



The
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Search for direct scalar b-quark pair production with the ATLAS detector

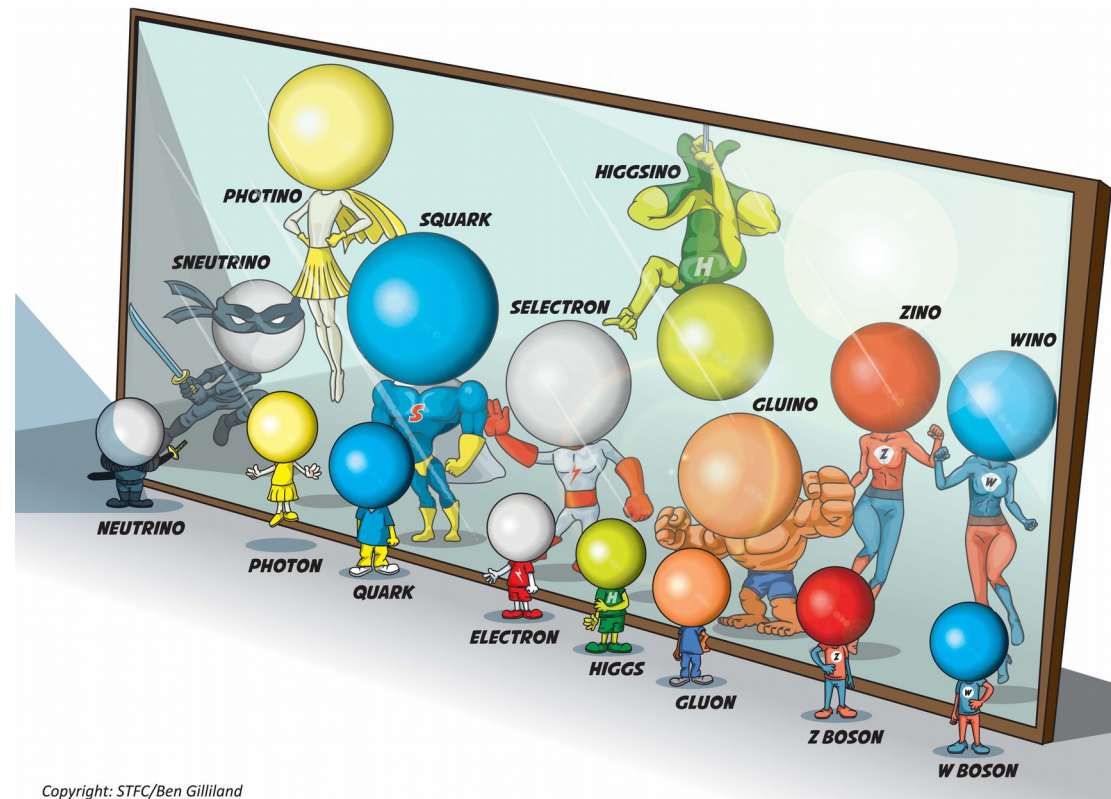
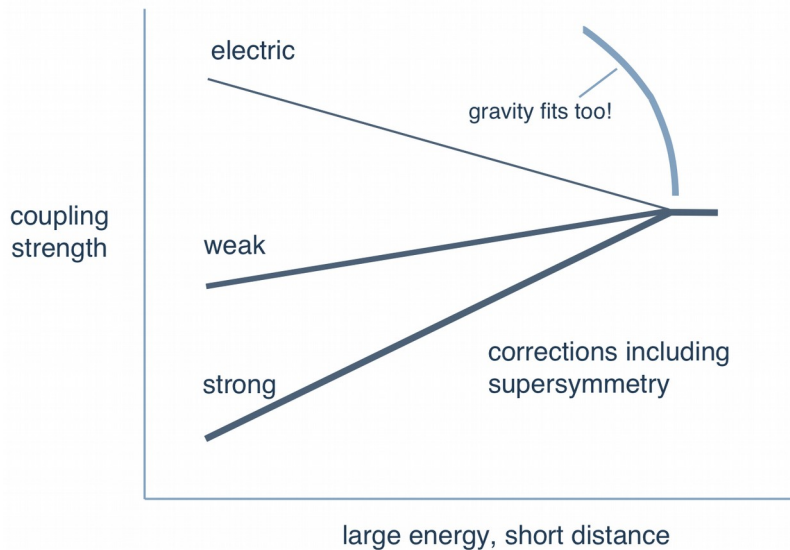
HEP2016 – Conference on Recent developments in High Energy Physics and Cosmology
Thessaloniki, Greece

Evangelos Kourlitis

12.05.2016

Supersymmetry Overview

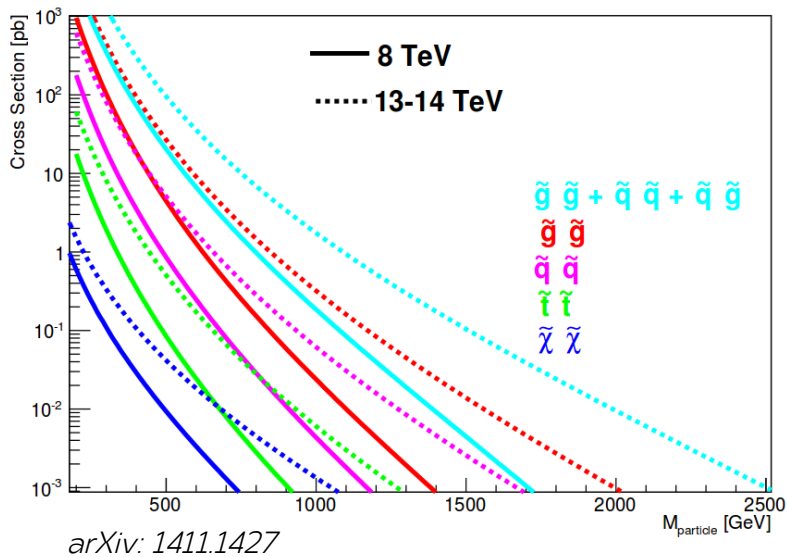
- Theoretical framework beyond the Standard Model
 - Predicts superpartners of the known particles – Spin differs by 1/2
- Offers solutions to known physics problems:
 - Hierarchy problem
 - Dark Matter candidate
 - Unification of forces



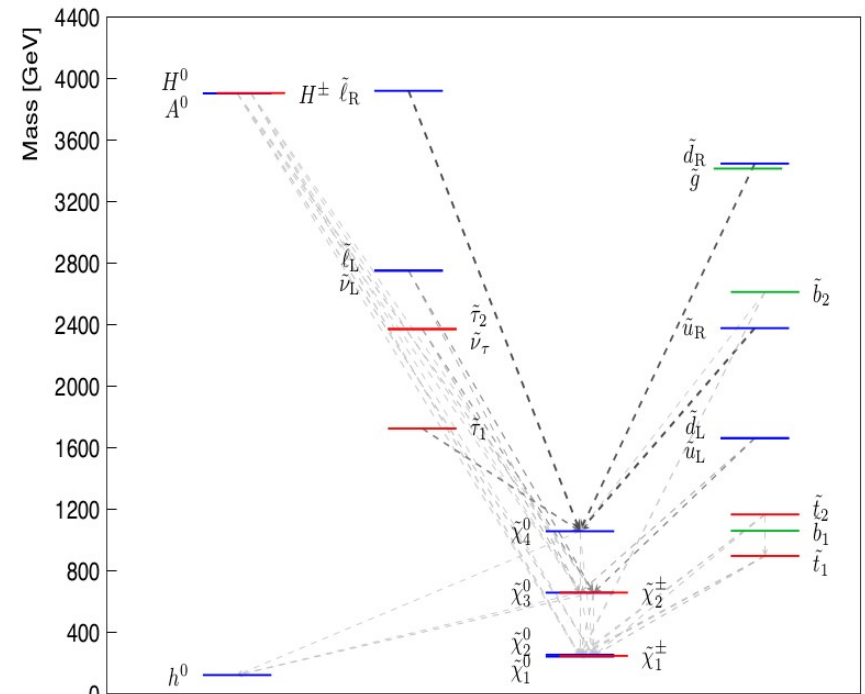
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3rd Generation SUSY

- To protect Higgs sector from unnatural loop corrections the scalar partners of top and bottom quark should have mass $O(\text{TeV})$
- Reachable by the LHC!
 - Enhanced production cross-section, Run 2 might be a game changer



A natural (and viable) SUSY mass spectrum



The pMSSM

- The **M**inimal **S**upersymmetric **S**tandard **M**odel implies 120 parameters
- Well motivated assumptions reduce the number of parameters to 19

phenomenological MSSM



Assumptions

Experimental Constrains



R-parity* Conservation



No additional FCNC

Parameters $\in \mathbb{R}$



1st and 2nd Generation
mass degeneracy

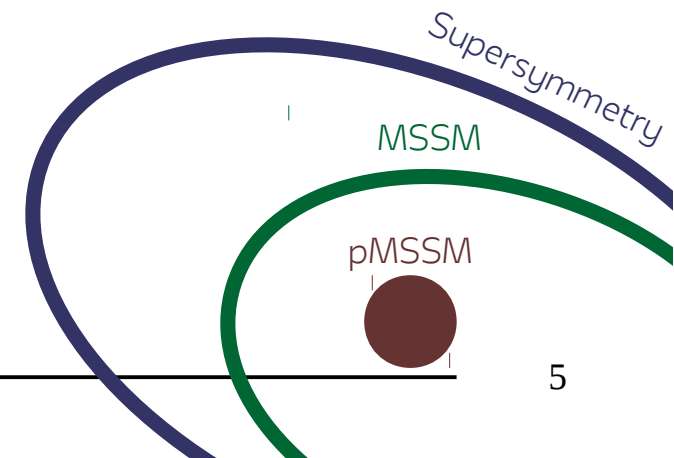
- EW measurements
- Collider constrains on mass (LEP, Tevatron)
- Dark Matter constrains ($\Omega_{\text{CDM}} h^2$ from Plank)

- Sparticles produced in *pairs*
- The lightest (LSP) is *stable* ($\tilde{\chi}_0^1$)

$$\tilde{\chi}_0^1 = N_{11} \tilde{B} + N_{12} \tilde{W}^0 + N_{13} \tilde{H}_d^0 + N_{14} \tilde{H}_u^0$$

