Searches for strong production of supersymmetric particles with the ATLAS detector

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(INFN Bologna)

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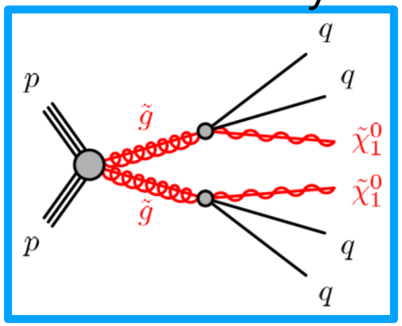
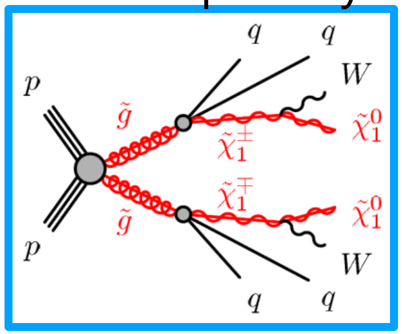
2021/8/23-28

Overview

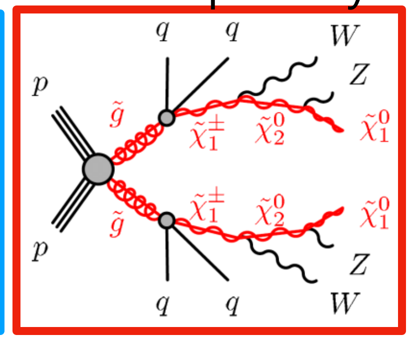
Direct decay

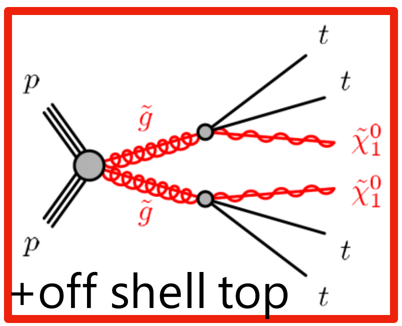


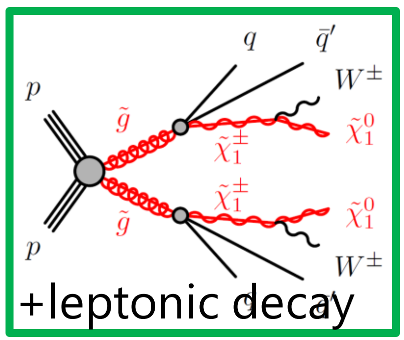
One step decay

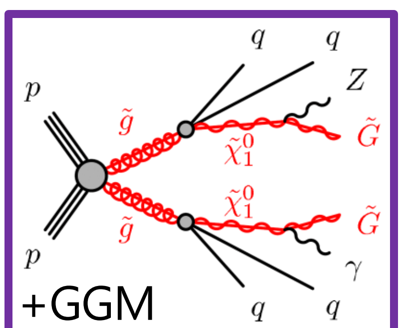


Two step decay







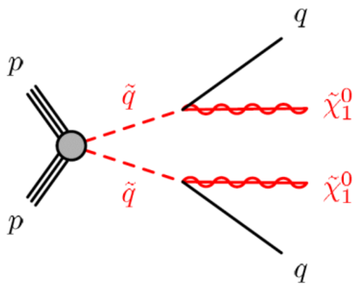


3rd generation squark talk by Carlos

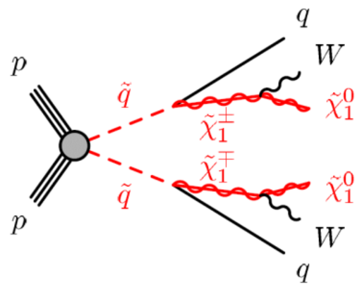
- This talk introduce recent searches for squarks (1st + 2nd generation) and gluinos
- All results are based on 139 fb^{-1} of proton-proton collision data collected in 2015-2018 with $\sqrt{s} = 13$ TeV

- Multi jets: (arXiv:2010.14293v2)
  - At least 2 jets and $E_T{}^{miss}$
- Large jet multiplicities: (arXiv:2008.06032v2)
  - At least 8 jets and $E_T{}^{miss}$
- With lepton: (arXiv:2101.01629v1)
  - At least 2 jets, 1 lepton, and $E_T{}^{miss}$
- With photon: (ATLAS-CONF-2021-028)
  - Jets, at least 1 photon and $E_T{}^{miss}$

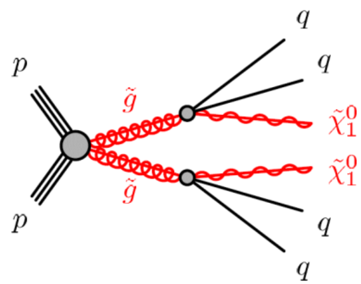
I. Multi jets



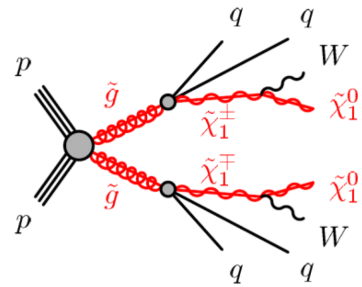
SS direct



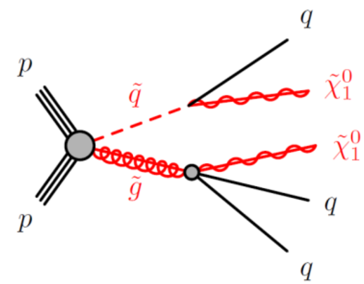
SS one step



GG direct



GG one step

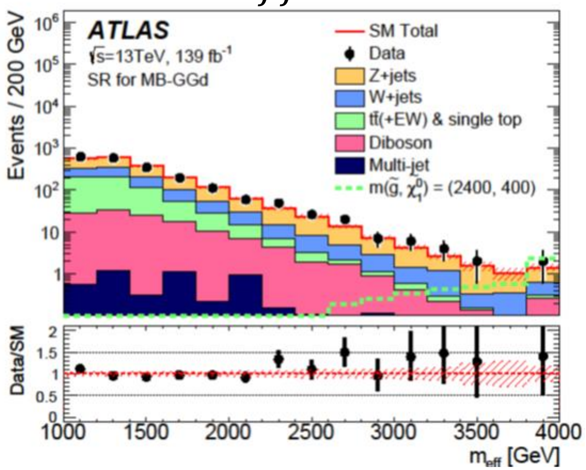


inclusive

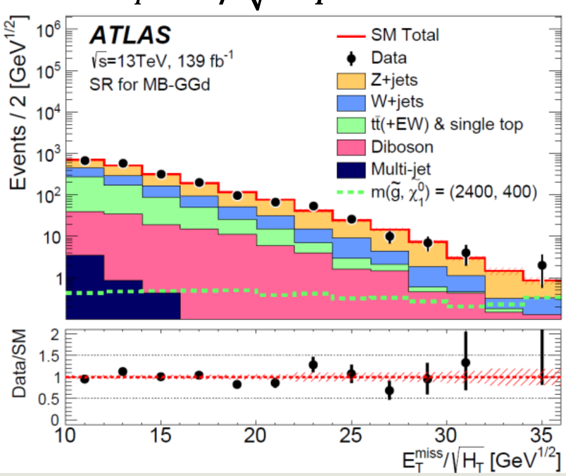
- Targeted final states: at least 2 jets and $E_T{}^{miss}$ but no leptons
  - Large signal yields due to high cross section
  - Huge irreducible backgrounds
- Two approaches are employed for exclusion of the model
  - Multi-bin search
  - BDT search (new approach)

