University of Zurich[UZH]

# *Pseudo Observables, developments and tools*

Gino Isidori
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- Introduction [*Why PO?*]
- PO in Higgs decays
- PO in Higgs EW production
- PO vs. EFT
- Recent developments and Tools
- Conclusions

## *Introduction* [*Why PO?*]

- The aim of the Higgs PO is to

  *characterize the properties of h(125) in generic BSM (with heavy NP) encoding the exp. results in terms of a limited set of simplified/idealized observables of easy theoretical interpretation (minimum th. bias ↔ close to experiments)*

## Introduction [*Why PO?*]

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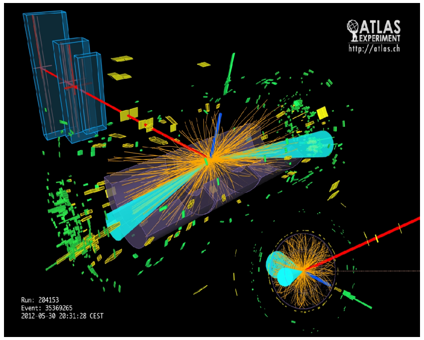
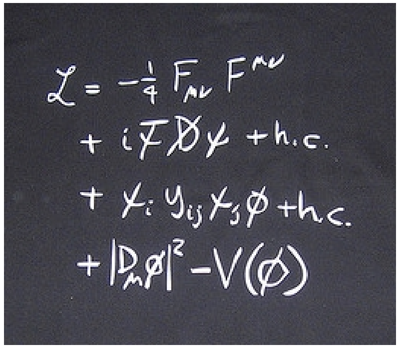
- The experimental determination of an appropriate set of PO will "help" and not "replace" any explicit NP approach to Higgs physics (*including the EFT*)




Experimental data ⟷ Pseudo Observables ⟷ Lagrangian parameters

> The PO can be computed in terms of Lagrangian parameters in any specific th. framework

- Old idea - heavily used and developed at LEP [Bardin, Grunewald, Passarino, '99]

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↓

- The PO should be defined from kinematical properties of on-shell processes (*no problems of renormalization, scale dependence, gauge dependence,…* )
- The theory corrections applied to extract them should be universally accepted as "NP-free" (*soft QCD and QED radiation*)

## *Introduction* [*Why PO?*]

*I took some time before the concept of PO started to be accepted in the "Higgs community"*. The situation is much better now than a few years ago... but there are still people asking the following question:

*Why do we need to measure PO, given we can go to a "more fundamental level" and directly extract the Wilson coefficients of the EFT from data?*

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Answer (I):

*What is "more fundamental"?*

A) The combination: $c_W(\mu)+c_{HW}(\mu)+\tan(\theta_W)[c_B(\mu)+c_{HW}(\mu)]$,

- *defined assuming a linear realization of the EWSB & employing the SILH basis for the EFT Lagrangian*
- *extracted computing amplitudes at LO in the EFT expansion, setting the renormalization scale $\mu$=1 TeV (and assuming that at that scale NLO-EW effects are negligible)*

B) The partial width $\Gamma(h \to W_L W_L)$

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Answer (II):

There is no reason to consider Wilson coefficients and, more generally, Lagrangian parameters "more fundamental" than on-shell physical amplitudes (*or the elements of the S matrix*). Actually it is the opposite.

*Lagrangians are noting but tools...*

Extracting their parameters requires a series of additional assumptions, that we may change in the future with more data and/or better understanding of the underlying (BSM) physics theory.

*...the "physics" is in the scattering amplitudes, hence in the PO.*

## *Introduction*

There are two main categories of PO:

A) "Ideal observables"

$M_W$, $\Gamma(Z \to ff)$, …

$M_h$, $\Gamma(h \to \gamma\gamma)$, $\Gamma(h \to Z\mu\mu)$, …
but also $d\sigma(pp \to hZ)/dp_{T_Z}$ ...

B) "Effective on-shell couplings"

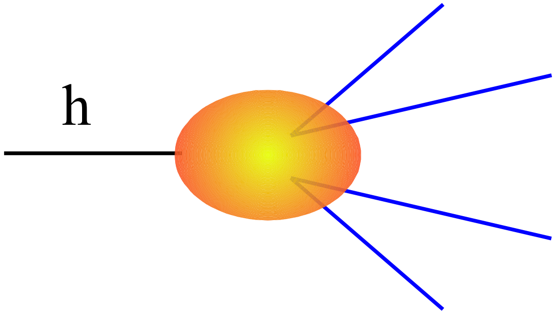
$$g_Z^f,\ g_W^f, \ldots \leftrightarrow\ \Gamma(Z \to ff) = C\,[\,|g_Z^{f_L}|^2 + |g_Z^{f_R}|^2],\ \ldots$$

- Both categories are useful !
(*there is redundancy in having both, but that's not an issue...*

  - A) certainly more convenient in diff. measurements with low-statistics + large spread of kin. variables *(e.g. h production far from threshold)*

  - For B) one can write effective Feynman rules, not to be used beyond tree-level (its just a practical way to re-write, *and code in existing tools,* an on-shell amplitude).

# PO in Higgs decays



## *PO in Higgs decays*

I. Two-body (on-shell) decays [e.g. $h \to \gamma\gamma, \mu\mu, \tau\tau, bb, \ldots$]

Somehow trivial relation between *physical PO* (the $\Gamma_i$) and *Higgs-coupling PO* ( $\leftrightarrow$ the beloved $\kappa_i$): no particular advantage in using one or the other

II. Multi-body modes [e.g. $h \to 4\ell, \ell\ell\gamma, \ldots$ ]

Here the relation between *physical PO* (several partial $\Gamma_i$) and *Higgs-coupling PO* is more involved $\leftrightarrow$ significant advantage in using appropriate on-shell effective couplings to analyze data while describing NP effects in full generality

General decomposition of the on-shell amplitudes based on Lorentz symmetry, Crossing symmetry, and Unitarity

Momentum expansion of the *f.f.* around leading poles

E.g.: $$f_i^{SM+NP} = \frac{\kappa_i}{s - m_Z^2 + i m_Z \Gamma_Z} + \frac{\epsilon_i}{m_Z^2} + O(s/m_Z^4)$$

Gonzales-Alonso *et al.* 1412.6038

## *PO in Higgs decays*

II. Multi-body modes [e.g. $h \to 4\ell$, $\ell\ell\gamma$, … ]

↓

General decomposition of the on-shell amplitudes (based on Lorentz symmetry, Crossing symmetry, and Unitarity) → *form factors*

↓

Momentum expansion of the *f.f.* around leading poles

E.g.: $$f_i^{\mathrm{SM+NP}} = \frac{\kappa_i}{s - m_Z^2 + i m_Z \Gamma_Z} + \frac{\epsilon_i}{m_Z^2} + O(s/m_Z^4)$$

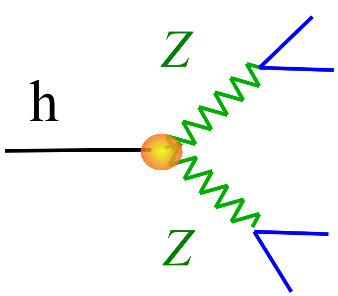
- No need to specify any detail about the underlying theory but for the absence of light new states [*momentum expansion fully justified by Higgs kinematic*]
- The $\{\kappa_i, \epsilon_i\}$ thus defined are well-defined PO [*pole decomposition → gauge-invariant terms*] → systematic inclusion of higher-order QED and QCD (soft) corrections possible (and necessary...)

