A fully differential SMEFT analysis of the golden channel using the Method of Moments

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In collaboration with

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Outline

1. Motivation
2. SMEFT and HD Operators
3. The golden channel in the SMEFT
4. Angular Moments
5. Collider analysis
6. Moments estimates and bounds
7. Summary and conclusions

Motivation: Where are we standing?

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

SM 10 years ago: gauge and matter fields

SM today: gauge, matter, and Higgs fields

2012 boson: SM-like Higgs

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Motivation: Where are we standing?

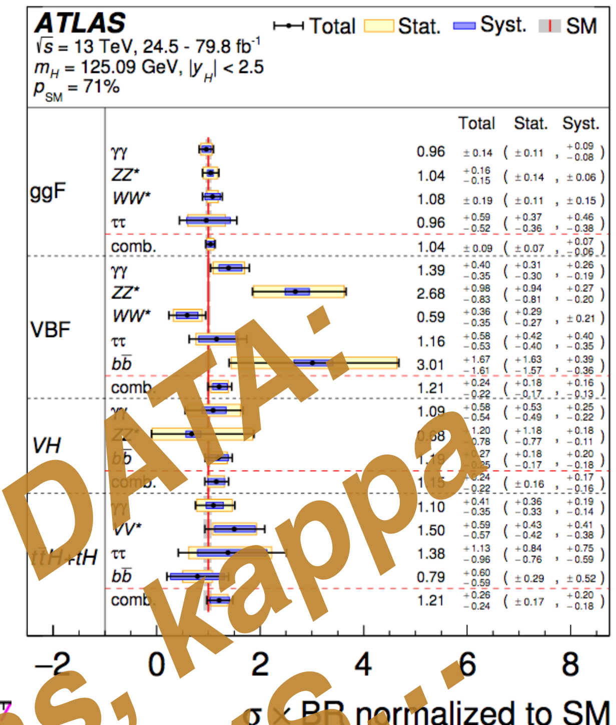
$$\mathcal{L} = \boxed{\boxed{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c.} + \boxed{\bar{\psi}\mathcal{Y}_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)}}$$

SM 10 years ago: gauge and matter fields

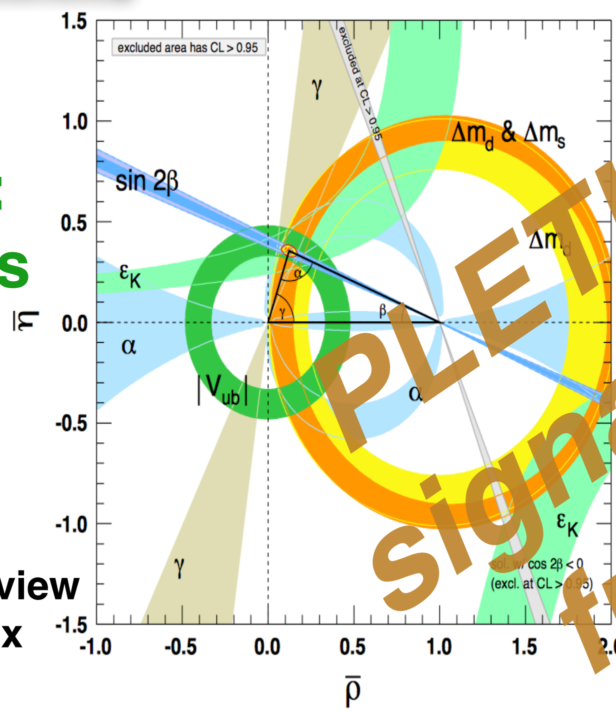
SM today: gauge, matter, and Higgs fields

2012 boson: SM-like Higgs

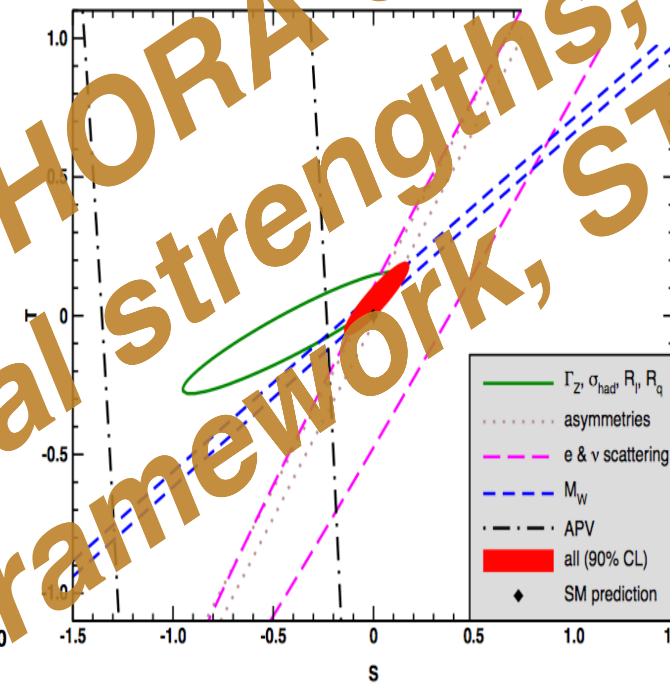
PLETHORA OF DATA: signal strengths, kappa framework, STXS...



Phys. Rev. D 101, 012002 (2020)



PDG 2019 Review CKM Matrix



PDG 2019 Review Electroweak Model and Constraints on New Physics

Motivation: What can be done?

Absence at the LHC of new physics BSM ⁉

Reconstruct TeV-scale Lagrangian with current data?

Rates are not enough. Include differential information?

What observables are best to anticipate to incoming data?

Motivation: What can be done?

EFT: PARAMETERISE NEW PHYSICS IN A "MODEL-INDEPENDENT" WAY 💪😎

Wilson coefficients **Higher-dimensional operators**

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\boxed{c_i}\boxed{\mathcal{O}_i^{(6)}}}{\boxed{\Lambda^2}} + \sum_j \frac{\boxed{d_j}\boxed{\mathcal{O}_j^{(8)}}}{\boxed{\Lambda^4}} + \dots$$

- **Respect SM gauge symmetry (SU(2) x U(1))**
- **Include only SM fields**

Mass scale of new physics (should be large)

SMEFT: HD operators, choice of basis, …

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2} + \sum_j \frac{d_j \mathcal{O}_j^{(8)}}{\Lambda^4} + \dots$$

- SM here is a low-energy effective theory *valid below a cut-off scale* $\boldsymbol{\Lambda}$*,* superseded by a bigger theory above such scale.

- Appelquist-Carazzone theorem: at the perturbative level, all heavy (> $\boldsymbol{\Lambda}$) DOF are decoupled from the low-energy theory.

SMEFT: HD operators, choice of basis, …

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \boxed{\frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2}} + \sum_j \boxed{\frac{d_j \mathcal{O}_j^{(8)}}{\Lambda^4}} + \dots$$

d = 5: Majorana mass term to neutrinos

Leading BSM effects (59 independent B-conserving operators)

d = 7: Breaks B, L

Neutral TGC interactions

Many deformations from a single operator: correlated interactions

15 boson + 19 single fermion + 25 four fermion. Lowest dimension, after d=4, inducing hXY, hXYZ, charged TGCs

(Nucl. Phys. B 268 (1986) 621-653; Phys.Rev.D 48 (1993) 2182-2203; JHEP 10 (2010) 085; …)

- SM here is a low-energy effective theory *valid below a cut-off scale Λ*, superseded by a bigger theory above such scale.
- Appelquist-Carazzone theorem: at the perturbative level, all heavy (> Λ) DOF are decoupled from the low-energy theory.

SMEFT: HD operators, choice of basis, …

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2} + \sum_j \frac{d_j \mathcal{O}_j^{(8)}}{\Lambda^4} + \ldots$$

New vertices ensuing from EFT can produce novel/enhanced effects in certain PS regions

Observables to study the effects of certain operators/processes?

In the Higgs sector, precisely measure their couplings to gauge bosons and fermions

Indirect constraints (S, T), precision physics at LEP, correlations… Need more and better measurements to improve current bounds

SMEFT: HD operators, choice of basis, …

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \boxed{\frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2}} + \sum_j \frac{d_j \mathcal{O}_j^{(8)}}{\Lambda^4} + \ldots$$

- SM here is a low-energy effective theory *valid below a cutoff scale Λ*, superseded by a bigger theory above such scale.

★ **Bottom-up approach: find set of independent new interactions that can arise and are the experimentally best tested ones.**

- Appelquist-Carazzone theorem: at the perturbative level, all heavy ($> \Lambda$) DOF are decoupled from the low-energy theory.

