Higgs as a BSM probe

David Marzocca

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Based on works with various subsets of
{M. Bordone, M.Gonzalez-Alonso, A. Greljo, A. Falkowski, 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
Phys.Rev.Lett. 116 (2016) 1, 011801 arXiv: 1508.00581
arXiv: 1512.06135 Accepted in Eur. Phys. J

Introduction

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

The SM is complete.

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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: 2-step approach

1

Measure all the physical properties of the Higgs,
in production and decay,
with the highest possible accuracy.

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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, …

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

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

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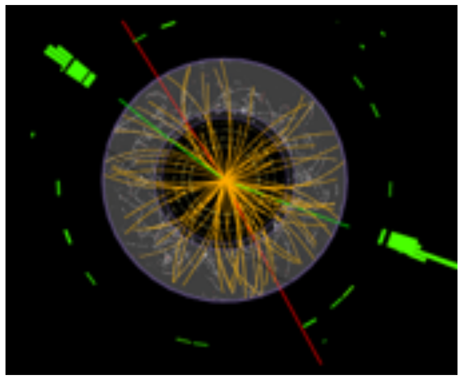

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

Realistic Observables

Raw data,
Fiducial cross sections,
etc…

Lagrangian parameters

Couplings,
running masses,
Wilson coefficients
etc …

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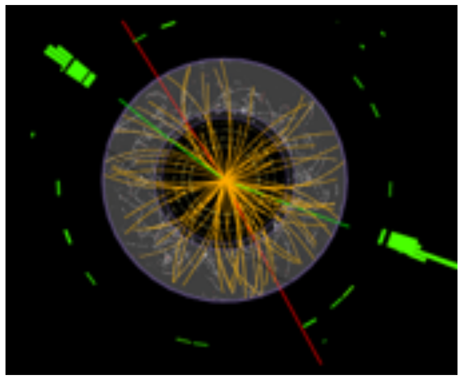

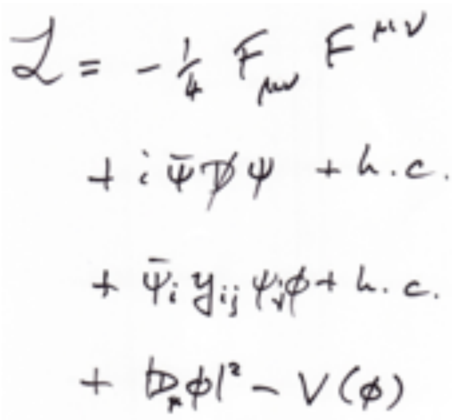

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Pole masses, decay widths, kappas, form factors, etc..

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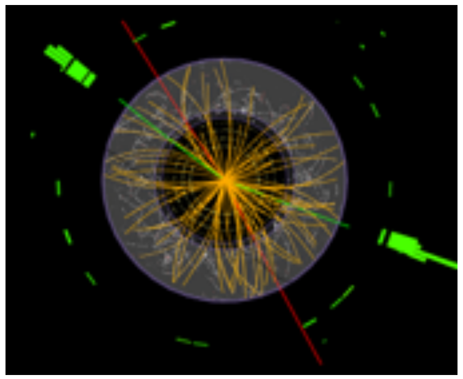

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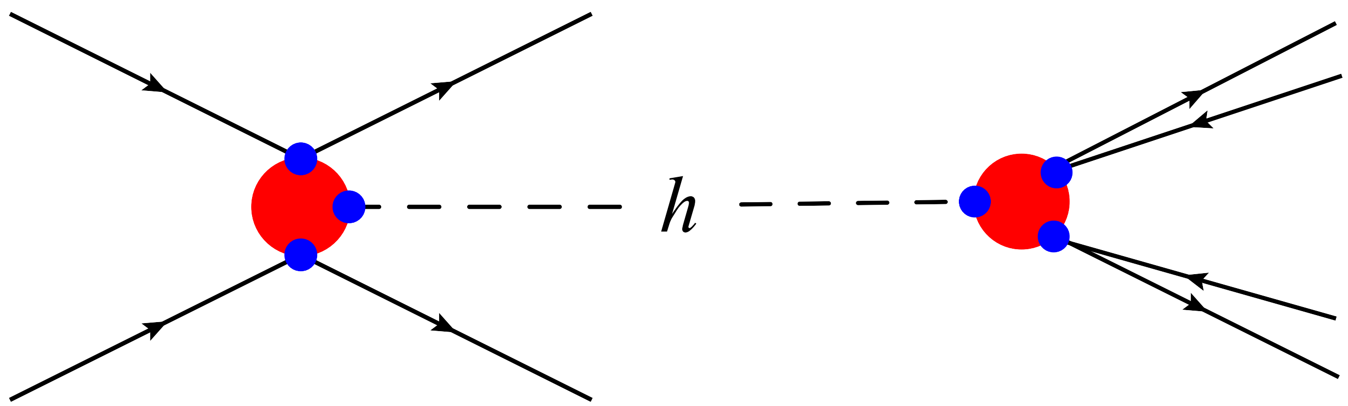
The goal of pseudo observables is to encode all the experimental information on a given physical process in a few parameters with a well-defined theoretical interpretation.

Higgs PO: QFT definition

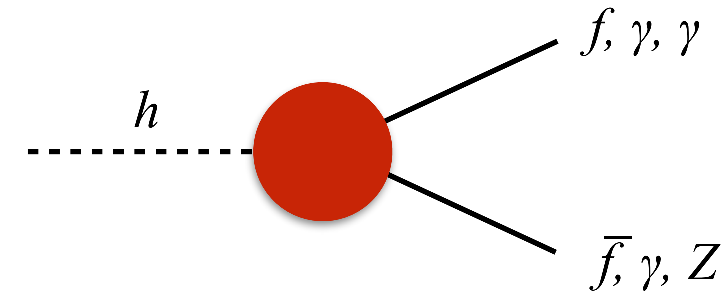
Defined from:

decomposition of **on-shell amplitudes** (NWA),
based on Lorentz invariance, unitarity, 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.

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

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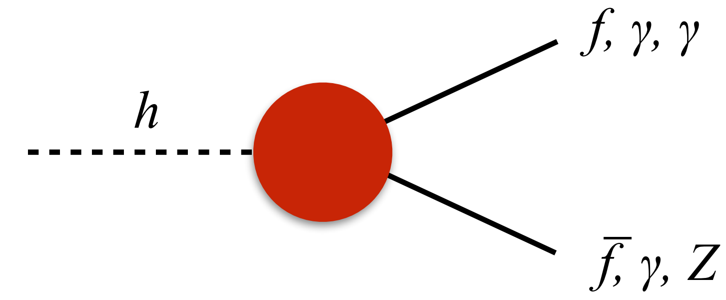
$\epsilon_X^{\rm SM,eff}$ $y_{\rm eff}^{f,\rm SM}$ from best SM prediction of the decay rate.

In the SM

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

Two-body Higgs decays



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

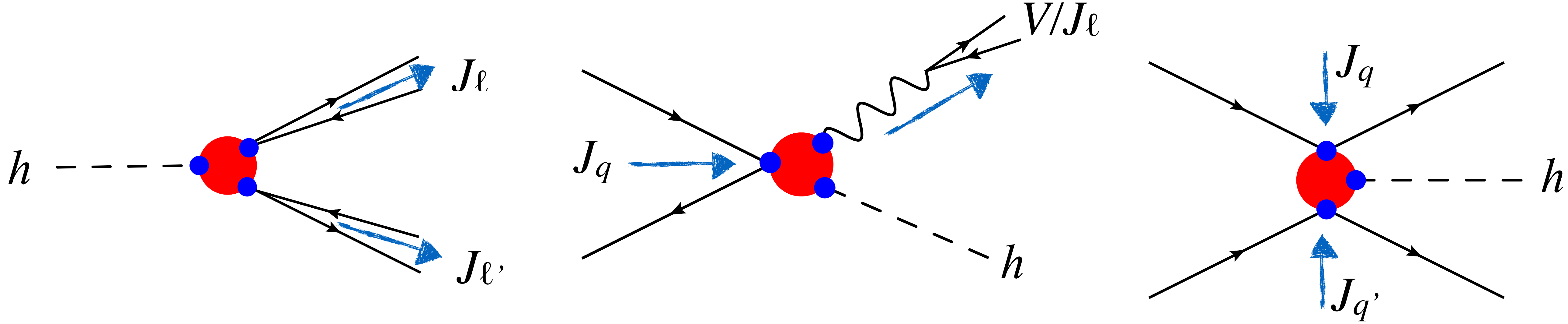
The kinematics is fixed.

No polarisation information is retained.

(maybe possible to measure in ττ channel)

the total rate is all that can be extracted from data

4-fermion Higgs decays and EW Higgs Production



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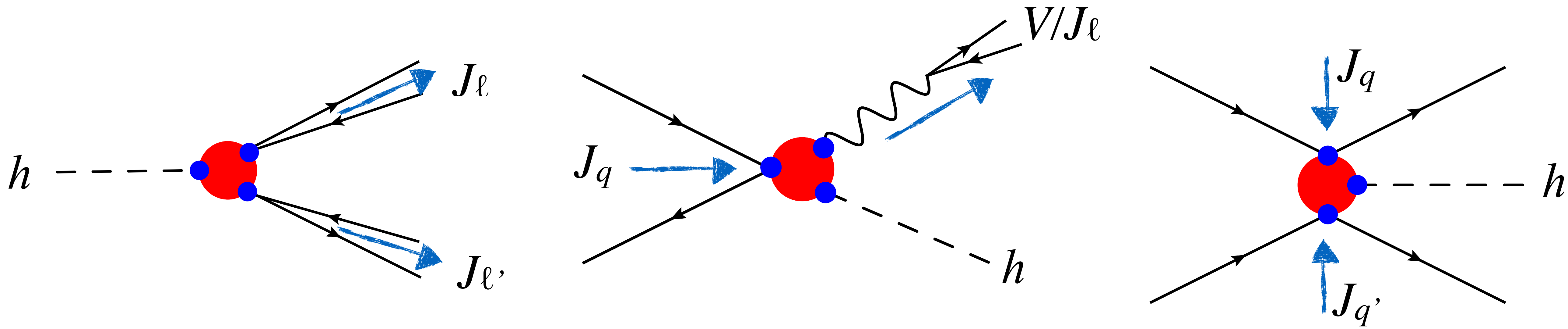

By crossing symmetry, all these processes are described in full generality by the same correlation function.
(in a different kinematical region and with different fermionic currents)

On-shell Higgs and two on-shell EW currents

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

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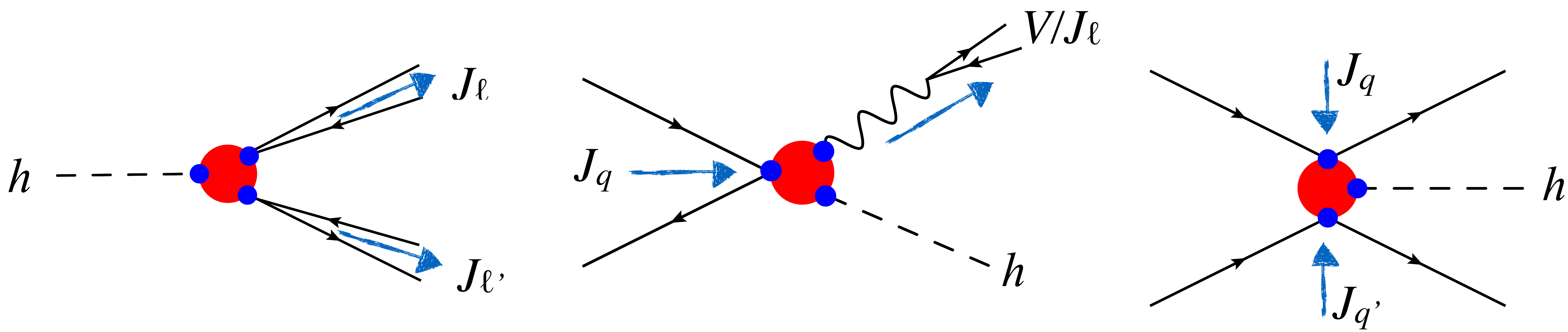

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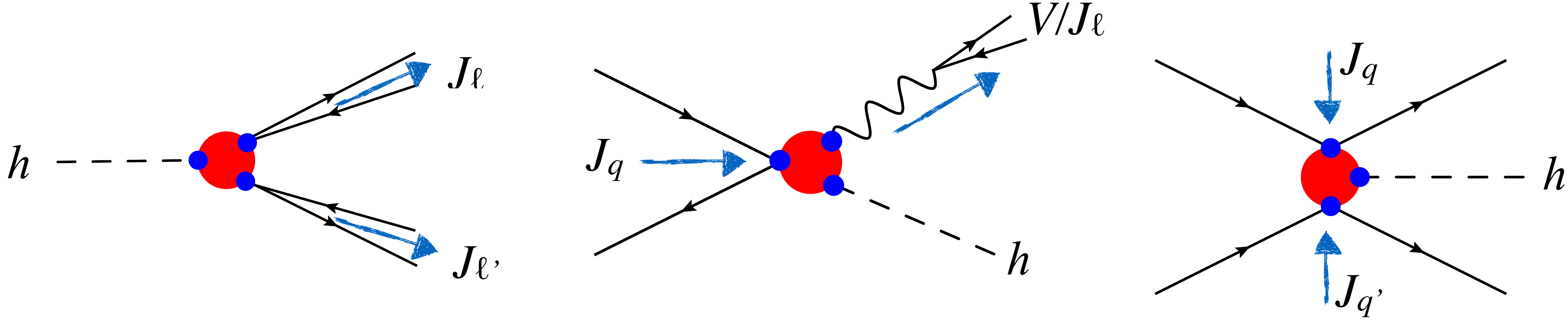
Use the same parametrization of Higgs decays also for the production.



