



The Geometric SMEFT...

VILLUM FONDEN



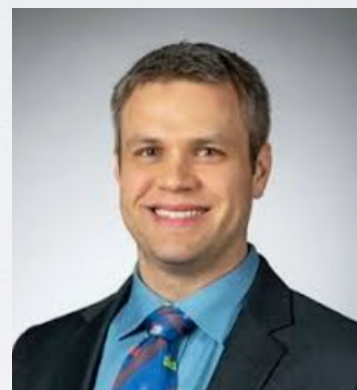
Key collaborators and developments in geoSMEFT:



A. Helset



T. Corbett



A. Martin



C. Hays



J. Talbert

1803.08001 Helset, Paraskevas, Trott.

2001.01453 Helset, Martin, Trott.

2010.08451 Corbett, Trott

2010.15852 Corbett,

2107.03951 Talbert, Trott.

2106.10284 Corbett,

2110.03694 Corbett, Rasmussen

Other groups joining in:

2202.06965 Cohen, Craig, Lu, Sutherland

2202.06972 Cheung, Helset, Parra-Martinez

1909.08470

2007.00565

2102.02819

2106.13794

2107.07470

2109.05595

2210.08000

2111.03045

Corbett, Helset, Trott

Hays, Helset, Martin, Trott

Helset, Corbett, Martin, Trott

Trott

Corbett, Martin, Trott

Martin, Trott

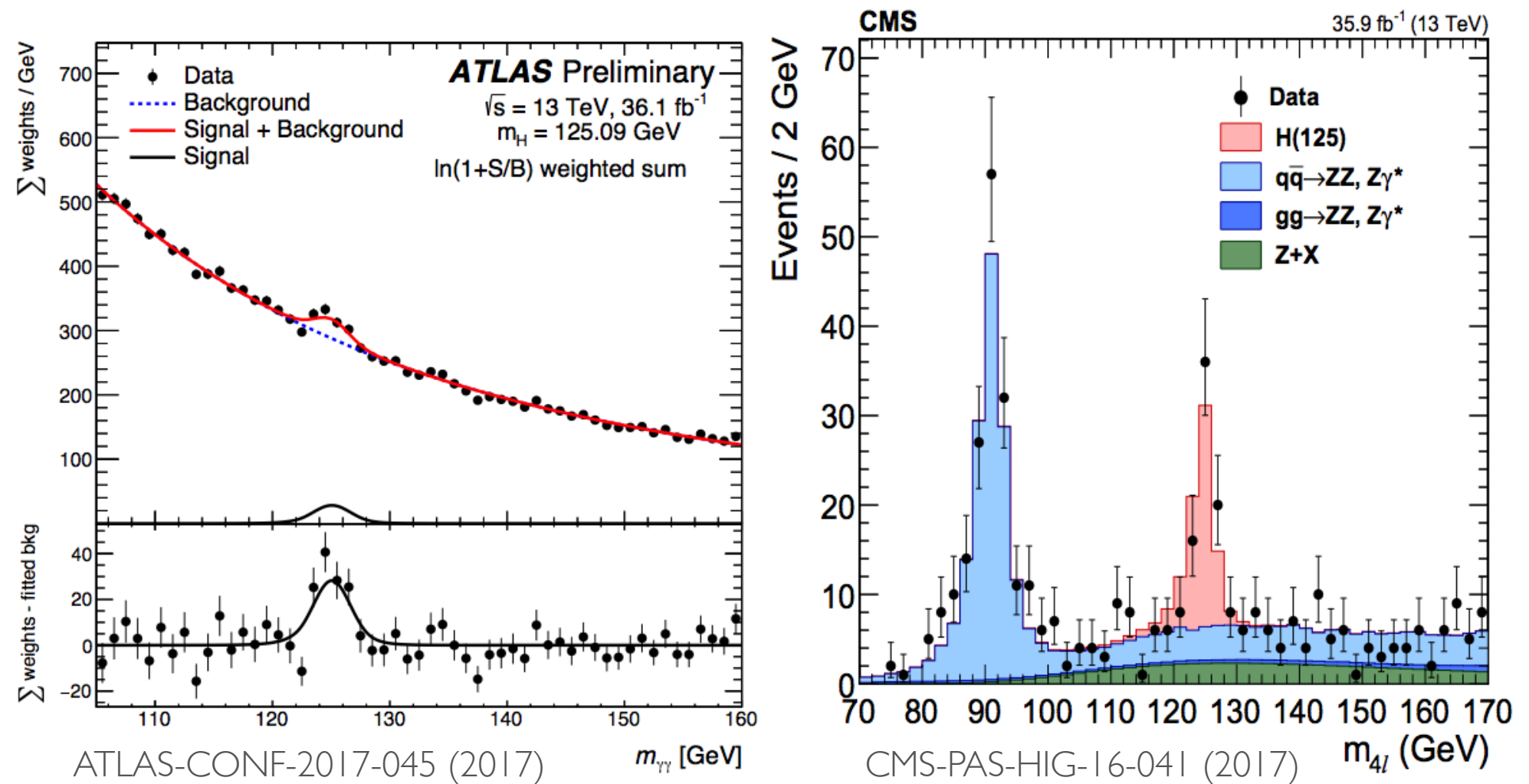
Helset, Jenkins, Manohar

Cheung, Helset, Parra-Martinez

Why all the SMEFT stuff.

What was discovered at LHC, a particle

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



What wasn't discovered at LHC

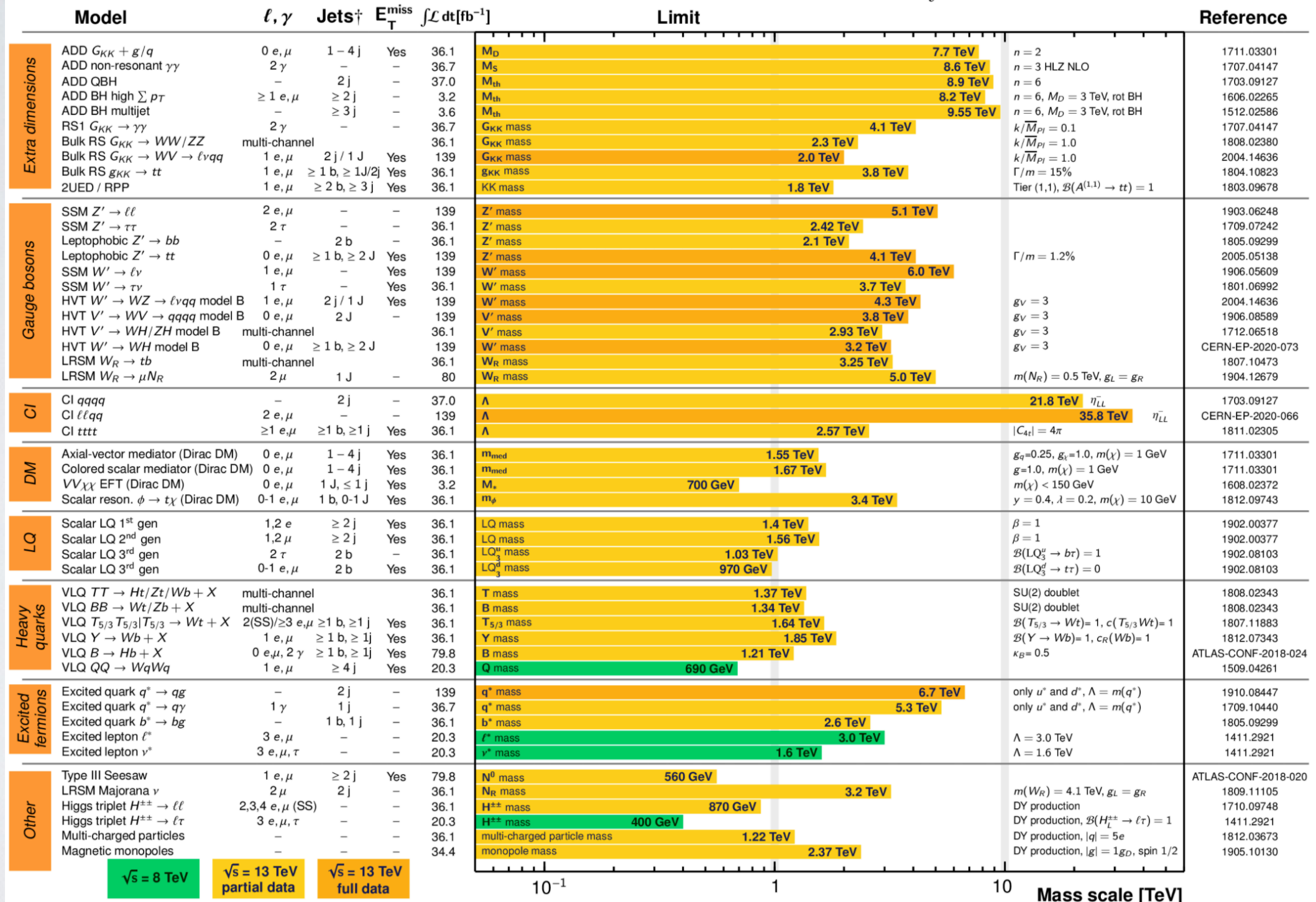
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

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

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



*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).

What wasn't discovered at LHC

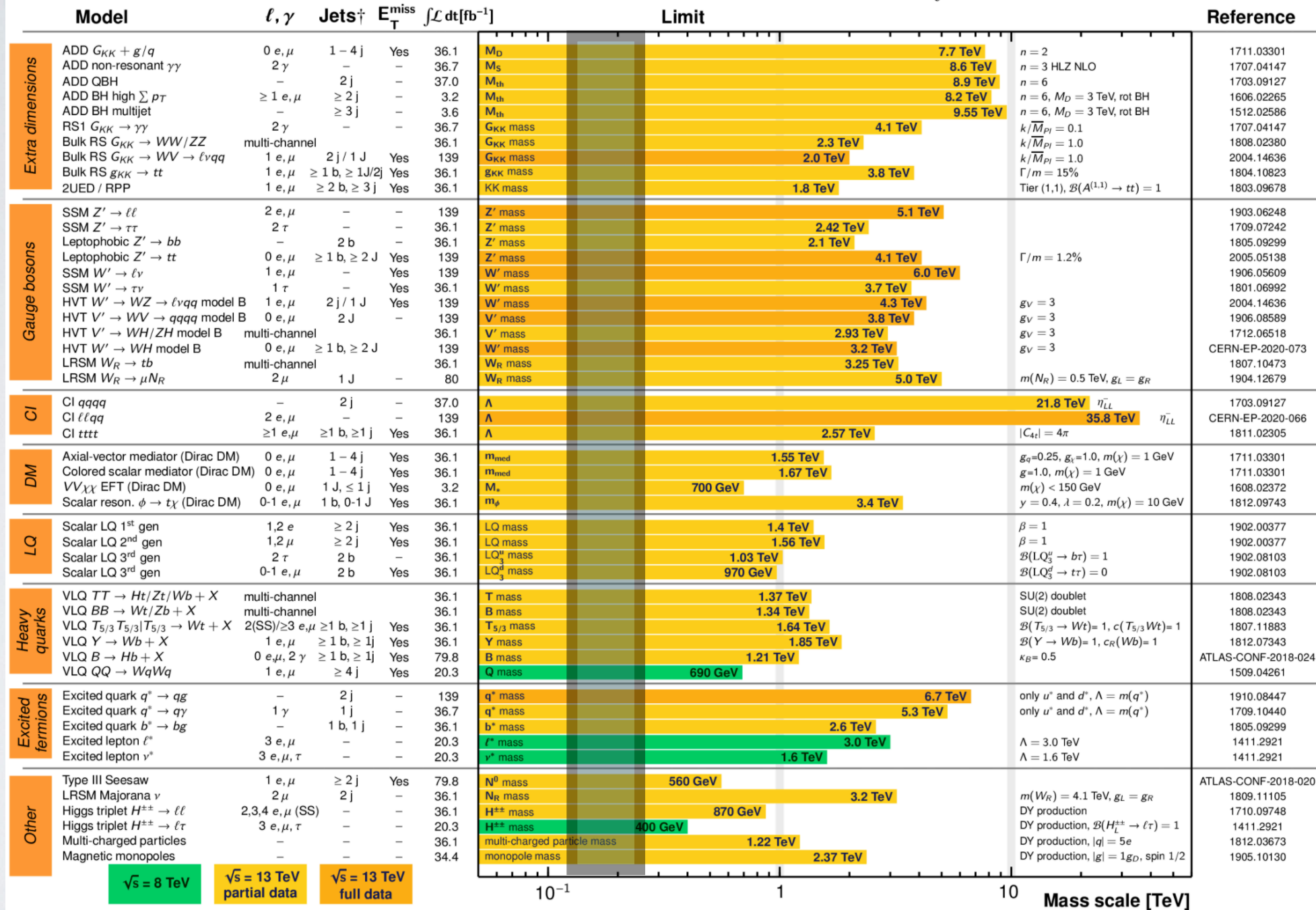
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

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

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



*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 ($\sim g v$) states m_W, m_Z, m_t, m_h

Michael Trott, NBI

What wasn't discovered at LHC

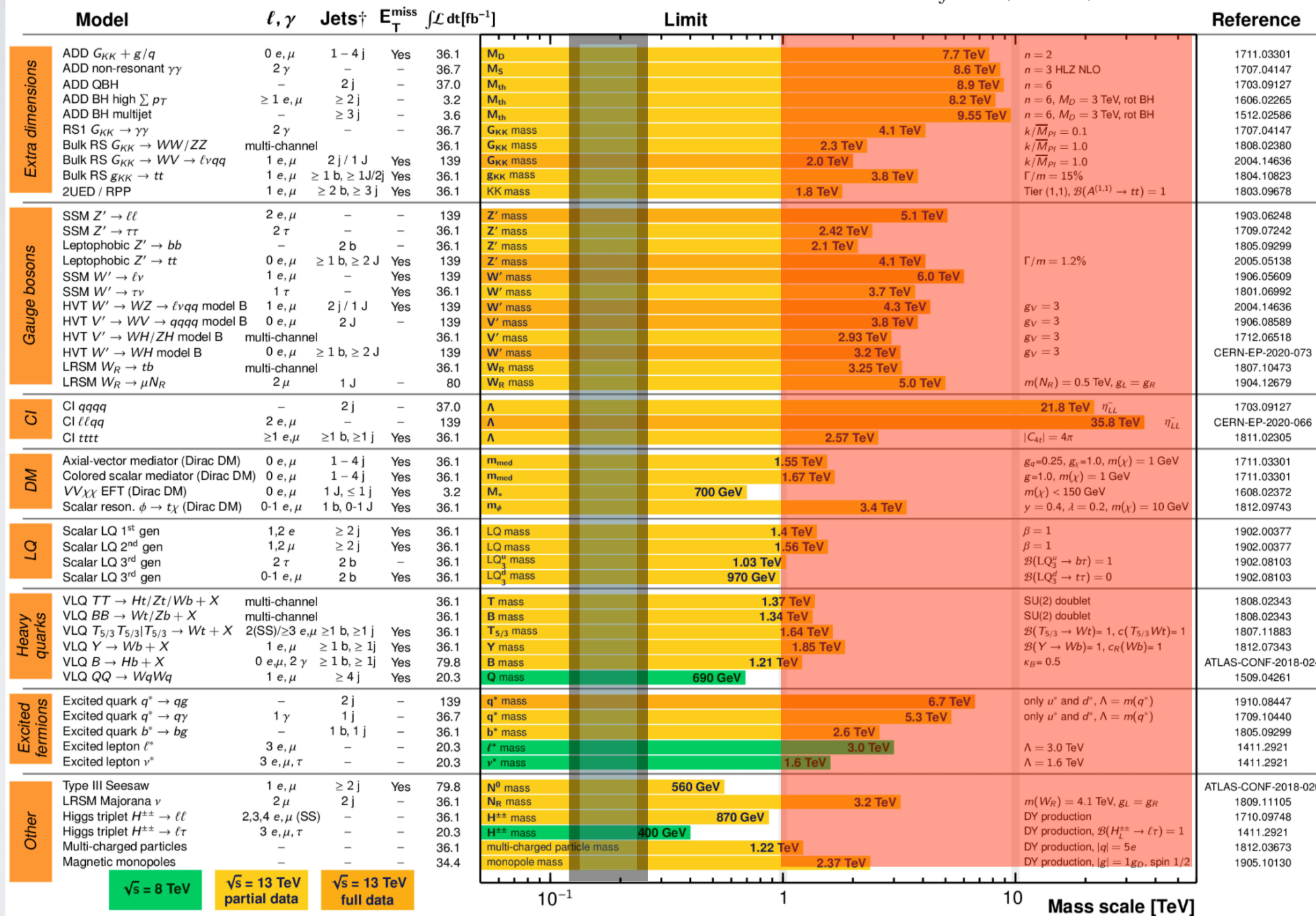
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

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

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



*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 $v \sim m_h$

What wasn't discovered at LHC

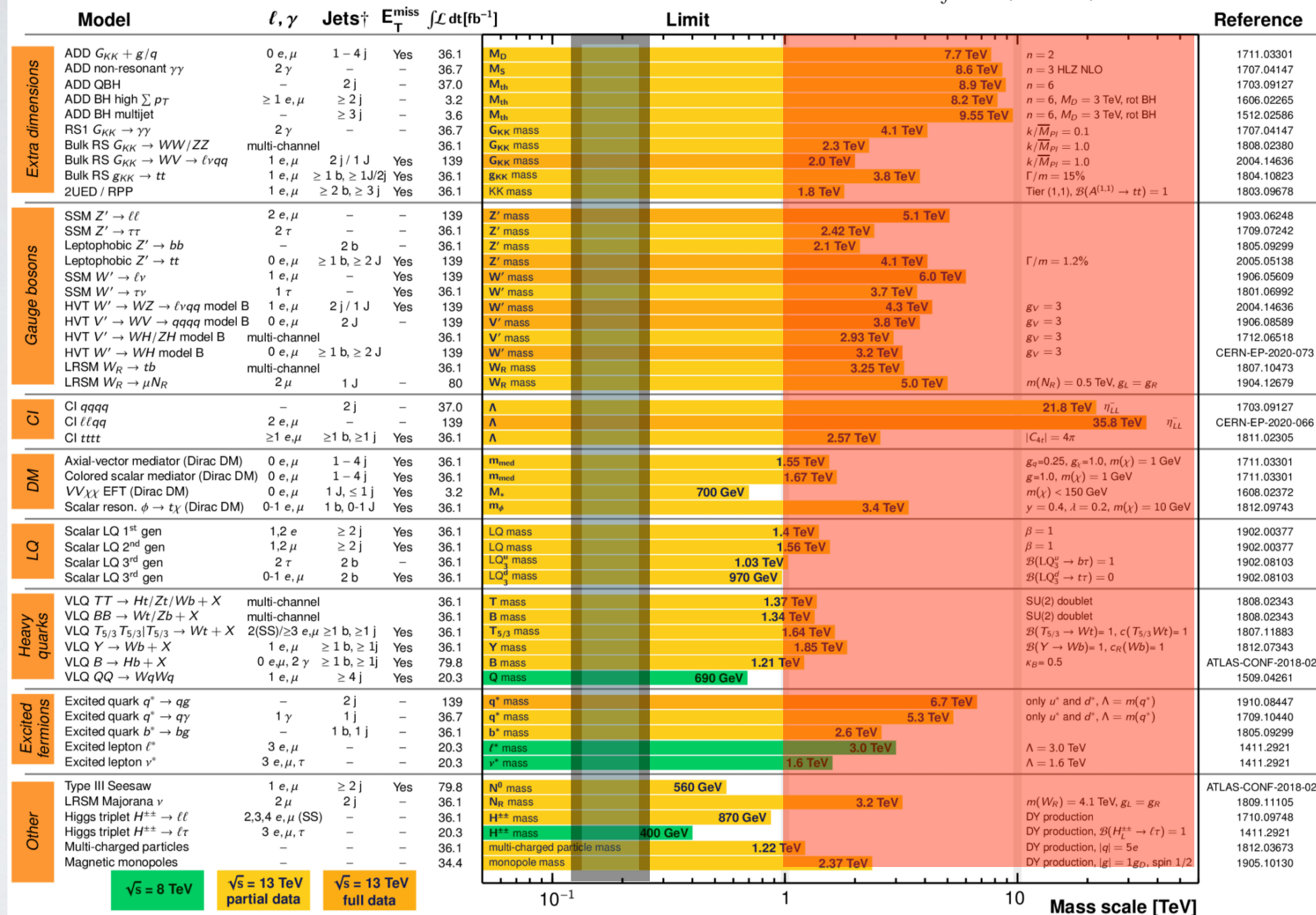
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

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

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



*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

$$v/M < 1$$

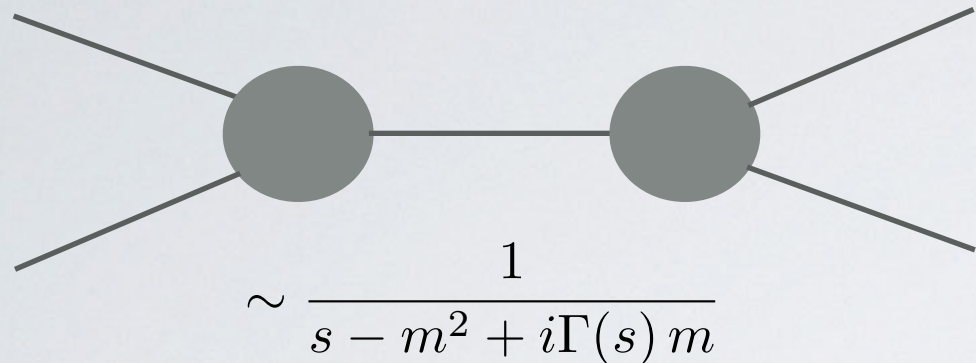
to simplify/for stronger conclusions:

bound many models at once

bound multiple resonances at same time

Deviations then look like local contact operator effects in EFT

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 massive fields

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

- You can Taylor expand in LOCAL functions (operators)

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

This is the core idea of EFT interpretations of the data.

