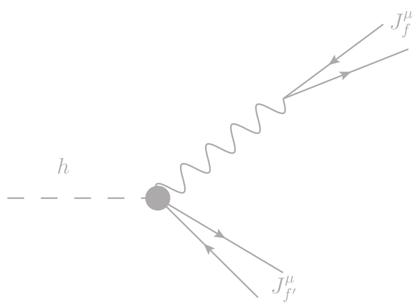
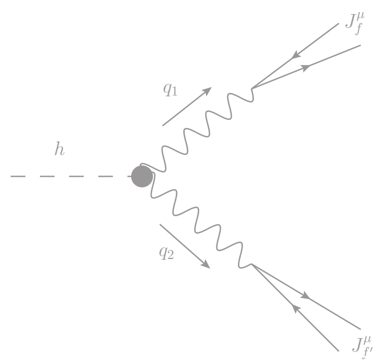
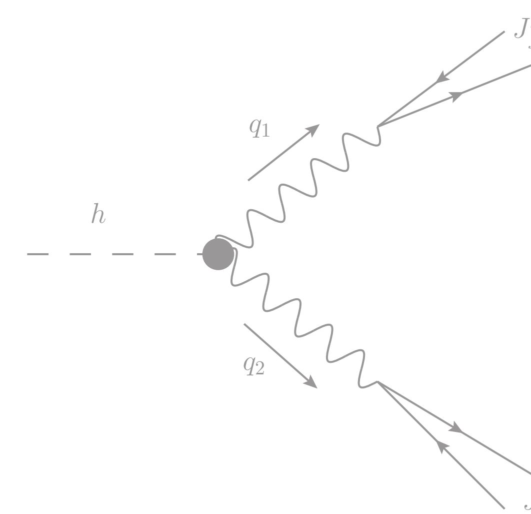


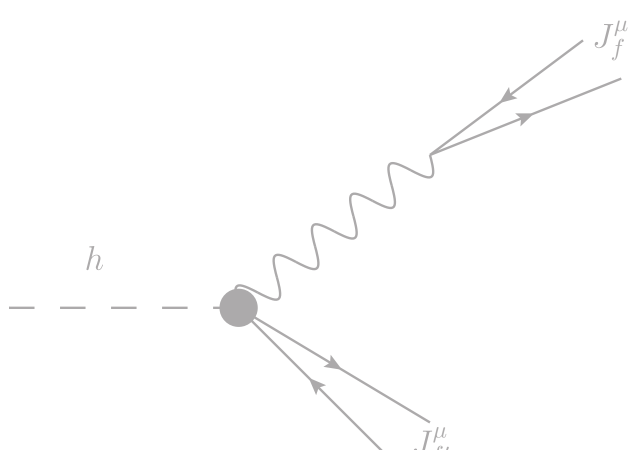
Pseudo-Observables in Higgs decays





David Marzocca

Universität Zürich[UZH]



M.Gonzalez-Alonso, A. Greljo, G. Isidori, D.M.

Eur. Phys. J. C 75 (2015) 3, 128 arXiv: 1412.6038
and arXiv: 1504.04018

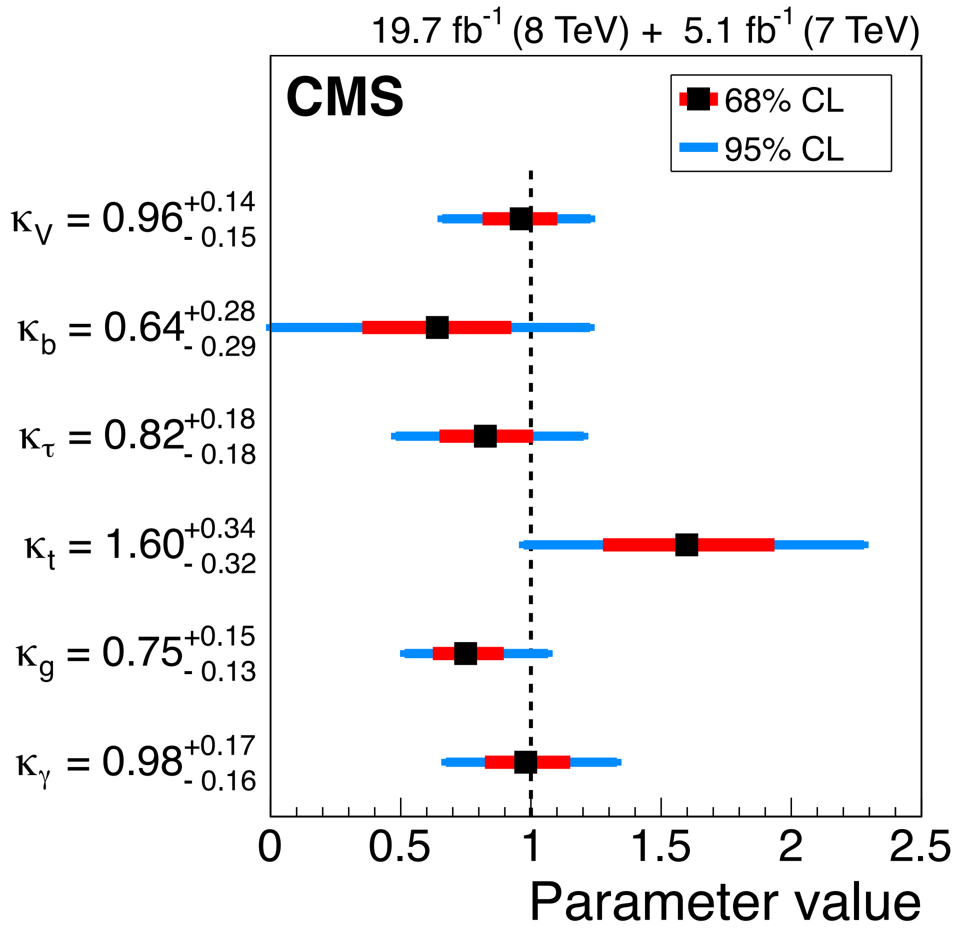
Rencontres de Blois
03/06/2015

Introduction

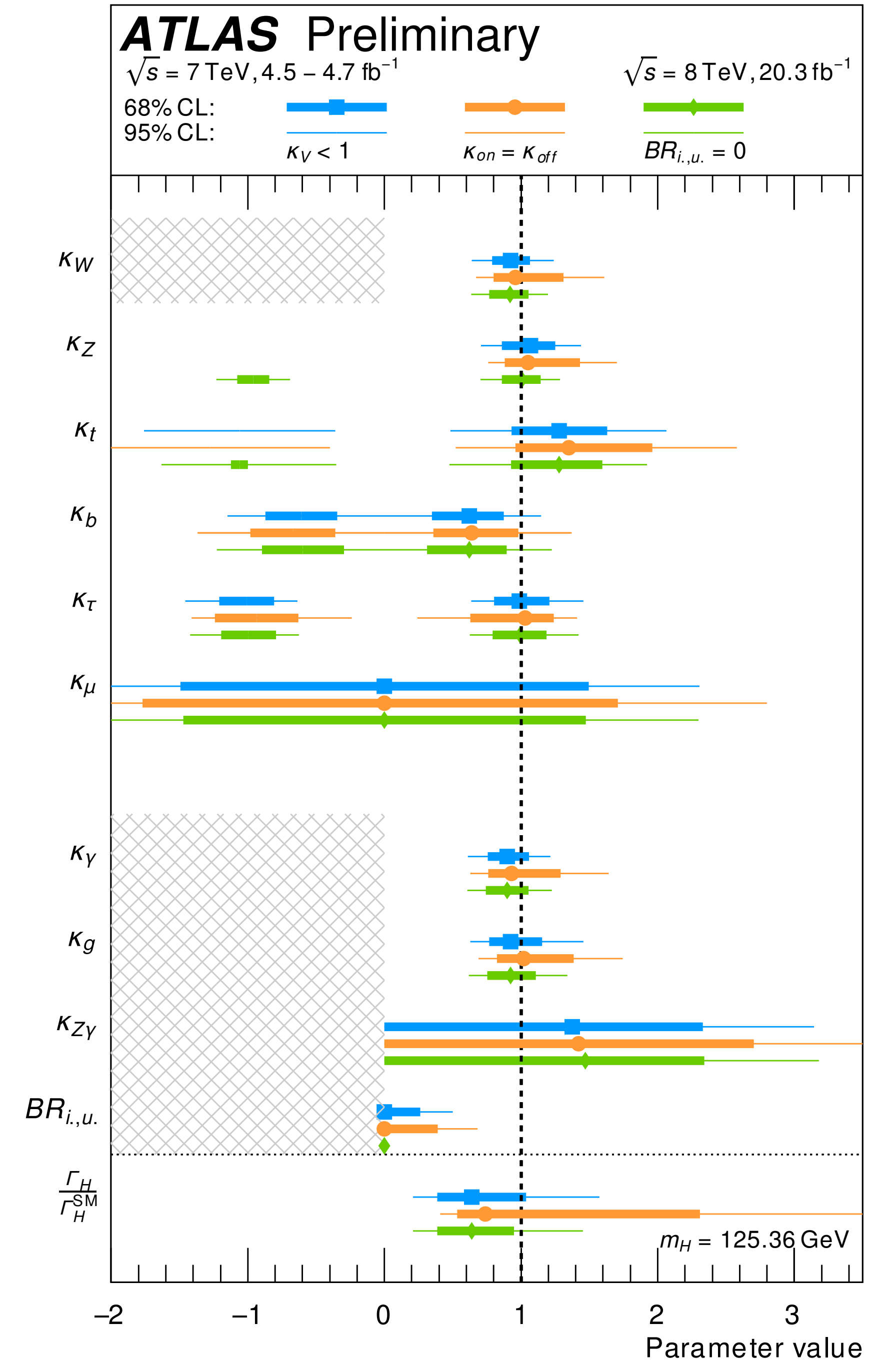
After the Higgs discovery at the LHC,
already at Run 1 we entered the era of Higgs precision.

