Squark production with R-symmetry beyond NLO at the LHC

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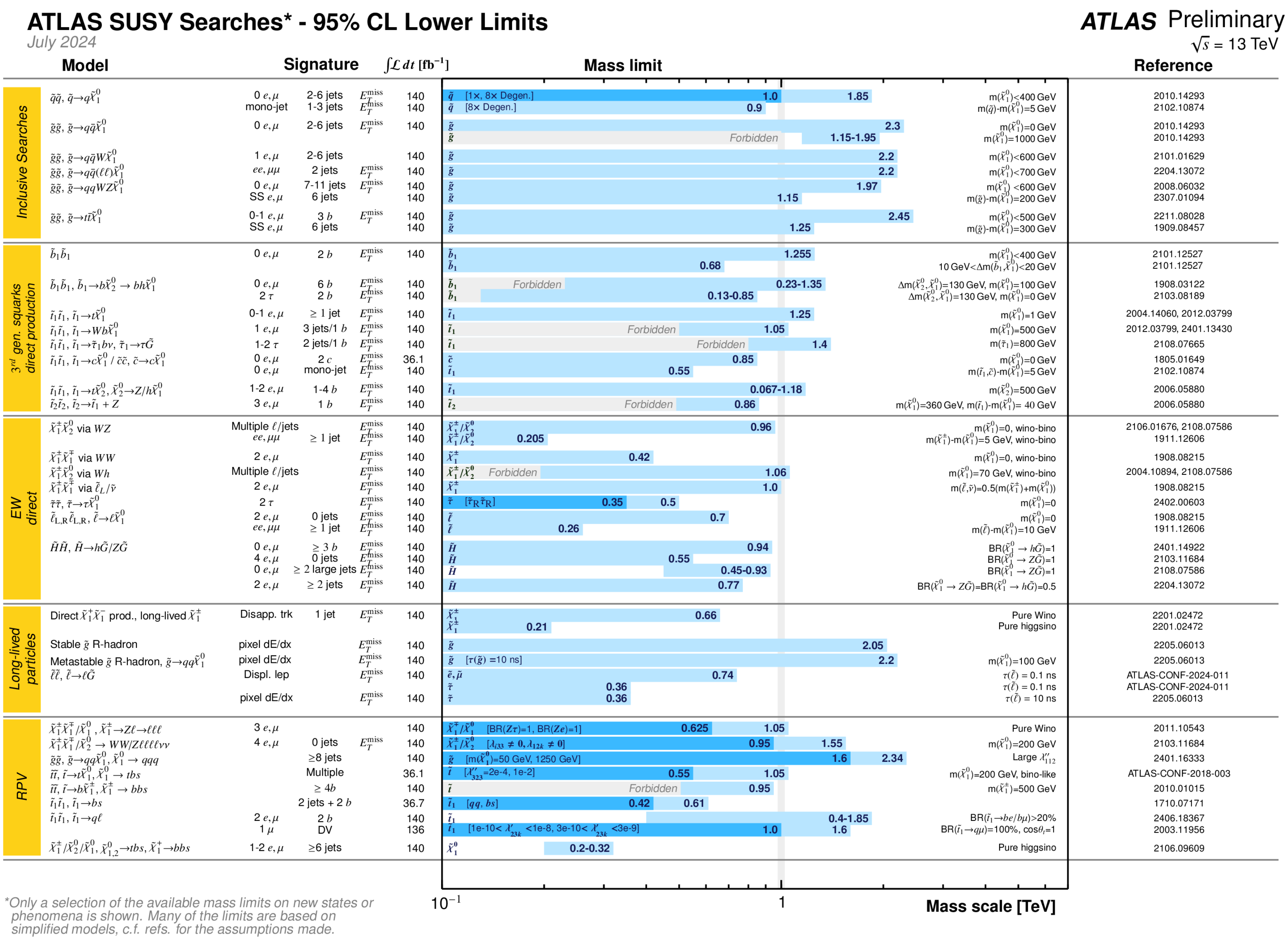
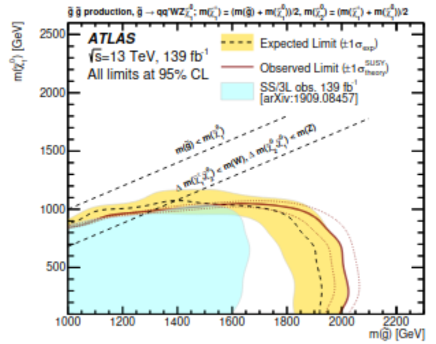
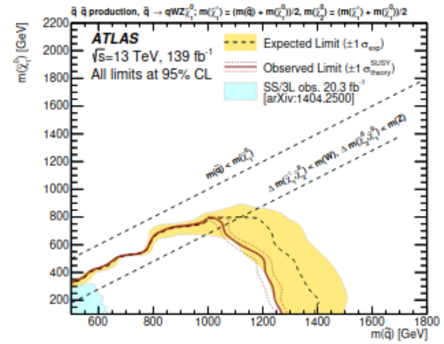
LHC BSM limits (example)



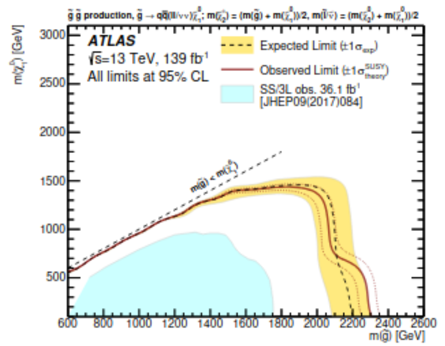
LHC squark – gluino limits



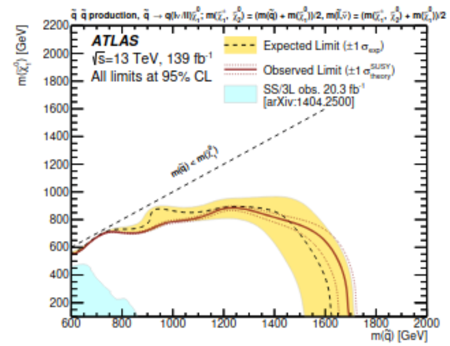
(a) $\tilde{g} \to qq'WZ\tilde{\chi}_1^0$.



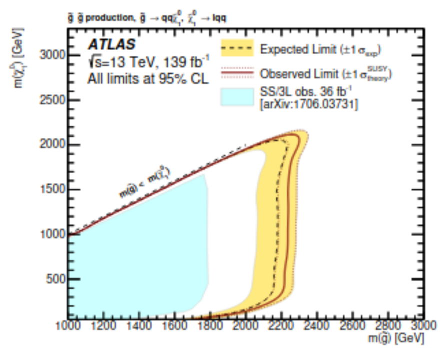
(b) $\tilde{q} \to q'WZ\tilde{\chi}_1^0$.



