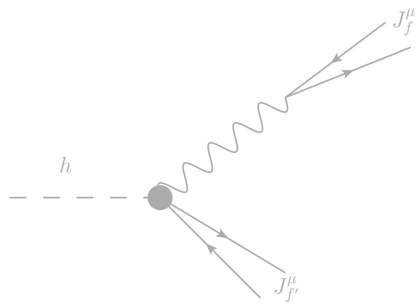
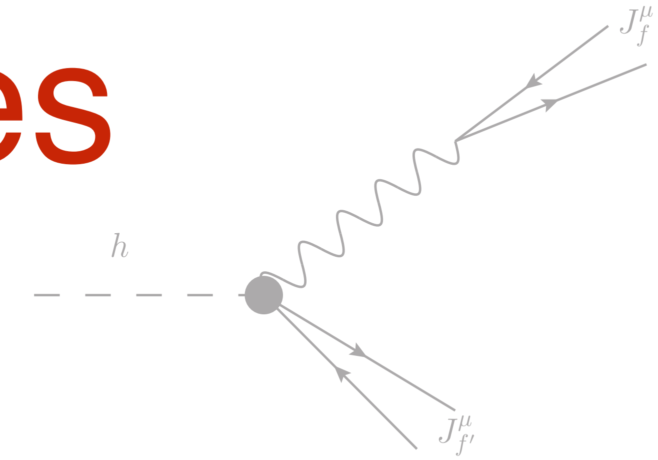
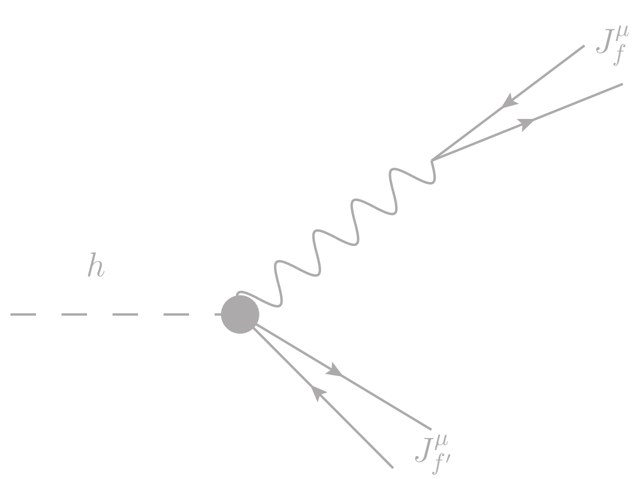


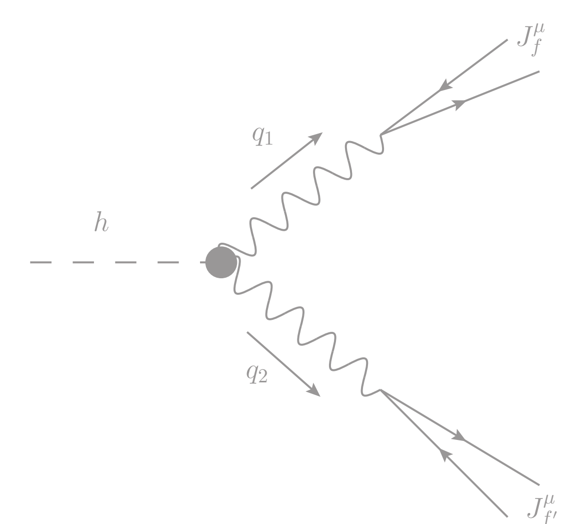
Pseudo-observables in Higgs Physics





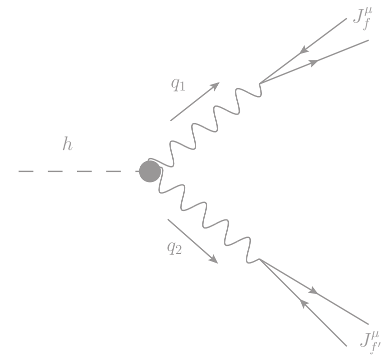
David Marzocca

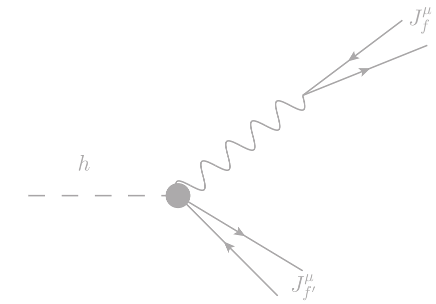
Universität Zürich[UZH]



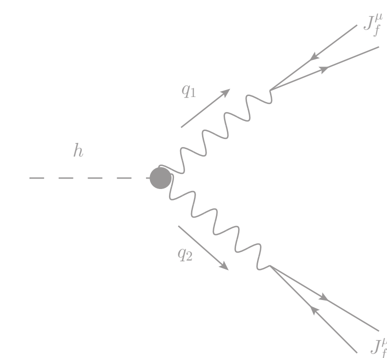
HEFT, Copenhagen, 28/10/2016

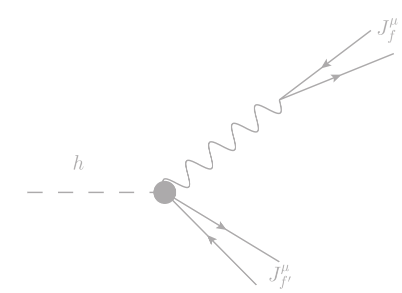
Outline





- Motivation and introduction.
- What are pseudo-observables (PO)?
- PO in Higgs Decay. & Electroweak Higgs Production.
- NLO corrections.
- Matching to the SMEFT at LO





Based on works with various subsets of
{M. Bordone, M.Gonzalez-Alonso, A. Greljo, A. Falkowski, G. Isidori, J. Lindert, D.M., A. Pattori}
and many discussions with the community

PO in decay: Eur. Phys. J. C75 (2015) 3, 128 arXiv: 1412.6038 & Eur. Phys. J. C75 (2015) 8, 385 arXiv: 1507.02555

PO in production: Eur. Phys. J. C76 (2016) 3, 158 arXiv: 1512.06135

PO & linear EFT: Eur. Phys. J. C75 (2015) 7, 341 arXiv: 1504.04018
Phys.Rev.Lett. 116 (2016) 1, 011801 arXiv: 1508.00581

PO Chapter in YR4: arXiv: 1610.07922

Introduction

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

The SM is complete.

★ So far, from direct searches: Scale of New Physics is high**

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

What else can the LHC tells about the Higgs?

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

Search for smooth deviations from the SM.

Learning on BSM from the Higgs

… Given we do not know what the New Physics will be like

1

Measure all the physical properties of the Higgs,
in production and decay,
with the highest possible accuracy
as much model-independently as possible.

Learning on BSM from the Higgs

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Measure all the physical properties of the Higgs,
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2

Interpret the results of these measurements
in explicit BSM scenarios to learn about the UV.

Eg. SMEFT, SUSY, Composite Higgs, ***??****, …*

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

How should the experiments present their result

Experimental data

Experiments

Unfolding of collider & soft radiation effects.

Unfolded distributions, fiducial cross sections

PO

idealized observables,
well defined quantities (in QFT).

Theorists

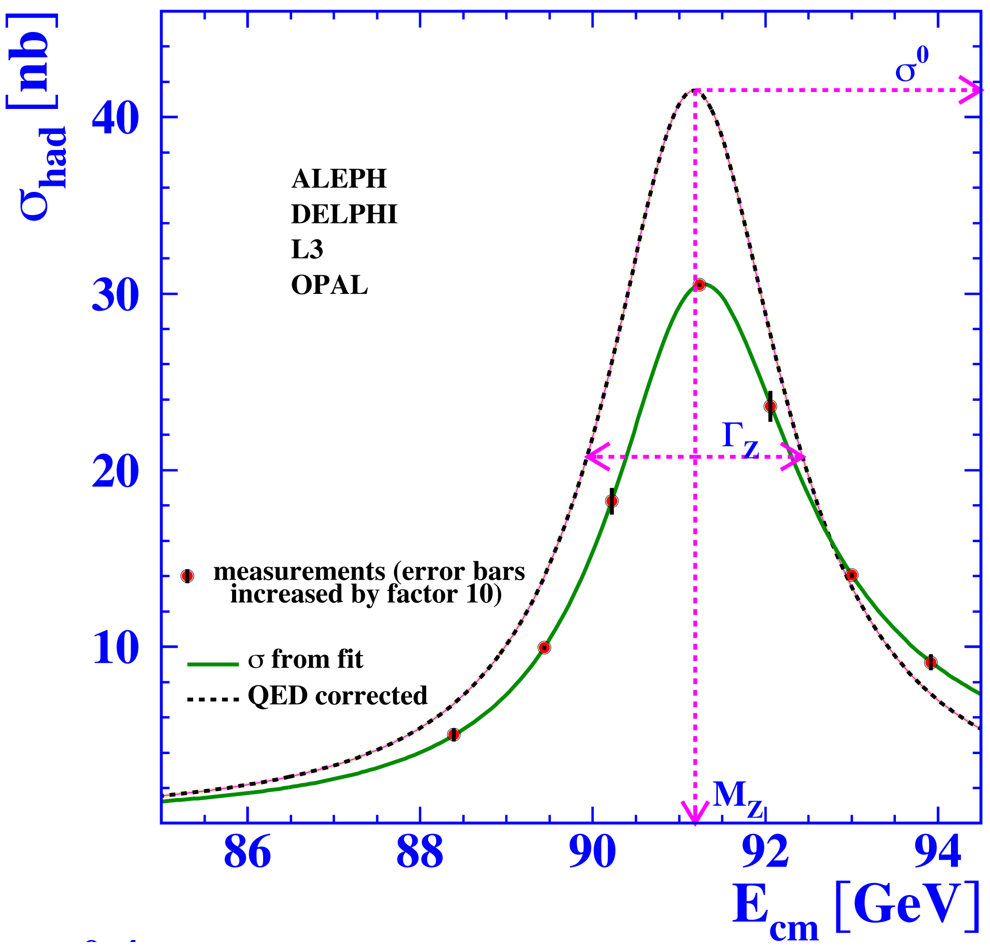
Matching to a given model at given order in pert. theory

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

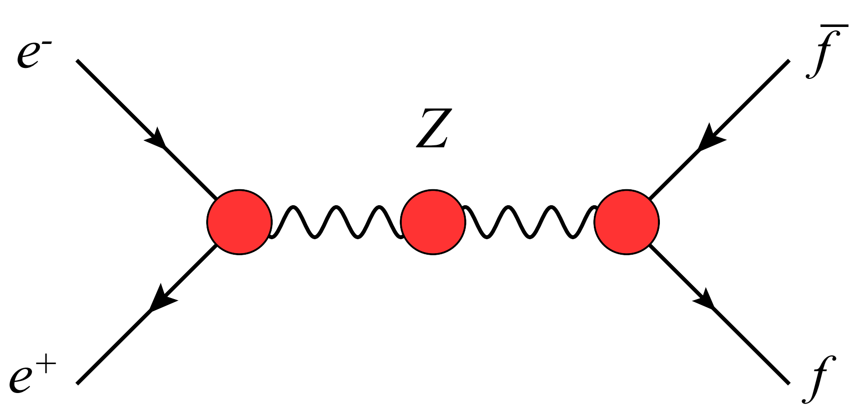
$$\sigma(s) = \int_{4m_f^2/s}^{1} dz\, H_{\rm QED}^{\rm tot}(z,s)\sigma_{\rm ew}(zs).$$

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

$$m_Z,\ \Gamma_Z$$

Lineshape

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



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

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

3) Fit the PO from data

PO used at Run 1: the κ-framework

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

On-shell Higgs in the narrow width approximation:

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

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Pros:

Clear SM limit ($\kappa \to 1$),
theoretically well defined,
systematically improvable,
model independent (on-shell Higgs is key),
can be matched to any EFT in any basis.

