High-precision calculations of Higgs properties

Giampiero Passarino

Dipartimento di Fisica Teorica, Università di Torino, Italy

INFN, Sezione di Torino, Italy

Precision Observables and Radiative Corrections relevant for future e^+e^- colliders, 13–14 July 2015,CERN

This talk is about why NLO SMEFT + POs[1], it is not

- ✗ how NLO[2]
- ✗ what NLO[3] however, see backup material ▸ go now
- ✗ why POs[4]

fuel for discussion . . . nothing more

[1] What can be said at all should be said clearly and whereof one cannot speak thereof one must be silent

[2] Covered in “ATLAS Higgs (N)NLO MC and Tools Workshop for LHC RUN-2”, https://indico.cern.ch/event/345455/, see also https://indico.desy.de/conferenceDisplay.py?confId=476

[3] same as above

[4] Covered in “Pseudo-observables: from LEP to LHC”, https://indico.cern.ch/event/373667/

Part I

Warming up: mostly Lep

POs at Lep, the role of the Z-pole

From $$\frac{V^{\mu}_{\mathrm{e}^+\mathrm{e}^-\gamma}\, V^{\mu}_{\bar{\mathrm{f}}\mathrm{f}\gamma}}{s} + \frac{V^{\mu}_{\mathrm{e}^+\mathrm{e}^-\mathrm{Z}}\, V^{\mu}_{\bar{\mathrm{f}}\mathrm{f}\mathrm{Z}}}{s - M^2_{\mathrm{Z}}} + \text{Boxes}$$

To $$\sigma^{\text{peak}}_{\mathrm{f}} = 12\pi \frac{\Gamma_{\mathrm{e}}\Gamma_{\mathrm{f}}}{M^2_{\mathrm{Z}}\Gamma^2_{\mathrm{Z}}}$$

Caution: unstable particles present

From on-shell mass M_{Z} $\longmapsto$ To complex pole s_{Z}

DIAGRAMMATICA
at Lep1

role of theory:
delivering boxes and crosses
with maniacal care for gauge invariance

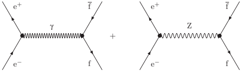


Figure 1: The process $e^+e^- \to (Z,\gamma) \to f\bar{f}$ in the Born approximation.

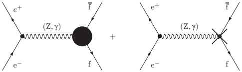


Figure 2: The process $e^+e^- \to (Z,\gamma) \to f\bar{f}$; final fermion vertex and its counter-terms.

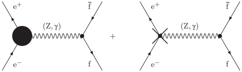


Figure 3: Process $e^+e^- \to (Z,\gamma) \to f\bar{f}$; electron vertex and its counter-terms

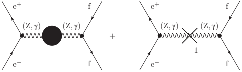


Figure 4: Process $e^+e^- \to (Z,\gamma) \to f\bar{f}$; self-energies and kinetic counter-terms

The complete amplitude for the four-fermion process should be presented in all schemes and all gauges with a general structure,

$$\begin{aligned}\mathscr{A} \quad \sim \quad & \frac{1}{s}\Big\{\alpha^{\mathrm{fer}}(s)\gamma^{\mu}\otimes\gamma_{\mu}+\chi(s) \\ & \Big[\mathscr{F}^{\mathrm{ef}}_{\mathrm{QQ}}(s,t)\,\gamma^{\mu}\otimes\gamma_{\mu}+\mathscr{F}^{\mathrm{ef}}_{\mathrm{LL}}(s,t)\,\gamma^{\mu}\gamma_{+}\otimes\gamma_{\mu}\,\gamma_{+} \\ & +\mathscr{F}^{\mathrm{ef}}_{\mathrm{QL}}(s,t)\,\gamma^{\mu}\otimes\gamma_{\mu}\,\gamma_{+}+\mathscr{F}^{\mathrm{ef}}_{\mathrm{LQ}}(s,t)\,\gamma^{\mu}\,\gamma_{+}\otimes\gamma_{\mu}\Big]\Big\}\end{aligned}$$

$$\chi(s)=s\,\chi_{\mathrm{Z}}(s)$$

Again the *raison d'être* of any renormalization scheme is deeply connected to the possibility of defining the form factors in a gauge-invariant manner.

Where are the PO's?

$$\frac{d\sigma_f}{d\Omega} = \frac{\alpha^2}{4s} N_f^c \beta_f \left[\left(1 + c^2\right) \mathscr{F}_1(s) \right.$$
$$\left. + \; 4\mu_f^2 (1 - c^2) \mathscr{F}_2(s) + 2\beta_f c \mathscr{F}_3(s) \right]$$

where $c = \cos\theta$ is the cosine of the scattering angle and $\beta_f^2 = 1 - 4\mu_f^2$ with $\mu_f^2 = m_f^2/s$.

