(In)dependence of various LFV observables in the non-minimal SUSY

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in collaboration with D. Stöckinger and H. Stöckinger-Kim

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

- superpotential example

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

- Superpotential is polynomial in fields. For W to transform homogeneously superfields must have definite R-charges

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

- Similarly one can work out other parts of the Lagrangian

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(we want it to be) R-invariant → $\mathcal{L} \ni \int d^2\theta \; W$

$\int d^2\theta$: transforms as $e^{-2\imath\alpha}$

W: transforms as $e^{2\imath\alpha}$

- Superpotential is polynomial in fields. For W to transform homogeneously superfields must have definite R-charges

$$\underset{e^{\imath\alpha Q_R}}{\Phi} = \underset{e^{\imath\alpha Q_R}}{\phi(y)} + \underset{e^{\imath\alpha (Q_R-1)}}{\sqrt{2}\theta\psi(y)} + \theta\theta F(y)$$

- Similarly one can work out other parts of the Lagrangian

Low-energy R-symmetry realization

- Different possible models that one can construct
- "Natural" choice

	$e^{\imath\alpha Q_R}$		$e^{\imath\alpha Q_R}$		$e^{\imath\alpha(Q_R-1)}$		
	Φ	$=$	$\phi(y)$	$+$	$\sqrt{2}\theta\psi(y)$	$+$	$\theta\theta F(y)$
leptons and quarks	$Q_R = 1$		$Q_R = 1$		$Q_R = 0$		
Higgs	$Q_R = 0$		$Q_R = 0$		$Q_R = -1$		

- 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

- superpotencial

$$\mu \hat{H}_u \hat{H}_d$$

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

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

- superpotencial

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

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

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

- soft-SUSY breaking terms
  - B_μ -term
  - soft scalar masses
  - Dirac gaugino masses
  - no A-terms

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Kribs, Popitz, Weiter (2008)

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

- soft-SUSY breaking terms
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- superpotencial

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

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

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

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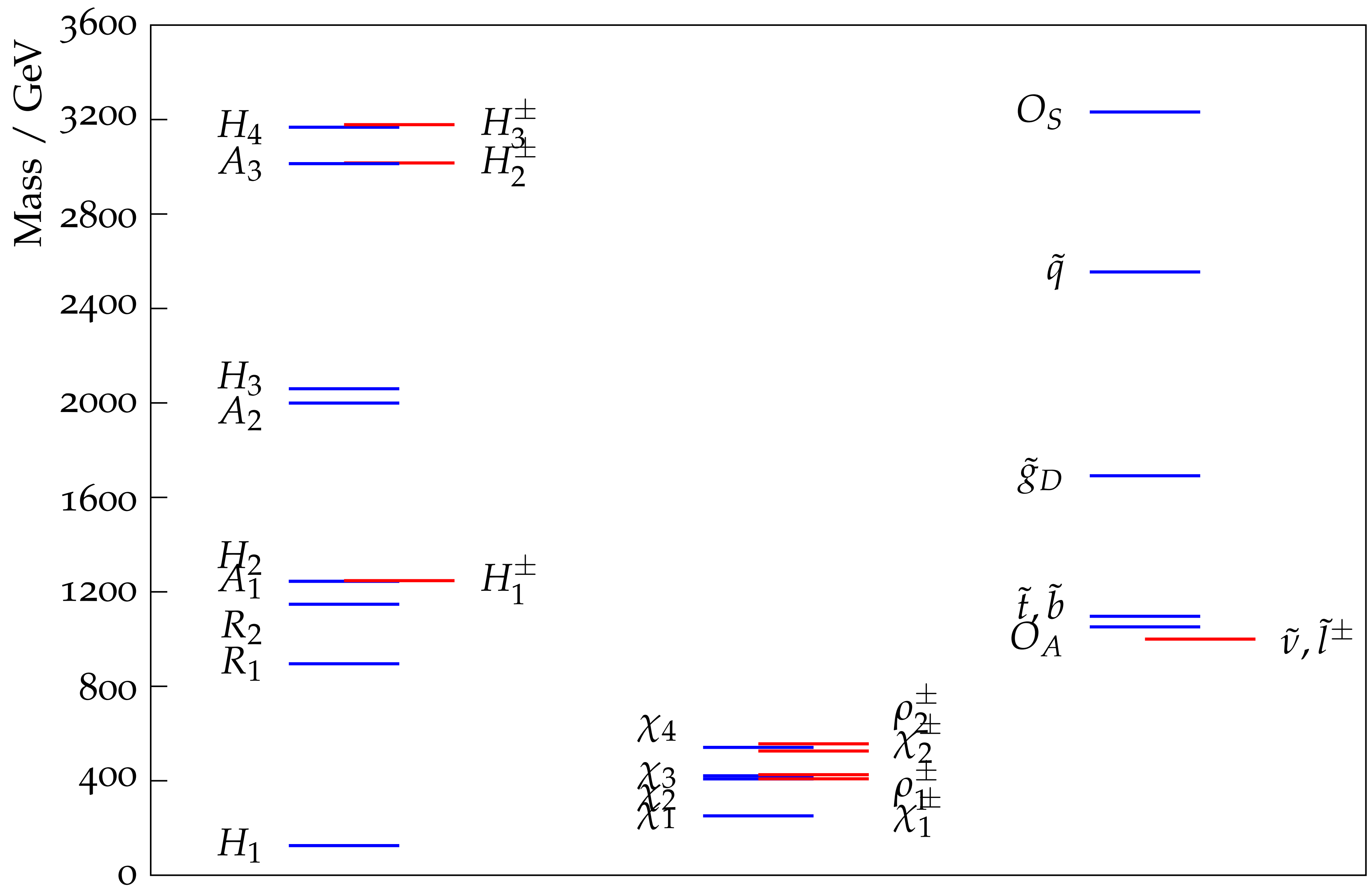
Particle content summary: MSSM vs. MRSSM

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



arXiv:1410.4791
Higgs mass at 1-loop level + EWPO

arXiv:1504.05386
2-loop corrections to Higgs mass

arXiv:1511.09334
DM in light single scenario

arXiv:1707.04557
NLO SQCD corrections to squark - (anti)squark pair production

Previous and future low energy experiments

- As the LHC still sees nothing, we look into low energy experiments:
  - prospects for g-2 measurement

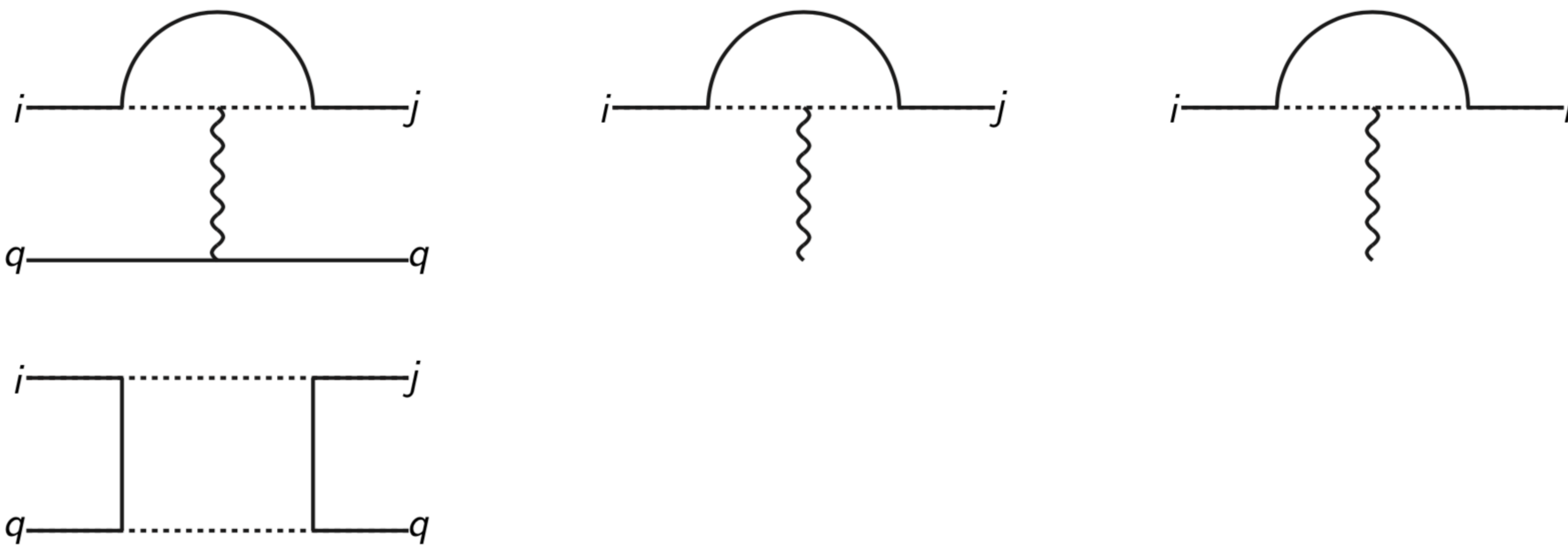
    $a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.1 \pm 6.3^{\rm exp} \pm 3.6^{\rm th}) \times 10^{-10}$ $a_\mu^{\rm exp} - a_\mu^{\rm SM} = (??? \pm 1.6^{\rm exp} \pm 3.4^{\rm th}) \times 10^{-10}$
  - prospect for $\mu \to e\gamma$

