GeoSMEFT: recent developments

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Motivation: In SMEFT framework

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_d \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}(Q, u_c, d_c, L, e_c, H, D_\mu, F_{\mu\nu} \cdots)$$

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

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

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

Dual expansion: need to match dimensions, so numerator ~ powers of $v, \partial_\mu \sim E$

$A_6(v^2, vE, E^2;\ c_i)$ $A_8(v^4, v^2E^2, \cdots\ E^4;\ c_i)$

Motivation: In SMEFT framework

At high energy $\left(\frac{E^n}{\Lambda^n}\right) > \left(\frac{v^n}{\Lambda^n}\right)$:

Assuming Wilson coefficients similar size, operators/ coefficients with energy-dependent contributions will dominate in kinematic tails

big advantage of SMEFT at LHC

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

- To know error on $1/\Lambda^2$ piece, we should know next order…
- Additionally, there are circumstances where interference is suppressed. Then $1/\Lambda^4$ is the leading SMEFT piece
- Top down: $1/\Lambda^2$ fails to capture some UV models

[Dawson et al 2305.0789, Ellis et al 2304.06663]

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

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

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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 $\mathcal{O}(1/\Lambda^4)$ …

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

Especially dangerous if $|\text{dim} - 6|^2 > SM \times (\text{dim} - 6)$
without a good reason!!

geoSMEFT-ist perspective

[2001.01453 Helset, AM, Trott]

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. Clarifies E vs. v counting

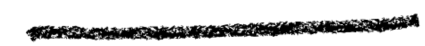
Calculate away, forming a library of process to use as a laboratory to study ‘truncation error’.

geoSMEFT

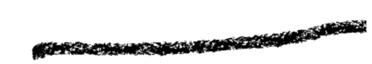
[2001.01453 Helset, AM, Trott]

Organize operators by the smallest vertex (# of particles that enter) they can impact at tree level: 2, 3,4, etc. Minimize the # of operators affecting 2, 3-particle vertices by strategically placing derivatives (IBP)

- $(H^\dagger D_\mu H)^*(H^\dagger D^\mu H) \supset v^2\,(\partial_\mu h)^2$ contributes to 2-particle vertex



$(\psi^\dagger \psi)^2$ contributes to 4-particle vertex

- $\Box\,(H^\dagger H)\,\Box\,(H^\dagger H) \supset v^4\,(\partial_\mu h)^2$ would contribute to 

but can use IBP to manipulate to

$(D_\mu H^\dagger\, D^\mu H\, D_\nu H^\dagger\, D^\nu H)$ which only affects 4+ particle vertices

At dimension-6, assuming B,L, flavor universal (59 total)

Min vertex:

Operator type:
[X = field strength,
D = deriv]

H^6	X^3	ψ^4	
$H^4 D^2$	$\psi^2 H X$		
$H^2 X^2$	$\psi^2 H^2 D$		
$\psi^2 H^3$			

Number: 14 20 25 0

At dimension-8, assuming B,L, flavor universal (993 total)

Min vertex:

Operator type: [X = field strength, D = deriv]	H^8	H^2X^3	X^4	$\psi^4 X$
	H^6D^2	$\psi^2 H^3 X$	H^4D^4	
	H^4X^2	$\psi^2 H^4 D$	$X^2H^2D^2$	
	$\psi^2 H^5$	H^4D^2X	...	
Number:	**19**	**47**	**927!**	

At dimension-8, assuming B,L, flavor universal (993 total)

Min vertex:

Operator type:
[X = field strength,
D = deriv]

H^8	H^2X^3	X^4	$\psi^4 X$
H^6D^2	ψ^2H^3X	H^4D^4	
H^4X^2	ψ^2H^4D	$X^2H^2D^2$	
ψ^2H^5	H^4D^2X	...	

Number: **19** **47** **927!**

If we also impose CP, U(3)⁵ (remember, must interfere to enter $1/\Lambda^4$)

8 **22**

[trend continues to dim > 8 too!]

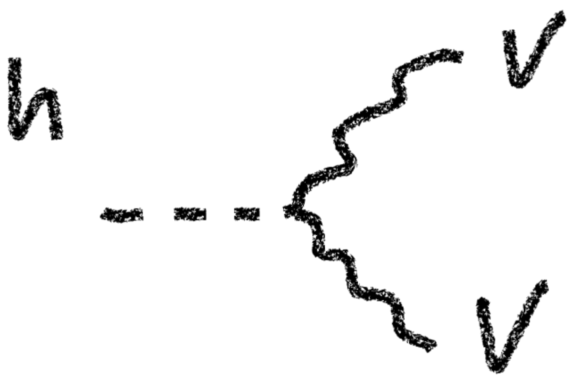
Why is this a good idea?

- “Universal” corrections related to inputs ~ O(10) new operators. Simplest building block vertices ~ O(20) ops

- Bulk of operators pushed to more process-specific, 4+-particle interactions

- 2-, 3- particle interactions: going from dim-6 to dim-8 doesn’t change kinematics — just added additional H^2! Additional derivatives aren’t possible, as all momentum products reduce to masses = constants. So the energy/vev scaling of these terms is set by whatever happens at dim-6

Ex.)



$$\sim \frac{E^2\, v}{\Lambda^2} \text{ at dim-6} \qquad \sim \frac{E^2\, v}{\Lambda^2}\left(\frac{v^2}{\Lambda^2}\right) \text{ at dim-8}$$

$$H^\dagger H X_{\mu\nu} X^{\mu\nu} \qquad (H^\dagger H)^2\, X_{\mu\nu} X^{\mu\nu}$$

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- 2-, 3- particle interactions: going from dim-6 to dim-8 doesn't change kinematics — just added additional H^2! Additional derivatives aren't possible, as all momentum products reduce to masses = constants. So the energy/vev scaling of these terms is set by whatever happens at dim-6

So, if we're hunting for energy enhanced effects —> energy enhanced dim-6 3-particle + dim-6, dim-8 contact vertices only

What's with the name?

operators in 2-particle, 3-particle class saturate, form can be determined to all orders , e.g $h(H^\dagger, H)\, D^\mu H^\dagger D_\mu H$.

In terms of real Higgs d.o.f. $h_{IJ}(\phi)\left(D_\mu\phi\right)^I\left(D_\mu\phi\right)^J$ = a metric on field space

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

SM, $h_{IJ} = \mathbf{1} \rightarrow$ flat space, SMEFT $h_{IJ} \neq \mathbf{1} \rightarrow$ curved { 'geometric' SMEFT or `geoSMEFT'

Connects to larger work on geometry of EFT: Active research area!

[Alonso, Jenkins, Manohar '15, '16] [Helset et at 1803.08001] [Cohen et al 2202.06965]

[Helset et al 2210.08000] [Cheung et al 2202.06972] [Assi et al 2307.03187]

[Alminawi et al 2308.00017] + several others

Ok, what do I do with this?

1.) Simplest LHC processes: resonances, 2 -> 2 can be done 'fully' to $\mathcal{O}(1/\Lambda^4)$ without an order of magnitude increase in operators

$gg \to h \to \gamma\gamma, \gamma Z$ Z-pole, Drell-Yan $pp \to V(\ell\ell)\, h$

$pp \to W(\ell\nu)\, \gamma$

[Kim, AM 2203.11976] [Boughezal et al 2106.05337, 2207.01703

[Corbett, AM, Trott 2107.07470] [AM, Trott 2305.05879] [Hays, Helset, AM, Trott 2007.00565]

For these, can use $\mathcal{O}(1/\Lambda^4)$ as an uncertainty on extraction of dim-6 operators [how to do this systematically?]

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For these, can use $\mathcal{O}(1/\Lambda^4)$ as an uncertainty on extraction of dim-6 operators [how to do this systematically?]

