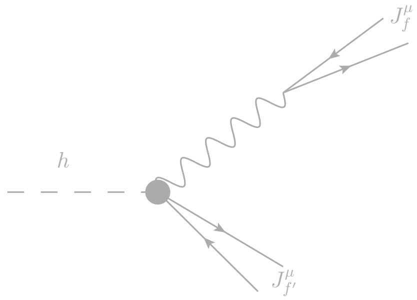
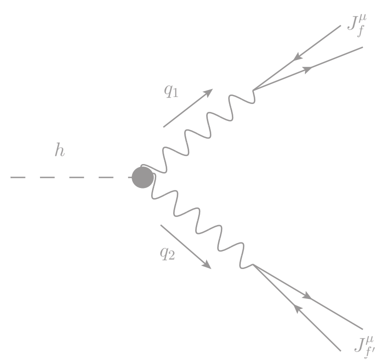
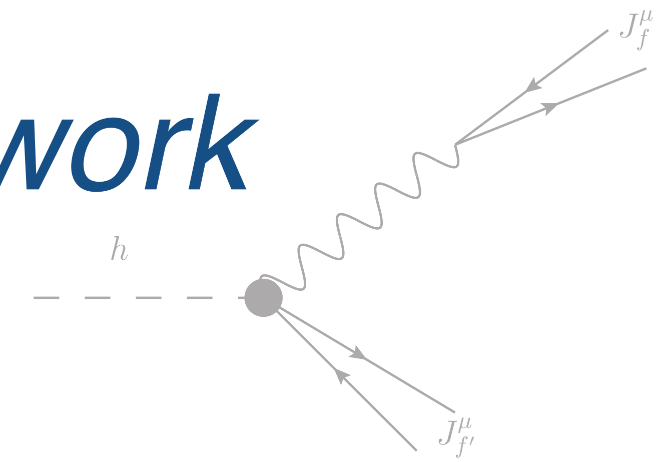


Higgs PO

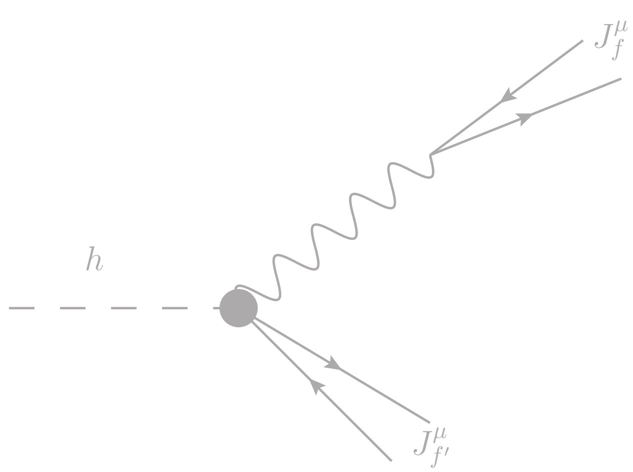
Production and decay beyond the kappa-framework

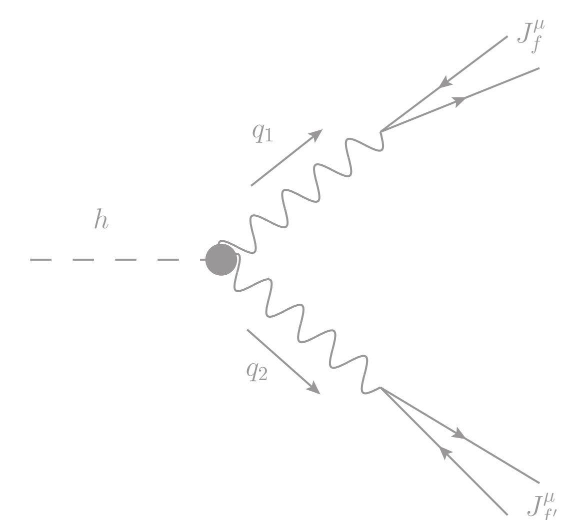




David Marzocca

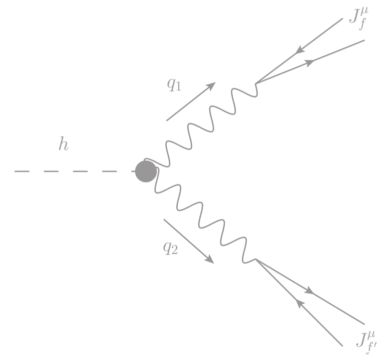
Universität Zürich[UZH]

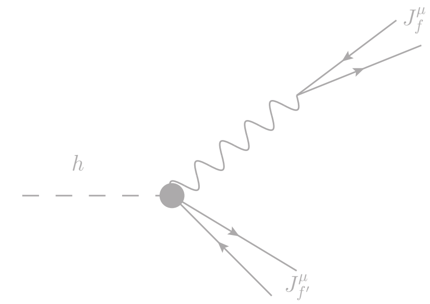




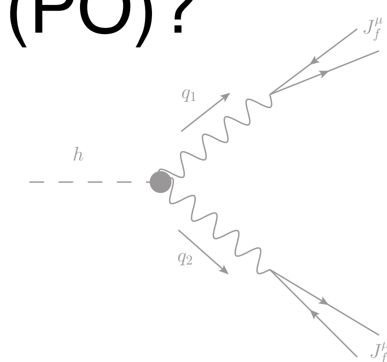
Particle Theory Seminar, UZH, 13/10/2015

Outline

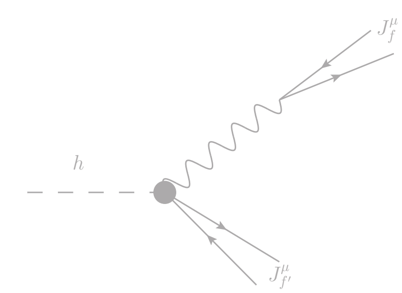




- Motivation and introduction. What are pseudo-observables (PO)?



- PO in Higgs Decay.
- PO in Electroweak Higgs Production.
- Linear EFT and Higgs PO.



Based on:

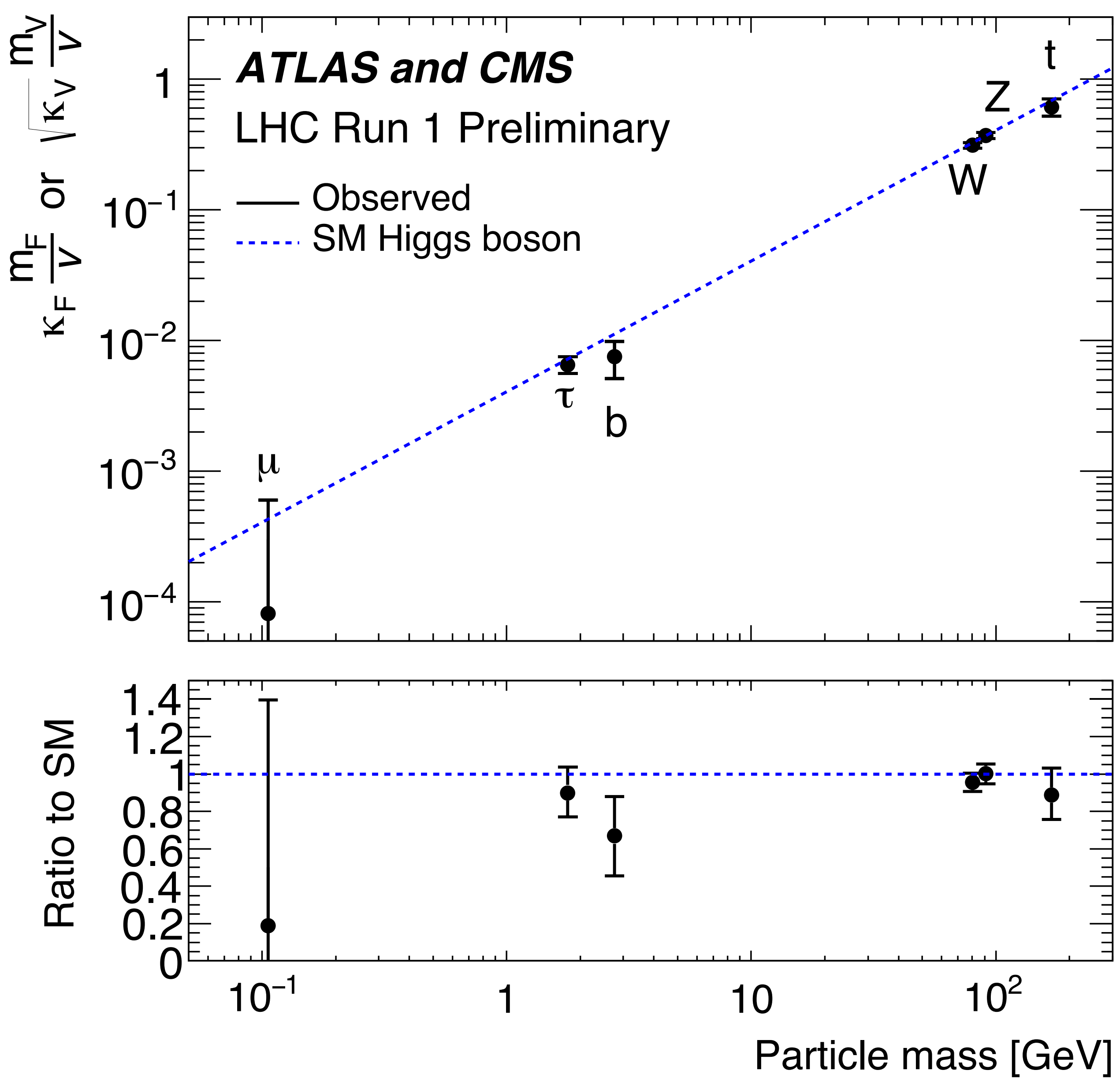
works with various subsets of
{M. Bordone, A. Falkowski, M.Gonzalez-Alonso, A. Greljo, G. Isidori, J. Lindert, D.M., A. Pattori}

Eur. Phys. J. C75 (2015) 3, 128 arXiv: 1412.6038
Eur. Phys. J. C75 (2015) 7, 341 arXiv: 1504.04018
Eur. Phys. J. C75 (2015) 8, 385 arXiv: 1507.02555
arXiv: 1508.00581
+ some work in progress

Introduction: LHC Run-1 in one slide

★ discovery of the Higgs and
good measurement of many of its couplings.

The **Standard Model** is complete.



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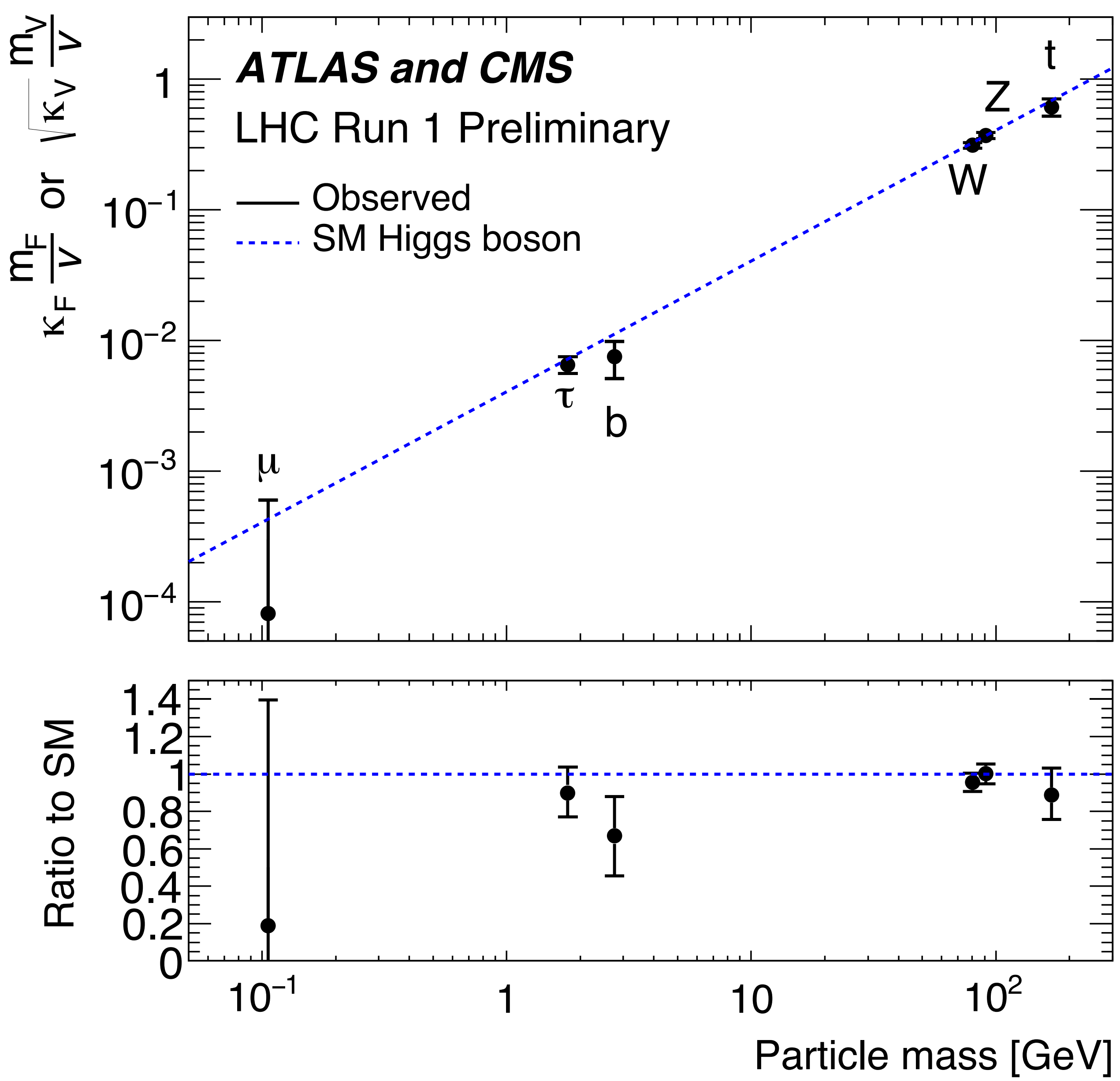


★ So far, no compelling evidence of new physics from direct searches:

Scale of New Physics is high

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

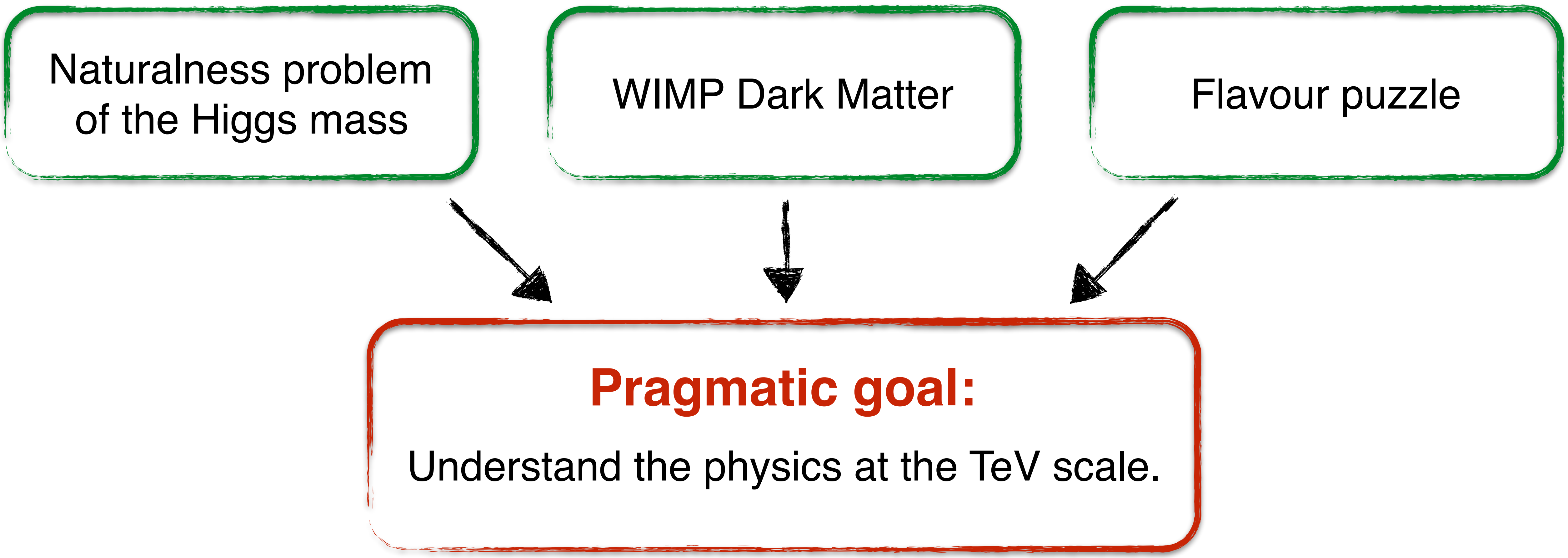
Questions we still have to find answers to:

Naturalness problem of the Higgs mass

WIMP Dark Matter

Flavour puzzle

Questions we still have to find answers to:



Questions we still have to find answers to:

Naturalness problem of the Higgs mass

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Pragmatic goal:

Understand the physics at the TeV scale.

