Search for pair production of gluinos or electroweakinos with two same-sign or three leptons final states at $\sqrt{s}$=13 TeV with the ATLAS detector

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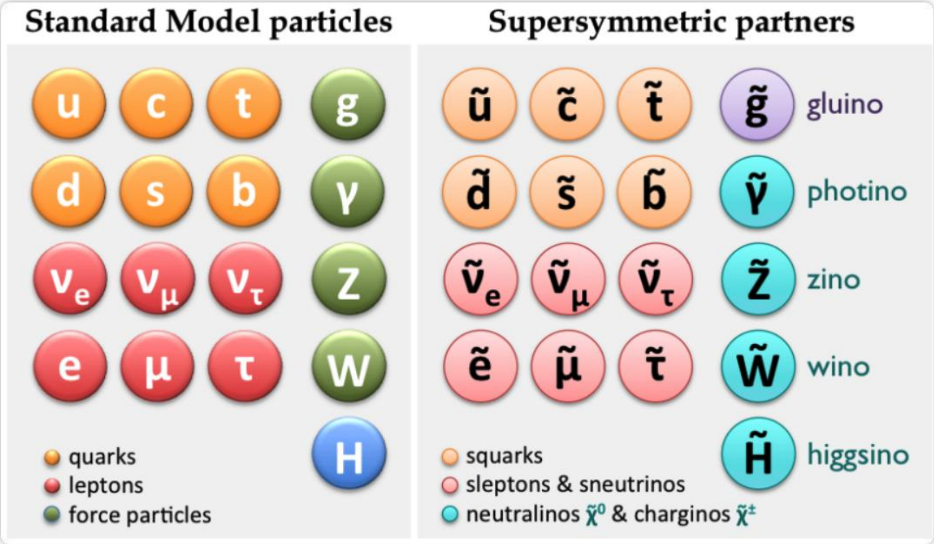
Introduction of SUSY



Minimal Supersymmetric Model

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	$+1$	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	-1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	-1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	-1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	-1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	-1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	-1	$\widetilde{G}$	(same)

R-parity: $P_R = (-1)^{3(B-L)+2S}$: SUSY particles →odd R-parity; SM-particles →even R-parity

R-parity conserved:

SUSY particles produced in pairs, Lightest SUSY particle(LSP) stable as a dark matter candidate

R-parity violated:

New terms added in superpotential: λ_{ijk}, λ'_{ijk} , λ''_{ijk} (lepton/quark superfield coupling)

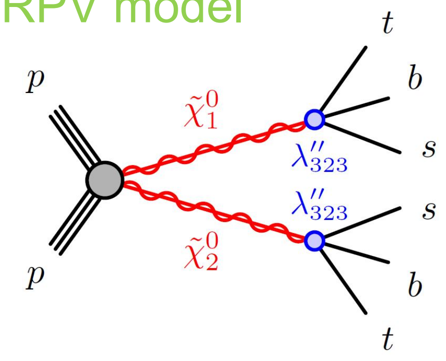
R-parity violation implies lepton/baryon number violation

Searches with same-sign/three leptons final state

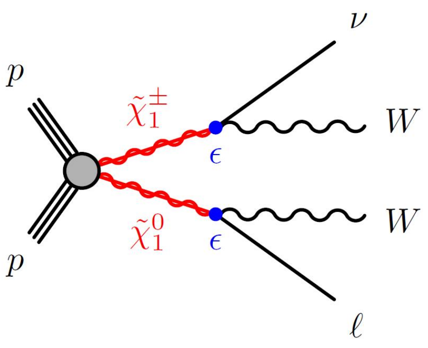
- Search for pair production of **gluinos or electroweakinos** with two same-sign or three leptons final states
  - Input: full run2 data of 139 fb^{-1} from ATLAS detector.
  - Final state: two same-sign or three leptons
  - This final state have low SM backgrounds thus it allows the use of relatively loose kinematic requirements to increase sensitivity to compressed scenarios.
  - Signal model:
    - EWK production: pair production electroweakinos, include RPC and RPV model.
    - Strong production: gluinos pair production with cascade decays via sleptons or W/Z bosons.
  - Status
    - SS/3L EWK: CONF note public[ATLAS-CONF-2022-057]
    - SS/3L strong: ongoing

SS/3L EWK

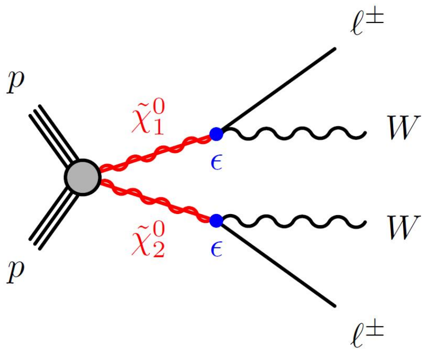
RPV model



(f) higgsino N1N2 RPV

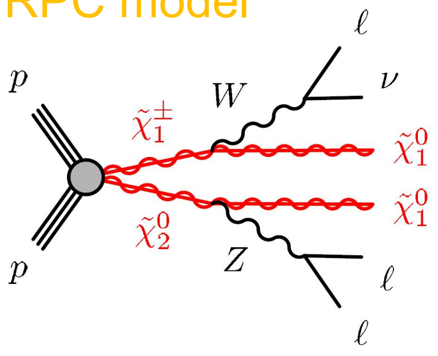


(d) higgsino C1N1 bRPV



(e) higgsino N1N2 bRPV

RPC model



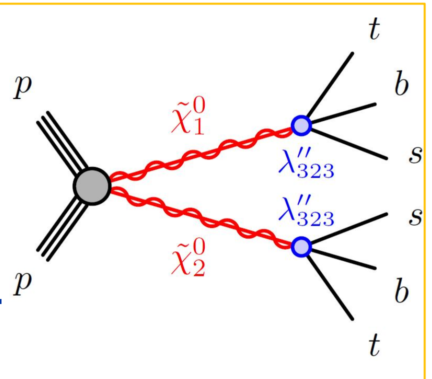
(a) wino C1N2 WZ on-shell

Higgsino N1N2 RPV

$$W_R = \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda''_{ijk}\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k + \epsilon_i\hat{L}_i\hat{L}_j$$

RPV UDD: λ'_{323} dominant under **minimal flavour violation hypothesis,** and sufficiently strong to have prompt decays.

- The main target is the very low LSP mass region, SRs for higher LSP masses are also defined.
- SRs are orthogonal by $\boldsymbol{N_{b-jets}}$ are statistically combined.



