广州大学 GUANGZHOU UNIVERSITY

HIGGS POTENTIAL 2024
HIGGS POTENTIAL AND BSM OPPORTUNITIES

Electroweak corrections to the rare decay process $H \to Z\gamma$

Zi-Qiang Chen

In collaboration with Long-Bin Chen, Cong-Feng Qiao, Ruilin Zhu

Phy. Rev. D 110, L051301 (2024) [2404.11441]

Dec 20th, 2024, Hefei

OutLine

- Introduction
- Some technical details
- Numerical results
- Summary

01

Introduction

- Experimental evidence
- Previous calculations

Experimental evidence

3.4 σ

Evidence for the Higgs Boson Decay to a Z Boson and a Photon at the LHC

ATLAS and CMS Collaborations • Georges Aad (Marseille, CPPM) Show All(5264)

Sep 7, 2023

32 pages

Published in: *Phys.Rev.Lett.* 132 (2024) 2, 021803

Published: Jan 11, 2024

e-Print: 2309.03501 [hep-ex]

DOI: 10.1103/PhysRevLett.132.021803 (publication)

PDG: $H \to Z\gamma$ Show All(2)

Report number: CERN-EP-2023-157

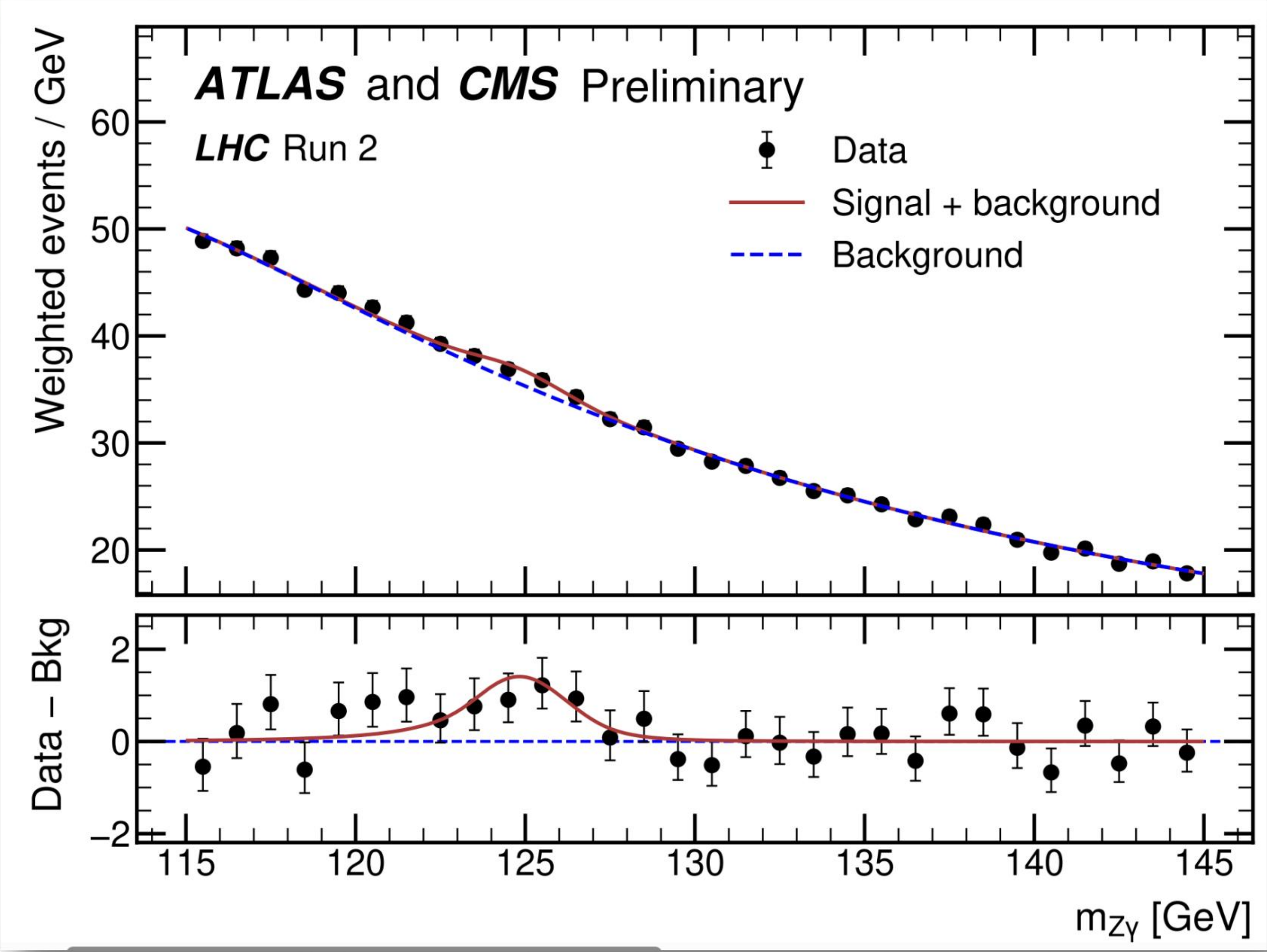
Experiments: CERN-LHC-ATLAS, CERN-LHC-CMS

- Evidence (2309.03501) obtained from a combination of ATLAS (2005.05382) and CMS (2204.12945).

- Previous searches: 1806.05996, 1402.3051, 1307.5515, 0806.0611 ...

ATLAS and CMS, PRL 132 (2024) 021803 [2309.03501]

Experimental evidence



ATLAS and CMS, PRL 132 (2024) 021803 [2309.03501]

Branching Ratio:

$$(3.4 \pm 1.1) \times 10^{-3}$$

Signal strength:

$$\mu = 2.2 \pm 0.7$$

$$(\mu = \sigma_{\mathrm{exp}}/\sigma_{\mathrm{SM}})$$

Motivation: provide SM prediction as precise as possible.

Previous calculations

- Leading order:

J.R. Ellis, M. K. Gaillard, D. V. Nanopoulos, Nucl. Phys. B 106 (1976) 292

R.N. Cahn, M. S. Chanowitz, N. Fleishon, Phys. Lett. B 82 (1979) 113-116

- QCD corrections:

M. Spira, A. Djouadi, P. M. Zerwas, Phys. Lett. B 276 (1992) 350-353

T. Gehrmann, S. Guns, D. Kara, JHEP 09 (2015) 038 [1505.00561]

R. Bonciani, V. D. Duca, H. Frellesvig, et al, JHEP 08 (2015) 108 [1505.00567]

Previous calculations

Why NLO EW?

The QCD corrections amount to 0.22% of the LO width. It is resonable to expect that the EW corrections will yield a larger contribution.

