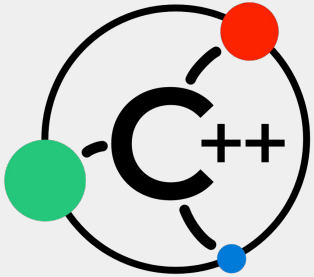
UNIVERSITÉ DE GENÈVE



MARTY

Modern **AR**tificial **T**heoretical ph**Y**sicist

Automated loop-level calculations beyond the Standard Model.

Website: https://marty.in2p3.fr

Main publication: **G.U.** et. al., Comp. Phys. Commun. 264 (2021) 107928 [arXiv: 2011.02478]

Grégoire Uhlrich (Postdoc, Geneva University)
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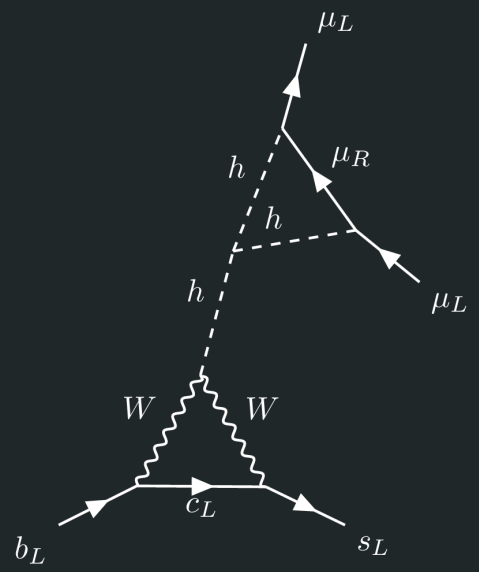
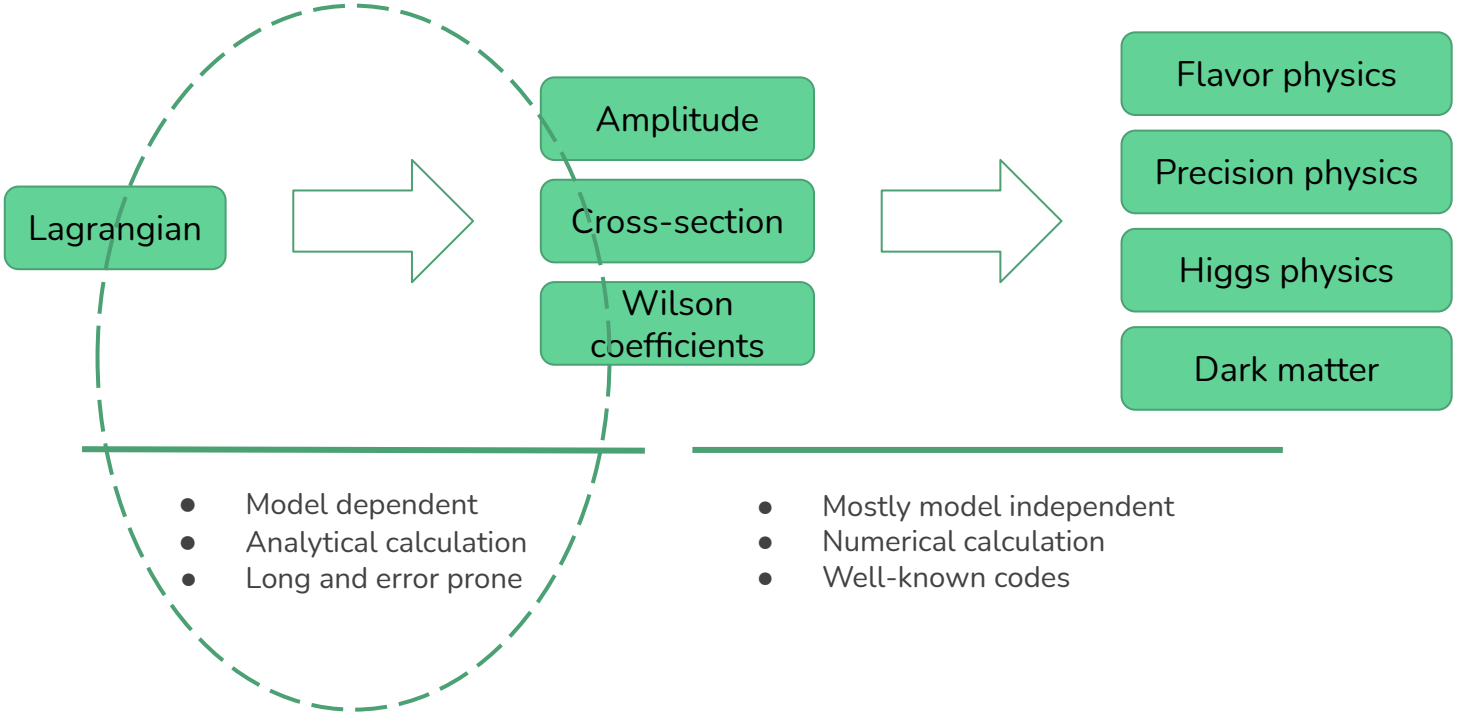
Computational Tools for High Energy Physics and Cosmology - 26/11/2021