(f) higgsino N1N2 RPV

➢ Signal region

1 b-jets SR

$N^{\text{signal}}_{\text{lept}}$ ($N^{\text{base}}_{\text{lept}}$), $p_T > 25$ GeV	$N_{b\text{-jets}}$ [20 GeV]	N_{jets} [25 GeV]	E^{miss}_T [GeV]
= 2 (= 2)	= 1	≥ 1 and ≤ 6	> 50

SR name	N_{jets} [25 GeV]	$\sum p_T^{b\text{-jet}}/\sum p_T^{\text{jet}}$	$\sum p_T$(jet) [GeV]	$\Delta R(\ell_1, \text{jet})$	E^{miss}_T [GeV]	$\sum p_T$(lept)	$\Delta R(\ell_1, \ell_2)$
Rpv2L1bL	≤ 2	> 0.70	> 120	< 1.2	> 100	> 100	> 2.0
Rpv2L1bM	= 2 or = 3	> 0.45	> 400	< 1.0	–	> 100	> 2.5

2 b-jets SR

$N^{\text{signal}}_{\text{lept}}$ ($N^{\text{base}}_{\text{lept}}$), $p_T > 25$ GeV	$N_{b\text{-jets}}$ [20 GeV]	N_{jets} [25 GeV]	E^{miss}_T
= 2 (= 2)	= 2	≥ 1 and ≤ 6	> 80

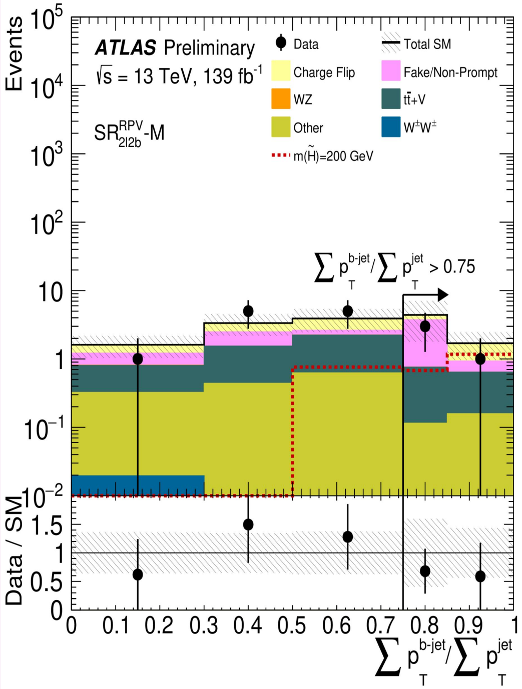
SR name	N_{jets} [25 GeV]	$\sum p_T^{b\text{-jet}}/\sum p_T^{\text{jet}}$	$\sum p_T$(jet) [GeV]	$\Delta R(\ell_1, \text{jet})$	$\Delta R(\ell_1, \ell_2)$
Rpv2L2bL	≤ 3	> 0.90	> 300	< 1.0	> 2.5
Rpv2L2bM	= 3 or = 4	> 0.75	> 420	< 1.0	> 2.5
Rpv2L2bH	≥ 5	–	> 420	< 1.0	> 2.0

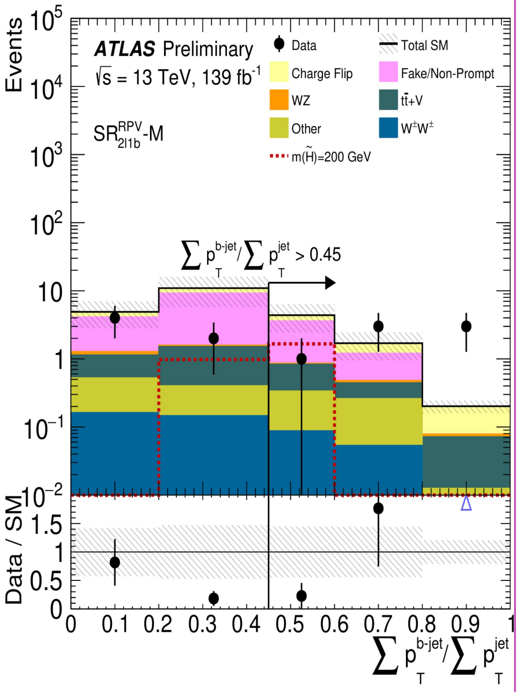
3 b-jets SR

$N^{\text{signal}}_{\text{lept}}$ ($N^{\text{base}}_{\text{lept}}$), $p_T > 25$ GeV	$N_{b\text{-jets}}$ [20 GeV]	N_{jets} [25 GeV]	E^{miss}_T [GeV]
= 2 (= 2)	≥ 3	≥ 1 and ≤ 6	> 20

SR name	N_{jets} [25 GeV]	$\sum p_T^{b\text{-jet}}/\sum p_T^{\text{jet}}$	$\sum p_T$(jet) [GeV]	$\Delta R(\ell_1, \ell_2)$	$\Delta R(\ell_1, \text{jet})$
Rpv2L3bL	≤ 3	> 0.8	–	> 2.0	< 1.5
Rpv2L3bM	≤ 3	> 0.8	–	–	–
Rpv2L3bH	≤ 6	> 0.5	> 350	> 2.0	< 1.0

➢ Kinematic distribution in signal regions

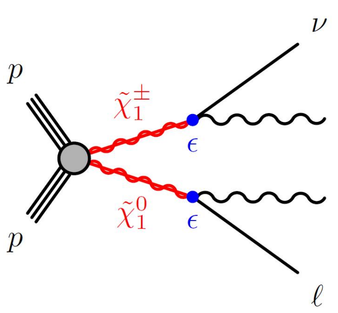




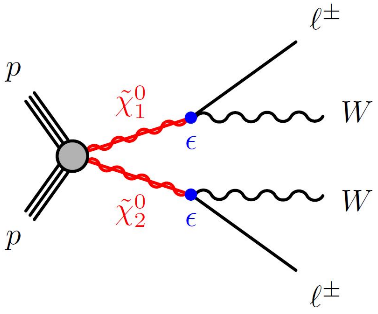
Higgsino C1N2/N1N2 Bilinear RPV

$$W_R = \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k + \lambda''_{ijk}\,\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k + \epsilon_i\hat{L}_i\hat{L}_j$$

- Motivation: Sneutrino vacuum expectation values (VEVs) introduce a mixing between neutrinos and neutralinos, leading to see-saw mechanism. The same VEVs are also involved in the decay of the LSP.
- The two SRs are orthogonal and are statistical combined.