2.) Initial step: focus on terms that grow with energy (fully, to $\mathcal{O}(1/\Lambda^4)$). Assuming all WC are same size, these effects will be largest

$pp \to W^+W^-, W^\pm Z$ $VBF\, pp \to hjj$

[2303.10493 Degrande] [Assi,AM in prep]

geoSMEFT applications: $h \to \gamma\gamma$

Can combine SM loops x $\mathcal{O}(1/\Lambda^2)$ with $\mathcal{O}(1/\Lambda^4)$

$1/\Lambda^2$

Only 4 dim-8 operators needed!

$1/\Lambda^4$

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

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

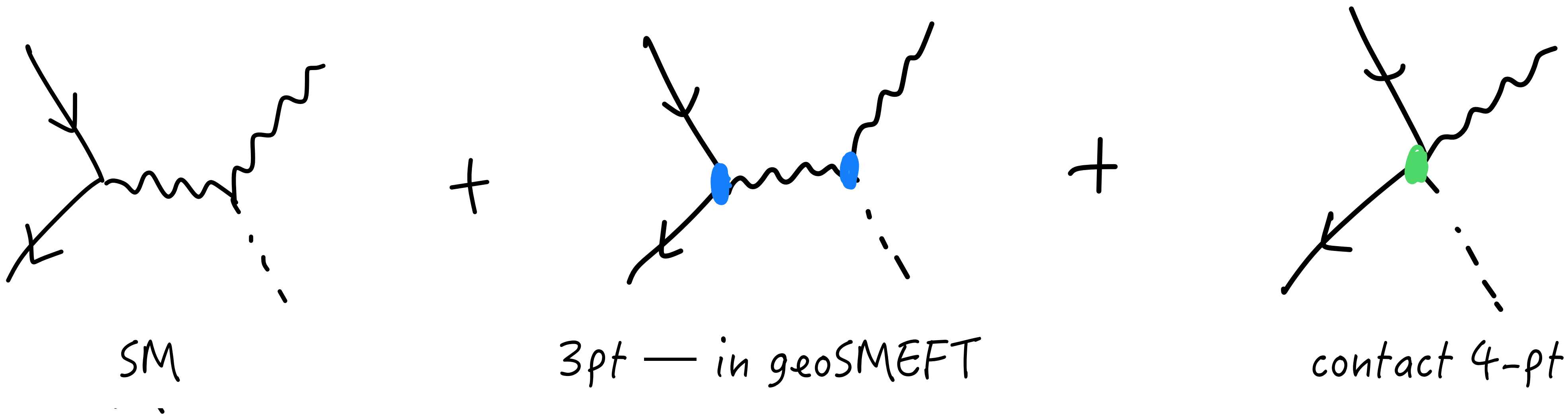
$$
\begin{aligned}
\delta G_F^{(6)} &= \frac{1}{\sqrt{2}} \left(\tilde{C}^{(3)}_{\substack{Hl \\ ee}} + \tilde{C}^{(3)}_{\substack{Hl \\ \mu\mu}} - \frac{1}{2} (\tilde{C}'_{\substack{ll \\ \mu e e \mu}} + \tilde{C}'_{\substack{ll \\ e \mu\mu e}}) \right), \\
f_1^{\hat{m}_W} &= \left[\tilde{C}^{(6)}_{HB}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

Combined result informs on how assumptions about coefficients affect uncertainty

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

Do I gain something vs. using |dim-6|²

Example: VH



Energy enhanced effects

dim-6: vertex $H^\dagger H\, W_{\mu\nu} W^{\mu\nu}$

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

dim-8: contact $\psi^2 H^2 D^3 \supset (Q^\dagger \sigma^\mu D^\nu Q)(D^\mu H^\dagger D_\nu H)$

$\psi^2 H^2 X\, D \supset (Q^\dagger \bar{\sigma}^\mu Q) D^\nu (H^\dagger H) B_{\mu\nu}$

[2306.00053 Corbett, AM]

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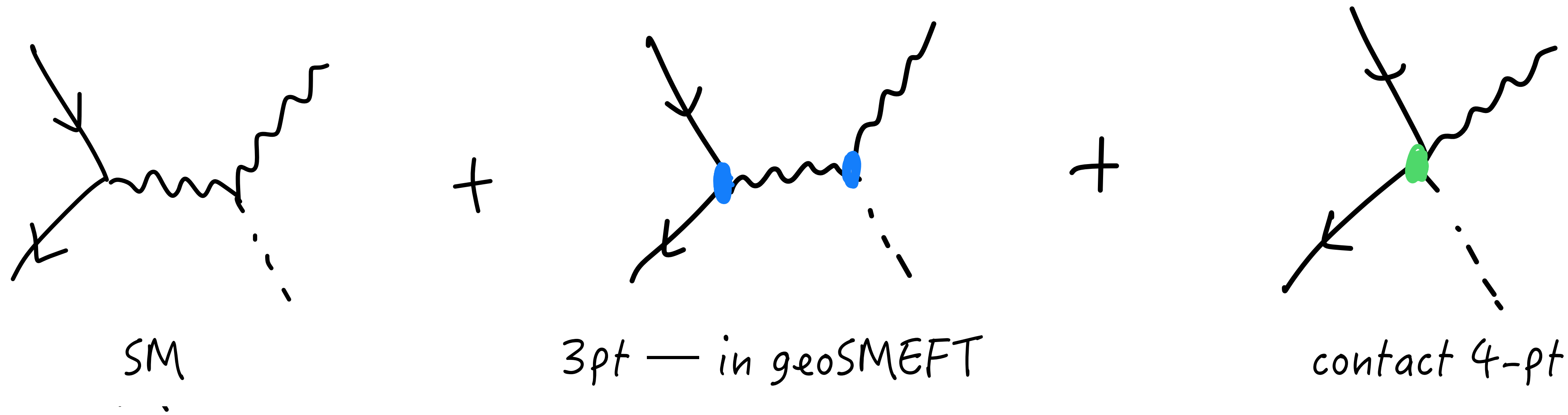

Energy enhanced effects

dim-6: vertex ~~$H^\dagger H W_{\mu\nu} W^{\mu\nu}$~~

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

SM dominantly V_L, suppressed interference with these!

dim-8: contact $\psi^2 H^2 D^3 \supset (Q^\dagger \sigma^\mu D^\nu Q)(D^\mu H^\dagger D_\nu H)$

~~$\psi^2 H^2 X D \supset (Q^\dagger \bar{\sigma}^\mu Q) D^\nu (H^\dagger H) B_{\mu\nu}$~~

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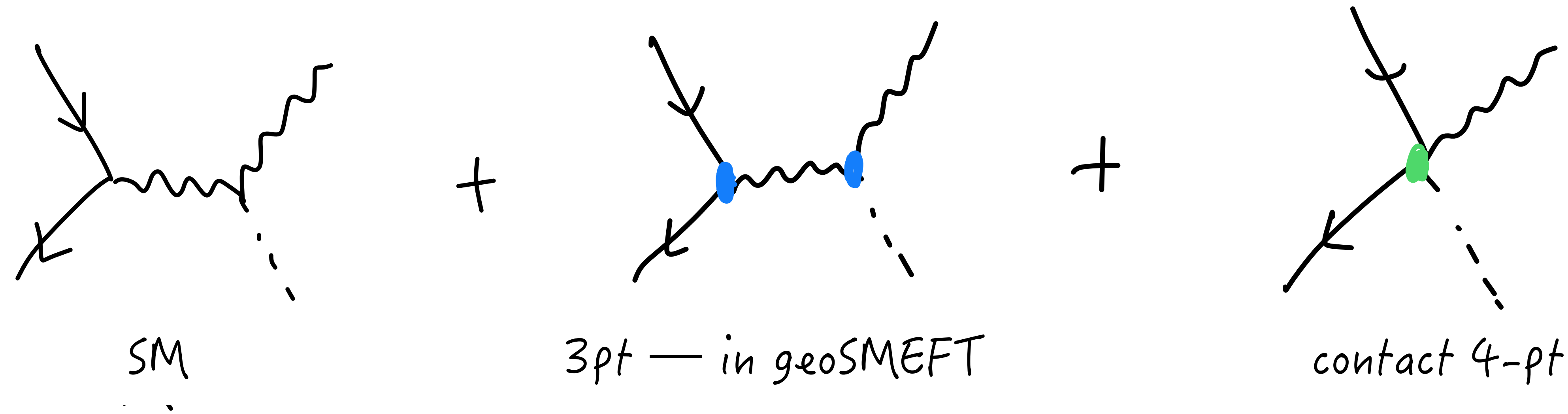
Example: VH



