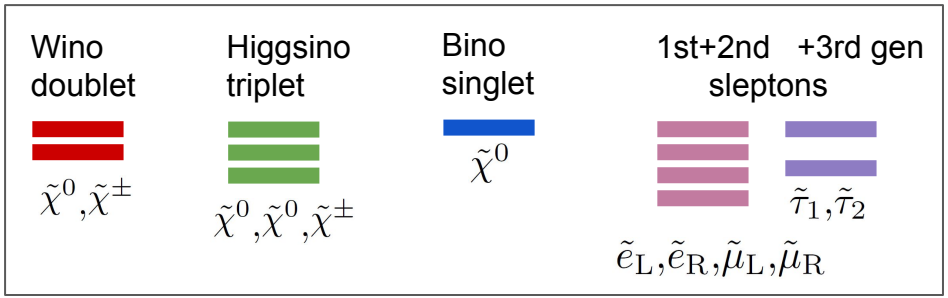
# A critical summary of EWK SUSY searches (including LLP)

Tina Potter

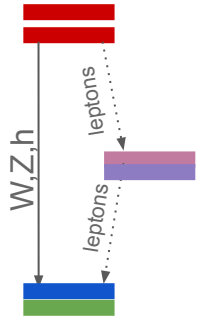
September 2019

# The electroweak SUSY landscape

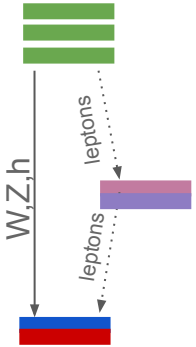



Phenomenology depends on
wino-bino-higgsino mixing,
mass hierarchy,
and decay channels

\+ small couplings / small mass splittings can result in long-lived sparticles

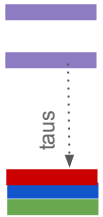



High $\sigma$,
hard final state




Low $\sigma$,
hard final state


Low $\sigma$



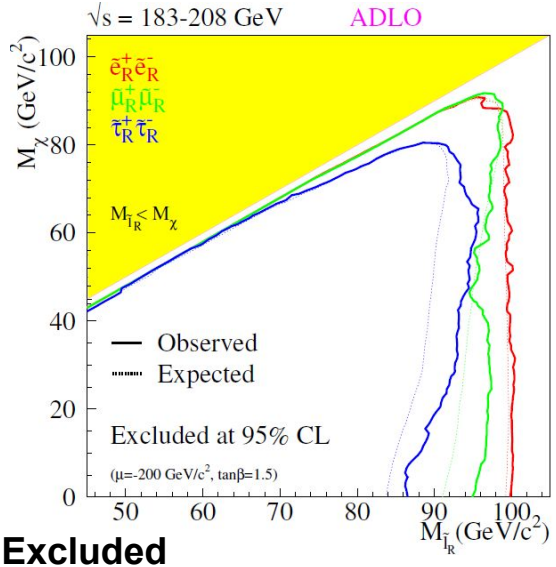

Low $\sigma$,
Taus in
final state


High $\sigma$,
soft final state,
Non-prompt decays

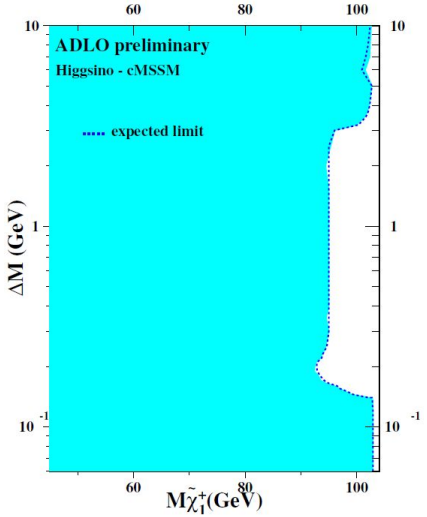

Low $\sigma$,
soft final state,

# From LEP to the LHC

In 2004 LEP combined the results of their SUSY searches… cutting a huge chunk into SUSY parameter space, but leaving vast areas still viable.




**Excluded**
Selectrons with mass < 100 GeV
Smuons with mass < 95 GeV
Staus with mass < 86 GeV




**Excluded**
Charginos with mass
< 92 (103) GeV for small (large) Δm

The Higgs discovery in 2012 helped to constrain SUSY (and SUSY may help to stablilize the Higgs mass!).
For "natural" SUSY:

$$\frac{m_H^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2$$

***Light higgsinos!***

$$\delta m_H^2\Big|_{stop} \cong -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{TeV}\right)$$

*Light stop (<1TeV)*

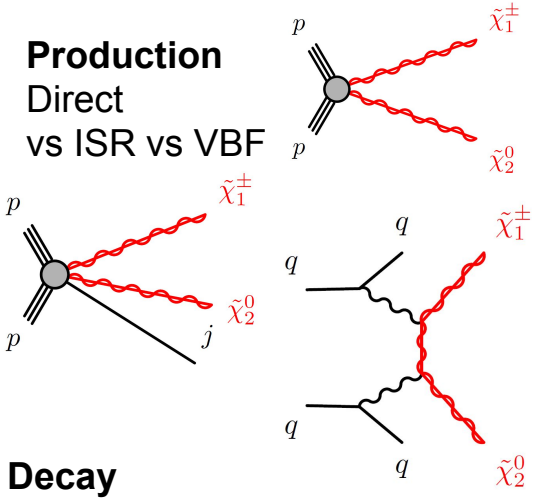
$$\delta m_H^2\Big|_{gluino} \cong -\frac{2y_t^2}{\pi^2}\left(\frac{\alpha_s}{\pi}\right)|M_3|^2\ln^2\left(\frac{\Lambda}{TeV}\right)$$

*Light gluinos (<1-2 GeV)*

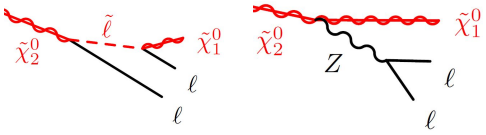
Weak-scale SUSY should be seen at the LHC!

