Decay of the Higgs Boson into a Z Boson – Photon Pair in the SM and Beyond

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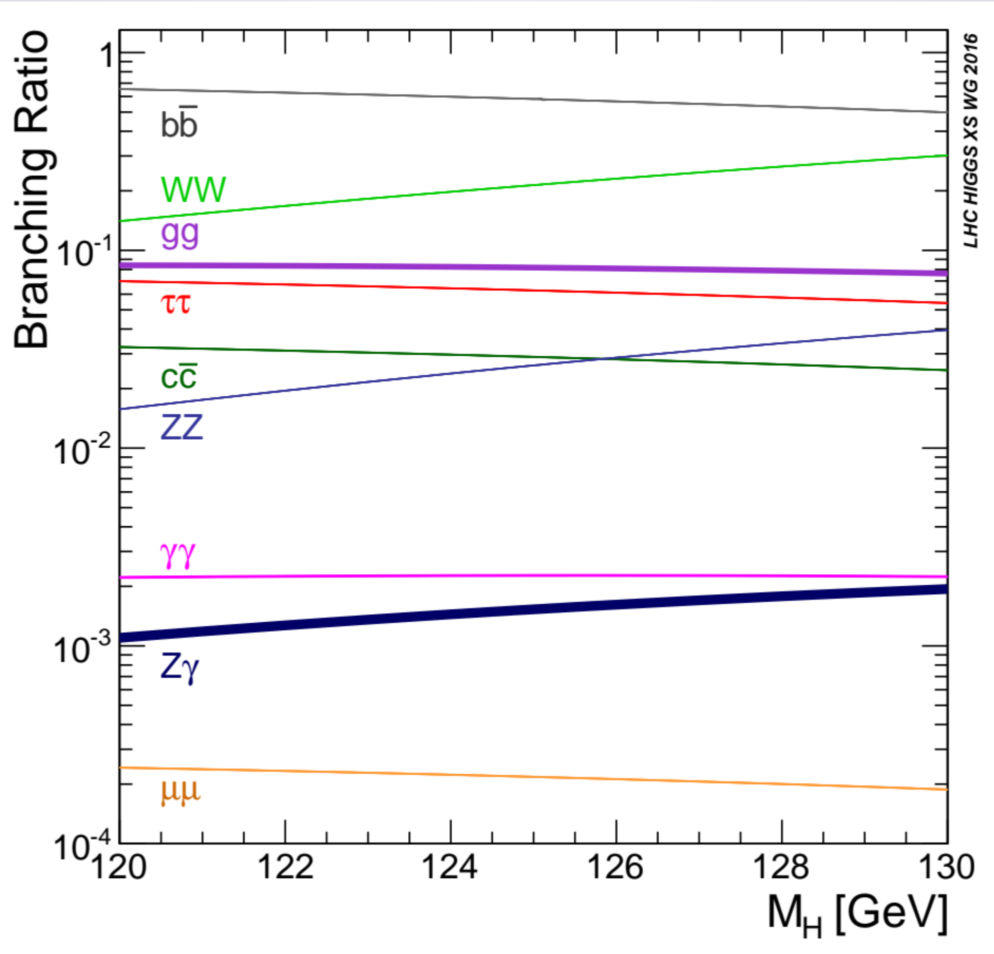
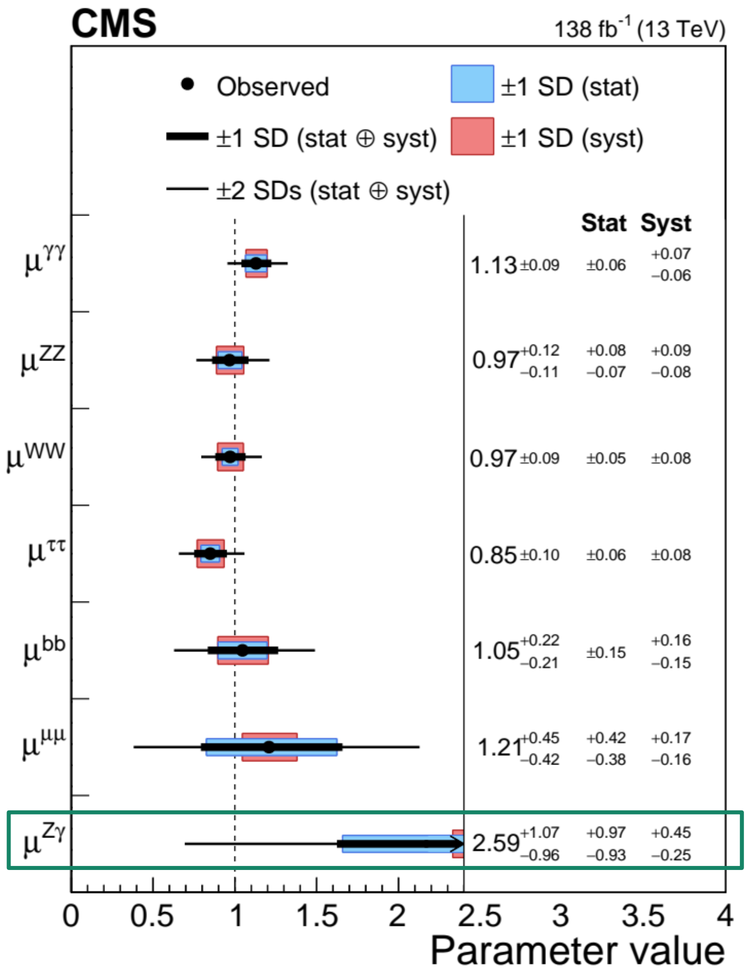
Motivation and Context



