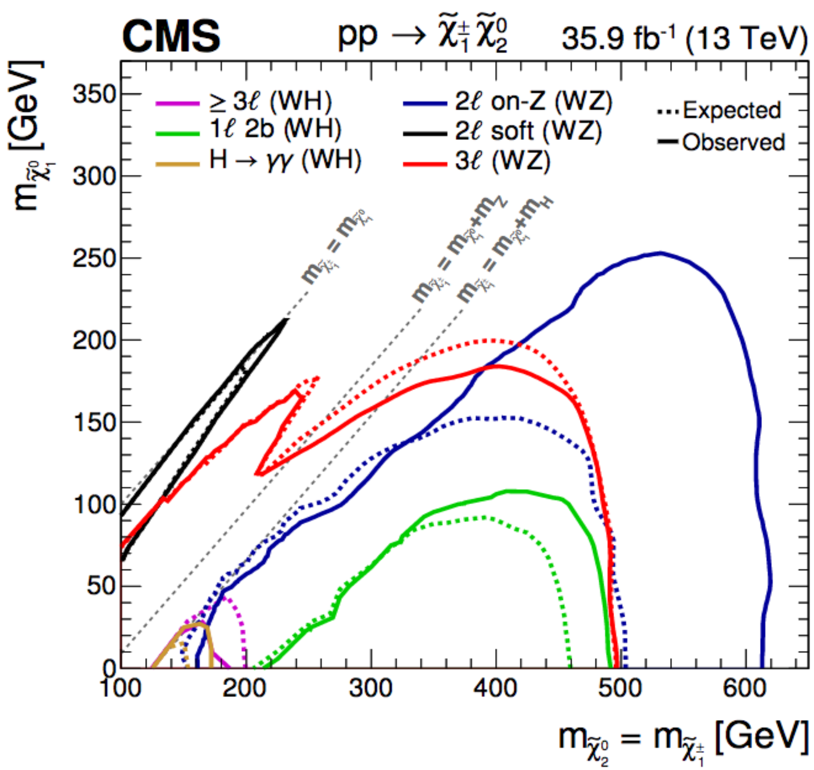
CMS: JHEP 03 (2018) 160

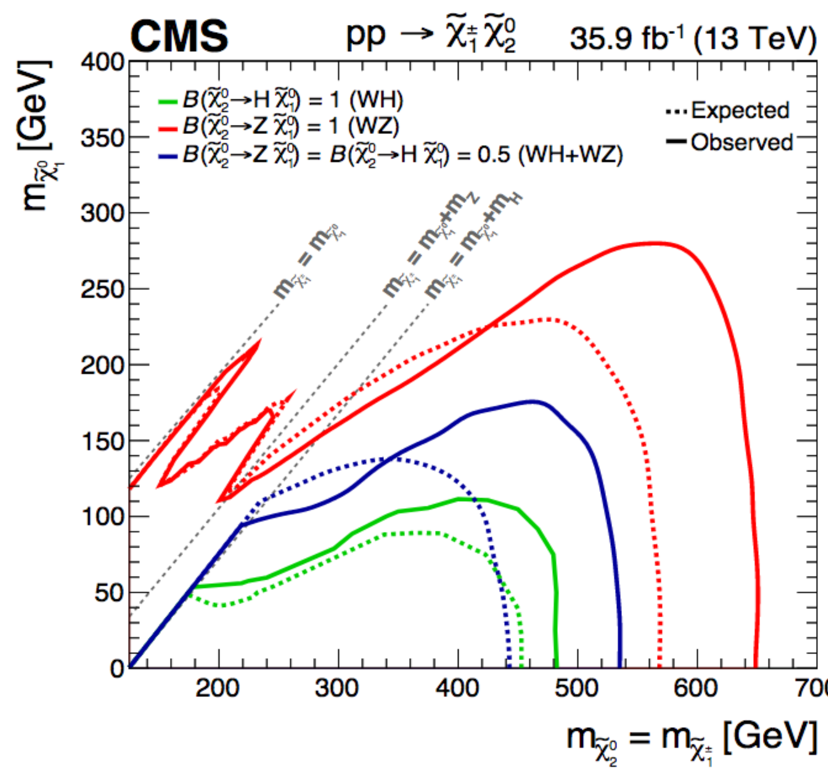
- Statistical combination of all CMS analyses targeting direct decays of neutralino/chargino pairs to SM bosons. 6 main publications of CMS

- Setting even higher limits in the electroweak SUSY energy scale



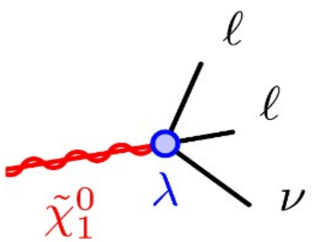




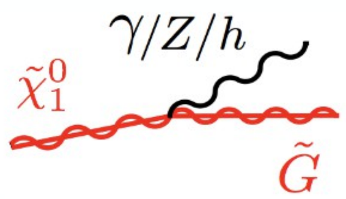


Classical SUSY EWK signals

- Lightest neutralino decays in a class of scenarios:
  - Decay into SM particles (RPV)
  - Decay into gravitino LSP (GMSB), etc...



- Decay one step further
  - More additional associated objects
  - Better experimental sensitivity in general



Summary gaugino searches: decaying lightest $\tilde{\chi}_1^0$

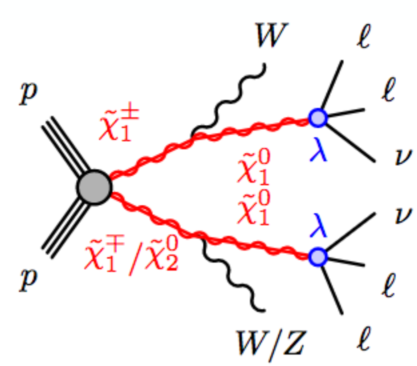
Topology	Final state	ATLAS	CMS
RPV decay of $\tilde{\chi}_1^0$		**1804.03602 (4L)**	SUS-13-010 (Run 1, 4L)
$\tilde{\chi}_1^0 \rightarrow Z/h\ \tilde{G}$			JHEP 03 (2018) 166 (leptons) JHEP 03 (2018) 076 (leptons) Phys. Rev. D 97, 032007 (2018) (bb) Phys. Lett. B 779 (2018) 166 ($\gamma\gamma$) JHEP 03 (2018) 160
$\tilde{h} \rightarrow h\ \tilde{G}$	(will talk about Higgsinos later)	1806.04030 (multi-b + MET)	JHEP 03 (2018) 166 (leptons) Phys. Rev. D 97, 032007 (2018) (bb) Phys. Lett. B 779 (2018) 166 ($\gamma\gamma$) JHEP 03 (2018) 160
$\tilde{\chi}_1^0 \rightarrow \gamma\ \tilde{G}$	**γ+MET**	Phys. Rev. D 97, 092006 (2018)	**Phys. Lett. B 780 (2018) 118**
	Z+γ+MET	**ATLAS-CONF-2018-019**	
	W+γ+MET		**SUS-17-012**

4L

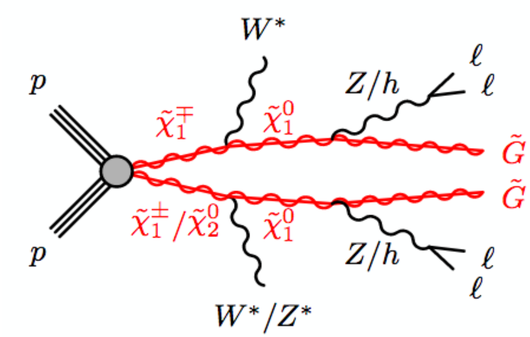
ATLAS: 1804.03602

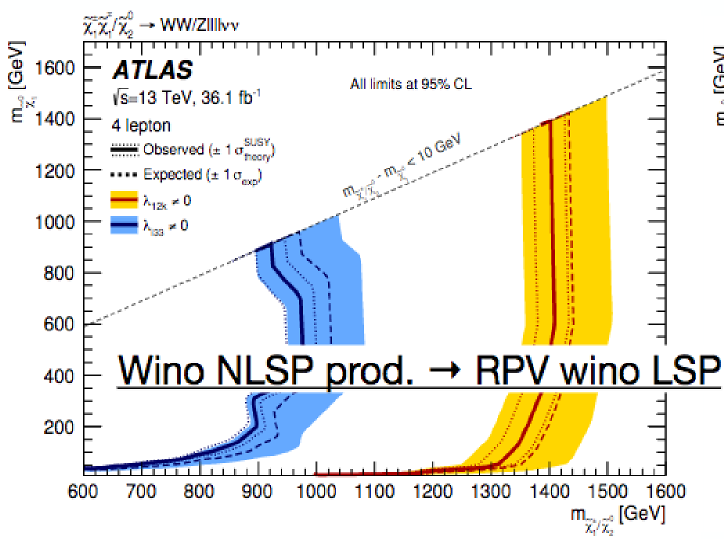
- RPV wino decay, gauginos decaying via ZZ
  - High lepton multiplicity in final state
- >=4 leptons, 0 - 2 hadronically decaying taus
- 6 different SRs to gain sensitivity to different models
- Cutting on m_{eff} or MET and veto or requirements on Z boson
- Main backgrounds: ZZ, ttZ and fakes
- No significant excess seen
  - Mild excess observed (2.3 σ) in 0 tau, on-shell Z

