The Hunt for Off-Shellness
how it should be

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Higgs Hunting 2015, Jul 30 - Aug 1, LAL

Highlights The successful search for the on-shell Higgs-like boson did put little emphasis on the potential of the off-shell events

Wind of change is blowing

Off-shell measurements are (much) more than consistency checks on Γ_{H}

Observing an excess in the off-shell measurement will be a manifestation of BSM physics, which night or might not need to be in relation with the H width. We need to extend the SM with dynamics (SMEFT).

This will act as an intermediate step toward the new SM, distancing the experimental analysis from repeated refinements due to ever-improving calculations (POs).

What can be said at all can be said clearly and whereof one cannot speak thereof one must be silent

Off-shell bounding Γ_H
Past

Constructing the theory of SM deviations
Present

Understanding H couplings
Future

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

André David, Michael Duehrssen

When a particle physicist describes something as "off mass-shell", they could be referring to a precise bit of quantum mechanics, or denouncing an unrealistic budget estimate (J. Butterworth)

A short History of beyond ZWA

(don't try fixing something that is already broken in the first place)

There is an enhanced Higgs tail[1]: away from the narrow peak ($s_{\mathrm{H}} = \mu_{\mathrm{H}}^2 - i\,\mu_{\mathrm{H}}\,\gamma_{\mathrm{H}}$) the H propagator and the off-shell H width behave like ➥

$$\Delta_{\mathrm{H}} \sim \frac{1}{M_{\mathrm{VV}}^2 - \mu_{\mathrm{H}}^2} \qquad ✔\,\frac{\Gamma_{\mathrm{H}\to\mathrm{VV}}\,(M_{\mathrm{VV}})}{M_{\mathrm{VV}}} \sim G_{\mathrm{F}}\,M_{\mathrm{VV}}^2$$

to be more precise $\quad |\,\Delta_{\mathrm{H}}\,|^2 = \dfrac{\pi}{\mu_{\mathrm{H}}\,\gamma_{\mathrm{H}}}\,\delta\left(M_{\mathrm{VV}}^2 - \mu_{\mathrm{H}}^2\right) + \mathrm{PV}\left[\dfrac{1}{\left(M_{\mathrm{VV}}^2 - \mu_{\mathrm{H}}^2\right)^2}\right]$

What are the potential uses of off-shellness to constrain the Higgs properties?

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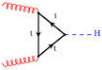
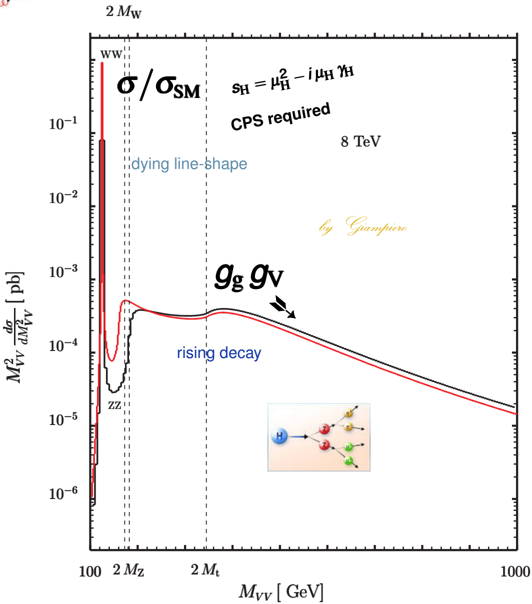
[1] Kauer - Passarino (arXiv:1206.4803)



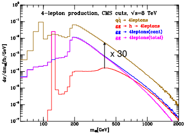


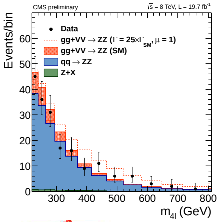
The big picture @ 8TeV

- Peak at Z mass due to singly resonant diagrams.
- Interference is an important effect.
- Destructive at large mass, as expected.
- With the standard model width, γ_H, challenging to see enhancement/deficit due to Higgs channel.

$p_{T,\mu} > 5$ GeV, $|\eta_\mu| < 2.4$, $p_{T,e} > 7$ GeV, $|\eta_e| < 2.5$, $m_{ll} > 4$ GeV, $m_{4l} > 100$ GeV.

CMS cuts
CMS PAS HIG-13-002

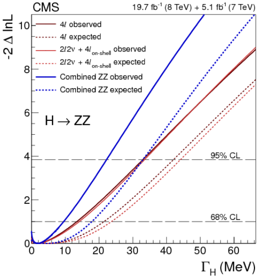




dynamic QCD scales

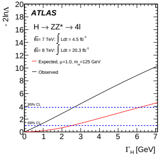
CMS-HIG-14-002, ATLAS-CONF-2014-042

Facts of life



Direct Higgs width measurement

- *N.B.: see earlier talk in this session for indirect width measurement.*
- Analytical m_{4l} (non-relativistic Breit-Wigner) model convoluted with detector resolution with width Γ_H (m_H and μ free parameters) ($\Gamma_H = 4$ MeV at 125 GeV)
- Analysis assumes no interference with background processes
- $H \to ZZ^* \to 4l$:
  - Event-by-event modelling of detector resolution
  - Per-lepton resolution functions use sums of 2(3) Gaussians for muons (electrons)
  - Validated by fitting mass peak for $Z \to 4l$ using convolution of detector response with BW for Z mass
  - 95% CL: $\Gamma_H < 2.6$ GeV (exp. limit 3.5 GeV for $\mu = 1.7$, 6.2 GeV for $\mu = 1$)
- $H \to \gamma\gamma$:
  - 95% CL: $\Gamma_H < 5.0$ GeV (expected limit 6.2 GeV for $\mu = 1$)