M. Carena, C. Grojean, M. Kado, and V. Sharma, Review of Particle Physics, Chin. Phys., Chin. Phys. C40 (2016) 100001.

$$\mathrm{BR}\,(H \to Z\gamma) = 3.4 \pm 1.1$$



CMS Collaboration,Nature 607 (2022) 60

$$\mu^{Z\gamma} = 2.2 \pm 0.7$$

ATLAS, CMS Collaborations. Phys. Rev. Lett. 132 (2024) 021803

Electroweak Standard Model

$\mathrm{SU}(2) \otimes \mathrm{U}(1)$

$$\mathcal{L}_{\mathrm{YM}} = -\frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} W^{i\mu\nu} W^{i}_{\mu\nu}, \quad \textbf{(1)}$$

$$B^{\mu\nu} = \partial^{\mu} B^{\nu} - \partial^{\nu} B^{\mu}, W_i^{\mu\nu} = \partial^{\mu} W_i^{\nu} - \partial^{\nu} W_i^{\mu} + g \varepsilon_{ijk} W_j^{\mu} W_k^{\nu}$$

$$\begin{pmatrix} B^{\mu} \\ W_3^{\mu} \end{pmatrix} = \begin{pmatrix} c_W & s_W \\ -s_W & c_W \end{pmatrix} \begin{pmatrix} A^{\mu} \\ Z^{\mu} \end{pmatrix},$$

Higgs Sector

$$\mathcal{L}_{\mathrm{Higgs}} = (D_{\mu}\phi)^{\dagger} (D^{\mu}\phi) - V(\phi); \qquad \text{with} \qquad V(\phi) = m^2 |\phi|^2 + \lambda |\phi|^4,$$

$$D^{\mu} = \partial^{\mu} - i g W_i^{\mu} T_i - i g' \frac{Y}{2} B^{\mu},$$

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} G^{\pm}(x) \\ [v + H(x) + i G^0(x)] \end{pmatrix}, \qquad G^{+}(x) = [G^{-}(x)]^{\dagger},$$

$$\mathcal{L}_{Higgs} \approx \frac{1}{2} \partial_{\mu} H \partial^{\mu} H - \frac{1}{2} M_H^2 H^2 + \left(M_W^2 W^{\mu +} W_{\mu}^{-} + \frac{1}{2} M_Z^2 Z^{\mu} Z_{\mu} \right) \left(1 + \frac{H}{v} \right)^2, \quad \textbf{(2)}$$

Theoretical Fundaments II

Functional Quantum Field Theory

$$\langle \Omega \left| T \left\{ \Phi_1^i \left(x_1 \right) \ldots \Phi_n^j \left(x_n \right) \right\} \right| \Omega \rangle = \frac{\delta^{(n)}}{\delta J_1(x_1)_i \ldots \delta J_n(x_n)_j} \left(\frac{Z[J_1,\ldots,J_n]}{Z[0,\ldots,0]} \right)_{J_k=0}. \quad \textbf{(3)}$$

$$Z\left[J_1, \ldots, J_n \right] = \int \mathcal{D}\Phi_1 \ldots \mathcal{D}\Phi_n e^{i \int d^4x \, \left(\mathcal{L}_{\text{free}} + \mathcal{L}_{\text{int}} - i J_1^i \Phi_1^i - \ldots - i J_n^j \Phi_n^j \right)}. \quad \textbf{(4)}$$

