Precision LHC processes to $\mathcal{O}(1/\Lambda^4)$

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Looking for heavy new physics

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In SMEFT framework

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

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

Determining Λ is THE goal of the SMEFT strategy — it's the scale where you build the next collider

Want to know Λ as well as we can …

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

What's the impact from $1/\Lambda^4$ corrections?

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

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

Why do $1/\Lambda^4$?

- it's a form of uncertainty; 'theory error' on extracted scale Λ

(loop $\times$ $1/\Lambda^2$ vs. $1/\Lambda^4$? Effect changes with energy, so role of $1/\Lambda^4$ different for inclusive xsec vs. high energy bins)

- there are instances where $1/\Lambda^4$ can have an exaggerated impact
    - Hierarchy in coefficients, either from e.g. tree/loop origin or impact of existing constraints
    - Polarization mismatch suppresses $1/\Lambda^2$ interference
    - New kinematics

With **geoSMEFT** organization, can actually calculate $1/\Lambda^4$ without drowning in operators!

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With **geoSMEFT** organization, can actually calculate $1/$
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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

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

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

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

✗ ✓

geoSMEFT:

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

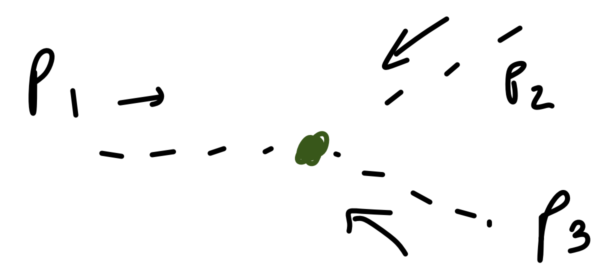
While total # grows exponentially with mass dimension, # operators that can contribute to 2-, 3- particle vertices stays small, nearly constant

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 $H\,\bar{\psi}\,\psi$: not 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 = δ_{IJ} , or triplet.

Can be worked out to all orders in ϕ!

geoSMEFT: Allowed 2, 3-pt structures:

[+ versions with G^A]

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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

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

[Burgess, Lee, Trott '10, Alonso, Jenkins, Manohar '15, '16]

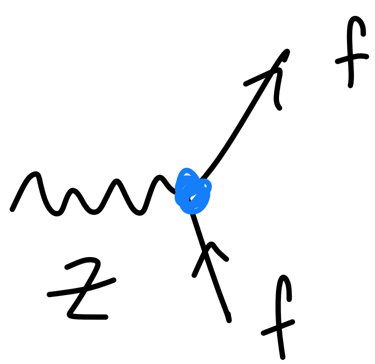
More recently [Cohen et al '22, Cheung et al '21, '22, Helset et al '22]

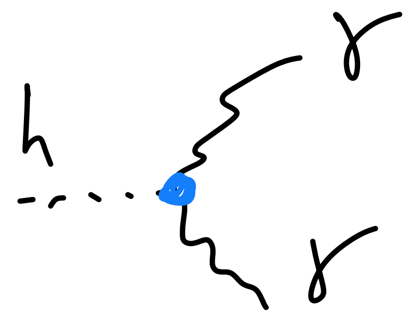
geoSMEFT at work:

SMEFT phenomenology for processes involving 2, 3-pt interactions now doable to any order in v^2/Λ^2

Specifically, $\mathcal{O}(1/\Lambda^4)$ easily calculated for a large set of processes

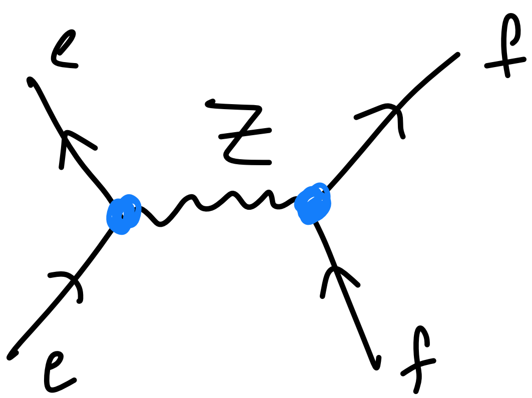
includes



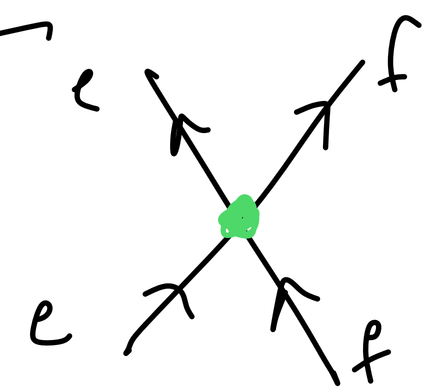


[2007.00565 Hays, Helset, AM, Trott]

and

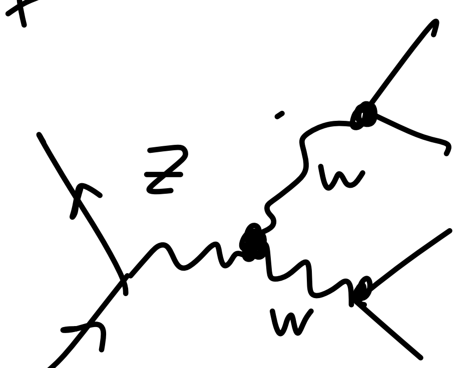


resonant

[

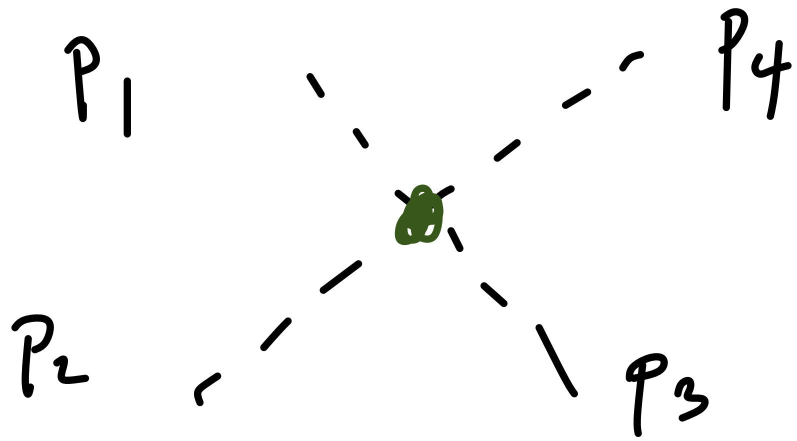
suppressed by $\frac{\Gamma_Z m_Z}{v^2}$]

[2102.02819 Corbett, Helset, AM, Trott]

(also 

!)

