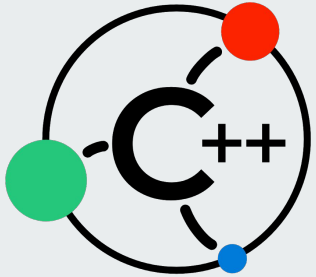


MARTY

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

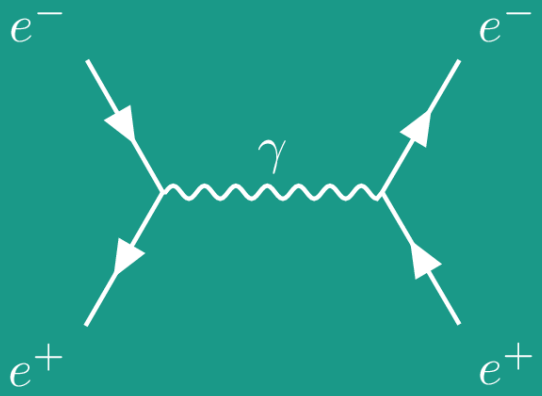
A C++ framework for easy Beyond the Standard Model (BSM) phenomenology.

https://marty.in2p3.fr
[arXiv:1120.3214]

Grégoire Uhlrich (PhD student)
Nazila Mahmoudi (Advisor)
Alexandre Arbey

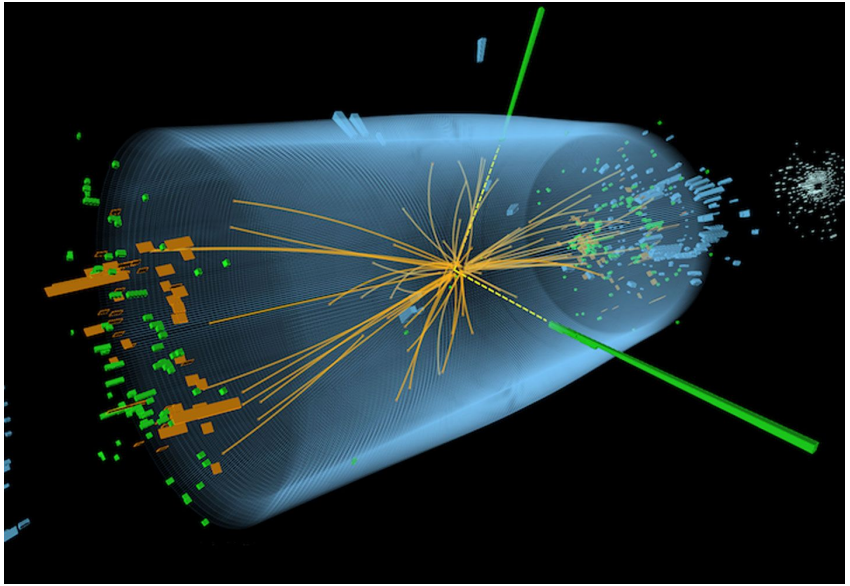
Ph.D. day - 27/01/2021

Introduction

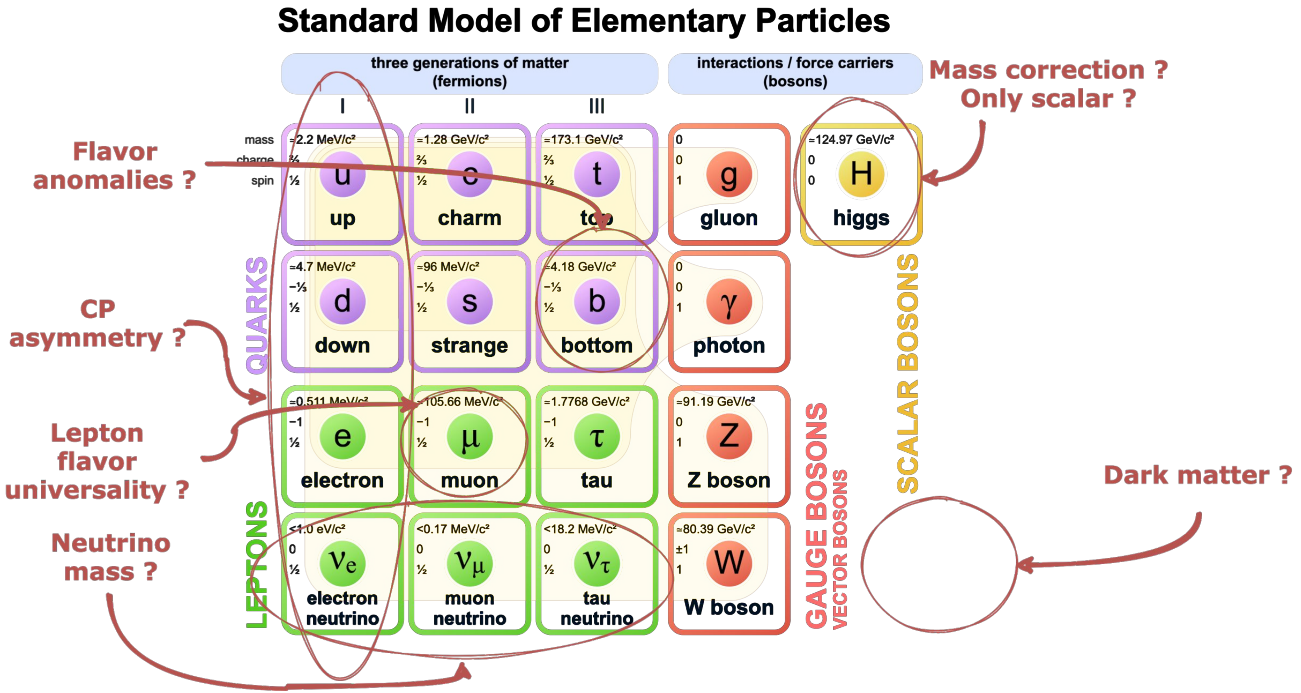


Phenomenology in High Energy Physics

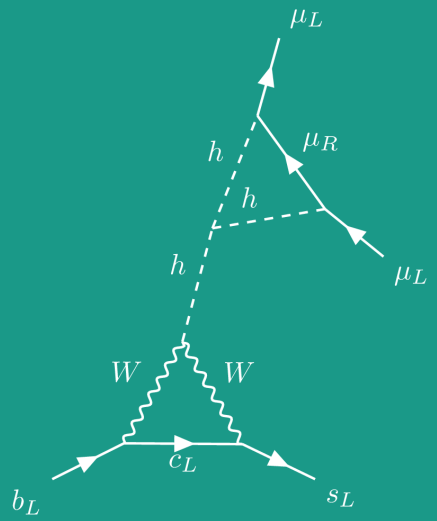
- **Experiments**
  - Astro / Cosmo measurements
  - Colliders
  - Number of events
- **Theory**
  - The Standard Model …
  - … and beyond
  - Predict the number of events
  - Search for New Physics