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

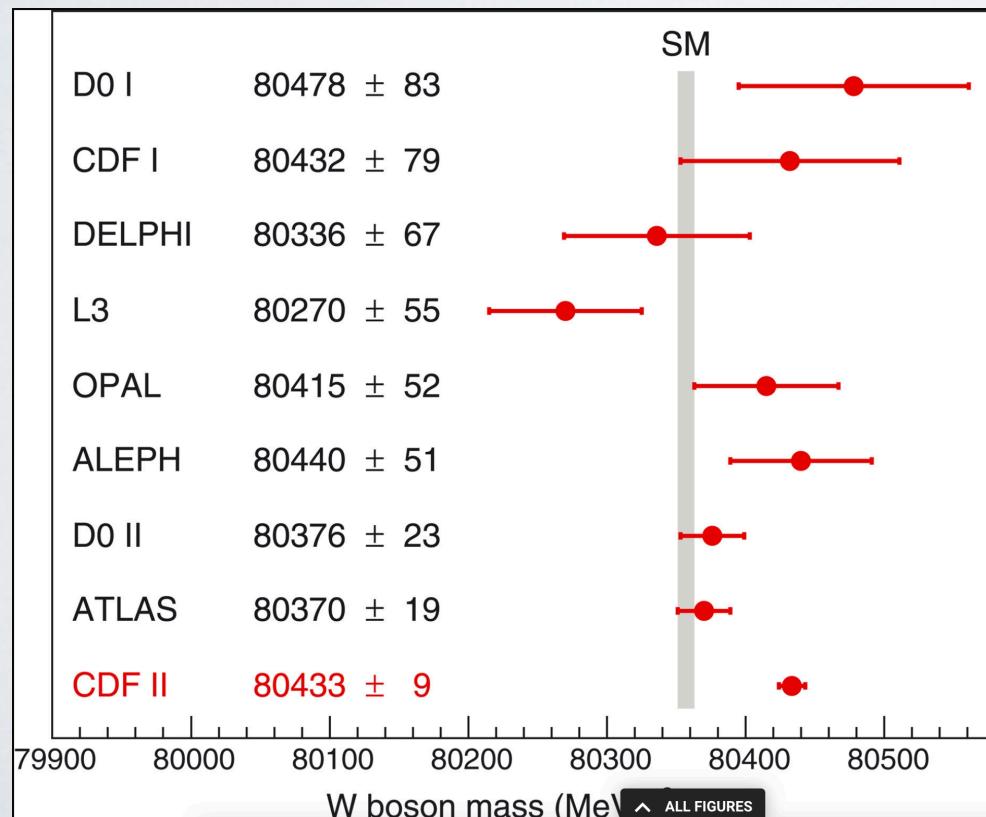
UV dependent Wilson coefficient
and suppression scale

IR operator form

The SMEFT is a key tool for interpreting deviations like:



Last week!



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

CDF COLLABORATION††, T. AALTONEN, S. AMERIO, D. AMIDEI, A. ANASTASSOV, A. ANNOVI, J. ANTOS, G. APOLLINARI, J. A. APPEL, [et al.] S. ZUCHELLI +389 authors

[Authors Info & Affiliations](#)

SCIENCE • 7 Apr 2022 • Vol 376, Issue 6589 • pp. 170-176 • DOI:10.1126/science.abk1781

97,942 views, 1 citation

- Any one measurement can just dictate a parameter in a theory. But a PATTERN of measurements can show a theory does not describe Global data.

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

- SMEFT Game plan: (we are ready for deviations!)

Find deviations → Map to pattern in SMEFT

Follow pattern to underlying model

SMEFT challenges.

Parameters in the SMEFT

In Warsaw basis arXiv:1008.4884 (SMEFT standard basis)

Class	N_{op}	CP -even			CP -odd		
		n_g	1	3	n_g	1	3
1 $g^3 X^3$	4	2	2	2	2	2	2
2 H^6	1	1	1	1	0	0	0
3 $H^4 D^2$	2	2	2	2	0	0	0
4 $g^2 X^2 H^2$	8	4	4	4	4	4	4
5 $y\psi^2 H^3$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
6 $gy\psi^2 XH$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
7 $\psi^2 H^2 D$	8	$\frac{1}{2}n_g(9n_g + 7)$	8	51	$\frac{1}{2}n_g(9n_g - 7)$	1	30
8 : $(\bar{L}L)(LL)$	5	$\frac{1}{4}n_g^2(7n_g^2 + 13)$	5	171	$\frac{7}{4}n_g^2(n_g - 1)(n_g + 1)$	0	126
8 : $(\bar{R}R)(\bar{R}R)$	7	$\frac{1}{8}n_g(21n_g^3 + 2n_g^2 + 31n_g + 2)$	7	255	$\frac{1}{8}n_g(21n_g + 2)(n_g - 1)(n_g + 1)$	0	195
ψ^4 8 : $(\bar{L}L)(\bar{R}R)$	8	$4n_g^2(n_g^2 + 1)$	8	360	$4n_g^2(n_g - 1)(n_g + 1)$	0	288
8 : $(\bar{L}R)(\bar{R}L)$	1	n_g^4	1	81	n_g^4	1	81
8 : $(\bar{L}R)(\bar{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
8 : All	25	$\frac{1}{8}n_g(107n_g^3 + 2n_g^2 + 89n_g + 2)$	25	1191	$\frac{1}{8}n_g(107n_g^3 + 2n_g^2 - 67n_g - 2)$	5	1014
Total	59	$\frac{1}{8}(107n_g^4 + 2n_g^3 + 213n_g^2 + 30n_g + 72)$	53	1350	$\frac{1}{8}(107n_g^4 + 2n_g^3 + 57n_g^2 - 30n_g + 48)$	23	1149

Table 2. Number of CP -even and CP -odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4 + 2n_g^3 + 135n_g^2 + 60)/4$, which is 76 for $n_g = 1$ and 2499 for $n_g = 3$.

2499

1312.2014 Alonso, Jenkins, Manohar, Trott

- That's a lot of parameters in general.
- Linearly realised symmetries (exact or softly broken) of the SMEFT relate parameters

Dim 6 SMEFT EW Lagrangian terms

- SMEFT at dimension 6 with all operators is already complicated.
- EW sector parameters redefined in the SMEFT

$$\begin{bmatrix} \mathcal{W}_\mu^3 \\ \mathcal{B}_\mu \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} v_T^2 C_{HWB} \\ -\frac{1}{2} v_T^2 C_{HWB} & 1 \end{bmatrix} \begin{bmatrix} \cos \bar{\theta} & \sin \bar{\theta} \\ -\sin \bar{\theta} & \cos \bar{\theta} \end{bmatrix} \begin{bmatrix} \mathcal{Z}_\mu \\ \mathcal{A}_\mu \end{bmatrix},$$

Mass redefinitions

$$M_W^2 = \frac{\bar{g}_2^2 v_T^2}{4},$$

$$M_Z^2 = \frac{v_T^2}{4} (\bar{g}_1^2 + \bar{g}_2^2) + \frac{1}{8} v_T^4 C_{HD} (\bar{g}_1^2 + \bar{g}_2^2) + \frac{1}{2} v_T^4 \bar{g}_1 \bar{g}_2 C_{HWB}.$$

Mixing angle redefinitions

$$\sin \bar{\theta} = \frac{\bar{g}_1}{\sqrt{\bar{g}_1^2 + \bar{g}_2^2}} \left[1 + \frac{v_T^2}{2} \frac{\bar{g}_2}{\bar{g}_1} \frac{\bar{g}_2^2 - \bar{g}_1^2}{\bar{g}_2^2 + \bar{g}_1^2} C_{HWB} \right]$$

$$\cos \bar{\theta} = \frac{\bar{g}_2}{\sqrt{\bar{g}_1^2 + \bar{g}_2^2}} \left[1 - \frac{v_T^2}{2} \frac{\bar{g}_1}{\bar{g}_2} \frac{\bar{g}_2^2 - \bar{g}_1^2}{\bar{g}_2^2 + \bar{g}_1^2} C_{HWB} \right]$$

Interactions to remaining SM fields via:

$$D_\mu = \partial_\mu + i \frac{\bar{g}_2}{\sqrt{2}} [\mathcal{W}_\mu^+ T^+ + \mathcal{W}_\mu^- T^-] + i \bar{g}_Z [T_3 - \bar{s}^2 Q] \mathcal{Z}_\mu + i \bar{e} Q \mathcal{A}_\mu,$$

$$\bar{e} = \frac{\bar{g}_1 \bar{g}_2}{\sqrt{\bar{g}_2^2 + \bar{g}_1^2}} \left[1 - \frac{\bar{g}_1 \bar{g}_2}{\bar{g}_2^2 + \bar{g}_1^2} v_T^2 C_{HWB} \right]$$

$$\bar{g}_Z = \sqrt{\bar{g}_2^2 + \bar{g}_1^2} + \frac{\bar{g}_1 \bar{g}_2}{\sqrt{\bar{g}_2^2 + \bar{g}_1^2}} v_T^2 C_{HWB}$$

1312.2014 Alonso, Jenkins, Manohar, Trott

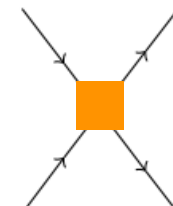
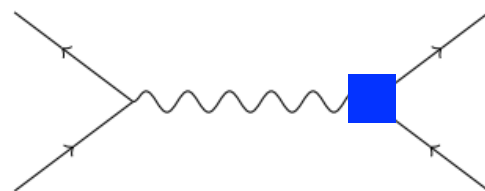
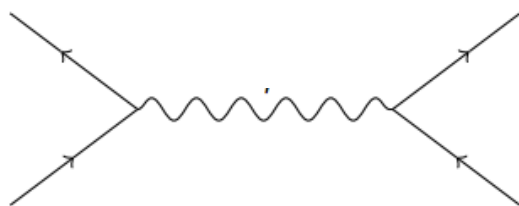
$$\bar{s}^2 = \sin^2 \bar{\theta} = \frac{\bar{g}_1^2}{\bar{g}_2^2 + \bar{g}_1^2} + \frac{\bar{g}_1 \bar{g}_2 (\bar{g}_2^2 - \bar{g}_1^2)}{(\bar{g}_1^2 + \bar{g}_2^2)^2} v_T^2 C_{HWB}.$$

- Note the complications are proportional to the vev.

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

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



So now

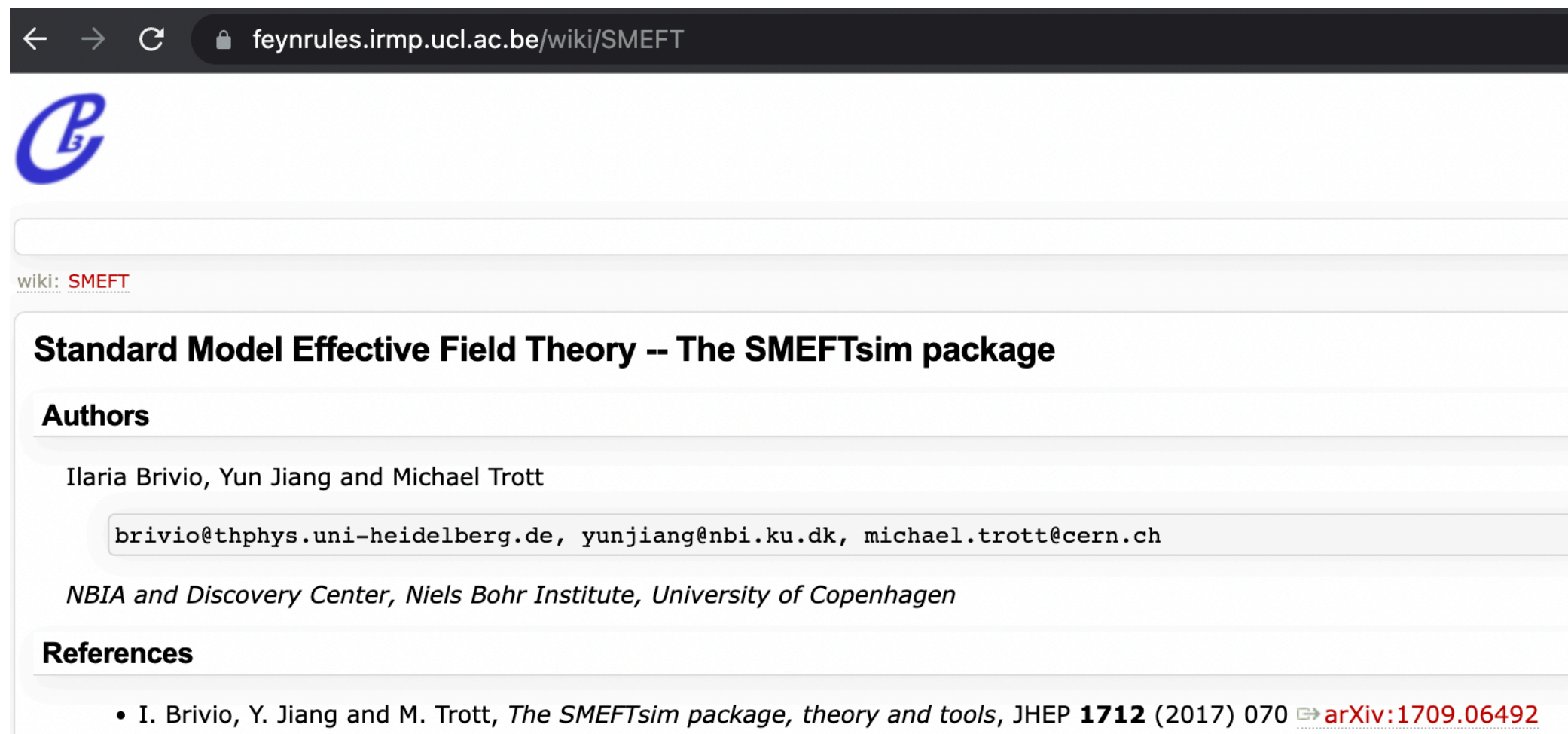
$$-\frac{4\mathcal{G}_F}{\sqrt{2}} = -\frac{2}{v_T^2} + \left(C_{\mu e e \mu}^{ll} + C_{e \mu \mu e}^{ll} \right) - 2 \left(C_{ee}^{(3)Hl} + C_{\mu\mu}^{(3)Hl} \right)$$

δG_F

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

Automation of this approach

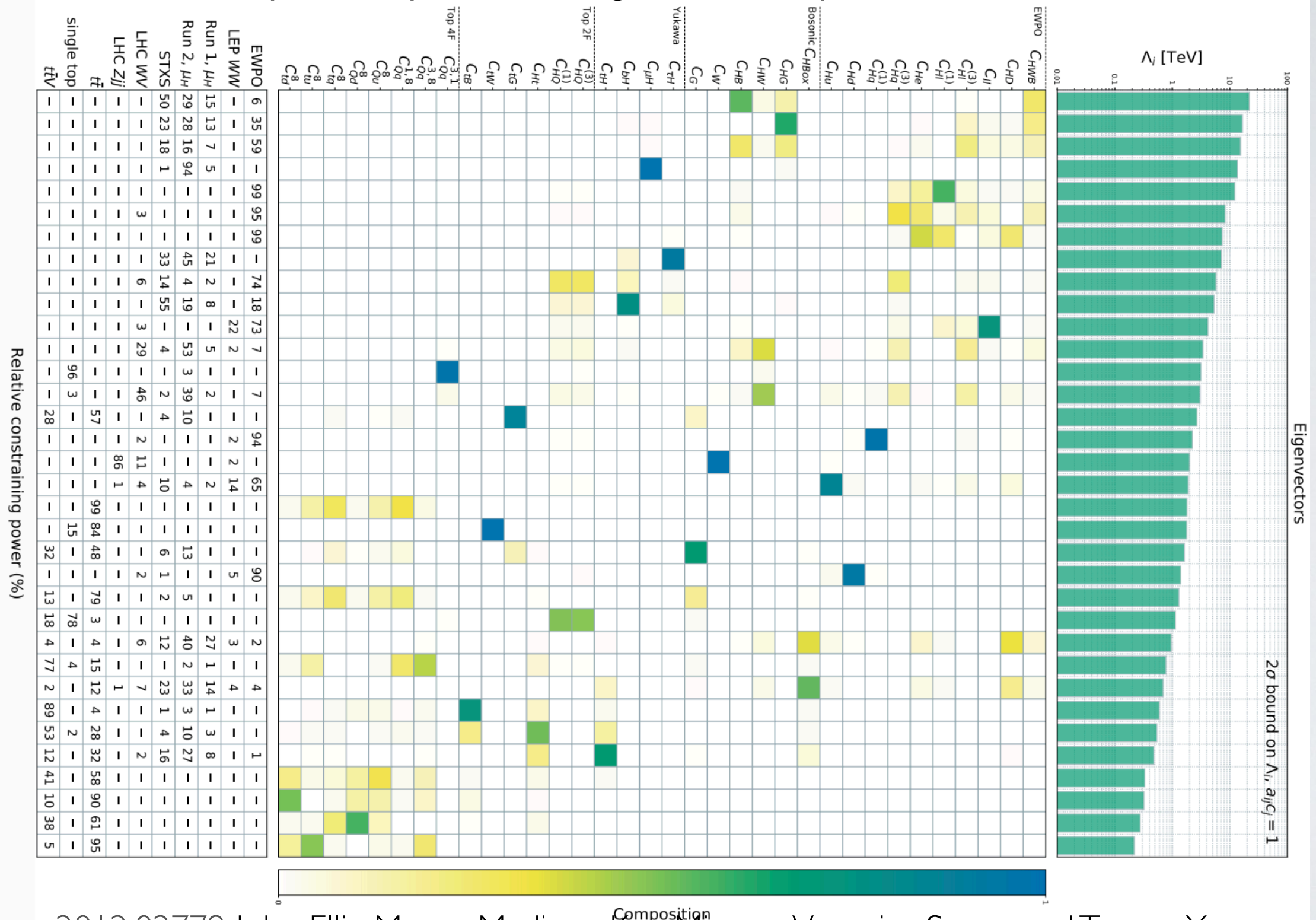
- Need to keep all operators and carefully compute S matrix elements avoiding uncontrolled approximations (and human error) - hard even at $\mathcal{L}_6$
- Automation of $\mathcal{L}_6$ SMEFT in the SMEFTsim package has enabled The experimental program to do this [1709.06492](https://arxiv.org/abs/1709.06492) Brivio, Jiang, Trott.



The screenshot shows a web browser window with the address bar displaying `feynrules.irmp.ucl.ac.be/wiki/SMEFT`. Below the address bar is a blue logo consisting of a stylized 'G' with a subscript '6'. The main content area of the page has a header `wiki: SMEFT` and a title **Standard Model Effective Field Theory -- The SMEFTsim package**. Under the **Authors** section, the authors listed are Ilaria Brivio, Yun Jiang and Michael Trott. Their email addresses are provided in a code box: `brivio@thphys.uni-heidelberg.de, yunjiang@nbi.ku.dk, michael.trott@cern.ch`. Below this, the affiliation is given as *NBIA and Discovery Center, Niels Bohr Institute, University of Copenhagen*. The **References** section contains a single entry: I. Brivio, Y. Jiang and M. Trott, *The SMEFTsim package, theory and tools*, JHEP **1712** (2017) 070, with a link to [arXiv:1709.06492](https://arxiv.org/abs/1709.06492).

Keep all operators gives eigenvectors of constraint

Interpret this pattern as it gets firmed up to find the UV.



2012.02779 John Ellis, Maeve Madigan, Ken Mimasu, Veronica Sanze, and Tevong You

Michael Trott, NBI

Aside: Strong input scheme dependence in SMEFT

$\{\hat{\alpha}_{ew}, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

$$\delta m_Z^2 = \frac{\hat{M}_Z^2}{2} \tilde{C}_{HD} + \frac{2^{3/4} \sqrt{\pi \hat{\alpha}} \hat{M}_Z}{\hat{G}_F^{1/2}} \tilde{C}_{HWB},$$

$$\delta s_\theta^2 = 0.17 \tilde{C}_{HD} + 0.79 \tilde{C}_{HWB} + 0.76 \tilde{C}_{Hl}^{(3)} - 0.34 \tilde{C}'_{ll},$$

$$\frac{\delta \Gamma_Z}{\Gamma_Z^{SM}} = -0.82 \tilde{C}_{HWB} - 0.67 \tilde{C}_{HD} - 0.19 \tilde{C}_{Hl}^{(1)} - 2.06 \tilde{C}_{Hl}^{(3)} - 0.19 \tilde{C}_{He} \\ + 0.47 \tilde{C}_{Hq}^{(1)} + 1.61 \tilde{C}_{Hq}^{(3)} + 0.26 \tilde{C}_{Hu} - 0.19 \tilde{C}_{Hd} + 1.35 \tilde{C}'_{ll}$$

$$\frac{\delta \alpha}{2 \hat{\alpha}} = 0,$$

$$\frac{\delta M_W^2}{\hat{M}_W^2} = -\frac{s_{2\hat{\theta}}}{4 c_{2\hat{\theta}}} \left(\frac{c_{\hat{\theta}}}{s_{\hat{\theta}}} \tilde{C}_{HD} + \frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} 2\sqrt{2} \delta G_F + 4 \tilde{C}_{HWB} \right),$$

$$\frac{\delta \Gamma_W}{\Gamma_W^{SM}} = -3.97 \tilde{C}_{HWB} - 1.80 \tilde{C}_{HD} - 3.52 \tilde{C}_{Hl}^{(3)} + 1.33 \tilde{C}_{Hq}^{(3)} + 2.10 \tilde{C}'_{ll}.$$

$\{\hat{M}_W, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

$$\delta m_Z^2 = \frac{\hat{M}_Z^2}{2} \tilde{C}_{HD} + 2 \hat{M}_Z \hat{M}_W \sqrt{1 - \frac{\hat{M}_W^2}{\hat{M}_Z^2}} \tilde{C}_{HWB},$$

$$\delta s_\theta^2 = -0.39 \tilde{C}_{HD} - 0.42 \tilde{C}_{HWB},$$

$$\frac{\delta \Gamma_Z}{\Gamma_Z^{SM}} = 0.46 \tilde{C}_{HWB} - 0.07 \tilde{C}_{HD} - 0.18 \tilde{C}_{Hl}^{(1)} - 1.37 \tilde{C}_{Hl}^{(3)} - 0.18 \tilde{C}_{He} \\ + 0.47 \tilde{C}_{Hq}^{(1)} + 1.61 \tilde{C}_{Hq}^{(3)} + 0.24 \tilde{C}_{Hu} - 0.18 \tilde{C}_{Hd} + \tilde{C}'_{ll},$$

$$\frac{\delta \alpha}{2 \hat{\alpha}} = -\frac{\delta G_F}{\sqrt{2}} + \frac{\delta m_Z^2}{\hat{M}_Z^2} \frac{\hat{M}_W^2}{2 (\hat{M}_W^2 - \hat{M}_Z^2)} - \tilde{C}_{HWB} \frac{\hat{M}_W}{\hat{M}_Z} \sqrt{1 - \frac{\hat{M}_W^2}{\hat{M}_Z^2}},$$

$$\frac{\delta M_W^2}{\hat{M}_W^2} = 0,$$

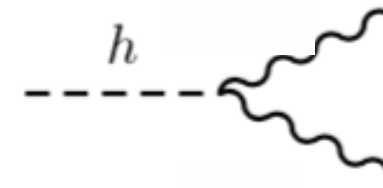
$$\frac{\delta \Gamma_W}{\Gamma_W^{SM}} = \frac{4}{3} \left(\tilde{C}_{Hq}^{(3)} - \tilde{C}_{Hl}^{(3)} \right) + \tilde{C}'_{ll}.$$

- Completely expected from AC decoupling theorem. **UV physics preserving SM symmetries being absorbed into measured low scale parameters now.**

Can we do better re basis independence? Yes.