Introduction

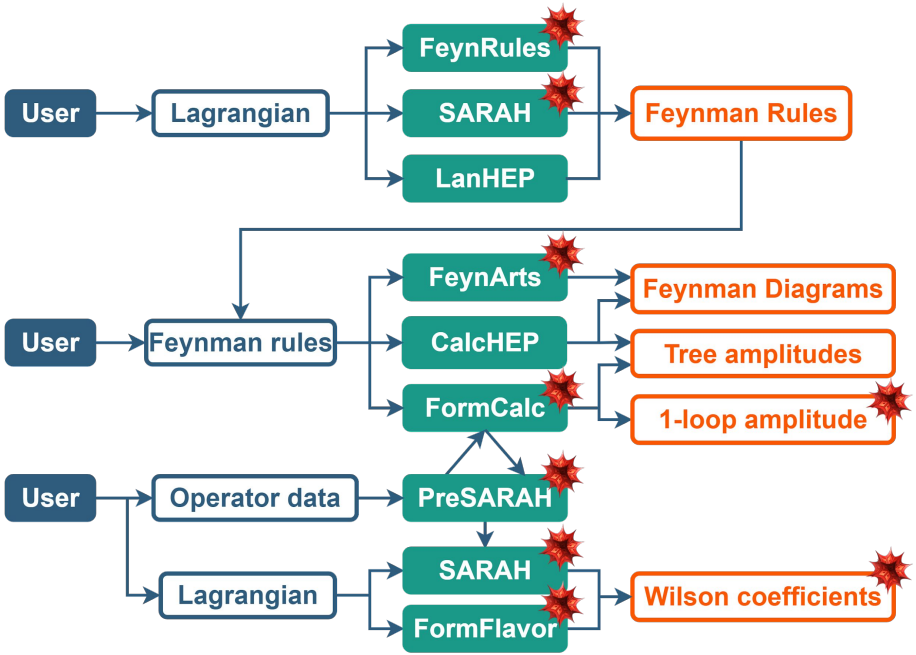


The challenge of BSM phenomenology

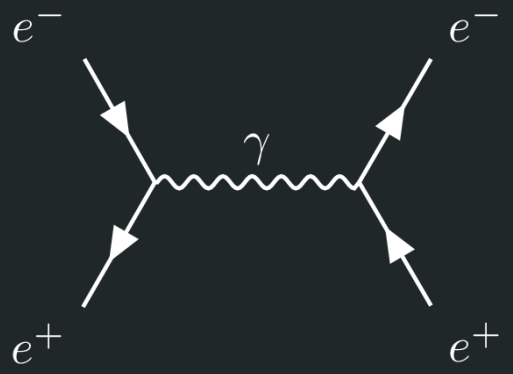


Present ecosystem

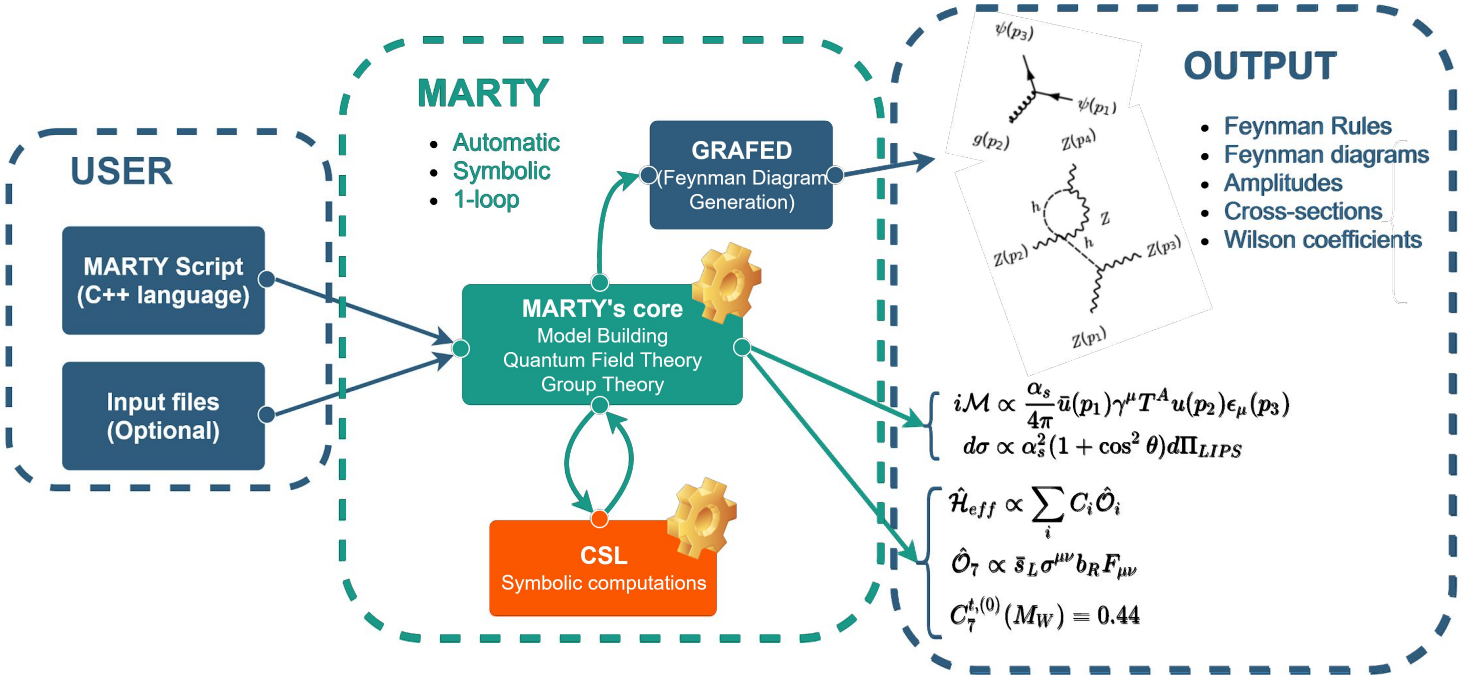
- Efficient and well-known codes
- Many distinct codes
- **Several user inputs**
- Depending on **Mathematica**
- Lacks in the calculation of Wilson coefficients at one-loop



