University of Zurich[UZH]

The HXSWG2 note on Higgs Pseudo Observables

Pseudo Observables in Higgs physics

Higgs decays

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

↓

There is more to extract from data other than the κ_i

Two-body (on-shell) decays

[*no polarization properties of the final state accessible*]

e.g. $h \to \gamma\gamma, \mu\mu, \tau\tau, bb$

↓

The κ_i $(\leftrightarrow \Gamma_i)$ *is all what one can extract from data*

[+ *one more parameter if the polarization is accessible*]

Pseudo Observables in Higgs physics

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Multi-body modes
e.g. $h \to 4\ell$, $\ell\ell\gamma$, ...

form factors $\to f_i(s)$ [E.g.: $s = m^2_{\ell\ell}$]

Two-body (on-shell) decays
[*no polarization properties of the final state accessible*]

e.g. $h \to \gamma\gamma$, $\mu\mu$, $\tau\tau$, bb

E.g.: $\mathcal{A}(h \to Z\, ee) \sim \varepsilon^Z_\mu J^{e_L}_\mu \left[f_1^{Ze_L}(q^2) g^{\mu\nu} + f_3^{Ze_L}(q^2)(pq\, g^{\mu\nu} - q^\mu p^\nu) + \ldots \right]$

N.B.: There is noting "wrong" or "dangerous" in using *f.f.*, provided

- they are defined from on-shell amplitudes
  [*hill-defined for* $h \to WW^*$, ZZ^* *but perfectly ok for* $h \to 4\ell$]
- no model-dependent assumptions are made on their functional form

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↓

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Momentum expansion of the *f.f.* around leading poles, e.g.:

$$f_i^{SM+NP}(s_1,s_2) = \frac{\kappa_i}{(s_1 - m_Z^2 + i m_Z \Gamma_Z)(s_2 - m_Z^2 + i m_Z \Gamma_Z)} + \frac{\varepsilon_i}{(s_1 - m_Z^2 + i m_Z \Gamma_Z)} + \ldots$$

Two-body (on-shell) decays

[*no polarization properties of the final state accessible*]

e.g. $h \to \gamma\gamma,\ \mu\mu,\ \tau\tau,\ bb$

- No need to specify any detail about the underlying theory, but for the absence of light new particles → momentum exp. well justified by the Higgs kinematic
- The $\{\kappa_i, \varepsilon_i\}$ thus defined are well-defined PO → systematic inclusion of higher-order QED and QCD (soft) corrections possible (and necessary...)

Pseudo Observables in Higgs physics

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$$f_i^{SM+NP}(s_1,s_2) = \frac{\kappa_i}{(s_1-m_Z^2+im_Z\Gamma_Z)(s_2-m_Z^2+im_Z\Gamma_Z)} + \frac{\varepsilon_i}{(s_1-m_Z^2+im_Z\Gamma_Z)} + \ldots$$

Two-body (on-shell) decays
[*no polarization properties of the final state accessible*]
e.g. $h \to \gamma\gamma,\ \mu\mu,\ \tau\tau,\ bb$

The PO thus defined are based on a minimal set of QFT assumptions: analiticity, unitarity, crossing-symmetry + no new light particles in the theory.

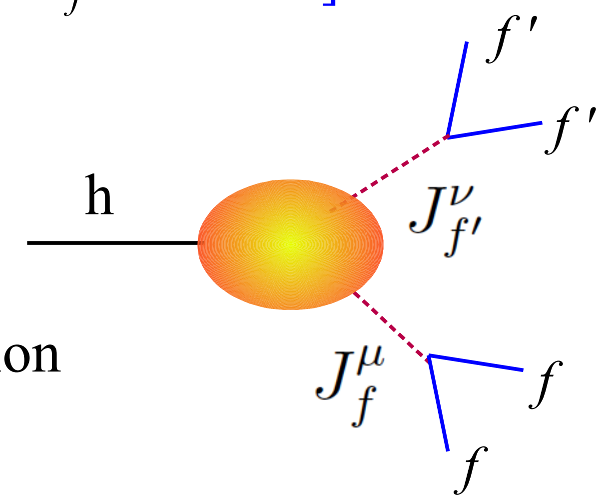
The $h \to 4f$ case

Two main hypotheses:

I. Fermion couples to the Higgs via helicity-conserving local currents
[↔ neglect helicity-violating interactions, naturally linked to m_f also BSM]

↓

$$G_{[JJh]} = \langle 0 | \mathcal{T} \left\{ J^\mu_f(x), J^\nu_{f'}(y), h(0) \right\} |0\rangle$$



