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

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In collaboration with Martin Beneke (TU Munich) and Yu-Ming Wang (U. of Vienna)

-- M Beneke, DB, Y.-M. Wang, JHEP 1411 (2014) [arXiv:1406.1361]

IFSC ICTP SAIFR FAPESP ICTP unesp IFT

- ~ 80 faculty
- ~ 100 post-docs
- ~ 210 grad. students
- Research: a little bit of everything, but a lot of optics and applied physics.

- Attilio Cucchieri
- Betti Hartmann
- Tereza Mendes
- Luiz Vitor de Souza
- Manuela Vecchi
- DB

Gauge theories on the lattice (**AC** and **TM**), AdS/CFT (**BH**), Astroparticles-AMS (**MV**), Pierre Auger (**LVS**), QCD, Hadrons,Higgs (**DB**)

Outline

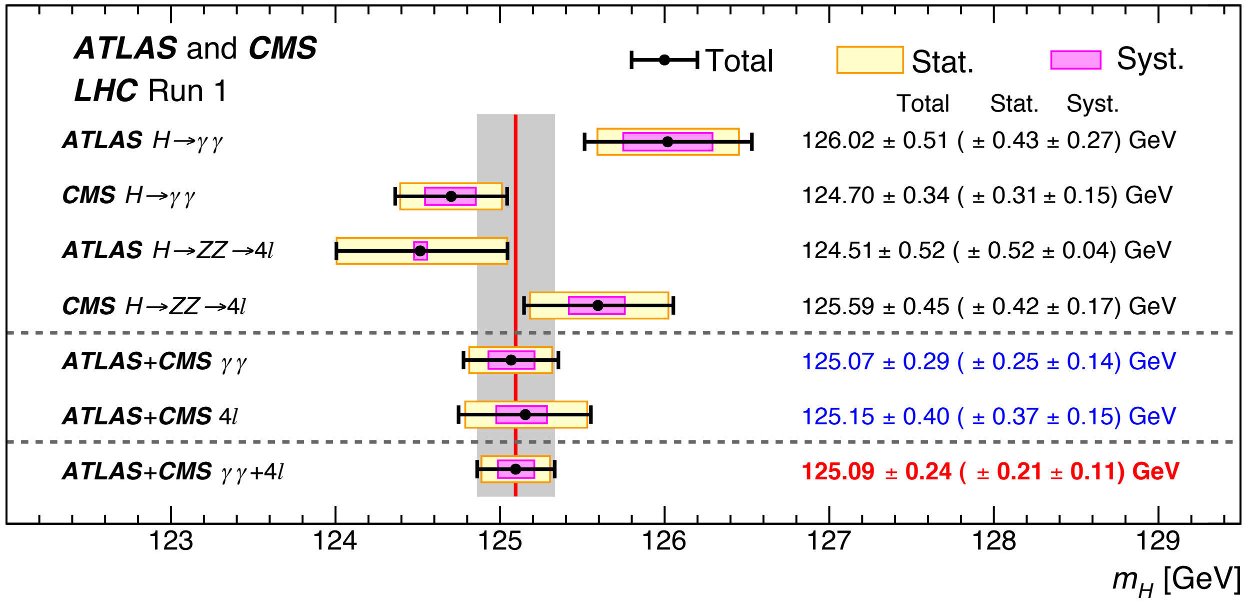
- Introduction
- Lagrangian and bases
- Operators and couplings
- Form factors and angular structures
- Main results

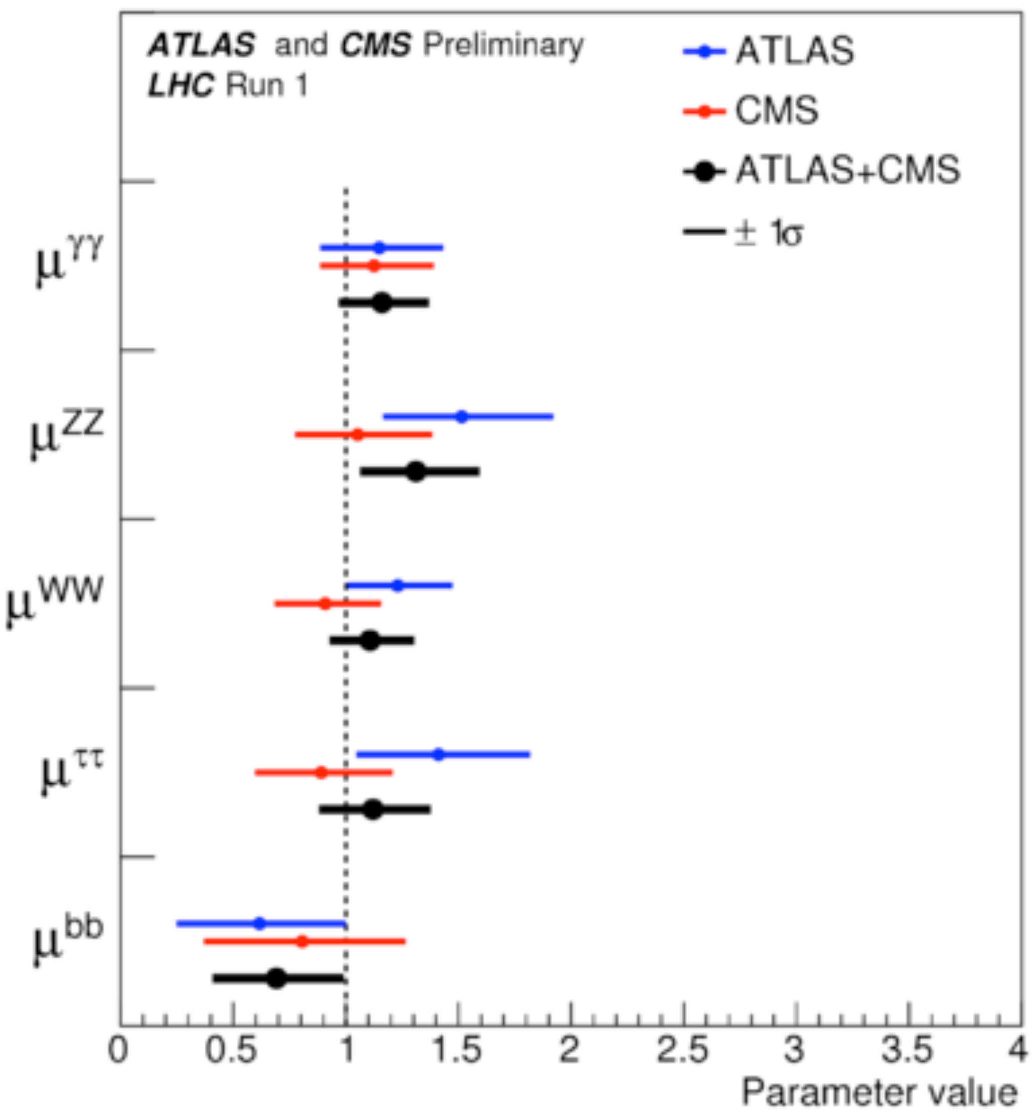
The Higgs looks like the SM Higgs

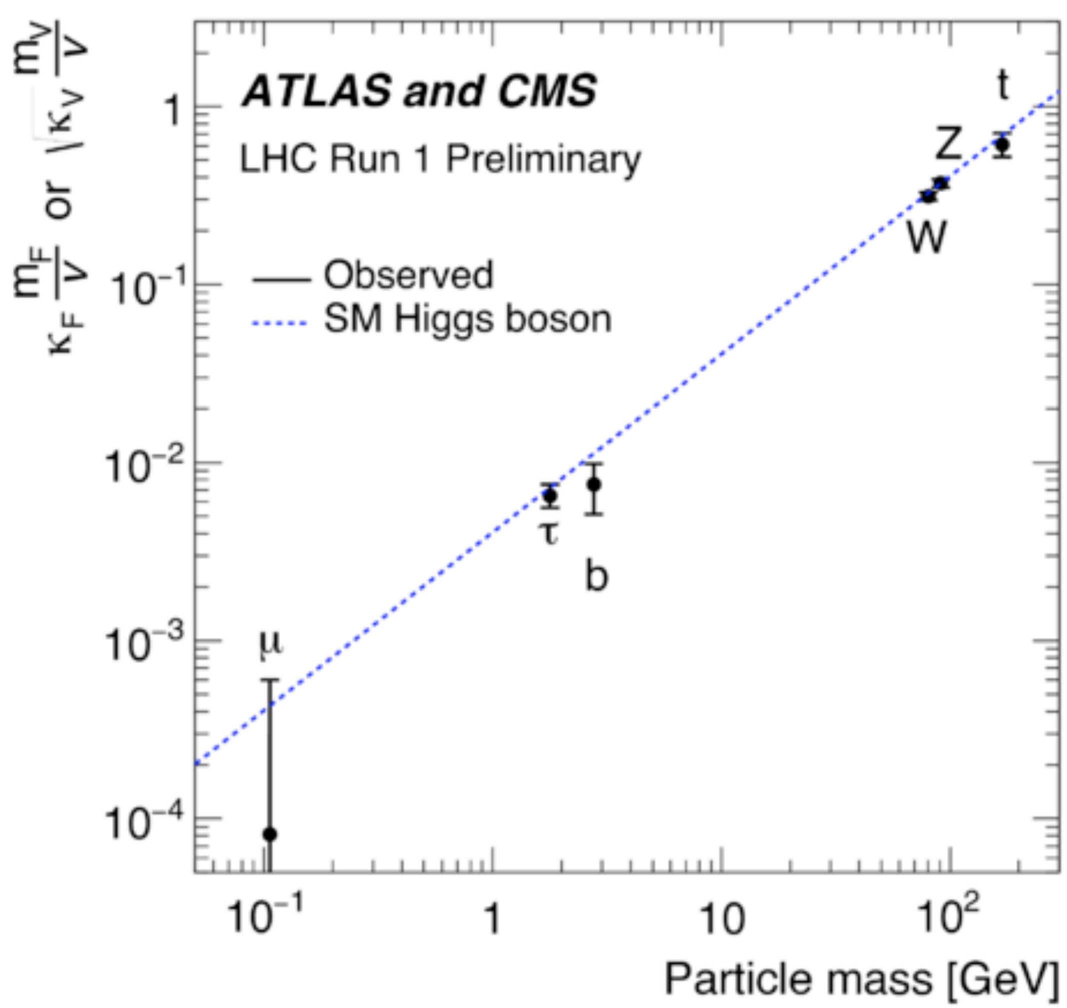
- Higgs properties consistent with SM

$$m_H = 125.09 \pm 0.21_{\rm stat} \pm 0.11_{\rm syst} \;\; {\rm GeV}$$

ATLAS+CMS, PRL 114 (2015)







ATLAS+CMS (2015)

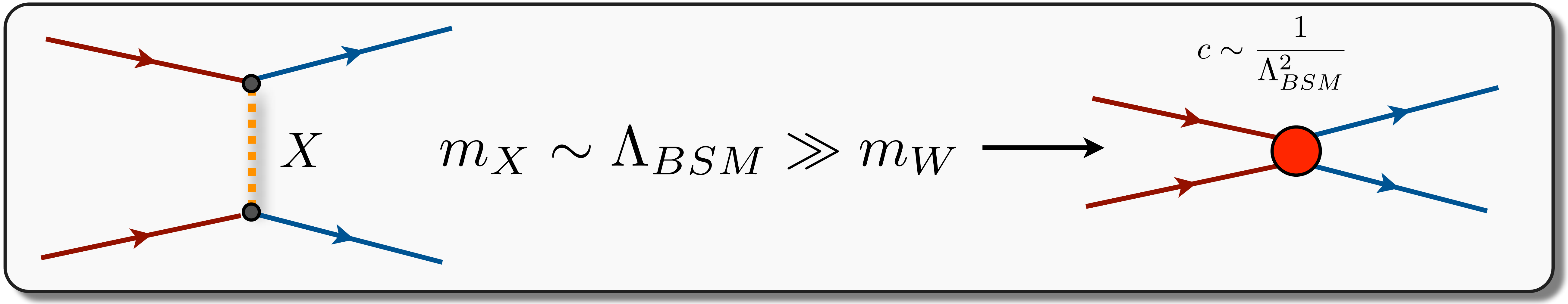
Standard problems

- The Higgs is probably not the end of particle physics. The SM is not perfect.
    - Neutrino masses
    - Predominance of matter in the universe (not enough CP violation)
    - What is dark matter made of?
    - Fine tuning problems (e.g. hierarchy problem)
    - Hierarchy of masses
    - Unification of forces?
    - etc