The theoretical uncertainty has not been fully discussed

1505.00561:

$$\Gamma = \frac{G_F^2\,\alpha\,m_W^2}{4\,m_H^3\left(m_H^2 - m_Z^2\right)}\,|A|^2$$

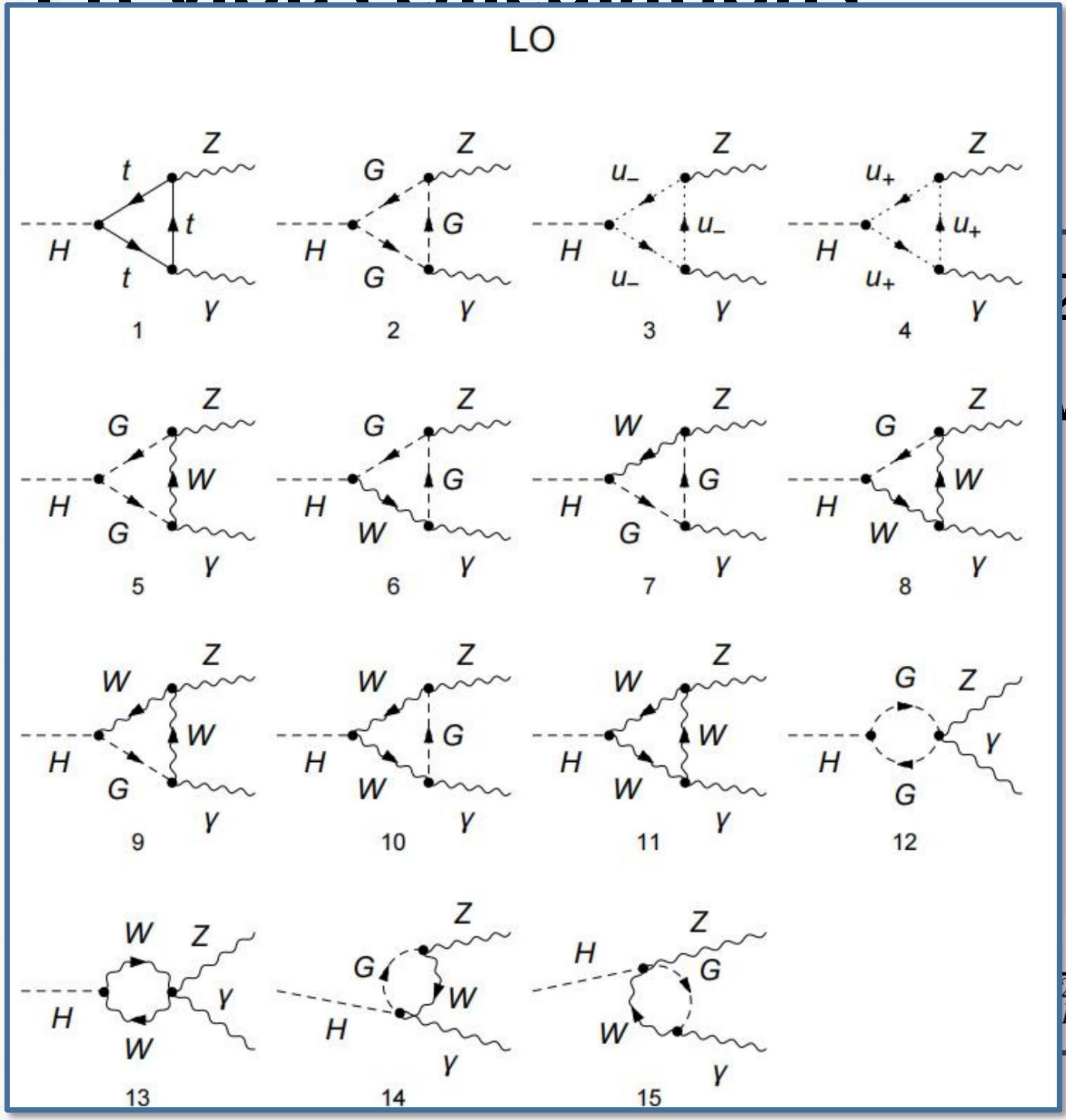
7.09 keV

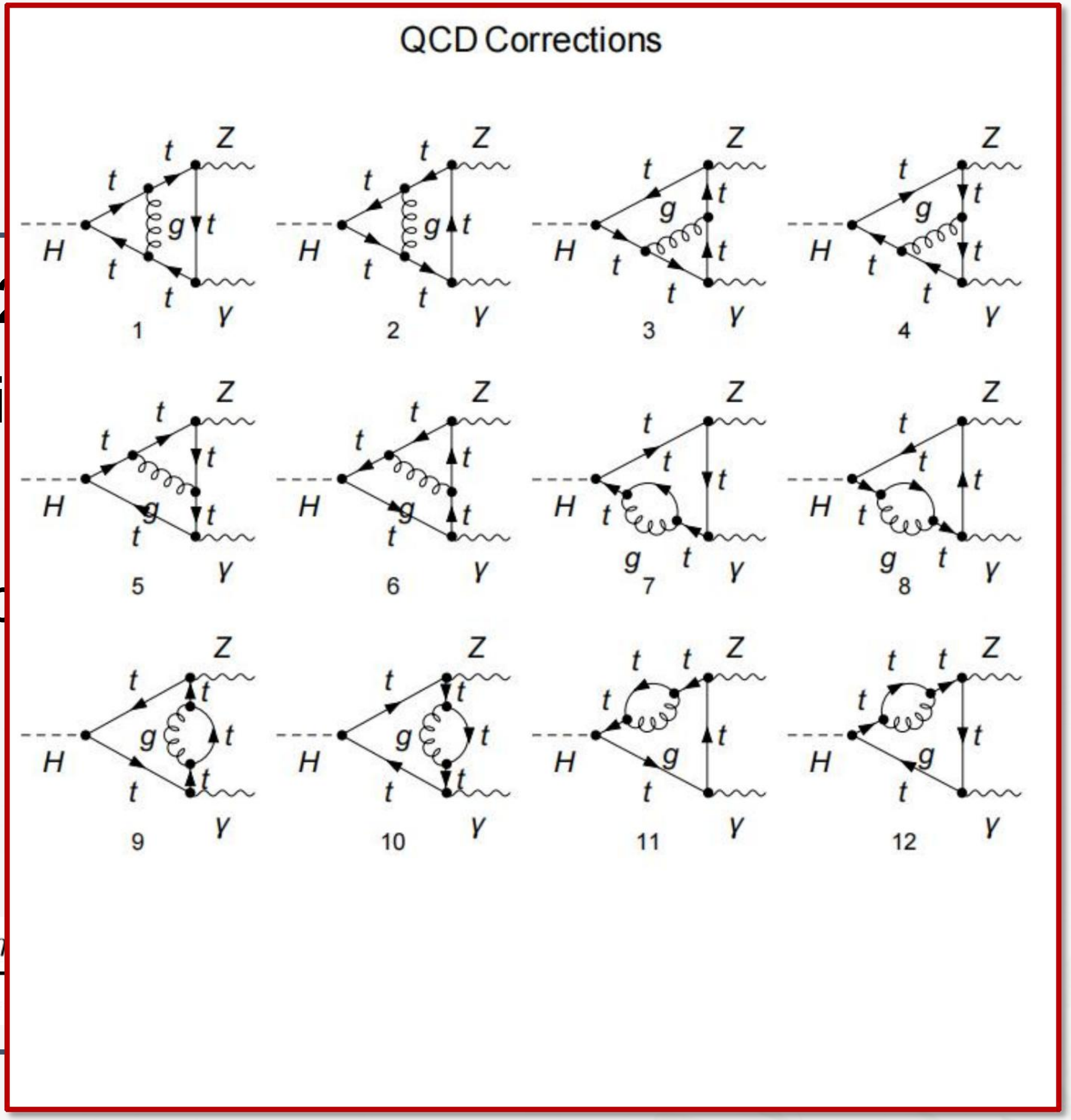
1505.00567:

$$\Gamma_{H\to Z\gamma} = \frac{G_F\alpha^2}{64\sqrt{2}\pi^3 m_H}\,\frac{(m_H^2 - m_Z^2)^3}{m_H^2}\,|\mathcal{F}|^2$$

