

LCWS2026
11 November 2026

Higgs production via vector-boson fusion at future lepton colliders in SMEFT

(Work in progress...)

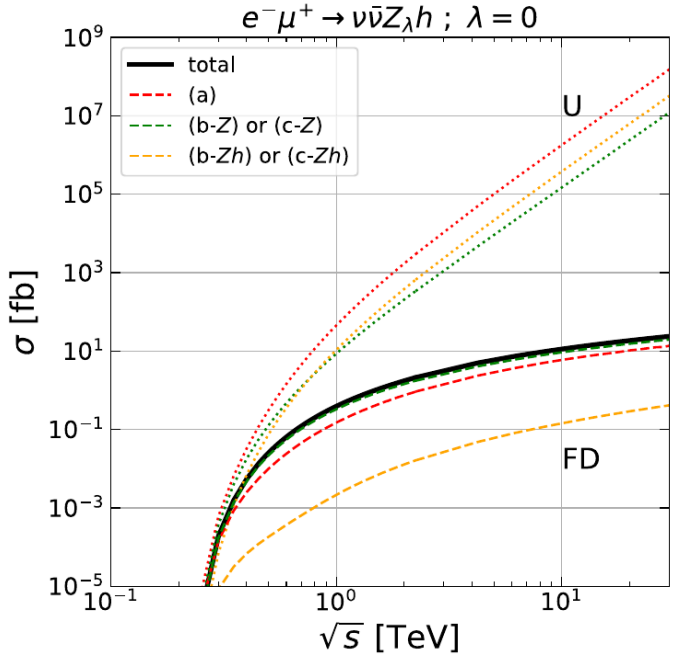
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岩手大学
IWATE UNIVERSITY

Our previous work: SM Higgs and Z production

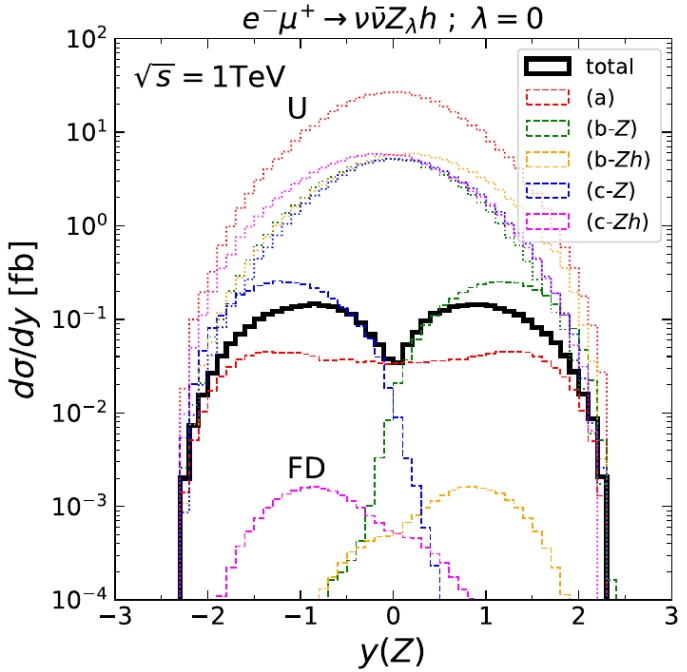
The Feynman-Diagram gauge revealed which amplitude groups dominate each kinematic region [1].

Energy dependence



In the unitary gauge, each category of amplitudes grows with energy. The large terms cancel among categories to give the physical cross section.

Z rapidity distribution at 1 TeV



In the FD gauge, the categories show no such energy growth. Their sizes and shapes tell us which diagrams dominate in specific regions of phase space.

The FD gauge helps us understand how SM amplitudes shape the distributions, helping us interpret possible New-Physics deviations. Next, we turn to Higgs production via VBF at high-energy lepton colliders.

[1] H. Furusato, S. Hosoya, K. Mawatari, S. Suzuki, Phys. Lett. B 883 (2026) 141084

Why do we study Higgs production above 250 GeV?

Higgsstrahlung has a large cross section near 250 GeV:

$$e^-e^+ \rightarrow Z\,h$$

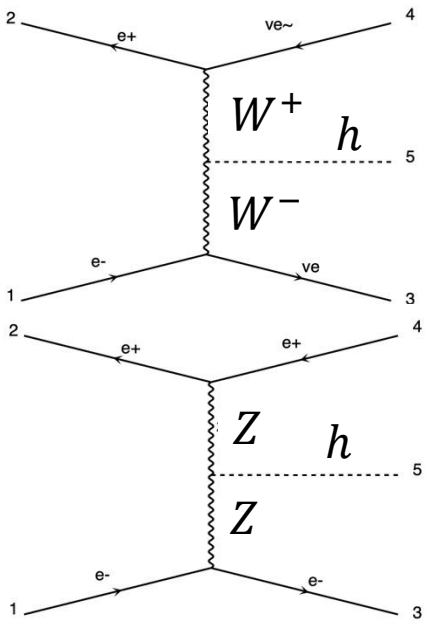
At higher energies, vector-boson fusion (VBF) becomes increasingly important.

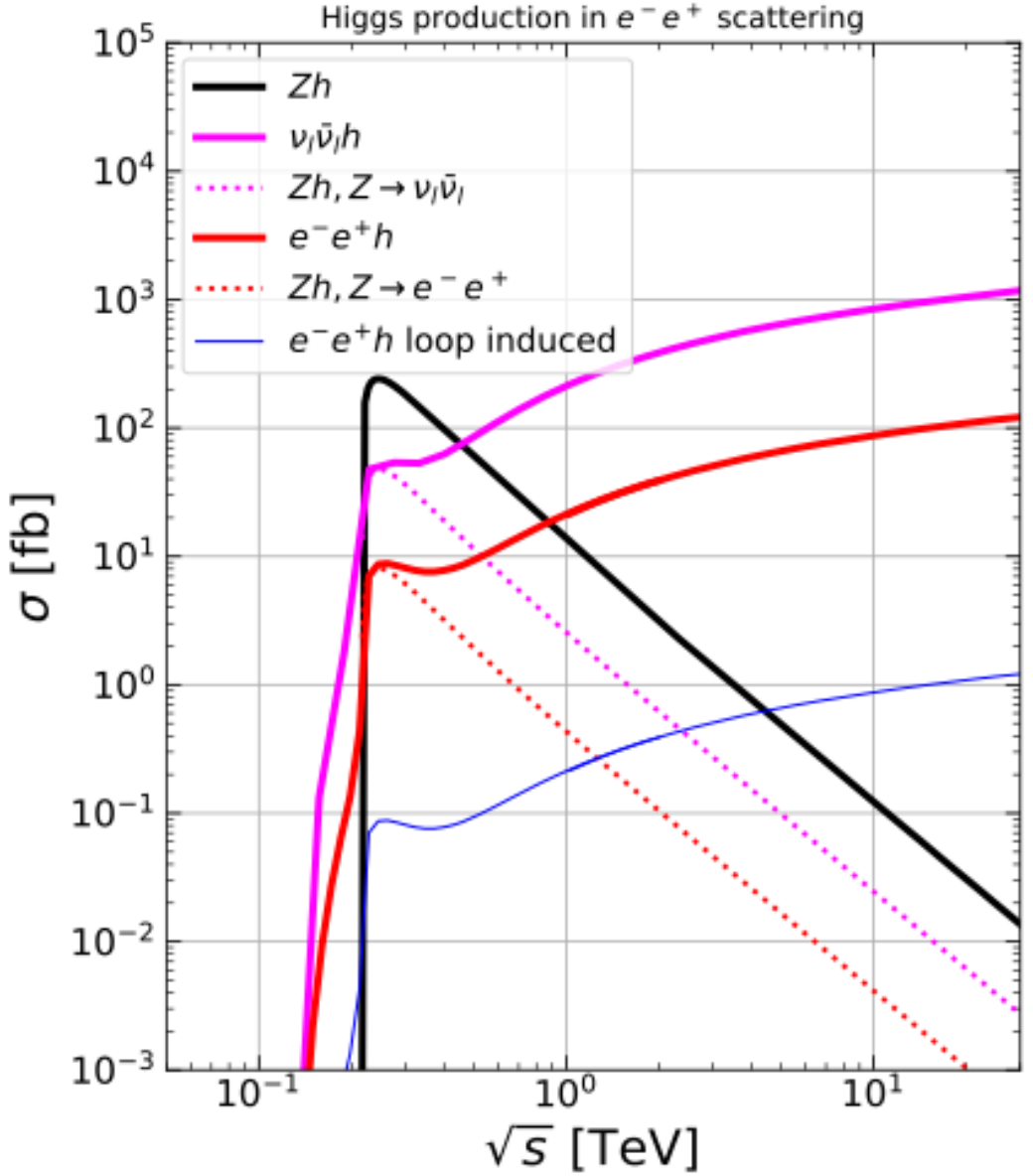
Charged-current VBF

$$e^-e^+ \rightarrow \nu_l\bar{\nu}_l h$$

Neutral-current VBF

$$e^-e^+ \rightarrow e^-e^+h$$





The charged-current VBF SM xsec is larger, while in the neutral-current VBF, scattered charged leptons give more information through the measured lepton momenta and angles.