## *PO in Higgs decays* [e.g.: $h \to 4l$]

The "physical meaning" of the parameters appearing in the $\{\kappa_i, \epsilon_i\}$ decomposition is not obvious at first sight, but it is actually quite simple [→ *physical PO*]:

$$
\begin{aligned}
\mathcal{A} =& i\frac{2m_Z^2}{v_F}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times \\
& \left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right) g^{\alpha\beta} + \Delta^{\rm SM}_{\text{non-loc}}(q_1^2, q_2^2)^{\alpha\beta}\right. \\
& + \left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right) T^{\alpha\beta} + \\
& \left. + \left(\epsilon_{ZZ}^{\rm CP}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\rm CP}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{\rm CP}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2}\right]
\end{aligned}
$$

*"double Z-pole"*




$$\boxed{\Gamma(h \to Z_L Z_L)} \equiv \frac{\Gamma(h \to 2e2\mu)[\kappa_{ZZ}]}{\mathcal{B}(Z \to 2e)\mathcal{B}(Z \to 2\mu)} = 0.209\ |\kappa_{ZZ}|^2\ \text{MeV}$$

$$\boxed{\Gamma(h \to Z_T Z_T)} \equiv \frac{\Gamma(h \to 2e2\mu)[\epsilon_{ZZ}]}{\mathcal{B}(Z \to 2e)\mathcal{B}(Z \to 2\mu)} = 0.0189\ |\epsilon_{ZZ}|^2\ \text{MeV}$$

$$\boxed{\Gamma^{\rm CPV}(h \to Z_T Z_T)} \equiv \frac{\Gamma(h \to 2e2\mu)[\epsilon_{ZZ}^{\rm CP}]}{\mathcal{B}(Z \to 2e)\mathcal{B}(Z \to 2\mu)} = 0.00799\ |\epsilon_{ZZ}^{\rm CP}|^2\ \text{MeV}$$

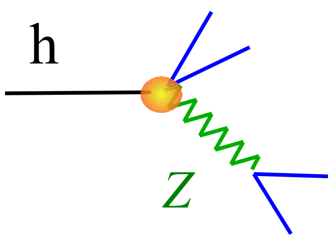
## ▶ *PO in Higgs decays* [e.g.: $h \to 4l$]

The "physical meaning" of the parameters appearing in the $\{\kappa_i, \epsilon_i\}$ decomposition is not obvious at first sight, but it is actually quite simple [→ *physical PO*]:

$$\mathcal{A} = i\frac{2m_Z^2}{v_F}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times$$
$$\left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right) g^{\alpha\beta} + \Delta^{\rm SM}_{\rm non\text{-}loc}(q_1^2, q_2^2)^{\alpha\beta}\right.$$

N.B.: these contact terms are the only possible sources of flavor non-universality. Strong interest in measuring/constraining them in view of recent B-physics anomalies (*the only indication we have today of some NP close to the EW scale...*)

*"single Z-pole"*




$$\boxed{\Gamma(h \to Z\ell^+\ell^-)} = 0.0366\,|\epsilon_{Ze}|^2\ \mathrm{MeV}$$

## PO in Higgs decays

The "physical meaning" of the parameters appearing in the $\{\kappa_i, \epsilon_i\}$ decomposition is not obvious at first sight, but it is actually quite simple [→ *physical PO*]:

| PO | Physical PO | | Relation to the eff. coupl. |
|---|---|---|---|
| $\kappa_f,\ \lambda_f^{\rm CP}$ | $\Gamma(h\to f\bar f)$ | $=$ | $\Gamma(h\to f\bar f)^{\rm (SM)}[(\kappa_f)^2+(\lambda_f^{\rm CP})^2]$ |
| $\kappa_{\gamma\gamma},\ \lambda_{\gamma\gamma}^{\rm CP}$ | $\Gamma(h\to\gamma\gamma)$ | $=$ | $\Gamma(h\to\gamma\gamma)^{\rm (SM)}[(\kappa_{\gamma\gamma})^2+(\lambda_{\gamma\gamma}^{\rm CP})^2]$ |
| $\kappa_{Z\gamma},\ \lambda_{Z\gamma}^{\rm CP}$ | $\Gamma(h\to Z\gamma)$ | $=$ | $\Gamma(h\to Z\gamma)^{\rm (SM)}[(\kappa_{Z\gamma})^2+(\lambda_{Z\gamma}^{\rm CP})^2]$ |
| $\kappa_{ZZ}$ | $\Gamma(h\to Z_L Z_L)$ | $=$ | $(0.209\ {\rm MeV})\times\lvert\kappa_{ZZ}\rvert^2$ |
| $\epsilon_{ZZ}$ | $\Gamma(h\to Z_T Z_T)$ | $=$ | $(1.9\times10^{-2}\ {\rm MeV})\times\lvert\epsilon_{ZZ}\rvert^2$ |
| $\epsilon_{ZZ}^{\rm CP}$ | $\Gamma^{\rm CPV}(h\to Z_T Z_T)$ | $=$ | $(8.0\times10^{-3}\ {\rm MeV})\times\lvert\epsilon_{ZZ}^{\rm CP}\rvert^2$ |
| $\epsilon_{Zf}$ | $\Gamma(h\to Zf\bar f)$ | $=$ | $(3.7\times10^{-2}\ {\rm MeV})\times N_c^f\ \lvert\epsilon_{Zf}\rvert^2$ |
| $\kappa_{WW}$ | $\Gamma(h\to W_L W_L)$ | $=$ | $(0.84\ {\rm MeV})\times\lvert\kappa_{WW}\rvert^2$ |
| $\epsilon_{WW}$ | $\Gamma(h\to W_T W_T)$ | $=$ | $(0.16\ {\rm MeV})\times\lvert\epsilon_{WW}\rvert^2$ |
| $\epsilon_{WW}^{\rm CP}$ | $\Gamma^{\rm CPV}(h\to W_T W_T)$ | $=$ | $(6.8\times10^{-2}\ {\rm MeV})\times\lvert\epsilon_{WW}^{\rm CP}\rvert^2$ |
| $\epsilon_{Wf}$ | $\Gamma(h\to Wf\bar f')$ | $=$ | $(0.14\ {\rm MeV})\times N_c^f\ \lvert\epsilon_{Wf}\rvert^2$ |