No new \cancel{CP}

$$* P_R = (-1)^{3B+L+2s}$$

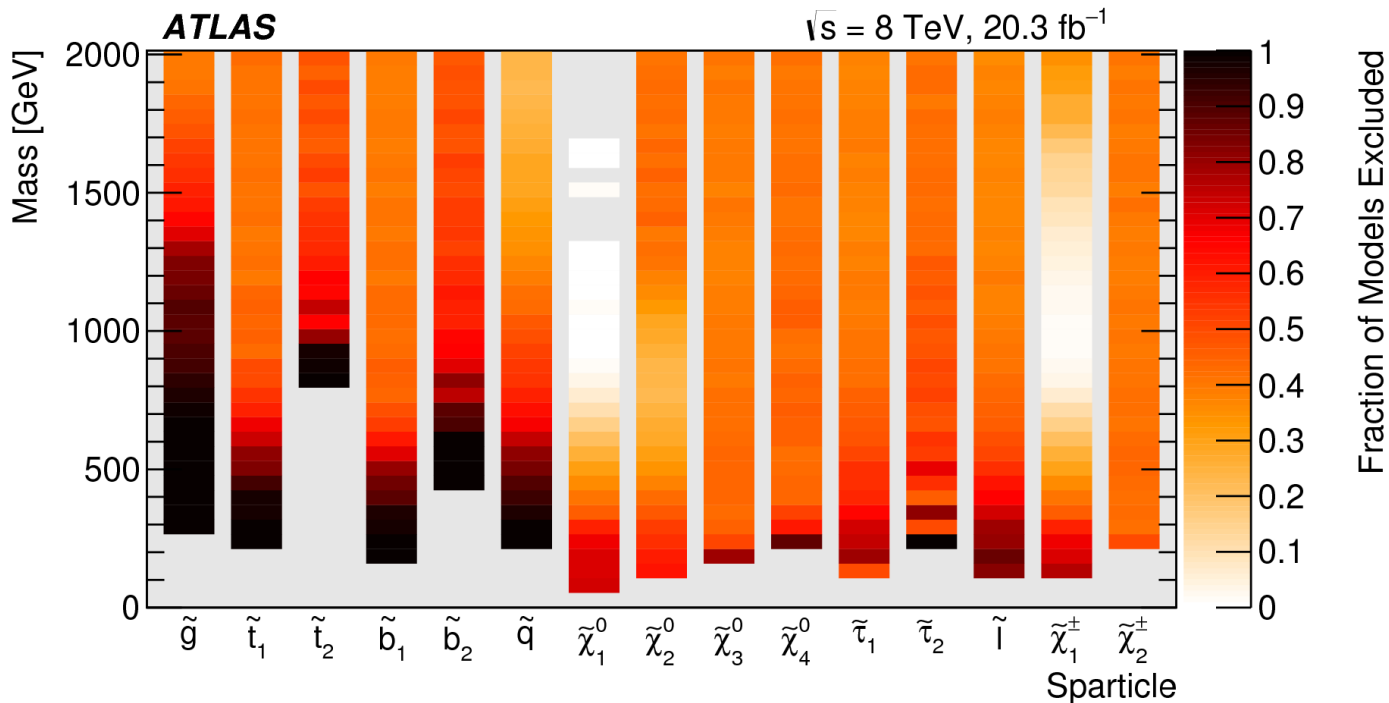


Where do we stand on pMSSM?

- After the assumptions, ATLAS generated >300k model-points
 - Random set of parameters selection
 - Interpreted by 22 Run I analyses

arXiv: 1508.06608

Search summary:



Inclusive

- 0-lepton + 2–6 jets + E_T^{miss}
- 0-lepton + 7–10 jets + E_T^{miss}
- 1-lepton + jets + E_T^{miss}
- $\tau(\tau/\ell) + \text{jets} + E_T^{\text{miss}}$
- SS/3-leptons + jets + E_T^{miss}
- 0/1-lepton + 3b-jets + E_T^{miss}
- Monojet

3rd generation

- 0-lepton stop
- 1-lepton stop
- 2-leptons stop
- Monojet stop
- Stop with Z boson
- 2b-jets + E_T^{miss}
- $t b + E_T^{\text{miss}}, \text{ stop}$

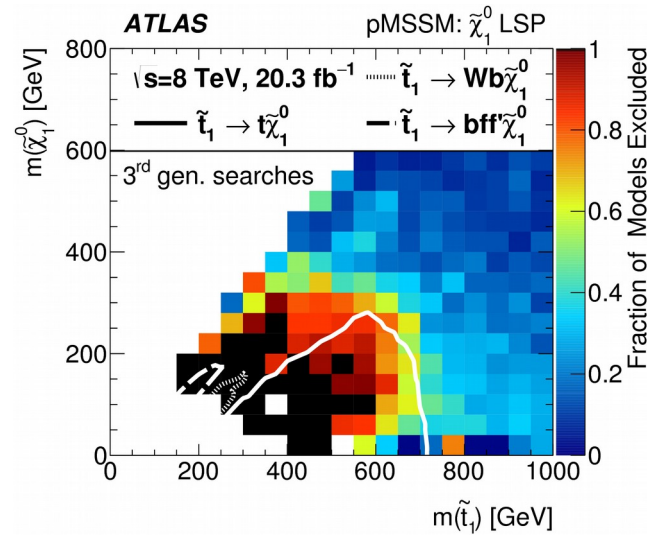
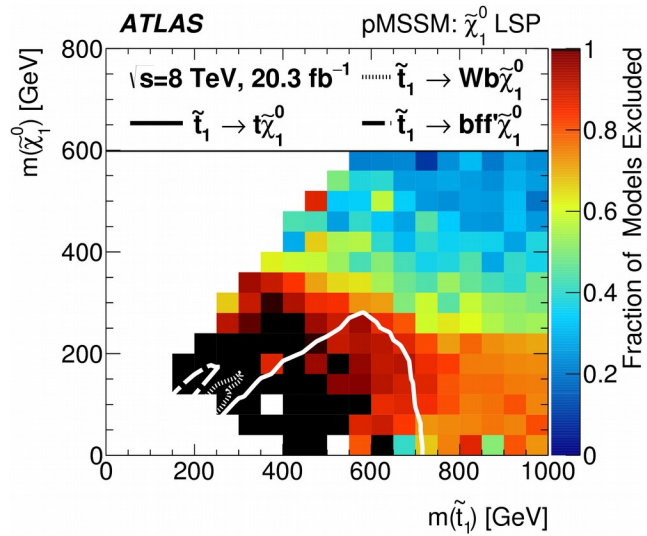
Electroweak

- ℓh
- 2-leptons
- 2- τ
- 3-leptons
- 4-leptons
- Disappearing Track

Other

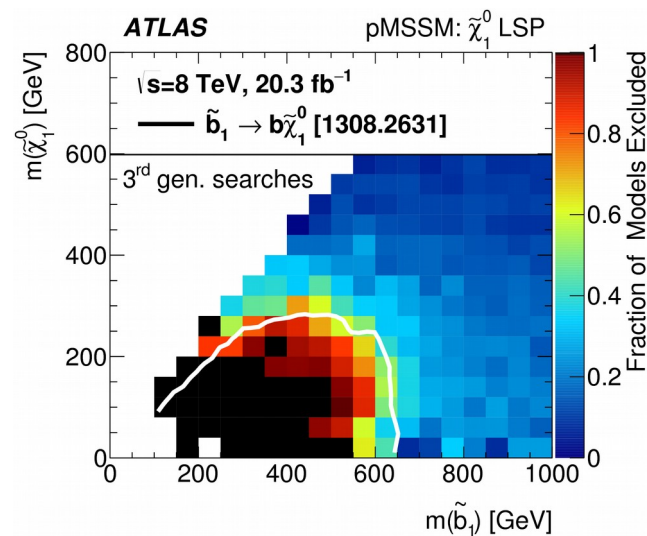
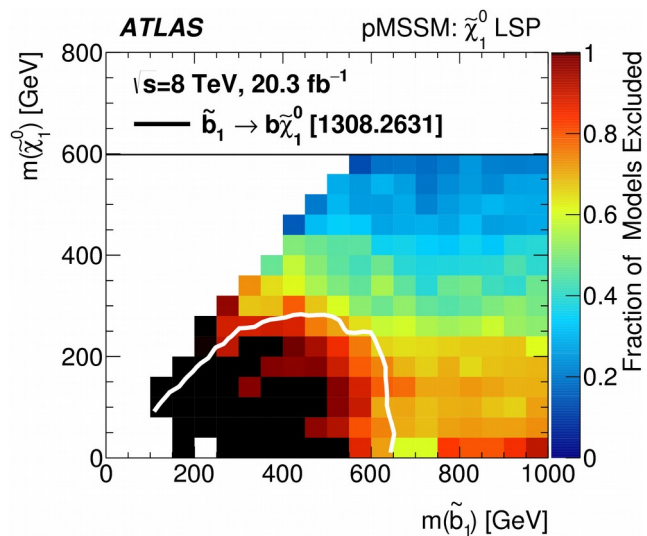
- Long-lived particles
- $H/A \rightarrow \tau^+ \tau^-$

3rd Generation on pMSSM



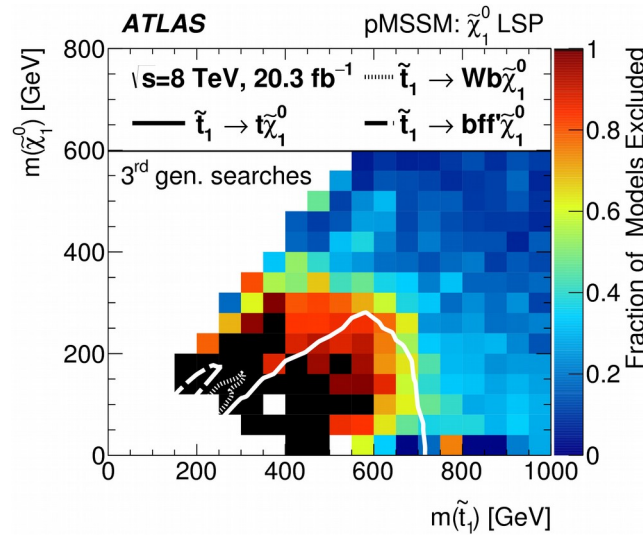
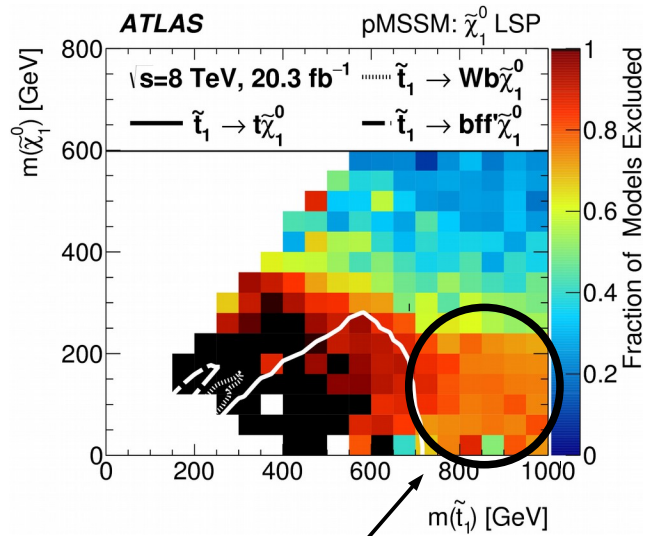
Most points excluded for **stop** mass below 600 GeV

