New Physics Through Polarized Observables

SILAFAE 2024

A. I. Hernández-Juárez,
alan.hernandez@cuautitlan.unam.mx
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H* evidence at the LHC

nature physics
ARTICLES
https://doi.org/10.1038/s41567-022-01682-0
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OPEN

Measurement of the Higgs boson width and evidence of its off-shell contributions to ZZ production

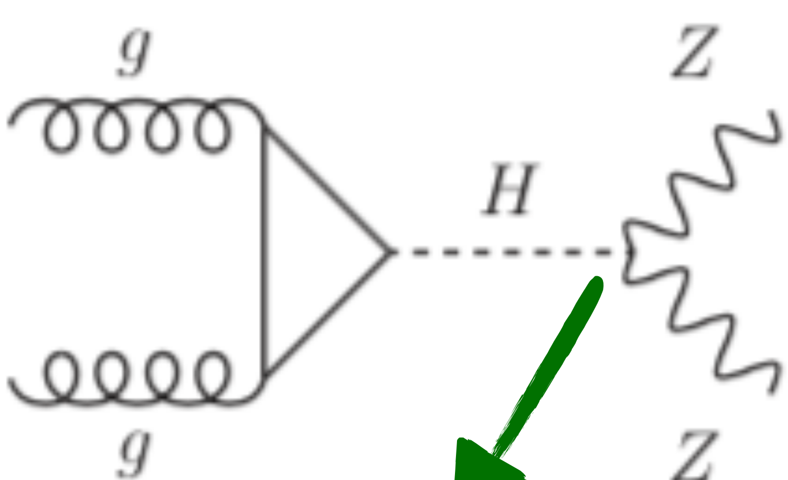
The CMS Collaboration*✉

ATLAS EXPERIMENT
Submitted to: Phys. Lett. B.
CERN-EP-2023-03
5th April 2023

Evidence of off-shell Higgs boson production from ZZ leptonic decay channels and constraints on its total width with the ATLAS detector

The ATLAS Collaboration

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \textbf{MeV}$$

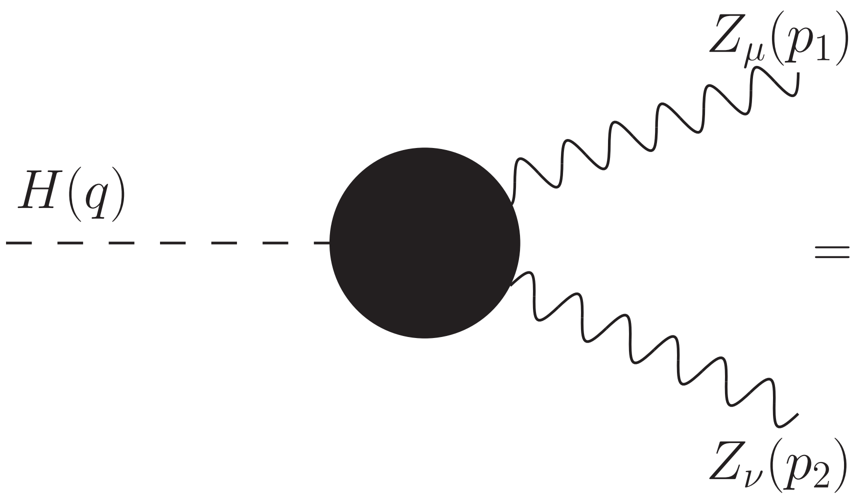


$$m_H < 2m_Z$$

The Higgs boson must to be off-shell to produce two on-shell Z bosons

HZZ vertex function

Anomalous couplings for the ZZH vertex can be also induced



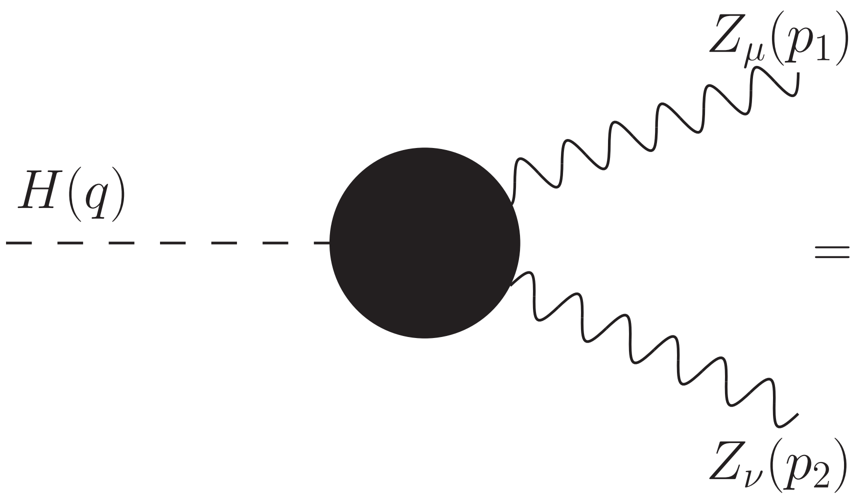
$= i\frac{g}{c_W} m_Z \Gamma^{ZZH}_{\mu\nu}(p_1^2, p_2^2, q^2)$

h_i^V in terms of the anomalous couplings

$$\Gamma^{ZZH}_{\mu\nu} = h_1^V g_{\mu\nu} + \frac{h_2^V}{m_Z^2} p_{1\nu} p_{2\mu} + \frac{h_3^V}{m_Z^2} \epsilon_{\mu\nu\alpha\beta} p_1^\alpha p_2^\beta,$$

HZZ vertex function

Anomalous couplings for the ZZH vertex can also be induced



$$= i\frac{g}{c_W} m_Z \Gamma^{ZZH}_{\mu\nu}(p_1^2, p_2^2, q^2)$$

Similar for the $HW^{\pm}W^{\mp}$ case

h_i^V in terms of the anomalous couplings

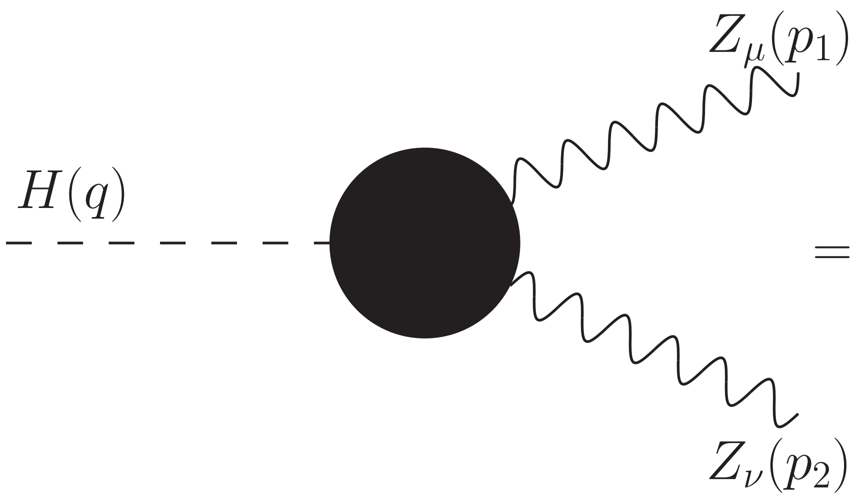
$$\Gamma^{ZZH}_{\mu\nu} = h_1^V g_{\mu\nu} + \frac{h_2^V}{m_Z^2} p_{1\nu} p_{2\mu} + \frac{h_3^V}{m_Z^2} \epsilon_{\mu\nu\alpha\beta} p_1^\alpha p_2^\beta,$$

Induced at one-loop level in the SM.

¿Induced at three-loop level in the SM?

HZZ vertex function

Anomalous couplings for the ZZH vertex can be also induced



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Similar for the $HW^\pm W^\mp$ case

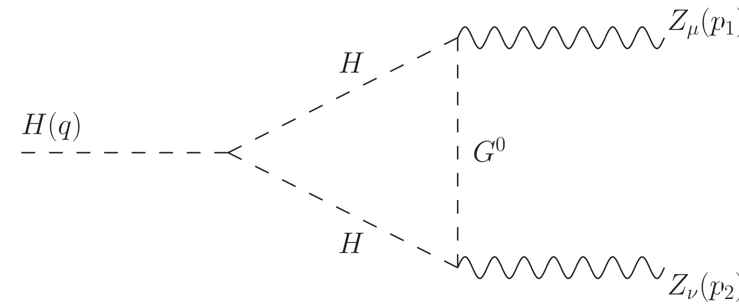
h_i^V in terms of the anomalous couplings

$$\Gamma^{ZZH}_{\mu\nu} = h_1^V g_{\mu\nu} + \frac{h_2^V}{m_Z^2} p_{1\nu} p_{2\mu} + \frac{h_3^V}{m_Z^2} \epsilon_{\mu\nu\alpha\beta} p_1^\alpha p_2^\beta,$$

