Hands-on Start to MadGraph

1st Workshop on New Light Physics and Photon-beam Experiments, 03/08/2021

Yi-Ming Zhong (KICP, UChicago)
ymzhong@kicp.uchicago.edu

Slides available at https://github.com/ymzhong/mg5_aMC_tutorial

Who am I?

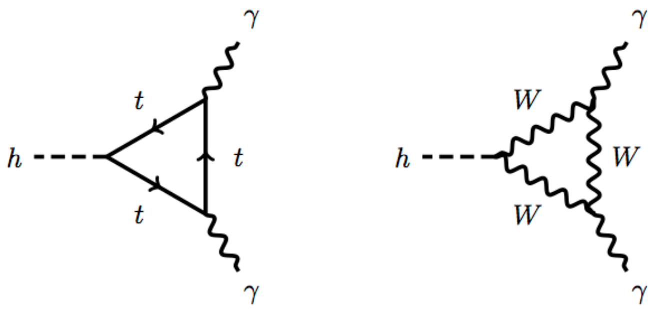
- Yiming Zhong is a postdoc follow at Kavli Institute for Cosmological Physics at the University of Chicago.
- Working on theoretical particle physics, dark matter/dark sector searches.
- Not affiliated with the MadGraph team.
- Using MadGraph for years. Writing new physics models for it.

Goal for this tutorial

- What is MadGraph?
- Generate events for *tree-level* processes
- Play with outputs

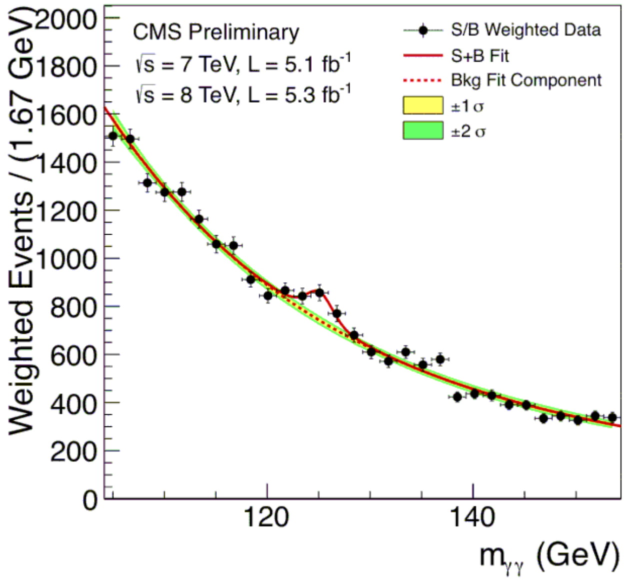
- Add a form-factor for fixed-target processes

What is MadGraph?



