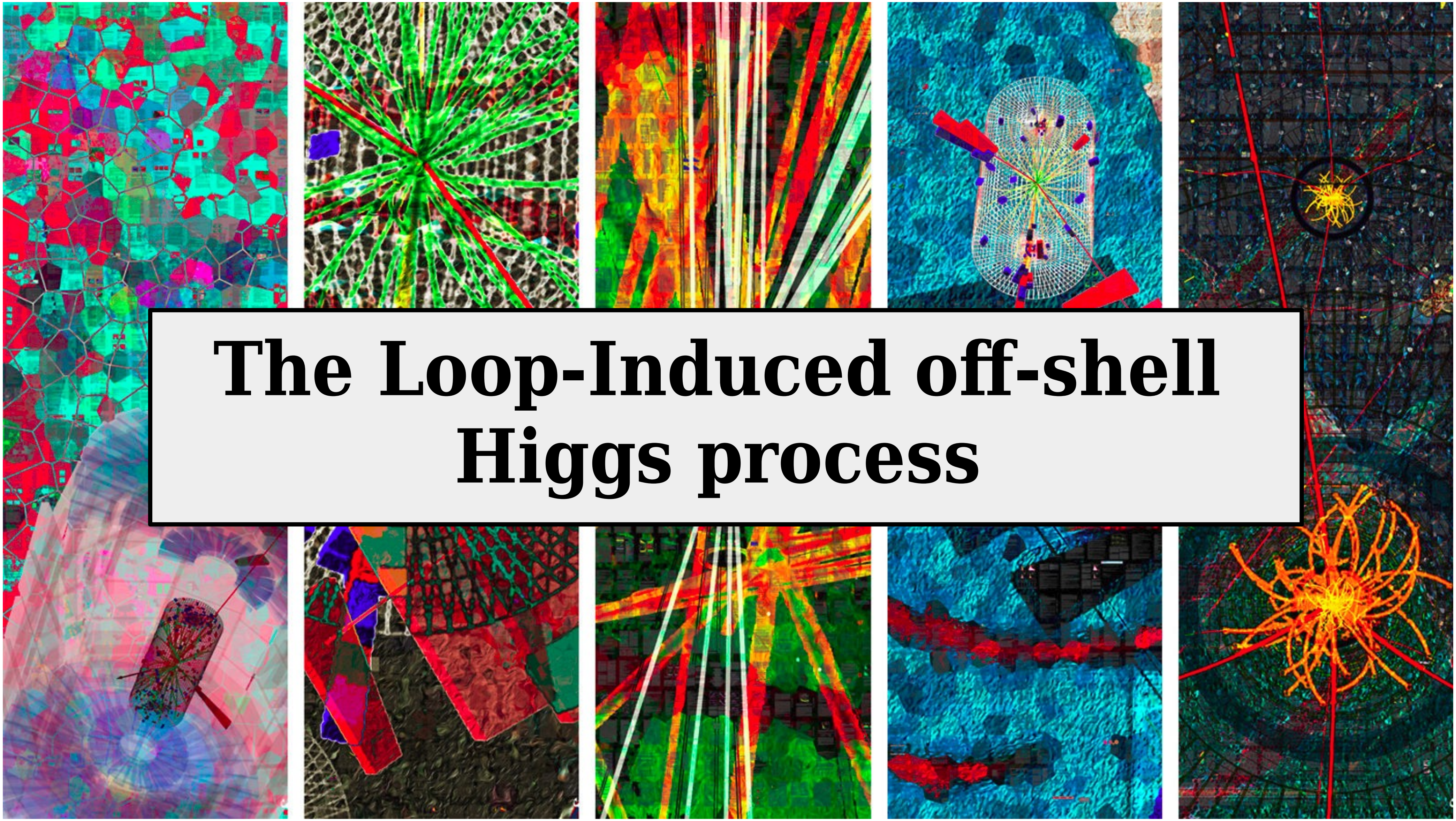

The Loop-Induced off-shell Higgs process

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PGF5228 - Física de Anéis de Colisão (2021)

Outline

1. Loop-induced processes - MadLoop

2. Off-shell Higgs in the SM

3. BSM off-shell Higgs

Part 1

Loop induced processes and MadLoop

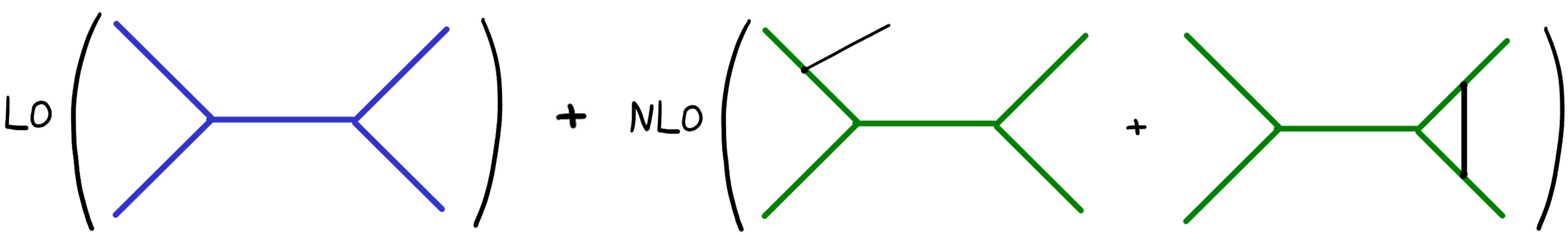
1. NLO calculations

Hadron Collisions:

$$\sigma_{\text{tot}}(\mu_F, \mu_R) = \sum_{i,j} \int_0^1 dx_1 \int_0^1 dx_2 d\Pi_n \, f_i(x_1, \mu_f) f_j(x_2, \mu_f) \hat{\sigma}_{ij}(\hat{s}, \mu_F, \mu_R)$$

Perturbative Expansion:

$$\hat{\sigma} = \underbrace{\sigma^{\text{Born}}}_{\text{LO}} \left(1 + \underbrace{\frac{\alpha_s}{2\pi}\sigma^{(1)}}_{\text{NLO}} + \underbrace{\left(\frac{\alpha_s}{2\pi}\right)^2 \sigma^{(2)}}_{\text{NNLO}} + \underbrace{\left(\frac{\alpha_s}{2\pi}\right)^3 \sigma^{(3)}}_{\text{N3LO}} + \dots \right)$$



1. NLO calculations

Automated one-loop matrix element tools

- **MadLoop**
- FeynArts, FormCalc, ...
- OpenLoops
- GoSam

3-step program to automate NLO

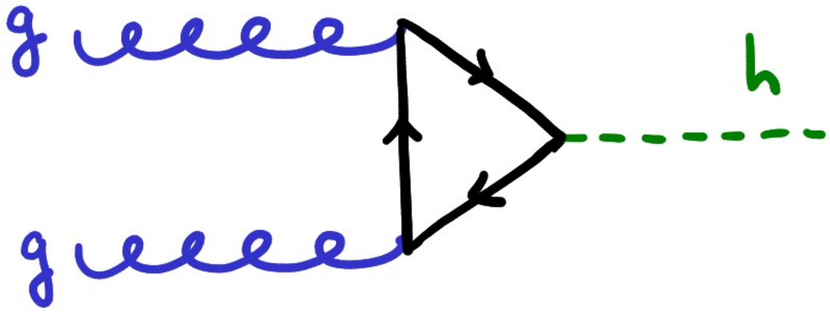
1. Renormalization
2. Integral reduction
3. Rational terms

This seminar: Limit to a particular case

1. Loop-Induced (LI) Processes

LI process → No tree-level contributions

i.e.1 – Gluon Fusion dominates the inclusive Higgs production.



i.e.2 – L.I. gg→ZZ is 60% of the full NNLO corrections to had. ZZ production.

i.e.3 – BSM models → Loop suppressed production helps to evade experimental constraints

1. Loop-Induced (LI) Processes

Dealing with LI processes

- Integrate out heavy loops → Effective point-like vertices (i.e. heft)

  ⤷ **Valid in only a limited kinematic range.**

- Automated implementation of LI processes.

  ⤷ **Done in 2015! (MG5@NLO).** **[1507.00020]**

- Dedicated implementations (i.e. pp→h in N3LO QCD + NLO EW).

  ⤷ **Used in state-of-the-art calculations.**

1. Loop-Induced (LI) Processes

LI versus general NLO

- **Advantage:** LI amplitudes are finite!

  → **No UV divergences if the model is renormalizable**

- **Disadvantage:** Speed

In usual NLO, bulk contributions come from **born** and **real** emissions.

→ Limited statistics to the evaluation of virtual contributions.

Computation time	$\propto$	Execution speed of the LI matrix element

1. Loop-Induced (LI) Processes

Loop-integrals reduction

$$I^{(t)} = \sum_i d_i \text{ box}_i + \sum_i c_i \text{ triangle}_i + \sum_i b_i \text{ bubble}_i + \sum_i a_i \text{ tadpole}_i + R$$

Scalar integral basis - available in many libraries i.e. OneLoop, QCDLoop,...

→ Loop amplitude computation reduces to determining d_i, c_i, b_i, a_i, R

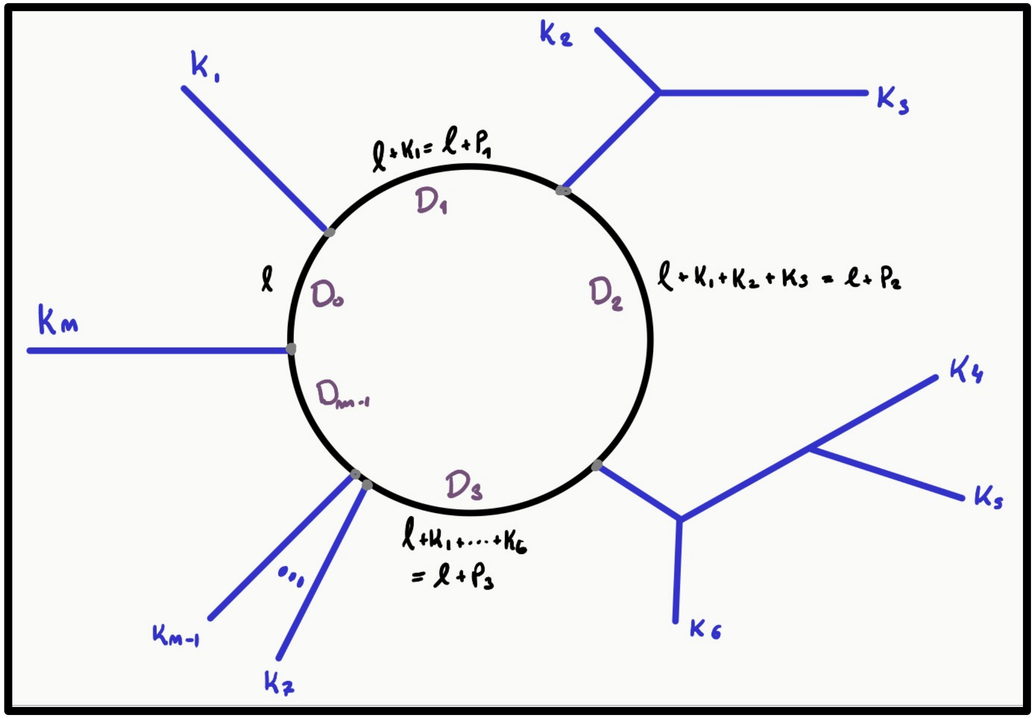
Methods:

1. **OPP reduction:** Ossola, Papadopoulos and Pittau.
   → Reduction at the integrand level.
   Tools: CutTools, Ninja

2. **TIR:** Tensor Integral Reduction.
   → Passarino-Veltman integrals.
   Tools: Collier, PJFry, GOLEM

Question: **which one is better?** (for LI)

1. Loop-Induced (LI) Processes



d-dimensional Amplitude

$$\mathcal{A}_d = \sum_{l_1=1}^{L} \lambda_{l_1} \int d^d \bar{\ell} \, \frac{\mathcal{N}_{h,l_1}(\ell)}{\prod_{i=1}^{n_{l_1}} \bar{D}_{i,l_1}}$$

Split the numerator:

$$\overline{\mathcal{N}}(\bar{l}) = \underbrace{\mathcal{N}(l)}_{\text{4d part}} + \epsilon \tilde{N}(\bar{l})$$

4d part

$$\mathcal{A}_d = \mathcal{A} + \mathcal{A}_{R2}$$

→ Finite contribution

Rational terms: R2 counterterms in UFO (ask me later - Backup slides)