The amplitude is fully determined by this Green function that contains long-distance modes (↔ non-local terms in x and y due to the exchange of EW gauge bosons) & short-distance modes (↔ contact terms for x or $y \to 0$)

Only 3 Lorentz structures allowed, e.g.:

$$\mathcal{A} = i\frac{2m_Z^2}{v_F} \sum_{e=e_L,e_R} \sum_{\mu=\mu_L,\mu_R} (\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu) \times \left[F_1^{e\mu}(q_1^2, q_2^2) g^{\alpha\beta} + F_3^{e\mu}(q_1^2, q_2^2) \frac{q_1 \cdot q_2 \; g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2, q_2^2) \frac{\varepsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \right]$$

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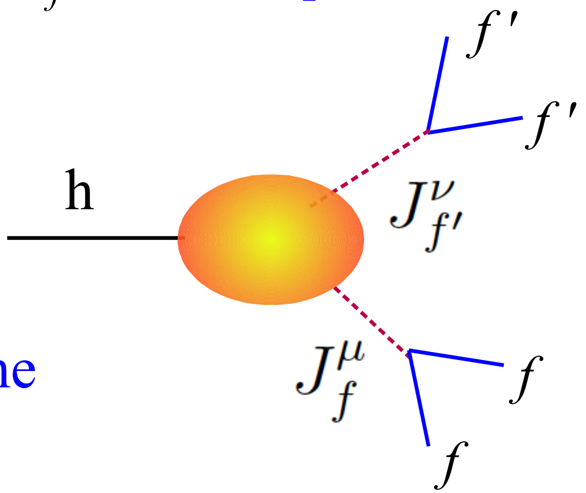
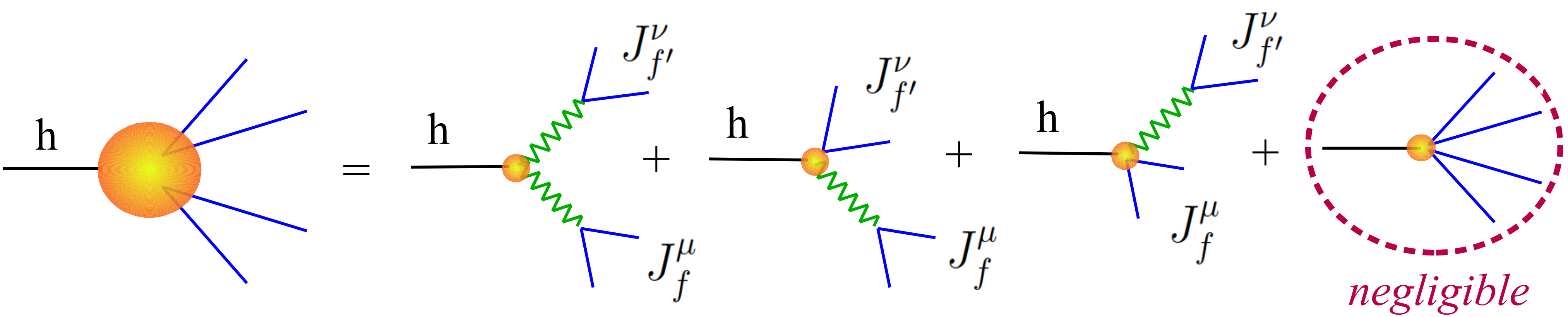
[$\leftrightarrow$ neglect helicity-violating interactions, naturally linked to m_f also BSM]

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



II. Kinematical (momentum) expansion of $G_{[JJh]}$ around the leading SM poles:



The $h \to 4f$ case

Following these hypotheses we can expand the form factors around the physical poles and retain only the leading terms (in the momentum expansion), e.g.:

$$\epsilon_{\gamma\gamma}^{\text{SM-1L}} \simeq 3.8\times 10^{-3} \qquad \epsilon_{Z\gamma}^{\text{SM-1L}} \simeq 6.7\times 10^{-3}$$

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

$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$$

- The $\{\kappa_i, \varepsilon_i\}$ are defined from the residues of the amplitude on the physical poles → well-defined PO that can be extracted from data and computed to desired accuracy in a given BSM framework

- By construction, the g_Z^f are the PO from Z-pole measurements, while $\kappa_{\gamma\gamma}$ and $\kappa_{Z\gamma}$ are the standard "kappas" from on-shell $h \to \gamma\gamma$ and $h \to Z\gamma$

