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Constraining HWW and HZZ anomalous couplings with quantum tomography @ the LHC

Luca Marzola
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Based on: "*Stringent bounds on HWW and HZZ anomalous couplings with quantum tomography at the LHC*", M. Fabbrichesi, R. Floreanini, E. Gabrielli, LM. — *JHEP 09 (2023) 195*

Quantum Observables for Collider Physics Mini Workshop, Galileo Galilei Institute, Florence

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We consider possible modifications of the Higgs-Vector bosons vertex from its Standard Model form

$$\begin{aligned}\mathcal{L}_{HVV} \;&=\; g\,M_W W^+_\mu W^{-\mu} H + \frac{g}{2\cos\theta_W} M_Z Z_\mu Z^\mu H \\ &\quad - \frac{g}{M_W}\left[\frac{a_W}{2} W^+_{\mu\nu} W^{-\mu\nu} + \frac{\widetilde{a}_W}{2} W^+_{\mu\nu} \widetilde{W}^{-\mu\nu} + \frac{a_Z}{4} Z_{\mu\nu} Z^{\mu\nu} + \frac{\widetilde{a}_Z}{4} Z_{\mu\nu} \widetilde{Z}^{\mu\nu}\right] H\end{aligned}$$

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The Standard Model bit

The new bit, where a_V and $\tilde{a}_V$, $V \in \{W, Z\}$, parametrize the deviation, $V_{\mu\nu}$ are field strength tensors and $\tilde{V}_{\mu\nu}$ their duals

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yielding the *effective HVV vertex*

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Can we use *quantum tomography to constrain the anomalous couplings*?

Theoretical quantum tomography

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Projector; S_i ($i \in \{1,2,3\}$) are the *spin matrices* and n_i are the *linear polarizations versors boosted by -p/m*

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spin-2 guys

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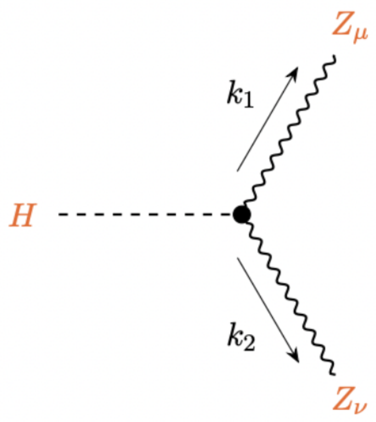
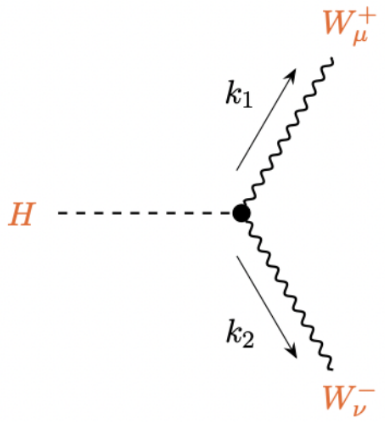
Information about vector and tensor polarizations

spin correlations

So we start computing…





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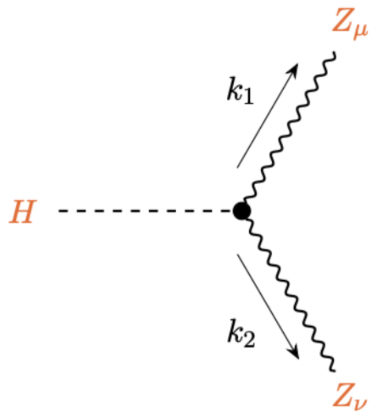

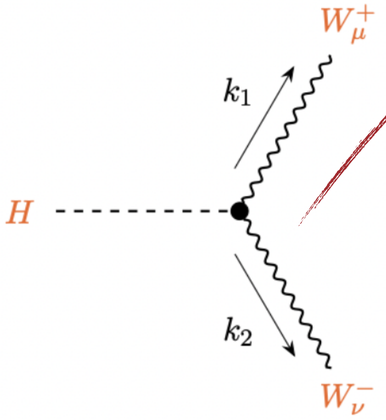

$H \to V(k_1, \lambda_1)\, V^*(k_2, \lambda_2)$ $V \in \{W, Z\}$

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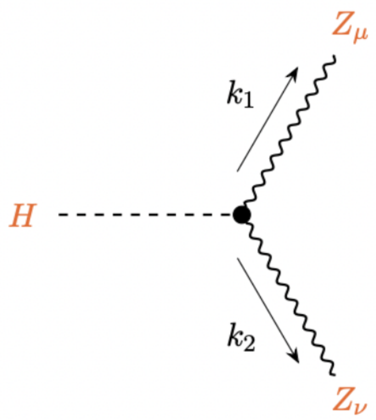

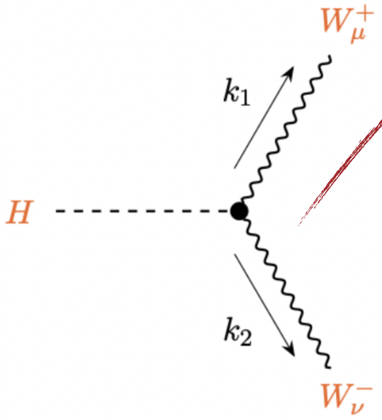

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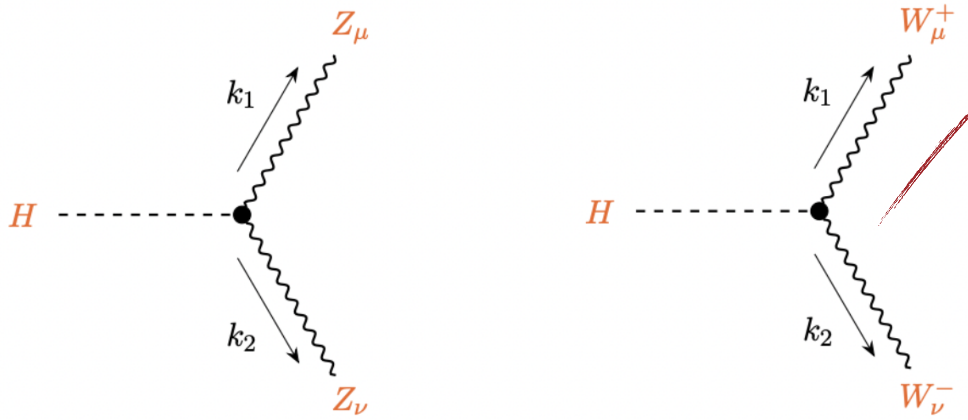

