Pseudo-Observables at LHC
an independent safety assessment

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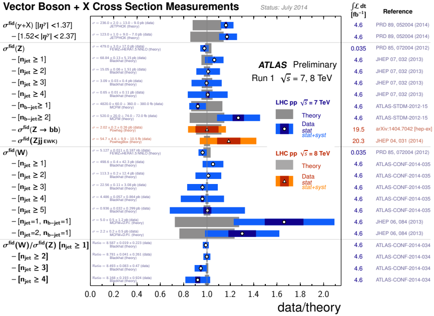
Disclaimer: friends in WG2 asked me to present an independent/external overview of POs at LHC nothing more, nothing less ......

chronicle of an idiosyncratic research

Appetizer



✗ Fiducial cross sections

Pro: maximal information
Pro: low-level extrapolation
Con: not universal, NAN

✗ Pseudo-observables

Pro: universal
Pro: simple
Con: almost model independent†

✗ easily accommodate SM deformations

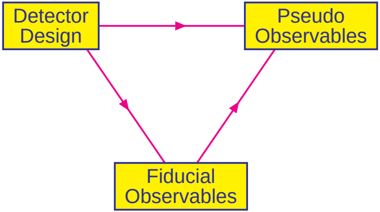
for nice introductions: David, Denner Hamburg Workshop on Higgs Physics

for comprehensive EFT reading Murayama et al. arXiv:1412.1837

definition PO any, uniquely defined, QFT-consistent, expression giving one number

PO can be defined in any SM deformation

† assuming $\Delta B \ll \Delta S$



by popular demand

POs at Lep: a short guided tour to one historical venue

Precision calculation project report e-Print: hep-ph/9902452

http://arxiv.org/abs/hep-ex/0509008

Exp strategy

Technically, each LEP experiment extracts a set of Fiducial Observables (FO), from their measured $\boldsymbol{\sigma}$s and asymmetries. The **4** sets are combined, taking correlated errors into account

$$\Rightarrow \text{LEP-average set of POs, } < \boldsymbol{PO} >_{\mathbf{Lep}} \ \Rightarrow$$

then interpreted, e.g. within the SM. Practical attitude: to stay with a MI fit,

① from FOs $\rightarrow$ POs ($\oplus$ a SM remnant) for each experiment

② and these sets of POs are averaged (across experiments)

③ The extraction of $\boldsymbol{M_{\mathrm{Z}}}, \boldsymbol{M_{\mathrm{t}}}, \boldsymbol{M_{\mathrm{H}}}$, $\boldsymbol{\alpha_{\mathrm{s}}}(\boldsymbol{M_{\mathrm{Z}}})$ and $\boldsymbol{\alpha}(\boldsymbol{M_{\mathrm{Z}}})$, is based on $< \boldsymbol{PO} >_{\mathbf{Lep}}$.

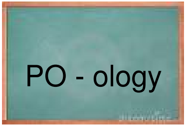
Within the context of the SM the FOs are described in terms of some set of amplitudes

$$A_{\rm SM} \quad = \quad A_{\gamma} + A_{\rm Z} + \textbf{non-factorizable},$$

$$\sigma\left(\hat{s}\right) \quad = \quad \int dz \, H_{\rm in}\left(z,\hat{s}\right) H_{\rm fin}\left(z,\hat{s}\right) \hat{\sigma}\left(z,\hat{s}\right)$$

One needs to specify $M_{\rm Z}$, the (remaining) relevant SM parameters for the SM-complement,

$$\mathrm{FO} = \mathrm{PO} + \overline{\mathrm{SM}}$$



The explicit formulae for the $\mathrm{Z\bar{f}f}$ vertex are

$$\rho_{\mathrm{Z}}^{\mathrm{f}}\,\gamma^{\mu}\left[\left(I_{\mathrm{f}}^{(3)} + i\,a_{\mathrm{L}}\right)\gamma_{+} - 2\,Q_{\mathrm{f}}\,\kappa_{\mathrm{Z}}^{\mathrm{f}}\,\sin^2\theta + i\,a_{\mathrm{Q}}\right] \;=\; \gamma^{\mu}\left(\mathcal{G}_{\mathrm{V}}^{\mathrm{f}} + \mathcal{G}_{\mathrm{A}}^{\mathrm{f}}\,\gamma^{5}\right)$$

where $\gamma_{+} = 1 + \gamma^5$ and $a_{\mathrm{Q,L}}$ are the SM imaginary parts.