★ **Use BSM primary effects to constrain new physics (broken phase).**

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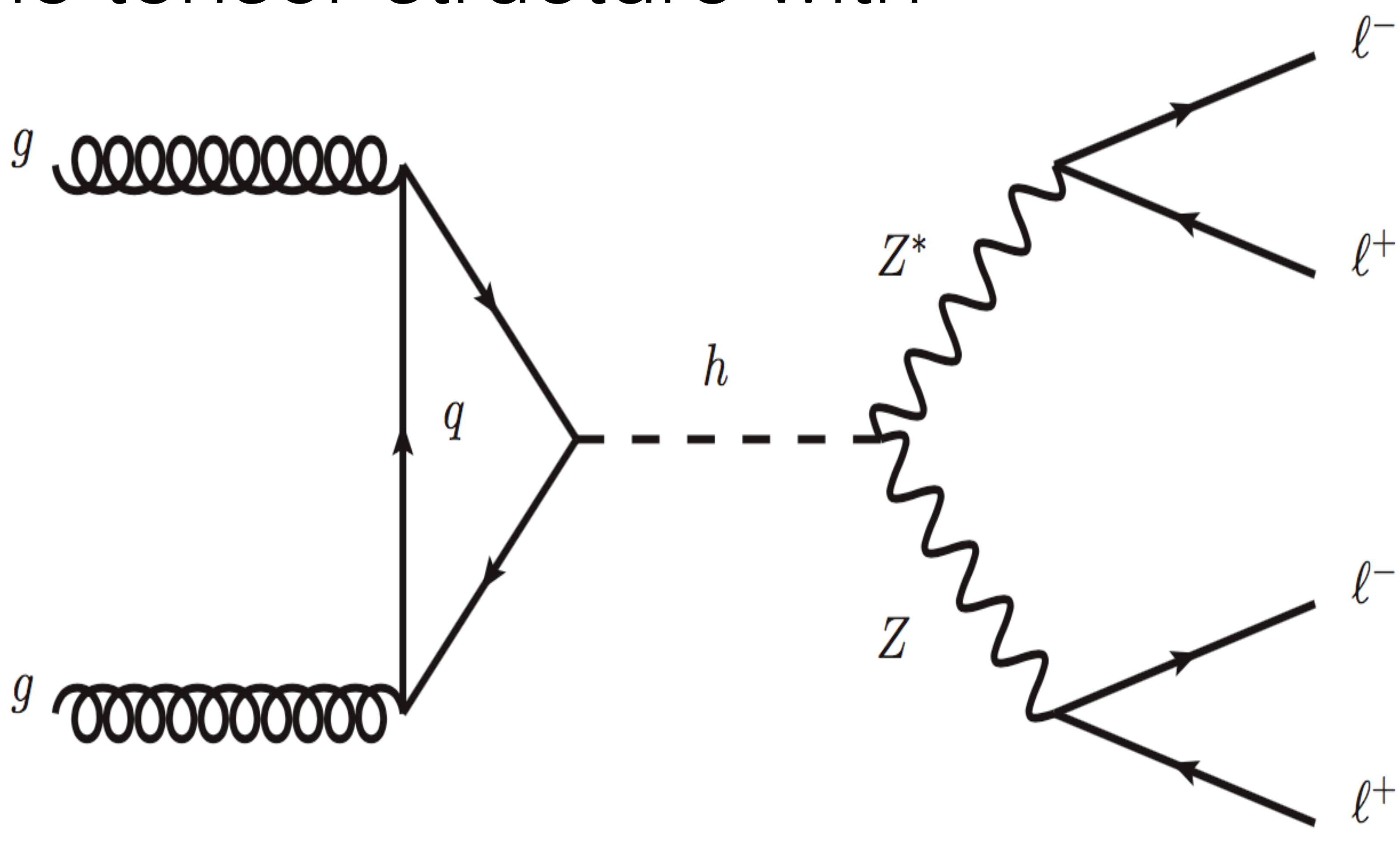
The golden channel: SM

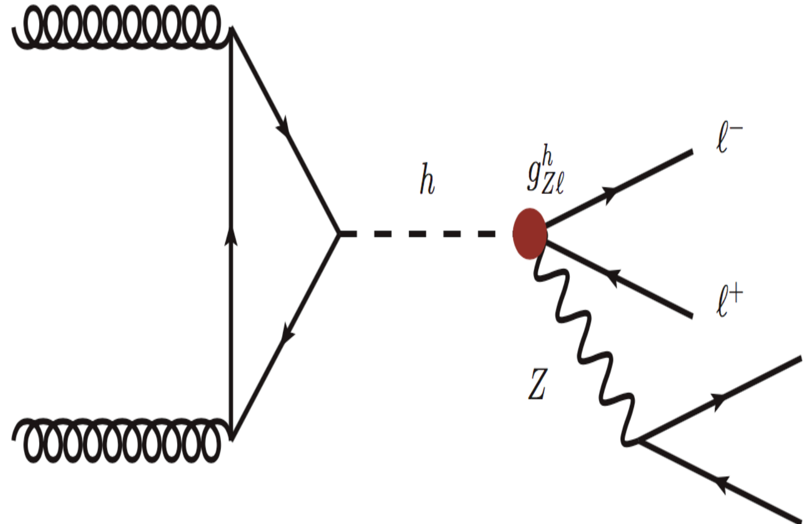
- Probe of Higgs-gauge boson couplings at the LHC: resolution of the tensor structure with differential study.

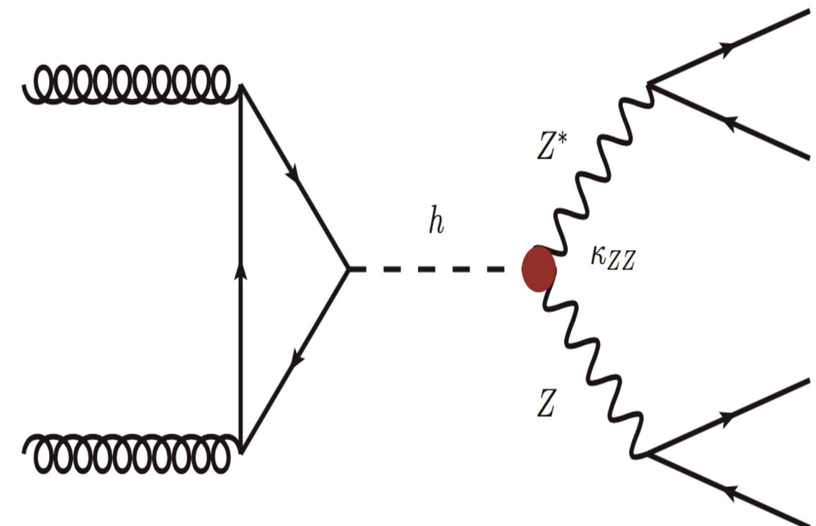
- Angular distribution with the ***Method of Moments*** in the Higgs golden channel $h \to 4\ell$.

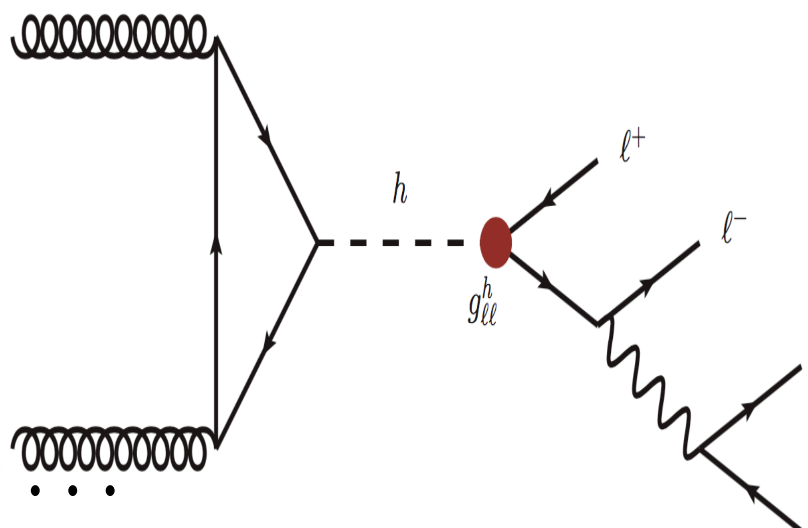


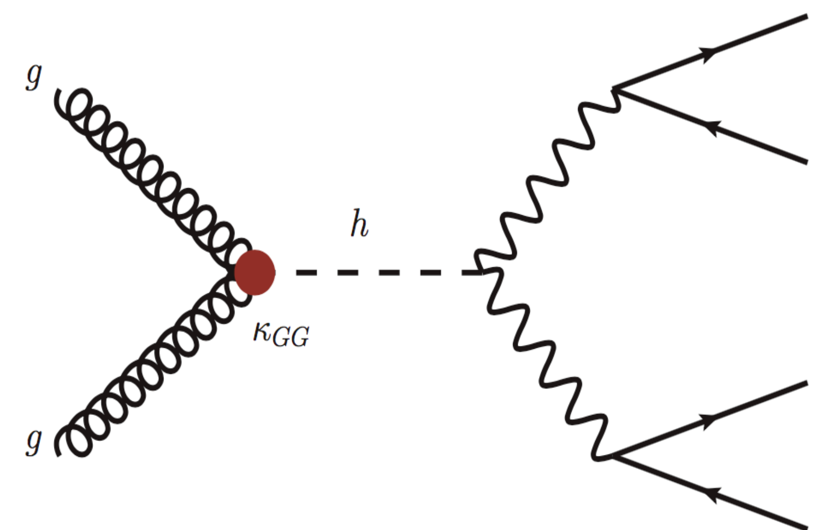
The golden channel: SMEFT

$$
\begin{aligned}
\Delta\mathcal{L} \supset \sum_{f=\ell} g^h_{Zf}\frac{h}{v}Z_\mu \bar{f}\gamma^\mu f \\
+\kappa_{ZZ}\frac{h}{v}Z^{\mu\nu}Z_{\mu\nu} \\
+\sum_{f=\ell} g^h_{ff} h \bar{f}_L f_R \\
+\kappa_{GG}\frac{h}{v}G^{A\mu\nu}G^A_{\mu\nu} + \dots
\end{aligned}
$$