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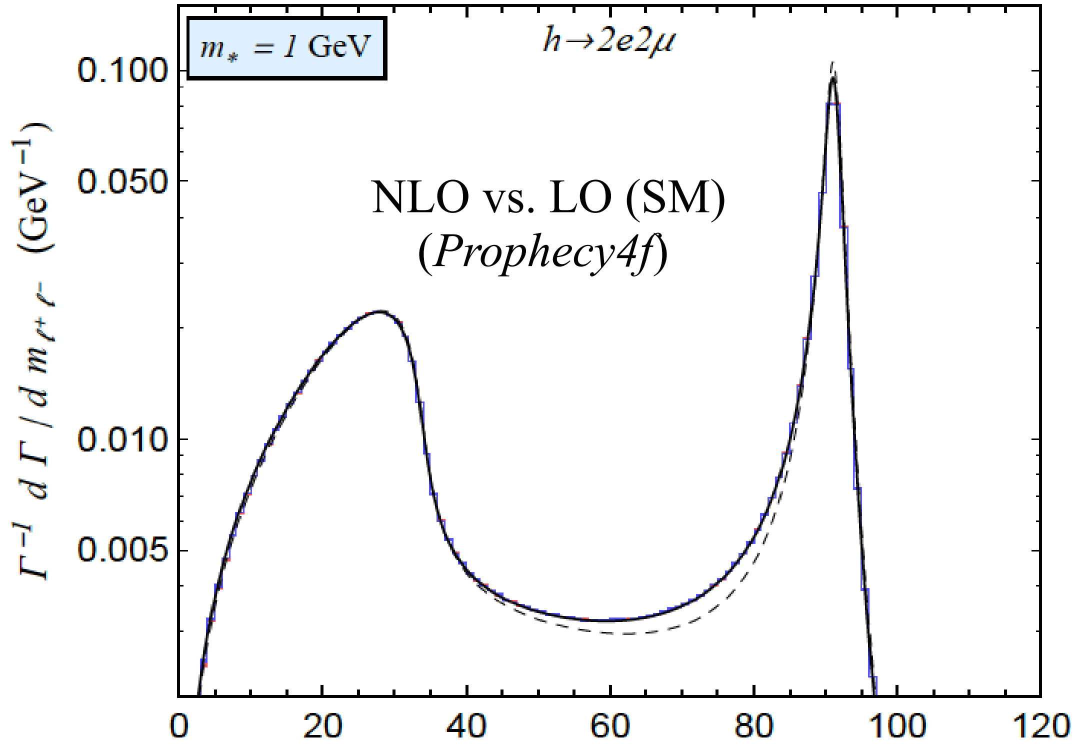
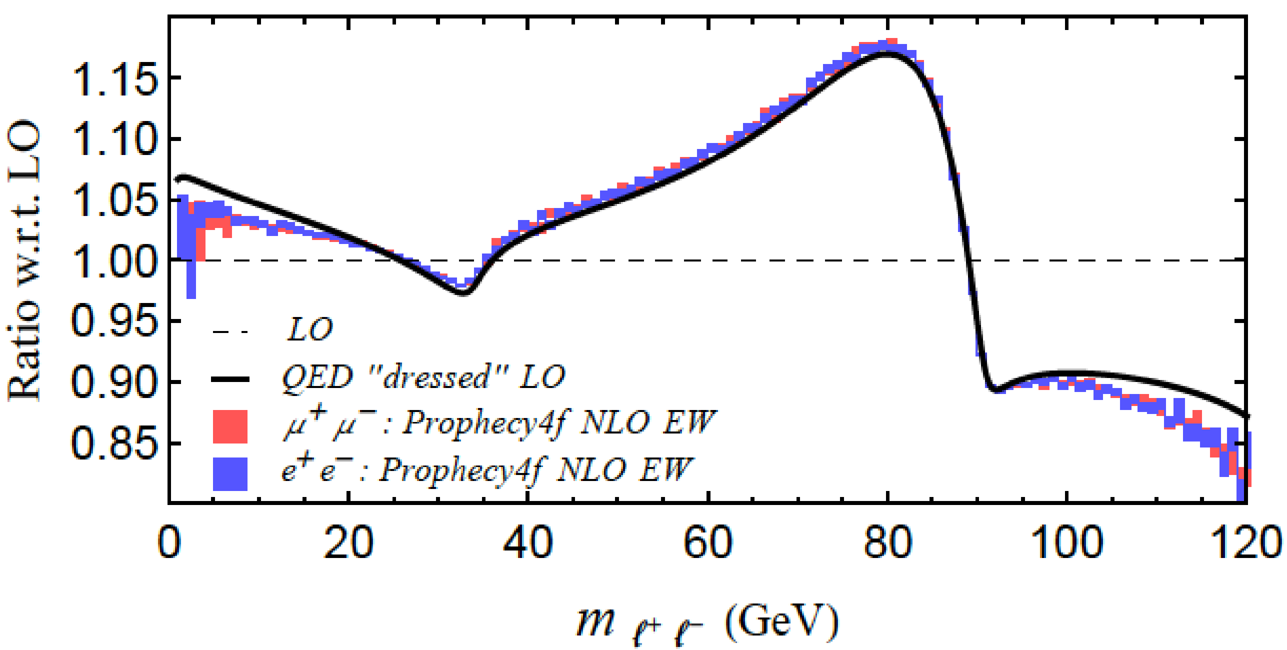
$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$$

