Electroweak Restoration: SMEFT and HEFT

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Based on 2605.08433
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SM/SMEFT

Linear realization

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} -\sqrt{2}\, i\, G^+ \\ v + h + i\, G^0 \end{pmatrix},$$

- Operators built from Higgs doublet H
- G^a and h are symmetry partners
- $G^a G^b$ and $G^a h$ amplitudes can be correlated
- Leading E^2 growth doublet correlation

SM/SMEFT

Linear realization

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} -\sqrt{2}\, i\, G^+ \\ v + h + i\, G^0 \end{pmatrix},$$

- Operators built from Higgs doublet H
- G^a and h are symmetry partners
- G^aG^b and G^ah amplitudes can be correlated
- Leading E^2 growth doublet correlation

HEFT

Non-linear realization

$$U(x) = \exp\left(\frac{i\,\sigma^I \pi^I(x)}{v}\right) \quad , \qquad h \text{ singlet}$$

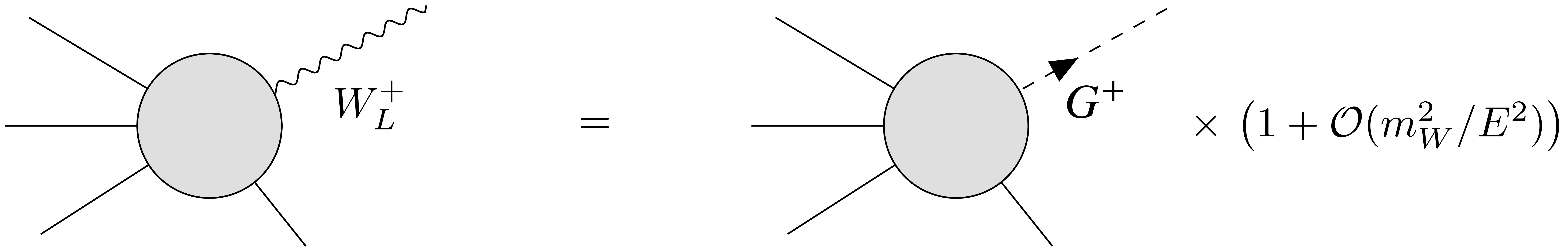
- Goldstones live in $U(x)$
- Motivated by strong coupling scenario
- Higgs interaction enter through generic function:

$$\mathcal{F}_i(h) = \left(1 + 2\kappa_i \frac{h}{v} + \kappa_i^{(2)} \frac{h^2}{v^2} + \mathcal{O}(h^3)\right)$$

- G^aG^b and G^ah amplitudes can vary independently

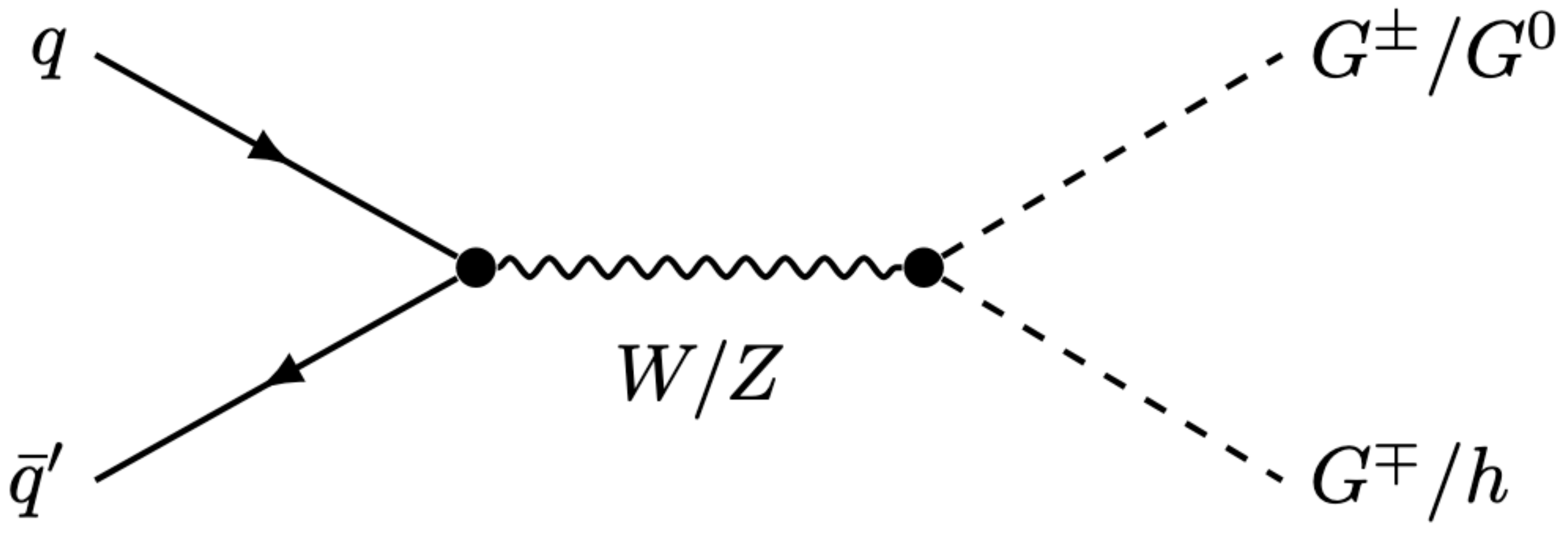
EW Restoration

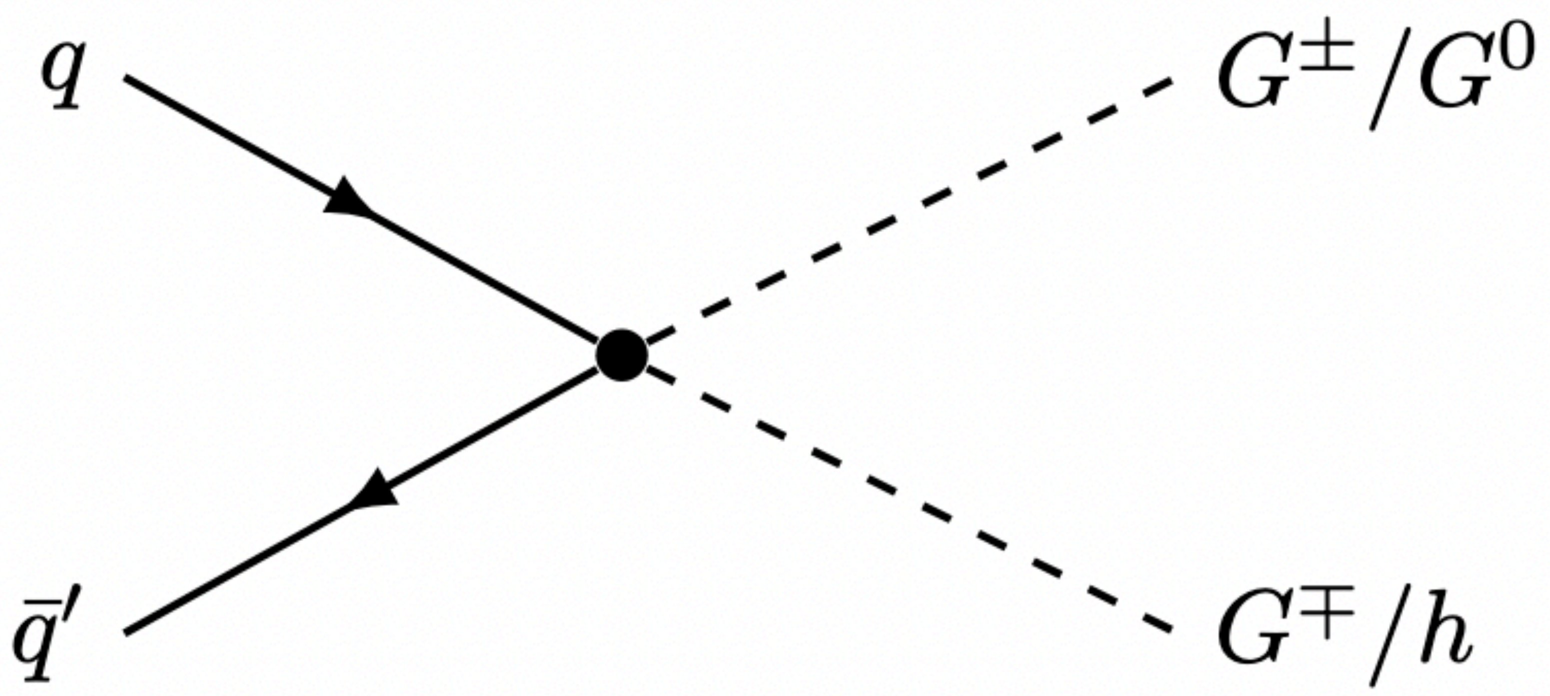
- We are probing energy far above the electroweak symmetry breaking scale $E \gg v \simeq 246\,\mathrm{GeV}$.
  - We start probing the limit $m_W, m_Z, m_h \to 0$. Massive amplitudes start converging to the massless amplitude predicted by SM
  - Goldstone Boson Equivalence predicts $W_L, Z_L \to$ Goldstones up to $\mathcal{O}(m_V/E)$.



Cornwall, Levin, Tiktopoulos (1974), Lee, Quigg, Thacker (1977), Chanowitz, Gaillard (1985), Bagger, Schmidt (1990), Cuomo, Vecchi, Wulzer (2020) …

Correlation among di-boson production?





$$q\bar{q} \to W_L^+ W_L^-,\ q\bar{q}' \to W_L^\pm Z_L,\ q\bar{q}' \to W_L^\pm h,\ q\bar{q} \to Z_L h$$

Goldstone equivalence at high energy

$$W_L^\pm Z_L \longleftrightarrow G^\pm G^0 \qquad W_L^\pm h \longleftrightarrow G^\pm h$$
$$W_L^+ W_L^- \longleftrightarrow G^+ G^- \qquad Z_L h \longleftrightarrow G^0 h$$

The question is not just “is there energy growth?” but “which channels grow together?”

