Confronting the coloured sector of the MRSSM with LHC data

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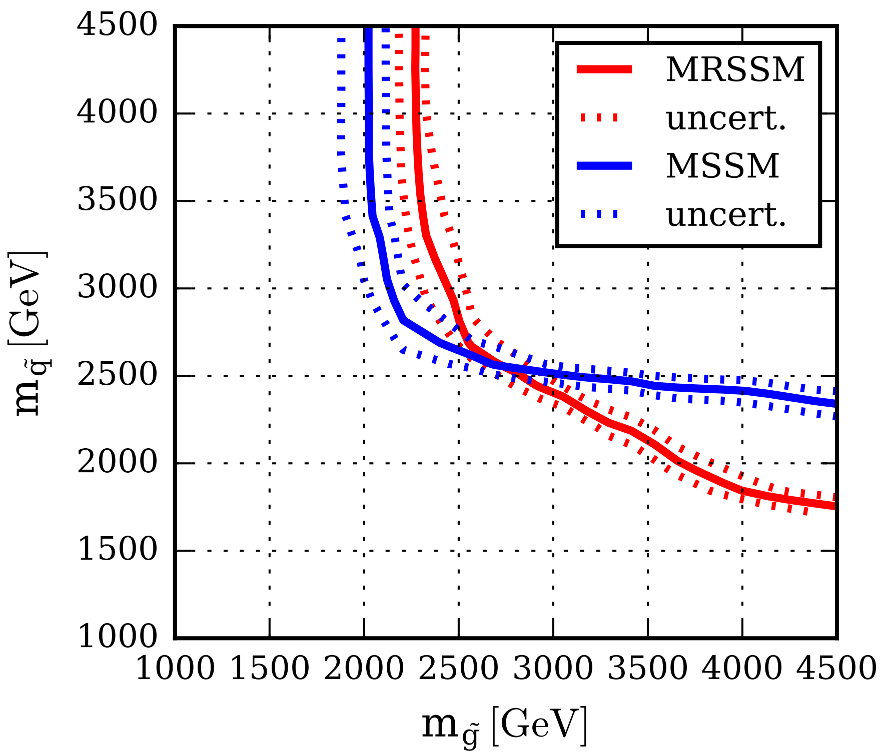
The goal of this talk



- `if MRSSM == ❤ then`
  - find out what are the exclusion limits on squark and gluino masses in this model
- `else`
  - Show how exclusion limits in squark-gluino mass plane change beyond the MSSM
  - Specifically, show that in the some model (MRSSM), for heavy gluino, squark mass limits are ~600 GeV lower than in the MSSM.
  - This contextualises the "model independent" bounds given by experimentalists

R-symmetry

- additional symmetry of the SUSY algebra allowed by the Haag - Łopuszański - Sohnius theorem [Fayet, Salam, Strathdee, ….]
- 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 K term is automatically invariant

$$\mathcal{L} \ni \int d^2\theta d^2\bar{\theta} \; K$$

  - R-charge of the superpotential W must be 2

$$\mathcal{L} \ni \int d^2\theta W$$

  - soft-breaking terms must have R-charge 0

Low-energy R-symmetry realization

- freedom in the choice of chiral superfield charge

R charges of component fields

	Q_R	scalar	vector	fermionic
vector superfield	0	-	0	1
chiral superfield	Q	Q	-	$Q-1$

- we choose SM fields to have R=0 ➜ Higgs superfields Q_R=0, lepton and quark superfields have Q_R=±1
- with the above assignment R-symmetry forbids
  - $\mu \hat{H}_u \hat{H}_d$
  - $\lambda \hat{E}\hat{L}\hat{L}, \kappa \hat{U}\hat{D}\hat{D}, e\hat{H}\hat{L}$
  - 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

			$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_R$
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