CERN Courier Apr 30, 2014

CMS sets new constraints on the width of the Higgs boson

Further reading

N Kauer and G Passarino 2012 JHEP 08 116

F Caola and K Melnikov 2013 Phys. Rev. D 88 054024

G Passarino 2013 Eur.Phys.J. C74 (2014) 2866

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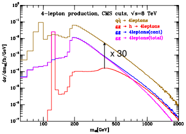
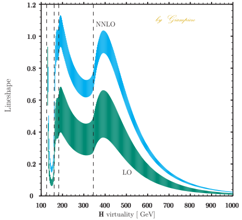




A short update

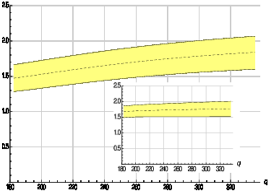
Several tools exist for $gg \to 4l$ at LO

Full NNLO known for $\bar{q}q \to VV$
Gehrmann et al.; Cascioli et al. (2014)

ZZ production in NNLO QCD
Grazzini et al. (2015)

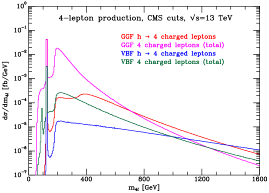
2-loop amplitudes for massless $gg \to VV$
Caola et al.; Manteuffel, Tancredi (2014)

2-loop amplitudes for massive $gg \to VV$ out of reach, NLO in $1/m_t$-expansion



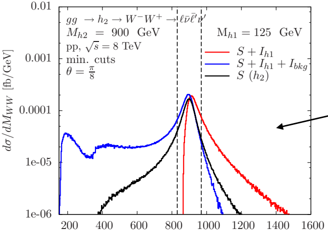
Dowling, Melnikov (2015)

Off-shell studies in VBF



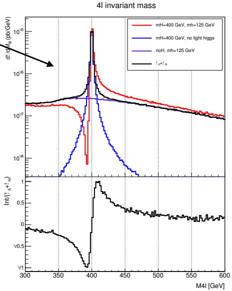
Campbell, Ellis (2015)

Beyond the SM: heavy/light Higgs interference

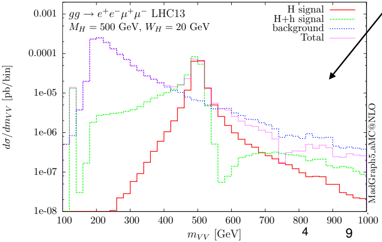


[Maina (2015)]

[NK, O'Brien (2015)]



[Vryonidou, MadGraph5_aMC@NLO]



- Singlet extensions of the SM / 2HDM models
- Large shape distortion from interferences

Computing is not interpreting:
How was off-shellness used? Shortly:

① Introduce the notion of ∞-**degenerate** solutions for the Higgs couplings to $\mathcal{SM}$ particles Dixon - Li (arXiv:1305.3854), Caola - Melnikov(arXiv:1307.4935)

② Observe that the enhanced tail is obviously $\gamma_{\rm H}$-independent and that this could be exploited to constrain the Higgs width model-independently

③ Use a matrix element method (e.g. MELA) to construct a kinematic discriminant to sharpen the constraint Campbell, Ellis and Williams (arXiv:1311.3589)

How can off-shellness be used?

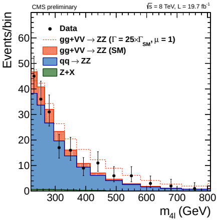
$$\sigma_{i\to \mathrm{H}\to f} = (\sigma\cdot \mathrm{BR}) = \frac{\sigma_i^{\mathrm{prod}}\,\Gamma_f}{\gamma_{\mathrm{H}}} \qquad \sigma_{i\to \mathrm{H}\to f} \propto \frac{g_i^2\, g_f^2}{\gamma_{\mathrm{H}}} \qquad g_{i,f} = \boxed{\xi}\; g_{i,f}^{\mathrm{SM}} \quad \gamma_{\mathrm{H}} = \boxed{\xi^4}\; \gamma_{\mathrm{H}}^{\mathrm{SM}}$$

a consistent BSM interpretation?

On the whole, we have a constraint in the multidimensional κ-space

$$\kappa_g^2 = \kappa_g^2(\kappa_t, \kappa_b)\quad \kappa_{\mathrm{H}}^2 = \kappa_{\mathrm{H}}^2(\kappa_j, \forall j)$$

On-shell ∞-degeneracy
arXiv:1305.3854, 1307.4935, 1311.3589



$g_i \Longleftrightarrow \kappa_j$

$g_i(M_{\mathrm{H}})\,?\,g_i(\sqrt{s})$

The generalization is an ∞^2-degeneracy

$g_i^2\, g_f^2 = \gamma_{\mathrm{H}}$

Only on the assumption of degeneracy one can prove that off-shell effects measure γ_{H}

