Technische Universität München

Anomalous Higgs couplings in angular asymmetries of $H \to Z\ell^+\ell^-$ and $e^+e^- \to HZ$

Diogo Boito

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-- M Beneke, DB, Y.-M. Wang, arXiv:1406.1361

ICHEP14, Valencia, 2 - 9 of July 2014

Outline

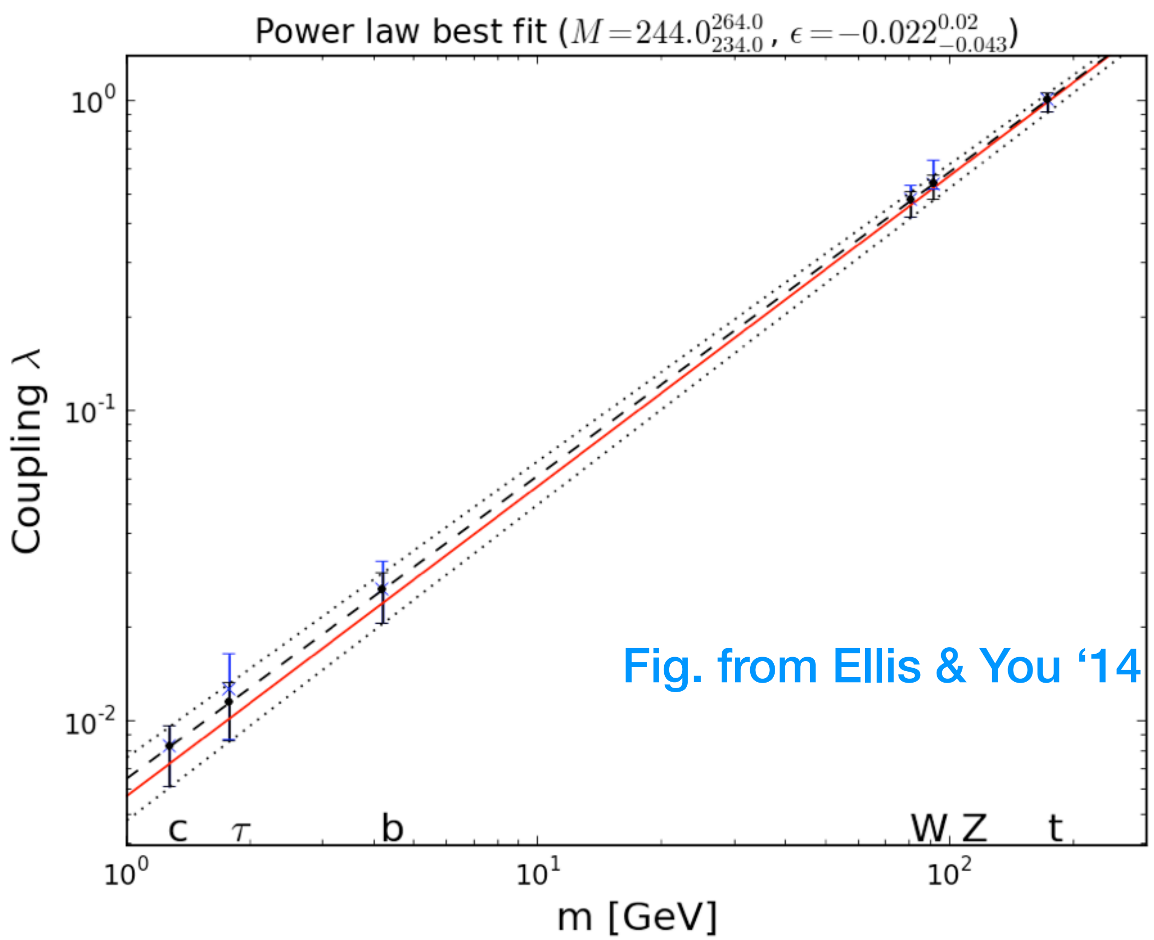
- **Introduction**
- **Operators and couplings**
- **Form factor and angular structures**
- **Main results**

Beyond Standard Model physics is elusive

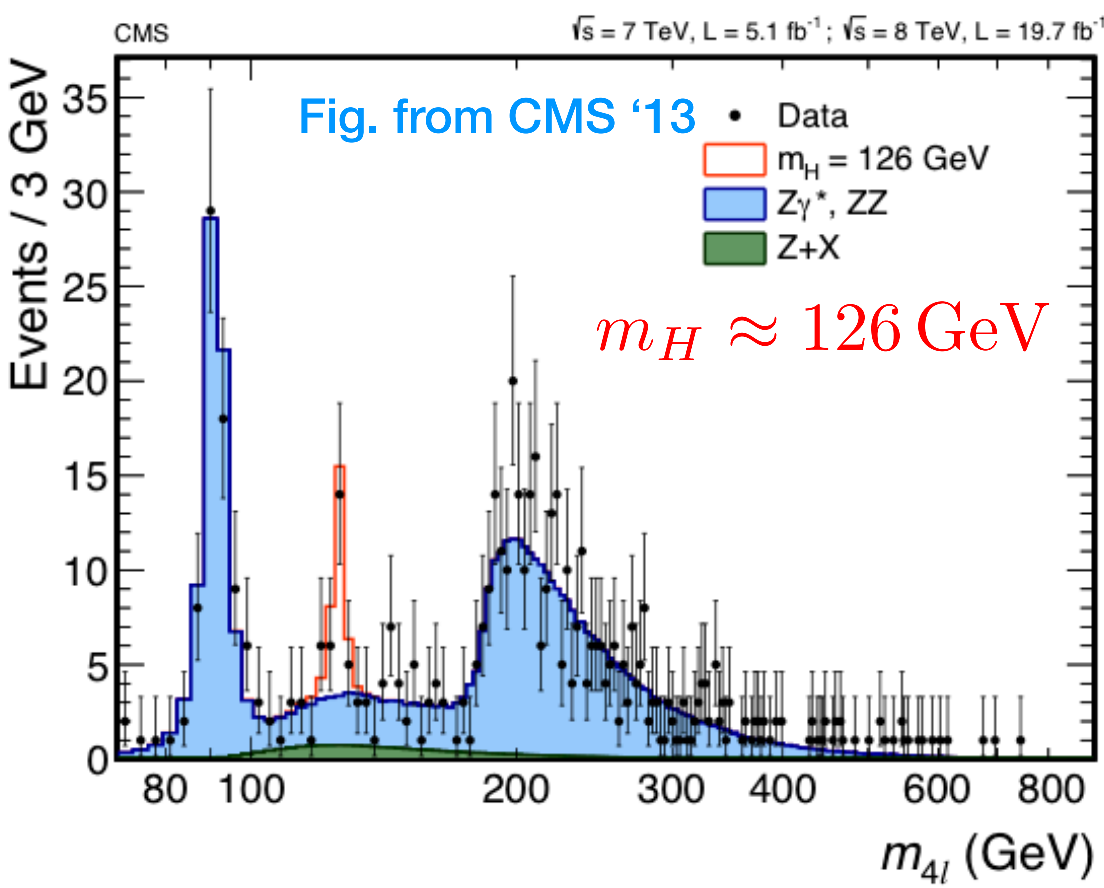
- The Higgs seems to be the one from the SM.
- Quantum numbers compatible with SM predictions

ATLAS arXiv:1307.1432; CMS arXiv:1312.5353

- Couplings proportional to the mass



- Higgs in 4l



- Parametrization of BSM physics assuming SM symmetry *SU*(3)*xSU*(2)*xU*(1) (linearly realized)

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}^{(4)}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\sum_{k=1}^{59} \alpha_k \mathcal{O}_k,$$

Buchmüller&Wyler '86
Grzadkowski et al '10

We also employ $\widehat{\alpha}_k = \frac{v^2}{\Lambda^2}\alpha_k$

- Many different operator basis allowed and in use.