The Higgs discovery

EPJC 74 (2014) 3076



The master formula

Feyn Rules

efficiency

$$N = L\epsilon\sigma \sim L\epsilon \int \mathrm{d}\Phi \, |\mathcal{M}|^2$$

Event

Integrated luminosity

cross section

Phase space

Matrix element

Monte-Carlo Integral

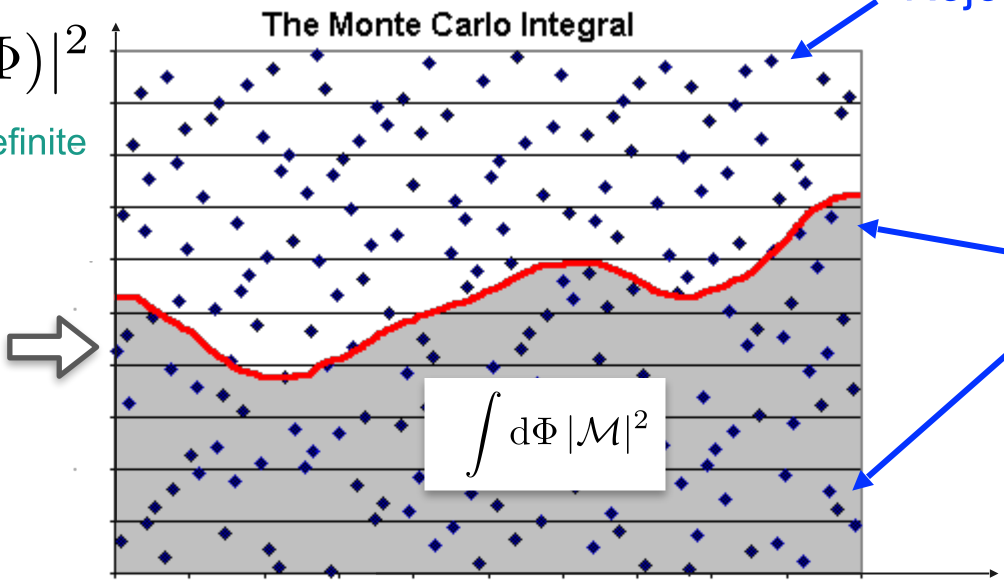
see Sjöstrand's lectures for more

Integral

$|\mathcal{M}(\Phi)|^2$

positive definite

Random number generator



Rejected events

Accepted events

for a process w/ *n* particles

$\Phi \in \mathbb{R}^{3n-4}$

What is MadGraph?

- **MadGraph5_aMC@NLO** (MG5_aMC) computes the matrix elements and generates Monte-Carlo events.
  Use helicity amplitudes
  Use Multi Channel Monte-Carlo
- + loop computation
- + interfaces with parton shower & hadronization event generators Pythia/Herwig
- + ……

Just keep in mind, MG5_aMC

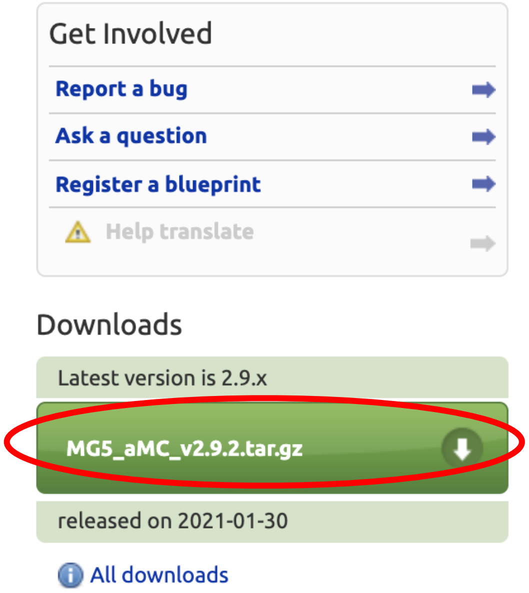
- Parton-level, fixed parton multiplicity, no control of large logs.
- Does not fully support polarized initial states.
- Is not good at sampling process with large t-channel cancellations. *
- Important to cross-check with other general event generators, such as Pythia, WHIZARD, CalcHEP, or specific event generators, such as esepp

Useful resource

- MG5_aMC Launchpad (https://launchpad.net/mg5amcnlo) Q&A
- MG5_aMC Wiki (https://cp3.irmp.ucl.ac.be/projects/madgraph)
- ‘`help`’ command inside MG5_aMC

Installation

- Requirement: gcc & gfortran >= 4.6, Python 2.7 or 3.7
- Setup/active suitable Python environment
  `python --version`
- Download MG5_aMC at https://launchpad.net/mg5amcnlo
- If you use Python 2.6, download MG5_aMC_v2.7.3.tar.gz at https://launchpad.net/mg5amcnlo/+download
- Untar and cd MG5_aMC folder



What is inside?