Three SMEFT operators in Higgs production via VBF

We consider three CP-even Higgs-gauge dimension-six operators.

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \tilde{c}_{HW}\mathcal{O}_{HW} + \tilde{c}_{HB}\mathcal{O}_{HB} + \tilde{c}_{HWB}\mathcal{O}_{HWB} \ , \qquad \tilde{c}_i \equiv \frac{c_i}{\Lambda^2}$$

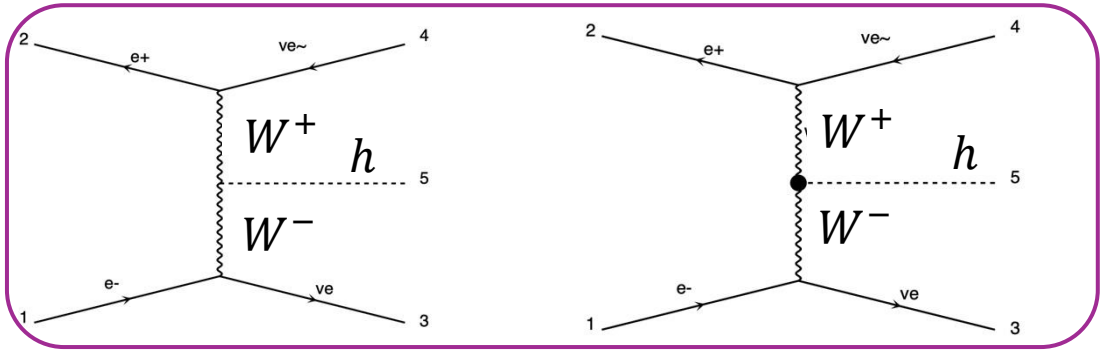
$$\mathcal{O}_{HW} = \phi^\dagger\phi W^I_{\mu\nu}W^{I\mu\nu}$$
$$\mathcal{O}_{HB} = \phi^\dagger\phi B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{HWB} = \phi^\dagger\sigma^I\phi\, W^I_{\mu\nu}B^{\mu\nu}$$

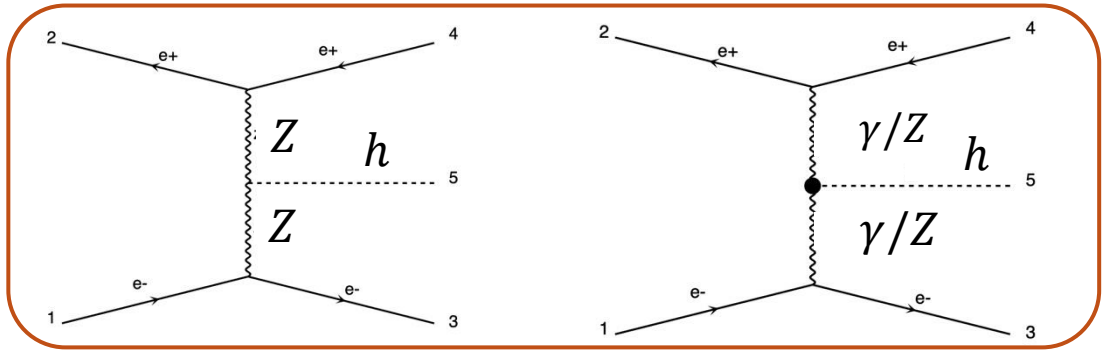
$$W^I_{\mu\nu} = \partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g\epsilon^{IJK}W^J_\mu W^K_\nu$$
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

Charged-current VBF

Neutral-current VBF

SM D6 contribution





Charged-current VBF depends on the HW operator. Neutral-current VBF receives contributions from all three operators. The $h\gamma\gamma$ and $hZ\gamma$ interactions are absent at tree level in the SM.

Three SMEFT operators in Higgs production via VBF

We retain three CP-even bosonic dimension-six field-strength operators.

Operator definitions

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \tilde{c}_{HW}\mathcal{O}_{HW} + \tilde{c}_{HB}\mathcal{O}_{HB} + \tilde{c}_{HWB}\mathcal{O}_{HWB} \ , \qquad \tilde{c}_i \equiv \frac{c_i}{\Lambda^2}$$

$$\mathcal{O}_{HW} = \phi^\dagger \phi W^I_{\mu\nu} W^{I\mu\nu}$$
$$\mathcal{O}_{HB} = \phi^\dagger \phi B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{HWB} = \phi^\dagger \sigma^I \phi W^I_{\mu\nu} B^{\mu\nu}$$

$$W^I_{\mu\nu} = \partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g\epsilon^{IJK} W^J_\mu W^K_\nu$$
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

Current bound

95% CL intervals in 10^{-7} GeV^{-2}

Fit	$\tilde{c}_{HW}$	$\tilde{c}_{HB}$	$\tilde{c}_{HWB}$
Individual	[−0.18, 0.060]	[−0.050, 0.020]	[−0.070, 0.030]
Global	[−2.73, 7.07]	[−3.10, 5.73]	[−5.25, 5.04]

[2] E. Celada et al., JHEP 09 (2024) 091.

The individual-fit bounds are narrower than the global-fit bounds, where correlations among operators are allowed. This difference motivates studying the operators together.

Charged-current VBF depends on the HW operator. Neutral-current VBF receives correlated contributions from all three operators. The photon-mediated Higgs interactions are absent at tree level in the SM.

SMEFT framework and benchmarks

$$\mathcal{L}_{hVV} = vh\left[\frac{\kappa_{hWW}}{2}W^{+}_{\mu\nu}W^{-\mu\nu} + \frac{\kappa_{hZZ}}{4}Z_{\mu\nu}Z^{\mu\nu} + \frac{\kappa_{h\gamma\gamma}}{4}A_{\mu\nu}A^{\mu\nu} + \frac{\kappa_{hZ\gamma}}{2}Z_{\mu\nu}A^{\mu\nu}\right],$$

$$\kappa_{hWW} = 4\tilde{c}_{HW},$$

$$\kappa_{hZZ} = 4\left(c_W^2\tilde{c}_{HW} + s_W^2\tilde{c}_{HB} + s_W c_W \tilde{c}_{HWB}\right)$$

$$\kappa_{h\gamma\gamma} = 4\left(s_W^2\tilde{c}_{HW} + c_W^2\tilde{c}_{HB} - s_W c_W \tilde{c}_{HWB}\right)$$

$$\kappa_{hZ\gamma} = 2\left[2s_W c_W(\tilde{c}_{HW} - \tilde{c}_{HB}) - (c_W^2 - s_W^2)\tilde{c}_{HWB}\right]$$

$s_W = \sin\theta_W$, $c_W = \cos\theta_W$

In this talk, we focus on the SM–dimension-six interference and its kinematic dependence.

Benchmark directions and hVV couplings: $\tilde{c} = \pm 10^{-7}$ GeV^{-2}

Benchmark: $(\tilde{c}_{HW}, \tilde{c}_{HB}, \tilde{c}_{HWB})$	$\kappa_{hWW}/\tilde{c}$	$\kappa_{hZZ}/\tilde{c}$	$\kappa_{h\gamma\gamma}/\tilde{c}$	$\kappa_{hZ\gamma}/\tilde{c}$
A: $\tilde{c}(1,0,0)$	4	$4c_W^2$	$4s_W^2$	$4s_W c_W$
B: $\tilde{c}(1,\tan^2\theta_W, 2\tan\theta_W)$	4	$4/c_W^2$	0	0
C: $\tilde{c}(1,1,1)$	4	$4(1+s_W c_W)$	$4(1-s_W c_W)$	$-2\cos 2\theta_W$

In Benchmark B, the hγγ and vertices are absent.