How we are doing this

- **Direct searches** of new particles: LHC, DM, …
- **Precision** SM measurements: **Higgs**, **Electroweak**, Flavour, Neutrinos, …
- **Cosmology**: CMB, Large Scale Structures, BBN, …

We do not know what the New Physics will be like.

How to approach its search?

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How to approach its search?

Top-down approach Suitable for: **LHC direct searches**

Choose some well motivated explicit model and study its predictions.

Pro: very predictive
Cons: very model-dependent

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Work in a well-defined framework with the least possible number of assumptions, in order to cover as many new physics scenarios as possible.

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***Generality* × *Predictivity* ~ const.**

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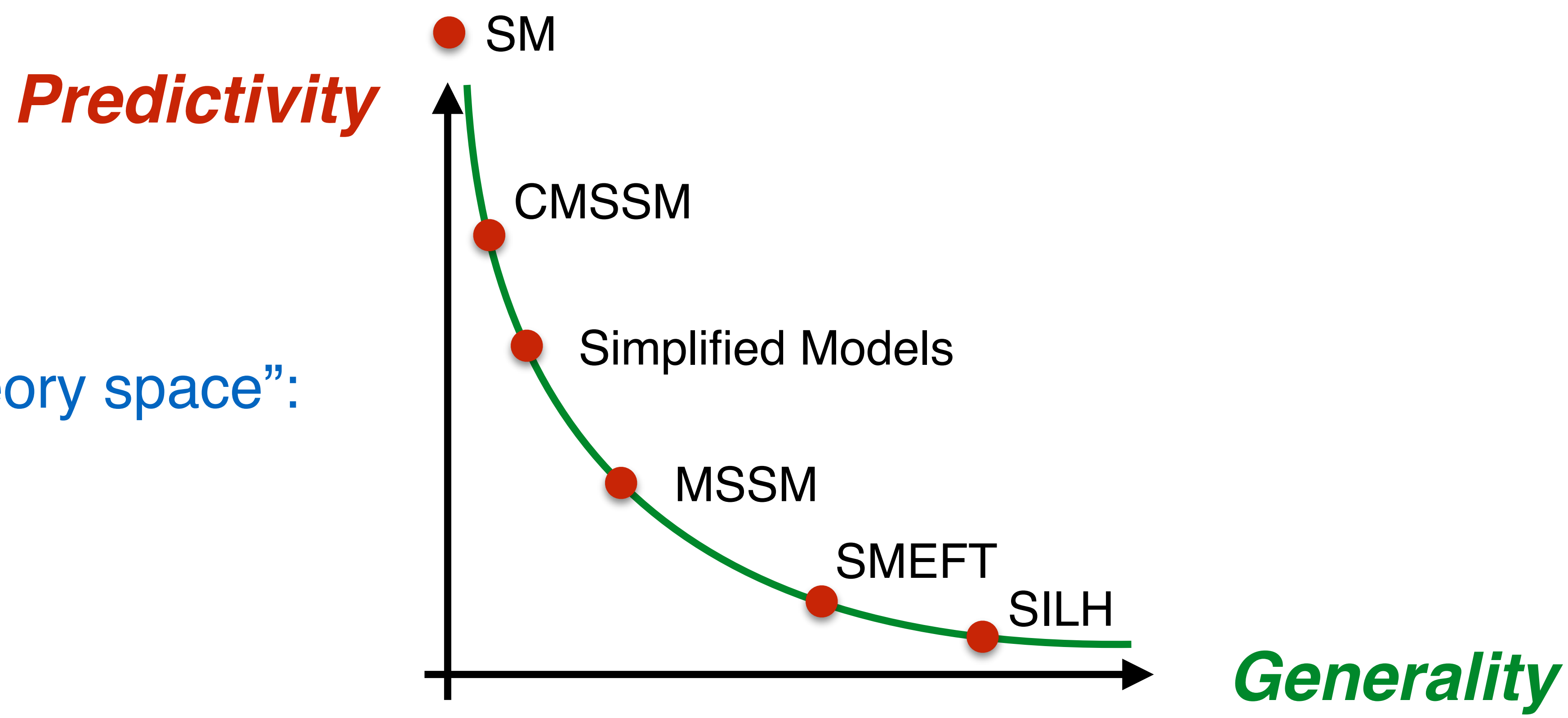
In “Theory space”:



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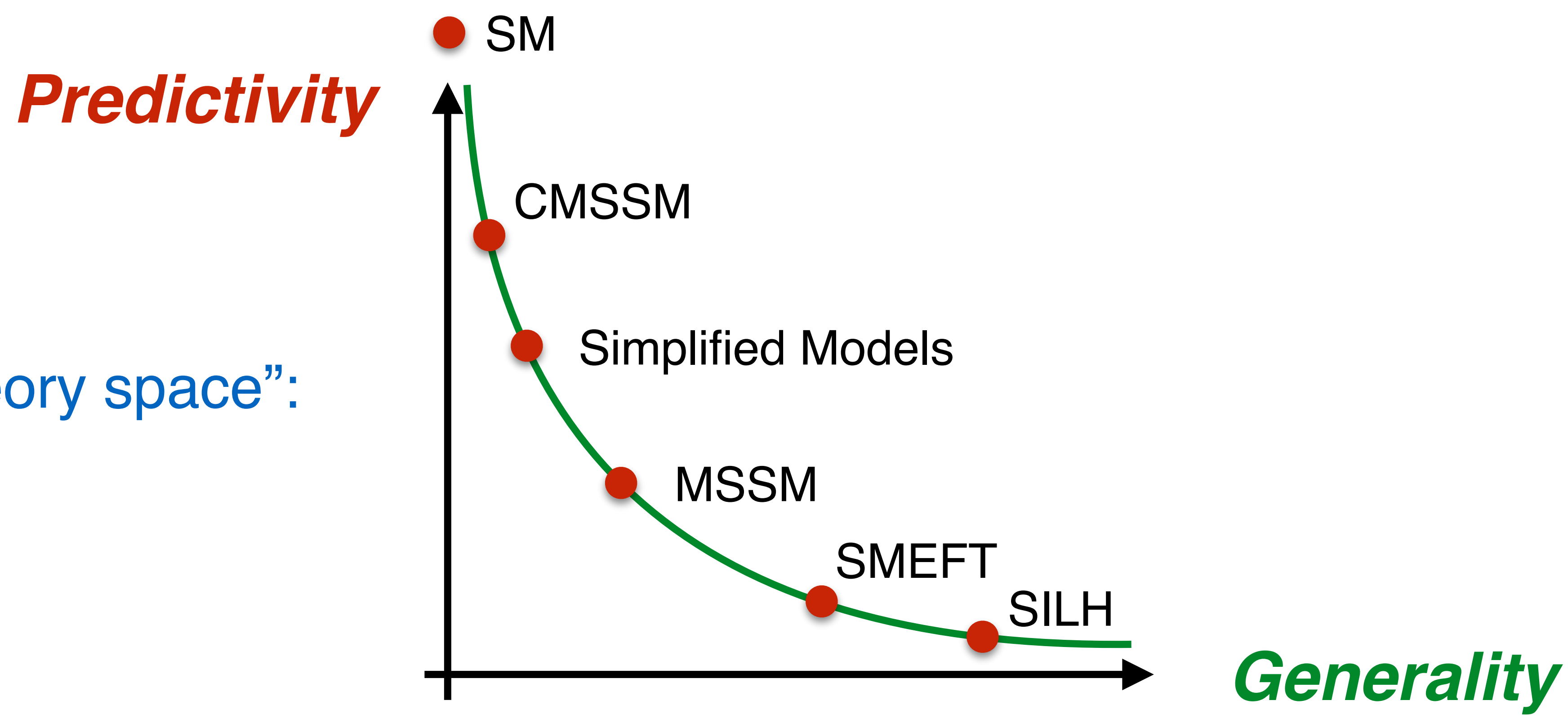


LHC - Higgs Legacy

How to collect all available information on a the Higgs, in the most general and theoretically unbiased way?

We want to be able to come back to LHC Higgs data in the future and still be able to reinterpret it in terms of any New Physics model which would have been discovered.

It will be extremely difficult to be able to repeat many experimental analysis.

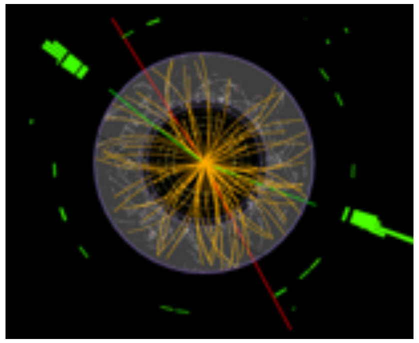
How should the experiments present their result

Generality

Predictivity

Generality

How should the experiments present their result



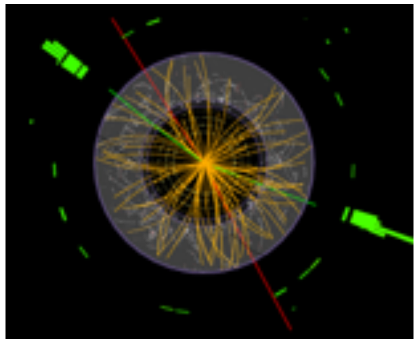
Physical observables

Fiducial cross sections,
Number of events in a given bin, etc …

Predictivity

Generality

How should the experiments present their result



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ALL the observables??
Difficult for theorists to control experimental effects.

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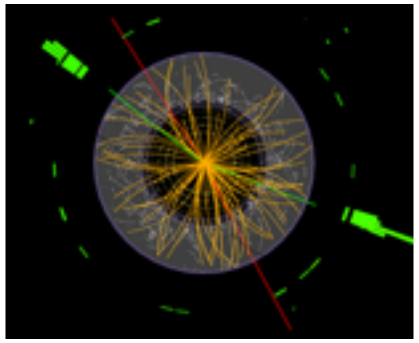

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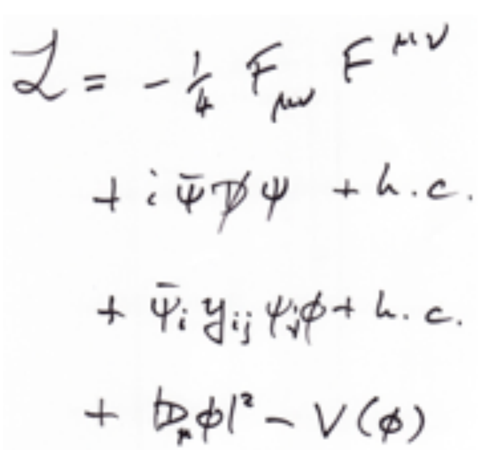

Lagrangian parameters

Couplings, running masses,
Wilson coefficients, etc …

Predictivity

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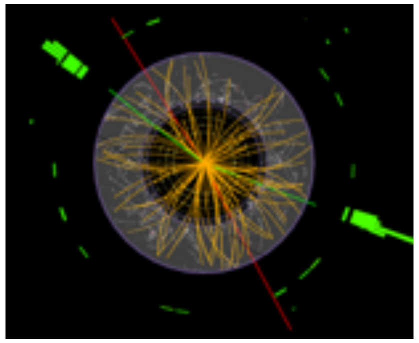

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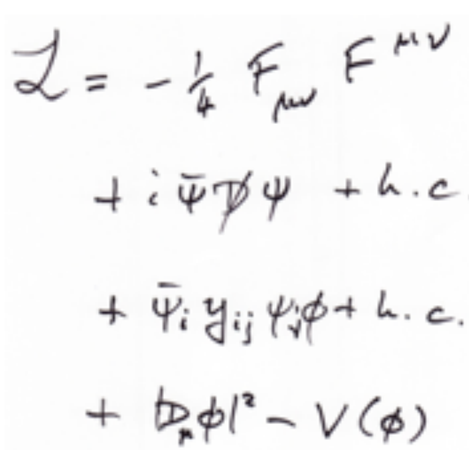

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Which model?
Which parameters?
Fit at LO, NLO..?

Predictivity

Generality

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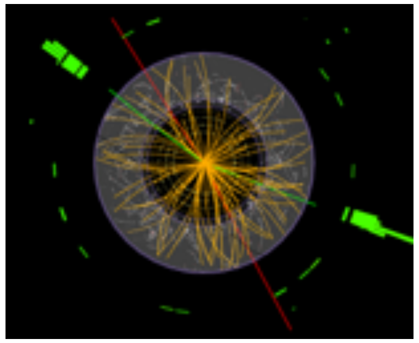

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ALL the observables??
Difficult for theorists to control experimental effects.

Pseudo-observables

Pole masses, decay widths,
kappas, form factors, etc …

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

Lagrangian parameters

Couplings, running masses,
Wilson coefficients, etc …

Which model?
Which parameters?
Fit at LO, NLO..?

Predictivity

Experimental data

Experiments

Unfolding of collider &
soft radiation effects

PO

idealized observables,
well defined (in QFT) quantities.

Theorists

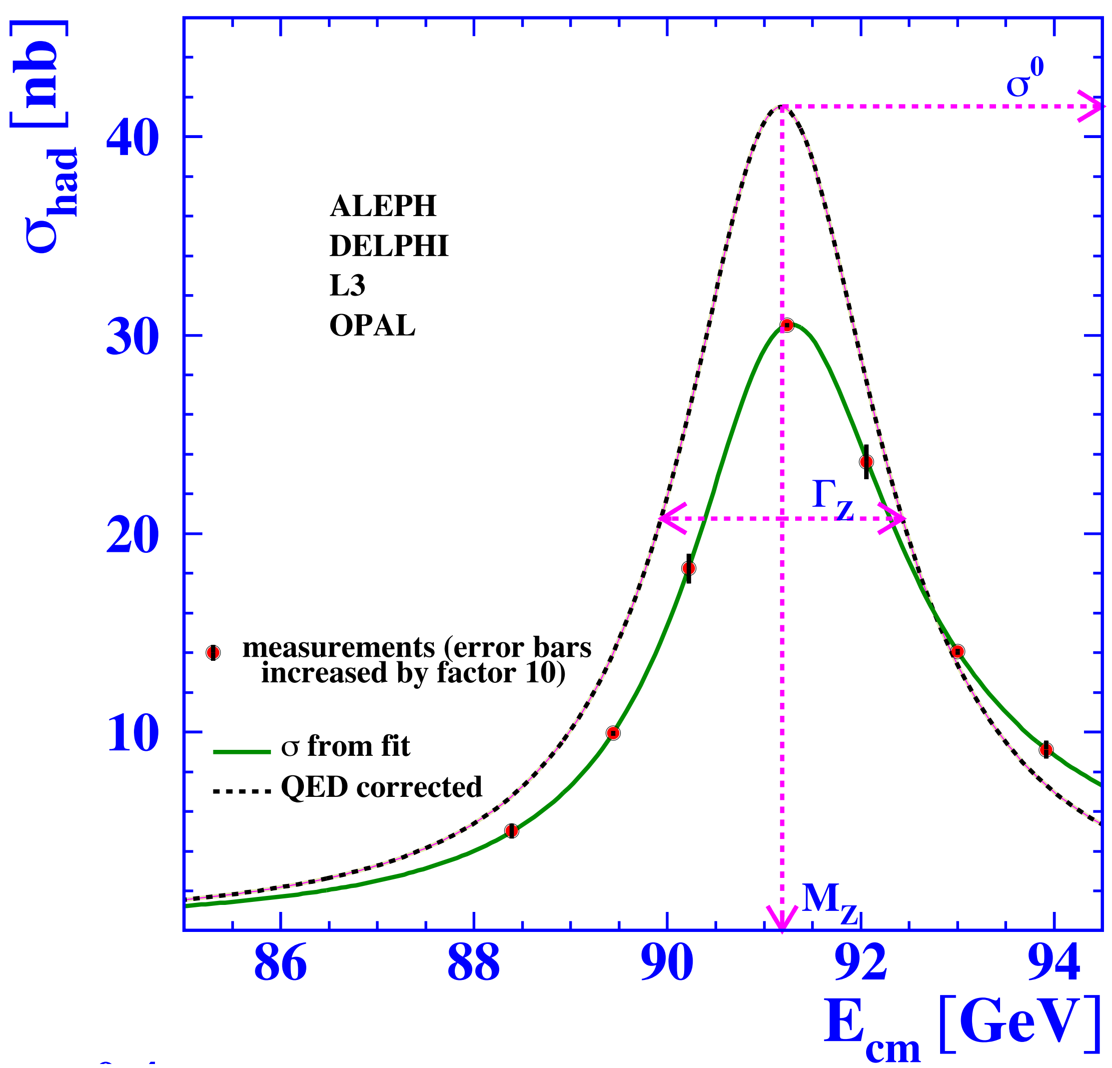
Matching to a given model
at given order in pert. theory

Constraints/measurements on theories

LEP-1 Strategy: on-shell Z decays

[hep-ex/0509008; Bardin, Grunewald, Passarino '99]

The goal was to parametrise on-shell Z decays as much model-independently as possible.