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GeV}$$

Many of the Higgs couplings to SM particles have been measured.



CMS-HIG-14-009



ATLAS-CONF-2015-007

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

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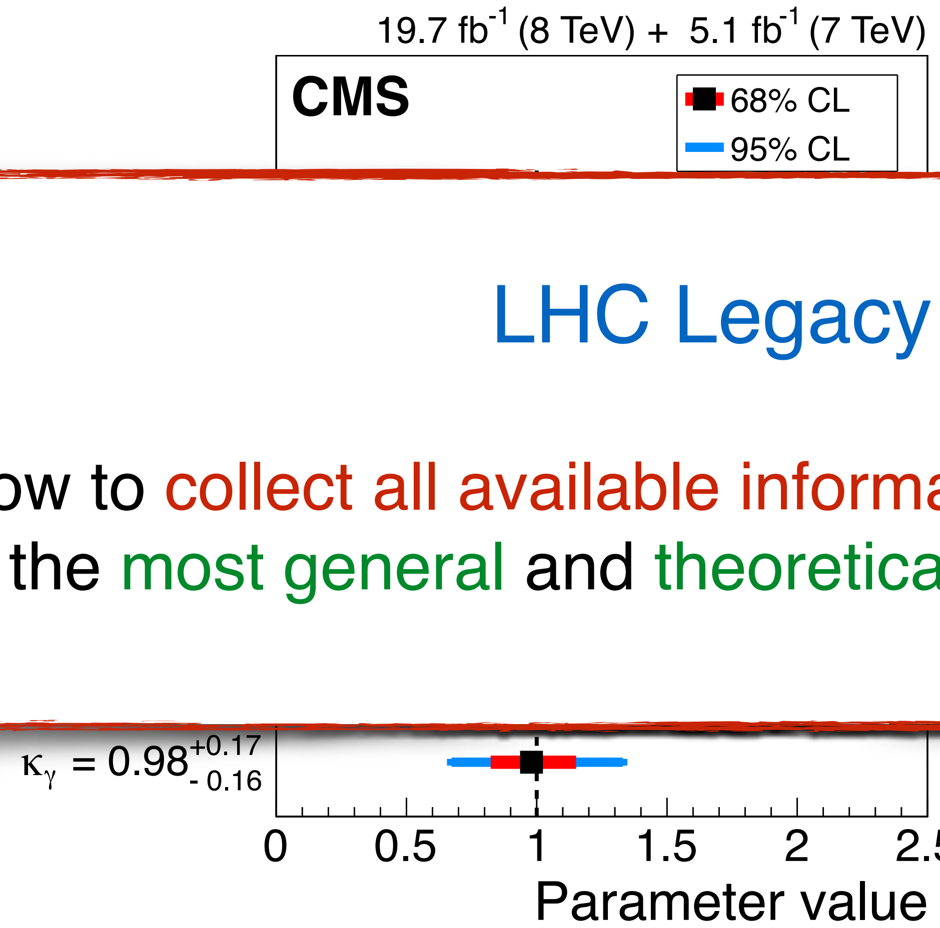

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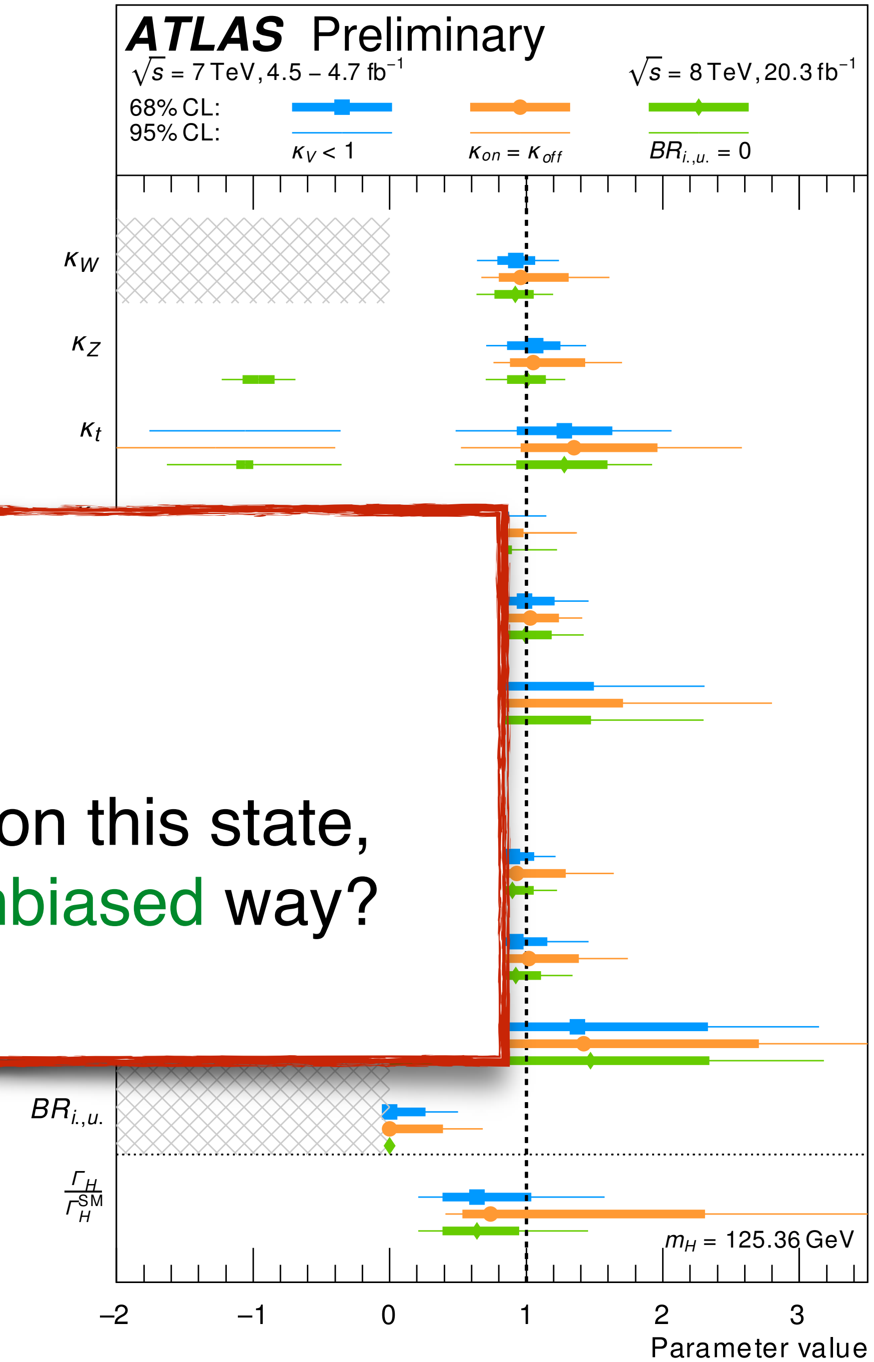

ATLAS-CONF-2015-007

LHC Legacy

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

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

Pseudo-observables

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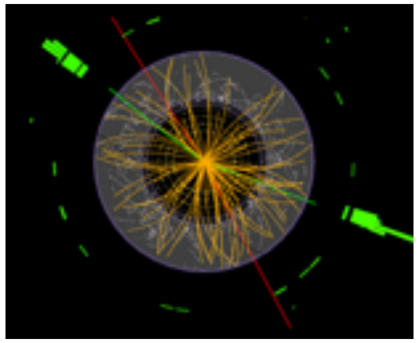

Realistic
Observables

Raw data,
Fiducial cross sections,
etc…

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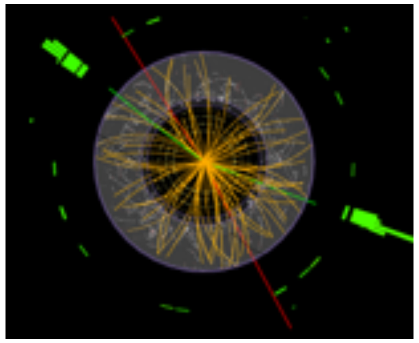

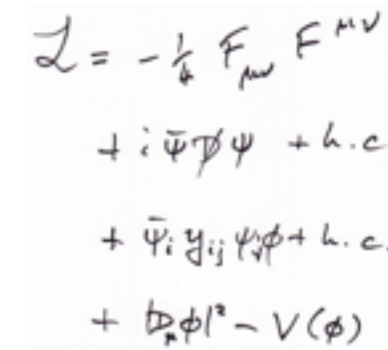

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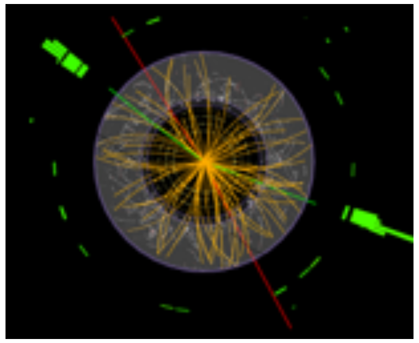

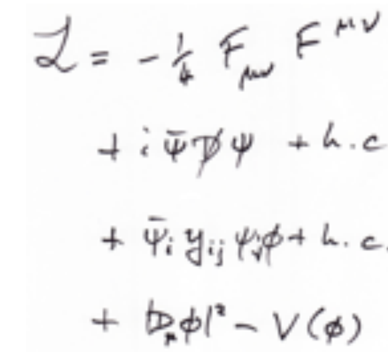

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Pole masses, decay widths,
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PO encode experimental information in idealized observables, of easy theoretical interpretation. This approach is old: developed at LEP to describe the Z properties.