Energy enhanced effects

dim-6: vertex ~~$H^\dagger H\, W_{\mu\nu} W^{\mu\nu}$~~

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

interference $\sim g_{SM}^2\, c_6 \dfrac{\hat s}{\Lambda^2}$

squared $\sim c_6^2 \dfrac{\hat s^2}{\Lambda^4}$

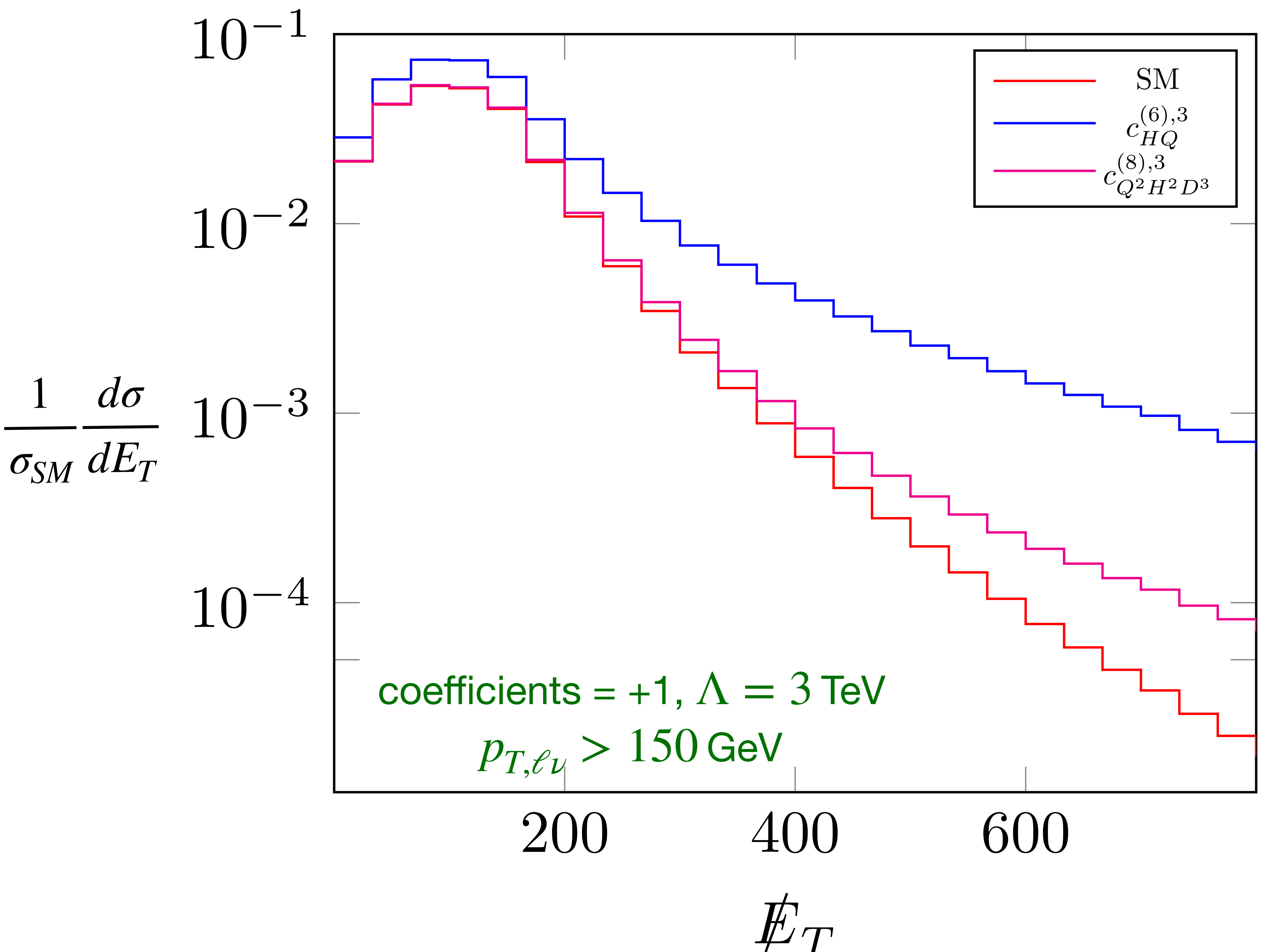
dim-8: contact $\psi^2 H^2 D^3 \supset (Q^\dagger \sigma^\mu D^\nu Q)(D^\mu H^\dagger D_\nu H)$

~~$\psi^2 H^2 X D \supset (Q^\dagger \bar\sigma^\mu Q) D^\nu (H^\dagger H) B_{\mu\nu}$~~