1. Loop-Induced (LI) Processes

$$\mathcal{N}(\ell)_{l,h} = \sum_{r=0}^{r_{max}} C^{(r)}_{\mu_1 \ldots \mu_r; h,l}\, \ell^{\mu_1} \ldots \ell^{\mu_r}$$

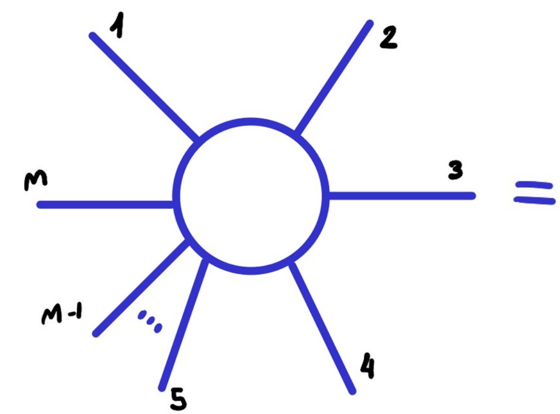
Reduction operation:

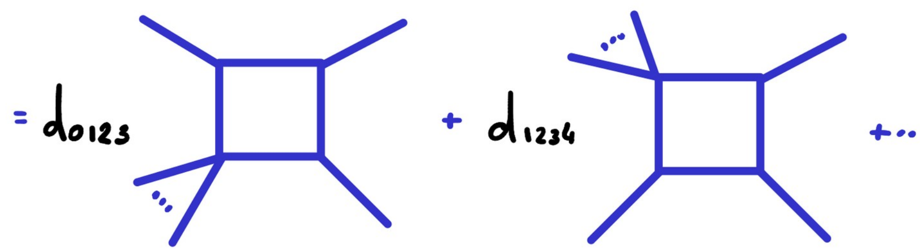
$$\mathrm{Red}\left[\frac{\mathcal{N}_{l,h}(\ell)}{\prod_{i=0}^{n_l} \bar{D}_{i,l}}\right] = \begin{cases} \mathrm{OPP}\left[\dfrac{\sum_{r=0}^{r_{max}} C^{(r)}_{\mu_1 \ldots \mu_r; h,l}\, \ell^{\mu_1} \ldots \ell^{\mu_r}}{\prod_{i=1}^{n_l} \bar{D}_{i,l}}\right] \\ \\ \sum_{r=0}^{r_{max}} C^{(r)}_{\mu_1 \ldots \mu_r; h,l}\, \mathrm{TIR}\left[\dfrac{\ell^{\mu_1} \ldots \ell^{\mu_r}}{\prod_{i=1}^{n_l} \bar{D}_{i,l}}\right] \end{cases}$$

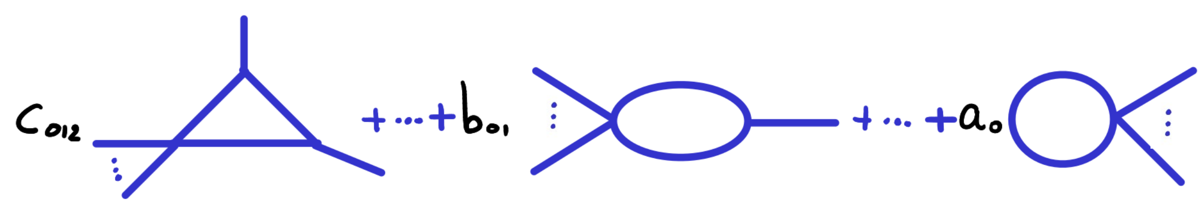
1. Brief overview of OPP method

OPP: Decompose the numerator into a **basis of products of the denominators**

$$
\begin{aligned}
N(q) = & \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3)\right] \prod_{i \neq i_0, i_1, i_2, i_3}^{N_t - 1} D_i \\
& + \sum_{i_0<i_1<i_2}^{N_t-1} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2)\right] \prod_{i \neq i_0, i_1, i_2}^{N_t - 1} D_i \\
& + \sum_{i_0<i_1}^{m-1} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1)\right] \prod_{i \neq i_0, i_1}^{N_t - 1} D_i \\
& + \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q; i_0)\right] \prod_{i \neq i_0}^{N_t - 1} D_i \\
& + \tilde{P}(q) \prod_{i}^{N_t - 1} D_i .
\end{aligned}
$$







1. Brief overview of OPP method

Algorithm: Sample the numerator by choosing special values for the loop momenta

1. Choose $l^{\pm}$ such as $D_0(l^{\pm}) = \cdots = D_3(l^{\pm}) = 0$

→ All terms in the OPP cancel except:

$$N(l^{\pm}) = \left[d_{0123} + \tilde{d}_{0123}(l^{\pm})\right] \prod_{i \neq 0,1,2,3}^{n-1} D_i(l^{\pm})$$

$$d_{0123} = \frac{1}{2}\left[\frac{N(l^+)}{\prod_{i\neq 0,1,2,3}^{n-1} D_i(l^+)} + \frac{N(l^-)}{\prod_{i\neq 0,1,2,3}^{n-1} D_i(l^-)}\right]$$

2. Compute all box coefficients.
3. Triple cuts to determine triangle coefficients. Use box coefficients from step 2.
4. Proceed to Bubbles, Tadpole and R1.

1. Brief overview of TIR method

TIR Example:

$$\mathcal{I}^{(1)\mu}_{p_1,p_2} = \int d^d\bar{q}\, \frac{\bar{q}^\mu}{\bar{q}^2(\bar{q}+p_1)^2(\bar{q}+p_2)^2}$$

$$\mathcal{I}^{(1)\mu}_{p_1,p_2} = C_1 p_1^\mu + C_2 p_2^\mu$$

- Contract with external momentum: $[2q\cdot p_1] = \int d^d\bar{q}\, \frac{2q\cdot p_1}{\bar{q}^2(\bar{q}+p_1)^2(\bar{q}+p_2)^2}$

$$\begin{pmatrix} [2q\cdot p_1] \\ [2q\cdot p_2] \end{pmatrix} = \begin{pmatrix} 2p_1\cdot p_1 & 2p_1\cdot p_2 \\ 2p_1\cdot p_2 & 2p_2\cdot p_2 \end{pmatrix} \begin{pmatrix} C_1 \\ C_2 \end{pmatrix}$$

- Complete squares of $[2q.p_i]$ integrals: ***i.e.*** $[2q\cdot p_1] = \mathcal{I}^{(0)}_{p_2} - \mathcal{I}^{(0)}_{p_2-p_1} - p_1^2\mathcal{I}^{(0)}_{p_1,p_2}$

- *Invert the system of equations to obtain C_1 and C_2.*

1. Loop-Induced (LI) Processes

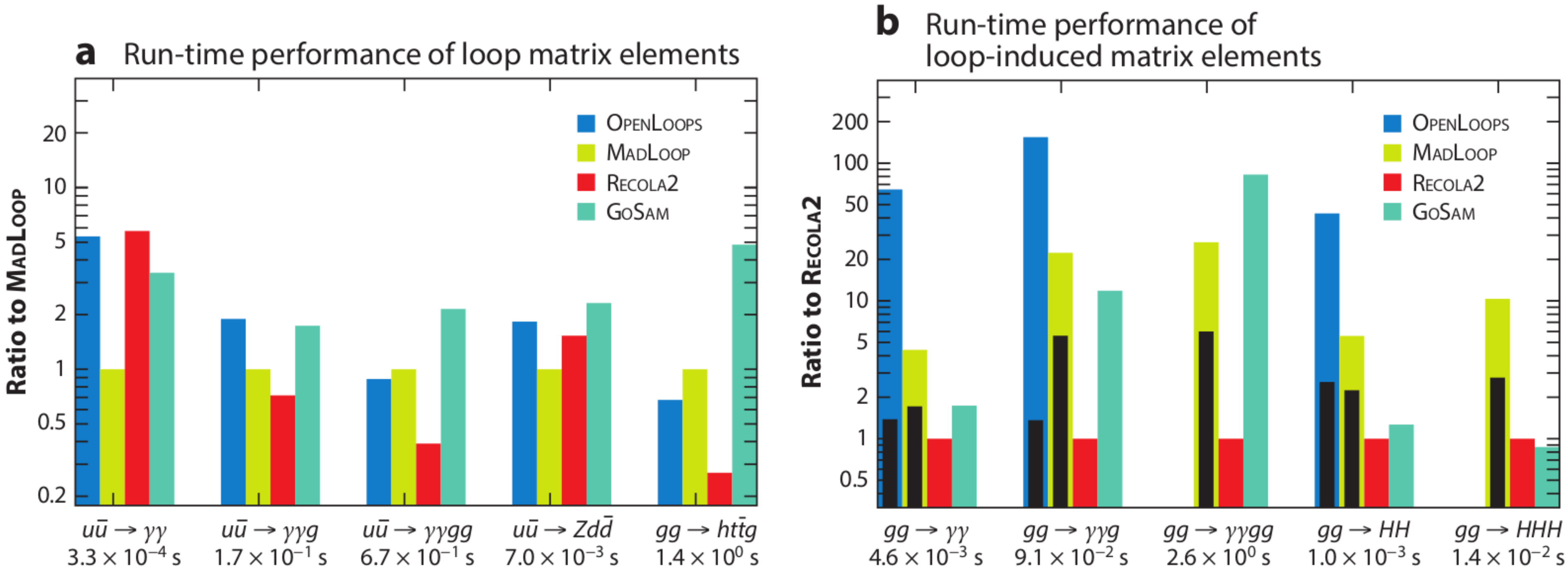
Which to use?

- TIR has a factorial growth in terms of the recursion depth of the algorithm, proportional to both the rank and # of external legs.
- Output of the **OPP reduction depends on both the loop and helicity**, while **TIR depends only on the loop considered**.

OPP recursions = **L** **x** **H**
TIR recursions = **L**

TIR is usually better for LI processes.

1. Loop-Induced (LI) Processes



Helicity sum	Monte-Carlo	Exact	
Loop Reduction	CutTools	CutTools	TIR
Survey			
$pp \to hj$	13m (125k)	32m (260k)	**9m (260k)**
$pp \to hjj$	**2d4h (1.2M)**	16d10h (5.4M)	9d13h (5.4M)*
$gg \to zz$	**1h06m (34k)**	12h50m (255k)	1h44m (255k)
$gg \to zhg$	**11h13m (110k)**	1d8h (516k)	1d4h (516k)*

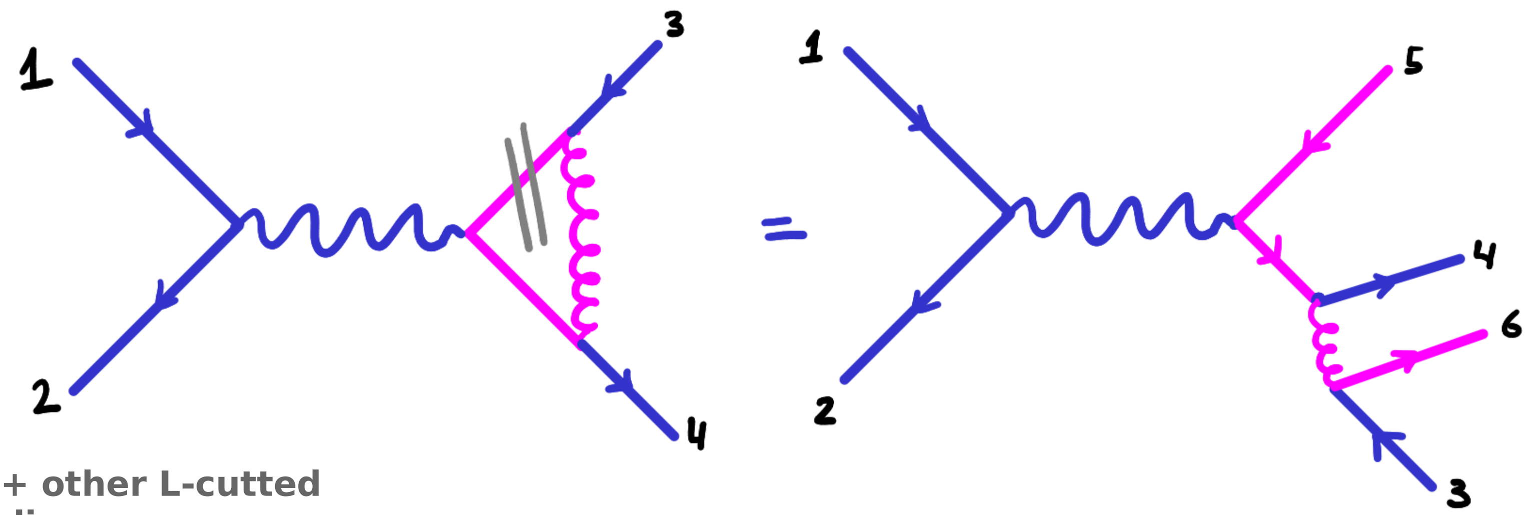
Helicity sum	Monte-Carlo	Exact	
Loop Reduction	CutTools	CutTools	TIR
Refine			
$pp \to hj$	1h43m (385k)	23m (431k)	**6m (431k)**
$pp \to hjj$	**7d17h (2.18M)**	75d1h (20.6M)	51d19h (20.6M)*
$gg \to zz$	**7h20m (407k)**	4d13h (4.55M)	23h07m (5.78M)
$gg \to zhg$	**23h03m (277k)**	2d22h (1.13M)	3d14h (1.4M)*

1. Loop-Induced (LI) Processes

Event Generation: MadLoop in Madgraph

- Madgraph is great at constructing tree-level matrix elements.
- **MadLoop:** generate loop diagrams from tree-level ones.

