(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 →

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transforms as $e^{-2\imath\alpha}$

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R-invariant $\longrightarrow$ $\boxed{\mathcal{L}} \ni \boxed{\int d^2\theta}\quad W$

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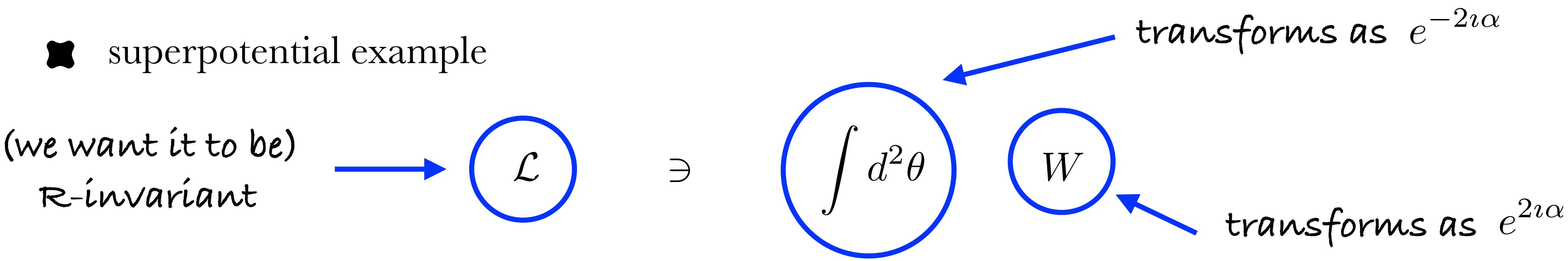

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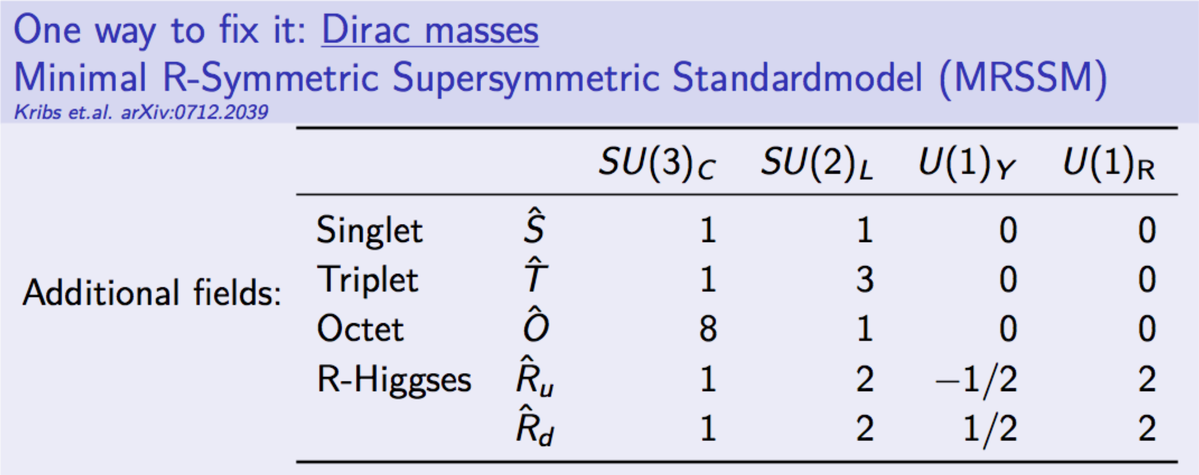
Low-energy R-symmetry realization

- Different possible models that one can construct
- “Natural” choice

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

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 ❗

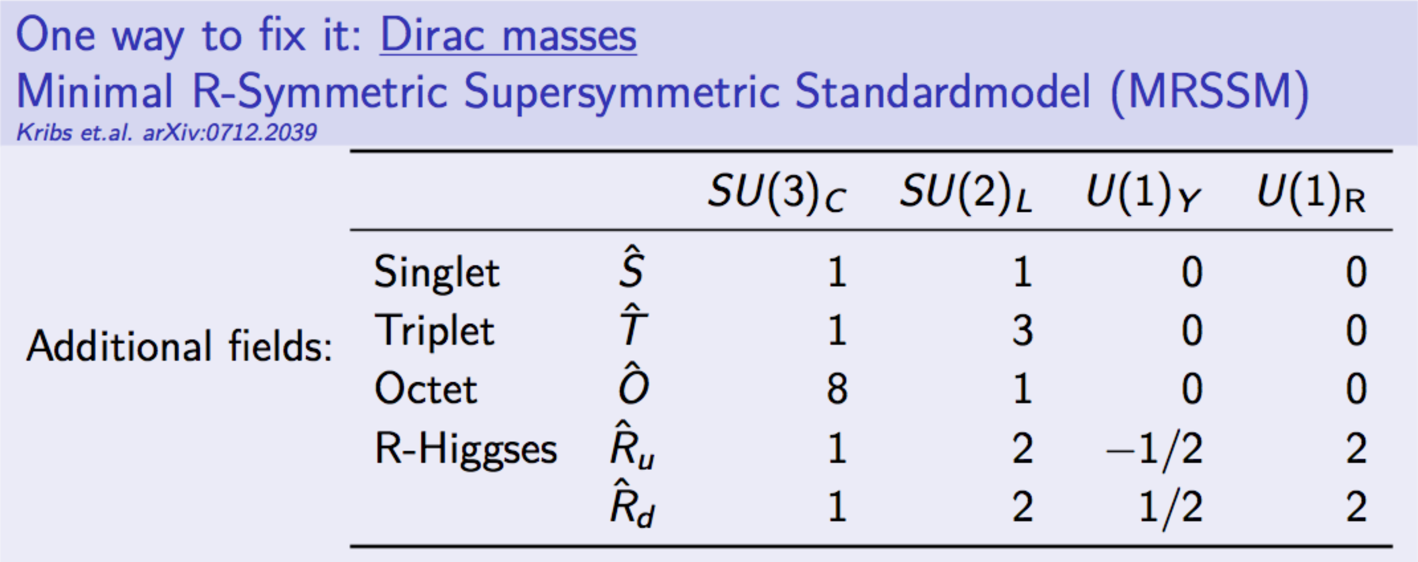
- superpotencial

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

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

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

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



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Kribs, Popitz, Weiter (2008)

MSSM vs. MRSSM

- superpotencial

$$\mu \hat{H}_u \hat{H}_d$$ ❗

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

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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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  - B_μ -term
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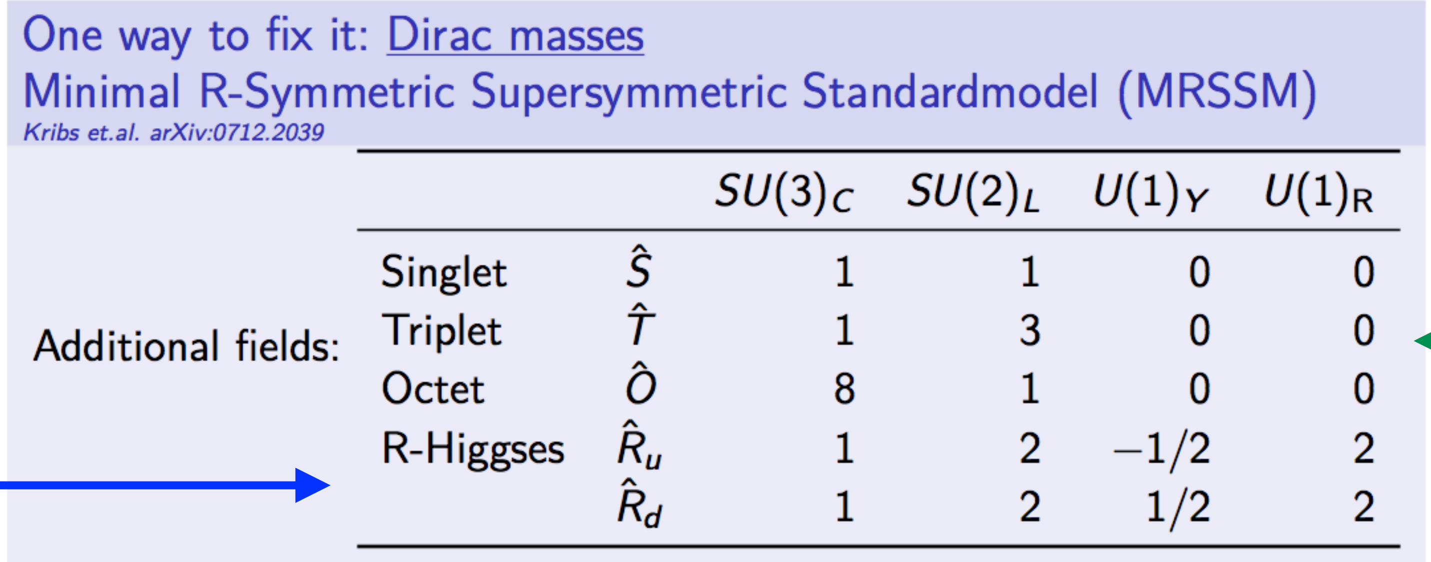

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Kribs, Popitz, Weiter (2008)