Literature Review

- Restoration via test of **Goldstone Boson Equivalence**

Huang, Lane, Lewis and Liu (2021)

Take the zero-vev theory and compare to the SM in high-p_T for Vh channel

- Restoration test via **Radiation Zero**

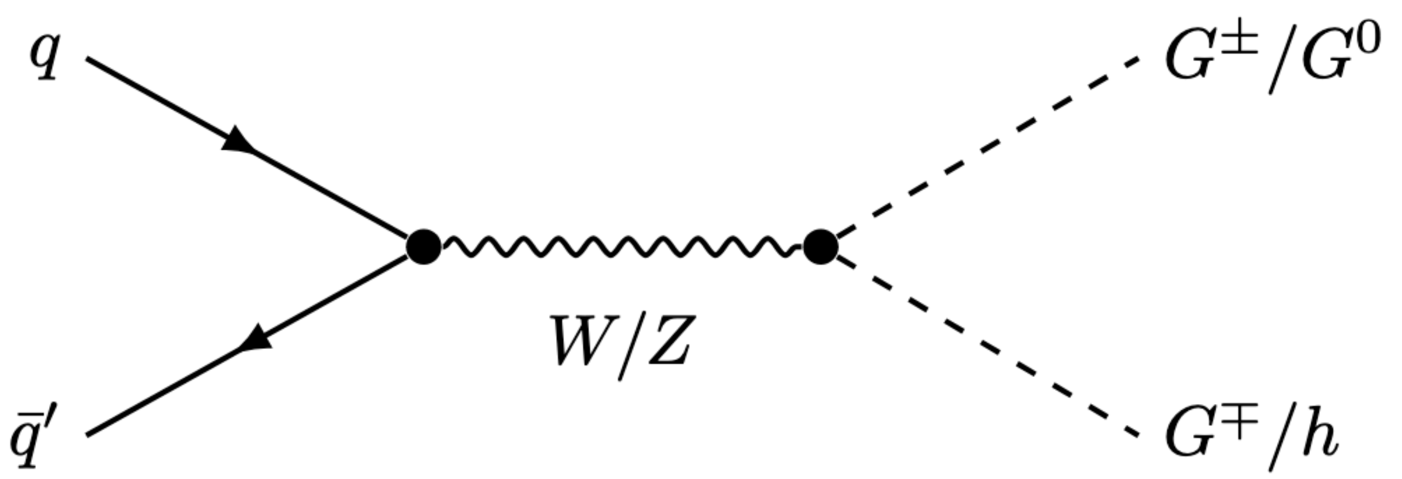
Capdevilla, Han (2024)

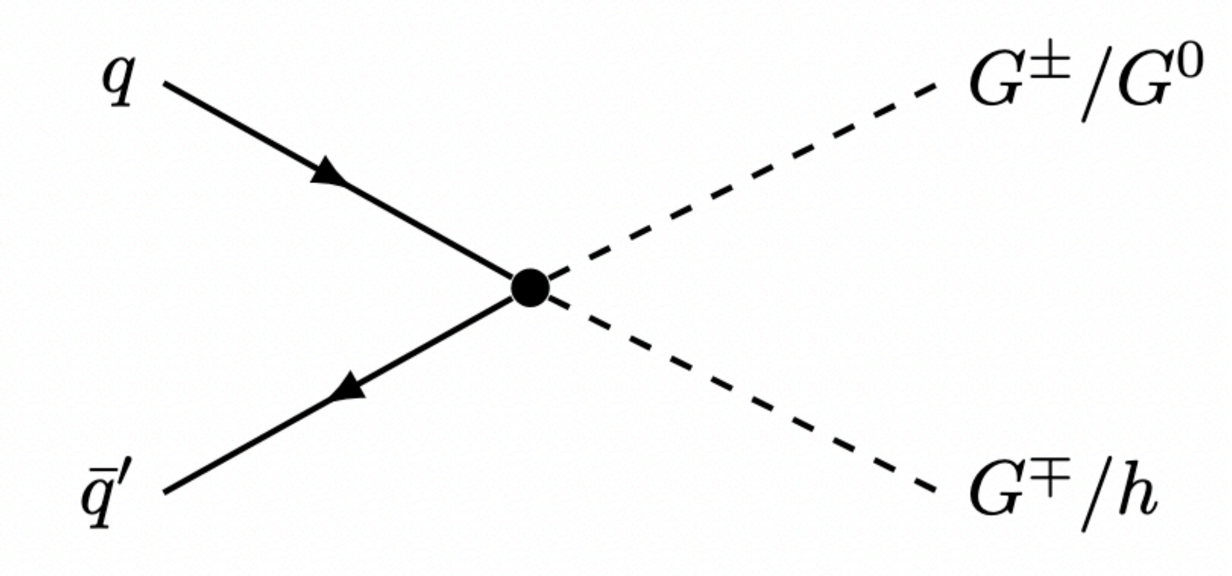
Transverse sector → restoration of gauge symmetry. EW restoration shows up as a characteristic **radiation-zero** in the amplitude.

- Correlation among di-boson production in SMEFT

Franceschini, Panico, Pomarol, Riva, Wulzer (2017)

Dimension-six SMEFT





$$q\bar{q} \to W_L^+ W_L^-,\ q\bar{q}' \to W_L^\pm Z_L,\ q\bar{q}' \to W_L^\pm h,\ q\bar{q} \to Z_L h$$

Relevant Dimension-six SMEFT operators

$$\mathcal{Q}_{Hq} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_R \gamma^\mu q_R),$$
$$\mathcal{Q}_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L),$$
$$\mathcal{Q}_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{Q}_L \sigma^I \gamma^\mu Q_L),$$
$$\mathcal{Q}_{Hud} = (\widetilde{H}^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu d_R),$$

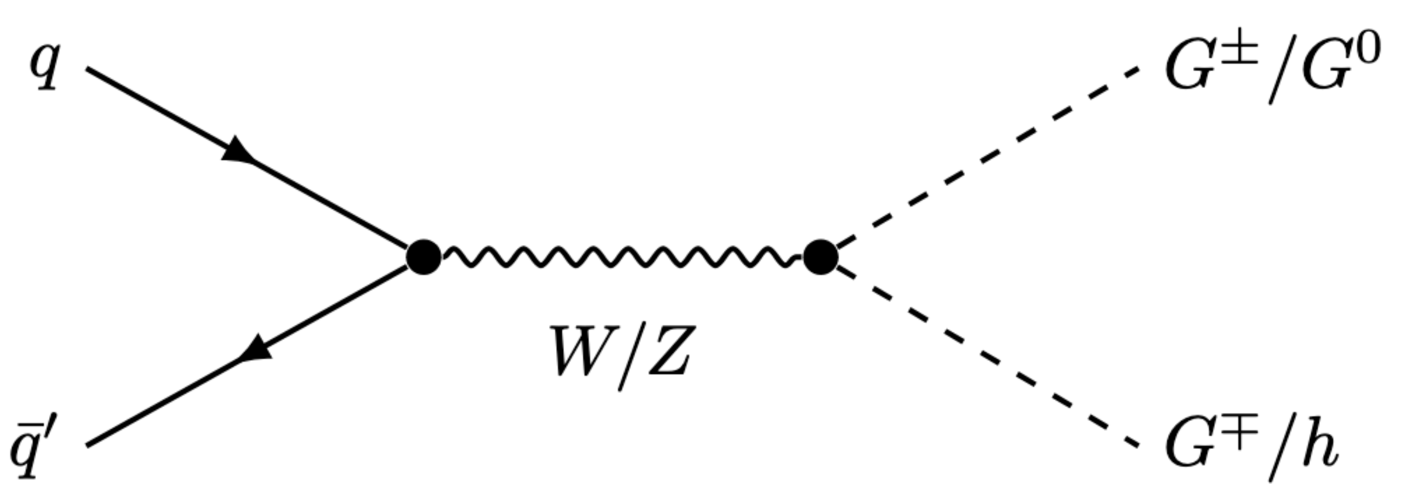
They contribute to quadratic energy growth

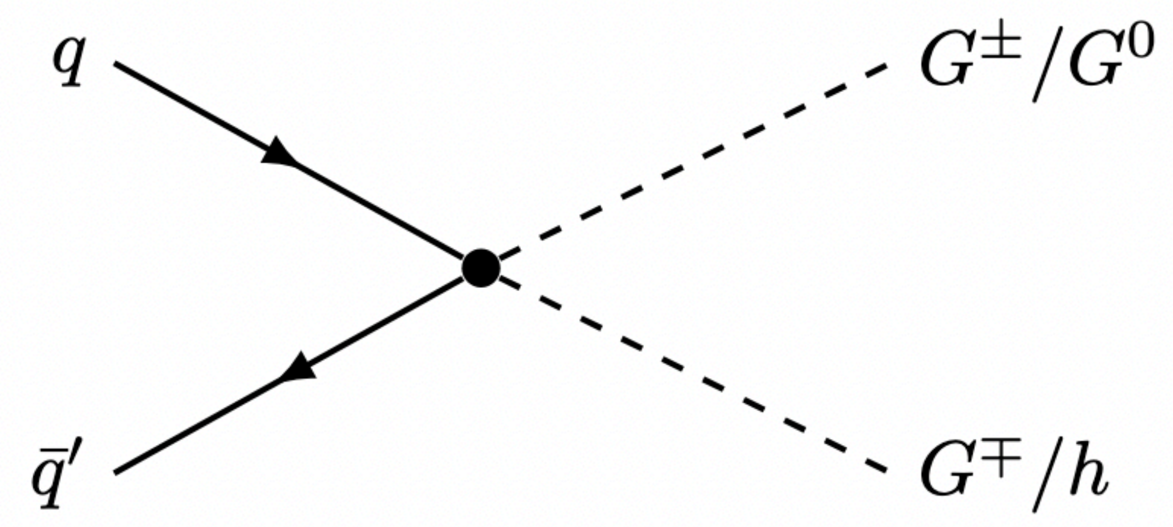
$$|\mathscr{M}|^2 \sim \frac{c_i}{\Lambda^2} E^2$$