- The LHC didn't find any BSM particle. New states probably live at a much higher scale

$$m_X \sim \Lambda_{BSM} \gg m_W$$

- Interactions mediated by the particle(s) *X* generate contact interactions at the EW scale

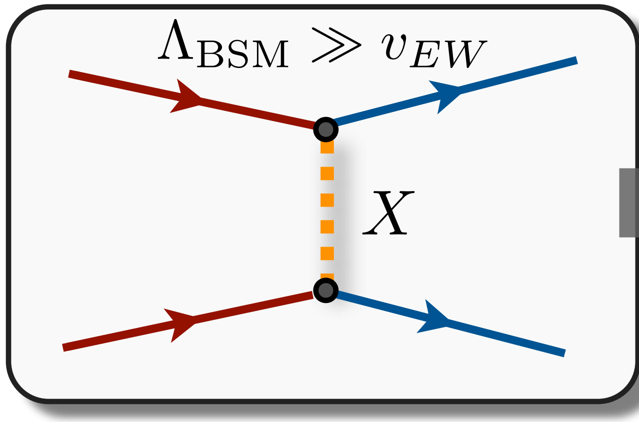


Since we don't see *X* it may be better to work with the effective operators

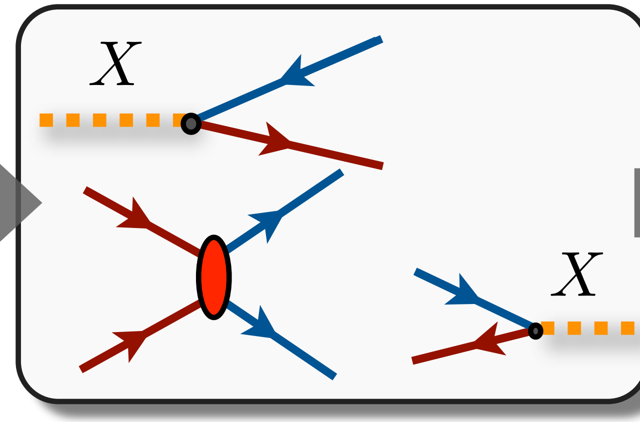
Two different strategies to look for BSM physics

1.

write a theory



make predictions



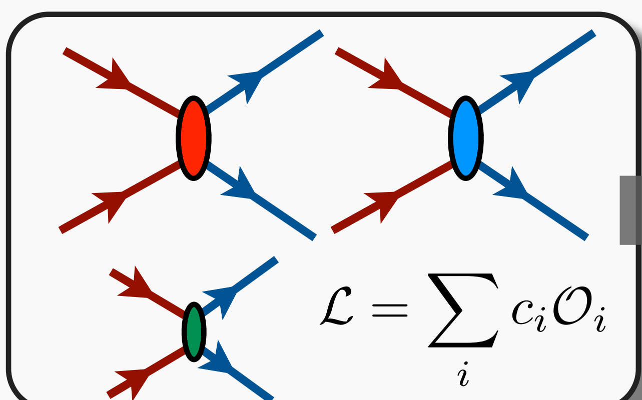
confirm/reject

:-) go to Sthlm

:-(go back two steps

2.

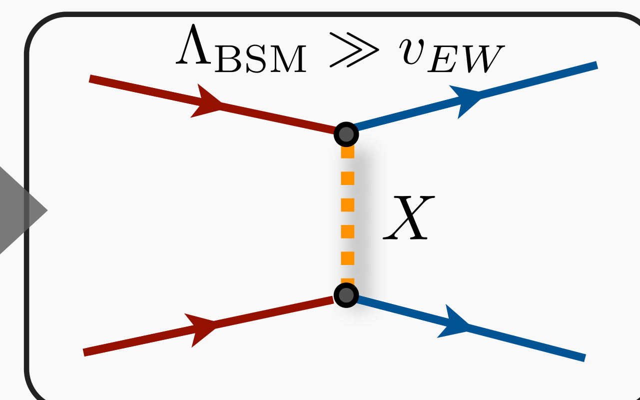
write the EFT



look for any effect

$c_1 = 0, \; c_2 = 0, \; c_3 \neq 0, \; \cdots$

try to infer the UV theory

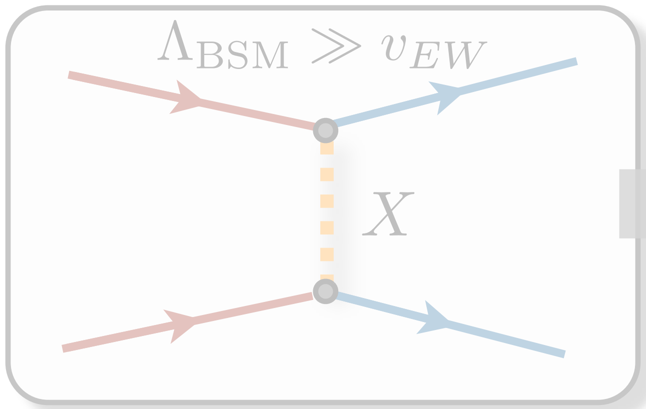


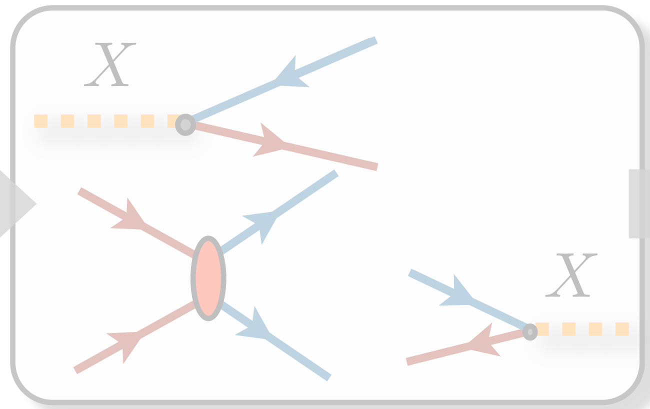
Certainly less ambitious. More straightforward way to use LHC data at present.

Two different strategies to look for BSM physics

write a theory → make predictions → confirm/reject

1.





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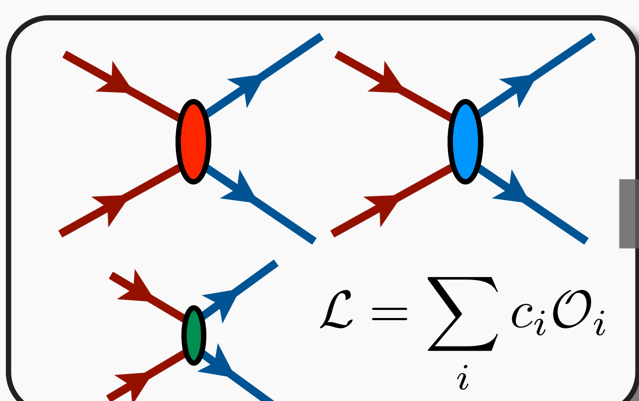
write the EFT → look for any effect → try to infer the UV theory

2.



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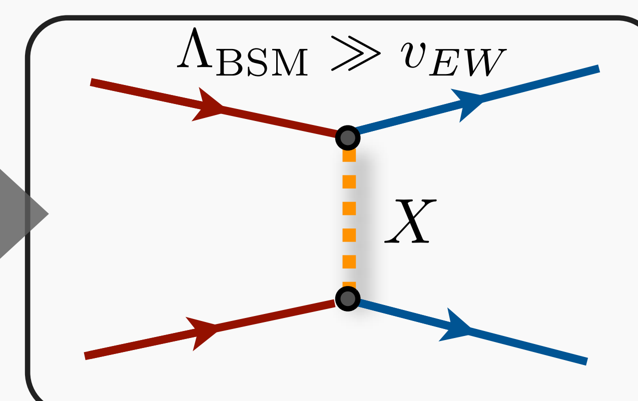

Certainly less ambitious. More straightforward way to use LHC data at present.

Lagrangians and bases

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

Many assumptions to get only 59 ops.
- B conserv.
- L conserv.
- MFV

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

Buchmüller&Wyler '86
Grzadkowski et al '10

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

- Symmetry linearly realized
- Power counting: $\mathcal{L}^{(6)} \sim \dfrac{v^2}{\Lambda^2}, \qquad \mathcal{L}^{(8)} \sim \dfrac{v^4}{\Lambda^4}, \cdots$
- Leading effects from interference with SM

$$\boxed{\mathcal{L}^{(6)} \times \mathcal{L}^{(4)} \sim \frac{v^2}{\Lambda^2}}$$

- Many different operator bases allowed and in use.
- Here we use the "Warsaw basis"

B. Grzadkowski, M. Iskrzynski, M. Misiak, J. Rosiek, JHEP '10

- Motivated mainly by (some idea of) simplicity (less derivatives)
- First complete basis of all 59 operators that was not redundant
- Corrects redundancies found in the pioneering work of Buchmüller&Wyler '86

$\boxed{1} : X^3$ $\quad\boxed{2} : \varphi^6$ $\quad\boxed{3} : \varphi^4 D^2$ $\quad\boxed{4} : \psi^2 \varphi^3$

$\boxed{5} : X^2 \varphi^2$ $\quad\boxed{6} : \psi^2 X \varphi$ $\quad\boxed{7} : \psi^2 \varphi^2 D$ $\quad\boxed{8} : \psi^4$

$$\psi = q, u, d, l, e, \qquad X = G^A_{\mu\nu}, W^I_{\mu\nu}, B_{\mu\nu} \qquad \varphi \equiv \Phi$$

1	X^3	2	φ^6 and $\varphi^4 D^2$	3	$\psi^2\varphi^3$
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

4	$X^2\varphi^2$	5	$\psi^2 X\varphi$	6	$\psi^2\varphi^2 D$
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

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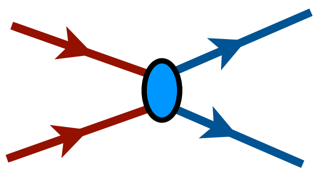
Warsaw basis

$\boxed{8}$



$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

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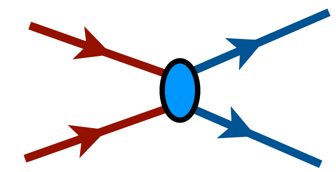

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$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
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$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Correlations: not everything is allowed (symmetries).

- Example: an operator from the class $\boxed{6}$

$$\mathcal{O}_{\Phi\,\ell}^{(1)} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{\ell}\gamma^\mu \ell)$$

Correlations: not everything is allowed (symmetries).

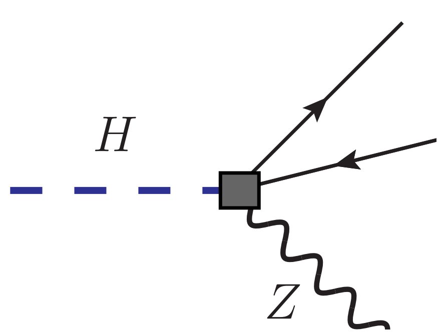
- Example: an operator from the class $\boxed{6}$

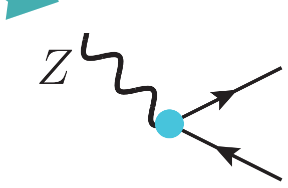
$$D_\mu = \partial_\mu + ig\frac{\tau^I}{2}W^I_\mu + ig'YB_\mu,$$

$$\frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$$

$$\mathcal{O}^{(1)}_{\Phi\,\ell} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{\ell}\gamma^\mu\ell)$$

$$\sqrt{2}\,G_F\,m_Z\,\frac{v^2}{\Lambda^2}\alpha^{(1)}_{\Phi\ell}HZ_\mu\bar{\ell}\gamma^\mu\ell + \frac{m_Z}{2}\,(\sqrt{2}G_F)^{1/2}\,\frac{v^2}{\Lambda^2}\alpha^{(1)}_{\Phi\ell}\,Z_\mu\bar{\ell}\gamma^\mu\ell + \cdots$$