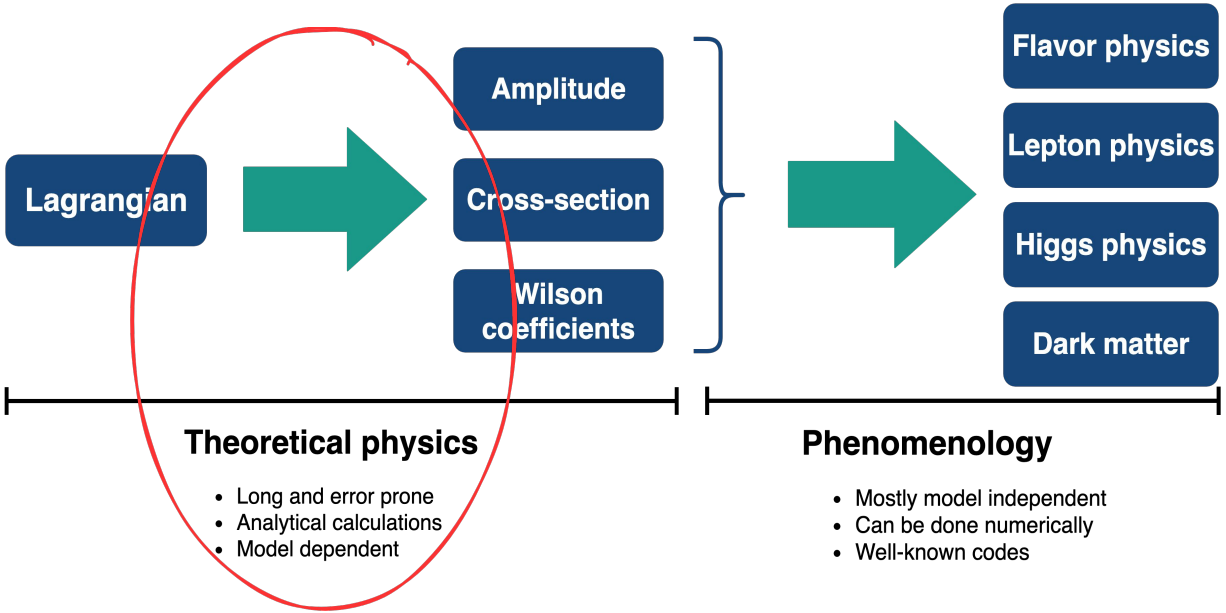
Motivation for BSM



A challenge for theoreticians

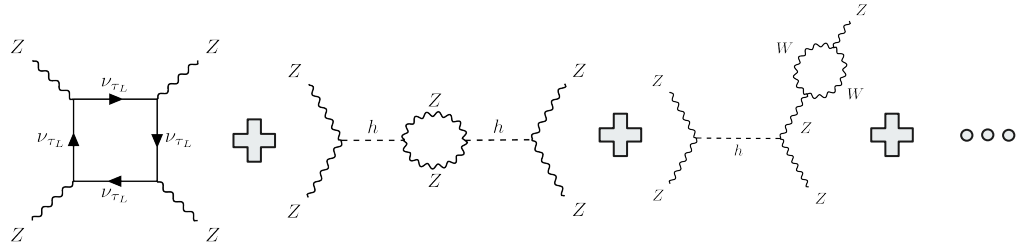


Phenomenology for BSM models



Computation challenges

$\mathcal{A}(ZZ \to ZZ)_{\text{SM, 1-loop}} =$



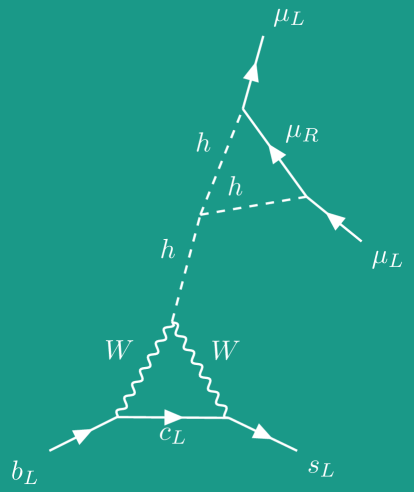
Hard to calculate by hand

- Calculating one feynman diagram is long
- Many diagrams per process
- Many processes to calculate
- **For only one BSM model !**

Hard to automate

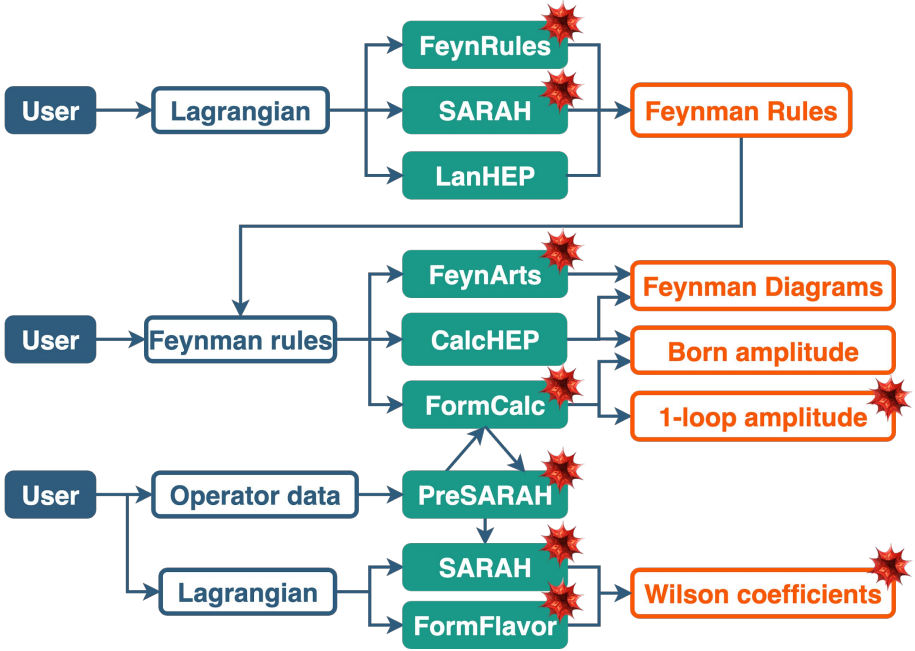
- Model dependent
- **Symbolic manipulation mandatory**
  - Divergent integrals
  - **Huge number of terms**

Automated BSM calculations



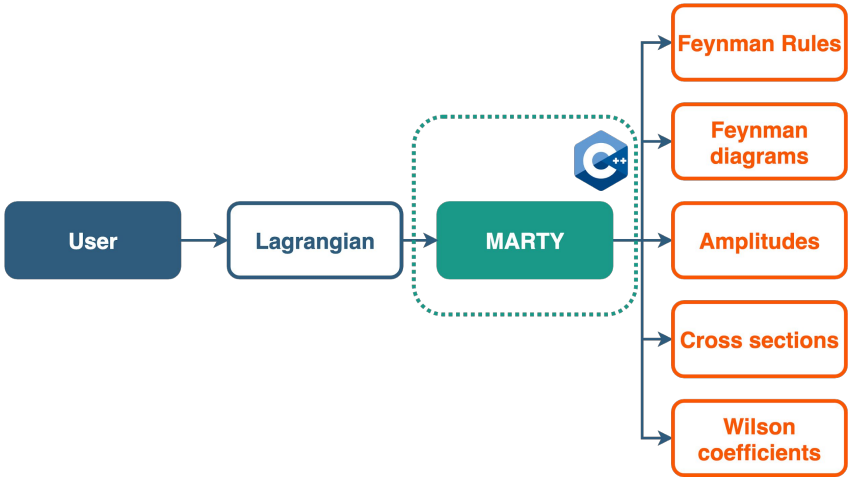
Present ecosystem

- Efficient and well-known codes
- Many distinct codes
- **Many user inputs necessary**
- Depending on **Mathematica**
- Hard to automate calculation of Wilson coefficients at NLO

