

Title: Two loops and Higgs field space geometries; pushing the interpretation of LHC data forward in the SMEFT

Speakers: Michael Trott

Series: Particle Physics

Date: May 12, 2023 - 11:00 AM

URL: <https://pirsa.org/23050084>

Abstract: Getting the strongest physics conclusions from collider particle physics experiments regarding the (in)consistency of the Standard Model with actual measurements requires Effective Field Theory techniques. This approach (known as the SMEFT) has been rapidly advanced in recent years, leading to new analyses of the data being executed by Atlas and CMS. The current state of the theoretical art is not precise enough as such EXP studies are continued into the future, as the measurements continue to become more precise. We need to be able to calculate more precisely in the SMEFT to keep up. After an intro to this area of research, I will discuss some recent calculations that have pushed things to the two loop level in precision for higgs production/decay in the SMEFT, and how thinking geometrically (in terms of field space connections and the resulting Higgs geometries) in EFT is the key to keep advancing the theoretical state of the art.

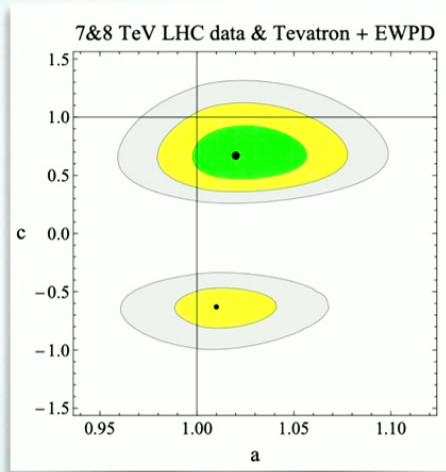
Zoom link: <https://pitp.zoom.us/j/99931154202?pwd=SUMzK2JIS0prNk5KaGZWakphckZhdz09>

Two loops and Higgs Field Space geometries.

Mike Trott (Perimeter/Caltech)

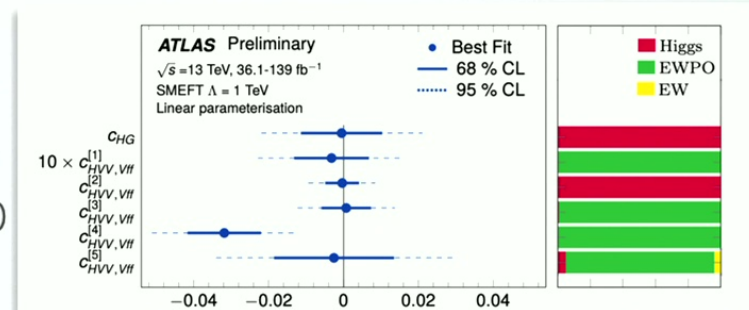
Related paper this week: Martin and Trott <https://arxiv.org/abs/2305.05879>

VILLUM FONDEN



Pre-Higgs discovery Kappa/HEFT :2012!

Higgs@10



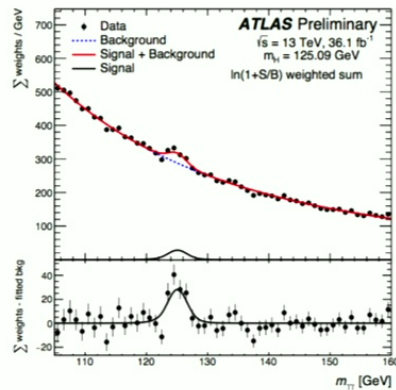
Modern SMEFT Analysis: ATLAS-PHYS-PUB-2022-037

What was discovered at LHC, a particle

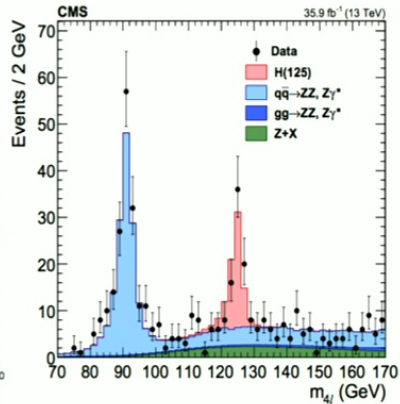
- Discovery of (Higgs like) particle in 2012
Meaning $J^P \sim 0^+$

THE STANDARD MODEL

	Fermions			Bosons		
Quarks	u up	c charm	t top	γ photon	Force carriers	✓
	d down	s strange	b bottom	Z Z boson		
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson		
Leptons	e electron	μ muon	τ tau	g gluon		
	Higgs boson					



ATLAS-CONF-2017-045 (2017)



CMS-PAS-HIG-16-041 (2017)

- The SM, an $SU(3) \times SU(2) \times U(1)$ linearly realized gauge theory :

$$\mathcal{L}_{SM} = -\frac{1}{4}G_{\mu\nu}^A G^{A\mu\nu} - \frac{1}{4}W_{\mu\nu}^I W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \bar{\psi} i \not{D} \psi - \lambda \left(H^\dagger H - \frac{1}{2}v^2 \right)^2 - \left[H^{\dagger j} \bar{d} Y_d q_j + \tilde{H}^{\dagger j} \bar{u} Y_u q_j + H^{\dagger j} \bar{e} Y_e l_j + \text{h.c.} \right],$$

Michael Trott, Caltech/Perimeter

What wasn't discovered at LHC

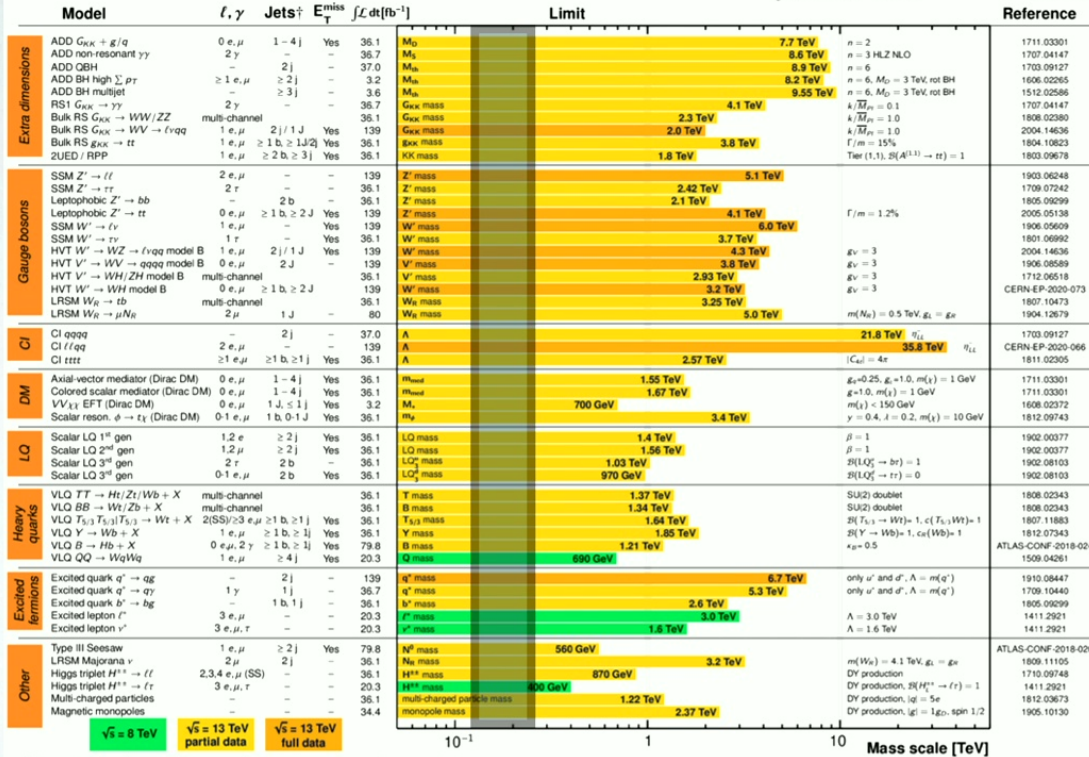
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

$$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$$

ATLAS Preliminary

$$\sqrt{s} = 8, 13 \text{ TeV}$$



*Only a selection of the available mass limits on new states or phenomena is shown.

[†]Small-radius (large-radius) jets are denoted by the letter j (J).

Masses of EW scale ($\sim gv$) states m_W, m_Z, m_t, m_h

Michael Trott, Caltech/Perimeter

What wasn't discovered at LHC

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

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$$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$$

ATLAS Preliminary

$$\sqrt{s} = 8, 13 \text{ TeV}$$

Model	ℓ, γ	Jets [†]	$E_{\text{miss}}^{\text{†}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1-4 j	Yes	36.1	M_0 7.7 TeV $n=2$
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_0 8.6 TeV $n=3$ HLZ NLO
	ADD QBH	-	2 j	-	37.0	M_{BH} 8.9 TeV $n=6$
	ADD BH high Σp_T	$> 1 e, \mu$	$> 2 j$	-	3.2	M_{BH} 8.2 TeV $n=6, M_0 = 3 \text{ TeV}$, not BH
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{BH} 9.55 TeV $n=6, M_0 = 3 \text{ TeV}$, not BH
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	36.7	G_{KK} mass 4.1 TeV $k/\bar{M}_0 = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV $k/\bar{M}_0 = 1.0$
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu q\bar{q}$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV $k/\bar{M}_0 = 1.0$
	Bulk RS $G_{KK} \rightarrow t\bar{t}$	1 e, μ	$\geq 1 b, \geq 1 j, 2 j$	Yes	36.1	G_{KK} mass 3.8 TeV $\Gamma/m = 15\%$
	ZUED / RPP	1 e, μ	$\geq 2 b, \geq 3 j$	Yes	36.1	G_{KK} mass 1.8 TeV $\text{Tan}(\beta), \beta(A^{(1)} \rightarrow t\bar{t}) = 1$
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	139	Z' mass 5.1 TeV
	SSM $Z' \rightarrow \tau\tau$	2 τ	-	-	36.1	Z' mass 2.42 TeV
	Leptophobic $Z' \rightarrow b\bar{b}$	-	2 b	-	36.1	Z' mass 2.1 TeV
	Leptophobic $Z' \rightarrow t\bar{t}$	0 e, μ	$\geq 1 b, \geq 2 j$	Yes	139	Z' mass 4.1 TeV $\Gamma/m = 1.2\%$
	SSM $W' \rightarrow \ell\nu$	1 e, μ	-	Yes	139	W' mass 6.0 TeV
	SSM $W' \rightarrow \tau\nu$	1 τ	-	Yes	36.1	W' mass 3.7 TeV
	HVT $W' \rightarrow WZ \rightarrow \ell\nu q\bar{q}$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV
	HVT $V' \rightarrow WV \rightarrow qq\bar{q}$ model B	0 e, μ	2 j	-	139	V' mass 3.8 TeV
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	V' mass 2.93 TeV
	HVT $W' \rightarrow WH$ model B	0 e, μ	$\geq 1 b, \geq 2 j$	-	139	W' mass 3.2 TeV
CI	LRSM $W_R \rightarrow b\bar{b}$	multi-channel	-	-	36.1	W_R mass 3.25 TeV
	LRSM $W_R \rightarrow \mu N_R$	2 μ	1 j	-	80	W_R mass 5.0 TeV $m(N_R) = 0.5 \text{ TeV}, g_u = g_\nu$
	CI $\ell\ell q\bar{q}$	-	2 j	-	37.0	A 21.8 TeV η_{11}
	CI $\ell\ell q\bar{q}$	2 e, μ	-	-	139	A 35.8 TeV η_{11}
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1-4 j	Yes	36.1	\tilde{M}_{DM} 1.55 TeV $g_u = 0.25, g_\nu = 1.0, m(\chi) = 1 \text{ GeV}$
Colored scalar mediator (Dirac DM)	0 e, μ	1-4 j	Yes	36.1	\tilde{M}_{DM} 1.67 TeV $g = 1.0, m(\chi) = 1 \text{ GeV}$	
VV $\chi\chi$ EFT (Dirac DM)	0 e, μ	1 j, $\leq 1 j$	Yes	3.2	M, 700 GeV $m(\chi) < 150 \text{ GeV}$	
Scalar reson. $\phi \rightarrow t\bar{t}$ (Dirac DM)	0-1 e, μ	1 b, 0-1 j	Yes	36.1	\tilde{M}_ϕ 3.4 TeV $y = 0.4, t = 0.2, m(\chi) = 10 \text{ GeV}$	
LO	Scalar LO 1 st gen	1, 2 e	$\geq 2 j$	Yes	36.1	LO mass 1.4 TeV $\beta = 1$
	Scalar LO 2 nd gen	1, 2 μ	$\geq 2 j$	Yes	36.1	LO mass 1.56 TeV $\beta = 1$
	Scalar LO 3 rd gen	2 τ	2 b	-	36.1	LO mass 1.03 TeV $\beta L Q_1^2 \rightarrow b\bar{b} = 1$
	Scalar LO 3 rd gen	0-1 e, μ	2 b	Yes	36.1	LO mass 970 GeV $\beta L Q_1^2 \rightarrow \tau\bar{\tau} = 0$
Heavy quarks	VLO $TT \rightarrow H\tau/Z\tau/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV
	VLO $BB \rightarrow WZ/WX$	multi-channel	-	-	36.1	B mass 1.34 TeV
	VLO $T_{31} T_{31} T_{31} \rightarrow Wt + X$	$2(SS)/3 e, \mu \geq 1 b, \geq 1 j$	Yes	36.1	T_{31} mass 1.64 TeV $\beta(T_{31} \rightarrow Wt) = 1, c(T_{31} W) = 1$	
	VLO $Y \rightarrow Wb + X$	1 e, μ	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV $\beta(Y \rightarrow Wb) = 1, c_\ell(Wb) = 1$
	VLO $B \rightarrow Hb + X$	0 $e, \mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV $\kappa_B = 0.5$
Excited fermions	VLO $QQ \rightarrow WqWq$	1 e, μ	$\geq 4 j$	Yes	20.3	Q^* mass 690 GeV
	Excited quark $q^* \rightarrow qg$	-	2 j	-	139	q^* mass 6.7 TeV
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	-	36.7	q^* mass 5.3 TeV
	Excited quark $q^* \rightarrow b\bar{g}$	-	1 b, 1 j	-	36.1	q^* mass 2.6 TeV
	Excited lepton ℓ^*	3 e, μ	-	-	20.3	ℓ^* mass 3.0 TeV
Other	Excited lepton ν^*	3 e, μ, τ	-	-	20.3	ν^* mass 1.8 TeV
	Type III Seesaw	1 e, μ	$> 2 j$	Yes	79.8	N^* mass 560 GeV
	LRSM Majorana ν	2 μ	2 j	-	36.1	N_ν mass 3.2 TeV
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2, 3, 4 e, μ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV
Magnetic monopoles	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	-	-	20.3	$H^{\pm\pm}$ mass 600 GeV
	Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.
[†]Small-radius (large-radius) jets are denoted by the letter j (J).