Where you add your models

```
 $ls MG5_aMC_v2_9_2
HELAS          PLUGIN            VERSION     doc.tgz     models
INSTALL        README            aloha       input       proc_card.dat
LICENSE        Template          bin         madgraph    tests
MadSpin        UpdateNotes.txt   doc         mg5decay    vendor
```

Mg5_configuration: setup MG5 environment

First example: Bhabha Scattering at BaBar

1. Launch the interface
   `./bin/mg5_aMC` or `python3 ./bin/mg5_aMC`
2. Load the Standard Model with massive electrons and muons
   `MG5_aMC>import model sm-full --modelname`
3. Generate Bhabha Scattering
   `MG5_aMC>generate e+ e- > e+ e-`
4. Output
   `MG5_aMC>output newprocess`
5. Launch
   `MG5_aMC>launch newprocess`

Don't forget the "spaces"

Ask MG5 not to change (BSM) particle names

Change parameters in param_card and run_card

```
Do you want to edit a card (press enter to bypass editing)?
/------------------------------------------------------------\
|  1. param : param_card.dat                                 |
|  2. run   : run_card.dat                                   |
\------------------------------------------------------------/
 you can also
   - enter the path to a valid card or banner.
   - use the 'set' command to modify a parameter directly.
     The set option works only for param_card and run_card.
     Type 'help set' for more information on this command.
   - call an external program (ASperGE/MadWidth/...).
     Type 'help' for the list of available command
 [0, done, 1, param, 2, run, enter path][90s to answer]
>
```

```
>set aEWM1 = 132
>set run_tag = BaBar
>set ebeam1 = 5.5
>set ebeam2 = 5.5
>set ptl = 0
>set etal = 5
>set drll = 0
>0
```

The web portal

file:///home/zym/Downloads/MG5_aMC_v2_9_2/newprocess/crossx.html

Results in the sm-full for e+ e- > e+ e-

Run_card,
param_card
…

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action	
run_01	e+ e- 5.5 x 5.5 GeV	BaBar	5.087e+07 ± 8.5e+04	10000	parton madevent	LHE	remove run	launch detector simulation

Main Page

Events zipped
in LHE format

Check the process

- main page > process information > html
- Better do it before launching the simulation

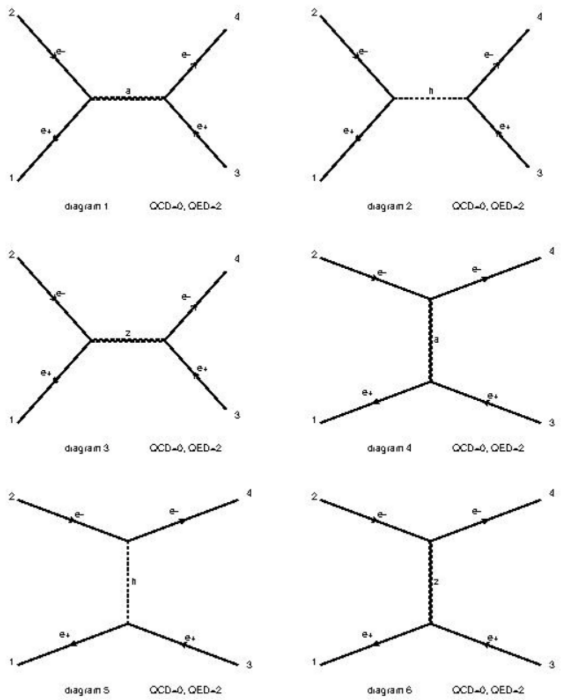
SubProcesses and Feynman diagrams

Directory	# Diagrams	# Subprocesses	FEYNMAN DIAGRAMS	SUBPROCESS
P1_epem_epem	6	1	html	e+ e- > e+ e-

6 diagrams (6 independent).

