Z polarization for Higgs self coupling

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ECFA meeting
March 18, 2024

arXiv:1805.03417
arXiv:2109.11134

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Outline

- Triple Higgs coupling at hadron collider
- Triple Higgs coupling at an e^+e^- collider
- $e^+e^- \rightarrow ZH$ production for triple Higgs coupling

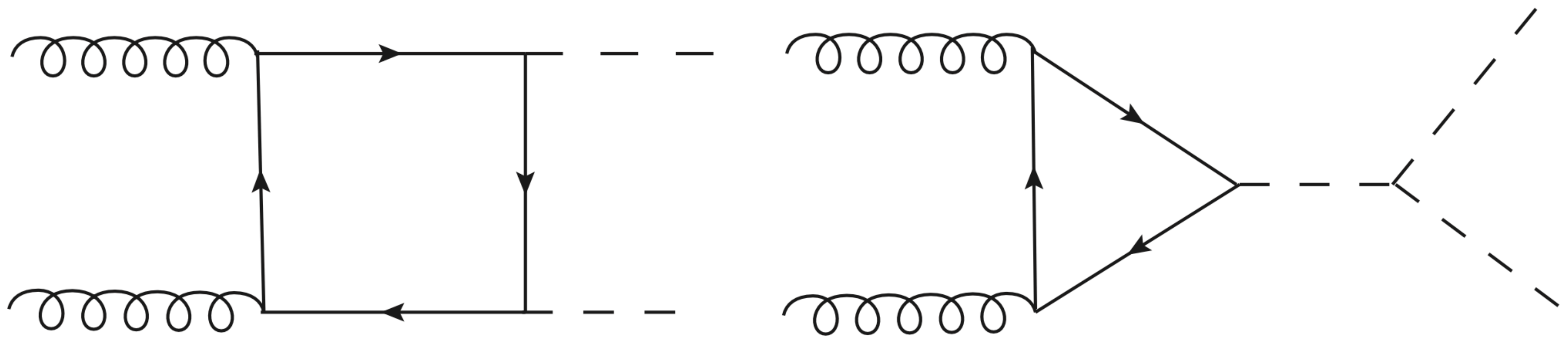
  Int.J.Mod.Phys.A 35 (2020) 04, 2050011

- Angular distributions in Z decay
- Z polarization and triple Higgs coupling

  Nucl.Phys.B 975 (2022) 115649

Triple Higgs coupling

- Direct probe for triple Higgs coupling is $gg \to HH$



λ_{3H} at leading order (LO) ⟶ direct channel

NPB 309 (1988) 282

Accuracy of the determination of λ_{3H} is low

- Cancellation between box and triangle diagrams: destructive interference
- Destructive interference leads to extremely small cross-section
- High beam energy is required

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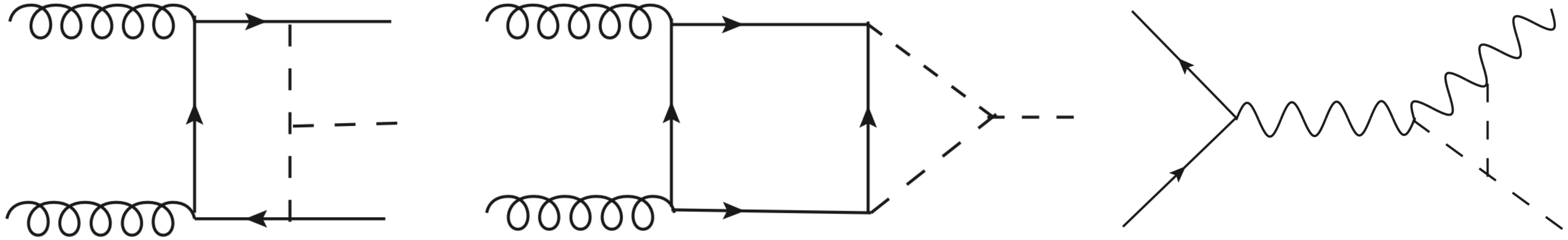
- Indirect channel: λ_{3H} enters at NLO



HL-LHC

$$-0.8 < \frac{\lambda_{3H}}{\lambda_{SM}} < 7.7$$

ATL-PHYS-PUB-2017-001

Trilinear coupling with e^+e^- beam

- Higgs associated production is sensitive to λ_{3H} at NLO in e^+e^- collider: Indirect measurement

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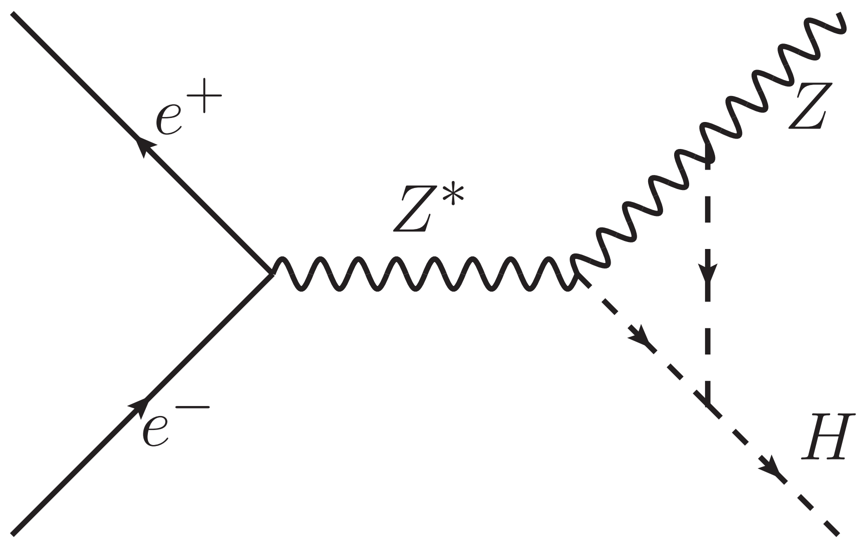