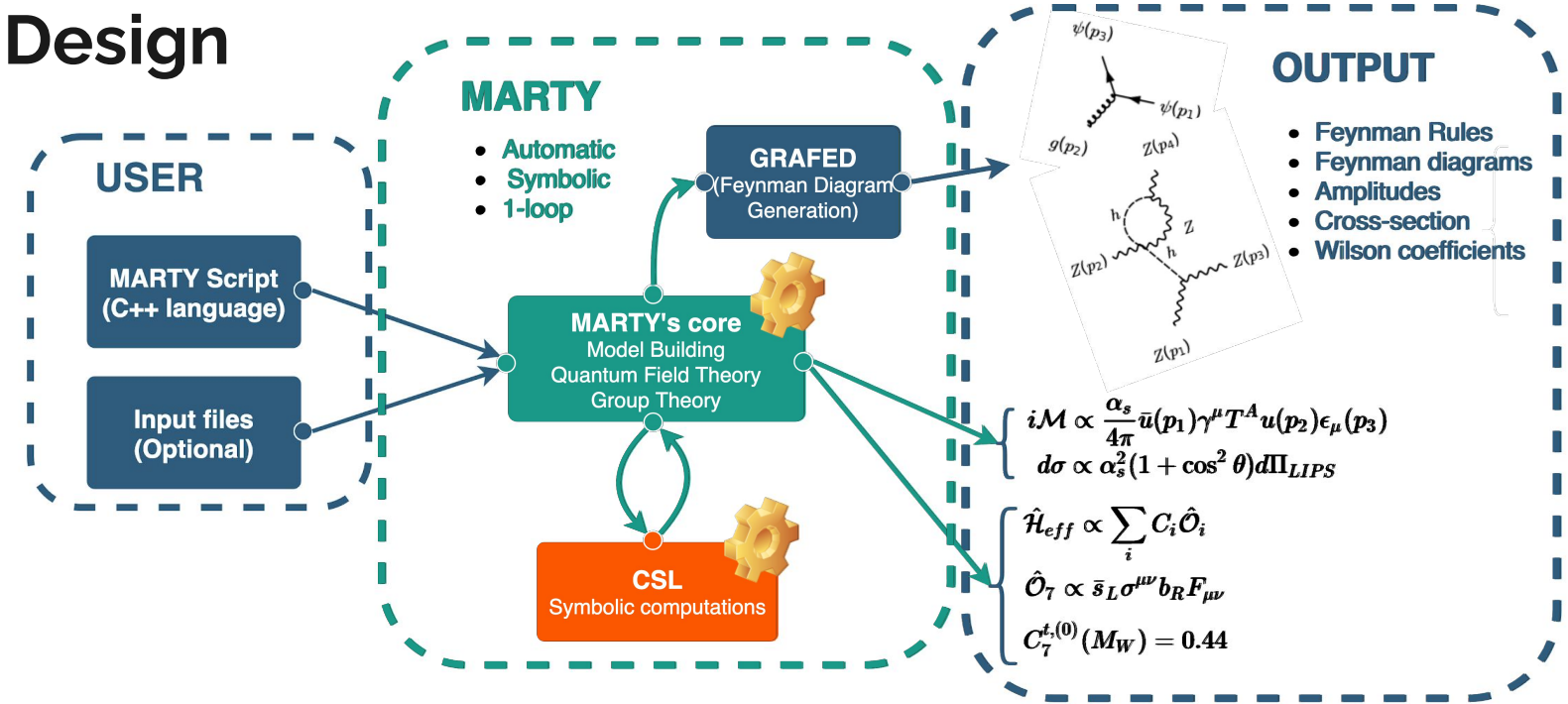


MARTY's ecosystem

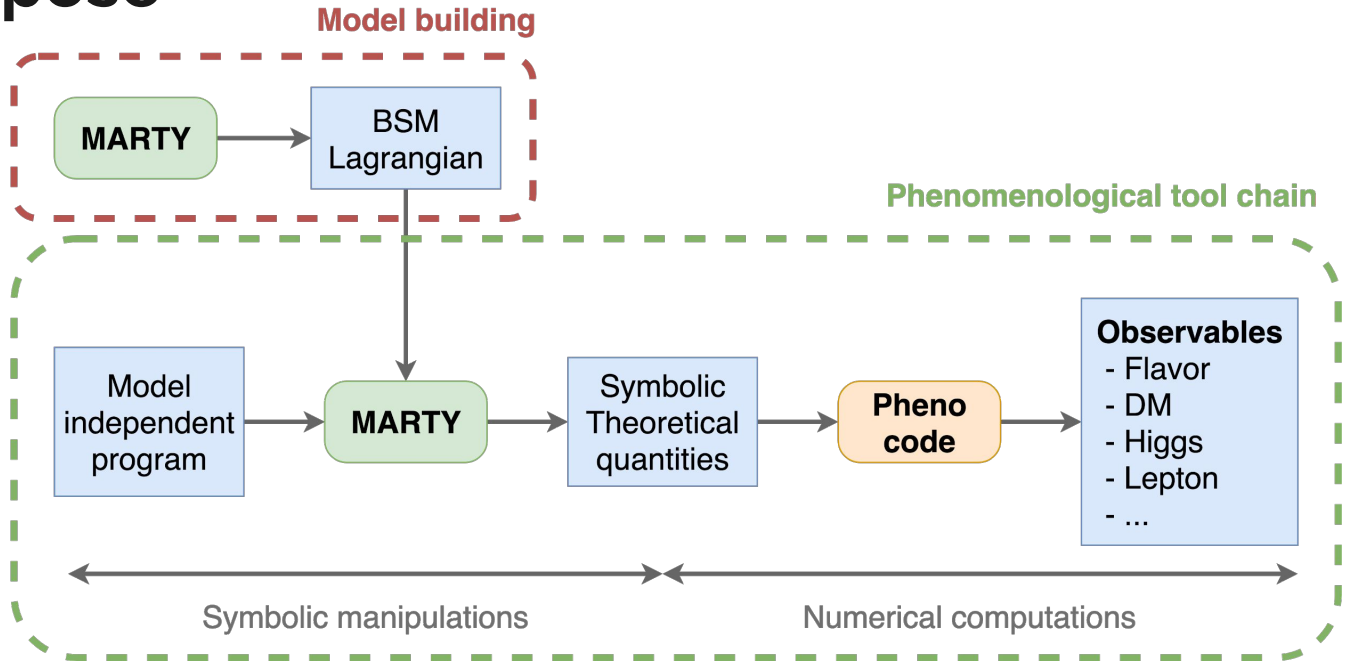
- **Unique user input**
- **C++** (fast, modern, popular)
- No painful dependency
- Embedded **C++ Symbolic computation Library (CSL)**
- Embedded **Generating and Rendering Application for FEynman Diagrams (GRAFED)**



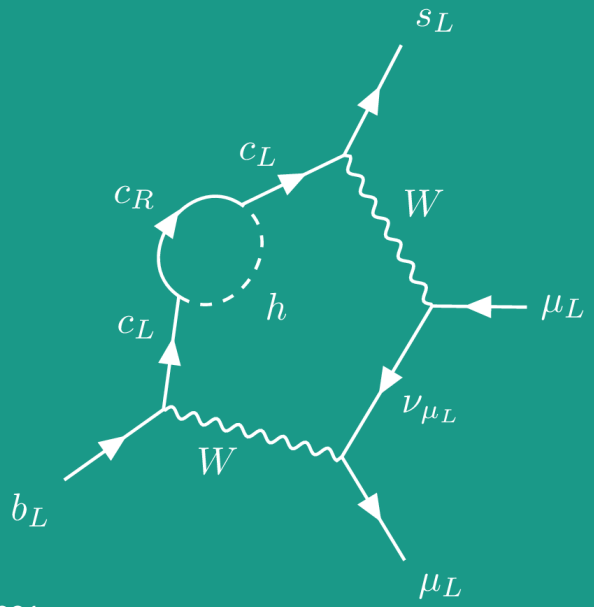
Design


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-section
Wilson coefficients
$\psi(p_3)$
$\psi(p_1)$
$g(p_2)$
Z(p4)
h
Z
h
Z(p2)
Z(p3)
Z(p1)
$i\mathcal{M} \propto \frac{\alpha_s}{4\pi}\bar{u}(p_1)\gamma^\mu T^A u(p_2)\epsilon_\mu(p_3)$
$d\sigma \propto \alpha_s^2(1+\cos^2\theta)d\Pi_{LIPS}$
$\hat{\mathcal{H}}_{eff} \propto \sum_i C_i\hat{\mathcal{O}}_i$
$\hat{\mathcal{O}}_7 \propto \bar{s}_L\sigma^{\mu\nu}b_R F_{\mu\nu}$
$C_7^{t,(0)}(M_W) = 0.44$

