MARTY

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

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

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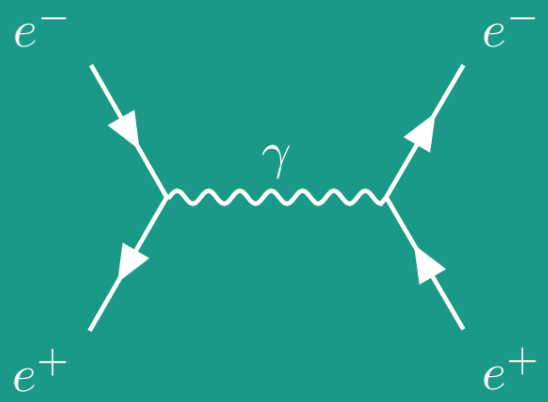
ICHEP Conference
Computing section
30 / 07 / 2020

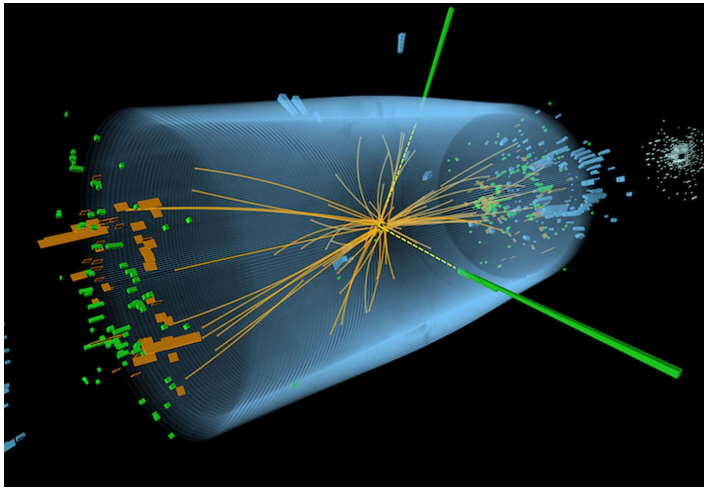
Introduction



Calculations in High-Energy Physics

- **Beyond The Standard Model (BSM)** searches
- Test on **experimental data**

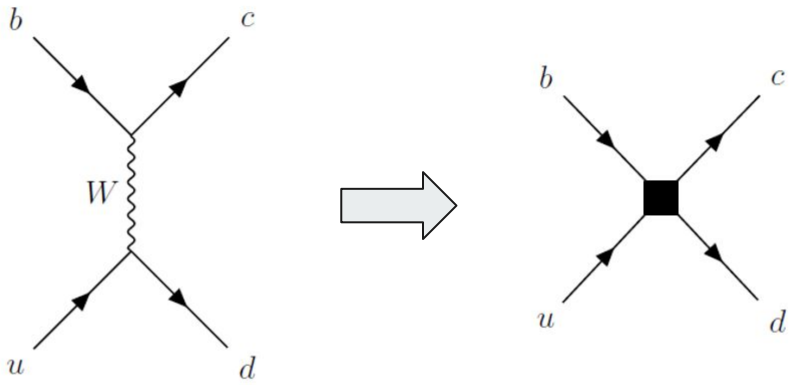
- **Theoretical calculations:**
  - Transition amplitudes
  - Cross-sections
  - Wilson coefficients
- 1-loop quantities are necessary
- **Very involved and error prone**



Need for automated BSM calculations

Wilson coefficients in flavor physics

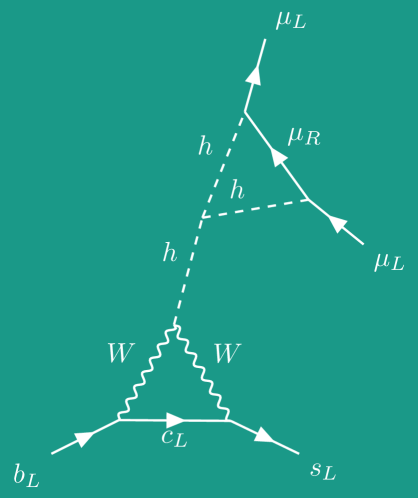
- **Low energy** effective field theory (EFT)
- **Effective Hamiltonian**
- $\hat{\mathcal{O}}_i$ are hadronic matrix elements:
  - non-perturbative quantities
  - **model independent**
- C_i are **Wilson coefficients:**
  - perturbative quantities
  - **model dependent**



$$\mathcal{A}(b \to c\bar{u}d) \propto \langle c\bar{u}d|\mathcal{H}_{\text{eff}}|b\rangle = \sum_i C_i \langle c\bar{u}d|\hat{\mathcal{O}}_i|b\rangle$$