$$\lambda_{3H} = \lambda_{SM}(1 + \delta_h)$$

δ_h Parameterises deviation to self coupling

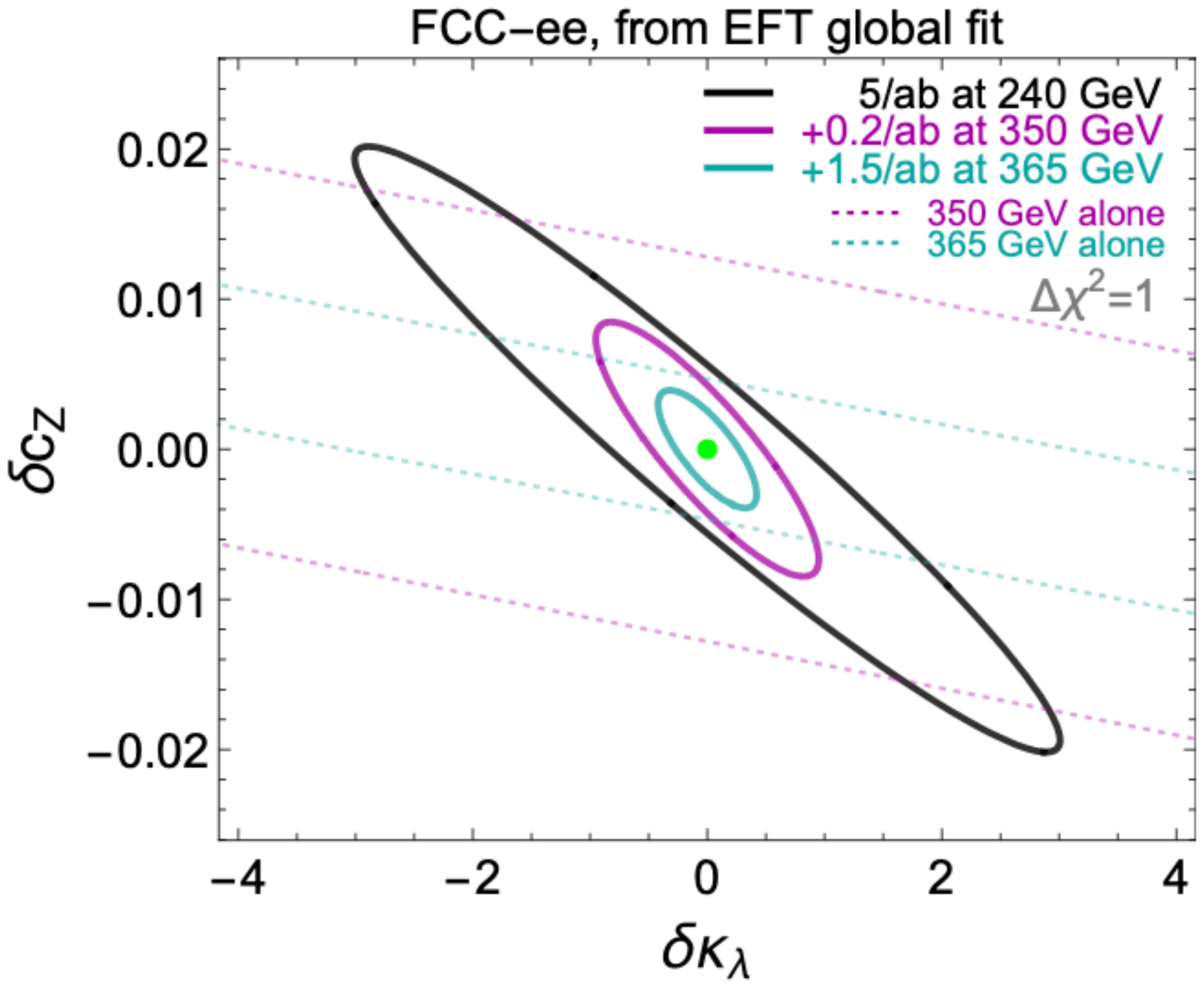
Can constrain δ_h in a model dependent way ⟶ FCC-ee at $\sqrt{s} = 240$ GeV by 28%