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

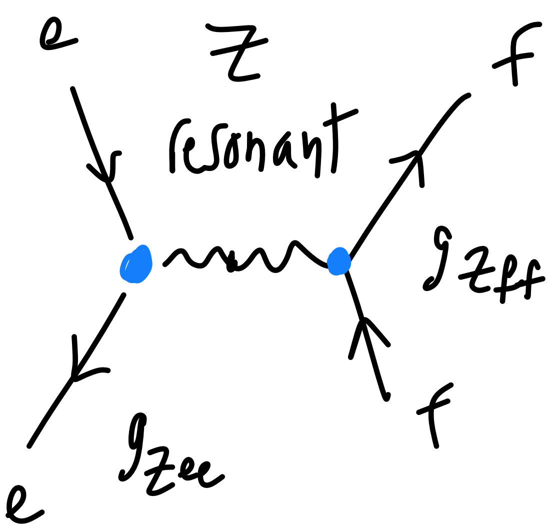
dim-8 effects enter $\mathcal{O}(1/\Lambda^4)$ by interfering with SM, therefore need to match SM helicity/color/flavor structure

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

[though need a 'geoSMEFT compliant basis… neither 2005.00009 Murphy or 2005.00008 Li et al are!]

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



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

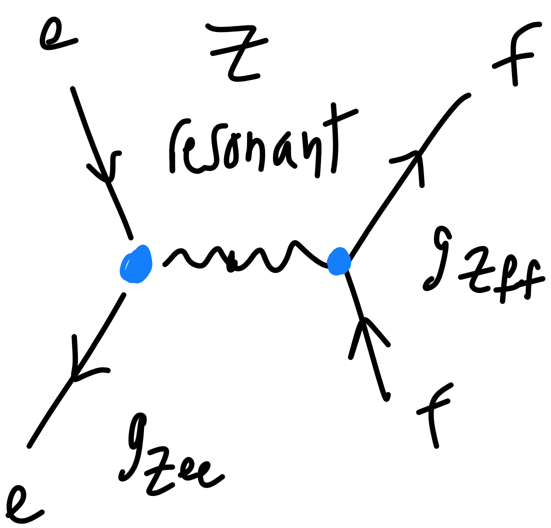
Using:

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

SMEFT corrections in $\{\hat m_W, \hat m_Z, \hat G_F\}/\{\hat\alpha, \hat m_Z, \hat G_F\}$ scheme			
$\mathcal{O}(\frac{v^4}{\Lambda^4})$	$\langle g^{\mathcal{Z},u_R}_{\rm eff,pp}\rangle$	$\langle g^{\mathcal{Z},d_R}_{\rm eff,pp}\rangle$	$\langle g^{\mathcal{Z},\ell_R}_{\rm eff,pp}\rangle$
$\langle g^{\mathcal{Z},\psi}_{\rm eff}\rangle^2$	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
$\tilde C_{HD}\langle g^{\mathcal{Z},\psi}_{\rm eff}\rangle$	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
$\tilde C^{(6)}_{H\psi}\langle g^{\mathcal{Z},\psi}_{\rm eff}\rangle$	-6.7/-5.8	13/12	4.5/3.9
$\tilde C_{HWB}\, \langle g^{\mathcal{Z},\psi}_{\rm eff}\rangle$	3.7/0.26	3.7/0.26	3.7/0.26
$\tilde C_{HW}\, C_{HWB}$	-0.21/0.39	0.10/-0.19	0.31/-0.58
$\tilde C^{(8)}_{HD}$	-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]

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



$$g^{\mathcal{Z},\psi}_{\mathrm{eff,pr}} = \frac{\bar g_Z}{2}\left[(2s^2_{\theta_Z}Q_\psi - \sigma_3)\delta_{pr} + \bar v_T\langle L^{\psi,pr}_{3,4}\rangle + \sigma_3 \bar v_T \langle L^{\psi,pr}_{3,3}\rangle\right]$$
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Using:

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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

