NLO (S)QCD corrections in R-symmetric supersymmetry

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Triumph of the Standard Model



"SUSY" status at the beginning of Run II

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

Sta	atus: August 2016						ML.	$\sqrt{s} = 7, 8, 13 \text{ TeV}$
	Model	e, μ, τ, γ	Jets	$E_{ m T}^{ m miss}$	∫ <i>L dt</i> [fb	⁻¹] Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$ $\sqrt{s} = 13 \text{ TeV}$	Reference
Inclusive Searches	$ \begin{array}{l} \text{MSUGRA/CMSSM} \\ \widetilde{q}\widetilde{q}, \widetilde{q} \rightarrow \widetilde{q}\widetilde{\chi}_{1}^{0} \\ \widetilde{q}\widetilde{q}, \widetilde{q} \rightarrow \widetilde{q}\widetilde{\chi}_{1}^{0} \text{ (compressed)} \\ \widetilde{g}\widetilde{s}, \widetilde{g} \rightarrow \widetilde{q}\widetilde{q}\widetilde{\chi}_{1}^{0} \\ \widetilde{g}\widetilde{s}, \widetilde{g} \rightarrow \widetilde{q}\widetilde{q}\widetilde{\chi}_{1}^{0} \\ \widetilde{g}\widetilde{s}, \widetilde{g} \rightarrow \widetilde{q}q\widetilde{\chi}_{1}^{\pm} \rightarrow \widetilde{q}qW^{\pm}\widetilde{\chi}_{1}^{0} \\ \widetilde{g}\widetilde{s}, \widetilde{g} \rightarrow \widetilde{q}q(\ell\ell/\gamma)\widetilde{\chi}_{1}^{0} \\ \widetilde{g}\widetilde{s}, \widetilde{g} \rightarrow \widetilde{q}qWZ\widetilde{\chi}_{1}^{0} \\ \text{GMSB}(\widetilde{\ell} \text{ NLSP}) \\ \text{GGM (bino NLSP)} \\ \text{GGM (higgsino-bino NLSP)} \\ \text{GGM (higgsino-bino NLSP)} \\ \text{GGM (higgsino NLSP)} \\ \text{GGM (higgsino NLSP)} \\ \text{Gravitino LSP} \end{array} $	$\begin{array}{c} 0-3 \ e, \mu/1-2 \ \tau \\ 0 \\ mono-jet \\ 0 \\ 0 \\ 3 \ e, \mu \\ 2 \ e, \mu \ (SS) \\ 1-2 \ \tau + 0-1 \ e \\ 2 \ \gamma \\ \gamma \\ 2 \ e, \mu \ (Z) \\ 0 \end{array}$	2-10 jets/3 2-6 jets 1-3 jets 2-6 jets 2-6 jets 4 jets 0-3 jets 0-3 jets 0-2 jets 2 jets 2 jets mono-jet	 b Yes Yes 	20.3 13.3 3.2 13.3 13.3 13.2 13.2 3.2 3.2 20.3 13.3 20.3 20.3	$ ilde{q}, ilde{g}, ilde{g}$ $ ilde{q}$ $ ilde{q}$ $ ilde{q}$ $ ilde{q}$ $ ilde{q}$ $ ilde{g}$ $ ilde{g}$	$\begin{array}{c c} \textbf{1.85 TeV} & \textbf{m}(\tilde{q}) = \textbf{m}(\tilde{g}) \\ \textbf{5 TeV} & \textbf{m}(\tilde{\chi}_1^0) < 200 \mbox{ GeV}, \mbox{ m}(1^{st} \mbox{ gen.} \tilde{q}) = \textbf{m}(2^{nd} \mbox{ gen.} \tilde{q}) \\ & \textbf{m}(\tilde{q}) - \textbf{m}(\tilde{\chi}_1^0) < 5 \mbox{ GeV} \\ \textbf{1.86 TeV} & \textbf{m}(\tilde{\chi}_1^0) = 0 \mbox{ GeV} \\ \textbf{1.83 TeV} & \textbf{m}(\tilde{\chi}_1^0) < 400 \mbox{ GeV}, \mbox{ m}(\tilde{\chi}^\pm) = 0.5(\textbf{m}(\tilde{\chi}_1^0) + \textbf{m}(\tilde{g})) \\ \textbf{1.7 TeV} & \textbf{m}(\tilde{\chi}_1^0) < 400 \mbox{ GeV} \\ \textbf{1.66 TeV} & \textbf{m}(\tilde{\chi}_1^0) < 500 \mbox{ GeV} \\ \textbf{2.0 TeV} \\ \textbf{1.65 TeV} & cr(\textbf{NLSP}) < 0.1 \mbox{ mm} \\ \textbf{7 TeV} & \textbf{m}(\tilde{\chi}_1^0) < 950 \mbox{ GeV}, cr(\textbf{NLSP}) < 0.1 \mbox{ mm}, \mu < 0 \\ \textbf{m}(\tilde{\chi}_1^0) > 680 \mbox{ GeV}, cr(\textbf{NLSP}) < 0.1 \mbox{ mm}, \mu > 0 \\ \textbf{m}(\textbf{NLSP}) > 430 \mbox{ GeV} \\ \textbf{m}(\tilde{g}) = \textbf{1.5 TeV} \end{array}$	1507.05525 ATLAS-CONF-2016-078 1604.07773 ATLAS-CONF-2016-078 ATLAS-CONF-2016-078 ATLAS-CONF-2016-037 ATLAS-CONF-2016-037 1607.05979 1606.09150 1507.05493 ATLAS-CONF-2016-066 1503.03290 1502.01518