    current: 4.2×10^{-13} (MEG) future: $\approx 4 \times 10^{-14}$
  - prospect for $\mu \to e$ conversion

    current: 7×10^{-13} (SINDRUM-II) future: $\lesssim 10^{-16}$

Relation between $(g-2)_\mu$ and LFV observables

$\mu \to e$ $\quad$ $\mu \to e\gamma$ $\quad$ $(g-2)_\mu$



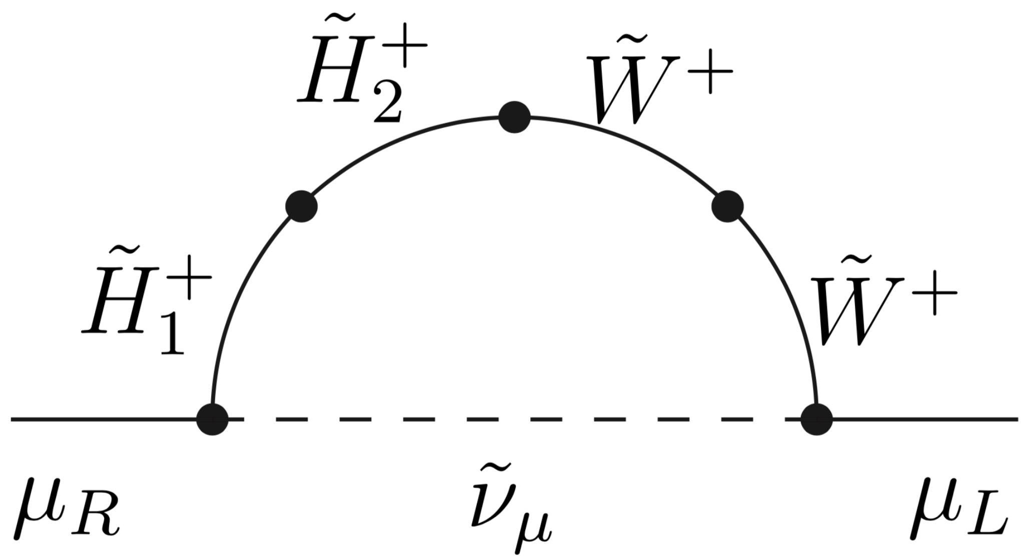
D, A_1^{21}, A_2^{21} $\quad$ A_2^{21} $\quad$ A_2^{22}

each observable requires a dedicated experiment

$(g-2)_\mu$ in the MSSM

chargino

$$\propto m_\mu^2 \tan\beta \mu M_2$$



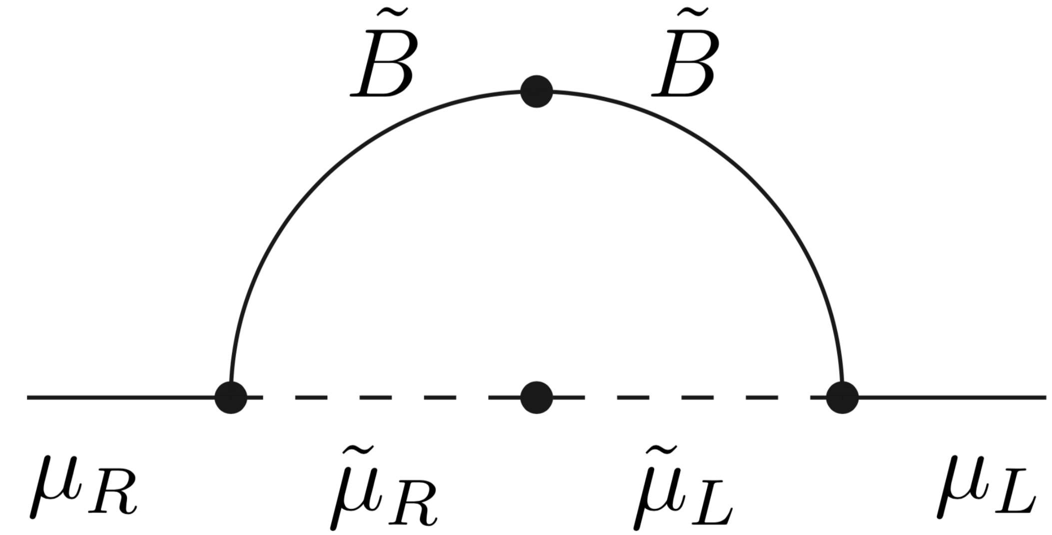
and similarly for $\mu \to e\gamma$ and $\mu \to e$ - as long as $\tan\beta$ is not very small all considered observables are dominated by the dipole contributions and therefore strongly correlated

$$\mathrm{CR}(\mu \to e) \propto \alpha \cdot \mathrm{BR}(\mu \to e\gamma)$$

$$\mathrm{CR}(\mu \to e) \leq 3 \cdot 10^{-15}$$

neutralino

$$\propto m_\mu^2 \tan\beta \mu M_1$$



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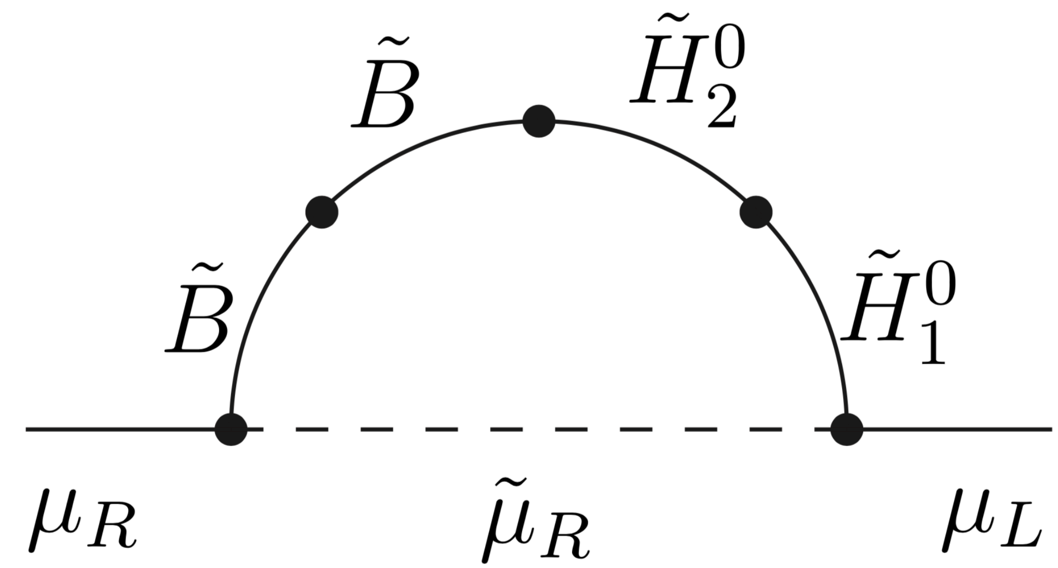
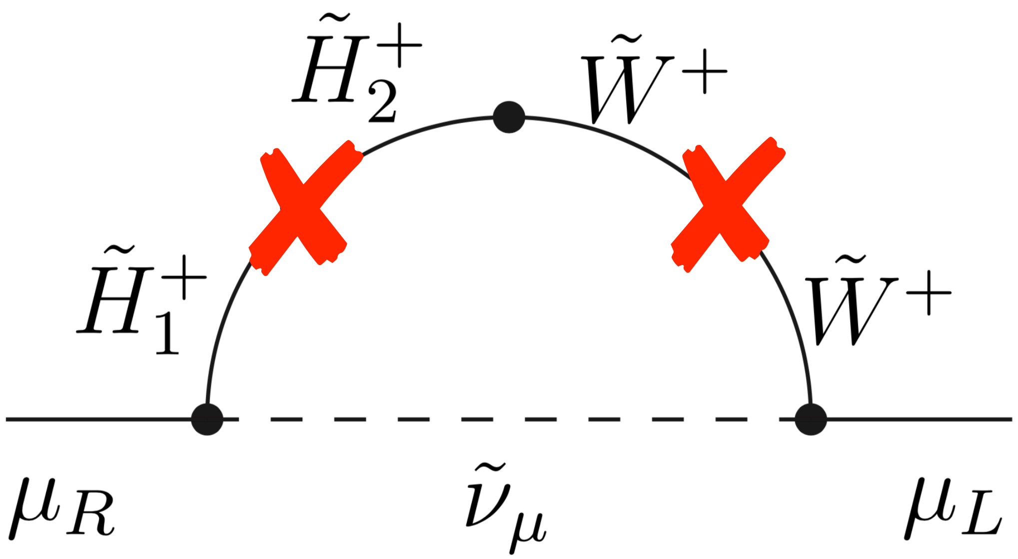


