Recontres de Physique, La Thuile 2019/03/15

Searches for SUSY at the LHC

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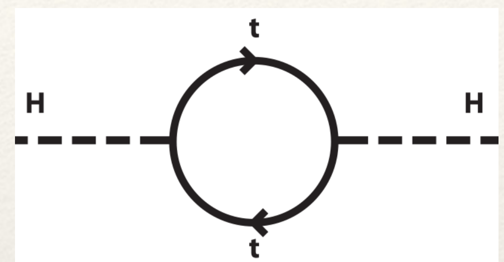
WHY SUSY IS COOL

- Electroweak symmetry breaking predicted and natural
- Dark Matter candidate
- Unification of forces
- …
- Rich variety of signatures for the experiment to measure
- No SUSY particles has been observed yet ☹



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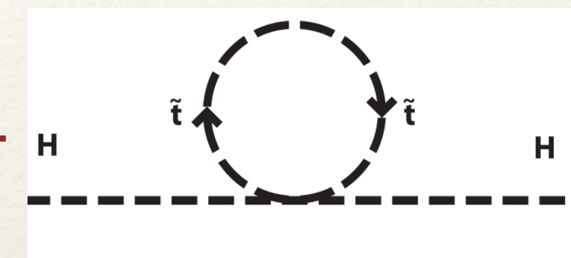

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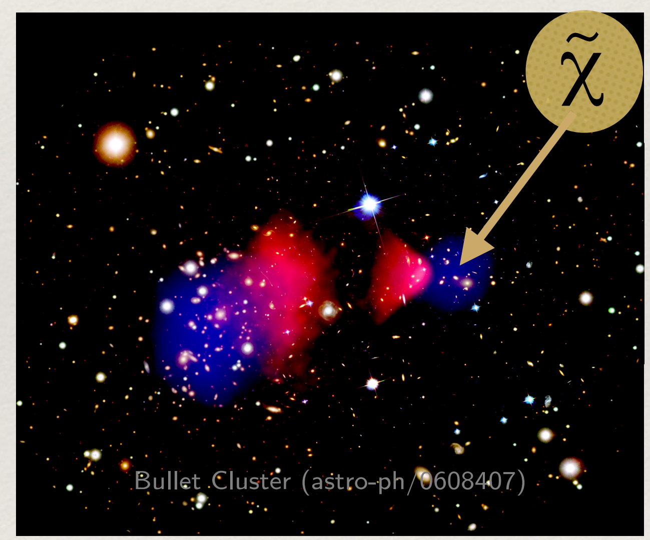
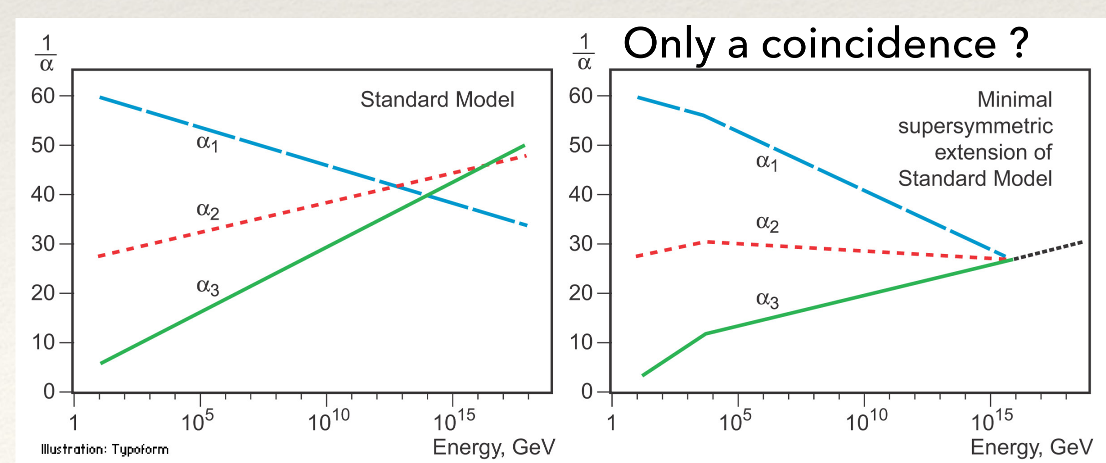
Only works if stop not much heavier than top and Higgs !



- Requires R-parity conservation
- Constraints from relic density and direct detection limits

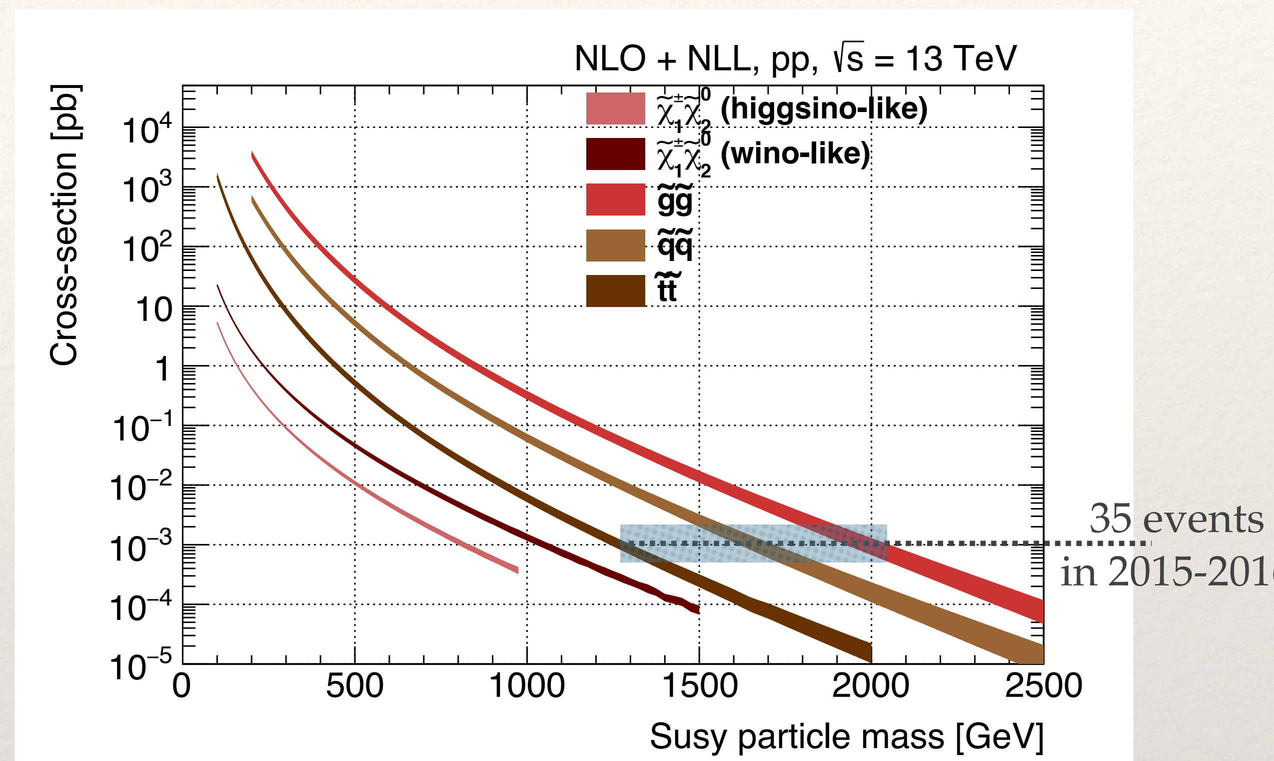


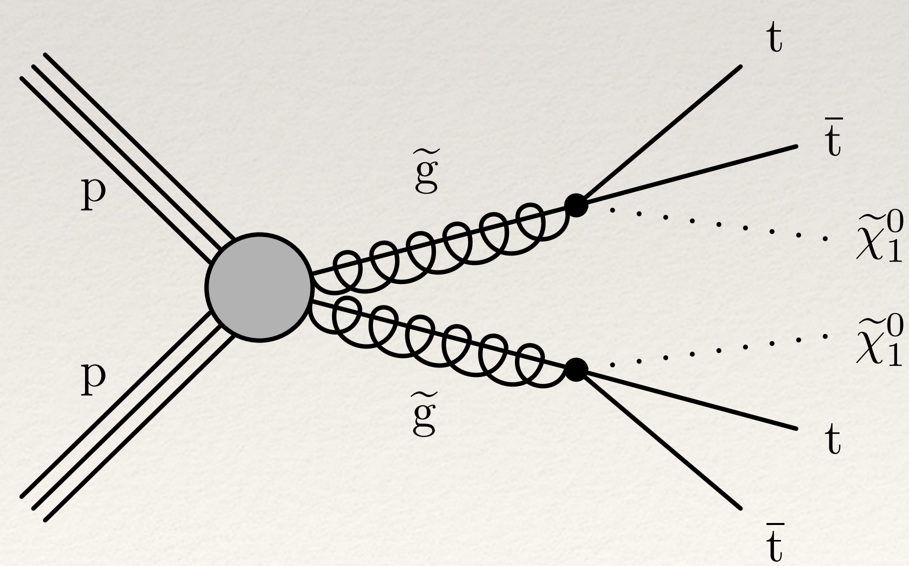
LOTS OF SUSY RESULTS

- SUSY searches at experiments pursued vigorously : 22 new ATLAS or CMS papers submitted since La Thuile last year
  - Only papers from SUSY working group, not including those with relevant SUSY interpretations from other working groups.
- Here I will give a broad overview and more details on some recent results (since November)
- For everything else, check the experiments pages :
  - **https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults**
  - **https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS**

STRONG PRODUCTION

- High cross section => probing high masses
- R-parity conservation => lightest particle (LSP) stable, missing momentum
- High-p_T jets
- Depending on decay chain, possibly leptons and photons
- “Easy” - but strong limits from previous searches!
- Example : CMS Razor search [1812.06302]





CMS RAZOR : STRATEGY AND SELECTION

- Several event categories
- Visible momenta clustered in two mega jets and used to compute Razor variables
  - M_R peaking at new particle mass
  - R sensitive to weakly interacting particles momenta

$$M_R \equiv \sqrt{(|\vec{p}^{j_1}| + |\vec{p}^{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2},$$

$$M_T^R \equiv \sqrt{\frac{p_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{p}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}},$$

$$R \equiv \frac{M_T^R}{M_R}$$

Category	Preselection	Additional requirements	Trigger requirement
Lepton multijet	$M_R > 550\,GeV$ & $R^2 > 0.20$	$m_T > 120\,GeV$	Single lepton
Lepton seven-jet	$M_R > 550\,GeV$ & $R^2 > 0.20$	$m_T > 120\,GeV$	Single lepton
Boosted W 4–5 jet	$M_R > 800\,GeV$ & $R^2 > 0.08$	$\Delta\phi_R < 2.8$	H_T, jet p_T
Boosted W 6 jet	$M_R > 800\,GeV$ & $R^2 > 0.08$	$\Delta\phi_R < 2.8$	H_T, jet p_T
Boosted top	$M_R > 800\,GeV$ & $R^2 > 0.08$	$\Delta\phi_R < 2.8$	H_T, jet p_T
Dijet	$M_R > 650\,GeV$ & $R^2 > 0.30$	$\Delta\phi_R < 2.8$	Hadronic razor
Multijet	$M_R > 650\,GeV$ & $R^2 > 0.30$	$\Delta\phi_R < 2.8$	Hadronic razor
Seven-jet	$M_R > 650\,GeV$ & $R^2 > 0.30$	$\Delta\phi_R < 2.8$	Hadronic razor

lepton veto

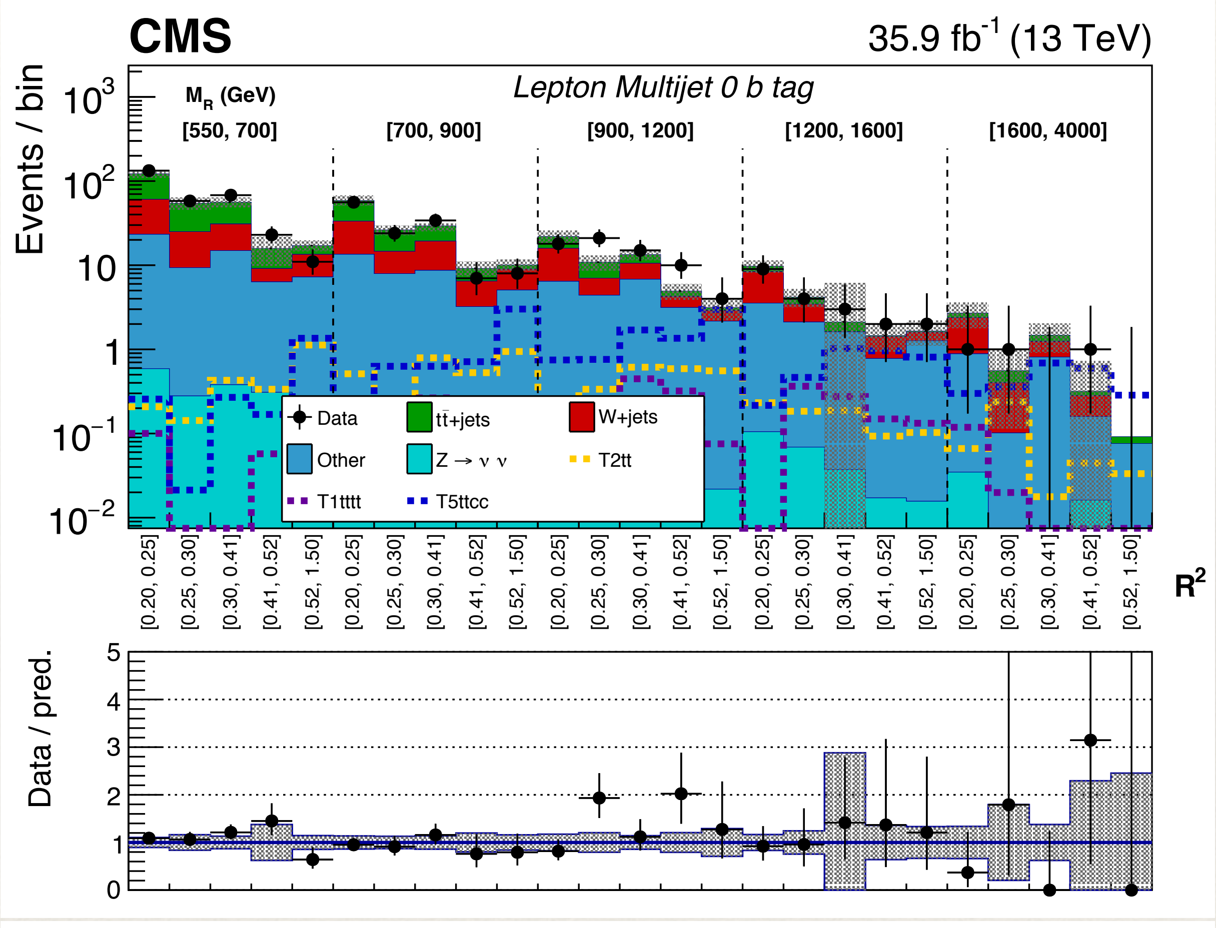
signal region (SR) binned in M_R and R

BACKGROUND ESTIMATE AND RESULTS

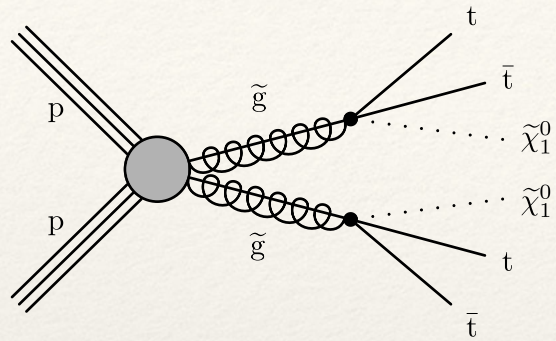
Background estimate :

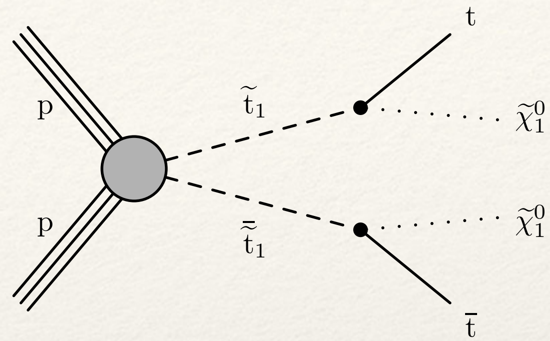
- W(lν), tt, Z(νν) : MC with corrections to M_R and R^2 derived in control samples (1L0b, 1L, γ+jets)
- Validation and systematics in additional control samples
- QCD multijet control samples inverting $\Delta\phi_R$

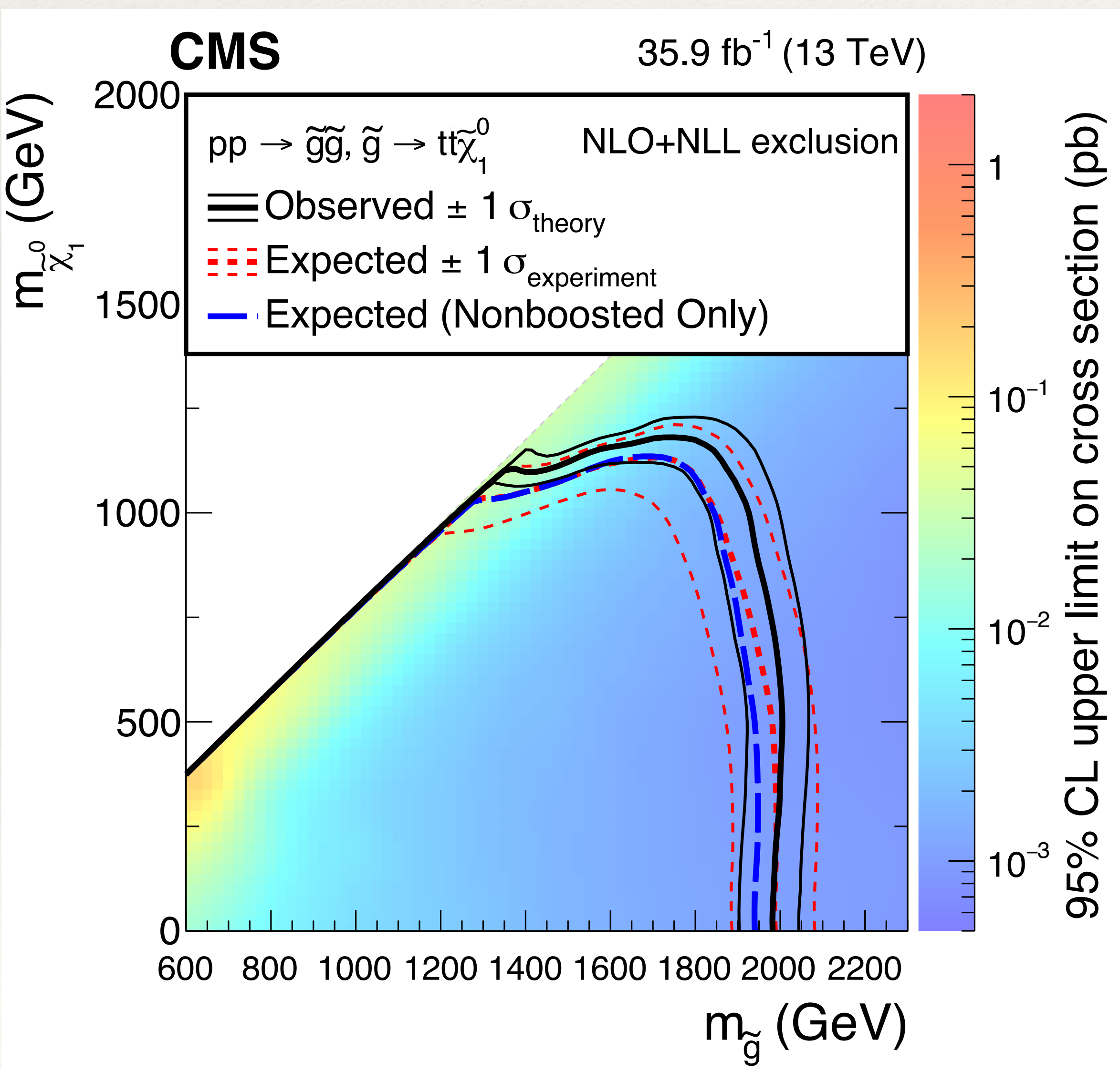
Results for one of the eight categories :