The golden channel: SMEFT

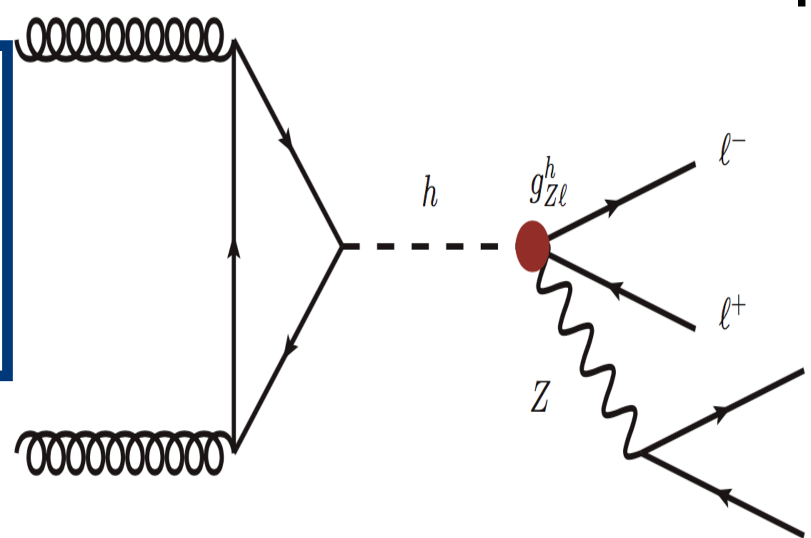
(JHEP 02 (2015) 039;
https://cds.cern.ch/record/2285934)

$$\Delta\mathcal{L} \supset \boxed{\sum_{f=\ell} g^h_{Zf}\frac{h}{v}Z_\mu \bar{f}\gamma^\mu f}$$

$$+ \kappa_{ZZ}\frac{h}{v}Z^{\mu\nu}Z_{\mu\nu}$$

$$+ \sum_{f=\ell} g^h_{ff} h \bar{f}_L f_R$$

$$+ \kappa_{GG}\frac{h}{v}G^{A\mu\nu}G^A_{\mu\nu} + \ldots$$



$$\boxed{\delta\kappa_\gamma} = [-0.063, 0.026]$$

$$\boxed{\delta g^Z_{e,L}} = [-0.0001, 0.0009]$$

$$\boxed{\delta g^Z_{e,R}} = [-0.0004, 0.0002]$$

$$\boxed{\delta g^Z_1} = [-0.03, 0.013]$$

$$g^h_{Z\ell} = \frac{2g}{c_{\theta_W}} Y_\ell t^2_{\theta_W} \boxed{\delta\kappa_\gamma} + 2\boxed{\delta g^Z_\ell} - \frac{2g}{c_{\theta_W}}(T^\ell_3 c^2_{\theta_W} + Y_\ell s^2_{\theta_W})\boxed{\delta g^Z_1}$$

Constrain this operator at future lepton colliders.
arXiv:2105.ABCDE (in preparation)

NEGLECTED

The golden channel: SMEFT

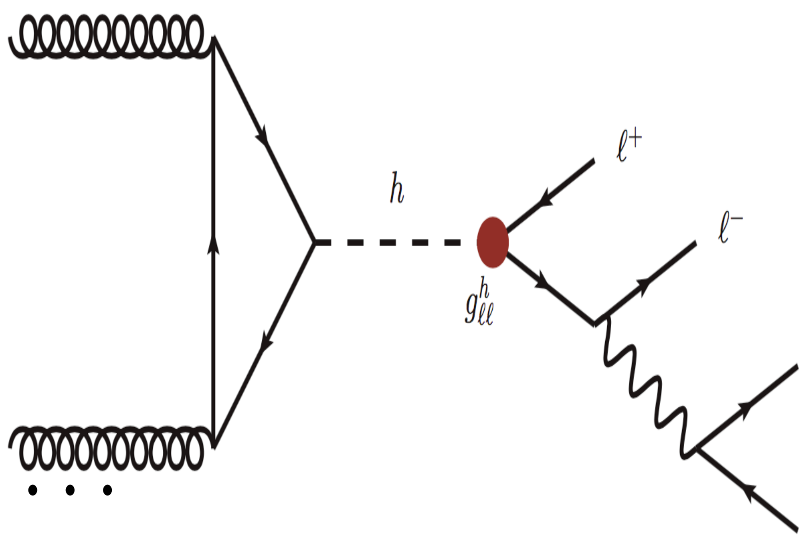
$$\Delta\mathcal{L} \supset \cancel{\sum_{f=\ell} g^h_{Zf} \frac{h}{v} Z_\mu \bar{f} \gamma^\mu f}$$

$$+ \kappa_{ZZ} \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu}$$

$$+ \boxed{\sum_{f=\ell} g^h_{ff} h \bar{f}_L f_R}$$

$$+ \kappa_{GG} \frac{h}{v} G^{A\mu\nu} G^A_{\mu\nu} + \cdots$$

Already strongly constrained.
(JHEP 1505 (2015) 125,
Phys. Lett. B 812 (2021) 135980)



NEGLECTED

The golden channel: SMEFT

$$\Delta\mathcal{L} \supset \cancel{\sum_{f=\ell} g^h_{Zf} \frac{h}{v} Z_\mu \bar{f}\gamma^\mu f}$$

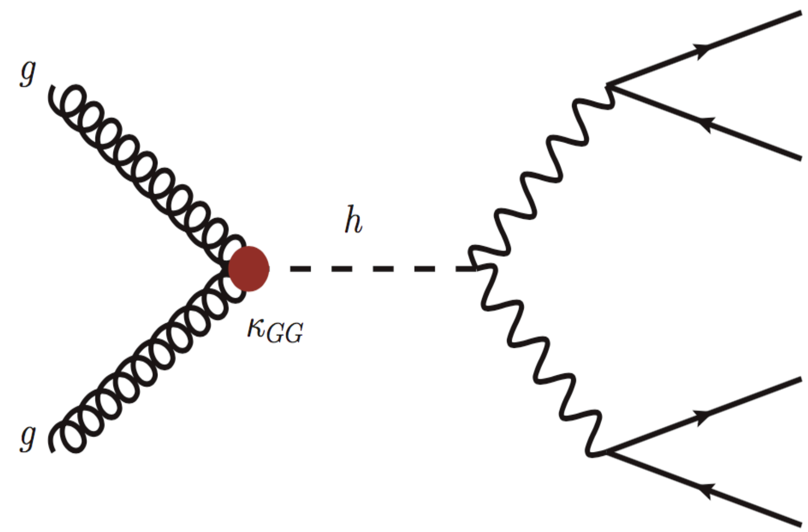
$$+ \kappa_{ZZ} \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu}$$

$$+ \cancel{\sum_{f=\ell} g^h_{ff} h \bar{f}_L f_R}$$

$$+ \boxed{\kappa_{GG} \frac{h}{v} G^{A\mu\nu} G^A_{\mu\nu}} + \dots$$

Affects the total rate,
not the angular distributions.

NEGLECTED



The golden channel: SMEFT

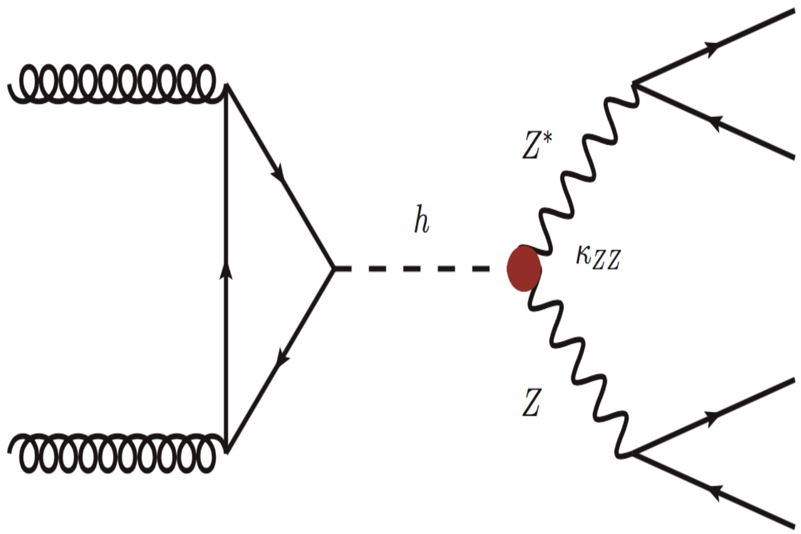
$$\Delta\mathcal{L} \supset \cancel{\sum_{f=\ell} g^h_{Zf} \frac{h}{v} Z_\mu \bar{f} \gamma^\mu f}$$

$$+ \boxed{\kappa_{ZZ} \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu}}$$