interference $g_{SM}^2\, c_8 \dfrac{\hat s^2}{\Lambda^4}$

Do I gain something vs. using |dim-6|²

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

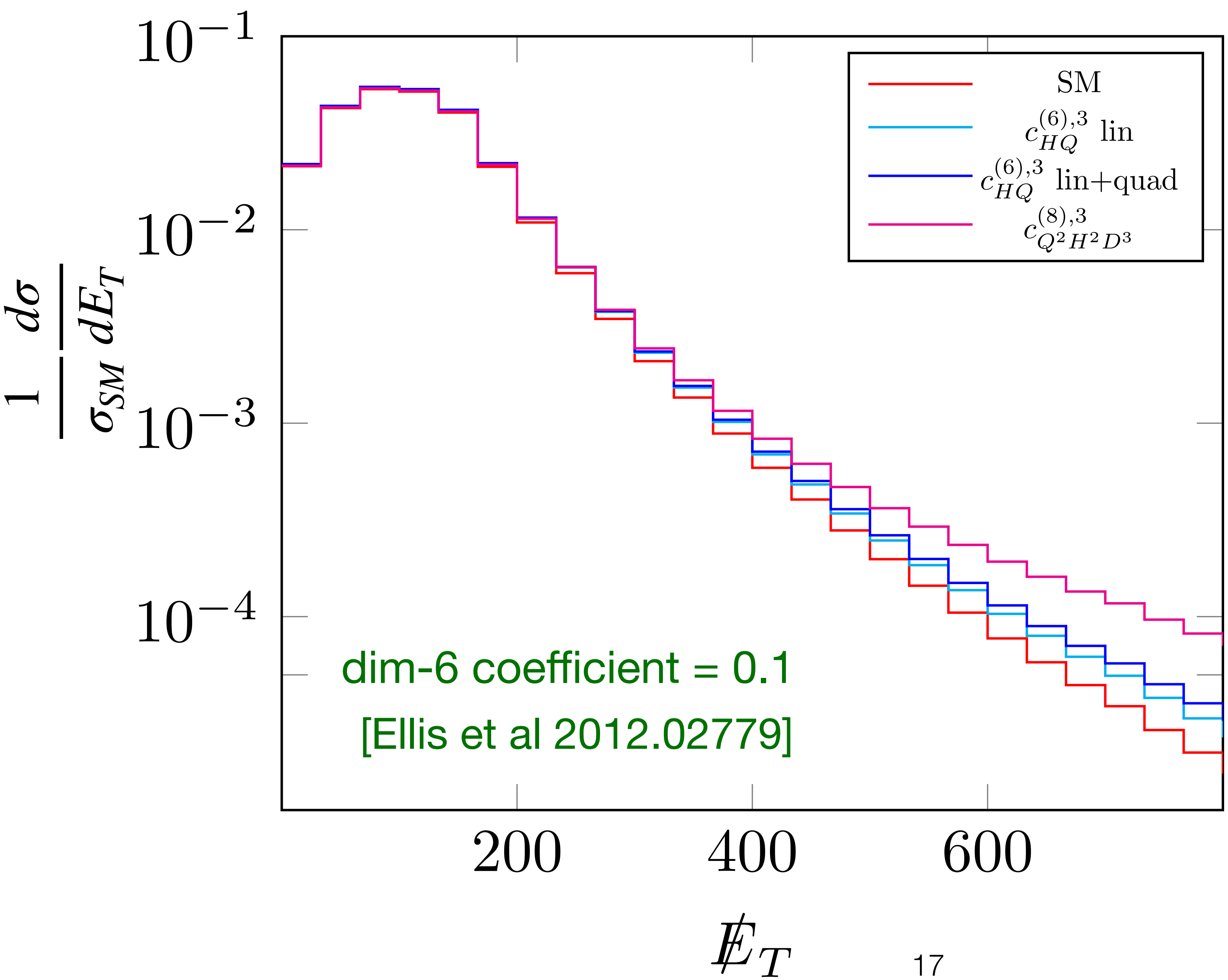


$(Q^\dagger \bar{\sigma}^\mu \tau^I Q)\, H^\dagger \overleftrightarrow{D}_\mu \tau^I H$

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

Do I gain something vs. using |dim-6|²

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



complying with those constraints, dim-8 terms have $\mathcal{O}(1)$ effect at high energy

$$\frac{\textbf{dim-8}}{\textbf{dim-6}} \sim \frac{1}{c_6}\left(\frac{\hat{s}}{\Lambda^2}\right)$$

[while $\frac{\textbf{dim-10}}{\textbf{dim-8}} \sim \left(\frac{\hat{s}}{\Lambda^2}\right)$]

Do I gain something vs. using |dim-6|²

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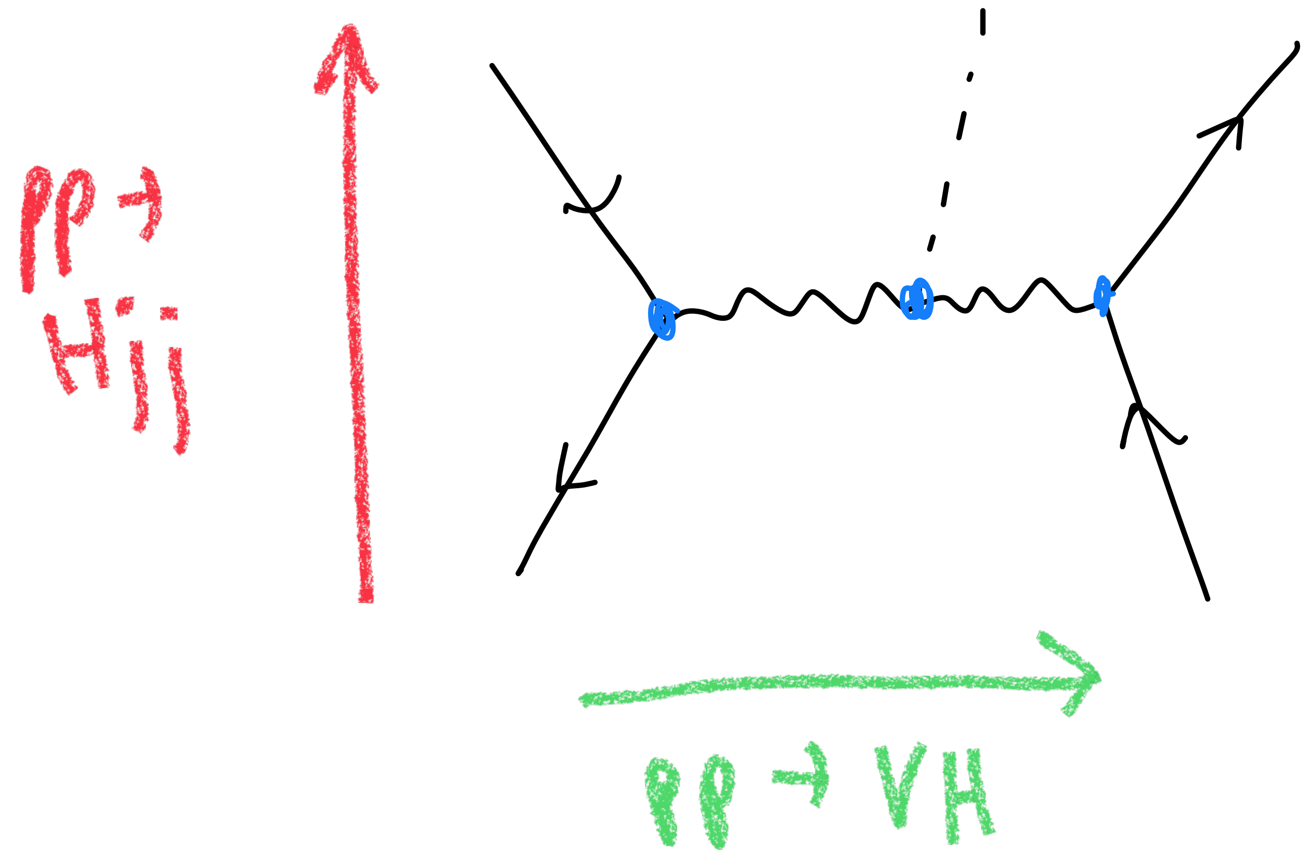
$\bar{q}q \to V(\bar{q}q)H$ + crossing symmetry gets us VBF

Therefore, expect similar operators to dominate, though kinematics and cuts are slightly different



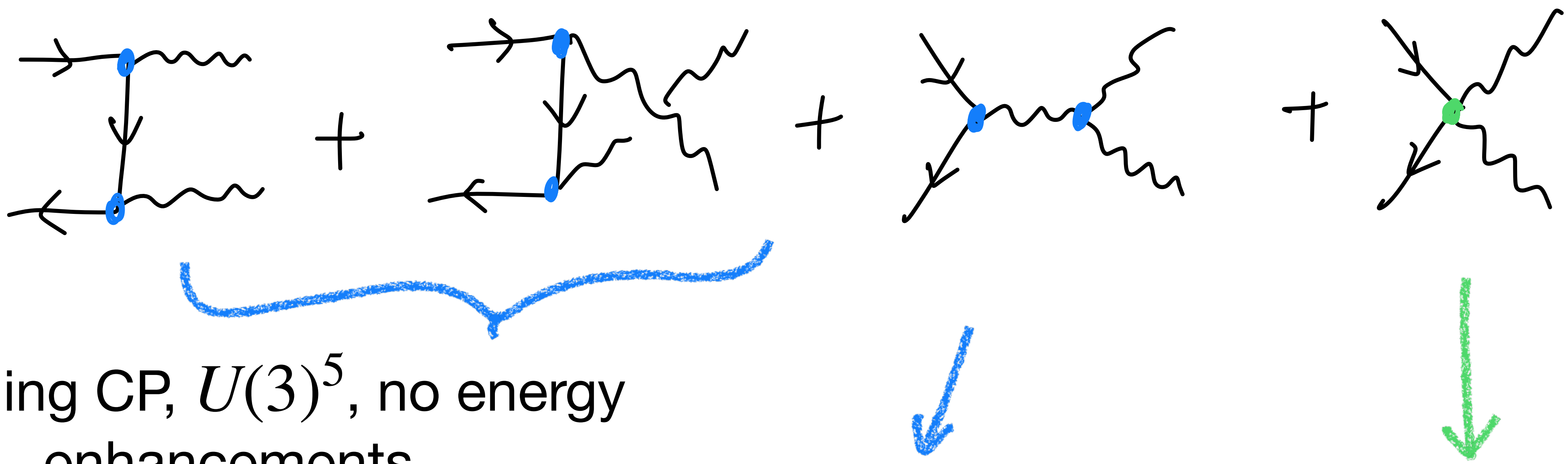
i.e.

