ICEPP
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ATLAS EXPERIMENT

Searches for Strongly Produced SUSY Particles including R-parity Violating Decays with ATLAS

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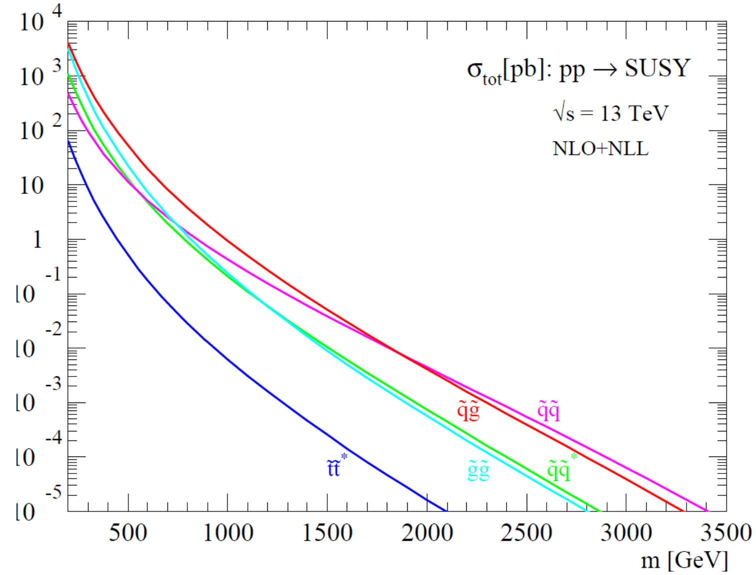
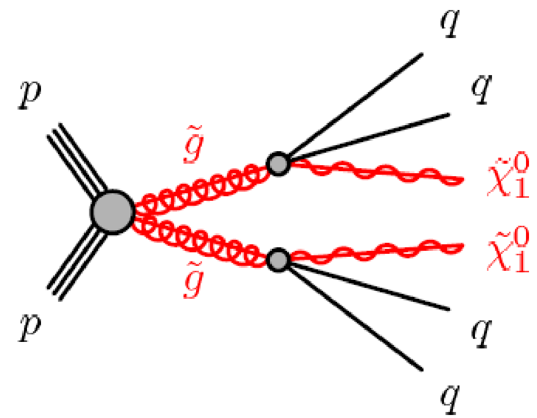
on behalf of the ATLAS Collaboration

Introduction

- Supersymmetry (SUSY) is one of the most promising extensions of the Standard Model.
  - It can solve the hierarchy problem.
- Strongly interacting SUSY particles (gluinos and squarks) can be produced in large cross sections at the LHC.
- If R-parity ($P_R = (-1)^{3B+L+2s}$) is conserved, the lightest SUSY particle (LSP) becomes stable.
  - LSP is seen as missing momentum in collider.
  - LSP can be dark matter candidate.

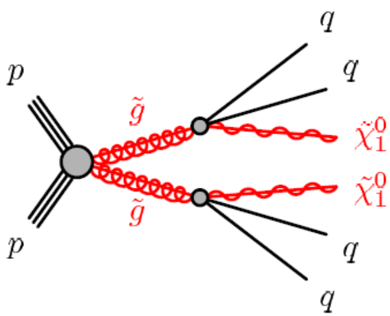


arXiv:1407.5066

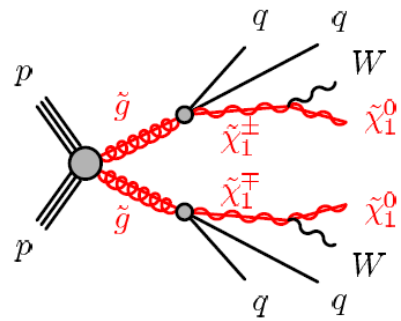


Strongly Produced SUSY Searches So Far

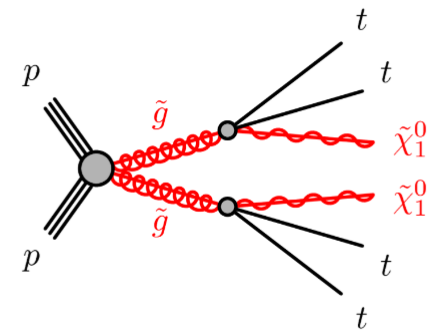
- In the searches at √s=13 TeV using ~15 fb^{-1} so far, no significant excess was seen in analyses targeting strongly produced SUSY assuming R-parity conservation.



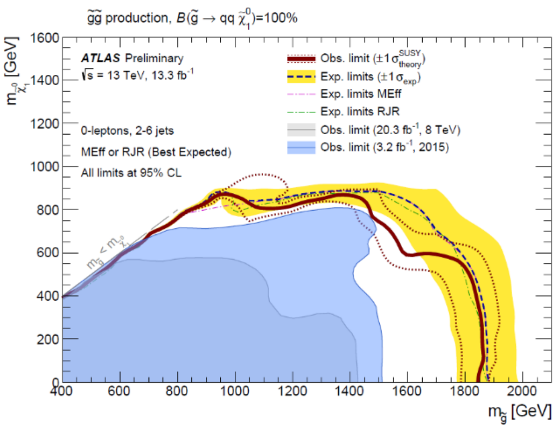
0-lepton+jets+E_T^{miss}
ATLAS-CONF-2016-078

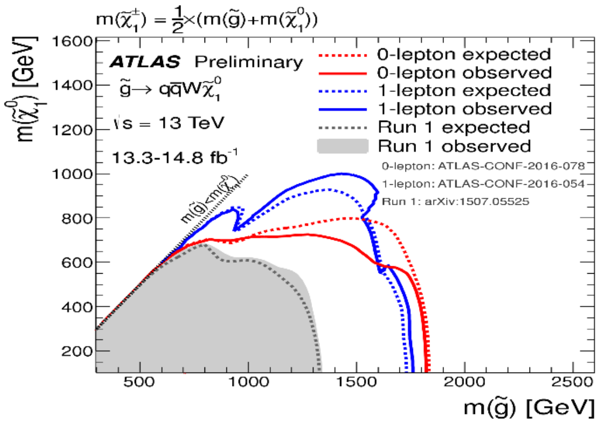


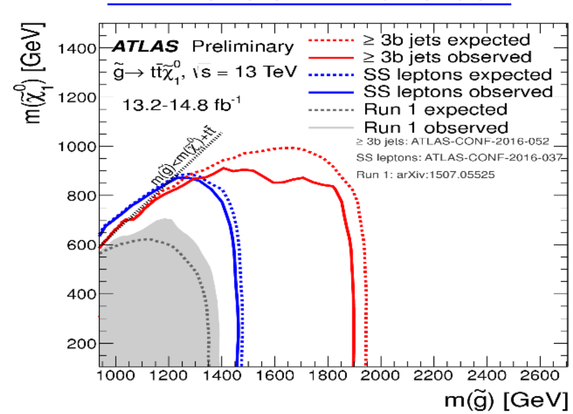
0/1-lepton+jets+E_T^{miss}
ATLAS-CONF-2016-078
ATLAS-CONF-2016-054



0/1/2-lepton+(b)jets+E_T^{miss}
ATLAS-CONF-2016-052
ATLAS-CONF-2016-037





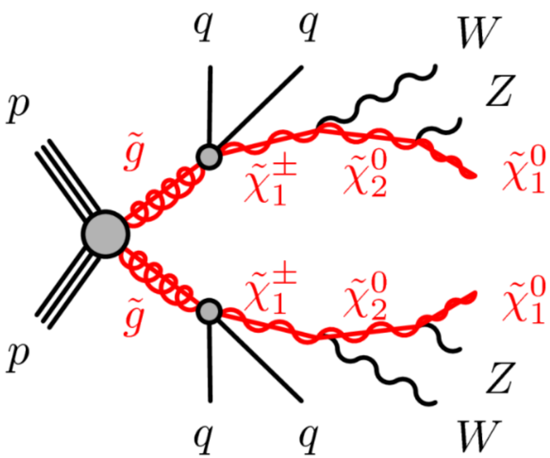


Contents

- More complex final states are searched for R-parity conserving models.
  - 0-lepton+8-10 jets+E_T^{miss} (18.2 fb^{-1})
    - ATLAS-CONF-2016-095
  - SFOS (Same-Flavor Opposite-Sign) 2-lepton+jets+E_T^{miss} (14.7 fb^{-1})
    - arXiv:1611.05791
  - Photon+jets+E_T^{miss} (13.3 fb^{-1})
    - ATLAS-CONF-2016-066
- R-parity violation (RPV) scenario is also considered.
  - RPV multijets (14.8 fb^{-1})
    - ATLAS-CONF-2016-057
  - RPV 1-lepton+multijets (14.8 fb^{-1})
    - ATLAS-CONF-2016-094

0-lepton+Multijets+E_T^{miss}

- SUSY particles can decay in cascade and produce more particles in final state.
  - Each particle become soft.
- Event selection
  - ATLAS-CONF-2016-095