3 rd gen. <u>8</u> med.	$\begin{array}{c} \tilde{g}\tilde{g}, \ \tilde{g} \rightarrow b \bar{b} \tilde{\chi}^0_1 \\ \tilde{g}\tilde{g}, \ \tilde{g} \rightarrow t \bar{t} \tilde{\chi}^0_1 \\ \tilde{g}\tilde{g}, \ \tilde{g} \rightarrow b \bar{t} \tilde{\chi}^1_1 \end{array}$	0 0-1 <i>e</i> ,μ 0-1 <i>e</i> ,μ	3 b 3 b 3 b	Yes Yes Yes	14.8 14.8 20.1	rg B B B B B B B B B B B B B B B B B B B	$\begin{array}{c c} \textbf{1.89 TeV} & \textbf{m}(\tilde{\chi}_1^0){=}0 \text{ GeV} \\ \hline \textbf{1.89 TeV} & \textbf{m}(\tilde{\chi}_1^0){=}0 \text{ GeV} \\ \textbf{37 TeV} & \textbf{m}(\tilde{\chi}_1^0){<}300 \text{ GeV} \end{array}$	ATLAS-CONF-2016-052 ATLAS-CONF-2016-052 1407.0600
3 rd gen. squarks direct production	$ \begin{split} \tilde{b}_{1}\tilde{b}_{1}, \tilde{b}_{1} \to b\tilde{\chi}_{1}^{0} \\ \tilde{b}_{1}\tilde{b}_{1}, \tilde{b}_{1} \to b\tilde{\chi}_{1}^{1} \\ \tilde{h}_{1}\tilde{b}_{1}, \tilde{h}_{1} \to b\tilde{\chi}_{1}^{+} \\ \tilde{h}_{1}\tilde{h}_{1}, \tilde{h}_{1} \to b\tilde{\chi}_{1}^{0} \text{ or } t\tilde{\chi}_{1}^{0} \\ \tilde{h}_{1}\tilde{h}_{1}, \tilde{h}_{1} \to W\tilde{\chi}_{1}^{0} \text{ or } t\tilde{\chi}_{1}^{0} \\ \tilde{h}_{1}\tilde{h}_{1}, \tilde{h}_{1} \to \tilde{\chi}_{1}^{0} \\ \tilde{h}_{1}\tilde{h}_{1} = \tilde{\chi}_{1}^{0} \\ \tilde{h}_{1}\tilde{h}_{1} = \tilde{\chi}_{1}^{0} \\ \tilde{h}_{1}\tilde{h}_{1} = \tilde{h}_{1}^{0} \\ \tilde{h}_{1}\tilde{h}_{1} = \tilde{h}_{1}^{0} \\ \tilde{h}_{1}\tilde{h}_{1} = \tilde{h}_{1}^{0} \\ \tilde{h}_{1}\tilde{h}_{1} = \tilde{h}_{1}^{0} \\ \tilde{h}_{1} = \tilde{h}_$	$\begin{matrix} 0\\2 \ e, \mu \ (SS)\\0-2 \ e, \mu\\0-2 \ e, \mu\\0\\2 \ e, \mu \ (Z)\\3 \ e, \mu \ (Z)\\1 \ e, \mu\end{matrix}$	2 b 1 b 1-2 b 0-2 jets/1-2 mono-jet 1 b 1 b 6 jets + 2 b	Yes Yes Yes Yes Yes Yes b Yes	3.2 13.2 1.7/13.3 1.7/13.3 3.2 20.3 13.3 20.3	Š1 840 GeV Š1 325-685 GeV V7-170 GeV 200-720 GeV V1 90-198 GeV 205-850 GeV V1 90-323 GeV 150-600 GeV V1 150-600 GeV 12 V2 320-700 GeV 12	$\begin{array}{l} m(\tilde{\chi}_{1}^{0}) < 100 \text{GeV} \\ m(\tilde{\chi}_{1}^{0}) < 150 \text{GeV}, m(\tilde{\chi}_{1}^{+}) = m(\tilde{\chi}_{1}^{0}) + 100 \text{GeV} \\ m(\tilde{\chi}_{1}^{+}) = 2m(\tilde{\chi}_{1}^{0}), m(\tilde{\chi}_{1}^{0}) = 55 \text{GeV} \\ m(\tilde{\chi}_{1}^{0}) = 1 \text{GeV} \\ m(\tilde{\chi}_{1}^{0}) = 15 \text{GeV} \\ m(\tilde{\chi}_{1}^{0}) > 150 \text{GeV} \\ m(\tilde{\chi}_{1}^{0}) < 300 \text{GeV} \\ m(\tilde{\chi}_{1}^{0}) = 0 \text{GeV} \end{array}$	1606.08772 ATLAS-CONF-2016-037 1209.2102, ATLAS-CONF-2016-077 1506.08616, ATLAS-CONF-2016-077 1604.07773 1403.5222 ATLAS-CONF-2016-038 1506.08616
