New analytical calculations in NMFV-MSSM scenarios

→ For $(g-2)_\mu$ and B anomalies

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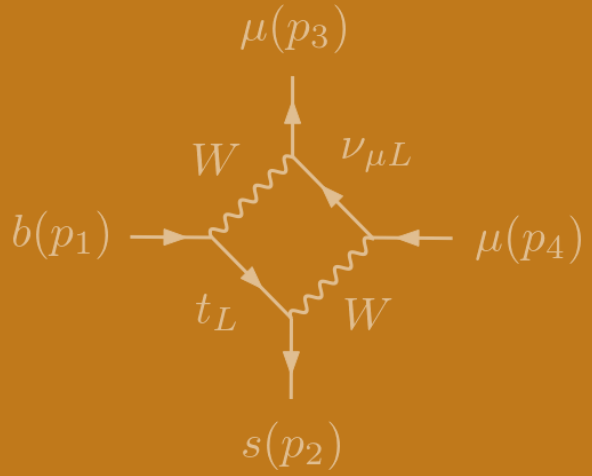
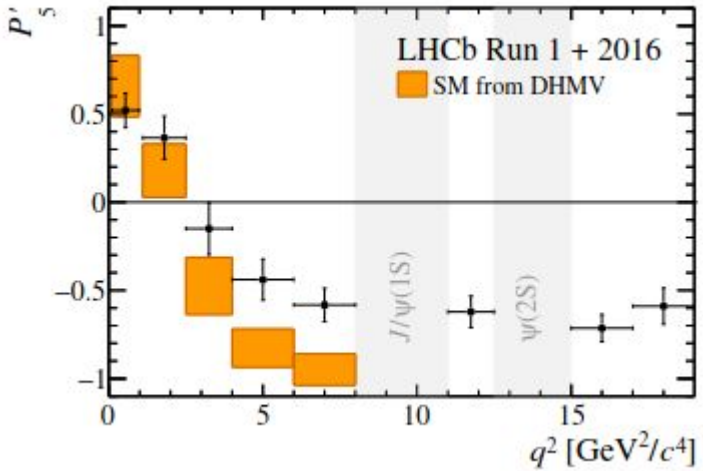
Motivations

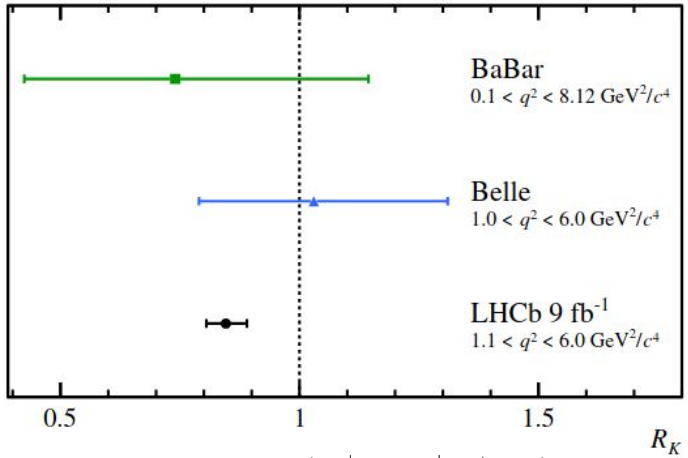


Flavor anomalies: $B \to K^{(*)}\mu^+\mu^-$



Angular observable **P'$_5$** : 2.5σ and 2.9σ tensions in the [4, 6[and [6, 8[bins

[arxiv:2003.04831]



$$R_K = \frac{\mathrm{BR}(B^+ \to K^+ \mu^+ \mu^-)}{\mathrm{BR}(B^+ \to K^+ e^+ e^-)}$$

R$_K$ recent update: 3.1σ tension with the SM.
[arxiv:2103.11769]

Wilson coefficients and best fit for μ

Effective Hamiltonian:

$$\mathcal{H}_{\text{eff}} \ni -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\frac{e}{16\pi^2} m_b C_7^{(\prime)} \left(\bar{s} \sigma^{\mu\nu} P_{R(L)} b \right) F_{\mu\nu} + \frac{e^2}{16\pi^2} C_{9(10)} \left(\bar{s} \gamma^\mu P_L b \right) \left(\bar{\mu} \gamma_\mu (\gamma^5) \mu \right) \right]$$

