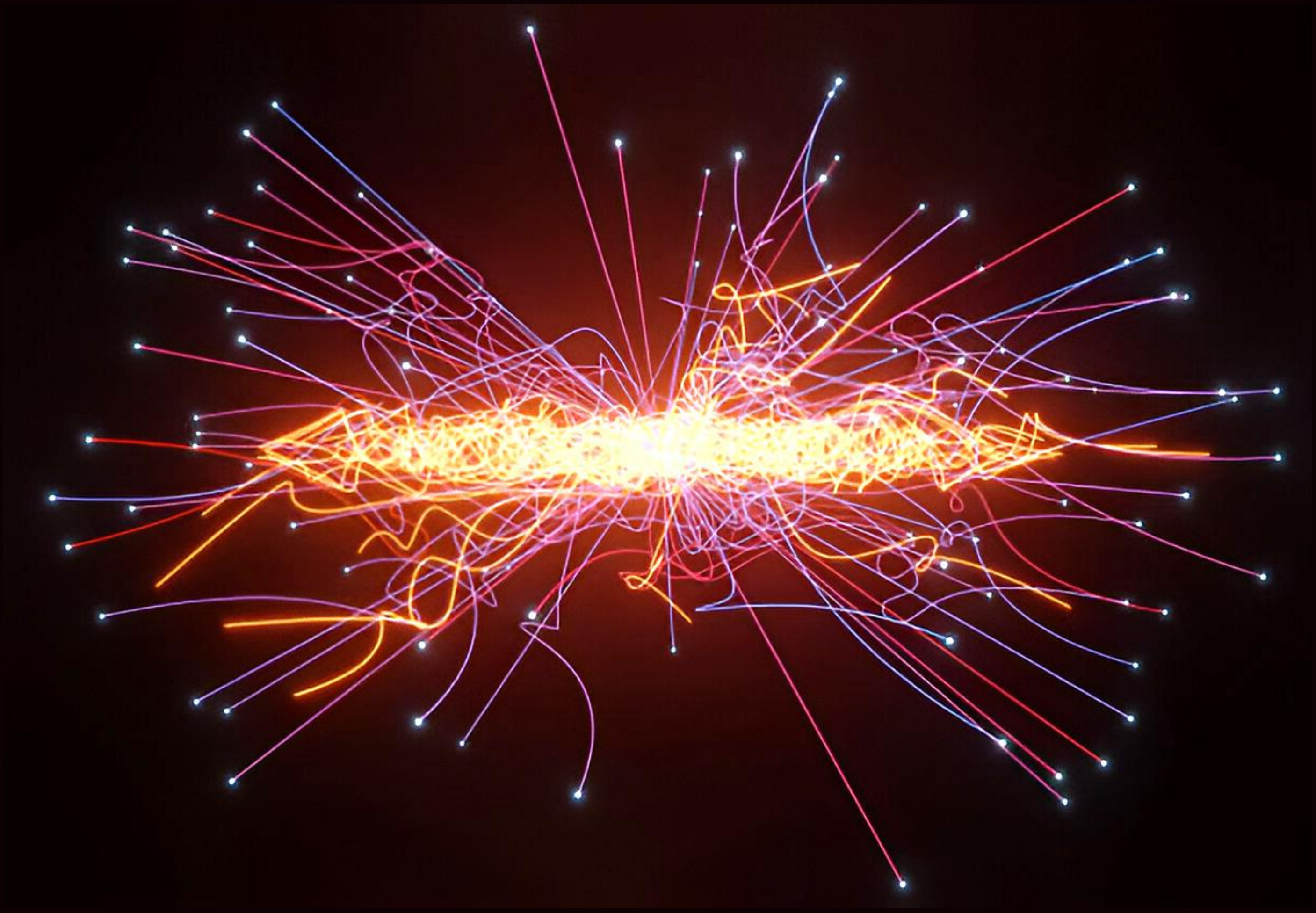
RE-INTERPRETATION OF SEARCHES FOR LONG LIVED PARTICLES

Supervised by GOUDELIS Andreas & CORPE Louie

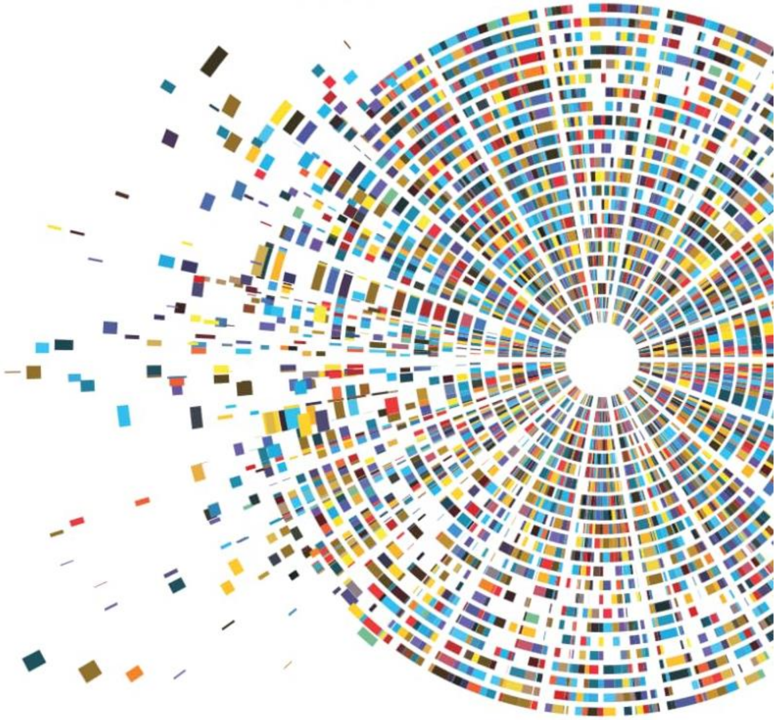
MILLOT Louise – Master's internship presentation- June, 19th 2024

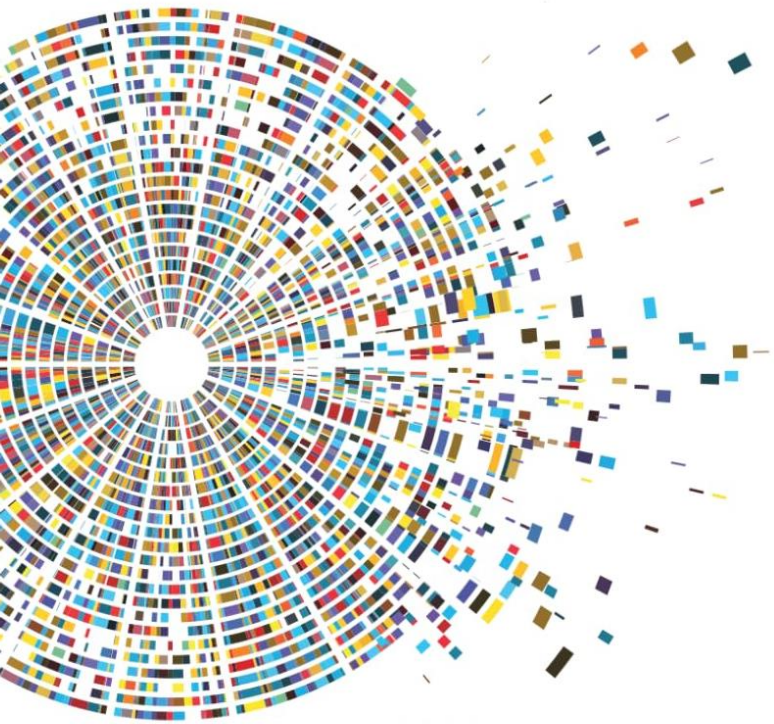


Overview of the internship

Re-interpretation of searches for long-lived particles (LLP)

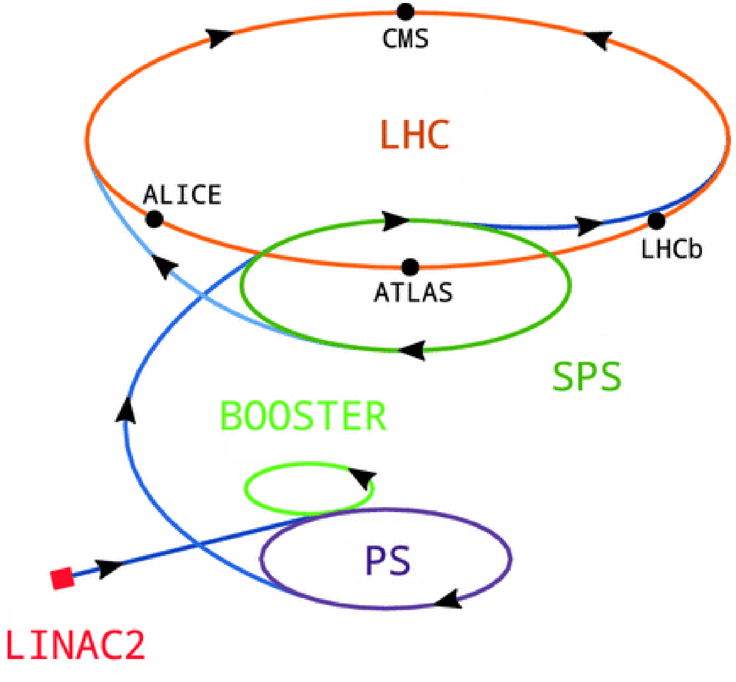
Contents:
- Elements of introduction, context
- Exploiting the ATLAS search: Closure tests
- Theory side: model used for LLP search in ATLAS
- Results obtained
- Perspectives & Conclusion





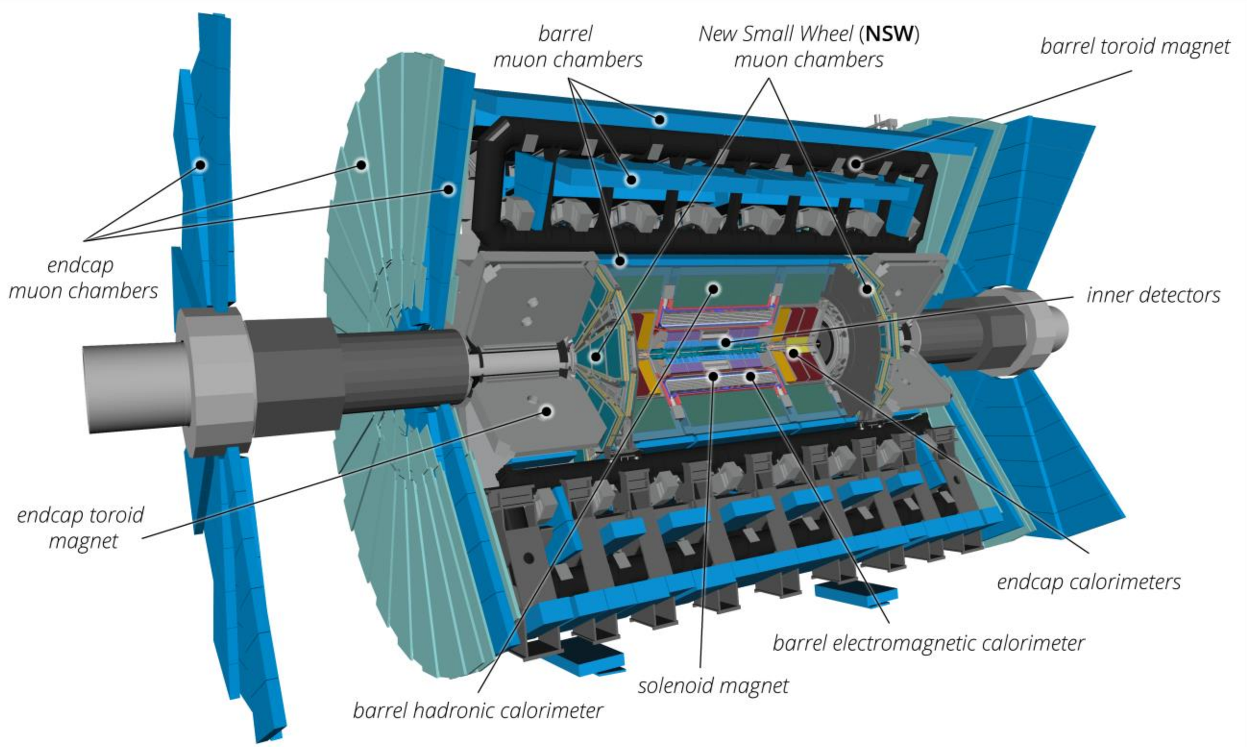
Elements of introduction

What is LHC (Large Hadron Collider) & ATLAS (A Toroidal LHC ApparatuS) collaboration ?



The pre-accelerator system, the collider and the main LHC experiments.

https://indico.cern.ch/event/797767/contributions/3682915/attachments/1965781/3268753/QEIC_SunilBansal.pdf

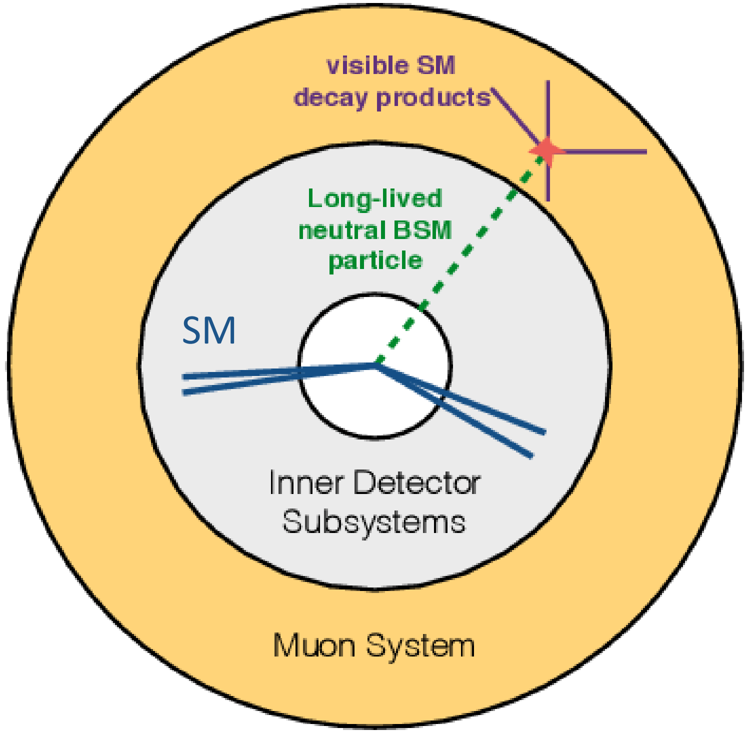


The inner structure of the ATLAS detector

https://arxiv.org/abs/2305.16623

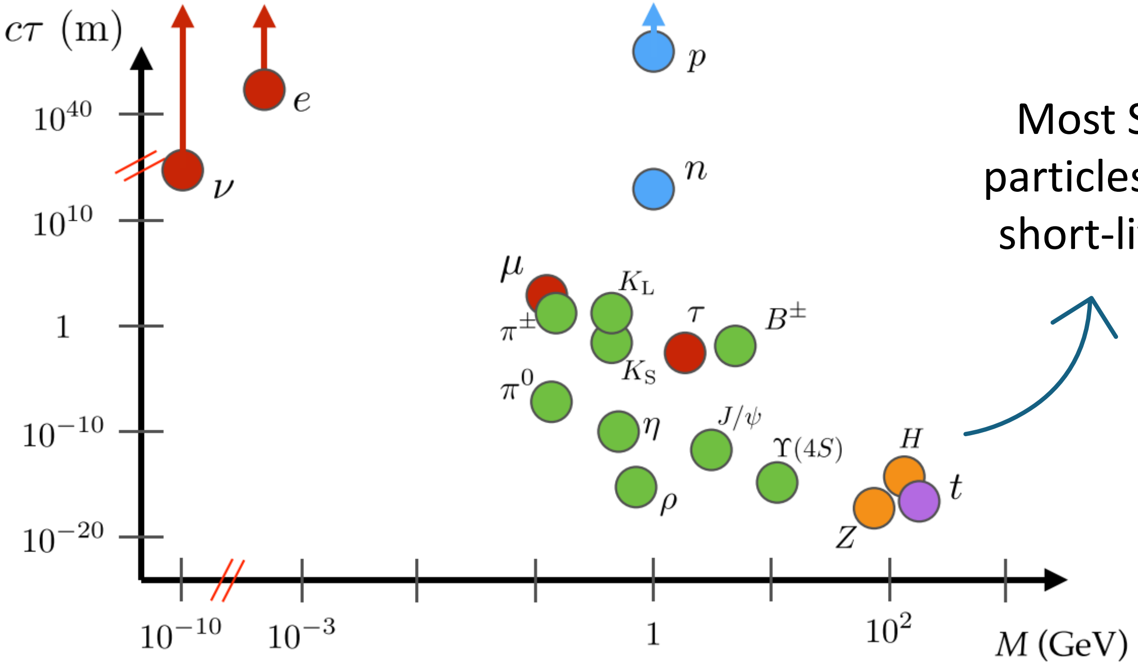
Reinterpretation of searches for **long-lived particles (LLPs)**

What is a LLP ? particle whose lifetime is long enough for its decay to be significantly distant from the interaction point.