Particle content summary: MSSM vs. MRSSM

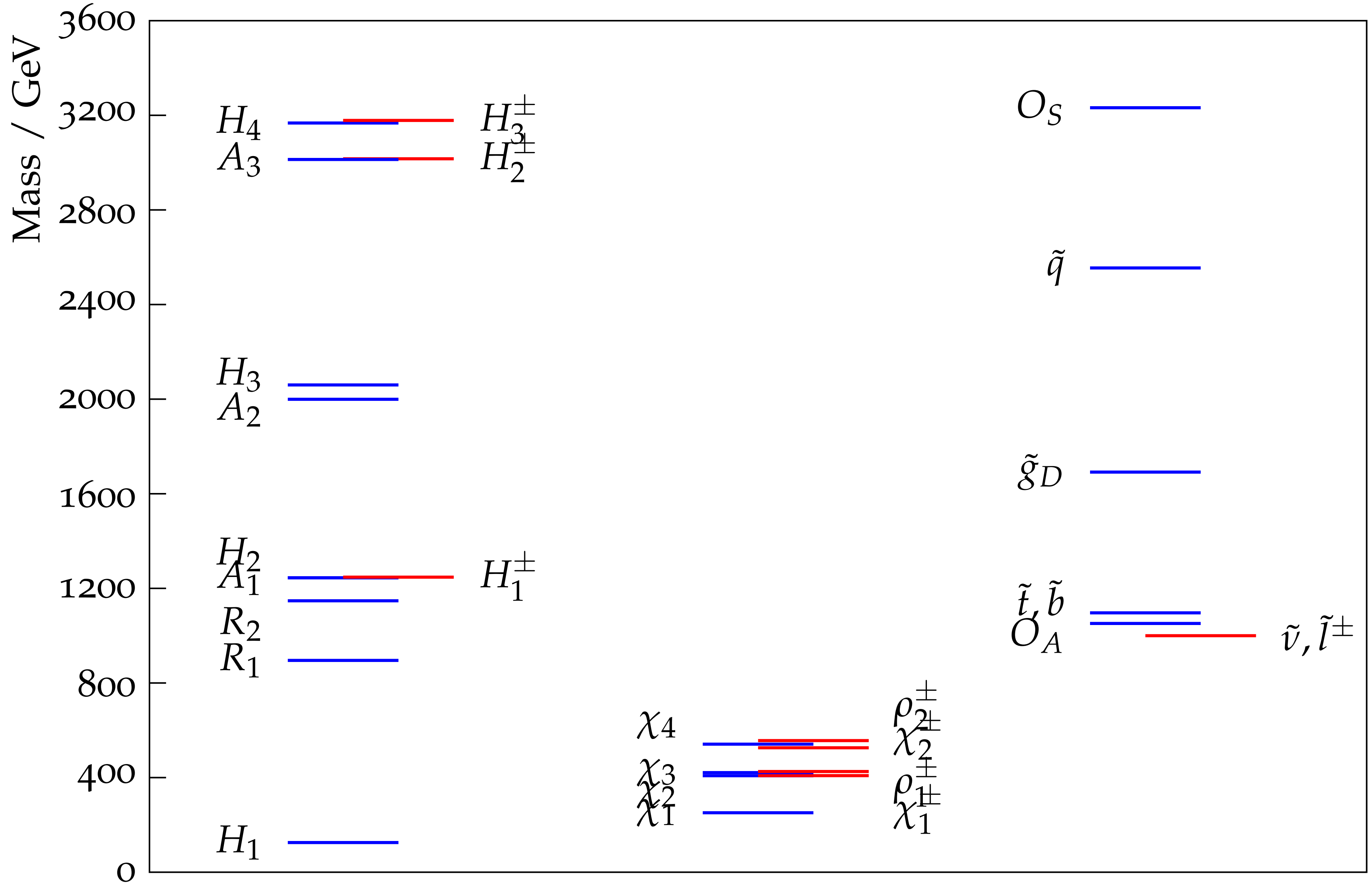
different number of physical states

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

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

  - prospect for μ→eγ

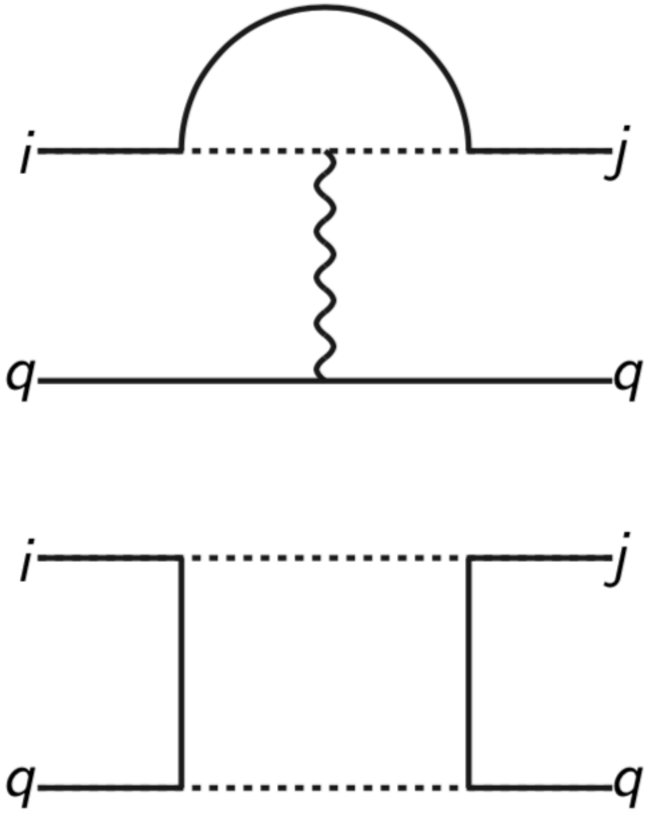
current: 4.2×10^{-13} (MEG) future: $\approx 4\times10^{-14}$

  - prospect for μ→e conversion

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

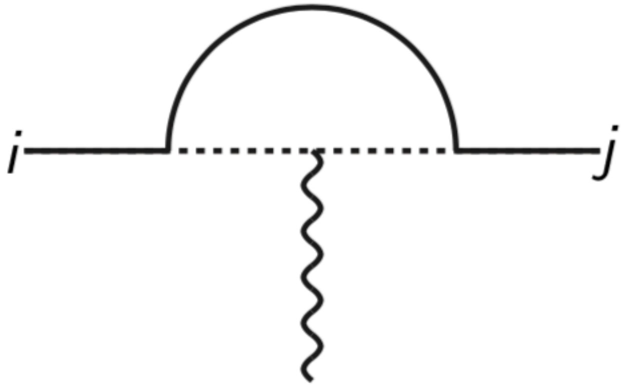
Relation between $(g-2)_\mu$ and LFV observables

$\mu \to e$



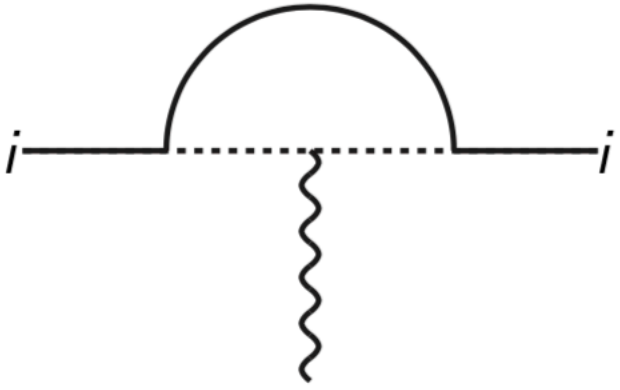
D, A_1^{21}, A_2^{21}

$\mu \to e\gamma$



A_2^{21}

$(g-2)_\mu$



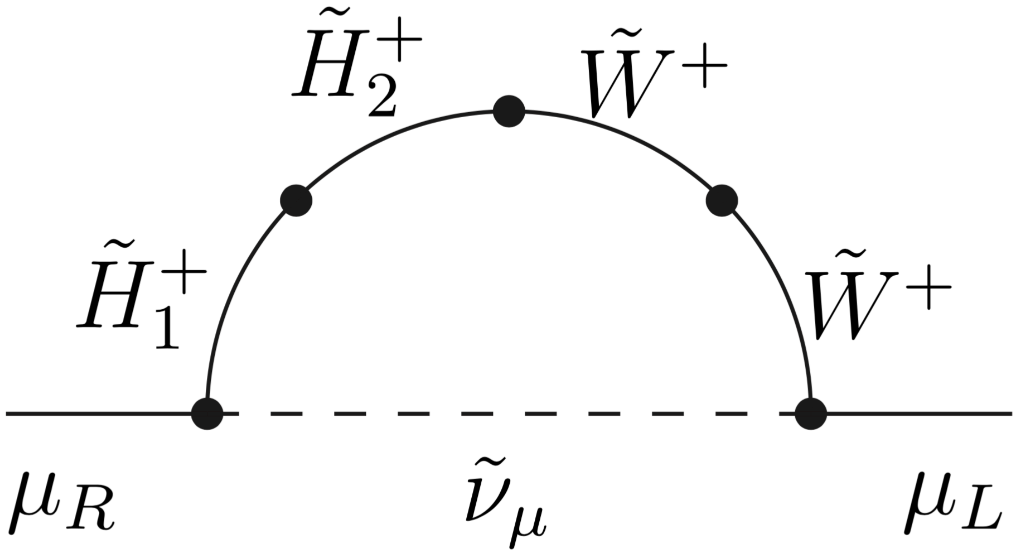
A_2^{22}

each observable requires a dedicated experiment

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

chargino

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



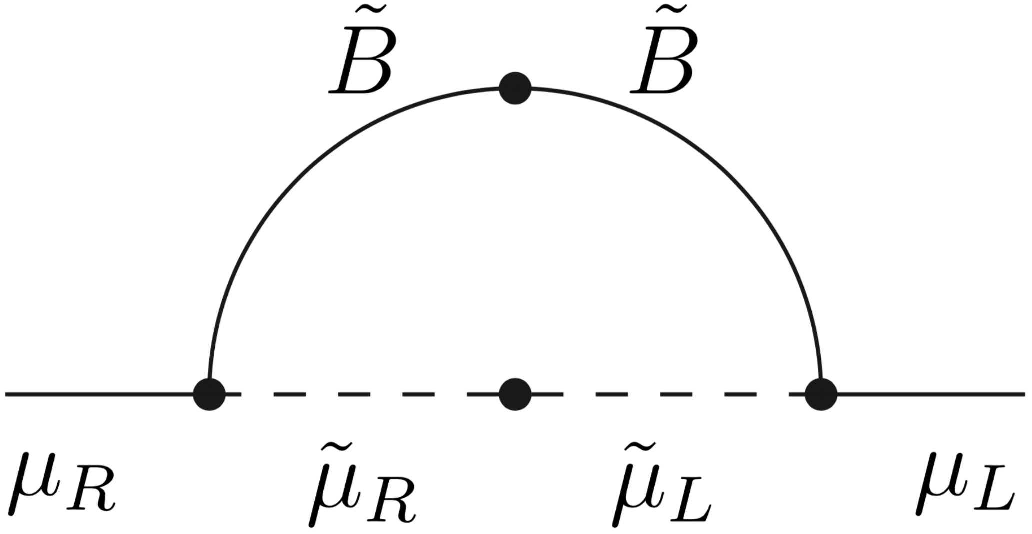
and similarly for μ→eγ and μ→e - as long as tan β is not very small all considered observables are dominated by the dipole contributions and therefore strongly correlated

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

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

neutralino

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



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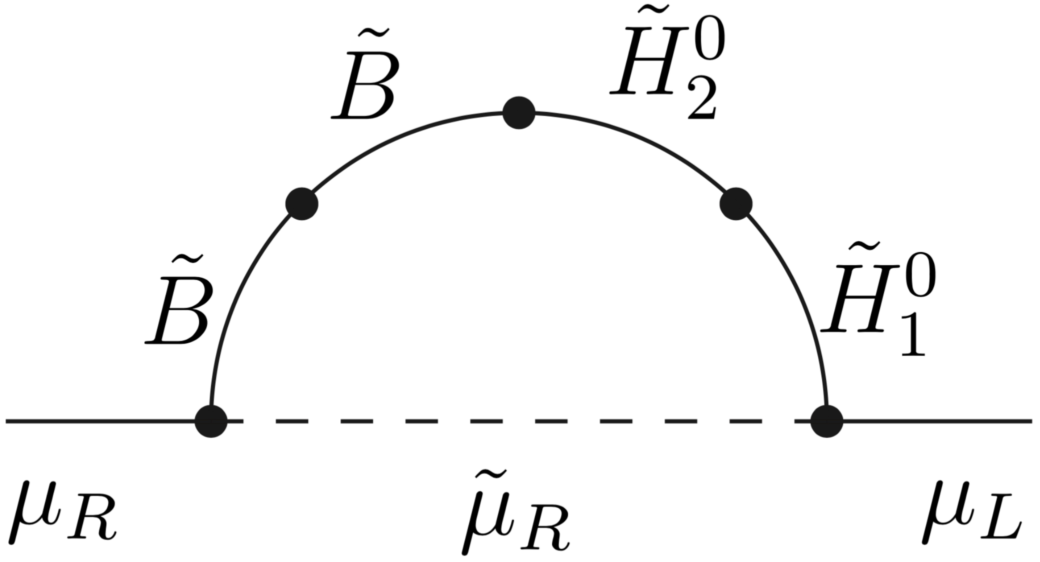
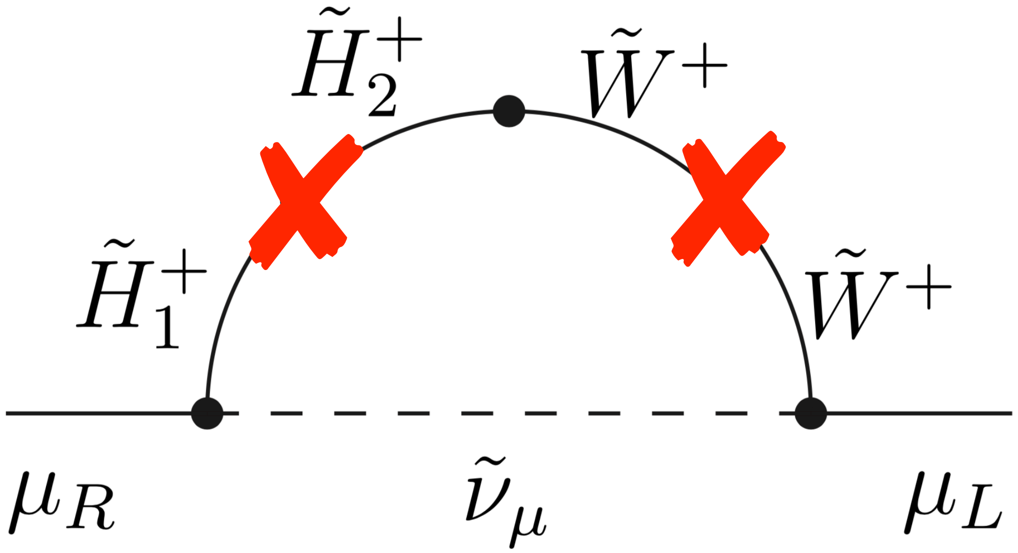