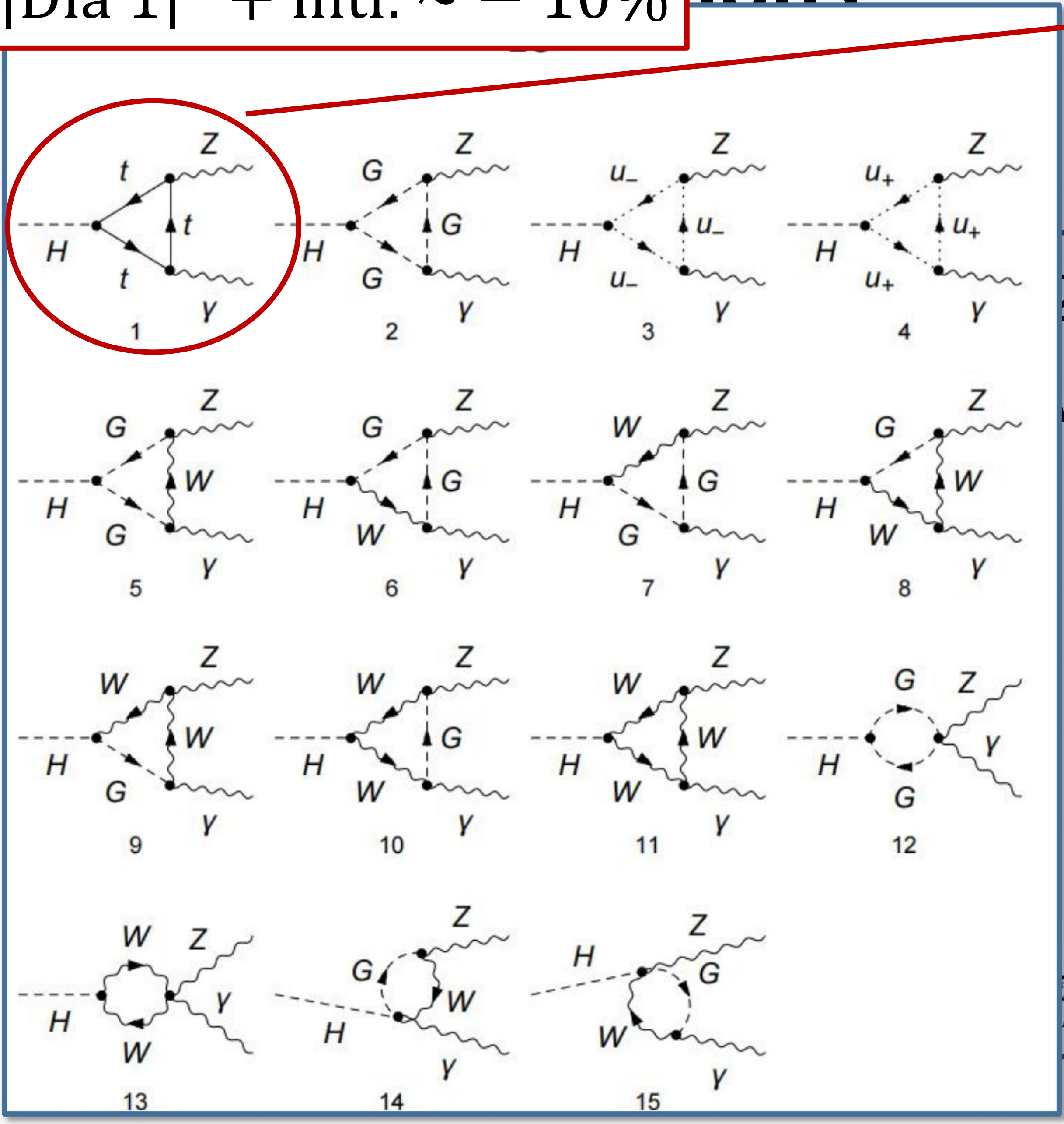
6.68 keV

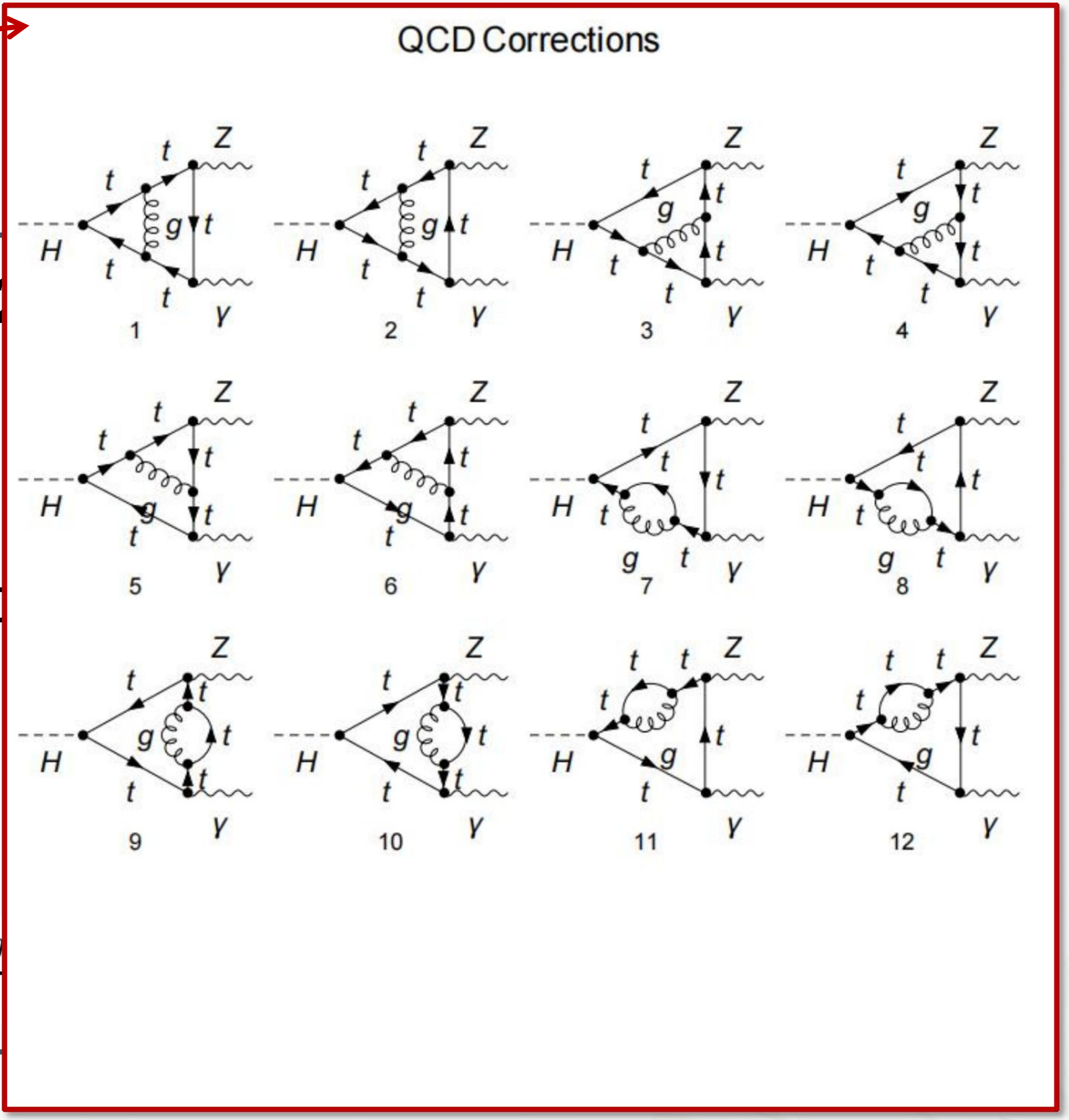
Previous calculations





$|\mathrm{Dia}\ 1|^2 + \mathrm{intf.} \sim -10\%$





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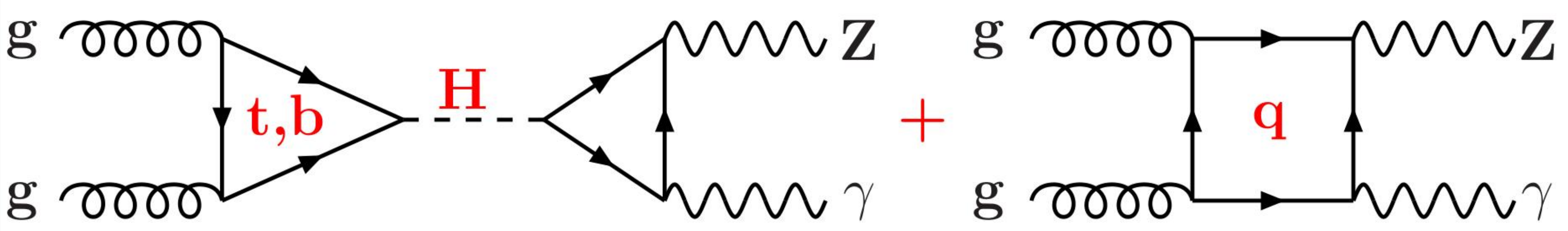
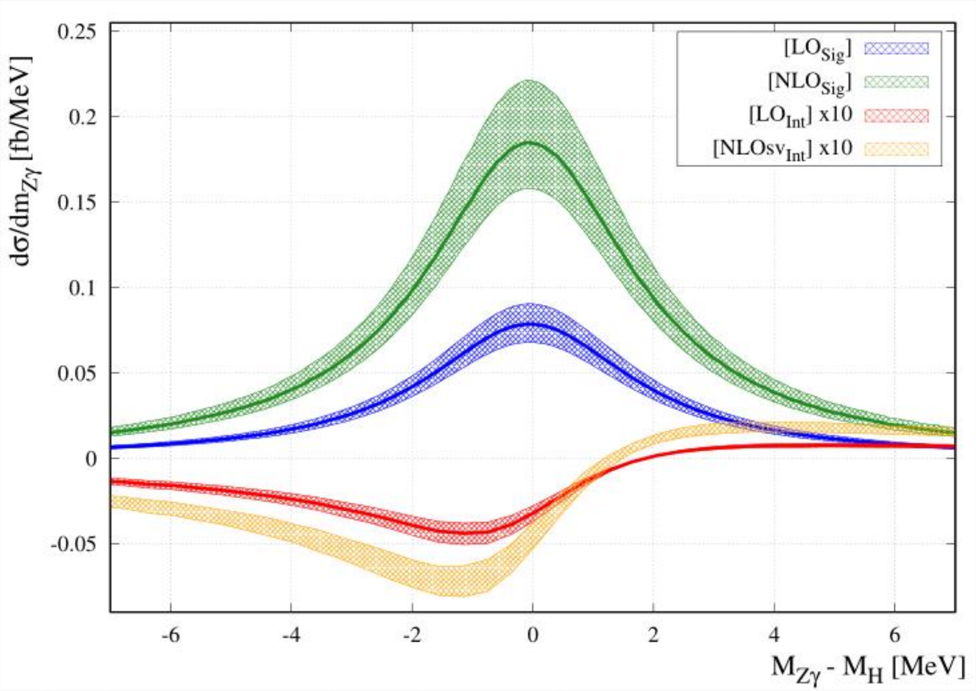