MARTY Generalities



Design


USER
MARTY Script
(C++ language)
Input files
(Optional)
MARTY
Automatic
Symbolic
1-loop
GRAFED
(Feynman Diagram
Generation)
MARTY's core
Model Building
Quantum Field Theory
Group Theory
CSL
Symbolic computations
OUTPUT
Feynman Rules
Feynman diagrams
Amplitudes
Cross-sections
Wilson coefficients
$i\mathcal{M} \propto \frac{\alpha_s}{4\pi}\bar{u}(p_1)\gamma^\mu T^A u(p_2)\epsilon_\mu(p_3)$
$d\sigma \propto \alpha_s^2(1+\cos^2\theta)d\Pi_{LIPS}$
$\hat{\mathcal{H}}_{eff} \propto \sum_i C_i\hat{\mathcal{O}}_i$
$\hat{\mathcal{O}}_7 \propto \bar{s}_L\sigma^{\mu\nu}b_R F_{\mu\nu}$
$C_7^{t,(0)}(M_W) = 0.44$

Generality

Model Building

- 4D Minkowski space-time
- Spin 0,
- Spin ½ (Weyl, Dirac, Majorana)
- Spin 1
- SU(N), SO(N), Sp(N), E_6, E_7, E_8, F_4, G_2

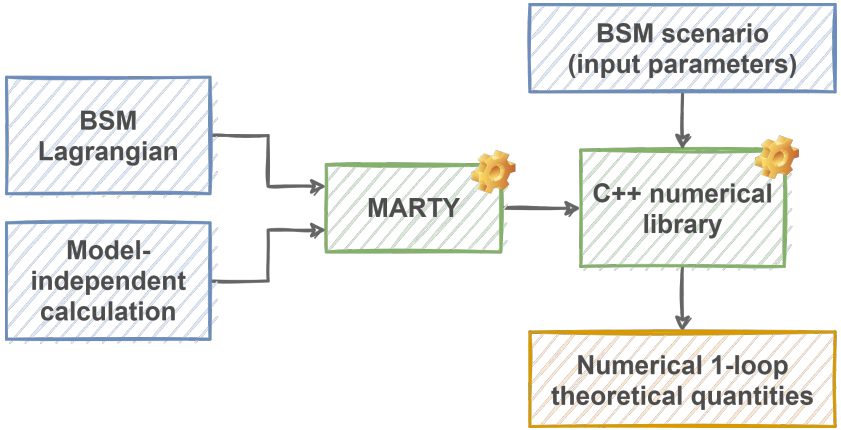
Calculations

- 1-loop fully automated
- Squared amplitudes
- Wilson coefficients

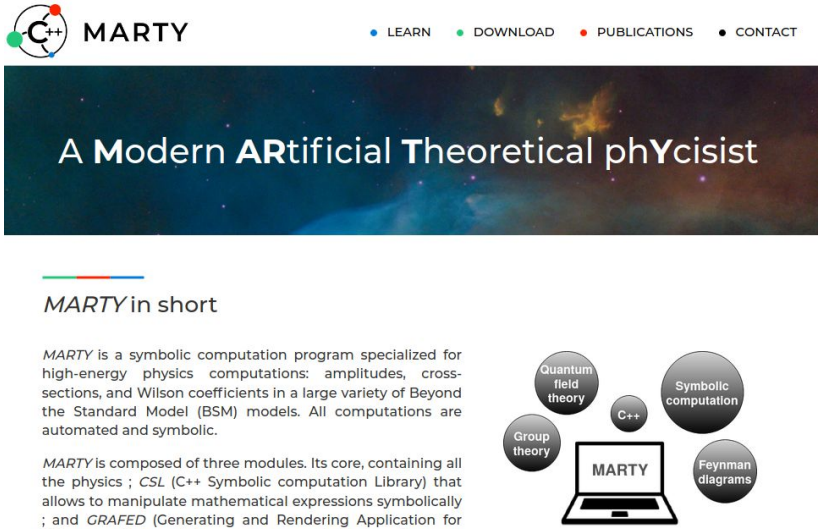
- Index contractions
- Dirac algebra, traces
- Group algebra, traces
- Equations of motion
- Tensor reduction
- Introduction of abbreviations

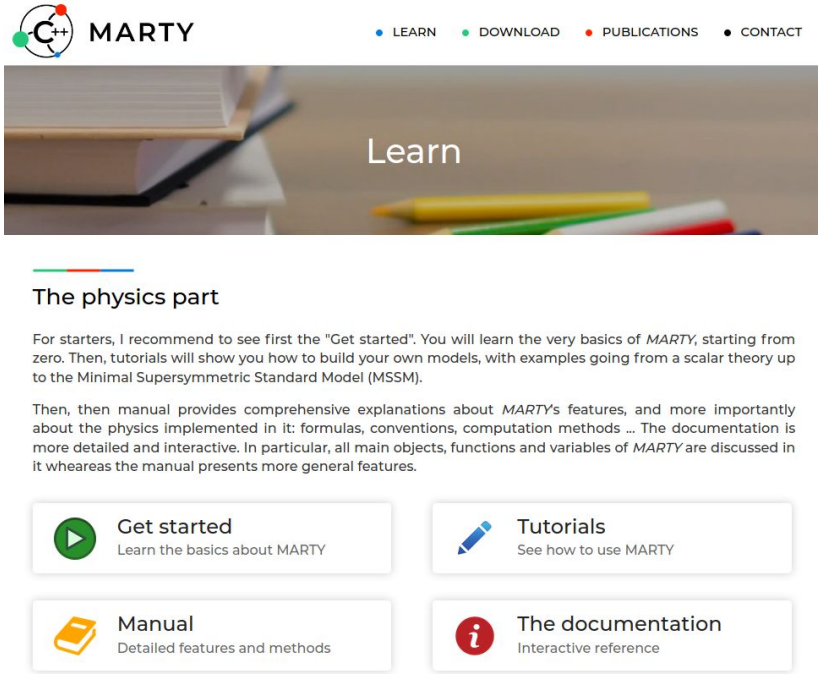
Code generation

- Main output of MARTY
- Translate maths into C++ functions
- Scalar expressions (no free index)
  - Squared amplitudes
  - Wilson coefficients
- Self-contained library
  - Spectrum generator
  - Analytical results in numerical functions