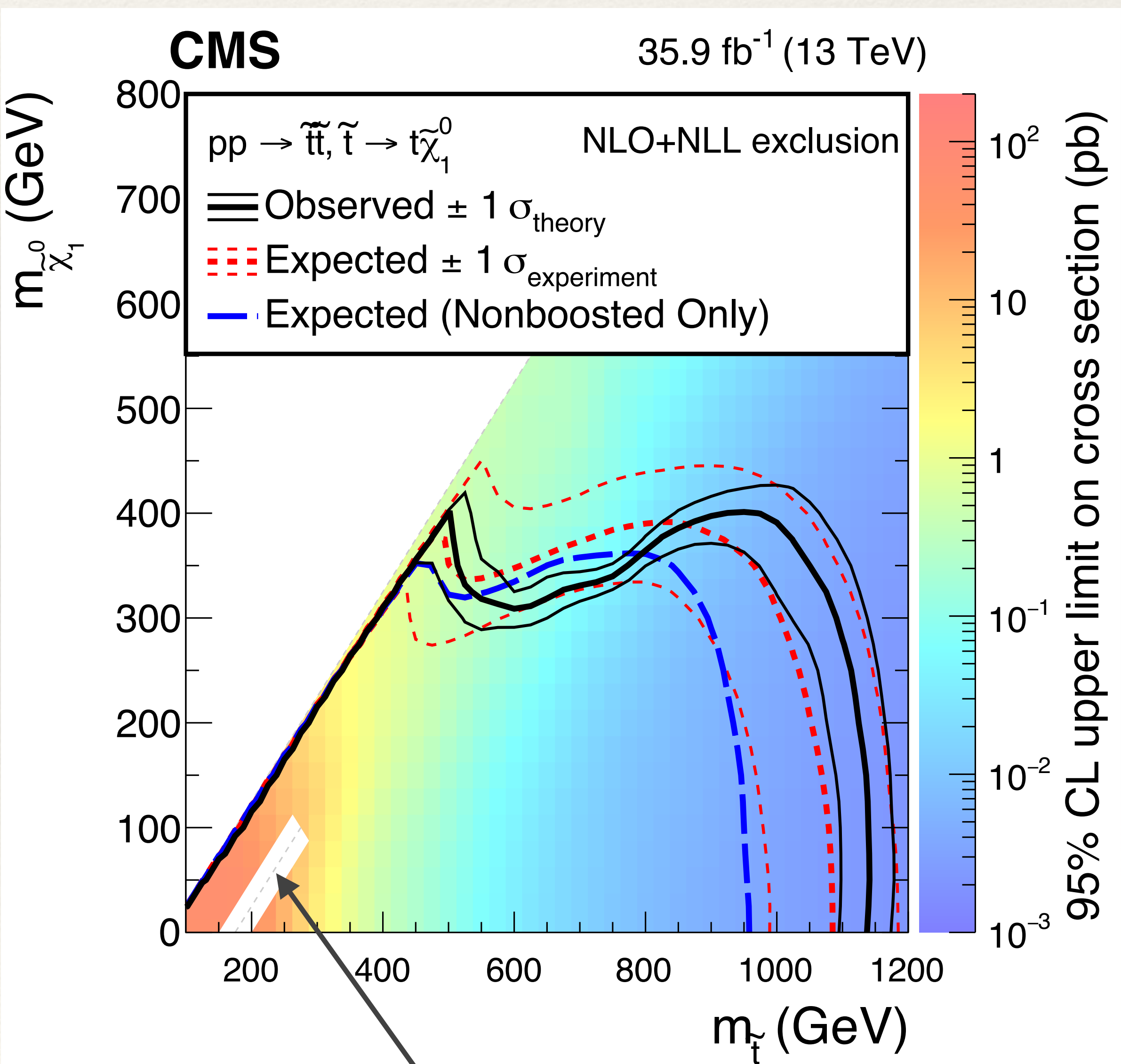


RAZOR INTERPRETATIONS





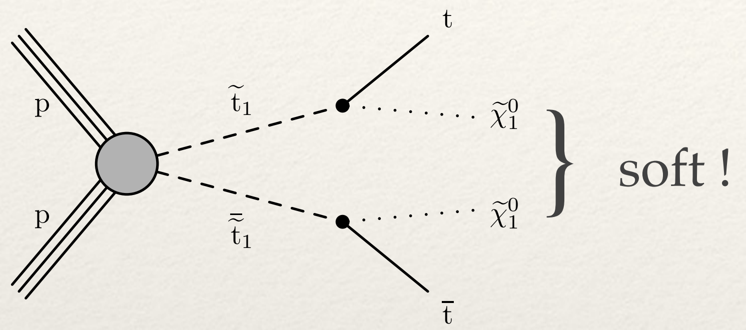




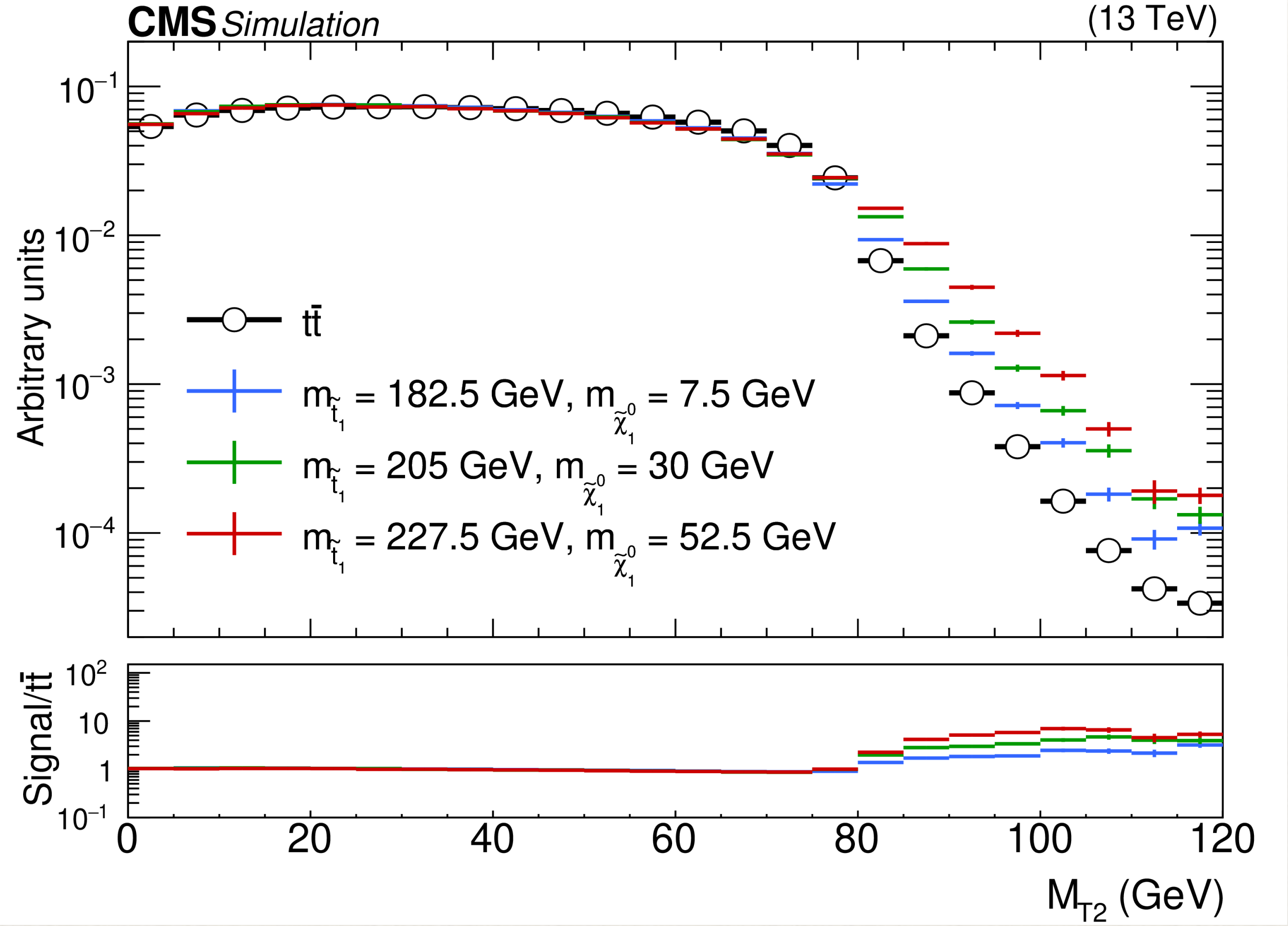
Stealth stop region, see next slide

STEALTH STOP SEARCHES

Near decay threshold, kinematics very similar to tt events !

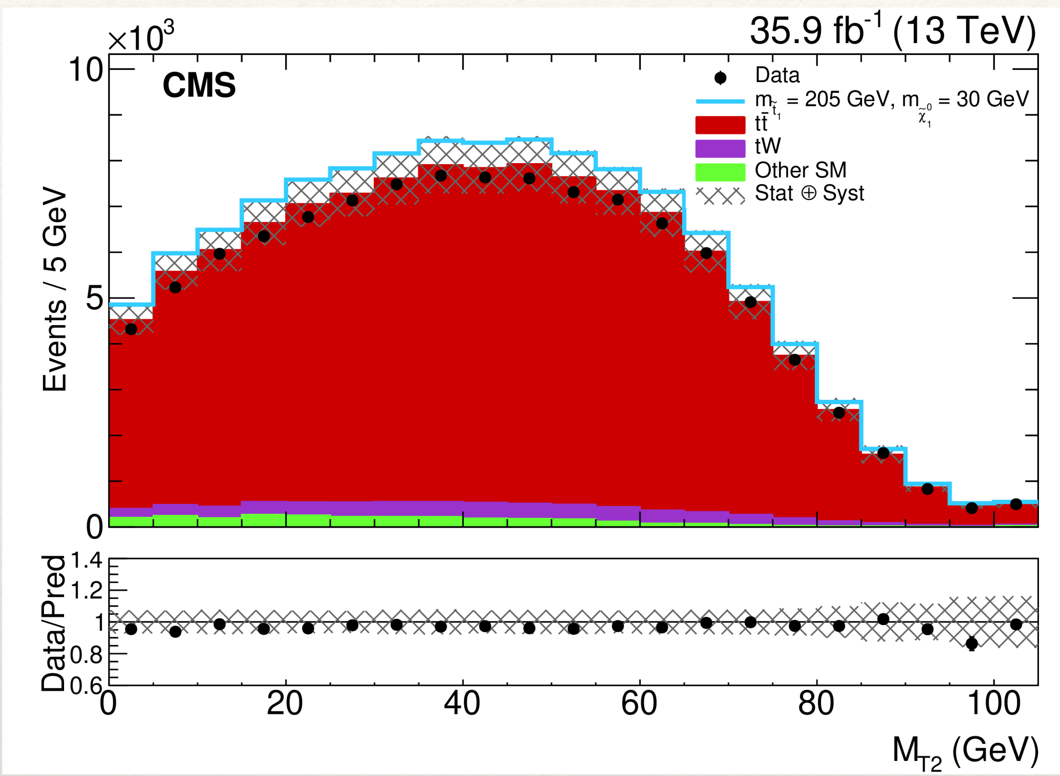


- High m_{LSP} : neutralinos carry a significant fraction of stop boost : extra MET.
- Low m_{LSP} : soft neutralinos but extra cross section and weaker spin correlation effects (stop are scalars!)
- New CMS search : use M_{T2} shape and normalization to achieve sensitivity across different masses

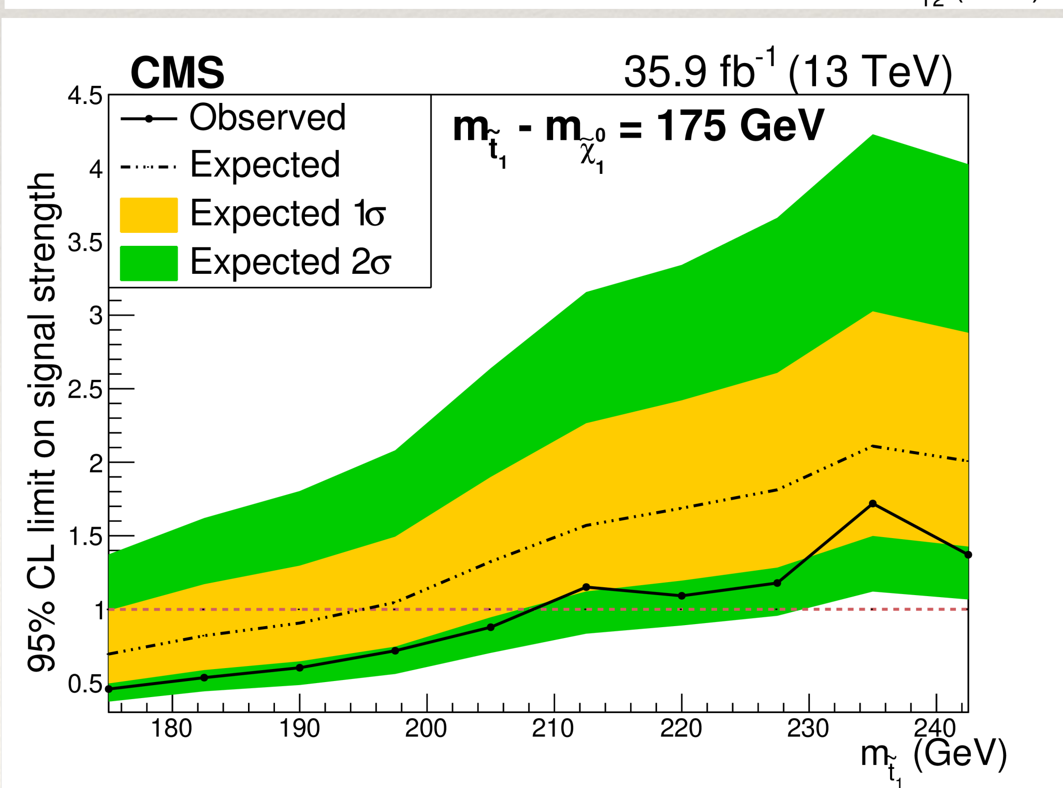


Selection : eμ, 2 jets, 1 b-jet (in SM 98% pure top)

CMS STEALTH STOP



M_{T2} (used in exclusion fit) : good agreement with SM.

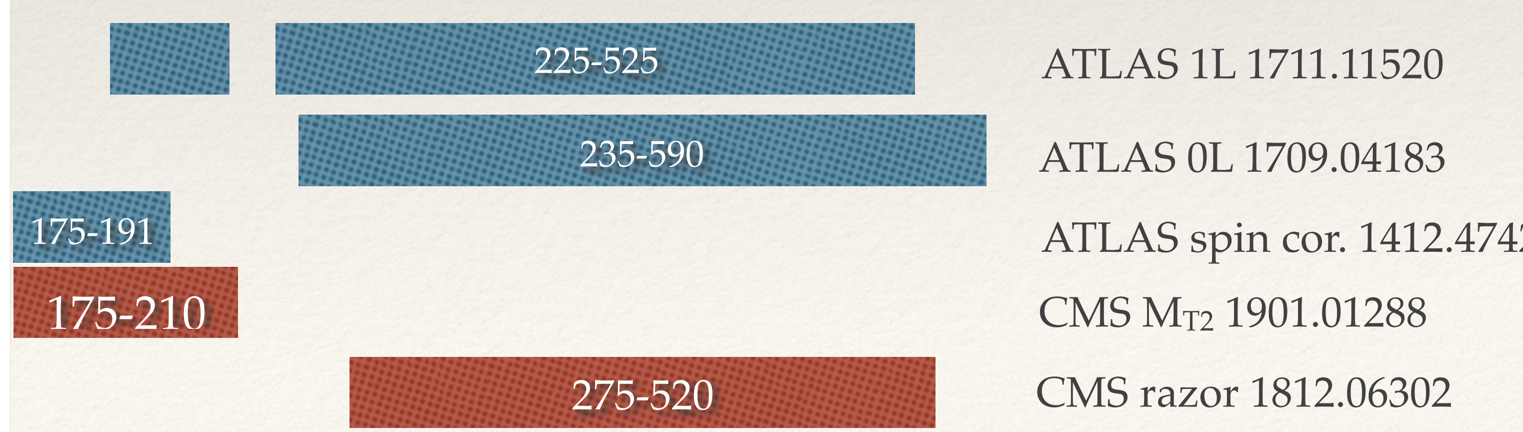


$m(\tilde{t}) < 210$ GeV excluded for ΔM at threshold

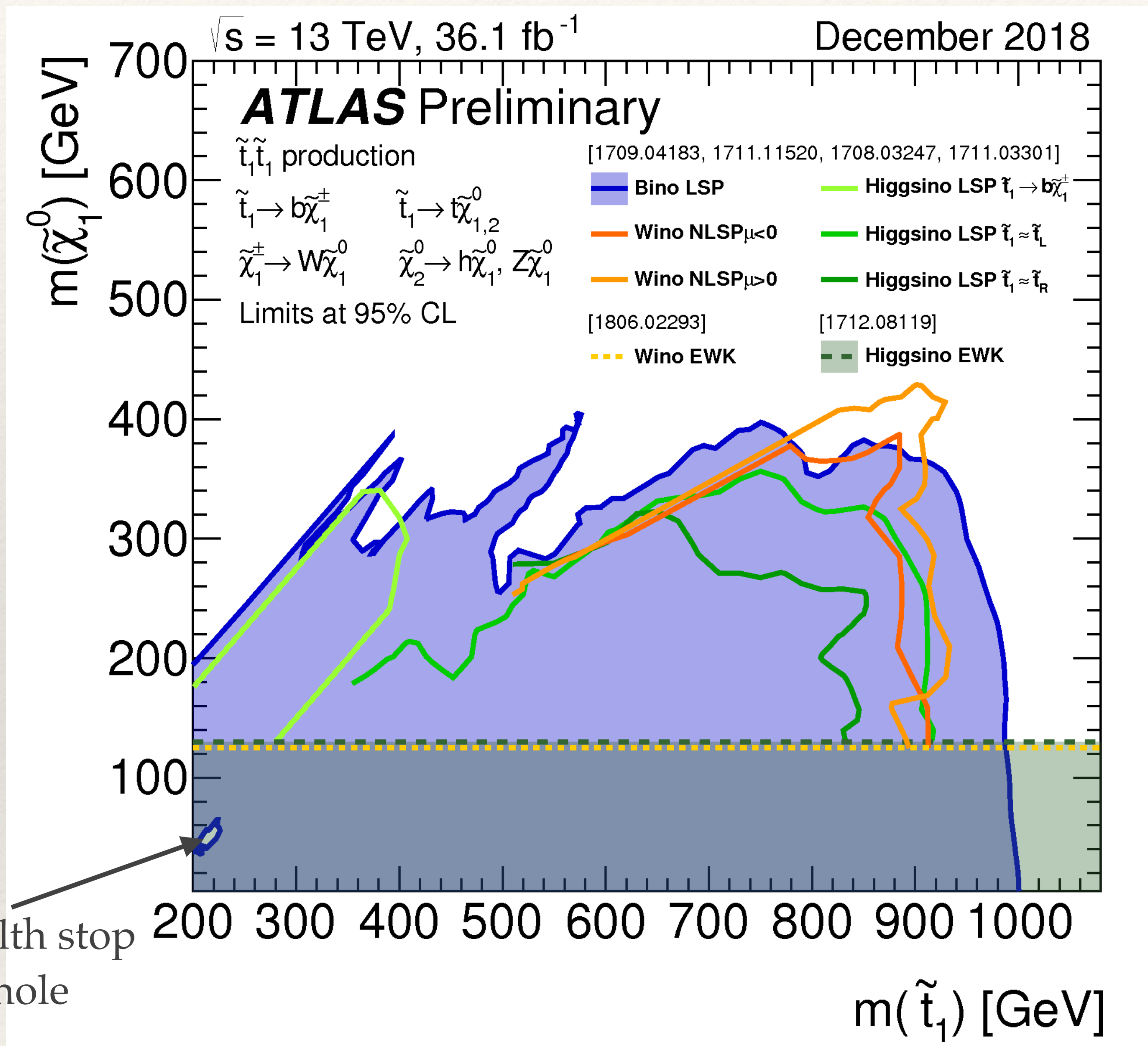
Results for smaller (3-body decay) and larger ΔM in backup

The ΔM=175 GeV "stealth stop" corridor is under pressure…

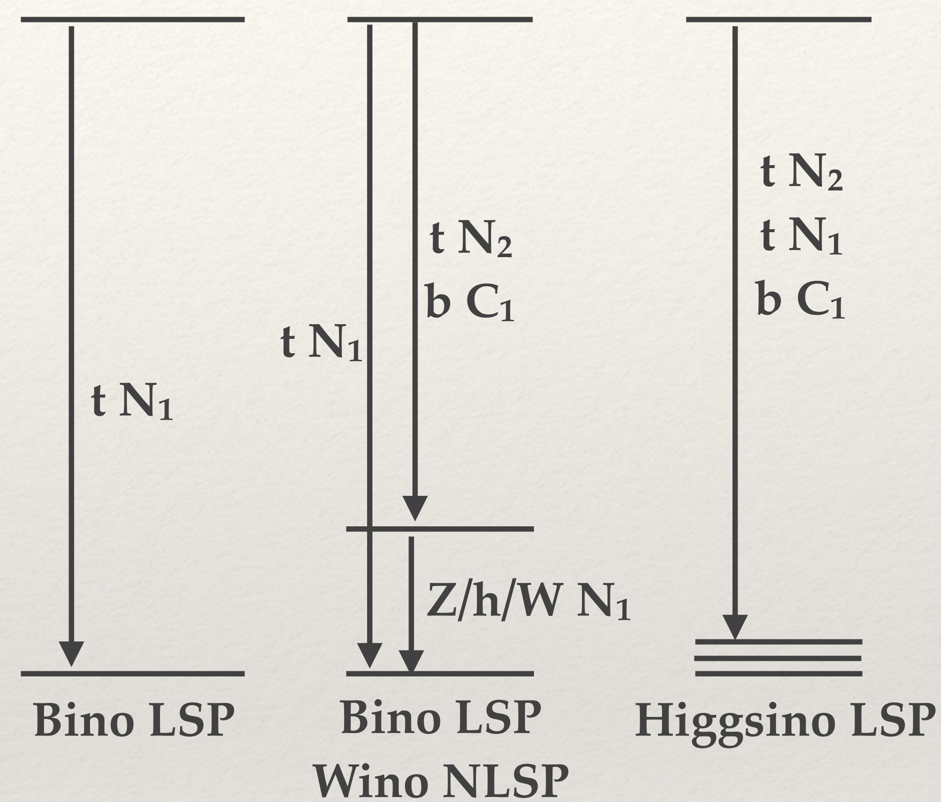
my summary from the published plots :



STOP - MORE COMPLEX DECAYS



Stealth stop hole



- Naturalness (need light higgsinos) and relic density consideration make an 100% stop decay to the LSP not very likely. **With more complex decay patterns, limits are weaker**
- **For 300 GeV LSP mass, any stop mass is likely viable for some decay modes**