Simplified version

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{\mathrm{SM}}(\mu_{\mathrm{H}})} = \frac{\kappa_t^2\cdot\Gamma_{gg}^{tt}(\mu_{\mathrm{H}}) + \kappa_b^2\cdot\Gamma_{gg}^{bb}(\mu_{\mathrm{H}}) + \kappa_t\kappa_b\cdot\Gamma_{gg}^{tb}(\mu_{\mathrm{H}}}{\Gamma_{gg}^{tt}(\mu_{\mathrm{H}}) + \Gamma_{gg}^{bb}(\mu_{\mathrm{H}}) + \Gamma_{gg}^{tb}(\mu_{\mathrm{H}})}$$

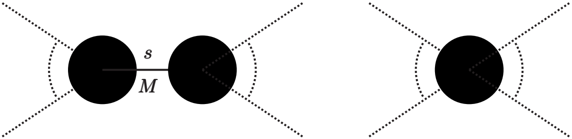
a combination of on-shell effects measuring
$g_i^2\, g_f^2/\gamma_{\mathrm{H}}$
and off-shell effects measuring
$g_i^2\, g_f^2$
gives information on γ_{H}
without prejudices

original κ-language arXiv:1209.0040

although it may not be the outcome that was originally hoped for or expected

Preliminary Assessments

Off-shellness and gauge invariance



Once again we describe an arbitrary process with two components:

① a resonant one, with the exchange of a particle of mass $\boldsymbol{M}$ and virtuality $\boldsymbol{s}$

② a the continuum (N)

The corresponding amplitude is

$$\mathscr{A} = \frac{V_i(\xi,s,M,\ldots)\, V_f(\xi,s,M,\ldots)}{s-M^2} + \mathrm{N}(\xi,s,\ldots)$$

where $V_i(V_f)$ are the inital(final) sub-amplitudes in the resonant part, ξ is a gauge parameter and the dependence on additional invariants is denoted by $\ldots$. It can be shown, in full generality, that

$$V_{i,f}(\xi,s,M\ldots) = V_{i,f}^{\text{inv}}\left(M^2=s,\ldots\right) + (s-M^2)\,\Delta V_{i,f}(\xi,s,M,\ldots)$$

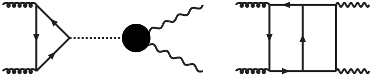
☛ ☛ only the on-shell production $\times$ decay is gauge-parameter independent

Therefore, we need to expand the resonant part,

$$\mathscr{A} = \frac{V_i^{\text{inv}}\left(M^2=s,\ldots\right)\, V_f^{\text{inv}}\left(M^2=s,\ldots\right)}{s-M^2} + \mathrm{B}(s,\ldots)$$

with an impact for the number of off-shell events. Note that $B \neq N$ is the remainder of the Laurent expansion around the pole. Technically speaking, the mass M should be replaced by the corresponding complex pole.

Facts of life (frequently forgotten)



prod decay(ξ) n/av two-loop bckg(ξ)

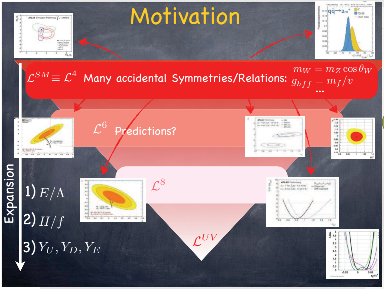
① Put all gluons you want in production (still gauge invariant)

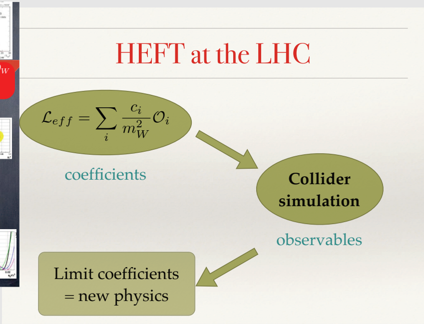
② NLO decay: shift off-shell (ξ-dependent) part to non-resonant

③ this would require the two-loop (non-resonant) box

If you come out of your shell, you become more interested in other people and more willing to talk and take part in social activities (Cambridge Dictionaries)

SMEFT *is needed*





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 accommodating factorizable QCD but not EW corrections
- ☛☛ it is not QFT-compatible (ad-hoc variation of the SM parameters, violates gauge symmetry and unitarity)

The role of SMEFT in rehabilitating the κ-framework[2]

The role of $\mathcal{SMEFT}$ in paving the (as) Model Independent (as possible) road cannot be undermined.

HXSWG-crumpling the Warsaw basis (Grzadkowski et al.) to capture your favorite scenario (NONO-to-NLO) is not the solution, bringing $\mathcal{SMEFT}$ to NLO is the correct way for focusing in consistency of the κ-framework. The latter is crucial in describing SM deviations. 

No NLO SMEFT 

[2] Hartmann, Trott (arXiv:1505.02646), arXiv:1505.03706

In the next few slides I will show you beauty in a handful of κs

- Start with SMEFT at a given order (possibly NLO)
- write any amplitude as a sum of κ-deformed SM sub-amplitudes
- add another sum of κ-deformed non-SM sub-amplitudes
- show that κs are linear combinations of Wilson coefficients
- discover correlations among the κs

Rationale for this course of action (Hypothesis Testing)

- 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_H $(\alpha_s(M_Z), \dots)$

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 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 to be systematised)

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

- 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 deformations into a SM basis with the correct (low energy) behavior[3]

[3] If you stay in the neighbourhood of the peak any function will work, if you run you have to know more of the analytical properties

Scenarios for understanding SM deviations in (especially tails of) distributions:

A use SMEFT and stop where you have to stop, it is an honest assessment of our ignorance

B improve SMEFT with $\dim = 8$ (but this will not be enough)

C use the kappa–BSM-parameters connection, i.e. replace SMEFT with BSM models, especially in the tails, optimally matching to SMEFT at lower scales

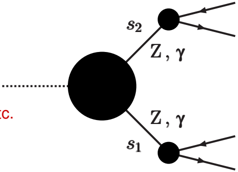
D introduce binned POs

MultiPoleExpansion & POs

In any process, the residues of the poles (starting from maximal degree) are numbers.
The non-resonant part is a multivariate function and requires some basis.