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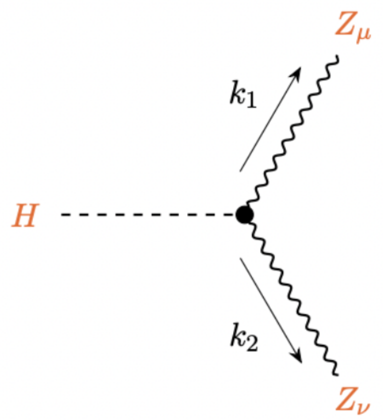

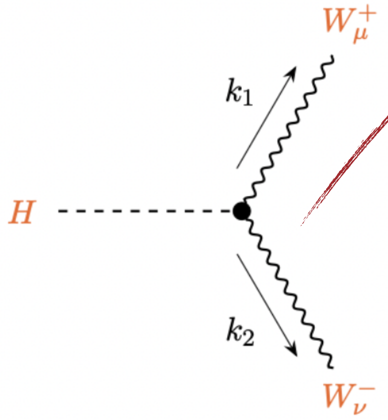

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$$|\overline{\mathcal{M}}|^2 = \frac{g^2}{4f^2M_V^2}\Phi_H$$

Spin-summed squared amplitude

$$\begin{aligned}\Phi_H &= \Big[1 + 2\,f^2\left(\widetilde{a}_V^2 + a_V^2\right)\Big]m_H^4 - 2\Big[1 + f^2\Big(1 + 2\widetilde{a}_V^2 + 2a_V^2 - 6a_V\Big)\\ &+ 2\,f^4\Big(\widetilde{a}_V^2 + a_V^2\Big)m_H^2M_V^2 + \Bigg[1 + 2f^6\Big(\widetilde{a}_V^2 + a_V^2\Big)\\ &+ 2f^2\Big(5 + \widetilde{a}_V^2 + a_V^2 - 6a_V\Big) + f^4\Big(1 - 4\widetilde{a}_V^2 + 8a_V^2 - 12a_V\Big)\Bigg]M_V^4\end{aligned}$$

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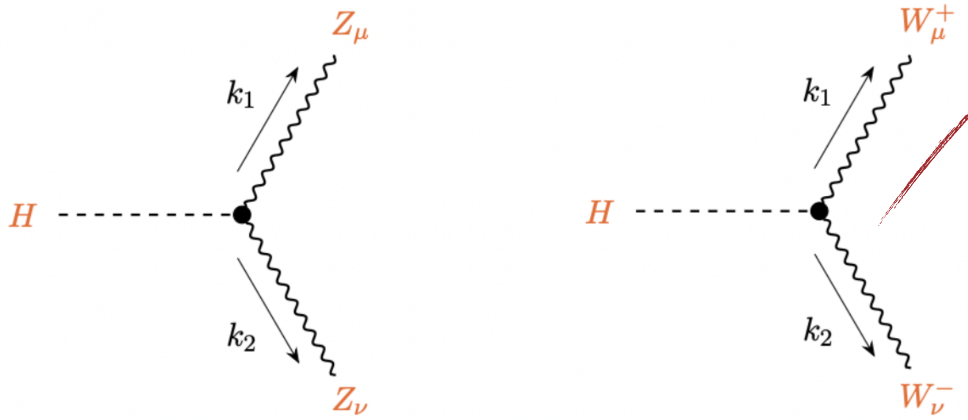

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$$|\overline{\mathcal{M}}|^2 \;=\; \frac{g^2}{4f^2M_V^2}\Phi_H$$

Spin-summed squared amplitude

…and for the density matrix we obtain:

$$\rho_{1\otimes 1} = \frac{M_{\mu\nu}M^\dagger_{\rho\sigma}}{|\overline{\mathcal{M}}|^2}[\mathcal{P}^{\mu\rho}(k_1)\otimes\mathcal{P}^{\nu\sigma}(k_2)] = \frac{1}{|\overline{\mathcal{M}}|^2}\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & h_+h_+^* & 0 & h_+h_0^* & 0 & h_+h_-^* & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & h_0h_+^* & 0 & h_0h_0^* & 0 & h_0h_-^* & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & h_-h_+^* & 0 & h_-h_0^* & 0 & h_-h_-^* & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