EW direct	$ \begin{array}{l} \tilde{\ell}_{LR}\tilde{\ell}_{LR}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_{1}^{0} \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\ell}\nu(\ell\tilde{\nu}) \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\nu}\nu(\tau\tilde{\nu}) \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{2}^{0} \rightarrow \tilde{\ell}_{L}\nu\tilde{\ell}_{L}\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_{L}\ell(\tilde{\nu}\nu) \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{2}^{0} \rightarrow W\tilde{\chi}_{1}^{0}Z\tilde{\chi}_{1}^{0} \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{2}^{0} \rightarrow W\tilde{\chi}_{1}^{0}h\tilde{\chi}_{1}^{0}, h \rightarrow b\bar{b}/WW/ \\ \tilde{\chi}_{2}^{0}\tilde{\chi}_{3}^{0}, \tilde{\chi}_{2,3}^{0} \rightarrow \tilde{\ell}_{R}\ell \\ GGM (wino NLSP) weak processing of the set of t$	$\begin{array}{c} 2 \ e, \mu \\ 2 \ e, \mu \\ 2 \ \tau \\ 3 \ e, \mu \\ 2 \ -3 \ e, \mu \\ 2 \ -3 \ e, \mu \\ 4 \ e, \mu \\ 4 \ e, \mu \\ 4 \ e, \mu \\ 1 \ e, \mu + \gamma \\ 1 \ 2 \ \gamma \end{array}$	0 0 - 0-2 jets 0-2 b 0 -	Yes Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{split} & m(\tilde{\chi}_{1}^{0}){=}0 GeV \\ & m(\tilde{\chi}_{1}^{0}){=}0 GeV, m(\tilde{\ell}, \tilde{\nu}){=}0.5(m(\tilde{\chi}_{1}^{\pm}){+}m(\tilde{\chi}_{1}^{0})) \\ & m(\tilde{\chi}_{1}^{0}){=}0 GeV, m(\tilde{\tau}, \tilde{\nu}){=}0.5(m(\tilde{\chi}_{1}^{\pm}){+}m(\tilde{\chi}_{1}^{0})) \\ & m(\tilde{\chi}_{1}^{\pm}){=}m(\tilde{\chi}_{2}^{0}), m(\tilde{\chi}_{1}^{0}){=}0, m(\tilde{\ell}, \tilde{\nu}){=}0.5(m(\tilde{\chi}_{1}^{\pm}){+}m(\tilde{\chi}_{1}^{0})) \\ & m(\tilde{\chi}_{1}^{\pm}){=}m(\tilde{\chi}_{2}^{0}), m(\tilde{\chi}_{1}^{0}){=}0, \tilde{\ell} decoupled \\ & m(\tilde{\chi}_{1}^{\pm}){=}m(\tilde{\chi}_{2}^{0}), m(\tilde{\chi}_{1}^{0}){=}0, m(\tilde{\ell}, \tilde{\nu}){=}0.5(m(\tilde{\chi}_{2}^{0}){+}m(\tilde{\chi}_{1}^{0})) \\ & c\tau{<}1 mm \\ & c\tau{<}1 mm \end{split}$	1403.5294 1403.5294 1407.0350 1402.7029 1403.5294, 1402.7029 1501.07110 1405.5086 1507.05493 1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived. Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived. Stable, stopped \tilde{g} R-hadron Stable \tilde{g} R-hadron Metastable \tilde{g} R-hadron GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) +$ GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$, long-lived $\tilde{\chi}_1^0$ $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow ev/e\mu\nu/\mu\mu\nu$ GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$	$ \begin{array}{c} \tilde{\chi}_{1}^{\pm} & \text{Disapp. trk} \\ \tilde{\chi}_{1}^{\pm} & \text{dE/dx trk} \\ 0 & \text{trk} \\ \text{dE/dx trk} \\ \sigma(e,\mu) & 