- The κ_i are normalized such that the SM is recovered in the limit $\kappa_i \to 1$
- The ε_i describe terms not present in the SM at the tree level (*and always sub-leading*): SM recovered for $\varepsilon_i^{(SM)} = O(10^{-3}) \to 0$
- To this amplitude we can apply a "radiation function" to take into account QED radiation → excellent description of SM (and NP) beyond the tree level.

The $h \to 4f$ case

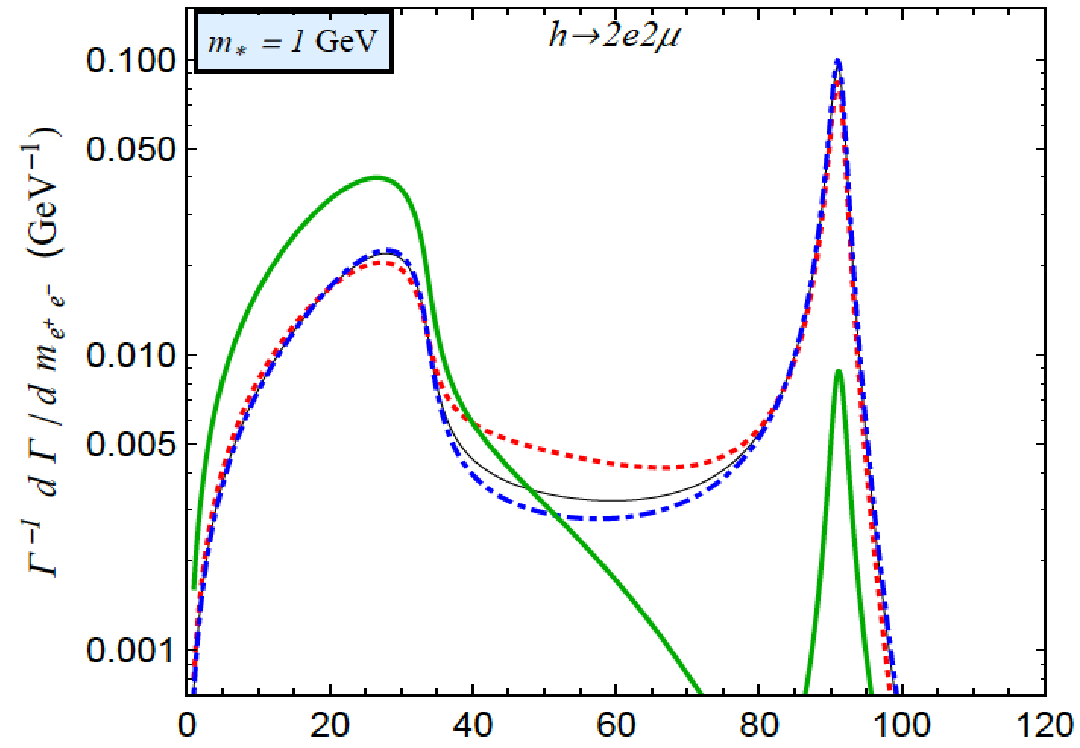
"Dressing" with QED radiation → excellent description of SM beyond the tree level