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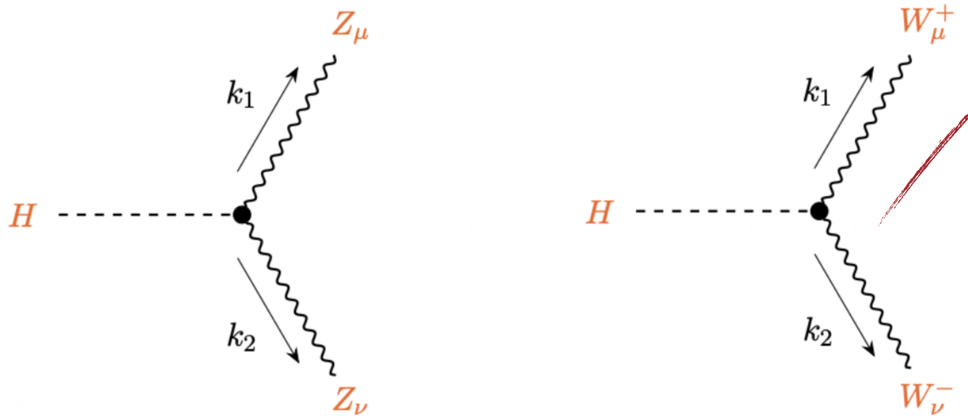
So we start computing…



$$H \to V(k_1,\lambda_1)\, V^*(k_2,\lambda_2)$$ V∈{W,Z}

f models the *offshellness*(?) of *V**: $M_V^* = f M_V$

$$\mathcal{M}(\lambda_1,\lambda_2) = M_{\mu\nu}\varepsilon^{\mu\star}(k_1,\lambda_1)\varepsilon^{\nu\star}(k_2,\lambda_2)$$

$$M^{\mu\nu} = g\, M_V \xi_V\, g^{\mu\nu} - \frac{g}{M_W}\left[a_V\,(k_1^\nu k_2^\mu - g^{\mu\nu} k_1\cdot k_2) + \tilde{a}_V \epsilon^{\mu\nu\alpha\beta} k_{1\alpha} k_{2\beta}\right]$$

ξW=1, ξZ=1/(2 cosθW)

$$\begin{aligned}\Phi_H \;=\;& \Big[1 + 2\, f^2\,(\widetilde{a}_V^2 + a_V^2)\,\Big] m_H^4 - 2\Big[1 + f^2\Big(1 + 2\widetilde{a}_V^2 + 2a_V^2 - 6a_V\Big)\\ +\;& 2\, f^4\Big(\widetilde{a}_V^2 + a_V^2\Big) m_H^2 M_V^2 + \Bigg[1 + 2f^6\Big(\widetilde{a}_V^2 + a_V^2\Big)\\ +\;& 2f^2\Big(5 + \widetilde{a}_V^2 + a_V^2 - 6a_V\Big) + f^4\Big(1 - 4\widetilde{a}_V^2 + 8a_V^2 - 12a_V\Big)\Bigg] M_V^4\end{aligned}$$

$$|\overline{\mathcal{M}}|^2 \;=\; \frac{g^2}{4f^2M_V^2}\Phi_H$$

Spin-summed squared amplitude

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The two vector bosons are in a pure state regardless of the anomalous-coupling values

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In terms of the coefficients of Kronecker products of Gell-Mann matrices:

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The *coefficients* of Gell-Mann matrices (or their spherical friends) can be *reconstructed* experimentally *from the decay products of the massive vector bosons*.

A. J. Barr, Phys. Lett. B 825 (2022) 136866

J. A. Aguilar-Saavedra, A. Bernal, J. A. Casas, and J. M. Moreno, Phys. Rev. D 107 (2023), no. 1 016012

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$\mathscr{C}_2$>0 *witnesses the presence of entanglement.*

F. Mintert and A. Buchleitner, Phys. Rev. Lett. 98 (Apr, 2007) 140505.

- The third observables we use singles out the *antisymmetric part* of the density matrix

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- As for the sensitivities of these observable on the anomalous couplings:
  - the *entropy of entanglement*, at the lowest order, is *linear in a_V and quadratic in $\tilde{a}_V$*

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- The third observables we use singles out the *antisymmetric part* of the density matrix

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ideal situation for constraining the parameters: linear dependence on each anomalous coupling and cross correlations (quadratic) expected to be negligible in the considered ranges

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To constrain the anomalous couplings we use a χ^2 test set for a 95% CL:

$$\sum_i \left[\frac{O_i(a_V,\widetilde{a}_V) - O_i(0,0)}{\sigma_i}\right]^2 \leq 5.991$$

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- half (hopefully) for semi-leptonic decays (*s*-jets identified via *c*-tagging of the companion jet)

F. Fabbri, J. Howarth, and T. Maurin, arXiv:2307.13783.

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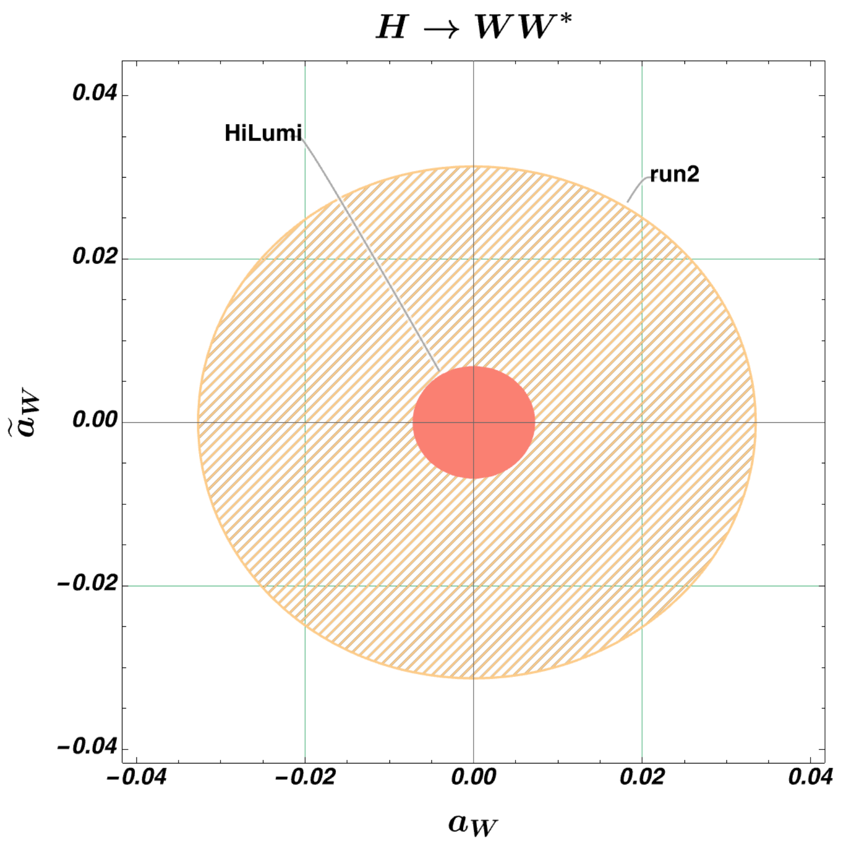