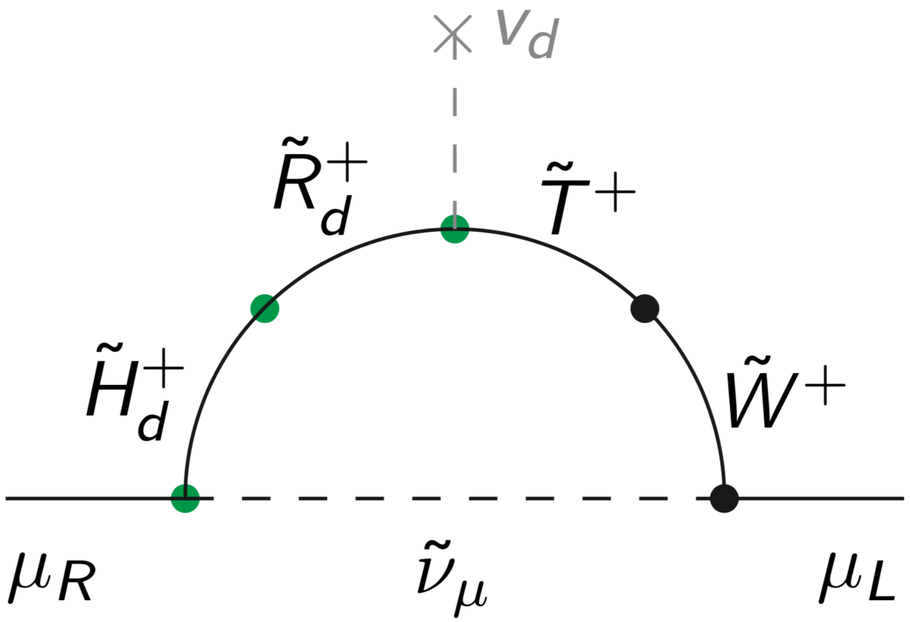
$(g-2)_\mu$ in the MRSSM

chargino

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



there is one class of
enhanced diagram though



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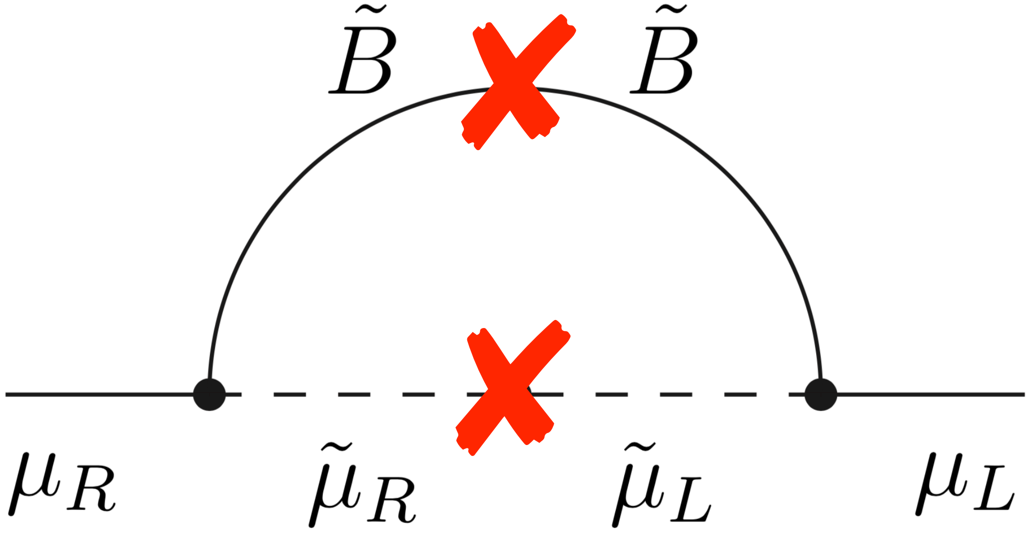

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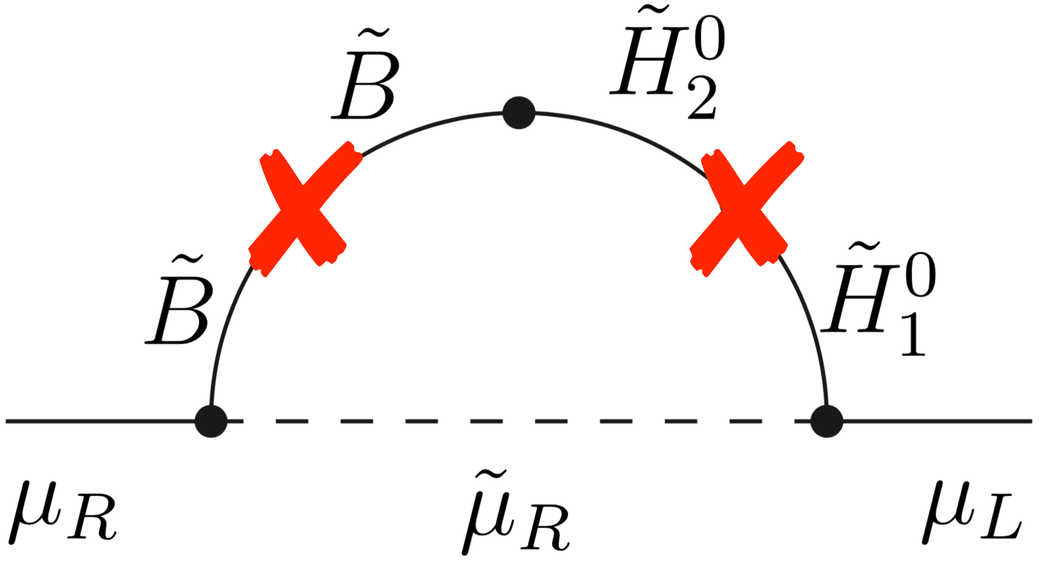
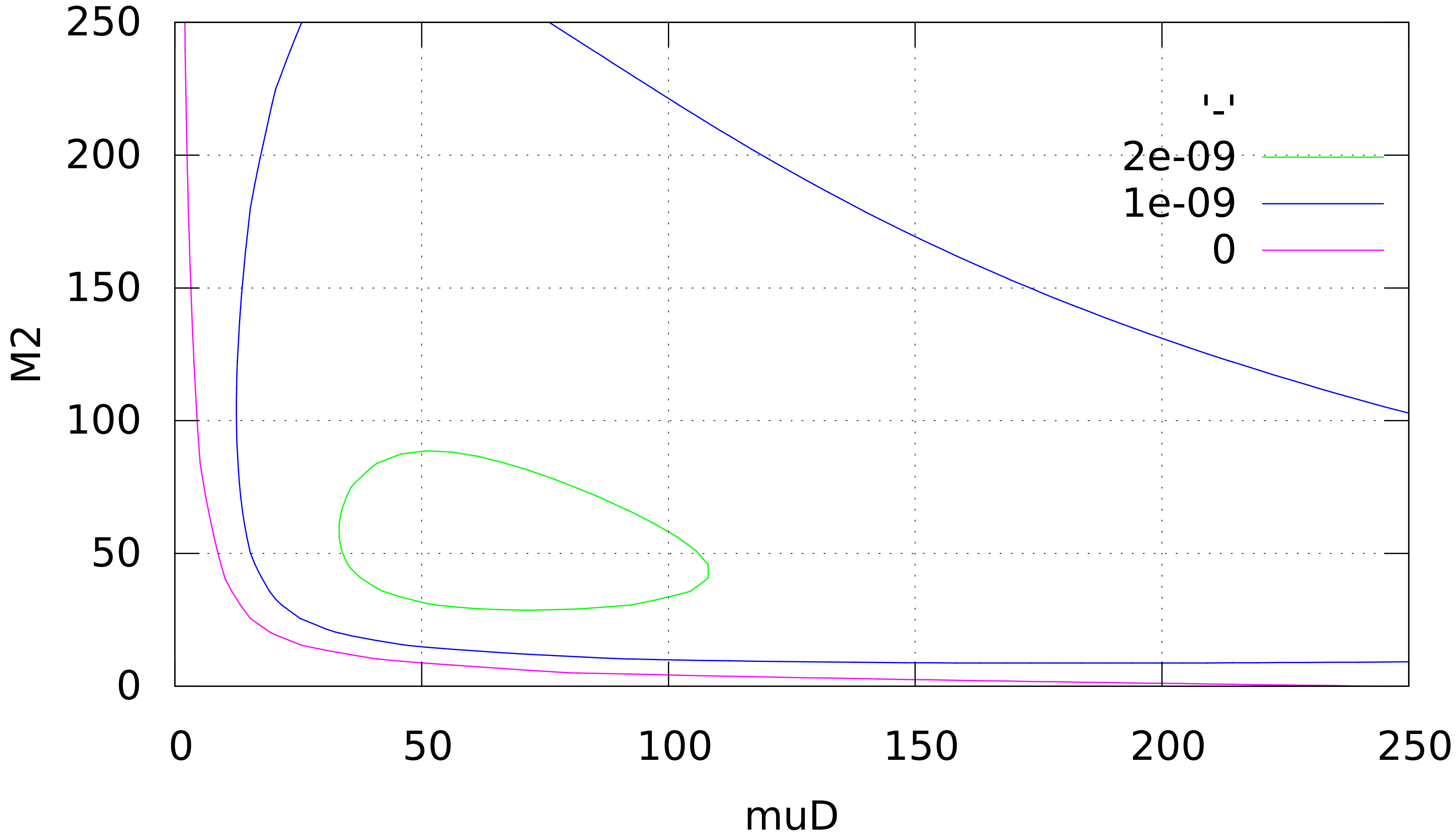