$\mathcal{O}(\frac{v^4}{\Lambda^4})$	$\langle g^{\mathcal{Z},u_R}_{\mathrm{eff,pp}}\rangle$	$\langle g^{\mathcal{Z},d_R}_{\mathrm{eff,pp}}\rangle$	$\langle g^{\mathcal{Z},\ell_R}_{\mathrm{eff,pp}}\rangle$
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$\tilde C^{(6)}_{H\psi}\langle g^{\mathcal{Z},\psi}_{\mathrm{eff}}\rangle$	-6.7/-5.8	13/12	4.5/3.9
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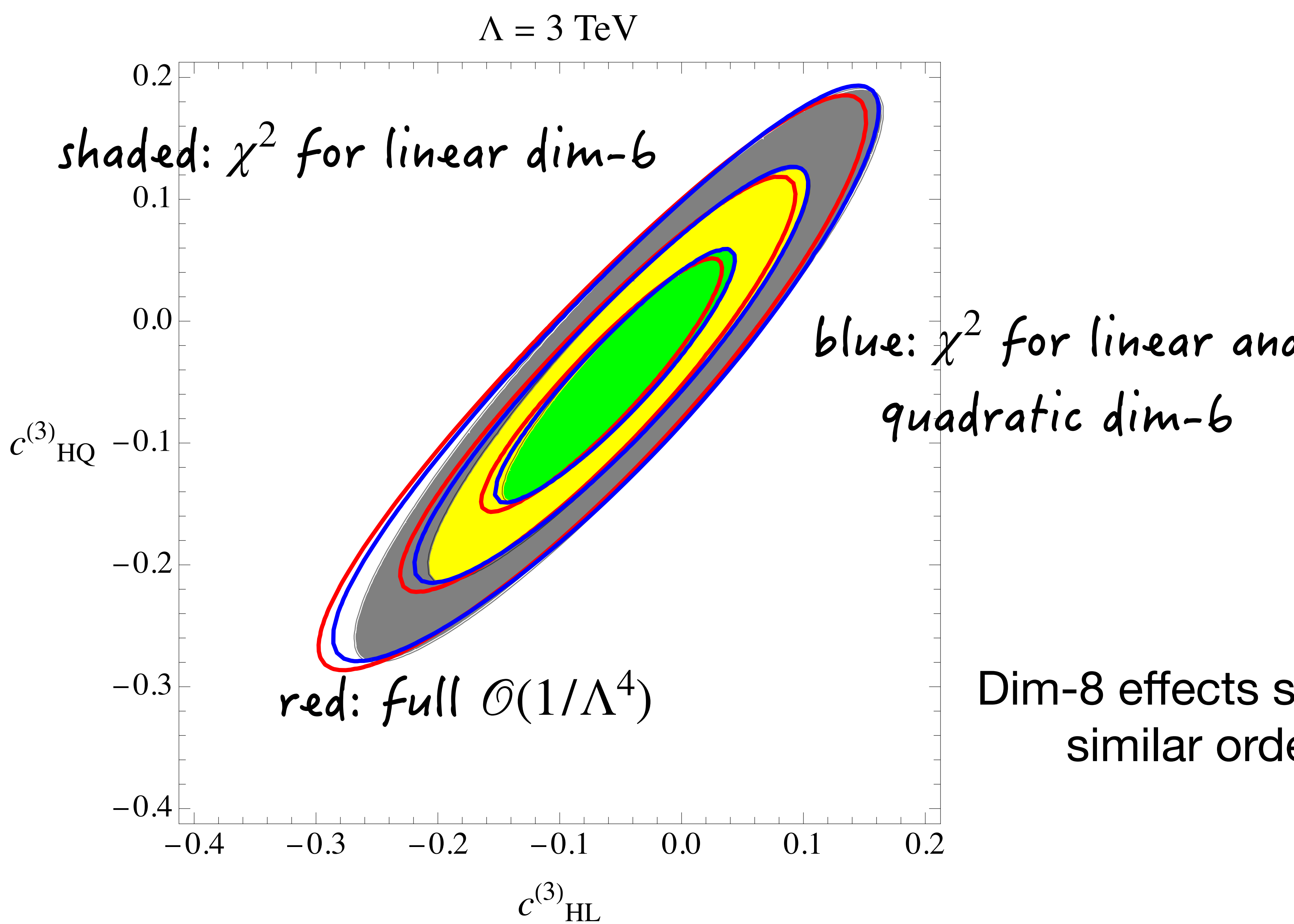
$\tilde C^{(8)}_{H\psi}$	0.19/0.19	0.19/0.19	0.19/0.19
$\tilde C^{(8)}_{HW,2}$	-0.38 [illegible]	[illegible]	[illegible]

[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 Λ, then compare χ^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 $\mathcal{O}(1/\Lambda^2) \times \text{SM loop}$. 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 $\times\, 1/\Lambda^2$

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

[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!

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

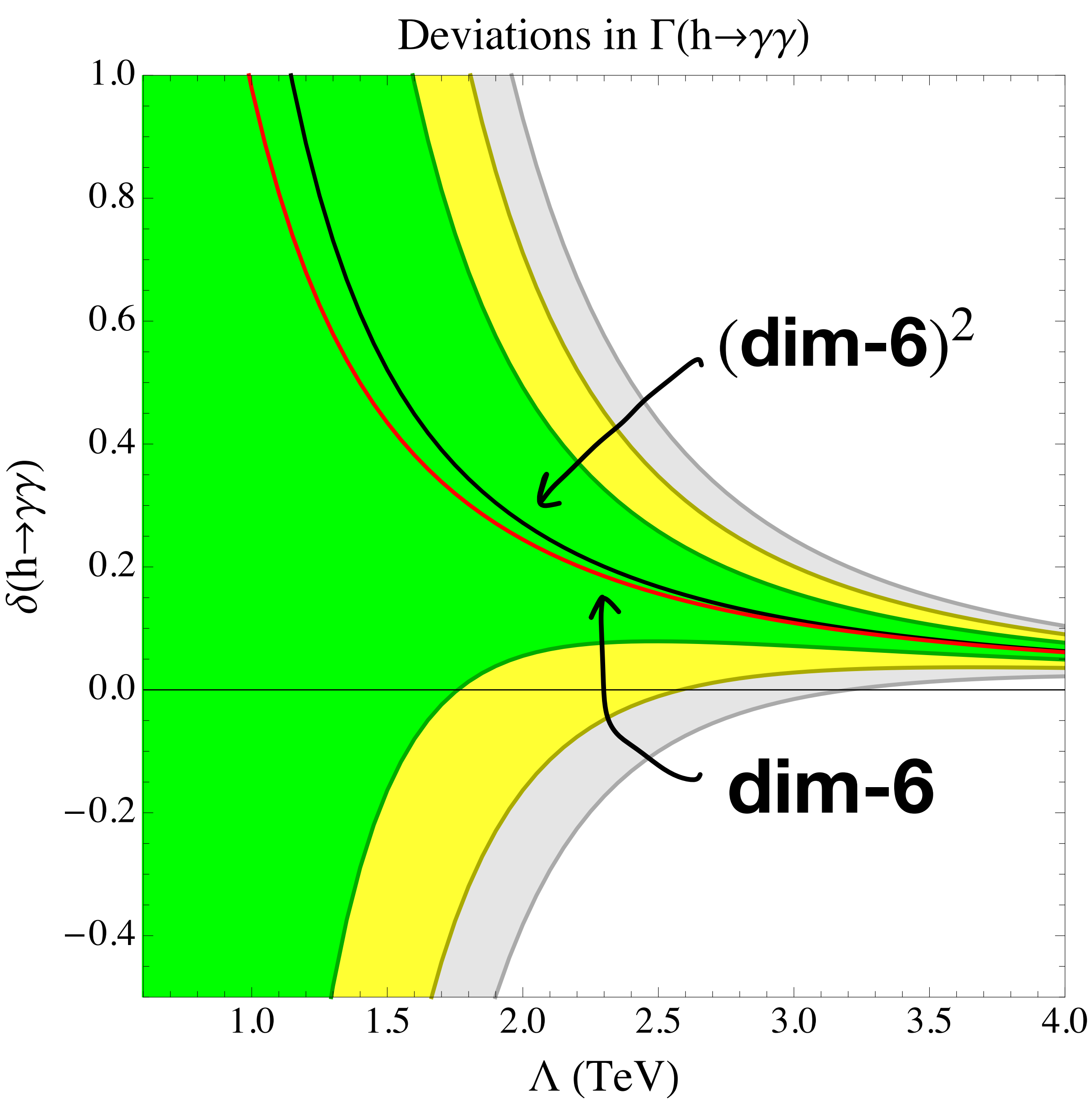
$$\delta G_F^{(6)} = \frac{1}{\sqrt{2}}\left(\tilde{C}^{(3)}_{\substack{Hl\\ee}} + \tilde{C}^{(3)}_{\substack{Hl\\\mu\mu}} - \frac{1}{2}(\tilde{C}'_{\substack{ll\\\mu ee\mu}} + \tilde{C}'_{\substack{ll\\e\mu\mu e}})\right),$$
$$f_1^{\hat{m}_W} = \left[\tilde{C}^{(6)}_{HB} + 0.29\;\tilde{C}^{(6)}_{HW}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

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.