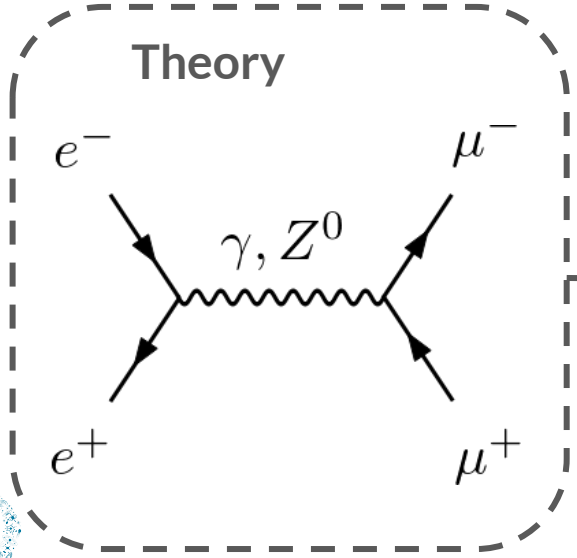
Purpose


Model building
MARTY
BSM Lagrangian
Phenomenological tool chain
Model independent program
MARTY
Symbolic Theoretical quantities
Pheno code
Observables
- Flavor
- DM
- Higgs
- Lepton
- ...
Symbolic manipulations
Numerical computations

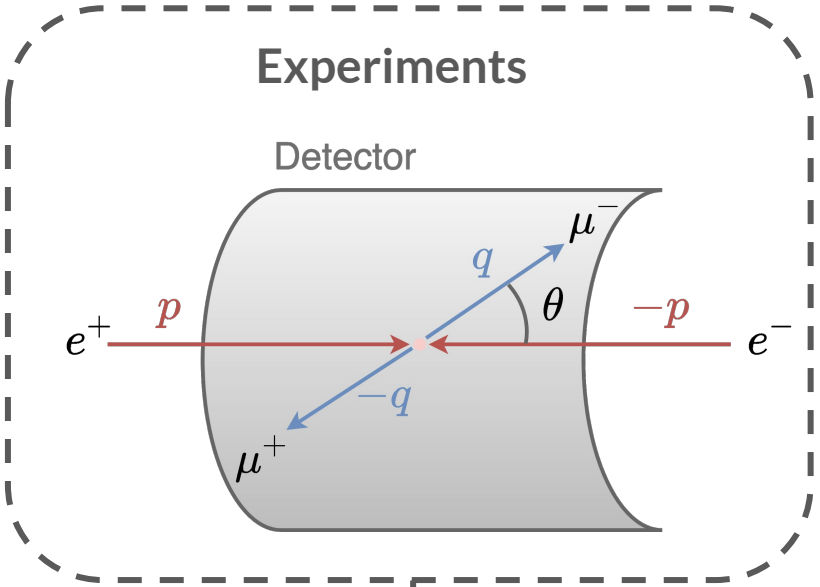
Concrete examples



A LEP example



Calculation

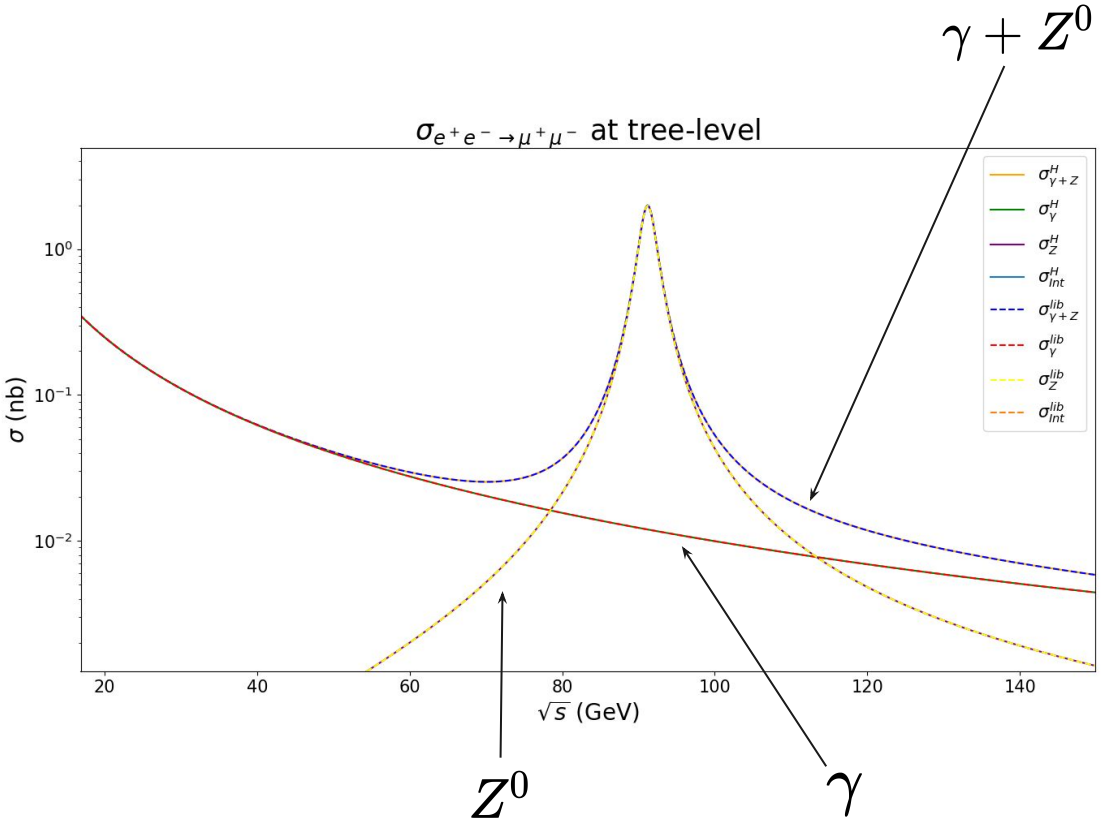


Measurement

$$N_{e^+e^- \to \mu^+\mu^-}(p, q, \theta)$$

A LEP example

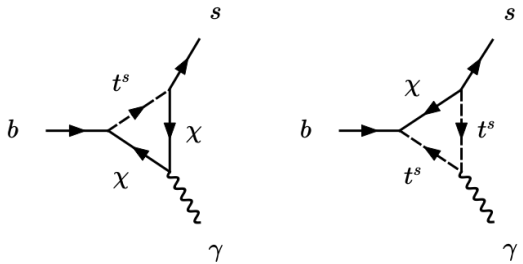
- **Center of mass energy**
- **Z resonance** ~ 91 GeV
- Exact match with known results
- $N = L \cdot \sigma$
- $\sigma_{peak} \approx 2$ nb