By definition, the total and partial widths of the Z boson include also QED and QCD corrections.

Relations among POs

$$\Gamma_f \equiv \Gamma\left(Z \to \bar{f}f\right) = 4\,c_f\,\Gamma_0\left(\left|\mathscr{G}_V^f\right|^2 R_V^f + \left|\mathscr{G}_A^f\right|^2 R_A^f\right) + \Delta_{EW/QCD}$$

where $c_f = 1$ or 3 for leptons or quarks and $R^f_{V,A}$ describe the final state QED and QCD corrections and take into account the fermion mass. The last term,

$$\Delta_{EW/QCD} = \Gamma^{(2)}_{EW/QCD} - \frac{\alpha_s}{\pi}\Gamma^{(1)}_{EW}$$

accounts for the non-factorizable corrections.

The standard partial width, Γ_0, is

$$\Gamma_0 = \frac{G_F M_Z^3}{24\sqrt{2}\pi} = 82.945(7)\ MeV$$

✓ The peak hadronic and leptonic cross-sections are defined by

$$\sigma_h^0 = 12\pi \frac{\Gamma_e \Gamma_h}{M_Z^2 \Gamma_Z^2} \qquad \sigma_l^0 = 12\pi \frac{\Gamma_e \Gamma_l}{M_Z^2 \Gamma_Z^2}$$

where Γ_Z is the total decay width of the Z boson, i.e, the sum of all partial decay widths.

✓ The effective electroweak mixing angles (*effective sinuses*) are always defined by

$$4|Q_f| \sin^2 \theta_{eff}^f = 1 - \frac{\mathrm{Re}\ \mathscr{G}_V^f}{\mathrm{Re}\ \mathscr{G}_A^f} = 1 - \frac{g_V^f}{g_A^f}$$

✓ where we define

$$g_V^f = \mathrm{Re}\ \mathscr{G}_V^f \qquad g_A^f = \mathrm{Re}\ \mathscr{G}_A^f$$

To Summarize the Lep Strategy:

① One starts with the SM, which introduces complex-valued couplings, calculated to some order in perturbation theory

② Next we define $g_{\mathbf{V}}^{\mathbf{f}}, g_{\mathbf{A}}^{\mathbf{f}}$ as the real parts of the effective couplings and $\boldsymbol{\Gamma}_{\mathbf{f}}$ as the physical partial width absorbing all radiative corrections including the imaginary parts of the couplings and fermion mass effects

③ Furthermore,

$$R_{\mathrm{q}} = \frac{\Gamma_{\mathrm{q}}}{\Gamma_{\mathrm{h}}} \qquad R_{\mathrm{l}} = \frac{\Gamma_{\mathrm{h}}}{\Gamma_{\mathrm{l}}}$$

for quarks and leptons, respectively.

The experimental collaborations report POs for the following sets:

$$(R_{\mathrm{f}}, A^{0,\mathrm{f}}_{\mathrm{FB}}), \qquad (g^{\mathrm{f}}_{\mathrm{V}}, g^{\mathrm{f}}_{\mathrm{A}}), \qquad (\sin^2\theta^{\mathrm{f}}_{\mathrm{eff}}, \rho_{\mathrm{f}})$$

1. In order to extract $g^{\mathrm{f}}_{\mathrm{V}}, g^{\mathrm{f}}_{\mathrm{A}}$ from Γ_{f} one has to get the SM-remnant, all else is trivial
2. However, the parameter transformation cannot be completely MI, due to the residual SM dependence.