Partial Decay Width

$$d\Gamma(1 \to \beta) = \frac{1}{2E_1} (2\pi)^4 \delta^{(4)} \left(p_1^\mu - \sum p_\beta^\mu \right) \left| \overline{\mathcal{M}}_{\beta\alpha}(1 \to \beta) \right|^2 \prod_f \frac{1}{(2\pi)^3} \frac{d^3 p_f}{2E_f}, \quad \textbf{(5)}$$

$$\Gamma_H = 3.7 \times 10^{-3} \text{ GeV}, \; M_H = 125.10 \pm 0.14 \text{ GeV}$$

Particle Data Group

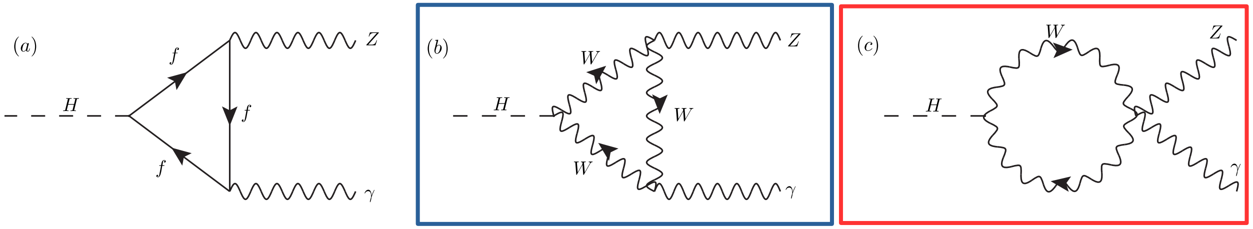
S Matrix

$$\langle f \left| S \right| i \rangle = \delta_{fi} + i \left(2\pi \right)^4 \delta^{(4)} \left(p_f - p_i \right) \mathcal{M}_{fi}. \quad \textbf{(6)}$$

Feynman Diagrams

This contribution is finite!

The dominant contribution is given by the W boson loop!



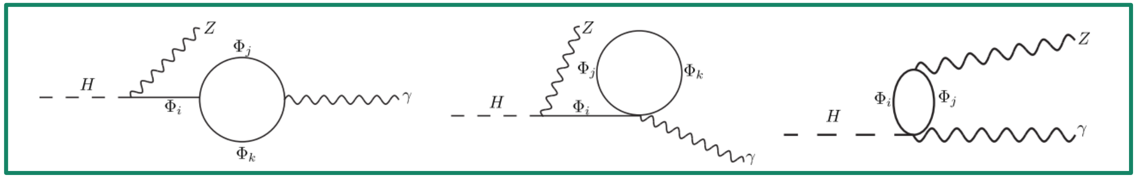
$$\Gamma^{(1)}_{tt} \approx 2.2 \times 10^{-2}\ \text{KeV}$$

$$\Gamma^{(1)}_{WW} \approx 7.8\ \text{KeV}$$

T. Gehrmann, S. Guns, and D. Kara. JHEP 09, 038 (2015).

Only 1PI diagrams are required in the unitary gauge ($\xi \to \infty$) and the Yennie Gauge ($\xi = -3$)

$$\Delta_\varepsilon = \frac{-i\pi^2 e^3 M_W\,(\xi+3)}{2 c_W s_W^2}\frac{1}{\varepsilon}.$$



Non 1PI diagrams

Interaction Lagrangian for LO contribution

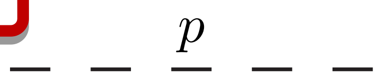
$$\mathcal{L}_{\mathrm{HWW}} = \frac{e M_W}{s_W} H W^+_\mu W^\mu_-,$$
$$\mathcal{L}_{\mathrm{AWW}} = i\ e\left(W^+_{\mu\nu} W^\mu_- A^\nu - W^-_{\mu\nu} W^\mu_+ A^\nu + F_{\mu\nu} W^\mu_+ W^\nu_-\right),$$
$$\mathcal{L}_{\mathrm{ZWW}} = -i\frac{e\ c_W}{s_W}\left(W^+_{\mu\nu} W^\mu_- Z^\nu - W^-_{\mu\nu} W^\mu_+ Z^\nu + Z_{\mu\nu} W^\mu_+ W^\nu_-\right), \qquad \textbf{(7)}$$

$$\mathcal{L}_{\mathrm{WWZA}} = \frac{e^2 c_W}{s_W}\left(2 g^{\mu\nu} g^{\rho\sigma} - g^{\mu\rho} g^{\nu\sigma} - g^{\mu\sigma} g^{\nu\rho}\right) W^+_\mu W^-_\nu A_\rho Z_\sigma. \qquad \textbf{(8)}$$