- Several operators affect Higgs physics. Many are constrained by data.

Operators and couplings

- We employ the "Polish" basis (with MFV). Relevant operators: Grzadkowski et al '10

$\Phi^4 D^2$	$X^2 \Phi^2$	$\psi^2 \Phi^2 D$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi)W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}^{(1)}_{\Phi\ell} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar\ell\gamma^\mu\ell)$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}^{(3)}_{\Phi\ell} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar\ell\gamma^\mu\tau^I\ell)$
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	$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$ ←	

- Additionally, a four-fermion operator contributes to the redefinition of G_F

$$\mathcal{O}^{prst}_{4L} = (\bar\ell_p\gamma_\mu\ell_r)(\bar\ell_s\gamma^\mu\ell_t)$$

$$m_Z = m_{Z\circ}\,(1+\delta_Z)\,, \qquad G_F = G_{F\circ}\,(1+\delta_{G_F})\,, \qquad \alpha_{\rm em} = \alpha_{\rm em\circ}\,(1+\delta_A)\,,$$

$$\delta_Z = \widehat\alpha_{ZZ} + \frac{1}{4}\widehat\alpha_{\Phi D}, \qquad \delta_{G_F} = -\widehat\alpha_{4L} + 2\widehat\alpha^{(3)}_{\Phi\ell}, \qquad \delta_A = 2\widehat\alpha_{AA}$$

$$\alpha_{ZZ} = c_W^2\alpha_{\Phi W} + s_W^2\alpha_{\Phi B} + s_W c_W\alpha_{\Phi WB} \qquad \alpha_{AA} = s_W^2\alpha_{\Phi W} + c_W^2\alpha_{\Phi B} - s_W c_W\alpha_{\Phi WB}$$

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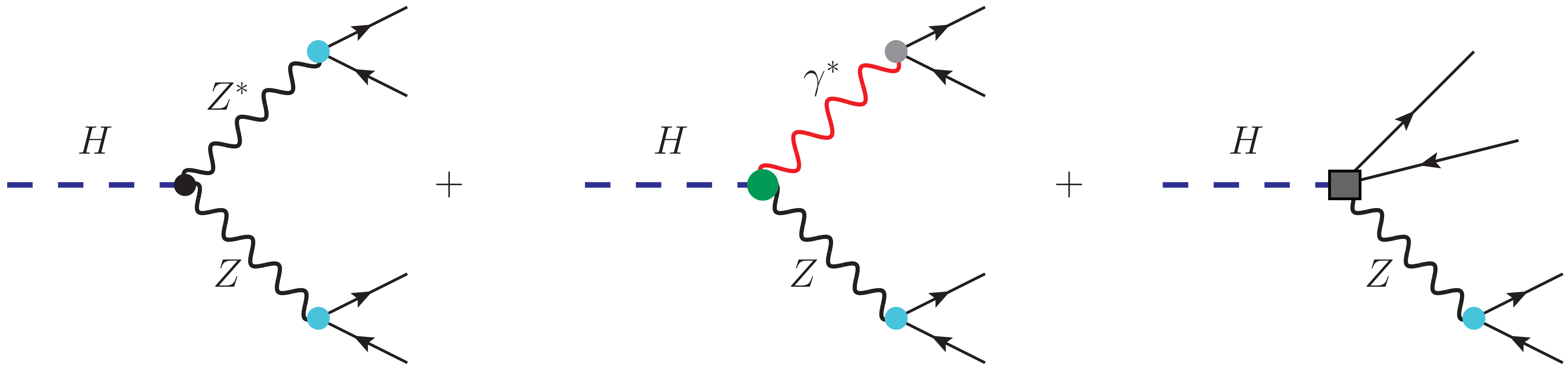
- New interactions and modifications to SM vertices

$$\mathcal{L}_{\rm eff} \supset c^{(1)}_{ZZ}\, H Z_\mu Z^\mu + c^{(2)}_{ZZ} H\, Z_{\mu\nu} Z^{\mu\nu} + c_{Z\widetilde{Z}} H\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu} + c_{AZ} H\, Z_{\mu\nu} A^{\mu\nu} + c_{A\widetilde{Z}} H Z_{\mu\nu} \widetilde{A}^{\mu\nu}$$
$$+ H Z_\mu \bar{\ell}\gamma^\mu \left(c_V + c_A\gamma_5\right)\ell + Z_\mu \bar{\ell}\gamma^\mu (g_V - g_A\gamma_5)\ell - g_{\rm em} Q_\ell A_\mu \bar{\ell}\gamma^\mu \ell,$$



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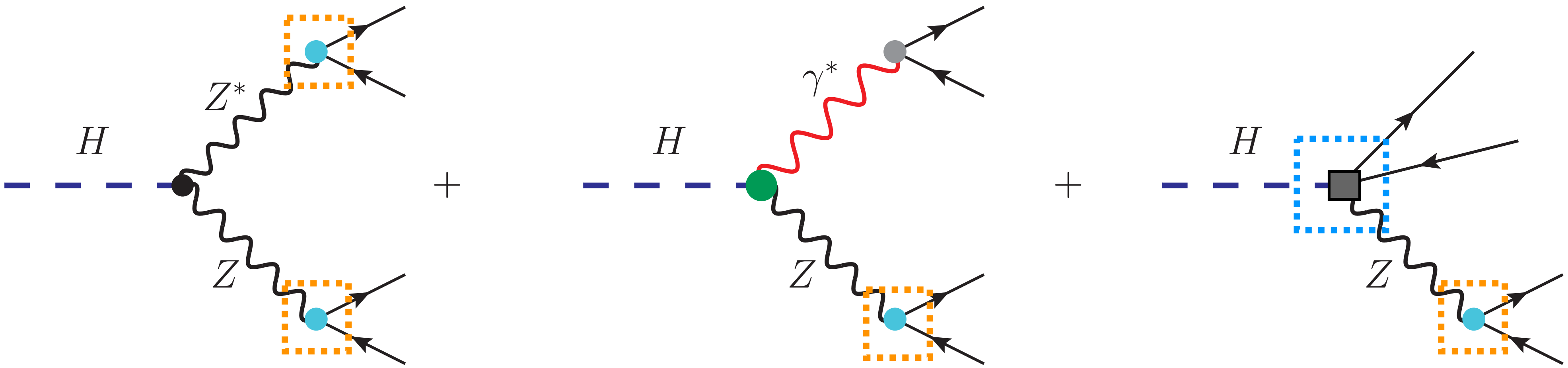