[Bardin, Grunewald, Passarino '99]

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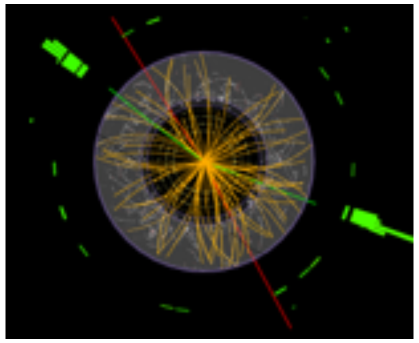

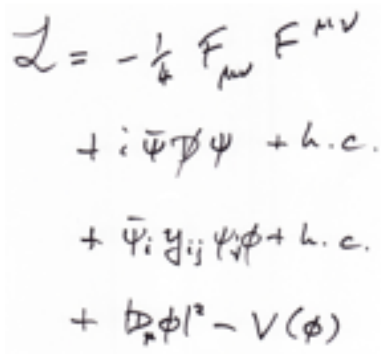

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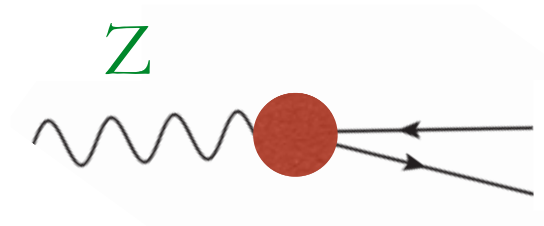
PO can then be matched, by theorists, to any explicit scenario — SM EFT, SUSY, Composite Higgs, etc.. — at the desired order in perturbation theory.

LEP-1 Strategy: on-shell Z decays

The goal was to parametrise on-shell Z decays as much model-independently as possible, in a way which would decouple infrared radiation (QED & QCD) effects.

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



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

The PO are defined as

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

Radiators: final state radiation

$$\Gamma_f \equiv \Gamma\left(Z \to f\overline{f}\right) = 4\,c_f\,\Gamma_0\left(|\mathcal{G}_V^f|^2\,R_V^f + |\mathcal{G}_A^f|^2\,R_A^f\right) + \Delta_{\mathrm{EW/QCD}}$$

[Bardin, Grunewald, Passarino '99]

non-factorizable SM corrections, very small.

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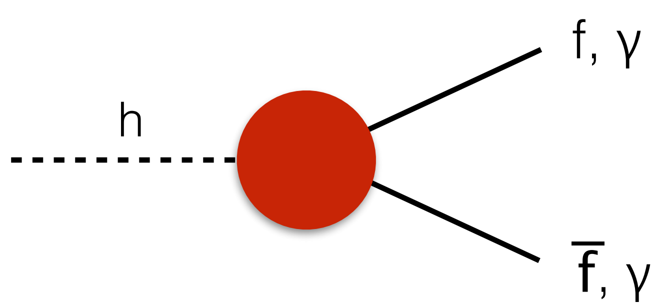
Need to extend the κ-framework retaining all its good properties:

Higgs pseudo-observables

LHC and on-shell Higgs decays: extending the κ-framework

Two-body decays
$h \to 2f, \gamma\gamma$



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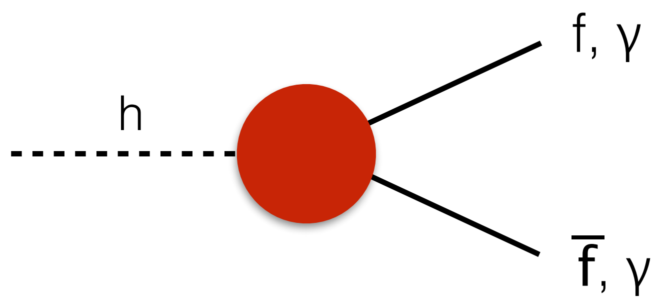

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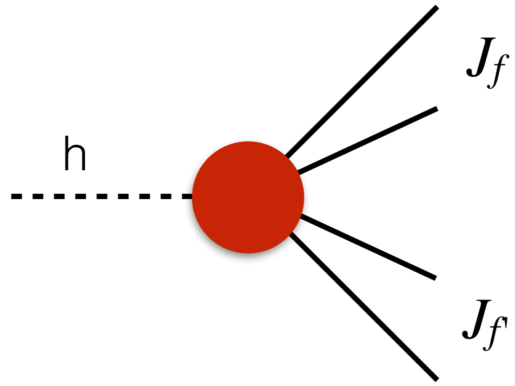
$$\mathcal{A}(h \to f\bar{f}) = -\frac{i}{\sqrt{2}}\left[(y_S^f + i y_P^f)\bar{f}_L f_R + (y_S^f - i y_P^f)\bar{f}_R f_L\right] \xrightarrow{\Gamma_f} |y_S^f|^2 + |y_P^f|^2$$

$$\mathcal{A}[h \to \gamma(q,\epsilon)\gamma(q',\epsilon')] = i\frac{2}{v_F}\epsilon'_\mu \epsilon_\nu [\epsilon_{\gamma\gamma}(g^{\mu\nu} q\cdot q' - q^\mu q'^\nu) + \epsilon_{\gamma\gamma}^{CP}\epsilon^{\mu\nu\rho\sigma} q_\rho q'_\sigma] \xrightarrow{\Gamma_{\gamma\gamma}} |\epsilon_{\gamma\gamma}|^2 + |\epsilon_{\gamma\gamma}^{\text{CP}}|^2$$

$$\kappa_{\gamma\gamma} \equiv \frac{\epsilon_{\gamma\gamma}}{\epsilon_{\gamma\gamma}^{\text{SM-1L}}}$$

LHC and on-shell Higgs decays: extending the κ-framework

Four-body decays
h → 4f



The kinematics is much richer: kinematical distributions.

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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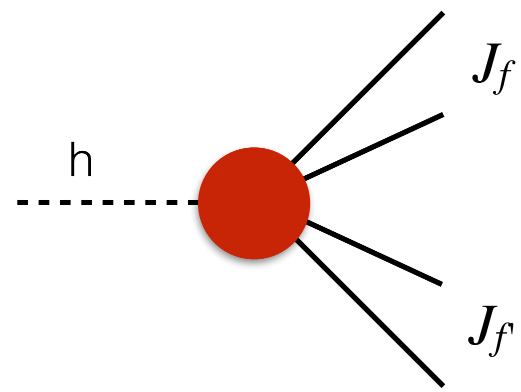

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Only 3 tensor structures allowed by Lorentz symmetry:

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

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

Higgs to 4-fermion decays

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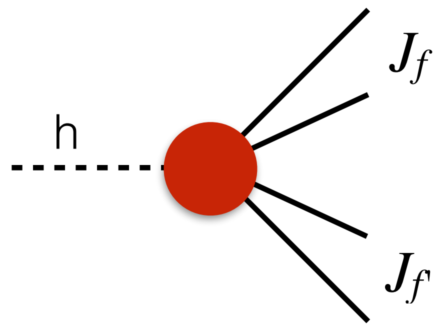

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Long-distance (non-local) modes (poles): propagation of EW gauge bosons.

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

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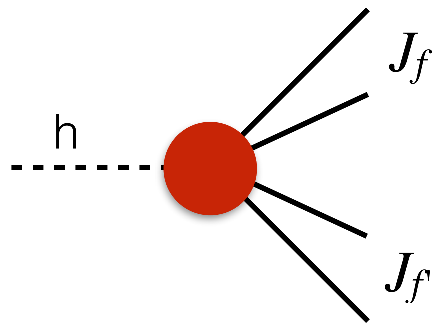

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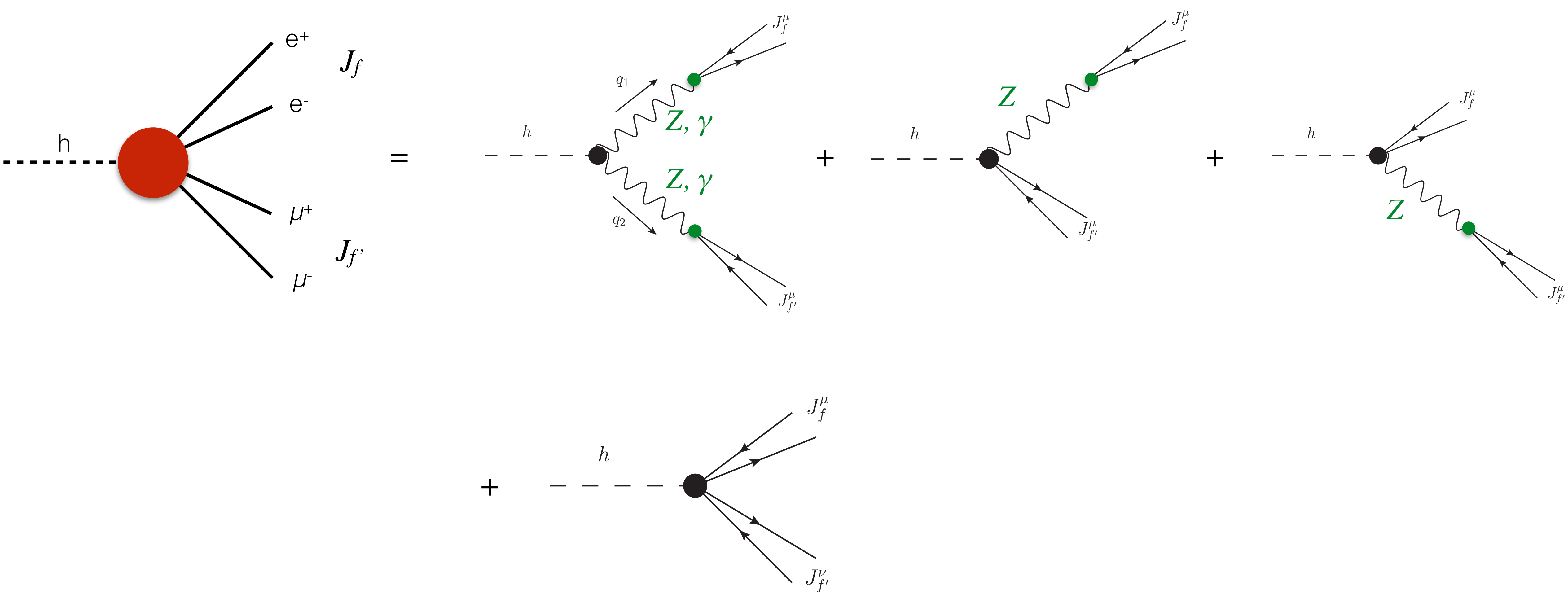
We expand around the physical poles:

contact terms



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No new light state can mediate this amplitude.