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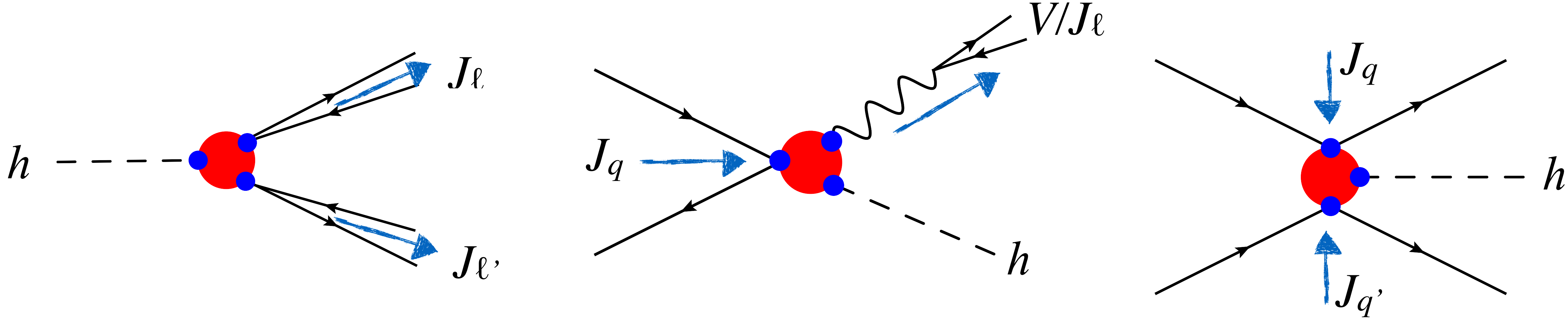
Only 3 tensor structures allowed by Lorentz symmetry:

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*



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Ultimate experimental goal for any of these processes:

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

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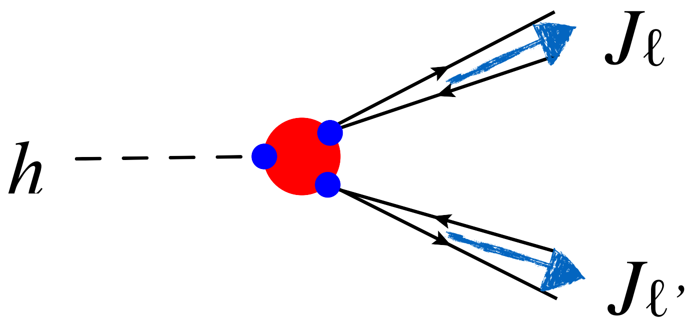

includes

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

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

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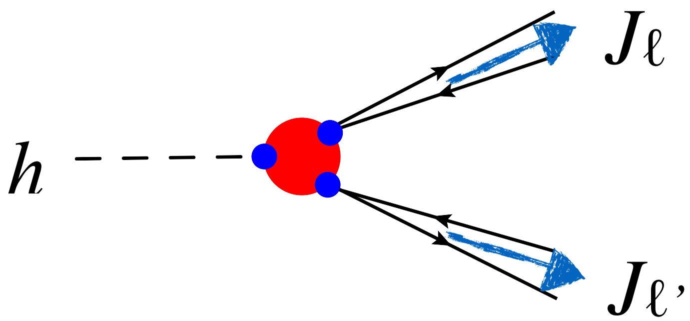

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Assuming: *New Physics scale > Energy scale of the process*

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

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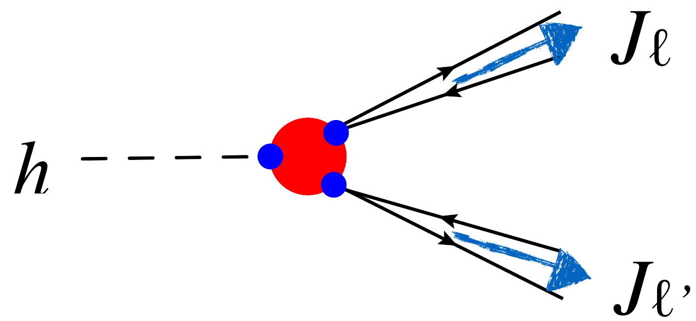

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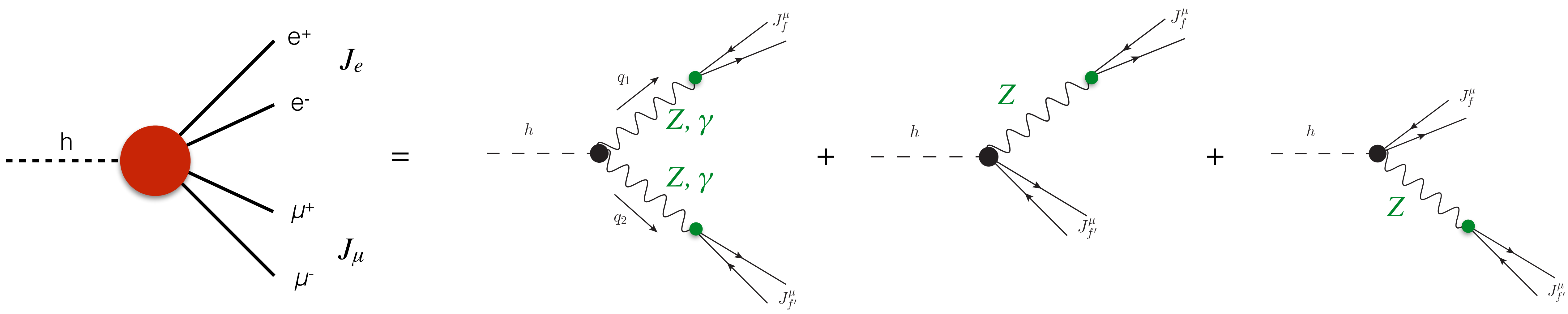
Given a maximal value $q^2{}_{\mathrm{max}}$,
the validity of the expansion can be checked a posteriori with data.

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



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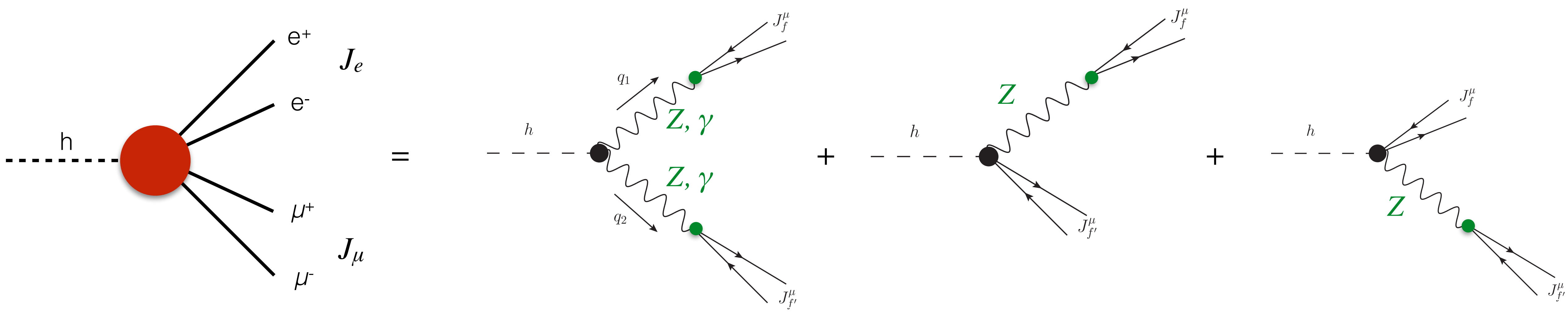
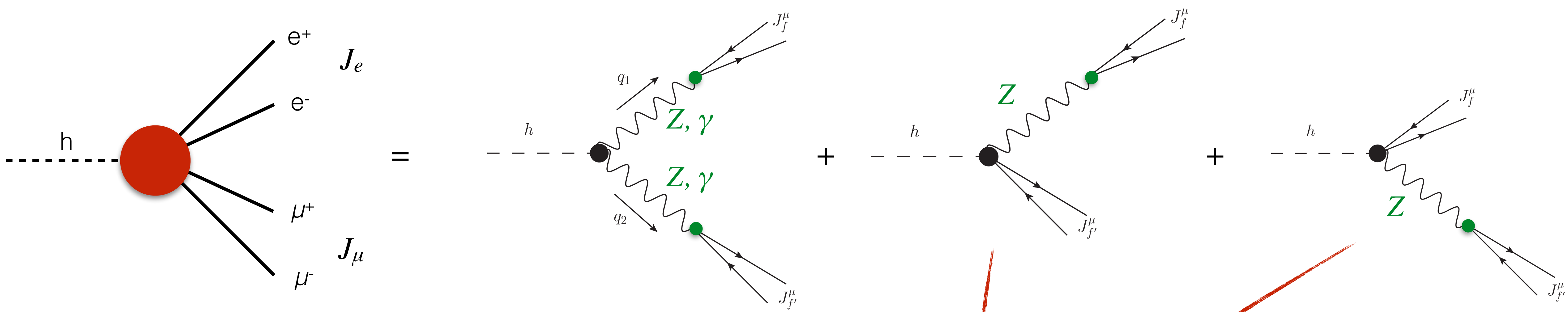


$$\mathcal{A} = i\frac{2m_Z^2}{v_F}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times$$
$$\Bigg[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right) g^{\alpha\beta} +$$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

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

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

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



contact terms
only new 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 \\
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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}^{\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} + \\
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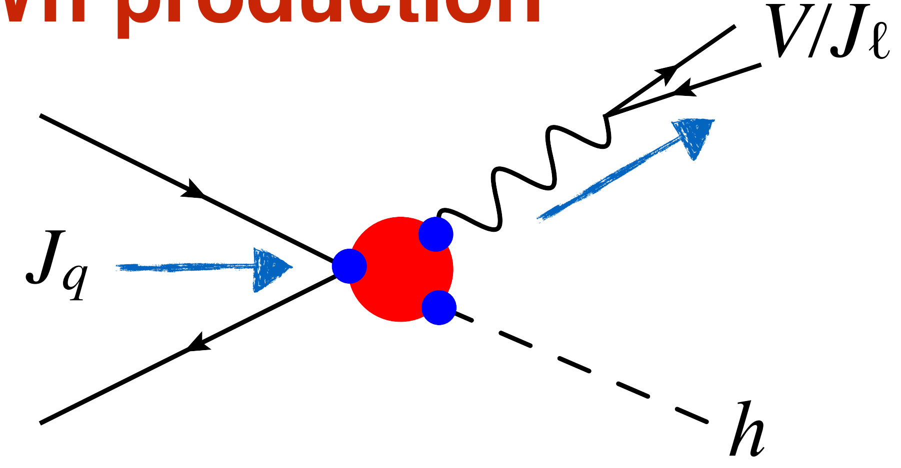
Associate Zh/Wh production

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



Goal: measure the differential distribution in m_{Zh}.