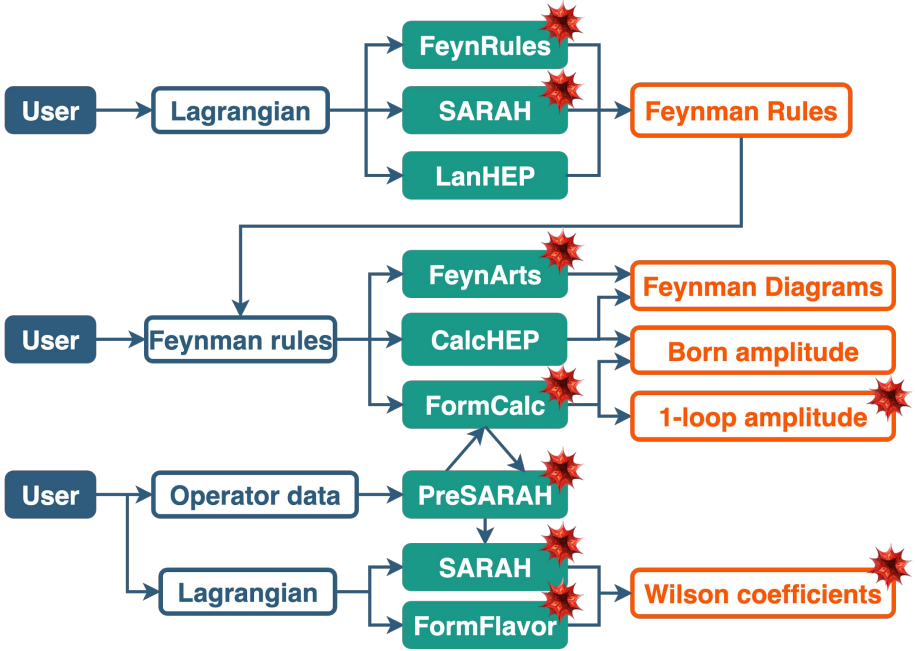
BSM dependence in Wilson coefficients!