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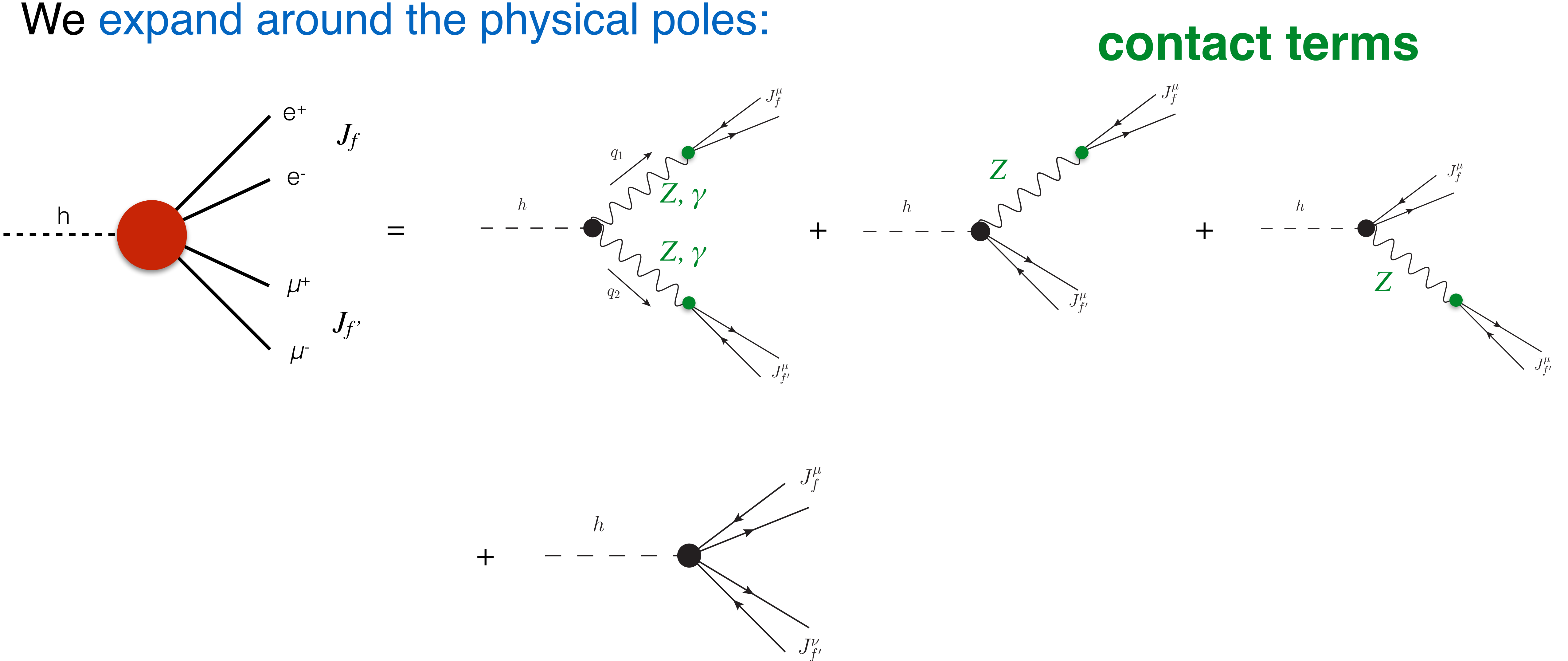

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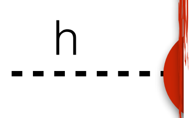

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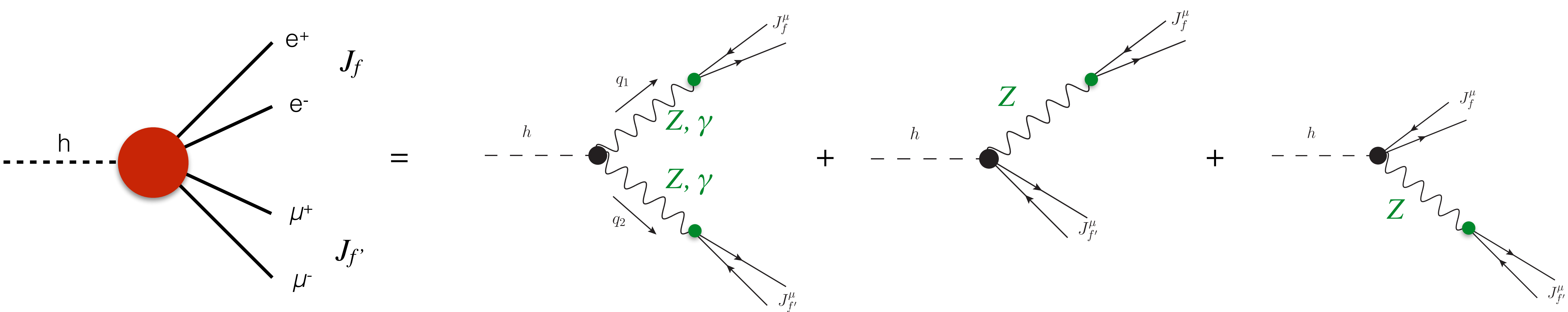

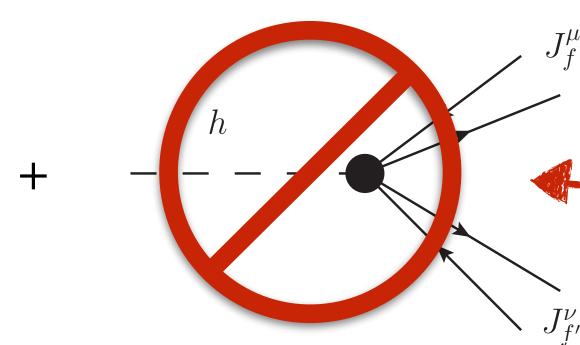

We neglect completely local terms, corresponding to operators with d > 6: EFT assumption.

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

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

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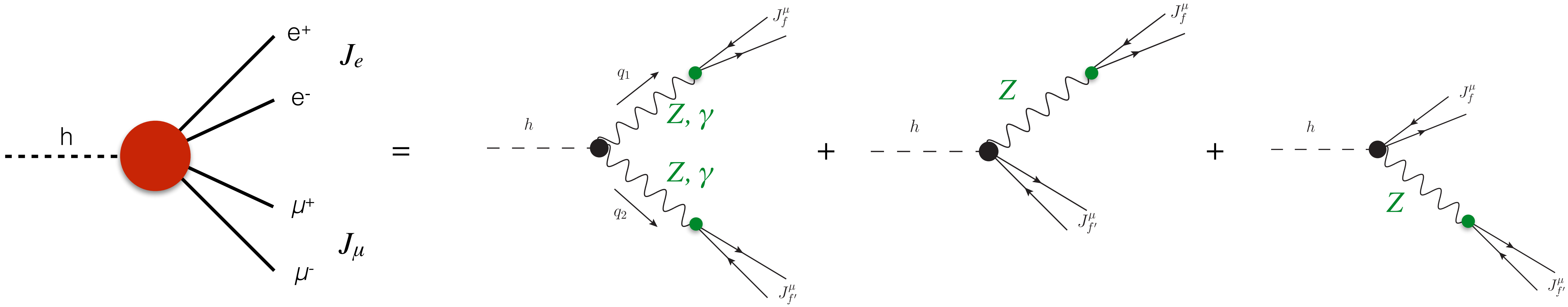

$$
\begin{aligned}
\mathcal{A} =& i\frac{2m_Z^2}{v_F}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times \\
&\left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right) g^{\alpha\beta}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

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

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

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

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

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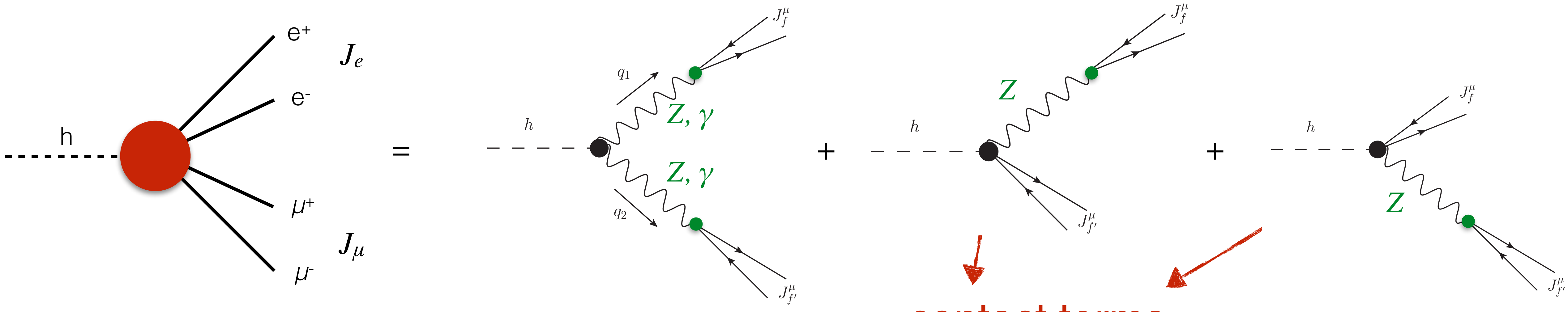

