A fully differential SMEFT analysis of the golden channel using the method of moments

Elena Venturini

14/04/2021

Based on arXiv:2012.11631
with Oscar Ochoa-Valeriano, Shankha Banerjee, Rick S. Gupta, Michael Spannowsky

HEFT 2021

New Physics Searches and Effective Field Theories

- **Direct** searches of new particles

Null Result

- **Indirect** searches in precision tests

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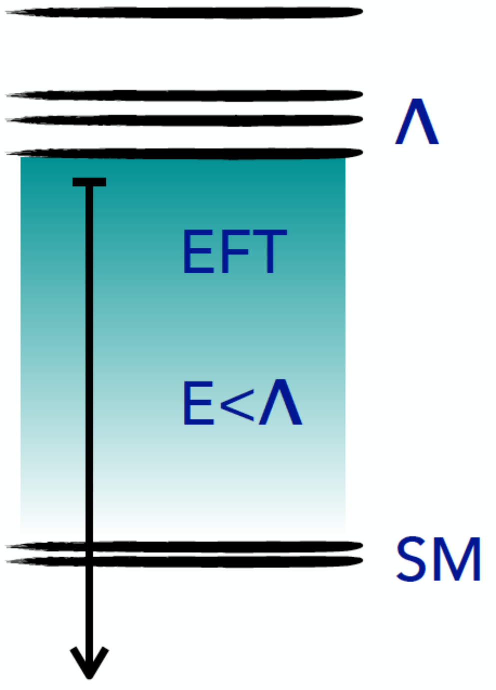
Model independent description ➔ EFT at $E < \Lambda$

$$\mathcal{L}_{EFT}(\varphi) = \mathcal{L}_{ren}(\varphi) + \sum_{i,d>4} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}(\varphi)\,.$$



Higgs Golden Channel

- Probe of Higgs-gauge boson couplings @LHC:

  Resolution of the tensor structure with differential study

- Angular Distribution with the **method of moments**

  in the Higgs Golden Channel: $h \to 4\ell$

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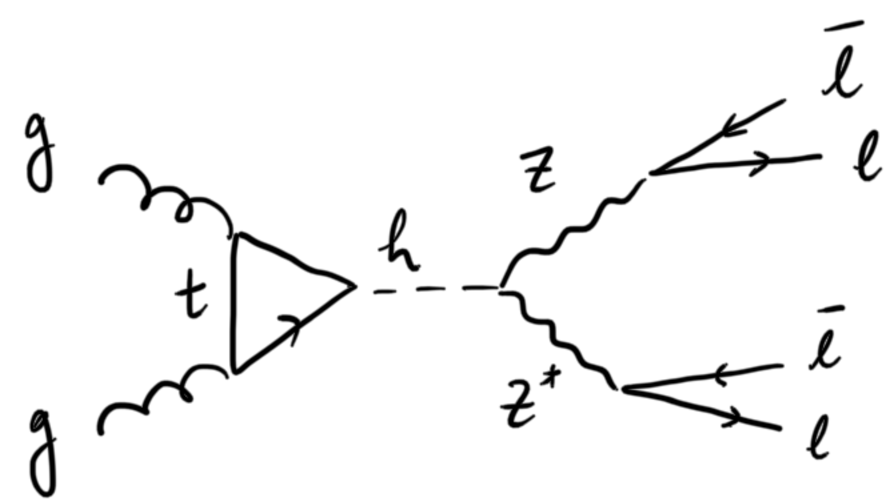
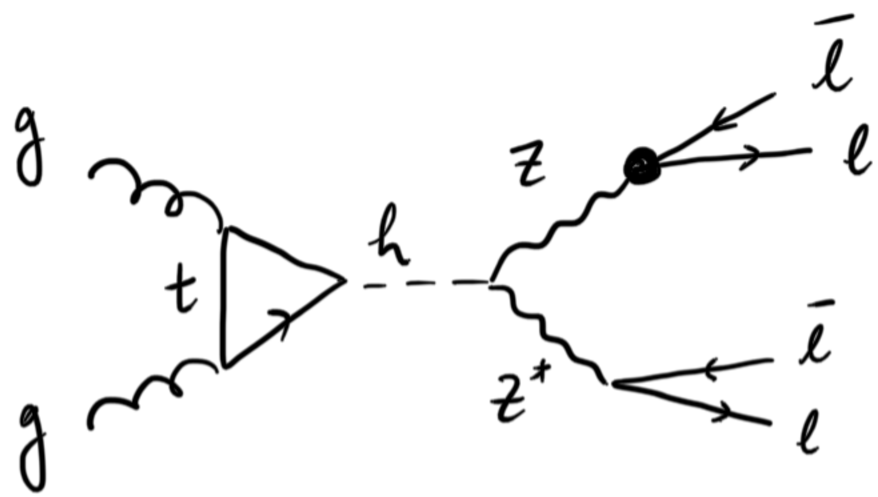
SM →

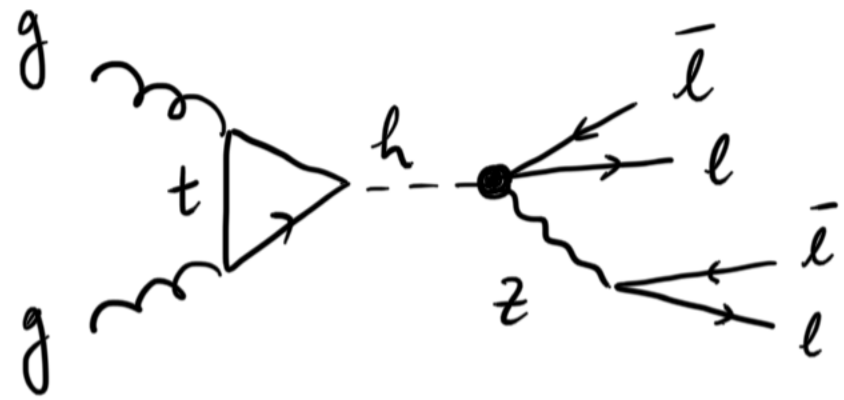


Higgs Golden Channel in the SMEFT



$$\sum_\ell \delta g_\ell^Z Z_\mu \bar{\ell}\gamma^\mu \ell$$ ➡

Bounded at per-mille level at LEP1 $[\Gamma(Z \to \bar{\ell}\ell)]$



$$\sum_\ell g_{Z\ell}^h \frac{h}{v} Z_\mu \bar{\ell}\gamma^\mu \ell$$ ➡

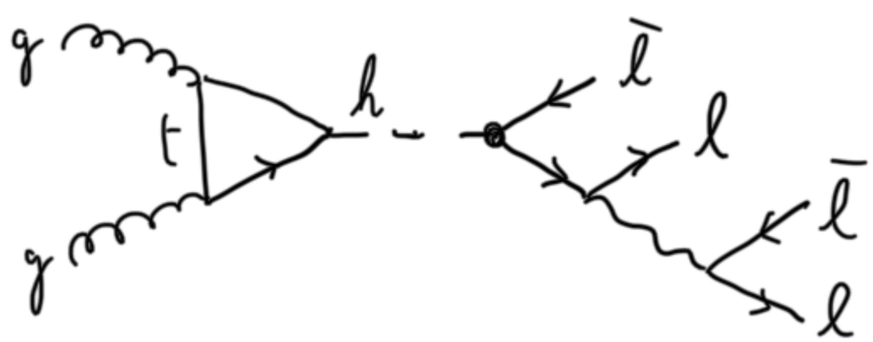
[With D6 gauge invariant SMEFT]

$$g_{Z\ell}^h = \frac{2g}{c_{\theta_W}} Y_\ell t_{\theta_W}^2 \delta\kappa_\gamma + 2\delta g_\ell^Z - \frac{2g}{c_{\theta_W}}(T_3^\ell c_{\theta_W}^2 + Y_\ell s_{\theta_W}^2)\delta g_1^Z$$