[3] S. Dutta, K. Hagiwara, Y. Matsumoto, Phys. Rev. D 78 (2008) 115016

The SMEFT changes sign in azimuthal separation

Benchmark B: photon-mediated vertices cancel

$$\sqrt{s} = 1\,TeV, \qquad p_{T\ell} > 10\,GeV$$

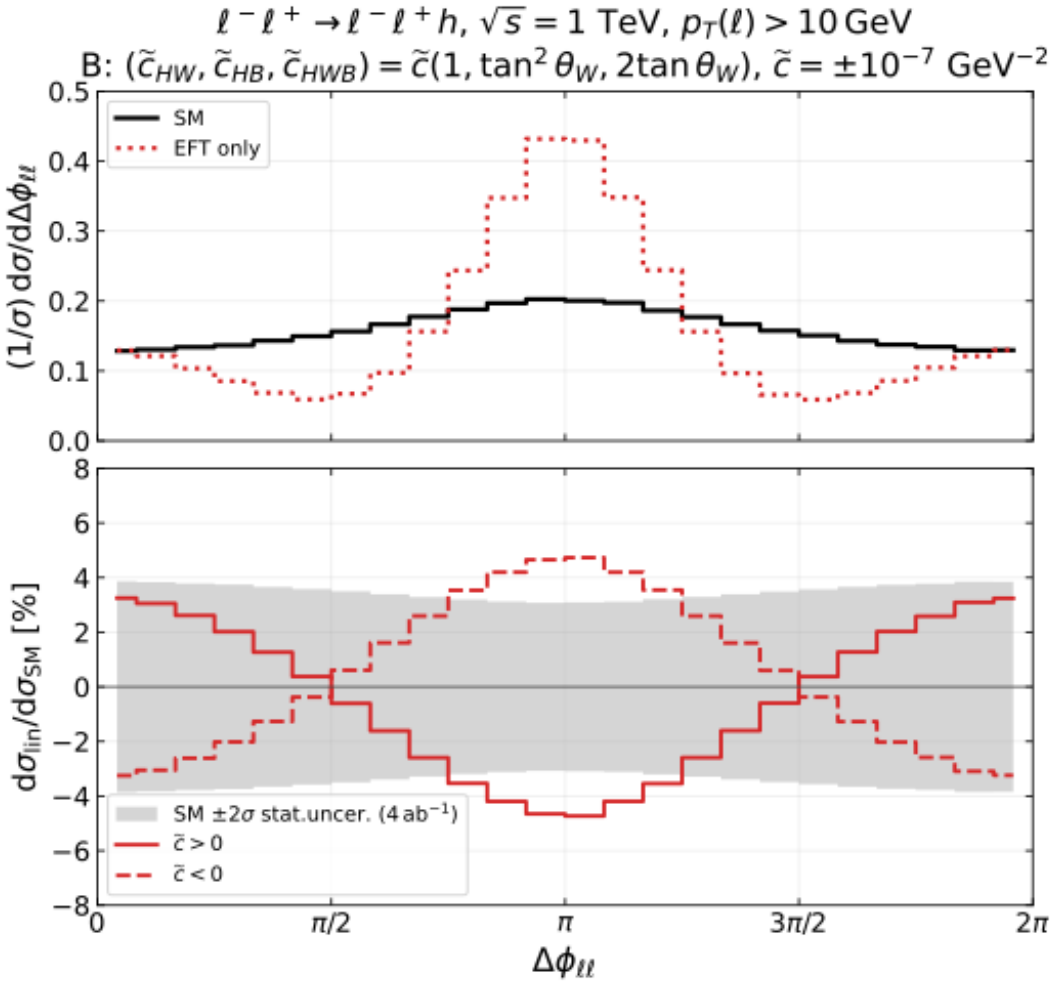
For $\tilde{c} > 0$,

$d\sigma_{lin} > 0$ in $0 < \Delta\varphi_{ll} < \frac{\pi}{2}$ or $\frac{3\pi}{2} < \Delta\varphi_{ll} < 2\pi$

$d\sigma_{lin} < 0$ in $\frac{\pi}{2} < \Delta\varphi_{ll} < \frac{3\pi}{2}$

The two contributions partly cancel after integration over the full phase space.

Inclusive integration can suppress an interference that is locally sizable and sign changing.



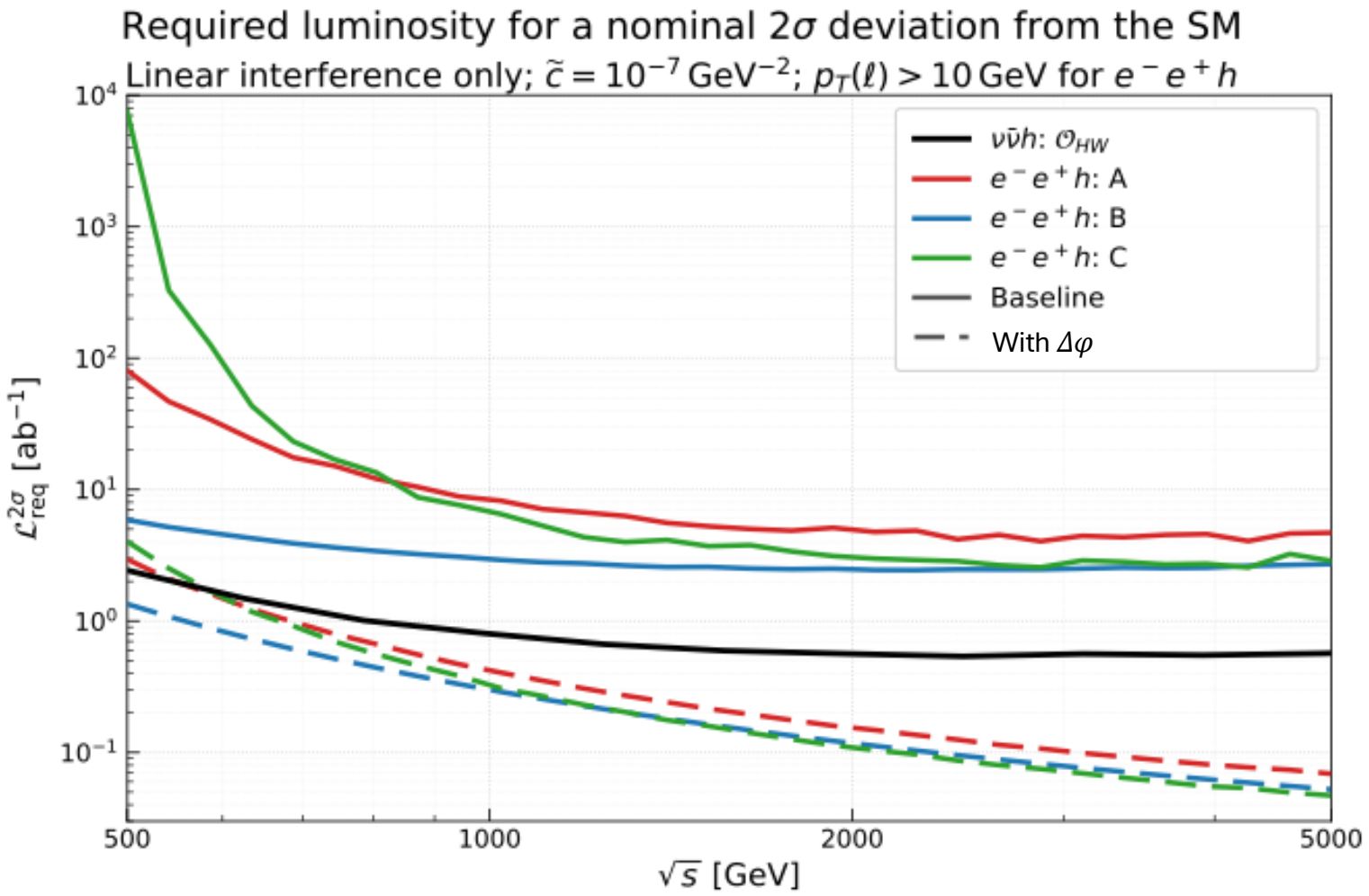
$$d\sigma_{SMEFT} = d\sigma_{SM} + d\sigma_{lin} + d\sigma_{quad}$$

$$\propto |\mathcal{M}_{SM}|^2 + 2\sum_i \tilde{c}_i\, \mathrm{Re}(\mathcal{M}_{SM}^{*}\, \mathcal{M}_i) + \sum_{i,j} \tilde{c}_i\, \tilde{c}_j\, \mathcal{M}_i^{*}\, \mathcal{M}_j$$

So, I use the measured lepton angle to reduce this cancellation.

[4] C. Degrande and M. Maltoni, Phys. Rev. D **103** (2021) 095009.

With angular information, the required luminosity is lower



Events in the outer regions receive a weight of +1, while events in the central region receive a weight of -1.

We then subtract the central-region rate from the outer-region rate. All baseline events are retained.