Previous calculations

- Signal background interference: F. Buccioni, F. Devoto, A. Djouadi, J. Ellis, et. al, Phys. Lett. B 851 (2024) 138596 [2312.12384]





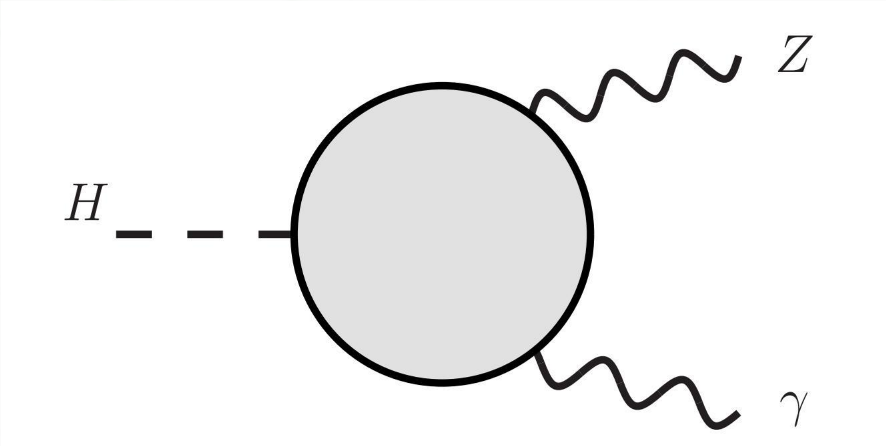
Interference effect (Higgs resonance & nonresonance) is negative and small (about -3%)...