The energy dependence is confined in the $\mathscr{F}$ -functions

$$
\begin{aligned}
\mathscr{F}_1(s) &= Q_e^2 Q_f^2 + 2\, Q_e Q_f g_V^e g_V^f \ \mathrm{Re}\ \chi(s) \\
&+ \left[(g_V^e)^2 + (g_A^e)^2 \right] \left[\left(g_V^f\right)^2 + \left(g_A^f\right)^2 - 4\,\mu_f^2 \right] \left|\chi(s)\right|^2, \\
\mathscr{F}_2(s) &= Q_e^2 Q_f^2 + 2\, Q_e Q_f g_V^e g_V^f \ \mathrm{Re}\ \chi(s) \\
&+ \left[(g_V^e)^2 + (g_A^e)^2 \right] \left(g_V^f\right)^2 \left|\chi(s)\right|^2, \\
\mathscr{F}_3(s) &= 2\, Q_e Q_f g_A^e g_A^f \,\mathrm{Re}\ \chi(s) + 4\, g_V^e g_V^f g_A^e g_A^f \left|\chi(s)\right|^2
\end{aligned}
$$

χ is the reduced $\gamma/\mathbf{Z}$ propagator ratio. The form factors $\mathscr{F}$ include weak loop corrections but, in their construction, we have completely ignored a few ingredients:

- ♣ QED radiation,
- ♢ weak boxes and
- ♠ all the imaginary parts

Usually, 25 POs were introduced and discussed

- the mass of the $\mathbf{W}$ ($M_{\mathbf{W}}$)
- the hadronic peak cross-section ($\sigma_{\mathbf{h}}$)
- the partial leptonic and hadronic widths ($\Gamma_{\mathbf{f}}$, $\mathbf{f} = \nu, e, \mu, \tau, u, d, c, s, b$)
- the total width ($\Gamma_{\mathbf{Z}}$)
- the total hadronic width ($\Gamma_{\mathbf{h}}$)
- the total invisible width ($\Gamma_{\mathbf{inv}}$)
- various ratios ($R_{\mathbf{l}}$, $R_{\mathbf{b}}$, $R_{\mathbf{c}}$)
- the asymmetries and polarization ($A^{\mu}_{FB}, A^{e}_{LR}, A^{b}_{FB}, A^{c}_{FB}, P^{\tau}, P^{b}$)
- effective sines ($\sin^2\theta_{\mathbf{e}}, \sin^2\theta_{\mathbf{b}}$)

Queen of new POs σ_{ZH}

Part II

Learning from LHC: mostly SMEFT

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

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

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)

No NP yet?

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

$$\mathbf{H} \to \gamma\gamma$$

✓ κ-approach: write the amplitude as

$$\mathbf{A} = \sum_{i=\mathrm{t,b,W}} \kappa_i \mathscr{A}^i + \kappa_c$$

$\mathscr{A}^{\mathrm{t}}$ being the SM t-loop etc. The contact term (which is the LO SMEFT) is given by κ_c. Furthermore

$$\kappa_i = 1 + \Delta\kappa_i \qquad i \neq c$$

✓ For the sake of simplicity assume

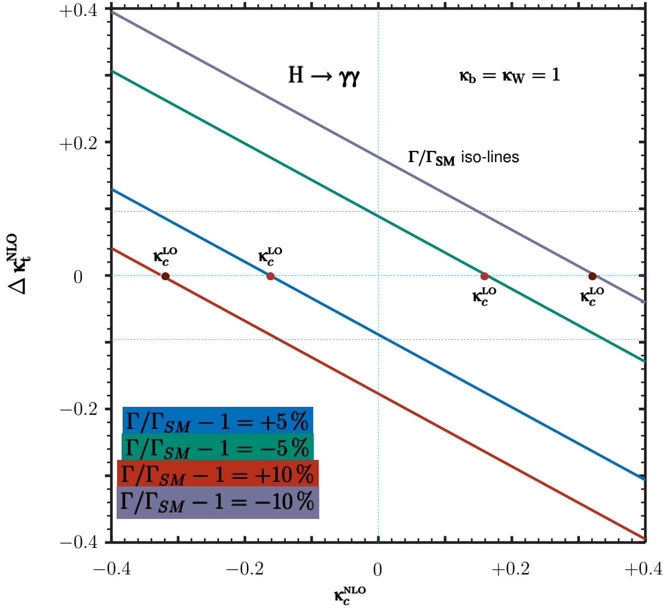
$$\kappa_b = \kappa_W = 1 \quad \left(\kappa_W^{\rm exp} = 0.95^{+0.14}_{-0.13} \mathit{ATLAS}\ \ 0.96^{+35}_{-16} \mathit{CMS}\right)$$

and compute

$$✎ \quad \kappa_\gamma \mapsto R = \Gamma\left(\kappa_t, \kappa_c\right)/\Gamma_{SM} - 1 \quad [\%]$$

In LO SMEFT κ_c is non-zero and $\kappa_t = 1$ [5]. You measure a deviation and you get a value for κ_c. However, at NLO $\Delta\kappa_t$ is non zero and you get a degeneracy. The interpretation in terms of $\kappa_c^{\rm LO}$ or in terms of $\{\kappa_c^{\rm NLO}, \Delta\kappa_t^{\rm NLO}\}$ could be rather different.