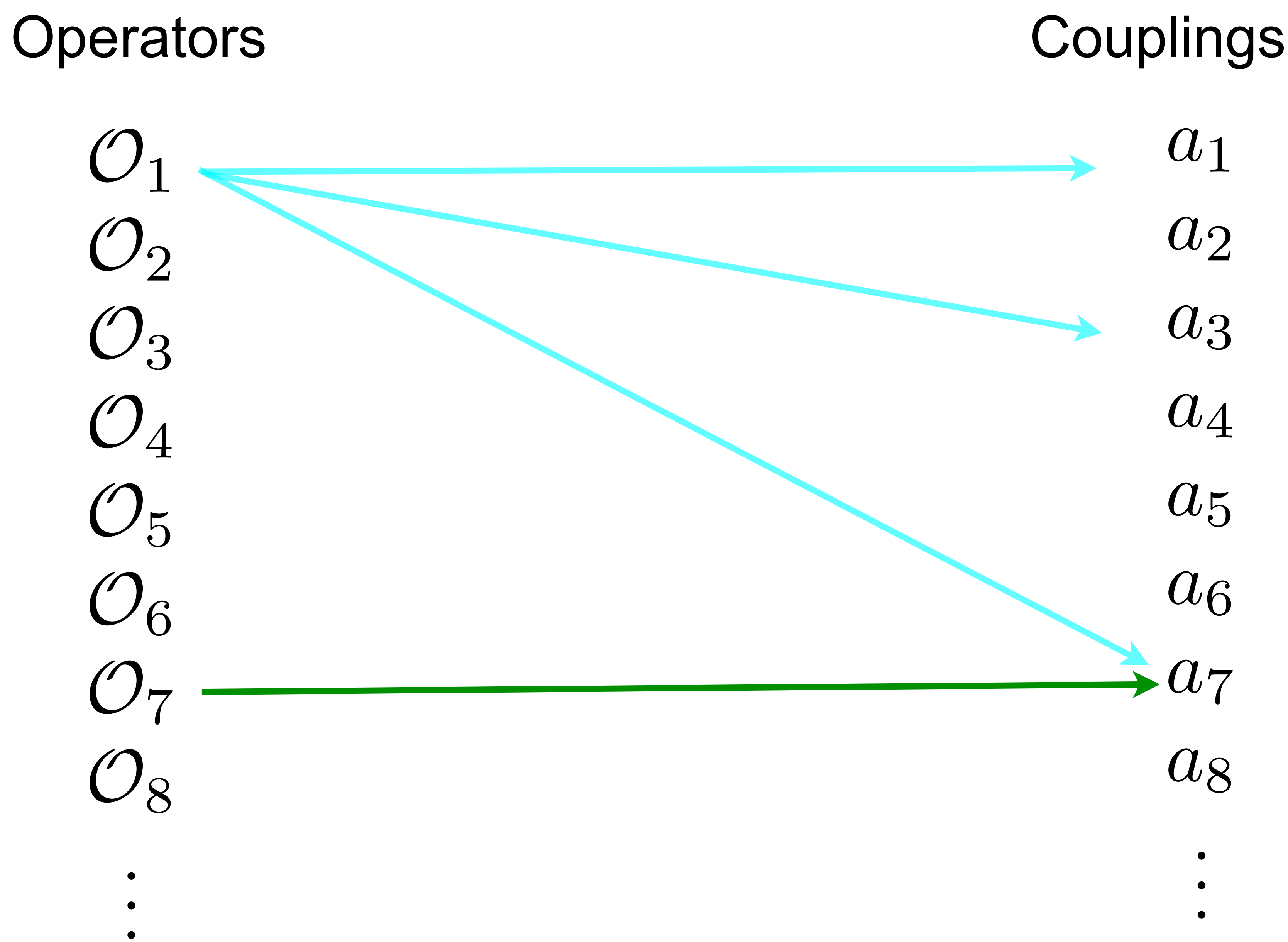




Effects are correlated

Operators	Couplings
$\mathcal{O}_1$	a_1
$\mathcal{O}_2$	a_2
$\mathcal{O}_3$	a_3
$\mathcal{O}_4$	a_4
$\mathcal{O}_5$	a_5
$\mathcal{O}_6$	a_6
$\mathcal{O}_7$	a_7
$\mathcal{O}_8$	a_8
$\vdots$	$\vdots$

Effects are correlated



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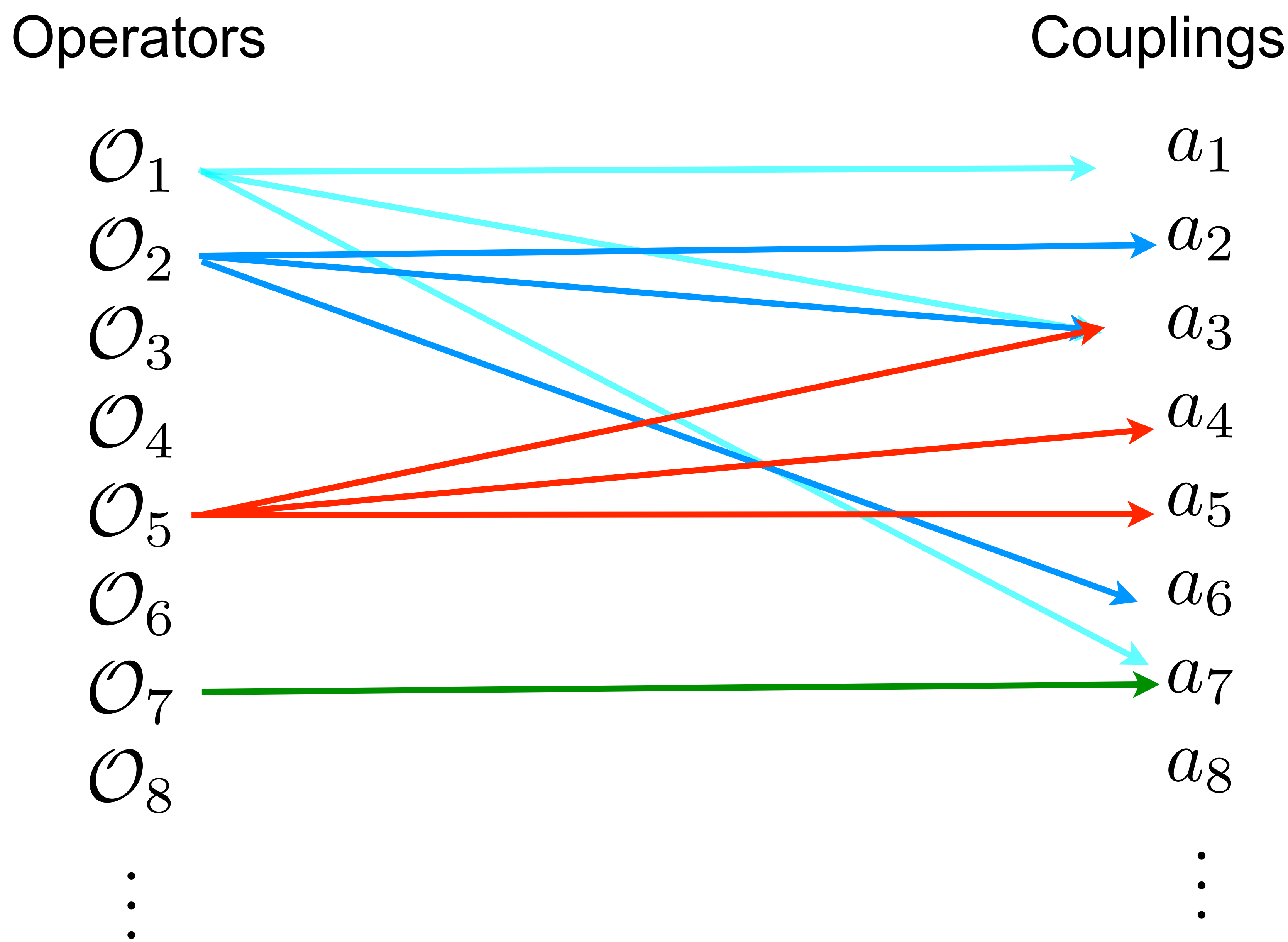


Recent developments

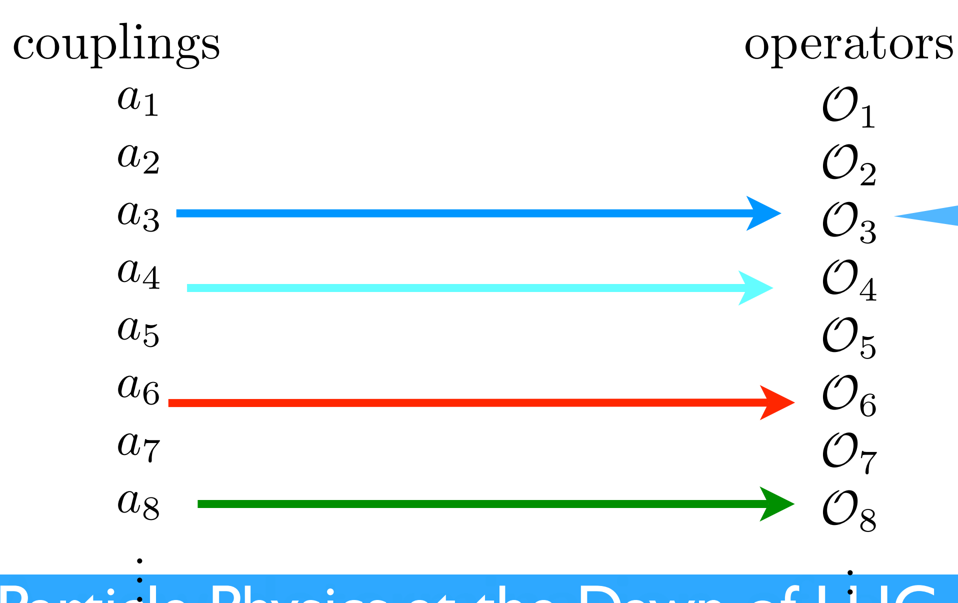
- Relations between bases, possible hierarchy of operators etc

  R. Alonso, E. Jenkins, A. Falkowski, A. Manohar, E. Massó, A. Pomarol, F. Riva, V. Sanz, M. Trott....

- Automatic translation between bases:
  Falkowski, Fuks, Mawatari, Mimasu, Riva, Sanz [1508.05895]

- Bases where the observables play a key role
  “Coupling basis” E. Massó, 1406.6376, (see also A. Falkowki, 1505.00046)

Choose a set of couplings that can be measured: $a_{h\bar{f}f}, a_{hgg}, a_{h\gamma\gamma}, \dots$ → Define as operators in the basis those related to the couplings → Additional effects are parametrized in terms of the observable couplings



Warsaw basis

$$\hat{\mathcal{O}}_i = \sum_j d_{ij} \mathcal{O}_j$$

$$a_{(hWW)_{\rm nc}} = \# a_{h\gamma\gamma} + \# a_{hZ\gamma} + \# a_{\kappa\gamma}$$

Operators and couplings

- We employ the Warsaw 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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	$\mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$ ←	
	$\mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu}B^{\mu\nu}$ ←	CP odd
	$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$ ←	

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

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

- Redefinitions

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

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

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

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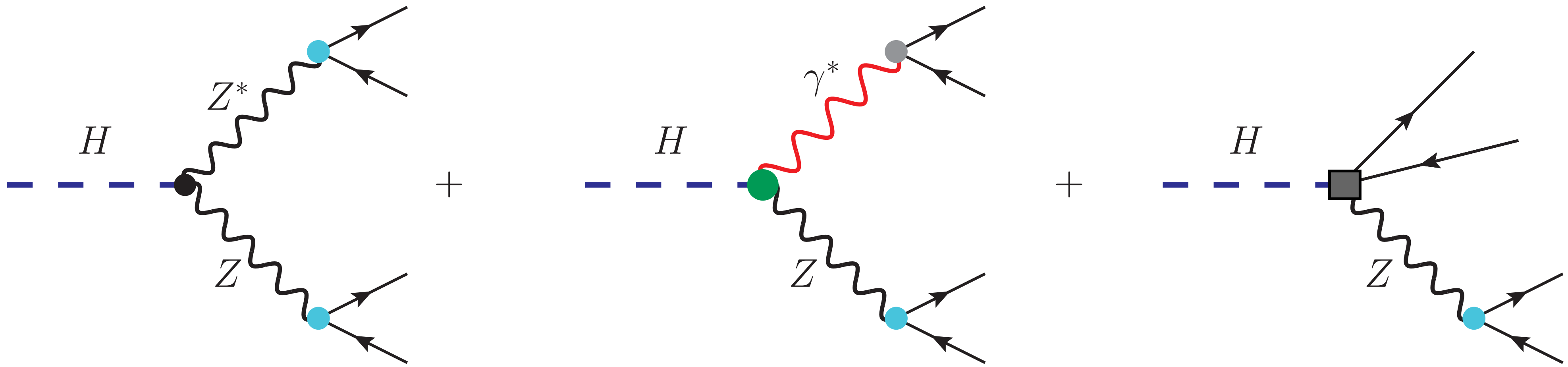
- New interactions and modifications to SM vertices

