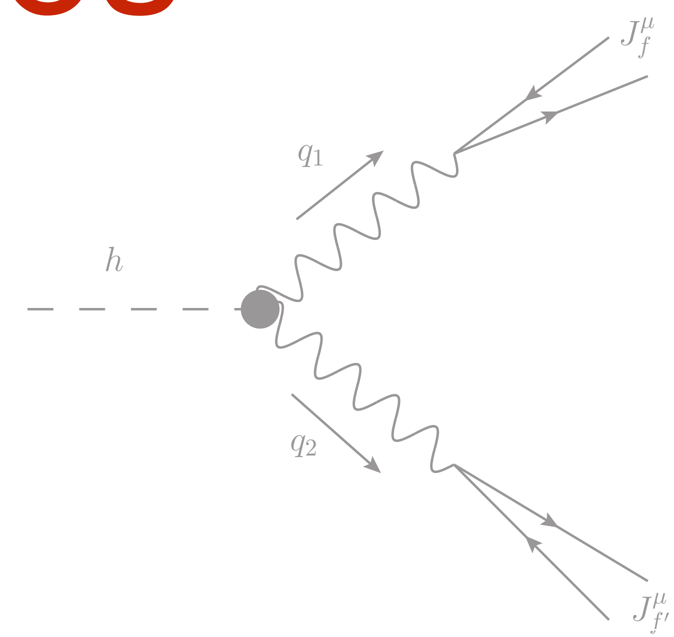
Pseudo-observables in Higgs decays



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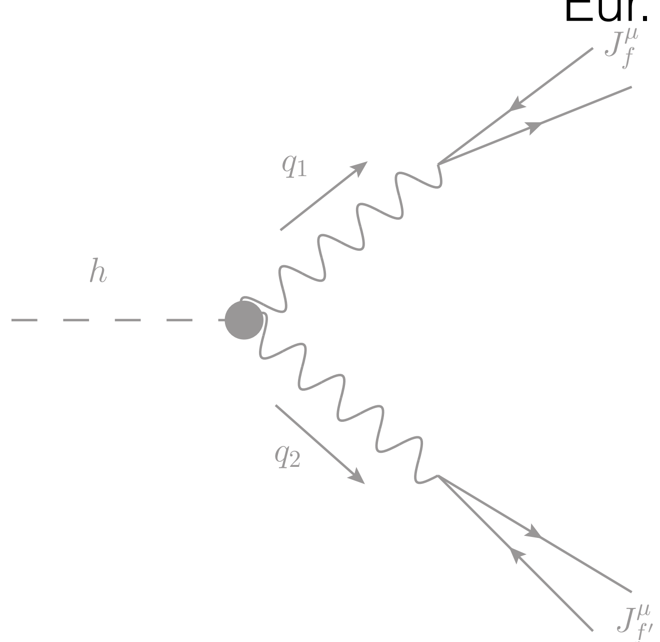
M.Gonzalez-Alonso, A. Greljo, G. Isidori, D.M.

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



DIS 2015, SMU, Dallas

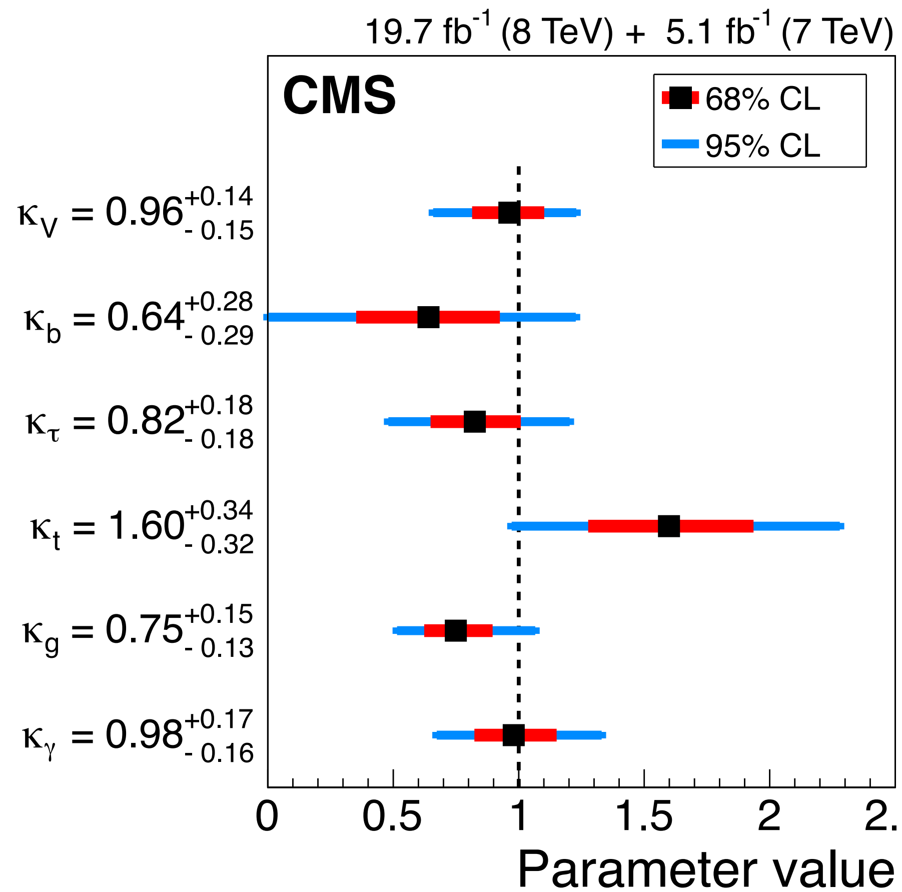
28/05/2015

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.



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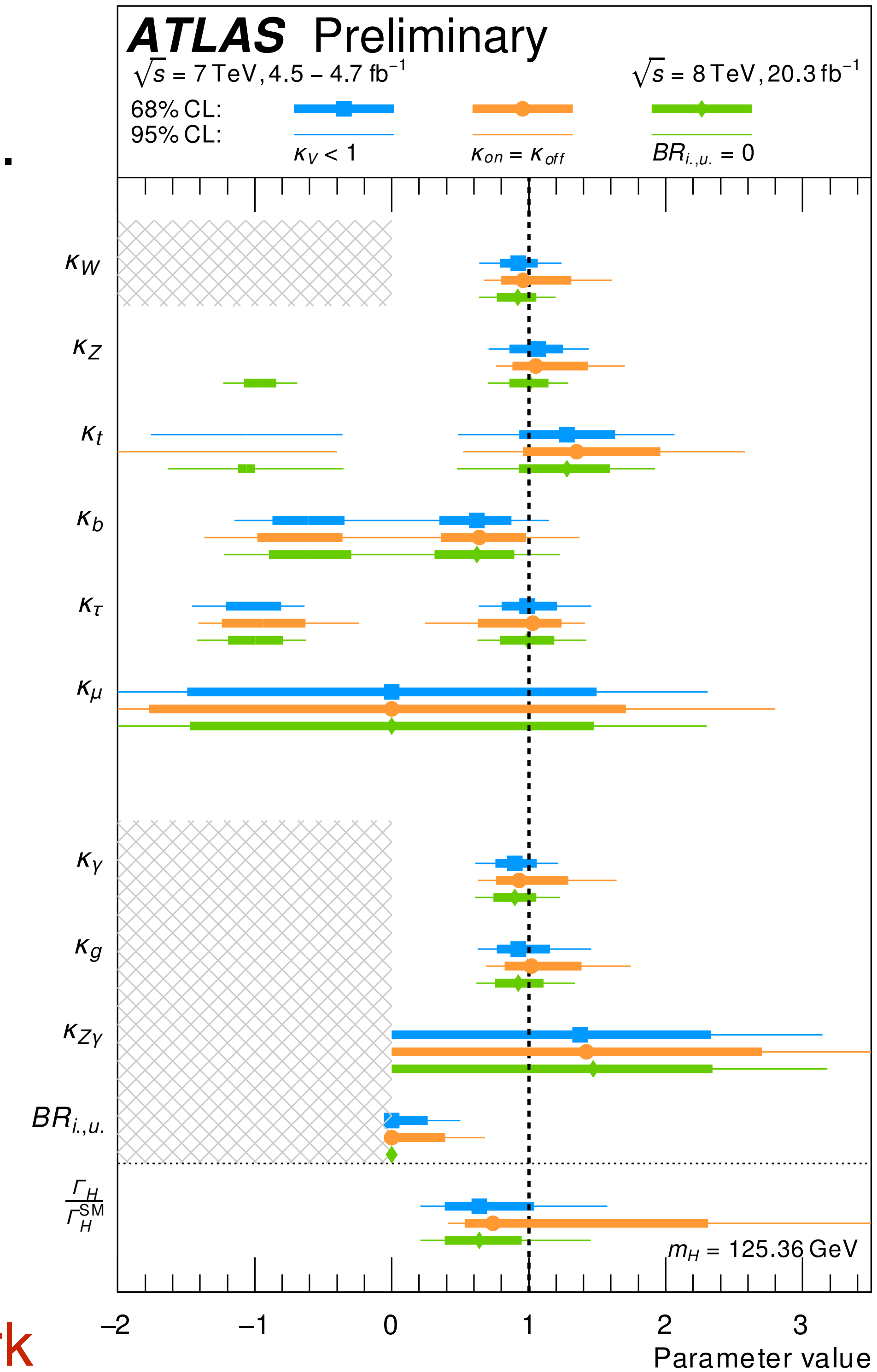


ATLAS-CONF-2015-007

Preparing for Run 2, and beyond, we need a framework capable of collecting, in a systematic way, all available experimental information on the h(125) particle with the least theoretical bias possible: LHC legacy.

Future Higgs studies

this talk

High-precision Higgs physics

Exotic decays

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

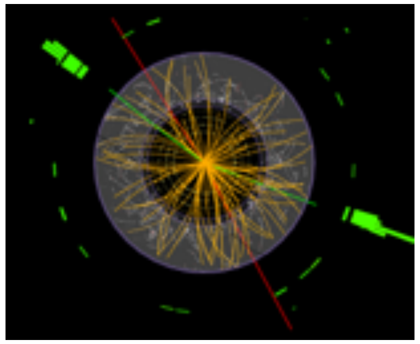
$$\sigma(ii \to \mathrm{h}+X) \times \mathrm{BR}(\mathrm{h} \to ff) = \sigma_{ii} \frac{\Gamma_{ff}}{\Gamma_{\mathrm{h}}} = \frac{\kappa_{ii}^2 \, \kappa_{ff}^2}{\kappa_{\mathrm{h}}^2} \sigma_{SM} \times \mathrm{BR}_{SM}$$

Pros: Clear SM limit ($\kappa \to 1$), theoretically well defined, model independent, can be matched to match to any EFT in any basis.