More basis independent results are possible!

All orders expression for Higgs to gamma gamma can be defined in closed form as:



Yes! Its a Vielbein of a Higgs space defining asy. particle states in SMEFT

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

Kinematic structure

Geometric Dressings

No explicit SMEFT expansion op forms. But all orders in vev expansion

How do we get to such results?

Why all the geoSMEFT stuff.

We needed a physics principle that is active at $\mathcal{L}_6$ and $\mathcal{L}_8$ to efficiently organise the physics. Is there one?

YES THERE IS - THE MOST BASIC ONE.

Field coord. invariance leads to field space geometry

geoSMEFT

- Field coordinate choice invariance in amplitudes
- Mathematical quantities: metrics, Curvature, tensors of INTERACTION TERMS (field spaces)

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

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{bmatrix} \quad \mathcal{W}^A = (W^1, W^2, W^3, B)$$

General Relativity.

- Space-time coordinate general covariance
- Mathematical quantities: metrics, Curvature, tensors for SPACE TIME

$$R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

Field coord. invariance leads to field space geometry

geoSMEFT

- Field coordinate choice invariance in amplitudes
- Mathematical quantities: metrics, Curvature, tensors of INTERACTION TERMS (field spaces)

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

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{bmatrix} \quad \mathcal{W}^A = (W^1, W^2, W^3, B)$$

In general terms: G. A. Vilkovisky, Nucl. Phys. B234 (1984) 125.

Modern uptake:

[1002.2730](#) Burgess, Lee, Trott

[1511.00724](#) Alonso, Jenkins, Manohar

[1605.03602](#) Alonso, Jenkins, Manohar

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

[1909.08470](#) [Corbett](#), [Helset](#), Trott

General Relativity.

- Space-time coordinate general covariance
- Mathematical quantities: metrics, Curvature, tensors for SPACE TIME

$$R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

Field coord. invariance leads to field space geometry

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

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

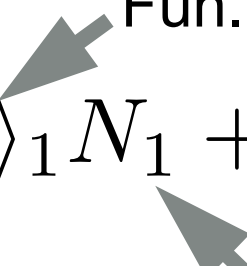
$$\sqrt{h}^{IJ} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 - \frac{1}{4}\tilde{C}_{HD} & 0 \\ 0 & 0 & 0 & 1 + \tilde{C}_{H\Box} - \frac{1}{4}\tilde{C}_{HD} \end{bmatrix}$$

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

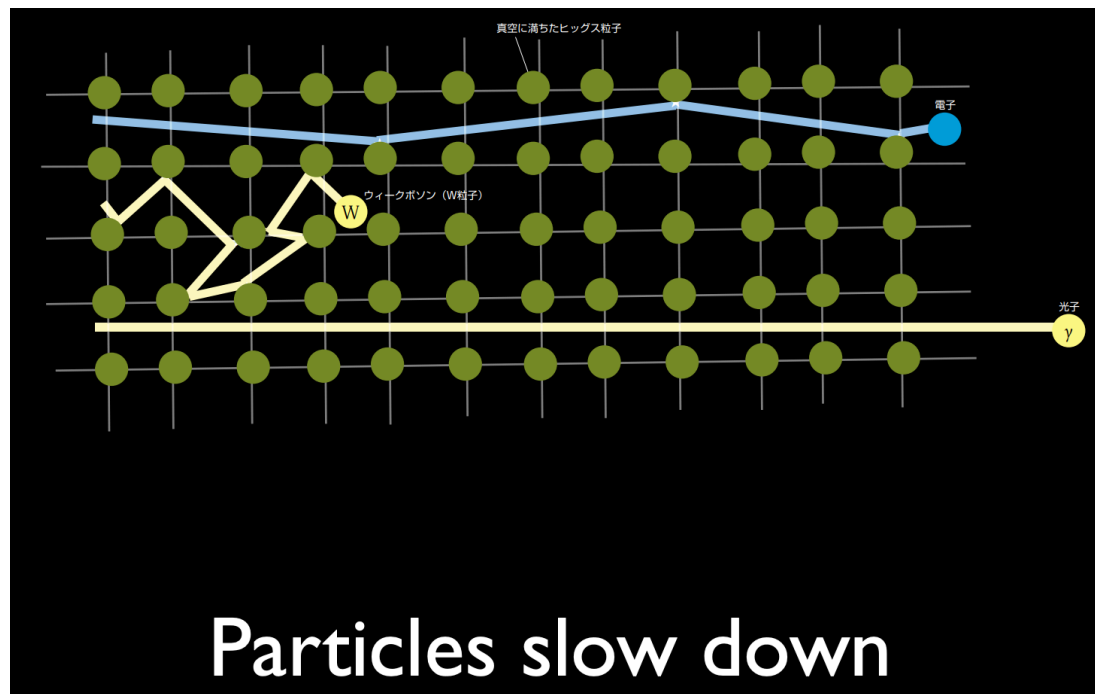
(Small perturbations so positive semi-definite matrix and unique square root)

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

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



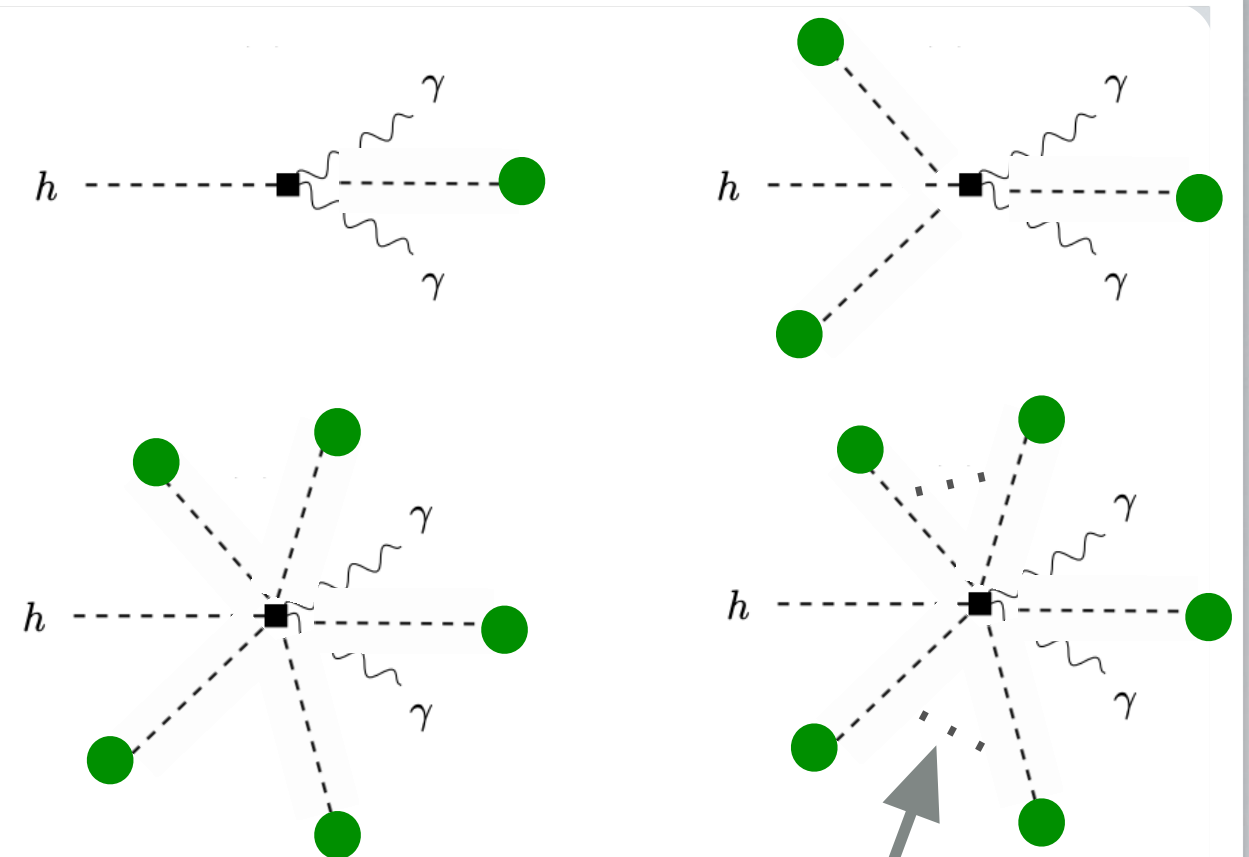
What is the Geometric SMEFT?



$$\mathcal{L}_{SM}$$

$$D \leq 4$$

Gives masses, mass eigenstate fields.

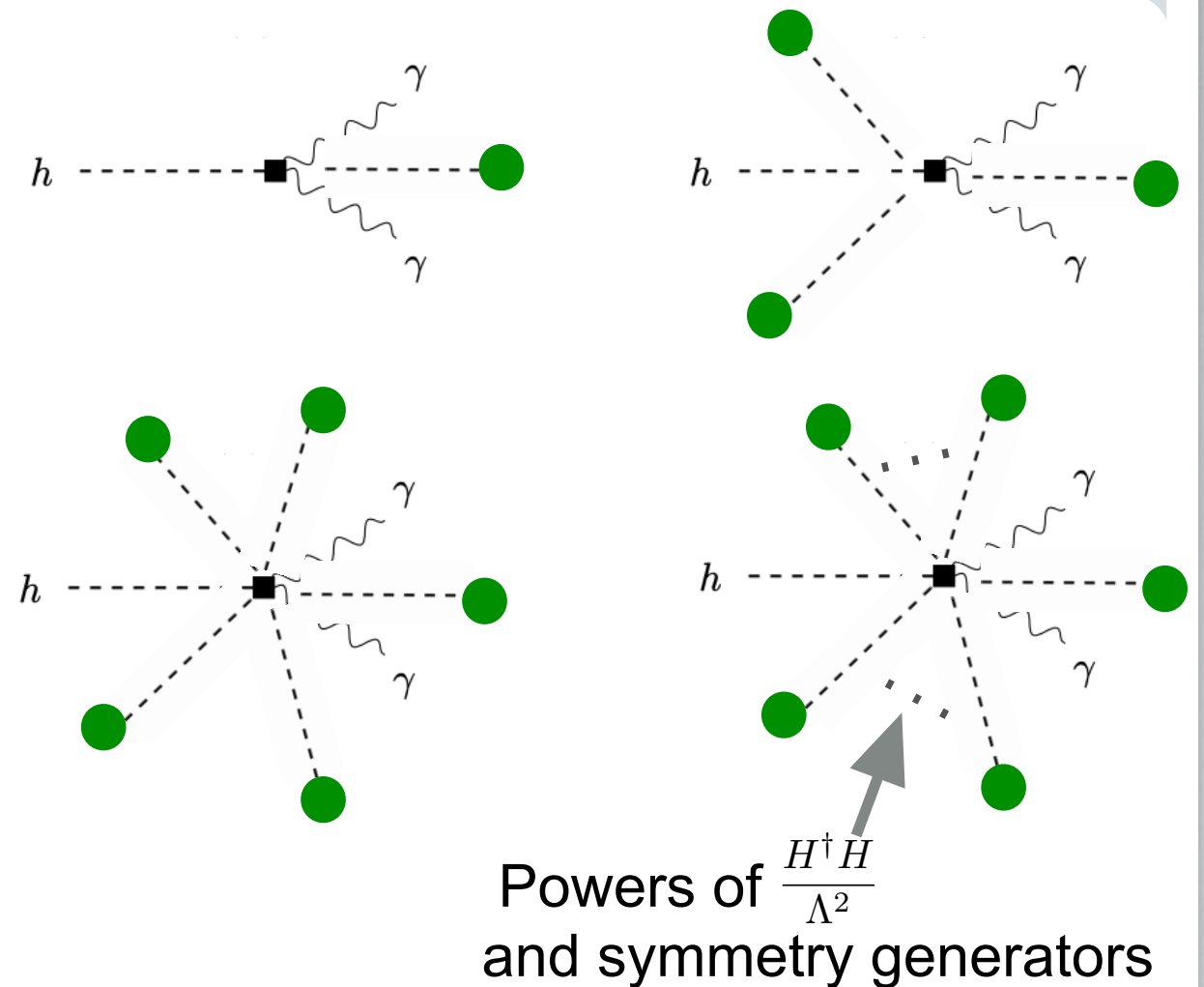
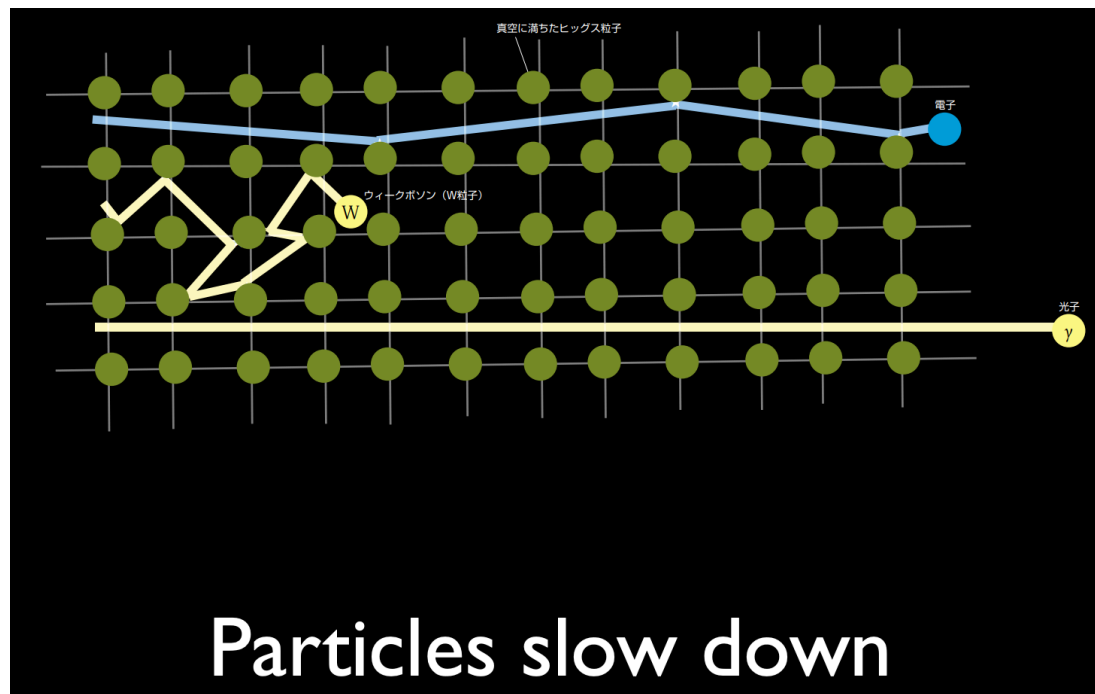


$$\mathcal{L}_{SMEFT}$$

$$D > 4$$

Gives geometries that define the mass eigenstate fields and interactions in the EFT

What is the Geometric SMEFT?



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

Kinematic structure

Geometric Dressings

Geometric couplings

Curved SMEFT spaces: scalar fields

- Curved SMEFT field space manifest in background field formulation

In general terms: G. A. Vilkovisky, Nucl. Phys. B234 (1984) 125.

Metric on Higgs field space, SM a **FLAT** field space

$$\mathcal{L}_{\text{scalar,kin}} = \frac{1}{2} h_{IJ}(\phi) (D_\mu \phi)^I (D^\mu \phi)^J, \quad \text{Where} \quad H = \frac{1}{\sqrt{2}} \begin{bmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{bmatrix}$$

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

here $\tilde{C}_i = \frac{\langle H^\dagger H \rangle}{\Lambda^2} C_i$

Small perturbations so positive semi-definite Matrix and unique square root

(sqrt) Metric in SMEFT, a *curved* field space

$$R_{JKL}^I \neq 0$$

[1002.2730](#) Burgess, Lee, Trott
[1511.00724](#) Alonso, Jenkins, Manohar
[1605.03602](#) Alonso, Jenkins, Manohar

Curved SMEFT space: gauge fields

- Similarly in the gauge coupling space a curved field space

Metric on gauge field space, SM a **FLAT** field space

$$\mathcal{L}_{\text{gauge,kin}} = -\frac{1}{4} g_{AB}(\phi) \mathcal{W}_{\mu\nu}^A \mathcal{W}^{B,\mu\nu}, \quad \text{Where} \quad \mathcal{W}^A = (W^1, W^2, W^3, B)$$

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

here $\tilde{C}_i = \frac{\langle H^\dagger H \rangle}{\Lambda^2} C_i$

(sqrt) Metric in SMEFT, a *curved* field space

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

[1909.08470](#) [Corbett](#), [Helset](#), Trott

All orders SM Lagrangian parameters

- Low n-point interactions of fields are parameterised in terms of couplings,

1909.08470 Corbett, Helset, Trott

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

- Masses

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

- Mixing angles:

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

(Interesting way to think of the Weinberg angle)

All orders expressions are known now

- All orders scalar metric -leading to gauge boson masses in SMEFT

$$h_{IJ} = \left[1 + \phi^2 C_{H\Box}^{(6)} + \sum_{n=0}^{\infty} \left(\frac{\phi^2}{2} \right)^{n+2} \left(C_{HD}^{(8+2n)} - C_{H,D2}^{(8+2n)} \right) \right] \delta_{IJ} \\ + \frac{\Gamma_{A,J}^I \phi_K \Gamma_{A,L}^K \phi^L}{2} \left(\frac{C_{HD}^{(6)}}{2} + \sum_{n=0}^{\infty} \left(\frac{\phi^2}{2} \right)^{n+1} C_{H,D2}^{(8+2n)} \right).$$

- All orders gauge metric - gives mass eigenstate couplings in SMEFT

$$g_{AB}(\phi_I) = \left[1 - 4 \sum_{n=0}^{\infty} \left(C_{HW}^{(6+2n)} (1 - \delta_{A4}) + C_{HB}^{(6+2n)} \delta_{A4} \right) \left(\frac{\phi^2}{2} \right)^{n+1} \right] \delta_{AB} \\ - \sum_{n=0}^{\infty} C_{HW,2}^{(8+2n)} \left(\frac{\phi^2}{2} \right)^n (\phi_I \Gamma_{A,J}^I \phi^J) (\phi_L \Gamma_{B,K}^L \phi^K) (1 - \delta_{A4})(1 - \delta_{B4}) \\ + \left[\sum_{n=0}^{\infty} C_{HWB}^{(6+2n)} \left(\frac{\phi^2}{2} \right)^n \right] [(\phi_I \Gamma_{A,J}^I \phi^J) (1 - \delta_{A4}) \delta_{B4} + (A \leftrightarrow B)],$$

- Number of operator forms saturate in geosmeft.
This is due to reducing possible generator insertions on the Higgs manifold

$$T_{ij}^a T_{kl}^a = \frac{1}{2} \left(\delta_{il} \delta_{jk} - \frac{1}{N} \delta_{ij} \delta_{kl} \right)$$

SM weak-mass eigenstate relations

- Weak eigenstates

Mass eigenstate

$$\begin{aligned}\hat{\mathcal{W}}^{A,\nu} &= \delta^{AB} U_{BC} \hat{\mathcal{A}}^{C,\nu}, \\ \hat{\alpha}^A &= \delta^{AB} U_{BC} \hat{\beta}^C, \\ \hat{\phi}^J &= \delta^{JK} V_{KL} \hat{\Phi}^L,\end{aligned}$$

Rotations

Flat field space's.
Due to $D \leq 4$

$$U_{BC} = \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{i}{\sqrt{2}} & \frac{-i}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & c_{\bar{\theta}} & s_{\bar{\theta}} \\ 0 & 0 & -s_{\bar{\theta}} & c_{\bar{\theta}} \end{bmatrix} \quad V_{JK} = \begin{bmatrix} \frac{-i}{\sqrt{2}} & \frac{i}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\phi^J = \{\phi_1, \phi_2, \phi_3, \phi_4\}, \Phi^K = \{\Phi^-, \Phi^+, \chi, h\}$$

$$\alpha^A = \{g_2, g_2, g_2, g_1\},$$

$$\mathcal{W}^A = \{W_1, W_2, W_3, B\},$$

$$\beta^C = \left\{ \frac{g_2(1-i)}{\sqrt{2}}, \frac{g_2(1+i)}{\sqrt{2}}, \sqrt{g_1^2 + g_2^2}(c_{\bar{\theta}}^2 - s_{\bar{\theta}}^2), \frac{2g_1g_2}{\sqrt{g_1^2 + g_2^2}} \right\}, \quad \mathcal{A}^C = (\mathcal{W}^+, \mathcal{W}^-, \mathcal{Z}, \mathcal{A}).$$

What else could you write?