Postscript Diagrams for e+ e- > e+ e- WEIGHTED<=4 @1

page 1/1



Diagrams made by MadGraph5_aMC@NLO

Contributions from different channels

s= 5.0865e+07 ± 8.54e+04 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/zym/Downloads/MG5_aMC_v2_9_2/newprocess/SubProcesses/P1_epem_epem	5.087e+07	8.54e+04	247.194	13861.0	0

s= 5.0865e+07 ± 8.54e+04 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G4	5.086e+07	8.54e+04	226.164	12730.0	0.00025
G2.2	4899	43.5	7.01	369.0	0.0753
G3.2	118.4	0.633	7.01	375.0	3.17
G1	22.02	0.156	7.01	387.0	17.6

- Contribution from each integration channels (see launchpad discussion*, **)
- The exact channel to diagram mapping can be found at `/MG5_aMC/newprocess/SubProcesses/config_subproc_map.inc`

Run MG5_aMC wo the interface

- Put everything into a single file, then `./bin/mg5_aMC proc_card.dat`
- If you already output a directory, `cd` the folder and try `./bin/generate_events proc_card.dat` (only need commands after `launch` command)

proc_card_bhabha.dat
~/Downloads/MG5_aMC_v2_9_2

```
#************************************************************
#*                    MadGraph 5                            *
#*                                                          *
#*                *                       *                 *
#*                  *        * *        *                   *
#*                    * * * * 5 * * * *                     *
#*                  *        * *        *                   *
#*                *                       *                 *
#*                                                          *
#*                                                          *
#*    The MadGraph Development Team - Please visit us at    *
#*    https://server06.fynu.ucl.ac.be/projects/madgraph     *
#*                                                          *
#************************************************************
#*                                                          *
#*               Command File for MadGraph 5                *
#*                                                          *
#*     run as ./bin/mg5  filename                           *
#*                                                          *
#************************************************************
import model sm-full --modelname
# Define multiparticle labels
define p = g u c d s u~ c~ d~ s~
define j = g u c d s u~ c~ d~ s~
define l+ = e+ mu+
define l- = e- mu-
define vl = ve vm vt
define vl~ = ve~ vm~ vt~
# Specify process(es) to run
generate e+ e- > e+ e-
# Output processes to MadEvent directory
output newprocess_2
launch newprocess_2
set aEWM1 = 132
set run_tag = BaBar
set ebeam1 = 5.5
set ebeam2 = 5.5
set ptl = 0
set etal = 5

# To generate events, you can go to the created directory and
# run ./bin/generate_events
```

Parameter scan w/ MG5_aMC

- One parameters

```
set me scan:[0.1, 0.5 ,1]
set me scan:range(0.1,1,0.1)
set me scan:[0.001*i for i in range(100,105)]
```

- Can be extended for more parameters
- Two correlated parameters

```
set ebeam1 scan1:[4.5, 5., 5.5]
set ebeam2 scan1:[4.5, 5., 5.5]
```

- check cross sections from the scan

```
launch newprocess -i
print_results --path=./cross_section.txt --format=short
```

Exercise 1

- Generate Compton process $\gamma e^- \rightarrow \gamma e^-$ for a fixed-target photon-beam experiment with $E_\gamma = 100$ MeV and $\eta_{max} = 5$.

  Q1: How to set up a fixed-target experiment?

  Q2: Why we need a cut on the pseudo-rapidity?

- Generate Compton process $\gamma N \rightarrow \gamma N$ for a fixed-target photon-beam experiment with $E_\gamma = 10$ MeV and $\eta_{max} = 5$.

  Q3: Nucleon is not defined in the model. How to get around?