$$+ \cancel{\sum_{f=\ell} g^h_{ff} h \bar{f}_L f_R}$$

$$+ \cancel{\kappa_{GG} \frac{h}{v} G^{A\mu\nu} G^A_{\mu\nu}} + \ldots$$

OUR ANALYSIS



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

Shift of the SM coupling

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

New tensor structures

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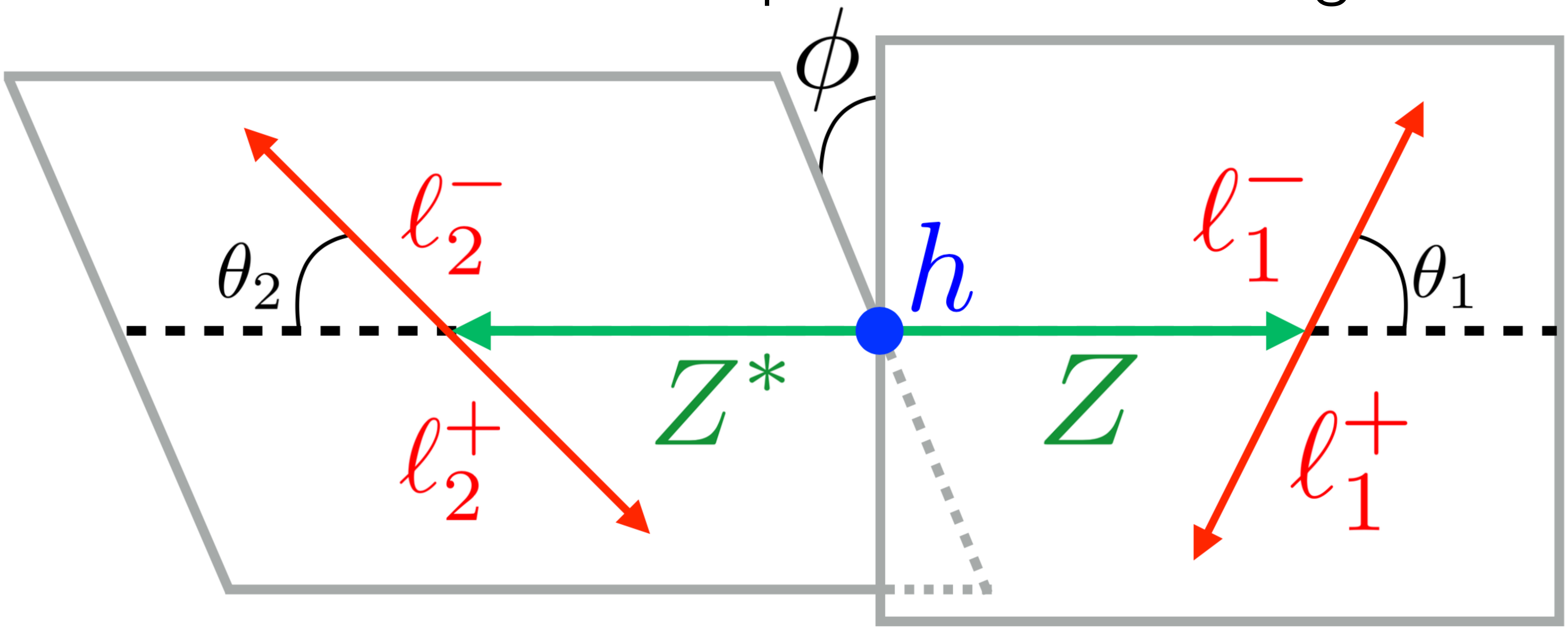
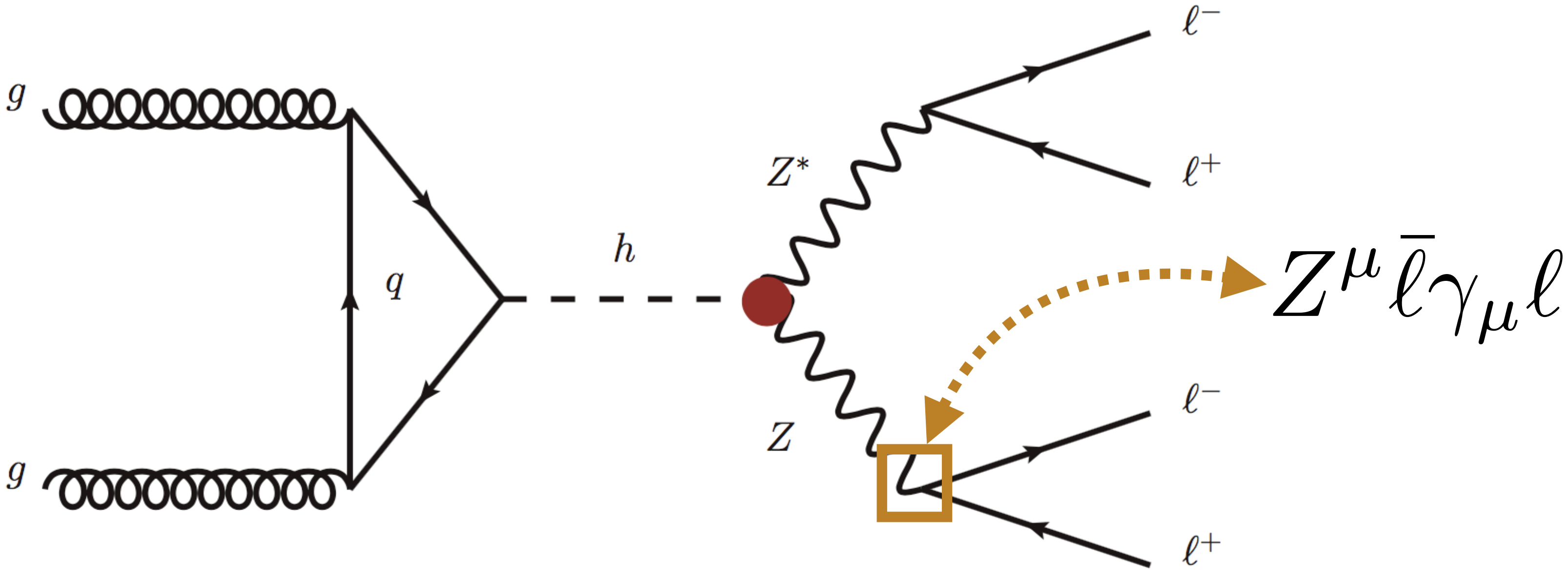
Angular distribution

$$\sigma\left(gg \to h \to 4\ell\right)$$

computed in the Higgs rest frame, and its differential distribution in the lepton emission angles.



Angular dependence in HELAS



2 pairs of opposite-charge and opposite-helicity leptons

$$\bar{\ell}_\pm \ell_\mp$$

For such a system, the dependence on the emission angles is determined by the angular momentum quantum numbers (*J*, *M*), in their rest frame.

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

$$Z_{\lambda_Z} \to \bar{\ell}\ell \Rightarrow J = 1,\ M = \lambda_Z$$

$$d^1_{-1,\Delta\lambda=1}\left(\theta_i,\phi_i\right) = \sin^2(\theta_i/2)e^{-i\phi_i}$$
$$d^1_{+1,\Delta\lambda=1}\left(\theta_i,\phi_i\right) = \cos^2(\theta_i/2)e^{+i\phi_i}$$
$$d^1_{0,\Delta\lambda=1}\left(\theta_i,\phi_i\right) = \frac{\sin\theta_i}{\sqrt{2}}$$

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$h \to ZZ^*$ HELAS

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

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

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

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

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

$h \to ZZ^*$ amplitudes.

Boost factors.

$$\gamma_a = \frac{1}{m_Z\,m_{Z*}}\,(E_1 E_2 + |\vec{q}|^2) = \frac{1}{m_Z\,m_{Z*}}\,q_Z \cdot q_{Z^*}$$

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

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$h \to ZZ^* \to \ell_+\ell_-\ell_+\ell_-$ HELAS

Full helicity amplitude, with h production factorised out.

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

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

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

Breit-Wigner propagators (helicity-independent):
common factor in the angular distribution.

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$h \to ZZ^* \to \ell_+ \ell_- \ell_+ \ell_-$ HELAS

Full helicity amplitude, with h production factorised out.

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

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

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

BSM corrections in *h* → *ZZ amplitudes (helicity-dependent):**
modification of the angular distribution.

$$\propto \delta\hat{g}^h_{ZZ}, \kappa_{ZZ}, \tilde\kappa_{ZZ}$$

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Visible angular modulation

Angular distribution **not for λ = +1/2 leptons,**
but for negatively charged leptons instead.

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

Q = -1 fermions →

- RH: **λ = +1/2**
- LH: **λ = -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

$$\sigma\left(gg \to h \to 4\ell\right)$$

Linear combination of the following 9 functions of the final lepton angles:

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

Angular Moments

Coefficients of the previously shown 9 angular functions, in the differential cross-section evaluated in the Higgs rest frame.

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

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

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

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

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

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

CP-odd

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

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

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

1 → SM

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

$$b = \kappa_{ZZ}$$

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

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

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

Small → *a_5, a_6, a_8* suppressed

Method of Moments

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

(Phys. Rev. D 43, 2193 (1991), Phys. Rev. D 91, 114012 (2015))

Transparent and advantageous when statistics are low.

Assume there exists a dual basis $\{w_i\}_i$ orthonormal to $\{f_i\}_i$,

$\int \mathrm{d}\Omega w_j f_i = \delta_{ij}$, and such that:

$$w_i = \lambda_{ij} f_j \Rightarrow \lambda = M^{-1}, \text{ with } M_{ij} = \int \mathrm{d}\Omega f_i f_j$$

$$\int \mathrm{d}\Omega \sum_i (a_i f_i)\, w_j = a_j$$

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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:

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

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

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

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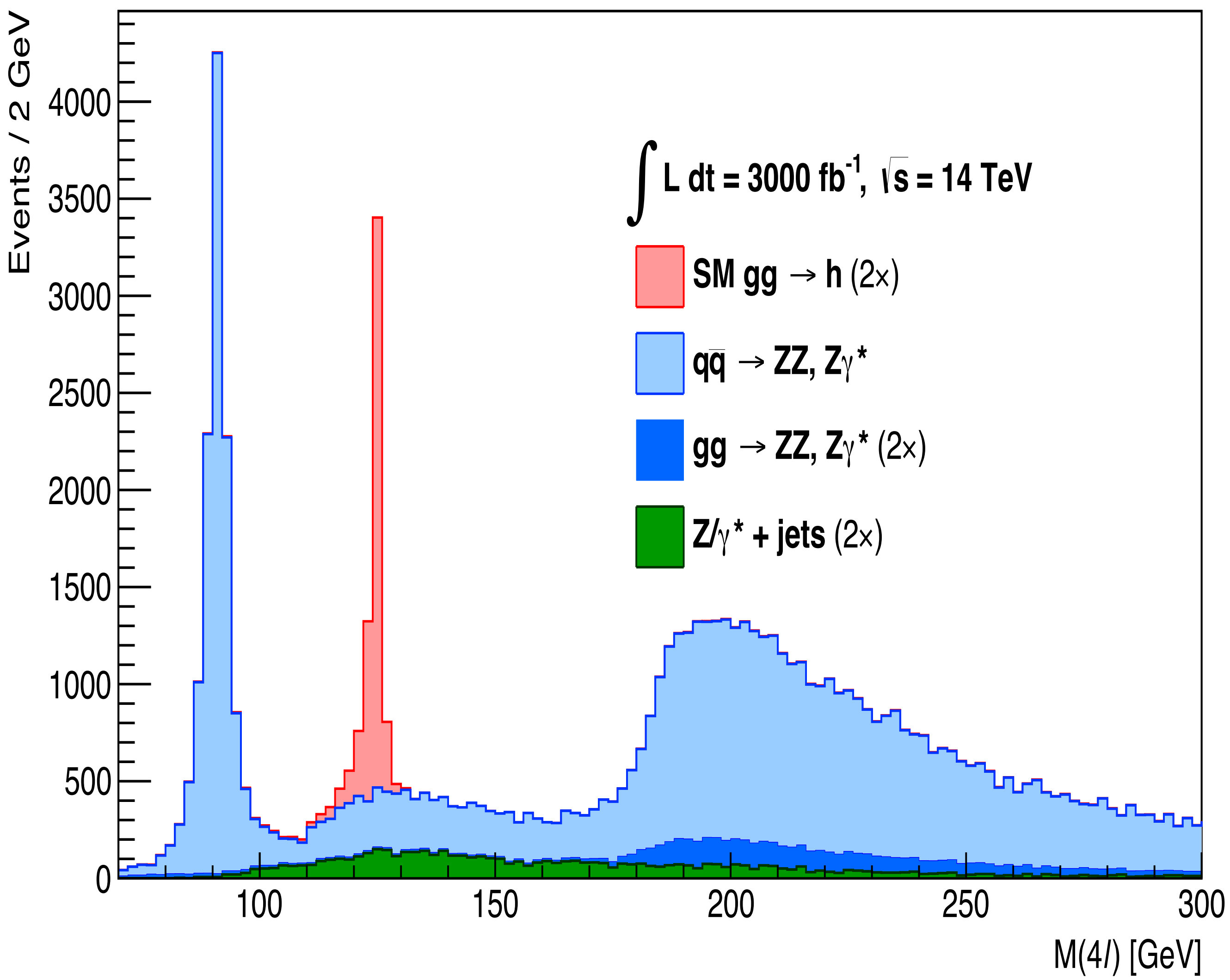
Collider analysis

Validated against **(CMS-PAS-HIG-19-001):** 96% agreement with experimental numbers.
We target the HL-LHC.

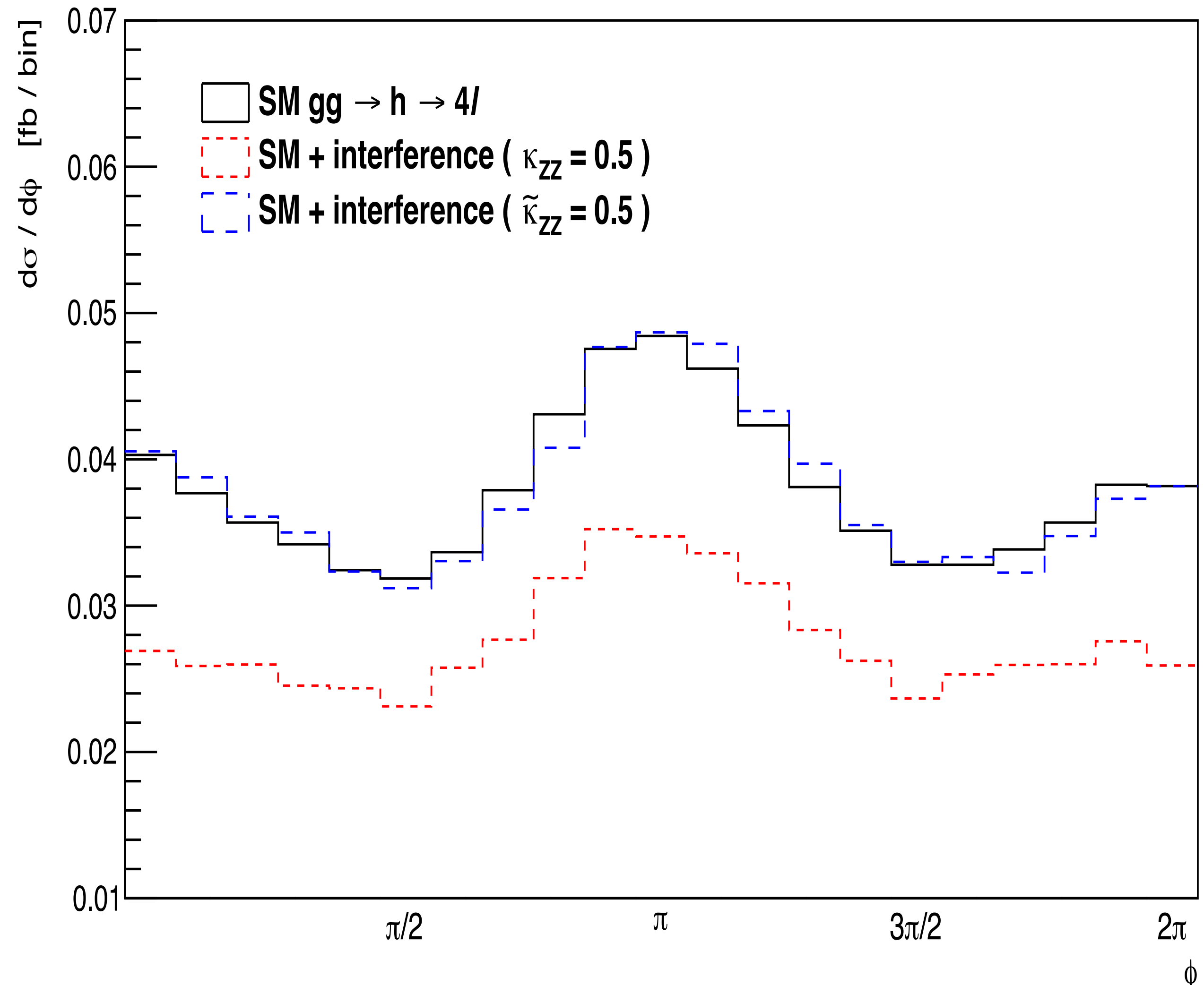
Selection cut	SM $gg \to h$	$q\bar{q} \to 4\ell$	$gg \to 4\ell$
Jet veto	0.419	0.779	0.319
$\not{E}_T < 25$ GeV	0.348	0.667	0.248
2 pairs of isolated OSSF leptons, $\Delta R(\ell_i, \ell_j) > 0.02$, $M_{\ell^+,\ell'^-} > 4$ GeV	0.127	0.036	0.130
$p_{T,\ell_1} > 20\,\mathrm{GeV}$, $p_{T,\ell_2} > 10\,\mathrm{GeV}$, $p_{T,\ell_3} > 10\,\mathrm{GeV}$	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

Table Set of cuts 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.

Collider analysis



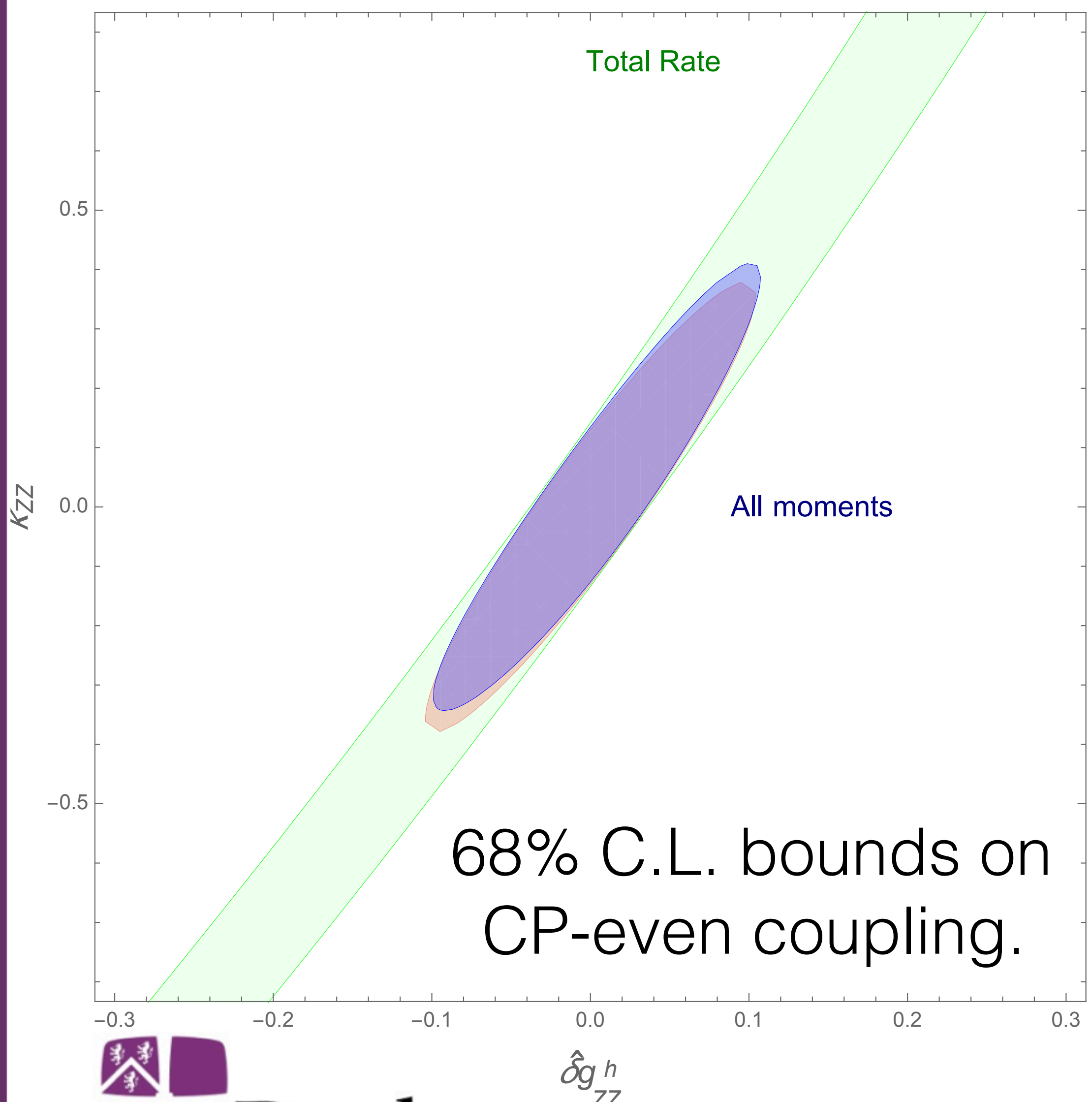
M(4ℓ) **distribution.**



Azimuthal distribution $\ell^{-}{}_{1}$.