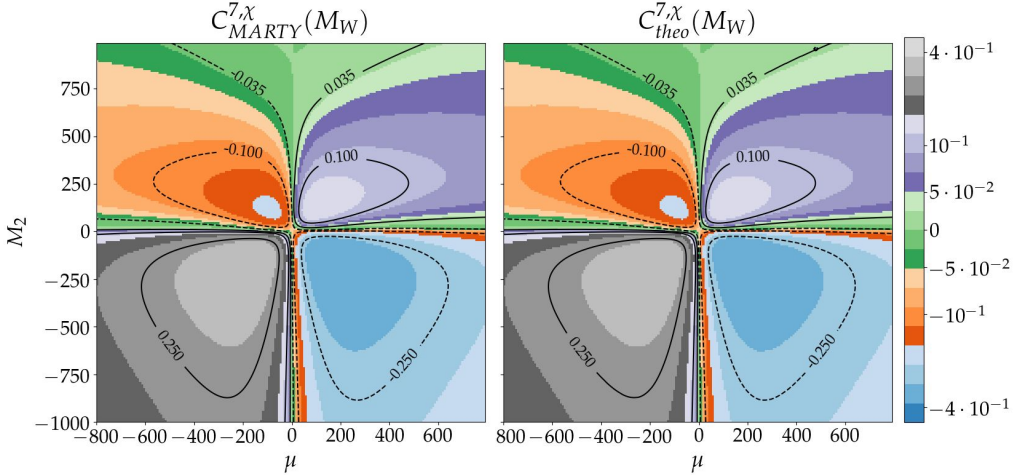


One loop b → sγ in SUSY

- Chargino stop contributions
- Heavy calculation by hand
- Few seconds with MARTY
- Possible in all BSM models …

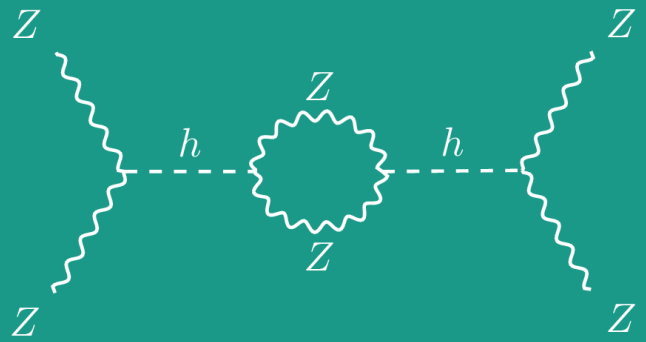
Source: hep-ph/9806308





$$\tan\beta = 50$$

Strengths of MARTY



Generality

Model Building

- 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

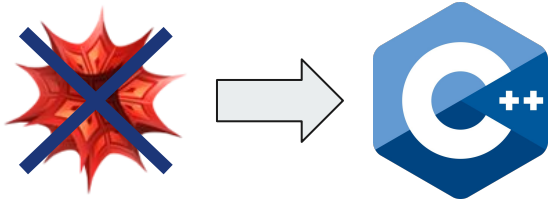
- Symmetry breaking
- Replacements
- Rotations
- Mass diagonalization

Calculations

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

- Dirac algebra, traces
- Group algebra, traces
- Equations of motion
- Dimensional regularization

Independence



MARTY

- Free
- Open-source
- Performant
- Independent (C++ 2017 standard)
  - Symbolic computation
  - Group theory
  - Quantum Field Theory
  - Calculations
- Convenient for a community effort !

Documentation: *https://marty.in2p3.fr*

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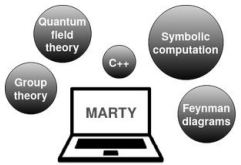
A Modern ARtificial Theoretical phYcisist

MARTY in short

MARTY is a symbolic computation program specialized for high-energy physics computations: amplitudes, cross-sections, and Wilson coefficients in a large variety of Beyond the Standard Model (BSM) models. All computations are automated and symbolic.

MARTY is composed of three modules. Its core, containing all the physics ; *CSL* (C++ Symbolic computation Library) that allows to manipulate mathematical expressions symbolically ; and *GRAFED* (Generating and Rendering Application for FEynman diagrams) that generates and displays Feynman diagrams.

Discover its features more in detail in the tutorials and the documentation.



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Learn

The physics part

For starters, I recommend to see first the "Get started". You will learn the very basics of *MARTY*, starting from zero. Then, tutorials will show you how to build your own models, with examples going from a scalar theory up to the Minimal Supersymmetric Standard Model (MSSM).

Then, then manual provides comprehensive explanations about *MARTY*'s features, and more importantly about the physics implemented in it: formulas, conventions, computation methods ... The documentation is more detailed and interactive. In particular, all main objects, functions and variables of *MARTY* are discussed in it whereas the manual presents more general features.

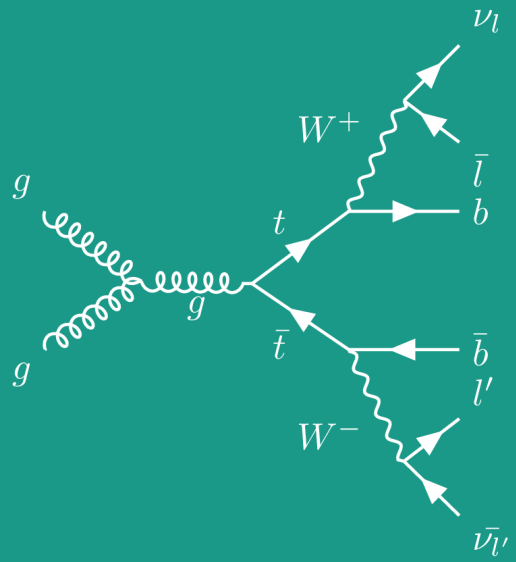
Get started
Learn the basics about MARTY

Tutorials
See how to use MARTY

Manual
Detailed features and methods

The documentation
Interactive reference

Conclusion



Conclusion - Ongoing projects

Leptogenesis

→ Tree-level squared amplitude
→ Fermion number violating interactions

Collaborator: Arnab Dasgupta

Dark Matter

→ Tree-level squared amplitude (a lot)
→ DM relic density

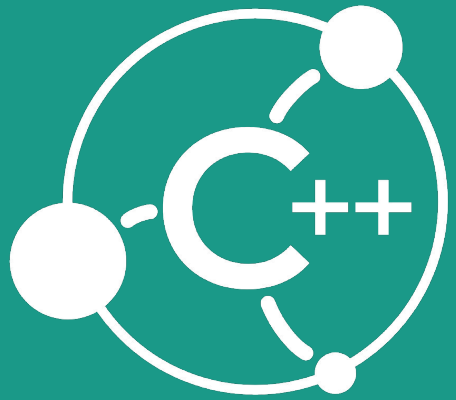
Collaborator: Marco Palmiotto

Flavor anomalies

→ One-loop Wilson coefficients
→ Rare B decays (b → s)

Collaborator: Amine Boussejra

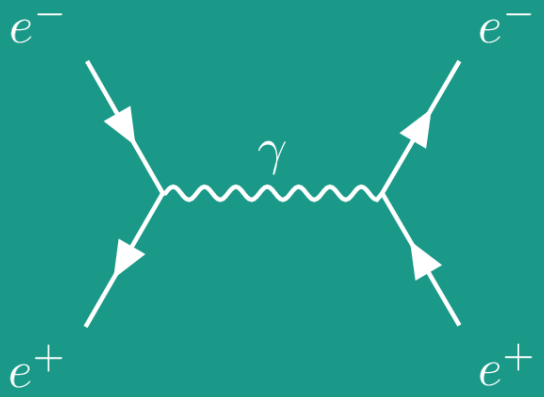
More to come ...