Transverse view of a detector: LLP signal

https://api.semanticscholar.org/CorpusID:118829632



Most SM particles are short-lived

Decay length with respect to the mass of SM particles

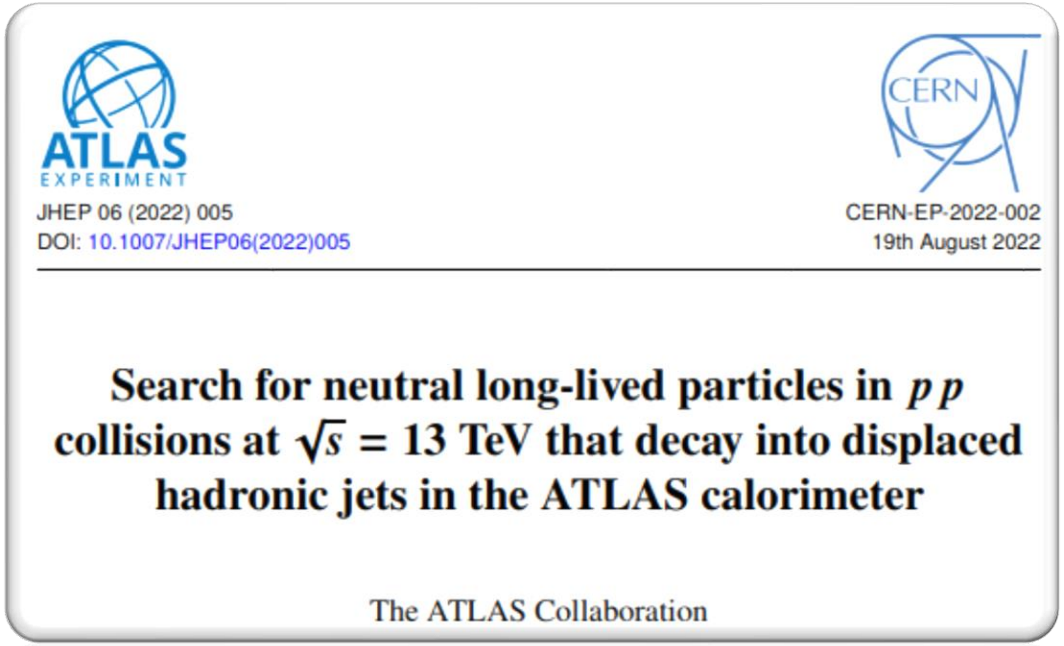
https://arxiv.org/abs/1903.04497

Reinterpretation of searches for **long-lived particles (LLPs)**

Motivations for LLP ?

Involved in BSM physics : appear in dark-matter models, M/A asymmetry, neutrinos masses…
Blind spot for ATLAS until recent years : many searches on LLPs

My work: re-use a search on LLP especially on 'displaced jets'
Why this search ? Re-interpretation



JHEP 06 (2022) 005
DOI: 10.1007/JHEP06(2022)005

CERN-EP-2022-002
19th August 2022

Search for neutral long-lived particles in pp collisions at $\sqrt{s}$ = 13 TeV that decay into displaced hadronic jets in the ATLAS calorimeter

The ATLAS Collaboration

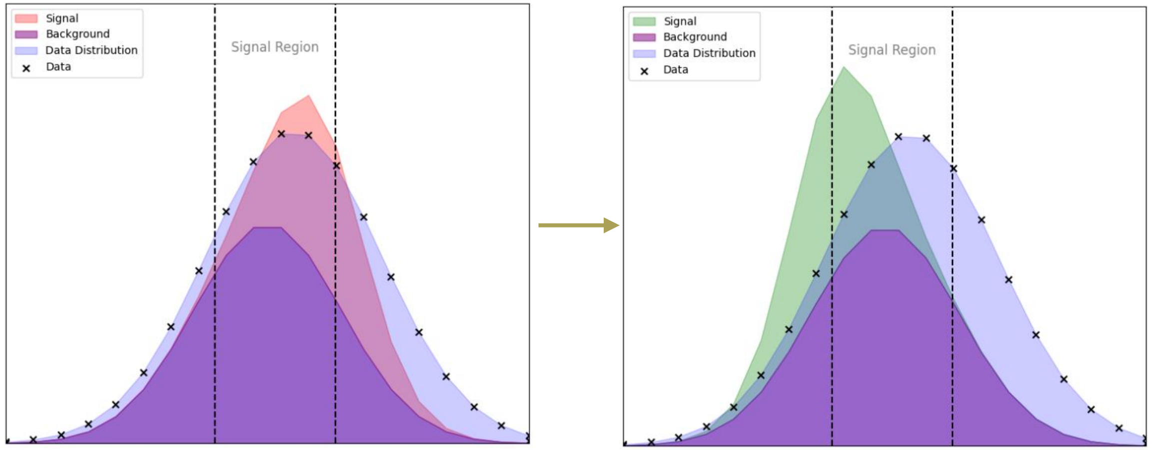
arxiv.org/pdf/2203.01009

Reinterpretation of searches for long-lived particles (LLP)

Context: Monte Carlo Event Generator + time-consuming analysis

Problem: Extract the constraints on a new model ? Create another model ? time-consuming analysis

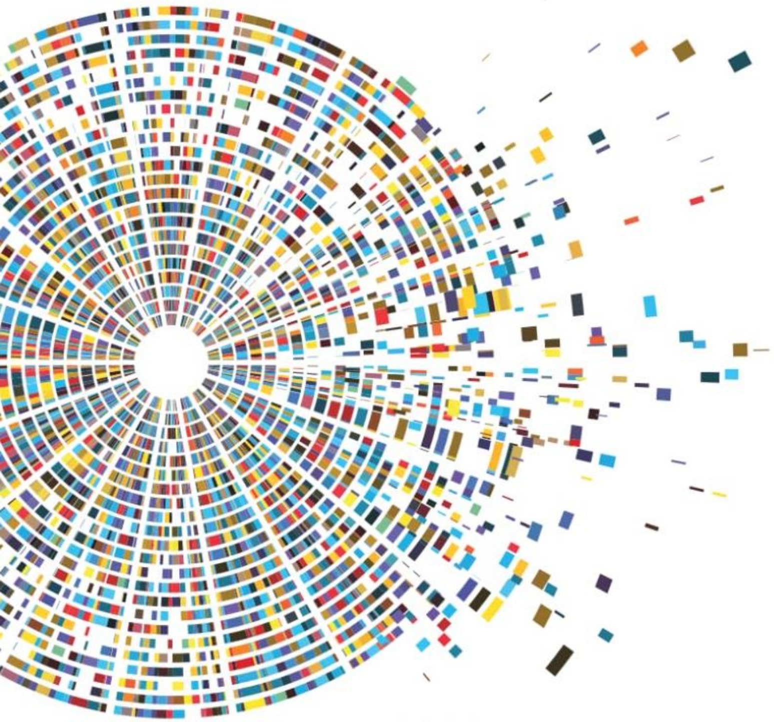
Solution : Find a re-interpretation tool. Using existing published results, (ATLAS, CMS, or LHCb) to test a model that was not considered in the original study « recycling » data



Straightforward? Not for external users

How? Analysis preservation -> publish methods to estimate signal efficiencies, allowing statistical analysis
Otherwise : analysis remains a single-use result

Why?: It is impossible to test all the models during the lifetime of the LHC.
Performing single-use searches is an unbearable waste of human (and financial) resources.
If PhD student involved into an analysis -> spend all his time on it



Exploiting the ATLAS search: Closure tests

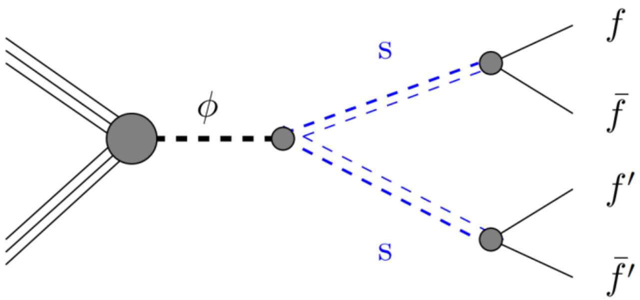
Steps of the analysis using re-interpretation tool: efficiency map

INPUT **:**

m_Φ

m_s

Nb_events



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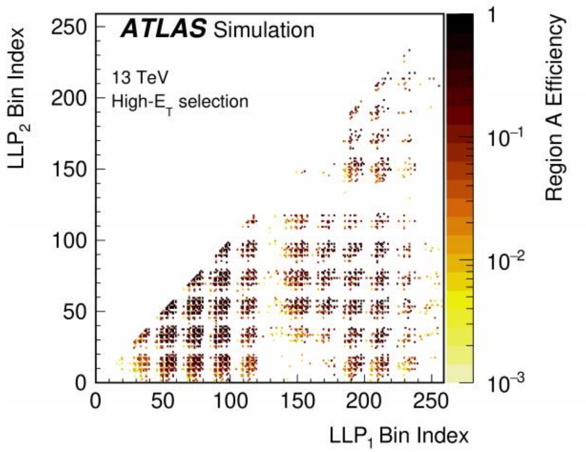
Entire analysis :

- Depends on the model (single use)
- Time consuming

Decay used as a benchmark model = $\Phi \rightarrow ss \ \rightarrow f\bar{f}f'\bar{f}'$

Events generated by MCEG : **`MadGraph5_aMC@NLO`**
`+PYTHIA8 (hadronisation)`

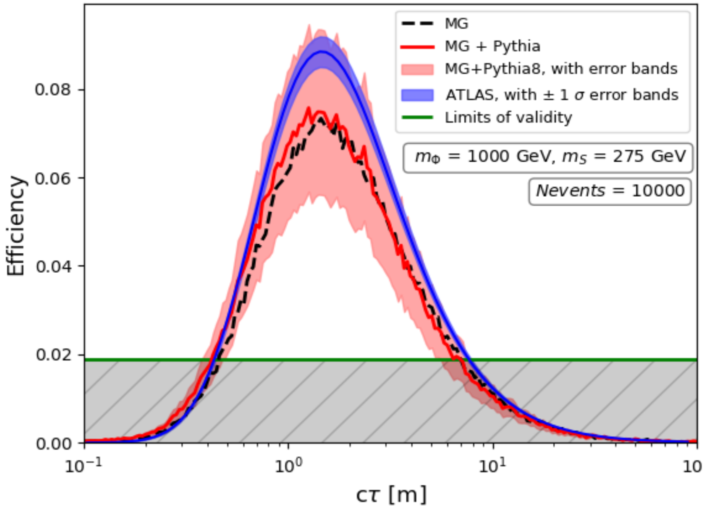
2

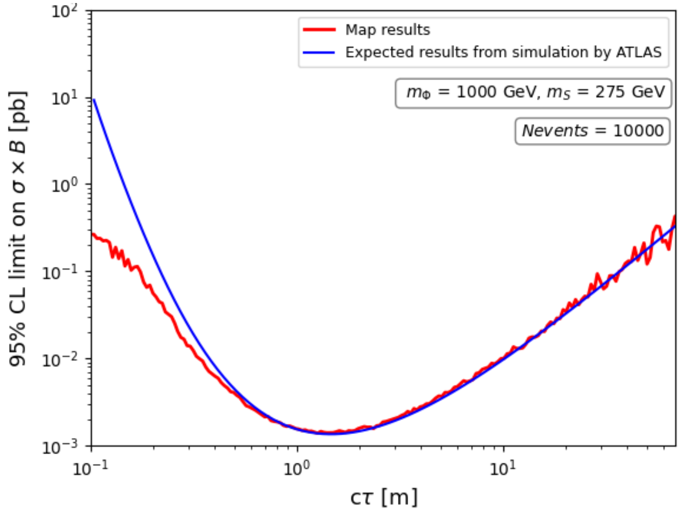


Efficiency map:

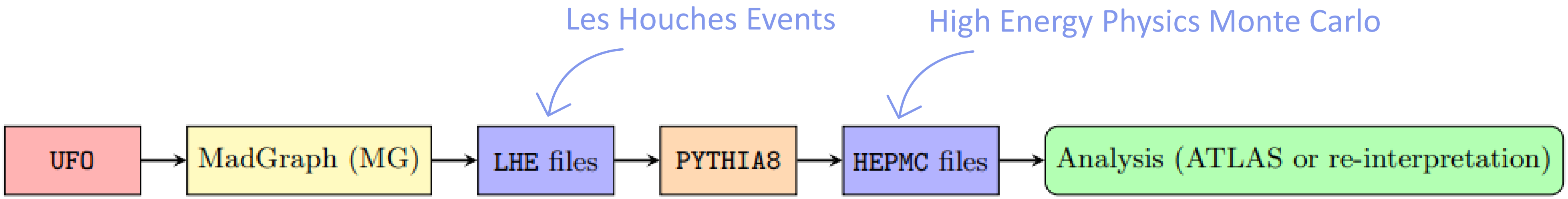
No matter what is the model (re-usable)

- Efficiency results + constraints on the model





How is done event generation ?



Symbol	Description
🟥	Output from `FeynRules`
🟨	Event generation
🟧	Hadronization
🟦	Output files
🟩	Analysis work

Flowchart from `FeynRules` `UFO` files to analysis work

Samples generated with MG

	m_ϕ in GeV	m_s in GeV	Nb events
Other benchmarks	200	100	5000
	200	100	15000
ATLAS	125	55	10000
	200	50	10000
	400	100	10000
	600	150	10000
	1000	275	10000

Structure of the efficiency map

Efficiency map: links **truth-level information** about the LLP → **detector response** and **selection probability**

divided into multiple bins.