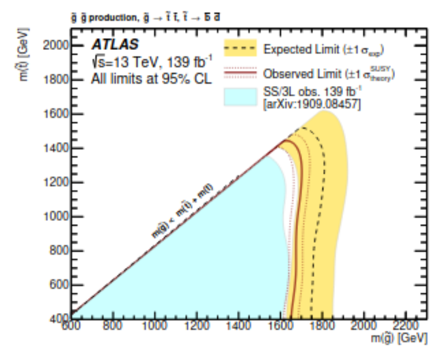
(c) $\tilde{g} \to q\bar{q}(\ell\ell/\nu\nu)\tilde{\chi}_1^0$.



(d) $\tilde{q} \to q(\ell\nu/\ell\ell/\nu\nu)\tilde{\chi}_1^0$.



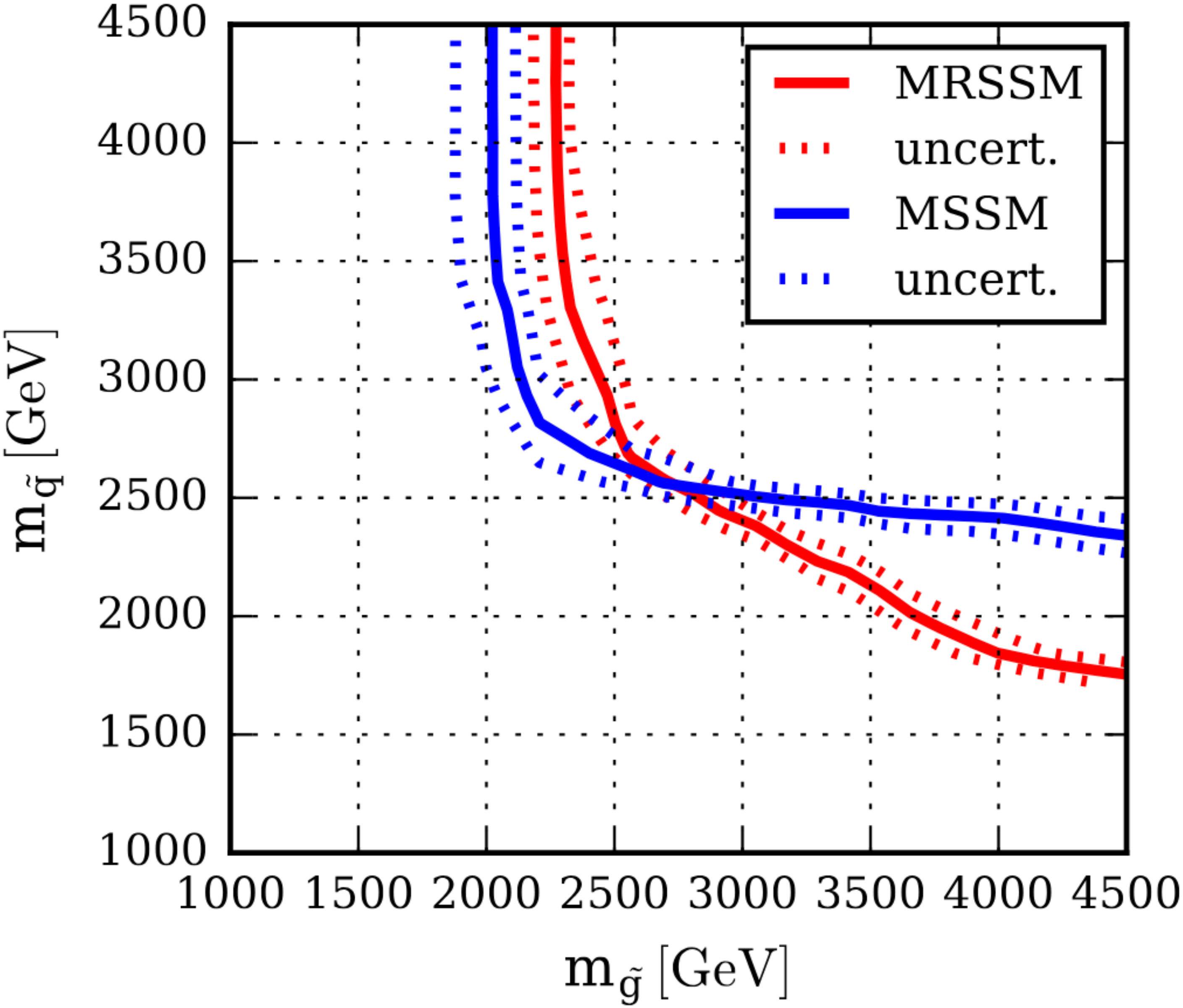
(e) $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to \ell qq$.



(f) $\tilde{g} \to \bar{t}t$, $\tilde{t} \to \bar{b}\bar{d}$.

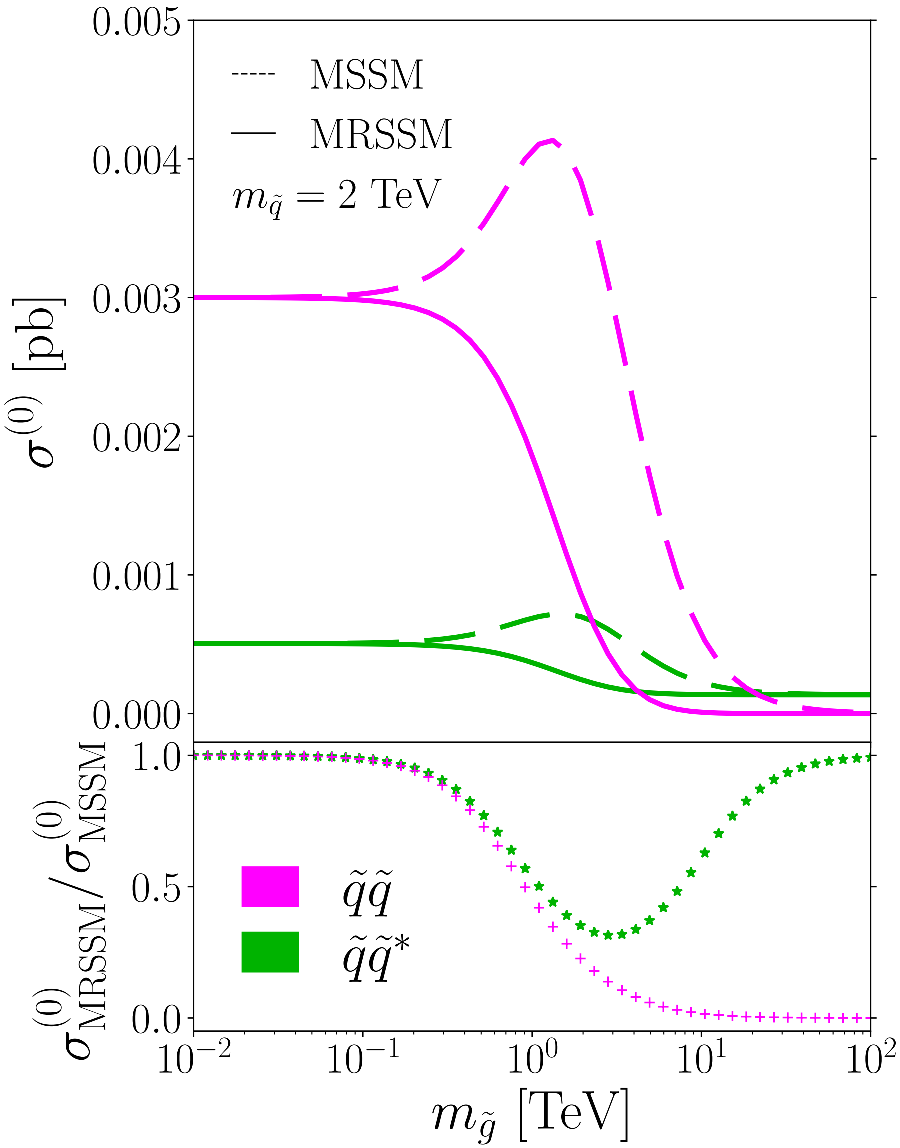
[JHEP02(2024)107]