Automated BSM calculations



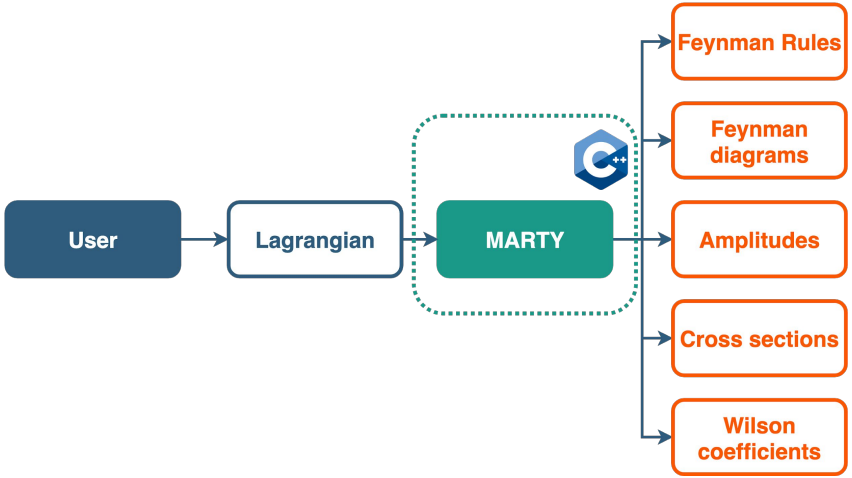
Present Ecosystem

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

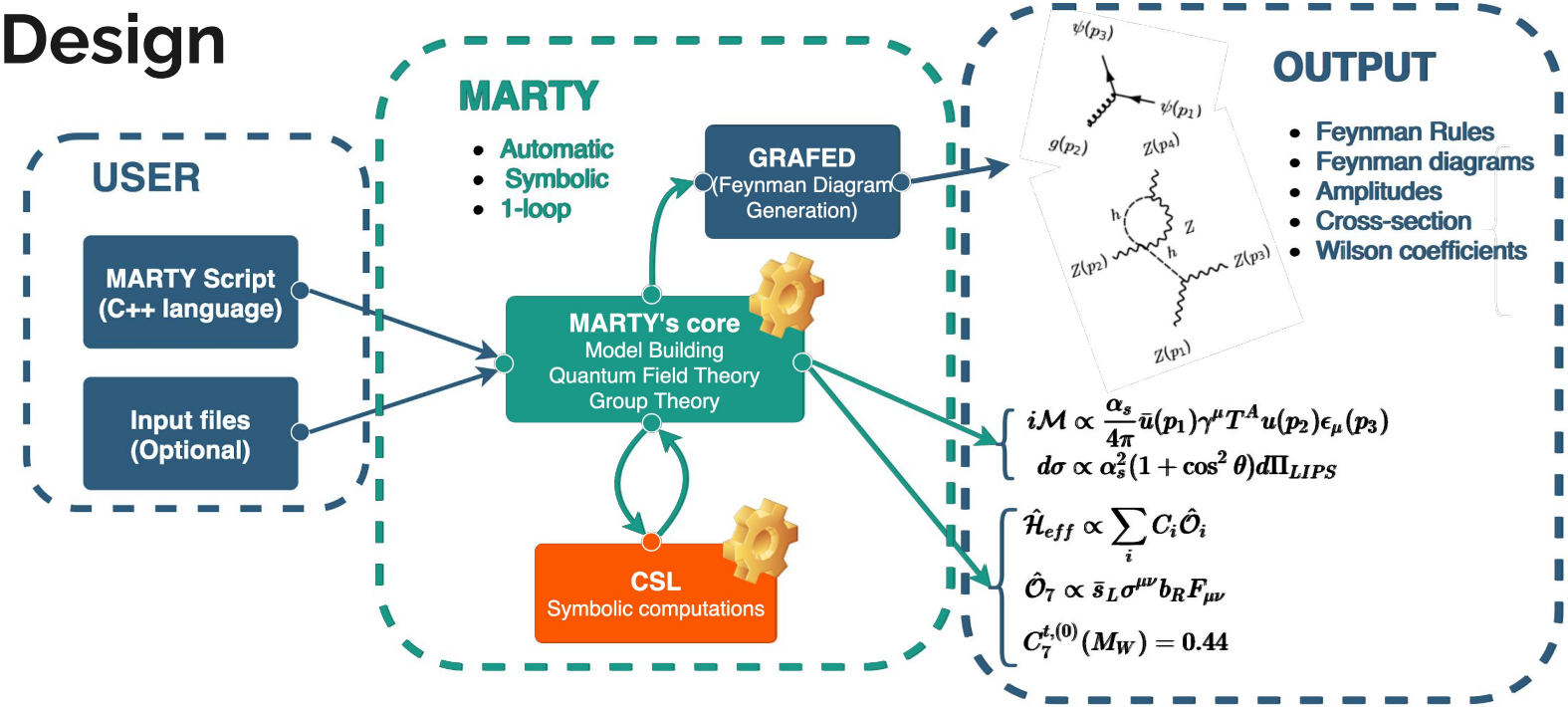


MARTY's ecosystem

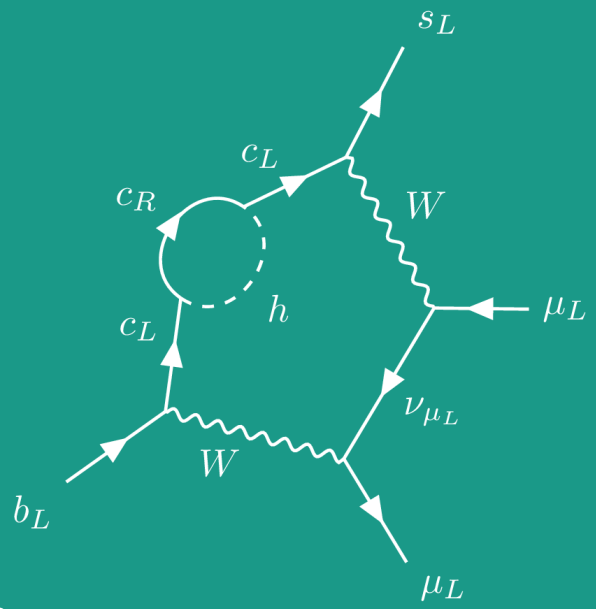
- Unique user input
- C++ (fast, modern, popular)
- No painful dependency
- Embedded C++ Symbolic computation Library (CSL)
- Embedded Generating and Rendering Application for FEynman Diagrams (GRAFED)



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
$\psi(p_3)$
$\psi(p_1)$
$g(p_2)$
$Z(p_4)$
h
Z
h
$Z(p_2)$
$Z(p_3)$
$Z(p_1)$
$i\mathcal{M} \propto \frac{\alpha_s}{4\pi}\bar{u}(p_1)\gamma^\mu T^A u(p_2)\epsilon_\mu(p_3)$
$d\sigma \propto \alpha_s^2(1+\cos^2\theta)d\Pi_{LIPS}$
$\hat{\mathcal{H}}_{eff} \propto \sum_i C_i\hat{O}_i$
$\hat{O}_7 \propto \bar{s}_L\sigma^{\mu\nu}b_R F_{\mu\nu}$
$C_7^{t,(0)}(M_W) = 0.44$

What MARTY can do for you ?



MARTY's current BSM capabilities

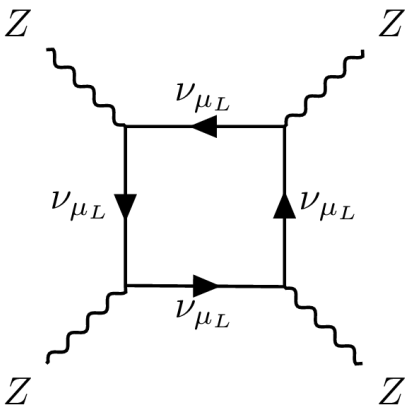
- **Quantum Field Theory**
  - 4-dimensional Minkowski space-time
  - Spin 0, ½, 1
  - Model building utilities
- **Group theory**
  - Semi-simple groups (SU(N), SO(N), Sp(N), E_6, E_7, E_8, F_4, G_2)
  - Representation theory
  - Algebra generators
  - Simplifications, traces

