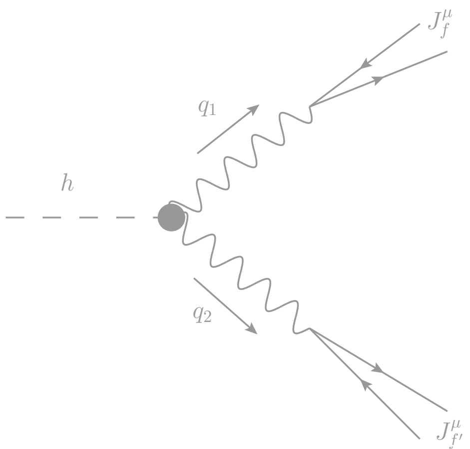
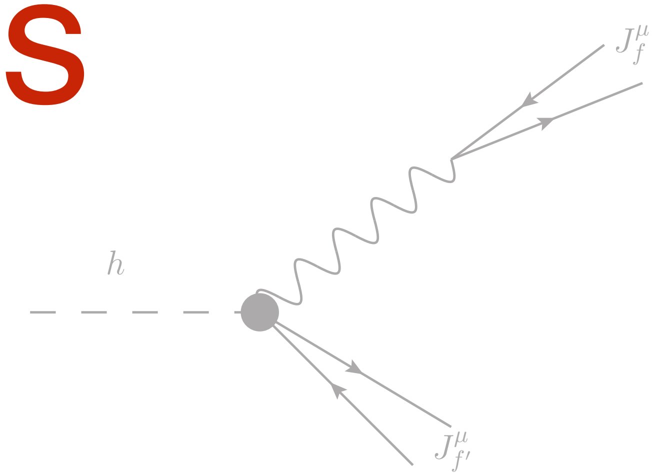


EFT, or

Higgs physics with heavy new physics

David Marzocca

Universität Zürich[UZH]



St. Petersburg: 31/08/2015

Introduction

★ Run 1 at LHC: discovery of the Higgs and
good measurement of many of its couplings…

The SM is complete.

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Run 2 (and beyond): High Precision Higgs era.

Search for smooth deviations from the SM → **Effective Field Theory**

In an EFT analysis further assumptions are needed:

- dynamical assumptions (e.g. if Higgs ∈ doublet)
- a basis has to be specified
- fix order in perturbation theory
- flavor assumptions

LHC Legacy: How to collect all available information on this state, in the most general and theoretically unbiased way?

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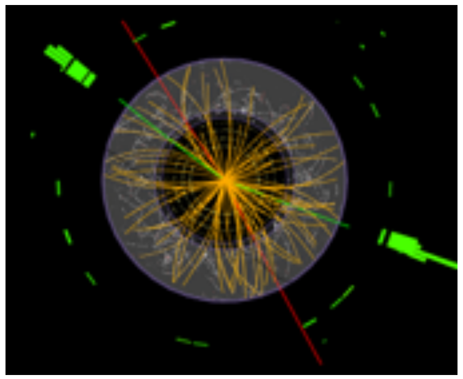

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Realistic Observables

Raw data,
Fiducial cross sections,
etc…

Lagrangian parameters

Couplings,
running masses,
Wilson coefficients
etc …

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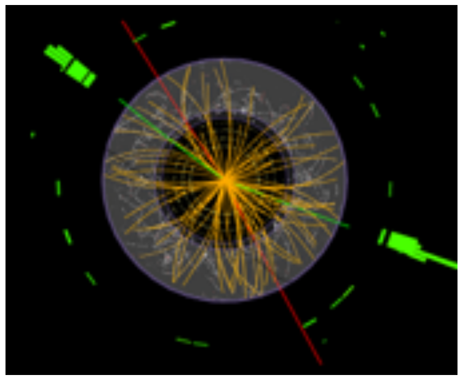

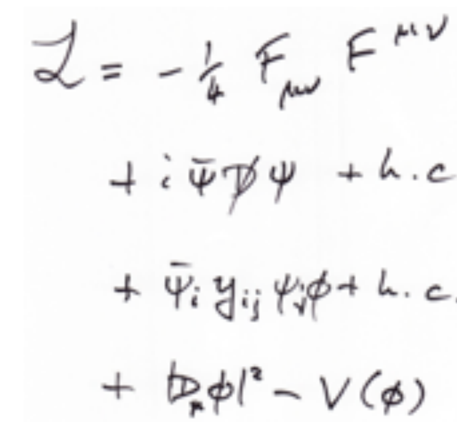

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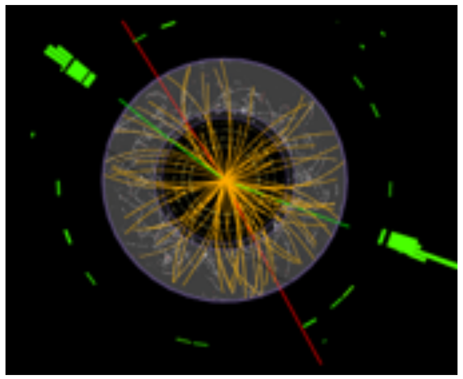

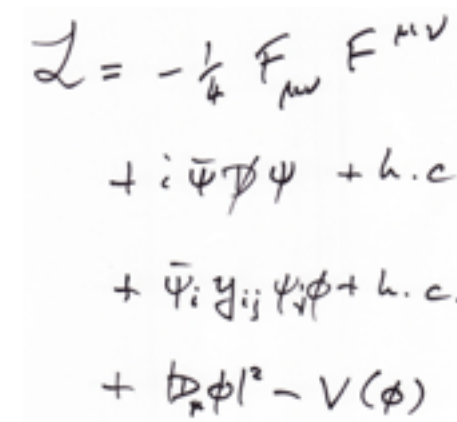

Realistic Observables	Pseudo Observables	Lagrangian parameters
Raw data, Fiducial cross sections, etc…	*Pole masses, decay widths, kappas, form factors, etc..*	*Couplings, running masses, Wilson coefficients etc …*

PO encode experimental information in idealized observables, of easy theoretical (QFT) interpretation [e.g. Z-pole PO]. [Bardin, Grunewald, Passarino '99]

PO can then be matched, by theorists, to any explicit scenario at the desired order in perturbation theory.

PO used at Run 1: the κ-framework

At Run-1, measurements of Higgs properties were reported in the κ-framework:

Narrow width approximation (& on-shell Higgs):

$$\sigma(ii \to h+X) \times BR(h \to ff) = \sigma_{ii} \frac{\Gamma_{ff}}{\Gamma_h} = \frac{\kappa_{ii}^2 \kappa_{ff}^2}{\kappa_h^2} \sigma_{SM} \times BR_{SM}$$

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Pros: Clear SM limit ($\kappa \to 1$),
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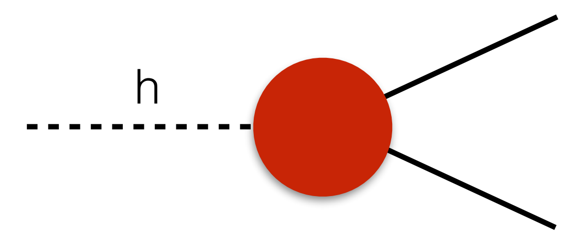
Need to extend the κ-framework retaining all its good properties:

Higgs pseudo-observables

Two-body Higgs decays



Higgs PO: parametrize the relevant on-shell amplitude.

$$\mathcal{A}(h \to f\bar{f}) = -i\frac{y_{\rm eff}^{f,\rm SM}}{\sqrt{2}}\bar{f}\left(\kappa_f + i\lambda_f^{\rm CP}\gamma_5\right)f$$

$$\mathcal{A}\left[h \to \gamma(q,\epsilon)\gamma(q',\epsilon')\right] = i\frac{2\,\epsilon_{\gamma\gamma}^{\rm SM,eff}}{v_F}\,\epsilon'_\mu\epsilon_\nu\left[\kappa_{\gamma\gamma}(g^{\mu\nu}\;q{\cdot}q' - q^\mu q'^\nu) + \lambda_{\gamma\gamma}^{\rm CP}\varepsilon^{\mu\nu\rho\sigma}q_\rho q'_\sigma\right]$$

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$\epsilon_X^{\rm SM,eff}$ $y_{\rm eff}^{f,\rm SM}$ from best SM prediction of the decay rate.