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



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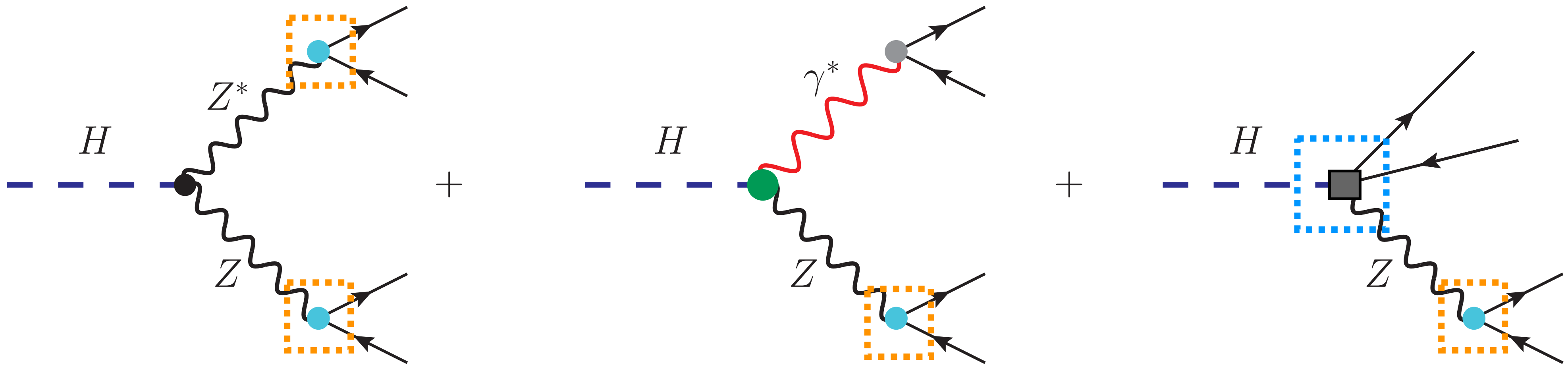

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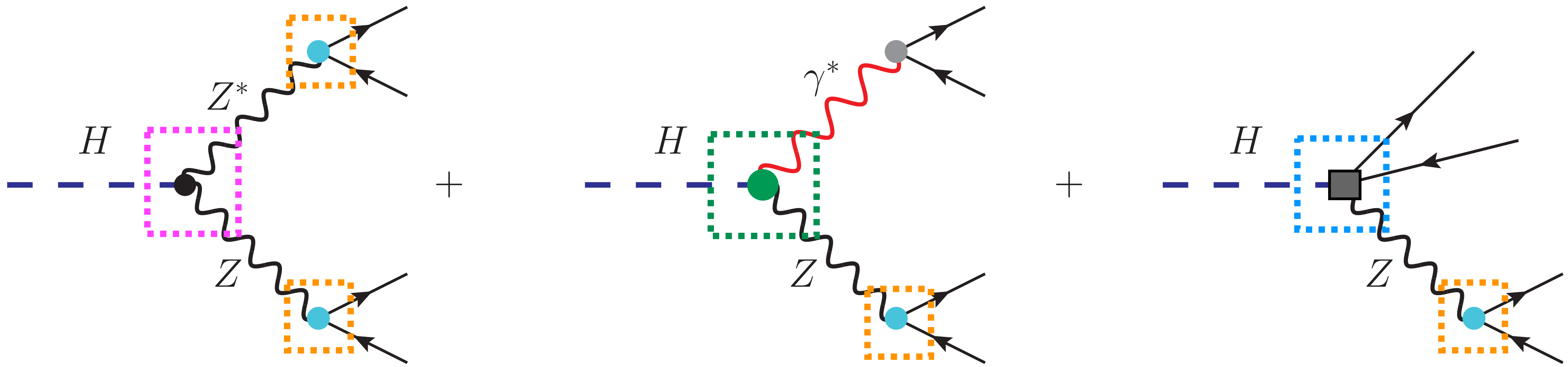

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$$\widehat{\alpha}_{AZ} \in [-1.3, 2.6] \times 10^{-2} \qquad \widehat{\alpha}_{\Phi\ell}^{V,A} \in [-5, 5] \times 10^{-3}$$

Pomarol and Riva '14

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

- Contact $HZ\ell\ell$ in the "Warsaw" basis

Grzadkowski et al '10

$$H Z_\mu \bar{\ell}\gamma^\mu\,(c_V + c_A\gamma_5)\,\ell \longrightarrow c_{V,A} = \sqrt{2}\,G_F\, m_Z\, \widehat{\alpha}_{\Phi,\ell}^{V,A} \qquad \boxed{\widehat{\alpha}_{\Phi,\ell}^{V,A} = \widehat{\alpha}_{\Phi e} \pm \left(\widehat{\alpha}_{\Phi\ell}^{(1)} + \widehat{\alpha}_{\Phi\ell}^{(3)}\right)}$$

- In other bases two 4-fermion ops. traded for two operators of the type $\Phi^2 D^2 X$

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

Elias-Miró, Espinosa, Massó, Pomarol '13

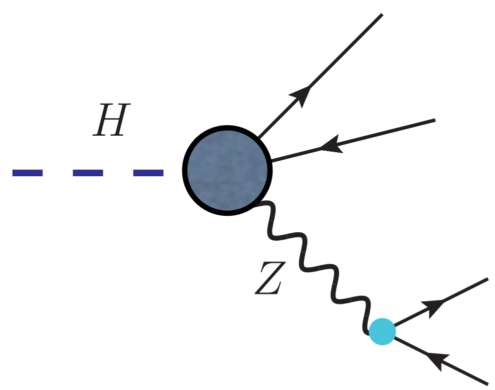
only right-handed couplings are non-vanishing: $c_L = 0$

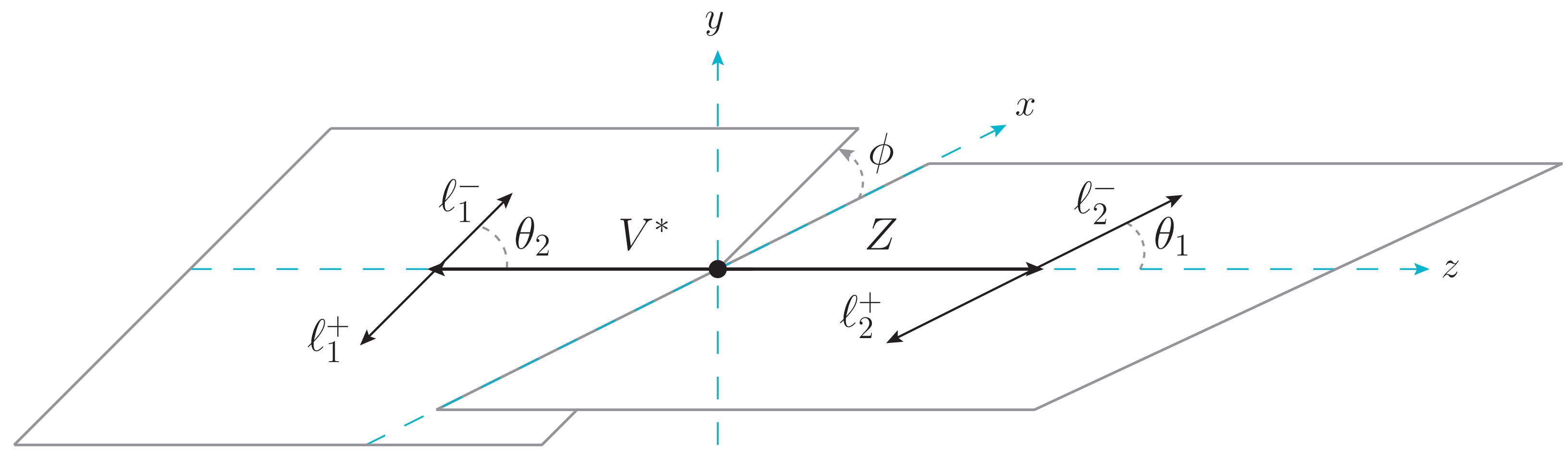
- Order of magnitude agreement with the constraints on c_R from Pomarol and Riva '14

see also Alonso, Jenkins, Manohar and Trott '13

Form factors and angular structures

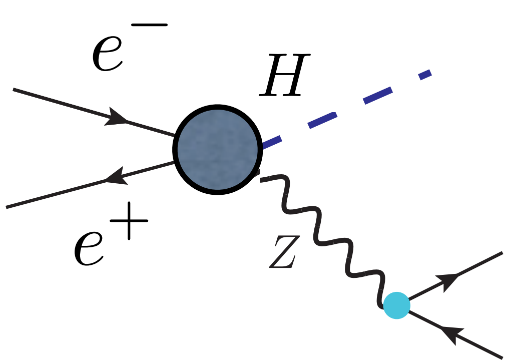
- Two crossing symmetric processes

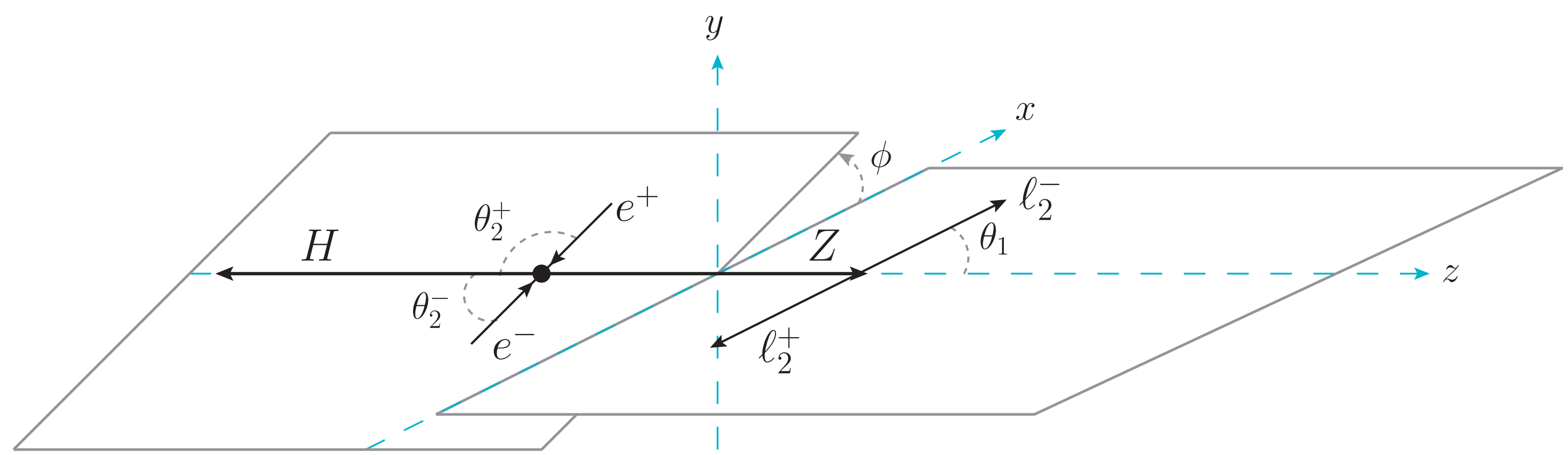




$$H \to Z\ell^+\ell^- \to 4\ell$$

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





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

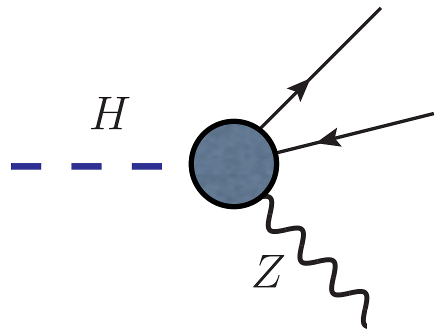
$$\frac{d\sigma}{d\cos\theta_1\, d\cos\theta_2 d\phi} = \frac{1}{m_H^2}\mathcal{N}_\sigma(q^2)\,\mathcal{J}(q^2,\theta_1,\theta_2,\phi),$$

Approximations

- 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 $\mathcal{O}(1/\Lambda^2)$ (with one exception to be discussed)
- $m_\ell = 0$

