Phenomenological tools for the next SM

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Disclaimer

- I do NOT report on the status of my PhD project
- I do report on the part of the HT handbook I'm taking care of
- I do assume you didn't look into it
- this concerns the 3rd chapter of the 2nd working group $\rightarrow$ 2.3

Summary of chapter (2.)3 of the handbook

Of course, as a member of a team

- I am responsible for the other parts in the project
- other people contributed to this part of the project

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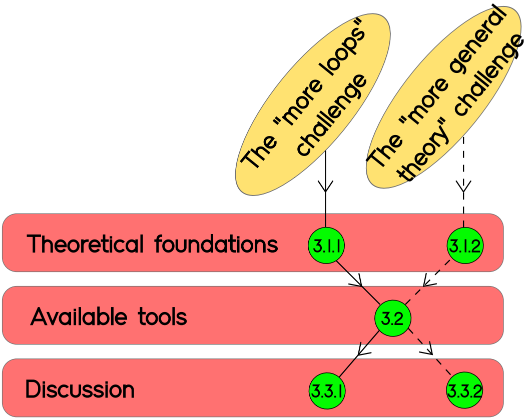
† eventually included in the 'Tools section' for lack of content


The "more loops" challenge
The "more general theory" challenge
Theoretical foundations
3.1.1
3.1.2
Available tools
3.2
Discussion
3.3.1
3.3.2

In section 1 (see Giulia's talk)

- κ-framework has been discussed
- flaws have been recognised and illustrated

$\Rightarrow$ κ framework successfully used, but need an upgrade for Run 2

It is important to understand limitations and figure out improvements, but in order to

- interface theory and experiment
- maximise the profit of LHC

$\Rightarrow$ Specific tools are required no new tools $\Rightarrow$ no observations of NP!!!

Also, be careful with simplifications...

- of course it is necessary in many cases
- could lead to high uncertainty (e.g. in theory)

$\Rightarrow$ very important to find the right balance

Goal of chapter 3 is

- give a short overview of MC generators available on the market
- present theoretical basis that underpin the implementations
- as for the phenomenological models
  - which are already usable? (i.e. tool already available)
  - which does exist only in the phenomenologists mind? (i.e. still no implementation available)

- Discussion on
  - easy improvements that could be easily implemented
  - impact of such improvements?

  So far
  - the most ambitious part of chapter 3
  - nothing came out. . .

Goal:

- Give an idea on the challenges to improve precision in theoretical predictions
- Prepare the reader to the "tools section"
- NLO is a standard in QCD
  - many processes known also at NLO QCD and EW
  - two Higgs production channels up to N3LO (!)

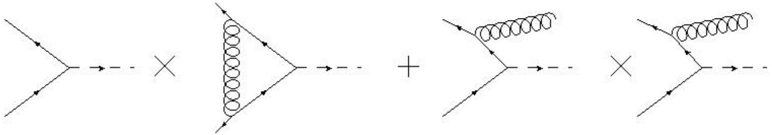
Generally speaking

$$\alpha_{\mathsf{EW}} \sim \alpha_{\mathsf{S}}^2$$

$$\mathsf{N}^j\mathsf{LO\ EW} \sim \mathsf{N}^{j+1}\mathsf{LO\ QCD}$$

automation (i.e. process-indep.) up to NLO QCD

Must consider



Two types of contribution

- virtual
- real

⇒ Two types of divergence

- IR in tree-level (soft, collinear)
- UV in loop diagrams

$\Rightarrow$ Two cancellations, arising from

- phase-space integration (KLM theorem)
- renormalization procedure

$\Downarrow$

Challenges for automation

- handling infinities in numerical integration
- renormalization procedure (model-dependent)

Fact: best predictions are provided for SM (or a well-defined BSM theory)

- valuable results, of course!
- as we don't know about the next SM, less model-dependency in automation is desirable

κs as an example, but more solid theoretical foundations and/or more BSM features

$\Downarrow$

Phenomenological models

- introduced to mimic BSM phenomenology
- NOT a specific BSM model

Phenomenological models

- Pros:
  - less free parameters $\{p_i\}$ than full EFT
  - not completely model-indep., but better than complete BSM theory
- Cons:
  - must be chosen carefully
  - must be used carefully

Not necessary to redo analysis when theory predictions improve

Constraints on $\{p_i\}$ can be mapped to constraints on parameters of full BSM theory, indicating the right direction in the space of possible theories

Still limited theoretical consistence

Keep in mind what is allowed within a given pheno model

Considered models/frameworks are (so far)

- Strongly-Interacting Light Higgs (SILH)
  [Giudice,Grojean,Pomarol,Rattazzi 2007]
  [Contino,Ghezzi,Grojean,Muhlleitner,Spira 2013]
- Higgs Characterization framework
  [Artoisenet,. . . 2013]
- BSM Characterization framework
  [Falkowski 2016]

SILH

- SM supplemented by a heavy, strongly-interacting sector
- Higgs is a CP-even weak scalar doublet
- baryon and lepton numbers are conserved
- written in terms of gauge eigenstates

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{\text{SM}} + \Delta\mathcal{L}_{\text{SILH}} + \Delta\mathcal{L}_{F_1} + \Delta\mathcal{L}_{F_2}$$

Equivalent to Warsaw basis

Lots of free parameters!