In the SM
$\kappa_X \to 1,\;\; \lambda_X^{\rm CP} \to 0$

[Gonzalez-Alonso, Greljo, Isidori, D.M. 1412.6038]

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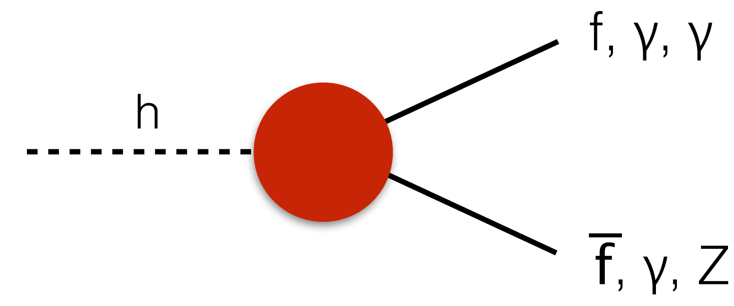

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$$\Gamma(h \to f\bar{f})_{\rm (incl)} = \left[\kappa_f^2 + (\lambda_f^{\rm CP})^2\right]\Gamma(h \to f\bar{f})_{\rm (incl)}^{\rm (SM)}$$

The kinematic is fixed.

No polarisation information is retained.

(maybe possible to measure in ττ channel)

→ the total rate is all that can be extracted from data

[Gonzalez-Alonso, Greljo, Isidori, D.M. 1412.6038]

Four-body Higgs decays: h → 4f

The process is **completely described by this Green function** of ON-SHELL states:

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

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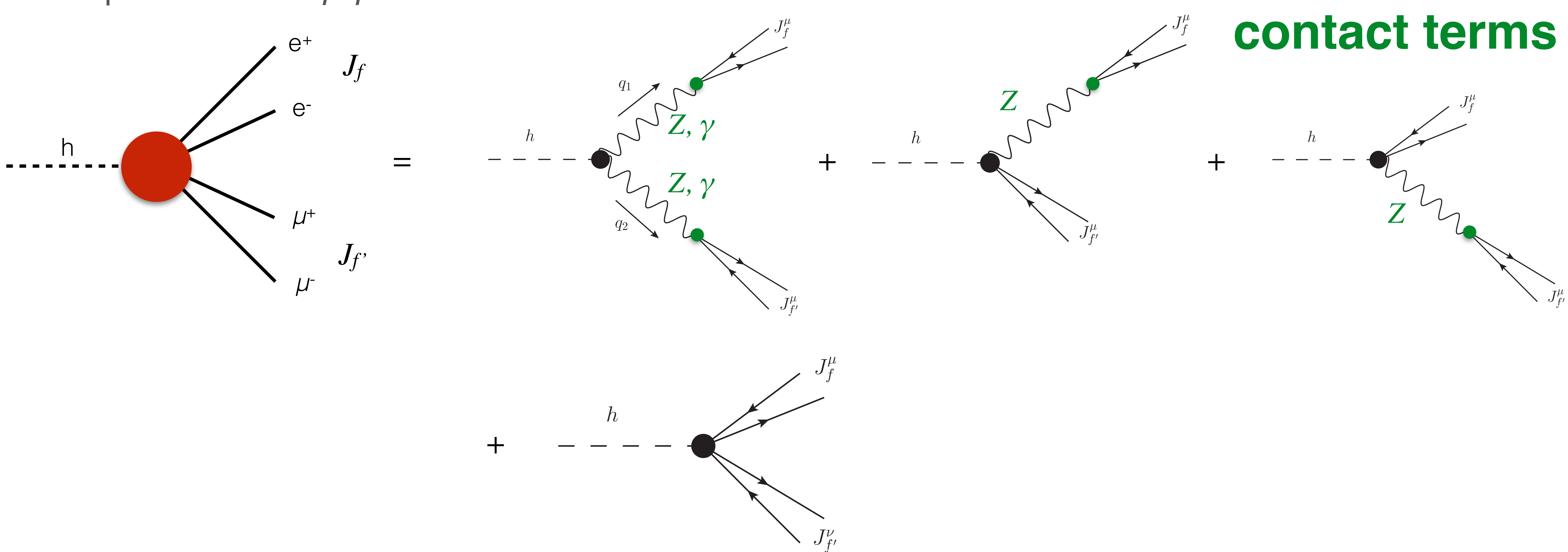
We expand around the physical poles of the Green function:

Example: $h \to e^+e^- \mu^+\mu^-$



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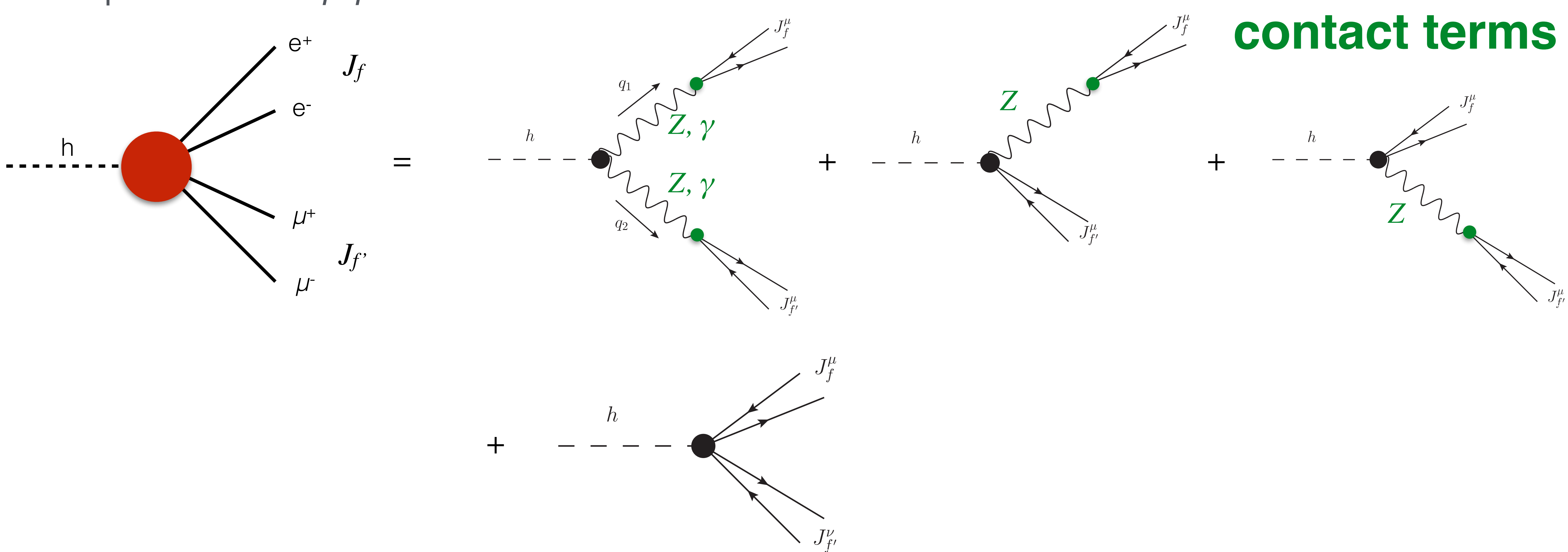

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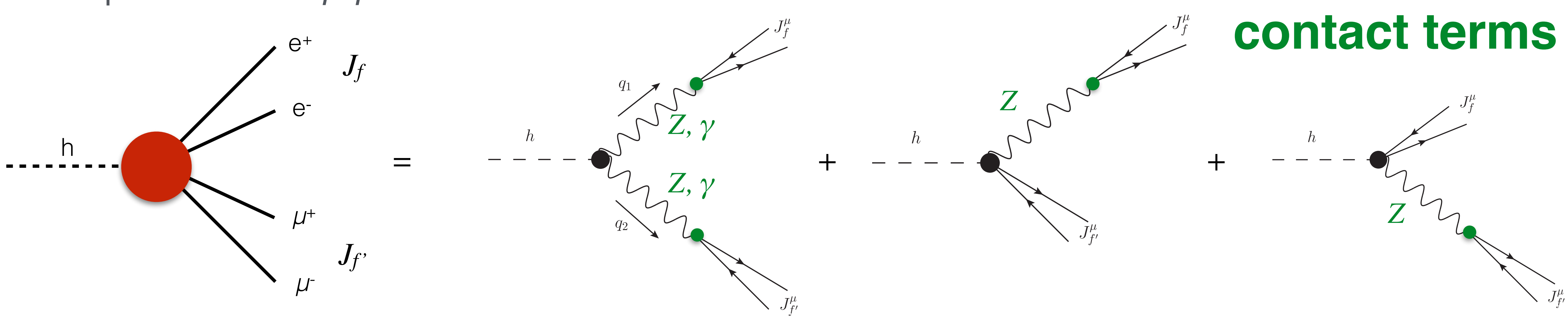