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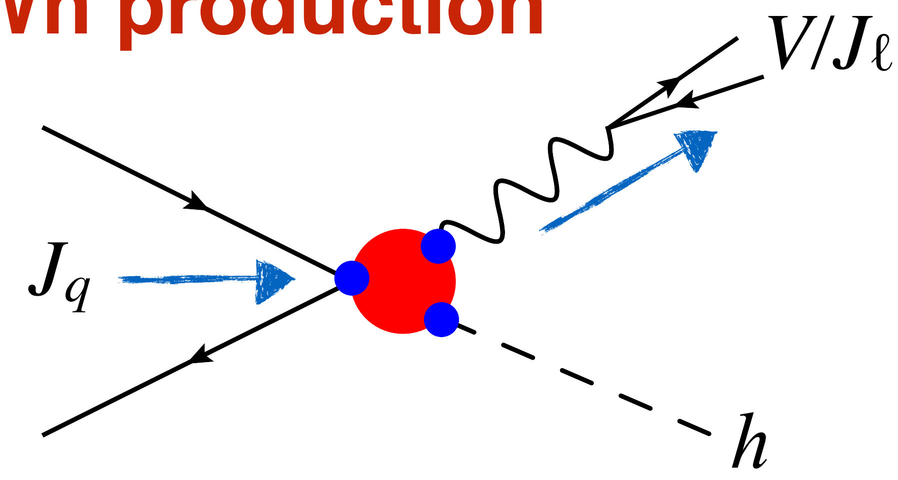

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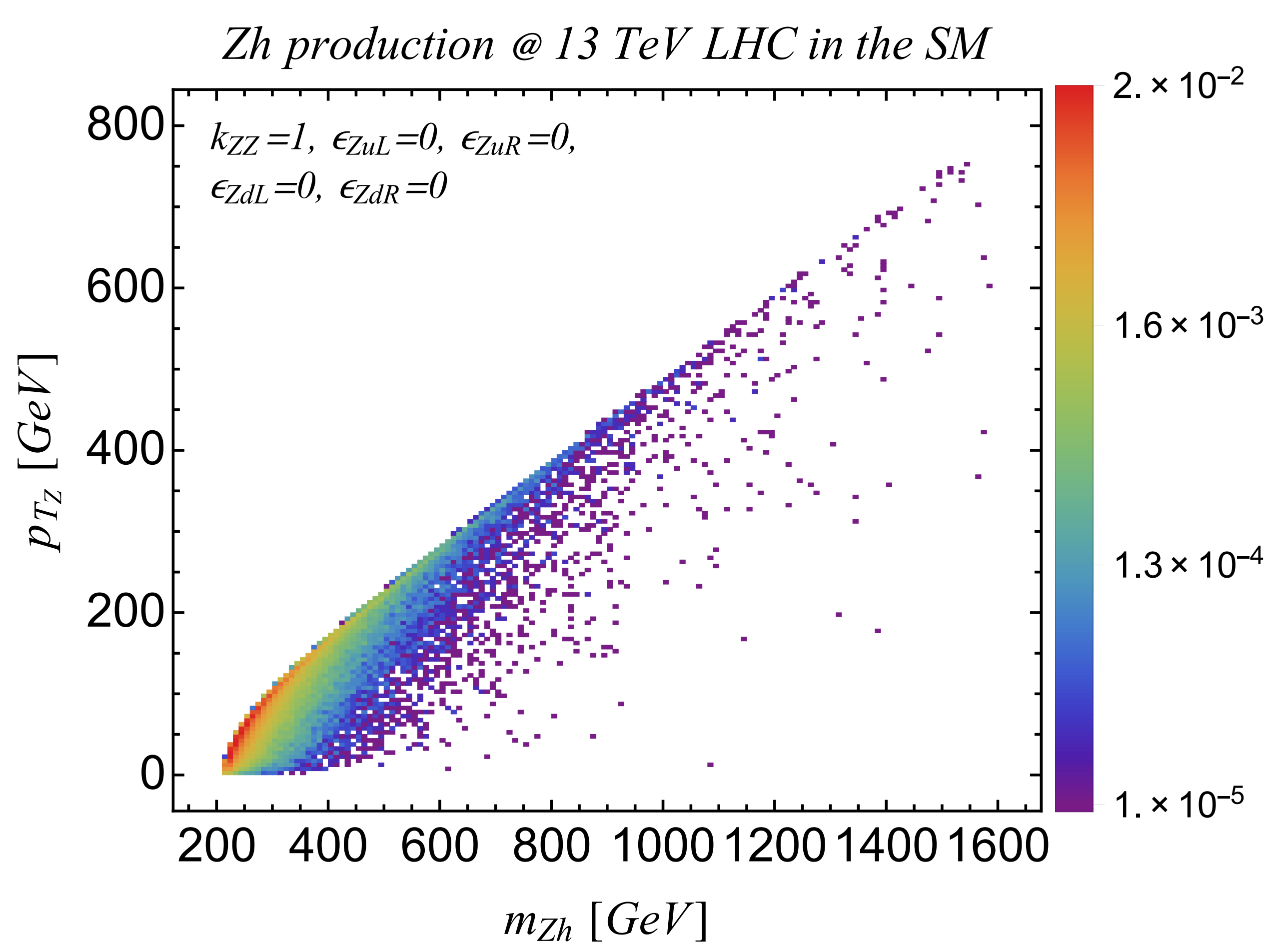
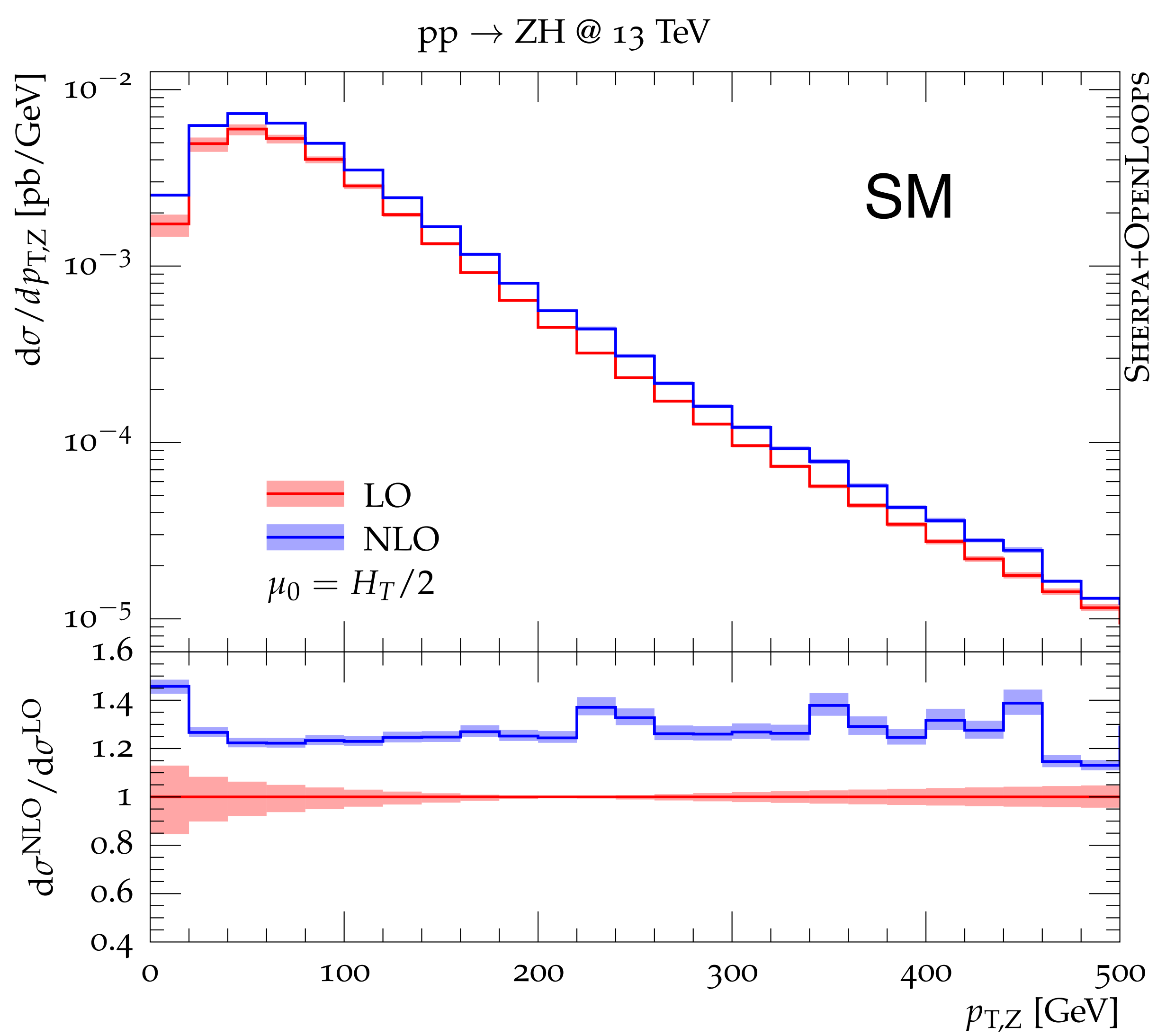
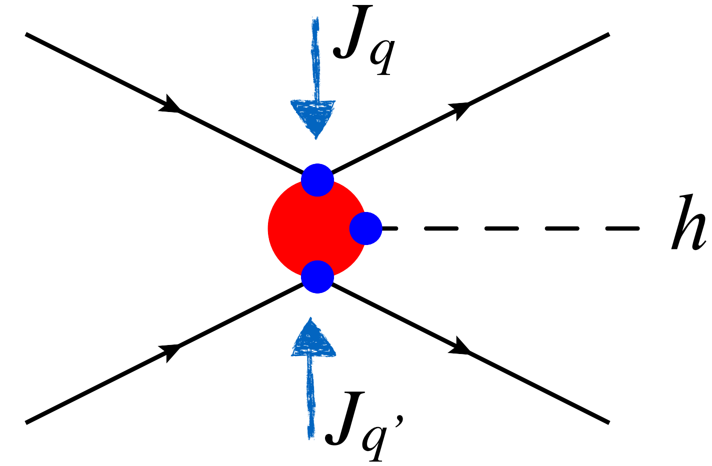
m_{Zh} correlates with the $p_T{}^Z$.



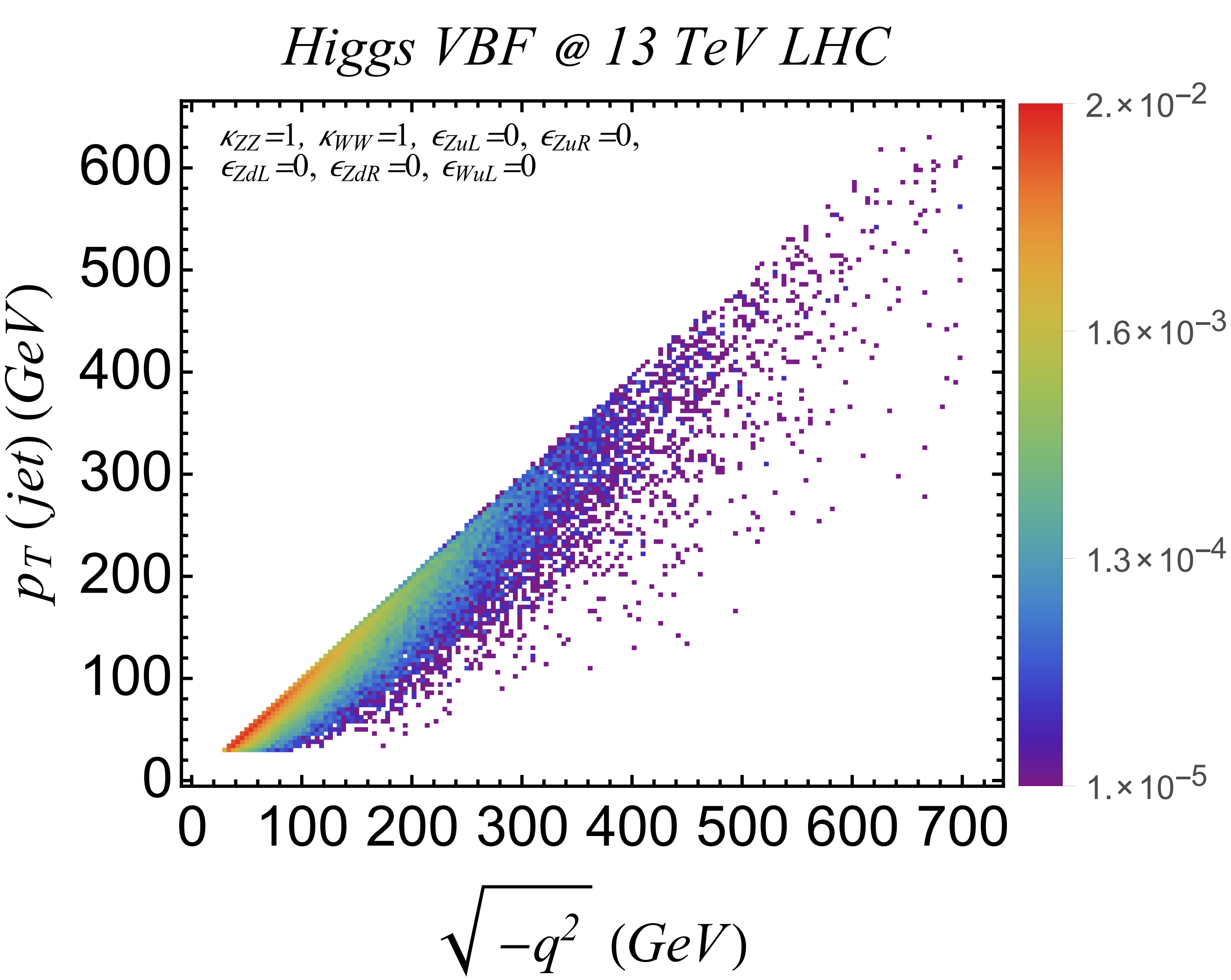


VBF Higgs production



q_i^2 correlates with the p_{Tjet_i}

$q_i^2 \sim p_{Tjet_i}$



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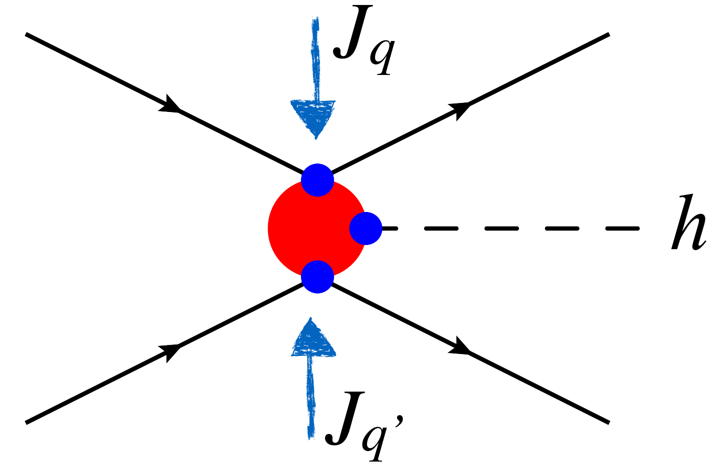