02

Some technical details

- Lorentz structure
- Feynman integral
- Electroweak coupling

Lorentz structure



$$H \to Z(p_1)\gamma(p_2)$$

$$\mathcal{M} = T^{\mu\nu}\varepsilon_\mu^*(p_1)\varepsilon_\nu^*(p_2)$$

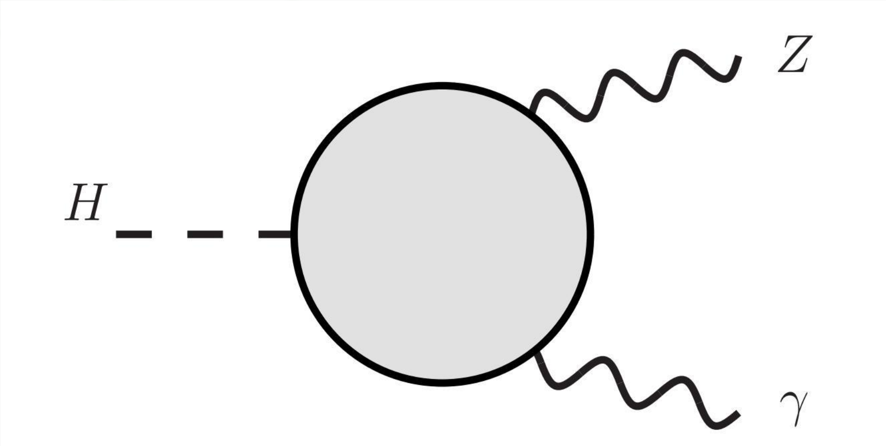
$$T^{\mu\nu} = T_1 p_1^\mu p_1^\nu + T_2 p_2^\mu p_2^\nu + T_3 p_1^\mu p_2^\nu + T_4 p_2^\mu p_1^\nu + T_5 g^{\mu\nu} + T_6 \epsilon^{\mu\nu\rho\sigma} p_{1\rho} p_{2\sigma}$$

Constraint:

$T_1 = 0, T_5 = -p_1 \cdot p_2\, T_4$ (Gauge invariance).

T_2, T_3, T_6 do not contribute to $|\mathcal{M}|^2$.

Lorentz structure



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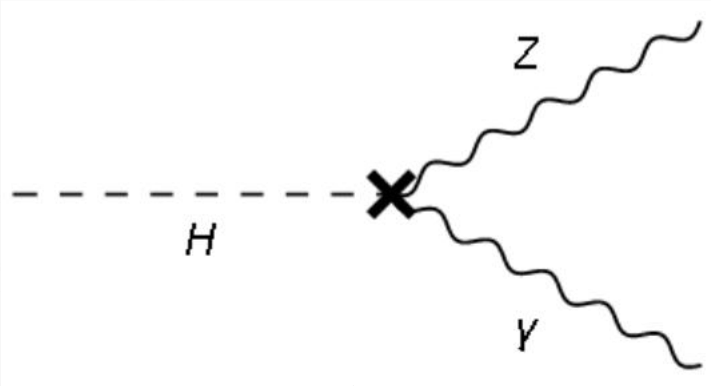
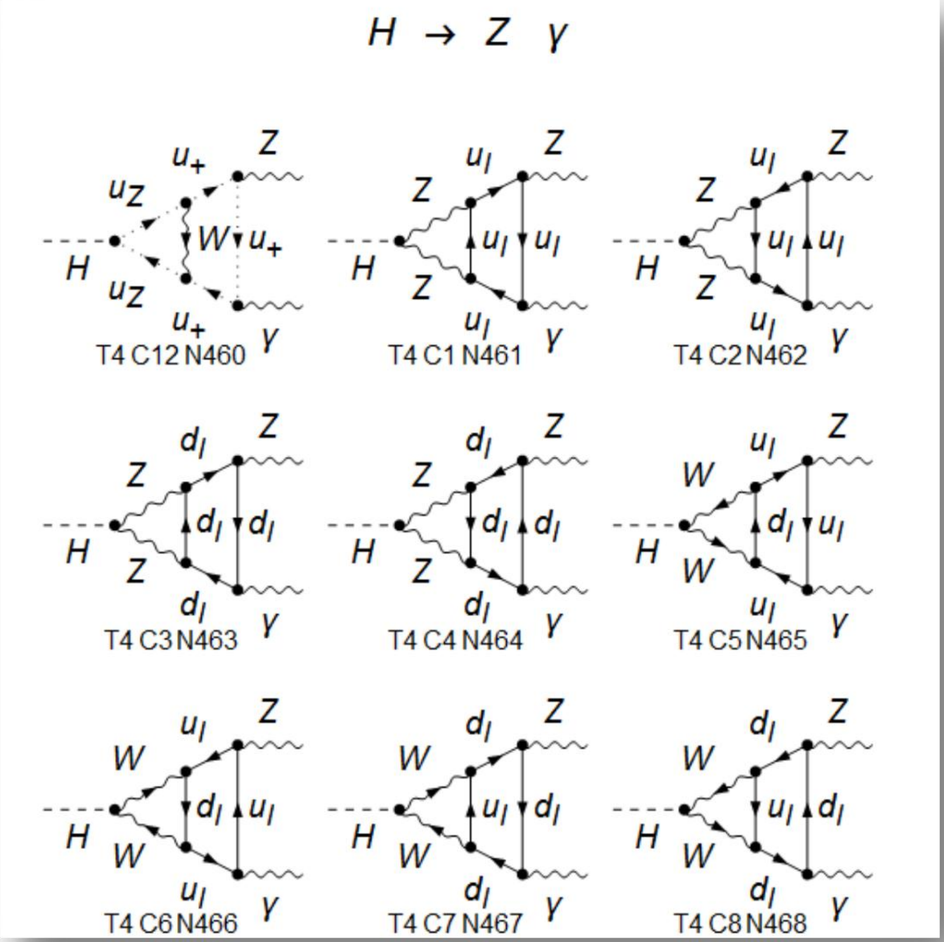
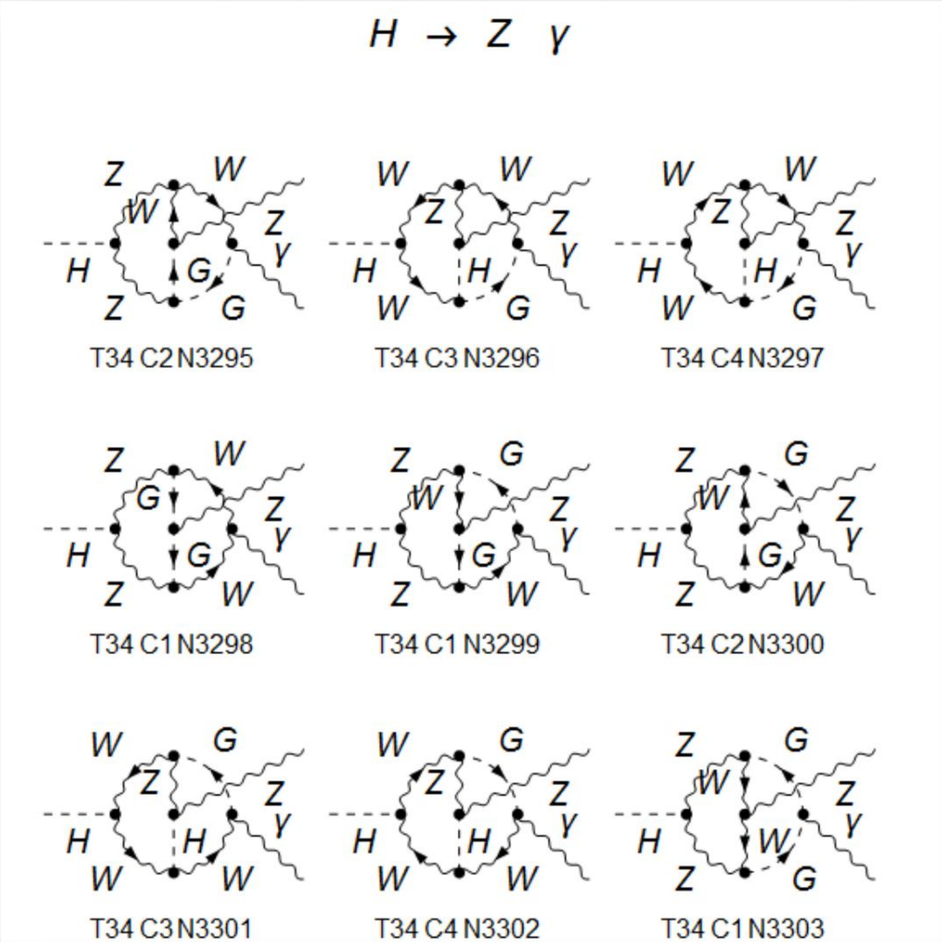


Do not need in the calculation of T_4.