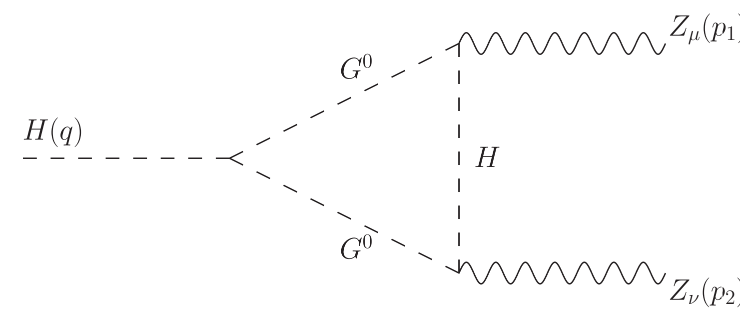
CP-conserving

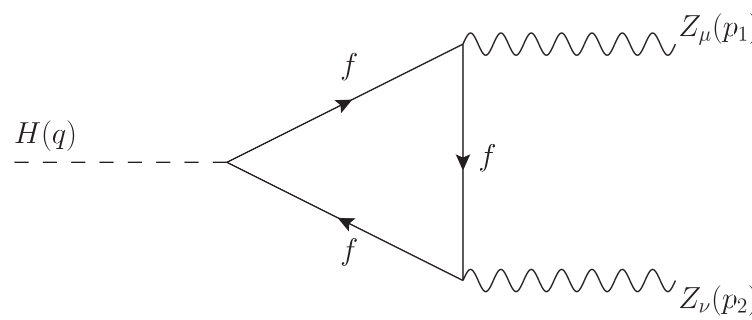
CP-violating

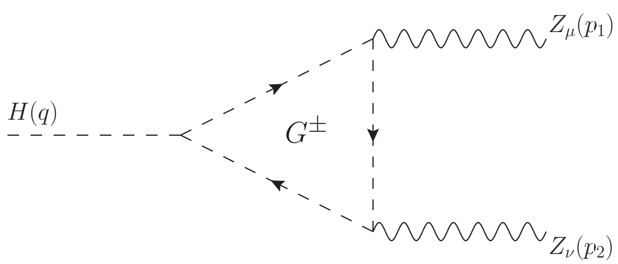
One-loop contributions

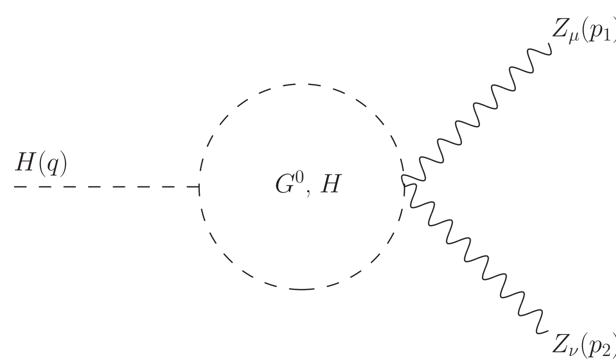


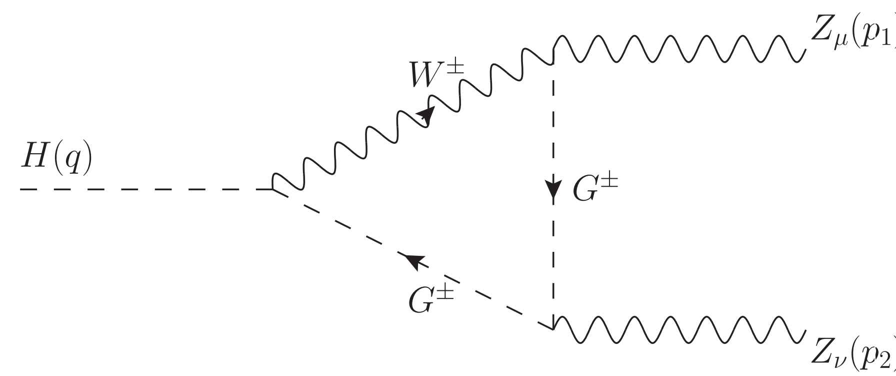
ZZH in the SM

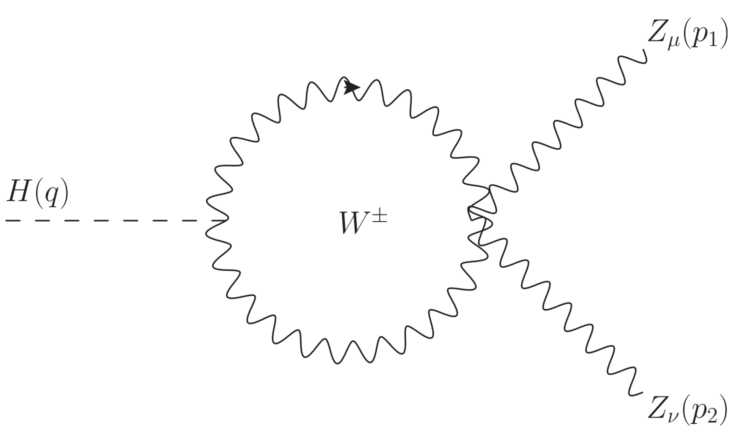


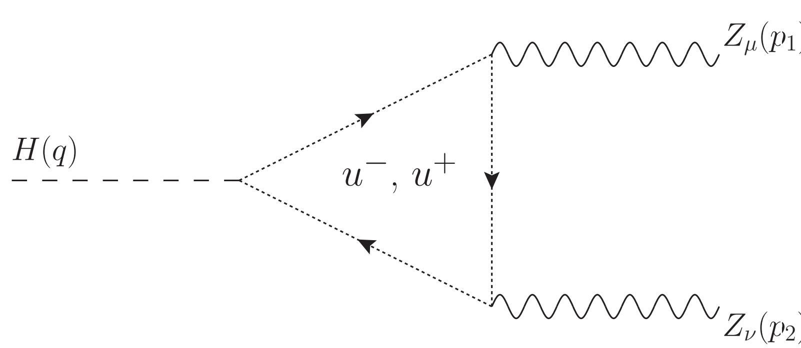


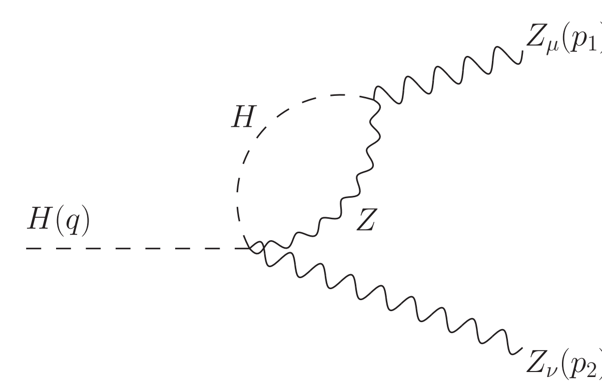








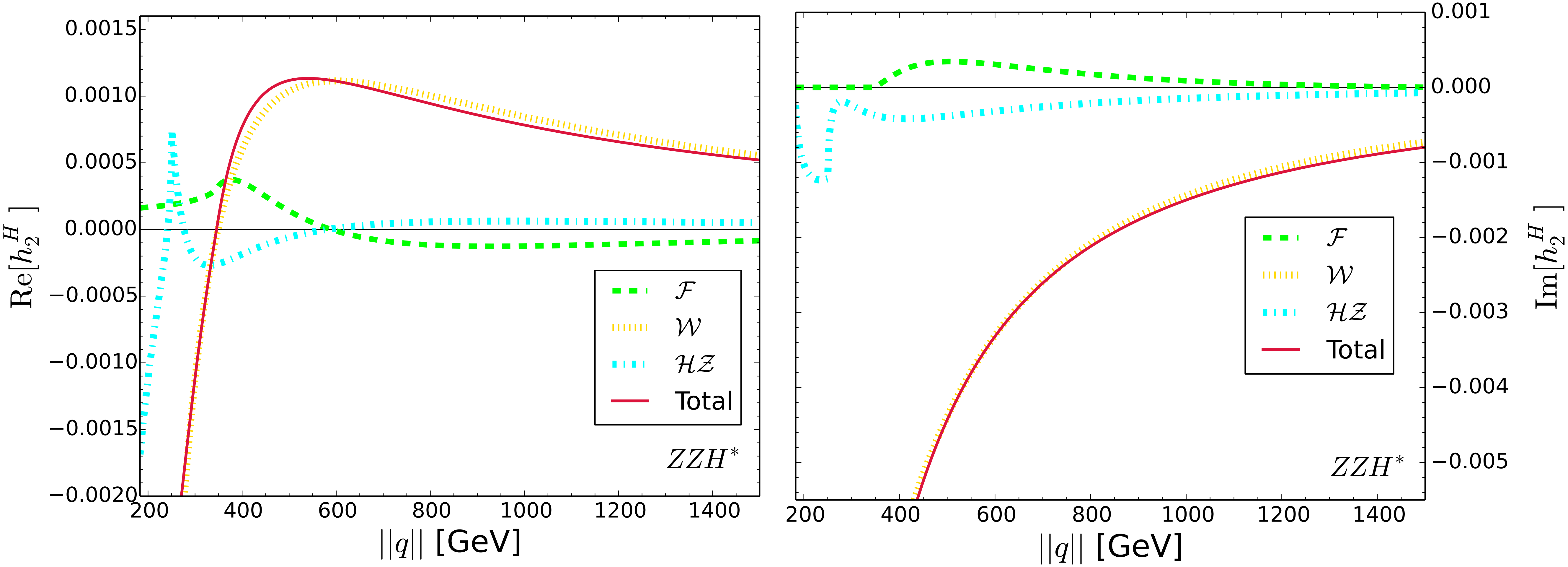




More diagrams…..

ZZH^* in the SM

The from factor h_2^H is complex



A. I. Hernández-Juárez, G. Tavares-Velasco, and A. Fernández-Téllez, New evaluation of the HZZ coupling: Direct bounds on anomalous contributions and CP-violating effects via a new asymmetry, Phys. Rev. D 107, 115031 (2023), arXiv:2301.13127 [hep-ph].

Unpolarized decay

We considere the anomalous couplings as complex → $h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$