Not the end of the story



[1907.11641]

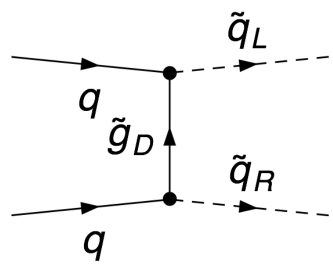
Gluino mass dependence

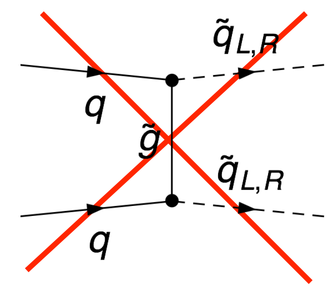


- Large difference in the intermediate $m_{\tilde{g}}$ region
  - $m_{\tilde{g}} \to 0$: Dirac vs. Majorana nature becomes neglidgeble
  - $m_{\tilde{g}} \to \infty$: t-channel diagrams become negligible
  - in the $\tilde{g}$-decoupling limit $\sigma^{(0)}_{\tilde{q}\tilde{q}} \to 0$ but:
    - MRSSM: $\sigma^{(0)}_{\tilde{q}\tilde{q}} \propto m_{\tilde{g}}^{-4}$
    - MSSM: $\sigma^{(0)}_{\tilde{q}\tilde{q}} \propto m_{\tilde{g}}^{-2}$

Overwiev of models with Dirac gauginos

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

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

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 $U(1)_R$ symmetry under which the SUSY generators are charged
- implies that the spinorial coordinates are also charged

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

- Lagrangian invariance
  - Kähler potential is automatically invariant
  - R-charge of the superpotential W must be 2

$Q_R(d^2\theta)=-2$

$Q_R(\mathcal{L})=0 \longrightarrow \mathcal{L} \ni \int d^2\theta\, W$

$Q_R(W)=+2$

  - soft-breaking terms must have R-charge 0

Low-energy R-symmetry realization

- Charges of component fields

$$\begin{array}{ccccccccc} e^{\imath\alpha Q_R} & & e^{\imath\alpha Q_R} & & e^{\imath\alpha(Q_R-1)} & & \\ \Phi & = & \phi(y) & + & \sqrt{2}\theta\psi(y) & + & \theta\theta F(y) \end{array}$$

- "Natural" choice

Higgs	$Q_R = 1$	$Q_R = 1$	$Q_R = 0$
leptons and quarks	$Q_R = 0$	$Q_R = 0$	$Q_R = -1$

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

One way to fix it: Dirac masses
Minimal R-Symmetric Supersymmetric Standardmodel (MRSSM)
Kribs et.al. arXiv:0712.2039

			$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_R$
Additional fields:	Singlet	$\hat{S}$	1	1	0	0
	Triplet	$\hat{T}$	1	3	0	0
	Octet	$\hat{O}$	8	1	0	0
	R-Higgses	$\hat{R}_u$	1	2	$-1/2$	2
		$\hat{R}_d$	1	2	$1/2$	2

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

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
  - B_μ - term
  - soft scalar masses
  - Majorana gaugino masses
  - A - terms

- MRSSM superpotencial

$$\mu_d\,\hat{R}_d\,\hat{H}_d + \mu_u\,\hat{R}_u\,\hat{H}_u$$

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

$$\Lambda_d\,\hat{R}_d\,\hat{T}\,\hat{H}_d + \Lambda_u\,\hat{R}_u\,\hat{T}\,\hat{H}_u + \lambda_d\,\hat{S}\,\hat{R}_d\,\hat{H}_d + \lambda_u\,\hat{S}\,\hat{R}_u\,\hat{H}_u$$

- MRSSM soft-SUSY breaking terms
  - B_μ - term (though no B_{μ_u}, B_{μ_d})
  - soft scalar masses
  - Dirac gaugino masses
  - no A-terms

One way to fix it: Dirac masses

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R-symmetry vs. matter parity

- Consider R-symmetric transformation of a generic supermultiplet

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

- 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 $P_R = (-1)^{3(\mathrm{B}-\mathrm{L})+2s}$
  - This is also equivalent to R-symmetry $R = e^{\imath\varphi R_\Phi}$ 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