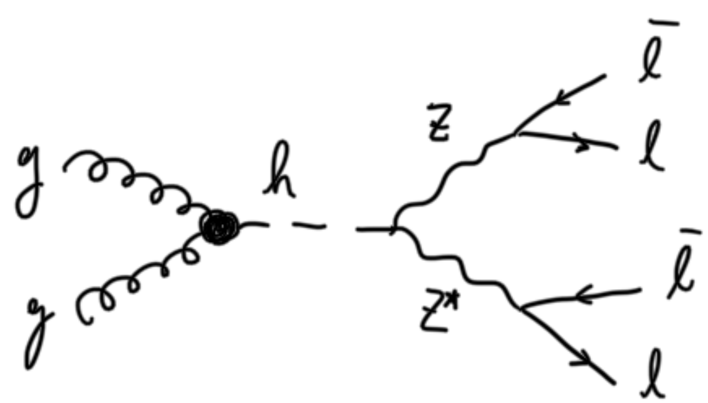
Neglected

- δg_ℓ^Z bounded at per-mille level at LEP1
- δg_1^z and $\delta\kappa_\gamma$ aTGCs bounded at per-mille level at HL-LHC

Higgs Golden Channel in the SMEFT



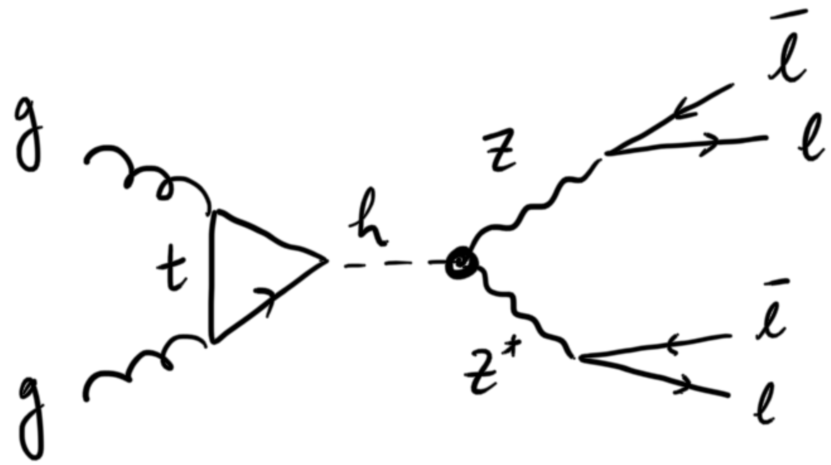
$h\bar{\ell}\ell$ strongly bounded
(Altmannshofer *et al.* 1503.04830,
ATLAS coll. 2007.07830)



Affecting the total rate,
but not the lepton angular distribution

Neglected

Higgs Golden Channel in the SMEFT



hZZ ← **Our analysis**

$$\Delta\mathcal{L} \supset \delta\hat{g}^h_{ZZ}\,\frac{2m_Z^2}{v}h\frac{Z^\mu Z_\mu}{2} +$$

→ Shift of the SM coupling

$$+\,\kappa_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

→ New tensor structures

D6 SMEFT with linearly realised $SU(2)_L \times U(1)_Y$

Warsaw basis

$$\delta \hat{g}^h_{ZZ} = \frac{v^2}{\Lambda^2}\left(c_{H\Box} + \frac{c_{HD}}{4}\right)$$

$$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$

$$\mathcal{O}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$$

$$\kappa_{ZZ} = \frac{2v^2}{\Lambda^2}(c^2_{\theta_W} c_{HW} + s^2_{\theta_W} c_{HB} + s_{\theta_W} c_{\theta_W} c_{HWB})$$

$$\tilde{\kappa}_{ZZ} = \frac{2v^2}{\Lambda^2}(c^2_{\theta_W} c_{H\tilde{W}} + s^2_{\theta_W} c_{H\tilde{B}} + s_{\theta_W} c_{\theta_W} c_{H\tilde{W}B}),$$

$$\mathcal{O}_{HB} = |H|^2 B_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{HWB} = H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{HW} = |H|^2 W_{\mu\nu} W^{\mu\nu}$$

$$\mathcal{O}_{H\tilde{B}} = |H|^2 B_{\mu\nu} \tilde{B}^{\mu\nu}$$

$$\mathcal{O}_{H\tilde{W}B} = H^\dagger \sigma^a H W^a_{\mu\nu} \tilde{B}^{\mu\nu}$$

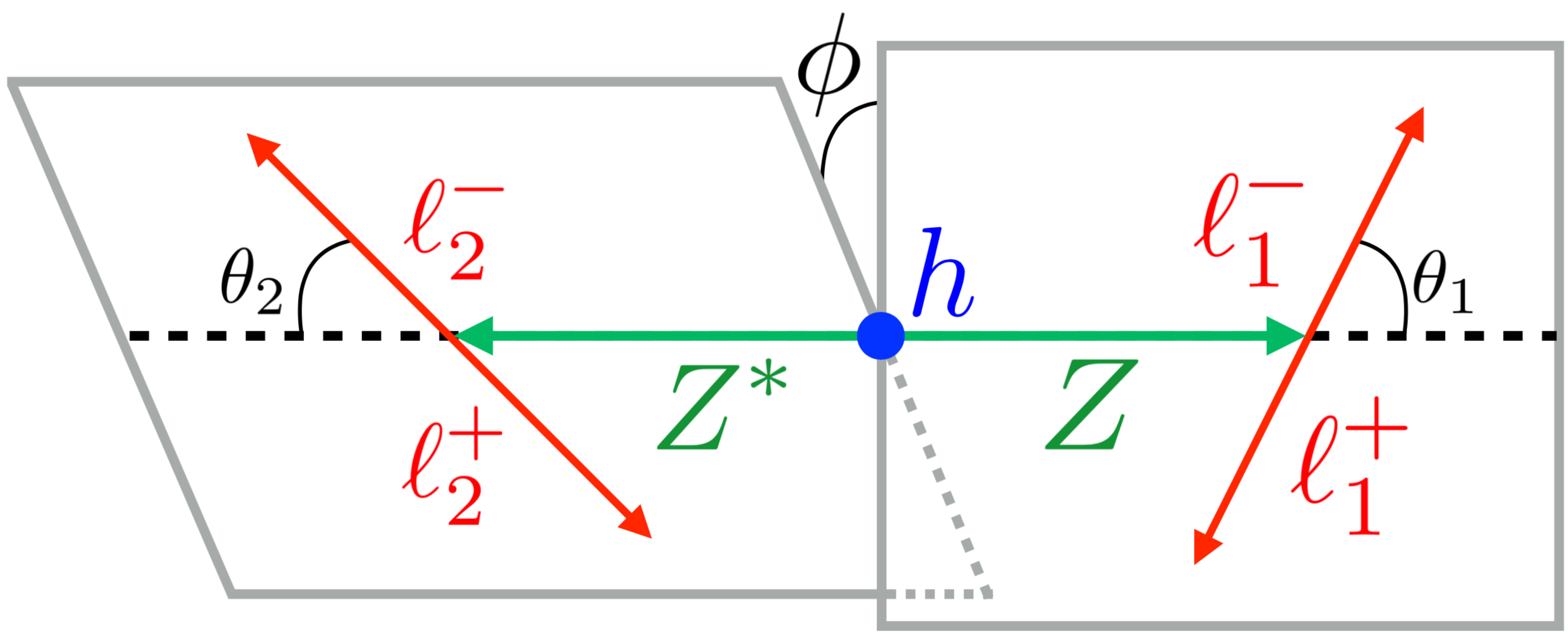
$$\mathcal{O}_{H\tilde{W}} = |H|^2 W^a_{\mu\nu} \tilde{W}^{a\mu\nu}$$