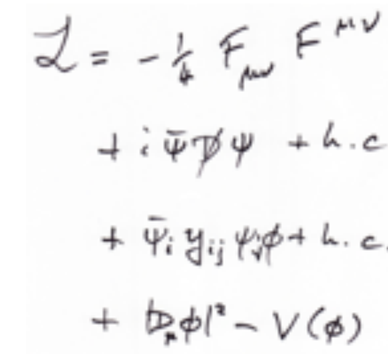
Cons: Limited to total rates:
can't describe deviations in differential distributions, e.g. CPV or h → 4f

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

Pseudo-observables



$$\mathcal{A}(Z(\varepsilon) \to f\bar{f}) = i \sum_{f=f_L,f_R} g_Z^f \, \varepsilon_\mu \, \bar{f}\gamma^\mu f$$



Realistic Observables

Raw data,
Fiducial cross sections,
etc…

Pseudo Observables

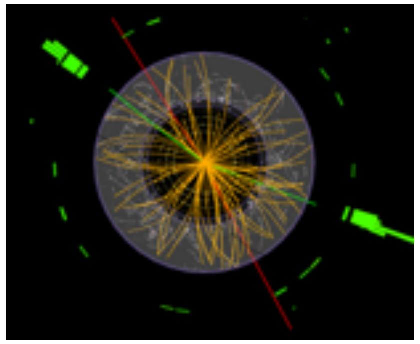
Pole masses, decay widths,
kappas, distributions, etc..

Lagrangian parameters

Couplings,
running masses,
Wilson coefficients
etc …

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

Pseudo-observables



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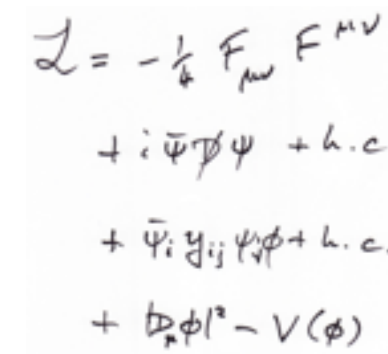

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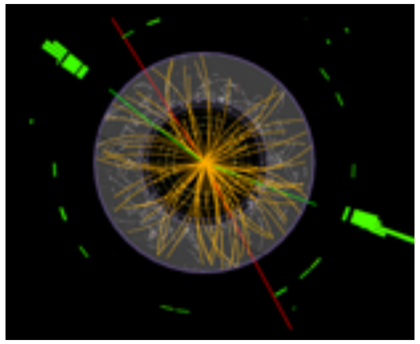
PO encode experimental information in idealized observables, of easy theoretical interpretation. This approach is old: developed at LEP to describe the Z properties.

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

Pseudo-observables



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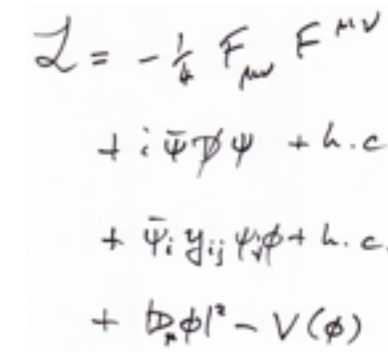

Realistic Observables

Raw data,
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PO encode experime … theoretical interpretation. This a… properties.

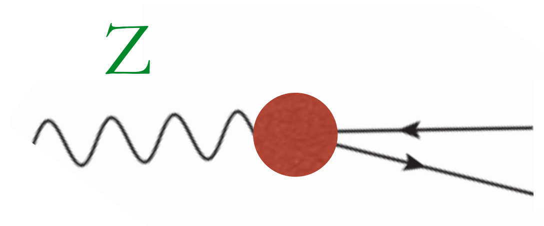
PO can then be mat… EFT, SUSY, Composite Higgs, et…

PO is the place where experimentalists (data) and theorists (EFT) should meet.

LEP-1 Strategy: on-shell Z decays

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

Parametrize 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

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

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

Radiators: final state radiation

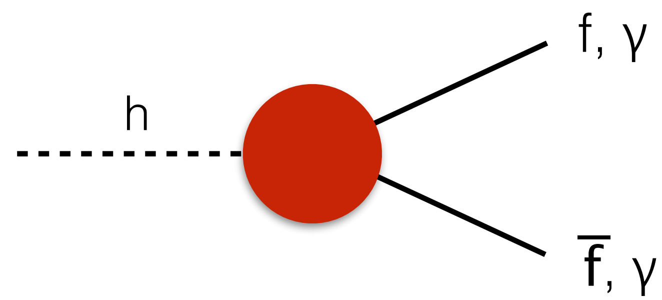
$$\Gamma_f \equiv \Gamma\left(Z \to f\overline{f}\right) = 4\, c_f\, \Gamma_0 \left(|\mathcal{G}_V^f|^2\, R_V^f + |\mathcal{G}_A^f|^2\, R_A^f\right) + \Delta_{\mathrm{EW/QCD}}$$

[Bardin, Grunewald, Passarino '99]

non-factorizable SM corrections, very small.

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

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



The kinematic is fixed.

No polarization information is retained. → the total rate (κ) is all that can be extracted from data

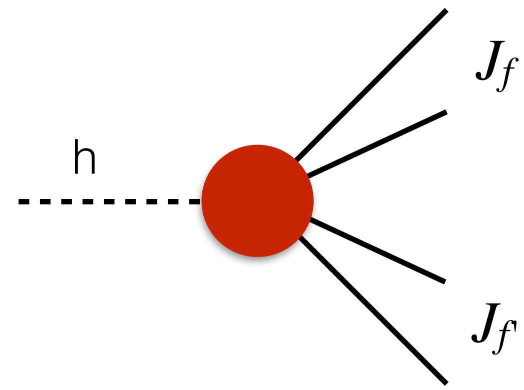
$$\mathcal{A}(h \to f\bar{f}) = -\frac{i}{\sqrt{2}}\left[\underline{(y_S^f + i y_P^f)}\bar{f}_L f_R + \underline{(y_S^f - i y_P^f)}\bar{f}_R f_L\right] \xrightarrow{\Gamma_f} \boxed{|y_S^f|^2 + |y_P^f|^2}$$

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

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

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

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.

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

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

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

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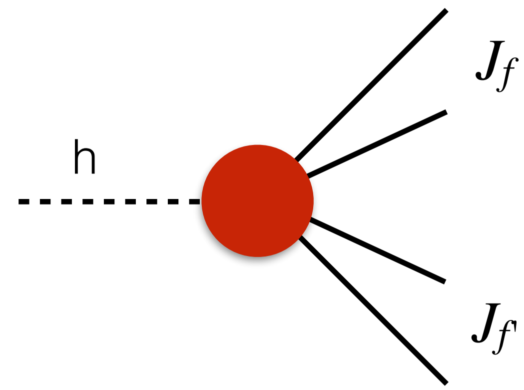

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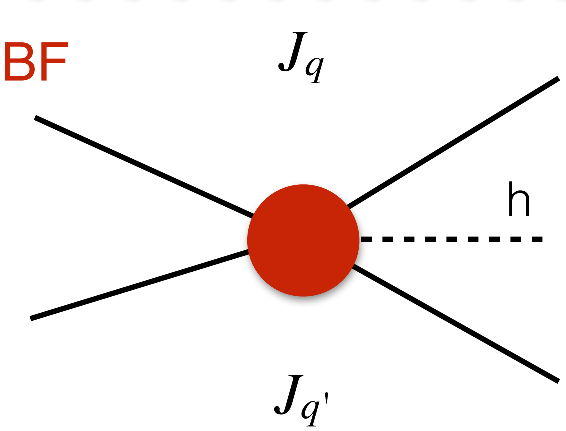
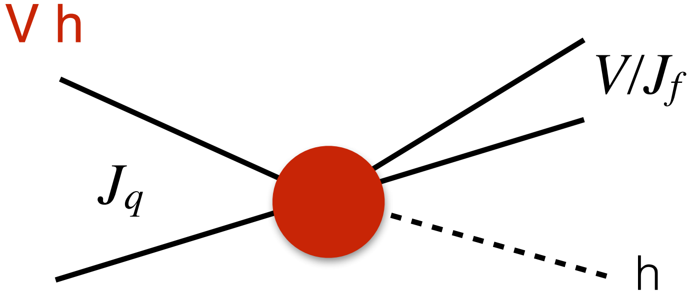
Note: the same correlation function, in a different kinematical region, enters also in EW Higgs production.

VBF



V h



Higgs to 4-fermion decays

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

Only 3 Lorentz structures allowed by $\mathrm{U(1)_{em}}$ gauge symmetry:

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

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

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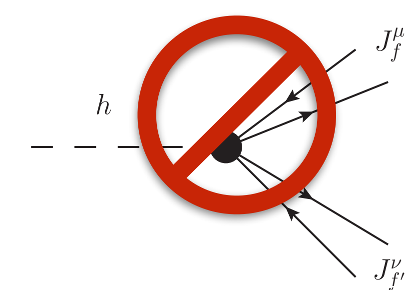
$$\boxed{\langle 0|\mathcal{T}\left\{J_f^\mu(x), J_{f'}^\nu(y), h(0)\right\}|0\rangle}$$

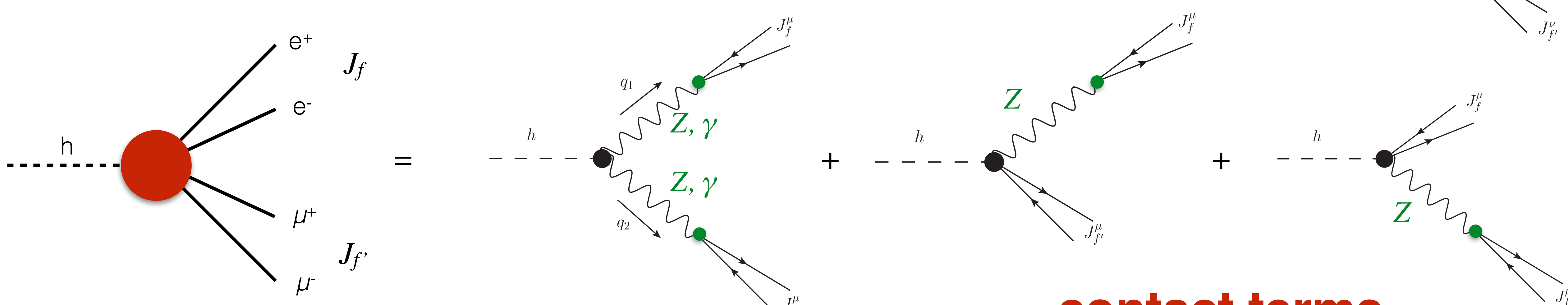
includes

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

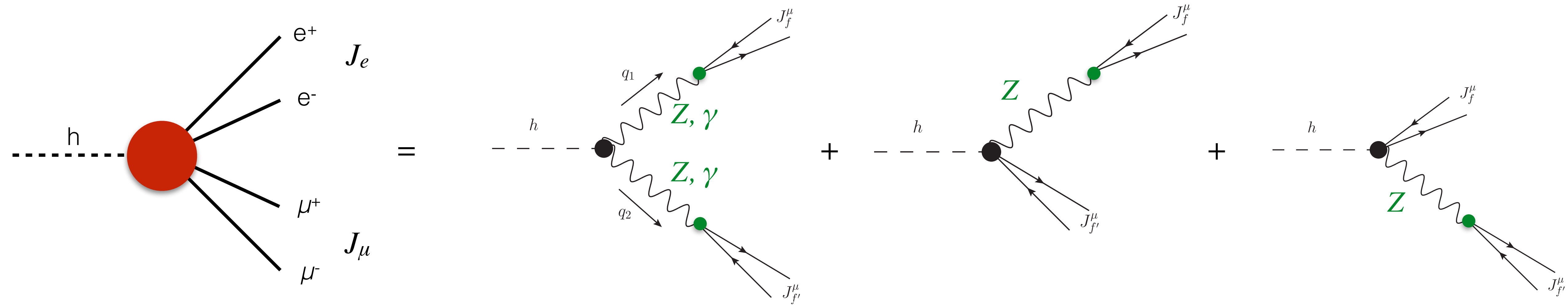
Short-distance modes: contact terms, x and/or $y \to 0$