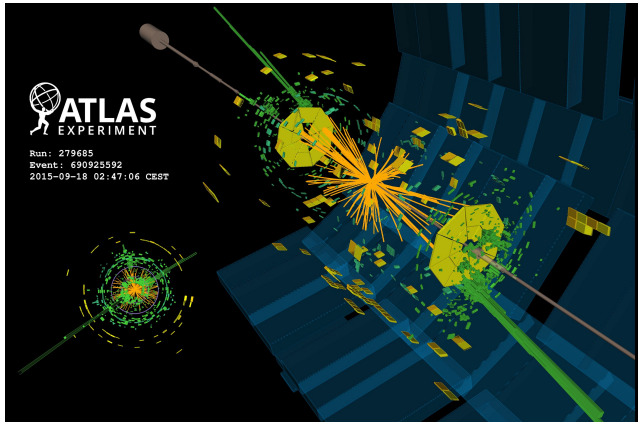
# EWK SUSY Searches at Hadron Colliders

**Production**
Direct
vs ISR vs VBF




**Decay**
Prompt vs Long lived
Via on/off-shell resonances
Short vs long decay chains



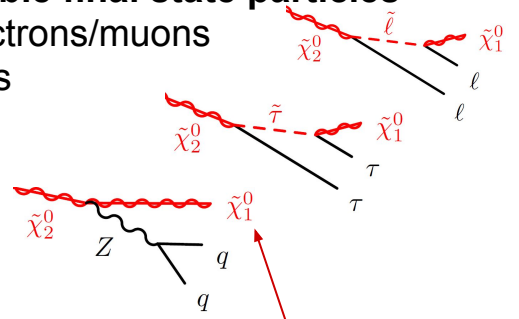




Put these all together to form a **coherent search strategy.**

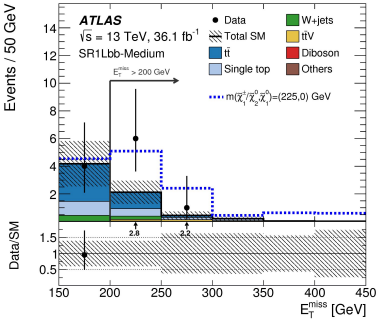
+ Optimise selection (sensitivity + SM background discrimination)
+ Accurately estimate background
+ Control systematic uncertainties

**= SUSY discovery?**

**Visible final state particles**
Electrons/muons
Taus
Jets



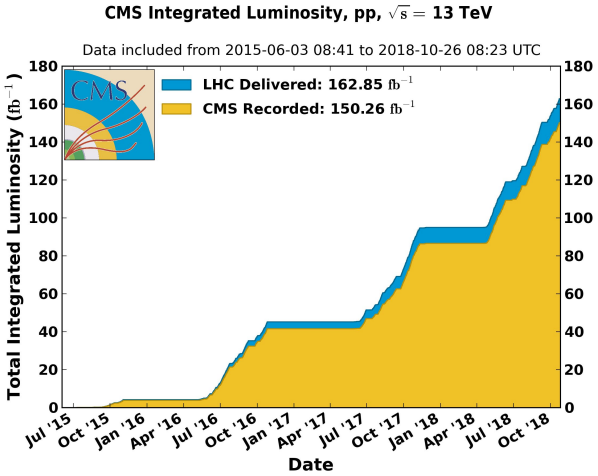

**Missing Energy**
Escaping massive LSPs -- smoking gun signature of SUSY

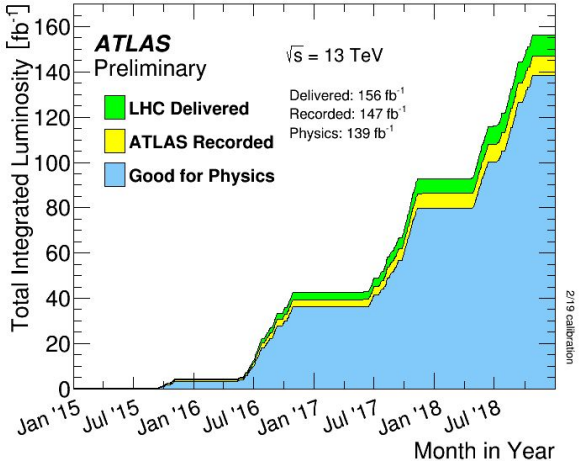


# The status today

ATLAS and CMS have recorded ~150ifb each at 13 TeV.

No signs of SUSY yet.

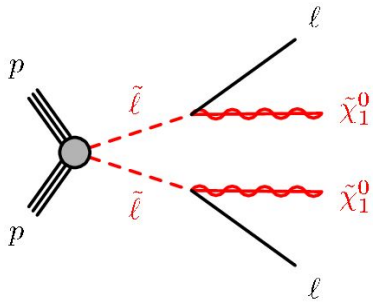


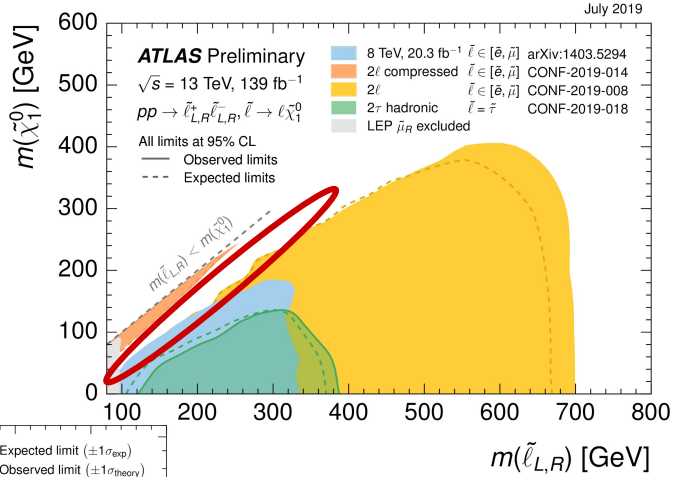



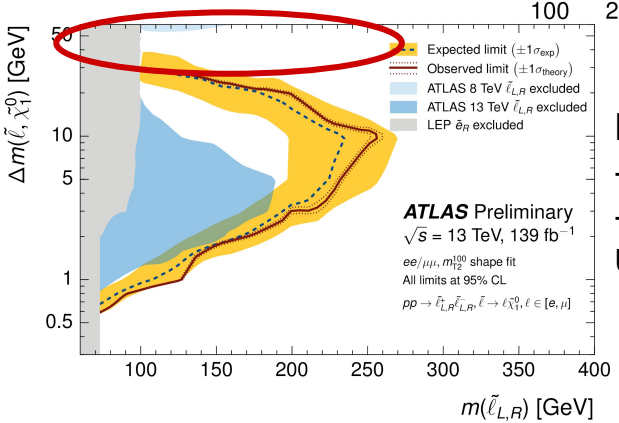

CMS results
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
For EWK SUSY
10 partial Run2 results

ATLAS results
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
For EWK SUSY
11 partial Run2 results
**6 full Run2 results**

# Sleptons: selectrons/smuons

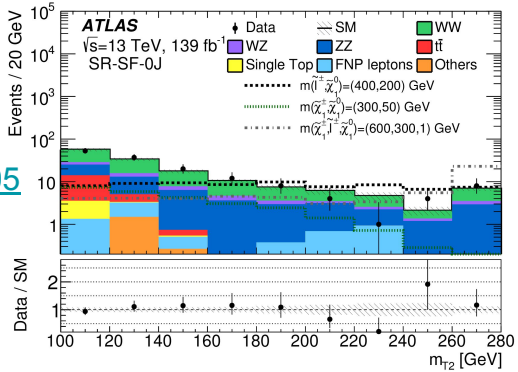


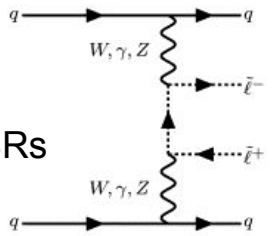

Clean 2$e$/$\mu$ final state! mT2 used for background discrimination (binned SRs)

ATLAS 139ifb
1908.08215
CMS 36ifb
PLB 790 (2019) 005

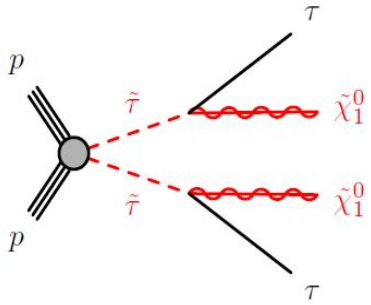



Dedicated efforts for compressed sleptons
- ATLAS 139ifb ATLAS-CONF-2019-014
- CMS 36ifb JHEP 03 (2018) 076
Using 2$e$/$\mu$, 1$e$/$\mu$+track, +ISR jets

