

Learning from Higgs decays at NLO in SMEFT

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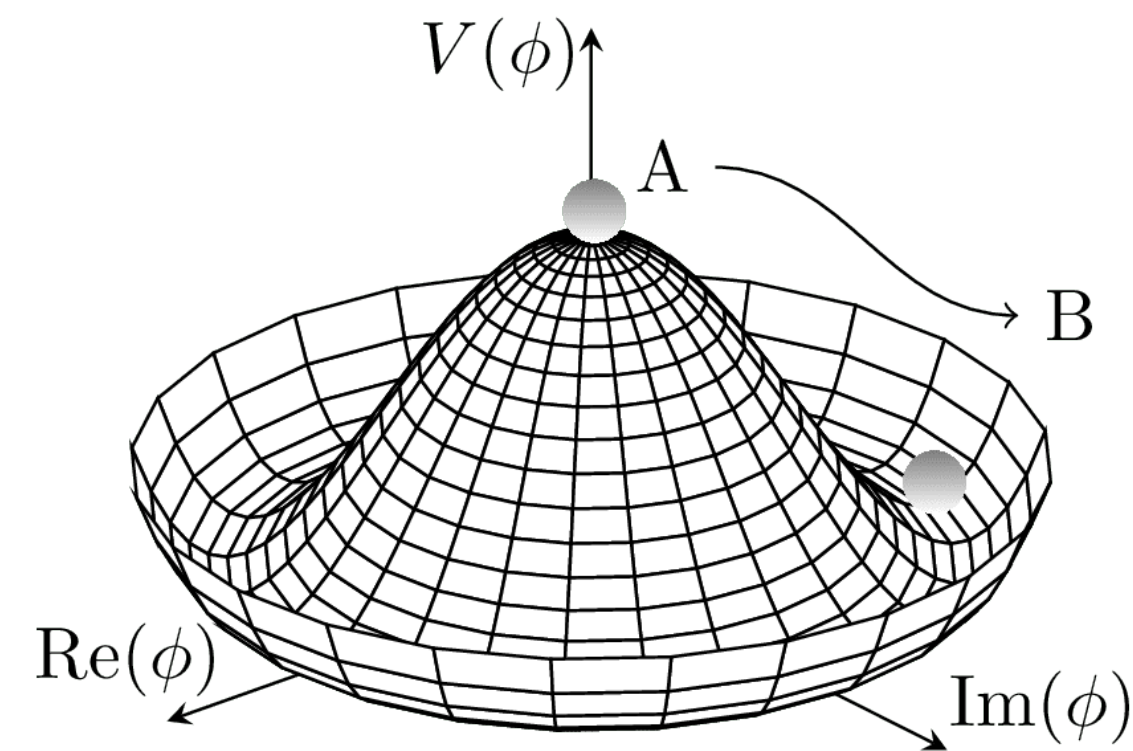
Brookhaven
National Laboratory



The Higgs sector

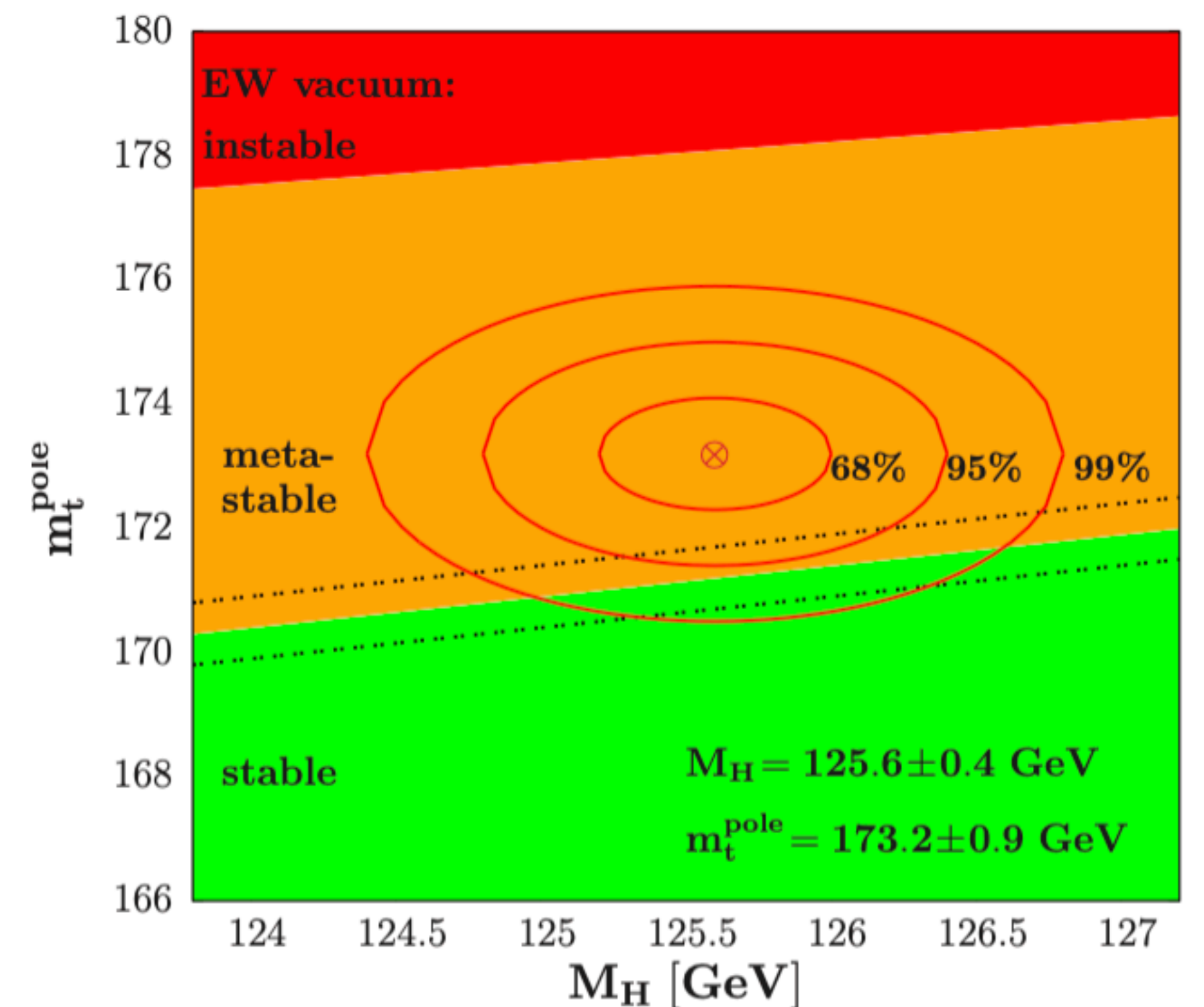
$$V(\phi) = m^2 \phi^2 + \lambda \phi^4 \quad \rightarrow \quad V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

$\lambda_3^{\text{SM}} = \lambda v$
 $\lambda_4^{\text{SM}} = \lambda/4$



EW Symmetry Breaking mechanism

Near-criticality of m_H
and stability of the minimum of the potential



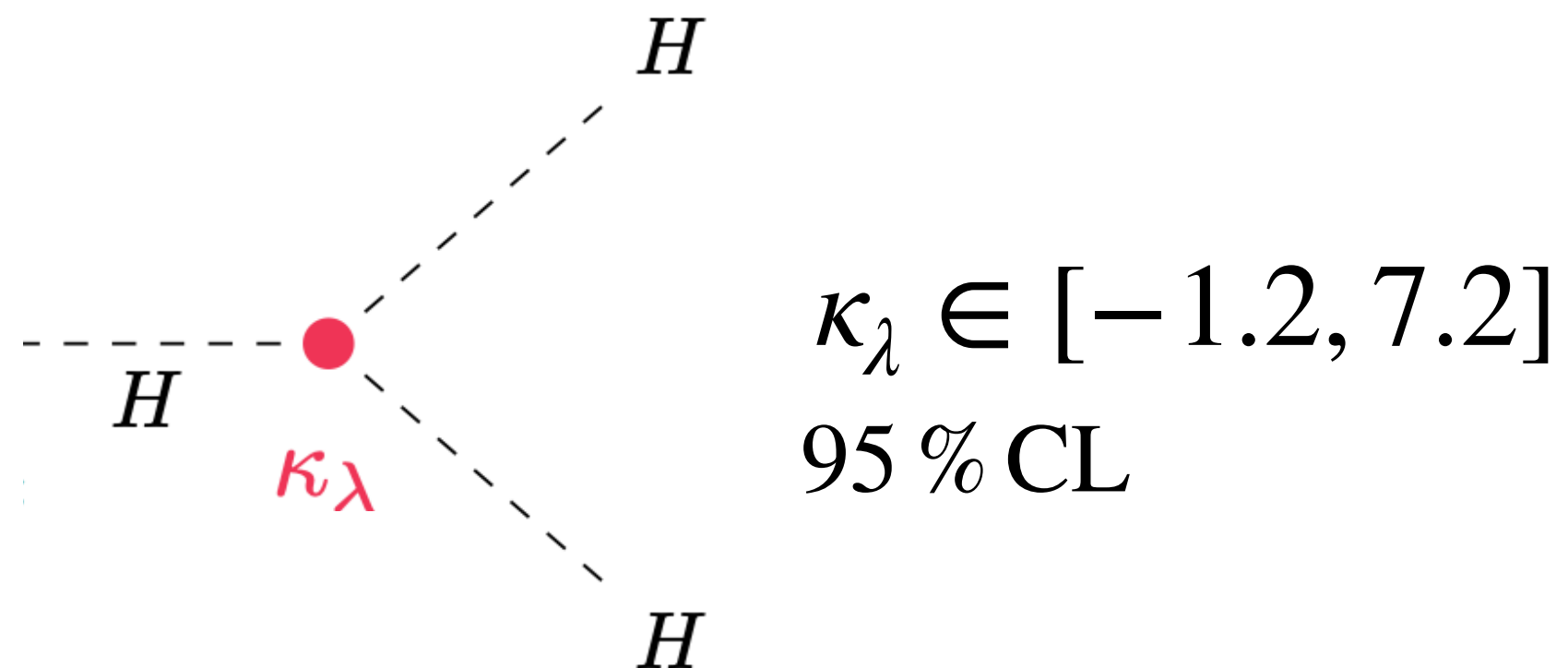
Alekhin et al., Phys.Lett.B 716 (2012) 214-219