1{-}2\mu \\ 2\gamma \\ \text{displ. } ee/e\mu/\mu \\ \text{displ. vtx + je} \end{array} $	1 jet - 1-5 jets - - - μμ - ts -	Yes Yes - - Yes - Yes	20.3 18.4 27.9 3.2 19.1 20.3 20.3 20.3	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c} m(\tilde{\chi}_{1}^{+})\text{-}m(\tilde{\chi}_{1}^{0})\text{-}160~MeV,~\tau(\tilde{\chi}_{1}^{+})\text{=}0.2~\mathrm{ns}\\ m(\tilde{\chi}_{1}^{+})\text{-}m(\tilde{\chi}_{1}^{0})\text{-}160~MeV,~\tau(\tilde{\chi}_{1}^{+})\text{<}15~\mathrm{ns}\\ m(\tilde{\chi}_{1}^{0})\text{=}100~GeV,~10~\mu\mathrm{s}\text{-}\tau(\tilde{g})\text{<}1000~\mathrm{s}\\ \hline \textbf{1.57~TeV}\\ \textbf{1.57~TeV}\\ m(\tilde{\chi}_{1}^{0})\text{=}100~GeV,~\tau\text{>}10~\mathrm{ns}\\ 10\text{<}tan\beta\text{<}50\\ 1\text{<}\tau(\tilde{\chi}_{1}^{0})\text{<}3~\mathrm{ns},~SPS8~model\\ 7\text{<}c\tau(\tilde{\chi}_{1}^{0})\text{<}740~\mathrm{mm},~m(\tilde{g})\text{=}1.3~TeV\\ 6\text{<}c\tau(\tilde{\chi}_{1}^{0})\text{<}480~\mathrm{mm},~m(\tilde{g})\text{=}1.1~TeV\\ \end{array}$	1310.3675 1506.05332 1310.6584 1606.05129 1604.04520 1411.6795 1409.5542 1504.05162 1504.05162
RPV	LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu$ Bilinear RPV CMSSM $\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow W\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow eev, e\mu\nu$ $\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow W\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow \tau\tau v_{e}, e\tau$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqq$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qqq$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t_{1}t, \tilde{t}_{1} \rightarrow bs$ $\tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow b\ell$	$\begin{array}{c c} \tau & e\mu, e\tau, \mu\tau \\ 2 \ e, \mu \ (SS) \\ \mu\mu\nu & 4 \ e, \mu \\ \gamma_{\tau} & 3 \ e, \mu+\tau \\ & 0 & 4 \\ 2 \ e, \mu \ (SS) \\ & 0 \\ 2 \ e, \mu \end{array}$	5 large- <i>R</i> j 5 large- <i>R</i> j 0-3 <i>b</i> 2 jets + 2 2 <i>b</i>	- Yes Yes ets - ets - Yes b - -	3.2 20.3 13.3 20.3 14.8 14.8 13.2 15.4 20.3	$ \begin{array}{c} \tilde{v}_{\tau} \\ \bar{q}, \tilde{g} \\ \tilde{\chi}_{1}^{*} \\ 1.14 \\ \tilde{\chi}_{1}^{*} \\ 1.08 \\ \tilde{g} \\ 1.08 \\ 1.0$	$\begin{array}{c c} \textbf{1.9 TeV} & \lambda_{311}'=0.11, \lambda_{132/133/233}=0.07\\ \textbf{45 TeV} & \textbf{m}(\tilde{q})=\textbf{m}(\tilde{g}), c\tau_{LSP}<1 \text{ mm}\\ \textbf{V} & \textbf{m}(\tilde{\chi}_{1}^{0}) \!$	1607.08079 1404.2500 ATLAS-CONF-2016-075 1405.5086 ATLAS-CONF-2016-057 ATLAS-CONF-2016-057 ATLAS-CONF-2016-037 ATLAS-CONF-2016-022, ATLAS-CONF-2016-084 ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c} \rightarrow c \tilde{\chi}_1^0$	0	2 c	Yes	20.3	õ 510 GeV	m($ ilde{\chi}_{1}^{0}$)<200 GeV	1501.01325
*Onl sta	y a selection of the availates or phenomena is sho	able mass limi wn.	its on nev	V	1)-1	1 Mass scale [TeV]	