$(g-2)_\mu$ in the MRSSM

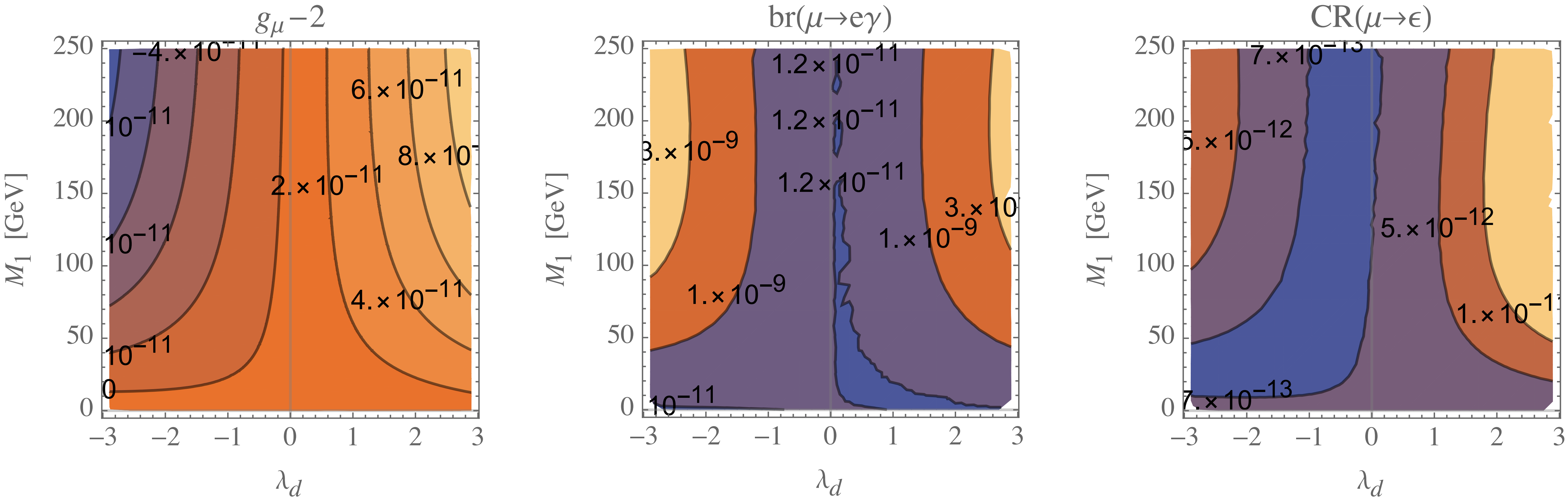
- It is possible to obtain large contribution to g-2



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

Photonic penguin dominance

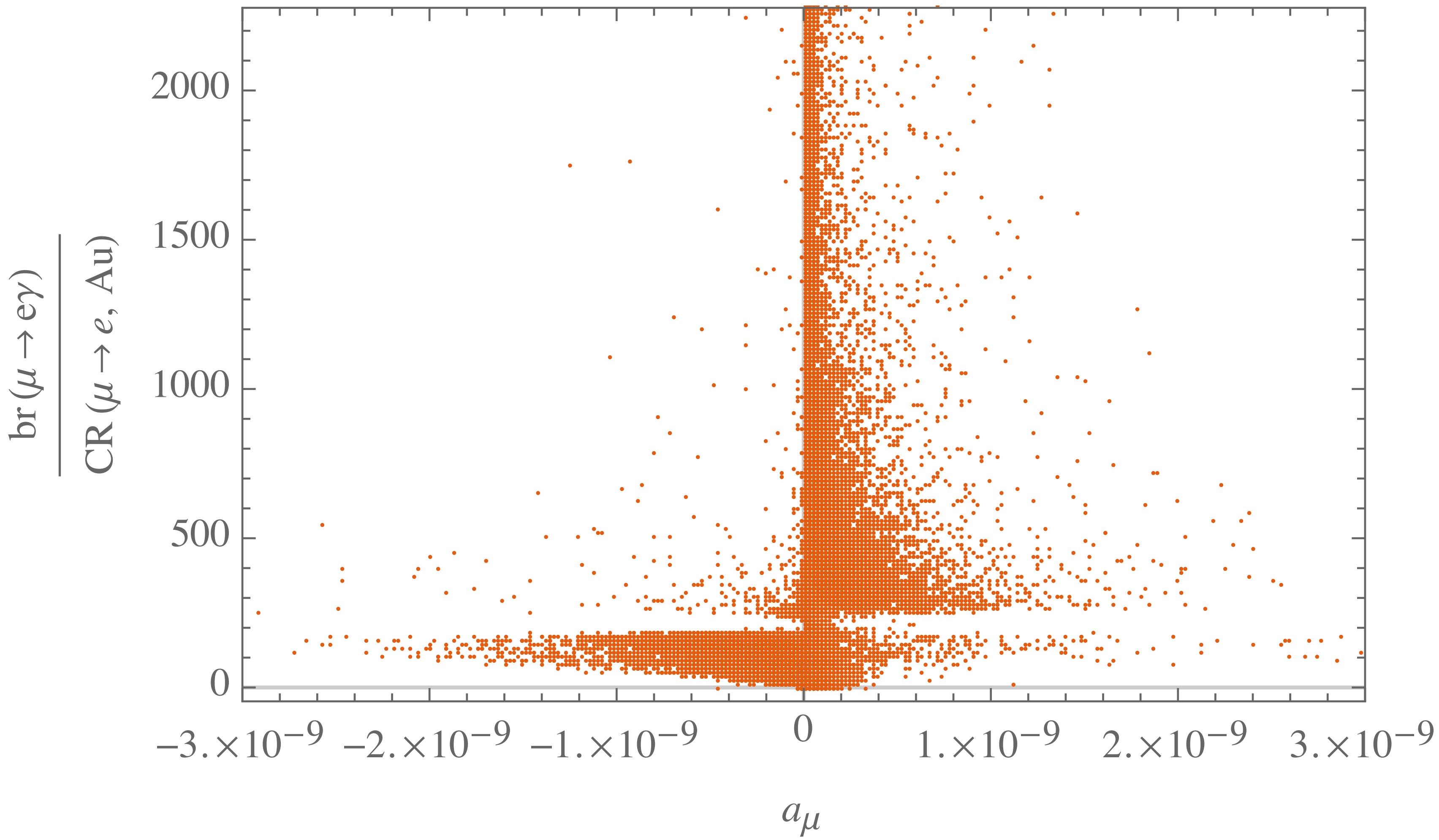
- For $|\lambda_d| \gtrsim 1$ the dipoles dominate: g-2 scales linearly with λ_d, while $\mu \to e\gamma$ and $\mu \to e$ quadratically



- 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 1 or less

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



- In the region dominated by the dipoles the $br(\mu \to e\gamma) \sim \sin^2 2\theta \cdot a_\mu^2$

- In the MRSSM this is a region of $|\lambda_d| \gtrsim 1$, in the MSSM $\tan\beta \gtrsim 5$

6 distinct regions of parameter space

- At least 2 light masses needed

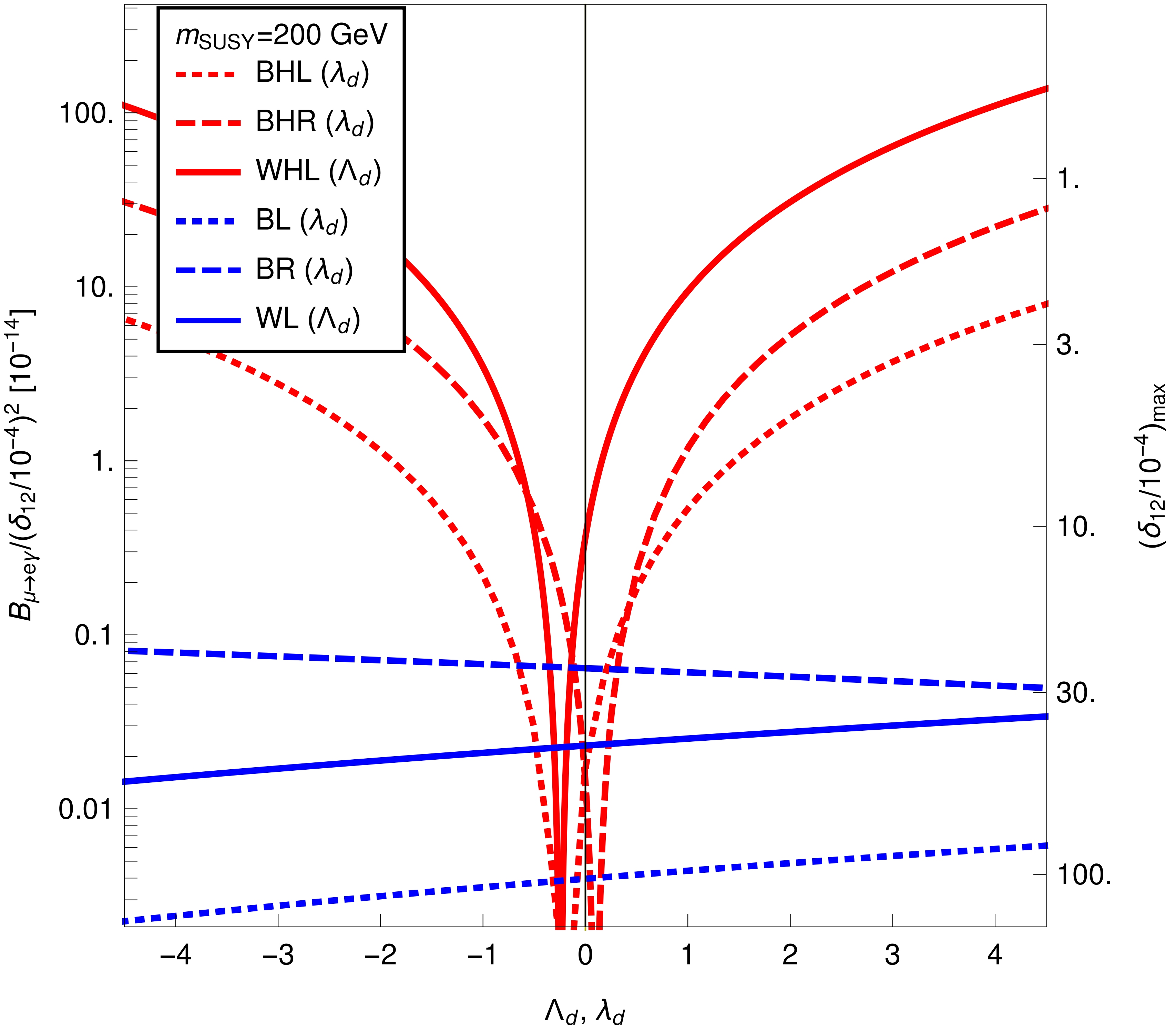
- 6 distinct parameter regions

BL: light M_B^D, $m_{\tilde{l}}$
BR: light M_B^D, $m_{\tilde{e}}$
WL: light M_W^D, $m_{\tilde{l}}$