Standard Model predictions:

$$C_7^{(\text{SM})}(m_b) \approx -0.3$$
$$C_9^{(\text{SM})}(m_b) \approx +4.2$$

Global fit with 20 operators:

$$\delta C_7^{(\text{SM})}(m_b) \approx +0.05 \pm 0.03$$
$$\delta C_9^{(\text{SM})}(m_b) \approx -1.16 \pm 0.17$$

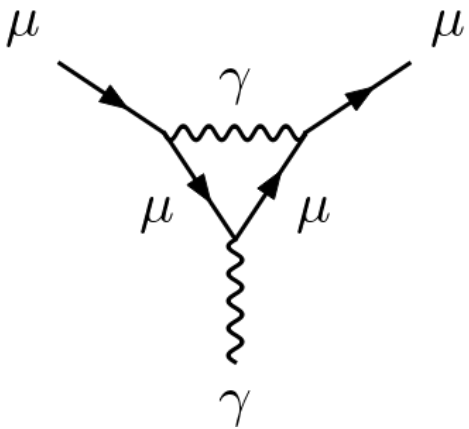
[arxiv:2104.10058]

Muon anomalous magnetic dipole moment

Magnetic dipole operator at the loop level:

$$i\mathcal{M} \ni a_\mu \frac{ie}{4m_\mu}(\bar{\mu}\sigma^{\mu\nu}\mu)\,F_{\mu\nu}$$

$$\hookrightarrow a_\mu = \frac{g_\mu - 2}{2}$$



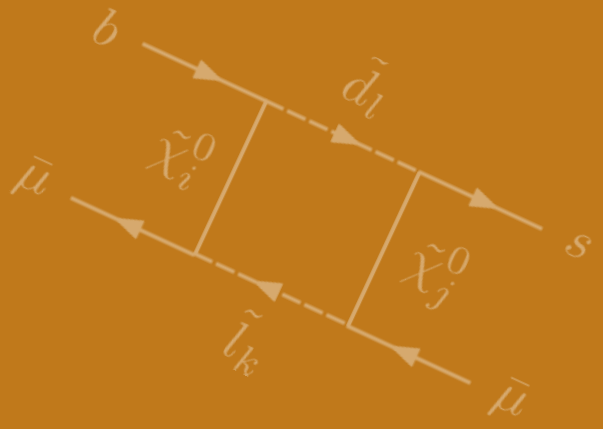
Recent measurements at Fermilab:

$$a_\mu^{\mathrm{EXP}} = 116\ 592\ 061(41) \times 10^{-11}$$

$$a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (251 \pm 59) \times 10^{-11}$$

⇒ 4.2σ tension

[arxiv:2104.03281]



Generalities on NMFV-MSSM scenarios

Soft Supersymmetry breaking

$$
\begin{aligned}
\mathcal{L}_{\text{soft}} = & -\frac{1}{2}\left(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g} + \text{c. c.}\right) \\
& - \left(\tilde{\bar{u}}\mathbf{a_u}\tilde{Q}H_u - \tilde{\bar{d}}\,\mathbf{a_d}\tilde{Q}H_d - \tilde{\bar{e}}\mathbf{a_e}\tilde{L}H_d + \text{c. c.}\right) \\
& - \tilde{Q}^\dagger \mathbf{m_Q^2}\tilde{Q} - \tilde{L}^\dagger \mathbf{m_L^2}\tilde{L} - \tilde{\bar{u}}\mathbf{m_{\bar{u}}^2}\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\,\mathbf{m_{\bar{d}}^2}\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\mathbf{m_{\bar{e}}^2}\tilde{\bar{e}}^\dagger \\
& - m_{H_u}^2 H_u^\dagger H_u - m_{H_d}^2 H_d^\dagger H_d - (bH_u H_d + \text{c. c.})
\end{aligned}
$$