Well captured sensitivity by simplified models



For **sbottom** this limit drops to 550 GeV

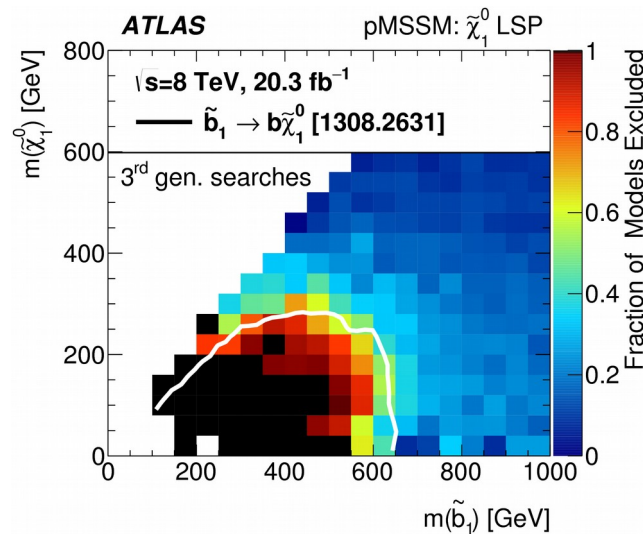
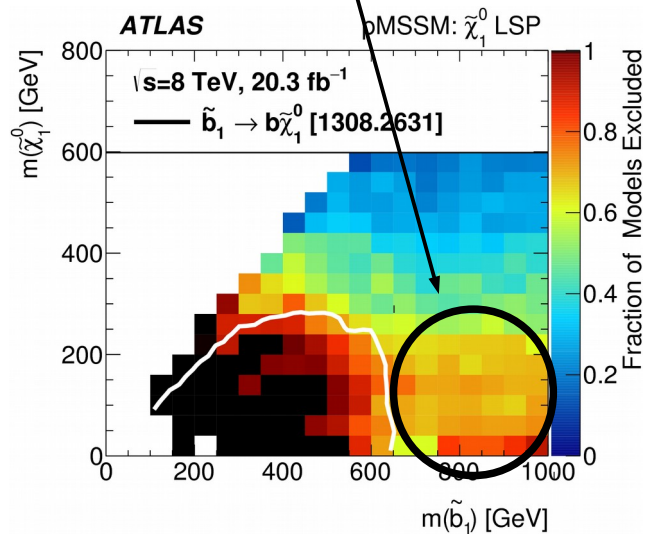
3rd Generation on pMSSM



Most points excluded for **stop** mass below 600 GeV

Disappearing Tracks from long-lived charginos searches

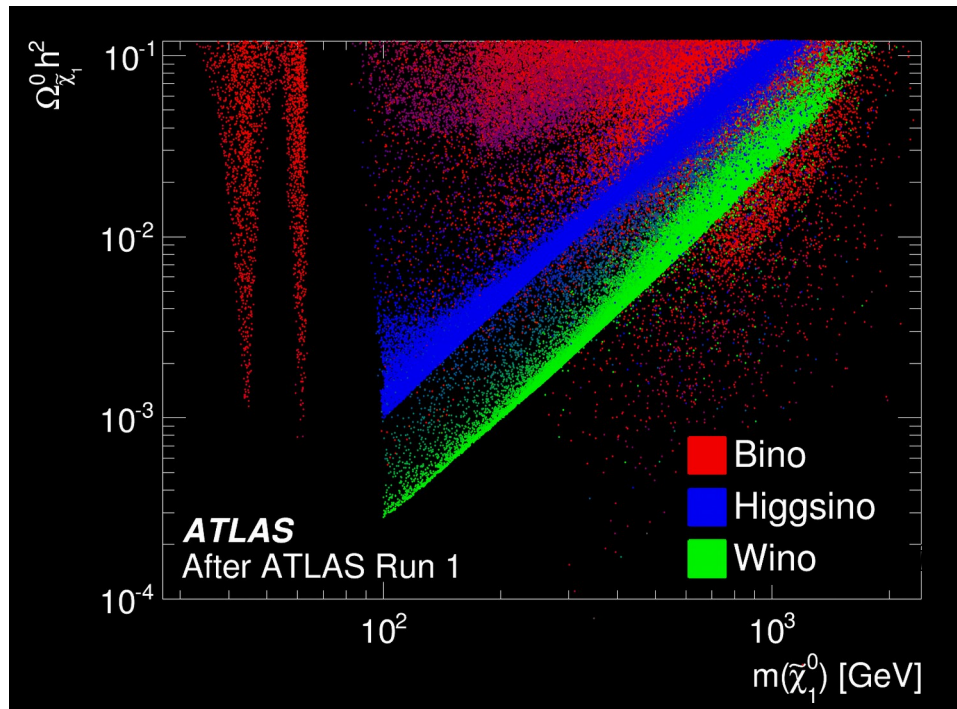
Cases with wino-like LSP and: $\Delta m(\tilde{\chi}_1^0, \tilde{\chi}_1^\pm) < 200$ GeV



For **sbottom** this limit drops to 550 GeV

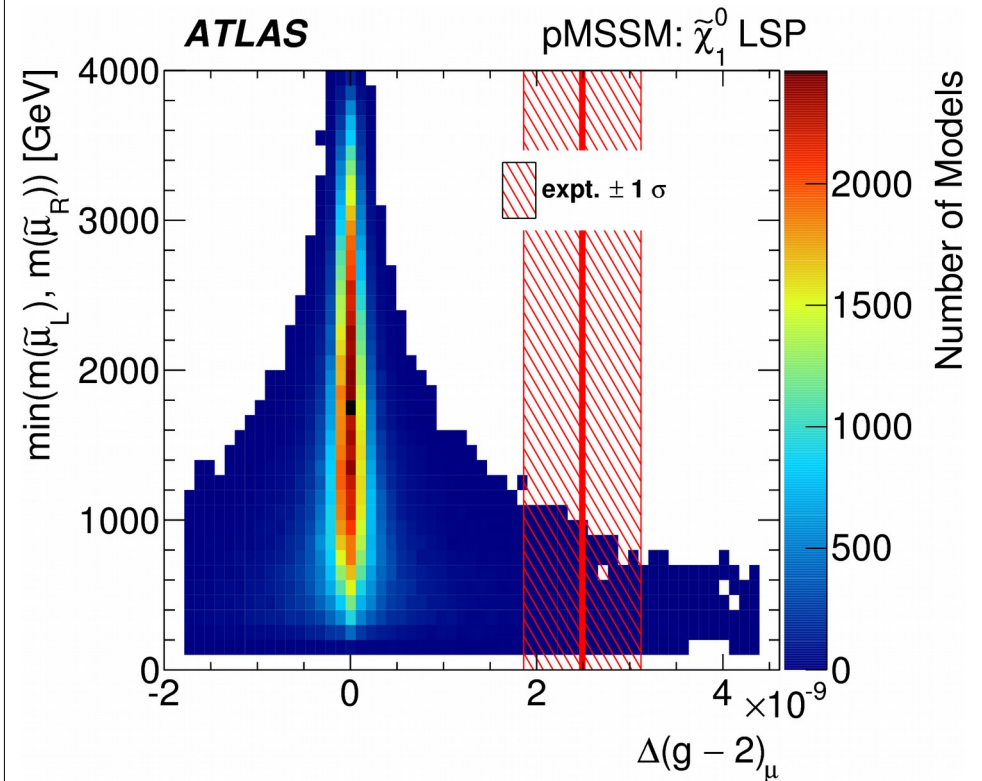
Dark Matter and other fancies

Z and h funnels: $\chi_1^0 \chi_1^0 \rightarrow Z \rightarrow SM$ predicts $m_\chi \approx m_Z/2 \sim 45$ GeV
 $\chi_1^0 \chi_1^0 \rightarrow h \rightarrow SM$ predicts $m_\chi \approx m_h/2 \sim 63$ GeV



Low mass \tilde{H} or \tilde{W} -like LSP predicts low mass NLSP ($\tilde{\chi}_1^\pm$)
 Excluded by **LEP**

Muon anomalous magnetic moment: 3.4σ tension with SM
 arXiv: hep-ph/0611102



- Generally small SUSY contribution
- Larger sensitivity on tails as lighter particles are predicted