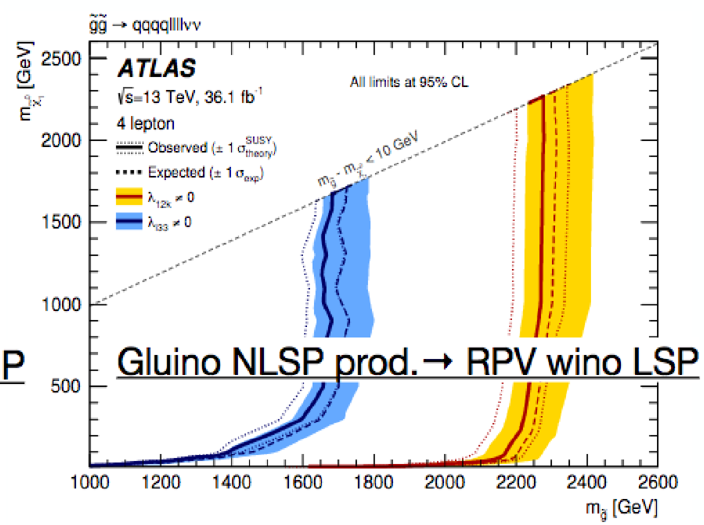
RPV wino LSP decay

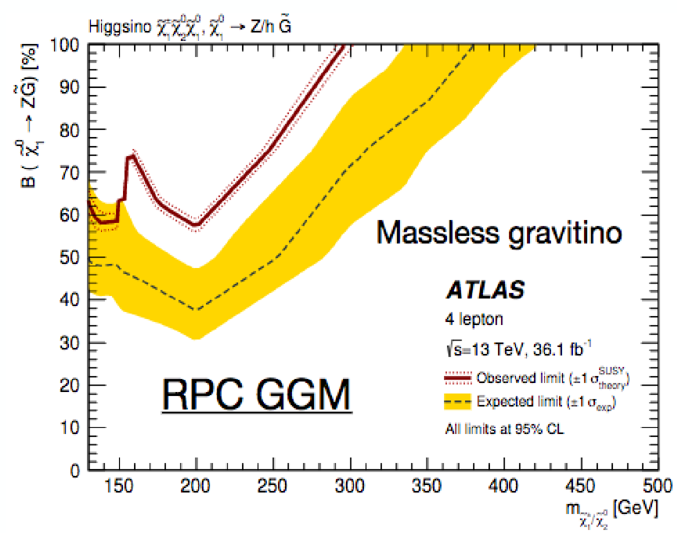


RPC higgsino GGM







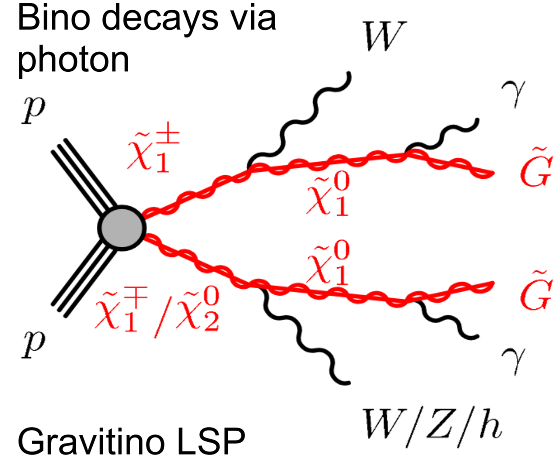


Searches with photons: γ+MET

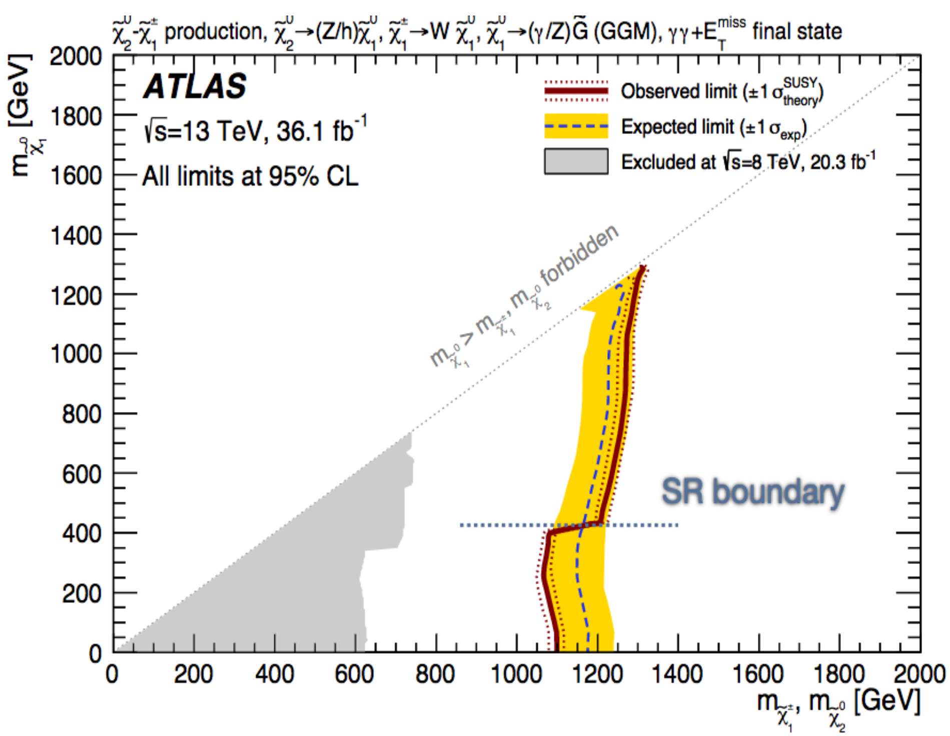
CMS: Phys. Lett. B 780 (2018) 118 ATLAS: Phys. Rev. D 97, 092006

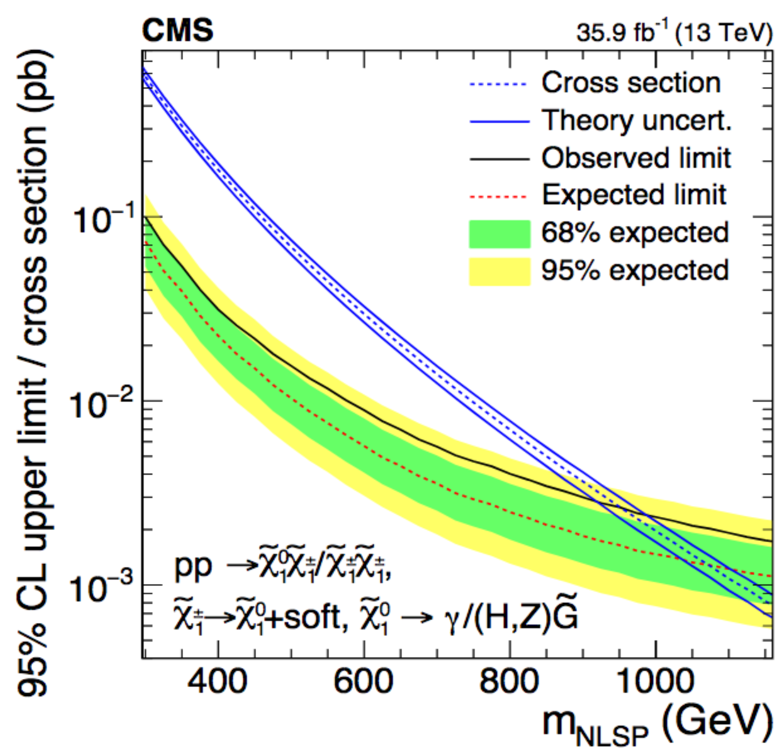
- Diphoton signature with MET
- Selection:
  - CMS requires 1 photon, ATLAS requires 2 photons
  - Jet agnostic
  - MET > 150, 250 GeV (ATLAS), >300 GeV (CMS)
  - High energy scale (event-wide p_T sum)
- Main backgrounds: diphotons and fakes
- No significant excess. Exclude up to 1.2 TeV chargino/neutralino