Angular distribution

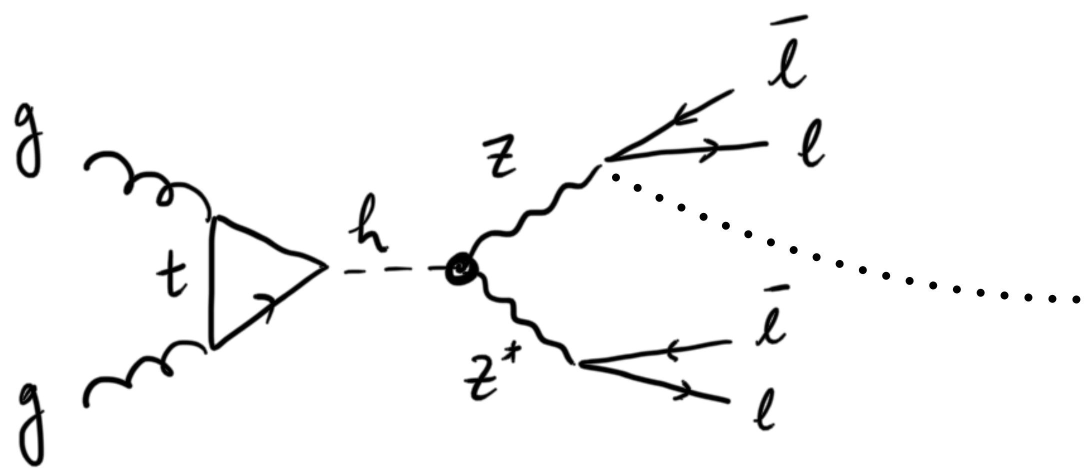
- We compute the cross section $\sigma(pp \to h \to ZZ \to 4\ell)$, in the h rest frame,

  and its differential distribution in the lepton emission angles

  $\rightarrow$ Towards the extraction of the maximal information from the measurements

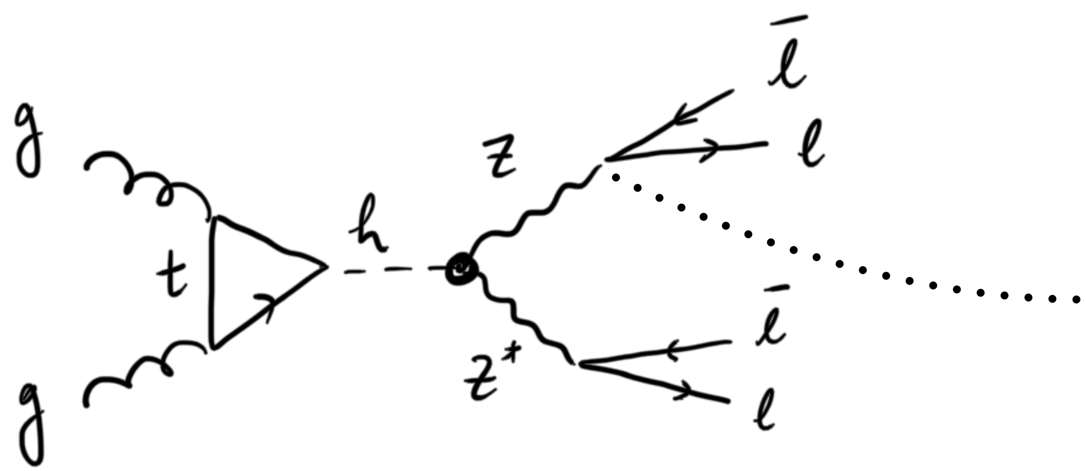


Angular dependence in helicity amplitudes



$Z^\mu \bar{\ell} \gamma_\mu \ell$ → 2 pairs of opposite-charge and opposite-helicity leptons

Angular dependence in helicity amplitudes



$Z^\mu \bar{\ell} \gamma_\mu \ell$ → 2 pairs of opposite-charge and opposite-helicity leptons $\bar{\ell}_\pm \ell_\mp$

- Convenient to analyse angular distribution for particles with **definite helicity**

- For $\bar{\ell}_\pm \ell_\mp$ the dependence on the emission angles is determined by the angular momentum quantum numbers (J, M) of the $\bar{\ell}\ell$ system, in the $\bar{\ell}\ell$ rest frame

Scattering amplitudes $\propto d^J_{M,\Delta\lambda}(\theta_i, \varphi_i)$

- In $Z_{\lambda_Z} \to \bar{\ell}\ell, \quad J = 1, \quad \mathbf{M} = \lambda_\mathbf{Z}$ →

$$d^1_{-1,\Delta\lambda=1}(\theta_i, \varphi_i) = \sin^2(\theta_i/2) e^{-i\varphi_i}$$

$$d^1_{+1,\Delta\lambda=1}(\theta_i, \varphi_i) = \cos^2(\theta_i/2) e^{+i\varphi_i}\,,$$

$$d^1_{0,\Delta\lambda=1}(\theta_i, \varphi_i) = \frac{\sin\theta_i}{\sqrt{2}}\,.$$

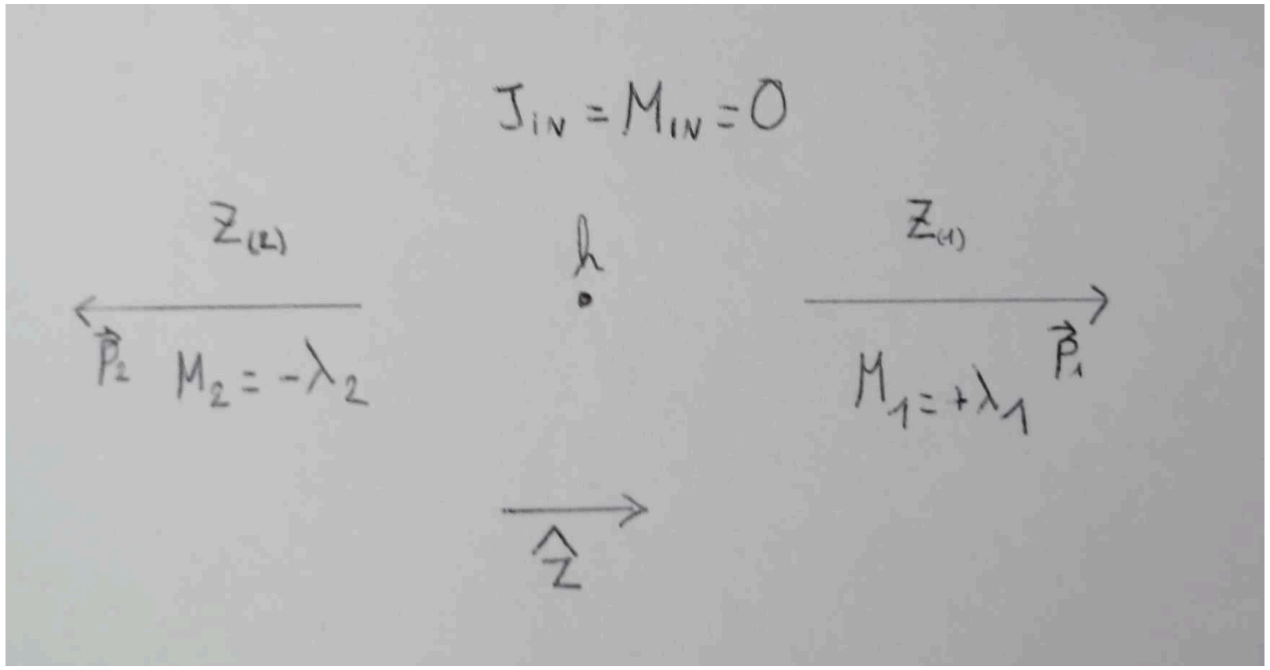
Angles of the lepton with $\lambda = +1/2$

Helicity $h \to ZZ$ amplitudes

- Starting point: $h \to Z_{\lambda_1} Z_{\lambda_2}$ decay with definite helicity for the final Z

Which are the possible helicities λ_1 and λ_2?