$(g-2)_\mu$ in the MRSSM

chargino

$$\propto m_\mu^2 \tan\beta \mu M_2$$



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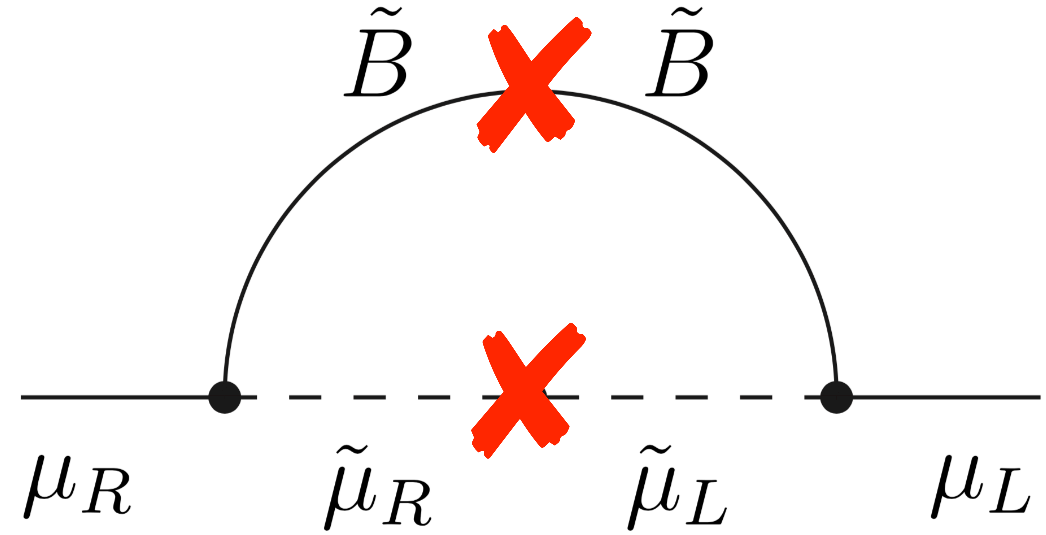
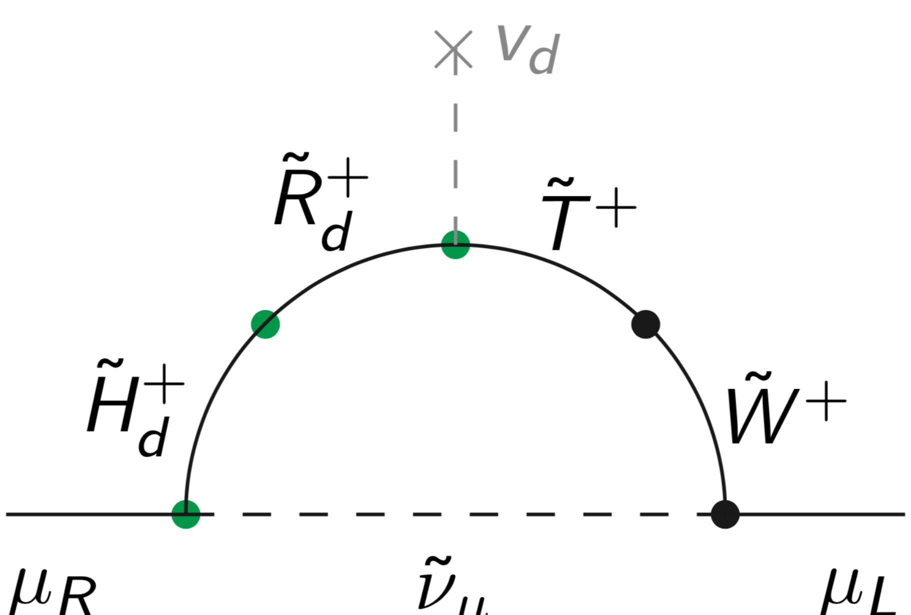


there is one class of
enhanced diagram though



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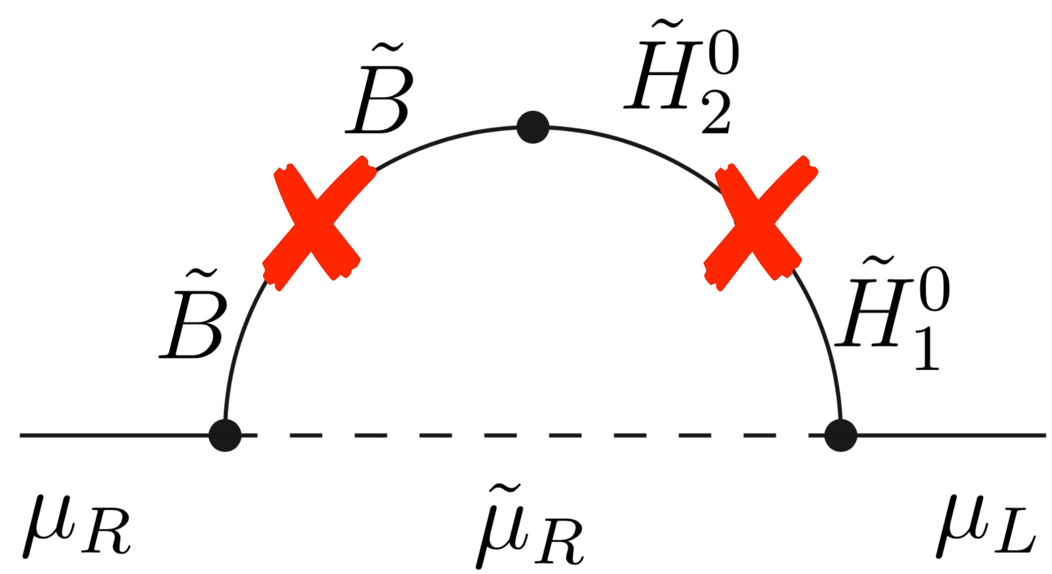
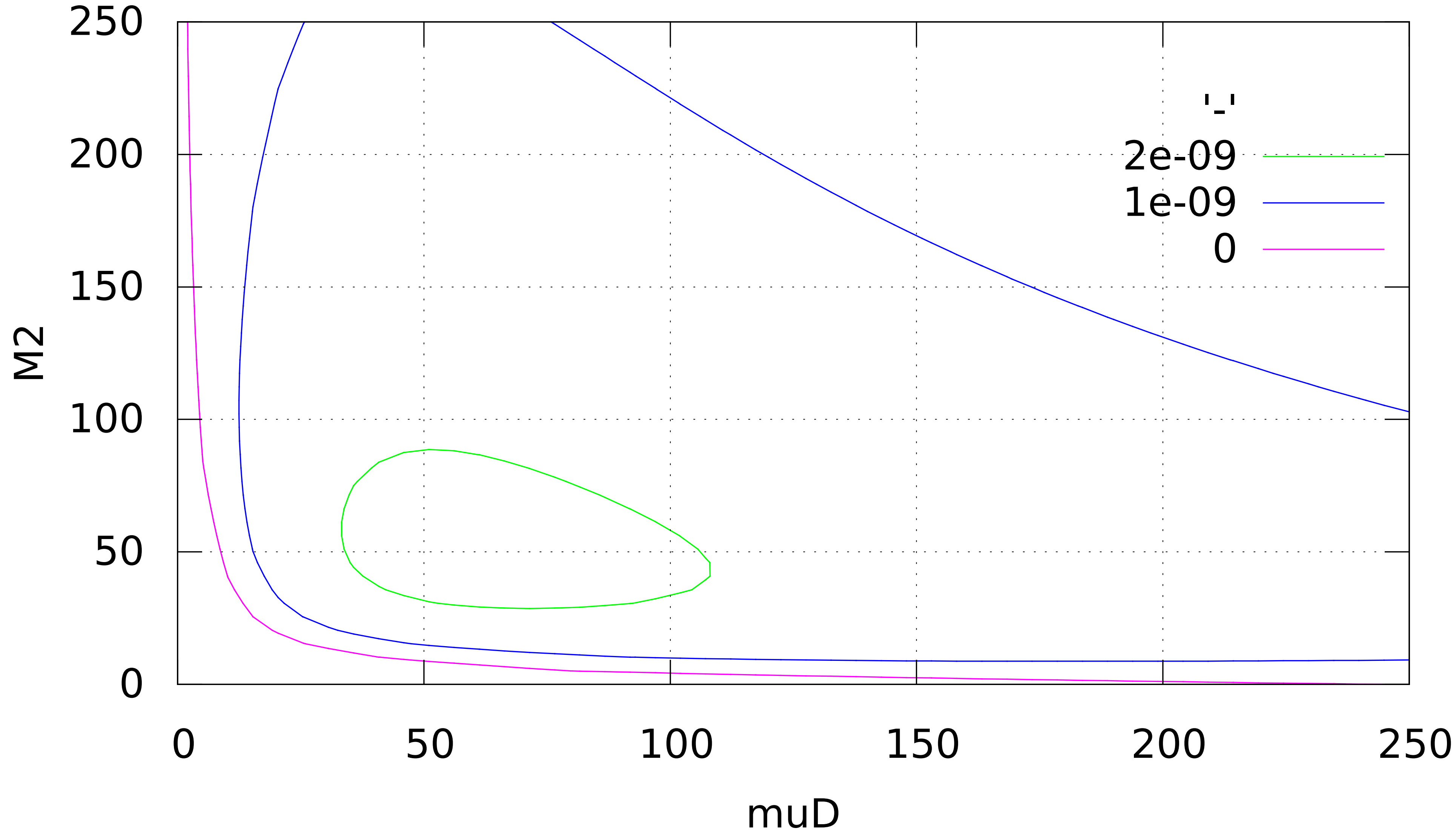


