# Precision SMEFT with geoSMEFT

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FNAL, Sept 5, 2023


## Looking for heavy new physics


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# In SMEFT framework

$$|A|^2 = |A_{SM}|^2 + \frac{2Re(A_{SM}^* A_6)}{\Lambda^2} + \frac{1}{\Lambda^4}\Big( |A_6|^2 + 2Re(A_{SM}^* A_8) \Big) + \cdots$$

interference piece,
usually largest effect.
State of the art
SMEFT

'Higher order'
$\mathcal{O}(1/\Lambda^4)$
corrections

Dual expansion: gotta match dimensions, so numerator ~ powers of

$$v, \partial_\mu \sim E$$

At high energy $\left(\frac{E}{\Lambda}\right)^n > \left(\frac{v}{\Lambda}\right)^n$: main advantage of SMEFT at LHC

# In SMEFT framework

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$v, \partial \sim E$

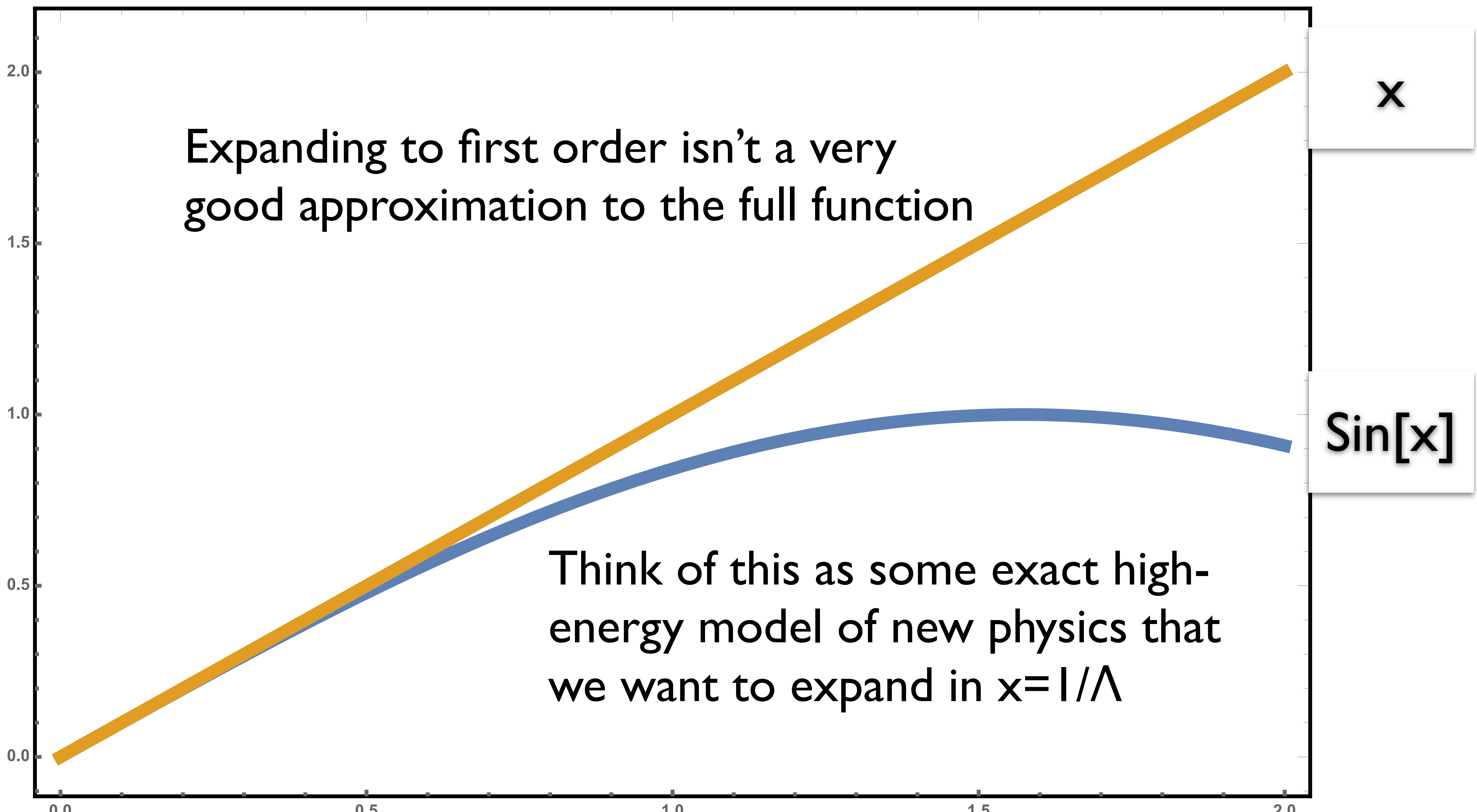
At

C

**But, larger expansion parameter = more sensitive to higher orders!**

# SMEFT as a series expansion

- Since the SMEFT is a series expansion in $1/\Lambda$, let's recall some facts about series expansions with an elementary example.



[taken from Petriello, Snowmass talk TF06]

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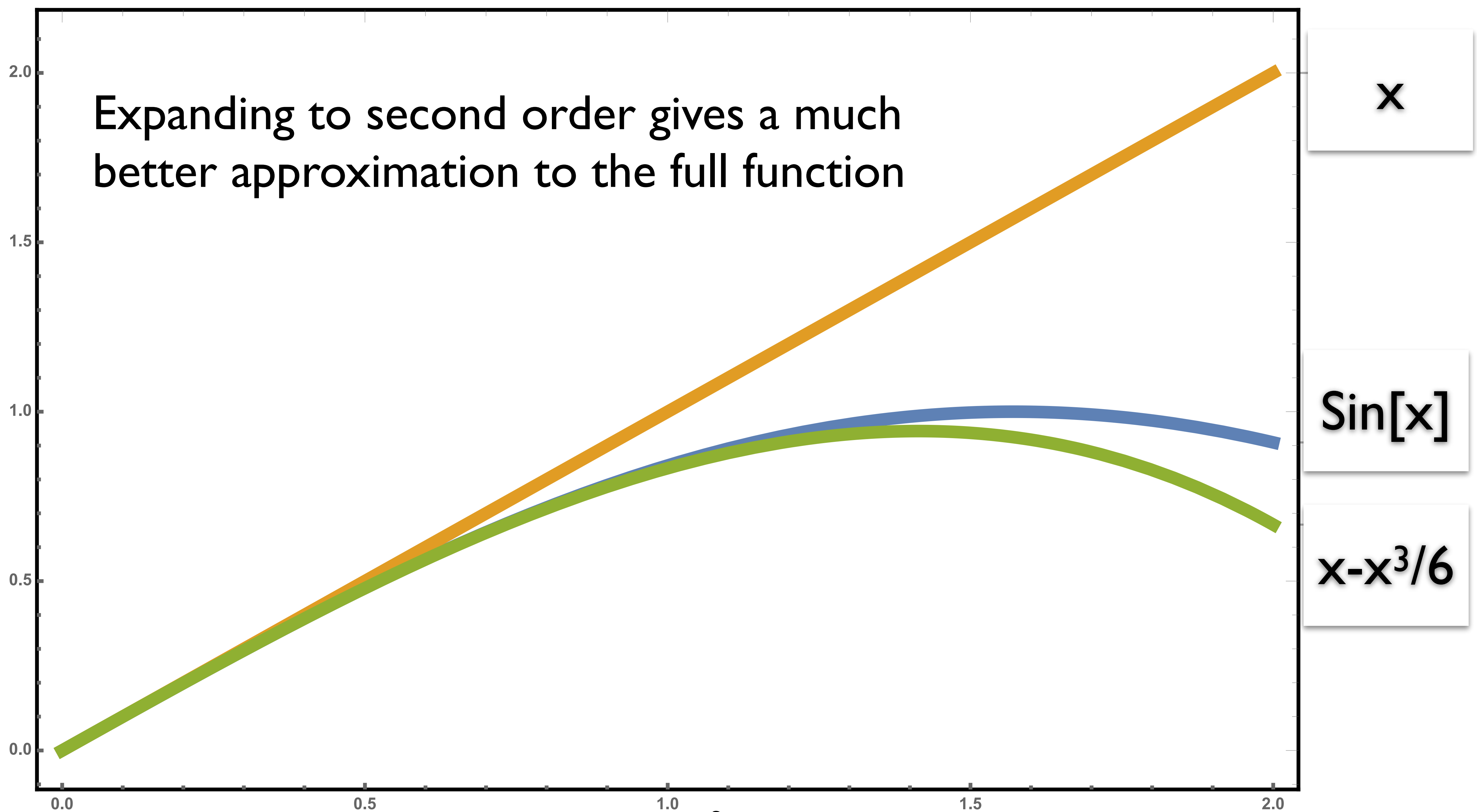

## OK, so we'd like to include $\mathcal{O}(1/\Lambda^4)$ effects

**BUT!**

SMEFT Warsaw basis: $\mathcal{O}(60)$ operators at dim-6

(flavor universal, CP) $\boxed{\mathcal{O}(1000) \text{ operators at dim-8}}$

**Can't we just do $|\mathrm{dim}-6|^2$?**

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EFT purist perspective: no, NOT consistent

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**Can't we just do $|\text{dim}-6|^2$?**

EFT realist perspective: can be okay if nothing else, but **lots** of pitfalls

- $|\text{dim}-6|^2$ is positive definite, total $\mathcal{O}(1/\Lambda^4)$ need not be
- $|\text{dim}-6|^2$ limited to $\text{dim}-6$ operators…

  limited structure, some already bounded, small in some UV setups

**Can lead to wildly inaccurate estimates of $\mathcal{O}(1/\Lambda^4)$ ...**

**Especially dangerous if $|\text{dim}-6|^2 > SM \times (\text{dim}-6)$ !!**

# geoSMEFT-ist perspective

**geoSMEFT** = re-organization of SMEFT that makes many key processes (for LHC SMEFT global fit) calculable $\mathcal{O}(1/\Lambda^4)$ without needing 1000 operators

Calculate away, forming a library of process to use as a laboratory to study ‘truncation error’.