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \left(D^{\mu}H\right)^{\dagger} D_{\mu}H + \mu H^{\dagger}H - \lambda\left(H^{\dagger}H\right)^{2},$$

$$H \rightarrow \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix}$$

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", "libs/SMWil");
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,
      LibraryTensor<double> const &p_1,
      LibraryTensor<double> const &p_2
      );
```

Simple to use

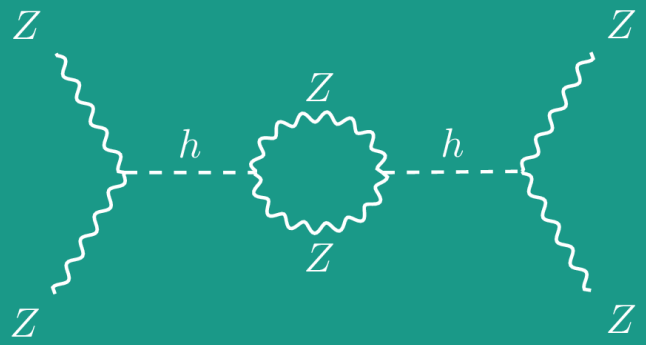
C++

```
#include <SMWil>

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

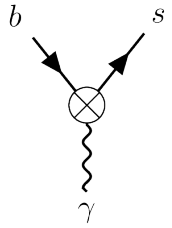
Python

```
import SMWil

SMWil.C7(...)
```

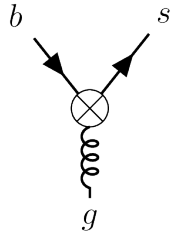
A 1-loop Wilson example



C^t_7 - C^t_8 at LO with MARTY

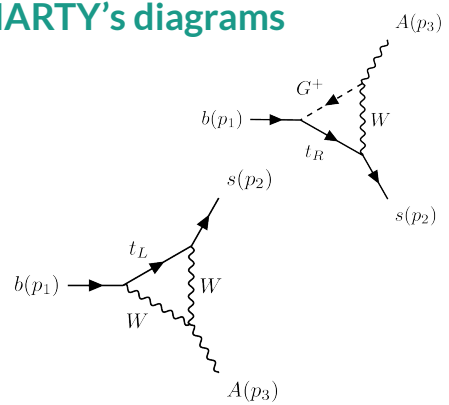


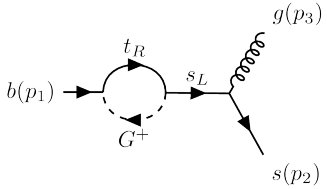
$$\propto C_7\langle\hat{O}_7\rangle + C_7'\langle\hat{O}_7'\rangle = C_7 \cdot \bar{s}_L\sigma^{\mu\nu}b_R F_{\mu\nu} + C_7' \cdot \bar{s}_R\sigma^{\mu\nu}b_L F_{\mu\nu}.$$