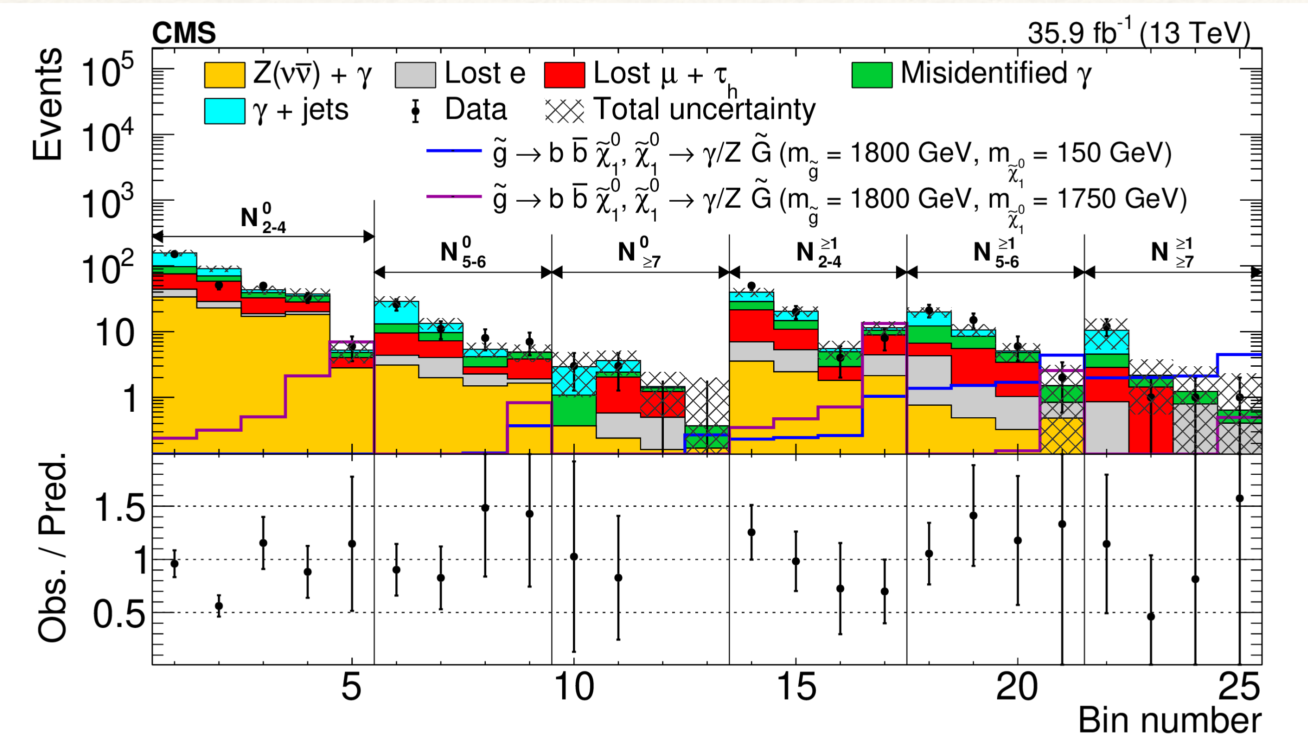
SUSY with photons - signatures

- If gravitino LSP, the neutralino is no longer stable.
- A new CMS paper [**arXiv:1901.06726**] targets gluino and stop production with a **photon+(b)-jets+MET** final state
- An other [**arXiv:1812.04066**] targets **photon+lepton+MET** final states

	γ+jets+MET	γ+lep+MET
triggers	γ and γ+jet	2γ ($e\gamma$ channel) $\gamma\mu$ ($\mu\gamma$ channel)
selection	p_T^{γ}, H_T^{γ} > 100,800 or 190,500 GeV 2 jets p_T^{miss} > 100 GeV	m_T > 100 GeV p_T^{miss} > 120 GeV
SR binning	p_T^{miss}, N_{jets}, N_{bjets}	p_T^{γ}, p_T^{miss}, H_T

SUSY with photons - results

arXiv:1901.06726



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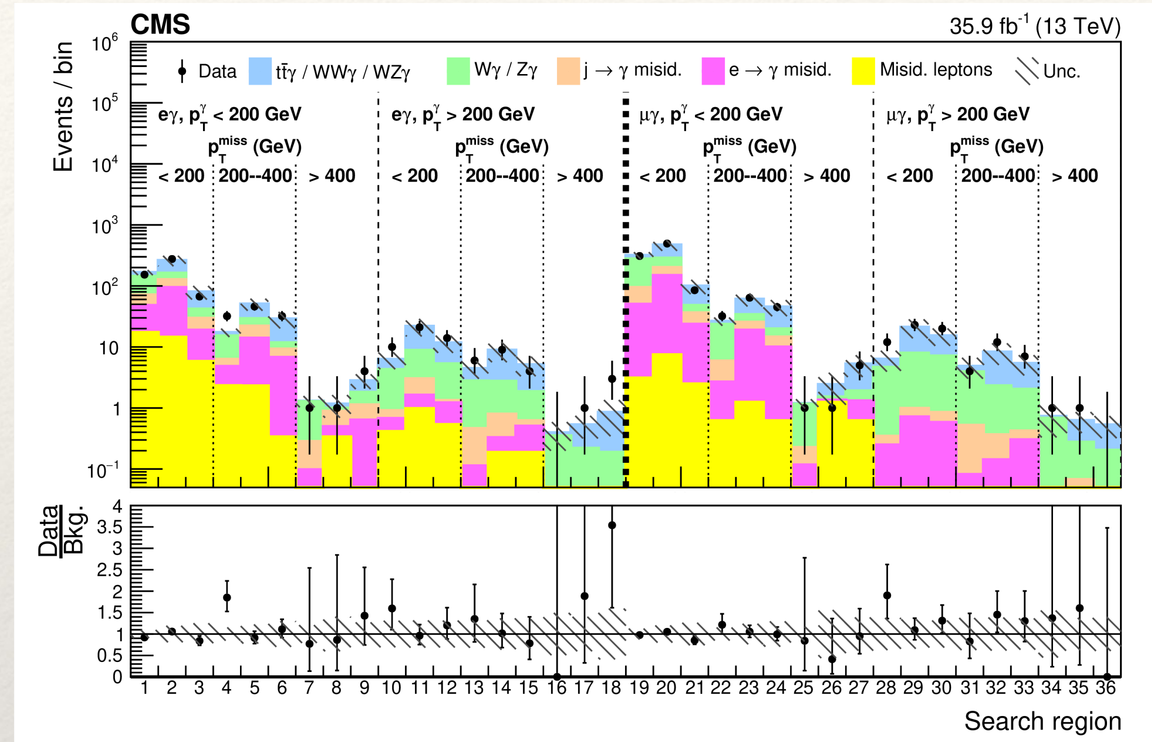
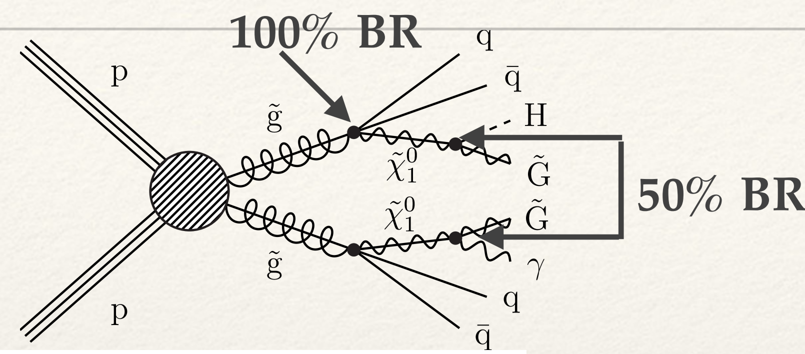
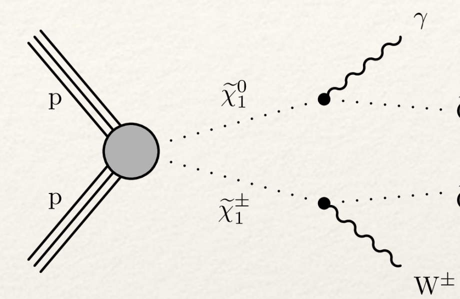


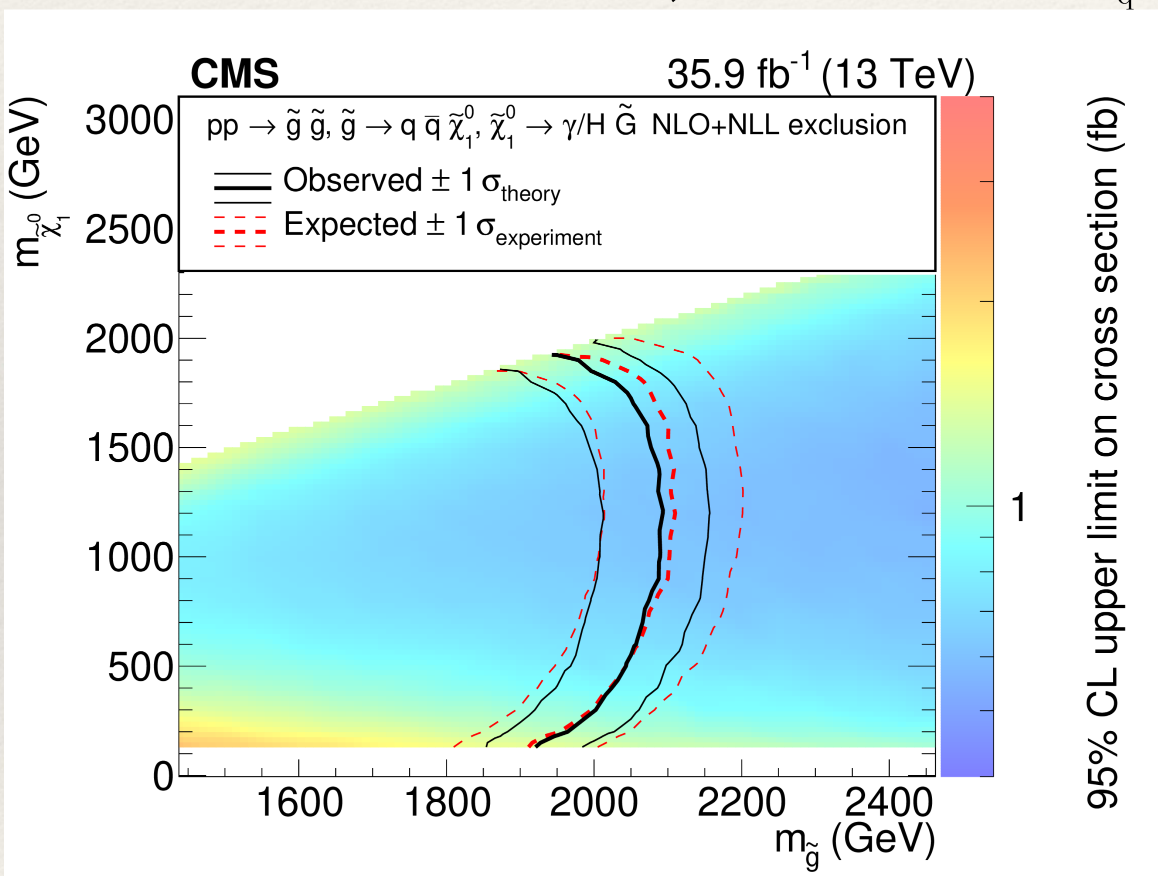
- Reducible background estimated with control selection and transfer factors / fake rates
- Irreducible background with simulation normalized to control selections
- **Good agreement between data and estimated background everywhere**

SUSY with photons - interpretations





arXiv:1901.06726



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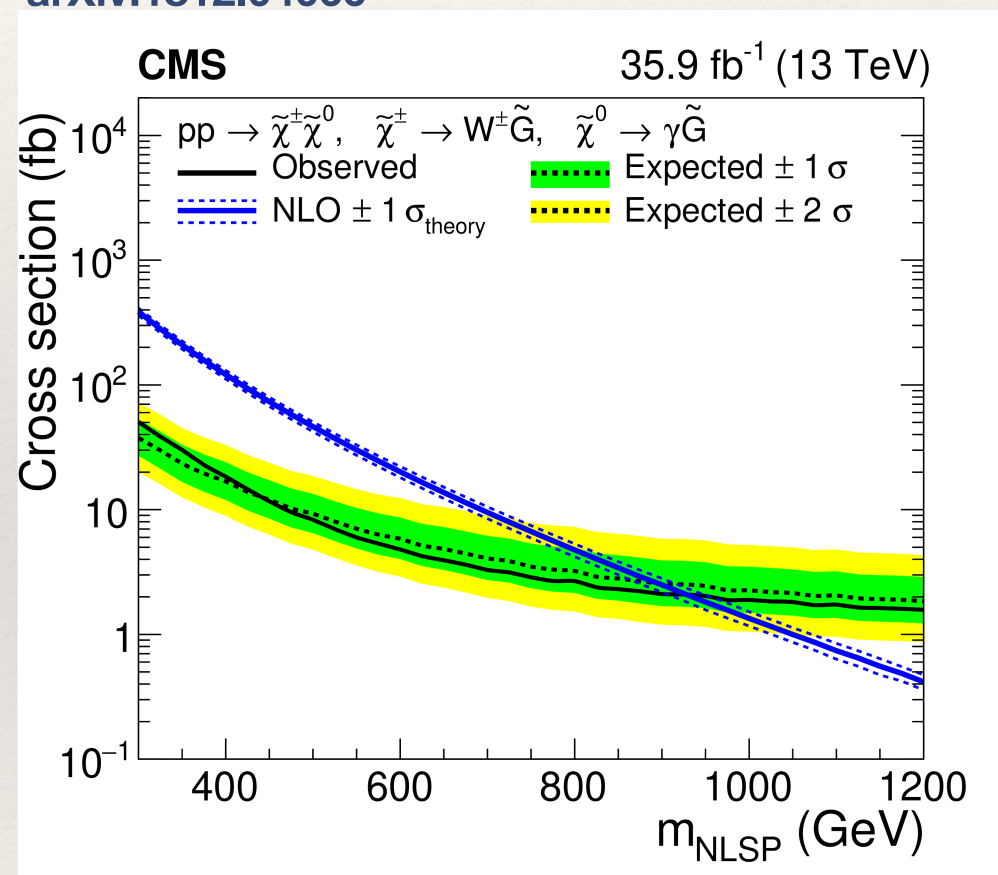
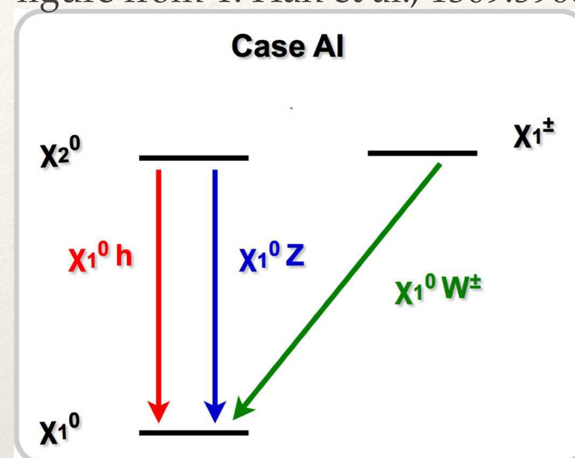


- Limits between 1.35 and 2.1 TeV on gluinos, and 930 GeV on directly produced chargino NLSP, for the simplified models considered [other interpretations in backup]
- Real models likely to have different (generally lower) σ x BRs in each final state. Cross section limits are provided for each mass for easy reinterpretation

Electroweak production

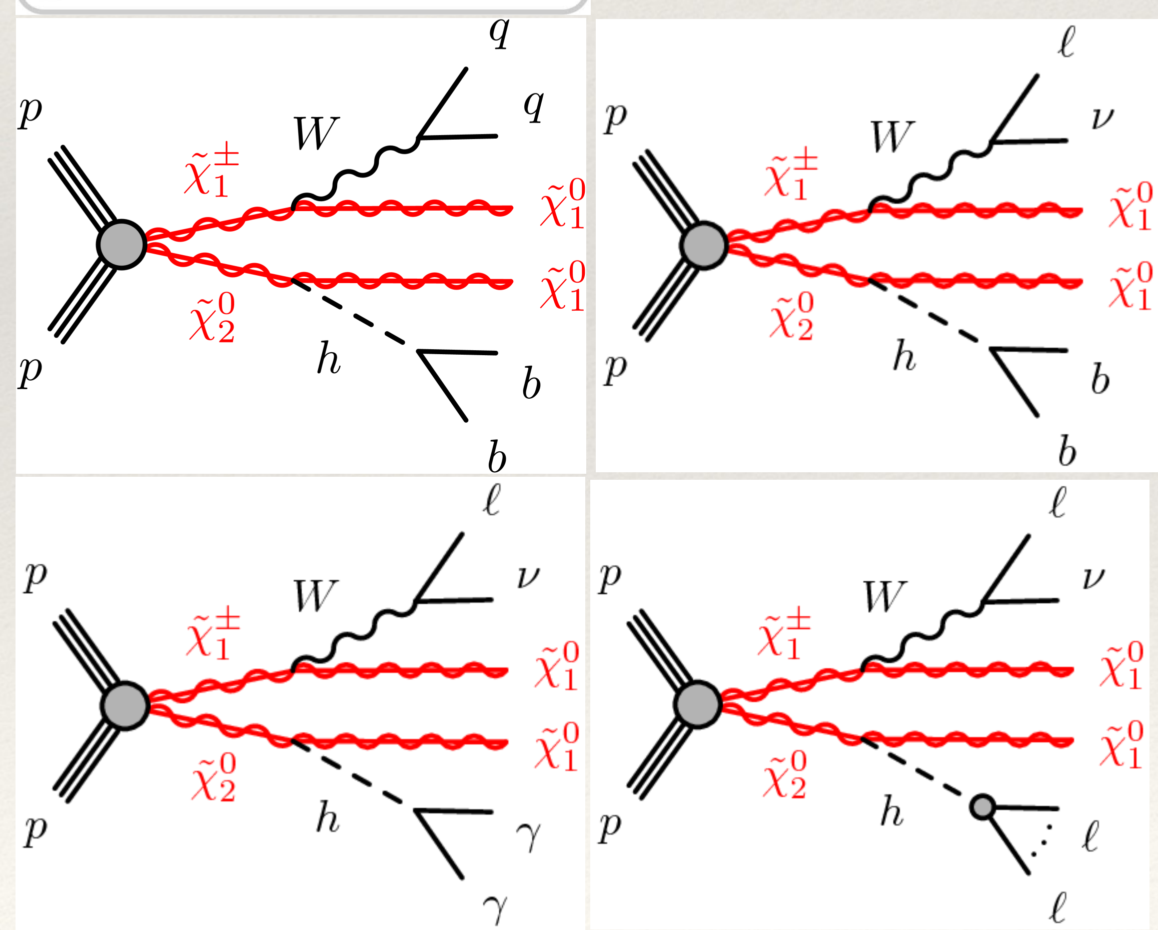
- Lower cross sections => we probe lower masses => potentially large backgrounds
- Electroweak states might be much lighter than strongly interacting ones. Higgsinos most directly linked to naturalness
- A new ATLAS paper **[arXiv:1812.09432]** addresses the WH+MET final state in four different channels
  - multilepton (2LSS/3L) +MET
  - diphoton (H(γγ)+MET)
  - 1 lepton (1Lbb+MET)
  - **Fully hadronic** (qqbb+MET) [never done in previous papers, best sensitivity at high masses!]

figure from T. Han et al., 1309.5966

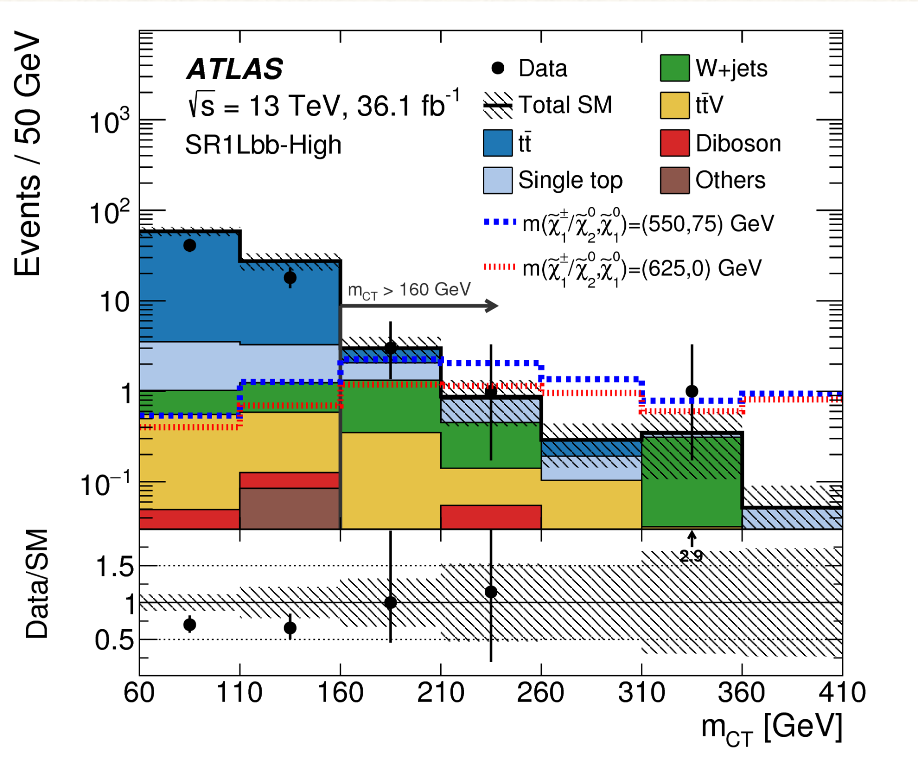


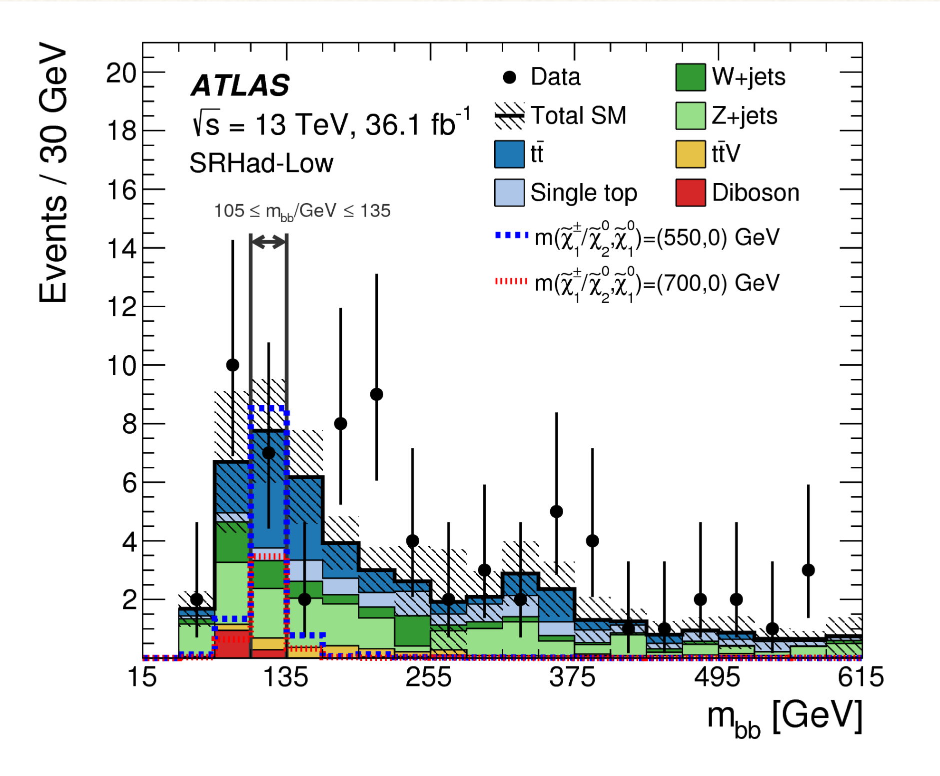
Wino NLSP, bino LSP.
Final states :