MRSSM lagrangian

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

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

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

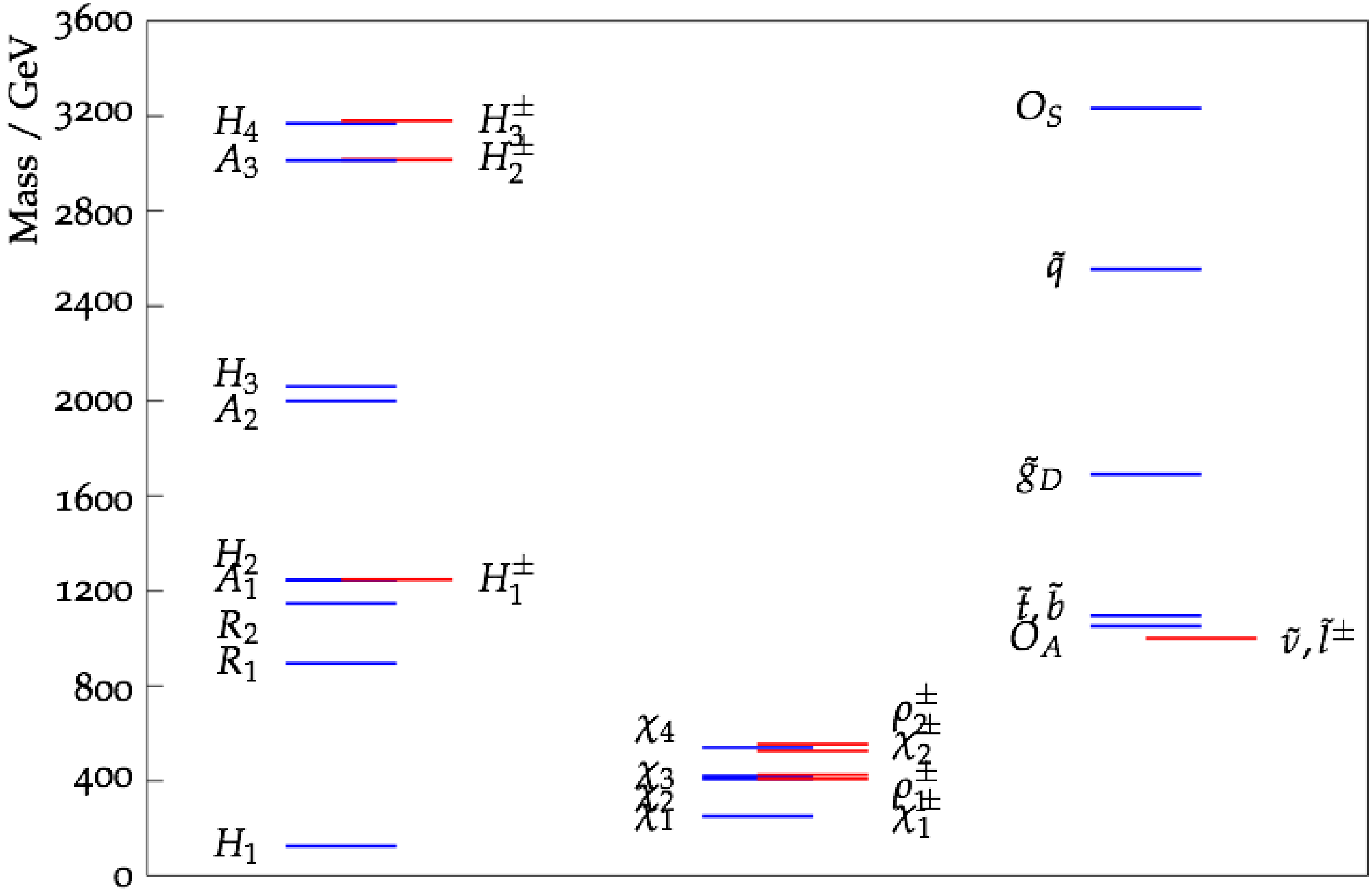
Particle content summary: MSSM vs. MRSSM

different number of physical states — 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	1

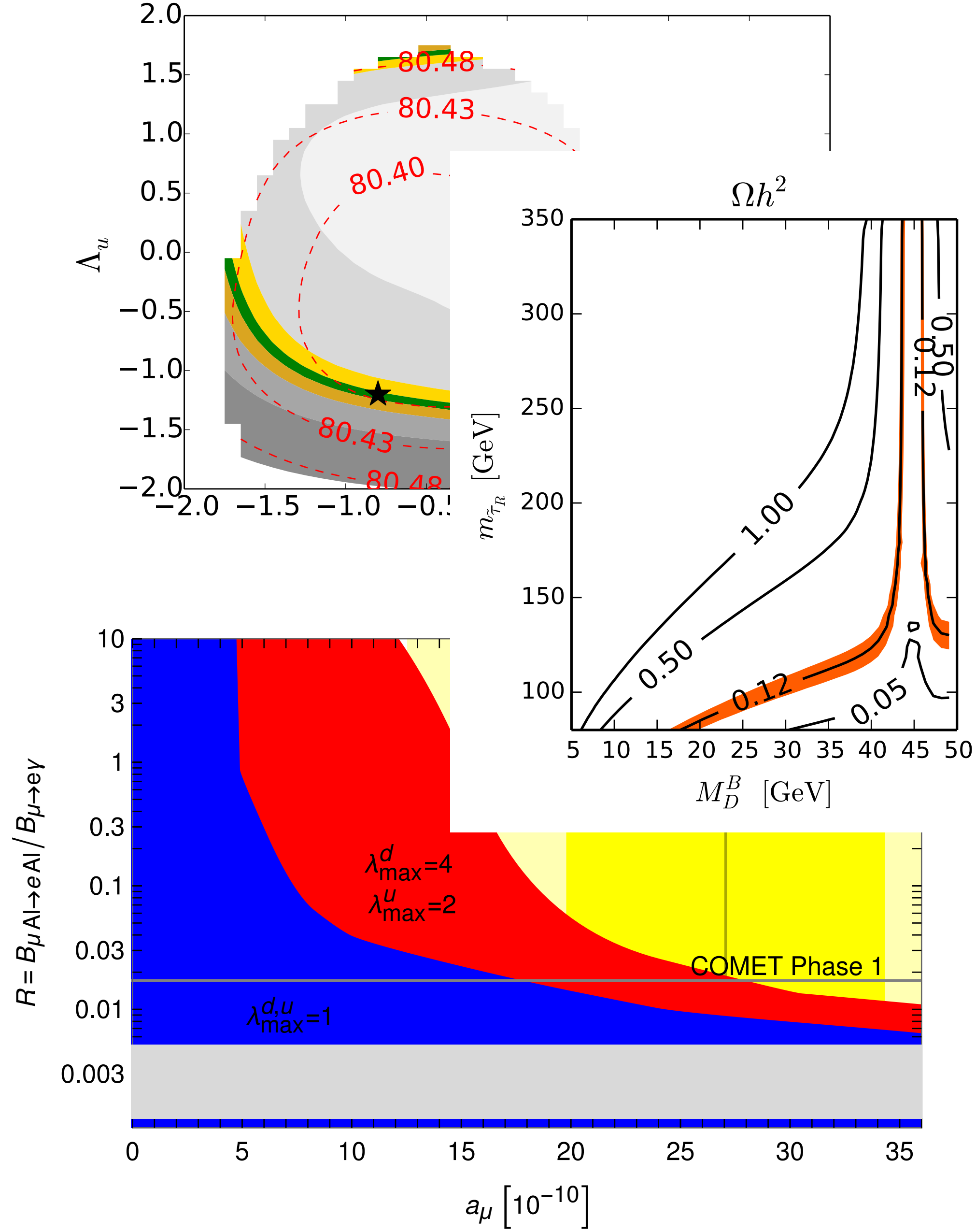
	neutralino	gluino	
MSSM	4	1	Majorana fermions
MRSSM	4	1	Dirac fermions