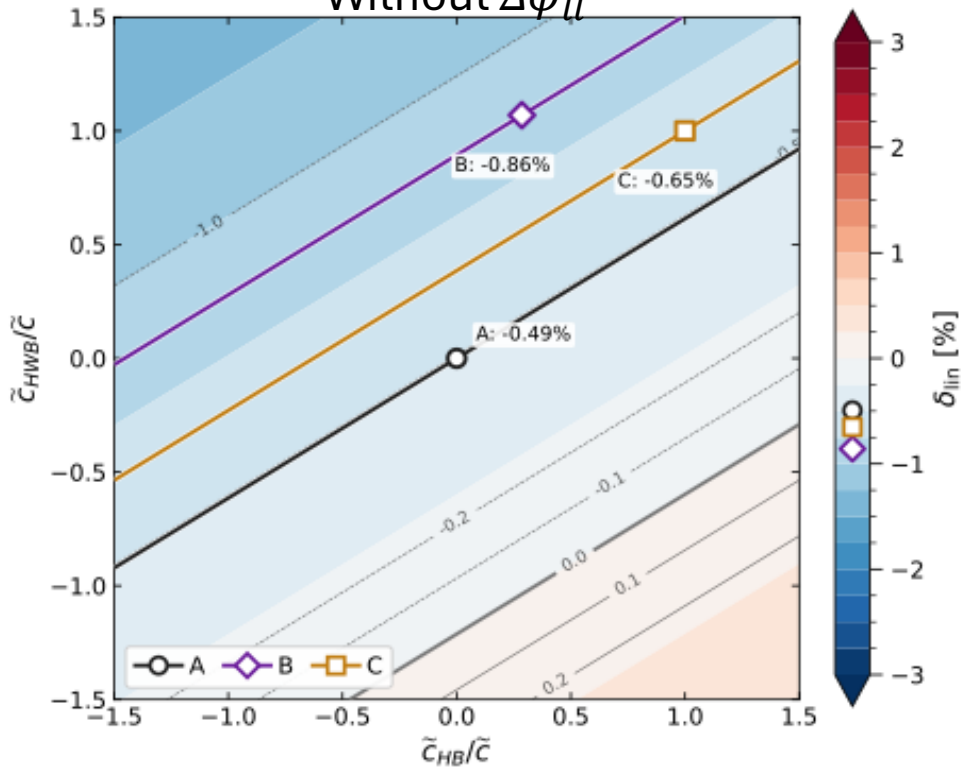
Since every weight has magnitude one, events in both regions contribute to the Standard Model statistical uncertainty. This $\Delta\varphi$ weighting reduces the cancellation of the linear interference.

The information of $\Delta\varphi$ can reduce angular cancellation without removing baseline events.

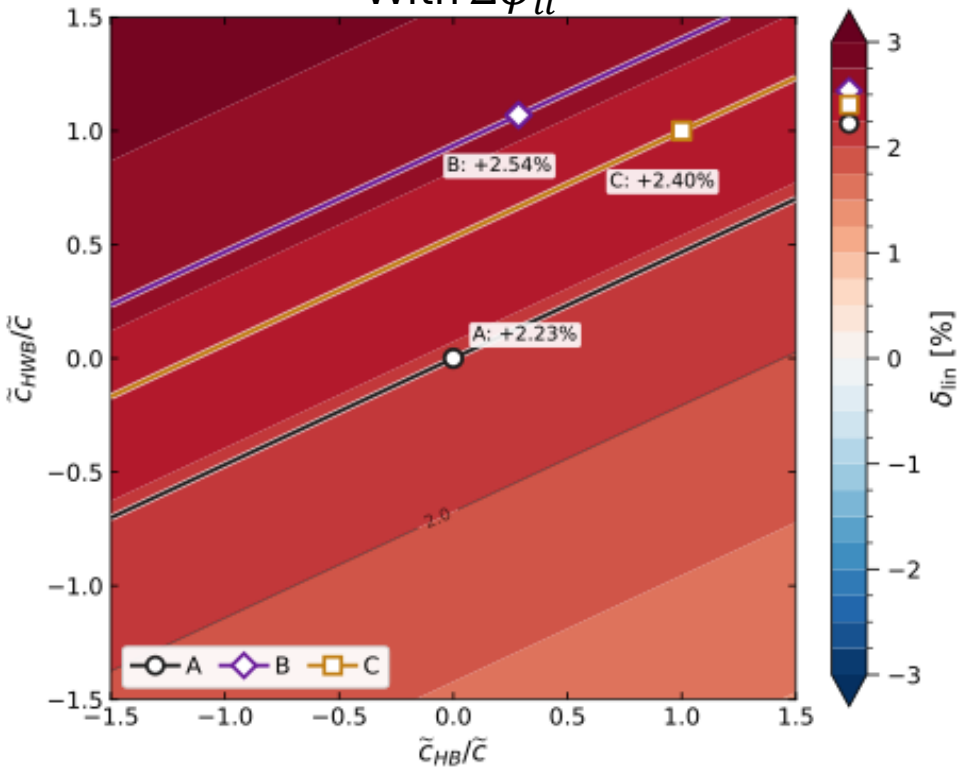
Inclusive rates leave correlated coefficient directions

$\tilde{c}_{HW} = 10^{-7}\,GeV^{-2}, \quad \tilde{c}_{HB}, \tilde{c}_{HWB} \in [-1.5, 1.5] \times 10^{-7}\,GeV^{-2}$

Without $\Delta\varphi_{ll}$



With $\Delta\varphi_{ll}$



On the left, different (HB) and (HWB) combinations can cancel the rate shift associated with the fixed (HW) coefficient. That produces a zero-deviation direction. A single inclusive rate therefore does not determine these coefficients independently.

Now compare benchmark B in the two maps. Its labeled deviation changes from about **minus 0.86 percent** on the left to **plus 2.54 percent** on the right. The angular weights also shift the zero-deviation direction outside the range displayed in the right map.

Angular information therefore changes both the size of the measured interference and the operator combinations to which the observable responds."

The black contours mark zero linear deviation from the SM. At fixed HW coefficient, different HB and HWB combinations can cancel the inclusive rate shift. The angular weights shift this cancellation direction; at 1 TeV, it leaves the displayed coefficient range.

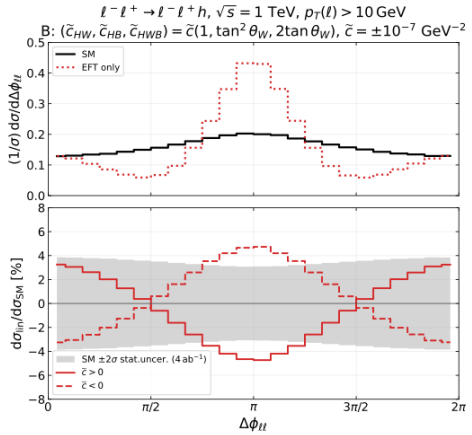
Conclusions

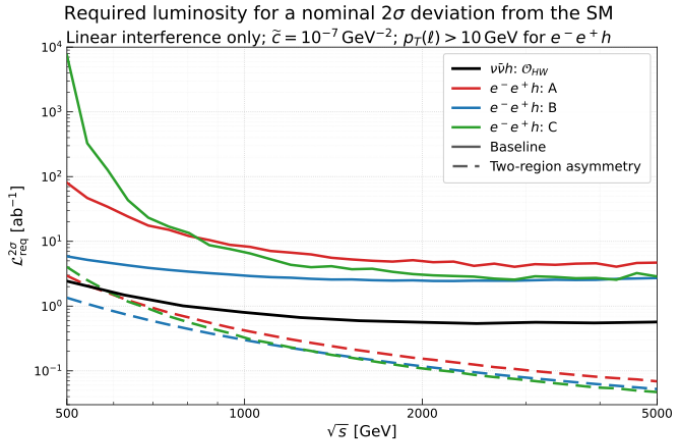
1. Higgs production via charged-current VBF has the larger SM cross section while one via neutral-current VBF gives access to scattered charged lepton kinematics.

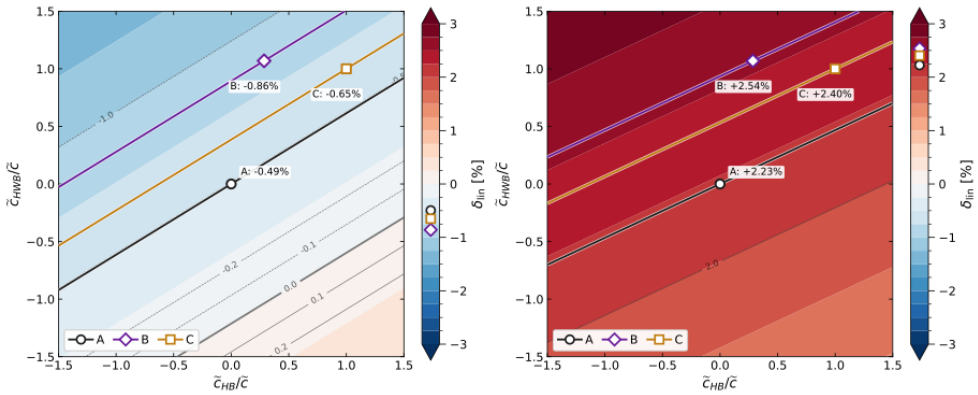
2. The SMEFT effect changes sign across the azimuthal separation and partly cancels in the inclusive rate. By taking into account the azimuthal separation of the leptons, we can recover the SMEFT effect.

3. Angular information and operator correlations matter when interpreting Higgs production via VBF within SMEFT.

With angular information, neutral-current VBF can require less luminosity than charged-current VBF in this statistics-only study.