SMEFT weak-mass eigenstate relations

- Weak eigenstates

Mass eigenstate

$$\hat{\mathcal{W}}^{A,\nu} = \sqrt{g}^{AB} U_{BC} \hat{\mathcal{A}}^{C,\nu},$$

$$\hat{\alpha}^A = \sqrt{g}^{AB} U_{BC} \hat{\beta}^C,$$

$$\hat{\phi}^J = \sqrt{h}^{JK} V_{KL} \hat{\Phi}^L,$$

Generator transform

$$\gamma_{C,J}^I = \frac{1}{2} \tilde{\gamma}_{A,J}^I \sqrt{g}^{AB} U_{BC}.$$

1909.08470 Corbett, Helset, Trott

SMEFT Field space metrics
(Now known to all orders)

Rotations

$$U_{BC} = \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{i}{\sqrt{2}} & \frac{-i}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & c_{\bar{\theta}} & s_{\bar{\theta}} \\ 0 & 0 & -s_{\bar{\theta}} & c_{\bar{\theta}} \end{bmatrix} \quad V_{JK} = \begin{bmatrix} \frac{-i}{\sqrt{2}} & \frac{i}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\phi^J = \{\phi_1, \phi_2, \phi_3, \phi_4\}, \Phi^K = \{\Phi^-, \Phi^+, \chi, h\}$$

$$\alpha^A = \{g_2, g_2, g_2, g_1\},$$

$$\mathcal{W}^A = \{W_1, W_2, W_3, B\},$$

$$\beta^C = \left\{ \frac{g_2(1-i)}{\sqrt{2}}, \frac{g_2(1+i)}{\sqrt{2}}, \sqrt{g_1^2 + g_2^2}(c_{\bar{\theta}}^2 - s_{\bar{\theta}}^2), \frac{2g_1g_2}{\sqrt{g_1^2 + g_2^2}} \right\}, \quad \mathcal{A}^C = (\mathcal{W}^+, \mathcal{W}^-, \mathcal{Z}, \mathcal{A}).$$

What else could you write? Nothing that generalises to all orders.

Dim 6 SMEFT EW Lagrangian terms

- EW sector parameters redefined in the SMEFT (already in SMEFTsim)

$$\begin{bmatrix} \mathcal{W}_\mu^3 \\ \mathcal{B}_\mu \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} v_T^2 C_{HWB} \\ -\frac{1}{2} v_T^2 C_{HWB} & 1 \end{bmatrix} \begin{bmatrix} \cos \bar{\theta} & \sin \bar{\theta} \\ -\sin \bar{\theta} & \cos \bar{\theta} \end{bmatrix} \begin{bmatrix} \mathcal{Z}_\mu \\ \mathcal{A}_\mu \end{bmatrix},$$

Mass redefinitions

$$M_W^2 = \frac{\bar{g}_2^2 v_T^2}{4},$$

$$M_Z^2 = \frac{v_T^2}{4} (\bar{g}_1^2 + \bar{g}_2^2) + \frac{1}{8} v_T^4 C_{HD} (\bar{g}_1^2 + \bar{g}_2^2) + \frac{1}{2} v_T^4 \bar{g}_1 \bar{g}_2 C_{HWB}.$$

Mixing angle redefinitions

$$\sin \bar{\theta} = \frac{\bar{g}_1}{\sqrt{\bar{g}_1^2 + \bar{g}_2^2}} \left[1 + \frac{v_T^2}{2} \frac{\bar{g}_2}{\bar{g}_1} \frac{\bar{g}_2^2 - \bar{g}_1^2}{\bar{g}_2^2 + \bar{g}_1^2} C_{HWB} \right]$$

$$\cos \bar{\theta} = \frac{\bar{g}_2}{\sqrt{\bar{g}_1^2 + \bar{g}_2^2}} \left[1 - \frac{v_T^2}{2} \frac{\bar{g}_1}{\bar{g}_2} \frac{\bar{g}_2^2 - \bar{g}_1^2}{\bar{g}_2^2 + \bar{g}_1^2} C_{HWB} \right]$$

Interactions to remaining SM fields via:

$$D_\mu = \partial_\mu + i \frac{\bar{g}_2}{\sqrt{2}} [\mathcal{W}_\mu^+ T^+ + \mathcal{W}_\mu^- T^-] + i \bar{g}_Z [T_3 - \bar{s}^2 Q] \mathcal{Z}_\mu + i \bar{e} Q \mathcal{A}_\mu,$$

$$\bar{e} = \frac{\bar{g}_1 \bar{g}_2}{\sqrt{\bar{g}_2^2 + \bar{g}_1^2}} \left[1 - \frac{\bar{g}_1 \bar{g}_2}{\bar{g}_2^2 + \bar{g}_1^2} v_T^2 C_{HWB} \right]$$

$$\bar{g}_Z = \sqrt{\bar{g}_2^2 + \bar{g}_1^2} + \frac{\bar{g}_1 \bar{g}_2}{\sqrt{\bar{g}_2^2 + \bar{g}_1^2}} v_T^2 C_{HWB}$$

- Dim 8,10 etc solved in closed form. Just expand. $\bar{s}^2 = \sin^2 \bar{\theta} = \frac{\bar{g}_1^2}{\bar{g}_2^2 + \bar{g}_1^2} + \frac{\bar{g}_1 \bar{g}_2 (\bar{g}_2^2 - \bar{g}_1^2)}{(\bar{g}_1^2 + \bar{g}_2^2)^2} v_T^2 C_{HWB}.$

Generalisation for composite ops

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



$$\mathcal{L}_{SMEFT} = \sum_i f_i(\alpha \dots) G_i(I, A \dots),$$

Derivative expansion

Composite operator form
With minimal scalar field
coordinate dependence

Vev expansion

Scalar field coordinate dependence
And insertions of symmetry generators

$$D^\mu \phi$$

Mixes expansions, but grouped with derivative forms.

Generalisation for composite ops

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

Fun. of 4 vectors (kinematics)

Defined by field space geometries

Making this decomposition more manifest from the start
The usual operator focused language is not particularly helpful.

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

Generalisation for composite ops



Reformulate!
Reformulate!

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

$$\mathcal{L}_{\text{SMEFT}} = \sum_i f_i(\alpha \dots) G_i(I, A \dots),$$

Derivative expansion

Composite operator form
With minimal scalar field
coordinate dependence

Vev expansion

Scalar field coordinate dependence
And insertions of symmetry generators

$$D^\mu \phi$$

Mixes expansions, but grouped with derivative forms.

The intermediate language between
Pure amplitudes, and pure operators,
is field space geometry.

Generalisation for composite ops

- Such connections can be defined from the Lagrangian expansion constructively

$$h_{IJ}(\phi) = \frac{g^{\mu\nu}}{d} \frac{\delta^2 \mathcal{L}_{\text{SMEFT}}}{\delta(D_\mu \phi)^I \delta(D_\nu \phi)^J} \Big|_{\mathcal{L}(\alpha, \beta \dots) \rightarrow 0}.$$

non-trivial Lorentz-index-carrying Lagrangian terms and spin connections $\{\mathcal{W}_{\mu\nu}^A, (D^\mu \Phi)^K, \bar{\psi} \sigma^\mu \psi, \bar{\psi} \psi \dots\}$

- Limited number of such connections for up to three point functions

$$V(\phi) \quad h_{IJ}(\phi)(D_\mu \phi)^I (D_\mu \phi)^J, \quad g_{AB}(\phi) \mathcal{W}_{\mu\nu}^A \mathcal{W}^{B, \mu\nu}, \quad k_{IJ}^A(\phi)(D_\mu \phi)^I (D_\nu \phi)^J \mathcal{W}_A^{\mu\nu}, \\ f_{ABC}(\phi) \mathcal{W}_{\mu\nu}^A \mathcal{W}^{B, \nu\rho} \mathcal{W}_\rho^{C, \mu},$$

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

Gluon fields $k_{\mathcal{A}\mathcal{B}}(\phi) G_{\mu\nu}^{\mathcal{A}} G^{B, \mu\nu}, \quad k_{\mathcal{A}\mathcal{B}\mathcal{C}}(\phi) G_{\nu\mu}^{\mathcal{A}} G^{B, \rho\nu} G^{C, \mu\rho}, \quad c(\phi) \bar{\psi}_1 \sigma^{\mu\nu} T_{\mathcal{A}} \psi_2 G_{\mu\nu}^{\mathcal{A}}.$

Generalisation for composite ops

- Such connections can be defined from the Lagrangian expansion constructively

$$h_{IJ}(\phi) = \frac{g^{\mu\nu}}{d} \frac{\delta^2 \mathcal{L}_{\text{SMEFT}}}{\delta(D_\mu \phi)^I \delta(D_\nu \phi)^J} \Big|_{\mathcal{L}(\alpha, \beta \dots) \rightarrow 0}.$$

non-trivial Lorentz-index-carrying Lagrangian terms and spin connections $\{\mathcal{W}_{\mu\nu}^A, (D^\mu \Phi)^K, \bar{\psi} \sigma^\mu \psi, \bar{\psi} \psi \dots\}$

- Limited number of such connections for up to three point functions

This is a non trivial fact proven in [2001.01453](#) Helset, Martin, Trott

There is a theory choice here - its REMOVE DERIVATIVE OPS, USE EOM.

Same reasoning built into, and led to the “Warsaw basis”.

Also why we were able to renormalise the Warsaw basis completely in 2013.

EFT Industry standard in flavour physics, chiral pert theory etc.

An instant pay off of this approach

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

	Mass Dimension				
Field space connection	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
$k_{IJA}(\phi)(D^\mu\phi)^I(D^\nu\phi)^J\mathcal{W}_{\mu\nu}^A$	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
$Y_{pr}^u(\phi)\bar{Q}u + \text{h.c.}$	$2 N_f^2$	$2 N_f^2$	$2 N_f^2$	$2 N_f^2$	$2 N_f^2$
$Y_{pr}^d(\phi)\bar{Q}d + \text{h.c.}$	$2 N_f^2$	$2 N_f^2$	$2 N_f^2$	$2 N_f^2$	$2 N_f^2$
$Y_{pr}^e(\phi)\bar{L}e + \text{h.c.}$	$2 N_f^2$	$2 N_f^2$	$2 N_f^2$	$2 N_f^2$	$2 N_f^2$
$d_A^{e,pr}(\phi)\bar{L}\sigma_{\mu\nu}e\mathcal{W}_A^{\mu\nu} + \text{h.c.}$	$4 N_f^2$	$6 N_f^2$	$6 N_f^2$	$6 N_f^2$	$6 N_f^2$
$d_A^{u,pr}(\phi)\bar{Q}\sigma_{\mu\nu}u\mathcal{W}_A^{\mu\nu} + \text{h.c.}$	$4 N_f^2$	$6 N_f^2$	$6 N_f^2$	$6 N_f^2$	$6 N_f^2$
$d_A^{d,pr}(\phi)\bar{Q}\sigma_{\mu\nu}d\mathcal{W}_A^{\mu\nu} + \text{h.c.}$	$4 N_f^2$	$6 N_f^2$	$6 N_f^2$	$6 N_f^2$	$6 N_f^2$
$L_{pr,A}^{\psi_R}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,R}\gamma_\mu\sigma_A\psi_{r,R})$	N_f^2	N_f^2	N_f^2	N_f^2	N_f^2
$L_{pr,A}^{\psi_L}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,L}\gamma_\mu\sigma_A\psi_{r,L})$	$2 N_f^2$	$4 N_f^2$	$4 N_f^2$	$4 N_f^2$	$4 N_f^2$

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

Mases

Couplings and mixing angles

TGC, Higgs to ZZ, WW

QGC, TGC + Higgs

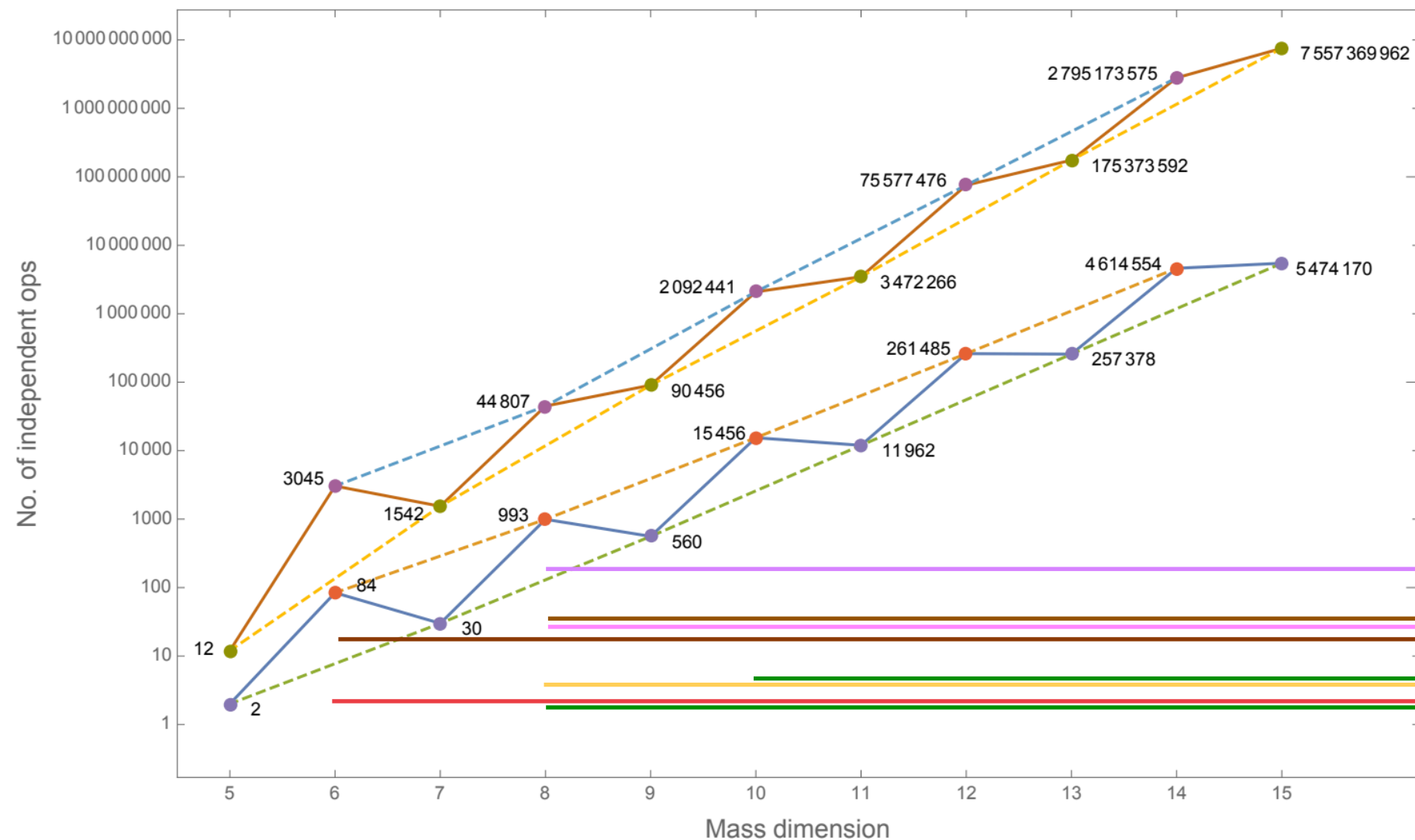
Yukawas

Dipoles

W, Z couplings to fermions + higgs

2001.01453 Helset, Martin, Trott

Application to theory error

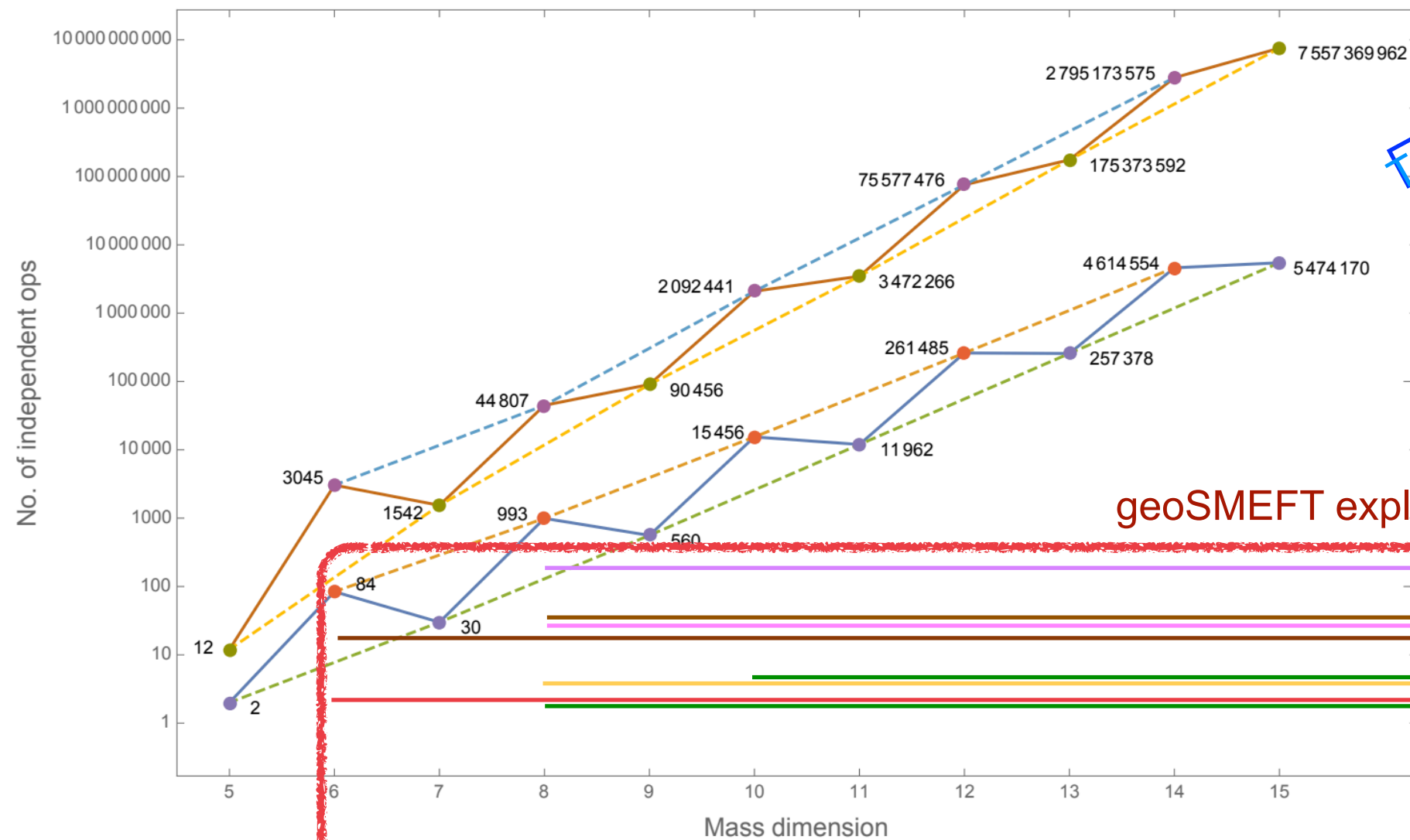


- General growth in operator forms from Hilbert series

1503.07537 Lehman, Martin. 1512.03433 Henning, Lu, Melia, Murayama

1510.00372 Lehman, Martin. 1706.08520 Henning, Lu, Melia, Murayama

Application to theory error



Tails built of 4pts/higher
Number of parameters
Grows with a factorial
In general with mass dim

geoSMEFT exploits this structure

Pole(s) built of 2,3 pts

Parameters $O(10's)$
Number of parameters
saturates to a constant
with mass dim

- General growth in operator forms from Hilbert series

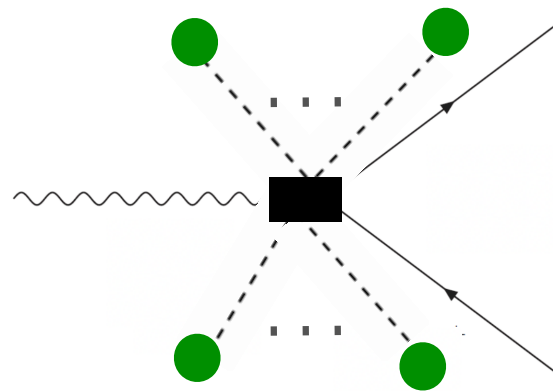
1503.07537 Lehman, Martin. 1512.03433 Henning, Lu, Melia, Murayama

1510.00372 Lehman, Martin. 1706.08520 Henning, Lu, Melia, Murayama

GeoSMEFT example

- What does this allow one to do?

2001.01453 Helset, Martin, Trott



Consider a $W^\pm, Z$ coupling to a fermion bilinear.

The all orders coupling in the SMEFT is a sum of two field space connections.

$\bar{\psi} i \not{D} \psi$:with a consistent change weak to mass eigenstates in SMEFT

Added to this is the scalar, fermion connection
(with a background field expectation)

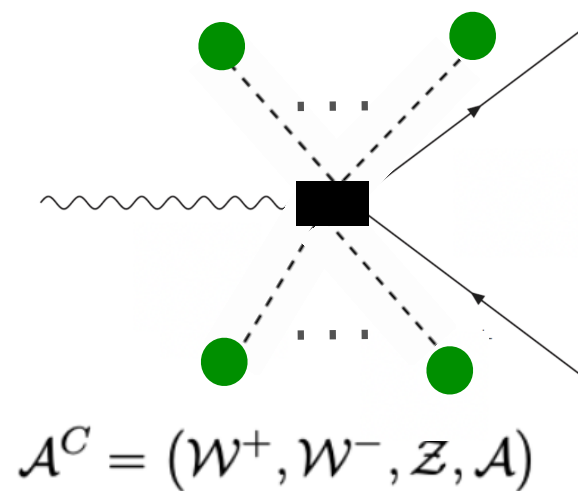
$$L_{pr,A}^{\psi_R}(\phi)(D^\mu \phi)^J(\bar{\psi}_{p,R} \gamma_\mu \sigma_A \psi_{r,R})$$

$$L_{pr,A}^{\psi_L}(\phi)(D^\mu \phi)^J(\bar{\psi}_{p,L} \gamma_\mu \sigma_A \psi_{r,L})$$

GeoSMEFT example

- What does this allow one to do?

2001.01453 Helset, Martin, Trott



Consider a $W^\pm, Z$ coupling to a fermion bilinear.