Moderate dM uncovered
Target with reoptimised SRs
MVA with 1/2L
VBF production



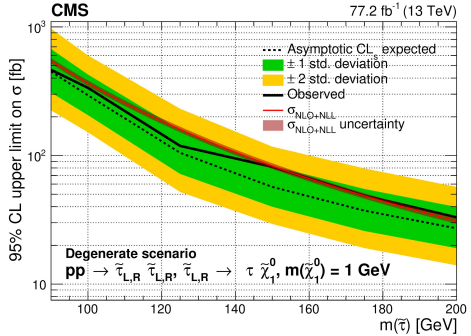
# Sleptons: staus

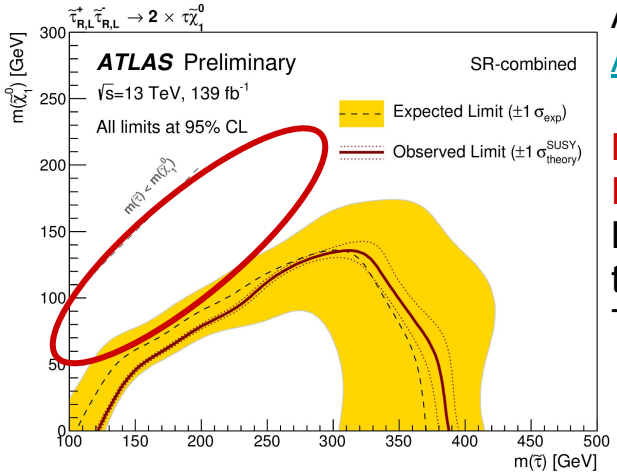



If tan$\beta$ is large, staus may be the only light sleptons.

CMS 77ifb covers 2$\tau$ (12 C&C SRs) and 1$\tau$1e/$\mu$ (3 BDTs)
ATLAS 139ifb covers 2$\tau$ (2 C&C SRs) with a tighter selection, 2$\tau$+MET trigger, lower uncertainties

CMS 77ifb sensitivity is low
CMS-SUS-18-006



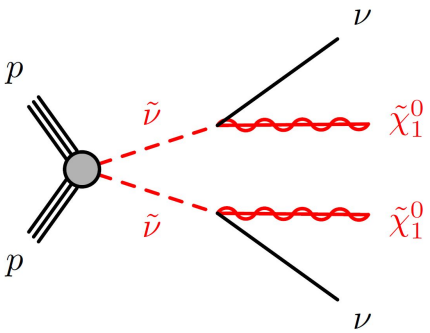

ATLAS sensitivity is high
ATLAS-CONF-2019-018

Moderate-compressed dM uncovered
Favoured by co-annihilation models!
Leading issue is high tau & trigger pT thresholds.
Target with:

- Leptonic tau decays
- Hadronic tau decays & VBF production

# Sleptons: sneutrinos

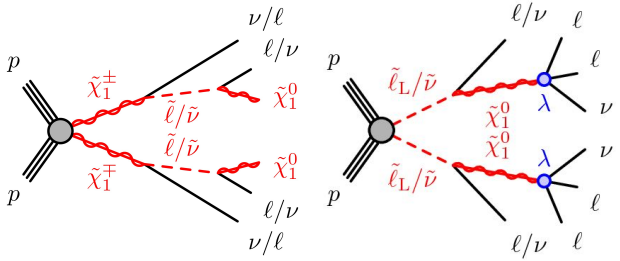
What about **sneutrinos**?



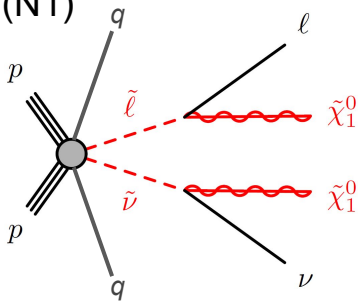

Low production cross-section.
No detectable final state.

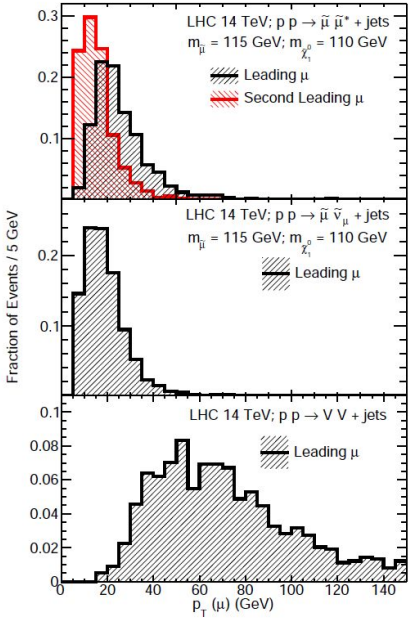
Reinterpret ISR+MET, VBF+MET analyses?

So far, only considered as intermediate step in decay chain, or in RPV scenarios

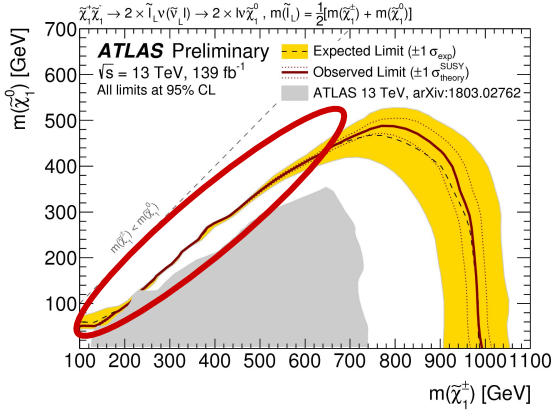



Consider VBF slepton-sneutrino production [PRD 91, 055025 (2015)] with softish 1L final state m(slep)>m(snu)>m(N1)

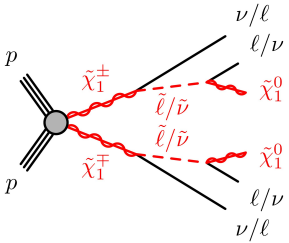


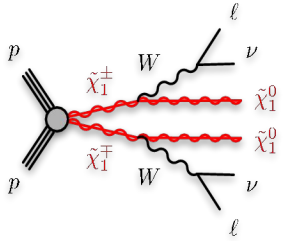



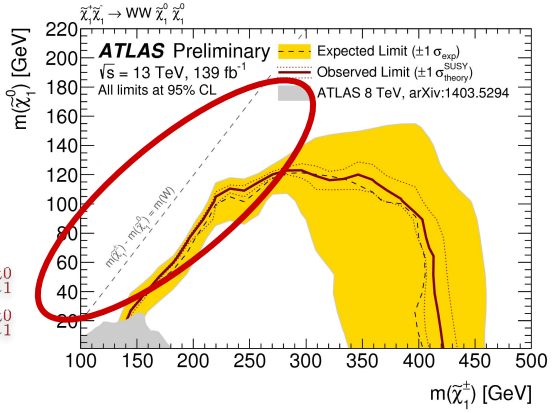
# Charginos



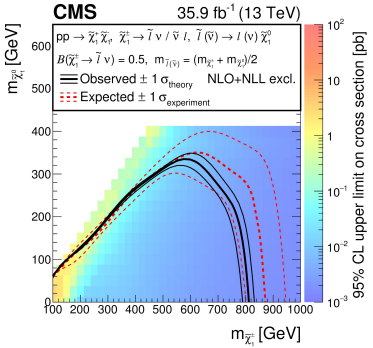

ATLAS 139ifb [1908.08215](1908.08215) result steamrolled past previous sensitivity to charginos via WW. More information used: DFOS leptons + binned mT2 SRs.