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# geoSMEFT:

[2001.01453 Helset, AM, Trott]

Generic ops have the form $D^a H^b \bar{\psi}^c \psi^d F^x$

While total # grows exponentially with mass dimension, # operators that can contribute to 2-, 3- particle vertices stays small, nearly constant

1.) can't have too many non-Higgs fields

$$F^2\psi\psi^\dagger D \qquad \psi^4\phi^2$$
$$\psi^4 D^2 \qquad F\,\psi^4 \qquad \cdots$$
$$F\psi^2\phi D^2 \qquad F^3\phi^2$$

2.) can be smart about where to put derivatives (IBP, EOM)

$$\mathcal{O}(D^4H^4): \qquad (\Box H^\dagger H)(\Box H^\dagger H) \qquad (DH^\dagger)(DH)(DH^\dagger)(DH)$$

# <u>geoSMEFT:</u>

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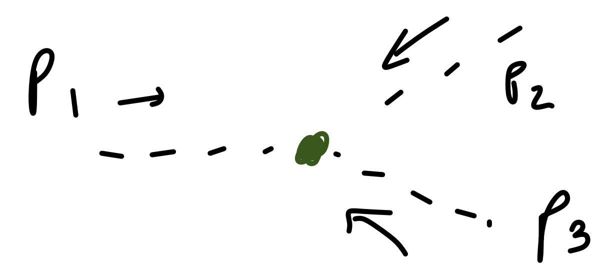
3.) kinematics for 2-,3- body interactions is trivial

e.g. $D_\mu H \, (D^\mu \bar{\psi}) \, \psi$

$$\sim (p_H \cdot p_{\bar{\psi}}) \, H \, \bar{\psi} \, \psi$$

$$\sim \left( \frac{m_\psi^2 - m_H^2 - m_{\bar{\psi}}^2}{2} \right) H \, \bar{\psi} \, \psi$$




$$p_H + p_{\bar{\psi}} + p_\psi = 0$$

Just changes coefficient of $H \, \bar{\psi} \, \psi$ : <u>not</u> a new operator structure

# geoSMEFT: Allowed 2, 3-pt structures:

[+ versions with G$^A$]

$$h_{IJ}(\phi)(D_\mu\phi)^I(D_\mu\phi)^J, \quad g_{AB}(\phi)\mathcal{W}^A_{\mu\nu}\mathcal{W}^{B,\mu\nu}$$

$$k^A_{IJ}(\phi)(D_\mu\phi)^I(D_\nu\phi)^J\,\mathcal{W}^{\mu\nu}_A, \quad f_{ABC}(\phi)\mathcal{W}^A_{\mu\nu}\mathcal{W}^{B,\nu\rho}\mathcal{W}^{C,\mu}_\rho,$$

$$Y(\phi)\bar{\psi}_1\psi_2, \quad L_{I,A}(\phi)\bar{\psi}_1\gamma^\mu\tau_A\psi_2(D_\mu\phi)^I, \quad d_A(\phi)\bar{\psi}_1\sigma^{\mu\nu}\psi_2\mathcal{W}^A_{\mu\nu},$$

Can't have derivatives in them, so only thing left is $H^\dagger H/\Lambda^2 \equiv \phi^2$

Additionally, # of possible EW structures for the functions **saturates**

Ex.) $h_{IJ}$ multiplies two doublets: can either be singlet = $\delta_{IJ}$ , or triplet.

Can be worked out to <u>all orders</u> in $\phi$!

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Can't have derivatives in them, so only thing left is $H^\dagger H/\Lambda^2 \equiv \phi^2$

Ex.) $$h_{IJ} = \left[1 + \phi^2 C^{(6)}_{H\Box} + \sum_{n=0}^{\infty}\left(\frac{\phi^2}{2}\right)^{n+2}\left(C^{(8+2n)}_{HD} - C^{(8+2n)}_{H,D2}\right)\right]\delta_{IJ} + \frac{\Gamma^I_{A,J}\phi_K\Gamma^K_{A,L}\phi^L}{2}\left(\frac{C^{(6)}_{HD}}{2} + \sum_{n=0}^{\infty}\left(\frac{\phi^2}{2}\right)^{n+1} C^{(8+2n)}_{H,D2}\right)$$

Dim-6 : 2 terms

Dim-8$^+$: 2 terms

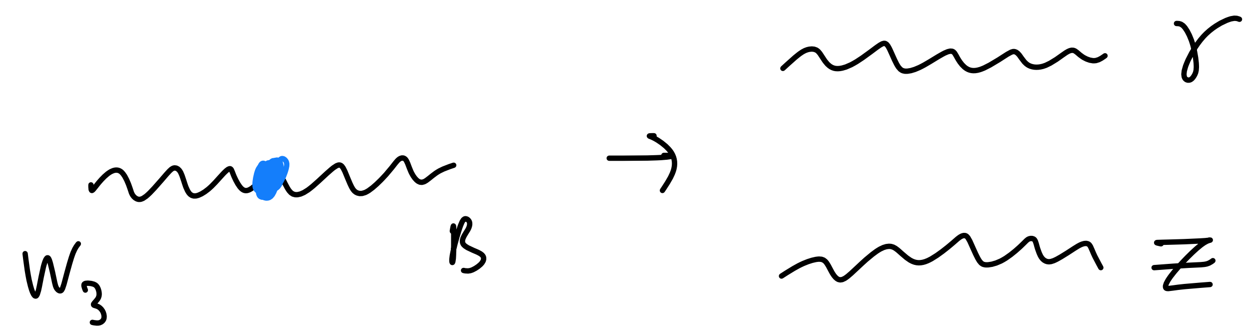
<u>Flat</u> 'metric' in SM, <u>curved</u> in SMEFT. Geometric perspective -> **geoSMEFT**

# geoSMEFT at work:

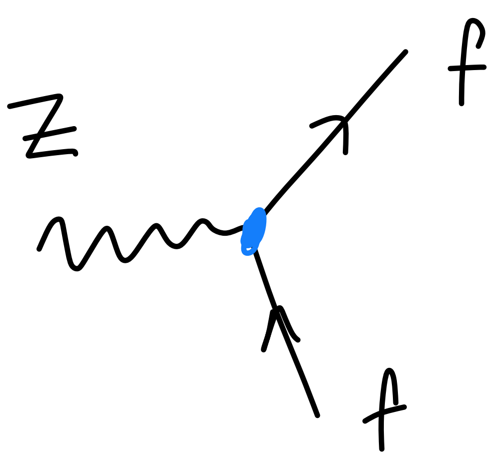
SMEFT phenomenology for processes involving 2, 3-pt interactions now easily doable to $\mathcal{O}(1/\Lambda^4)$ and only involve a few new operators

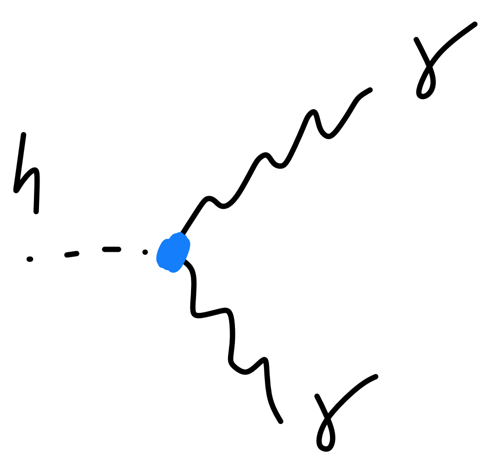
Ex.)

Gauge $\rightarrow$ mass eigenstates, EW inputs

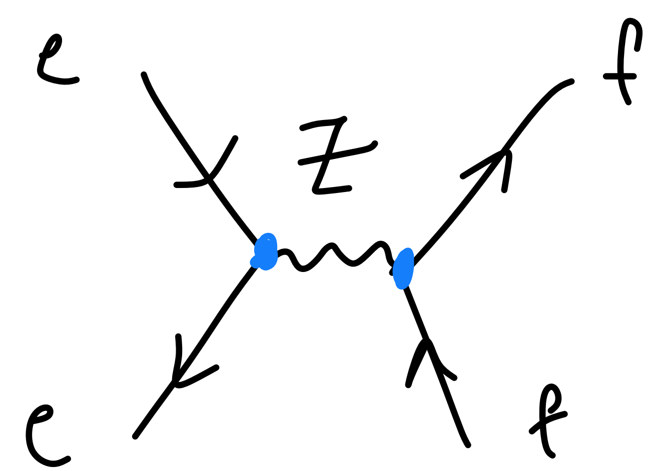



## $1 \rightarrow 2$ decays

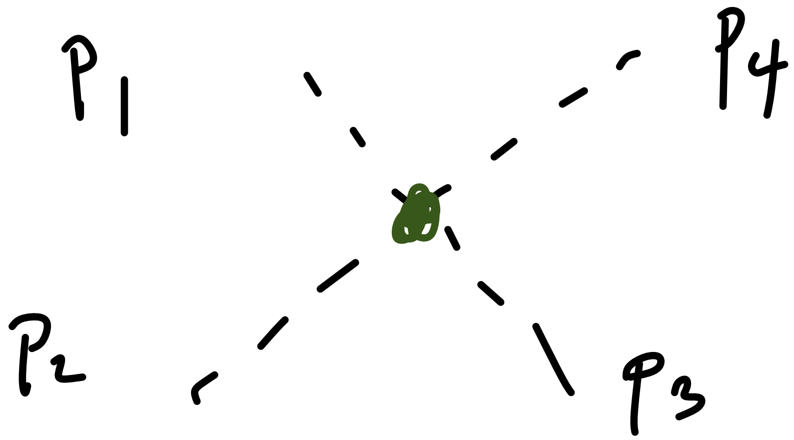



## Resonant $2 \rightarrow 2$



# 4+-pt interactions: can we go 'full metric'?




Key part of 2- and 3-pt result is that special kinematics made all momentum products trivial

No longer true at $\geq$ 4-pt interactions, i.e. for 4-pt: $\mathcal{O} \sim s^n\, t^m$

$\longrightarrow$ infinite set of higher derivative operators can contribute, so we can't find 'all orders' results

Need to add results at each new mass dimension 'by hand'…

# But:

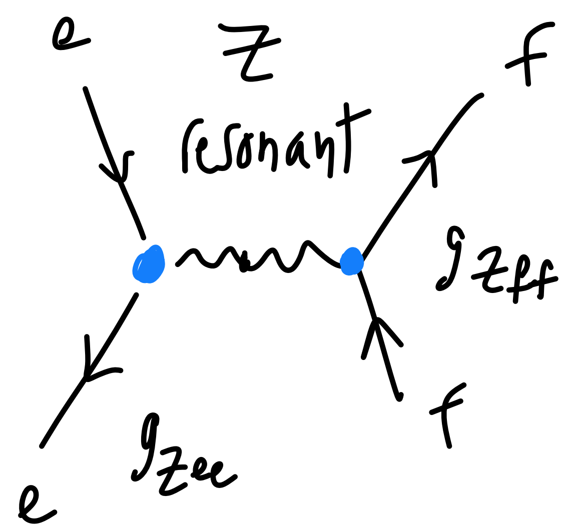
Can still manipulate derivatives to minimize # operators

dim-8 effects enter $\mathcal{O}(1/\Lambda^4)$ by interfering with SM, therefore need to match SM helicity/color/flavor structure