Bounds have been pushed away from $v \sim m_h$

USE that

$$v/M < 1$$

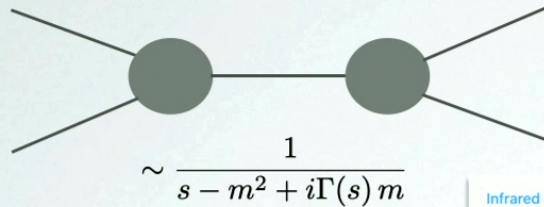
to simplify/for stronger conclusions:

- bound many models at once
- bound multiple resonances at same time

Deviations then look like local contact operator effects in EFT

Michael Trott, Caltech/Perimeter

When you do measurements below a particle threshold..



IF the collision probe does not reach $\sim m_{heavy}^2$
THEN observable's dependence on that scale simplified

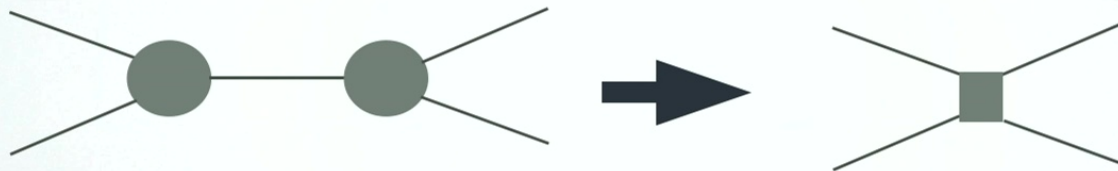
Infrared singularities and small distance behavior analysis
 K. Symanzik (DESY) (Apr, 1973)
 Published in: *Commun.Math.Phys.* 34 (1973) 7-36

Infrared singularities and massive fields
 Thomas Appelquist and J. Carazzone
 Phys. Rev. D **11**, 2856 – Published 15 May 1975

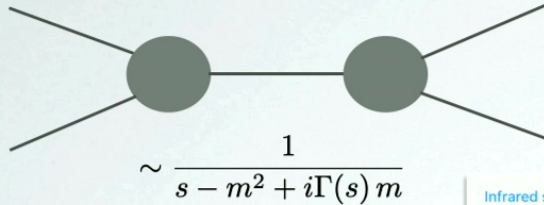
- The effects of heavy physics are localised, essentially, by the uncertainty principle

$$\Delta t \Delta E \sim \Delta t M > 1 \rightarrow \Delta t \sim \frac{1}{M}, \quad \Delta|x| \Delta|p| \sim \Delta|x| M > 1 \rightarrow \Delta|x| \sim \frac{1}{M}.$$

$$\hbar = 1 = c.$$



When you do measurements below a particle threshold



IF the collision probe does not reach $\sim m_{heavy}^2$
THEN observable's dependence on that scale simplified

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- You can Taylor expand in LOCAL functions (operators)

$$\langle \rangle \sim O_{SM}^0 + \frac{f_1(s, t, u)}{M_{heavy}^2} + \frac{f_2(s, t, u)}{M_{heavy}^4} + \dots$$

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \dots, \quad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$

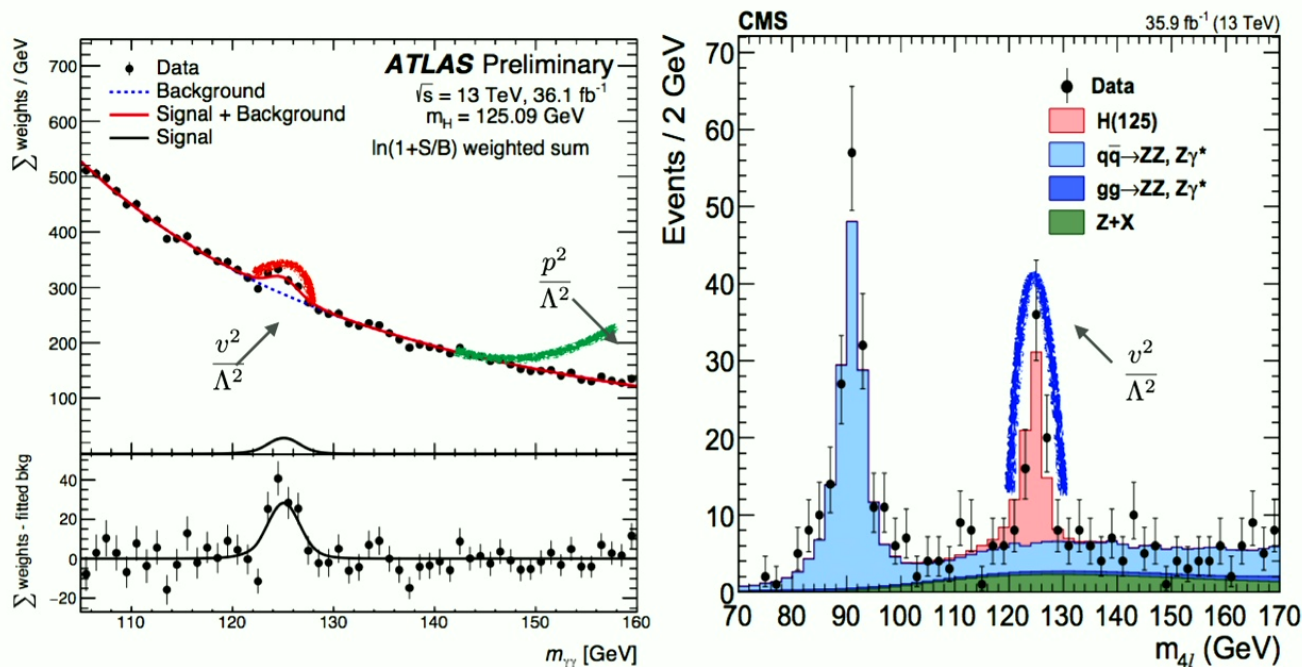
IR operator form

Λ v.s. M_{heavy}

UV dependent Wilson coefficient
and suppression scale

How does it help to have this simplification?

- What sort of deviations are then allowed experimentally?

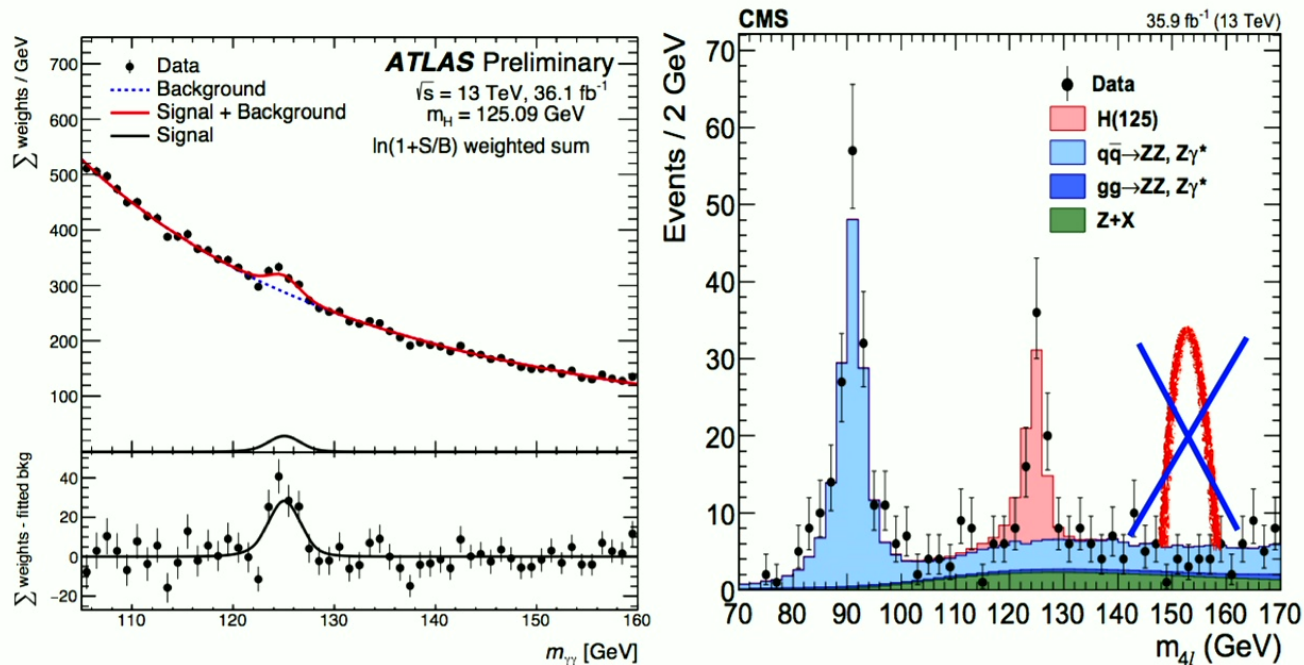


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How does it help to have this simplification?

- What sort of deviations are then allowed experimentally?



- BY FAR the majority of experimental analysis effort has been about bumps

This simplification is extremely helpful!

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary
 $\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$
 $\sqrt{s} = 8, 13 \text{ TeV}$

Model	ℓ, γ	Jets†	E_{miss}	$[\mathcal{L} dt] [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1-4j	Yes	36.1	M_{Pl} 7.7 TeV $n=2$
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_{Pl} 6.5 TeV $n=3$ HLZ NLO
	ADD OBH	-	2j	-	37.0	M_{Pl} 6.9 TeV $n=6$
	ADD BH High Σp_T	$\geq 1 e, \mu$	$\geq 2j$	-	3.2	M_{Pl} 8.2 TeV $n=6, M_{\text{Pl}} = 3 \text{ TeV}$, rot BH
	ADD BH multijet	-	$\geq 3j$	-	3.6	M_{Pl} 9.55 TeV $n=6, M_{\text{Pl}} = 3 \text{ TeV}$, rot BH
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	36.7	G_{KK} mass $k/M_{\text{Pl}} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass $k/M_{\text{Pl}} = 3.0$
	Bulk RS $G_{KK} \rightarrow WV \rightarrow f\nu q$	1 e, μ	2j/1J	Yes	139	G_{KK} mass $k/M_{\text{Pl}} = 1.0$
	Bulk RS $G_{KK} \rightarrow t\bar{t}$	1 e, μ	$\geq 1 b, \geq 1J/2$	Yes	36.1	G_{KK} mass $k/M_{\text{Pl}} = 1.0$
	2UED / RPP	1 e, μ	$\geq 2 b, \geq 3j$	Yes	36.1	KK mass Tier (1,1), $2\ell(A^{(1,1)} \rightarrow t\bar{t}) = 1$
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	139	Z' mass 5.1 TeV
	SSM $Z' \rightarrow \tau\tau$	2 τ	-	-	36.1	Z' mass 2.42 TeV
	Leptophobic $Z' \rightarrow b\bar{b}$	-	2b	-	36.1	Z' mass 2.1 TeV
	Leptophobic $Z' \rightarrow t\bar{t}$	0 e, μ	$\geq 1 b, \geq 2J$	Yes	139	Z' mass 4.1 TeV $\Gamma/m = 1.2\%$
	SSM $W' \rightarrow \ell\nu$	1 e, μ	-	-	139	W' mass 6.0 TeV
	SSM $W' \rightarrow \tau\nu$	1 τ	-	-	36.1	W' mass 3.7 TeV
	HVT $W' \rightarrow WZ \rightarrow f\nu q$ model B	1 e, μ	2j/1J	Yes	139	W' mass 4.3 TeV $g_V = 3$
	HVT $V' \rightarrow WV \rightarrow q\bar{q}$ model B	0 e, μ	2j	-	139	V' mass 3.8 TeV $g_V = 3$
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	V' mass 2.93 TeV $g_V = 3$
	HVT $V' \rightarrow WH$ model B	0 e, μ	$\geq 1 b, \geq 2J$	Yes	139	V' mass 3.2 TeV
	LRSM $W_{\mu} \rightarrow t\bar{b}$	multi-channel	-	-	36.1	W_{μ} mass 3.25 TeV
	LRSM $W_{\mu} \rightarrow \mu N_{\mu}$	2 μ	1J	-	90	W_{μ} mass 5.0 TeV $m(N_{\mu}) = 0.5 \text{ TeV}, g_{\ell} = g_{\mu}$
CI	CI $qqqq$	-	2j	-	37.0	A 21.8 TeV η_{CI}
	CI $t\bar{t}qq$	2 e, μ	-	-	139	A 35.8 TeV η_{CI}
	CI $t\bar{t}t\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	A $ C_{\text{CI}} = 4\alpha$ η_{CI}
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1-4j	Yes	36.1	m_{DM} 1.55 TeV $g_{\ell} = -0.25, g_{\mu} = 1.0, m(\chi) = 1 \text{ GeV}$
	Colored scalar mediator (Dirac DM)	0 e, μ	1-4j	Yes	36.1	m_{DM} 1.67 TeV $g_{\ell} = 1.0, m(\chi) = 1 \text{ GeV}$
	$VV_{\ell\ell}$ EFT (Dirac DM)	0 e, μ	1j, $\leq 1j$	Yes	3.2	M_{ℓ} 700 GeV $m(\chi) < 150 \text{ GeV}$
	Scalar reson. $\phi \rightarrow t\bar{t}$ (Dirac DM)	0-1 e, μ	1b, 0-1J	Yes	36.1	m_{ϕ} 3.4 TeV $y = 0.4, \lambda = 0.2, m(\chi) = 10 \text{ GeV}$
LO	Scalar LQ 1 st gen	1, 2 e	$\geq 2j$	Yes	36.1	LQ mass 1.4 TeV $\beta = 1$
	Scalar LQ 2 nd gen	1, 2 μ	$\geq 2j$	Yes	36.1	LQ mass 1.56 TeV $\beta = 1$
	Scalar LQ 3 rd gen	2 τ	2b	-	36.1	LQ mass 1.03 TeV $\Re(LQ) \rightarrow b\bar{c} = -1$
	Scalar LQ 3 rd gen	0-1 e, μ	2b	Yes	36.1	LQ mass 970 GeV $\Re(LQ) \rightarrow t\bar{t} = 0$
Heavy quarks	VLO $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV SU(2) doublet
	VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV SU(2) doublet
	VLO $T_{5,3} \rightarrow T_{5,3} \rightarrow Wt + X$	2(SS)/ $\geq 3 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	$T_{5,3}$ mass 1.64 TeV $\Re(T_{5,3} \rightarrow Wt) = 1, c(T_{5,3}W) = 1$
	VLO $Y \rightarrow Wb + X$	1 e, μ	$\geq 1 b, \geq 1j$	Yes	36.1	Y mass 1.85 TeV $\Re(Y \rightarrow Wb) = 1, c_{\ell}(Wb) = 1$
	VLO $B \rightarrow Hb + X$	0 $e, \mu, 2 \gamma$	$\geq 1 b, \geq 1j$	Yes	79.8	B mass 1.21 TeV $\kappa_{\mu} = 0.5$
	VLO $QQ \rightarrow WqWq$	1 e, μ	$\geq 4j$	Yes	20.3	Q mass 680 GeV
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2j	-	139	q^* mass 6.7 TeV only u' and d' , $\Lambda = m(q')$
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1j	-	36.7	q^* mass 5.3 TeV only u' and d' , $\Lambda = m(q')$
	Excited quark $b^* \rightarrow b\bar{g}$	-	1b, 1j	-	36.1	b^* mass 2.6 TeV
	Excited lepton ℓ^*	3 e, μ	-	-	20.3	ℓ^* mass 3.0 TeV $\Lambda = 3.0 \text{ TeV}$
	Excited lepton ν^*	3 e, μ, τ	-	-	20.3	ν^* mass 1.6 TeV $\Lambda = 1.6 \text{ TeV}$
Other	Type III Seesaw	1 e, μ	$\geq 2j$	Yes	79.8	N^c mass 560 GeV
	LRSM Majorana ν	2 μ	2j	-	36.1	N_{μ} mass 3.2 TeV $m(W_{\mu}) = 4.1 \text{ TeV}, g_{\ell} = g_{\mu}$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2, 3, 4 e, μ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV D^{\pm} production
	Higgs triplet $H^{\pm\pm} \rightarrow t\bar{t}$	3 e, μ, τ	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV D^{\pm} production, $\Re(H^{\pm\pm} \rightarrow t\bar{t}) = 1$
	Multi-charged particles	-	-	-	36.1	multi-charged particle mass D^{\pm} production, $ g = 5e$
	Magnetic monopoles	-	-	-	34.4	monopole mass 1.22 TeV D^{\pm} production, $ g = 1g_{\text{p}}, \text{spin } 1/2$