Bino decays via photon



Gravitino LSP with m~keV





Searches with photons: Z+γ+MET

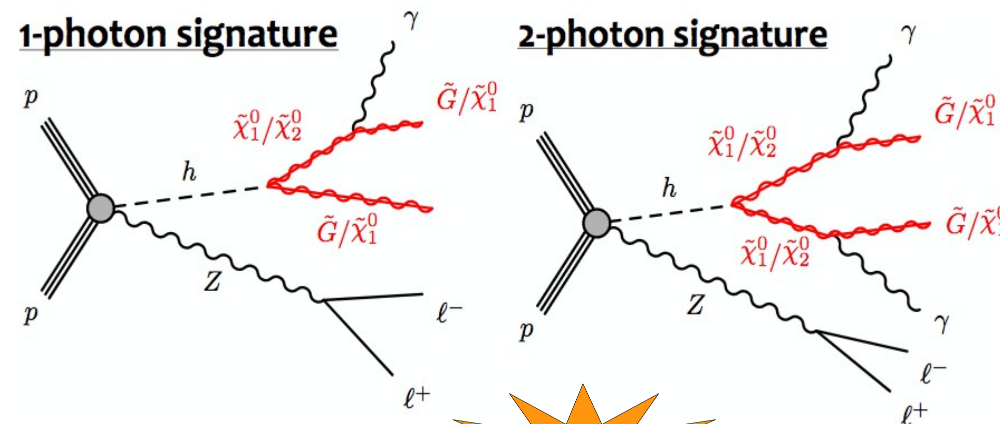
ATLAS: ATLAS-CONF-2018-019

- First 80/fb SUSY result from ATLAS, Zh with h→neutralino

- Selection:
    - Z→ll, MET>95 GeV and >=1 photon
    - Jet veto and cuts on angular/Z-h p_T-balance

- Main backgrounds: >95% from jet/electron faking photons, data-driven estimation

- No significant excess observed. 10-60% improvement wrt Run-1 limits on Higgs BR



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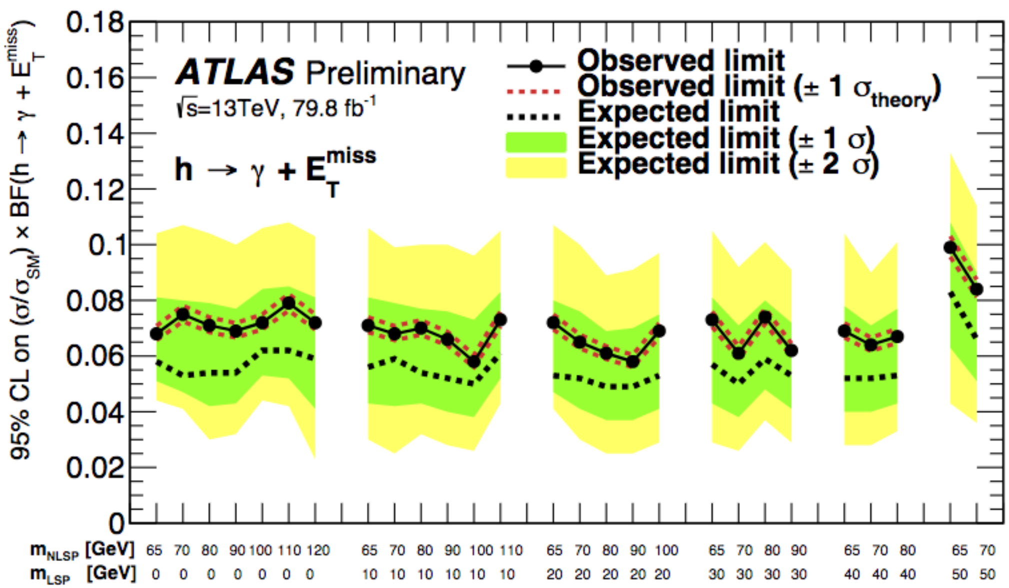
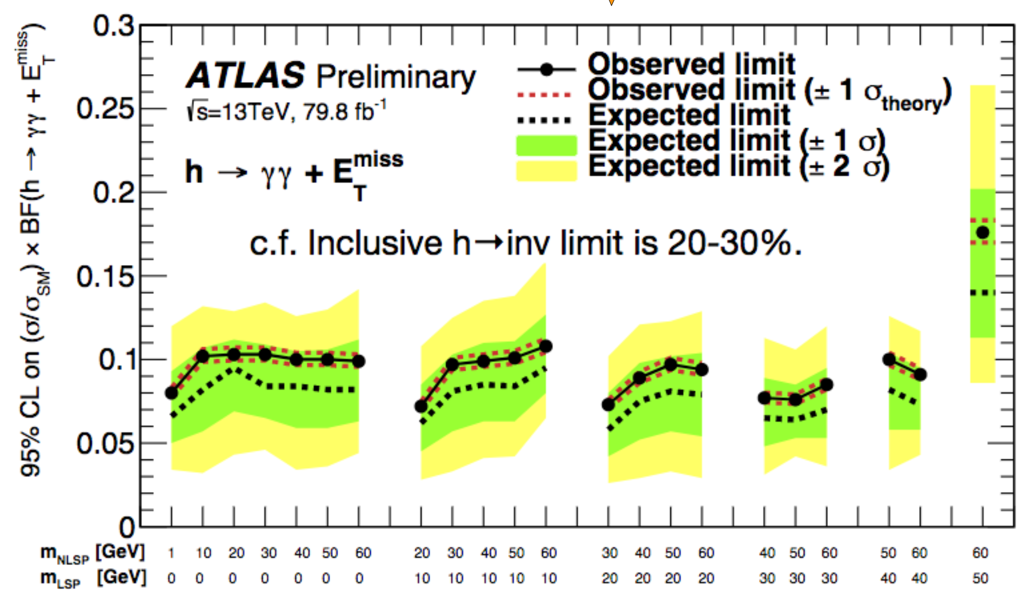




Check Johannes Schulz's talk

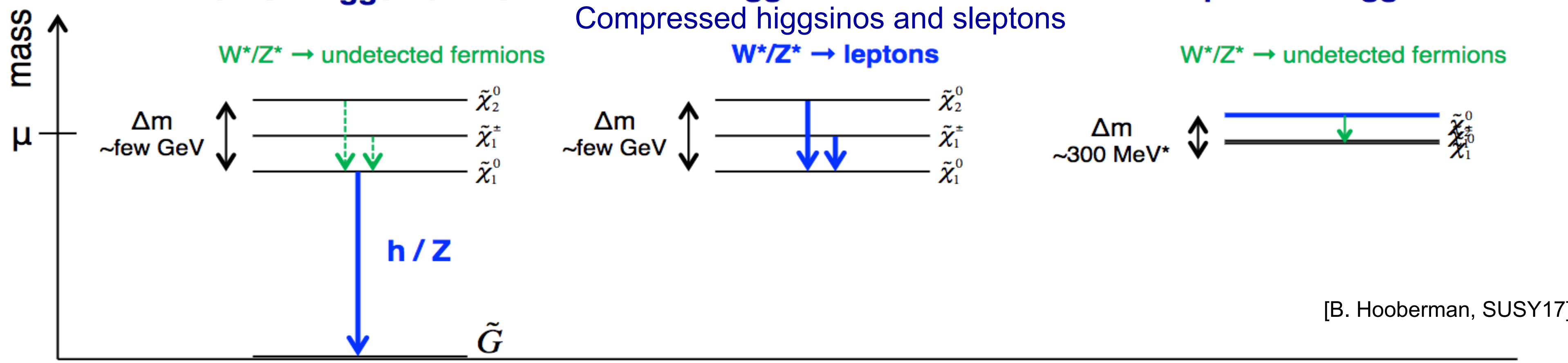
Challenges: Higgsinos and compressed scenarios

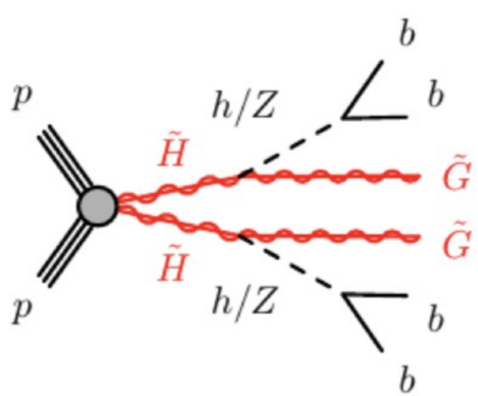
- In "natural" SUSY models, Higgsinos should be light
- If the lightest $\tilde{\chi}_0^1$ and $\tilde{\chi}_1^{\pm}$ are dominated by the Higgsino, expect O(0.1 – 10 GeV) mass splittings and very difficult signatures!