We only keep upto interference term:

$$\mathcal{M}^2 = |\mathcal{M}_{\rm SM}|^2 + \underbrace{2{\rm Re}\mathcal{M}_{\rm SM}\mathcal{M}^*_{\rm BSM}}_{\propto \frac{c}{\Lambda^2}} + \underbrace{|\mathcal{M}_{\rm BSM}|^2}_{\propto \frac{c^2}{\Lambda^4}}$$

Dimension-six SMEFT





$$q\bar{q} \to W_L^+ W_L^-,\ q\bar{q}' \to W_L^{\pm} Z_L,\ q\bar{q}' \to W_L^{\pm} h,\ q\bar{q} \to Z_L h$$

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$$\mathcal{Q}_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}{}^I_\mu H)(\bar{Q}_L \sigma^I \gamma^\mu Q_L)\,,$$
$$\mathcal{Q}_{Hud} = (\widetilde{H}^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu d_R)\,,$$

These operators are built out of

Triplet curret:

$$J^I_{H,\mu} = H^\dagger \sigma^I i \overleftrightarrow{\partial}_\mu H, \qquad J^I_{Q,\mu} = \bar{Q}_L \gamma_\mu \sigma^I Q_L$$

$$J_Q^{I,\mu} J^I_{H,\mu}$$

Singlet curret:

$$J_{H,\mu} = H^\dagger i \overleftrightarrow{\partial}_\mu H \qquad J_{q,\mu} = \bar{q}_R \gamma^\mu q_R, \qquad J_{Q,\mu} = \bar{Q}_L \gamma^\mu Q_L$$

$$J_Q^\mu J_{H,\mu} \qquad J_q^\mu J_{H,\mu}$$

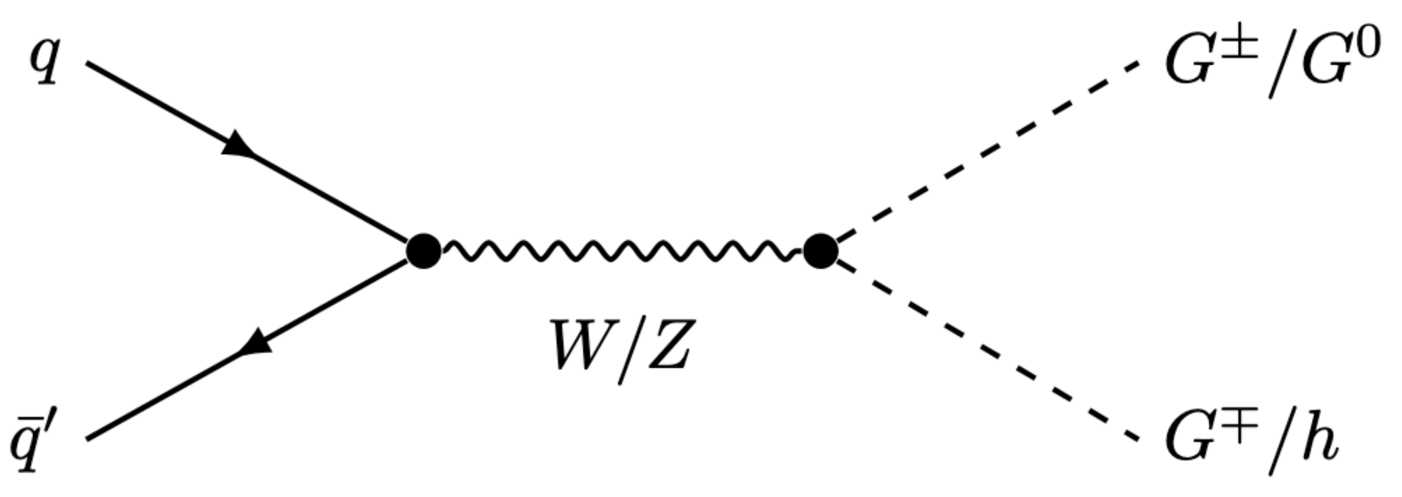
SMEFT Correlation

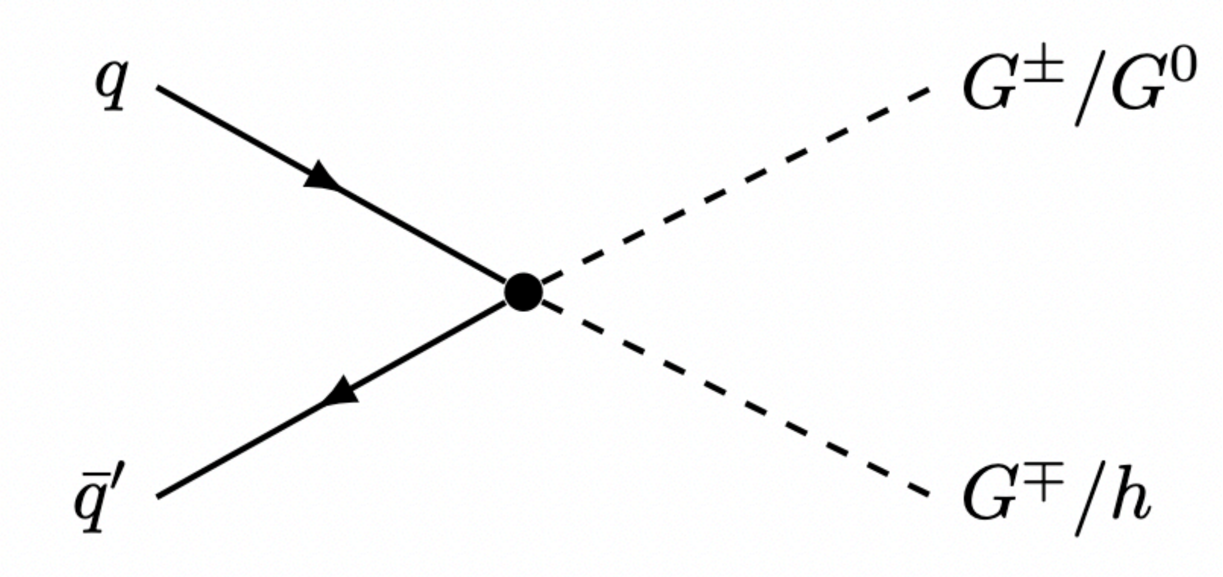
To $\mathcal{O}(m^2/s)$	SM	SMEFT
$\dfrac{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm Z_L)}{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm h)}$	± 1	± 1
$\dfrac{\mathcal{M}(q_-\bar{q}_+ \to Z_L h) - \mathcal{M}(q_-\bar{q}_+ \to W_L^+ W_L^-)}{\sqrt{2}\,\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm h)}$	$2\,T_3^q$	$2\,T_3^q$
$\dfrac{\mathcal{M}(q_+\bar{q}_- \to W_L^+ W_L^-)}{\mathcal{M}(q_+\bar{q}_- \to Z_L h)}$	1	1
$\dfrac{\mathcal{M}(q_+\bar{q}'_- \to W_L^\pm Z_L)}{\mathcal{M}(q_+\bar{q}'_- \to W_L^\pm h)}$	$-$	∓ 1
$\dfrac{\mathcal{M}(q_-\bar{q}_+ \to Z_L h) - \mathcal{M}(q_-\bar{q}_+ \to W_L^+ W_L^-)}{\mathcal{M}(q_-\bar{q}_+ \to Z_L h) + \mathcal{M}(q_-\bar{q}_+ \to W_L^+ W_L^-)}$	$-\dfrac{g^2 T_3^q}{g'^2 Y_L^q}$	$-2\,T_3^q \dfrac{C_{Hq}^{(3)}}{C_{Hq}^{(1)}}$

If these predictions are not confirmed, one of our assumptions must have been wrong:

1. h not part of a doublet.
2. Scale of new physics not very high and dimension 8 operators cannot be ignored

HEFT upto NLO operators





$$q\bar{q} \to W_L^+ W_L^-,\ q\bar{q}' \to W_L^{\pm} Z_L,\ q\bar{q}' \to W_L^{\pm} h,\ q\bar{q} \to Z_L h$$

Relevant HEFT operators

$$\mathcal{N}_1^Q(h) = i\,\bar{Q}_L \gamma^\mu V_\mu Q_L\,\mathcal{F}_1(h),$$
$$\mathcal{N}_2^Q(h) = i\,\bar{Q}_R \gamma^\mu U^\dagger V_\mu U\,Q_R\,\mathcal{F}_2(h),$$
$$\mathcal{N}_4^Q(h) = \bar{Q}_R \gamma_\mu U^\dagger [V^\mu, T] U Q_R F_4(h)$$
$$\mathcal{N}_5^Q(h) = i\,\bar{Q}_L \gamma_\mu \{V^\mu, T\} Q_L\,F_5(h)$$
$$\mathcal{N}_6^Q(h) = i\,\bar{Q}_R \gamma_\mu U^\dagger \{V^\mu, T\} U Q_R F_6(h)$$
$$\mathcal{N}_7^Q(h) = i\,\bar{Q}_L \gamma^\mu T V_\mu T\,Q_L\,\mathcal{F}_7(h),$$
$$\mathcal{N}_8^Q(h) = i\,\bar{Q}_R \gamma^\mu U^\dagger T V_\mu T U\,Q_R\,\mathcal{F}_8(h)$$
$$\mathcal{P}_3(h) = \frac{i}{4\pi}\,\mathrm{Tr}\big(W_{\mu\nu}[V^\mu, V^\nu]\big)\,\mathcal{F}_3(h).$$