(d) higgsino C1N1 bRPV

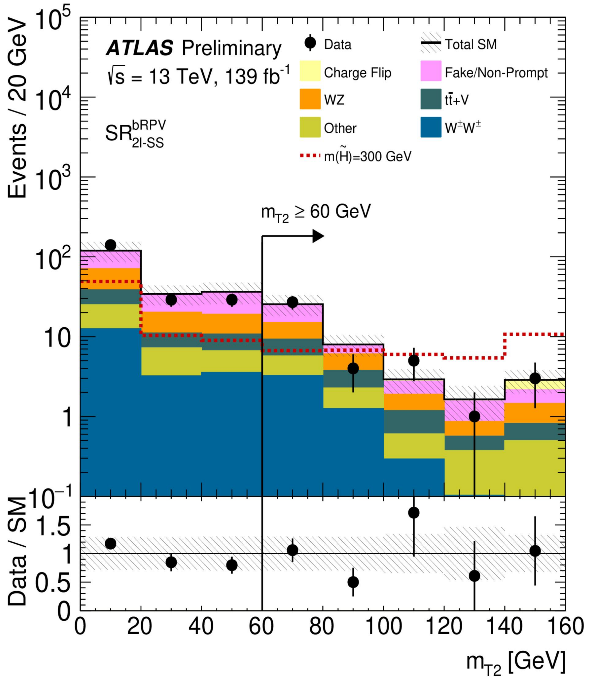


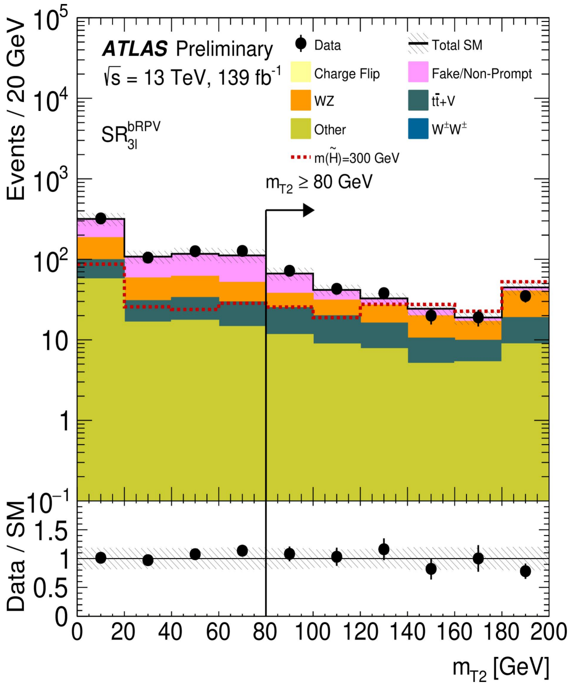
(e) higgsino N1N2 bRPV

➢ Signal region

Variables	Two leptons final state	Three leptons final state
$N_{\mathrm{Sig}}(\ell)$	$= 2$	$= 3$
isSameSign	Yes	-
leading lepton p_{T}	20 GeV	20 GeV
subleading lepton p_{T}	20 GeV	20 GeV
third lepton p_{T}	-	10 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	≥ 100 GeV	≥ 120 GeV
m_{eff}	-	≥ 350 GeV
m_{T2}	≥ 60 GeV	≥ 80 GeV
$N_{b-\mathrm{jets}}(p_{\mathrm{T}} > 20$ GeV $)$	$= 0$	-
$N_{\mathrm{jets}}(p_{\mathrm{T}} > 25$ GeV$)$	≥ 1	≥ 1
$N_{\mathrm{jets}}(p_{\mathrm{T}} > 40$ GeV$)$	≥ 4	-
$M_{ee}/M_{\mu\mu}$ SFOS pairs	-	< 81 or > 101 GeV

➢ Kinematic distribution in signal regions

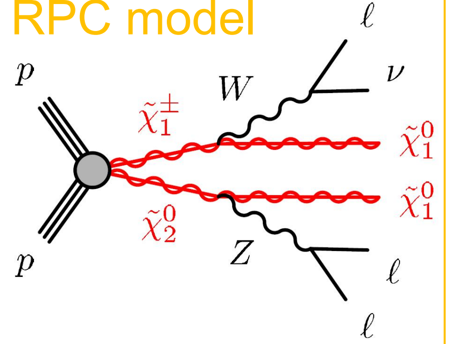




Wino C1N2 WZ on-shell

- SR-WZonshell1 is designed for boosted region. Multi-bin fit is applied to SR-WZonshell1.
- SR-WZonshell2 is designed for relatively low mass splitting region.
- Two orthogonal SRs are statistically combined.