More on the syntax: add process

- ```
  MG5_aMC>generate e+ e- > e+ e-
  MG5_aMC>add process e+ e- > e+ e- a
  MG5_aMC>add process e+ e- > e+ e- a a
  MG5_aMC>display diagrams
  ```
  ```

More on the syntax: select process

- `MG5_aMC>generate e+ e- > e+ e- /z h` — remove diagrams w/ z, h
  `(MG5_aMC>display diagrams)`
- `MG5_aMC>generate e+ e- > z > e+ e-` — only includes diagrams w/ s-channel z
- `MG5_aMC>generate e+ e- > e+ e- $$ z h` — remove diagrams w/ s-channel z, h
- `MG5_aMC>generate e+ e- > e+ e- $$ z /h` — remove diagrams w/ s-channel z and diagrams w/ h

More on the syntax: add the decay chain

Use , and ()

- `MG5_aMC>generate e+ e- > z h, z > l+ l-`

  l+ = e+ mu+

- `MG5_aMC>generate e+ e- > z h, z > ta+ ta-, h > b b~`
- `MG5_aMC>generate e+ e- > z h, (z > ta+ ta-, ta+ > j j vl~, ta- > l- vl vl~),h > b b~`

  j = g u c d s u~ c~ d~ s~

- `MG5_aMC>generate e+ e- > z h, (z > ta+ ta-, ta+ > j j vl~, (ta- > mu- vt vm~, mu- > all all all)),h > b b~`

Want tau to decay to pions? `add model taudecay_UFO`

Alternative ways to perform the decays

- Use MadSpin `MG5_aMC>generate e+ e- > z h`

```
The following switches determine which programs are run:
/================ Description =================|=========== values ===========|
| 1. Choose the shower/hadronization program   |   shower = Not Avail.        |
| 2. Choose the detector simulation program    | detector = Not Avail.        |
| 3. Choose an analysis package (plot/convert) | analysis = Not Avail.        |
| 4. Decay onshell particles                   |  madspin = ON                |
| 5. Add weights to events for new hypp.       | reweight = OFF               |
\=============================================================================
```

- ```
  >decay h > b b~
  >decay z > ta+ ta-
  >decay ta+ > all all all
  >decay ta- > all all all
  ```

  Only include the decay channels that kinematically accessible!

- Output to Pythia, let Pythia do the decays

  The decays are always in isotropic way
  ```

More on the decays

- Using narrow width approximation
  - `MG5_aMC>generate e+ e- > z h, z > l+ l-`
  - `MG5_aMC>generate e+ e- > z h` then use MadSpin
    `>decay z > l+ l-`

    Only includes on-shell contributions

- Not using narrow width approximation
  `MG5_aMC>generate e+ e- > l+ l- h`

  Include non-resonant contributions

More on the decays

- What is the "`bwcutoff` " in run_card? Defines what means on-shell.
  Breit-Wigner
  - A resonate is considered to be on-shell if the invariant mass is within [mass - `bwcutoff`*width, mass + `bwcutoff`*width].
  - Affects the cross section of the decay process (ab > cd, c > ef …)
    `bwcutoff` ↑ ⇒ cross section ↑; `bwcutoff` ↓ ⇒ cross section ↓
- How to set the decay width (for BSM particles) in param_card?
  Use "`auto`" when possible.

Exercise 2

- Import the dark photon model then generate Compton-like process $\gamma e^- \to A' e^- \to (e^+ e^-) e^-$ for a fixed-target photon-beam experiment with $E_\gamma = $ 100 MeV. A' is the dark photon and we set its mass to be 5 MeV. Its coupling to the electrons is $g_V = 10^{-3}$.
- Q1: How to generate a process if we only want on-shell A'?
- Q2: How to generate a process if we want both on-shell and off-shell A'? (also without SM background.)
- Q3: How to generate a process if we only want off-shell A'? (also without SM background.)

Play with the simulated events

- The resulting events can be found inside `/newprocess/Events/run_xx/unweighted_events.lhe.gz`
- It is a zipped LHE file
- Unzip
- Open
- It contains: proc_card, run_card, param_card, number of events, cross section, an event list

all the events have the same probability of occurrence

Events in Les Houches Accord (LHE)