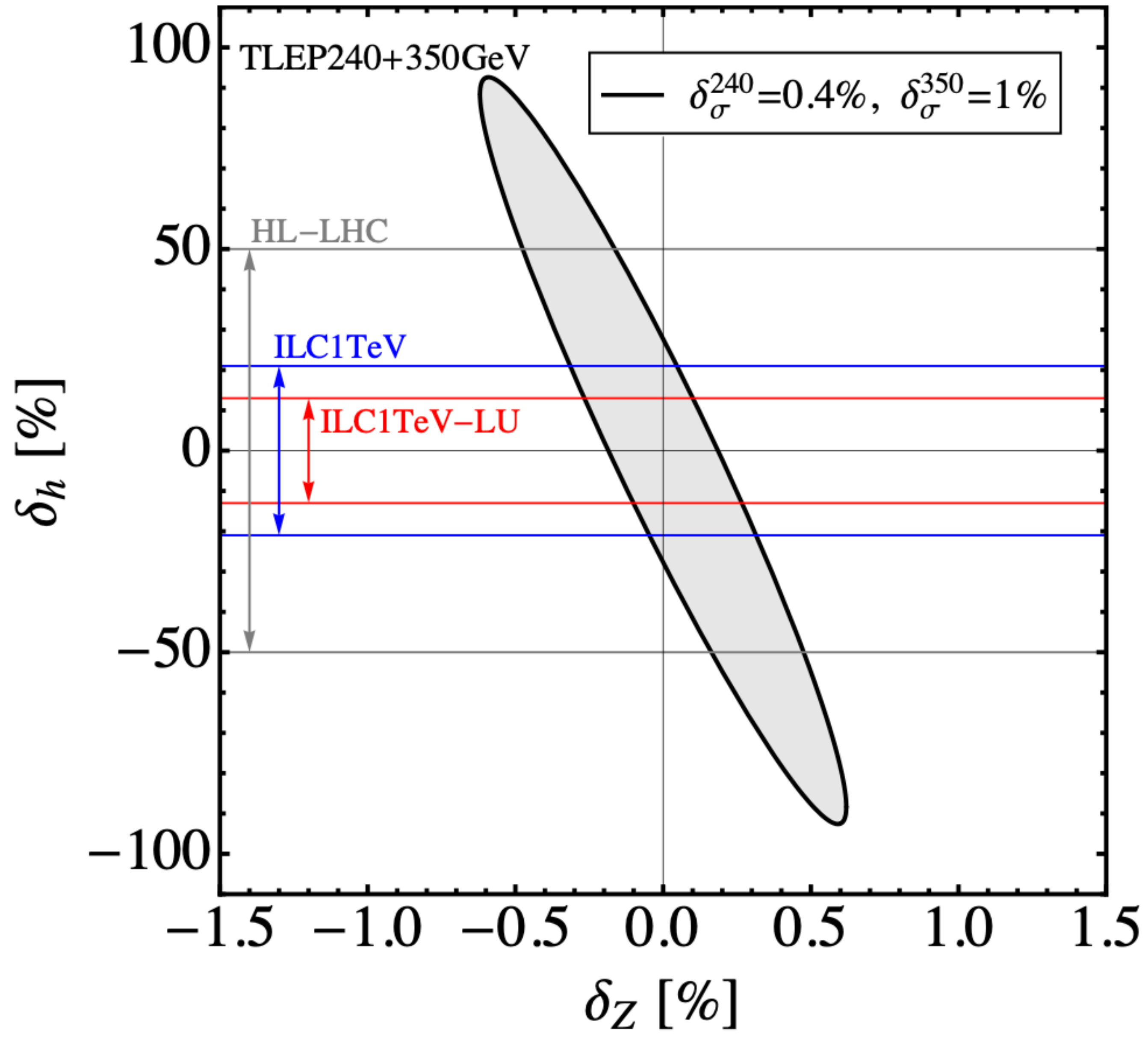
$\mathscr{L} \sim 10$ ab^{-1}

1809.10041

- With HZZ (δ_Z), combination of δ_Z and δ_h can be constrained

- Precision measurements at different c.o.m energies can be useful to constrain the combination of δ_h and δ_Z





Sensitivity can be improved if δ_Z can be removed somehow!

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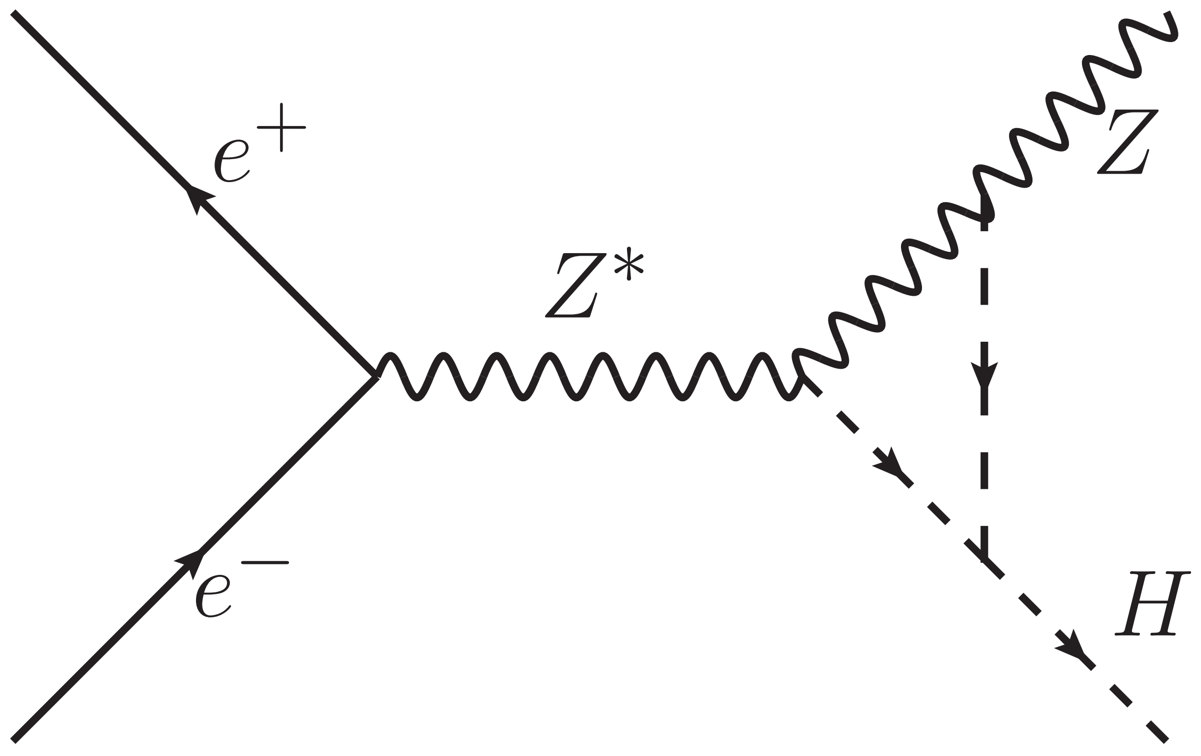
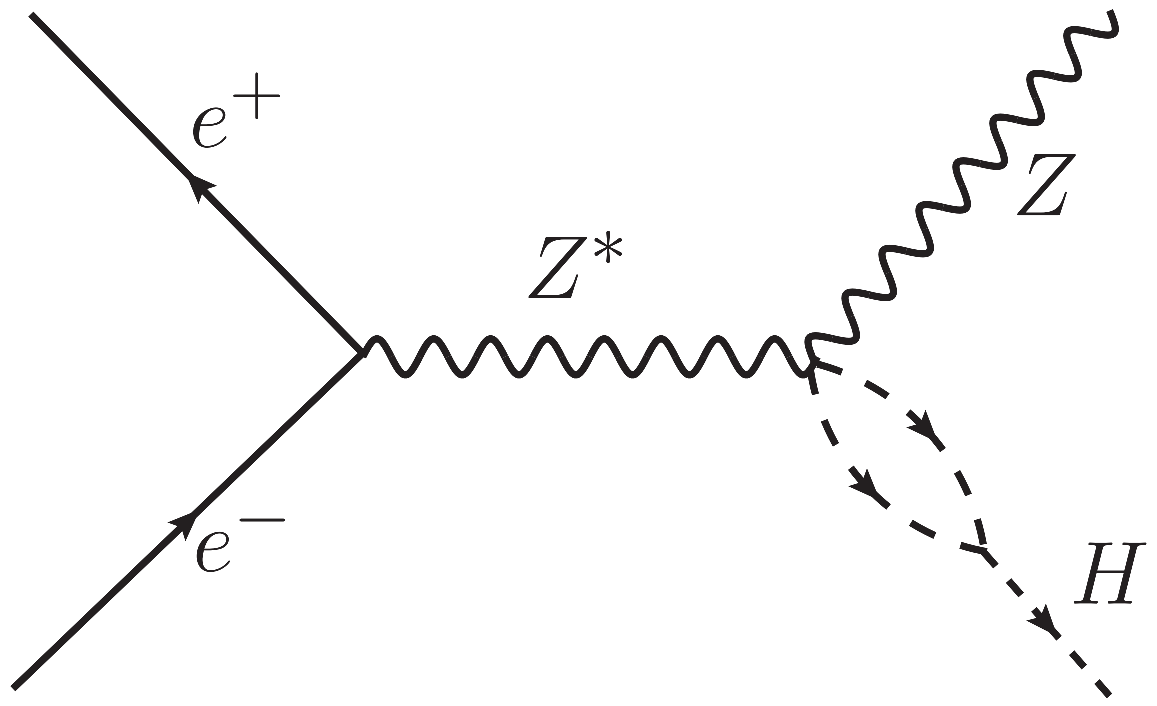
Trilinear coupling at $e^+e^- \to ZH$