Angular structures

- 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

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

- 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

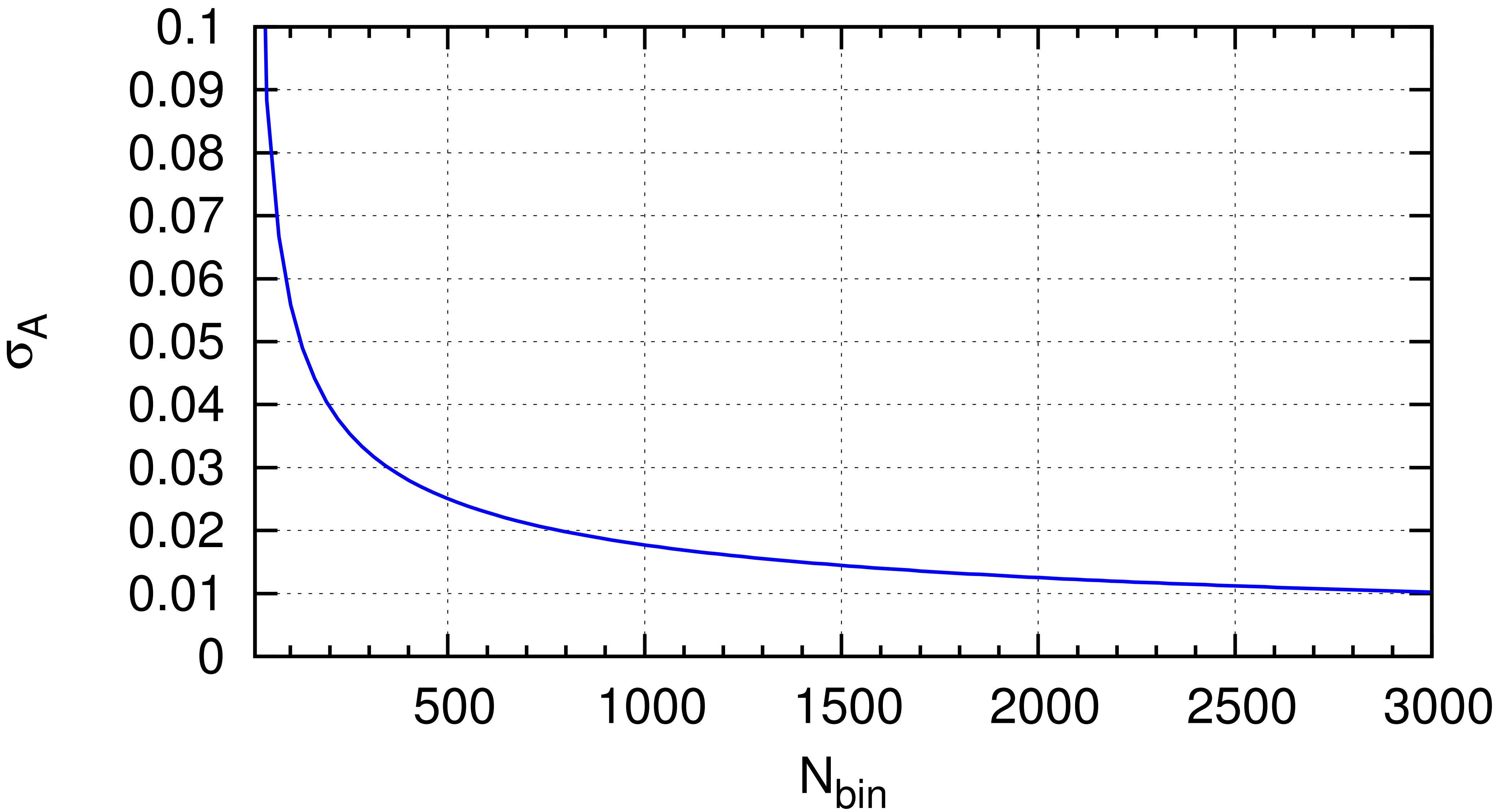
- Enhancement of anomalous couplings in asymmetries is possible due to:
  - Di-lepton invariant mass
  - Smallness of the vector coupling of *Z* to fermions in SM

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

$$\mathcal{A} = \frac{N_+ - N_-}{N_{\rm bin}} = \frac{2N_+ - N_{\rm bin}}{N_{\rm bin}}$$

- N_+ and N_bin are strongly correlated. For a small asymmetry (N+ ~ N_bin/2)

$$\sigma_A = \sqrt{\frac{3 - 2\sqrt{2}\rho}{N_{\rm bin}}} \approx 0.6\sqrt{\frac{1}{N_{\rm bin}}}$$

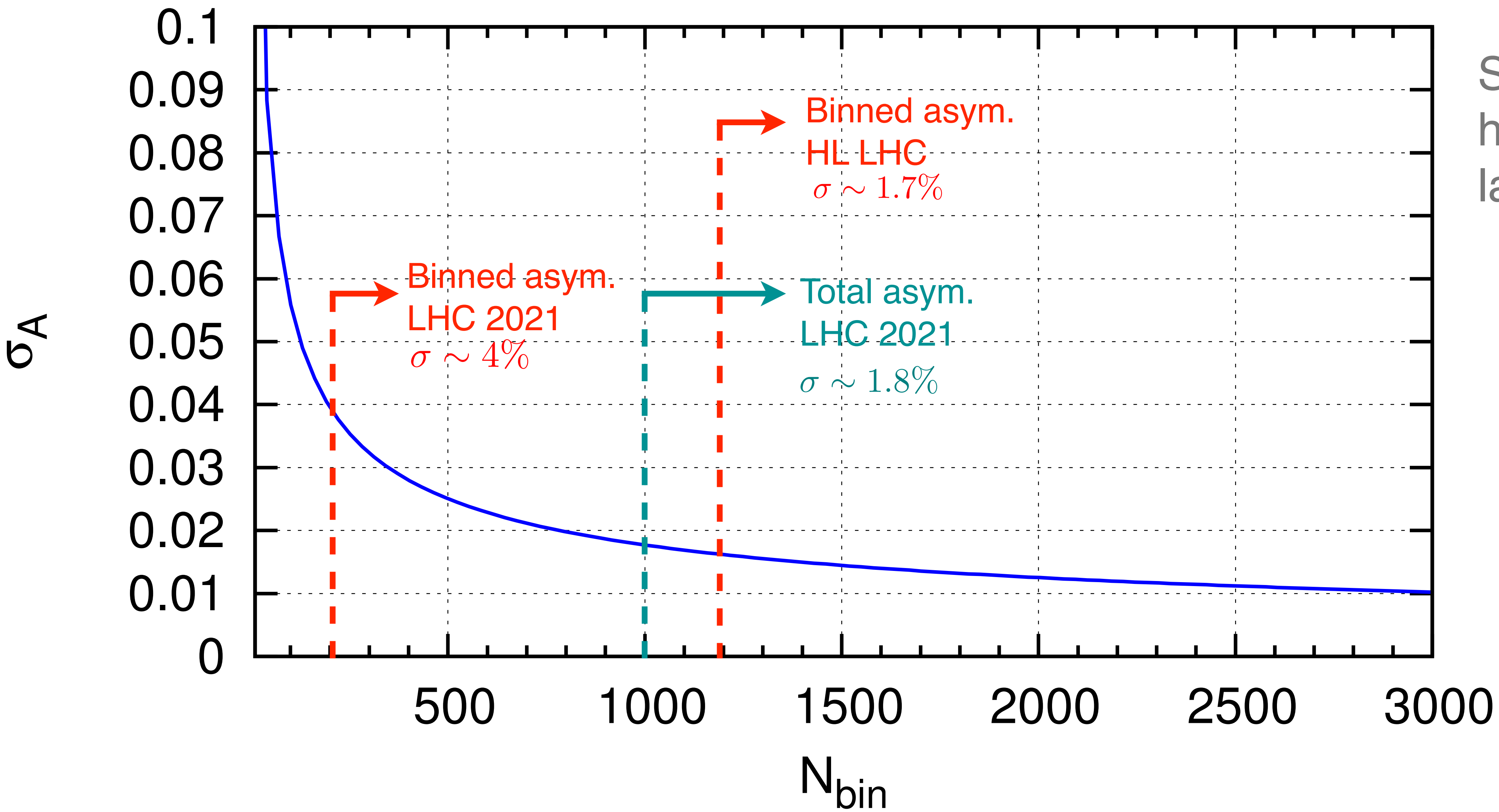


How well can an asymmetry be measured at LHC?

$$\mathcal{A} = \frac{N_+ - N_-}{N_{\rm bin}} = \frac{2N_+ - N_{\rm bin}}{N_{\rm bin}}$$

- N_+ and N_bin are strongly correlated. For a small asymmetry (N+ ~ N_bin/2)

$$\sigma_A = \sqrt{\frac{3-2\sqrt{2}\rho}{N_{\rm bin}}} \approx 0.6\sqrt{\frac{1}{N_{\rm bin}}}$$