Exemplary mass spectrum



Rich phenomenology

- Agreement with precision electroweak observables [10.1007/JHEP12(2014)124]
- Correct Higgs-boson mass at 1- or 2-loop levels [10.1007/JHEP12(2014)124,10.1155/2015/760729]
- Provides a candidate for dark matter, in agreement with relic density and direct detection [10.1007/JHEP03(2016)007]
- (g-2)$_\mu$ and lepton flavour violation (see Dominik's talk on Thursday) [10.1007/JHEP08(2019)082]

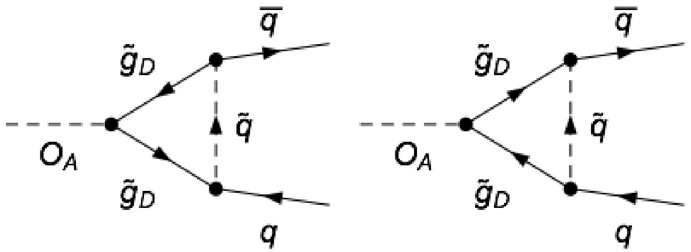


MRSSM SQCD sector pheno

- sgluon pair production
  - complex field O split by D-term into scalar (S) and pseudoscalar (A) parts

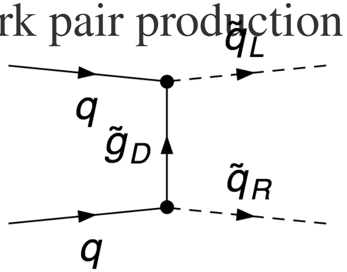
$$m^2_{O_A} = m^2_O \qquad m^2_{O_S} = m^2_O + 4(M^D_O)^2$$

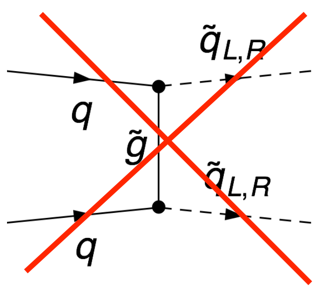
  - O_S naturally heavy, O_A might decay into quarks through loop-induced coupling



  - Coupling proportional to m_q. If O_A is lighter than other SUSY particles but heavien then $2m_t$ O_A decays exclusively to top quarks