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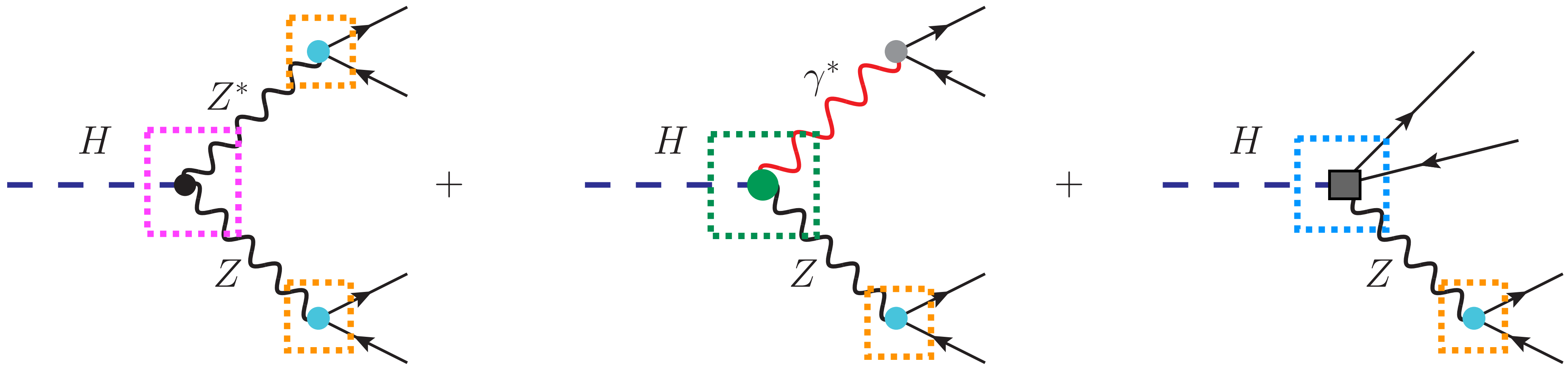

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$$\widehat{\alpha}_{AZ} \in [-1.3, 2.6] \times 10^{-2} \qquad \widehat{\alpha}_{\Phi\ell}^{V,A} \in [-5, 5] \times 10^{-3}$$

Pomarol and Riva '14

estimate using data for
$\Delta S,\ \Delta T,\ m_W,\ g_{V,A}$
Beneke, DB, Wang '14

- Contact $HZ\ell\ell$ in the "Polish" basis
Grzadkowski et al '10

$$H Z_\mu \bar{\ell}\gamma^\mu (c_V + c_A\gamma_5)\,\ell \longrightarrow c_{V,A} = \sqrt{2}\,G_F\, m_Z\, \widehat{\alpha}_{\Phi,\ell}^{V,A}$$

$$\widehat{\alpha}_{\Phi,\ell}^{V,A} = \widehat{\alpha}_{\Phi e} \pm \left(\widehat{\alpha}_{\Phi\ell}^{(1)} + \widehat{\alpha}_{\Phi\ell}^{(3)}\right)$$

- In the basis used by Pomarol and Riva '14
Elias-Miró, Espinosa, Massó, Pomarol '13

$$\mathcal{O}_{\Phi\ell}^{(1)} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{\Phi\ell}^{(3)} = (\Phi^\dagger i \overleftrightarrow{D}_\mu^I \Phi)(\bar{\ell}\gamma^\mu \tau^I \ell) \longrightarrow c_V = c_A$$

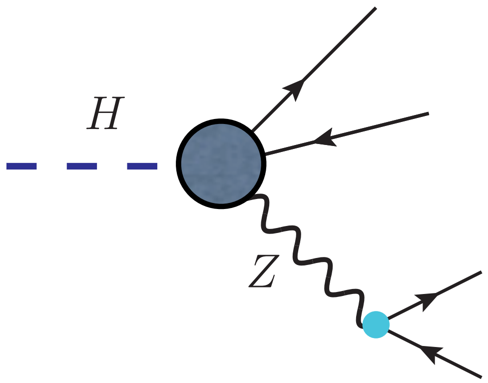
only right-handed couplings are non-vanishing: $c_L = 0$

- Order of magnitude agreement with the constraints on c_R from Pomarol and Riva '14

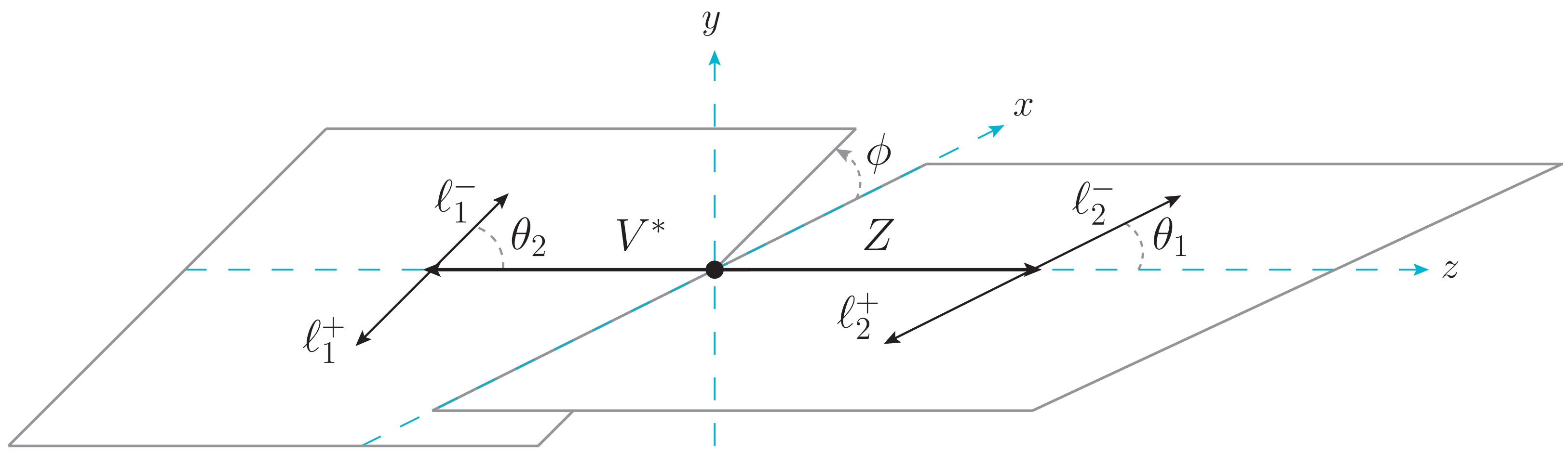
see also Alonso, Jenkins, Manohar and Trott '13