ATLAS Preliminary

Fine print: MSSM status at the beginning of Run II

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

	Model	e, μ, τ, γ	′ Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	$\int \mathcal{L} dt [\mathbf{fb}]$	⁻¹]	Mass limit	$\sqrt{s} = 7, 8$	TeV $\sqrt{s} = 13$ TeV	
Inclusive Searches	MSUGRA/CMSSM $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_{1}^{0}$ $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_{1}^{0}$ (compressed) $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{\pm} \rightarrow qqW^{\pm}\tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{\pm} \rightarrow qqW^{\pm}\tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\nu\nu)\tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_{1}^{0}$ GMSB (ℓ NLSP) GGM (bino NLSP) GGM (higgsino-bino NLSP) GGM (higgsino-bino NLSP)	$\begin{array}{c} 0-3 \ e, \mu/1-2 \ \tau \\ 0 \\ mono-jet \\ 0 \\ 3 \ e, \mu \\ 2 \ e, \mu \ (SS) \\ 1-2 \ \tau + 0-1 \\ 2 \ \gamma \\ \gamma \\ \gamma \\ \gamma \end{array}$	2-10 jets/3 2-6 jets 1-3 jets 2-6 jets 2-6 jets 4 jets 0-3 jets ℓ 0-2 jets 1 b 2 jets 2 jets	b Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 13.3 3.2 13.3 13.3 13.2 13.2 13.2 3.2 3.2 20.3 13.3 20.2	ĨŢ, Ĩġ ĨŢ, Ĩġ ĨŢ, Ĩġ ĨŢ ĨŢ	1 608 GeV	I 1.85 TeV .35 TeV 1.86 TeV 1.83 TeV 1.7 TeV 1.6 TeV 2.0 Te 1.65 TeV .37 TeV 1.8 TeV	$m(\tilde{q})=m(\tilde{g})$ $m(\tilde{\chi}_{1}^{0})<200 \text{ GeV}, m(1^{\text{st}} \text{ gen. }\tilde{q})=m(2^{\text{nd}}g)$ $m(\tilde{q})-m(\tilde{\chi}_{1}^{0})<5 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})<400 \text{ GeV}, m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_{1}^{0})+m(\tilde{\chi}_{1}^{0})<400 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})<400 \text{ GeV}$ $r(\text{NLSP})<0.1 \text{ mm}$ $m(\tilde{\chi}_{1}^{0})<950 \text{ GeV}, c\tau(\text{NLSP})<0.1 \text{ mm}$ $m(\tilde{\chi}_{1}^{0})>680 \text{ GeV}, c\tau(\text{NLSP})<0.1 \text{ mm}$ $m(\tilde{\chi}_{1}^{0})>680 \text{ GeV}, c\tau(\text{NLSP})<0.1 \text{ mm}$	gen. q̃) -m(g̃)) n, μ<0 n, μ>0
	Gravitino LSP	2 e,μ (Σ) 0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV		$m(\tilde{G}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g}) = m(\tilde{q}) = 1.$.5 TeV
3 ^{ra} gen. <u>§</u> med.	$ \begin{array}{l} \tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{b}\tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{t}\tilde{\chi}_{1}^{+} \end{array} $	0 0-1 <i>e</i> ,μ 0-1 <i>e</i> ,μ	3 b 3 b 3 b	Yes Yes Yes	14.8 14.8 20.1	ັຮ ເຮ ຮ		1.89 TeV 1.89 TeV .37 TeV	$(\tilde{x}_{1}^{0})=0 \text{ GeV}$ $(\tilde{x}_{1}^{0})=0 \text{ GeV}$ $m(\tilde{x}_{1}^{0})<300 \text{ GeV}$	

Fine print: MSSM status at the beginning of Run II

MSUGRA/CMSSM

ATLAS SUST Searches* - 95% CL Lower Limits

Status:	August	2016
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	Model	e, μ, τ, γ	′ Jets	$E_{\rm T}^{\rm miss}$	$\int \mathcal{L} dt [\mathbf{fb}]$	⁻¹]	Mass limit	$\sqrt{s} = 7, 8$	TeV	$\sqrt{s} = 13$	TeV	
Inclusive Searches	MSUGRA/CMSSM $\tilde{q}q, \tilde{q} \rightarrow q\tilde{\chi}_{1}^{0}$ $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_{1}^{0}$ (compressed) $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{\pm} \rightarrow qqW^{\pm}\tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\nu\nu)\tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_{1}^{0}$ GMSB (ℓ NLSP) GGM (bino NLSP) GGM (higgsino-bino NLSP) GGM (higgsino-bino NLSP) GGM (higgsino NLSP) GGM (higgsino NLSP) GGM (higgsino NLSP)	$\begin{array}{c} 0.3 \ e, \mu/1-2 \ \tau \\ 0 \\ \text{mono-jet} \\ 0 \\ 0 \\ 3 \ e, \mu \\ 2 \ e, \mu \ (\text{SS}) \\ 1-2 \ \tau + 0-1 \\ 2 \ \gamma \\ \gamma \\ \gamma \\ 2 \ e, \mu \ (Z) \\ 0 \end{array}$	2-10 jets/3 2-6 jets 1-3 jets 2-6 jets 2-6 jets 2-6 jets 4 jets 0-3 jets ℓ 0-2 jets - 1 b 2 jets 2 jets 2 jets mono-iet	b Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 13.3 3.2 13.3 13.3 13.2 13.2 3.2 3.2 20.3 13.3 20.3	q q q q g 		1.85 TeV 1.35 TeV 1.86 TeV 1.83 TeV 1.7 TeV 1.6 TeV 2.0 Te 1.65 TeV 1.37 TeV 1.8 TeV	$m(\tilde{q})=m(m(\tilde{\chi}_{1}^{0})<20)$ $m(\tilde{q})-m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\chi}_{1}^{0})<4$ $m(\tilde{\chi}_{1}^{0})<4$ $m(\tilde{\chi}_{1}^{0})<5$ $c\tau(NLSF)$ $m(\tilde{\chi}_{1}^{0})<9$ $m(\tilde{\chi}_{1}^{0})>6$ $m(NLSP)$ $m(\tilde{G})>1$	\tilde{g}) 0 GeV, m(1 st g \tilde{t}_{1}^{0})<5 GeV GeV 00 GeV, m($\tilde{\chi}^{\pm}$ 00 GeV \tilde{t}_{2}^{0})<0.1 mm 50 GeV, $c\tau$ (N 80 GeV, $c\tau$ (N 80 GeV 8 x 10 ⁻⁴ eV r	$(en. \tilde{q}) = m(2)$ $) = 0.5(m(\tilde{X})$ LSP) < 0.1 r LSP) < 0.1 r $n(\tilde{q}) = m(\tilde{q})$	2^{nd} gen. \tilde{q}) p_{1}^{0})+m(\tilde{g})) mm, $\mu < 0$ mm, $\mu > 0$ =1.5 TeV
3 ^{ra} gen. ẽ med.	$ \begin{array}{l} \tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{b}\tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{t}\tilde{\chi}_{1}^{+} \end{array} $	0 0-1 <i>e</i> ,μ 0-1 <i>e</i> ,μ	3 b 3 b 3 b	Yes Yes Yes	14.8 14.8 20.1	າດ ເດິດ ເດິດ ເດິດ ເດິດ ເດິດ ເດິດ ເດິດ ເດ		1.89 TeV 1.89 TeV 1.37 TeV	$(\tilde{\chi}_{1}^{0})=0$ $(m(\tilde{\chi}_{1}^{0})=0)$ $m(\tilde{\chi}_{1}^{0})<3$	GeV GeV 00 GeV		