- WW+MET
- **Wh+MET**
- WZ+MET



1Lbb and had channels

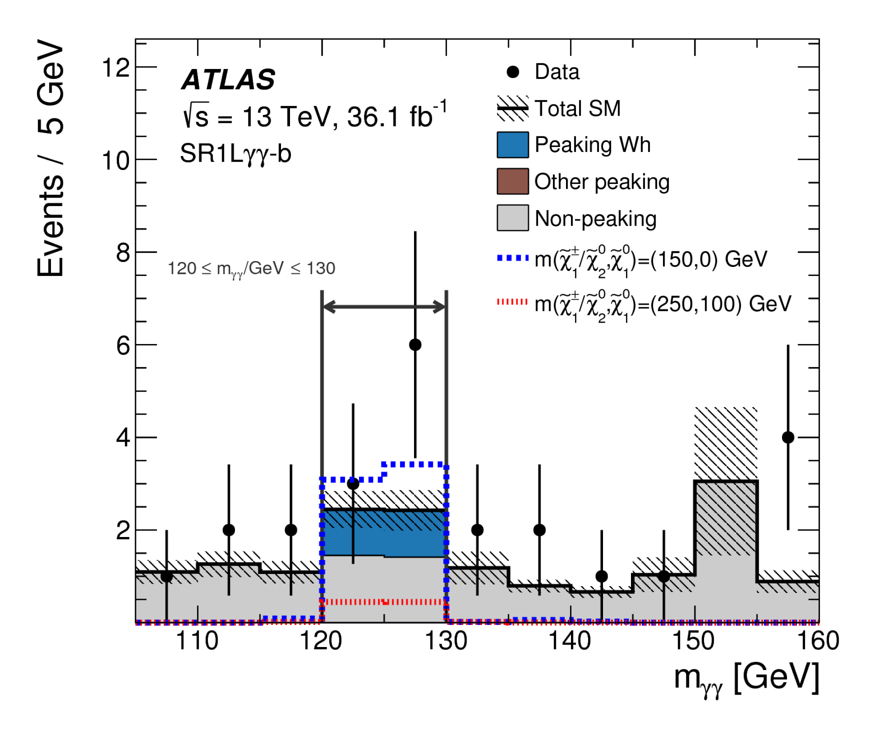


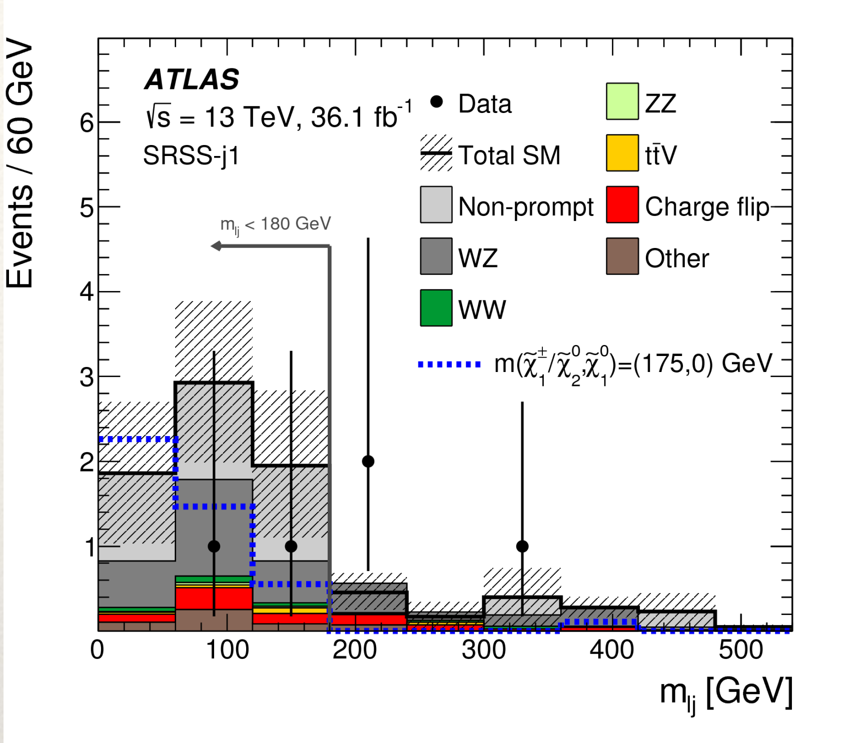


- **1Lbb :** Single lepton trigger, 2 or 3 jets, 2 b-tagged jets, large p_T^{miss}, (co)transverse mass cuts, m_{bb} in Higgs widow
- Three orthogonal selections (SR) optimized for increasing mass, combined for exclusion
- Largest background from top and W+jets; normalized in dedicated CRs, CR=>SR from simulation

- **Had :** p_T^{miss} trigger, 4-5 jets, 2 b-jets, large $m_{eff} = H_T + p_T^{miss}$, (co)transverse mass cuts, m_{bb} in Higgs window
- Two selections (SR) optimized for medium / high mass
- Largest background from top and Z+jets; normalized in dedicated CRs, CR=>SR from simulation

1Lγγ AND MULTI-LEPTON CHANNELS

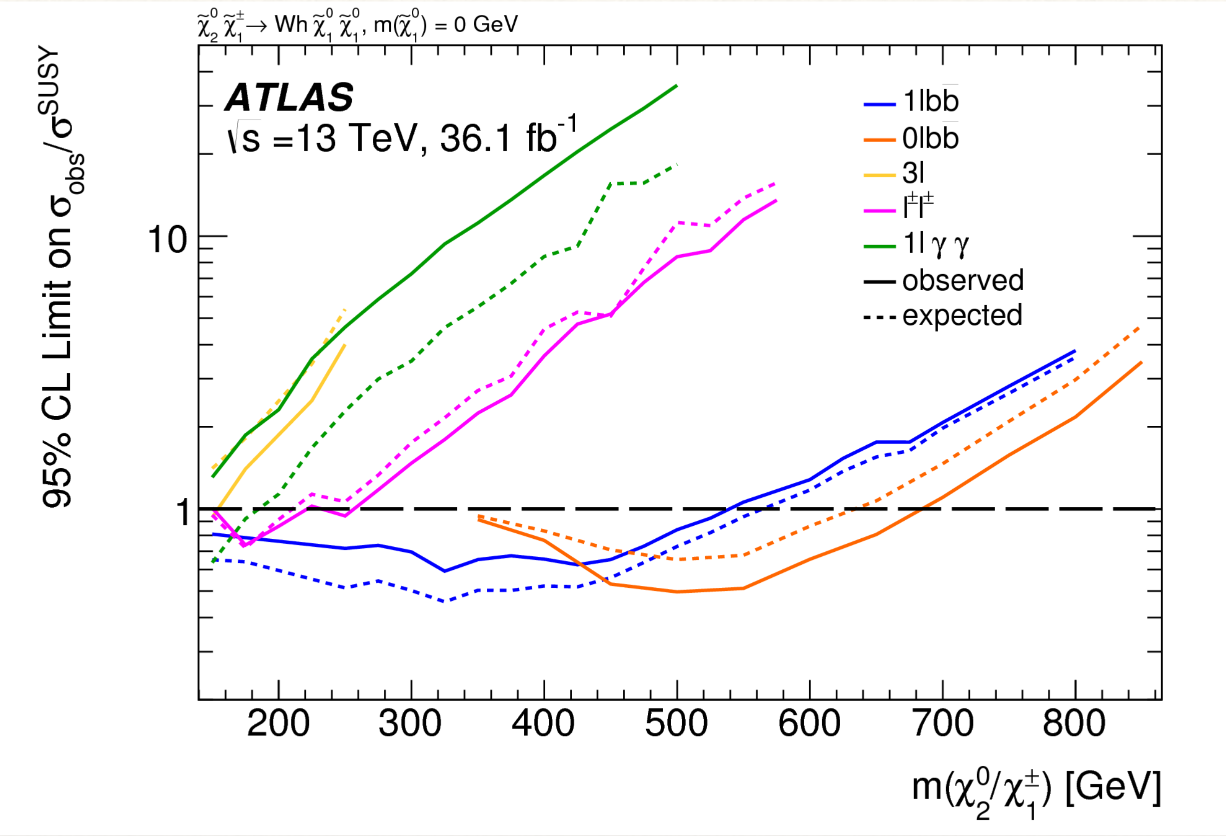


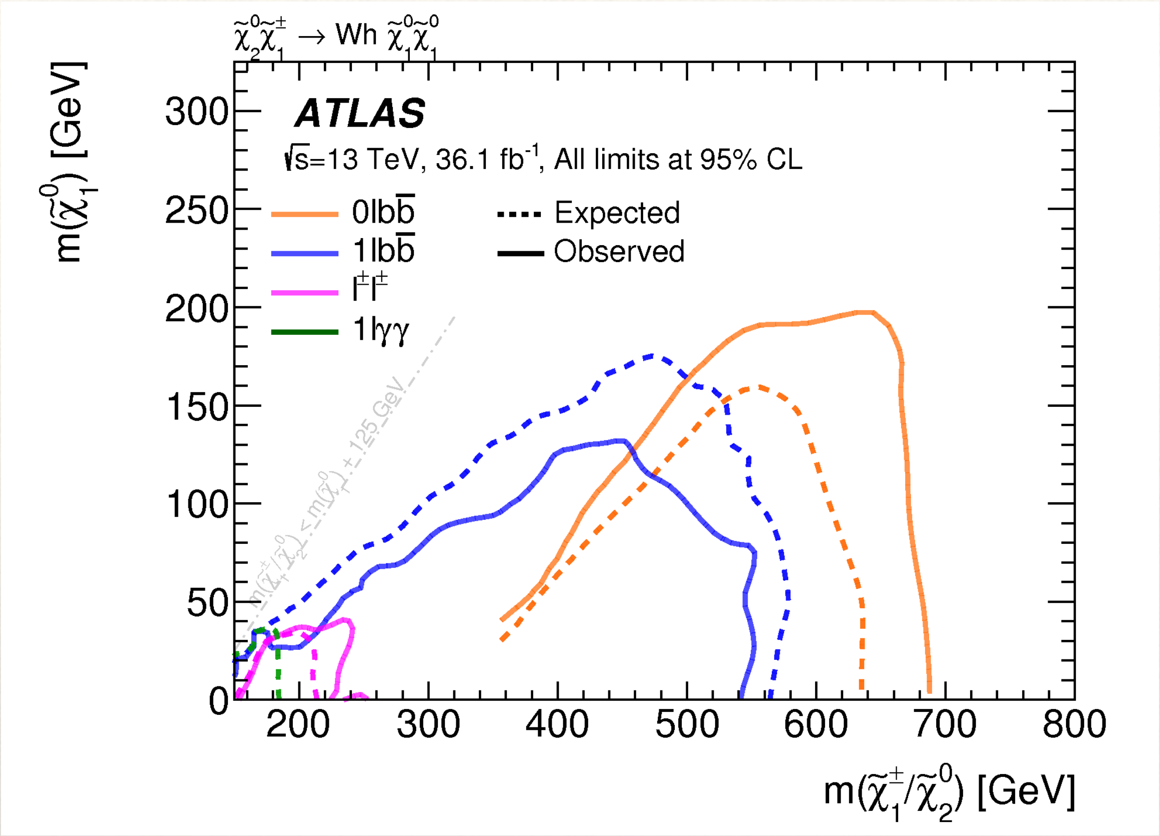


- **1Lγγ :** Di-photon trigger, one lepton, b-jets veto, p_T^{miss}, (co)transverse mass, and angular cuts, m_{gg} in Higgs widow
- Two orthogonal selections (SR), combined for exclusion
- Non-peaking background from sideband fits; H(γγ) background (mostly WH) from MC

- **Multileptons :** 2 same sign or 3 leptons, selections on p_T^{miss}, N(jets), mass combinations and angles.
- 8 orthogonal selections (SR) combined
- Largest background from fake leptons (data driven) and WZ (from MC, normalized to data for 3L)

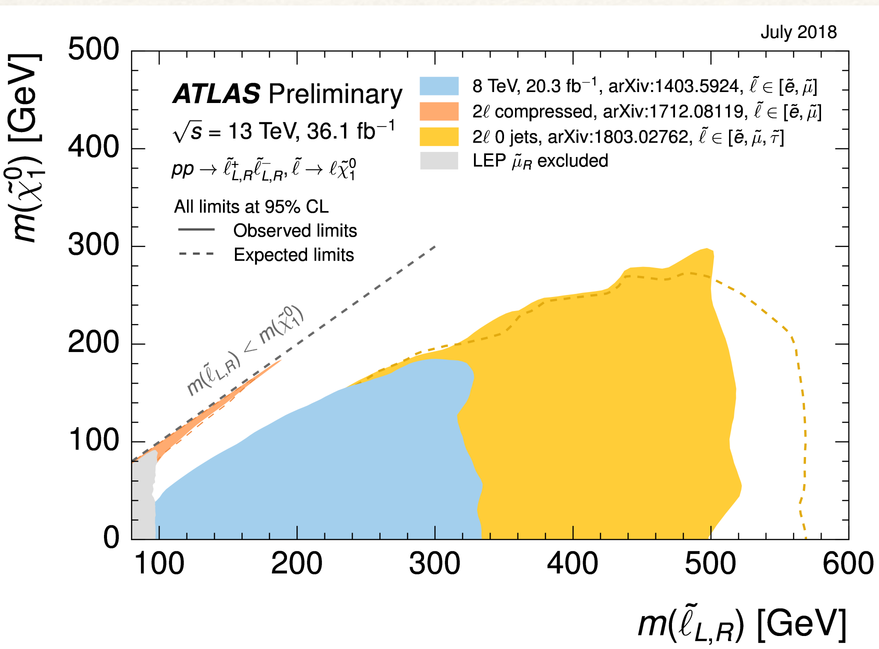
INTERPRETATION

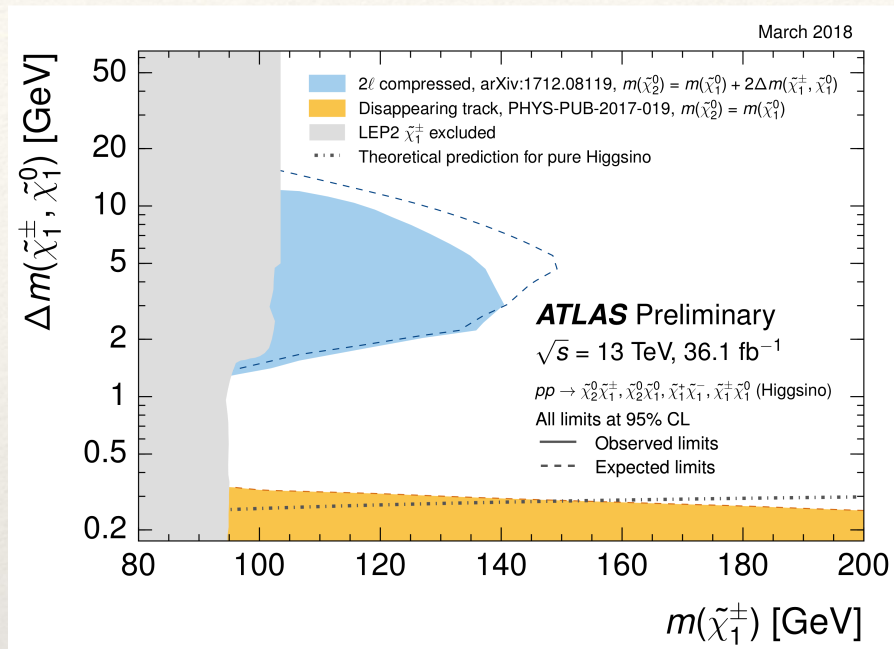


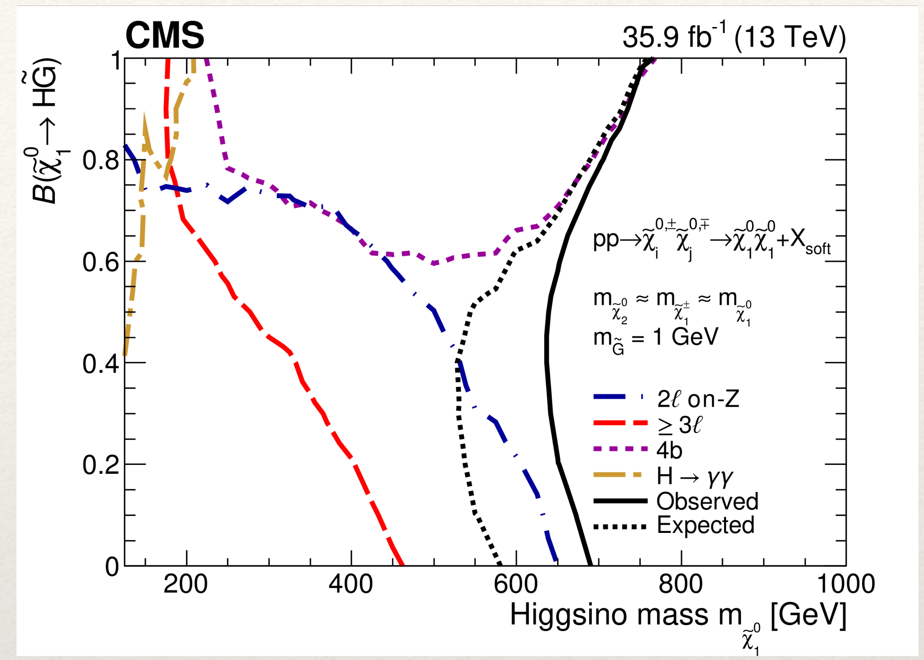


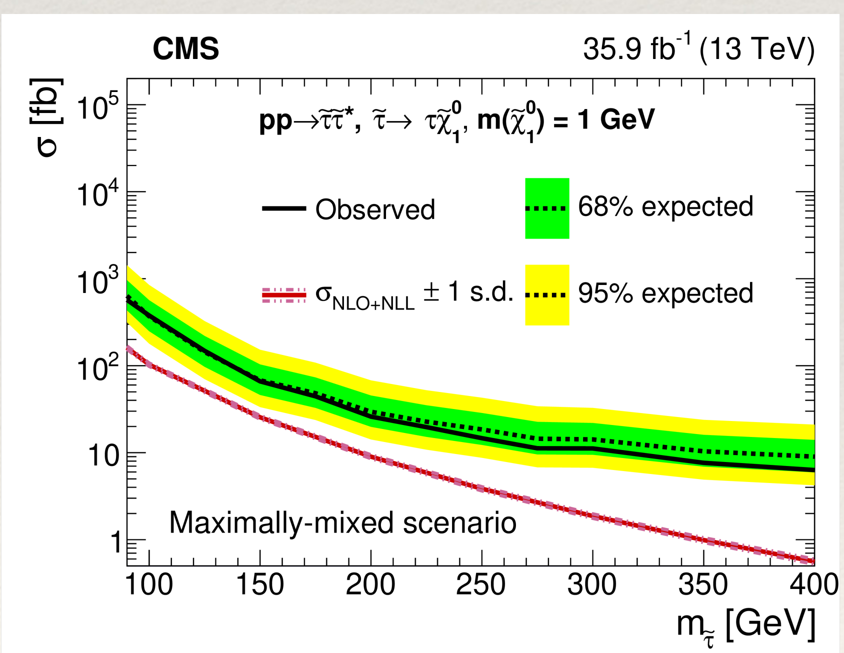
- Nice complementarity between channels
- BIG improvement over run1 results [270 GeV exclusion for massless LSP] and best limit to date for this simplified model
- Read the fine print : at deepest point the excluded cross section is 60% of nominal
  - The $\tilde{\chi}^0_2$ might decay into $\tilde{\chi}^0_1 Z$ and $\tilde{\chi}^0_1 h$ with comparable BRs
  - chargino-neutralino production cross section is lower for higgsino-like NLSP

OTHER SUSY EWK



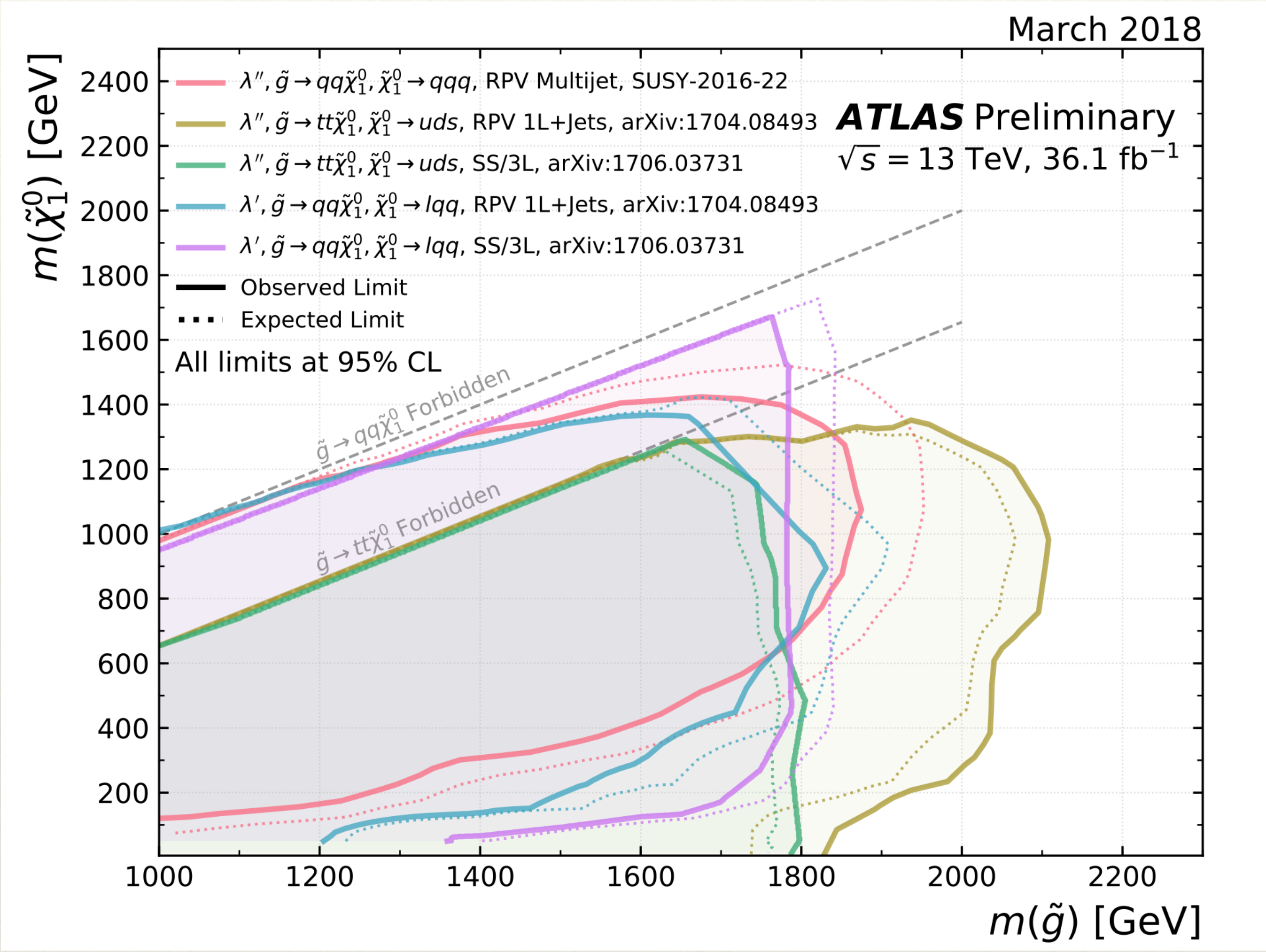






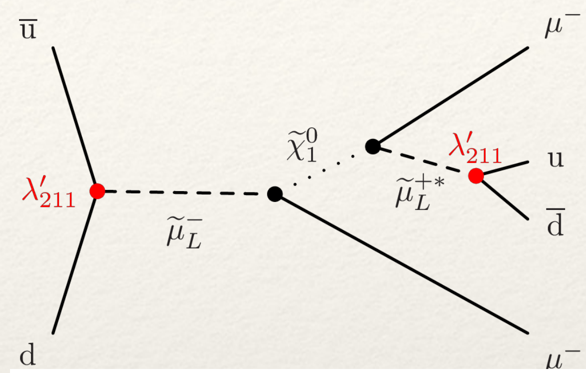
- Direct production with compressed spectrum (higgsino LSP) : well motivated by naturalness, first limit beyond LEP
- Higgsino decaying to gravitino LSP well covered
- Direct sleptons : Δm gap in sensitivity. Motivated by Dark Matter and g-2
- No sensitivity to direct stau production yet !