They contribute to quadratic energy growth

We only keep upto interference term

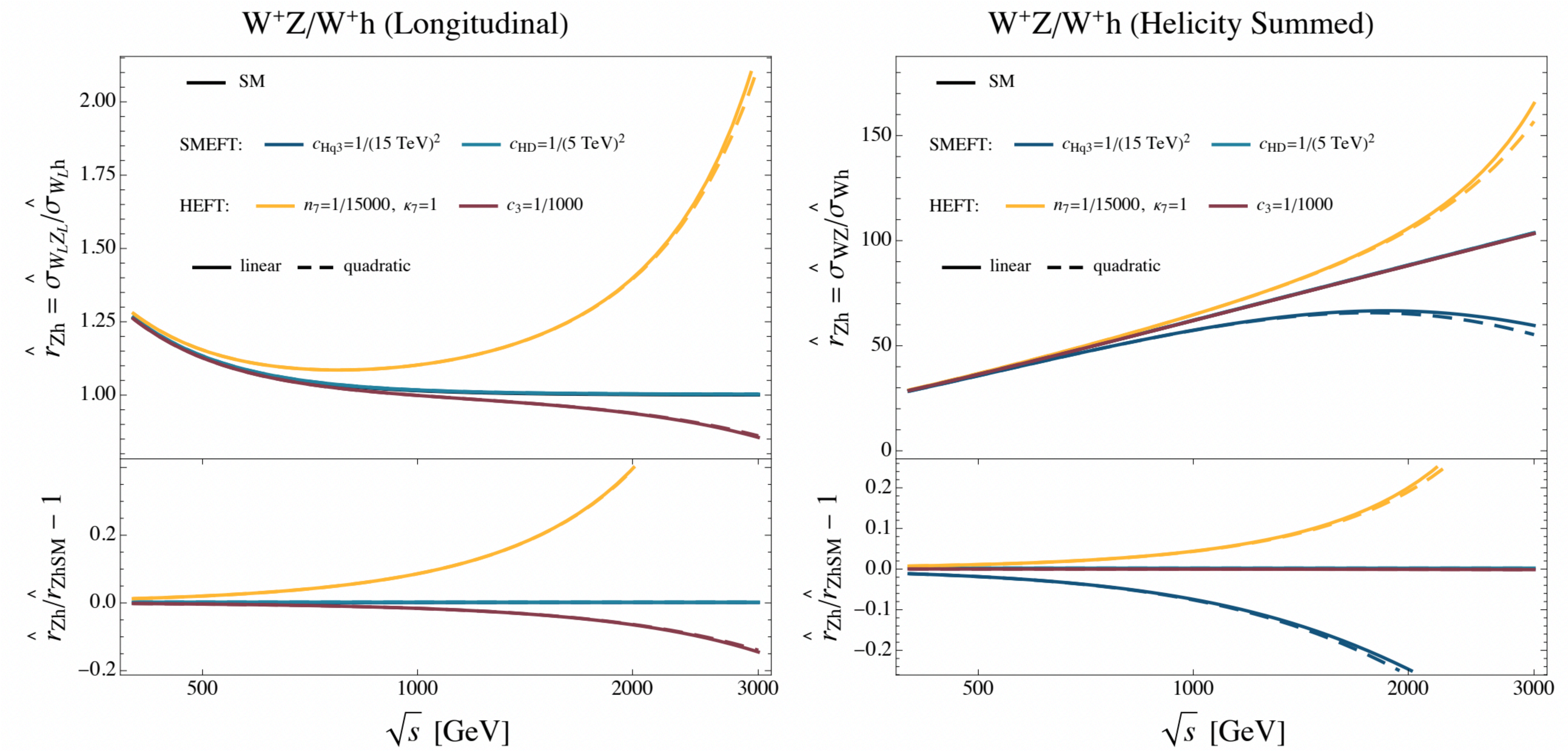
Higgs interaction enter through generic function:

$$\mathcal{F}_i(h) = \left(1 + 2\kappa_i \frac{h}{v} + \kappa_i^{(2)} \frac{h^2}{v^2} + \mathcal{O}(h^3)\right)$$

HEFT Decorrelation

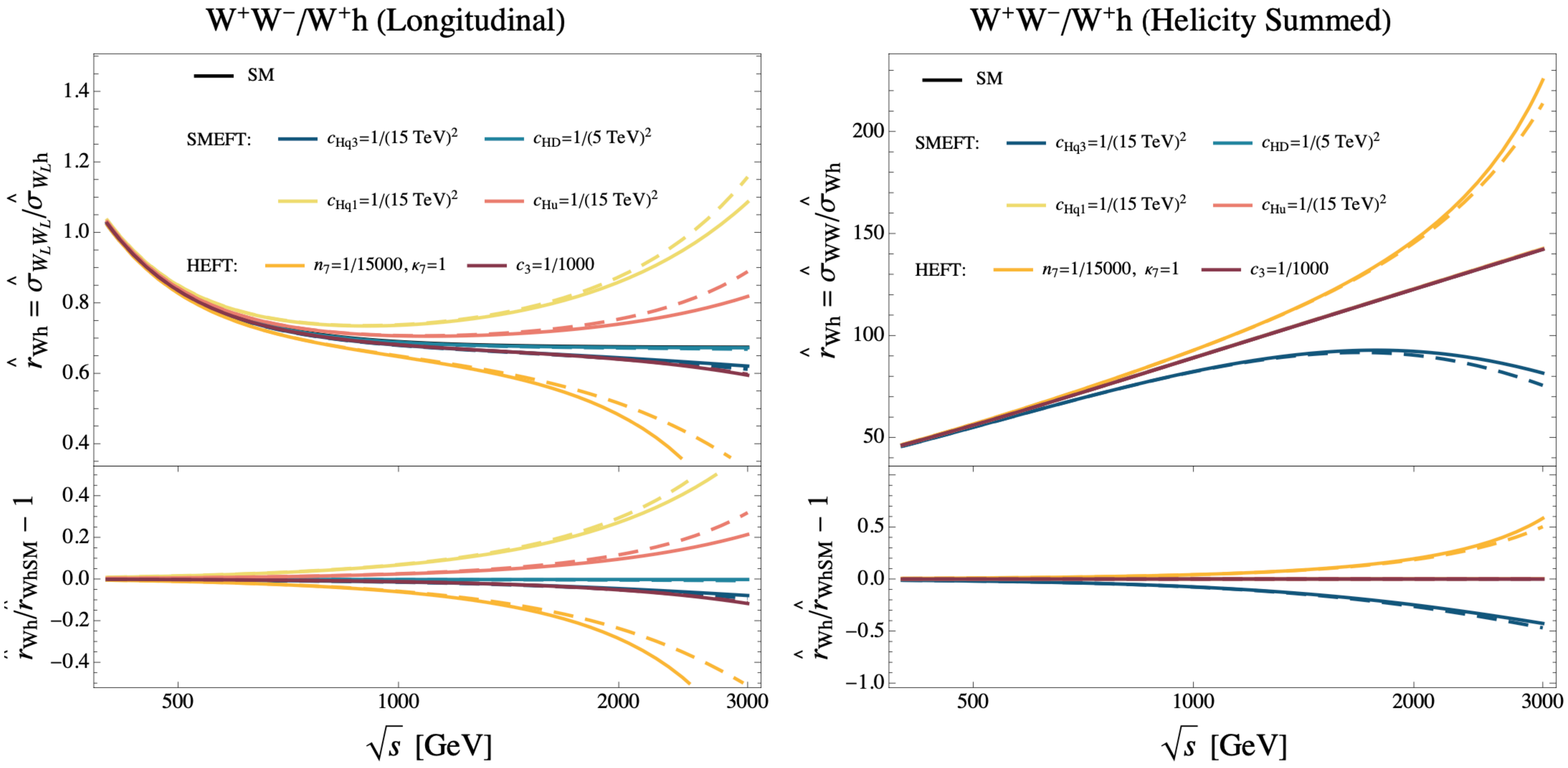
To $\mathcal{O}(m^2/s)$	SM	SMEFT	HEFT
$\frac{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm Z_L)}{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm h)}$	± 1	± 1	$\mp \frac{c_3 g - 8\pi\,(n_1^Q + n_7^Q)}{8\pi\,(\kappa_1 n_1^Q - \kappa_7 n_7^Q)}$
$\frac{\mathcal{M}(q_-\bar{q}_+ \to Z_L h) - \mathcal{M}(q_-\bar{q}_+ \to W_L^+ W_L^-)}{\sqrt{2}\,\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm h)}$	$2\,T_3^q$	$2\,T_3^q$	$-\frac{8\pi(1-\kappa_5)n_5^Q + T_3^q\left(c_3 g - 8\pi\left[(1+\kappa_1)n_1^Q + (\kappa_7 - 3)n_7^Q\right]\right)}{8\pi\,(\kappa_1 n_1^Q - \kappa_7 n_7^Q)}$
$\frac{\mathcal{M}(q_+\bar{q}_- \to W_L^+ W_L^-)}{\mathcal{M}(q_+\bar{q}_- \to Z_L h)}$	1	1	$\frac{n_6^Q + T_3^q(n_2^Q + n_8^Q)}{\kappa_6 n_6^Q + T_3^q(\kappa_2 n_2^Q + \kappa_8 n_8^Q)}$
$\frac{\mathcal{M}(q_+\bar{q}'_- \to W_L^\pm Z_L)}{\mathcal{M}(q_+\bar{q}'_- \to W_L^\pm h)}$	–	∓ 1	$\mp \frac{n_2^Q - n_8^Q \mp 2\,i\,n_4^Q}{\kappa_2 n_2^Q - \kappa_8 n_8^Q \mp 2\,i\,\kappa_4 n_4^Q}$
$\frac{\mathcal{M}(q_-\bar{q}_+ \to Z_L h) - \mathcal{M}(q_-\bar{q}_+ \to W_L^+ W_L^-)}{\mathcal{M}(q_-\bar{q}_+ \to Z_L h) + \mathcal{M}(q_-\bar{q}_+ \to W_L^+ W_L^-)}$	$-\frac{g^2 T_3^q}{g'^2 Y_L^q}$	$-2\,T_3^q \frac{C_{Hq}^{(3)}}{C_{Hq}^{(1)}}$	$-\frac{8\pi(1-\kappa_5)n_5^Q + T_3^q\left(c_3 g - 8\pi\left[(1+\kappa_1)n_1^Q + (\kappa_7 - 3)n_7^Q\right]\right)}{8\pi(1+\kappa_5)n_5^Q + T_3^q\left(c_3 g - 8\pi\left[(1-\kappa_1)n_1^Q - (\kappa_7 + 3)n_7^Q\right]\right)}$