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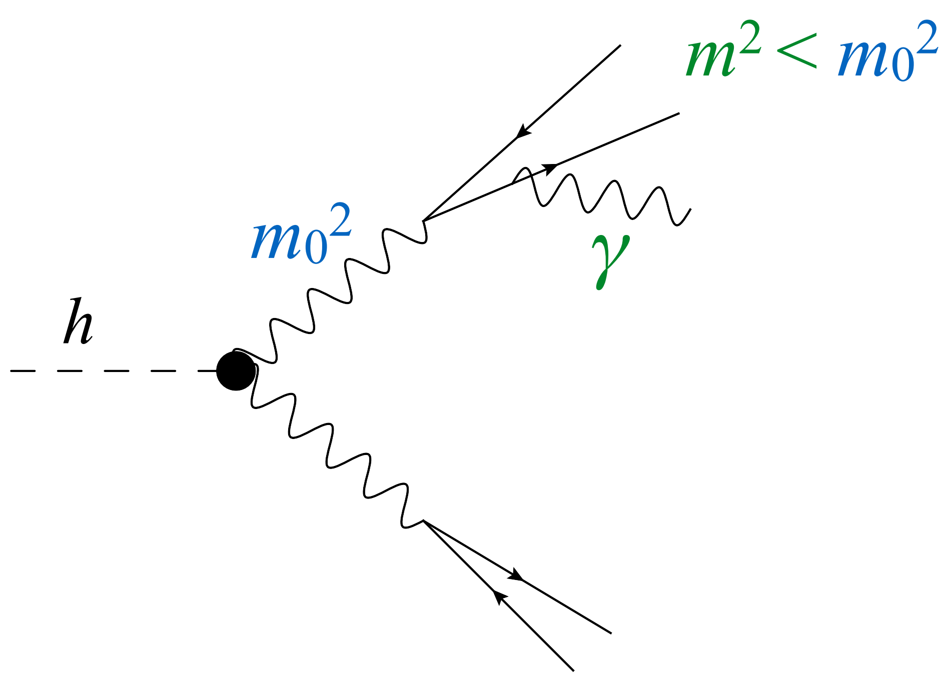
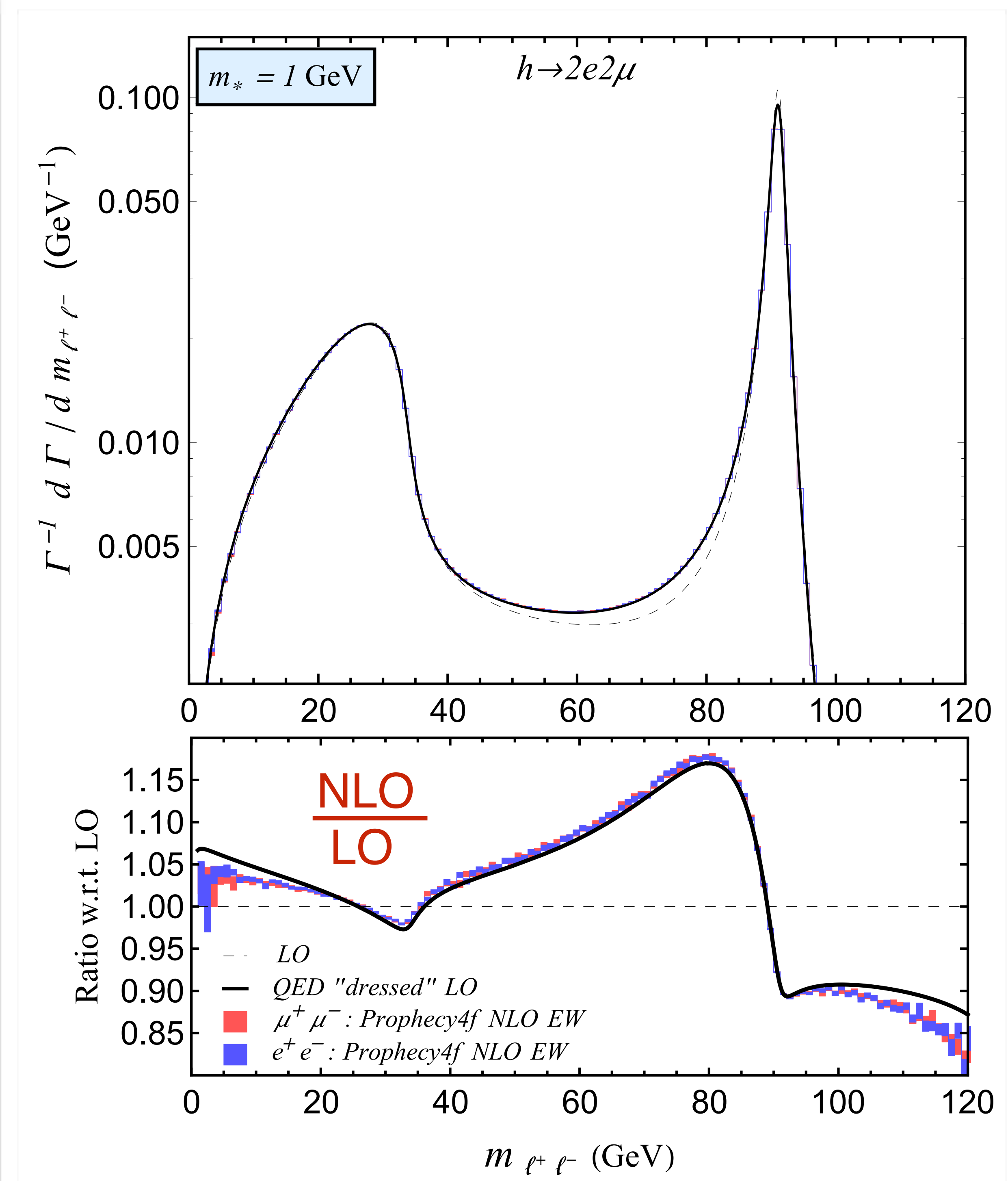
In the SM $\quad \kappa_X \to 1,\ \epsilon_X \to 0$

Radiative Corrections

[M. Bordone, A. Greljo, G. Isidori, D. M., A. Pattori, work in progress]

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:

$$\frac{d\Gamma_{NLO}}{dm_{01}dm_{02}dx_1dx_2} = \frac{d\Gamma_{LO}}{dm_{01}dm_{02}}\omega(x_1)\omega(x_2)$$

$$x = \frac{m^2}{m_0^2}$$

~15% effect!

Other NLO corrections are small.

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)

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N. & C. interference

$h \to e^+e^-\nu\nu$
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others +
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Flavor universality

$$\epsilon_{Ze_L} = \epsilon_{Z\mu_L} \ ,$$
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$\epsilon_{We_L} = \epsilon_{W\mu_L}$.

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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CP Invaria

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

Custodial symmetry

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

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

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

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

★ Accidentally true also in the linear EFT.

Parameter counting and symmetry assumptions

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$\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$,
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Symmetries i

20 (general case) → **7** (max symm.)

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

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★ Accidentally true also in the linear EFT.

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$h \to \gamma\gamma$

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.)

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$\epsilon_{Ze_L} = \epsilon_Z$

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

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

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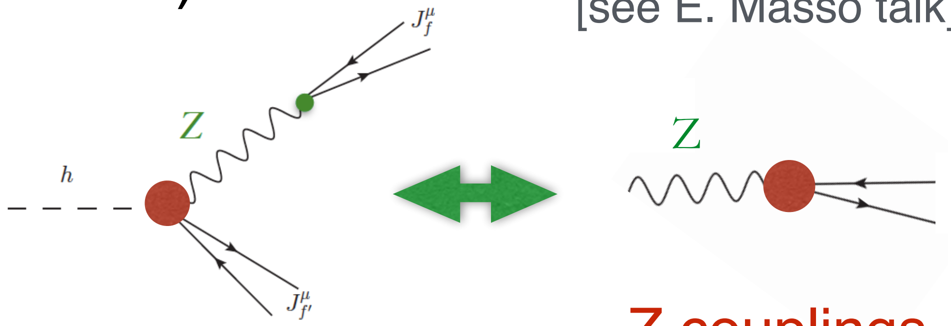
★ Accidentally true also in the linear EFT.

