Looking for R-symmetric SUSY directly and indirectly at the LHC

Philip Diessner

Corfu Summer Institute, Sep. 3th, 2018

Outline

R-Symmetric SUSY and the MRSSM

R-symmetric SQCD at the LHC

- NLO Calculation of squark production
- SQCD Phenomenology

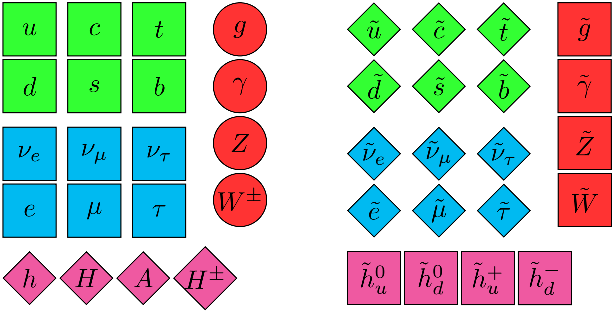
Prediction for the W boson mass in the MRSSM

- From muon decay to M_W
- Results

Conclusion

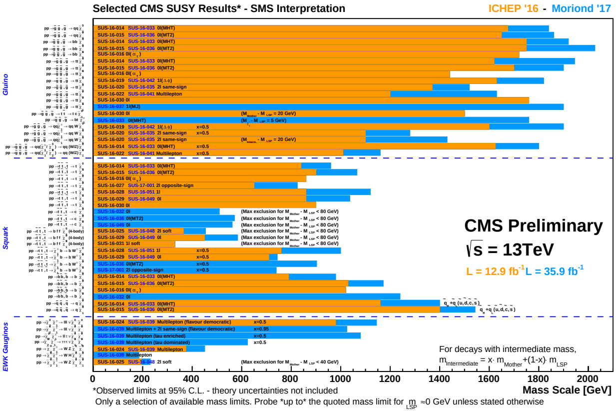
Minimal Supersymmetry

- Still well motivated extension of SM
- Predicts SM Higgs boson mass in right range
- Dark matter candidate
- Solution to Hierarchy problem



Going beyond the MSSM

- > LHC Run 2 on-going
- > So far no obvious sign of MSSM



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> Look into non-minimal models for range of alternative predictions

Possibilities

> Less symmetry (RPV)
> More symmetry (UMSSM,BLMSSM)
> More Higgs states (NMSSM,TMSSM)
> …

Going beyond the MSSM

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R-Symmetry

- Includes solution to flavor problem of the MSSM
- Dirac gauginos (esp. gluino) might explain SUSY non-discovery
- Extended Higgs sector, different predictions than (N)MSSM

R-symmetry

- Additional symmetry allowed by SUSY algebra: $[Q_\alpha, R] = Q_\alpha \ , \quad [\overline{Q}_{\dot\alpha}, R] = -\overline{Q}_{\dot\alpha}$
- For $N = 1$ SUSY it is a global $U(1)_{\mathrm{R}}$ symmetry
  $\rightarrow$ Different charges for Superpartners
- SM fields have $Q_{\mathrm{R}} = 0$
- SUSY partners carry charge
- Lagrangian has to be invariant (MRSSM Kribs et.al. (Phys.Rev. D78 (2008) 055010))

Symmetry forbids terms in Lagrangian

- Superpotential ($Q_{\mathrm{R}} = 2$): $\mu \hat{H}_u \hat{H}_d$, $\lambda \hat{E}\hat{L}\hat{L}$, $\kappa \hat{U}\hat{D}\hat{D}$
- Soft breaking ($Q_{\mathrm{R}} = 0$): $M_i \tilde{\lambda}_i \tilde{\lambda}_i$, $A y_e h_d \tilde{l} \tilde{e}_R$, $A y_u h_u \tilde{q} \tilde{u}_R$, $A y_d h_d \tilde{q} \tilde{d}_R$