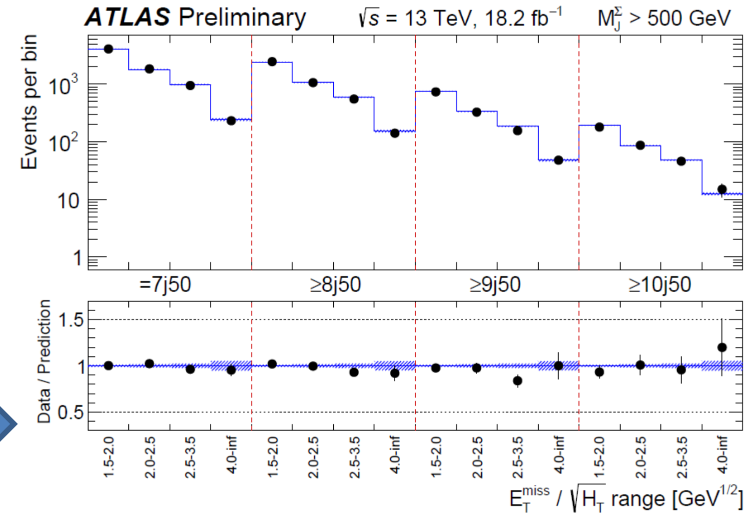
Signal region	8j50	9j50	10j50
$R = 0.4$ jet $\|\eta\|$		< 2.0 for all SRs	
$R = 0.4$ jet p_T		> 50 GeV for all SRs	
N_{jet}	≥ 8	≥ 9	≥ 10
M_J^Σ		> 340 GeV or > 500 GeV	
$E_T^{miss}/\sqrt{H_T}$		$> 4\,\text{GeV}^{1/2}$ for all SRs	

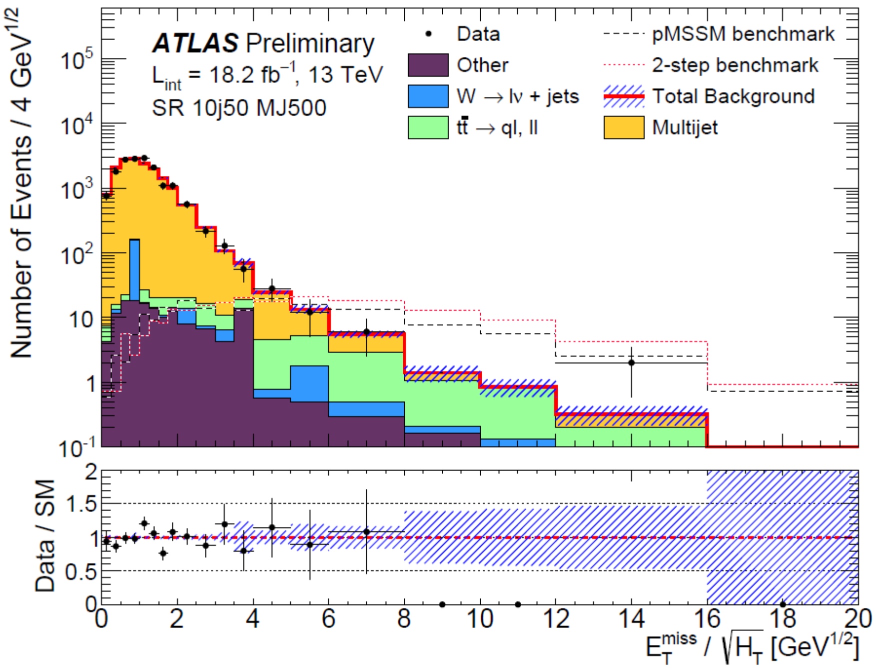
$$M_J^\Sigma = \sum_j m_j^{R=1.0}$$

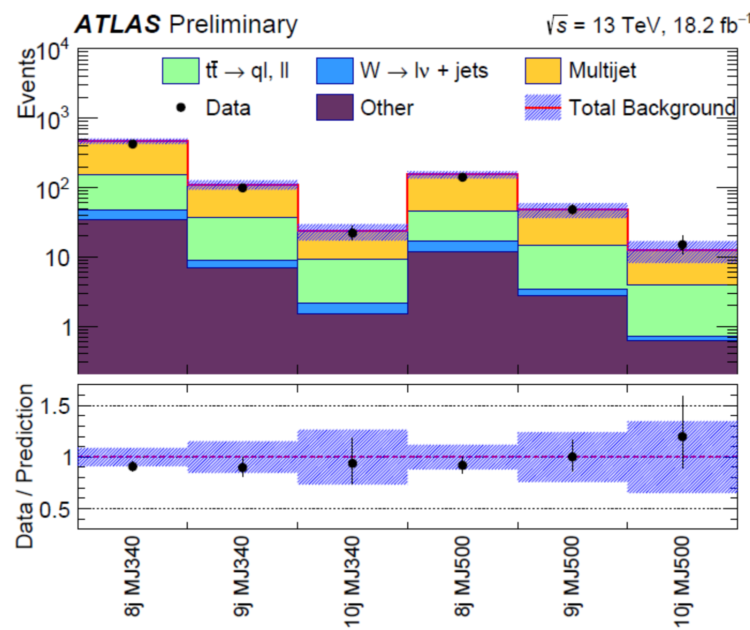
Reclustered jet mass with R=1.0 using anti-k_t R=0.4 jets as input

Background Estimation

- Leptonic background ($t\bar{t}$, W+jets):
  - MC simulation is normalized in 1-lepton control region.
- Multijet background
  - Measure $E_T^{miss}/\sqrt{H_T}$ shape in 6-jet region.
  - 7-jet region is for validation.



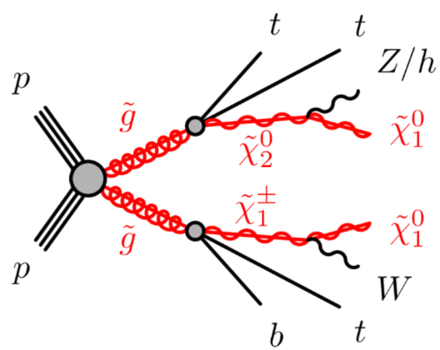


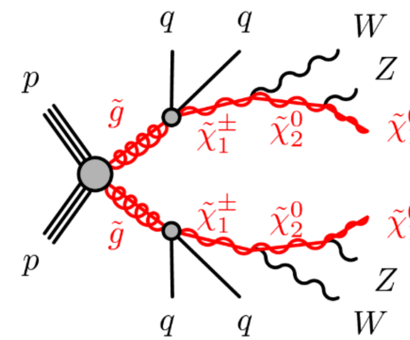


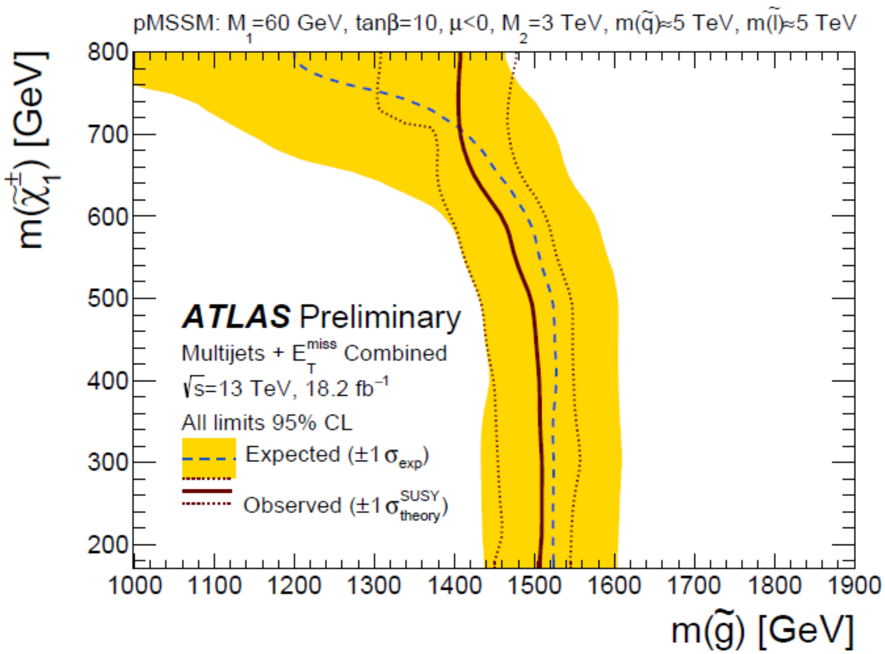
Interpretation

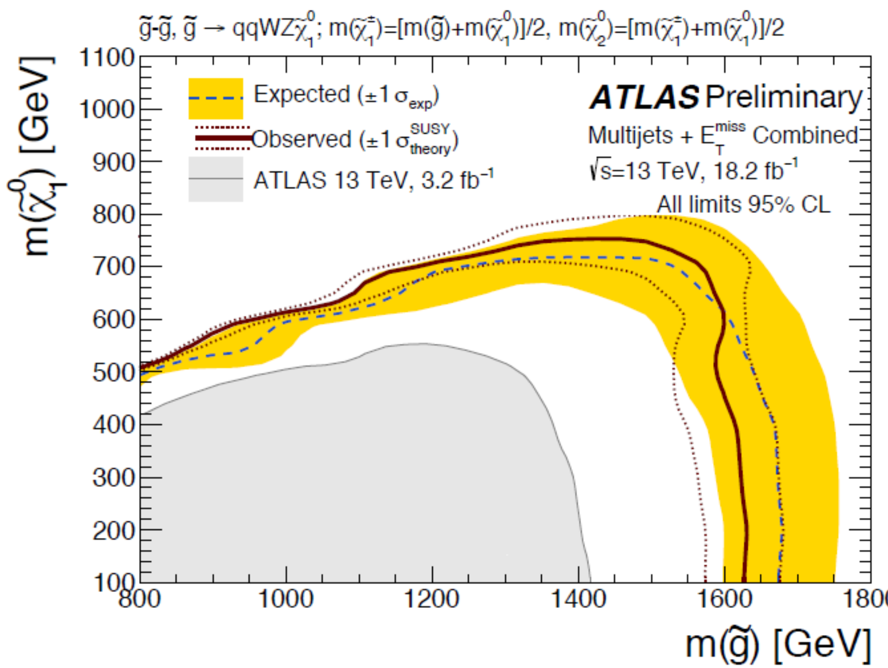
- Results are interpreted in pMSSM and simplified models.