- Triple-higgs coupling can be measured through its contribution in one-loop diagram in single Higgs production





$$\lambda_{3H} = \lambda_{SM}(1+\kappa)$$

$$\Gamma^{VVH}_{\mu\nu} = g_V m_V[(1+F_1)g_{\mu\nu} + F_2 k_{1\nu} k_{2\mu}]$$

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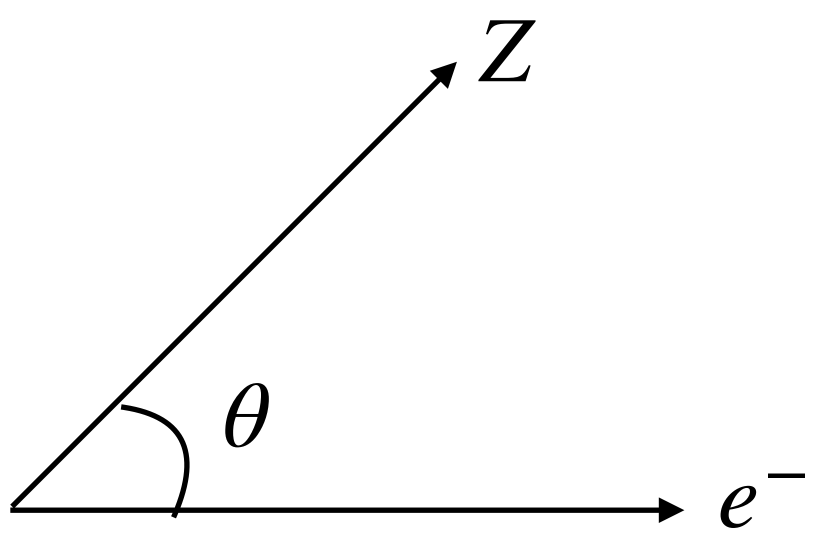

Production cross-section: $$\frac{d\sigma_L}{d\Omega} = (1 - P_L \bar{P}_L)[A_L + B_L \sin^2\theta]$$

$$A_L = A_L^{\rm SM} + \Delta A_L, \qquad B_L = B_L^{\rm SM} + \Delta B_L$$

$$\Delta A_L = 2F_1(g_V^2 + g_A^2 - 2g_V g_A P_L^{\rm eff})K^{\rm SM}$$

$$\Delta B_L = 2\left(F_1 + F_2\sqrt{s}q^0\right)\frac{|q|^2}{2m_Z^2}(g_V^2 + g_A^2 - 2g_V g_A P_L^{\rm eff})K^{\rm SM}$$

θ is angle between Z and electron direction

ΔA_L, ΔB_L contribution from triple Higgs

$F_{1,2}$ form factor for $Z^* \to ZH$

Higgs top anomalous couplings will be suppressed at low c.o.m energy

Trilinear coupling at $e^+e^- \to ZH$

- Fractional change in cross-section and 1σ limit on κ
- Polarized beam can improve sensitivity
- Fractional change is independent of polarization

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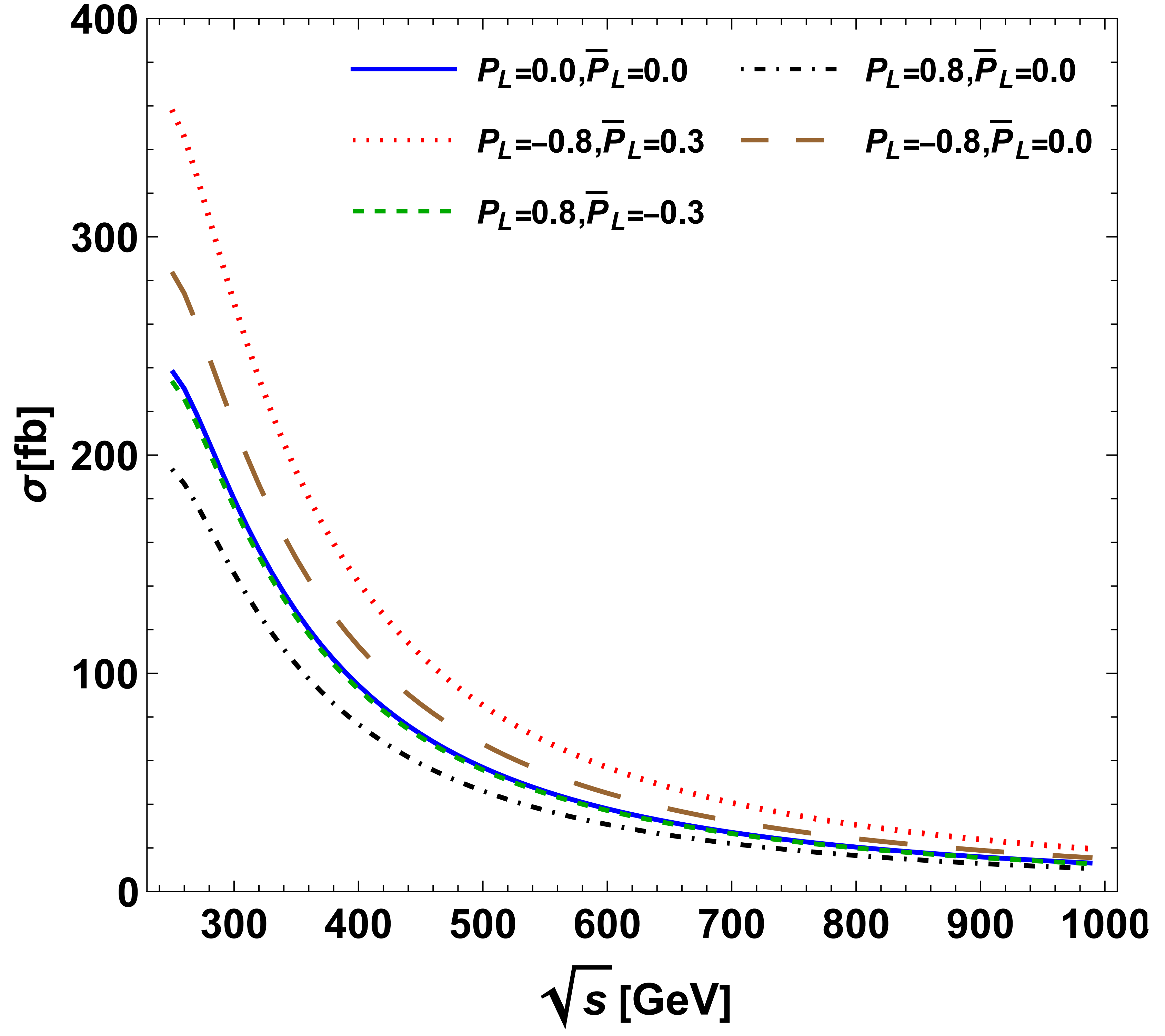
$\mathscr{L} \sim 2$ ab^{-1}