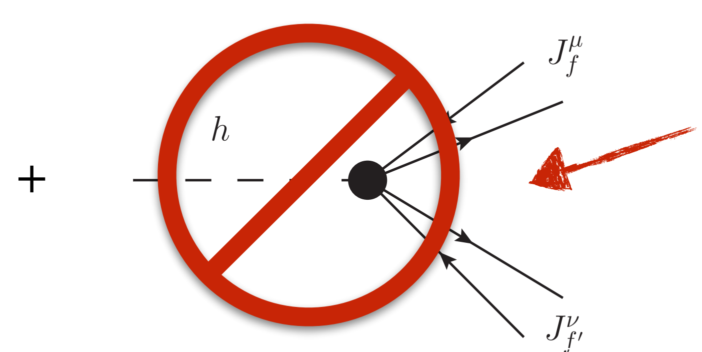

We neglect completely local terms, corresponding to operators with d > 6: EFT assumption.

$$\mathcal{O}(x) = h(x)\ \bar{e}(x)\gamma_\mu e(x)\ \bar{\mu}(x)\gamma^\mu \mu(x)$$

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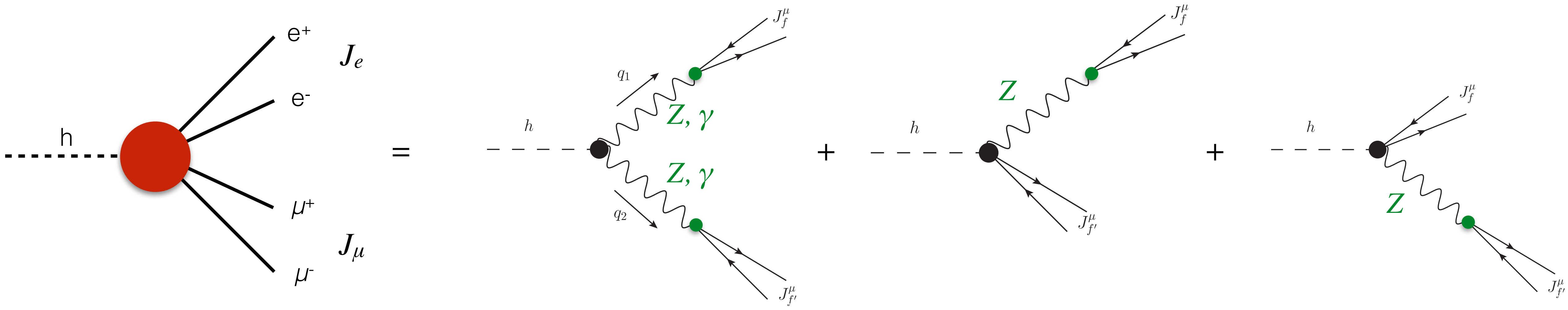
The Higgs PO are defined from the residues on the physical poles.



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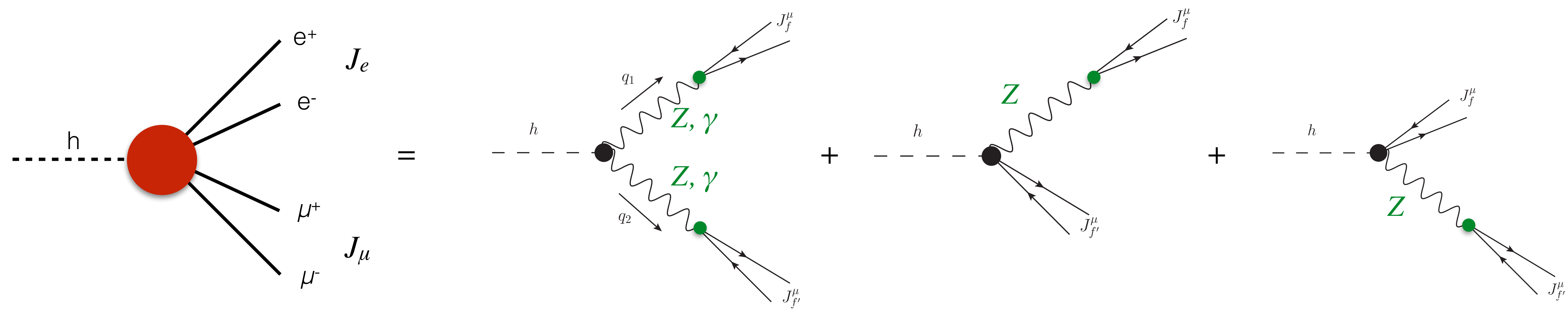

Only 3 tensor structures allowed by Lorentz symmetry.

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

In the SM $\kappa_X \to 1,\ \epsilon_X \to 0,\ \lambda_X^{\mathrm{CP}} \to 0$

$$e = e_L, e_R, \qquad \mu = \mu_L, \mu_R$$
$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$$

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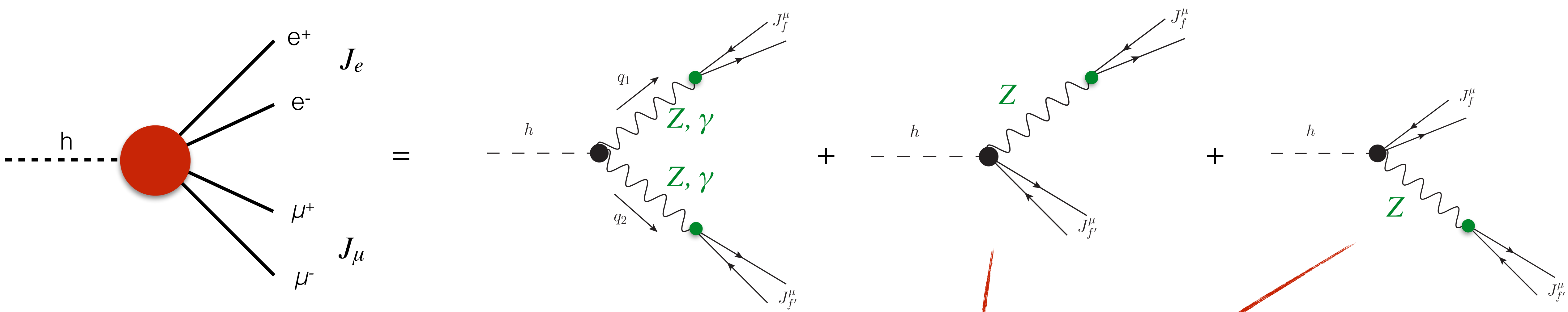
The Higgs PO are defined from the residues on the physical poles.



Only 3 tensor structures allowed by Lorentz symmetry.

contact terms
only new source of flavor dependence

$$\mathcal{A} = i\frac{2m_Z^2}{v_F}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times$$
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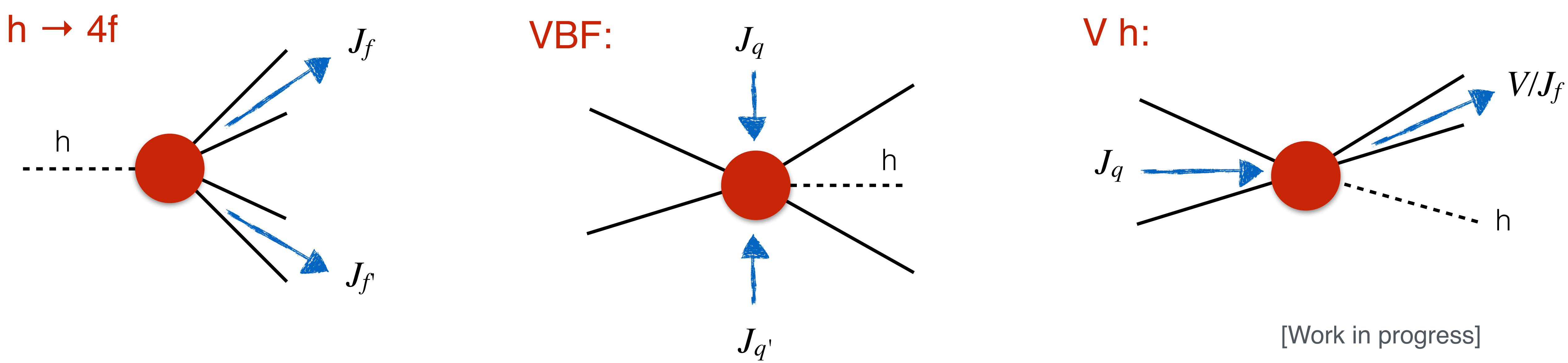
PO in EW Higgs Production

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

By crossing symmetry, the same correlation function
(in a different kinematical region and with different fermionic currents)
enters also in EW Higgs production.