Scenario 1
GMSB higgsino NLSP

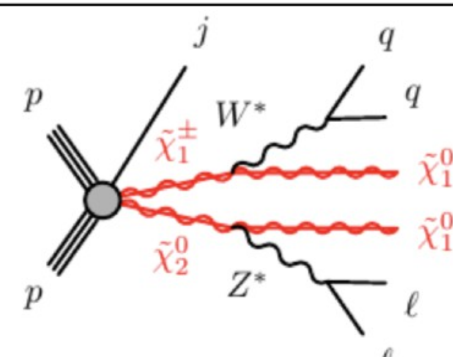
Scenario 2:
higgsino LSP
Compressed higgsinos and sleptons

Scenario 3:
ultra-compressed higgsino LSP

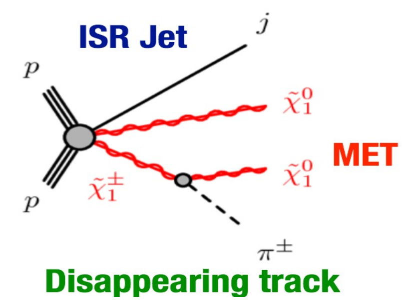




ATLAS: 1806.04030
CMS: PRD 97 (2018) 032007
Decays via on-shell h/Z
Already presented last December: big impact from JSS techniques!



CMS: Phys. Lett. B 782 (2018) 440
ATLAS: Phys. Rev. D 97, 052010 (2018)
Also presented last December
Emphasize the importance of looking at the corners! Which usually means thinking outside the box also for performance as was the case of soft leptons!

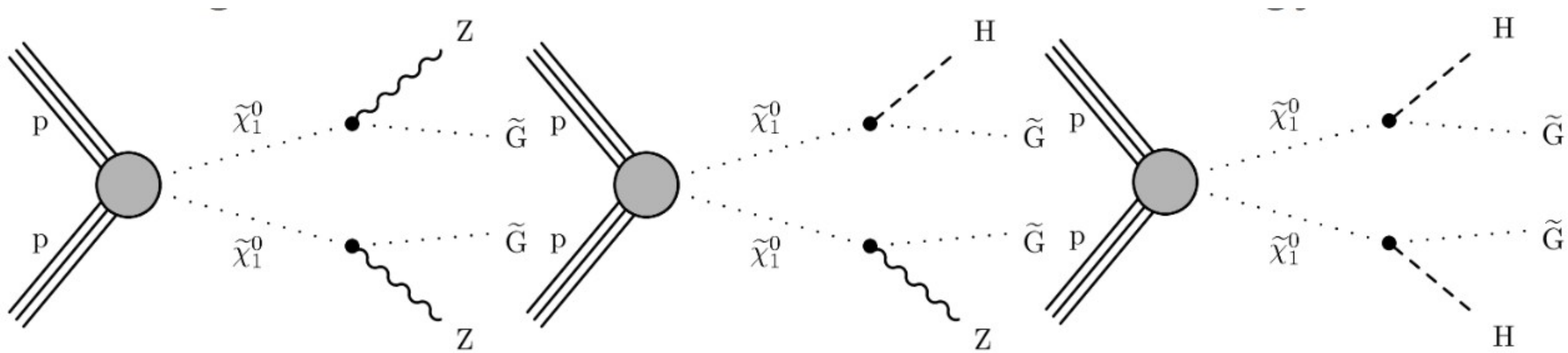


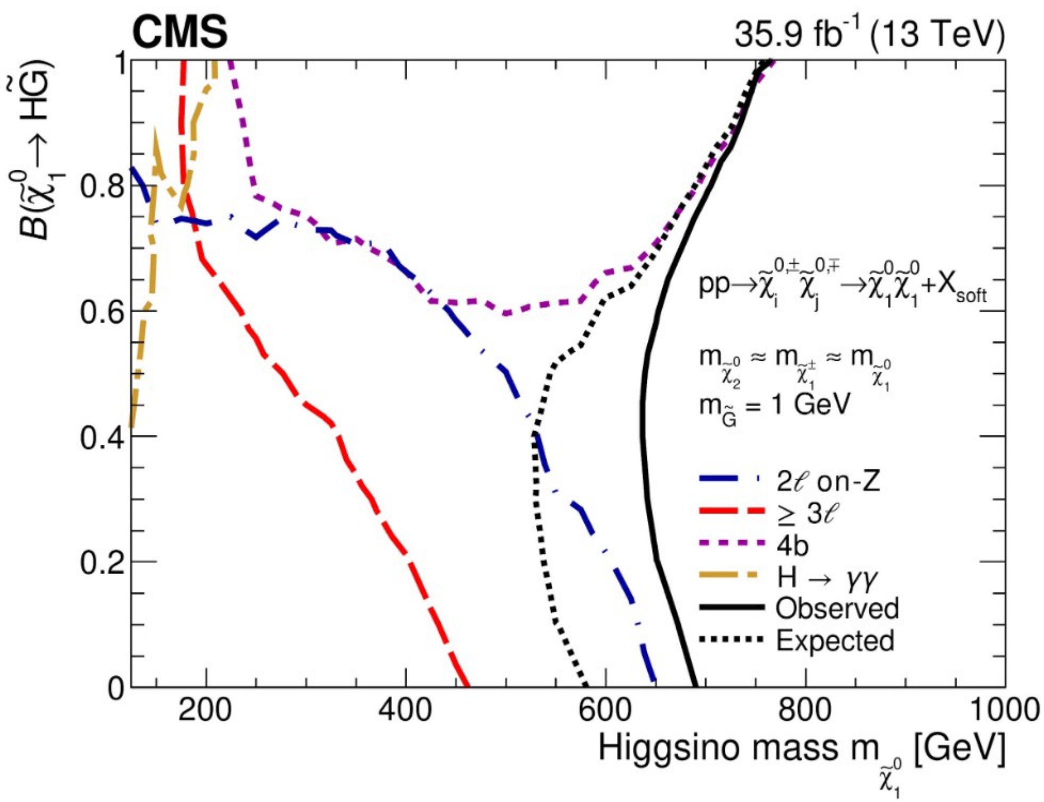
ATLAS: JHEP 06 (2018) 022
CMS: 1804.07321 (just accepted by JHEP!)
Heavy degenerate EW gauginos → disappearing tracks. Another example of thinking outside the box