Form factors and angular structures

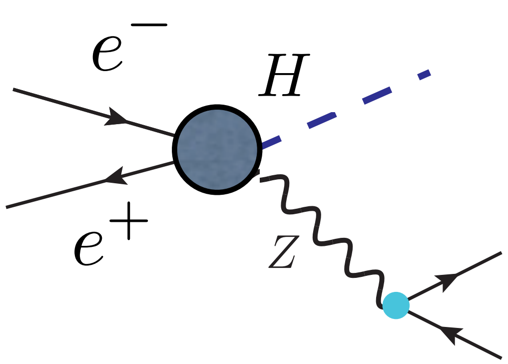
- Two crossing symmetric processes



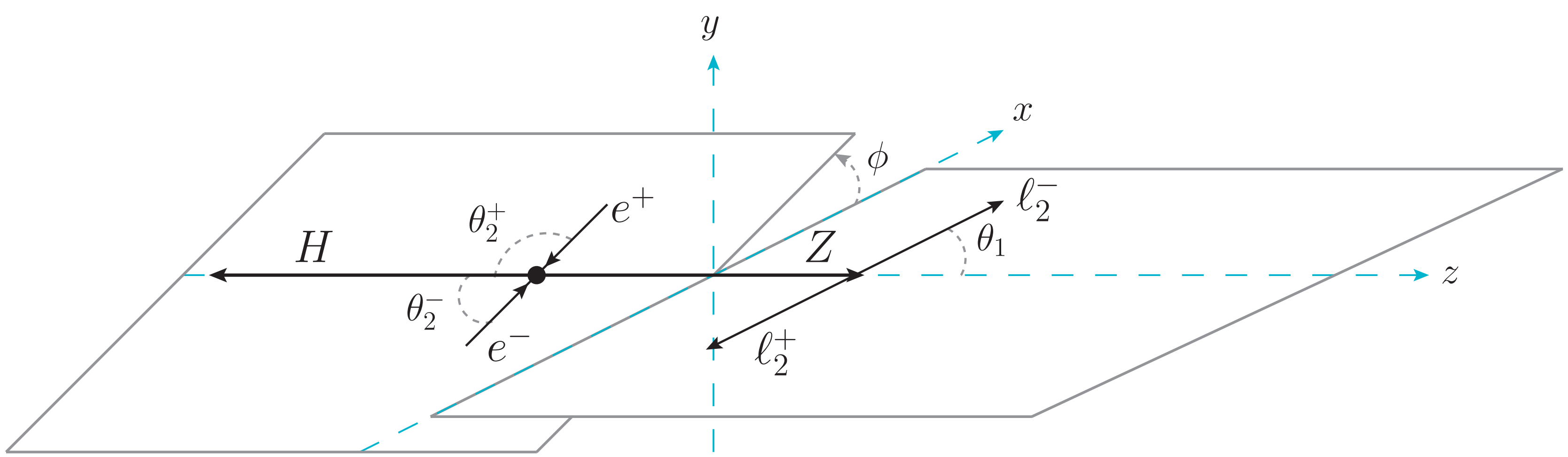
$H \to Z\ell^+\ell^- \to 4\ell$



$$\frac{d^4\Gamma}{dq^2 d\cos\theta_1 d\cos\theta_2 d\phi} = \frac{1}{m_H}\mathcal{N}(q^2)\,\mathcal{J}(q^2,\theta_1,\theta_2,\phi).$$



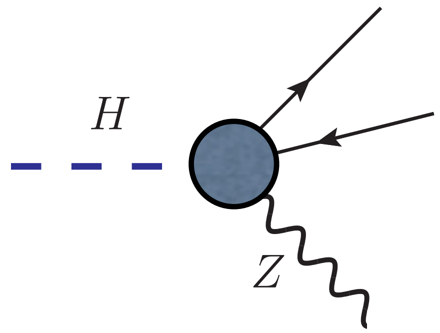
$e^+e^- \to HZ \to H\ell\ell$



$$\frac{d\sigma}{d\cos\theta_1\, d\cos\theta_2 d\phi} = \frac{1}{m_H^2}\mathcal{N}_\sigma(q^2)\,\mathcal{J}(q^2,\theta_1,\theta_2,\phi),$$

- Higgs on shell.
- Narrow-width approximation for the *Z* propagator (on-shell *Z*).
- SM tree level + d=6 terms at tree level.
- We only keep terms up to $\mathcal{O}(1/\Lambda^2)$
- $m_\ell = 0$

- Form factors



$$\mathcal{M}^{\mu}_{HZ\ell\ell} = \frac{1}{m_H}\,\bar{u}\left[\gamma^{\mu}\,(H_{1,V} + H_{1,A}\,\gamma_5) + \frac{q^{\mu}\not{p}}{m_H^2}\,(H_{2,V} + H_{2,A}\,\gamma_5) + \frac{\epsilon^{\mu\nu\sigma\rho}p_{\nu}q_{\sigma}}{m_H^2}\,\gamma_{\rho}\,(H_{3,V} + H_{3,A}\,\gamma_5)\right]v$$

SM + $d = 6$ $d = 6$ only $d = 6$ only, CP odd

- Angular structure at order $1/\Lambda^2$

$$\begin{aligned}\mathcal{J}(q^2,\theta_1,\theta_2,\phi) \;=\;& J_1(1+\cos^2\theta_1\cos^2\theta_2+\cos^2\theta_1+\cos^2\theta_2)\\ &+J_2\sin^2\theta_1\sin^2\theta_2+J_3\cos\theta_1\cos\theta_2\\ &+(J_4\sin\theta_1\sin\theta_2+J_5\sin 2\theta_1\sin 2\theta_2)\sin\phi\\ &+(J_6\sin\theta_1\sin\theta_2+J_7\sin 2\theta_1\sin 2\theta_2)\cos\phi\\ &+J_8\sin^2\theta_1\,\sin^2\theta_2\,\sin 2\phi+J_9\sin^2\theta_1\,\sin^2\theta_2\,\cos 2\phi.\end{aligned}$$

- Decay width and cross-section only probe a specific combination

$$\frac{d\Gamma}{dq^2} \propto 4J_1 + J_2 \qquad \sigma(q^2) \propto 4J_1 + J_2$$

- Angular asymmetries that probe other angular functions

$$\mathcal{A}_\phi^{(1)} = \frac{1}{d\Gamma/dq^2}\int_0^{2\pi} d\phi\ \mathrm{sgn}(\sin\phi)\,\frac{d^2\Gamma}{dq^2 d\phi} = \frac{9\,\pi}{32}\frac{J_4}{4J_1+J_2},$$

$$\mathcal{A}_\phi^{(2)} = \frac{1}{d\Gamma/dq^2}\int_0^{2\pi} d\phi\ \mathrm{sgn}(\sin(2\phi))\,\frac{d^2\Gamma}{dq^2 d\phi} = \frac{2}{\pi}\frac{J_8}{4J_1+J_2},$$

$$\mathcal{A}_\phi^{(3)} = \frac{1}{d\Gamma/dq^2}\int_0^{2\pi} d\phi\ \mathrm{sgn}(\cos\phi)\,\frac{d^2\Gamma}{dq^2 d\phi} = \frac{9\,\pi}{32}\frac{J_6}{4J_1+J_2},$$

$$\mathcal{A}_{c\theta_1,c\theta_2} = \frac{1}{d\Gamma/dq^2}\int_{-1}^{1} d\cos\theta_1\,\mathrm{sgn}(\cos\theta_1)\int_{-1}^{1} d\cos\theta_2\,\mathrm{sgn}(\cos\theta_2)\frac{d^3\Gamma}{dq^2 d\cos\theta_1 d\cos\theta_2} = \frac{9}{16}\frac{J_3}{4J_1+J_2}.$$