That is to say, residue of the poles can be POs by themselves, expressing them in terms of other objects is an operation the can be postponed. The very end of the chain, no poles left, requires (almost) model independent SMEFT or model dependent BSM. Numerically speaking, it depends on the impact of the non-resonant part which is small in ggF but not in Vector Boson Scattering (VBS)

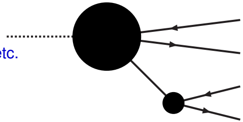
MPE: crab expansion



$\Gamma(H \to ZZ)$ etc.

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

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

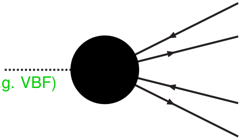


$\Gamma(H \to \bar{f} f \gamma)$ etc.

$$\frac{\mathscr{A}_{\rm SR}(s_1; \dots)}{s_1 - s_Z} = \frac{\mathscr{A}_{\rm SR}(s_Z; \dots)}{s_1 - s_Z} + \mathscr{A}^{\rm rest}_{\rm SR}(s_1; \dots)$$

remember LEP

$$\sigma_f^{\rm peak} = 12\pi \frac{\Gamma_e \Gamma_f}{M_Z^2 \Gamma_Z^2}$$



the difficult part (e.g. VBF)

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

$$+ \ (Z \to \gamma)$$

directly POs

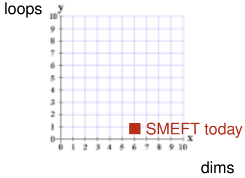
residue of poles $\Rightarrow$ one number $\Leftarrow$ interpretation: $\kappa\times$ sub-amplitudes

non-resonant $\Rightarrow$ NAN $\Leftarrow$ $\kappa\times$ sub-amplitudes needed even before interpretation

or dense binning in (say) p_{T} $\Leftarrow$ interpretation: $\kappa\times$ sub-amplitudes (C used to "interpret" D! Sl. 23)

POs are a platform between realistic observables and theory parameters, allowing experimentalists and theorists to meet half way between, without theorists having to run full simulation and reconstruction and experimentalists fully unfolding to model-dependent parameter spaces

Synopsis



① Each loop = multiply by g^2 (g is the $SU(2)$ coupling constant)

② Each $\mathrm{dim}{+}2$ = multiply by $g_6 = 1/(G_F \Lambda^2)$

③ Warning: when squaring the amplitude respect the order in powers of g and of g_6

④ be careful with Λ or you will claim NP simply because you are missing 2 loops SM.


KEEP
CALM
AND
LET'S
PRACTICE

No NP yet?

A study of $\mathcal{SM}$-deviations: here the reference process is

$$\mathbf{gg \to H}$$

✓ κ-approach: write the amplitude as

$$\mathbf{A^{gg}} = \sum_{\mathbf{q=t,b}} \kappa_{\mathbf{q}}^{\mathbf{gg}} \mathscr{A}_{\mathbf{q}}^{\mathbf{gg}} + \kappa_{c}^{\mathbf{gg}}$$

$\mathscr{A}_{\mathbf{t}}^{\mathbf{gg}}$ being the SM t-loop etc. The contact term (which is the LO SMEFT) is given by $\kappa_{c}^{\mathbf{gg}}$. Furthermore

$$\kappa_{\mathbf{q}} = 1 + \Delta\,\kappa_{\mathbf{q}}$$

Compute

$$\kappa_{gg} \mapsto R = \sigma\left(\kappa_q^{gg}, \kappa_c^{gg}\right)/\sigma_{SM} - 1 \quad [\%]$$

In LO SMEFT κ_c is non-zero and $\kappa_q = 1$ [4].

You measure a deviation and you get a value for κ_c. However, at NLO $\Delta\kappa_q$ is non zero and you get a degeneracy

The interpretation in terms of κ_c^{LO} or in terms of $\{\kappa_c^{NLO}, \Delta\kappa_q^{NLO}\}$ could be rather different.

[4] Certainly true in the linear realization

Going interpretational

$$
\begin{aligned}
\mathbf{A}^{\mathrm{gg}}_{\mathrm{SMEFT}} &= \frac{g\, g_S^2}{\pi^2} \sum_{\mathrm{q=t,b}} \kappa^{\mathrm{gg}}_{\mathrm{q}}\, \mathscr{A}^{\mathrm{gg}}_{\mathrm{q}} \\
&+ 2\, g_S\, g_6\, \frac{s}{M_W^2}\, a_{\phi\mathrm{g}} + \frac{g\, g_S^2\, g_6}{\pi^2} \sum_{\mathrm{q=t,b}} \mathscr{A}^{\mathrm{NF;gg}}_{\mathrm{q}}\, a_{\mathrm{qg}}
\end{aligned}
$$

✓ **Assumption**: use arXiv:1505.03706, adopt Warsaw basis (arXiv:1008.4884), eventually work in the Einhorn-Wudka PTG scenario (arXiv:1307.0478)