[5] Certainly true in the linear realization



$$\Gamma\left(\Delta\kappa_t\,,\,\kappa_c\right) = \left(42.29 - 23.87\,\Delta\kappa_t - 13.01\,\kappa_c\right)\,\frac{G_F\alpha^2}{128\sqrt{2}\pi^3}\,M_H^3$$

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]

hi-tech center 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

Going interpretational

$$\mathrm{A}_{\mathrm{SMEFT}} = \frac{g^2 s_\theta^2}{8\pi^2}\Big[\sum_{i=\mathrm{t,b,w}} \kappa_i \mathscr{A}^i + \frac{g_6}{g^2 s_\theta^2}\frac{M_{\mathrm{H}}^2}{M_{\mathrm{W}}^2} 8\pi^2 a_{\mathrm{AA}}\Big]$$

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

① LO SMEFT: $\kappa_i = 1$ and a_{AA} is scaled by $1/16\pi^2$ being LG

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

At NLO, $\Delta\kappa = g_6\,\rho$ and $a_{\mathrm{AA}} = s_\theta^2\, a_{\phi\mathrm{W}} + c_\theta^2\, a_{\phi\mathrm{B}} + s_\theta c_\theta\, a_{\phi\mathrm{WB}}$

$$\mathscr{A}_{\mathrm{SMEFT}} = \sum_{i=\mathrm{t,b,w}} (1 + g_6\,\rho_i)\,\mathscr{A}^i + g_c\, a_{\mathrm{AA}}$$

Warsaw basis

$$g_6^{-1} = \sqrt{2}\, G_{\mathrm{F}}\, \Lambda^2$$

$$g_c = \frac{1}{2}\, \frac{g_6}{g^2 s_\theta^2}\, \frac{M_{\mathrm{H}}^2}{M_{\mathrm{W}}^2}$$

$$\rho_{\mathrm{t}} = -\frac{1}{2} \left[a_{\phi \mathrm{D}} - 2\, s_\theta^2 \left(a_{\mathrm{t}\phi} + 2\, a_{\phi \Box} \right) \right] \frac{1}{s_\theta^2}$$

$$\rho_{\mathrm{b}} = -\frac{1}{2} \left[a_{\phi \mathrm{D}} + 2\, s_\theta^2 \left(a_{\mathrm{b}\phi} - 2\, a_{\phi \Box} \right) \right] \frac{1}{s_\theta^2}$$

$$\rho_{\mathrm{W}} = -\frac{1}{2} \left[a_{\phi \mathrm{D}} - 4\, s_\theta^2\, a_{\phi \Box} \right] \frac{1}{s_\theta^2}$$

$$\Gamma_{\mathrm{SMEFT}} = \frac{\alpha^2\, G_{\mathrm{F}}\, M_{\mathrm{H}}^3}{32\sqrt{2}\,\pi^3}\, \frac{M_{\mathrm{W}}^4}{M_{\mathrm{H}}^4} \mid \mathscr{A}_{\mathrm{SMEFT}} \mid^2 \qquad \Gamma_{\mathrm{SM}} = \Gamma_{\mathrm{SMEFT}} \Big|_{\Delta\kappa_i = 0,\, \kappa_c = 0}$$

hi-tech center

Relaxing the PTG assumption introduces non-factorizable sub-amplitudes proportional to $a_{\mathrm{tW}}, a_{\mathrm{tB}}, a_{\mathrm{bW}}, a_{\mathrm{bB}}, a_{\phi\mathrm{W}}, a_{\phi\mathrm{B}}, a_{\phi\mathrm{WB}}$ with a mixing among $\{a_{\phi\mathrm{W}}, a_{\phi\mathrm{B}}, a_{\phi\mathrm{WB}}\}$. Meanwhile, renormalization has made one-loop SMEFT finite, e.g. in the G_{F}-scheme, with a residual μ_{R}-dependence

Einhorn, Wudka

Grzadkowski, Iskrzynski, Misiak, Rosiek

Appendix C. Dimension-Six Basis Operators for the SM[22].

X^3 **(LG)**		φ^6 and $\varphi^4 D^2$ **(PTG)**		$\psi^2\varphi^3$ **(PTG)**	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$ **(LG)**		$\psi^2 X\varphi$ **(LG)**		$\psi^2\varphi^2 D$ **(PTG)**	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) \varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) \varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Table C.1: Dimension-six operators other than the four-fermion ones.

[22] These tables are taken from [5], by permission of the authors.

✓ Demonstration strategy:

① Allow each Wilson coefficient to vary in the interval $\mathbf{I_2} = [-2, +2]$ (naturalness[7]; put $\Lambda = 3$ *TeV* (conventional point)

② LO: generate points from $\mathbf{I_2}$ for a_{AA} with uniform probability and calculate $\mathbf{R_{LO}}$

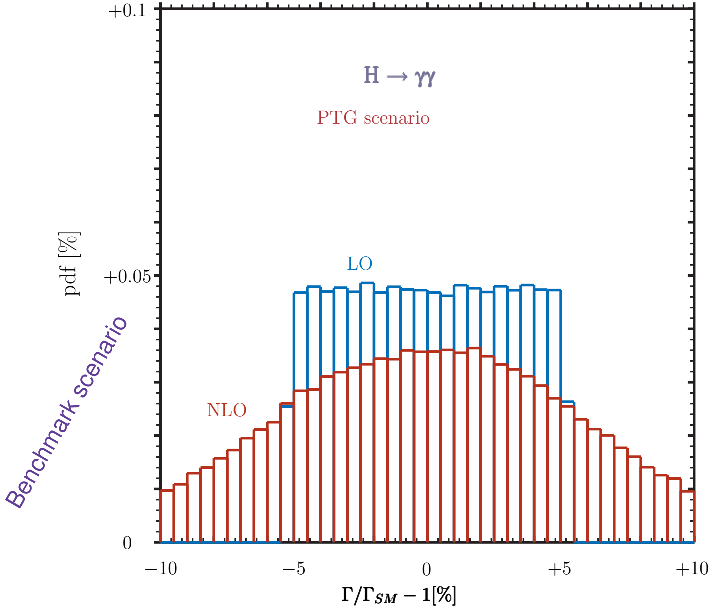
② NLO: generate points from $\mathbf{I_2^5}$ for $\{a_{\phi D}, a_{\phi \square}, a_{t\phi}, a_{b\phi}, a_{AA}\}$ with uniform probability and calculate $\mathbf{R_{NLO}}$