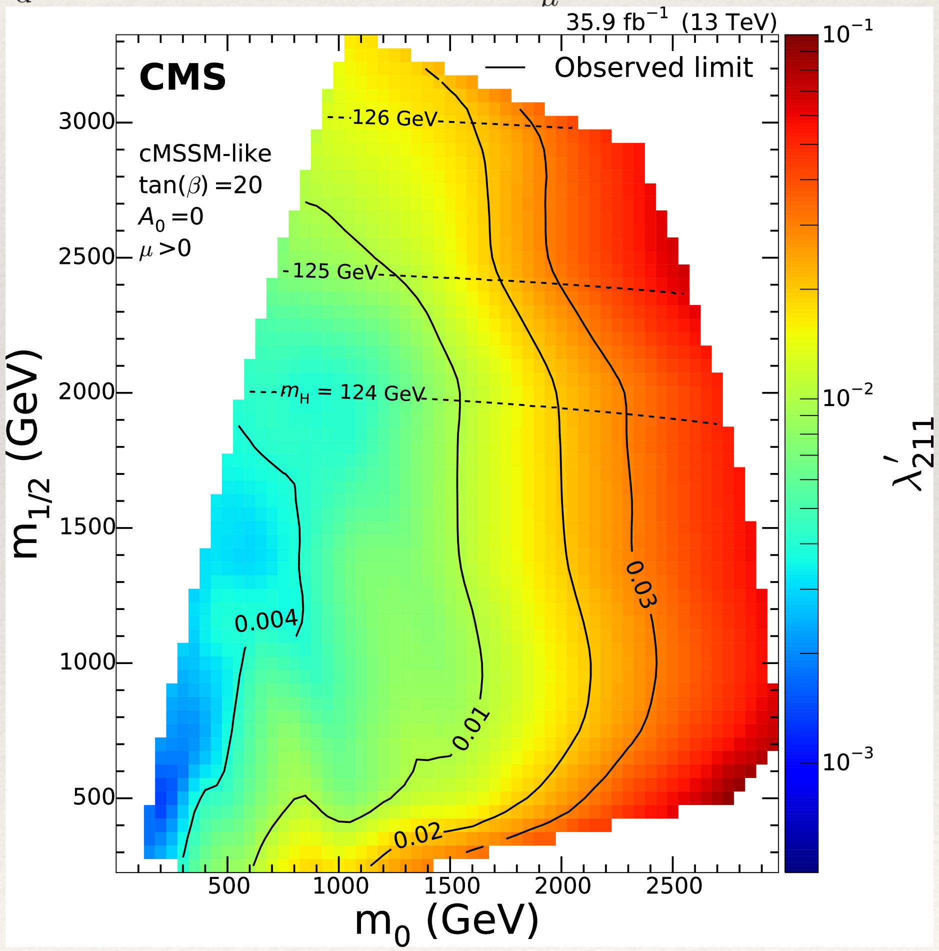
RPV SUSY



ATLAS summary of RPV gluino searches

arXiv:1811.09760





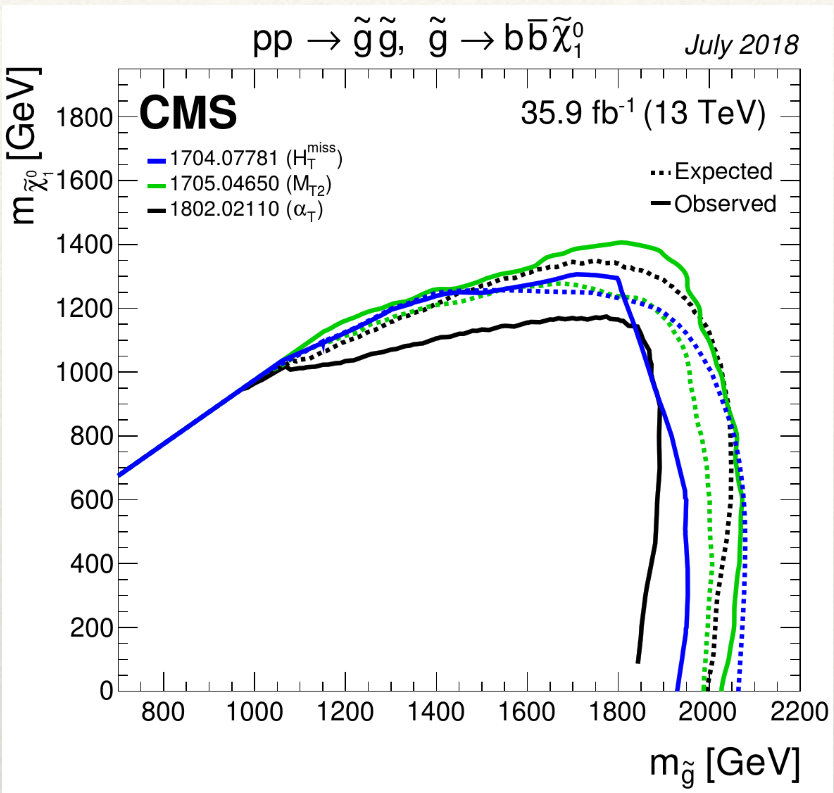
CMS search for resonant smuon / sneutrino production in 2μ+2jets

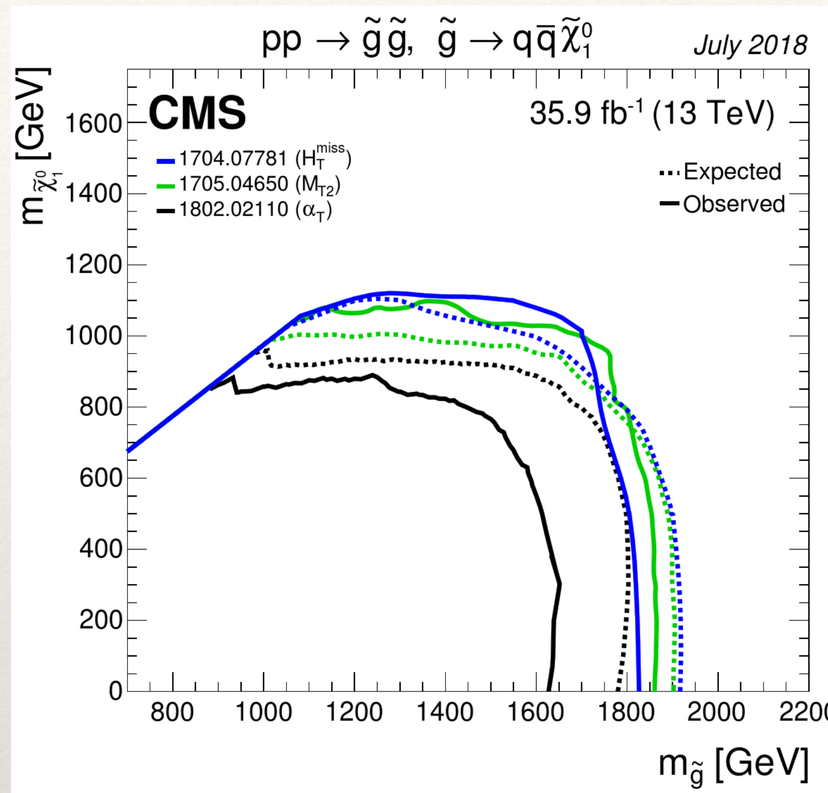
CONCLUSIONS

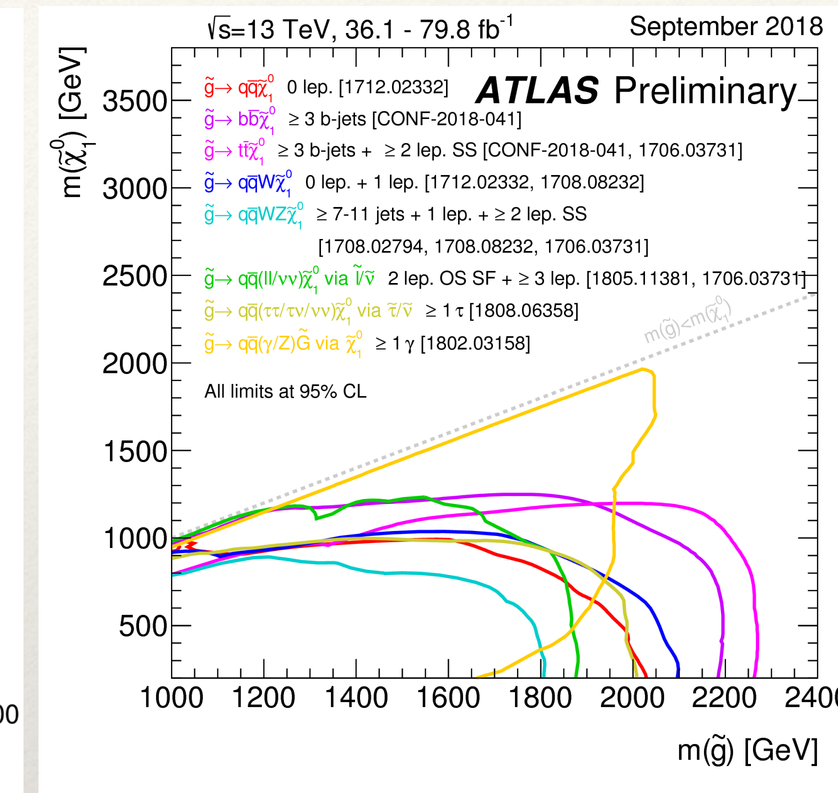
- SUSY searches being pursued vigorously by both experiments
- Pushing limits outwards, but also covering holes (difficult scenarios) at low mass, like the stop stealth window
- We haven’t giving up hope to find supersymmetric particles, and we will continue doing this for a long time to come - see M. Goblirsch talk for the high luminosity LHC prospects