The Higgs sector

$$V(\phi) = m^2\phi^2 + \lambda\phi^4 \quad \rightarrow \quad V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

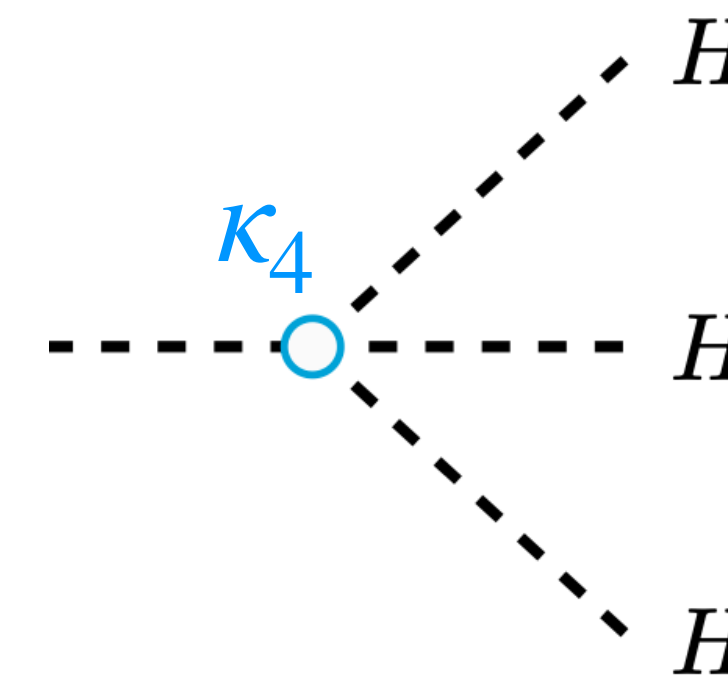
$\lambda_3^{\text{SM}} = \lambda v$ $\lambda_4^{\text{SM}} = \lambda/4$

κ framework $\kappa_P = \frac{\lambda_P}{\lambda_P^{\text{SM}}}$



ATLAS, Phys. Rev. Lett. 133 (2024) 101801

CMS, Phys.Lett.B 861 (2025) 139210



$$\kappa_4 \sim \mathcal{O}(10^2)$$

ATLAS, Phys. Rev. D 111 (2025) 032006

Alekhin et al., Phys.Lett.B 716 (2012) 214-219

Beyond the Standard Model

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$$

$$\sqrt{s} = 13 \text{ TeV}$$

Model		ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit		Reference
Extra dimen.	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	$1 - 4 j$	Yes	139	M_D	11.2 TeV	$n = 2$ 2102.10874
	ADD non-resonant $\gamma\gamma$	2γ	—	—	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO 1707.04147
	ADD QBH	—	$2 j$	—	139	M_{th}	9.4 TeV	$n = 6$ 1910.08447
	ADD BH multijet	—	$\geq 3 j$	—	3.6	M_{th}	9.55 TeV	$n = 6, M_D = 3 \text{ TeV}$, rot BH 1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	—	—	139	G_{KK} mass	4.5 TeV	$k/\overline{M}_{Pl} = 0.1$ 2102.13405
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	—	—	36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$ 1808.02380
	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$ 1804.10823
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$ 1803.09678
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	—	—	139	Z' mass	5.1 TeV	$\Gamma/m = 1.2\%$ 1903.06248
	SSM $Z' \rightarrow \tau\tau$	2τ	—	—	36.1	Z' mass	2.42 TeV	
	Leptophobic $Z' \rightarrow bb$	—	$2 b$	—	36.1	Z' mass	2.1 TeV	
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass	4.1 TeV	
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	—	Yes	139	W' mass	6.0 TeV	$g_V = 3$ $g_V c_H = 1, g_r = 0$ 2004.14636
	SSM $W' \rightarrow \tau\nu$	1τ	—	Yes	139	W' mass	5.0 TeV	
	SSM $W' \rightarrow tb$	—	$\geq 1 b, \geq 1 J$	—	139	W' mass	4.4 TeV	
	HVT $W' \rightarrow WZ$ model B	$0-2 e, \mu$	$2 j / 1 J$	Yes	139	W' mass	4.3 TeV	
	HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell'\ell'$ model C	$3 e, \mu$	$2 j$ (VBF)	Yes	139	W' mass	340 GeV	ATLAS-CONF-2021-025 ATLAS-CONF-2021-043
	HVT $Z' \rightarrow WW$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	Z' mass	3.9 TeV	
CI	LRSB $W_R \rightarrow \mu N_R$	2μ	$1 J$	—	80	W_R mass	5.0 TeV	$m(N_R) = 0.5 \text{ TeV}$, $g_L = g_R$ 1904.12679
	CI $qqqq$	—	$2 j$	—	37.0	Λ	21.8 TeV	η_{LL}^- 1703.09127
	CI $\ell\ell qq$	$2 e, \mu$	—	—	139	Λ	35.8 TeV	η_{LL}^- 2006.12946
	CI $eebs$	$2 e$	$1 b$	—	139	Λ	1.8 TeV	$g_s = 1$ 2105.13847
	CI $\mu\mu bs$	2μ	$1 b$	—	139	Λ	2.0 TeV	$g_s = 1$ 2105.13847
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Λ	2.57 TeV	$ C_{4t} = 4\pi$ 1811.02305
DM	Axial-vector med. (Dirac DM)	—	$2 j$	—	139	m_{med}	3.8 TeV	$g_q = 0.25, g_\chi = 1, m(\chi) = 10 \text{ GeV}$ ATL-PHYS-PUB-2022-036
	Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1 - 4 j$	Yes	139	m_{med}	376 GeV	$g_q = 1, g_\chi = 1, m(\chi) = 1 \text{ GeV}$ 2102.10874
	Vector med. Z' -2HDM (Dirac DM)	$0 e, \mu$	$2 b$	Yes	139	$m_{Z'}$	3.0 TeV	$\tan\beta = 1, g_Z = 0.8, m(\chi) = 100 \text{ GeV}$ 2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel	—	—	139	m_a	800 GeV	$\tan\beta = 1, g_\chi = 1, m(\chi) = 10 \text{ GeV}$ ATLAS-CONF-2021-036
LQ	Scalar LQ 1 st gen	$2 e$	$\geq 2 j$	Yes	139	LQ mass	1.8 TeV	$\beta = 1$ 2006.05872
	Scalar LQ 2 nd gen	2μ	$\geq 2 j$	Yes	139	LQ mass	1.7 TeV	$\beta = 1$ 2006.05872
	Scalar LQ 3 rd gen	1τ	$2 b$	Yes	139	LQ_3^u mass	1.9 TeV	$\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$ 2303.01294
	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	LQ_3^d mass	1.24 TeV	$\mathcal{B}(LQ_3^d \rightarrow t\nu) = 1$ 2004.14060
	Scalar LQ 3 rd gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 j, \geq 1 b$	—	—	139	LQ_3^s mass	1.4 TeV	$\mathcal{B}(LQ_3^s \rightarrow t\tau) = 1$ 2101.11582
	Scalar LQ 3 rd gen	$0 e, \mu, \geq 1 \tau, 0 - 2 j, 2 b$	—	—	139	LQ_3^s mass	1.26 TeV	$\mathcal{B}(LQ_3^s \rightarrow t\tau) = 1$ 2101.12527
	Vector LQ mix gen	multi-channel	$\geq 1 j, \geq 1 b$	Yes	139	LQ_3^V mass	2.0 TeV	$\mathcal{B}(LQ_3^V \rightarrow b\nu) = 1$ ATLAS-CONF-2022-052
	Vector LQ 3 rd gen	$2 e, \mu, \tau$	$\geq 1 b$	Yes	139	LQ_3^V mass	1.96 TeV	$\mathcal{B}(LQ_3^V \rightarrow b\tau) = 1$, Y-M coupl. 2303.01294
Vector-like fermions	VLQ $TT \rightarrow Zt + X$	$2e/2\mu \geq 3e, \mu$	$\geq 1 b, \geq 1 j$	—	139	T mass	1.6 TeV	SU(2) doublet 2210.15413
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	—	—	36.1	B mass	1.34 TeV	SU(2) doublet 1808.02343
	VLQ $T_{5/3} T_{5/3} / T_{5/3} \rightarrow Wt + X$	$2(SS) \geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass	64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$ 1807.11883
	VLQ $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	139	T mass	1.8 TeV	SU(2) singlet, $\kappa_T = 0.5$ ATLAS-CONF-2021-040
	VLQ $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ 1812.07343
	VLQ $B \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1j, \geq 1J$	—	139	B mass	2.0 TeV	SU(2) doublet, $\kappa_B = 0.3$ ATLAS-CONF-2021-018
	VLL $\tau' \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	τ' mass	898 GeV	SU(2) doublet 2303.05441
Exotic ferm.	Excited quark $q^* \rightarrow qg$	—	$2 j$	—	139	q^* mass	6.7 TeV	only u^* and d^* , $\Lambda = m(q^*)$ 1910.08447
	Excited quark $q^* \rightarrow q\gamma$	1γ	$1 j$	—	36.7	q^* mass	5.3 TeV	only u^* and d^* , $\Lambda = m(q^*)$ 1709.10440
	Excited quark $b^* \rightarrow bg$	—	$1 b, 1 j$	—	139	b^* mass	3.2 TeV	1910.08447
	Excited lepton τ^*	2τ	$\geq 2 j$	—	139	τ^* mass	4.6 TeV	$\Lambda = 4.6 \text{ TeV}$ 2303.09444
Other	Type III Seesaw	$2, 3, 4 e, \mu$	$\geq 2 j$	Yes	139	N^0 mass	910 GeV	$m(W_R) = 4.1 \text{ TeV}$, $g_L = g_R$ DY production 2101.11961
	LRSB Majorana ν	2μ	$2 j$	—	36.1	N_R mass	3.2 TeV	
	Higgs triplet $H^{\pm\pm} \rightarrow W^\pm W^\pm$	$2, 3, 4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass	350 GeV	
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	—	—	139	$H^{\pm\pm}$ mass	1.08 TeV	
	Multi-charged particles	—	—	—	139	multi-charged particle mass	59 TeV	DY production, $ q = 5e$ ATLAS-CONF-2022-034
	Magnetic monopoles	—	—	—	34.4	monopole mass	2.37 TeV	DY production, $ g = 1g_D$, spin 1/2 1905.10130