③ Calculate the $\mathbf{R}$ pdf

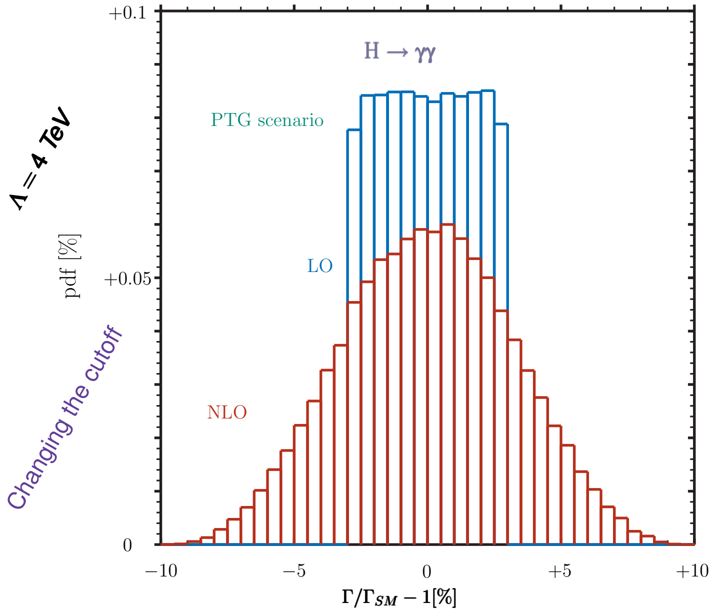
N.B. $| a_{AA} | < 1$ is equivalent to $| g_c\, a_{AA} | < 8.6\, 10^{-2}$

---

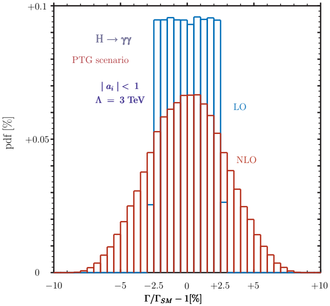
[7] Disregarding TH bias for the sign (Sect. D of arXiv:0907.5413)

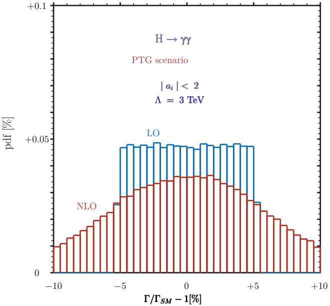


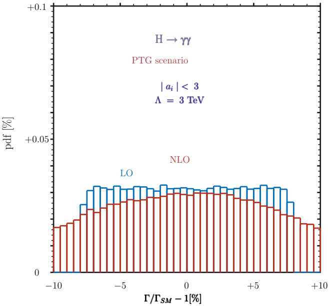
H → γγ
PTG scenario
LO
NLO
Benchmark scenario
pdf [%]
+0.1
+0.05
0
−10
−5
0
+5
+10
Γ/Γ_SM − 1[%]



Λ = 4 TeV
Changing the cutoff
pdf [%]
+0.1
+0.05
0
H → γγ
PTG scenario
LO
NLO
−10
−5
0
+5
+10
Γ/Γ_SM − 1[%]







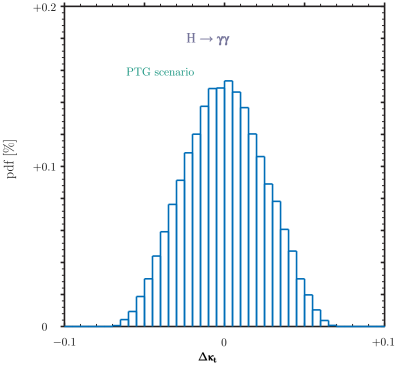
Changing the interval

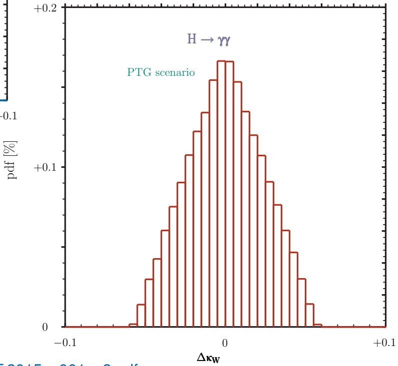
From Wilson coefficients (a) to κ

$$\Lambda = 3\ TeV$$

$$-2 \leq a_i \leq +2$$

ATLAS: $\kappa_\gamma = 0.90^{+0.16}_{-0.14}$
CONFNOTES/ATLAS-CONF-2015-007/tab-08.png
CMS: $\kappa_\gamma = 1.14^{+0.12}_{-0.13}$
http://arxiv.org/pdf/1412.8662.pdf
these unc. cannot be underestimated