If we only care about energy enhanced effects, # is even smaller, easy to identify for a given process via derivative/vev/propagator counting

**In practice means # of `by-hand' operators is small for many relevant n = 4 processes**

# Redo classic SMEFT LEP1 analysis to $\mathcal{O}(1/\Lambda^4)$




$$g^{\mathcal{Z},\psi}_{\text{eff,pr}} = \frac{\bar{g}_Z}{2}\left[(2s^2_{\theta_Z}\,Q_\psi - \sigma_3)\delta_{pr} + \bar{v}_T\langle L^{\psi,pr}_{3,4}\rangle + \sigma_3\bar{v}_T\langle L^{\psi,pr}_{3,3}\rangle\right]$$
$$= \langle g^{\mathcal{Z},\psi}_{\text{SM,pr}}\rangle + \langle g^{\mathcal{Z},\psi}_{\text{eff,pr}}\rangle_{\mathcal{O}(v^2/\Lambda^2)} + \langle g^{\mathcal{Z},\psi}_{\text{eff,pr}}\rangle_{\mathcal{O}(v^4/\Lambda^4)} + \cdots .$$

Using:

$$\tilde{C}^{(6)} = C^{(6)}\frac{v^2}{\Lambda^2},\ \tilde{C}^{(8)} = C^{(8)}\frac{v^4}{\Lambda^4}$$

SMEFT corrections in $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}/\{\hat{\alpha}, \hat{m}_Z, \hat{G}_F\}$ scheme

| $\mathcal{O}(\frac{v^4}{\Lambda^4})$ | $\langle g^{\mathcal{Z},u_R}_{\text{eff,pp}}\rangle$ | $\langle g^{\mathcal{Z},d_R}_{\text{eff,pp}}\rangle$ | $\langle g^{\mathcal{Z},\ell_R}_{\text{eff,pp}}\rangle$ |
|---|---|---|---|
| $\langle g^{\mathcal{Z},\psi}_{\text{eff}}\rangle^2$ | 14/5.5 | -27/-11 | -9.1/-3.6 |
| $\tilde{C}_{HB}\,C_{HWB}$ | -0.21/0.39 | 0.10/-0.19 | 0.31/-0.58 |
| $\tilde{C}^2_{HD}$ | 0.28/-0.026 | -0.14/0.013 | -0.42/0.040 |
| $\tilde{C}_{HD}\,\tilde{C}^{(6)}_{H\psi}$ | -0.83/-0.19 | -0.83/-0.19 | -0.83/-0.19 |
| $\tilde{C}_{HD}\,\tilde{C}_{HWB}$ | 0.59/-0.19 | -0.29/0.097 | -0.88/0.29 |
| $\tilde{C}_{HD}\langle g^{\mathcal{Z},\psi}_{\text{eff}}\rangle$ | 4.0/0.50 | 4.0/0.50 | 4.0/0.50 |
| $(\tilde{C}^{(6)}_{H\psi})^2$ | 0.62/1.4 | -1.2/-2.8 | -0.42/-0.93 |
| $\tilde{C}_{HWB}\,\tilde{C}^{(6)}_{H\psi}$ | -0.69/0.58 | -0.69/0.58 | -0.69/0.58 |
| $\tilde{C}^{(6)}_{H\psi}\langle g^{\mathcal{Z},\psi}_{\text{eff}}\rangle$ | -6.7/-5.8 | 13/12 | 4.5/3.9 |
| $\tilde{C}_{HWB}\,\langle g^{\mathcal{Z},\psi}_{\text{eff}}\rangle$ | 3.7/0.26 | 3.7/0.26 | 3.7/0.26 |
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| $\tilde{C}^{(8)}_{HD}$ | -0.014/0.026 | 0.0069/-0.013 | 0.021/-0.040 |
| $\tilde{C}^{(8)}_{HD,2}$ | -0.21/0.026 | 0.10/-0.013 | 0.31/-0.040 |
| $\tilde{C}^{(8)}_{H\psi}$ | 0.19/0.19 | 0.19/0.19 | 0.19/0.19 |
| $\tilde{C}^{(8)}_{HW,2}$ | -0.38 | | |

[2102.02819 Corbett, Helset, AM, Trott]

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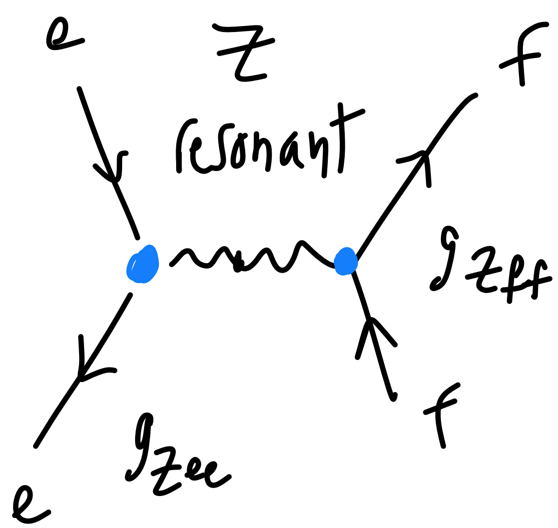


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\end{aligned}
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Using:

$$\tilde C^{(6)} = C^{(6)}\frac{v^2}{\Lambda^2}, \tilde C^{(8)} = C^{(8)}\frac{v^4}{\Lambda^4}$$

Lowest order.
Excludes 4-fermi terms, dipole operators.

| SMEFT corrections in $\{\hat m_W, \hat m_Z, \hat G_F\}/\{\hat\alpha, \hat m_Z, \hat G_F\}$ scheme | | | |
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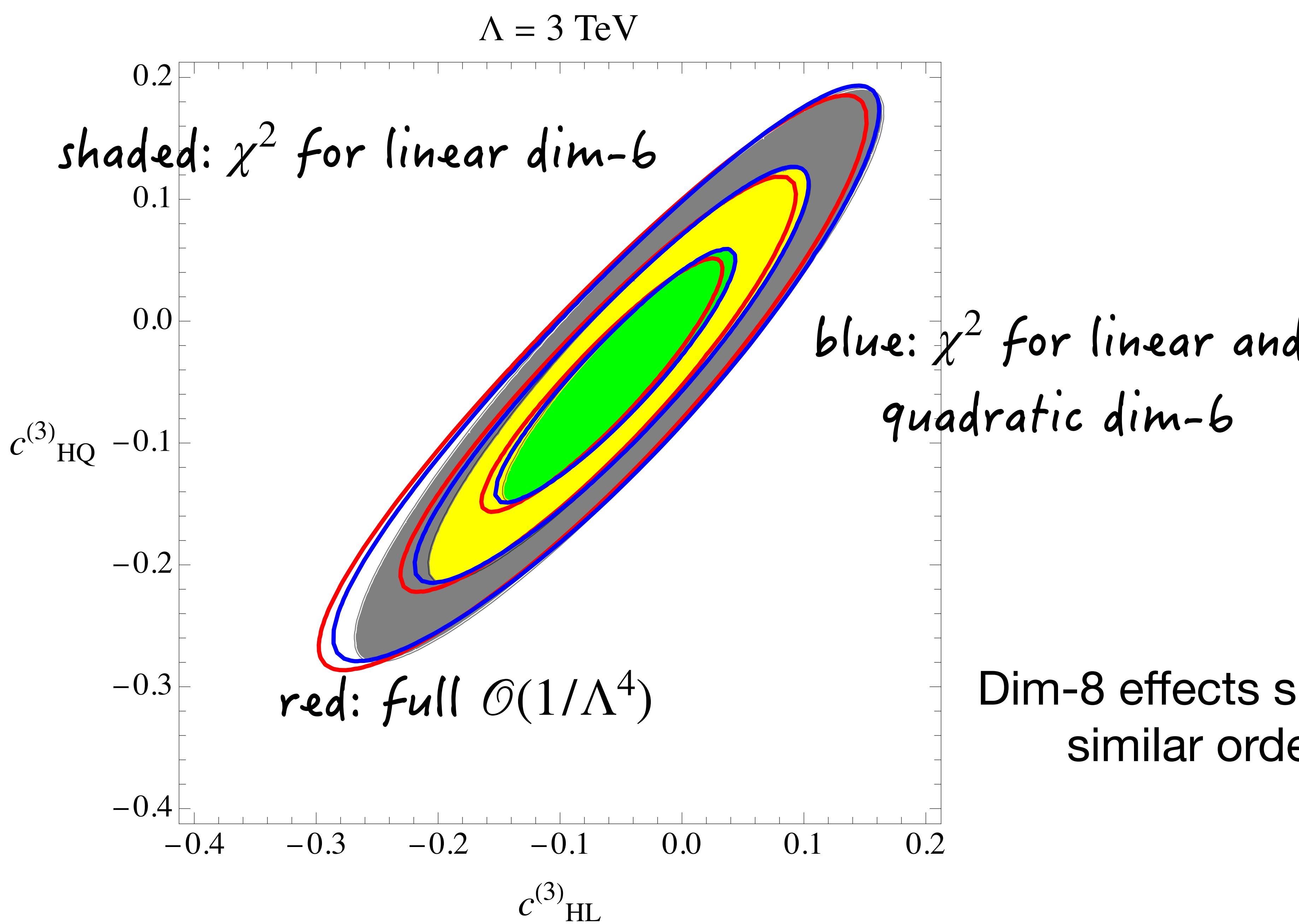
[2102.02819 Corbett, Helset, AM, Trott]

# Redo classic SMEFT LEP1 analysis to $\mathcal{O}(1/\Lambda^4)$

Ex.) 2D projections: Zero all dimension-6 operators except two but leave all dimension-8 on with coefficients +1. Fix $\Lambda$, then compare $\chi^2$ ellipses with and without dimension-8 terms




Dim-8 effects small but present, similar order to (dim-6)²

# Truncation error: Combining SM loops with $\mathcal{O}(1/\Lambda^4)$

Can combine $\mathcal{O}(1/\Lambda^4)$ with $\mathcal{O}(1/\Lambda^2) \times \mathrm{SM\,loop}$. Worked out for $gg \to h,\ h \to \gamma\gamma$ = key processes for SMEFT global fit.