Typical decay in this model







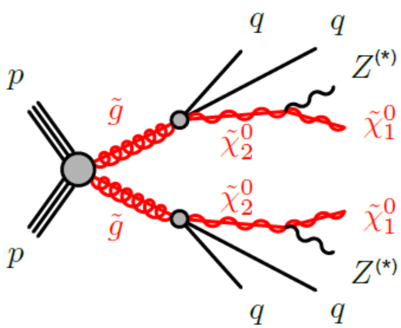


SFOS 2-lepton+Jets+E_T^{miss}

- Small excesses have been seen in SFOS 2-lepton+jets+E_T^{miss} searches.
  - They need to be investigated in $\sqrt{s}$=13 TeV with higher statistics.

Local significance observed in each analysis

	ATLAS (EJPC75(2015)318, ATLAS-CONF-2015-082)	CMS (JHEP04(2015)124, CMS-PAS-SUS-16-021)
On-shell Z	2.2 σ (13 TeV, 3.2 fb^{-1}) 3.0 σ (8 TeV, 20 fb^{-1})	No excess (13 TeV, 12.9 fb^{-1}) No excess (8 TeV, 19.4 fb^{-1})
m_{ll} "edge"	-- No excess (8 TeV, 20 fb^{-1})	2.0 σ (13 TeV, 12.9 fb^{-1}) 2.4 σ (8 TeV, 19.4 fb^{-1})



- Event selection
  arXiv:1611.05791

On-shell Z regions	E_T^{miss} [GeV]	H_T^{incl} [GeV]	n_{jets}	$m_{\ell\ell}$ [GeV]	SF/DF	$\Delta\phi(\text{jet}_{12}, p_T^{miss})$
Signal region						
SRZ	> 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	> 0.4

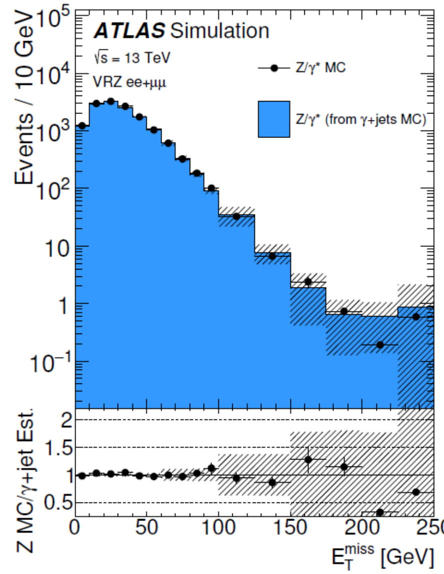
m_{ll} is segmented in multi-bins for "edge" analysis.

Edge regions	E_T^{miss} [GeV]	H_T [GeV]	n_{jets}	$m_{\ell\ell}$ [GeV]	SF/DF	OS/SS	$\Delta\phi(\text{jet}_{12}, p_T^{miss})$	$m_{\ell\ell}$ ranges
Signal regions								
SR-low	> 200	–	≥ 2	> 12	SF	OS	> 0.4	9
SR-medium	> 200	> 400	≥ 2	> 12	SF	OS	> 0.4	8
SR-high	> 200	> 700	≥ 2	> 12	SF	OS	> 0.4	7

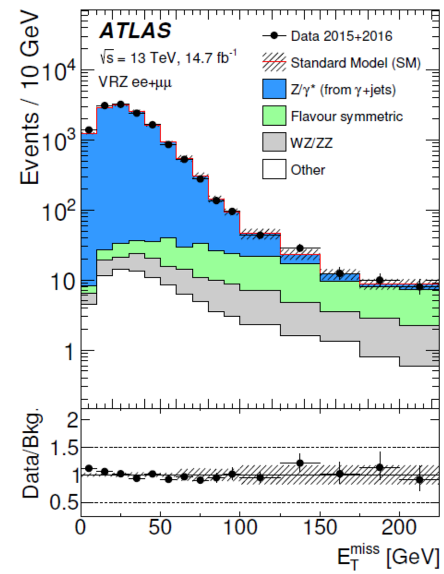
Background Estimation

- Flavor symmetric background ($t\bar{t}$, WW):
  - Estimated from Different-flavor (DF) OS 2-lepton data events correcting ee,μμ/eμ acceptance
  - Cross-checked by m_{ll} side-band estimation for on-shell Z SR.
- Z/γ*+jets background:
  - E_T^{miss} distribution is estimated from γ+jets events.
  - Photon p_T is smeared according to Z→ee and Z→μμ resolution.
  - m_{ll} shape is extracted from MC simulation.
- Fake lepton background (W+jets):
  - Estimated by the events passing loose-lepton ID to tight-lepton ID.

$$N_{\mathrm{pass}}^{\mathrm{fake}} = \frac{N_{\mathrm{fail}} - (1/\epsilon^{\mathrm{real}} - 1) \times N_{\mathrm{pass}}}{1/\epsilon^{\mathrm{fake}} - 1/\epsilon^{\mathrm{real}}}$$



MC closure test for Z+jets estimation

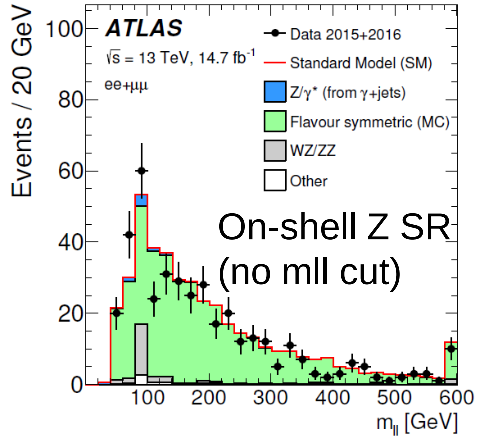


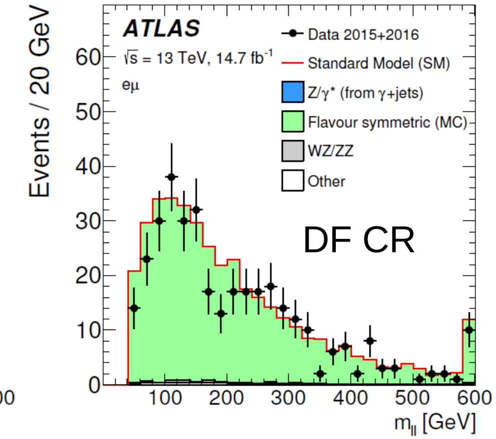
Low E_T^{miss} validation region

Results

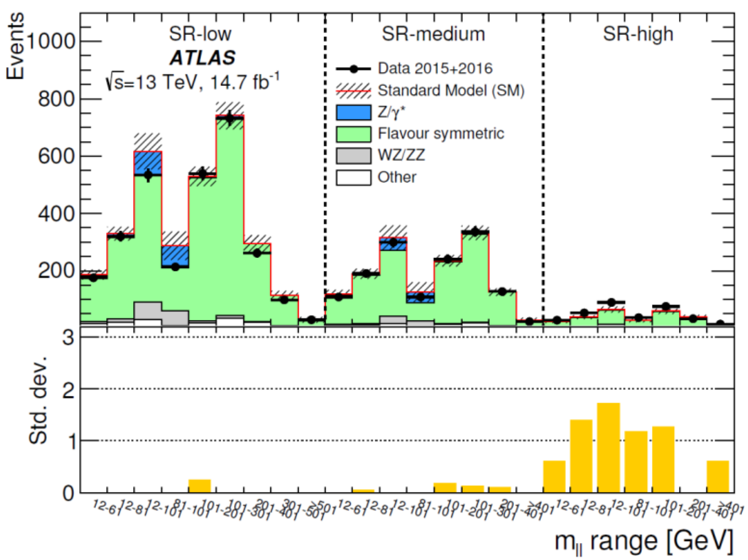
- On-shell Z

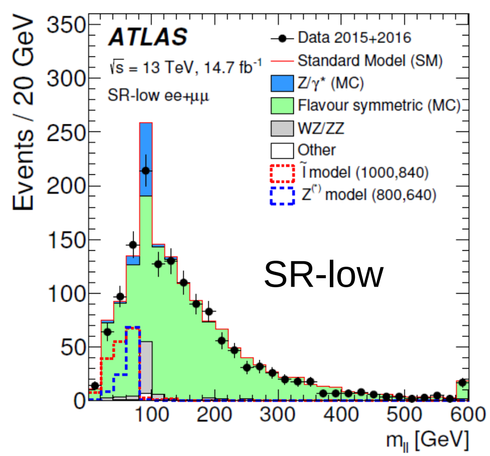
	SRZ	SRZ ee	SRZ $\mu\mu$
Observed events	60	35	25
Total expected background events	53.5 ± 9.3	27.1 ± 5.1	26.8 ± 4.4
Flavour-symmetric ($t\bar{t}$, Wt, WW and $Z \to \tau\tau$) events	33.2 ± 3.9	16.5 ± 2.1	16.7 ± 2.0
Z/γ^{*} + jets events	3.1 ±2.8	$1.0^{+1.3}_{-1.0}$	2.1 ±1.4
WZ/ZZ events	14.2 ± 7.7	7.8 ±4.3	6.4 ±3.5
Rare top events	2.9 ±0.8	1.4 ±0.4	1.5 ±0.4
Fake-lepton events	$0.1^{+0.8}_{-0.1}$	$0.5^{+0.7}_{-0.5}$	$0^{+0.2}$
$p(s = 0)$	0.32	0.15	0.5
Significance (σ)	0.47	1.02	0
Observed (Expected) S^{95}	28.2 ($24.5^{+8.9}_{-6.7}$)	22.0 ($15.8^{+6.5}_{-4.5}$)	12.9 ($14.0^{+5.7}_{-3.9}$)
$\langle\epsilon\sigma\rangle^{95}_{\mathrm{obs}}$ [fb]	1.9	1.5	0.88