105 parameters in the general MSSM

- 3 Higgs parameters $(m_{H_u}^2, m_{H_d}^2, b) \leftrightarrow (M_A^2, \mu, \tan\beta)$
- 3 Bino, Wino and Gluino masses (M_1, M_2, M_3)
- 54 trilinear parameters $(\mathbf{a_u}, \mathbf{a_d}, \mathbf{a_e})$
- 45 sfermion mass parameters $(\mathbf{m_Q^2}, \mathbf{m_L^2}, \mathbf{m_{\bar{u}}^2}, \mathbf{m_{\bar{d}}^2}, \mathbf{m_{\bar{e}}^2},)$

Non-Minimal Flavor Violation (NMFV)

pMSSM, 19 parameters:

- General scenario with no universality assumption at the GUT scale
- 3 trilinear parameters (a_t, a_b, a_τ)
- 10 sfermion mass parameters (diagonal entries, 1st and 2nd generations degenerate) $(m_{\tilde{q}_{1L}}, m_{\tilde{q}_{3L}}, m_{\tilde{u}_R}, m_{\tilde{t}_R}, m_{\tilde{d}_R}, m_{\tilde{b}_R}, m_{\tilde{e}_L}, m_{\tilde{\tau}_L}, m_{\tilde{e}_R}, m_{\tilde{\tau}_R})$

NMFV, allows non-diagonal entries

- Up to 105 parameters (general MSSM)
- Up to three 6x6 mixing matrices (up squarks, down squarks and sleptons)
- Up to a 3x3 mixing matrix for sneutrinos

→ 19 (pMSSM) + 24 (NMFV) free parameters

Usual technique in NMFV scenarios

Mass Insertion Approximation (MIA)

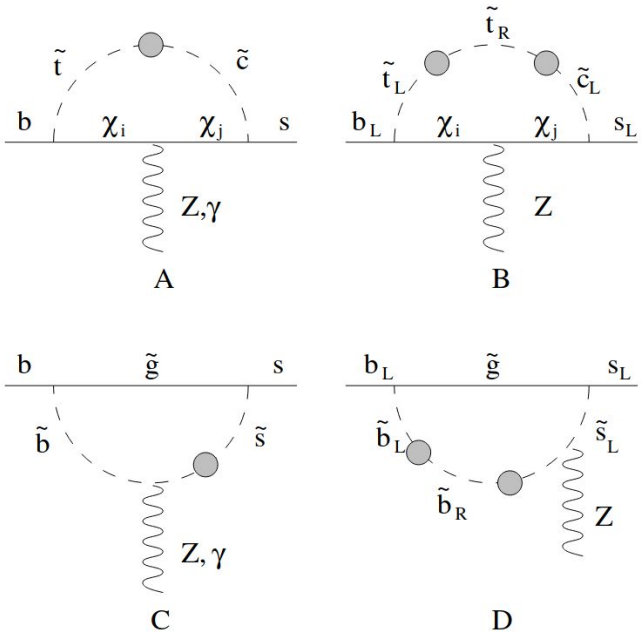
- Small off-diagonal SUSY breaking matrix elements

$$\delta_{ij} \equiv \frac{m_{ij}^2}{\Lambda^2}$$

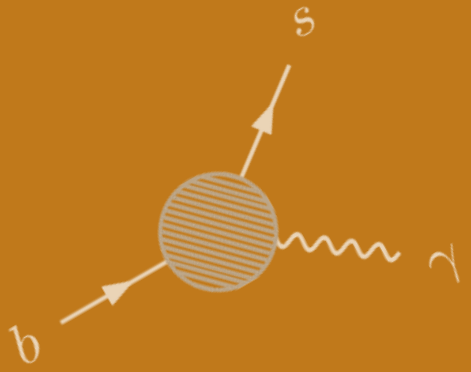
- Calculation in flavor basis
- MFV spectrum calculation
- Wilson coefficients are known.