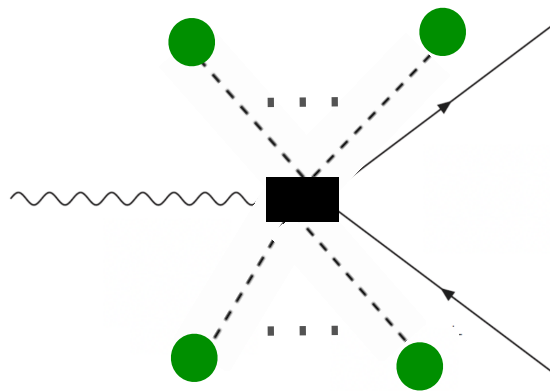
$$-\mathcal{A}^{A,\mu}(\bar{\psi}_p \gamma_\mu \bar{\tau}_A \psi_r) \delta_{pr} + \mathcal{A}^{C,\mu}(\bar{\psi}_p \gamma_\mu \sigma_A \psi_r) \langle L_{I,A}^{\psi,pr} \rangle (-\gamma_{C,4}^I) \bar{v}_T,$$

Compact all $\bar{v}_T/\Lambda$ orders answer!

GeoSMEFT example

- What does this allow one to do?

2001.01453 Helset, Martin, Trott



Consider a $W^\pm, Z$ coupling to a fermion bilinear.

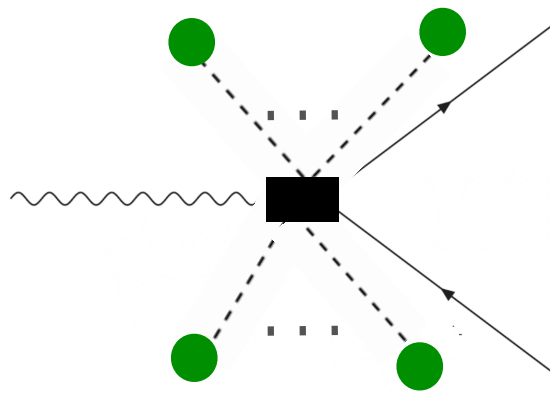
$$-\mathcal{A}^{A,\mu}(\bar{\psi}_p \gamma_\mu \bar{\tau}_A \psi_r) \delta_{pr} + \mathcal{A}^{C,\mu}(\bar{\psi}_p \gamma_\mu \sigma_A \psi_r) \langle L_{I,A}^{\psi,pr} \rangle (-\gamma_{C,4}^I) \bar{v}_T,$$

The coupling of the canonically normalised mass eigenstate fields is then

$$\begin{aligned} \langle \mathcal{Z} | \bar{\psi}_p \psi_r \rangle &= \frac{\bar{g}_Z}{2} \bar{\psi}_p \not{\epsilon}_Z \left[(2s_{\theta_Z}^2 Q_\psi - \sigma_3) \delta_{pr} + \sigma_3 \bar{v}_T \langle L_{3,3}^{\psi,pr} \rangle + \bar{v}_T \langle L_{3,4}^{\psi,pr} \rangle \right] \psi_r, \\ \langle \mathcal{A} | \bar{\psi}_p \psi_r \rangle &= -\bar{e} \bar{\psi}_p \not{\epsilon}_A Q_\psi \delta_{pr} \psi_r, \\ \langle \mathcal{W}_\pm | \bar{\psi}_p \psi_r \rangle &= -\frac{\bar{g}_2}{\sqrt{2}} \bar{\psi}_p (\not{\epsilon}_{\mathcal{W}^\pm}) T^\pm \left[\delta_{pr} - \bar{v}_T \langle L_{1,1}^{\psi,pr} \rangle \pm i \bar{v}_T \langle L_{1,2}^{\psi,pr} \rangle \right] \psi_r. \end{aligned}$$

GeoSMEFT example

- Can build up observable quantities, such as a decay width.



Consider a $W^\pm, Z$ coupling to a fermion bilinear.

$$-\mathcal{A}^{A,\mu}(\bar{\psi}_p\gamma_\mu\bar{\tau}_A\psi_r)\delta_{pr} + \mathcal{A}^{C,\mu}(\bar{\psi}_p\gamma_\mu\sigma_A\psi_r)\langle L_{I,A}^{\psi,pr}\rangle(-\gamma_{C,4}^I)\bar{v}_T,$$

- Two body decay widths:

$$\bar{\Gamma}_{Z\rightarrow\bar{\psi}\psi} = \sum_{\psi} \frac{N_c^\psi}{24\pi} \sqrt{\bar{m}_Z^2} |g_{\text{eff}}^{Z,\psi}|^2 \left(1 - \frac{4\bar{M}_\psi^2}{\bar{m}_Z^2}\right)^{3/2}$$

$$g_{\text{eff}}^{Z,\psi} = \frac{\bar{g}_Z}{2} \left[(2s_{\theta_Z}^2 Q_\psi - \sigma_3)\delta_{pr} + \bar{v}_T \langle L_{3,4}^{\psi,pr} \rangle + \sigma_3 \bar{v}_T \langle L_{3,3}^{\psi,pr} \rangle \right]$$

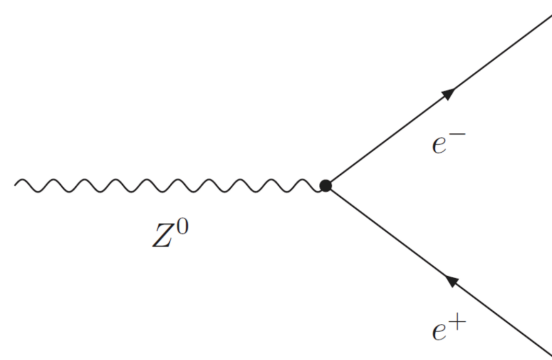
$$\bar{\Gamma}_{W\rightarrow\bar{\psi}\psi} = \sum_{\psi} \frac{N_c^\psi}{24\pi} \sqrt{\bar{m}_W^2} |g_{\text{eff}}^{W,\psi}|^2 \left(1 - \frac{4\bar{M}_\psi^2}{\bar{m}_W^2}\right)^{3/2}$$

$$g_{\text{eff}}^{W,q_L} = -\frac{\bar{g}_2}{\sqrt{2}} \left[V_{\text{CKM}}^{pr} - \bar{v}_T \langle L_{1,1}^{q_L,pr} \rangle \pm i\bar{v}_T \langle L_{1,2}^{q_L,pr} \rangle \right],$$

$$g_{\text{eff}}^{W,\ell_L} = -\frac{\bar{g}_2}{\sqrt{2}} \left[U_{\text{PMNS}}^{pr,\dagger} - \bar{v}_T \langle L_{1,1}^{\ell_L,pr} \rangle \pm i\bar{v}_T \langle L_{1,2}^{\ell_L,pr} \rangle \right],$$

SMEFT expansion correction error estimate by process.

- Process by process many of the dimension 8 corrections are also fully known now. We can examine process by process to be informed in defining the error. Ex. [2102.02819](#) Helset, Corbett, Martin, Trott



$$= \langle g_{\text{SM},\text{pr}}^{\mathcal{Z},\psi} \rangle + \langle g_{\text{eff},\text{pr}}^{\mathcal{Z},\psi} \rangle \mathcal{O}(v^2/\Lambda^2) + \langle g_{\text{eff},\text{pr}}^{\mathcal{Z},\psi} \rangle \mathcal{O}(v^4/\Lambda^4) + \dots$$

- LO SMEFT in SMEFTsim

SMEFT corrections in the $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}/\{\hat{\alpha}, \hat{m}_Z, \hat{G}_F\}$ scheme							
$\mathcal{O}(v^2/\Lambda^2)$	$\langle g_{\text{eff},\text{pp}}^{\mathcal{Z},u_R} \rangle$	$\langle g_{\text{eff},\text{pp}}^{\mathcal{Z},d_R} \rangle$	$\langle g_{\text{eff},\text{pp}}^{\mathcal{Z},\ell_R} \rangle$	$\langle g_{\text{eff},\text{pp}}^{\mathcal{Z},u_L} \rangle$	$\langle g_{\text{eff},\text{pp}}^{\mathcal{Z},d_L} \rangle$	$\langle g_{\text{eff},\text{pp}}^{\mathcal{Z},\ell_L} \rangle$	$\langle g_{\text{eff},\text{pp}}^{\mathcal{Z},\nu_L} \rangle$
$\delta G_F^{(6)}$	-0.08/0.15	0.04/-0.07	0.12/-0.22	0.18/0.41	-0.22/-0.34	-0.15/-0.49	0.26/0.26
$\tilde{C}_{HD}^{(6)}$	-0.22/0.05	0.11/-0.03	0.33/-0.08	-0.13/0.15	0.02/-0.12	0.24/-0.17	0.09/0.09
$\tilde{C}_{HWB}^{(6)}$	-0.21/0.39	0.10/-0.19	0.31/-0.58	-0.21/0.39	0.10/-0.19	0.31/-0.58	
$\tilde{C}_{H\psi}^{(6)}$	0.37/0.37	0.37/0.37	0.37/0.37	0.37/0.37	0.37/0.37	0.37/0.37	0.37/0.37
$\tilde{C}_{H\psi}^{3,(6)}$				-0.37/-0.37	0.37/0.37	0.37/0.37	-0.37/-0.37

SMEFT expansion correction error estimate by process.

- EWPD to dim 8 now known in both input parameter schemes.

2102.02819 Helset, Corbett, Martin, Trott

Many cross terms
NOT in quadratics
but known for error
Estimates

Few new dimension
Eight parameters

SMEFT corrections in $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}/\{\hat{\alpha}, \hat{m}_Z, \hat{G}_F\}$ scheme			
$\mathcal{O}(\frac{v^4}{\Lambda^4})$	$\langle g_{\text{eff,pp}}^{\mathcal{Z},u_R} \rangle$	$\langle g_{\text{eff,pp}}^{\mathcal{Z},d_R} \rangle$	$\langle g_{\text{eff,pp}}^{\mathcal{Z},\ell_R} \rangle$
$\langle g_{\text{eff}}^{\mathcal{Z},\psi} \rangle^2$	14/5.5	-27/-11	-9.1/-3.6
$\tilde{C}_{HB} \tilde{C}_{HWB}$	-0.21/0.39	0.10/-0.19	0.31/-0.58
$\tilde{C}_{HD}^2$	0.28/-0.026	-0.14/0.013	-0.42/0.040
$\tilde{C}_{HD} \tilde{C}_{H\psi}^{(6)}$	-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
$\tilde{C}_{HD} \langle g_{\text{eff}}^{\mathcal{Z},\psi} \rangle$	4.0/0.50	4.0/0.50	4.0/0.50
$(\tilde{C}_{H\psi}^{(6)})^2$	0.62/1.4	-1.2/-2.8	-0.42/-0.93
$\tilde{C}_{HWB} \tilde{C}_{H\psi}^{(6)}$	-0.69/0.58	-0.69/0.58	-0.69/0.58
$\tilde{C}_{H\psi}^{(6)} \langle g_{\text{eff}}^{\mathcal{Z},\psi} \rangle$	-6.7/-5.8	13/12	4.5/3.9
$\tilde{C}_{HWB} \langle g_{\text{eff}}^{\mathcal{Z},\psi} \rangle$	3.7/0.26	3.7/0.26	3.7/0.26
$\tilde{C}_{HW} \tilde{C}_{HWB}$	-0.21/0.39	0.10/-0.19	0.31/-0.58
$\tilde{C}_{HD}^{(8)}$	-0.014/0.026	0.0069/-0.013	0.021/-0.040
$\tilde{C}_{HD,2}^{(8)}$	-0.21/0.026	0.10/-0.013	0.31/-0.040
$\tilde{C}_{H\psi}^{(8)}$	0.19/0.19	0.19/0.19	0.19/0.19
$\tilde{C}_{HW,2}^{(8)}$	-0.38/0	0.19/0	0.58/0
$\tilde{C}_{HWB}^{(8)}$	-0.10/0.19	0.051/-0.097	0.15/-0.29
$\delta G_F^{(8)}$	-0.078/0.15	0.039/-0.075	0.12/-0.22
$(\tilde{C}_{HWB}^{(6)})^2$	0.19/-0.35	-0.096/0.18	-0.29/0.53

General lessons learned

If a process is un-suppressed in the SM

- $\mathcal{L}_8$ effects on naive $\mathcal{L}_6$ conclusions can be very minor

General lessons learned

If a process is un-suppressed in the SM

- $\mathcal{L}_8$ effects on naive $\mathcal{L}_6$ conclusions can be very minor

$W^\pm, Z$ coupling to a fermion bilinear.

Dim 8 effects on Z decay now known

$$-\mathcal{A}^{A,\mu}(\bar{\psi}_p\gamma_\mu\bar{\tau}_A\psi_r)\delta_{pr} + \mathcal{A}^{C,\mu}(\bar{\psi}_p\gamma_\mu\sigma_A\psi_r)\langle L_{I,A}^{\psi,pr}\rangle(-\gamma_{C,4}^I)\bar{v}_T,$$

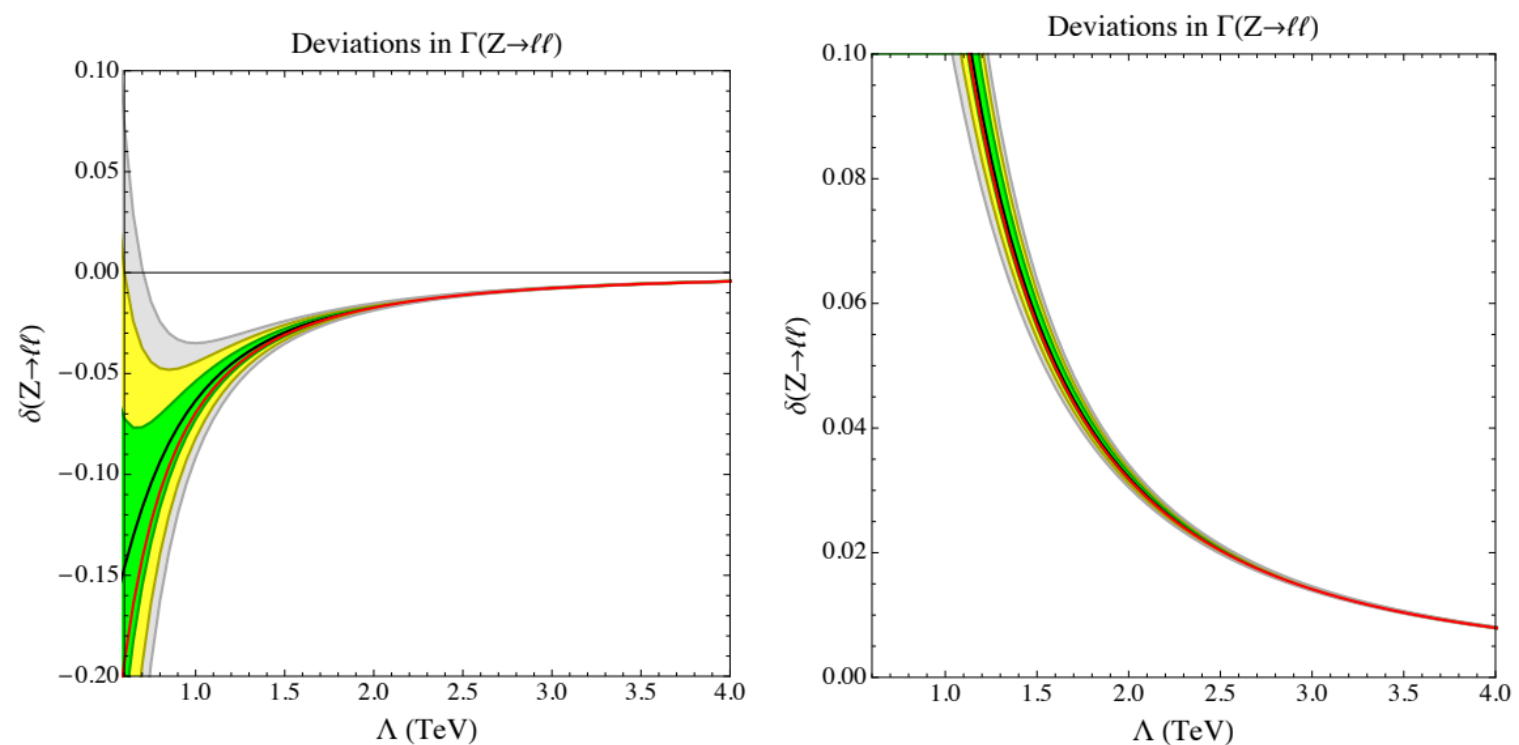


Figure 3. The deviations in $Z \rightarrow \ell\ell$ from the $\mathcal{O}(v^2/\Lambda^2)$ (red line) and partial-square (black line) results, and the full $\mathcal{O}(v^4/\Lambda^4)$ results (green $\pm 1\sigma_\delta$, yellow $\pm 2\sigma_\delta$, and grey $\pm 3\sigma_\delta$ regions). In the left panel the coefficients determining the $\mathcal{O}(v^2/\Lambda^2)$ and partial-square results are $C_{H\ell}^{1,(6)} = -0.46$, $C_{H\ell}^{3,(6)} = 1.24$, $C_{He}^{(6)} = 1.53$, $C_{HD}^{(6)} = -0.79$, $C_{HWB}^{(6)} = 0.007$, and $\delta G_F^{(6)} = 0.16$. In the right panel they are $C_{H\ell}^{1,(6)} = 1.55$, $C_{H\ell}^{3,(6)} = -0.71$, $C_{He}^{(6)} = 0.23$, $C_{HD}^{(6)} = -0.51$, $C_{HWB}^{(6)} = -0.008$, and $\delta G_F^{(6)} = -0.44$.

2102.02819 Helset, Corbett, Martin, Trott

General lessons learned

If a process is un-suppressed in the SM

- $\mathcal{L}_8$ effects on naive $\mathcal{L}_6$ conclusions can be very minor

If a process is **numerically suppressed** in the SM

- $\mathcal{L}_8, \mathcal{L}_6^2$ effects on naive $\mathcal{L}_6$ conclusions can be significant

Be careful with LEP EWPD in EFT

- Doubts were raised that $\mathcal{L}_8$ neglect and loop neglect in EWPD can significantly impact naive $\mathcal{L}_6$ bounds. Here is how it worked out:

1502.02570, 1508.05060, Berthier, MT, 1606.06693 Berthier, Bjorn, MT, arXiv:1701.06424 Brivio, MT

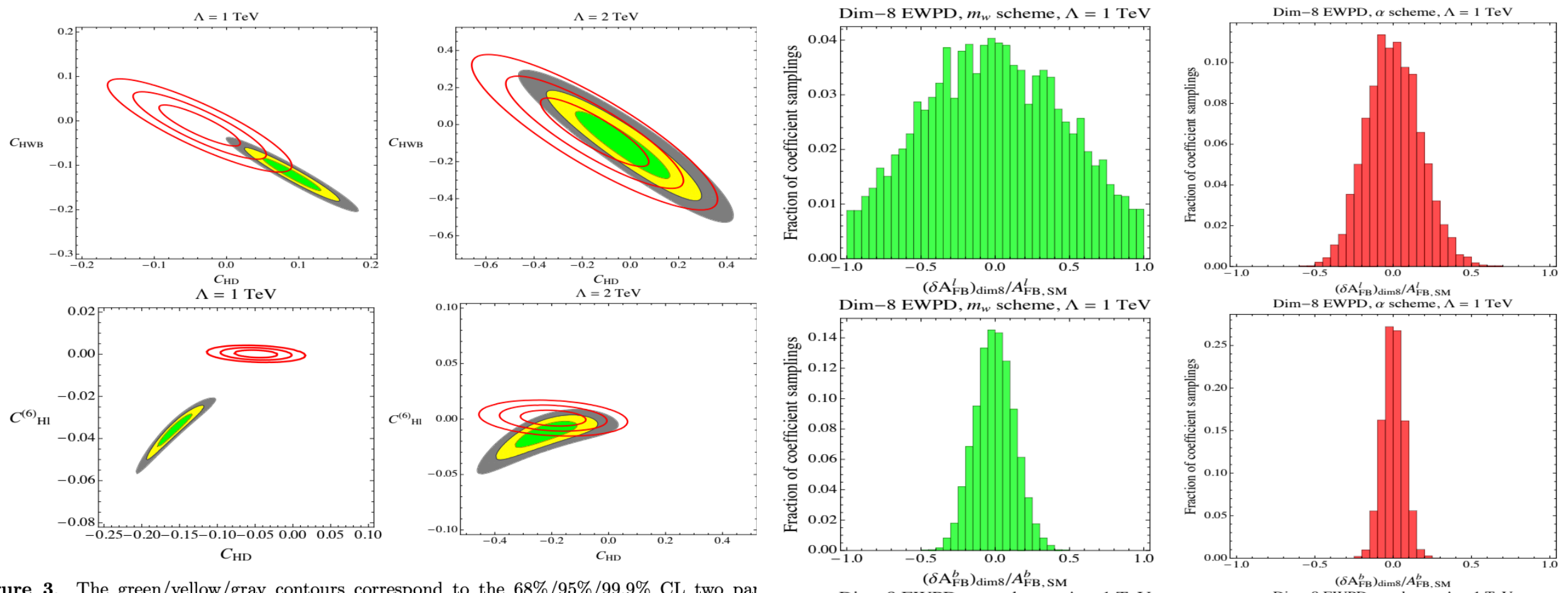


Figure 3. The green/yellow/gray contours correspond to the 68%/95%/99.9% CL two parameter fit determined by $\Delta\chi^2_{O(v^4/\Lambda^4)}$, while the red rings correspond to the same CL determined using $\Delta\chi^2_{O(v^2/\Lambda^2)}$. In the top panels the free parameters are C_{HD} and C_{HWB} , while in the bottom panels the free parameters are C_{HD} and $C_{HL}^{(6)}$. Note that the axes ranges vary from panel to panel. In the left panels, we have taken the scale $\Lambda = 1$ TeV, while in the right panels $\Lambda = 2$ TeV. All calculations use the $\hat{m}_W$ scheme.