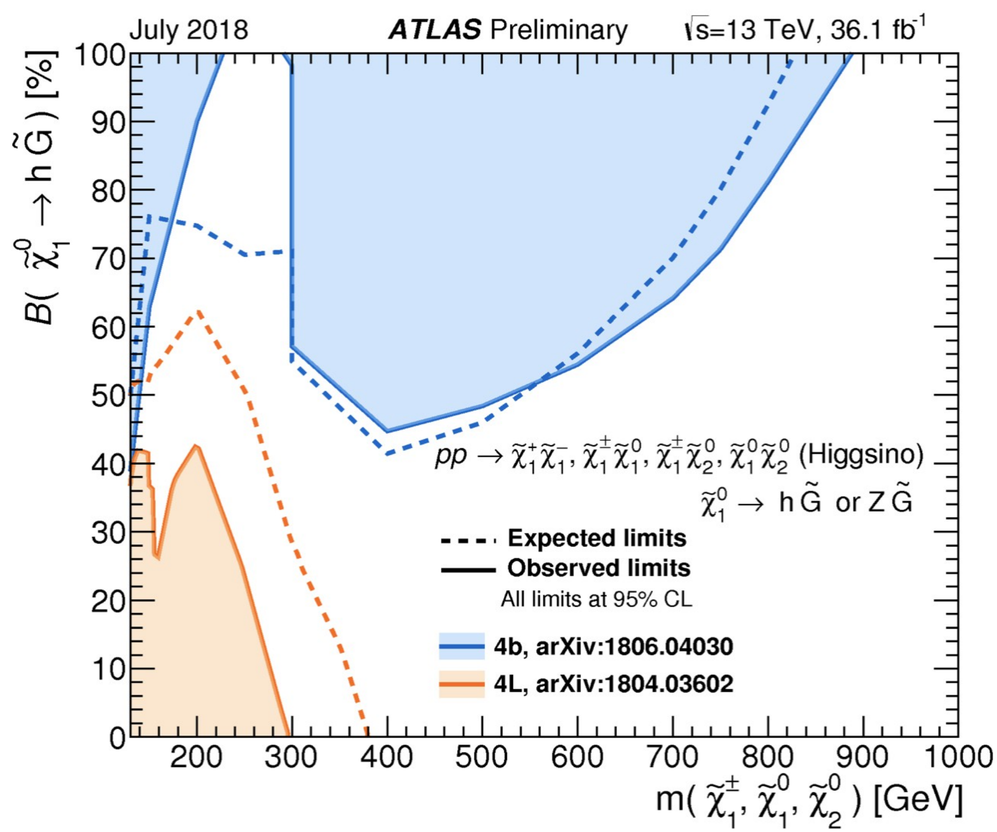
Combined Higgsino limits

CMS: JHEP 03 (2018) 160

SUSY ATLAS public







Part of the statistical combination effort from CMS mentioned before

*Check Rakhi Mahbubani's talk

Summarizing

- A brief overview presented of the new high quality results made public by both collaboration
  - More details in the parallel sessions!

- All results available at CMS and ATLAS SUSY public website

- EWK SUSY becoming more and more interesting with increasing stats accumulated

- Standard signatures well covered. Now we need to think outside the box:
  - Corners and signatures not explored?
  - Improvements in our reconstruction process needed? Push the boundaries of new physics searches using new techniques rather than $\sqrt{N}$ and $\sqrt{s}$!

- Stay tuned!

BACKUP

Chargino/neutralino production: 2L/3L + MET RJR

ATLAS: 1806.02293

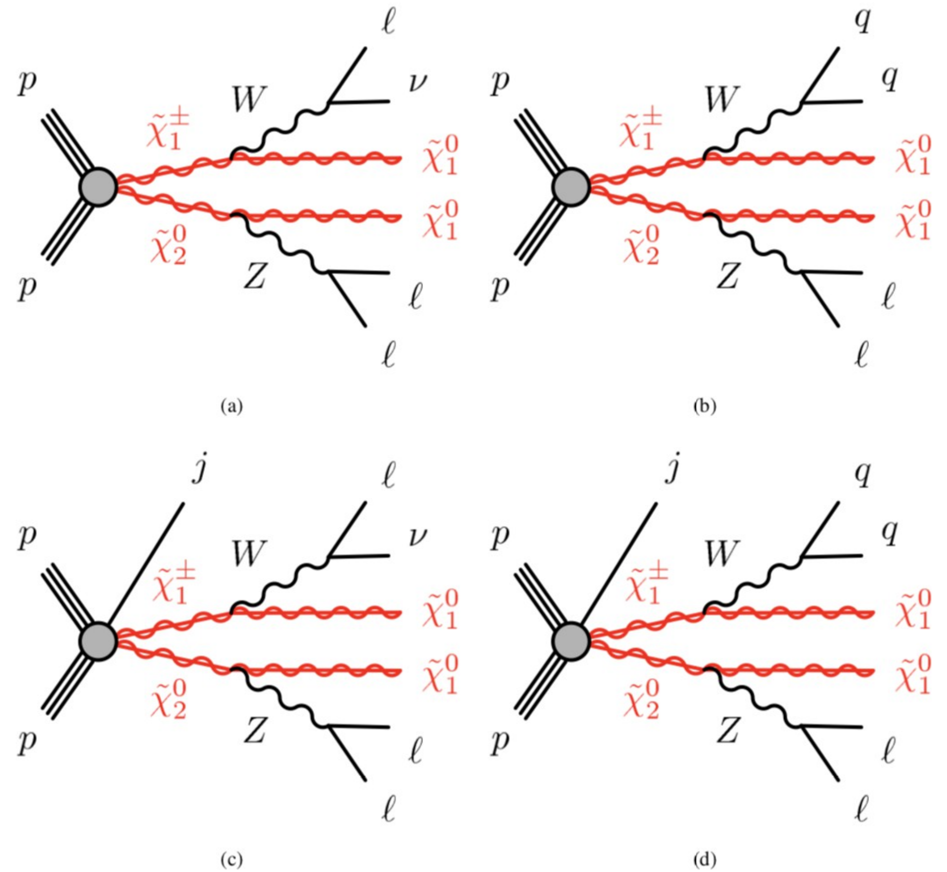


Figure 1: Diagrams for the physics scenarios studied in this paper: (a) $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ with decays via leptonically decaying W and Z bosons, (b) $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ with decays to two-lepton plus two-jet plus $E_{\mathrm{T}}^{\mathrm{miss}}$ final states through a hadronically decaying W boson and a leptonically decaying Z boson, (c) $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production in association with an initial state radiation jet (labeled 'j' in the figure) with decays via leptonically decaying W and Z bosons and (d) $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production in association with an initial state radiation jet with decays to two-lepton plus two-jet plus $E_{\mathrm{T}}^{\mathrm{miss}}$ final states through a hadronically decaying W boson and a leptonically decaying Z boson.