Same PO as decays, only need to add quark contact terms.

In this case since the possible high momentum transfer at the LHC
could cause issues with the validity of the EFT expansion. Not an issue with form factors.

The Linear SM Effective Field Theory

Integrate out the heavy BSM dof.

Low energy theory specified by Symmetries & Field content

Assuming h(125) is a $SU(2)_L$ doublet (linear EFT)

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

and

Scale of New Physics is high

$$\Lambda_{NP} \gg m_h$$

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Assuming L and B conservation

$$\mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + (\text{dim} \;\; > 6)$$

Standard Model Lagrangian (d ≤ 4)

Leading deformations of the SM

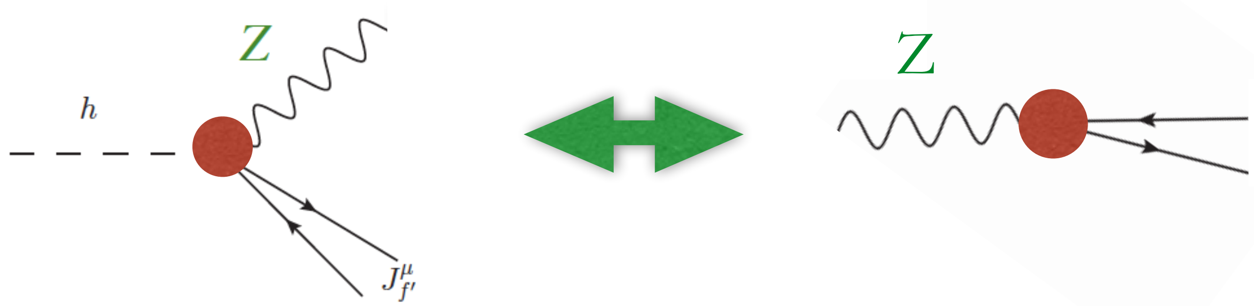
59 independent dim-6 operators if flavour universality.
2499 parameters for a generic flavour structure.

[Grzadkowski et al. 1008.4884, Alonso et al. 1312.2014]

The power of the EFT: relating different observables

The same operator can contribute to different processes.

For example: $$O_{Hf} = i(H^\dagger \overleftrightarrow{D}_\mu H)\bar{f}\gamma^\mu f = -\frac{1}{2}\sqrt{g^2+g'^2}Z_\mu(v+h)^2\bar{f}\gamma^\mu f$$



Z couplings δg_{Zf}

Higgs decay & production

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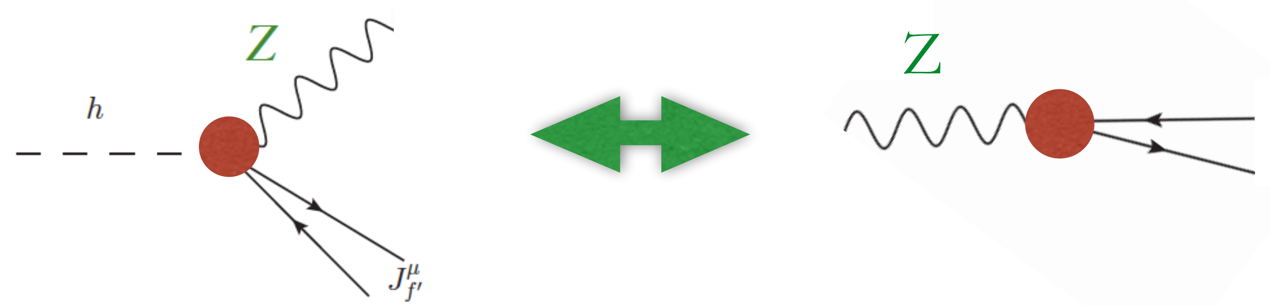

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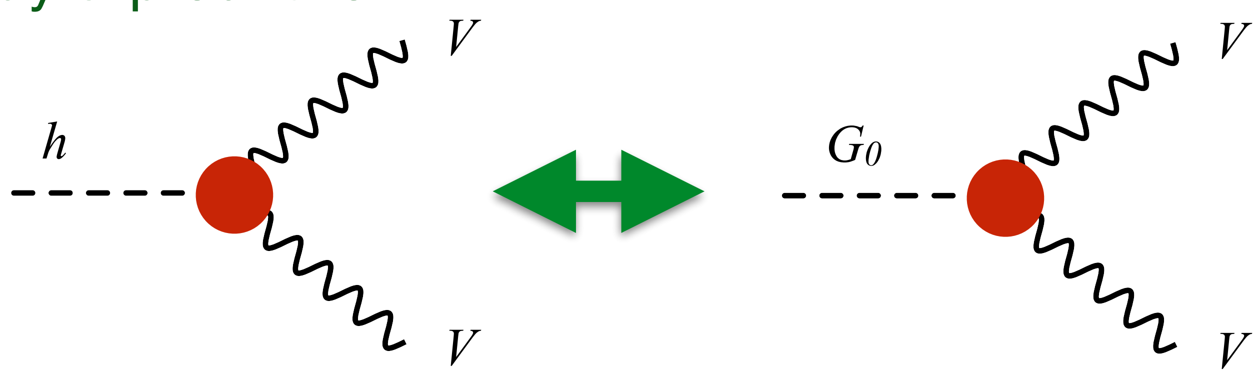
or

&



Triple Gauge Couplings
$\delta\kappa_z$, $\delta g_{1,z}$, λ_Z

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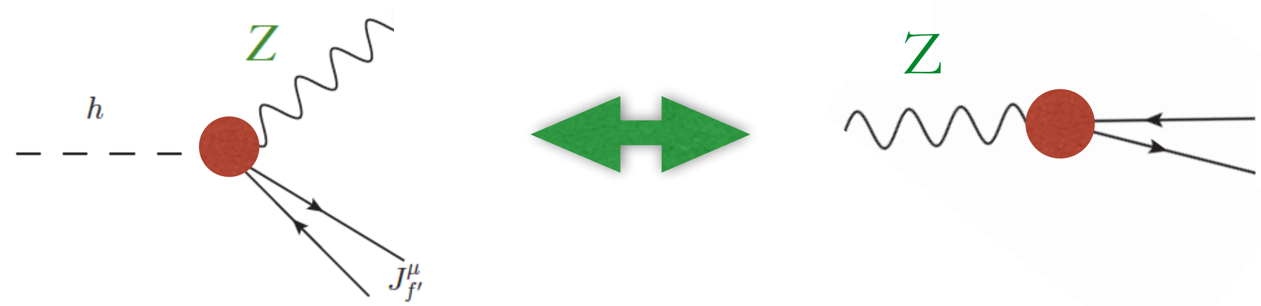

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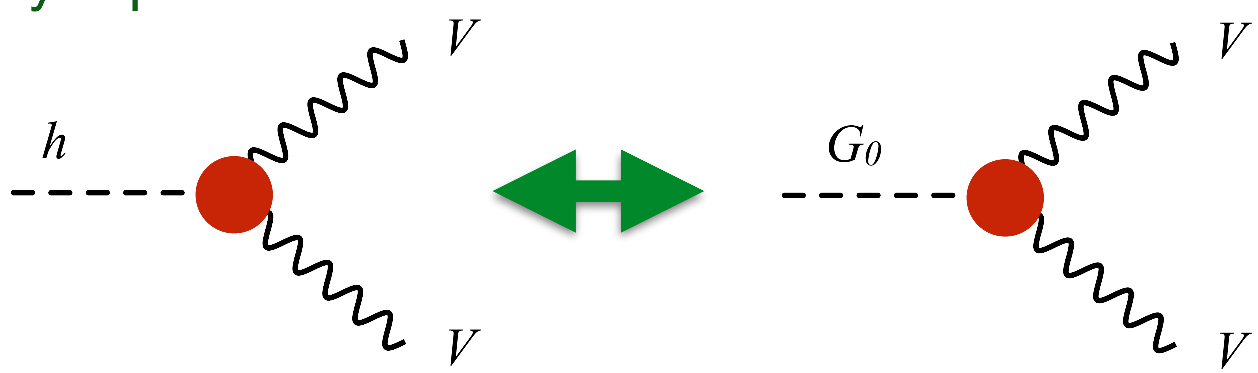

Triple Gauge Couplings
$\delta\kappa_z,\ \delta g_{1,z},\ \lambda_Z$

- Use LEP 1 and LEP 2 data
  to obtain bounds on some Higgs PO.
- Combine LEP data with Higgs data
  to derive stronger constraints for the EFT.