2102.02819 Helset, Corbett, Martin, Trott

- **Significant implications for future collider studies.**

General lessons learned

If a process is un-suppressed in the SM

- $\mathcal{L}_8$ effects on naive $\mathcal{L}_6$ conclusions can be very minor

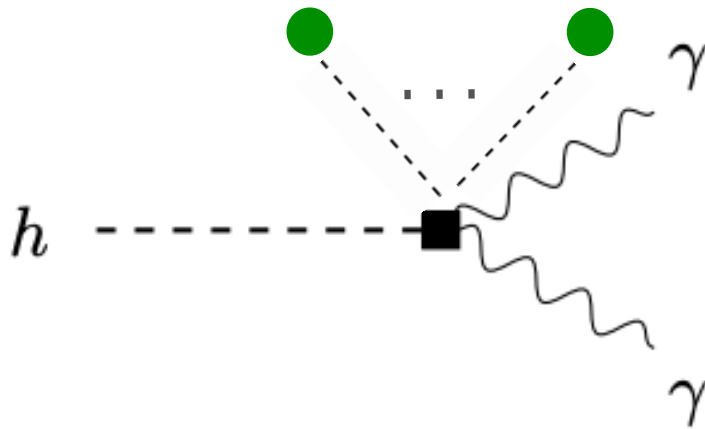
If a process is **numerically suppressed** in the SM

- $\mathcal{L}_8, \mathcal{L}_6^2$ effects on naive $\mathcal{L}_6$ conclusions can be significant

If a process is **loop suppressed** in the SM

- $\mathcal{L}_8, \mathcal{L}_6^2$ effects on naive $\mathcal{L}_6$ conclusions can be VERY significant
And subtle

GeoSMEFT for the Higgs



- EFT studies that ignore this geoSMEFT enabled information can be misleading.

- How much does dim 8 effect things? A lot.
2007.00565 Hays, Helset, Martin, Trott

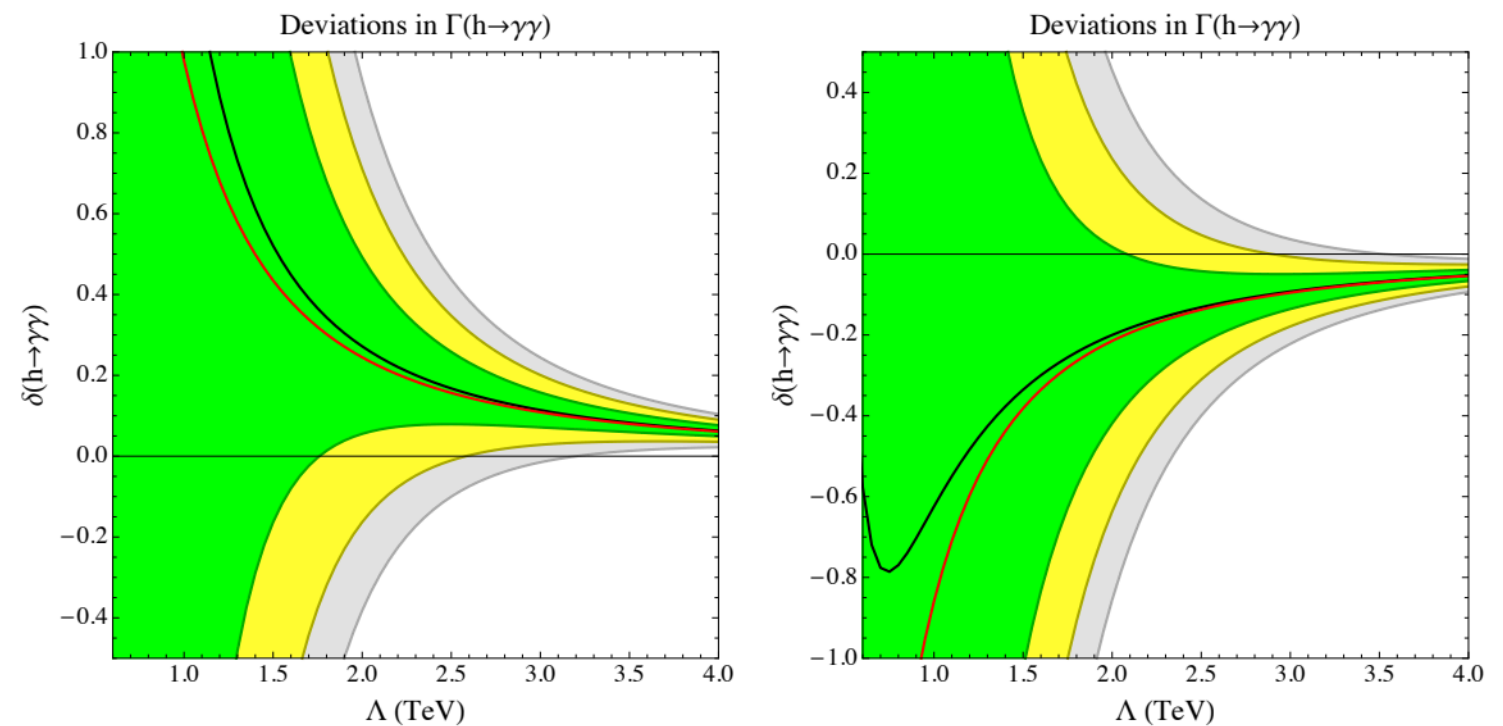


Figure 1. The deviations in $h \rightarrow \gamma\gamma$ from the $\mathcal{O}(v^2/\Lambda^2)$ (red line) and partial-square (black line) results, and the full $\mathcal{O}(v^4/\Lambda^4)$ results (green $\pm 1\sigma_\delta$, yellow $\pm 2\sigma_\delta$, and grey $\pm 3\sigma_\delta$ regions). In the left panel the coefficients determining the $\mathcal{O}(v^2/\Lambda^2)$ and partial-square results are $C_{HB}^{(6)} = -0.01$, $C_{HW}^{(6)} = 0.004$, $C_{HWB}^{(6)} = 0.007$, $C_{HD}^{(6)} = -0.74$, and $\delta G_F^{(6)} = -1.6$. In the right panel they are $C_{HB}^{(6)} = 0.007$, $C_{HW}^{(6)} = 0.007$, $C_{HWB}^{(6)} = -0.015$, $C_{HD}^{(6)} = 0.50$, and $\delta G_F^{(6)} = 1.26$.

ggh

- Can use geoSMEFT to get $\mathcal{L}_8$ in many cases

$$\frac{\sigma_{\text{SMEFT}}^{\hat{\alpha}}(\mathcal{G}\mathcal{G} \rightarrow h)}{\sigma_{\text{SM}}^{\hat{\alpha}, 1/m_t^2}(\mathcal{G}\mathcal{G} \rightarrow h)} \simeq 1 + 519 \tilde{C}_{HG}^{(6)} + 504 \tilde{C}_{HG}^{(6)} \left(\tilde{C}_{H\Box}^{(6)} - \frac{1}{4} \tilde{C}_{HD}^{(6)} \right) + 8.15 \times 10^4 (\tilde{C}_{HG}^{(6)})^2 + 504 \tilde{C}_{HG}^{(8)}$$

$$+ 1.58 \left(\tilde{C}_{H\Box}^{(6)} - \frac{1}{4} \tilde{C}_{HD}^{(6)} \right) + 362 \tilde{C}_{HG}^{(6)} - 1.59 \tilde{C}_{uH}^{(6)} - 12.6 \text{Re} \tilde{C}_{uG}^{(6)} - 1.12 \delta G_F^{(6)} - 7.70 \text{Re} \tilde{C}_{uG}^{(6)} \log \left(\frac{\hat{m}_h^2}{\Lambda^2} \right)$$

$$- 0.19 \text{Re} \tilde{C}_{dG}^{(6)} \log \left(\frac{\hat{m}_h^2}{\Lambda^2} \right) - 0.09 \text{Re} \tilde{C}_{dG}^{(6)} + 3.54 \tilde{C}_{dH}^{(6)}.$$

This is being 2 loop improved now..

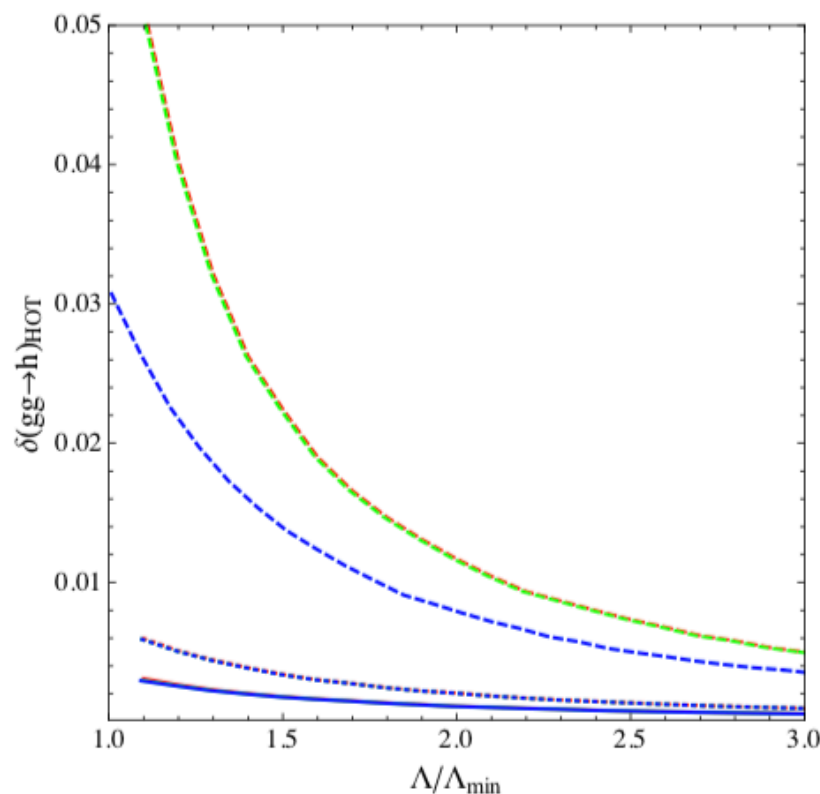


FIG. 1: Uncertainty on $\sigma(gg \rightarrow h)$ from higher order terms as a function of the new physics scale Λ relative to the min-

- Justified triage for the SMEFT global fit program with theory errors

- Otherwise

2109.05595 Martin, Trott

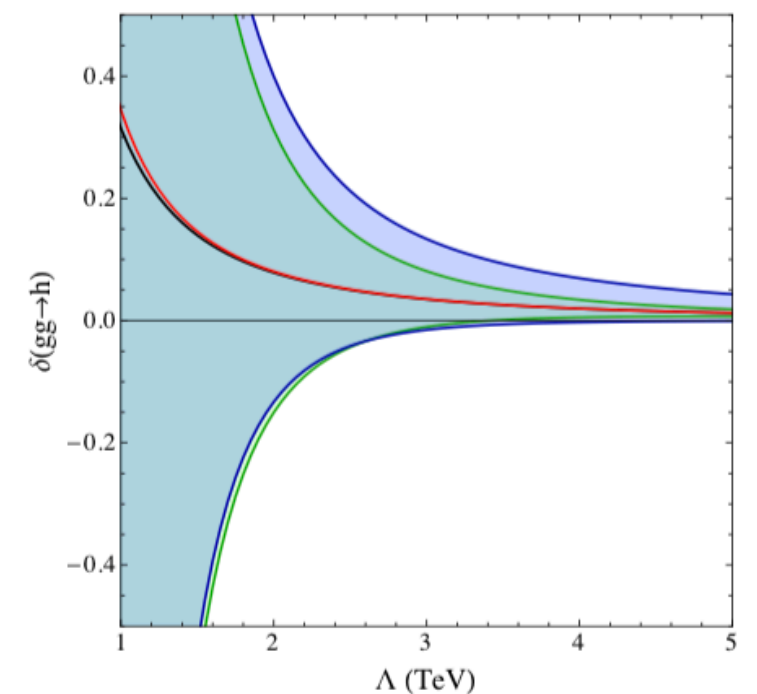


FIG. 4: Deviation in $\sigma(\mathcal{G}\mathcal{G} \rightarrow h)$ relative to the SM with $C_{HG}^{(6)} = 0.01$, and all other coefficients sampled according to gaussian distributions with zero mean and width of either 1.0 or .01 depending on whether the corresponding operator is generated at tree or loop level following the classification in Ref. [7–9]. The deviation is plotted as a function of Λ , and the color scheme for the lines and bands is the same as in Figs. 2, 3.

Effects of higher orders is not simple.
We need to assign an error with the
actual NLO result, process by process

GeoSMEFT based Theory error.

- GeoSMEFT efficiently organised the physics for dimension 8 calc that follow from rescaling dimension 6 results with the same kinematics.
- An algorithm to develop calc to dimension 8 efficiently to use, and also inform theory errors [2106.13794](#) Trott “Methodology...”

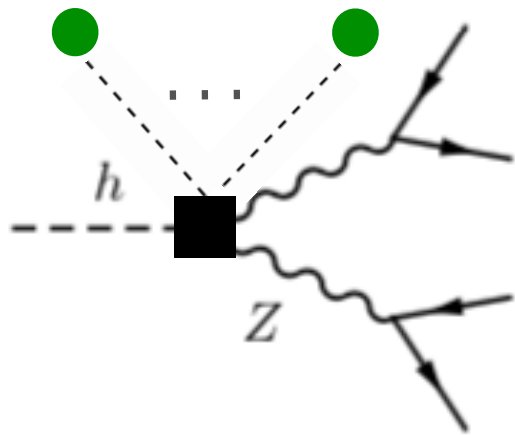
SMEFT RGE is transparent to simulation chain. Thus infer logs of missing pert corrections for theory error.

Use geoSMEFT to rescale dim 6 results with common kinematics to post-facto (avoid redundant Monte Carlo) get dim 8 from SMEFTsim

Extra dim 8 bits with novel kinematics define in geoSMEFT consistent basis. Put in code. (SMEFTsim mod ongoing of this form with T Corbett)

- Being applied to associated production, already done for $\Gamma(h \rightarrow \gamma\gamma)$
 $\sigma(\mathcal{G}\mathcal{G} \rightarrow h), \Gamma(h \rightarrow \mathcal{G}\mathcal{G})$

GeoSMEFT for the Higgs

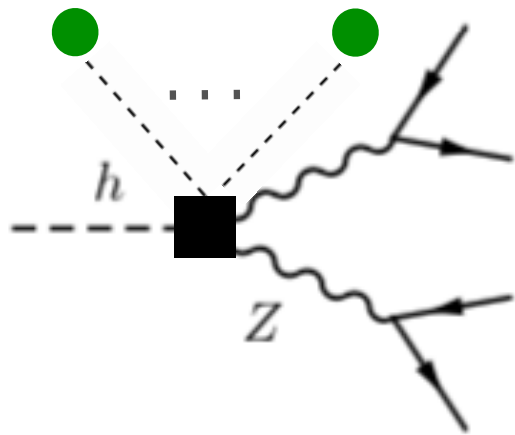


- All orders SMEFT higgs coupling to $W^\pm, Z$
[2001.01453](#) Helset, Martin, Trott

$$\begin{aligned} \langle h | \mathcal{Z}(p_1) \mathcal{Z}(p_2) \rangle = & -\frac{\sqrt{h}^{44}}{4} \bar{g}_Z^2 \left[\left\langle \frac{\delta g_{33}(\phi)}{\delta \phi_4} \right\rangle \frac{c_{\theta_Z}^4}{g_2^2} - 2 \left\langle \frac{\delta g_{34}(\phi)}{\delta \phi_4} \right\rangle \frac{c_{\theta_Z}^2 s_{\theta_Z}^2}{g_1 g_2} + \left\langle \frac{\delta g_{44}(\phi)}{\delta \phi_4} \right\rangle \frac{s_{\theta_Z}^4}{g_1^2} \right] \langle h \mathcal{Z}_{\mu\nu} \mathcal{Z}^{\mu\nu} \rangle \\ & + \sqrt{h}^{44} \frac{\bar{g}_Z^2}{2} \left[\left\langle \frac{\delta h_{33}(\phi)}{\delta \phi_4} \right\rangle \left(\frac{\bar{v}_T}{2} \right)^2 + \langle h_{33}(\phi) \rangle \frac{\bar{v}_T}{2} \right] \langle h \mathcal{Z}_\mu \mathcal{Z}^\mu \rangle \\ & + \sqrt{h}^{44} \bar{g}_Z^2 \bar{v}_T \left[\langle k_{34}^3 \rangle \frac{c_{\theta_Z}^2}{g_2} - \langle k_{34}^4 \rangle \frac{s_{\theta_Z}^2}{g_1} \right] \langle \partial^\nu h \mathcal{Z}_\mu \mathcal{Z}^{\mu\nu} \rangle, \end{aligned}$$

$$\begin{aligned} \langle h | \mathcal{W}(p_1) \mathcal{W}(p_2) \rangle = & -\frac{\sqrt{h}^{44}}{2} \bar{g}_2^2 \left[\left\langle \frac{\delta g_{11}(\phi)}{\delta \phi_4} \right\rangle \frac{1}{g_2^2} \right] \langle h \mathcal{W}_{\mu\nu} \mathcal{W}^{\mu\nu} \rangle \\ & + \sqrt{h}^{44} \bar{g}_2^2 \left[\left\langle \frac{\delta h_{11}(\phi)}{\delta \phi_4} \right\rangle \left(\frac{\bar{v}_T}{2} \right)^2 + \langle h_{11}(\phi) \rangle \frac{\bar{v}_T}{2} \right] \langle h \mathcal{W}_\mu \mathcal{W}^\mu \rangle \\ & + 2 \sqrt{h}^{44} \frac{\bar{g}_2^2}{g_2} \frac{\bar{v}_T}{4} [i \langle k_{42}^1 \rangle - \langle k_{42}^2 \rangle] \langle (\partial^\mu h) (\mathcal{W}_{\mu\nu}^+ W_-^\nu + \mathcal{W}_{\mu\nu}^- W_+^\nu) \rangle. \end{aligned}$$

GeoSMEFT for the Higgs

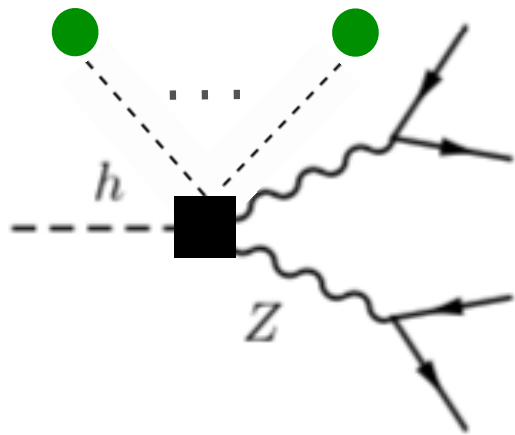


- All orders SMEFT higgs coupling to $W^\pm, Z$
[2001.01453](#) Helset, Martin, Trott

$$\begin{aligned} \langle h | \mathcal{Z}(p_1) \mathcal{Z}(p_2) \rangle = & -\frac{\sqrt{h}^{44}}{4} \bar{g}_Z^2 \left[\left\langle \frac{\delta g_{33}(\phi)}{\delta \phi_4} \right\rangle \frac{c_{\theta_Z}^4}{g_2^2} - 2 \left\langle \frac{\delta g_{34}(\phi)}{\delta \phi_4} \right\rangle \frac{c_{\theta_Z}^2 s_{\theta_Z}^2}{g_1 g_2} + \left\langle \frac{\delta g_{44}(\phi)}{\delta \phi_4} \right\rangle \frac{s_{\theta_Z}^4}{g_1^2} \right] \langle h \mathcal{Z}_{\mu\nu} \mathcal{Z}^{\mu\nu} \rangle \\ & + \sqrt{h}^{44} \frac{\bar{g}_Z^2}{2} \left[\left\langle \frac{\delta h_{33}(\phi)}{\delta \phi_4} \right\rangle \left(\frac{\bar{v}_T}{2} \right)^2 + \left\langle h_{33}(\phi) \right\rangle \frac{\bar{v}_T}{2} \right] \langle h \mathcal{Z}_\mu \mathcal{Z}^\mu \rangle \leftarrow \text{SM like kinematics} \\ & + \sqrt{h}^{44} \bar{g}_Z^2 \bar{v}_T \left[\left\langle k_{34}^3 \right\rangle \frac{c_{\theta_Z}^2}{g_2} - \left\langle k_{34}^4 \right\rangle \frac{s_{\theta_Z}^2}{g_1} \right] \langle \partial^\nu h \mathcal{Z}_\mu \mathcal{Z}^{\mu\nu} \rangle, \end{aligned}$$

$$\begin{aligned} \langle h | \mathcal{W}(p_1) \mathcal{W}(p_2) \rangle = & -\frac{\sqrt{h}^{44}}{2} \bar{g}_2^2 \left[\left\langle \frac{\delta g_{11}(\phi)}{\delta \phi_4} \right\rangle \frac{1}{g_2^2} \right] \langle h \mathcal{W}_{\mu\nu} \mathcal{W}^{\mu\nu} \rangle \\ & + \sqrt{h}^{44} \bar{g}_2^2 \left[\left\langle \frac{\delta h_{11}(\phi)}{\delta \phi_4} \right\rangle \left(\frac{\bar{v}_T}{2} \right)^2 + \left\langle h_{11}(\phi) \right\rangle \frac{\bar{v}_T}{2} \right] \langle h \mathcal{W}_\mu \mathcal{W}^\mu \rangle \\ & + 2 \sqrt{h}^{44} \frac{\bar{g}_2^2}{g_2} \frac{\bar{v}_T}{4} [i \langle k_{42}^1 \rangle - \langle k_{42}^2 \rangle] \langle (\partial^\mu h) (\mathcal{W}_{\mu\nu}^+ W_-^\nu + \mathcal{W}_{\mu\nu}^- W_+^\nu) \rangle. \end{aligned}$$

GeoSMEFT for the Higgs



- All orders SMEFT higgs coupling to $W^\pm, Z$
[2001.01453](#) Helset, Martin, Trott

$$\begin{aligned}
 \langle h | \mathcal{Z}(p_1) \mathcal{Z}(p_2) \rangle = & -\frac{\sqrt{h}^{44}}{4} \bar{g}_Z^2 \left[\left\langle \frac{\delta g_{33}(\phi)}{\delta \phi_4} \right\rangle \frac{c_{\theta_Z}^4}{g_2^2} - 2 \left\langle \frac{\delta g_{34}(\phi)}{\delta \phi_4} \right\rangle \frac{c_{\theta_Z}^2 s_{\theta_Z}^2}{g_1 g_2} + \left\langle \frac{\delta g_{44}(\phi)}{\delta \phi_4} \right\rangle \frac{s_{\theta_Z}^4}{g_1^2} \right] \langle h \mathcal{Z}_{\mu\nu} \mathcal{Z}^{\mu\nu} \rangle \\
 & + \sqrt{h}^{44} \frac{\bar{g}_Z^2}{2} \left[\left\langle \frac{\delta h_{33}(\phi)}{\delta \phi_4} \right\rangle \left(\frac{\bar{v}_T}{2} \right)^2 + \langle h_{33}(\phi) \rangle \frac{\bar{v}_T}{2} \right] \langle h \mathcal{Z}_\mu \mathcal{Z}^\mu \rangle \leftarrow \text{SM like kinematics} \\
 & + \sqrt{h}^{44} \bar{g}_Z^2 \bar{v}_T \left[\langle k_{34}^3 \rangle \frac{c_{\theta_Z}^2}{g_2} - \langle k_{34}^4 \rangle \frac{s_{\theta_Z}^2}{g_1} \right] \langle \partial^\nu h \mathcal{Z}_\mu \mathcal{Z}^{\mu\nu} \rangle, \quad \text{Anomalous kinematic population correction factor - not many!}
 \end{aligned}$$

$$\begin{aligned}
 \langle h | \mathcal{W}(p_1) \mathcal{W}(p_2) \rangle = & -\frac{\sqrt{h}^{44}}{2} \bar{g}_2^2 \left[\left\langle \frac{\delta g_{11}(\phi)}{\delta \phi_4} \right\rangle \frac{1}{g_2^2} \right] \langle h \mathcal{W}_{\mu\nu} \mathcal{W}^{\mu\nu} \rangle \\
 & + \sqrt{h}^{44} \bar{g}_2^2 \left[\left\langle \frac{\delta h_{11}(\phi)}{\delta \phi_4} \right\rangle \left(\frac{\bar{v}_T}{2} \right)^2 + \langle h_{11}(\phi) \rangle \frac{\bar{v}_T}{2} \right] \langle h \mathcal{W}_\mu \mathcal{W}^\mu \rangle \\
 & + 2 \sqrt{h}^{44} \frac{\bar{g}_2^2}{g_2} \frac{\bar{v}_T}{4} [i \langle k_{42}^1 \rangle - \langle k_{42}^2 \rangle] \langle (\partial^\mu h) (\mathcal{W}_{\mu\nu}^+ \mathcal{W}_-^\nu + \mathcal{W}_{\mu\nu}^- \mathcal{W}_+^\nu) \rangle.
 \end{aligned}$$

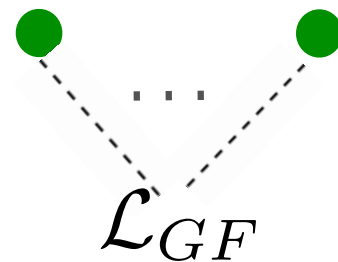
In the hands of ATLAS for kinematic studies
 Thx to Tyler Corbett for coding SMEFTsim mod.