Angular momentum conservation in the decay of a scalar (s=0) at rest ➡ $\lambda_1 = \lambda_2$



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$$A_{++} = -2\,\frac{(\delta\hat{g}^h_{ZZ}+1)\,m_Z^2}{v} + 2\,\frac{\kappa_{ZZ}}{v}\,\gamma_a\, m_Z\, m_{Z*} - 2i\,\frac{\tilde{\kappa}_{ZZ}}{v}\,\gamma_b\, m_Z\, m_{Z*}$$

$$A_{--} = -2\,\frac{(\delta\hat{g}^h_{ZZ}+1)\,m_Z^2}{v} + 2\,\frac{\kappa_{ZZ}}{v}\,\gamma_a\, m_Z\, m_{Z*} + 2i\,\frac{\tilde{\kappa}_{ZZ}}{v}\,\gamma_b\, m_Z\, m_{Z*}$$

$$A_{00} = -2\,\frac{(\delta\hat{g}^h_{ZZ}+1)\,m_z^2}{v}\,\gamma_a - 2\,\frac{\kappa_{ZZ}}{v}\,\frac{1}{m_Z\, m_{Z^*}}$$

$$\gamma_a = \frac{1}{m_z\, m_{Z*}}(E_1E_2 + |\vec{q}|^2) = \frac{1}{m_z\, m_{Z*}}\, q_Z \cdot q_{Z^*}$$

$$\gamma_b = \frac{1}{m_z\, m_{Z*}}\,|\vec{q}|(E_1+E_2) = \frac{1}{m_z\, m_{Z*}}\,|\vec{q}|m_h$$

Helicity $h \to ZZ \to \ell_+\ell_-\ell_+\ell_-$ amplitudes

- Full helicity amplitude (with h production factorised out)

$$\mathcal{M}(h \to ZZ^* \to \ell_+^1\ell_-^1\ell_+^2\ell_-^2) = g_{\ell_1}^Z g_{\ell_2}^{Z^*} A(h \to ZZ^* \to \ell_+^1\ell_-^1\ell_+^2\ell_-^2) \sim \tag{3.7}$$

$$\sum_{\bar\lambda\bar\lambda'} A(h \to Z_{\bar\lambda} Z^*_{\bar\lambda'}) \frac{-g_{\ell_1}^Z}{q_Z^2 - m_Z^2 + i\Gamma_Z m_Z} A(Z_{\bar\lambda} \to \ell_+^1\ell_-^1) \frac{-g_{\ell_2}^{Z^*}}{q_{Z^*}^2 - m_Z^2 + i\Gamma_Z m_Z} A(Z^*_{\bar\lambda'} \to \ell_+^2\ell_-^2) \tag{3.8}$$

$$\propto \sum_{\bar\lambda} A(h \to Z_{\bar\lambda} Z^*_{\bar\lambda}) \frac{-g_{\ell_1}^Z}{q_Z^2 - m_Z^2 + i\Gamma_Z m_Z} d^1_{\bar\lambda,\Delta\lambda=1}(\theta_1, \varphi_1) \frac{-g_{\ell_2}^{Z^*}}{q_{Z^*}^2 - m_Z^2 + i\Gamma_Z m_Z} d^1_{\bar\lambda,\Delta\lambda=1}(\theta_2, -\varphi_2) \tag{3.9}$$

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- Breit-Wigner propagators (helicity independent) →

  Common factor in the angular distribution

Helicity $h \to ZZ \to \ell_+\ell_-\ell_+\ell_-$ amplitudes

- Full helicity amplitude (with h production factorised out)

$$\mathcal{M}(h \to ZZ^* \to \ell^1_+\ell^1_-\ell^2_+\ell^2_-) = g^Z_{\ell_1} g^{Z^*}_{\ell_2} A(h \to ZZ^* \to \ell^1_+\ell^1_-\ell^2_+\ell^2_-) \sim \tag{3.7}$$

$$\sum_{\bar\lambda\bar\lambda'} A(h \to Z_{\bar\lambda} Z^*_{\bar\lambda'}) \frac{-g^Z_{\ell_1}}{q^2_Z - m^2_Z + i\Gamma_Z m_Z} A(Z_{\bar\lambda} \to \ell^1_+\ell^1_-) \frac{-g^{Z^*}_{\ell_2}}{q^2_{Z^*} - m^2_Z + i\Gamma_Z m_Z} A(Z^*_{\bar\lambda'} \to \ell^2_+\ell^2_-) \tag{3.8}$$

$$\propto \sum_{\bar\lambda} A(h \to Z_{\bar\lambda} Z^*_{\bar\lambda}) \frac{-g^Z_{\ell_1}}{q^2_Z - m^2_Z + i\Gamma_Z m_Z} d^1_{\bar\lambda,\Delta\lambda=1}(\theta_1, \varphi_1) \frac{-g^{Z^*}_{\ell_2}}{q^2_{Z^*} - m^2_Z + i\Gamma_Z m_Z} d^1_{\bar\lambda,\Delta\lambda=1}(\theta_2, -\varphi_2) \tag{3.9}$$

- BSM corrections in $h \to ZZ$ amplitudes (helicity dependent) →

Modification of the angular distribution $\propto \delta\hat{g}^h_{ZZ}, \kappa_{ZZ}, \tilde{\kappa}_{ZZ}$

Visible angular modulation

- Angular distribution not for $\lambda = +\,1/2$ leptons

BUT for negatively charged leptons

$$|\mathcal{M}(h \to \bar{\ell}^1 \ell^1 \bar{\ell}^2 \ell^2)|^2 = \sum_{\lambda,\lambda'} |\mathcal{M}(h \to \bar{\ell}^1_{-\lambda} \ell^1_{\lambda} \bar{\ell}^2_{-\lambda'} \ell^2_{\lambda'})|^2$$

Q=-1 fermions ➔

- RH: $\lambda = +\,1/2$
- LH: $\lambda = -\,1/2$

$$|\mathcal{M}(h \to \bar{\ell}^1 \ell^1 \bar{\ell}^2 \ell^2)|^2 = \Big({g^{Z}_{l_R}}^2 {g^{Z^*}_{l_R}}^2 |A(\theta_1, \theta_2, \phi)|^2 + {g^{Z}_{l_L}}^2 {g^{Z^*}_{l_L}}^2 |A(\pi - \theta_1, \pi - \theta_2, \phi)|^2 + \\ + {g^{Z}_{l_L}}^2 {g^{Z^*}_{l_R}}^2 |A(\pi - \theta_1, \theta_2, \pi + \phi)|^2 + {g^{Z}_{l_R}}^2 {g^{Z^*}_{l_L}}^2 |A(\theta_1, \pi - \theta_2, \pi + \phi)|^2 \Big)$$

Angular moments

- Angular differential distributions

$$
\begin{aligned}
f_1 &= \sin^2(\theta_1)\sin^2(\theta_2) \\
f_2 &= (\cos^2(\theta_1)+1)(\cos^2(\theta_2)+1) \\
f_3 &= \sin(2\theta_1)\sin(2\theta_2)\cos(\phi) \\
f_4 &= (\cos^2(\theta_1)-1)(\cos^2(\theta_2)-1)\cos(2\phi) \\
f_5 &= \sin(\theta_1)\sin(\theta_2)\cos(\phi) \\
f_6 &= \cos(\theta_1)\cos(\theta_2) \\
f_7 &= (\cos^2(\theta_1)-1)(\cos^2(\theta_2)-1)\sin(2\phi) \\
f_8 &= \sin(\theta_1)\sin(\theta_2)\sin(\phi) \\
f_9 &= \sin(2\theta_1)\sin(2\theta_2)\sin(\phi),
\end{aligned}
$$