RPC model

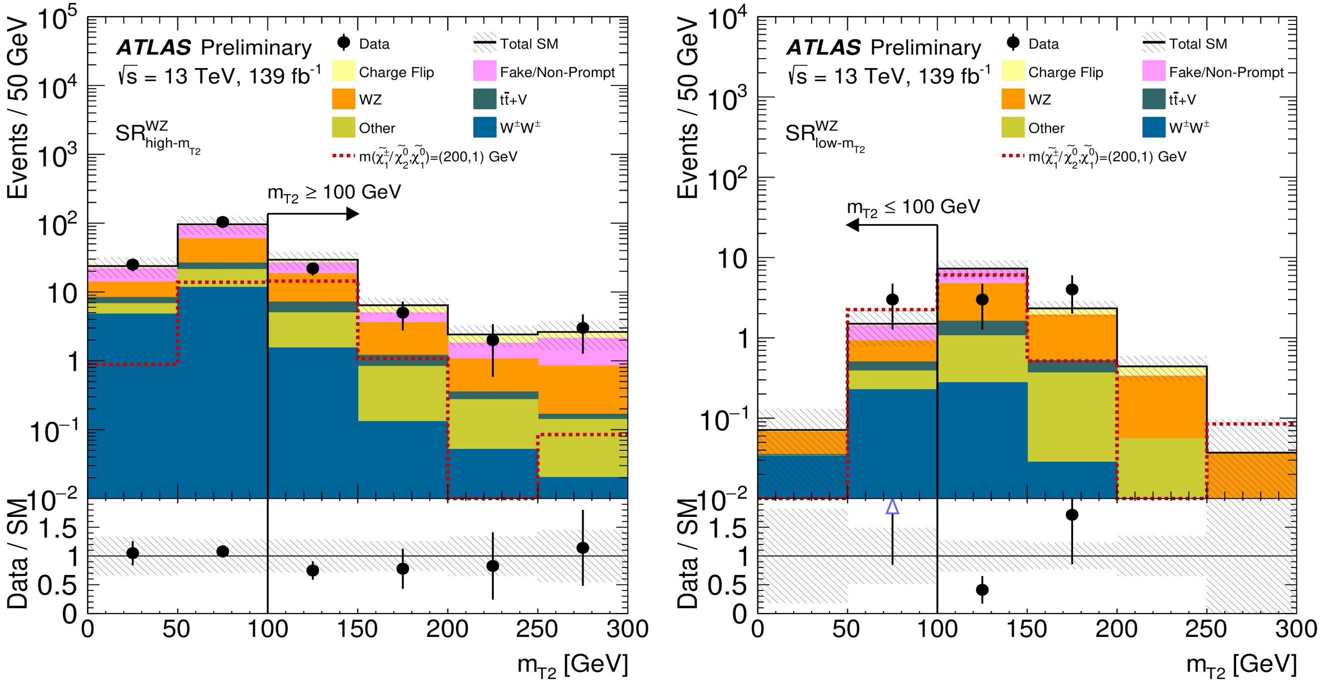


(a) wino C1N2 WZ on-shell

➢ Signal region

	SR-WZonshell1	SR-WZonshell2
$N_{Comb}(l)$	=2	
$N_{BL}(l)$	=2	
$N_{Sig}(l)$	=2	
Charge(l)	Same-Sign	
$p_T(l)$	≥25 GeV	
$N_{jets}(p_T > 25\text{ GeV})$	≥1	
N_{b-jets}	=0	
m_{jj}	≤350 GeV	
m_{T2}	≥100 GeV	≤100 GeV
m_T^{min}	≥100 GeV	≥130 GeV
E_T^{miss}	≥100 GeV	≥140 GeV
m_{eff}	-	≤600 GeV
$\Delta R(\ell^{\pm}, \ell^{\pm})$	-	≤3
Bins	$Sig(E_T^{miss})$: [0-10], Spread(Φ) ≥2.2; $Sig(E_T^{miss})$: [10-13]; $Sig(E_T^{miss})$: [13-∞], $\Delta R(\ell^{\pm}, \ell^{\pm})$ ≥1	-

➢ Kinematic distribution in signal regions

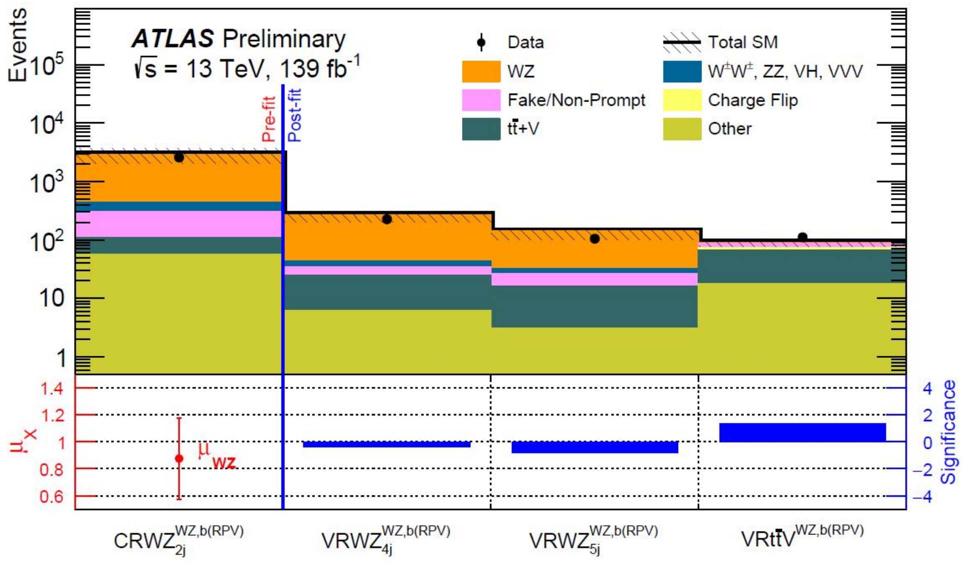


Background Estimation

- Prompt (irreducible) backgrounds
  - Diboson (except WZ+jets), tt+V, multibosn and other: estimated with MC samples
  - WZ+jets: based on MC, with a correction factor obtained from CR fit.
- Detector (reducible) backgrounds
  - Charge flip: data-driven method, cross-check with MC-template method
  - Fake lepton: matrix method, cross-check with MC-template method