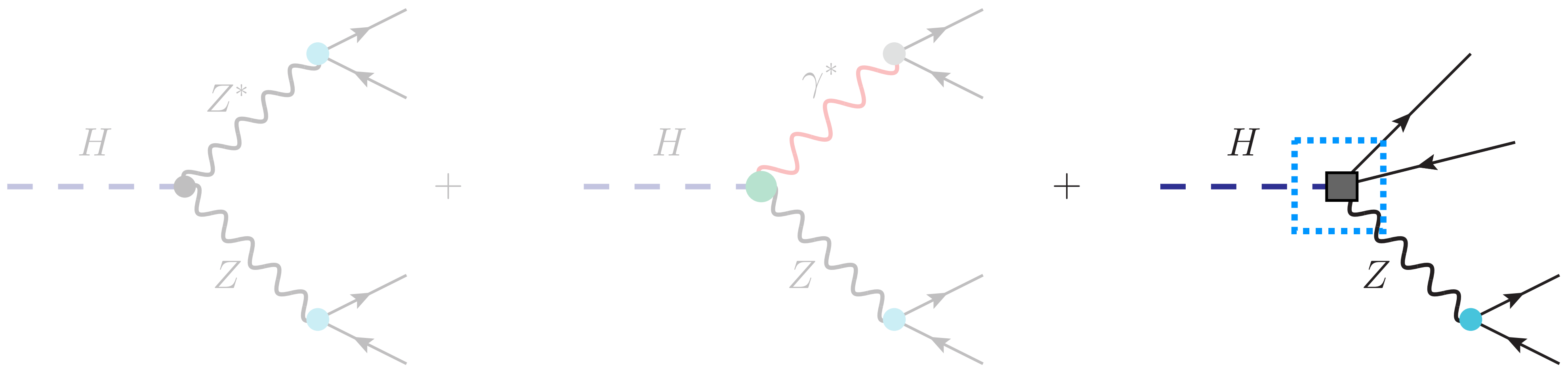
see also Buchalla, Catà, D'Ambrosio '13

- Enhancement of anomalous couplings in asymmetries is possible due to:
    - Di-lepton invariant mass
    - Smallness of the vector coupling of Z to fermions in SM

$$g_V \propto (1-4s_W^2)$$

Main results

Contact *HZll* couplings



$\alpha_{V,A}$

Main results: contact *HZll* couplings

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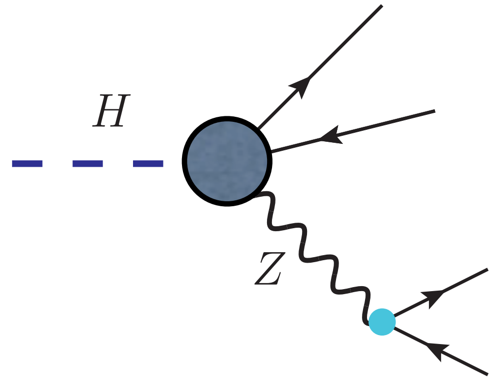
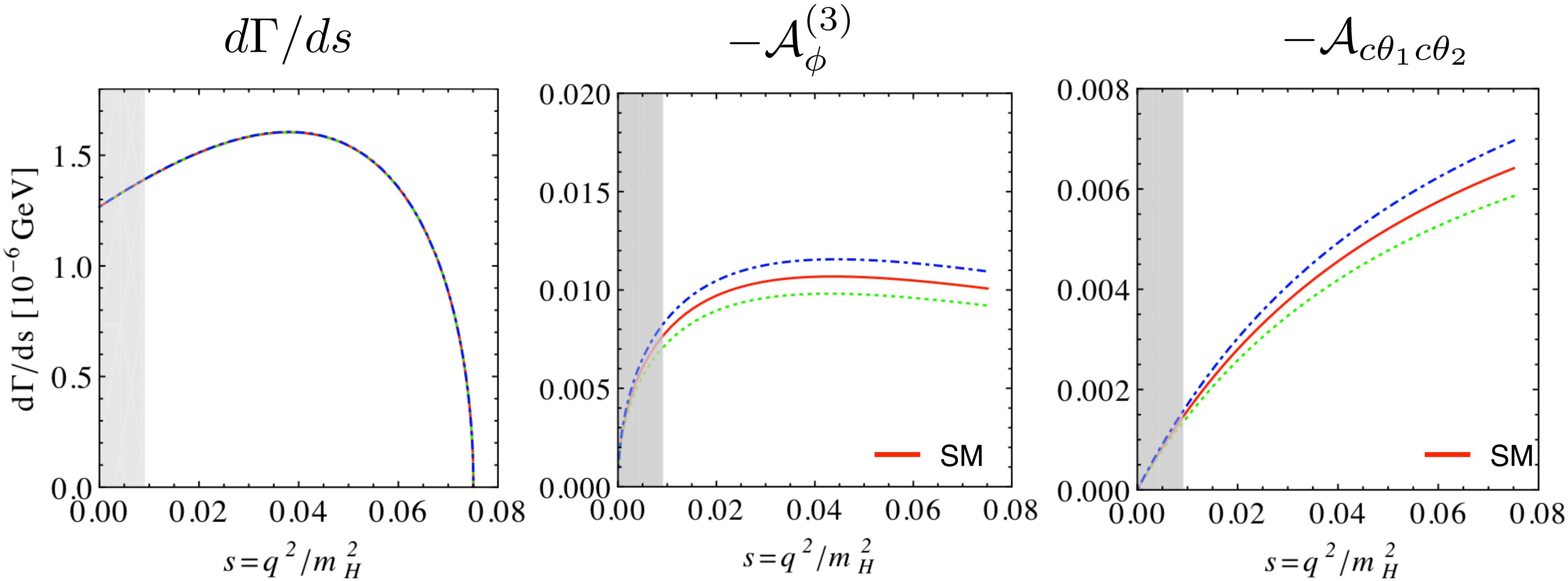


- Vector contact coupling $HZ\ell\ell$



see also Buchalla, Catà, D'Ambrosio '13

$\widehat{\alpha}^{V,A}_{\Phi\ell} \in [-5,5]\times 10^{-3}$

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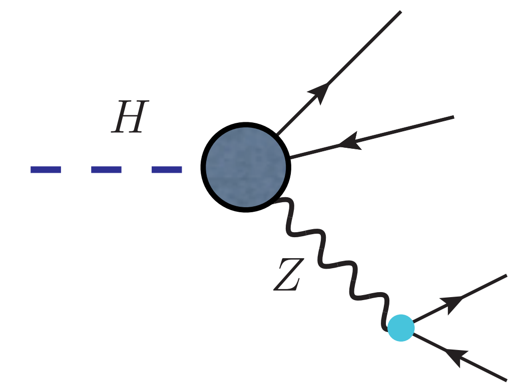

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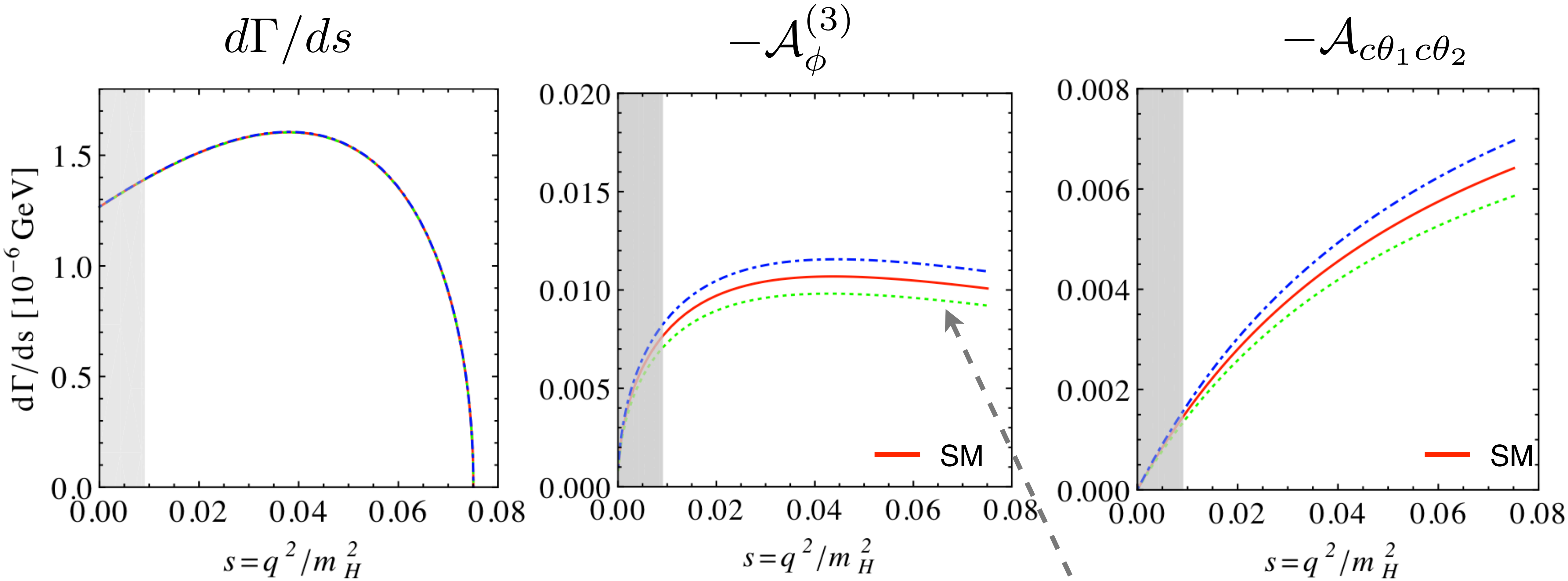