Angular moments

- Angular differential distributions, modified in the EFT

$$a_1 = \mathcal{G}^4 \left((1+\delta a) + \frac{b m_{Z^*} \gamma_b^2}{m_Z \gamma_a} \right)^2$$

$$a_2 = \mathcal{G}^4 \left(\frac{(1+\delta a)^2}{2\gamma_a^2} + \frac{2c^2 m_{Z^*}^2 \gamma_b^2}{m_Z^2 \gamma_a^2} \right)$$

$$a_3 = -\mathcal{G}^4 \left(\frac{1+\delta a}{2\gamma_a} + \frac{b m_{Z^*} \gamma_b^2}{2 m_Z \gamma_a} \right)^2$$

$$a_4 = \mathcal{G}^4 \left(\frac{(1+\delta a)^2}{2\gamma_a^2} - \frac{2c^2 m_{Z^*}^2 \gamma_b^2}{m_Z^2 \gamma_a^2} \right)$$

$$a_5 = -\epsilon^2 \mathcal{G}^4 \left(\frac{2(1+\delta a)^2}{\gamma_a} + \frac{2(1+\delta a) b m_{Z^*} \gamma_b^2}{m_Z \gamma_a^2} \right)$$

$$a_6 = \epsilon^2 \mathcal{G}^4 \left(\frac{2(1+\delta a)^2}{\gamma_a^2} + \frac{8c^2 m_{Z^*}^2 \gamma_b^2}{m_Z^2 \gamma_a^2} \right)$$

$$a_7 = \mathcal{G}^4 \frac{2(1+\delta a) c m_{Z^*} \gamma_b}{m_Z \gamma_a^2}$$

$$a_8 = -\epsilon^2 \mathcal{G}^4 \left(\frac{4(1+\delta a) c m_{Z^*} \gamma_b}{m_Z \gamma_a} + \frac{4 b c m_{Z^*}^2 \gamma_b^3}{m_Z^2 \gamma_a^2} \right)$$

$$a_9 = \mathcal{G}^4 \left(\frac{(1+\delta a) c m_{Z^*} \gamma_b}{m_Z \gamma_a} + \frac{b c m_{Z^*}^2 \gamma_b^3}{m_Z^2 \gamma_a^2} \right),$$

1 → SM

$$\delta a = \delta \hat{g}^h_{ZZ} - \kappa_{ZZ} \gamma_a \frac{m_{Z^*}}{m_Z} \frac{m_Z^2 - m_{Z^*}^2}{2 m_Z^2}$$

$$b = \kappa_{ZZ}$$

$$c = -\frac{\tilde{\kappa}_{ZZ}}{2}$$

$$\mathcal{G}^4 = ((g^Z_{l_L})^2 + (g^Z_{l_R})^2)((g^{Z^*}_{l_L})^2 + (g^{Z^*}_{l_R})^2)$$

$$\epsilon^2 \mathcal{G}^4 = ((g^Z_{l_L})^2 - (g^Z_{l_R})^2)((g^{Z^*}_{l_L})^2 - (g^{Z^*}_{l_R})^2),$$

↓

Small → a_5**,** a_6 **and** a_8 **suppressed**

a_7**,** a_8**,** a_9 **CP-odd**

Method of Moments

- Extraction of the a_i's coefficients with the **Method of Moments**

Dunietz *et al.*, PRD43 (1991) 2193-2208;
James, Statistical methods in experimental physics, 2006
Beaujean *et al.*, 1503.04100

Transparent and advantageous when statistics is low

- Let's assume there exists a dual basis $\{w_i\}_i$ orthonormal to $\{f_i\}_i$, $\int d\Omega\, w_j f_i = \delta_{ij}$,

and such that $w_i = \lambda_{ij} f_j$ → $\lambda = M^{-1}$, with $M_{ij} = \int d\Omega f_i f_j$

$$\int d\Omega \sum_i (a_i f_i) w_j = a_j$$

Method of Moments

- In our analysis

$$M = \begin{pmatrix} \frac{512\pi}{225} & \frac{128\pi}{25} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{128\pi}{25} & \frac{6272\pi}{225} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{256\pi}{225} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{256\pi}{225} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{16\pi}{9} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{8\pi}{9} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{256\pi}{225} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{16\pi}{9} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{256\pi}{225} \end{pmatrix},$$

- Diagonalisation

$$\hat{f}_1 = \cos\beta f_1 - \sin\beta f_2,$$
$$\hat{f}_2 = \sin\beta f_1 + \cos\beta f_2,$$

$$\tan\beta = -\frac{1}{2}(5+\sqrt{29}).$$

$$\hat{M} = \hat{\lambda}_{ij}^{-1} = \mathrm{diag}\left(\frac{64\pi}{225}\xi_+, \frac{64\pi}{225}\xi_-, \frac{256\pi}{225}, \frac{256\pi}{225}, \frac{16\pi}{9}, \frac{8\pi}{9}, \frac{256\pi}{225}, \frac{16\pi}{9}, \frac{256\pi}{225}\right) \qquad \xi_\pm = (53 \pm 9\sqrt{29})$$

$pp \to h \to ZZ \to 4\ell$ @LHC
Simulated events

- **Monte Carlo simulation** (500k events) of $gg \to h \to 4\ell$ (MadGraph, Pythia 8)

  @14TeV @LO [N^{3}LO $k = 3.155$] in the scenarios: **SM**, $\kappa_{ZZ} = \pm 0.5$, $\tilde{\kappa}_{ZZ} = \pm 0.5$

- Selection of 4ℓ final state, with **2 pairs of OSSF leptons** (opposite sign, same flavour)

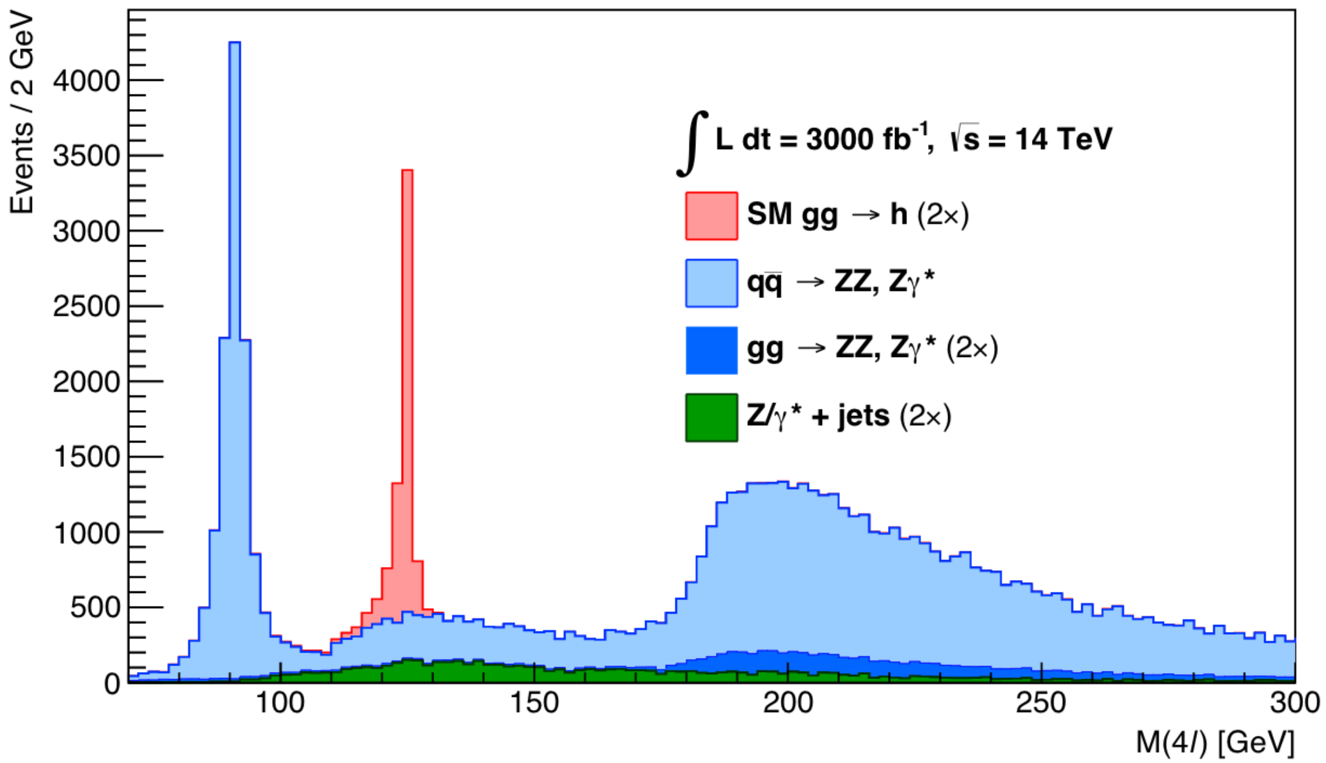
  But also **irreducible background** $pp \to 4\ell$: $q\bar{q} \to 4\ell$ and $gg \to 4\ell$