In conclusion, the flow of the calculation requested by the experimental Collaborations is:

1. pick the Lagrangian parameters $M_{\mathrm{t}}, M_{\mathrm{H}}$ etc. for the explicit calculation of the residual SM-dependent part
2. perform the SM initialisation of everything, such as imaginary parts etc. giving, among other things, the complement $\overline{\mathbf{SM}}$
3. select $g_{\mathrm{V}}^{\mathrm{f}}, g_{\mathrm{A}}^{\mathrm{f}}$
4. perform a SM-like calculation of Γ_{f}, but using arbitrary values for $g_{\mathrm{V}}^{\mathrm{f}}, g_{\mathrm{A}}^{\mathrm{f}}$, and only the rest, namely

$$R_{\mathrm{V}}^{\mathrm{f}}, \quad R_{\mathrm{A}}^{\mathrm{f}} \qquad \Delta_{\mathrm{EW/QCD}} \qquad \mathrm{Im}\,\mathscr{G}_{\mathrm{V}}^{\mathrm{f}}, \quad \mathrm{Im}\,\mathscr{G}_{\mathrm{A}}^{\mathrm{f}}$$

from the SM.

☛ Therefore, the expression for FO = FO(PO), at arbitrary $\hat{s}$, requires a careful examination and should be better understood as FO = FO(PO,$\overline{\mathrm{SM}}$) that is, for example:

$$\sigma \;=\; \sigma\Big(R_{\mathrm{l}}, A^{0,\mathrm{l}}_{\mathrm{FB}}, \cdots \to g^{\mathrm{f}}_{\mathrm{V}}, g^{\mathrm{f}}_{\mathrm{A}} \to \rho_{\mathrm{f}}, \sin^2\theta^{\mathrm{f}}_{\mathrm{eff}}; \text{residual SM}\Big)$$

As long as the procedure does not violate gauge invariance there is nothing wrong with the calculations.

☞ Another approach exists, extraction of lagrangian parameters directly from the FOs, which are not (of course) raw data but rather educated manipulations of raw data, e.g. distributions defined for some simplified setup.

From Lep to LHC, does history repeat itself? Why should it?

Because the POs are a platform between realistic observables and theory parameters, allowing EXP and TH to meet half way between TH having to run full simulation and reconstruction and EXP fully unfolding to model-dependent parameter spaces. However

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

It is the highest form of self-respect to admit our errors and mistakes and make amends for them

When A_{LR} was derived an old version of ZFITTER was used to deconvolute IS QED radition. Few years later, when it became clear that they should have used another version, we kept asking for a revision . . . and we were told “you are beating a dead horse”.

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

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

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 $\mathrm{H} \to \mathrm{e}\nu\mathrm{qq}$

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

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

$$- \quad 2\,\frac{g g_6}{M}\,a_{\mathrm{ZZ}}\left(p_1 \cdot p_2\, g^{\mu\nu} - p_2^{\mu} p_1^{\nu}\right)$$

EFT Intermezzo

The role of EFT in paving the (as) Model Independent (as possible) road cannot be undermined.

Crumple the Warsaw basis (e.g. MAGA† basis) to capture your favorite scenario (LO κ-vectors) is not the solution, bringing EFT to NLO is the correct way for focusing in consistency of the $\boldsymbol{\kappa}$-framework. The latter is crucial in describing SM deviations.

No NLO EFT 

see "HEFT beyond LO approximation" https://indico.cern.ch/event/345455/

†) Michael Adam Gino Andrè, WG2 draft

Off-shell POs 

✗ Going off-shell explains that there is no free lunch in search and optimization (see next slides)

Furthermore, POs should be as inclusive as possible, without requiring extrapolation of FOs; we can nevertheless define off-shell POs, e.g.

$$R^{4l}_{\mathrm{off}} = \frac{N^{4l}_{\mathrm{off}}}{N^{4l}_{\mathrm{tot}}}, \quad N^{4l}_{\mathrm{off}} = N^{4l}\left(M_{4l} > M_0\right)$$

where N^{4l} is the number of 4-leptons events.

Since the K-factor has a relatively small range of variation with virtuality, the ratio is much less sensitive also to higher order terms.