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can't describe deviations in differential distributions, e.g. CPV or $h \to 4f$

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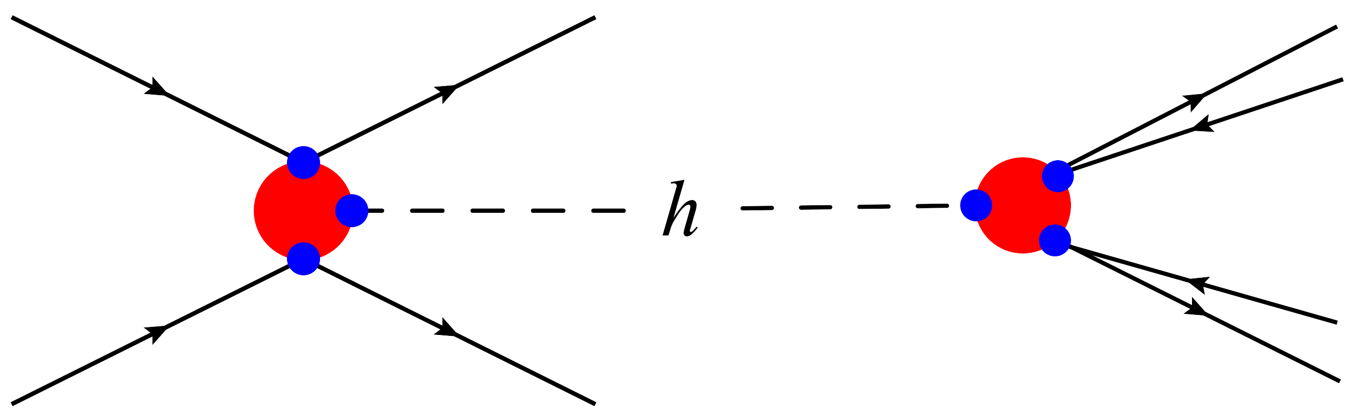
Need to extend the κ-framework retaining all its good properties:

Higgs pseudo-observables

Higgs PO: QFT definition

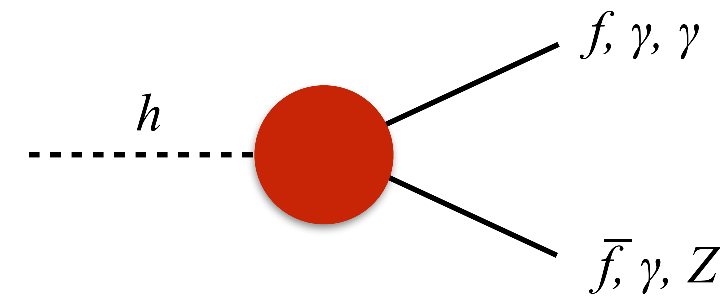
PO are defined from:

decomposition of **on-shell amplitudes** (NWA),
based on Lorentz invariance and crossing symmetry,



and a momentum expansion (on measurable quantities)
based on analytic properties of the amplitudes (physical poles),
assuming no new light states in the kinematical regime of interest.

Two-body Higgs decays



Higgs PO: parametrize the relevant on-shell amplitude.

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

2 possible Lorentz structures: CP-even & CP-odd.

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

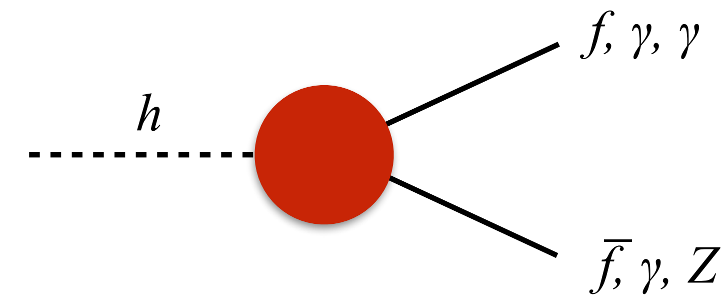
Same decomposition for $h{\to}Z\gamma$

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

In the SM

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

Two-body Higgs decays



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In the SM

$\kappa_X \to 1,\ \lambda_X^{\text{CP}} \to 0$

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

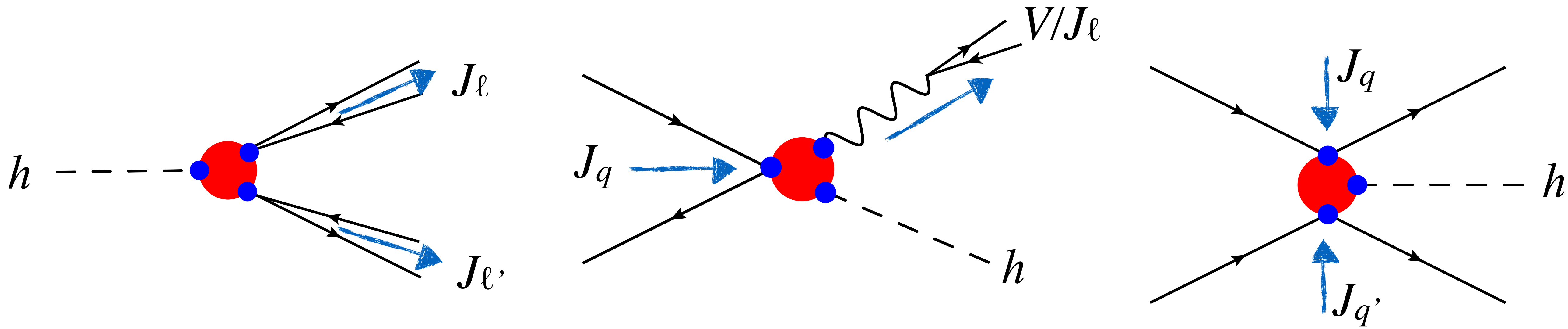
The kinematics is fixed.

No polarisation information is retained.

(maybe possible to measure in ττ channel)

$\longrightarrow$ the total rate is all that can be extracted from data

4-fermion Higgs decays and EW Higgs Production



By crossing symmetry, all these processes are described by the same correlation function.
(in a different kinematical region and with different fermionic currents)

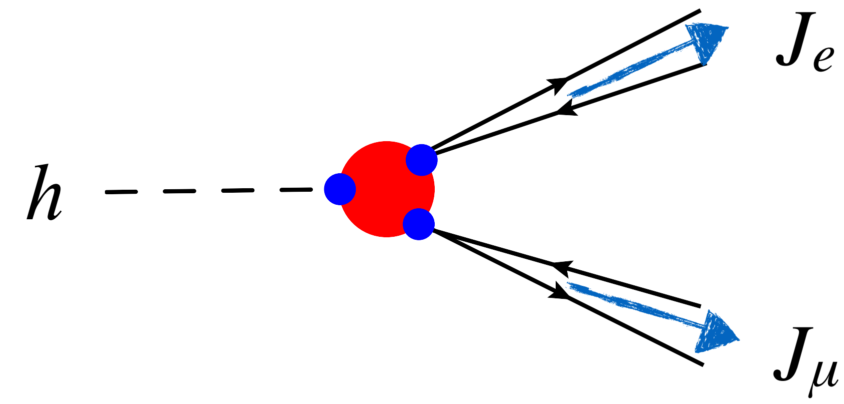
On-shell Higgs and two on-shell EW currents

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

Assumption: neglect chirality-flipping terms, expected to be suppressed by y_f.

> Use the same parametrization of Higgs decays also for the production.

As an example, let's focus on
$h \to e^+e^- \mu^+\mu^-$



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

Only 3 tensor structures allowed by Lorentz symmetry:

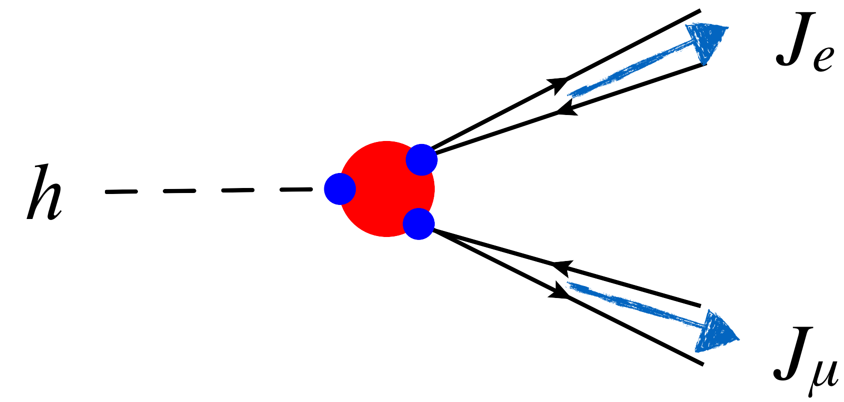
e.g. $h \to e^+e^- \mu^+\mu^-$

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

$$\left[F_L^{e\mu}(q_1^2, q_2^2) g^{\alpha\beta} + F_T^{e\mu}(q_1^2, q_2^2)\frac{q_1\cdot q_2\ g^{\alpha\beta} - {q_2}^\alpha {q_1}^\beta}{m_Z^2} + F_{\rm CP}^{e\mu}(q_1^2, q_2^2)\frac{\varepsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2} \right]$$

Longitudinal *Transverse* *CP-odd*

As an example, let's focus on
h → e⁺e⁻ μ⁺μ⁻



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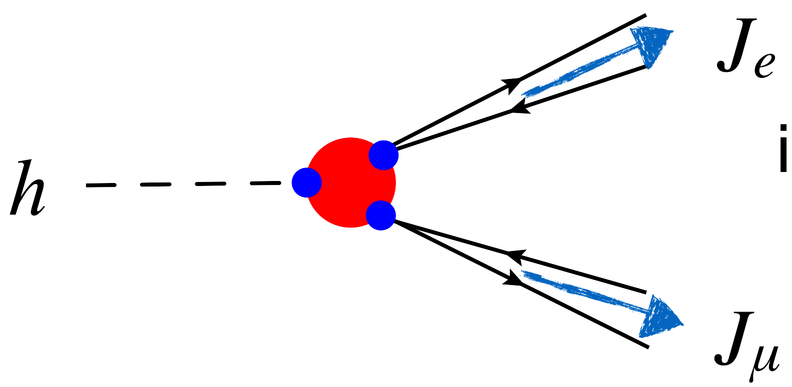
Longitudinal *Transverse* *CP-odd*

Ultimate experimental goal for any of these processes:

measure the double differential distributions in (q_1^2, q_2^2)

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



includes

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

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

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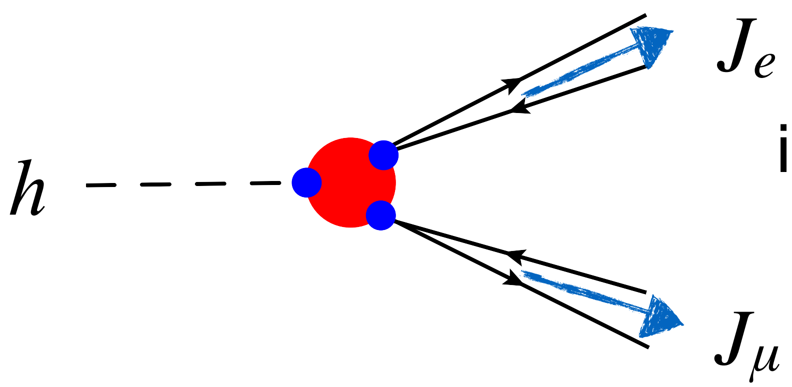


includes

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

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

Assuming: *New Physics scale > Energy scale of the process*

We perform a momentum expansion around the physical poles of the SM states:

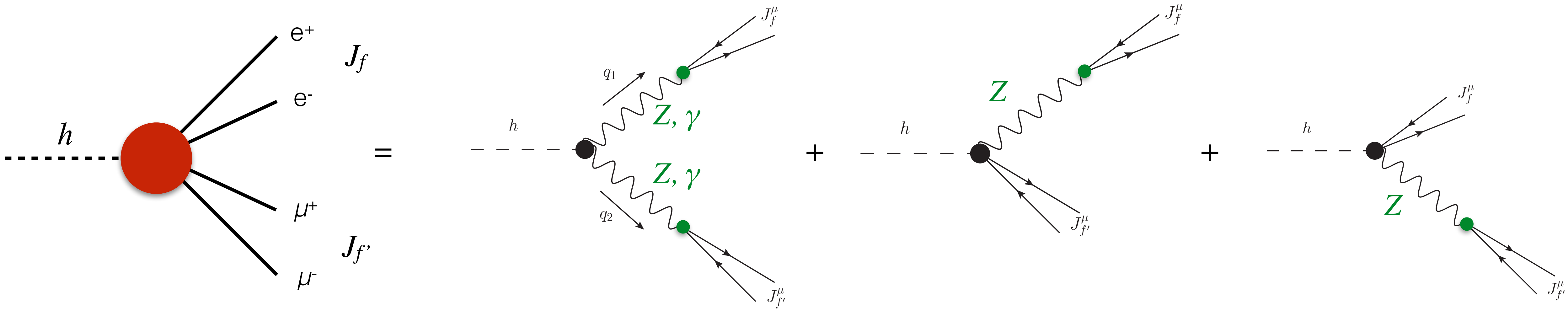
$$F_X(q_1^2, q_2^2) = \sum_V \frac{(\mathrm{const})_{2V}}{(q_1^2 - m_V^2)(q_2^2 - m_V^2)} + \frac{(\mathrm{const})_{1V}}{(q_{1,2}^2 - m_V^2)} + (\mathrm{const}) + f_{\mathrm{reg}}(q_1^2, q_2^2)$$

2 poles 1 pole no poles

To truncate the expansion, we have to assume $q^2{}_{\mathrm{max}} \ll \Lambda^2$

No problem in Higgs decays.

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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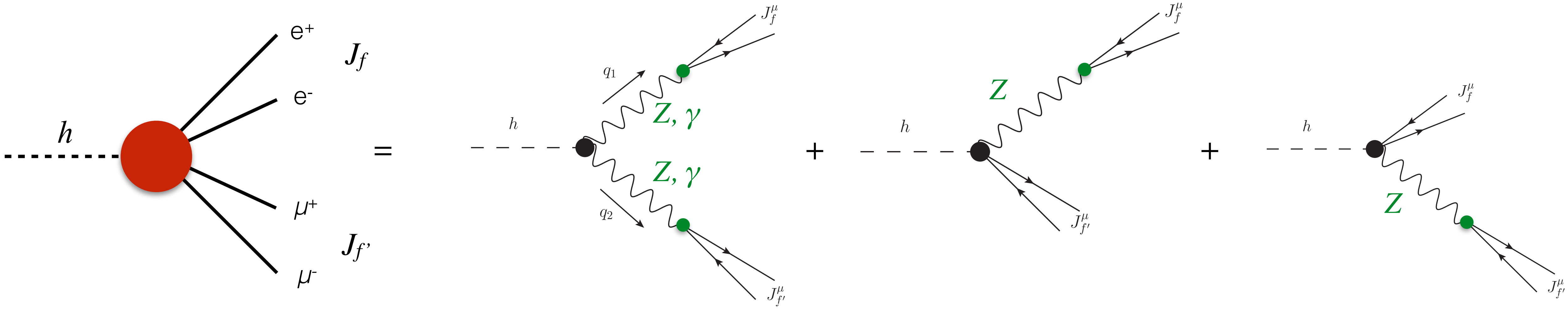

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$$+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\rm SM\text{-}1L}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\rm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

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

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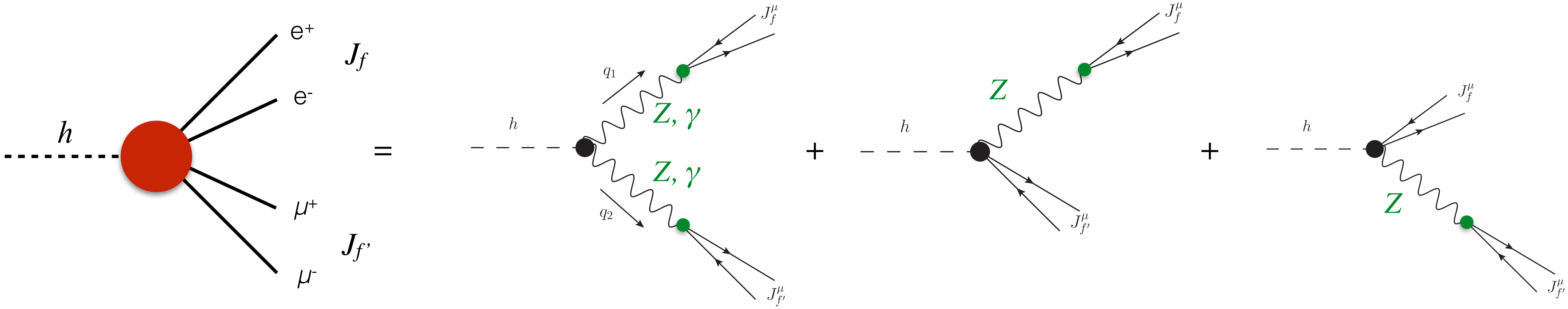

$e = e_L, e_R, \qquad \mu = \mu_L, \mu_R$

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

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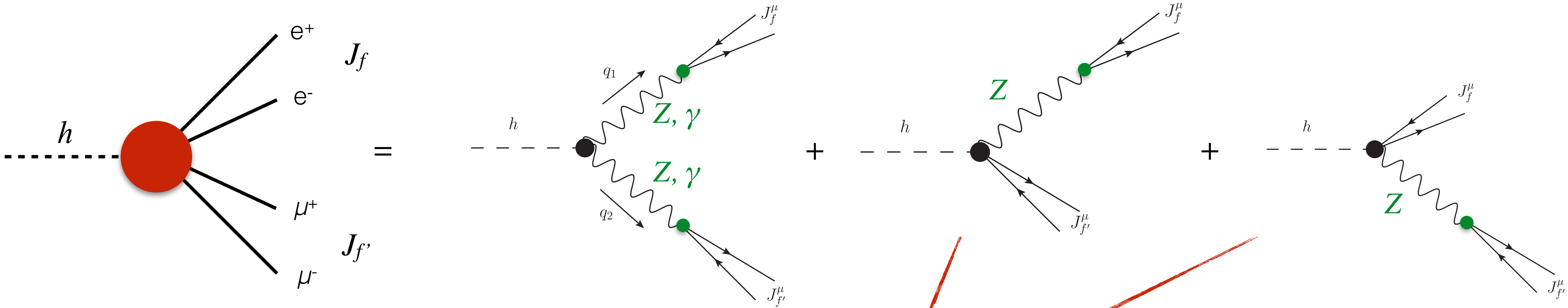

contact terms
only source of
flavor dependence

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

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

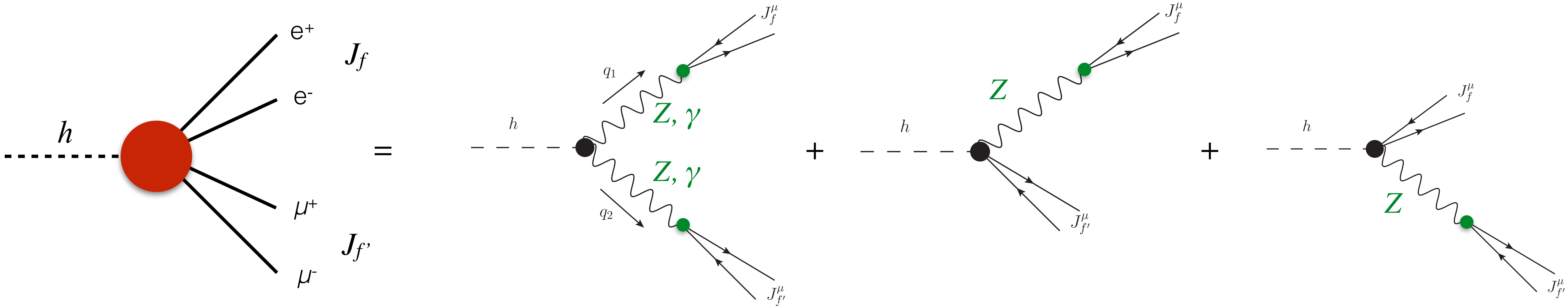
$$\left. + \left(\epsilon_{ZZ}^{\rm CP}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\rm CP}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{\rm CP}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma}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

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

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

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

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)

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

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

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

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

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

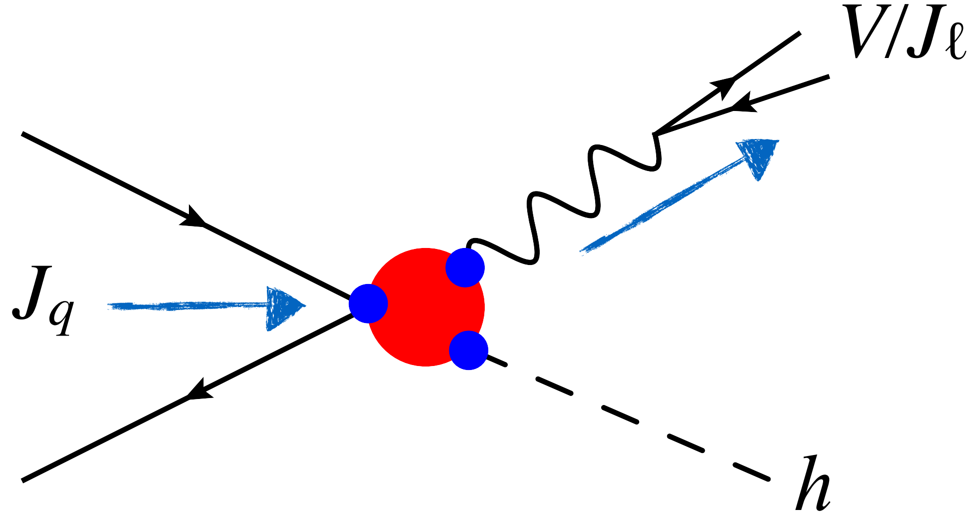
In the SM $\kappa_X \to 1, \;\; \epsilon_X \to 0$