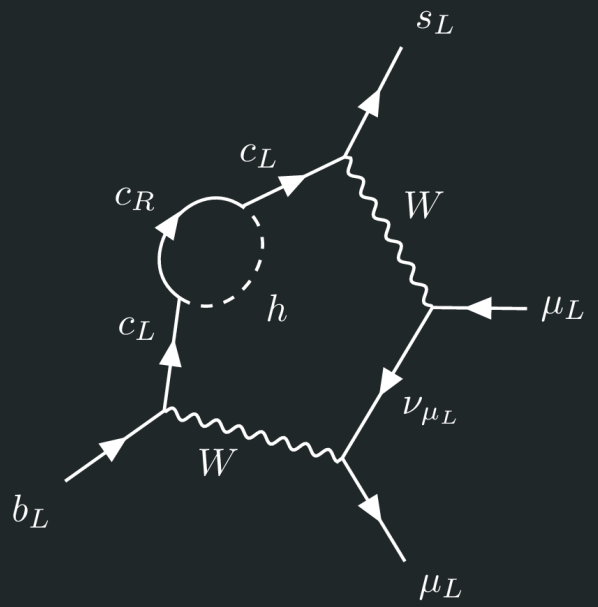


Documentation ➜ https://marty.in2p3.fr





Selection of results



Validation principle

Show the possible range of applications for MARTY

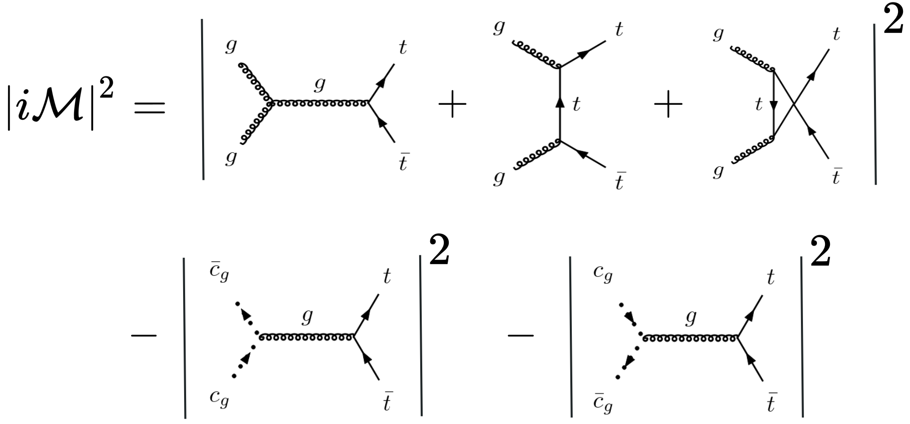
- Only known examples
- Squared amplitudes and Wilson coefficients
- Tree-level and one-loop results
- Fully simplified results
- Straight-forward generalization to other BSM scenarios

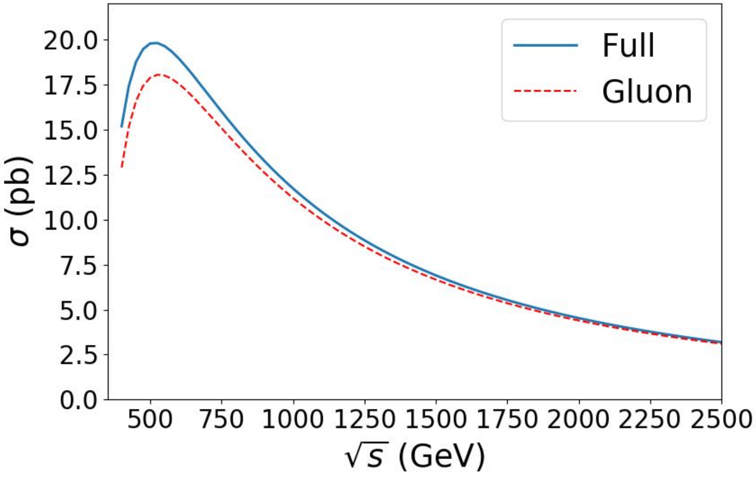
All sample programs can be downloaded

Squared amplitudes

gg ➜ tt (SM)

Typical LHC process:

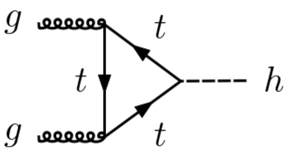




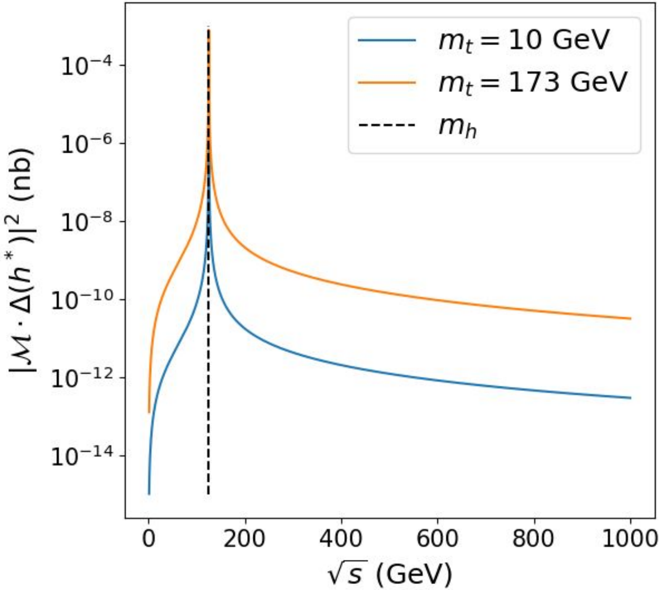
gg → h (SM)

Leading contribution at the LHC:

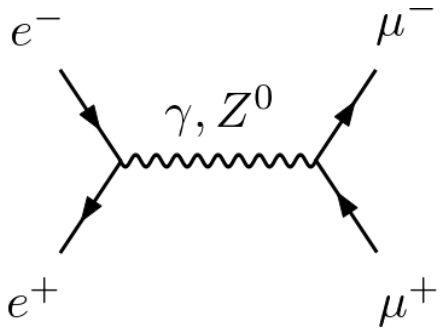
$$|i\mathcal{M}\cdot\Delta(h^*)|^2 \approx \left| \quad \right|^2$$