- same sign squark pair production

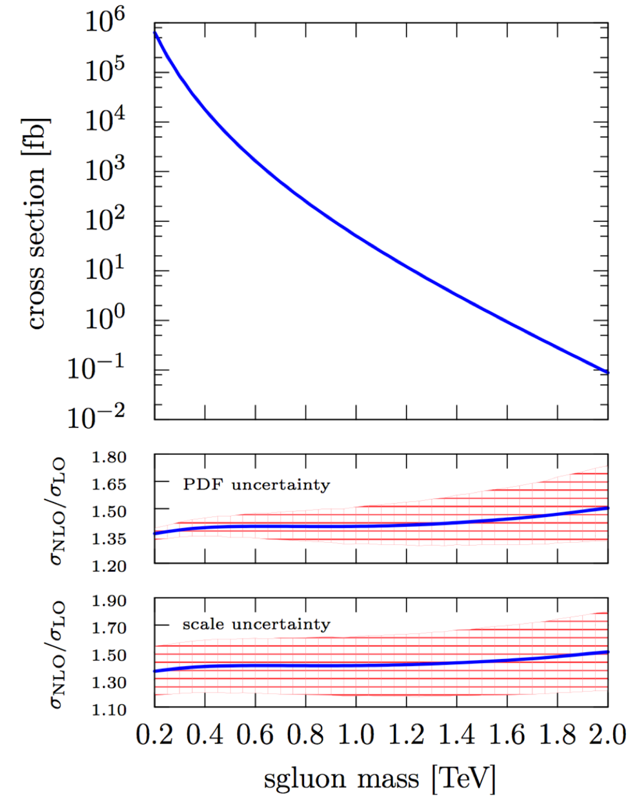


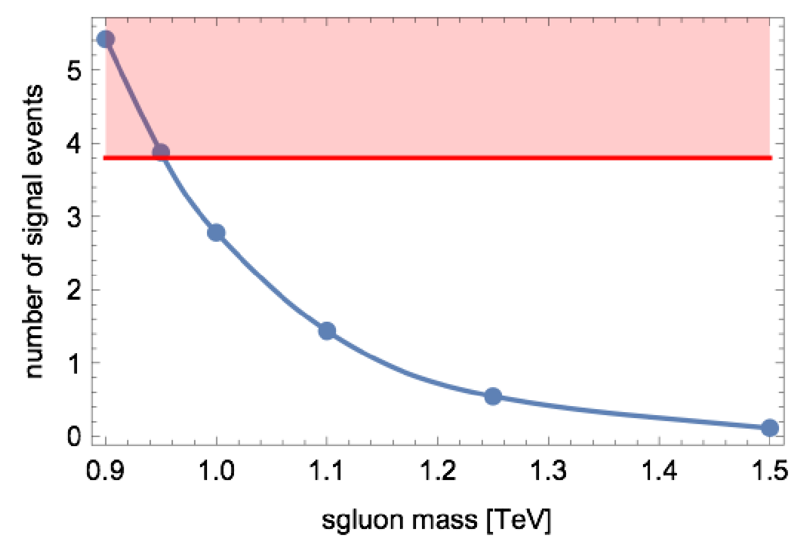


- Dirac gluino pair production, with cross section roughly twice as large as in the MSSM

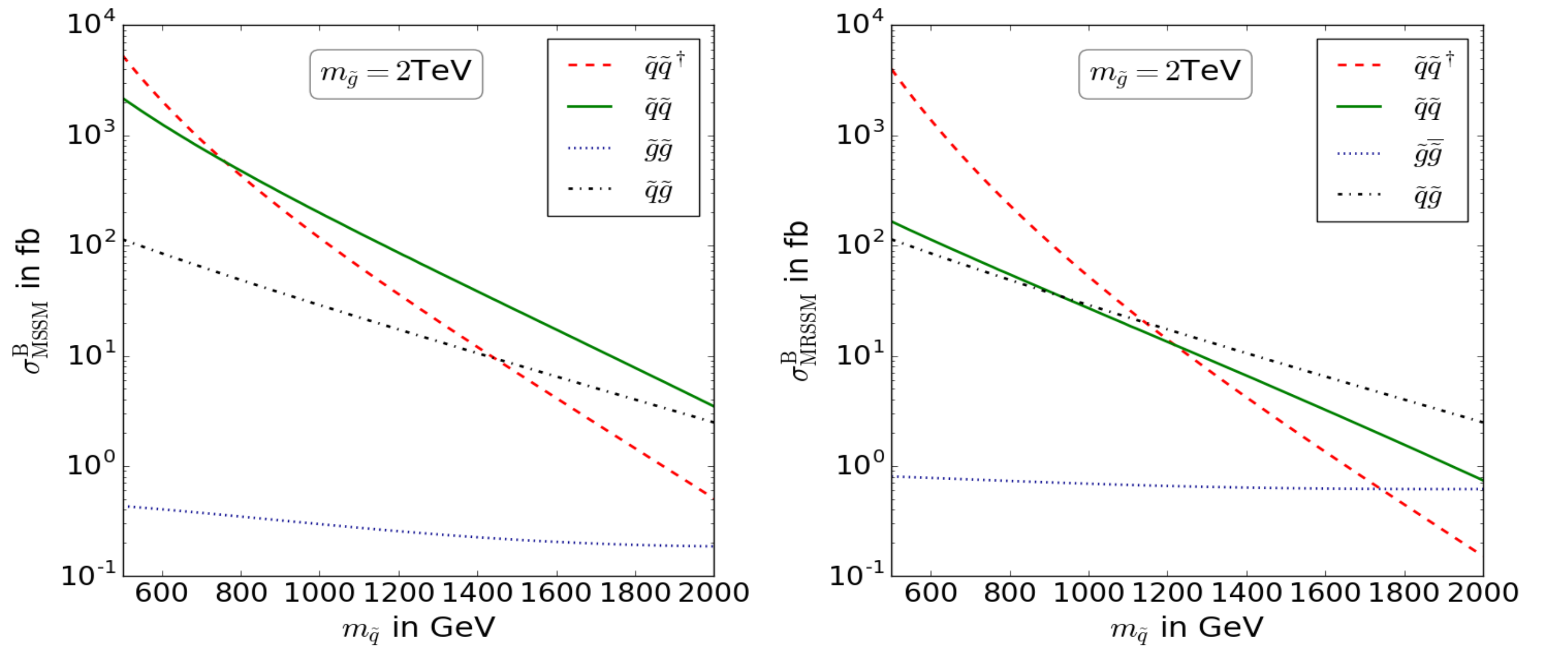
Sgluon pair production

- 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 sgluons decaying with $\mathrm{BR}(O \to t\bar{t}) = 1$ excluded up to 950 GeV