Fine print: MSSM status at the beginning of Run II

MSUGRA/CMSSM

Searches* - 95% CL Lower Limits

0

0-1 e, µ

0-1 e,μ

 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$

 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$

 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{t}\tilde{\chi}$

3 b

3b

3 b

518	alus. August 2016										
	Model	e, μ, τ, γ	′ Jets	$E_{ m T}^{ m miss}$	∫ <i>L dt</i> [ft	b ⁻¹]	Mass limit	$\sqrt{s} = 7$	7, 8 TeV	$\sqrt{s} = 13 \text{ TeV}$	
Inclusive Searches	MSUGRA/CMSSM $\tilde{q}q, \tilde{q} \rightarrow q\tilde{\chi}_{1}^{0}$ $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_{1}^{0}$ (compressed) $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$ (compressed) $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0} \rightarrow qqW^{\pm}\tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\nu\nu)\tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_{1}^{0}$ GMSB (ℓ NLSP) GGM (bino NLSP) GGM (higgsino-bino NLSP) GGM (higgsino-bino NLSP) GGM (higgsino NLSP) GGM (higgsino NLSP) Gravitino LSP	$\begin{array}{c} 0-3 \ e, \mu/1-2 \ \tau \\ 0 \\ mono-jet \\ 0 \\ 3 \ e, \mu \\ 2 \ e, \mu \ (SS) \\ 1-2 \ \tau + 0-1 \ e \\ 2 \ \gamma \\ \gamma \\ 2 \ e, \mu \ (Z) \\ 0 \end{array}$	2-10 jets/3 2-6 jets 1-3 jets 2-6 jets 2-6 jets 4 jets 0-3 jets ℓ 0-2 jets 1 b 2 jets 2 jets mono-jet	 b Yes Yes 	20.3 13.3 3.2 13.3 13.3 13.2 13.2 13.2 3.2 20.3 13.3 20.3 20.3	$ ilde{q}, ilde{g}$ $ ilde{q}$ $ ilde{q}$ $ ilde{g}$ $ ilde{g}$	608 GeV 900 GeV 865 GeV	1.85 T 1.35 TeV 1.86 T 1.83 T 1.7 TeV 1.6 TeV 2.0 1.65 TeV 1.37 TeV 1.8 Te	$ \begin{array}{c} \mathbf{FeV} & \mathbf{m}(\tilde{q}) = \mathbf{m} \\ & \mathbf{m}(\tilde{\chi}_{1}^{0}) < 2 \\ & \mathbf{m}(\tilde{q}) - \mathbf{m} \\ \mathbf{FeV} & \mathbf{m}(\tilde{\chi}_{1}^{0}) = \\ \mathbf{eV} & \mathbf{m}(\tilde{\chi}_{1}^{0}) < \\ & \mathbf{m}(\tilde{\chi}_{1}^{0}) > \\ & \mathbf{m}(\tilde{M}) > \\ & \mathbf{m}$	n(\tilde{g}) 00 GeV, m(1 st gen. \tilde{q})=m(2 nd ($\tilde{\chi}_{1}^{0}$)<5 GeV 0 GeV 400 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_{1}^{0}$)- 400 GeV 500 GeV 500 GeV 60 GeV, $c\tau$ (NLSP)<0.1 mr 680 GeV, $c\tau$ (NLSP)<0.1 mr P)>430 GeV 1.8 × 10 ⁻⁴ eV, m(\tilde{g})=m(\tilde{q})=1	gen. q̃) +m(g̃)) n, μ<0 n, μ>0
-											

14.8

14.8

20.1

ĝ

Yes

Yes

Yes

those limits are model dependent and can be much weaker

1.89 TeV m($\tilde{\chi}_1^0$)=0 GeV

1.89 TeV m($\tilde{\chi}_{1}^{0}$)=0 GeV

1.37 TeV

 $m(\tilde{\chi}_1^0) < 300 \, \text{GeV}$

Landscape of supersymmetric models

MSSM

Landscape of supersymmetric models

singlet extended SSM SUSY with R-parity violation additional U(1)'s MSSM R-symmetry models with Dirac gauginos triplet extended SSM

and many others....