Moments estimates and bounds

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



68% C.L. bounds on CP-even coupling.

Expected events at **L = 3 ab^{-1}**.

$$\chi^2(\delta\hat{g}^h_{ZZ}, \kappa_{ZZ}, \tilde{\kappa}_{ZZ}) = \sum_{ij} \left(a_i^{EFT} - a_i^{SM}\right) \boxed{\Sigma_{ij}^{-1}} \left(a_j^{EFT} - a_j^{SM}\right)$$

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

$$\kappa_{\text{syst}} = 0.02$$

(ATL-PHYS-PUB-2018-054)

Angular distribution allows to set bounds along a flat direction.

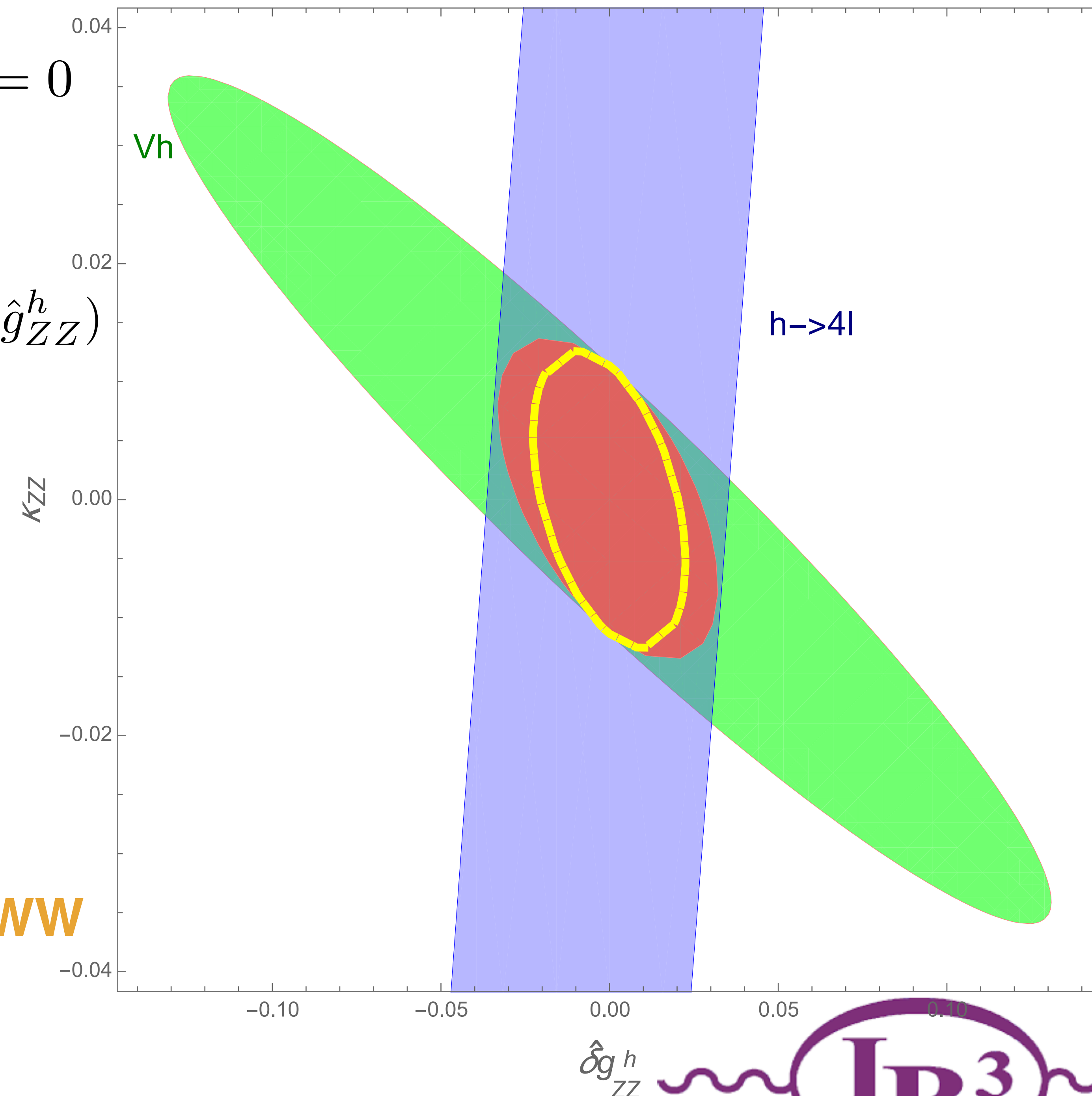
Moments estimates and bounds

With $\kappa_{\rm syst} = 0, |\kappa_{ZZ}| < 0.05$ 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 $\chi^2]$

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

- Purple: gg → h → 4ℓ
- Green: pp → Vh
(JHEP 09 (2020) 170)
- Red: Combination
- Yellow ellipse: + pp → h → WW
(ATL-PHYS-PUB-2018-054)



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Summary and conclusions

- 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 MELA framework, in a more transparent way.
- Angular analysis lifts the flat direction in $(\delta\hat{g}^{h}_{ZZ}, \kappa_{ZZ})$.

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A fully differential SMEFT analysis of the golden channel using the Method of Moments

👏🙌

Questions/Comments/Suggestions?

Backup slides

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

$$\delta g_\ell^Z = -\frac{gY_\ell s_{\theta_W}}{c_{\theta_W}^2}\frac{v^2}{\Lambda^2}c_{HWB} - \frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(|T_3^\ell|c_{HL}^{(1)} - T_3^\ell c_{HL}^{(3)} + (1/2-|T_3^\ell|)c_{H\ell})$$
$$+\frac{\delta m_Z^2}{m_Z^2}\frac{g}{2c_{\theta_W}s_{\theta_W}^2}(T_3c_{\theta_W}^2 + Y_\ell s_{\theta_W}^2)$$

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

$$g_{Z\ell}^h = -\frac{2g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(|T_3^\ell|c_{HL}^{(1)} - T_3^\ell c_{HL}^{(3)} + (1/2-|T_3^\ell|)c_{H\ell})$$

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

$$\kappa_{GG} = \frac{2v^2}{\Lambda^2}c_{HG}$$

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

$$\frac{\delta m_Z^2}{m_Z^2} = \frac{v^2}{\Lambda^2}(2t_{\theta_W}c_{HWB} + \frac{c_{HD}}{2})$$

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

$$\delta g_1^Z = \frac{1}{2s_{\theta_W}^2}\frac{\delta m_Z^2}{m_Z^2}$$

$$\delta\kappa_\gamma = \frac{1}{t_{\theta_W}}\frac{v^2}{\Lambda^2}c_{HWB}$$

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

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

$g^{h}_{Z\ell}$ contribution to $h \to Z2\ell \to 4\ell$ can be expressed as a shift in $g^{Z^*}_{\ell_2}$ in $\mathcal{M}(h \to ZZ^* \to 4\ell)$

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

Deformations and correlated interactions

Operator $(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}$

Expanding, get terms like: $\hat{h}^2 \left[\hat{W}^3_{\mu\nu} B^{\mu\nu} + 2igc_{\theta_W} W^-_\mu W^+_\nu (A^{\mu\nu} - t_{\theta_W}) Z^{\mu\nu} \right]$

Considering $\hat{h} = v + h$ and expanding further:

$hA_{\mu\nu}A^{\mu\nu}, hA_{\mu\nu}Z^{\mu\nu}, hZ_{\mu\nu}Z^{\mu\nu}, hW^+_{\mu\nu}W^{-,\mu\nu} \rightarrow$ Higgs deformations

$2igc_{\theta_W} W^-_\mu W^+_\nu (A^{\mu\nu} - t_{\theta_W} Z^{\mu\nu}) \rightarrow \delta\kappa_\gamma, \delta\kappa_Z$ (TGCs)

$\hat{W}_{\mu\nu} B^{\mu\nu} \rightarrow$ S-parameter

7 deformations from a single operator

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IP3

Anomalous Higgs Couplings

Interactions *constrained by LEP*:

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ}\frac{v}{2c^2_{\theta_W}}hZ^\mu Z_\mu + g^h_{Zff}\frac{h}{2v}(Z_\mu J^\mu_N + h.c.) + g^h_{Wff'}\frac{h}{v}(W^+_\mu J^\mu_C + h.c.)$$
$$+ \kappa_{WW}\frac{h}{v}W^{+\mu\nu}W^-_{\mu\nu} + \kappa_{ZZ}\frac{h}{v}Z^{\mu\nu}Z_{\mu\nu}$$