Neglecting local terms, corresponding to operators with d > 6:





contact terms



We expand around the physical poles:

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

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

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

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

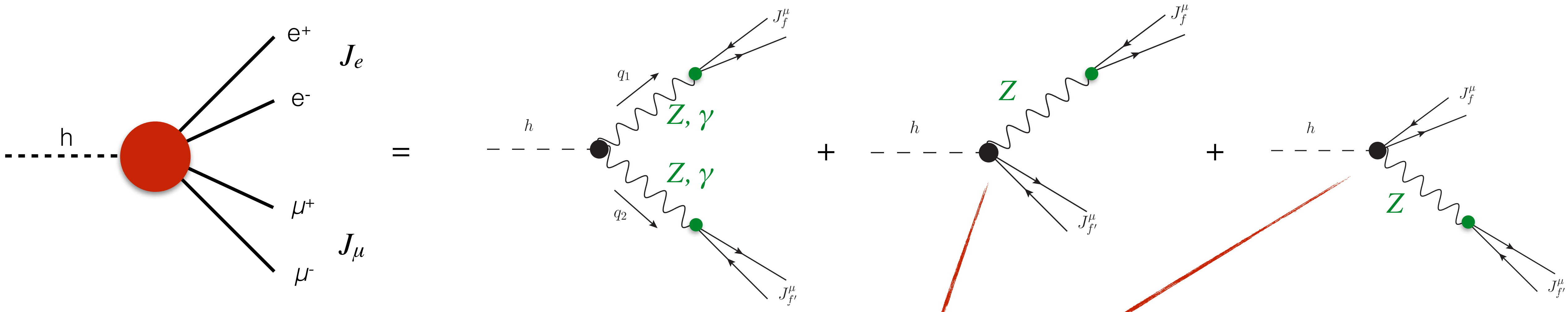
$$\times\frac{q_1\cdot q_2\; g^{\alpha\beta} - {q_2}^\alpha {q_1}^\beta}{m_Z^2} +$$

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

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

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

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



We expand around the physical poles:

contact terms
only source of
flavor dependence

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

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

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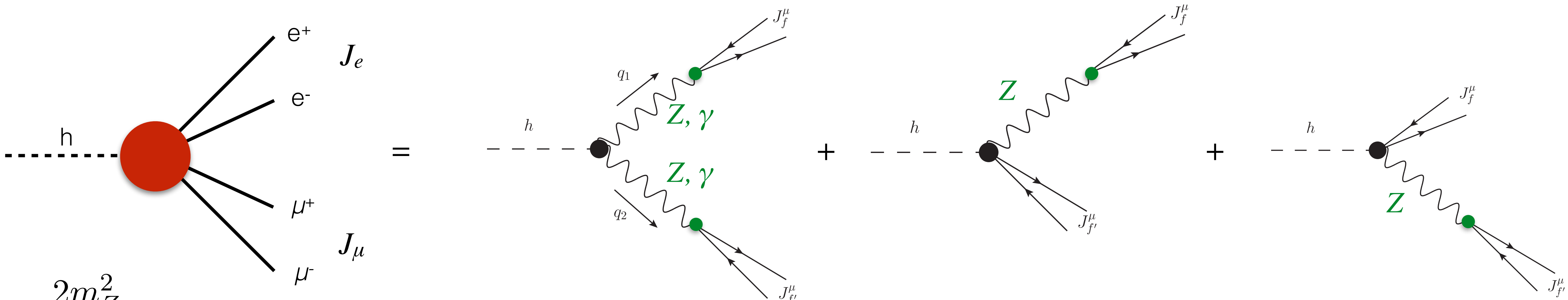

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$$

$$
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$$

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

Higgs PO :

- related to physical distributions, measurable experimentally.
- defined from the residues of the Green function on its poles.
- Can be matched with Wilson coefficients at the desired order.
  (at tree level they are a simple linear combination of coefficients)
- QED radiation corrections (radiator functions) are being computed.

[Isidori et al, work in progress]

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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Charged current

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

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Symmetries impose relations among these observables.

Flavor universality

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

Parameter counting and symmetry assumptions

Neutral current

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

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

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Charged current

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

$\kappa_{WW}, \epsilon_{WW}, \epsilon_{WW}^{CP}$,
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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

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

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

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.

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

$$\bigstar\ \epsilon_{WW} = c_w^2\epsilon_{ZZ} + 2c_w s_w \epsilon_{Z\gamma} + s_w^2 \epsilon_{\gamma\gamma} ,$$
$$\bigstar\ \epsilon^{CP}_{WW} = c_w^2\epsilon^{CP}_{ZZ} + 2c_w s_w \epsilon^{CP}_{Z\gamma} + s_w^2 \epsilon^{CP}_{\gamma\gamma} ,$$
$$\boxed{\kappa_{WW} - \kappa_{ZZ} = -\frac{2}{g}\left(\sqrt{2}\epsilon_{We^i_L} + 2c_w\epsilon_{Ze^i_L}\right)} ,$$
$$\bigstar\ \epsilon_{We^i_L} = \frac{c_w}{\sqrt{2}}(\epsilon_{Z\nu^i_L} - \epsilon_{Ze^i_L}) ,$$

★ Accidentally true also in the linear EFT.

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

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

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

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$$\star\ \epsilon_{WW}^{CP} = c_w^2\epsilon_{ZZ}^{CP} + 2c_w s_w \epsilon_{Z\gamma}^{CP} + s_w^2 \epsilon_{\gamma\gamma}^{CP} ,$$
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Parameter counting and symmetry assumptions

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

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

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

$h \to \gamma\gamma$

Charged $h \to e^+\mu^-\nu$ κ_{WW}, ϵ_{WW}, ϵ^{CP}_{WW} ,

nplex)

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

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

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

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

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

Custodial symmetry

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

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

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

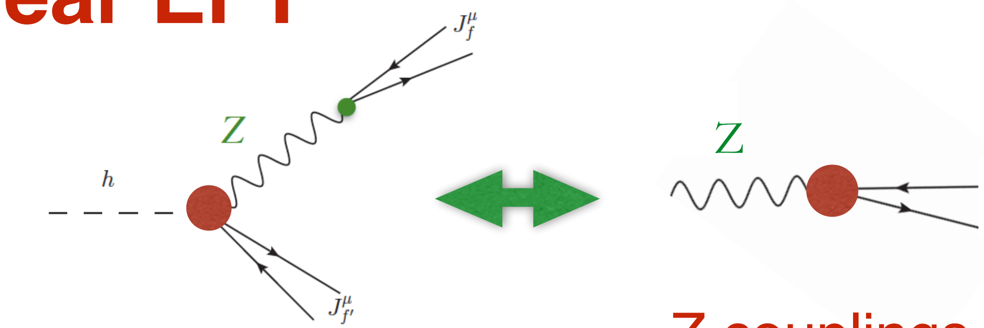
$$\bigstar\ \epsilon_{We^i_L} = \frac{c_w}{\sqrt{2}}\left(\epsilon_{Z\nu^i_L} - \epsilon_{Ze^i_L}\right) ,$$

★ Accidentally true also in the linear EFT.

Higgs PO and linear EFT

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

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



Higgs PO

Z couplings &
Triple Gauge Couplings

Higgs PO and linear EFT

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

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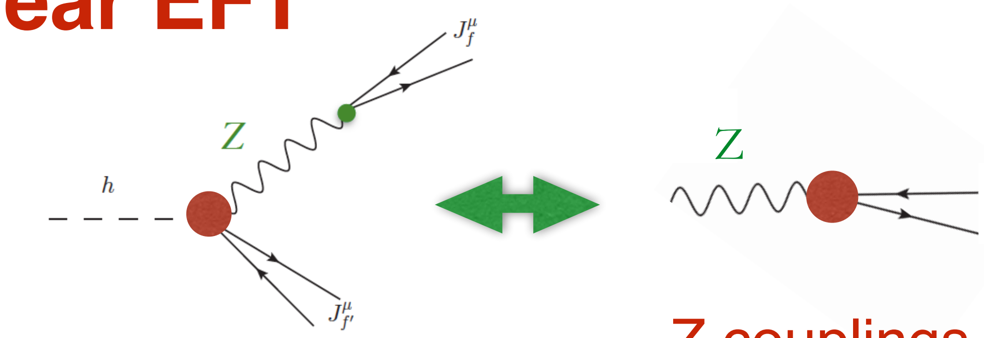


Higgs PO

Z couplings &
Triple Gauge Couplings

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

["Higgs basis", LHCHXSWG 2015]

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

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

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

$$\delta\epsilon_X = \epsilon_X - \epsilon_X^{\rm SM}$$

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

Flavor universality from data!