$\sqrt{s}$	P_L	$\bar{P}_L$	σ_L (fb)	$\frac{\delta\sigma}{\sigma}/\kappa$	κ_{lim} (%)
250	0	0	242	1.278	70.0
	−0.8	0	288	1.278	64.2
	−0.8	+0.3	364	1.278	57.2
350	0	0	129	0.284	315
	−0.8	0	153	0.284	289
	−0.8	+0.3	193	0.284	257
500	0	0	56.9	−0.203	−440
	−0.8	0	67.6	−0.203	−403
	−0.8	+0.3	85.3	−0.203	−359
1000	0	0	12.7	−0.433	−206
	−0.8	0	15.1	−0.433	−189
	−0.8	+0.3	19.1	−0.433	−169

- For $P_{e^-} = -0.8$ and $P_{e^+} = 0.3$ the accuracy to measure κ is about 57 %

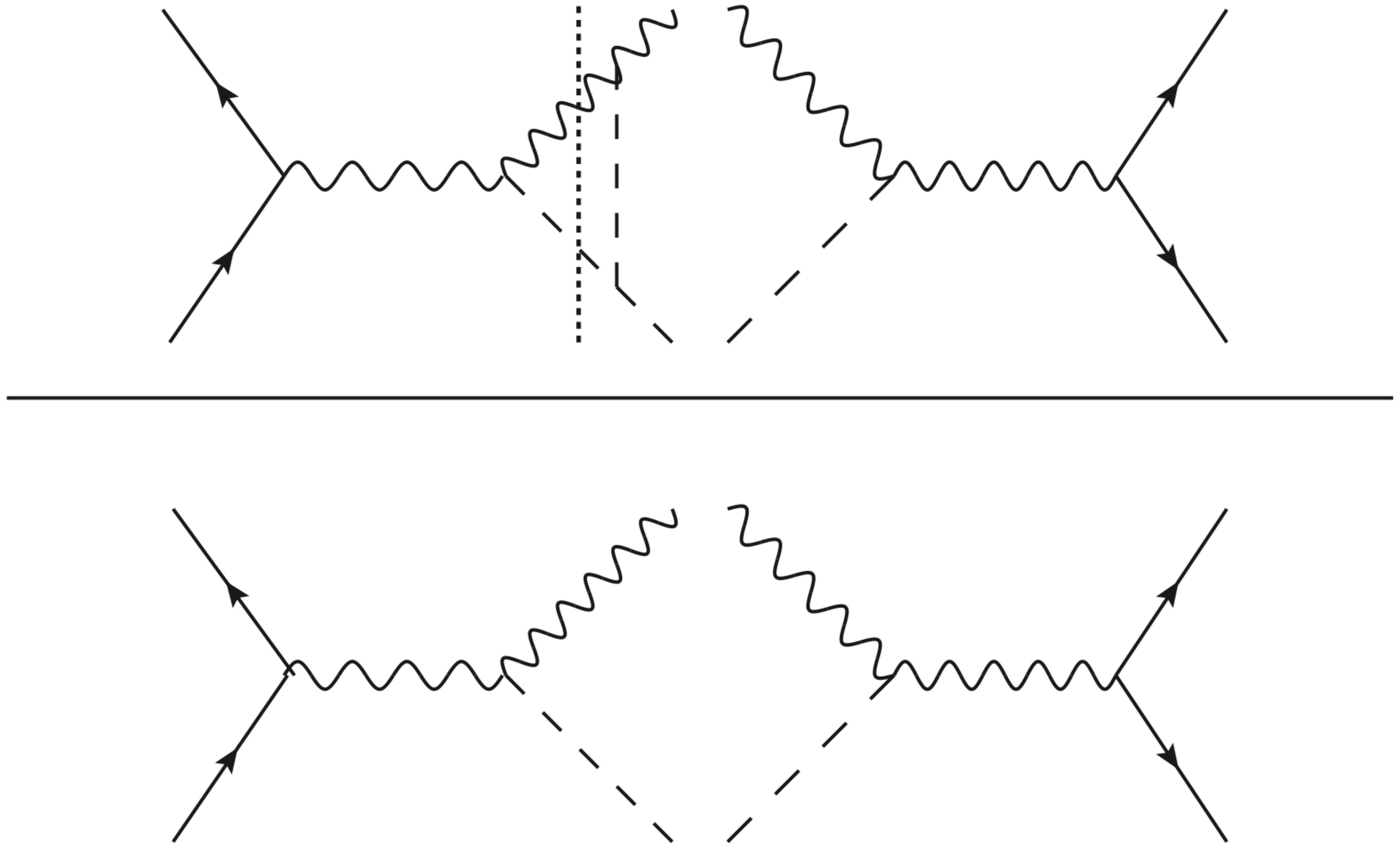
T-odd distributions

- Extraction of trilinear coupling from ZH production is overwhelmed by tree level anomalous couplings