Full analytical calculation

- Some contributions have been calculated [arxiv:0812.4320]
- C_7, C_9, $(g-2)_\mu$ are not known



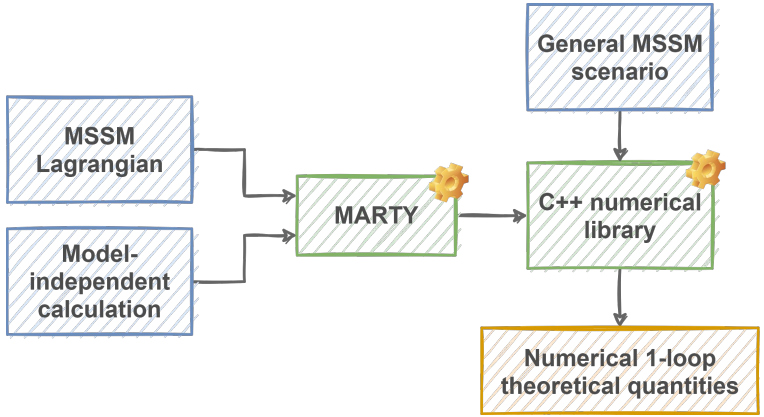
[arxiv:hep-ph/9906286]



Methods

MARTY [https://marty.in2p3.fr]

- C++ framework for **general BSM scenarios**
- **Automated** and **Symbolic** calculations
- **Tree-level** and **One-loop**
  - **Amplitudes**
  - **Squared amplitudes**
  - **Wilson coefficients**
- Library generation
  - C++ numerical library
  - Tree-level spectrum generator included
  - Detailed phenomenological analyses



[G.U., arXiv:2011.02478]

Phenomenological analysis

MSSM spectrum

- NMFV parameters are highly constrained
- **SPheno** [arxiv:1104.1573]
- SLHA2 input files
- 6x6 sfermion mixings matrices
- Loop corrections
- Phenomenological constraints

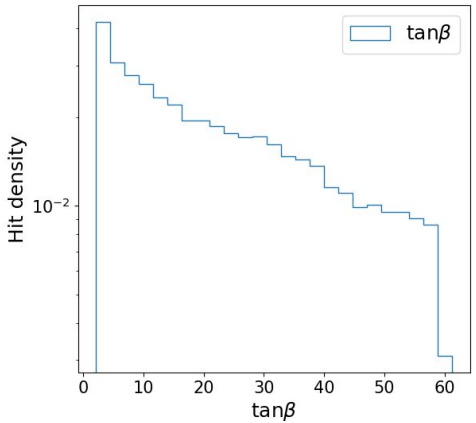
Wilson coefficients at $\mu = m_b$

- Comparison with standard analyses
- **SuperIso** [arxiv:0808.3144]
- SM contribution
- Operator mixing
- RGE evolution for Wilson coefficients

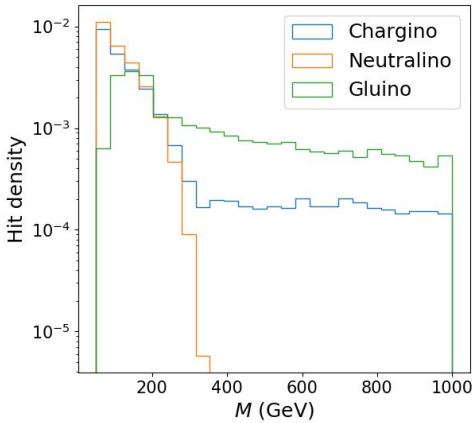
Some posteriors of the random scan

(Proof of concept with 41 000 points)