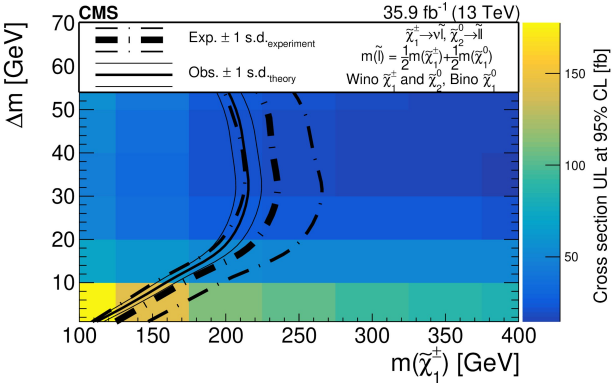

CMS 36ifb [JHEP 11 (2018) 079](JHEP 11 (2018) 079)



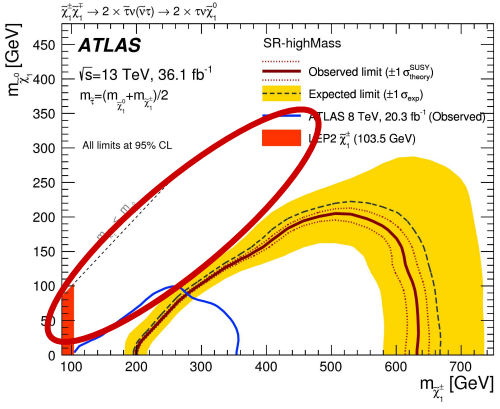

Moderate-compressed dM uncovered

Target with

- MVA
- Improve soft lepton ID
- VBF [a la CMS](a la CMS) →
- 2L/1L selection

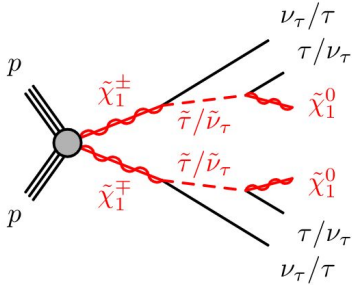


# Charginos




Moderate-compressed dM uncovered

Similar approach as for stau production.

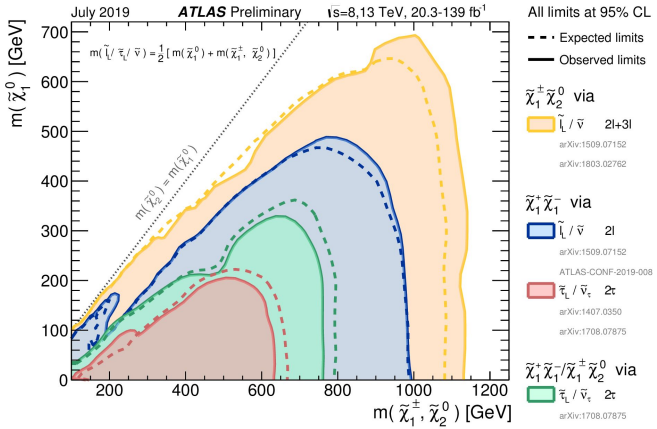



Target with

- Leptonic tau decays
- Hadronic tau decays & VBF production

# Charginos+Neutralinos

Optimistic scenario with decays via sleptons is generally well covered. Improvements to be made at low dM, target in a similar way to slepton prod.

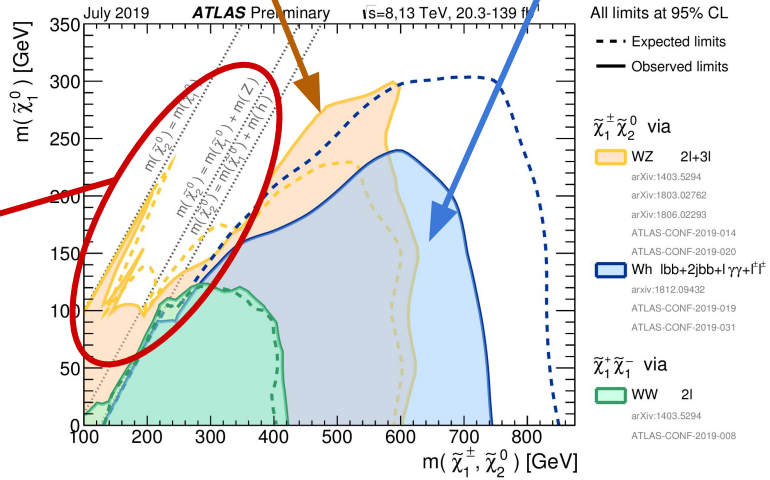



More difficult scenarios with decays via SM bosons are making huge leaps in sensitivity.

3L + 2L2J
ATLAS EPJC 78 (2018) 995
CMS JHEP 03 (2018) 160
Potential to add all-hadronic channels

1Lbb
ATLAS-CONF-2019-031/
+ all-hadronic channels
PRD 100, 012006 (2019)

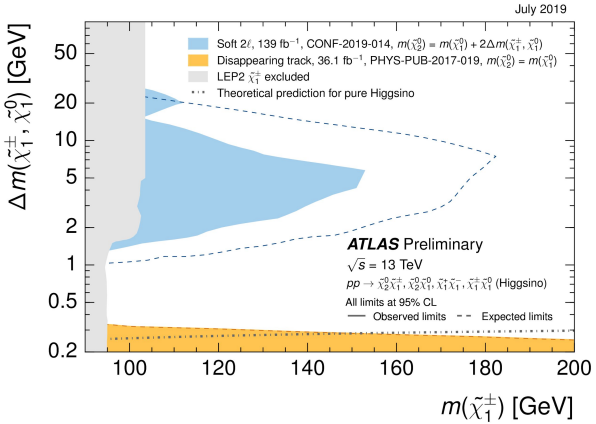
Lots of room for improvement in low dM and on-shell V diagonals