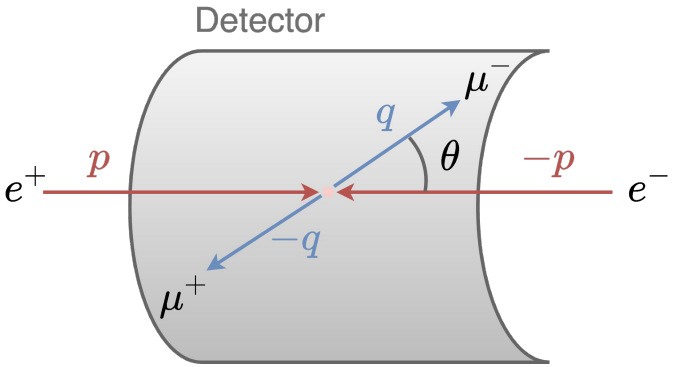


$$\times \left| \frac{1}{s - m_h^2 + i\Gamma_h m_h} \right|^2$$

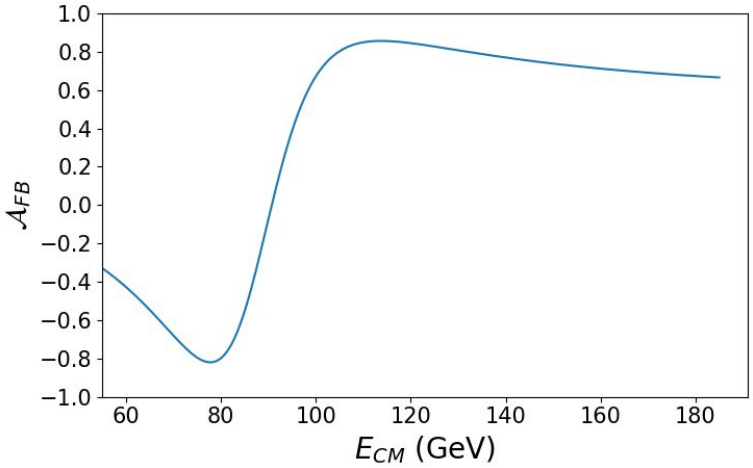


Forward-backward asymmetry (SM)

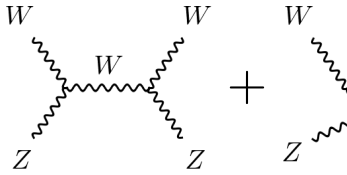


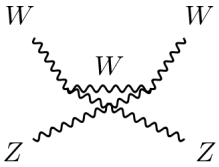


$$\mathcal{A}_{FB} \equiv 2\pi \frac{\int_0^{\pi/2} \frac{d\sigma}{d\theta} d\theta - \int_{\pi/2}^{\pi} \frac{d\sigma}{d\theta} d\theta}{\sigma}$$