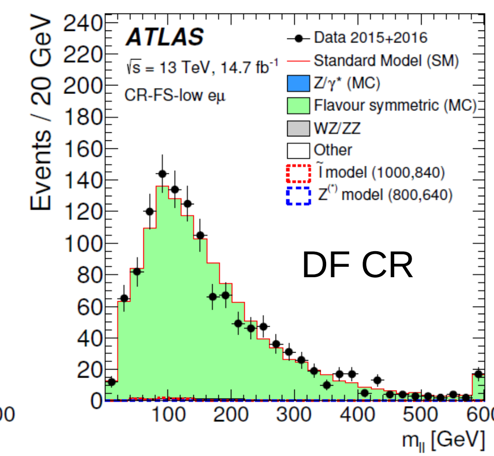




- m_{ll} edge

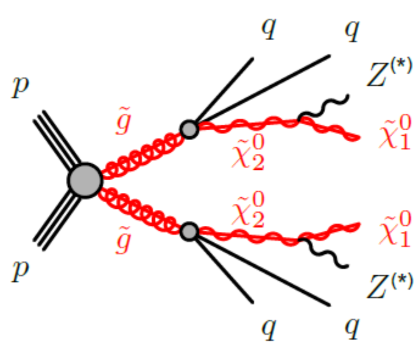


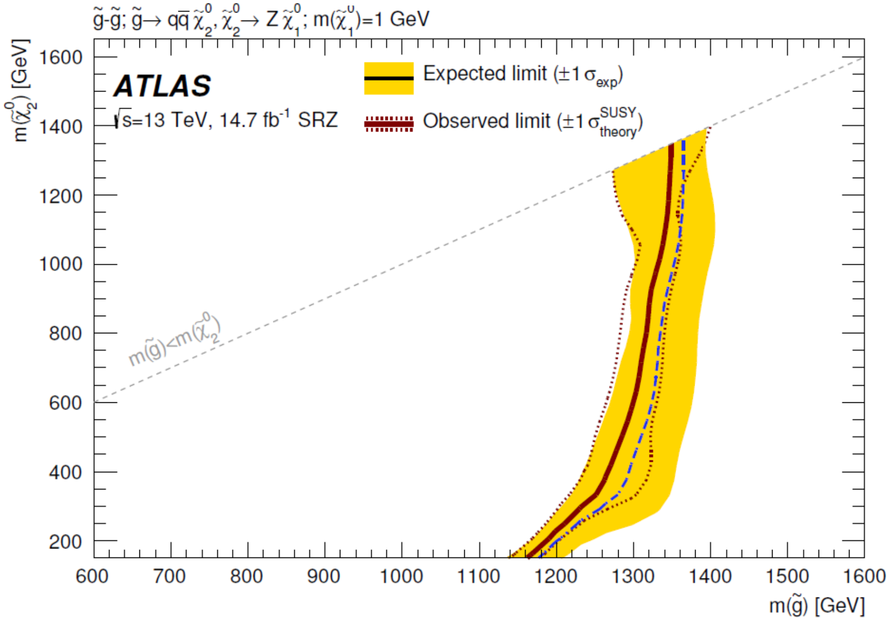


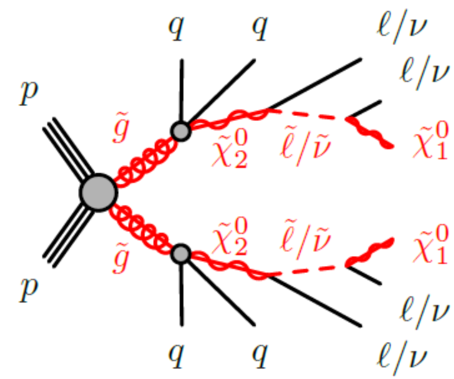


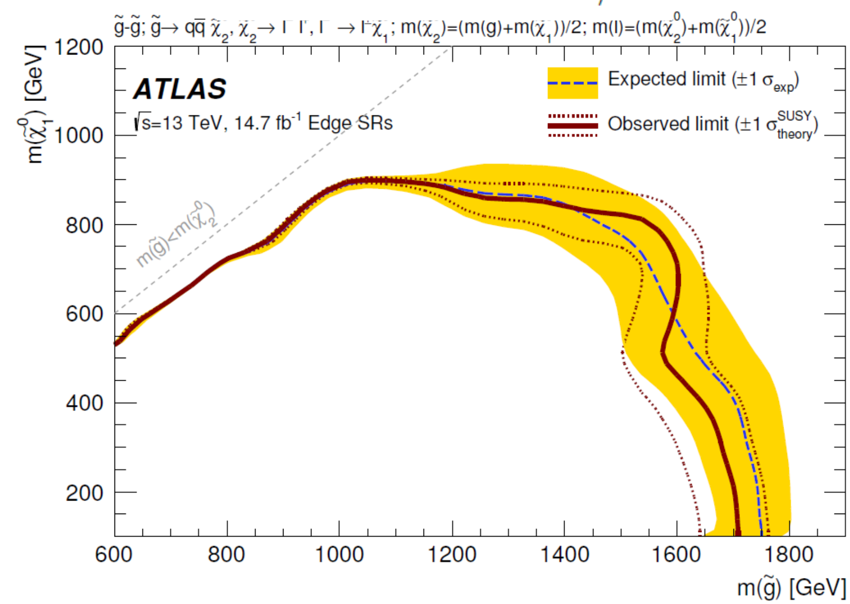
Interpretation

- No significant excess is seen in any of the SRs, this result is used to set limits on models.



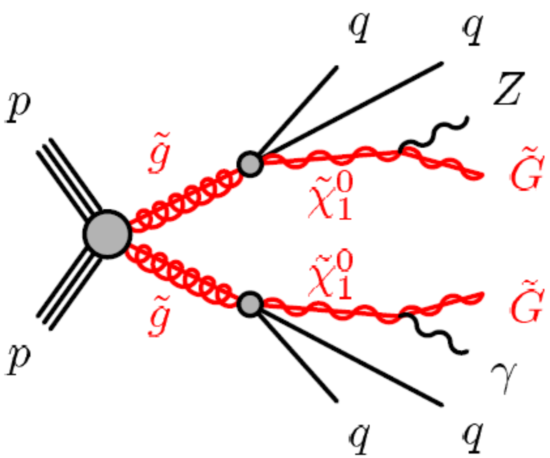






Photon+Jets+E_T^{miss}

- In Gauge Mediated Supersymmetry Breaking (GMSB) models, a photon can be expected in the final state as well as Z or Higgs boson depending on component of NLSP.
- Event selection



ATLAS-CONF-2016-066

	SR_L	SR_H
$N_{photons}$	> 0	> 0
$p_T^{leading-\gamma}$	> 145 GeV	> 400 GeV
$N_{leptons}$	0	0
N_{jets}	> 4	> 2
$\Delta\phi(\text{jet}, E_T^{miss})$	> 0.4	> 0.4
$\Delta\phi(\gamma, E_T^{miss})$	> 0.4	> 0.4
E_T^{miss}	> 200 GeV	> 400 GeV
m_{eff}	> 2000 GeV	> 2000 GeV
R_T^4	< 0.90	-

Background component

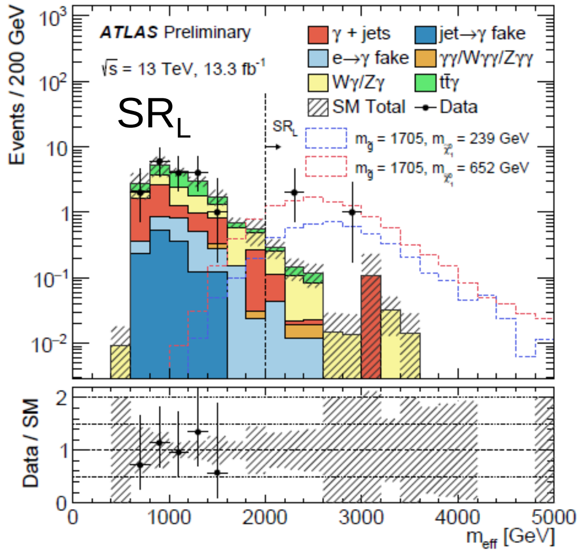
- $W\gamma$, $t\bar{t}\gamma$
- Fake photon from a jet
- Fake photon from an electron

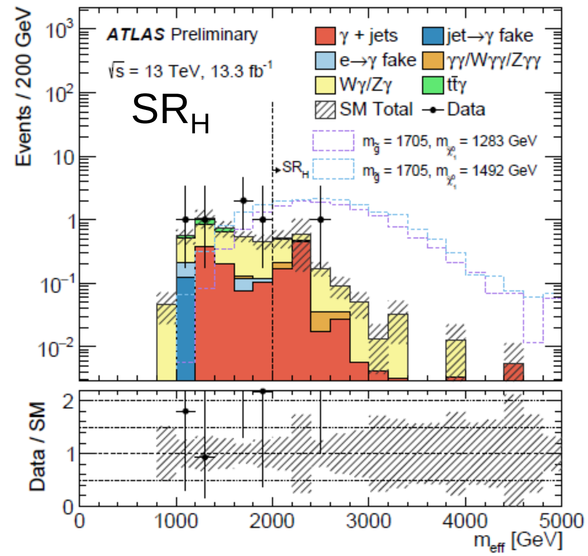
$$R_T^4 = \frac{\sum_{i=1}^{4} p_T^i}{\sum_{\text{jets}} p_T^j}$$