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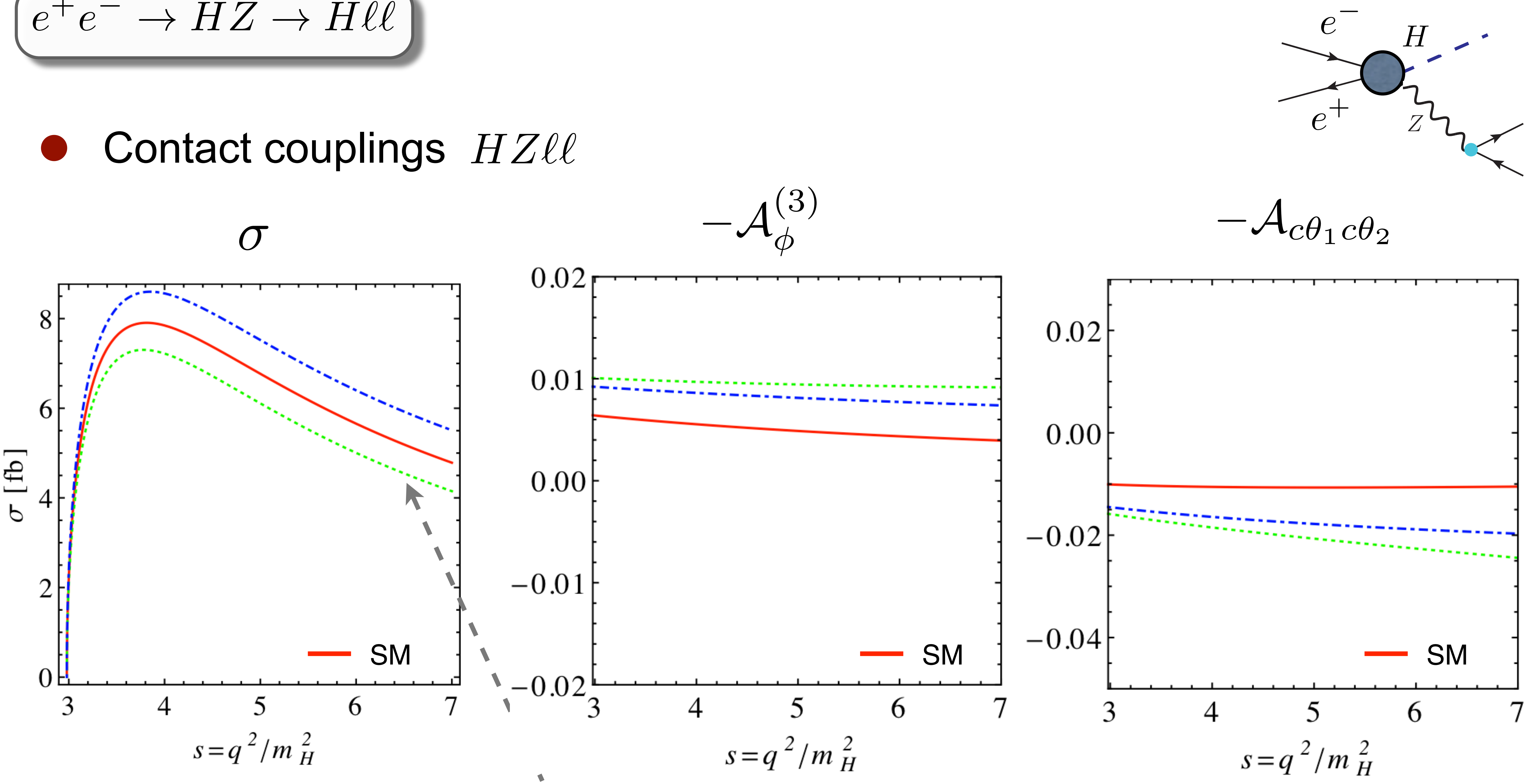
$$-\mathcal{A}_\phi^{(3)} \simeq \frac{9\pi\sqrt{2}}{2}\frac{\bar{g}_V^2}{\bar{g}_A^2}\frac{\sqrt{s}}{1+16s}\left(1+\hat{\alpha}^A_{\Phi\ell}+\frac{\bar{g}_A}{\bar{g}_V}\hat{\alpha}^V_{\Phi\ell}\right)$$

- No enhancement of the axial couplings

$\hat{\alpha}^{V,A}_{\Phi\ell} \in [-5,5]\times 10^{-3}$

$e^+e^- \to HZ \to H\ell\ell$

- Contact couplings $HZ\ell\ell$

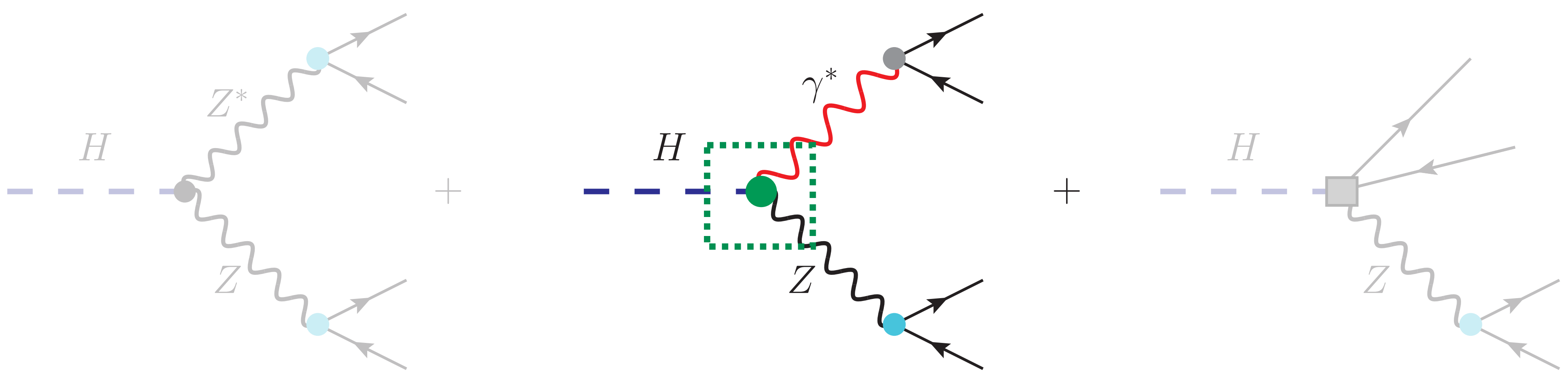


$$\sigma \simeq \sqrt{2}\, m_H^2\, G_F\, \bar{g}_A^4\, \frac{s+3}{s-1}\, [1 - 2(1+2s)\,\widehat{\alpha}_{\Phi\ell}^A]$$