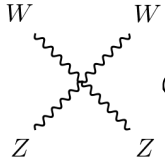


Vector boson scattering and Unitarity

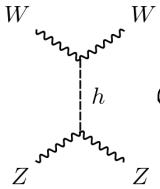
$$i\mathcal{M}_{3V} =$$ 

$$+$$ 

$$\propto E^4$$

$$i\mathcal{M}_{4V} =$$ 

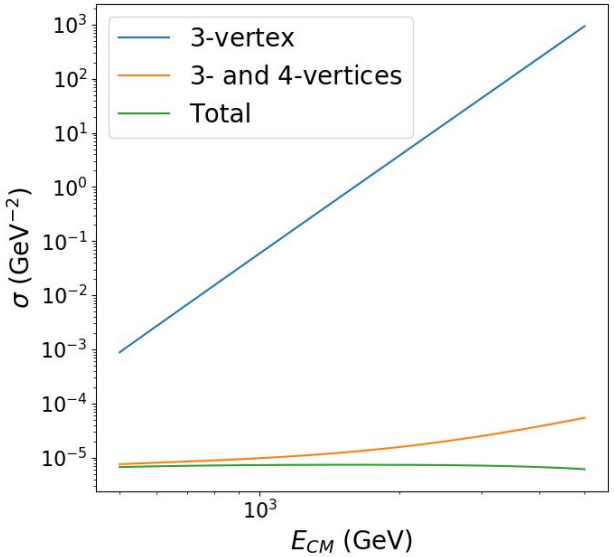
$$\propto E^4$$

$$i\mathcal{M}_{h} =$$ 

$$\propto E^2$$

Cancellations

$$i\mathcal{M}_{3V+4V} \propto E^2$$
$$i\mathcal{M}_{3V+4V+h} \propto E^0$$



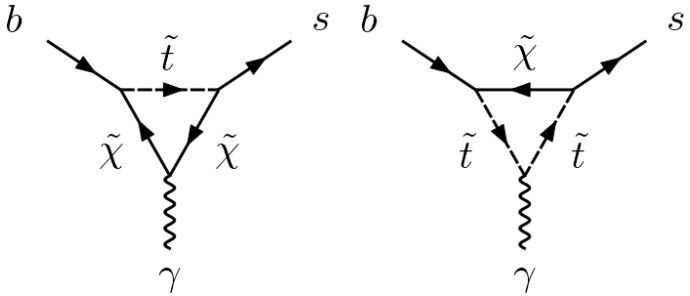
Wilson coefficients

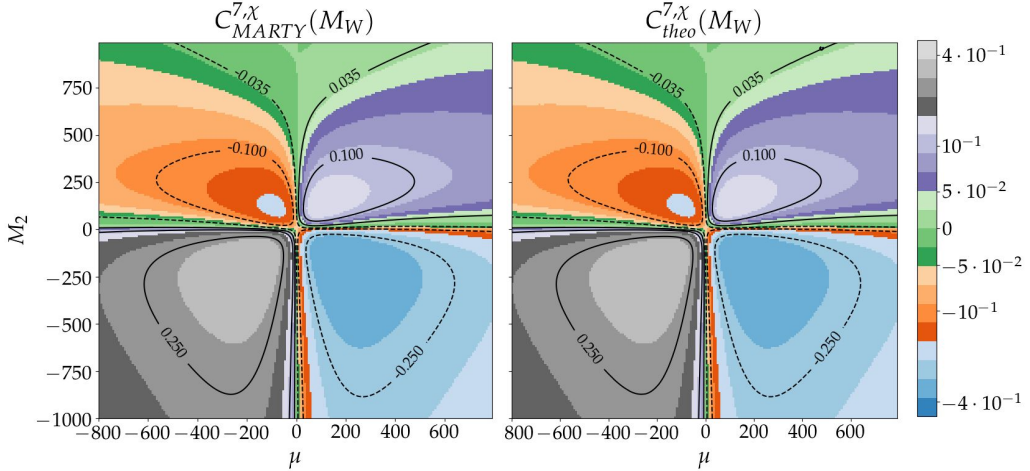
b ➔ sγ (pMSSM)