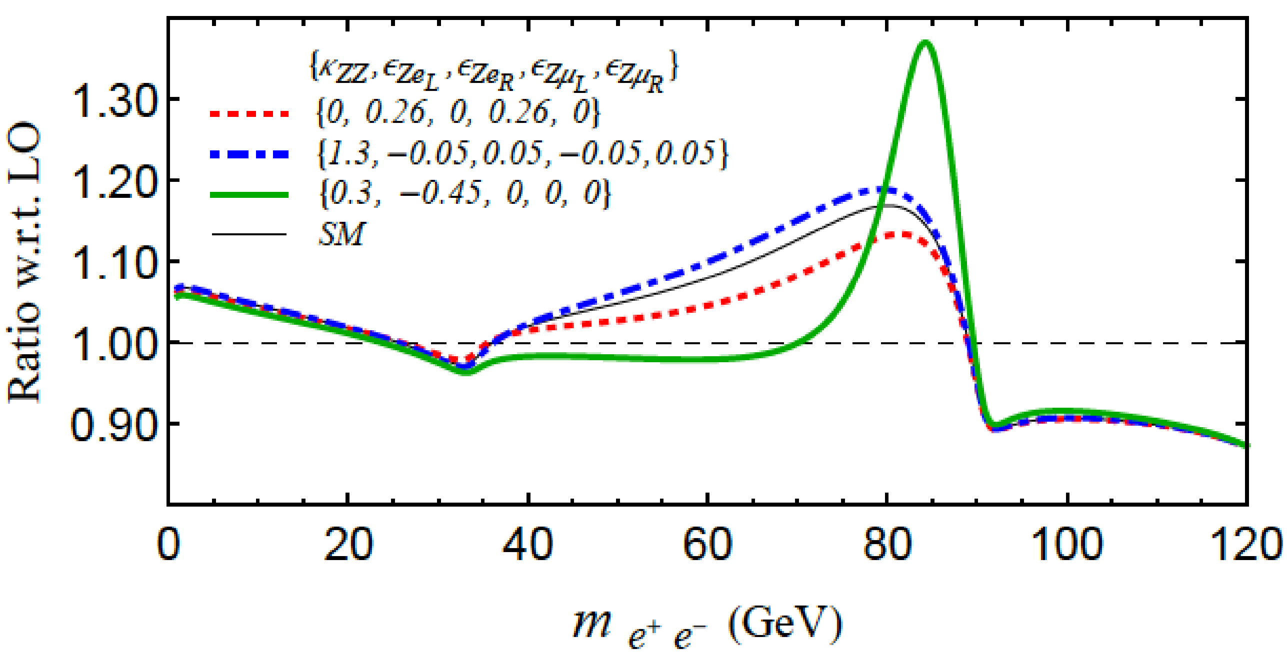




The $h \to 4f$ case

"Dressing" with QED radiation → excellent description of SM beyond the tree level & relevant impact for BSM @ NLO



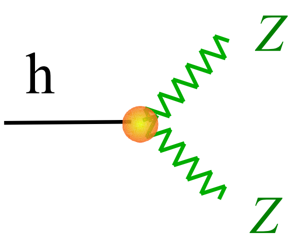


▶ *The $h \to 4f$ case*

The “physical meaning” of the parameters appearing in this decomposition is not obvious at first sight, but it is actually quite simple [→ *physical PO*]:

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

“double Z-pole”



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

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

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

The $h \to 4f$ case

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

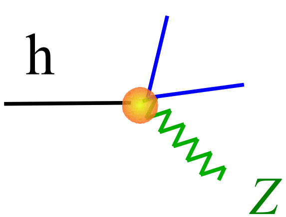
$$\mathcal{A} = i\frac{2m_Z^2}{v_F} \sum_{e=e_L,e_R} \sum_{\mu=\mu_L,\mu_R} (\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times$$

$$\Bigg[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)} \right) g^{\alpha\beta} +$$

$$+ \left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}} \left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) \frac{q_1\cdot q_2\, g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} +$$

$$+ \left(\epsilon_{ZZ}^{\text{CP}}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\text{CP}} \left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \epsilon_{\gamma\gamma}^{\text{CP}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) \frac{\varepsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \Bigg]$$

"single Z-pole"



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

The $h \to 4f$ case

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

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

The $h \to 4f$ case

N. independent PO for a complete description of $h \to 4\ell$ (ℓ=e,μ,ν) + $\ell\ell\gamma$ + $\gamma\gamma$, with or without specific symmetry assumptions:

Decay modes	*flavor +CP symm.*	*flavor non univ.*	*CP violation*
$h \to \gamma\gamma, 2e\gamma, 2\mu\gamma$ $4e, 4\mu, 2e2\mu$	$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}$ $\epsilon_{ZZ}, \epsilon_{Ze_L}, \epsilon_{Ze_R}$ (6)	$\epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$ (2)	$\epsilon^{CP}_{ZZ}, \epsilon^{CP}_{Z\gamma}, \epsilon^{CP}_{\gamma\gamma}$ (3)