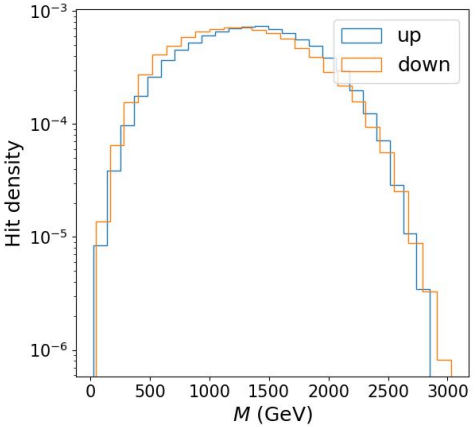
tan β



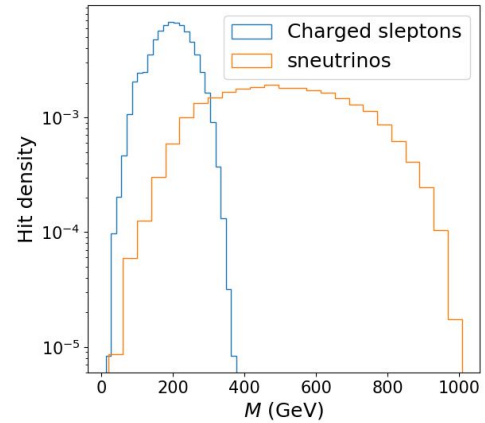
Gaugino masses



Squark masses



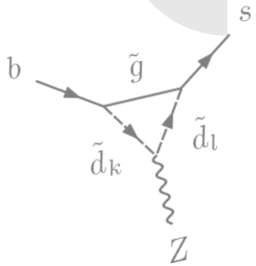
Slepton masses

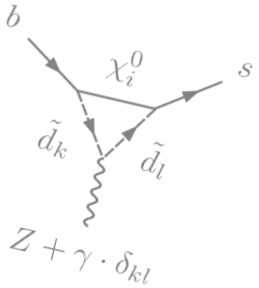


Summary of contributions

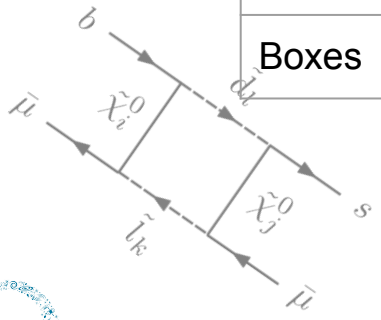
	Chargino	Neutralino	Gluino	Charged Higgs	Neutral Higgs
$(g-2)_\mu$ γ-penguin	pMSSM	pMSSM	✗	pMSSM	pMSSM
C_7 γ-penguin	pMSSM	NMFV	NMFV	pMSSM	✗
C_9 γ-penguin	pMSSM	NMFV	NMFV	pMSSM	✗
C_9 Z penguins	pMSSM	NMFV	NMFV	pMSSM	✗
C_9 Boxes	pMSSM	NMFV	✗	pMSSM	✗

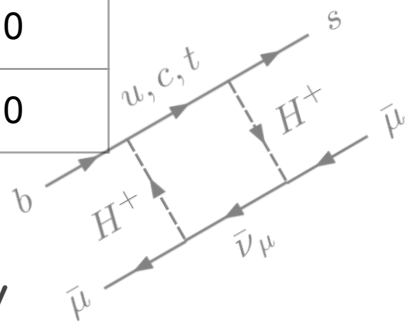
A closer look to the diagrams for C_9





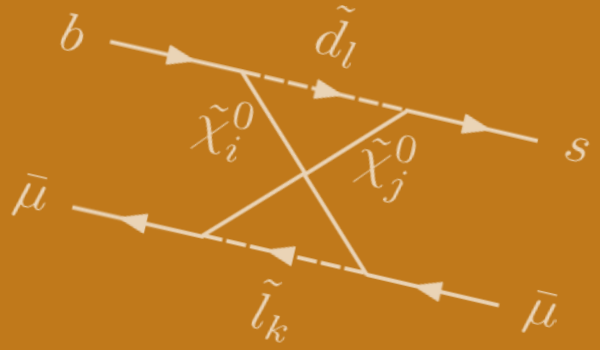
	Chargino	Neutralino	Gluino	Charged Higgs	Neutral Higgs
γ-penguins	240	96	24	24	0
Z-penguins	624	1344	240	78	0
Boxes	864	13824	0	12	0