W^+Z/W^+h



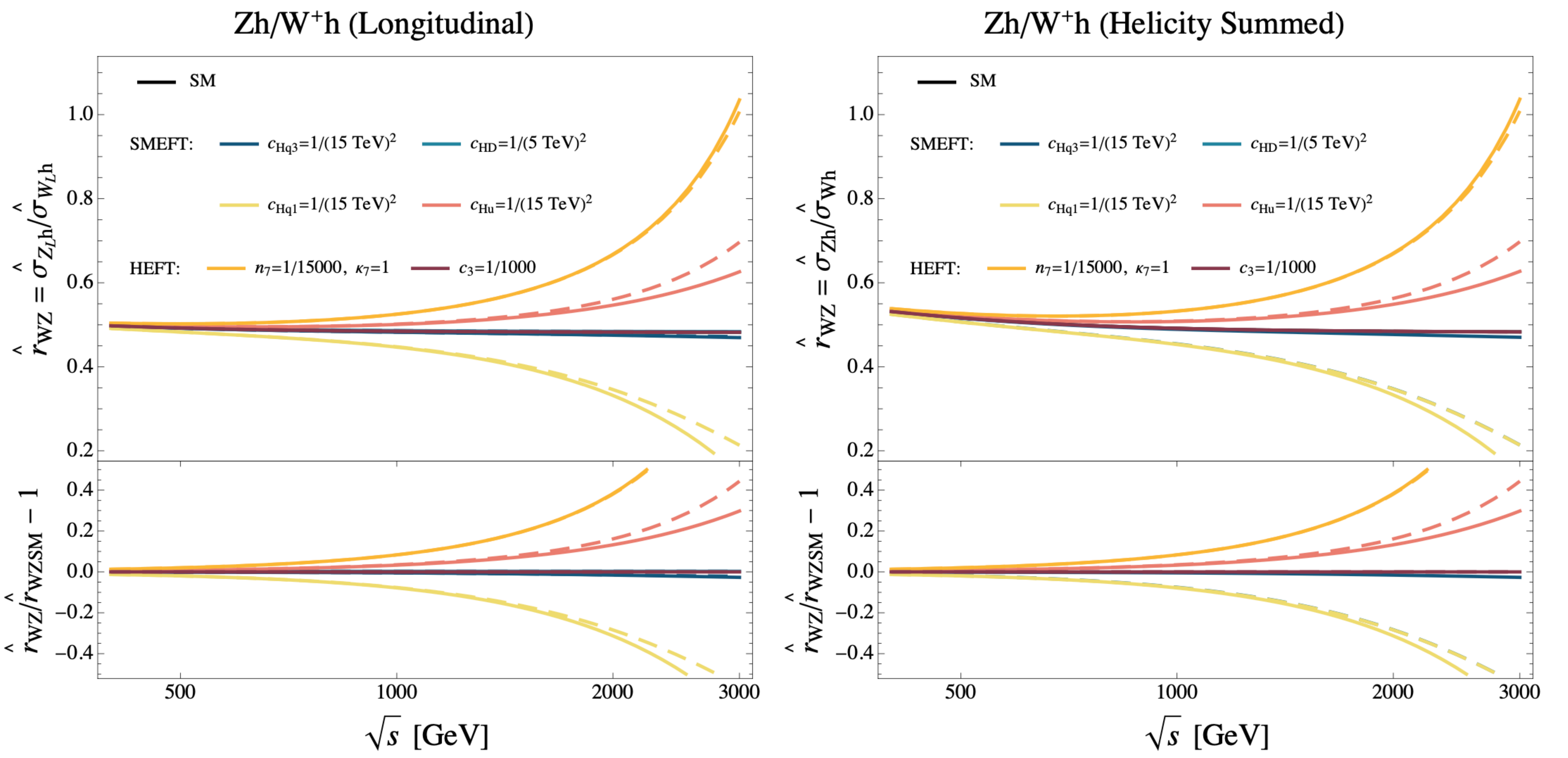
Tagging gauge boson polarizations and comparing W^+Z/W^+h at high energies probe *linear vs. non-linear realizations* of the EW symmetry

W^+W^-/W^+h



SMEFT/HEFT seperation not clear when comparing neutral current and charged current final states

Zh/W^+h



SMEFT/HEFT seperation not clear when comparing neutral current and charged current final states

Phenomenological Observable

Define binned longitudinal ratio:

$$r^{\pm}_{Zh} \equiv \frac{d\sigma(pp \to W^{\pm}Z)/dp_T^W}{d\sigma(pp \to W^{\pm}h)/dp_T^W}$$

Small HEFT coefficient can produce large deviation at high-p_T

- $W^{\pm}_L Z_L$ has already been observed through joint longitudinal polarization measurements.

G. Aad et al. (ATLAS) (2025)

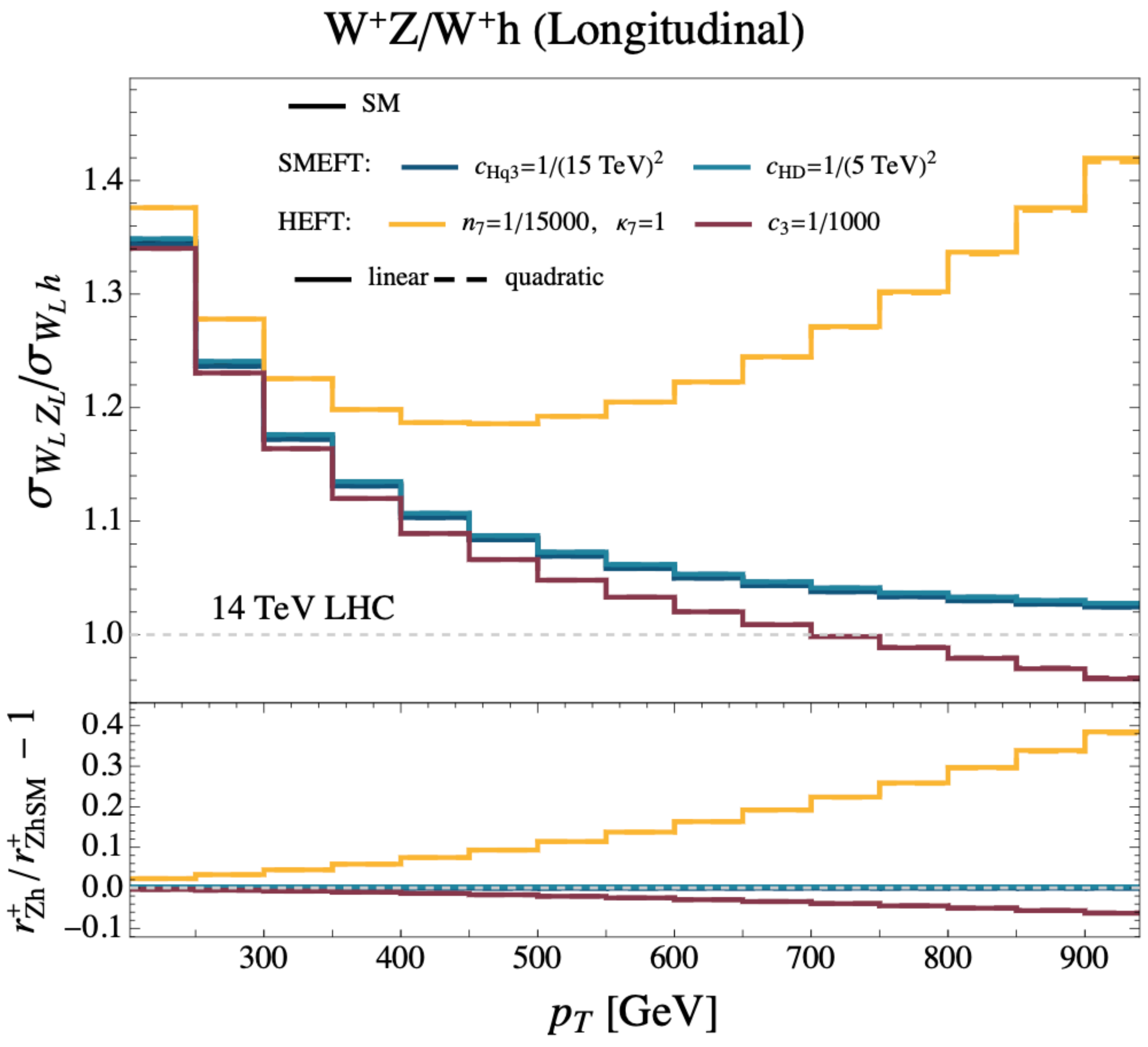
- $W^{\pm}h$ provides proming HL-LHC target