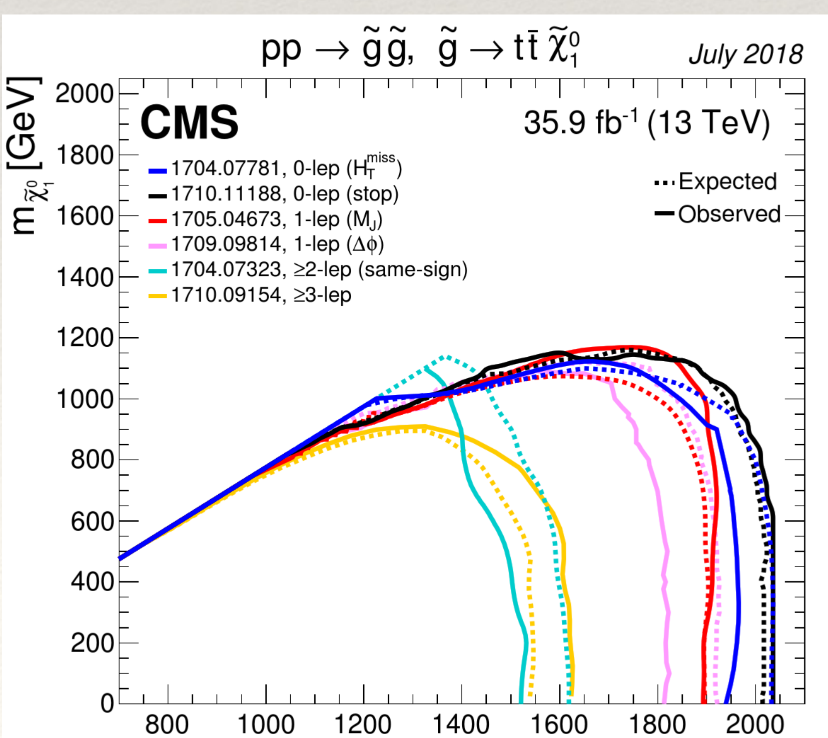
BACKUP

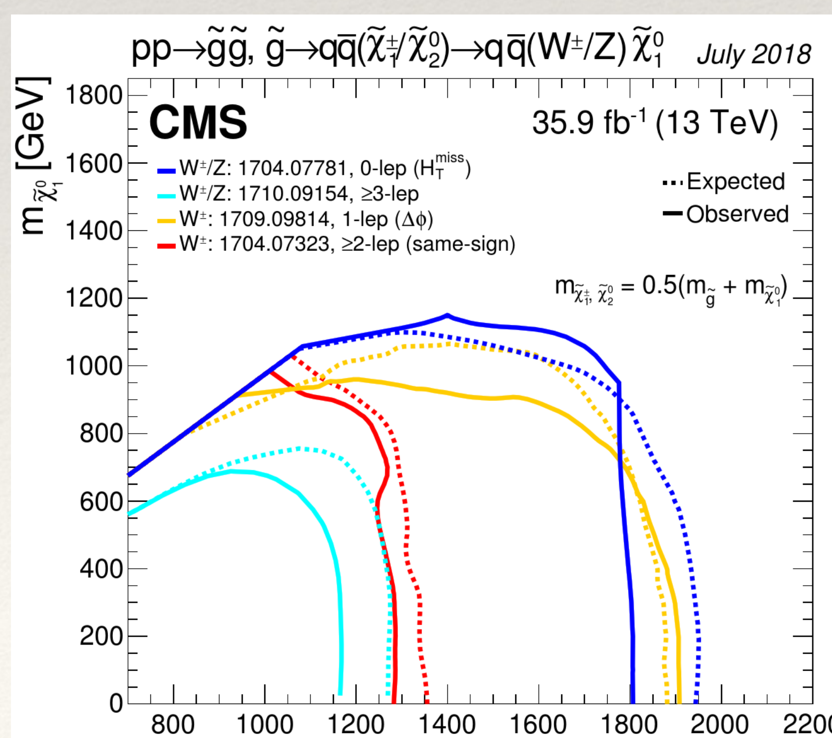
gluino limits

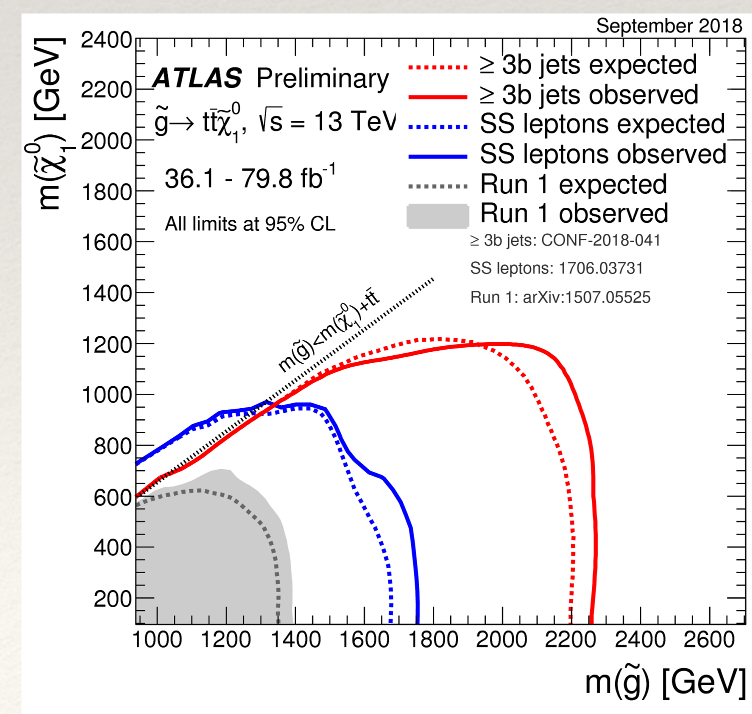






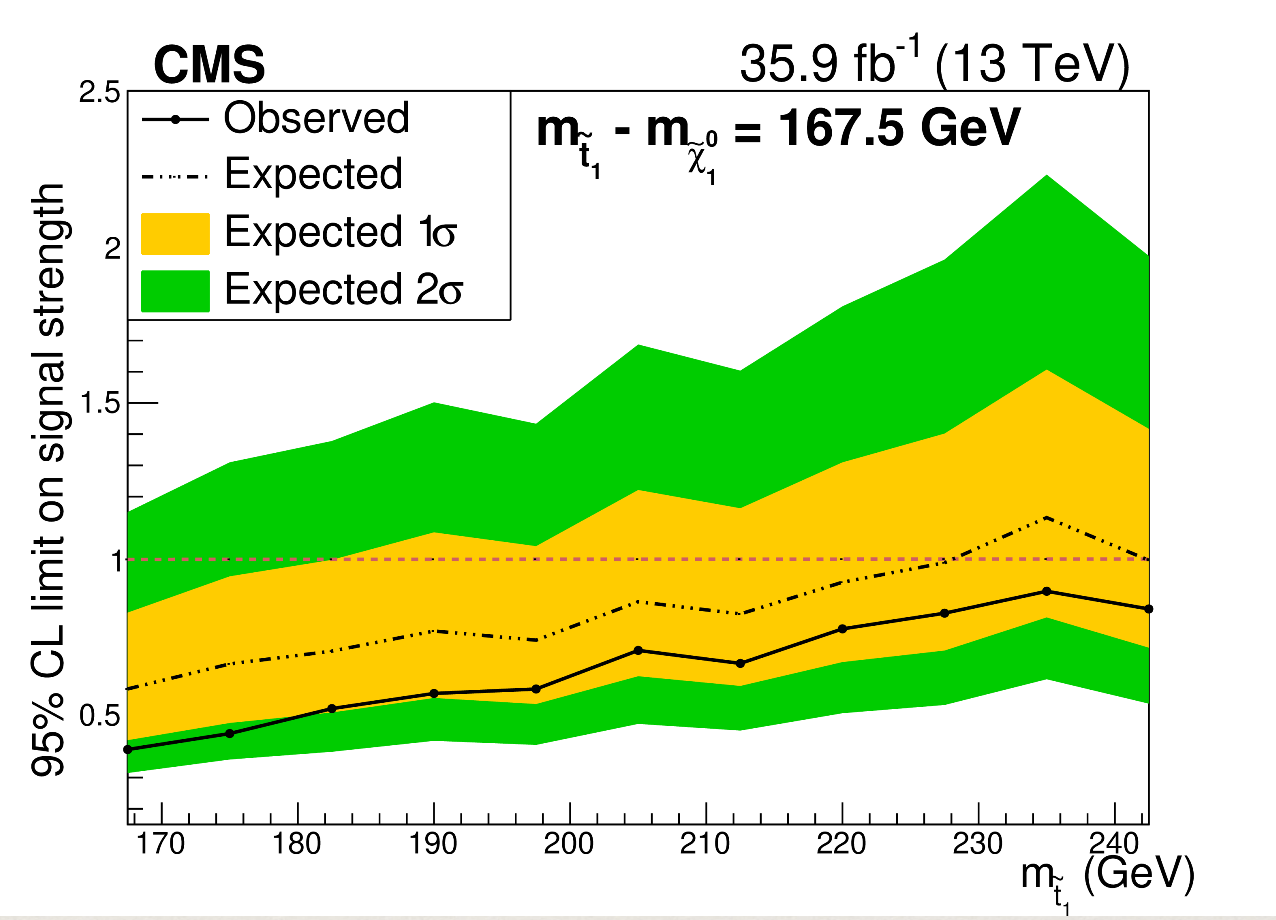


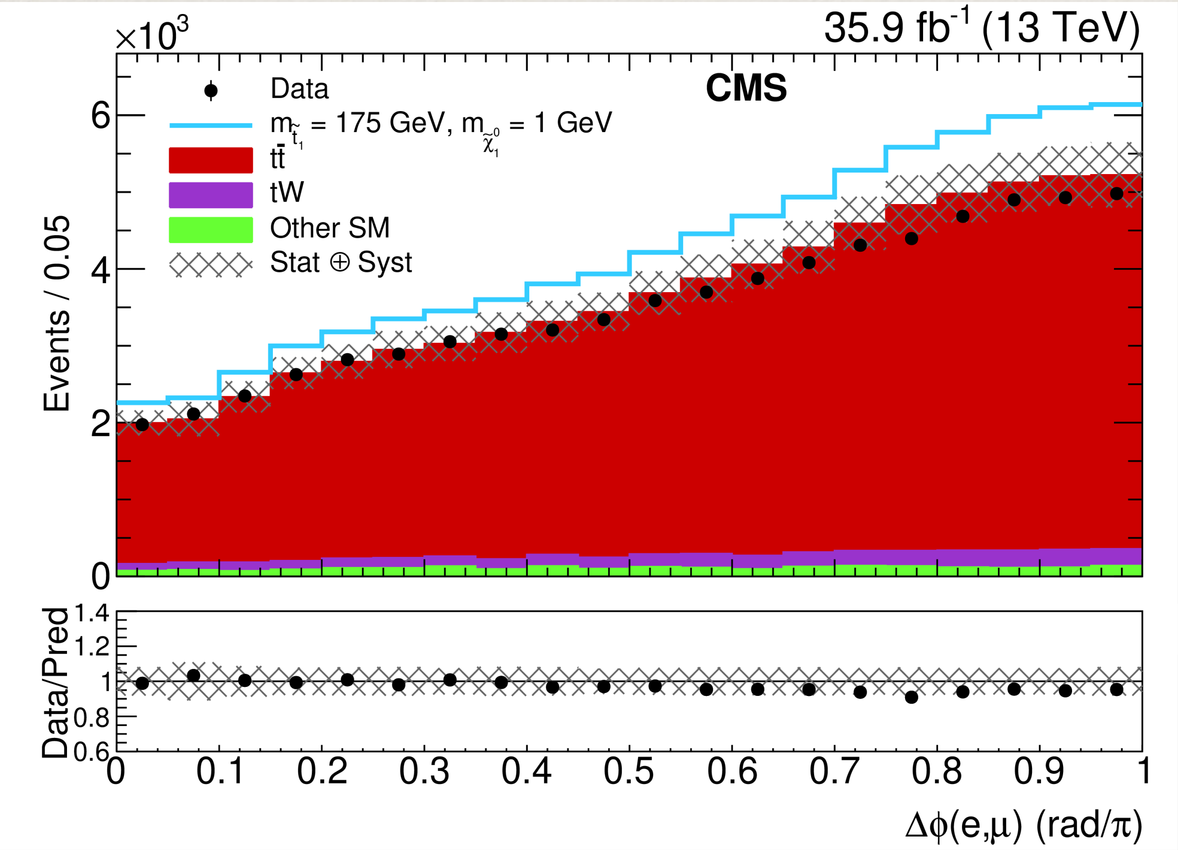


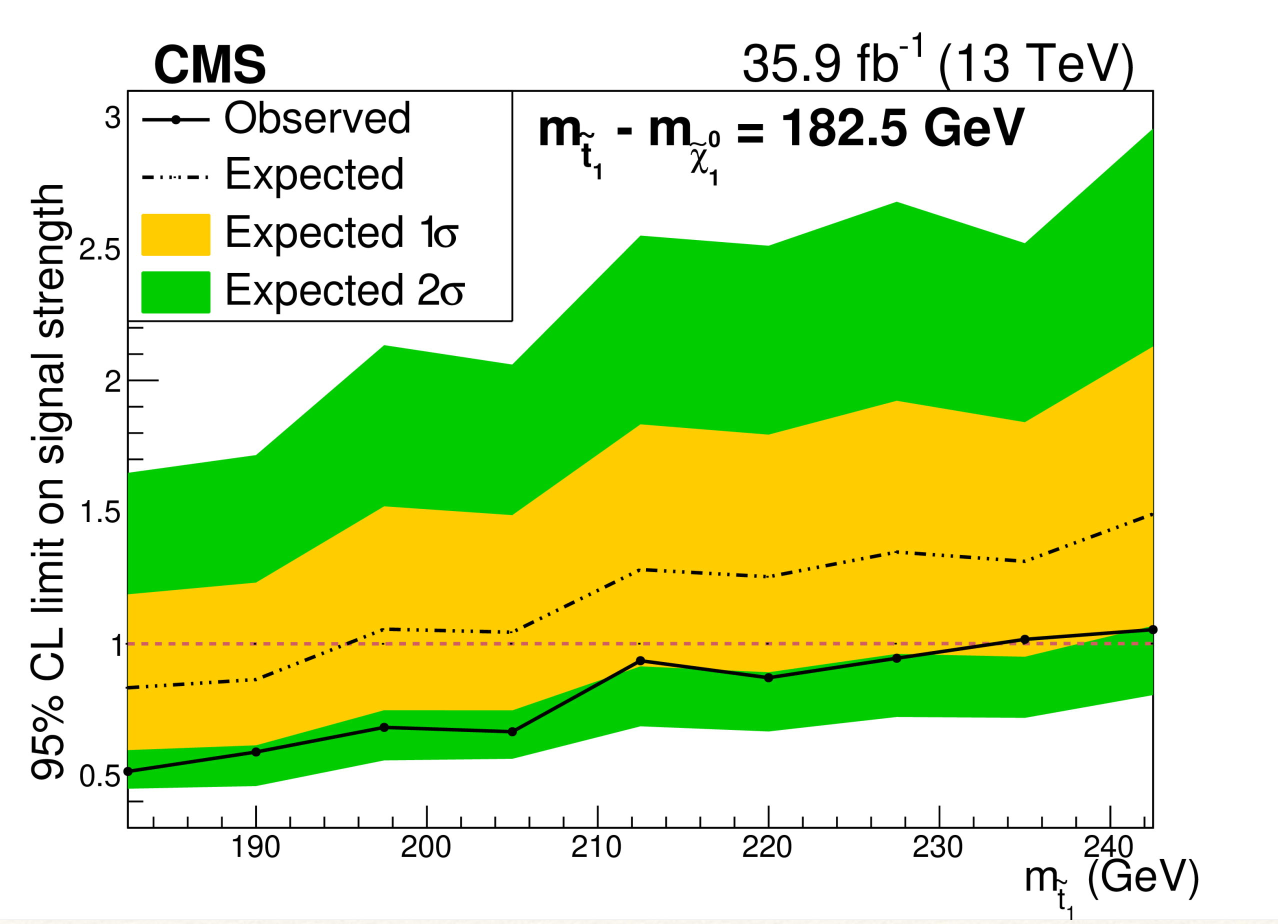


Source	Range (%)
μ_F and μ_R scales	0.3–1.0
PDF	≈0.6
Initial-state radiation	0.5–1.0
Final-state radiation	0.6–1.2
ME/PS matching (h_{damp})	0.3–2.0
Underlying event	≈0.8
Colour reconnection	≈1.5
Top quark p_T reweighting	0.1–0.5
Top quark mass (acceptance)	≈1.0

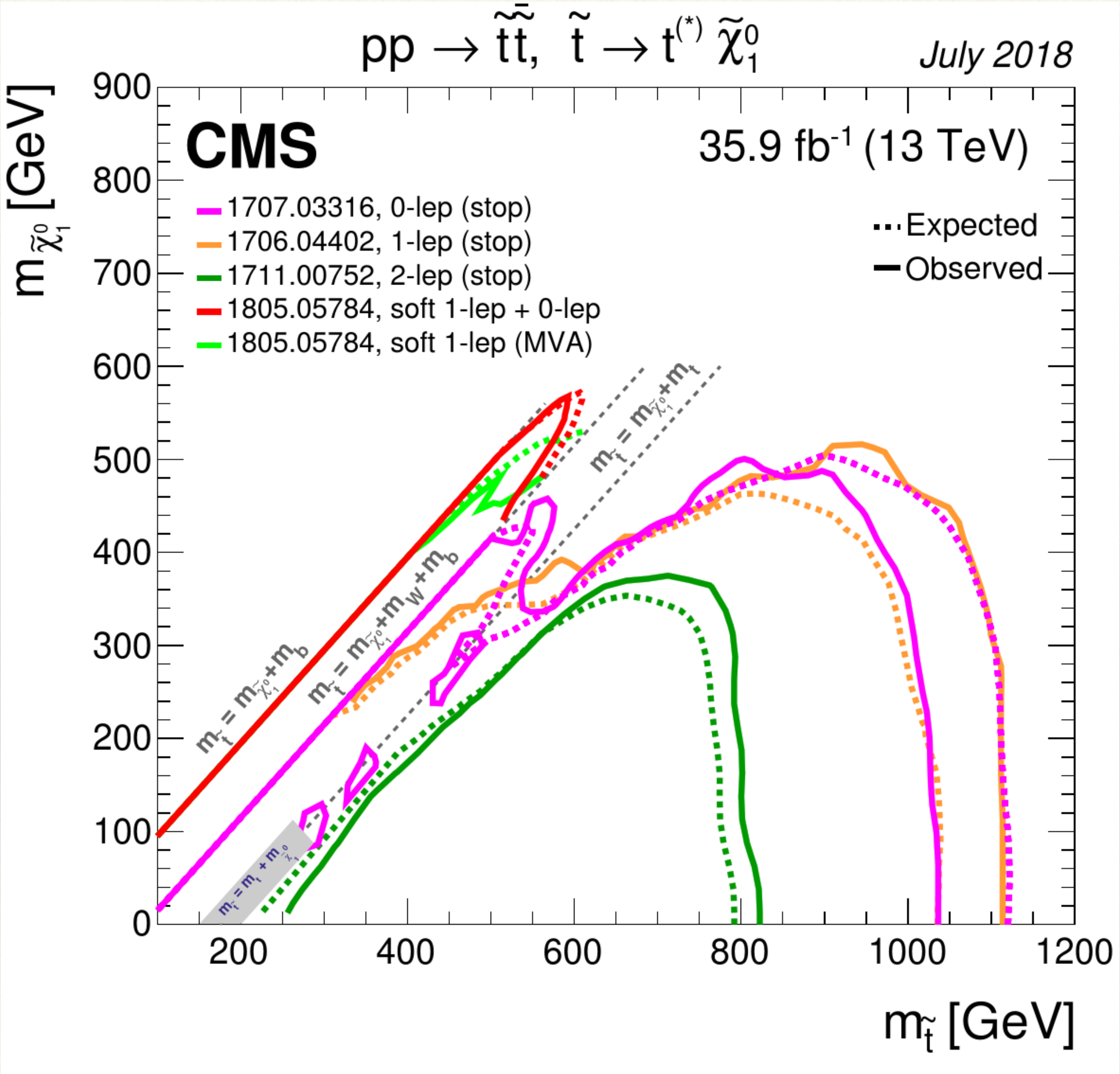
Source	Range for $t\bar{t}$ and signal (%)
Muon efficiencies	≈1.4
Electron efficiencies	≈1.5
Trigger efficiency	≈0.6
Lepton energy scale	0.5–2.0
Jet energy scale	1.5–3.0
Jet energy resolution	0.3–3.5
btagging efficiency	1.2–2.0
Mistag efficiency	0.2–0.6
Unclustered energy	0.5–1.5
Pileup	0.5–3.5





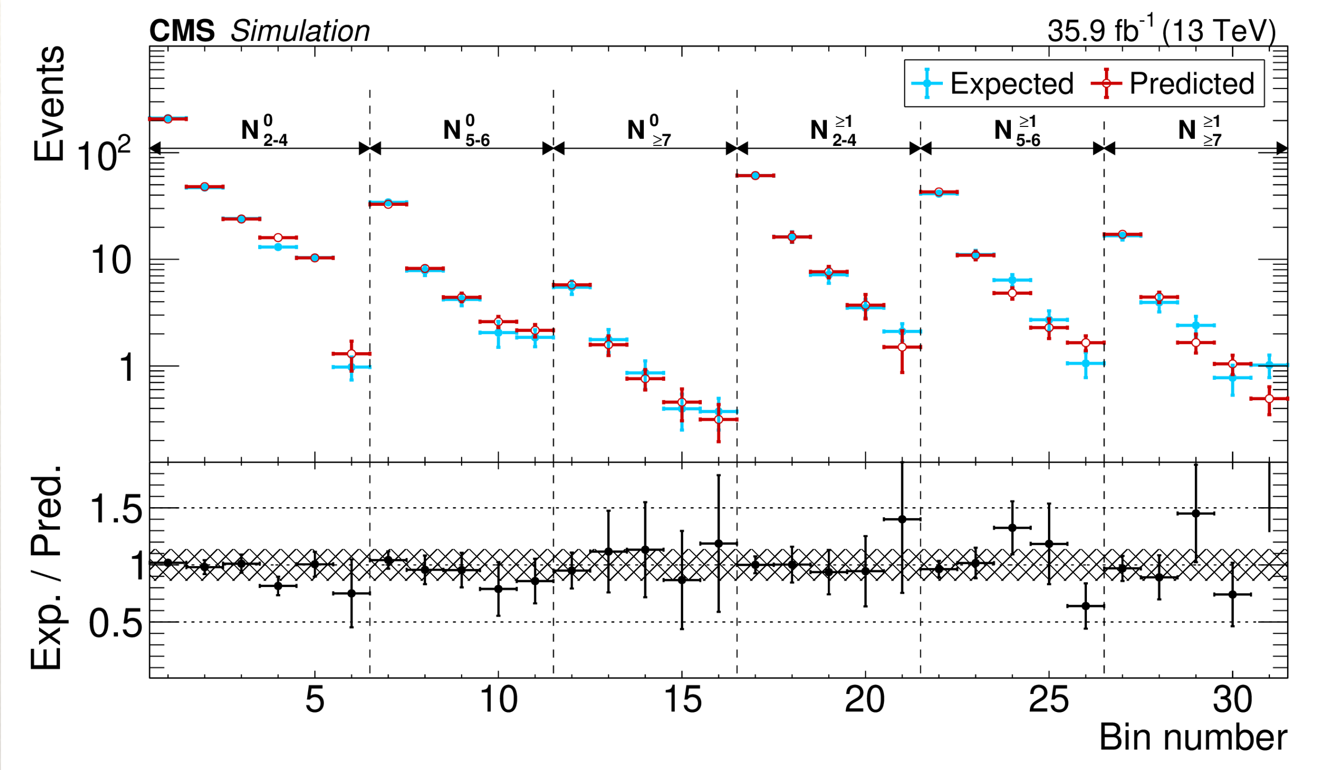


CMS stop limits



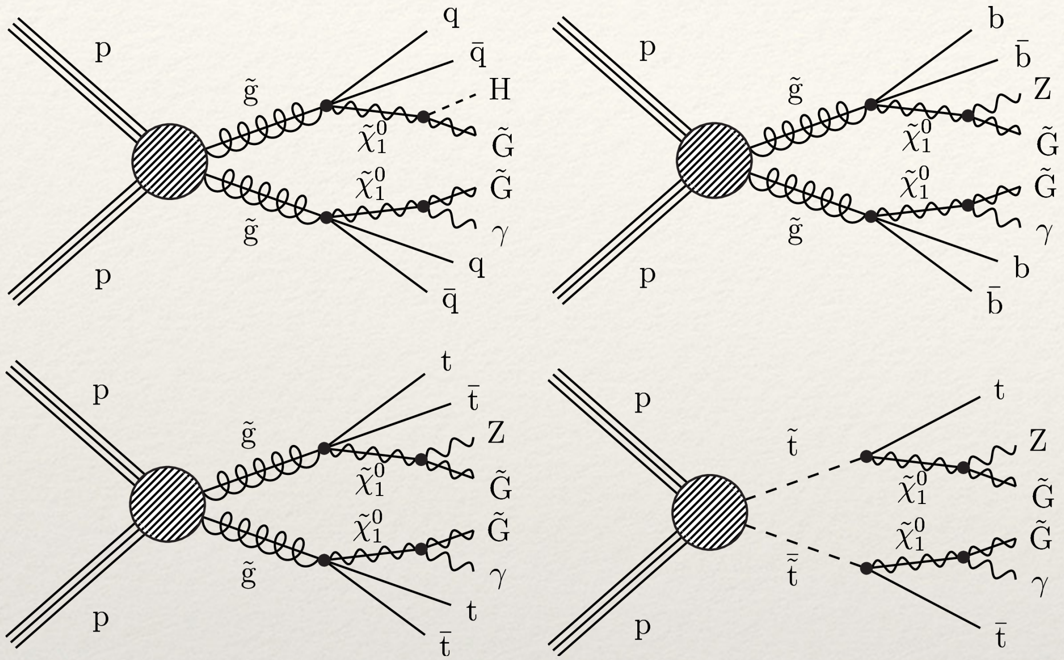
photon+jets+MET background estimate

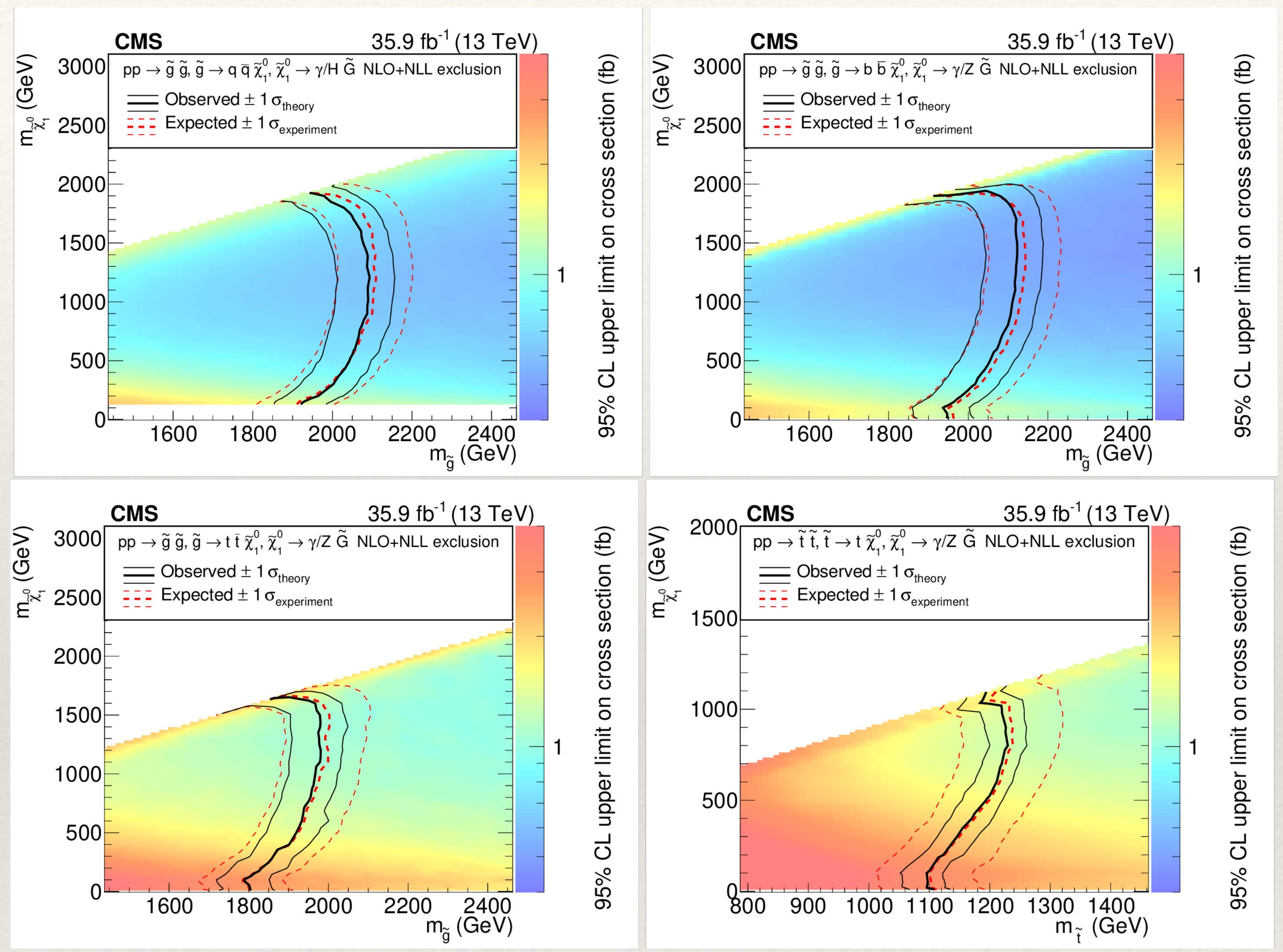
- Lost lepton (Wγ, ttγ) from eγ and μγ control regions, 1=>0 lepton ratio from simulation
- W(eν)+jets, e=>γ, electron control region weighted by misID rate
- Z(νν)+jets, simulation with normalization from Z(ll)+jets
- γ+jets, low Δϕ(jets, MET) control region, ratio R= high Δϕ/low Δϕ measured at low MET, and extrapolated at high MET with simulation



MC closure for lost lepton background

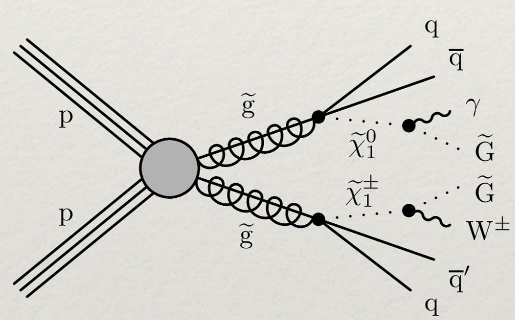
photon+jets+MET other interpretations

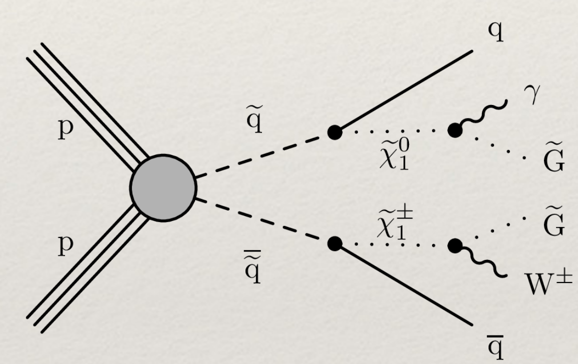


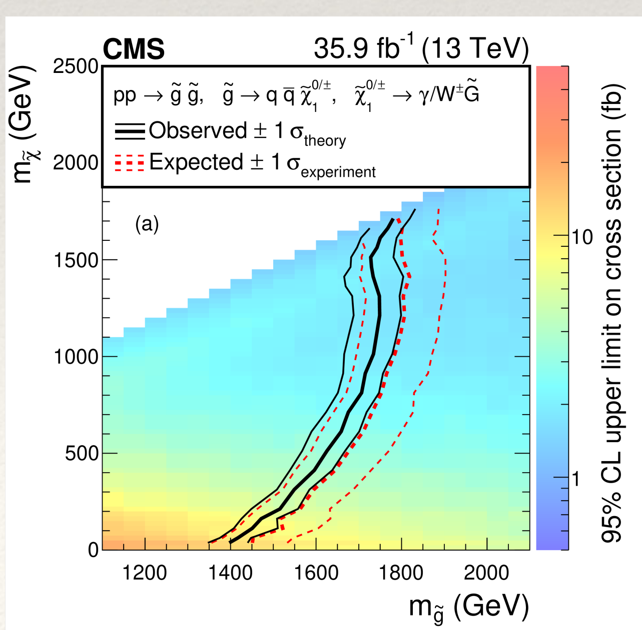


γ+lepton+MET

- Reducible backgrounds (e => γ, jet => γ, fake leptons) with data driven methods (control selection weighted by fake rates)
- Irreducible backgrounds (Wγ, Zγ) from MC, normalized to data in control selection