→ PO section in YR4

## ▶ PO in Higgs decays [e.g.: $h \to 4l$]

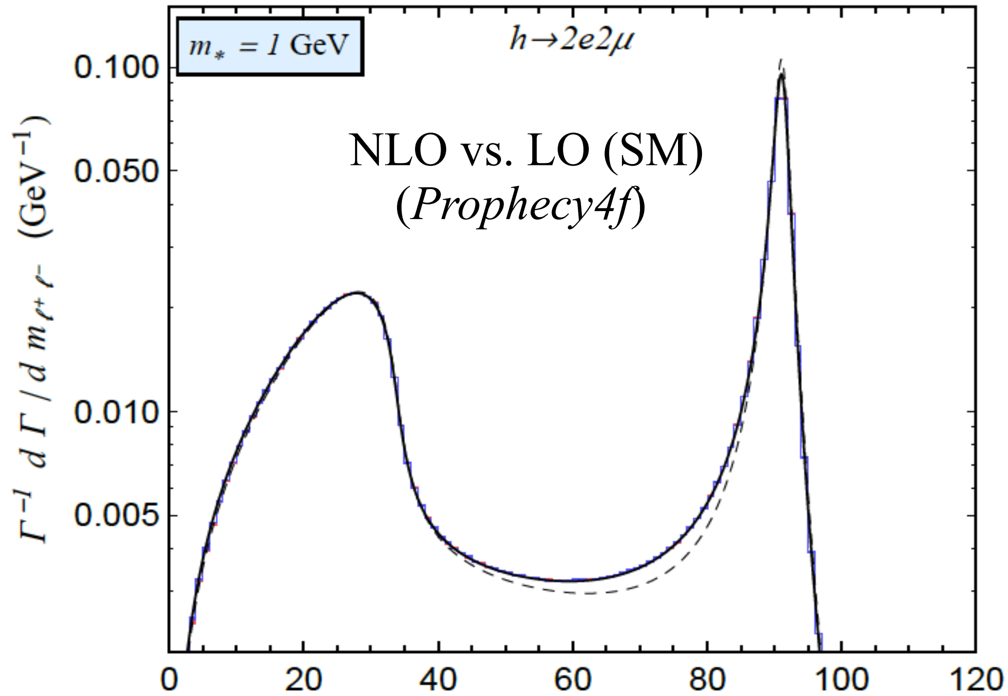
"Dressing" with QED radiation

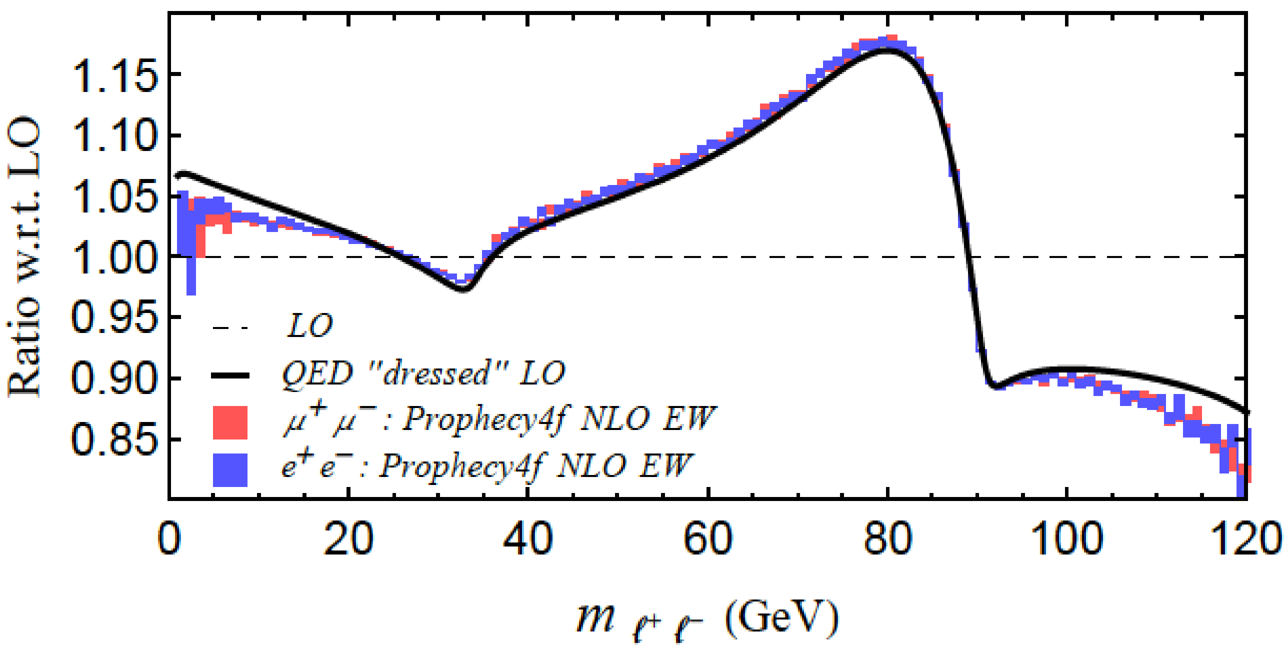
↓

excellent description of NLO SM
(*when setting PO to SM values*)

↓

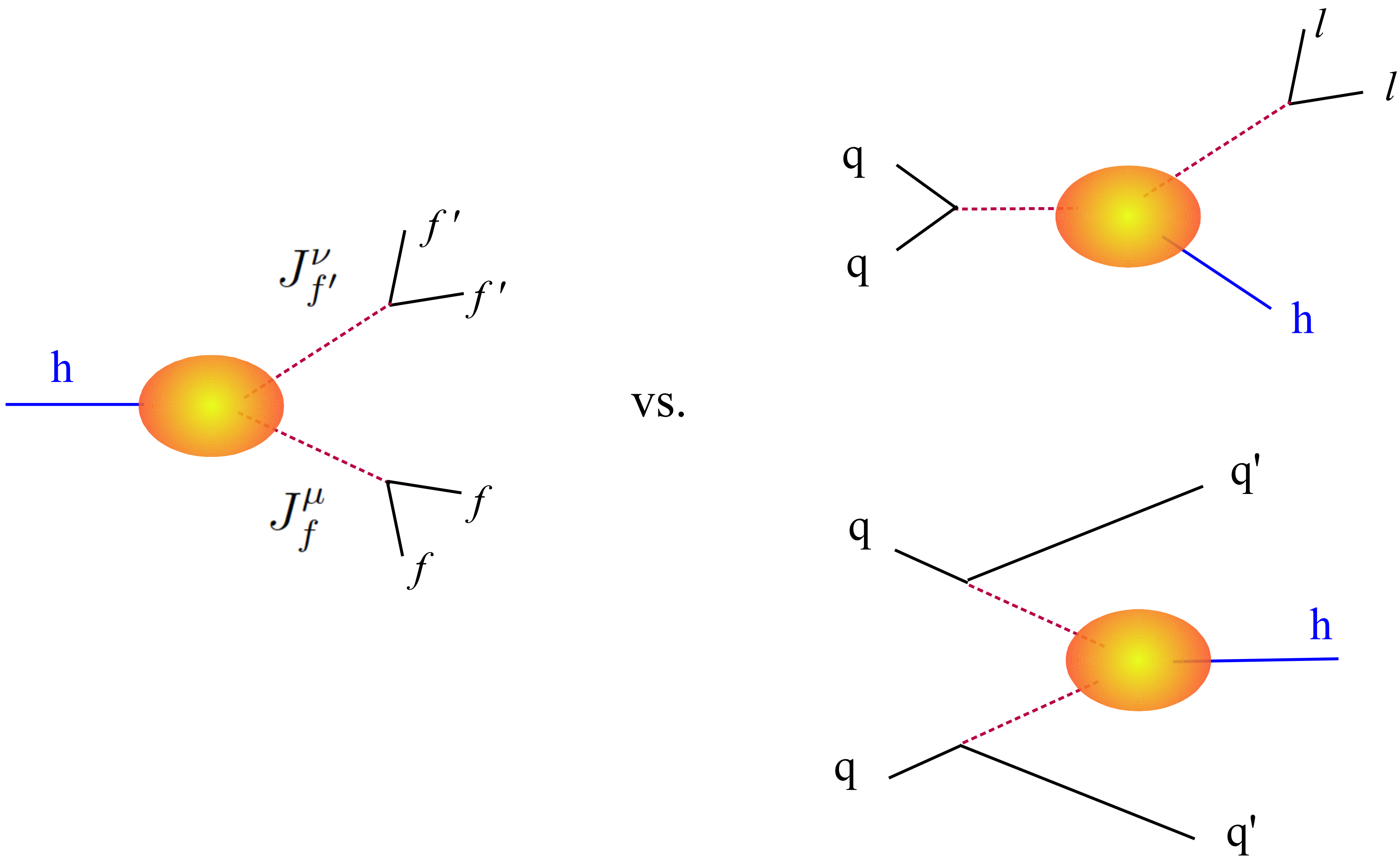
tool able to describe
(*general*) NP beyond LO