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Beyond the Standard Model

Effective Field Theory approach

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$

$\sqrt{s} = 13 \text{ TeV}$

Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimen.	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	$1 - 4 j$	Yes	139	M_D 11.2 TeV $n = 2$
	ADD non-resonant $\gamma\gamma$	2γ	—	—	36.7	M_S 8.6 TeV $n = 3 \text{ HLZ NLO}$
	ADD QBH	—	$2 j$	—	139	M_{th} 9.4 TeV $n = 6$
	ADD BH multijet	—	$\geq 3 j$	—	3.6	M_{th} 9.55 TeV $n = 6, M_D = 3 \text{ TeV, rot BH}$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	—	—	139	$G_{KK} \text{ mass}$ 4.5 TeV $k/\overline{M}_{Pl} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	—	—	36.1	$G_{KK} \text{ mass}$ 2.3 TeV $k/\overline{M}_{Pl} = 1.0$
	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	$g_{KK} \text{ mass}$ 3.8 TeV $\Gamma/m = 15\%$
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	$KK \text{ mass}$ 1.8 TeV Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	—	—	139	$Z' \text{ mass}$ 5.1 TeV
	SSM $Z' \rightarrow \tau\tau$	2τ	—	—	36.1	$Z' \text{ mass}$ 2.42 TeV
	Leptophobic $Z' \rightarrow bb$	—	$2 b$	—	36.1	$Z' \text{ mass}$ 2.1 TeV
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	$Z' \text{ mass}$ 4.1 TeV $\Gamma/m = 1.2\%$
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	—	Yes	139	$W' \text{ mass}$ 6.0 TeV
	SSM $W' \rightarrow \tau\nu$	1τ	—	Yes	139	$W' \text{ mass}$ 5.0 TeV
	SSM $W' \rightarrow tb$	—	$\geq 1 b, \geq 1 J$	—	139	$W' \text{ mass}$ 4.4 TeV
	HVT $W' \rightarrow WZ$ model B	$0-2 e, \mu$	$2 j / 1 J$	Yes	139	$W' \text{ mass}$ 4.3 TeV
	HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell'\ell'$ model C	$3 e, \mu$	$2 j$ (VBF)	Yes	139	$W' \text{ mass}$ 340 GeV
	HVT $Z' \rightarrow WW$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	$Z' \text{ mass}$ 3.9 TeV
CI	LRSB $W_R \rightarrow \mu N_R$	2μ	$1 J$	—	80	$W_R \text{ mass}$ 5.0 TeV $m(N_R) = 0.5 \text{ TeV, } g_L = g_R$
	CI $qqqq$	—	$2 j$	—	37.0	Λ 21.8 TeV η_{LL}^-
	CI $\ell\ell qq$	$2 e, \mu$	—	—	139	Λ 35.8 TeV η_{LL}^-
	CI $e\bar{e} b\bar{b}$	$2 e$	$1 b$	—	139	Λ 1.8 TeV $g_s = 1$
	CI $\mu\mu b\bar{b}$	2μ	$1 b$	—	139	Λ 2.0 TeV $g_s = 1$
	CI $t\bar{t} t\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Λ 2.57 TeV $ C_{4t} = 4\pi$
DM	Axial-vector med. (Dirac DM)	—	$2 j$	—	139	m_{med} 3.8 TeV $g_q = 0.25, g_\chi = 1, m(\chi) = 10 \text{ TeV}$
	Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1 - 4 j$	Yes	139	m_{med} 376 GeV $g_q = 1, g_\chi = 1, m(\chi) = 1 \text{ GeV}$
	Vector med. Z' -2HDM (Dirac DM)	$0 e, \mu$	$2 b$	Yes	139	$m_{Z'}$ 3.0 TeV $\tan\beta = 1, g_Z = 0.8, m(\chi) = 100 \text{ GeV}$
	Pseudo-scalar med. 2HDM+a	multi-channel	—	—	139	m_a 800 GeV $\tan\beta = 1, g_\chi = 1, m(\chi) = 10 \text{ GeV}$
LQ	Scalar LQ 1 st gen	$2 e$	$\geq 2 j$	Yes	139	LQ mass 1.8 TeV $\beta = 1$
	Scalar LQ 2 nd gen	2μ	$\geq 2 j$	Yes	139	LQ mass 1.7 TeV $\beta = 1$
	Scalar LQ 3 rd gen	1τ	$2 b$	Yes	139	$LQ_3^u \text{ mass}$ 1.9 TeV $\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$
	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	$LQ_3^d \text{ mass}$ 1.24 TeV $\mathcal{B}(LQ_3^d \rightarrow t\nu) = 1$
	Scalar LQ 3 rd gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 j, \geq 1 b$	—	—	139	$LQ_3^s \text{ mass}$ 1.4 TeV $\mathcal{B}(LQ_3^s \rightarrow t\tau) = 1$
	Scalar LQ 3 rd gen	$0 e, \mu, \geq 1 \tau, 0 - 2 j, 2 b$	Yes	139	139	$LQ_3^s \text{ mass}$ 1.26 TeV $\mathcal{B}(LQ_3^s \rightarrow b\nu) = 1$
	Vector LQ mix gen	multi-channel	$\geq 1 j, \geq 1 b$	Yes	139	$LQ_3^v \text{ mass}$ 2.0 TeV $\mathcal{B}(U_1 \rightarrow t\mu) = 1, \text{Y-M coupl.}$
	Vector LQ 3 rd gen	$2 e, \mu, \tau$	$\geq 1 b$	Yes	139	$LQ_3^v \text{ mass}$ 1.96 TeV $\mathcal{B}(LQ_3^v \rightarrow b\tau) = 1, \text{Y-M coupl.}$
Vector-like fermions	VLQ $TT \rightarrow Zt + X$	$2e/2\mu/\geq 3e, \mu$	$\geq 1 b, \geq 1 j$	—	139	T mass 1.6 TeV SU(2) doublet
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	—	—	36.1	B mass 1.34 TeV SU(2) doublet
	VLQ $T_{5/3} T_{5/3} / T_{5/3} \rightarrow Wt + X$	$2(SS)/\geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3} \text{ mass}$ 64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$
	VLQ $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	139	T mass 1.8 TeV SU(2) singlet, $\kappa_T = 0.5$
	VLQ $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$
	VLQ $B \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1j, \geq 1J$	—	139	B mass 2.0 TeV SU(2) doublet, $\kappa_B = 0.3$
	VLL $\tau' \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	$\tau' \text{ mass}$ 898 GeV SU(2) doublet
Excited ferm.	Excited quark $q^* \rightarrow qg$	—	$2 j$	—	139	$q^* \text{ mass}$ 6.7 TeV only u^* and d^* , $\Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	1γ	$1 j$	—	36.7	$q^* \text{ mass}$ 5.3 TeV only u^* and d^* , $\Lambda = m(q^*)$
	Excited quark $b^* \rightarrow bg$	—	$1 b, 1 j$	—	139	$b^* \text{ mass}$ 3.2 TeV $\Lambda = 4.6 \text{ TeV}$
	Excited lepton τ^*	2τ	$\geq 2 j$	—	139	$\tau^* \text{ mass}$ 4.6 TeV
Other	Type III Seesaw	$2,3,4 e, \mu$	$\geq 2 j$	Yes	139	$N^0 \text{ mass}$ 910 GeV
	LRSB Majorana ν	2μ	$2 j$	—	36.1	$N_R \text{ mass}$ 3.2 TeV
	Higgs triplet $H^{\pm\pm} \rightarrow W^\pm W^\pm$	$2,3,4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm} \text{ mass}$ 350 GeV
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2,3,4 e, \mu$ (SS)	—	—	139	$H^{\pm\pm} \text{ mass}$ 1.08 TeV
	Multi-charged particles	—	—	—	139	multi-charged particle mass 59 TeV
	Magnetic monopoles	—	—	—	34.4	monopole mass 2.37 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