Higgs PO and linear EFT

Assuming h(125) ∈ $SU(2)_L$ doublet (linear EFT):

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

[see E. Masso talk]



Higgs PO

Z couplings &
Triple Gauge Couplings

Higgs PO and linear EFT

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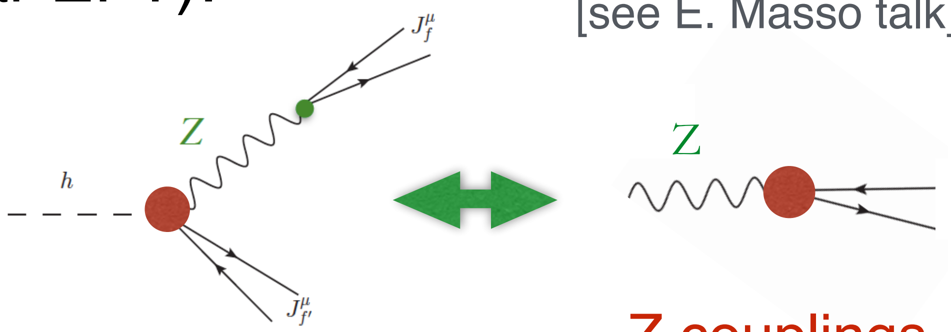


Higgs PO

Z couplings & Triple Gauge Couplings

e.g h→4ℓ:

["Higgs basis", LHCHXSWG 2015]
["Primaries" Gupta, Pomarol, Riva, 2014]

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

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

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

LEP-I: $\delta g^{Z\ell} \lesssim 10^{-3}$

Flavour universality from data!

[Efrati, Falkowski, Soreq 2015]

TGC (LEP-II):

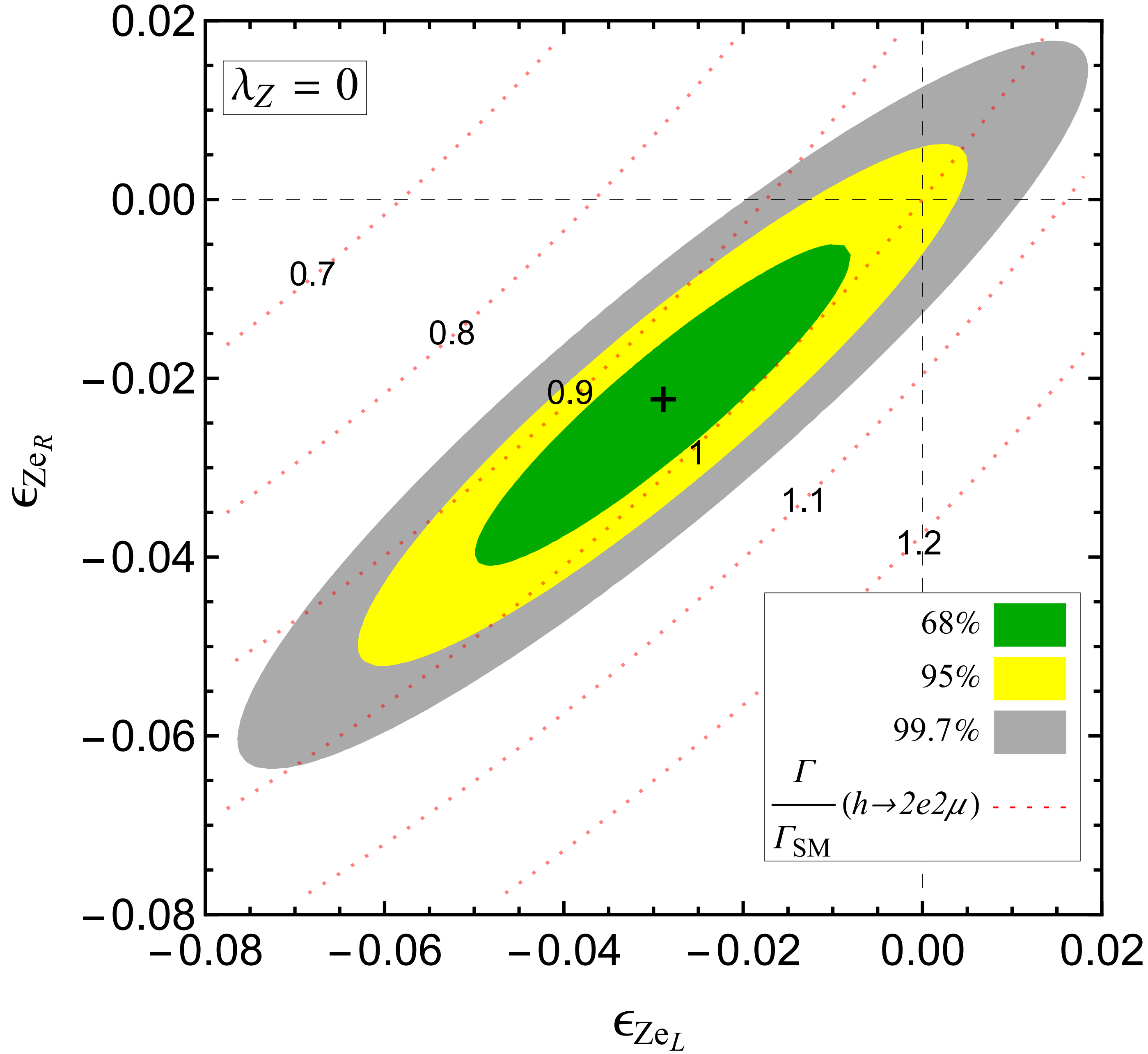
$\delta g_{1,z}$, $\delta\kappa_\gamma \lesssim 10^{-2}$ $(\lambda_Z = 0)$

[Falkowski, Riva 2014, …]

Constraints on the PO in the linear EFT

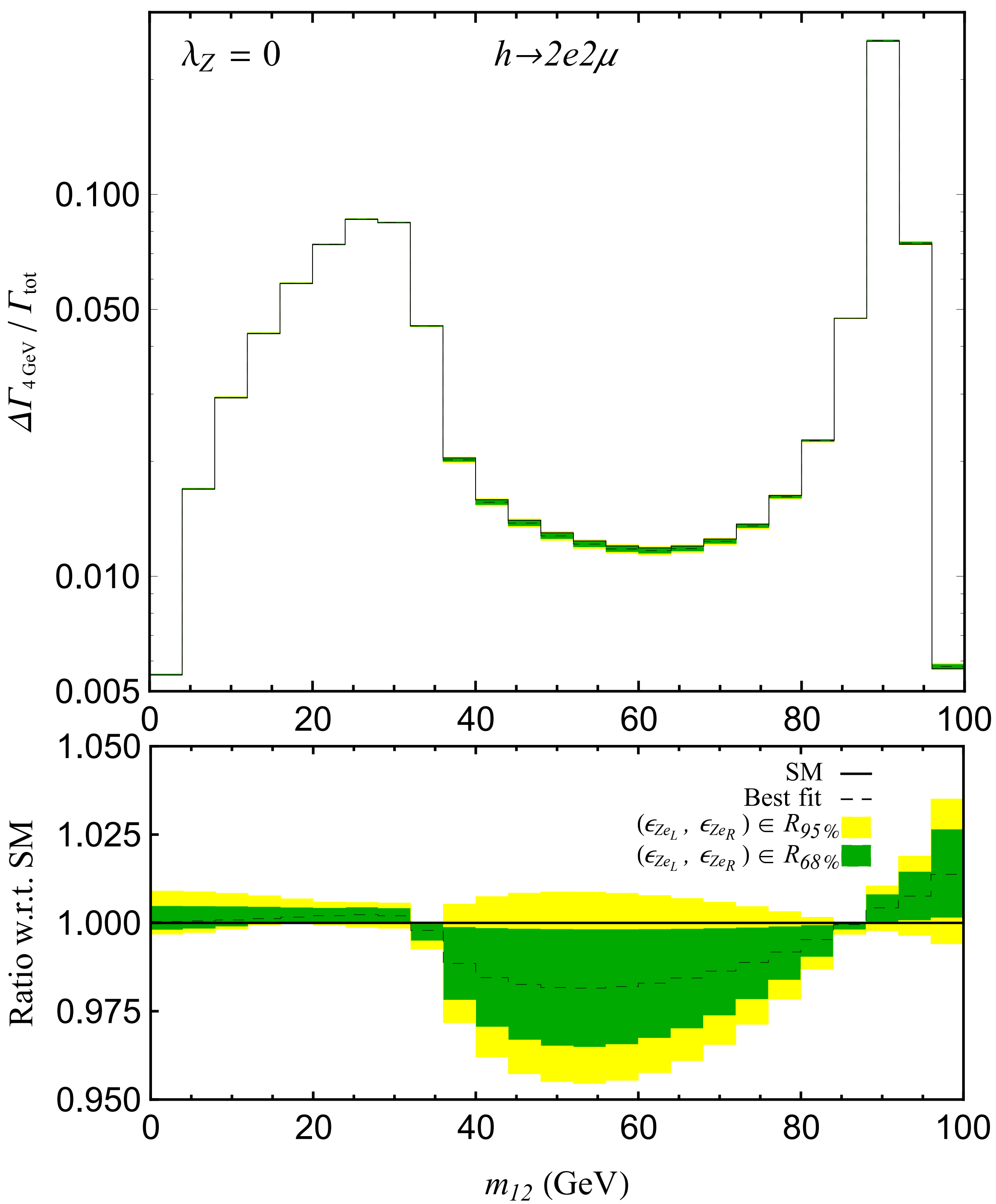
$$\epsilon_{Zf} = \frac{2m_Z}{v}\left(\delta g^{Zf} - (c_\theta^2 T_f^3 + s_\theta^2 Y_f)\mathbf{1}_3\delta g_{1,z} + t_\theta^2 Y_f \mathbf{1}_3 \delta\kappa_\gamma\right)$$

From the LEP-II bounds on anomalous triple-gauge couplings:

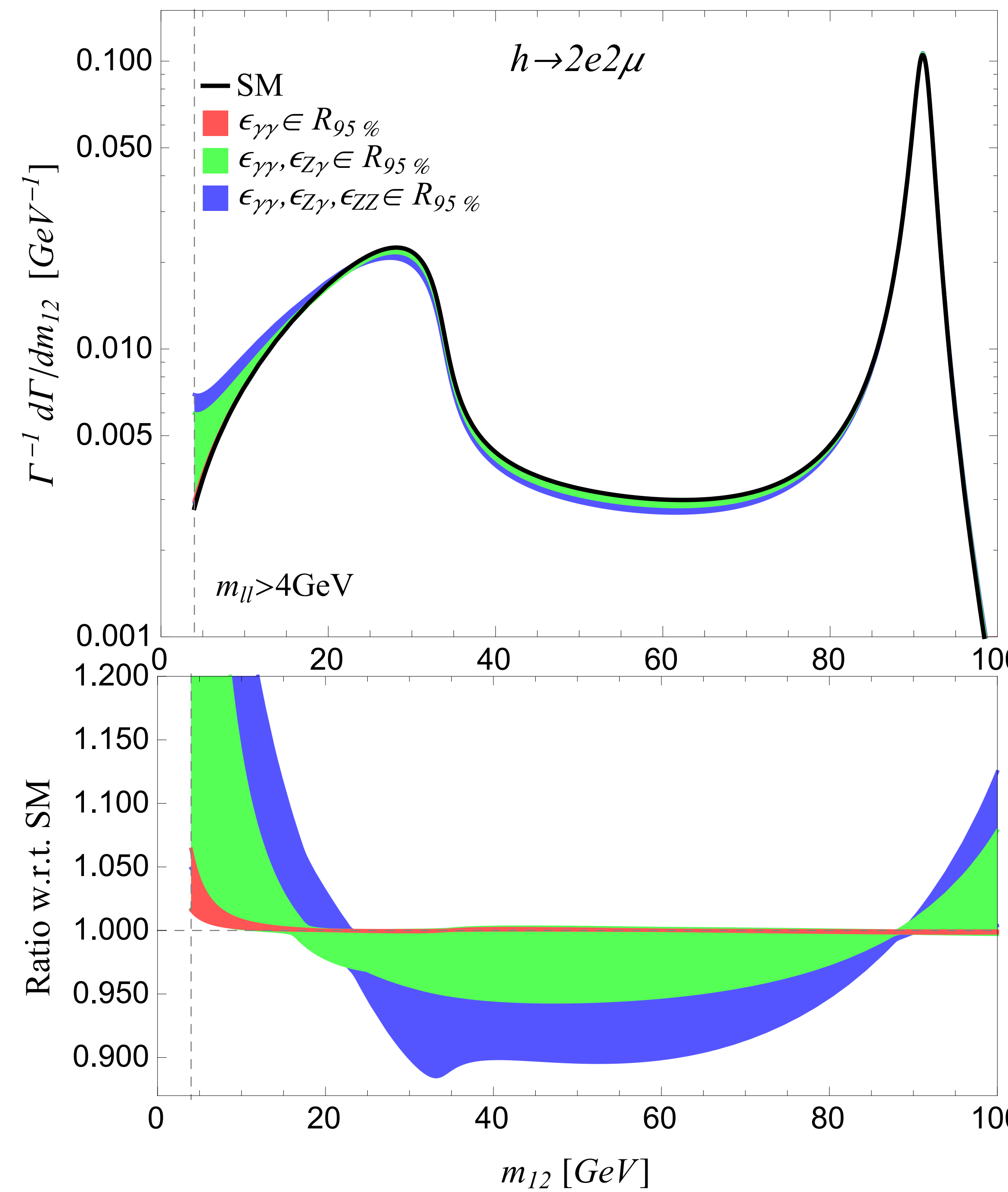


Predictions for h → 4ℓ in the linear EFT

From these bounds we can extract precise predictions for Higgs data, such as total decay rates or di-lepton invariant mass spectra:



Small deviations allowed in the shape.



These PO can be studied also from angular distributions.

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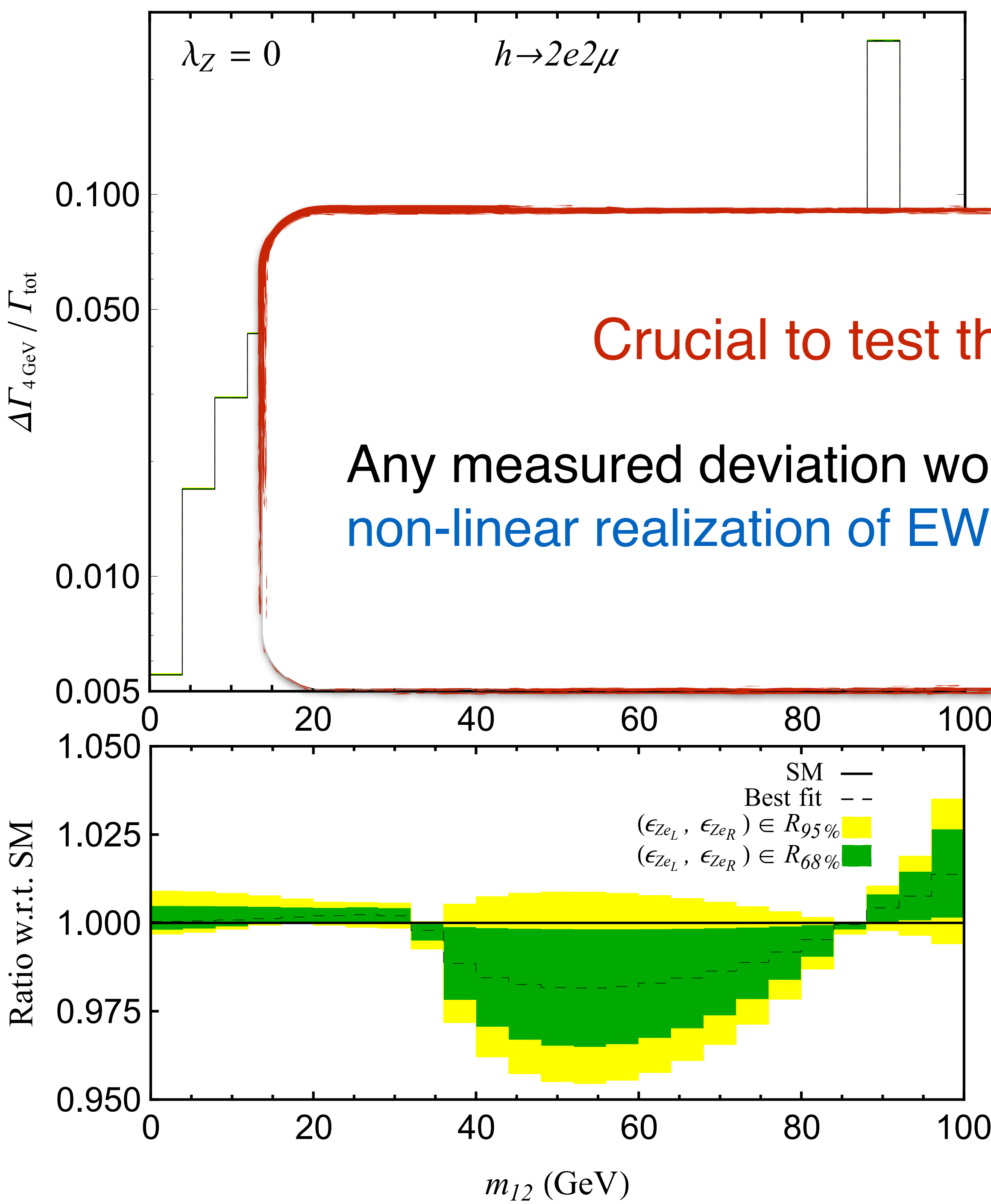