Squark pair production



Scenarios

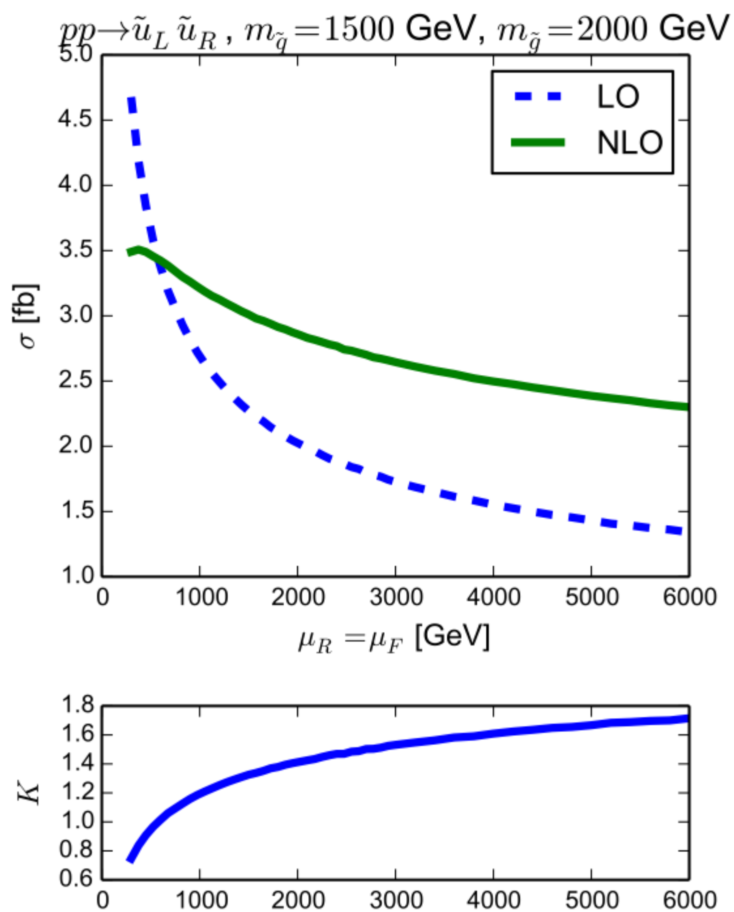
- **Scenario A**: squarks of the first and second generation degenerate in mass; no flavour mixing and LSP is assumed massless.
- **Scenario B**: mass splitting between left- and right-handed squarks, no flavour mixing one common mass left-handed squark mass and one common right-handed squark mass; LSP is assumed to be massless
- **Scenario C**: flavour mixing between first and third generation; LSP is assumed massless and $m_g = 5$ TeV

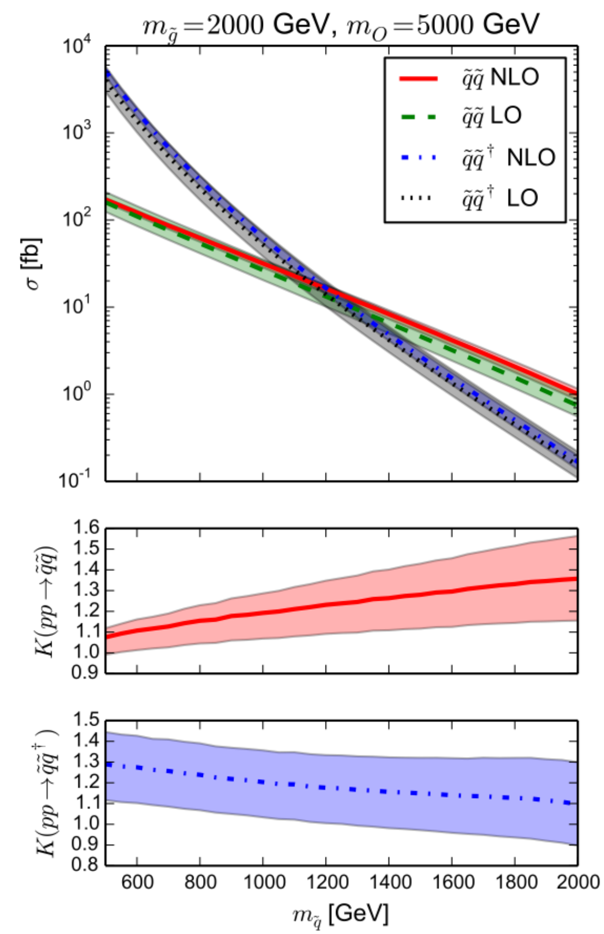
Computation setup

- Herwig-7.1.2 is used for leading order event generation and decays using Sarah generated UFO model
- Parameter spectra are generated using SARAH generated Spheno module
- Global K-factors application:
  - MSSM: We use NLLfast. We don't use NLL resummation in derivation of limits as it's not available in the MRSSM
  - MRSSM: we use our own, dedicated calculation of NLO corrections in the MRSSM using MadGraph5_aMC@NLO-2.5.5 and GoSam-2
- Limits are then calculated using CheckMATE-2.0.26