#s are SM inputs, pdf factors, constants (**all known analytically**)

$1/\Lambda^2$

$1/\Lambda^4$

loop $\times\, 1/\Lambda^2$

$$
\begin{aligned}
\frac{\sigma^{\hat\alpha}_{\mathrm{SMEFT}}(\mathcal{G}\mathcal{G}\to h)}{\hat\sigma_{\mathrm{SM},m_t\to\infty}(\mathcal{G}\mathcal{G}\to h)} \simeq 1 &+ 289\,\tilde C^{(6)}_{HG} \\
&+ 289\,\tilde C^{(6)}_{HG}\left(\tilde C^{(6)}_{H\Box} - \frac{1}{4}\tilde C^{(6)}_{HD}\right) + 4.68\times 10^4\,(\tilde C^{(6)}_{HG})^2 + 289\,\tilde C^{(8)}_{HG} \\
&+ 0.85\left(\tilde C^{(6)}_{H\Box} - \frac{1}{4}\tilde C^{(6)}_{HD}\right) + 369\,\tilde C^{(6)}_{HG} - 0.91\,\tilde C^{(6)}_{uH} - 7.26\,\mathrm{Re}\,\tilde C^{(6)}_{uG} \\
&- 0.60\,\delta G^{(6)}_F - 4.42\,\mathrm{Re}\,\tilde C^{(6)}_{uG}\,\log\left(\frac{\hat m_h^2}{\Lambda^2}\right) - 0.126\,\mathrm{Re}\,\tilde C^{(6)}_{dG}\,\log\left(\frac{\hat m_h^2}{\Lambda^2}\right) \\
&- 0.057\,\mathrm{Re}\,\tilde C^{(6)}_{dG} + 2.06\,\tilde C^{(6)}_{dH}.
\end{aligned}
$$

[NNPDF3.0, w/ $\mu = \mu_F = m_h$, BFM, $\hat m_W$ scheme]

[2107.07470 Corbett, AM, Trott]
[2305.05879 AM, Trott]

# Truncation error: Combining SM loops with $\mathcal{O}(1/\Lambda^4)$

$$
\begin{aligned}
\frac{\Gamma^{\hat{m}_W}_{SMEFT}}{\Gamma^{\hat{m}_W}_{\rm SM}} \simeq 1 &- 788 f_1^{\hat{m}_W}, \\
&+ 394^2\,(f_1^{\hat{m}_W})^2 - 351\,(\tilde{C}^{(6)}_{HW} - \tilde{C}^{(6)}_{HB})\,f_3^{\hat{m}_W} + 2228\,\delta G_F^{(6)}\,f_1^{\hat{m}_W}, \\
&+ 979\,\tilde{C}^{(6)}_{HD}(\tilde{C}^{(6)}_{HB} + 0.80\;\tilde{C}^{(6)}_{HW} - 1.02\,\tilde{C}^{(6)}_{HWB}) - 788\left[\left(\tilde{C}^{(6)}_{H\Box} - \frac{\tilde{C}^{(6)}_{HD}}{4}\right) f_1^{\hat{m}_W} + f_2^{\hat{m}_W}\right], \\
&+ 2283\,\tilde{C}^{(6)}_{HWB}(\tilde{C}^{(6)}_{HB} + 0.66\;\tilde{C}^{(6)}_{HW} - 0.88\,\tilde{C}^{(6)}_{HWB}) - 1224\,(f_1^{\hat{m}_W})^2, \\
&- 117\,\tilde{C}^{(6)}_{HB} - 23\,\tilde{C}^{(6)}_{HW} + \left[51 + 2\log\left(\frac{\hat{m}_h^2}{\Lambda^2}\right)\right]\tilde{C}^{(6)}_{HWB} + \left[-0.55 + 3.6\log\left(\frac{\hat{m}_h^2}{\Lambda^2}\right)\right]\tilde{C}^{(6)}_{W}, \\
&+ \left[27 - 28\log\left(\frac{\hat{m}_h^2}{\Lambda^2}\right)\right]\mathrm{Re}\,\tilde{\mathrm{C}}^{(6)}_{\substack{uB\\33}} + 5.5\mathrm{Re}\,\tilde{\mathrm{C}}^{(6)}_{\substack{uH\\33}} + 2\,\tilde{\mathrm{C}}^{(6)}_{\mathrm{H}\Box} - \frac{\tilde{\mathrm{C}}^{(6)}_{\mathrm{HD}}}{2}, \\
&- 3.2\,\tilde{C}^{(6)}_{HD} - 7.5\,\tilde{C}^{(6)}_{HWB} - 3\sqrt{2}\,\delta G_F^{(6)}.
\end{aligned}
$$

$$
\begin{aligned}
\delta G_F^{(6)} &= \frac{1}{\sqrt{2}}\left(\tilde{C}^{(3)}_{\substack{Hl\\ee}} + \tilde{C}^{(3)}_{\substack{Hl\\\mu\mu}} - \frac{1}{2}(\tilde{C}'_{\substack{ll\\\mu ee\mu}} + \tilde{C}'_{\substack{ll\\e\mu\mu e}})\right), \\
f_1^{\hat{m}_W} &= \left[\tilde{C}^{(6)}_{HB} + 0.29\;\tilde{C}^{(6)}_{HW} - 0.54\,\tilde{C}^{(6)}_{HWB}\right], \\
f_2^{\hat{m}_W} &= \left[\tilde{C}^{(8)}_{HB} + 0.29\;(\tilde{C}^{(8)}_{HW} + \tilde{C}^{(8)}_{HW,2}) - 0.54\,\tilde{C}^{(8)}_{HWB}\right], \\
f_3^{\hat{m}_W} &= \left[\tilde{C}^{(6)}_{HW} - \tilde{C}^{(6)}_{HB} - 0.66\,\tilde{C}^{(6)}_{HWB}\right],
\end{aligned}
$$

Combined result informs on how assumptions about coefficients affect uncertainty

# Truncation error: Combining SM loops with $\mathcal{O}(1/\Lambda^4)$

Coefficient choice: i.e. $C^{(6)}_{GH}$ vs. $g_3^2\, C^{(6)}_{GH}$ intertwines loop and SMEFT expansions!

$$
\begin{aligned}
\frac{\Gamma^{\hat{m}_W}_{SMEFT}}{\Gamma^{\hat{m}_W}_{\rm SM}} \simeq\ & 1 - 788 f_1^{\hat{m}_W}, \\
& + 394^2\, (f_1^{\hat{m}_W})^2 - 351\, (\tilde{C}^{(6)}_{HW} - \tilde{C}^{(6)}_{HB})\, f_3^{\hat{m}_W} + 2228\, \delta G_F^{(6)}\, f_1^{\hat{m}_W}, \\
& + 979\, \tilde{C}^{(6)}_{HD} (\tilde{C}^{(6)}_{HB} + 0.80\ \tilde{C}^{(6)}_{HW} - 1.02\, \tilde{C}^{(6)}_{HWB}) - 788 \left[ \left( \tilde{C}^{(6)}_{H\Box} - \frac{\tilde{C}^{(6)}_{HD}}{4} \right) f_1^{\hat{m}_W} + f_2^{\hat{m}_W} \right], \\
& + 2283\, \tilde{C}^{(6)}_{HWB} (\tilde{C}^{(6)}_{HB} + 0.66\ \tilde{C}^{(6)}_{HW} - 0.88\, \tilde{C}^{(6)}_{HWB}) - 1224\, (f_1^{\hat{m}_W})^2, \\
& - 117\, \tilde{C}^{(6)}_{HB} - 23\, \tilde{C}^{(6)}_{HW} + \left[ 51 + 2 \log \left( \frac{\hat{m}_h^2}{\Lambda^2} \right) \right] \tilde{C}^{(6)}_{HWB} + \left[ -0.55 + 3.6 \log \left( \frac{\hat{m}_h^2}{\Lambda^2} \right) \right] \tilde{C}^{(6)}_{W}, \\
& + \left[ 27 - 28 \log \left( \frac{\hat{m}_h^2}{\Lambda^2} \right) \right] \mathrm{Re}\, \tilde{\mathrm{C}}^{(6)}_{\substack{uB \\ 33}} + 5.5 \mathrm{Re}\, \tilde{\mathrm{C}}^{(6)}_{\substack{uH \\ 33}} + 2\, \tilde{\mathrm{C}}^{(6)}_{\mathrm{H}\Box} - \frac{\tilde{\mathrm{C}}^{(6)}_{\mathrm{HD}}}{2}, \\
& - 3.2\, \tilde{C}^{(6)}_{HD} - 7.5\, \tilde{C}^{(6)}_{HWB} - 3\sqrt{2}\, \delta G_F^{(6)}.
\end{aligned}
$$