different number of physical state

completely new states

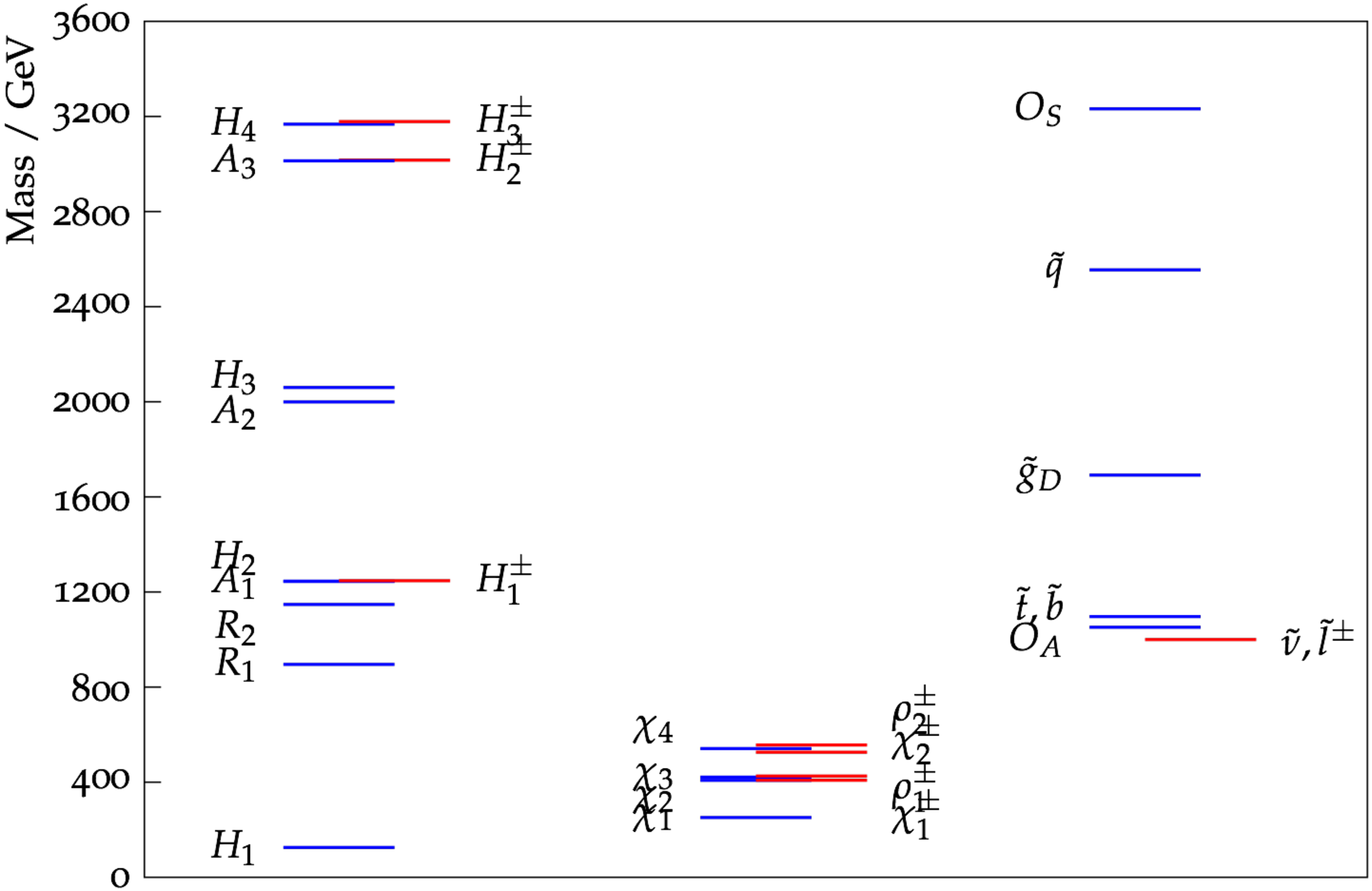
	Higgs				R-Higgs		
	CP-even	CP-odd	charged	charginos	neutral	charged	sgluon
MSSM	2	1	1	2	0	0	0
MRSSM	4	3	3	2+2	2	2	2