① LO SMEFT: $\kappa_{\mathrm{q}} = 1$ and $a_{\phi\mathrm{g}}$ is scaled by $1/16\,\pi^2$ being LG (blue color)

② NLO PTG-SMEFT: $\kappa_{\mathrm{q}} \neq 1$ but only PTG operators inserted in loops (non-factorizable terms absent), $a_{\phi\mathrm{g}}$ scaled as above

③ NLO full-SMEFT: $\kappa_{\mathrm{q}} \neq 1$ LG/PTG operators inserted in loops (non-factorizable terms present), LG coefficients scaled as above

At NLO, $\Delta\kappa = g_6\, \rho$

Warsaw basis

$$\begin{aligned} g_6^{-1} &= \sqrt{2}\, G_F\, \Lambda^2 \\ 4\,\pi\,\alpha_s &= g_S^2 \\ \rho_t^{gg} &= a_{\phi W} + a_{t\phi} + 2\,a_{\phi\Box} - \frac{1}{2}\,a_{\phi D} \\ \rho_b^{gg} &= a_{\phi W} - a_{b\phi} + 2\,a_{\phi\Box} - \frac{1}{2}\,a_{\phi D} \end{aligned}$$

Relaxing the PTG assumption introduces non-factorizable sub-amplitudes proportional to a_{tg}, a_{bg} with a mixing among $\{a_{\phi g}, a_{tg}, a_{bg}\}$. Meanwhile, renormalization has made one-loop SMEFT finite, e.g. in the G_F-scheme, with a residual μ_R-dependence.

What are POs? Experimenters collapse some “primordial quantities” (say number of observed events in some pre-defined set-up) into some “secondary quantities” which we feel closer to the theoretical description of the phenomena.

Residues of resonant poles, κ-parameters and Wilson coefficients are different layers of POs

Going off-shell r.h.s. of the full process: here we consider

$\mathbf{H} \rightarrow \mathbf{ZZ}$ off-shell Higgs

Amplitude

$$\mathscr{A}^{\mu\nu}_{\mathrm{ZZ}} = \mathscr{D}_{\mathrm{ZZ}}\, \delta^{\mu\nu} + \mathscr{P}_{\mathrm{ZZ}}\, p_2^{\mu}\, p_1^{\nu}$$

$$\begin{aligned}
\mathscr{D}_{\mathrm{ZZ}} &= g\, \kappa^{\mathrm{ZZ}}_{\mathrm{LO}}\, \mathscr{D}^{\mathrm{LO}}_{\mathrm{ZZ}} + \frac{g^3}{16\,\pi^2} \sum_{i=\mathrm{t,b,W}} \kappa^{\mathrm{ZZ\,;\,D}}_{\mathrm{NLO\,;\,i}}\, \mathscr{D}^{\mathrm{LO\,;\,i}}_{\mathrm{ZZ}} \\
&+ \frac{g^3 g_6}{16\,\pi^2} \sum_{a \in \mathrm{A_{ZZ}}} \mathscr{D}^{\mathrm{LO\,;\,nf\,;\,a}}_{\mathrm{ZZ}}\, a
\end{aligned}$$

$$\begin{aligned}
\mathscr{P}_{\mathrm{ZZ}} &= 2\, \frac{g g_6}{M_{\mathrm{W}}}\, a_{\mathrm{ZZ}} + \frac{g^3}{16\,\pi^2} \sum_{i=\mathrm{t,b,W}} \kappa^{\mathrm{ZZ\,;\,P}}_{\mathrm{NLO\,;\,i}}\, \mathscr{P}^{\mathrm{LO\,;\,i}}_{\mathrm{ZZ}} \\
&+ \frac{g^3 g_6}{16\,\pi^2} \sum_{a \in \mathrm{A_{ZZ}}} \mathscr{P}^{\mathrm{LO\,;\,nf\,;\,a}}_{\mathrm{ZZ}}\, a
\end{aligned}$$

kappas et al

$$\Delta\kappa^{\mathrm{ZZ}}_{\mathrm{LO}} = 2\,a_{\phi\,\square} + s^2_\theta\,a_{\mathrm{AA}} + s_\theta\,c_\theta\,a_{\mathrm{AZ}} + \left[4 + c^2_\theta\,(1 - \frac{s}{M^2_{\mathrm{W}}})\right]\,a_{\mathrm{ZZ}}$$

$$\Delta\kappa^{\mathrm{ZZ}\,;\,\mathrm{D}}_{\mathrm{NLO}\,;\,\mathrm{t}} = a_{\mathrm{t}\,\phi} + 2\,a_{\phi\,\square} - \frac{1}{2}\,a_{\phi\,\mathrm{D}} + 2\,a_{\mathrm{ZZ}} + s^2_\theta\,a_{\mathrm{AA}}$$

$$\Delta\kappa^{\mathrm{ZZ}\,;\,\mathrm{D}}_{\mathrm{NLO}\,;\,\mathrm{b}} = -a_{\mathrm{b}\,\phi} + 2\,a_{\phi\,\square} - \frac{1}{2}\,a_{\phi\,\mathrm{D}} + 2\,a_{\mathrm{ZZ}} + s^2_\theta\,a_{\mathrm{AA}}$$