L-cut diagrams:



+ other L-cutted diagrams.

- Madgraph generate all L-cutted diagrams.
- **Sew them together to reconstruct loop topology.**

Examples and Madloop options

pedro@Matilda: ~

```
************************************************************
*                                                          *
*                     W E L C O M E  to                    *
*              M A D G R A P H 5 _ a M C @ N L O           *
*                                                          *
*                                                          *
*                 *                       *                *
*                   *        * *        *                  *
*                     * * * * 5 * * * *                    *
*                   *        * *        *                  *
*                 *                       *                *
*                                                          *
*         VERSION 2.9.3                 2021-03-25         *
*                                                          *
*    The MadGraph5_aMC@NLO Development Team - Find us at   *
*    https://server06.fynu.ucl.ac.be/projects/madgraph     *
*                            and                           *
*            http://amcatnlo.web.cern.ch/amcatnlo/         *
*                                                          *
*               Type 'help' for in-line help.              *
*           Type 'tutorial' to learn how MG5 works         *
*    Type 'tutorial aMCatNLO' to learn how aMC@NLO works   *
*    Type 'tutorial MadLoop' to learn how MadLoop works    *
*                                                          *
************************************************************
```

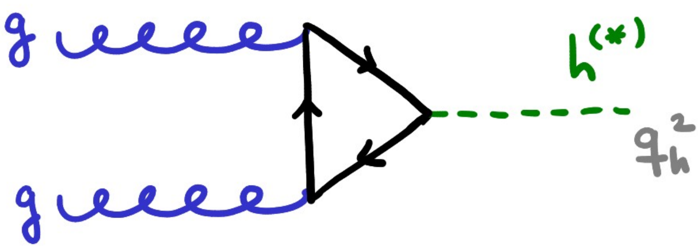
Part 2

Off-Shell Higgs in the Standard Model

2. Off-shell Higgs in the SM

$gg \to h^{(*)} \to Z^{(*)}Z^{(*)} \to 4l$

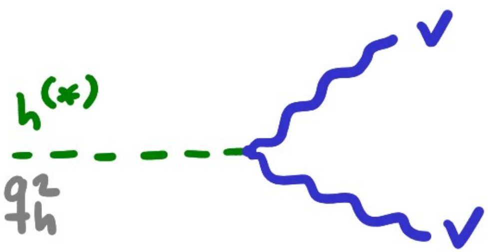
Production



$$\mathcal{L} = \frac{\alpha_s}{4\pi v} g_{ggh}(q_h^2) H G_{\mu\nu} G^{\mu\nu}$$

→ **Triangle loop.**

Decay



$$\sum_{\lambda} |\mathcal{M}_{h\to VV}|^2 = \frac{4M_V^4}{v^2}\left(3 + \frac{q_h^4}{4M_V^4} - \frac{q_h^2}{M_V^2}\right)$$

Expectation: **(on-shell production) x BR** should reproduce the total cross-section with good accuracy.

2. Off-shell Higgs in the SM

Expectation: **(on-shell production) x BR** should reproduce the total cross-section with good accuracy.

Reason: We expect the **Narrow Width approximation** (NWA) to be good for the Higgs.

$$\frac{\Gamma_h}{m_h} \sim 10^{-4}$$

$$m_h = 125 \text{ GeV} \qquad \Gamma_h = 4.03 \text{ MeV}$$

$$D_h^2(q_h^2) = \frac{1}{(q_h^2 - m_h^2)^2 + \Gamma_h^2 m_h^2} \xrightarrow{\text{NWA}} \frac{\pi}{m_h \Gamma_h} \delta(q_h^2 - m_h^2) + \mathcal{O}(\Gamma_h / m_h)$$

2. Off-shell Higgs in the SM

$$\sigma = \frac{1}{2s}\int_{q^2_{min}}^{q^2_{max}} \frac{dq^2}{2\pi}\left(\int d\phi_p |\mathcal{M}_p(q_h^2)|^2 \, D_h^2(q_h^2) \, \int d\phi_p |\mathcal{M}_d(q_h^2)|^2\right)$$

$$\sigma^{\mathbf{NWA}} = \frac{1}{2s}\left(\int d\phi_p |\mathcal{M}_p(q_h^2)|^2\right) \frac{1}{2m_h\Gamma_h} \left(\int d\phi_p |\mathcal{M}_d(q_h^2)|^2\right)$$

10^{-4} error... **Or is it?...**

2. Off-shell Higgs in the SM

$$\sigma = \frac{1}{2s}\int_{q^2_{min}}^{q^2_{max}} \frac{dq^2}{2\pi}\left(\int d\phi_p |\mathcal{M}_p(q_h^2)|^2\, D_h^2(q_h^2)\int d\phi_p |\mathcal{M}_d(q_h^2)|^2\right)$$

$$\sigma^{\mathbf{NWA}} = \frac{1}{2s}\left(\int d\phi_p |\mathcal{M}_p(q_h^2)|^2\right)\frac{1}{2m_h\Gamma_h}\left(\int d\phi_p |\mathcal{M}_d(q_h^2)|^2\right)$$

10^{-4} error... **Or is it?...**

Assumptions of the NWA approximation

1. Total width is much smaller than the resonance mass. **Ok**

2. There are no relevant thresholds. **False!**

3. There is no significant interference with non-resonant processes. **False!**

2. Off-shell Higgs in the SM

Assumption 2: **Thresholds.**

Exact propagator:

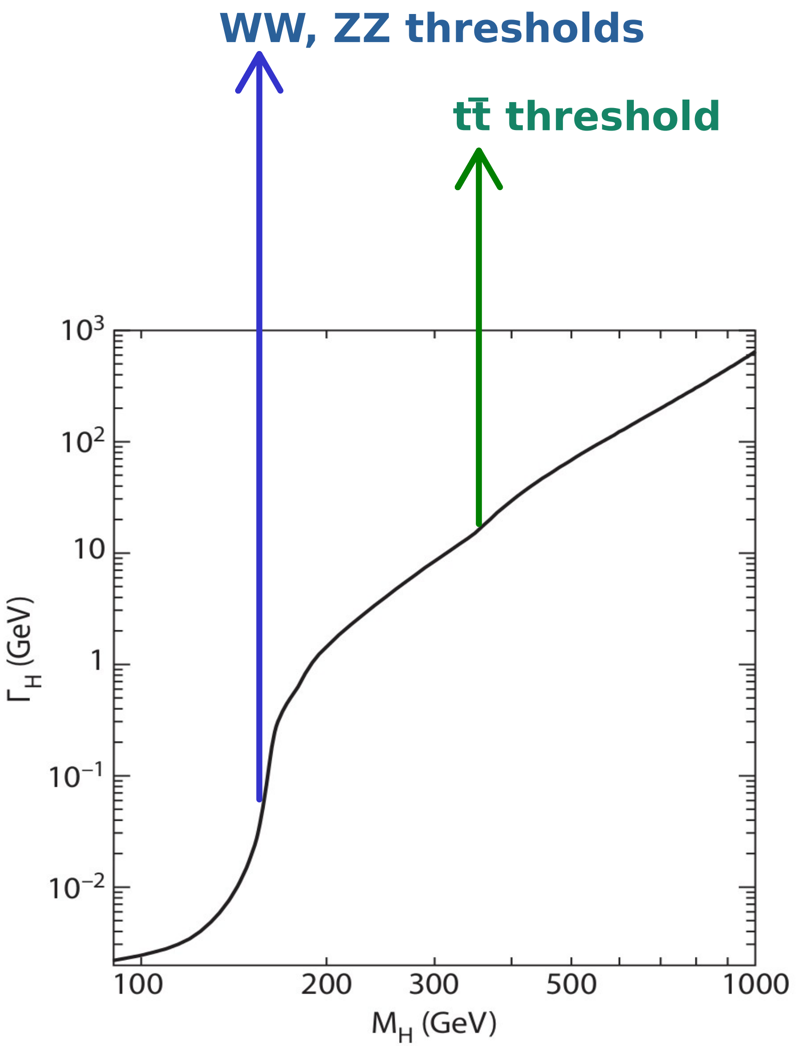
$$D_h(q^2) = \frac{i}{q^2 - m_0^2 + \Sigma(q^2)} = \frac{iZ}{q^2 - m_h^2 + iIm\tilde{\Sigma}(q^2)}$$

Use the optical theorem.

$$\Gamma_{X^* \to 1+2+\ldots} = \frac{1}{2\sqrt{s}} \sum_a |\mathcal{M}|^2 d\Pi_n$$

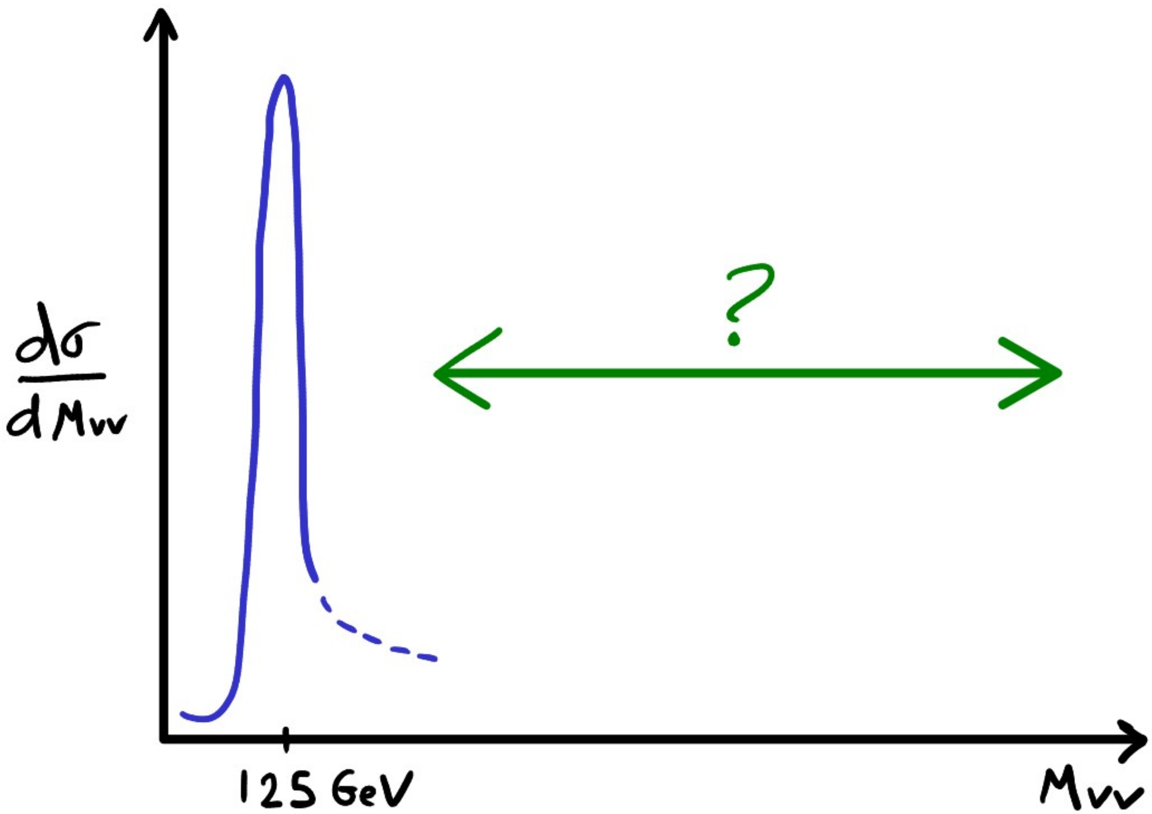
$$= \frac{iIm\tilde{\Sigma}(s)}{\sqrt{s}}$$

$$D_h(q^2) = \frac{iZ}{q^2 - m_h^2 + i\sqrt{s}\Gamma(s)}$$



2. Off-shell Higgs in the SM

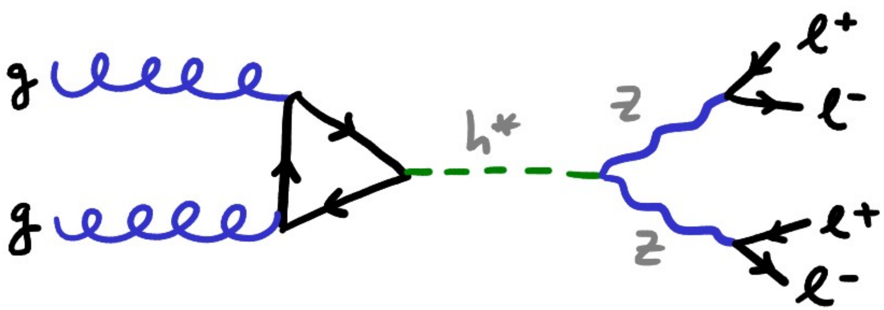
Question: What is the behaviour of the distribution at the high energy regime?