$\widehat{\alpha}_{\Phi\ell}^{V,A} \in [-5, 5] \times 10^{-3}$

- Enhanced contribution of axial couplings to the cross-section

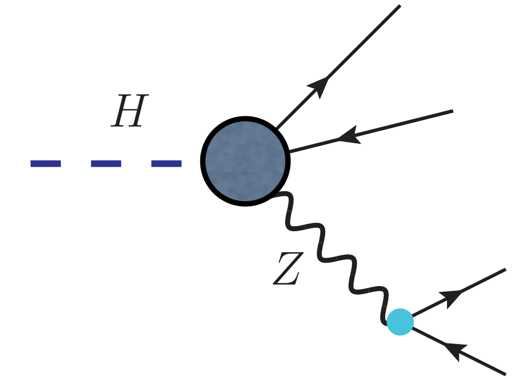
HAZ coupling



α_{AZ}

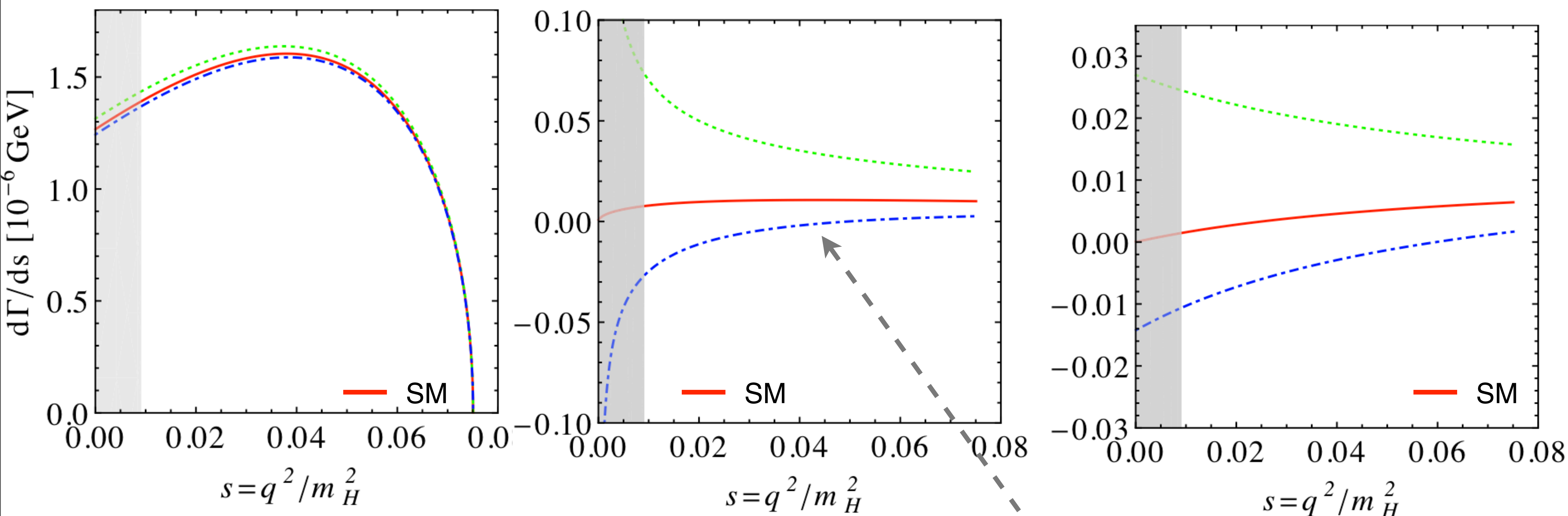
Main results: *HAZ* coupling

$H \to Z\ell^+\ell^- \to 4\ell$



- Contact couplings *HAZ*

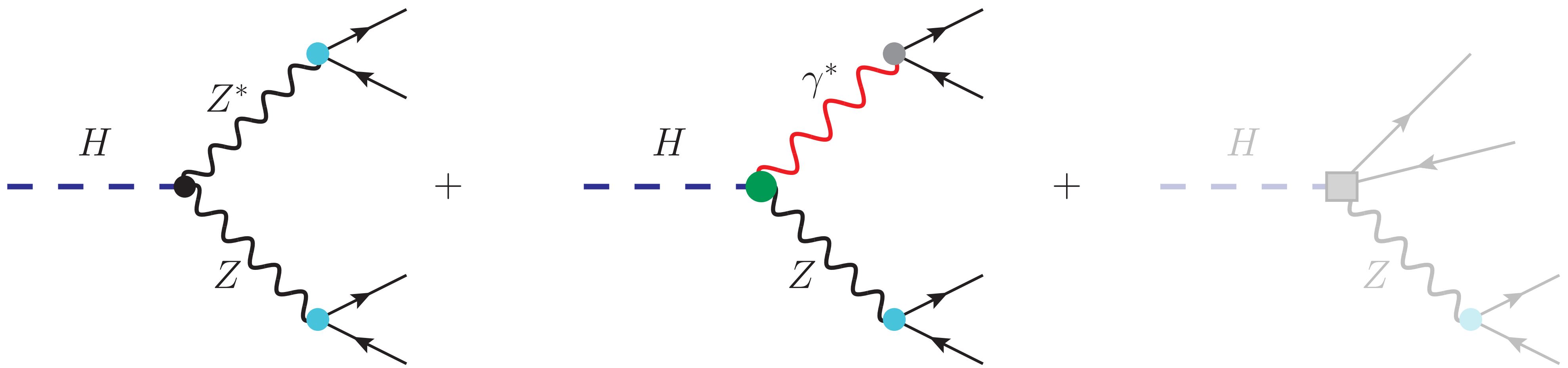
$d\Gamma/ds$ $\qquad -\mathcal{A}_{\phi}^{(3)}$ $\qquad -\mathcal{A}_{c\theta_1 c\theta_2}$



$$-\mathcal{A}_{\phi}^{(3)} \simeq \frac{9\pi\sqrt{2}}{2}\frac{\bar{g}_V^2}{\bar{g}_A^2}\frac{\sqrt{s}}{1+16s}\left(1-\frac{g_{\rm em}\,Q_\ell}{8\,\bar{g}_V\,s}\widehat{\alpha}_{AZ}\right)$$