The power of the EFT: relating different observables

Once the strong LEP I constraints (≲1%) are imposed,

[Pomarol Riva 2013; Efrati et al. 2015; Berthier, Trott 2015]

Assuming MFV, only 10 independent combinations of coefficients contribute at tree-level to Higgs and LEP II (WW) observables.

[Corbett et al. 2013; J. Elias-Miro et al. 2013; Pomarol Riva 2013; Gupta et al 2014; Falkowski 2015]

Global fit in the 'Higgs basis' [LHCHXSWG 2015]

[Falkowski, Gonzalez-Alonso, Greljo, D.M. 1508.00581]

$$\delta c_z, \quad c_{\gamma\gamma}, \ c_{z\gamma}, \ c_{gg}, \ \delta y_u, \ \delta y_d, \ \delta y_e, \ \delta g_{1,z}, \ \delta\kappa_\gamma, \ \lambda_z.$$

Higgs (from δc_z through $\delta\kappa_\gamma$) **TGC** ($\delta g_{1,z}, \delta\kappa_\gamma, \lambda_z$)

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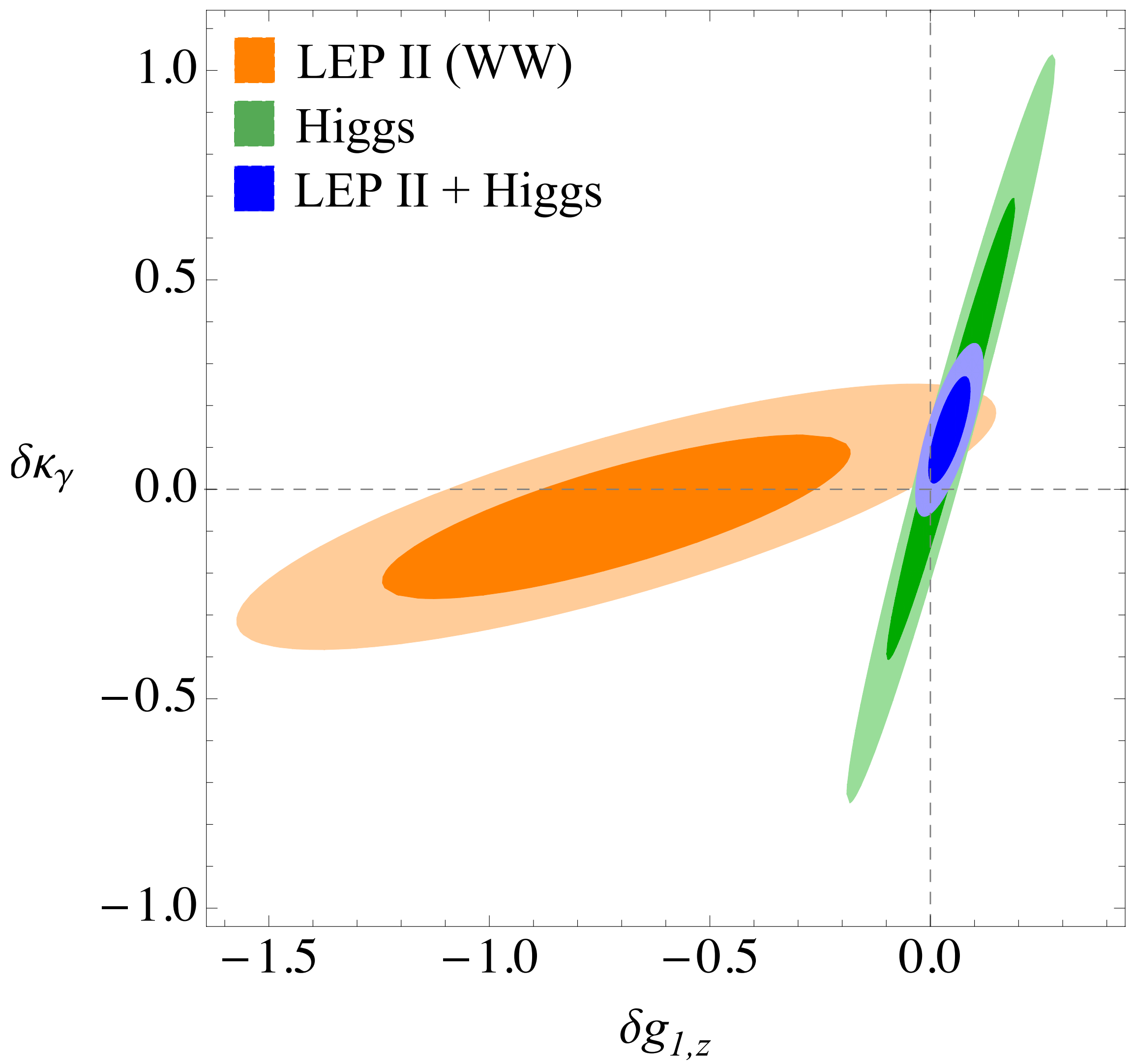
[Pomarol Riva 2013; Efrati et al. 2015; Berthier, Trott 2015]

Assuming MFV, only 10 independent combinations of coefficients contribute at tree-level to Higgs and LEP II (WW) observables.

[Corbett et al. 2013; J. Elias-Miro et al. 2013; Pomarol Riva 2013; Gupta et al 2014; Falkowski 2015]

Constraints on TGCs

[Falkowski, Gonzalez-Alonso, Greljo, D.M. 1508.00581]



All other coefficients have been marginalised.

LEP II data alone suffers from a flat direction in the TGC fit. [Falkowski, Riva 1411.0669]

+

Higgs data (mainly via VH and VBF production) is sensitive to a different direction.

[Falkowski 1505.00046]

=

Together they provide **strong and robust constraints on the TGC**.

Constraints on the Higgs PO in the linear EFT

We match the Higgs PO to the SM EFT: relations with LEP observables.

e.g $h \to 4\ell$:

$$\epsilon_{Zf} = \frac{2m_Z}{v}\left(\delta g^{Zf} - (c_\theta^2 T_f^3 + s_\theta^2 Y_f)\mathbf{1}_3 \delta g_{1,z} + t_\theta^2 Y_f \mathbf{1}_3 \delta\kappa_\gamma\right)$$

$$\delta\epsilon_{ZZ} = \delta\epsilon_{\gamma\gamma} + \frac{2}{t_{2\theta}}\delta\epsilon_{Z\gamma} - \frac{1}{c_\theta^2}\delta\kappa_\gamma$$

[Gonzalez-Alonso, Greljo, Isidori, D.M. 1504.04018]

LEP-I: $\delta g^{Z\ell} \lesssim 10^{-2}$ [Efrati, Falkowski, Soreq 2015]

Naively $\sim 10^{-3}$ bounds, however the theoretical error is of ~1%.

[Berthier, Trott 2015]

No qualitative influence for Higgs physics at present precision.

From LHC: $\delta\varepsilon_{\gamma\gamma} \lesssim 10^{-3}$, $\delta\varepsilon_{Z\gamma} \lesssim 10^{-2}$

The less constrained coefficients are the TGC.

We use our combined LEP II + Higgs global fit to derive constraints on the Higgs PO.