We calculate the partial width

$$\Gamma_{H^* \to ZZ}$$

$$\begin{aligned}\Gamma_{H^*\to ZZ} =& \frac{g^2\sqrt{q^2-4m_Z^2}}{512\pi q^2 c_W^2 m_Z^6}\Big\{4q^6 m_Z^2\Big(\left(\mathrm{Im}[h_1^H]-2\mathrm{Im}[h_2^H]\right)\mathrm{Im}[h_2^H]+\left(\mathrm{Re}[h_1^H]-2\mathrm{Re}[h_2^H]\right)\mathrm{Re}[h_2^H]\Big)\\ &+4q^4m_Z^4\Big(2\left(2\mathrm{Im}[h_2^H]^2+\mathrm{Im}[h_3^H]^2+2\mathrm{Re}[h_2^H]^2+\mathrm{Re}[h_3^H]^2\right)+\mathrm{Im}[h_1^H]^2-6\mathrm{Im}[h_2^H]\mathrm{Im}[h_1^H]\\ &+\mathrm{Re}[h_1^H]^2-6\mathrm{Re}[h_1^H]\mathrm{Re}[h_2^H]\Big)-16q^2m_Z^6\Big(2\left(\mathrm{Im}[h_3^H]^2+\mathrm{Re}[h_3^H]^2\right)+\mathrm{Im}[h_1^H]^2-2\mathrm{Im}[h_2^H]\mathrm{Im}[h_1^H]\\ &+\mathrm{Re}[h_1^H]^2-2\mathrm{Re}[h_1^H]\mathrm{Re}[h_2^H]\Big)+48m_Z^8\left(\mathrm{Im}[h_1^H]^2+\mathrm{Re}[h_1^H]^2\right)+q^8\left(\mathrm{Im}[h_2^H]^2+\mathrm{Re}[h_2^H]^2\right)\Big\},\end{aligned} \quad ($$

$$\Gamma^{\mathrm{Tree}}_{H^*\to ZZ} = \frac{g^2\sqrt{q^2-4m_Z^2}}{512\pi c_W^2 m_Z^6}\left(4q^2m_Z^4-16m_Z^6+48\frac{m_Z^8}{q^2}\right).$$

$$\mathscr{R} = \frac{\Gamma_{H^*\to ZZ}}{\Gamma^{Tree}_{H^*\to ZZ}}.$$

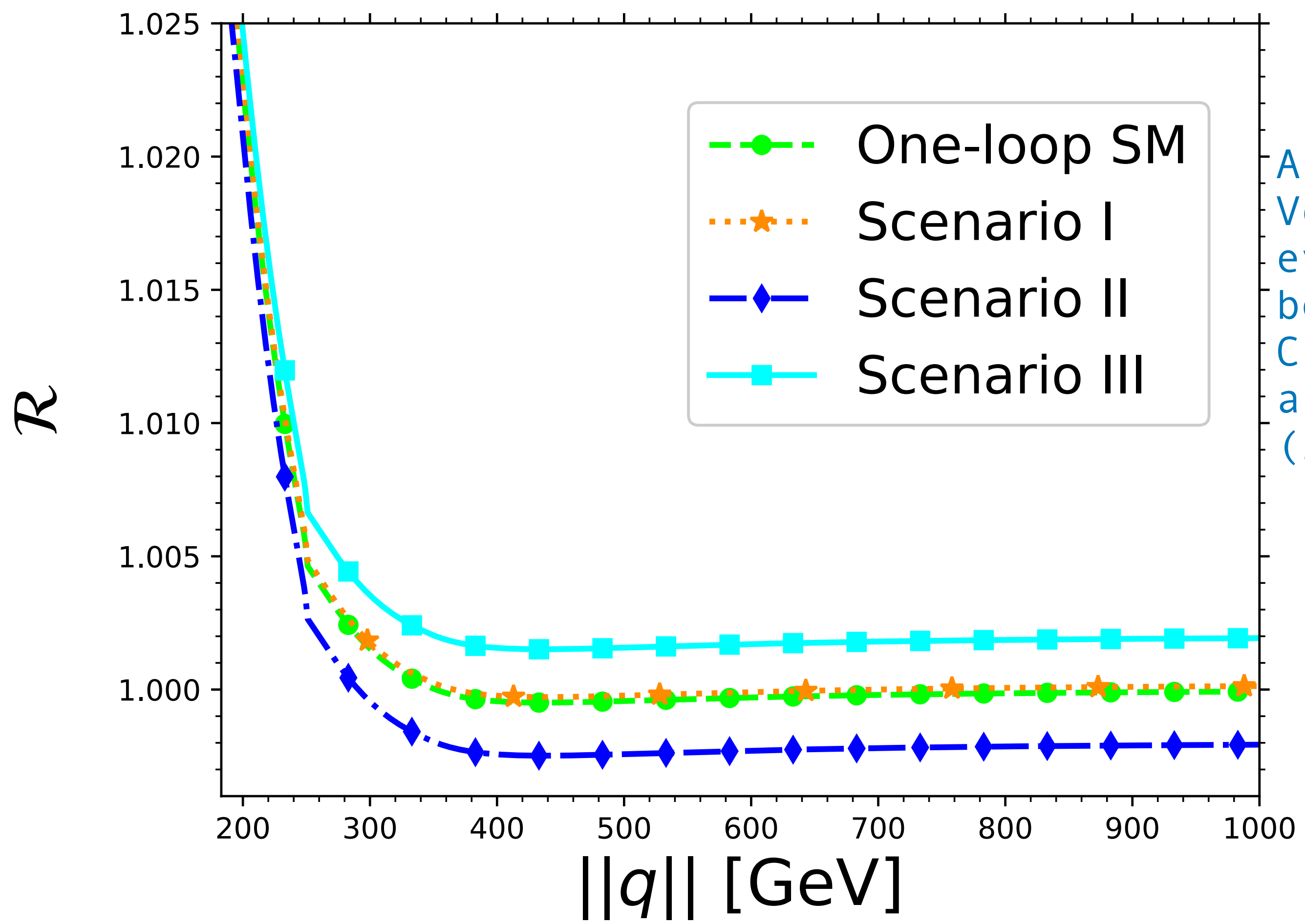
Unpolarized decay

We considere the anomalous couplings as complex → $h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$

We calculate the partial width

$$\Gamma_{H^* \to ZZ}$$

No difference between tree level results and the anomalous couplings contributions.



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$$\mathscr{R} = \frac{\Gamma_{H^* \to ZZ}}{\Gamma^{Tree}_{H^* \to ZZ}}.$$

Polarized decay

We considere the anomalous couplings as complex → $h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$

↓ We calculate the partial width

$$\Gamma_{H^*\to ZZ} = \Gamma_{H^*\to Z_R Z_R} + \Gamma_{H^*\to Z_L Z_L} + \Gamma_{H^*\to Z_0 Z_0}$$

Polarized decay

We considere the anomalous couplings as complex → $h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$

We calculate the partial width

$$\Gamma_{H^* \to ZZ} = \Gamma_{H^* \to Z_R Z_R} + \Gamma_{H^* \to Z_L Z_L} + \Gamma_{H^* \to Z_0 Z_0}$$

Asymmetry

$$\mathscr{A}_{LR} = \frac{\Gamma_{H^* \to Z_L Z_L} - \Gamma_{H^* \to Z_R Z_R}}{\Gamma_{H^* \to Z_L Z_L} + \Gamma_{H^* \to Z_R Z_R}}$$

Polarized decay

We considere the anomalous couplings as complex

$$h_i^V = \mathrm{Re}[h_i^V] + i\,\mathrm{Im}[h_i^V]$$

We calculate the partial width

$$\Gamma_{H^*\to ZZ} = \Gamma_{H^*\to Z_R Z_R} + \Gamma_{H^*\to Z_L Z_L} + \Gamma_{H^*\to Z_0 Z_0}$$

Asymmetry

$h_3^H = 0$ **in the SM at tree level**

$\mathscr{A}_{LR} = 0$

$$\mathscr{A}_{LR} = \frac{4m_Z^2 \|q\| \sqrt{q^2 - 4m_Z^2}\left(\mathrm{Re}\left[h_1^H\right]\mathrm{Im}\left[h_3^H\right] - \mathrm{Re}\left[h_3^H\right]\mathrm{Im}\left[h_1^H\right]\right)}{q^2\left(q^2 - 4m_Z^2\right)\left(\mathrm{Re}\left[h_3^H\right]^2 + \mathrm{Im}\left[h_3^H\right]^2\right) + 4m_Z^4\left(\mathrm{Im}\left[h_1^H\right]^2 + \mathrm{Re}\left[h_1^H\right]^2\right)}$$

Polarized decay

We considere the anomalous couplings as complex → $h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$

We calculate the partial width

$$\Gamma_{H^* \to ZZ} = \Gamma_{H^* \to Z_R Z_R} + \Gamma_{H^* \to Z_L Z_L} + \Gamma_{H^* \to Z_0 Z_0}$$

Asymmetry

CP-violation

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$\mathscr{A}_{LR} = 0$

$$\mathscr{A}_{LR} = \frac{4m_Z^2 \|q\| \sqrt{q^2 - 4m_Z^2} \left(\mathrm{Re}\left[h_1^H\right] \mathrm{Im}\left[h_3^H\right] - \mathrm{Re}\left[h_3^H\right] \mathrm{Im}\left[h_1^H\right] \right)}{q^2 \left(q^2 - 4m_Z^2\right) \left(\mathrm{Re}\left[h_3^H\right]^2 + \mathrm{Im}\left[h_3^H\right]^2 \right) + 4m_Z^4 \left(\mathrm{Im}\left[h_1^H\right]^2 + \mathrm{Re}\left[h_1^H\right]^2 \right)}$$

Polarized decay

We considere the anomalous couplings as complex → $h_i^V = \mathrm{Re}[h_i^V] + i\,\mathrm{Im}[h_i^V]$

We calculate the partial width

$$\Gamma_{H^*\to ZZ} = \Gamma_{H^*\to Z_R Z_R} + \Gamma_{H^*\to Z_L Z_L} + \Gamma_{H^*\to Z_0 Z_0}$$

Asymmetry

$h_3^H = 0$ in the SM at tree level

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CP-violation

$$\mathcal{A}_{LR} = \frac{4m_Z^2\|q\|\sqrt{q^2-4m_Z^2}\left(\mathrm{Re}\left[h_1^H\right]\mathrm{Im}\left[h_3^H\right] - \mathrm{Re}\left[h_3^H\right]\mathrm{Im}\left[h_1^H\right]\right)}{q^2\left(q^2-4m_Z^2\right)\left(\mathrm{Re}\left[h_3^H\right]^2+\mathrm{Im}\left[h_3^H\right]^2\right)+4m_Z^4\left(\mathrm{Im}\left[h_1^H\right]^2+\mathrm{Re}\left[h_1^H\right]^2\right)}$$

Imaginary parts

Polarized decay

We considere the anomalous couplings as complex → $h_i^V = \mathrm{Re}[h_i^V] + i\mathrm{Im}[h_i^V]$