*Only a selection of the available mass limits on new states or phenomena is shown.

† Small-radius (large-radius) jets are denoted by the letter j (J).

One can compare against data in a model dependent way:

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{model}$$

Calc observables at tree level



Calc observables at loop level



This simplification is extremely helpful!

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Map to specific studies:

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	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV $k/M_{\text{Pl}}=1.0$
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu$	$1 e, \mu$	2j/1J	Yes	139	G_{KK} mass 2.0 TeV $k/M_{\text{Pl}}=1.0$
	Bulk RS $G_{KK} \rightarrow t\bar{t}$	$1 e, \mu$	$\geq 1 b, \geq 1J/2$	Yes	36.1	G_{KK} mass 3.8 TeV $f/m=15\%$
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3j$	Yes	36.1	KK mass 1.8 TeV Tier (1.1), $2\ell(A^{(1,1)} \rightarrow t\bar{t})=1$
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass 5.1 TeV
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass 2.42 TeV
	Leptophobic $Z' \rightarrow b\bar{b}$	-	2b	-	36.1	Z' mass 2.1 TeV
	Leptophobic $Z' \rightarrow t\bar{t}$	$0 e, \mu$	$\geq 1 b, \geq 2J$	Yes	139	Z' mass 4.1 TeV
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	-	139	W' mass 6.0 TeV
	SSM $W' \rightarrow \tau\nu$	1τ	-	-	36.1	W' mass 3.7 TeV
	HVT $W' \rightarrow WZ \rightarrow \ell\nu q\bar{q}$ model B	$1 e, \mu$	2j/1J	Yes	139	W' mass 4.3 TeV $g_V=3$
	HVT $V' \rightarrow WV \rightarrow q\bar{q} q\bar{q}$ model B	$0 e, \mu$	2J	-	139	V' mass 3.8 TeV $g_V=3$
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	V' mass 2.93 TeV $g_V=3$
	HVT $V' \rightarrow WH$ model B	$0 e, \mu$	$\geq 1 b, \geq 2J$	Yes	139	W' mass 3.2 TeV $g_V=3$
CI	LRSM $W_{\mu} \rightarrow t\bar{b}$	multi-channel	-	-	36.1	W_{μ} mass 3.25 TeV
	LRSM $W_{\mu} \rightarrow \mu N_{\mu}$	2μ	1J	-	90	W_{μ} mass 5.0 TeV $m(N_{\mu})=0.5 \text{ TeV, } g_{\mu} = g_{\nu}$
DM	CI $\ell\ell q\bar{q}$	-	2j	-	37.0	A 21.8 TeV η_{ℓ}
	CI $t\bar{t} q\bar{q}$	$2 e, \mu$	-	-	139	A 5.8 TeV η_{ℓ}
DM	CI $t\bar{t} t\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	A 2.57 TeV $\langle C_{\mu} \rangle = 4e$
	Scalar reson. $\phi \rightarrow \tau\tau$ (Dirac DM)	$0-1 e, \mu$	1b, 0-1J	Yes	36.1	m_{ϕ} 700 GeV $g_{\tau} = -0.25, g_{\mu} = 1.0, m_{\phi} = 1 \text{ GeV}$
LO	Scalar $LQ 1^{st}$ gen	$1, 2 e$	$\geq 2j$	Yes	36.1	LQ mass 1.4 TeV $\beta=1$
	Scalar $LQ 2^{nd}$ gen	$1, 2 \mu$	$\geq 2j$	Yes	36.1	LQ mass 1.56 TeV $\beta=1$
	Scalar $LQ 3^{rd}$ gen	2τ	2b	-	36.1	LQ mass 1.03 TeV $2\Re(LQ) \rightarrow b\tau = 1$
	Scalar $LQ 3^{rd}$ gen	$0-1 e, \mu$	2b	Yes	36.1	LQ mass 970 GeV $2\Re(LQ) \rightarrow \tau\tau = 0$
Heavy quarks	VLO $TT \rightarrow H\tau/Z\tau/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV $SU(2)_C$ triplet
	VLO $BB \rightarrow W\tau/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV $SU(2)_C$ triplet
	VLO $T_{S,3} \rightarrow T_{S,3} \rightarrow W\tau + X$	$2(SS)/\geq 3 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	$T_{S,3}$ mass 1.64 TeV $2\Re(T_{S,3} \rightarrow W\tau) = 1, c(T_{S,3}W) = 1$
	VLO $Y \rightarrow Wb + X$	$1 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	Y mass 1.80 TeV $2\Re(Y \rightarrow Wb) = 1, c(Wb) = 1$
	VLO $B \rightarrow Hb + X$	$0 e, \mu, 2\gamma$	$\geq 1 b, \geq 1j$	Yes	79.8	B mass 1.21 TeV $2\Re(B \rightarrow Hb) = 1, c(Wb) = 1$
	VLO $QQ \rightarrow WqWq$	$1 e, \mu$	$\geq 4j$	Yes	20.3	Q mass 680 GeV 1509.04261
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2j	-	139	q^* mass 6.7 TeV only u' and d' , $A = m(q)$
	Excited quark $q^* \rightarrow q\gamma$	1γ	1j	-	36.7	q^* mass 5.3 TeV only u' and d' , $A = m(q)$
	Excited quark $b^* \rightarrow b\gamma$	-	1b, 1j	-	36.1	b^* mass 2.6 TeV $A = 3.0 \text{ TeV}$
	Excited lepton ℓ^*	$3 e, \mu$	-	-	20.3	ℓ^* mass 3.0 TeV $A = 1.6 \text{ TeV}$
	Excited lepton ν^*	$3 e, \mu, \tau$	-	-	20.3	ν^* mass 1.6 TeV $A = 1.6 \text{ TeV}$
Other	Type III Seesaw	$1 e, \mu$	$\geq 2j$	Yes	79.8	N^c mass 560 GeV $m(W_{\mu}) = 4.1 \text{ TeV, } g_{\mu} = g_{\nu}$
	LRSM Majorana ν	2μ	2j	-	36.1	N_{μ} mass 870 GeV $m(W_{\mu}) = 4.1 \text{ TeV, } g_{\mu} = g_{\nu}$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 400 GeV D^{\pm} production, $2\Re(H^{\pm\pm} \rightarrow \ell\ell) = 1$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV D^{\pm} production, $2\Re(H^{\pm\pm} \rightarrow \ell\tau) = 1$
	Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV D^{\pm} production, $ g = 5e$
Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV D^{\pm} production, $ g = 1g_{\text{Dirac}}, \text{spin } 1/2$	

*Only a selection of the available mass limits on new states or phenomena is shown.

† Small-radius (large-radius) jets are denoted by the letter j (J).

Michael Trott, Caltech/Perimeter

This simplification is extremely helpful!

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$

Model	ℓ, γ	Jets†	E_{miss}	$[\mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1-4j	Yes	36.1	M_{Pl} 7.7 TeV $n=2$
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_{Pl} 6.5 TeV $n=3$ HLZ NLO
	ADD OBH	-	2j	-	37.0	M_{Pl} 6.9 TeV $n=6$
	ADD BH high Σp_T	$\geq 1 e, \mu$	$\geq 2j$	-	3.2	M_{Pl} 8.2 TeV $n=6, M_{\text{Pl}}=3 \text{ TeV}$, rot BH
	ADD BH multi-jet	-	$\geq 3j$	-	3.6	M_{Pl} 9.55 TeV $n=6, M_{\text{Pl}}=3 \text{ TeV}$, rot BH
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	36.7	G_{KK} mass $k/\overline{M}_{\text{Pl}} = 0$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass $k/\overline{M}_{\text{Pl}} = 1.0$
	Bulk RS $G_{KK} \rightarrow WV \rightarrow f\nu q$	1 e, μ	2j/1J	Yes	139	G_{KK} mass 2.3 TeV $k/\overline{M}_{\text{Pl}} = 3.0$
	Bulk RS $G_{KK} \rightarrow tt$	1 e, μ	$\geq 1 b, \geq 1J/2$	Yes	36.1	G_{KK} mass 2.0 TeV $f/m = 15\%$
	2UED / RPP	1 e, μ	$\geq 2 b, \geq 3j$	Yes	36.1	KK mass 1.8 TeV Tier (1,1), $\mathcal{R}(A^{(1,1)} \rightarrow tt) = 1$
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	139	Z' mass 5.1 TeV
	SSM $Z' \rightarrow \tau\tau$	2 τ	-	-	36.1	Z' mass 2.42 TeV
	Leptophobic $Z' \rightarrow bb$	-	2b	-	36.1	Z' mass 2.1 TeV
	Leptophobic $Z' \rightarrow \tau\tau$	0 e, μ	$\geq 1 b, \geq 2J$	Yes	139	Z' mass 4.1 TeV $f/m = 1.2\%$
	SSM $W' \rightarrow \ell\nu$	1 e, μ	-	-	139	W' mass 6.0 TeV
	SSM $W' \rightarrow \tau\nu$	1 τ	-	-	36.1	W' mass 3.7 TeV
	HVT $W' \rightarrow WZ \rightarrow f\nu q$ model B	1 e, μ	2j/1J	Yes	139	W' mass 4.3 TeV $g_V = 3$
	HVT $V' \rightarrow WV \rightarrow q\nu q$ model B	0 e, μ	2j	-	139	V' mass 3.8 TeV $g_V = 3$
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	V' mass 2.93 TeV $g_V = 3$
	HVT $V' \rightarrow WH$ model B	0 e, μ	$\geq 1 b, \geq 2J$	Yes	139	W' mass 3.2 TeV $g_V = 3$
	LRSM $W_{\mu} \rightarrow tb$	multi-channel	-	-	36.1	W_{μ} mass 3.25 TeV
	LRSM $W_{\mu} \rightarrow \mu N_{\mu}$	2 μ	1J	-	90	W_{μ} mass 5.0 TeV $m(N_{\mu}) = 0.5 \text{ TeV}, g_{\mu} = g_{\mu}$
CI	CI $qqqq$	-	2j	-	37.0	A 21.8 TeV η_{CI}
	CI $t\bar{t}qq$	2 e, μ	-	-	139	A 35.8 TeV η_{CI}
	CI $t\bar{t}tt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	A 2.57 TeV $(C_{\text{CI}}) = 4e$
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1-4j	Yes	36.1	m_{Med} 1.55 TeV $g_{\mu} = -0.25, g_{\tau} = 1.0, m(\chi) = 1 \text{ GeV}$
	Colored scalar mediator (Dirac DM)	0 e, μ	1-4j	Yes	36.1	m_{Med} 1.67 TeV $g_{\tau} = 1.0, m(\chi) = 1 \text{ GeV}$
	VV_{EFT} (Dirac DM)	0 e, μ	1j, $\leq 1j$	Yes	3.2	M_{Pl} 700 GeV $m(\chi) = 150 \text{ GeV}$
	Scalar reson. $\phi \rightarrow \tau\tau$ (Dirac DM)	0-1 e, μ	1b, 0-1J	Yes	36.1	m_{ϕ} 3.4 TeV $y = 0.4, \lambda = 0.2, m(\chi) = 10 \text{ GeV}$
LO	Scalar LO 1 st gen	1, 2 e	$\geq 2j$	Yes	36.1	LO mass 1.4 TeV $\beta = 1$
	Scalar LO 2 nd gen	1, 2 μ	$\geq 2j$	Yes	36.1	LO mass 1.56 TeV $\beta = 1$
	Scalar LO 3 rd gen	2 τ	2b	-	36.1	LO mass 1.03 TeV $\mathcal{R}(LQ_{\mu} \rightarrow b\tau) = 1$
	Scalar LO 3 rd gen	0-1 e, μ	2b	Yes	36.1	LO mass 979 GeV $\mathcal{R}(LQ_{\tau} \rightarrow \tau\tau) = 0$
Heavy quarks	VLO $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV SU(2) doublet
	VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV SU(2) doublet
	VLO $T_{5,3} T_{5,3} \rightarrow Wt + X$	2(SS)/ $\geq 3 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	$T_{5,3}$ mass 1.64 TeV $\mathcal{R}(T_{5,3} \rightarrow Wt) = 1, c(T_{5,3}W) = 1$
	VLO $Y \rightarrow Wb + X$	1 e, μ	$\geq 1 b, \geq 1j$	Yes	36.1	Y mass 1.85 TeV $\mathcal{R}(Y \rightarrow Wb) = 1, c_{\text{cb}}(Wb) = 1$
	VLO $B \rightarrow Hb + X$	0 $e, \mu, 2 \gamma$	$\geq 1 b, \geq 1j$	Yes	79.8	B mass 1.21 TeV $\mathcal{R}(Y \rightarrow Wb) = 1, c_{\text{cb}}(Wb) = 1$
	VLO $QQ \rightarrow WqWq$	1 e, μ	$\geq 4j$	Yes	20.3	Q mass 680 GeV $x_{\text{q}} = 0.5$
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2j	-	139	q^* mass 6.7 TeV only u' and d' , $\Lambda = m(q')$
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1j	-	36.7	q^* mass 5.3 TeV only u' and d' , $\Lambda = m(q')$
	Excited quark $b^* \rightarrow bg$	-	1b, 1j	-	36.1	b^* mass 2.6 TeV
	Excited lepton ℓ^*	3 e, μ	-	-	20.3	ℓ^* mass 3.0 TeV $\Lambda = 3.0 \text{ TeV}$
	Excited lepton ν^*	3 e, μ, τ	-	-	20.3	ν^* mass 1.6 TeV $\Lambda = 1.6 \text{ TeV}$
Other	Type III Seesaw	1 e, μ	$\geq 2j$	Yes	79.8	N^c mass 560 GeV ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2j	-	36.1	N_{μ} mass 3.2 TeV $m(W_{\mu}) = 4.1 \text{ TeV}, g_{\mu} = g_{\mu}$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2, 3, 4 e, μ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV D^{\pm} production
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV D^{\pm} production, $\mathcal{R}(H^{\pm\pm} \rightarrow \ell\tau) = 1$
	Multi-charged particles	-	-	-	36.1	multi-charged particle mass D^{\pm} production, $ g = 5e$
	Magnetic monopoles	-	-	-	34.4	monopole mass 1.22 TeV D^{\pm} production, $ g = 1g_{\text{p}}, \text{spin } 1/2$

*Only a selection of the available mass limits on new states or phenomena is shown.