Results and Interpretation

- Result

Signal Region	SR_L	SR_H
Observed events	3	1
Expected SM events	0.78 ± 0.18	1.49 ± 0.45
γ + jets	0.18 ± 0.11	0.70 ± 0.24
$W\gamma$	0.30 ± 0.07	0.37 ± 0.09
$Z\gamma$	0.08 ± 0.08	0.32 ± 0.32
$t\bar{t}\gamma$	0.10 ± 0.04	0.03 ± 0.01
$e \rightarrow \gamma$ fakes	0.07 ± 0.03	0.00 ± 0.00
jet $\rightarrow \gamma$ fakes	0.04 ± 0.01	0.00 ± 0.00
$\gamma\gamma/W\gamma\gamma/Z\gamma\gamma$	0.01 ± 0.00	0.07 ± 0.01

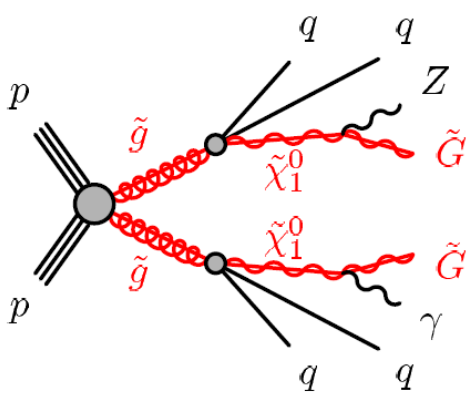


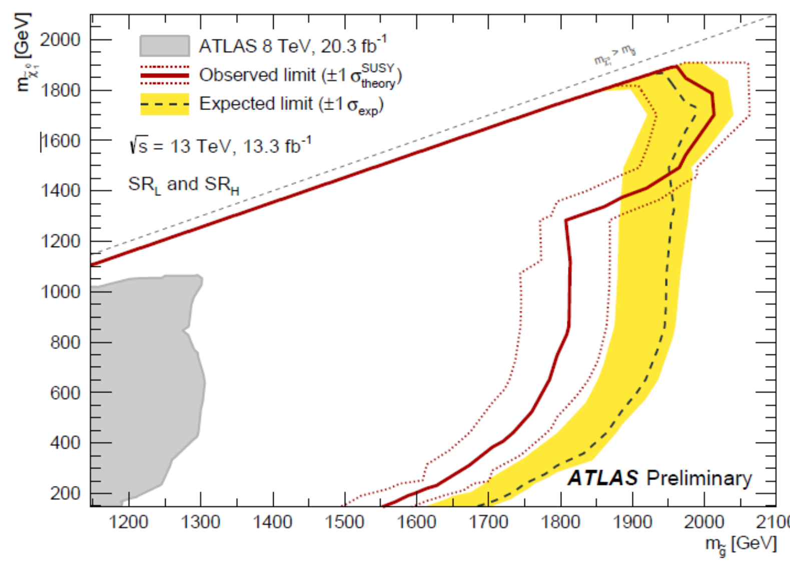


Interpretation in GGM models

scanning M_3 and $\mu(>0)$

Typical decay mode



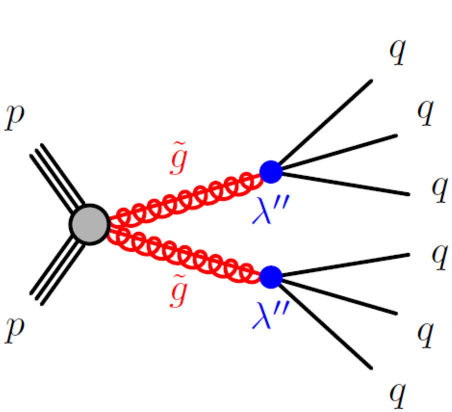


RPV 1-lepton+Multijets

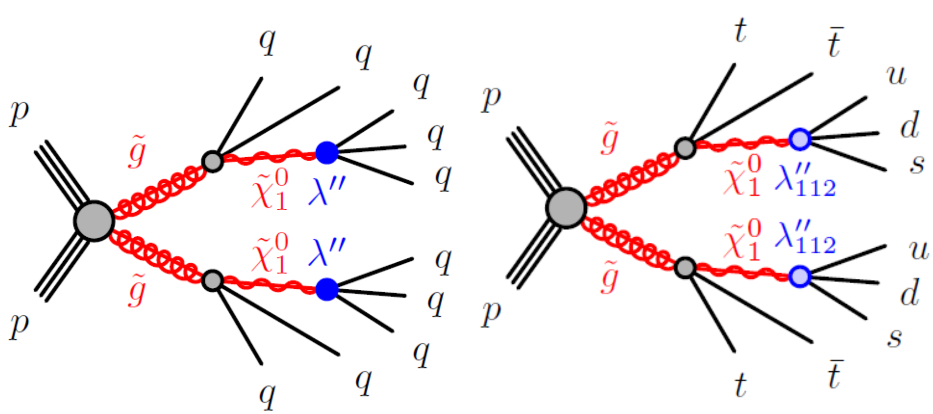
- If RPV is allowed, LSP is not stable anymore and no E_T^{miss} from SUSY particles.

$$W_{\not{R}_p} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2$$

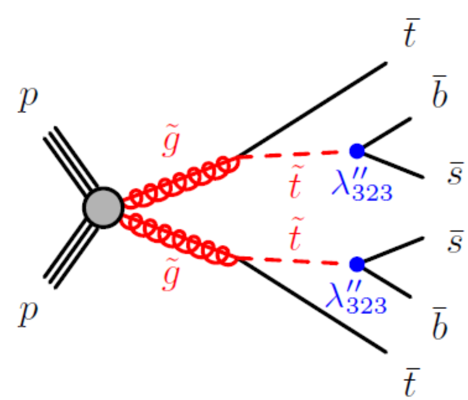
- If there are many particles in final state from cascade decay and RPV decays of SUSY particles, signal events can be distinguished from SM background.



gluino direct decay



neutralino decay via gluino cascade decay



stop decay via gluino cascade decay

Event Selection

- Two searches are preformed for RPV models in multi-object final states.

RPV Multijets

ATLAS-CONF-2016-057

Event selection
- $N_{jets} \geq 4$ or 5 with R=1.0, $p_T > 200$ GeV, $|\eta| < 2.0$
- $N_{b\text{-}jets} \geq 0$ or 1 with R=0.4, $p_T > 50$ GeV, $|\eta| < 2.5$
- $|\Delta\eta_{12}| < 1.4$ for leading 2 R=1.0 jets
- $M_J^{\Sigma} = \Sigma_{R=1.0}^{4} m^{jet} > 0.8$ TeV ($N_{jet} \geq 4$) or 0.6 TeV ($N_{jet} \geq 5$)

RPV 1-lepton+multijets

ATLAS-CONF-2016-094

Event selection
- at least 1-lepton
- 2D bins of

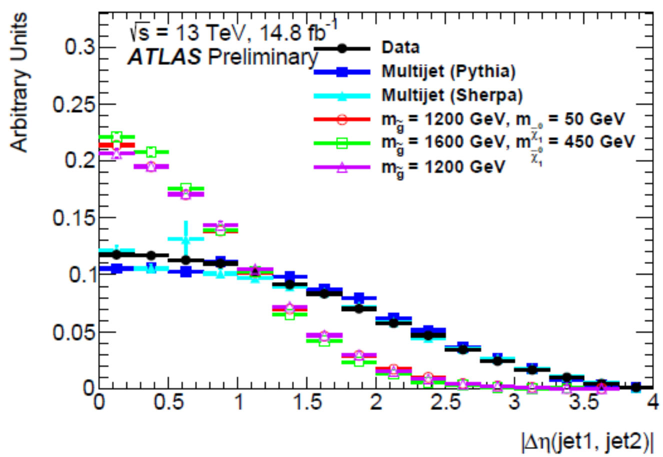
N_{jets}=[5,6,7,8,9,$\geq$10]
$N_{b\text{-}jets}$=[0,1,2,3,$\geq$4]
with $p_T > 40$ GeV or 60 GeV

Background Estimation for RPV Multijets

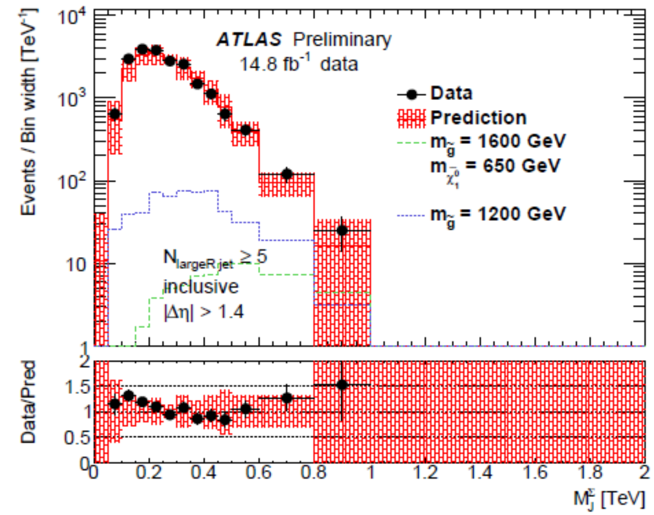
- Jet mass template is obtained from control regions as a function of jet p_T and η.
  - Soft jets with 100 GeV$<p_T<$200 GeV are used in CRs.