R-symmetry

- additional symmetry of the SUSY algebra allowed by the Haag Łopuszański Sohnius theorem
- for N=1 it is a global $U_R(1)$ symmetry under which the SUSY generators are charged
- implies that the spinorial coordinates are also charged

$$Q_R(\theta) = 1, \ \theta \to e^{i\alpha}\theta$$

- Lagrangian invariance
 - □ Kähler potential invariant if R-charge of vector superfield is 0
 - **R**-charge of the superpotential must be 2
 - \Box soft-breaking terms must have R-charge 0

Low-energy R-symmetry realization

R charges of component fields									
		Q _R	scalar	vector	fermionic				
	vector superfield	0	-	0	1				
	chiral superfield	Q	Q	-	Q-1				

- freedom in the choice of chiral superfield charge
- we choose SM fields to have $R=0 \rightarrow$ Higgs superfields $Q_R=0$, lepton and quark superfields have $Q_R=+1$
- with the above assignment R-symmetry forbids
 - $\square \quad \mu \hat{H}_u \hat{H}_d$
 - $\label{eq:linear_line$
 - □ soft SUSY breaking Majorana masses and trilinear scalar couplings
 - flavor problem ameliorated but now gauginos and higgsinos are masses → possible solution - Dirac gauginos

One way to fix it: Dirac masses									
Minimal R-Symmetric Supersymmetric Standardmodel (MRSSM) Kribs et.al. arXiv:0712.2039									
			<i>SU</i> (3) _C	$SU(2)_L$	$U(1)_Y$	$U(1)_{R}$			
	Singlet	Ŝ	1	1	0	0			
Additional fields:	Triplet	Ť	1	3	0	0			
	Octet	Ô	8	1	0	0			
	R-Higgses	Â _u	1	2	-1/2	2			
		Â _d	1	2	1/2	2			

other realizations:

Davies, March-Russell, McCullough (2011) Lee, Raby, Ratz, Schieren, Schmidt-Hoberg, Vaudrevange (2011) Frugiuele, Gregoire (2012)

MRSSM lagrangian

Superpotential — Choi, Choudhury, Freitas, Kalinowski, Zerwas (2011)

$$W = \mu_d \hat{R}_d \hat{H}_d + \mu_u \hat{R}_u \hat{H}_u$$
$$+ \Lambda_d \hat{R}_d \hat{T} \hat{H}_d + \Lambda_u \hat{R}_u \hat{T} \hat{H}_u + \lambda_d \hat{S} \hat{R}_d \hat{H}_d + \lambda_u \hat{S} \hat{R}_u \hat{H}_u$$
$$- Y_d \hat{d} \hat{q} \hat{H}_d - Y_e \hat{e} \hat{l} \hat{H}_d + Y_u \hat{u} \hat{q} \hat{H}_u$$

- **□** µ-type terms
- \Box terms with λ , Λ couplings generate quartic Higgs couplings in the potential
- □ MSSM-like Yukawa terms
- Allowed soft SUSY-breaking terms
 - \Box conventional MSSM B_{μ} -term: $V \ni B_{\mu}(H_d^-H_u^+ H_d^0H_u^0) + h.c.$
 - \square Dirac mass terms for gauginos $M^D \, \tilde{g} \tilde{g}'$
 - \square scalar soft masses $m^2 |\Phi|^2$

Particle content summary: MSSM vs. MRSSM

different number of physical states compl

completely new states

		Higgs			R-H		
	CP-even	CP-odd	charged	charginos	neutral	charged	sgluon
MSSM	2	1	1	2	0	0	0
MRSSM	4	3	3	2+2	2	2	1

	neutralino	gluino
MSSM	4	1
MRSSM	4	1

Majorana fermions

Dirac fermions

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	neutralino	gluino		most important difference from the point of view
MSSM	4	1	Majorana fermions	of direct
MRSSM	4	1	Dirac fermions	searches of supersymmetry at the LHC

Exemplary mass spectrum



EW sector of the MRSSM (status)

- The SM-like Higgs boson mass in the MRSSM has been calculated including full 1-loop and leading 2-loop corrections^{1,2}
- Impact of EWPO was analyzed¹
- MRSSM can predicts correct dark matter relic density while being in agreement with dark matter direct detection bounds³
 - Its EW signatures were checked against available 7 and 8 TeV data³

1. P. Dießner, J. Kalinowski, W. Kotlarski and D. Stöckinger, JHEP 1412 (2014) 124

 P. Dießner, J. Kalinowski, W. Kotlarski and D. Stöckinger, Adv. High Energy Phys. 2015 (2015) 760729

3. P. Dießner, J. Kalinowski, W. Kotlarski and D. Stöckinger, JHEP **1603** (2016) 007



MRSSM signatures at the LHC

sgluon pair production $pp \rightarrow OO$

 $\square \quad \text{complex fields O split by D-term contribution into scalar (S) and pseudoscalar (A) parts} \\ m_{O_A}^2 = m_O^2 \qquad m_{O_S}^2 = m_O^2 + 4(M_O^D)^2 \\ \end{array}$

 \Box O_S naturally heavy, O_A might decay into quarks through loop-induced coupling