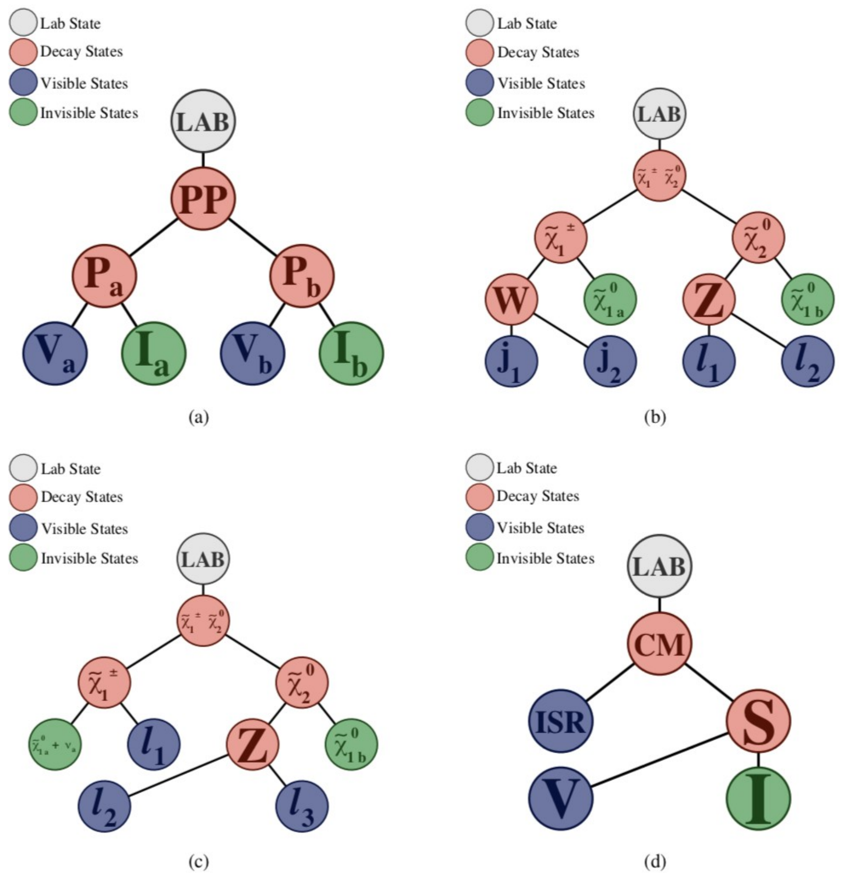
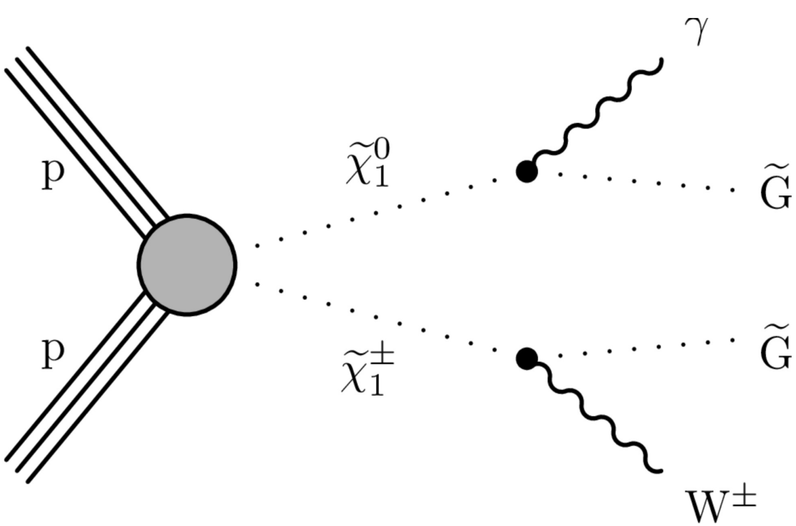
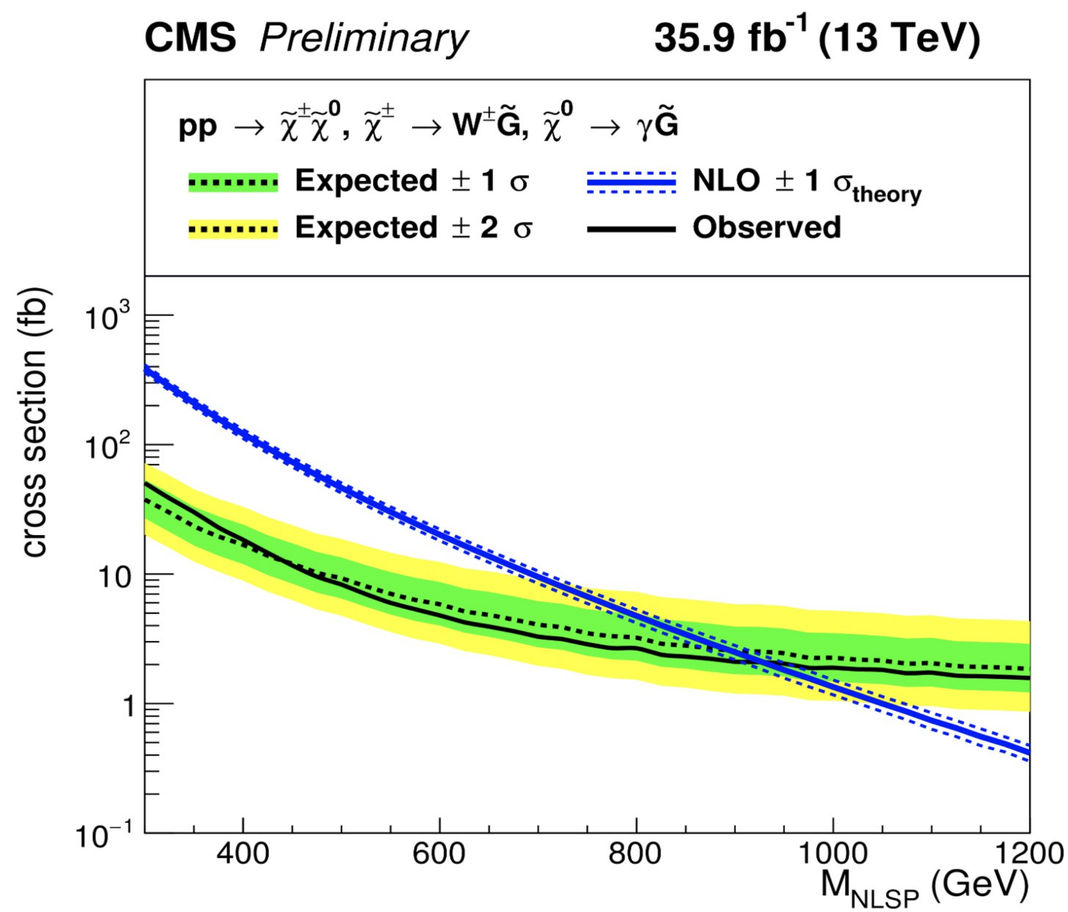


Figure 2: (a) The "standard" decay tree applied to pair-produced sparticles ("parent" objects), P, decaying to visible states "V" and invisible states "I". (b) Decay trees for the $2\ell + 2$ jets final state and (c) 3ℓ final state. (d) The "compressed" decay tree. A signal sparticle system S decaying to a set of visible momenta V and invisible momentum I recoils from a jet-radiation system ISR.