Bordone *et al.* 1507.02555

# PO in Higgs EW production



## ▶ *PO in Higgs EW production*

The same Green Function controlling $h \to 4f$ decays is accessible also in $pp \to hV$ and $pp \to h$ via VBF, i.e. the two leading EW-type Higgs production processes (*N.B.: this follows from crossing symmetry no need to invoke any EFT...*)

$$\langle 0|\mathcal{T}\left\{J_f^\mu(x), J_{f'}^\nu(y), h(0)\right\}|0\rangle$$

Same approach as in $h \to 4f$ (and, to some extent, same PO) but for three important differences:

*Greljo et al.* 1512.06135

- different flavor composition ($q \leftrightarrow \ell$) $\to$ new param. associated to the physical PO $\Gamma(h \to Zqq)$ & $\Gamma(h \to Wud)$

trivial

- large impact of (facotrizable) QCD corrections

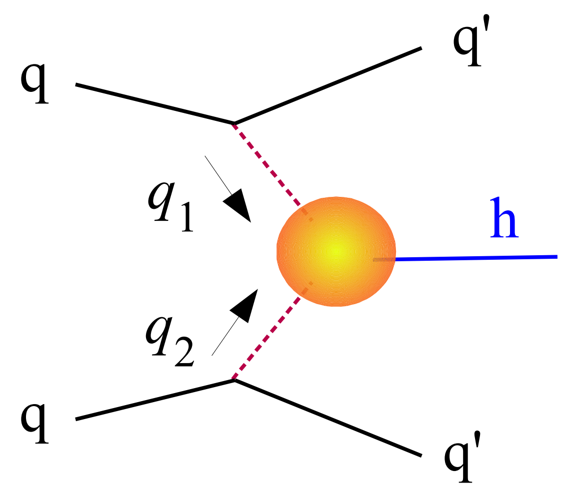
conceptually easy

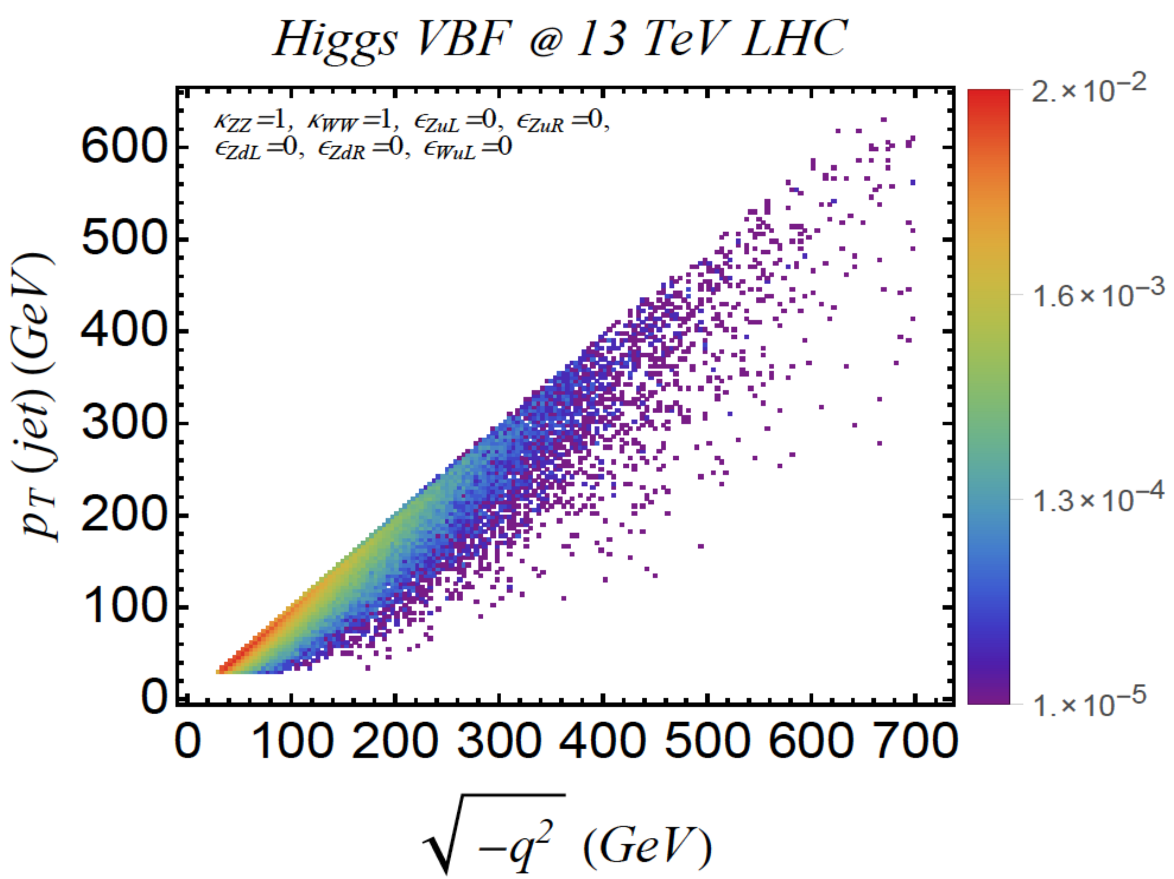
- different kinematical regime: momentum exp. not always justified (*large momentum transfer*)

delicate point

## PO in Higgs EW production [the VBF case]

A practical problem is also posed by the difficulty to directly access the key variables for the f.f. decomposition → need to construct a proxy