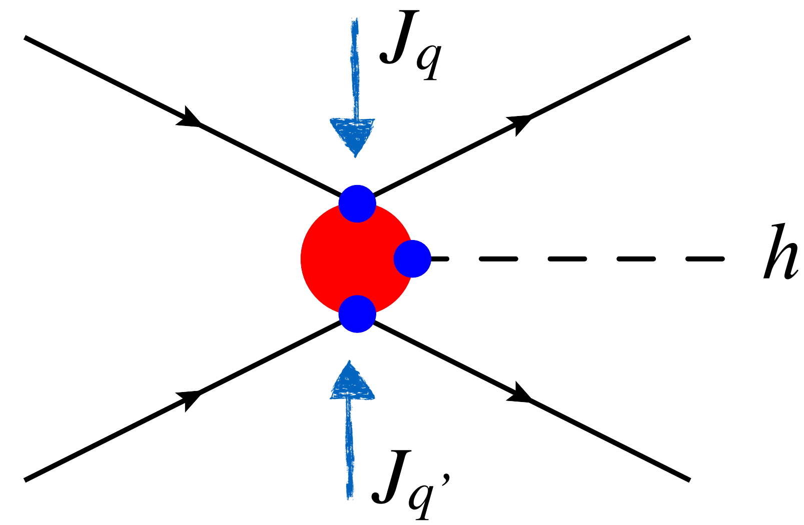
$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z\Gamma_Z$$

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

EW Higgs production

The hard contribution to these scattering processes is:

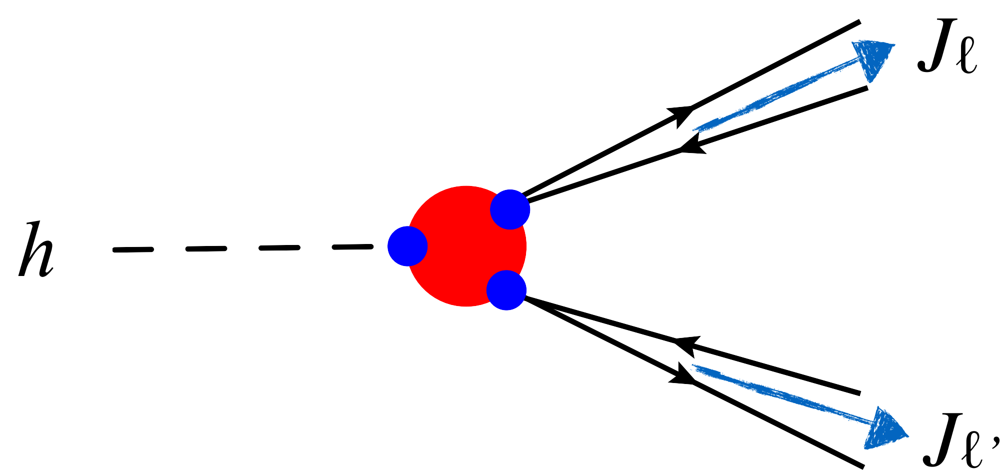




Physical process: all external particles are on-shell.

Higgs + 2 EW currents

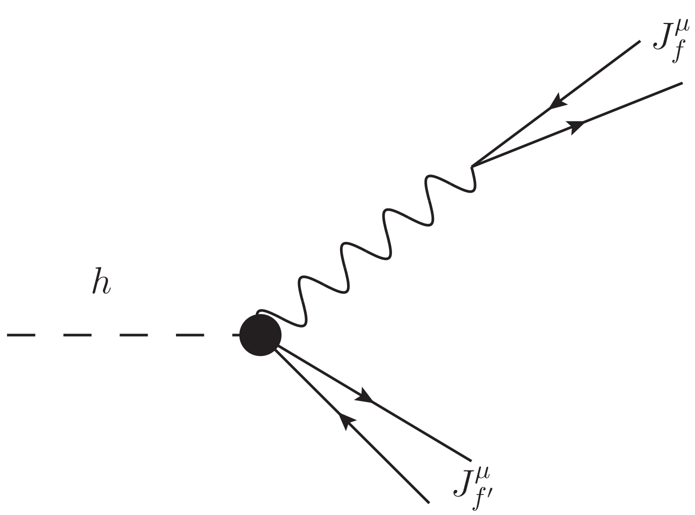
Same as 4-fermion Higgs decays:



New PO not accessible in $h \to 4\ell$

Only quark contact terms are not probed also in $h \to 4\ell$ decays.

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



$\epsilon_{Zu_L}, \epsilon_{Zu_R}$

$\epsilon_{Zd_L}, \epsilon_{Zd_R}$

$\mathrm{Re}(\epsilon_{Wu_L})$

+ *Flavor*

$\epsilon_{Zc_L}, \epsilon_{Zc_R}$

$\epsilon_{Zs_L}, \epsilon_{Zs_R}$

$\mathrm{Re}(\epsilon_{Wc_L})$

+ *CP-violation*

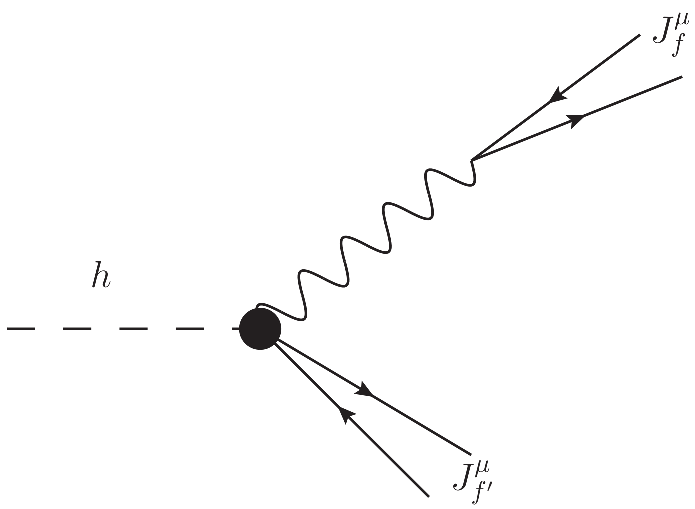
$\mathrm{Im}(\epsilon_{Wu_L})$

$\mathrm{Im}(\epsilon_{Wc_L})$

New PO not accessible in $h \to 4\ell$

Only quark contact terms are not probed also in $h \to 4\ell$ decays.

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



	+ Flavor	+ CP-violation
$\epsilon_{Zu_L}, \epsilon_{Zu_R}$ $\epsilon_{Zd_L}, \epsilon_{Zd_R}$ $\mathrm{Re}(\epsilon_{Wu_L})$	$\epsilon_{Zc_L}, \epsilon_{Zc_R}$ $\epsilon_{Zs_L}, \epsilon_{Zs_R}$ $\mathrm{Re}(\epsilon_{Wc_L})$	$\mathrm{Im}(\epsilon_{Wu_L})$ $\mathrm{Im}(\epsilon_{Wc_L})$

Vh: $q_1^2 > (m_h + m_V)^2$ $\quad q_2^2 \sim m_V^2$ (if V experimentally taken on-shell)

VBF: $q_1^2, q_2^2 < 0$ (t-channel)

Need to be careful with the validity of the momentum expansion around the physical poles.

Parameter Counting & Symmetries

EW decay and production:

Higgs (EW) decay amplitudes

Amplitudes	Flavor + CP	Flavor Non Univ.	CPV
$h \to \gamma\gamma, 2e\gamma, 2\mu\gamma$ $4e, 4\mu, 2e2\mu$	6 $\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$ $\epsilon_{Ze_L}, \epsilon_{Ze_R}$	$\epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$	$\epsilon^{CP}_{ZZ}, \lambda^{CP}_{Z\gamma}, \lambda^{CP}_{\gamma\gamma}$
$h \to 2e2\nu, 2\mu 2\nu, e\nu\mu\nu$	4 $\kappa_{WW}, \epsilon_{WW}$ $\epsilon_{Z\nu_e}$, $\mathrm{Re}(\epsilon_{We_L})$	$\epsilon_{Z\nu_\mu}$, $\mathrm{Re}(\epsilon_{W\mu_L})$ $\mathrm{Im}(\epsilon_{W\mu_L})$	ϵ^{CP}_{WW}, $\mathrm{Im}(\epsilon_{We_L})$

Test UV symmetries!

Higgs (EW) production amplitudes

Amplitudes	Flavor + CP	Flavor Non Univ.	CPV
VBF neutral curr. and Zh	4 $[\kappa_{ZZ}, \kappa_{Z\gamma}, \epsilon_{ZZ}]$ $\epsilon_{Zu_L}, \epsilon_{Zu_R}, \epsilon_{Zd_L}, \epsilon_{Zd_R}$	$\epsilon_{Zc_L}, \epsilon_{Zc_R}$ $\epsilon_{Zs_L}, \epsilon_{Zs_R}$	$[\epsilon^{CP}_{ZZ}, \lambda^{CP}_{Z\gamma}]$
VBF charged curr. and Wh	1 $[\kappa_{WW}, \epsilon_{WW}]$ $\mathrm{Re}(\epsilon_{Wu_L})$	$\mathrm{Re}(\epsilon_{Wc_L})$ $\mathrm{Im}(\epsilon_{Wc_L})$	$\mathrm{Im}(\epsilon_{Wu_L})$

15 coefficients for 12 independent processes & lots of differential distributions!!