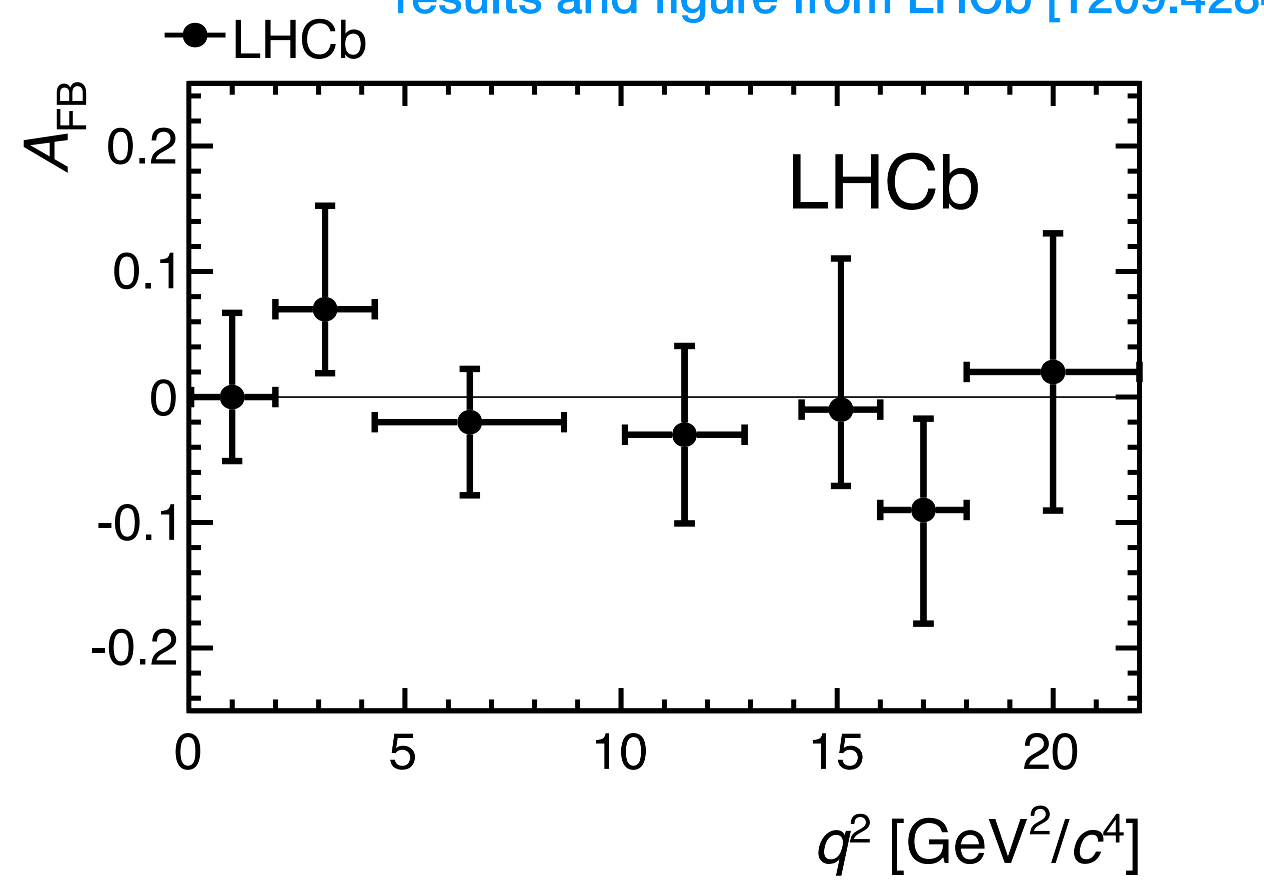


Small asymmetries have relatively large uncertainties

- $B^+ \to K^+\mu^+\mu^-$

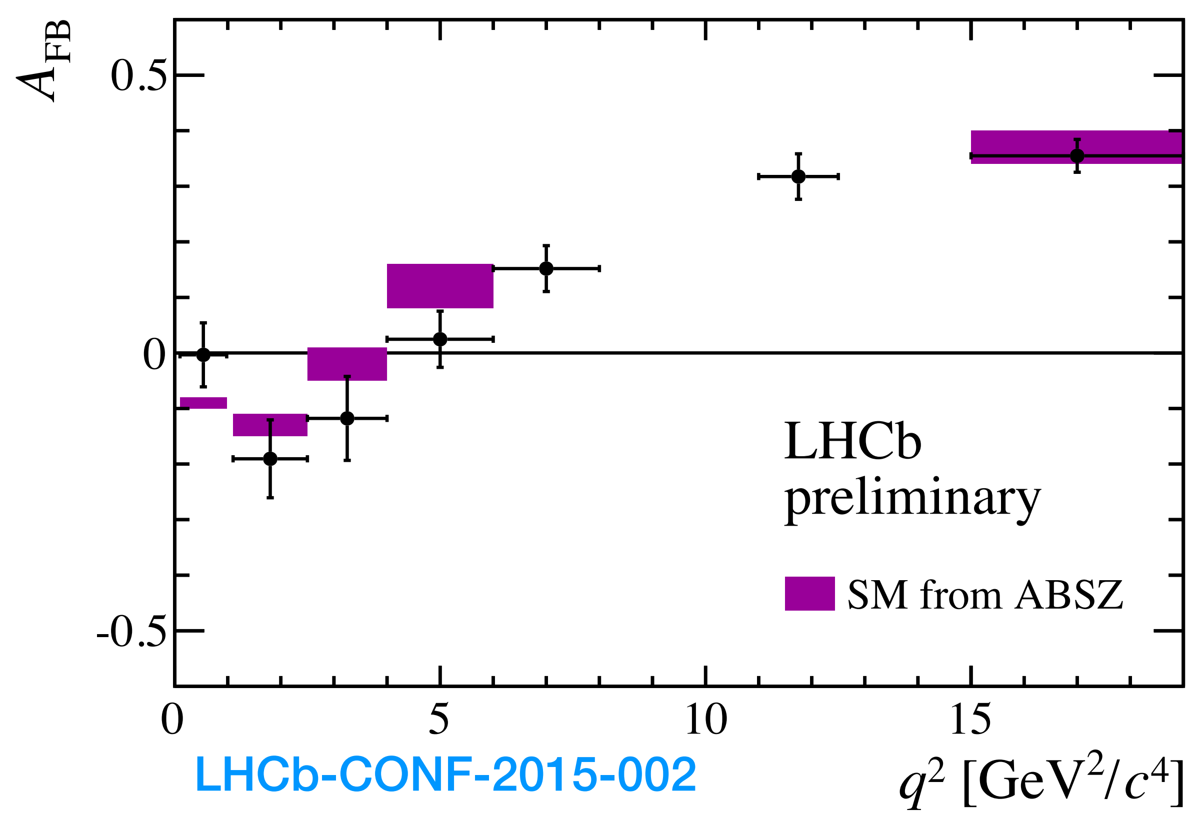
results and figure from LHCb [1209.4284]

q^2 (GeV^2/c^4)	N_{sig}	A_{FB}
$0.05 - 2.00$	159 ± 14	$0.00\ ^{+0.06}_{-0.05}\ ^{+0.03}_{-0.01}$
$2.00 - 4.30$	164 ± 14	$0.07\ ^{+0.08}_{-0.05}\ ^{+0.02}_{-0.01}$
$4.30 - 8.68$	327 ± 20	$-0.02\ ^{+0.03}_{-0.05}\ ^{+0.03}_{-0.03}$
$10.09 - 12.86$	211 ± 17	$-0.03\ ^{+0.07}_{-0.07}\ ^{+0.01}_{-0.01}$
$14.18 - 16.00$	148 ± 13	$-0.01\ ^{+0.12}_{-0.06}\ ^{+0.01}_{-0.01}$
$16.00 - 18.00$	141 ± 13	$-0.09\ ^{+0.07}_{-0.09}\ ^{+0.02}_{-0.01}$
$18.00 - 22.00$	114 ± 13	$0.02\ ^{+0.11}_{-0.11}\ ^{+0.01}_{-0.01}$
$1.00 - 6.00$	357 ± 21	$0.02\ ^{+0.05}_{-0.03}\ ^{+0.02}_{-0.01}$



- $B \to K^*\ell\ell$

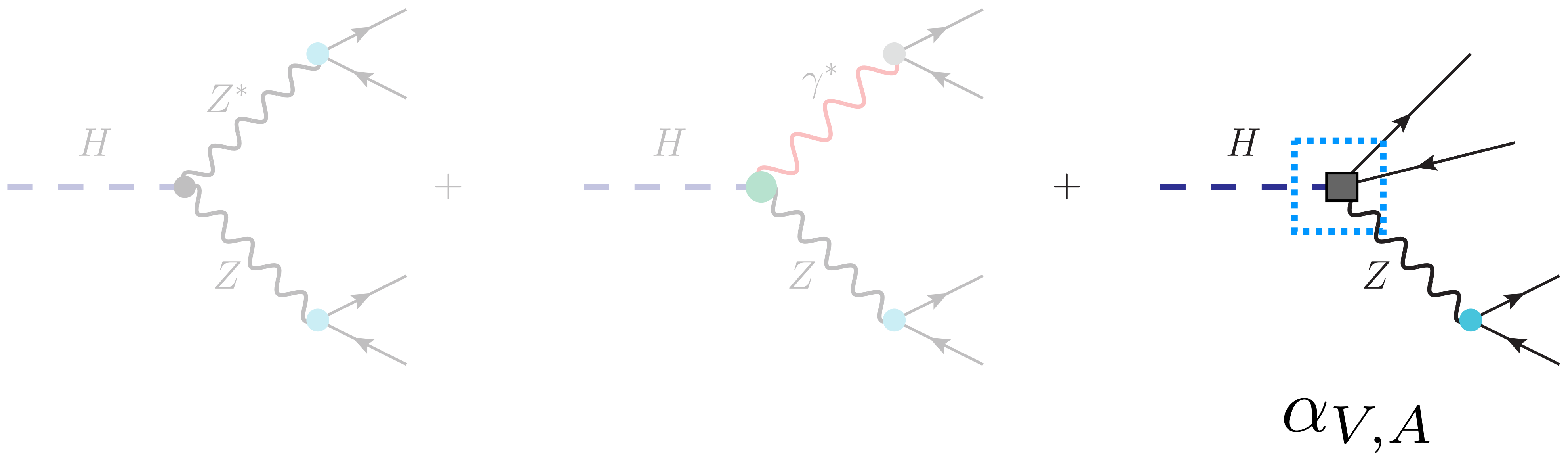
Good agreement with our estimate of the uncertainties