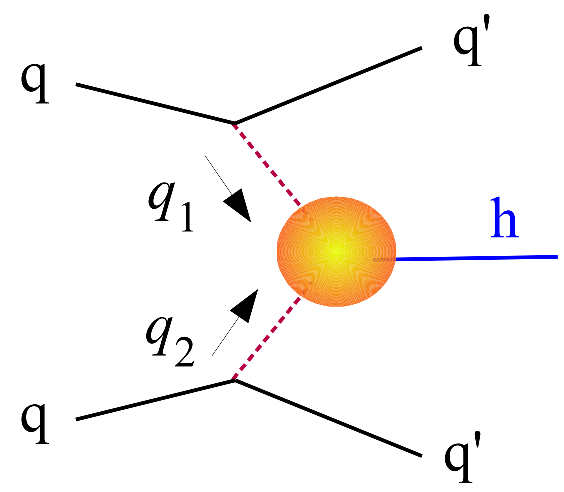




strong correlation

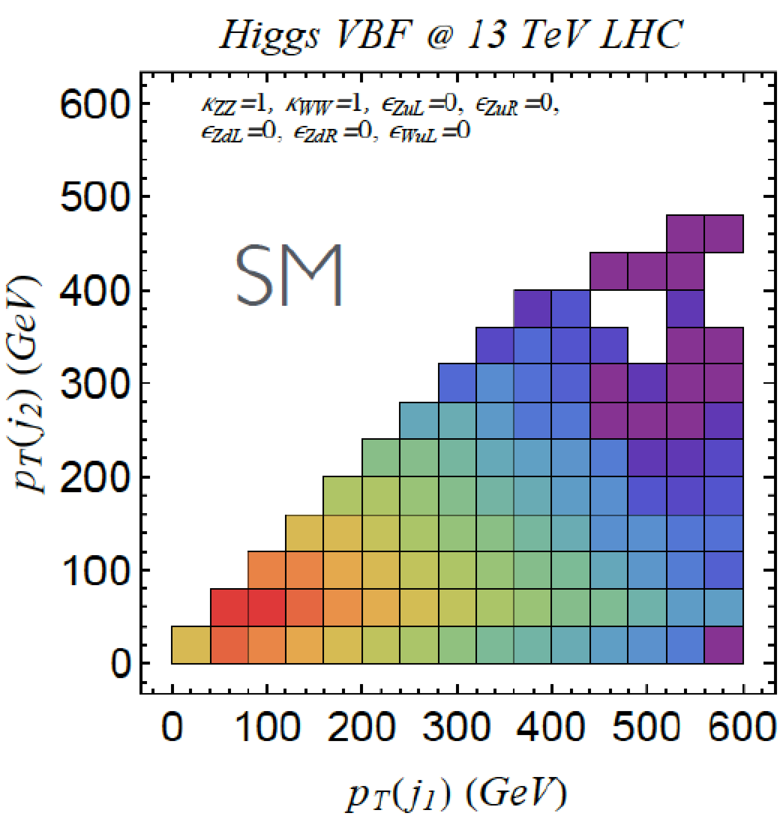
$$q_i^{\,2} \leftrightarrow -\,p_{T_i}^{\;2}$$

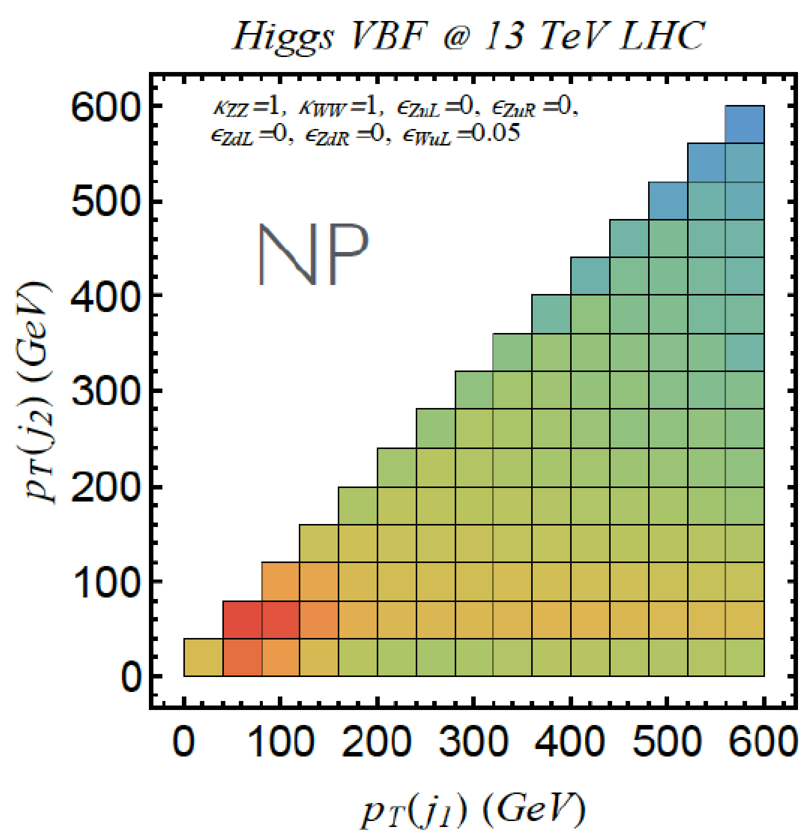
$$F(q_1^{\,2},q_2^{\,2}) \leftrightarrow \frac{d^2\sigma}{dp_{T_1}dp_{T_2}}$$

## ▸ PO in Higgs EW production [the VBF case]




Key experimental distribution: $$\frac{d^2\sigma}{dp_{T_1} dp_{T_2}}$$



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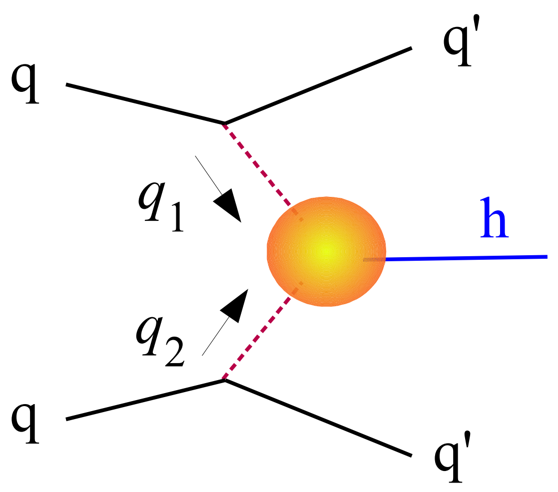