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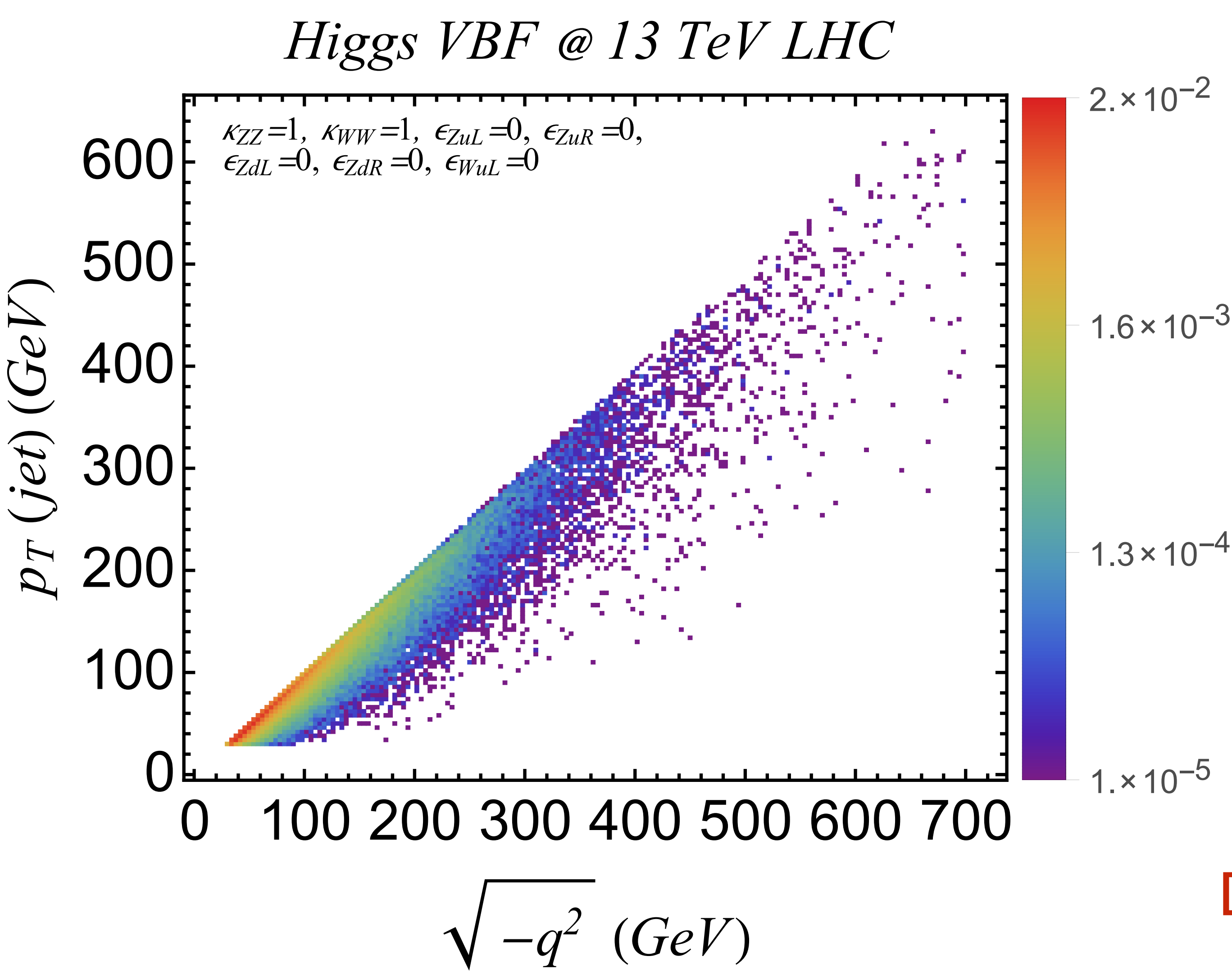

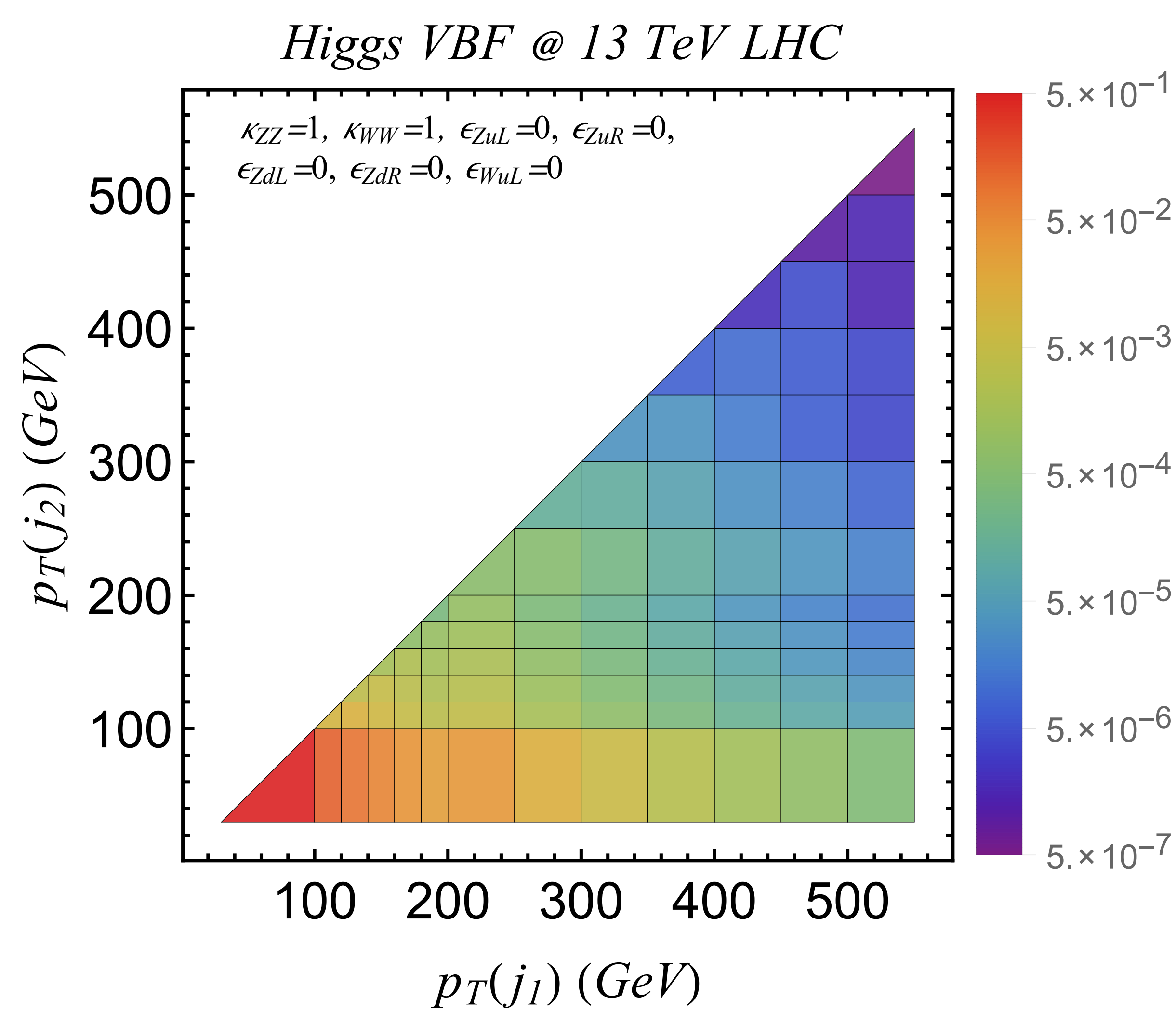

$$F(q_1^2, q_2^2) \to \tilde{F}(p_{T1}^2, p_{T2}^2)$$

Double-differential distribution in the jets pT.

Parameter counting and symmetry assumptions

EW decay and production:

Higgs (EW) decay amplitudes

<table>
<tr><th>Amplitudes</th><th>Flavor + CP</th><th>Flavor Non Univ.</th><th>CPV</th></tr>
<tr><td>$h \to \gamma\gamma, 2e\gamma, 2\mu\gamma$
$4e, 4\mu, 2e2\mu$</td><td>6 $\kappa_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}, \epsilon_{ZZ}$
$\epsilon_{Ze_L}, \epsilon_{Ze_R}$</td><td>$\epsilon_{Z\mu_L}, \epsilon_{Z\mu_R}$</td><td>$\epsilon^{CP}_{ZZ}, \lambda^{CP}_{Z\gamma}, \lambda^{CP}_{\gamma\gamma}$</td></tr>
<tr><td rowspan="2">$h \to 2e2\nu, 2\mu2\nu, e\nu\mu\nu$</td><td rowspan="2">4 $\kappa_{WW}, \epsilon_{WW}$
$\epsilon_{Z\nu_e}$, $\mathrm{Re}(\epsilon_{We_L})$</td><td>$\epsilon_{Z\nu_\mu}$, $\mathrm{Re}(\epsilon_{W\mu_L})$</td><td>$\epsilon^{CP}_{WW}$, $\mathrm{Im}(\epsilon_{We_L})$</td></tr>
<tr><td colspan="2">$\mathrm{Im}(\epsilon_{W\mu_L})$</td></tr>
</table>

Test UV symmetries!

Higgs (EW) production amplitudes

<table>
<tr><th>Amplitudes</th><th>Flavor + CP</th><th>Flavor Non Univ.</th><th>CPV</th></tr>
<tr><td>VBF neutral curr.
and Zh</td><td>4 $[\ \kappa_{ZZ}, \kappa_{Z\gamma}, \epsilon_{ZZ}\ ]$
$\epsilon_{Zu_L}, \epsilon_{Zu_R}, \epsilon_{Zd_L}, \epsilon_{Zd_R}$</td><td>$\epsilon_{Zc_L}, \epsilon_{Zc_R}$
$\epsilon_{Zs_L}, \epsilon_{Zs_R}$</td><td>$\left[\ \epsilon^{CP}_{ZZ}, \lambda^{CP}_{Z\gamma}\ \right]$</td></tr>
<tr><td rowspan="2">VBF charged curr.
and Wh</td><td rowspan="2">1 $[\ \kappa_{WW}, \epsilon_{WW}\ ]$
$\mathrm{Re}(\epsilon_{Wu_L})$</td><td>$\mathrm{Re}(\epsilon_{Wc_L})$</td><td>$\mathrm{Im}(\epsilon_{Wu_L})$</td></tr>
<tr><td colspan="2">$\mathrm{Im}(\epsilon_{Wc_L})$</td></tr>
</table>

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

Tool for signal simulation: NLO description

Higgs PO have been implemented in a FeynRules/**UFO model**:

www.physik.uzh.ch/data/HiggsPO/

Decays:

Hard process *QED / QCD soft radiation*

MadGraph5 / Sherpa × **Photos / Pythia**

$\simeq$ **1% precision** (NLO EW) differential & for BSM points

$h \rightarrow 4\ell$ checked with Prophecy4f

EW Production @ NLO:

OpenLoops

NLO QCD description differential & for BSM points

(in progress)

×

Sherpa

Matched showering at NLO

The Linear SM Effective Field Theory

Integrate out the heavy BSM states.

Low energy theory specified by Symmetries & Field content

Assuming h(125) is a $SU(2)_L$ doublet:
(linear) ***SMEFT***

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

and

Scale of New Physics is high

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

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and

Scale of New Physics is high

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

Assuming L and B conservation

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

Standard Model
Lagrangian (d ≤ 4)

Leading deformations of the SM

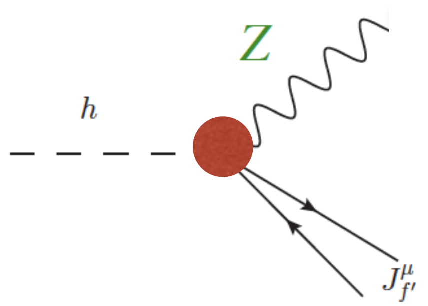
59 independent dim-6 operators if flavour universality.
2499 parameters for a generic flavour structure.