PDG code

QUARKS		LEPTONS		GAUGE AND HIGGS BOSONS	
d	1	e^-	11	g	(9) 21
u	2	ν_e	12	γ	22
s	3	μ^-	13	Z^0	23
c	4	ν_μ	14	W^+	24
b	5	τ^-	15	h^0/H_1^0	25
t	6	ν_τ	16		

```
<MGGenerationInfo>
#  Number of Events         :       10000
#  Integrated weight (pb)   :       50865039.465
</MGGenerationInfo>
</header>
<init>
-11 11 5.500000e+00 5.500000e+00 0 0 247000 247000 -4 1
5.086504e+07 8.539401e+04 5.086504e+07 1
<generator name='MadGraph5_aMC@NLO' version='2.9.2'>please cite 1405.0301 </generator>
</init>
<event>
 4      1 +5.0865039e+07 5.50000000e+00 7.57575800e-03 2.06766100e-01
       -11 -1    0    0    0    0 +0.0000000000e+00 +0.0000000000e+00 +5.4999999763e+00 5.5000000000e+00 5.1100000000e-04 0.0000e+00 1.0000e+00
        11 -1    0    0    0    0 -0.0000000000e+00 -0.0000000000e+00 -5.4999999763e+00 5.5000000000e+00 5.1100000000e-04 0.0000e+00 1.0000e+00
       -11  1    1    2    0    0 +1.6106200894e-01 +4.0548438748e-02 +5.4974916637e+00 5.5000000000e+00 5.1100000000e-04 0.0000e+00 1.0000e+00
        11  1    1    2    0    0 -1.6106200894e-01 -4.0548438748e-02 -5.4974916637e+00 5.5000000000e+00 5.1100000000e-04 0.0000e+00 1.0000e+00
</event>
```

initialization

cross section [pb]

beam ID beam energy [GeV]

statistical error on cross section [pb]

an event

proc ID scale [GeV] α α_s

# of particles

PDG code | parents | color flow | p_1 [GeV] | p_2 [GeV] | p_3 [GeV] | p_4 [GeV] | mass [GeV] | distance traveled [mm] | helicity

Status: -1 incoming, 1 outgoing, 2 intermediate

Time to open Jupyter notebook

- copy your *.lhe.gz/*.lhe file to the Jupyter notebook folder

Exercise 3

taken from Tanedo's tutorial

- The forward-backward symmetry is defined by

$$A_{FB} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)},$$

where is the scattering angle of one of the outgoing fermions in the center-of-mass frame. It measures the net fraction of events move in the forward direction.

Now consider the SM process $e^+e^- \to e^+e^-$ at LEP. How does A_{FB} changes with respect to the central energy?

(scan over $\sqrt{s} = [60,70,80,85,90,95,100,110,120]$ GeV)

Add a form factor

- For fixed-target collisions with nuclei, interactions take place inside the nuclei environment rather than the vacuum environment. This difference is taken account by the form factor.
- In many case, the form factor can be viewed as dressing a vertex with some functions, which usually have some momentum-dependence.
- How to add the form factor?

The Universal FeynRules Output (UFO) models

- Degrande et al (2012)
- `__init__.py`, `object_library.py`, `function_library.py`, `write_param_card.py`
- `particles.py`, `parameters.py`, `vertices.py`, `lorentz.py`, `couplings.py`, `coupling_orders.py`, `decays.py`, `propagators.py`, (`CT_parameters.py`, `CT_vertices.py`, `CT_couplings.py`)

$$V(a_1 \ldots a_n l_1 \ldots l_n; p_1 \ldots p_n) = \sum_{ij} C_i(a_1 \ldots a_n) G_{ij} L_j(l_1 \ldots l_n; p_1 \ldots p_n)$$

Vertex — Color factor — Couplings — Spin/Lorentz factor

Add a form factor

Example: add to $\log \frac{p_{W^+} \cdot p_{W^-}}{m_W^2}$ to the W^+W^-H vertex

1. Make a folder with name "`Fortran`" inside the UFO model folder and make a file with name "`function.f`" inside the `Fortran` folder
2. Define a COMPLEX function for the form factor inside `function.f`

```
double complex function FormFactor(S1)
double complex S1
include 'input.inc' ! include all model parameter
FormFactor = LOG(S1/MW**2)
return
end
```