MARTY

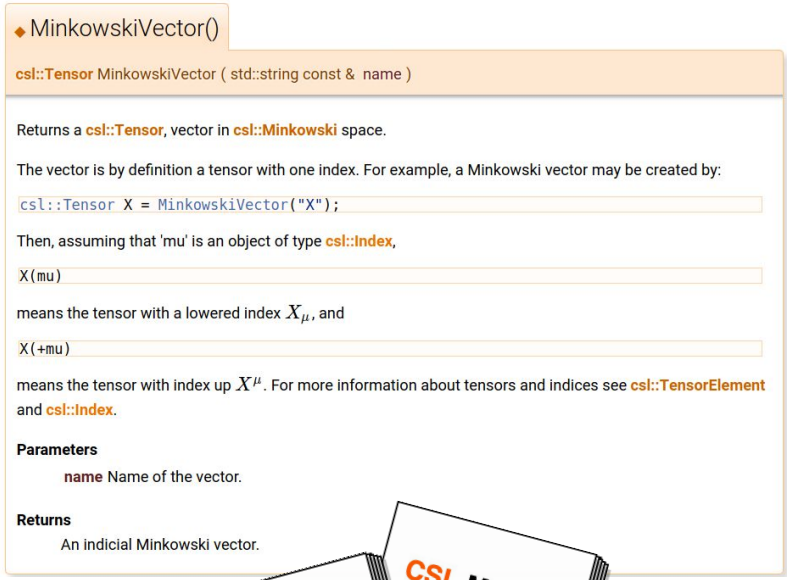
Thank you for your attention!

Backup



Manual & Documentation

- About **150 000 lines** of C++
- Comprehensive **documentation** (HTML)
- Very detailed **manuals**
- Many examples
  - Scalar theory
  - sQED
  - QED, QCD, Electro-Weak
  - SM
  - 2HDM



◆ MinkowskiVector()

csl::Tensor MinkowskiVector (std::string const & name)

Returns a **csl::Tensor**, vector in **csl::Minkowski** space.

The vector is by definition a tensor with one index. For example, a Minkowski vector may be created by:

```
csl::Tensor X = MinkowskiVector("X");
```

Then, assuming that 'mu' is an object of type **csl::Index**,

```
X(mu)
```

means the tensor with a lowered index X_μ, and

```
X(+mu)
```

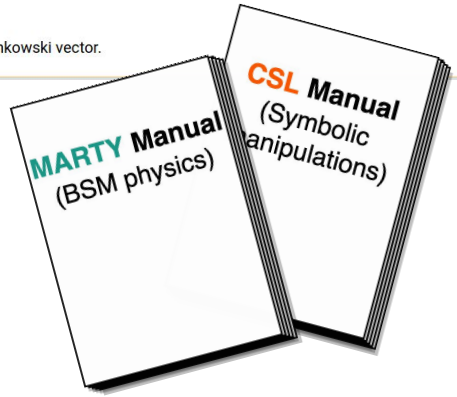
means the tensor with index up X^μ. For more information about tensors and indices see **csl::TensorElement** and **csl::Index**.

Parameters

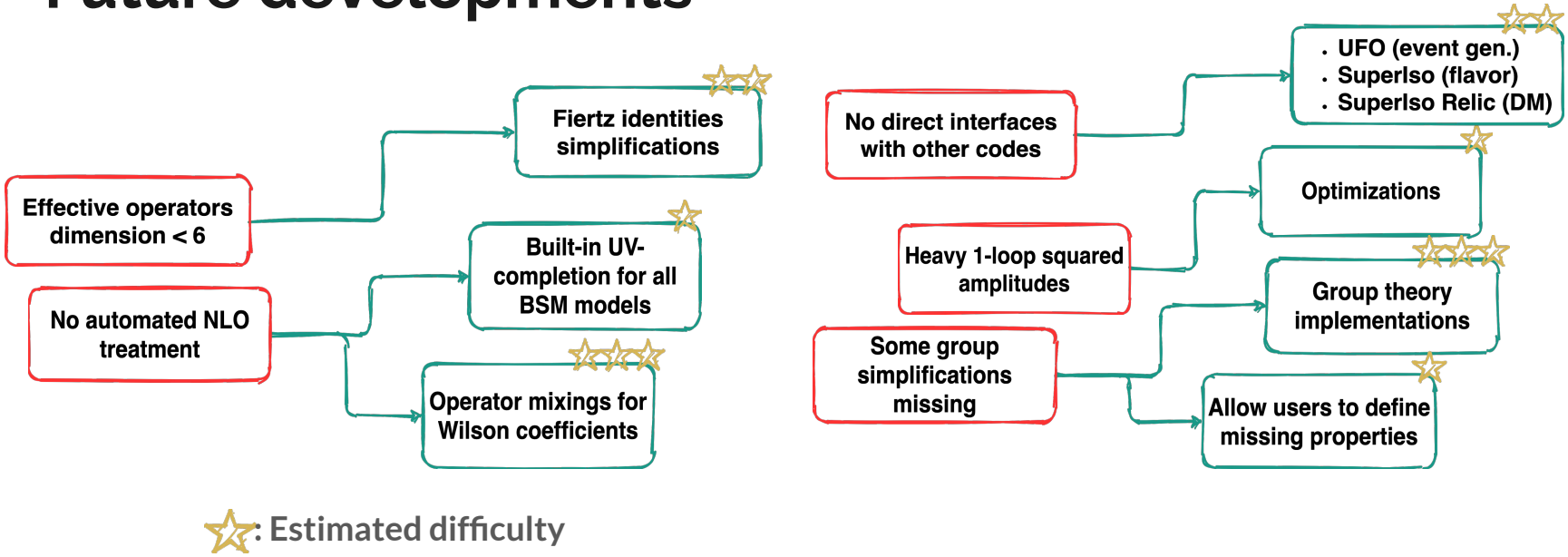
name Name of the vector.

Returns

An indicial Minkowski vector.



Future developments



: Estimated difficulty

Dependencies

- **C++ Standard Library (2017 version)**
- Numerical matrix diagonalization: **GNU Scientific Library (GSL)**
- Numerical integrals: **LoopTools**
  - **FF, Fortran**
- Feynman diagram drawing / edition: **Qt (open-source and free version)**

MARTY's user interface

$h \to \gamma\gamma$ (SM, 1-loop)

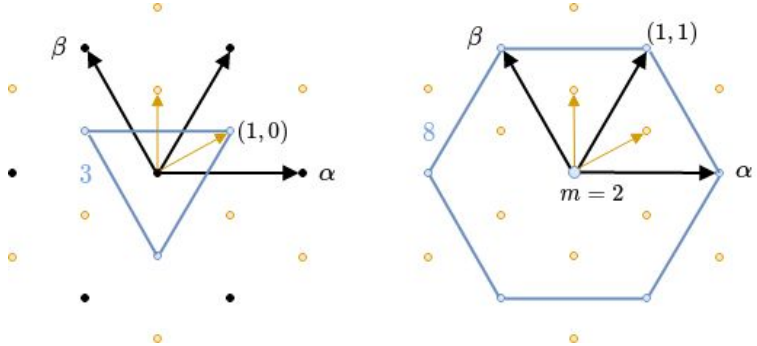
```
SM_Model SM;

auto res = ComputeAmplitude(
      Order::OneLoop,
      {
       Incoming("h"),
       Outgoing("A"),
       Outgoing("A")
      }
);

Display(res); // expressions
Show(res);    // diagrams
```

$b \to s\gamma$ (2HDM, 1-loop)

```
THDM_Model THDM;

DisableParticle("H^+"); // SM-like
ForceParticle("t");     // Only top quark

auto res = ComputeAmplitude(
      Order::OneLoop,
      {
       Incoming("b"),
       Outgoing("s"),
       Outgoing("A")
      }
);
```

Group theory

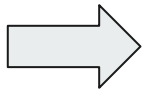
- **All semi-simple algebras**
- SU(3) is **A_2: 2 dinkin labels**
- Tensor product decomposition