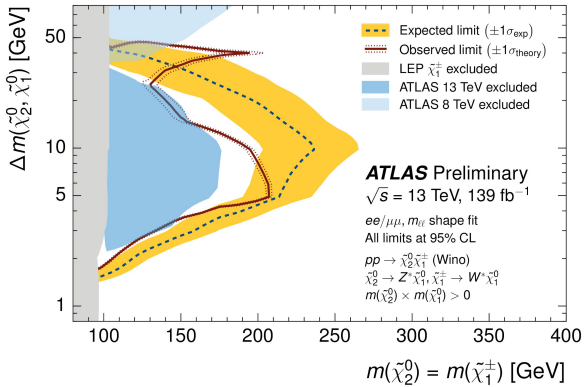


# Compressed SUSY: so hot right now

UNIVERSITY OF CAMBRIDGE

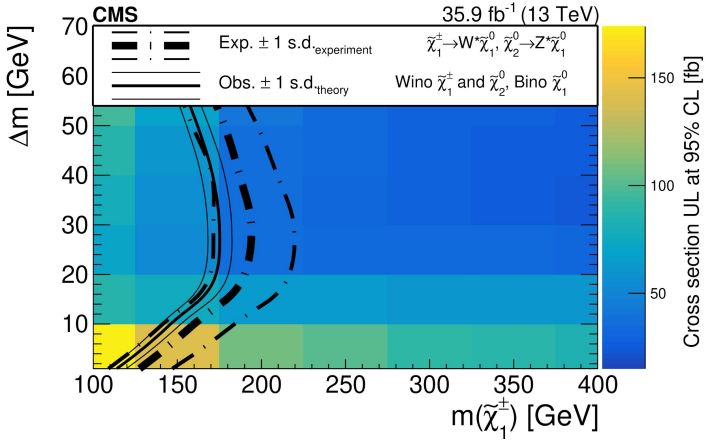
ATLAS EXPERIMENT

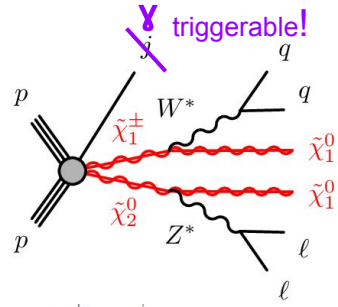



Many holes in sensitivity could be filled by growing the compressed programme.
Target with

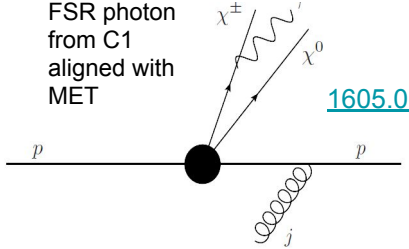
- Isolated track(s) see [ATLAS-CONF-2019-014]
- Initial/[Final state photons]
- Monojet (reinterpretation?)
- VBF [a la CMS] ↓

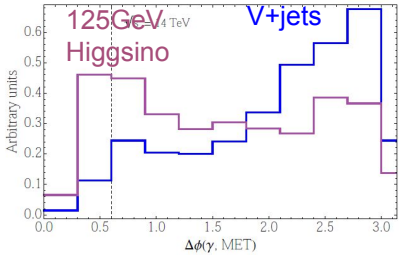



FSR photon from C1 aligned with MET

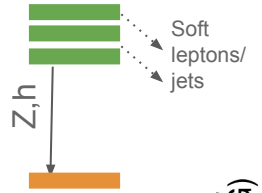
[1605.00658]



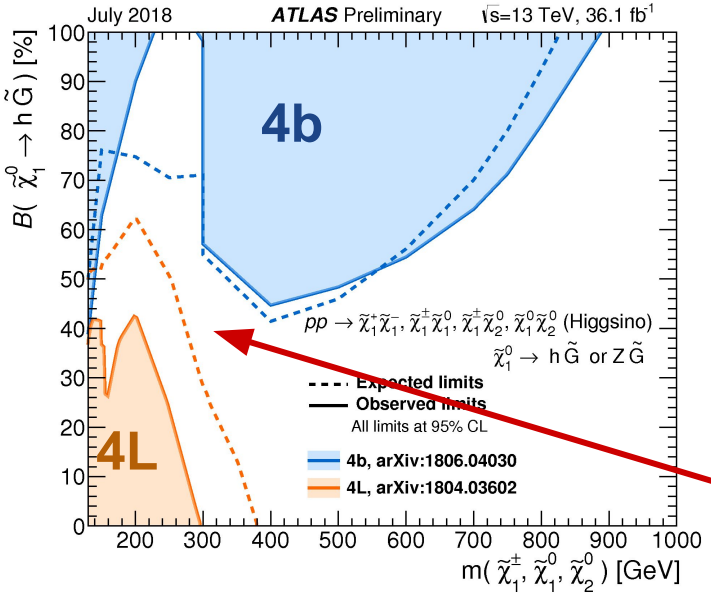



# GGM scenarios

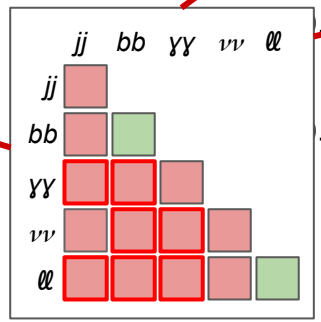
Higgsino triplet, close in mass.
Gravitino LSP.



