PO's and NLO couplings at LHC

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to Andrè David and Michael Duehrssen for keeping me away from elliptic polylogarithms and busy with dreams

outline The Higgs coupling vademecum

① Never introduce quantities that are not well-defined

② the Higgs couplings can be extracted from Green's functions in well-defined kinematical limits

☛ e.g. residue of the poles after extracting the parts which are 1P reducible

These are well-defined QFT objects, that we can probe both in production and in decays. From this perspective, VH or VBF are on equal footing with ggF and Higgs decays

Now, some general considerations ...

At LEP we had the SM with one missing ingredient, therefore the strategy was:

☞ Test the SM hypothesis versus M_{H}

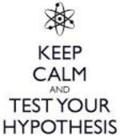
a) Fit FOs to derive $M_{\mathrm{H}}, \alpha_{\mathrm{s}}(M_{\mathrm{Z}})$ etc.

b) Introduces POs, fit them, compute them, fit $M_{\mathrm{H}}, \alpha_{\mathrm{s}}(M_{\mathrm{Z}})$ etc.

At LHC the SM is complete, therefore the strategy is:

☛ Study SM-deviations, which requires a larger environment, e.g. EFT (for the whole set of processes)

Beyond the SM, from the predictive (SM) phase to the “partially predictive (fitting)” one.



HEP phases

- PREDICTIVE phase: in any (strictly) renormalizable theory with $\boldsymbol{n}$ parameters you need to match $\boldsymbol{n}$ data points, the $(\boldsymbol{n}+\mathbf{1})$th calculation is a prediction, e.g. as doable in the SM
- FITTING (approximate predictive) phase: there are $(\boldsymbol{N_6}+\boldsymbol{N_8}+\cdots=\boldsymbol{\infty})$ renormalized Wilson coefficients that have to be fitted, e.g. measuring SM deformations due to a single $\mathscr{O}^{(6)}$ insertion ($\boldsymbol{N_6}$ enough for per mille accuracy)

of the POs

TH 

To give a conventional, QFT-compatible, definition of non-existing quantities

EXP 

To avoid having to redo the analysis if theory changes

☞ Of course, EXPs could stick to fiducial observables

☛ Of course, Run II could show NP at the screen level

Fiducial answers

☞ ATLAS/CMS should publish their fiducial cross sections (this was not the case at Lep), “fiducial” and “pseudo” are alternative but not antithetic

☛ ATLAS/CMS will discover the anti-Higgs[1] (opening the road for Higgsogenesis), X-Kryptonite[2] etc. Does that change the issue?

I don’t think so. Studying SM deviations or trying to understand how the Higgs also interacts with dark matter requires understanding SM/BSM couplings/properties that are universal and not volume dependent.

[1] Tulin and Servant, PRL

[2] Action Comics 261 (Jan. 1960)

The LHC problem[3]

Generally speaking, at LHC the EW core is always embedded into a QCD environment, subject to large perturbative corrections and we expect considerable progess in the "evolution" of these corrections. Even worse is the situation when the t-quark is involved (multi-scale, two classes of logarithms to be resummed). The same considerations apply to PDFs when studying high-mass (large x) final states.

☛ Does it make sense to 'fit' the EW core? Note that this is not confined to introducing POs.

☞ If your answer is "stay fiducial", please use next exit.

[3] discussing with S. Forte

From Lep to LHC

1. What POs do is just collapsing (and/or transforming) some "primordial quantities" (say number of observed events in some pre-defined set-up) into some "secondary quantities" which we fill closer to the theoretical description of the phenomena.

2. if the number of quantities is reduced, this implies that

   ☛ some assumptions have been made on the behaviour of the primordial quantities

   The validity of these assumptions is judged on statistical grounds. Within these assumptions (for Lep: QED deconvolution, resonance approach, etc.) the secondary quantities are as "observable" as the first ones.

Therefore, the LHC problem is a) list the assumptions, b) judge them on statistical grounds

What will happen when theory changes (e.g. new higher order included)? Consider primordial POs: the κ-framework.