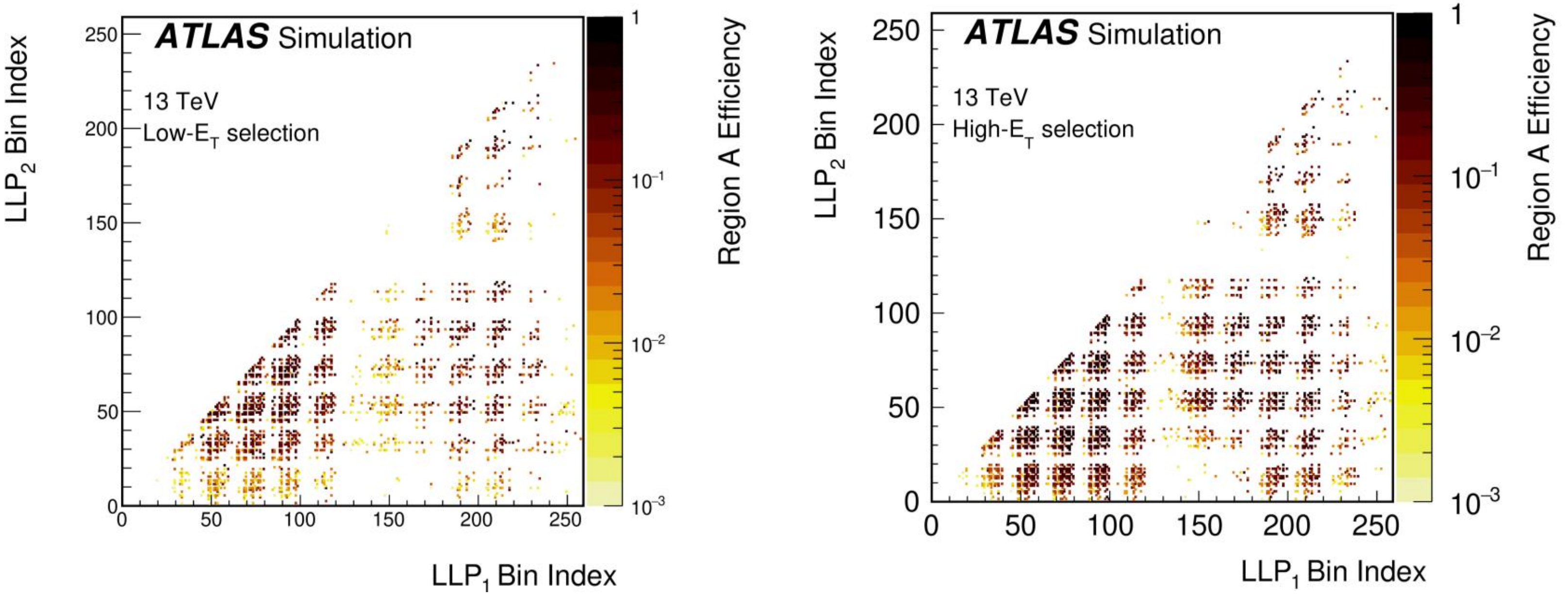
Bin Index :

p_T : $[0, 50, 100, 200, 400, 1600]$ GeV

L_{xy} : $[0, 1.5, 2, 2.5, 3, 3.5, 3.9, \infty]$ m

L_z : $[0, 3.6, 4.2, 4.8, 5.5, 6, \ \infty]$ m

$decay\ modes : [c, b, t, \tau]$



Bin ouput: **probability** of an event being selected (in a specific region) for a pair of LLPs

The sum of the output across a sample $\sim$ total number of events passing the selection

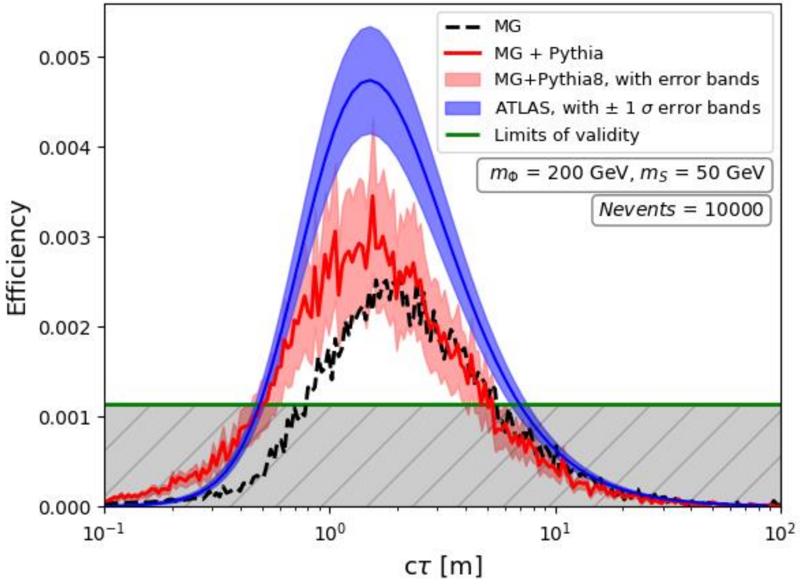
$$\longrightarrow \quad Efficiency = \frac{sum\ of\ selection\ probabilities\ of\ the\ events}{Nb\ events}$$

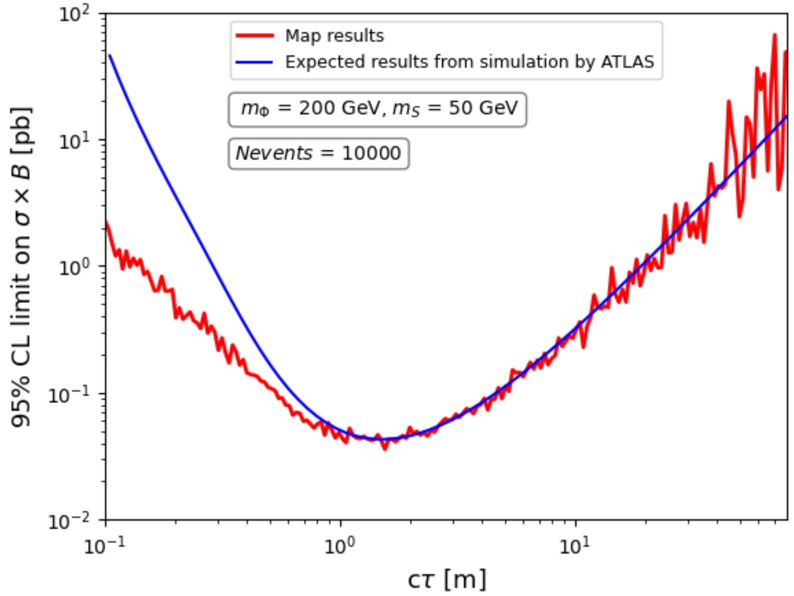
Closure tests

Efficiency results

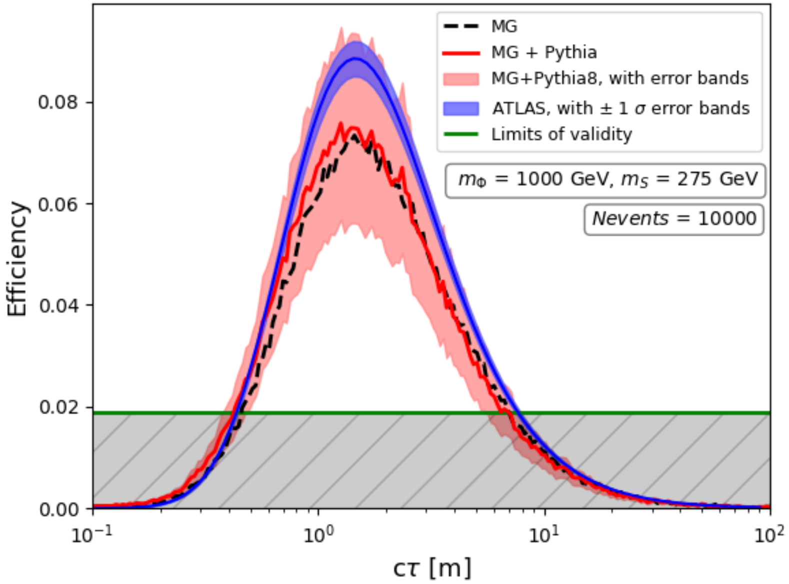
Cross section limits

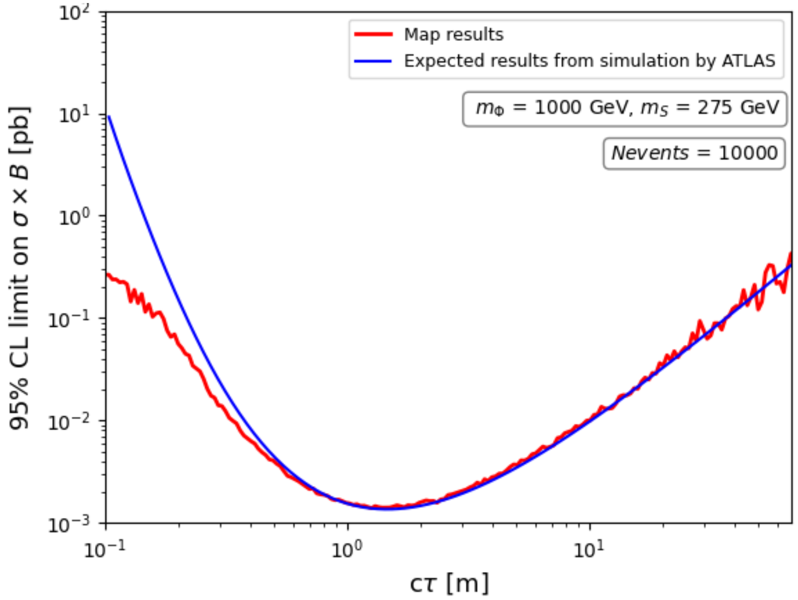
Low-E_T

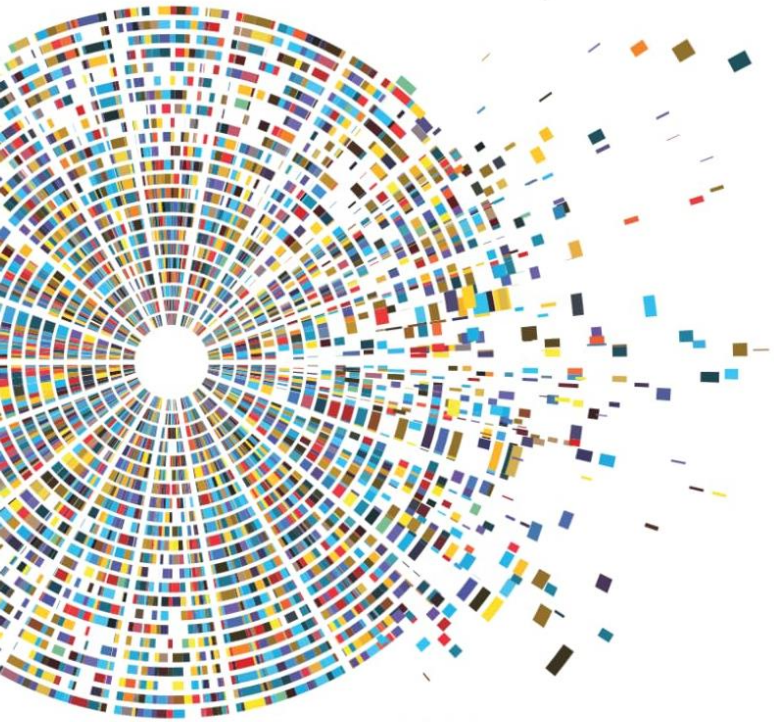




High-E_T



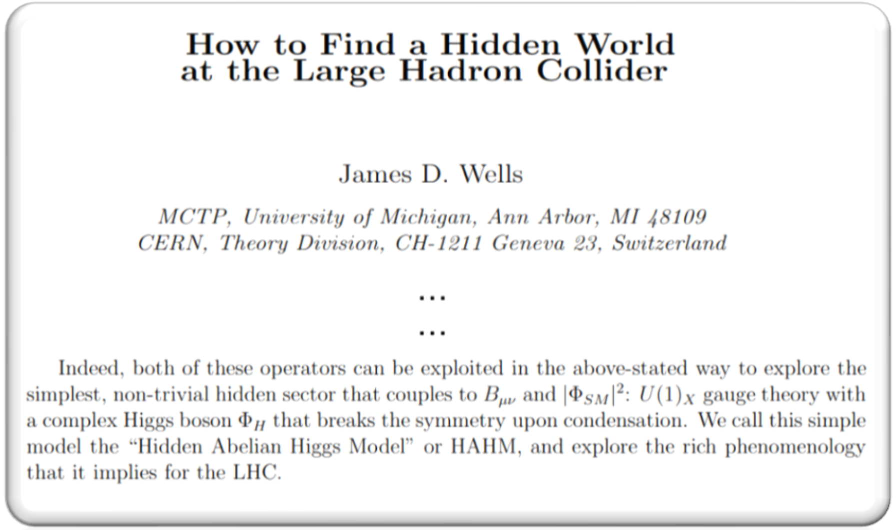




Theory side

The Hidden Abelian Higgs model (HAHM)

Extension of the SM : HAHM



How to Find a Hidden World at the Large Hadron Collider

James D. Wells

MCTP, University of Michigan, Ann Arbor, MI 48109
CERN, Theory Division, CH-1211 Geneva 23, Switzerland

…
…

Indeed, both of these operators can be exploited in the above-stated way to explore the simplest, non-trivial hidden sector that couples to $B_{\mu\nu}$ and $|\Phi_{SM}|^2$: $U(1)_X$ gauge theory with a complex Higgs boson Φ_H that breaks the symmetry upon condensation. We call this simple model the "Hidden Abelian Higgs Model" or HAHM, and explore the rich phenomenology that it implies for the LHC.

arXiv:0803.1243

Add an extra $U(1)$ group:

- introduces new associated gauge boson: $Z\,'$
- requires a new complex singlet scalar field $\boldsymbol{\Phi}_H$ to break the extra symmetry
- Two scalar fields: $\boldsymbol{\Phi}_{SM} = \begin{pmatrix} 0 \\ \frac{v+\phi_{SM}}{\sqrt{2}} \end{pmatrix}$, $\boldsymbol{\Phi}_H = \left(\frac{\xi+\phi_H}{\sqrt{2}}\right)$

The Lagrangian in the Higgs sector:

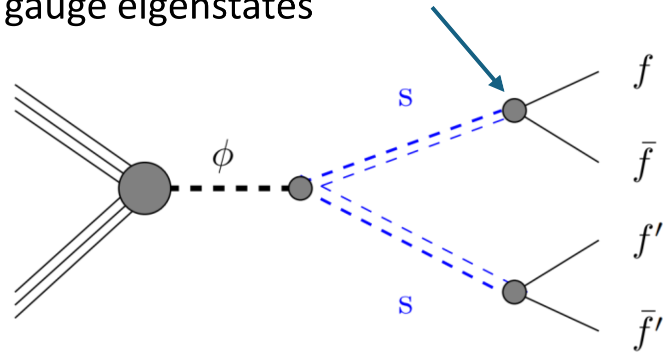
$$\mathcal{L}_{Higgs} = \left|D_\mu \boldsymbol{\Phi}_{SM}\right|^2 + \left|D_\mu \boldsymbol{\Phi}_H\right|^2 + m^2_{\boldsymbol{\Phi}SM}|\boldsymbol{\Phi}_{SM}|^2 + m^2_{\boldsymbol{\Phi}H}|\boldsymbol{\Phi}_H|^2 - \lambda|\boldsymbol{\Phi}_{SM}|^4 - \rho|\boldsymbol{\Phi}_H|^4 - \kappa|\boldsymbol{\Phi}_{SM}|^2|\boldsymbol{\Phi}_H|^2$$

Mixing after symmetry breaking:

$$\begin{pmatrix} \phi_{SM} \\ \phi_H \end{pmatrix} = \begin{pmatrix} cos\theta_h & sin\theta_h \\ -sin\theta_h & cos\theta_h \end{pmatrix} \begin{pmatrix} \phi \\ s \end{pmatrix}$$

gauge eigenstates

mass eigenstates



Through the mixing between ϕ_{SM} and ϕ_H, the LLPs interact with SM fermions in a Yukawa-like manner

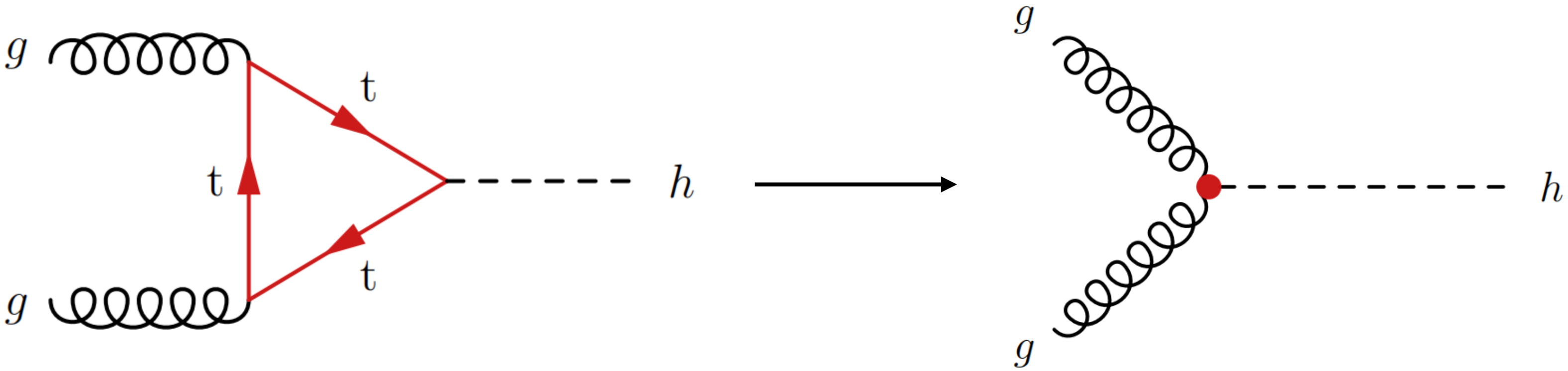
Implementation of the HAHM for experimental physics

The HAHM has been encoded in the `Universal FeynRules Output` (`UFO`) format by David Curtin

`FeynRules` is a `Mathematica®` package -> the calculation of Feynman rules for any QFT physics model.