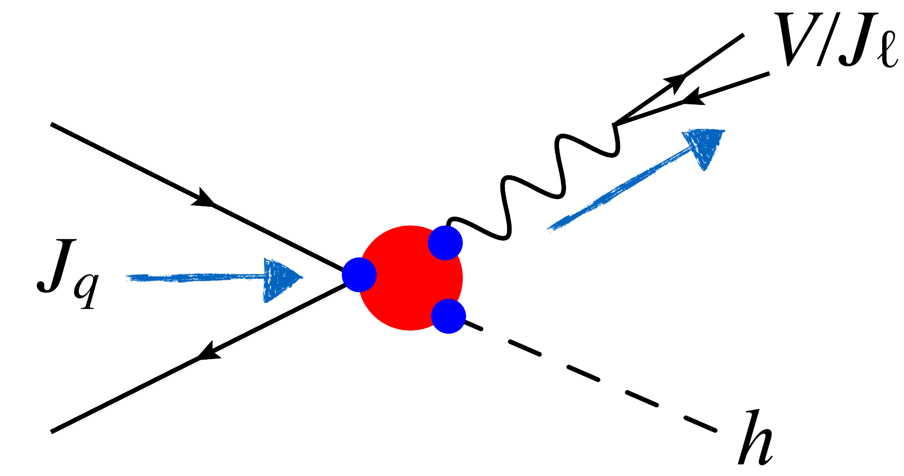
Associate Zh/Wh production

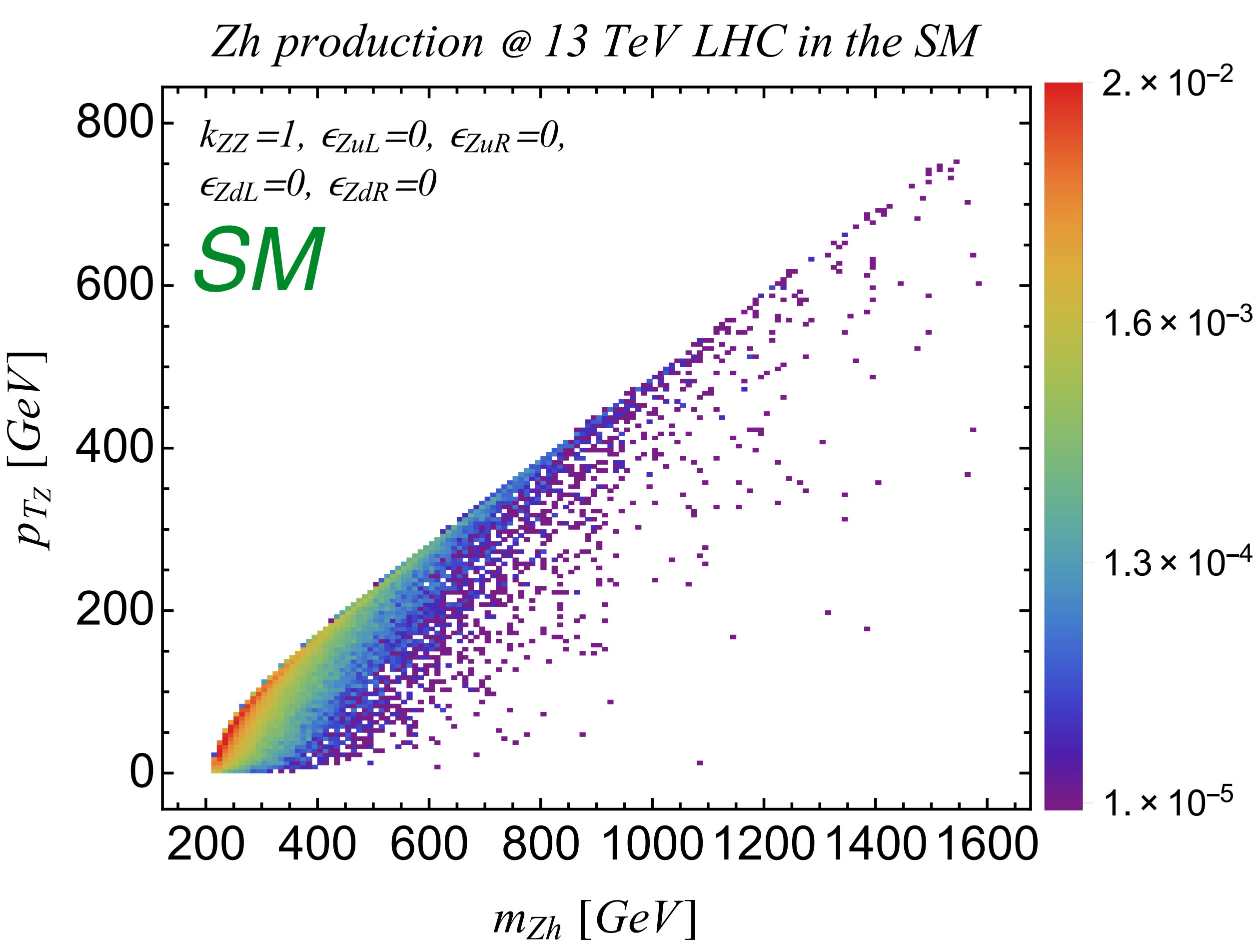
To extract the contact terms:

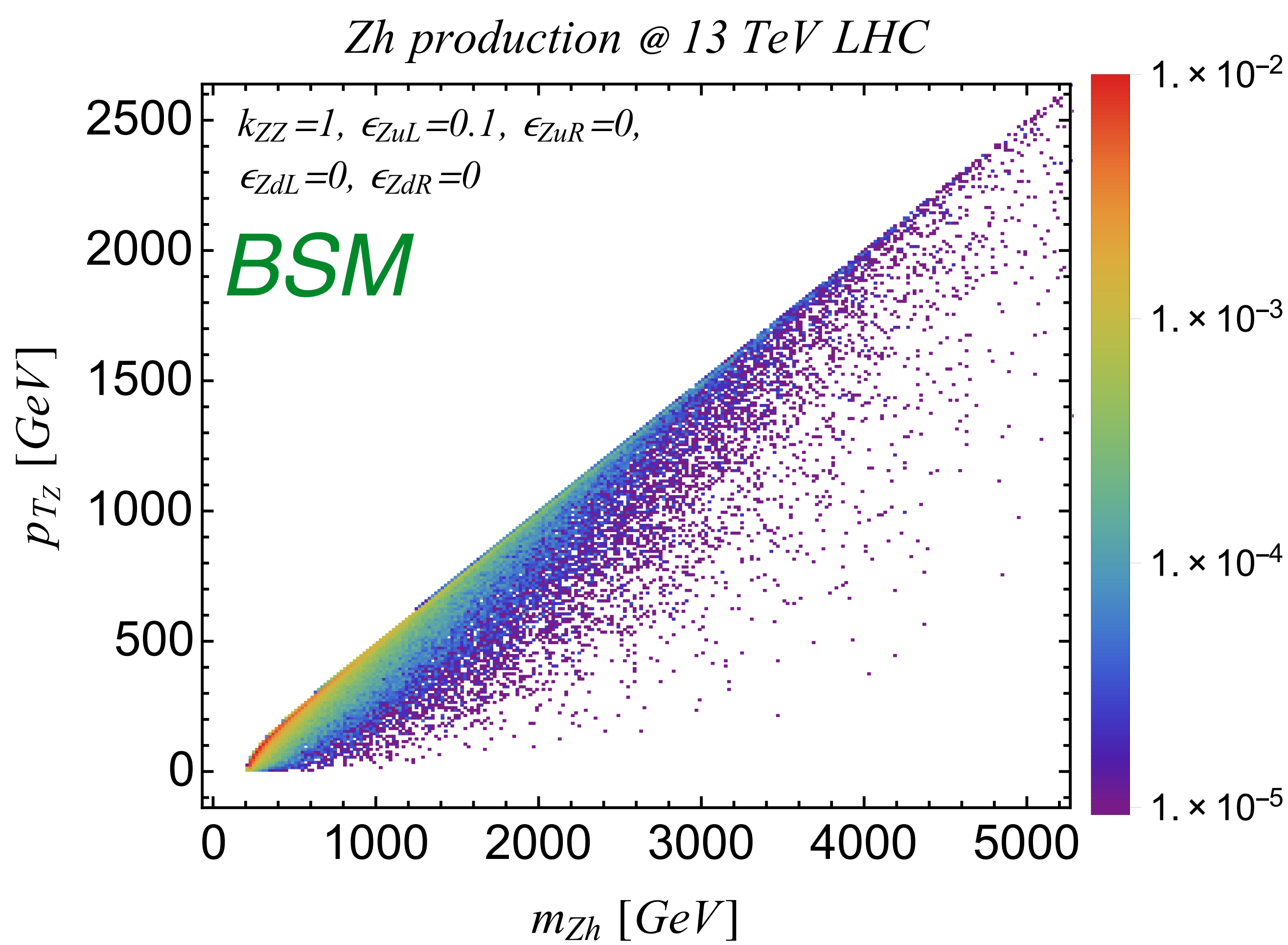
measure the differential distribution in m_{Zh}.

m_{Zh} correlates with the p_T^Z.

[See also Ellist et al. 1410.7703 and Englert et al. 1511.05170]

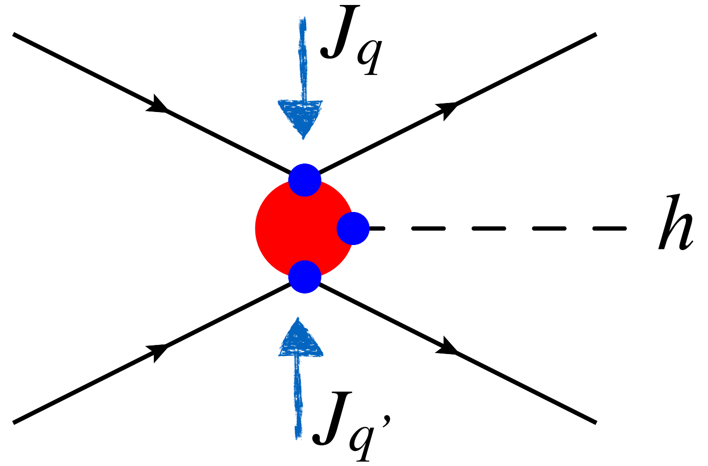






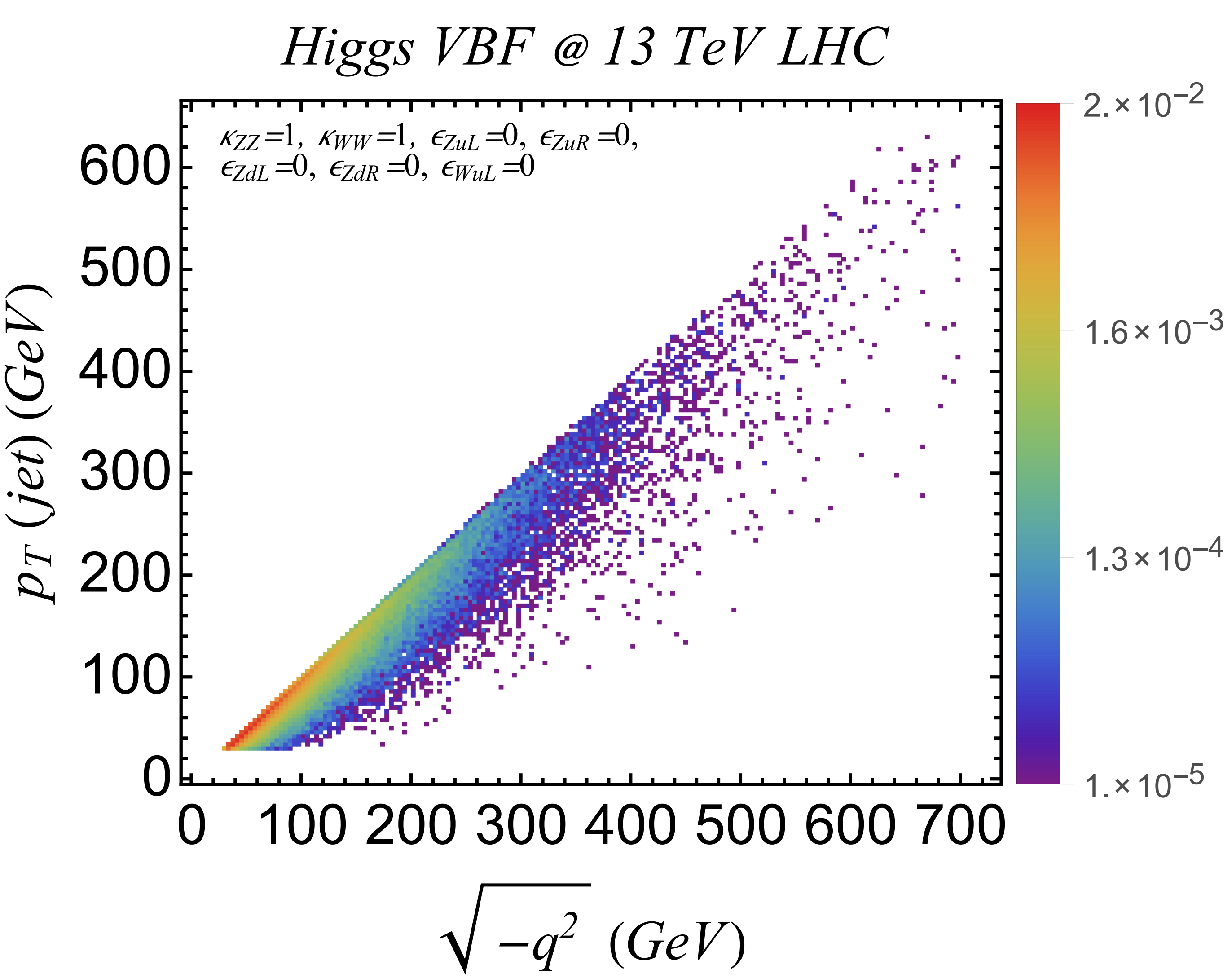
Same variables also relevant for assessing the validity of the momentum expansion.