Well constrained experimentally

➔ Important to evaluate

$$i\mathcal{M} \propto C_7 \left(\bar{s}\sigma^{\mu\nu} P_R b\right) F_{\mu\nu}$$





(Spectrum generated by MARTY)

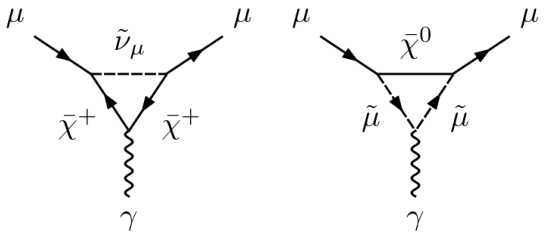
$(g-2)_\mu$ (pMSSM)

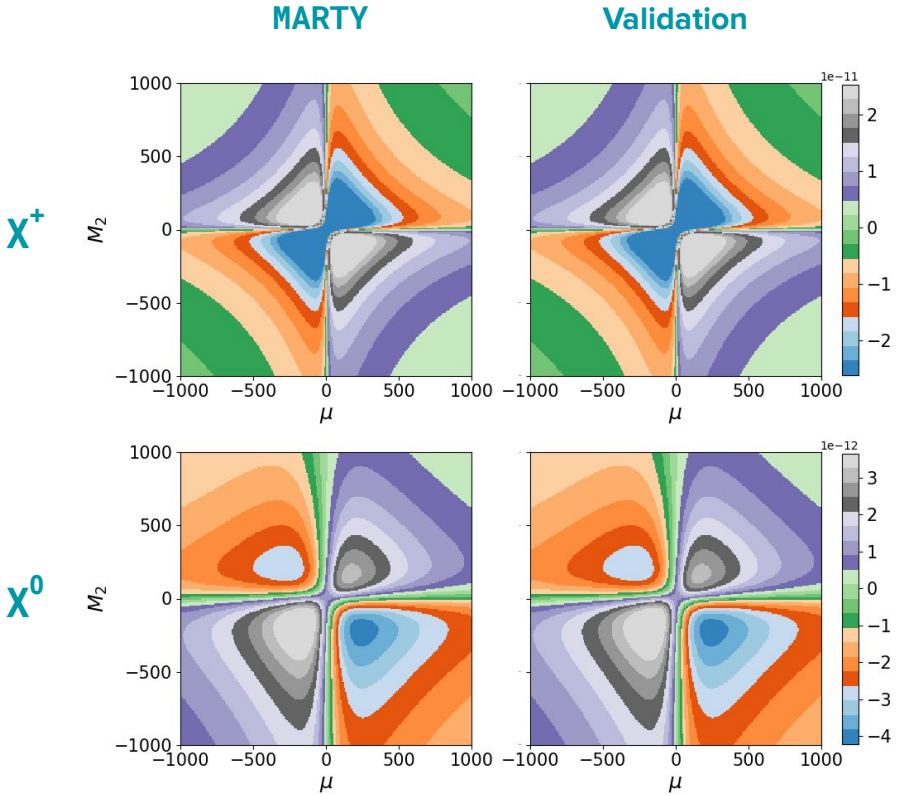
Magnetic dipole moment

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

Tension with experiments

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



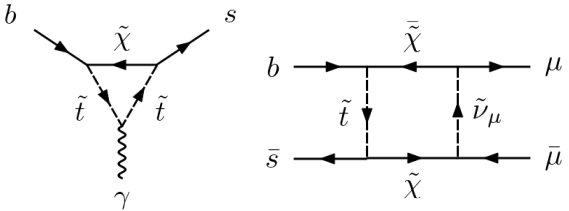


b ➜ sμμ (pMSSM)