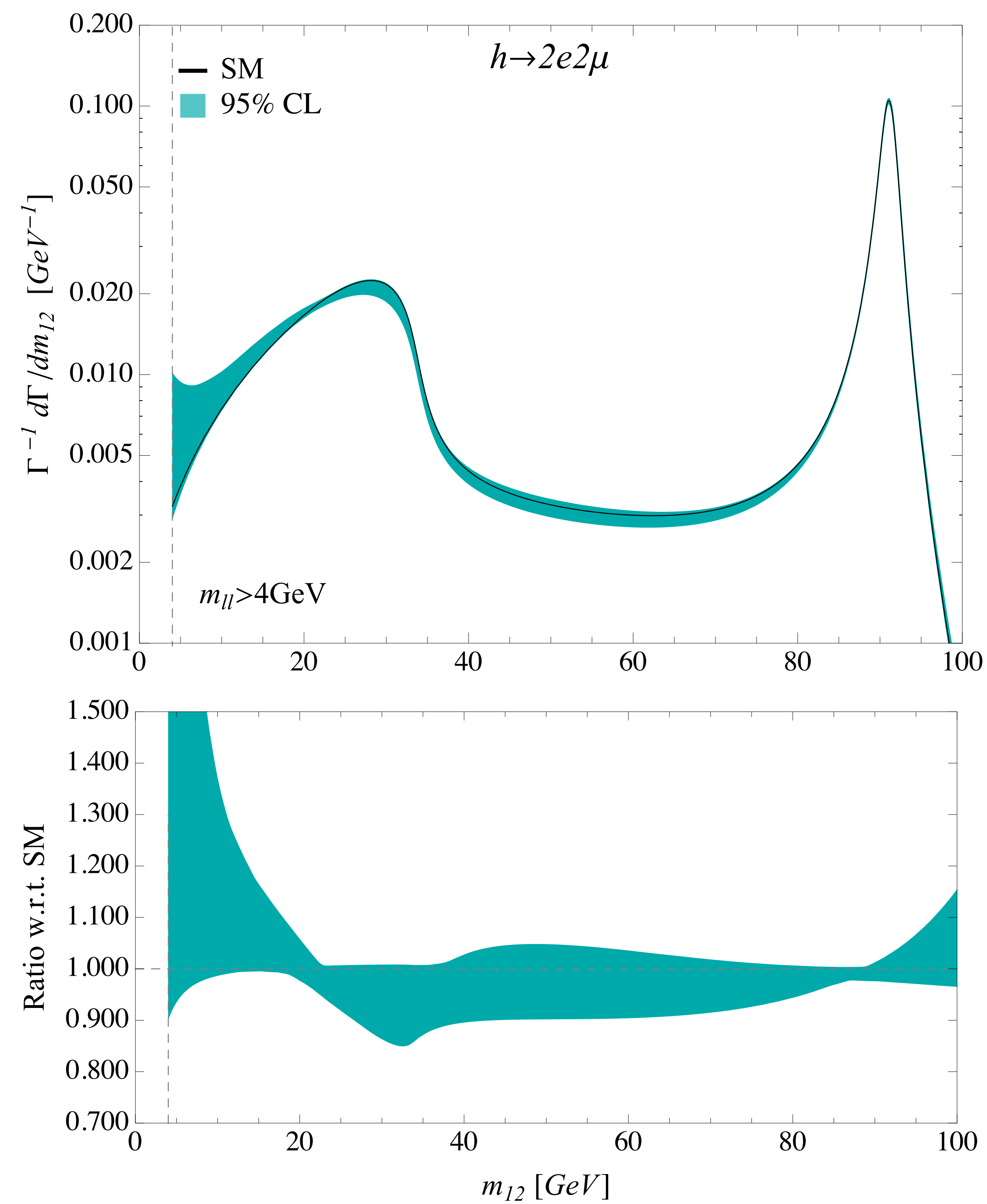
Predictions for h → 4ℓ in the linear EFT

5 independent PO only, in the linear EFT.

$$\begin{pmatrix} \kappa_{ZZ} \\ \epsilon_{Z\ell_L} \\ \epsilon_{Z\ell_R} \\ \kappa_{Z\gamma} \\ \kappa_{\gamma\gamma} \end{pmatrix} = \begin{pmatrix} 0.85 \pm 0.17 \\ -0.0001 \pm 0.0078 \\ -0.025 \pm 0.015 \\ 0.96 \pm 1.6 \\ 0.88 \pm 0.19 \end{pmatrix},$$

$$\rho = \begin{pmatrix} 1 & .72 & .60 & .19 & .83 \\ \cdot & 1 & .35 & -.16 & .62 \\ \cdot & \cdot & 1 & .02 & .47 \\ \cdot & \cdot & \cdot & 1 & .20 \\ \cdot & \cdot & \cdot & \cdot & 1 \end{pmatrix}.$$

From these bounds we can extract precise predictions for Higgs data, such as di-lepton invariant mass spectra.



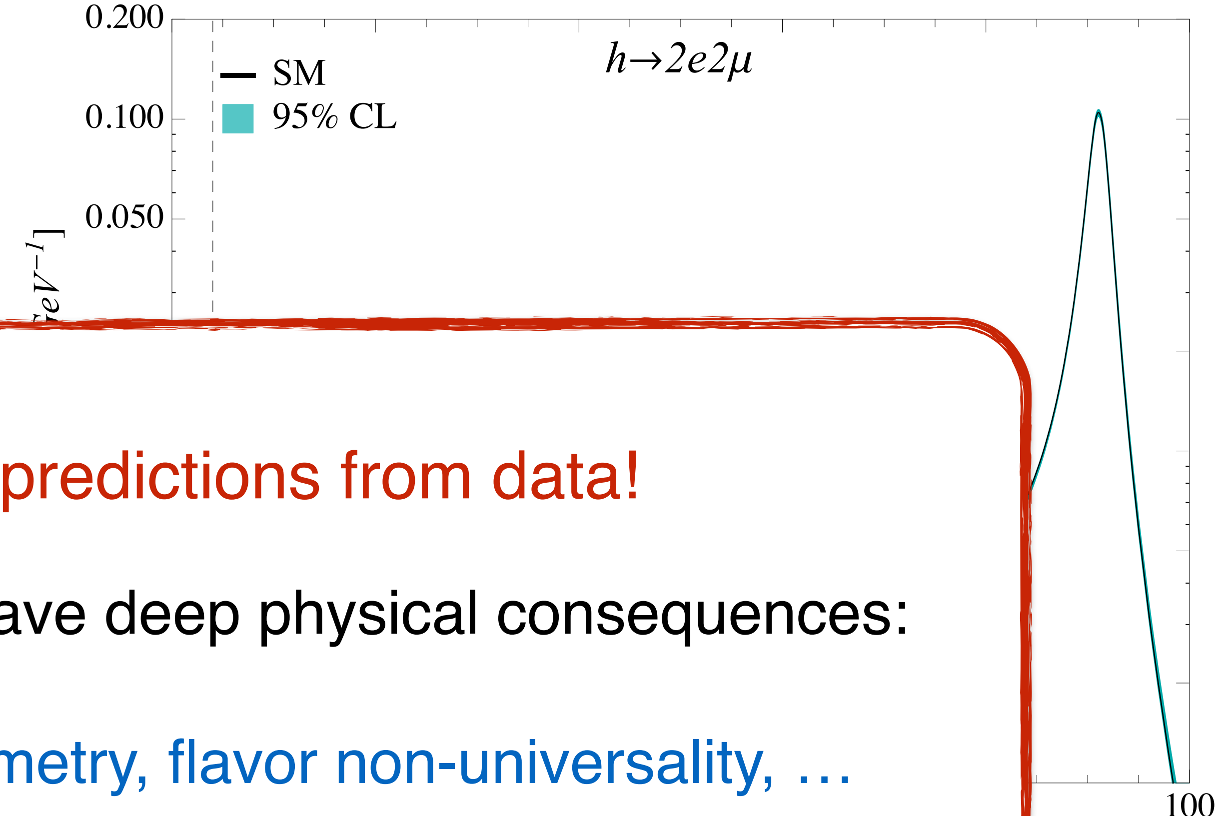
Small deviations allowed in the shape.