1) Unfold QED (and/or QCD) soft radiation effect

$$\sigma(s) = \int_{4m_f^2/s}^{1} dz\, H_{QED}^{tot}(z,s)\sigma_{ew}(zs).$$

2) Parametrize the shape with some PO defined at amplitude level:

$$m_Z,\ \Gamma_Z$$

Lineshape

$$\chi(s) = \frac{G_F m_Z^2}{8\pi\sqrt{2}} \frac{s}{s - m_Z^2 + is\Gamma_Z/m_Z}$$

3) Fit the PO from data

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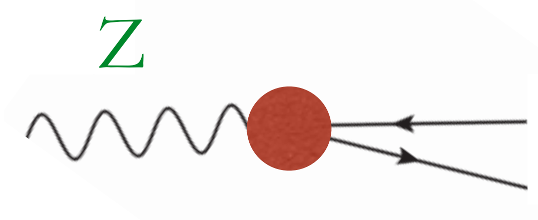
Parametrise the on-shell $Z\bar{f}f$ vertex as $\gamma_\mu \left(\mathcal{G}_V^f + \mathcal{G}_A^f \gamma_5\right)$



The PO are defined as

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

To be model-independent it is important to work with on-shell initial and final states.

Radiators: final state radiation

$$\Gamma_{\mathrm{f\bar{f}}} = N_c^{\mathrm{f}} \frac{G_{\mathrm{F}} m_{\mathrm{Z}}^3}{6\sqrt{2}\pi} \left(|\mathcal{G}_{\mathrm{Af}}|^2 R_{\mathrm{Af}} + |\mathcal{G}_{\mathrm{Vf}}|^2 R_{\mathrm{Vf}}\right) + \Delta_{\mathrm{ew/QCD}}$$

non-factorizable SM corrections, very small.

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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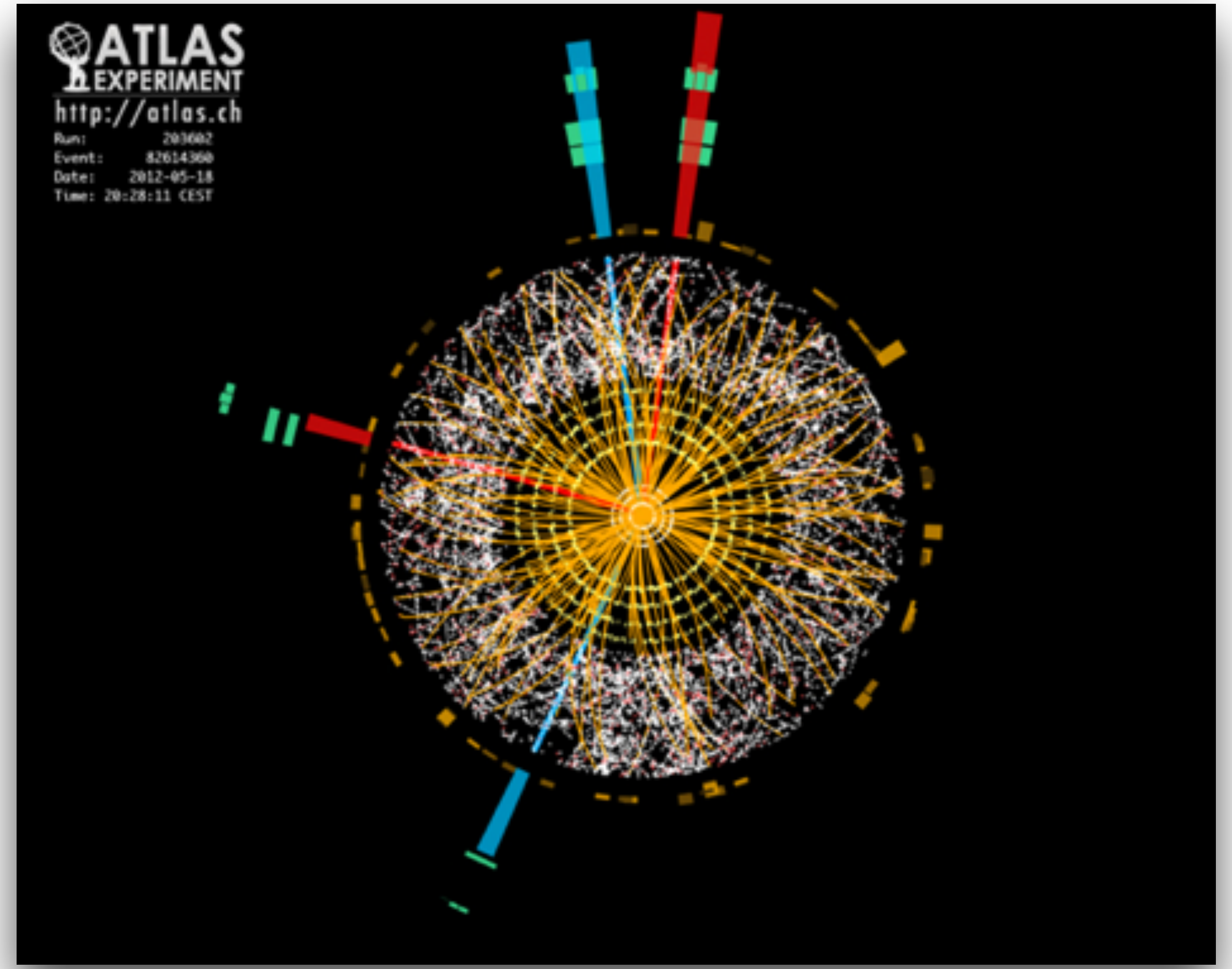
Need to extend the κ-framework retaining all its good properties:

Higgs pseudo-observables

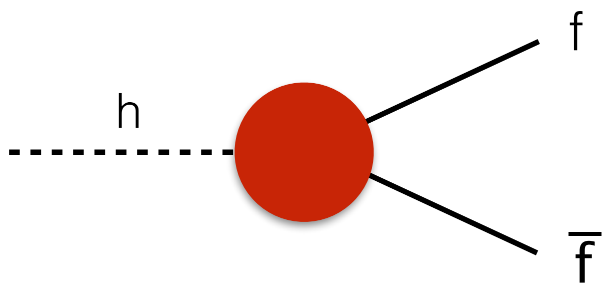
Pseudo observables

in

Higgs Decays



Higgs decays to two fermions



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

"Effective coupling" PO:

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

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

"Physical" PO:

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

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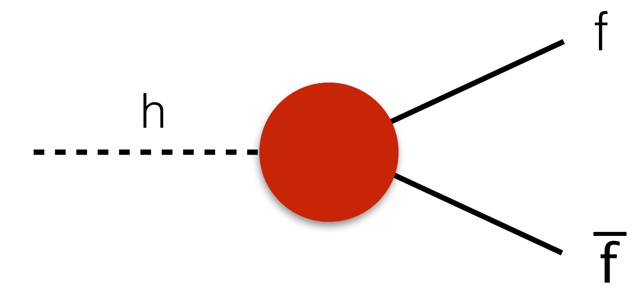

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$y_{\text{eff}}^{f,\text{SM}}$ from best SM prediction:

$$\Gamma(h \to f\bar{f})^{(\text{SM})}_{(\text{incl})} = N_c^f\frac{|y_{\text{eff}}^{f,\text{SM}}|^2}{16\pi}m_H$$

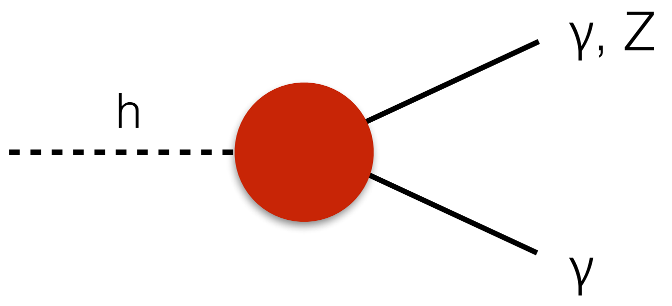
YR2

	$\bar{b}b$	$\bar{\tau}\tau$
$\text{Br}(h \to \bar{f}f)$	5.77×10^{-1}	6.32×10^{-2}
$\|y_{\text{eff}}^{f,\text{SM}}\|$	1.77×10^{-2}	1.02×10^{-2}

	$\bar{c}c$	$\bar{\mu}\mu$
$\text{Br}(h \to \bar{f}f)$	2.91×10^{-2}	2.19×10^{-4}
$\|y_{\text{eff}}^{f,\text{SM}}\|$	3.98×10^{-3}	5.99×10^{-4}

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR

Higgs decays to γγ and Zγ (on-shell)



"Effective coupling" PO:

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

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

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

"Physical" PO:

$$\Gamma(h\to\gamma\gamma) = \left[\kappa_{\gamma\gamma}^2 + (\lambda_{\gamma\gamma}^{\rm CP})^2\right]\Gamma(h\to\gamma\gamma)^{\rm (SM)}$$

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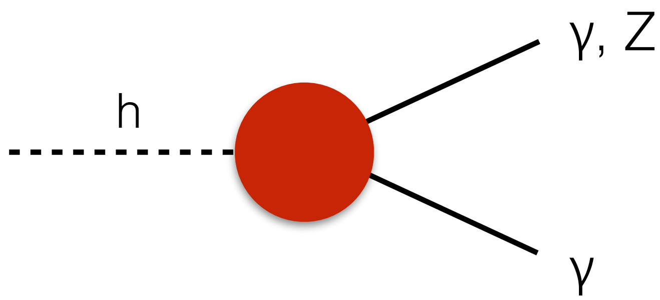
Higgs decays to γγ and Zγ (on-shell)



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

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$$\Gamma(h\to Z\gamma) = \left[\kappa^2_{Z\gamma} + (\lambda^{\rm CP}_{Z\gamma})^2\right]\Gamma(h\to Z\gamma)^{\rm (SM)}$$

$\epsilon^{\rm SM,eff}_X$ from best SM prediction:

$$\Gamma(h\to\gamma\gamma)^{\rm (SM)} = \frac{|\epsilon^{\rm SM,eff}_{\gamma\gamma}|^2}{16\pi}\frac{m_H^3}{v_F^2}\,,$$

$$\Gamma(h\to Z\gamma)^{\rm (SM)} = \frac{|\epsilon^{\rm SM,eff}_{Z\gamma}|^2}{8\pi}\frac{m_H^3}{v^2}\left(1-\frac{m_Z^2}{m_H^2}\right)^3$$

YR2 →

VV	$\gamma\gamma$	$Z\gamma$
$\mathrm{Br}(h\to VV)$	2.28×10^{-3}	1.54×10^{-3}
$\epsilon^{\rm SM,eff}_{VV}$	3.8×10^{-3}	6.9×10^{-3}

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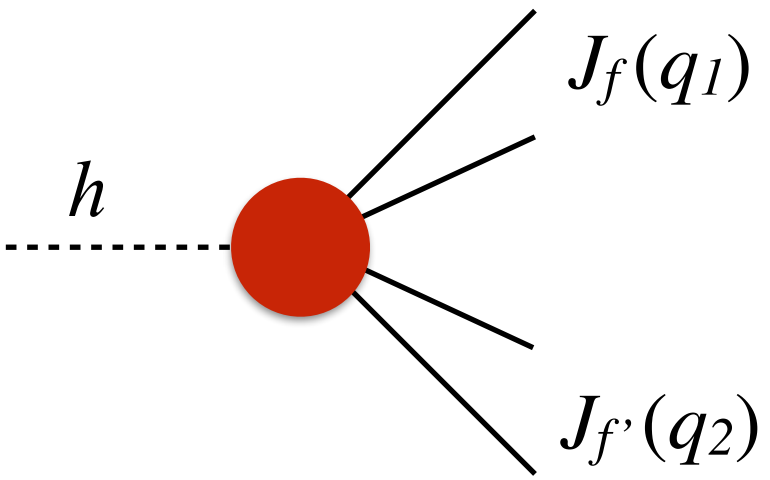
Higgs to 4-fermion decays

Four-body decays
h → 4f



The kinematics is much richer: kinematical distributions.

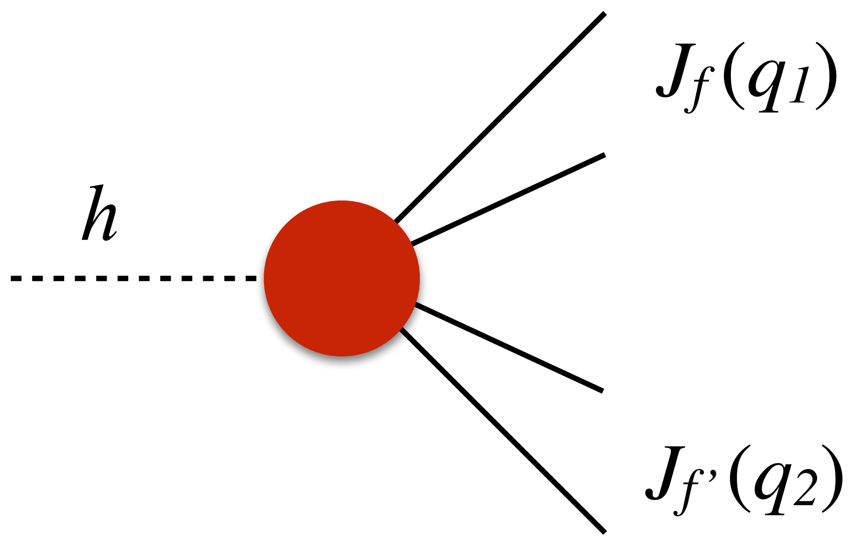
Assumption: Neglect helicity-violating interactions, naturally suppressed by m_f also in BSM.

e.g.: $h \to e_R e_L \mu_L \mu_R \quad \propto y_e y_\mu$

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

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

Higgs to 4-fermion decays



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

Only 3 tensor structures allowed by Lorentz symmetry:

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

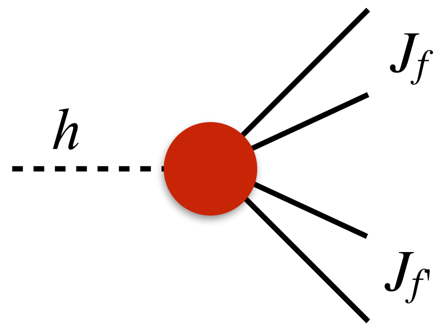
$$\mathcal{A} = i\frac{2m_Z^2}{v_F}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times$$
$$\left[F_1^{e\mu}(q_1^2,q_2^2)g^{\alpha\beta} + F_3^{e\mu}(q_1^2,q_2^2)\frac{q_1\cdot q_2\ g^{\alpha\beta} - {q_2}^\alpha {q_1}^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2,q_2^2)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

Longitudinal *Transverse* *CP-odd*

General approach: measure the double differential distribution in (q_1^2, q_2^2)

Higgs to 4-fermion decays

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



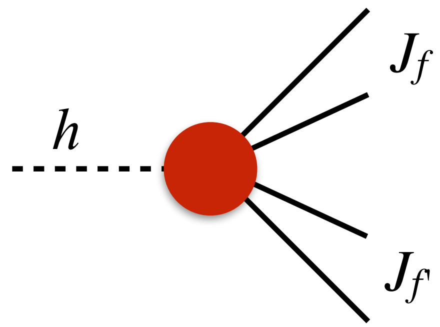
includes

Long-distance (non-local) modes (poles): propagation of EW gauge bosons.

Short-distance modes: contact terms, x and/or $y \to 0$

Higgs to 4-fermion decays

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

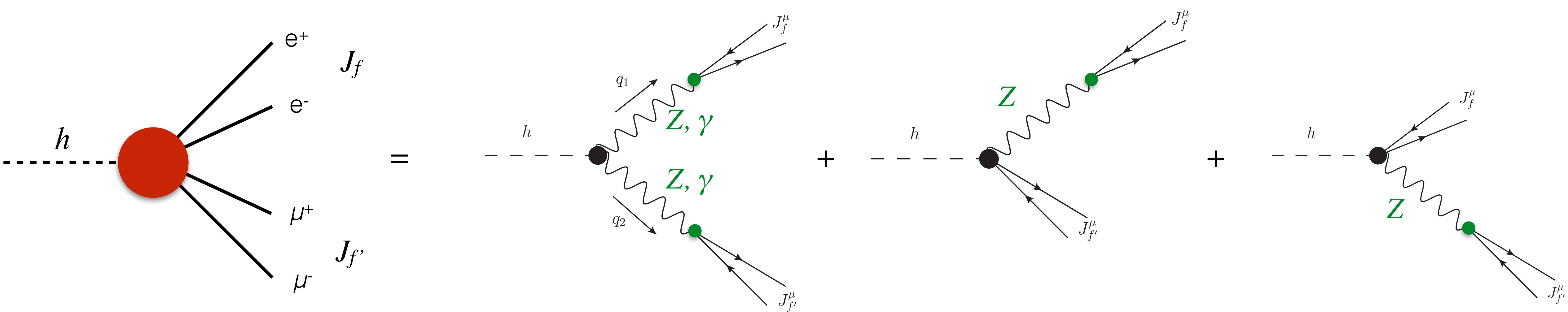


includes

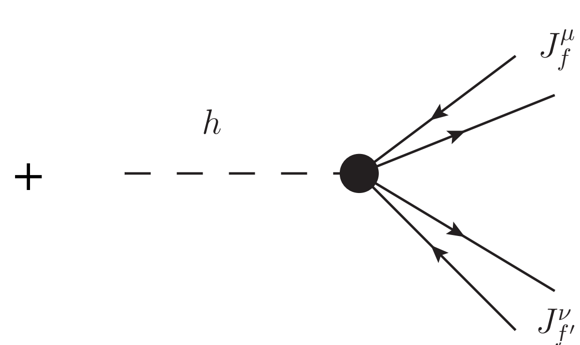
Long-distance (non-local) modes (poles): propagation of EW gauge bosons.