☞ The κ-framework, as seen from the point of view of EFT, allows you to deform both S and B in a consistent way. All “dynamical” parts are SM induced and they are deformed by constant κ-parameters, e.g.

$$\begin{aligned}\rho_{\mathrm{H}}^{\gamma\mathrm{Z}} = \mathscr{A}(\mathrm{H} \to \gamma\mathrm{Z}) \quad &= \quad \kappa_{\mathrm{W}}^{\gamma\mathrm{Z}}\,\mathscr{A}_{\mathrm{W}}^{(4)} + \kappa_{\mathrm{t}}^{\gamma\mathrm{Z}}\,\mathscr{A}_{\mathrm{t}}^{(4)} + \kappa_{\mathrm{b}}^{\gamma\mathrm{Z}}\,\mathscr{A}_{\mathrm{b}}^{(4)} + i\,g g_6\,\frac{M_{\mathrm{H}}^2}{M_{\mathrm{W}}}\,a_{\mathrm{AZ}} \\ &+ \quad a_{\phi D}\,\mathscr{A}_{\mathrm{W}}^{\mathrm{NF}} + \sum_{\mathrm{f=t,b}} \left(a_{\phi \mathrm{q}}^{(3)} - a_{\phi \mathrm{q}}^{(1)} - a_{\phi \mathrm{f}} \right) \mathscr{A}_{\mathrm{f}}^{\mathrm{NF}}\end{aligned}$$

If the calculation is at some given order and the κ-parameters have been fitted, then apply the “new” K-factor and derive the updated (κ) deviation. $\kappa_{\mathrm{new}} = \kappa_{\mathrm{old}} / \mathrm{K}$

Of course, this cannot be trivially extended to PDFs or to QED/QCD final state radiation etc.
This means that (understating the problem) we face a decomposition

$$\mathbf{FO} = \mathbf{PO} \otimes \mathbf{T}_{\textbf{remnant}} \qquad \otimes \mapsto \quad \text{convolution}$$

and the choice of PO must be such that $\mathbf{T}_{\textbf{remnant}}$ is not a source of large errors due to bias (as using a phonebook to select participants in a survey). For example, as more terms are added to $\mathbf{T}_{\textbf{remnant}}$, the greater the resulting model's complexity will be. This represents a severe constraint on our "conventional" choice of POs. Optimally, part of the factorizing QCD corrections could enter the PO definition.

The κ-framework: origin and problems.

The original framework is defined in **e-Print: arXiv:1209.0040** and has the following limitations:

- ☛ no κ touches kinematics. Therefore it works at the level of total cross-sections, not for differential distributions
- ☛ it is LO, partially accomodating factorizable QCD but not EW corrections
- ☛ ☛ it is not QFT-compatible (ad-hoc variation of the SM parameters, violates gauge symmetry and unitarity)

Proposition

NLO EFT provides the general framework★ for consistent calculation of higher orders and allows for global fits, superseding any ad-hoc variation of the SM parameters. Furthermore, it allows for consistently branching out loops in loop-induced processes, in the spirit of the original framework.

★) within a (well defined) set of assumptions

EFT perturbative expansion

$$\mathscr{A} = \sum_{n=\mathrm{N}}^{\infty} g^n \mathscr{A}_n^{(4)} + \sum_{n=\mathrm{N}_6}^{\infty} \sum_{l=0}^{n} \sum_{k=1}^{\infty} g^n g_{4+2k}^l \mathscr{A}_{nlk}^{(4+2k)}$$

☞ g is the $SU(2)$ coupling constant, $g_{4+2k} = 1/(\sqrt{2}\, G_F \Lambda^2)^k$. For each process N defines the $\mathrm{dim} = 4$ LO (e.g. $N = 1$ for $\mathrm{H} \to \mathrm{VV}$ etc. But $N = 3$ for $\mathrm{H} \to \gamma\gamma$). $N_6 = N$ for tree initiated processes and $N - 2$ for loop initiated ones.