- How small compared to the peak?
- Does it really decreases with M_{VV}?
- Is there a plateau?
- How does that affects the total cross-section?

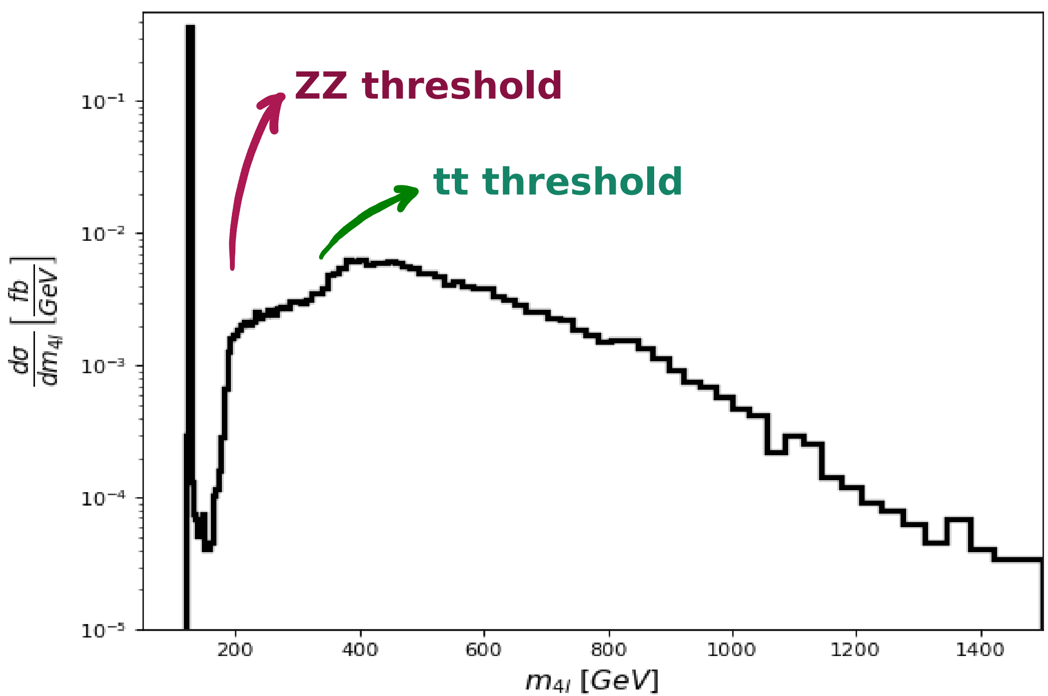
2. Off-shell Higgs in the SM

Signal




```
MG5_aMC>generate g g > l+ l- l+ l- [QCD]
----------------------------------------------------------------
 No Born diagrams found. Now switching to the loop-induced
 Please cite ref. 'arXiv:1507.00020' when using results fro
----------------------------------------------------------------
3 processes with 20 diagrams generated in 3.430 s
Total: 3 processes with 20 diagrams
```

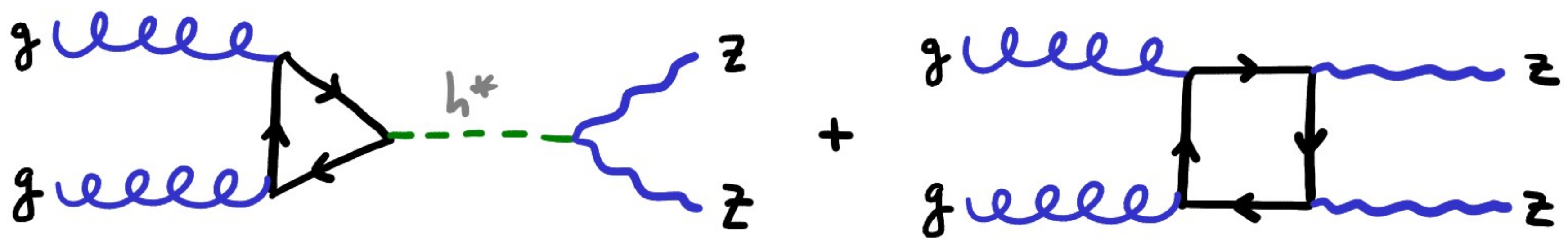
Modify loop_SM UFO → set Zqq coupling to zero to remove irreducible bg (Box diagrams)



~15% net-effect in the total cross-section of $M_{zz} > 2M_z$ region.

2. Off-shell Higgs in the SM

Assumption 3: **Interference with non-resonant processes.**



Box must be included: Irreducible background with important interference.

Unitarizing nature of the Higgs $h^* \to Z_L Z_L$

$$m_{ZZ} \gg m_t, m_h, m_Z$$

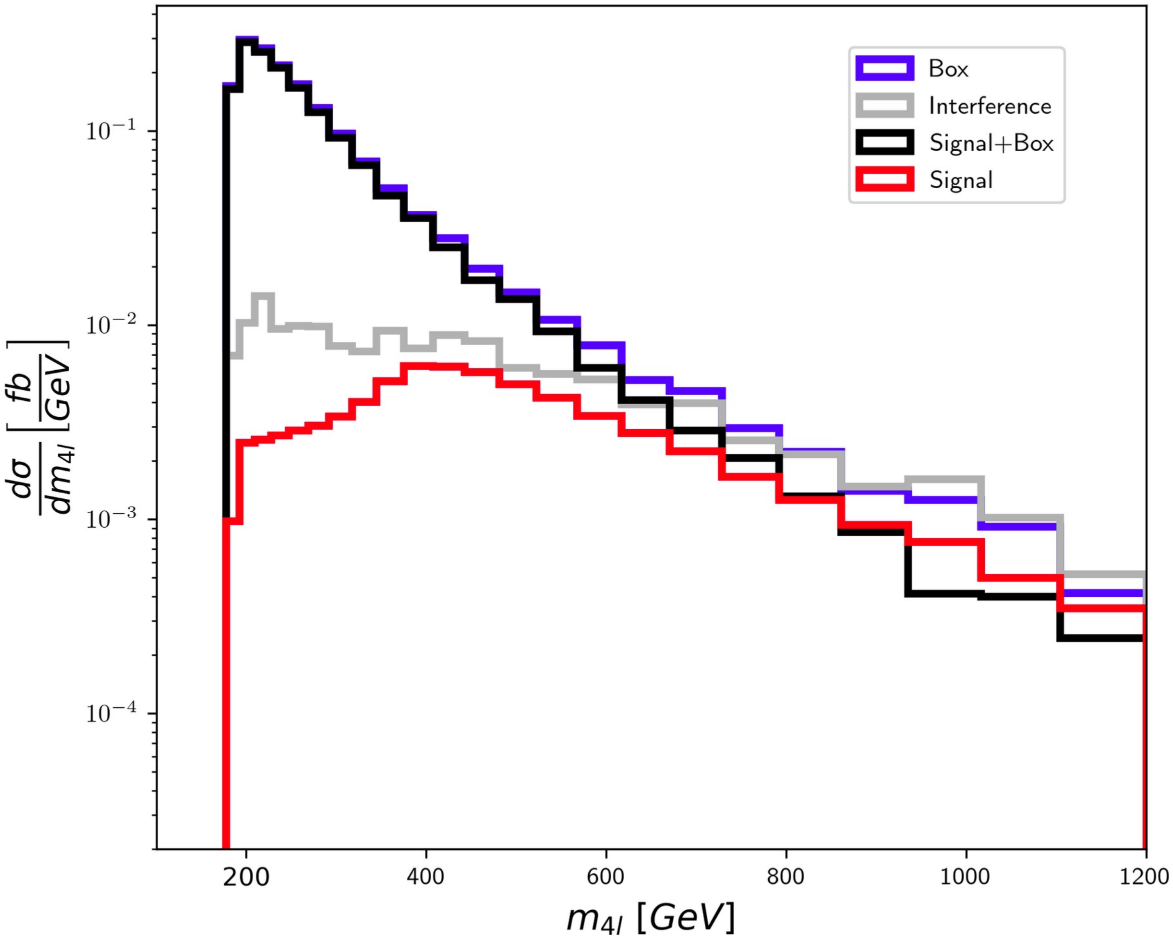
$$\mathcal{M}^{++00}_{\text{triangle}} = +\frac{m_t^2}{2m_Z^2}\log^2\frac{m_{ZZ}^2}{m_t^2}$$

$$\mathcal{M}^{++00}_{\text{box}} = -\frac{m_t^2}{2m_Z^2}\log^2\frac{m_{ZZ}^2}{m_t^2}$$

Destructive interference

2. Off-shell Higgs in the SM

$$\frac{d\sigma_{gg\to ZZ}}{dm_{ZZ}} = \frac{d\sigma_{\text{Sig}}}{dm_{ZZ}} + \frac{d\sigma_{\text{Box}}}{dm_{ZZ}} + \frac{d\sigma_{\text{Int}}}{dm_{ZZ}}$$



MG5@NLOaMC

On-shell Z's

- Signal: gg→h*→ZZ
- Box: gg→ZZ /h
- Total: gg→ZZ
- Interference: Subtraction

m_{4l} >180 GeV

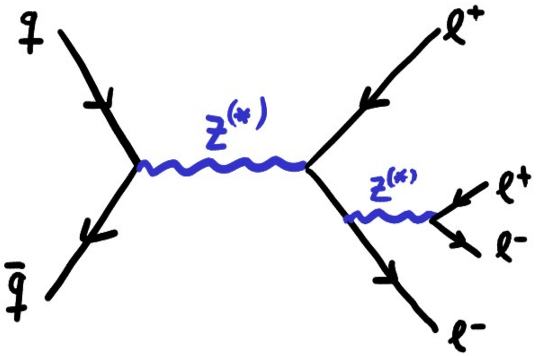
Universal K-factor: 1.76

$$\frac{d\sigma_{gg\to ZZ}}{dm_{ZZ}} = BR^2(Z\to l^+l^-)\frac{d\sigma_{gg\to 4l}}{dm_{4l}}$$