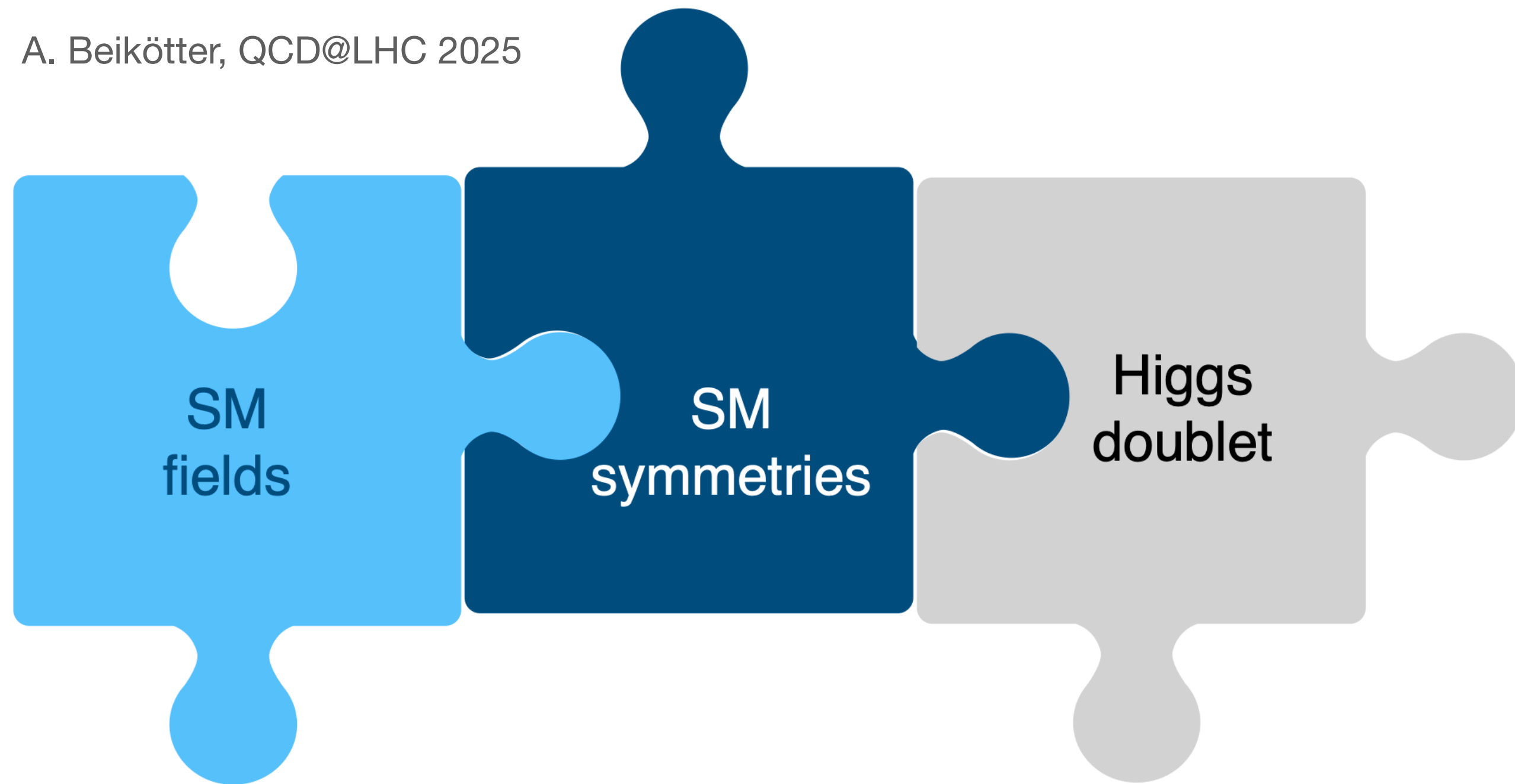
No New Physics

$\Lambda \gg M_W$

M_W

The Standard Model Effective Theory

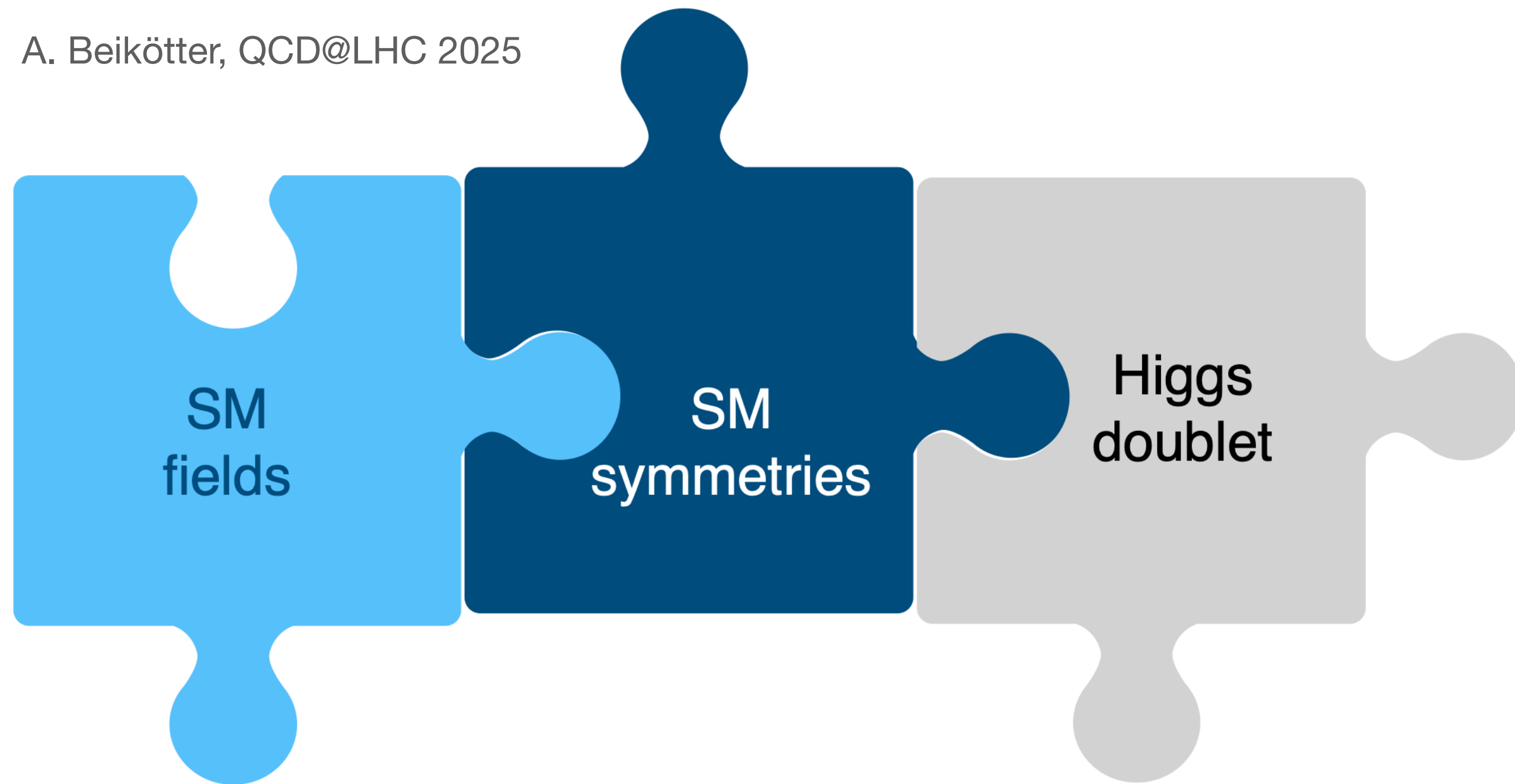
A. Beikötter, QCD@LHC 2025



$$\mathcal{L} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda} \sum_i C_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} O_i^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

The Standard Model Effective Theory

A. Beikötter, QCD@LHC 2025



New physics effects contained in the matching Wilson coefficients C_i

$C_i \neq 0$ means new Physics!

Expansion in $1/\Lambda$ and couplings

Theory is renormalizable order-by-order in $1/\Lambda$

Consistent and systematic approach for data interpretation!

$$\mathcal{L} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda} \sum_i C_i^{(5)} \mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} \mathcal{O}_i^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Precision in SMEFT

Why higher orders?

$$\boxed{\Delta o_n} = \boxed{o_n^{\text{EXP}}} - \boxed{o_n^{\text{SM}}} = \sum_i \boxed{\frac{a_{n,i}^{(6)}(\mu) c_i^{(6)}(\mu)}{\Lambda^2}} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Precise **experimental data** and **SM predictions**

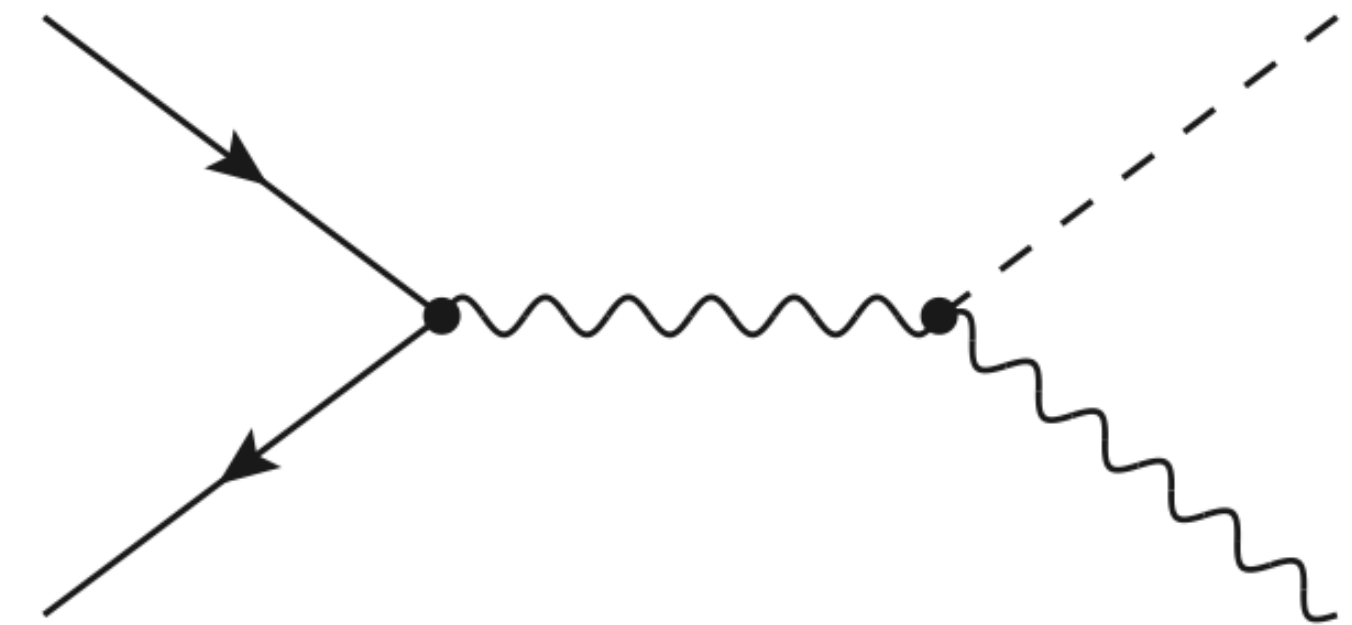
Precise SMEFT predictions
to determine Wilson coefficients