Former are ‘loop-level’, while latter `tree-level’, following classification of [Arzt’93, Craig et al ’20] (weakly coupled UV completion)



Ex.) pick random values, study impact

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

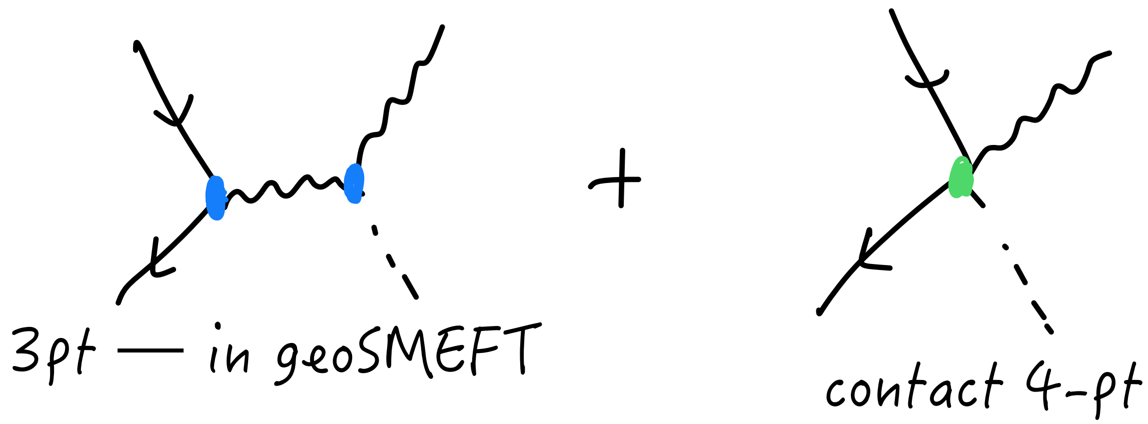
tree = $\mathcal{O}(1)$

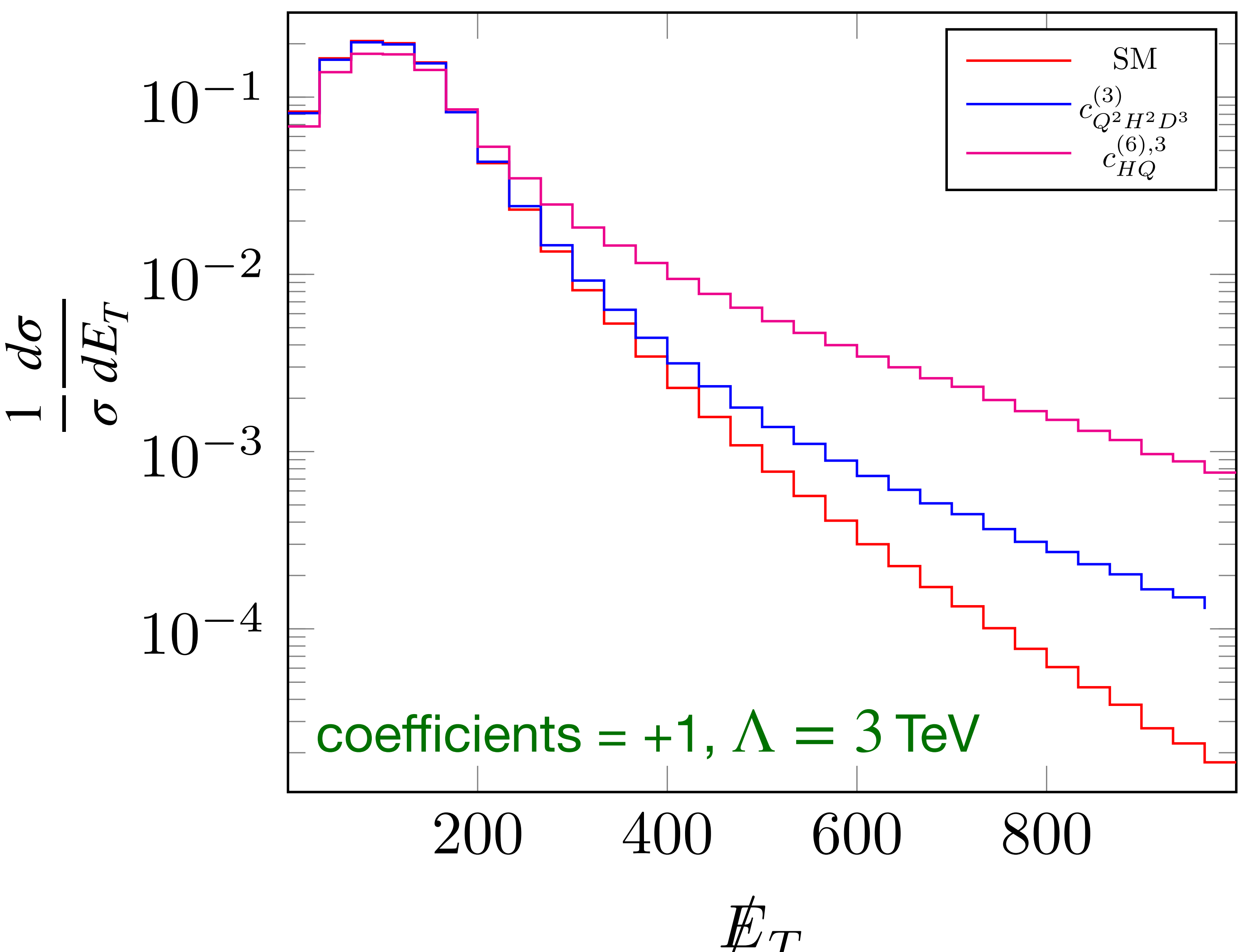
Large effect from dim-8, as coefficient hierarchy compensates for extra powers of v^2/Λ^2