[Efrati, Falkowski, Soreq 2015]

TGC (LEP-II):

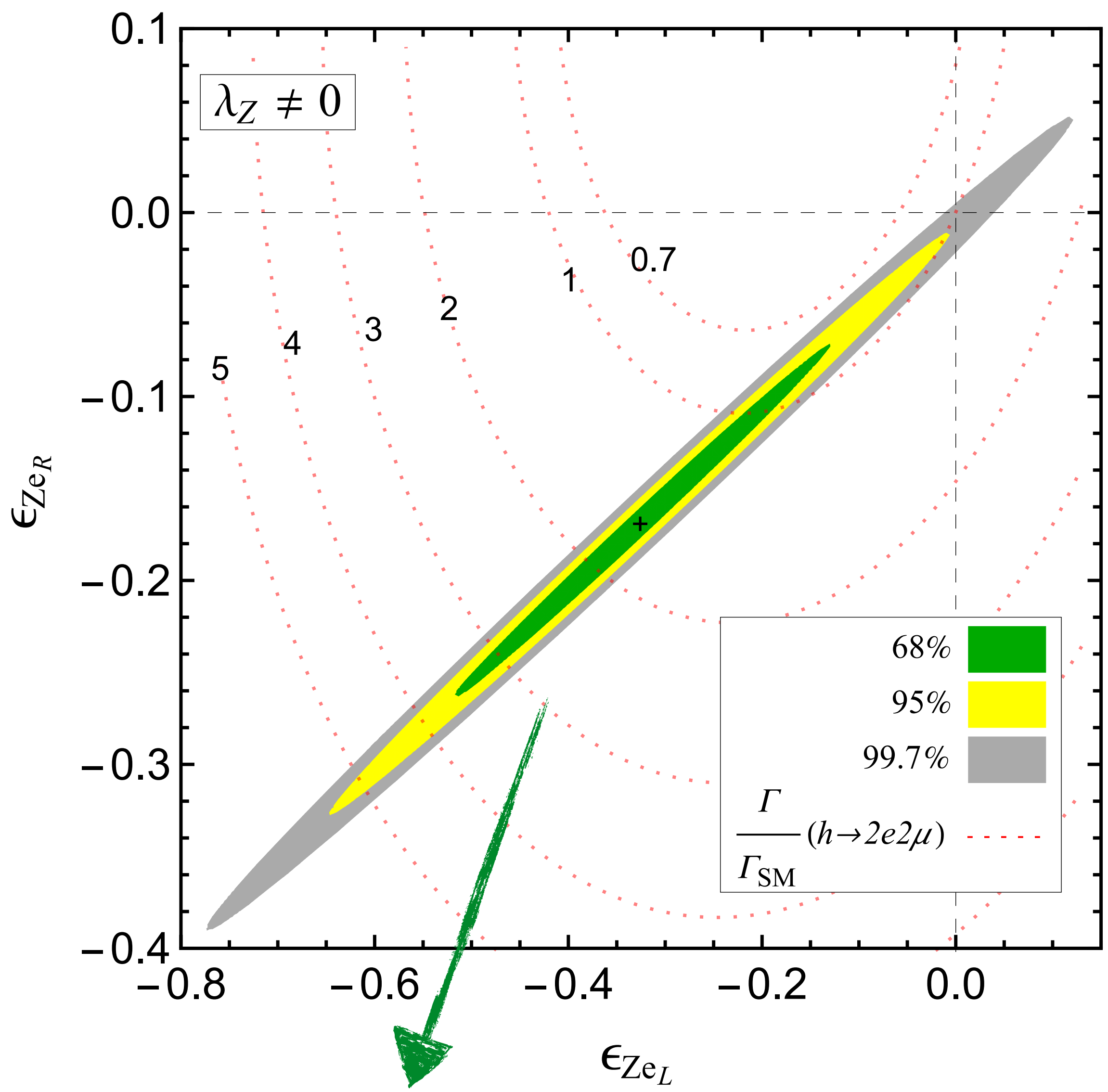
any λ_Z: $\delta g_{1,z} \lesssim O(1)$, $\delta\kappa_\gamma \lesssim 10^{-2}$

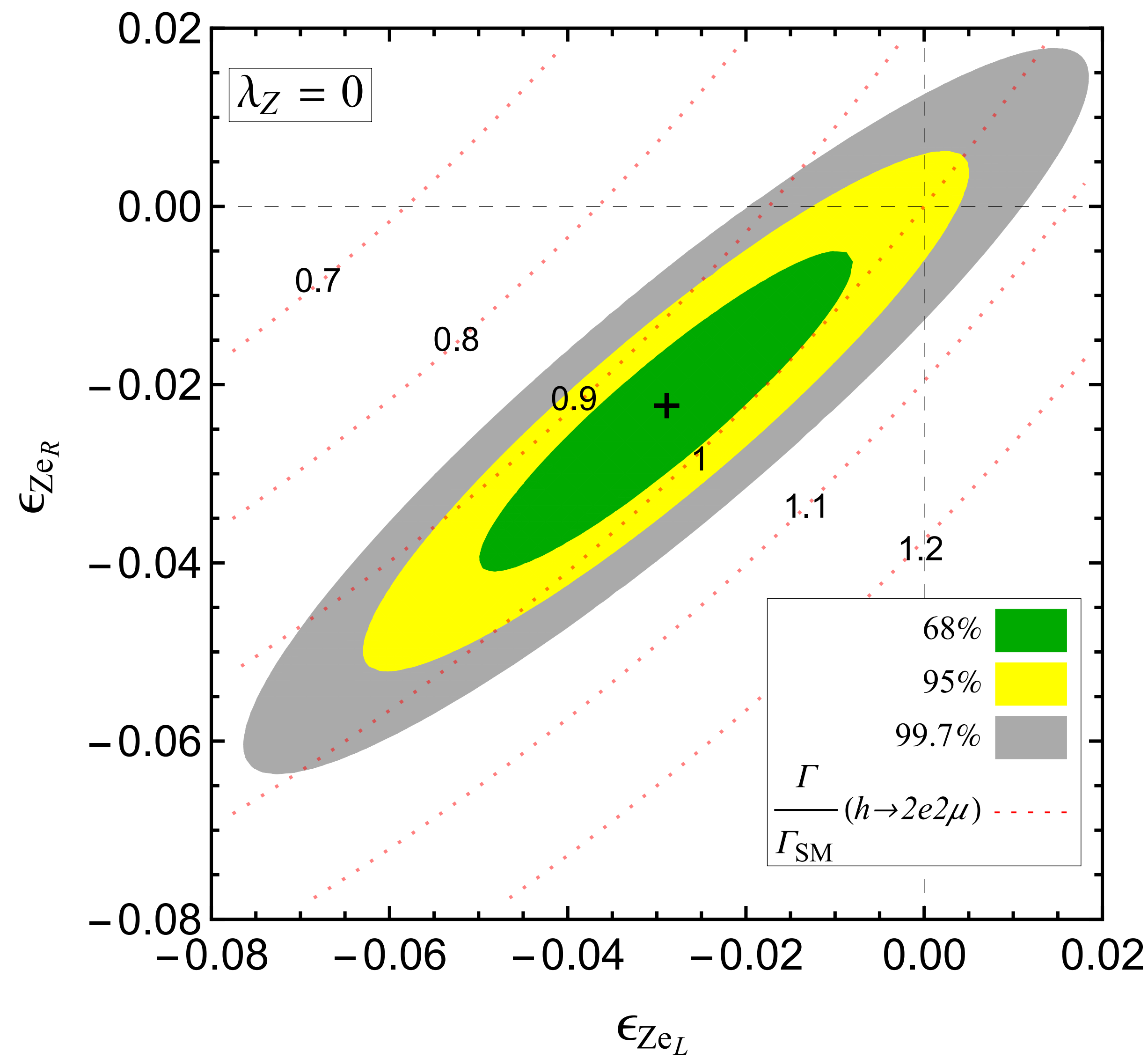
$\lambda_Z = 0$: $\delta g_{1,z}$, $\delta\kappa_\gamma \lesssim 10^{-2}$

[Falkowski, Riva 2014, …]

Constraints on the PO in the linear EFT

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





$$\varepsilon_{Ze_R} \approx 2s_w^2 \varepsilon_{Ze_L}$$

Using fits from:

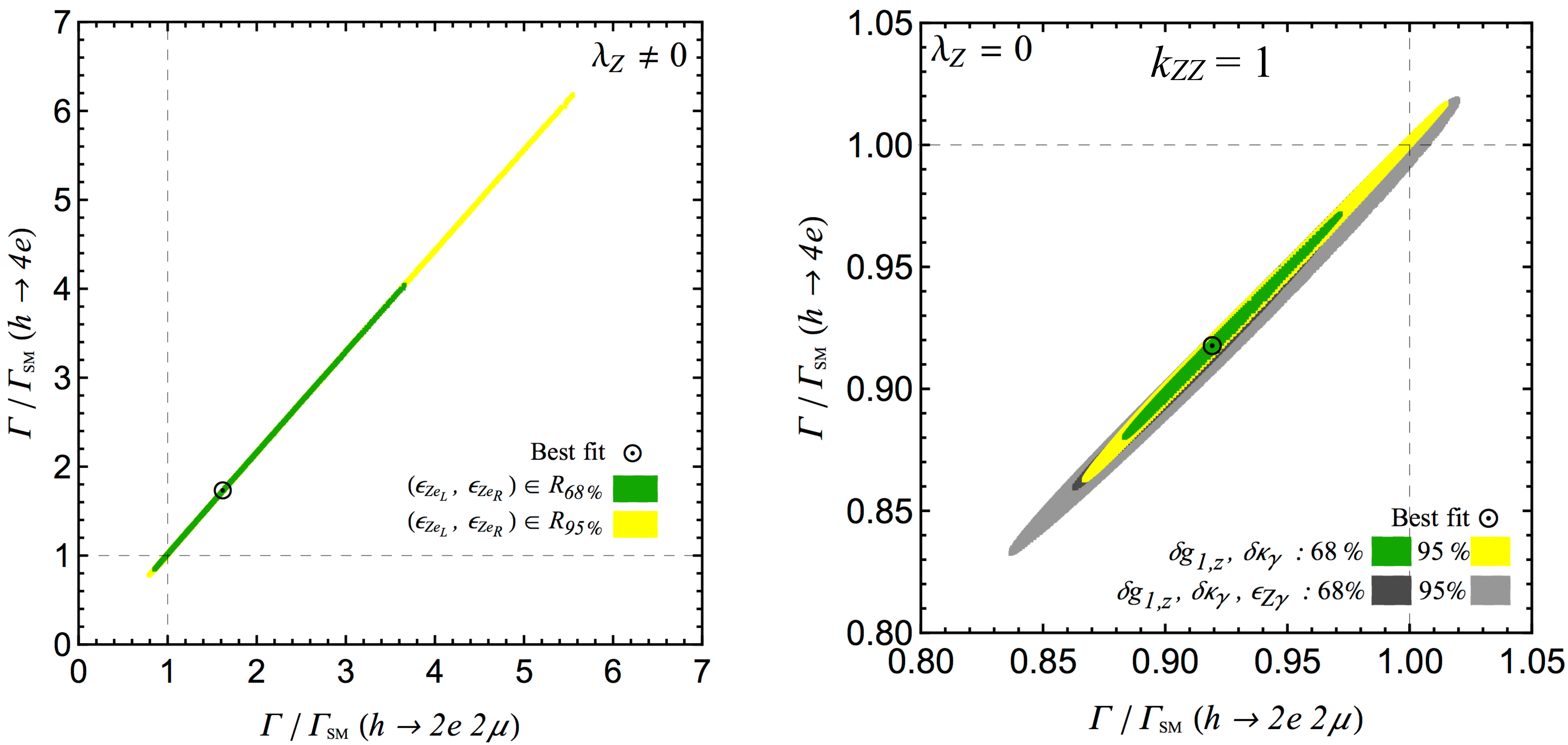
[Falkowski, Riva 2014]