Leading Contribution II

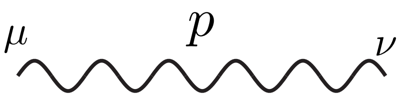
Feynman Rules

Higgs propagator



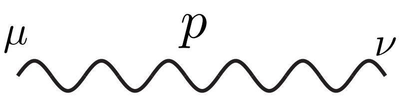
$$= \widetilde{\Delta}_F(p) = \frac{i}{p^2 - M_H^2}$$

Massive vector propagator



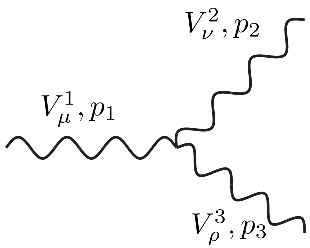
$$= \widetilde{\Delta}_V^{\mu\nu}(p) = \frac{i}{p^2 - M_V^2}\left(-g^{\mu\nu} + (1-\xi)\,\frac{p^\mu p^\nu}{p^2 - \xi M_V^2}\right)$$

Photon propagator

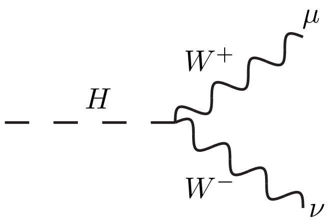


$$= \widetilde{\Delta}_\gamma^{\mu\nu}(p) = \frac{i}{p^2}\left(-g^{\mu\nu} + (1-\xi)\,\frac{p^\mu p^\nu}{p^2}\right)$$

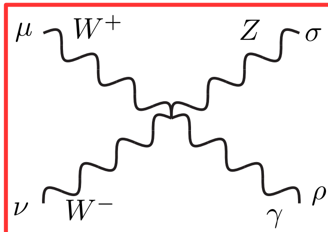
$V^1V^2V^3$	C
AW^+W^-	1
ZW^+W^-	$-\frac{c_W}{s_W}$



$$= ieC\mathcal{V}_{\mu\nu\rho}(p_1, p_2, p_3)$$



$$= i\frac{eM_W}{s_W}g_{\mu\nu}$$



$$= ie^2\frac{c_W}{s_W}\mathcal{B}_{\mu\nu\sigma\rho}$$

$$\mathcal{V}_{\mu\nu\rho}(p_1, p_2, p_3) = g_{\mu\nu}(p_1 - p_2)_\rho + g_{\nu\rho}(p_2 - p_3)_\mu + g_{\rho\mu}(p_3 - p_1)_\nu\,.$$

$$\mathcal{B}_{\mu\nu\sigma\rho} = 2g^{\mu\nu}g^{\sigma\rho} - g^{\nu\rho}g^{\mu\sigma} - g^{\rho\mu}g^{\nu\sigma}\,.$$

LSZ Reduction Formula

$$\left\langle f\left|S^{(1)}\right|i\right\rangle = i^{1+2}\int d^4x_1\; e^{-ip_1x_1}\left(\partial_1^2+M_H^2\right)\int d^4x_2\;\varepsilon_{\lambda_2}^{\mu*}\left(p_2\right)e^{+ip_2x_2}\left(\partial_2^2+M_Z^2\right)$$
$$\times\int d^4x_3\varepsilon_{\lambda_3}^{\nu*}\left(p_3\right)e^{+ip_3x_3}\left(\partial_3^2\right)\left\langle\Omega\left|T\left\{H\left(x_1\right)Z_\mu\left(x_2\right)A_\nu\left(x_3\right)\right\}\right|\Omega\right\rangle, \tag{9}$$