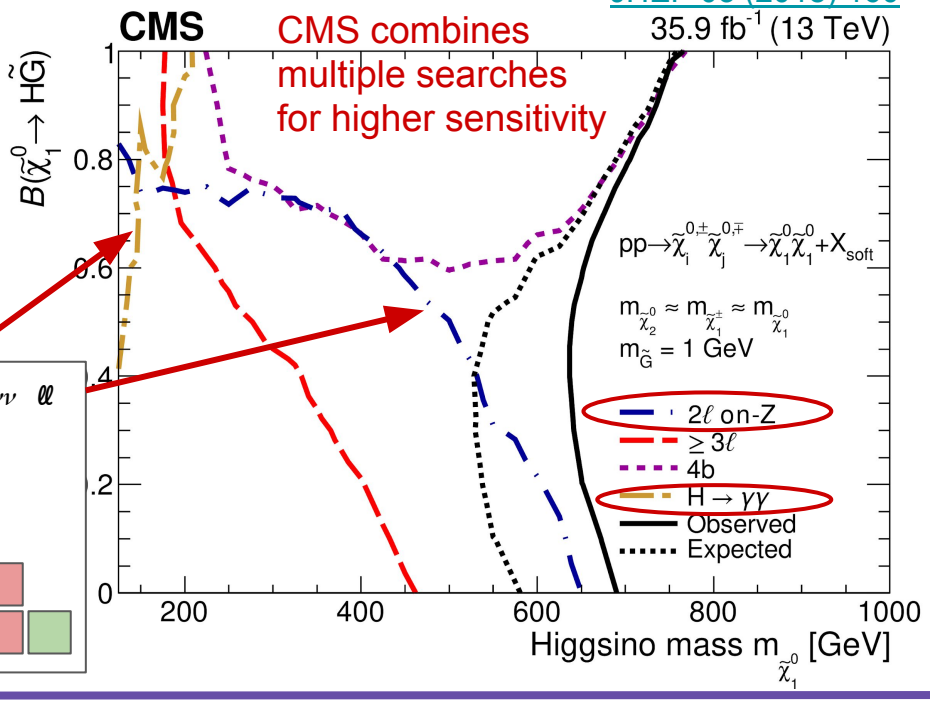

$\tilde{\chi}_1^0 \rightarrow h\tilde{G}$ or $Z\tilde{G}$




Add channels for mixed decays



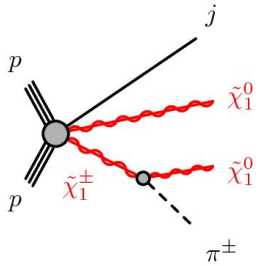

JHEP 03 (2018) 160

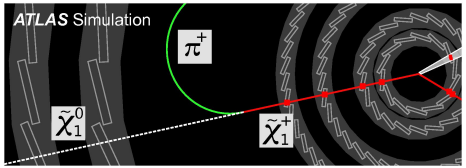


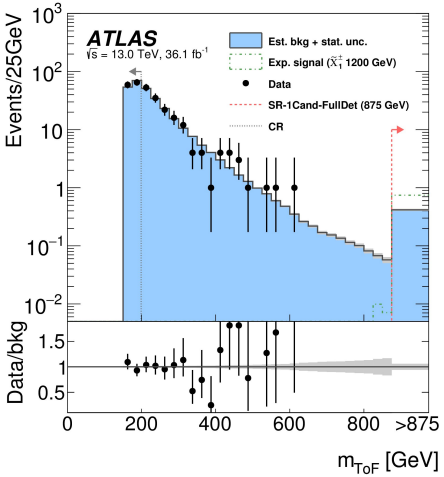
# Long Lived Electroweakinos

If the NLSP is charged and close in mass to the LSP, then NLSP can be long-lived. Two approaches:

- NLSP is **stable** on detector scale ---> **Tracking + ToF** (& ionization loss for heavy particles)
  ATLAS 36ifb PRD 99 (2019) 092007



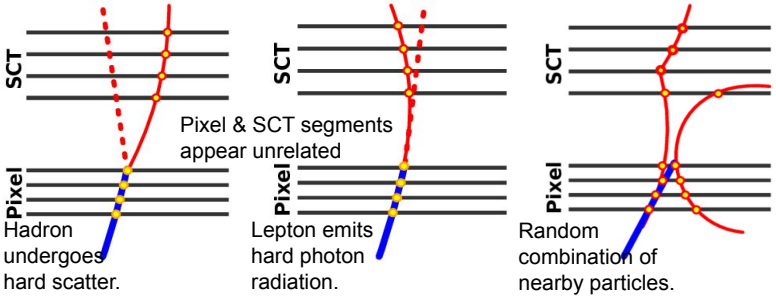



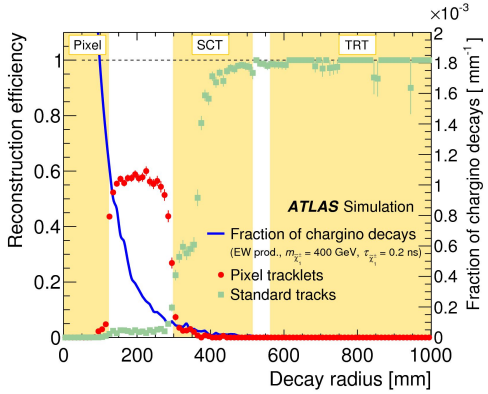

- NLSP **short-lived** & decays within the detector ---> **disappearing tracks**

ATLAS 36ifb JHEP 06 (2018) 022

Innovative use of Pixel tracklets pT>5GeV to search for long-lived charged particle decays.
Better reco efficiency than standard tracking alone.

Backgrounds from….

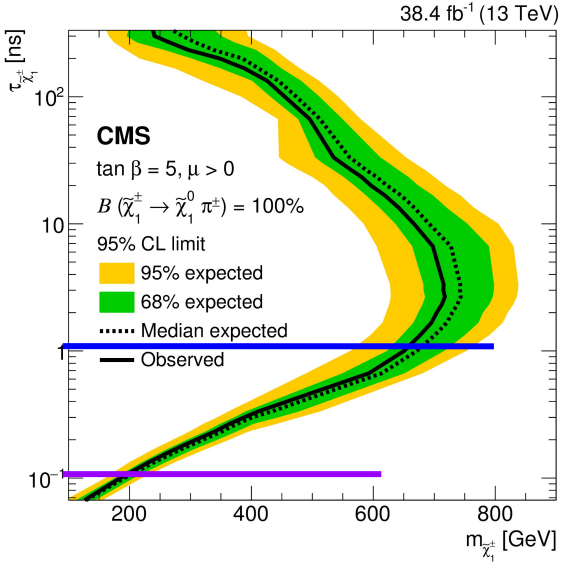


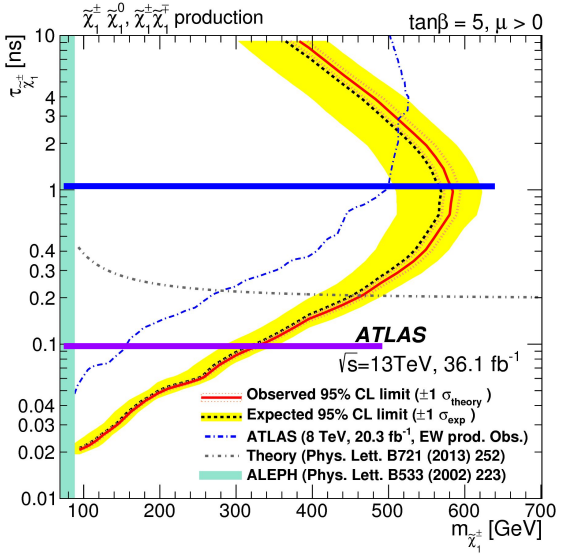
# Long Lived Electroweakinos

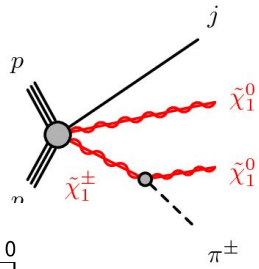
CMS 38ifb result on disappearing tracks JHEP 08 (2018) 016
High pT tracks pT>55 GeV with missing outer hits

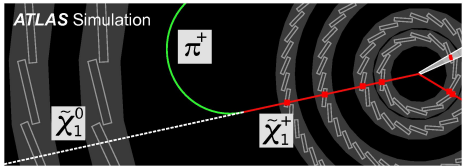
CMS more sensitive to longer lived charginos τ~1-10s