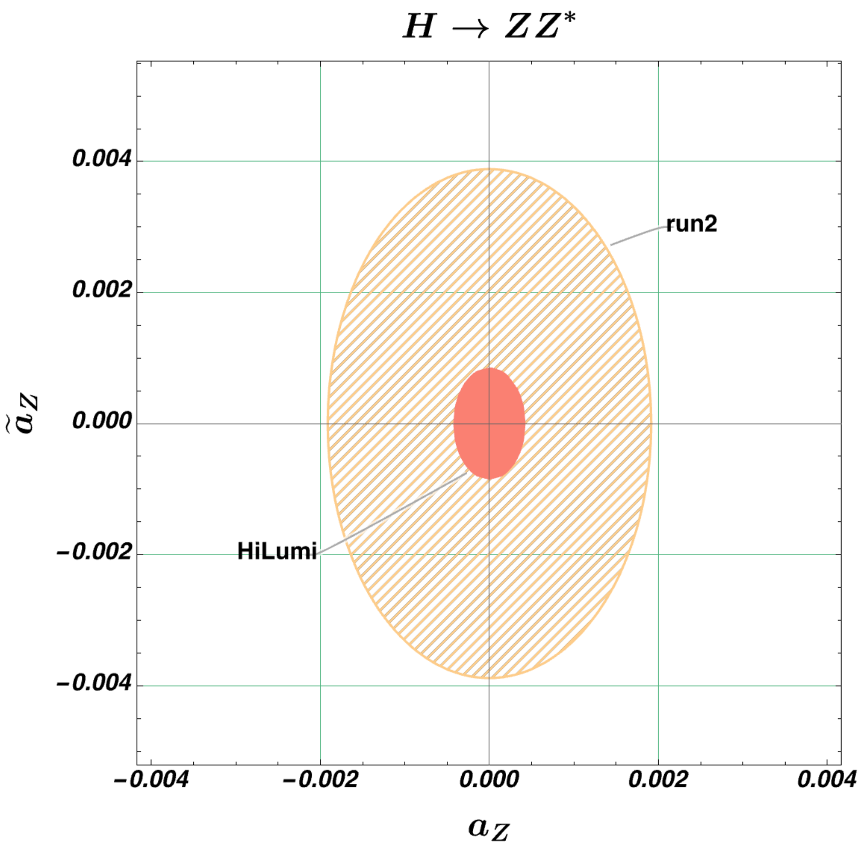

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LHC run2: $\mathcal{L}_{int} = 140\ \text{fb}^{-1}$

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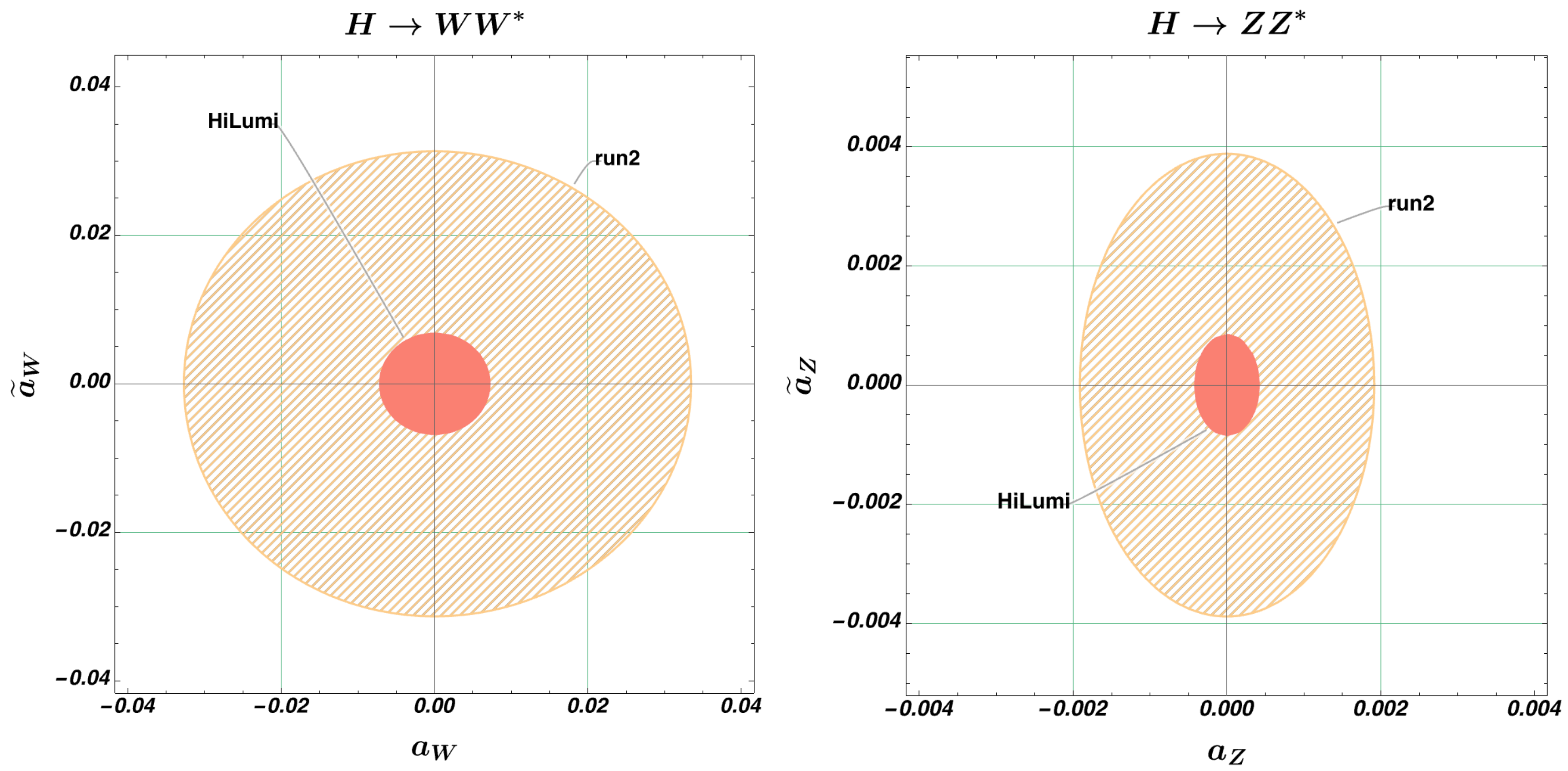

