# Squark production with **R-symmetry beyond NLO at the** LHC



Christoph Borschensky, Philip Diessner, Fausto Frisenna, Jan Kalinowski, Wojciech Kotlarski, Anna Kulesza, Sebastian Liebschner, Dominik Stöckinger



ΝΔΤΙΟΝΔΙ



NATIONAL SCIENCE CENTRE

# LHC BSM limits (example)

#### ATLAS SUSY Searches\* - 95% CL Lower Limits

**ATLAS** Preliminary  $\sqrt{s} = 13 \text{ TeV}$ 

July 2024
-----------

Model	Signature	∫ <i>£ dt</i> [fb <sup>−1</sup>	Mass limit			Reference
$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	$0 e, \mu$ 2-6 jets $H$ mono-jet 1-3 jets $H$	$E_T^{ m miss}$ 140 $E_T^{ m miss}$ 140		1.0 1.85 0.9	m(𝔅̃1)<400 GeV m(𝔅)-m(𝔅̃1)=5 GeV	2010.14293 2102.10874
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i> 2-6 jets <i>B</i>	$E_T^{miss}$ 140	Ĩġ	2. Forbidden 1.15-1.95	3 $m(\tilde{\chi}_{1}^{0})=0 \text{ GeV} \\ m(\tilde{\chi}_{1}^{0})=1000 \text{ GeV}$	2010.14293 2010.14293
$\widetilde{\mathcal{S}}_{\tilde{g}\tilde{g}}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$	1 e, µ 2-6 jets	140	ĝ	2.2	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	2101.01629
$\mathfrak{g} \tilde{g}, \tilde{g} \rightarrow q \bar{q} (\ell \ell) \tilde{\chi}_{1}^{0}$	ee, μμ 2 jets I	$E_{T_{\perp}}^{\text{miss}}$ 140	Ĩ	2.2	m( $\tilde{\chi}_{1}^{0}$ )<700 GeV	2204.13072
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	$\begin{array}{ccc} 0 \ e, \mu & 7-11 \ { m jets} & P \ { m SS} \ e, \mu & 6 \ { m jets} \end{array}$	E <sub>T</sub> 140 140	23, 93,	1.97 1.15	m(𝔅˜₁) <600 GeV m(𝔅̃)-m(𝔅̃₁)=200 GeV	2008.06032 2307.01094
$\underline{\xi}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\chi}_1^0$	$\begin{array}{cccc} 0\text{-1} \ e,\mu & 3 \ b \\ \mathrm{SS} \ e,\mu & 6 \ \mathrm{jets} \end{array} \right.$	$E_T^{\text{miss}}$ 140 140	محة محة	1.25	.45 $m(\tilde{\chi}_{1}^{0}) < 500 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_{1}^{0}) = 300 \text{ GeV}$	2211.08028 1909.08457
$ ilde{b}_1 ilde{b}_1$	0 <i>e</i> , <i>µ</i> 2 <i>b B</i>	$E_T^{\text{miss}}$ 140	$\tilde{b}_1 \\ \tilde{b}_1$	1.255	$\begin{array}{c} m(\tilde{\chi}_1^0){<}400GeV \\ 10GeV{<}\Deltam(\tilde{b}_1\tilde{\chi}_1^0){<}20GeV \end{array}$	2101.12527 2101.12527
$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$E_T^{miss}$ 140 $E_T^{miss}$ 140	$\tilde{b}_1$ Forbidden $\tilde{b}_1$ Image: Second s	0.23-1.35 0.13-0.85	$\begin{array}{l} \Delta m(\tilde{\chi}^0_2,\tilde{\chi}^0_1) \!=\! 130 \; \text{GeV}, \; m(\tilde{\chi}^0_1) \!=\! 100 \; \text{GeV} \\ \Delta m(\tilde{\chi}^0_2,\tilde{\chi}^0_1) \!=\! 130 \; \text{GeV}, \; m(\tilde{\chi}^0_1) \!=\! 0 \; \text{GeV} \end{array}$	1908.03122 2103.08189
$\tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow t\tilde{\chi}_{1}^{0}$	0-1 $e, \mu \ge 1$ jet $L$	$E_T^{\text{miss}}$ 140	Ĩ <sub>1</sub>	1.25	$m(\tilde{\chi}_1^0)=1 \text{ GeV}$	2004.14060, 2012.03799