LHC is not Lep, mostly due to the non-perturbative character of the Higgs boson

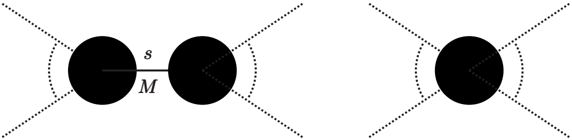
- Even for a light $\mathbf{H}$ the imaginary part of the **3** loop $\mathbf{H}$ self-energy is comparable to the corresponding **1** loop quantity
- seriously, 4f decays are 40$\%$ of 2f decays $\dots$

Consequence: most of the time we face off-shell unstable particles, even at the $\mathbf{H}$ peak cross-section. Therefore, how to interpret

$$\boldsymbol{\Gamma}\left(\mathbf{H} \to \mathbf{WW} \to \nu \mathbf{l} \nu' \mathbf{l}'\right) \quad \text{vs.} \quad \boldsymbol{\Gamma}\left(\mathbf{H} \to \mathbf{W}^{*}\mathbf{W}\right) \quad \text{etc ?}$$

Users may want to produce a new amplitude for $\mathrm{H} \to \mathrm{VV}$ without having to worry about the full process

Signal and Background - perfectly tied together



$s =$ virtuality
$M =$ mass
$\xi =$ gauge parameter

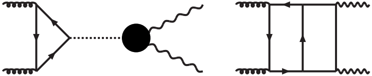
$$\frac{V_i(\xi, s, \ldots)\,V_f(\xi, s, \ldots)}{s - M^2} + N(\xi, s, \ldots)$$

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

$$\frac{V^{\text{inv}}_i(M^2 = s, \ldots)\,V^{\text{inv}}_f(M^2 = s, \ldots)}{s - M^2} + B(s, \ldots)$$

Impact: off-shell $\mathbf{H}$ events
definition of $\mathbf{H} \to \mathbf{Z}\mathbf{f}\bar{\mathbf{f}}$ etc.

Facts of life (frequently forgotten)



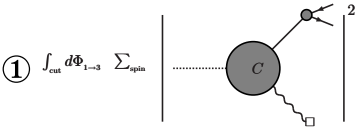
prod decay(ξ) n/a two-loop bckg(ξ)

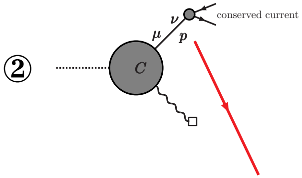
① Put all gluons you want in production (still gauge invariant)

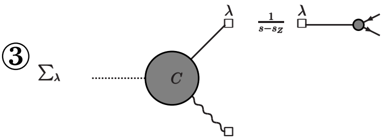
② NLO decay: shift off-shell, ξ-dependent, part to non-resonant

③ this would require the two-loop non-resonant

PO building manual







$\square =$ *polarization*

$$\delta_{\mu\nu} \to \sum_\lambda \left[e^\lambda_\mu(p)\right]^* e^\lambda_\nu(p)$$

$$|\sum_\lambda f(\lambda)|^2 = \sum_\lambda |f(\lambda)|^2 + \text{rest}$$

HZZ PO has been described in
Sect. 7 of arXiv:1209.5538
App. C of arXiv:1112.5517

Next job for LHC is high precision study of SM-deviations[†]

❶ take $\mathbf{H} \to \gamma \bar{f} f$ or $\mathbf{H} \to 4f$ and use PROPHECY4F (or similar). However, PROPHECY4F is on-shell SM and there will be no PROPHECY4F for each BSM

❷ Off-shell is Newfoundland

❸ *ergo*, move to the LHC M-code

†) see arXiv:1412.6038

The LHC M-code:

- ✗ For each process write down some (QFT-compatible) amplitude allowing for SM-deviations, both for signal and background (NLO EFT is a good example). Compute FOs.
- ✗ Insert Signal expressed through POs without altering the total. Please, do not subtract SM background (B changes too)
- ✗ Fit POs, $\Gamma_{\mathbf{ZZ}}$ (conventionally defined), $\boldsymbol{A}_{\mathbf{F}}^{\mathbf{ZZ}}$, $\boldsymbol{A}_{\mathbf{FB}}^{\mathbf{eW}}$ etc., or $\boldsymbol{\rho}_{\mathbf{H}}^{\mathbf{V}}, \mathscr{G}_{\mathbf{L}}^{\mathbf{V}}$ etc.
- ✗ Derive Wilson coefficients or BSM Lagrangian parameters
- ✗ Publish the full list of FOs (with modern rivet technology) and POs à la Lep (LHC legacy)