Short-distance modes: contact terms, x and/or $y \to 0$

We expand around the physical poles:



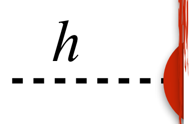
contact terms



Higgs to 4-fermion decays

$\langle 0|\mathcal{T}\{J_f^\mu($

(poles):



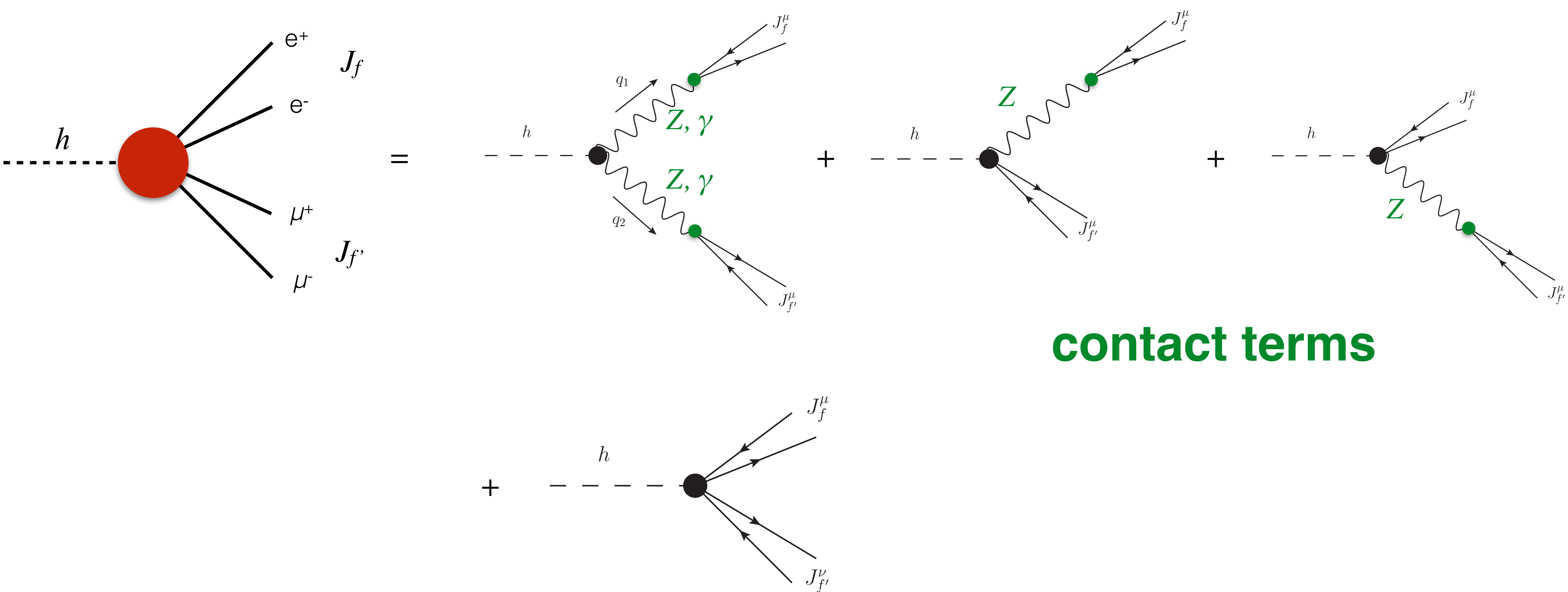
Assumption:

(To troncate the expansion)

No new light state can mediate this amplitude.

New Physics scale > Higgs mass scale

We expand around the physical poles:



Higgs to 4-fermion decays

$\langle 0|\mathcal{T}\{J_f^{\mu}($ … (poles):

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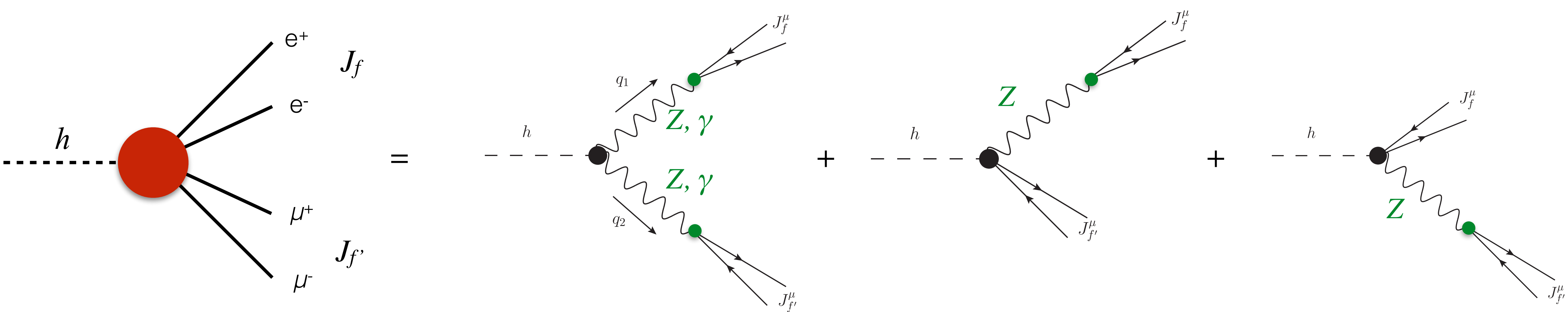
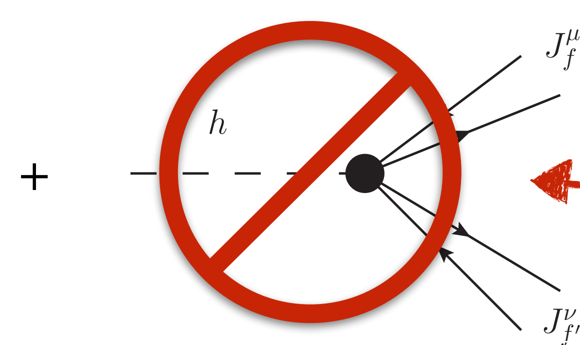


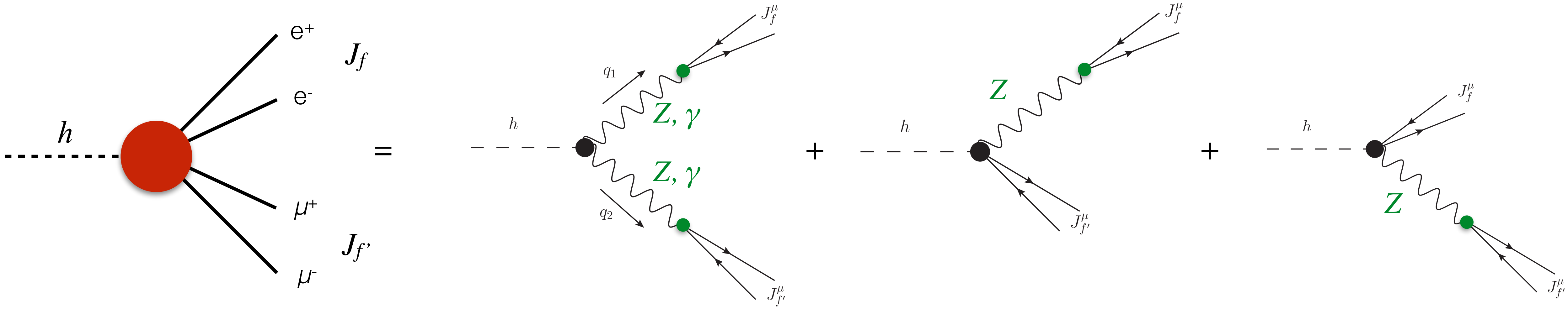
contact terms



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

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

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



$$e = e_L, e_R, \qquad \mu = \mu_L, \mu_R$$

$$\mathcal{A} = i\frac{2m_Z^2}{v_F}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times$$
$$\left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)} + \Delta_1^{\rm SM}(q_1^2, q_2^2)\right) g^{\alpha\beta} +\right.$$

In the SM $\kappa_X \to 1, \ \epsilon_X \to 0$

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

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

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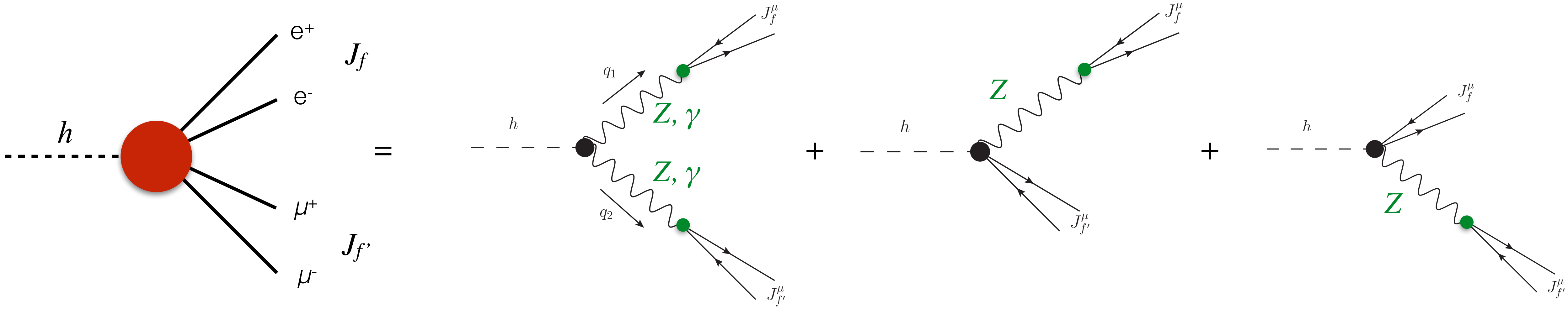

$e = e_L, e_R, \qquad \mu = \mu_L, \mu_R$

$$
\begin{aligned}
\mathcal{A} =& i\frac{2m_Z^2}{v_F}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times \\
&\left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)} + \Delta_1^{\rm SM}(q_1^2,q_2^2)\right) g^{\alpha\beta} + \right.\\
&+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\rm SM\text{-}1L}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\rm SM\text{-}1L}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} + \Delta_3^{\rm SM}(q_1^2,q_2^2)\right)\times \\
&\times \frac{q_1\cdot q_2\ g^{\alpha\beta} - {q_2}^\alpha {q_1}^\beta}{m_Z^2} +
\end{aligned}
$$

In the SM $\kappa_X \to 1,\ \epsilon_X \to 0$

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

$\epsilon_{\gamma\gamma}^{\rm SM\text{-}1L} \simeq 3.8\times 10^{-3}$,
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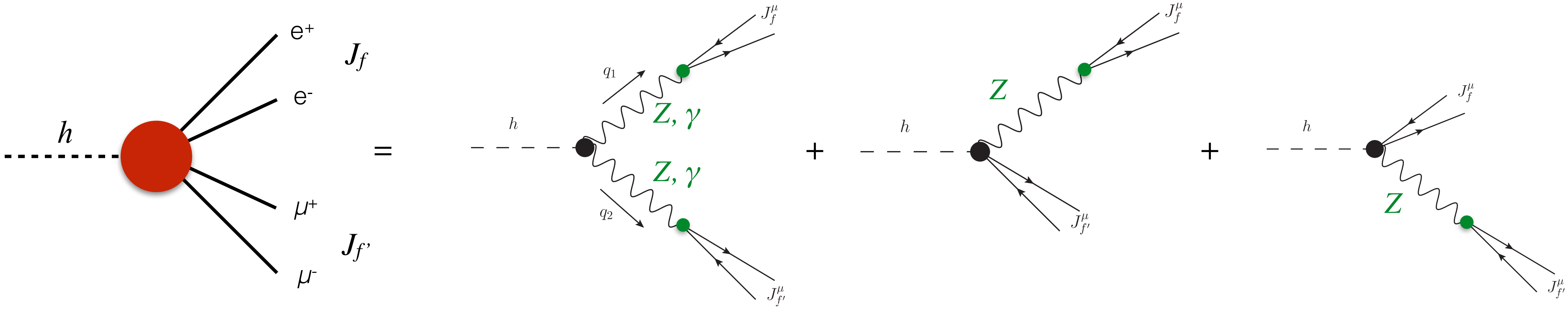

$$e = e_L, e_R, \qquad \mu = \mu_L, \mu_R$$

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

$$\left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)} + \Delta_1^{\rm SM}(q_1^2,q_2^2)\right) g^{\alpha\beta} +\right.$$

$$+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\rm SM\text{-}1L}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\rm SM\text{-}1L}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} + \Delta_3^{\rm SM}(q_1^2,q_2^2)\right)\times$$

$$\times\frac{q_1\cdot q_2\; g^{\alpha\beta} - {q_2}^\alpha {q_1}^\beta}{m_Z^2} +$$

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

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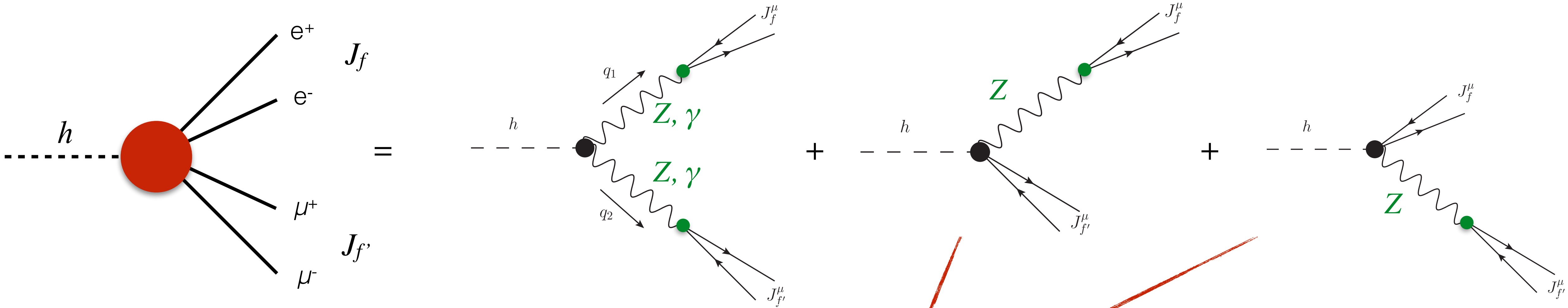

$e = e_L, e_R, \qquad \mu = \mu_L, \mu_R$

contact terms
only source of
flavor dependence

$$
\begin{aligned}
\mathcal{A} = & i \frac{2m_Z^2}{v_F} (\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu) \times \\
& \left[\left(\kappa_{ZZ} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2} \frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2} \frac{g_Z^e}{P_Z(q_1^2)} + \Delta_1^{\mathrm{SM}}(q_1^2, q_2^2) \right) g^{\alpha\beta} + \right. \\
& + \left(\epsilon_{ZZ} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2)} + \kappa_{Z\gamma} \epsilon_{Z\gamma}^{\mathrm{SM\text{-}1L}} \left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \kappa_{\gamma\gamma} \epsilon_{\gamma\gamma}^{\mathrm{SM\text{-}1L}} \frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} + \Delta_3^{\mathrm{SM}}(q_1^2, q_2^2) \right) \times \\
& \times \frac{q_1 \cdot q_2 \; g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} + \\
& \left. + \left(\epsilon_{ZZ}^{\mathrm{CP}} \frac{g_Z^e g_Z^\mu}{P_Z(q_1^2) P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\mathrm{CP}} \left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)} \right) + \epsilon_{\gamma\gamma}^{\mathrm{CP}} \frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} \right) \frac{\varepsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \right]
\end{aligned}
$$

In the SM $\kappa_X \to 1, \;\; \epsilon_X \to 0$

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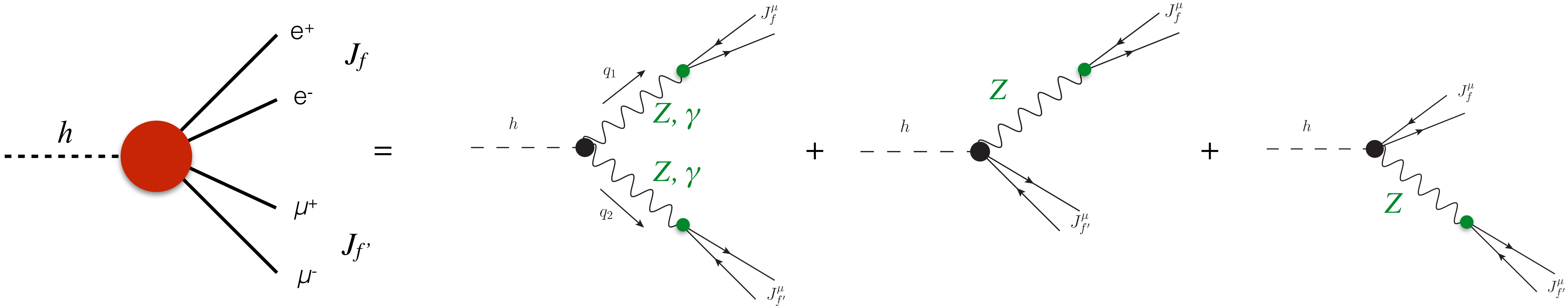
The Higgs PO are defined from the residues on the physical poles.