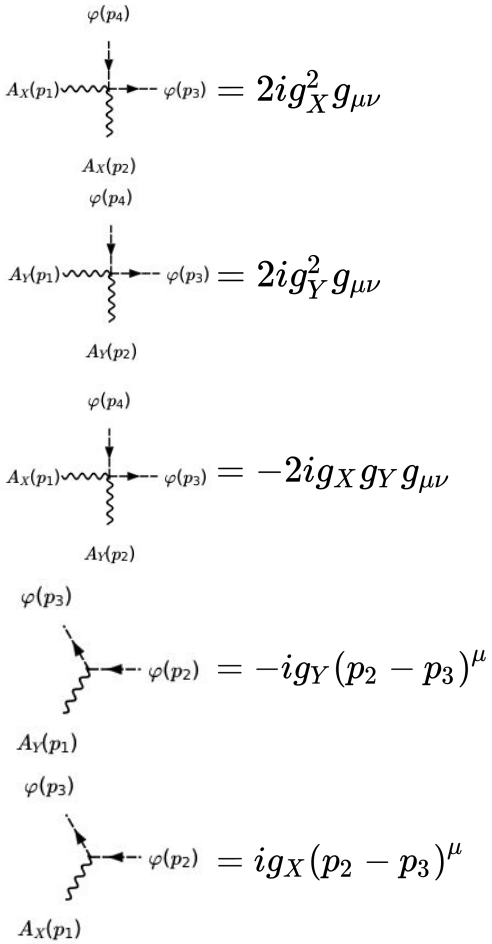



```cpp
auto SU3 = CreateAlgebra(AlgebraType::A, 2);

auto q     = GetIrrep(SU3, {1, 0});
auto q_bar = GetIrrep(SU3, {0, 1});
auto gluon = GetIrrep(SU3, {1, 1});

cout << "3 x 3 x 3 = " << q * q * q << endl;
// >> 3 x 3 x 3 = 1 + 8 + 8 + 10  (Total dim = 27)

cout << "8 x 8     = " << gluon * gluon << endl;
// >> 8 x 8     = 1 + 8 + 8 + 10 + 10 + 27  (Total dim = 64)
```

Scalar $U(1)_X$ x $U(1)_Y$

```
Model sQED;
AddGaugedGroup(sQED, GroupType::U1, "X");
AddGaugedGroup(sQED, GroupType::U1, "Y");
Init(sQED);

Particle phi = scalarboson_s("\\phi", sQED);
SetMass(phi, "m");
SetGroupRep(phi, "X", 1);
SetGroupRep(phi, "Y", -1);
AddField(sQED, phi);

cout << sQED << endl;

auto rules = ComputeFeynmanRules(sQED);
Display(rules);
Show(rules);
```

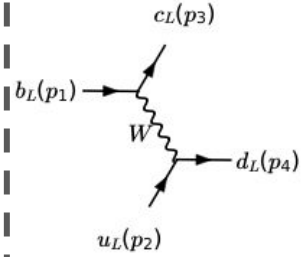




Amplitude (SM)

```
SM_model SM;

Particle bL = GetParticle(SM, "b_L");
Particle cL = GetParticle(SM, "c_L");
Particle uL = GetParticle(SM, "u_L");
Particle dL = GetParticle(SM, "d_L");

auto bu_to_cd = ComputeAmplitudesWithDiagrams(
        Order::TreeLevel,
        SM,
        {Incoming(bL), Incoming(uL),
        Outgoing(cL), Outgoing(dL)}
        );

Display(bu_to_cd);
Show(bu_to_cd);
```

Bare result



$$= -iAb_{0045}\,Prop(p1-p3, M_W^2)$$
$$\cdot P_{L\beta_1\gamma_1} P_{L\beta_2\gamma_2} \gamma^{\mu}_{\alpha_1\beta_1} \gamma_{\mu\alpha_2\beta_2} EXT^{ijkl}_{\alpha_1\alpha_2\gamma_1\gamma_2}$$

$$Ab_{0045} = Ab_{0031} \cdot Ab_{0039}$$
$$= \sqrt{\frac{2\pi\alpha_{em}}{\sin^2\theta_W}}|V_{ud}| \cdot \sqrt{\frac{2\pi\alpha_{em}}{\sin^2\theta_W}}|V_{cb}| = \frac{2\pi\alpha_{em}}{\sin^2\theta_W} V_{ud} V_{cd}$$

$$EXT^{ijkl}_{\alpha_1\alpha_2\gamma_1\gamma_2} = \bar{c}^k_{\alpha_1}(p_3) b^i_{\gamma_1}(p_1) \bar{d}^l_{\alpha_2}(p_4) u^j_{\gamma_2}(p_2)$$

Translated result

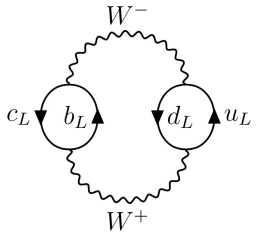
$$i\mathcal{M}^{ijkl} = -i\frac{2\pi\alpha_{em}}{\sin^2\theta_W (t-M_W^2)} V_{ud} V_{cb} \left(\bar{c}^k(p_3)\gamma^{\mu} P_L b^i(p_1)\right) \left(\bar{d}^l(p_4)\gamma_{\mu} P_L u^j(p_2)\right)$$

Cross-section (SM)

- Polarization sums
  - $\sum_i v^i(p)\bar{v}^i(p) = \gamma^\mu p_\mu - m$
  - $\sum_i u^i(p)\bar{u}^i(p) = \gamma^\mu p_\mu + m$
- Dirac traces
  - Non chiral $Tr\left(\gamma^{\mu_1} \dots \gamma^{\mu_n}\right)$
  - Chiral $Tr\left(\gamma^5 \gamma^{\mu_1} \dots \gamma^{\mu_n}\right)$
- Color traces $Tr\left(T_R^{A_1} \dots T_R^{A_N}\right)$

$$d\sigma = \frac{1}{2^2} \sum_{ijkl=\pm 1/2} (M^{ijkl})^\dagger M^{ijkl} d\Pi_{LIPS}$$

$$= \frac{1}{4}$$



$$d\Pi_{LIPS}$$

```
Expr xSection = SM.computeCrossSection(bu_to_cd.expressions);
std::cout << xSection << std::endl;
```

$$m_q = 0$$

$$\epsilon_{\mu\nu\rho\sigma} p_1^\mu p_2^\nu p_3^\rho p_4^\sigma = 0$$

$$\frac{d\sigma}{d\Pi_{LIPS}} = \frac{144\pi^2 \alpha_{em}^2}{\sin^4 \theta_W} V_{ud}^2 V_{cb}^2 \frac{p_1^\mu p_{2\mu} p_3^\nu p_{4\nu}}{(M_W^2 - 2p_1^\mu p_{3\mu})^2}$$

$$= \frac{144\pi^2 \alpha_{em}^2}{\sin^4 \theta_W} V_{ud}^2 V_{cb}^2 \frac{s^2}{(M_W^2 - t)^2}$$

MARTY's extension possibilities

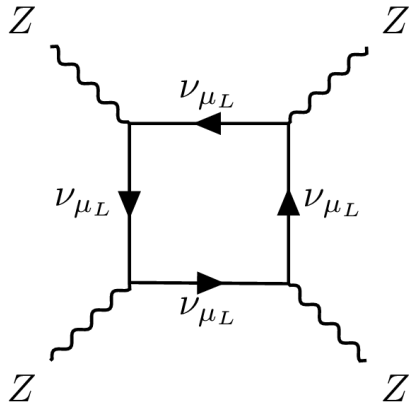
- **All theoretical tools in one** C++ program
  - Symbolic computations (CSL)
  - Group Theory
  - Quantum Field Theory
- **Independent** of any other framework
- Mathematica-free
- **Nothing is hard-coded**
- Fully **general and extendable**

For a C++ programmer

- **Full control** on the code
- Possibility to **implement new rules**
  - Model definition
  - Simplifications
- **Possibility to extend MARTY** to
  - New models (S > 1, D > 4, ...)
  - Other computations