GeoSMEFT based loop corrections?

- The simplicity of the results for two and three point functions points to radiative corrections being more elegant than expected.

The renormalisation follows the dependence on the Wilson coefficients.

- Do we have hints of this yet? Yes.



- Background field gauge fixing with preserved background Gauge invariance [1803.08001](#) [Helset](#), Paraskevas, Trott.

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

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

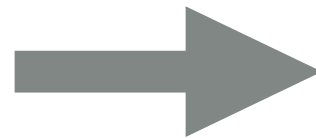
- Gauge fixing confusion directly solved generalising to GeoSMEFT

GeoSMEFT based loop corrections?

- Will this simplify the NLO SMEFT radiative correction program?(Yes)

Immediate BFM Ward Identities have already been derived:

$$\frac{\delta\Gamma[\hat{F}, 0]}{\delta\hat{\alpha}^B} = 0.$$



Background field gauge transformation

1909.08470 Corbett, Helset, Trott

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

Photon identities:

$$0 = \partial^\mu \frac{\delta^2\Gamma}{\delta\hat{\mathcal{A}}^{4\mu}\delta\hat{\mathcal{A}}^{Y\nu}}, \quad 0 = \partial^\mu \frac{\delta^2\Gamma}{\delta\hat{\mathcal{A}}^{4\mu}\delta\hat{\Phi}^I}.$$



$$\Sigma_{L,\text{SMEFT}}^{\hat{\mathcal{A}},\hat{\mathcal{A}}}(k^2) = 0, \quad \Sigma_{T,\text{SMEFT}}^{\hat{\mathcal{A}},\hat{\mathcal{A}}}(0) = 0.$$

One loop behaviour works!

Z identities:

Geometric mass

$$0 = \partial^\mu \frac{\delta^2\Gamma}{\delta\hat{\mathcal{A}}^{3\mu}\delta\hat{\mathcal{A}}^{Y\nu}} - \bar{M}_Z \frac{\delta^2\Gamma}{\delta\hat{\Phi}^3\delta\hat{\mathcal{A}}^{Y\nu}},$$

$$0 = \partial^\mu \frac{\delta^2\Gamma}{\delta\hat{\mathcal{A}}^{3\mu}\delta\hat{\Phi}^I} - \bar{M}_Z \frac{\delta^2\Gamma}{\delta\hat{\Phi}^3\delta\hat{\Phi}^I}$$

$$+ \frac{\bar{g}_Z}{2} \frac{\delta\Gamma}{\delta\hat{\Phi}^4} \left(\sqrt{h}_{[4,4]} \sqrt{h}^{[3,3]} - \sqrt{h}_{[4,3]} \sqrt{h}^{[4,3]} \right) \delta_I^3$$

$$- \frac{\bar{g}_Z}{2} \frac{\delta\Gamma}{\delta\hat{\Phi}^4} \left(\sqrt{h}_{[4,4]} \sqrt{h}^{[3,4]} - \sqrt{h}_{[4,3]} \sqrt{h}^{[4,4]} \right) \delta_I^4,$$

GeoSMEFT based loop corrections?

- Expanding out the Ward ID you get expressions like this:

$$0 = \Sigma_L^{\hat{Z}\hat{Z}}(k^2) - i\bar{M}_Z \Sigma^{\hat{Z}\hat{\chi}}(k^2),$$

Consider the operator C_{HWB}

Geometric mass

$$\begin{aligned} -i\bar{M}_Z \Sigma^{\hat{Z}\hat{\chi}}(k^2) &= -i \frac{\sqrt{g_1^2 + g_2^2} \bar{v}_T}{2} \left[\Sigma^{\hat{Z}\hat{\chi}}(k^2) \right]_{\tilde{C}_{HWB}}^{div} - i \frac{g_1 g_2 \tilde{C}_{HWB} \bar{v}_T}{2 \sqrt{g_1^2 + g_2^2}} \left[\Sigma^{\hat{Z}\hat{\chi}}(k^2) \right]_{SM}^{div}, \\ &= -\tilde{C}_{HWB} \bar{v}_T^2 (\xi + 3) \left[\frac{g_1 g_2 (3 g_1^2 + 5 g_2^2)}{256 \pi^2 \epsilon} + \frac{g_1 g_2 (g_1^2 + 3 g_2^2)}{256 \pi^2 \epsilon} \right], \\ &= -\tilde{C}_{HWB} \bar{v}_T^2 (\xi + 3) \frac{g_1^2 (g_1^2 + 2 g_2^2)}{64 \pi^2 \epsilon}. \end{aligned}$$

2010.08451 [Corbett, Trott](#)

2010.15852 [Corbett](#)

Which exactly cancels: $\left[\Sigma_L^{\hat{Z}\hat{Z}}(k^2) \right]_{\tilde{C}_{HWB}}^{div} = \tilde{C}_{HWB} \bar{v}_T^2 (\xi + 3) \frac{g_1^2 (g_1^2 + 2 g_2^2)}{64 \pi^2 \epsilon}.$

All one and two point ward ID working out at one loop. Powerful new NLO code tool is being developed using this as a theory cross check by Tyler Corbett.

Conclusions.

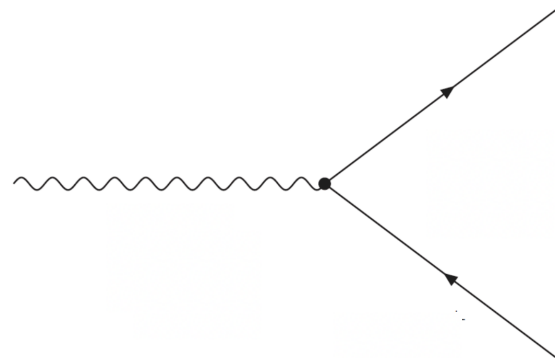
**Higgs/SMEFT physics is the physics
of curved field space(s).**

Backup slides for discussion.

Current geosmeft limitations

GeoSMEFT Pushing to higher n points

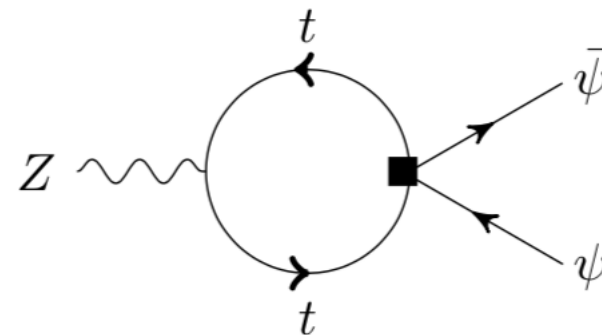
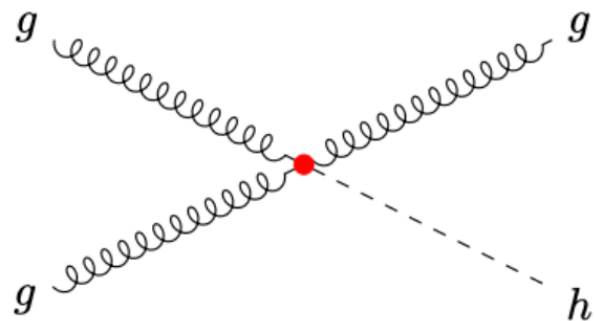
- Can build up observable quantities, such as a decay width.



Consider a $W^\pm, Z$ coupling to a fermion bilinear.

$$-\mathcal{A}^{A,\mu}(\bar{\psi}_p \gamma_\mu \bar{\tau}_A \psi_r) \delta_{pr} + \mathcal{A}^{C,\mu}(\bar{\psi}_p \gamma_\mu \sigma_A \psi_r) \langle L_{I,A}^{\psi,pr} \rangle (-\gamma_{C,4}^I) \bar{v}_T,$$

- Not all physics is derivable from two and three point functions



GeoSMEFT Pushing to higher n points

- Limited number of such connections for up to three point functions

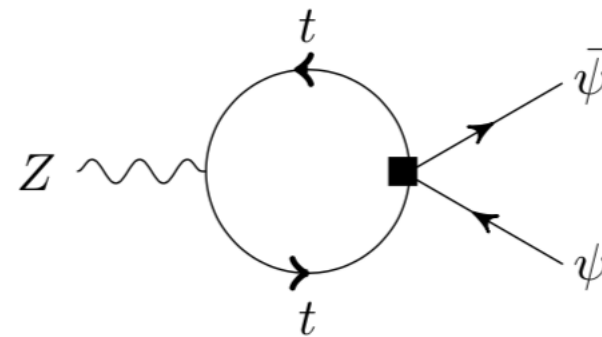
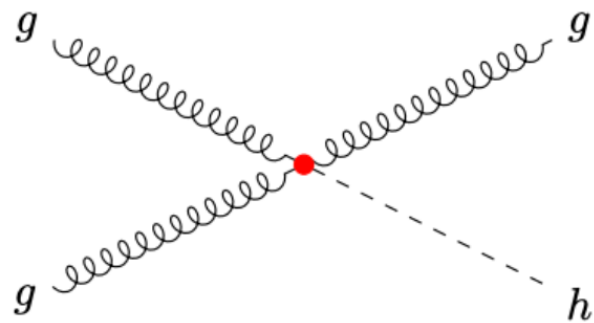
This is a non trivial fact proven for: $F = \{H, \psi, \mathcal{W}^{\mu\nu}\}$ via the following:

$$D^2 F \Rightarrow \boxed{\text{EOM}} \text{ and higher-points,}$$

2001.01453 Helset, Martin, Trott

$$f(H)(D_\mu F_1)(D_\nu F_2)D_{\{\mu\nu\}}F_3 \Rightarrow \boxed{\text{EOM}} \text{ and higher-points.}$$

$$f(\phi) F_1 (D_\mu F_2) (D_\mu F_3) \Rightarrow (D_\mu f(\phi)) (D_\mu F_1) F_2 F_3 + \frac{1}{2}(D^2 f(\phi)) F_1 F_2 F_3 + \boxed{\text{EOM}},$$



- How to incorporate such higher n-point effects is the key challenge.
- Pert corrections advancing fast- higher n points also moving.

GeoSMEFT Pushing to higher n points

- Note these integration by parts steps were used

$$\begin{aligned} & f(H)(D_\mu F_1)(D_\nu F_2)D_{\{\mu\nu\}}F_3 \\ &= -f(H) \left[(D^2 F_1)(D_\nu F_2) + (D_\mu F_1)(D_\mu D_\nu F_2) + (D_\mu D_\nu F_1)(D_\mu F_2) + (D_\nu F_1)(D^2 F_2) \right] (D_\nu F_3) \\ & \quad - (D_\mu f(H)) \left[(D_\mu F_1)(D_\nu F_2) + (D_\nu F_1)(D_\mu F_2) \right] (D_\nu F_3) \end{aligned}$$

$$f(\phi) F_1 (D_\mu F_2) (D_\mu F_3) \Rightarrow (D_\mu f(\phi)) (D_\mu F_1) F_2 F_3 + \frac{1}{2}(D^2 f(\phi)) F_1 F_2 F_3 + \boxed{\text{EOM}},$$

These steps were critical to reducing the number of connections for two and three point functions. This just fails for four points and higher.

One knows that there are an infinite set of higher derivative terms lurking
In higher n points, dependent on $\{D_\mu \phi^I, D_{\{\mu,\nu\}} \phi^I, D_{\{\mu,\nu,\rho\}} \phi^I, \dots\},$

This is a problem for measurements away from SM resonances.

Flat directions and vev scaling

GeoSMEFT and flat directions

- Deep irony of the GeoSMEFT. As soon as people started to use the full SMEFT - immediately data analysis indicated this hidden structure.

Key early one going in right direction: Han, Skiba 0412166

They found flat directions in LEP data. We now know due an invariance.

Weak eigenstates

Mass eigenstate

1909.08470 Corbett, Helset, Trott

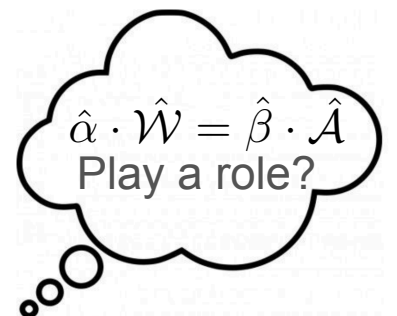
$$\hat{\mathcal{W}}^{A,\nu} = \sqrt{g^{AB}} U_{BC} \hat{\mathcal{A}}^{C,\nu},$$

$$\hat{\alpha}^A = \sqrt{g^{AB}} U_{BC} \hat{\beta}^C,$$

$$\hat{\phi}^J = \sqrt{h^{JK}} V_{KL} \hat{\Phi}^L,$$

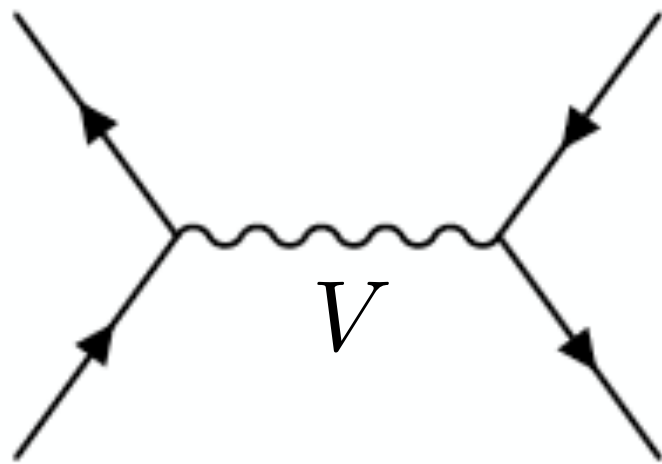
Field space metrics

Rotations



EWPD flat directions

- Flat directions due the invariance, fundamentally its $\hat{\alpha} \cdot \hat{\mathcal{W}} = \hat{\beta} \cdot \hat{\mathcal{A}}$



1701.06424 Brivio Trott Reparameterization!

$$(V, g) \leftrightarrow (V' (1 + \epsilon), g' (1 - \epsilon)) ,$$

$\bar{\psi}\psi \rightarrow \bar{\psi}\psi$ scattering has a reparameterization invariance

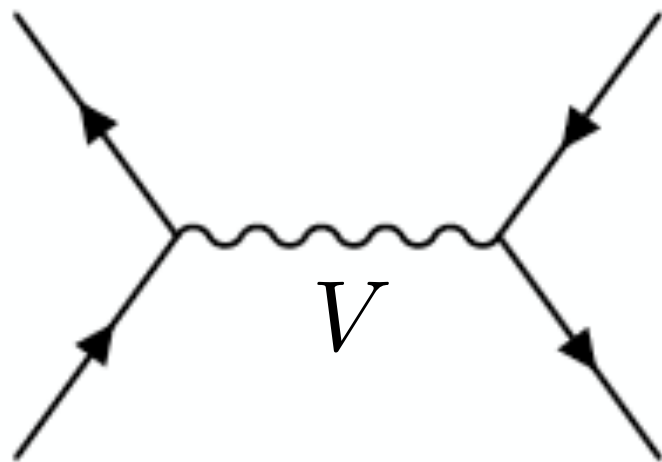
- LEP data can't see EOM equivalent to parameters cancelling in $\hat{\alpha} \cdot \hat{\mathcal{W}} = \hat{\beta} \cdot \hat{\mathcal{A}}$

$$\langle y_h g_1^2 Q_{HB} \rangle_{S_R} = \langle \sum_{\substack{\psi_\kappa=u,d, \\ q,e,l}} y_\kappa g_1^2 \bar{\psi}_\kappa \gamma_\beta \psi_\kappa (H^\dagger i \overleftrightarrow{D}_\beta H) + \frac{g_1^2}{2} (Q_{H\Box} + 4Q_{HD}) - \frac{1}{2} g_1 g_2 Q_{HWB} \rangle_{S_R},$$

$$\langle g_2^2 Q_{HW} \rangle_{S_R} = \langle g_2^2 (\bar{q} \tau^I \gamma_\beta q + \bar{l} \tau^I \gamma_\beta l) (H^\dagger i \overleftrightarrow{D}_\beta^I H) + 2 g_2^2 Q_{H\Box} - 2 g_1 g_2 y_h Q_{HWB} \rangle_{S_R}.$$

EWPD flat directions

- Flat directions due the invariance, fundamentally its $\hat{\alpha} \cdot \hat{\mathcal{W}} = \hat{\beta} \cdot \hat{\mathcal{A}}$



1701.06424 Brivio Trott Reparameterization!

$$(V, g) \leftrightarrow (V' (1 + \epsilon), g' (1 - \epsilon)),$$

$\bar{\psi}\psi \rightarrow \bar{\psi}\psi$ scattering has a reparameterization invariance

- Flat directions in many data sets project onto EOM equivalents to what cancels in the invariant $\hat{\alpha} \cdot \hat{\mathcal{W}} = \hat{\beta} \cdot \hat{\mathcal{A}} \quad (\tilde{C}_{HB}, \tilde{C}_{HW})$

$$\begin{aligned} w_1^\alpha &= -w_B - 2.59 w_W \\ w_2^\alpha &= -w_B + 4.31 w_W, \end{aligned}$$

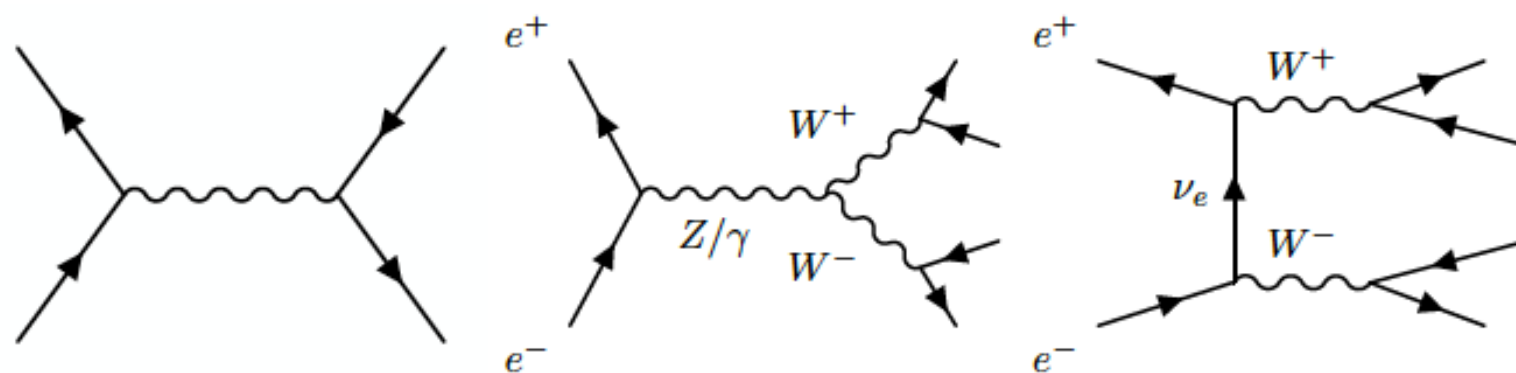
$$\begin{aligned} w_1^{m_W} &= -w_B - 2.48 w_W \\ w_2^{m_W} &= -w_B + 4.40 w_W. \end{aligned}$$

be careful and keep all operators!

- Input scheme independent.