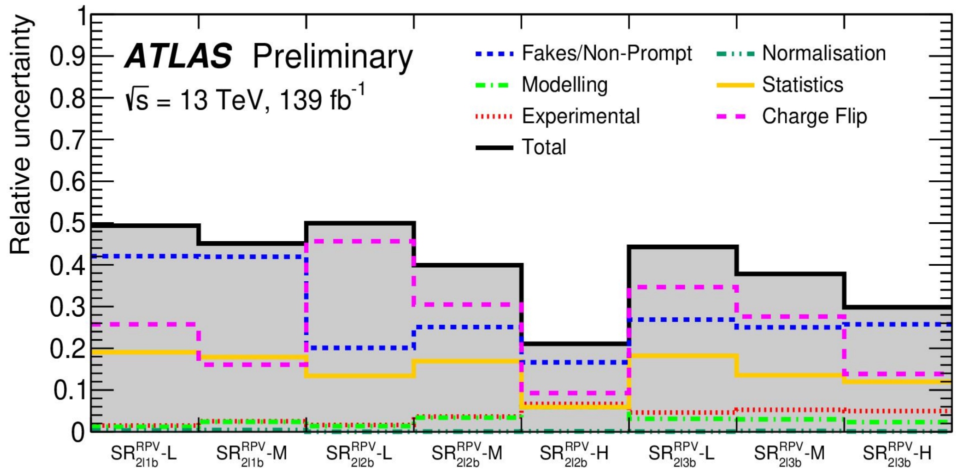
Definition of CR and VR

	$\mathrm{CR}WZ_{2j}^{WZ,\text{(b)RPV}}$	$\mathrm{VR}WZ_{4j}^{WZ,\text{(b)RPV}}$	$\mathrm{VR}WZ_{5j}^{WZ,\text{(b)RPV}}$	$\mathrm{VR}t\bar{t}V^{WZ,\text{(b)RPV}}$
$N_{\mathrm{BL}}(\ell)$	$= 3$			≥ 2
$N_{\mathrm{Sig}}(\ell)$	$= 3$			≥ 2
Charge(ℓ)	–			same-sign
$p_{\mathrm{T}}(\ell)$	$p_{\mathrm{T}} > 20$ GeV for (sub)leading leptons			$p_{\mathrm{T}} > 30$ GeV for SS pair leptons
$n_{b\text{-jets}}$	$= 0$			≥ 1
n_{jets} ($p_{\mathrm{T}} \geq 25$ GeV)	≥ 2	≥ 4	≥ 5	≥ 3 with $p_{\mathrm{T}} > 40$ GeV
Other selections	$50 < E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV	$50 < E_{\mathrm{T}}^{\mathrm{miss}} < 250$ GeV		–
	$m_{\mathrm{eff}} < 1$ TeV	$m_{\mathrm{eff}} < 1.5$ TeV		–
	$81 < m_{\mathrm{SFOS}} < 101$ GeV	$81 < m_{\mathrm{SFOS}} < 101$ GeV		–
	–			$\Delta R(\ell_1, jet)_{\min} > 1.1$
	–			$\sum p_{\mathrm{T}}^{b\text{-jet}} / \sum p_{\mathrm{T}}^{\mathrm{jet}} > 0.4$
	–			$E_{\mathrm{T}}^{\mathrm{miss}} / m_{\mathrm{eff}} > 0.1$
	vetoing $\mathrm{SR}^{WZ}_{\mathrm{high}-m_{\mathrm{T2}}}$ & $\mathrm{SR}^{WZ}_{\mathrm{low}-m_{\mathrm{T2}}}$ & $\mathrm{SR}^{\mathrm{bRPV}}_{2\ell-\mathrm{SS}}$ & $\mathrm{SR}^{\mathrm{bRPV}}_{3\ell}$ events			
	vetoing other possible BSM events			
	$n_{b\text{-jets}} \geq 3$ $n_{b\text{-jets}} \geq 1$, $n_{\mathrm{jets}} \geq 4$ ($p_{\mathrm{T}} > 50$ GeV), $E_{\mathrm{T}}^{\mathrm{miss}} > 130$ GeV $n_{b\text{-jets}} = 0$, $n_{\mathrm{jets}} \geq 3$ ($p_{\mathrm{T}} > 50$ GeV), $E_{\mathrm{T}}^{\mathrm{miss}} > 130$ GeV $n_{b\text{-jets}} = 0$, $n_{\mathrm{jets}} \geq 5$ ($p_{\mathrm{T}} > 50$ GeV)			
Purity	85%	84%	77%	62%

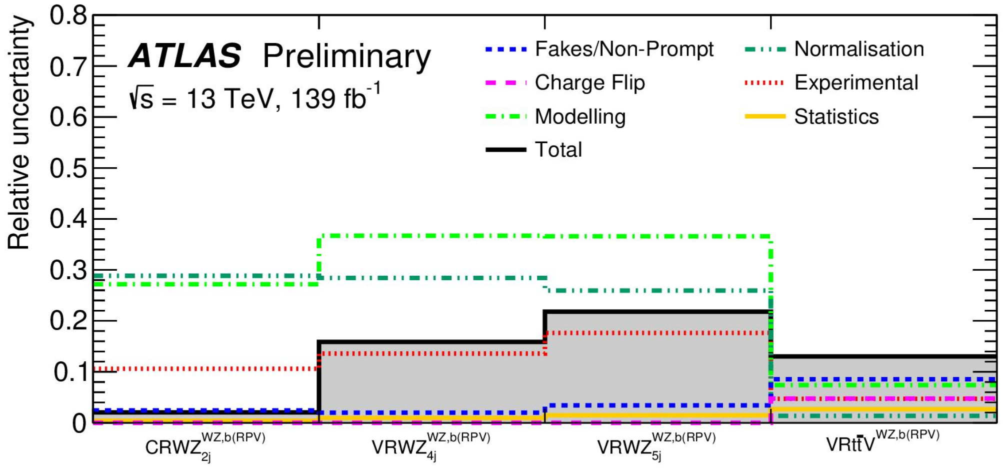


Expected SM backgrounds and data yields in CR and VRs

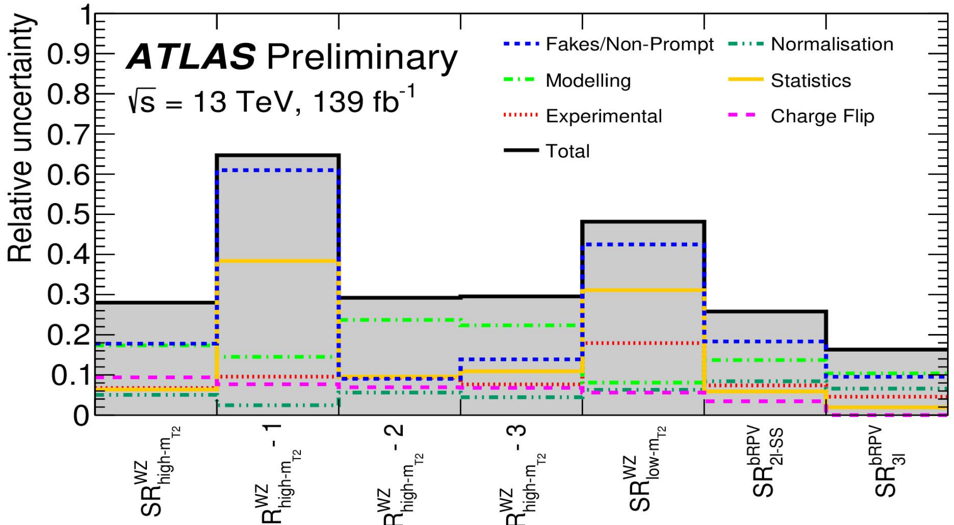
Systematic uncertainties



Relative contributions from experimental and theoretical uncertainties in SRs defined for the UDD RPV model. The individual components can be correlated and therefore do not necessarily add up in quadrature to the total systematic uncertainty.