We consider the contributions given by
dim-6 operators in the Warsaw basis at NLO

Uncertainty and correlation estimation crucial for data interpretation

Higgs-strahlung production

- At LHC easier to identify some decays e.g. $H \rightarrow b\bar{b}$ in this channel
- At FCC-ee will be main production channel



- $e^+e^- \rightarrow ZH$ known up to NLO in the SM

NNLO EW+QCD and EW partial results for polarised initial states

[Fleischer, Jegerlehner, Phys.Rev.D 23 \(1981\) 2001-2026](#)

[Kniehl, Z.Phys.C 55 \(1992\) 605-618](#)

[Denner et al., Z.Phys.C 56 \(1992\) 261-272](#)

[Freitas et al., Phys.Rev.D 108 \(2023\) 5, 053006](#)

[Freitas, Song, Phys.Rev.Lett. 130 \(2023\) 3, 031801](#)

[Chen et al., 2209.14953 \[hep-ph\]](#)

[Gong et al., Phys. Rev. D 95, 093003](#)

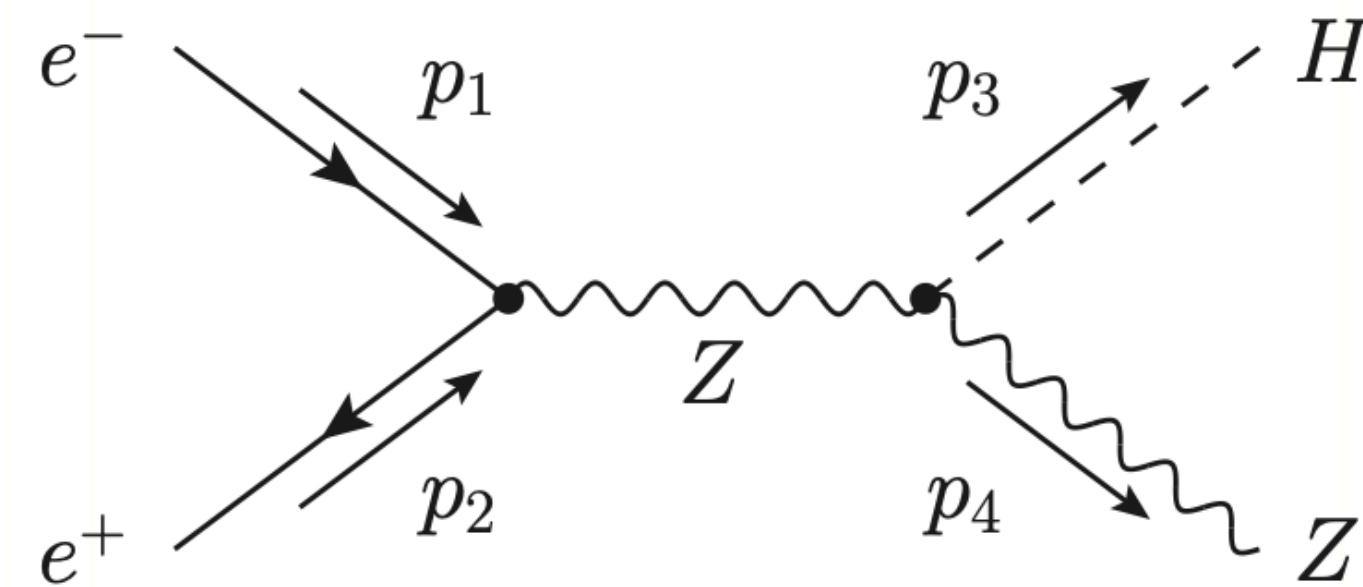
[Sun et al., Phys.Rev.D 96 \(2017\) 5, 051301](#)