$\psi^4 H^2$

[Assi, AM in progress]

Do I gain something vs. using |dim-6|²

Diboson



Assuming CP, $U(3)^5$, no energy enhancements

VVV is energy enhanced ($C_W W^3$). Important in global fit program, as first place triple gauge operators as appear.

Contact terms only show up at dim-8, ex. class $\psi^2 X^2 D$

Example: $\gamma W^{\pm}$, organize calculation by the polarizations of the W, γ

Do I gain something vs. using |dim-6|²

Energy scaling of different polarization amplitudes

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

$\hat{s} \gg m_W^2$

$$|A_{SM}|^2 + \frac{2Re(A_{SM}^* A_6)}{\Lambda^2} + \frac{1}{\Lambda^4}|A_6|^2$$

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

$$|\textbf{dim-6}\ C_W|^2 \sim g_{SM}^2\, c_6^2\, \frac{s^2}{\Lambda^4}$$

Do I gain something vs. using |dim-6|²

[AM, 2312.09867]

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

$\hat{s} \gg m_W^2$

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

$$+\frac{2Re(A^*_{SM}A_8)}{\Lambda^4}$$

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

$$SM \times \textbf{dim-8} \sim g^2_{SM}\, c_8 \frac{s^2}{\Lambda^4}$$

Again, dim-8 terms have $\mathcal{O}(1)$ effect at high energy. See also Degrande 2303.10493 (for WW, WZ). Motivates polarization studies

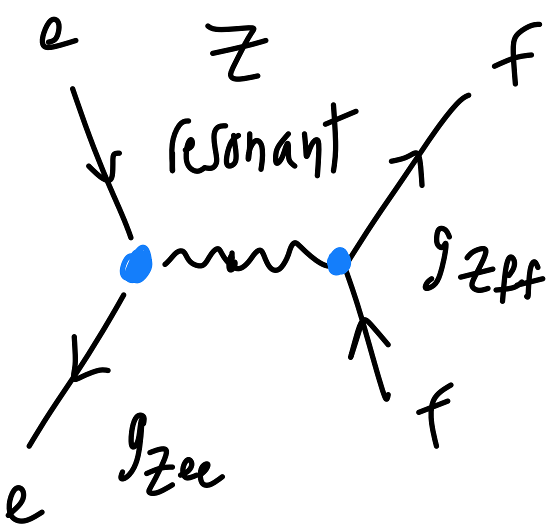
Takeaways

- To take advantage of 'energy frontier' at LHC, need to know next order SMEFT corrections.
- |dim-6|^2 is an unreliable estimate at best! (And |dim-6|^2 > dim-6 x SM without good reason I don't trust at all)
- geoSMEFT organization: minimizes operators that enter smallest (& most universal) vertices. Pushes new energy-enhanced effects to process-specific 4+ particle vertices
- Facilitates full $\mathcal{O}(1/\Lambda^4)$ calculations. Several key processes relevant for global SMEFT program worked out. From examples worked out so far, impact of $\mathcal{O}(1/\Lambda^4)$ strongly depends on process and kinematic regime…
- Easy energy vs. vev counting: as first step, focus on energy enhanced terms to $\mathcal{O}(1/\Lambda^4)$. Assuming all WC are the same size, these will dominate kinematic tails

Thank you!

Extras

geoSMEFT applications: redo 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:

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

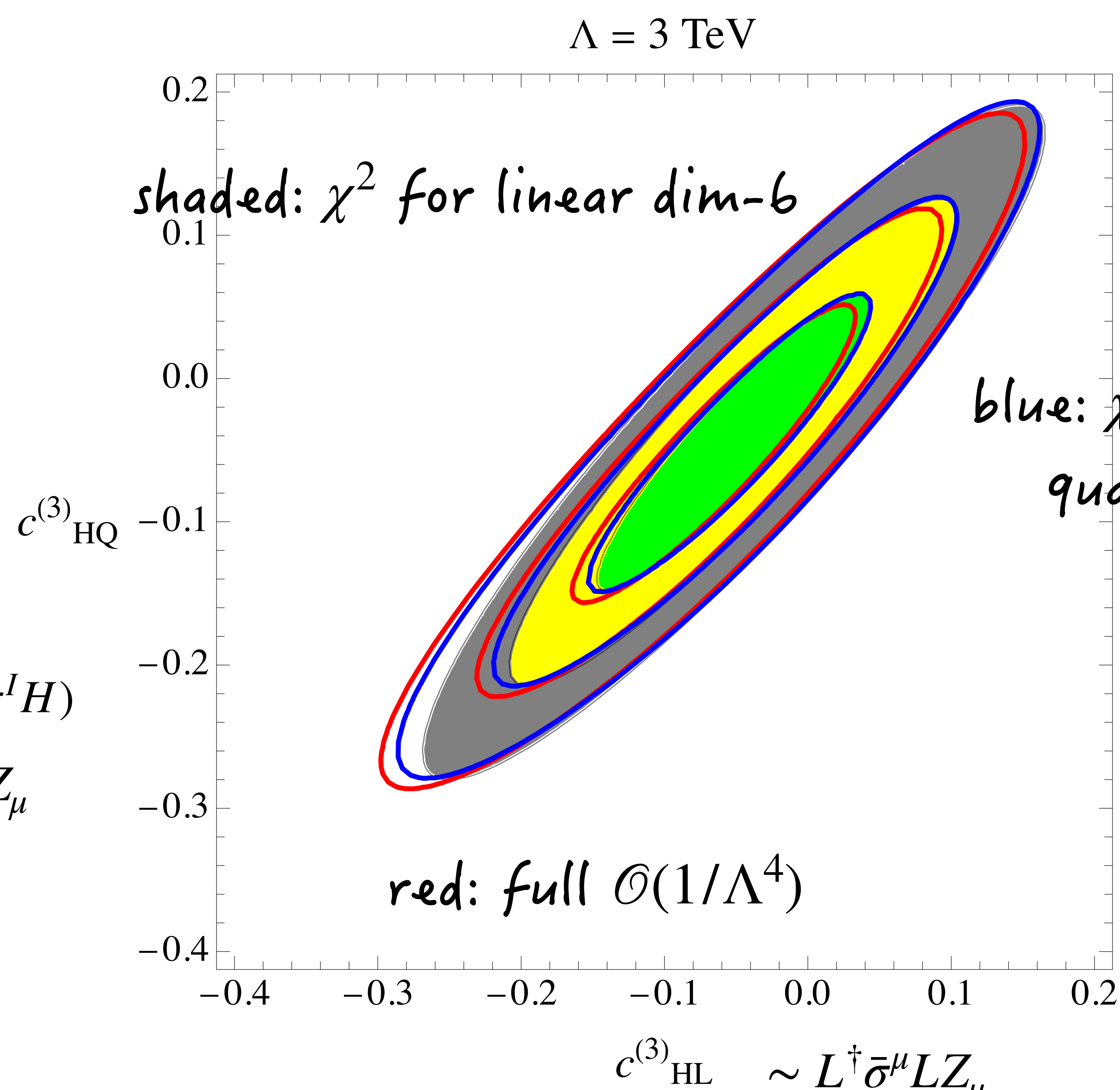
SMEFT corrections in $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}/\{\hat{\alpha}, \hat{m}_Z, \hat{G}_F\}$ scheme