† Small-radius (large-radius) jets are denoted by the letter j (J).

Alternate approach

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{model}$$



\mathcal{L}_{SMEFT}

And perform a global SMEFT fit once and for all.

Benefit: many IR physics
Parts of calc are the SAME
And this is captured in EFT

The SMEFT is a key tool for interpreting ?deviations? like:



High-precision measurement of the W boson mass with the CDF II detector

CDF COLLABORATION††† J. AALTONEN, S. AMERI, G. AMISE, A. ANASTASSOV, A. ANNOVI, J. ANTOS, G. APOLLINARI, J. A. APPEL, L. J. S. ZUCCHELLI +389 authors

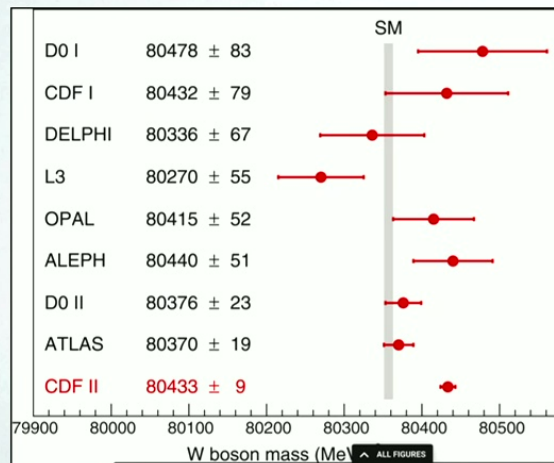
[Authors Info & Affiliations](#)

SCIENCE · 7 Apr 2022 · Vol 376, Issue 6589 · pp. 170-176 · DOI:10.1126/science.aba1781

97,942



- Any one measurement will just dictate a parameter in a theory. But a PATTERN of measurements can falsify a theory. We need to study the Global data set in SMEFT.



- SMEFT allows the experimental pattern to deviation From the SM expectation - while still doing well Defined field theory.

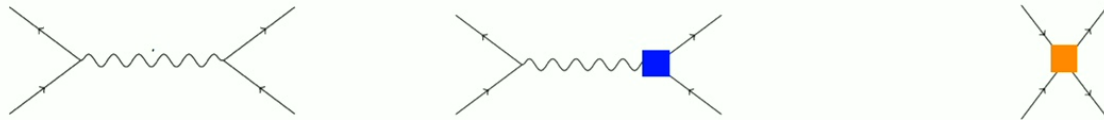
Find deviations → Map to pattern in SMEFT

↓
Follow pattern to underlying model

Inputs also needed -SMEFT Muon decay

- Decay of $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$ still measured far below the W pole.
1312.2014 Alonso, Jenkins, Manohar, Trott
- Still probes the effective lagrangian

$$\mathcal{L}_{G_F} = -\frac{4G_F}{\sqrt{2}} (\bar{\nu}_\mu \gamma^\mu P_L \mu) (\bar{e} \gamma_\mu P_L \nu_e)$$



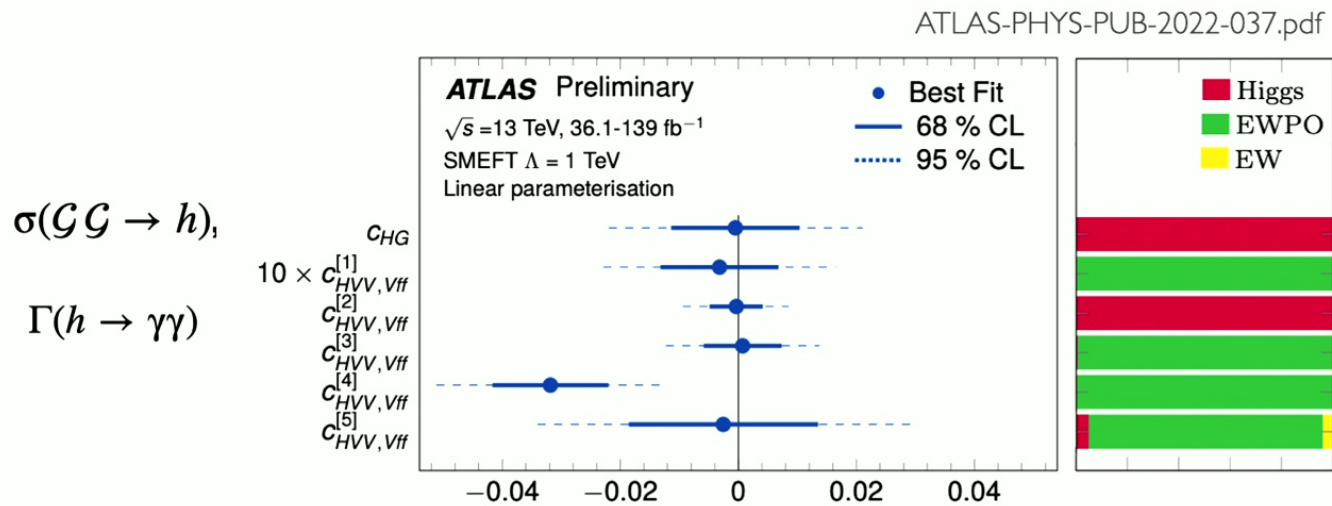
So now

$$-\frac{4G_F}{\sqrt{2}} = -\frac{2}{v_T^2} + \left(\frac{C_{\mu e e \mu}}{\Lambda^2} + \frac{C_{e \mu \mu e}}{\Lambda^2} \right) - 2 \left(\frac{C_{Hl}^{(3)}}{\Lambda^2} + \frac{C_{\mu\mu}^{(3)}}{\Lambda^2} \right)$$

δG_F

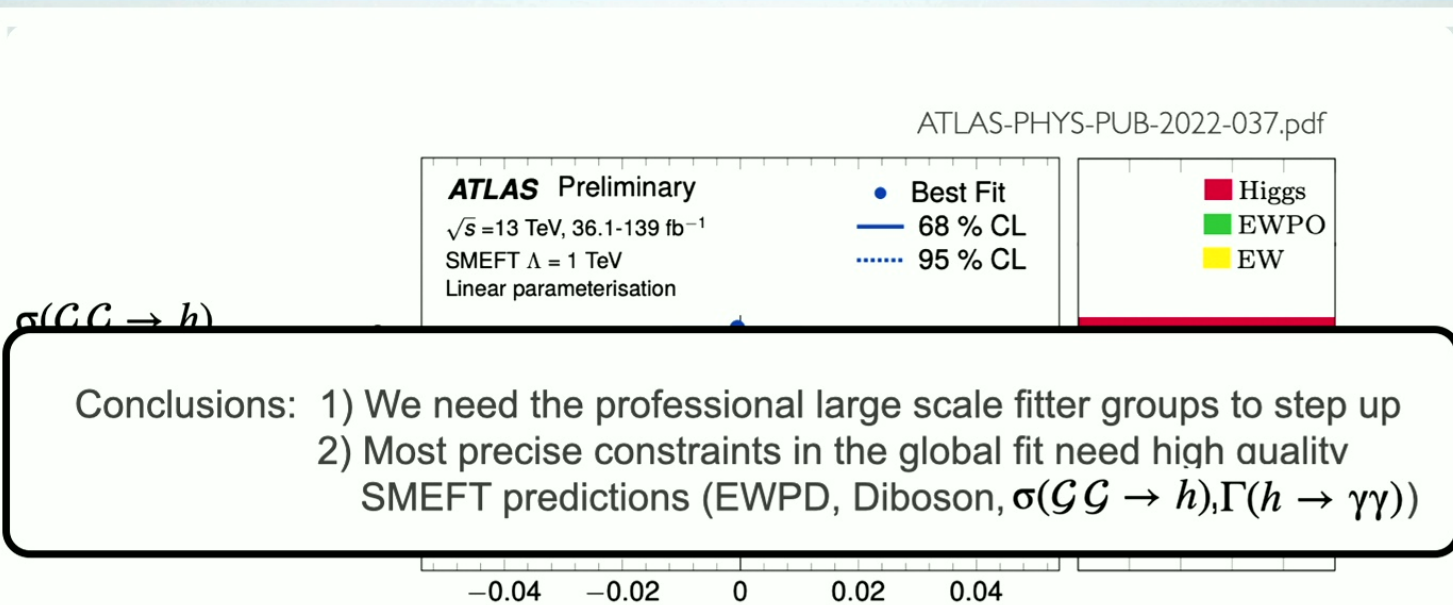
- Tons of work to redefine things at dim 6, can we go to dim 8?

Due to SMEFTsim the experimentalists have stepped up



- As this evolves forward, we need precise and consistent SMEFT results for these LHC two processes, and EWPD in particular.

Due to SMEFTsim the experimentalists have stepped up



- As this evolves forward, we need precise and consistent SMEFT results for these LHC two processes, and EWPD in particular.

An instant pay off of “geoSMEFT”

- Growth in operator forms in connections
Always saturate to fixed number, this is just the simplest organization exploiting this

- Once we have things to dim eight it is sufficient in many observables

Field space connection	Mass Dimension				
	6	8	10	12	14
$h_{IJ}(\phi)(D_\mu\phi)^I(D^\mu\phi)^J$	2	2	2	2	2
$g_{AB}(\phi)\mathcal{W}_{\mu\nu}^A\mathcal{W}^{B,\mu\nu}$	3	4	4	4	4
$\kappa_{IJA}(\phi)(D^\mu\phi)^I(D^\nu\phi)^J\mathcal{W}_{\mu\nu}^A$	0	3	4	4	4
$f_{ABC}(\phi)\mathcal{W}_{\mu\nu}^A\mathcal{W}^{B,\nu\rho}\mathcal{W}_\rho^{C,\mu}$	1	2	2	2	2
$Y_{pr}^u(\phi)\bar{Q}u + \text{h.c.}$	$2N_f^2$	$2N_f^2$	$2N_f^2$	$2N_f^2$	$2N_f^2$
$Y_{pr}^d(\phi)\bar{Q}d + \text{h.c.}$	$2N_f^2$	$2N_f^2$	$2N_f^2$	$2N_f^2$	$2N_f^2$
$Y_{pr}^e(\phi)\bar{L}e + \text{h.c.}$	$2N_f^2$	$2N_f^2$	$2N_f^2$	$2N_f^2$	$2N_f^2$
$d_A^{e,pr}(\phi)\bar{L}\sigma_{\mu\nu}e\mathcal{W}_A^{\mu\nu} + \text{h.c.}$	$4N_f^2$	$6N_f^2$	$6N_f^2$	$6N_f^2$	$6N_f^2$
$d_A^{u,pr}(\phi)\bar{Q}\sigma_{\mu\nu}u\mathcal{W}_A^{\mu\nu} + \text{h.c.}$	$4N_f^2$	$6N_f^2$	$6N_f^2$	$6N_f^2$	$6N_f^2$
$d_A^{d,pr}(\phi)\bar{Q}\sigma_{\mu\nu}d\mathcal{W}_A^{\mu\nu} + \text{h.c.}$	$4N_f^2$	$6N_f^2$	$6N_f^2$	$6N_f^2$	$6N_f^2$
$L_{pr,A}^{\psi R}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,R}\gamma_\mu\sigma_A\psi_{r,R})$	N_f^2	N_f^2	N_f^2	N_f^2	N_f^2
$L_{pr,A}^{\psi L}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,L}\gamma_\mu\sigma_A\psi_{r,L})$	$2N_f^2$	$4N_f^2$	$4N_f^2$	$4N_f^2$	$4N_f^2$

Mases

Couplings and mixing angles

TGC, Higgs to ZZ, WW

QGC, TGC + Higgs

Yukawas

Dipoles

W,Z couplings to fermions +higgs

2001.01453 Helset, Martin, Trott

Field coord. invariance leads to field space geometry

$$\mathcal{L}_{SMEFT} = \frac{1}{2} h_{IJ}(\phi) (D_\mu \phi)^I (D_\mu \phi)^J - \frac{1}{4} g_{AB}(\phi) \mathcal{W}_{\mu\nu}^A \mathcal{W}_{\mu\nu}^B + \dots$$

- Dimensionless expansion into operator bases $\tilde{C}_i = \frac{\langle H^\dagger H \rangle}{\Lambda^2} C_i$

$$\sqrt{h}^{IJ} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 - \frac{1}{4} \tilde{C}_{HD} & 0 \\ 0 & 0 & 0 & 1 + \tilde{C}_{H\Box} - \frac{1}{4} \tilde{C}_{HD} \end{bmatrix}$$

$$\sqrt{g}^{AB} = \begin{bmatrix} 1 + \tilde{C}_{HW} & 0 & 0 & 0 \\ 0 & 1 + \tilde{C}_{HW} & 0 & 0 \\ 0 & 0 & 1 + \tilde{C}_{HW} & -\frac{\tilde{C}_{HWB}}{2} \\ 0 & 0 & -\frac{\tilde{C}_{HWB}}{2} & 1 + \tilde{C}_{HB} \end{bmatrix}$$