Towards Run II

➤ Even with only 3.2 fb⁻¹ Run II was able to surpass important Run I limits

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2016

ATLAS Preliminary

√s = 7, 8, 13 TeV

Model	e, μ, τ, γ	Jets	E _T ^{miss}	[L dt(fb ⁻¹)	Mass limit		Reference			
					√s = 7, 8 TeV	√s = 13 TeV				
Inclusive Searches	MSUGRA/CMSSM	0-3 e, μ/1-2 τ	2-10 jets/3 b	Yes	20.3	\tilde{g}, \tilde{g}	1.85 TeV	m(\tilde{g})=m(\tilde{g})	1507.05525	
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	3.2	\tilde{q}	980 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1 st gen. \tilde{q})=m(2 nd gen. \tilde{q})	ATLAS-CONF-2015-062	
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	\tilde{q}	610 GeV	m(\tilde{q})-m($\tilde{\chi}_1^0$)<5 GeV	To appear	
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\ell(\ell/\nu)/\nu\tilde{\chi}_1^0$	2 e, μ (off-Z)	2 jets	Yes	20.3	\tilde{q}	820 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1503.03290	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	3.2	\tilde{g}	1.52 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2015-062	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0 \rightarrow qqW^\pm\tilde{\chi}_1^0$	1 e, μ	2-6 jets	Yes	3.3	\tilde{g}	1.6 TeV	m($\tilde{\chi}_1^0$)<350 GeV, m($\tilde{\chi}_2^0$)=0.5(m($\tilde{\chi}_1^0$))+m(\tilde{g})	ATLAS-CONF-2015-076	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\ell(\ell/\nu)/\nu\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20	\tilde{g}	1.38 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1501.03555	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0	7-10 jets	Yes	3.2	\tilde{g}	1.4 TeV	m($\tilde{\chi}_1^0$)=100 GeV	1502.06194	
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	\tilde{g}	1.63 TeV	tanβ > 20	1407.0603	
	GGM (bino NLSP)	2 γ	-	Yes	20.3	\tilde{g}	1.34 TeV	cτ(NLSP)<0.1 mm	1507.05493	
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	\tilde{g}	1.37 TeV	m($\tilde{\chi}_1^0$)<950 GeV, cτ(NLSP)<0.1 mm, μ<0	1507.05493	
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	\tilde{g}	1.3 TeV	m($\tilde{\chi}_1^0$)<850 GeV, cτ(NLSP)<0.1 mm, μ>0	1507.05493	
GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	\tilde{g}	900 GeV	m(NLSP)>430 GeV	1503.03290		
Gravitino LSP	0	mono-jet	Yes	20.3	F ^{1/2} scale	865 GeV	m(\tilde{G})>1.8 × 10 ⁻³ eV, m(\tilde{g})=m(\tilde{q})=1.5 TeV	1502.01518		
3rd gen. \tilde{g} med.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	3.3	\tilde{g}	1.78 TeV	m($\tilde{\chi}_1^0$)<800 GeV	ATLAS-CONF-2015-067	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	3.3	\tilde{g}	1.76 TeV	m($\tilde{\chi}_1^0$)=0 GeV	To appear	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	\tilde{g}	1.37 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600	
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	\tilde{b}_1	840 GeV	m($\tilde{\chi}_1^0$)<100 GeV	ATLAS-CONF-2015-066	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 b	Yes	3.2	\tilde{b}_1	325-540 GeV	m($\tilde{\chi}_1^0$)=50 GeV, m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_1^0$)+100 GeV	1602.09058	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	1-2 e, μ	1-2 b	Yes	4.7/20.3	\tilde{t}_1	117-170 GeV	m($\tilde{\chi}_1^0$)=2m($\tilde{\chi}_2^0$), m($\tilde{\chi}_2^0$)=55 GeV	1209.2102, 1407.0583	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3	\tilde{t}_1	90-198 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1508.08616, ATLAS-CONF-2016-007	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	\tilde{t}_1	90-245 GeV	m(\tilde{t}_1)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608	
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1	150-600 GeV	m($\tilde{\chi}_1^0$)<150 GeV	1403.5222	
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_2	290-610 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222	
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1 e, μ	6 jets + 2 b	Yes	20.3	\tilde{t}_2	320-620 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1506.08616	
EW direct	$\tilde{L}_R\tilde{L}_R, \tilde{L} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	\tilde{L}	90-335 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294	
	$\tilde{X}_1^+\tilde{X}_1^-, \tilde{X}_1^+ \rightarrow \tilde{\nu}(\tilde{\nu})$	2 e, μ	0	Yes	20.3	\tilde{X}_1^\pm	140-475 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m(\tilde{X}_1^\pm))+m($\tilde{\chi}_1^0$)	1403.5294	
	$\tilde{X}_1^+\tilde{X}_1^-, \tilde{X}_1^+ \rightarrow \tilde{\nu}(\tilde{\nu})$	3 e, μ	-	Yes	20.3	\tilde{X}_1^\pm	355 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m(\tilde{X}_1^\pm))+m($\tilde{\chi}_1^0$)	1407.0350	
	$\tilde{X}_1^+\tilde{X}_2^0 \rightarrow \tilde{\ell}_1\nu\tilde{\ell}_1(\tilde{\nu}\tilde{\nu}), \tilde{\ell}\tilde{\nu}\tilde{\ell}_1(\tilde{\nu}\tilde{\nu})$	3 e, μ	0	Yes	20.3	$\tilde{X}_1^\pm, \tilde{X}_2^0$	715 GeV	m($\tilde{\chi}_1^0$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_2^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m(\tilde{X}_1^\pm))+m($\tilde{\chi}_1^0$)	1402.7029	
	$\tilde{X}_1^+\tilde{X}_2^0 \rightarrow W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	20.3	$\tilde{X}_1^\pm, \tilde{X}_2^0$	425 GeV	m($\tilde{\chi}_1^0$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_2^0$)=0, sleptons decoupled	1403.5294, 1402.7029	
	$\tilde{X}_1^+\tilde{X}_2^0 \rightarrow W\tilde{\chi}_1^0h\tilde{\chi}_1^0, h \rightarrow b\tilde{b}/W/\tau/\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{X}_1^\pm, \tilde{X}_2^0$	270 GeV	m($\tilde{\chi}_1^0$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_2^0$)=0, sleptons decoupled	1501.07110	
	$\tilde{X}_2^+\tilde{X}_2^0 \rightarrow \tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	\tilde{X}_2^\pm	635 GeV	m($\tilde{\chi}_1^0$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_2^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m(\tilde{X}_2^\pm))+m($\tilde{\chi}_1^0$)	1405.5086	
	GGM (wino NLSP) weak prod.	1 e, μ + γ	-	Yes	20.3	\tilde{W}	115-370 GeV	cτ<1 mm	1507.05493	
	Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	1310.3675
		Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$	495 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^\pm$)<15 ns	1506.05332
Stable, stopped \tilde{g} R-hadron		0	1-5 jets	Yes	27.9	\tilde{g}	850 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ(\tilde{g})<1000 s	1310.6584	
Metastable \tilde{g} R-hadron		dE/dx trk	-	-	3.2	\tilde{g}	1.54 TeV	m($\tilde{\chi}_1^0$)=100 GeV, τ>10 ns	To appear	
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{\tau}, \tilde{\mu}) + \tau(e, \mu)$		1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	10<tanβ<50	1411.6795	
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$		2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	1<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542	
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow ee/\mu\mu/\mu\nu$		displ. ee/μμ/μν	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	7<cτ($\tilde{\chi}_1^0$)<740 mm, m(\tilde{g})=1.3 TeV	1504.05162	
GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	6<cτ($\tilde{\chi}_1^0$)<480 mm, m(\tilde{g})=1.1 TeV	1504.05162		
RPV	LFV $pp \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e\mu/\tau/\mu/\tau$	eμ, eτ, μτ	-	-	20.3	$\tilde{\nu}_e$	1.7 TeV	$\lambda_{111}^e=0.11, \lambda_{132}/\lambda_{33}/\lambda_{233}=0.07$	1503.0430	
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{q}, \tilde{g}	1.45 TeV	m(\tilde{q})=m(\tilde{g}), cτ _{LSP} <1 mm	1404.2500	
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow ee\nu_e, e\mu\nu_e$	4 e, μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$	760 GeV	m($\tilde{\chi}_1^\pm$)>0.2×m($\tilde{\chi}_1^0$), $\lambda_{121}\neq 0$	1405.5086	
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow \tau\tau\nu_e, e\tau\nu_e$	3 e, μ + τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$	450 GeV	m($\tilde{\chi}_1^\pm$)>0.2×m($\tilde{\chi}_1^0$), $\lambda_{133}\neq 0$	1405.5086	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{q}$	0	6-7 jets	-	20.3	\tilde{g}	917 GeV	BR(\tilde{g})=BR(\tilde{b})=BR(\tilde{c})=0%	1502.05686	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{q}$	0	6-7 jets	-	20.3	\tilde{g}	980 GeV	m($\tilde{\chi}_1^0$)=600 GeV	1502.05686	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}_1t_1, \tilde{t}_1 \rightarrow bs$	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{g}	880 GeV		1404.2500	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	0	2 jets + 2 b	-	20.3	\tilde{t}_1	320 GeV		1601.07453	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\ell$	2 e, μ	2 b	-	20.3	\tilde{t}_1	0.4-1.0 TeV	BR($\tilde{t}_1 \rightarrow b\ell/\mu$)>20%	ATLAS-CONF-2015-015		
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	\tilde{c}	510 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325	

*Only a selection of the available mass limits on new states or phenomena is shown.

10⁻¹

1

Mass scale [TeV]