$e = e_L, e_R, \qquad \mu = \mu_L, \mu_R$

Z-pole PO

As measured at LEP-I

non-local NLO SM contribution

(very small)

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

$$\left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)} + \Delta_1^{\rm SM}(q_1^2, q_2^2)\right) g^{\alpha\beta} + \right.$$

$$+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\rm SM\text{-}1L}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\rm SM\text{-}1L}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2} + \Delta_3^{\rm SM}(q_1^2, q_2^2)\right)\times$$

$$\times\frac{q_1\cdot q_2\; g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} +$$

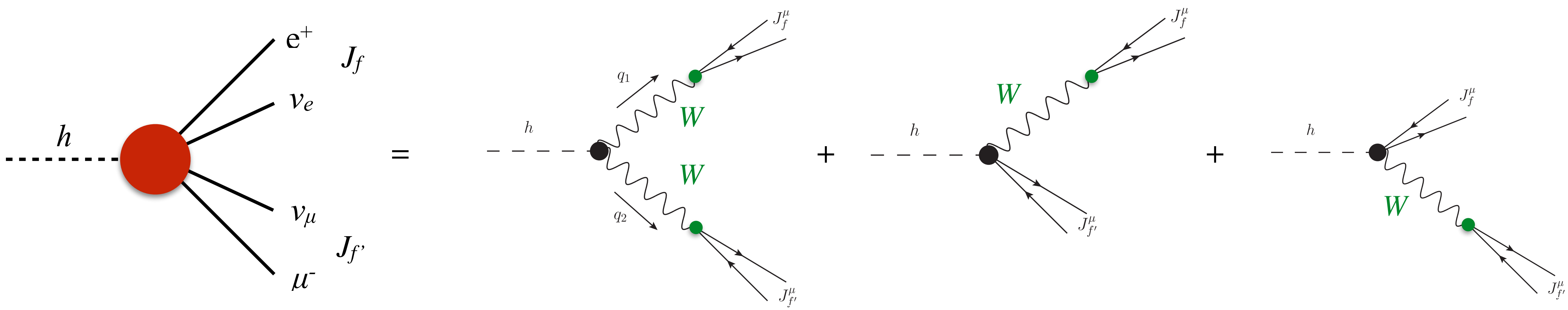
$$\left. +\left(\epsilon_{ZZ}^{\rm CP}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\rm CP}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{\rm CP}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

In the SM $\kappa_X \to 1, \;\; \epsilon_X \to 0$

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

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

Charged current decays



The same approach can be extended to charged current decays

Only c.c: $h \to \bar{\nu}_e e \bar{\mu} \nu_\mu$

Interference of c.c. and n.c.: $h \to e^+ e^- \nu\bar{\nu}$ $\quad h \to \mu^+ \mu^- \nu\bar{\nu}$

$$\mathcal{A} = i\frac{2m_W^2}{v_F}(\bar{e}_L\gamma_\alpha\nu_e)(\bar{\nu}_\mu\gamma_\beta\mu_L)\times$$

$$\left[\left(\kappa_{WW}\frac{(g_W^e)^* g_W^\mu}{P_W(q_1^2)P_W(q_2^2)} + \frac{(\epsilon_{We_L})^*}{m_W^2}\frac{g_W^\mu}{P_W(q_2^2)} + \frac{\epsilon_{W\mu_L}}{m_Z^2}\frac{(g_W^e)^*}{P_W(q_1^2)}\right) g^{\alpha\beta} + \right.$$

$$\left. + \epsilon_{WW}\frac{(g_W^e)^* g_W^\mu}{P_W(q_1^2)P_W(q_2^2)} \times \frac{q_1 \cdot q_2\ g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_W^2} + \epsilon_{WW}^{\mathrm{CP}}\frac{(g_W^e)^* g_W^\mu}{P_W(q_1^2)P_W(q_2^2)}\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_W^2}\right]$$

Parameter counting and symmetry assumptions

Neutral current

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

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

11

Charged current

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

$\kappa_{WW}, \epsilon_{WW}, \epsilon_{WW}^{CP}$,
$\epsilon_{We}, \epsilon_{W\mu}$, (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

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

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

11

Charged current

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

$\kappa_{WW}, \epsilon_{WW}, \epsilon_{WW}^{CP}$,
$\epsilon_{We}, \epsilon_{W\mu}$, (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.

Flavor universality

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

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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Charged current

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

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

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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.

Flavor unive

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

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

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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Charged current

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

$\kappa_{WW}, \epsilon_{WW}, \epsilon_{WW}^{CP}$, $\epsilon_{We}, \epsilon_{W\mu}$, (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.

Flavor unive

$\epsilon_{Ze_L} = \epsilon_{Z}$

$\epsilon_{Ze_R} = \epsilon_{Z}$

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

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

CP Invaria

$\epsilon_{ZZ}^{CP} = \epsilon_{Z\gamma}^{CP} = \epsilon_{\gamma\gamma}^{CP} = \epsilon_{WW}^{CP} =$

Custodial symmetry

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

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

$$\kappa_{WW} - \kappa_{ZZ} = -\frac{2}{g}\left(\sqrt{2}\epsilon_{We_L^i} + 2c_w\epsilon_{Ze_L^i}\right),$$

★ $\epsilon_{We_L^i} = \frac{c_w}{\sqrt{2}}(\epsilon_{Z\nu_L^i} - \epsilon_{Ze_L^i})$,

★ Accidentally true also in the linear EFT.

Parameter counting and symmetry assumptions

Neutral current

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

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

11

Charged current

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

$\kappa_{WW}, \epsilon_{WW}, \epsilon_{WW}^{CP}$,
$\epsilon_{We}, \epsilon_{W\mu}$, (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 i

20 (general case) → **7** (max symm.)

Flavor unive

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

CP Invaria

$\epsilon_{ZZ}^{CP} = \epsilon_{Z\gamma}^{CP} = \epsilon_{\gamma\gamma}^{CP} = \epsilon_{WW}^{CP} =$

Custodial symmetry

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

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

$$\kappa_{WW} - \kappa_{ZZ} = -\frac{2}{g}\left(\sqrt{2}\epsilon_{We_L^i} + 2c_w\epsilon_{Ze_L^i}\right),$$

★ $\epsilon_{We_L^i} = \frac{c_w}{\sqrt{2}}(\epsilon_{Z\nu_L^i} - \epsilon_{Ze_L^i})$,

★ Accidentally true also in the linear EFT.

Parameter counting and symmetry assumptions

Neutral current

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

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

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

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

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

$h \to \gamma\gamma$

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...

$\epsilon_{Ze_L} = \epsilon_Z$...

$\epsilon_{Ze_R} = \epsilon_Z$...

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

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

CP Invaria...

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

Custodial symmetry

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

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

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

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

★ Accidentally true also in the linear EFT.

Prospects in $h \to 4\ell$

[Work in progress]

At HL-LHC (2037) we will have ~ 8000 events in $h \to 4\ell$

ATLAS Selected signal event rates

	ttH	ZH	WH	VBF	ggH
$3000fb^{-1}$	35	5.7	67	97	3800

[From Aleandro Nisati's talk at LHCP 2015]

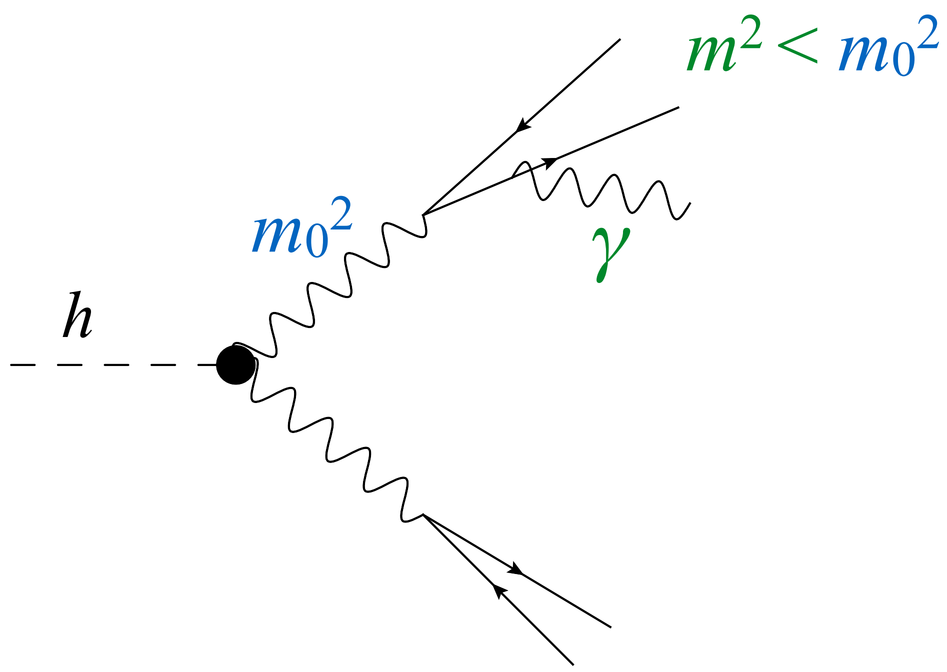
few % precision in $h \to \gamma\gamma$
~ 10% precision in $h \to Z\gamma$

→ They already fix 4 PO to be really small.

A precise 11 parameter global fit is very reasonable.

Radiative Corrections

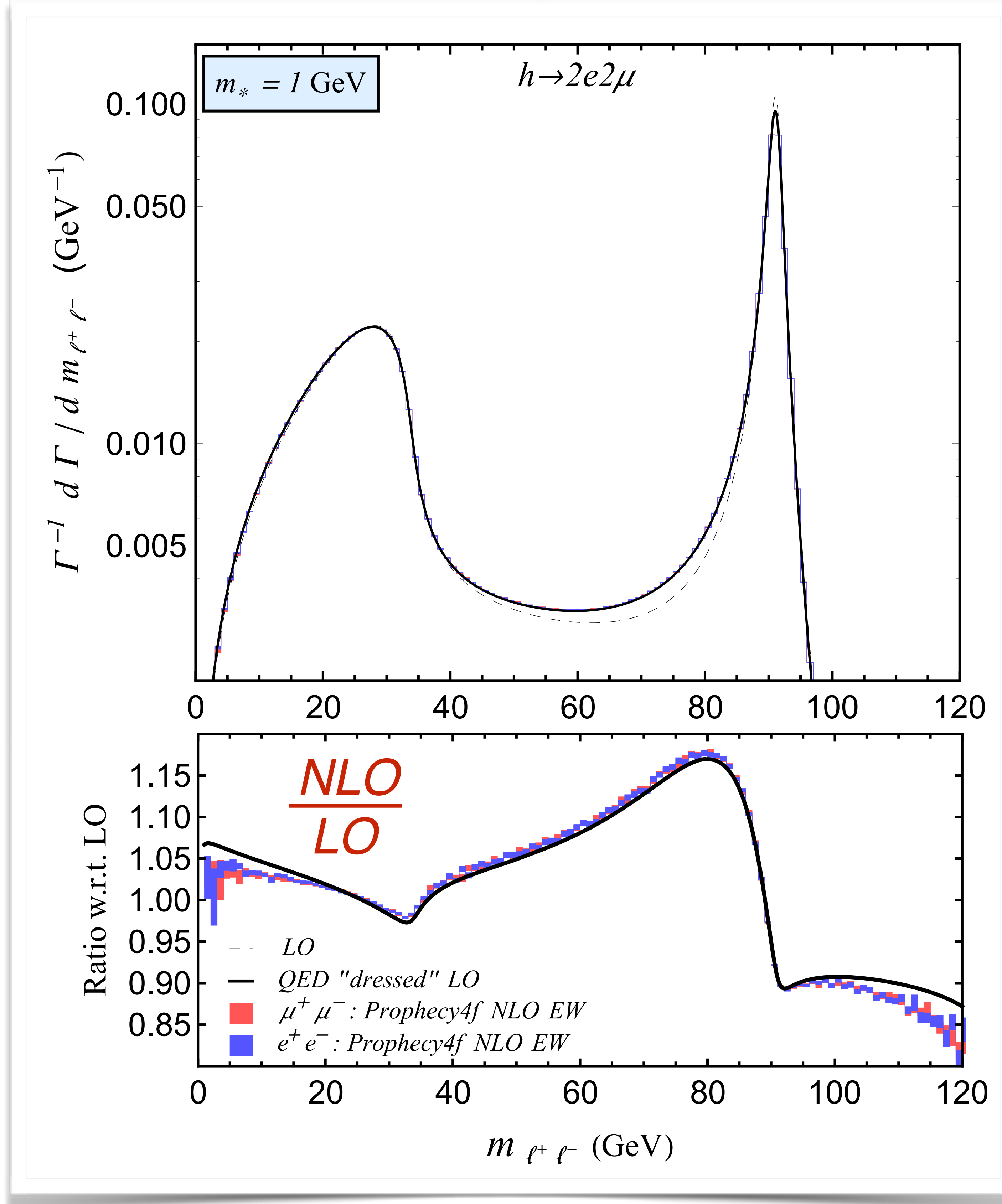
The most important radiative corrections are given by soft QED radiation effects since they distort the spectrum.



Effect described by simple and universal radiator functions.

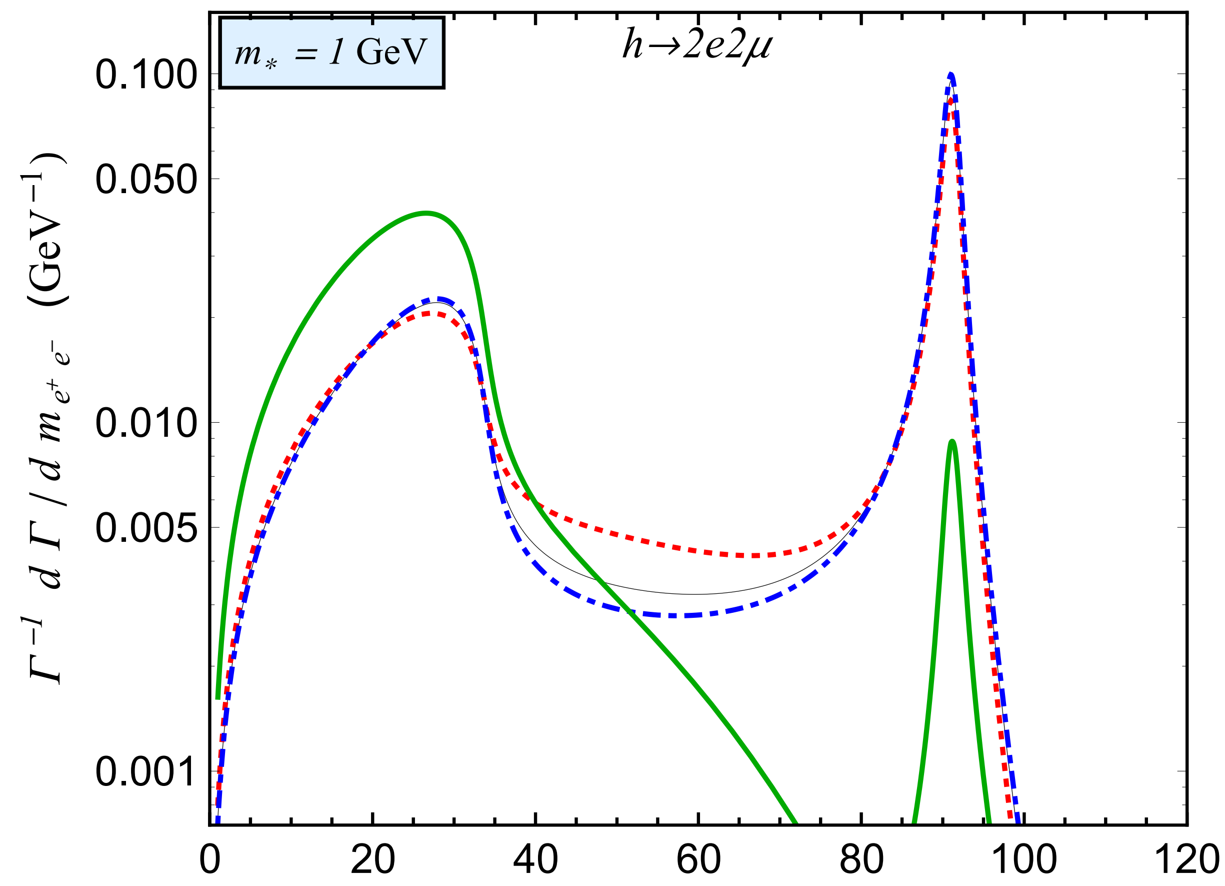
~15% effect!