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

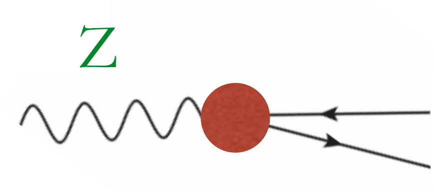
The power of the EFT: relating different observables

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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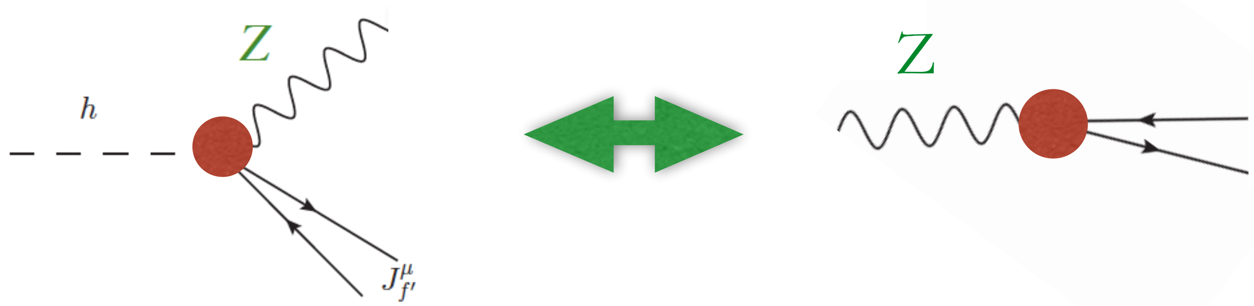
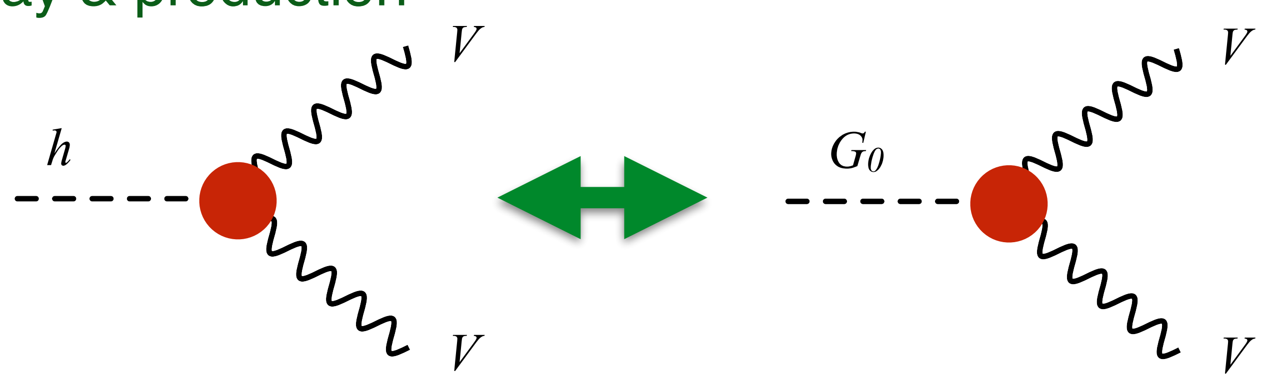


Z couplings δg_{Zf}

Higgs decay & production

or

&



Triple Gauge Couplings

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

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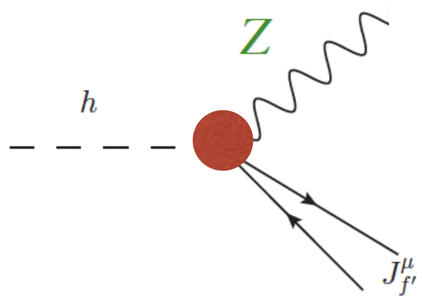

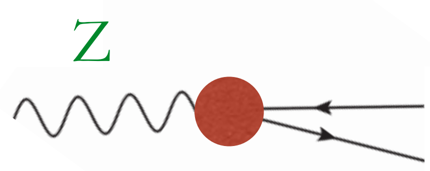

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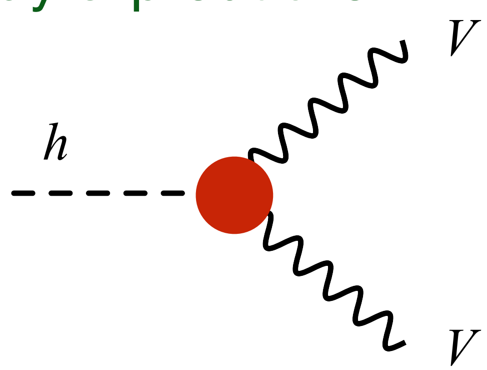
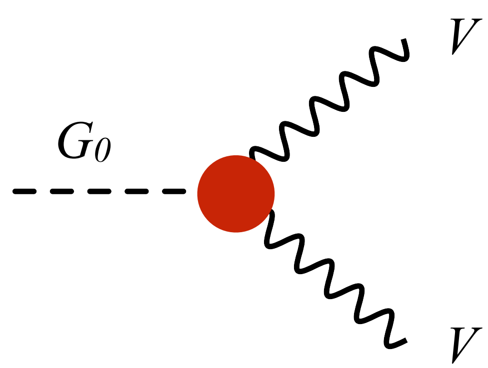




Triple Gauge Couplings
$\delta\kappa_z,\ \delta g_{1,z},\ \lambda_Z$

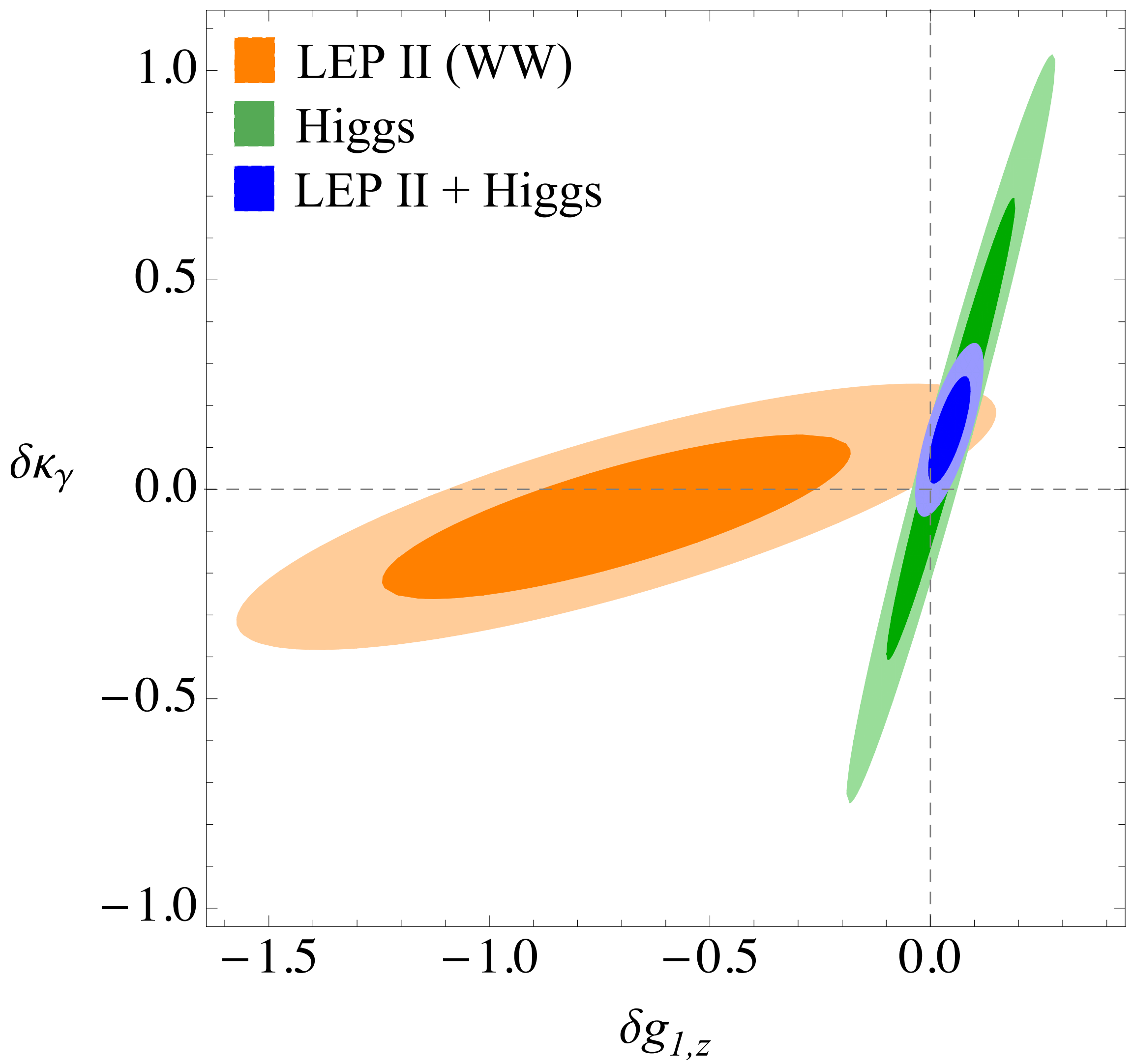
- Use LEP 1 and LEP 2 data to obtain bounds on some Higgs PO.
- Combine LEP data with Higgs data to derive stronger constraints for the EFT.

The power of the EFT: relating different observables

Assuming the strong LEP I constraints (≲1%) [Pomarol Riva 2013; Efrati et al. 2015; Berthier, Trott 2015] and MFV, only 10 independent combinations of coefficients contribute at tree-level to Higgs and LEP II (WW) observables. [Corbett et al. 2013; J. Elias-Miro et al. 2013; Pomarol Riva 2013; Gupta et al 2014; Falkowski 2015]

Constraints on TGCs from a **Global fit**

[Falkowski, Gonzalez-Alonso, Greljo, D.M. PRL 116 (2016) 1, 011801 - arXiv 1508.00581]



All other coefficients have been marginalised.

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

+

Higgs data (mainly via VH and VBF production) is sensitive to a different direction. [Falkowski 1505.00046]

=

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

Constraints on the Higgs PO in the linear EFT

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

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

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

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

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

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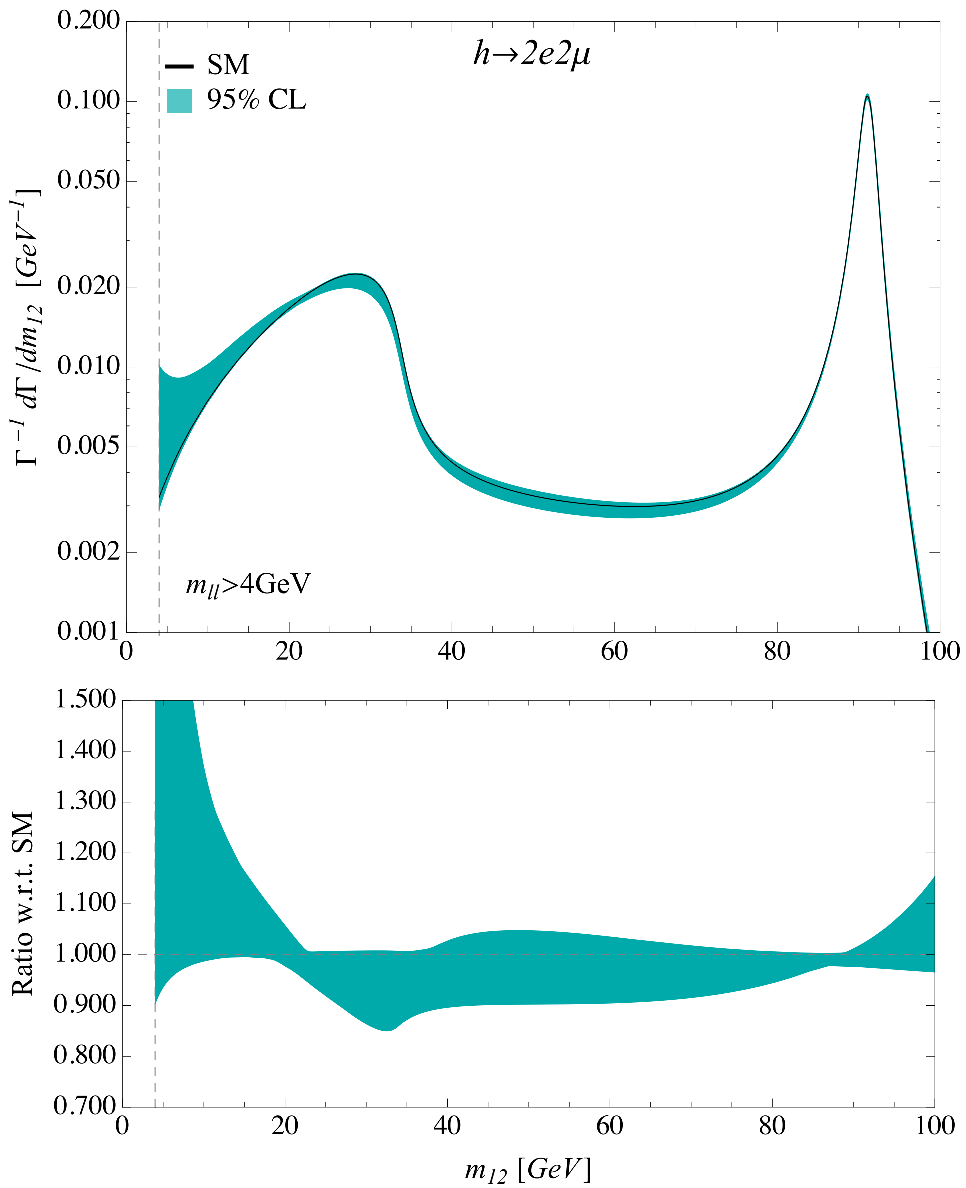
[Gonzalez-Alonso, Greljo, Isidori, D.M. 1504.04018]

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

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



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

Constraints on the Higgs PO in the linear EFT

W s.

e.g h→4ℓ:

Crucial to test these predictions from data!