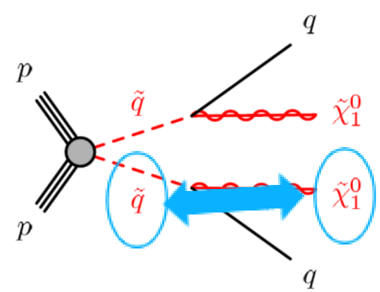
I. Multi jets – Multi bin search

m_{eff}



$E_T{}^{miss}/\sqrt{H_T}$





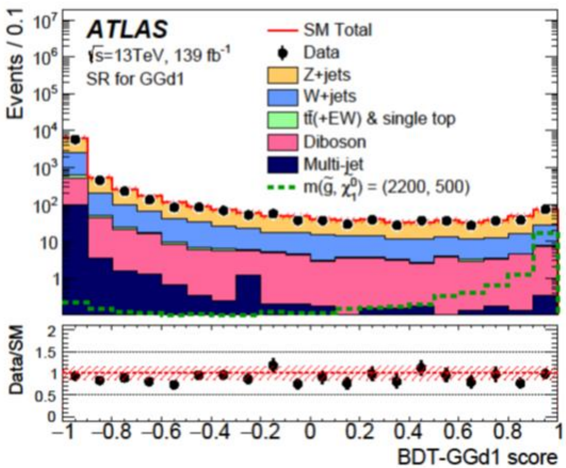
	MB-SSd	MB-GGd	MB-C
N_j	≥ 2	≥ 4	≥ 2
$p_T(j_1)$ [GeV]	> 200	> 200	> 600
$p_T(j_{i=2,\ldots,N_{j\min}})$ [GeV]	> 100	> 100	> 50
$\lvert\eta(j_{i=1,\ldots,N_{j\min}})\rvert$	< 2.0	< 2.0	< 2.8
$\Delta\phi(j_{1,2,(3)}, \boldsymbol{p}_T^{miss})$ min	> 0.8	> 0.4	> 0.4
$\Delta\phi(j_{i>3}, \boldsymbol{p}_T^{miss})$ min	> 0.4	> 0.4	> 0.2
Aplanarity	-	> 0.04	-
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$]	> 10	> 10	> 10
m_{eff} [GeV]	> 1000	> 1000	> 1600

- Three region are optimized
  - MB-SSd: for non compressed squarks
  - MB-GGd: for non compressed gluinos
  - MB-C: for compressed scenarios
- Likelihood is calculated using multiple 2D bins

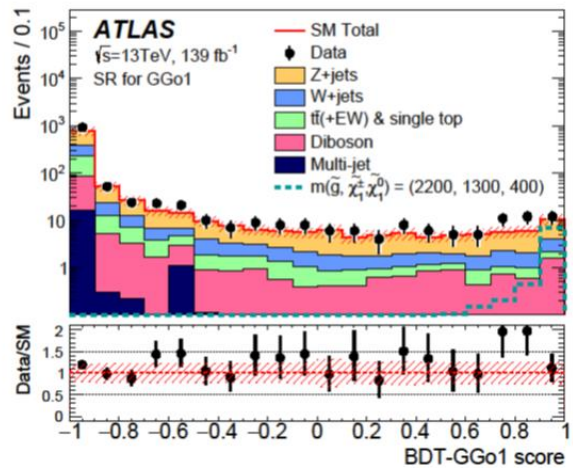
$N_j = [4, \infty)$		m_{eff} [TeV]					
		[1.0, 1.6)	[1.6, 2.2)	[2.2, 2.8)	[2.8, 3.4)	[3.4, 4.0)	[4.0, ∞)
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$]	[10, 16)						
	[16, 22)						
	[22, ∞)						

I. Multi jets – BDT search

BDT-GGd



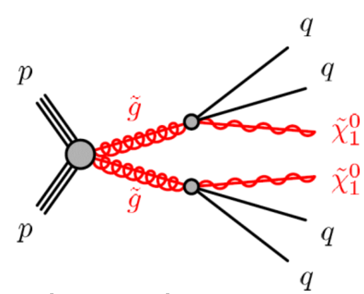
BDT-GGo

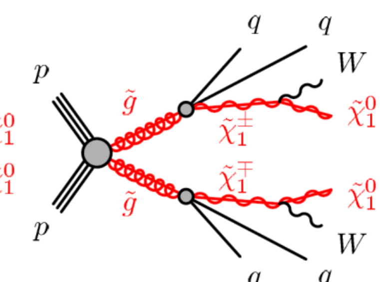


	BDT-GGd1	BDT-GGd2	BDT-GGd3	BDT-GGd4
N_j	≥ 4			
$\Delta\phi(j_{1,2,(3)}, \boldsymbol{p}_T^{miss})_{min}$	> 0.4			
$\Delta\phi(j_{i>3}, \boldsymbol{p}_T^{miss})_{min}$	> 0.4			
$E_T^{miss}/m_{eff}(N_j)$	> 0.2			
m_{eff} [GeV]	> 1400		> 800	
BDT score	> 0.97	> 0.94	> 0.94	> 0.87
$\Delta m(\tilde{g}, \tilde{\chi}_1^0)$ [GeV]	1600–1900	1000–1400	600–1000	200–600

	BDT-GGo1	BDT-GGo2	BDT-GGo3	BDT-GGo4
N_j	≥ 6		≥ 5	
$\Delta\phi(j_{1,2,(3)}, \boldsymbol{p}_T^{miss})_{min}$	> 0.4			> 0.2
$\Delta\phi(j_{i>3}, \boldsymbol{p}_T^{miss})_{min}$	> 0.4			> 0.2
$E_T^{miss}/m_{eff}(N_j)$	> 0.2			
m_{eff} [GeV]	> 1400		> 800	
BDT score	> 0.96	> 0.87	> 0.92	> 0.84
$\Delta m(\tilde{g}, \tilde{\chi}_1^0)$ [GeV]	1400–2000	1200–1400	600–1000	200–400

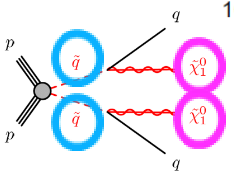
- Boosted Decision Tree (BDT) score is used
  - BDT-GGd: optimized for direct gluino decays
  - BDT-GGo: optimized for one step gluino decays

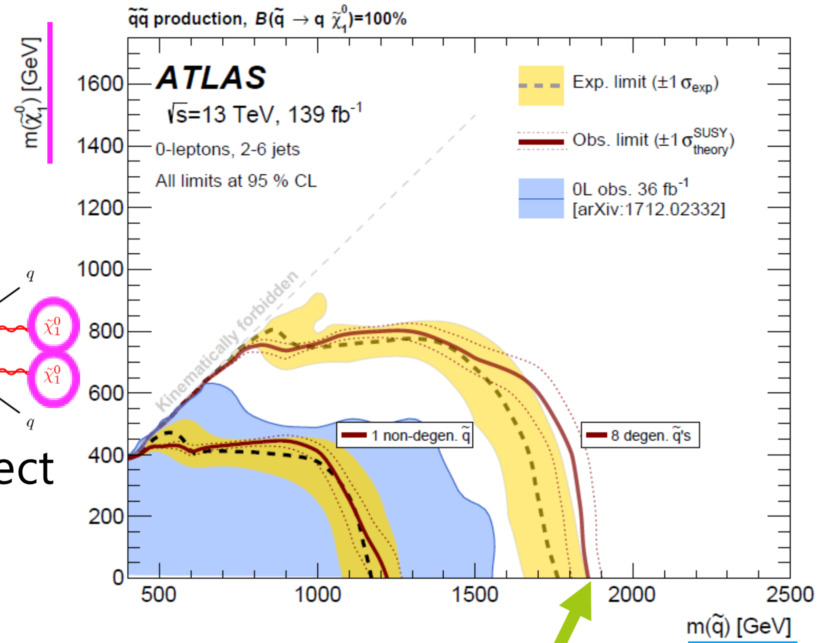




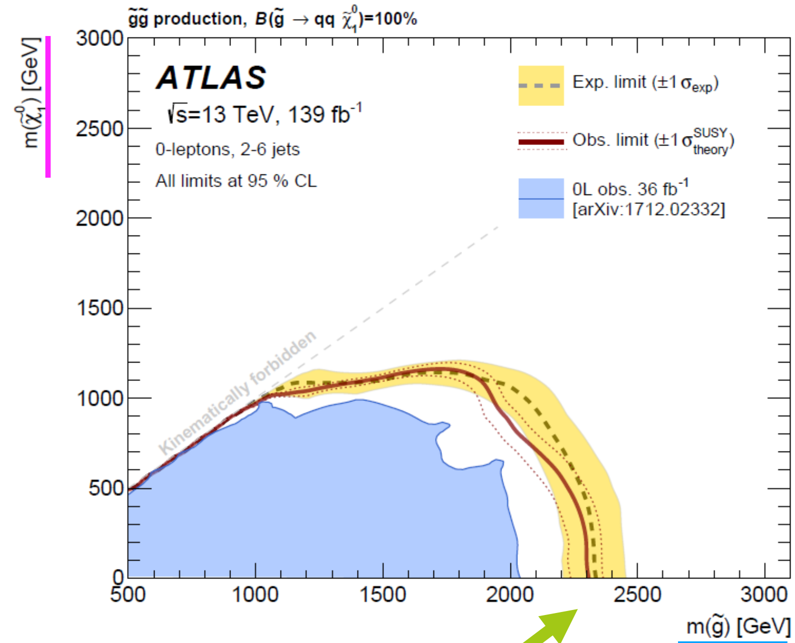
  - Each set separated in 4 independent signal regions depending on $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$
  - Up to 12 variables are selected among $E_T{}^{miss}$, m_{eff}, aplanarity, p_T and η of selected jets