[Falkowski, Gonzalez-Alonso, Greljo, D.M. 1508.00581]

Predictions for h → 4ℓ in the linear EFT

5 independent PO only, in the linear EFT.

$$\begin{pmatrix} \kappa_{ZZ} \\ \epsilon_{Z\ell_L} \\ \epsilon_{Z\ell_R} \\ \kappa_{Z\gamma} \\ \kappa_{\gamma\gamma} \end{pmatrix} = \begin{pmatrix} 0.85 \pm 0.17 \\ -0.0001 \pm 0.0078 \\ -0.025 \pm 0.015 \\ 0.96 \pm 1.6 \end{pmatrix},$$

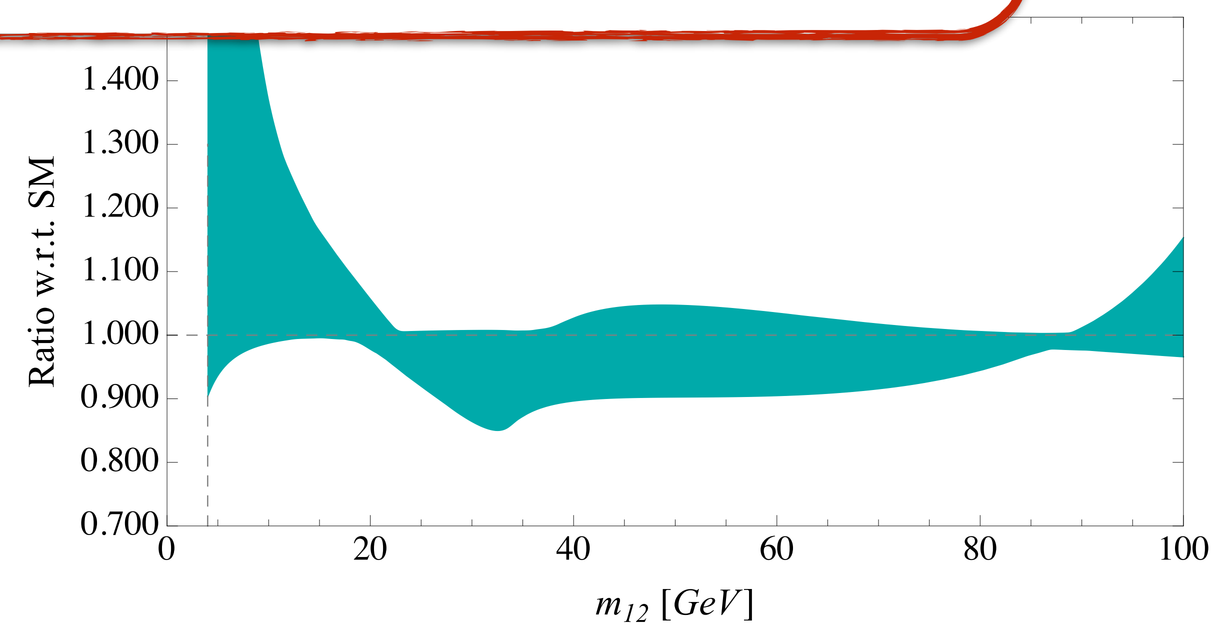


Crucial to test these predictions from data!

Any measured deviation would have deep physical consequences:

non-linear realization of EW symmetry, flavor non-universality, …

From these bounds we can extract precise predictions for Higgs data, such as di-lepton invariant mass spectra.



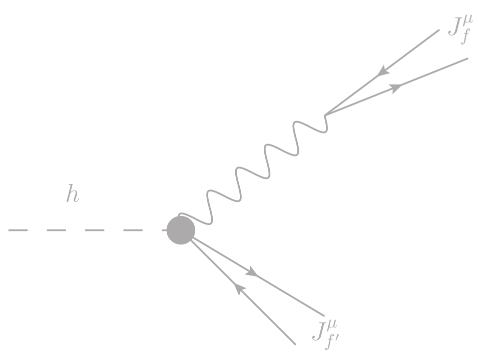
Small deviations allowed in the shape.

[Falkowski, Gonzalez-Alonso, Greljo, D.M. 1508.00581]

Conclusions

Higgs PO

- general framework to describe on-shell Higgs properties
- defined from physical properties of the Green functions
- easy to match to specific scenarios
- clear implementation of QED soft radiation (leading HO effect)



Implemented in FeynRules/UFO model:
www.physik.uzh.ch/data/HiggsPO/

The **linear EFT** provides relations among Higgs and non-Higgs processes:

- combine LEP and Higgs data to derive stronger constraints
- derive predictions for h → 4ℓ processes
  Testing these predictions: important test for the linear EFT.

Спасибо !

Backup

Parameter counting and symmetry assumptions

Neutral current

$h \to e^+e^-\mu^+\mu^-$
$h \to \mu^+\mu^-\mu^+\mu^-$
$h \to e^+e^-e^+e^-$
$h \to \gamma e^+e^-$
$h \to \gamma\mu^+\mu^-$
$h \to \gamma\gamma$

$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$,
$\epsilon^{CP}_{Z\gamma}, \epsilon^{CP}_{\gamma\gamma}, \epsilon^{CP}_{ZZ}$,
$\epsilon_{Ze_L}, \epsilon_{Ze_R}, \epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$

11

Charged current

$h \to e^+\mu^-\nu\nu$
$h \to e^-\mu^+\nu\nu$

$\kappa_{WW}, \epsilon_{WW}, \epsilon^{CP}_{WW}$,
$\epsilon_{We}, \epsilon_{W\mu}$, (complex)

7

N. & C. interference

$h \to e^+e^-\nu\nu$
$h \to \mu^-\mu^+\nu\nu$

others +
$\epsilon_{Z\nu_e}, \epsilon_{Z\nu_\mu}$

2

Symmetries impose relations among these observables.

Parameter counting and symmetry assumptions

Neutral current

$h \to e^+e^-\mu^+\mu^-$
$h \to \mu^+\mu^-\mu^+\mu^-$
$h \to e^+e^-e^+e^-$
$h \to \gamma e^+e^-$
$h \to \gamma\mu^+\mu^-$
$h \to \gamma\gamma$

$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$,
$\epsilon_{Z\gamma}^{CP}, \epsilon_{\gamma\gamma}^{CP}, \epsilon_{ZZ}^{CP}$,
$\epsilon_{Ze_L}, \epsilon_{Ze_R}, \epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$

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Symmetries impose relations among these observables.

Flavor universality

$$\epsilon_{Ze_L} = \epsilon_{Z\mu_L} \ ,$$
$$\epsilon_{Ze_R} = \epsilon_{Z\mu_R} \ ,$$
$$\epsilon_{Z\nu_e} = \epsilon_{Z\nu_\mu} \ ,$$
$$\epsilon_{We_L} = \epsilon_{W\mu_L} \ .$$

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$\epsilon_{Ze_R} = \epsilon_{Z}$
$\epsilon_{Z\nu_e} = \epsilon_{Z\nu_\mu}$,
$\epsilon_{We_L} = \epsilon_{W\mu_L}$.

CP Invariance

$$\epsilon_{ZZ}^{CP} = \epsilon_{Z\gamma}^{CP} = \epsilon_{\gamma\gamma}^{CP} = \epsilon_{WW}^{CP} = \mathrm{Im}\epsilon_{We_L} = \mathrm{Im}\epsilon_{W\mu_L} = 0$$

Parameter counting and symmetry assumptions

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$h \to \mu^+\mu^-\mu^+\mu^-$
$h \to e^+e^-e^+e^-$
$h \to \gamma e^+e^-$
$h \to \gamma\mu^+\mu^-$
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$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$,
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CP Invaria

$\epsilon^{CP}_{ZZ} = \epsilon^{CP}_{Z\gamma} = \epsilon^{CP}_{\gamma\gamma} = \epsilon^{CP}_{WW} =$

Custodial symmetry

$$★\ \epsilon_{WW} = c_w^2\epsilon_{ZZ} + 2c_w s_w \epsilon_{Z\gamma} + s_w^2\epsilon_{\gamma\gamma} ,$$

$$★\ \epsilon^{CP}_{WW} = c_w^2\epsilon^{CP}_{ZZ} + 2c_w s_w \epsilon^{CP}_{Z\gamma} + s_w^2\epsilon^{CP}_{\gamma\gamma} ,$$

$$\kappa_{WW} - \kappa_{ZZ} = -\frac{2}{g}\left(\sqrt{2}\epsilon_{We^i_L} + 2c_w\epsilon_{Ze^i_L}\right) ,$$

$$★\ \epsilon_{We^i_L} = \frac{c_w}{\sqrt{2}}\left(\epsilon_{Z\nu^i_L} - \epsilon_{Ze^i_L}\right) ,$$

★ Accidentally true also in the linear EFT.