Other NLO corrections are small: ≲1%

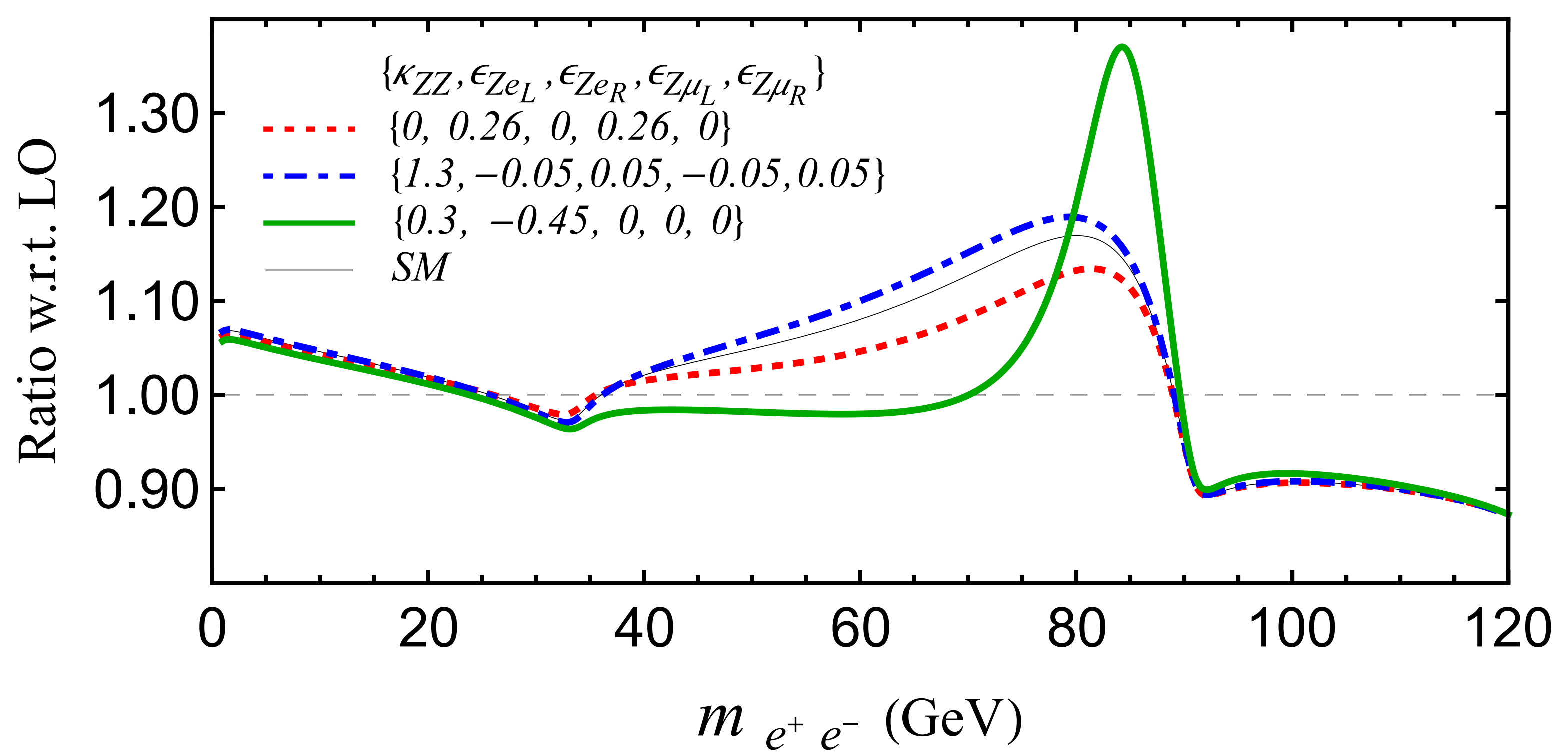


Radiative Corrections

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



All these benchmark points give a SM-like total rate.



Showering algorithms (e.g. PHOTOS or PYTHIA) correctly describe these corrections.

Tools: *HiggsPO*

In collaboration with Admir Greljo and Gino Isidori

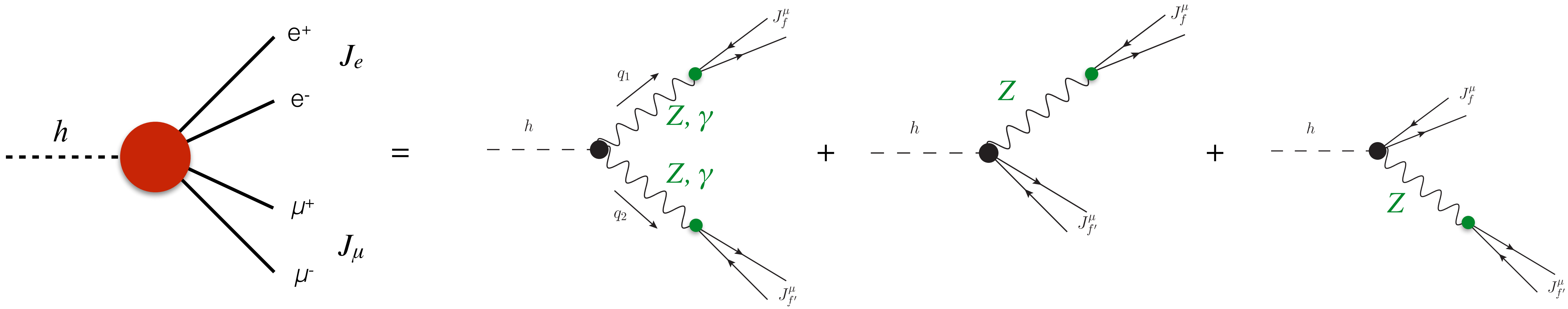
www.physik.uzh.ch/data/HiggsPO

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)

Extensively validated by comparing to our analytic results and other codes (Higgs Characterization, MEKD).



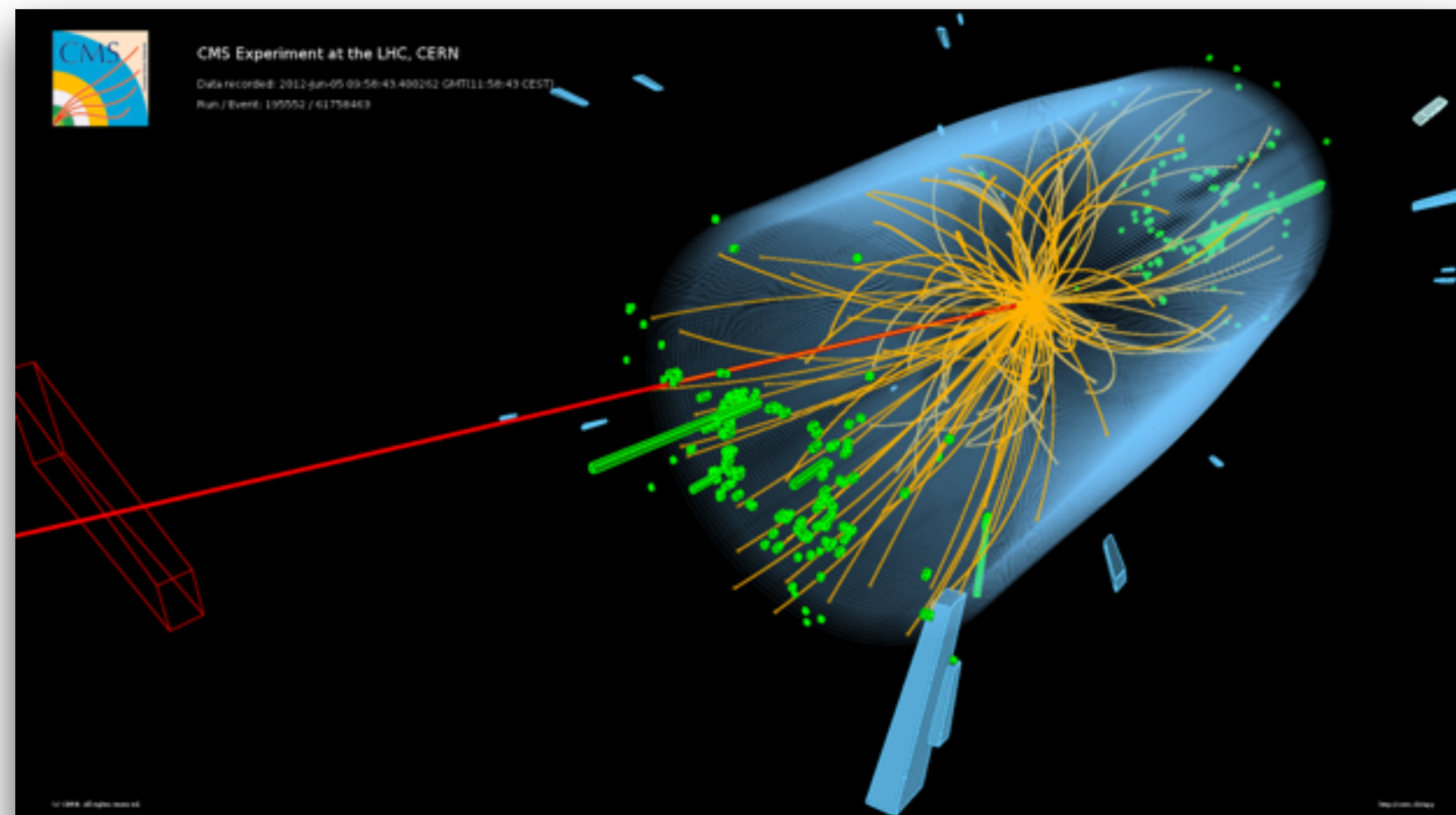
To summarize. **Higgs PO in decay**

- Related to physical distributions, measurable experimentally.
- Defined from the residues of the Green function on its poles.
  (valid at all orders in perturbation theory)
- Can be used to test symmetries and/or dynamics of the NP sector.
- QED radiation corrections are easily implemented.
- Implemented a Montecarlo tool for event generation.

Pseudo observables

in

Electroweak Higgs Production

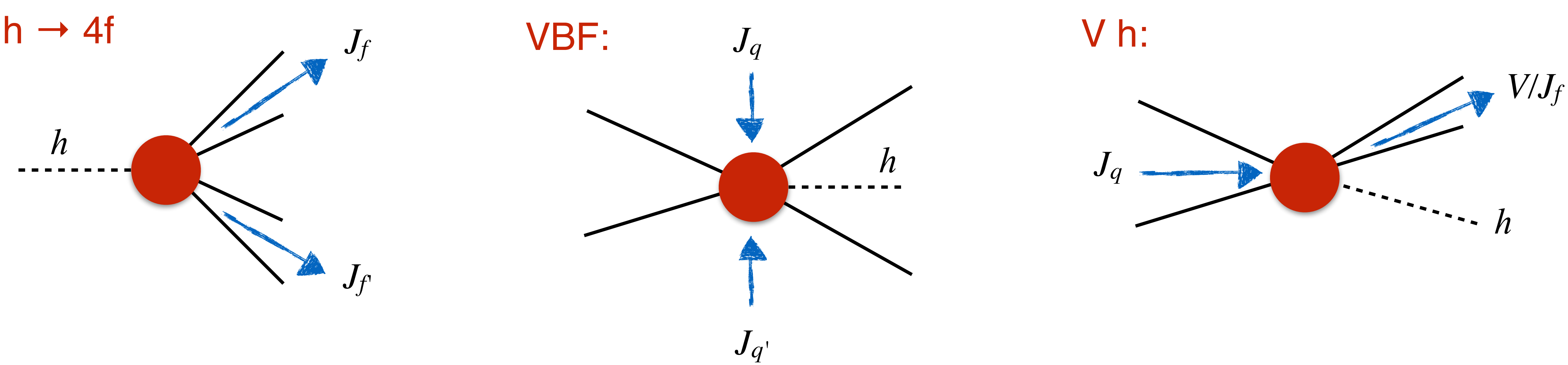


PO in EW Higgs Production

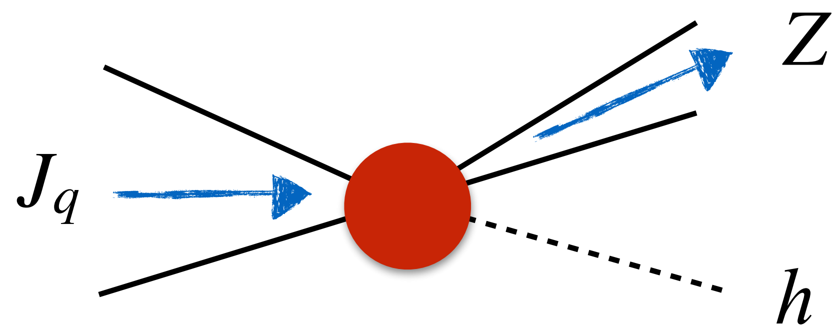
[Work in progress with Admir, Gino and Jonas]

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

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



Associate Zh production



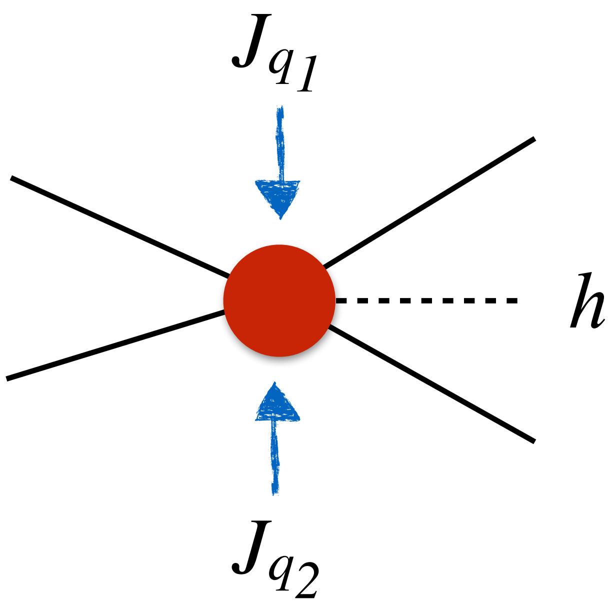
The amplitude is the same as for the decays:

$$\mathcal{A}(q_i(p_1)\bar{q}_i(p_2) \to h(p)Z(k)) = i\frac{2m_W^2}{v}\bar{q}_i(p_2)\gamma_\nu q_i(p_1)\epsilon_\mu^{Z*}(k)\left[\left(\kappa_{ZZ}\frac{g_{Zq_i}}{P_Z(q^2)} + \frac{\epsilon_{Zq_i}}{m_Z^2}\right)g^{\mu\nu} + \left(\epsilon_{ZZ}\frac{g_{Zq_i}}{P_Z(q^2)} + \epsilon_{Z\gamma}\frac{eQ_q}{q^2}\right)\frac{-(q\cdot k)g^{\mu\nu} + q^\mu k^\nu}{m_Z^2} + \left(\tilde{\epsilon}_{ZZ}\frac{g_{Zq_i}}{P_Z(q^2)} + \tilde{\epsilon}_{Z\gamma}\frac{eQ_q}{q^2}\right)\frac{-\epsilon^{\mu\nu\alpha\beta}q_\alpha k_\beta}{m_Z^2}\right]$$

Only quark contact terms are not probed in h → 4ℓ decays.

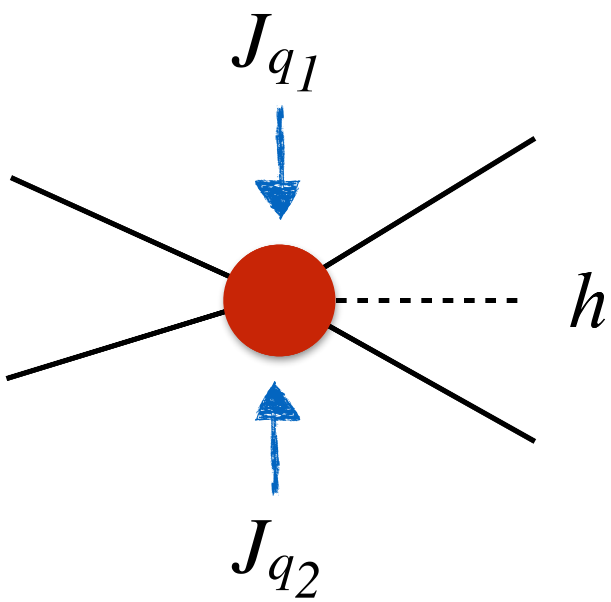
Form factor,
mom. expansion validity

only 1 observable: $q^2 = (p_h + k_Z)^2$



VBF Higgs production

Again, same amplitude as decays.