What to do with $\left|\mathscr{A}\right|^2$ in the truncated version? Is $\mathrm{dim}_6 \otimes \mathrm{dim}_4$ interference enough? Do we need dim_6^2 and $\mathrm{dim}_8 \otimes \mathrm{dim}_4$? Examine the $\mathrm{dim}_6 \otimes \mathrm{dim}_4$ scenario

① Λ cannot be too small, otherwise one cannot neglect $\mathrm{dim} = 8$

② Λ cannot be too large, otherwise

☛ $1/(\sqrt{2}G_F\Lambda^2) \approx g^2/(4\pi)$

i.e. dim_4 higher loops are more important than dim_6 interference.

Remark It does not mean that EFT becomes inconsistent! It only means that higher dimensional operators must be included as well …

Remark Push Λ, neglect higher EW orders and you will end up discovering NP ...

Remark The scale at which EFT can be tested is a completely different issue

$Q^2 \ll \Lambda^2$ 

Remark Introducing form factors, with another (completely different) cutoff, ... do we want to go back to the sixties (unitarization, $N/D, \ldots$)?

$\varkappa$ building manual

① Split the SM amplitude (e.g. $\mathbf{t},\mathbf{b}$ loops and bosonic loops in $\mathbf{H}\to\gamma\gamma$)

$$\mathscr{A}_{\mathrm{SM}} = \sum_{i=1,n} \mathscr{A}_i^{(4)}$$

② Recover these sub-amplitudes in the full answer

③ Classify the (non-factorizable) remainder and obtain

$$\mathscr{A}_{\mathrm{prc}} = \sum_{i=1,n} \kappa_i^{\mathrm{prc}} \mathscr{A}_i^{(4)} + \sum_{i=1,m} \kappa_i^{\mathrm{prc\,NF}} \mathscr{A}_i^{(6\,\mathrm{NF})}$$

Primordial POs: the κ-framework

➲ Of course, any amplitude admits a decomposition

Form factors(invariants) $\times$ Lorentz Structures

☛ Avoid using Form Factors, whose parametrization is arbitrary and does not reproduce the correct analytic structure (normal thresholds)

☞ The κ-framework, as seen from the point of view of EFT, allows you to deform both S and B in a consistent way. All "dynamical" parts are SM induced and they are deformed by constant κ-parameters, e.g.

$$\rho_{\mathrm{H}}^{\gamma\mathrm{Z}} = \mathscr{A}(\mathrm{H}\to\gamma\mathrm{Z}) = \kappa_{\mathrm{W}}^{\gamma\mathrm{Z}}\,\mathscr{A}_{\mathrm{W}}^{(4)} + \kappa_{\mathrm{t}}^{\gamma\mathrm{Z}}\,\mathscr{A}_{\mathrm{t}}^{(4)} + \kappa_{\mathrm{b}}^{\gamma\mathrm{Z}}\,\mathscr{A}_{\mathrm{b}}^{(4)} + i\,g g_6\,\frac{M_{\mathrm{H}}^2}{M_{\mathrm{W}}}\,a_{\mathrm{AZ}}$$
$$+\; a_{\phi D}\,\mathscr{A}_{\mathrm{W}}^{\mathrm{NF}} + \sum_{\mathrm{f}=\mathrm{t,b}}\left(a_{\phi\mathrm{q}}^{(3)} - a_{\phi\mathrm{q}}^{(1)} - a_{\phi\mathrm{f}}\right)\mathscr{A}_{\mathrm{f}}^{\mathrm{NF}}$$

Rationale for this course of action

- Physics is symmetry plus dynamics
- Symmetry is quintessential (gauge invariance etc.)
- Symmetry without dynamics don't bring you this far

① At Lep dynamics was SM, unknowns were $M_{\mathrm{H}}\,(\alpha_{\mathrm{s}}(M_{\mathrm{Z}}),\dots)$

② At LHC (post SM) unknowns are SM-deviations, dynamics?

☛ BSM is a choice. Something more model independent?

❶ An unknown form factor?

❷ A decomposition where dynamics is controlled by $\dim = 4$ amplitudes (with known analytical properties) and deviations (with a direct link to UV completions) are Wilson coefficients?