(Small perturbations so positive semi-definite matrix and unique square root)

- Geometric field space quantities are useful (True independent of mass dimension of ops)
Amp. perturb. are:

$$\mathcal{A} \simeq \mathcal{A}_{SM} + \langle \mathcal{O} \rangle_1 N_1 + \langle \mathcal{O} \rangle_2 N_2 + \dots$$

↖ Fun. of 4 vectors (kinematics)
↖ Defined by field space geometries

Simple all orders results for the vev expansion

- Glue Glue higgs

$$\langle h | \mathcal{G}\mathcal{G} \rangle = -\frac{\sqrt{h}^{44}}{4} \langle h \mathcal{G}_{\mu\nu} \mathcal{G}^{\mu\nu} \rangle \frac{\delta \kappa_{AA}}{\delta \phi_4}$$

- Higgs to gamma gamma

$$\langle h | \mathcal{A}(p_1) \mathcal{A}(p_2) \rangle = -\langle h A^{\mu\nu} A_{\mu\nu} \rangle \frac{\sqrt{h}^{44}}{4} \left[\left\langle \frac{\delta g_{33}(\phi)}{\delta \phi_4} \right\rangle \frac{\bar{e}^2}{g_2^2} + 2 \left\langle \frac{\delta g_{34}(\phi)}{\delta \phi_4} \right\rangle \frac{\bar{e}^2}{g_1 g_2} + \left\langle \frac{\delta g_{44}(\phi)}{\delta \phi_4} \right\rangle \frac{\bar{e}^2}{g_1^2} \right],$$

- Where the geometric electric charge is $\bar{e} = g_2 (s_{\bar{\theta}} \sqrt{g}^{33} + c_{\bar{\theta}} \sqrt{g}^{34})$

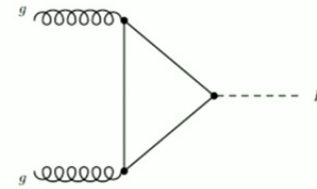
$$s_{\bar{\theta}}^2 = \frac{(g_1 \sqrt{g}^{44} - g_2 \sqrt{g}^{34})^2}{g_1^2 [(\sqrt{g}^{34})^2 + (\sqrt{g}^{44})^2] + g_2^2 [(\sqrt{g}^{33})^2 + (\sqrt{g}^{34})^2] - 2g_1 g_2 \sqrt{g}^{34} (\sqrt{g}^{33} + \sqrt{g}^{44})}$$

LO SMEFT perturbation to the SM predictions

- **Modifications to the properties of the Higgs boson**

Aneesh V. Manohar (UC, San Diego), Mark B. Wise (Caltech) (Jan, 2006)

Published in: *Phys.Lett.B* 636 (2006) 107-113 • e-Print: [hep-ph/0601212](https://arxiv.org/abs/hep-ph/0601212) [hep-ph]



$$\frac{\sigma(gg \rightarrow h)}{\sigma^{\text{SM}}(gg \rightarrow h)} \simeq \frac{\Gamma(h \rightarrow gg)}{\Gamma^{\text{SM}}(h \rightarrow gg)} \simeq \left| 1 - \frac{8\pi^2 v^2 c_G}{\Lambda^2 I^g} \right|^2$$

$$\delta\mathcal{L} = -\frac{c_G g_3^2}{2\Lambda^2} H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$$

$$I^g = I_f(m_h^2/(4m_t^2), 0) \left(1 + \frac{11}{4} \frac{\alpha_s}{\pi} \right), \quad \leftarrow \text{Partial 2 loop result, the 2 loop matching}$$

$$I_f(a, b) = \int_0^1 dx \int_0^{1-x} dy \frac{1 - 4xy}{1 - 4(a-b)xy - 4by(1-y) - i0^+}$$

SM results at LO:

H. M. Georgi, S. L. Glashow, M. E. Machacek and D. V. Nanopoulos, *Higgs Bosons from Two Gluon Annihilation in Proton Proton Collisions*, *Phys. Rev. Lett.* **40** (1978) 692.

M. A. Shifman, A. I. Vainshtein, M. B. Voloshin and V. I. Zakharov, *Low-Energy Theorems for Higgs Boson Couplings to Photons*, *Sov. J. Nucl. Phys.* **30** (1979) 711.

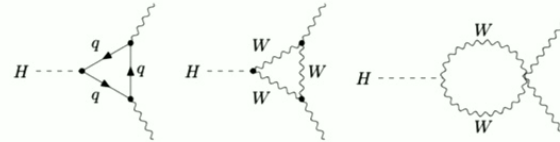
LO SMEFT perturbation to the SM predictions

- **Modifications to the properties of the Higgs boson**

Aneesh V. Manohar (UC, San Diego), Mark B. Wise (Caltech) (Jan, 2006)

Published in: *Phys.Lett.B* 636 (2006) 107-113 • e-Print: [hep-ph/0601212](https://arxiv.org/abs/hep-ph/0601212) [hep-ph]

$$\frac{\Gamma(h \rightarrow \gamma\gamma)}{\Gamma^{\text{SM}}(h \rightarrow \gamma\gamma)} \simeq \left| 1 - \frac{4\pi^2 v^2 c_{\gamma\gamma}}{\Lambda^2 I_\gamma} \right|^2$$



$$c_{\gamma\gamma} = c_W + c_B - c_{WB}$$

$$\delta\mathcal{L} = -\frac{c_B g_1^2}{2\Lambda^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} - \frac{c_{WB} g_1 g_2}{2\Lambda^2} H^\dagger \tau^a H B_{\mu\nu} W^{a\mu\nu} - \frac{c_W g_2^2}{2\Lambda^2} H^\dagger H W_{\mu\nu}^a W^{a\mu\nu} - \frac{c_G g_3^2}{2\Lambda^2} H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$$

- We have improved both of these processes to consistent dimension 8 and one more loop order. (A short 17 years later!)

LO SMEFT perturbation to the SM predictions

- Modifications to the properties of the Higgs boson

Aneesh V. Manohar (UC, San Diego), Mark B. Wise (Caltech) (Jan, 2006)

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$$\frac{\Gamma(h \rightarrow \gamma\gamma)}{\Gamma^{\text{SM}}(h \rightarrow \gamma\gamma)} \simeq \left| 1 - \frac{4\pi v^2 c_{\gamma\gamma}}{\Lambda^2 I_\gamma} \right|^2$$

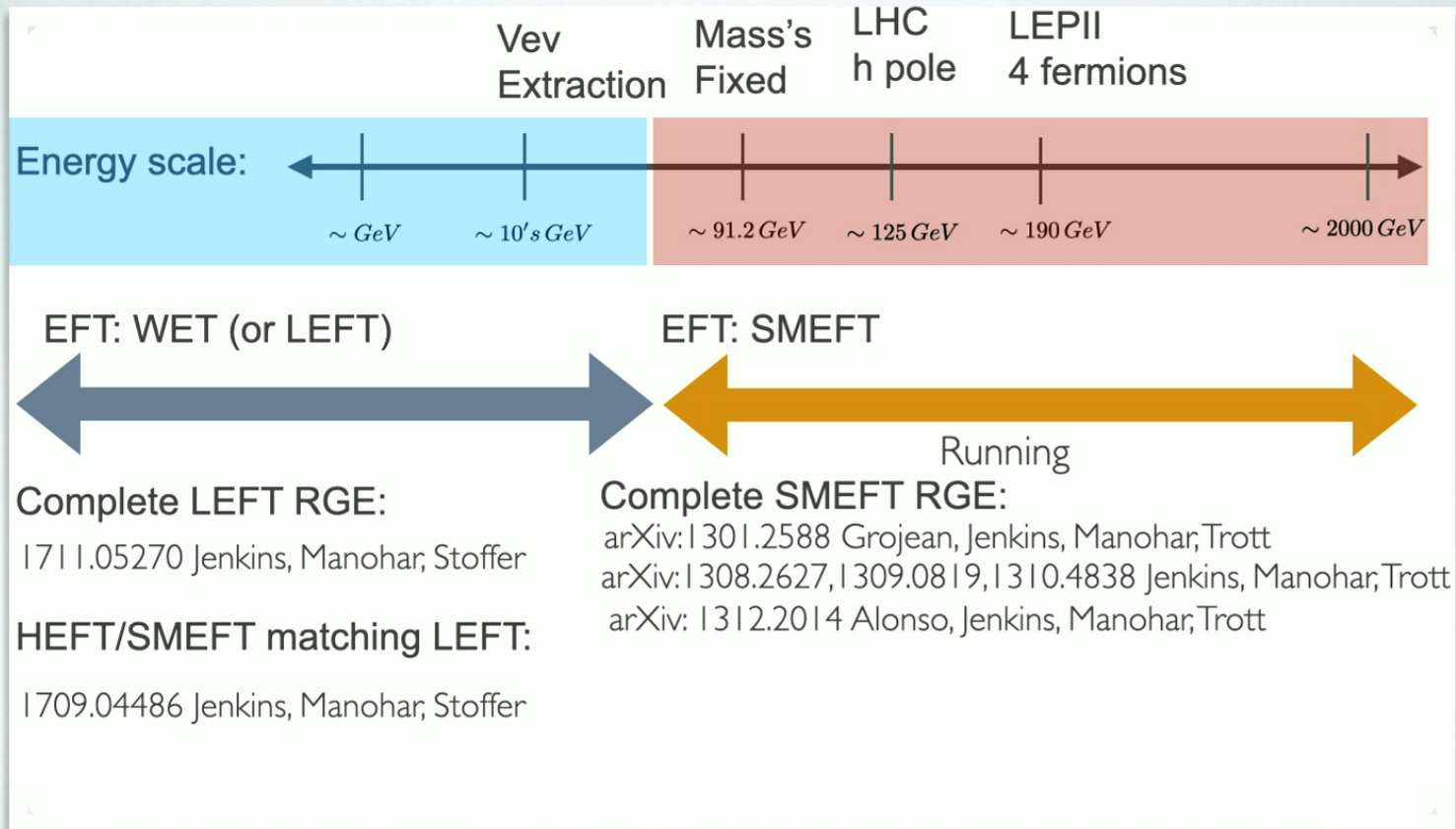
$$c_{\gamma\gamma} = c_W + c_B - c_{WB}$$

$$\delta\mathcal{L} = -\frac{c_1 g_1^2}{2\Lambda^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} - \frac{c_W B g_1 g_2}{2\Lambda^2} H^\dagger \tau^a H B_{\mu\nu} W^{a\mu\nu} - \frac{c_V g_2^2}{2\Lambda^2} H^\dagger H W_{\mu\nu}^a W^{a\mu\nu} - \frac{c_G g_3^2}{2\Lambda^2} H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$$

- Doing this in that timeframe is actually not so bad!

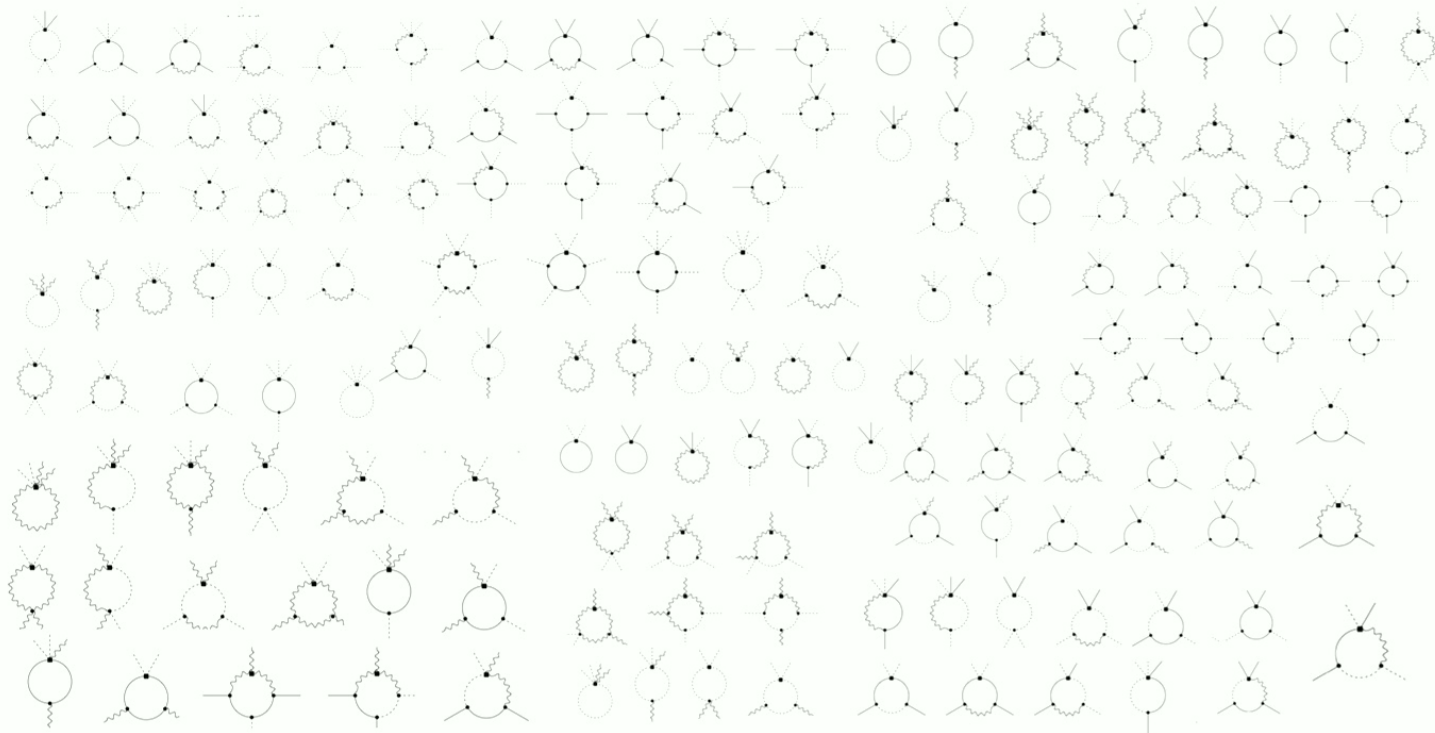
Need to include SMEFT loop corrections and operator corrections to actual processes AND the input parameter processes used to fix the Lagrangian terms.