	neutralino	gluino
MSSM	4	1
MRSSM	4	1

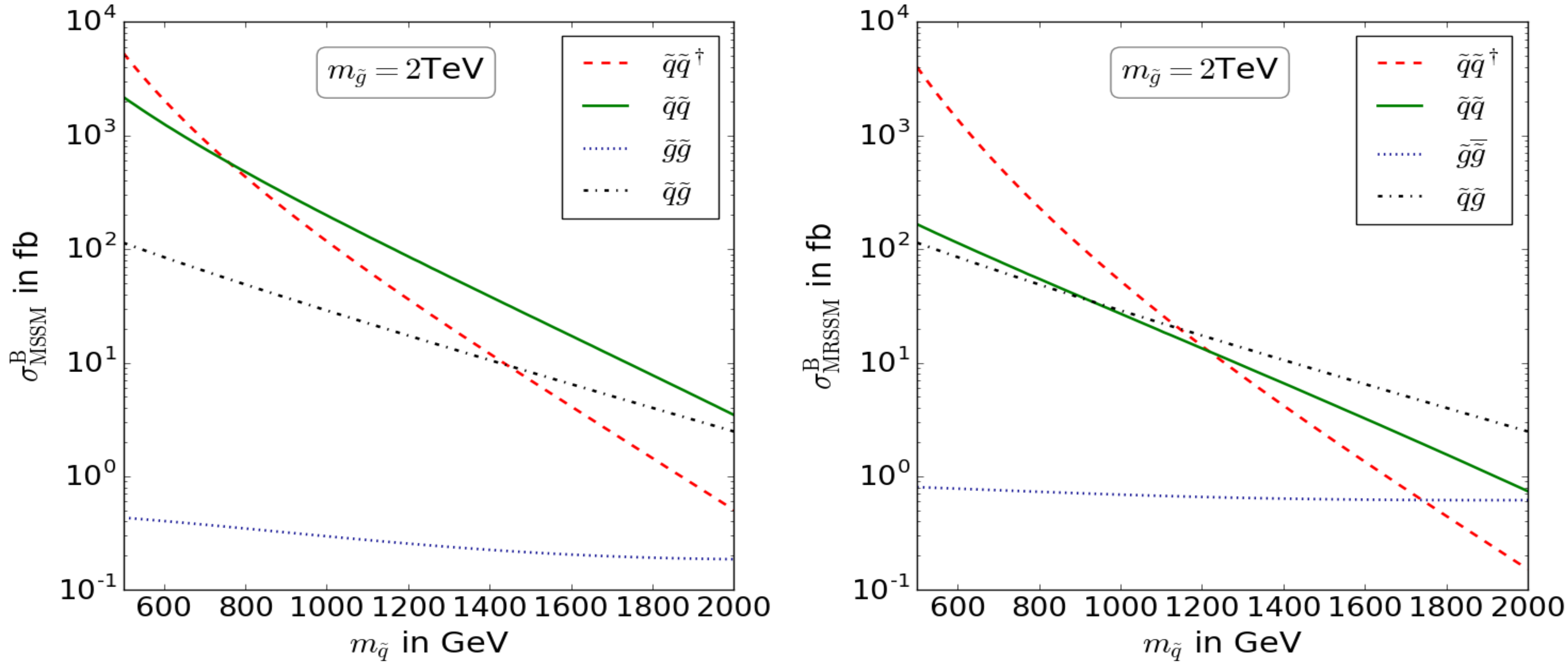
Majorana fermions

Dirac fermions

Example of a mass spectrum



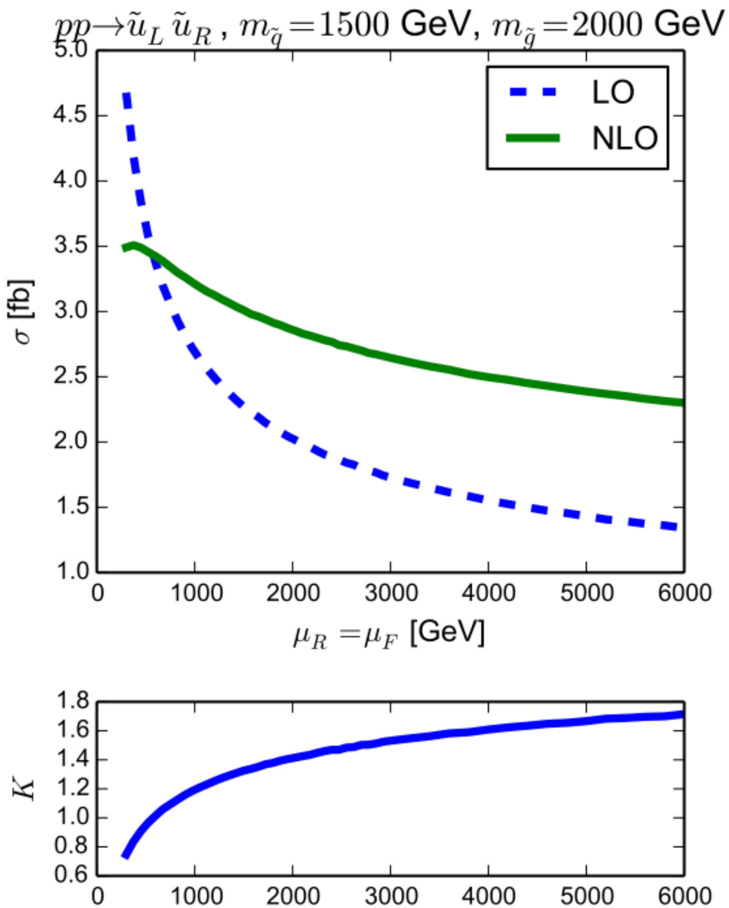
Squark pair production @ LO

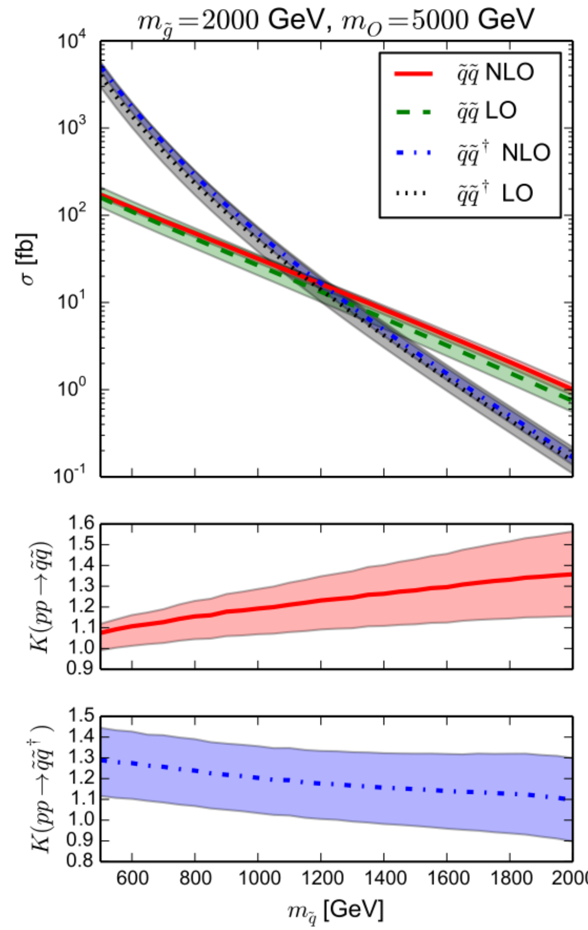


NLO setup

- 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

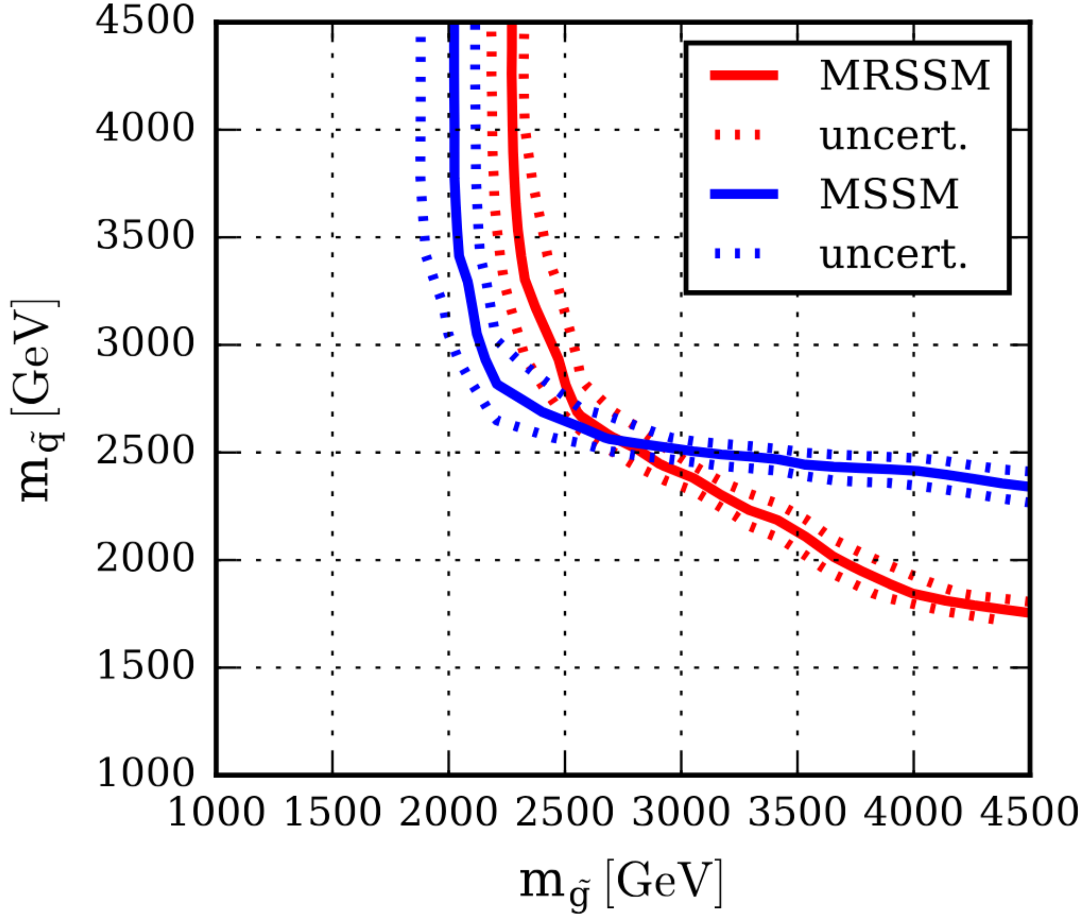
K-factors and reduction of theoretical uncertainty