$$\widehat{\alpha}_{AZ} \in [-1.3, 2.6] \times 10^{-2}$$

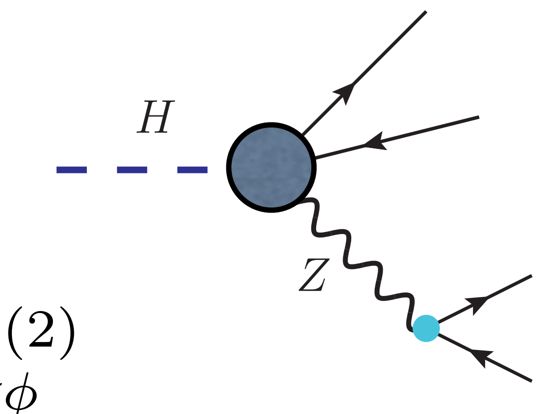
CP odd couplings



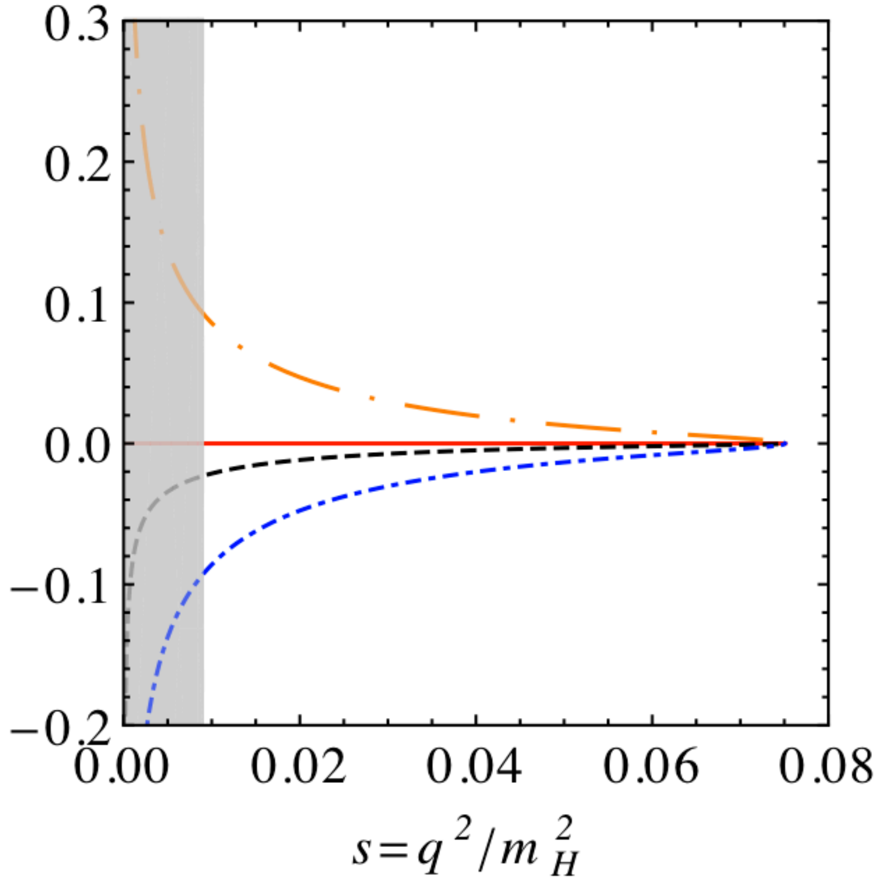
$\alpha_{Z\widetilde{Z}}$ $\alpha_{A\widetilde{Z}}$

Main results: CP odd couplings

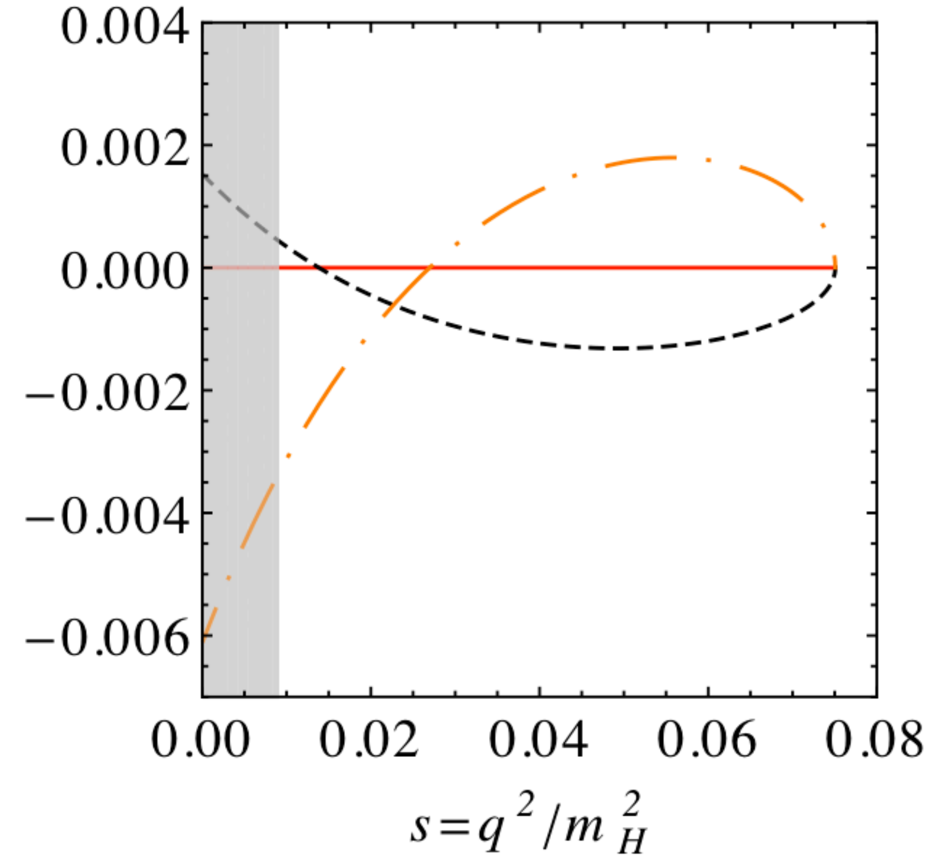
$H \to Z\ell^+\ell^- \to 4\ell$



$\mathcal{A}_\phi^{(1)}$



$\mathcal{A}_\phi^{(2)}$



- Dominated by $\alpha_{A\widetilde{Z}}$
- Interplay between $\alpha_{A\widetilde{Z}}$ and $\alpha_{Z\widetilde{Z}}$

$(\widehat{\alpha}_{Z\widetilde{Z}}, \widehat{\alpha}_{A\widetilde{Z}}) = (4, -4) \times 10^{-2}$

$(\widehat{\alpha}_{Z\widetilde{Z}}, \widehat{\alpha}_{A\widetilde{Z}}) = (4, 4) \times 10^{-2}$

$(\widehat{\alpha}_{Z\widetilde{Z}}, \widehat{\alpha}_{A\widetilde{Z}}) = (-2, -1) \times 10^{-2}$

$$\mathcal{A}_\phi^{(2)} \simeq \frac{16\sqrt{1-12s}}{\pi(1+16s)} \left(s\,\alpha_{Z\widetilde{Z}} + \frac{\bar{g}_V\, g_{\rm em}\, Q_\ell}{4\bar{g}_A^2} \widehat{\alpha}_{A\widetilde{Z}} \right)$$

Conclusions

Conclusions

- Some angular asymmetries are much more sensitive to anomalous couplings than the decay width or the cross section.

- Relatively large effects from *HAZ* are still allowed.

- Effects of *HZll* couplings are small (couplings are quite constrained by data).

see also Buchalla, Catà, D'Ambrosio '13

- Interesting asymmetries are small in absolute terms (<10%)

- e+e- is in general better suited for the study of *HZll* anomalous couplings.