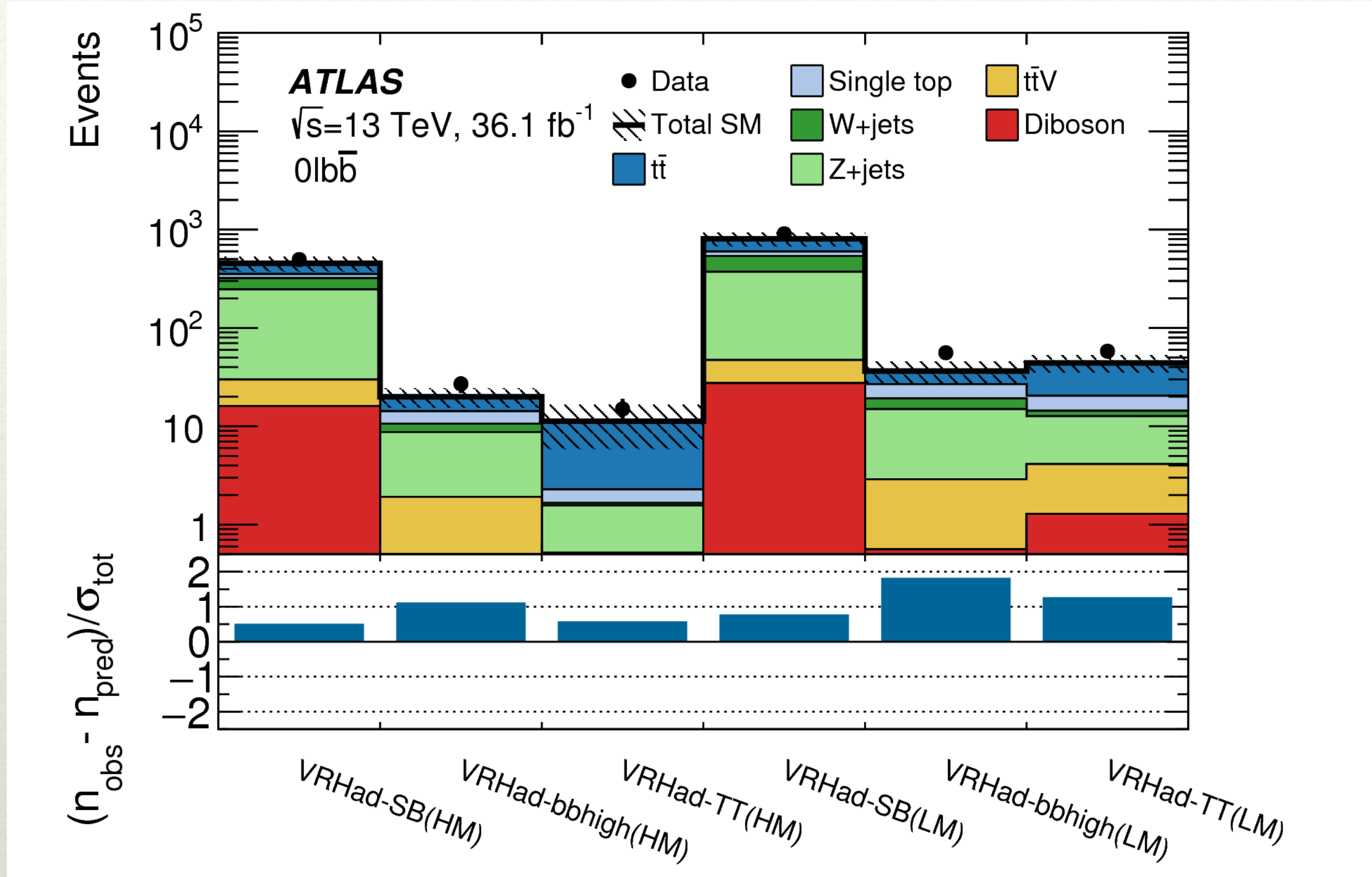






ATLAS WH fully hadronic

Variable	SRHad-High	SRHad-Low
N_{lepton}	$= 0$	$= 0$
N_{jet} ($p_T > 30$ GeV)	$\in [4,\ 5]$	$\in [4,\ 5]$
$N_{b\text{-jet}}$	$= 2$	$= 2$
$\Delta\phi^{4j}_{\text{min}}$	> 0.4	> 0.4
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 250	> 200
m_{eff} [GeV]	> 900	> 700
$m_{b\bar{b}}$ [GeV]	$\in [105, 135]$	$\in [105, 135]$
$m_{q\bar{q}}$ [GeV]	$\in [75, 90]$	$\in [75, 90]$
m_{CT} [GeV]	> 140	> 190
$m_{\text{T}}^{b,\text{min}}$ [GeV]	> 160	> 180

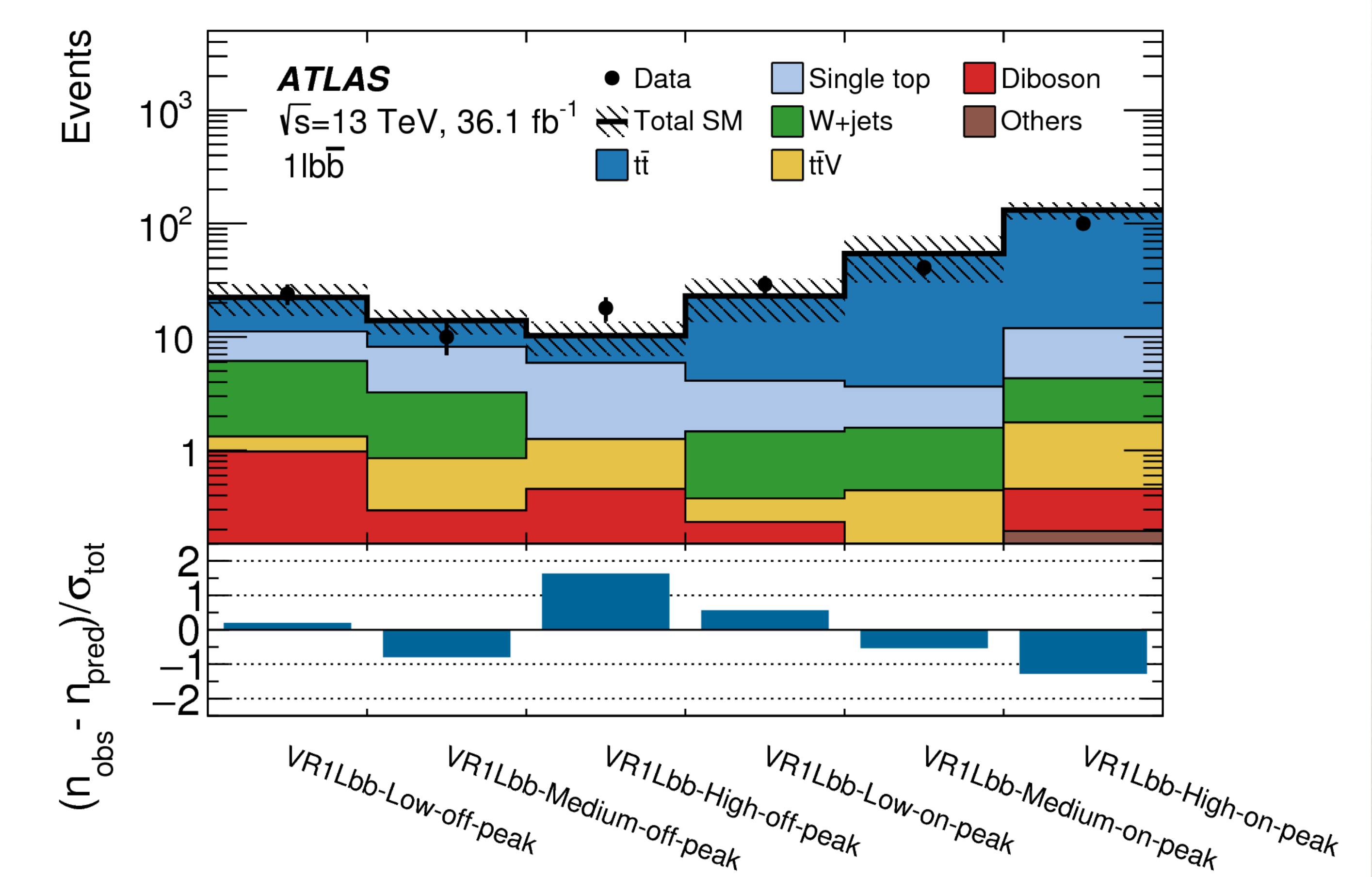


$0\ell b\bar{b}$ channel		
Uncertainty of region	SRHad-High	SRHad-Low
Total background expectation	2.5	8
Total background uncertainty	±1.3	±4
Systematic, experimental	±0.9	±1.2
Systematic, theoretical	±0.7	±3
Statistical, MC samples	±0.5	±0.8
Statistical, $\mu_{\text{TT,ST,Zj}}$ scale-factors	±0.25	±0.5

- **Control regions** :
  - **tt** : low m_{CT}, $m_T^{b,min}$, $m_{bb} > 135$ GeV
  - **Wt** : 1 lepton, m_{CT}, $m_T^{b,min}$ above the top mass, $m_{bb} > 195$ GeV
  - **Z+jets** : ee,μμ events in Z peak, leptons treated as invisible
- **Validation regions** :
  - **TT** : top dominated, low m_{CT}, mbb > 135 GeV, $m_T^{b,min}$ as in SR
  - **SB** : sideband in m_{bb} and m_{qq}
  - **high** : $m_{bb} > 135$ GeV, m_{qq} in W window

ATLAS WH 1 lepton

Variable	SR1Lbb-Low	SR1Lbb-Medium	SR1Lbb-High
N_{lepton}		$= 1$	
p_{T}^{ℓ} [GeV]		> 27	
N_{jet} ($p_{\text{T}} > 25\ GeV$)		$= 2$ or 3	
$N_{b\text{-jet}}$		$= 2$	
$E_{\text{T}}^{\text{miss}}$ [GeV]		> 200	
m_{CT} [GeV]		> 160	
m_{T} [GeV]	$\in [100, 140]$	$\in [140, 200]$	> 200
$m_{b\bar{b}}$ [GeV]		$\in [105, 135]$	



- **Control regions** :
  - **tt** : low m_{CT}, Higgs mass veto
  - **Wt** : $m_{bb} > 195$ GeV
  - **W+jets** : $40 < m_T < 100$ GeV, $m_{bb} < 80$ GeV
- **Validation regions** :
  - **on peak** : Higgs mass window, low M_{CT}
  - **off peak** : $m_{bb} < 95$ or 145-195 GeV

$1\ell b\bar{b}$ channel			
Uncertainty of region	SR1Lbb-Low	SR1Lbb-Medium	SR1Lbb-High
Total background expectation	5.7	2.8	4.6
Total background uncertainty	±2.3	±1.0	±1.2
Systematic, experimental	±1.3	±0.7	±0.6
Systematic, theoretical	±2.2	±0.9	±0.7
Statistical, MC samples	±1.1	±0.5	±0.6
Statistical, $\mu_{\text{TT,ST,Wj}}$ scale-factors	±0.8	±0.6	±1.3

ATLAS WH 1Lγγ

Variable	SR1L$\gamma\gamma$-a	SR1L$\gamma\gamma$-b
N_γ	$= 2$	
p_{T}^{γ} [GeV]	$> (40, 31)$	
N_{lepton}	$= 1$	
p_{T}^{ℓ} [GeV]	> 25	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 40	
$\Delta\phi_{W,h}$	> 2.25	
$m_{\gamma\gamma}$ [GeV]	$\in [120, 130]$	
$N_{b\text{-jet}}$ ($p_{\mathrm{T}} > 30\ GeV$)	$= 0$	
$m_{\mathrm{T}}^{W\gamma_1}$ [GeV]	≥ 150	
$m_{\mathrm{T}}^{W\gamma_2}$ [GeV]	> 140	$\in [80, 140]$
m_{T} [GeV]	> 110	< 110

$1\ell\gamma\gamma$ channel

Uncertainty of region	SR1L$\gamma\gamma$-a	SR1L$\gamma\gamma$-b
Total background expectation	0.36	5.3
Total background uncertainty	±0.22	±1.0
Systematic, experimental	±0.018	±0.27
Systematic, theoretical	±0.008	±0.11
Statistical, MC samples	±0.006	±0.024
Statistical, non-peaking	±0.22	±0.9

ATLAS WH multilepton

Variable	SRSS-j1	SRSS-j23
$\Delta\eta_{\ell\ell}$	< 1.5	-
N_{jet} $(p_{\mathrm{T}} > 20\ GeV)$	$= 1$	$= 2$ or 3
$N_{b\text{-jet}}$	$= 0$	$= 0$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 100	> 100
m_{T} [GeV]	> 140	> 120
m_{eff} [GeV]	> 260	> 240
$m_{\ell j(j)}$ [GeV]	< 180	< 130
m_{T2} [GeV]	> 80	> 70

$\ell^{\pm}\ell^{\pm}$ channel

Uncertainty of region	SRSS-j1	SRSS-j23
Total background expectation	6.7	5.3
Total background uncertainty	±2.2	±1.6
Systematic, experimental	±2.1	±1.6.
Systematic, theoretical	±0.21	±0.28
Statistical, MC samples	±0.4	±0.34
Statistical, μ_{WZ} scale-factors	–	–

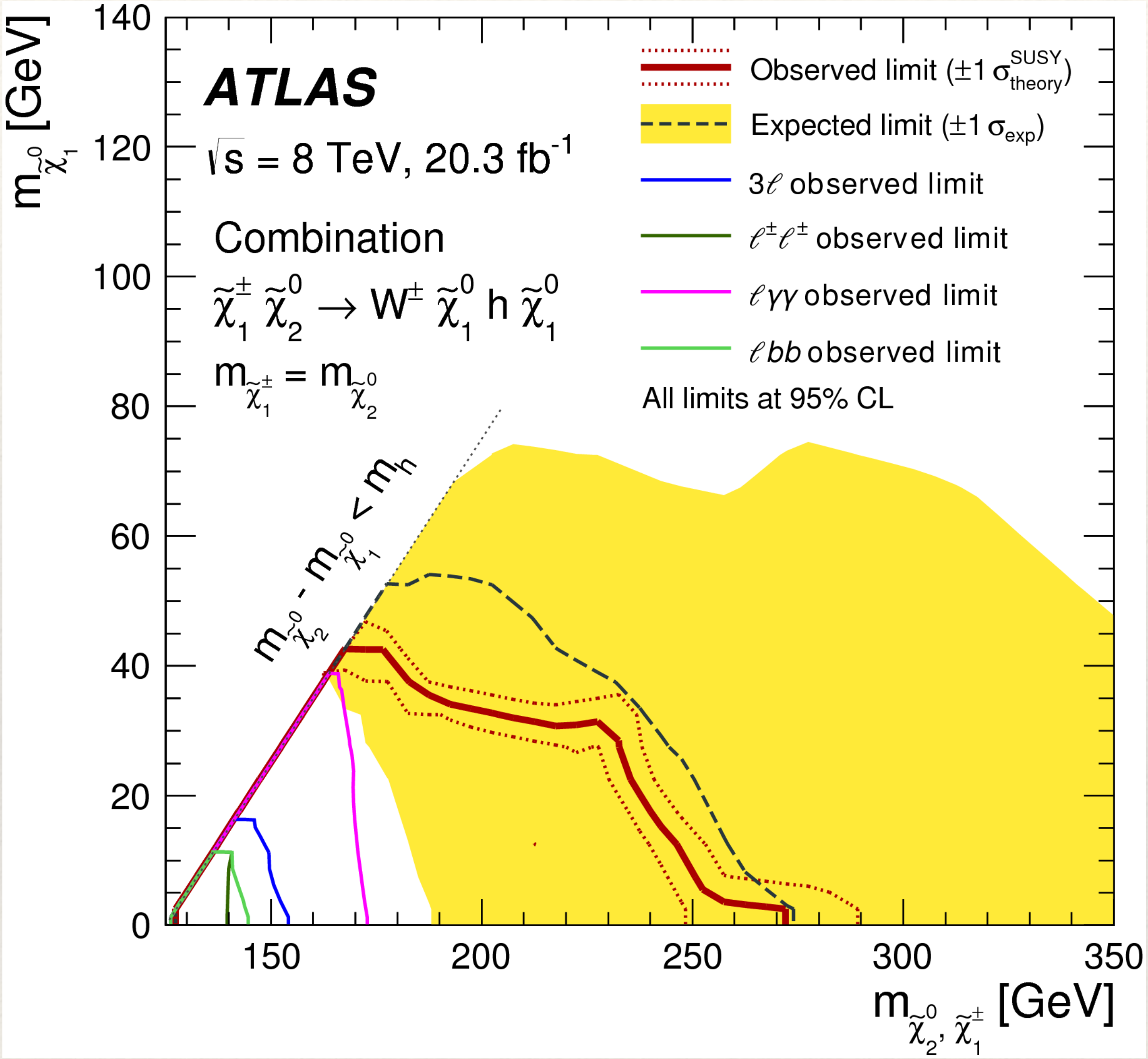
3ℓ channel

Uncertainty of region	SR3L-DFOS-0J	SR3L-DFOS-1Ja (b)	SR3L-SFOS-0Ja (b)	SR3L-SFOS-1J
Total background expectation	2.05	8(1.7)	3.8(2.37)	11.4
Total background uncertainty	±0.98	±4 (±0.7)	±1.7 (±0.96)	±2.6
Systematic, experimental	±0.8	±4 (±0.5)	±1.7 (±0.8)	±2.0
Systematic, theoretical	±0.11	±0.25 (±0.16)	±0.15 (±0.22)	±1.5
Statistical, MC samples	±0.6	±1.2 (±0.4)	±0.6 (±0.4)	±0.9
Statistical, μ_{WZ} scale-factors	±0.022	±0.12(±0.06)	±0.30(±0.24)	±0.9

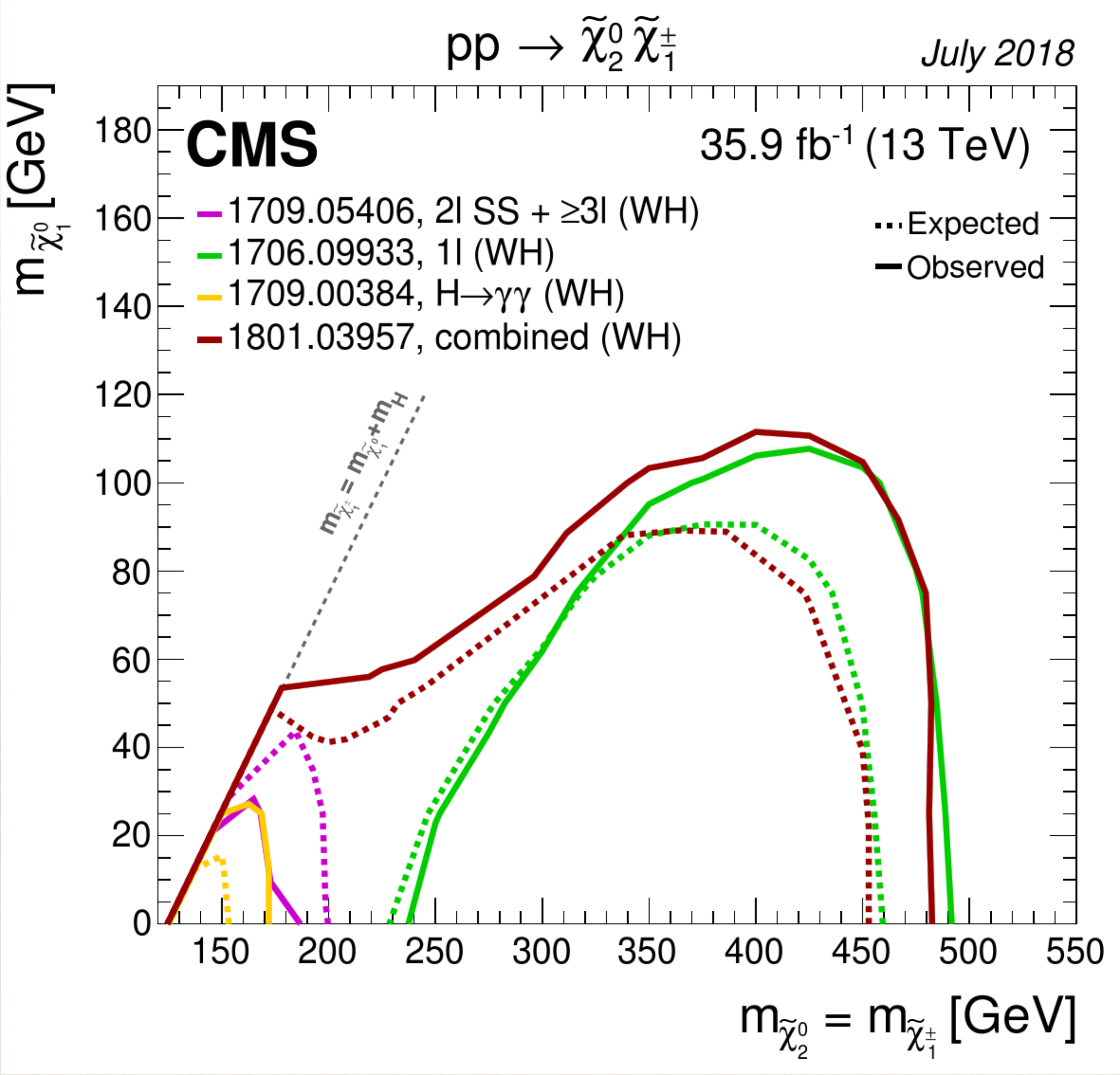
Variable	SR3L-DFOS-0J	SR3L-DFOS-1Ja	SR3L-DFOS-1Jb
N_{jet} $(p_{\mathrm{T}} > 20\ GeV)$	$= 0$	> 0	> 0
$N_{b\text{-jet}}$	$= 0$	$= 0$	$= 0$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 60	$\in [30, 100]$	> 100
$m_{\ell_{\mathrm{DFOS}}+\ell_{\mathrm{near}}}$ [GeV]	< 90	< 60	< 70
$\Delta R_{\mathrm{OS,near}}$	-	< 1.4	< 1.4
$\Delta\phi_{\mathrm{SS}}$	-	-	< 2.8