VBF Higgs production

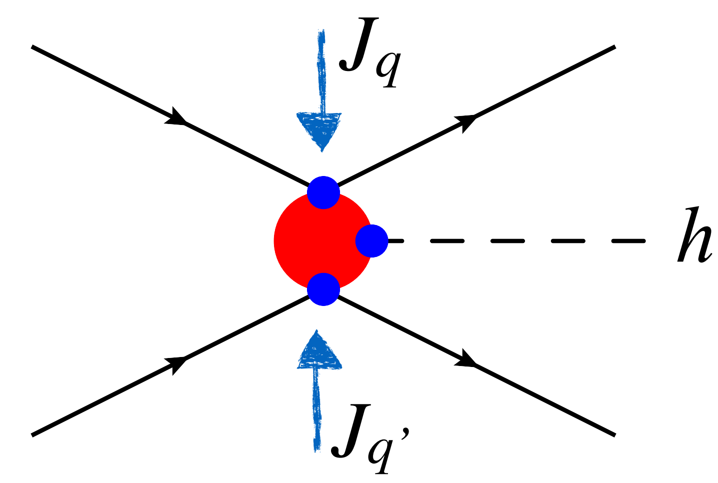


q_i^2 correlates with the p_{Tjet_i}

$q_i^2 \sim p_{Tjet_i}$

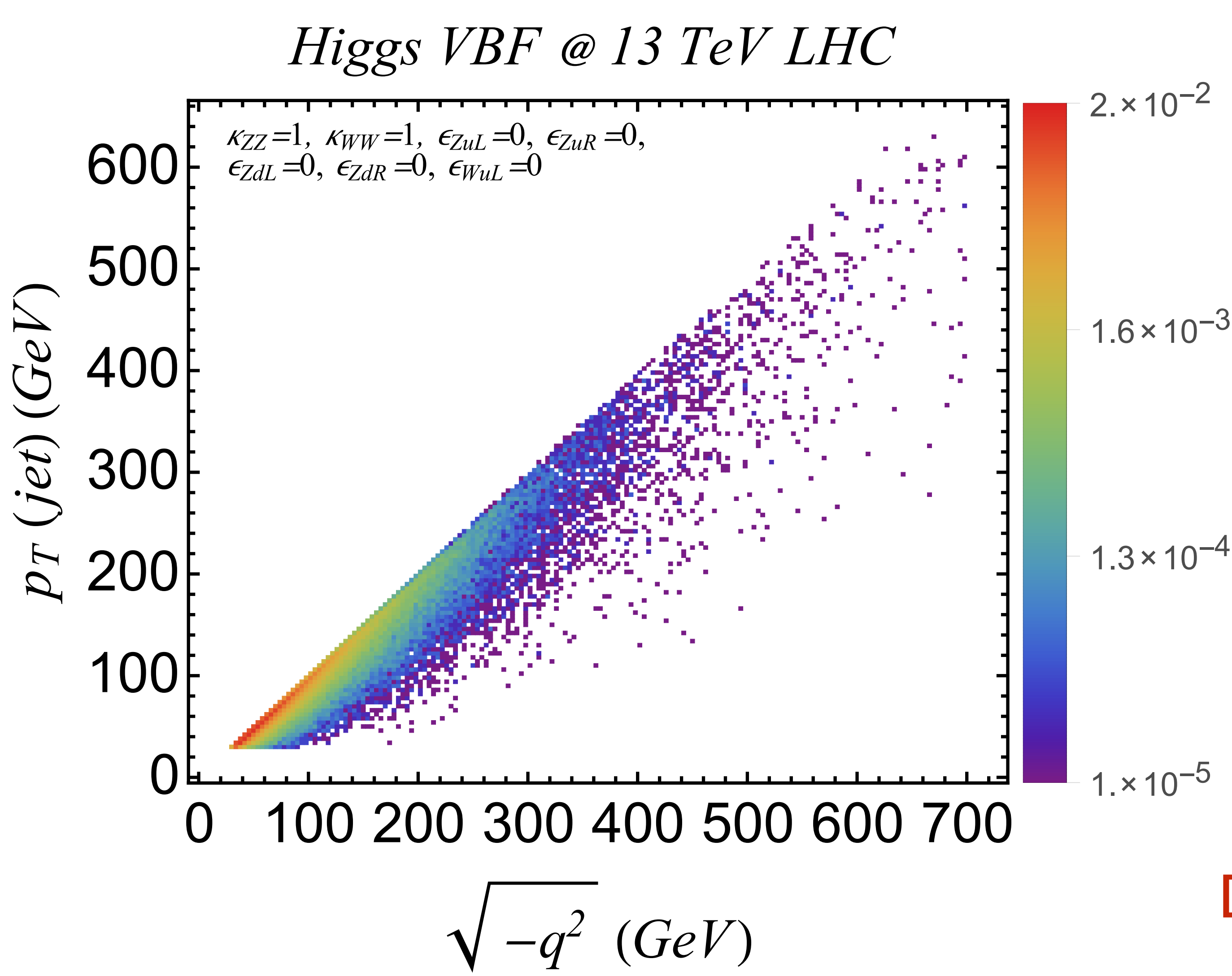


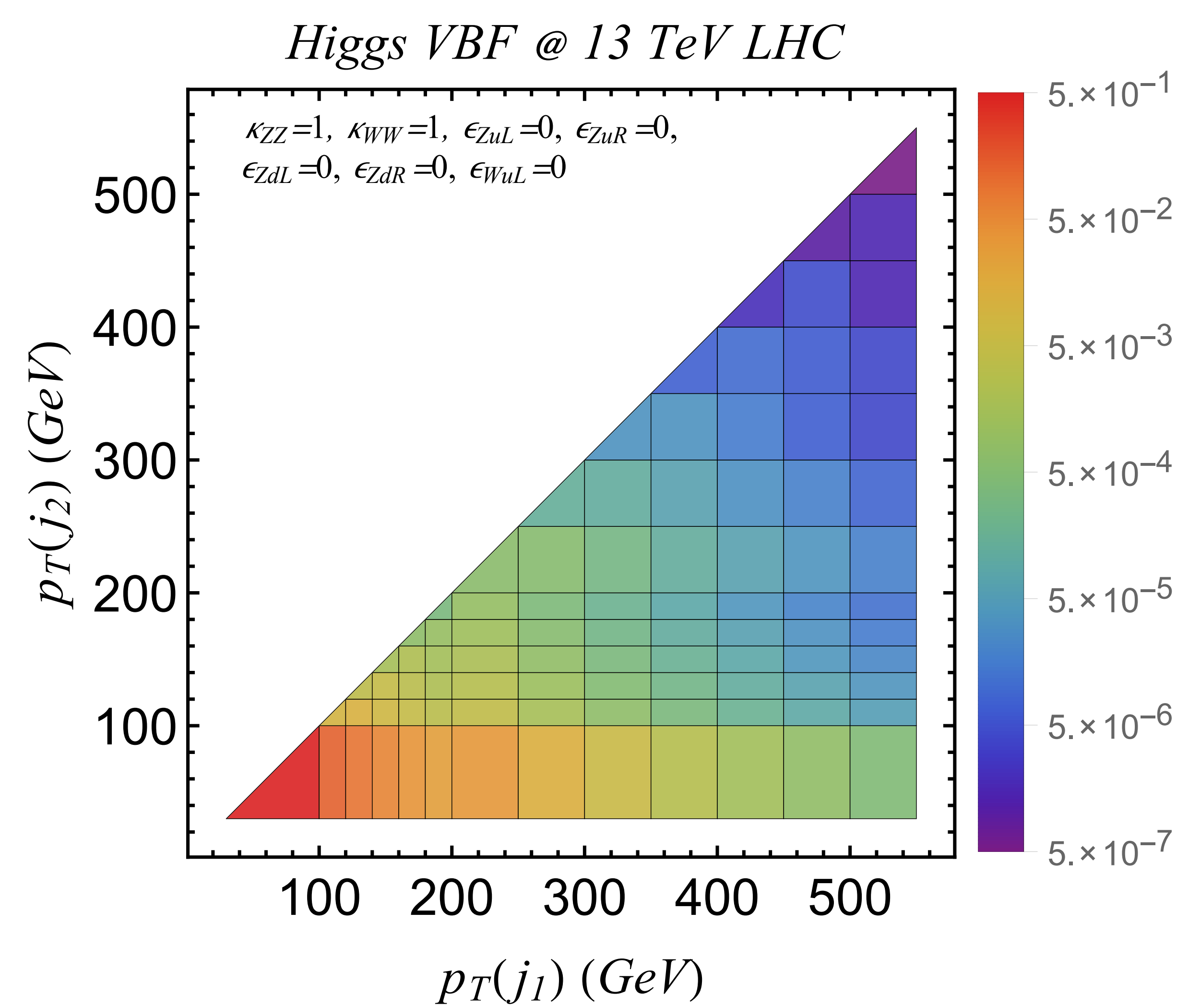
VBF Higgs production



q_i^2 correlates with the p_{Tjet_i}

$q_i^2 \sim p_{Tjet_i}$



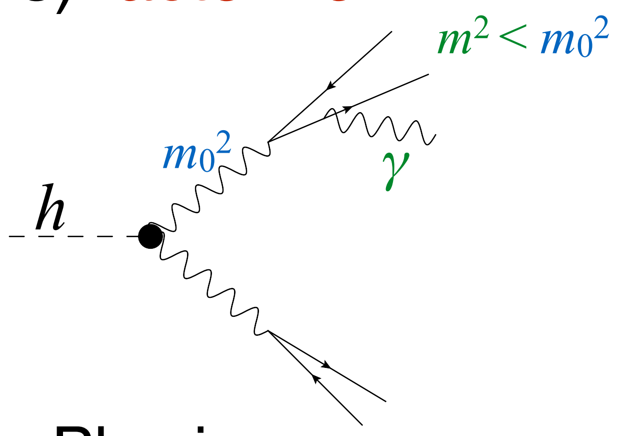


$$F(q_1^2, q_2^2) \rightarrow \tilde{F}(p_{T1}^2, p_{T2}^2)$$

Double-differential distribution in the jets pT.

NLO corrections

- PO describe the small-scale (local) contribution to the amplitude
- QCD & QED IR radiation effects (largest NLO corrections) factorize.



Assumption: IR physics (QED & QCD) is unaffected by New Physics.

Universal description of IR corrections

Goal: fully differential QCD NLO description of the process for arbitrary PO.
Done for the decays, in progress for EW production.