$\mathcal{O}(\frac{v^4}{\Lambda^4})$	$\langle g^{\mathcal{Z},u_R}_{\text{eff,pp}}\rangle$	$\langle g^{\mathcal{Z},d_R}_{\text{eff,pp}}\rangle$	$\langle g^{\mathcal{Z},\ell_R}_{\text{eff,pp}}\rangle$
$\langle g^{\mathcal{Z},\psi}_{\text{eff}}\rangle^2$	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
$\tilde{C}_{HW}\,C_{HWB}$	-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]

geoSMEFT applications: redo 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



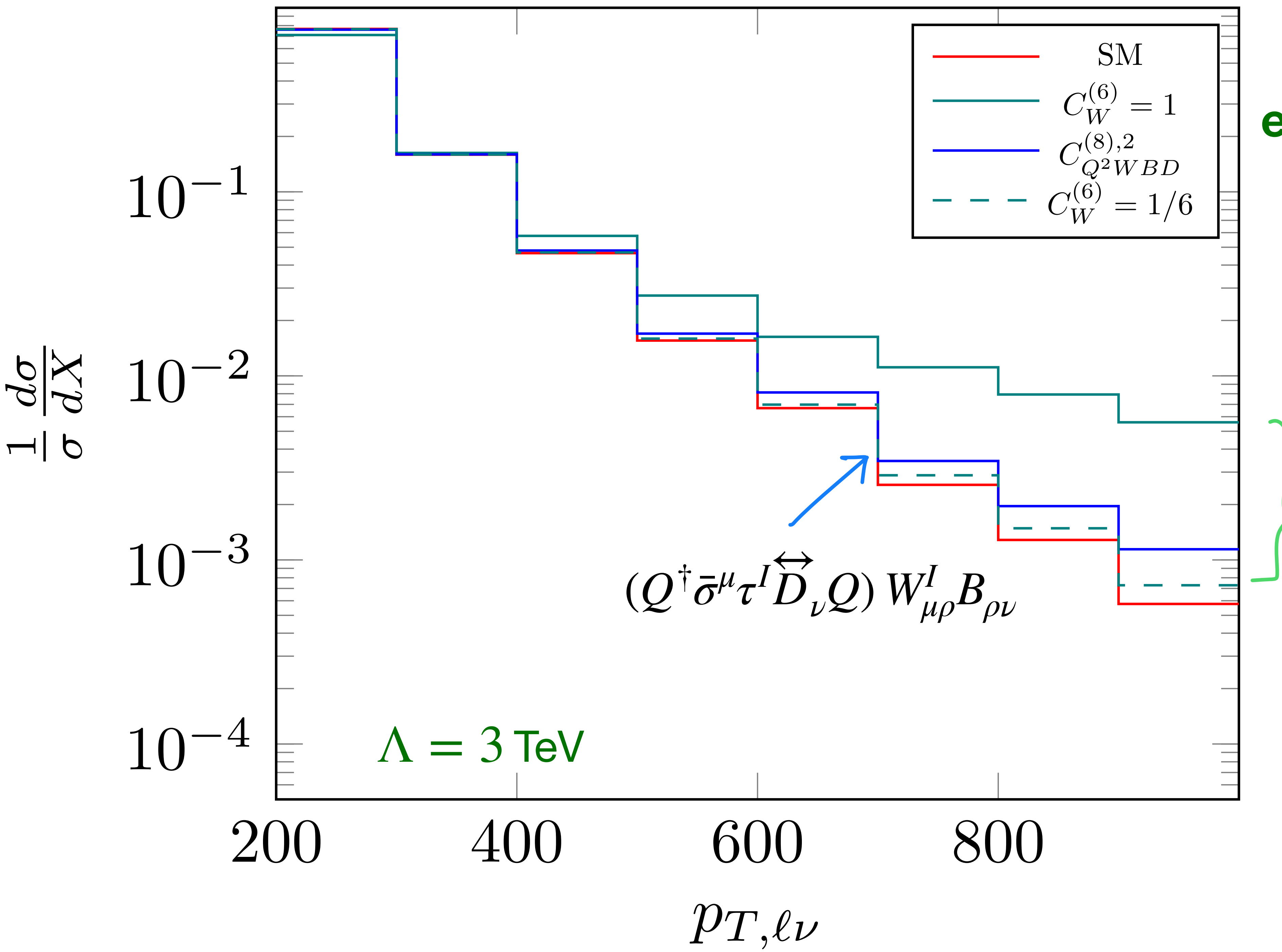
$(Q^\dagger \bar{\sigma}^\mu \tau^I Q)(H^\dagger \overleftrightarrow{D}_\mu \tau^I H)$

$\supset Q^\dagger \bar{\sigma}^\mu Q Z_\mu$

$\sim L^\dagger \bar{\sigma}^\mu L Z_\mu$

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

Do I gain something vs. using |dim-6|²?: $W\gamma$



As in VH, dim-8 effects non-negligible, even dominant

$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

Motivates polarization studies, 'taggers'

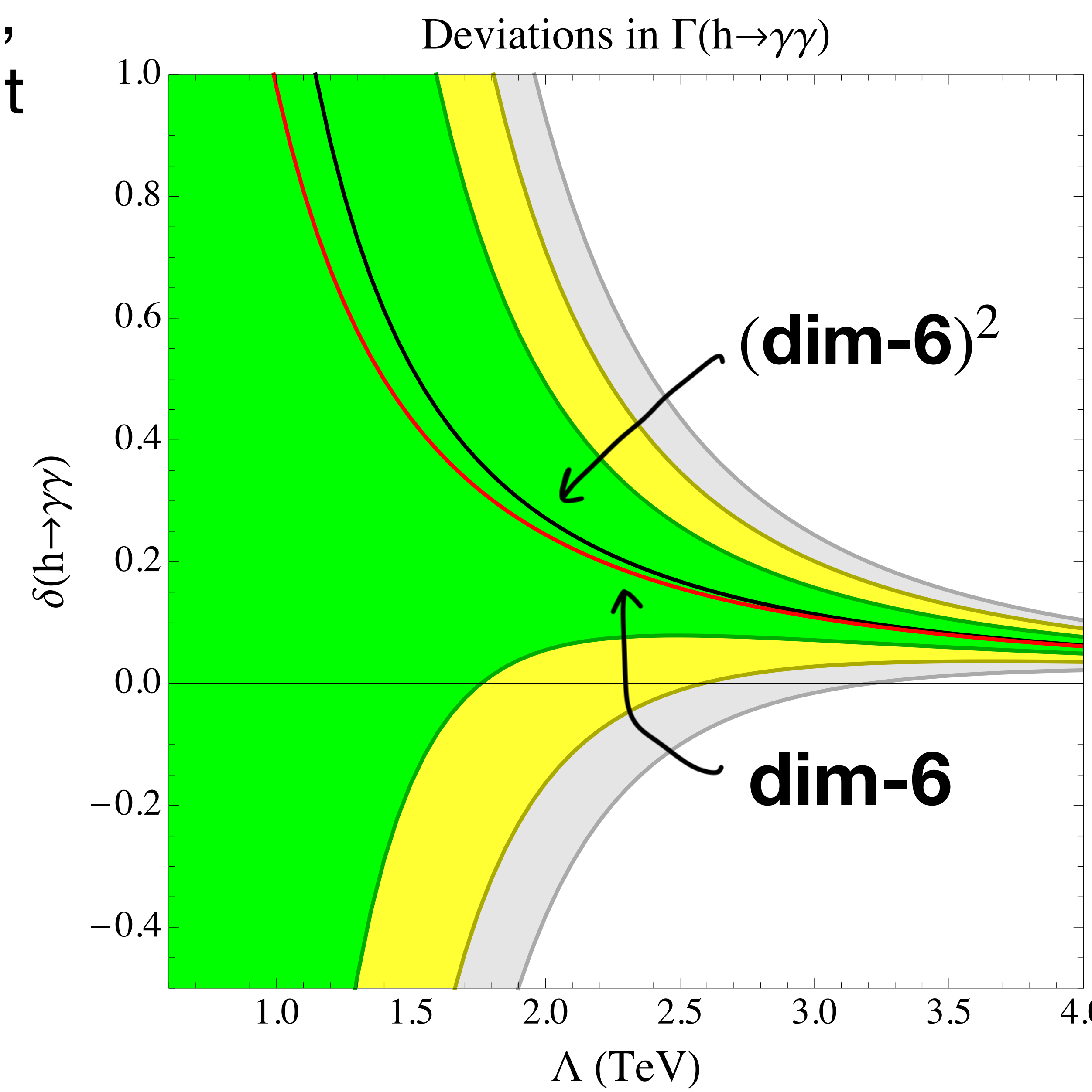
Do I gain something vs. using |dim-6|²?: $h \to \gamma\gamma$