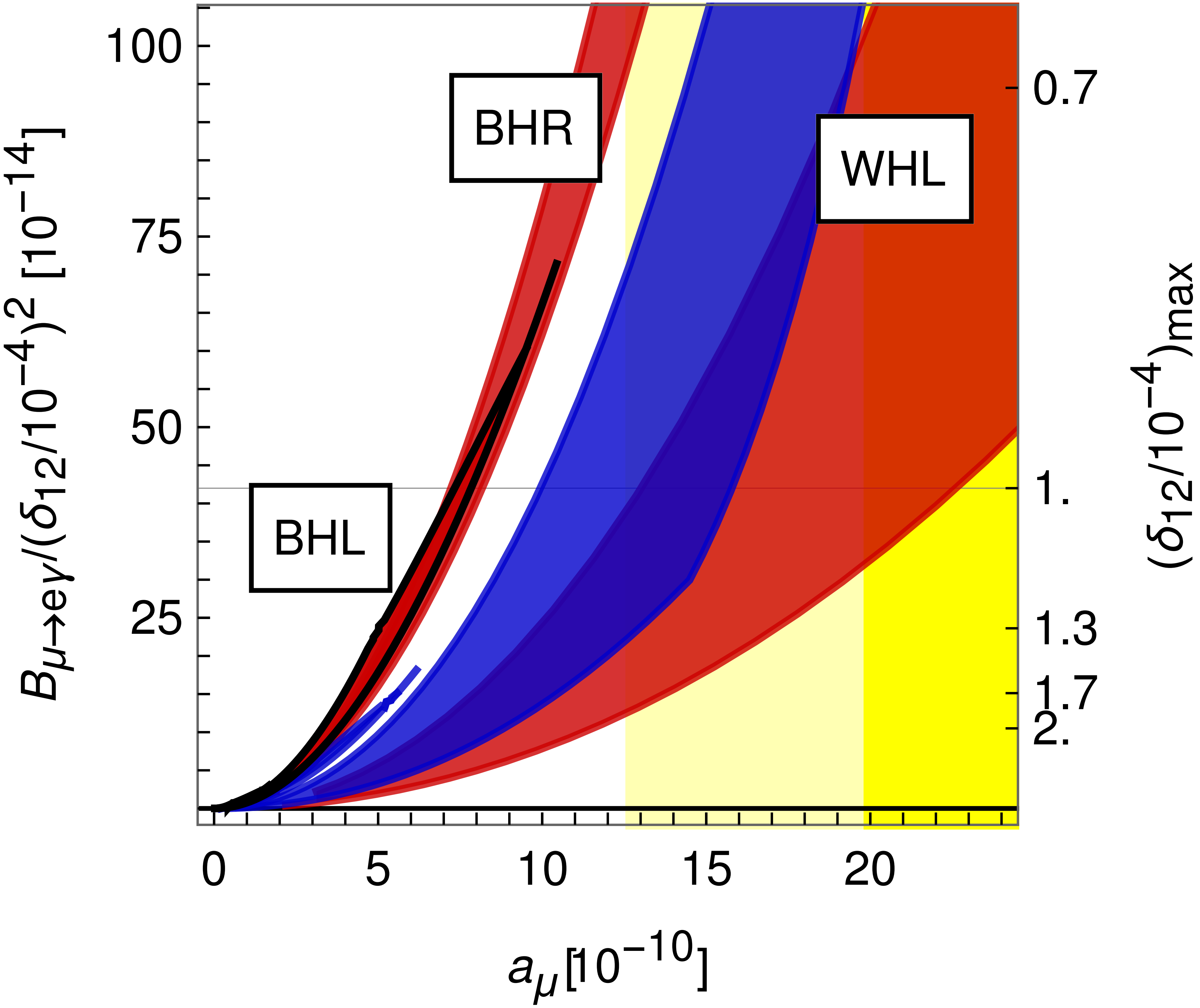
BHL: light M_B^D, μ_d, $m_{\tilde{l}}$
BHR: light M_B^D, μ_d, $m_{\tilde{e}}$
WHL: light M_W^D, μ_d, $m_{\tilde{l}}$

- Only red ones exhibit λ_d or Λ_d enhancement

Numerical analysis of λ_d and Λ_d enhancement



Summary plot



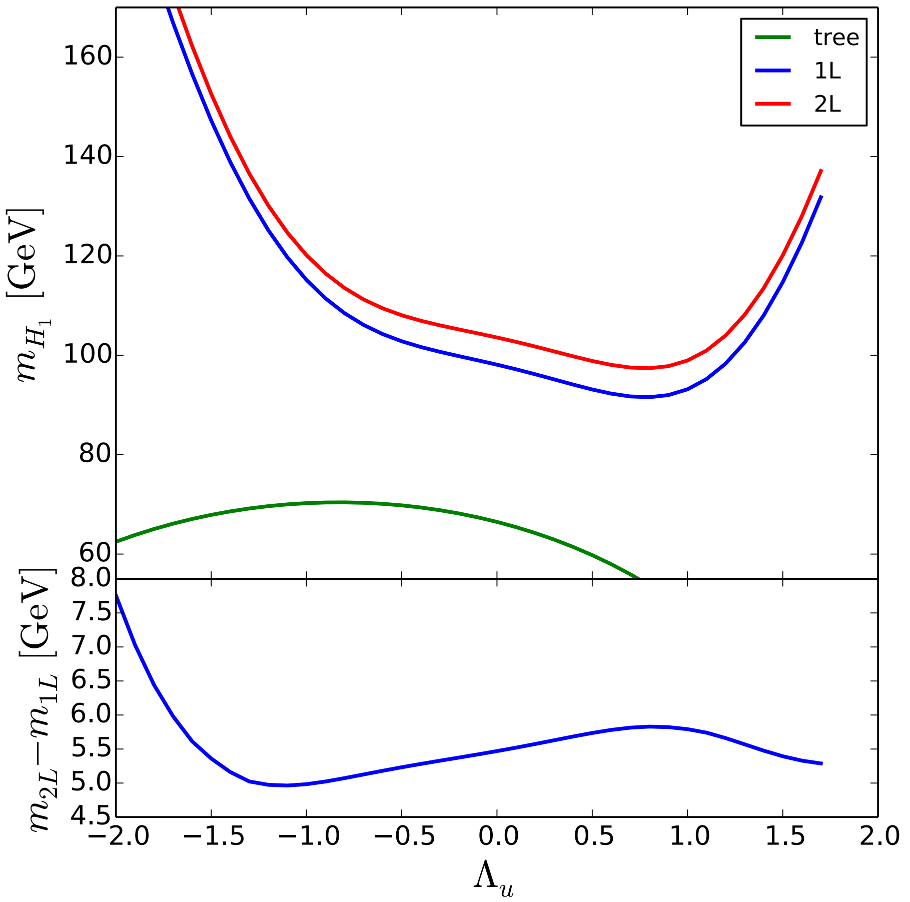
Conclusions:

- Two distinct cases: $|\lambda_d| \approx 0$, $|\lambda_d| > 0$
- For large $|\lambda_d|$ observables might get dominated by photon „penguins" and 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