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

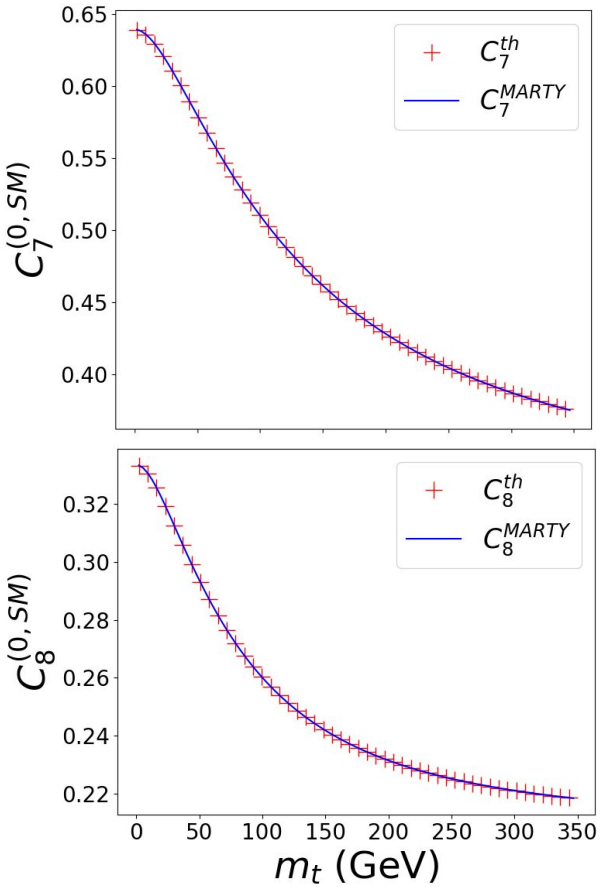
MARTY's diagrams





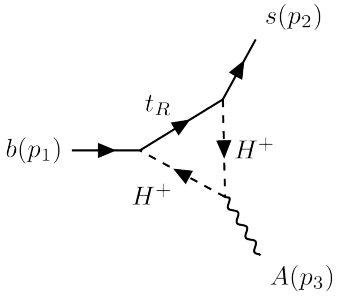
Results in the SM

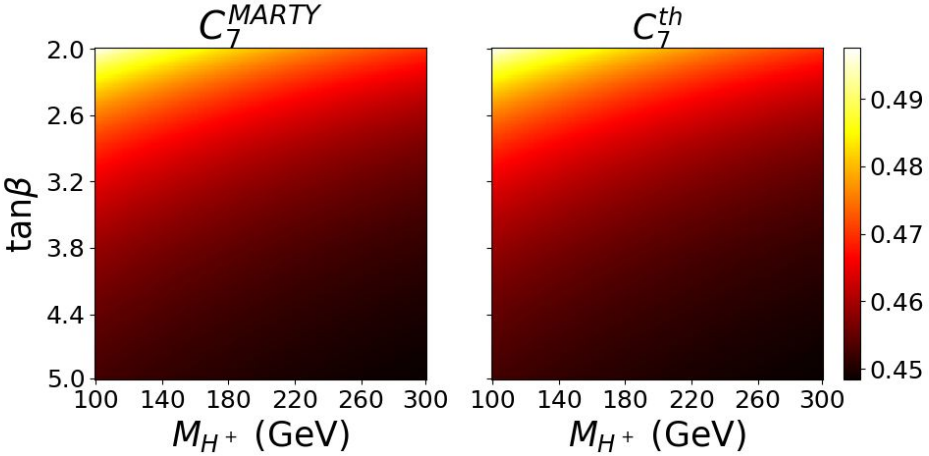
- Evaluation at $\mu = M_W$
- **Multiple gauges**
  - Unitary (W contributions)
  - Feynman (W and Goldstone contributions)
- ~ 1 s in Feynman gauge
- Automatic C++ code generation
- Plot with python
- **Source:** SuperIso manual (arXiv: 0808.3144)



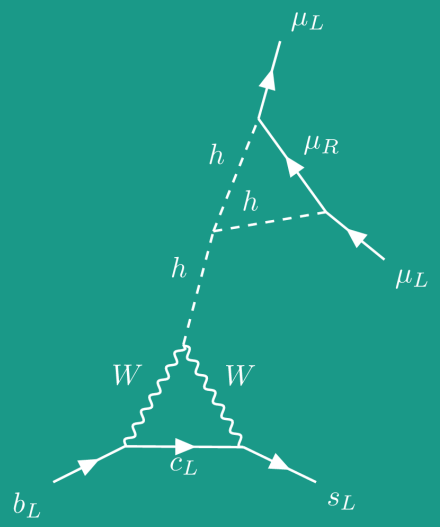
Results in the 2HDM (type IV)

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





MARTY's users



Manual & Documentation

- About **120 000 lines** of C++
- Comprehensive **documentation** (HTML)
- Very detailed **manuals**
- Many examples
  - Scalar theory
  - sQED
  - QED, QCD, Electro-Weak
  - SM
  - 2HDM
  - MSSM