Relaxes flavor problem, but no masses for gauginos and higgsinos

Particles of the MRSSM

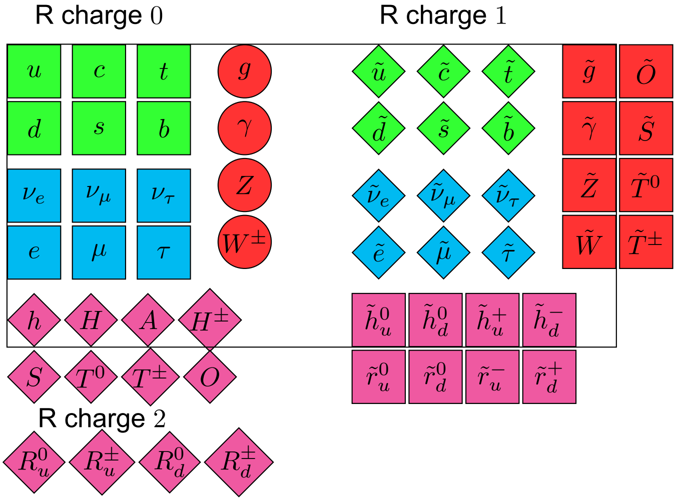
Adding to the MSSM

		$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{\text{R}}$
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

$$\mathcal{W} = -Y_d \,\hat{\bar{D}}\,(\hat{Q}\hat{H}_d) - Y_e \,\hat{\bar{E}}\,(\hat{L}\hat{H}_d) + Y_u \,(\hat{\bar{U}}\,\hat{Q}\hat{H}_u)$$
$$+ \Lambda_d\,(\hat{R}_d\hat{T})\,H_d + \Lambda_u\,(\hat{R}_u\hat{T})\,\hat{H}_u + \lambda_d\,\hat{S}\,(\hat{R}_d\hat{H}_d) + \lambda_u\,\hat{S}\,(\hat{R}_u\hat{H}_u)$$
$$\mu_d\,(\hat{R}_d\hat{H}_d) + \mu_u\,(\hat{R}_u\hat{H}_u)$$

$$-\mathcal{L}_{\text{soft}} \supset M_i^D \tilde{\lambda}_i^a \psi_j^a + h.c. \quad \{i,j\} \in \{\{G,O\},\{W,T\},\{B,S\}\}$$

Particles of the MRSSM



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MRSSM at the LHC

- Dirac gaugino masses are “super-soft”

  (Fox, et.al., [hep-ph/0206096])

- $\rightarrow$ Scenario with heavy gluino and rather light squarks natural
- Here: Concentrate on squark production in the MRSSM

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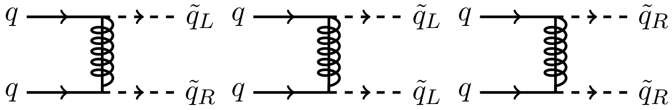

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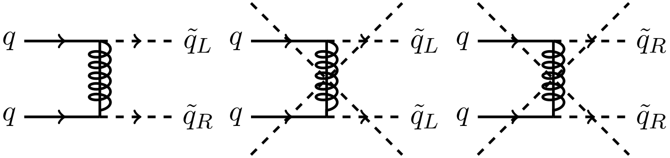

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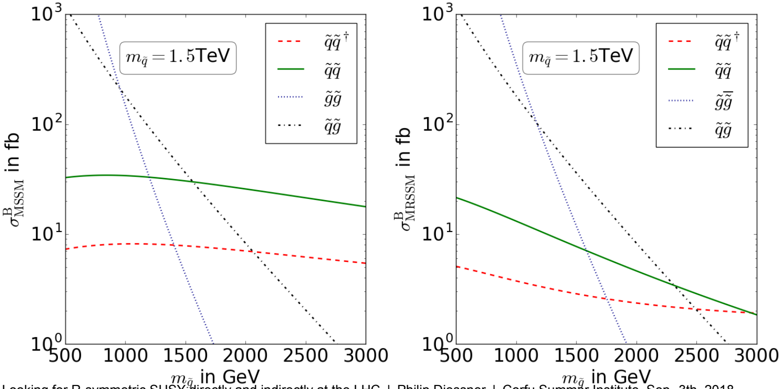

left: MSSM,

right: MRSSM

NLO calculation

> MSSM results known since many years used in form of (global) K-factors by experiments and pheno studies

$$K = \frac{\sigma_{NLO}}{\sigma_{LO}}$$

> "NLO revolution" for SM processes allows reliable and fast calculation of NLO corrections including matching