Parameter counting and symmetry assumptions

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2

Symmetries i

20 (general case) → **7** (max symm.)

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$h \to \gamma e^+e^-$

$h \to \gamma\mu^+\mu^-$

$h \to \gamma\gamma$

Charged $h \to e^+\mu^-\nu\nu$ $\kappa_{WW}, \epsilon_{WW}, \epsilon^{CP}_{WW}$,

mplex)

2

$\epsilon_{Z\nu_e}, \epsilon_{Z\nu_\mu}$

Possibility to test such hypotheses from Higgs data only.

Contact terms are extremely important for this goal.

Symmetries i

20 (general case) → **7** (max symm.)

Flavor unive

$\epsilon_{Ze_L} = \epsilon_Z$

$\epsilon_{Ze_R} = \epsilon_Z$

$\epsilon_{Z\nu_e} = \epsilon_{Z\nu_\mu}$,

$\epsilon_{We_L} = \epsilon_{W\mu_L}$.

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$\epsilon^{CP}_{ZZ} = \epsilon^{CP}_{Z\gamma} = \epsilon^{CP}_{\gamma\gamma} = \epsilon^{CP}_{WW} =$

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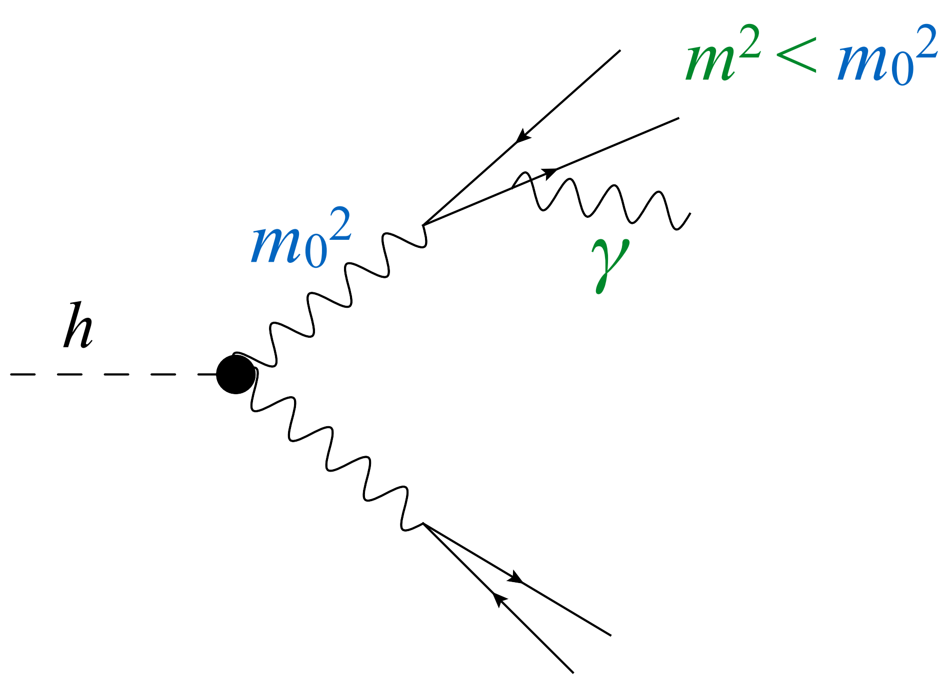
$$\star\ \epsilon_{We^i_L} = \frac{c_w}{\sqrt{2}}\left(\epsilon_{Z\nu^i_L} - \epsilon_{Ze^i_L}\right) ,$$

★ Accidentally true also in the linear EFT.

Radiative Corrections

[M. Bordone, A. Greljo, G. Isidori, D. M., A. Pattori, arXiv:1507.02555]

The most important radiative corrections are given by soft QED radiation effects since they distort the spectrum.

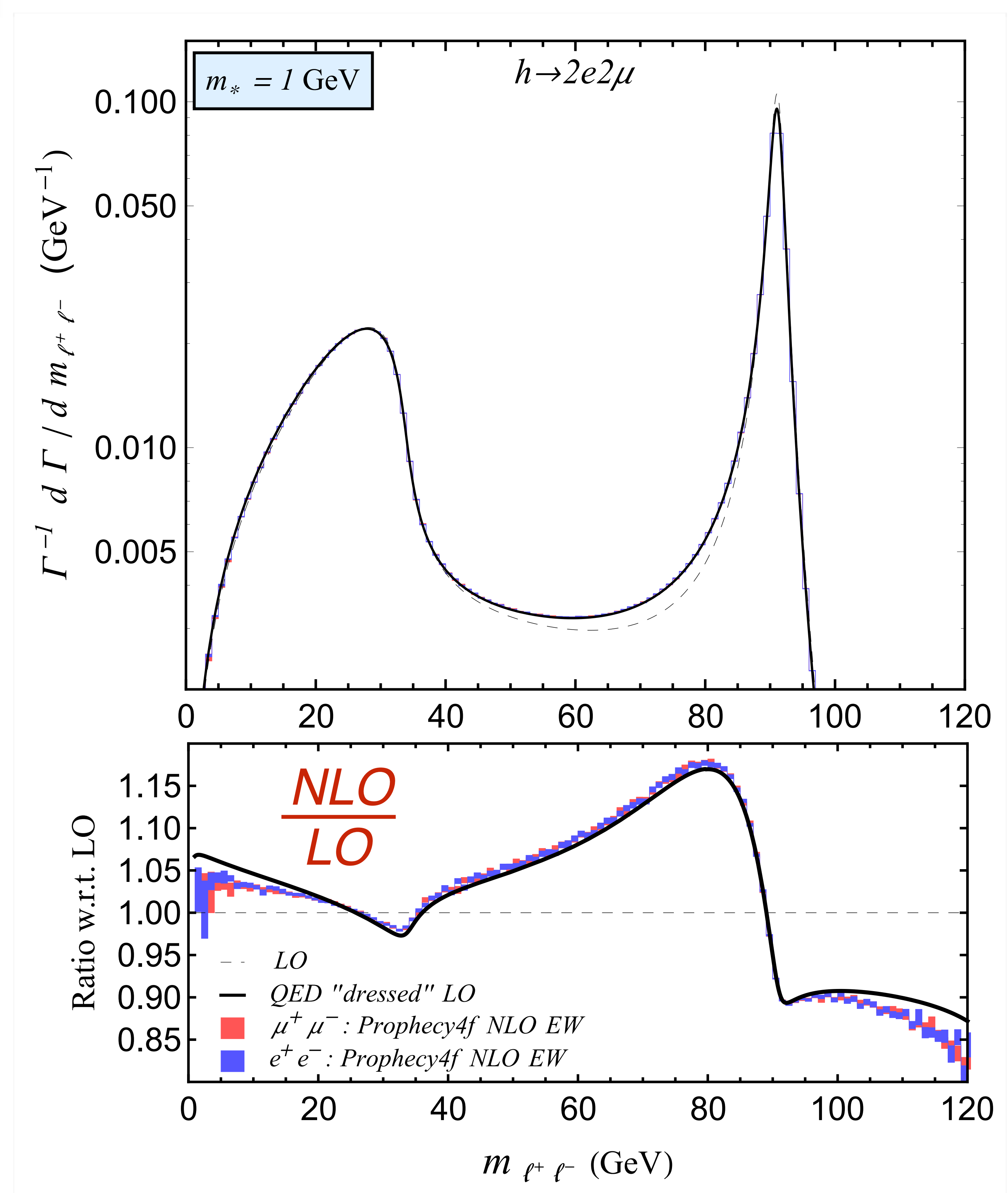


Effect described by simple and universal radiator functions.

~15% effect!

Other NLO corrections are small: ≲1%

Taking this effect into account is necessary to extract the PO from data.



Tools: *HiggsPO*

In collaboration with Admir Greljo and Gino Isidori

www.physik.uzh.ch/data/HiggsPO

A Universal FeynRules Output model for generating Higgs decays with MG5_aMC@NLO.

To be used to generate the on-shell Higgs decay amplitudes described before.

(use tree-level Feynman rules to generate the amplitude we need)

Warning:

NOT a EFT Lagrangian to be used beyond the tree-level, or for off-shell processes.

Manual, with description and examples at: http://www.physik.uzh.ch/data/HiggsPO/files/HiggsPO.pdf