Final Amplitude

$$D_0=\ell^2-M_W^2\;;\;D_1=\left(\ell-p_2\right)^2-M_W^2\;;\;D_2=\left(\ell-p_2-p_3\right)^2-M_W^2$$

$$\ell_2=\ell-p_2\;;\ell_3=\ell-p_2-p_3\;;\;p_1=p_2+p_3.$$

$$i\mathcal{M}^{(b)}\left(H\to Z\gamma\right)=-2\frac{e^3M_Wc_W}{s_W^2}\varepsilon_{\lambda_2}^{\mu*}\left(p_2\right)\varepsilon_{\lambda_3}^{\nu*}\left(p_3\right)\int\frac{d^4\ell}{\left(2\pi\right)^4}\frac{g_{\rho\sigma}}{D_0D_1D_2}\left(g^{\rho\alpha}-\frac{\ell^\rho\ell^\alpha}{M_W^2}\right)$$
$$\times\mathcal{V}_{\mu\alpha\tau}\left(-p_2,\ell,-\ell_2\right)\left(g^{\tau\varepsilon}-\frac{\ell_2^\tau\ell_2^\varepsilon}{M_W^2}\right)\mathcal{V}_{\nu\varepsilon\beta}\left(-p_3,\ell_2,-\ell_3\right)\left(g^{\beta\sigma}-\frac{\ell_3^\beta\ell_3^\sigma}{M_W^2}\right), \tag{10}$$

$$i\mathcal{M}^{(c)}\left(H\to Z\gamma\right)=\frac{e^3c_WM_W}{s_W^2}\varepsilon_{\lambda_2}^{\mu*}\left(p_2\right)\varepsilon_{\lambda_3}^{\nu*}\left(p_3\right)$$
$$\times\int\frac{d^4\ell}{\left(2\pi\right)^4}\frac{\mathcal{B}_{\mu\nu\rho\sigma}g_{\alpha\beta}}{D_0D_2}\left(g^{\alpha\rho}-\frac{\ell^\alpha\ell^\rho}{M_W^2}\right)\left(g^{\sigma\beta}-\frac{\ell_3^\sigma\ell_3^\beta}{M_W^2}\right). \tag{11}$$

Ward-Takahashi Identity

$$p_{3\mu}\mathcal{R}^{\mu\nu} = 0, \;\; \varepsilon_{\mu}^{\lambda_3 *}(p_3)\, p_3^{\mu} = 0$$

$$i\mathcal{M}\left(H \to Z\gamma\right) = i\mathcal{M}^{(b)} + \mathcal{M}^{(c)} = \varepsilon_{\mu}^{\lambda_2 *}(p_2)\,\varepsilon_{\nu}^{\lambda_3 *}\mathcal{R}^{\mu\nu}$$

$$i\mathcal{M} = \varepsilon_{\mu}^{\lambda_2 *}(p_2)\,\varepsilon_{\nu}^{\lambda_3 *}(p_3)\left[F_0 g^{\mu\nu} + F_1 p_2^{\mu} p_3^{\nu} + F_2 p_2^{\mu} p_2^{\nu} + F_3 p_3^{\mu} p_3^{\nu} + F_4 p_3^{\mu} p_2^{\nu}\right].$$

$$\to i\mathcal{M} = \varepsilon_{\mu}^{\lambda_2 *}(p_2)\,\varepsilon_{\nu}^{\lambda_3 *}(p_3)\, F_4\left[-\left(p_2 \cdot p_3\right) g^{\mu\nu} + p_3^{\mu} p_2^{\nu}\right]. \quad \textbf{(12)}$$

The amplitude is proportional only to two tensor structures!