[Efrati, Falkowski, Soreq 2015]

More details in arXiv:1504.04018

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:

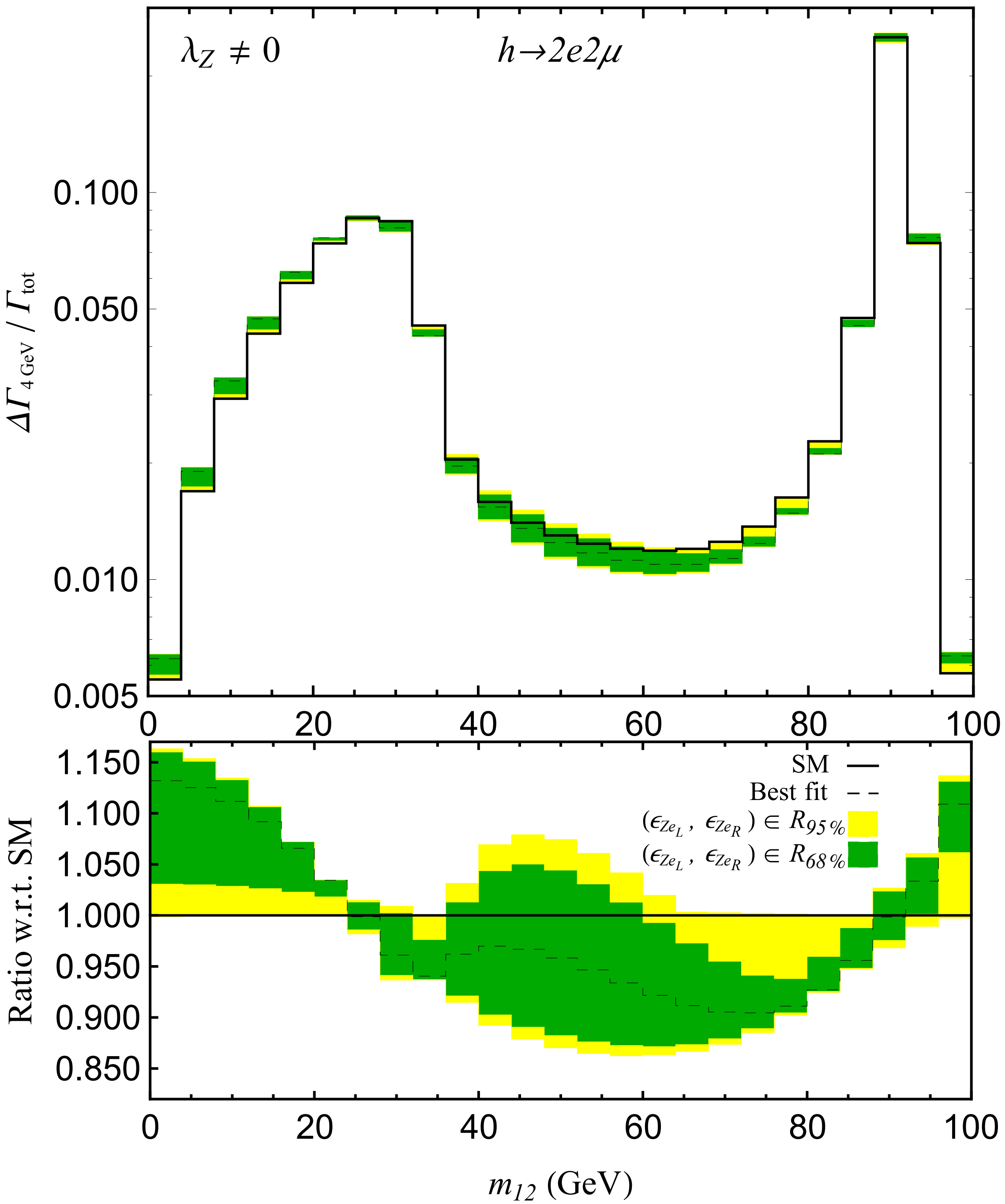


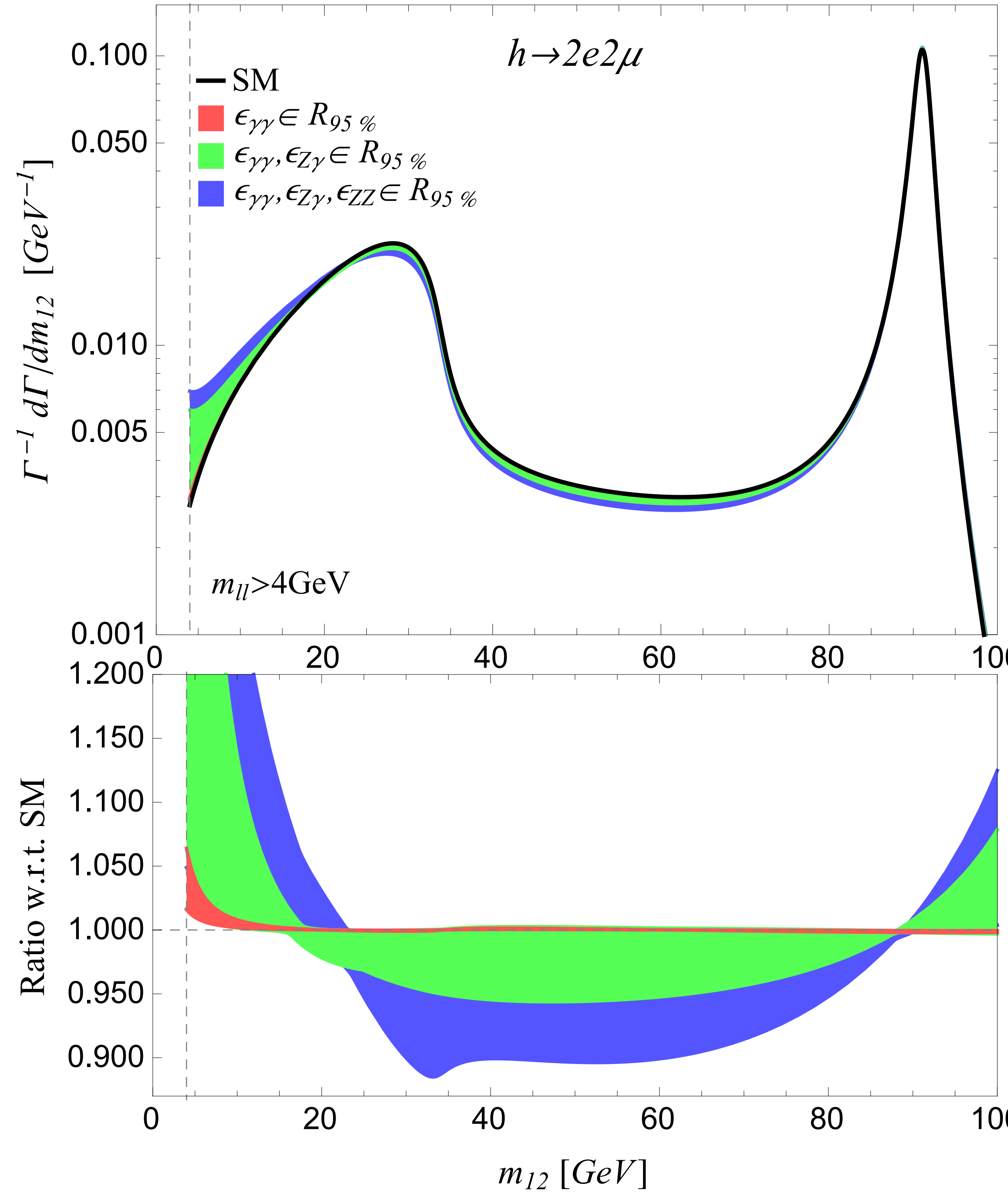
O(1) deviations allowed in the rate.

High correlation between different channels due to flavor universality (consequence of the linear EFT).

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:



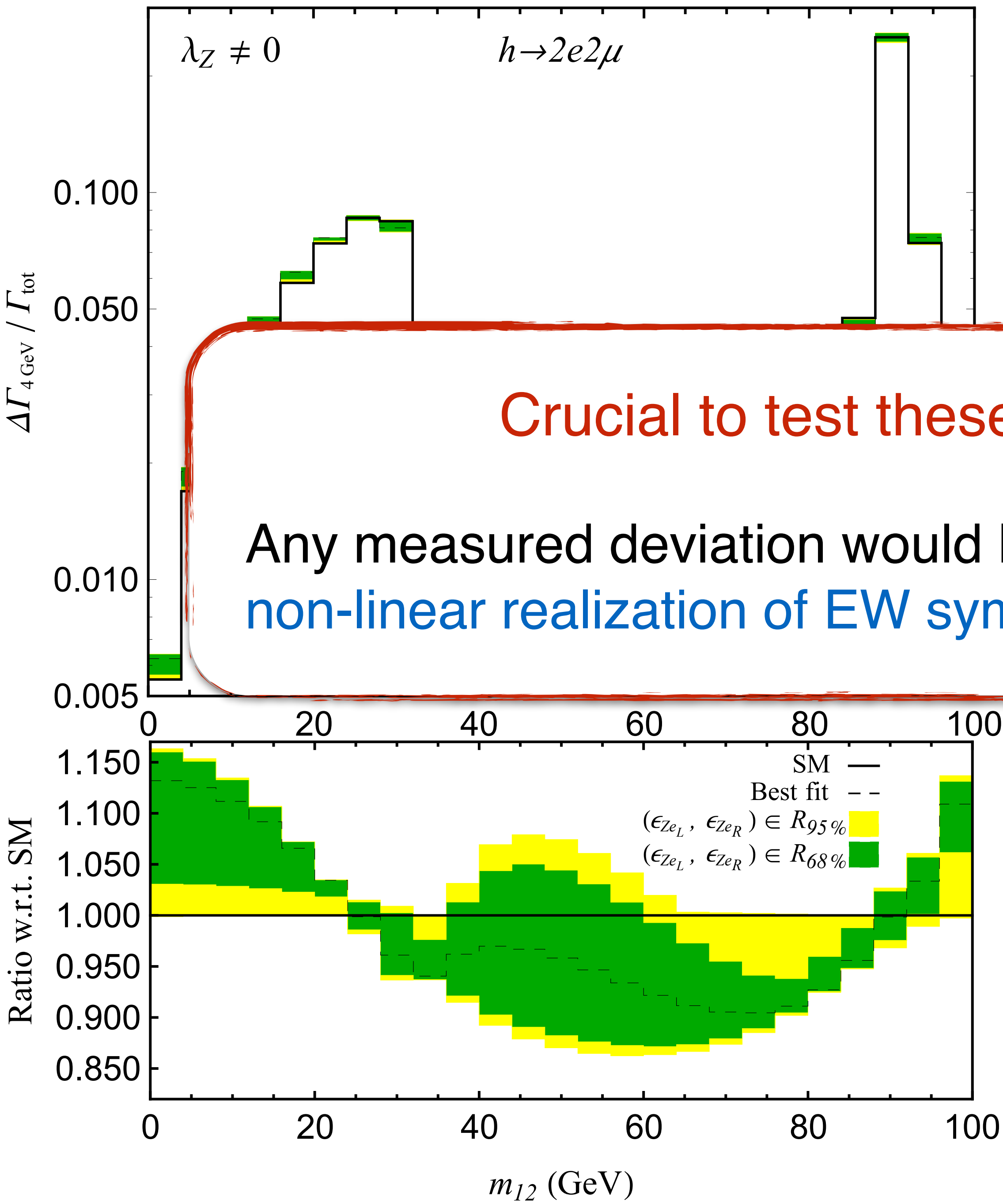


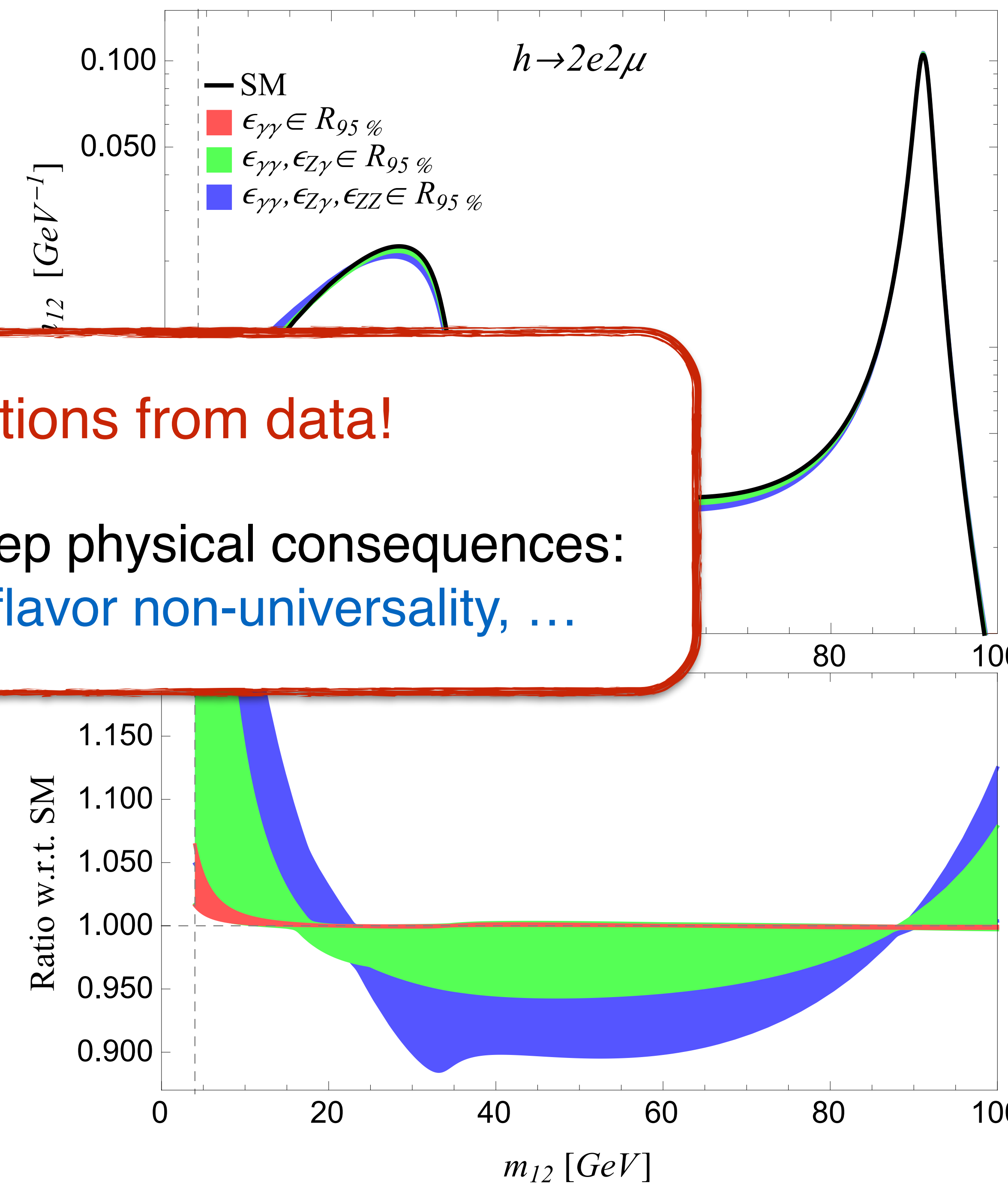
Small deviations allowed in the shape.

These PO can be studied also from angular distributions.

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:





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.

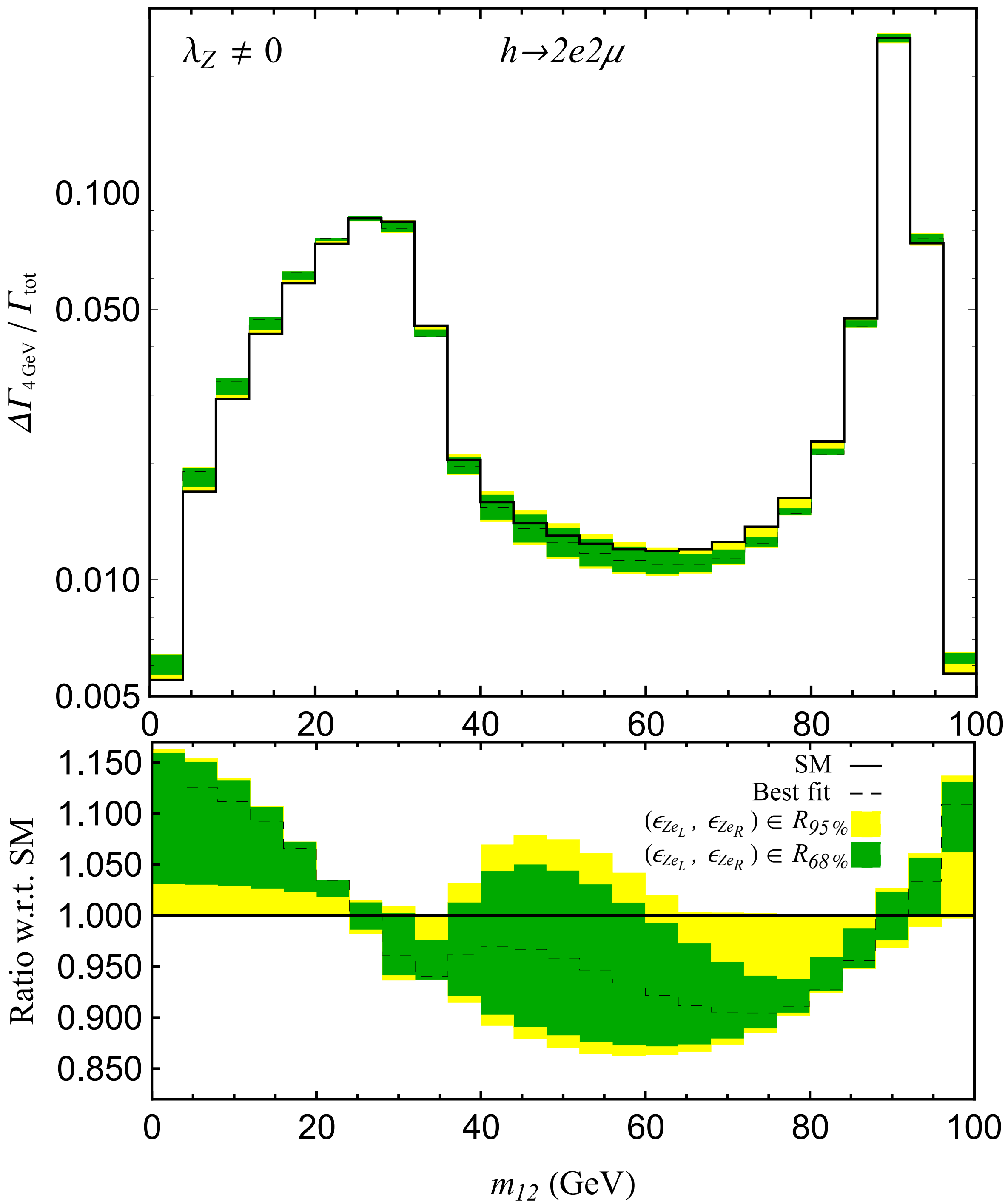
PO can be implemented both for Matrix Element Methods, and Montecarlo (MG5).

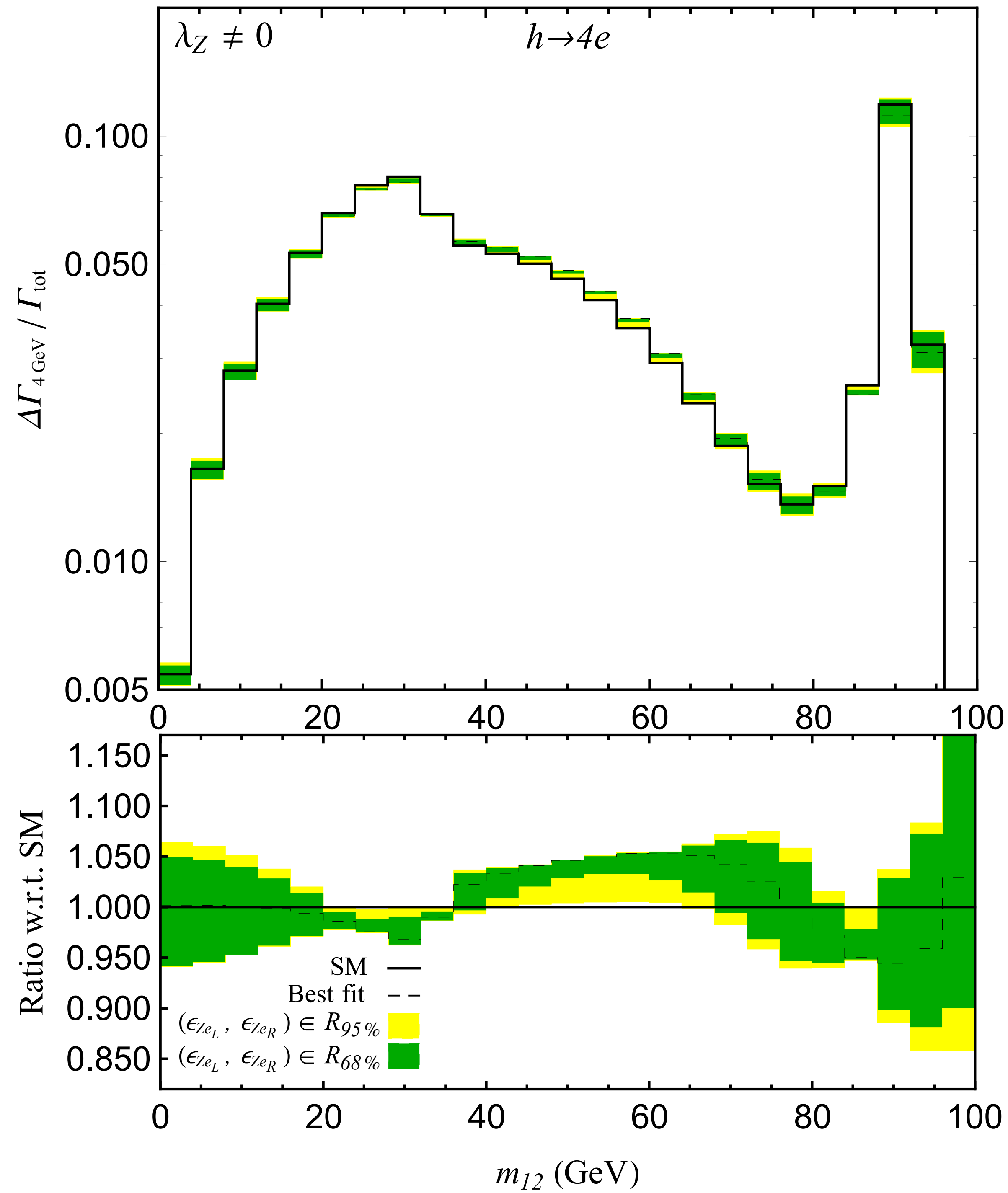
[A. Greljo, D.M. private code]