Feynman integrals

About 5000 Feynman diagrams (Feynman gauge)



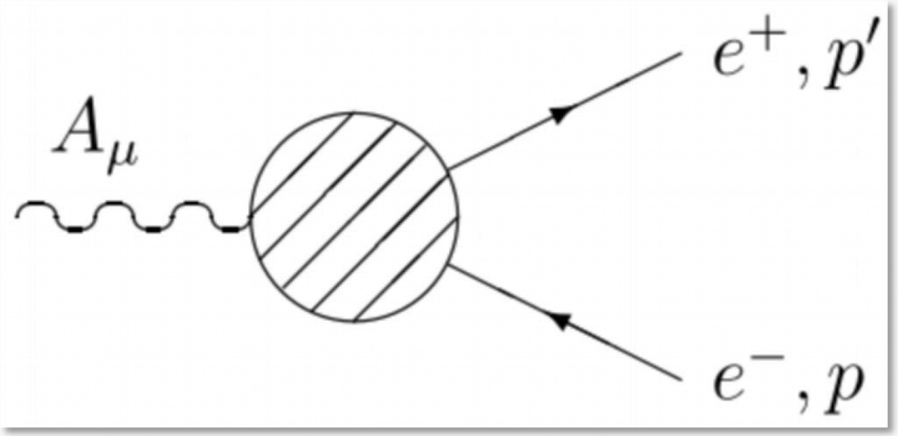


FeynArts
↓
FeynCalc
↓
FIRE
↓
AMFlow

Electroweak coupling

We work in the on-shell renormalization scheme.

- $\alpha(0) \approx 1/137$, $ee\gamma$-coupling in the zero momentum transfer limit ($p' = p$)



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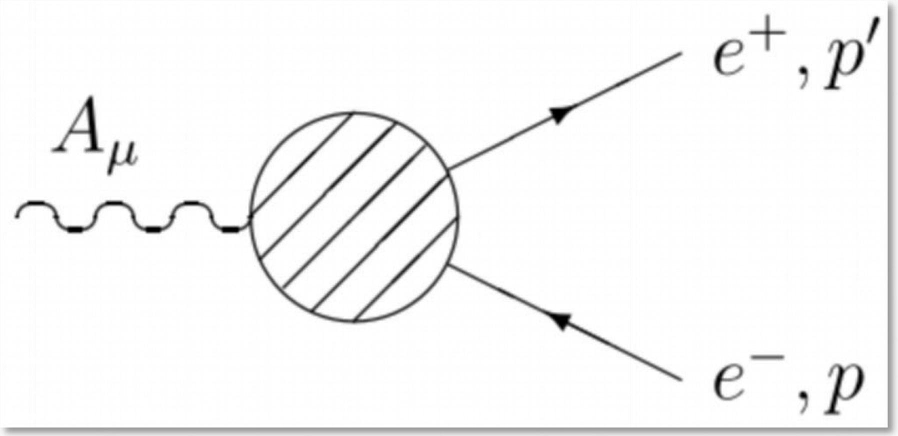

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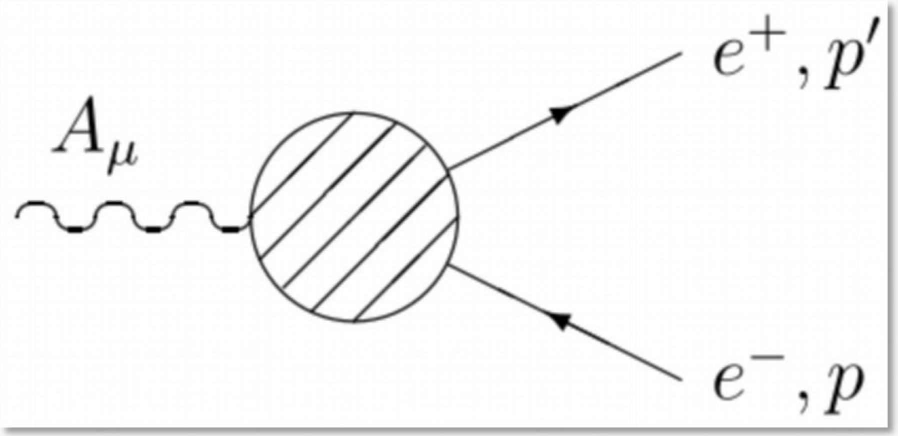

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- $\alpha_{G_\mu} = \sqrt{2} G_\mu M_W^2/\pi(1 - M_W^2/M_Z^2) \approx 1/132$, defined through muon decay, $\alpha_{G_\mu} = \alpha(0)\left(1 + \Delta r^{(1)}\right)$.

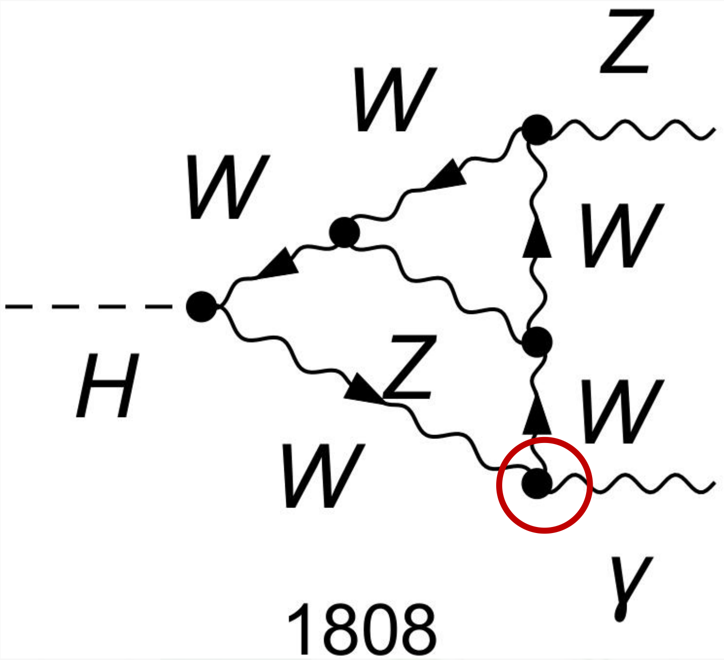
Electroweak coupling

We work in the on-shell renormalization scheme.