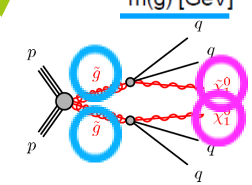
I. Multi jets – Results





$\tilde{q}\tilde{q}$ direct

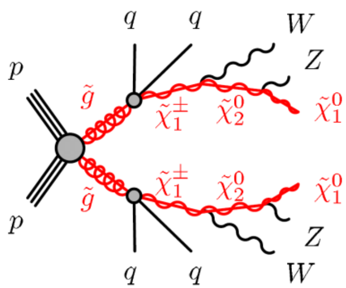




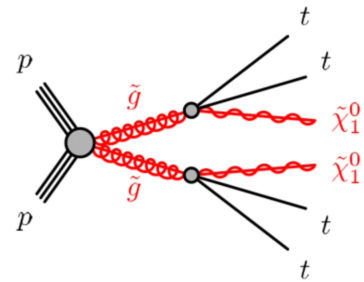
$\tilde{g}\tilde{g}$ direct

- No significant deviation is found
- Excluded for:
  - SS direct: $m(\tilde{q})$ < 1.94 TeV
  - SS one step: $m(\tilde{q})$ < 1.59 TeV
  - GG direct: $m(\tilde{g})$ < 2.35 TeV
  - GG one step: $m(\tilde{g})$ < 2.19 TeV
  - Inclusive: $m(\tilde{q}) = m(\tilde{g})$ < 3000 GeV

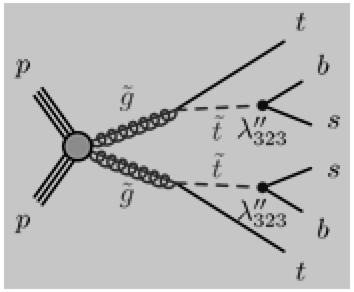
II. Large jet multiplicities



Two step decay



direct decay with
off-shell top squarks

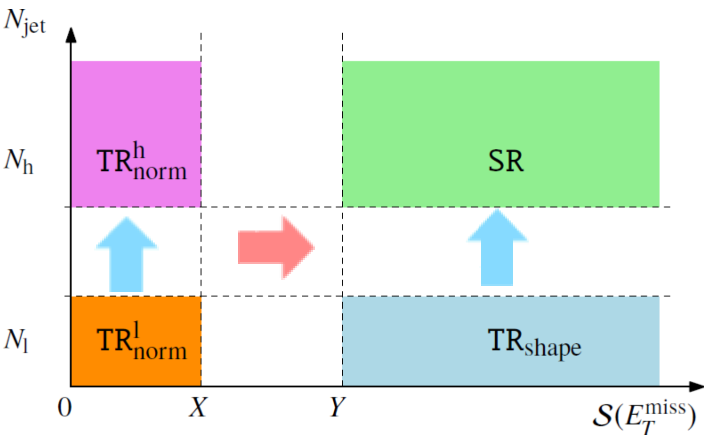


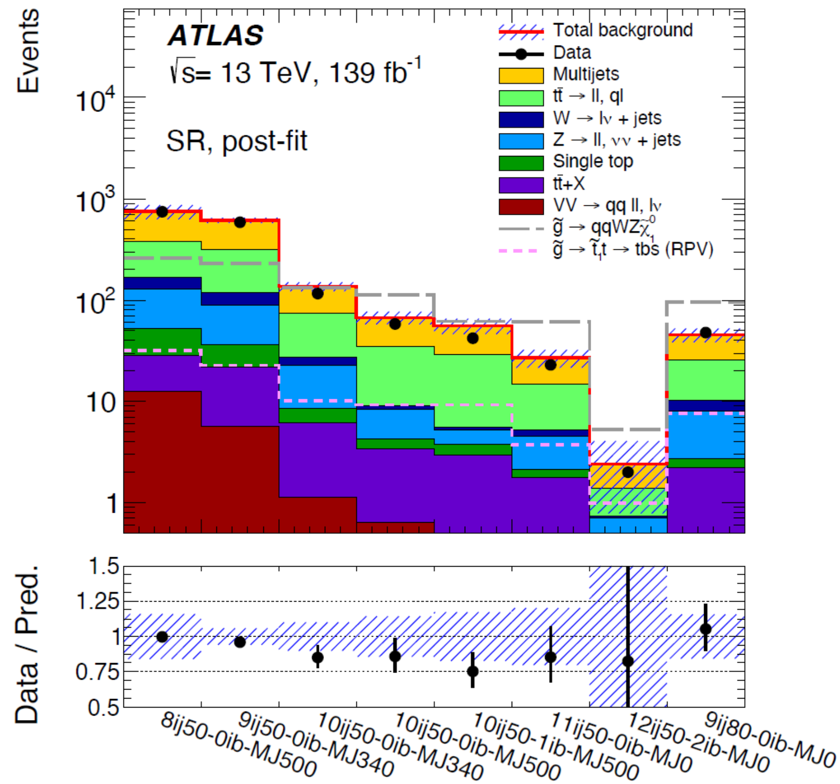
RPV
(not in today's scope)
Reported in Lorenzo's talk

- Targeted Final states: ≧8 jets and $E_T{}^{miss}$ but no leptons
  - Unusually high jet multiplicities suppress backgrounds
  - Background simulations with large jet multiplicities have large uncertainties
    - Data-driven method is employed for major background
- Newly improved techniques from the previous study
  - Particle flow jets and $E_T{}^{miss}$ reconstruction
  - $E_T{}^{miss}$ significance $S(E_T{}^{miss})$: $\mathcal{S}(E_T^{\text{miss}}) = \frac{E_T^{\text{miss}}}{\sqrt{\sigma_L^2(1-\rho_{LT}^2)}}$

Hypothesis test that the total $E_T{}^{miss}$ carried by invisible particles = 0 against ≠0

II. Large jet multiplicities – Data driven method

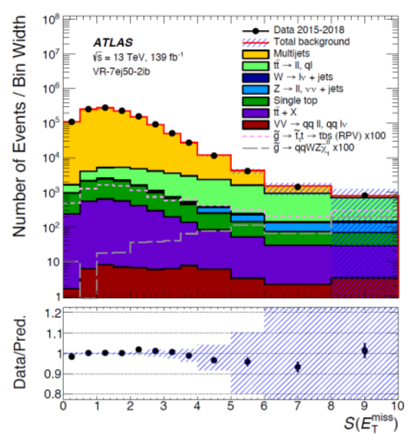




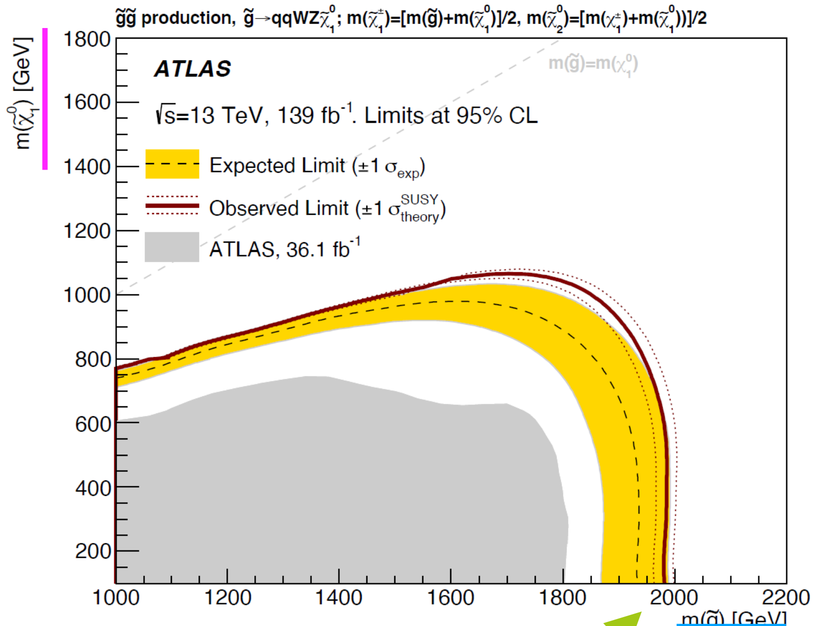
- Multijet background is obtained from

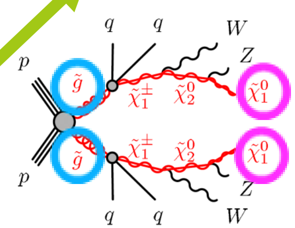
$$\hat{N}[a < \mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}}) < b] = \frac{N_{\mathrm{TR}^{\mathrm{h}}_{\mathrm{norm}}}}{N_{\mathrm{TR}^{\mathrm{l}}_{\mathrm{norm}}}} N_{\mathrm{TR}_{\mathrm{shape}}}[a < \mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}}) < b]$$