ATLAS more sensitive to shorter lived charginos τ~0.1s

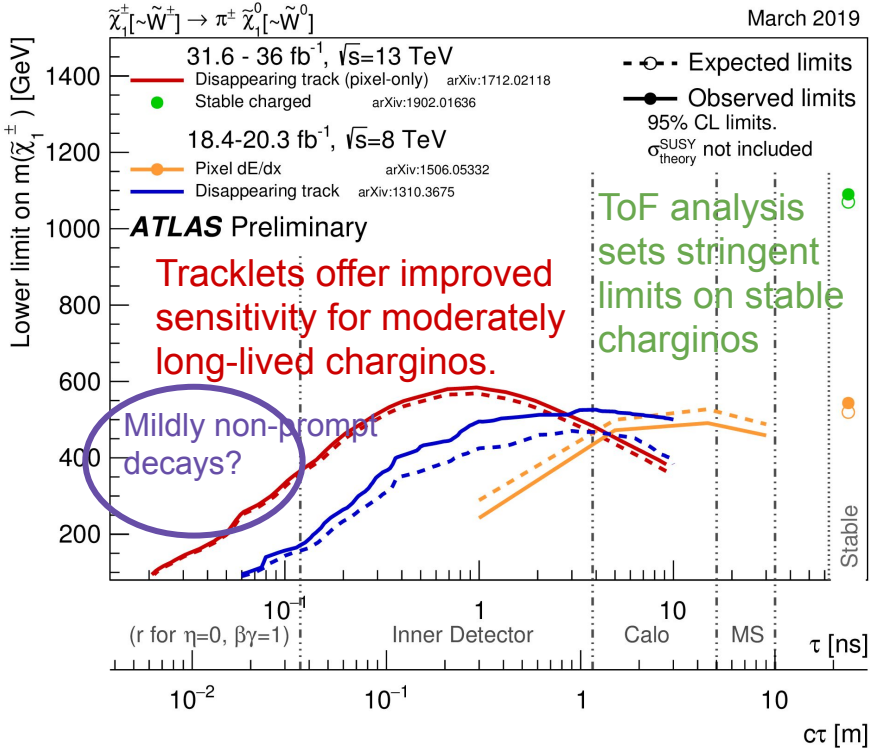


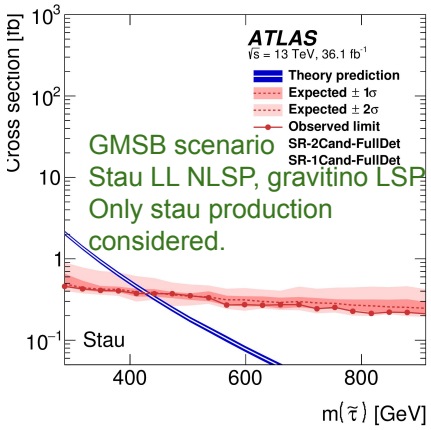



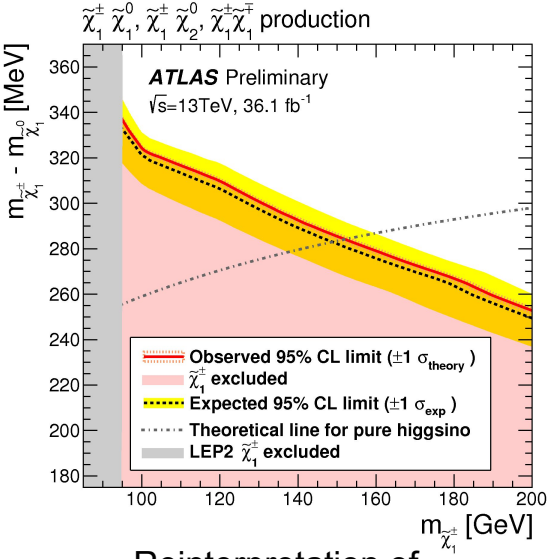




CMS stable charged particle search focus on gluinos PRD 94 (2016) 112004

# Long Lived Electroweakinos




Reinterpretation of disappearing tracks for compressed higgsino scenarios

ATL-PHYS-PUB-2017-019

# It's not all doom and gloom!

ATLAS sees some *interesting (not significant!)* excesses in the partial Run2 dataset

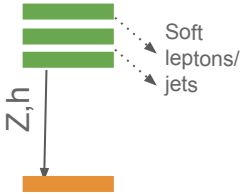
Update with full Run2 dataset in progress! + CMS results to come!

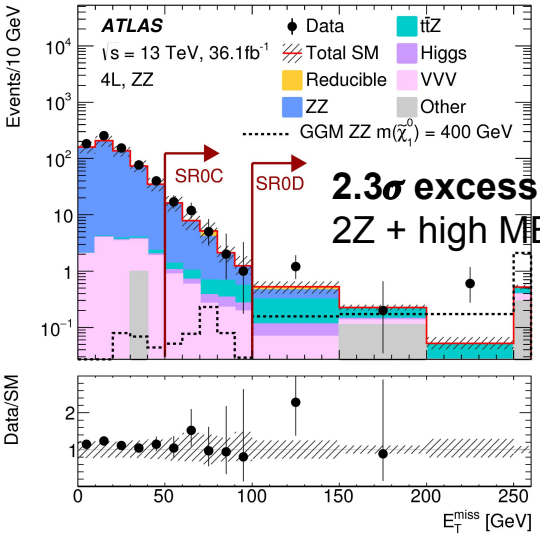
ATLAS 36ifb 4L PRD 98 032009 (2018)

Higgsino triplet, close in mass.

Gravitino LSP.