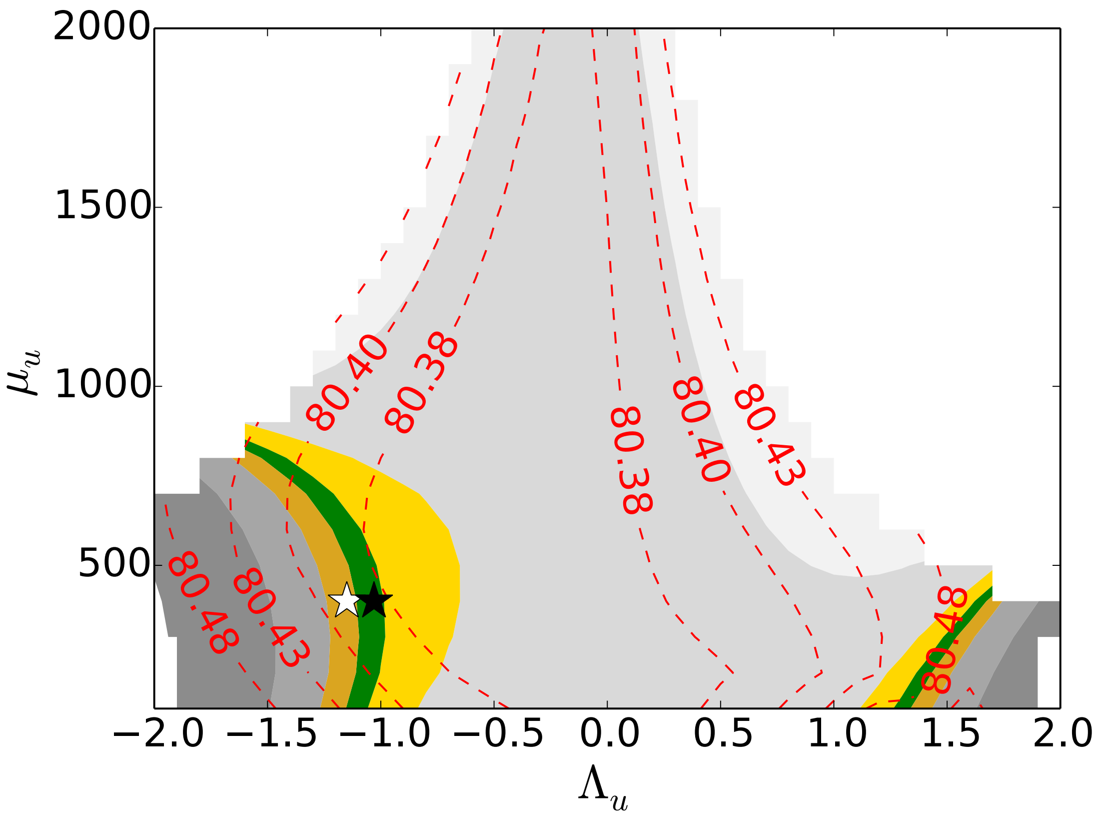
✦ 1-loop quantum corrections

✦ 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

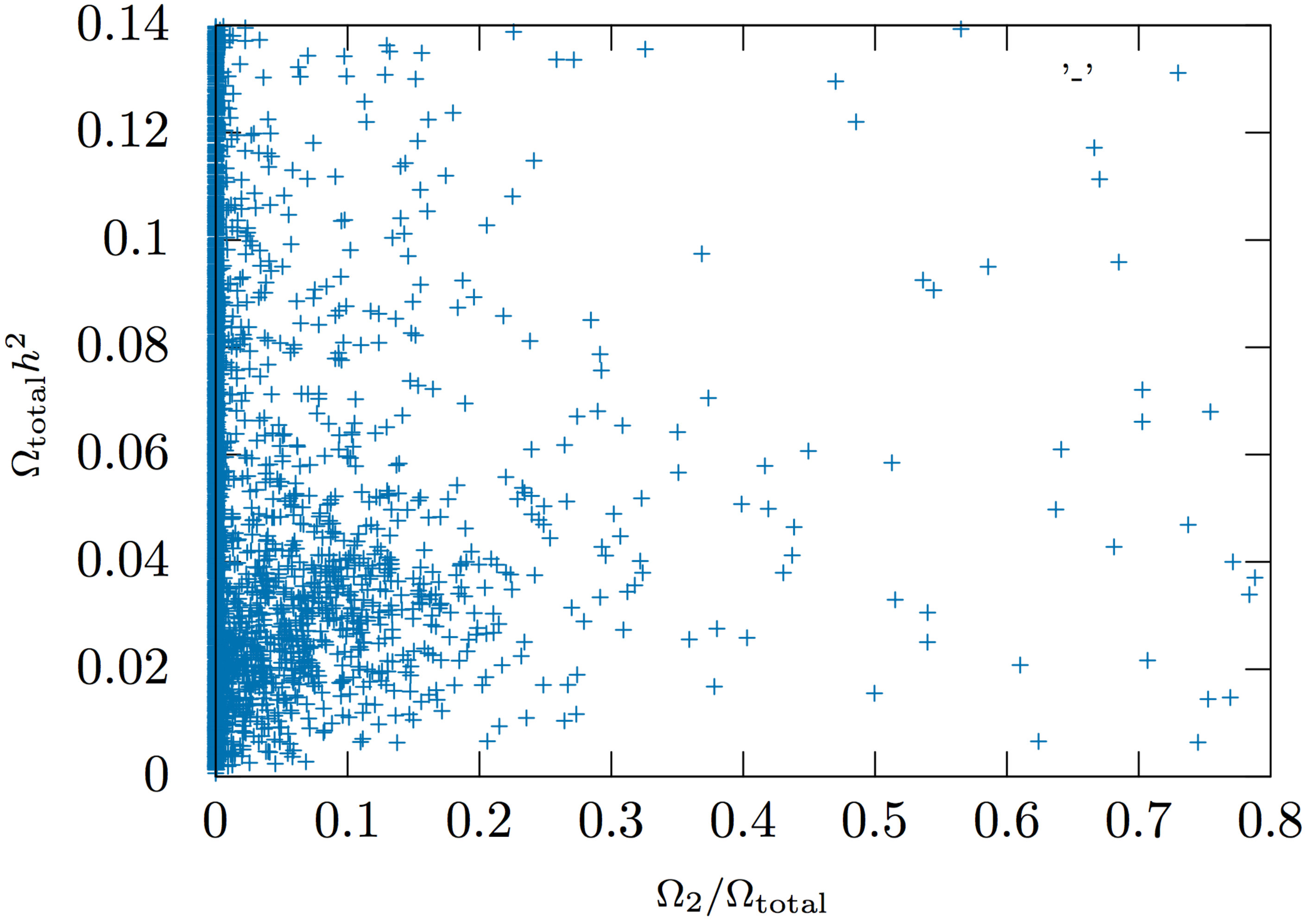


2 component dark matter

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

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

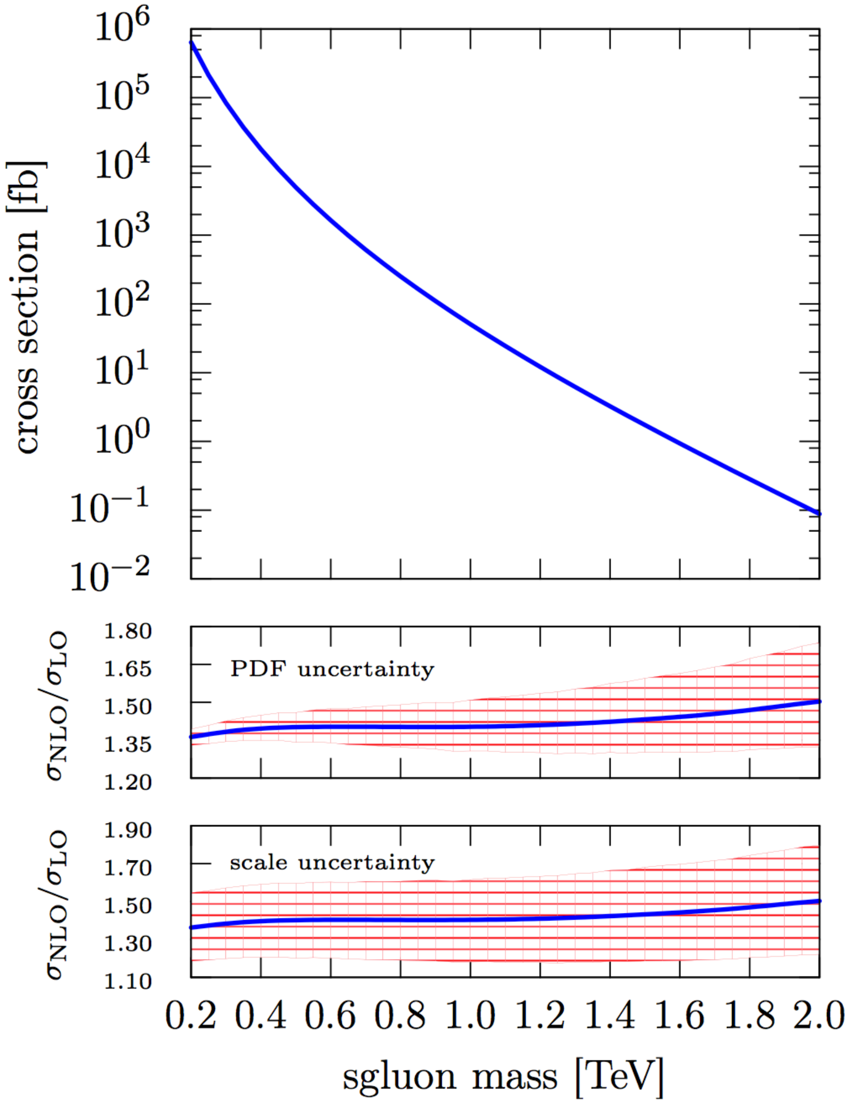
$$m_{R_1^0} = 571 \text{ GeV}$$

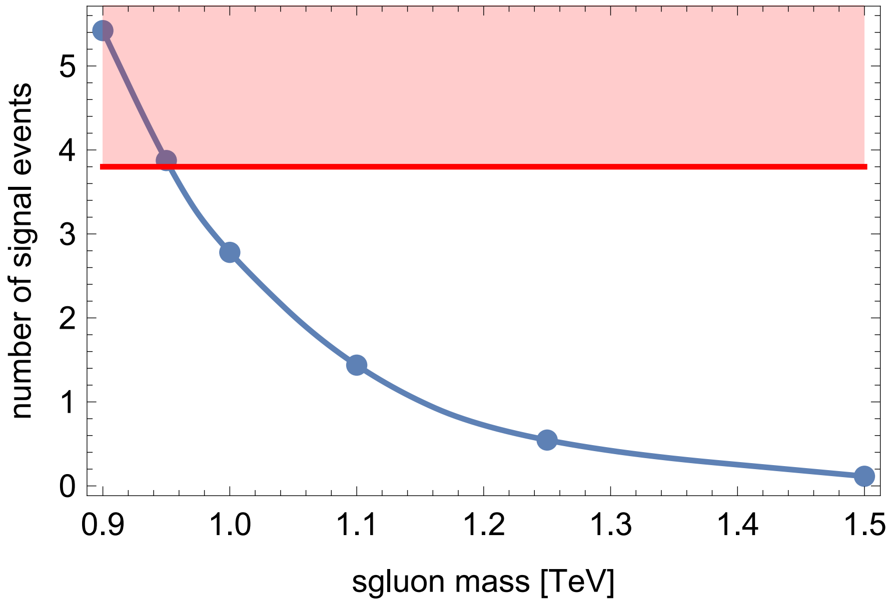


Sgluon pair production at 13 TeV LHC

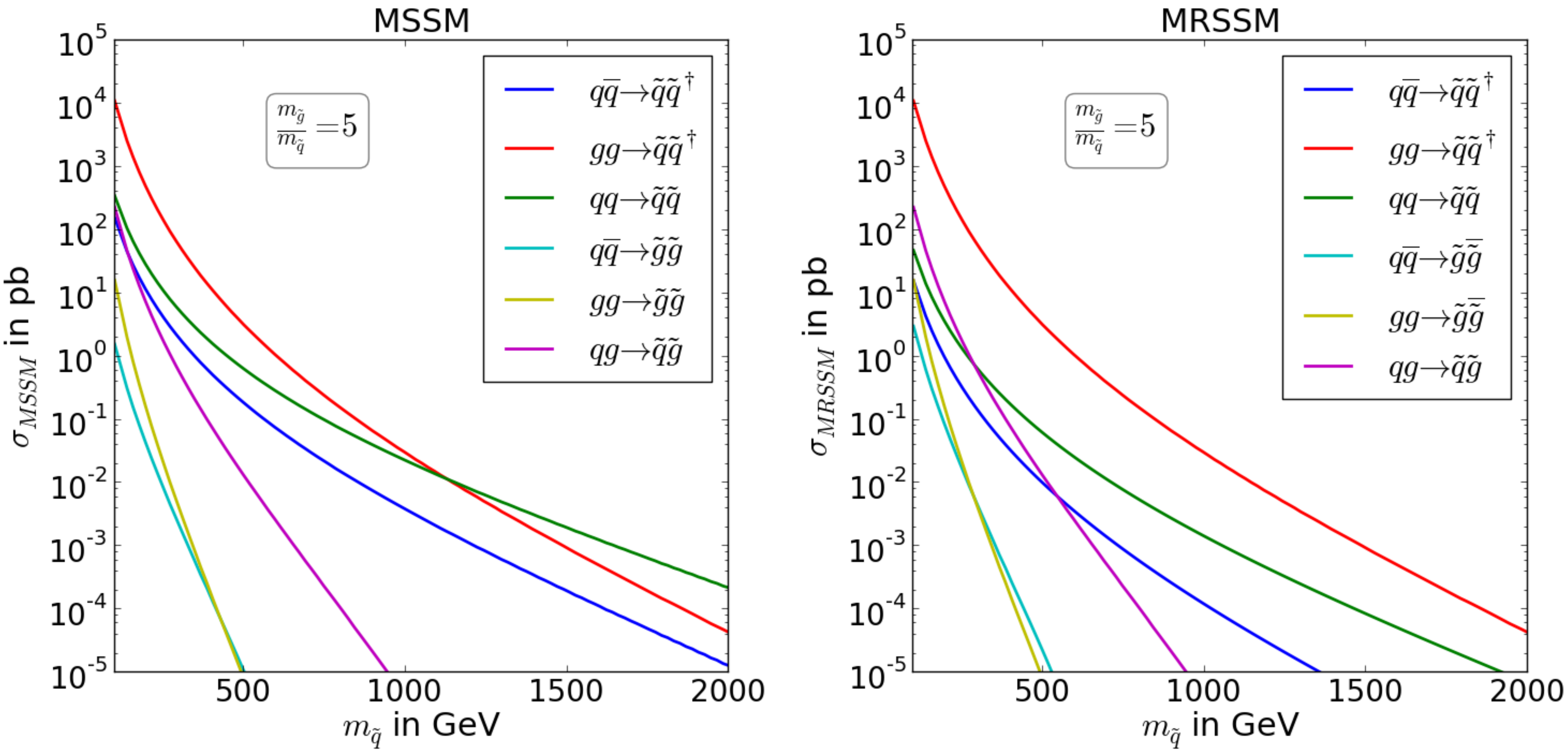
W. Kotlarski [arXiv:1608.00915]