Any measured deviation would have deep physical consequences:

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

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

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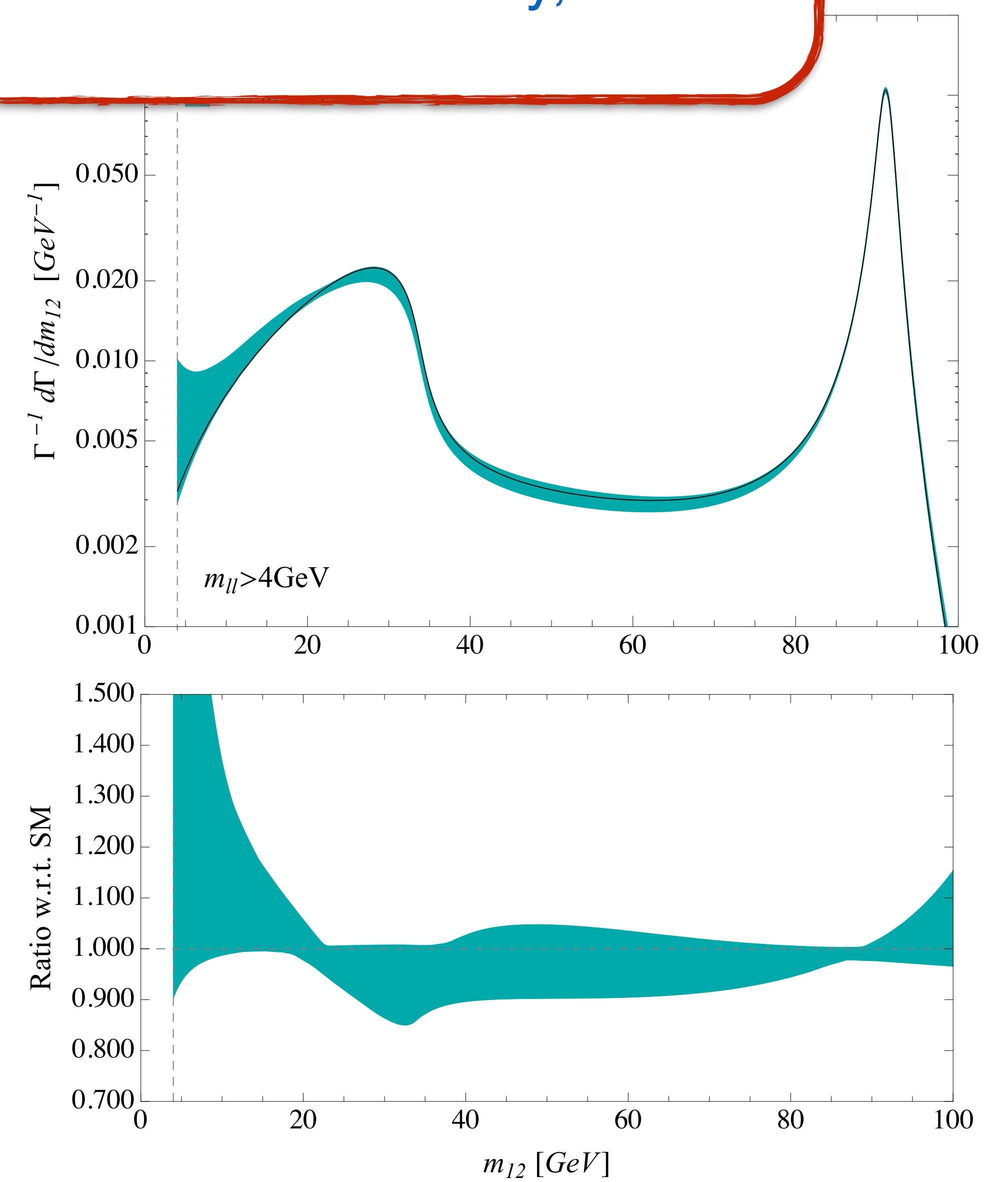

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Summary

Higgs PO

Characterize all the measurable properties of on-shell Higgs boson processes

in a robust and model-independent way.

This information can be fed to specific BSM models, such as **SMEFT**,

which allow us to derive:

1) stronger bounds via combination of different processes

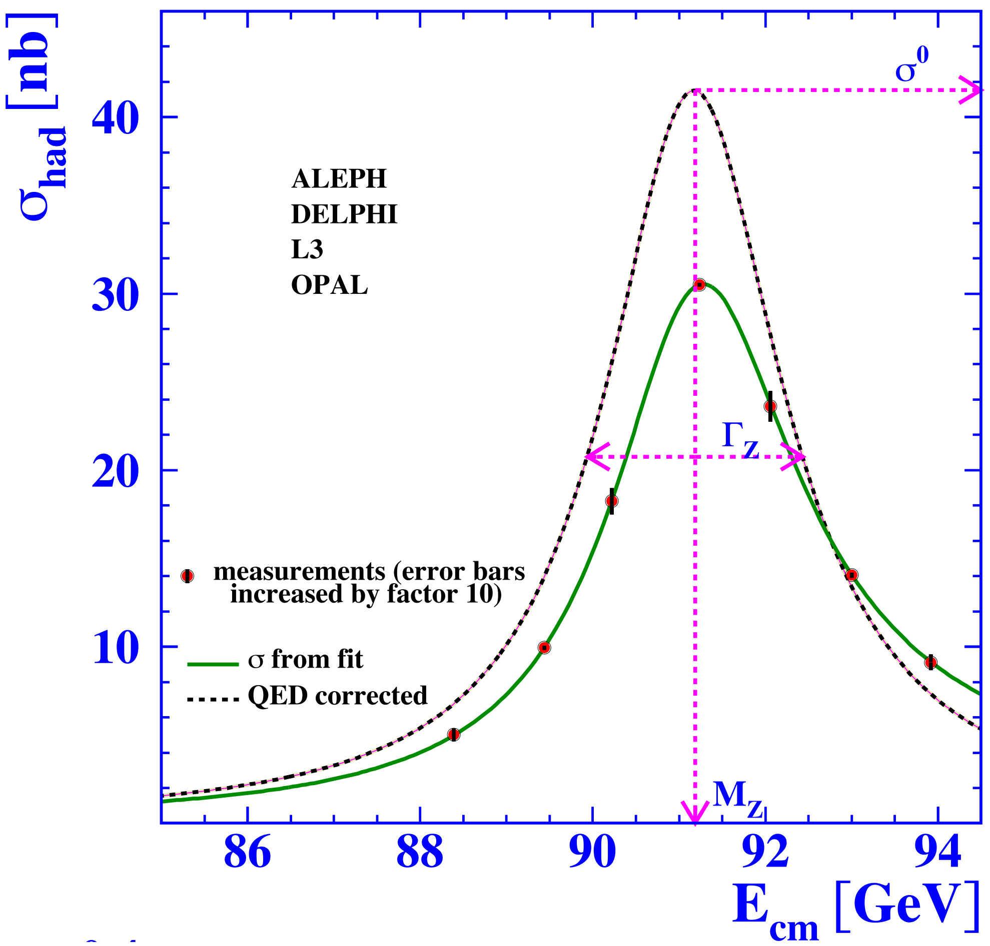
2) predictions to be tested directly in Higgs physics.

Backup

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

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

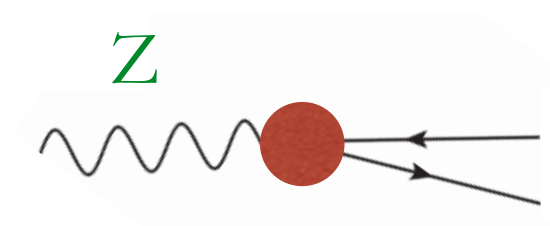
$$m_Z,\ \Gamma_Z$$

Lineshape

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

Parametrise the on-shell $Z\bar{f}f$ vertex as

$$\gamma_\mu \left(\mathcal{G}_V^f + \mathcal{G}_A^f\,\gamma_5\right)$$



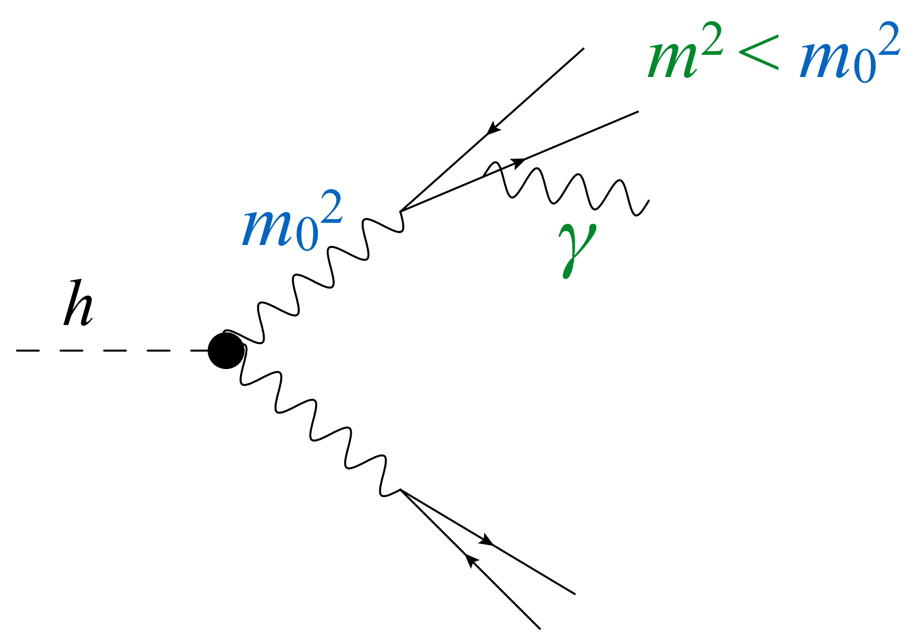
The PO are defined as

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

3) Fit the PO from data

Radiative Corrections in h→4ℓ

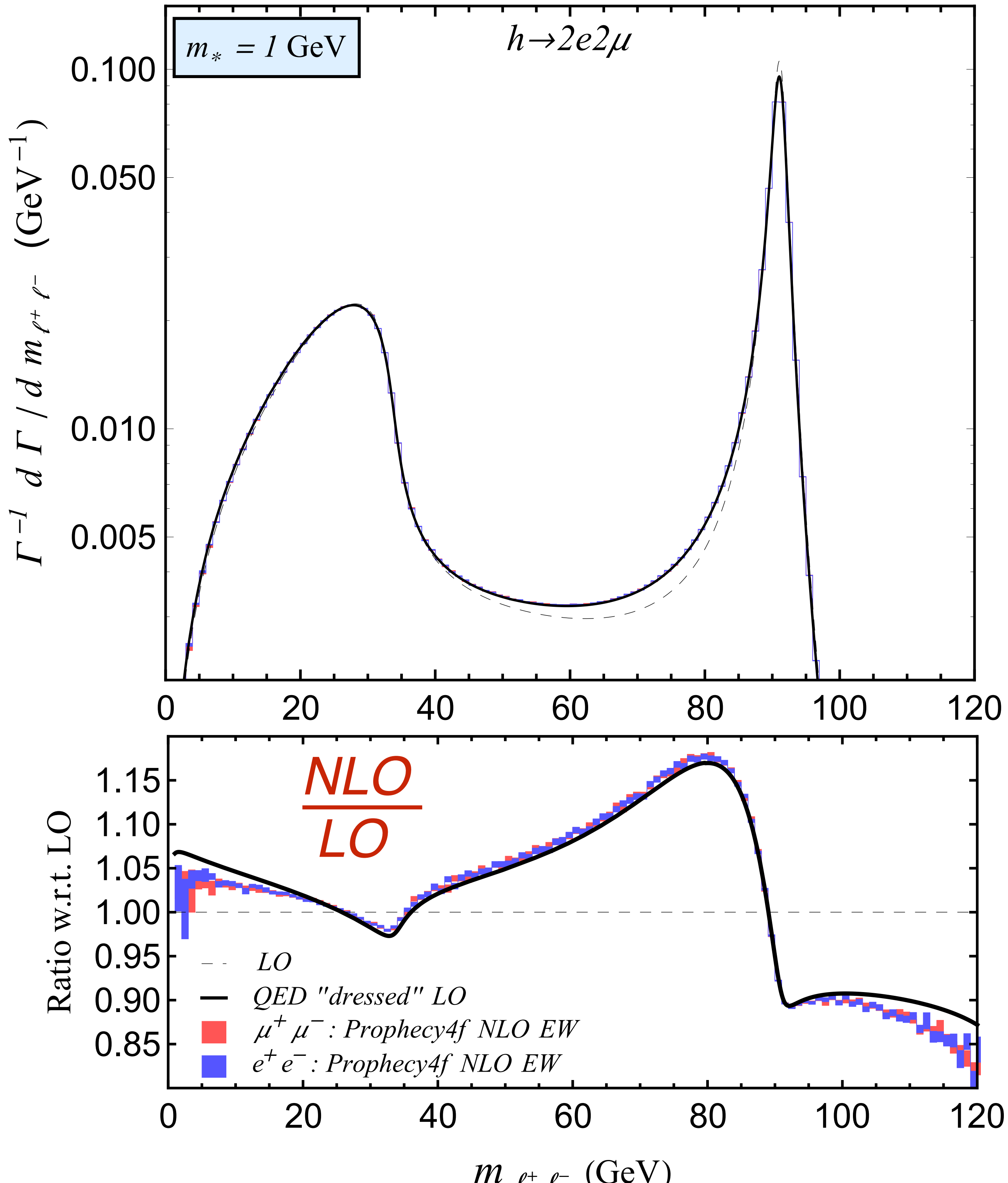
The most important radiative corrections are given by soft QED radiation effects since they distort the spectrum.