Add a form factor

3. Open `vertices.py` inside the UFO model folder. Find the vertex you want to modify

```
V_2 = Vertex(name = 'V_2',
             particles = [ P.W__minus__, P.W__plus__, P.H ],
             color = [ '1' ],
             lorentz = [ L.VVS1, L.VVS2 ],
             couplings = {(0,0):C.GC_1,(0,1):C.GC_3})
```

$$V = C \cdot G \cdot L$$

Add a form factor

4. Open `lorentz.py` inside the UFO model folder and changes the Lorentz structure with the newly defined `FormFactor` function

$$\log \frac{p_{W^+} \cdot p_{W^-}}{m_W^2}$$

```
VVS1 = Lorentz(name = 'VVS1',
               spins = [ 3, 3, 1 ],
               structure ='FormFactor(P(-1,1)*P(-1,2))*Metric(1,2)')
```

-1: Einstein sum with the metric

momentum of particle 1 momentum of particle 2

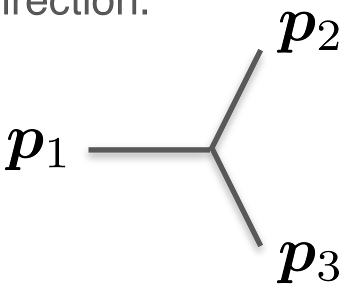
```
VVS2 = Lorentz(name = 'VVS2',
               spins = [ 3, 3, 1 ],
               structure ='FormFactor(P(-1,1)*P(-1,2))
*P(-1,1)*P(-1,2)*Metric(1,2)')
```

Add a form factor

5. `./bin/mg5_aMC` until `output` then pause
6. `cd /output_dir/Source/MODEL`, check if the form factor function is added to `model_function.f` and `model_functions.inc`. If not, add the function to the end of `model_function.f` and declaim it in `model_functions.inc`.
7. `cd /output_dir/Source/DHELAS`, check if the vertex contains the form factor.
8. `make clean; make all`
9. launch the simulation

ABC of the UFO language

- Degrande et al (2012)
- Follows (+ - - -) metric
- In the UFO convention, all momenta are along the incoming direction.



$$p_1 + p_2 + p_3 = 0$$

Table 6: Elementary Lorentz structures

Charge conjugation matrix: $C_{i_1 i_2}$	`C(1,2)`
Epsilon matrix: $\epsilon^{\mu_1\mu_2\mu_3\mu_4}$	`Epsilon(1,2,3,4)`
Dirac matrices: $(\gamma^{\mu_1})_{i_2 i_3}$	`Gamma(1, 2, 3)`
Fifth Dirac matrix: $(\gamma^5)_{i_1 i_2}$	`Gamma5(1,2)`
(Spinorial) Kronecker delta: $\delta_{i_1 i_2}$	`Identity(1,2)`
Minkowski metric: $\eta_{\mu_1 \mu_2}$	`Metric(1,2)`
Momentum of the N^{th} particle: $p_N^{\mu_1}$	`P(1,N)`
Right-handed chiral projector: $\left(\frac{1+\gamma 5}{2}\right)_{i_1 i_2}$	`ProjP(1,2)`
Left-handed chiral projector $\left(\frac{1-\gamma 5}{2}\right)_{i_1 i_2}$	`ProjM(1,2)`
Sigma matrices: $(\sigma^{\mu_1\mu_2})_{i_3 i_4}$	`Sigma(1,2,3,4)`

Exercise 4

- In the DarkPhoton model, pretend the electron to be a nucleon and add the elastic G_2 form factor, Eq. (A18) of https://arxiv.org/abs/0906.0580, to the $\gamma N \bar{N}$ vertex. Re-generate the Compton-like process $\gamma N \to A' N$ and compare it to the same process without adding the form factor.
(set $E_\gamma = 10$ MeV and $m_{A'} = 50$ MeV)

Thank you