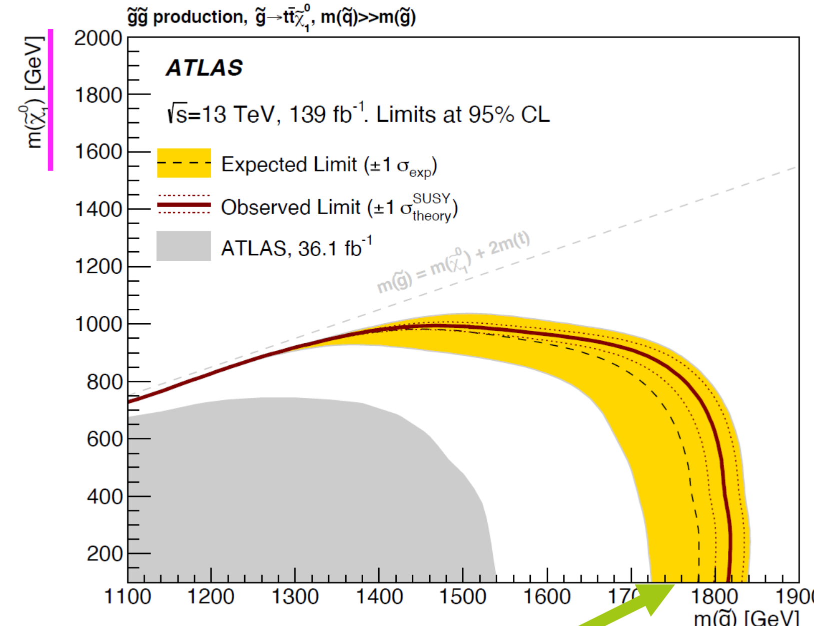
- Good agreements in VR

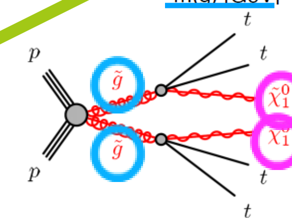


II. Large jet multiplicities – Results



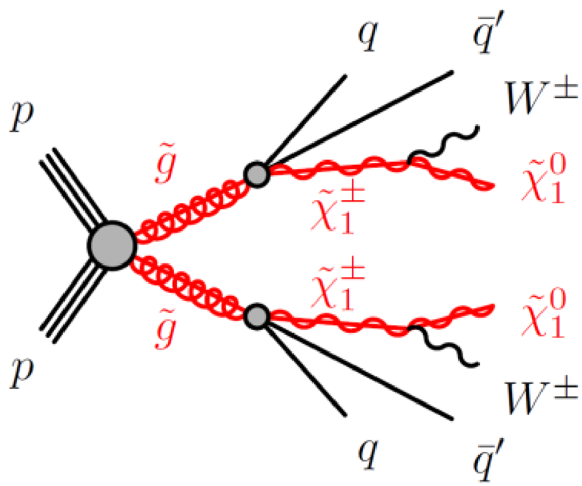


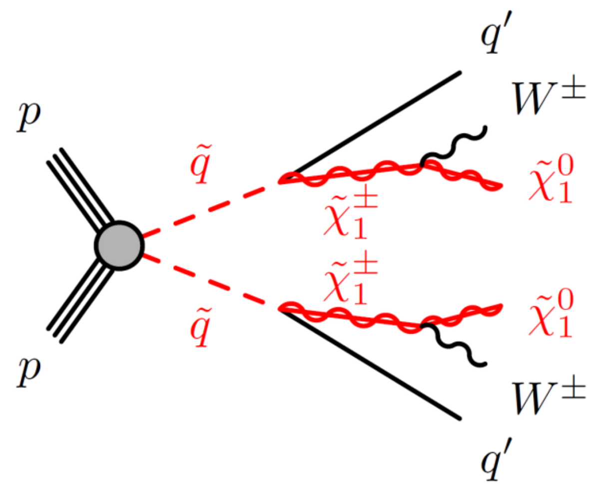




- No significant deviation is found
- Excluded for:
  - $m(\tilde{g}) <$ 2 TeV (two step decay)
  - $m(\tilde{g}) <$ 1.8 TeV for $m(\tilde{\chi}_1^0) <$ 700 GeV (direct decay + off shell top)

III. With single lepton

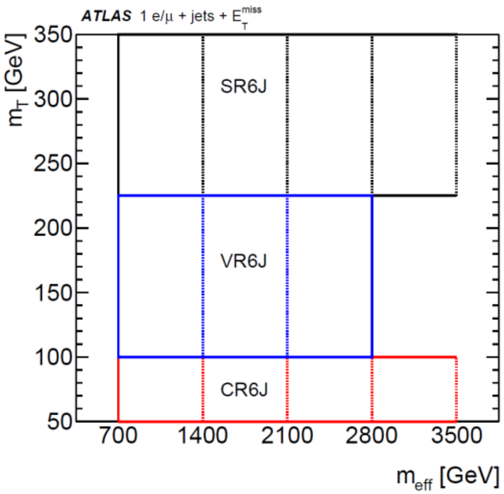


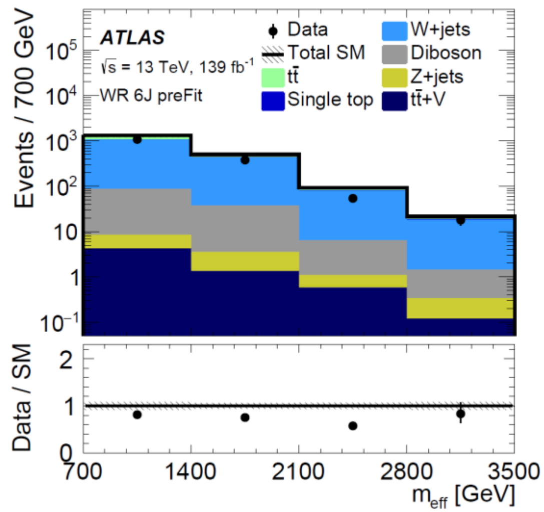


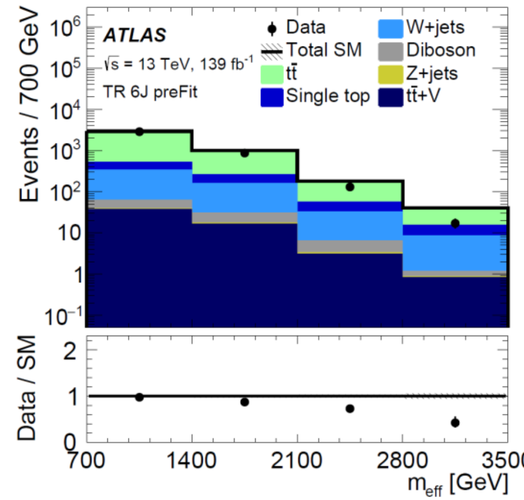
- Targeted Final states : at least 2 jets, E_T^{miss} and exactly one lepton (e or μ)
  - QCD backgrounds can be suppressed
  - ttbar and W+jets backgrounds need to be considered
- To improve sensitivity
  - Different jet multiplicity requirements (2J, 4J and 6J)
  - Categorize the region with b-jets and b-veto
    - This also helps background estimation

SR	2J	4J high-x	4J low-x	6J
N_ℓ		= 1		
p_T^ℓ [GeV]	> 7(6) for $e(\mu)$ and < $\min(10 \cdot N_{jet}, 25)$	> 25	> 25	> 25
N_{jet}	≥ 2	4–5	4–5	≥ 6
E_T^{miss} [GeV]	> 400	> 300	> 300	> 300
m_T [GeV]	> 100	> 520	150–520	> 225
Aplanarity	-	> 0.01	> 0.01	> 0.05
E_T^{miss}/m_{eff}	> 0.25	> 0.2	> 0.2	-
$N_{b\text{-jet}}$ (excl)		= 0 for the b-veto SR, ≥ 1 for the b-tag SR		
m_{eff} [GeV] (excl)	3 bins ∈ [700, 2500+]	3 bins ∈ [1000, 2800+]	3 bins ∈ [1000, 2800+]	4 bins ∈ [700, 3500+]
$N_{b\text{-jet}}$ (disc)		= 0		
m_{eff} [GeV] (disc)	> 1900 (1300) for gluino (squark)	> 2200	> 2200	> 2800 (2100) for gluino (squark)