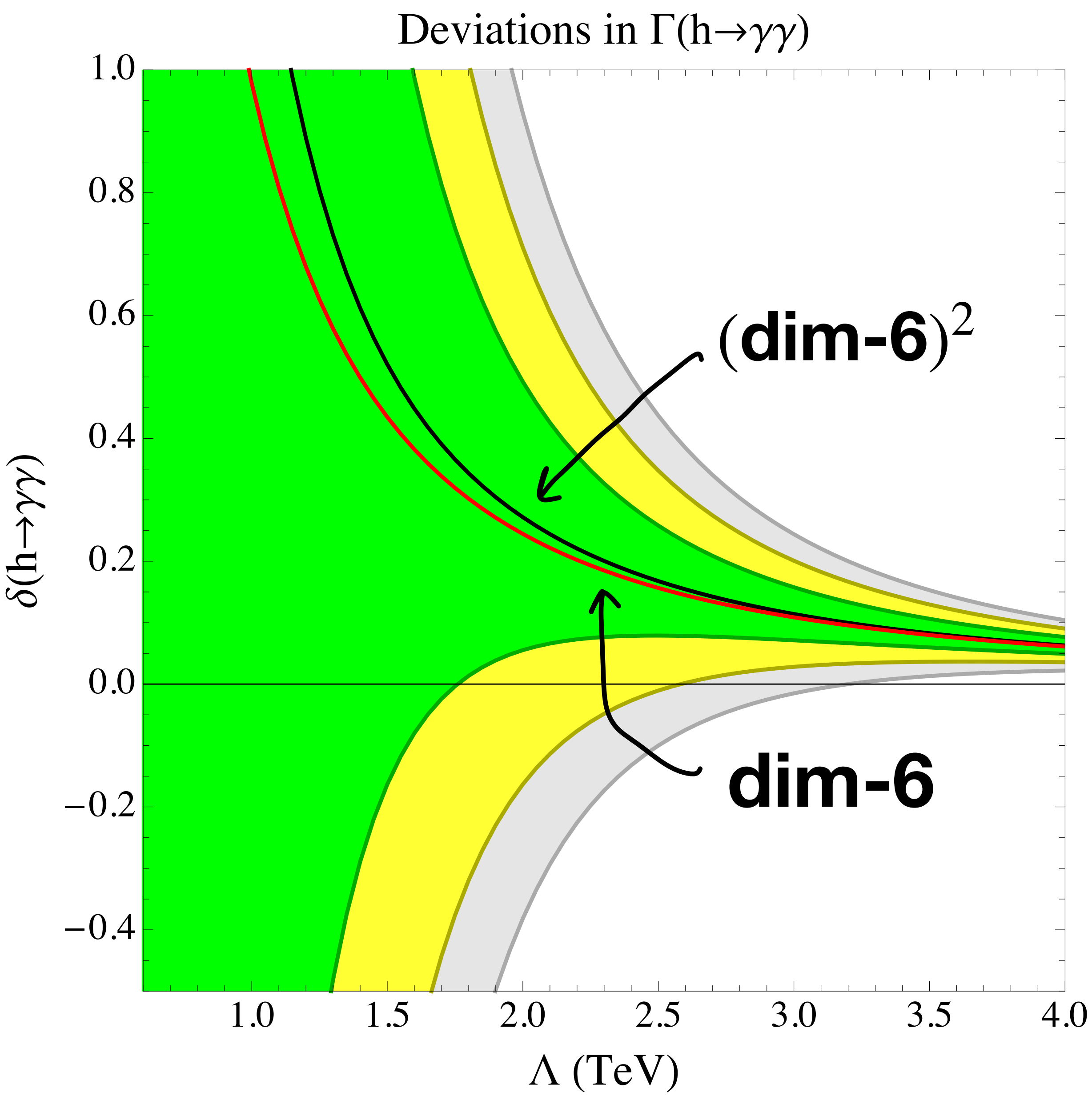
$$
\begin{aligned}
\delta G_F^{(6)} &= \frac{1}{\sqrt{2}} \left( \tilde{C}^{(3)}_{\substack{Hl \\ ee}} + \tilde{C}^{(3)}_{\substack{Hl \\ \mu\mu}} - \frac{1}{2} (\tilde{C}'_{\substack{ll \\ \mu ee\mu}} + \tilde{C}'_{\substack{ll \\ e\mu\mu e}}) \right), \\
f_1^{\hat{m}_W} &= \left[ \tilde{C}^{(6)}_{HB} + 0.29\ \tilde{C}^{(6)}_{HW} - 0.54\, \tilde{C}^{(6)}_{HWB} \right], \\
f_2^{\hat{m}_W} &= \left[ \tilde{C}^{(8)}_{HB} + 0.29\ (\tilde{C}^{(8)}_{HW} + \tilde{C}^{(8)}_{HW,2}) - 0.54\, \tilde{C}^{(8)}_{HWB} \right], \\
f_3^{\hat{m}_W} &= \left[ \tilde{C}^{(6)}_{HW} - \tilde{C}^{(6)}_{HB} - 0.66\, \tilde{C}^{(6)}_{HWB} \right],
\end{aligned}
$$

Combined result informs on how assumptions about coefficients affect uncertainty

# Sneaky large dimension-8 effects: $h \to \gamma\gamma$

$h \to \gamma\gamma$ affected by $H^\dagger H\, F^2$ at dim-6, $(H^\dagger H)^2\, F^2$ at dim-8.

But: following classification of [Arzt'93, Craig et al '20] (weakly coupled UV completion), the former are 'loop-level', while latter `tree-level',




Ex.) pick random values, study impact

loop = $\mathcal{O}(0.01)$

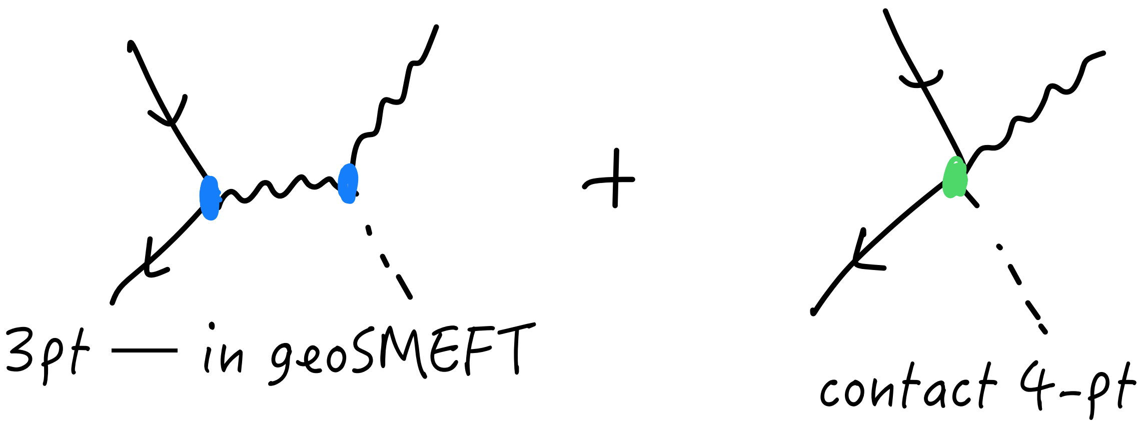
tree = $\mathcal{O}(1)$

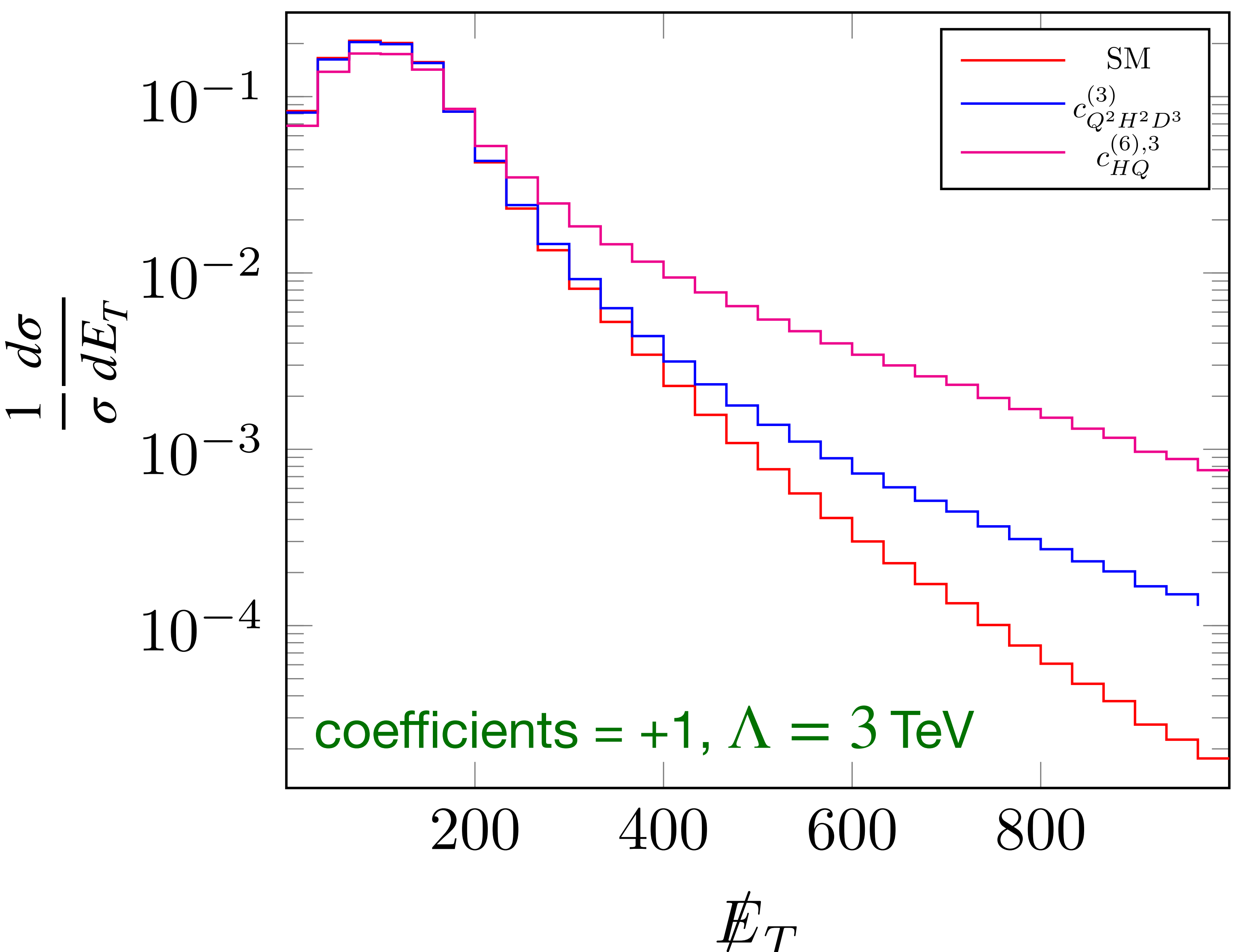
Large effect from dim-8, as coefficient hierarchy compensates for extra powers of $v^2/\Lambda^2$

[explicit UV example = kinetically mixed U(1): 2007.00565 Hays, Helset, AM, Trott]

# Sneaky large dimension-8 effects: VH

[2306.00053 Corbett, AM]