ZH production at FCC-ee in SMEFT

Asteriadis et al., JHEP 02 (2025) 162

LO contributions

Asteriadis et al., Phys.Rev.Lett. 133 (2024) 23, 231801

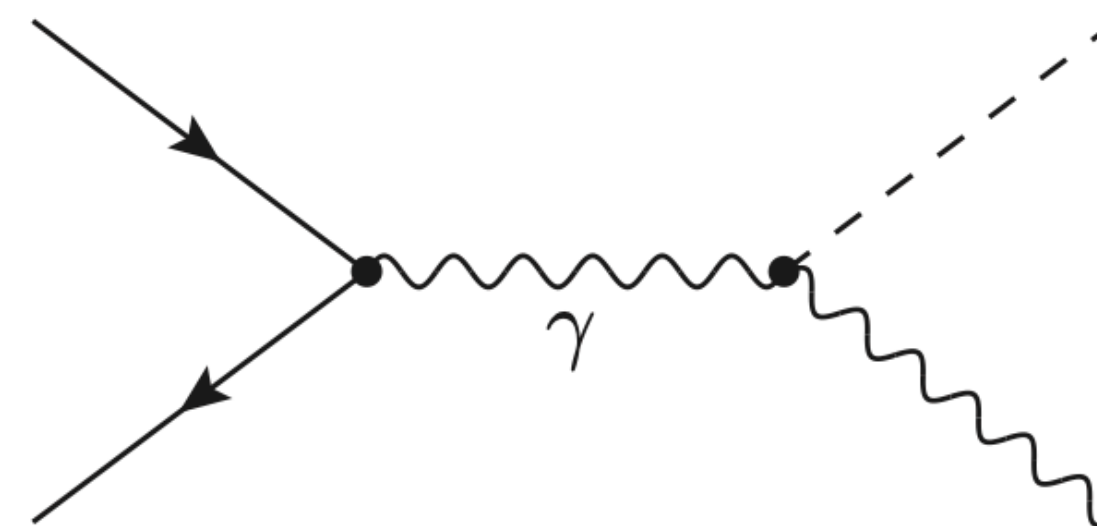


$C_{\phi D}, C_{\phi \square},$

ZZH vertex

$C_{\phi e},$

eeZ vertex



$C_{\phi l}^1, C_{\phi l}^3,$

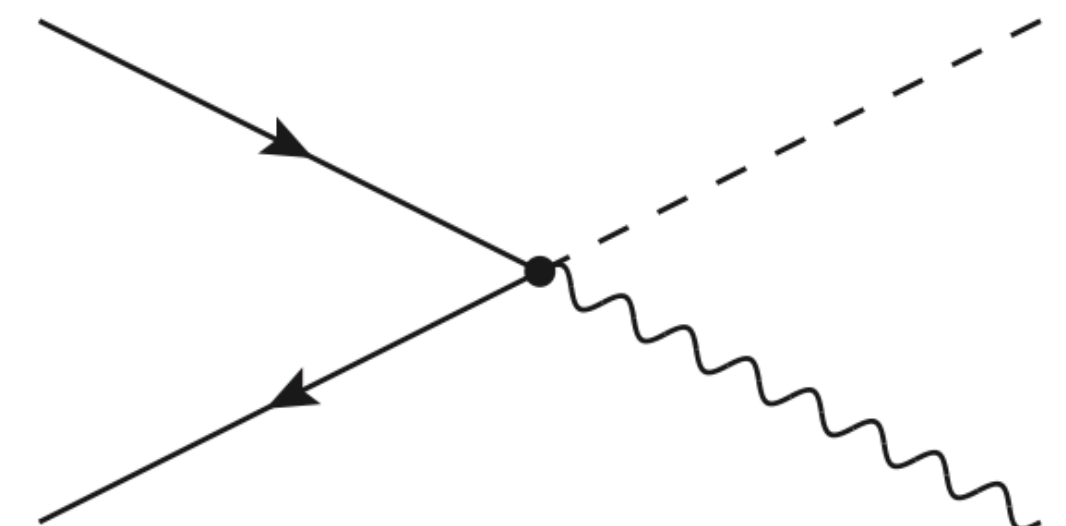
**4p interactions
eeZ vertex**

$C_{ll},$

G_F

$C_{\phi WB}, C_{\phi W}, C_{\phi B}$

ZZH and ZHγ vertices

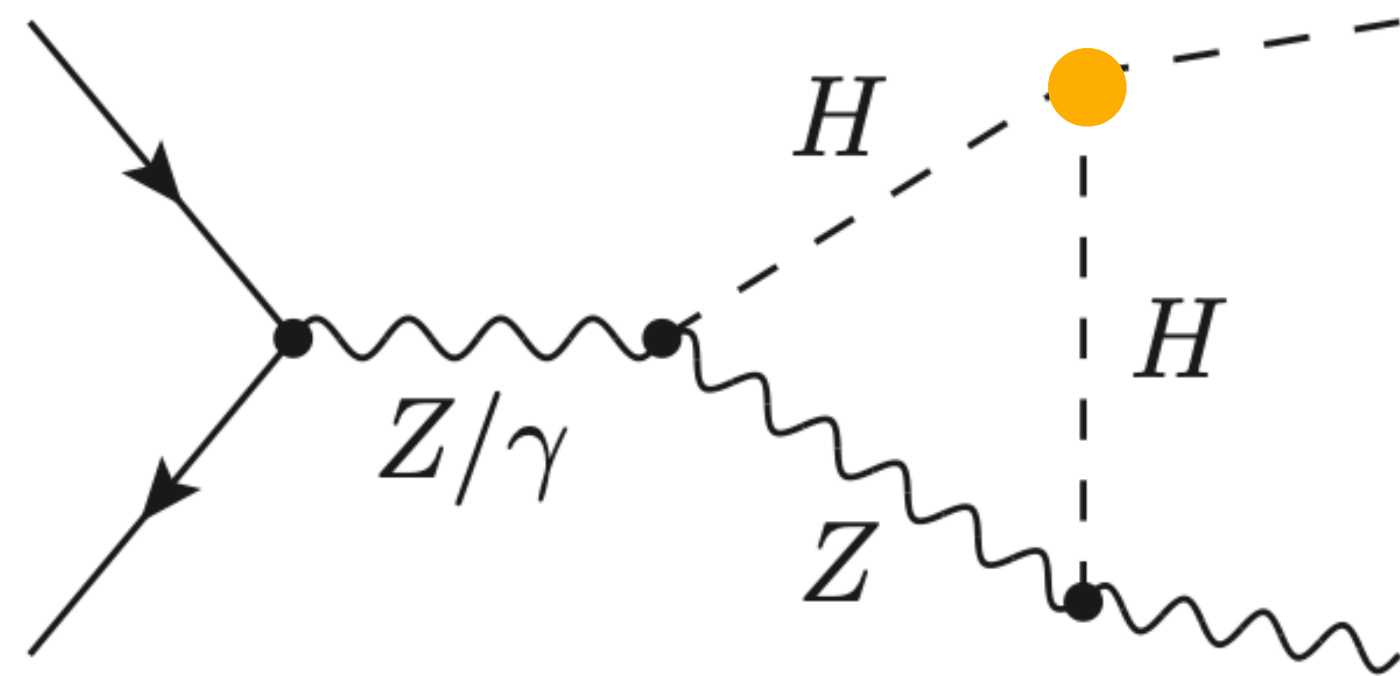


ZH production at FCC-ee in SMEFT

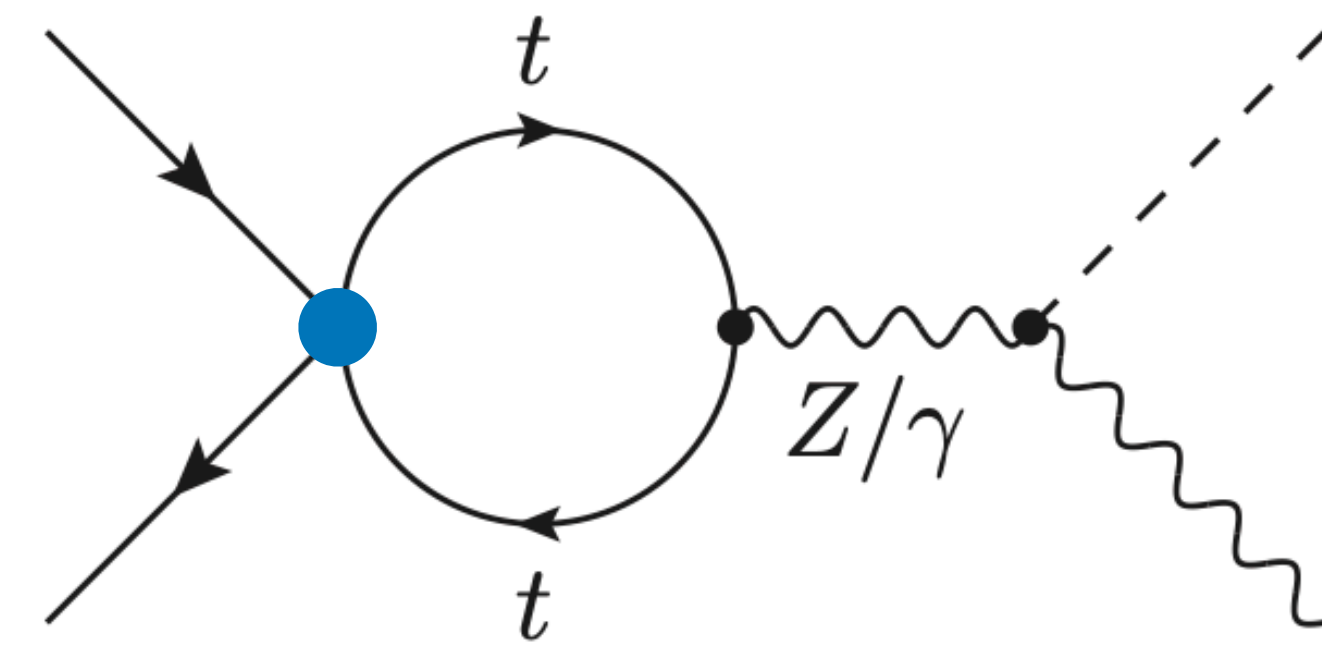
Asteriadis et al., JHEP 02 (2025) 162

NLO contributions: example

Asteriadis et al., Phys.Rev.Lett. 133 (2024) 23, 231801



C_ϕ $\longrightarrow$ trilinear coupling



C_{lq}^{1133} $\longrightarrow$ 4f interactions

70 SMEFT operators at NLO with no flavor assumptions

Let's decay the Higgs in SMEFT

$$H \rightarrow b\bar{b}$$

Gauld, Pecjak, Scott, Phys.Rev.D 94 (2016) 7, 074045

Cullen, Pecjak, Scott, JHEP 08 (2019) 173

$$H \rightarrow \tau^+\tau^-$$

Gauld, Pecjak, Scott, JHEP 05 (2016) 080

Cullen, Pecjak, JHEP 11 (2020) 079

$$H \rightarrow \gamma\gamma$$

Hartmann, Trott, Phys.Rev.Lett. 115 (2015) 19, 191801

Dawson, Giardino, Phys.Rev.D 98 (2018) 9, 095005

Hartmann, Trott, JHEP 07 (2015) 151

Dedes et al., JHEP 08 (2018) 103

$$H \rightarrow Z\gamma$$

Dawson, Giardino, Phys. Rev. D 97, 093003 (2018)

Dedes, Suxho, Trifyllis, JHEP 06 (2019) 115

$$H \rightarrow gg$$

Deutschmann et al., JHEP 12 (2017) 063

Martin, Trott, JHEP 01 (2024) 170

Corbett, Martin, Trott, JHEP 12 (2021) 147

$$H \rightarrow Zff\bar{f}$$

Dawson et al., Phys.Rev.D 111 (2025) 1, 015016

$$H \rightarrow Wff\bar{f}'$$

NEW!

Let's decay the Higgs in SMEFT

Bellafronte et al., 2508.14966 [hep-ph]

$$H \rightarrow b\bar{b}$$

$$H \rightarrow \tau^+\tau^-$$

$$H \rightarrow \gamma\gamma$$

$$H \rightarrow Z\gamma$$

$$H \rightarrow gg$$

$$H \rightarrow Zff$$

$$H \rightarrow Wff$$

NEW!