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Decay modes	*flavor +CP symm.*	*flavor non univ.*	*CP violation*
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$h \to 2e2\nu, 2\mu2\nu, e\nu\mu\nu$	κ_{WW} (4) $\epsilon_{WW}, \epsilon_{Z\nu_e}, \mathrm{Re}(\epsilon_{We_L})$	$\epsilon_{Z\nu_\mu}, \mathrm{Re}(\epsilon_{W\mu_L})$	$\epsilon^{CP}_{WW}, \mathrm{Im}(\epsilon_{We_L})$ $\mathrm{Im}(\epsilon_{W\mu_L})$ (5)

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$h \to 2e2\nu, 2\mu2\nu, e\nu\mu\nu$	κ_{WW} (4) $\epsilon_{WW}, \epsilon_{Z\nu_e}, \mathrm{Re}(\epsilon_{We_L})$	$\epsilon_{Z\nu_\mu}, \mathrm{Re}(\epsilon_{W\mu_L})$ $\mathrm{Im}(\epsilon_{W\mu_L})$ (5)	$\epsilon^{CP}_{WW}, \mathrm{Im}(\epsilon_{We_L})$
all modes *with custodial symmetry*	$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}$ $\epsilon_{ZZ}, \epsilon_{Ze_L}, \epsilon_{Ze_R}$ $\mathrm{Re}(\epsilon_{We_L})$ (7)	$\epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$	$\epsilon^{CP}_{ZZ}, \epsilon^{CP}_{Z\gamma}, \epsilon^{CP}_{\gamma\gamma}$

20 (no symmetries) → 7 (CP + Lepton Univ + Custodial)

The $h \to 4f$ case

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Decay modes	*flavor +CP symm.*	*flavor non univ.*	*CP violation*
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$h \to 2e2\nu, 2\mu 2\nu, e\nu\mu\nu$	κ_{WW} (4) $\epsilon_{WW}, \epsilon_{Z\nu_e}, \mathrm{Re}(\epsilon_{We_L})$	$\epsilon_{Z\nu_\mu}, \mathrm{Re}(\epsilon_{W\mu_L})$ $\mathrm{Im}(\epsilon_{W\mu_L})$ (5)	$\epsilon^{CP}_{WW}, \mathrm{Im}(\epsilon_{We_L})$
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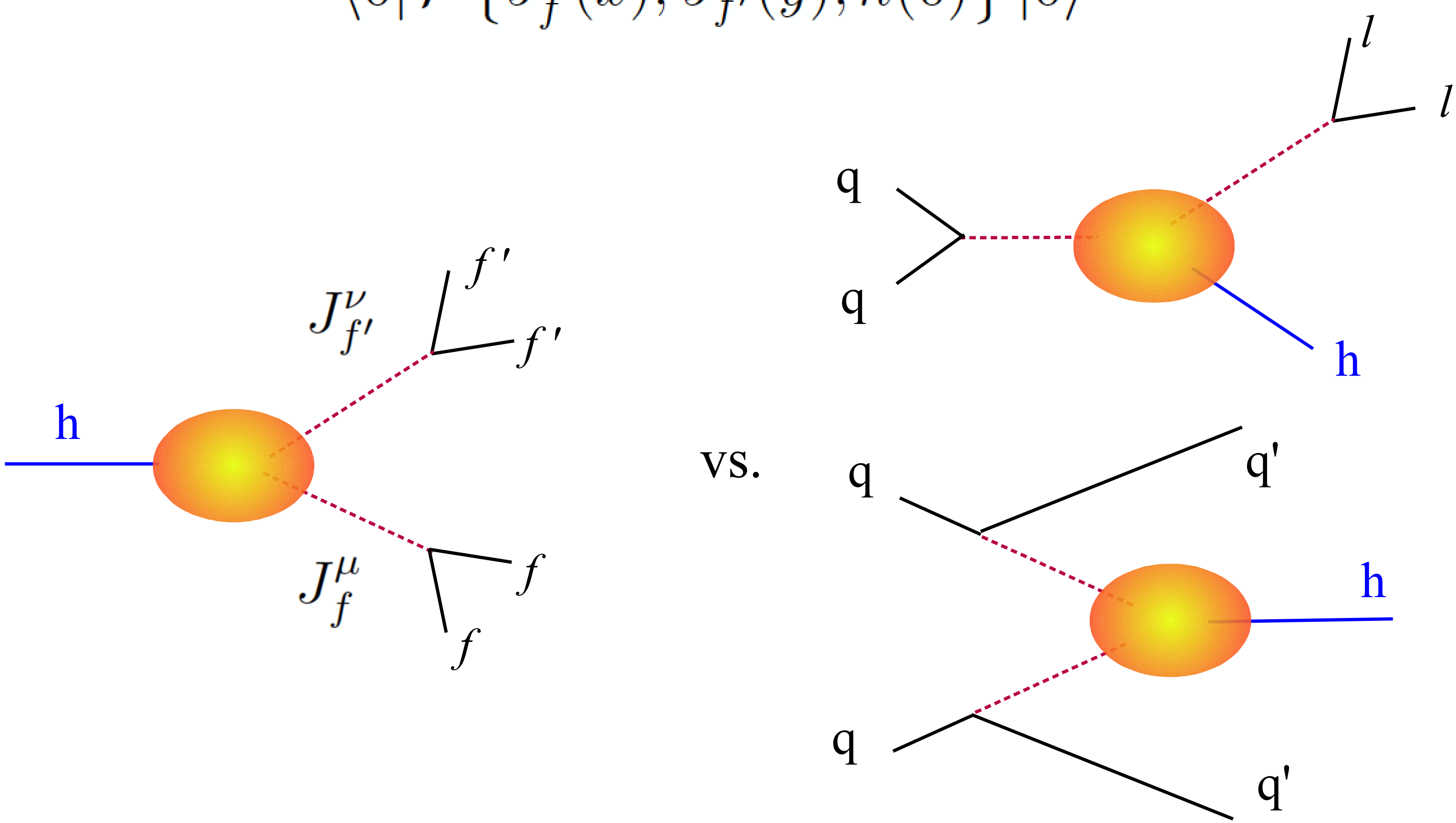
The symmetry assumptions can be directly tested from data, focusing on specific kinematical distributions sensitive to the relevant PO's [e.g. CPV-violating observables & LFU tests → key role played by the "contact terms" (ε_{Zl})]