[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 ~ $g^2_{SM} \frac{\hat{s}}{\Lambda^2}$

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

And

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

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

both contribute to V_L polarization, dominant SM piece

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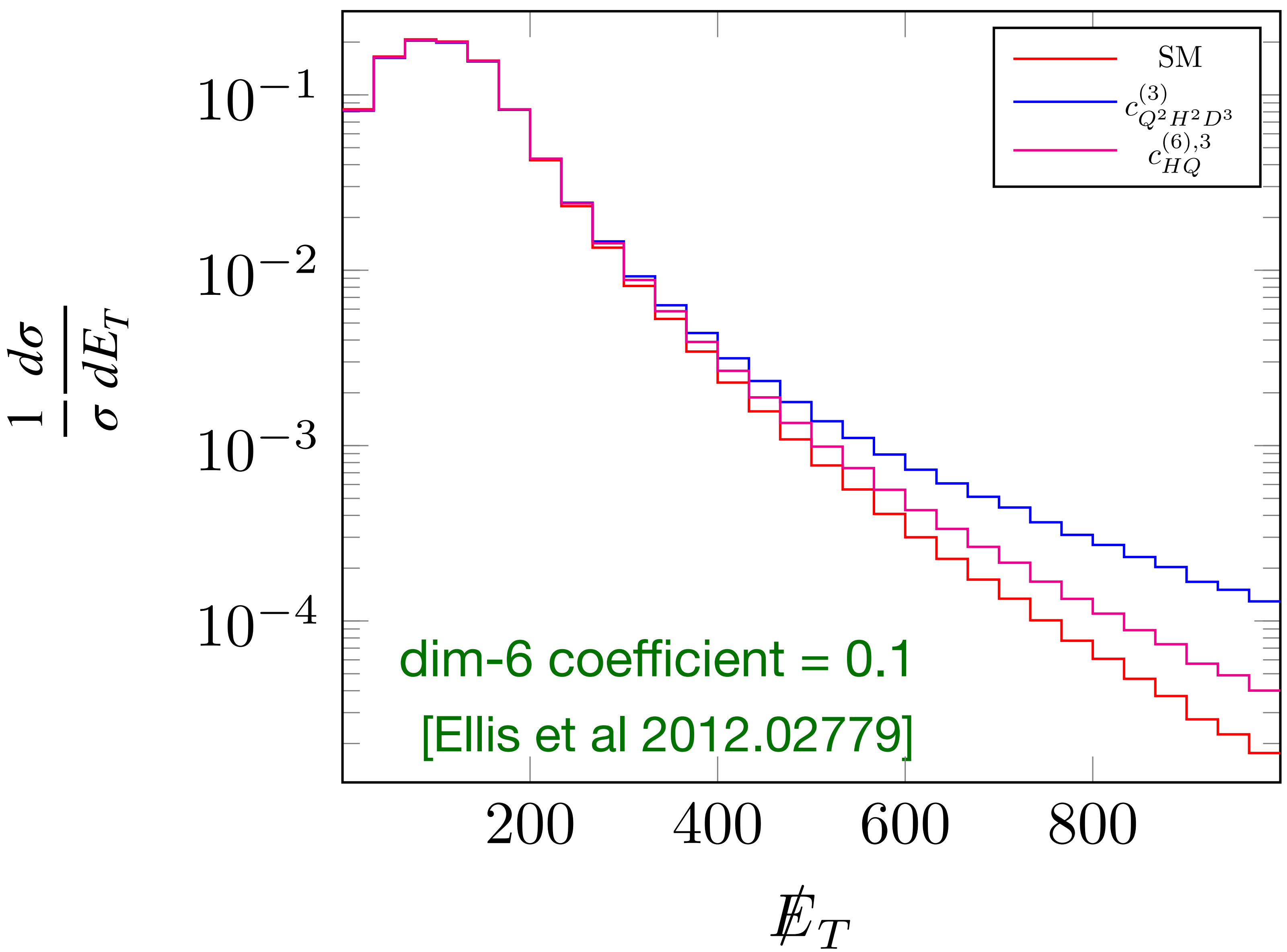
But, $Q^\dagger \bar{\sigma}^\mu \tau^I Q H^\dagger \overleftrightarrow{D}_I H$ etc. are constrained by LEP, while $Q^\dagger \bar{\sigma}^\mu \tau^I D_\nu Q \, D^\mu H^\dagger \tau_I D_{\{\mu,\nu\}} H$ are not

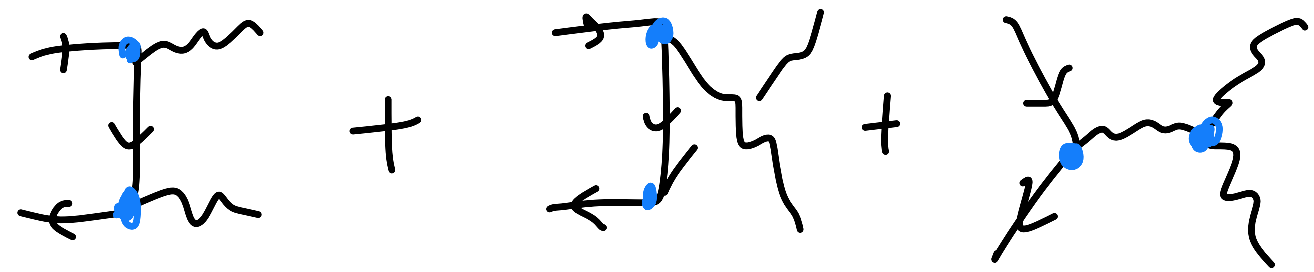


complying with those constraints, large $\hat{s}$ is a window into dim-8

Sneaky large dimension-8 effects: diboson

$\gamma W^{\pm}$

WWW

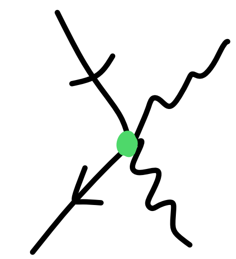


$\epsilon_\gamma \epsilon_W$	SM	dim-6 C_W
$++$	$\frac{v^2}{s}$	$\frac{s}{\Lambda^2}$
$+-$	1	0
$+0$	$\frac{v}{\sqrt{s}}$	$\frac{v\sqrt{s}}{\Lambda^2}$