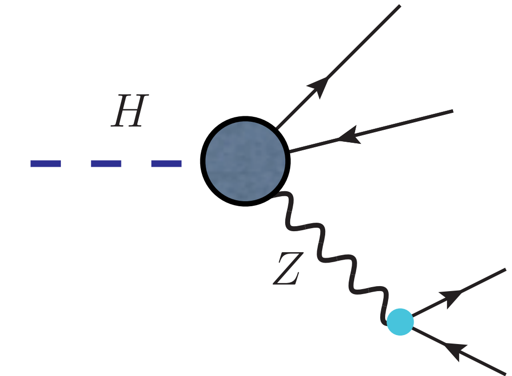
LHCb-CONF-2015-002

Main results

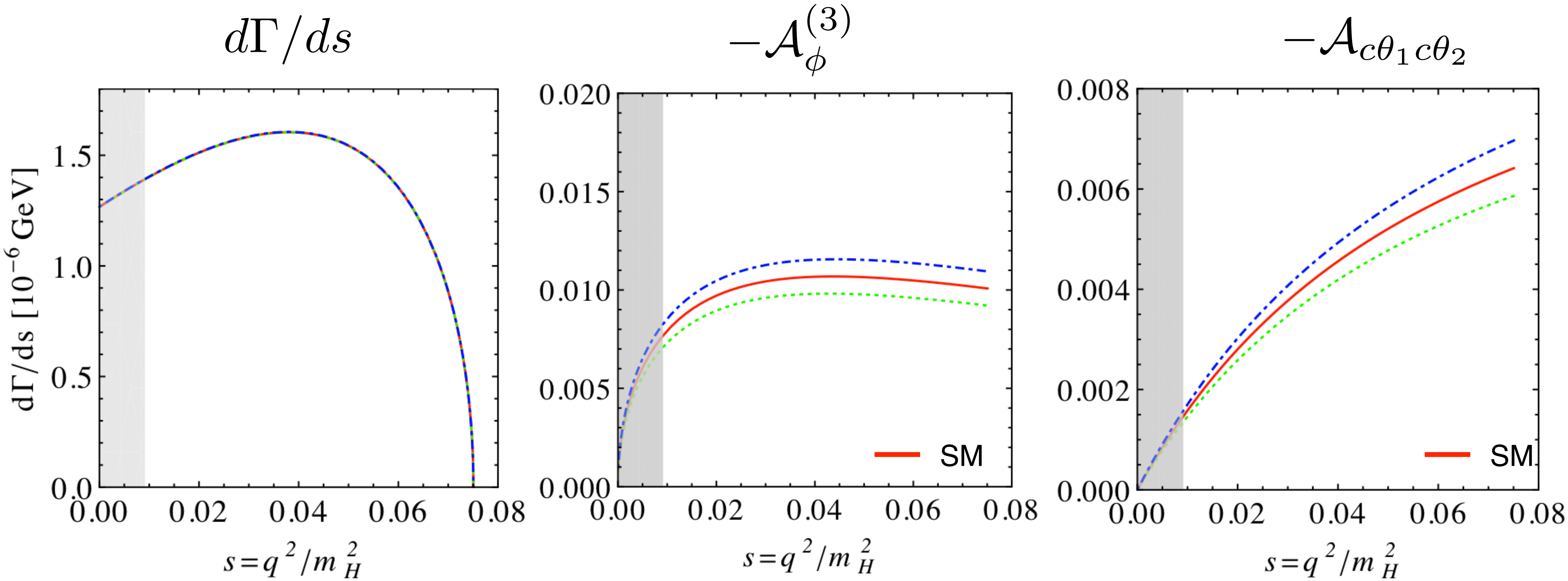
Contact *HZll* couplings



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



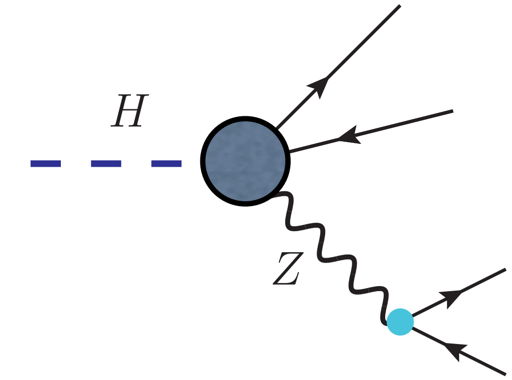
- Vector contact coupling $HZ\ell\ell$



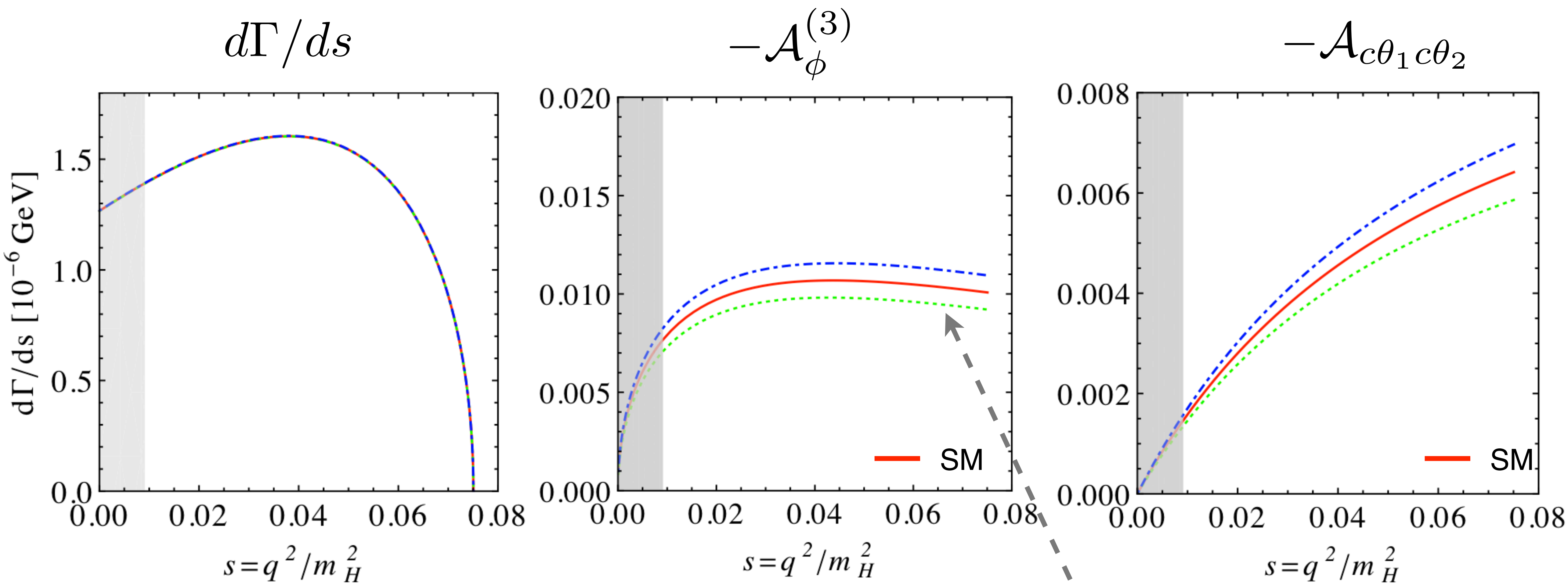
see also Buchalla, Catà, D'Ambrosio '13

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

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



- Vector contact coupling $HZ\ell\ell$



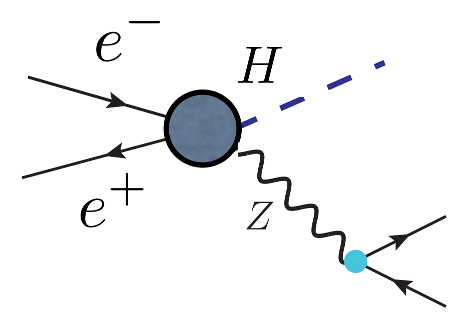
see also Buchalla, Catà, D'Ambrosio '13

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

- No enhancement of the axial couplings

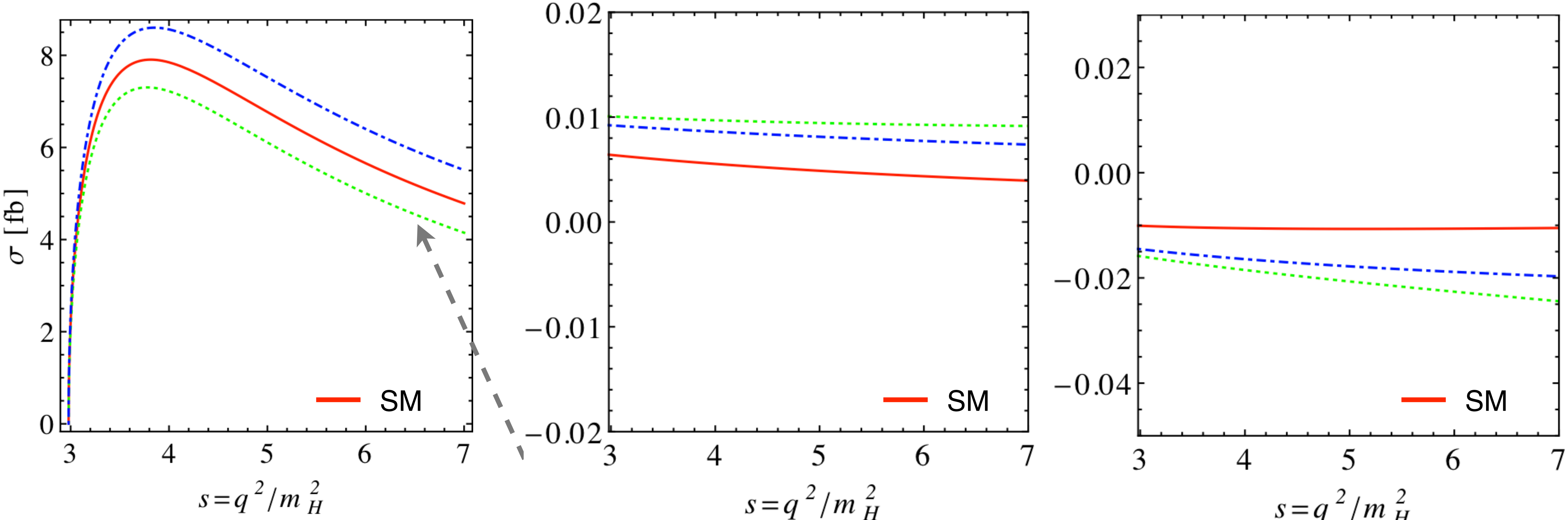
$$\widehat{\alpha}_{\Phi\ell}^{V,A} \in [-5,5]\times 10^{-3}$$

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



- Contact couplings $HZ\ell\ell$

σ $\qquad -\mathcal{A}_{\phi}^{(3)}$ $\qquad -\mathcal{A}_{c\theta_1 c\theta_2}$

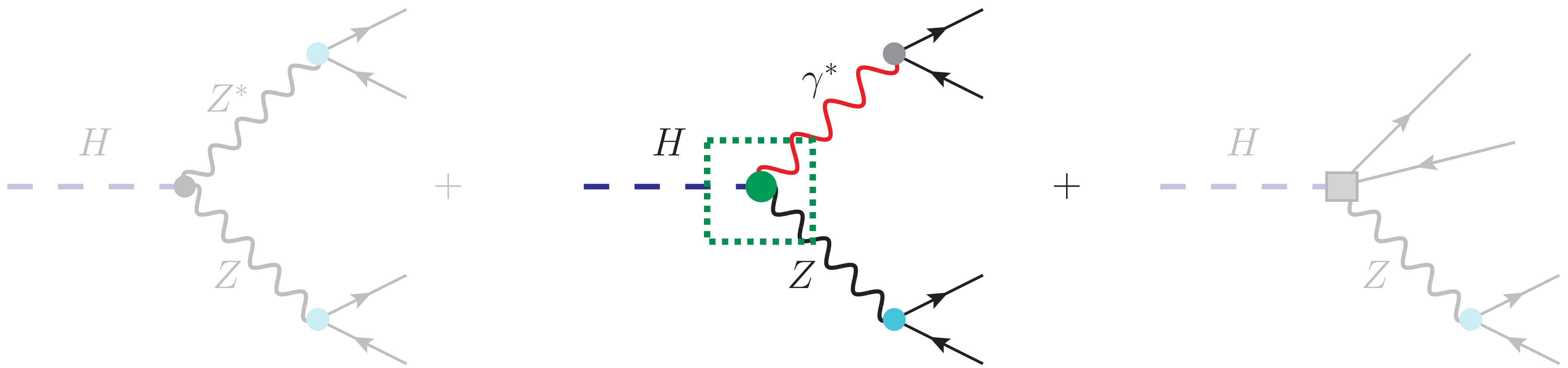


$$\sigma \simeq \sqrt{2}\, m_H^2\, G_F\, \bar{g}_A^4\, \frac{s+3}{s-1}\, [1 - 2(1+2s)\,\widehat{\alpha}_{\Phi\ell}^{A}]$$

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

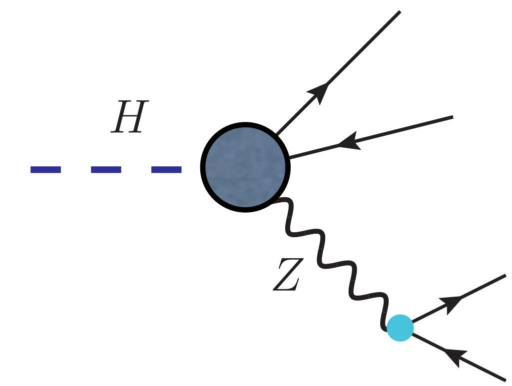
- Enhanced contribution of axial couplings to the cross-section

HAZ coupling

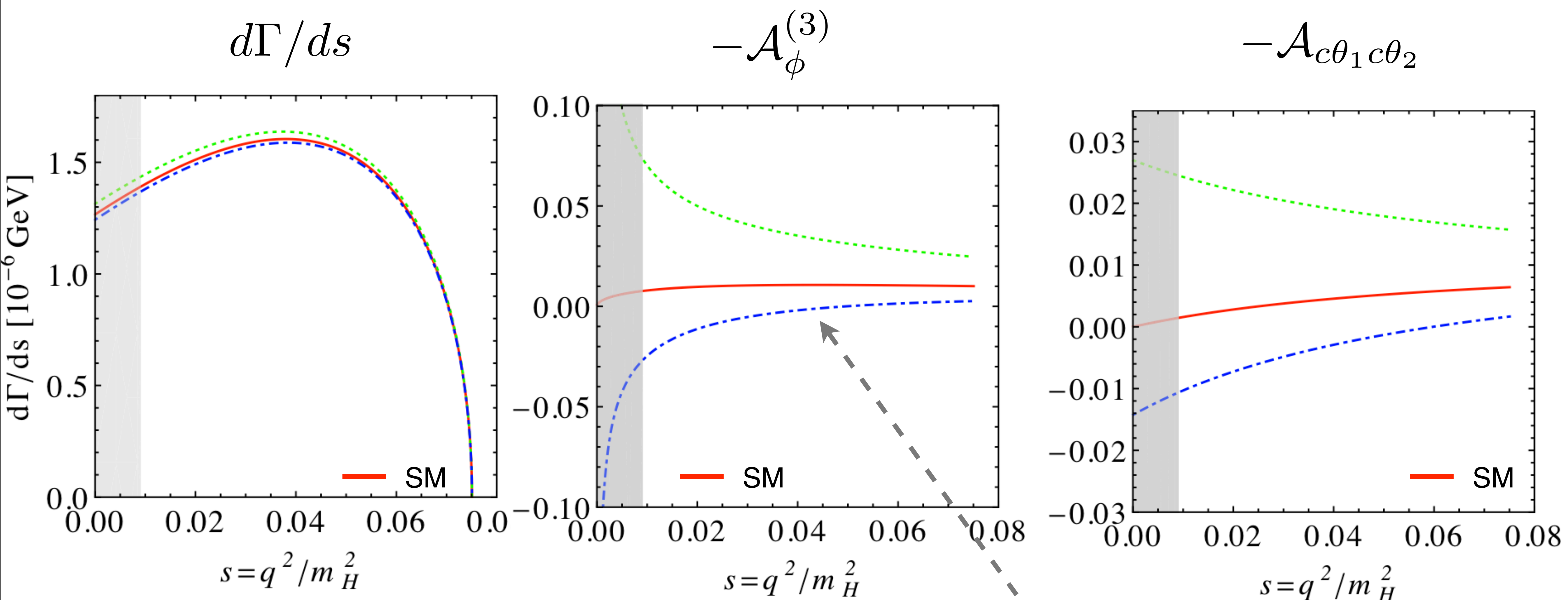


α_{AZ}

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



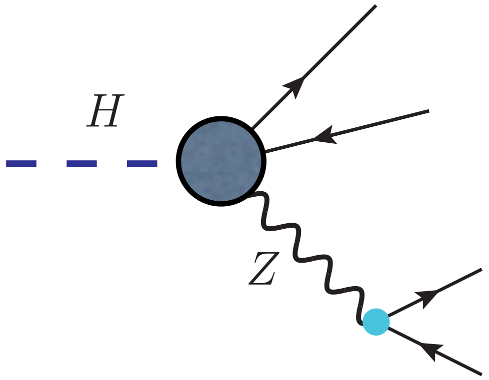
- Contact couplings *HAZ*



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

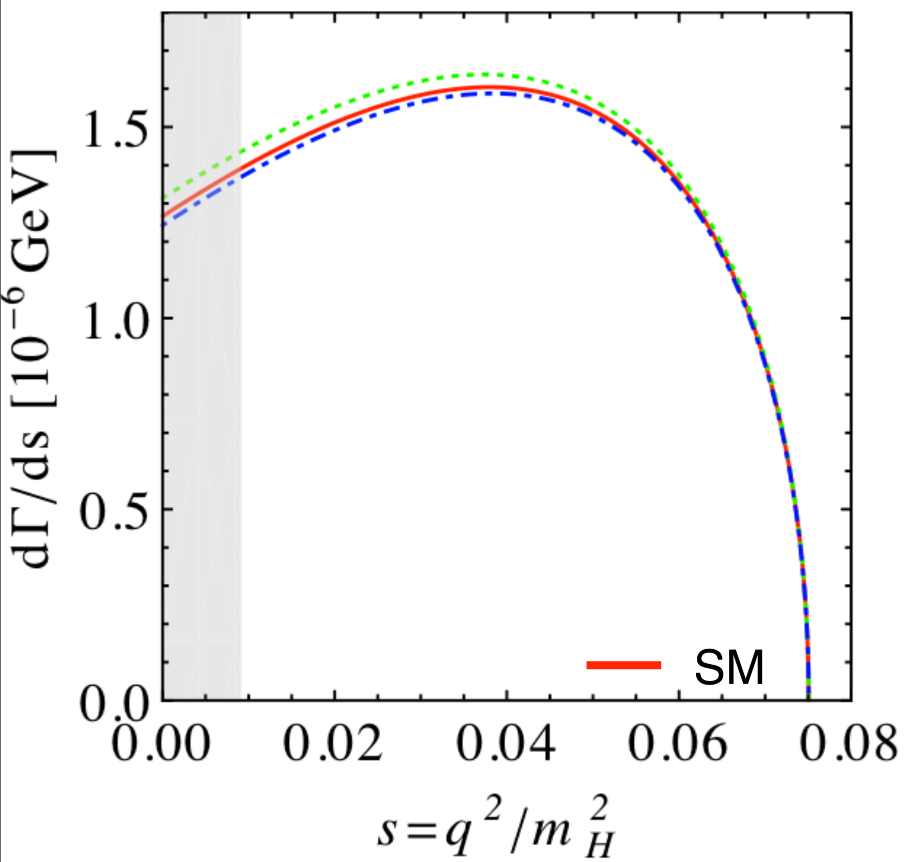
$$\widehat{\alpha}_{AZ} \in [-1.3, 2.6] \times 10^{-2}$$