NLO K-factors

- First computation of NLO correction to squark pair production in the MRSSM available since [10.1007/JHEP10(2017)142]





Uncertainty estimate

- We use NNLLfast to estimate uncertainty of

$$\Delta\sigma^{\mathrm{MSSM}} \equiv |\sigma_{\mathrm{tot}}(\mathrm{NNLL}) - \sigma_{\mathrm{tot}}(\mathrm{NLO})|$$

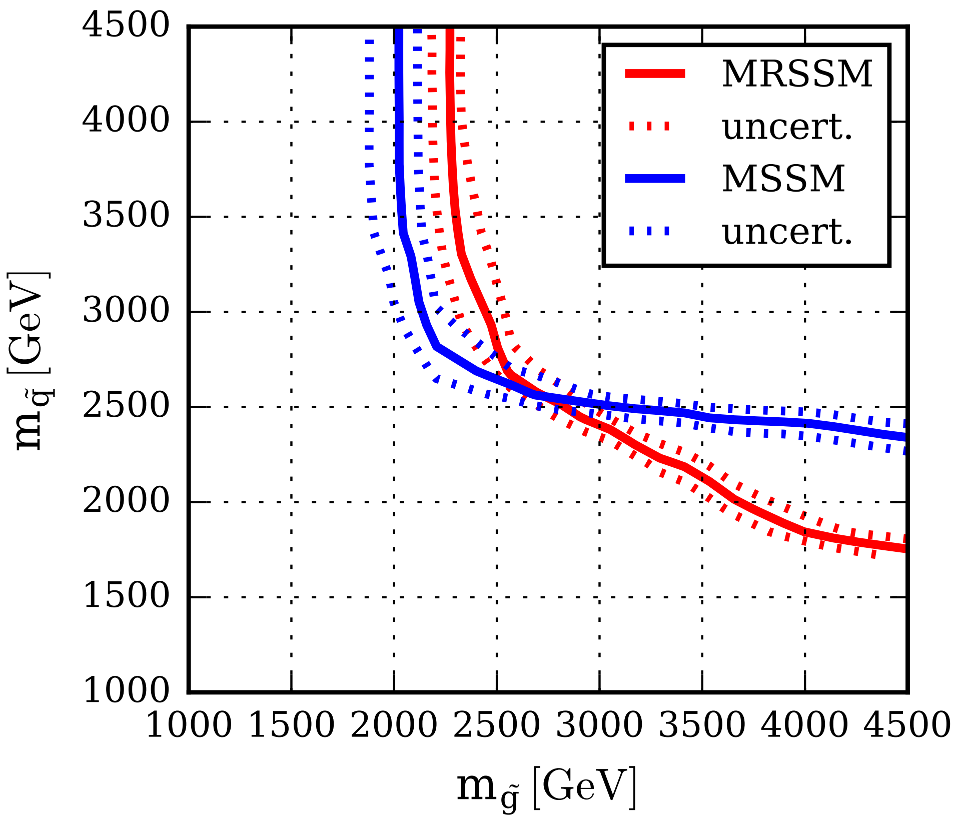
- For MRSSM

$$\Delta\sigma^{\mathrm{MRSSM}} = \left(\left(\frac{\sigma_{\mathrm{tot}}^{\mathrm{MSSM}}(\mathrm{NNLL}) - \sigma_{\mathrm{tot}}^{\mathrm{MSSM}}(\mathrm{NLO})}{\sigma_{\mathrm{tot}}^{\mathrm{MSSM}}(\mathrm{NLO})} \sigma_{\mathrm{tot}}^{\mathrm{MRSSM}}(\mathrm{NLO}) \right)^2 \right.$$
$$\left. + \left(\sigma_{\tilde{q}\tilde{q}+\tilde{q}\tilde{q}^*}(\mathrm{NLO}, m_O = m_O^{\mathrm{up/down}}) - \sigma_{\tilde{q}\tilde{q}+\tilde{q}\tilde{q}^*}(\mathrm{NLO}, m_O = m_O^{\mathrm{ref}}) \right)^2 \right)^{1/2} .$$

  - The last term comes from non decoupling effect of sgluons

$$\hat{g}_s - g_s = \frac{\alpha_s}{8\pi} \left(\log \frac{m_{O_s}^2}{m_{\tilde{g}}^2} + \log \frac{m_{O_p}^2}{m_{\tilde{g}}^2} \right)$$