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



$\gamma W^{\pm}$

WWW $\quad D\psi^2 W^2$

$\epsilon_\gamma \epsilon_W$	SM	dim-6 C_W	dim-8 contact
$++$	$\frac{v^2}{s}$	$\frac{s}{\Lambda^2}$	$\frac{s^2}{\Lambda^4}$
$+-$	1	0	$\frac{s^2}{\Lambda^4}$
$+0$	$\frac{v}{\sqrt{s}}$	$\frac{v\sqrt{s}}{\Lambda^2}$	$\frac{v s^{3/2}}{\Lambda^4}$

See also Degrande 2303.10493

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'

[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/Λ (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 $\to \bar{f}f$

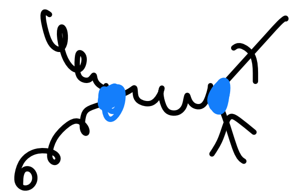
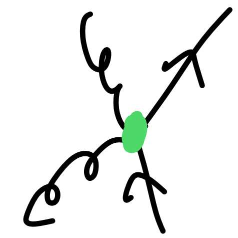
Drell Yan, $pp \to Vh$; diboson in progress

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
∴ 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

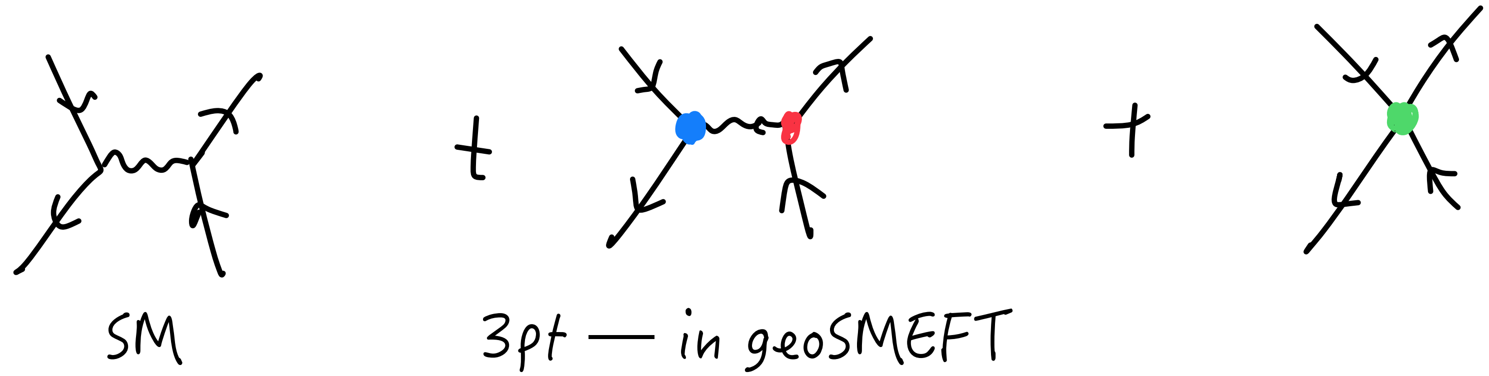
• I've focused on 'bottom up' results, but top down also important
[Dawson et al 2110.06929, 2205.01561, Mimasu et al 2304.06663]

• Interplay with positivity bounds?

Thank you!

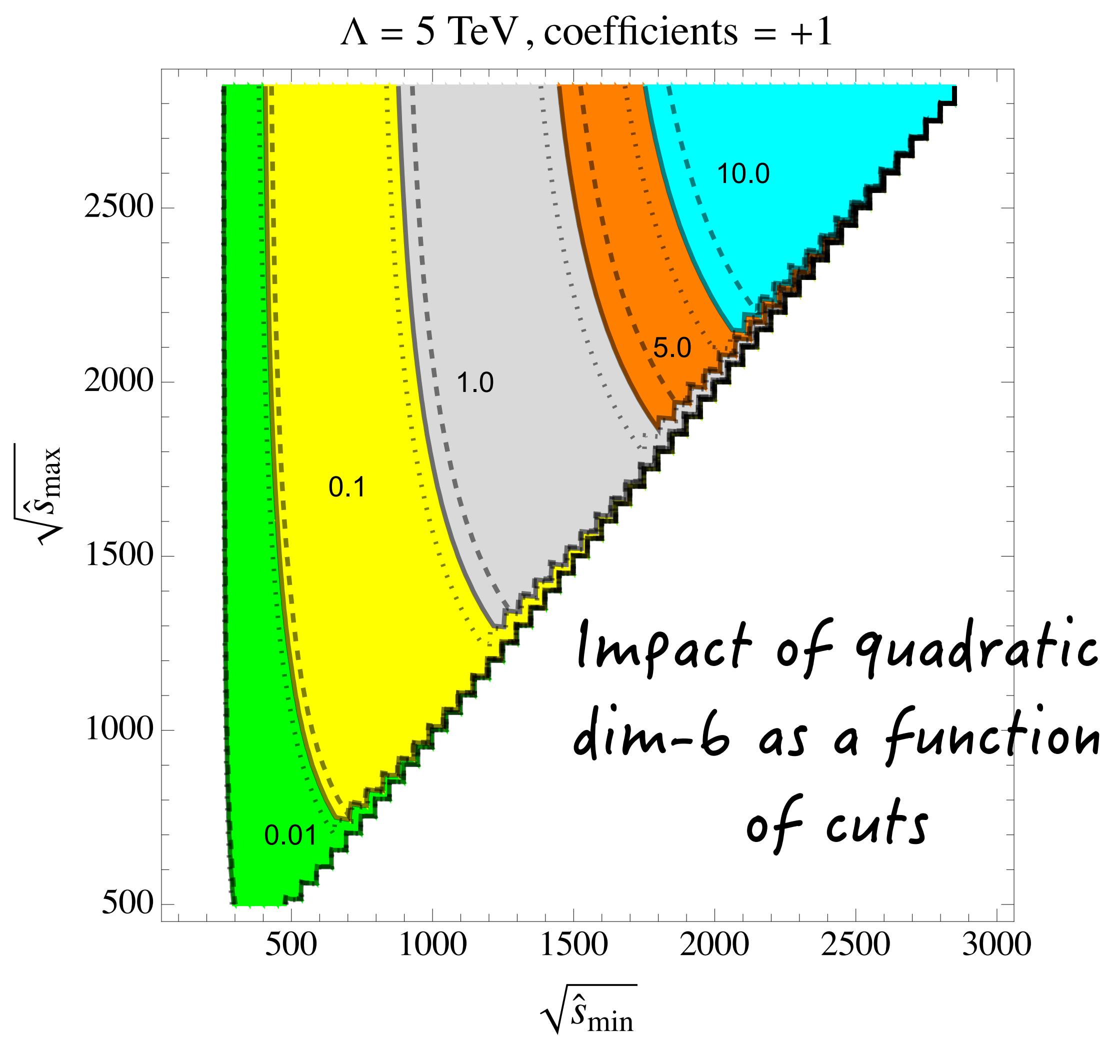
[Kim, AM 2203.11976]