Selection cut	SM $gg \to h$	$q\bar{q} \to 4\ell$	$gg \to 4\ell$
Jet veto	0.419	0.779	0.319
$\not{E}_T < 25$ GeV	0.348	0.667	0.248
2 pairs of isolated OSSF leptons, $\Delta R(\ell_i, \ell_j) > 0.02$, $M_{\ell^+, \ell'^-} > 4$ GeV	0.127	0.036	0.130
$p_{T,\ell_1} > 20\,\text{GeV}$, $p_{T,\ell_2} > 10\,\text{GeV}$, $p_{T,\ell_3} > 10\,\text{GeV}$	0.121	0.031	0.124
$M(Z_1) \in [40, 120]$ GeV, $M(Z_2) \in [12, 120]$ GeV	0.110	0.021	0.112
$M(4\ell) \in [118, 130]$ GeV	0.095	0.001	0.001

CMS, Tech. Rep. CMS-PAS-HIG-19-001

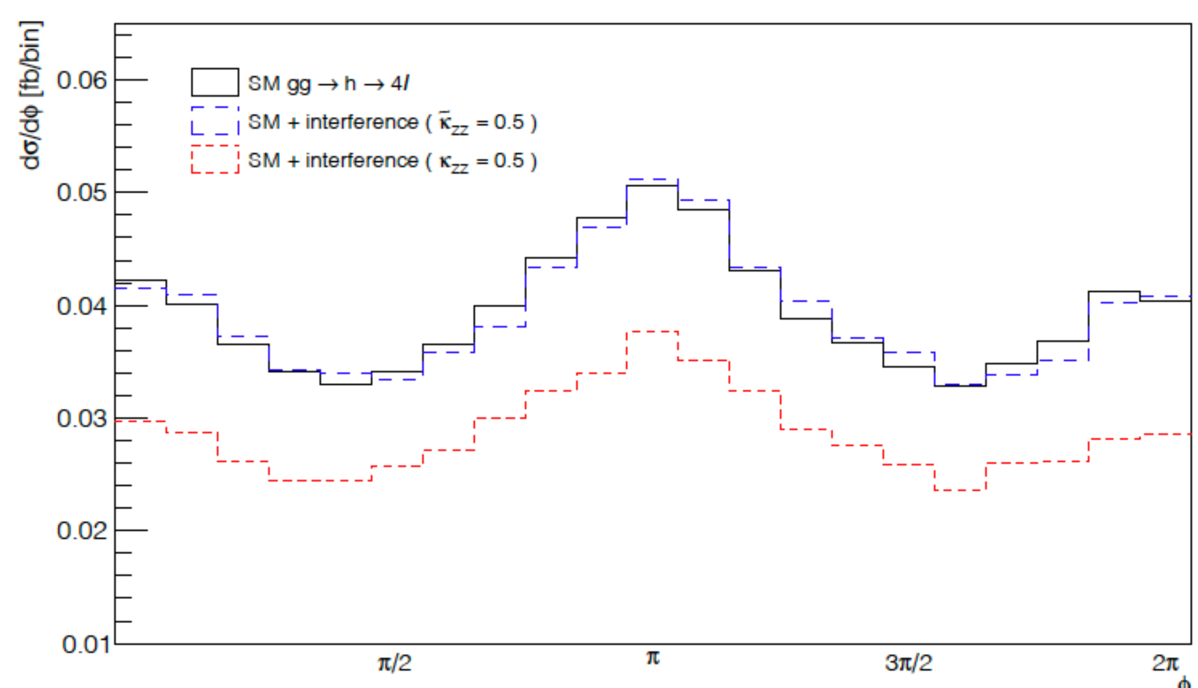
Cut-flow showing the impact of each stage of the selection on the fraction of retained Monte Carlo events for the SM-driven $gg \to h \to 4\ell$ process, as well as on the $q\bar{q} \to 4\ell$ and $gg \to 4\ell$ irreducible backgrounds.

$pp \to h \to ZZ \to 4\ell$ @LHC
Some differential distributions



$m_{4\ell}$ **invariant mass distribution**

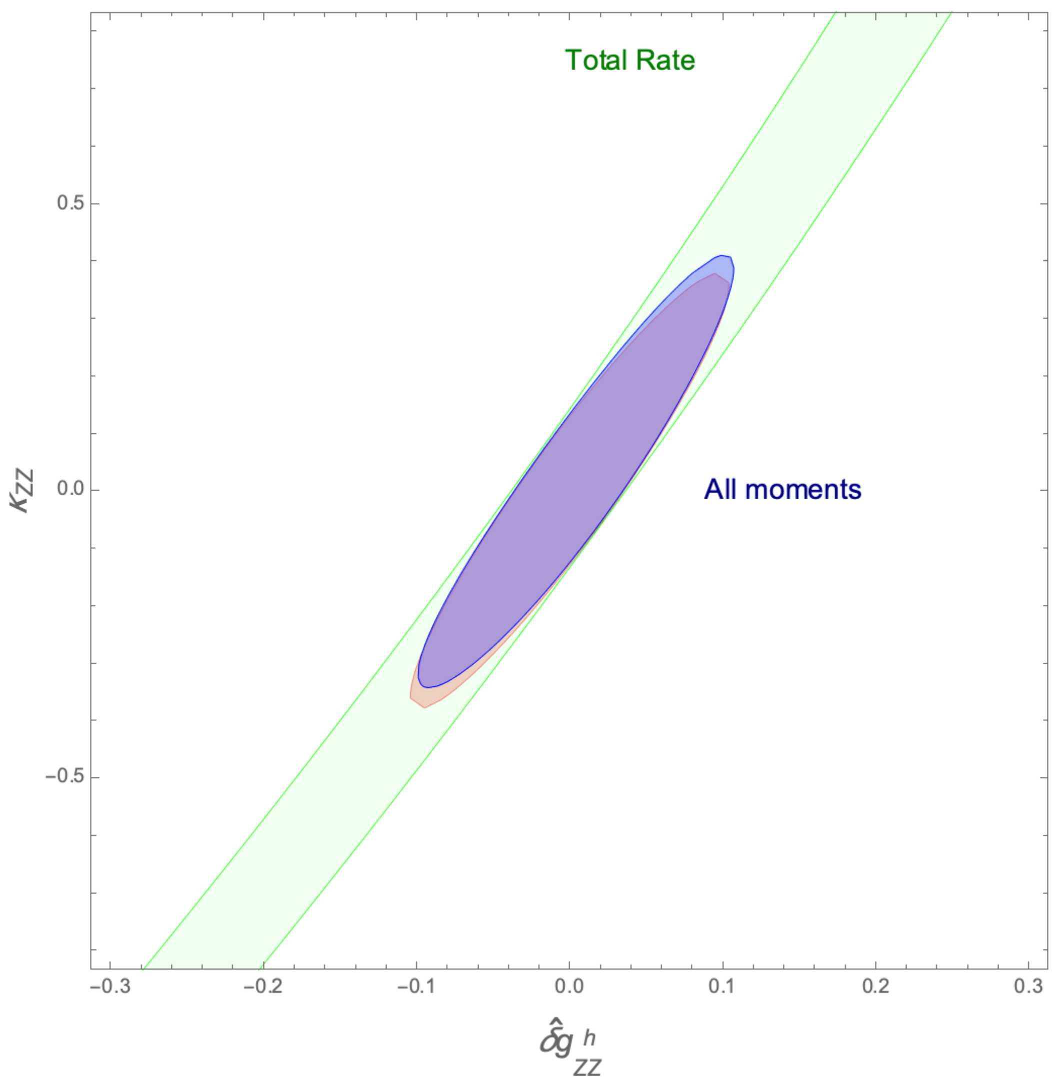
Azimuthal distribution



Moments estimates and bounds

- **MC estimated moments:** $a_i = \hat{N}\bar{w}_i$ with $\bar{w}_i = \frac{1}{N_{MC}} \sum_{n=1}^{N_{MC}} w_i(\theta_{1,n}, \theta_{2,n}, \phi_n)\,,$

$\hat{N}$ @3ab^{-1}



$$\chi^2(\delta g^h_{ZZ}, \kappa_{ZZ}, \tilde{\kappa}_{ZZ}) =$$

$$\sum_{ij} (a_i^{EFT} - a_i^{SM}) \Sigma_{ij}^{-1} (a_j^{EFT} - a_j^{SM})$$

with $\Sigma_{ij} = \left(\left(\frac{\sqrt{\hat{N}_{SM}}}{\hat{N}_{SM}} \right)^2 + \kappa_{\rm syst}^2 \right) a_i^{\rm SM} a_j^{\rm SM} + \hat{N}_{SM} \sigma_{ij}^{\rm SM}.$

Systematic uncertainty: $\kappa_{syst} = 0.02$ [ATLAS coll.]