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MRSSM

- Well-known from MSSM that NLO effects sizable
- Additional scalar octet: sgluon
- Dirac nature of gluino
- Squark production: squark-squark and squark-antisquark pair

Implementation

(PD, W. Kotlarski, S. Liebschner, D. Stöckinger [arxiv:1707:04557])

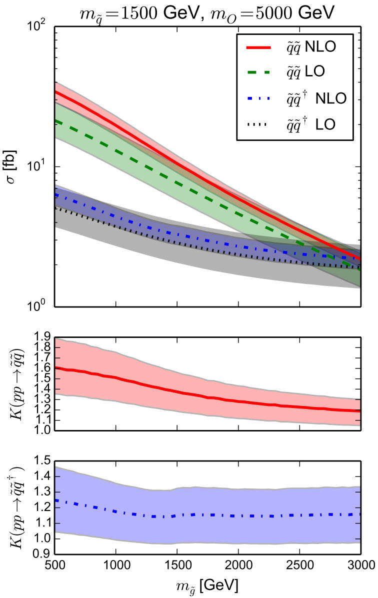
Combine popular programs and compare with own implementation of orthogonal methods

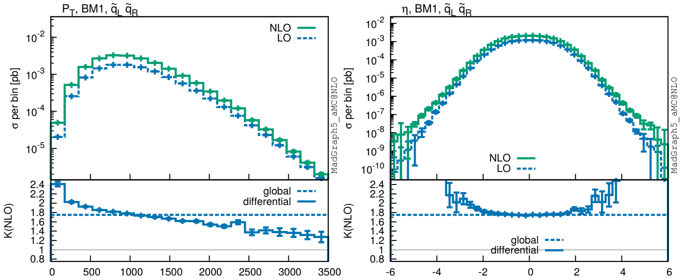
- `GoSam` and `MadGraph_aMC@NLO` (+ own implementation of renormalisation) using OPP reduction and FKS subtraction
- Independent calculation using classical PV functions and phase space slicing

Theoretical aspects

- Dimensional regularisation or reduction
- Cancellation of IR divergences
- On-shell renormalisability
- Treatment of on-shell resonances

Results



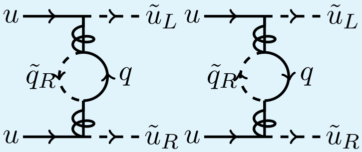


> Corrections behave similar as in MSSM
> Some prominent deviations exist

MRSSM effects

Dirac nature of the gluino

MSSM:



Example: squark-squark:

- only one Dirac gluino chirality couples to matter
- Diagrams proportional to Majorana mass not present

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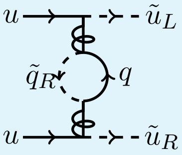

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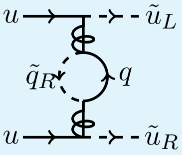

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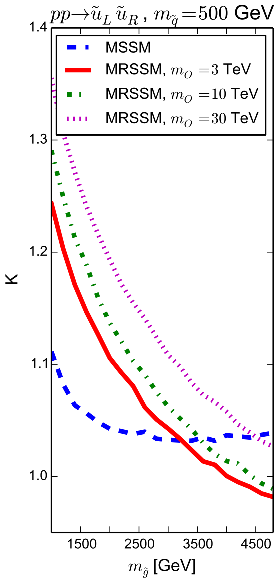
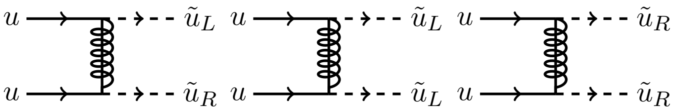
Presence of sgluon

$$\sigma(pp \Rightarrow \tilde{q}_L \tilde{q}_r)\big|^{1L}_{\text{sgl}} = \frac{\alpha_s}{4\pi}\left(\log \frac{m_O^2}{m_{\tilde{g}}^2}\right) \sigma(pp \to \tilde{q}_L \tilde{q}_r)\big|_{\text{LO}}$$