$(g-2)_\mu$ in the MRSSM

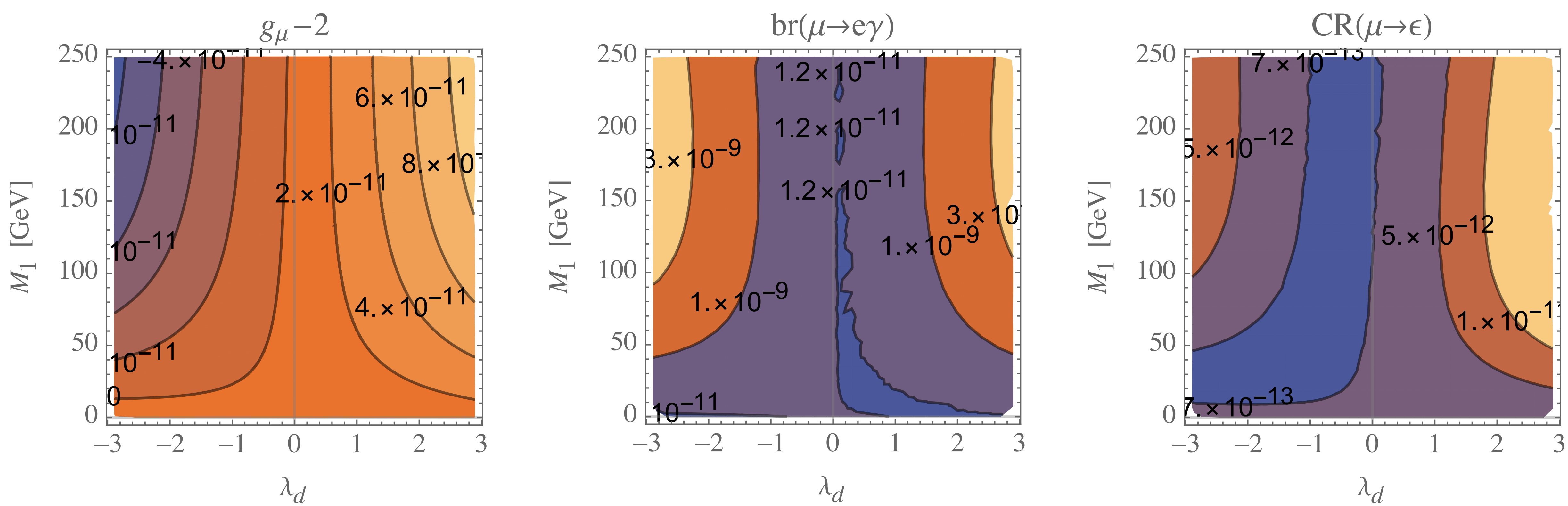
- It is possible to obtain large contribution to g-2



- The price to pay are light EW-inos, in tension with experiment

Photonic penguin dominance

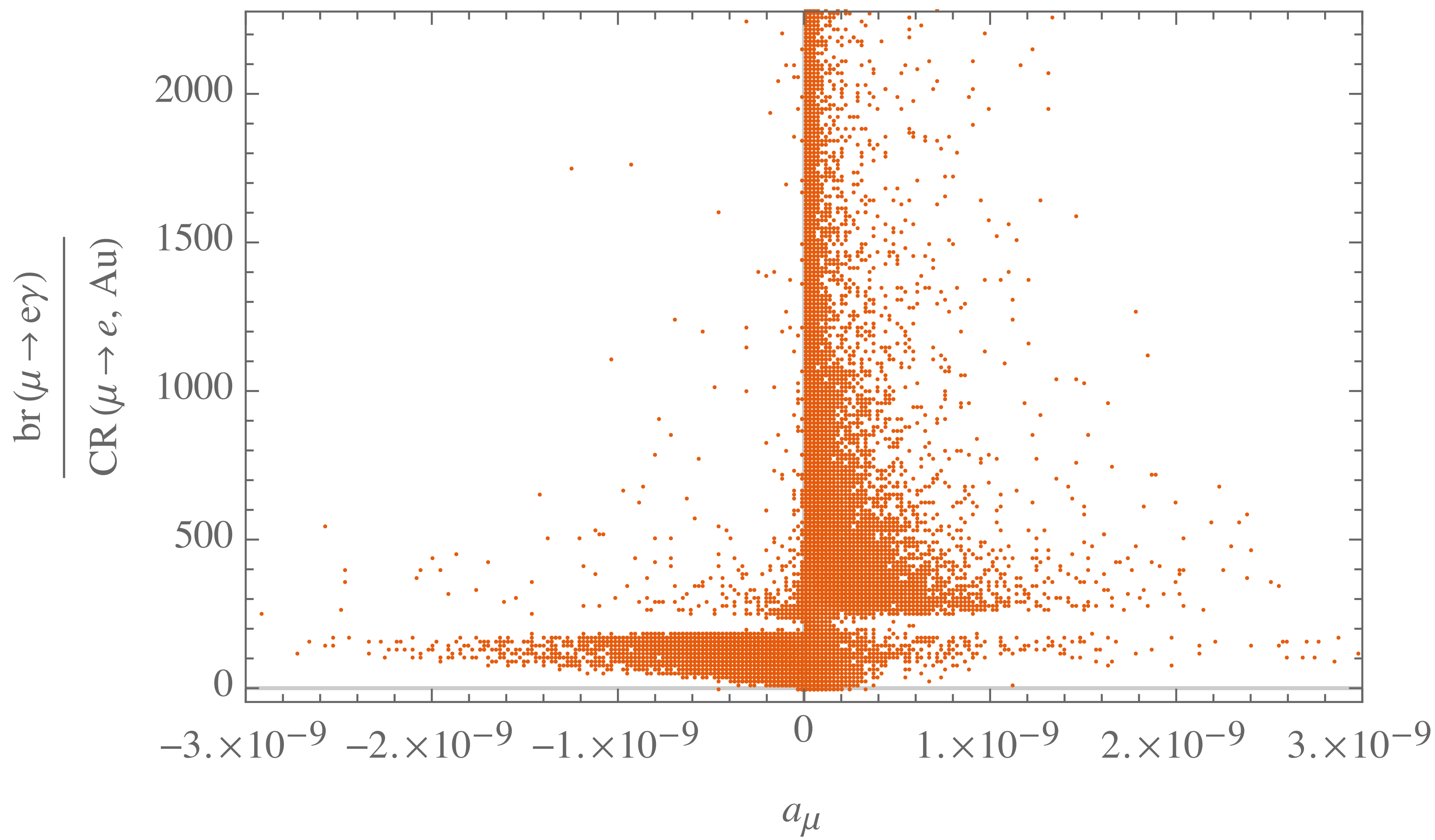
- For $|\lambda_d| \gtrsim 1$ the dipoles dominate: g-2 scales linearly with λ_d, while $\mu \to e\gamma$ and $\mu \to e$ quadratically



- For $|\lambda_d| \gtrsim 1$ the ratio of $\mu \to e\gamma$ over $\mu \to e$ is of the order 100, as in the MSSM where $\mathrm{CR}(\mu \to e) \propto \alpha \cdot \mathrm{BR}(\mu \to e\gamma)$

- Near $|\lambda_d| \approx 0$ the ratio is of order 10

a_μ vs. $\frac{br(\mu \to e\gamma)}{CR(\mu \to e, Au)}$



- In the region dominated by the dipoles the $br(\mu \to e\gamma) \sim \sin^2 2\theta \cdot a_\mu$
- In the MRSSM this is a region of $|\lambda_d| \gtrsim 1$, in the MSSM $\tan\beta \gtrsim 5$

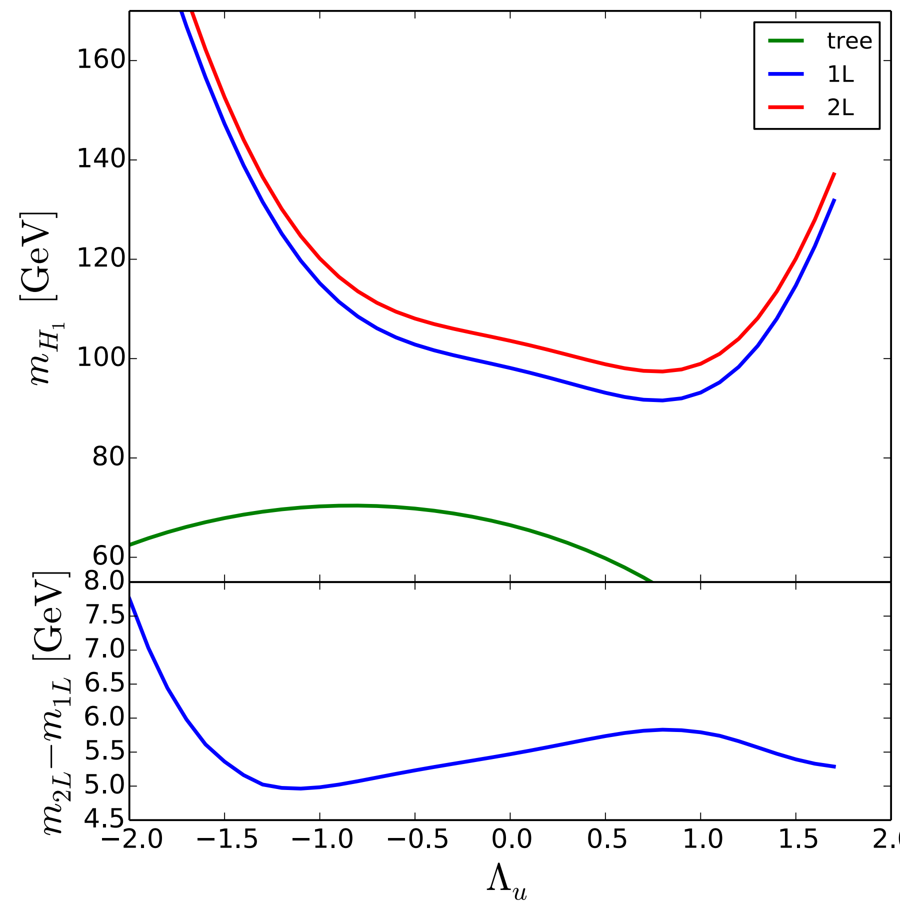
Conclusions:

- Two distinct cases: $|\lambda_d| \approx 0$, $|\lambda_d| > 0$
- For large $|\lambda_d|$ observables get dominated by photon „penguins" and are strongly correlated
- Generating sufficient contribution to g-2 through large λ_d overshots LFV observables (unless one fine-tunes the mixing angle)
- Similar things happen for Λ_d
- For $|\lambda_d| \approx 0$ the g-2 and $\mu \to e\gamma$ are still correlated but the $\mu \to e$ conversion rate can be dominated by so-called charge radius, Z-penguin and box contributions
- It is therefore possible to find a parameter points not excluded by current experimental results, within reach of the next $\mu \to e$ conversion (but not $\mu \to e\gamma$) experiment

Backup

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 analyzed[1]
- MRSSM can predicts correct dark matter relic density while being in agreement with dark matter direct detection bounds[3]
- Its EW signatures were checked against available 7 and 8 TeV data[3]

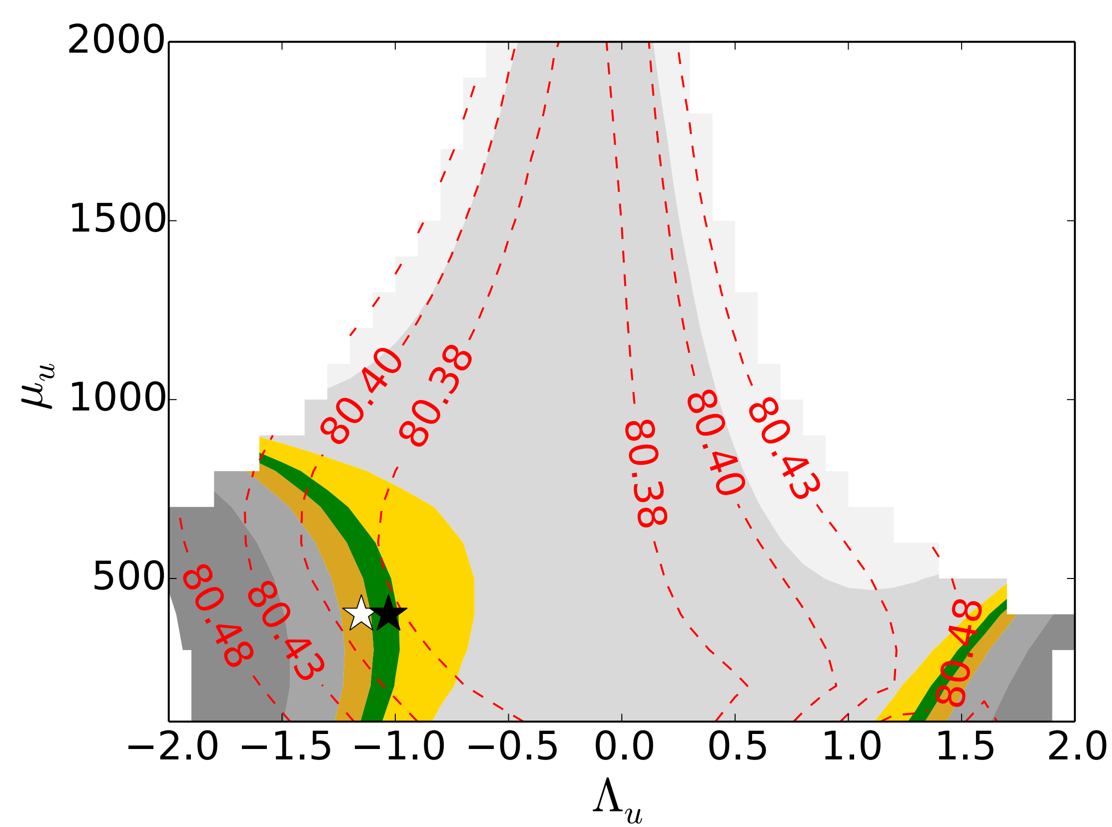


✦ tree-level result
✦ 1-loop quantum corrections
✦ leading 2-loop corrections

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

2. 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

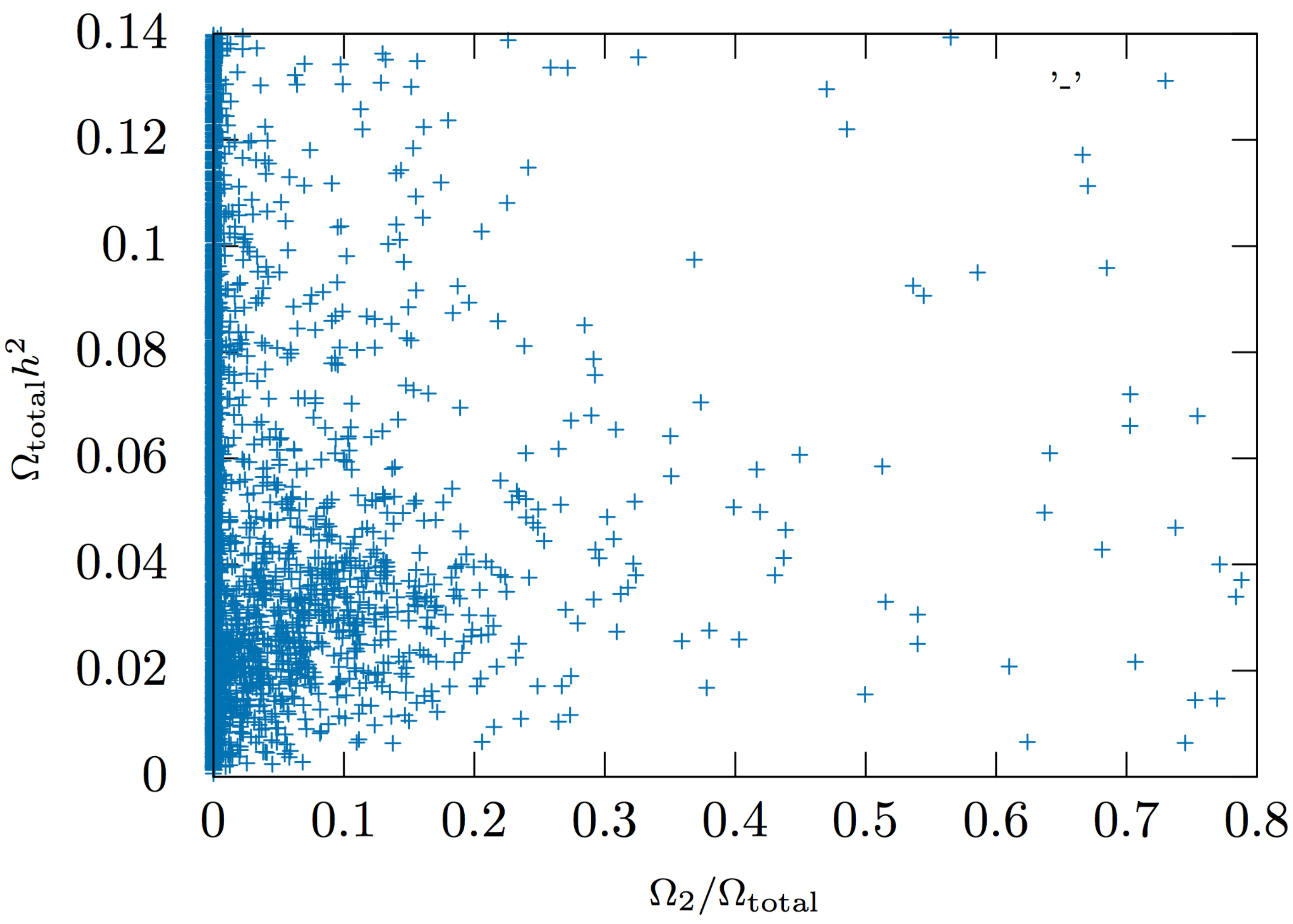


2 component dark matter

- consider scenarios where the lightest particle with R=1 is neutralino or sneutrino with mass m_{LSP1}
- if $m_{R_1^0} < 2\, m_{\rm LSP1}$, lightest neutral R-Higgs is also stable
- two SUSY dark matter candidates with relic densities Ω_1 and Ω_2
- requirements
  - $\Omega_{total}h^2 \equiv (\Omega_1 + \Omega_2)h^2 \simeq 0.11$
  - substantial fraction Ω_2/Ω_{total}
- (for now) best points are not collinear friendly:

$$m_{\tilde{\chi}_1^0} = 367 \text{ GeV}$$

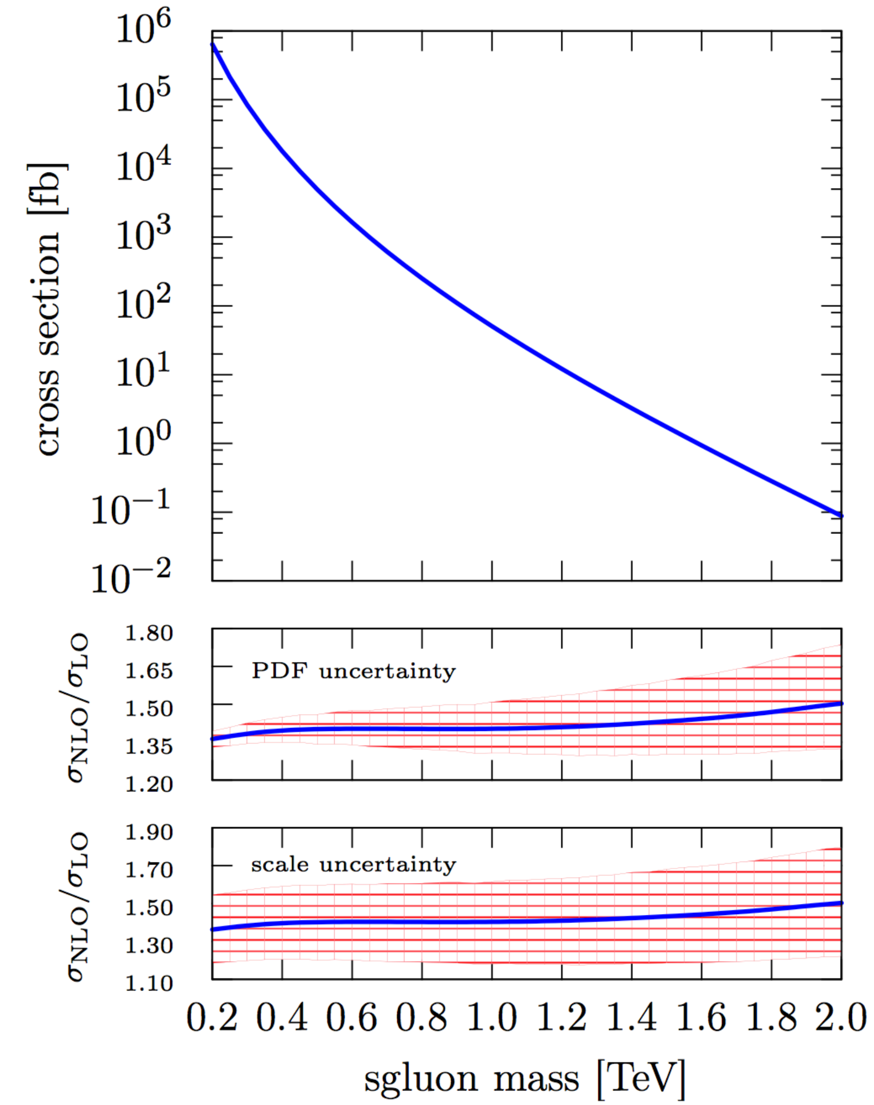
$$m_{R_1^0} = 571 \text{ GeV}$$

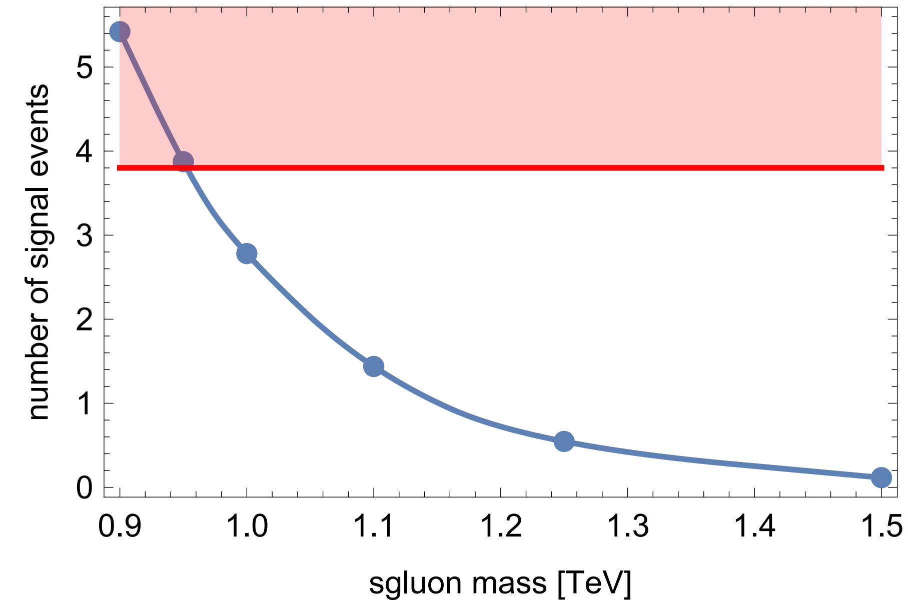


Sgluon pair production at 13 TeV LHC

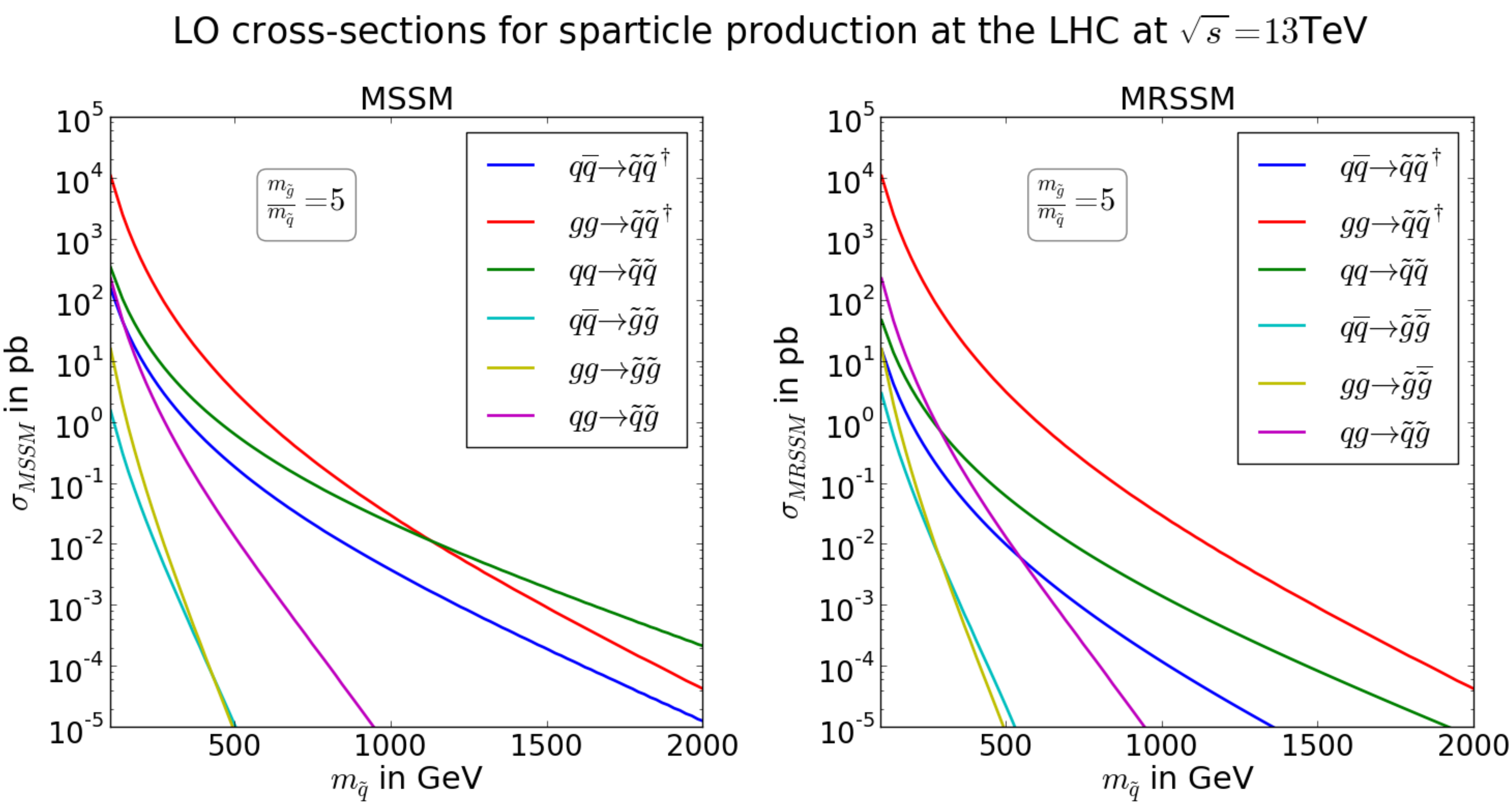
W. Kotlarski [arXiv:1608.00915]