Towards Run II

➤ Even with only 3.2 fb⁻¹ Run II was able to surpass important Run I limits

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2016

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13$ TeV

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit		Reference	
					$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV		
Inclusive Searches	MSUGRA/CMSSM	0-3 e, μ /1-2 τ	2-10 jets/3 b	Yes	20.3	\tilde{g}, \tilde{g} 1.85 TeV	$m(\tilde{g})=m(\tilde{g})$	
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	3.2	\tilde{q} 980 GeV	$m(\tilde{q})=0$ GeV, $m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$	
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	\tilde{q} 610 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0)<5$ GeV	
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q(\ell\ell)(\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ (off-Z)	2 jets	Yes	20.3	\tilde{q} 820 GeV	$m(\tilde{q})=0$ GeV	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	3.2	\tilde{g} 1.52 TeV	$m(\tilde{q})=0$ GeV	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0 \rightarrow qqW^\pm\tilde{\chi}_1^0$	1 e, μ	2-6 jets	Yes	3.3	\tilde{g} 1.6 TeV	$m(\tilde{q})<350$ GeV, $m(\tilde{\chi}_1^0)=0.5(m(\tilde{q})+m(\tilde{g}))$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20	\tilde{g} 1.38 TeV	$m(\tilde{q})=0$ GeV	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0	7-10 jets	Yes	3.2	\tilde{g} 1.4 TeV	$m(\tilde{q})=100$ GeV	
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	\tilde{g} 1.63 TeV	$\tan\beta > 20$	
	GGM (bino NLSP)	2 γ	-	Yes	20.3	\tilde{g} 1.34 TeV	$c\tau(\text{NLSP})<0.1$ mm	
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	\tilde{g} 1.37 TeV	$m(\tilde{q})<950$ GeV, $c\tau(\text{NLSP})<0.1$ mm, $\mu<0$	
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	\tilde{g} 1.3 TeV	$m(\tilde{q})<850$ GeV, $c\tau(\text{NLSP})<0.1$ mm, $\mu>0$	
	GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	\tilde{g} 900 GeV	$m(\text{NLSP})>430$ GeV	
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8 \times 10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})=1.5$ TeV	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	3 jets	Yes	3.3	\tilde{g} 1.78 TeV	$m(\tilde{q})<800$ GeV	
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	3.3	\tilde{g} 1.76 TeV	$m(\tilde{q})=0$ GeV		
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	\tilde{g} 1.37 TeV	$m(\tilde{q})<300$ GeV		
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	\tilde{b}_1 840 GeV	$m(\tilde{\chi}_1^0)<100$ GeV		
3 rd gen. squarks direct prod.	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	0-2 e, μ	1-2 b	Yes	4.7/20.3	\tilde{t}_1 17-170 GeV	$m(\tilde{t}_1)<30$ GeV, $m(\tilde{t}_2)<100$ GeV	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3	\tilde{t}_1 90-198 GeV	$m(\tilde{t}_1)=2m(\tilde{\chi}_1^0), m(\tilde{t}_2)=55$ GeV	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	\tilde{t}_1 90-245 GeV	$m(\tilde{t}_1)=1$ GeV	
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1 150-600 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)<85$ GeV	
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_2 290-610 GeV	$m(\tilde{t}_1)>150$ GeV	
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1 e, μ	6 jets + 2 b	Yes	20.3	\tilde{t}_2 320-620 GeV	$m(\tilde{t}_1)<200$ GeV	
	$\tilde{t}_1\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1 e, μ	6 jets + 2 b	Yes	20.3	\tilde{t}_2 320-620 GeV	$m(\tilde{t}_1)=0$ GeV	
	$\tilde{t}_1\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1 e, μ	6 jets + 2 b	Yes	20.3	\tilde{t}_2 320-620 GeV	$m(\tilde{t}_1)=0$ GeV	
EW direct	$\tilde{L}_R\tilde{L}_R, \tilde{L} \rightarrow \tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	\tilde{L} 90-335 GeV	$m(\tilde{L})=0$ GeV	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0(\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-475 GeV	$m(\tilde{L})=0$ GeV, $m(\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\nu}(\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 355 GeV	$m(\tilde{L})=0$ GeV, $m(\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow \tilde{L}_R\tilde{\nu}_L(\tilde{\nu})$	3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 715 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^\pm)=0, m(\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 425 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^\pm)=0, \text{sleptons decoupled}$	
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0h\tilde{\chi}_1^0, h \rightarrow b\tilde{b}/W/\tau/\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 270 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^\pm)=0, \text{sleptons decoupled}$	
	$\tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \tilde{L}_R\tilde{\ell}$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_2^0$ 635 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	
	GGM (wino NLSP) weak prod.	1 $e, \mu + \gamma$	-	Yes	20.3	\tilde{W} 115-370 GeV	$c\tau<1$ mm	
	Long-lived particles	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)\sim 160$ MeV, $\tau(\tilde{\chi}_1^\pm)=0.2$ ns
		Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$ 495 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)\sim 160$ MeV, $\tau(\tilde{\chi}_1^\pm)<15$ ns
Stable, stopped \tilde{g} R-hadron		0	1-5 jets	Yes	27.9	\tilde{g} 850 GeV	$m(\tilde{g})=100$ GeV, $10 \mu\text{s}<\tau(\tilde{g})<1000$ s	
Metastable \tilde{g} R-hadron		dE/dx trk	-	-	3.2	\tilde{g} 1.54 TeV	$m(\tilde{g})=100$ GeV, $\tau>10$ ns	
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$		1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	$10<\tan\beta<50$	
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma G$, long-lived $\tilde{\chi}_1^0$		2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 440 GeV	$1<\tau(\tilde{\chi}_1^0)<3$ ns, SPS8 model	
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow ee/\mu\mu/\mu\nu$		displ. $ee/\mu\mu/\mu\nu$	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	$7<c\tau(\tilde{\chi}_1^0)<740$ mm, $m(\tilde{g})=1.3$ TeV	
GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow ZG$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	$6<c\tau(\tilde{\chi}_1^0)<480$ mm, $m(\tilde{g})=1.1$ TeV		
RPV	LFV $pp \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e\mu/\tau/\mu/\tau$	$e\mu, e\tau, \mu\tau$	-	-	20.3	$\tilde{\nu}_e$ 1.7 TeV	$\lambda_{111}^e=0.11, \lambda_{132}/\lambda_{33}/\lambda_{233}=0.07$	
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{q}, \tilde{g} 1.45 TeV	$m(\tilde{g})=m(\tilde{g}), c\tau_{LSP}<1$ mm	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow ee\nu_e, e\mu\nu_e$	4 e, μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 760 GeV	$m(\tilde{\chi}_1^\pm)>0.2 \times m(\tilde{\chi}_1^0), \lambda_{121}\neq 0$	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow \tau\tau\nu_e, e\tau\nu_e$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^\pm)>0.2 \times m(\tilde{\chi}_1^0), \lambda_{133}\neq 0$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{q}$	0	6-7 jets	-	20.3	\tilde{g} 917 GeV	$BR(\tilde{g})=BR(\tilde{b})=BR(\tilde{c})=0\%$	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{q}, \tilde{\chi}_1^0 \rightarrow qq\tilde{q}$	0	6-7 jets	-	20.3	\tilde{g} 980 GeV	$m(\tilde{q})=600$ GeV	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{g} 880 GeV		
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	0	2 jets + 2 b	-	20.3	\tilde{t}_1 320 GeV		
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\ell$	2 e, μ	2 b	-	20.3	\tilde{t}_1 0.4-1.0 TeV	$BR(\tilde{t}_1 \rightarrow b\ell/\mu)>20\%$		
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	\tilde{c} 510 GeV	$m(\tilde{\chi}_1^0)<200$ GeV	

*Only a selection of the available mass limits on new states or phenomena is shown.

10⁻¹

1

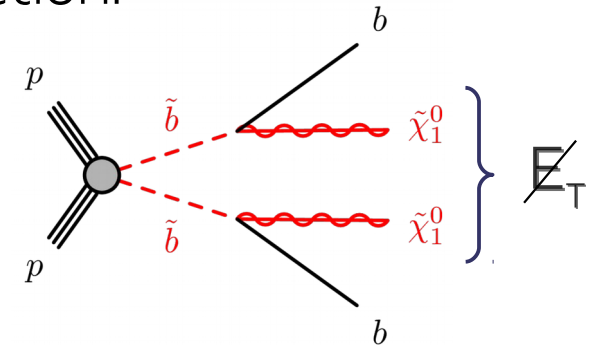
Mass scale [TeV]

Run II analysis review follows:

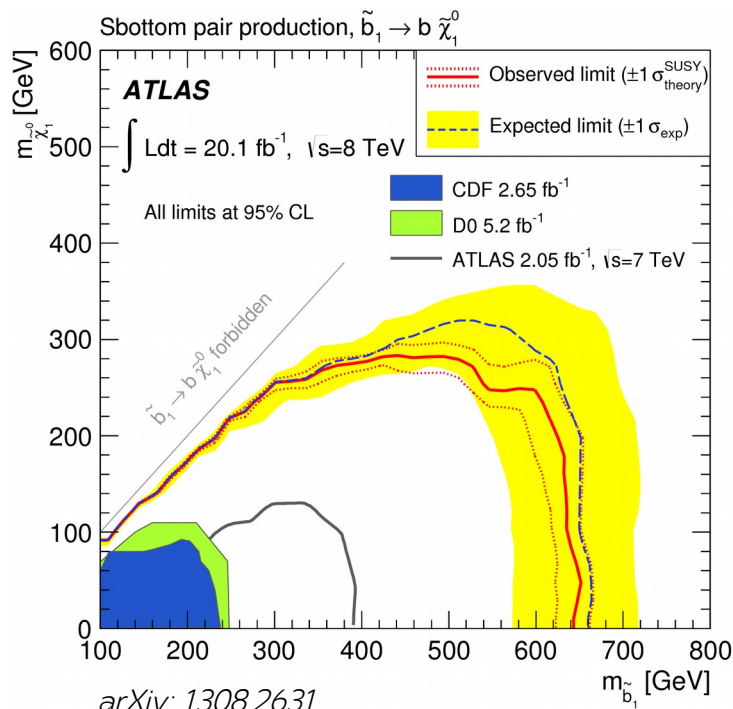
Overview (ATLAS-CONF-2015-066)

➤ Search for direct scalar bottom quark pair production:

- Final state consist of 2 b-jets and large missing transverse momentum



Analysis based on Run I strategy, targeting the exclusion of large sbottom masses

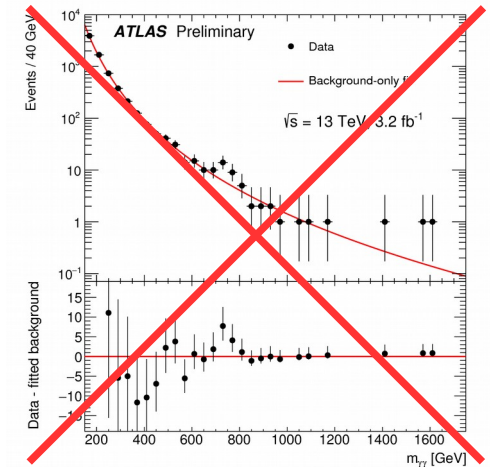


➤ Run II analysis sensitivity gain by E_{CMS} , 8 → 13 TeV:

- Signal $\sigma_{\tilde{b}}(800 GeV)$ increase by factor of ~10
- Major background $\sigma_{Z+ Jets}$ increase by factor of ~2

Analysis Strategy

- The decay products manifest themselves as E_T^{miss}
 - Invariant mass reconstruction impossible
- Simple and robust *Cut 'n' Count* approach employed



1 Define Signal Regions based on a model

- Aiming to reduce background – Discriminating variables used
- Optimized to provide maximum discovery significance

2 Define Control Regions each targeting a specific background

- Normalize the MC prediction to match the yield
- Extrapolate the normalization factors using a combined likelihood fit

3 Validation Regions to verify the prediction

- Intermediate step between CR and SR
- Kinematically close but orthogonal to SR

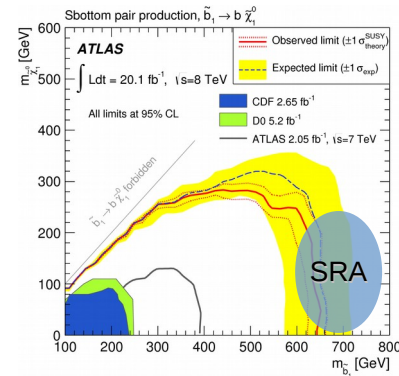
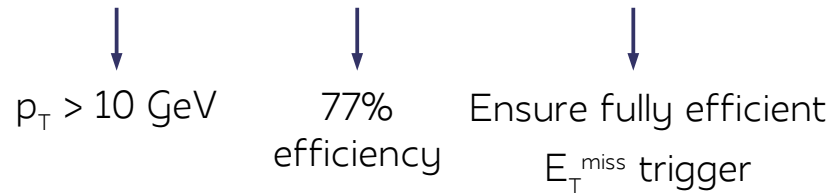
4 Open Pandora's box

- Compare the yield in SR with the SM prediction
- If no excess observed, derive exclusion limits on the model

Signal Region A – Bulk Region

➤ Class of regions targeting large mass splitting between \tilde{b} and $\tilde{\chi}_1^0$

➤ Containing: 0 leptons, 2 b-jets, large E_T^{miss}



➤ Main discriminating variable, contranverse mass:

- For the decay of two identical massive particles to two visible (v_1, v_2) and two invisible: $m_{CT}^2(v_1, v_2) = [E_T(v_1) + E_T(v_2)]^2 - [\mathbf{p}_T(v_1) - \mathbf{p}_T(v_2)]^2$
- Kinematic end-point for $t\bar{t}$ $m_{CT} = 135 \text{ GeV}$