Implemented in
fixed-order Monte Carlo code

total widths and branching ratios
at NLO in SMEFT

NEWiSH

NLO

ElectroWeak

in the

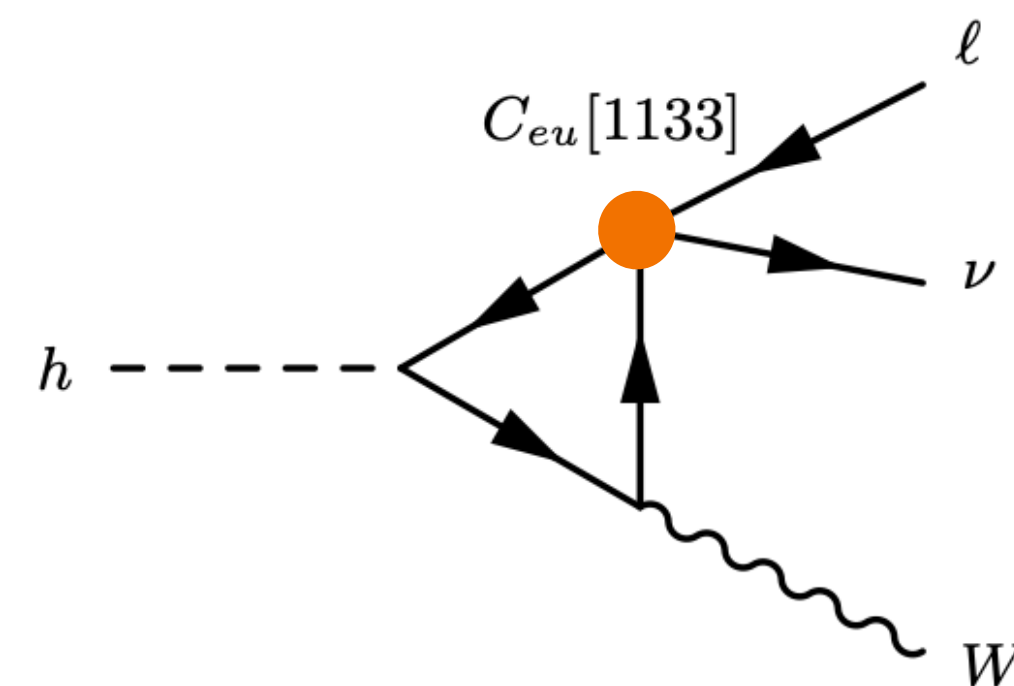
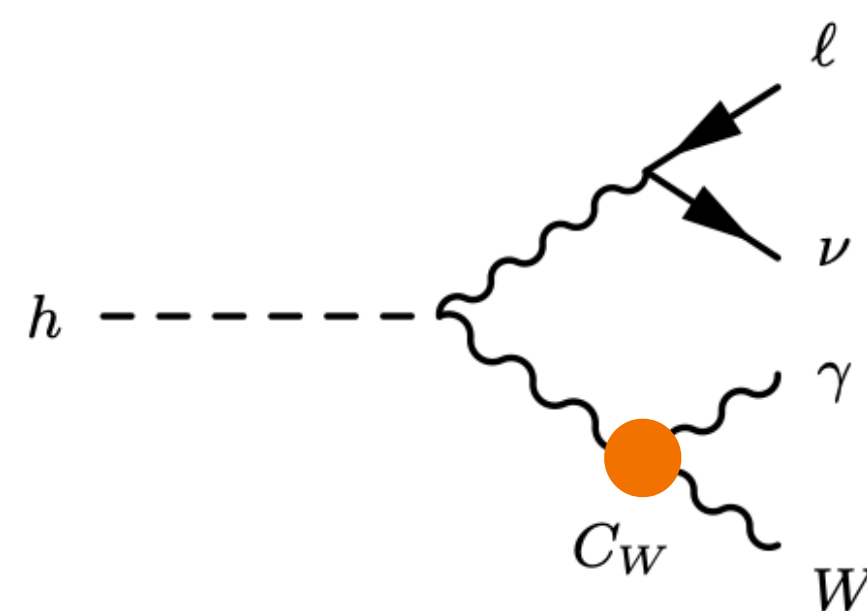
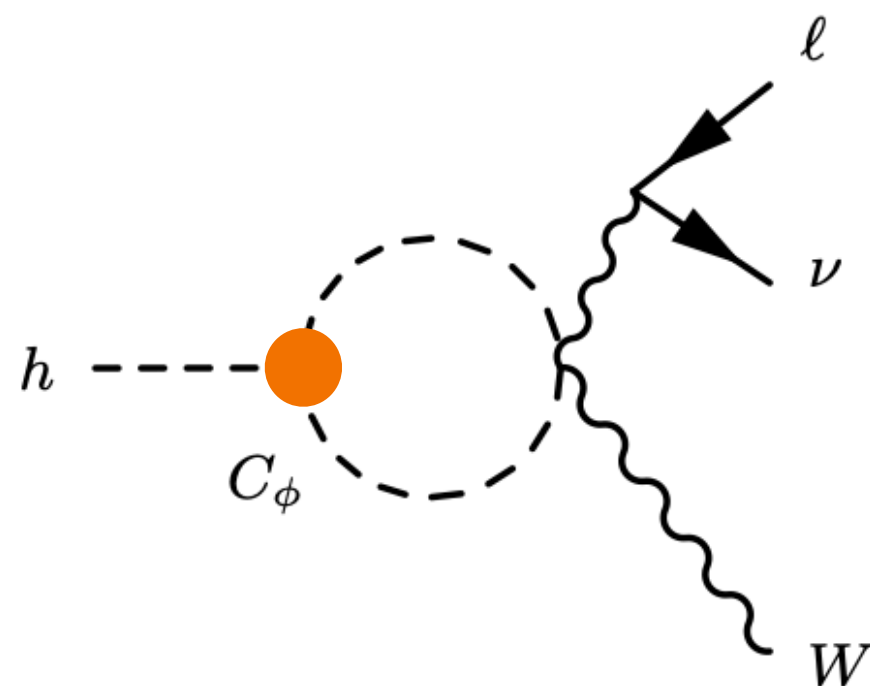
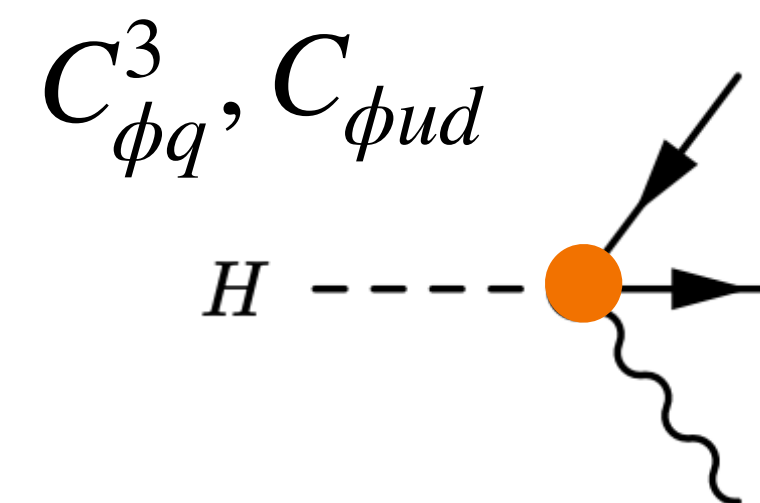
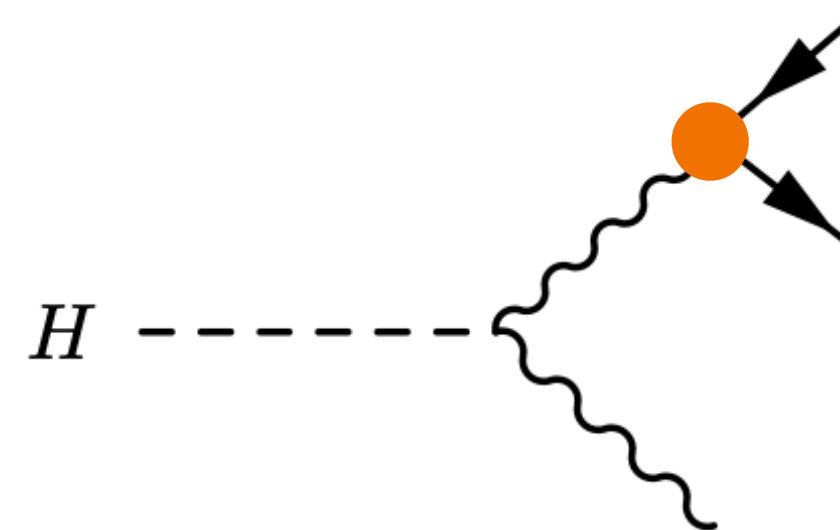
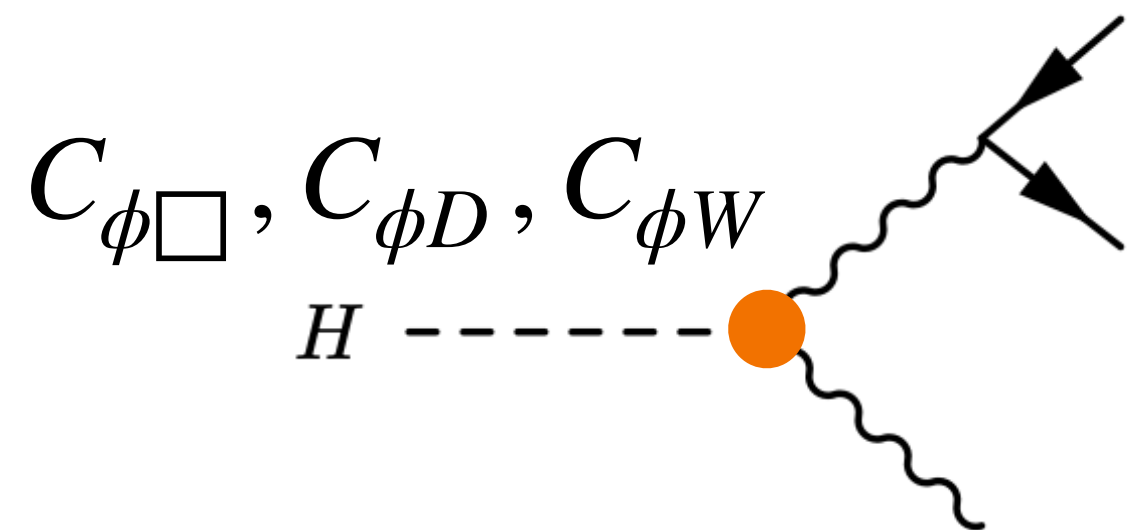
SMEFT for

Higgs widths

$H \rightarrow W f \bar{f}'$ at NLO EW in SMEFT

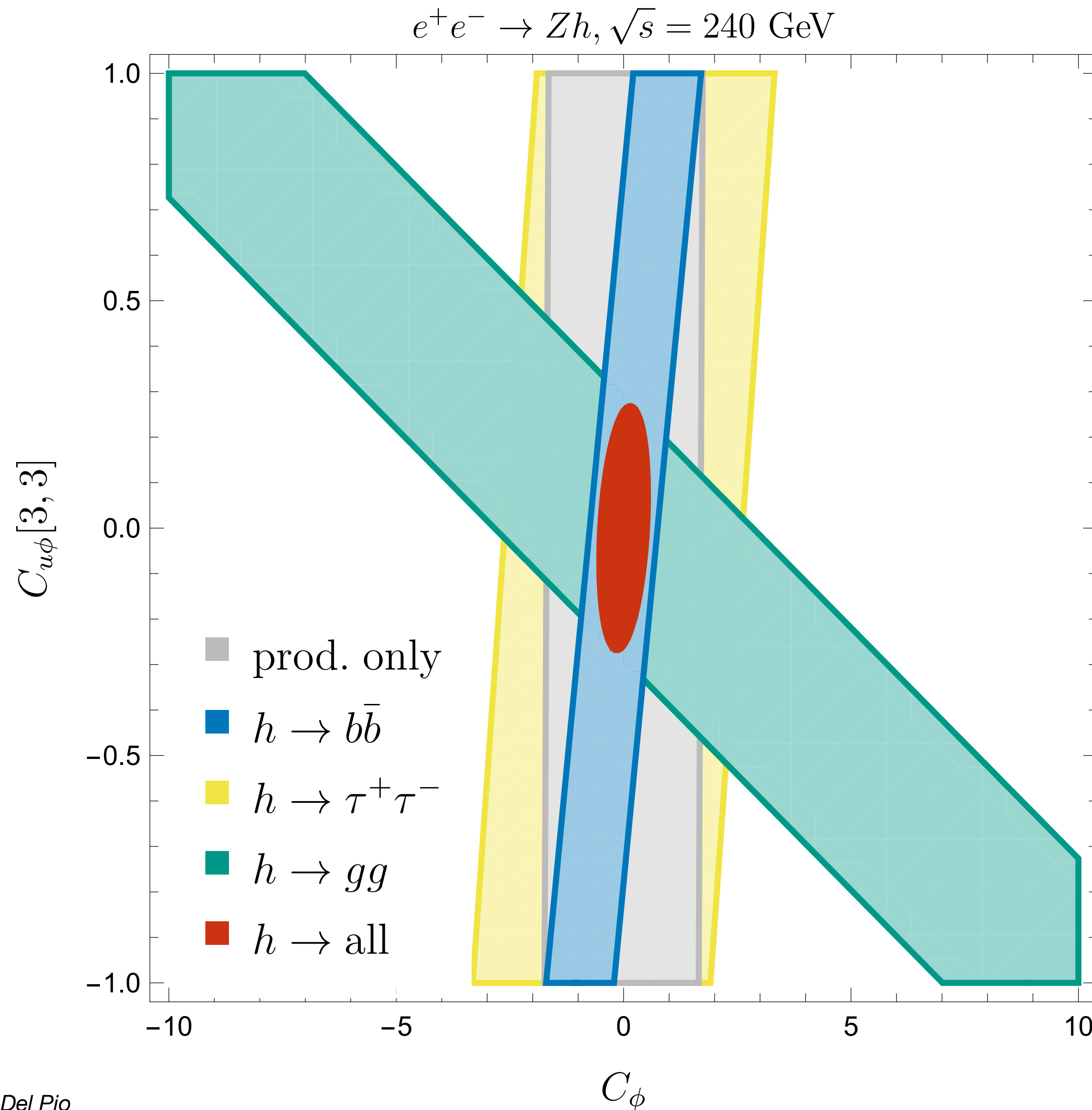
Bellafronte et al., 2508.14966 [hep-ph]

at LO $C_{\phi D}, C_{\phi \square}, C_{\phi l}^3/C_{\phi q}^3, C_{ll}, C_{\phi W}, C_{\phi ud}$