- ➢ requires modifications to build a fully self-consistent MadGraph model using `FeynRules2.3`

→ effective field theory (EFT): gluon fusion induced mediator production. The process that generates the SM Higgs via the **top loop** is reduced to an **effective operator**.



Simplified version of the HAHM

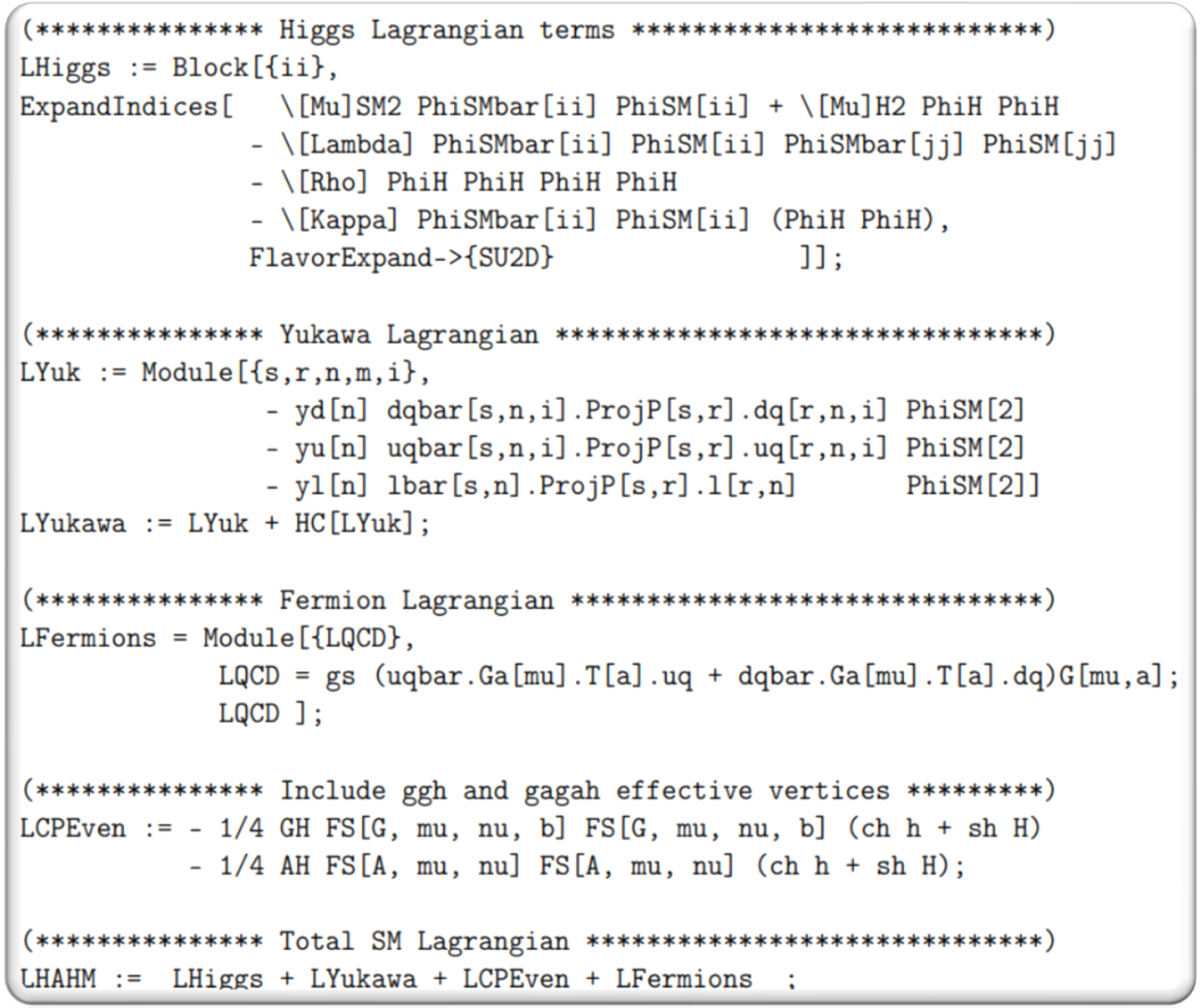
- contains ingredients which are irrelevant for the displaced jet searches

Simplified version:

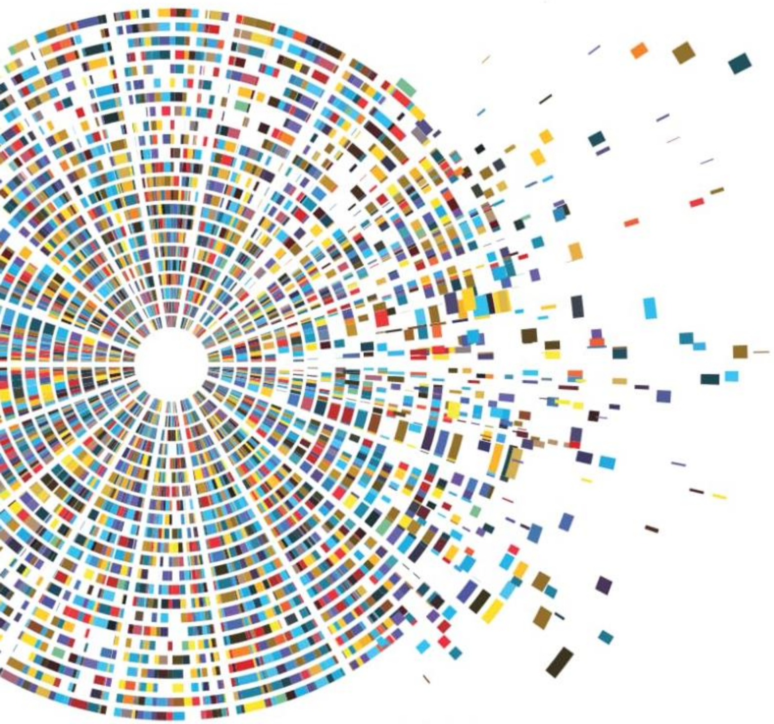
- keeping what was necessary for my study (scalar part instead of the gauge part)
- Some parameters of the initial model are linked to the gauge part -> Z'
- Rethink the way I was addressing these parameters

- **Why ?** More user-friendly model

Implemented in FeynRules:



```
(*************** Higgs Lagrangian terms ***************************)
LHiggs  := Block[{ii},
ExpandIndices[   \[Mu]SM2 PhiSMbar[ii] PhiSM[ii] + \[Mu]H2 PhiH PhiH
               - \[Lambda] PhiSMbar[ii] PhiSM[ii] PhiSMbar[jj] PhiSM[jj]
               - \[Rho] PhiH PhiH PhiH PhiH
               - \[Kappa] PhiSMbar[ii] PhiSM[ii] (PhiH PhiH),
               FlavorExpand->{SU2D}                ]];

(*************** Yukawa Lagrangian ********************************)
LYuk  := Module[{s,r,n,m,i},
                - yd[n] dqbar[s,n,i].ProjP[s,r].dq[r,n,i] PhiSM[2]
                - yu[n] uqbar[s,n,i].ProjP[s,r].uq[r,n,i] PhiSM[2]
                - yl[n] lbar[s,n].ProjP[s,r].l[r,n]       PhiSM[2]]
LYukawa := LYuk + HC[LYuk];

(*************** Fermion Lagrangian ******************************)
LFermions = Module[{LQCD},
             LQCD = gs (uqbar.Ga[mu].T[a].uq + dqbar.Ga[mu].T[a].dq)G[mu,a];
             LQCD ];

(*************** Include ggh and gagah effective vertices *********)
LCPEven := - 1/4 GH FS[G, mu, nu, b] FS[G, mu, nu, b] (ch h + sh H)
           - 1/4 AH FS[A, mu, nu] FS[A, mu, nu] (ch h + sh H);

(*************** Total SM Lagrangian ******************************)
LHAHM  :=  LHiggs + LYukawa + LCPEven + LFermions  ;
```



Results

Validation of the simplified model using the map

- Same mass but different number of events

$m_\phi = 200\text{ GeV}$
$m_s = 100\text{ GeV}$
$Nb_{events} = 5000, 15000$

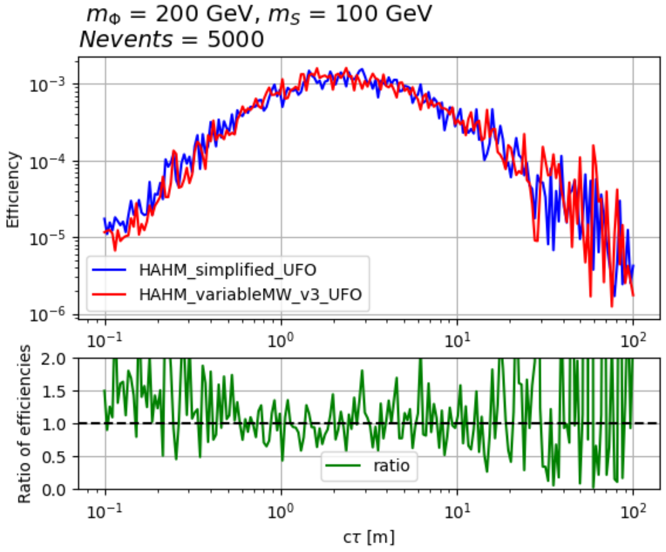
- ➢ Ratio ~ 1 : this indicates a good agreement between the two models.
- ➢ Less oscillation for a high Nb_{events}
- ➢ Studying efficiency results ~ cross section limits

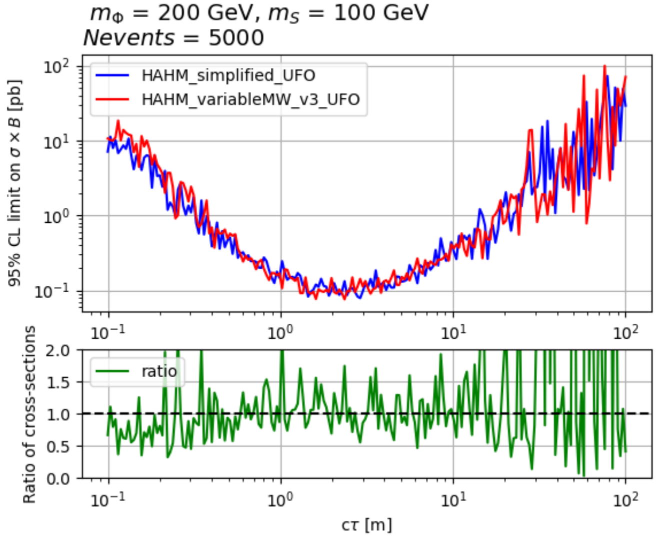
$Nb_{events} = 10000$
Only focusing on cross section limits

Efficiency results

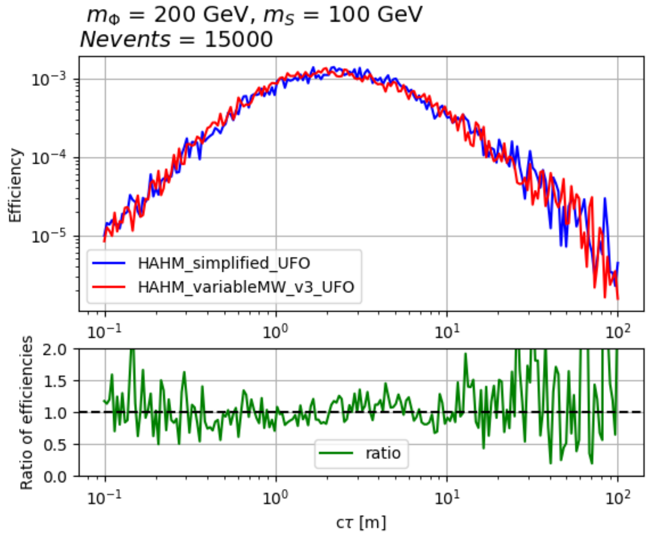
Cross section limits

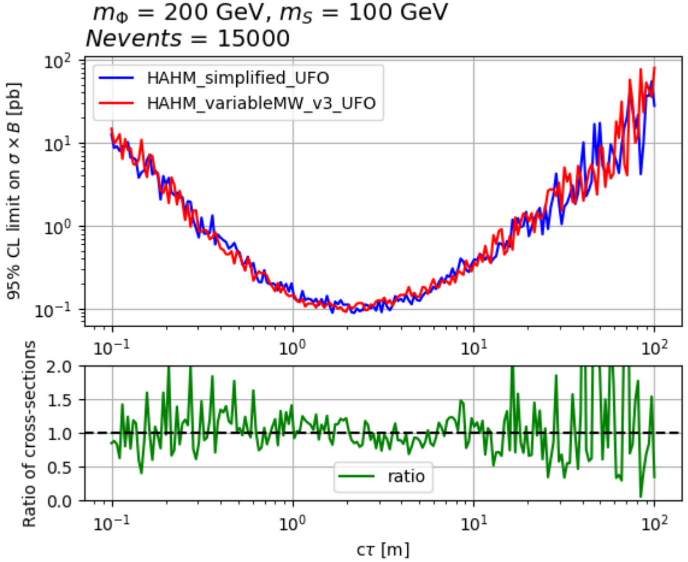
$Nb_{events} = 5000$





$Nb_{events} = 15000$



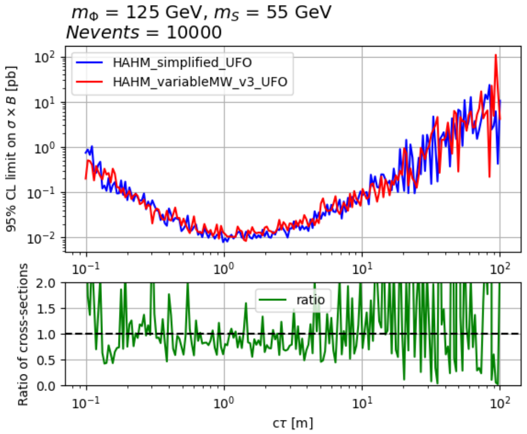


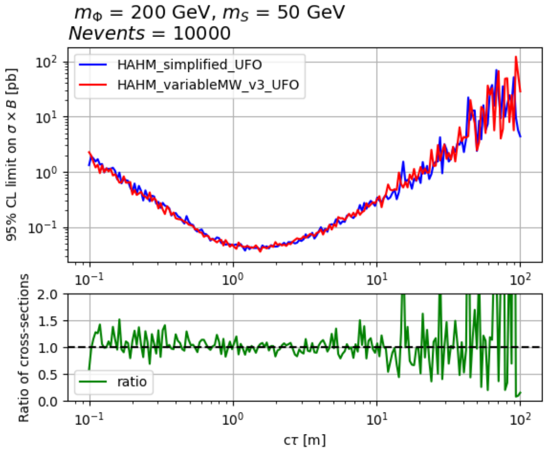
Validation of the simplified model using the map