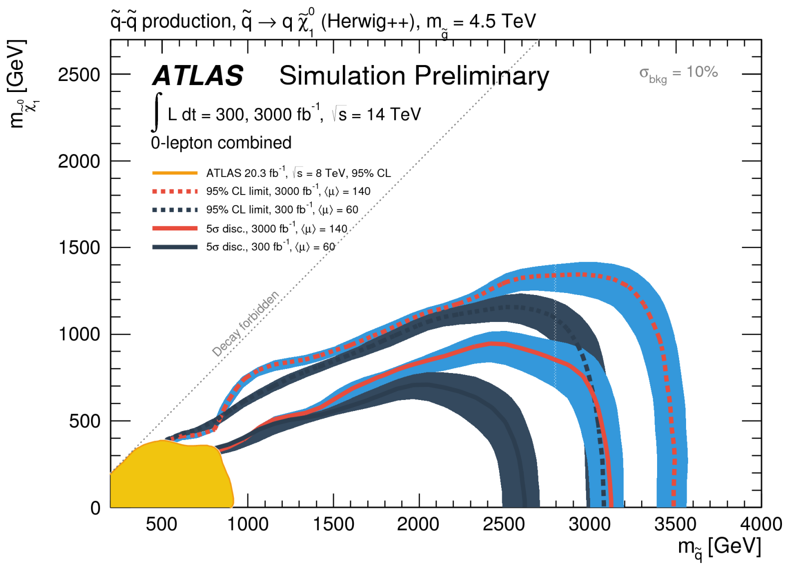
Phenomenological implications

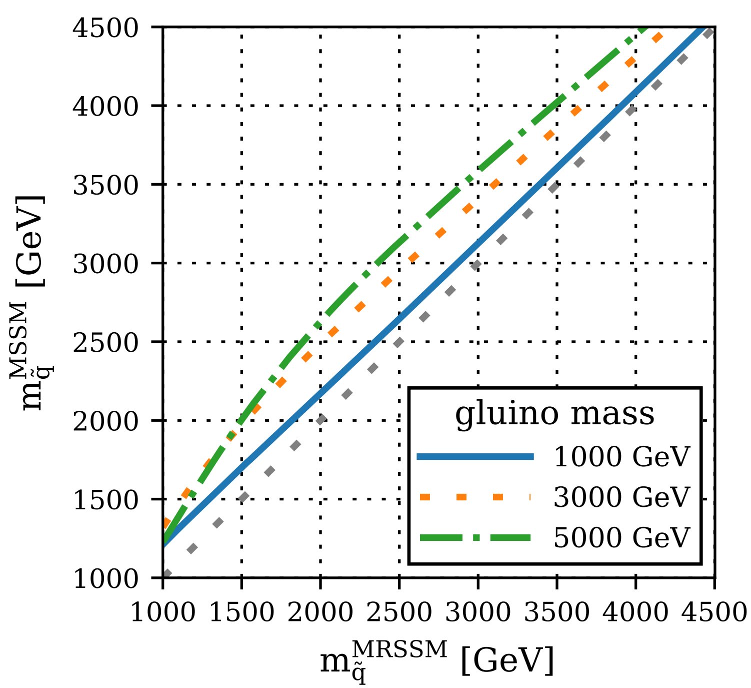
$$m_{\tilde{g}} > \begin{cases} 2.2 \text{ TeV (MRSSM)} \\ 2.0 \text{ TeV (MSSM)} \end{cases} \quad (m_{\tilde{q}} = 5 \text{ TeV})$$



$$m_{\tilde{q}} > \begin{cases} 1.7 \text{ TeV (MRSSM)} \\ 2.3 \text{ TeV (MSSM)} \end{cases} \quad (m_{\tilde{g}} = 5 \text{ TeV})$$

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^{-1} 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 resummation framework

- NLO partonic cross-section near threshold partonic threshold $\beta^2 \equiv 1 - 4m^2/\hat{s} \to 0$

$$\hat{\sigma}^{\mathrm{NLO}} = \hat{\sigma}^{(0)} \left[1 + \alpha_s \left(a \log^2 \beta^2 + b \log \beta^2 + c/\beta\right)\right]$$

soft-gluon correction Coulomb correction

- The resummation is performed in the Mellin space

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

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

- Resummed cross section up to NNLL accuracy

$$\begin{aligned}
\tilde{\hat{\sigma}}^{(\mathrm{res})}_{ij \to \tilde{q}\tilde{q}^{(*)}}(N, \{m^2\}, \mu^2) = \sum_I \tilde{\hat{\sigma}}^{(0)}_{ij \to \tilde{q}\tilde{q}^{(*)}, I}(N, \{m^2\}, \mu^2) \left(1 + \frac{\alpha_s}{\pi} \, C^{(1)}_{ij \to \tilde{q}\tilde{q}^{(*)}, I}(N, \{m^2\}, \mu^2)\right) \\
\times \, \exp\left[L g_1(\alpha_s L) + g_{2,I}(\alpha_s L) + \alpha_s g_{3,I}(\alpha_s L)\right]
\end{aligned}$$

Basics of resummation framework

where:

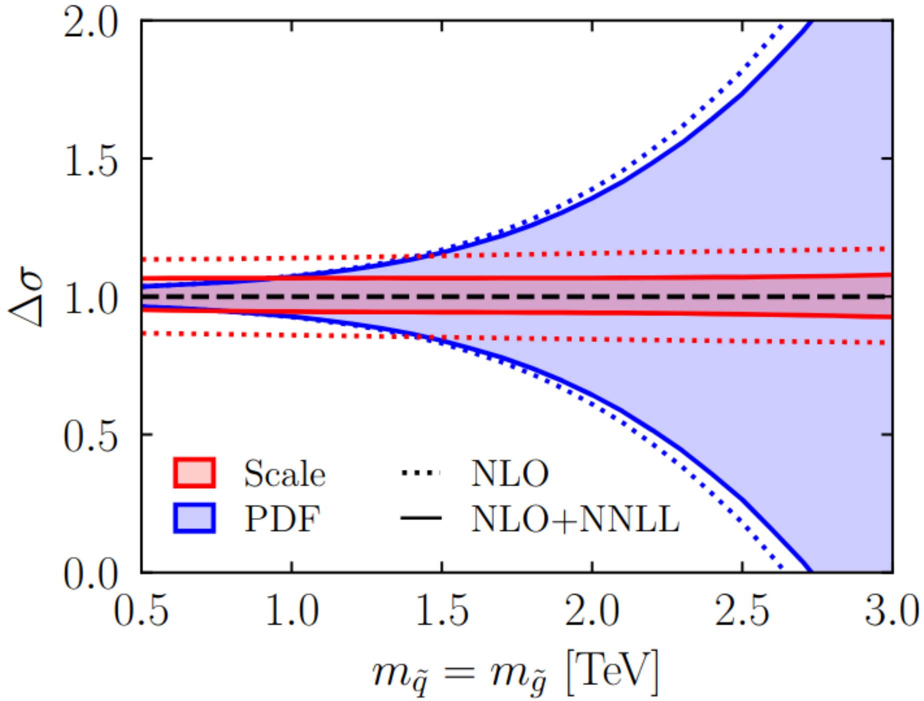
- $\tilde{\sigma}^{(0)}_{ij\to\tilde{q}\tilde{q}^{(*)},I}$ is the color decomposed LO cross section in the Mellin space
- $C^{(1)}_{ij\to\tilde{q}\tilde{q}^{(*)},I}$ collects all $\mathcal{O}(\alpha_s^3)$ non-logarithmic (in N) contributions which do not vanish at threshold