Effects at large $\hat{s}$ controlled by:

$$Q^\dagger \bar{\sigma}^\mu \tau^I Q H^\dagger \overleftrightarrow{D}_I H$$

interference ~ $\boxed{g^2_{SM}}\dfrac{\hat{s}}{\Lambda^2}$

squared ~ $\dfrac{\hat{s}^2}{\Lambda^4}$

And

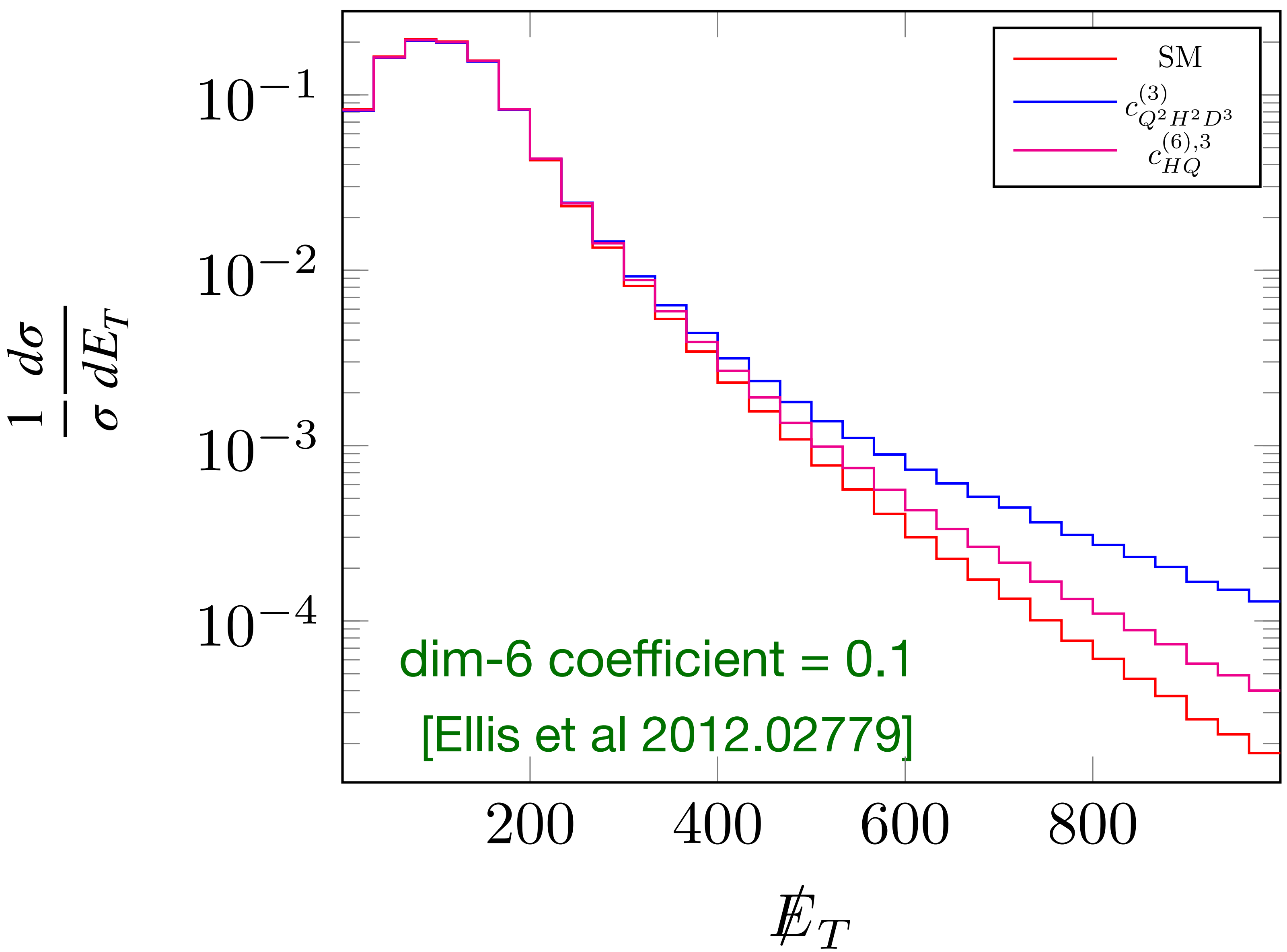
$$Q^\dagger \bar{\sigma}^\mu \tau^I D_\nu Q\, D^\mu H^\dagger \tau_I D_{\{\mu,\nu\}} H$$

interference ~ $\boxed{g^2_{SM}}\dfrac{\hat{s}^2}{\Lambda^4}$

both contribute to $V_L$ polarization, dominant SM piece

# Sneaky large dimension-8 effects: VH

But, $Q^\dagger \bar{\sigma}^\mu \tau^I Q H^\dagger \overleftrightarrow{D}_I H$ etc. are constrained by LEP, while $Q^\dagger \bar{\sigma}^\mu \tau^I D_\nu Q\, D^\mu H^\dagger \tau_I D_{\{\mu,\nu\}} H$ are not



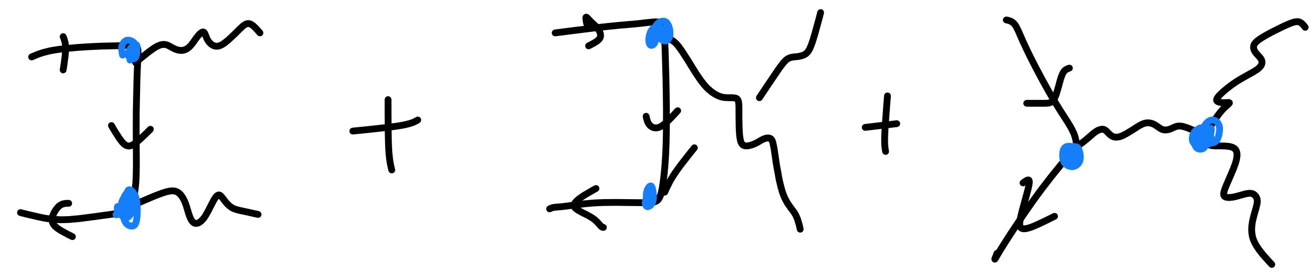

complying with those constraints, large $\hat{s}$ is a window into dim-8

# Sneaky large dimension-8 effects: diboson

$\gamma W^{\pm}$

$WWW$

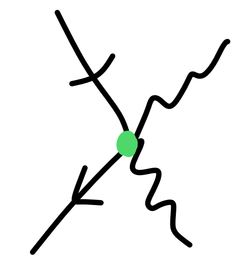
| $\epsilon_\gamma \epsilon_W$ | SM | dim-6 $C_W$ |
|---|---|---|
| $++$ | $\frac{v^2}{s}$ | $\frac{s}{\Lambda^2}$ |
| $+-$ | $1$ | $0$ |
| $+0$ | $\frac{v}{\sqrt{s}}$ | $\frac{v\sqrt{s}}{\Lambda^2}$ |



with dim-6 alone, largest energy enhancement (to $\mathcal{O}(1/\Lambda^4)$ ) comes from from

$$|\,\textbf{dim-6}\ C_W|^2 \sim \frac{s^2}{\Lambda^4}$$

# Sneaky large dimension-8 effects: diboson



$\gamma W^{\pm}$

| $\epsilon_\gamma \epsilon_W$ | SM | $WWW$<br>dim-6 $C_W$ | $D\psi^2 W^2$<br>dim-8 contact |
|---|---|---|---|
| $++$ | $\frac{v^2}{s}$ | $\frac{s}{\Lambda^2}$ | $\frac{s^2}{\Lambda^4}$ |
| $+-$ | $1$ | $0$ | $\frac{s^2}{\Lambda^4}$ |
| $+0$ | $\frac{v}{\sqrt{s}}$ | $\frac{v\sqrt{s}}{\Lambda^2}$ | $\frac{vs^{3/2}}{\Lambda^4}$ |

**But:** dim 8

$$(Q^\dagger \bar{\sigma}^\mu \tau^I \overleftrightarrow{D}_\nu Q)\, W^I_{\mu\rho} B_{\rho\nu}$$

can interfere with dominant SM polarization

$$SM \times \textbf{dim-8} \sim \frac{s^2}{\Lambda^4}$$

**∴ tails tell you about the sum, not just $C_W$**

Motivates polarization studies, 'taggers'

See also Degrande 2303.10493

[Kim, AM in progress]

[similar behavior for $W^{\pm}Z$]

# So where does this leave us?

- geoSMEFT: approach where 2 and 3 particle vertices sensitive to a minimal # of operators, # ~ constant with mass dimension.  Physics with 2-, 3-particle vertices doable to any order in $v/\Lambda$ (tree level)
- Can study select processes to $1/\Lambda^4$, use them to form guidelines for how to include truncation error more generally in SMEFT studies

**Several key processes for global fits already known to** $1/\Lambda^4$

Resonant $2 \to 2$: $gg \to h \to \gamma\gamma,\ pp \to$ Z $\to \bar{f}f$

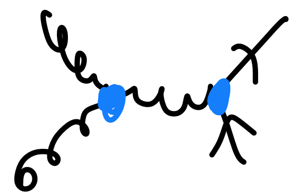
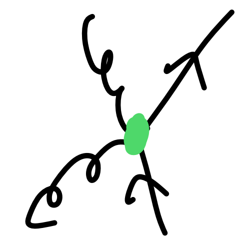
Drell Yan, $pp \to Vh$; diboson in progress

**ready for use/study**

[ex. 2109.05595 AM, Trott]

# So where does this leave us?

## Expanding the list of processes:

$gg \to t\bar{t}$ :  + t,u channel + 

- geoSMEFT pieces have same kinematics at dim 6 and 8

$\therefore$ can capture many effects by reweighing:

In MG already via SMEFTsim/ SMEFT@NLO

$\sigma(SM \times$ **dim-6)**

$$\frac{\textbf{couplings at } 1/\Lambda^4}{\textbf{couplings at } 1/\Lambda^2}$$

Known analytically

- Only need to add contact terms/novel kinematics

**Thank you!**

# Extras

# # operators small and remains ~fixed for increasing mass dimension

| Field space connection | Mass Dimension 6 | 8 | 10 | 12 | 14 |
|---|---|---|---|---|---|
| $k_{IJA}(\phi)(D^\mu\phi)^I(D^\nu\phi)^J\mathcal{W}^A_{\mu\nu}$ | 0 | 3 | 4 | 4 | 4 |
| $f_{ABC}(\phi)\mathcal{W}^A_{\mu\nu}\mathcal{W}^{B,\nu\rho}\mathcal{W}^{C,\mu}_\rho$ | 1 | 2 | 2 | 2 | 2 |
| $Y^u_{pr}(\phi)\bar{Q}u+$ h.c. | $2\,N_f^2$ | $2\,N_f^2$ | $2\,N_f^2$ | $2\,N_f^2$ | $2\,N_f^2$ |
| $Y^d_{pr}(\phi)\bar{Q}d+$ h.c. | $2\,N_f^2$ | $2\,N_f^2$ | $2\,N_f^2$ | $2\,N_f^2$ | $2\,N_f^2$ |
| $Y^e_{pr}(\phi)\bar{L}e+$ h.c. | $2\,N_f^2$ | $2\,N_f^2$ | $2\,N_f^2$ | $2\,N_f^2$ | $2\,N_f^2$ |
| $d^{e,pr}_A(\phi)\bar{L}\sigma_{\mu\nu}e\mathcal{W}^{\mu\nu}_A+$ h.c. | $4\,N_f^2$ | $6\,N_f^2$ | $6\,N_f^2$ | $6\,N_f^2$ | $6\,N_f^2$ |
| $d^{u,pr}_A(\phi)\bar{Q}\sigma_{\mu\nu}u\mathcal{W}^{\mu\nu}_A+$ h.c. | $4\,N_f^2$ | $6\,N_f^2$ | $6\,N_f^2$ | $6\,N_f^2$ | $6\,N_f^2$ |
| $d^{d,pr}_A(\phi)\bar{Q}\sigma_{\mu\nu}d\mathcal{W}^{\mu\nu}_A+$ h.c. | $4\,N_f^2$ | $6\,N_f^2$ | $6\,N_f^2$ | $6\,N_f^2$ | $6\,N_f^2$ |
| $L^{\psi_R}_{pr,A}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,R}\gamma_\mu\sigma_A\psi_{r,R})$ | $N_f^2$ | $N_f^2$ | $N_f^2$ | $N_f^2$ | $N_f^2$ |
| $L^{\psi_L}_{pr,A}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,L}\gamma_\mu\sigma_A\psi_{r,L})$ | $2\,N_f^2$ | $4\,N_f^2$ | $4\,N_f^2$ | $4\,N_f^2$ | $4\,N_f^2$ |