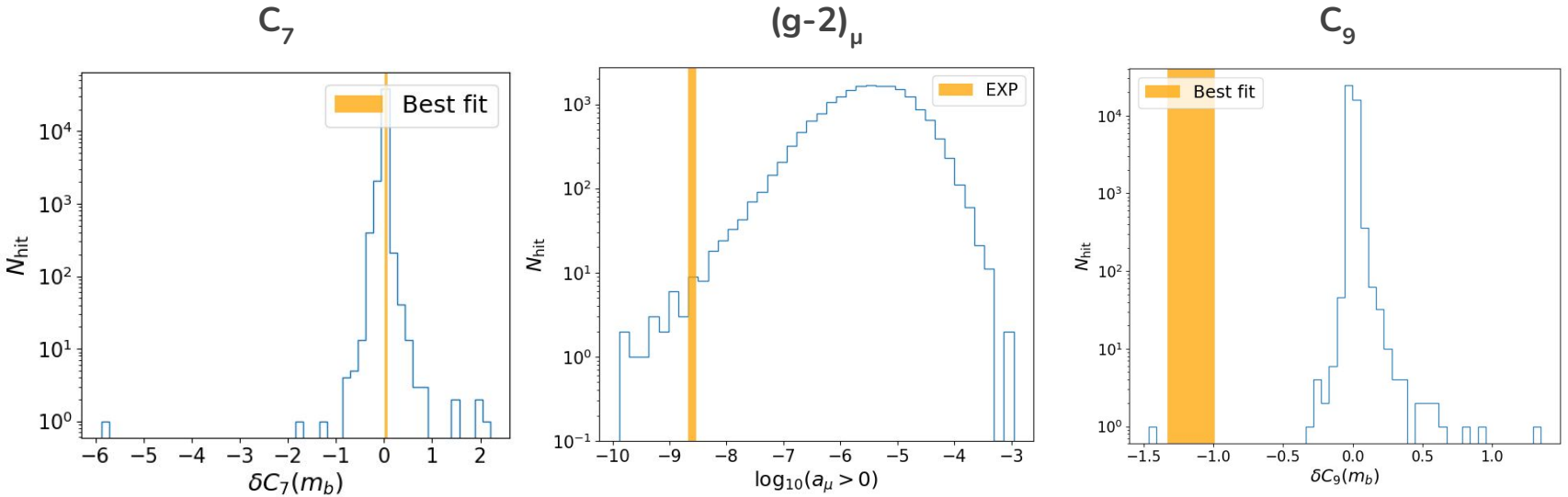
- About 18 000 diagrams calculated by MARTY!
- Merges diagrams and extracts C_9 automatically

→ Similarly for C_7 and $(g\text{-}2)_\mu$



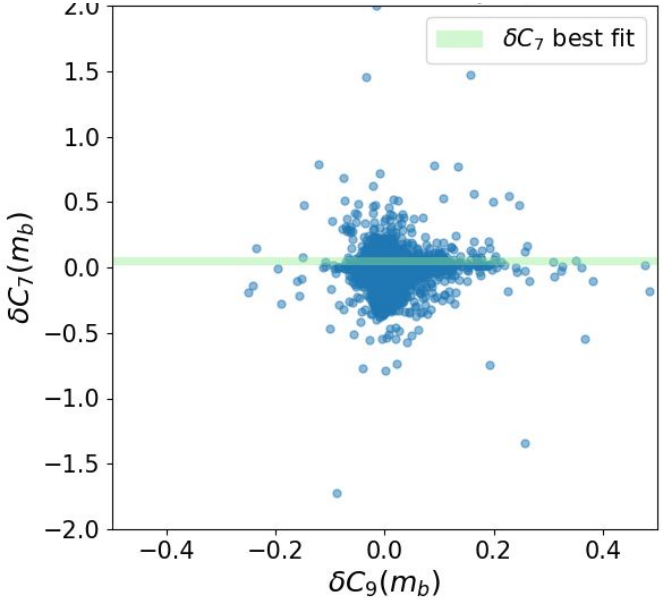
Results

Individual distributions



→ C_9 can be shifted of O(1)