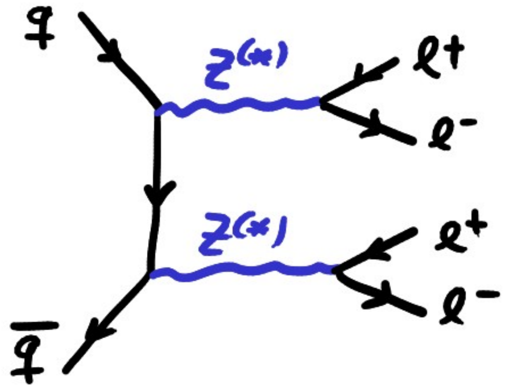
MadAnalysis+MatPlotLib

2. Off-shell Higgs in the SM

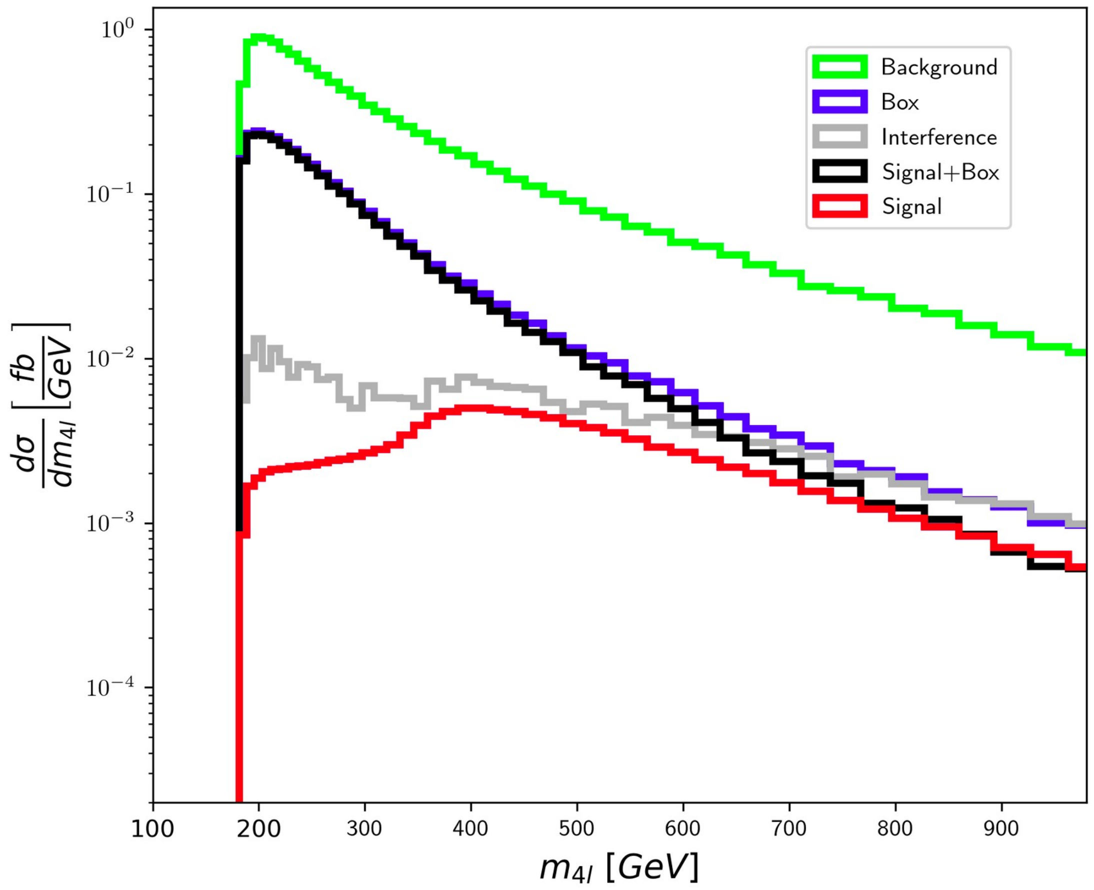
q$\bar{q}$→4l Background: reducible



Dominates near the Z peak

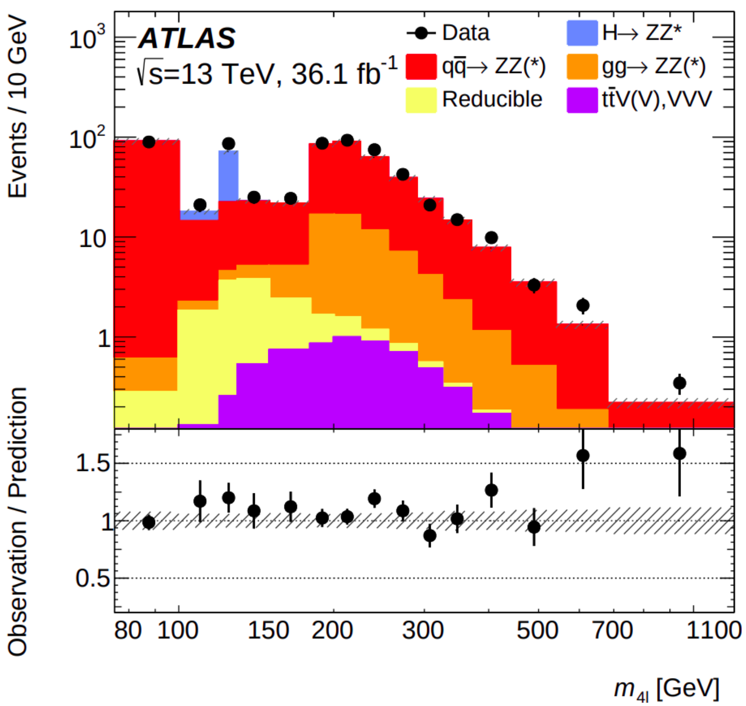


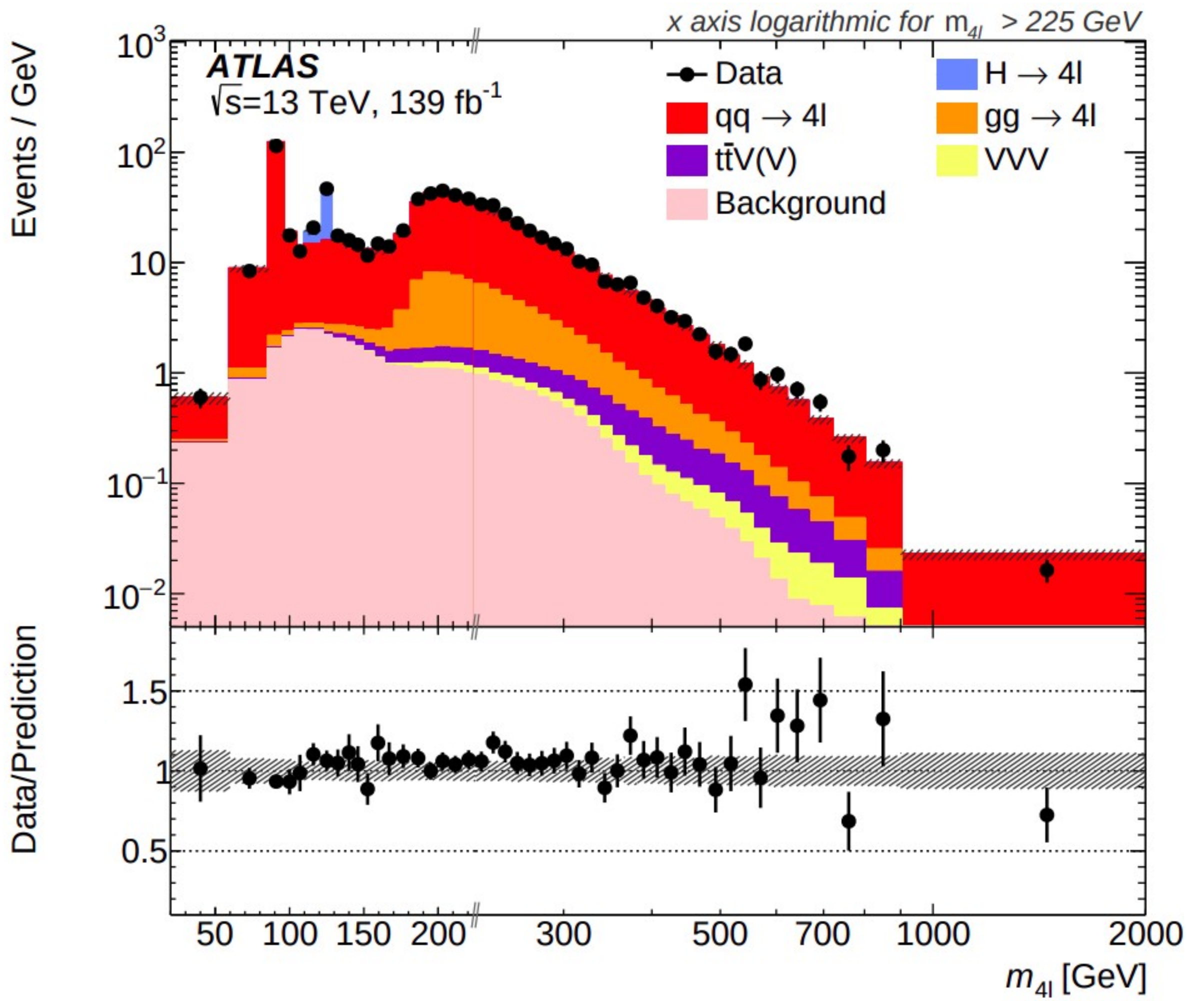
Main background for off-shell region.



2. Off-shell Higgs in the SM

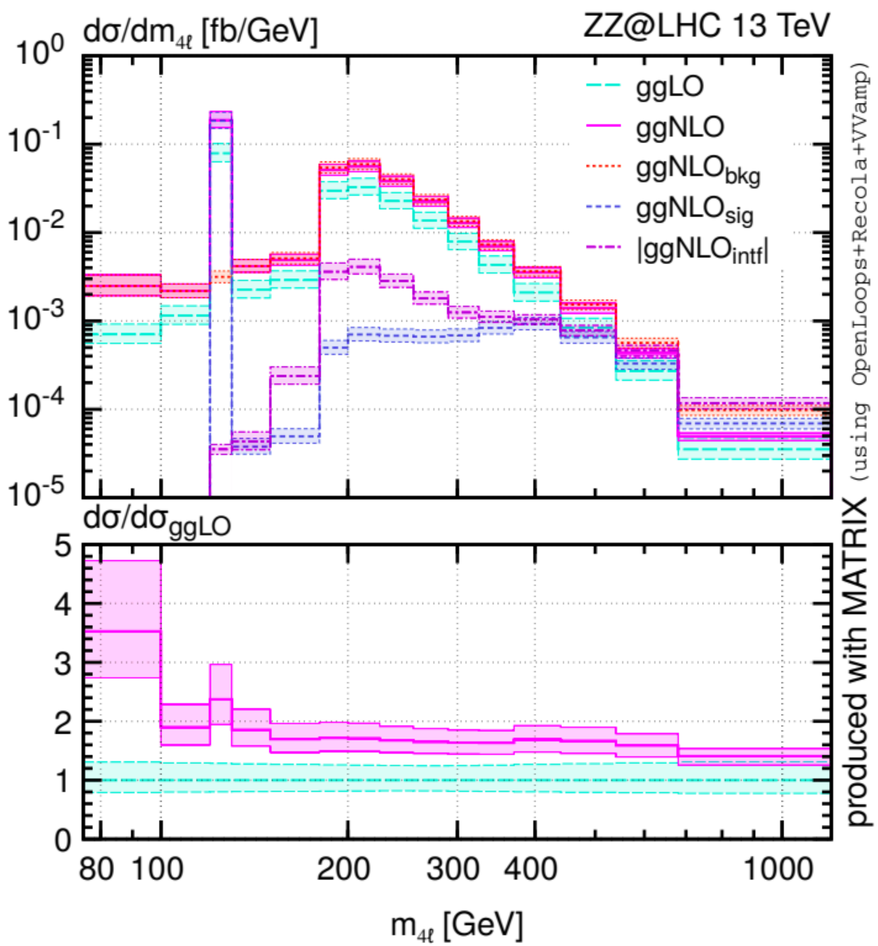
Experimental status

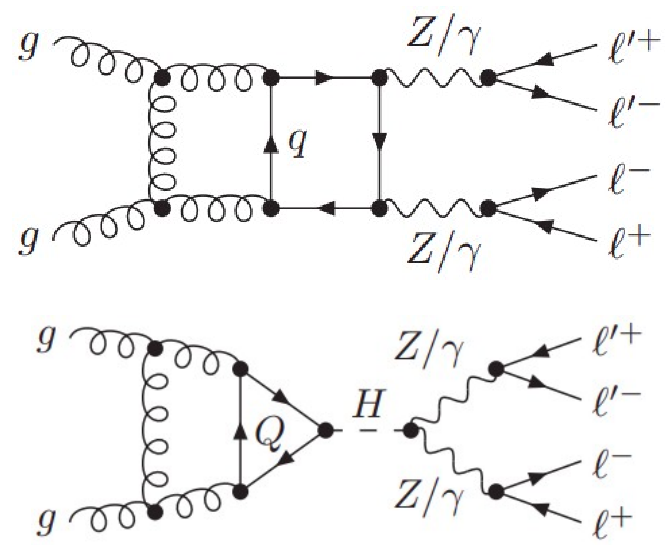




State-of-the-art simulations

- NLO (two-loop) gg→ZZ→4l
- NNLO QCD && NLO EW qq→4l





Large K-factors: +67.3% in m_{4l}>200 GeV region

Part 3

Off-Shell Higgs Beyond the Standard Model

3. BSM off-shell Higgs

So far, all the LHC Higgs measurements are in agreement with the SM

→ **Focus on on-shell Higgs production.**

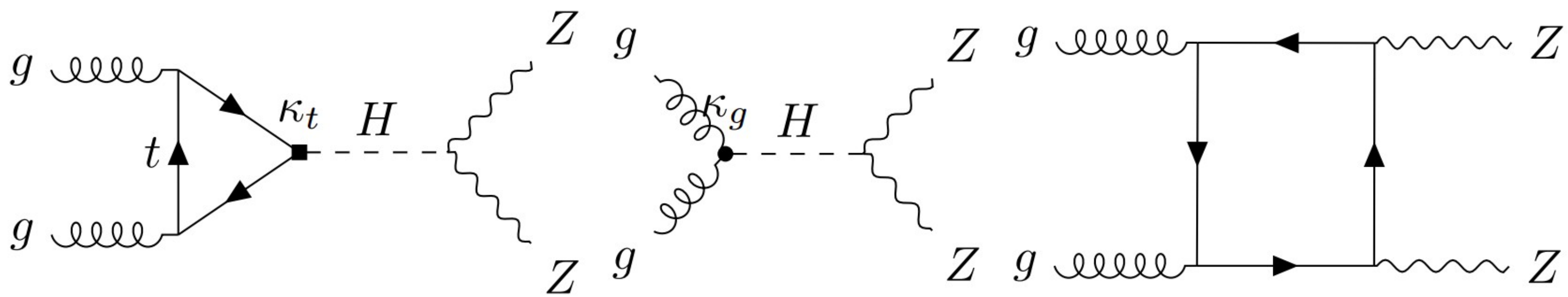
BSM effects should be of order v^2/Λ^2 for the on-shell Higgs.