The Relevant Tower of EFT's



SMEFT renormalised.. as was LEFT

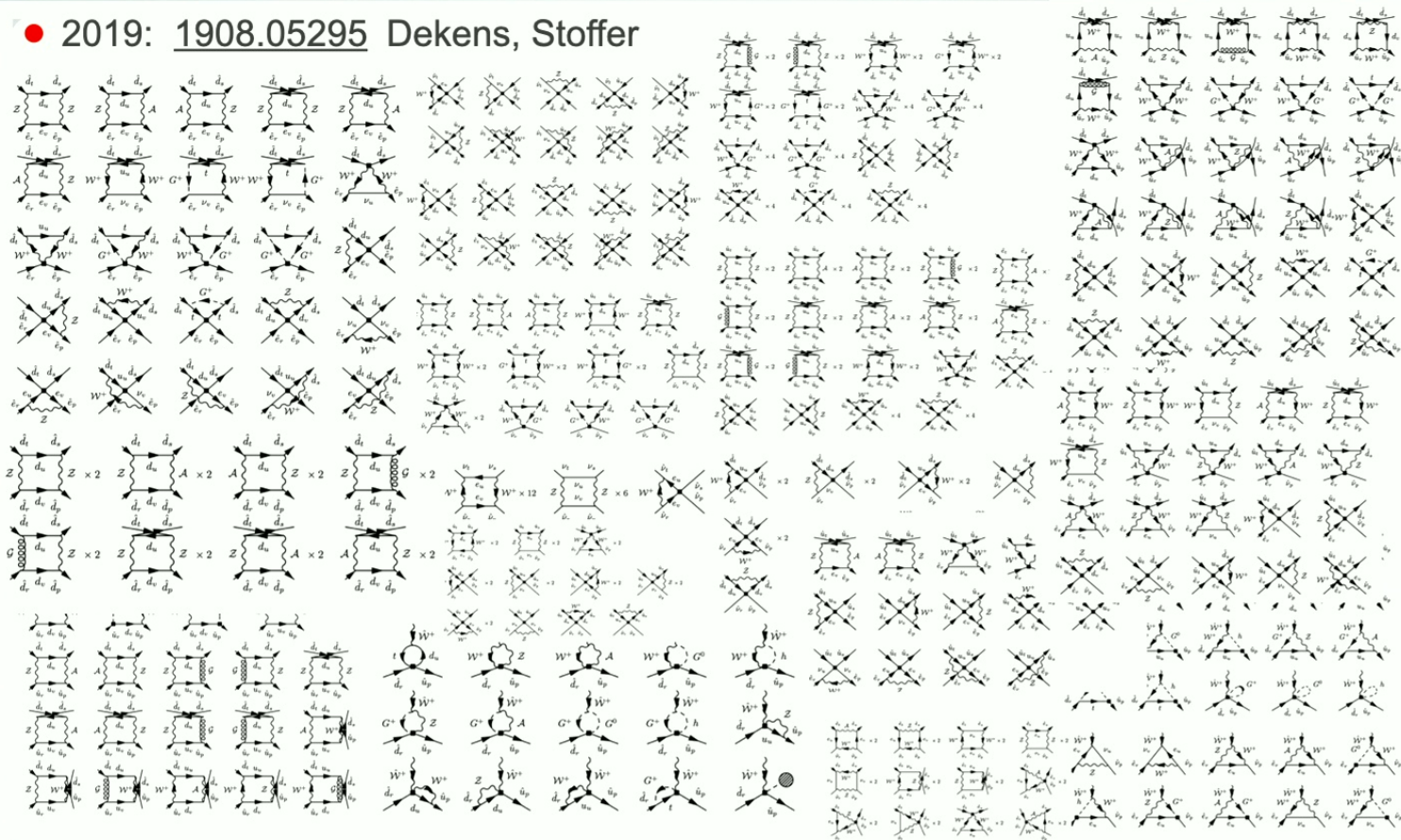
- SMEFT RGE's



- Each dot can be 59 types operator

Subset of the one loop matching.

● 2019: [1908.05295](#) Dekens, Stoffer



Michael Trott, Caltech/Perimeter

23

One loop vev extraction

One loop matching onto the LEFT operator:

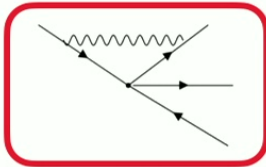
$$\mathcal{L}_{LEFT} \supset L^{V,LL}(\bar{\nu}_{L,\mu}\gamma^\mu\nu_{L,e})(\bar{e}_L\gamma_\mu\mu_L).$$

Δ : Loop expansion

δ : Higher dimensional op (vev) expansion

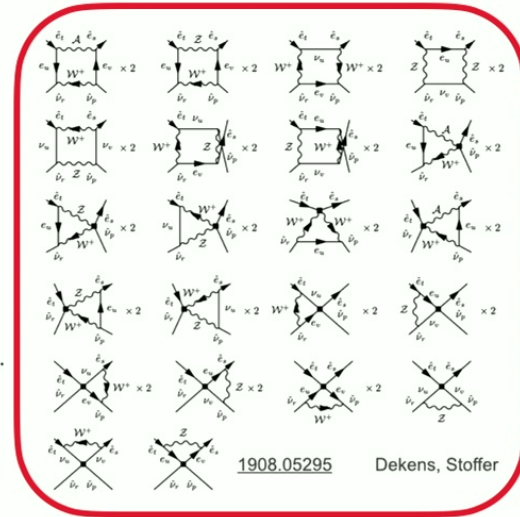
$$\begin{aligned} \bar{v}_T^2 \Delta L^{V,LL} = & \frac{(7\bar{m}_h^4 + \bar{m}_h^2(2m_t^2 N_c - 5(2\bar{m}_W^2 + \bar{m}_Z^2))) + 4(-4m_t^4 N_c + 2\bar{m}_W^4 + \bar{m}_Z^4)}{16\pi^2 \bar{m}_h^2 \bar{v}_T^2}, \\ & + \frac{3(\bar{m}_h^4 - 2\bar{m}_h^2 \bar{m}_W^2)}{8\pi^2 \bar{v}_T^2 (\bar{m}_h^2 - \bar{m}_W^2)} \log\left(\frac{\mu^2}{\bar{m}_h^2}\right) + \frac{m_t^2 N_c (\bar{m}_h^2 - 4m_t^2)}{4\pi^2 \bar{m}_h^2 \bar{v}_T^2} \log\left(\frac{\mu^2}{m_t^2}\right), \\ & + \frac{3(\bar{m}_h^2 (\bar{m}_Z^4 - 2\bar{m}_W^2 \bar{m}_Z^2) + 2\bar{m}_Z^4 (\bar{m}_W^2 - \bar{m}_Z^2))}{8\pi^2 \bar{m}_h^2 \bar{v}_T^2 (\bar{m}_W^2 - \bar{m}_Z^2)} \log\left(\frac{\mu^2}{\bar{m}_Z^2}\right), \\ & - \frac{3\bar{m}_W^2 (\bar{m}_h^4 (\bar{m}_W^2 - 2\bar{m}_Z^2) + \bar{m}_h^2 (7\bar{m}_W^2 \bar{m}_Z^2 - 6\bar{m}_W^4) + 4\bar{m}_W^4 (\bar{m}_W^2 - \bar{m}_Z^2))}{8\pi^2 \bar{m}_h^2 \bar{v}_T^2 (\bar{m}_h^2 - \bar{m}_W^2) (\bar{m}_W^2 - \bar{m}_Z^2)} \log\left(\frac{\mu^2}{\bar{m}_W^2}\right). \end{aligned}$$

Need to add back photon loops canceling in matching:



$$\Delta L_{ew}^{V,LL} = -\frac{\alpha}{4\pi} \left(\pi^2 - \frac{25}{4} \right). \quad \text{G. Kallen, Radiative corrections in elementary particle physics, Springer Tracts Mod. Phys. 46 (1968) 67.}$$

End result:
$$-\frac{4\hat{G}_F}{\sqrt{2}} = -\frac{2}{\bar{v}_T^2} (1 + \Delta L_{ew}^{V,LL}) + \Delta L^{V,LL} - 2\sqrt{2} \frac{\delta G_F}{\bar{v}_T^2}$$



GeoSMEFT based loop corrections.

- Many groups calculate in the background field gauge fixing with a geoSMEFT gauge fixing term

$$\mathcal{L}_{\text{GF}} = -\frac{\hat{g}_{AB}}{2\xi} \mathcal{G}^A \mathcal{G}^B,$$

$$\mathcal{G}^X \equiv \partial_\mu \mathcal{W}^{X,\mu} - \tilde{\epsilon}_{CD}^X \hat{\mathcal{W}}_\mu^C \mathcal{W}^{D,\mu} + \frac{\xi}{2} \hat{g}^{XC} \phi^I \hat{h}_{IK} \tilde{\gamma}_{C,J}^K \hat{\phi}^J.$$

[1803.08001](#) Helset, Paraskevas, Trott.

- Immediate BFM Ward Identities were derived:

$$0 = \left(\partial^\mu \delta_B^A - \tilde{\epsilon}_{BC}^A \hat{\mathcal{W}}^{C,\mu} \right) \frac{\delta \Gamma}{\delta \hat{\mathcal{W}}_A^\mu} - \frac{\tilde{\gamma}_{B,J}^I}{2} \hat{\phi}^J \frac{\delta \Gamma}{\delta \hat{\phi}^I} + \sum_j \left(\bar{f}_j \bar{\Lambda}_{B,i}^j \frac{\delta \Gamma}{\delta f_i} - \frac{\delta \Gamma}{\delta f_i} \Lambda_{B,j}^i f_j \right).$$

[1909.08470](#) Corbett, Helset, Trott

And checked

[2010.08451](#) Corbett, Trott [2010.15852](#) Corbett

- at one loop in the results. It works.

Consistency checks at one loop/dim8

Benefits of the Background Field method one loop approach in SMEFT.

- Cross checks/understanding afforded (Ward identities and more).
- One loop redefinition of input parameters INDIVIDUALLY gauge independent.

- Cross checks of $\Delta Z_e = -\frac{1}{2}\Delta Z_{\hat{A}}$, Our calc in [2107.07470](#)
 $\Delta R_e = -\frac{1}{2}\Delta R_{\hat{A}}$. Stoffer/Denkens in [1908.05295](#)

$$\Delta R_{\hat{A}} = \frac{\bar{g}_1^2 \bar{g}_2^2}{(\bar{g}_1^2 + \bar{g}_2^2)} \left[-\frac{7}{16\pi^2} \log\left(\frac{\mu^2}{\bar{m}_W^2}\right) + \sum_{\psi} \frac{N_c^{\psi} Q_{\psi}^2}{12\pi^2} \log\left(\frac{\mu^2}{\bar{m}_{\psi}^2}\right) - \frac{1}{24\pi^2} \right].$$

Cross checks worked out

Cancelation of large m_t dependent logs in relations between observables:
Expected and anticipated in [1505.02646](#) Hartmann, Trott

- Expected cancelation confirmed in [2107.07470](#) and [1908.05295](#)

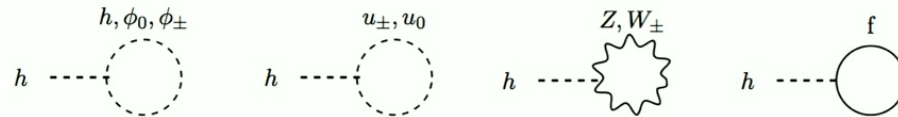
$$\bar{v}_T = \hat{v}_T \left[1 + \frac{2y_t^2}{16\pi^2} N_C \frac{m_f^2}{\bar{m}_h^2} \left[1 + \log \left(\frac{\mu^2}{m_f^2} \right) \right] + \dots \right].$$

$$\frac{\Delta v}{\bar{v}_T} \propto -\frac{2y_t^2}{16\pi^2} N_C \frac{m_f^2}{\bar{m}_h^2} \left[1 + \log \left(\frac{\mu^2}{m_f^2} \right) \right].$$

- Cancelation in single Higgs, single dev observables with tadpole term and GF extraction. We both use the FJ tadpole scheme.

NLO EFT - fix finite terms

- Define vev of the theory as the one point function vanishing - fixes Δv



$$T = m_h^2 h v \frac{1}{16\pi^2} \left[-16\pi^2 \frac{\Delta v}{v} + 3\lambda \left(1 + \log \left[\frac{\mu^2}{m_h^2} \right] \right) + \frac{m_W^2}{v^2} \xi \left(1 + \log \left[\frac{\mu^2}{\xi m_W^2} \right] \right), \right. \\ \left. + \frac{1}{2} \frac{m_Z^2}{v^2} \xi \left(1 + \log \left[\frac{\mu^2}{\xi m_Z^2} \right] \right) - \frac{1}{2} \sum_i y_i^4 N_c \frac{1}{\lambda} \left(1 + \log \left[\frac{\mu^2}{m_i^2} \right] \right), \right. \\ \left. + \frac{g_2^2}{2} \frac{m_W^2}{m_h^2} \left(1 + 3 \log \left[\frac{\mu^2}{m_W^2} \right] \right) + \frac{1}{4} (g_1^2 + g_2^2) \frac{m_Z^2}{m_h^2} \left(1 + 3 \log \left[\frac{\mu^2}{m_Z^2} \right] \right) \right].$$

- How do we deal with tadpoles? FJ tadpole scheme

J. Fleischer and F. Jegerlehner, *Radiative Corrections to Higgs Decays in the Extended Weinberg-Salam Model*, *Phys. Rev. D* **23** (1981) 2001.

One point function vanishes, so drop tadpoles. Include Δv when expanding around min.