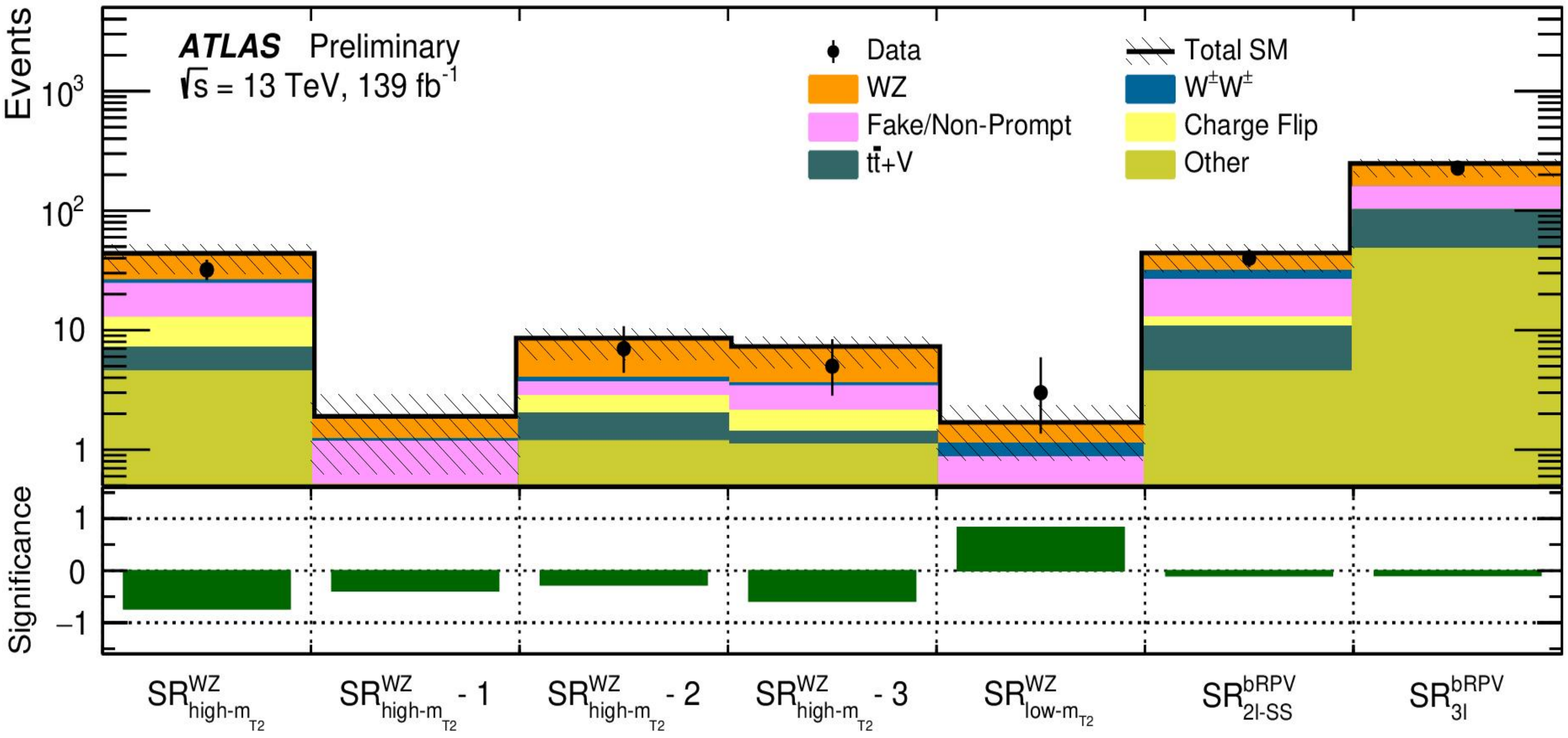
Breakdown of the total post-fit systematic uncertainties in the background prediction for the CRs and VRs



Breakdown of the total systematic uncertainties in the background prediction for the SRs of the WZ and bRPV models

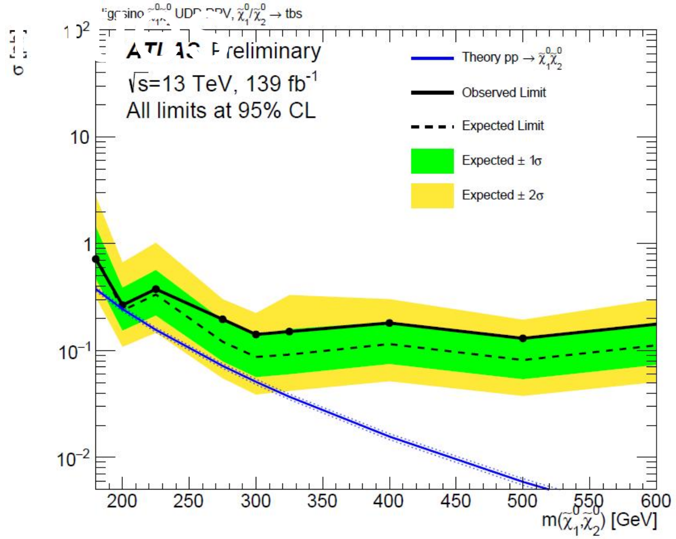
- For CRs and VRs, the total uncertainties are less than 1% to 20% with the largest contribution coming from the modelling of the simulated SM processes.
- For SRs, total uncertainties vary from 30% to 50% with the uncertainties from the estimations of Fakes/Non-Prompt and Charge flip events accounting for the largest contribution in most of the regions.

Expected SM background and data yields in SRs

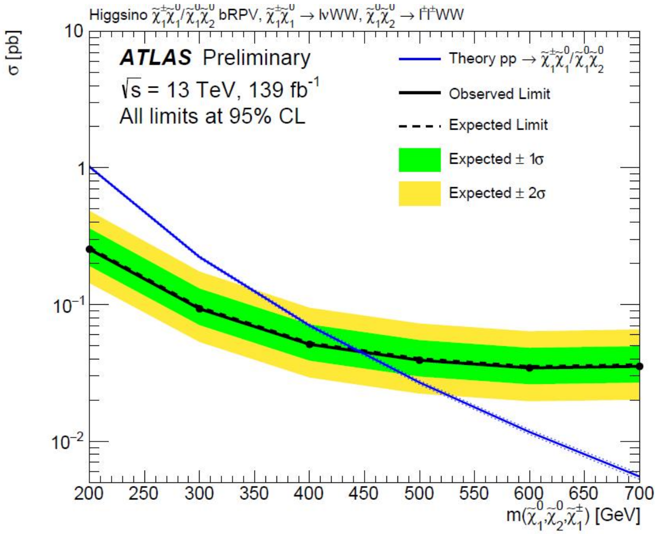


- The observed data are compatible with the SM prediction
- No significant excess over the expected background is observed.

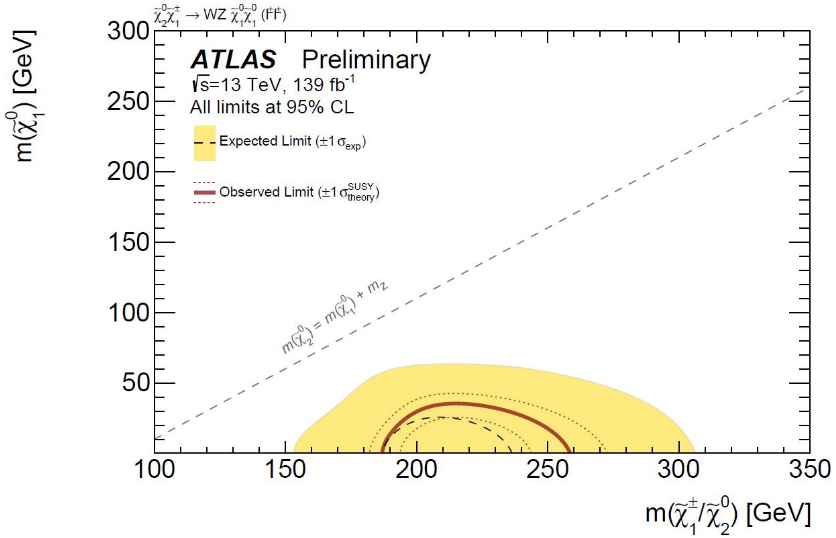
Model dependent statistical interpretation



Upper limits (black line) on Higgsino RPV model



Upper limits (black line) on bRPV Higgsino model.