We use five different electroweak coupling schemes:

1. $\alpha(0)$ scheme: all to $\alpha(0)$;
2. $\alpha(M_Z^2)$ scheme: all to $\alpha(M_Z^2)$;
3. α_{G_μ} scheme: all to α_{G_μ};
4. mixed 1: the one connecting to the external photon to $\alpha(0)$, others to $\alpha(M_Z^2)$;
5. mixed 1: the one connecting to the external photon to $\alpha(0)$, others to α_{G_μ}.

no $\ln(m_f)$ terms



03

Numerical results

- Numerical results
- Other potential uncertainty sources

Numerical results

TABLE I. The LO and NLO decay widths of $H \to Z\gamma$ under different coupling schemes. The relative EW corrections are also given.

Scheme	Input parameters	Γ^{LO} (keV)	$\Gamma_{\mathrm{EW}}^{\mathrm{NLO}}$ (keV)	δ_{EW} (%)
$\alpha(0)$	$\alpha(0)$, m_f	5.920	6.234	5.3
$\alpha(m_Z^2)$	$\alpha(m_Z^2)$, m_f	7.273	6.303	−13
G_μ	G_μ, m_f	6.599	6.343	−3.9
Mixed 1	$\alpha(0)$, $\alpha(m_Z^2)$	6.791	6.316	−7.0
Mixed 2	$\alpha(0)$, G_μ	6.364	6.316	−0.75

$$\Gamma^{\mathrm{LO}} = 6.364^{+0.909}_{-0.444}\ \mathrm{keV}, \Gamma_{\mathrm{EW}}^{\mathrm{NLO}} = 6.316^{+0.027}_{-0.082}\ \mathrm{keV}.$$

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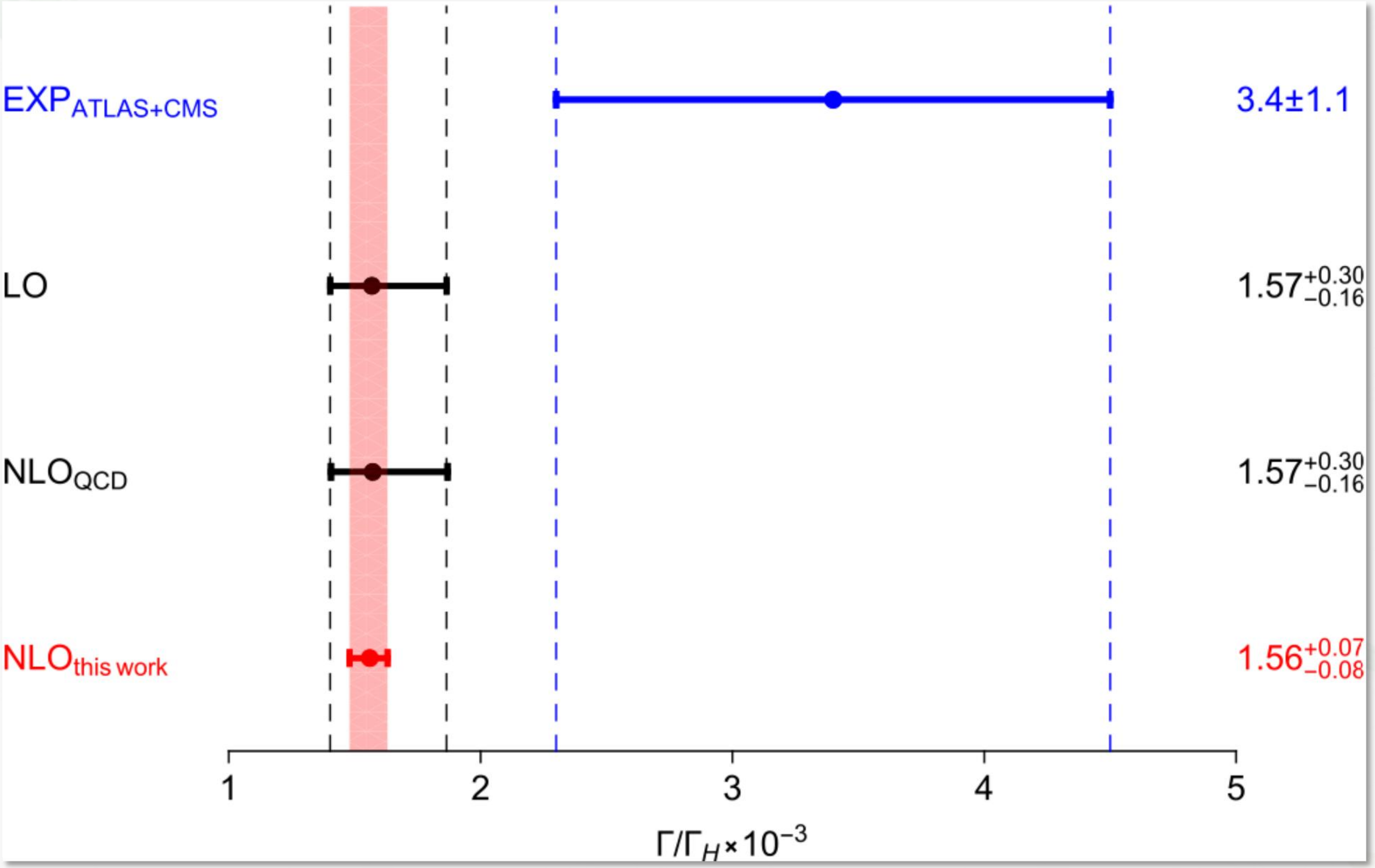
The EW corrections

- more significant than the QCD corrections
- greatly suppress the theoretical uncertainty

Numerical results

Combining EW, QCD, b-mass corrections: $\Gamma^{H\to Z\gamma} = 6.348^{+0.028}_{-0.085}$ keV

Branching ratio (with SM total width):