Bounds @68% C.L. on CP-even couplings

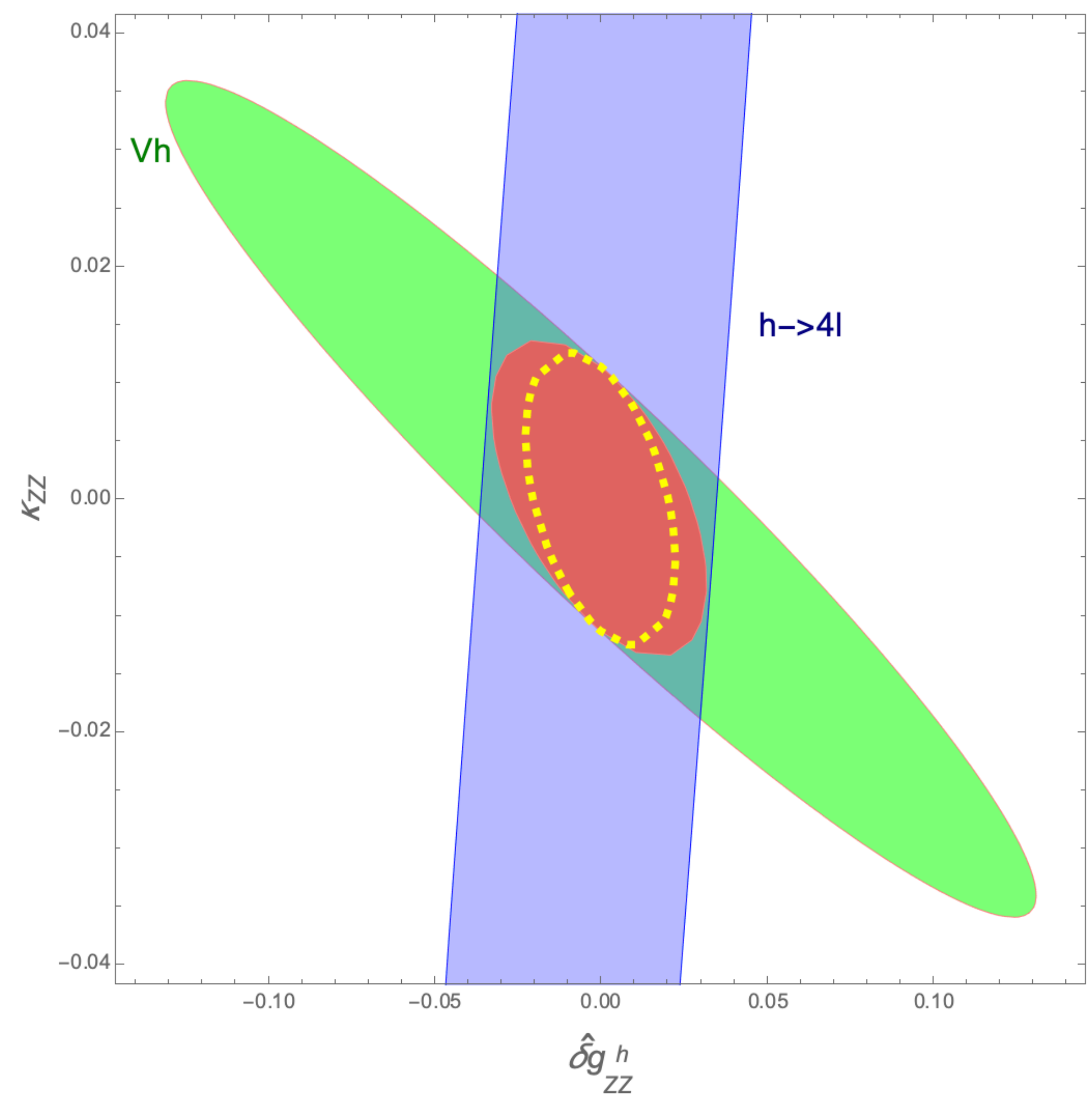
Angular Distribution allows to set bounds along a flat direction

Moments estimates and bounds

- With $\kappa_{syst} = 0$, $|\kappa_{ZZ}| < 0.05$ for $\delta\hat{g}^h_{ZZ} = 0$ (MELA $|\kappa_{ZZ}| < 0.04$)

- $|\tilde{\kappa}_{ZZ}| < 0.5$ (Marginalising over κ_{ZZ} and $\delta\hat{g}^h_{ZZ}$) [a_7, a_8, a_9: small contribution to χ^2]

- $1/\Lambda^4$ order negligible w.r.t. $1/\Lambda^2$



- Blue: $pp \to h \to ZZ$
- Green: $pp \to Vh$ [1912.07628]
- Combination
- Yellow ellipse: + $pp \to h \to WW$

Summary and outlooks

- Angular differential study to probe the tensor structure of the Higgs coupling to gauge bosons

- Angular moments extracted with the method of moments

  → Strong bounds as in the ML techniques in a more transparent way

- Angular analysis eliminates the flat direction in $(\delta g^h_{ZZ}, \kappa_{ZZ})$

Thank you

Backup

EFT Lagrangian

$$\Delta\mathcal{L}_6 \supset \delta\hat{g}^h_{ZZ}\,\frac{2m_Z^2}{v}h\frac{Z^\mu Z_\mu}{2} + \sum_\ell \delta g^Z_\ell Z_\mu\bar{\ell}\gamma^\mu\ell + \sum_\ell g^h_{Z\ell}\,\frac{h}{v}Z_\mu\bar{\ell}\gamma^\mu\ell$$
$$+ \kappa_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

EFT parameters and Warsaw basis

$$\delta g_\ell^Z = -\frac{gY_\ell s_{\theta_W}}{c^2_{\theta_W}}\frac{v^2}{\Lambda^2}c_{HWB} - \frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(|T_3^\ell|c_{HL}^{(1)} - T_3^\ell c_{HL}^{(3)} + (1/2 - |T_3^\ell|)c_{H\ell})$$
$$+ \frac{\delta m_Z^2}{m_Z^2}\frac{g}{2c_{\theta_W}s^2_{\theta_W}}(T_3 c^2_{\theta_W} + Y_\ell s^2_{\theta_W})$$
$$\delta \hat{g}^h_{ZZ} = \frac{v^2}{\Lambda^2}\left(c_{H\Box} + \frac{c_{HD}}{4}\right)$$
$$g^h_{Z\ell} = -\frac{2g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(|T_3^\ell|c_{HL}^{(1)} - T_3^\ell c_{HL}^{(3)} + (1/2 - |T_3^\ell|)c_{H\ell})$$
$$\kappa_{ZZ} = \frac{2v^2}{\Lambda^2}(c^2_{\theta_W}c_{HW} + s^2_{\theta_W}c_{HB} + s_{\theta_W}c_{\theta_W}c_{HWB})$$
$$\kappa_{GG} = \frac{2v^2}{\Lambda^2}c_{HG}$$
$$\tilde{\kappa}_{ZZ} = \frac{2v^2}{\Lambda^2}(c^2_{\theta_W}c_{H\tilde{W}} + s^2_{\theta_W}c_{H\tilde{B}} + s_{\theta_W}c_{\theta_W}c_{H\tilde{W}B}),$$
$$\delta g_1^Z = \frac{1}{2s^2_{\theta_W}}\frac{\delta m_Z^2}{m_Z^2}$$
$$\delta\kappa_\gamma = \frac{1}{t_{\theta_W}}\frac{v^2}{\Lambda^2}c_{HWB}\ .$$
$$\frac{\delta m_Z^2}{m_Z^2} = \frac{v^2}{\Lambda^2}(2t_{\theta_W}c_{HWB} + \frac{c_{HD}}{2}),$$