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

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

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



~15% effect!

Other NLO corrections are small: ≲1%

NLO (QCD) corrections in Vh Production

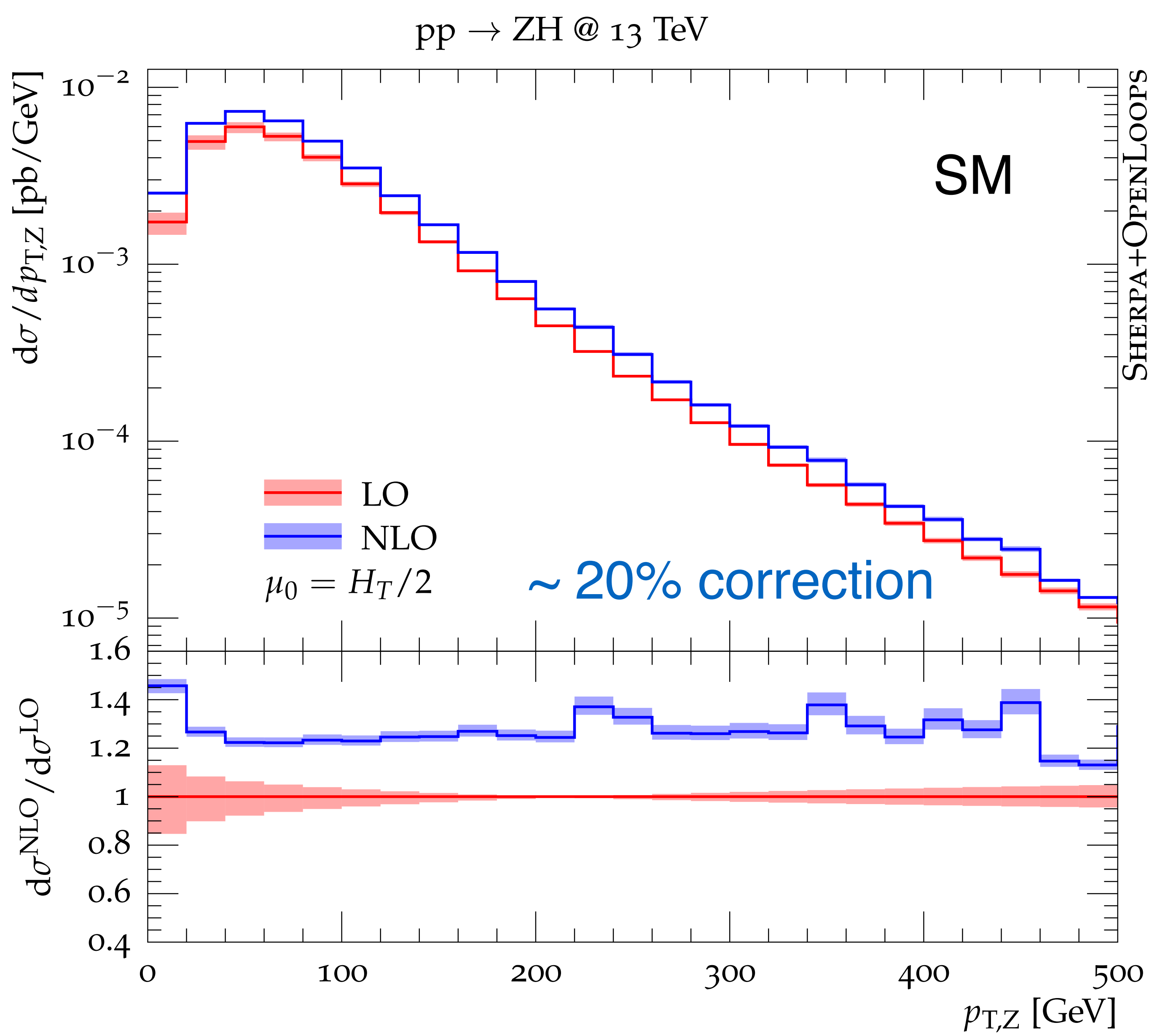
Dominant NNLO QCD correction in diff. distribution in the SM is known.
[Ferrera, Grazzini, Tramontano 1107.1164, 1312.1669, 1407.4747]

With ren. and fact. scale $H_T/2$
the NLO shape effects greatly reduced:
almost flat NLO correction.

Better convergence of the perturbative series.

$gg \to Zh$ treated as background
(different physical correlation function).

Effort to disentangle experimentally,
see template cross sections.



Leading NLO EW corrections up to ~ -15%: large Sudakov logs → factorize.
[Denner and Pozzorini hep-ph/0010201, hep-ph/0104127, Denner et al. 1112.5142]

NLO (QCD) corrections in VBF Production

Dominant NNLO QCD correction in diff. distribution in the SM has been computed very recently. [Cacciari et al. 1506.02660]

With ren. and fact. scale $H_T/2$ the NLO shape effects greatly reduced.

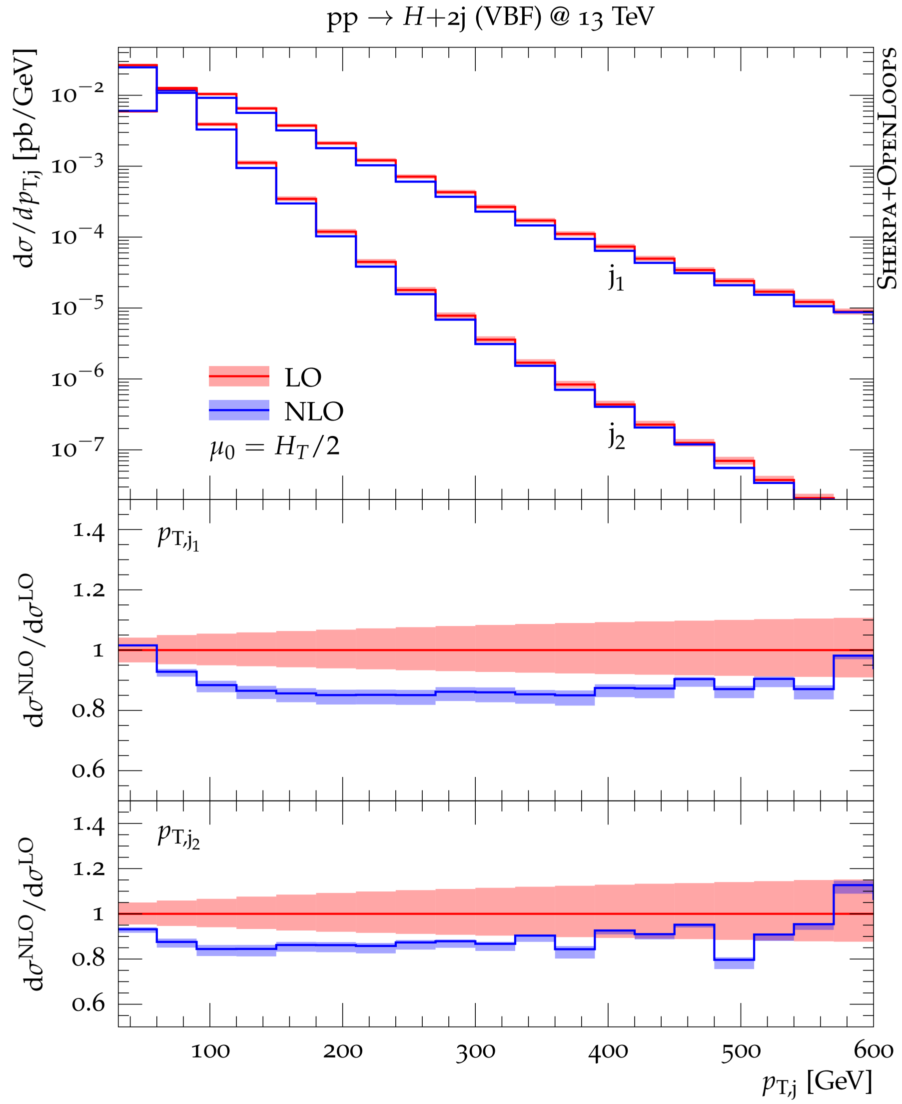
anti-k_T jets

$R=0.4$

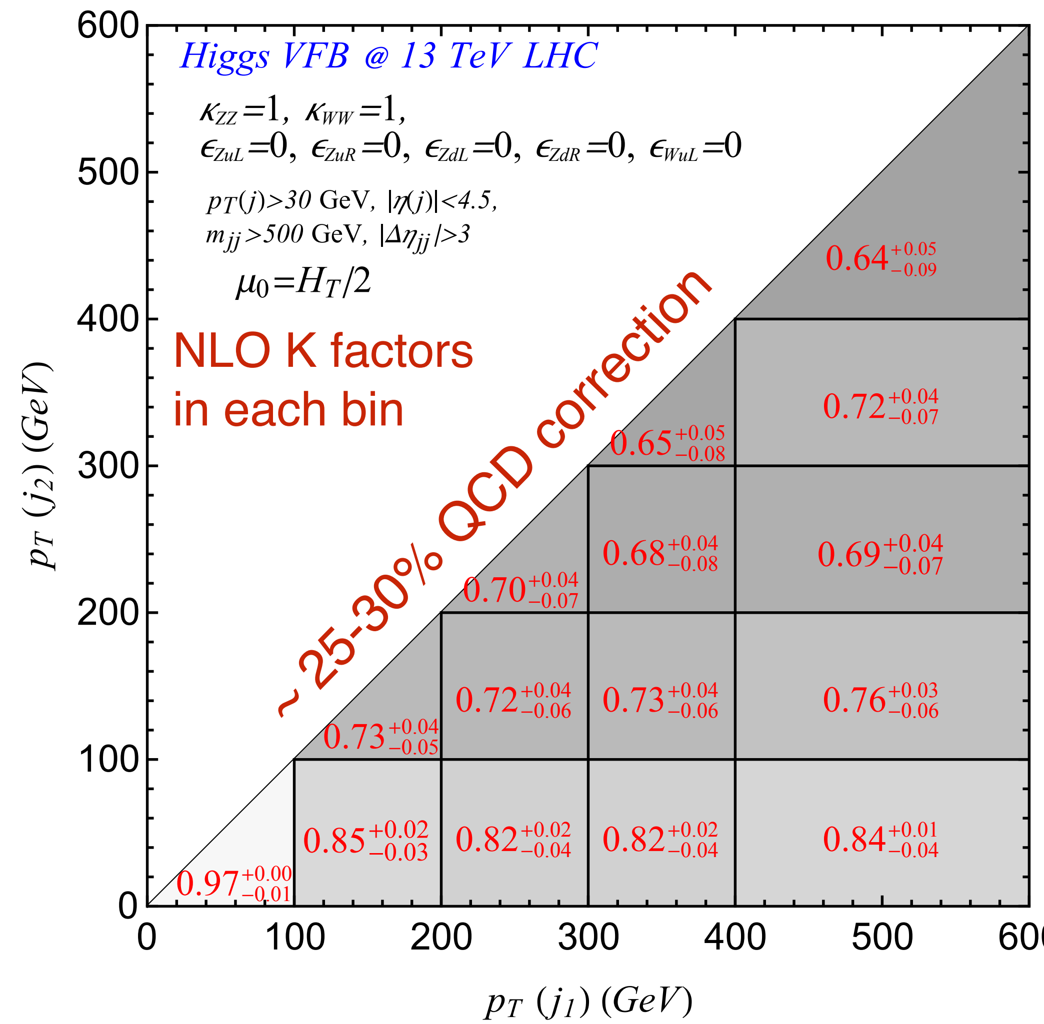
$\Delta\eta_{j_1 j_2} > 3$

Important cut for background reduction & stabilize NLO prediction in VBF

Leading and sub-leading jet pT:



2D jet pT distribution:



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[Denner and Pozzorini hep-ph/0010201, hep-ph/0104127, Ciccolini et al. 0710.4749, 0707.0381]

Prospects for PO in EW 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:

κ_{ZZ} , κ_{WW} , ϵ_{Zu_L} , ϵ_{Zu_R} , ϵ_{Zd_L} , ϵ_{Zd_R} , ϵ_{Wu_L}

We fix an upper cut on the q^2 of 600 GeV for controlling the momentum expansion validity.