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$	1 e,μ 3 jets/1 b E	$E_T^{\text{miss}}$ 140	ĩ, Forbidden	1.05	$m(\tilde{\chi}_1^0)=500 \text{ GeV}$	2012.03799, 2401.13430
$\begin{array}{c} 0 5  t_1 t_1, t_1 \rightarrow \tau_1 b v, \tau_1 \rightarrow \tau G \\ 0 5  \mathbf$	$1-2\tau = 2 \operatorname{pets}/10$ E	$E_T$ 140 $E_T^{miss}$ 36.1		0.85	$m(\tau_1) = 800 \text{ GeV}$ $m(\tilde{v}^0) = 0 \text{ GeV}$	2108.07665
	$0 e, \mu$ mono-jet $E$	$E_T^{\text{fniss}}$ 140	č <sub>1</sub> 0.55	0.00	$m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$	2102.10874
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	$1-2 e, \mu$ $1-4 b l$	$E_{T_{-}}^{\text{miss}}$ 140	Ĩ <sub>1</sub>	0.067-1.18	m( $\tilde{\chi}_{2}^{0}$ )=500 GeV	2006.05880
$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, µ 1 b l	$E_T^{\text{miss}}$ 140	i 2 Forbidden	0.86	$m(\tilde{\chi}_{1}^{0})=360 \text{ GeV}, m(\tilde{t}_{1})-m(\tilde{\chi}_{1}^{0})=40 \text{ GeV}$	2006.05880
$ ilde{\chi}_1^{\pm}  ilde{\chi}_2^0$ via $WZ$	$\begin{array}{ccc} \text{Multiple }\ell/\text{jets} & & H\\ ee, \mu\mu & \geq 1 \text{ jet} & H \end{array}$	$E_T^{miss}$ 140 $E_T^{miss}$ 140	$ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} \\ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}  $ 0.205	0.96	$m(\tilde{\chi}_1^0)=0$ , wino-bino $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606
$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	2 e, µ 1	$E_T^{\text{miss}}$ 140	$\tilde{\chi}_{1}^{\pm}$ 0.42		$m(\tilde{\chi}_{1}^{0})=0$ , wino-bino	1908.08215
$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via $Wh$	Multiple <i>l</i> /jets	$E_T^{\text{miss}}$ 140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ Forbidden	1.06	$m(\tilde{\chi}_1^0) = 70 \text{ GeV}, \text{ wino-bino}$	2004.10894, 2108.07586
$\lambda_1 \chi_1 \text{ Via } t_L/\nu$	2 e, µ [	$E_T$ 140 $E^{miss}$ 140	$\tilde{\tau}_{1}$ $\tilde{\tau}_{P}\tilde{\tau}_{P}$ 0.35 0.5	1.0	$m(\ell, \nu)=0.5(m(\ell_1)+m(\ell_1))$ $m(\tilde{\chi}^0)=0$	2402 00603
$\widetilde{\ell}_{L,R} \widetilde{\ell}_{L,R}, \widetilde{\ell} \to \ell \widetilde{\chi}_1^0$	$2 e, \mu$ 0 jets $E$ $ee, \mu\mu$ $\geq 1$ jet $E$	$E_T^{miss}$ 140 $E_T^{miss}$ 140	$\tilde{\ell}$ 0.26	0.7	$m(\tilde{\ell}_1)=0$ $m(\tilde{\ell})=0$ $m(\tilde{\ell})-m(\tilde{\chi}_1^0)=10 \text{ GeV}$	1908.08215 1911.12606
$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	$0 e, \mu \geq 3 b$	Emiss 140	Ĥ	0.94	$BR(\tilde{\chi}_{1}^{0} \rightarrow h\tilde{G})=1$	2401.14922
	$4 \ e, \mu$ 0 jets $E$ $0 \ e, \mu \ge 2$ large jets $E$	$E_T^{miss}$ 140 $E_T^{miss}$ 140	H 0.55 Ĥ	0.45-0.93	$BR(\chi_1^{\circ} \rightarrow ZG)=1$ $BR(\chi_1^{\circ} \rightarrow Z\tilde{G})=1$	2103.11684 2108.07586
	$2 e, \mu \ge 2$ jets $H$	$E_T^{\text{miss}}$ 140	Ĥ	0.77	$BR(\tilde{\chi}^0_1 \to Z\tilde{G}) = BR(\tilde{\chi}^0_1 \to h\tilde{G}) = 0.5$	2204.13072
Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk 1 jet B	$E_T^{\text{miss}}$ 140	$ \tilde{\chi}_{1}^{\pm} $ 0.21	0.66	Pure Wino Pure higgsino	2201.02472 2201.02472
Stable g R-hadron	pixel dE/dx E	$T_{T}^{\text{miss}}$ 140	ĝ	2.05		2205.06013
Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$	pixel dE/dx E	$T_T^{\text{miss}}$ 140	$\tilde{g}$ [ $\tau(\tilde{g})$ =10 ns]	2.2	m( $\bar{x}_{1}^{0}$ )=100 GeV	2205.06013
$\ell \ell, \ell \to \ell G$	Dispi. iep E	$E_T^{mass}$ 140	$\tilde{\tau}$ 0.36	0.74	$\tau(\ell) = 0.1 \text{ ns}$ $\tau(\tilde{\ell}) = 0.1 \text{ ns}$	ATLAS-CONF-2024-011 ATLAS-CONF-2024-011
	pixel dE/dx E	$E_T^{\text{miss}}$ 140	τ̃ 0.36		$ au(\hat{\ell}) = 10 \text{ ns}$	2205.06013
$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_1^0, \tilde{\chi}_1^{\pm} \rightarrow Z \ell \rightarrow \ell \ell \ell$	3 e, µ	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_1^0$ [BR( $Z\tau$ )=1, BR( $Ze$ )=1] <b>0.6</b>	25 1.05	Pure Wino	2011.10543
$\tilde{\chi}_1^* \tilde{\chi}_1^+ / \tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	$4 e, \mu$ 0 jets $B$	$E_T^{\text{mass}}$ 140	$\tilde{\chi}_{1}^{*}/\tilde{\chi}_{2}^{0} = [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0]$	0.95 1.55	m( $\tilde{\chi}_{1}^{0}$ )=200 GeV	2103.11684
$gg, g \to qq\chi_1, \chi_1^- \to qqq$ $\widetilde{t}_1^- \widetilde{t}_{-1} \chi_1^0, \widetilde{\chi}_1^0 \to the$	≥o jeis Multinle	140 36 1	$g = [m(x_1)=50 \text{ GeV}, 1250 \text{ GeV}]$ $\tilde{t} = [\lambda'_{-1}=2e-4, 1e-2]$ 0.55	1.05	$m(\tilde{\chi}_{1}^{0})=200 \text{ GeV bino.like}$	2401.16333 ATLAS-CONF-2018-003
$ \underbrace{ \begin{array}{c} u, i \rightarrow i \lambda_{1}, \lambda_{1} \rightarrow i b s \\ \tilde{t}, \tilde{t} \rightarrow b \tilde{\lambda}_{1}^{\pm}, \tilde{\lambda}_{1}^{\pm} \rightarrow b b s \end{array} }_{\tilde{t} t \tilde{t}, \tilde{t} \rightarrow b \tilde{t} \tilde{t} \tilde{t} \tilde{t} \tilde{t} \tilde{t} \tilde{t} \tilde{t}$	$\geq 4b$	140	ĩ Forbidden	0.95	$m(\tilde{\chi}_1^{\pm})=500 \text{ GeV}$	2010.01015
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 b	36.7	$\tilde{t}_1  [qq, bs] \qquad \qquad 0.42 0.42$	51	,	1710.07171
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e,μ 2 b 1 μ DV	140 136	$\tilde{t}_1$ $\tilde{t}_1$ [1e-10< $\lambda'_{11}$ <1e-8, 3e-10< $\lambda'_{11}$ <3e-9]	0.4-1.85	$BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$ $BR(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta = 1$	2406.18367 2003.11956
$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^+ \rightarrow bbs$	1-2 $e, \mu \ge 6$ jets	140	$\tilde{\chi}_1^0$ <b>0.2-0.32</b>		Pure higgsino	2106.09609
*Only a selection of the available r	nass limits on new states o	or 10	D <sup>-1</sup>	1	Mass scale [TeV]	

phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

# LHC squark – gluino limits



[JHEP02(2024)107]

# Not the end of the story



# Gluino mass dependence



- Large difference in the intermediate  $m_{\tilde{g}}$  region
  - $m_{\tilde{g}} \rightarrow 0$ : Dirac vs. Majorana nature becomes neglidgeble
  - $m_{\tilde{g}} \rightarrow \infty$ : t-channel diagrams become negligible
  - in the  $\tilde{g}$ -decoupling limit  $\sigma^{(0)}_{\tilde{q}\tilde{q}} \rightarrow 0$  but:
    - MRSSM:  $\sigma^{(0)}_{\tilde{q}\tilde{q}} \propto m_{\tilde{g}}^{-4}$

• MSSM: 
$$\sigma^{(0)}_{\tilde{q}\tilde{q}} \propto m^{-2}_{\tilde{g}}$$

# **Overwiev of models with Dirac gauginos**

Squarks at the LHC are produced as  $pp \rightarrow \tilde{q}\tilde{q}^*$  or  $pp \rightarrow \tilde{q}\tilde{q} + cc$ 

- $\tilde{q}\tilde{q}^*$  production goes via  $q\bar{q}$  and gg and therefore is most efficient for light squarks because of gluon and antiquark PDFs
- $\tilde{q}\tilde{q}$  consists of 3 combinations: LL, LR, RR. Same chiralities require chirality flip via Majorana gluino mass



For the allowed chiralities the t-channel propagator is effectively replaced by

$$\frac{\not p + m_{\tilde{g}}}{p^2 - m_{\tilde{g}}^2} \to \frac{\not p}{p^2 - m_{\tilde{g}}^2}$$

which leads to cross section scaling with  $m_{\tilde{g}}^{-4}$ , as opposed to  $m_{\tilde{g}}^{-2}$  in the MSSM

# **R-symmetry**

- R-symmetry is an additional symmetry of the SUSY algebra allowed by the Haag -Łopuszański - Sohnius theorem
- For N=1 SUSY it is a global U(1)<sub>R</sub> 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 is automatically invariant
- R-charge of the superpotential W must be 2

$$Q_{R}(\mathcal{L})=0 \longrightarrow \mathcal{L} \ni \int d^{2}\theta W$$
$$Q_{R}(W)=+2$$

- soft-breaking terms must have R-charge 0

#### Low-energy R-symmetry realization



	$e^{i lpha Q_R}$		$e^{i\alpha Q_R}$		$e^{i\alpha(Q_R-1)}$	L)	
	$\Phi$	=	$\phi(y)$	+	$\sqrt{2} heta\psi(y)$	+	heta heta F(y)
"Natural"	choice						
	Higgs		$Q_R = 1$		$Q_R$ :	= 1	$Q_R=0$
leptons	and qua	rks	$Q_R = 0$		$Q_R$ :	= 0	$Q_R = -1$

- Good: no barion and lepton number violating terms
- Bad: No Majorana masses for higgsinos and gauginos

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

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

# MSSM vs. MRSSM

MSSM superpotencial

 $\mu \hat{H}_u \hat{H}_d$  $-Y_d \,\hat{d} \,\hat{q} \,\hat{H}_d - Y_e \,\hat{e} \,\hat{l} \,\hat{H}_d + Y_u \,\hat{u} \,\hat{q} \,\hat{H}_u$ 

MSSM soft-SUSY breaking terms

Q

- $B_{\mu}$  term
- soft scalar masses
- Majorana gaugino masses
- A terms

MRSSM superpotencial  $\blacktriangleright \mu_d \hat{R}_d \hat{H}_d + \mu_u \hat{R}_u \hat{H}_u$  $-Y_d \,\hat{d} \,\hat{q} \,\hat{H}_d - Y_e \,\hat{e} \,\hat{l} \,\hat{H}_d + Y_u \,\hat{u} \,\hat{q} \,\hat{H}_u$  $\Lambda_d \hat{R}_d \hat{T} \hat{H}_d + \Lambda_u \hat{R}_u \hat{T} \hat{H}_u + \lambda_d \hat{S} \hat{R}_d \hat{H}_d + \lambda_u \hat{S} \hat{R}_u \hat{H}_u$ MRSSM soft-SUSY breaking terms -  $B_{\mu}$  - term (though no  $B_{\mu}$ ,  $B_{\mu}$ ) soft scalar masses Dirac gaugino masses no A-terms One way to fix it: Dirac masses Minimal R-Symmetric Supersymmetric Standardmodel (MRSSM)  $SU(3)_C$   $SU(2)_L$   $U(1)_Y$  $U(1)_{\rm R}$ Ŝ Singlet 1 1 0 0 Ť 1 3 0 Triplet 0 Additional fields: Ô Octet 8 1 0 0 Â<sub>u</sub> 2 **R-Higgses** 1 -1/22 Ŕд 1 2 1/22