Scenario A

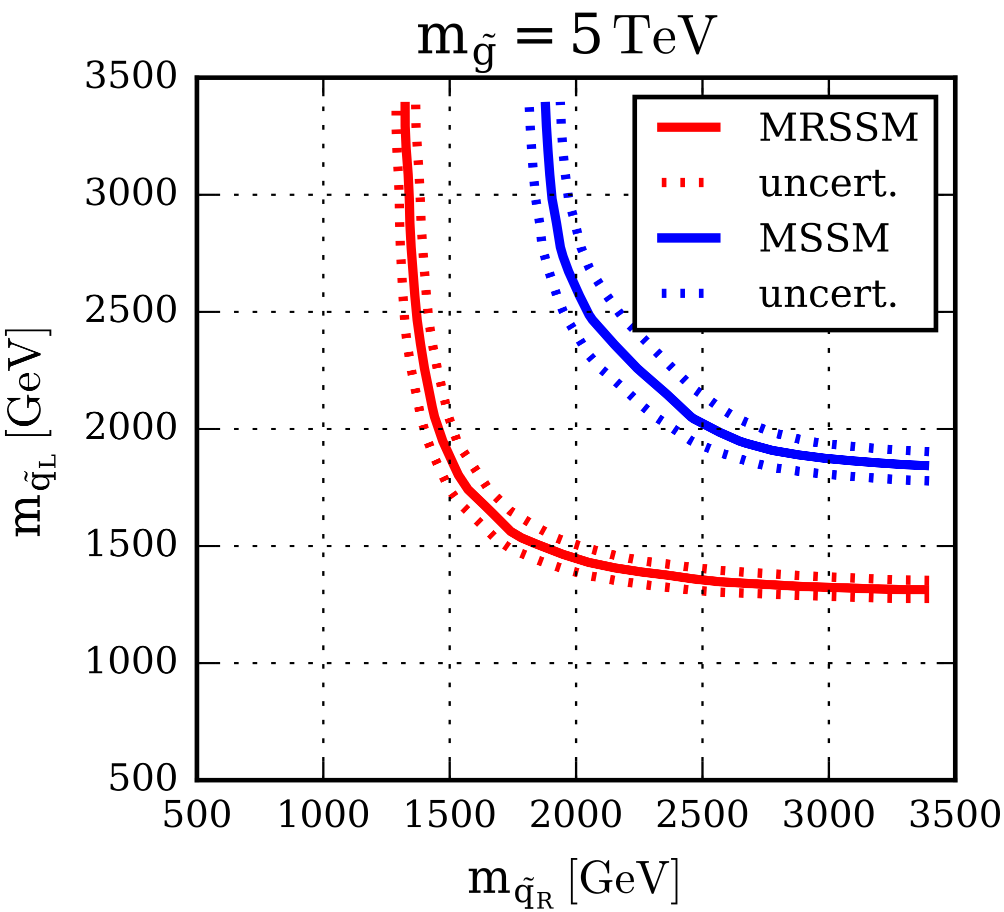


$$m_{\tilde{q}} > \begin{cases} 1.7 \text{ TeV (MRSSM)} \\ 2.3 \text{ TeV (MSSM)} \end{cases} \quad (m_{\tilde{g}} = 5 \text{ TeV})$$