Event Selection

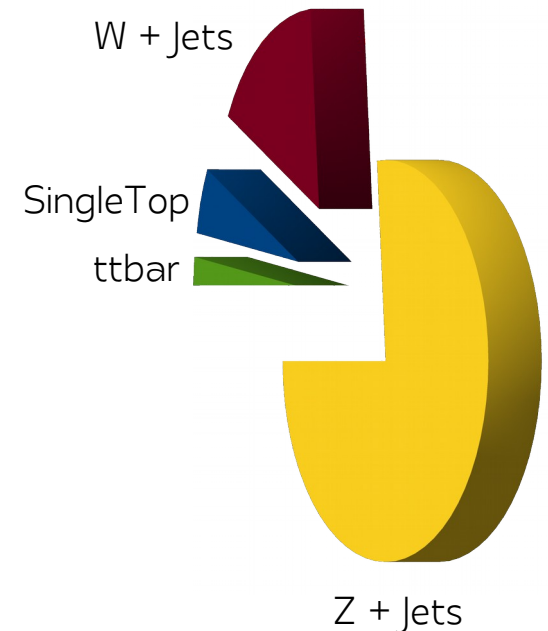
SRA250	SRA350	SRA450
No baseline electron or muon		
Leading (in p_T) two jets b -tagged		
$p_T > 130 \text{ GeV}$ for the leading jet		
$m_{bb} > 200 \text{ GeV}$		
$E_T^{\text{miss}} > 250 \text{ GeV}$		
Veto on 4 th jet with $p_T > 50 \text{ GeV}$		
$m_{CT} > 250 \text{ GeV}$	$m_{CT} > 350 \text{ GeV}$	$m_{CT} > 450 \text{ GeV}$

+ Multijet “killers”

• $\Delta\phi(j_1, E_T^{\text{miss}}) > 0.4$

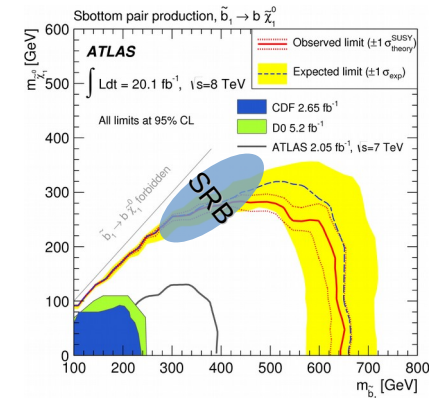
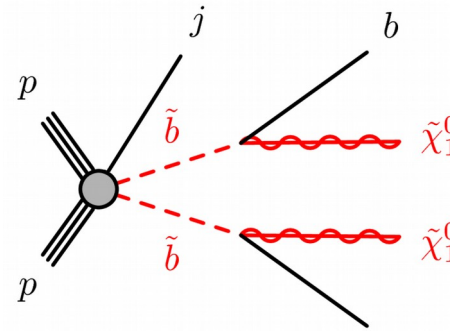
• $E_T^{\text{miss}} / m_{\text{eff}} > 0.25$

Major Backgrounds



Signal Region B – Compressed Scenarios

- Scenarios with small mass splitting between \tilde{b} and $\tilde{\chi}_1^0$ lead to softer b-jets, SRA is no more sensitive
- Initial State Radiation recoiling against the sbottom system exploited to discriminate the potential signal
- Containing a high- p_T non-b-tagged jet, large E_T^{miss} and additional b-jets

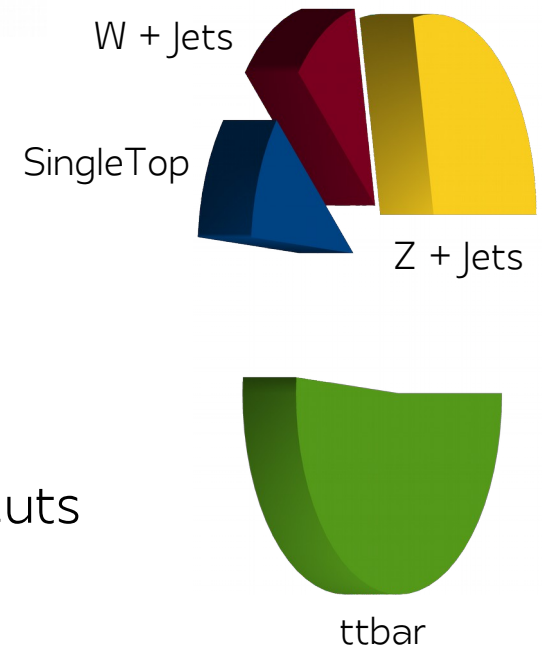


Event Selection

Lepton selection	No baseline electron or muon
Leading- p_T jet	not b -tagged, $p_T > 300$ GeV
SubLeading- p_T jet	b -tagged
$\Delta\phi(1^{\text{st}} \text{ jet}, E_T^{\text{miss}})$	> 2.5
JetVeto	$p_T(4^{\text{th}} \text{ jet}) < 50$ GeV
E_T^{miss}	> 400 GeV

+ same Multijet cuts

Major Backgrounds



Control Regions

- Dedicated Control Regions for each dominant background
- Due to kinematics, different CRs correspond to each SR type
 - **SRA:** Z+Jets, W+Jets, SingleTop, ttbar – **SRB:** ttbar, Z+Jets
- The rest of them are calculated using pure MC prediction

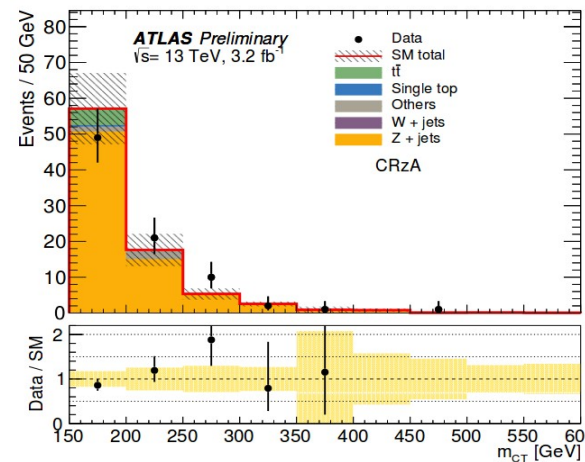
*Alternative estimation:
Data-driven using Υ +Jets
events*

CRAs

2Leptons

CRz

- SFOS leptons, $p_T^{\parallel} > 100$ GeV
- Z mass window
- $E_T^{\text{miss}} < 100$ GeV



CRBs

CRz

- SFOS leptons, $p_T^{\parallel} > 100$ GeV
- Z mass window
- $E_T^{\text{miss}} < 70$ GeV

1Lepton

CRtt

- $m_{bb} < 200$ GeV
- $E_T^{\text{miss}} > 100$ GeV

CRst

- $m_{bb} > 200$ GeV
- $E_T^{\text{miss}} > 100$ GeV

CRw

- 1 b-tagged jet
- $m_{bj} > 200$ GeV
- $E_T^{\text{miss}} > 100$ GeV

CRtt

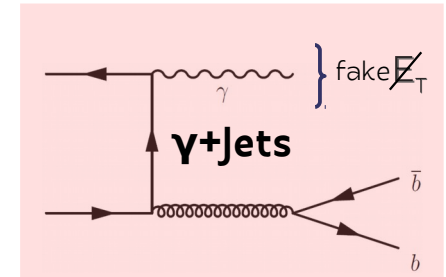
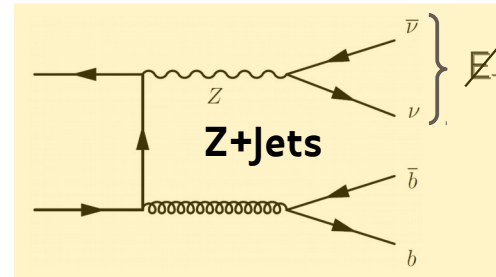
- $E_T^{\text{miss}} > 200$ GeV

Alternatively: Z from Photons

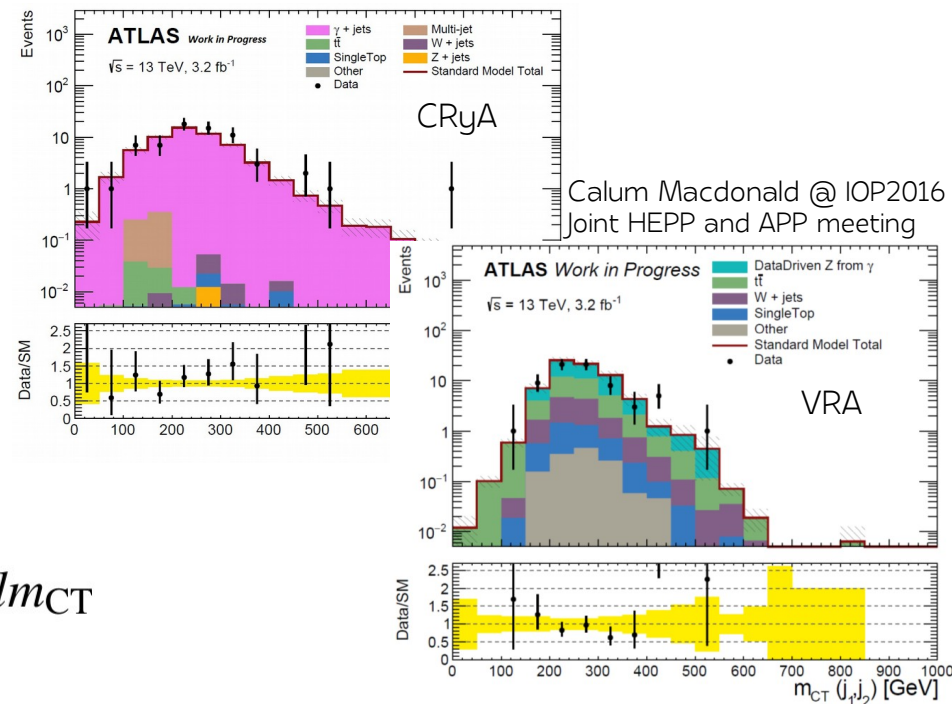
- Data-driven technique developed for cross-checking purposes
 - Exploiting the similar properties of the vector bosons Z and γ