We calculate the partial width

To induce a non-zero asymmetry 2 elements are required

1. **CP-violation**
2. **Complex anomalous couplings**

Asymmetry

$h_3^H = 0$ **in the SM at tree level**

$\mathscr{A}_{LR} = 0$

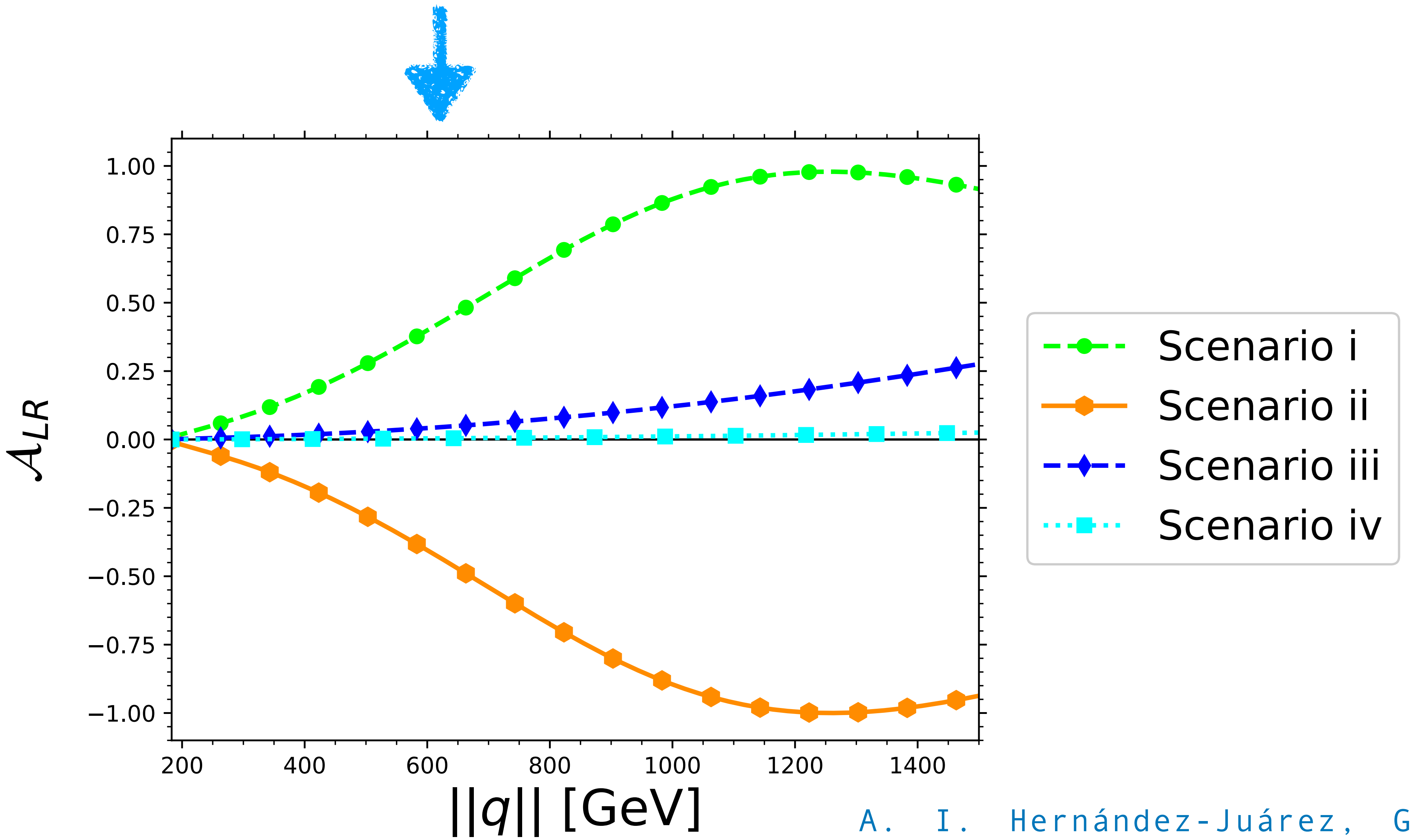
CP-violation

$$\mathscr{A}_{LR} = \frac{4m_Z^2\|q\|\sqrt{q^2 - 4m_Z^2}\left(\mathrm{Re}\left[h_1^H\right]\mathrm{Im}\left[h_3^H\right] - \mathrm{Re}\left[h_3^H\right]\mathrm{Im}\left[h_1^H\right]\right)}{q^2\left(q^2 - 4m_Z^2\right)\left(\mathrm{Re}\left[h_3^H\right]^2 + \mathrm{Im}\left[h_3^H\right]^2\right) + 4m_Z^4\left(\mathrm{Im}\left[h_1^H\right]^2 + \mathrm{Re}\left[h_1^H\right]^2\right)}$$

Imaginary parts

Polarized decay

$$\mathscr{A}_{LR} = \frac{4m_Z^2\|q\|\sqrt{q^2 - 4m_Z^2}\left(\mathrm{Re}\left[h_1^H\right]\mathrm{Im}\left[h_3^H\right] - \mathrm{Re}\left[h_3^H\right]\mathrm{Im}\left[h_1^H\right]\right)}{q^2\left(q^2 - 4m_Z^2\right)\left(\mathrm{Re}\left[h_3^H\right]^2 + \mathrm{Im}\left[h_3^H\right]^2\right) + 4m_Z^4\left(\mathrm{Im}\left[h_1^H\right]^2 + \mathrm{Re}\left[h_1^H\right]^2\right)}$$



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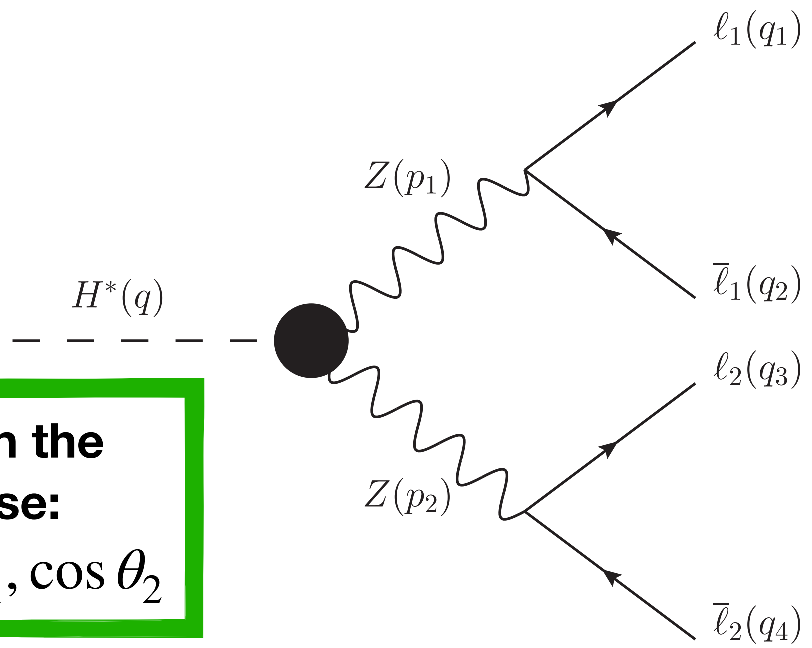
Polarized decay

$$gg \to H^* \to ZZ \to 4l$$



5 variables in the space phase: $p_1^2, p_2^2, \phi, \cos\theta_1, \cos\theta_2$

$$\frac{d\Gamma_{H^* \to \bar{\ell}_1 \ell_1 \bar{\ell}_2 \ell_2}}{dp_1 dp_2 d\cos\theta_1 d\cos\theta_2 d\phi} = \frac{1}{2Q} \frac{\sqrt{Q^2 - 4m_Z^2}}{256Q(2\pi)^6} \mathcal{M}^2_{H^* \to \bar{\ell}_1 \ell_1 \bar{\ell}_2 \ell_2}$$

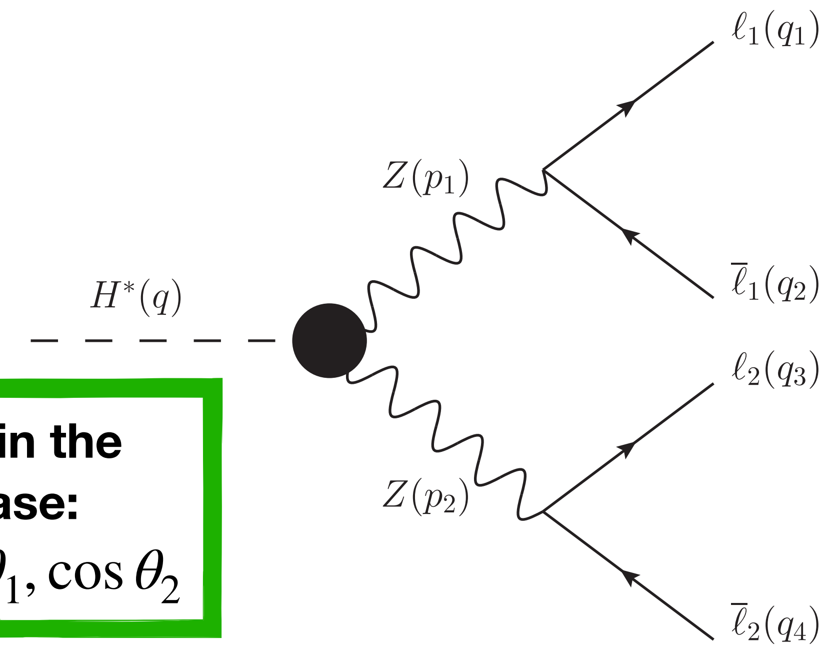
$$\mathcal{M}^2_{H^* \to \bar{\ell}_1 \ell_1 \bar{\ell}_2 \ell_2} = \frac{\sum_\lambda \mathcal{M}^2_{H^* \to Z(p_1)Z(p_2)}(\lambda,\lambda)\mathcal{M}^2_{Z(p_1)\to\bar{\ell}_1\ell_1}(\lambda)\mathcal{M}^2_{Z(p_2)\to\bar{\ell}_2\ell_2}(\lambda) + \mathcal{M}^2_{\text{int}}}{\left((p_1^2 - m_Z^2)^2 + \Gamma^2 m_Z^2\right)\left((p_2^2 - m_Z^2)^2 + \Gamma^2 m_Z^2\right)}.$$

λ indicates the polarization of the Z bosons

Unpolarized angular observables

Polarized decay

$$gg \to H^* \to ZZ \to 4l$$



5 variables in the space phase:
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$$\mathscr{A}_{LR\theta} = \frac{\dfrac{d\Gamma^L_{H^*\to e^-e^+\mu^-\mu^+}}{dc_{\theta_j}} - \dfrac{d\Gamma^R_{H^*\to e^-e^+\mu^-\mu^+}}{dc_{\theta_j}}}{\dfrac{d\Gamma^L_{H^*\to e^-e^+\mu^-\mu^+}}{dc_{\theta_j}} + \dfrac{d\Gamma^R_{H^*\to e^-e^+\mu^-\mu^+}}{dc_{\theta_j}}},$$