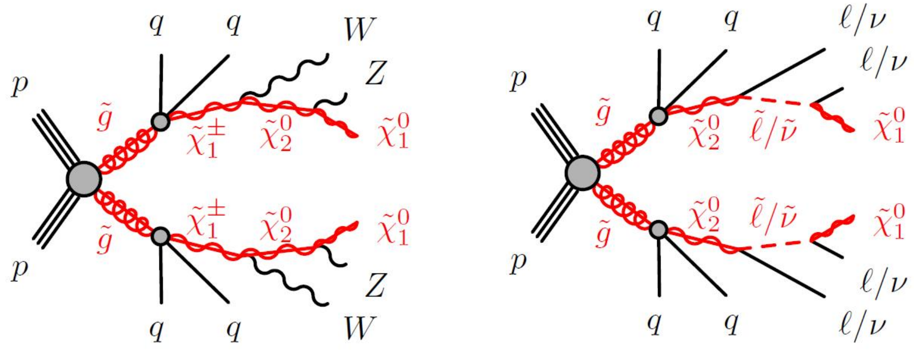


Exclusion limits on the WZ on-shell model

- Higgsino-like N1/N2 mass of 200 GeV is excluded for higgsino N1N2 RPV model.
- Higgsino masses smaller than 440 GeV are excluded for higgsino C1N2/N1N2 Bilinear RPV model.
- C1/N2 masses in the range 185-260 GeV are excluded for Wino C1N2 WZ on-shell model for massless bino.

SS/3L strong

RPC model

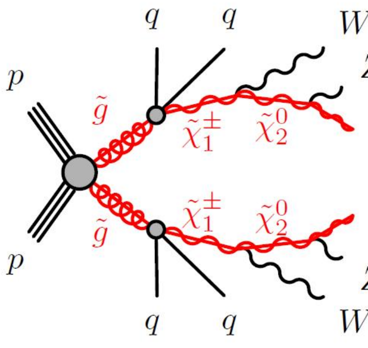


(d) RPC GG 2-step via WZ bosons

(c) RPC GG 2-step via sleptons

RPC GG 2-step via WZ bosons

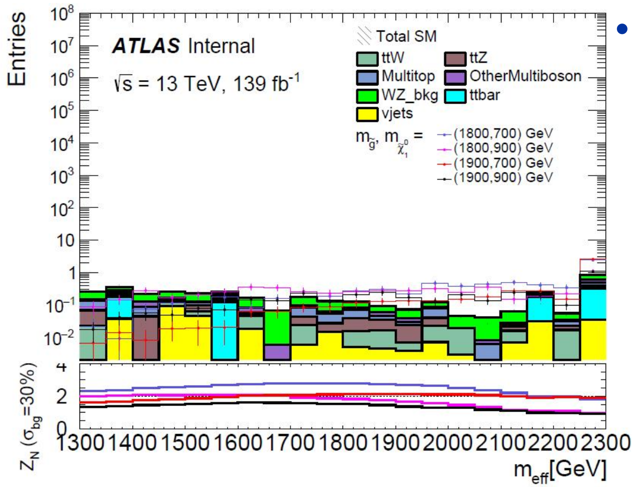
- For all RPC model, the masses of those mediated SUSY particles were set to be the half betw the parent SUSY particles masses and the daughter SUSY particles masses
- According to the mass splitting, both on-shell and off-shell bosons are considered.
- Design three signal regions target compressed region, middle region and boosted region.
- Use multi-bin fit of m_{eff} in RpcGGwz2.



(d) RPC GG 2-step via WZ bosons

➢ Signal region

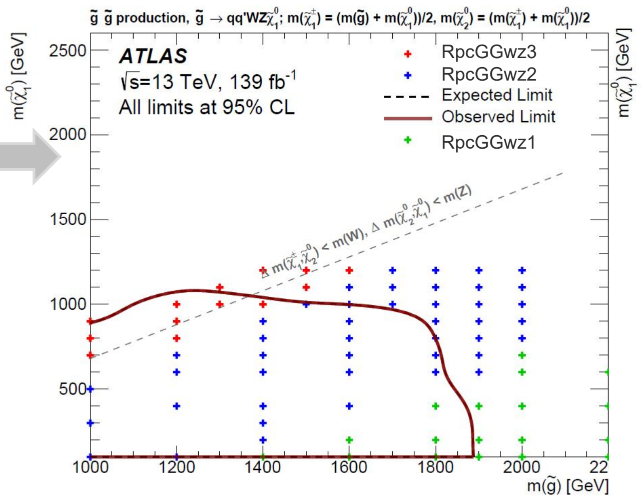
SR	$N_{\text{lept}}^{\text{signal}}$ ($N_{\text{lept}}^{\text{base}}$)	$N_{\text{b-jets}}^{\text{20GeV}}$	n_{jets}	Jet Pt threshold	E_T^{miss}	m_{eff}	$\Delta\phi(\ell 1\ell 2, E_T^{\text{miss}})$	$\text{Sig}(E_T^{\text{miss}})$	$m_{\text{eff}}/\sum p_T^{\text{lep}}$
RpcGGwz1	>=2 (-)	=0	>=6	40 GeV	>150 GeV	>2100 GeV	-	-	-
RpcGGwz2	>=2 (-)	=0	>=6	40 GeV	>190 GeV	>1300 GeV	>0.8	-	-
RpcGGwz3	>=2 (>= 3)	=0	>=6	25 GeV	>200 GeV	-	>0.2	>6	>8



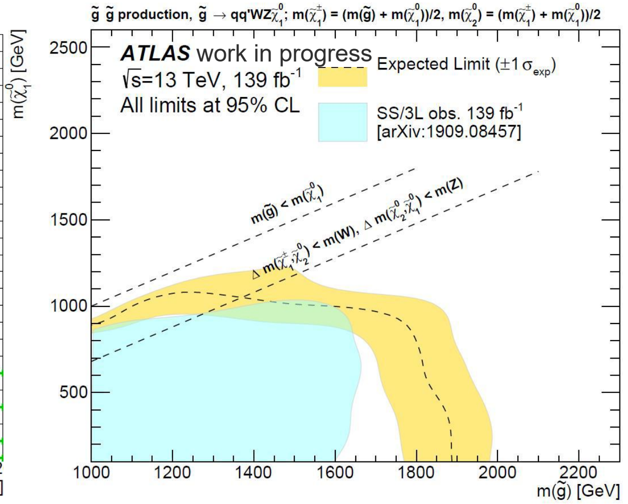
m_{eff} distribution in RpcGGwz2

- Multi-bin fit in other SRs are also tried. But multi-bin fit showed little signal sensetivity improvement. So we not use multi-bin fit in the.