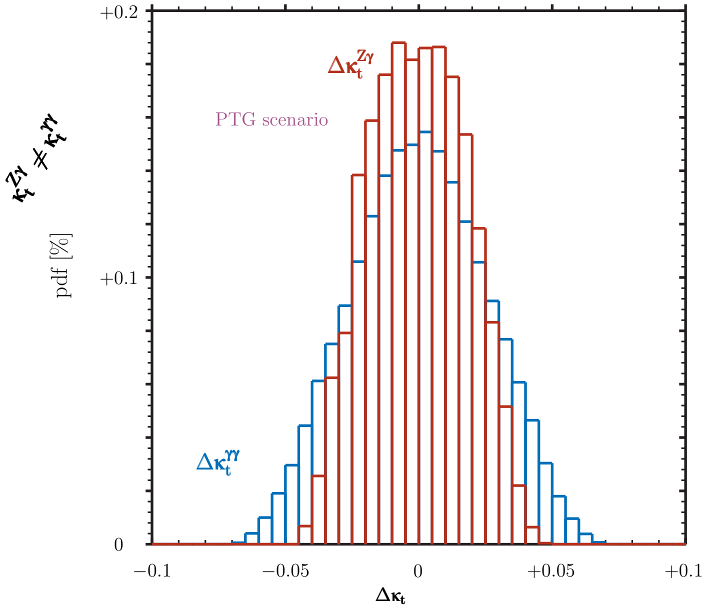




ATLAS $\kappa^t = 1.28 \pm 0.35$

CMS $\kappa^t = 1.60^{+0.34}_{-0.32}$, 2σ?

other couplings $< 10^{-2}$, MAGA note
https://cds.cern.ch/record/2001958/files/LHCHXSWG-INT-2015 – 001 – 2.pdf
Is κ^t the only window? Relax bounds compared to LO analysis (arXiv:1502.02570)?
Correctly define kappas? $\kappa_t^{ttH} \neq \kappa_t^{H\gamma\gamma}$ etc.



$\kappa_t^{Z\gamma} \neq \kappa_t^{\gamma\gamma}$
pdf [%]
+0.2
+0.1
0
$\Delta\kappa_t^{Z\gamma}$
PTG scenario
$\Delta\kappa_t^{\gamma\gamma}$
−0.1
−0.05
0
+0.05
+0.1
$\Delta\kappa_t$

Conclusions:

① For the SMEFT, (almost) regardless of the κ_c, to have more than $\mathbf{5\%}$ deviation (at $\Lambda = 3\ TeV$) you have to go NLO, or unnatural[8] (Wilson coefficients not $\mathcal{O}(1)$)

② The LO, NLO pdfs are different, therefore interpretation is different, how to reweight once your analysis was LO interpreted? It all depends on the new central value for $\kappa_\gamma^{\mathrm{exp}}$

presently ATLAS: $a_{\mathrm{AA}}^{\mathrm{LO}} = +3.79^{+5.31}_{-6.06}$ CMS: $a_{\mathrm{AA}}^{\mathrm{LO}} = -5.31^{+4.93}_{-4.55}$

naive dimensional estimate $a_{\mathrm{AA}} \approx 1$

③ *Chi ha avuto, ha avuto, ha avuto … chi ha dato, ha dato, ha dato … scurdammoce o ppassato*
Those who've taken, taken, taken … Those who've given, given, given … Let's forget about the past

---

[8] from the point of view of a weakly coupled UV completion

Other than Higgs (just one example): if we neglect LG operators in loops, the following result holds for vacuum polarization:

$$\Pi^{(\mathrm{dim}=6)}_{\mathrm{AA}}(0) = -8\,\frac{c_\theta^2}{s_\theta^2}\,a_{\phi\mathrm{D}}\,\Pi^{(\mathrm{dim}=4)}_{\mathrm{AA}}(0)$$

One of the key ingredients in computing precision (pseudo-)observables is α_{QED} at the mass of the Z. Define

$$\alpha\left(M_{\mathrm{Z}}\right) = \frac{\alpha(0)}{1 - \Delta\alpha^{(5)}\left(M_{\mathrm{Z}}\right) - \Delta\alpha_{\mathrm{t}}\left(M_{\mathrm{Z}}\right) - \Delta\alpha_{\mathrm{t}}^{\alpha\alpha_{\mathrm{s}}}\left(M_{\mathrm{Z}}\right)}$$

$$\Delta\alpha^{(5)}\left(M_{\mathrm{Z}}\right) = \Delta\alpha_{\mathrm{l}}\left(M_{\mathrm{Z}}\right) + \Delta\alpha^{(5)}_{\mathrm{had}}\left(M_{\mathrm{Z}}\right)$$

$$\begin{aligned}
\Delta\alpha^{(5)}_{\rm had}\left(M_Z\right) &= 0.0280398 \\
10^4 \times \Delta\alpha_{\rm l}\left(M_Z\right) &= 0.0314976 \\
10^4 \times \Delta\alpha_{\rm t}\left(M_Z\right) &\approx [-0.62\,,\,-0.55] \\
10^4 \times \Delta\alpha_{\rm t}^{\alpha\alpha_s}\left(M_Z\right) &\approx [-0.114\,,\,-0.095]
\end{aligned}$$