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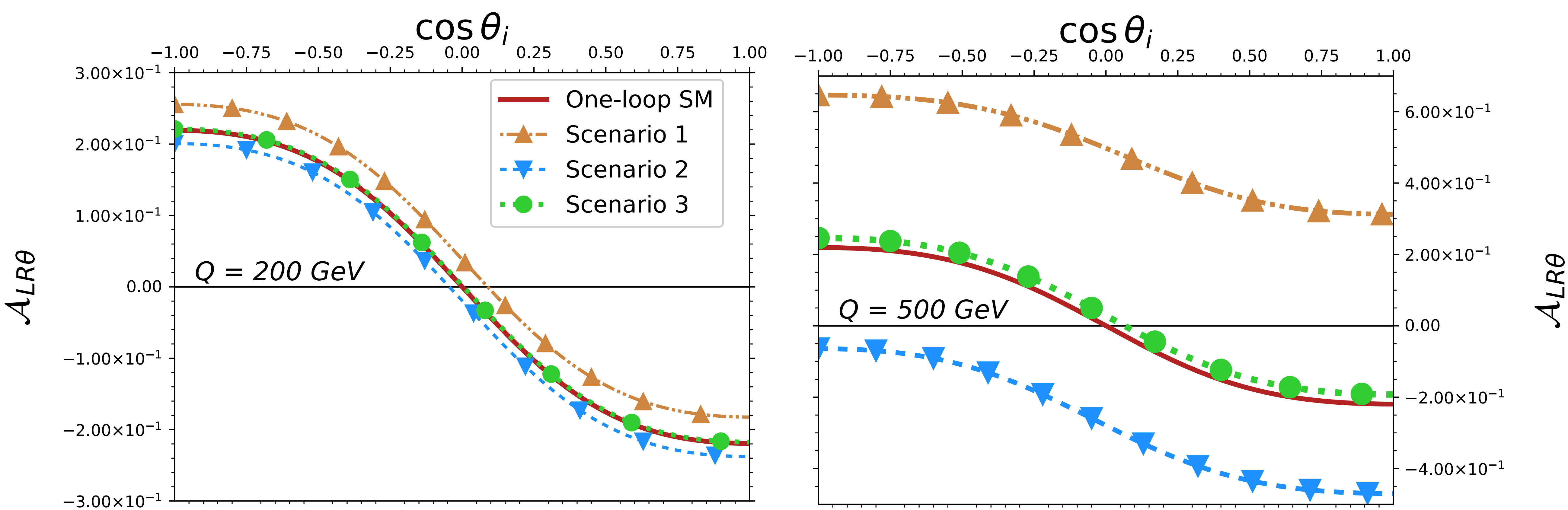
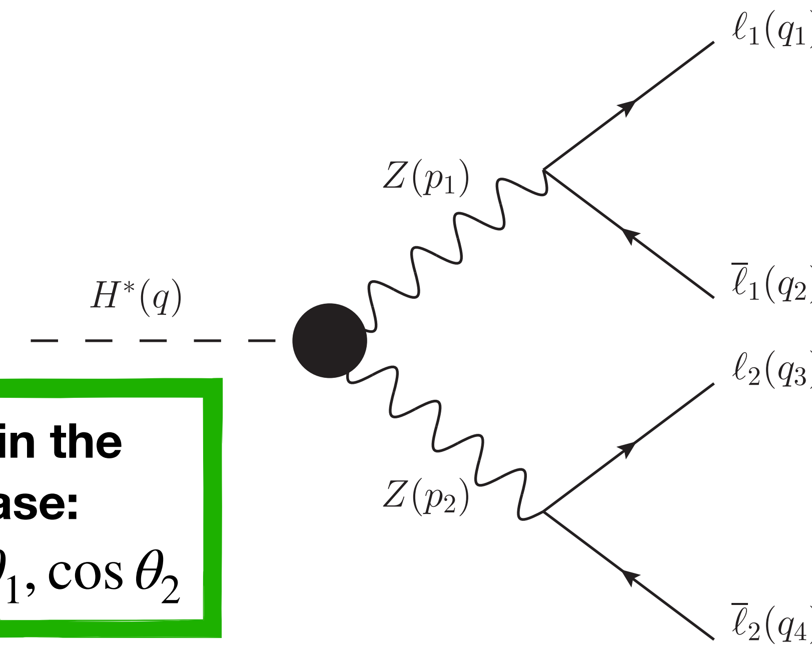


Polarized decay

$$gg \to H^* \to ZZ \to 4l$$



5 variables in the space phase:
$p_1^2, p_2^2, \phi, \cos\theta_1, \cos\theta_2$

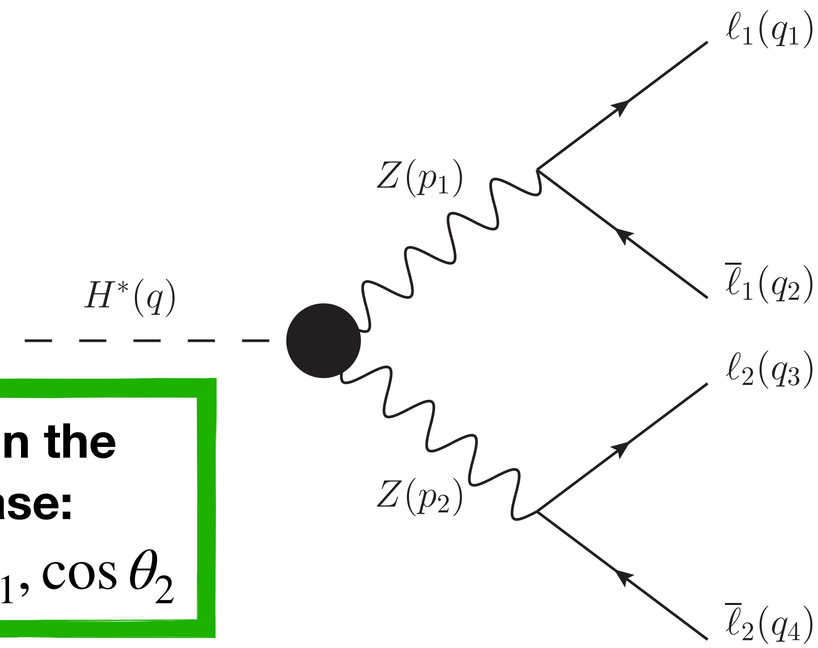
$$\mathscr{A}^{\lambda}_{FB} = \frac{\Gamma^{\lambda}_{F}(H^* \to \bar{f}_i f_i \bar{f}_j f_j) - \Gamma^{\lambda}_{B}(H^* \to \bar{f}_i f_i \bar{f}_j f_j)}{\Gamma^{\lambda}_{F}(H^* \to \bar{f}_i f_i \bar{f}_j f_j) + \Gamma^{\lambda}_{B}(H^* \to \bar{f}_i f_i \bar{f}_j f_j)},$$

$$\mathscr{A}^{L/R}_{FB} = \mp \frac{3 g_A g_V}{2\left(g_A^2 + g_V^2\right)}.$$

A constant

Unpolarized decay

$$gg \to H^* \to ZZ \to 4l$$



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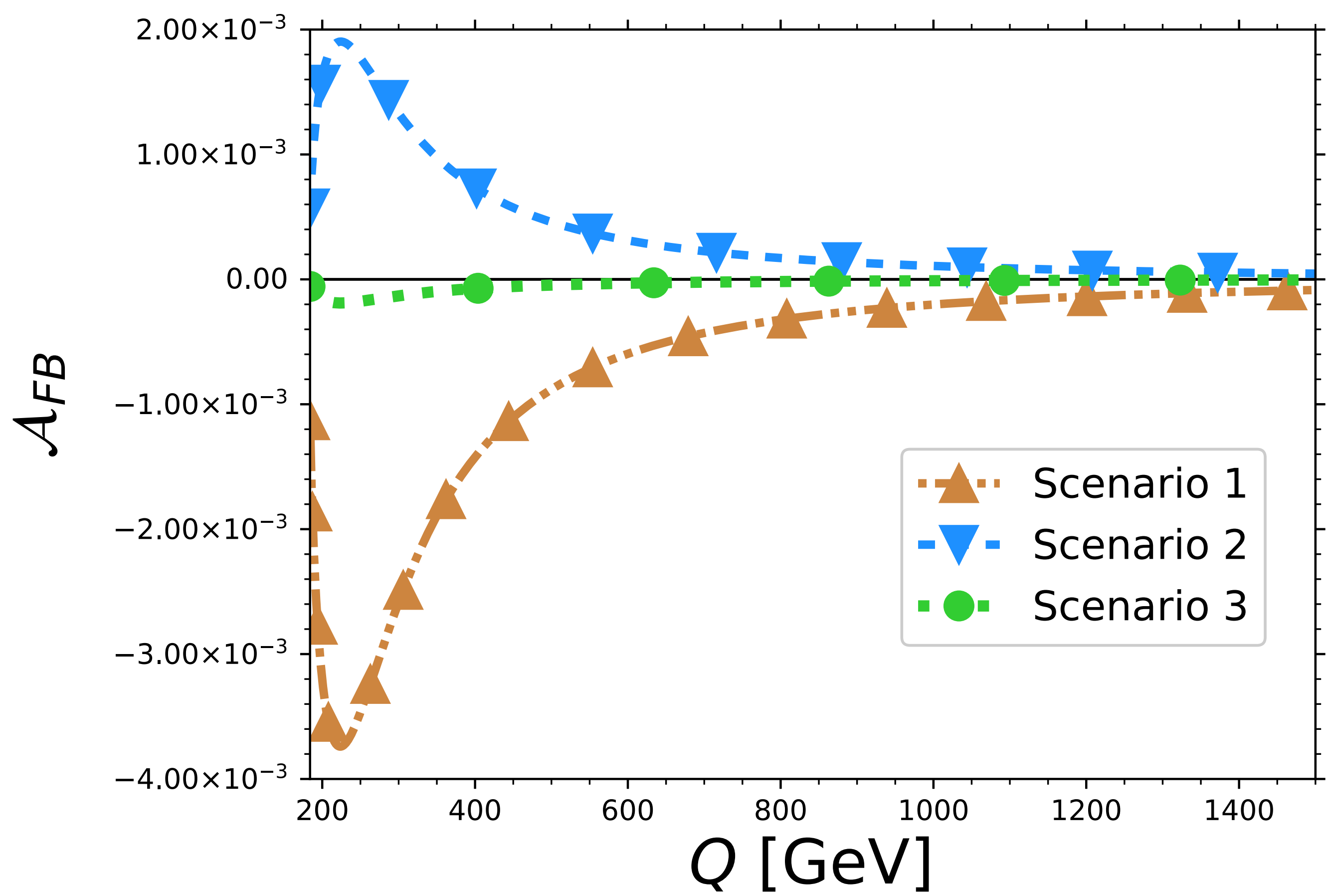
5 variables in the space phase:
$p_1^2, p_2^2, \phi, \cos\theta_1, \cos\theta_2$