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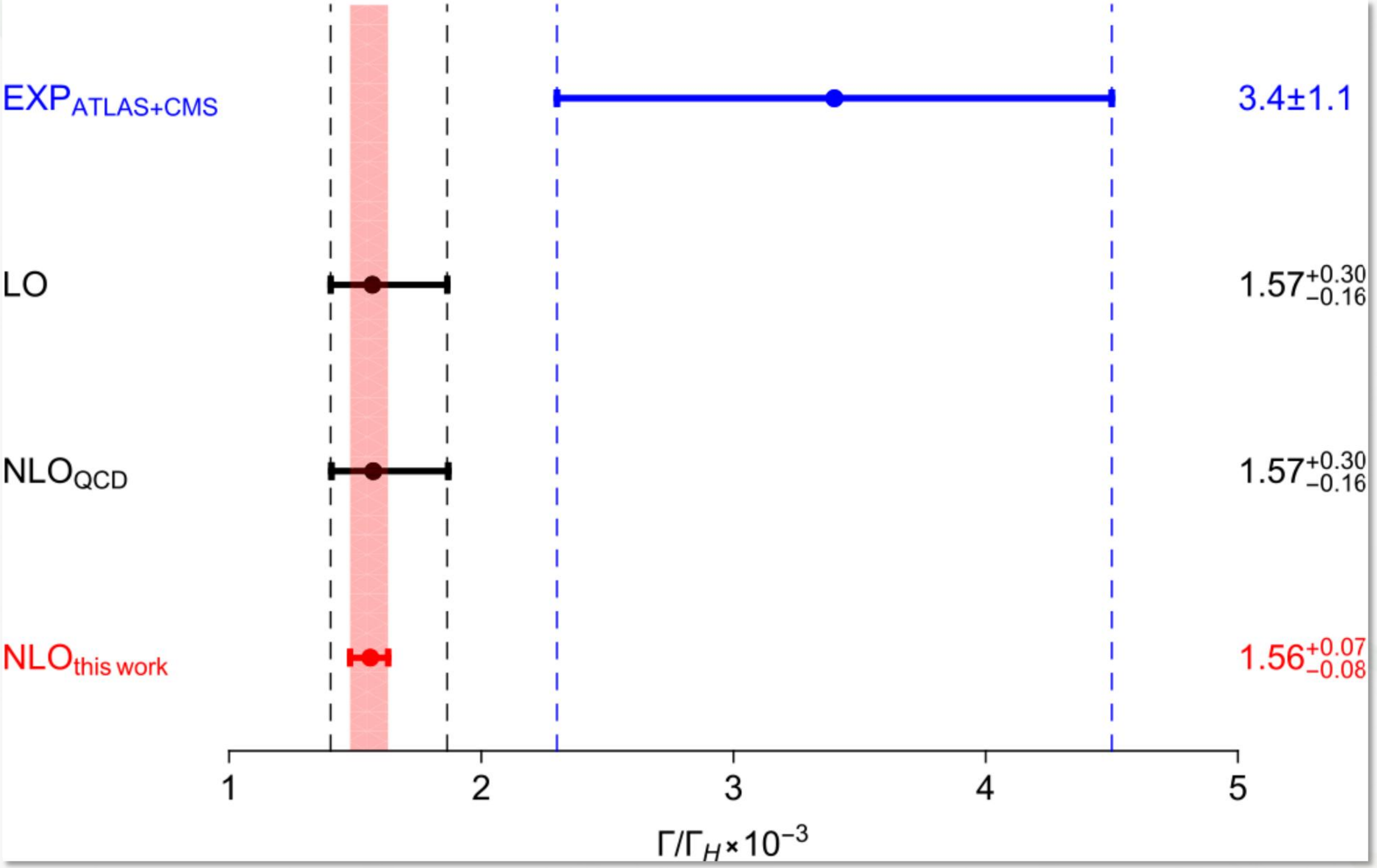
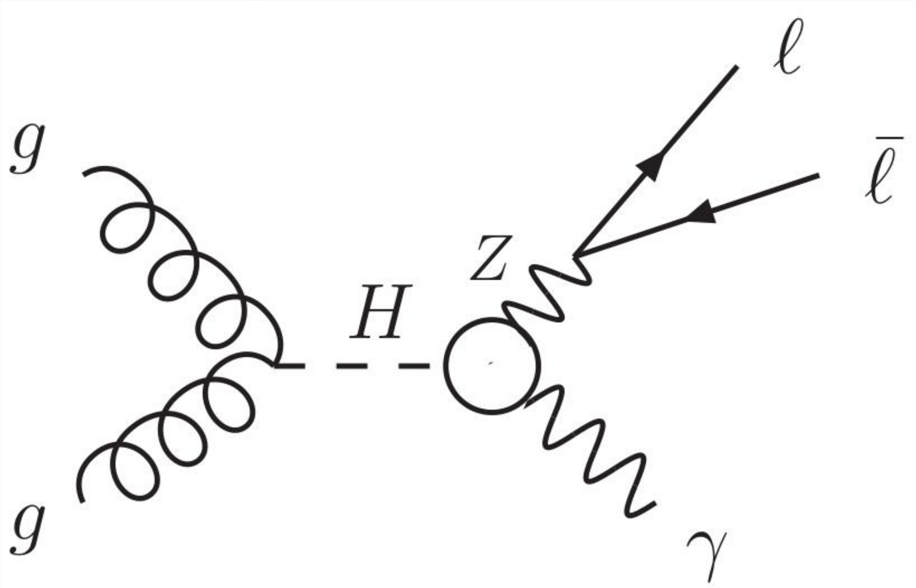


The EW corrections exacerbate the tension.

Other potential uncertainty sources

Finite width effect / proper definition of $H \to Z\gamma$ —— subtle in theory



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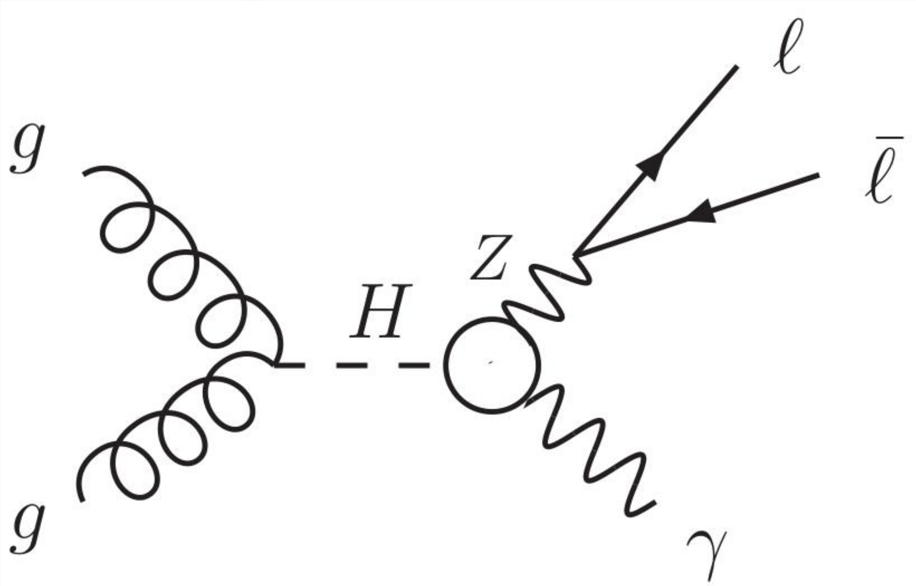

phenomenologically:

- H-width effect: about -3% [PLB 851 (2024) 138596]
- Z-width effect: may reach 10% [PLB 727 (2013) 424, PRD 89 (2014) 3, 033013]

larger than quick estimation $\mathcal{O}(\Gamma/M)$

Alternative way: study the $H \to \ell\bar{\ell}\gamma$ process, experimentally and theoretically.

04

Summary

- We obtain the most accurate prediction $\mathrm{Br}(H \to Z\gamma) = 1.56^{+0.07}_{-0.08} \times 10^{-3}$ by including the NLO EW corrections.
- The EW corrections are more significant than the QCD corrections, and can greatly suppress the theoretical uncertainty.
- The state-of-the-art SM prediction is significantly lower than the measured value. This could probably be attributed to the underestimated experimental uncertainties or the new physics beyond the SM.

Cross check:
W. L. Sang, F. Feng, Y. Jia, Phys. Rev. D 110 (2024) 5, L051302 [2405.03464]

Thank You!