Consistency checks at one loop/dim8

- Gauge independence of a common partial matrix element in single Higgs processes

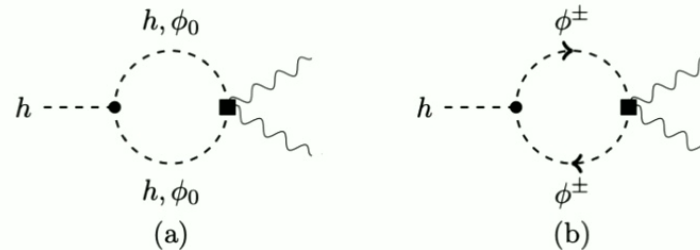


Figure 2. One loop contributions to $\langle \phi_4 | F F \rangle \langle \frac{\delta M_{AB}}{\delta \phi_4} \rangle$.

$$\frac{\langle \phi_4 F(p_1) F(p_2) \rangle^1}{\langle \phi_4 F^{\mu\nu} F_{\mu\nu} \rangle^0 \langle \frac{\delta M_{AB}(\phi)}{\delta \phi_4} \rangle^0} \propto M_1$$

- This common sub diagram contribution to $\sigma(\mathcal{G}\mathcal{G} \rightarrow h), \Gamma(h \rightarrow \gamma\gamma)$ is gauge independent:

$$M_1 \equiv \left(\frac{\Delta R_h}{2} + \frac{\Delta v}{v} + \frac{(\sqrt{3}\pi-6)\lambda}{16\pi^2} + \frac{1}{16\pi^2} \left(\frac{\bar{g}_1^2}{4} + \frac{3\bar{g}_2^2}{4} + 6\lambda \right) \log \left[\frac{\bar{m}_h^2}{\mu^2} \right] \right), \\ + \frac{1}{16\pi^2} \left(\frac{\bar{g}_1^2}{4} \mathcal{I}[\bar{m}_Z] + \left(\frac{\bar{g}_2^2}{4} + \lambda \right) (\mathcal{I}[\bar{m}_Z] + 2\mathcal{I}[\bar{m}_W]) \right).$$

Best practice example in SMEFT (3 schemes)

$$\begin{aligned} \frac{\Gamma_{SMEFT}}{\hat{\Gamma}_{SM}} \simeq & 1 + S_1 \left[f_1 + \left(\tilde{C}_{H\Box}^{(6)} - \frac{\tilde{C}_{HD}^{(6)}}{4} \right) f_1 + f_2 \right] + S_2 f_1^2 + S_3 (\tilde{C}_{HW}^{(6)} - \tilde{C}_{HB}^{(6)})^2 + S_4 \delta G_F^{(6)} \tilde{C}_{HB}^{(6)}, \\ & + S_5 \delta G_F^{(6)} \tilde{C}_{HW}^{(6)} + S_6 \delta G_F^{(6)} \tilde{C}_{HWB}^{(6)} + S_7 \tilde{C}_{HD}^{(6)} \tilde{C}_{HB}^{(6)} + S_8 \tilde{C}_{HD}^{(6)} \tilde{C}_{HW}^{(6)} + S_9 \tilde{C}_{HD}^{(6)} \tilde{C}_{HWB}^{(6)}, \\ & + S_{10} \tilde{C}_{HWB}^{(6)} \tilde{C}_{HB}^{(6)} + S_{11} \tilde{C}_{HWB}^{(6)} \tilde{C}_{HW}^{(6)} + S_{12} (\tilde{C}_{HWB}^{(6)})^2 + S_{13} \tilde{C}_{HB}^{(6)} + S_{14} \tilde{C}_{HW}^{(6)}, \\ & + \left[S_{15} + S_{16} \log \left(\frac{\hat{m}_h^2}{\Lambda^2} \right) \right] \tilde{C}_{HWB}^{(6)} + \left[S_{17} + S_{18} \log \left(\frac{\hat{m}_h^2}{\Lambda^2} \right) \right] \tilde{C}_W^{(6)}, \\ & + \left[S_{19} + S_{20} \log \left(\frac{\hat{m}_h^2}{\Lambda^2} \right) \right] \text{Re} \tilde{C}_{uB}^{(6)} + \left[S_{21} + S_{22} \log \left(\frac{\hat{m}_h^2}{\Lambda^2} \right) \right] \text{Re} \tilde{C}_{uW}^{(6)} + S_{23} \text{Re} \tilde{C}_{uH}^{(6)}, \\ & + S_{24} \text{Re} \tilde{C}_{dH}^{(6)} + S_{25} \left(\tilde{C}_{H\Box}^{(6)} - \frac{\tilde{C}_{HD}^{(6)}}{4} \right) + S_{26} \tilde{C}_{HD}^{(6)} + S_{27} \tilde{C}_{HWB}^{(6)} + S_{28} \sqrt{2} \delta G_F^{(6)}. \end{aligned}$$

• Here

$$\begin{aligned} \delta G_F^{(6)} &= \frac{1}{\sqrt{2}} \left(\tilde{C}_{ee}^{(3)} + \tilde{C}_{\mu\mu}^{(3)} - \frac{1}{2} (\tilde{C}'_{\mu e \mu} + \tilde{C}'_{e \mu e}) \right), \\ f_1^{\hat{m}_W} &= \left[\tilde{C}_{HB}^{(6)} + 0.29 \tilde{C}_{HW}^{(6)} - 0.54 \tilde{C}_{HWB}^{(6)} \right], \\ f_2^{\hat{m}_W} &= \left[\tilde{C}_{HB}^{(8)} + 0.29 (\tilde{C}_{HW}^{(8)} + \tilde{C}_{HW2}^{(8)}) - 0.54 \tilde{C}_{HWB}^{(8)} \right], \\ f_3^{\hat{m}_W} &= \left[\tilde{C}_{HW}^{(6)} - \tilde{C}_{HB}^{(6)} - 0.66 \tilde{C}_{HWB}^{(6)} \right]. \end{aligned}$$

- Significant input parameter Dependence in what you get. This is expected. 2305.05879

	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}
\hat{M}_W	-753	1.41×10^5	321	2041	586	-1093	897	721	-914	1880
$\hat{\alpha}_{ew}^{(\hat{M}_Z)}$	-724	1.30×10^5	-320	1402	-126	-269	149	-149	95.0	297
$\hat{\alpha}_{ew}^{(0)}$	-794	1.56×10^5	-317	1447	-105	-274	138	-138	97.0	227

	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}	S_{20}	S_{21}
\hat{M}_W	1587	-1843	-100	-21.2	46.2	1.87	-0.51	3.28	24.4	-25.6	13.1
$\hat{\alpha}_{ew}^{(\hat{M}_Z)}$	-297	320	-199	32.0	-16.0	1.80	-0.49	3.25	23.9	-25.0	43.6
$\hat{\alpha}_{ew}^{(0)}$	-227	317	-222	30.3	-20.7	1.95	-0.45	3.32	25.1	-26.3	48.4

	S_{22}	S_{23}	S_{24}	S_{25}	S_{26}	S_{27}	S_{28}
\hat{M}_W	-13.7	0.51	-0.28	2	-3.49	-7.5	$-3\sqrt{2}$
$\hat{\alpha}_{ew}^{(\hat{M}_Z)}$	-45.7	0.51	-0.28	2	0	0	$-\sqrt{2}$
$\hat{\alpha}_{ew}^{(0)}$	-50.7	5.04	-1.22	2	0	0	$-\sqrt{2}$

Table 3. Numerical coefficients for SMEFT perturbations to $\Gamma(h \rightarrow \mathcal{A}\mathcal{A})$ in three input parameter schemes, including two loop QCD interference effects.

Best practice example in SMEFT (3 schemes)

$$\begin{aligned}
 \frac{\Gamma_{SMEFT}}{\hat{\Gamma}_{SM}} \simeq & 1 + S_1 \left[f_1 + \left(\tilde{C}_{H\Box}^{(6)} - \frac{\tilde{C}_{HD}^{(6)}}{4} \right) f_1 - f_2 \right] + S_2 f_1^2 + S_3 (\tilde{C}_{HW}^{(6)} - \tilde{C}_{HB}^{(6)})^2 + S_4 \delta G_F^{(6)} \tilde{C}_{HB}^{(6)}, \\
 & + S_5 \delta G_F^{(6)} \tilde{C}_{HW}^{(6)} + S_6 \delta G_F^{(6)} \tilde{C}_{HWB}^{(6)} + S_7 \tilde{C}_{HD}^{(6)} \tilde{C}_{HB}^{(6)} + S_8 \tilde{C}_{HD}^{(6)} \tilde{C}_{HW}^{(6)} + S_9 \tilde{C}_{HD}^{(6)} \tilde{C}_{HWB}^{(6)}, \\
 & + S_{10} \tilde{C}_{HWB}^{(6)} \tilde{C}_{HB}^{(6)} + S_{11} \tilde{C}_{HWB}^{(6)} \tilde{C}_{HW}^{(6)} + S_{12} (\tilde{C}_{HWB}^{(6)})^2 + S_{13} \tilde{C}_{HB}^{(6)} + S_{14} \tilde{C}_{HW}^{(6)}, \\
 & + \left[S_{15} + S_{16} \log \left(\frac{\hat{m}_h^2}{\Lambda^2} \right) \right] \tilde{C}_{HWB}^{(6)} + \left[S_{17} + S_{18} \log \left(\frac{\hat{m}_h^2}{\Lambda^2} \right) \right] \tilde{C}_W^{(6)}, \\
 & + \left[S_{19} + S_{20} \log \left(\frac{\hat{m}_h^2}{\Lambda^2} \right) \right] \text{Re} \tilde{C}_{uB}^{(6)} + \left[S_{21} + S_{22} \log \left(\frac{\hat{m}_h^2}{\Lambda^2} \right) \right] \text{Re} \tilde{C}_{uW}^{(6)} + S_{23} \text{Re} \tilde{C}_{uH}^{(6)}, \\
 & + S_{24} \text{Re} \tilde{C}_{dH}^{(6)} + S_{25} \left(\tilde{C}_{H\Box}^{(6)} - \frac{\tilde{C}_{HD}^{(6)}}{4} \right) + S_{26} \tilde{C}_{HD}^{(6)} + S_{27} \tilde{C}_{HWB}^{(6)} + S_{28} \sqrt{2} \delta G_F^{(6)}.
 \end{aligned}$$

- The various contributions

$$\begin{aligned}
 |\mathcal{A}_{SM}^{a,ij} + \mathcal{A}_{SMEFT}^{a,ij}|^2 &= |\mathcal{A}_{SM}^{a,ij} + \frac{\mathcal{A}_{SMEFT,6}^{a,ij}}{\Lambda^2} + \frac{\mathcal{A}_{SMEFT,8}^{a,ij}}{\Lambda^4} + \dots|^2 \\
 &= |\mathcal{A}_{SM}^{a,ij}|^2 + \mathcal{A}_{SM}^{a,ij} \frac{\mathcal{A}_{SMEFT,6}^{a,ij}}{\Lambda^2} + \left| \frac{\mathcal{A}_{SMEFT,6}^{a,ij}}{\Lambda^2} \right|^2 + \mathcal{A}_{SM}^{a,ij} \frac{\mathcal{A}_{SMEFT,8}^{a,ij}}{\Lambda^4} + \text{h.c.} + \dots
 \end{aligned}$$

All was not perfect as yet....

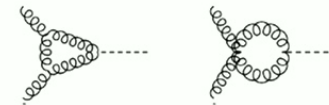
$$\sigma(\mathcal{G}\mathcal{G} \rightarrow h)$$

- The following challenges in 2107.07470:

- 1) SM results and literature are NOT in the BFM- but that seemed essential!?
- 2) 2 loop SM amplitudes were not presented in any transparent fashion
- 3) Two contributions:

$$\mathcal{O}(\alpha_s^2/(4\pi)^2) \longrightarrow \langle \mathcal{G}\mathcal{G}|h \rangle_{SM}^2 \times \langle \mathcal{G}\mathcal{G}|h \rangle_{\tilde{C}_{HG}}^0 \longleftarrow \mathcal{O}(v^2/\Lambda^2) C_{HG}$$

$$\mathcal{O}(\alpha_s/(4\pi)) \longrightarrow \langle \mathcal{G}\mathcal{G}|h \rangle_{SM}^1 \times \langle \mathcal{G}\mathcal{G}|h \rangle_{\tilde{C}_{HG}}^1 \longleftarrow \mathcal{O}(\alpha_s/(4\pi) v^2/\Lambda^2) C_{HG}$$



Improving $\sigma(\mathcal{G}\mathcal{G} \rightarrow h)$

- These contributions are the same in the $m_t \rightarrow \infty$ limit: 2305.05879 Martin, Trott

$$\begin{array}{ccc}
 & \langle \mathcal{G}\mathcal{G}|h \rangle_{SM}^2 \times \langle \mathcal{G}\mathcal{G}|h \rangle_{\tilde{C}_{HG}}^0 & \\
 & \updownarrow & \\
 \lim_{m_t \rightarrow \infty} \langle \mathcal{G}\mathcal{G}|h \rangle_{SM}^2 \frac{\tilde{C}_{HG}}{\bar{v}_T^0 \Delta C_{h\mathcal{G}\mathcal{G}}^{SM}} \rightarrow \langle \mathcal{G}\mathcal{G}|h \rangle_{\tilde{C}_{HG}}^1 & & \lim_{m_t \rightarrow \infty} \langle \mathcal{G}\mathcal{G}|h \rangle_{SM}^1 \equiv \langle \mathcal{G}\mathcal{G}|h \rangle_{\tilde{C}_{HG}}^0 \times \frac{\bar{v}_T^0 \Delta C_{h\mathcal{G}\mathcal{G}}^{SM}}{\tilde{C}_{HG}} \\
 & \downarrow & \\
 & \langle \mathcal{G}\mathcal{G}|h \rangle_{SM}^1 \times \langle \mathcal{G}\mathcal{G}|h \rangle_{\tilde{C}_{HG}}^1 &
 \end{array}$$

- After established by brute force!



Example of the utility of EFT, same composite operator form.

Renormalisation issue $\sigma(\mathcal{G}\mathcal{G} \rightarrow h)$

- The two loop amplitude in the $m_t \rightarrow \infty$ analytically with expansion in ϵ explicit: C. Anastasiou, N. Deuschmann and A. Schweitzer, *Quark mass effects in two-loop Higgs amplitudes*, *JHEP* **07** (2020) 113 [2001.06295].

$$S_\epsilon = (4\pi)^\epsilon \exp(-\epsilon\gamma_E)$$

(Mbar factor)

Gives analytically:

$$\mathcal{A}_{gg \rightarrow H}^0 = \frac{2i}{v^0} \frac{\alpha_s^0 S_\epsilon \mu^{-2\epsilon}}{4\pi} \left(-\frac{s}{\mu^2}\right)^{-\epsilon} \delta_{ab} (s(\epsilon_1 \cdot \epsilon_2) - 2(\epsilon_1 \cdot p_2)(\epsilon_2 \cdot p_1)) \times \left(M_{\text{LO}}^0 + \frac{\alpha_s^0 S_\epsilon \mu^{-2\epsilon}}{4\pi} \left(-\frac{s}{\mu^2}\right)^{-\epsilon} M_{\text{NLO}}^0 + \mathcal{O}((\alpha_s^0)^3)\right)$$

- LO result: $\Delta C_{hg\mathcal{G}}^{SM, m_t \rightarrow \infty} = -\frac{\alpha_s^{(r)}}{\bar{v}_T^0 16\pi} \left(\frac{\hat{m}_t^2}{\hat{\mu}^2}\right)^{-\epsilon} M_{t, SM}^{(0), m_t \rightarrow \infty}$,
 $= -\frac{\alpha_s^{(r)}}{\bar{v}_T^0 16\pi} \left[-\frac{4}{3} \left(1 + \frac{\pi^2}{12}\epsilon^2 - \epsilon L_{\hat{m}_t} + \frac{1}{2} L_{\hat{m}_t}^2 \epsilon^2 + \mathcal{O}(\epsilon^3)\right)\right]$, (Log defn)
 $L_m = \log(m^2/\hat{\mu}^2)$

- NLO result supplied as: $M_{t, SM}^{(1)} = M_{UV} + M_{UV, m} + M_{IR} + M_{fin} + M_{fin, s} \log\left(-\frac{s}{\hat{\mu}^2}\right)$



NOT in the BFM, so QFT surgery required



Where is the 2 loop matching ?