◆ 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)
```

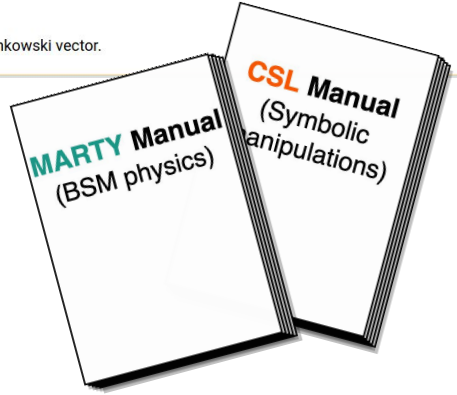
means the tensor with index up X^μ. For more information about tensors and indices see **csl::TensorElement** and **csl::Index**.

Parameters

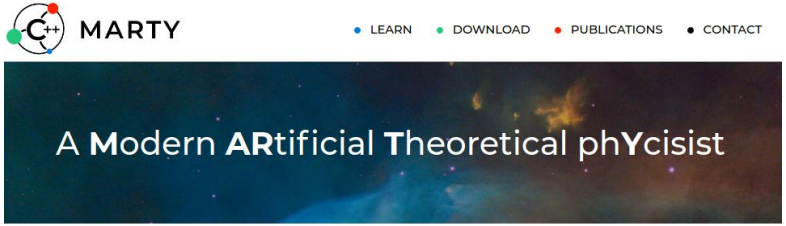
name Name of the vector.

Returns

An indicial Minkowski vector.



Website under construction: *https://marty.in2p3.fr*

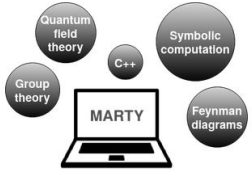


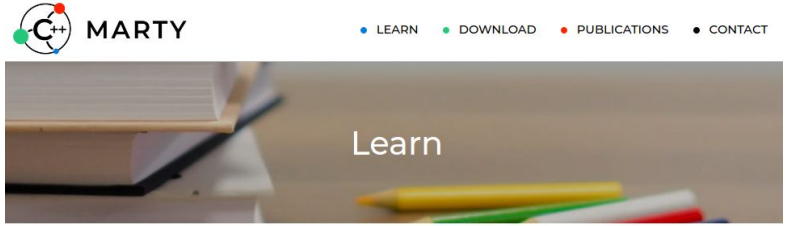
MARTY in short

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.





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.

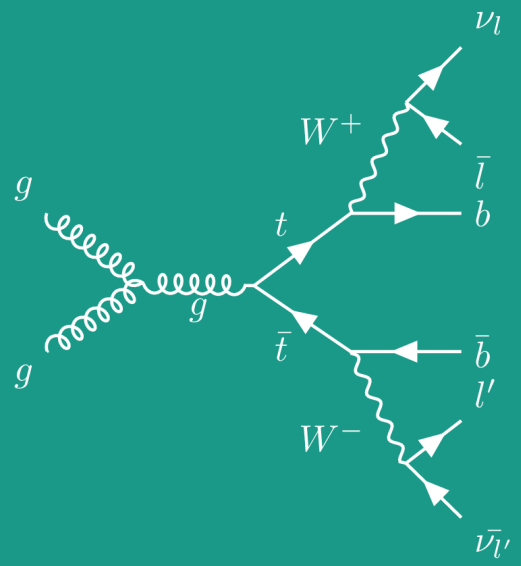
Get started
Learn the basics about MARTY

Tutorials
See how to use MARTY

Manual
Detailed features and methods

The documentation
Interactive reference

Status and perspectives



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

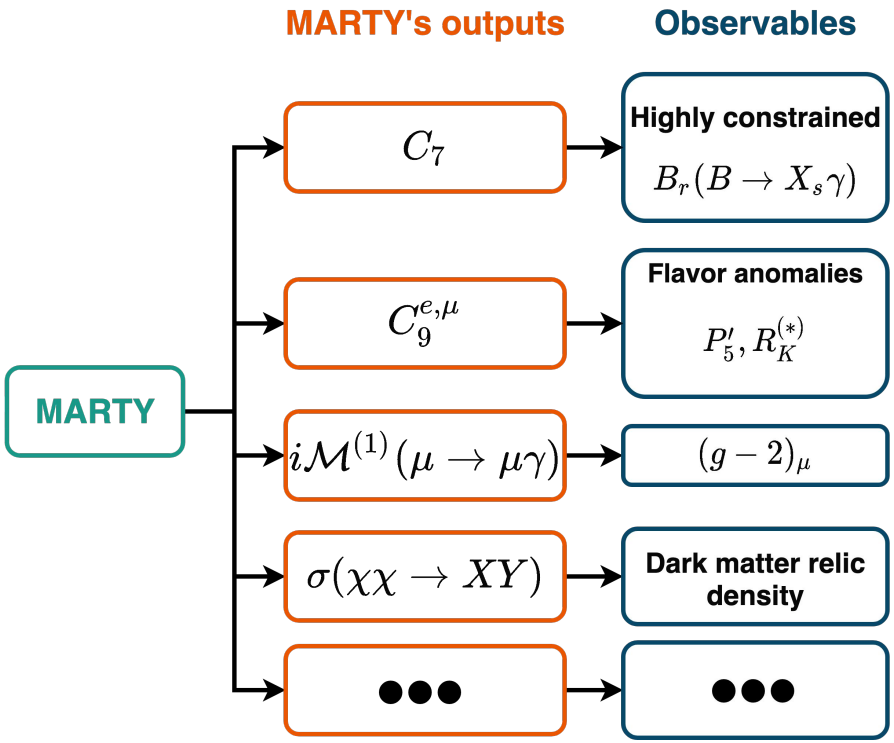
The NLO 1-loop computations (next)

- 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

Conclusion

What makes MARTY unique

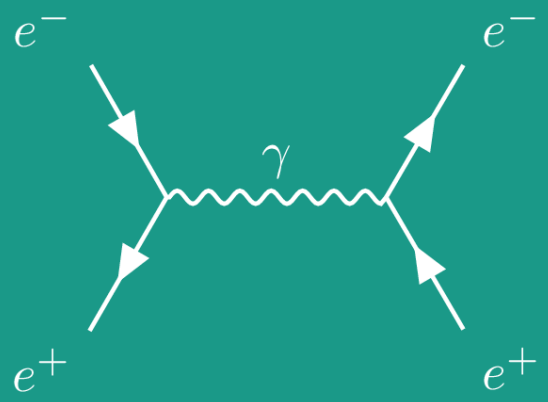
- All theoretical tools in one
- Very powerful
  - 1-loop
  - Amplitudes, cross-sections
  - Full NLO automated Wilson coefficients
- Independent of Mathematica



MARTY

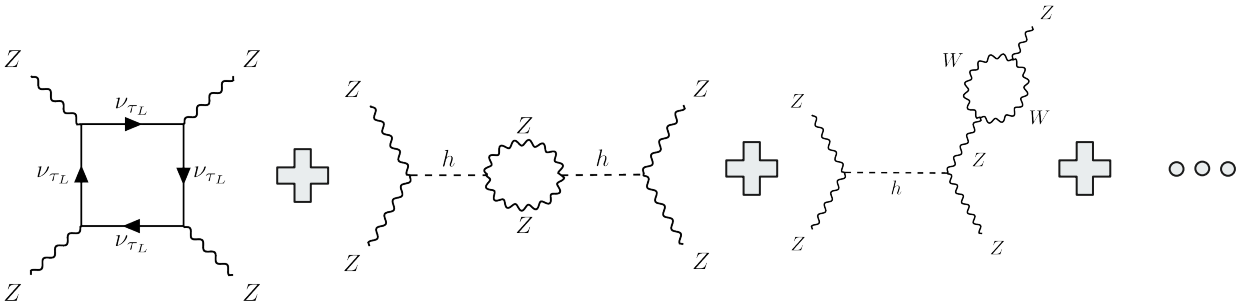
Coming next october...

Backup



Computation challenges

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



- Calculating one feynman diagram may be very long
- **Multiple diagrams in one amplitude**
- **Cross section is amplitude squared**
- **Wilson coefficient is amplitude with extra work**

Dependencies

- **C++ Standard Library (2017 version)**
- Numerical matrix diagonalization: **GNU Scientific Library (GSL)**
- Numerical integrals: **LoopTools**
  - **FF, Fortran**
- (temporary) Numerical integral of rank 5 five-point-function: **PJFry**
  - **OneLOop** or **QCDLoop**
  - **FF, Fortran**
- Feynman diagram drawing / edition: **Qt (open-source and free version)**

MARTY's user interface

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

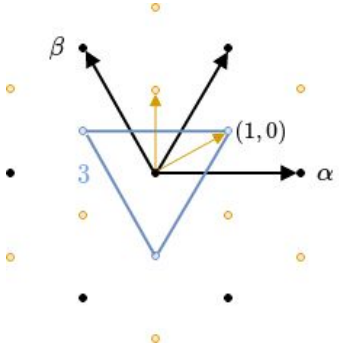
```
SM_Model SM;