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.

$$\rho_{\mathrm{H}}^{\gamma\mathrm{Z}} = \mathscr{A}\,(\mathrm{H} \to \gamma\mathrm{Z}) \quad = \quad \kappa_{\mathrm{W}}^{\gamma\mathrm{Z}}\,\mathscr{A}_{\mathrm{W}}^{(4)} + \kappa_{\mathrm{t}}^{\gamma\mathrm{Z}}\,\mathscr{A}_{\mathrm{t}}^{(4)} + \kappa_{\mathrm{b}}^{\gamma\mathrm{Z}}\,\mathscr{A}_{\mathrm{b}}^{(4)} + i\,g g_6\,\frac{M_{\mathrm{H}}^2}{M_{\mathrm{W}}}\,a_{\mathrm{AZ}}$$

$$+ \quad a_{\phi D}\,\mathscr{A}_{\mathrm{W}}^{\mathrm{NF}} + \sum_{\mathrm{f}=\mathrm{t,b}} \left(a_{\phi\mathrm{q}}^{(3)} - a_{\phi\mathrm{q}}^{(1)} - a_{\phi\mathrm{f}} \right) \mathscr{A}_{\mathrm{f}}^{\mathrm{NF}}$$

Intersecting $\mathbf{H} \to \gamma\gamma \bigcap \mathbf{H} \to \gamma Z \diamond \kappa_i^{\gamma Z} = 1 + g_6\, s_\theta^2\, \Delta\kappa_i^{\gamma\gamma} + g_6\, \Delta^{\text{rest}}\kappa_i^{\gamma Z}$

$$\begin{aligned}
\Delta^{\text{rest}}\kappa_{\rm t}^{\gamma Z} &= \left(\hat{s}_\theta^2 - 3\right) a_{\rm AA} + \frac{2 - s_\theta^2}{s_\theta} \left(s_\theta\, a_{\rm ZZ} - c_\theta\, a_{\rm AZ}\right) \\
&+ \frac{1}{2} \frac{c_\theta^2}{s_\theta^2} a_{\phi D} - \frac{3}{4} \frac{1 - 2\, s_\theta^2}{s_\theta} \frac{M_{\rm t}^2}{M_{\rm W}^2} a_{\rm tWB} + \frac{3}{2} \frac{M_{\rm t}^2}{M_{\rm W}^2} c_\theta\, a_{\rm tBW}
\end{aligned}$$

$$\begin{aligned}
\Delta^{\text{rest}}\kappa_{\rm b}^{\gamma Z} &= \left(s_\theta^2 - 3\right) a_{\rm AA} + \frac{2 - s_\theta^2}{s_\theta} \left(s_\theta\, a_{\rm ZZ} - c_\theta\, a_{\rm AZ}\right) \\
&+ \frac{1}{2} \frac{c_\theta^2}{s_\theta^2} a_{\phi D} - \frac{3}{2} \frac{M_{\rm b}^2}{M_{\rm W}^2} a_{\rm bWB}
\end{aligned}$$

$$\begin{aligned}
\Delta^{\text{rest}}\kappa_{\rm W}^{\gamma Z} &= -\frac{1}{3} \left\{ \left[5 + 2 \left(1 - \frac{M_{\rm H}^2}{M_{\rm W}^2}\right) s_\theta^2\right] a_{\rm AA} - \frac{3}{2} \frac{1}{s_\theta^2} a_{\phi D} \right. \\
&- \left. \left[9 - 2 \left(1 - \frac{M_{\rm H}^2}{M_{\rm W}^2}\right) c_\theta^2\right] a_{\rm ZZ} + \left[2 + \left(1 - \frac{M_{\rm H}^2}{M_{\rm W}^2}\right) s_\theta^2\right] a_{\rm AZ} \right\}
\end{aligned}$$