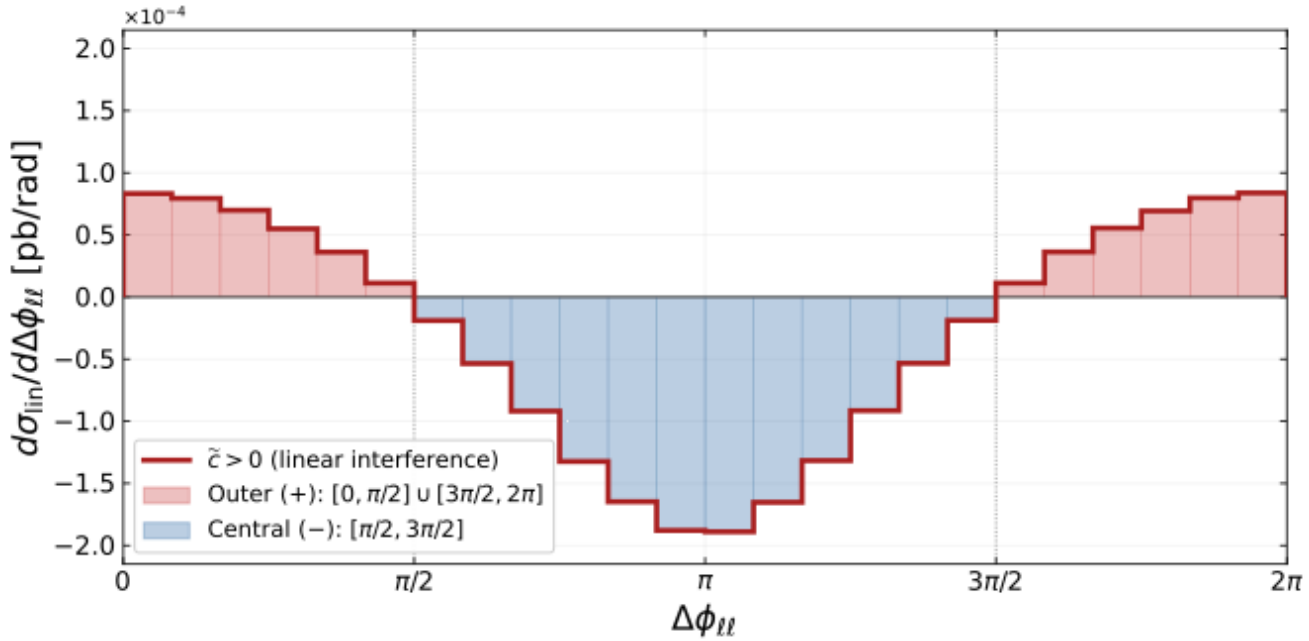


Back up

Two-region azimuthal asymmetry

Signed interference in Benchmark B at 1 TeV

$$d\sigma_{SMEFT} = d\sigma_{SM} + d\sigma_{lin} + d\sigma_{quad}$$
$$\propto |\mathcal{M}_{SM}|^2 + 2\sum_i \tilde{c}_i \, \mathrm{Re}(\mathcal{M}_{SM}^* \, \mathcal{M}_i) + \sum_{i,j} \tilde{c}_i \, \tilde{c}_j \, \mathcal{M}_i^* \, \mathcal{M}_j$$



Angle-based event weights

$$A_{\Delta\varphi} = \sigma_{outer} - \sigma_{central}$$
$$\frac{\pi}{2} < \Delta\varphi_{e\mu} < \frac{3\pi}{2}$$

Region	Δϕ interval	w
Outer	$[0, \frac{\pi}{2}]$ or $[\frac{\pi}{2}, 2\pi]$	+1
Central	$[\frac{\pi}{2}, \frac{3\pi}{2}]$	−1

For $\tilde{c} > 0$ (solid red), the outer interference is positive and the central interference is negative. Subtracting the center makes these contributions add.

The weight depends on the measured angle, not on the sign of an individual interference contribution.

The two-region asymmetry reduces cancellation of the linear interference without discarding events.

The interference changes sign with azimuthal separation

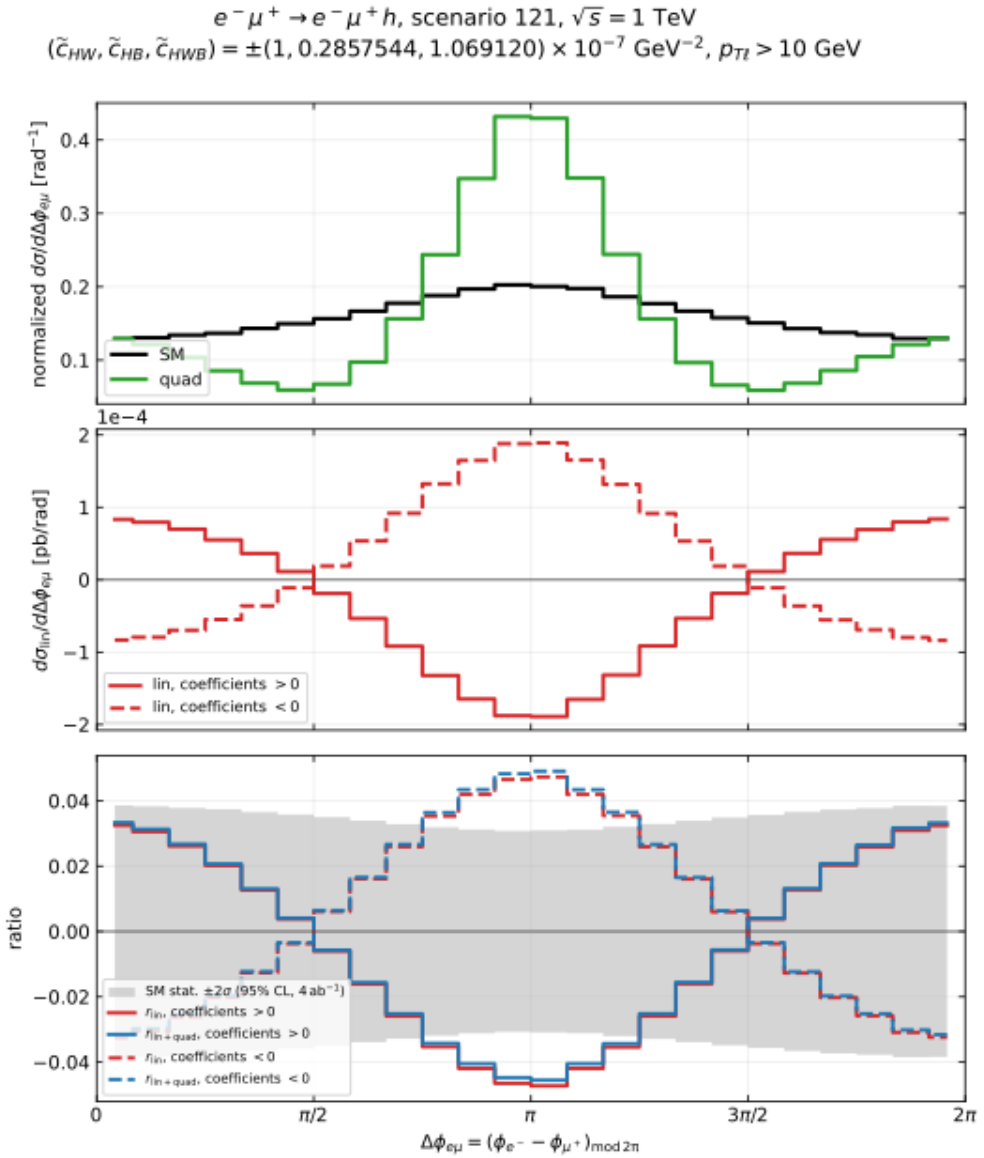
Representative photon-blind benchmark

$$\sqrt{s} = 1\,\mathrm{TeV}, \qquad p_{T\ell} > 10\,GeV$$

For positive coefficients, the signed interference is positive in the outer regions and negative in the central region.

The two contributions partly cancel after integration over the full phase space.
The sign change is also present when the photon-mediated vertices cancel.