The SMEFT effect is equivalent to replace

$$\Delta\alpha_{\rm l}\left(M_Z\right)+\Delta\alpha_{\rm t}\left(M_Z\right) \quad\rightarrow\quad \left(1-\kappa_\alpha\right)\left[\Delta\alpha_{\rm l}\left(M_Z\right)+\Delta\alpha_{\rm t}\left(M_Z\right)\right]$$

$$\kappa_\alpha = 8\,g_6\,\frac{c^2_\theta}{s^2_\theta}\,a_{\phi D} \quad=\quad 0.188\,a_{\phi D} \qquad \text{at } \Lambda = 3\ TeV$$

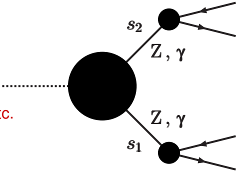
☛

$$\begin{aligned}
\mid \kappa_\alpha\,\Delta\alpha_{\rm t} \mid &> \Delta\alpha_{\rm l} \\
\mid \kappa_\alpha\,\Delta\alpha_{\rm t} \mid &\approx \mid \Delta\alpha_{\rm t}^{\alpha\alpha_s} \mid
\end{aligned}$$

Part III

Mostly POs

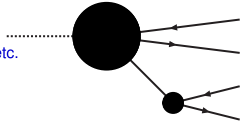
Expansion



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

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

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

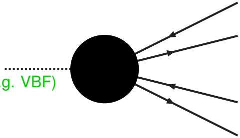


$\Gamma(H \to \bar{f} f \gamma)$ etc.

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

remember LEP

$$\sigma^{peak}_f = 12\pi \frac{\Gamma_e \Gamma_f}{M_Z^2 \Gamma_Z^2}$$



the difficult part (e.g. VBF)

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

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

interpretation: POs à la LEP

https://indico.cern.ch/event/373667/ arXiv:1504.04018

$$\mathrm{H} \to \gamma\gamma\,(\gamma \mathrm{Z}) \quad \mapsto \quad \rho_{\mathrm{H}}^{\gamma\gamma(\mathrm{Z})}\, \frac{p_1 \cdot p_2\, g^{\mu\nu} - p_2^{\mu} p_1^{\nu}}{M_{\mathrm{H}}}$$

$$\mathrm{H} \to \mathrm{VV} \quad \mapsto \quad \rho_{\mathrm{H}}^{\mathrm{V}} \left(M_{\mathrm{H}}\, g^{\mu\nu} + \frac{\mathcal{G}_{\mathrm{L}}^{\mathrm{V}}}{M_{\mathrm{H}}}\, p_2^{\mu} p_1^{\nu} \right)$$

$$\mathrm{H} \to \overline{\mathrm{b}}\mathrm{b} \quad \mapsto \quad \rho_{\mathrm{H}}^{\mathrm{b}}\, \overline{\mathrm{u}}\, \mathrm{v}$$

etc.

a middle way language

wolf, goat, and cabbage

POs (container) at LHC: summary table

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

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

② intermediate layer (similar to LEP $g_{V\,A}^{e}$)

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

③ internal layer: the kappas

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

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

How to inlude EWPD? The case of the **W** mass

Working in the α-scheme we can predict $M_{\rm W}$. The solution is

$$\begin{aligned}\frac{M_{\rm W}^2}{M_{\rm Z}^2} &= \hat{c}_\theta^2 + \frac{\alpha}{\pi}\,\mathrm{Re}\Bigg\{\left(1 - \frac{1}{2}\,g_6\,a_{\phi\,\rm D}\right)\Delta_{\rm B}^{(4)}(M_{\rm W}) \\ &+ \sum_{\rm gen}\left[\left(1 + 4\,g_6\,a_{\phi\,\rm l}^{(3)}\right)\Delta_{\rm l}^{(4)}(M_{\rm W}) + \left(1 + 4\,g_6\,a_{\phi\,\rm q}^{(3)}\right)\Delta_{\rm q}^{(4)}(M_{\rm W})\right] \\ &+ g_6\left[\Delta_{\rm B}^{(6)}(M_{\rm W}) + \sum_{\rm gen}\left(\Delta_{\rm l}^{(6)}(M_{\rm W}) + \Delta_{\rm q}^{(6)}(M_{\rm W})\right)\right]\Bigg\}\end{aligned}$$

The expansion can be improved when working within the SM ($\mathrm{dim} = 4$). Any equation that gives $\mathrm{dim} = 6$ corrections to the SM result will always be understood as

$$\mathscr{O} = \mathscr{O}^{\rm SM}\Big|_{\rm imp} + \frac{\alpha}{\pi}\,g_6\,\mathscr{O}^{(6)}$$

in order to match the *TOPAZ0/Zfitter* SM results whe $g_6 \to 0$.