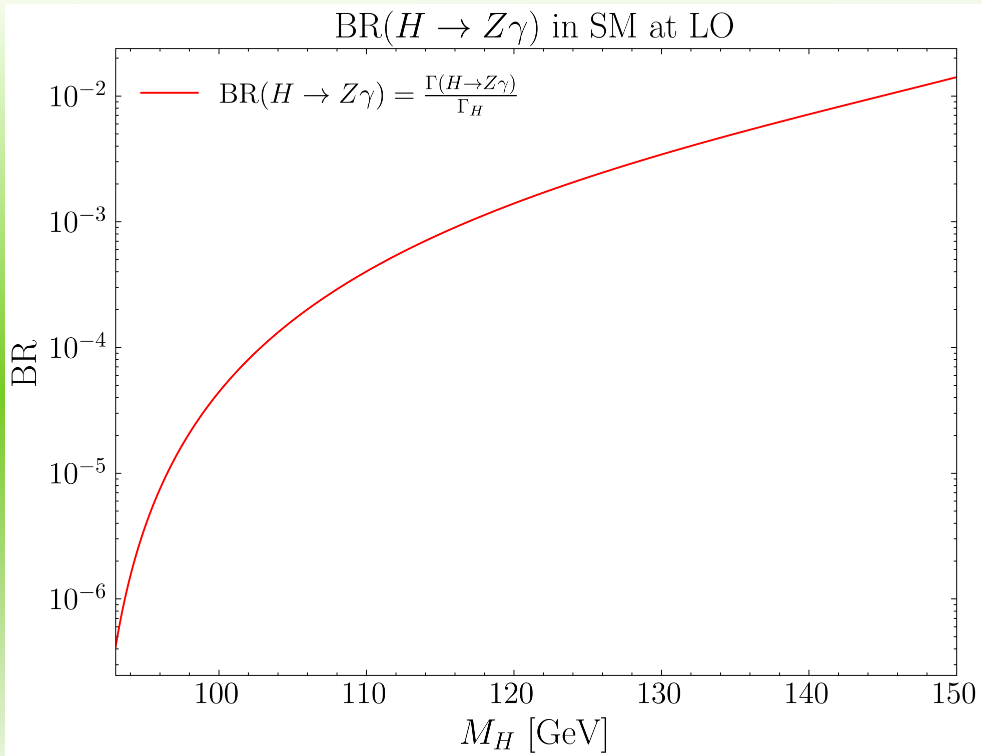
$$\Gamma\left(H \to Z\gamma\right) = \frac{M_H^3}{32\pi}\left(1 - \frac{M_Z^2}{M_H^2}\right)^3 |F_4|^2. \quad \textbf{(13)}$$

PV Functions

$$i\pi^2 B_0\left(p^2, M_W^2, M_W^2\right) = \mu^{4-d}\int \frac{d^d\ell}{(2\pi)^d}\frac{1}{D_0 D_i} \quad \textbf{(14)}$$

$$i\pi^2 C_0\left(p_1^2, p_2^2, (p_1+p_2)^2; m_1, m_2, m_3\right) = \mu^{4-d}\int \frac{d^d\ell}{(2\pi)^d}\frac{1}{D_0 D_1 D_2}. \quad \textbf{(15)}$$

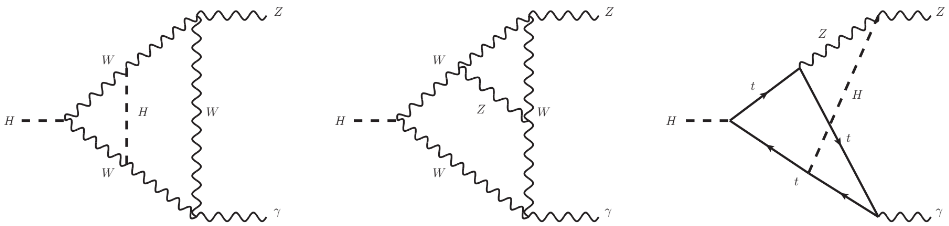
$$F_4 = \frac{-i\pi^2 c_W e^3}{M_W^2 s_W^2 \left(M_H^2 - M_Z^2\right)^2} \left\{ M_Z^2 \left[M_H^2 \left(M_Z^2 - 2M_W^2 \right) + 2M_W^2 \left(M_Z^2 - 6M_W^2 \right) \right] \right.$$
$$\times \left[B_0 \left(M_H^2, M_W^2, M_W^2 \right) - B_0 \left(M_Z^2, M_W^2, M_W^2 \right) \right]$$
$$- 2M_W^2 \left(M_H^2 - M_Z^2 \right) \left[M_H^2 \left(M_Z^2 - 6M_W^2 \right) + 12M_W^4 + 6M_W^2 M_Z^2 - 2M_Z^4 \right]$$
$$\left. \times C_0 \left(0, M_H^2, M_Z^2, M_W^2, M_W^2, M_W^2 \right) \right\} . \quad \textbf{(16)}$$