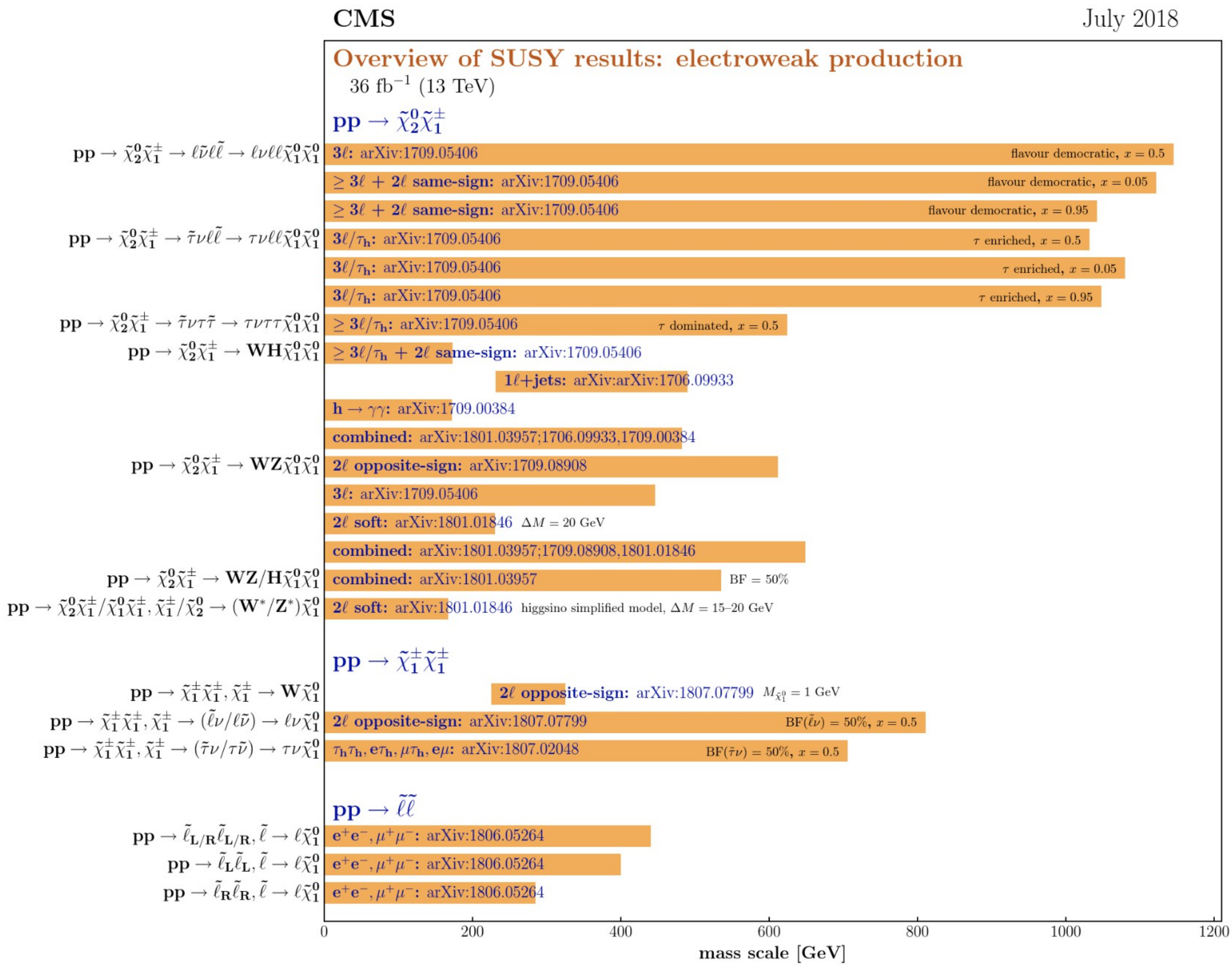
Searches with photons: W+γ+MET

CMS: PAS-SUS-17-012





*Check Johannes Schulz's talk



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

Jetless off-Z double lepton

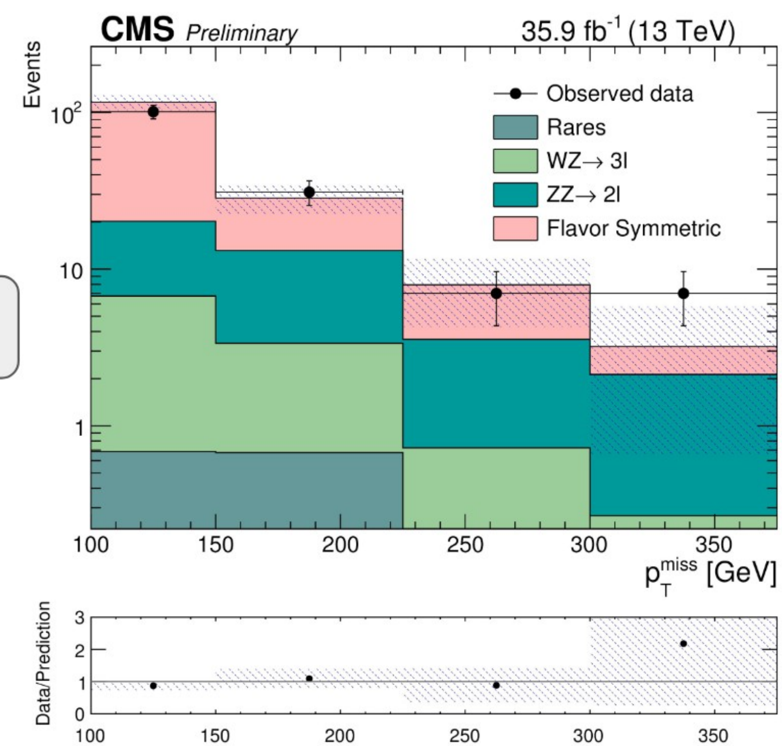
CMS: 1806.05264

- Events with a pair of opposite charge same flavor (OCSF) leptons.
- Stransverse mass variable:

Kinematical endpoint at m_W for tt, WW backgrounds

$$M_{T2}(\ell\ell) = \min_{\vec{p}_T^{\,miss1}+\vec{p}_T^{\,miss2}=\vec{p}_T^{\,miss}} \left(\max \left[M_T(\vec{p}_T^{\,lep1}, \vec{p}_T^{\,miss1}), M_T(\vec{p}_T^{\,lep2}, \vec{p}_T^{\,miss2}) \right] \right)$$

Reduce tt, QCD	Reduce resonances	Reduce WW, tt	Sensitive to multiple m_{LSP}
N_{jets}	$m_{\ell\ell}$ [GeV]	$M_{T2}(\ell\ell)$ [GeV]	p_T^{miss} [GeV]
0 (> 25 GeV)	> 20 and not in [76, 106]	> 90	100–150, 150–225, 225–300, >300



Dominated by multiple effects that alter the shape of p_T^{miss}

Source of uncertainty	Uncertainty (%)
Jet energy scale	1-15
Fast simulation p_T^{miss} modeling	0-20
Unclustered energy shifted p_T^{miss}	0-8
Muon energy scale shifted p_T^{miss}	0-20
Electron energy scale shifted p_T^{miss}	0-4

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SUS-17-010 (CDS)

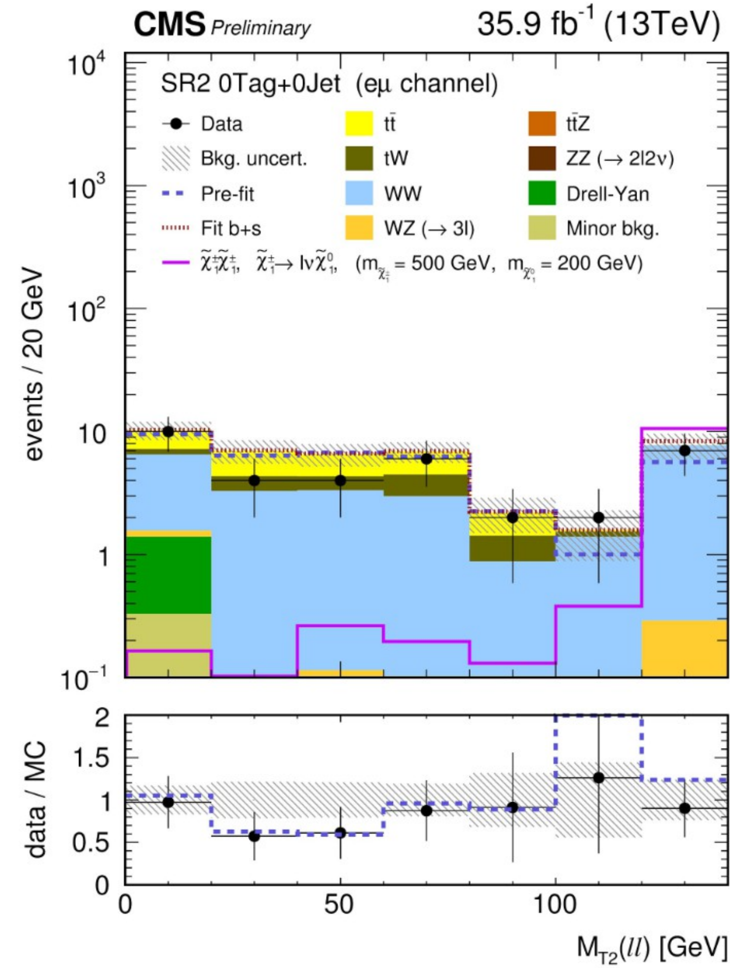
Jet inclusive off-Z double lepton

- Selecting events with an OC lepton pair. Veto third lepton.
- Minimal requirements to reject resonances.

Baseline selection (common)

Variable	Selection
$m_{\ell\ell}$	$\geq 20\,\mathrm{GeV}$
$\lvert m_{\ell\ell} - m_Z \rvert$	$> 15\,\mathrm{GeV}$ only for ee and $\mu\mu$ events
p_T^{miss}	$\geq 140\,\mathrm{GeV}$

- Search strategy based on multiple bins on N_{Jets}- $N_{b\text{-}Tag}$ classified by lepton composition.
- Exploit shape differences in the M_{T2}(ll) variable (multiple bins).



M_{T2} modelling for the backgrounds is crucial
Also different effects in the resolution of p_T^{miss}

Systematic	Change in yields	Change in $M_{T2}(\ell\ell)$ shape
JES	1-6%	3-15%
Unclustered energy	1-2%	2-16%
$M_{T2}(\ell\ell)$ shape (Top)	-	4-18%
$M_{T2}(\ell\ell)$ shape (WW)	-	1-15%
$M_{T2}(\ell\ell)$ shape (Drell-Yan)	-	1-13%

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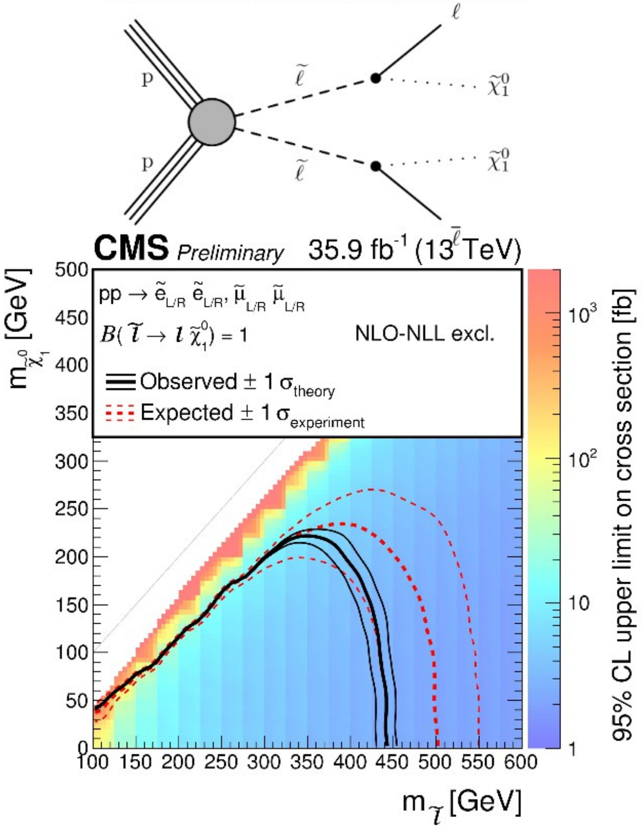
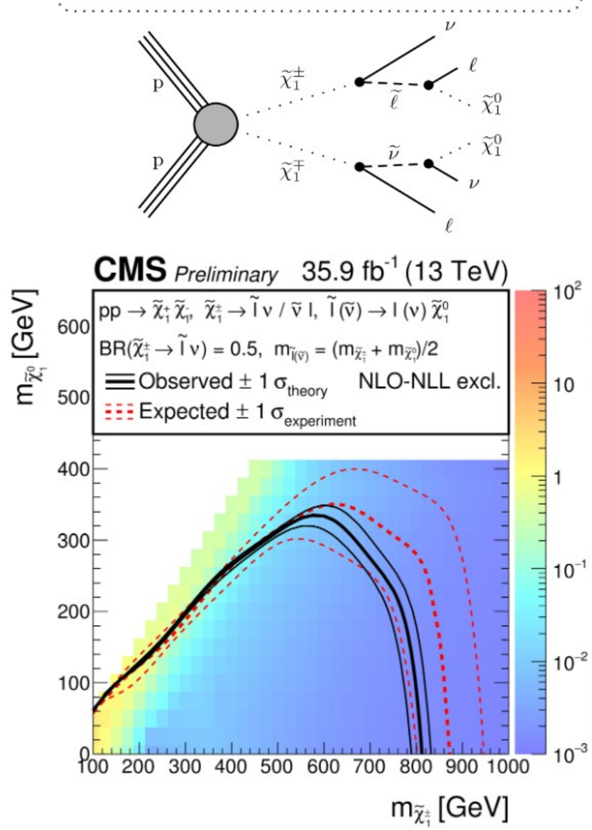
Double lepton final state interpretations