THE Example

$$
\begin{aligned}
S_{\rm WW} &= \frac{g^2}{16\,\pi^2}\,\Sigma_{\rm WW} \\
S_{\rm ZZ} &= \frac{g^2}{16\,\pi^2\,c_\theta^2}\,\Big(\Sigma_{33} - 2\,s_\theta^2\,\Sigma_{3Q} - s_\theta^4\,\Pi_{\rm AA}\,s\Big) \\
\Sigma_{\rm F} &= \Sigma_{\rm WW}(0) - {\rm Re}\,\Sigma_{33}(M_{\rm Z}^2) + {\rm Re}\,\Sigma_{3Q}(M_{\rm Z}^2)
\end{aligned}
$$

Define $\boldsymbol{\rho^{-1} = 1 + \frac{G_{\rm F}}{2\sqrt{2}\pi^2}\,\Sigma_{\rm F}} = 0.99490$, $\boldsymbol{\Delta\rho}$ contains (PTG only):
$\boldsymbol{a_{\phi D},\ a_{\Phi\Box},\ a_{\phi \rm f},\ a^{(1,3)}_{\phi \rm f},\quad \rm f = l,\ u,\ d}$

Leading term (don't use it for precision) is

$$
\begin{aligned}
\Delta\rho &= M_{\rm t}^2\left[\kappa_\rho\,\Delta\rho^{(4)} + g_6\sum_i F_i\,a_i\right] \qquad a_i = a_{\phi D},\ a_{\phi \rm t},\ a^{(1,3)}_{\phi \rm q} \\
\kappa_\rho &= 1 + \frac{g_6}{11}\left[\frac{7}{6}\,a_{\phi D} + 28\,(a^{(1)}_{\phi \rm q} + a^{(3)}_{\phi \rm q}) - 20\,a_{\phi \rm t}\right]
\end{aligned}
$$

How to inlude EWPD?

① By reducing (a priori) the number of $\mathbf{dim} = \mathbf{6}$ operators

② By imposing penalty functions ω on the global fit, that is functions defining an ω-penalized LS estimator for a set of global penalty parameters (perhaps using *merit functions* and the *homotopy method*)

③ Using a Bayesian approach, with a flat prior for the parameters. One κ at the time? Fit first to the EWPD and then to H observables? Combination of both?

Of course, all EWPO must be rewritten in the κ-EFT approach

…

Thank you for your attention

Backup Slides
(moving backward)

Return

How/what NLO?

- ✓ Start with Warsaw basis, full set, write down Lagrangian and Feynman rules ■
- ✓ Normalize the quadratic part of the Lagrangian and pay due attention to the FP ghost sector ■
- ✓ Compute (all) self-energies (up to one $\mathcal{O}_{\mathbf{dim=6}}$ insertion), write down counterterms, make self-energies UV finite ■
- ✓ Compute the set of processes you like/want (don't forget non-SM topologies), mix Wilson coefficients to make them UV finite, check closure under renormalization ■
- ✓ Perform finite renormalization, selecting a scheme (better the G_{F}-scheme), introduce wave-function factors, get the answer ■
- ✓ Start making approximations now (if you like), e.g. neglecting operators etc.■

How/what NLO? (cont.)

- ✓ Transform the answer in terms of κ-shifted SM sub-amplitudes and non SM factorizable sub-amplitudes ■
- ✓ Derive κ-parameters in terms of Wilson coefficients ■
- ✓ Write Pseudo-Observables in terms of κ-parameters ■
- ✓ Decide about strategy for including EWPD ■
- ✓ Claim you invented the whole procedure □

NLO is like biking, you learn it when you are a kid

■ Fade Out ■ Round House ■ Fast Pace □ Coked Pistol

SMEFT evolution

LO $\mathscr{A}^{\rm SMEFT} = \mathscr{A}^{\rm SM} + \boldsymbol{a_i}$, where $\boldsymbol{a_i} \in \mathbf{V_6}$ and $\mathbf{V_6}$ is the set of $\mathbf{dim} = \mathbf{6}$ Wilson coefficients

RGE $\boldsymbol{a_i} \to \mathrm{Z}_{\boldsymbol{ij}}(\mathrm{L})\,\boldsymbol{a^j}$, where $\mathrm{L} = \ln(\Lambda/M_{\rm H})$ and $\boldsymbol{j} \in \mathbf{H_6} \subset \mathbf{V_6}$

NLO $\mathscr{A}^{\rm SMEFT} = \mathscr{A}^{\rm SM} + \mathscr{A}_{\boldsymbol{k}}\,(\mathrm{L}, \mathrm{const})\,\boldsymbol{a^k}$, where $\boldsymbol{k} \in \mathbf{S_6}$ and $\mathbf{H_6} \subset \mathbf{S_6} \subset \mathbf{V_6}$

How/what NLO? FAQ

- ✓ Are there some pieces that contain the dominant NLO effects
- ✓ It depends on the TH bias:
  1. For EFT purists there is no model independent EFT statement on some operators being big and other small
  2. Remember, logarithms are not large, constants matter too
- ✓ which could be easily incorporated in other calculations/tools?
- ✓ Well, Well, Well, its certainly a compelling provocative exciting to think about idea

How/what NLO? FAQ

✓ NLO SMEFT availability? From arXiv:1505.03706 ▸ Return

① Counterterms (SM fields and parameters): all

② Mixing: those entries related to $\mathbf{H} \to \gamma\gamma, \mathbf{Z}\gamma, \mathbf{ZZ}, \mathbf{WW}$