Terms *not constrained by LEP*. First time probed at the LHC:

$$\mathcal{L}^{\text{primary}}_h = g^h_{VV}h\left[W^{+\mu}W^-_\mu + \frac{1}{2c^2_{\theta_W}}Z^\mu Z_\mu\right] + g_{3h}h^3 + g^h_{ff}(h\bar{f}_L f_R + h.c.)$$
$$+ \kappa_{GG}\frac{h}{v}G^{A\mu\nu}G^A_{\mu\nu} + \kappa_{\gamma\gamma}\frac{h}{v}A^{\mu\nu}A_{\mu\nu} + \kappa_{Z\gamma}t_{\theta_W}\frac{h}{v}A^{\mu\nu}Z_{\mu\nu}$$

(Phys. Rev. D 91, 035001)

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$$+ \boxed{\kappa_{WW}}\frac{h}{v}W^{+\mu\nu}W^-_{\mu\nu} + \boxed{\kappa_{ZZ}}\frac{h}{v}Z^{\mu\nu}Z_{\mu\nu}$$

$$\boxed{\delta g^h_{ZZ}} = \delta g^Z_1 e^2 - \delta\kappa_\gamma \frac{e^2}{c^2_{\theta_W}}$$

$$\boxed{g^h_{Wff'}} = 2\delta g^W_{ff'} - 2\delta g^Z_1 g^W_f c^2_{\theta_W}$$

$$\boxed{g^h_{Zff}} = 2\delta g^Z_{ff} - 2\delta g^Z_1\left(g^Z_f c_{2\theta_W} + eQ_f s_{2\theta_W}\right) + 2\delta\kappa_\gamma Y_f \frac{e s_{\theta_W}}{c^3_{\theta_W}}$$

$$\boxed{\kappa_{WW}} = \delta\kappa_\gamma + \kappa_{Z\gamma} + 2\kappa_{\gamma\gamma}$$

$$\boxed{\kappa_{ZZ}} = \frac{1}{2c^2_{\theta_W}}\left(\delta\kappa_\gamma + \kappa_{Z\gamma}c_{2\theta_W} + 2\kappa_{\gamma\gamma}c^2_{\theta_W}\right)$$

(1412.4410) (Phys. Rev. D 91, 035001)

Anomalous Higgs Couplings

Assuming flavour universality, some anomalous Higgs couplings first probed at the LHC are:

$hW^+_{\mu\nu}W^{-,\mu\nu}$

$hZ_{\mu\nu}Z^{\mu\nu}, hA_{\mu\nu}A^{\mu\nu}, hA_{\mu\nu}Z^{\mu\nu}, hG_{\mu\nu}G^{\mu\nu}$

$hf\bar{f}, h^2f\bar{f}$

$hW^+_{\mu}W^{-,\mu}$

h^3

$hZ_{\mu}\bar{f}_{L,R}\gamma^{\mu}f_{L,R}$

EW Anomalous Couplings:
9 EW Precision Observables

Z/W-pole measurements:

$Z_\mu \bar{f}_{L,R} \gamma^\mu f_{L,R}$

$W^+_\mu \bar{u}_L \gamma^\mu d_R$

3 TGCs measured at LEP by the $e^+e^- \to W^+W^-$ channel:

$g_1^Z c_{\theta_W} Z^\mu \left(W^{+,\nu} \hat{W}^-_{\mu\nu} - W^{-,\nu} \hat{W}^+_{\mu\nu} \right)$

$\kappa_\gamma s_{\theta_W} \hat{A}^{\mu\nu} W^+_\mu W^-_\nu$

$\lambda_\gamma s_{\theta_W} \hat{A}^{\mu\nu} W^{-,\rho}_\mu W^+_{\rho\nu}$

$QGCs$:

$Z^\mu Z^\nu W^-_\mu W^+_\nu$

$W^{-,\mu} W^{+,\nu} W^-_\mu W^+_\nu$

Collider setup @$\sqrt{s}$ = 14 TeV

- $\boldsymbol{gg \to h \to 4\ell}$**:** MadGraph5 @LO; NNPDF31_lo_as_0130 PDF set; N^{3}LO K-factor = 3.155. SM and EFT contributions, separately.

- $\boldsymbol{q\bar{q} \to 4\ell}$**:** POWHEG BOX v2 @NLO; NNPDF31_nlo_hessian_pdfas PDF set; N^{2}LO/NLO K-factor = 1.1.

- $\boldsymbol{gg \to 4\ell}$**:** MCFM 7 @LO; CTEQ6L PDF set; N^{2}LO/LO K-factor = 2.27.

- $\boldsymbol{pp \to \ell\ell jj}$**:** MadGraph5 @LO; K-factor = 0.91.

Collider setup @$\sqrt{s}$ = 14 TeV

- Pythia8 for parton shower and hadronisation.

- Gaussian smearing (electrons, muons, jets) → (energy, p_T, $\mathbf{p}$) to simulate detector response in the reconstruction of FS objects. **Leptons:** mass- and direction-preserving smearing. **Jets:** mass-preserving smearing.

- Leptonic reconstruction efficiency: 0.92.

- Jet-to-electron fake rate: 0.016 (0.044) for jets with $|y^j| < 1.48$ $(1.48 < |y^j| < 2.5)$. **Only for reducible-background samples.**

Momentum smearing

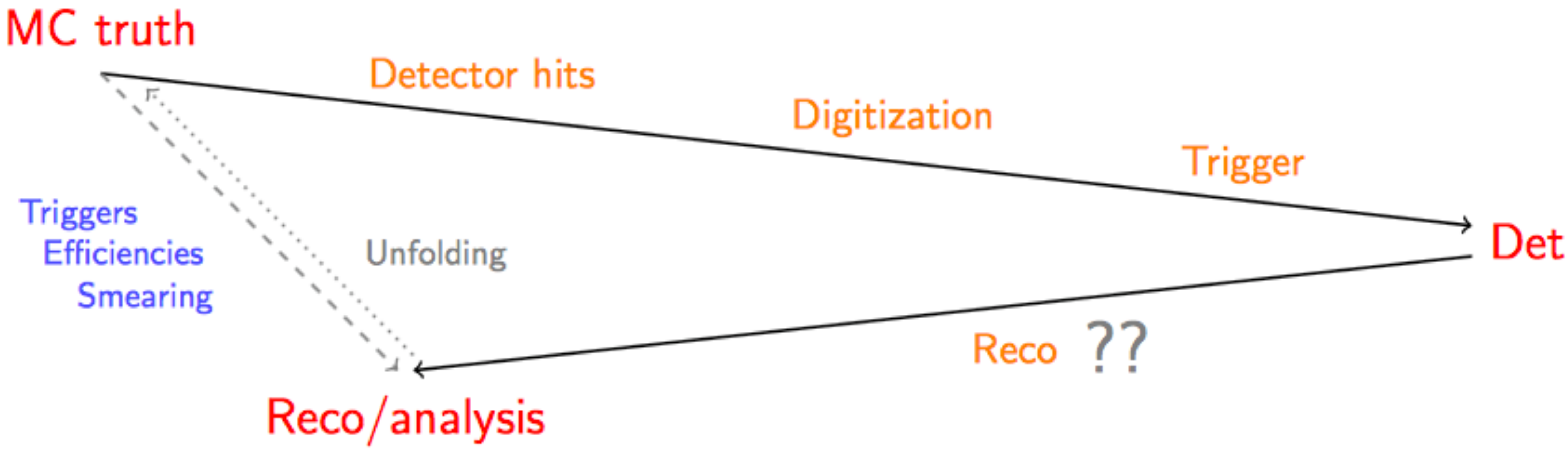

Figure 1: Smearing vs. explicit fast-simulation strategies compared, showing how a smearing approach short-circuits the little-known major effects of the detector and reconstruction processes individually, by instead parametrising the resultant relatively small effect of detector+reconstruction. The axes are arbitrary, but distances between points on the two trajectories represent the typical size of discrepancies between equivalent physics objects at the two stages of processing.

(SciPost Phys. 8, 025 (2020))

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S/B = 0.00734

S/B = 1.37

Table Set of cuts 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.

S/$\boxed{\text{B}_{\text{full}}}$ = 1.09

Irreducible + reducible backgrounds.