Anomalous ZZH coupling: Dimension-six operators in SMEFT

- T-odd distributions of the production cross-section can be used

PRL 47(1981)983
1812.01576



Tree level contributions are T-even

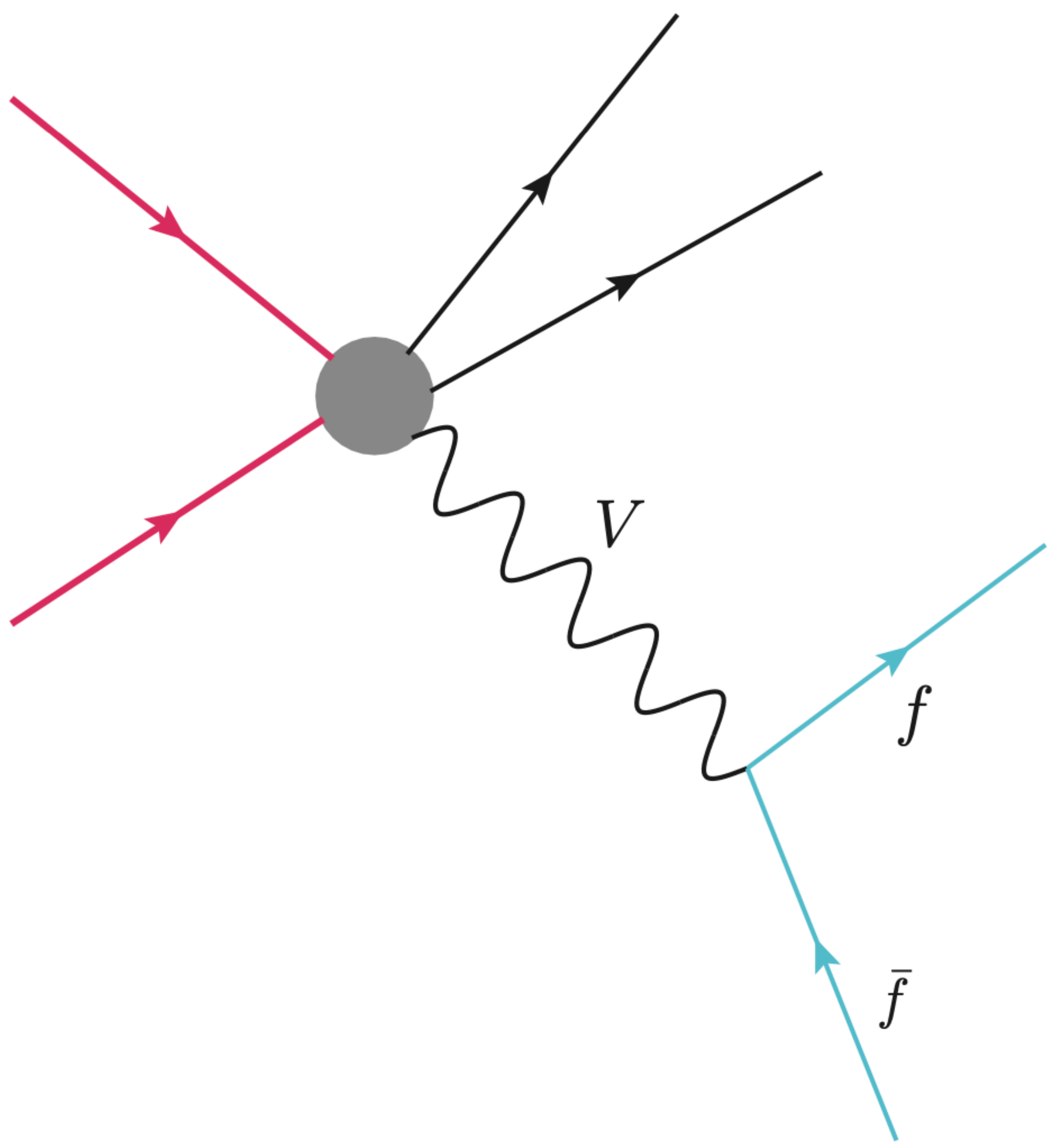
Can constrain λ_{3H} independent of tree level anomalous couplings