**Example:** $L_{I,A}(\phi)\bar{\psi}_1\gamma^\mu\tau_A\psi_2(D_\mu\phi)^I$

contributing operators

$$\left.\begin{aligned}\mathcal{Q}^{1,(6+2n)}_{\substack{H\psi\\pr}} &= (H^\dagger H)^n H^\dagger\, i\overleftrightarrow{D}^\mu H \bar{\psi}_p\gamma_\mu\psi_r,\\ \mathcal{Q}^{3,(6+2n)}_{\substack{H\psi\\pr}} &= (H^\dagger H)^n\, H^\dagger\, i\overleftrightarrow{D}^\mu_a H \bar{\psi}_p\gamma_\mu\sigma_a\psi_r,\end{aligned}\right\}$$

higher dim. versions of "class 7" operators

$$\left.\begin{aligned}\mathcal{Q}^{2,(8+2n)}_{\substack{H\psi\\pr}} &= (H^\dagger H)^n (H^\dagger\sigma_a H)\, H^\dagger\, i\overleftrightarrow{D}^\mu H \bar{\psi}_p\gamma_\mu\sigma_a\psi_r,\\ \mathcal{Q}^{\epsilon,(8+2n)}_{\substack{H\psi\\pr}} &= \epsilon^a_{bc}\,(H^\dagger H)^n\,(H^\dagger\sigma_c H)\,H^\dagger\, i\overleftrightarrow{D}^\mu_b H \bar{\psi}_p\gamma_\mu\sigma_a\psi_r.\end{aligned}\right\}$$

new effects from $d \geq 8$

compact form for connection:

$$\begin{aligned}L^{\psi,pr}_{J,A} &= -(\phi\,\gamma_4)_J\delta_{A4}\sum_{n=0}^{\infty}\boxed{C^{1,(6+2n)}_{\substack{H\psi\\pr}}}\left(\frac{\phi^2}{2}\right)^n - (\phi\,\gamma_A)_J(1-\delta_{A4})\sum_{n=0}^{\infty}\boxed{C^{3,(6+2n)}_{\substack{H\psi_L\\pr}}}\left(\frac{\phi^2}{2}\right)^n\\ &+ \frac{1}{2}(\phi\,\gamma_4)_J(1-\delta_{A4})\left(\phi_K\Gamma^K_{A,L}\phi^L\right)\sum_{n=0}^{\infty}\boxed{C^{2,(8+2n)}_{\substack{H\psi_L\\pr}}}\left(\frac{\phi^2}{2}\right)^n\\ &+ \frac{\epsilon^A_{BC}}{2}(\phi\,\gamma_B)_J\left(\phi_K\Gamma^K_{C,L}\phi^L\right)\sum_{n=0}^{\infty}\boxed{C^{\epsilon,(8+2n)}_{\substack{H\psi_L\\pr}}}\left(\frac{\phi^2}{2}\right)^n\end{aligned}$$

# What can we do with this? `EW inputs'

Bosonic kinetic terms used to define the gauge boson mass basis

$$W^3_\mu, B_\mu \longrightarrow A_\mu, Z_\mu$$

& couplings to mass eigenstates define: $e, g_Z, \ \sin^2\theta_Z$

$$D_\mu \psi = \left[\partial_\mu + i \bar{g}_3 \mathcal{G}^\mu_{\mathcal{A}} T^{\mathcal{A}} + i \frac{\bar{g}_2}{\sqrt{2}} \left(\mathcal{W}^+ T^+ + \mathcal{W}^- T^-\right) + i \bar{g}_Z \left(T_3 - s^2_{\theta_Z} Q_\psi\right) \mathcal{Z}^\mu + i\, Q_\psi\, \bar{e}\, \mathcal{A}^\mu\right] \psi.$$

SM: $e, g_Z, \ \sin^2\theta_Z$ = functions of $g, g'$ alone

SMEFT: relation altered by operators that feed into kinetic terms:

ex.) $C^{(6)}_{HW} H^\dagger H \, W^A_{\mu\nu} W^{A,\mu\nu}$

$\therefore \ e, g_Z, \ \sin^2\theta_Z$ = function of $g, g', C^{(n)}_i$ coefficients

‘Universal effect’, since all occurrences of $e, \ g_Z, \ \sin^2\theta_Z$ now carry coefficient dependence

# What can we do with this? `EW inputs’

With geoSMEFT setup, can set EW inputs to all orders:

$$e,\ g_Z,\ \sin^2\theta_Z \longrightarrow \text{functions of } g, g', h_{IJ}, g_{AB}$$

$$\left.\begin{aligned}
\bar{g}_2 &= g_2\sqrt{g}^{11} = g_2\sqrt{g}^{22}, \\
\bar{g}_Z &= \frac{g_2}{c^2_{\theta_Z}}\left(c_{\bar\theta}\sqrt{g}^{33} - s_{\bar\theta}\sqrt{g}^{34}\right) = \frac{g_1}{s^2_{\theta_Z}}\left(s_{\bar\theta}\sqrt{g}^{44} - c_{\bar\theta}\sqrt{g}^{34}\right), \\
\bar{e} &= g_2\left(s_{\bar\theta}\sqrt{g}^{33} + c_{\bar\theta}\sqrt{g}^{34}\right) = g_1\left(c_{\bar\theta}\sqrt{g}^{44} + s_{\bar\theta}\sqrt{g}^{34}\right),
\end{aligned}\right\} \text{ couplings}$$

**mixing angles**

$$s^2_{\theta_Z} = \frac{g_1(\sqrt{g}^{44}s_{\bar\theta} - \sqrt{g}^{34}c_{\bar\theta})}{g_2(\sqrt{g}^{33}c_{\bar\theta} - \sqrt{g}^{34}s_{\bar\theta}) + g_1(\sqrt{g}^{44}s_{\bar\theta} - \sqrt{g}^{34}c_{\bar\theta})},$$

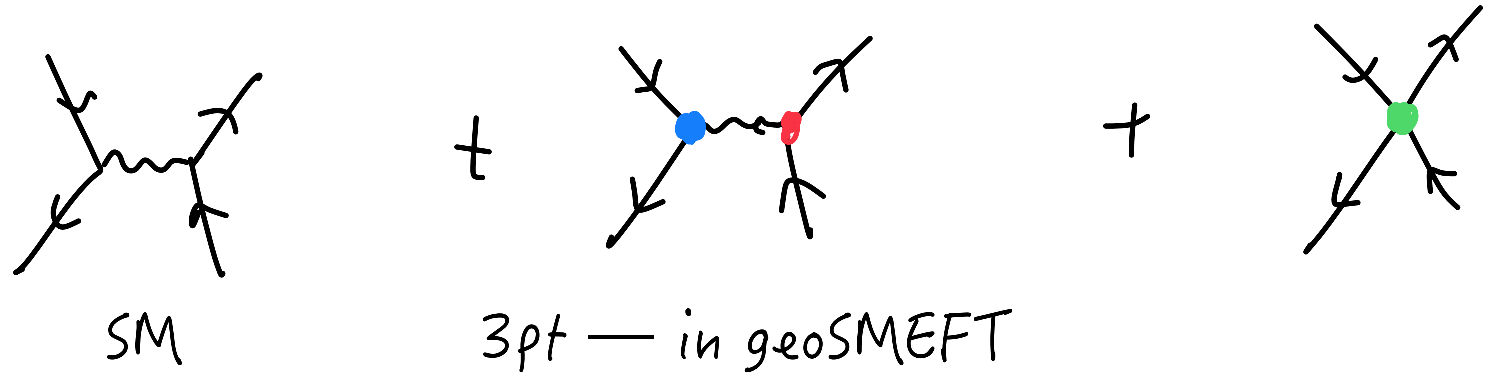
$$s^2_{\bar\theta} = \frac{(g_1\sqrt{g}^{44} - g_2\sqrt{g}^{34})^2}{g_1^2[(\sqrt{g}^{34})^2 + (\sqrt{g}^{44})^2] + g_2^2[(\sqrt{g}^{33})^2 + (\sqrt{g}^{34})^2] - 2g_1g_2\sqrt{g}^{34}(\sqrt{g}^{33} + \sqrt{g}^{44})}.$$

$$\left.\bar{m}_W^2 = \frac{\bar{g}_2^2}{4}\sqrt{h_{11}}^2\,\bar{v}_T^2, \qquad \bar{m}_Z^2 = \frac{\bar{g}_Z^2}{4}\sqrt{h_{33}}^2\,\bar{v}_T^2 \qquad \bar{m}_A^2 = 0.\right\} \text{ masses}$$

[Helset, Martin, Trott 2001.01453]