- With the same masses used in the ATLAS article

Low-E_T

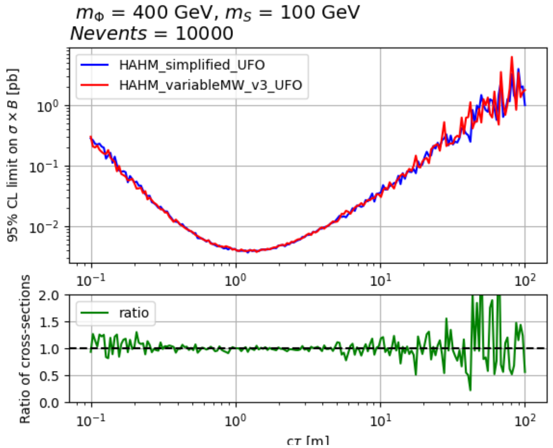
$m_{\Phi} = 125,200\ \mathrm{GeV};$
$m_s = 55,50\ \mathrm{GeV};$
$Nb_{events} = 10\ 000$

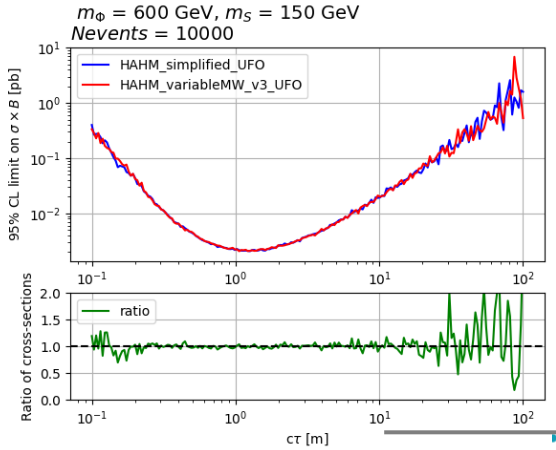


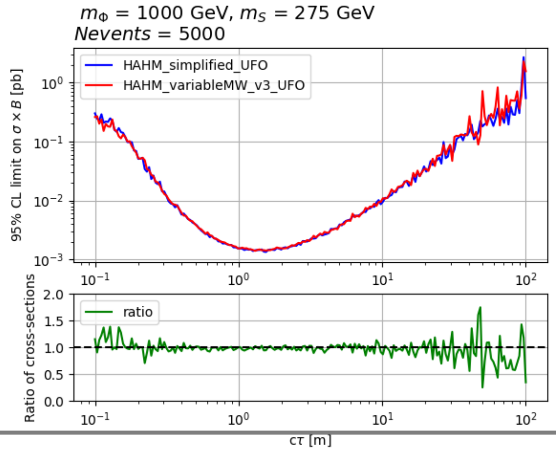


High-E_T

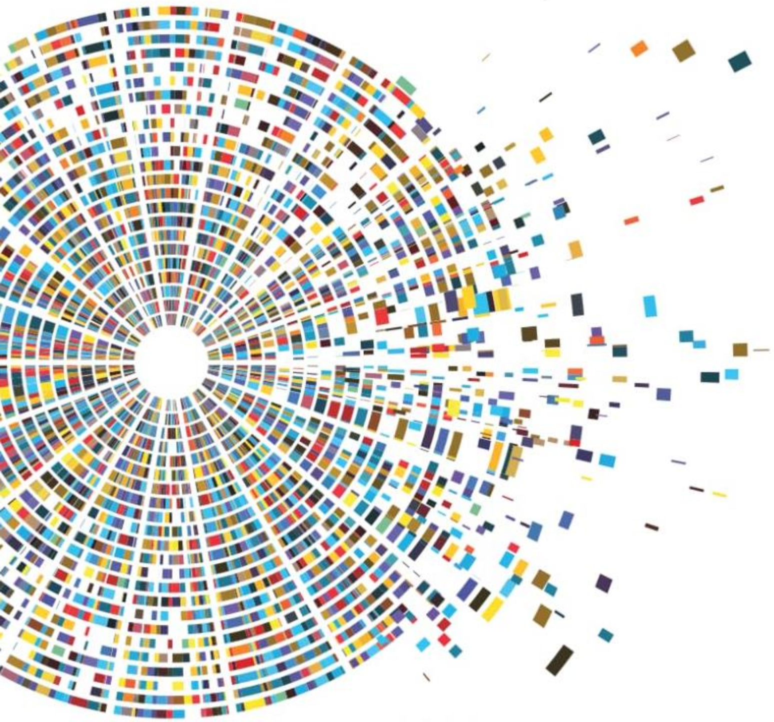
$m_{\Phi} = 400,600,1000\ \mathrm{GeV};$
$m_s = 100,150,275\ \mathrm{GeV};$
$Nb_{events} = 10\ 000, 5000$







- Ratio ~ 1
- Less oscillation for High-E_T
- Oscillations observed at low $c\tau$ and high $c\tau$: uncertainties on the map -> when low numbers of events are passing the selection, data become more sensitive to statistical fluctuations of the remaining events.

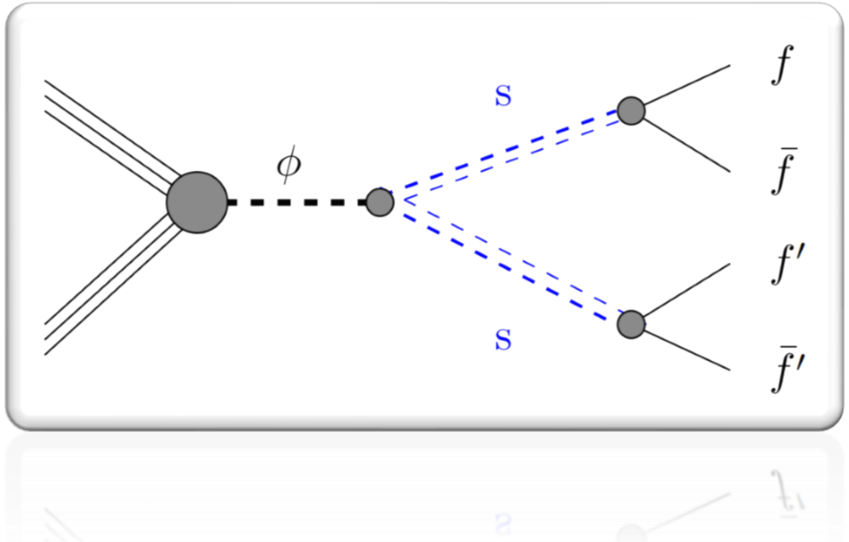


Perspectives & Conclusion

What remains to be done/ ongoing work

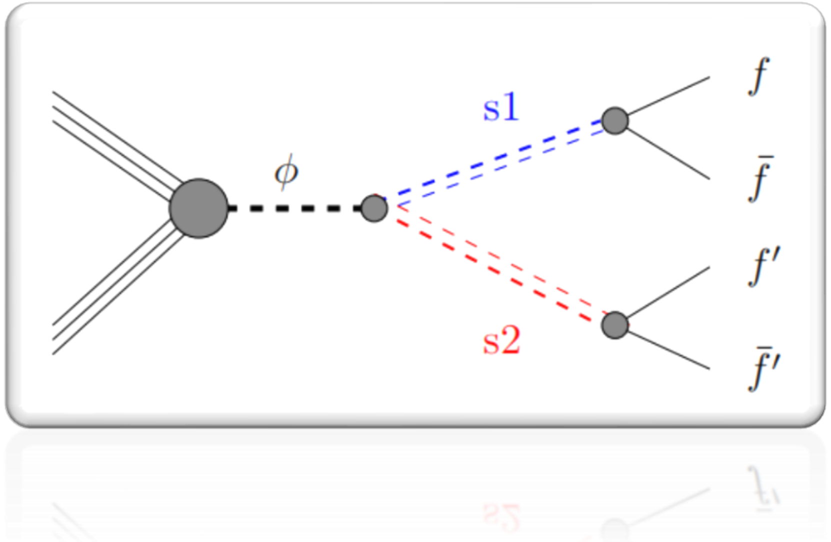
Symmetric model

$$\phi \rightarrow ss \ \rightarrow f\bar{f}f'\bar{f}'$$



Asymmetric model

$$\phi \rightarrow s1\ s2 \ \rightarrow f\bar{f}f'\bar{f}'$$



- ➢ A simplified model that can give rise to such an "asymmetric" decay is currently **under development**
- ➢ Goal: emphasize ease of use and easy incorporation in experimental analysis, rather than theoretical aspects

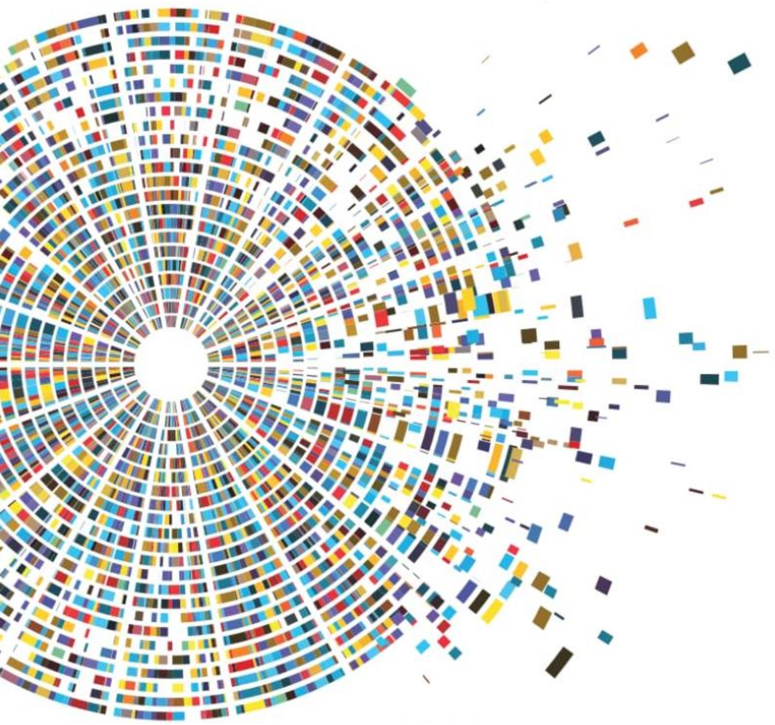
What are the constraints we obtained on the LLP from this displaced jet search that is performed by ATLAS ?

Conclusion

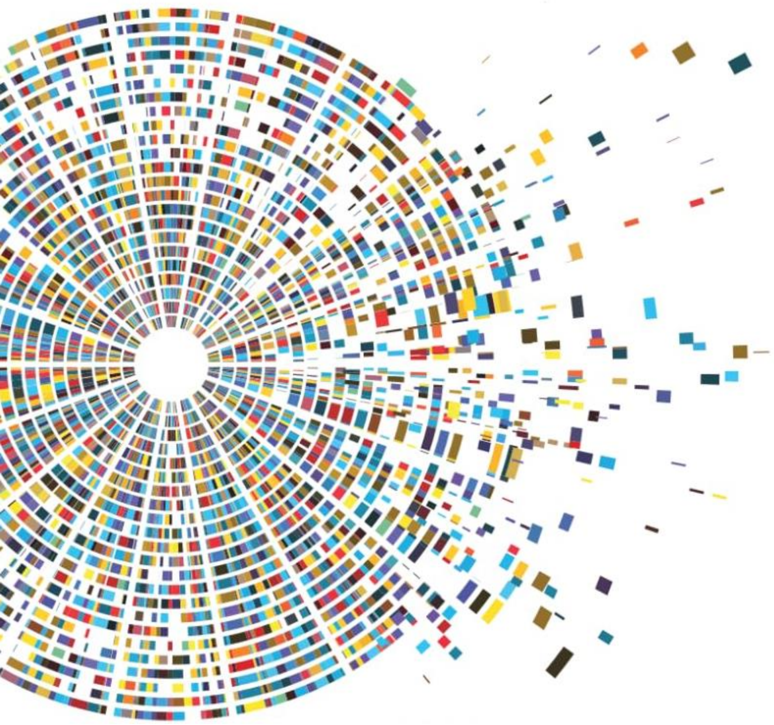
- The main objective : to understand and explore the **method of reinterpreting** experimental data in the field of particle physics.
  - ⇨ Focusing on the **validation and analysis of results** obtained from previous simulations and research
  - ⇨ Using **tools** such as Monte Carlo Event Generators & `FeynRules`

- Focused on the implementation of the **HAHM** in the context of particle physics and on the comparison between a **simplified version** of the model and the original version used by the ATLAS experiment.
  - ⇨ The aim was to understand and analyse the **experimental constraints** associated on the HAHM model, focusing on the **production of LLP through a scalar mediator**.

- The prospects for the rest of the internship involve the development of a **new ‘asymmetric’** model.
  - ⇨ Building the model **from scratch** and imposing the relevant experimental constraints.
  - ⇨ Both **theoretical & experimental aspects**: from model development to statistical analysis.

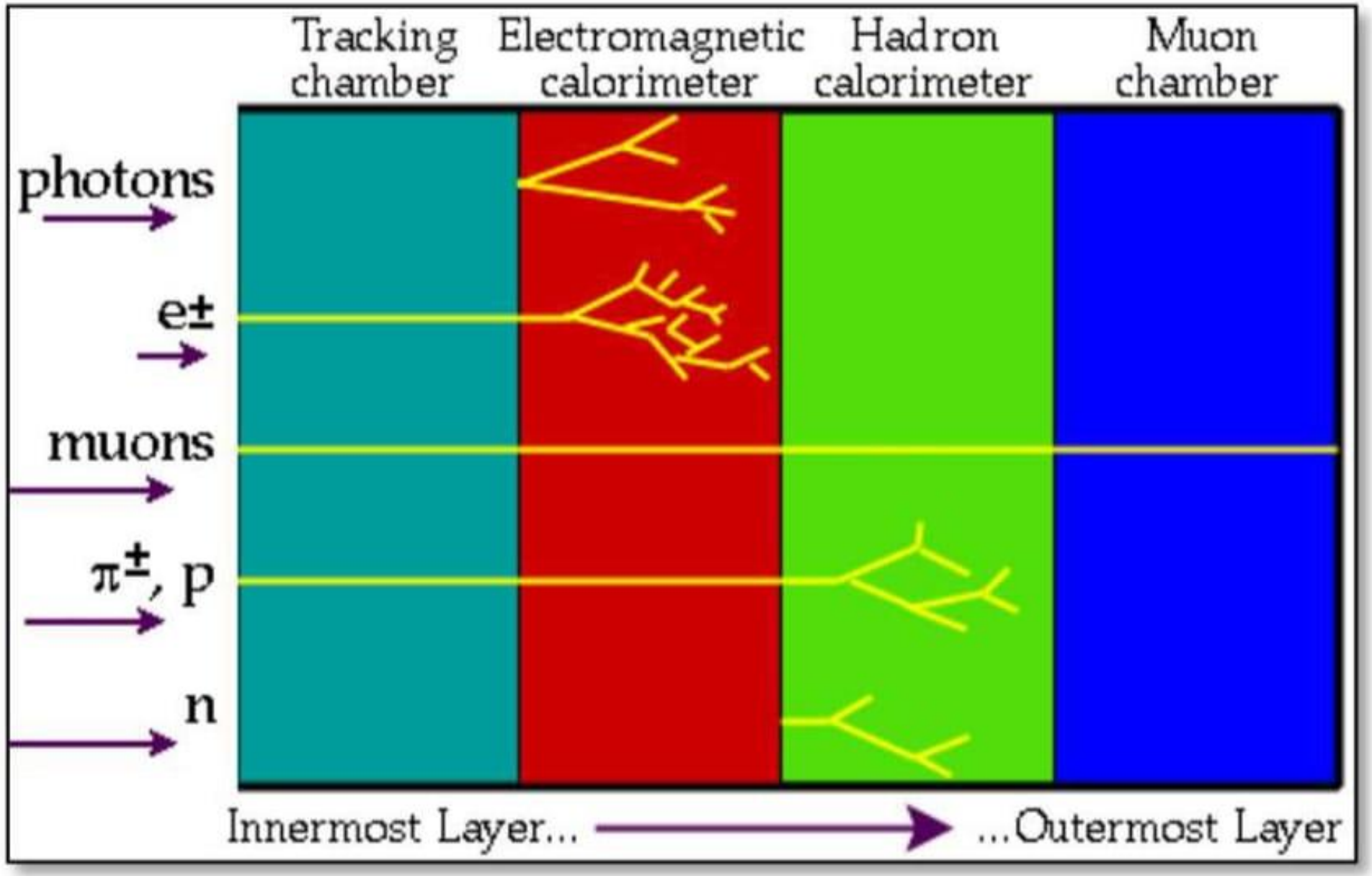


Thank you !