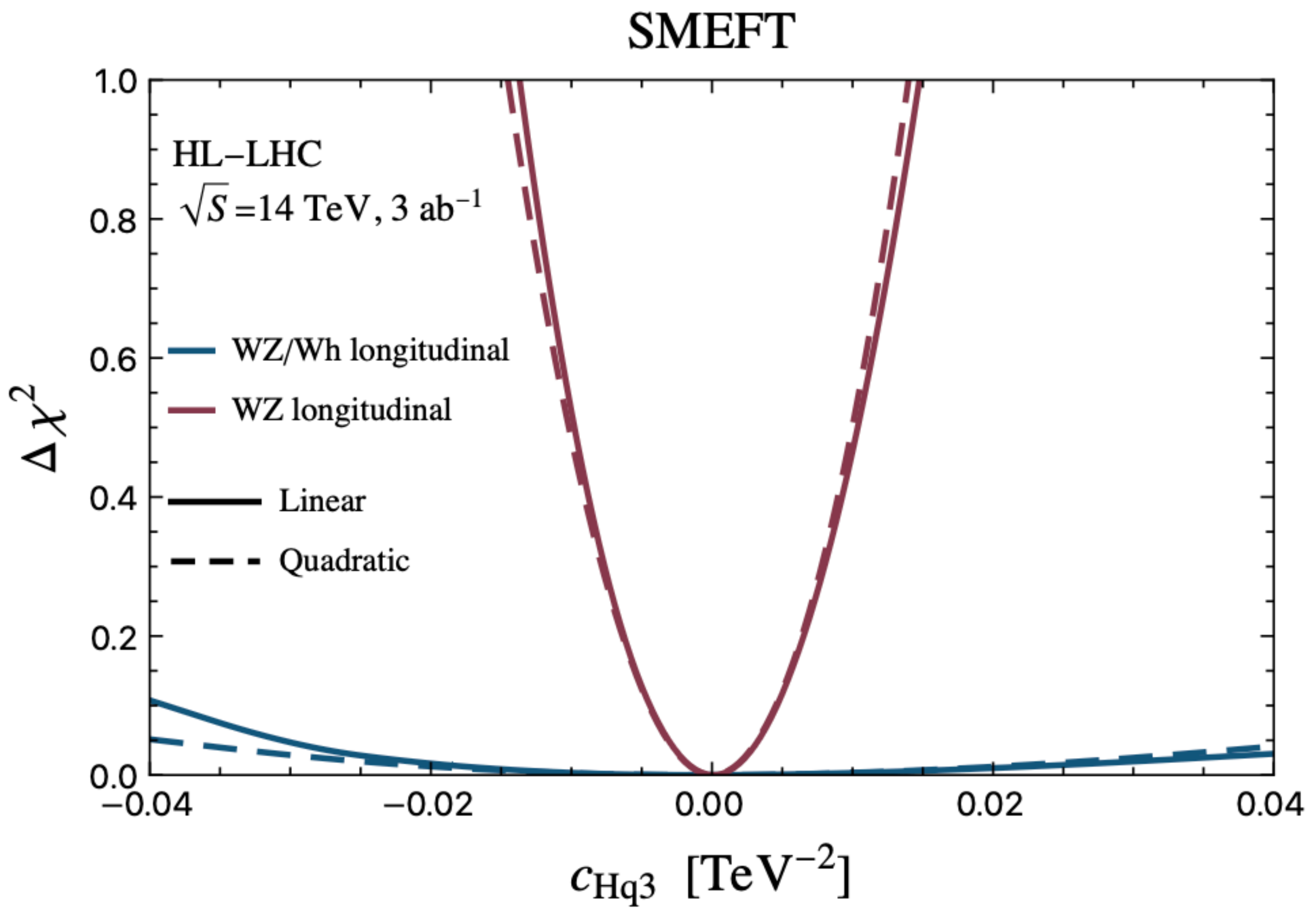
approximately 10% in $W^{\pm}h \to \ell^{\pm}\nu\,\gamma\gamma$

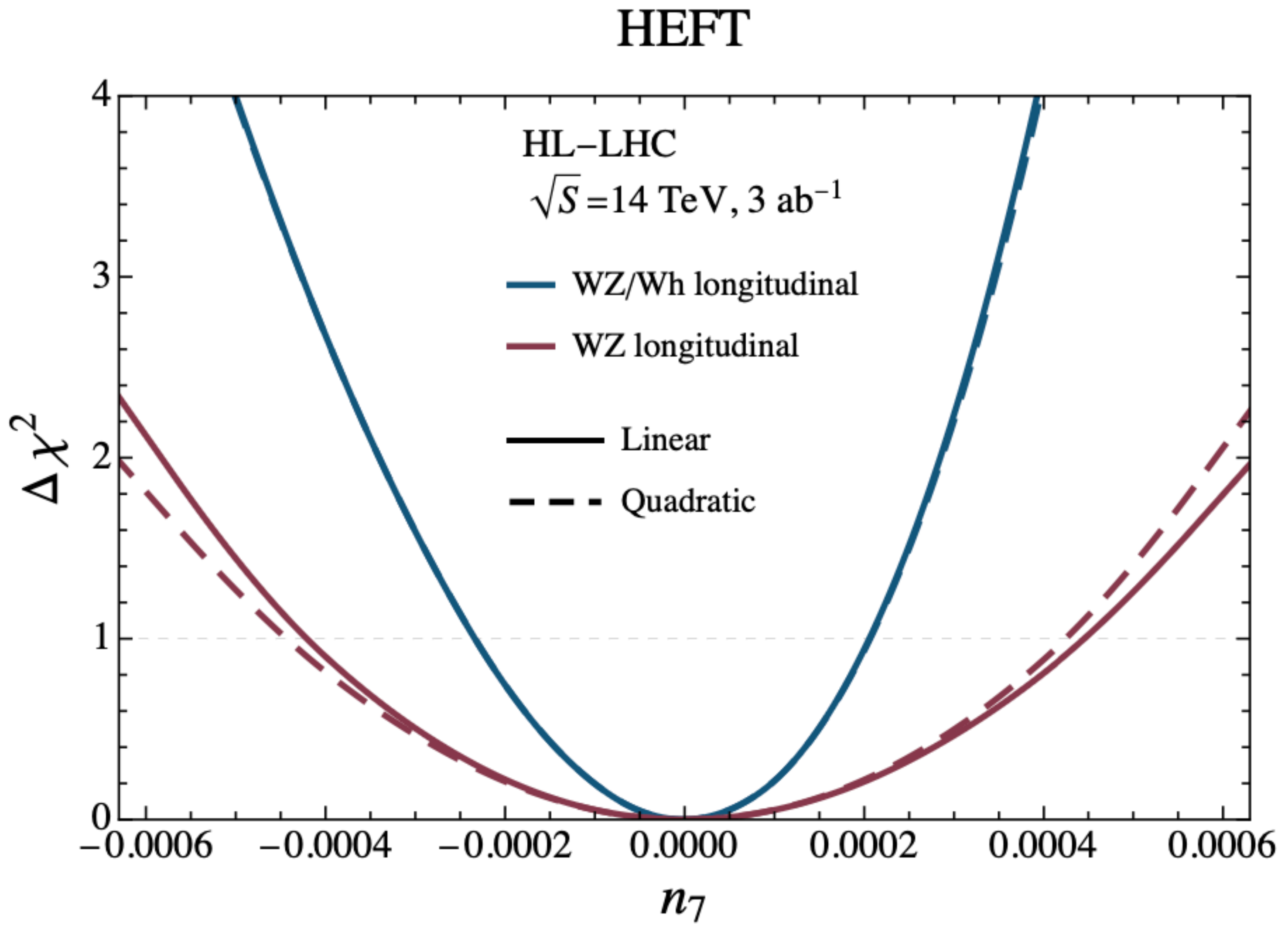
Colyer, Duda (2025)

Projected Sensitivity

$p_T < 1\text{TeV}$, HEFT deviation can be significant







Significant reduced sensitivity comparing WZ-only vs ratio analysis in SMEFT

In HEFT, n_7^Q has improved sensitivity in ratio analysis

Summary of Results

- $V_L V_L$ and $V_L h$ are correlated in SMEFT
- **Observable:** $$\frac{\sigma(pp \to W_L^{\pm} Z_L)}{\sigma(pp \to W_L^{\pm} h)}$$

Provides a probe to study deviation from SM/SMEFT pattern.

Ratios of longitudinal dibosons provides probes of the Higgs symmetry structure.

THANK YOU!