Consistency condition: $\epsilon_{X_f} \; |q^2_{\max}| \lesssim m_Z^2 \; g_X^f$

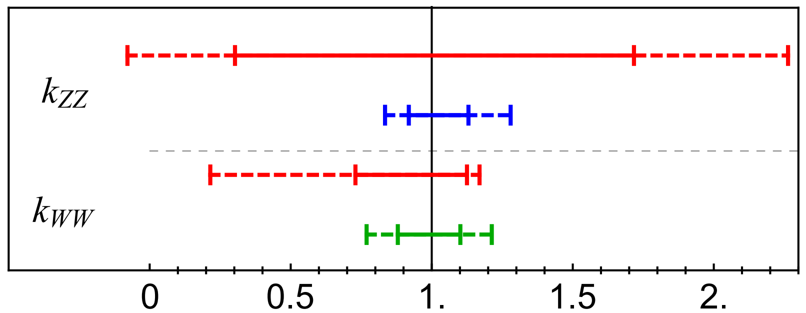
With 3000 fb^{-1}: ~ 2000 events in VBF ($h \to 2l2v$)
~ 130 events in all leptonic Zh
~ 67 events in all leptonic Wh

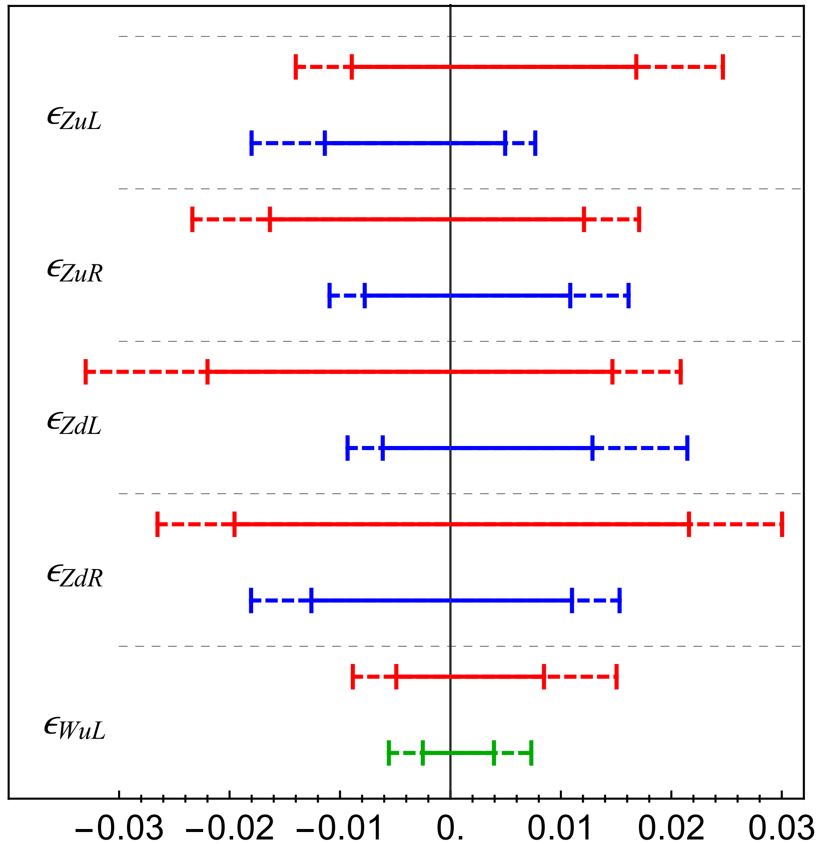
VBF: fit of the 2D p_T distribution.

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}



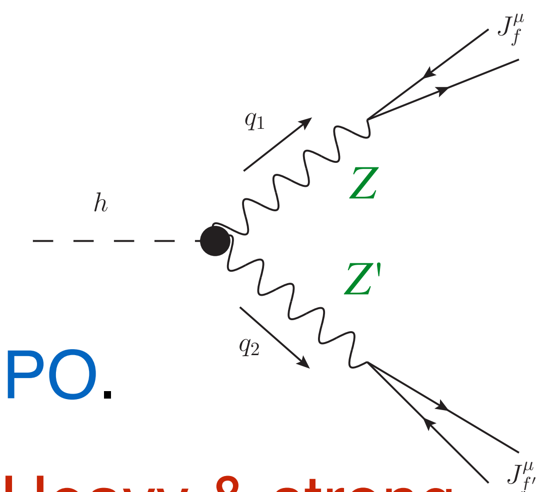


Validity of the momentum expansion (VBF)

The first check is given by the consistency condition $\epsilon_{X_f}\ |q^2_{\max}| \lesssim m_Z^2\ g_X^f$

Study in detail by considering an explicit NP contribution: Z' coupled to light quarks:

$$F_L(q_1^2,q_2^2)^{ff'} = F_{L,\mathrm{SM}}^{ff'}(q_1^2,q_2^2) - \frac{v}{m_Z} g_H \left[\frac{g_{Z'}^f g_Z^{f'}}{P_{Z'}(q_1^2)P_Z(q_2^2)} + \frac{g_Z^f g_{Z'}^{f'}}{P_Z(q_1^2)P_{Z'}(q_2^2)} \right]$$

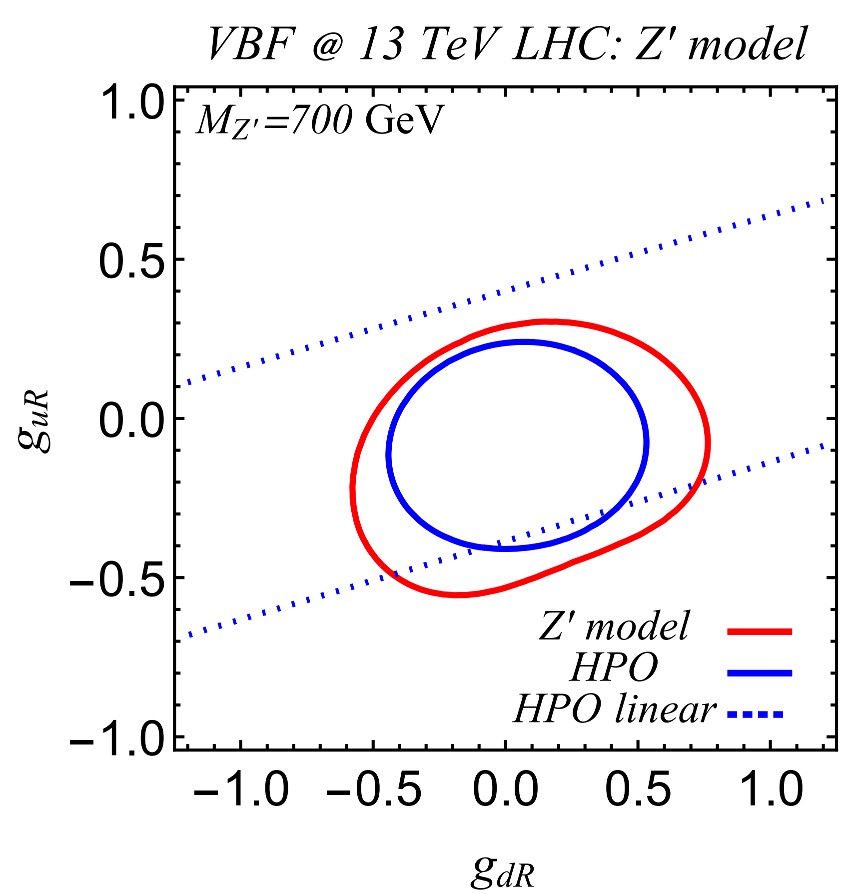


We can expand this form factor for $q^2 \ll M_{Z'}$ and match to the PO.

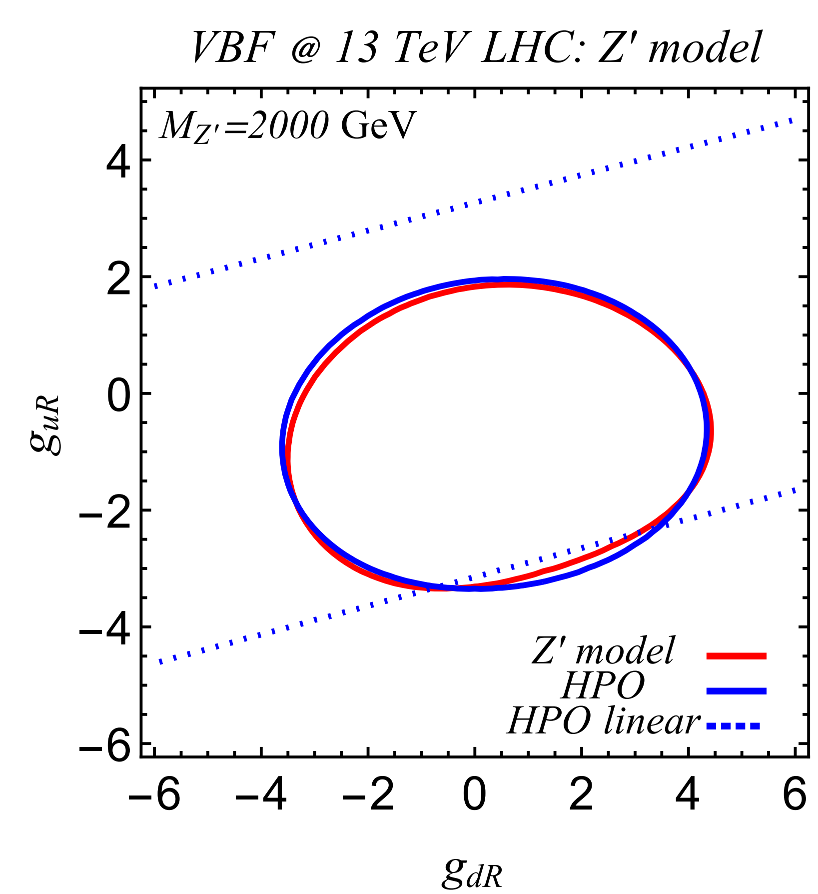
VBF fit with:

- Full model
- PO (linear)
- PO (quadratic)

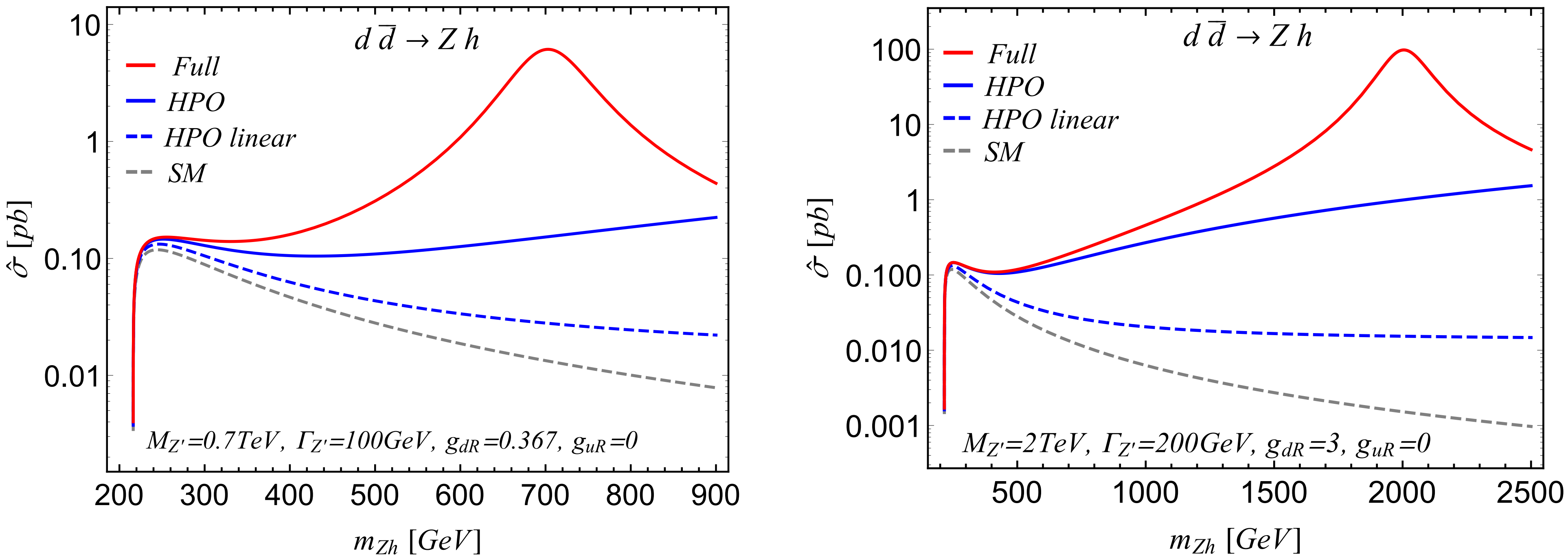
Light & weak



Heavy & strong



Validity of the momentum expansion (Zh)



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