Thank you!

Predictions for h → 4ℓ in the linear EFT

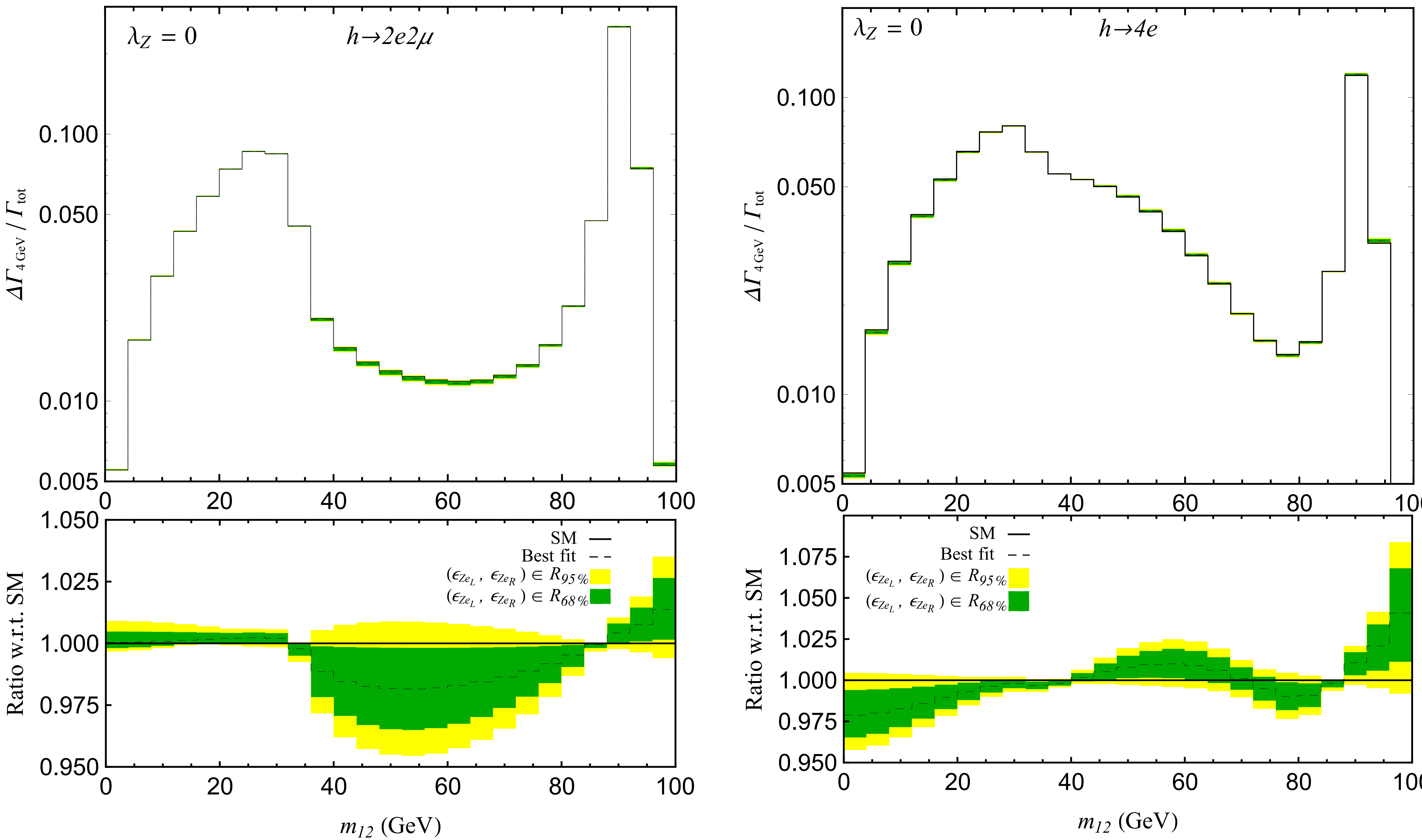
Backup





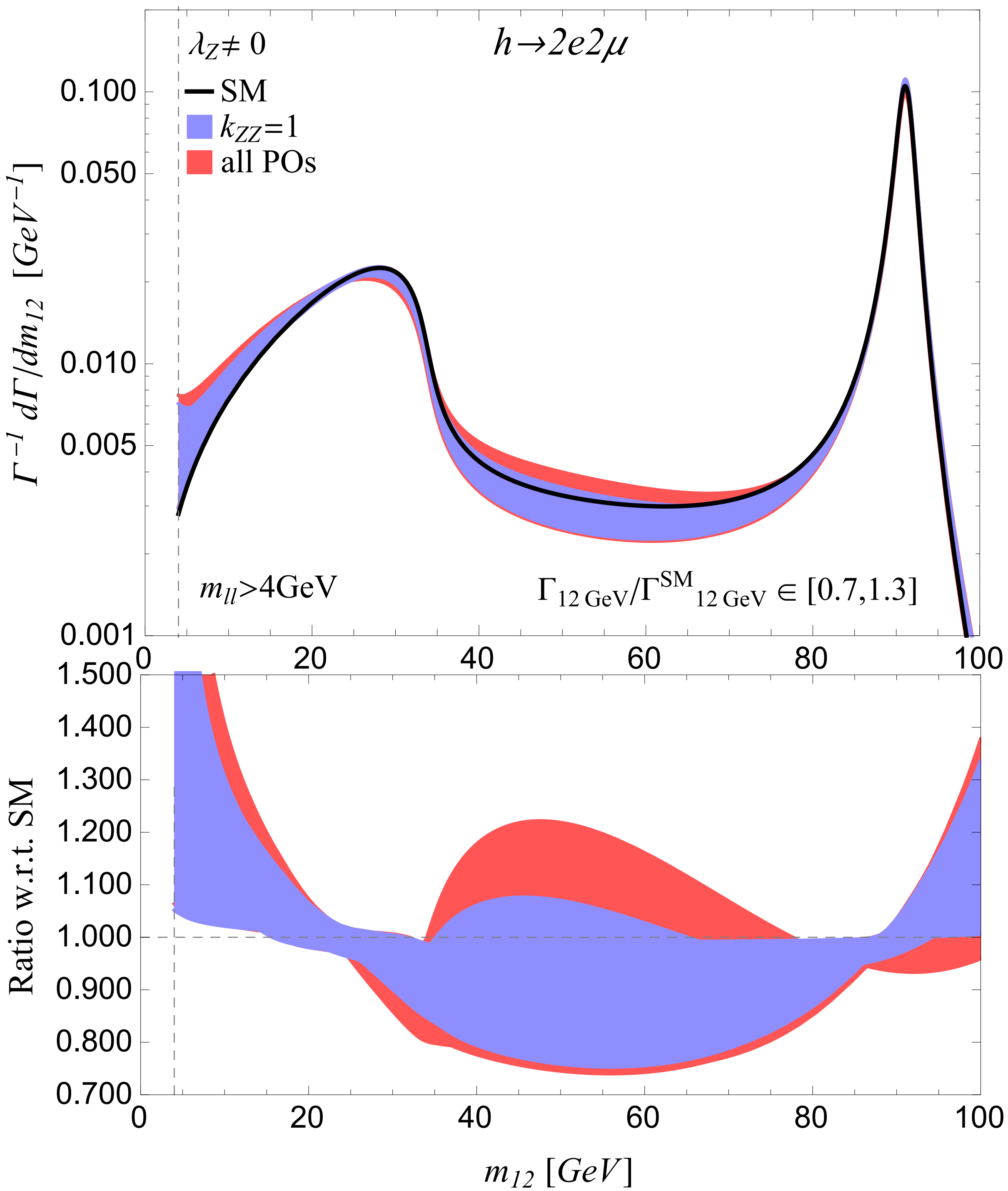
Predictions for h → 4ℓ in the linear EFT