BACK UP

HEFT Lagrangian

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

$$\begin{aligned}\mathcal{L}_0 = & -\frac{1}{4} G^{\alpha}_{\mu\nu} G^{\alpha\,\mu\nu} - \frac{1}{4} W^{a}_{\mu\nu} W^{a\,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\ & + \frac{1}{2} \partial_\mu h\, \partial^\mu h - \frac{v^2}{4}\, \mathrm{Tr}(V_\mu V^\mu)\, F_C(h) - V(h) \\ & + i\, \overline{Q}_L \not{D} Q_L + i\, \overline{Q}_R \not{D} Q_R + i\, \overline{L}_L \not{D} L_L + i\, \overline{L}_R \not{D} L_R \\ & - \frac{v}{\sqrt{2}} \left(\overline{Q}_L\, U\, Y_Q(h)\, Q_R + \text{h.c.} \right) - \frac{v}{\sqrt{2}} \left(\overline{L}_L\, U\, Y_L(h)\, L_R + \text{h.c.} \right) \\ & - \frac{g_s^2}{16\pi^2}\, \lambda_s\, G^{\alpha}_{\mu\nu} \tilde{G}^{\alpha\,\mu\nu}.\end{aligned}$$

$$F_C(h) = 1 + 2a_C \frac{h}{v} + b_C \frac{h^2}{v^2} + \cdots\,,$$

$$a_C = 1 + \Delta a_C, \qquad b_C = 1 + \Delta b_C,$$

$$V_\mu \equiv (D_\mu U) U^\dagger, \qquad T \equiv U \sigma_3 U^\dagger.$$

$$V_\mu \to g_L V_\mu g_L^\dagger, \qquad T \to g_L T g_L^\dagger.$$

$$g_L(x) \in SU(2)_L$$

$$g_Y(x) = \exp\big(i\alpha_Y(x)\sigma_3/2\big) \in U(1)_Y$$

$$U(x) = \exp\left(\frac{i\,\sigma^I \pi^I(x)}{v}\right) \qquad H(x) = \frac{v + h(x)}{\sqrt{2}}\, U(x) \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

To $\mathcal{O}(m^2/s)$	SM	SMEFT	HEFT
$\frac{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm Z_L)}{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm h)}$	± 1	± 1	$\mp \frac{c_3 g - 8\pi\,(n_1^Q + n_7^Q)}{8\pi\,(\kappa_1 n_1^Q - \kappa_7 n_7^Q)}$
$\frac{\mathcal{M}(q_-\bar{q}_+ \to W_L^+ W_L^-)}{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm h)}$	$-\sqrt{2}\left(T_3^q + \frac{s_W^2}{c_W^2} Y_L^q\right)$	$-\frac{C_{Hq}^{(1)} + 2\,T_3^q C_{Hq}^{(3)}}{\sqrt{2}\,C_{Hq}^{(3)}}$	$\sqrt{2}\frac{8\pi\,n_5^Q + T_3^q\left(c_3 g - 8\pi\,(n_1^Q - 3n_7^Q)\right)}{8\pi\,(\kappa_1 n_1^Q - \kappa_7 n_7^Q)}$
$\frac{\mathcal{M}(q_-\bar{q}_+ \to Z_L h)}{\mathcal{M}(q_-\bar{q}'_+ \to W_L^\pm h)}$	$\sqrt{2}\frac{g_L^{Zq}}{c_W^2}$	$-\frac{C_{Hq}^{(1)} - 2\,T_3^q C_{Hq}^{(3)}}{\sqrt{2}\,C_{Hq}^{(3)}}$	$\sqrt{2}\frac{\kappa_5 n_5^Q + T_3^q(\kappa_1 n_1^Q + \kappa_7 n_7^Q)}{\kappa_1 n_1^Q - \kappa_7 n_7^Q}$
$\frac{\mathcal{M}(q_+\bar{q}_- \to W_L^+ W_L^-)}{\mathcal{M}(q_-\bar{q}_+ \to W_L^+ W_L^-)}$	$-\frac{s_W^2 Y_R^q}{c_W^2 T_3^q + s_W^2 Y_L^q}$	$-\frac{C_{Hq}}{C_{Hq}^{(1)} + 2\,T_3^q C_{Hq}^{(3)}}$	$-\frac{8\pi\,(n_6^Q + T_3^q(n_2^Q + n_8^Q))}{8\pi\,n_5^Q + T_3^q(c_3 g - 8\pi\,(n_1^Q - 3n_7^Q))}$
$\frac{\mathcal{M}(q_+\bar{q}_- \to Z_L h)}{\mathcal{M}(q_-\bar{q}_+ \to Z_L h)}$	$-\frac{g_R^{Zq}}{g_L^{Zq}}$	$-\frac{C_{Hq}}{C_{Hq}^{(1)} - 2\,T_3^q\,C_{Hq}^{(3)}}$	$-\frac{\kappa_6 n_6^Q + T_3^q(\kappa_2 n_2^Q + \kappa_8 n_8^Q)}{\kappa_5 n_5^Q + T_3^q(\kappa_1 n_1^Q + \kappa_7 n_7^Q)}$
$\frac{\mathcal{M}(q_+\bar{q}'_- \to W_L^{-(+)} Z_L)}{\mathcal{M}(q_-\bar{q}'_+ \to W_L^{-(+)} Z_L)}$	0^*	$\frac{C_{Hud}^{(*)}}{2C_{Hq}^{(3)}}$	$-8\,\pi\frac{n_2^Q - n_8^Q + (-)2\,i\,n_4^Q}{c_3 g - 8\pi(n_1^Q + n_7^Q)}$
$\frac{\mathcal{M}(q_+\bar{q}'_- \to W_L^{-(+)} h)}{\mathcal{M}(q_-\bar{q}'_+ \to W_L^{-(+)} h)}$	0^*	$-\frac{C_{Hud}^{(*)}}{2\,C_{Hq}^{(3)}}$	$-\frac{\kappa_2 n_2^Q - \kappa_8 n_8^Q + (-)2\,i\,\kappa_4 n_4^Q}{\kappa_1 n_1^Q - \kappa_7 n_7^Q}$

SMEFT Amplitude

$$\mathcal{M}_{\text{SMEFT}}(q_-\bar{q}'_+ \to W_L^\pm Z_L) = \pm\sqrt{2}\,C_{Hq}^{(3)}\,s\,\sin\theta \pm \frac{m_W^2}{2\sqrt{2}}\left[C_{HD} + 4\,C_{Hq}^{(3)}\left(2+\frac{m_Z^2}{m_W^2}\right) + 4\sqrt{2}\,G_F\right]\sin\theta + \mathcal{O}\left(\frac{m^2}{s}\right), \quad (5a)$$

$$\mathcal{M}_{\text{SMEFT}}(q_+\bar{q}'_- \to W_L^+ Z_L) = \frac{C_{Hud}^*}{\sqrt{2}}\,s\,\sin\theta + \frac{m_Z^2}{\sqrt{2}}\,C_{Hud}^*\,\sin\theta + \mathcal{O}\left(\frac{m^2}{s}\right), \quad (5b)$$

$$\mathcal{M}_{\text{SMEFT}}(q_+\bar{q}'_- \to W_L^- Z_L) = -\frac{C_{Hud}}{\sqrt{2}}\,s\sin\theta - \frac{m_Z^2}{\sqrt{2}}\,C_{Hud}\,\sin\theta + \mathcal{O}\left(\frac{m^2}{s}\right), \quad (5c)$$

$$\begin{aligned}\mathcal{M}_{\text{SMEFT}}\left(q_-\bar{q}_+ \to W_L^+ W_L^-\right) = &-\left(C_{Hq}^{(1)} + 2\,T_3^q C_{Hq}^{(3)}\right)s\,\sin\theta - \left[-Q\,C_{HD}\,m_W^2 + C_{Hq}^{(1)}\,m_Z^2 + 2\,T_3^q C_{Hq}^{(3)}\,(4m_W^2 - m_Z^2)\right]\sin\theta \\ &- 2\sqrt{2}m_Z^2 G_F\,\left(c_W^2 T_3^q + s_W^2 Y_L^q\right)\sin\theta + \mathcal{O}\left(\frac{m^2}{s}\right), \end{aligned} \quad (5d)$$

$$\mathcal{M}_{\text{SMEFT}}\left(q_+\bar{q}_- \to W_L^+ W_L^-\right) = C_{Hq}\,s\,\sin\theta + \left[-Q\,C_{HD} m_W^2 + C_{Hq} m_Z^2\right]\sin\theta + 2\sqrt{2}m_Z^2 G_F s_W^2 Y_R^q \sin\theta + \mathcal{O}\left(\frac{m^2}{s}\right), \quad (5e)$$

SMEFT Amplitude

$$\mathcal{M}_{\rm SMEFT}(q_-\bar{q}'_+ \to W_L^{\pm} h) = \sqrt{2}\, C_{Hq}^{(3)}\, s \sin\theta + \frac{m_W^2}{2\sqrt{2}}\left[-C_{HD} + 4\sqrt{2}\, G_F + 4\, C_{Hq}^{(3)}\, \frac{2m_W^2 - m_h^2}{m_W^2}\right] \sin\theta + \mathcal{O}\left(\frac{m^2}{s}\right), \tag{5f}$$

$$\mathcal{M}_{\rm SMEFT}(q_+\bar{q}'_- \to W_L^{+} h) = -\frac{C_{Hud}^*}{\sqrt{2}} s \sin\theta - \frac{(2m_W^2 - m_h^2)}{\sqrt{2}}\, C_{Hud}^* \sin\theta + \mathcal{O}\left(\frac{m^2}{s}\right) \tag{5g}$$

$$\mathcal{M}_{\rm SMEFT}(q_+\bar{q}'_- \to W_L^{-} h) = -\frac{C_{Hud}}{\sqrt{2}} s \sin\theta - \frac{(2m_W^2 - m_h^2)}{\sqrt{2}}\, C_{Hud} \sin\theta + \mathcal{O}\left(\frac{m^2}{s}\right) \tag{5h}$$

$$\begin{aligned}\mathcal{M}_{\rm SMEFT}\left(q_-\bar{q}_+ \to Z_L h\right) = &-\left(C_{Hq}^{(1)} - 2\,T_3^q C_{Hq}^{(3)}\right) s \sin\theta + \left[Q\, C_{HD} m_W^2 - \left(C_{Hq}^{(1)} - 2\,T_3^q C_{Hq}^{(3)}\right)\left(2m_Z^2 - m_h^2\right)\right] \sin\theta \\ &+ 2\sqrt{2}\, m_Z^2\, G_F\, g_L^{Zq} \sin\theta + \mathcal{O}\left(\frac{m^2}{s}\right),\end{aligned} \tag{5i}$$

$$\begin{aligned}\mathcal{M}_{\rm SMEFT}\left(q_+\bar{q}_- \to Z_L h\right) = &\, C_{Hq}\, s \sin\theta - \left[Q\, C_{HD} m_W^2 - C_{Hq}\left(2\, m_Z^2 - m_h^2\right)\right] \sin\theta \\ &- 2\sqrt{2} m_Z^2 G_F g_R^{Zq} \sin\theta + \mathcal{O}\left(\frac{m^2}{s}\right).\end{aligned} \tag{5j}$$