Secondary POs:

$$
\begin{aligned}
\mathbf{H} \to \gamma\gamma\,(\gamma \mathbf{Z}) &\quad\mapsto\quad \rho_{\mathbf{H}}^{\gamma\gamma(\mathbf{Z})}\, \frac{p_1 \cdot p_2\, g^{\mu\nu} - p_2^{\mu} p_1^{\nu}}{M} \\
\mathbf{HVV} &\quad\mapsto\quad \rho_{\mathbf{H}}^{\mathbf{V}} \left(M g^{\mu\nu} + \frac{\mathscr{G}_{\mathbf{L}}^{\mathbf{V}}}{M}\, p_2^{\mu} p_1^{\nu} \right) \\
\Gamma(\mathbf{H} \to \gamma\gamma) &\qquad\qquad \text{etc.}
\end{aligned}
$$

- ☛ None of these parametrizations represent an approximation (IBA-like)
- ☞ The full FOs are complete (to the best of our technology) and will be written as FO(PO,rest).

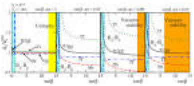
For each process compute the full answer within fiducial volumes

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

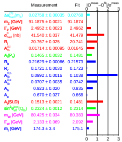
Can we make it rigorous while keeping the total intact ?

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



or



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

Alternatively one can express secondary POs in terms of some BSM lagrangian parameters, e.g. THDM (here type I)

$$
\begin{aligned}
\mathbf{H} \to \gamma\gamma \quad \mapsto \quad & i\,\frac{g^2 s_\theta^2}{8\,\pi^2}\,\left(p_1 \cdot p_2\, g^{\mu\nu} - p_2^{\mu} p_1^{\nu}\right) \\
\times \quad & \left\{ \frac{\cos\alpha}{\sin\beta} \sum_{\mathrm{f}} \mathscr{A}_{\mathrm{f}}^{\mathrm{SM}} - \sin(\alpha-\beta)\,\mathscr{A}_{\mathrm{bos}}^{\mathrm{SM}} \right. \\
+ \quad & \left[\left(M_{\mathrm{sb}}^2 + M_h^2 \right) \cos(\alpha-\beta)\,\cos 2\beta \right. \\
- \quad & \left. \left. \left(2\,M_{\mathrm{sb}}^2 + M_h^2 + 2\,M_{\mathrm{H}^+}^2 \right) \sin(\alpha-\beta)\,\sin 2\beta \right] \mathscr{A}_{\mathrm{H}^+}^{\mathrm{SM}} \right\}
\end{aligned}
$$

where M_{sb} is the Z_2 soft-breaking scale, $h(\mathrm{H})$ are the light(heavy) scalar Higg bosons.

aren't coeff κs?

A schetchy example technical, jump to s34 if needed

$$
\begin{aligned}
\mathrm{A} &= \frac{V_i(s, s_{\mathrm{H}}, \xi, \dots)\, V_f(s, s_{\mathrm{H}}, \xi, \dots)}{s - s_{\mathrm{H}}} + B(s, \xi, \dots) \\
V_{i,f}(s, s_{\mathrm{H}}, \xi, \dots) &= V_i^{\mathrm{inv}}(s, s, \dots) + (s - s_{\mathrm{H}})\,\Delta V_{i,f}(s, s_{\mathrm{H}}, \xi, \dots)
\end{aligned}
$$

where $\boldsymbol{s}_{\mathbf{H}}$ is the $\mathbf{H}$ complex pole, $\boldsymbol{s}$ the $\mathbf{H}$ virtuality, $\boldsymbol{\xi}$ the gauge parameter(s) and where $\dots$ represent other invariants

$$
\mathrm{A} = \mathrm{A_S} + \mathrm{A_B} \qquad\qquad \mathrm{A_S} = \frac{V_i^{\mathrm{inv}}\, V_f^{\mathrm{inv}}}{s - s_{\mathrm{H}}}
$$

$$
\begin{aligned}
\mathrm{FO} &= \int_{\mathrm{cut}} d\Phi \sum_{\mathrm{spin}} \Big|\mathrm{A_S} + \mathrm{A_B}\Big|^2 = \int_{\mathrm{cut}} d\Phi \sum_{\mathrm{spin}} \Big|\mathrm{A_S}\Big|^2 + \mathrm{FO}_{\mathrm{rest}} \\
&= \int d\Phi \sum_{\mathrm{spin}} \Big|\mathrm{A_S}\Big|^2 + \left(\int_{\mathrm{cut}} - \int\right) d\Phi \sum_{\mathrm{spin}} \Big|\mathrm{A_S}\Big|^2 + \mathrm{FO}_{\mathrm{rest}} \\
&= \mathrm{PO} + \mathrm{rest}
\end{aligned}
$$