- Photons mimic the $Z \rightarrow \nu\nu$ decays:

faking E_T^{miss} by vectorially adding the photon to real E_T^{miss}



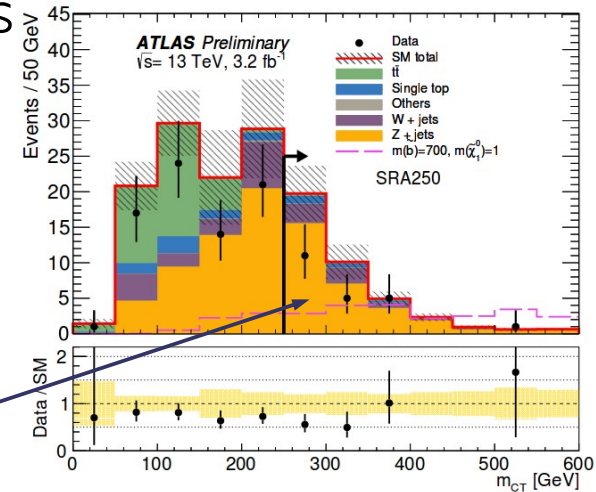
- Yield is measured in photon dominated CR
- Re-weighted, using simulations, to account for Z and γ mass difference
- Corrected for any MC miss-modeling using $Z \rightarrow \ell\ell$ events



$$N_{\text{SR}}^{Z\nu\nu} = \int_X \left(\underbrace{f_{\text{CR}\gamma}^{\text{data}}}_{\text{green}} - \underbrace{f_{\text{CR}\gamma}^{\text{non-}\gamma \text{ MC}}}_{\text{red}} \right) \cdot \underbrace{\frac{1}{K}}_{\text{yellow}} \cdot R_{Z/\gamma}(p_T(\gamma)) dm_{\text{CT}}$$

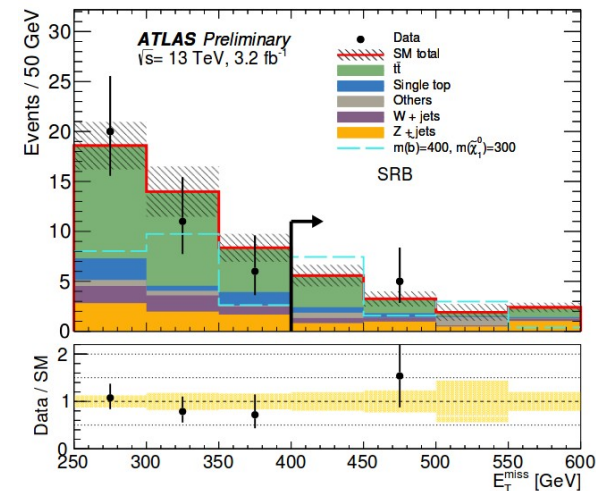
Results

- The observed number of events in each CR is used in a combined likelihood fit to determine the SM background in SRs
- Dominant sources of systematic uncertainties:
 - Experimental: JES (SRA), JER (SRB), b-tagging (both)
 - Theoretical: Z+Jets (25-50% of the total SRA unc.), $t\bar{t}$ (~70% of the total SRB unc.)



Resulted Yields

Signal region channels	SRA250	SRA350	SRA450	SRB
Observed events	22	6	1	5
Fitted bkg events	40 ± 8	9.5 ± 2.6	2.2 ± 0.6	13.1 ± 3.2
Fitted $t\bar{t}$ events	0.9 ± 0.4	0.37 ± 0.16	0.06 ± 0.03	5.9 ± 2.4
Fitted single top events	2.1 ± 1.3	0.54 ± 0.37	0.15 ± 0.10	1.2 ± 0.8
Fitted W+jets events	6.3 ± 2.4	1.3 ± 0.6	0.41 ± 0.23	1.2 ± 0.6
Fitted Z+jets events	30 ± 7	7.1 ± 2.4	1.5 ± 0.5	3.3 ± 1.4
Fitted "Other" events	0.7 ± 0.6	0.1 ± 0.1	0.02 ± 0.02	1.4 ± 0.4



No excess observed

Interpretation

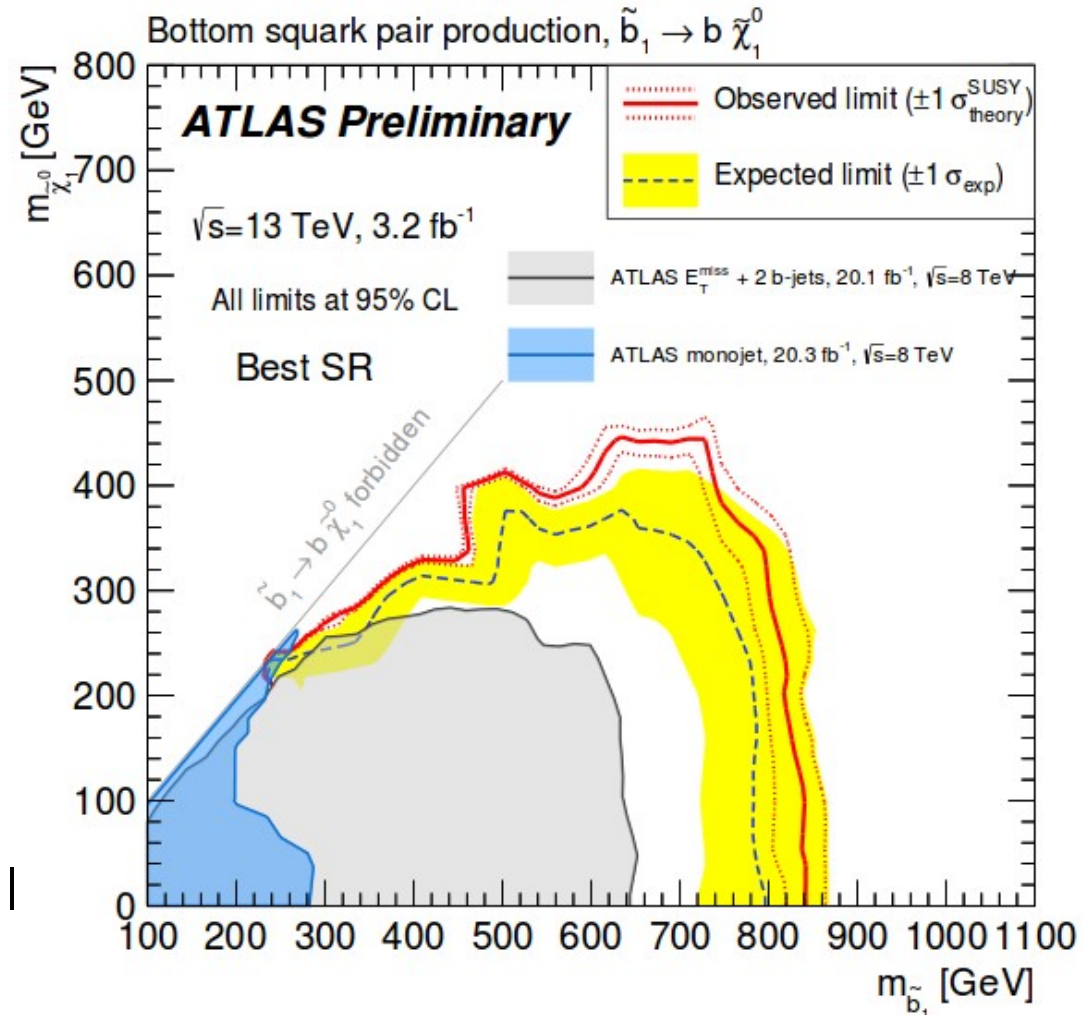
➤ The results are used to place exclusion limits at 95% CL on the supersymmetric mass plane

➤ Simplified model used:

- Only the sbottom quark and the LSP are kinematically accessible
- $BR(\tilde{b} \rightarrow b + \tilde{\chi}_1^0) = 1$

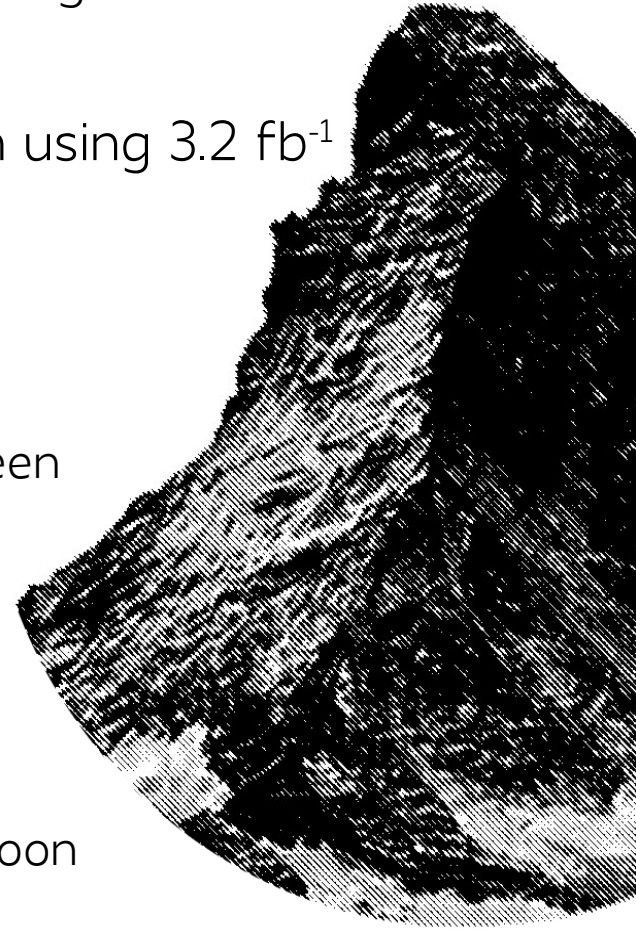
➤ Limit on sbottom mass stands at 800-840 GeV