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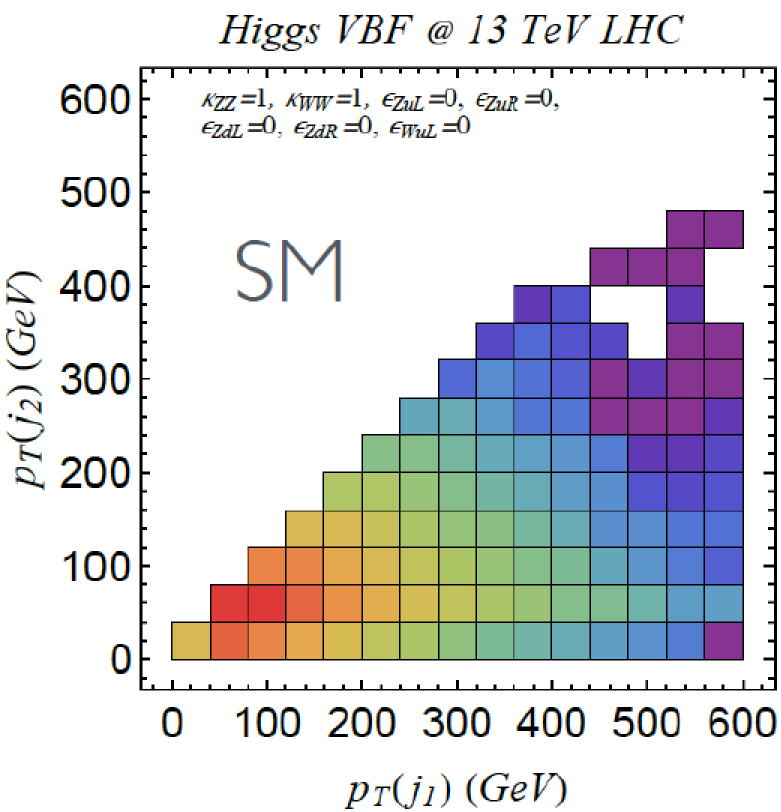
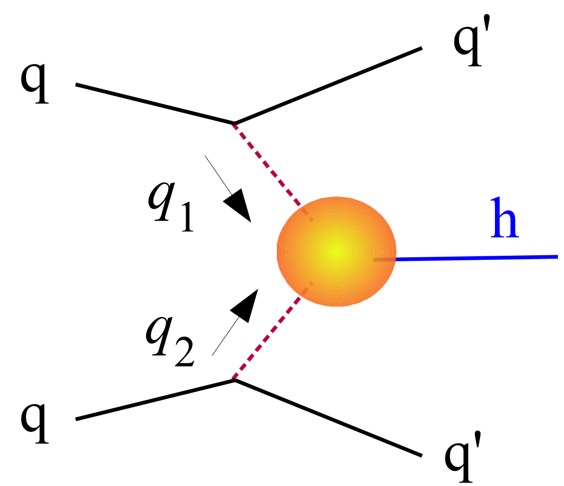



General procedure:

- Measure the *Higgs-coupling PO* ($\kappa_i$ & $\epsilon_i$) close to the threshold region (to be defined setting cuts on the "dangerous" kinematical variables) [→ a-posteriori data-driven check of the validity of the momentum expansion ↔ definition of threshold region]
- Report directly the cross-section as a function of $p_T$ in the high-momentum transfer region (i.e. switch to *physical PO* at large $p_T$) [→ natural link/merging with template cross-section approach]

## ▶ *PO in Higgs EW production* [the VBF case]

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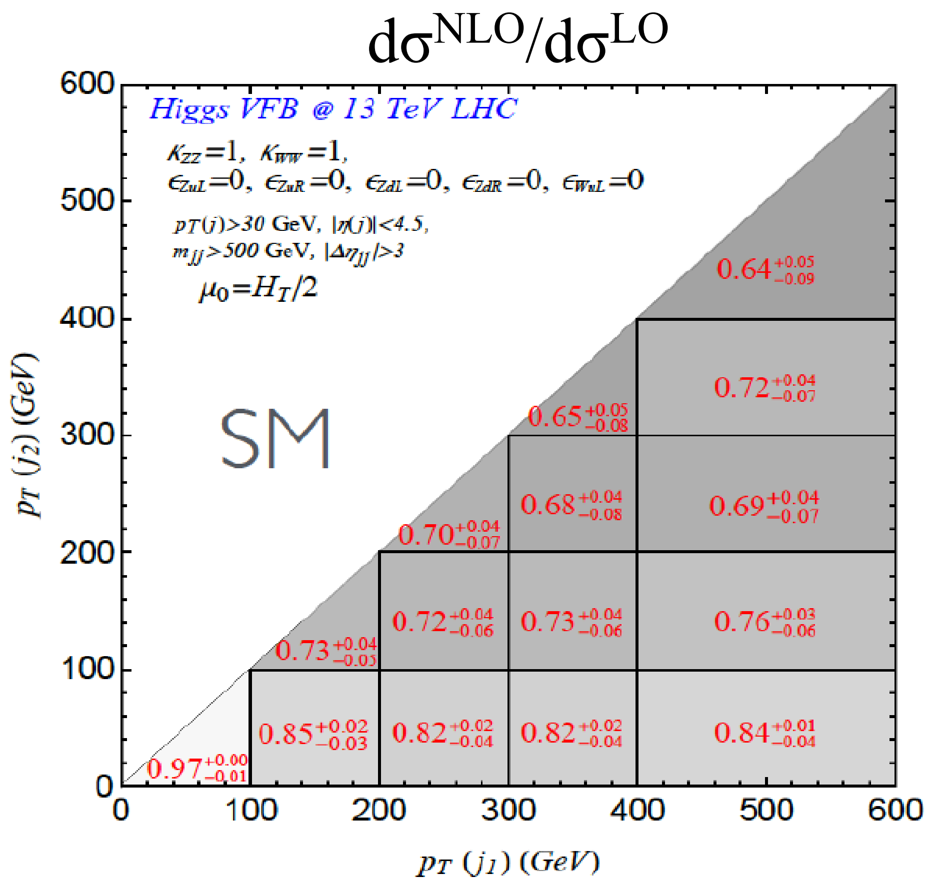
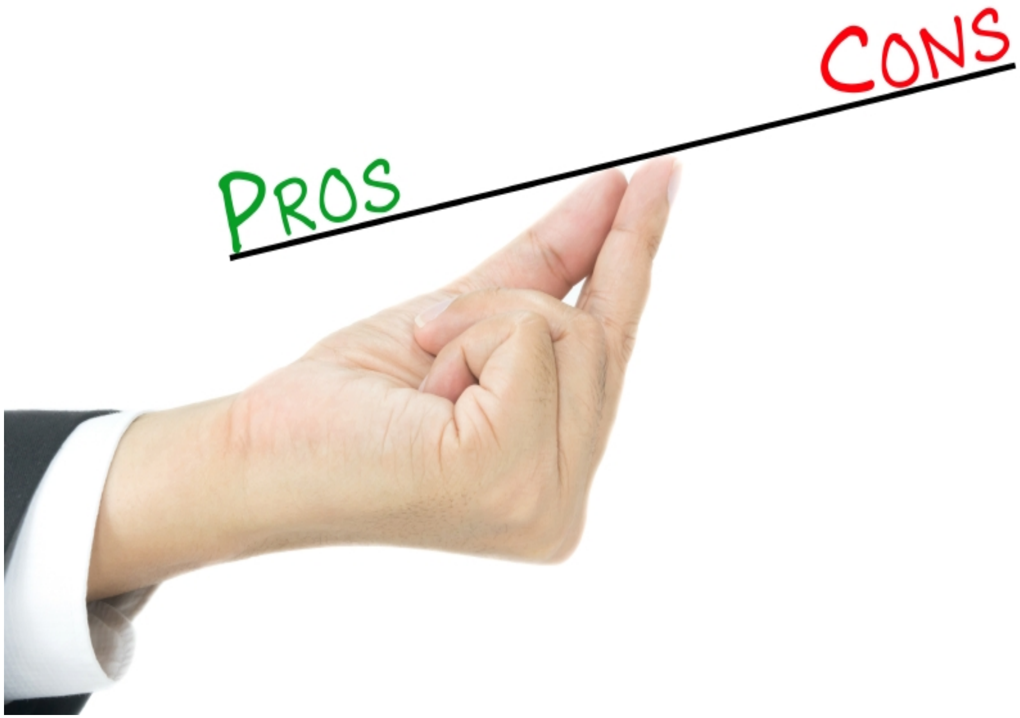