- It is for posterity to judge (for me deviations need a SM basis)

On-shell studies will tell us a lot, off-shell ones will tell us (hopefully) everything

- If we run away from the H peak with a SM-deformed theory, up to some reasonable value $s \ll \Lambda^2$, we need to reproduce (deformed) SM low-energy effects, e.g. VV and tt thresholds. The BSM loops will remain unresolved (as SM loops are unresolved in the Fermi theory).

- That is why you need to expand SM-deformed into a SM basis with the correct (low energy) behavior. If you stay in the neighbouhood of the peak any function will work, if you run you have to know more of the analytical properties

Next step: Introduce *effective* NLO $\mathbf{H}$ couplings, e.g.

$$\mathbf{HVV} \quad \mapsto \quad \rho_{\mathbf{H}}^{\mathbf{V}} \left(M g^{\mu\nu} + \frac{\mathscr{G}_{\mathbf{L}}^{\mathbf{V}}}{M} p_2^{\mu} p_1^{\nu} \right)$$

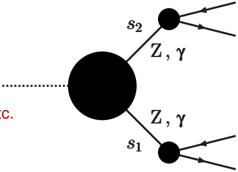
etc. After that start computing Γs and As

- ✗ e.g. F-asymmetry ($\pi/4$) WRT $|\cos\phi|$, ϕ being the angle between the decay planes of the reconstructed Z bosons, e.g. in the decay $\mathrm{H} \to \mathrm{eeqq}$
- ✗ e.g. FB-asymmetry in the angle between e and W reconstructed from qq pair in $\mathrm{H} \to \mathrm{e\nu qq}$

The same coupling can be expressed in terms of Wilson coefficients within EFT. N.B. $\{\rho, \mathscr{G}\}_{\mathrm{NLO}} \neq \kappa$

$$\textbf{At LO} \quad \mathbf{HZZ} \quad \mapsto \quad g\,\frac{M}{c_\theta^2}\,g^{\mu\nu}\left[1 + g_6\left(a_{\phi\mathrm{W}} + a_{\phi\Box} + \frac{1}{4}\,a_{\phi D}\right)\right] \qquad (\Longleftarrow \kappa)$$
$$- \quad 2\,\frac{g g_6}{M}\,a_{\mathrm{ZZ}}\left(p_1 \cdot p_2\, g^{\mu\nu} - p_2^{\mu} p_1^{\nu}\right)$$

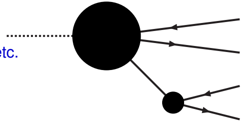
Expansion



$\Gamma(\mathrm{H} \to \mathrm{ZZ})$ etc.

$$\frac{\mathscr{A}_{\mathrm{DR}}(s_1, s_2; \dots)}{(s_1 - s_\mathrm{Z})(s_2 - s_\mathrm{Z})} = \frac{\mathscr{A}_{\mathrm{DR}}(s_\mathrm{Z}, s_\mathrm{Z}; \dots)}{(s_1 - s_\mathrm{Z})(s_2 - s_\mathrm{Z})} + \frac{\mathscr{A}^{(2)}_{\mathrm{DR}}(s_\mathrm{Z}, s_2; \dots)}{s_1 - s_\mathrm{Z}}$$

$$\dots + \mathscr{A}^{\mathrm{rest}}_{\mathrm{DR}}(s_1, s_2; \dots)$$

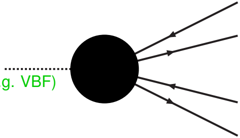


$\Gamma(\mathrm{H} \to \bar{\mathrm{f}}\mathrm{f}\gamma)$ etc.

$$\frac{\mathscr{A}_{\mathrm{SR}}(s_1; \dots)}{s_1 - s_\mathrm{Z}} = \frac{\mathscr{A}_{\mathrm{SR}}(s_\mathrm{Z}; \dots)}{s_1 - s_\mathrm{Z}} + \mathscr{A}^{\mathrm{rest}}_{\mathrm{SR}}(s_1; \dots)$$

remember LEP

$$\sigma_\mathrm{f}^{\mathrm{peak}} = 12\pi \frac{\Gamma_\mathrm{e}\Gamma_\mathrm{f}}{M_\mathrm{Z}^2 \Gamma_\mathrm{Z}^2}$$