A schetchy example (cont'd)

As far as Signal (for a given F final state) is concerned we can also write as follows:

$$\sigma\left(ij \to \mathrm{H} \to \mathrm{F}\right) = \frac{1}{\pi}\,\sigma_{ij\to\mathrm{H}}(s)\,\frac{s^2}{\left|s - s_{\mathrm{H}}\right|^2}\,\frac{\Gamma_{\mathrm{H}\to\mathrm{F}}(s)}{\sqrt{s}}$$

and write $\Gamma_{\mathrm{H}\to\mathrm{F}}$ in terms of POs, e.g. $\Gamma_{\mathrm{H}\to\mathrm{ZZ}}$ and $\Gamma_{\mathrm{Z}\to\mathrm{ll}}$ (see slide 21), where all unstable particles are computed at their complex pole.

☛ Compare $\mathrm{PO}_{\mathrm{ATLAS}}$, $\mathrm{PO}_{\mathrm{CMS}}$

$$\mathcal{M} \quad = \quad \mathcal{M}^{\nu\nu}_{\mathrm{fc}}\,(p_1\,,p_2)\,\Delta_{\mu\alpha}\,(p_1)\,\Delta_{\nu\beta}\,(p_2)\,J^{\alpha}\,(q_1\,,k_1)\,J^{\beta}\,(q_2,k_2) + \mathcal{M}_{\mathrm{nf}}\,(p_1\,,p_2)$$

$$J^{\mu}\,(q,k) \quad = \quad g\,\bar{u}(q)\,\gamma^{\mu}\,\Big(v_{\mathrm{f}} + a_{\mathrm{f}}\,\gamma^5\Big)\,v(k), \qquad p = q + k$$

$\Delta^{\mu\nu}(p)$ is the Z propagator and $\mathcal{M}_{\mathrm{nf}}$ collects all diagrams that are not doubly (Z) resonant

$$\mathcal{M}^{\mu\nu}_{\mathrm{fc}} \quad = \quad F_{\mathrm{D}}\,\delta^{\mu\nu} + F_{\mathrm{T}}\,T^{\mu\nu} \qquad T^{\mu\nu} = \frac{p_1^{\nu}\,p_2^{\mu}}{p_1 \cdot p_2} - \delta^{\mu\nu}$$

$$\Delta^{\mu\nu}(p) \to \sum_{\lambda} e_{\mu}\,(p,\lambda)\,e^{*}_{\nu}(p,\lambda)\,\Delta(p^2) \qquad \Delta(p^2) = \frac{1}{s - M_{\mathrm{Z}}^2}$$

Constructing POs in $\mathrm{H} \to 4\,\mathrm{f}$ (cont'd)

$$P_{ij} \quad = \quad \left[\mathscr{M}_{\mathrm{D}}\,\delta^{\mu\nu} + \mathscr{M}_{\mathrm{T}}\,T^{\mu\nu}\right] e_{\mu}(p_1, i)\, e_{\nu}(p_2, j)$$

$$D_{ij}(p) = \sum_{\text{spin}} E_i(p)\, E_j^{\dagger}(p) \qquad\qquad E_i(p) = J^{\mu}\,(q, k)\; e^{*}_{\mu}(p, i)$$

where $i, j = -1, 0, +1$ and $p = q + k$. We obtain

$$\begin{aligned}\sum_{\text{spin}} \left|\mathscr{M}_{\text{fc}}\right|^2 \quad &= \quad \sum_{ijkl} P_{ij}\, P^{\dagger}_{kl}\, D_{ik}(p_1)\, D_{jl}(p_2) \left|\Delta(s_1)\,\Delta(s_2)\right|^2 = \sum_{ijkl} A_{ijkl} \left|\Delta(s_1)\,\Delta(s_2)\right|^2 \\ &= \quad \left[\sum_i A_{iiii} + \sum_{ij} A_{ijij} + \sum_{\substack{k,j \neq i \\ l \neq j}} A_{ijkl}\right] \left|\Delta(s_1)\,\Delta(s_2)\right|^2\end{aligned}$$