[For analogous work in the EFT context see Maltoni et al. 1311.1829]

Higgs PO and the SMEFT

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

e.g $h \to 4\ell$:
'Higgs basis'

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

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

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

Predictions for h→4ℓ in the SMEFT

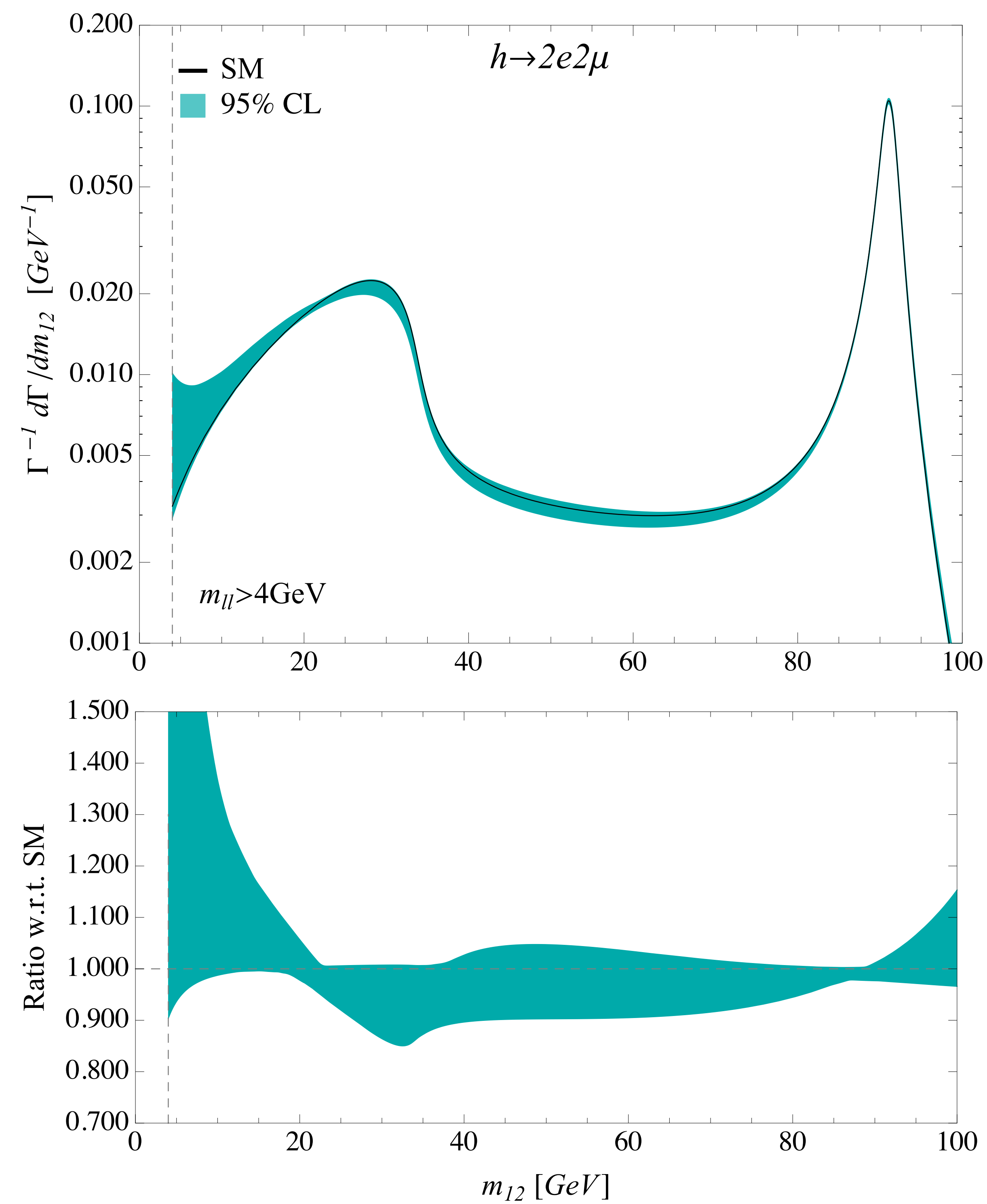
5 independent PO only, in the linear EFT.

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

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

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

LHC with Higgs data could test this.



Small deviations allowed in the shape.

PO vs. EFT
choose the right tool for the job

_PO_

Data parametrisation

- \+ Well defined QFT objects at all orders in perturbation theory: residues of poles in on-shell amplitudes
- \+ Naturally provide the best parametrisation for the process: what are the physically observable objects.
- \+ Can be matched to linear or non-linear EFT at LO or NLO, etc..
- − Can’t be used as couplings in loop computations
- − Can’t connect different classes of processes

EFT

Interpretation, global fits

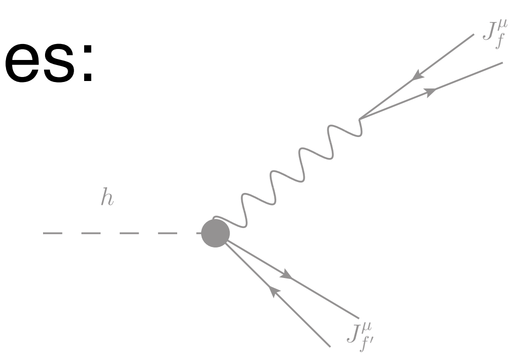
- − Choose the EW representation for the Higgs and a basis
- − Decide the order in perturbation theory and the scheme
- − Recognize the “independent observable parameters in each process”: e.g. Higgs basis.
- \+ Can be used in loop computations, e.g. SMEFT at NLO
- \+ Can connect different experiments and allow for global fits

Conclusions

Higgs PO

Characterize all the measurable properties of on-shell Higgs boson processes in a robust and model-independent way.

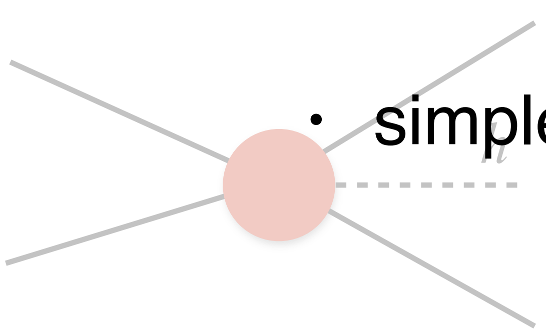
- general framework to describe on-shell Higgs properties:
  decay and production.



- defined from physical properties of the Green functions

- clear implementation of QED and QCD soft radiation (leading NLO effect)

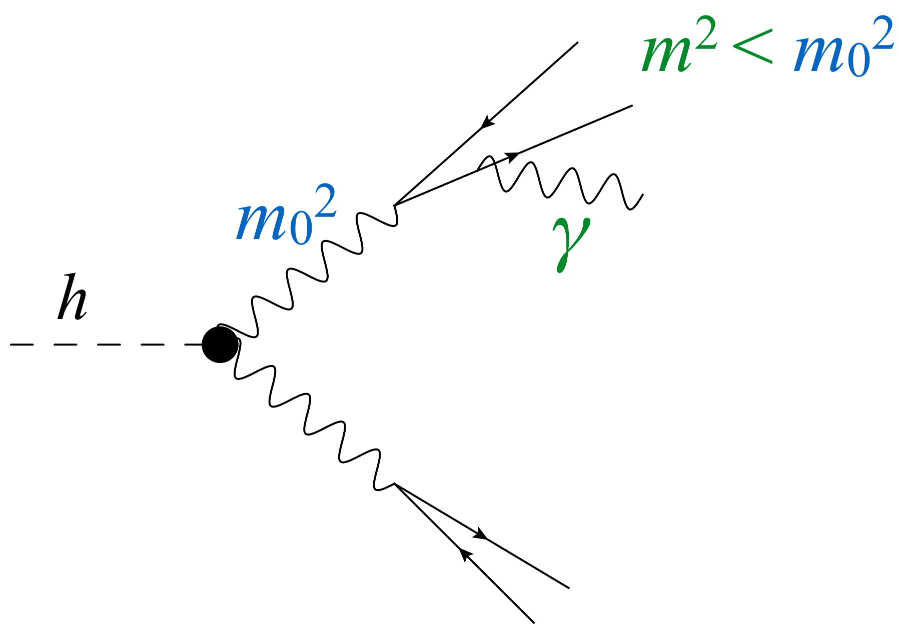
- simple matching with the SMEFT. Possible both at LO and at NLO.



Backup

Radiative Corrections in $h \to 4\ell$

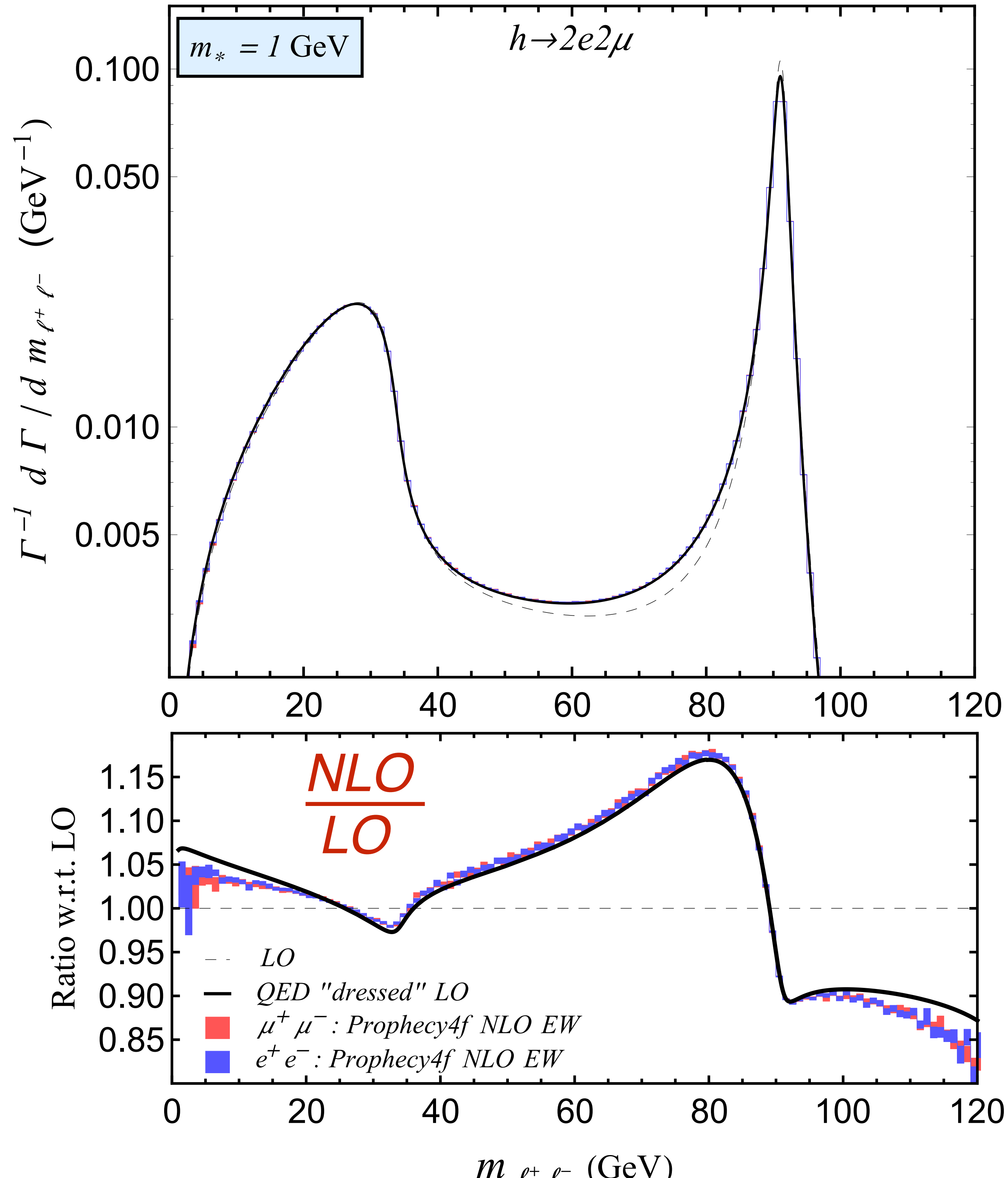
The most important radiative corrections are given by soft QED radiation effects since they distort the spectrum.



Effect described by simple and universal radiator functions ω. Also described by showering algorithms (e.g. Pythia).