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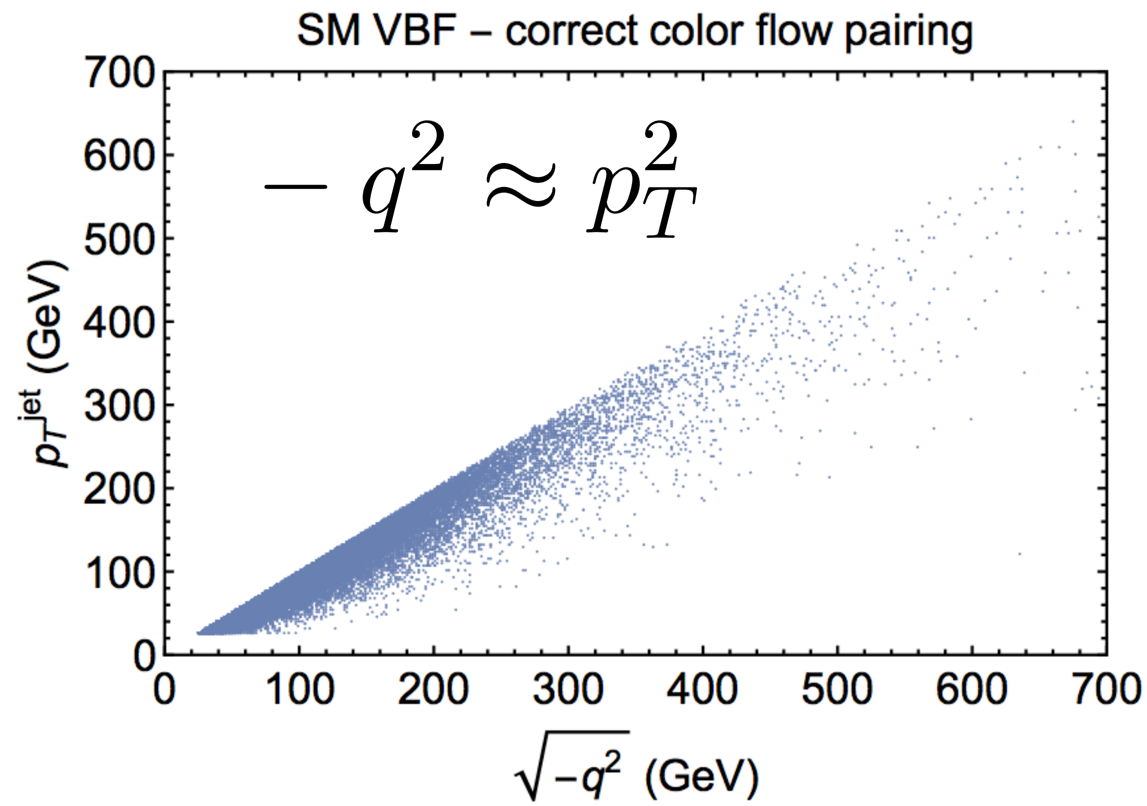
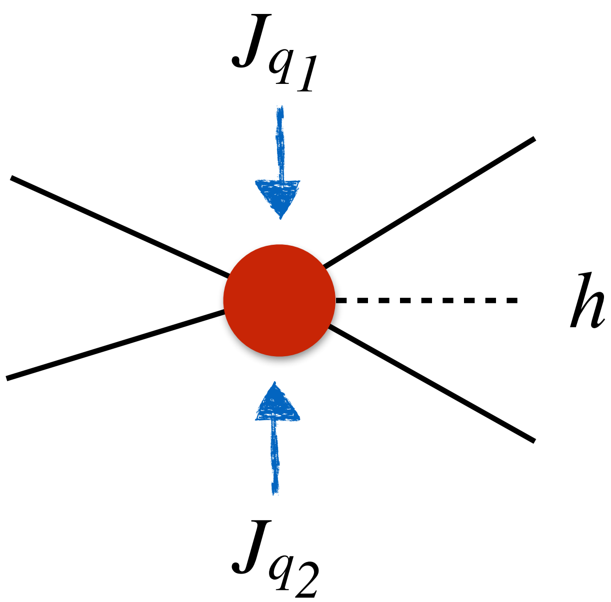


Initial state quarks are not accessible, so is q^2.

(unless Higgs is reconstructed)

p_T of the jets is a good proxy for the q^2.



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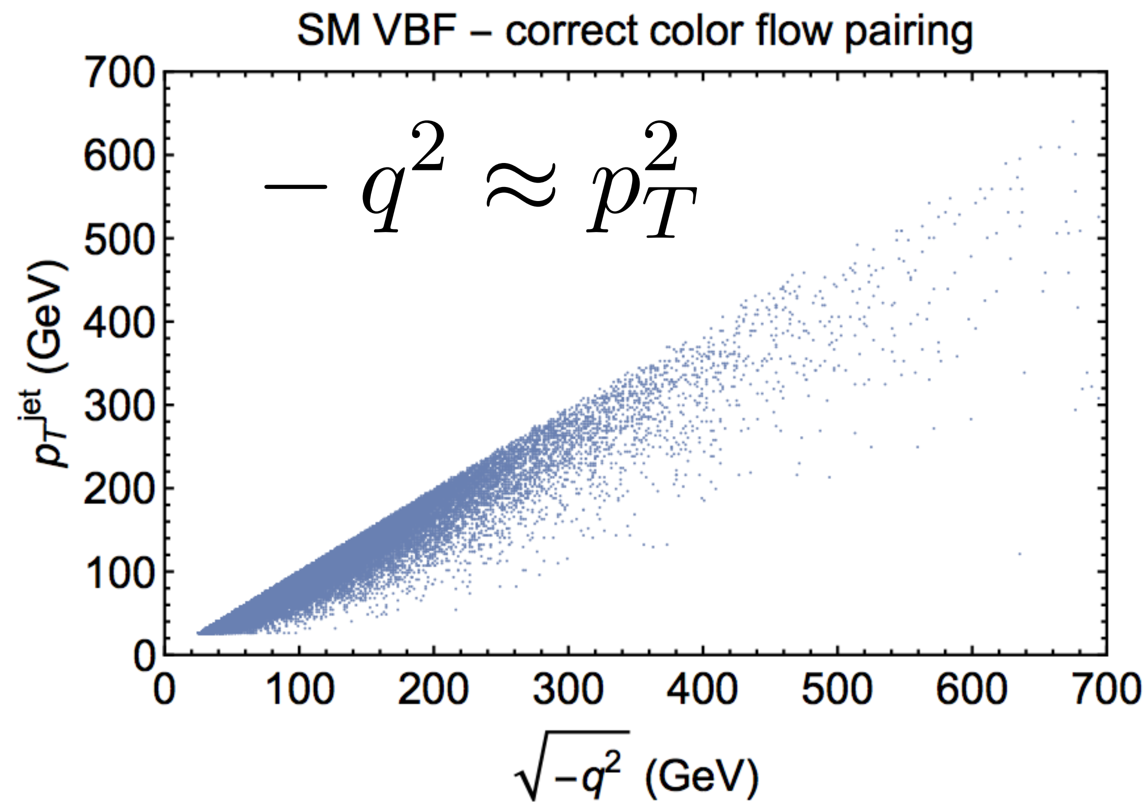

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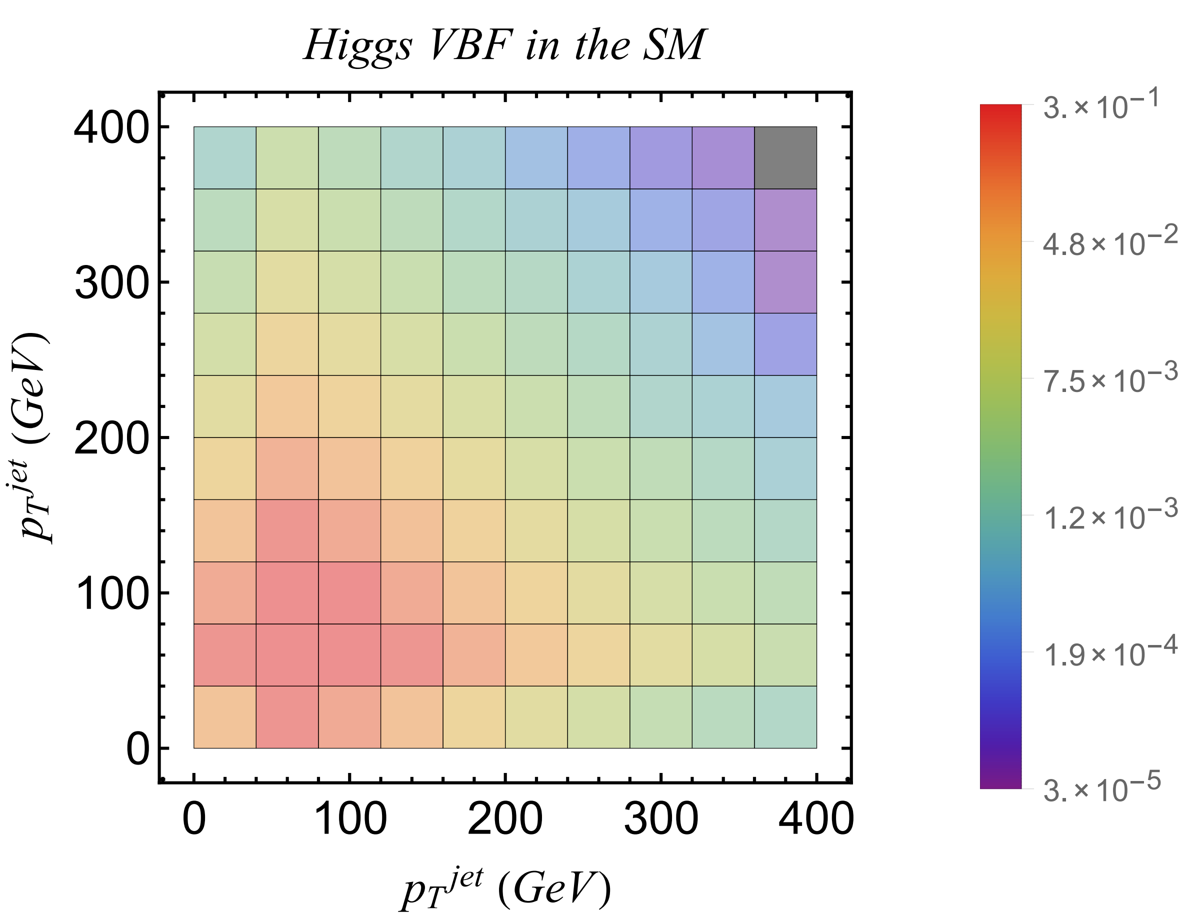

$$F(q_1^2, q_2^2) \rightarrow \tilde{F}(p_{T1}^2, p_{T2}^2)$$

General approach: measure the double differential distribution in ($p_{T1}{}^2$, $p_{T2}{}^2$)

With 3000 fb^{-1}: ~ 2000 events in VBF

precision physics!

2000 events in VBF Higgs production

Flavor-independent PO probed in $h \to 4\ell$ decay. → Focus on quark contact terms.

For simplicity let's assume Minimal Flavor Violation. Consider 7 PO:

$$\kappa_{ZZ}\ ,\quad \kappa_{WW}\ ,\quad \epsilon_{Zu_L}\ ,\quad \epsilon_{Zu_R}\ ,\quad \epsilon_{Zd_L}\ ,\quad \epsilon_{Zd_R}\ ,\quad \epsilon_{Wu_L}$$

Do a fit of the 2D p_T distribution, up to 600 GeV. ← Momentum expansion validity.

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Do a fit of the 2D p_T distribution, up to 600 GeV. ← Momentum expansion validity.

Very preliminary result. Only at parton level:

$$\begin{pmatrix} \kappa_{ZZ} \\ \kappa_{WW} \\ \epsilon_{Zu_L} \\ \epsilon_{Zu_R} \\ \epsilon_{Zd_L} \\ \epsilon_{Zd_R} \\ \epsilon_{Wu_L} \end{pmatrix} : \qquad \sigma = \begin{pmatrix} 0.46 \\ 0.17 \\ 0.015 \\ 0.023 \\ 0.021 \\ 0.031 \\ 0.004 \end{pmatrix}$$

Assuming expected 2000 events in the SM.

$$\rho = \begin{pmatrix} 1. & -0.98 & -0.04 & -0.18 & -0.31 & -0.25 & -0.04 \\ -0.98 & 1. & -0.03 & 0.14 & 0.25 & 0.18 & 0.1 \\ -0.04 & -0.03 & 1. & 0.22 & 0.55 & -0.13 & -0.33 \\ -0.18 & 0.14 & 0.22 & 1. & -0.22 & 0.03 & 0.14 \\ -0.31 & 0.25 & 0.55 & -0.22 & 1. & 0.12 & 0.22 \\ -0.25 & 0.18 & -0.13 & 0.03 & 0.12 & 1. & -0.29 \\ -0.04 & 0.1 & -0.33 & 0.14 & 0.22 & -0.29 & 1. \end{pmatrix}$$

LHC will be able to measure all the contact terms with percent accuracy!

Same conclusion also if no information on the total rate is retained.

Pseudo observables

and

the SM Effective Theory

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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Scale of New Physics is high

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

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

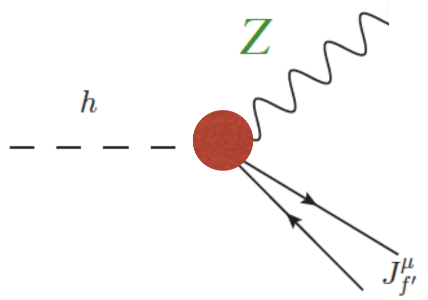
59 independent dim-6 operators if flavour universality.
2499 parameters for a generic flavour structure.

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

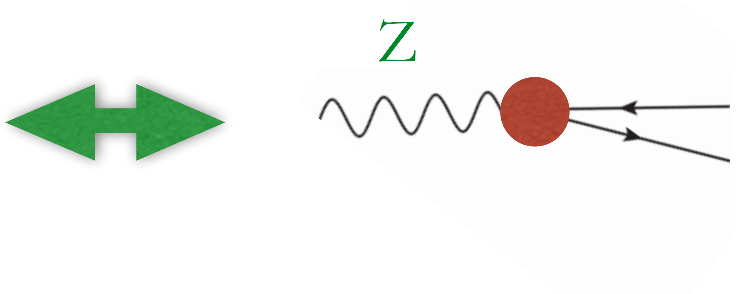
The power of the EFT: relating different observables

The same operator can contribute to different processes.

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



Higgs decay & production



Z couplings δg_{Zf}

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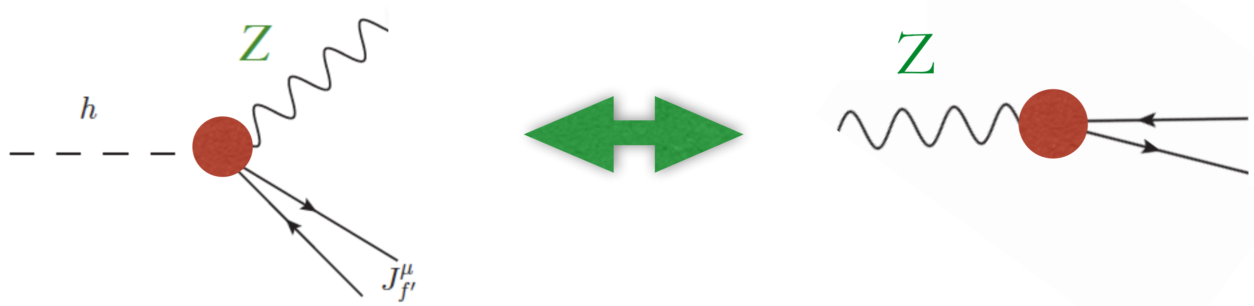
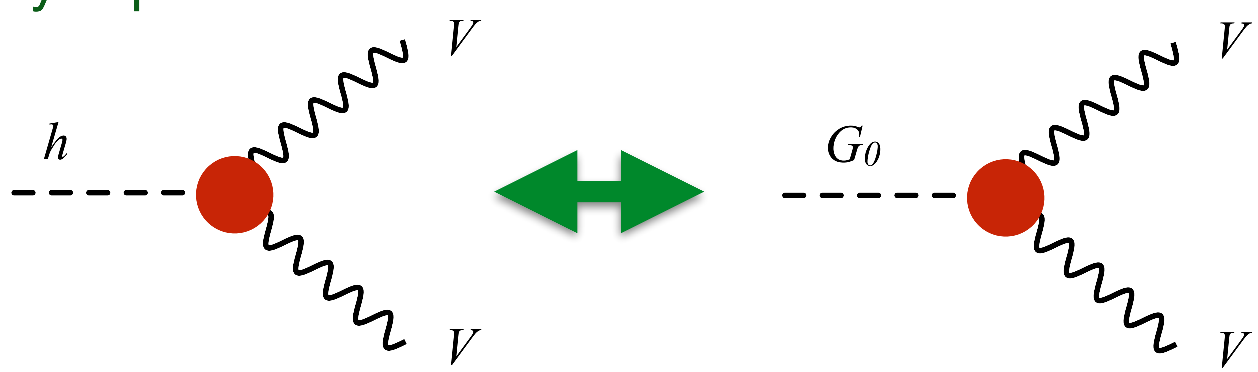


Z couplings δg_{Zf}

Higgs decay & production

or

&



Triple Gauge Couplings

$\delta\kappa_z,\ \delta g_{1,z},\ \lambda_Z$

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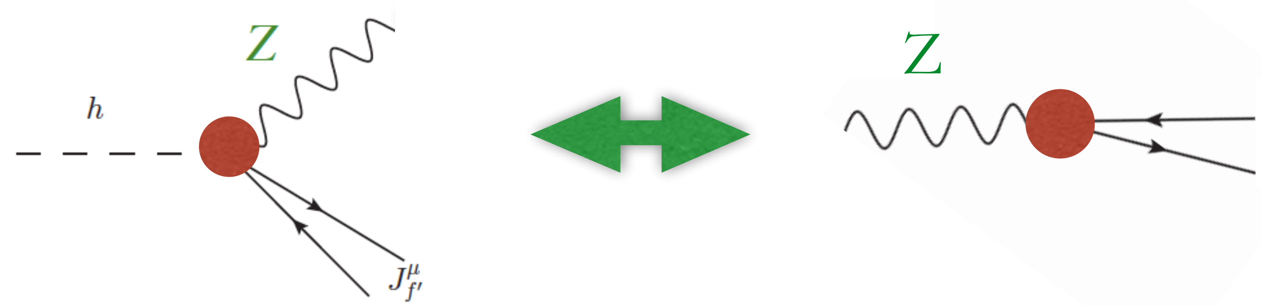

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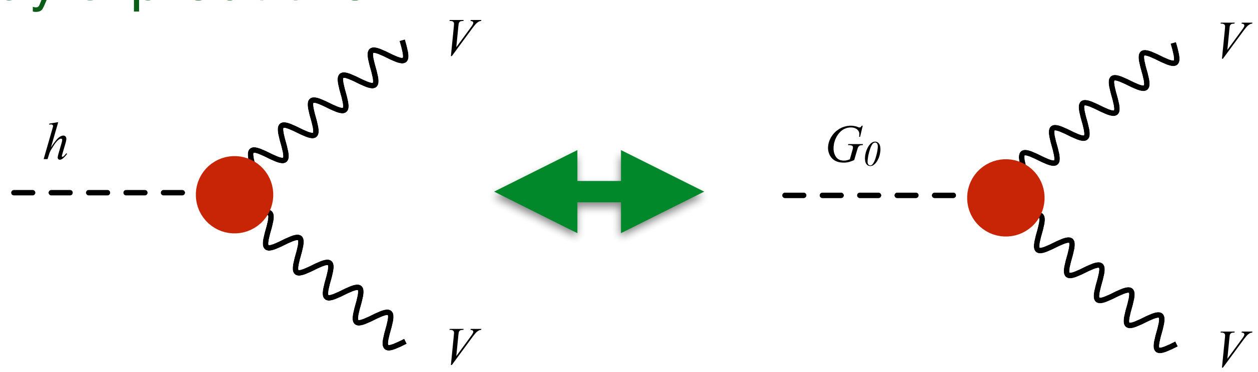

Triple Gauge Couplings
$\delta\kappa_z, \ \delta g_{1,z}, \ \lambda_Z$

- 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

Let us impose the strong LEP I constraints (≲1%).