$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{HB} = \|H\|^2 B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$	$\mathcal{O}_{HWB} = H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R\gamma^\mu e_R$	$\mathcal{O}_{HW} = \|H\|^2 W_{\mu\nu}W^{\mu\nu}$
$\mathcal{O}^{(1)}_{HL} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{L}\gamma^\mu L$	$\mathcal{O}_{H\tilde{B}} = \|H\|^2 B_{\mu\nu}\tilde{B}^{\mu\nu}$
$\mathcal{O}^{(3)}_{HL} = iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H \bar{L}\sigma^a\gamma^\mu L$	$\mathcal{O}_{H\tilde{W}B} = H^\dagger\sigma^a H W^a_{\mu\nu}\tilde{B}^{\mu\nu}$
$\mathcal{O}_{HtG} = \bar{Q}_3\tilde{H}T^A\sigma_{\mu\nu}t_R G^{A\mu\nu}$	$\mathcal{O}_{H\tilde{W}} = \|H\|^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$
$\mathcal{O}_{HbG} = \bar{Q}_3\tilde{H}T^A\sigma_{\mu\nu}b_R G^{A\mu\nu}$	$\mathcal{O}_{y_b} = \|H\|^2(\bar{Q}_3 H b_R + h.c).$
$\mathcal{O}_{HG} = (H^\dagger H)G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{y_t} = \|H\|^2(\bar{Q}_3 H t_R + h.c).$

$hZ\bar{\ell}\ell$ contact interaction

- $hZ\bar{\ell}\ell$: $\bar{\ell}_{\pm}\ell_{\mp}$ with $J=1$ and $M=\lambda_Z$

  $g^{h}_{Z\ell}$ contribution to $h \to Z2\ell \to 4\ell$ can be expressed as a

  shift in $g^{Z*}_{\ell_2}$ in $\mathscr{M}(h \to ZZ* \to 4\ell)$

$$g^{Z^*}_{\ell_2} \to g^{Z^*}_{\ell_2} - g^{h}_{Z\ell_2}\,\frac{m_Z^2 - m_{Z^*}^2 - i\Gamma_Z\, m_Z}{2m_Z^2}$$

Details of simulations

- **MC**: $gg \to h \to 4\ell$ signal @14TeV @LO with MadGraph and NNPDF31_lo_as_0130 PDF set;

  $q\bar{q} \to 4\ell$ bkg @14TeV @NLO with POWHEG BOX V2 and NNPDF31_nlo_hessian_pdfas set;

  $gg \to 4\ell$ bkg (one-loop) with MCFM 7 and CTEQ6L PDF set;

  $pp \to \ell\ell jj$ reducible bkg, with j to ℓ fake rate 0.016 (0.044) for jets with $|y^j| < 1.48$ ($1.48 < |y^j| < 2.5$)

- PYTHIA 8 for parton shower and hadronisation

- **K-factors**: $gg \to h$ with N^{3}LO $k = 3.155$ (LHC HXSWG), $q\bar{q} \to 4\ell$ with NNLO/NLO $k = 1.1$, $gg \to 4\ell$ with NNLO/LO $k = 2.27$, $pp \to \ell\ell jj$ with $k = 0.91$

- Gaussian smearing as implemented in RIVET to simulate the detector response

- Flat leptonic reconstruction efficiency of 0.92

Backgrouds

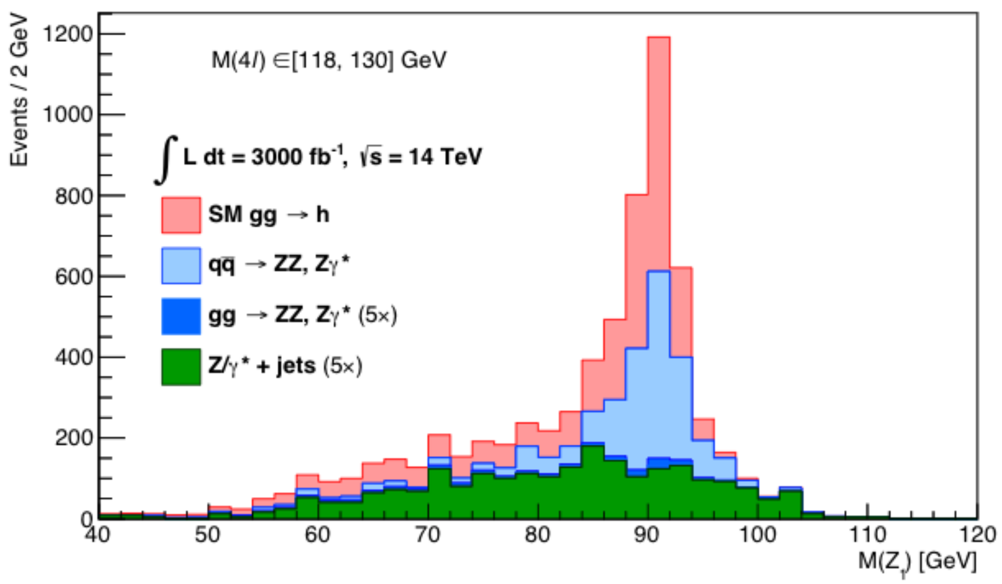
- Reducible backgrounds:

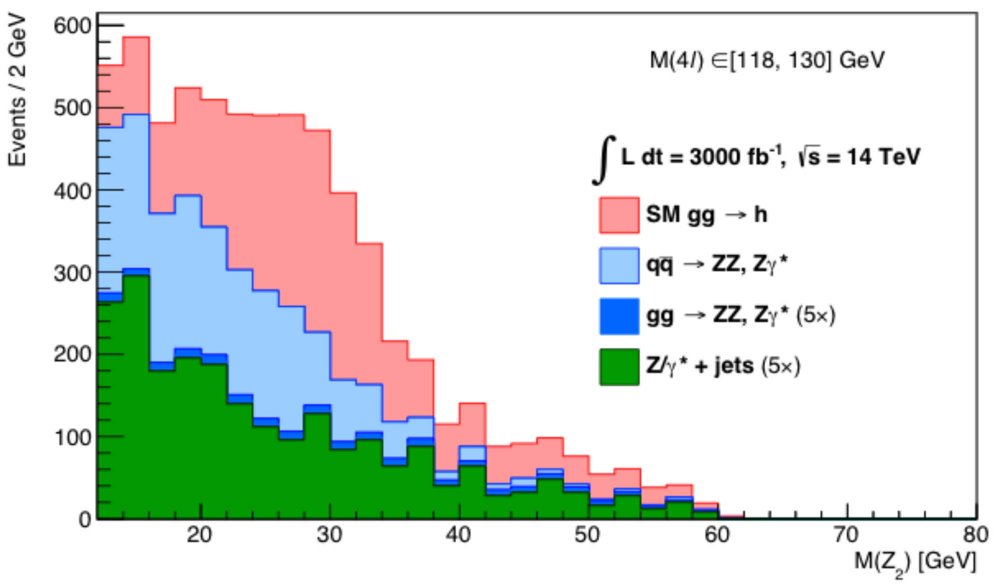
  jets as fake leptons → Mainly Z/γ^*+jets [$t\bar{t}$, WW, WZ +jets]

- Irreducible backgrounds:

  $gg \rightarrow 4\ell$ and $q\bar{q} \rightarrow 4\ell$

$M(Z)$ plots





Invariant mass distribution $M(Z_i)$ of the (left) Z_1 and (right) Z_2 candidates after defining the signal region $M(4\ell) \in [118, 130]$ GeV.