- 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

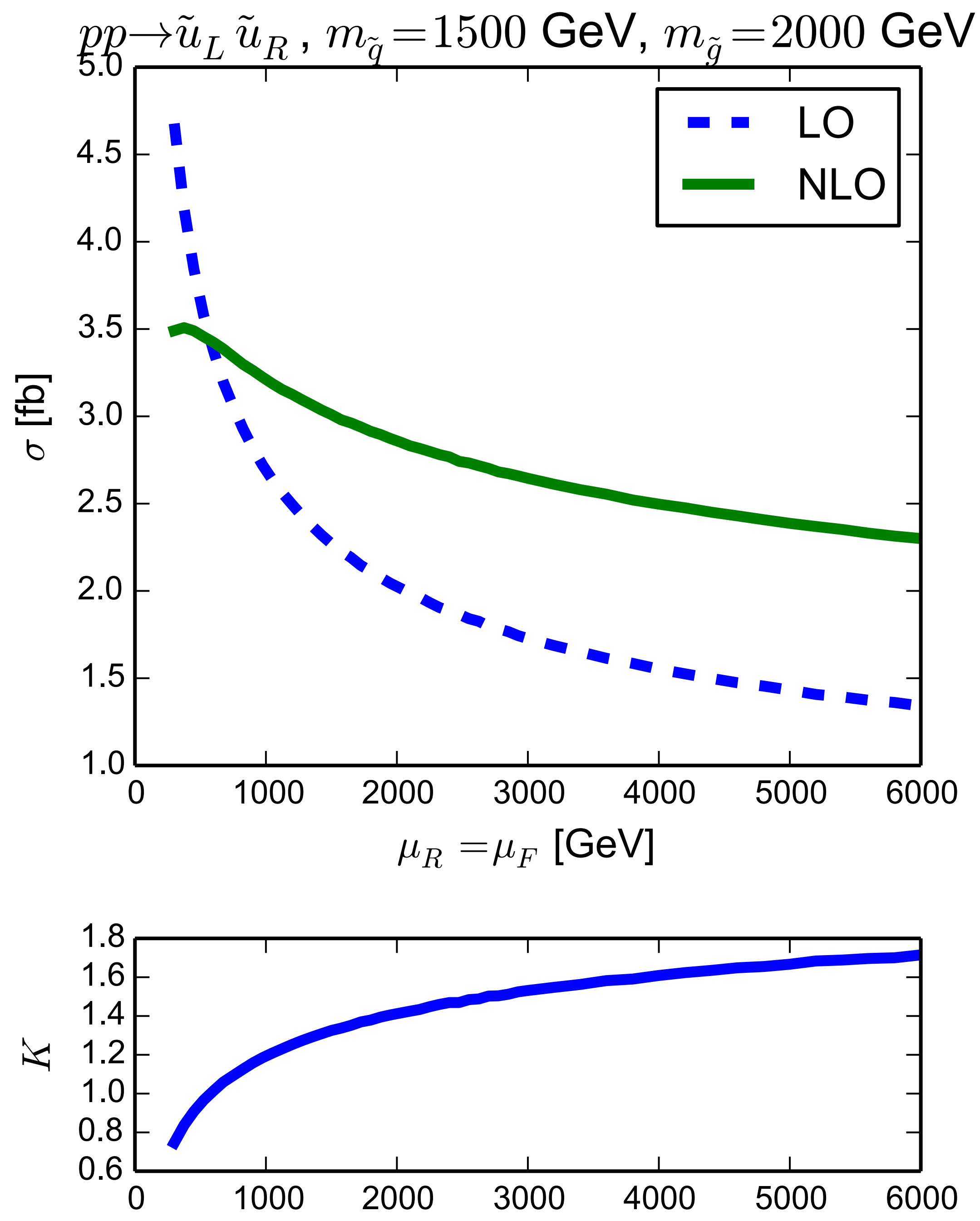


LO cross-sections for sparticle production at the LHC at $\sqrt{s}=13$TeV

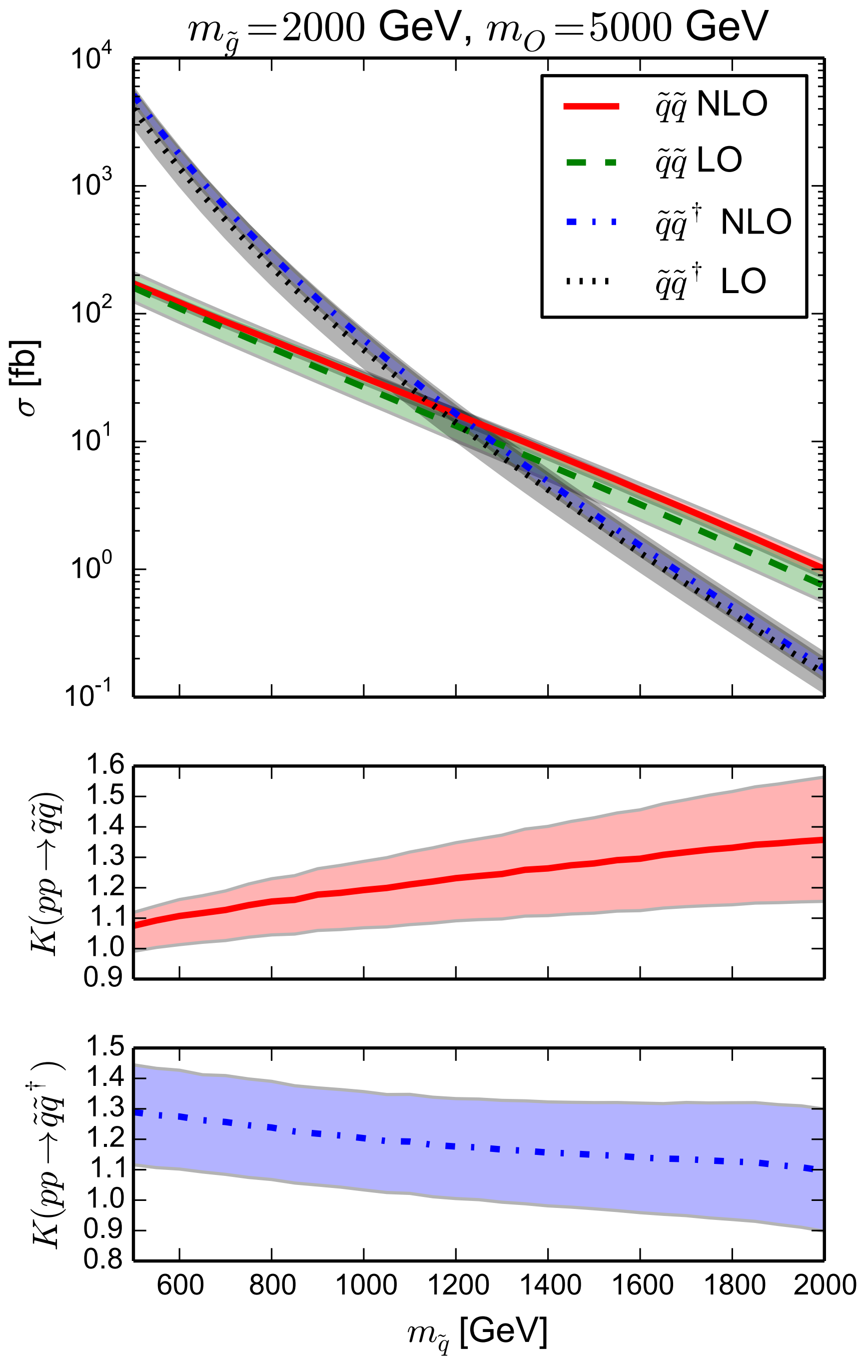
MSSM

MRSSM

NLO improvements



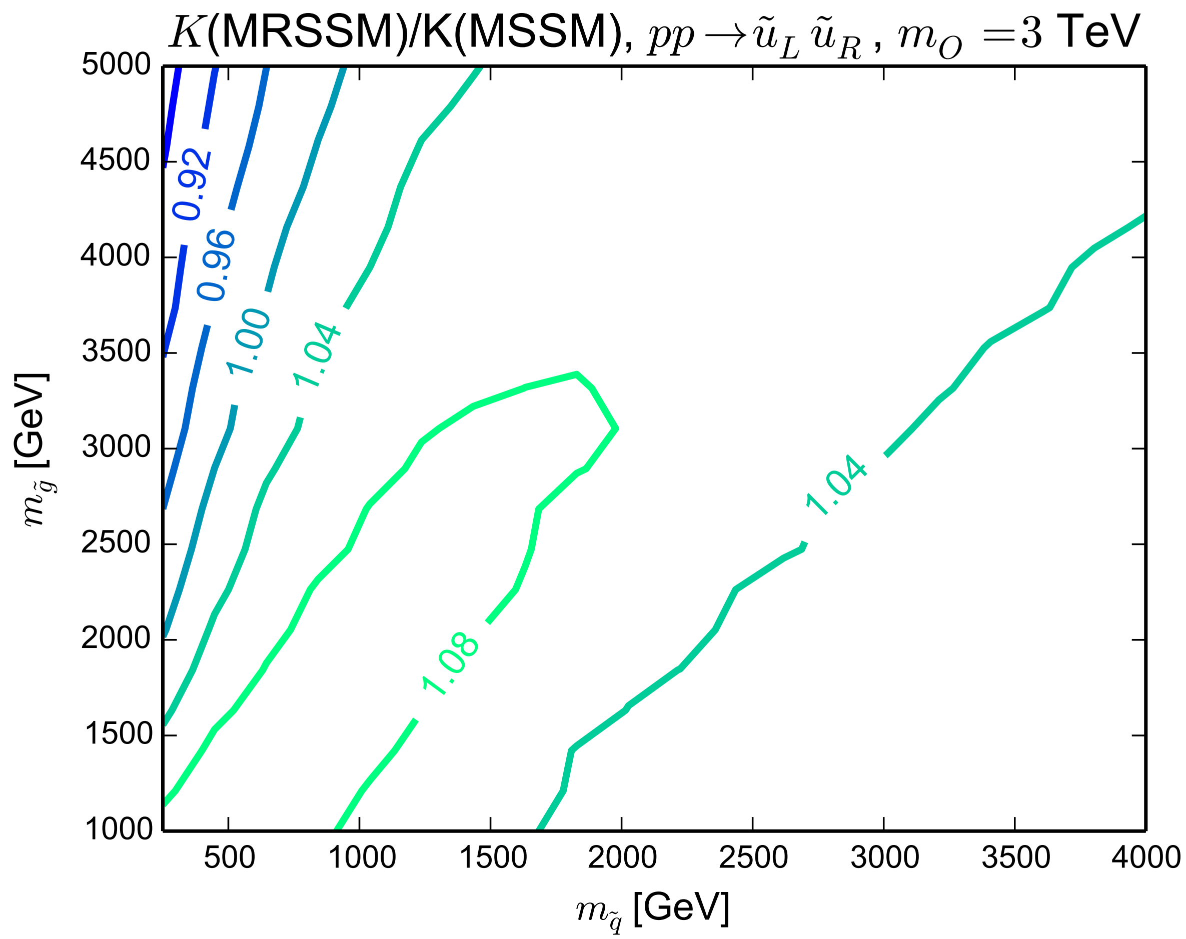
reduction of theoretical uncertainty

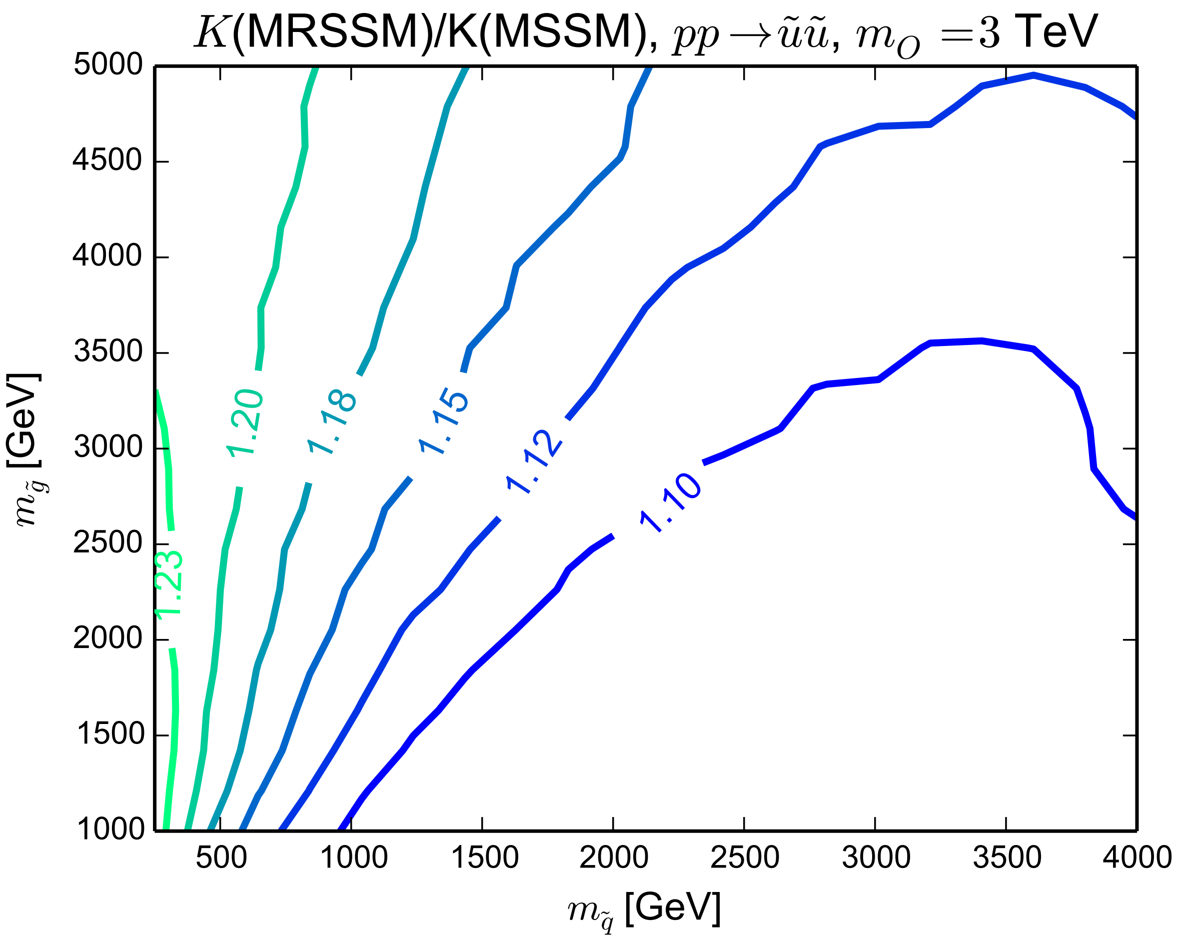


shift of cross-sections