#### R-symmetry vs. matter parity

Consider R-symmetric transformation of a generic supermultiplet

$$R: \Phi(x,\theta,\bar{\theta}) \to \Phi'(x,e^{i\varphi}\theta,e^{-i\varphi}\bar{\theta}) = e^{i\varphi R_{\Phi}}\Phi(x,\theta,\bar{\theta})$$

In the MSSM one imposes the so-called matter parity

$$M_p = (-1)^{3(B-L)}$$

- this is equivalent to R-pairity which is defined on components of a supermultiplet as  $P_R = (-1)^{3(B-L)+2s}$ 

- This is also equivalent to R-symmetry  $R = e^{i\varphi R_{\Phi}}$  with  $\varphi = \pi$  and  $R_{\Phi} = 3(B - L)$ 

R-charges

- MSSM:  $R_{\Phi} = 0, 1$
- MRSSM:  $R_{\Phi} = 0, 1, 2$
- R-symmetry is more restrictive than matter parity

# Particle content summary: MSSM vs. MRSSM

		Higgs			R-H	iggs	
	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	2

different number of physical state	completely new states
------------------------------------	-----------------------

	neutralino	gluino
MSSM	4	1
MRSSM	4	1

Majorana fermions

Dirac fermions

# Example of a mass spectrum



# Squark pair production @ LO



# NLO setup

Two independent calculations:

- analytic calculation: hand-made FeynArts model (based on SARAH FEYNARTS output) with 1-loop and real emission diagrams generated by FEYNARTS + FORMCALC. Infrared singularities removed via 2-cut phase space slicing method
- semi-automatic calculation in MADGRAPH: UFO model file based on SARAH UFO output. Unrenormalized virtual matrix elemenets generated by GoSam with by hand added renormalization. Soft and/or colinear divergences handled by MADFKS
- Full numerical cancelation of UV and IR poles in both cases for random phase space points
- Full numerical agreement for UV and IR poles between calculations for random phase space points
- Full numerical agreement for unrenormalized and renormalized amplitudes for random phase space points
- Agreement for total cross-sections between both methods withing uncertainty of numerical integration
- The C++ code called RSymSQCD that computes squark production cross-sections at the NLO in the MRSSM can be downloaded from github

# K-factors and reduction of theoretical uncertainty



# **Phenomenological implications**



# **Projection for the HL-LHC**



- The exclusion limits follow closely the difference in cross sections between model
- This allows to gauge the excluding power of the high-luminosity phase of the LHC: for  $m_{\tilde{g}} = 4.5$  TeV with 3000 fb<sup>-1</sup> light flavour squarks in the MRSSM can be excluded up to 3 TeV, as opposed to 3.5 TeV as in the MSSM

# **Beyond the NLO**

- In the case of production of a heavy-mass system, a significant contribution to the cross section comes from the region near threshold, where the partonic centre-of-mass-energy is close to the kinematic restriction for the on-shell production
  - Dominant contributions:
    - soft-gluon emission off the initial- or final-state legs
    - exchange of gluons between slowly moving coloured particles in the final state (Coulomb correction)
- Here we discuss the resummation of soft-gluons. In principle Coulomb corrections can be resummed as well.

# **Basics of resumation framework**

NLO partonic cross-section near threshold partonic threshold  $\beta^2 \equiv 1 - 4m^2/\hat{s} \to 0$  $\hat{\sigma}^{\text{NLO}} = \hat{\sigma}^{(0)} \left[ 1 + \alpha_s \left( a \log^2 \beta^2 + b \log \beta^2 + c/\beta \right) \right]$ soft-gluon correction Coulomb correction

The resummation is performed in the Mellin space

$$\begin{split} \tilde{\sigma}_{h_1 h_2 \to \tilde{q} \tilde{q}^{(*)}} (N, \{m^2\}) &\equiv \int_0^1 d\rho \; \rho^{N-1} \; \sigma_{h_1 h_2 \to \tilde{q} \tilde{q}^{(*)}} (\rho, \{m^2\}) \\ &= \sum_{i,j} \; \tilde{f}_{i/h_1} (N+1, \mu^2) \; \tilde{f}_{j/h_2} (N+1, \mu^2) \; \tilde{\hat{\sigma}}_{ij \to \tilde{q} \tilde{q}^{(*)}} (N, \{m^2\}, \mu^2) \end{split}$$

where  $\beta \to 0$  corresponds to  $N \to \infty.$  Mellin transoform changes convolution into product.