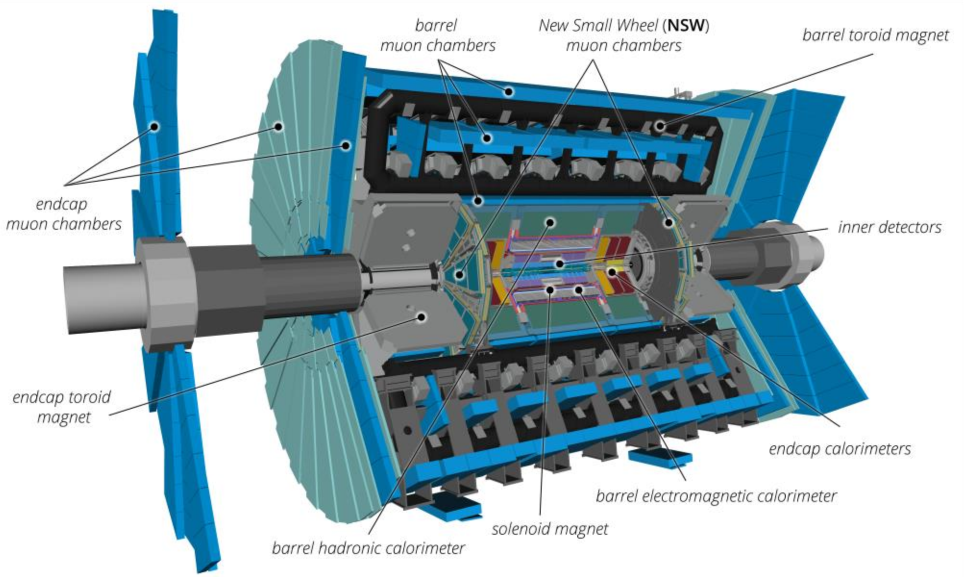


Backups

Tracker+Calorimeters+Muon chamber



Experimental particle physics lectures



ATLAS detector

Experimental consequences of boost

Particle	Lifetime τ (s)	Decay length $c\tau$ (m)	Mass (GeV)	$\gamma = {}^{p}/_{m}$ (p=10GeV)	$\gamma c\tau$ (m)	Comments
Neutron	878.4	2.63×10^{11}				
Muon	2.2×10^{-6}	600	0.106	94	56 400	Stable at detector level
Charged pion	2.6×10^{-8}	7.8	0.140	71	553	Stable at detector level
Neutral pion	8.6×10^{-17}	2.5×10^{-9}	0.135	74	1.85×10^{-7}	Prompt decay
Tau lepton	2.9×10^{-13}	8.7×10^{-5}	1.78	5.6	4.87×10^{-4}	13% displaced by more than 1 mm but the probability to reach the first layer (3cm) is $\sim 1 \times 10^{-27}$

Experimental particle physics lectures

In special relativity, time dilation is described by the formula : $t = \gamma t_O$

t is the time measured by an observer stationary relative to the particle

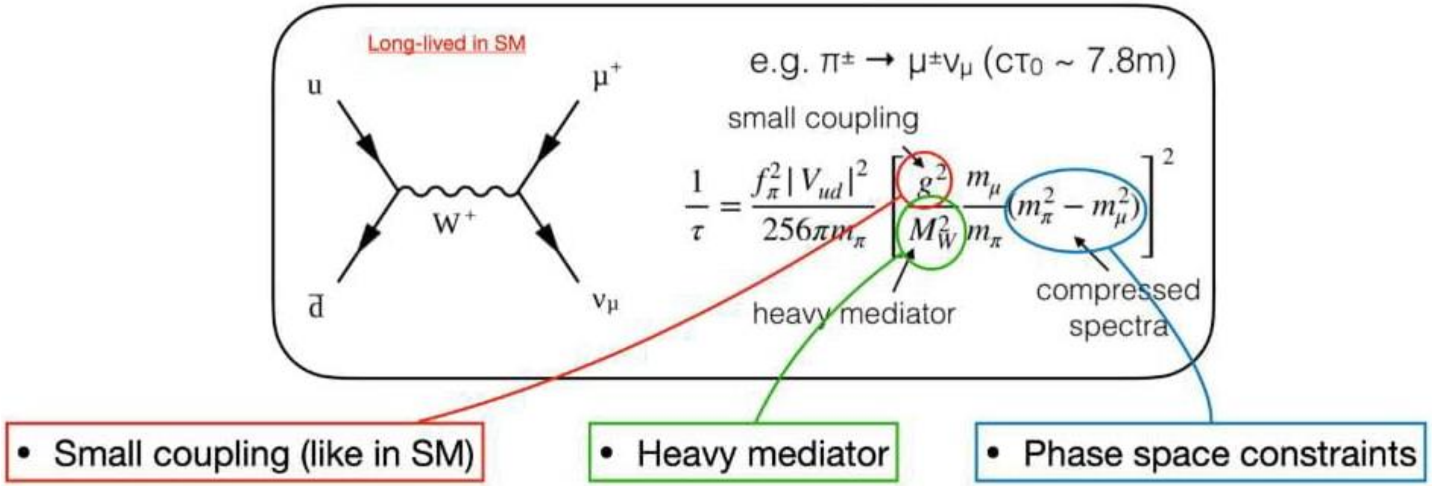
t_O is the proper lifetime measured in the particle's reference frame, i.e. where the particle is at rest

γ is the Lorentz factor, given by: $\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

LLP & BSM

How can long lived signatures point out new physics ?

Credit: Cristián H. Peña



- Small coupling (like in SM)
- Heavy mediator
- Phase space constraints

A given particle is long-lived when:

- ➢ The relevant coupling is small;
- ➢ The decay is suppressed by some large scale or heavy mediator;
- ➢ The allowed final state phase space is small

Cross section computation

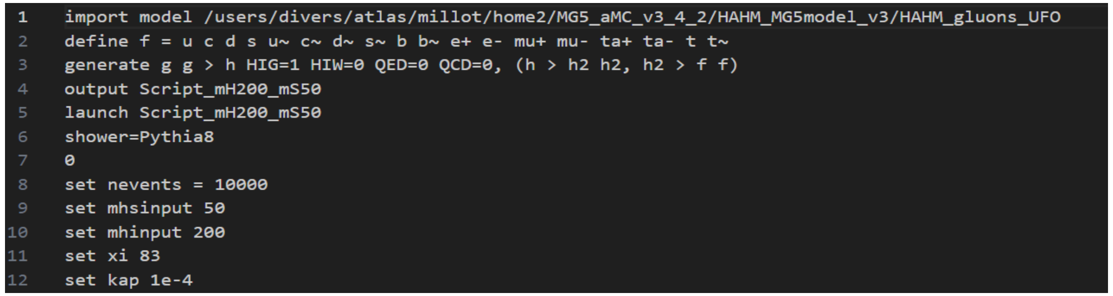
Analytically

Process → Feynman diagram → Frame & notation → M_{fi} → dσ/dΩ → σ

1. **Define** the process of interest
2. Draw the **LO Feynman diagram** for the process of interest
3. Define a **frame** and choice notation of the 4-momenta
4. Apply **Feynman rules** to compute the **matrix element**
5. Inject the matrix element in the **differential cross section** formula
6. **Integrate** to obtain the **total cross section**

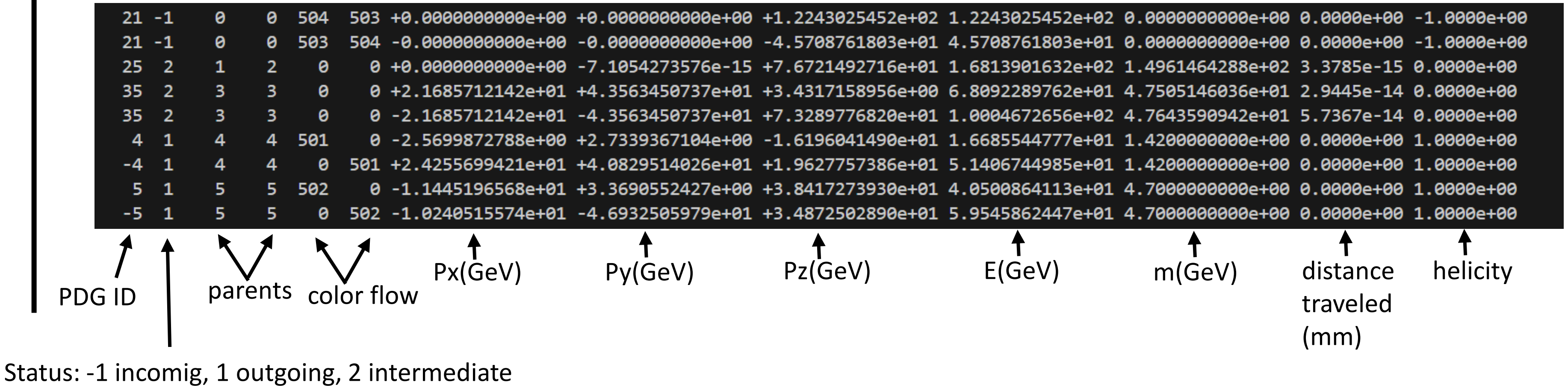
Numerically

Madgraph



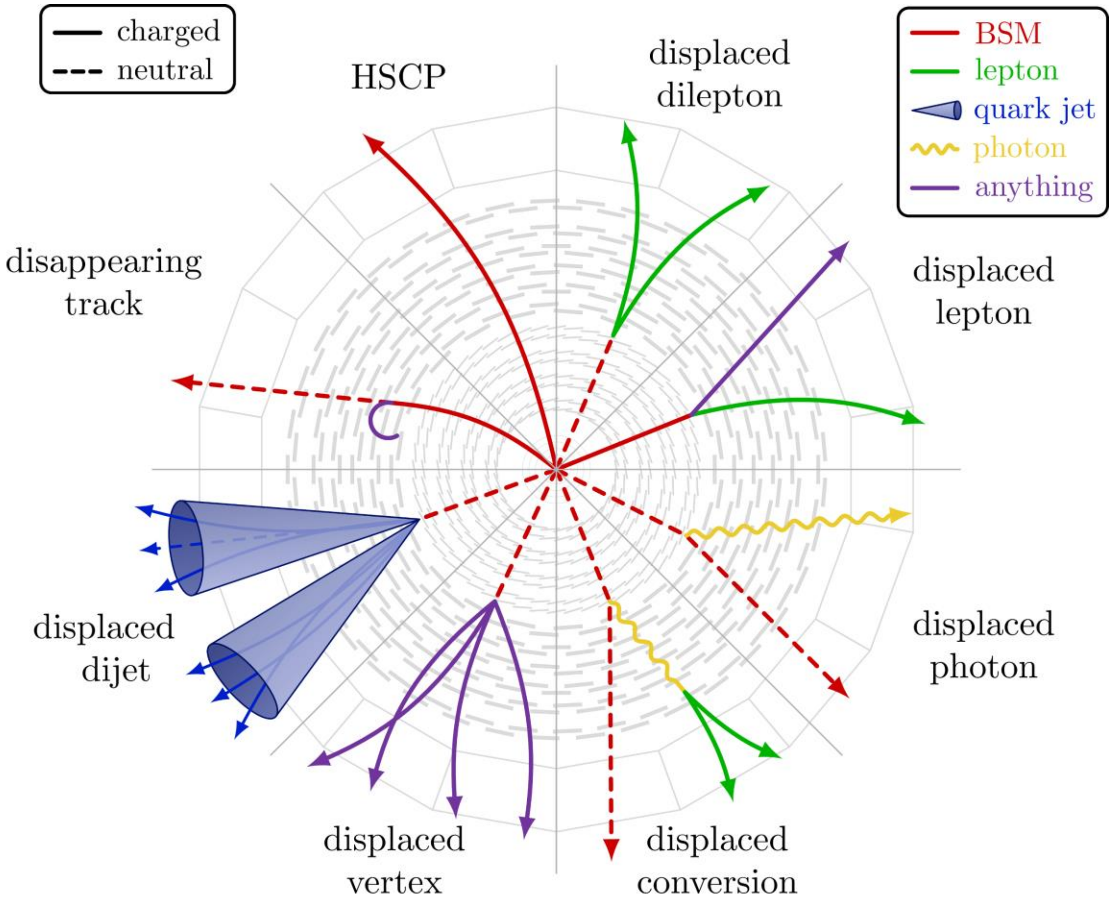
```
import model /users/divers/atlas/millot/home2/MG5_aMC_v3_4_2/HAHM_MG5model_v3/HAHM_gluons_UFO
define f = u c d s u~ c~ d~ s~ b b~ e+ e- mu+ mu- ta+ ta- t t~
generate g g > h HIG=1 HIW=0 QED=0 QCD=0, (h > h2 h2, h2 > f f)
output Script_mH200_mS50
launch Script_mH200_mS50
shower=Pythia8
0
set nevents = 10000
set mhsinput 50
set mhinput 200
set xi 83
set kap 1e-4
```

LHE file which contains all the kinematic information for each event:



```
 21 -1    0    0  504  503 +0.0000000000e+00 +0.0000000000e+00 +1.2243025452e+02 1.2243025452e+02 0.0000000000e+00 0.0000e+00 -1.0000e+00
 21 -1    0    0  503  504 -0.0000000000e+00 -0.0000000000e+00 -4.5708761803e+01 4.5708761803e+01 0.0000000000e+00 0.0000e+00 -1.0000e+00
 25  2    1    2    0    0 +0.0000000000e+00 -7.1054273576e-15 +7.6721492716e+01 1.6813901632e+02 1.4961464288e+02 3.3785e-15 0.0000e+00
 35  2    3    3    0    0 +2.1685712142e+01 +4.3563450737e+01 +3.4317158956e+00 6.8092289762e+01 4.7505146036e+01 2.9445e-14 0.0000e+00
 35  2    3    3    0    0 -2.1685712142e+01 -4.3563450737e+01 +7.3289776820e+01 1.0004672656e+02 4.7643590942e+01 5.7367e-14 0.0000e+00
  4  1    4    4  501    0 -2.5699872788e+00 +2.7339367104e+00 -1.6196041490e+01 1.6685544777e+01 1.4200000000e+00 0.0000e+00 1.0000e+00
 -4  1    4    4    0  501 +2.4255699421e+01 +4.0829514026e+01 +1.9627757386e+01 5.1406744985e+01 1.4200000000e+00 0.0000e+00 1.0000e+00
  5  1    5    5  502    0 -1.1445196568e+01 +3.3690552427e+00 +3.8417273930e+01 4.0500864113e+01 4.7000000000e+00 0.0000e+00 1.0000e+00
 -5  1    5    5    0  502 -1.0240515574e+01 -4.6932505979e+01 +3.4872502890e+01 5.9545862447e+01 4.7000000000e+00 0.0000e+00 1.0000e+00
```

Displaced jets

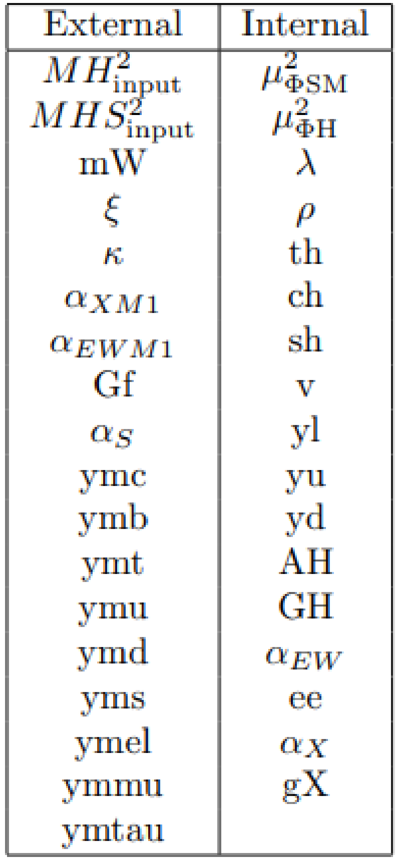


J. Antonelli’s presentation at ICHEP 2016

In particle physics, a ‘**displaced jet**’ refers to a phenomenon where a jet of particles, appears displaced from the point of origin of the main collision. This offset indicates that the particles responsible for forming the jet have travelled a certain distance before decaying into detectable particles.