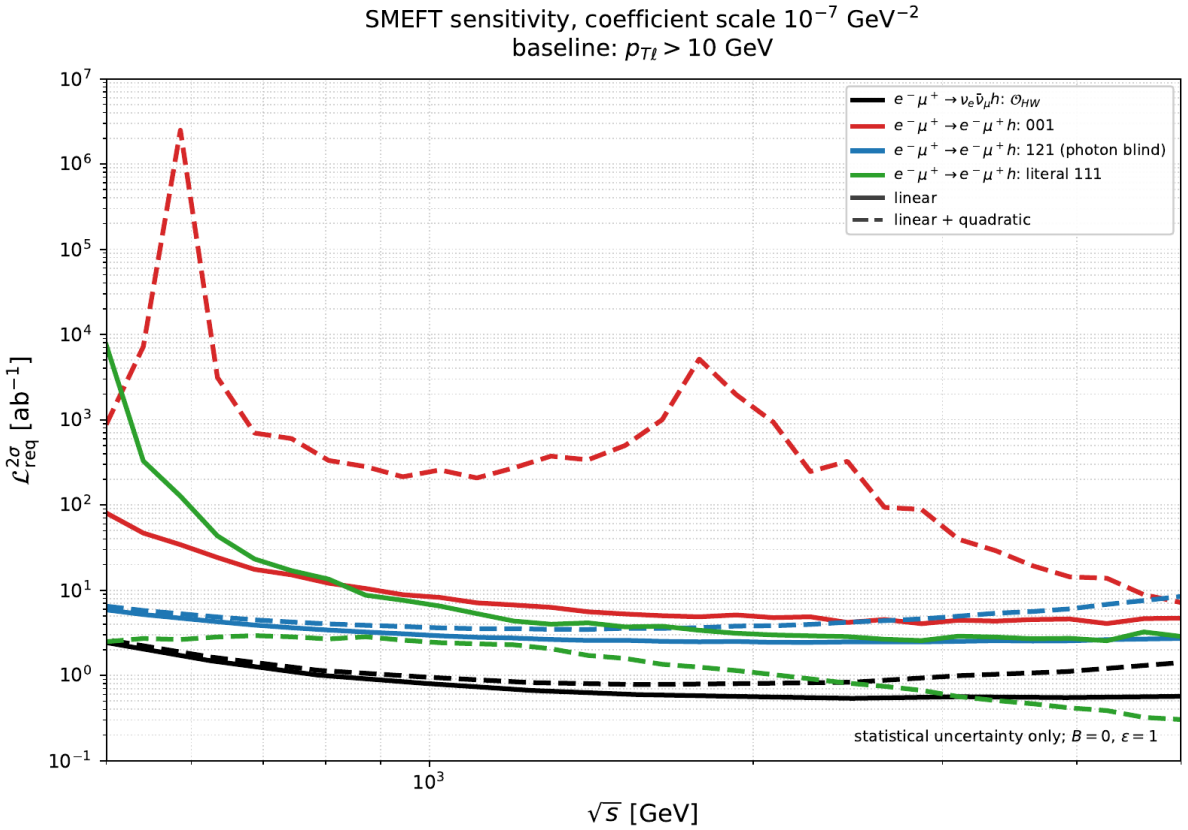
Inclusive integration can suppress an interference that is locally sizable and sign changing.



Statistical reach from the inclusive rate

We compare the integrated luminosity required for a nominal 2σ difference from the SM using the inclusive rate.

Baseline: pT(ℓ) > 10 GeV



What the curve shows

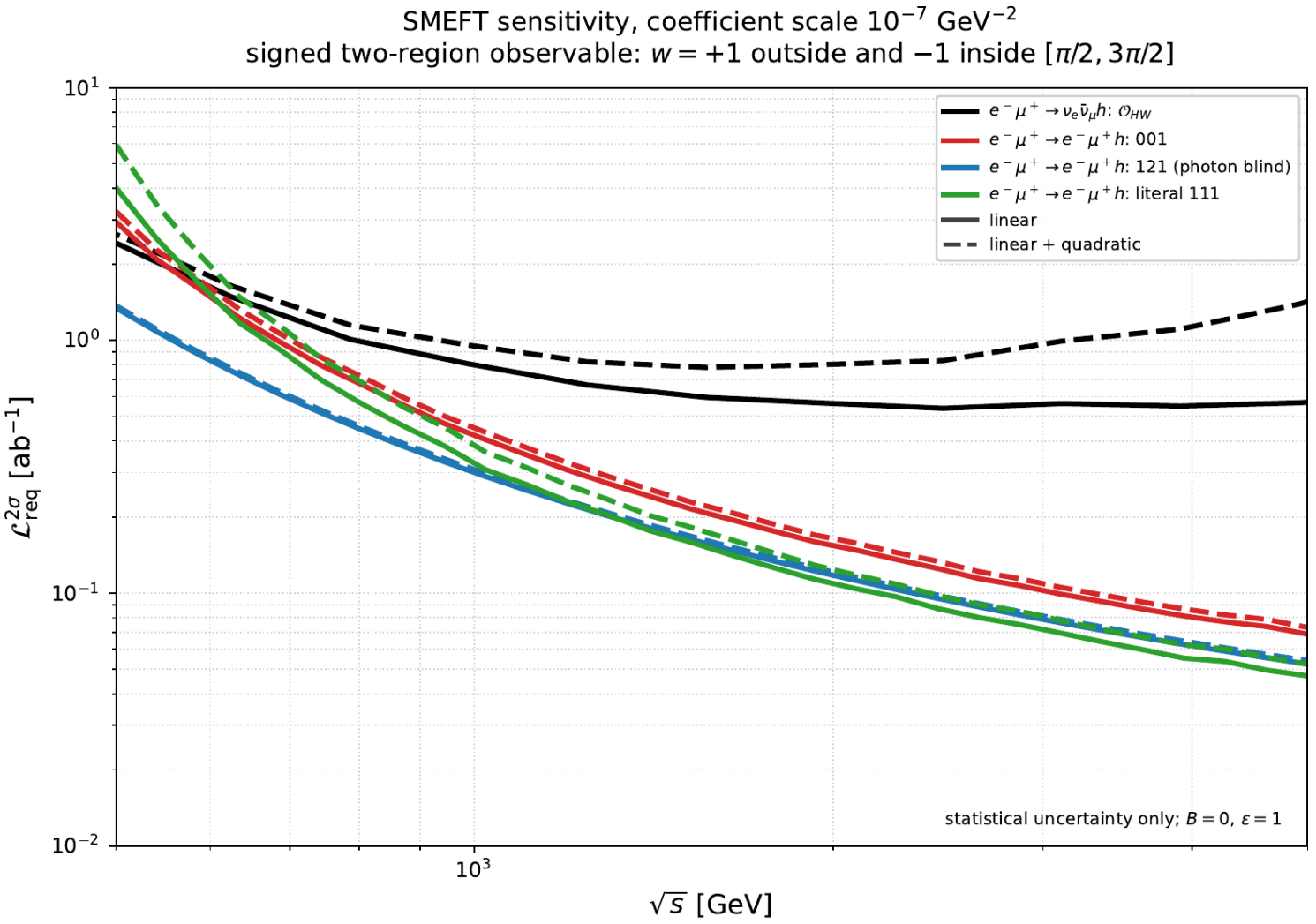
The signed interference can cancel after integration over the full azimuthal range.

A near-zero rate shift produces a sharp peak in the required luminosity.

Black: vvh
Red: A; blue: B; green: C
Solid: linear; dashed: linear + quadratic

The inclusive rate can hide a locally sizable interference through angular cancellation.

The two-region asymmetry improves the reach



$$A_{\Delta\varphi} = \sigma_{outer} - \sigma_{central}$$

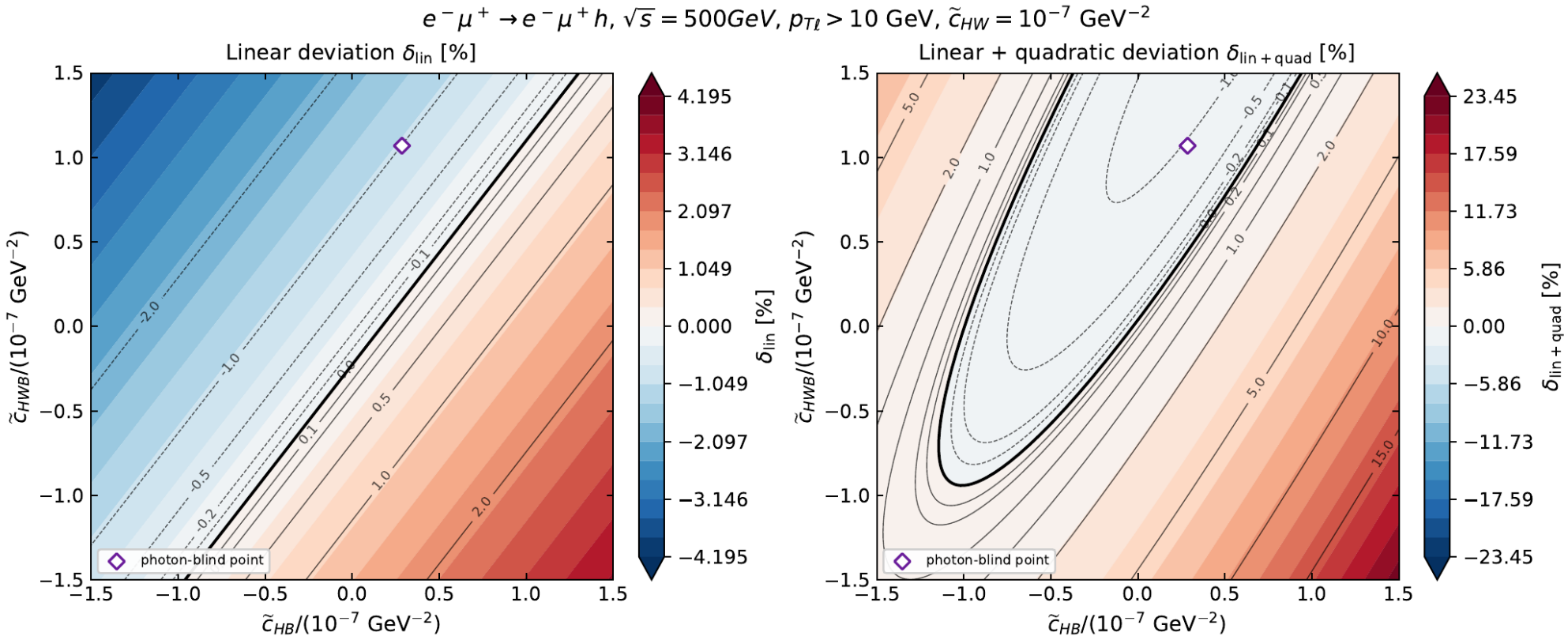
The fixed weights are +1 outside and −1 inside the central interval. The same rule applies to the SM and both SMEFT orders.