Comparison to the MSSM

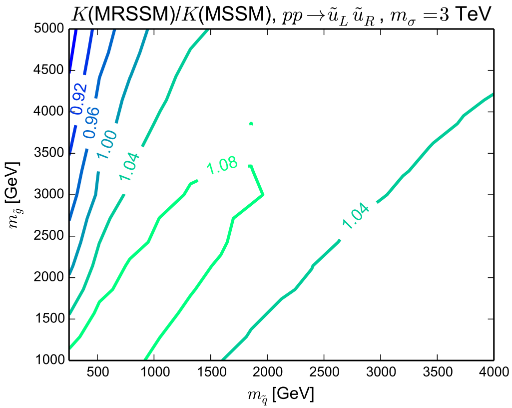
- Output from standard tools (Prospino, NNLLfast) is $K(pp \to \tilde{u}\tilde{u})$
- But $K(pp \to \tilde{u}\tilde{u}) \neq K(pp \to \tilde{u}_L\tilde{u}_R)$ in MSSM

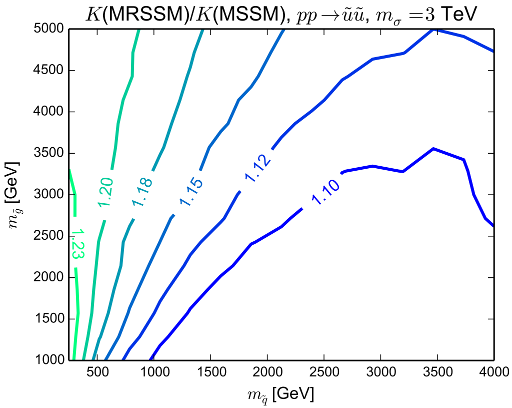


Compare $\frac{K(MRSSM)}{K(MSSM)}(pp \to \tilde{u}_L\tilde{u}_R)$ and $\frac{K(MRSSM)}{K(MSSM)}(pp \to \tilde{u}\tilde{u})$

Comparison to the MSSM

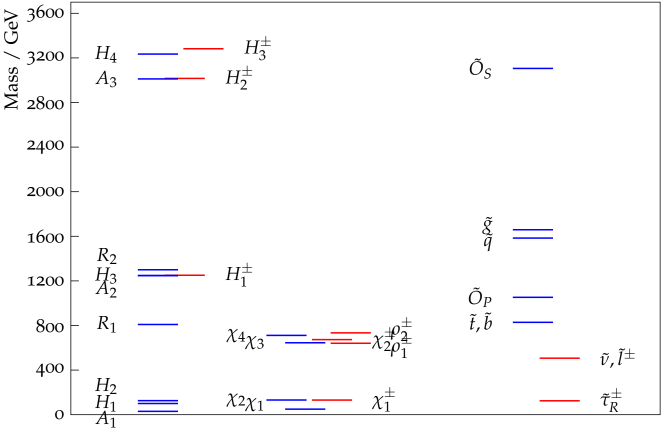
- Output from standard tools (Prospino, NNLLfast) is $K(pp \to \tilde{u}\tilde{u})$
- But $K(pp \to \tilde{u}\tilde{u}) \neq K(pp \to \tilde{u}_L\tilde{u}_R)$ in MSSM
- Leads to systematic error