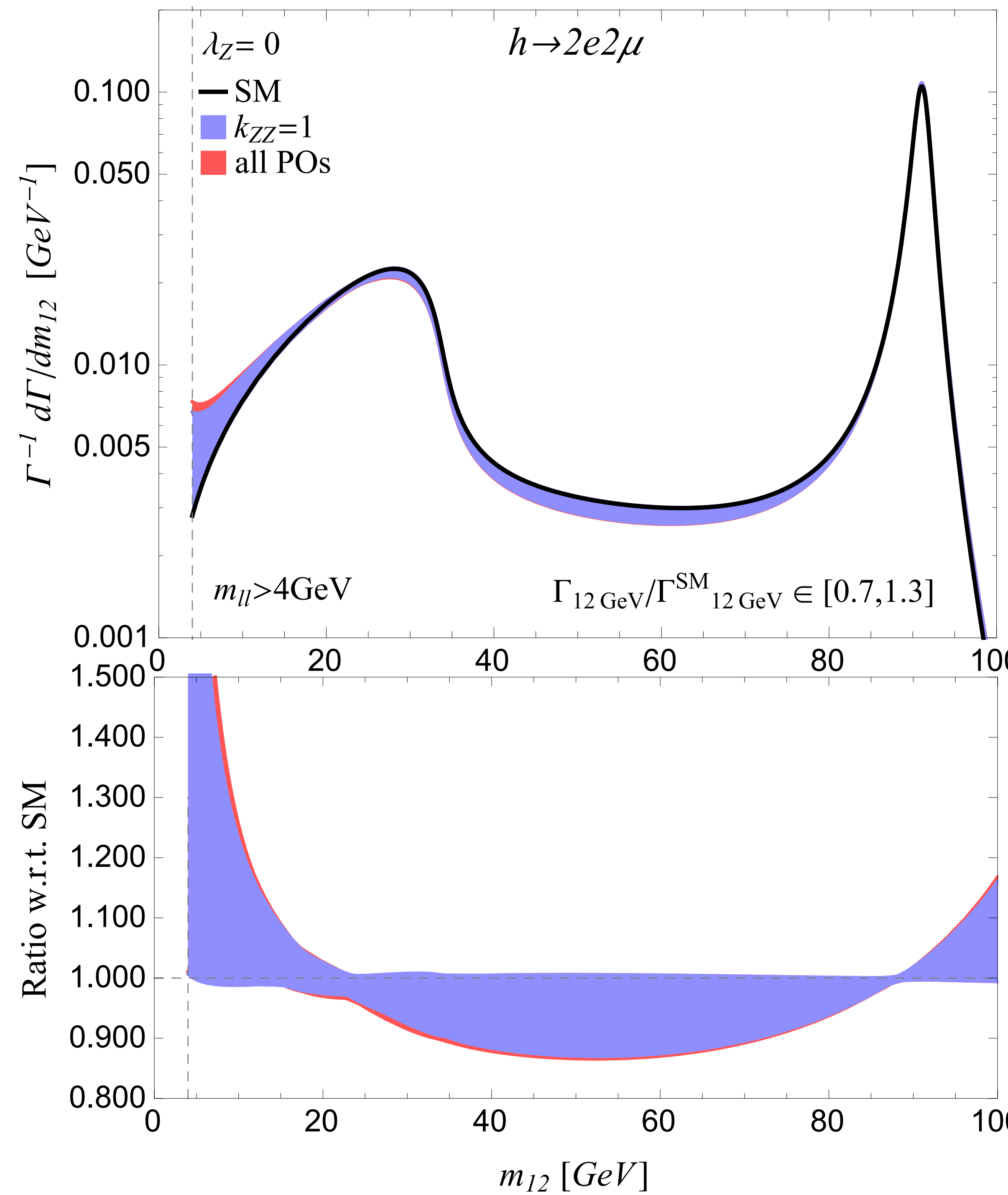
Backup



Predictions for h → 4ℓ in the linear EFT

Backup





Predictions for h → eμνν in the linear EFT

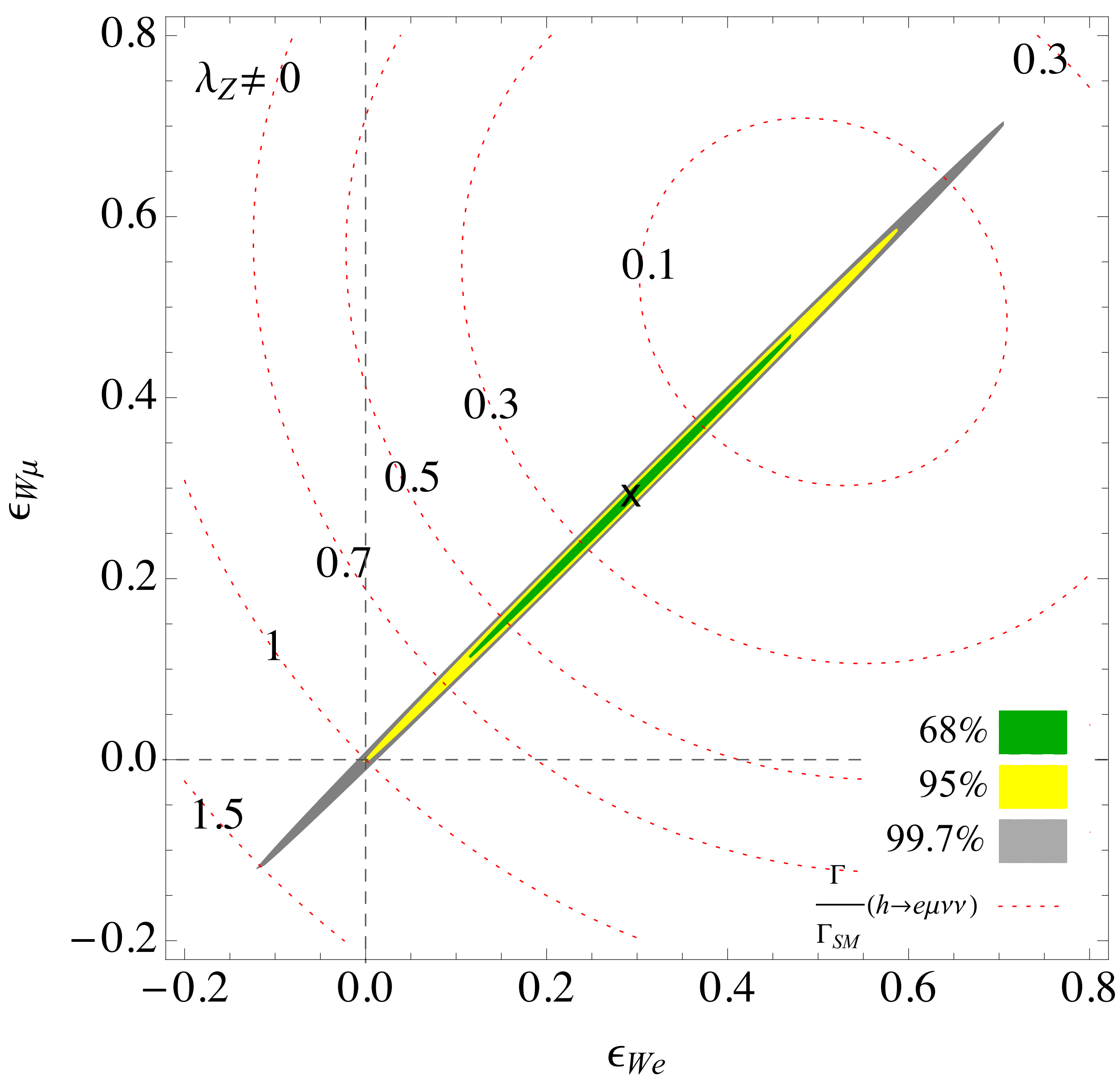
Backup

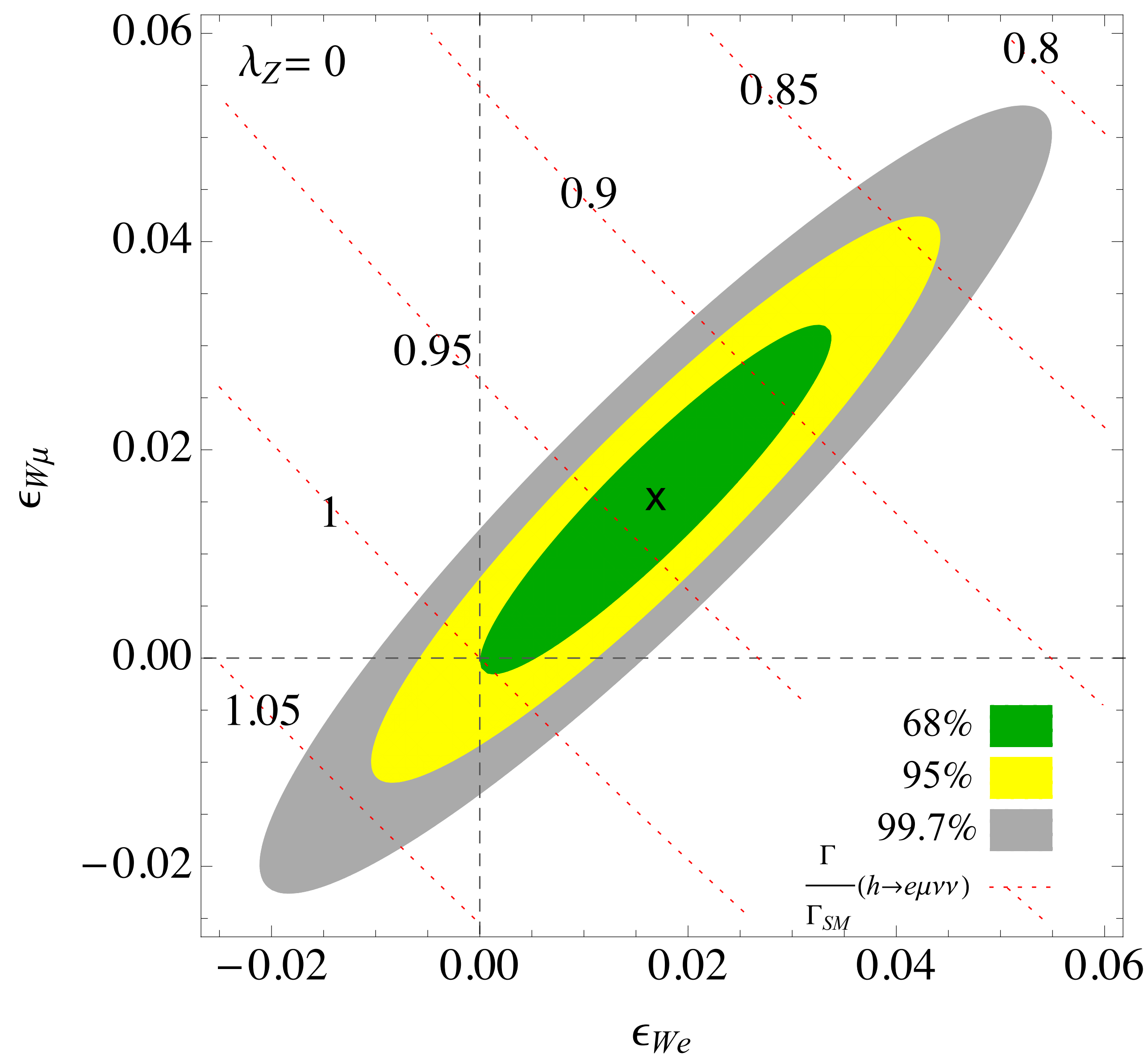
$$\varepsilon_{Wf} = \frac{\sqrt{2}m_W}{v}\left(\boxed{\delta g^{Wf}} - c_\theta^2 \mathbf{1}_3 \boxed{\delta g_{1,z}}\right)$$

$$\delta\varepsilon_{WW} = c_\theta^2\,\delta\varepsilon_{ZZ} + s_{2\theta}\,\delta\varepsilon_{Z\gamma} + s_\theta^2\,\delta\varepsilon_{\gamma\gamma}$$

Tevatron:

$\delta g^{W\ell} \lesssim 10^{-2}$





More details in arXiv:1504.04018

Predictions for h → eμνν in the linear EFT

Backup