The off-shell Higgs allow us to probe higher scales ($p \gg v$) with an enhanced p^2/Λ^2 sensitivity over the usual v^2/Λ^2.

- Higgs couplings at higher scales.
- Additional decays and the Higgs width.
- EFT anomalous contributions.
- Momentum-dependent effects.

3. BSM off-shell Higgs

EFT anomalous couplings



$$\mathcal{L} \supset c_g \frac{\alpha_s}{12\pi v^2}|H|^2 G_{\mu\nu}G^{\mu\nu} + c_t \frac{y_t}{v^2}|H|\overline{Q}_L \tilde{H} t_r + h.c.$$

$$= \kappa_g \frac{\alpha_s}{12\pi v^2} h G_{\mu\nu}G^{\mu\nu} - \kappa_t \frac{y_t}{v^2} h(\bar{t}_R t_L + h.c.)$$

$$\kappa_t = 1 - Re(c_t)$$

$$\kappa_g = c_g$$

$$\mathcal{M}^{++00}_{\text{triangle}} = +\kappa_t \frac{m_t^2}{2m_Z^2}\log^2\frac{m_{ZZ}^2}{m_t^2}$$

$$\mathcal{M}^{++00}_{\text{box}} = -\frac{m_t^2}{2m_Z^2}\log^2\frac{m_{ZZ}^2}{m_t^2}$$

$$\mathcal{M}^{++00}_{\text{g}} = -\kappa_g \frac{m_{ZZ}^2}{2m_z^2}$$

Destructive interference (triangle and box)

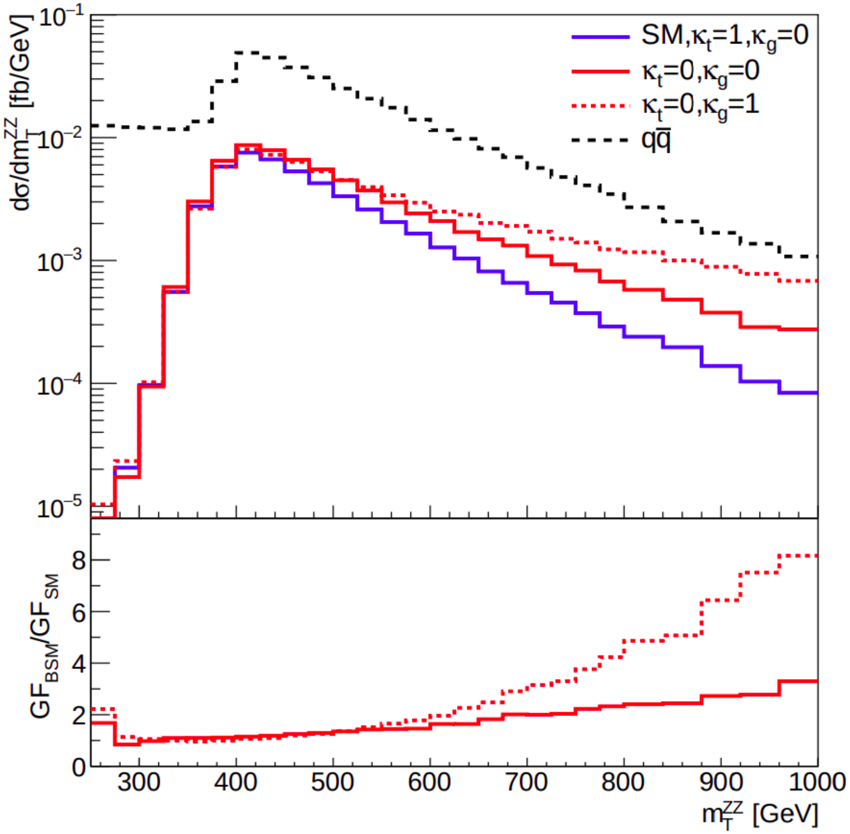
Constructive interference (box and g)

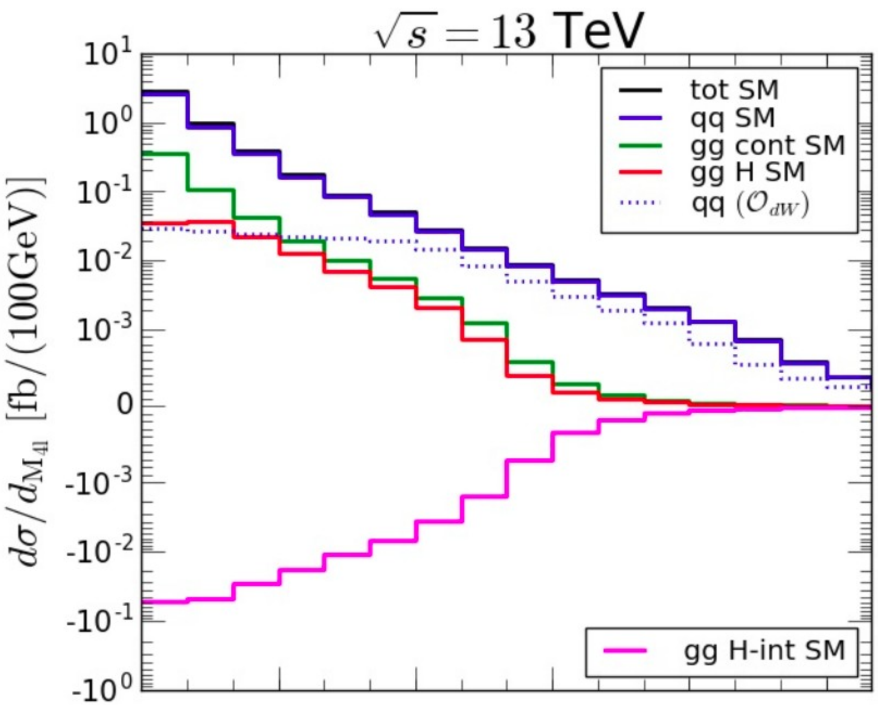
3. BSM off-shell Higgs

Other possibilities:

- Anomalous hVV couplings
- Anomalous Zqq couplings

2012.05272





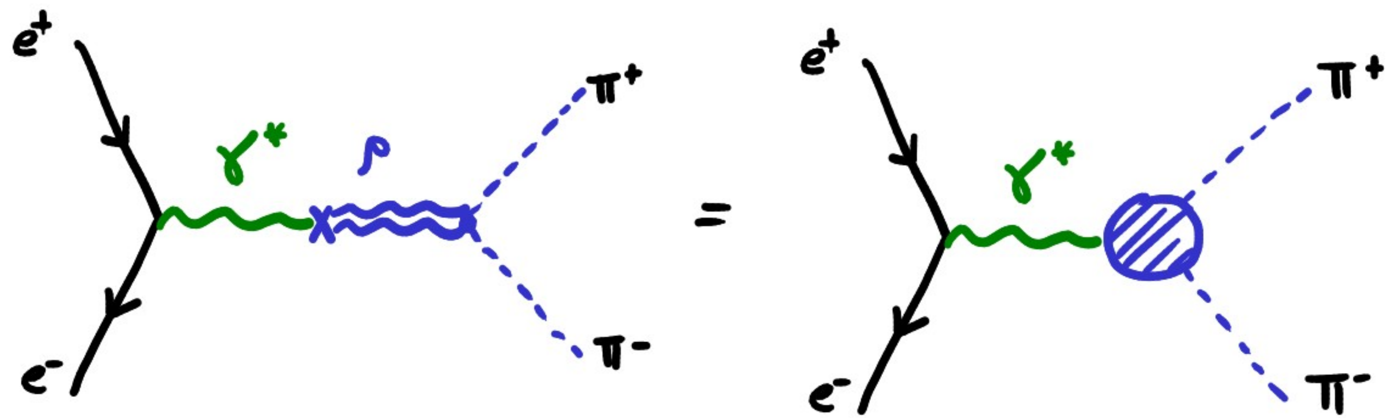
2007.15013

3. BSM off-shell Higgs

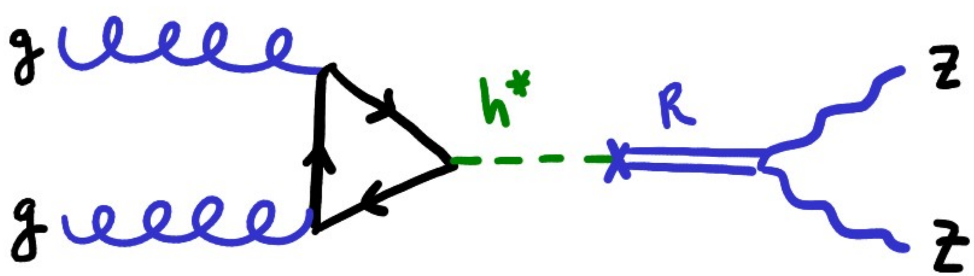
Momentum-dependent effects: Form Factors

Explore compositeness → Non-local momentum dependent Higgs couplings.

Example: Sakurai's Vector Meson Dominance.