③ Self-energies, complete and at $p^2 = \mathbf{0}$: all

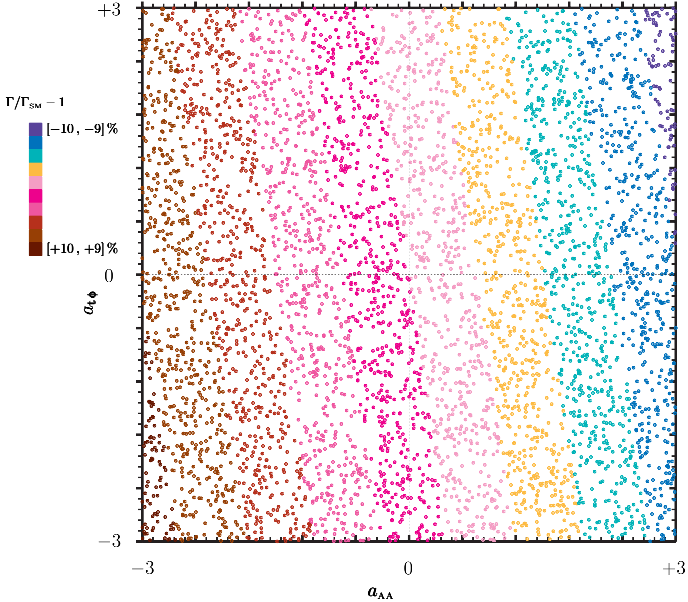
④ Amplitudes, sub-amplitudes (both SM and non-factorizable, full PTG $+$ LG scenario)

❶ $\mathbf{H} \to \gamma\gamma$ ❷ $\mathbf{H} \to \mathbf{Z}\gamma$ ❸ $\mathbf{H} \to \mathbf{ZZ}, \mathbf{WW}$[9] ❹ $\mathbf{H} \to \bar{\mathbf{f}}\mathbf{f}$ (the latter available, although not public)

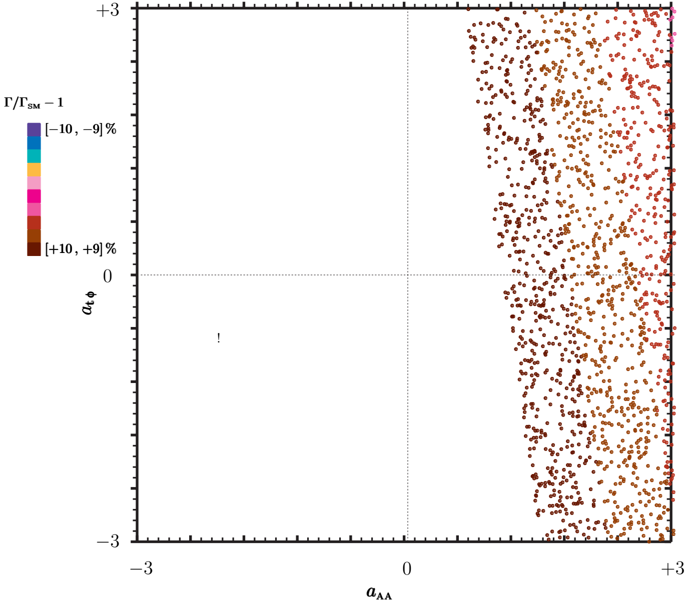
⑤ EWPD, $M_{\mathbf{W}}$, $\mathbf{T}$-parameter; $\mathbf{Z} \to \bar{\mathbf{f}}\mathbf{f}$ available, although not public.

[9] Green's functions in well-defined kinematic limit, i.e. residue of the poles after extracting the parts which are 1P reducible

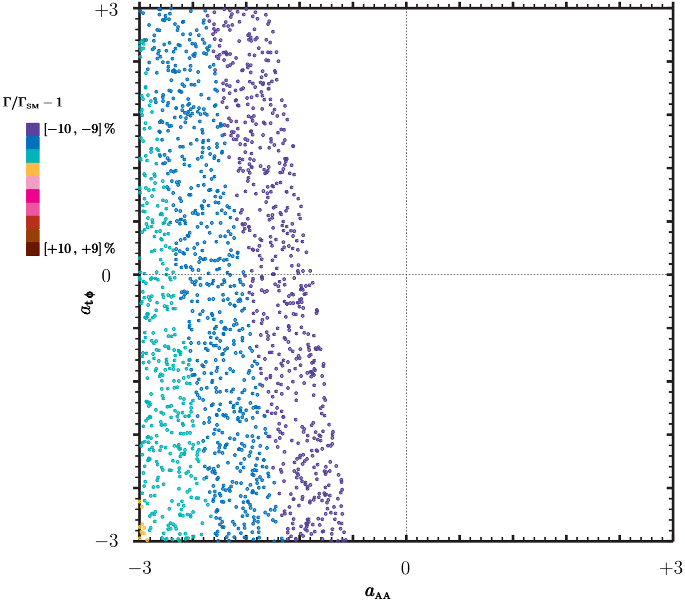
Backup Plots
(the role of κ_W)



$\Lambda = 3$ TeV $\quad \kappa_W = \kappa_b = 0$



$\Lambda = 3$ TeV $\kappa_W = 0.95$ $\kappa_b = 0$



$\Lambda = 3$ TeV $\kappa_W = 1.05$ $\kappa_b = 0$