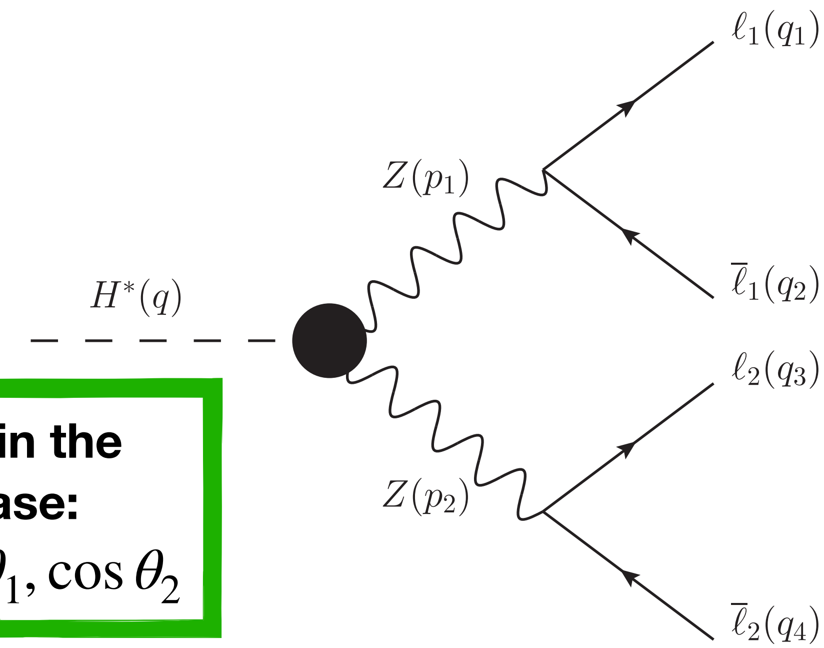
$$\mathscr{A}_{FB} = \frac{\Gamma_F(H^* \to ZZ \to \overline{\ell}_1\ell_1\overline{\ell}_2\ell_2) - \Gamma_B(H^* \to ZZ \to \overline{\ell}_1\ell_1\overline{\ell}_2\ell_2)}{\Gamma_F(H^* \to ZZ \to \overline{\ell}_1\ell_1\overline{\ell}_2\ell_2) + \Gamma_B(H^* \to ZZ \to \overline{\ell}_1\ell_1\overline{\ell}_2\ell_2)}.$$

Zero in the SM



Unpolarized decay

$$gg \to H^* \to ZZ \to 4l$$



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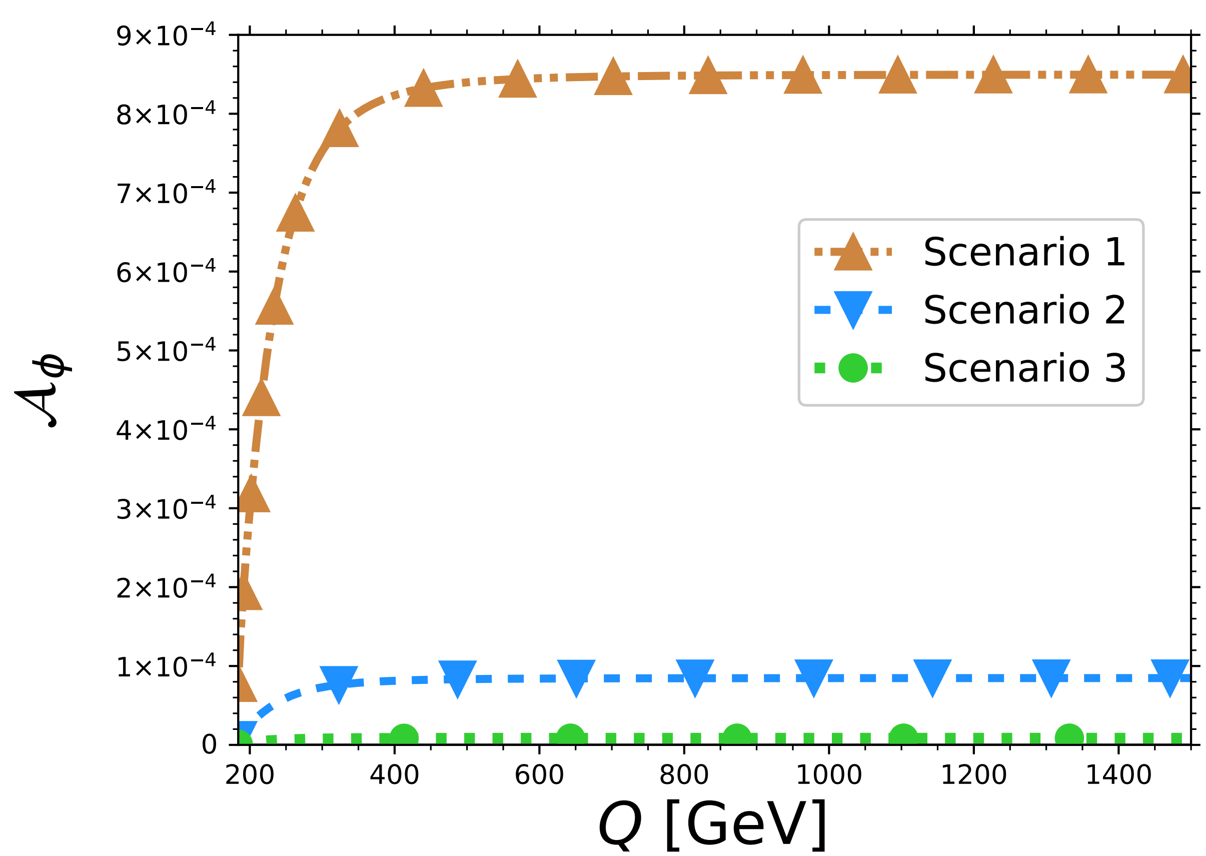
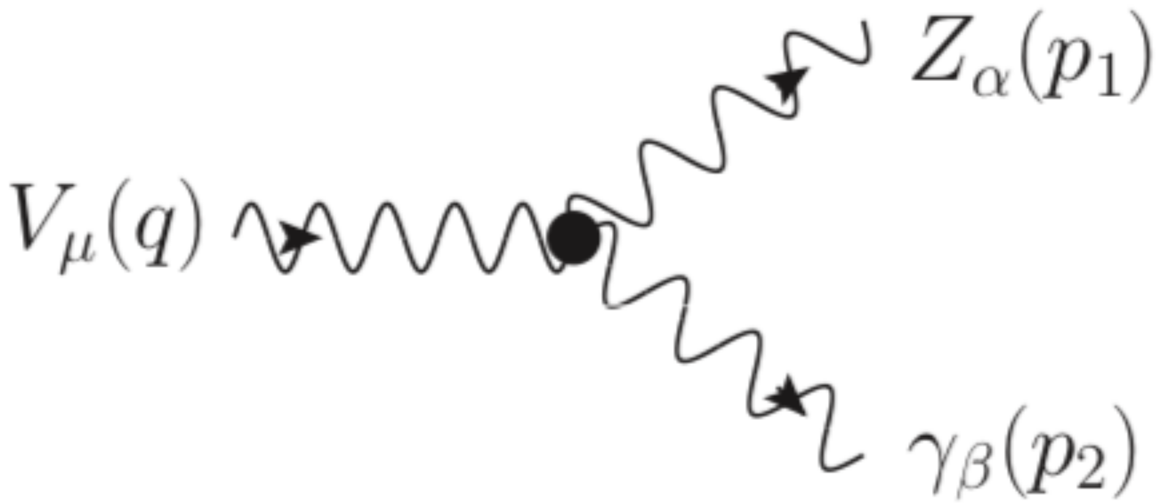
5 variables in the space phase:
$p_1^2, p_2^2, \phi, \cos\theta_1, \cos\theta_2$

$$\mathscr{A}_\phi = \frac{\int_\pi^{2\pi} d\phi \frac{d}{d\phi}\Gamma_{H^*\to ZZ\to e^-e^+\mu^-\mu^+} - \int_0^{\pi} d\phi \frac{d}{d\phi}\Gamma_{H^*\to ZZ\to e^-e^+\mu^-\mu^+}}{\int_\pi^{2\pi} d\phi \frac{d}{d\phi}\Gamma_{H^*\to ZZ\to e^-e^+\mu^-\mu^+} + \int_0^{\pi} d\phi \frac{d}{d\phi}\Gamma_{H^*\to ZZ\to e^-e^+\mu^-\mu^+}}.$$