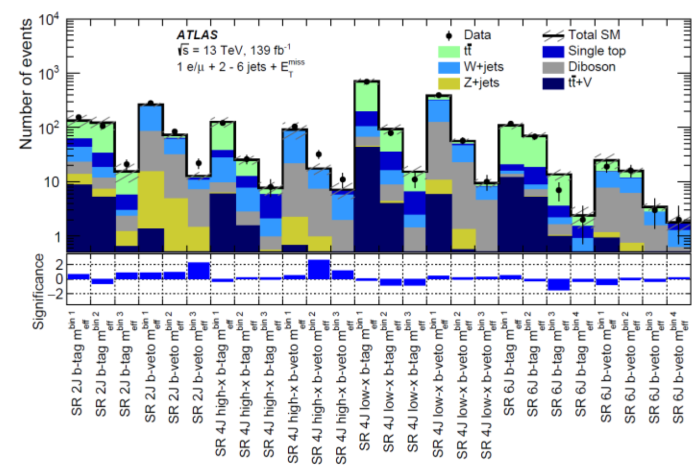
III. With single lepton – background estimation



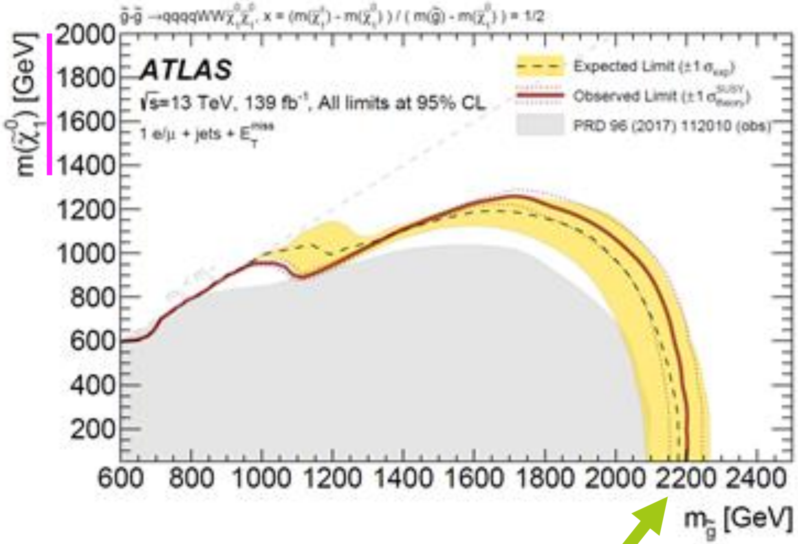


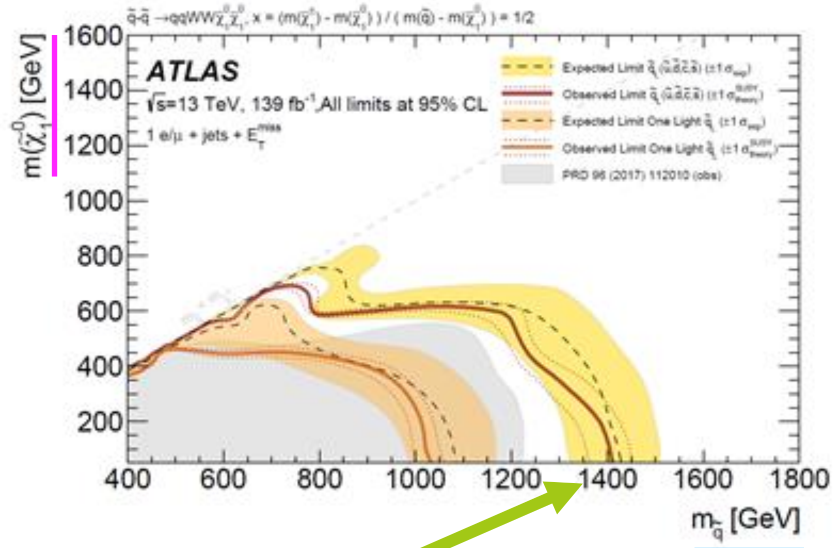


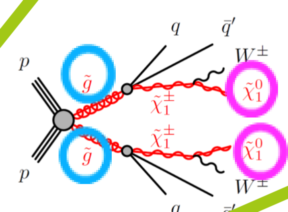
- Backgrounds are estimated in low $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} \left(1 - \cos[\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\ell}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}})]\right)}$
  - W+jets and semileptonic ttbar background has low m_T
  - Further discriminated with b-veto for W+jets and with b-jets for ttbar
- All regions are binned in Effective mass
  - It helps to distinguish between different signal mass

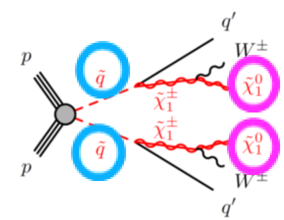


III. With single lepton – results



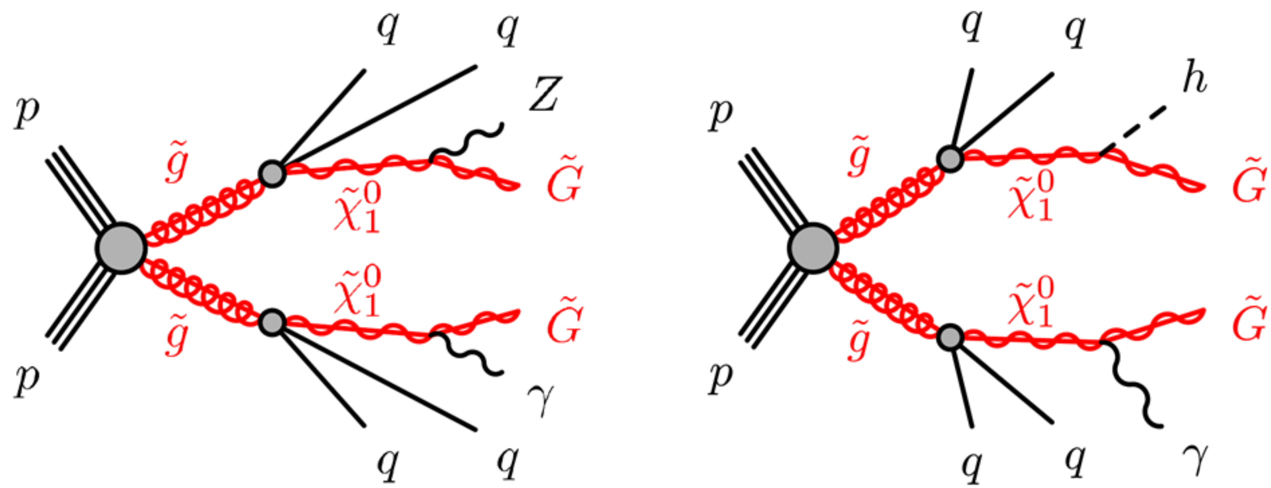






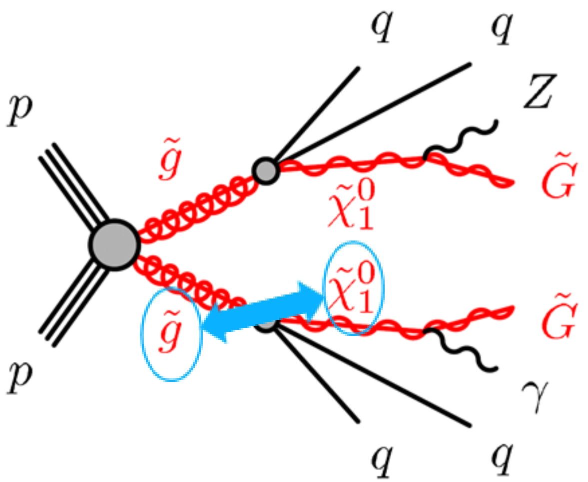
- No significant deviation is found
- Excluded for:
  - $m(\tilde{g}) < 2.2$ TeV
  - $m(\tilde{q}) < 1.4$ TeV

IV. With photon



- Targeted Final states : Jets, at least 1 photon and $E_T{}^{miss}$
  - By assuming General Gauge Mediation (GGM) model, NLSP neutralino decays to gravitino and photon
  - Wγ, ttγ and prompt photon + jets are dominant backgrounds
- Analysis has been designed as model independent as possible