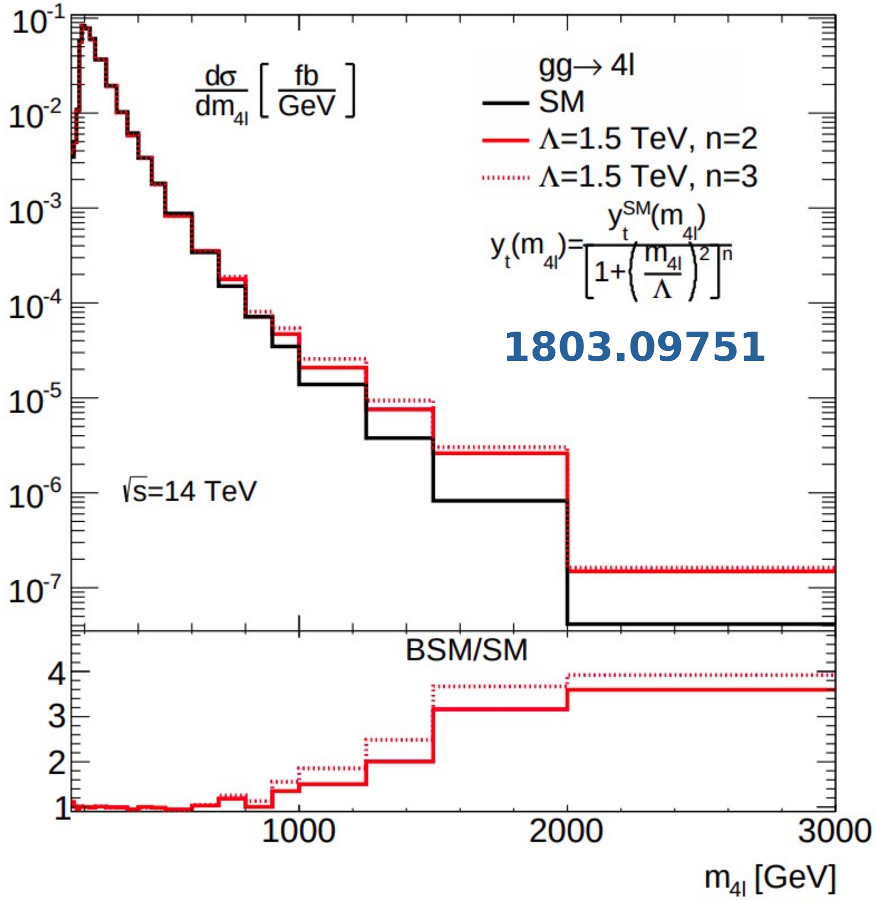
The ρ dominates the EM pion current



$$F(q^2) = \frac{g_R \mu^2}{q^2 - M_R^2}$$

3. BSM off-shell Higgs

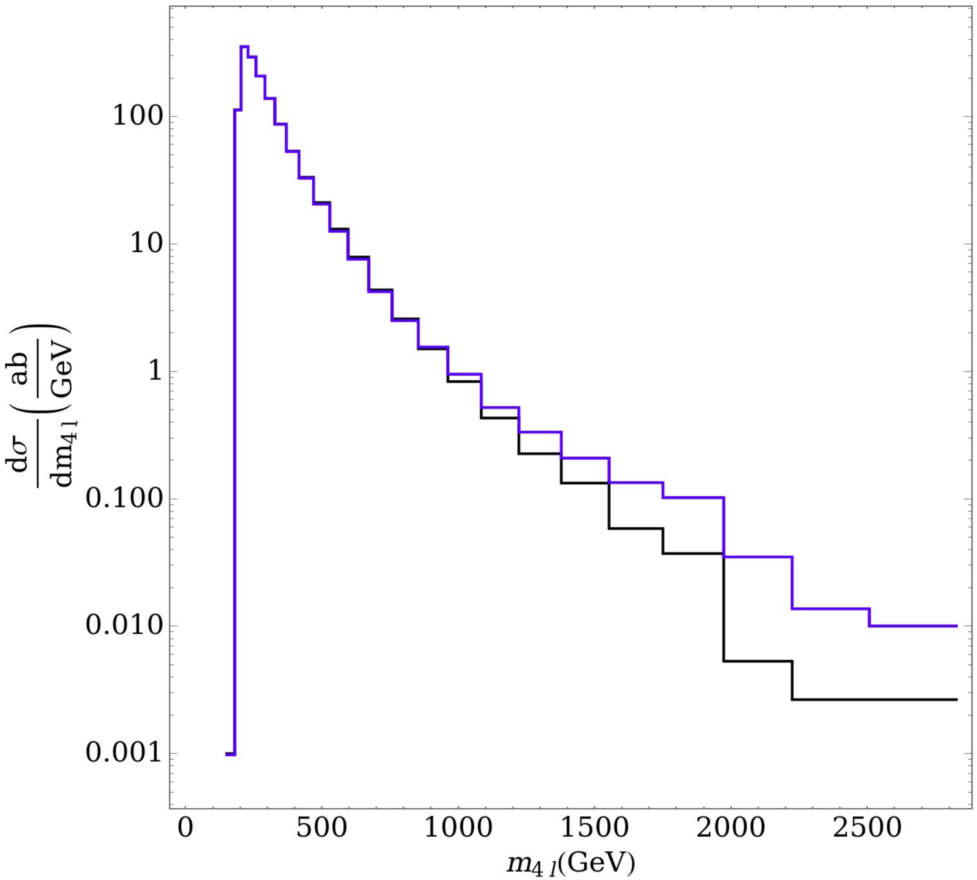
Momentum-dependent effects: Form Factors

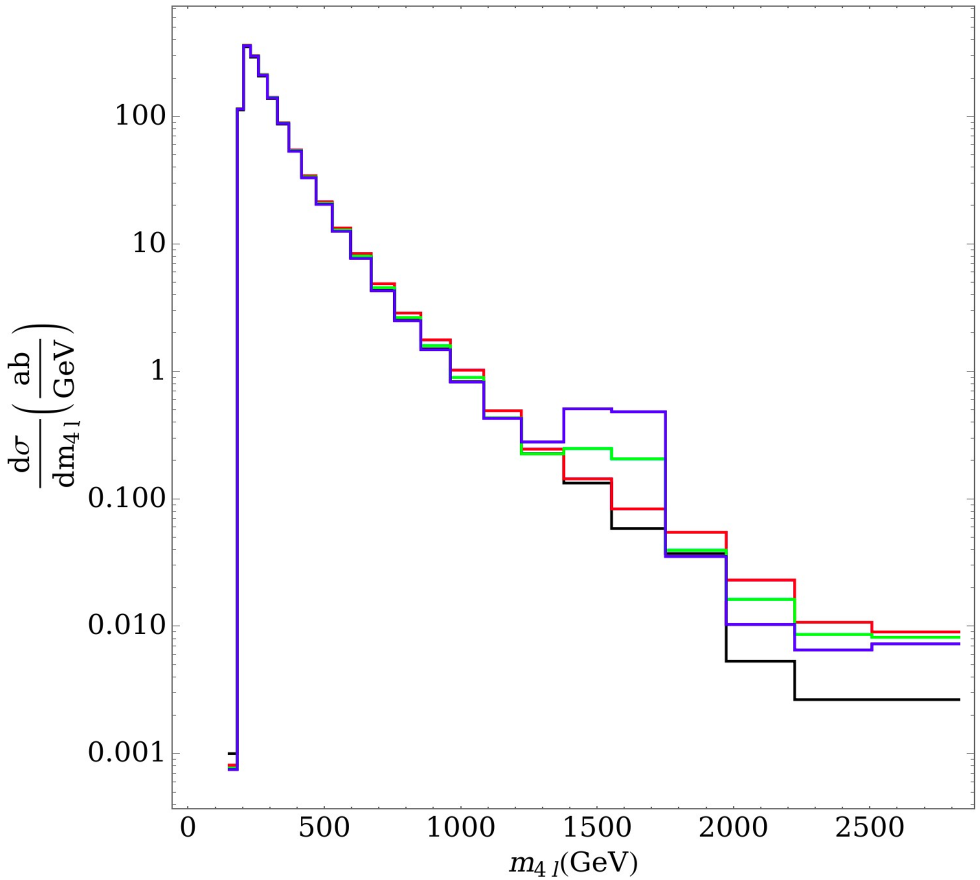


$$F(q^2) = \frac{1}{(1 + q^2/\Lambda^2)^n}$$

3. BSM off-shell Higgs

Momentum-dependent effects: Form Factors





$$F(q^2) = \frac{1}{(1 + q^2/\Lambda^2)^n}$$

$$F(q^2) = \frac{\mu^2}{q^2 - M_R^2 - i\Gamma M_R}$$

3. BSM off-shell Higgs

Momentum-dependent effects in the EFT

$$F(q^2) = c_1 + c_{q^2}\frac{q^2}{\Lambda^2} + c_{q^4}\frac{q^4}{\Lambda^4} + \ldots$$

Induce effective operators like $\frac{c_{q^2}}{\Lambda^2} v\partial^2 h V_\mu V^\mu$

$$\partial^2 h V_\mu V^\mu \to -m_h^2 h V_\mu V^\mu + \frac{3m_h^2}{2v} h^2 V_\mu V^\mu + y_d \bar{d} q V_\mu V^\mu + \ldots$$

Not q^2 dependent

Off-shell sensitivity enhancement is lost in SMEFT since the reduction of the basis eliminates the derivative operators via EoM.

Missing off-shell effects in SMEFT

Conclusions

- Automatization of NLO is broadly available and very useful.
- Choosing between OPP v.s. TIR in MC simulations can save some time.
- Sizable contributions in off-shell Higgs region → Inadequacy of the NWA.
- BSM physics in high energy tails of the off-shell Higgs distributions.

References – Part 1

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References – Part 2

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- Aad, Georges, et al. "**Measurements of four-lepton production in pp collisions at s= 8 TeV with the ATLAS detector.**" Physics Letters B 753 (2016): 552-572.
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- **https://www.hepdata.net/record/ins1849535**

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- Gonçalves, D., Han, T., & Mukhopadhyay, S. (2018). **Higgs couplings at high scales.** Physical Review D, 98(1), 015023.
- Gonçalves, Dorival, et al. "**Off-shell Higgs couplings in $H^* \to ZZ \to \ell\ell\nu\nu$.**" Physics Letters B 817 (2021): 136329.
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- Azatov, Aleksandr, et al. "**Taming the off-shell Higgs boson.**" Journal of Experimental and Theoretical Physics 120.3 (2015): 354-368.

Form Factor tutorial: https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/FormFactors

Backup

Rational terms

$R = R_1 + R_2$

R_1 : Originates from the ε part of the integral denominator.

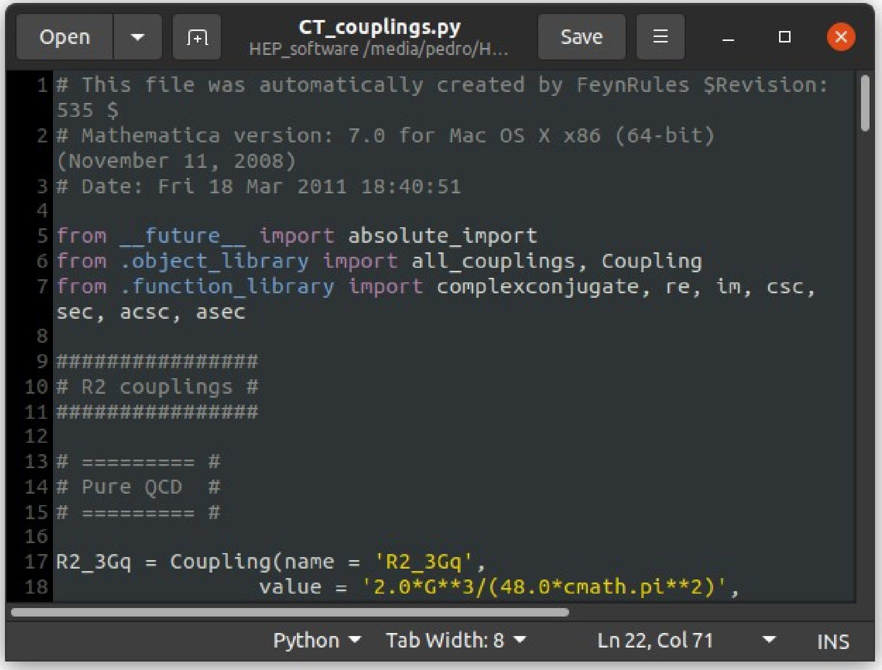
Computed using the reduction methods.

R_2 : Originates from the ε part of the integral denominator.

$$R_2 \equiv \lim_{\epsilon \to 0} \sum_{c}^{N_c} C^{(c)} \sum_{t}^{N_t} \int d^d \bar{q} \, \frac{\tilde{\mathcal{N}}^{(c,t)}(\bar{q})}{\bar{D}_0^{(t)} \cdots \bar{D}_{N_t}^{(t)}}$$

R2 Counterterms must be included in UFO model.

Feynrules level.




```
# This file was automatically created by FeynRules $Revision:
535 $
# Mathematica version: 7.0 for Mac OS X x86 (64-bit)
(November 11, 2008)
# Date: Fri 18 Mar 2011 18:40:51

from __future__ import absolute_import
from .object_library import all_couplings, Coupling
from .function_library import complexconjugate, re, im, csc,
sec, acsc, asec

################
# R2 couplings #
################

# ========= #
# Pure QCD  #
# ========= #

R2_3Gq = Coupling(name = 'R2_3Gq',
                value = '2.0*G**3/(48.0*cmath.pi**2)',
```

Bounding the Higgs width

Constraints set by considering the relationship between the on-shell (105<m4l<140GeV) and off-shell (m4l> 220GeV) regions.

$$\sigma^{\text{on-shell}}_{\text{vv}\to\text{H}\to4\ell} \propto \mu_{\text{vvH}} \quad \text{and} \quad \sigma^{\text{off-shell}}_{\text{vv}\to\text{H}\to4\ell} \propto \mu_{\text{vvH}}\,\Gamma_{\text{H}}$$

$$\hookrightarrow \sigma^{\text{on-shell}}_{i\to H\to f} \propto \frac{g_i^2(m_H)g_f^2(m_H)}{\Gamma_H}$$