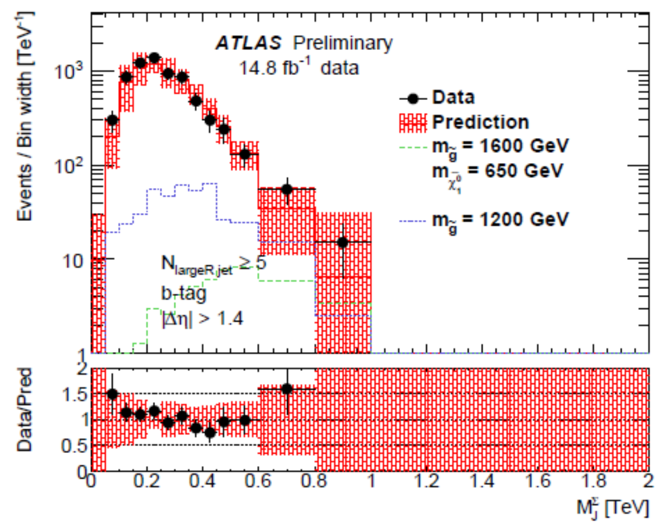
N_{jet}	b-tag		b-veto	inclusive	
	$\lvert\Delta\eta_{12}\rvert > 1.4$	$\lvert\Delta\eta_{12}\rvert < 1.4$	-	$\lvert\Delta\eta_{12}\rvert > 1.4$	$\lvert\Delta\eta_{12}\rvert < 1.4$
$= 3$	3jCRb1_4j	-	3jCRb0_4j	3jCR_5j	
≥ 4	4jVRb1	4jSRb1	-	4jVR	4jSR
≥ 5	5jVRb1	5jSRb1	-	5jVR	5jSR

Background estimation is validated in the region with $|\Delta\eta_{12}|>1.4$



Validation regions

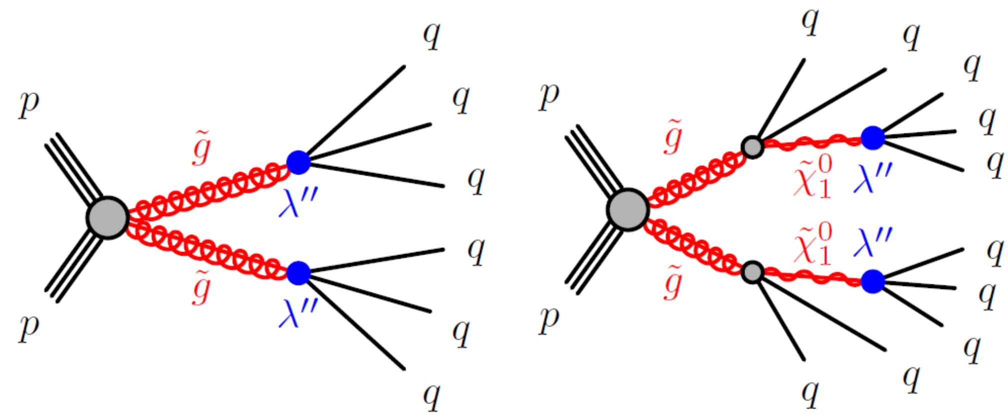




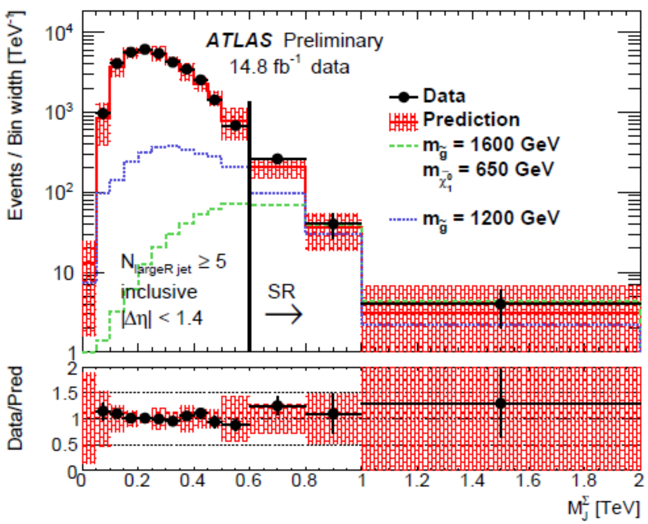
Result and Interpretation

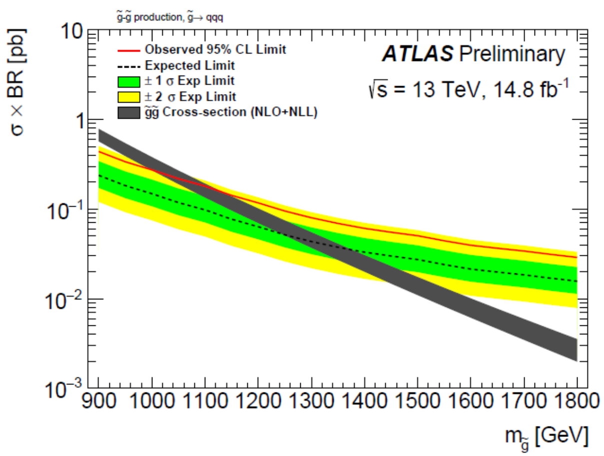
- Result is interpreted in RPV models.

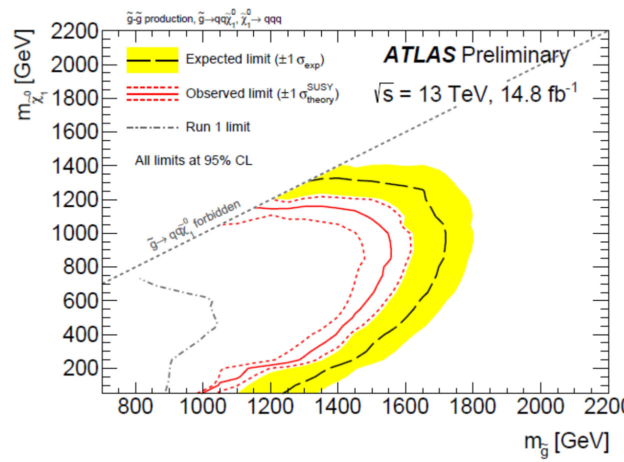
Region	M_J^{Σ} cut	observed	SM predicted
4jSRb1	> 0.8 TeV	46	61 ± 10 ± 6 ± 12
4jSR		122	151 ± 15 ± 17 ± 20
5jSRb1	> 0.6 TeV	30	18.2 ± 4.2 ± 2.5 ± 3.0
5jSR		64	51.4 ± 7.7 ± 7.2 ± 6.5



5jet signal region



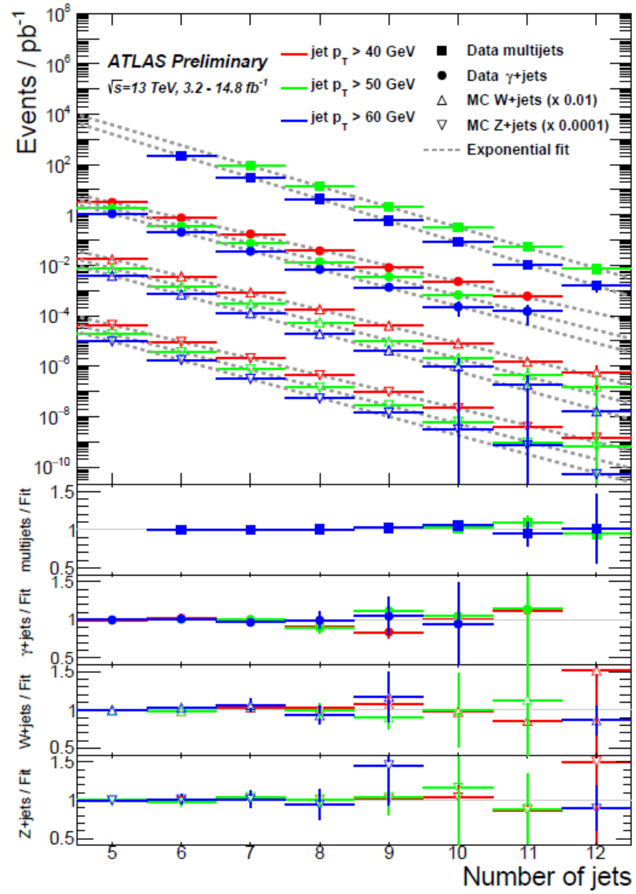




Background Estimation for RPV 1-lepton+Multijets

- W/Z+jets
  - b-jet multiplicity spectra is from simulation
  - Jet multiplicity spectra is from data assuming $r = N_{j+1}^{W/Z\text{+jets}} / N_j^{W/Z\text{+jets}}$ is constant. Then,

$$N_{j,b}^{W/Z\text{+jets}} = \frac{\mathrm{MC}_{j,b}^{W/Z\text{+jets}}}{\mathrm{MC}_{j}^{W/Z\text{+jets}}} \cdot k^{W/Z\text{+jets}} \cdot \mathrm{MC}_5^{W/Z\text{+jets}} \cdot r^{(j-5)}$$



- $t\bar{t}$+jets
  - b-jet multiplicity spectra is obtained from low jet multiplicity data $N_{j,b}^{t\bar{t}\text{+jets}} = N_j^{t\bar{t}\text{+jets}} \cdot f_{j,b}$