IV. With photon – region definition



	SRL	SRM	SRH
N_{photons}	≥ 1	≥ 1	≥ 1
$p_{\text{T}}^{\text{leading}-\gamma}$	> 145 GeV	> 300 GeV	> 400 GeV
N_{leptons}	0	0	0
N_{jets}	≥ 5	≥ 5	≥ 3
$\Delta\phi(\text{jet}, E_{\text{T}}^{\text{miss}})$	> 0.4	> 0.4	> 0.4
$\Delta\phi(\gamma, E_{\text{T}}^{\text{miss}})$	> 0.4	> 0.4	> 0.4
$E_{\text{T}}^{\text{miss}}$	> 250 GeV	> 300 GeV	> 600 GeV
H_{T}	> 2000 GeV	> 1600 GeV	> 1600 GeV
R_{T}^4	< 0.90	< 0.90	-

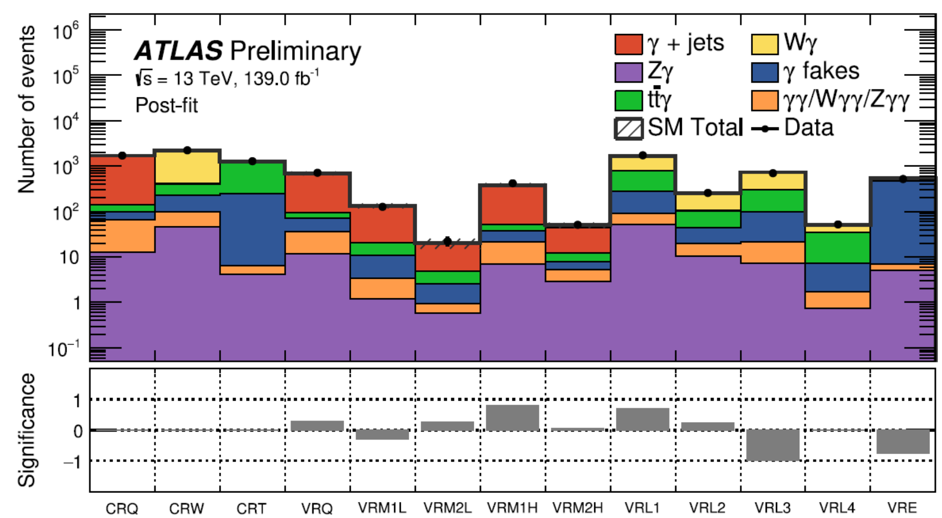
- SRL: large mass difference $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$
  - Large jet multiplicity, moderate $E_T{}^{miss}$
- SRH: compressed scenario
  - Large $E_T{}^{miss}$, higher pT photons
- SRM: intermediate phase space

IV. With photon – background estimation

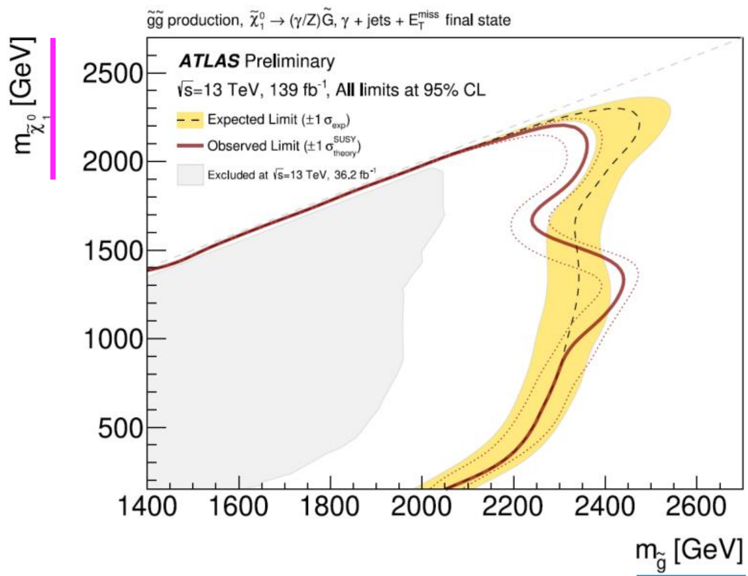
Regions	N_{photons}	$p_T^{\text{leading}\gamma}$(GeV)	N_{leptons}	N_{jets}	$N_{b-\text{jets}}$	$\Delta\phi(\text{jet}, E_T^{\text{miss}})$	$\Delta\phi(\gamma, E_T^{\text{miss}})$	E_T^{miss} (GeV)	H_T(GeV)	R_T^4
CRQ	≥ 1	> 145	0	≥ 3	-	< 0.4	> 0.4	> 100	> 1600	-
CRW	≥ 1	> 145	≥ 1	≥ 1	0	> 0.4	-	$[100, 200]$	> 400	-
CRT	≥ 1	> 145	≥ 1	≥ 2	≥ 2	> 0.4	-	$[50, 200]$	> 400	-
VRL1	≥ 1	> 145	≥ 1	≥ 2	-	> 0.4	-	$[50, 200]$	> 800	-
VRL2	≥ 1	> 145	≥ 1	≥ 2	-	> 0.4	-	$[50, 200]$	> 1300	-
VRL3	≥ 1	> 145	≥ 1	≥ 2	-	> 0.4	-	> 200	$[600, 1600]$	-
VRL4	≥ 1	> 145	≥ 1	≥ 2	-	< 0.4	-	> 200	> 1100	-
VRQ	≥ 1	> 145	0	≥ 3	-	> 0.4	> 0.4	$[100, 200]$	> 1600	-
VRM1L	≥ 1	> 145	0	≥ 5	-	> 0.4	> 0.4	$[100, 200]$	> 1600	< 0.90
VRM2L	≥ 1	> 145	0	≥ 5	-	> 0.4	> 0.4	$[150, 200]$	> 1600	< 0.90
VRM1H	≥ 1	> 300	0	≥ 3	-	> 0.4	> 0.4	$[100, 200]$	> 1600	-
VRM2H	≥ 1	> 300	0	≥ 3	-	> 0.4	> 0.4	$[150, 200]$	> 1600	-
VRE	≥ 1	> 145	-	≥ 1	≥ 1	> 0.4	< 0.4	> 200	$[100, 1600]$	-

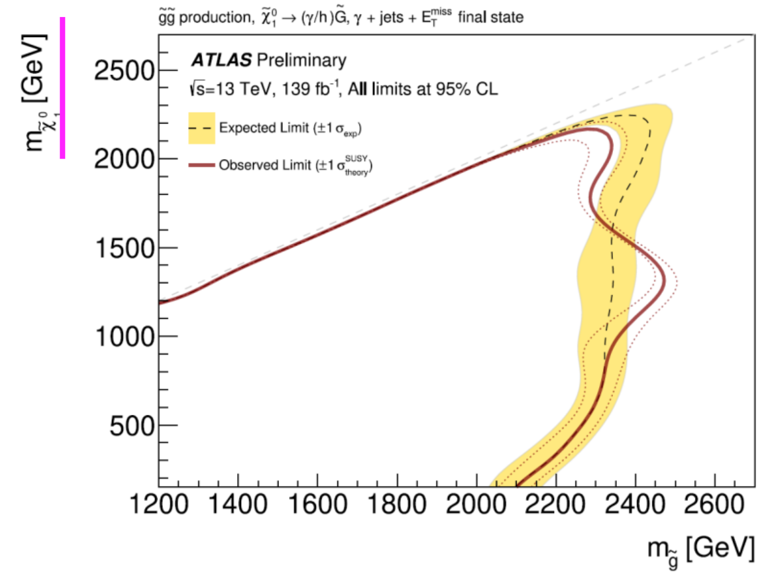
- VRL:
  Wγ & ttγ enrich regions
- VRQ:
  SR like but with low E_T^{miss}
- VRM:
  γ + jets enrich regions
- VRE:
  γ fake enrich region

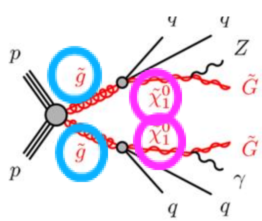
- CRQ: for γ + jet
  - SRL + low E_T^{miss} + inverted $\Delta\phi$(jet, E_T^{miss})
- CRW: for Wγ
  - Photon + lepton + mild E_T^{miss} with b-veto
- CRT: for ttγ
  - Photon + lepton + mild E_T^{miss} +jet with b-tag