- Common points: light sleptons models.
- Additional interpretation on terms of chargino pair production.

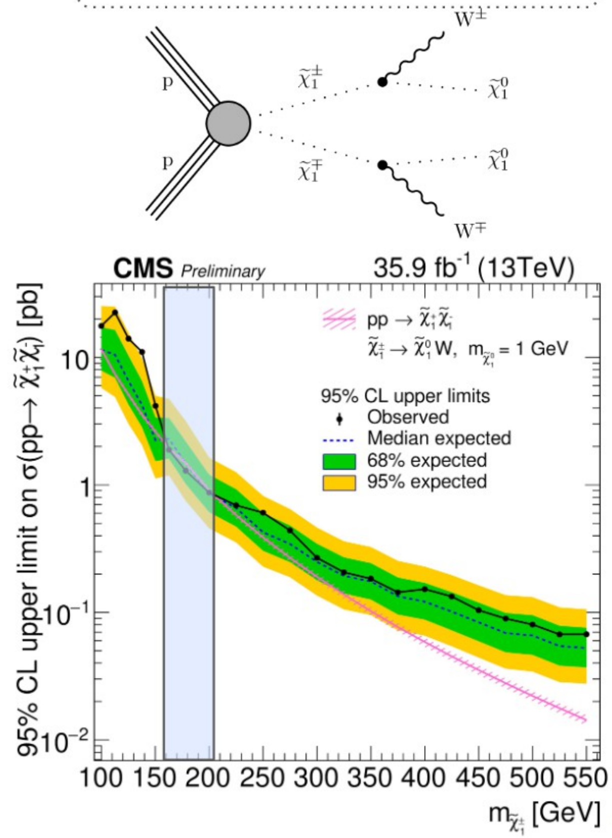
CMS: 1806.05264



SUS-17-010 (Jet inclusive)



SUS-17-010 (Jet inclusive)



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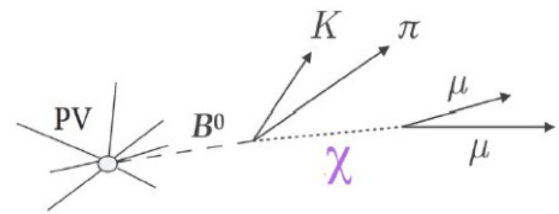
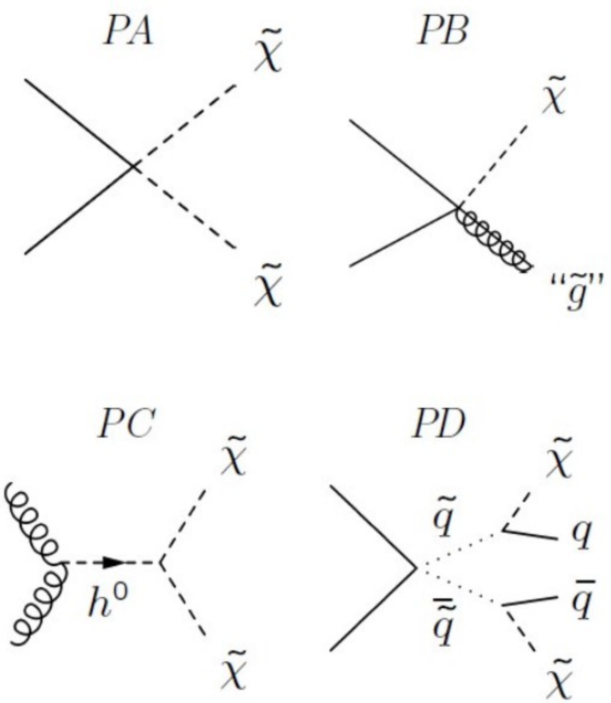
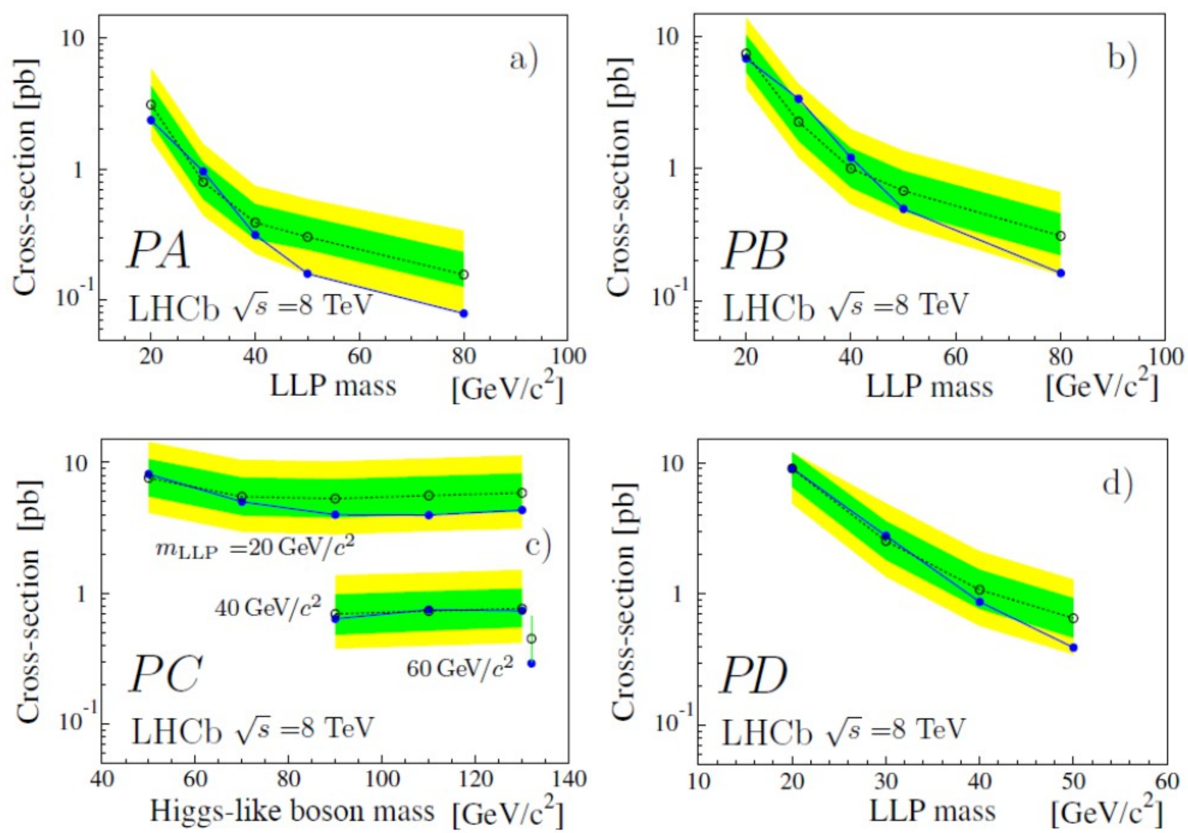
Semileptonic LLP decays

- Search for long-lived particles through a displaced vertex with several tracks including a high p_T muon.
- Forward coverage ($2<\eta<5$) and low trigger p_T threshold gives sensitivity to small LLP masses.
- Cover LLP lifetimes from 5 ps up to 100 ps and masses in the range 20–80 GeV.



1612.00945





- Also neutralino production in RPV models with mass in 23-98 GeV range.