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



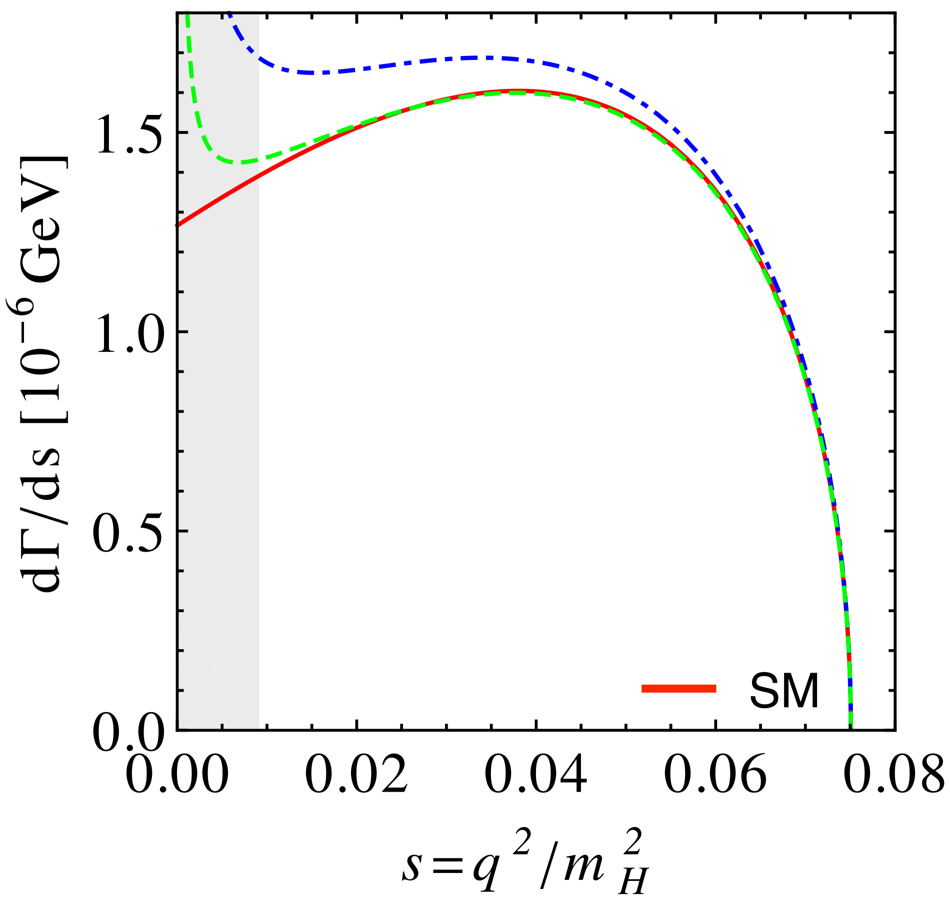
- Contact couplings *HAZ*

$d\Gamma/ds$



$$\mathcal{L}^{(6)} \times \mathcal{L}^{(4)}$$

$d\Gamma/ds$

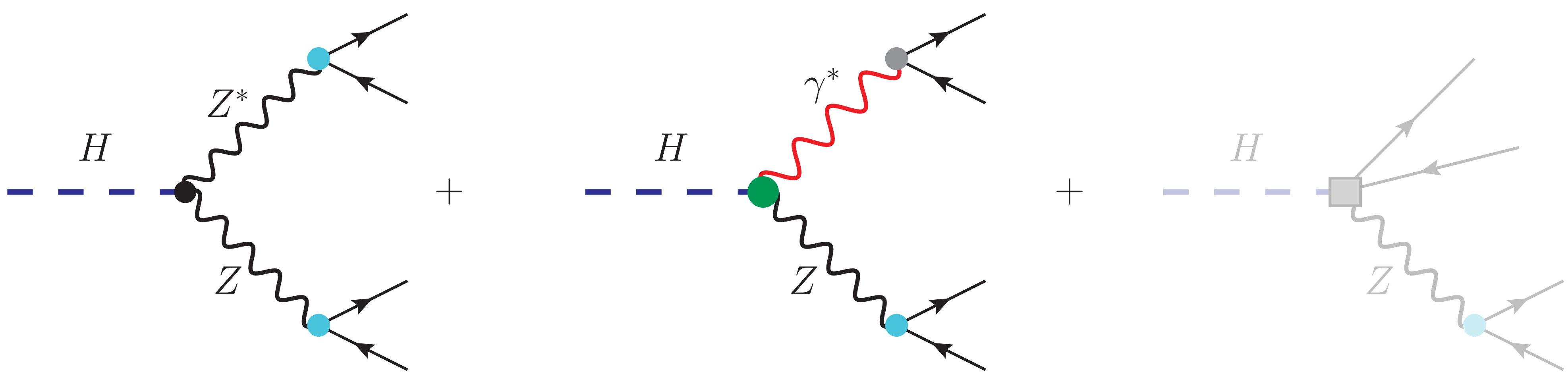


$$\mathcal{L}^{(6)} \times \mathcal{L}^{(4)} + \mathcal{L}^{(6)} \times \mathcal{L}^{(6)}$$

- Effects of the order of *d* = 8 operators

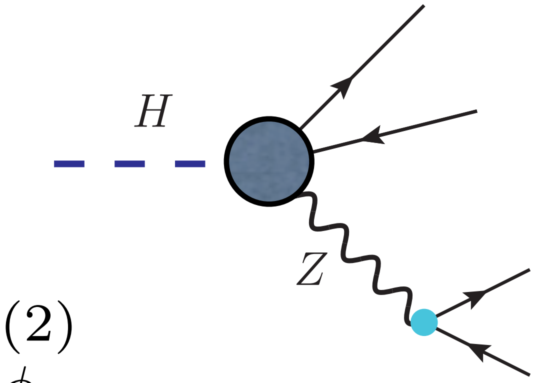
$$\widehat{\alpha}_{AZ} \in [-1.3, 2.6] \times 10^{-2}$$

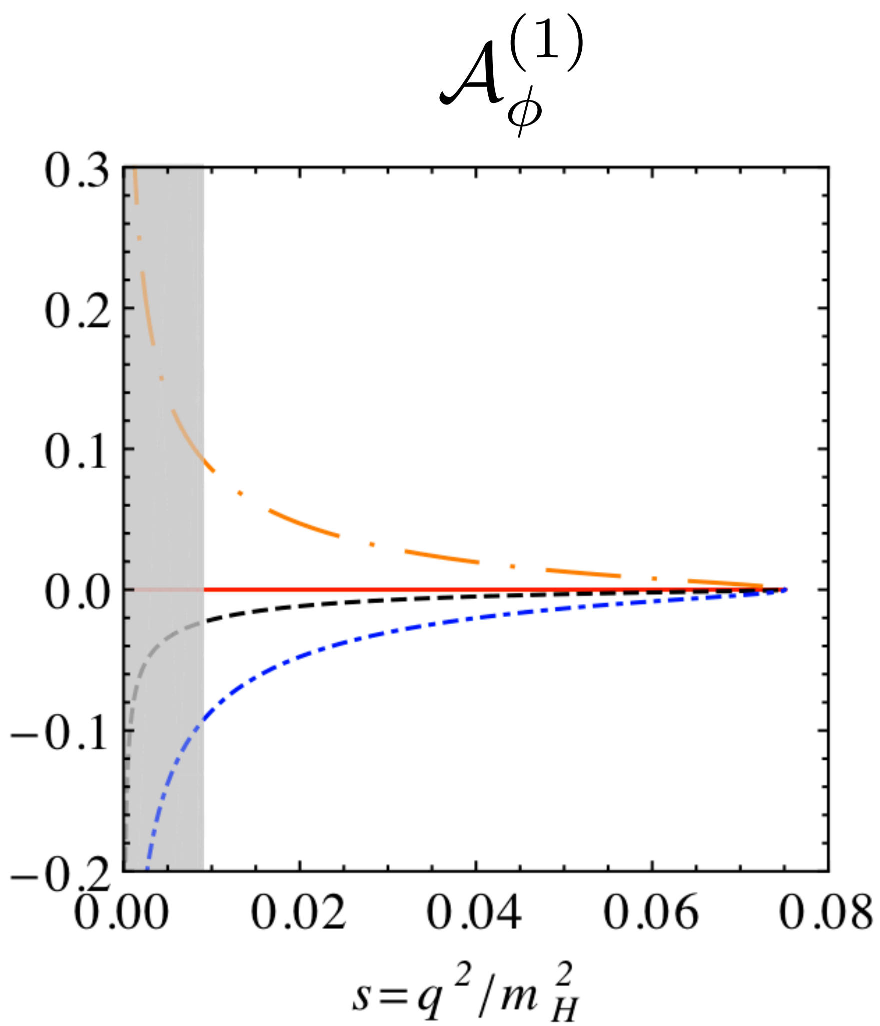
CP odd couplings

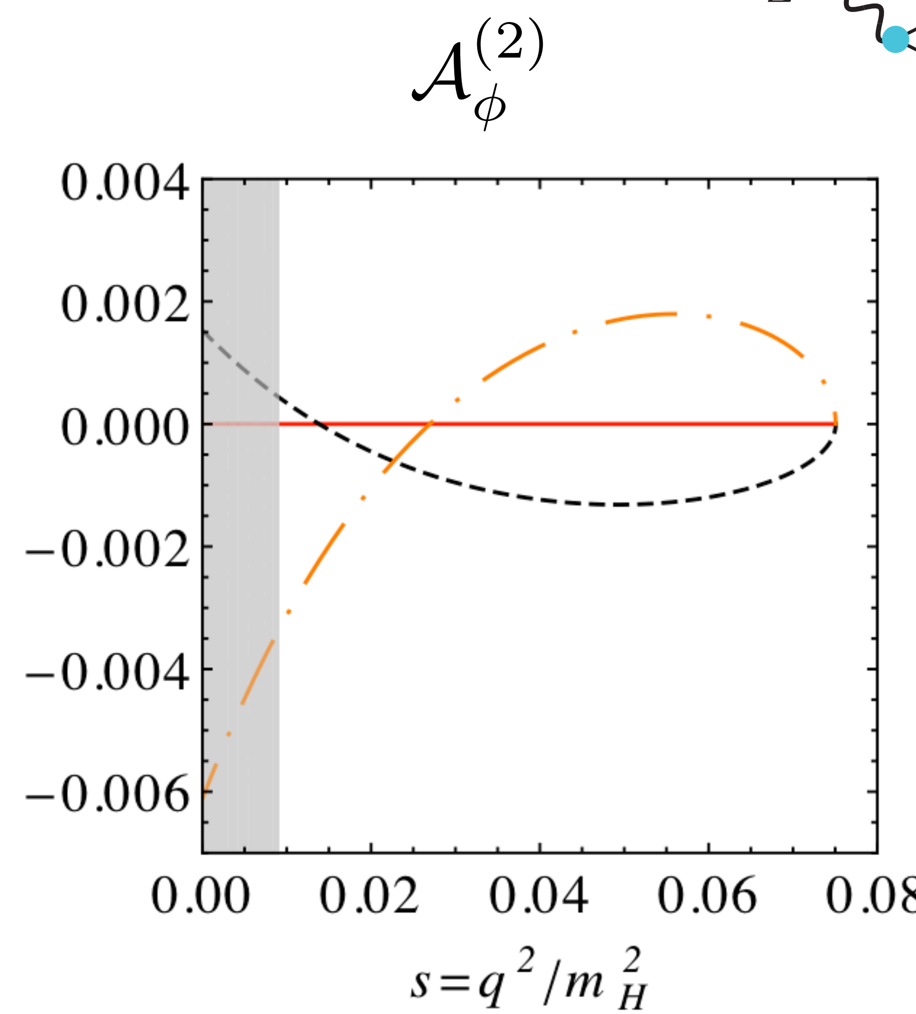


$\alpha_{Z\widetilde{Z}}$ $\alpha_{A\widetilde{Z}}$

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







- 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

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

- 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 measurements of other processes).

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