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The marginalized bounds are:

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$\lvert a_W \rvert \leq 0.033$	$\lvert a_W \rvert \leq 0.0070$
$\lvert \tilde{a}_W \rvert \leq 0.031$	$\lvert \tilde{a}_W \rvert \leq 0.0068$
$\lvert a_Z \rvert \leq 0.0019$	$\lvert a_Z \rvert \leq 0.00040$
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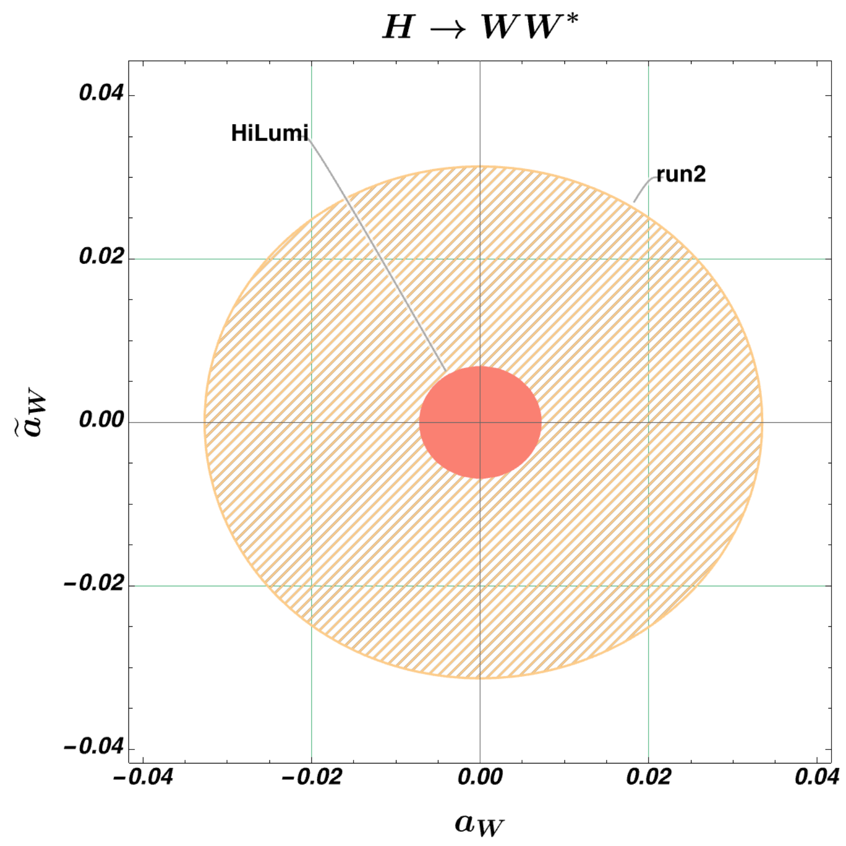