Combined Wilson analysis

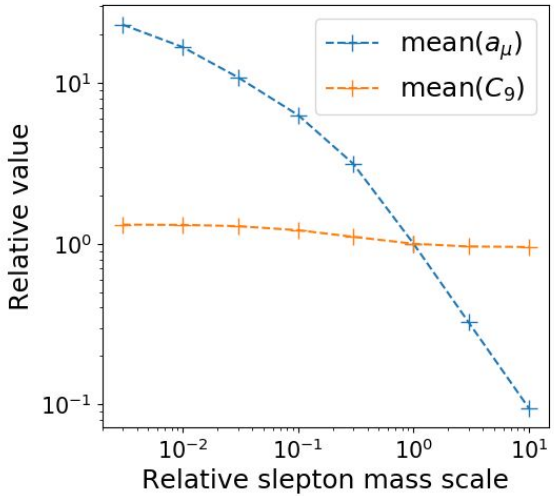


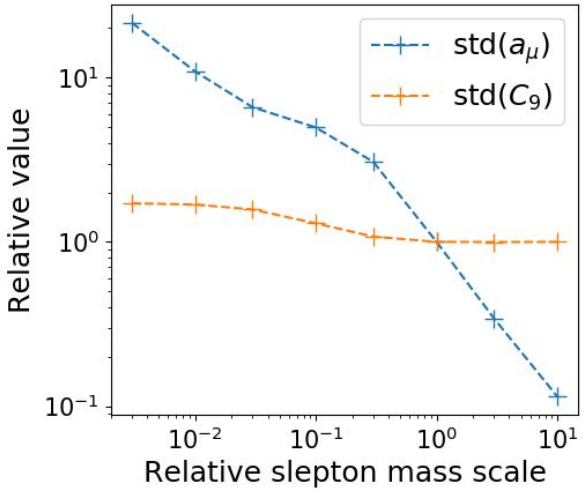
→ Possible to address C_7 and C_9

→ Need more statistics

Explain flavor anomalies and $(g-2)_\mu$

Rescale slepton masses to shift a_μ only





→ Possible to address $(g-2)_\mu$ by adjusting slepton masses without changing C_9

Discussion

Possible improvements

- Improve statistics
- **Scan weighted** by the parameter posterior distributions
- **Find correlations** to address the spectrum constraints
- Consider NMFV in the lepton sector
- Phenomenology, link with LHC direct search bounds

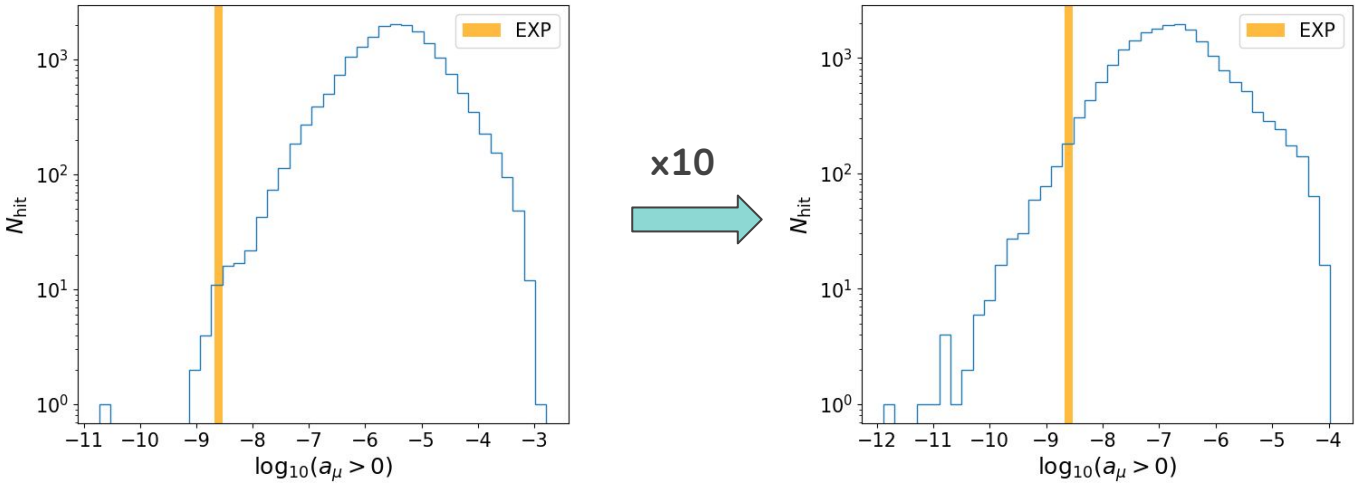
Conclusion

We presented for the first time the full 1-loop analytical calculations in the general MSSM for C_7, C_9 and $(g-2)_\mu$

- $(g-2)_\mu$ can be addressed by adjusting the absolute slepton mass scale
- C_9 can be shifted to reach the best fit region
- A more optimized scan is required
- Analytical results have been obtained with the public code MARTY
  (See the talk about MARTY in the New Tools session)

Thank you for your attention !

Slepton mass rescaling to address $(g-2)_\mu$



MARTY sub-steps