Straightforward inclusion of (factorizable) NLO QCD corrections, which have a sizable impact on the distribution

PO vs. EFT



## *PO vs. EFT*

PO and couplings in EFT Lagrangians are *intimately related but are not the same thing* (on-shell amplitudes vs. Lagrangians parameters) → full complementarity

- The PO are calculable in any EFT approach (*linear, non-linear, LO, NLO...*)
  - In the limit where we work at the tree-level in the EFT there is a simple linear relation between PO and EFT couplings: each PO represent a unique linear combination of couplings of the most general Higgs EFT.
  - This does not hold beyond the tree-level (the PO do not change, but their relation to EFT couplings is more involved....)

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⬇

*PO essential ingredient for EFT beyond LO*

Ghezzi *et al.* 1505.03706
Passarino & Trott, YR4

More generally (*linear, non-linear, LO, NLO...*):

- PO → inputs for EFT coupling fits
- EFT → predictions of relations between different PO sets (that can be tested)

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- For Higgs production also the PO involve an expansion in momenta; however, this is different than the operator expansion employed within the EFT
  - To define the PO we expand only on a measurable kinematical variables, this is why the validity of the *expansion can be checked directly by data* (on the same process used to determine the PO)

- In each process the PO are the maximum number of independent observables that can be extracted by that process only → naturally optimized for data analyses

## *PO vs. EFT*

Number of independent PO for EW Higgs decays + EW production + Yukawa modes ($h \to ff$):

PO set with maximal symmetry [CP + Lepton Univ + cust.] $\longrightarrow$ no symmetry

| | *Minimal set:* | *Without custodial symm.:* |
|---|---|---|
| Prod. & decays | $\kappa_{ZZ}, \kappa_{Z\gamma}, \epsilon_{ZZ}$ | $\kappa_{WW}, \epsilon_{WW}$ |
| EW decays only | $\kappa_{\gamma\gamma}, \epsilon_{Ze_L}, \epsilon_{Ze_R}, \epsilon_{We_L}$ | $\epsilon_{Z\nu_\mu}$ |
| EW prod. only | $\epsilon_{Zu_L}, \epsilon_{Zu_R}, \epsilon_{Zd_L}, \epsilon_{Zd_R}$ | $\epsilon_{Wu_L}$ |
| | | 11 $\longrightarrow$ 15 (no CS) $\longrightarrow$ 32 (no symm.) |
| Yukawa modes | $\kappa_b, \kappa_\tau, \kappa_c, \kappa_\mu$ | 4 $\longrightarrow$ 8 (no symm.) |
| | *(as in the original κ-formalism)* | |
| gg→h & ttH | $\kappa_g, \kappa_t$ | 2 $\longrightarrow$ 4 (no symm.) |

# Recent developments and Tools

## *Recent developments and Tools*

Three recent developments:

[Tools]
Automated public tool (*UFO model* for MG5_aMC@NLO) for generation of events with *generic PO* (both in production & in decays), with systematic inclusion of NLO QCD corrections is now fully available

[New channels]
Proposal of *physical PO* for pp → tth

[Theory]
Formalism developed for the inclusion of the leading EW corrections (universal large EW logs) in the PO framework for EW production cross sections (Vh & VBF) at large momentum transfer

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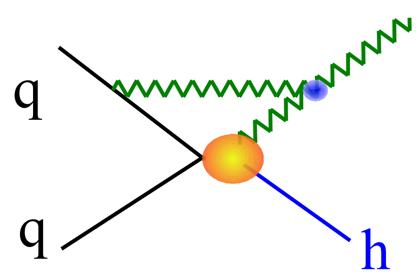


→ Leading kinematical corrections unambiguously determined (IR effect)

A. Pattori, G.I, work in prog.

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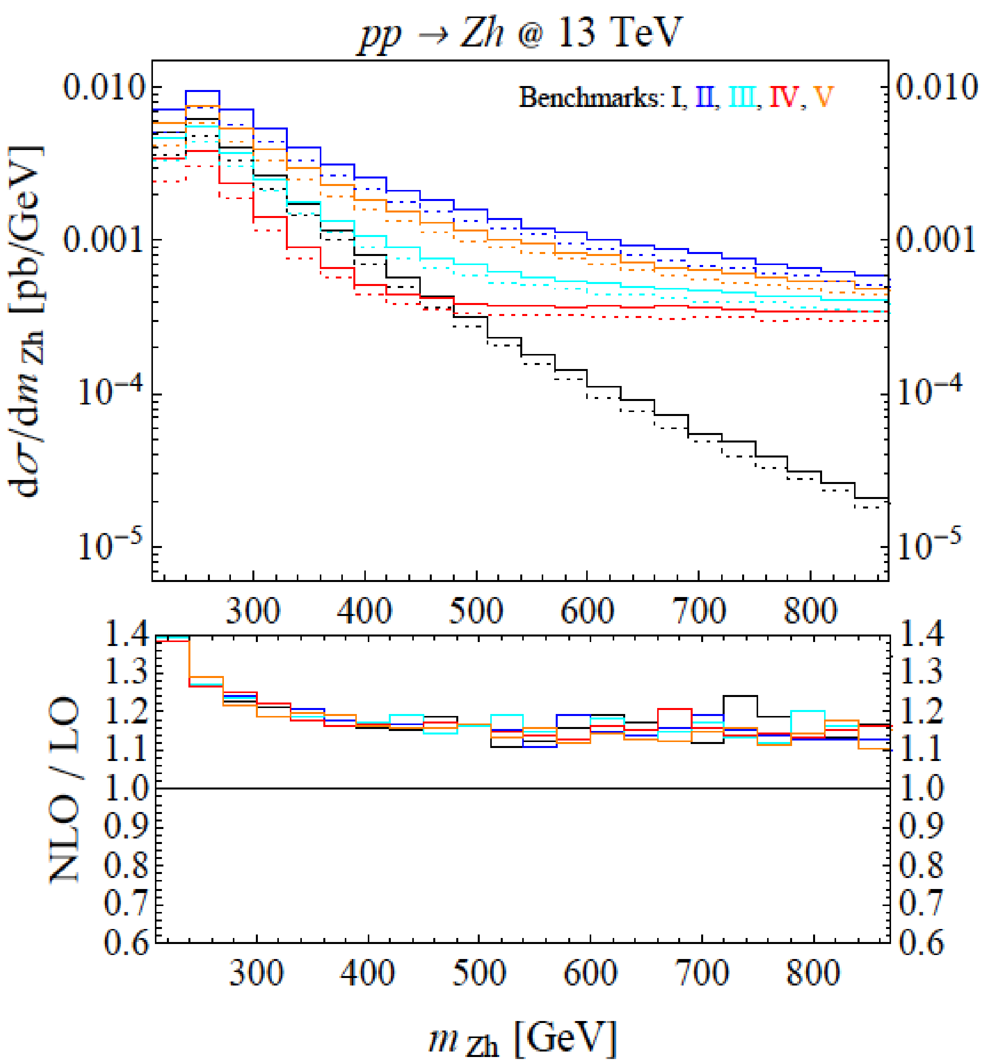


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Higgs PO

DESCRIPTION DOWNLOAD CONTACTS

http://www.physik.uzh.ch/data/HiggsPO

**Electroweak Higgs production with HIGGSPO at NLO QCD**

**Admir Greljo[1,2], Gino Isidori[1,3], Jonas M. Lindert[4], David Marzocca[1]**

**Abstract** We present the HIGGSPO UFO model for Monte Carlo simulations of electroweak Higgs production processes VH and VBF at NLO in QCD. Using this model we investigate the QCD corrections matched to parton showers for several benchmark points in the Higgs PO parameter space. The QCD higher-order corrections largely factorize, however, they still have to be considered in realistic experimental analyses.