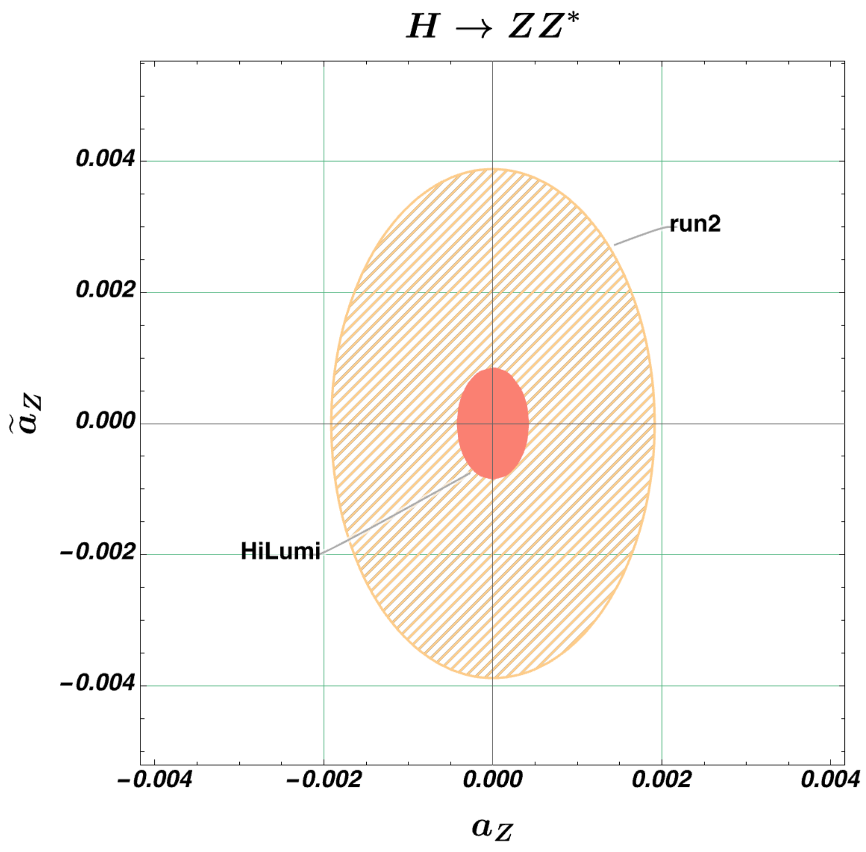

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To be compared with limits using polarization parameters (but *not entanglement*) of the *Z* boson in Higgstrahlung for $\sqrt{s}$=14 TeV and $\mathcal{L}_{\text{int}}$=1000 fb^{-1}

$$a_Z = 6.88 \times 10^{-3}\,, \quad \tilde{a}_Z = 9.53 \times 10^{-3}$$

K. Rao, S. D. Rindani, and P. Sarmah, Nucl. Phys. B 964 (2021) 115317

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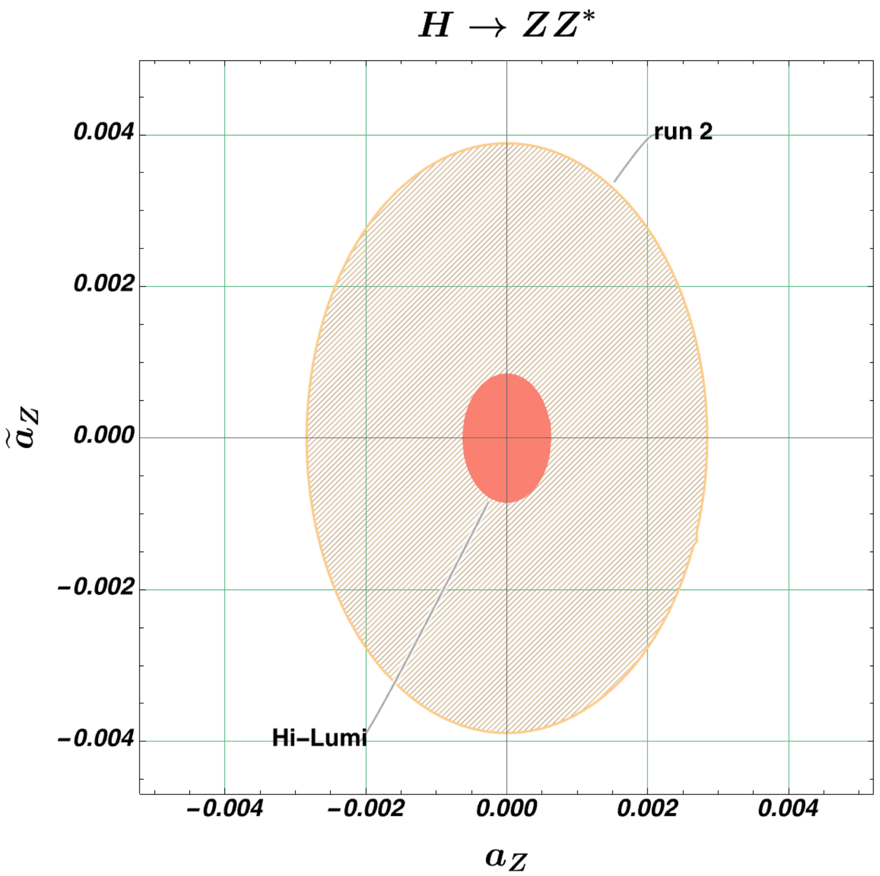

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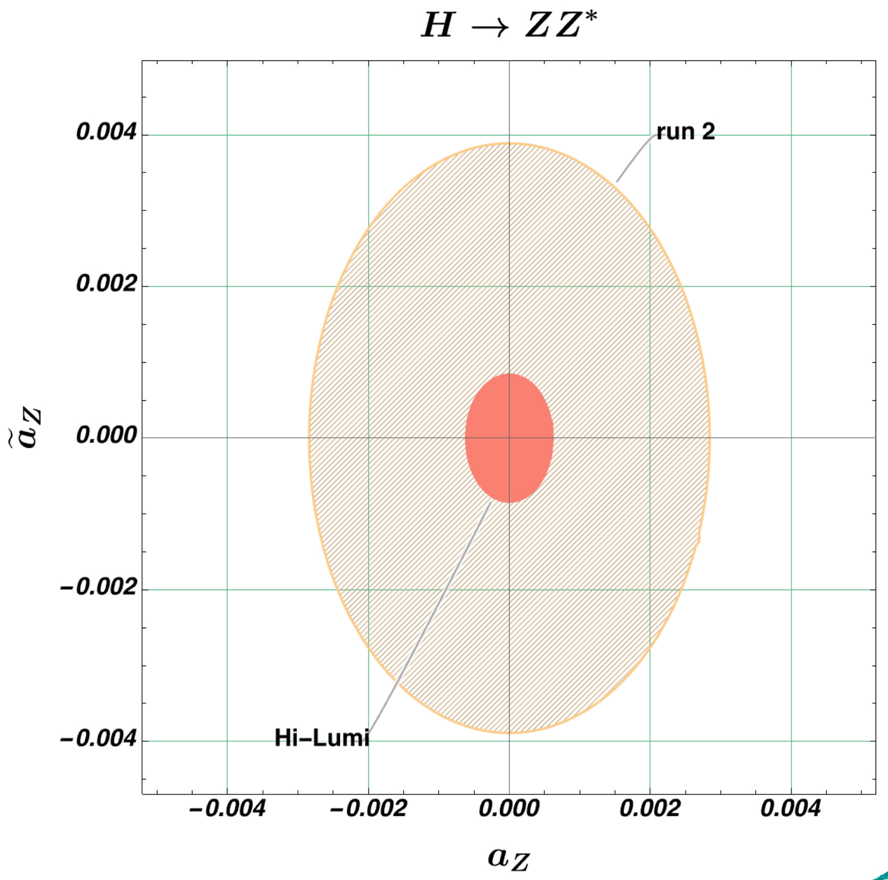