If dim-6 coefficients happen to be small, dim-8 can have a big effect even without energy enhancement

Weakly coupled UV: $(H^\dagger H)\, X^2$ loop level $\sim O(0.01)$, while $(H^\dagger H)^2\, X^2$ tree level $\sim O(1)$

[Arzt'93, Craig et al '20, Hays et al 2007.00565]

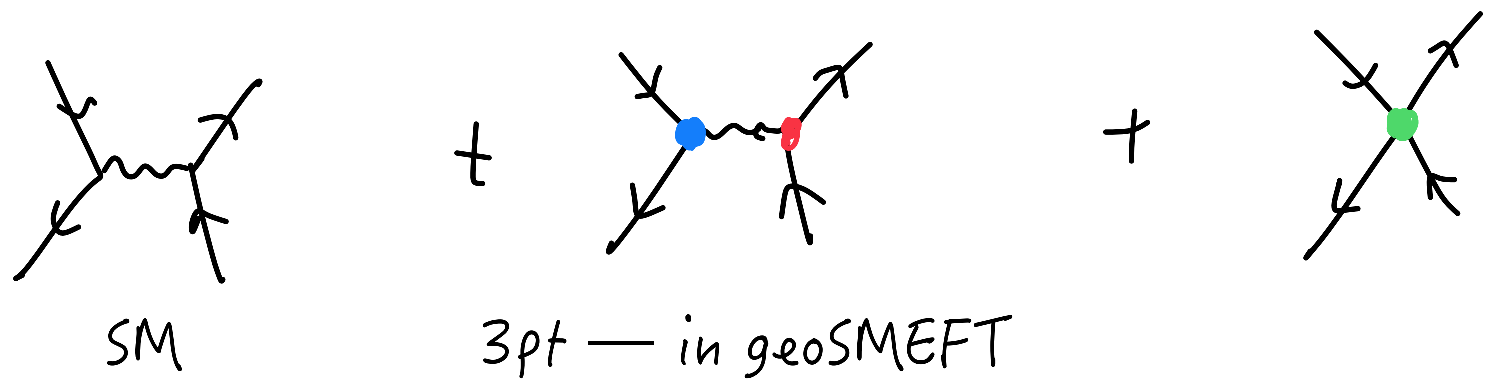
$$\frac{\textbf{dim-8}}{\textbf{dim-6}} \sim \left(\frac{c^{(8)}}{c^{(6)}}\right)\frac{v^2}{\Lambda^2} \sim 100\,\frac{v^2}{\Lambda^2}$$



In these scenarios, $\mathcal{O}(1)$ correction from dim-8

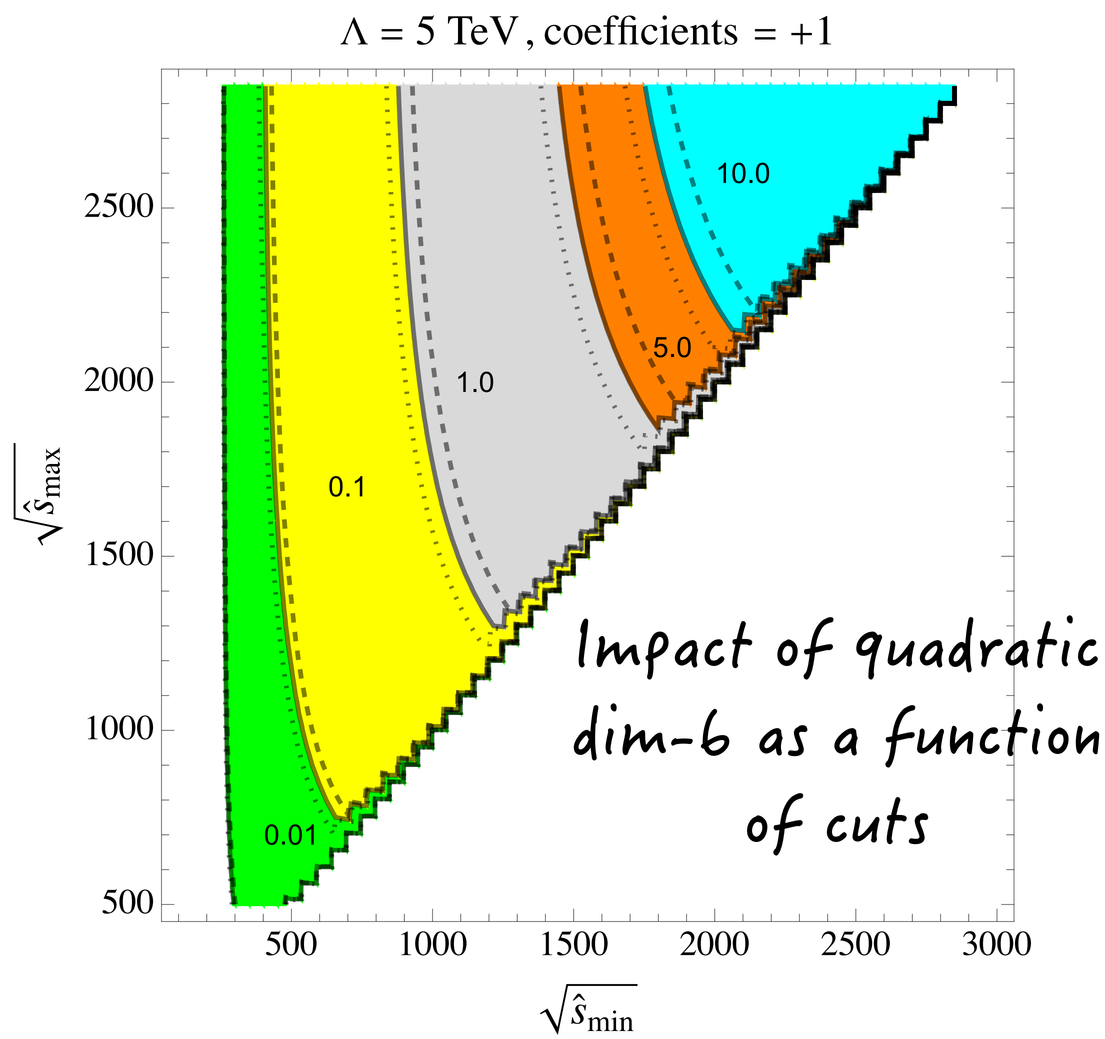
Ex. $pp \to \ell^+\ell^-, \ell^\pm\nu$ to $\mathcal{O}(1/\Lambda^4)$