MARTY's calculation capabilities

- Fully **symbolic and automatic (CSL)**
- Up to five external particles, at **1-loop**
- **Amplitudes, partonic cross-sections, Wilson coefficients**
- Feynman diagram generation **(GRAFED)**
- **Simplifications**
  - Index contractions as far as possible
  - Dirac algebra
  - Group algebra
  - Tensor reduction for momentum integrals
  - Equations of motion (Dirac equation)
  - Decomposition on an operator basis
  - Definition of abbreviations



Library generation

- Allows to get actual **numbers**
- **Fully automated**
- Symbols with values are replaced
- Other symbols must be passed as argument
- **Kinematics to be defined by the user**
- Easy call from **C++ and Python**

```
Library SMWil("SMWil", "marty_libs");
SMWil.addFunction("C7", C7);
SMWil.print();
SMWil.build();
```

⇩ Automatic generation

```
std::complex<double> C7(
      const double M_W,
      const double m_b,
      const double m_s,
      const double m_t,
      const double s_12
      );
```

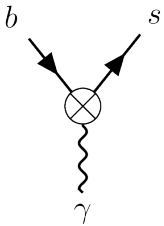
⇩ Simple to use

```
#include <SMWil>   C++

SMWil::C7(...);
```

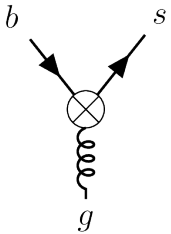
⇩ Upcoming ...

```
import SMWil  Python

SMWil.C7(...)
```

C^t_7 - C^t_8 at LO with MARTY

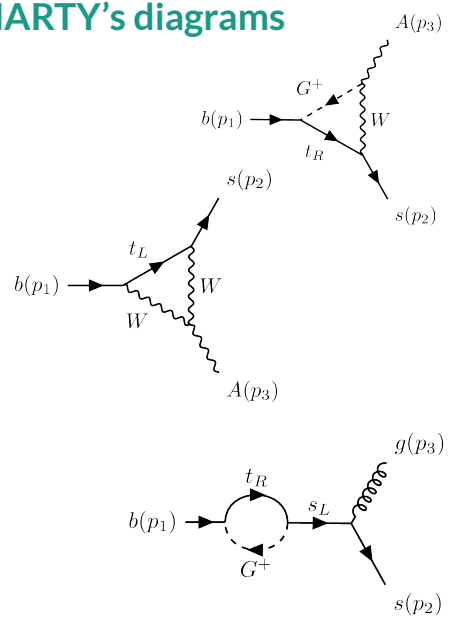


$$\propto C_7\langle\hat{O}_7\rangle + C'_7\langle\hat{O}'_7\rangle = C_7 \cdot \bar{s}_L\sigma^{\mu\nu}b_R F_{\mu\nu} + C'_7 \cdot \bar{s}_R\sigma^{\mu\nu}b_L F_{\mu\nu}.$$



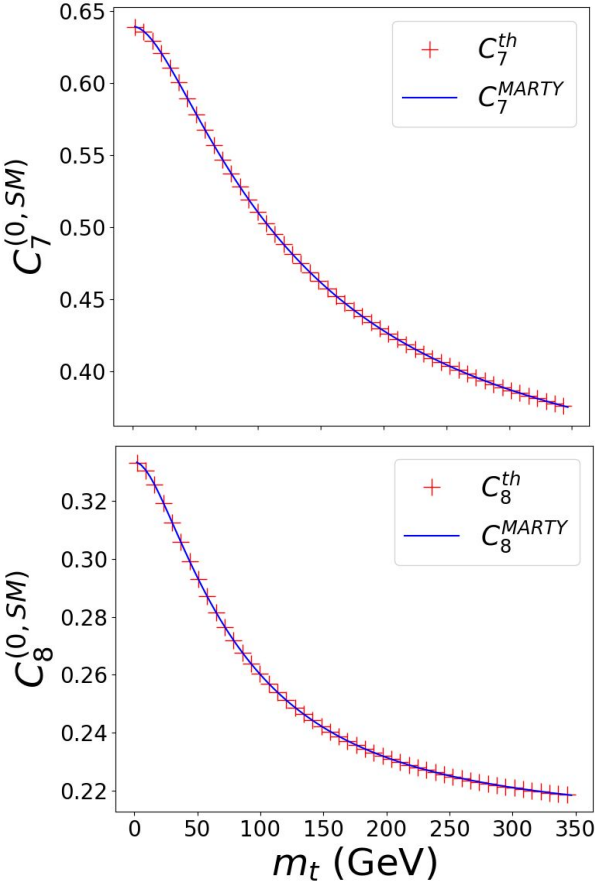
$$\propto C_8\langle\hat{O}_8\rangle + C'_8\langle\hat{O}'_8\rangle = C_8 \cdot \bar{s}_L\sigma^{\mu\nu}G_{\mu\nu}b_R + C'_8 \cdot \bar{s}_R\sigma^{\mu\nu}G_{\mu\nu}b_L.$$

MARTY's diagrams



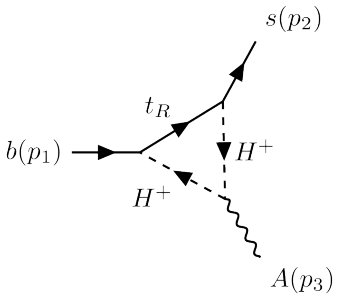
Results in the SM

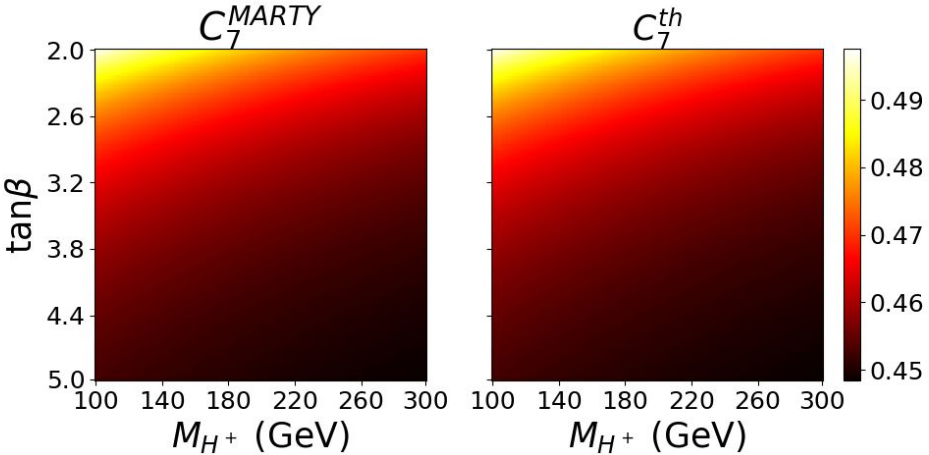
- Evaluation at $\mu = M_W$
- **Multiple gauges**
  - Unitary (W contributions)
  - Feynman (W and Goldstone contributions)
- ~ 1 s in Feynman gauge
- Automatic C++ code generation
- Plot with python
- **Source:** SuperIso manual (arXiv: 0808.3144)



Results in the 2HDM (type IV)

- **Charged Higgs** contributions
- Depend on
  - M_{H^+}
  - $\tan\beta$
- **Source:** SuperIso manual (arXiv: 0808.3144)





One loop LO, towards NLO

The LO 1-loop computation (now)

- No renormalization
- 1-loop quantities if LO (like C_7)
- All simplifications implemented
- Numerical integrals (**LoopTools hep-ph/9807565**)
- Allows to get all building blocks for NLO

The NLO 1-loop computations (next)

- When LO is the tree-level
- Renormalization
  - Masses
  - Couplings
- Renormalization group: $\frac{d}{d \log \mu}$
- Operator mixing
- RG-improved perturbation theory for Wilson coefficients