➢ Model dependent exclusion limit



SR providing lowest CLs

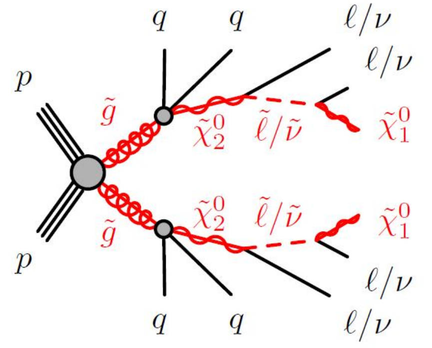


Final exclusion limit obtained for the RPC GG via WZ model

- Expected to exclude gluino masses up to 1900 GeV.

RPC GG 2-step via sleptons

- Design three signal regions target compressed region, middle region and boosted region.
- Use multi-bin fit in each signal region.
- For signal region optimization, BDT is also tried. But BDT show little improvement in signal sensetivity comparing to cut-and-count. So we not use BDT results in following analysis.



(c) RPC GG 2-step via sleptons

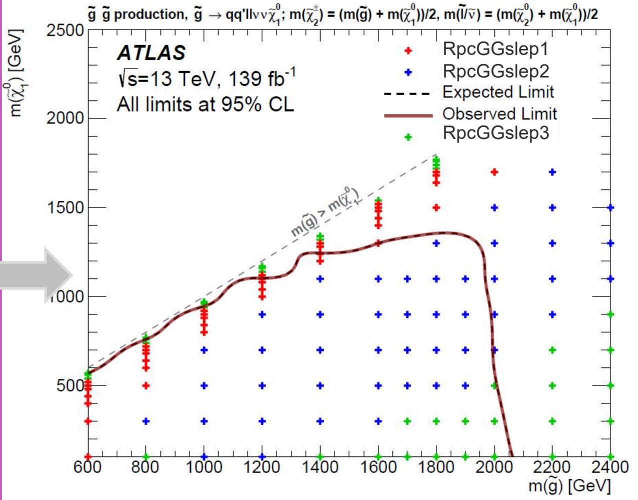
➢ Signal region

RpcGGslep1	RpcGGslep2	RpcGGslep3
$N_{\text{lept}}^{\text{signal}} \geq 3$		
$N_{\text{jets}}^{40\text{GeV}} \geq 4$		
$N_{\text{b-jets}}^{20\text{GeV}} == 0$		
veto $81 < m_{\text{SFOS}} < 101$ GeV		
$E_T^{\text{miss}}/\sum p_T^j \geq 0.4$	$E_T^{\text{miss}}/\sum p_T^j \geq 0.3$	-
$E_T^{\text{miss}}/\sum p_T^{\text{lep}} \geq 1.4$	$\Delta\phi(\ell 1\ell 2, E_T^{\text{miss}}) > 0.7$	-
$p_T^{\ell 2} \geq 30$ GeV	$p_T^{\ell 2} \geq 70$ GeV	$\sum p_T^j \geq 1200$ GeV
-	$E_T^{\text{miss}} \geq 150$ GeV	$E_T^{\text{miss}} \geq 100$ GeV

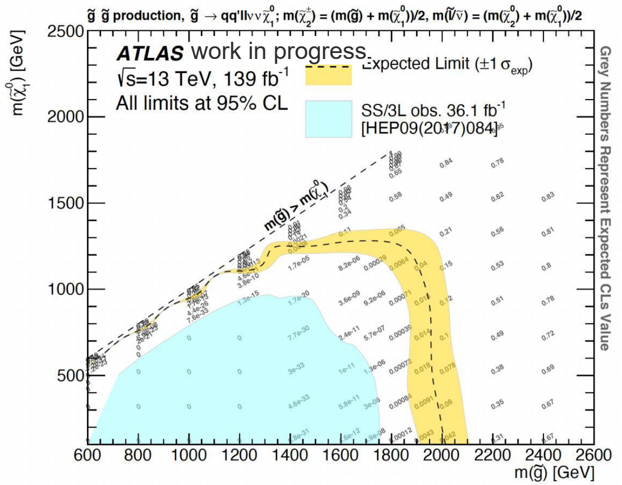
(a) Discovery SRs

RpcGGslep1B1	RpcGGslep1B2	RpcGGslep2B1	RpcGGslep2B2	RpcGGslep3B1	RpcGGslep3B2
$N_{\text{lept}}^{\text{signal}} \geq 3$					
$N_{\text{jets}}^{40\text{GeV}} \geq 4$					
$N_{\text{b-jets}}^{20\text{GeV}} == 0$					
veto $81 < m_{\text{SFOS}} < 101$ GeV					
$E_T^{\text{miss}}/\sum p_T^j \geq 0.4$		$E_T^{\text{miss}}/\sum p_T^j \geq 0.3$		$\sum p_T^j \geq 1200$ GeV	
$p_T^{\ell 2} \geq 30$ GeV		$\Delta\phi(\ell 1\ell 2, E_T^{\text{miss}}) > 0.7$		$E_T^{\text{miss}} - (100, 250)$ GeV	$E_T^{\text{miss}} \geq 250$ GeV
$E_T^{\text{miss}}/\sum p_T^{\text{lep}} - (1.4, 2.0)$	$E_T^{\text{miss}}/\sum p_T^{\text{lep}} \geq 2.0$	$p_T^{\ell 2} \geq 70$ GeV		-	
-		$E_T^{\text{miss}} - (150, 250)$ GeV	$E_T^{\text{miss}} \geq 250$ GeV	-	

➢ Model dependent exclusion limit



SR providing lowest CLs



Final exclusion limit obtained for the RPC GG via sleptons model

- Expected to exclude gluino masses up to 2000 GeV.

Summary

- A search for direct production of winos and higgsinos in two same-sign or three leptons final state is conducted. No significant excess over the Standard Model expectation is observed.
    - For Wino C1N2 WZ on-shell model, wino masses up to 260 GeV are excluded, respectively, for a bino of vanishing mass.
    - For higgsino C1N2/N1N2 Bilinear RPV model, higgsino masses smaller than 440 GeV are excluded.

- A search for pair production gluinos decaying in RPC signal model in two same-sign or three leptons final state is ongoing. We have got improvement in exclusion limit comparing to results in previous SS/3L strong search.