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 "plain QFT" no need to invoke any EFT...*)

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



PO in Higgs EW production

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

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

- 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

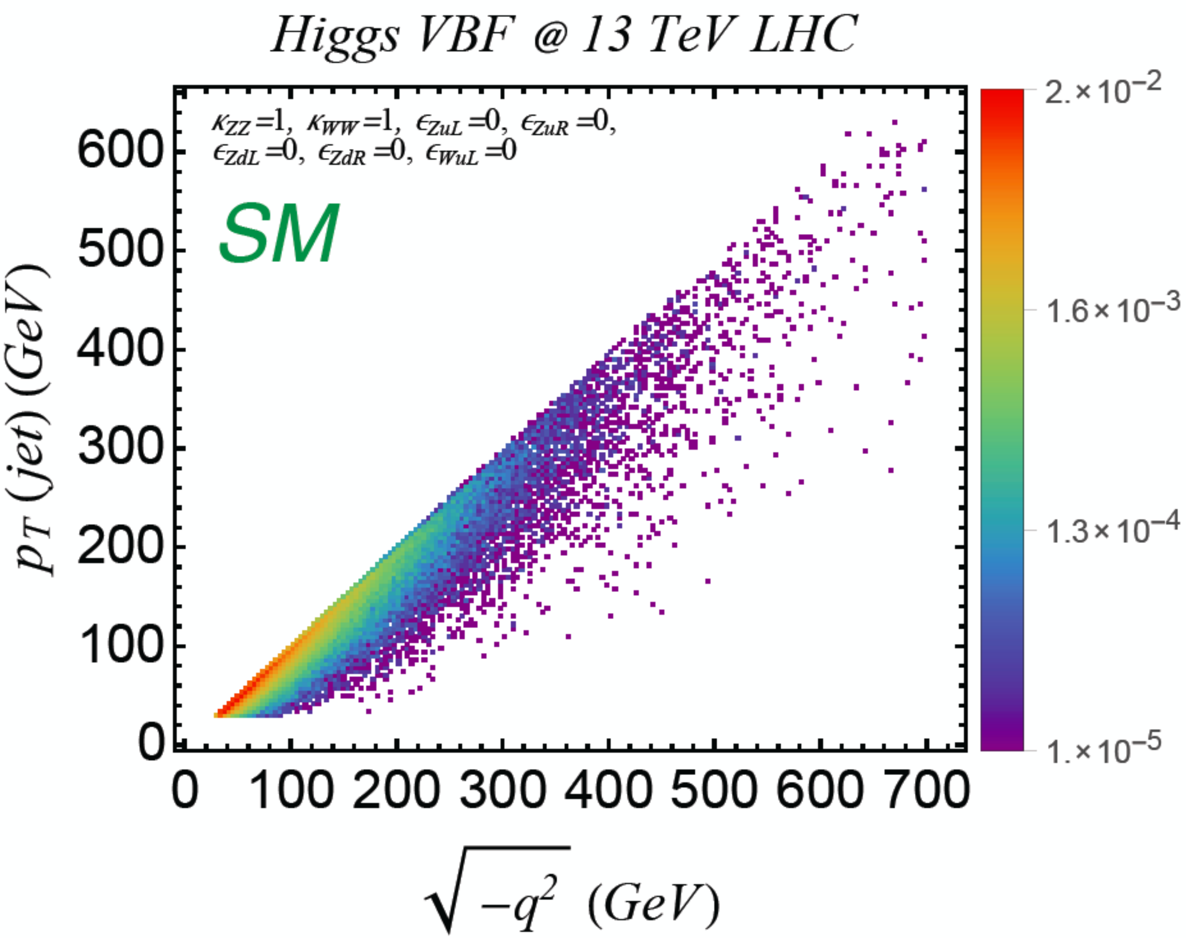
- different kinematical regime: momentum exp. not always justified (*large momentum transfer*)