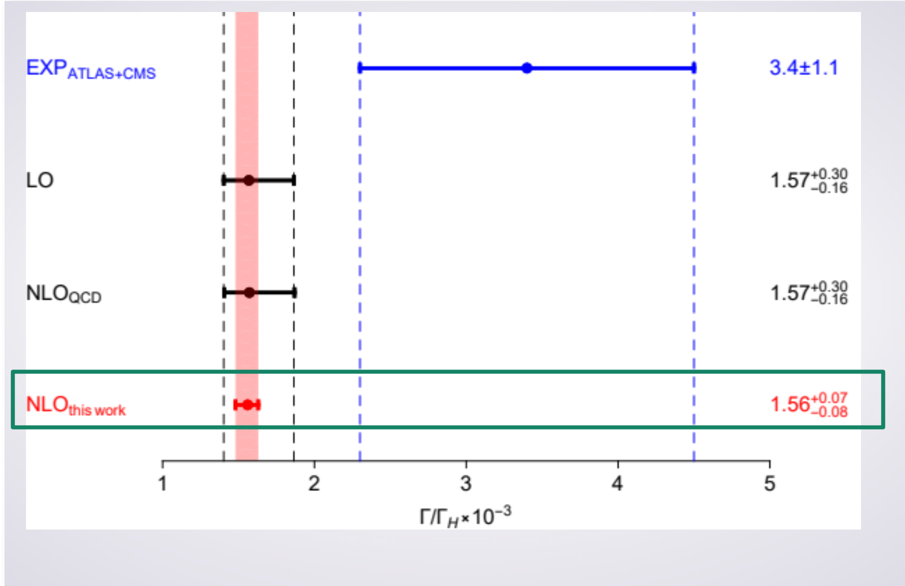


$$\Gamma\left(H \to Z\gamma\right) = 8.33 \text{ KeV},$$
$$\text{BR}\left(H \to Z\gamma\right) = 2.25 \times 10^{-3}.$$

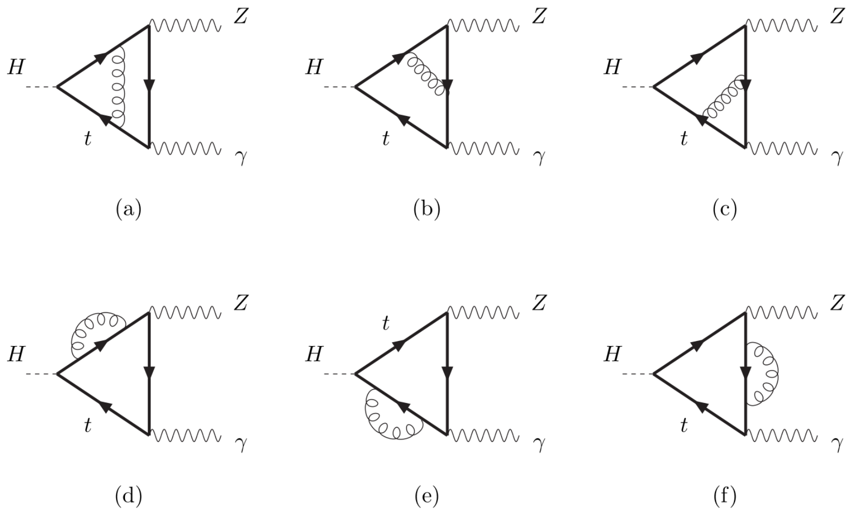
Prospects

Beyond LO



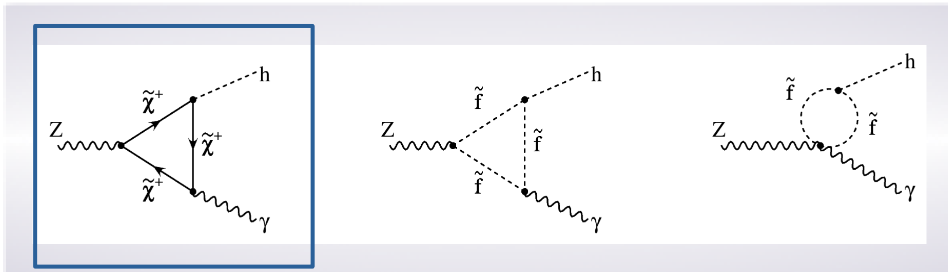


Z. Chen, L. Chen, C. Qiao, R. Zhu.Phys.Rev.D 110 (2024) 5, L051301, 2024.



R. Bonciani, V. Del Duca, H. Frellesvig, J. M. Henn, F. Moriello, V. A. Smirnov. JHEP 08 (2015) 108.

SUSY predictions



A. Djouadi, V. Driesen, W. Hollik and A. Kraft. Eur.Phys.J.C1:163-175,1998

Many Thanks For Your Attention!

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