Zero in the SM



Polarized decay in TNGBC



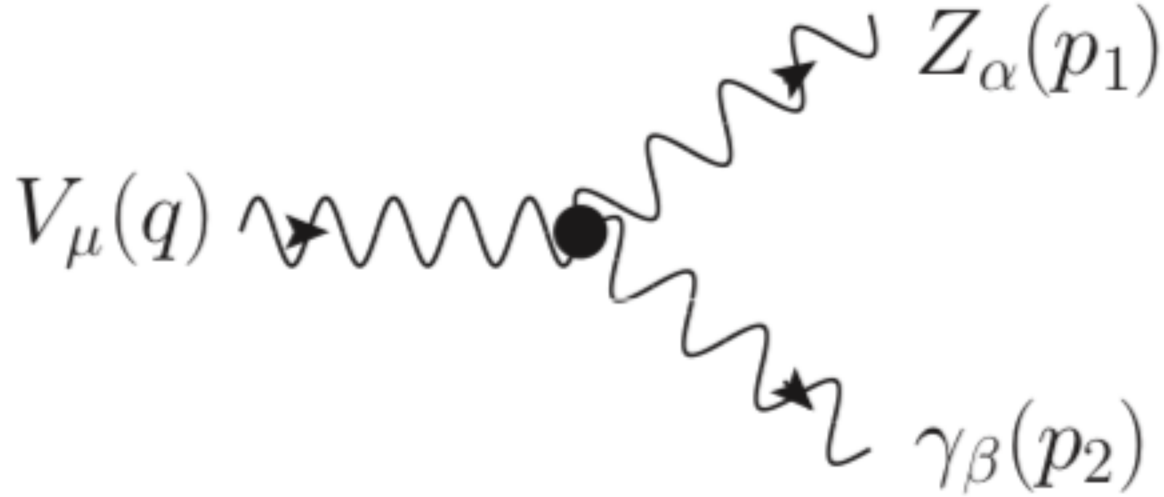
$$V = Z, \gamma$$

h_i^V are also complex

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V*}(p_1, p_2, q) = \frac{i(q^2 - m_V^2)}{m_Z^2}\Big[h_1^V\left(p_2^\mu g^{\alpha\beta} + p_2^\alpha g^{\mu\beta}\right) + \frac{h_2^V}{m_Z^2} q^\alpha\left(q\cdot p_2 g^{\mu\beta} - p_2^\mu q^\beta\right)$$
$$- h_3^V \epsilon^{\mu\alpha\beta\rho} p_{2_\rho} - \frac{h_4^V}{m_Z^2} q^\alpha \epsilon^{\mu\beta\rho\sigma} q_\rho p_{2_\sigma}\Big],$$

TNGBCs require at least one off-shell boson to exist

Polarized decay in TNGBC



$$V = Z, \gamma$$

h_i^V are also complex

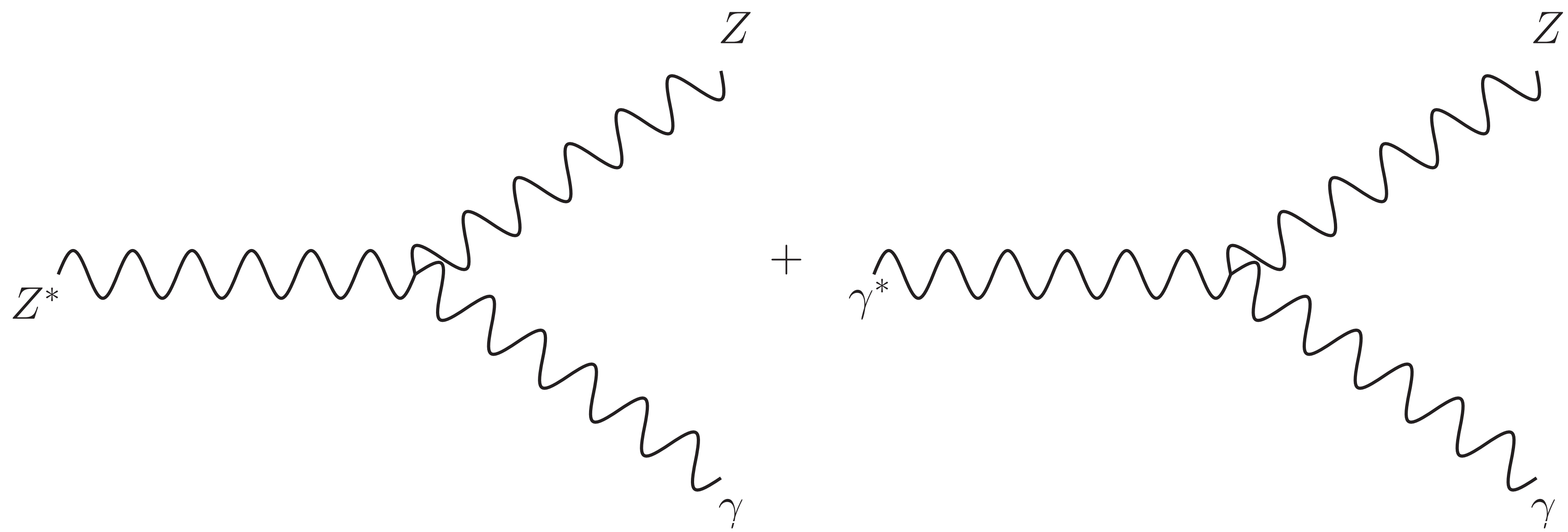
$$\Gamma^{\alpha\beta\mu}_{Z\gamma V*}(p_1, p_2, q) = \frac{i(q^2 - m_V^2)}{m_Z^2}\Big[h_1^V\left(p_2^\mu g^{\alpha\beta} + p_2^\alpha g^{\mu\beta}\right) + \frac{h_2^V}{m_Z^2} q^\alpha \left(q \cdot p_2 g^{\mu\beta} - p_2^\mu q^\beta\right)$$
$$- h_3^V \epsilon^{\mu\alpha\beta\rho} p_{2_\rho} - \frac{h_4^V}{m_Z^2} q^\alpha \epsilon^{\mu\beta\rho\sigma} q_\rho p_{2_\sigma}\Big],$$

CP-violating

TNGBCs require at least one off-shell boson to exist

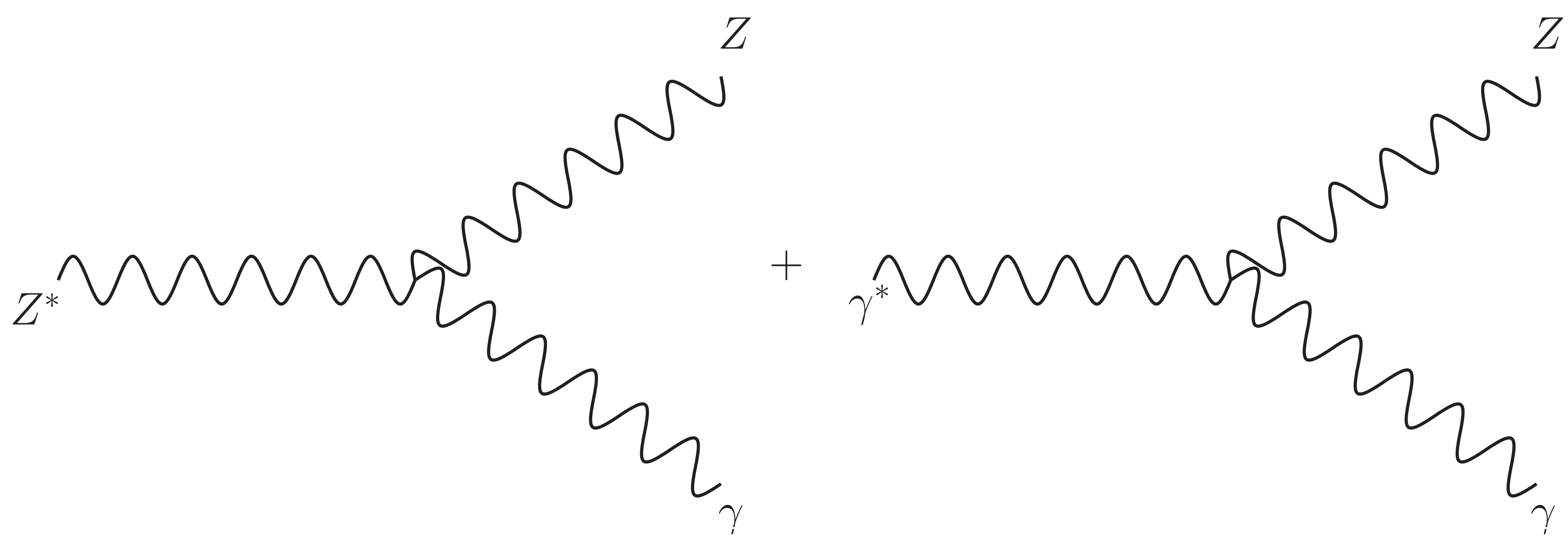
Polarized decay in TNGBC

At the LHC is not possible to distinguish if the $Z\gamma$ pair arise from an off-shell Z or γ



Polarized decay in TNGBC

At the LHC is not possible to distinguish if the $Z\gamma$ pair arise from an off-shell Z or γ



But if we consider the polarizations of the $Z\gamma$ final state…

Polarized decay in TNGBC

We can compute

$$\Gamma^{\lambda_1\lambda_2}(V^* \to Z(\lambda_1)\gamma(\lambda_2)) \qquad V = Z, \gamma$$

polarizations

Two different non-zero polarized final sates:

$$\Gamma^{0\lambda}(V^* \to Z(0)\gamma(\lambda)) \qquad V = Z, \gamma$$

Polarized decay in TNGBC

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Two different non-zero polarized final sates:

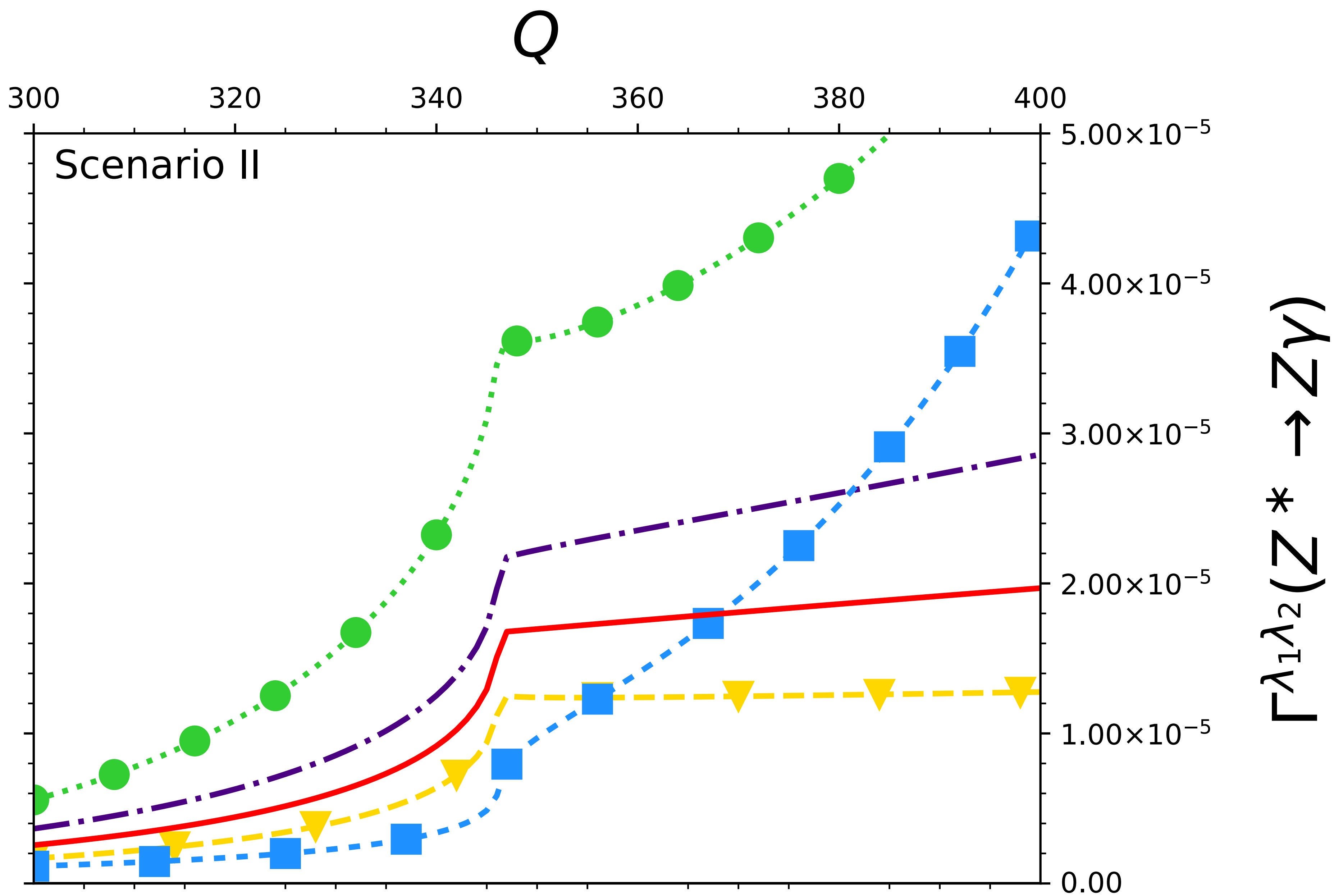
$$\Gamma^{0\lambda}(V^* \to Z(0)\gamma(\lambda)) \qquad V = Z, \gamma$$

$$\Gamma^{\lambda\lambda}(Z^* \to Z(\lambda)\gamma(\lambda))$$

Only for an off-shell Z boson

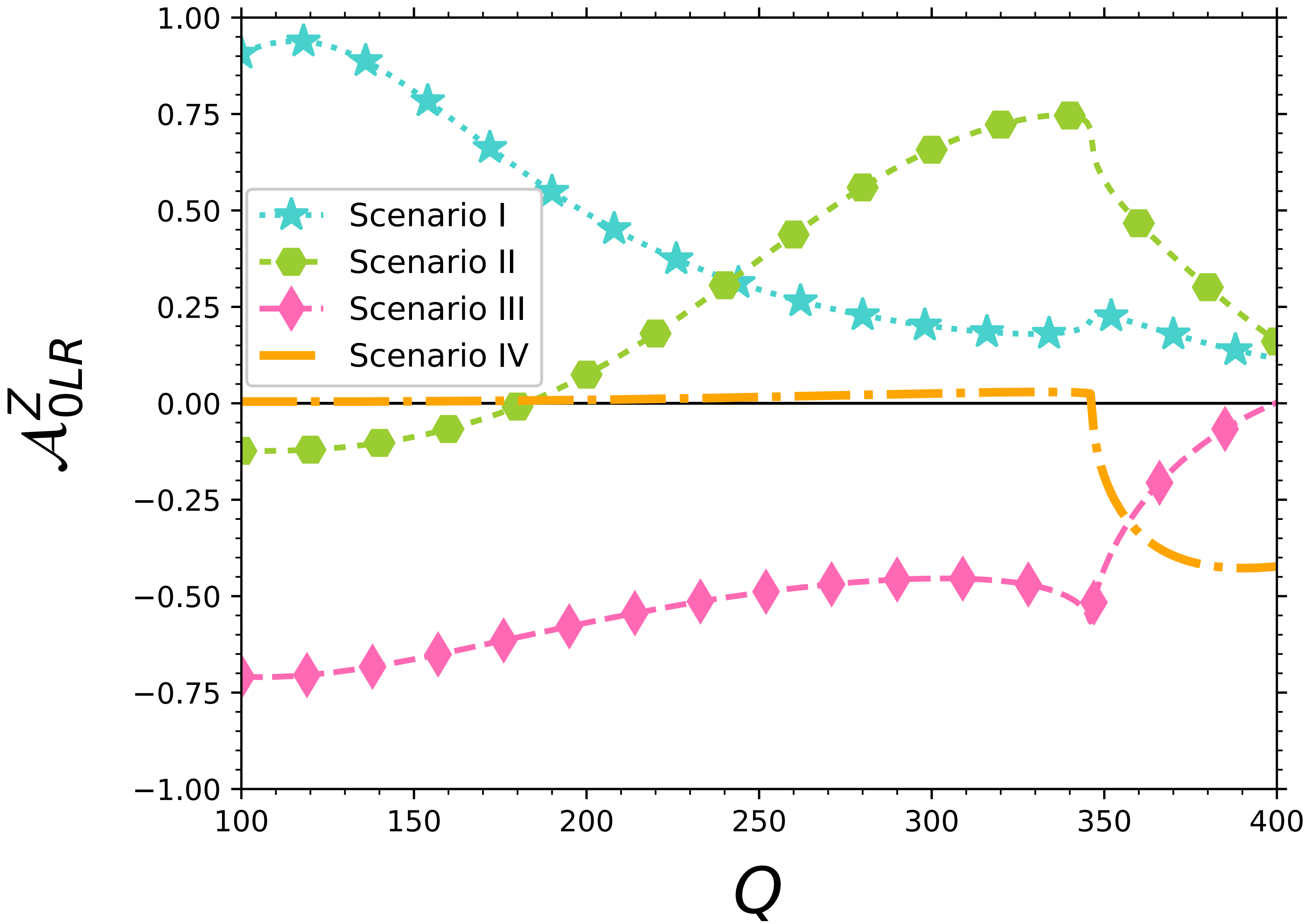
If we study transversally polarized $Z\gamma$ pairs, we can know if they arise from an Z or γ off-shell

Polarized decay in TNGBC



A. I. Hernández-Juárez, R. Gaitán, and G. Tavares-Velasco,Non-diagonal contributions to ZγV∗ vertex, polarizations and bounds on Ztq couplings, (2022), arXiv: 2203.16819 [hep-ph]

Polarized decay in TNGBC



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Summary

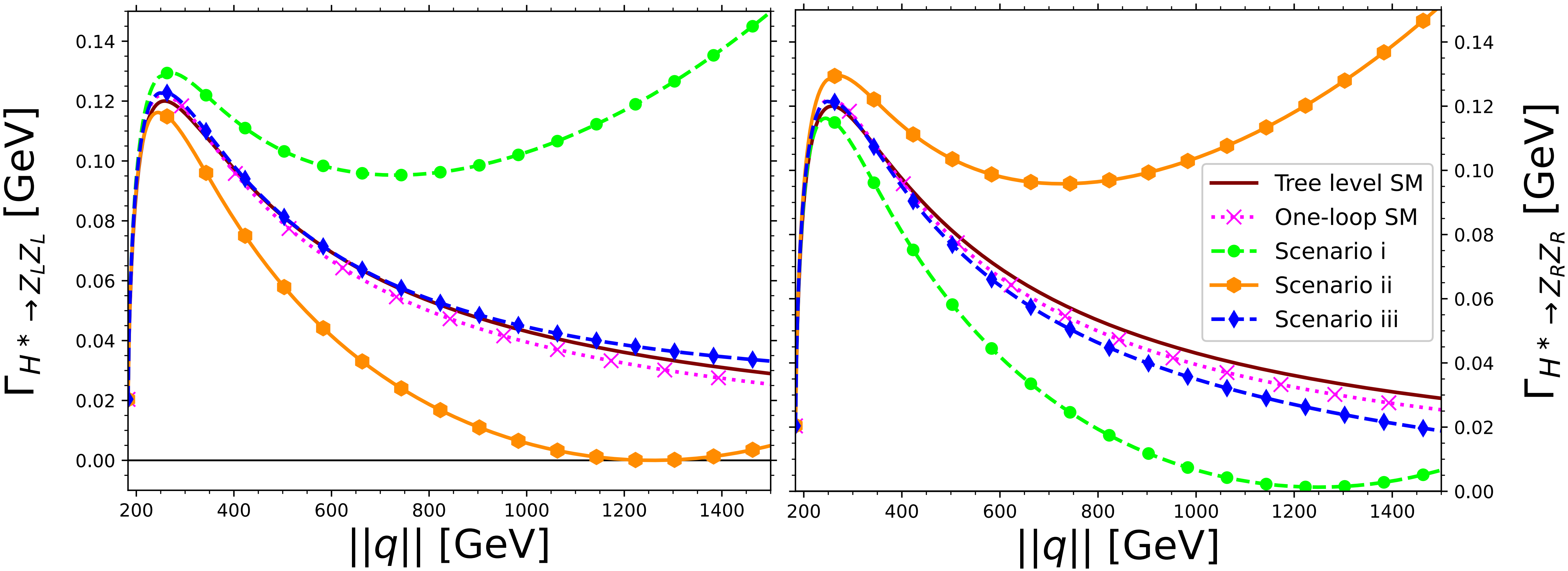
- Complex form factors and CP violation are necessary to induce new left-right asymmetries.
- Polarized observables can lead to interesting results in the HZZ coupling.
- Polarized observables can be useful to distinguish off-shell contributions.

¡Gracias!

Back up

IMAGINARY CONTRIBUTIONS

$$\Gamma_{H^* \to Z_L Z_L}, \Gamma_{H^* \to Z_R Z_R}$$



IMAGINARY CONTRIBUTIONS