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

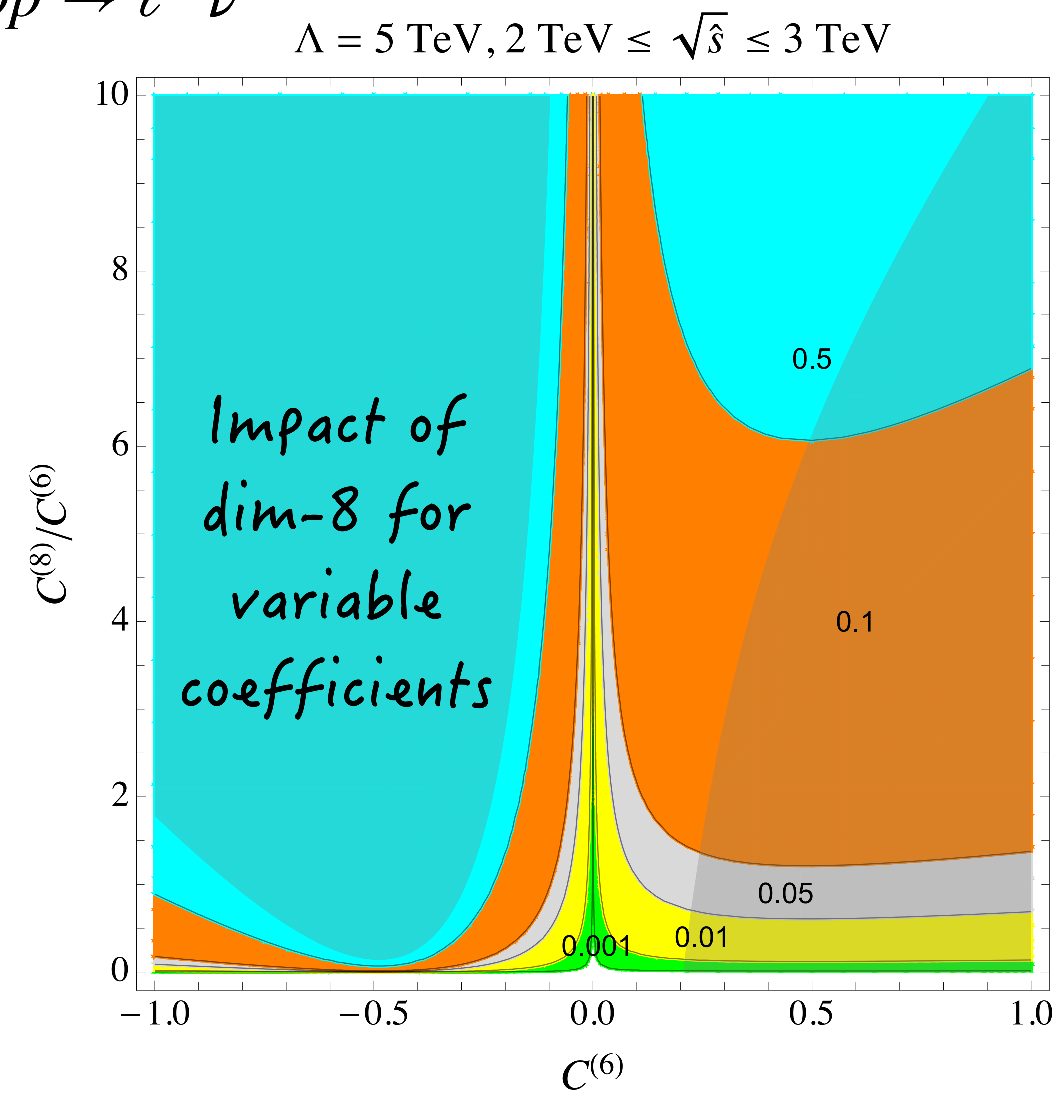


new at 4-pt, $\mathcal{O}(10)$ operators at $1/\Lambda^4$

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

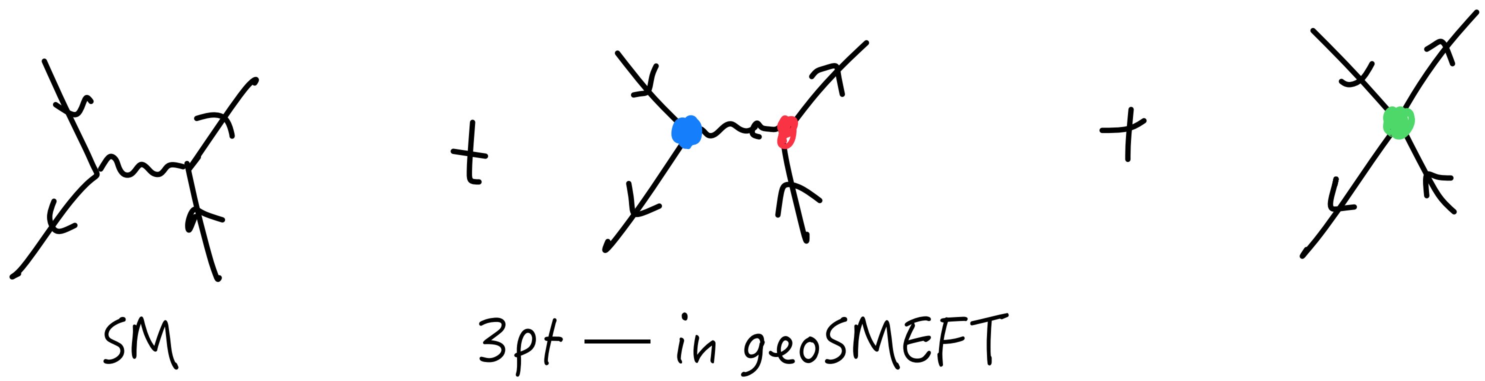


$pp \to \ell^\pm\nu$



[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 $1/\Lambda^4$

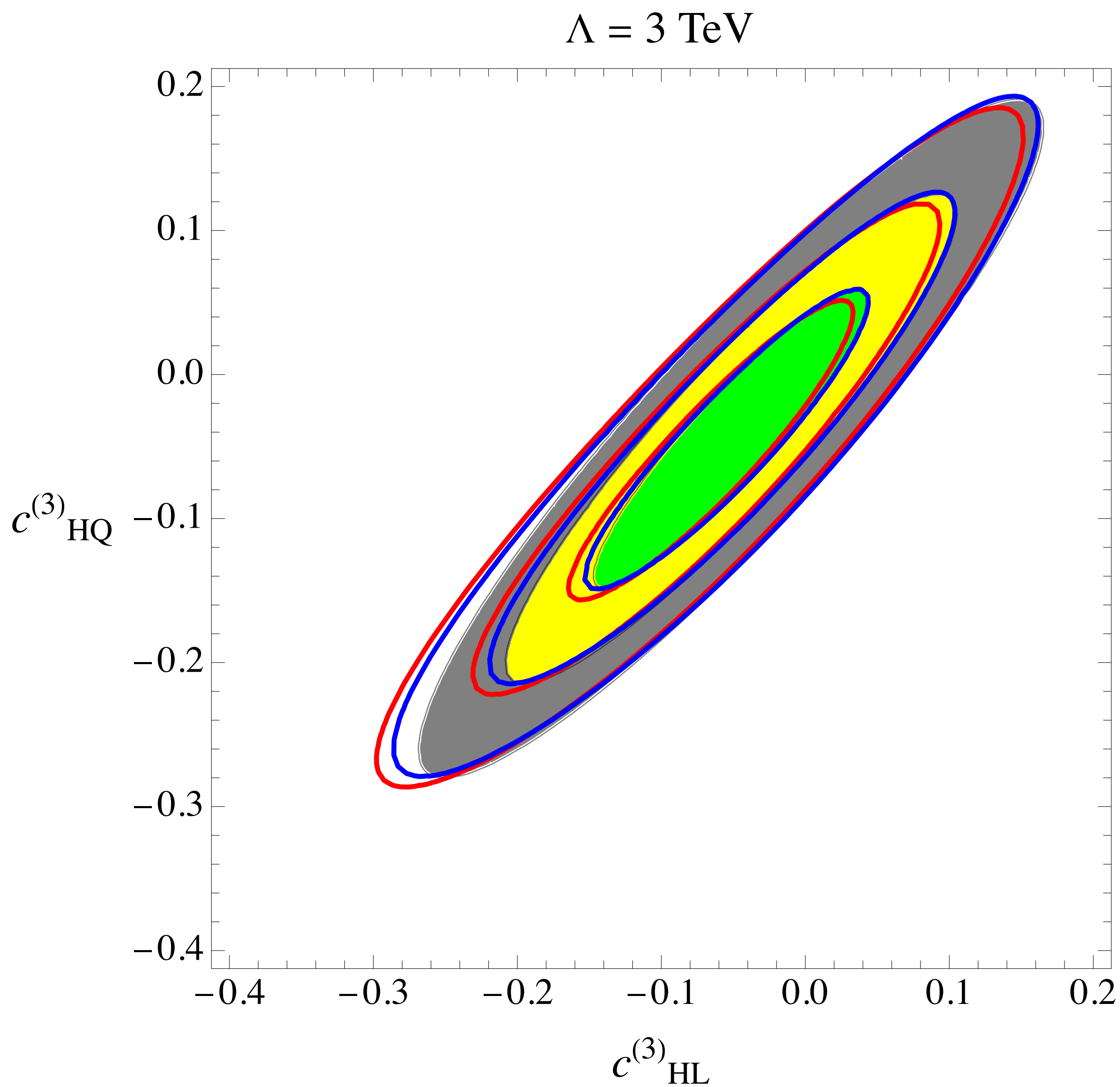
new spherical harmonics in angular distribution of Drell Yan show up at dimension-8 [2003.1615 Alioli et al]

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

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

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 Λ, then compare χ^2 ellipses with and without dimension-8 terms



$$\frac{\delta\chi^2_{quad}}{\chi^2_{lin}} \sim \frac{c^{(6)}v^2}{\Lambda^2}$$

$$\frac{\delta\chi^2_{dim-8}}{\chi^2_{lin}} \sim \frac{g^2_{SM}v^2}{c^{(6)}\,\Lambda^2}$$

Ratio $\sim \frac{(c^{(6)})^2}{g^2_{SM}}$

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

contributing operators

$$\mathcal{Q}^{1,(6+2n)}_{\substack{H\psi\\pr}} = (H^\dagger H)^n H^\dagger \, i\overleftrightarrow{D}^\mu H \bar{\psi}_p\gamma_\mu\psi_r,$$

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