The SM fermions from the LLP decay result in jets whose origins may be far from the interaction point (IP) of the colliding protons, leading to so-called displaced vertices or displaced jets.
If the LLP decay occurs in the calorimeters, the decay products are collimated enough to be reconstructed as a single jet which is narrow, trackless and with an unusually high proportion of its energy in the hadronic calorimeter.

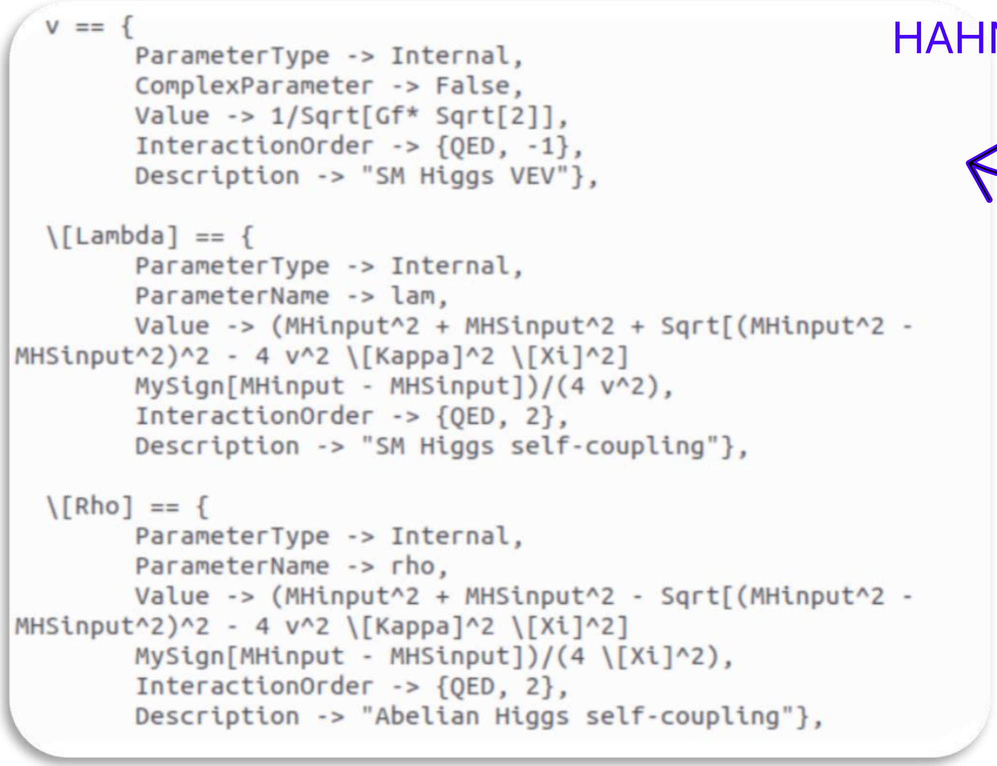
External/ internal parameters



External	Internal
MH^2_{input}	$\mu^2_{\Phi\text{SM}}$
MHS^2_{input}	$\mu^2_{\Phi\text{H}}$
mW	λ
ξ	ρ
κ	th
α_{XM1}	ch
α_{EWM1}	sh
Gf	v
α_S	yl
ymc	yu
ymb	yd
ymt	AH
ymu	GH
ymd	α_{EW}
yms	ee
ymel	α_X
ymmu	gX
ymtau	

$$\mu^2_{\Phi\text{SM}} = \lambda v^2 + \frac{\kappa\xi^2}{2}$$

$$\mu^2_{\Phi\text{H}} = \rho\xi^2 + \frac{\kappa v^2}{2}$$



```
 v == {
       ParameterType -> Internal,
       ComplexParameter -> False,
       Value -> 1/Sqrt[Gf* Sqrt[2]],
       InteractionOrder -> {QED, -1},
       Description -> "SM Higgs VEV"},

 \[Lambda] == {
       ParameterType -> Internal,
       ParameterName -> lam,
       Value -> (MHinput^2 + MHSinput^2 + Sqrt[(MHinput^2 -
MHSinput^2)^2 - 4 v^2 \[Kappa]^2 \[Xi]^2]
       MySign[MHinput - MHSinput])/(4 v^2),
       InteractionOrder -> {QED, 2},
       Description -> "SM Higgs self-coupling"},

 \[Rho] == {
       ParameterType -> Internal,
       ParameterName -> rho,
       Value -> (MHinput^2 + MHSinput^2 - Sqrt[(MHinput^2 -
MHSinput^2)^2 - 4 v^2 \[Kappa]^2 \[Xi]^2]
       MySign[MHinput - MHSinput])/(4 \[Xi]^2),
       InteractionOrder -> {QED, 2},
       Description -> "Abelian Higgs self-coupling"},
```

HAHM_simplified.fr

$$\lambda = \frac{MH^2_{\text{input}} + MHS^2_{\text{input}} + \sqrt{(MH^2_{\text{input}} - MHS^2_{\text{input}})^2 - 4v^2\kappa^2\xi^2}}{4v^2}$$

$$\rho = \frac{MH^2_{\text{input}} + MHS^2_{\text{input}} - \sqrt{(MH^2_{\text{input}} - MHS^2_{\text{input}})^2 - 4v^2\kappa^2\xi^2}}{4\xi^2}$$

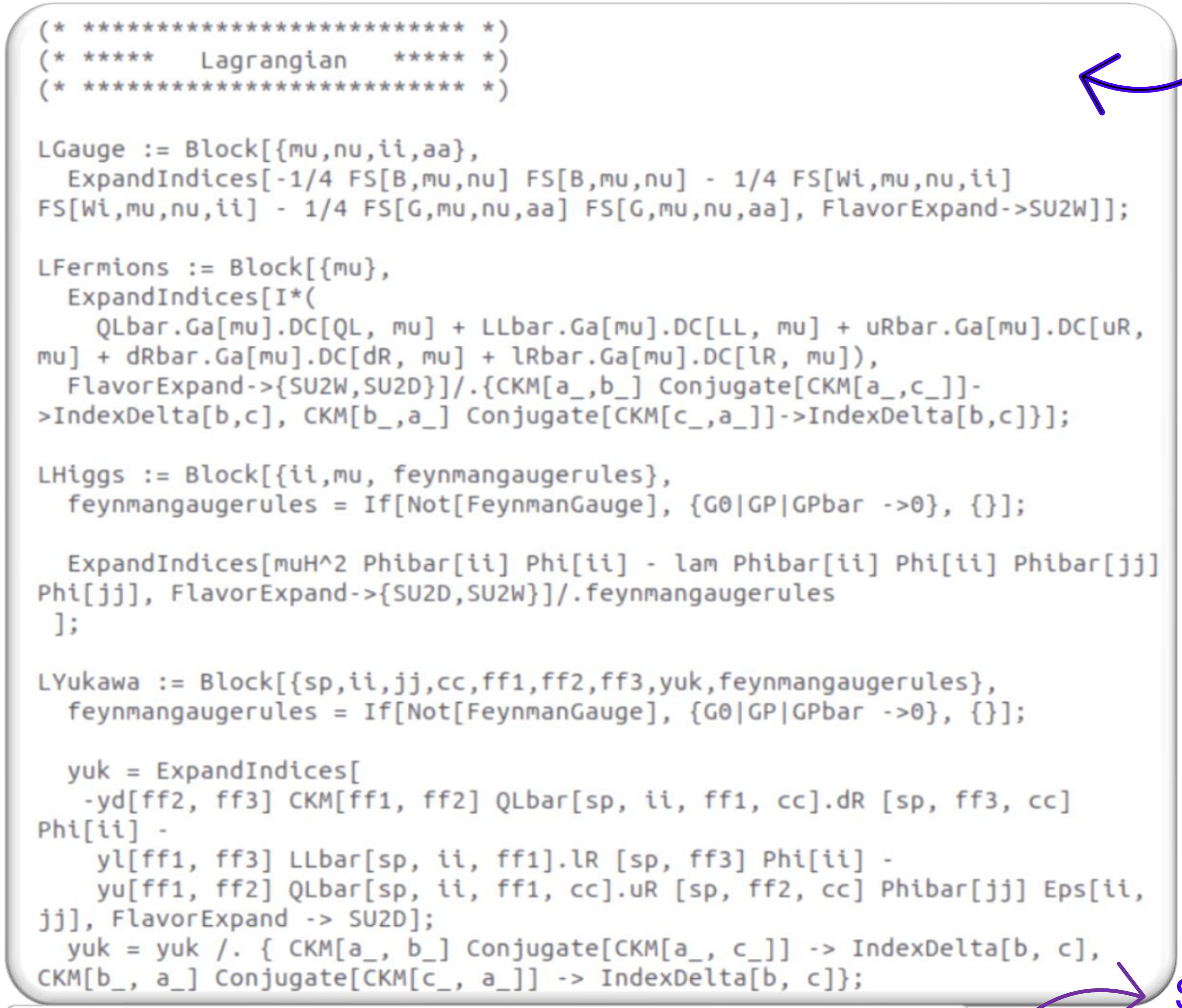
FeynRules and Mathematica

FeynRules is a Mathematica® package → the calculation of Feynman rules for any QFT physics model.

- provide FeynRules with the **minimal information required** to describe the new model (model-file)
- This information is then used to calculate the set of Feynman rules associated with the Lagrangian.
- The Feynman rules calculated by the code can then be used to implement new physics model into other **existing tools** (outputs them to a form appropriate for various programs such as CalcHep, FeynArts, MadGraph, Sherpa and Whizard)

FeynRules and Mathematica: Exemple with SM file

Lagrangians



```
(* ************************** *)
(* *****    Lagrangian    ***** *)
(* ************************** *)

LGauge := Block[{mu,nu,ii,aa},
  ExpandIndices[-1/4 FS[B,mu,nu] FS[B,mu,nu] - 1/4 FS[Wi,mu,nu,ii]
FS[Wi,mu,nu,ii] - 1/4 FS[G,mu,nu,aa] FS[G,mu,nu,aa], FlavorExpand->SU2W]];

LFermions := Block[{mu},
  ExpandIndices[I*(
    QLbar.Ga[mu].DC[QL, mu] + LLbar.Ga[mu].DC[LL, mu] + uRbar.Ga[mu].DC[uR,
mu] + dRbar.Ga[mu].DC[dR, mu] + lRbar.Ga[mu].DC[lR, mu]),
  FlavorExpand->{SU2W,SU2D}]/.{CKM[a_,b_] Conjugate[CKM[a_,c_]]-
>IndexDelta[b,c], CKM[b_,a_] Conjugate[CKM[c_,a_]]->IndexDelta[b,c]}];

LHiggs := Block[{ii,mu, feynmangaugerules},
  feynmangaugerules = If[Not[FeynmanGauge], {G0|GP|GPbar ->0}, {}];

  ExpandIndices[muH^2 Phibar[ii] Phi[ii] - lam Phibar[ii] Phi[ii] Phibar[jj]
Phi[jj], FlavorExpand->{SU2D,SU2W}]/.feynmangaugerules
 ];

LYukawa := Block[{sp,ii,jj,cc,ff1,ff2,ff3,yuk,feynmangaugerules},
  feynmangaugerules = If[Not[FeynmanGauge], {G0|GP|GPbar ->0}, {}];

  yuk = ExpandIndices[
   -yd[ff2, ff3] CKM[ff1, ff2] QLbar[sp, ii, ff1, cc].dR [sp, ff3, cc]
Phi[ii] -
    yl[ff1, ff3] LLbar[sp, ii, ff1].lR [sp, ff3] Phi[ii] -
    yu[ff1, ff2] QLbar[sp, ii, ff1, cc].uR [sp, ff2, cc] Phibar[jj] Eps[ii,
jj], FlavorExpand -> SU2D];
  yuk = yuk /. { CKM[a_, b_] Conjugate[CKM[a_, c_]] -> IndexDelta[b, c],
CKM[b_, a_] Conjugate[CKM[c_, a_]] -> IndexDelta[b, c]};
```

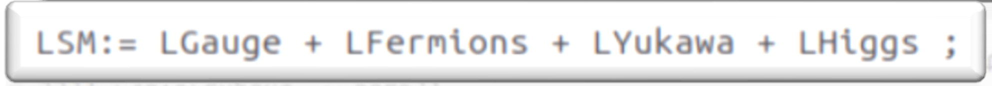
$$\mathcal{L}_{Gauge} = -\frac{1}{4}F_a^{\mu\nu}F_{\mu\nu}^a - \frac{1}{4}W_a^{\mu\nu}W_{\mu\nu}^a - \frac{1}{4}G_a^{\mu\nu}G_{\mu\nu}^a$$

$$\mathcal{L}_{Fermions} = i\sum_{fermion\ f}\left(\overline{\psi}_f\gamma^\mu D_\mu\psi_f\right)$$

$$\mathcal{L}_{Higgs} = \mu_H^2|\Phi|^2 - \lambda|\Phi|^4$$

$$\mathcal{L}_{Yukawa} = -\sum_f\left(y_d^f\overline{Q}_L d_R + y_l^f\overline{L}_L l_R + y_u^f\overline{Q}_L u_R\right)\Phi + \boldsymbol{h.c.}$$