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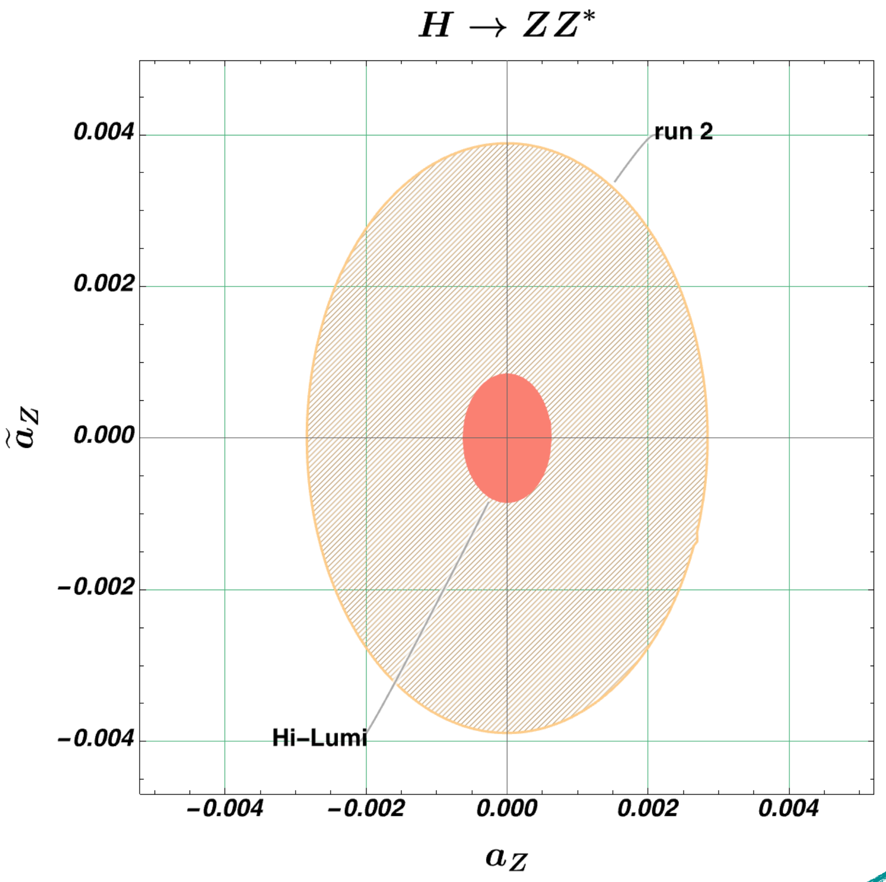

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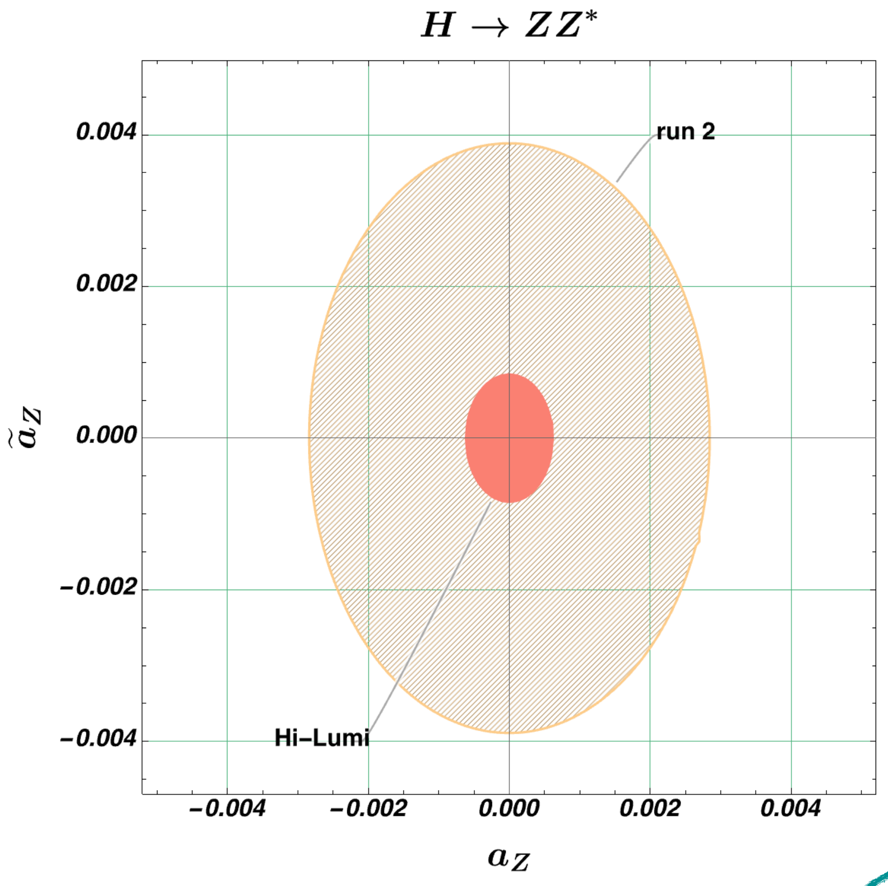