Resummed cross section up to NNLL accuracy

$$\tilde{\hat{\sigma}}_{ij \to \tilde{q}\tilde{q}^{(*)}}^{(\text{res})}(N, \{m^2\}, \mu^2) = \sum_{I} \tilde{\hat{\sigma}}_{ij \to \tilde{q}\tilde{q}^{(*)}, I}^{(0)}(N, \{m^2\}, \mu^2) \left(1 + \frac{\alpha_{\text{s}}}{\pi} C_{ij \to \tilde{q}\tilde{q}^{(*)}, I}^{(1)}(N, \{m^2\}, \mu^2)\right) \\ \times \exp\left[Lg_1(\alpha_{\text{s}}L) + g_{2,I}(\alpha_{\text{s}}L) + \alpha_{\text{s}}g_{3,I}(\alpha_{\text{s}}L)\right]$$

# **Basics of resumation framework**

where:

- $\tilde{\sigma}^{(0)}_{ij \to \tilde{q}\tilde{q}^{(*)},I}$  is the color decomposed LO cross section in the Mellin space
- $C^{(1)}_{ij \to \tilde{q}\tilde{q}^{(*)},I}$  collects all  $\mathcal{O}(\alpha_s^3)$  non-logarithmic (in N) contributions which do not vanish at threshold

The hadronic cross-section in physical space at the NLO+NNLL accuracy (without doublecounting) is given by

$$\begin{split} \sigma_{h_1h_2 \to \tilde{q}\tilde{q}^{(\text{NLO}+(\text{N})\text{NLL})}(\rho, \{m^2\}, \mu^2) &= \sum_{i,j} \int_{\text{CT}} \frac{dN}{2\pi i} \rho^{-N} \tilde{f}_{i/h_1}(N+1, \mu^2) \tilde{f}_{j/h_2}(N+1, \mu^2) \\ &\times \left[ \tilde{\hat{\sigma}}_{ij \to \tilde{q}\tilde{q}^{(*)}}^{(\text{res})}(N, \{m^2\}, \mu^2) - \left. \tilde{\hat{\sigma}}_{ij \to \tilde{q}\tilde{q}^{(*)}}^{(\text{res})}(N, \{m^2\}, \mu^2) \right|_{(\text{NLO})} \right] + \sigma_{h_1h_2 \to \tilde{q}\tilde{q}^{(*)}}^{(\text{NLO})}(\rho, \{m^2\}, \mu^2) \end{split}$$

# **Reduction of theoretical uncertainty**

pp→qq\*





# NNLL K-factors [ $\sigma$ (NLO+NNLL)/ $\sigma$ (NLO)]



# $\sigma(MRSSM)/\sigma(MSSM)$ @ NLO+NNLL



# **Conclusions and outlook**

MRSSM is a valid alternative to the MSSM, with rich and distinct phenomenology It alieviates some of the MSSM constraints:

- colider limits from strongly interacting particles [1707.04557][1907.11641][2402.10160]
- FCNC constraints in quark sector
- FCNC constraints in lepton sector [1902.06650]
- is in agreement with EW precision and Higgs data [1410.4791][1504.05386]
- provides a viable dark matter candidate [1511.09334]
- can accommodate a 95 GeV "excess" in conjuntion with DM (see next talk)
   [2403.08720]
- predicts small muon g-2 [1902.06650]
- features unique particles like color-octet scalars and Dirac gluinos and neutralinos [0812.3586][1005.0818][1608.00915]
- MRSSM (and MSSM) results for squak pair production at NLO+NNLL accuracy are included in the NNLL-fast code [Beenakker, Borschensky, Krämer, Kulesza, Laenen (2016)][Beenakker, Borschensky, Krämer, Kulesza, Laenen, Mamužić, Moreno Valero (2024)]