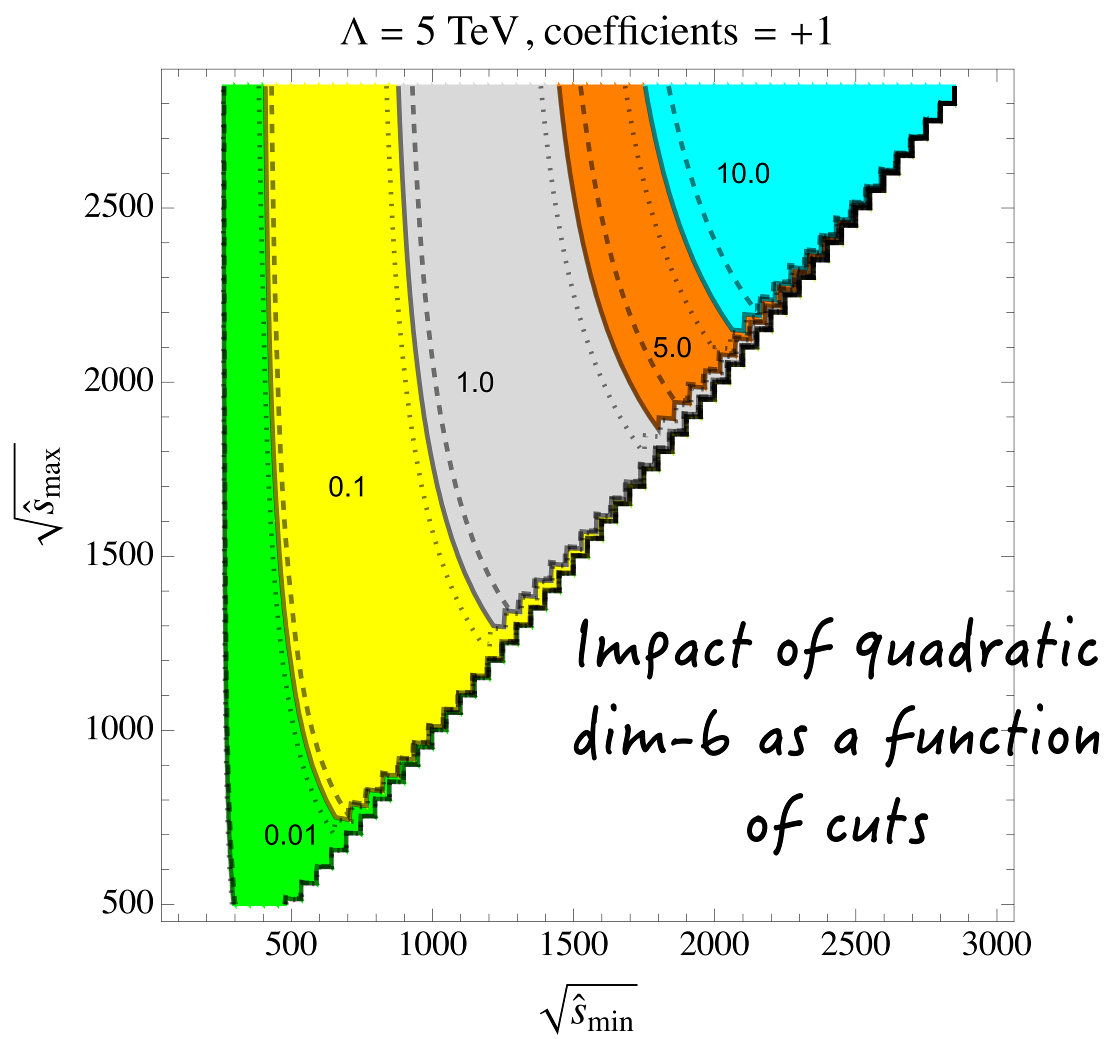
# Ex. $pp \to \ell^+\ell^-, \ell^\pm\nu$ to $\mathcal{O}(1/\Lambda^4)$

[Kim, AM 2203.11976]

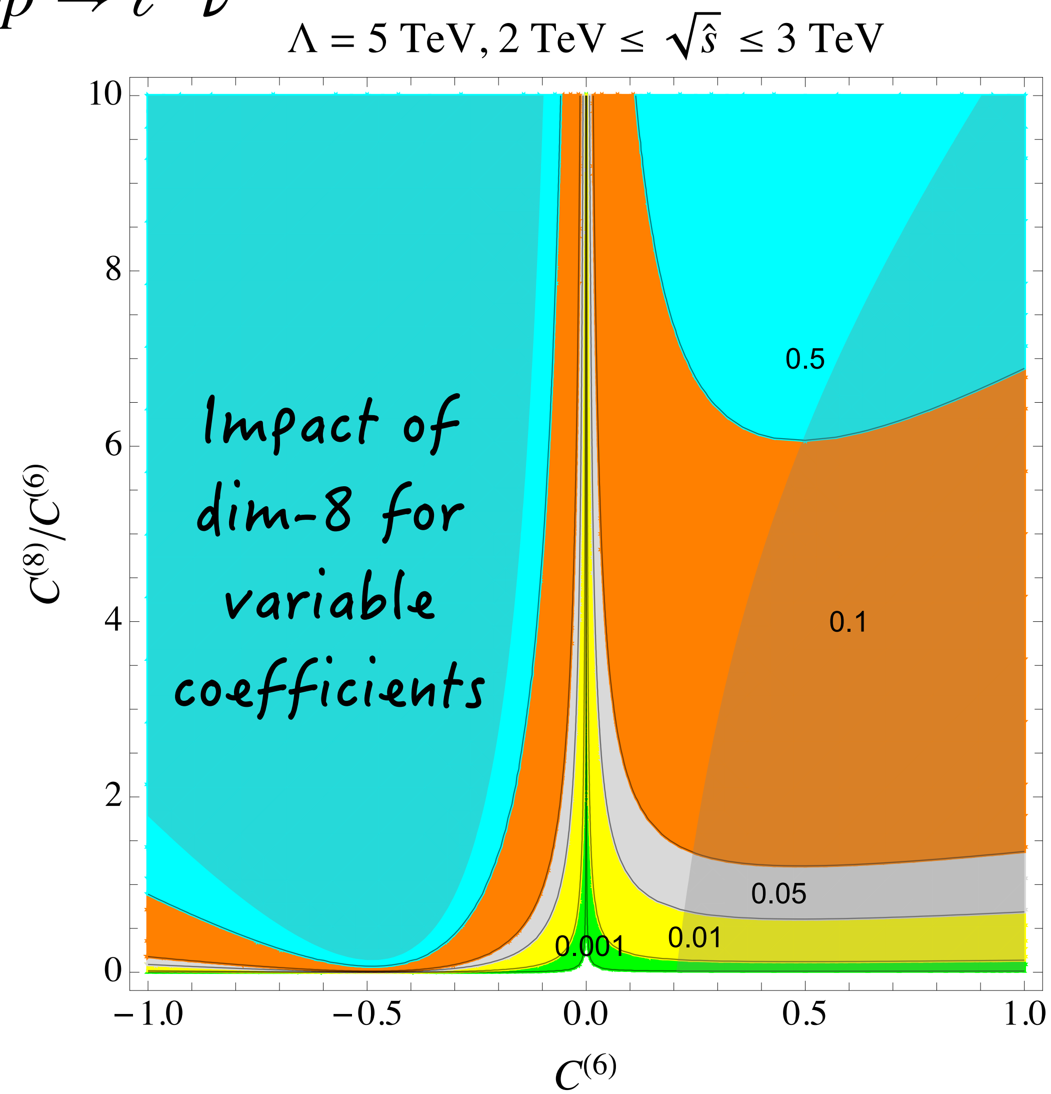



new at 4-pt, $\mathcal{O}(10)$ operators at $1/\Lambda^4$

$pp \to \ell^+\ell^-$

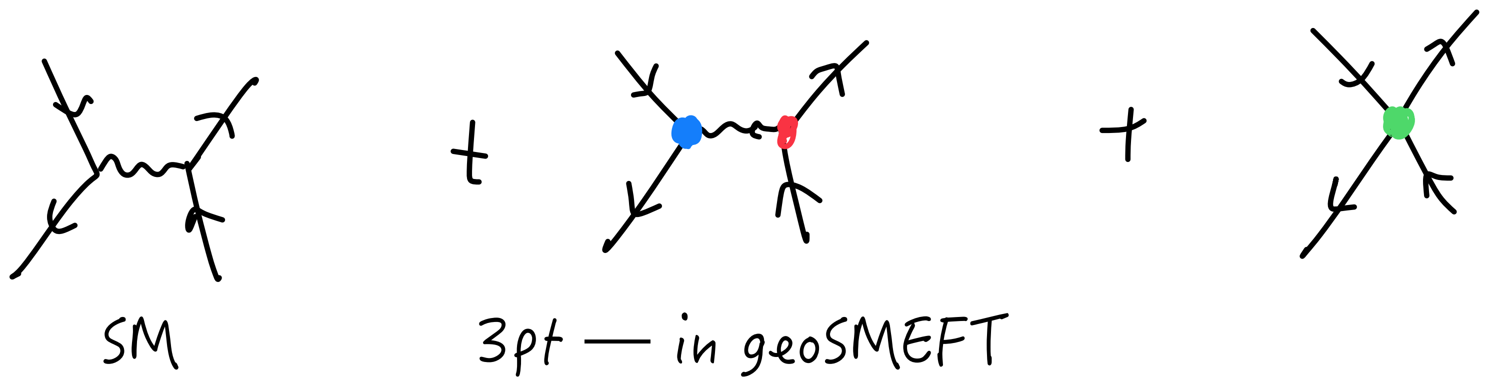



$pp \to \ell^\pm\nu$




[see also Boughezal et al 2106.05337, 2207.01703, Allwicher et al 2207.10714]

# New kinematics from dimension-8




new at 4-pt, $\mathcal{O}(10)$ operators at $1/\Lambda^4$

new spherical harmonics in angular distribution of Drell Yan show up at dimension-8 [2003.1615 Alioli et al]

$$
\begin{aligned}
\mathcal{O}_{8,ed\partial 2} &= (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d),\\
\mathcal{O}_{8,eu\partial 2} &= (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u),\\
\mathcal{O}_{8,ld\partial 2} &= (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d),\\
\mathcal{O}_{8,lu\partial 2} &= (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u),\\
\mathcal{O}_{8,qe\partial 2} &= (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q).
\end{aligned}
$$

$\longrightarrow$

$$
\begin{aligned}
\frac{d\sigma}{dm_{ll}^2\,dy\,d\Omega_l} = \frac{3}{16\pi}\frac{d\sigma}{dm_{ll}^2\,dy}\Big\{&(1+c_\theta^2) + \frac{A_0}{2}(1-3c_\theta^2)\\
&+A_1 s_{2\theta}c_\phi + \frac{A_2}{2}s_\theta^2 c_{2\phi} + A_3 s_\theta c_\phi + A_4 c_\theta\\
&+A_5 s_\theta^2 s_{2\phi} + A_6 s_{2\theta}s_\phi + A_7 s_\theta s_\phi\\
&+B_3^e s_\theta^3 c_\phi + B_3^o s_\theta^3 s_\phi + B_2^e s_\theta^2 c_\theta c_{2\phi}\\
&+B_2^o s_\theta^2 c_\theta s_{2\phi} + \frac{B_1^e}{2}s_\theta(5c_\theta^2-1)c_\phi\\
&+\frac{B_1^o}{2}s_\theta(5c_\theta^2-1)s_\phi + \frac{B_0}{2}(5c_\theta^3-3c_\theta)\Big\}.
\end{aligned}
$$