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where σ_i are cross sections involving only the *i-th* anomalous coupling and σ the total cross section, finding:

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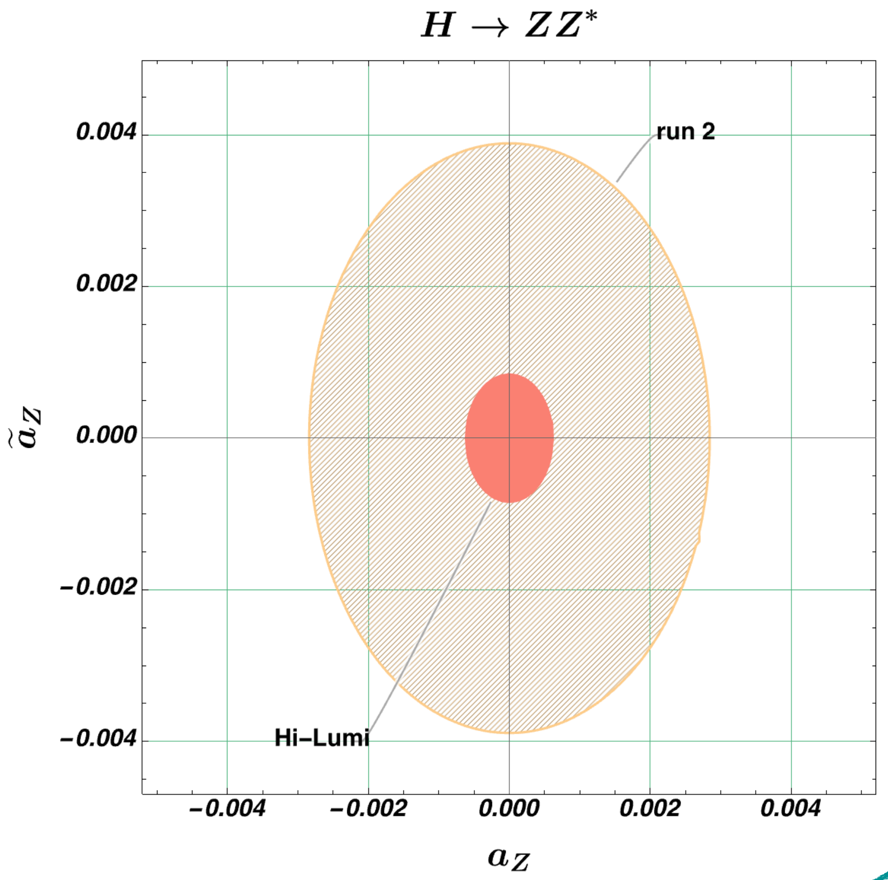

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With the results for the *LHC run2 data* we have:

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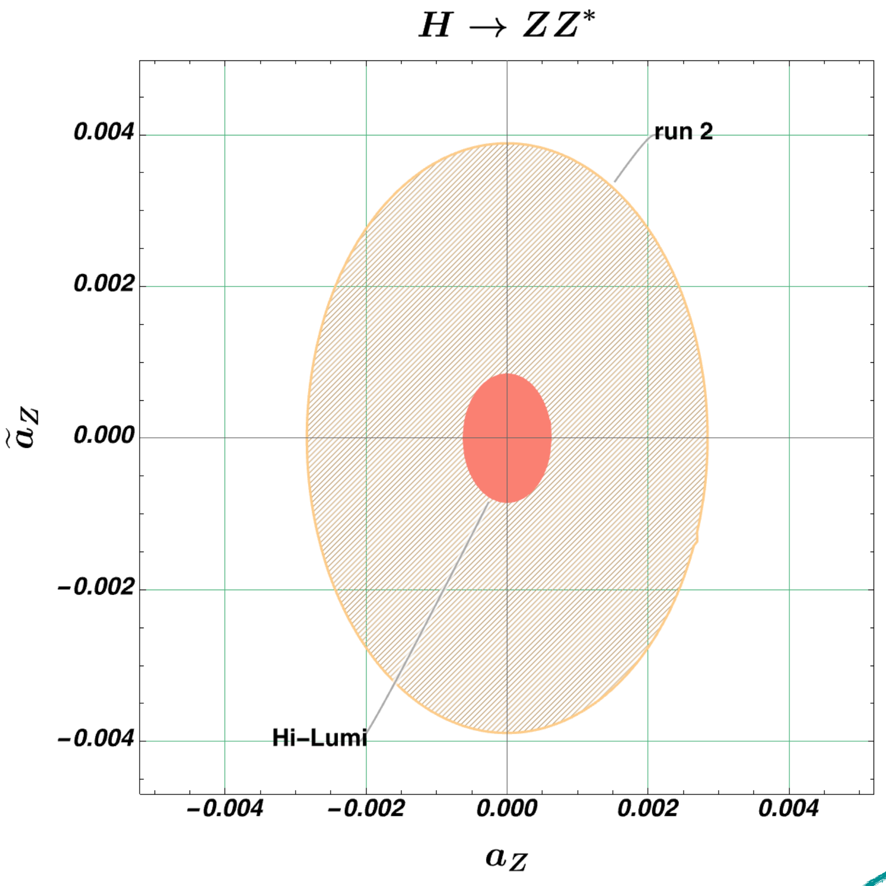

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where σ_i are cross sections involving only the *i-th* anomalous coupling and σ the total cross section, finding:

$$f^V_{g2} < 3.4 \times 10^{-3} \qquad f^V_{g3} < 1.4 \times 10^{-2}$$

With the results for the *LHC run2 data* we have:

$$\boxed{f^Z_{g2} < 7.8 \times 10^{-6} \qquad f^Z_{g3} < 1.5 \times 10^{-5}}$$

Not hopeless at all

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it could be worth to include these observables in routine experimental analyses