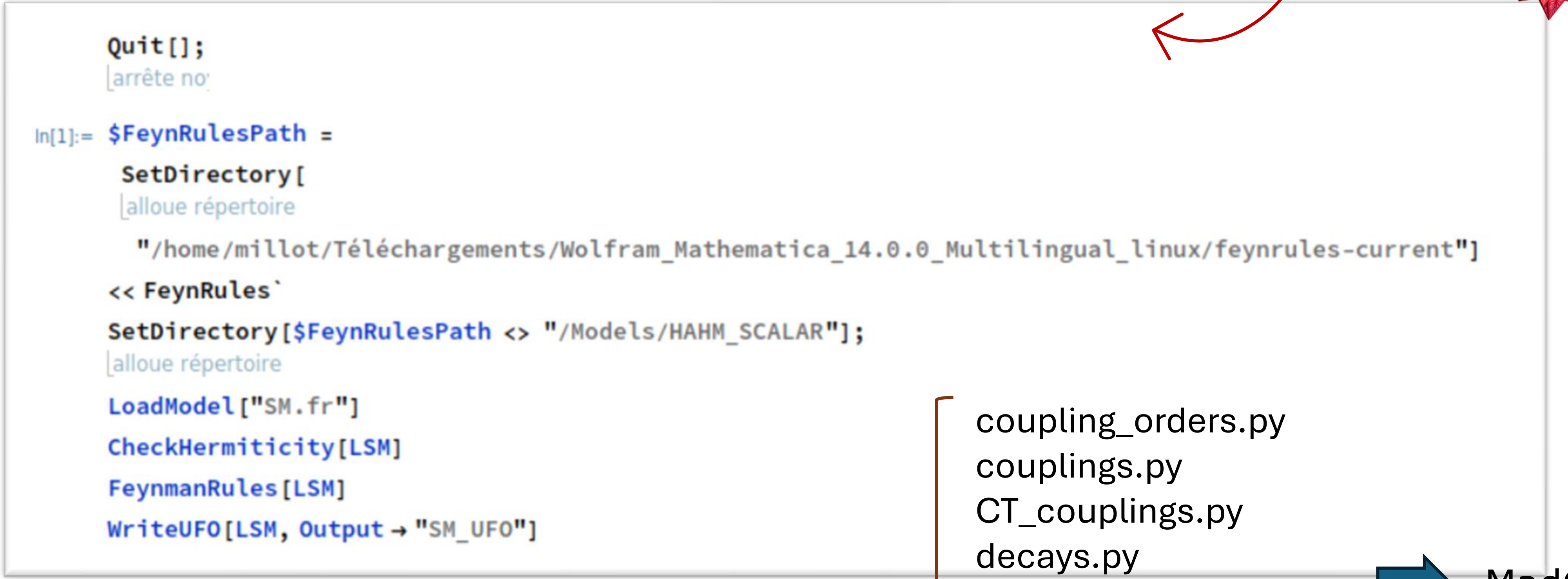
SM Lagrangian



```
LSM:= LGauge + LFermions + LYukawa + LHiggs ;
```

Use of Mathematica to load a model (SM.fr)

Mathematica



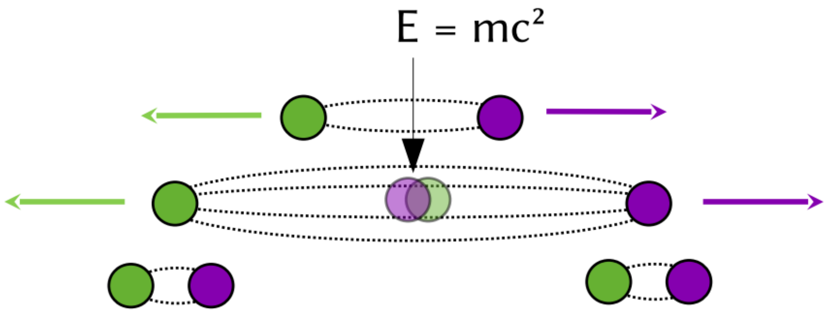
```
      Quit[];
      arrête no

In[1]:= $FeynRulesPath =
        SetDirectory[
        alloue répertoire
          "/home/millot/Téléchargements/Wolfram_Mathematica_14.0.0_Multilingual_linux/feynrules-current"]
      << FeynRules`
      SetDirectory[$FeynRulesPath <> "/Models/HAHM_SCALAR"];
      alloue répertoire
      LoadModel["SM.fr"]
      CheckHermiticity[LSM]
      FeynmanRules[LSM]
      WriteUFO[LSM, Output → "SM_UFO"]
```

SM_UFO file

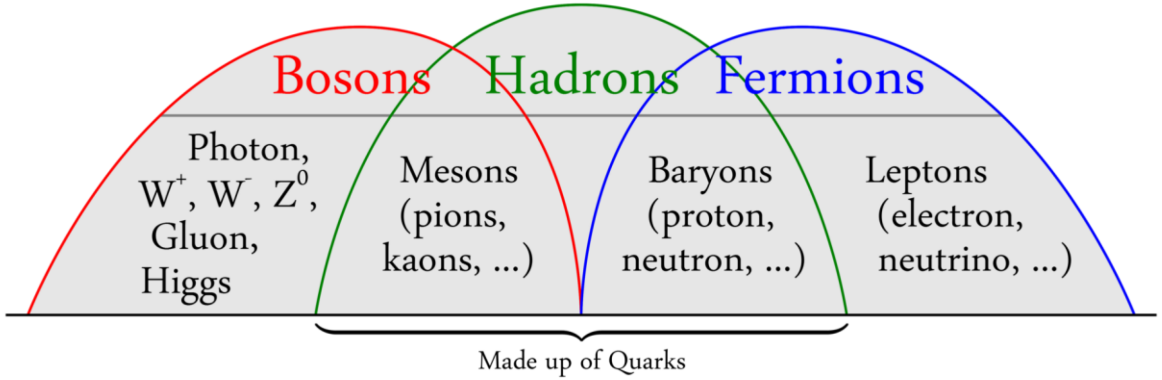
- coupling_orders.py
- couplings.py
- CT_couplings.py
- decays.py
- lorentz.py
- parameters.py
- particles.py
- vertices.py
- …

MadGraph …

Hadronisation & jets



QCD lectures

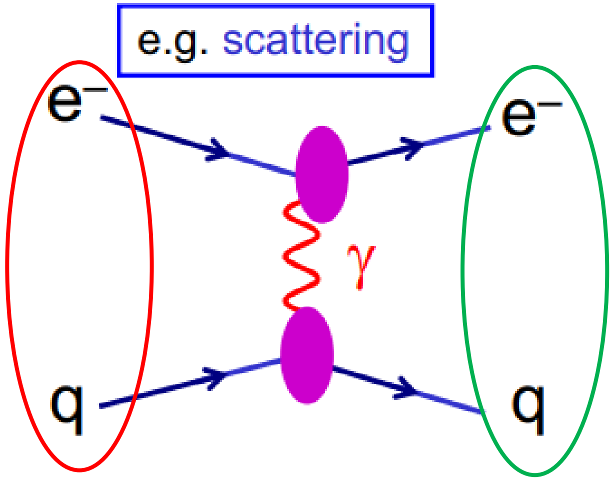


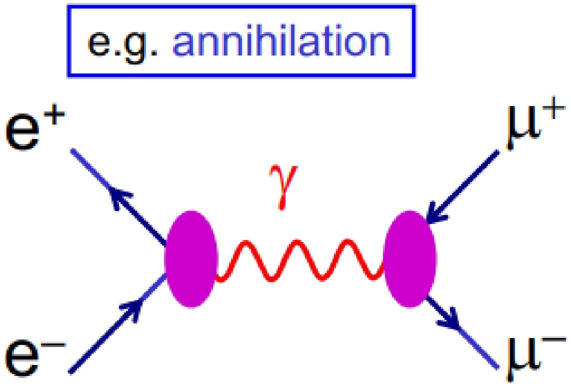
Jet : experimental signatures of **quarks** and **gluons**.
As quark and gluons have a net colour charge and cannot exist freely dur to colour confinement, they are not directly observed in nature. Instead, they come together to form colour-neutral hadrons, a process called hadronization that leads to a collimated spray of hadrons called jet

- PYTHIA8: program for the generation of high-energy physics collision events,
- Hadron ?

Feynman Diagrams

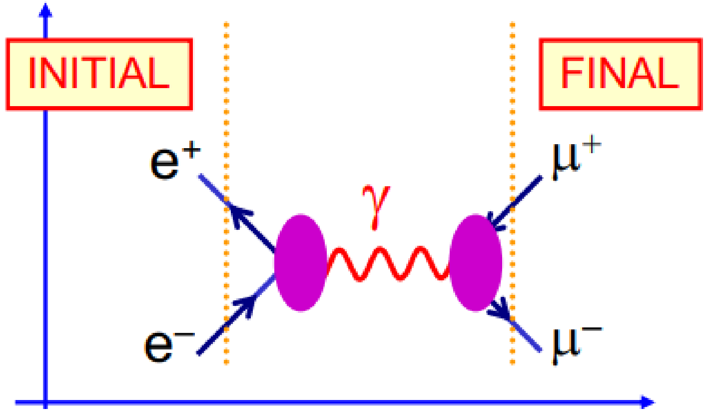
★ Particle interactions described in terms of Feynman diagrams





★ IMPORTANT POINTS TO REMEMBER:

- "time" runs from left – right, only in the sense that:
  - LHS of diagram is initial state
  - RHS of diagram is final state
  - Middle is "how it happened"
- anti-particle arrows in –ve "time" direction
- Energy, momentum, angular momentum, etc. conserved at all interaction vertices
- All intermediate particles are "virtual"

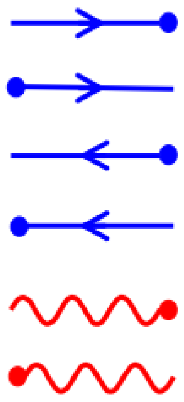


Feynman Rules (QED)

Experimental particle physics lectures

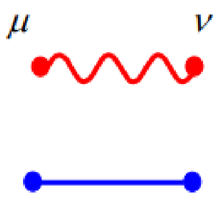
- External lines
  - → Real particles

spin ½ → Dirac Spinor	incoming particle	$u(p)$
	outgoing particle	$\bar{u}(p)$
	incoming antiparticle	$\bar{v}(p)$
	outgoing antiparticle	$v(p)$
spin 1	incoming photon	$\varepsilon^{\mu}(p)$
	outgoing photon	$\varepsilon^{\mu}(p)^{*}$



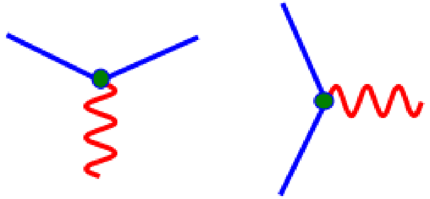
- Internal lines (propagators)
  - → Virtual particles

spin 1	photon	$-\dfrac{ig_{\mu\nu}}{q^2}$
spin 1/2	fermion	$\dfrac{i(\gamma^{\mu}q_{\mu}+m)}{q^2-m^2}$



- Vector factors

spin 1/2 fermion (charge -|*e*|) $ie\gamma^{\mu}$



- Matrix Elements

$$\boxed{-iM \;=\; \text{product of all factors}}$$

Some ref

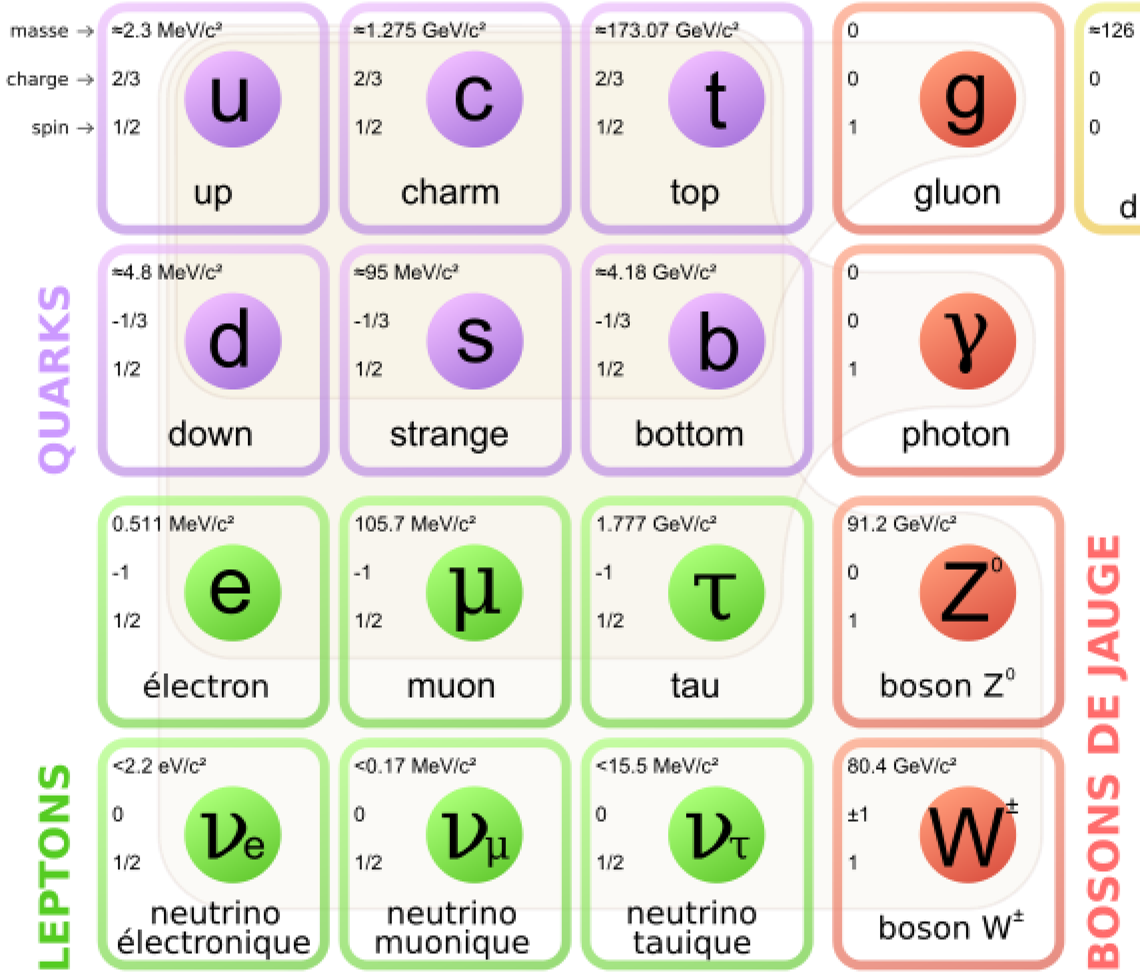
UV standpoint

Ultraviolet (UV) dependence: physical quantities (such as coupling constants, particle masses, etc.) vary as a function of very high energies (or small length scales).
In **QFT**: calculations often involve **integrals** over all possible particle energies. Some of these integrals can diverge when they include contributions from very high energies (high frequencies, hence the term "ultraviolet").
⇨ **renormalisation** technique is used: This allows the physical quantities to be 'renormalised' to make the theory's predictions finite and physically meaningful.

The UV dependence then refers to the way in which the parameters of the theory (such as the coupling constants) must be adjusted as a function of the energy scale (or UV 'cut-off') to maintain the coherence of the theory.

⇨ **Asymmetric model:** The goal is to emphasize ease of use and easy incorporation in experimental analyses, rather than theoretical aspects which, from a UV standpoint, can be highly model-dependent.
    ⇨ Lagrangian: Gauge eigenstates/mass eigenstates, not gauge invariance, not renormalizable

SM



≈2.3 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈173.07 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c² 0 0 H boson de Higgs
≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon	
0.511 MeV/c² -1 1/2 e électron	105.7 MeV/c² -1 1/2 μ muon	1.777 GeV/c² -1 1/2 τ tau	91.2 GeV/c² 0 1 Z^0 boson Z^0	
<2.2 eV/c² 0 1/2 ν_e neutrino électronique	<0.17 MeV/c² 0 1/2 ν_μ neutrino muonique	<15.5 MeV/c² 0 1/2 ν_τ neutrino tauique	80.4 GeV/c² ±1 1 $W^\pm$ boson $W^\pm$	

https://fr.wikipedia.org/wiki/Modèle_standard_de_la_physique_des_particules