$$\Delta\kappa^{\mathrm{ZZ}\,;\,\mathrm{D}}_{\mathrm{NLO}\,;\,\mathrm{W}} = 2\,a_{\phi\,\square} + \frac{1}{12}\,\frac{1 + 4\,c^2_\theta}{c^2_\theta}\,a_{\phi\,\mathrm{D}} + s^2_\theta\,a_{\mathrm{AA}} + \frac{1}{3}\,s_\theta\,(\frac{5}{c_\theta} + 9\,c_\theta)\,a_{\mathrm{AZ}} + (4 + c^2_\theta)\,a_{\mathrm{ZZ}}$$

$$\Delta\kappa^{\mathrm{ZZ}\,;\,\mathrm{P}}_{\mathrm{NLO}\,;\,\mathrm{t}} = \Delta\kappa^{\mathrm{ZZ}\,;\,\mathrm{D}}_{\mathrm{NLO}\,;\,\mathrm{t}}$$

$$\Delta\kappa^{\mathrm{ZZ}\,;\,\mathrm{P}}_{\mathrm{NLO}\,;\,\mathrm{b}} = \Delta\kappa^{\mathrm{ZZ}\,;\,\mathrm{D}}_{\mathrm{NLO}\,;\,\mathrm{b}}$$

$$\Delta\kappa^{\mathrm{ZZ}\,;\,\mathrm{P}}_{\mathrm{NLO}\,;\,\mathrm{W}} = 4\,a_{\phi\,\square} + \frac{5}{2}\,a_{\phi\,\mathrm{D}} + 3\,s^2_\theta\,a_{\mathrm{AA}} + 12\,a_{\mathrm{ZZ}}$$

Scaling couplings at the peak is not the same thing as scaling them off-peak [5]

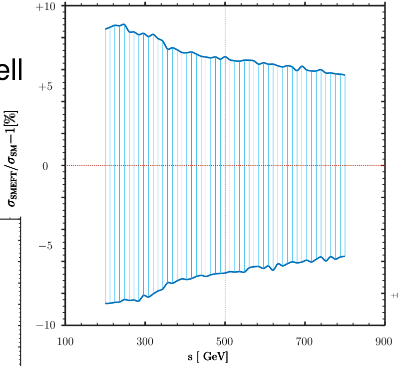
$$\sigma_{\text{SMEFT}}(s) = |\underbrace{\kappa_{\text{prod}}(s)\,\kappa_{\text{dec}}(s)}_{\mu_{ZZ}^{\text{off}}(s)}|^2\, \sigma_{\text{SM}}(s)$$

It is an error to believe that rigour is the enemy of simplicity. On the contrary we find it confirmed by numerous examples that the rigorous method is at the same time the simpler and the more easily comprehended

[5] Englert et al. (arXiv:1405.0285), arXiv:1405.1925

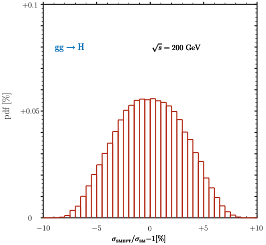
support $|a_i| \in [-1, +1]$

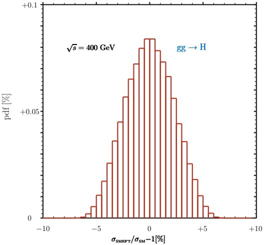
$gg \to H$ off-shell

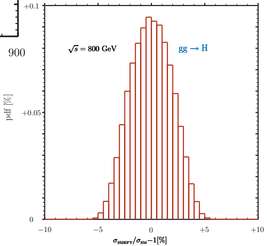


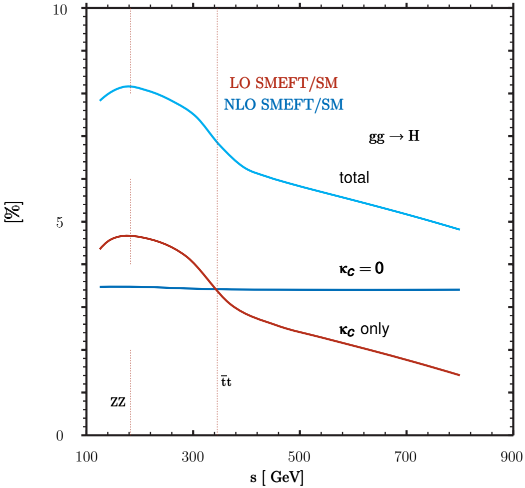
unif$(-1, 1)$

$\Lambda = 3$ *TeV*









Another reason to go NLO

The contact term is real … $\kappa_c^{\mathrm{gg}} \in \mathbb{R}$

$$\frac{g\, g_S^2\, g_6}{\pi^2} \sum_{\mathrm{q=t,b}} \left[\Delta\kappa_{\mathrm{q}}^{\mathrm{gg}}\, \mathscr{A}_{\mathrm{q}}^{\mathrm{gg}} + \mathscr{A}_{\mathrm{q}}^{\mathrm{NF;gg}}\, a_{\mathrm{qg}}\right] \in \mathbb{C}$$

$$2\, g_S\, g_6\, \frac{s}{M_{\mathrm{W}}^2}\, a_{\phi \mathrm{g}} \in \mathbb{R}$$

$$a_i = 1,\ \forall i$$

$$\Lambda = 3\ TeV$$

How to treat the Background?

It is done similar to the previously examined signal.

The amplitude is decomposed into Lorentz structures compatible with symmetries (e.g. Bose symmetry in $\mathbf{gg} \to \mathbf{VV}$) and with Ward identities.