the difficult part (e.g. VBF)

$$\mathscr{A}_{\mathrm{NR}}(\dots)$$

$$+ \; (\mathrm{Z} \to \gamma)$$

POs (container) at LHC: summary table

① external layer (similar to σ_f^{peak} at LEP)

$$\Gamma_{VV} \quad A_{FB}^{ZZ} \quad N_{off}^{4l} \quad \text{etc}$$

② intermediate layer (similar to g_{VA}^{e} at LEP)

$$\rho_H^V \quad \mathscr{G}_L^V \quad \rho_H^{\gamma\gamma}, \rho_H^{\gamma Z} \quad \rho_H^f$$

③ internal layer

$$\kappa_f^{\gamma\gamma} \quad \kappa_W^{\gamma\gamma} \quad \kappa_i^{\gamma\gamma\, NF} \quad \text{etc}$$

④ innermost layer: Wilson coeff. or non-SM parameters in BSM (e.g. α, β, M_{sb} etc. in THDMs)

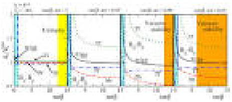
POs as a way to “compress” results. LHC legacy.

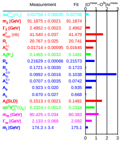
For each process compute the full answer within fiducial volumes

Another language: something is decaying into something else (on-shell) further decaying etc.

Can we make it rigorous while keeping keeping the total intact? Yes, it’s PO!

Nobody will memorize what κ^{XYZ}_{ijk} is, but will remember what an asymmetry is, even when “spoiled” enough to become a PO. Let’s keep κ as a tool to (partly) get the UV-completion





PO is the language which the deaf can hear and the blind can see

Synopsis

① opinion spreading and consensus formation on

We don't hope that in 20 years from now we'll have a table with LHC Higgs results which will contain the ratio of the coefficients in front of certain $\mathbf{H} \to \mathbf{VV}$ Lorentz structures with form factor expansion up to $\boldsymbol{p^2}$

② Build a simple platform between realistic observables and theory parameters working in the space of signals but having in mind the space of theories

③ Beware of gauge invariance issues when going off-shell

Have a look at date and place

Pos: a few other things

PO CPs

now, Soviet of HXSWG workers

Formely

LHC Higgs Cross Section Working Group 12 - 13 April 2010, Freiburg

… and content

Perhaps I should stop, what do you say?

Strategy

- go via idealised (model-independent?) **RO** distributions and from there then going to the **POs**.
  - Step 0) Use a (new) **MCT** – the **PO code** – to fit **ROs**
  - Step 1) Understand **differences** with a *standard* event generator plus detector simulation plus *calibrating* the method/event generator used (which differ from the PO-code in its theoretical content)
  - Step $\geq$ 2) Let's see ……

CONCLUSIONS

learn from the Past,
live for the Present,
dream of the Future.

Of course, there are other opinions ...... *People who have visions should go see a doctor* (Quoting Karl Jakobs quoting Helmut Schmidt)

Thank you for your attention

Backup Slides

To repeat the argument: we oscillate between

① you will fit only my “optimized” (reduced) Wilson coefficients

② the huge QCD background and the associated uncertainty are such that, yes, fit whatever you want but for each new QCD calculation your result will change substantially and not multiplicatively

It is obvious that ② has nothing to do with PO’s but with fitting the EW core, no matter how it is parametrized. The suggested procedure is:

❶ write the answer in terms of SM deviations, i.e. the dynamical parts are SM/dim_4 and

❷ certain combinations of the deviation parameters will define the POs and will be fitted

The suggested procedure is based on

★ The parametrization must be as general as possible, no a priori dropping of terms

☞ this will allow us to “reweight” when new (differential) K-factors become available. New input will touch only the dim_4 components

☛ From this point of view we will differ from Lep where the number of quantities was reduced

☛ PDFs changing is the most serious problem. At Lep the $\mathrm{e}^+\mathrm{e}^-$ structure functions were know to very high accuracy (we tested the effect by using different QED radiators, differing by higher orders treatment). A change of PDFs at LHC will change the convolution …… Sic transic gloria mundi