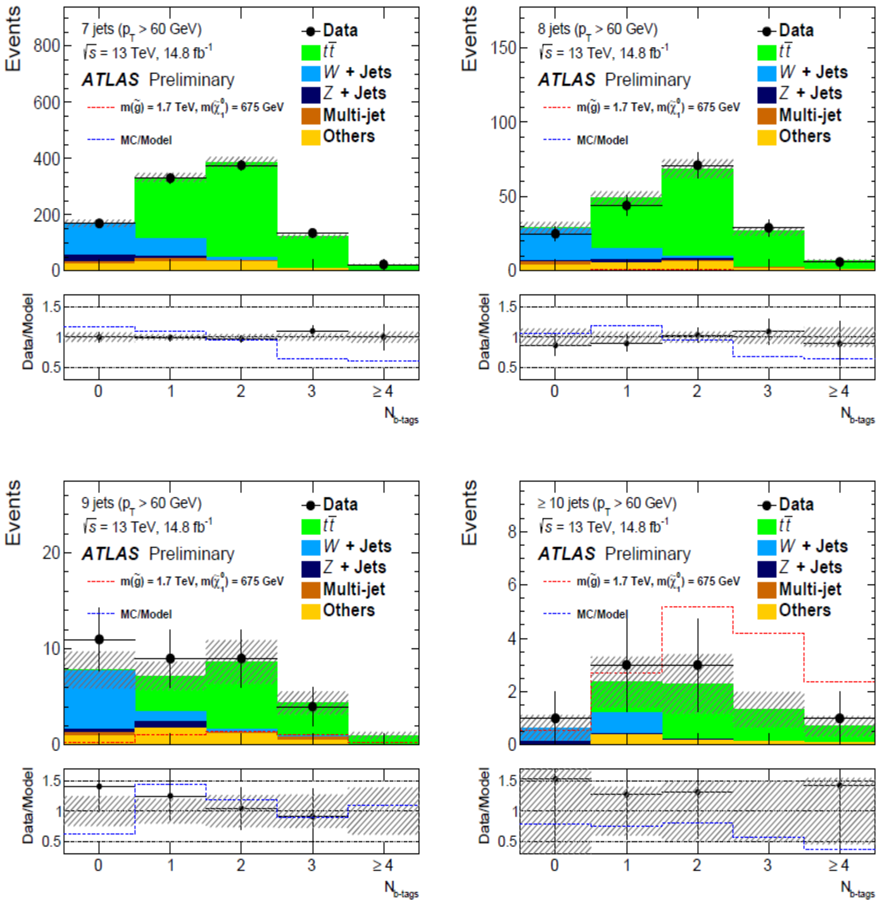
$$f_{(j+1),b} = f_{j,b} \cdot x_0 + f_{j,(b-1)} \cdot x_1 + f_{j,(b-2)} \cdot x_2$$

additional jet is not b-tagged (x_0), b-tagged (x_1), b-tagged and another jet is b-tagged (x_2)

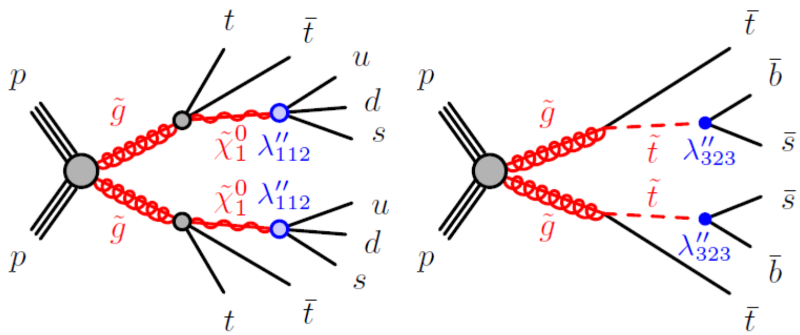
- Background is normalized to match data separately in each N_j slice.

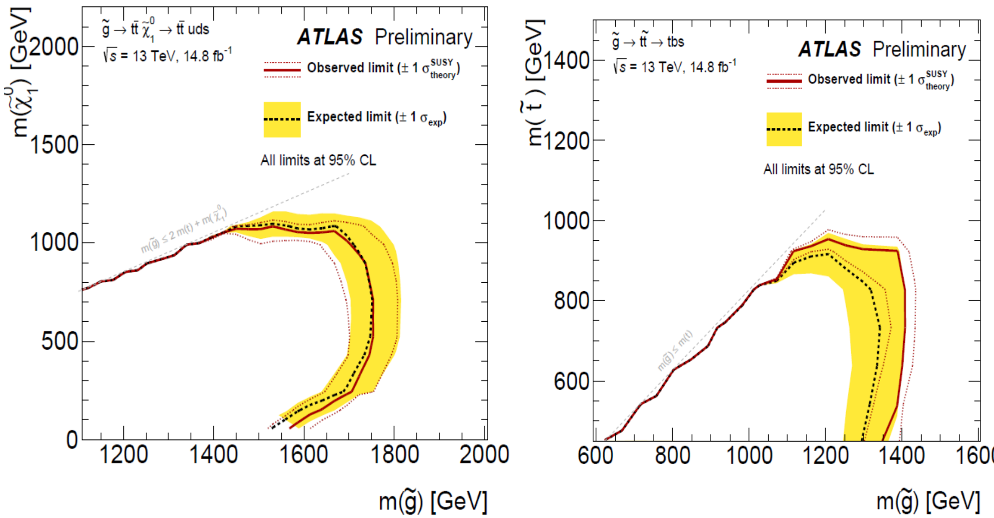
Result and Interpretation

Nb-jets distributions



- Result is interpreted in RPV signal models.





Conclusion

- Extended searches for strongly produced SUSY particles including R-parity violation have been performed in ATLAS using Run 2 dataset up to 18 fb^{-1}.
- Still no significant excess from SM prediction is seen.
- We expect to provide new results with ~36 fb^{-1} soon, please stay tuned!

See you soon!

Backup

Systematic Uncertainties on SFOS Search

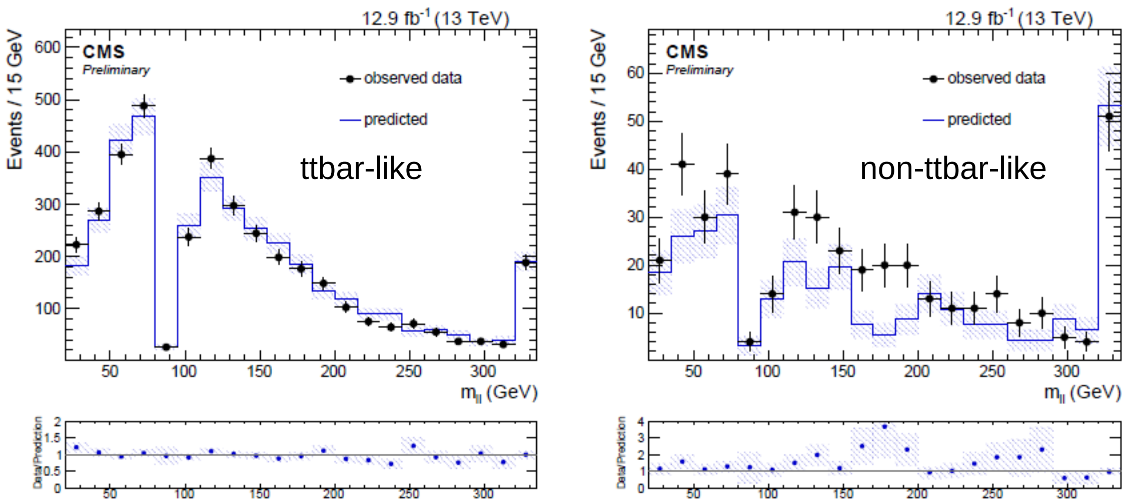
- Overview of dominant systematic uncertainties for SFOS 2-lepton+Jets+ETmiss search.

Source	Relative systematic uncertainty [%]			
	SRZ	SR-low	SR-medium	SR-high
Total systematic uncertainty	17	8–30	6–34	10–45
WZ/ZZ generator uncertainty	13	0–7	0–6	0–10
Flavour symmetry (statistical)	7	3–16	5–16	7–28
WZ/ZZ scale uncertainty	6	0–1	0–1	0–2
$Z/\gamma^* + \text{jets}$ (systematic)	4	0–15	0–25	0–15
Flavour symmetry (systematic)	3	2–23	2–15	4–25
$Z/\gamma^* + \text{jets}$ (statistical)	2	0–3	0–5	0–1
Fake leptons	1	0–17	2–18	2–20

m_{ll} Edge Analysis Comparison

- Comparison of m_{ll} edge analysis between ATLAS and CMS at Run2.

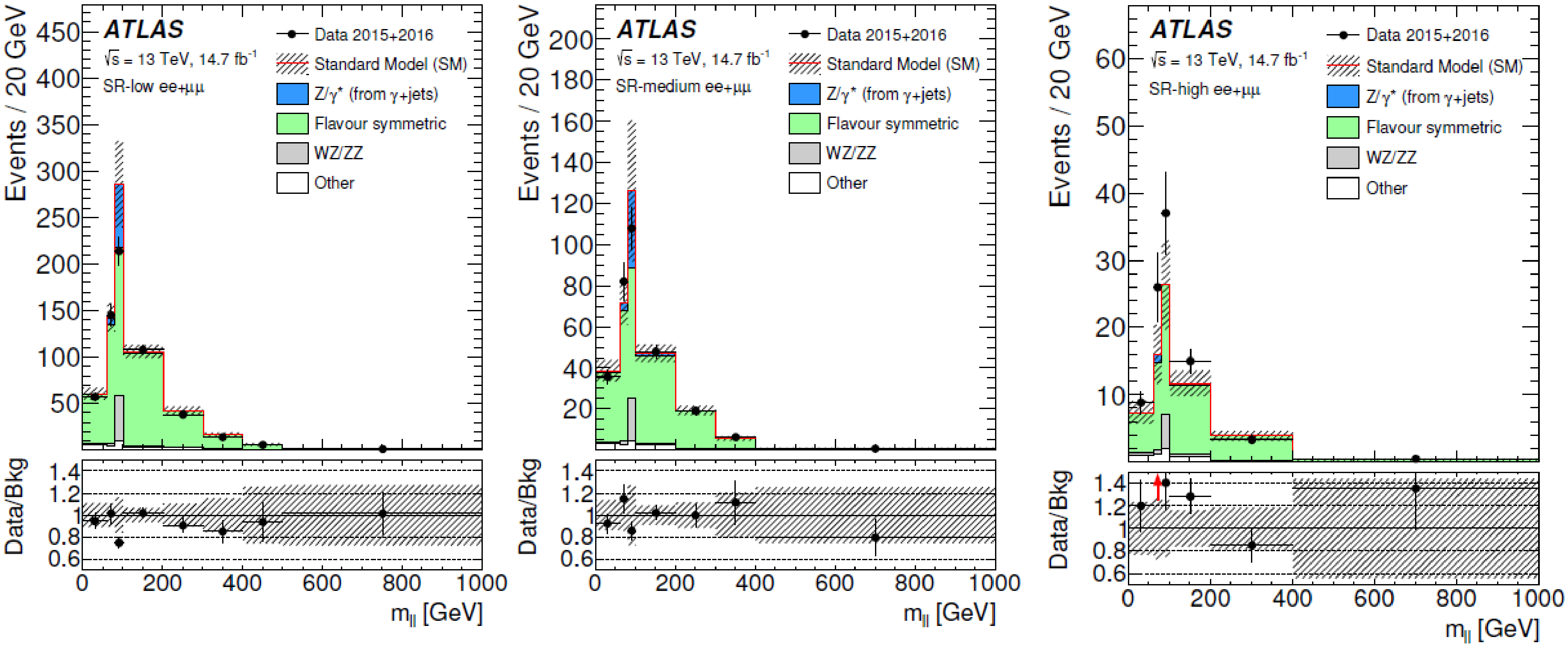
	ATLAS	CMS
N_{jet}	$\geq$2 (p_T>30 GeV)	$\geq$2 (p_T>35 GeV)
p_T(lepton)	>25,10 GeV	>25,20 GeV
m_{ll}	>12 GeV (binned)	>20 GeV (unbinned)
E_T^{miss}	>200 GeV	>150 GeV
H_T	>0(,400,700) GeV	--
ttbar selection	--	NLL