[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]

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

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

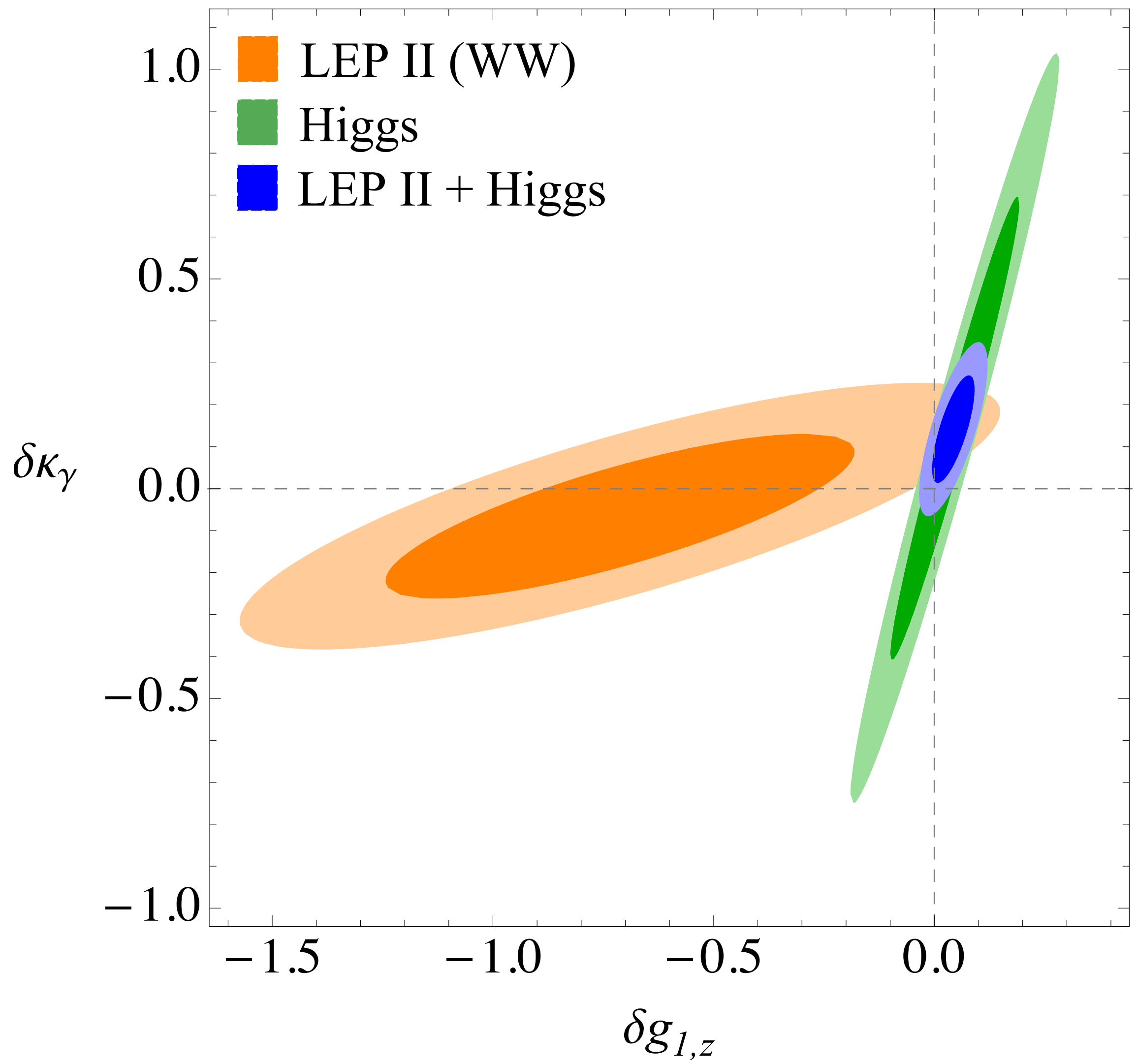
$$\delta c_z,\quad c_{\gamma\gamma},\quad c_{z\gamma},\quad c_{gg},\quad \delta y_u,\quad \delta y_d,\quad \delta y_e,\quad \delta g_{1,z},\quad \delta\kappa_\gamma,\quad \lambda_z.$$

Higgs **TGC**

The power of the EFT: relating different observables

Constraints on TGCs

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 at LO: relations with LEP observables.

e.g h→4ℓ:

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

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

[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.

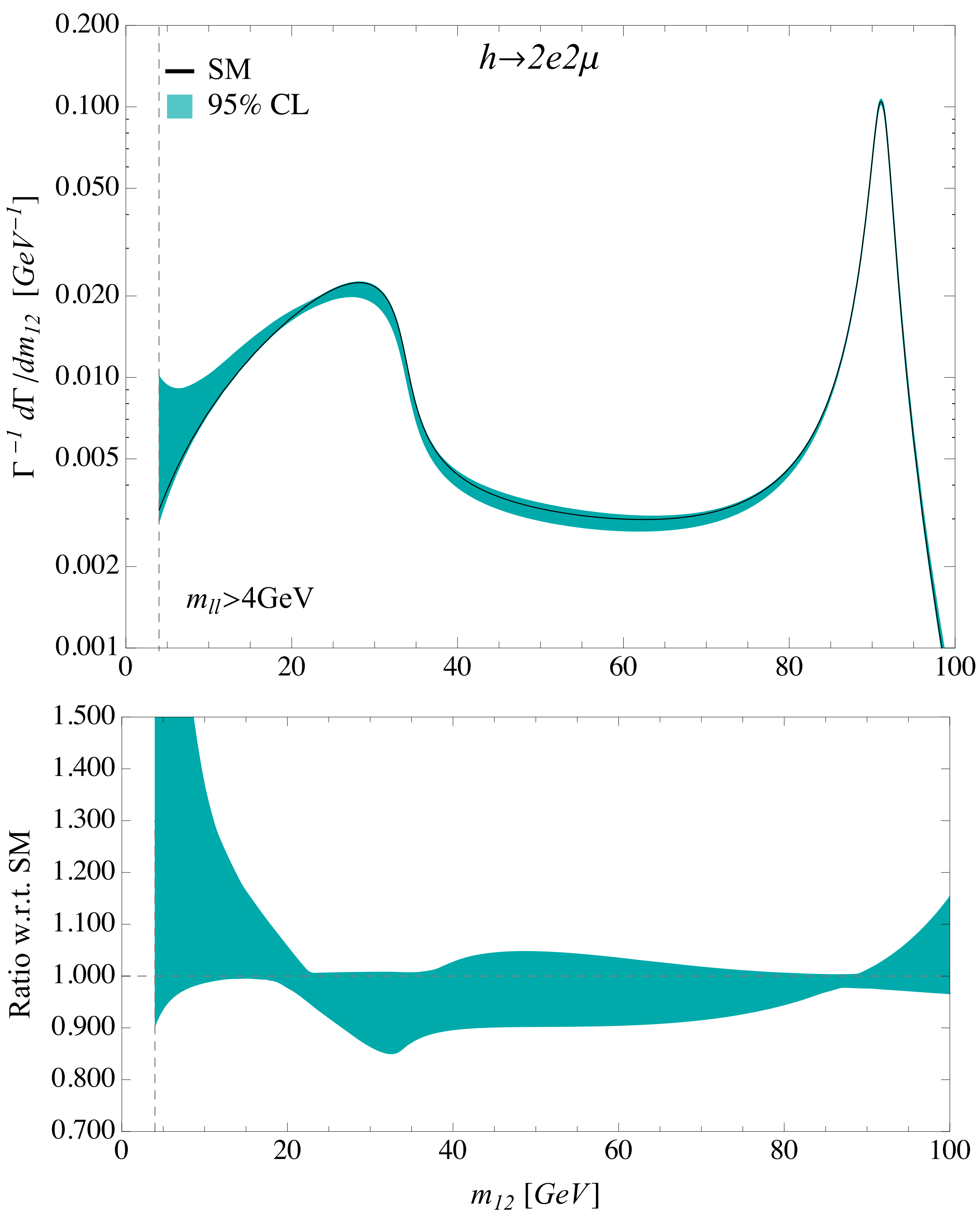
We use our combined LEP II + Higgs global fit to derive constraints on the Higgs PO.

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.

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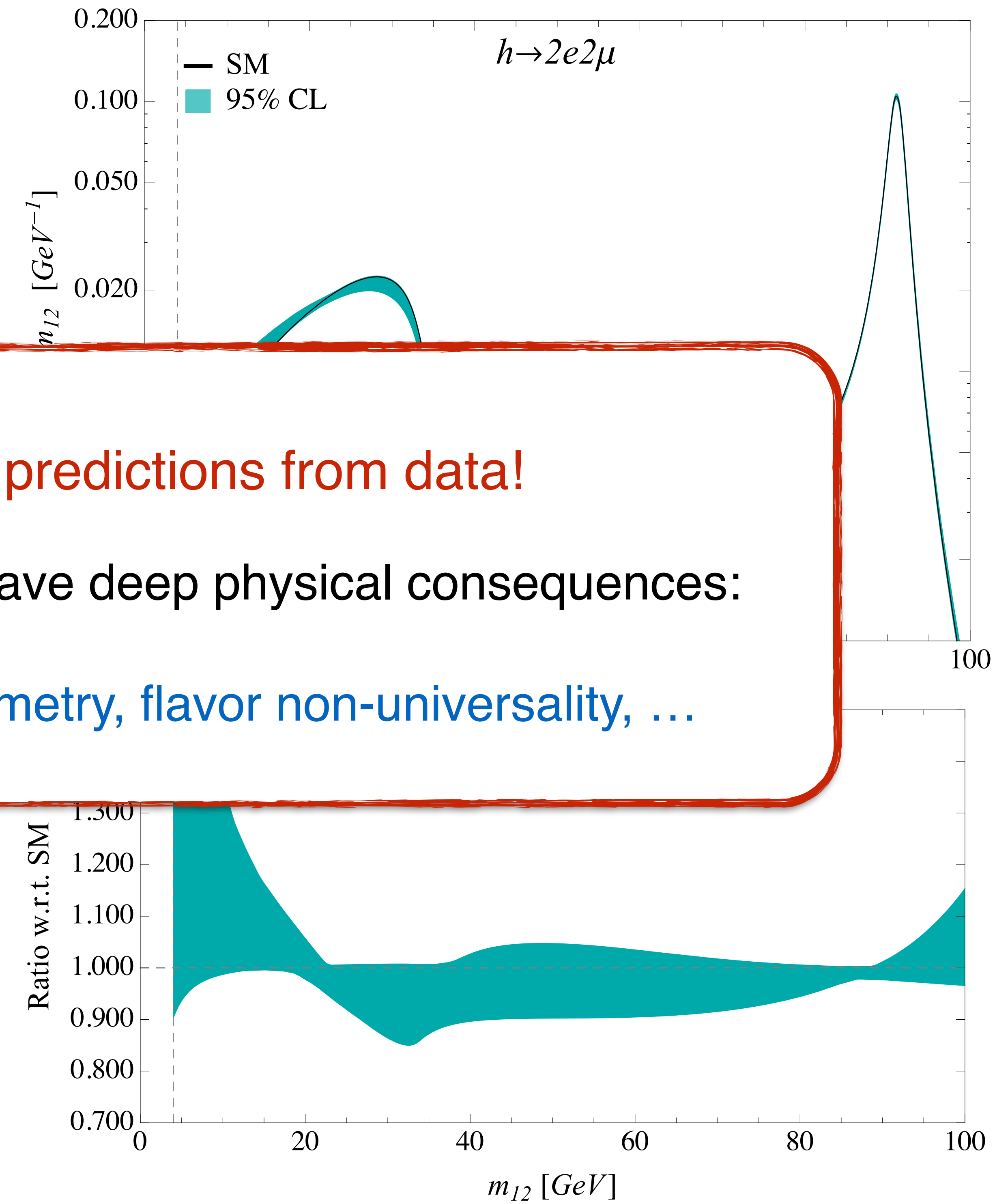


Crucial to test these predictions from data!

Any measured deviation would have deep physical consequences:

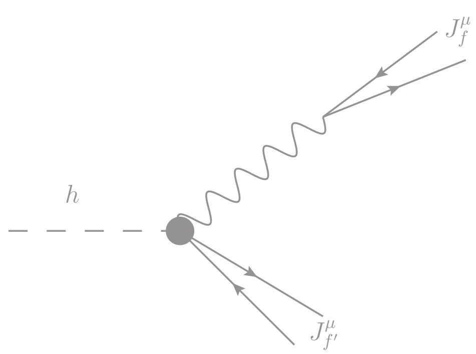
non-linear realization of EW symmetry, flavor non-universality, …

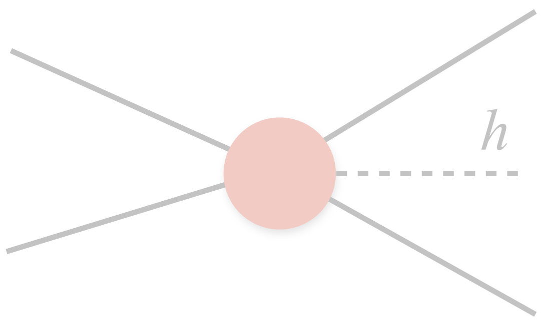
From these bounds we can extract precise predictions for Higgs data, such as di-lepton invariant mass spectra.

Small deviations allowed in the shape.

Conclusions

Higgs PO





- general framework to describe on-shell Higgs properties:
  decay and production.
- defined from physical properties of the Green functions
- easy to match to specific scenarios: test hypotheses.
- clear implementation of QED soft radiation (leading NLO 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 $h \to 4\ell$ processes
  Testing these predictions: important test for the linear EFT.

Backup

"Physical" PO in h→4ℓ

Goal: provide a simple interpretation for the PO.

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

$\Gamma(h\to Z\gamma)$ $\Gamma(h\to\gamma\gamma)$

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

Single Z-pole.

Decay width if only the contact term is present:

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

“Physical” PO in h→4ℓ

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

Double Z-pole. $h \longrightarrow ZZ$ not accessible kinematically.

We define the physical PO from $h \longrightarrow 2e2\mu$:

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

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

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

NLO effects in production

QCD

As for the decay, the most important effect can be described by soft QCD radiation.

Complete NLO QCD corrections, for generic PO, can be implemented in automatic tools for event generation. Work in progress.

[see also Maltoni, Mawatari, Zaro 1311.1829]

[NNLO corrections also dominated by real radiation effects: Cacciari, Dreyer, Karlberg, Salam, Zanderighi 1506.02660]

EW

Electroweak corrections can be divided in:

- Local contributions. Such terms are parametrised as SM contributions to the PO (e.g. $\varepsilon^{SM}{}_{Z\gamma,\gamma\gamma}$)

- Non-local terms. Unlike decay, in VBF such terms could be relevant. Would need a dedicated study.

Slide from Aleandro Nisati's talk at LHCP 2015

slide 19

Precision on signal strength

channel	Prec. (%) 100 fb^{-1}	Prec. (%) 300 fb^{-1}		Prec. (%) 3000 fb^{-1}	
ttH H→γγ	~65	38	36	17	12
ttH H→ZZ*→4l	~85	49	48	20	16
VBF H→γγ	~80	47	43	22	15
VBF H→ZZ*→4l	~60	36	33	21	16
H→μμ	~70	39	38	16	12
H→ττ	~18	14	8	8	5
H→bb	~20	14	11	7	5
H→γγ	~15	12	6	8	4
H→4l	~15	11	7	9	4
H→4l	~15	11	7	7	4

My personal estimates

ATLAS: experimental & theory uncertianties; only exp. uncertainty

CMS: current exp.l & theory uncertianties; exp. uncertainty ∝ 1/√L and ½ theory unc.

ATLAS assumed luminosity uncertainty: 3%