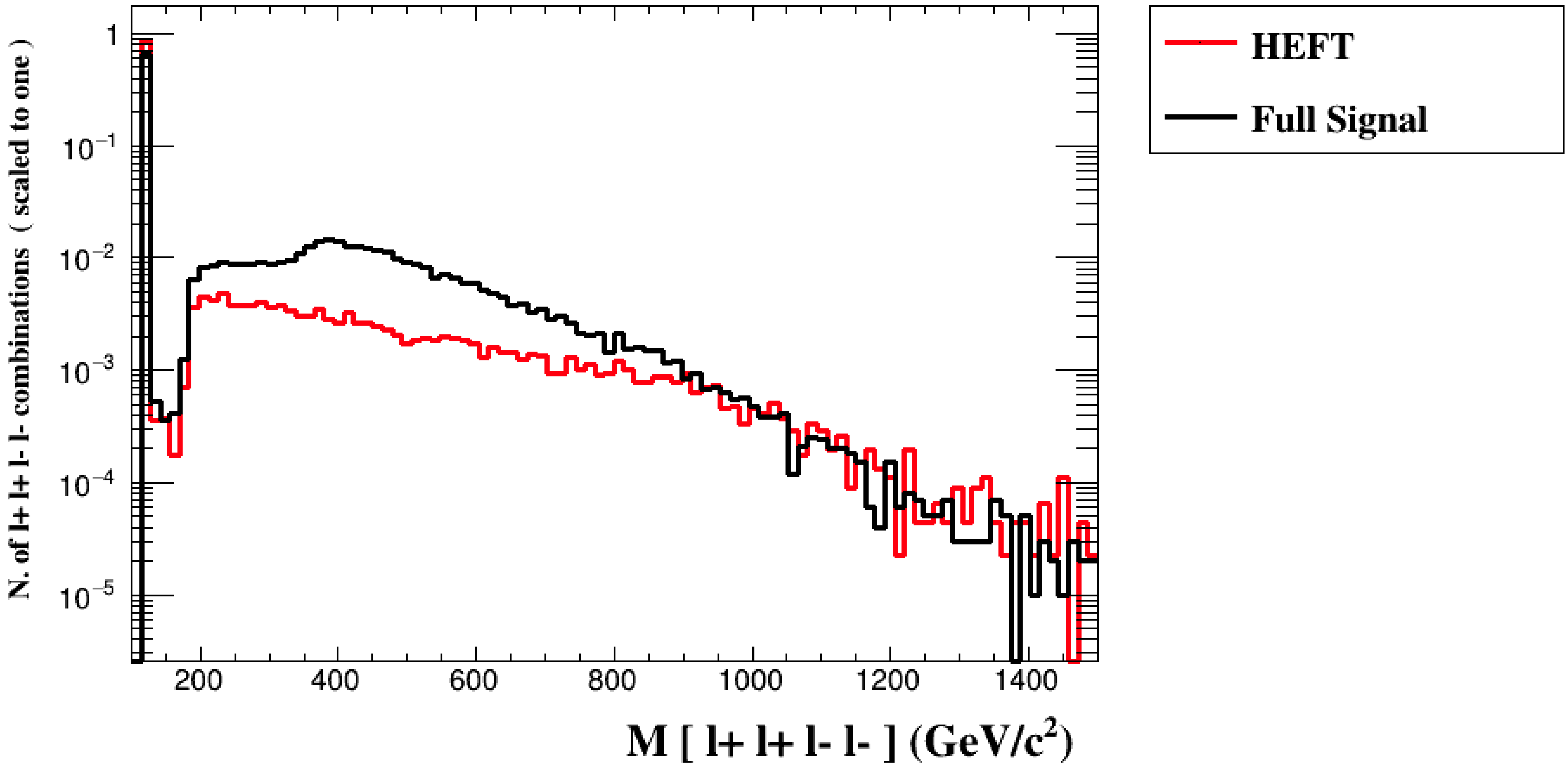
On-shell degeneracy

$$g_{i,f}(m_H) \to \xi g_{i,f}(m_H)$$
$$\Gamma_H \to \xi^4\Gamma_H$$

$$\hookrightarrow \sigma^{\text{off-shell}}_{i\to H^*\to f} \propto g_i^2(\sqrt{\hat{s}})g_f^2(\sqrt{\hat{s}})$$

$$\boxed{\mu_{\text{off-shell}}/\mu_{\text{on-shell}} = \Gamma_H/\Gamma_H^{SM}}$$

Full Off-shell Higgs v.s. heft

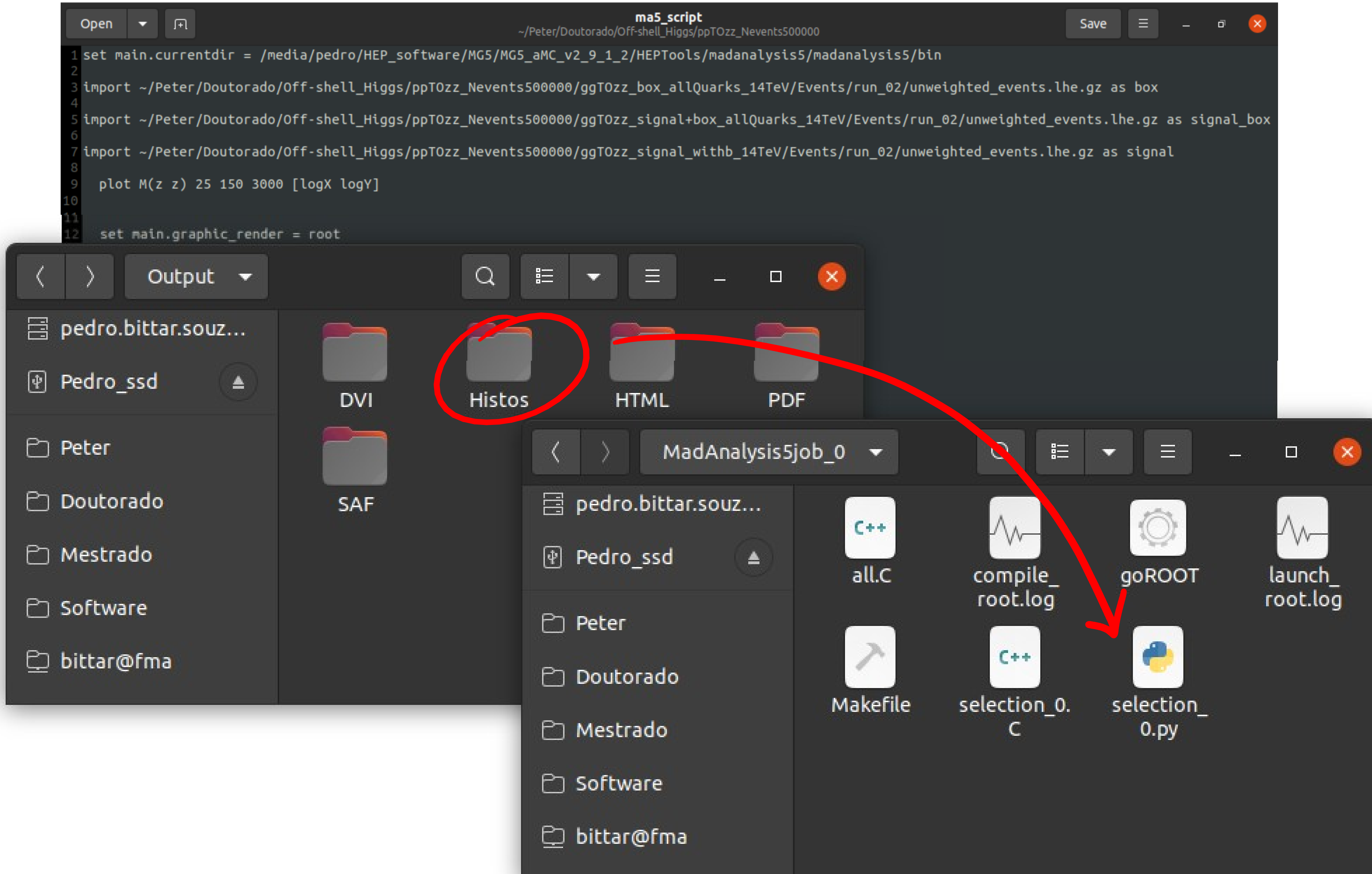


MadAnalysis + MatPlotLib

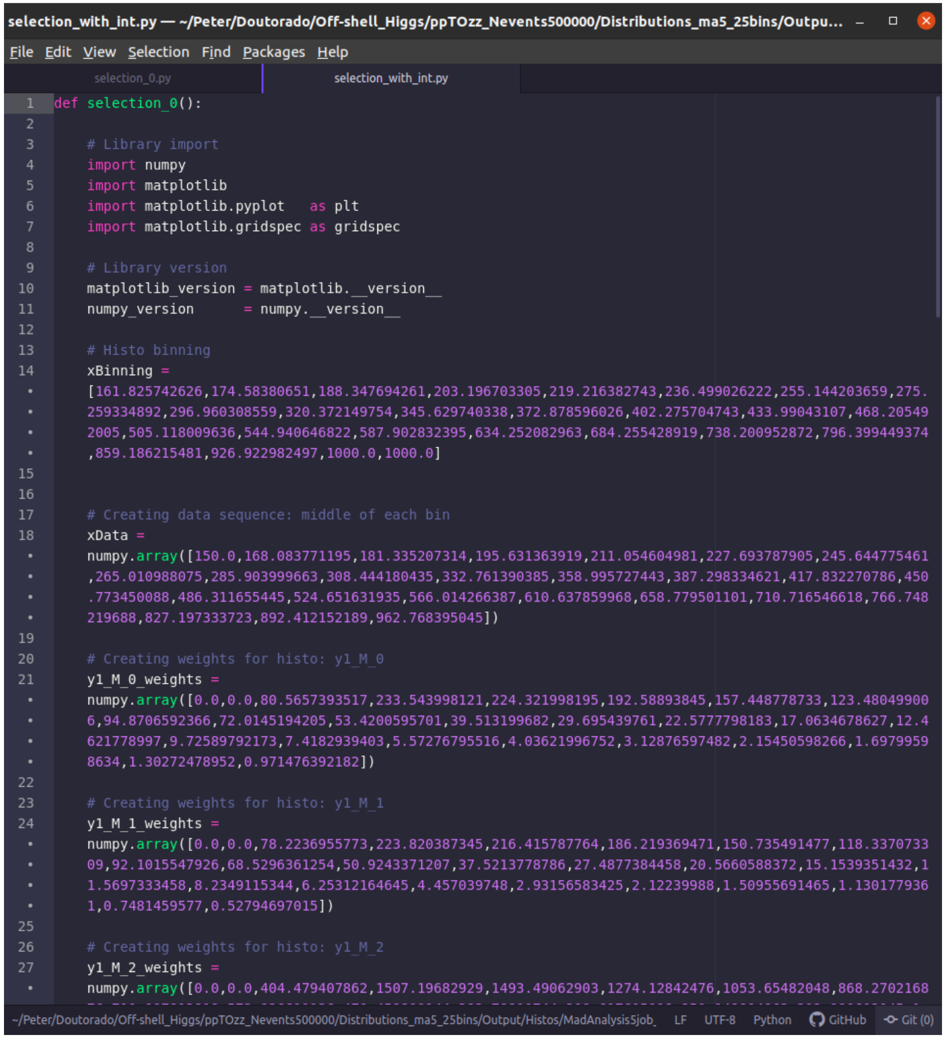
ma5_script
~/Peter/Doutorado/Off-shell_Higgs/ppTOzz_Nevents500000

```
set main.currentdir = /media/pedro/HEP_software/MG5/MG5_aMC_v2_9_1_2/HEPTools/madanalysis5/madanalysis5/bin

import ~/Peter/Doutorado/Off-shell_Higgs/ppTOzz_Nevents500000/ggTOzz_box_allQuarks_14TeV/Events/run_02/unweighted_events.lhe.gz as box

import ~/Peter/Doutorado/Off-shell_Higgs/ppTOzz_Nevents500000/ggTOzz_signal+box_allQuarks_14TeV/Events/run_02/unweighted_events.lhe.gz as signal_box

import ~/Peter/Doutorado/Off-shell_Higgs/ppTOzz_Nevents500000/ggTOzz_signal_withb_14TeV/Events/run_02/unweighted_events.lhe.gz as signal

  plot M(z z) 25 150 3000 [logX logY]


  set main.graphic_render = root

  set signal.title = "Signal"
  set signal.backcolor = none
  set signal.linewidth = 3
  set signal.linecolor = black

  set box.title = "Box"
  set box.backcolor = none
  set box.linewidth = 3
  set box.linecolor = grey

  set signal_box.title = "Signal+Box"
  set signal_box.backcolor = none
  set signal_box.linewidth = 3
  set signal_box.linecolor = blue


  set main.lumi = 1
  set main.stacking_method = superimpose
  submit ~/Peter/Doutorado/Off-shell_Higgs/ppTOzz_Nevents500000/Distributions_ma5
```

MadAnalysis + MatPlotLib



MadAnalysis + MatPlotLib



Modify weights, add K-factor ...

```
# Creating a new Stack
BR = 0.034
Kfactor=1.76 #arxiv 1311.3589
y1_M_0_weights = Kfactor*BR**2*pbtofb*y1_M_0_weights
y1_M_1_weights = Kfactor*BR**2*pbtofb*y1_M_1_weights
y1_M_2_weights = BR**2*pbtofb*y1_M_2_weights
y1_M_3_weights = Kfactor*BR**2*pbtofb*y1_M_3_weights
interf = -y1_M_1_weights+y1_M_3_weights+y1_M_0_weights
```