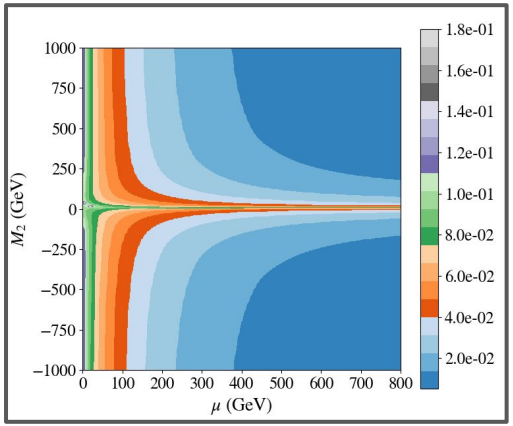
- Main interest for flavor anomalies
- 4-fermion operators

$$i\mathcal{M} \propto C_9 \left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\mu}\gamma_\mu \mu\right)$$

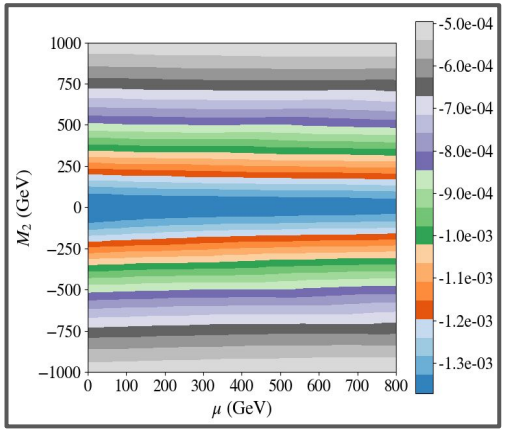
Best fit: $\dfrac{\delta C_9^\mu}{C_9^{\mu,\mathrm{SM}}} \approx -0.25$



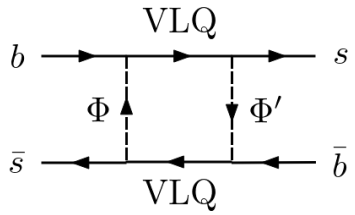
Photon penguins



Boxes



B_s- mixing with Vector-Like Quarks (VLQ)



$$D = (3, 1, -1/3)$$
$$Q_d = (3, 2, -5/6)$$
$$Q_v = (3, 2, +1/6)$$
$$T_d = (3, 3, -1/3)$$
$$T_u = (3, 3, +2/3)$$

$$\mathcal{O}_{\mathrm{LR1}} = (\bar{s}\gamma^\mu P_L b) \cdot (\bar{s}\gamma_\mu P_R b)$$
$$\mathcal{O}_{\mathrm{VLL(VRR)}} = \left(\bar{s}\gamma^\mu P_{L(R)} b\right) \cdot \left(\bar{s}\gamma_\mu P_{L(R)} b\right)$$
$$i\mathcal{M} \propto C_{\mathrm{LR1}}\mathcal{O}_{\mathrm{LR1}} + C_{\mathrm{VLL(VRR)}}\mathcal{O}_{\mathrm{VLL(VRR)}}$$

$$M_{\mathrm{VLQ}} \gg m_h, M_Z$$

(F_m, F_n)	D	Q_d	Q_v	T_d	T_u
D	VLL, $+1/8$	LR1, $+1/4$	LR1, $-1/4$	VLL, $+1/8$	VLL, $-1/4$
Q_d	$\times$	VRR, $+1/4$	VRR, $-1/2$	LR1, $+3/8$	LR1, $-3/8$
Q_v	$\times$	$\times$	VRR, $+1/4$	LR1, $-3/8$	LR1, $+3/8$
T_d	$\times$	$\times$	$\times$	VLL, $+5/32$	VLL, $-1/4$
T_u	$\times$	$\times$	$\times$	$\times$	VLL, $+5/32$

Conclusion

- **MARTY is a very general tool for BSM phenomenology**
  - Fully independent and open-source C++ code
  - Tree-level & One-loop
  - Squared amplitudes & Wilson coefficients
- **Interfaces are currently being developed**
  - SuperIso (flavor observables), *see the talk of Siavash Neshatpour on Tuesday*
  - SuperIso Relic (dark matter observables), *see the tutorial of Alexandre Arbey on Monday*
  - UFO output for MARTY
- **Other developments are possible**
  - Model building from FeynRules, SARAH model files
  - More EFT features (EFT definition, automated NLO corrections)
- **Contributions are welcome!**

Thank you for your attention!