- 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

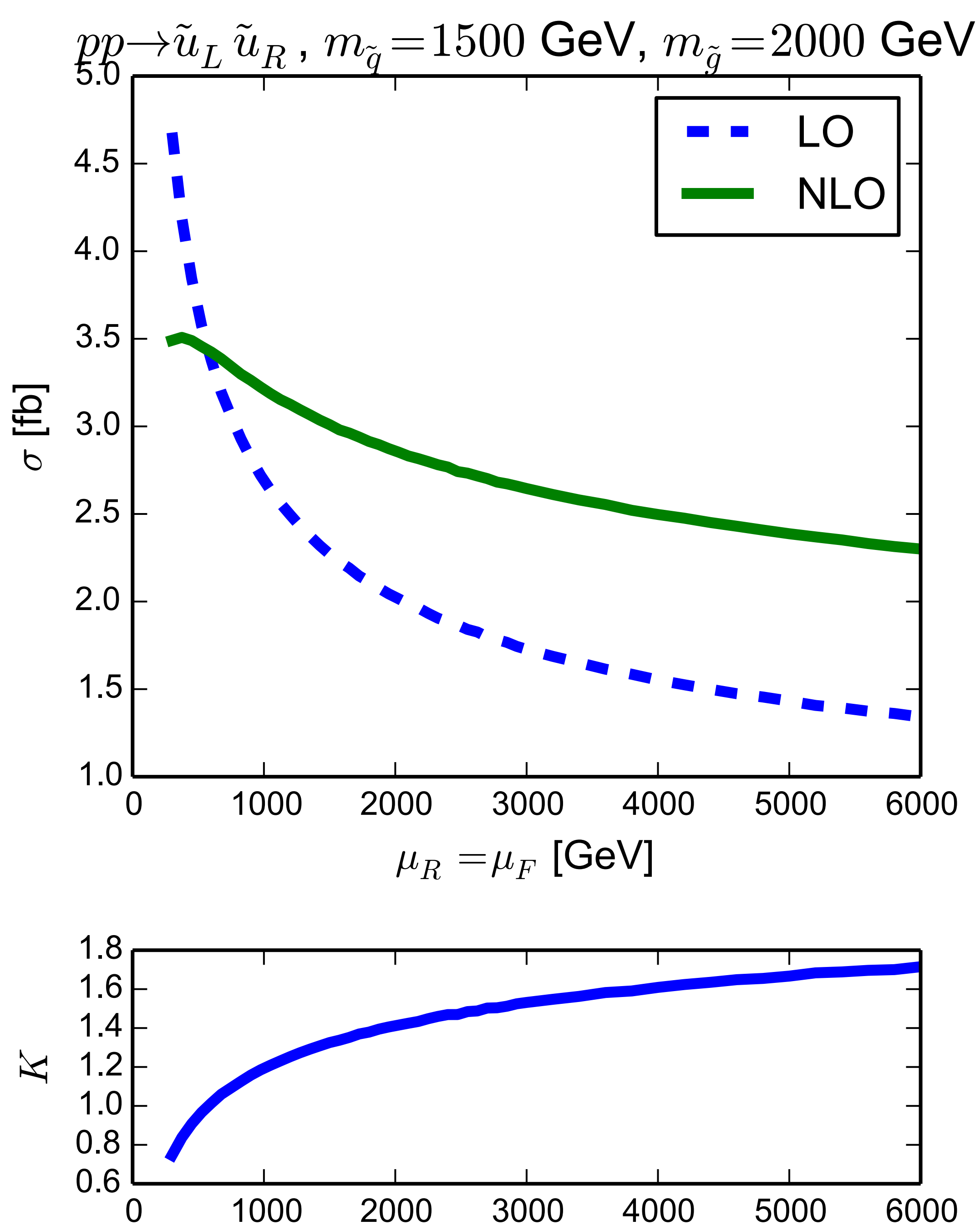


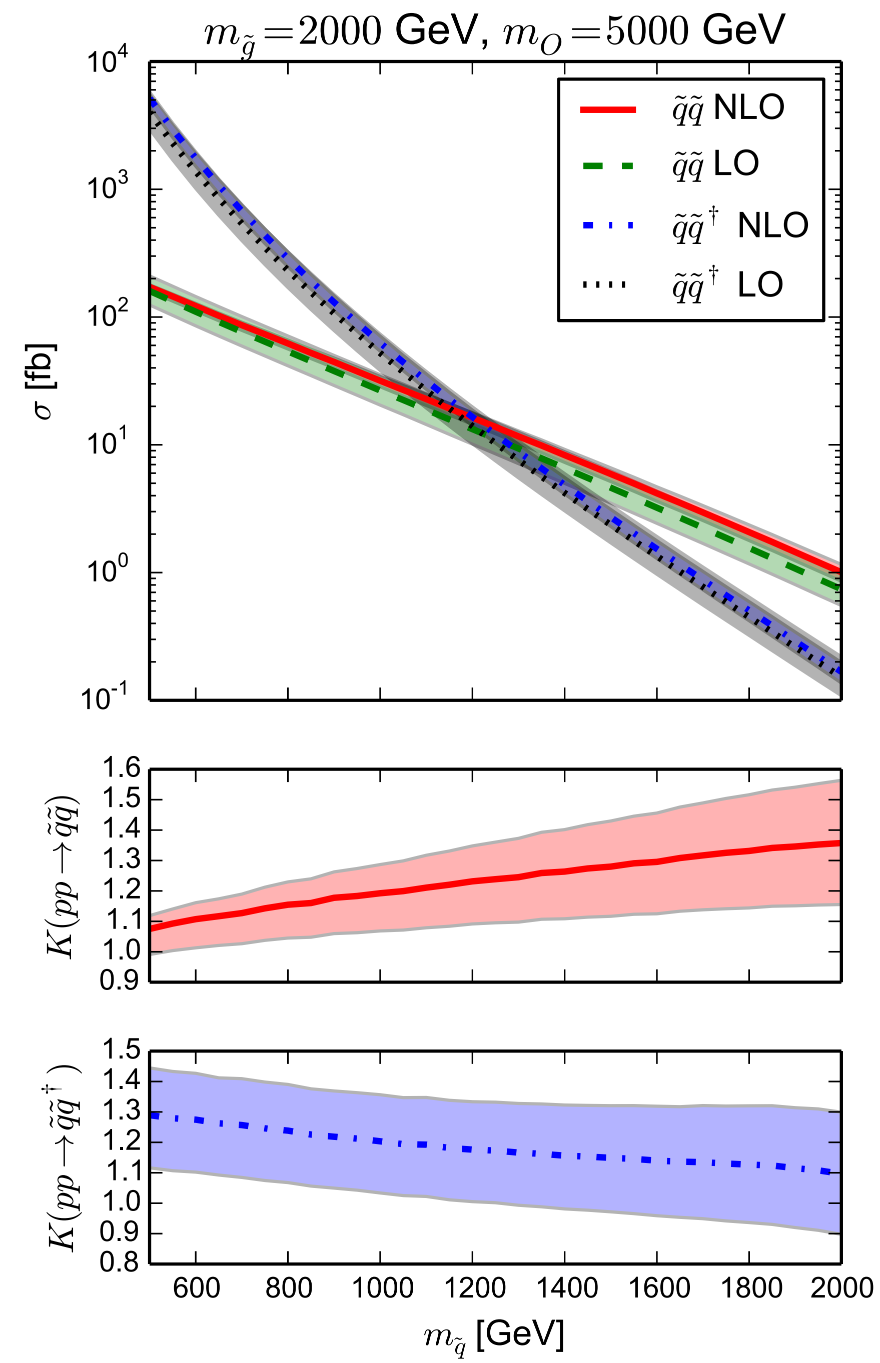


Leading order analysis



NLO improvements



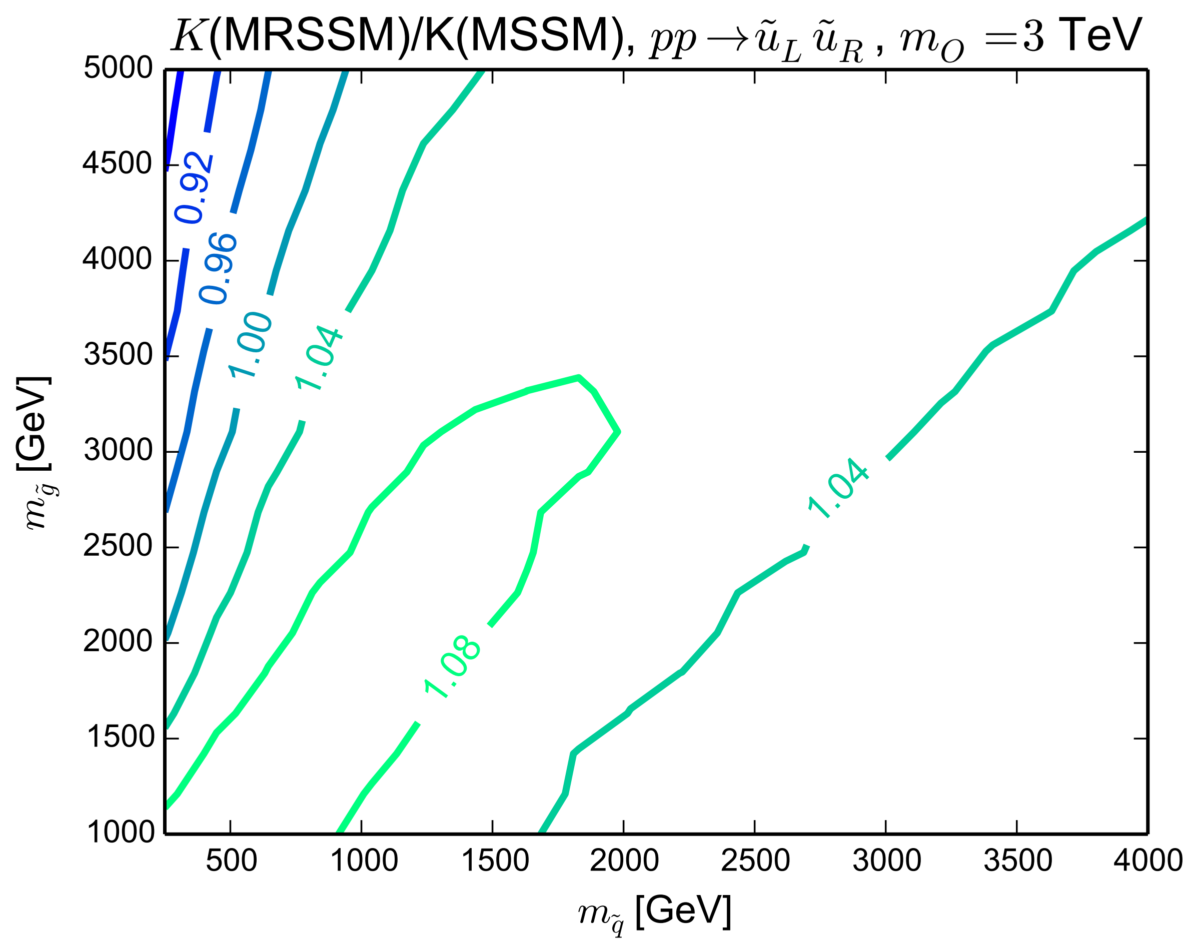


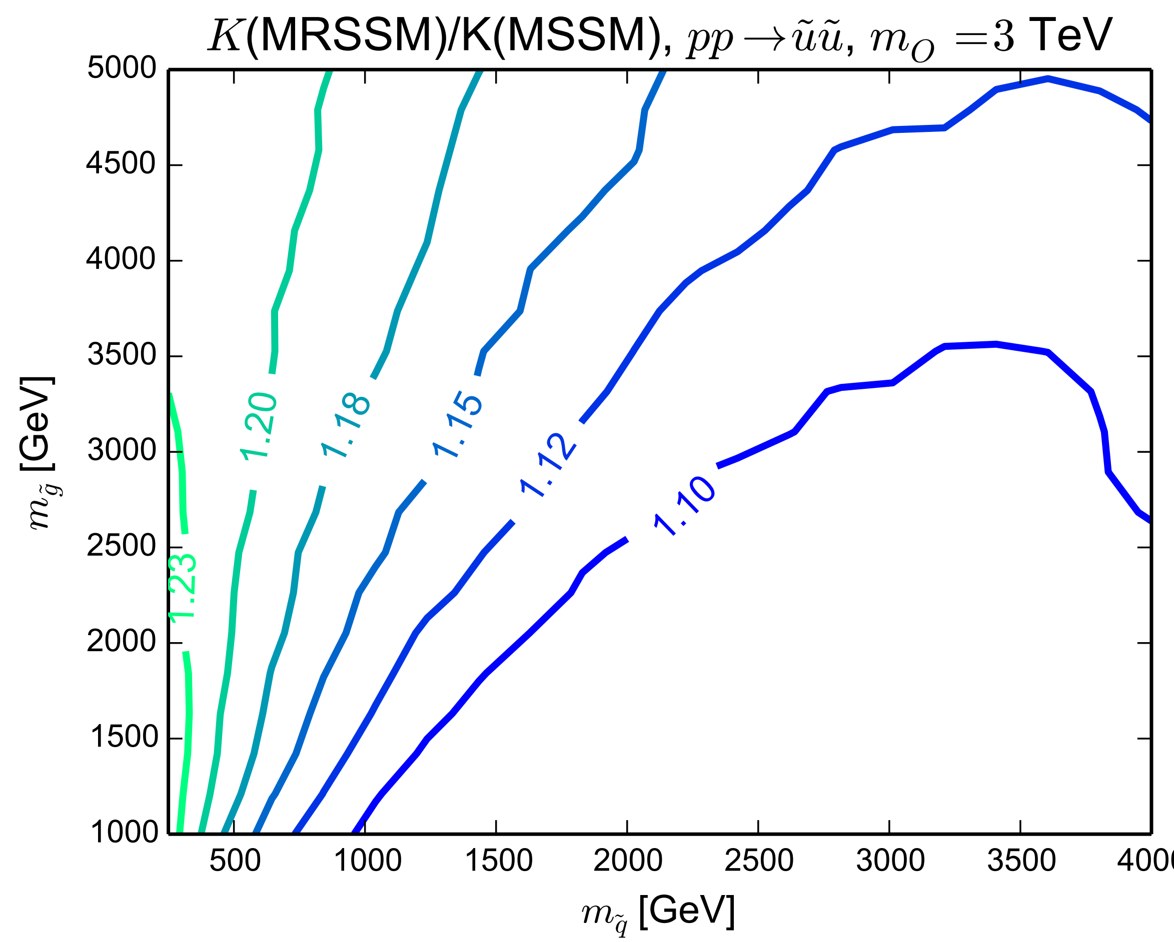
right figure summed over flavors

reduction of theoretical uncertainty

shift of cross-sections

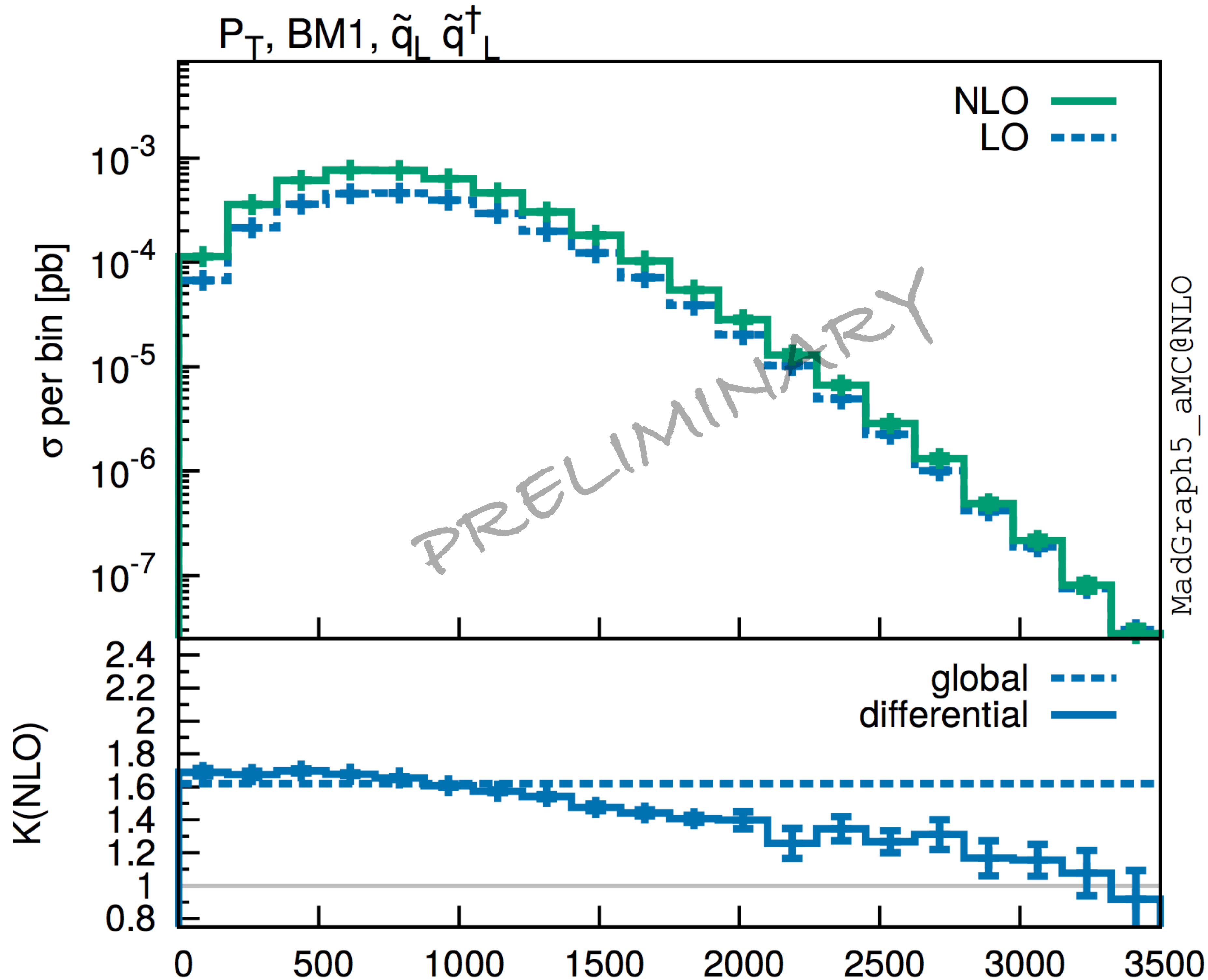
Comparison with the MSSM





- Two possible definitions of K-factors:
  - unsummed over L- and R-squarks
  - summed

Differential distributions



$\mu \to e\gamma$ in the MRSSM

- first analysis performed by Fok and Kribs [*Phys. Rev. D 82, 035010 (2010)*]
- simplifying assumptions: $M_2, \mu_u \to \infty$, only 2 neutralinos containing $\tilde{B}, \tilde{H}_d$ contribute
  $m_{\tilde{l}_2} = \frac{3}{2} m_{\tilde{l}}$