Higgs Characterization

- operators invariant under $SU(2)_L \times U(1)_Y$
- the 125 GeV resonance has spin $0, 1$ or 2
- only operators that enter three-point Higgs interactions
- only operators affecting one Higgs field
- written in terms of mass eigenstates

Extremely compact

Example: fermion-Higgs Lagrangian for spin-0

$$\mathcal{L}_0^f = -\sum_f \bar{\psi}_f (c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff} \gamma_5) \psi_f X_0$$

Good for LO, and not in all processes involving Higgs

BSM Characterization

Extension of the Higgs Characterization framework, written in terms of mass eigenstates

- equivalent to Warsaw basis
- more transparent connection to measurable quantities

Goal: give a general description of some commonly used tools/techniques

3.2.1 `MadGraph5_aMC@NLO`

[Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro 2014]

3.2.2 `POWHEG`

[Nason 2004]

[Frixione, Nason, Oleari 2007]

[Alioli, Nason, Oleari, Re 2010]

3.2.3 Tools for EW corrections (SM)

MadGraph5_aMC@NLO

In principle

Monte Carlo generator for arbitrary process up to NLO, in a wide variety of models

Practically

- NLO QCD in SM

⇒ very flexible, can be interfaced with other tools

UFO standard

- LO straightforward in any BSM model (e.g. from FeynRules)
- NLO requires more work (?)

Used for

- Higgs Characterization framework
- BSM Characterization framework
- ...

see FeynRules Model database

http://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

POWHEG

Not meant to be fully general (differently from MadGraph5_aMC@NLO)

- calculations are implemented one-by-one
- different methods for different processes

Not suitable for model-independent studies

Full NLO for many calculations (EW + QCD)

Reweighting

Give as example what proposed in [Biedermann, Denner, Dittmaier, Hofer, Jager 2016] for the NLO EW corrections to the process $pp \to ZZ \to 4l$.

Best possible predictions can be obtained by combination of

- most accurate QCD predictions
- electroweak corrections

$\Rightarrow$ Reweight the differential distributions @ NLO QCD with EW correction factors

What still has to be done in Chapter 3

- some sections are still incomplete (see repo)
- “Discuss discussion” (just drop it?)
- check and polish

My contributions in other sections

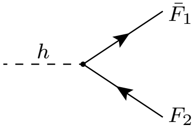
κ framework NLO example (in Chapter 1, see Giulia's talk)

Goal: show inconsistency of κ framework when computing

$h \to b\bar{b}$ decay width @ NLO

In a "simplified κ framework" i.e. SM with

only one coupling modifier κ_{ffS}



$$= ie\,\kappa_{ffS}\left(C_L\frac{1-\gamma_5}{2} + C_R\frac{1+\gamma_5}{2}\right),$$

$S\bar{F}_1F_2$	$h\bar{f}_if_j$	$\chi\bar{f}_if_j$	$\phi^+\bar{u}_id_j$	$\phi^-\bar{d}_ju_i$
C_L	$-\frac{1}{2s}\frac{m_{f,i}}{M_W}\delta_{ij}$	$-\frac{i}{2s}2I^3_{W,f}\frac{m_{f,i}}{M_W}\delta_{ij}$	$\frac{1}{\sqrt{2}s}\frac{m_{u,i}}{M_W}V_{ij}$	$-\frac{1}{\sqrt{2}s}\frac{m_{d,j}}{M_W}V^\dagger_{ji}$
C_R	$-\frac{1}{2s}\frac{m_{f,i}}{M_W}\delta_{ij}$	$\frac{i}{2s}2I^3_{W,f}\frac{m_{f,i}}{M_W}\delta_{ij}$	$-\frac{1}{\sqrt{2}s}\frac{m_{d,j}}{M_W}V_{ij}$	$\frac{1}{\sqrt{2}s}\frac{m_{u,i}}{M_W}V^\dagger_{ji}$

The NLO matrix element

$$\mathcal{M} = \mathcal{M}_0 \left[1 + \frac{\alpha}{4\pi} \left(\delta_{\text{loop}} + \delta_{\text{CT}} \right) \right]$$

is computed, and it is shown that

$$\mathcal{M}\Big|_{\text{UV}} = \frac{\alpha}{4\pi} \frac{\mathcal{M}_0}{4 s^2 M_W^2} \Delta \left(1 - \kappa_{ffS}^2\right) \left(\sum_l m_l^2 + 3 \sum_q m_q^2 \right)$$

$\neq 0$ for $\kappa_{ffS} \neq 1$

$\Rightarrow \mathcal{M}$ gets a UV-divergent contribution

The BFM has been introduced to preserve gauge invariance in every step of the calculation of a physical quantity

quantization without losing gauge invariance

Basic idea:

split fields $\phi_i \to \hat{\phi}_i + \phi_i$ in $\mathcal{L}$

After splitting:

- $\hat{\phi}_i$ classical field
- ϕ_i quantum fluctuation

Good bookkeeping framework to integrate out heavy degrees of freedom from the path integral, indeed in $\mathcal{L}$ (after splitting classical and quantum)

- coupling terms with exactly one quantum field (e.g. $\propto \phi_1 \hat{\phi}_2^2$) are not relevant for one-loop diagrams
- coupling terms with more than two quantum fields (e.g. $\propto \phi_1 \phi_2^2$) are only needed beyond one loop

$\Rightarrow$ care about $\propto \phi_i \phi_j$

$\Rightarrow$ path integral over a heavy DOF takes a Gaussian form

Summary

So far

- coordinate writing of Chapter (2.)3, bridge between κ-framework and EFTs
  - theory is discussed
  - some tools are presented
- worked out
  - pedagogical example of NLO calculation in κ-framework
  - paragraph on BFM in Chapter (2.)4

TODOs in Chapter 3

- fill in missing/incomplete parts
- check and polish the text