SMEFT calculation is performed and $\boldsymbol{\kappa}$ factors (w or w/o factorization) are extracted.

☛ The whole process changes …

Example: $\mathrm{g}(p_1)\mathrm{g}(p_2) \to \mathrm{Z}(p_3)\mathrm{Z}(p_4)$ polarization tensor

$$\mathrm{Z}_\mu\, \overline{\mathrm{q}}\, \gamma^\mu \left(v_\mathrm{q} + a_\mathrm{q}\, \gamma^5\right) \mathrm{q} \qquad \mapsto \qquad P^{\mu\nu\alpha\beta} \propto v_\mathrm{q}^2\, P_\mathrm{V}^{\mu\nu\alpha\beta} + a_\mathrm{q}^2\, P_\mathrm{A}^{\mu\nu\alpha\beta}$$

① charge conjugation invariance $\mapsto$ no $v_\mathrm{q}\, a_\mathrm{q}$

② P transversal to gluon momenta, P_V transversal to Z momenta, P_A also transversal for light quarks ($m_\mathrm{q} = 0$)

$$P^{\mu\nu\alpha\beta} = \mathrm{A}_1^{(4)} \left(g^{\mu\nu} + \frac{p_1^\nu p_2^\mu}{p_1 \cdot p_2}\right) g^{\alpha\beta} + \cdots \;\to\; \kappa_1^{\mathrm{ggZZ}}\, \mathrm{A}_1^{(4)} \left(g^{\mu\nu} + \frac{p_1^\nu p_2^\mu}{p_1 \cdot p_2}\right) g^{\alpha\beta} + \cdots$$

involving $a_{\phi\,\mathrm{g}}, a_{\mathrm{u\,g}}$ etc.

Nature's music is never over; her silences are pauses, not conclusions

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

The long and short of it is, we need more rigor in all kinds of programs

Thank you for your attention


Backup Slides

Fitting is not interpreting

Of course, depending on what you measure, the corresponding interpretation could tell us that the required kappas or Wilson coefficients are too large to allow for a meaningful interpretation in terms of a weakly coupled UV completion[6]

Caveat: SMEFT interpretation should include LO SMEFT and (at least) RGE modified predictions (arXiv:1301.2588); furthermore, full one-loop SMEFT gives you (new) logarithmic and constant terms that are not small compared to the one from RGE, see arXiv:1505.02646, arXiv:1505.03706

For interpretations other than weakly coupled renormalizable, see arXiv:1305.0017

EFT purist: there is no model independent EFT statement on some operators being big and other small (arXiv:1305.0017)

[6] Simpler theories are preferable to more complex ones because they are better testable and falsifiable

Not only decay (cf. arXiv:1502.02990)

$$\mathrm{u}(p_1)+\mathrm{u}(p_2)\to\mathrm{u}(p_3)+\mathrm{e}^-(p_4)+\mathrm{e}^+(p_5)+\mu^-(p_6)+\mu^+(p_7)+\mathrm{u}(p_8)\quad \text{LO SMEFT}$$

$$\begin{aligned}
J^{\mu}_{\pm}(p_i\,,p_j) &= \overline{u}(p_i)\,\gamma^{\mu}\,\gamma_{\pm}\,u(p_j)\\
\mathscr{A}^{\mathrm{TR}}_{\mathrm{LO}} &= \Big[J^{\mu}_{-}(p_4\,,p_5)\,(1-v_{\mathrm{l}})+J^{\mu}_{+}(p_4\,,p_5)\,(1+v_{\mathrm{l}})\Big]\\
&\times \Big[J^{-}_{\mu}(p_6\,,p_7)\,(1-v_{\mathrm{l}})+J^{+}_{\mu}(p_6\,,p_7)\,(1+v_{\mathrm{l}})\Big]\\
&\times \Big[J^{\nu}_{-}(p_3\,,p_2)\,(1-v_{\mathrm{u}})+J^{\nu}_{+}(p_3\,,p_2)\,(1+v_{\mathrm{u}})\Big]\\
&\times \Big[J^{-}_{\nu}(p_8\,,p_1)\,(1-v_{\mathrm{u}})+J^{+}_{\nu}(p_8\,,p_1)\,(1+v_{\mathrm{u}})\Big]\\
\Delta^{-1}_{\Phi}(p) &= p^2+M^2_{\Phi}
\end{aligned}$$

$$\mathscr{A}^{\mathrm{TR}}_{\mathrm{SMEFT}} = \frac{g^6}{4096}\,\Delta_{\mathrm{H}}(q_1+q_2)\prod_{i=1,4}\Delta_{\mathrm{Z}}(q_i)\,\frac{M^2_{\mathrm{W}}}{c^8_{\theta}}\,\kappa_{\mathrm{LO}}\,\mathscr{A}^{\mathrm{TR}}_{\mathrm{LO}}+g^6\,g_6\,\mathscr{A}^{\mathrm{TR;nf}}_{\mathrm{SMEFT}}$$

$$\Delta\kappa_{\mathrm{LO}} = 2\,a_{\phi\,\Box}+\frac{2\,M^2_{\mathrm{Z}}-2\,M^2_{\mathrm{H}}+q_1\cdot q_2+q_2\cdot q_2}{M^2_{\mathrm{W}}}\,c^2_{\theta}\,a_{\mathrm{ZZ}}$$

$$q_1=p_8-p_1,\; q_2=p_3-p_2,\; q_3=p_4+p_5,\; q_4=p_6+p_7$$

The dual role of MPE

① Poles and their residues are intimately related to the gauge invariant splitting of the amplitude (Nielsen identities)