Since every weight has magnitude one, the SM variance is the sum of both region yields.

The asymmetry can reduce angular cancellation without removing baseline events.

Inclusive rates leave correlated coefficient directions

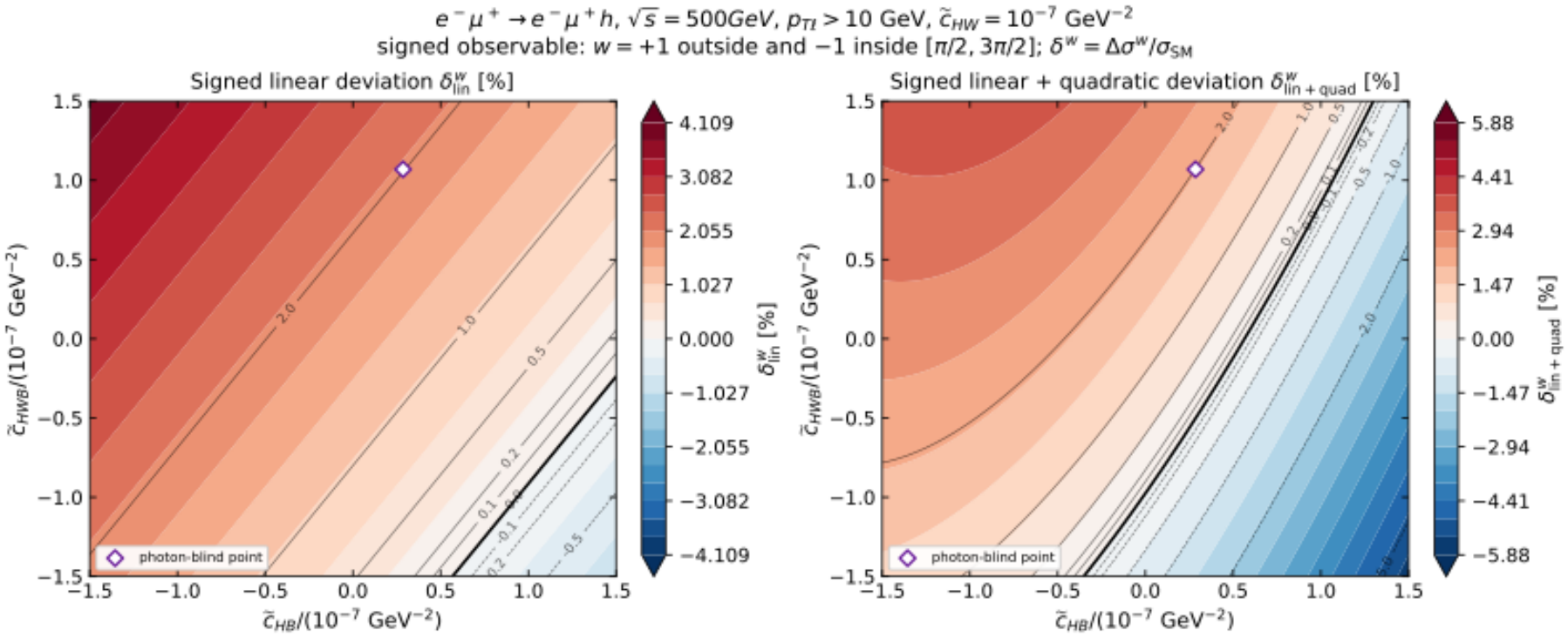
$$\tilde{c}_{HW} = 10^{-7}\,GeV^{-2}, \qquad \tilde{c}_{HB}, \tilde{c}_{HWB} \in [-1.5, 1.5] \times 10^{-7}\,GeV^{-2}$$



The black contours mark SM-like rates. At fixed HW coefficient, different HB and HWB combinations can cancel the rate shift; the quadratic term bends the zero-deviation contour.

The asymmetry shifts the coefficient correlations

$$\tilde{c}_{HW} = 10^{-7}\,GeV^{-2}, \qquad \tilde{c}_{HB}, \tilde{c}_{HWB} \in [-1.5, 1.5] \times 10^{-7}\,GeV^{-2}$$



The fixed angular weights shift the SM-like contours. The quadratic term bends the zero-deviation line.

U gauge vs FD gauge

U gauge (Covariant R_ξ gauge with $\xi \to \infty$)

Only weak gauge bosons (Nambu-Goldstone bosons are decoupled.)

$$\beta = \frac{q}{E} = \sqrt{1 - \frac{m^2}{E^2}}, \qquad \gamma = \frac{E}{m} = \frac{1}{\sqrt{1-\beta^2}}.$$

- propagator $(\mu, \nu = 0, 1, 2, 3)$

$$P^{\mathrm{U}}_{\mu\nu} = \frac{i}{q^2 - m^2 + i\epsilon}\left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{m^2}\right)$$

- polarization vector

$$\epsilon^\mu(q,0) = \frac{1}{m}(q,0,0,E) = \gamma\,(\beta,0,0,1)$$

FD gauge (Non-covariant light-cone gauge with $n^\mu = \left(\mathrm{sgn}(q^0), -\frac{\vec{q}}{|\vec{q}|}\right)$

Weak gauge bosons and Nambu-Goldstone bosons are in Superposition state.

- 5×5 propagator $(M, N = 0, 1, 2, 3, 4)$

$$P^{\mathrm{FD}}_{MN} = \frac{i}{q^2 - m^2 + i\epsilon}\begin{pmatrix} -\tilde{g}_{\mu\nu} & im\frac{n_\mu}{n\cdot q} \\ -im\frac{n_\nu}{n\cdot q} & 1 \end{pmatrix}$$

$$-\tilde{g}_{\mu\nu} = -g_{\mu\nu} + \frac{n_\mu q_\nu + q_\mu n_\nu}{n\cdot q}$$

- 5 component polarization vector

$$\epsilon^M(q,0) = (\tilde{\epsilon}^\mu(q,0),\ i)$$

$$\tilde{\epsilon}^\mu(q,0) = \epsilon^\mu(q,0) - \frac{q^\mu}{Q}$$

$$= \frac{1}{\gamma(1+\beta)}(-1,0,0,1)$$

4. SMEFT

We study how the SMEFT contribution modifies each amplitude group in the FD gauge.
We introduce the dimension-6 operator O_{HW}.

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c_{HW}}{\Lambda^2}\mathcal{O}_{HW}$$