- 2 loop matching part of answer: (after typo corrections)

$$\langle \mathcal{G}\mathcal{G}|h \rangle_{SM}^{2,F} \equiv i \delta_{ab} \frac{K_{ab}}{\bar{v}_T^0} \left[\left(-\frac{s}{\hat{\mu}^2} \right)^{-\epsilon} \frac{\alpha_s^0 S^\epsilon \hat{\mu}^{-2\epsilon}}{4\pi} \right]^2 \left(M_{t,SM}^{(1)} - M_{UV} - M_{UV,m} - M_{IR} \right)$$

Explicitly:

$$\langle \mathcal{G}\mathcal{G}|h \rangle_{SM}^{2,F} = \frac{\alpha_s^{(r)}}{4\pi} \left[11 + c_1 \epsilon + (-\beta_0 + c_2 \epsilon) \log \left(-\frac{\hat{m}_h^2}{\hat{\mu}^2} \right) \right] \langle \mathcal{G}\mathcal{G}|h \rangle_{SM,\epsilon \rightarrow 0}^1,$$

Where:

$$c_1 = \left[-\frac{\pi^2 \beta_0}{12} + 28 \log(z) + 12 \zeta_3 - \frac{40}{3} \right], \quad (\text{Log defn})$$

$$c_2 = \left[-\frac{1}{2} \beta_0 \log \left(\frac{-s}{\mu^2} \right) - 2\beta_0 \log(z) + 8 \right]. \quad \log(z) = \log(-s/m_t^2)/2.$$

The 2 loop matching result is not a good approximation .

Renormalisation soln $\sigma(\mathcal{G}\mathcal{G} \rightarrow h)$

- SM lit, and past SMEFT results (including [2107.07470](#)) followed a mixed scheme

$$Z_g^2 Z_{\hat{G}} \left(-\frac{s}{\hat{\mu}^2}\right)^{-\epsilon} i \delta_{ab} K_{ab} \frac{1}{\bar{v}_T^{(r)}} \frac{\alpha_s^{(r)}}{4\pi} M_{t,SM}^{(0)} = - \left[\frac{\alpha_s^{(r)}}{4\pi}\right]^2 \frac{\beta_0}{\epsilon} \left(-\frac{s}{\hat{\mu}^2}\right)^{-\epsilon} i \delta_{ab} K_{ab} \frac{1}{\bar{v}_T^{(r)}} M_{t,SM}^{(0)}.$$

Renormalise as:

$$Z_{\alpha_s} = 1 - \frac{\alpha_s}{4\pi} \frac{1}{\epsilon} \left(\beta_0 - \frac{2}{3} \left(\frac{\mu^2}{m_t^2} \right)^\epsilon \right)$$

$$Z_g = 1 + \frac{\alpha_s}{4\pi} \frac{2}{3\epsilon} \left(\frac{\mu^2}{m_t^2} \right)^\epsilon.$$

But in the BFM: $\mu^{2\epsilon} Z_g^2 Z_{\hat{G}} \equiv 1$, how do we modify to the BFM?

Treat the EFT, as an EFT: Just renormalise the composite operator.

$$\langle \mathcal{G}\mathcal{G}|h \rangle_{\mathcal{O}(v^2/\Lambda^2)}^0 \rightarrow Z_{HG} \frac{\tilde{C}_{HG}^{(6)}}{\bar{v}_T} \langle \mathcal{G}^{\mu\nu} \mathcal{G}_{\mu\nu} h \rangle_0. \quad Z_{HG} = 1 - \frac{\beta_0 \alpha_s}{4\pi \epsilon} + \dots$$

IR problems $\sigma(\mathcal{G}\mathcal{G} \rightarrow h)$



- Such renormalisation (re) introduces a β_0 IR pole:

(Log defn)

$$L_+ = L_{\hat{m}_h} + L_{\hat{m}_t}$$

$$\frac{\Delta^2 \delta\sigma(\mathcal{G}\mathcal{G} \rightarrow h)}{\Delta^2 \hat{\sigma}_{LO, \epsilon \rightarrow 0}^{SM}(\mathcal{G}\mathcal{G} \rightarrow h; z)} = 6 \left[-\frac{6}{\epsilon^2} - \frac{\beta_0}{\epsilon} + 6\frac{L_+}{\epsilon} - \frac{6}{\epsilon} + \beta_0 L_{\hat{m}_t} + 3\pi^2 + 5 - \beta_0 - 3L_+^2 + 6L_+ \right] \tilde{C}_{HG}^{(6)},$$

This is why it seemed a mixed scheme was/is required to many in the lit.

This IR behavior is consistent with the Catani-Seymour subtraction:

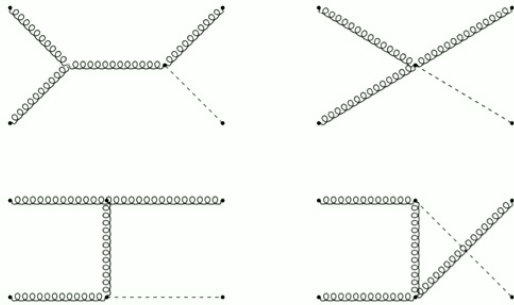
$$\mathcal{M}_{t,IR}^{(1)} = \frac{-e^{\epsilon\gamma_E}}{\Gamma(1-\epsilon)} \left[\frac{2N_c}{\epsilon^2} + \frac{\beta_0}{\epsilon} \right] M_{t,SM}^{(0)}$$

Z. Kunszt, A. Signer and Z. Trocsanyi, *Singular terms of helicity amplitudes at one loop in QCD and the soft limit of the cross-sections of multiparton processes*, *Nucl. Phys. B* **420** (1994) 550 [[hep-ph/9401294](#)].

S. Catani and M. H. Seymour, *A General algorithm for calculating jet cross-sections in NLO QCD*, *Nucl. Phys. B* **485** (1997) 291 [[hep-ph/9605323](#)].

Canceled by considering IR limit of $\sigma(\mathcal{G}\mathcal{G} \rightarrow \mathcal{G}h)$

IR problems $\sigma(\mathcal{G}\mathcal{G} \rightarrow h)$



- Appropriate re-interpretation of:

S. Dawson, *Radiative corrections to Higgs boson production*, *Nucl. Phys.* **B359** (1991) 283.

[Higgs boson production at the LHC](#)

M. Spira (Hamburg U.), A. Djouadi (Montreal U. and DESY), D. Graudenz (CERN), P.M. Zerwas (DESY) (Feb, 1995)

Published in: *Nucl.Phys.B* 453 (1995) 17-82 • e-Print: [hep-ph/9504378](#) [hep-ph]

$$\Delta\delta|\mathcal{A}(\mathcal{G}\mathcal{G} \rightarrow h\mathcal{G})|^2 = \frac{768\pi\alpha_s^{(0)}}{\bar{v}_T^0} 2\text{Re} \left(\frac{\Delta C_{h\mathcal{G}\mathcal{G}}^{SM}}{\mu^{2\epsilon}} \tilde{C}_{HG} \right) \frac{(\hat{m}_h^8 + s^4 + t^4 + u^4)(1 - 2\epsilon) + \frac{1}{2}\epsilon(\hat{m}_h^4 + s^2 + t^2 + u^2)^2}{s t u},$$

- Results in ratio: (IR cancels poles in both inf. terms)

$$\begin{aligned} & 6 \left[\frac{6}{\epsilon^2} - 6 \frac{L_+}{\epsilon} + \frac{6}{\epsilon} + 3 L_+^2 - 6 L_+ - \pi^2 + 6 \right] \delta(1-z) \tilde{C}_{HG}, \\ & + 6 \left[(12 f_1(z) (L_{\hat{m}_h} - \log(z)) - 11 f_1(z) + 11 z) f_1(z) + 11 (1-z)^2 z \right] \left(\frac{1}{1-z} \right)_+ \tilde{C}_{HG} \\ & + 144 f_1^2(z) \left(\frac{\log(1-z)}{1-z} \right)_+ \tilde{C}_{HG} - 72 f_1^2(z) \left[\frac{1}{\epsilon} + 1 - L_{\hat{m}_t} \right] \left(\frac{1}{1-z} \right)_+ \tilde{C}_{HG}. \end{aligned}$$

SMEFT splitting functions

- To cancel all poles two steps, regulate end-point singularities: (on-shellness equiv?) add $\sigma(\mathcal{G}\mathcal{G} \rightarrow \mathcal{G}h), \sigma(\mathcal{G}\mathcal{G} \rightarrow h)$ AND

$$(1-z)^{-1-2\epsilon} = \left(\frac{1}{1-z}\right)_+ - 2\epsilon \left(\frac{\log(1-z)}{1-z}\right)_+ - \frac{1}{2\epsilon} \delta(1-z)$$

introduce counter-term for AP splitting fund: (this means SMEFT pdf's)

$$\Delta^2 \delta\sigma_{DRc.t}^{AP} \equiv 36 \Delta^2 \hat{\sigma}_{LO, \epsilon \rightarrow 0}^{SMEFT}(\mathcal{G}\mathcal{G} \rightarrow h) \left[\left(\frac{\mu^2}{\mu_F^2}\right)^\epsilon \right] (4\pi)^\epsilon \frac{\Gamma(1+\epsilon)\Gamma(1-\epsilon)^2}{\Gamma(1-2\epsilon)} \left[\frac{1}{\epsilon} \right] z p_{\mathcal{G}\mathcal{G}}(z) \tilde{C}_{HG}$$

Where:

$$p_{\mathcal{G}\mathcal{G}}(z) = 2z \left(\left(\frac{1}{1-z}\right)_+ - z + \frac{f_1(z)}{z^2} \right) + \frac{\beta_0}{6} \delta(1-z).$$

- Need to upgrade the α_s input, certainly if extracted from PDF's

NLO Compact Final Answer

$$\frac{\Delta^2 \delta\sigma^{SMEFT}}{\Delta^2 \hat{\sigma}_{LO, \epsilon \rightarrow 0}^{SM}} \frac{1}{2\tilde{C}_{HG}^{(6)}} = 12 \left[\pi^2 + \frac{11}{2} \right] \delta(1-z) - 66(1-z)^3 + 144 f_1^2(z) \left(\frac{\log(1-z)}{1-z} \right)_+ ,$$

$$+ 72 f_1^2(z) [L_+ - \log(z) - 1] \left(\frac{1}{1-z} \right)_+ + 36 z p_{GG}(z) \log \left(\frac{\hat{\mu}^2}{\mu_F^2} \right) .$$

Notation:

$$L_m = \log(m^2/\hat{\mu}^2)$$

$$L_+ = L_{\hat{m}_h} + L_{\hat{m}_t}$$

$$z = \hat{m}_h^2/s$$

$$f_1(z) = z^2 - z + 1$$

$$p_{GG}(z) = 2z \left(\left(\frac{1}{1-z} \right)_+ - z + \frac{f_1(z)}{z^2} \right) + \frac{\beta_0}{6} \delta(1-z) .$$

$$\int_0^1 dx \frac{f(x)}{(x)_+} = \int_0^1 dx \frac{f(x) - f(0)}{x} ,$$

$$\int_0^1 dx f(x) \left(\frac{\log(x)}{x} \right)_+ = \int_0^1 dx \frac{(f(x) - f(0)) \log(x)}{x} .$$

SMEFT $\sigma(\mathcal{G}\mathcal{G} \rightarrow h)$ perturbation

- Numerically the result is:

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

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- Operator Definitions:

$$\begin{aligned} \mathcal{L}_{\text{SMEFT}} \supset & \frac{C_{HG}^{(6)}}{\Lambda^2} H^\dagger H G_A^{\mu\nu} G_{\mu\nu}^A + \frac{C_{HG}^{(8)}}{\Lambda^4} (H^\dagger H)^2 G_A^{\mu\nu} G_{\mu\nu}^A + \frac{C_{H\Box}^{(6)}}{\Lambda^2} (H^\dagger H) \Box (H^\dagger H) + \frac{C_{HD}^{(6)}}{\Lambda^2} (H^\dagger D_\mu H)^* (H^\dagger D_\mu H) \\ & + \frac{C_{uH}^{(6)}}{\Lambda^2} (H^\dagger H) (\bar{q}_p u_r \tilde{H}) + \frac{C_{dH}^{(6)}}{\Lambda^2} (H^\dagger H) (\bar{q}_p d_r H) + \frac{C_{uG}^{(6)}}{\Lambda^2} (\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{H} G_{\mu\nu}^A + \frac{C_{dG}^{(6)}}{\Lambda^2} (\bar{q}_p \sigma^{\mu\nu} T^A d_r) H G_{\mu\nu}^A \end{aligned}$$

SMEFT $\sigma(\mathcal{G}\mathcal{G} \rightarrow h)$ perturbation

- Numerically the result is:

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

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- The various contributions

$$\begin{aligned} |\mathcal{A}_{SM}^{a,ij} + \mathcal{A}_{\text{SMEFT}}^{a,ij}|^2 &= |\mathcal{A}_{SM}^{a,ij} + \frac{\mathcal{A}_{\text{SMEFT},6}^{a,ij}}{\Lambda^2} + \frac{\mathcal{A}_{\text{SMEFT},8}^{a,ij}}{\Lambda^4} + \dots|^2 \\ &= |\mathcal{A}_{SM}^{a,ij}|^2 + \mathcal{A}_{SM}^{a,ij} \frac{\mathcal{A}_{\text{SMEFT},6}^{a,ij}}{\Lambda^2} + \left| \frac{\mathcal{A}_{\text{SMEFT},6}^{a,ij}}{\Lambda^2} \right|^2 + \mathcal{A}_{SM}^{a,ij} \frac{\mathcal{A}_{\text{SMEFT},8}^{a,ij}}{\Lambda^4} + \text{h.c.} + \dots \end{aligned}$$