② Residues of poles (eventually after integration over residual variables) can be interpreted as POs (factorization)

Gauge invariant splitting is not the same as “factorization” of the process into sub-processes, indeed

Phase space factorization requires the pole to be inside the physical region

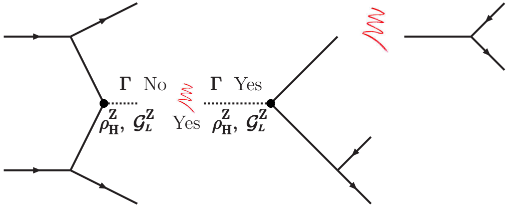
$$\Delta = \frac{1}{\left(s - M^2\right)^2 + \Gamma^2 M^2} = \frac{\pi}{M\Gamma}\,\delta\left(s - M^2\right) + \mathrm{PV}\left[\frac{1}{\left(s - M^2\right)^2}\right]$$

$$d\Phi_n\left(P, p_1 \dots p_n\right) = \frac{1}{2\pi}\, dQ^2\, d\Phi_{n-j+1}\left(P, Q, p_{j+1} \dots p_n\right)\, d\Phi_j\left(Q, p_1 \dots p_j\right)$$

To “complete” the decay ($d\Phi_j$) we need the δ-function …

The δ-part of the resonant propagator opens the line

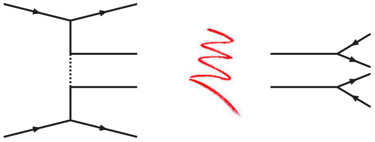
the right cut



$$\boldsymbol{\sigma}(\mathrm{qq} \to \bar{\mathrm{f}}\mathrm{f}\bar{\mathrm{f}}'\mathrm{f}' jj) \xrightarrow{PO} \boldsymbol{\sigma}(\mathrm{qq} \to \mathrm{H}jj) \otimes \Gamma(\mathrm{H} \to \mathrm{Z}\bar{\mathrm{f}}\mathrm{f}) \otimes \Gamma(\mathrm{Z} \to \bar{\mathrm{f}}'\mathrm{f}')$$

The δ-part of the resonant propagator opens the line

t-channel propagators cannot be cut



$$\sigma(qq \to \bar{f}f\bar{f}'f'jj) \xmapsto{PO} \sigma(qq \to ZZjj) \otimes \Gamma(Z \to \bar{f}f) \otimes \Gamma(Z \to \bar{f}'f')$$

External and intermediate layers are complementary

but not always interchangeable

$\mathscr{G}$

Factorizing into "physical" sub-processes (external POs): fine points

❶ Process: $\mathscr{A} = \mathscr{A}^{(1)}_{\mu}\, \Delta_{\mu\nu}(p)\, \mathscr{A}^{(2)}_{\nu}$

❷ Replace: $\Delta_{\mu\nu} \to \frac{1}{s-s_c} \sum_{\lambda} \varepsilon_{\mu}(p,\lambda)\, \varepsilon^{*}_{\nu}(p,\lambda)$

❸ Obtain

$$| \mathscr{A} |^2 = \frac{1}{| s - s_c |^2} \Big| \Big[\mathscr{A}^{(1)} \cdot \varepsilon \Big] \Big[\mathscr{A}^{(2)} \cdot \varepsilon^{*} \Big] \Big|^2$$

❹ Extract the δ from the propagator, factorize phase space
… but you don't have what you need, i.e.

$$\sum_{\lambda} \Big| \mathscr{A}^{(1)} \cdot \varepsilon(p,\lambda) \Big|^2 \sum_{\sigma} \Big| \mathscr{A}^{(2)} \cdot \varepsilon(p,\sigma) \Big|^2$$

Factorization continued

❺ *iff* cuts are not introduced, the interference terms among different helicities oscillate over the phase space and drop out

❻ MPE or "asymptotic expansion" means that no NWA is performed but, instead, the phase space decompostion obtains by using the two parts in the propagator expansion.

① The δ-term is what we need to reconstruct (external) POs

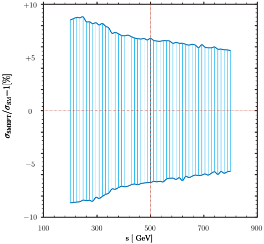
② the PV-term gives the remainder

Since the problem is extracting pseudo-observables, analytic continuation is performed only after integrating over residual variables.

No NP yet? Construct a consistent theory of $\mathcal{SM}$-deviations:

Past: Off-shell bounding Γ_{H} Present: SMEFT at NLO Future: Understanding H couplings

$\mathbf{gg} \to \mathbf{H}$ off-shell

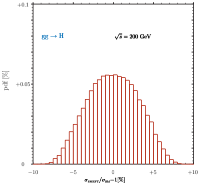


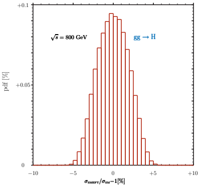
The successful search for the on-shell H did put little emphasis on the potential of the off-shell events

Wilson coefficients

$|\, a_i \,| \in [-1, +1]$

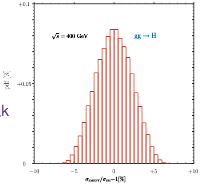
$\Lambda = 3$ *TeV*





Scaling couplings at the peak

is not the same thing as scaling them off-peak



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