[Kim, AM 2203.11976]

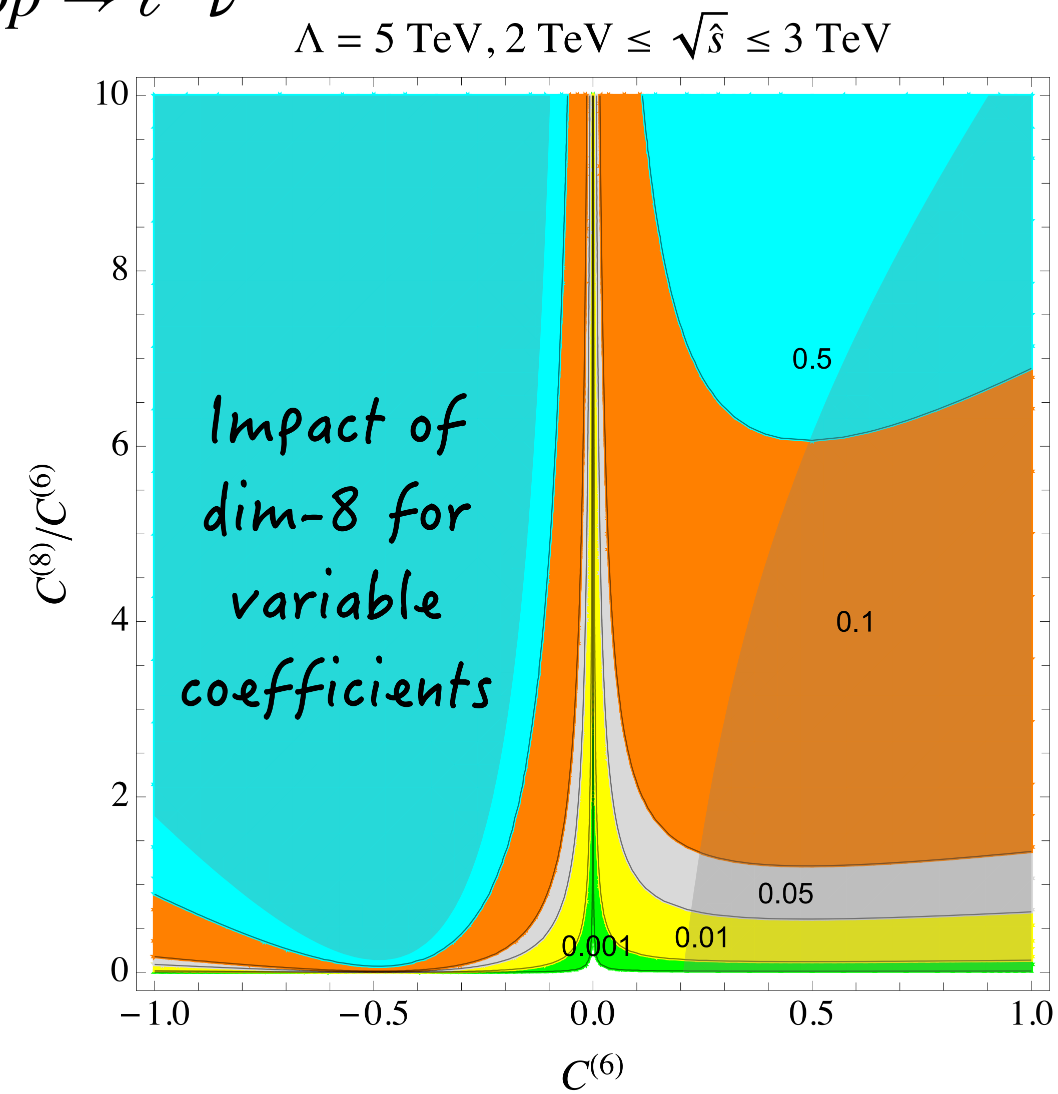


new at 4-pt, $\mathcal{O}(10)$ operators at $1/\Lambda^4$

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

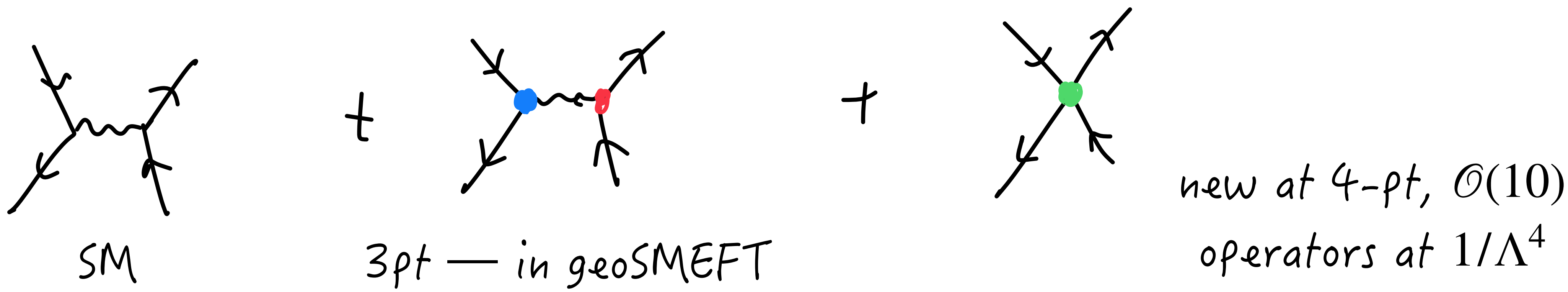


$pp \to \ell^\pm\nu$



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

New kinematics from dimension-8



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

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

→

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

What about dimension-10?

$pp \to W\gamma, WZ$ all coefficients ~ 1

dim-6 ~ 0 , |**dim-6**|$^2 \sim g_{SM}^2 c_6^2 \frac{E^4}{\Lambda^4}$, **dim-8** $\sim g_{SM}^2 c_8 \frac{E^4}{\Lambda^4}$, $1/\Lambda^6 \sim g_{SM}^2 c_{10} \frac{E^6}{\Lambda^6}$

$$\frac{\textbf{dim-8}}{|\textbf{dim-6}|^2} \sim \frac{c_8}{c_6} \sim 1 \qquad \frac{1/\Lambda^6}{\textbf{dim-8}} \sim \frac{c_{10}}{c_8}\left(\frac{E^2}{\Lambda^2}\right) \sim \left(\frac{E^2}{\Lambda^2}\right)$$

$pp \to \ell\ell$ four fermi contact interactions have strongest energy growth

dim-6 $\sim g_{SM}^2\, c_6 \left(\frac{E^2}{\Lambda^2}\right)$ |**dim-6**|$^2 \sim c_6^2 \left(\frac{E^4}{\Lambda^4}\right)$ **dim-8** $\sim g_{SM}^2 c_8 \frac{E^4}{\Lambda^4}$ $1/\Lambda^6 \sim g_{SM}^2 c_{10} \frac{E^6}{\Lambda^6}, c_6\, c_8 \frac{E^6}{\Lambda^6}$

$$\frac{|\textbf{dim-6}|^2}{\textbf{dim-6}} \sim \frac{c_6}{g_{SM}^2}\left(\frac{E^2}{\Lambda^2}\right) \qquad \frac{\textbf{dim-8}}{|\textbf{dim-6}|^2} \sim \frac{g_{SM}^2 c_8}{c_6^2} \qquad \frac{1/\Lambda^6}{|\textbf{dim-6}|^2} \sim \frac{c_6}{g_{SM}^2}\left(\frac{E^2}{\Lambda^2}\right)$$

For coefficients $\sim 1 > g_{SM}^2$, dim-8 subdominant