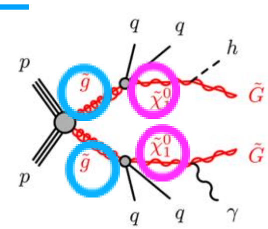


IV. With photon – results







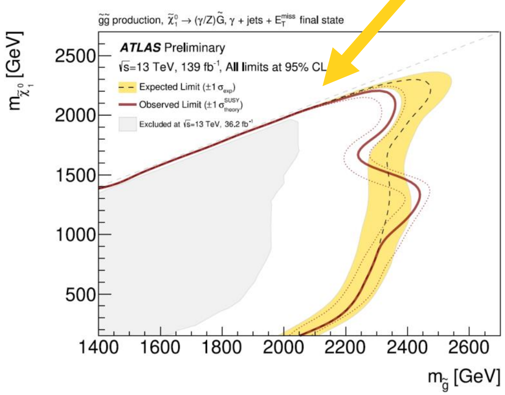


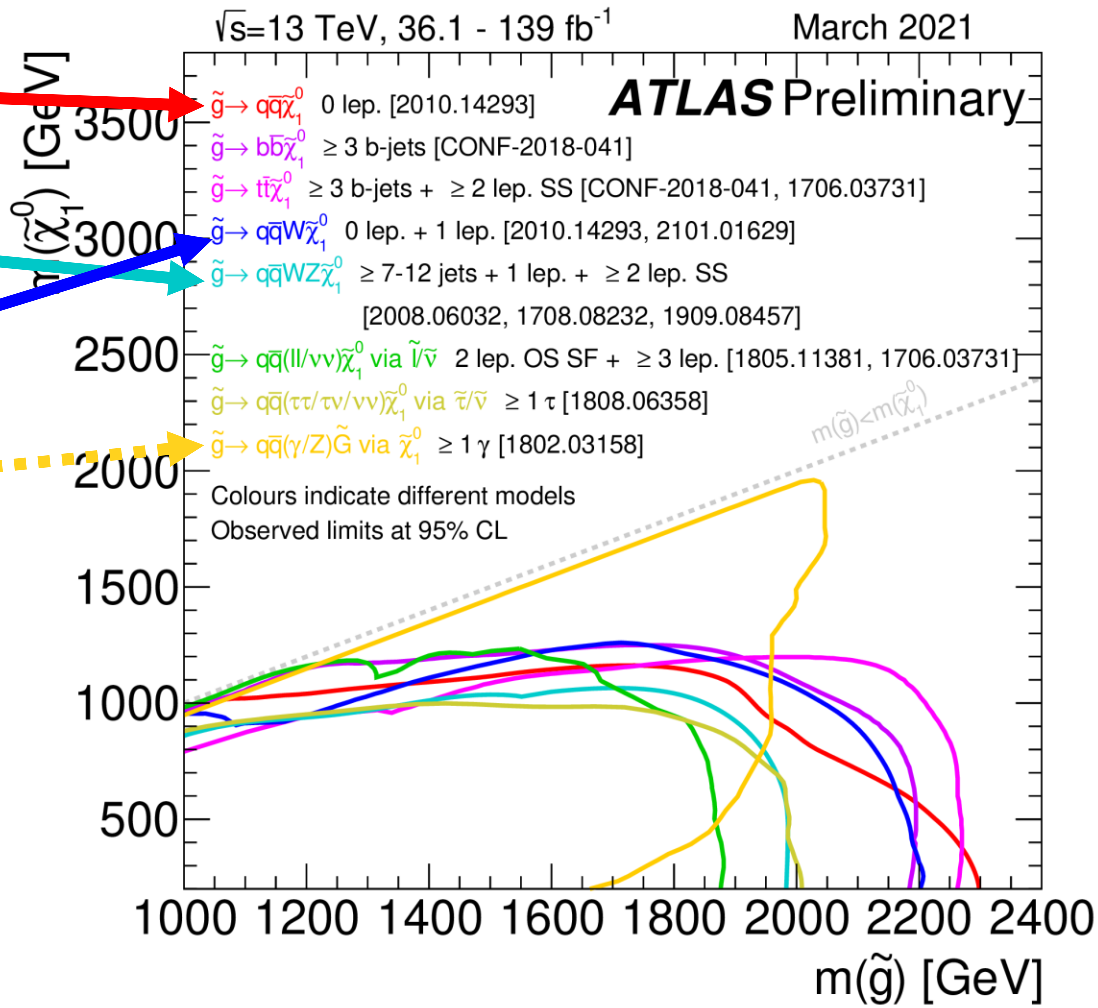
- No significant deviation is found
- Excluded for $m(\tilde{g}) < 2.2$ TeV for most of the NLSP mass

	SRL	SRM	SRH
Observed events	2	0	5
Expected SM events	2.67 ± 0.75	2.55 ± 0.64	2.55 ± 0.44
$t\bar{t}\gamma$	0.70 ± 0.18	0.87 ± 0.18	0.22 ± 0.05
$W\gamma$	0.55 ± 0.37	0.70 ± 0.42	1.08 ± 0.21
γ + jets	0.49 ± 0.29	0.17 ± 0.10	0.07 ± 0.01
$Z(\to \nu\nu)\gamma$	0.31 ± 0.11	0.35 ± 0.12	0.94 ± 0.28
$\gamma\gamma/W\gamma\gamma/Z\gamma\gamma$	0.23 ± 0.11	0.25 ± 0.10	0.08 ± 0.01
Fake photons from e	0.22 ± 0.08	0.04 ± 0.03	0.06 ± 0.04
Fake photons from jets	0.15 ± 0.09	0.14 ± 0.09	0.09 ± 0.07
$Z(\to \ell\ell)\gamma$	0.03 ± 0.03	0.03 ± 0.01	–

Summary

- Multi jets (arXiv:2010.14293v2)
- Large jet multiplicities (arXiv:2008.06032v2)
- With lepton (arXiv:2101.01629v1)
- With photon (ATLAS-CONF-2021-028)