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

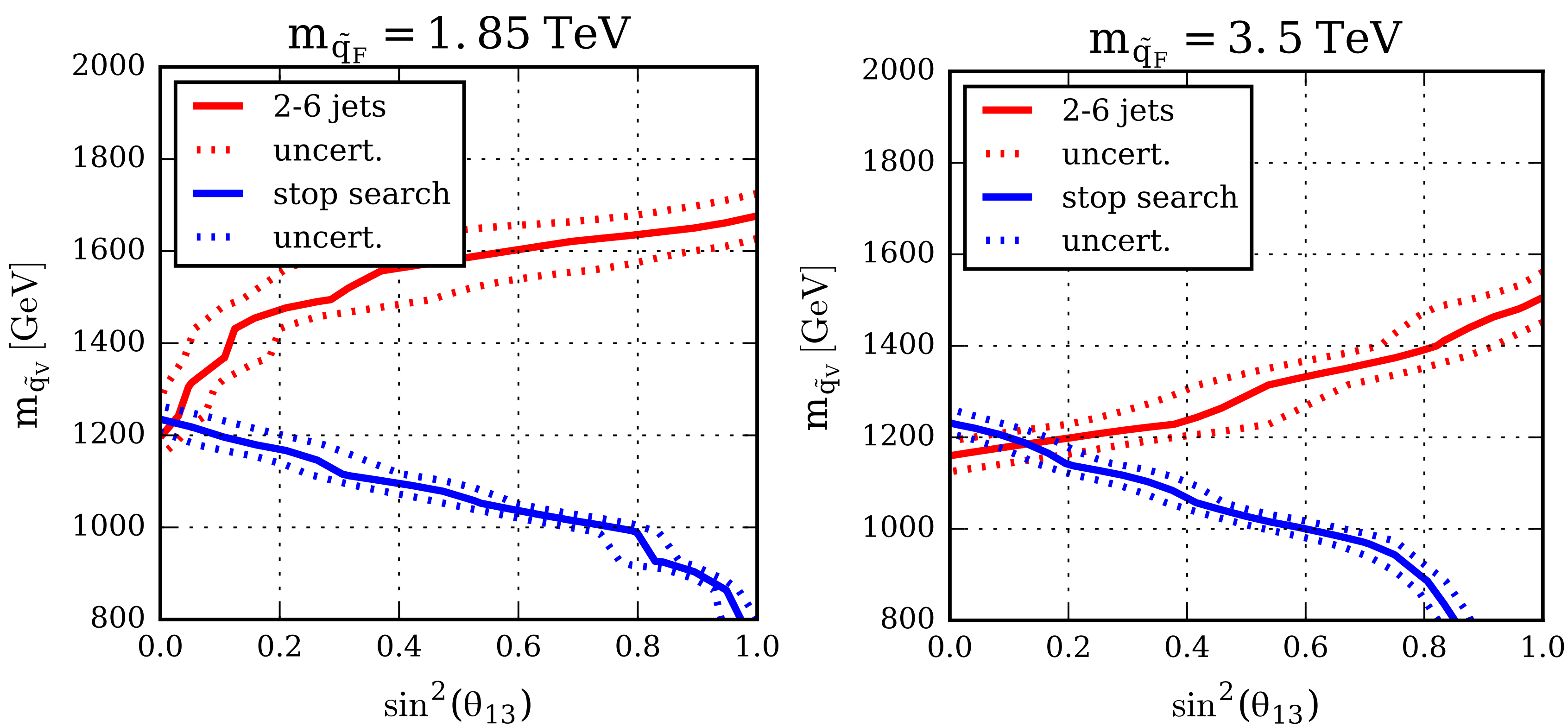
Scenario B

$$m_{\tilde{q}_L} > \begin{cases} 1.3 \text{ TeV (MRSSM)} \\ 1.8 \text{ TeV (MSSM)} \end{cases} \quad (m_{\tilde{q}_R} = m_{\tilde{g}} = 5 \text{ TeV})$$

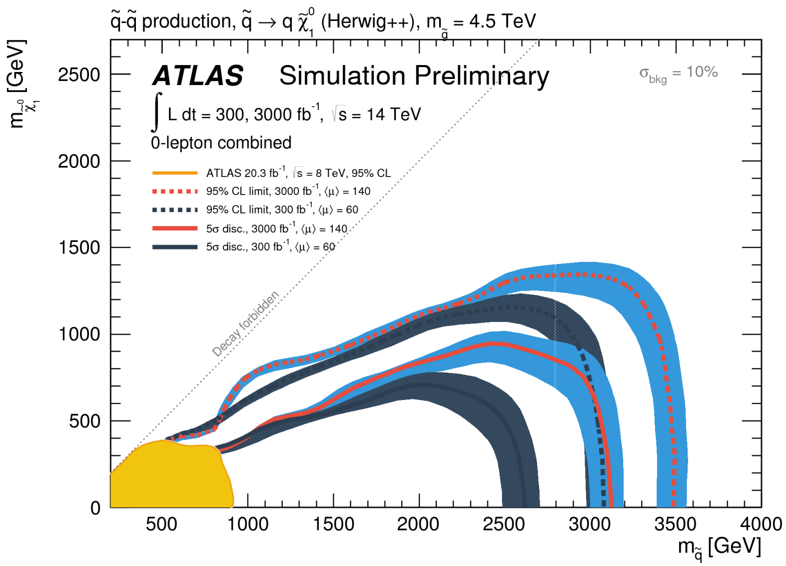


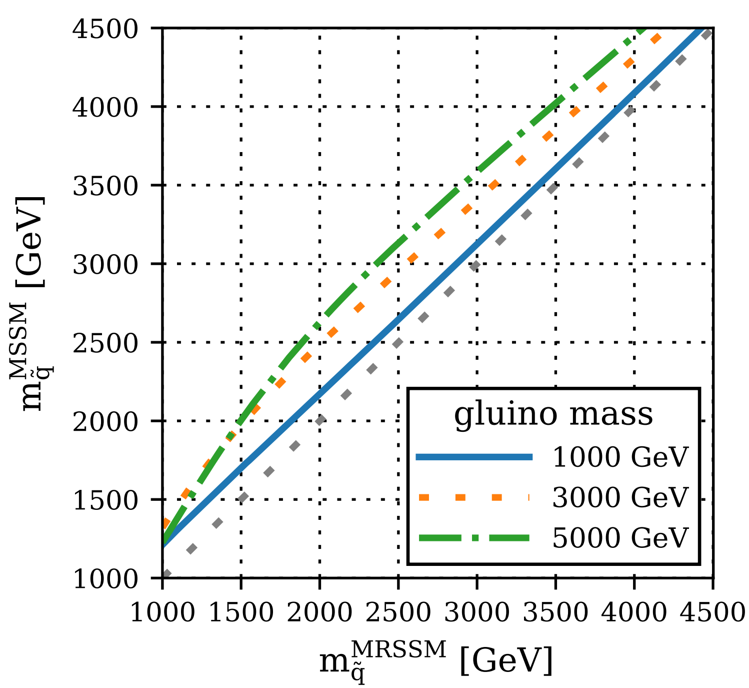
Scenario C

$$\tilde{q}_V(\text{lighter squark type}) = \cos\theta_{13}\tilde{q}_3 + \sin\theta_{13}\tilde{q}_1$$
$$\tilde{q}_F(\text{heavier squark type}) = -\sin\theta_{13}\tilde{q}_3 + \cos\theta_{13}\tilde{q}_1$$



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_{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

Summary

- MRSSM presents a viable alternative to the MSSM, without some of the MSSM drawbacks
- Its collider phenomenology might be quite different from the MSSM
- I presented the first concrete, solid limits on squark masses in the MRSSM
- The results we've obtained are important also for other models. They put in context exclusion plots given by the experimental collaborations.
- In the end, it's not about the MRSSM. It's about analysing the data more broadly. To make sure that nothing slips through the cracks.