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

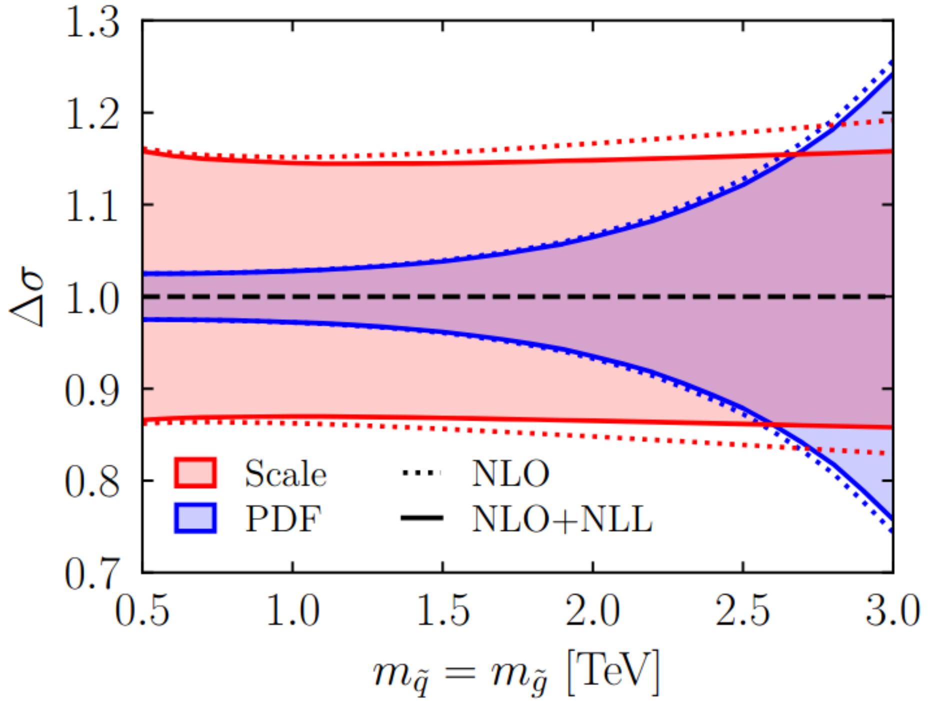
$$\sigma^{(\mathrm{NLO+(N)NLL})}_{h_1h_2\to\tilde{q}\tilde{q}^{(*)}}(\rho,\{m^2\},\mu^2) = \sum_{i,j}\int_{\mathrm{CT}}\frac{dN}{2\pi \mathrm{i}}\,\rho^{-N}\tilde{f}_{i/h_1}(N+1,\mu^2)\tilde{f}_{j/h_2}(N+1,\mu^2)$$
$$\times\left[\tilde{\hat{\sigma}}^{(\mathrm{res})}_{ij\to\tilde{q}\tilde{q}^{(*)}}(N,\{m^2\},\mu^2)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