Adding the decays

Bellafronte et al., 2508.14966 [hep-ph]



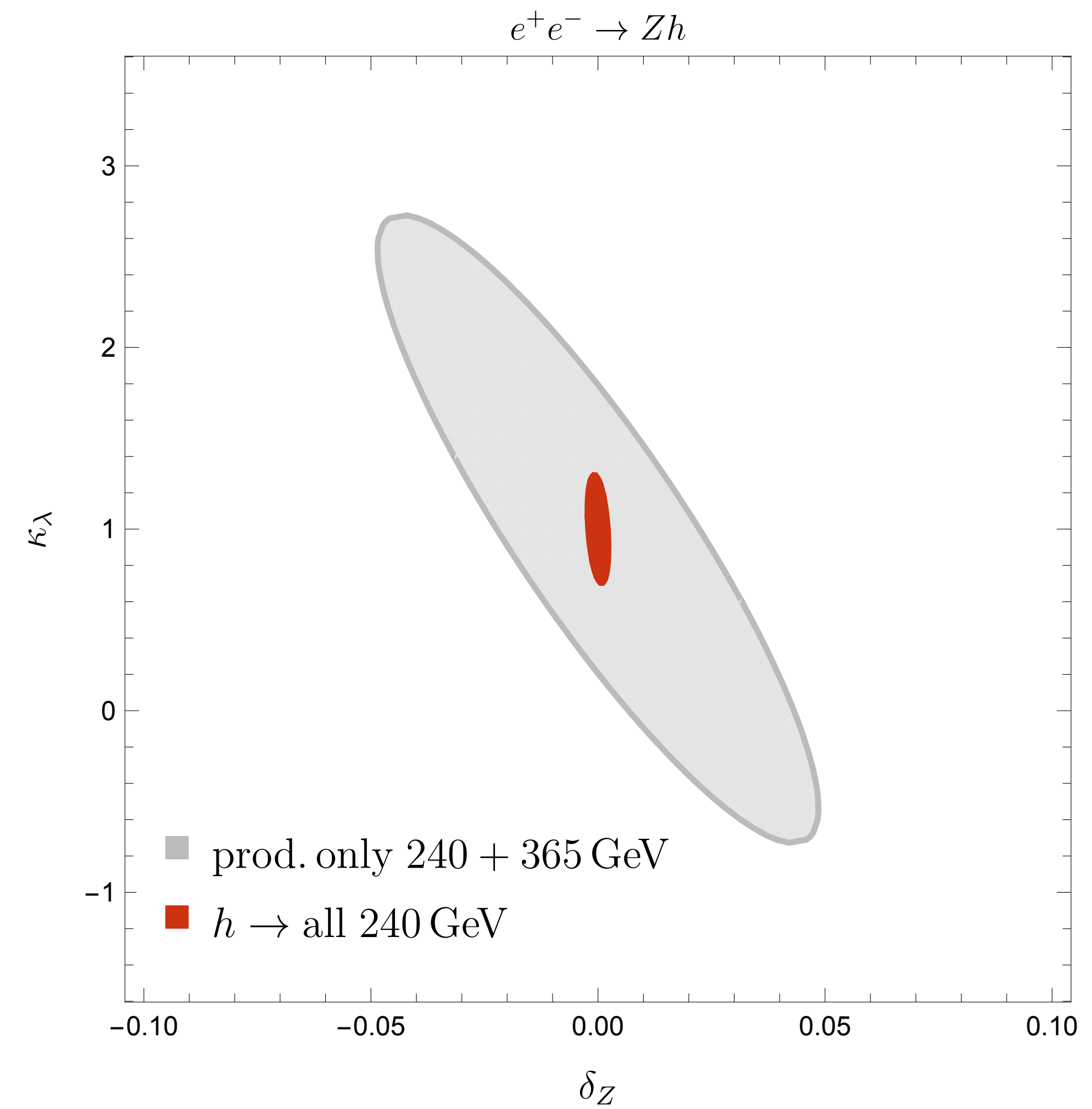
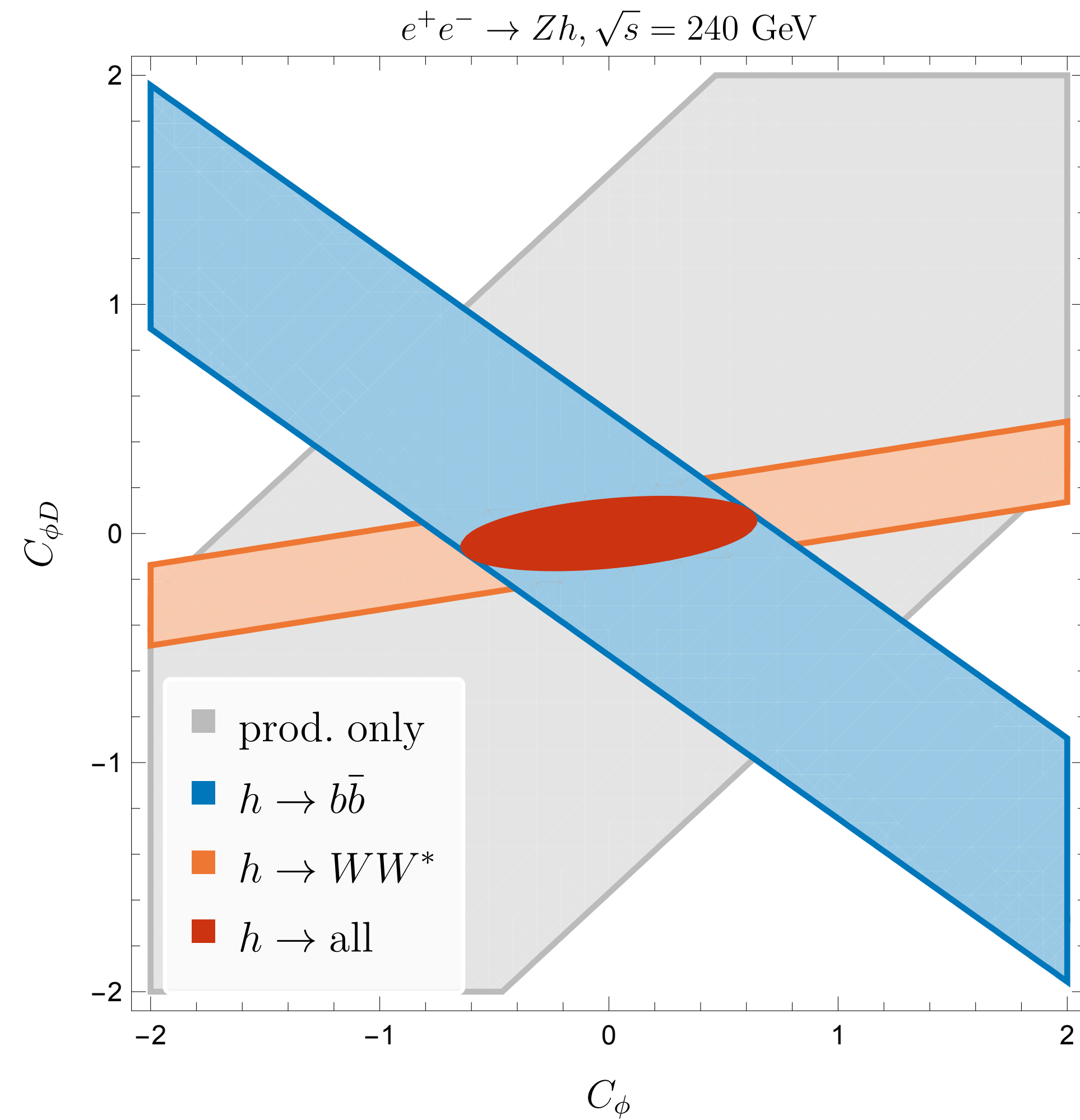
Narrow width approximation

$$\sigma(e^+e^- \rightarrow HZ; H \rightarrow XZ) = \sigma(e^+e^- \rightarrow HZ) \text{BR}(H \rightarrow XZ)$$

Adding the information of the decays provides much better constraints!

Higgs couplings

Bellafronte et al., 2508.14966 [hep-ph]



$$C_{\phi\Box} = 0$$

$$\delta_Z = \frac{1}{4} \frac{v^2}{\Lambda^2} C_{\phi D}$$

$$\kappa_\lambda = 1 + \frac{v^2}{\Lambda^2} \left(\frac{3}{4} C_{\phi D} - 2 \frac{v^2}{m_H^2} C_\phi \right)$$

Outlook

The Higgs sector is fundamental for understanding the SM and the physics beyond

Consistent parameterisation of New Physics effects in **Higgs production and decay** with **SMEFT at NLO**

Inclusion of the decays **improves bounds** on many coefficients at **FCC-ee**

Thank you!