higher dim. versions of "class 7" operators

$$\mathcal{Q}^{2,(8+2n)}_{\substack{H\psi\\pr}} = (H^\dagger H)^n (H^\dagger\sigma_a H) \, H^\dagger \, i\overleftrightarrow{D}^\mu H \bar{\psi}_p\gamma_\mu\sigma_a\psi_r,$$

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

new effects from $d \geq 8$

compact form for connection:

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

What can we do with this? `EW inputs'

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

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

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

couplings

mixing angles

$$\begin{aligned}
s^2_{\theta_Z} &= \frac{g_1(\sqrt{g}^{44} s_{\bar{\theta}} - \sqrt{g}^{34} c_{\bar{\theta}})}{g_2(\sqrt{g}^{33} c_{\bar{\theta}} - \sqrt{g}^{34} s_{\bar{\theta}}) + g_1(\sqrt{g}^{44} s_{\bar{\theta}} - \sqrt{g}^{34} c_{\bar{\theta}})}, \\
s^2_{\bar{\theta}} &= \frac{(g_1 \sqrt{g}^{44} - g_2 \sqrt{g}^{34})^2}{g_1^2[(\sqrt{g}^{34})^2 + (\sqrt{g}^{44})^2] + g_2^2[(\sqrt{g}^{33})^2 + (\sqrt{g}^{34})^2] - 2 g_1 g_2 \sqrt{g}^{34}(\sqrt{g}^{33} + \sqrt{g}^{44})}.
\end{aligned}$$

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

masses

[Helset, Martin, Trott 2001.01453]