right figure summed over flavors

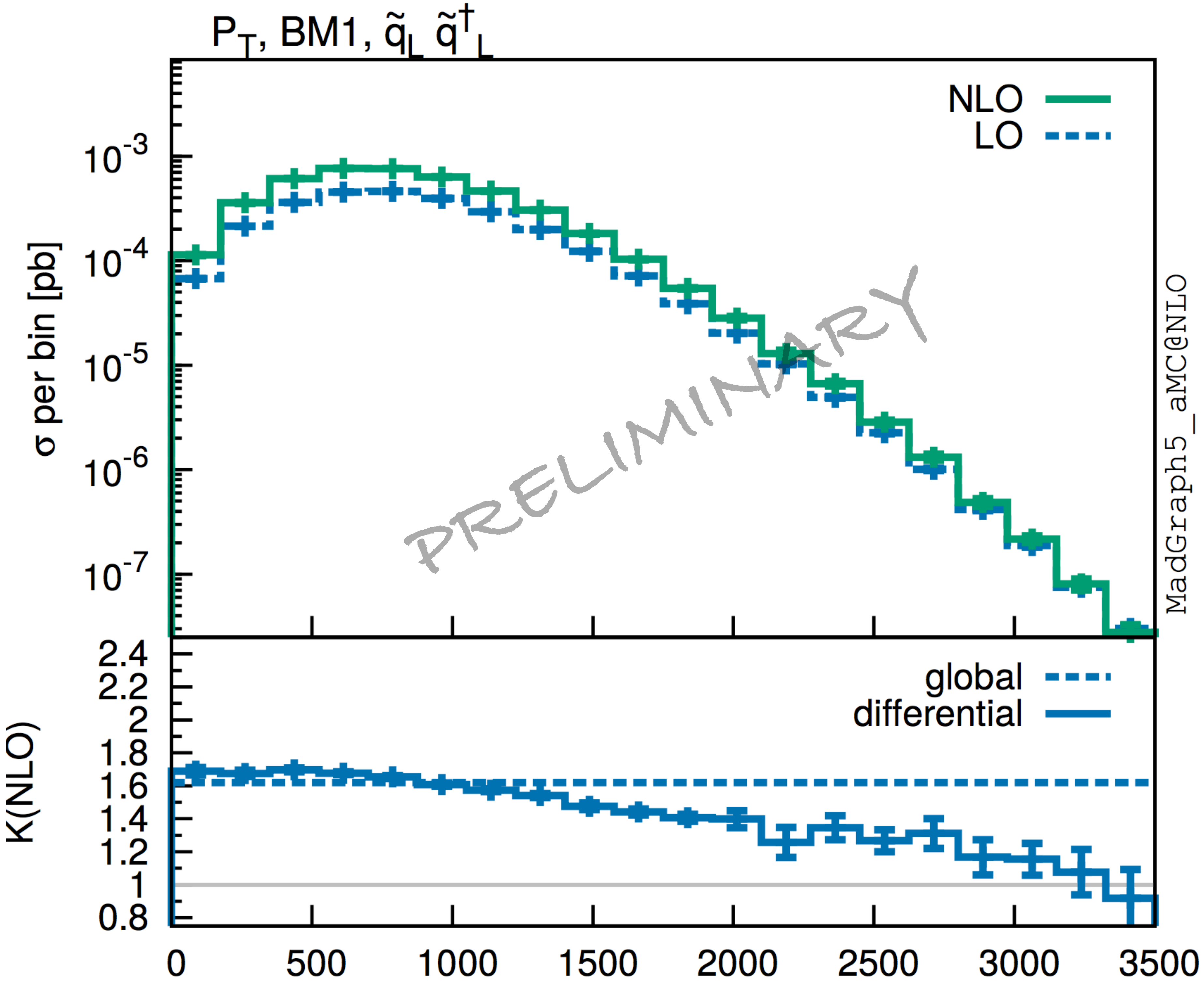
Comparison with the MSSM





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

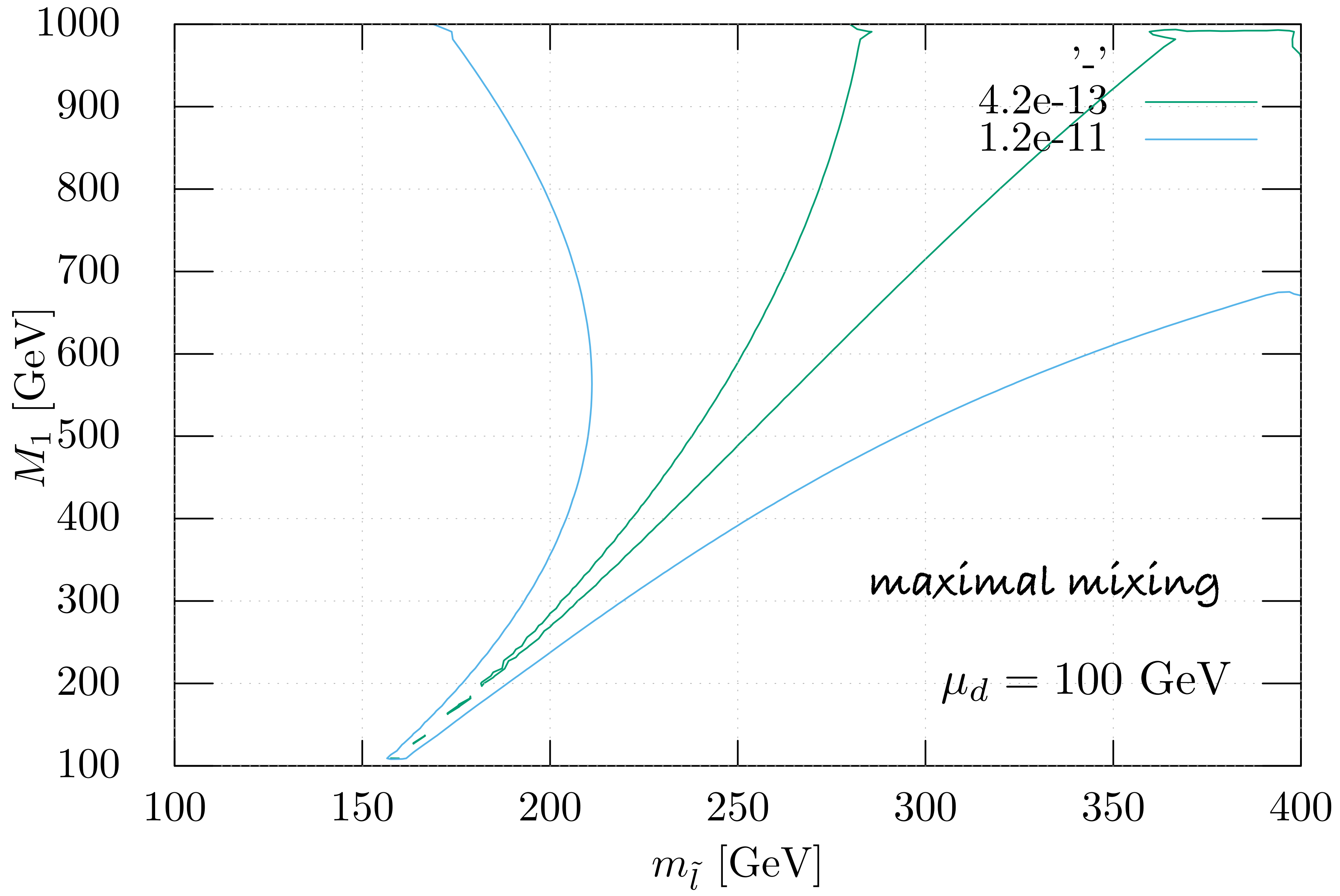
Differential distributions



$\mu \to e\gamma$ 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

$$m_{\tilde{l}_2} = \frac{3}{2} m_{\tilde{l}}$$



maximal mixing

$\mu_d = 100$ GeV

new MEG results

old MEG results