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

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

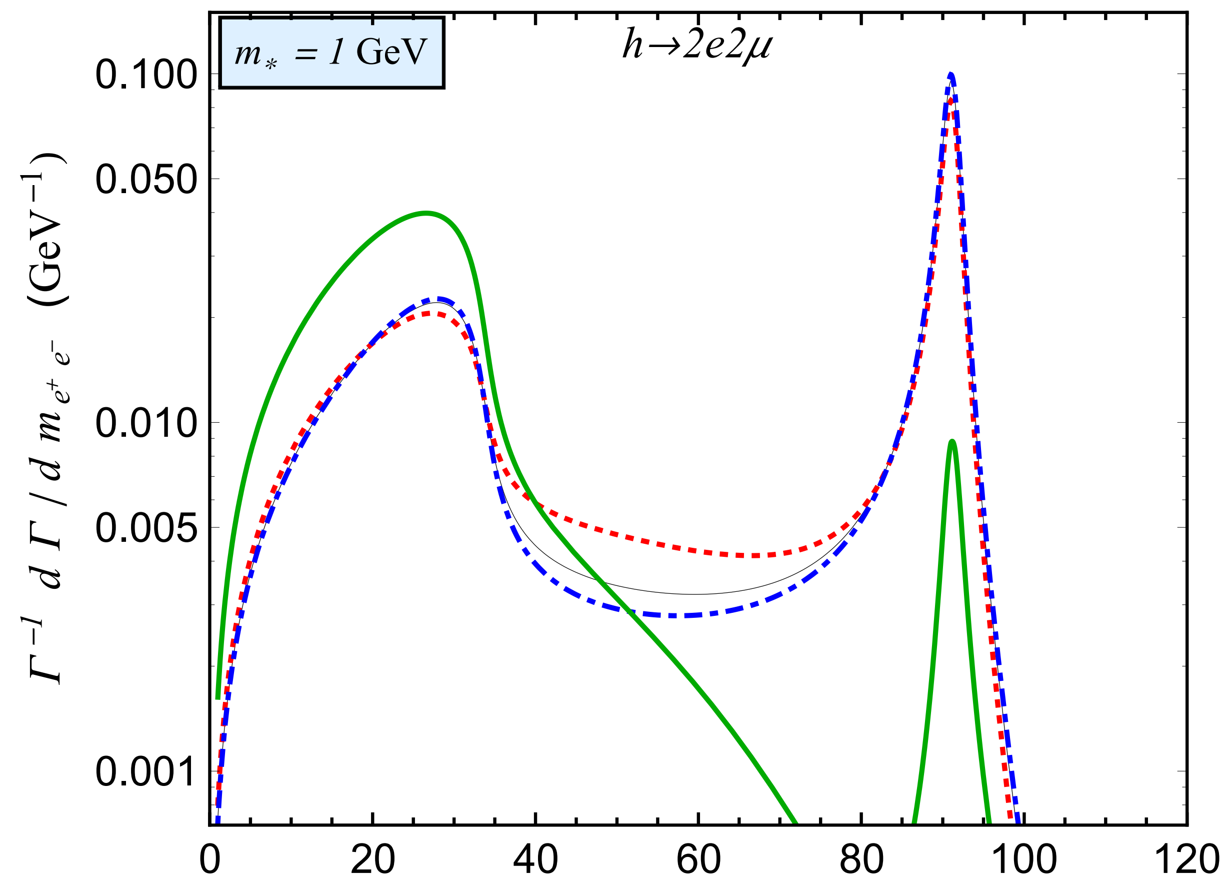


~15% effect!

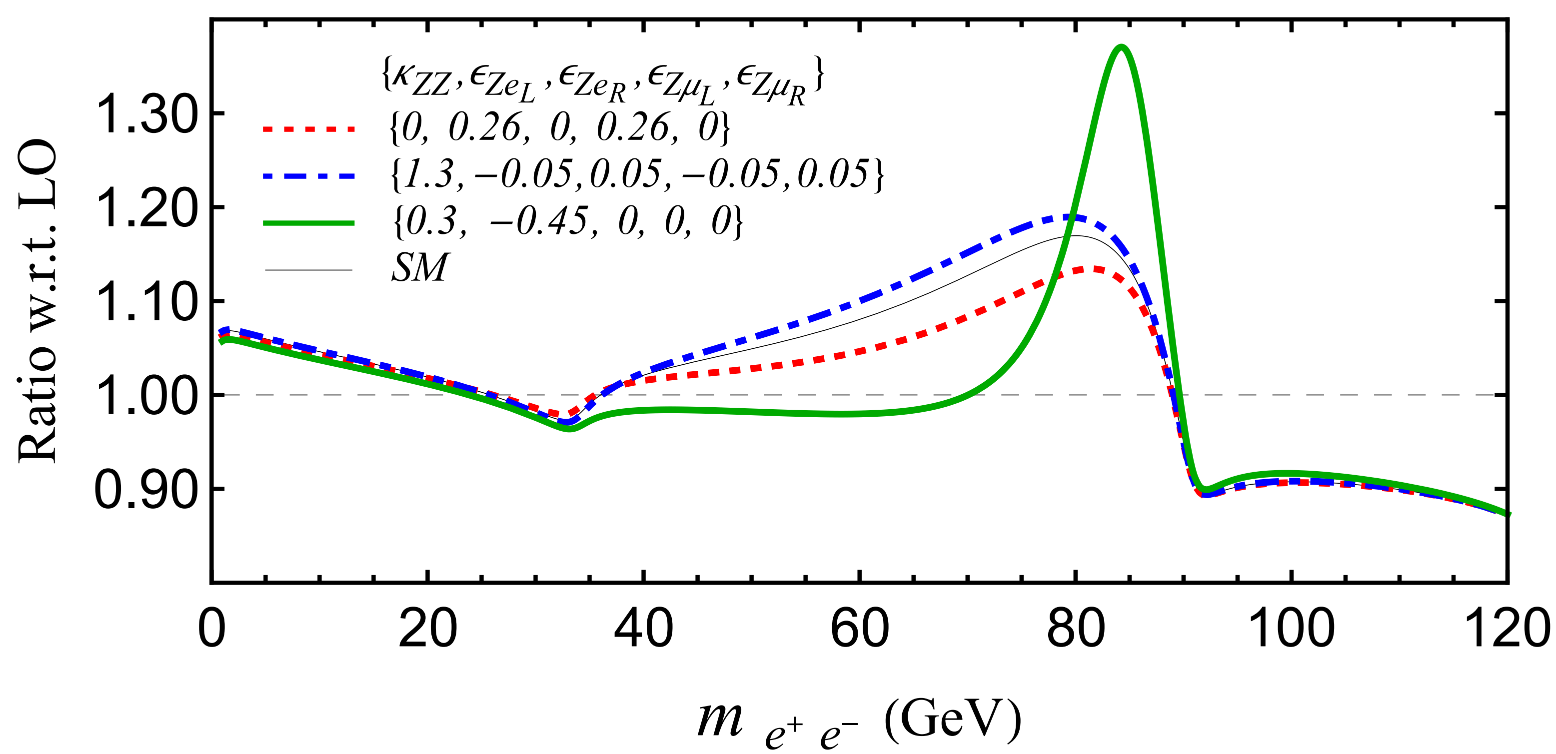
Other NLO corrections are small: ≲1%

Radiative Corrections in $h \rightarrow 4\ell$

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. PYTHIA) correctly describe these corrections.

Prospects for HL-LHC

Consider 7 PO: κ_{ZZ} , κ_{WW} , ϵ_{Zu_L} , ϵ_{Zu_R} , ϵ_{Zd_L} , ϵ_{Zd_R} , ϵ_{Wu_L}

We fix: $q^2_{\max} \simeq 600$ GeV
control the momentum expansion validity.

With 3000 fb^{-1}: ~ 2000 events in VBF ($h \to 2l\ell 2v$)
~ 130 events in Zh ($Z \to 2\ell$, $h \to 2l\ell 2v$)
~ 67 events in Wh ($W \to \ell v$, $h \to 4\ell$)

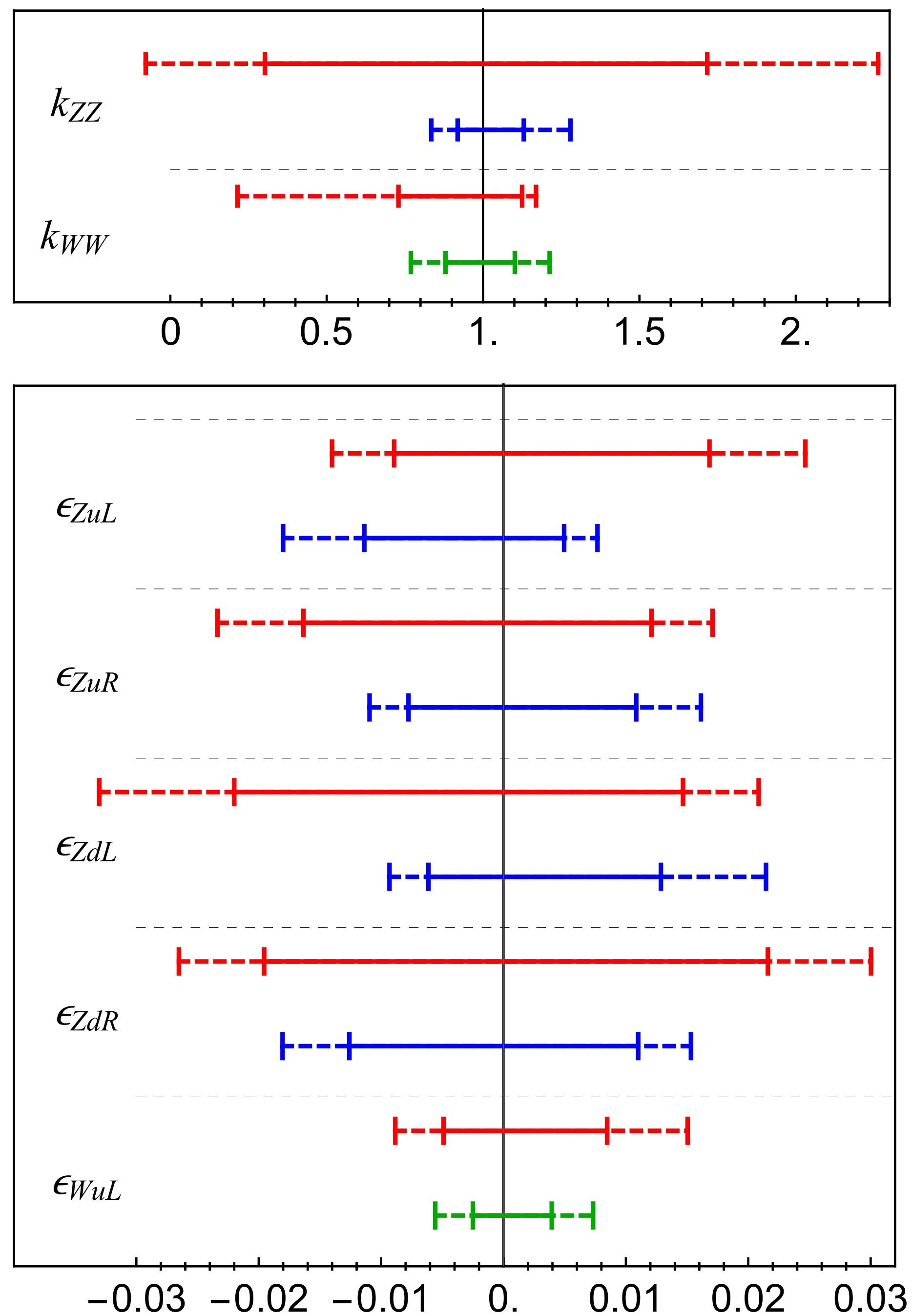
VBF: fit of the 2D p_T distribution.

Zh, Wh: fit of the 1D p_{TV} distribution.

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.

HL-LHC with 3 ab^{-1}



Marginalized 1 and 2σ bounds