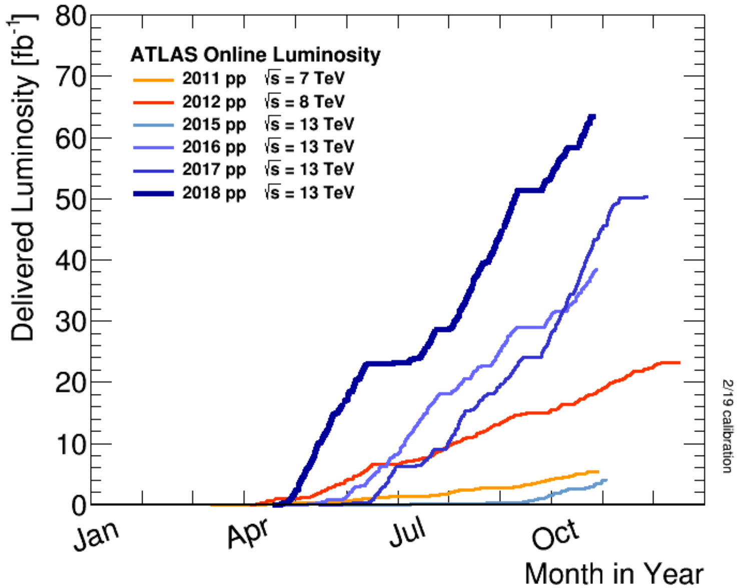


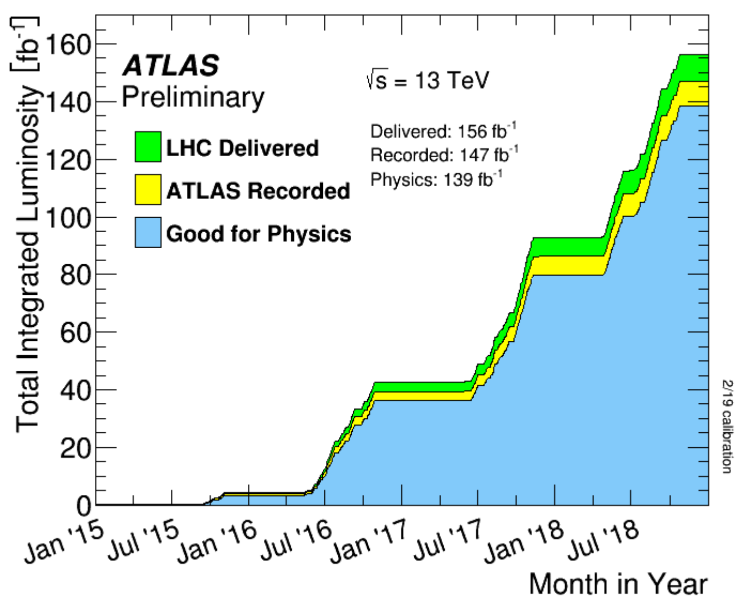


more results can be found at Summary web page

backup

ATLAS experiment



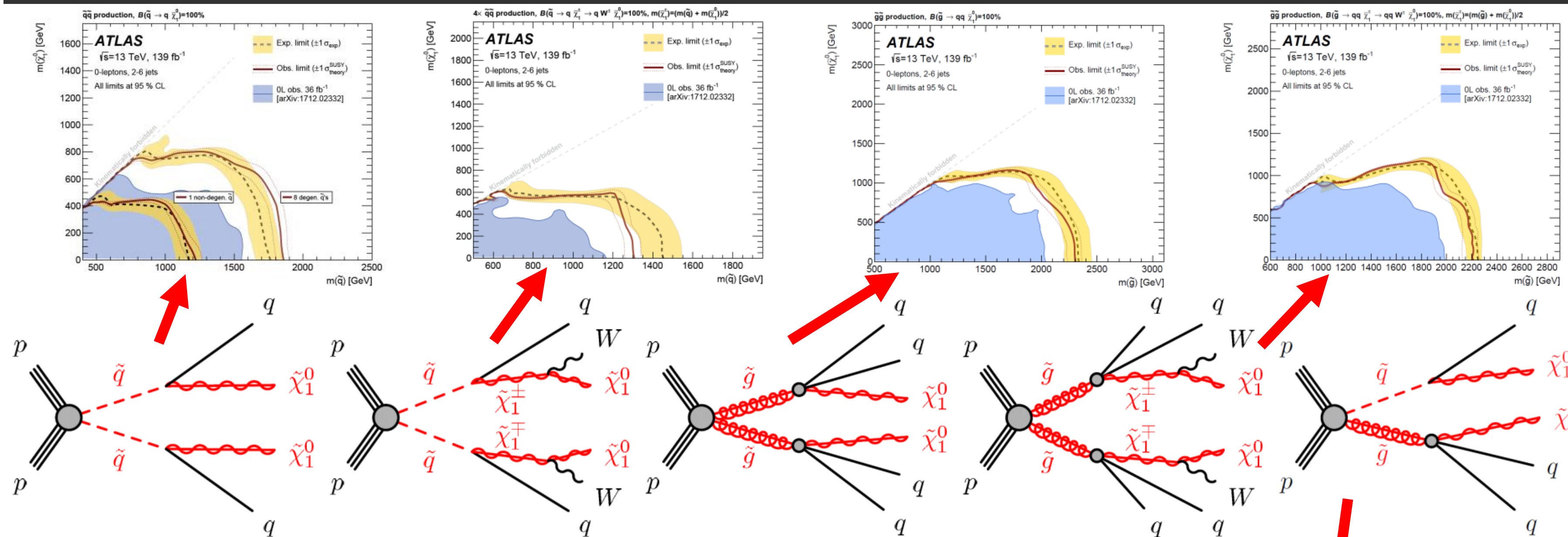


- The ATLAS detector at the LHC is a multi-purpose particle detector
- Run 2 performed in 2015 – 2018 with $\sqrt{s} = 13$ TeV
- 139 fb^{-1} of proton-proton collision data is collected
- All results reported today are based on those data
  - More general physics summary talk: ***

Strategy of analysis

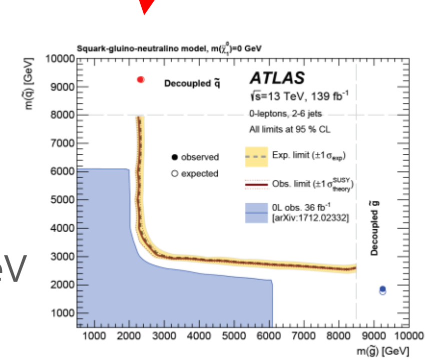
- Signal region (SR)
  - Construct to efficiently collect SUSY events
  - Ideally with small expected yields of SM events (backgrounds)
- Control region (CR)
  - For major SM background, dedicated Control Region is designed as the process enriched region
  - The expectation is extrapolated to SR
- Validation region (VR)
  - The region is designed to validate extrapolation from CR
  - It is constructed close to SR but with small expected yields of signal

I. Multi jets – more results



SS direct | SS one step | GG direct | GG one step | inclusive

- No significant deviation is found
- Excluded for:
  - SS direct: $m(\tilde{q}) < 1.85$ TeV
  - SS one step: $m(\tilde{q}) < 1.31$ TeV
  - GG direct: $m(\tilde{g}) < 2.30$ TeV
  - GG one step: $m(\tilde{g}) < 2.22$ TeV
  - Inclusive: $m(\tilde{q}) = m(\tilde{g}) < 3000$ GeV



II. Large jet multiplicities – SR definition

Selection criterion	Selection ranges	
Jet multiplicity, N_{jet}	$N_{\text{jet}}^{50} \geq \{8, 9, 10, 11, 12\}$	$N_{\text{jet}}^{80} \geq 9$
Trigger thresholds	2015–2016: 6 jets, $E_{\text{T}} > 45$ GeV	2015: 5 jets, $E_{\text{T}} > 70$ GeV 2016: 5 jets, $E_{\text{T}} > 65$ GeV
	2017–2018: 7 jets, $E_{\text{T}} > 45$ GeV	2017–2018: 5 jets, $E_{\text{T}} > 70$ GeV
Lepton veto	0 baseline leptons, $p_{\text{T}} > 10$ GeV	
$E_{\text{T}}^{\text{miss}}$ significance, $\mathcal{S}(E_{\text{T}}^{\text{miss}})$	$\mathcal{S}(E_{\text{T}}^{\text{miss}}) > 5.0$	

Signal region	N_{jet}^{50}	$N_{b\text{-jet}}$	M_{J}^{Σ} [GeV]
SR-8ij50 multi-bin	≥8	= 0, = 1, ≥ 2	(0, 340], (340, 500], (500, ∞)
SR-9ij50 multi-bin	≥9		
SR-10ij50 multi-bin	≥10		

Signal region	N_{jet}^{50}	N_{jet}^{80}	$N_{b\text{-jet}}$	M_{J}^{Σ} [GeV]
SR-8ij50-0ib-MJ500	≥8	-	-	≥500
SR-9ij50-0ib-MJ340	≥9	-	-	≥340
SR-10ij50-0ib-MJ340	≥10	-	-	≥340
SR-10ij50-0ib-MJ500	≥10	-	-	≥500
SR-10ij50-1ib-MJ500	≥10	-	≥1	≥500
SR-11ij50	≥11	-	-	-
SR-12ij50-2ib	≥12	-	≥2	-
SR-9ij80	-	≥9	-	-

- Multi-bin: to improve exclusion limit
- Single-bin: optimized for benchmark models
- For exclusion limit, the constraint selected by the most sensitive region

$\mathcal{S}(E_{\text{T}}^{\text{miss}})$ range	0–2	2–3	3–4	4–5	> 5
$N_{\text{jet}}^{80} = 5$	$\text{TR}_{\text{norm}}^{\text{l}}$	–	–	–	TR_{shape}
$N_{\text{jet}}^{80} = 6$	–	–	–	–	$\text{VR}_{N_{\text{jet}}}$
$N_{\text{jet}}^{80} \geq 9$	$\text{TR}_{\text{norm}}^{\text{h}}$	–	QCR	$\text{VR}_{\mathcal{S}(E_{\text{T}}^{\text{miss}})}$	SR

$\mathcal{S}(E_{\text{T}}^{\text{miss}})$ range	0–2	2–3	3–4	4–5	> 5
$N_{\text{jet}}^{50} = 6$, prescaled data	$\text{TR}_{\text{norm}}^{\text{l,prescale}}$	–	–	–	$\text{TR}_{\text{shape}}^{\text{prescale}}$
$N_{\text{jet}}^{50} = 7$, full dataset	$\text{TR}_{\text{norm}}^{\text{h,prescale}}$	–	–	–	$\text{VR}_{N_{\text{jet}}}$
$N_{\text{jet}}^{50} = 7$, full dataset	$\text{TR}_{\text{norm}}^{\text{l}}$	–	–	–	TR_{shape}
$N_{\text{jet}}^{50} \geq 8$, full dataset	$\text{TR}_{\text{norm}}^{\text{h}}$	–	QCR	$\text{VR}_{\mathcal{S}(E_{\text{T}}^{\text{miss}})}$	SR

Squark summary