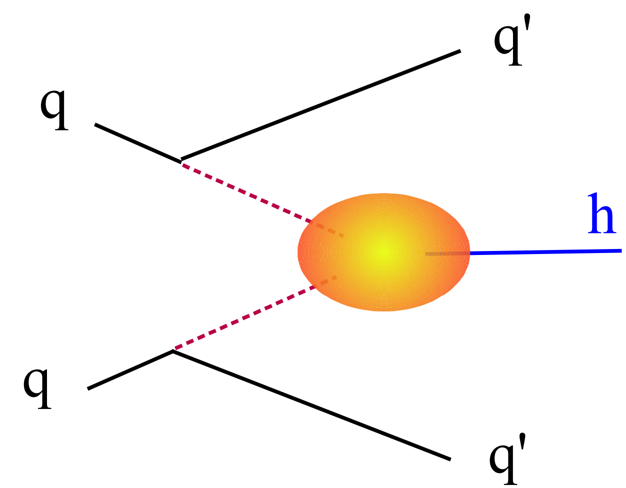
delicate point

PO in Higgs EW production

Twofold problem:

I. identify which are the "dangerous" kinematical variables, and how to access them when not directly measurable → p_T^{jet} in VBF, p_T^Z in Zh





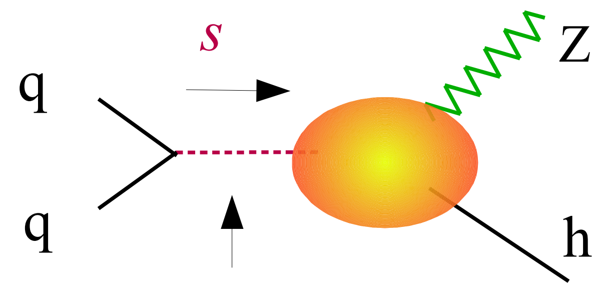
PO in Higgs EW production

Twofold problem:

I. identify which are the “dangerous” kinematical variables, and how to access them when not directly measurable → p_T^{jet} in VBF, p_T^{Z} in Zh

II. how to control the validity of the expansion

E.g.: $pp \to Zh$



$s = (m_{hZ})^2$

$$\frac{1}{s - m_Z^2} \left[\, g^Z_q\, \kappa_{ZZ} + \epsilon_{Zq}\, (s - m_Z^2)/m_Z^2 + \ldots \,\right]$$

Key point: since we expand on a measurable kinematical variable, <u>the validity of the expansion can be directly checked/validated by data</u>

PO in Higgs EW production

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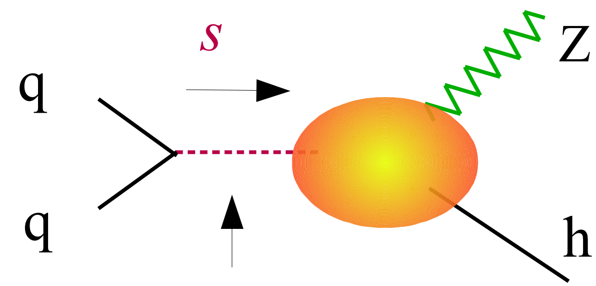

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General procedure:

- Measure the PO setting close to the threshold region, setting a cut on the "dangerous" kinematical variable [→ a-posteriori data-driven check of the validity of the momentum expansion = definition of a "threshold region"]
- Report the cross-section as a function of the kinematical variable in the high-momentum region [→ natural link/merging with template cross-section method]