Phenomenology - Basics

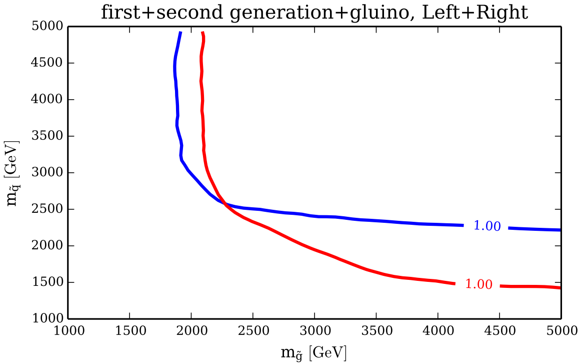
- R-charge leads to LSP/LRP
- Neutralinos are Dirac states
- For exclusion/discovery mass hierarchies are more important
- For now, NLO K-factors not included



Phenomenology-- Preliminary results

(PD, J. Kalinowski, W. Kotlarski, D. Stöckinger) in progress

- Limit derived with `Herwig` 7 and `CheckMate` 2
- ATLAS search for 0ℓ, 2-6 jets + E^T_{miss} , 36 fb^{-1} [1712.02332]
- Comparing MRSSM and MSSM
  - Stronger limits on gluino mass
  - Weaker for (first generations) squark masses



blue – MSSM; red – MRSSM

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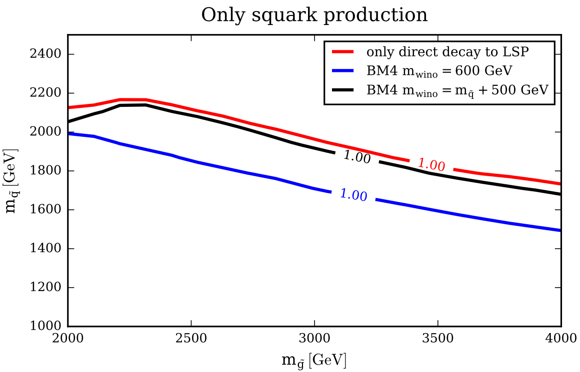
- Limit derived with `Herwig` 7 and `CheckMate` 2
- ATLAS search for 0ℓ, 2-6 jets + E^T_{miss} , 36 fb^{-1} [1712.02332]
- Scenarios in the MRSSM for squark production
  - Strongest bound from direct decay to light LSP
  - Intermediate (Dirac)-wino has strong influence



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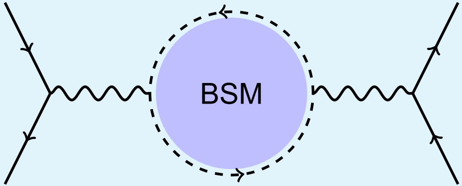
M_W as example EWPO

Loops matter



Requires precise theory prediction and experimental measurements

$$M_W^{\text{SM, on-shell}} = 80.358 \pm 0.008 \text{ GeV}$$

$$M_W^{\text{exp., LEP+Tevatron}} = 80.385 \pm 0.015 \text{ GeV},$$
$$M_W^{\text{ATLAS}} = 80.370 \pm 0.019 \text{ GeV}$$

LHC may provide new insight

Muon decay

$$\frac{G_\mu}{\sqrt{2}} = \frac{e^2}{8M_W^2 s_W^2}(1+\Delta r)$$

Precisely known: α, M_Z, G_μ, can solve for M_W

$$M_W^2 = M_Z^2\left(\frac{1}{2}+\sqrt{\frac{1}{4}-\frac{\alpha\pi}{\sqrt{2}G_\mu M_Z^2}(1+\Delta r)}\right)$$

(assuming no triplet vev for now)

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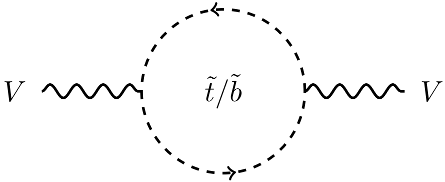
One-loop Δr in the SM

$$\Delta r = \Delta\alpha(\propto \text{log}\,\frac{M_Z}{m_f}, \approx 6\%) - \frac{c_W^2}{s_W^2}\Delta\rho(\propto M_t^2, \approx -3\%) + \Delta r_{\text{rem}}(\propto \text{log}\,\frac{M_h}{M_Z}, \approx 1\%)$$