$\tilde{\chi}_1^0 \rightarrow h\tilde{G}$ or $Z\tilde{G}$



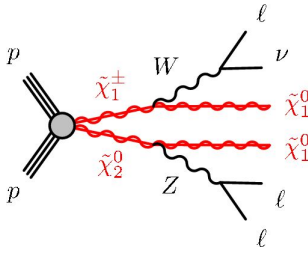

**2.3σ excess** in
2Z + high MET selection

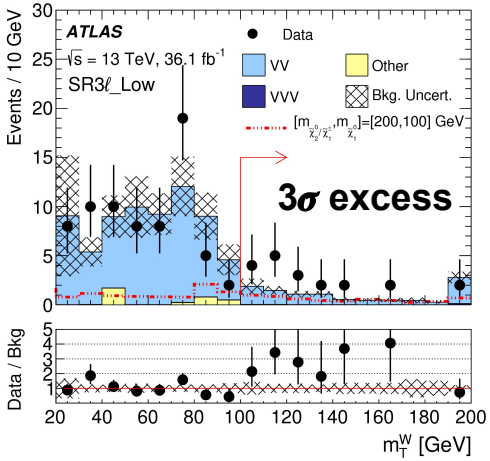
ATLAS 2L/3L RJR PRD 98 (2018) 092012

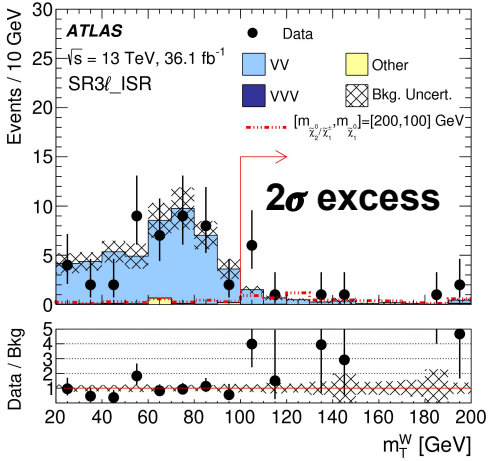
2σ,3σ excess in 2L,3L ISR SRs

2σ excess in low MET SR

Tension with conventional 2/3L results



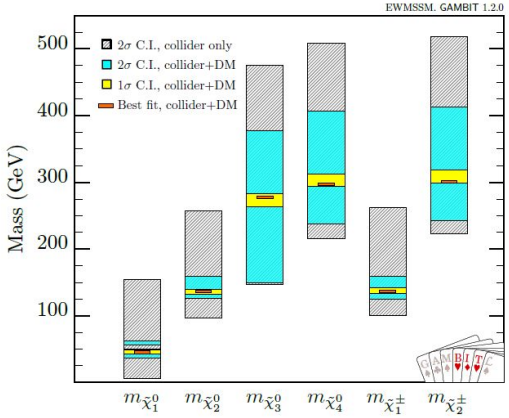



# Reinterpreting ATLAS & CMS results

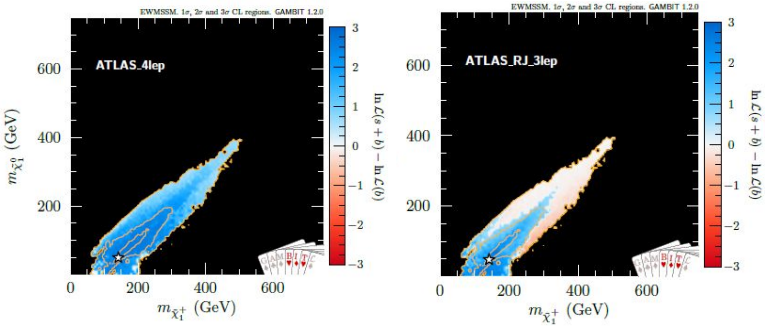
GAMBIT Combined collider constraints on neutralinos and charginos EPJC 79, 2019
Sample MSSM parameter space in M1, M2, $\mu$, tan$\beta$, run MC simulations
Joint likelihood calculations for analyses targeting the electroweakino sector
36ifb Run2 dataset (+LEP + Z/h -> invisible)
Likelihood driven by ATLAS excesses (3L RJR & 4L dominate)

"However, a pattern of excesses in several LHC analyses points towards a possible signal, with neutralino masses of m(N1, N2, N3, N4) = (8-155, 103-260, 130-473, 219-502) GeV and chargino masses of m(C1, C2) = (105-259, 24-507) GeV at the 95% CL."

N1 ~ bino, 3.3σ local significance (2.9σ if 8 TeV results added)




| Likelihood label | Source |
|---|---|
| ATLAS_4b | ATLAS Higgsino search [120] |
| ATLAS_4lep | ATLAS 4$\ell$ search [121] |
| ATLAS_MultiLep_2lep_0jet | ATLAS multilepton EW search [116] |
| ATLAS_MultiLep_2lep_jet | ATLAS multilepton EW search [116] |
| ATLAS_MultiLep_3lep | ATLAS multilepton EW search [116] |
| ATLAS_RJ_2lep_2jet | ATLAS recursive jigsaw EW search [117] |
| ATLAS_RJ_3lep | ATLAS recursive jigsaw EW search [117] |
| CMS_1lep_2b | CMS $Wh$ search [122] |
| CMS_2lep_soft | CMS 2 soft opposite-charge lepton search |
| CMS_2OSlep | CMS 2 opposite-charge lepton search [126 |
| CMS_MultiLep_2SSlep | CMS multilepton EW search [127] |
| CMS_MultiLep_3lep | CMS multilepton EW search [127] |

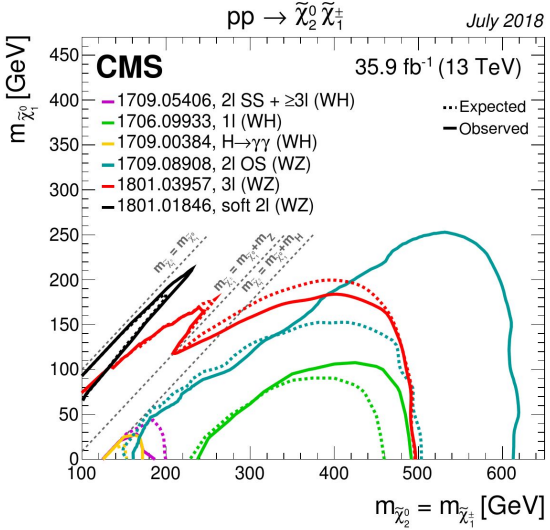


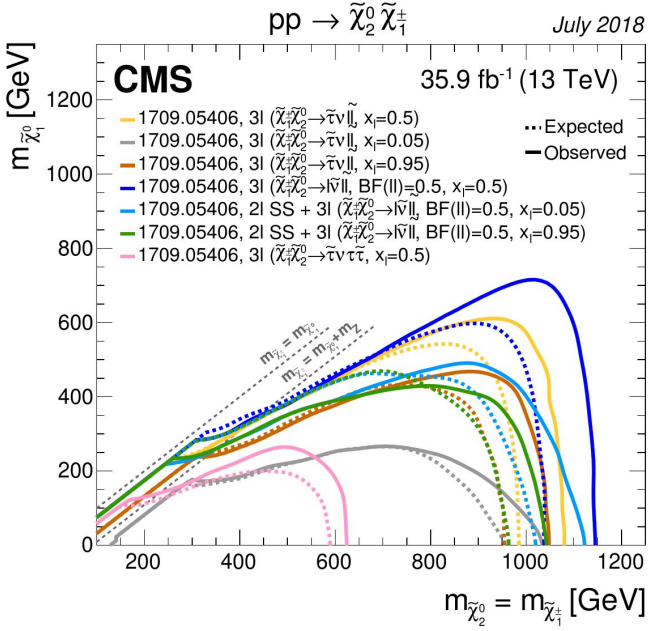

GAMBIT have provided some interesting models to look at:
Models with non-negligible N3,N4,C2 production
multileptons+multijets

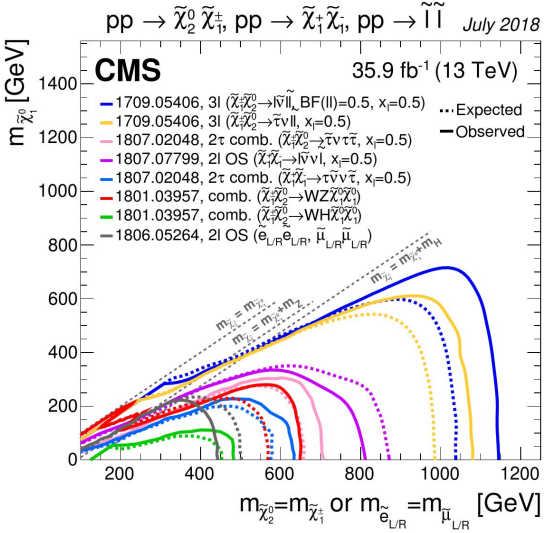
– $\tilde{\chi}_2^\pm\tilde{\chi}_4^0$ production, with e.g.
$\tilde{\chi}_2^\pm \to Z + \tilde{\chi}_1^\pm \to Z + W^\pm + \tilde{\chi}_1^0$,
$\tilde{\chi}_4^0 \to h + \tilde{\chi}_2^0 \to h + Z + \tilde{\chi}_1^0$

# What are we missing?

Full Run2 dataset updates from many analyses -- especially CMS!



# Outlook

General coverage is **very** impressive

Recent efforts to extend coverage for
- Compressed scenarios
- Direct staus
- Wh using hadronic channels
- WW using binning in mT2

Missing
- Sensitivity to moderately compressed scenarios
- Soft isolated track, soft photons, compressed staus
- Photon ISR, monojet/photon for EWK
- Mildly non-prompt decays
- Combination of more analyses
  (e.g. CMS GGM combination)

- **Discovery!** *(+huge gains to be made with HL-LHC)*