where $\mathscr{M}$ is the matrix element comprising all factorizable contributions, not only the SM ones. A_{iiii} gives informations on H decaying into two Z of the same helicity $(0, 0$ etc.$)$, A_{ijij} on mixed helicities $(0, 1$ etc.$)$ while the third term gives the interference

$$
\begin{aligned}
\mathscr{M}_{\mathrm{fc}} &= \sum_{ij} a_{ij}\,(s, s_1, s_2, \dots)\,\Delta(s_1)\,\Delta(s_2) \\
&= \sum_{ij} a_{ij}\,\left(s_{\mathrm{H}}, s_{\mathrm{Z}}, s_{\mathrm{Z}} \dots\right)\,\Delta(s_1)\,\Delta(s_2) + N\,(s, s_1, s_2, \dots)
\end{aligned}
$$

where N denotes the remainder of the double expansion around $s_{1,2} = s_{\mathrm{Z}}$, $s = -(p_1 + p_2)^2$ and

$$
\Delta(s) = \frac{1}{s - s_{\mathrm{Z}}},
$$

$s_{\mathrm{H}}, s_{\mathrm{Z}}$ being the H,Z complex poles. Therefore, we define pseudo-observables  PO-number!

$$
\Gamma_i = \int d\Phi_{1\to 4} \sum_{\text{spin}} \left| a_{ii}\,\left(s_{\mathrm{H}}, s_{\mathrm{Z}}, s_{\mathrm{Z}} \dots\right)\,\Delta(s_1)\,\Delta(s_2) \right|^2
$$

with similar definitions for Γ_{ij}

POs (container) at LHC: summary table

① the external layer:

$$\mathbf{\Gamma_{VV}} \quad \mathbf{A^{ZZ}_{FB}} \quad \mathbf{N^{4l}_{off}} \quad \textbf{etc}$$

② intermediate layer 1

$$\boldsymbol{\rho}^{\mathbf{V}}_{\mathbf{H}} \quad \mathscr{G}^{\mathbf{V}}_{\mathbf{L}} \quad \boldsymbol{\rho}^{\boldsymbol{\gamma\gamma}}_{\mathbf{H}}, \boldsymbol{\rho}^{\boldsymbol{\gamma}\mathbf{Z}}_{\mathbf{H}} \quad \boldsymbol{\rho}^{\mathbf{f}}_{\mathbf{H}}$$

③ intermediate layer 2

$$\boldsymbol{\kappa}^{\boldsymbol{\gamma\gamma}}_{\mathbf{f}} \quad \boldsymbol{\kappa}^{\boldsymbol{\gamma\gamma}}_{\mathbf{W}} \quad \boldsymbol{\kappa}^{\boldsymbol{\gamma\gamma}\,\mathbf{NF}}_{\boldsymbol{i}} \quad \textbf{etc}$$

④ internal layer (contained): Wilson coeff. or non-SM parameters in BSM (e.g. $\alpha, \beta, M_{\rm sb}$ etc. in THDMs)

Fine points to remember when building POs

❶ $\mathbf{H \to \bar{f} f \gamma}$ defines Dalitz decay for isolated photons but is part of the real corrections to $\mathbf{H \to \bar{f} f}$ for IR/collinear photons

❷ $\mathbf{H \to 4f}$ defines the four-body decays or pair production corrections to the two-body decays, depending on the invariant masses of the fermion pairs. Strategies? The whole $\mathbf{4f}$ is included in $\mathbf{H \to 2f}$ or part of it defines the $\mathbf{2f}$ signal and part the $\mathbf{4F}$ signal

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

CONCLUSIONS

Do we have a way of knowing whether “unobservable” theoretical entities really exist, or that their meaning is defined solely through measurable quantities?

The only truth that gets through will be what we force through: the victory of reason will be the victory of people who are prepared to reason, nothing else. Start thinking about the LHC M-code

Thank you for your attention