BSM contributions to Δr

$\Delta\rho$

- Quantifies difference between charged and neutral current interactions
- $\Delta\rho = \frac{\Sigma_T^{ZZ}(0)}{M_Z^2} - \frac{\Sigma_T^{WW}(0)}{M_W^2}$ (same as T parameter)
- In MSSM mainly stop/sbottom (Driven by top-Yukawa)



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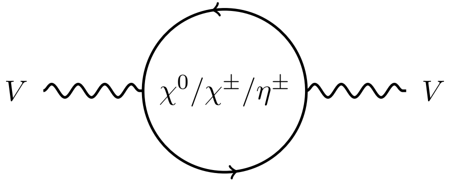
- In MRSSM additional effects from λ/Λ via charginos/neutralinos
- Generally, $\Delta\rho_{\text{MRSSM}} > 0$ and $\delta M_W^2 = M_W^2 \frac{c_W^2}{c_W^2 - s_W^2} \Delta\rho > 0$



Effects of a triplet vev

- Triplet with zero hyper-charge leads to tree-level contribution: $M_W^2 = \frac{g_2^2}{4}v^2 + g_2^2 v_T^2$
- Disturbs on-shell relation breaking custodial symmetry

$$\tilde{c}_W^2 \equiv \cos^2(\hat{\theta}_W) = \frac{g_2^2}{g_1^2 + g_2^2}\,, \qquad \frac{m_W^2}{m_Z^2} = \tilde{c}_W^2 + \frac{e^2 v_T^2}{(1-\tilde{c}_W^2)m_Z^2}\,.$$

- v_T depends on SUSY parameters via EWSB conditions
- Calculation of M_W from G_μ, α, M_Z, v_T

$$M_W^2 = M_Z^2 \left(\frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\alpha\pi}{\sqrt{2}G_\mu M_Z^2}(1 + \Delta\tilde{r} - 4\sqrt{2}G_\mu v_T^2)}\right) \cdot \left(\frac{1}{1 - \frac{4\sqrt{2}G_\mu v_T^2}{1+\Delta\tilde{r}}}\right)\,.$$

- Needs to be renormalized

Precision with more than one loop

SM prediction for M_W

- full one-loop
- full two-loop
- leading three- and four-loop contributions to $\Delta\rho$

MRSSM prediction for M_W

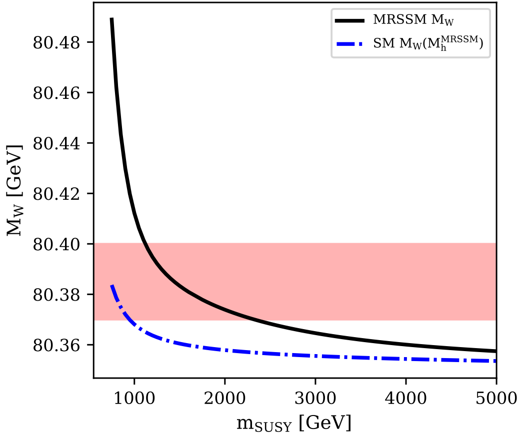
- all known SM contributions
- full MRSSM one-loop contributions
- Available MSSM two-loop results not applicable because Dirac nature of gluino

Precision

- intrinsic theory uncertainty: SM 4-6 MeV, MRSSM 9-12 MeV
- parametric uncertainty: from δM_t 5 MeV, $\delta\Delta\alpha_{\text{had}}$, δM_Z each 2 MeV
- experimental uncertainty: with LEP and Tevatron 15 MeV, +LHC 10 MeV
- ILC would reduce experimental and parametric unc.