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

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

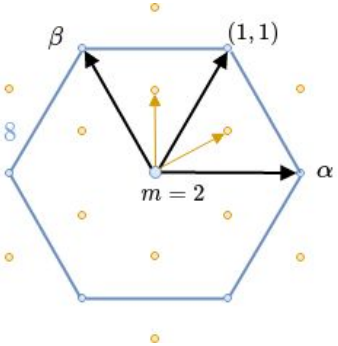
$b \to s\gamma$ **(2HDM, 1-loop)**

```
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

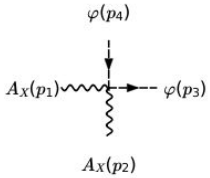




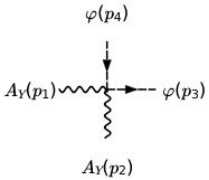

```
auto SU3 = CreateAlgebra(AlgebraType::A, 2);

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 $U(1)_X \times U(1)_Y$

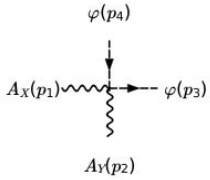
```
Model sQED;
AddGaugedGroup(sQED, GroupType::U1, "X");
AddGaugedGroup(sQED, GroupType::U1, "Y");
Init(sQED);

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);
```



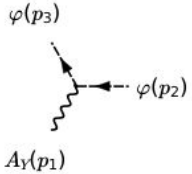
$$= 2ig_X^2 g_{\mu\nu}$$



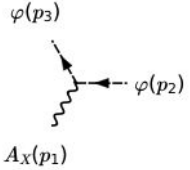
$$= 2ig_Y^2 g_{\mu\nu}$$



$$= -2ig_X g_Y g_{\mu\nu}$$



$$= -ig_Y (p_2 - p_3)^\mu$$

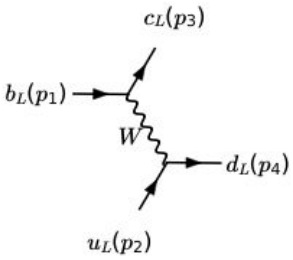


$$= ig_X (p_2 - p_3)^\mu$$

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

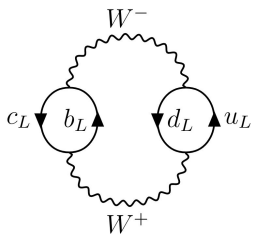
$$i\mathcal{M}^{ijkl} = -i\frac{2\pi\alpha_{em}}{\sin^2\theta_W (t - M_W^2)} V_{ud} V_{cb} \left(\bar{c}^k(p_3)\gamma^{\mu} P_L b^i(p_1)\right)\left(\bar{d}^l(p_4)\gamma_{\mu} P_L u^j(p_2)\right)$$