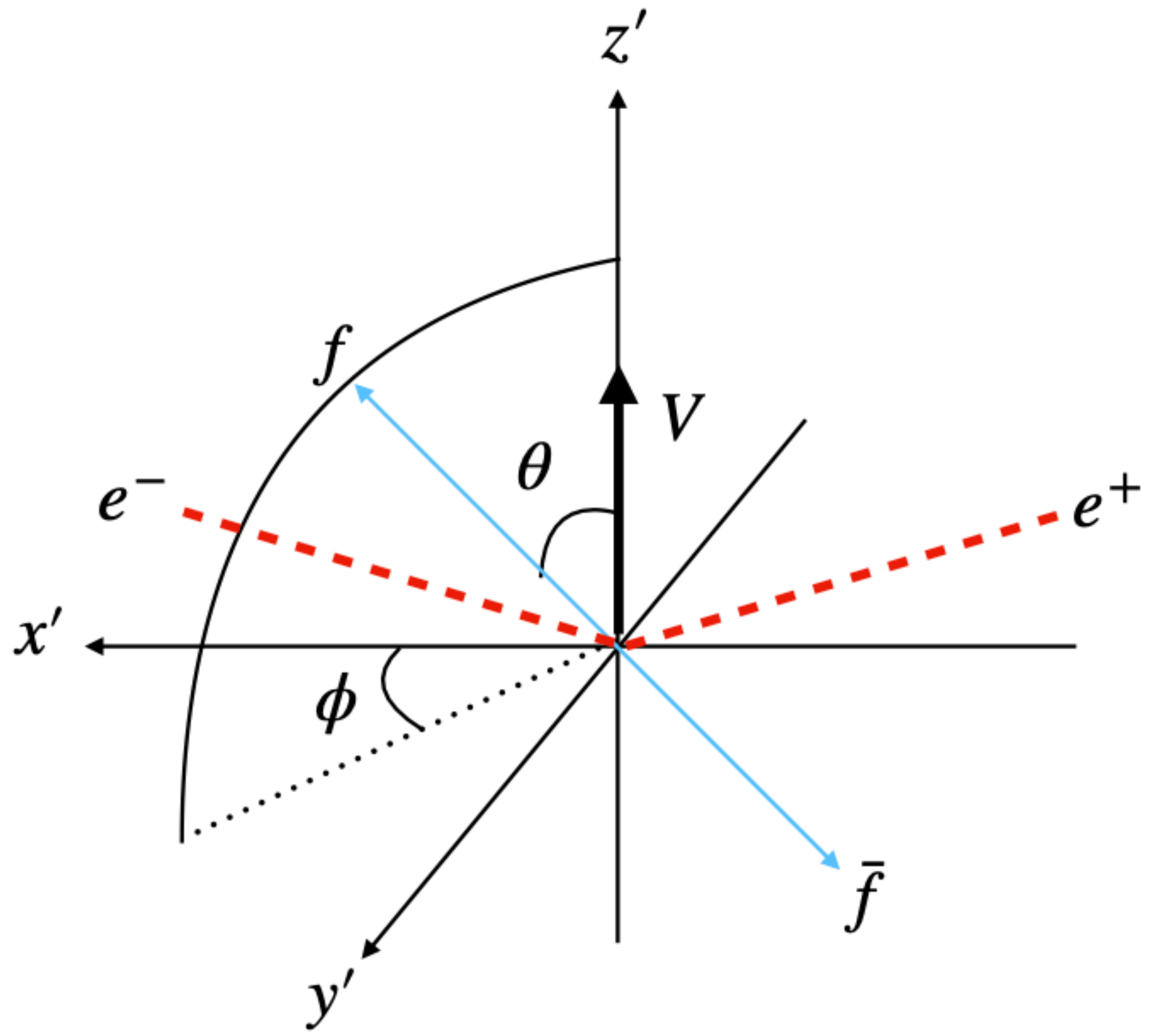
We explore the possibility of using Z polarization for measuring trilinear Higgs coupling

Either less sensitive to tree level ZZH coupling or independent of it

Z polarization parameters

- Angular asymmetries are related to polarization parameters





$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_f} \propto \sum_{\lambda\lambda'} P(\lambda,\lambda')\Gamma(\lambda,\lambda';\theta,\phi)$$

$$\lambda,\lambda' \in (-1,0,1)$$

$P(\lambda,\lambda') \longrightarrow$ Polarization density matrix

$\Gamma(\lambda,\lambda';\theta,\phi) \longrightarrow$ Decay density matrix

- θ and ϕ are polar and azimuthal angles of final state fermion in the rest frame of V
- Polarization parameters can be extracted from polarized matrix elements

Angular asymmetries

- In experiment one needs to compute asymmetries to extract polarization parameters

$$A_x = \frac{\sigma(\cos\phi > 0) - \sigma(\cos\phi < 0)}{\sigma(\cos\phi > 0) + \sigma(\cos\phi < 0)} = \frac{3\alpha P_x}{4} \qquad \alpha = -\frac{2c_V c_A}{c_V^2 + c_A^2}$$

Forward-backward asymmetry; CP even, T even

- Analysis needs to be done in the rest frame of Z
- Rest frame of Z is obtained by a combination of rotation and boost
- The polar and azimuthal angles of decay products are measured with respect to the would-be momenta of Z
- For triple Higgs we will be interested in A_{yz} which is T odd and CP even

T-odd angular asymmetry

- A_{yz} is odd under naive time reversal

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$$A_{yz} \equiv \frac{\sigma(\cos\theta\sin\phi > 0) - \sigma(\cos\theta\sin\phi < 0)}{\sigma(\cos\theta\sin\phi > 0) + \sigma(\cos\theta\sin\phi < 0)} = \frac{2}{\pi}\sqrt{\frac{2}{3}}T_{yz}$$

$T_{yz} \rightarrow$ Polarization component of Z

Can be realised from the transformation properties of $\cos\theta\sin\phi$

- Naive time reversal: Reversal of direction of all spins and momenta but not interchange of initial and final state

- CP-even angular asymmetry odd under naive time reversal is either less sensitive or independent of tree level anomalous couplings

	A_x	A_y	A_z	A_{xy}	A_{xz}	A_{yz}	A_{zz}	$A_{x^2-y^2}$
T	$+1$	-1	$+1$	-1	$+1$	-1	$+1$	$+1$
CP	$+1$	-1	-1	-1	-1	$+1$	$+1$	$+1$

Requires an absorptive part for non-zero value, CPT theorem!