➤ Almost 200 GeV higher than Run I



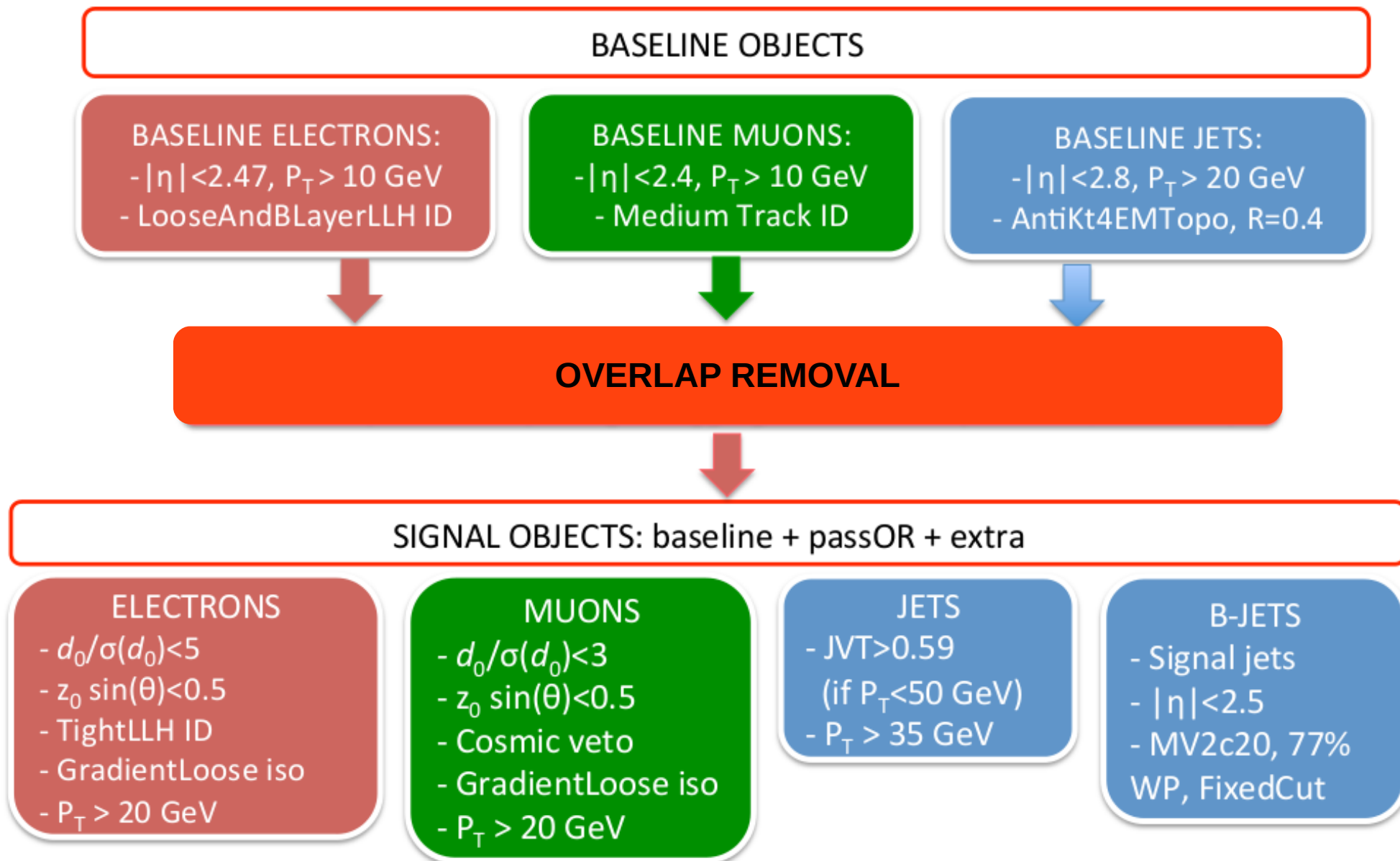
Conclusions

- Impact of ATLAS Run I searches on pMSSM
 - Few models with 3rd generation squarks lighter than 550-600 GeV remain
- Run II searches for direct bottom squark pair production using 3.2 fb⁻¹
 - Final states containing 2 b-jets and E_T^{miss}
 - A *cut'n'count* analysis shows no excess above expected background → exclusion limits on a simplified model have been placed
 - \tilde{b} masses up to 840 GeV have been excluded for $\tilde{\chi}_1^0$ masses below 100 GeV
 - New paper investigating the SRA deficit is being published soon



Backup Slides

Object Definitions



Signal Regions

Variable	SRA	SRB
Event cleaning	Common to all SR	
Lepton veto	No e/μ with $p_T > 10$ GeV after overlap removal	
E_T^{miss}	> 250 GeV	> 400 GeV
Leading jet $p_T(j_1)$	> 130 GeV	> 300 GeV
2nd jet $p_T(j_2)$	> 50 GeV	> 50 GeV
Fourth jet $p_T(j_4)$	vetoed if > 50 GeV	
$\Delta\phi_{\text{min}}^j$	> 0.4	> 0.4
$\Delta\phi(j_1,)$	-	> 2.5
b -tagging	j_1 and j_2	j_2 and (j_3 or j_4)
$E_T^{\text{miss}}/m_{\text{eff}}$	> 0.25	> 0.25
m_{CT}	$> 250, 350, 450$ GeV	-
m_{bb}	> 200 GeV	-

VRB ←

$250 < E_T^{\text{miss}} < 300$

VRmctA ←

VRmbbA ←

Control Regions

Variable	CRzA	CRttA	CRstA	CRwA	CRzB	CRttB
Number of lep.	2 SFOS	1	1	1	2 SFOS	1
Lead. lep. p_T [GeV]	> 26	> 26	> 26	> 26	> 26	> 26
2nd lep. p_T [GeV]	> 20	-	-	-	> 20	-
$m_{\ell\ell}$ [GeV]	[76 – 106]	-	-	-	[76 – 106]	-
m_T [GeV]	-	-	-	> 30	-	-
Lead. jet $p_T(j_1)$ [GeV]	-	> 130	-	> 130	50	130
4th jet $p_T(j_4)$			vetoed if > 50 GeV			
b -tagged jets	j_1 and j_2	j_1 and j_2	j_1 and j_2	j_1	j_2 and (j_3 or j_4)	j_2 and (j_3 or j_4)
E_T^{miss} [GeV]	< 100	> 100	> 100	> 100	< 70	> 200
$E_T^{\text{miss,cor}}$ [GeV]	> 100	-	-	-	> 100	-
m_{bb} [GeV]	-	< 200	> 200	(m_{bj}) > 200	-	-
m_{CT} [GeV]	> 150	> 150	> 150	> 150	-	-
$m_{b\ell}^{\text{min}}$ [GeV]	-	-	> 170	-	-	-
$\Delta\phi(j_1, E_T^{\text{miss}})$	-	-	-	-	> 2.0	> 2.5
Observed events	84	255	54	540	55	181
Fitted bkg events	84 ± 9	255 ± 16	54 ± 7	540 ± 23	55 ± 7	181 ± 13
Fitted $t\bar{t}$ events	4.7 ± 1.4	169 ± 25	8.3 ± 3.8	123 ± 29	14 ± 4	150 ± 15
Fitted single top events	0.4 ± 0.4	27 ± 13	22 ± 8	49 ± 25	0.4 ± 0.2	16.8 ± 2.9
Fitted W +jets events	-	52 ± 17	23 ± 6	350 ± 47	-	12.6 ± 4.9
Fitted Z +jets events	75 ± 9	2.3 ± 0.5	-	5.0 ± 1.6	41 ± 8	0.3 ± 0.1
Fitted “Other” events	3.6 ± 1.3	4.4 ± 0.9	0.8 ± 0.4	11.7 ± 2.1	-	1.3 ± 0.6
MC exp. SM events	54	283	56	491	49	196
MC exp. $t\bar{t}$ events	5.7	204	10	148	15	166
MC exp. single top events	0.5	34	28	62	0.4	17
MC exp. W +jets events	-	40	17	266	-	12.6
MC exp. Z +jets events	45	1.4	-	3.0	33	0.2
MC exp. “Other” events	3.6	4.4	0.8	11.7	-	1.3

Alternative Z+Jets from γ +Jets

- 1 Define high-purity photon regions to emulate SRs and VRs:

		CR γ Ax <i>SRAx emulation</i>	CR γ A-mbb <i>VRAmbb emulation</i>	CR γ B <i>SRB emulation</i>
Pre-selection		✓	✓	✓
Trigger		HLT_g120_loose	HLT_g120_loose	HLT_g120_loose
Photons		1 signal	1 signal	1 signal
Leading photon	GeV	> 130	> 130	> 130
Leptons (e or μ)		0 baseline	0 baseline	0 baseline
Leading jet p_T	GeV	> 130	> 130	> 300
$(E_T^{\text{miss}})^\gamma$	GeV	> 250	> 250	> 400
m_{bb}	GeV	> 200	< 200	-
m_{CT}	GeV	> x	> 150	-
b -jets (MV2c20 77%)		(1,2)	(1,2)	(2,3) or (2,4)

* The emulation of VRAmct is made with CR γ Ax; $x = 0$; with an upper cut on $m_{CT} < 150$.

- 2 Reweight P_γ^T to P_Z^T to correct Z mass effects :

$$R_{Z/\gamma} dp_T(B) = \frac{f_{\text{SR}}^{Z\nu\nu+\text{jets MC}} dp_T(\text{truth } B)}{f_{\text{CR}\gamma}^{\gamma+\text{jets MC}} dp_T(\text{reco } B)}$$

- Final computation of the expected Z events in SRs (and VRs):

$$N_{\text{SRAx}}^{Z\nu\nu} = \int_x^\infty (f_{\text{CR}\gamma\text{A}}^{\text{data}} - f_{\text{CR}\gamma\text{A}}^{\text{non-}\gamma \text{ MC}}) \cdot \frac{1}{K} \cdot R_{Z/\gamma}(p_T(\gamma)) dm_{CT}$$

$$N_{\text{SRB}}^{Z\nu\nu} = \int_0^\infty (f_{\text{CR}\gamma\text{B}}^{\text{data}} - f_{\text{CR}\gamma\text{B}}^{\text{non-}\gamma \text{ MC}}) \cdot \frac{1}{K} \cdot R_{Z/\gamma}(p_T(\gamma)) dm_{CT}$$

- 3 Define an additional κ -factor based on loose CRs to measure the γ -Z normalisation:

$$\kappa = \frac{\mu_{\gamma,\text{loose}}}{\mu_{Z,\text{loose}}} = \frac{N_{\text{CR}\gamma\text{L}}^{\gamma+\text{jets,data}}}{N_{\text{CRZL}}^{Z+\text{jets,data}}} \cdot \frac{N_{\text{CRZL}}^{Z+\text{jets,MC}}}{N_{\text{CR}\gamma\text{L}}^{\gamma+\text{jets,MC}}} = \frac{N_{\text{CR}\gamma\text{L}}^{\text{data}} - N_{\text{CR}\gamma\text{L}}^{\text{non-}\gamma \text{ MC}}}{N_{\text{CRZL}}^{\text{data}} - N_{\text{CRZL}}^{\text{non-Z MC}}} \cdot \frac{N_{\text{CRZL}}^{Z+\text{jets,MC}}}{N_{\text{CR}\gamma\text{L}}^{\gamma+\text{jets,MC}}}$$

Model Independent Limits

Table 5: Left to right: 95% CL upper limits on the visible cross-section ($\langle \epsilon A \sigma \rangle_{\text{obs}}^{95}$) and on the number of signal events (S_{obs}^{95}). The third column (S_{exp}^{95}) shows the 95% CL upper limit on the number of signal events, given the expected number (and $\pm 1\sigma$ excursions on the expectation) of background events.

Signal channel	$\langle \epsilon A \sigma \rangle_{\text{obs}}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}
SRA250	2.74	8.8	$15.8^{+6.3}_{-4.4}$
SRA350	1.90	6.1	$8.1^{+3.7}_{-2.3}$
SRA450	1.16	3.7	$4.4^{+2.6}_{-1.0}$
SRB	1.57	5.0	$8.5^{+3.9}_{-2.4}$