$$\mathcal{O}_{HW} = H^\dagger H \; W^a_{\mu\nu} W^{a\;\mu\nu}$$

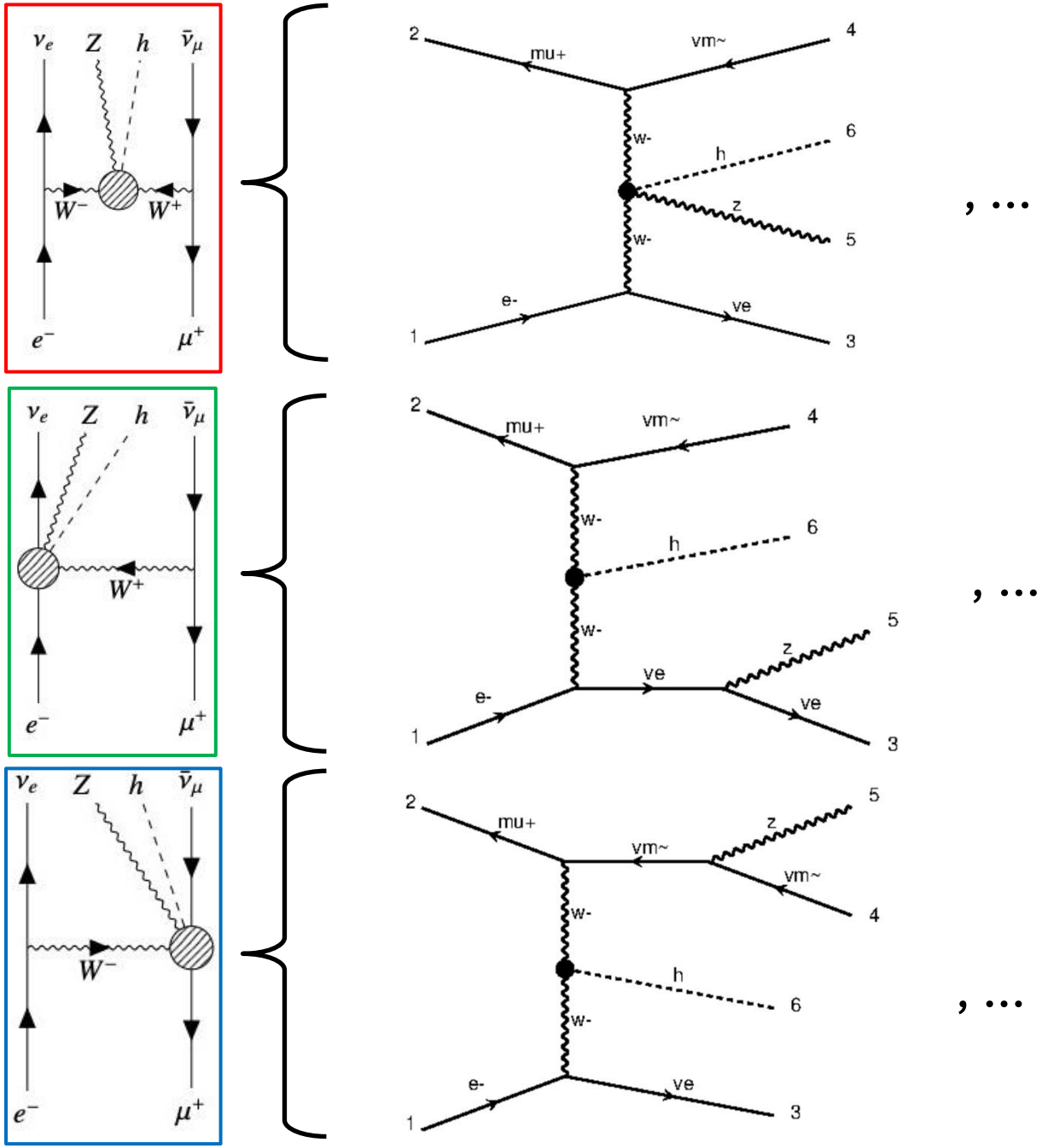
$$\supset v h \, W^a_{\mu\nu} W^{a\,\mu\nu}$$

$$\tilde{c}_{HW} = \frac{c_{HW}}{\Lambda^2}$$

hWW vertex

$$\mathcal{V}^{\mu\nu}_{HW} \propto \tilde{c}_{HW}\left[(q_1 \cdot q_2) g^{\mu\nu} - q_1^\nu q_2^\mu\right]$$

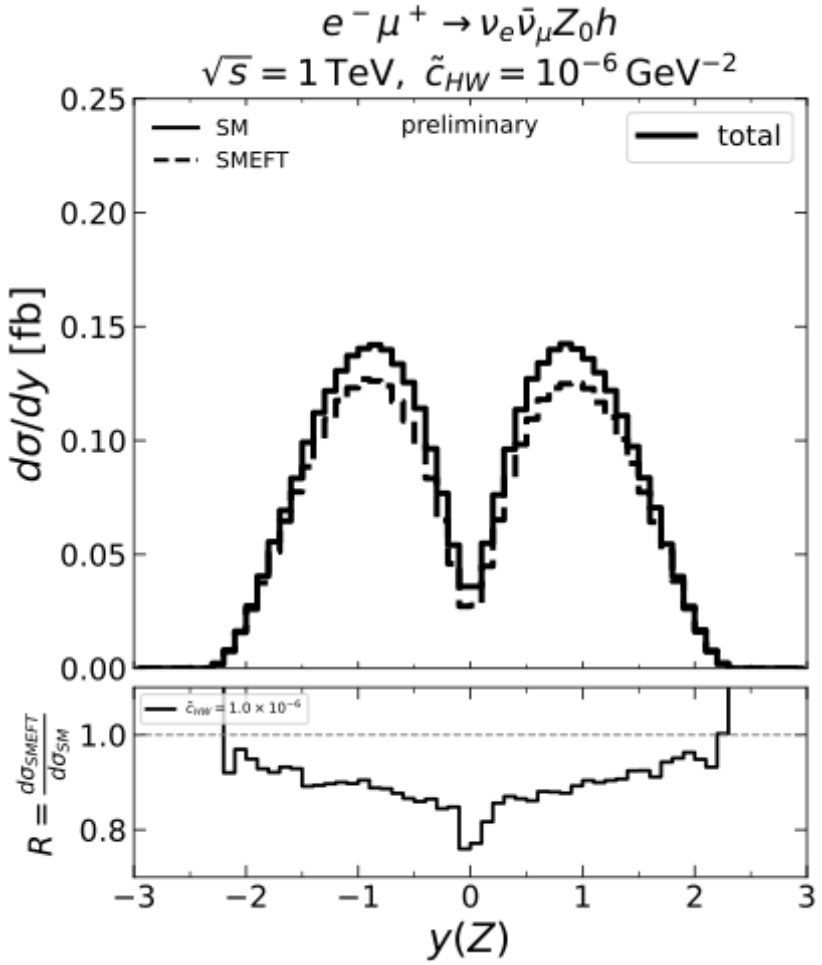
How does this modify in the FD gauge?

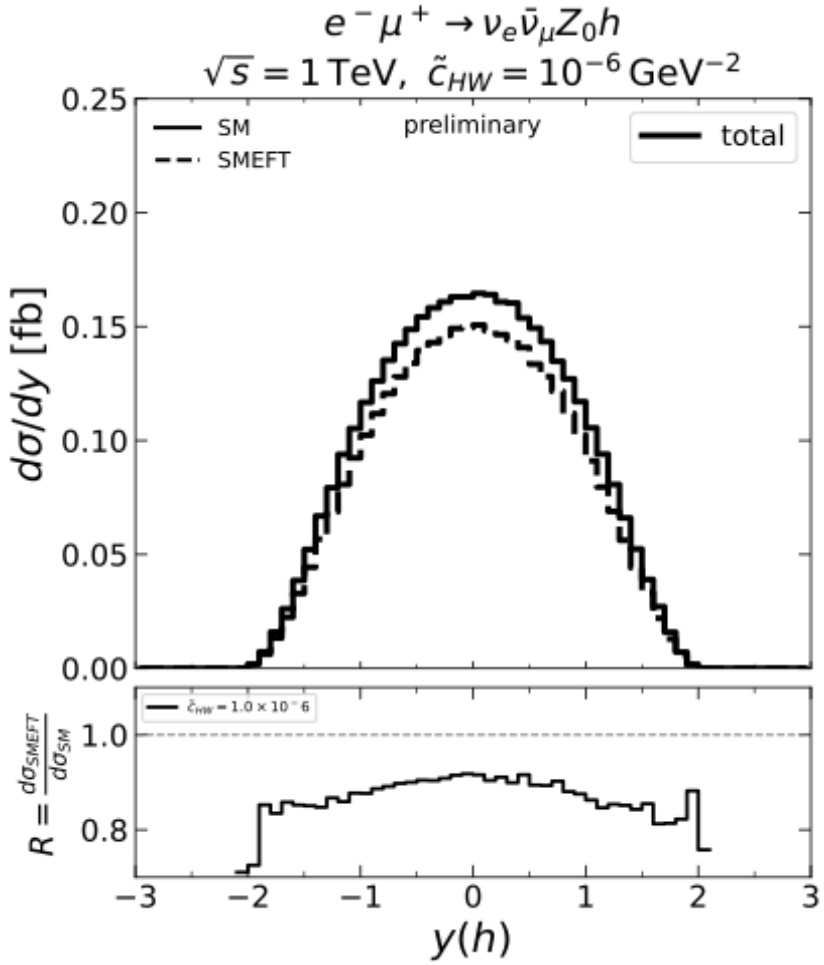


4. $e^-\mu^+ \to \nu_e \bar{\nu}_\mu Zh$ in SMEFT

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c_{HW}}{\Lambda^2}\mathcal{O}_{HW}, \quad \tilde{c}_{HW} = \frac{c_{HW}}{\Lambda^2},$$
$$\mathcal{O}_{HW} = H^\dagger H \, W^a_{\mu\nu} W^{a\,\mu\nu}$$

For $\tilde{c}_{HW} > 0$, the SMEFT contribution suppresses the cross section.
The deviation is particularly large in the central y(Z) region.





4. $e^-\mu^+ \to \nu_e \bar{\nu}_\mu Zh$ in SMEFT

$$\mathcal{V}_{HW}^{\mu\nu} \propto \tilde{c}_{HW}\left[(q_1 \cdot q_2)g^{\mu\nu} - q_1^\nu q_2^\mu\right]$$

The FD gauge reveals which amplitude is responsible for the SMEFT effect in each phase-space region.
The largest deviation from the SM is observed in the central y(Z) region, where contribution (a) is dominant.