CMS-PAS-SUS-16-021

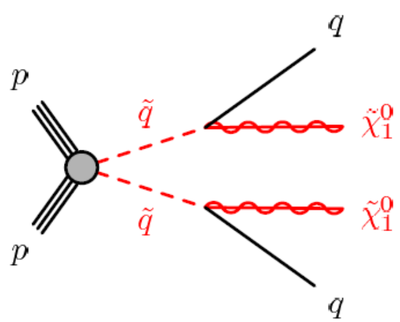
SFOS 2-lepton m_{ll} Edge

- Signal region distributions



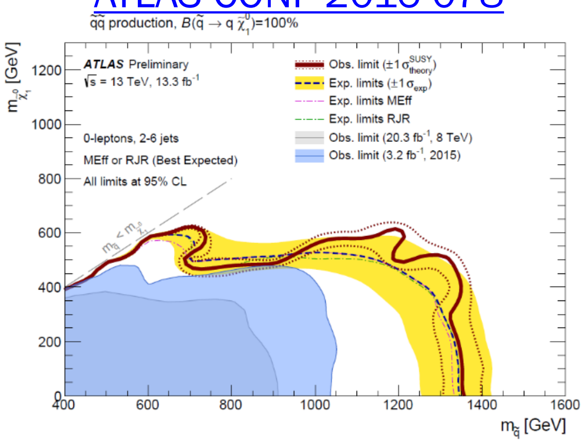
Interpretations in Squark Production

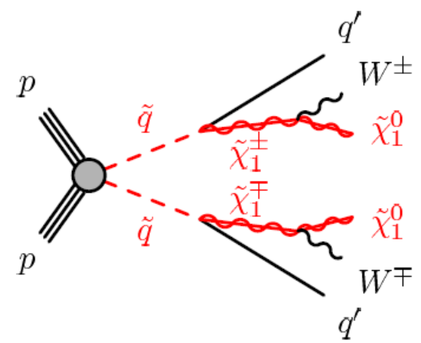
- Exclusion limits on squark-pair production models



0-lepton+jets+E_T^{miss}

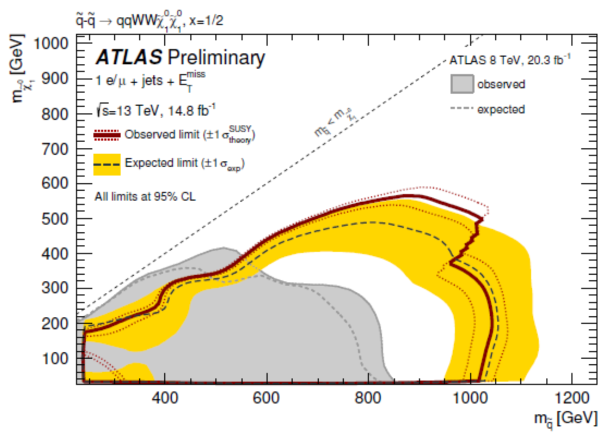
[ATLAS-CONF-2016-078]

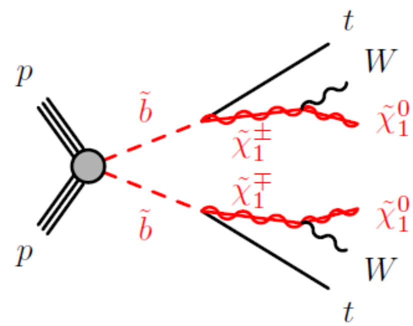




1-lepton+jets+E_T^{miss}

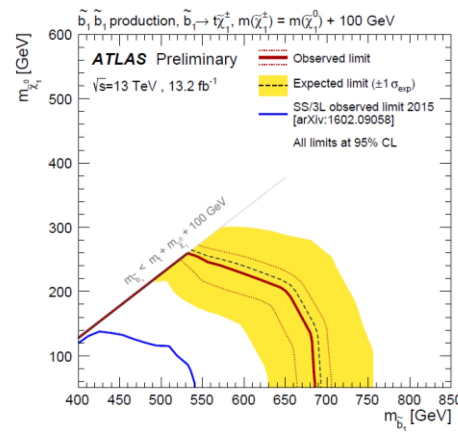
[ATLAS-CONF-2016-054]



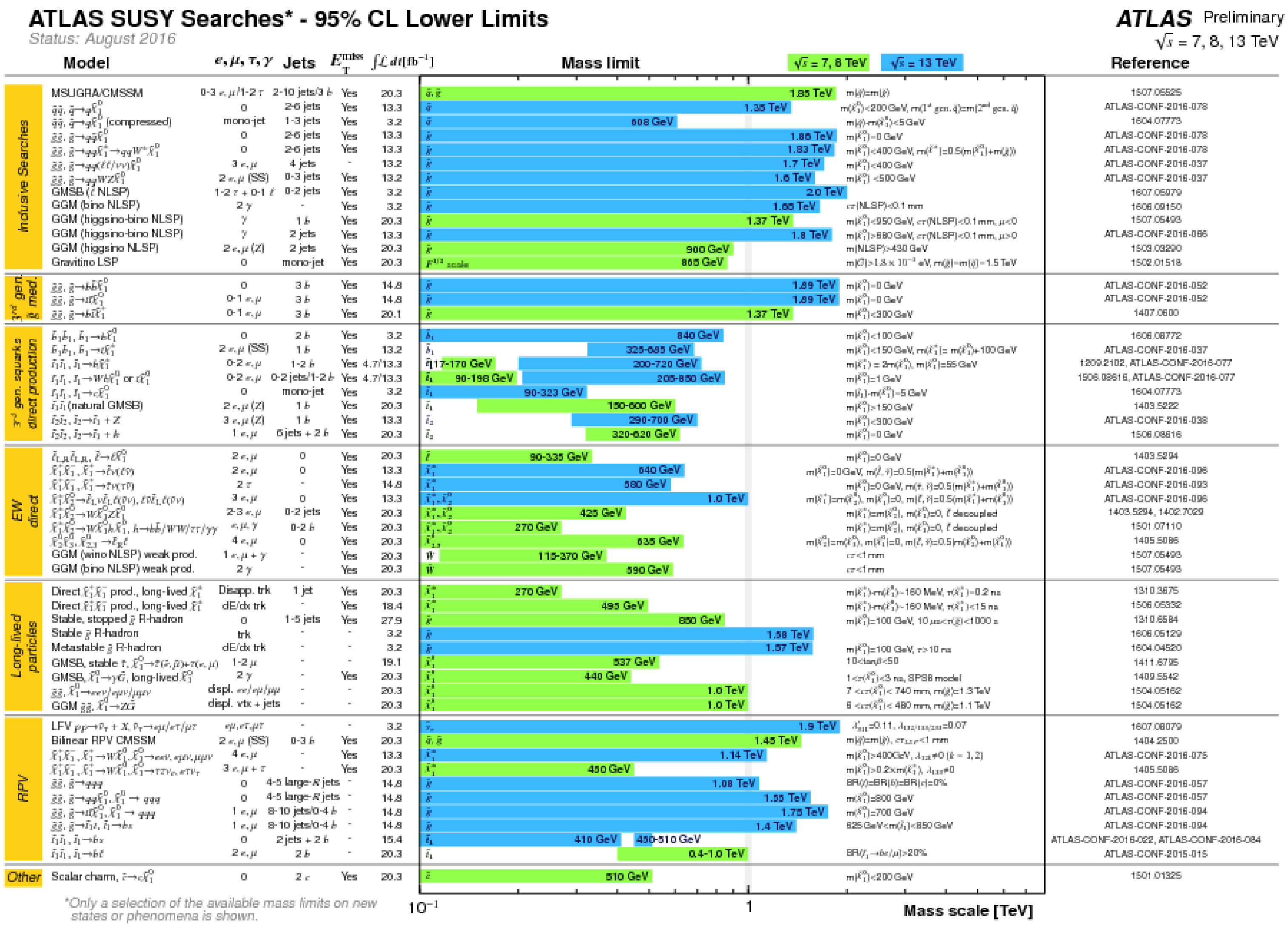


2-lepton+(b)jets+E_T^{miss}

[ATLAS-CONF-2016-037]



Summary of SUSY Searches at ATLAS



Long-lived Gluino Limits