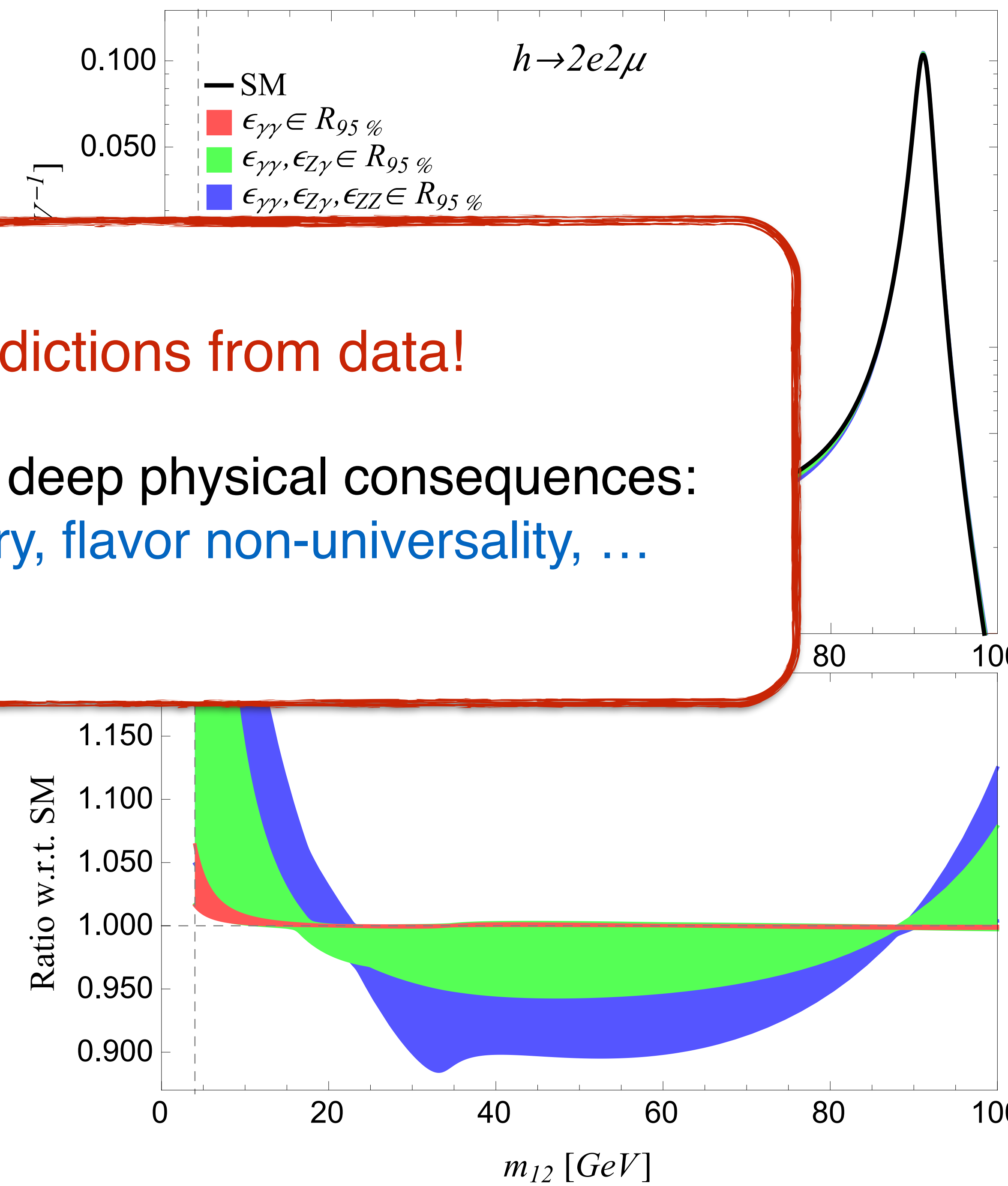

Crucial to test these predictions from data!

Any measured deviation would have deep physical consequences: non-linear realization of EW symmetry, flavor non-universality, …

Small deviations allowed in the shape.

These PO can be studied also from angular distributions.

Conclusions

Pseudo-observables

Clear connection to measurable distributions.

Directly related to physical properties of the amplitude.

Easy to match to any EFT in any basis.

Symmetries impose relations among Higgs PO, which can be tested by Higgs data only.

Assuming a underlying linear EFT we obtained relations among Higgs and non-Higgs processes. Given LEP constraints we derived detailed predictions for $h \to 4\ell$ processes.

Testing these predictions from data would provide an important test for the linear EFT.

PO can be implemented both for Matrix Element Methods, and Montecarlo (MG5).

Thank you!

Kinematical distributions

Backup

The matrix element squared is directly obtained analytically from the amplitude.

$$\sum_{\mathrm{s}} \mathcal{A}\mathcal{A}^*$$

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$$\sum_{s} \mathcal{A}\mathcal{A}^*$$

This can be used for Matrix Element Method experimental analysis, or to derive differential distributions:

Example for CP conserving terms

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

$$\frac{d\Gamma}{dq_1^2 dq_2^2} = \Pi_{4l} \int d\Omega \sum_{s} \mathcal{A}\mathcal{A}^* = \frac{d\Gamma^{11}}{dq_1^2 dq_2^2} + \frac{d\Gamma^{13}}{dq_1^2 dq_2^2} + \frac{d\Gamma^{33}}{dq_1^2 dq_2^2}$$

For example, the 11 term is simply:

$$\frac{d\Gamma^{11}}{dq_1^2 dq_2^2} = \frac{\lambda_p}{2^{10}(2\pi)^7 m_h} \left(\frac{2m_Z^2}{v_F}\right)^2 \frac{128\pi^2}{9} q_1^2 q_2^2 \frac{3 + 2\beta_1\beta_2 - 2(\beta_1^2 + \beta_2^2) + 3\beta_1^2\beta_2^2}{(1-\beta_1^2)(1-\beta_2^2)} \sum_{f,f'} \left| F_1^{ff'} \right|^2$$

$$\lambda_p = \sqrt{1 + \left(\frac{q_1^2 - q_2^2}{m_h^2}\right)^2 - 2\frac{q_1^2 + q_2^2}{m_h^2}} \qquad \beta_{1(2)} = \sqrt{1 - \frac{4q_{1(2)}^2 m_h^2}{(q_{1(2)}^2 - q_{2(1)}^2 + m_h^2)^2}}$$

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From this we can get the total rate dependence on the PO:

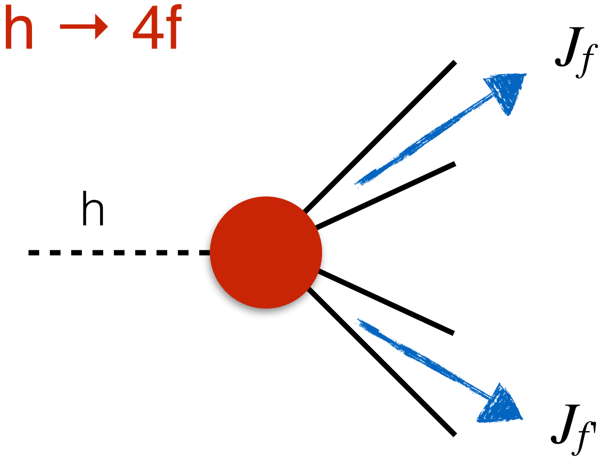
$$\frac{\Gamma_{e^+e^-\mu^+\mu^-}}{\Gamma_{e^+e^-\mu^+\mu^-}^{SM}} = 1 + 2\delta\kappa_{ZZ} - 2.5\epsilon_{Ze_R} + 2.9\epsilon_{Ze_L} - 2.5\epsilon_{Z\mu_R} + 2.9\epsilon_{Z\mu_L} + 0.5\epsilon_{ZZ} - 0.9\epsilon_{Z\gamma} + 0.01\epsilon_{\gamma\gamma}$$

PO in EW Higgs Production

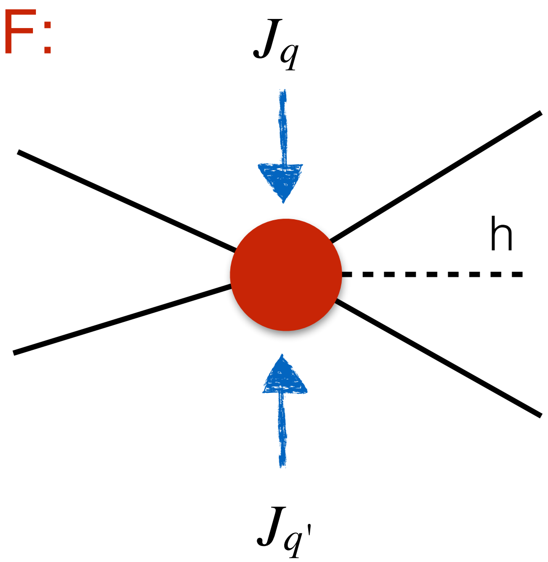
$$\langle 0|\mathcal{T}\left\{J_f^{\mu}(x), J_{f'}^{\nu}(y), h(0)\right\}|0\rangle$$

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

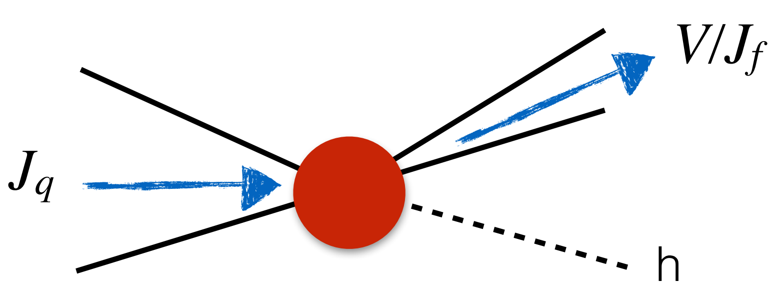
h → 4f



VBF:



V h:

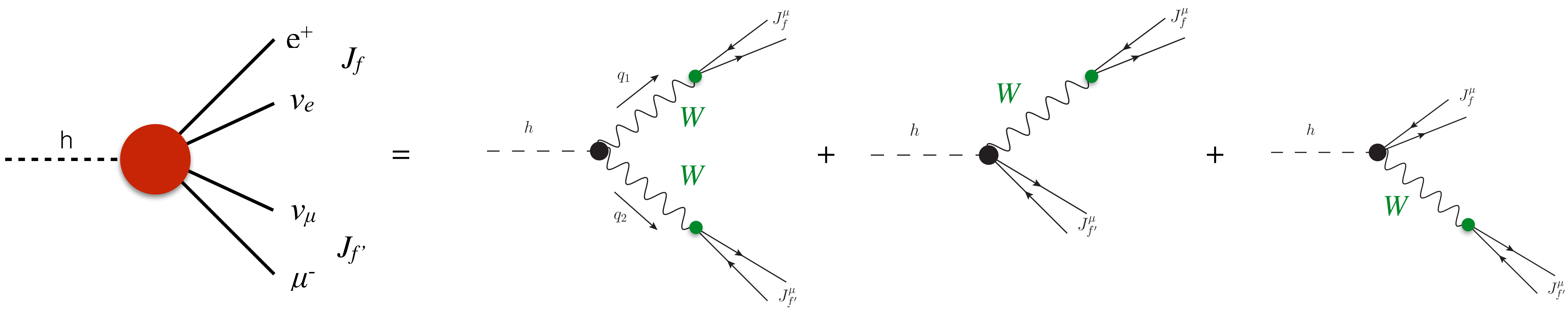


[Work in progress]

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.

Charged current decays

Backup



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.: $h \to e^+ e^- \nu\bar{\nu}$ $h \to \mu^+ \mu^- \nu\bar{\nu}$

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

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

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