*in a few days on the arXiv...*

## *Recent developments and Tools*

In pp → tth an approach based on *effective couplings PO* (as in h → 4l) is not feasible:

- Many independent amplitudes
- Few accessible discriminating kinematical variables
- Low statistics & high background

↓

More convenient an approach based directly on *physical PO*, i.e. a well defined set of partial σ's, satisfying the following requirements:

- Well-defined on the theory side
- Close to accessible exp. quantities (*minimum th. bias in the extrapolation*)
- Mutually exclusive & probing different regions of NP parameter space

↓

Proposal based on boosted/non-boosted topologies for top an h (→bb)

## Recent developments and Tools

In $pp \to tth$ an approach based on *effective couplings PO* (as in $h \to 4l$) is not feasible $\to$ proposal based on boosted/non-boosted topologies for top an Higgs

Six (mutually-exclusive) partial cross sections:

$$\boxed{\begin{array}{ll} \sigma(t_B t_B h_B) & \sigma(t_B t_B h_R) \\ \sigma(t_B t_R h_B) & \sigma(t_B t_R h_R) \\ \sigma(t_R t_R h_B) & \sigma(t_R t_R h_R) \end{array}}$$

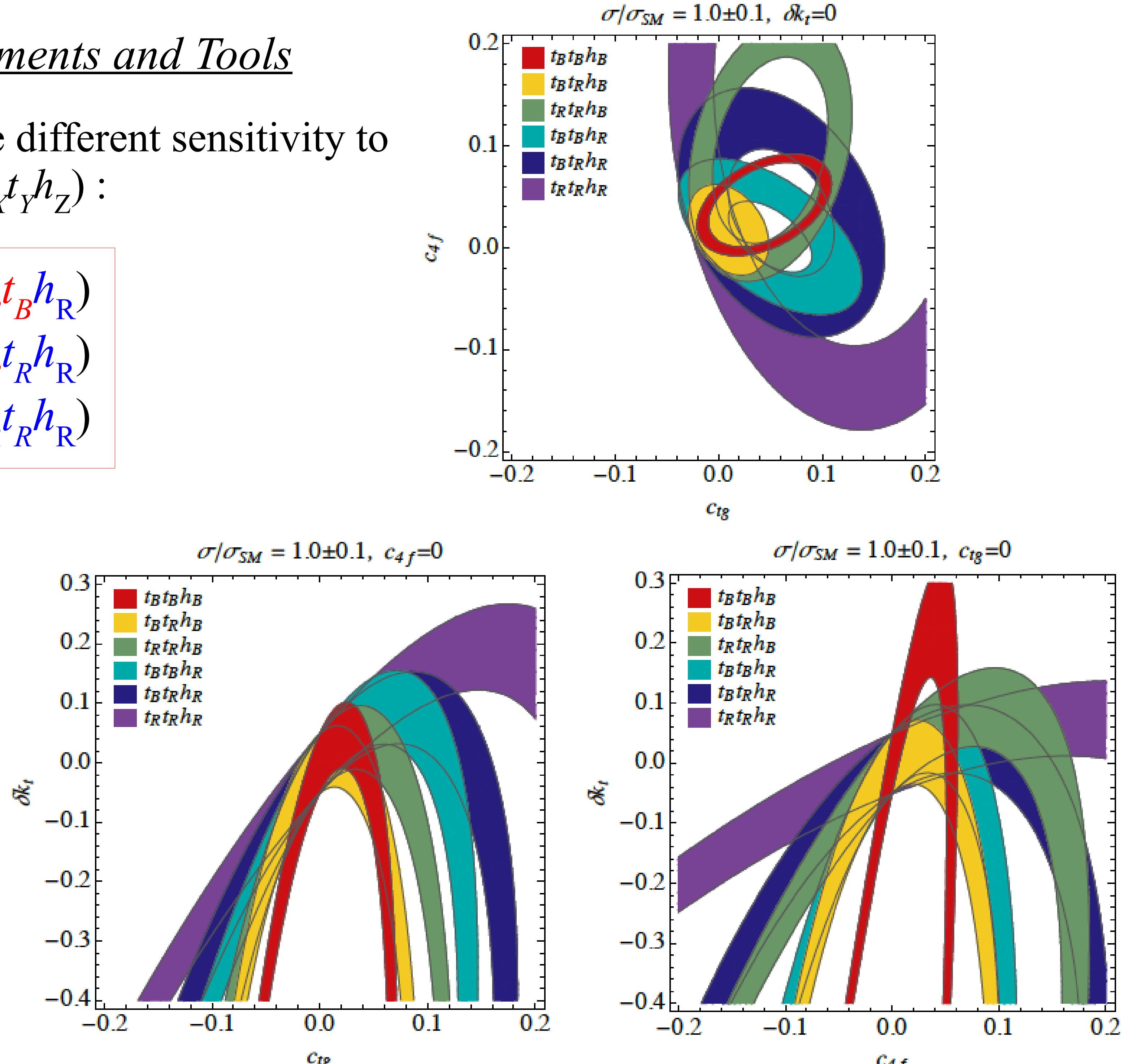
$t(h)_B =$ "boosted"
$=$ top(Higgs)" decay products within a cone of size $\Delta R_{t(h)}$
$t(h)_R =$ "rest" (non boosted)

*Faroughy, Greljo, GI, Kamenik, Marzocca, to appear*

## Recent developments and Tools

Illustration of the different sensitivity to NP of the six $\sigma(t_X t_Y h_Z)$ :

| | |
|---|---|
| $\sigma(t_B t_B h_B)$ | $\sigma(t_B t_B h_R)$ |
| $\sigma(t_B t_R h_B)$ | $\sigma(t_B t_R h_R)$ |
| $\sigma(t_R t_R h_B)$ | $\sigma(t_R t_R h_R)$ |

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# Conclusions

- The PO represent a general tool for the exploration of Higgs properties (in view of high-statistics data), with minimum loss of information and minimum theoretical bias → *full complementary to EFT* (and explicit BSM)

- Formalism and (NLO-QCD) tools fully developed for Higgs decays and Higgs EW production cross sections.

- On-going activity for tth (→ natural "merging" with template XS approach) and for the inclusion of large EW logs