Reduction of theoretical uncertainty

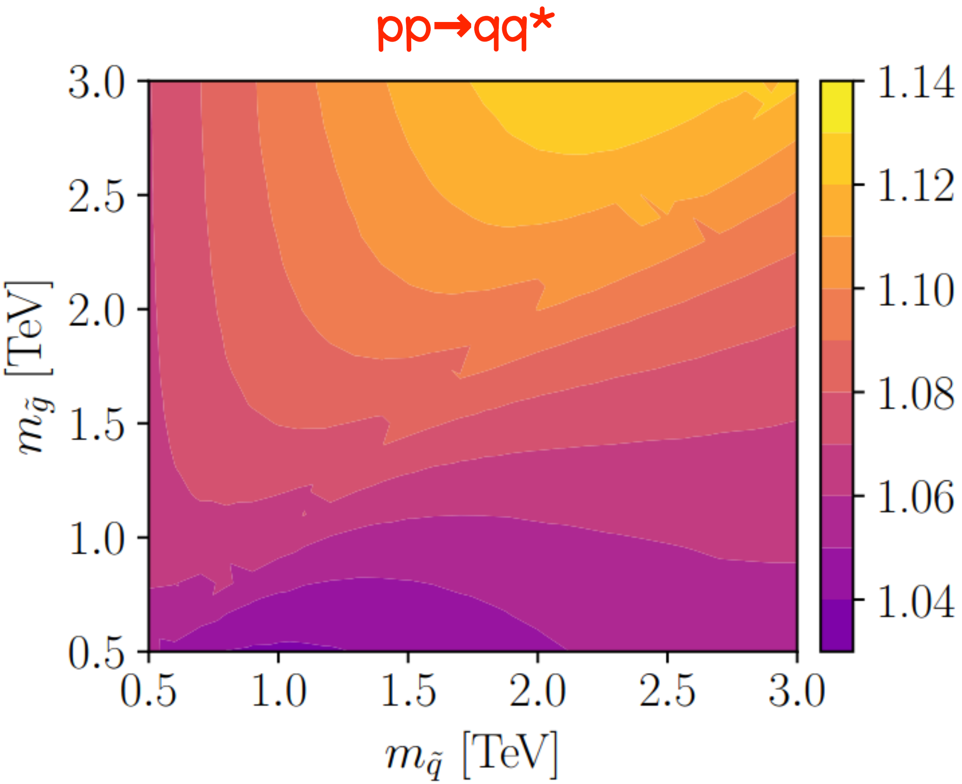
pp→qq*

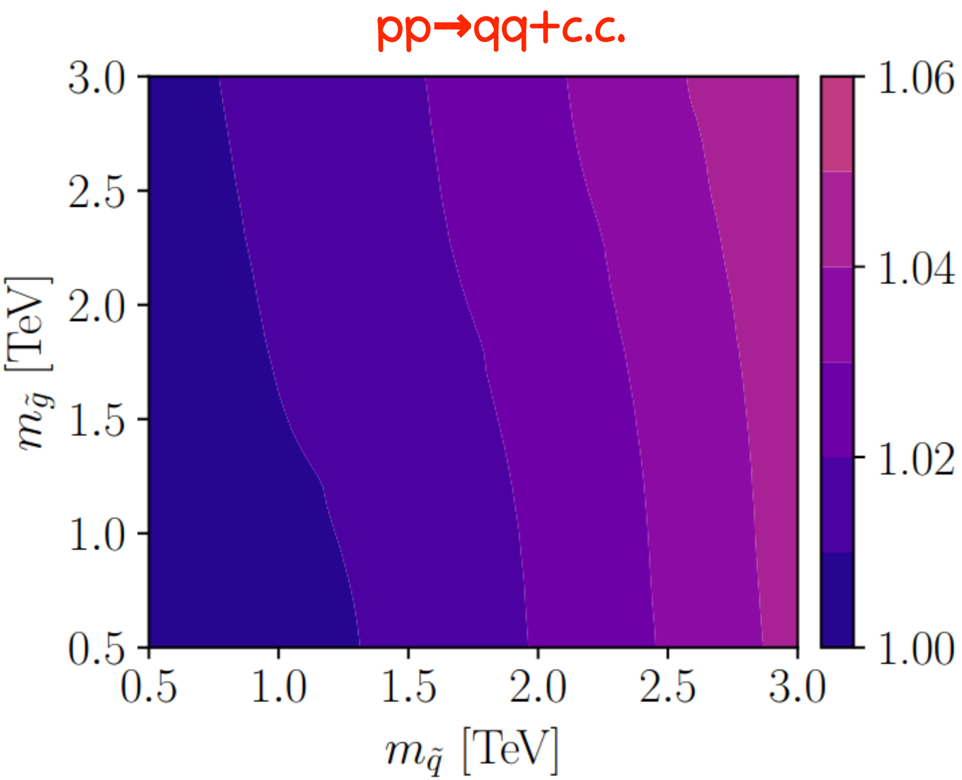


pp→qq+c.c.



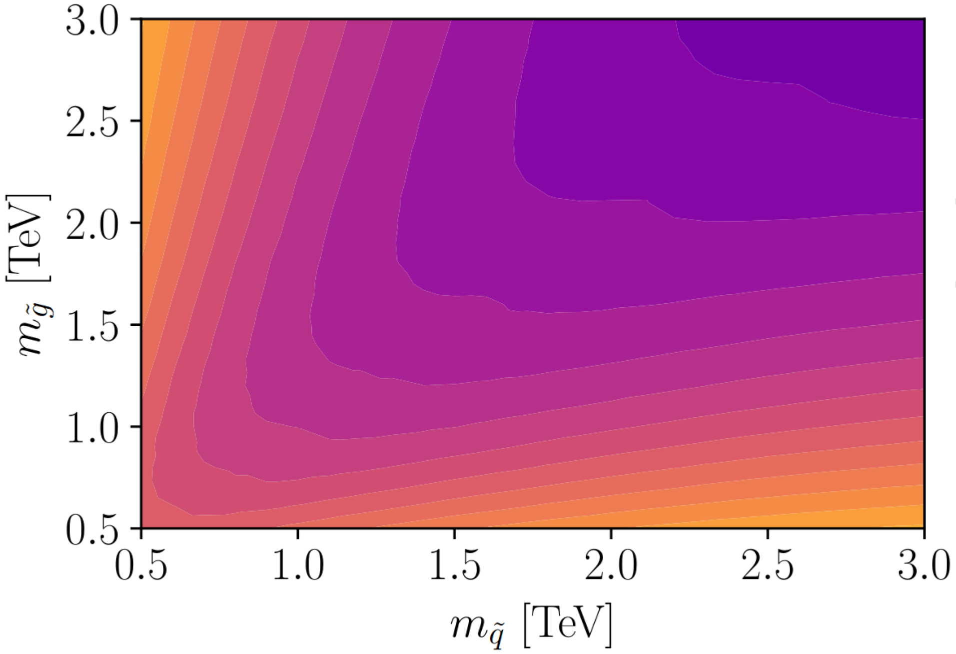
NNLL K-factors [σ(NLO+NNLL)/σ(NLO)]



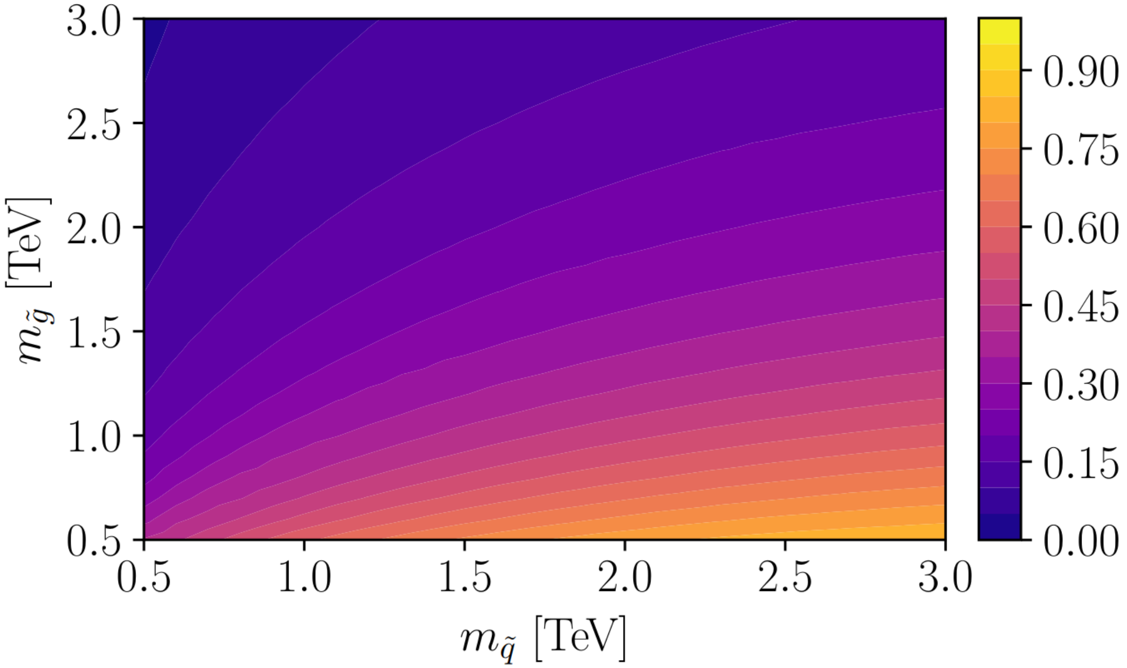


σ(MRSSM)/σ(MSSM) @ NLO+NNLL

pp→qq*



pp→qq+c.c.



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)]