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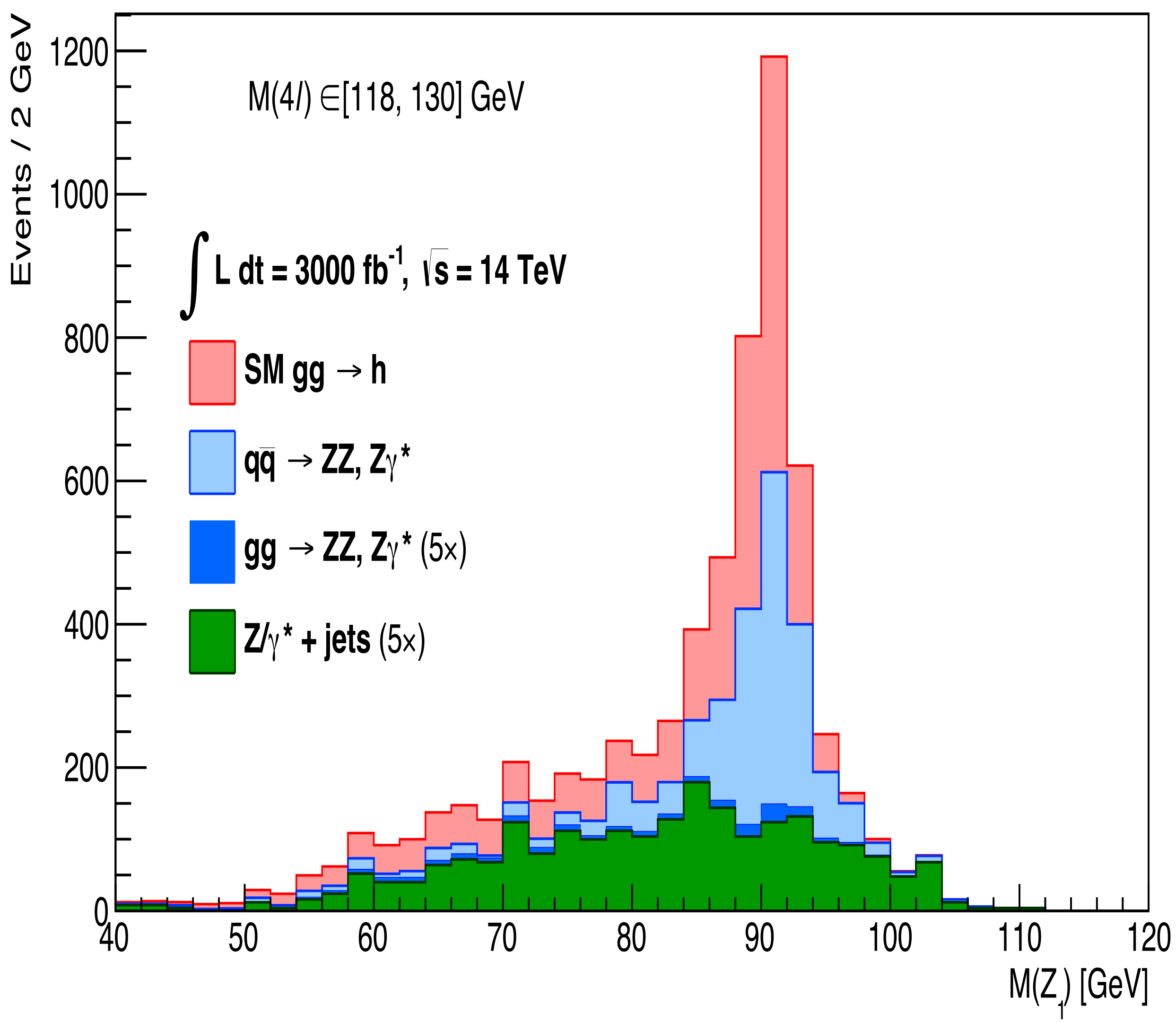
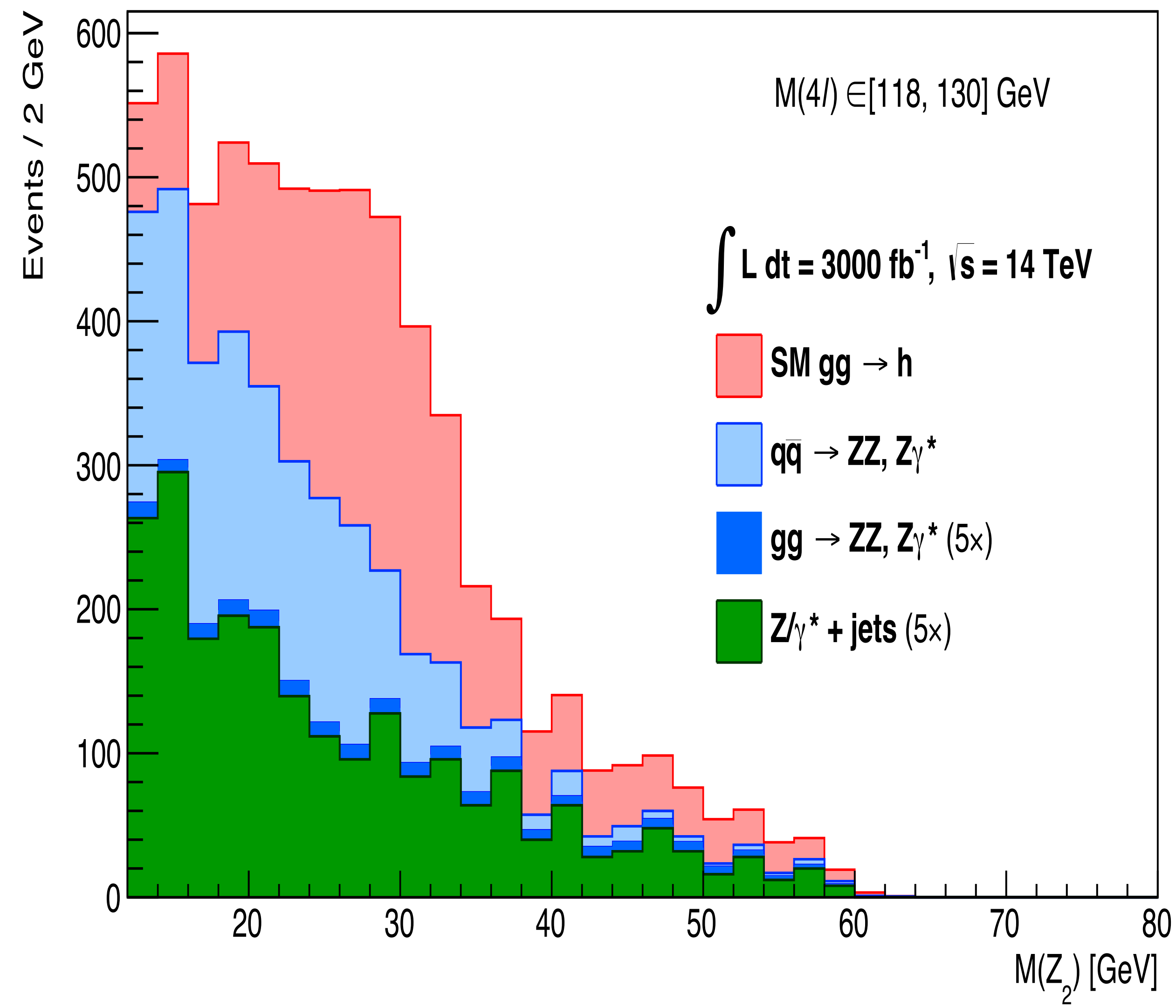
IP3

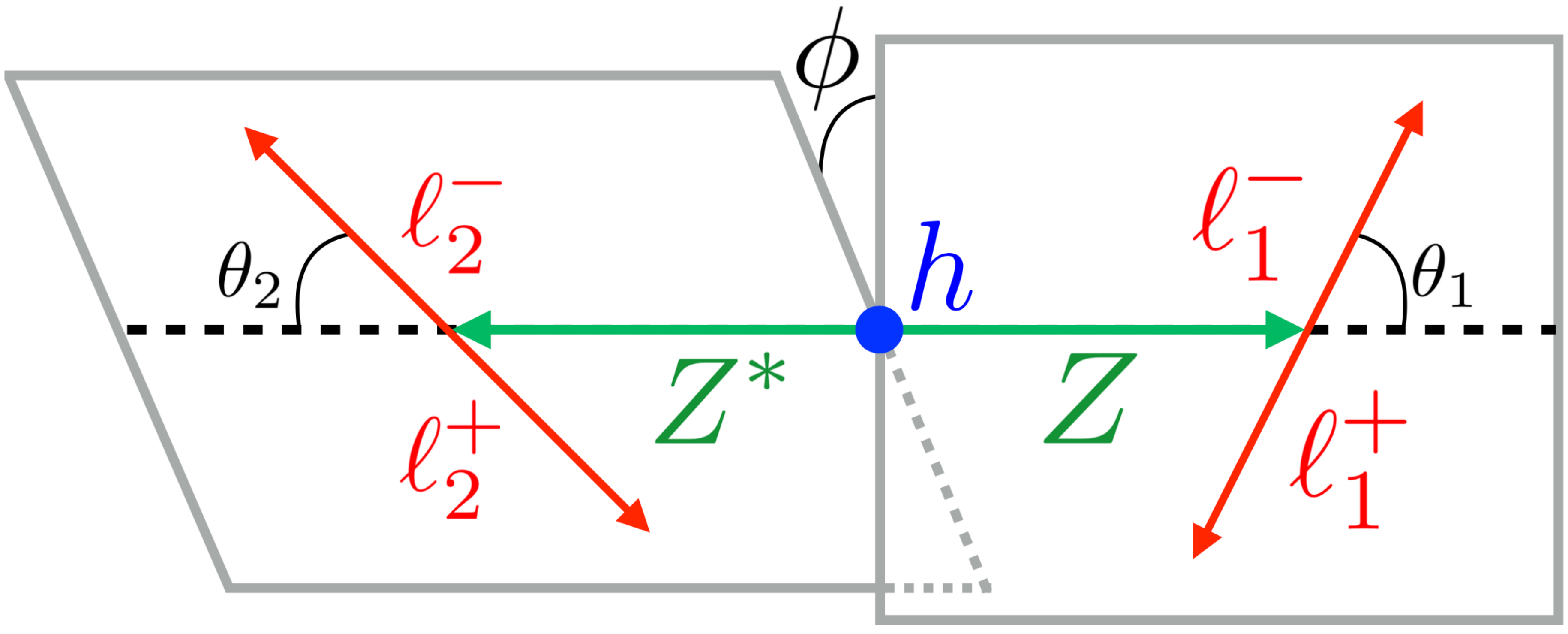
Collider analysis





Invariant mass distribution *M(Zi)* of the (left) Z_1 and (right) Z_2 candidates after defining the signal region 118 < M(4ℓ) < 130 GeV.

Angular extraction



$$\cos\theta_{i,S''} \equiv \frac{\vec{p}_{\ell_i^-,S''} \cdot \vec{q}_{Z_i,S'}}{\left|\vec{p}_{\ell_i^-,S''}\right| \left|\vec{q}_{Z_i,S'}\right|}$$

$$\tan\varphi_{i,S'} = \left(\frac{\ell^-_{i,\hat{y}}}{\ell^-_{i,\hat{x}}}\right) \rightarrow \tan\phi_{S'} \equiv \tan(\varphi_{2,S'} - \varphi_{1,S'})$$

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