Variable	SR3L-SFOS-0Ja	SR3L-SFOS-0Jb	SR3L-SFOS-1J
N_{jet} $(p_{\mathrm{T}} > 20\ GeV)$	$= 0$	$= 0$	> 0
$N_{b\text{-jet}}$	$= 0$	$= 0$	$= 0$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$\in [80, 120]$	> 120	> 110
$m_{\mathrm{T}}^{\mathrm{min}}$ [GeV]	> 110	> 110	> 110
$m_{\mathrm{SFOS}}^{\mathrm{min}}$	$> 20\ GeV, \notin [81.2, 101.2]$	$> 20\ GeV, \notin [81.2, 101.2]$	$> 20\ GeV, \notin [81.2, 101.2]$

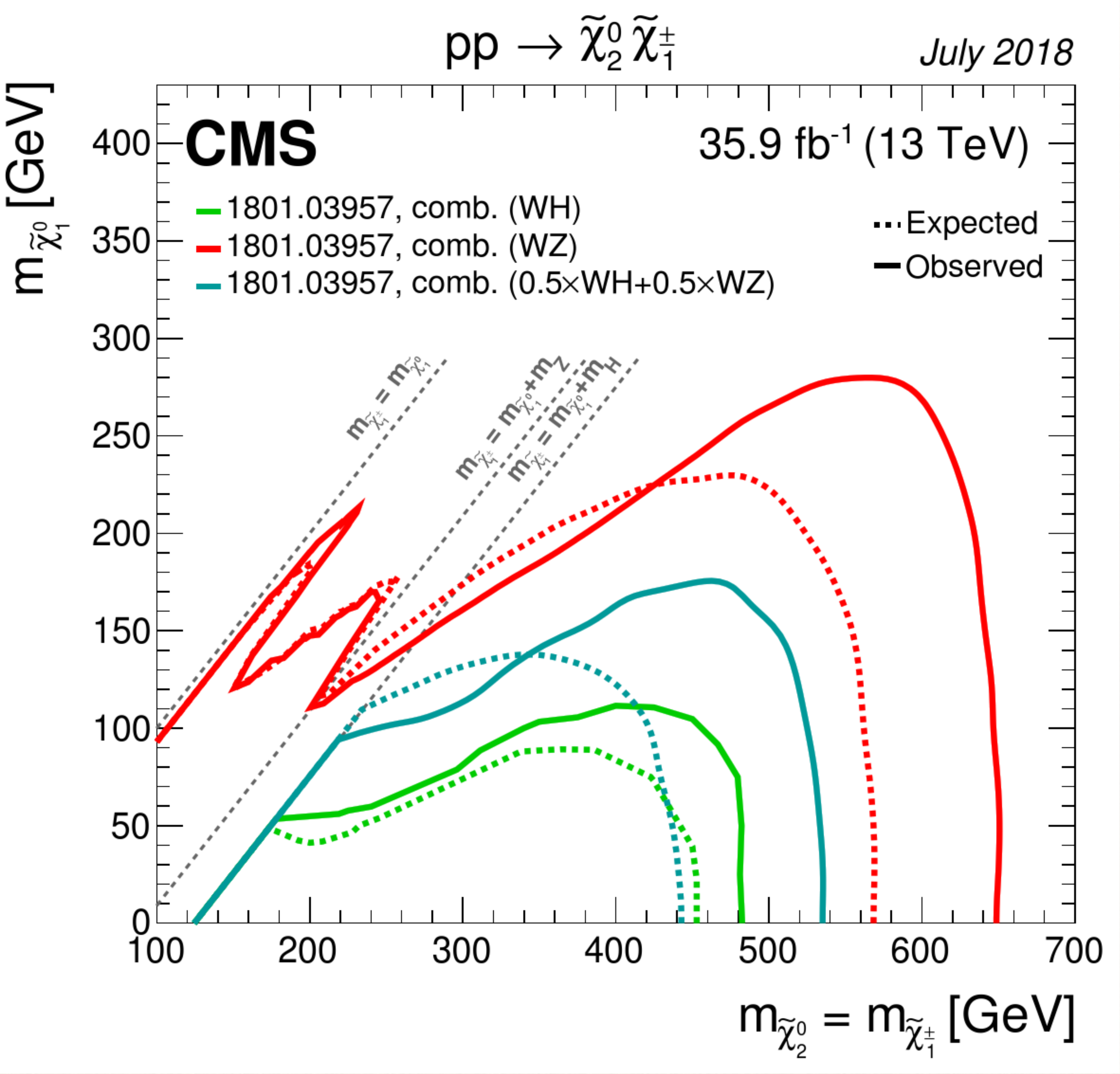
OTHER "WH" LIMITS



Previous ATLAS result (run1)



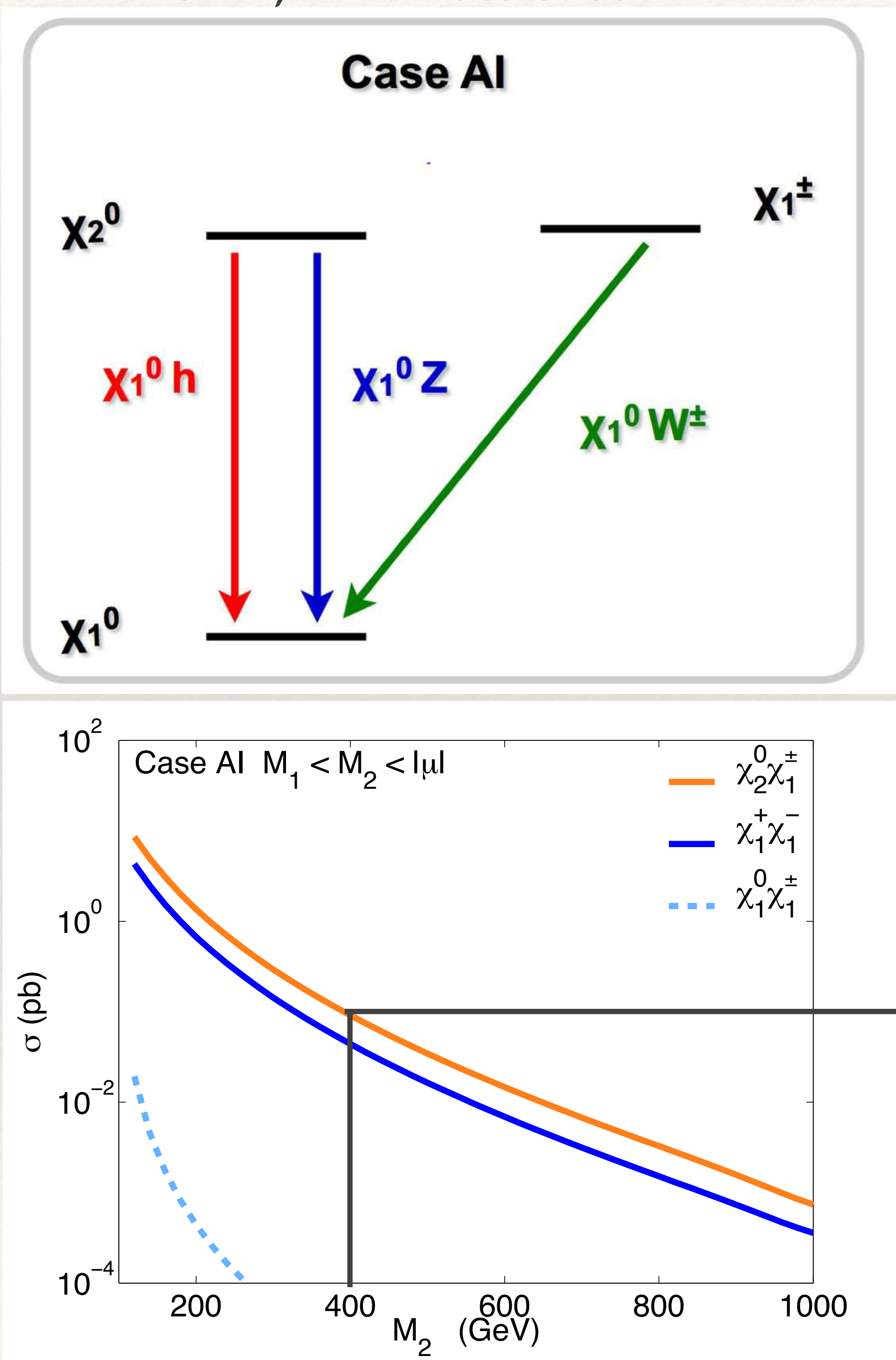
“WH” vs “WZ”



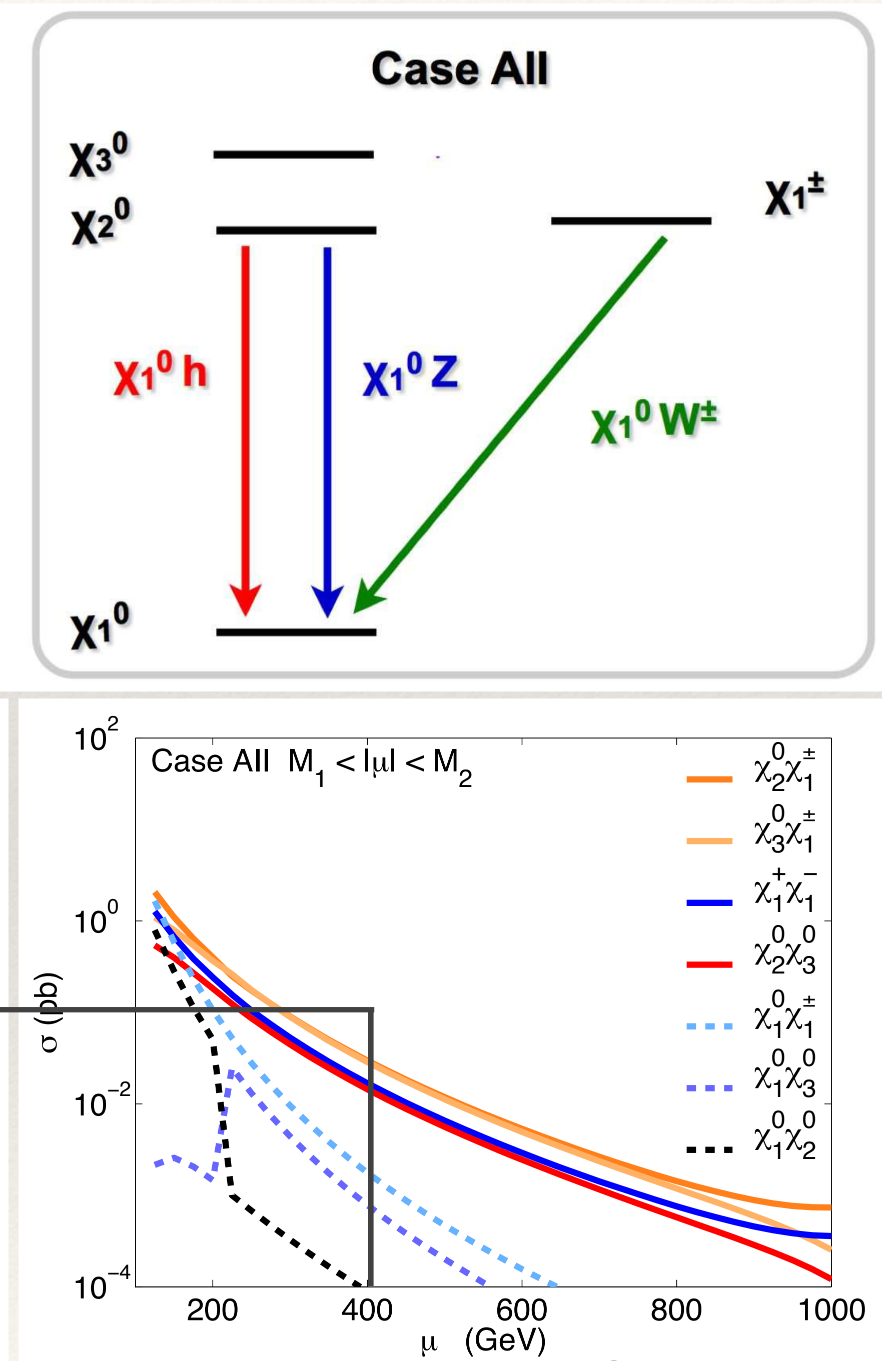
pp → $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$
July 2018
CMS
35.9 fb^{-1} (13 TeV)
1801.03957, comb. (WH)
1801.03957, comb. (WZ)
1801.03957, comb. (0.5×WH+0.5×WZ)
Expected
Observed
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}+m_Z$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}+m_H$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm}$ [GeV]
0
50
100
150
200
250
300
350
400
100
200
300
400
500
600
700

SUSY EWK cross sections

T. Han et al., arXiv:1309.5966

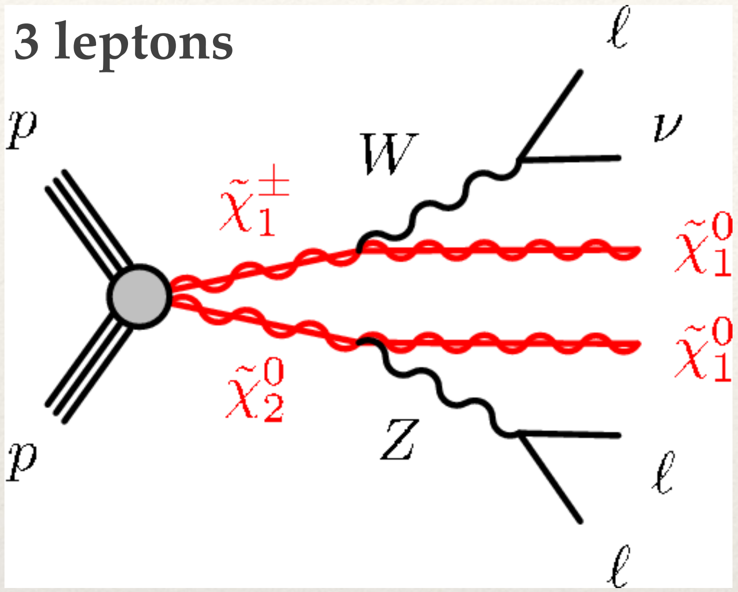


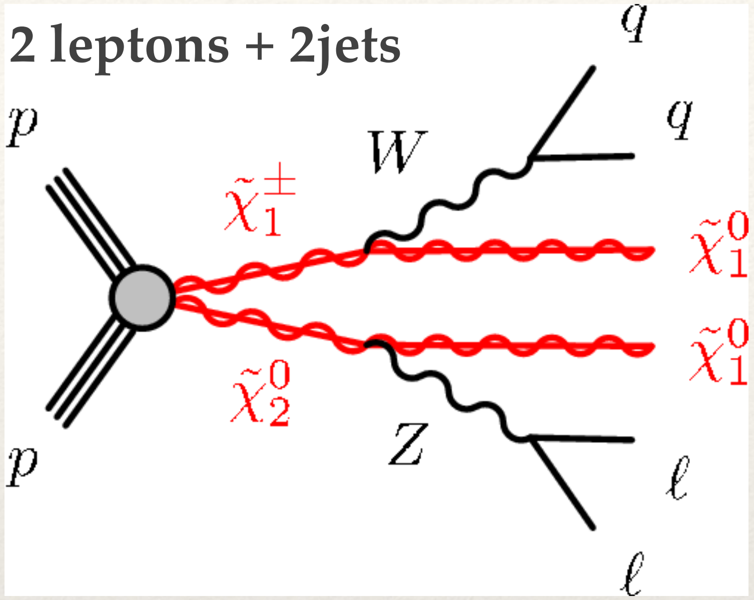
Wino NLSP

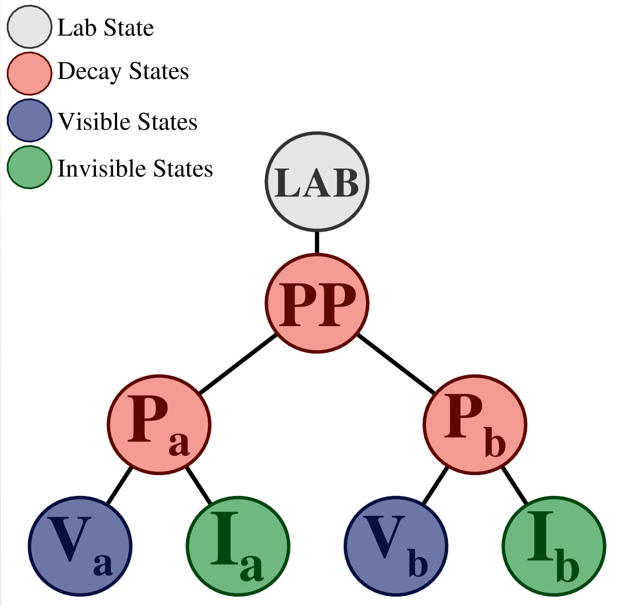


Higgsino NLSP

ATLAS RJR EWK SEARCH







Targeted by two papers :

- "conventional" discriminating variables [EPJ C78 (2018) 995, arXiv:1803.02762]
- Recursive Jigsaw Reconstruction [PRD 98 (2018) 092012, arXiv:1806.02293]

Complementary (similar sensitivity to target simplified model, but selecting different events / phase space)

What is Recursive Jigsaw Reconstruction ?

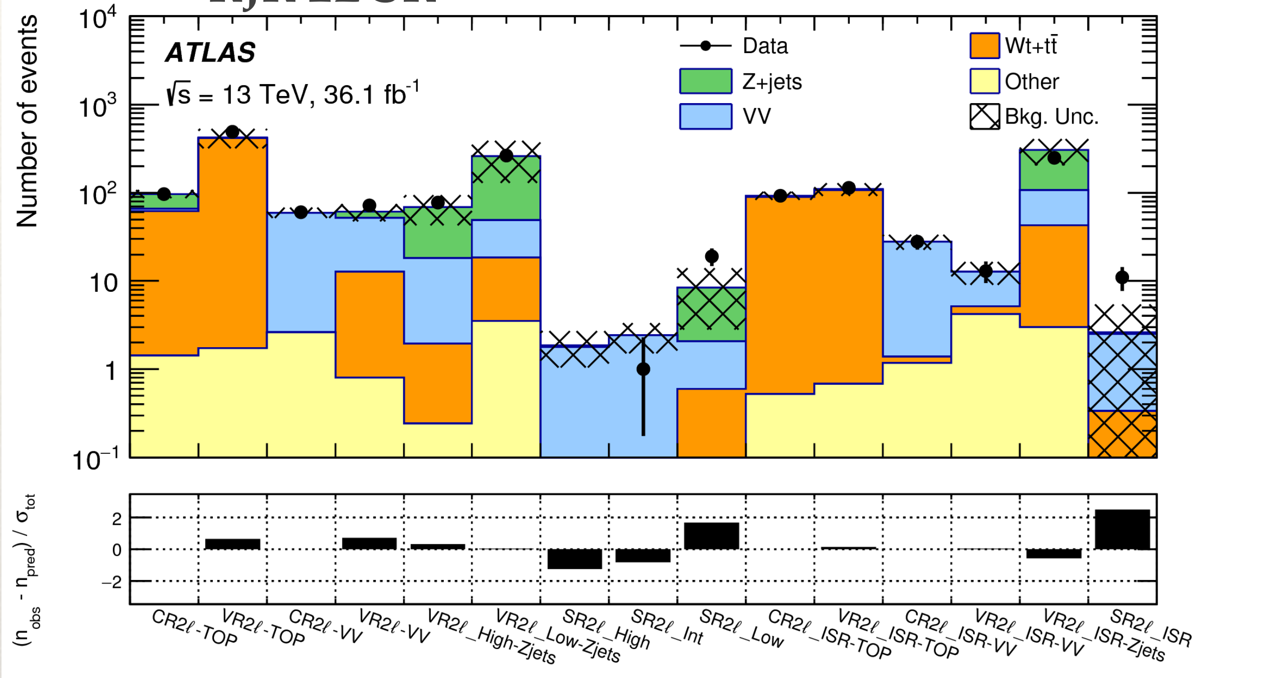
- Assume a specific decay chain
- Perform a series of Lorentz boosts between frames
- Determine unknowns (like pzmiss) with Jigsaw rules
- Provides 4-vector of each particle in the assumed decay chain

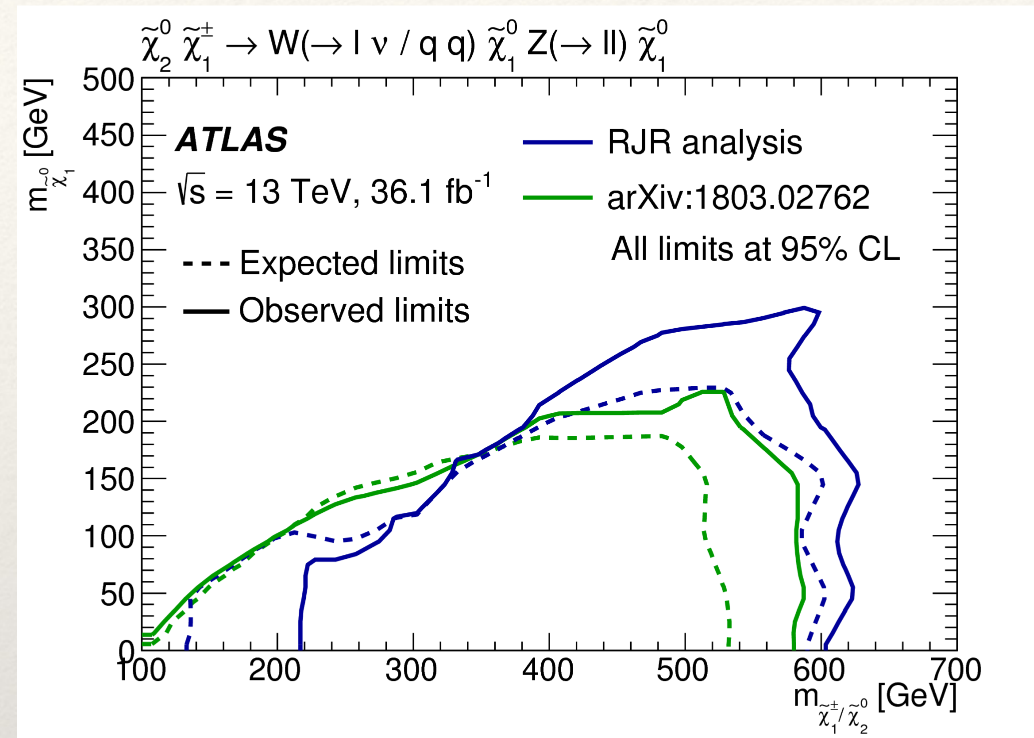
References :

Jackson, Rogan, Santini, PRD 95 (2017) 035031

http://restframes.com

RJR 2L SR





RJR 3L SR