General result

(PD, G. Weiglein [arxiv:1810:xxxxx])



- SUSY effects decouple
- M_W prediction generally larger than in MSSM for similar scale
- Caused by enlarged matter sector and new couplings

(SM depending on SUSY Higgs mass prediction)

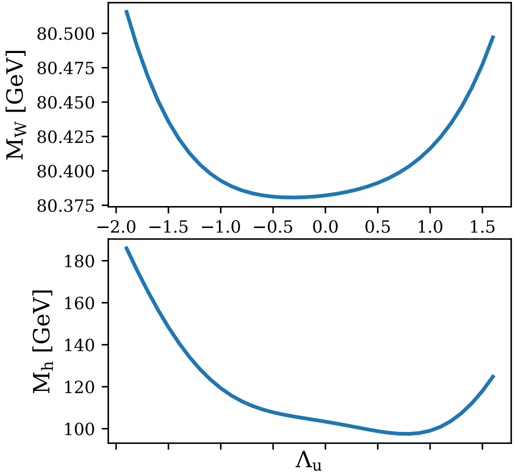
Influence of new parameters

Λ is Yukawa-like coupling

$$\mathcal{W} \supset \Lambda_d\,(\hat{R}_d\hat{T})\,H_d + \Lambda_u\,(\hat{R}_u\hat{T})\,H_u$$

contributes similarly to ρ

$$\Delta\rho_\Lambda = \frac{\alpha}{16\pi M_W^2 \tilde{s}_W^2}\frac{13\left(\Lambda_u^2 v_u^2 - \Lambda_d^2 v_d^2\right)^2}{96 M_{\text{wino}}^2}.$$



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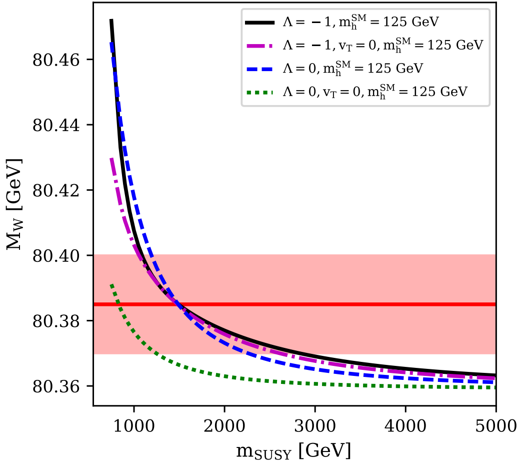
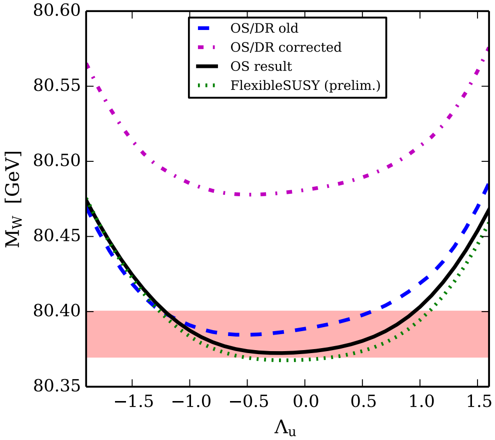
Triplet vev related via EWSB conditions

$$v_T = \frac{(\Lambda_u \mu_u + g_2 M_{\text{wino}}) v_u^2 - (\Lambda_d \mu_d + g_2 M_{\text{wino}})}{2 \left(m_{\text{triplet}}^2 + 4 M_{\text{wino}}^2\right)}$$



Comparison to other calculations



- Previous results in MRSSM from `SARAH/SPheno`
- Bug found adding 100 MeV to M_W
- Interestingly, OS result in line with old one
- Investigation underway
- fixed `FlexibleSUSY` OS/DR in development
  (points kindly provided by M. Bach)

Conclusions

- MRSSM as example of non-minimal SUSY accessible by LHC
- Directly accessible via strong production
  - Discussed NLO K factors
  - Presented how limits compare to MSSM
- Relevant to also study precision observables
  - Here: M_W calculation in on-shell scheme
  - Study difference to previous schemes
- When applying methods from know models (SM,MSSM) to models with new features subtle pitfalls need to be recognized
  - Correct usage of SQCD K factors when going from MSSM to MRSSM
  - Renormalisation scheme for M_W

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