HEFT Amplitude

$$\mathcal{M}_{\mathrm{HEFT}}(q_-\bar{q}'_+ \to W_L^\pm Z_L) = \pm\sin\theta \Bigg[\frac{G_F}{\pi}\, s\left(4\pi(n_1^Q + n_7^Q) - \frac{g}{2}\,c_3\right) + \frac{G_F}{\pi}\,\frac{g}{2}\,c_3\,(m_Z^2 - 2m_W^2) + 4G_F m_Z^2 n_7^Q + 4G_F(2m_W^2 + m_Z^2)n_1^Q + 2m_W^2 G_F \Bigg] + \mathcal{O}\left(\frac{m^2}{s}\right), \tag{9a}$$

$$\mathcal{M}_{\mathrm{HEFT}}(q_+\bar{q}'_- \to W_L^\pm Z_L) = \pm\Big(4G_F(n_2^Q - n_8^Q \mp 2i\, n_4^Q)\, s\, \sin\theta + 4\, G_F\, m_Z^2\,(n_2^Q - n_8^Q \mp 2\, i\, n_4^Q)\,\sin\theta\Big) + \mathcal{O}\left(\frac{m^2}{s}\right), \tag{9b}$$

$$\mathcal{M}_{\mathrm{HEFT}}(q_-\bar{q}_+ \to W_L^+ W_L^-) = \sqrt{2}\, G_F\, s\, \sin\theta\left[4\, n_5^Q + T_3^q\left(\frac{g}{2\pi}\,c_3 \;\; - 4\,(n_1^Q - 3n_7^Q)\right)\right] \tag{9c}$$

$$+ \sqrt{2}\, G_F\, \sin\theta\left[\frac{g}{2\pi}\Big((3Q - 2T_3^q)m_W^2 + 3m_Z^2(T_3^q - Q)\Big)c_3 + 4T_3^q\Big[(m_Z^2 - 4m_W^2)\,n_1^Q + (4m_W^2 + m_Z^2)\,n_7^Q\Big] + 4\,m_Z^2\,n_5^Q\right]$$

$$- 2\sqrt{2}m_Z^2 G_F\,(c_W^2 T_3^q + s_W^2 Y_L^q)\sin\theta + \mathcal{O}\left(\frac{m^2}{s}\right),$$

HEFT Amplitude

$$\mathcal{M}_{\rm HEFT}\big(q_+\bar{q}_- \to W_L^+W_L^-\big) = -\sqrt{2}G_F\sin\theta\left(4\left(n_6^Q + T_3^q\big(n_2^Q + n_8^Q\big)\right)\big(s+m_Z^2\big) + Q\big(m_W^2 - m_Z^2\big)\left[2+\frac{3g}{2\pi}c_3\right]\right) + \mathcal{O}\left(\frac{m^2}{s}\right), \tag{9d}$$

$$\mathcal{M}_{\rm HEFT}\big(q_-\bar{q}'_+ \to W_L^\pm h\big) = 4\,G_F\,\sin\theta\,\big(\kappa_1 n_1^Q - \kappa_7 n_7^Q\big)\left[s - m_h^2 + m_W^2\right] + 2\,G_F\,m_W^2\,\sin\theta\,\big(2n_1^Q - 2n_7^Q + 1\big) + \mathcal{O}\left(\frac{m^2}{s}\right), \tag{9e}$$

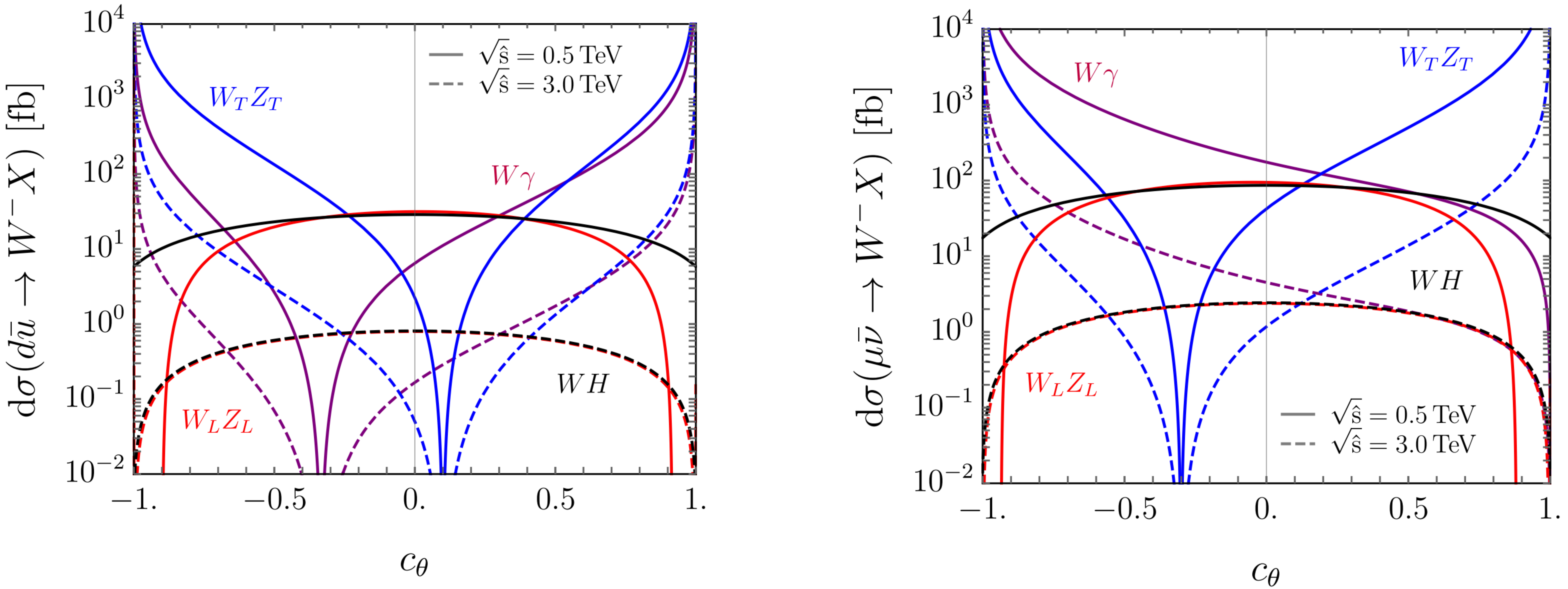
$$\begin{aligned}\mathcal{M}_{\rm HEFT}\big(q_+\bar{q}'_- \to W_L^\pm h\big) = &-4\,G_F\,\sin\theta\,\big(\kappa_2 n_2^Q - \kappa_8 n_8^Q \mp 2\,i\,\kappa_4 n_4^Q\big)\left[s - m_h^2 + m_W^2\right] \\ &- 4\,G_F m_W^2\sin\theta\left(n_2^Q - n_8^Q \mp 2\,i\,n_4^Q\right) + \mathcal{O}\left(\frac{m^2}{s}\right),\end{aligned} \tag{9f}$$

$$\begin{aligned}\mathcal{M}_{\rm HEFT}\big(q_-\bar{q}_+ \to Z_L h\big) = &\sqrt{2}\,G_F\,\sin\theta\left[4\left(\kappa_5 n_5^Q + T_3^q\big(\kappa_1 n_1^Q + \kappa_7 n_7^Q\big)\right)\left[s - m_h^2 + m_Z^2\right] + 4m_Z^2\left(n_5^Q + T_3^q\big(n_1^Q + n_7^Q\big)\right)\right] \\ &+ 2\sqrt{2}G_F m_Z^2\, g_L^{Zq}\sin\theta + \mathcal{O}\left(\frac{m^2}{s}\right),\end{aligned} \tag{9g}$$

$$\begin{aligned}\mathcal{M}_{\rm HEFT}\big(q_+\bar{q}_- \to Z_L h\big) = &-4\sqrt{2}\,G_F\,\sin\theta\left[\left(\kappa_6 n_6^Q + T_3^q\big(\kappa_2 n_2^Q + \kappa_8 n_8^Q\big)\right)\left[s - m_h^2 + m_Z^2\right] + m_Z^2\left(n_6^Q + T_3^q\big(n_2^Q + n_8^Q\big)\right)\right] \\ &- 2\sqrt{2}G_F m_Z^2\, g_R^{Zq}\sin\theta + \mathcal{O}\left(\frac{m^2}{s}\right).\end{aligned} \tag{9h}$$

Restoration via Radiation Zero

Capdevilla, Han (2024)



- Transverse sector → restoration of gauge symmetry. EW restoration shows up as a characteristic **radiation-zero** in the amplitude.

- Near radiation zero, one can isolate longitudinal contribution