Z polarization for trilinear coupling

- A_{yz} gets contribution only from absorptive part of the amplitude

Sensitive to triple Higgs coupling appearing at loop level

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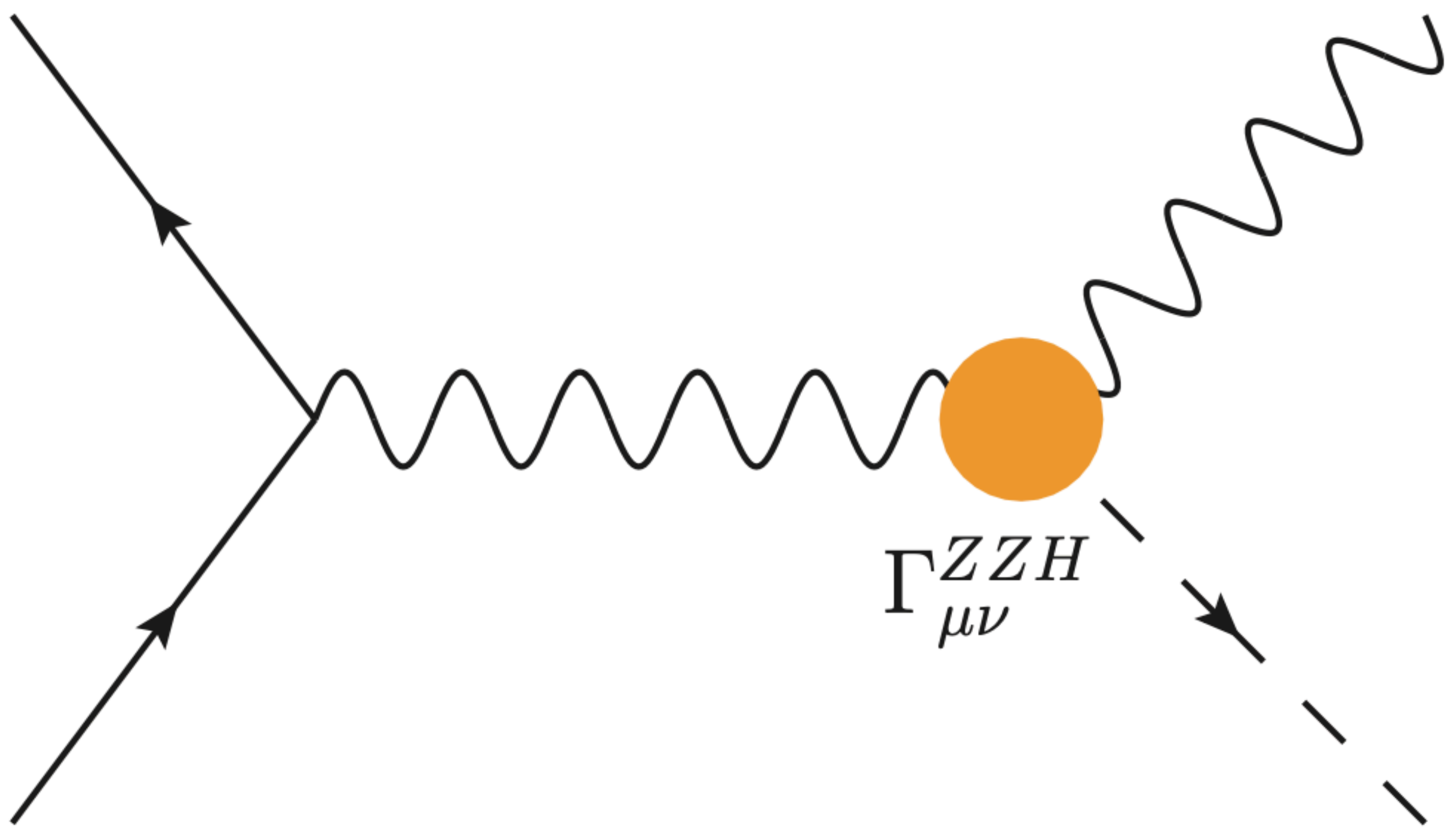
- A_{yz} measures interference between tree and loop level: leading contribution from loop level



$$\Gamma^{ZZH}_{\mu\nu} = \frac{g}{\cos\theta_W} m_Z \left[a_Z g_{\mu\nu} + \frac{b_Z}{m_Z^2}\left(q_\nu k_\mu - g_{\mu\nu} q \cdot k\right) + \frac{\tilde{b}_Z}{m_Z^2} \epsilon_{\mu\nu\alpha\beta} q^\alpha k^\beta \right]$$

CP even

$$a_Z = a_Z^0 + F_1 - (q \cdot k) F_2 \qquad b_Z = b_Z^0 - m_Z^2 F_2$$

At tree level SM: $a_z = 1$ and $b_z = 0$

- There can be other contribution at one loop like top Yukawa or WWH coupling which would already be well known

Z polarization for trilinear coupling

- In SMEFT a_Z, b_Z gets contribution from dimension-six operator $\Phi^\dagger \Phi F_{\mu\nu} F^{\mu\nu} / \Lambda^2$

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$$A_{yz} = \left(\frac{2c_V c_A - P_L^{\text{eff}}(c_V^2 + c_A^2)}{4(c_V^2 + c_A^2 - 2P_L^{\text{eff}} c_V c_A)} \right) \left(\frac{|\vec{k}_Z|^2 \sqrt{s}}{(E_Z^2 + m_Z^2) m_Z} \right) \text{Im } b_Z$$

$$\text{Im } b_Z = -m_Z^2 \text{ Im } F_2$$

$$P_L^{\text{eff}} = \frac{P_L - \bar{P}_L}{1 - P_L \bar{P}_L}$$

$\sqrt{s}$ (GeV)	Im b_Z (for $\kappa = 1$)
240	-3.62×10^{-4}
250	-4.91×10^{-4}
350	-8.22×10^{-4}
365	-8.09×10^{-4}
380	-7.93×10^{-4}
500	-6.13×10^{-4}

- Quadratic terms are suppressed by new physics scale
- Any tree level b_Z (real) will not contribute
- Initial polarized beam can improve sensitivity

Z polarization for trilinear coupling

Collider	c.m. energy (GeV)	$10^4 \times A_{yz}$ unpolarized beams	$10^4 \times A_{yz}$ polarized beams	Luminosity (ab^{-1})	Limit unpolarized beams	Limit polarized beams
CEPC	240	−0.159		10	506	
CEPC	240	−0.159		20	358	
CLIC	380	−2.88	−10.6	0.5	124	31.0
FCC	240	−0.159		10	506	
FCC	250	−0.314		5	362	
FCC	365	−2.64		1.5	78.2	
ILC	250	−0.314	−1.23	2	573	119
ILC	250	−0.314	−1.23	5	362	75.3
ILC	350	−2.39	−9.38	30	19.4	4.03
ILC	500	−4.00	−15.7	4	31.6	6.57
ILC	500	−4.00	−15.7	10	20.0	4.16
ILC	500	−4.00	−15.7	30	11.5	2.40

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Summary

- CP even and T-odd distributions can be useful to constrain triple Higgs coupling
- A_{yz} is the only CP even and T-odd asymmetry
- A_{yz} is proportional to the absorptive part of the amplitude, therefore isolates the loop level contributions
- e^+e^- polarized beam can be useful to improve accuracy
- For polarization combination $P_{e^-} = -0.8$ and $P_{e^+} = 0.3$ the accuracy to measure κ is about $57\ \%$ at $\mathscr{L} = 2\,\mathrm{ab}^{-1}$
- Sensitivity may be improved by incorporating hadronic decay channels of Z as well

Thank you

for your attention