Coupling proportional to m_q . If O_A is lighter than other SUSY particles but $m_{O_A} > 2m_t$ O_A decays exclusively to top quarks

same sign squark pair production $pp \rightarrow \tilde{q}_L \tilde{q}_R$



Dirac gluino \tilde{g}_D pair production, with cross section roughly twice as large as in the MSSM

Sgluon pair production at 13 TeV LHC

- Analysis of the sgluon pair production with subsequent decay into $t\bar{t}$ pairs. Recasting ATLAS search in the same-sign lepton channel using 3.2/ fb of integrated luminosity
- Signal simulated at NLO using MadGraph5_aMC@NLO + FeynRules + NLOCT and matched to parton shower in the MC@NLO scheme
 - Detector response parametrized using Delphes3
- Analysis validated on background processes $t\bar{t}l^+l^-, t\bar{t}l^\pm\nu$
- Mass of pair produced real spluons decaying with $BR(O \rightarrow t\bar{t}) = 1$ excluded up to 950 GeV



Leading order analysis



LO cross-sections for sparticle production at the LHC at \sqrt{s} =13TeV

Leading order analysis



squark anti-squark pair production becomes subdominant

NLO corrections

Detour - regularization in SUSY theories



D-2 ≠ 2

Solution - use dimensional reduction (DRED). In DRED, momenta are continued from 4 to D dimensions, while gauge fields and γ -matrices remain 4-dimensional objects.

- PDF are fitted in the $\overline{\text{MS}}$ scheme. Not trivial to combine them with matrix elements regularized using DRED.
- Solution: do the calculation in the $\overline{\text{MS}}$ scheme and derive $\overline{\text{MS}} \to \overline{\text{DR}}$ transition terms by matching off-shell Green's functions calculated in both schemes. This fixes UV-part without altering the IR one.

Virtual matrix element - technical side

- FeynArts model containing renormalization constants and $MS \rightarrow DR$ transition counterterms
- Amplitude generated using
 FeynArts and evaluated in
 FormCalc in terms of
 Passarino Veltman loop
 functions
 - Check of UV-finiteness





After renormalization the result is UV-finite but still IR divergent

Real emissions

IR divergences cancelled after including real emission diagrams (Kinoshita-Lee-Nauenberg theorem) and through mass factorization, e.g.



Split real emission phase space as (two-cut phase space slicing)

$$\sigma_{R} = \int d\sigma_{R}$$

$$= \int_{S} d\sigma_{R} + \int_{H} d\sigma_{R}$$

$$= \int_{S} d\sigma_{R} + \int_{HC} d\sigma_{R} + \int_{H\overline{C}} d\sigma_{R}$$

split gluon phase space according to its softness split hard gluon phase space according to its collinearity

S and HC parts integrated analytically in D-dimension

 \square soft and collinear part (S) is the source of ϵ_{IR}^{-2} , ϵ_{IR}^{-1}

 \square hard-collinear part (HC) is the source of $\epsilon_{\rm IR}^{-1}$

Framework's validation

- check of UV- and IR-finiteness, check of result independence on the phase space slicing parameters
- check of the selected MSSM processes against MadGrapgh5_aMC@NLO + FeynRules + NLOCT
- \Box ϵ expansion of the virtual matrix elements
- **d** total NLO cross sections
- sgluon pair production within an effective model (SM + octet)
- For MRSSM, independent implementation into MadGraph5_aMC@NLO + GoSam framework using UFO model with a hand encoded counterterms

Following processes were already validated (more are on the way):

- $\Box \qquad pp \to OO$
- $\Box \qquad pp \to \tilde{q}_L \tilde{q}_R$

Preliminary results for $uu \to u_L u_R(+g)$

Parameter point:

$$\sqrt{S} = 13 \text{ TeV}, m_{\tilde{q}} = 1.5 \text{ TeV}, m_{\tilde{g}_D} = 1 \text{ TeV}, \mu_R = \mu_F = m_{\tilde{q}}$$

D LO result with MMHT2014lo68cl PDFs

$$\sigma_{\rm MRSSM}^{\rm LO} = \sigma_{\rm MSSM}^{\rm LO} = 6.379 \pm 0.004 \, fb$$

□ NLO result with MMHT2014nlo68cl PDFs

 $\sigma_{\rm MSSM}^{\rm NLO} = 9.441 \pm 0.002\,fb$

 $\sigma_{\rm MRSSM}^{\rm NLO} = 9.93 \pm 0.01\,fb$

Summary and outlook

- MRSSM presents a viable alternative to the MSSM, without some of the MSSM drawbacks
 - □ 125 GeV SM-like Higgs boson with ~1 TeV stops
 - □ in agreement with EW precision observables, dark matter searches and collider bounds
- Its collider phenomenology might be quite different from the MSSM
- I presented first calculation of the SQCD NLO correction to $2 \rightarrow 2$ processes at the LHC within the R-symmetric SUSY
- Standalone C++ code, called RSymSQCD, allowing to calculate NLO cross sections for selected $2 \rightarrow 2$ processes is in the preparation. Version 0.1, containing processes involving squarks: $pp \rightarrow \tilde{q}_i \tilde{q}_j^{(*)}, i, j \in \{L, R\}$ should become public before the end of this year

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Thank you!