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;
```

$$m_q = 0$$

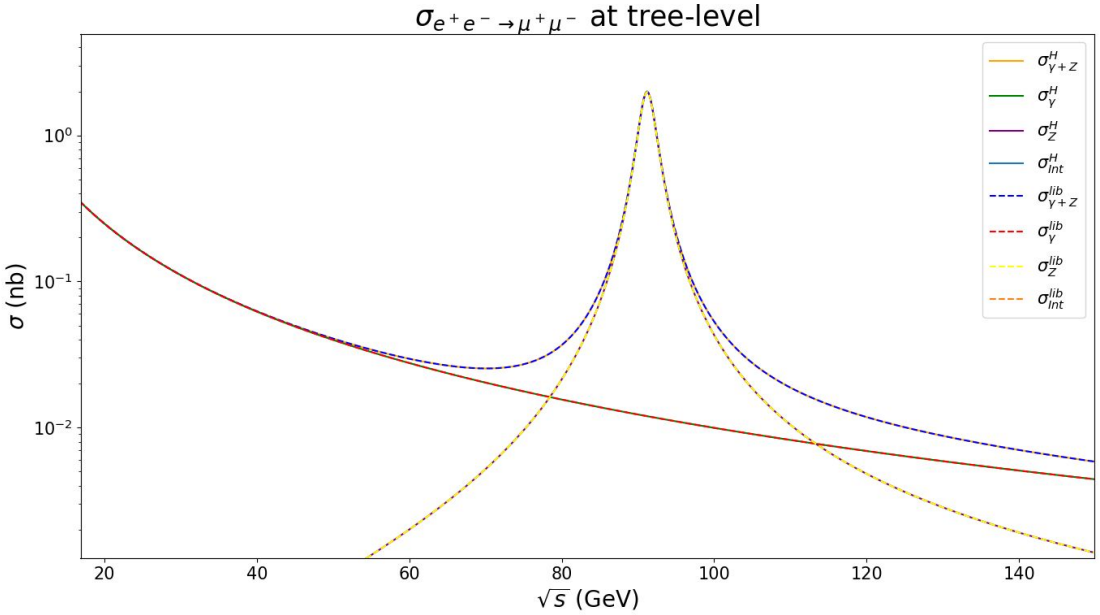
$$\epsilon_{\mu\nu\rho\sigma}p_1^\mu p_2^\nu p_3^\rho p_4^\sigma = 0$$

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

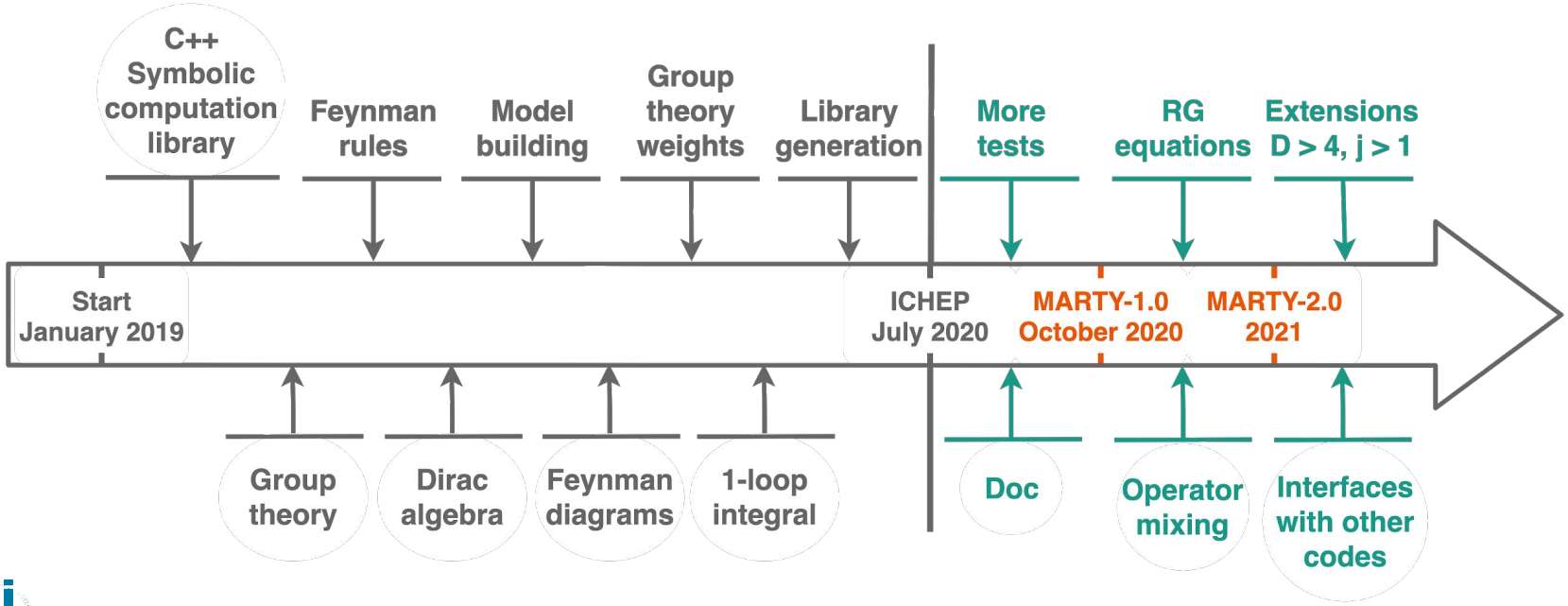
$$= \frac{144\pi^2\alpha_{em}^2}{\sin^4\theta_W}V_{ud}^2V_{cb}^2\frac{s^2}{(M_W^2 - t)^2}$$

Library example

- **Z resonance** ~ 91 GeV
- $\sigma_{SM}(e^+e^- \to \mu^+\mu^-)$
- Exact match with known results
- $\sigma_{peak} \approx 2$ nb
- $\Gamma_Z \approx 2.5$ GeV
- **May vary any parameter**
- **LEP** experiments



Road map


C++ Symbolic computation library
Feynman rules
Model building
Group theory weights
Library generation
More tests
RG equations
Extensions D > 4, j > 1
Start January 2019
ICHEP July 2020
MARTY-1.0 October 2020
MARTY-2.0 2021
Group theory
Dirac algebra
Feynman diagrams
1-loop integral
Doc
Operator mixing
Interfaces with other codes

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