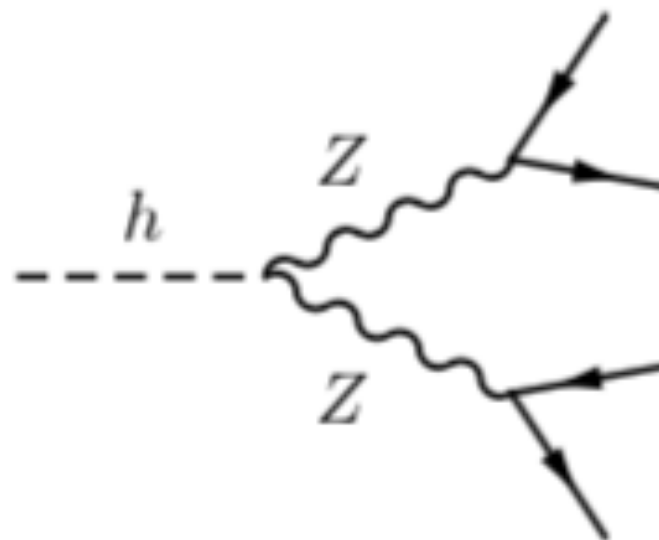
SMEFT reparameterization invariance

- Must combine data sets in a well defined SMEFT, so no matter what operator basis you choose you get consistent results



Breaks the invariance. This channel dominant at LEP2

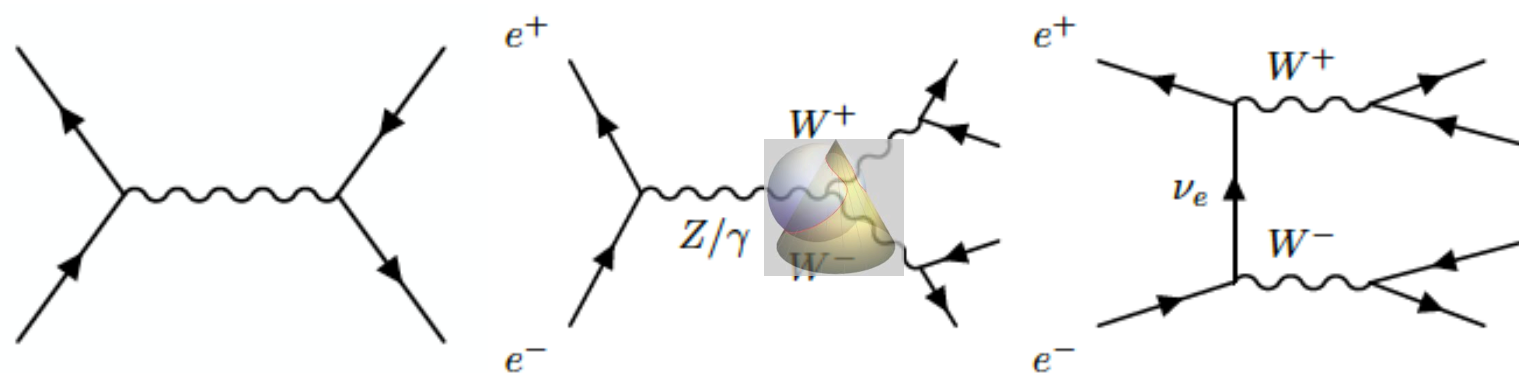
- Precision Higgs physics data will compete and we need to combine it consistently



Breaks the invariance.
Probes the scalar and gauge metric connections directly.

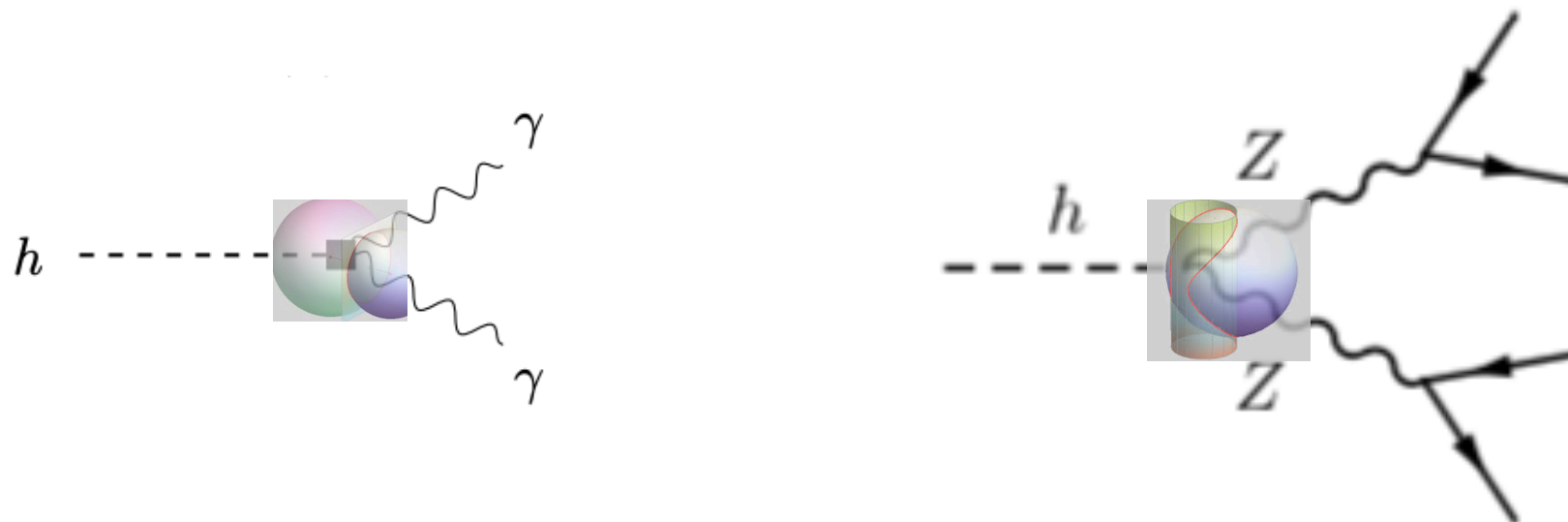
SMEFT reparameterization invariance

- Must combine data sets in a well defined SMEFT, so no matter what operator basis you choose you get consistent results

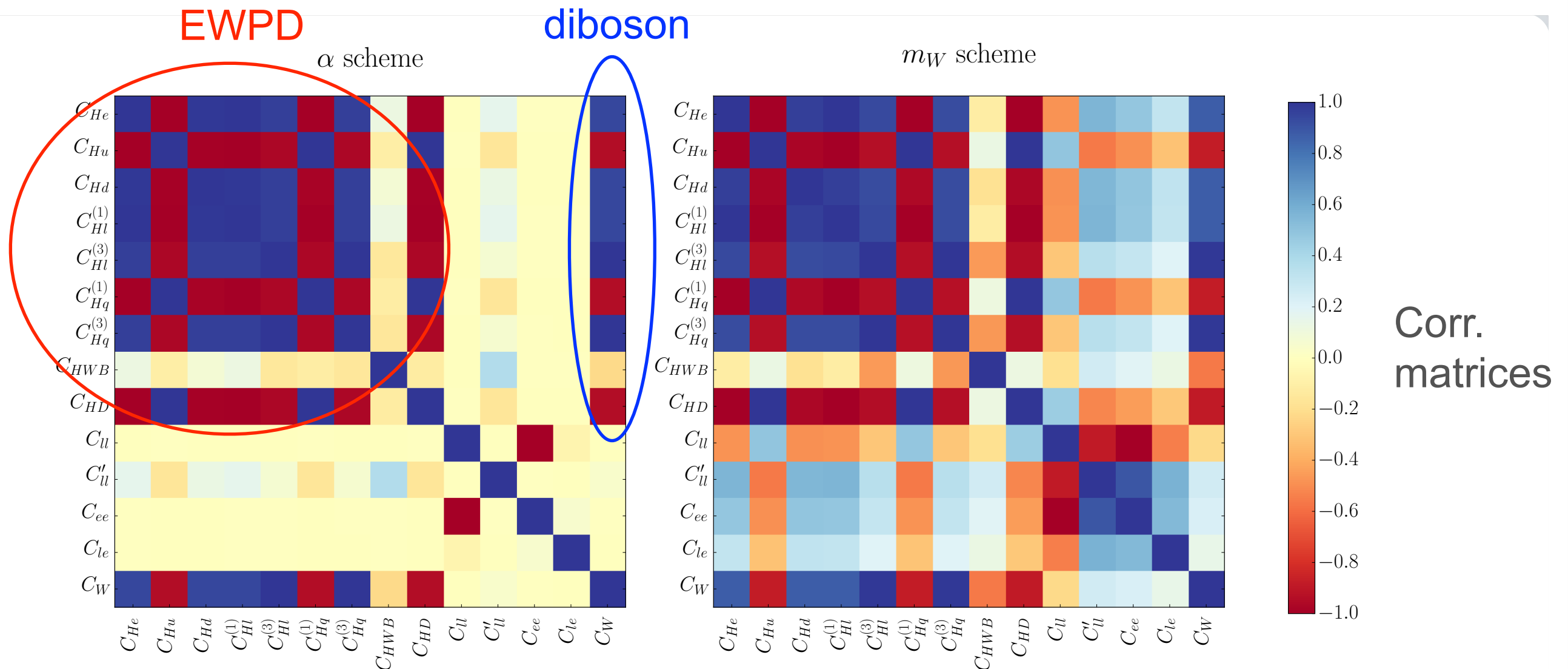


This channel dominant at LEP2

- Precision Higgs physics data will compete and we need to combine it consistently



Flat directions reflect a consistent analysis



- Global analysis of data from PEP, PETRA, TRISTAN, SpS, Tevatron, SLAC, LEP I and LEP II
- Correlation matrices in a likelihood for the SMEFT (before higgs data)

$$L(C) = \frac{1}{\sqrt{(2\pi)^n |V|}} \exp \left(-\frac{1}{2} (\hat{O} - \bar{O})^T V^{-1} (\hat{O} - \bar{O}) \right),$$

I 502.02570, I 508.05060, Berthier, MT , I 606.06693 Berthier, Bjorn, MT , arXiv: I 70 I.06424 Brivio, MT

Generators for SMEFT vs SM

Generators on scalar SMEFT space

- To think in a unified gauge space manifold need generators (reformulate SM generators)

$$(D^\mu \phi)^I = (\partial^\mu \delta_J^I - \frac{1}{2} \mathcal{W}^{A,\mu} \tilde{\gamma}_{A,J}^I) \phi^J$$

$$\tilde{\epsilon}_{BC}^A = g_2 \epsilon_{BC}^A, \quad \text{with } \tilde{\epsilon}_{23}^1 = +g_2,$$

$$\tilde{\gamma}_{A,J}^I = \begin{cases} g_2 \gamma_{A,J}^I, & \text{for } A = 1, 2, 3 \\ g_1 \gamma_{A,J}^I, & \text{for } A = 4. \end{cases}$$

$$\gamma_{1,J}^I = \begin{bmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad \gamma_{2,J}^I = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix},$$

$$\gamma_{3,J}^I = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad \gamma_{4,J}^I = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}.$$

(this last one also “i”)

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

- Some interesting math here, we also define

$$\Gamma_{A,K}^I = \gamma_{A,J}^I \gamma_{4,K}^J$$

$$\Gamma_{1,J}^I = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix}, \quad \Gamma_{2,J}^I = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad \Gamma_{3,J}^I = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \Gamma_{4,J}^I = -\mathbb{I}_{4 \times 4}.$$

Generators on scalar SMEFT space

- The mapping of operator forms works via:

$$\begin{aligned}
 H^\dagger \sigma_a H &= -\frac{1}{2} \phi_I \Gamma_{a,J}^I \phi^J, \\
 H^\dagger \overleftrightarrow{D}^\mu H &= -\phi_I \gamma_{4,J}^I (D^\mu \phi)^J = (D^\mu \phi)_I \gamma_{4,J}^I \phi^J, \\
 H^\dagger \overleftrightarrow{D}_a^\mu H &= -\phi_I \gamma_{a,J}^I (D^\mu \phi)^J = (D^\mu \phi)_I \gamma_{a,J}^I \phi^J, \\
 2\tilde{H}^\dagger D^\mu H &= \tilde{\phi}_I (-\Gamma_{4,J}^I + i \gamma_{4,J}^I) (D^\mu \phi)^J.
 \end{aligned}$$

It is useful to “real” the SM symmetry representation on the scalar manifold for lots of reasons. Makes more manifest possible contractions

$$\phi_I \Gamma_{A,J}^I \phi^J \neq 0, \quad \phi_I \gamma_{a,J}^I \phi^J = \phi_I \gamma_{4,J}^I \phi^J = 0.$$

- All orders results follow, for example:

$$\begin{aligned}
 h_{IJ} &= \left[1 + \phi^2 C_{H\Box}^{(6)} + \sum_{n=0}^{\infty} \left(\frac{\phi^2}{2} \right)^{n+2} \left(C_{HD}^{(8+2n)} - C_{H,D2}^{(8+2n)} \right) \right] \delta_{IJ} \\
 &\quad + \frac{\Gamma_{A,J}^I \phi_K \Gamma_{A,L}^K \phi^L}{2} \left(\frac{C_{HD}^{(6)}}{2} + \sum_{n=0}^{\infty} \left(\frac{\phi^2}{2} \right)^{n+1} C_{H,D2}^{(8+2n)} \right).
 \end{aligned}$$

Field space connections to all orders

2001.01453 Helset, Martin, Trott

- Field space connection for W,Z coupling to fermion pairs $(D^\mu \phi)^I \bar{\psi} \Gamma_\mu \psi$

$$\begin{aligned} \mathcal{Q}_{H\psi_{pr}}^{1,(6+2n)} &= (H^\dagger H)^n H^\dagger \overleftrightarrow{D}^\mu H \bar{\psi}_p \gamma_\mu \psi_r, \\ \mathcal{Q}_{H\psi_{pr}}^{3,(6+2n)} &= (H^\dagger H)^n H^\dagger \overleftrightarrow{D}_a^\mu H \bar{\psi}_p \gamma_\mu \sigma_a \psi_r, \\ \mathcal{Q}_{H\psi_{pr}}^{2,(8+2n)} &= (H^\dagger H)^n (H^\dagger \sigma_a H) H^\dagger \overleftrightarrow{D}^\mu H \bar{\psi}_p \gamma_\mu \sigma_a \psi_r, \\ \mathcal{Q}_{H\psi_{pr}}^{\epsilon,(8+2n)} &= \epsilon_{bc}^a (H^\dagger H)^n (H^\dagger \sigma_c H) H^\dagger \overleftrightarrow{D}_b^\mu H \bar{\psi}_p \gamma_\mu \sigma_a \psi_r. \end{aligned}$$

Not that many op forms. Closed form field space connection.

$$\begin{aligned} L_{J,A}^{\psi,pr} &= -(\phi \gamma_4)_J \delta_{A4} \sum_{n=0}^{\infty} C_{H\psi_{pr}}^{1,(6+2n)} \left(\frac{\phi^2}{2}\right)^n - (\phi \gamma_A)_J (1 - \delta_{A4}) \sum_{n=0}^{\infty} C_{H\psi_L}^{3,(6+2n)} \left(\frac{\phi^2}{2}\right)^n \\ &+ \frac{1}{2} (\phi \gamma_4)_J (1 - \delta_{A4}) (\phi_K \Gamma_{A,L}^K \phi^L) \sum_{n=0}^{\infty} C_{H\psi_L}^{2,(8+2n)} \left(\frac{\phi^2}{2}\right)^n \\ &+ \frac{\epsilon_{BC}^A}{2} (\phi \gamma_B)_J (\phi_K \Gamma_{C,L}^K \phi^L) \sum_{n=0}^{\infty} C_{H\psi_L}^{\epsilon,(8+2n)} \left(\frac{\phi^2}{2}\right)^n. \end{aligned}$$

Notice the clean form due to generator structure and real fields.

Field space connections to all orders

2001.01453 Helset, Martin, Trott

- Off shell operators contributing to three points $(D_\mu \phi)^I \sigma_A (D_\nu \phi)^J \mathcal{W}_{\mu\nu}^A$

$$\begin{aligned} Q_{HDHB}^{(8+2n)} &= i (H^\dagger H)^{n+1} (D_\mu H)^\dagger (D_\nu H) B^{\mu\nu}, \\ Q_{HDHW}^{(8+2n)} &= i \delta_{ab} (H^\dagger H)^{n+1} (D_\mu H)^\dagger \sigma^a (D_\nu H) W_b^{\mu\nu}, \\ Q_{HDHW,2}^{(8+2n)} &= i \epsilon_{abc} (H^\dagger H)^n (H^\dagger \sigma^a H) (D_\mu H)^\dagger \sigma^b (D_\nu H) W_c^{\mu\nu}, \\ Q_{HDHW,3}^{(10+2n)} &= i \delta_{ab} \delta_{cd} (H^\dagger H)^n (H^\dagger \sigma^a H) (H^\dagger \sigma^c H) (D_\mu H)^\dagger \sigma^b (D_\nu H) W_d^{\mu\nu}. \end{aligned}$$

This connection saturates last in op dimension. This is due to EOM reduction. No entries at dim 6 in Warsaw basis.

$$\begin{aligned} k_{IJ}^A(\phi) &= -\frac{1}{2} \gamma_{4,J}^I \delta_{A4} \sum_{n=0}^{\infty} C_{HDHB}^{(8+2n)} \left(\frac{\phi^2}{2} \right)^{n+1} - \frac{1}{2} \gamma_{A,J}^I (1 - \delta_{A4}) \sum_{n=0}^{\infty} C_{HDHW}^{(8+2n)} \left(\frac{\phi^2}{2} \right)^{n+1} \\ &\quad - \frac{1}{8} (1 - \delta_{A4}) [\phi_K \Gamma_{A,L}^K \phi^L] [\phi_M \Gamma_{B,L}^K \phi^N] \gamma_{B,J}^I \sum_{n=0}^{\infty} C_{HDHW,3}^{(10+2n)} \left(\frac{\phi^2}{2} \right)^n \\ &\quad + \frac{1}{4} \epsilon_{ABC} [\phi_K \Gamma_{B,L}^K \phi^L] \gamma_{C,J}^I \sum_{n=0}^{\infty} C_{HDHW,2}^{(8+2n)} \left(\frac{\phi^2}{2} \right)^n. \end{aligned}$$

Input parameter/scheme dependence

Strong input scheme dependence in SMEFT

$\{\hat{\alpha}_{ew}, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

$$\delta m_Z^2 = \frac{\hat{M}_Z^2}{2} \tilde{C}_{HD} + \frac{2^{3/4} \sqrt{\pi \hat{\alpha}} \hat{M}_Z}{\hat{G}_F^{1/2}} \tilde{C}_{HWB},$$

$$\delta s_\theta^2 = 0.17 \tilde{C}_{HD} + 0.79 \tilde{C}_{HWB} + 0.76 \tilde{C}_{Hl}^{(3)} - 0.34 \tilde{C}'_{ll},$$

$$\frac{\delta \Gamma_Z}{\Gamma_Z^{SM}} = -0.82 \tilde{C}_{HWB} - 0.67 \tilde{C}_{HD} - 0.19 \tilde{C}_{Hl}^{(1)} - 2.06 \tilde{C}_{Hl}^{(3)} - 0.19 \tilde{C}_{He} \\ + 0.47 \tilde{C}_{Hq}^{(1)} + 1.61 \tilde{C}_{Hq}^{(3)} + 0.26 \tilde{C}_{Hu} - 0.19 \tilde{C}_{Hd} + 1.35 \tilde{C}'_{ll}$$

$$\frac{\delta \alpha}{2 \hat{\alpha}} = 0,$$

$$\frac{\delta M_W^2}{\hat{M}_W^2} = -\frac{s_{2\hat{\theta}}}{4 c_{2\hat{\theta}}} \left(\frac{c_{\hat{\theta}}}{s_{\hat{\theta}}} \tilde{C}_{HD} + \frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} 2\sqrt{2} \delta G_F + 4 \tilde{C}_{HWB} \right),$$

$$\frac{\delta \Gamma_W}{\Gamma_W^{SM}} = -3.97 \tilde{C}_{HWB} - 1.80 \tilde{C}_{HD} - 3.52 \tilde{C}_{Hl}^{(3)} + 1.33 \tilde{C}_{Hq}^{(3)} + 2.10 \tilde{C}'_{ll}.$$

$\{\hat{M}_W, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

$$\delta m_Z^2 = \frac{\hat{M}_Z^2}{2} \tilde{C}_{HD} + 2 \hat{M}_Z \hat{M}_W \sqrt{1 - \frac{\hat{M}_W^2}{\hat{M}_Z^2}} \tilde{C}_{HWB},$$

$$\delta s_\theta^2 = -0.39 \tilde{C}_{HD} - 0.42 \tilde{C}_{HWB},$$

$$\frac{\delta \Gamma_Z}{\Gamma_Z^{SM}} = 0.46 \tilde{C}_{HWB} - 0.07 \tilde{C}_{HD} - 0.18 \tilde{C}_{Hl}^{(1)} - 1.37 \tilde{C}_{Hl}^{(3)} - 0.18 \tilde{C}_{He} \\ + 0.47 \tilde{C}_{Hq}^{(1)} + 1.61 \tilde{C}_{Hq}^{(3)} + 0.24 \tilde{C}_{Hu} - 0.18 \tilde{C}_{Hd} + \tilde{C}'_{ll},$$

$$\frac{\delta \alpha}{2 \hat{\alpha}} = -\frac{\delta G_F}{\sqrt{2}} + \frac{\delta m_Z^2}{\hat{M}_Z^2} \frac{\hat{M}_W^2}{2 (\hat{M}_W^2 - \hat{M}_Z^2)} - \tilde{C}_{HWB} \frac{\hat{M}_W}{\hat{M}_Z} \sqrt{1 - \frac{\hat{M}_W^2}{\hat{M}_Z^2}},$$

$$\frac{\delta M_W^2}{\hat{M}_W^2} = 0,$$

$$\frac{\delta \Gamma_W}{\Gamma_W^{SM}} = \frac{4}{3} \left(\tilde{C}_{Hq}^{(3)} - \tilde{C}_{Hl}^{(3)} \right) + \tilde{C}'_{ll}.$$

- At leading order (tree level) already strong input parameter dependence, different than case in SM!

Strong input scheme dependence in SMEFT

$\{\hat{\alpha}_{ew}, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

$$\delta m_Z^2 = \frac{\hat{M}_Z^2}{2} \tilde{C}_{HD} + \frac{2^{3/4} \sqrt{\pi \hat{\alpha}} \hat{M}_Z}{\hat{G}_F^{1/2}} \tilde{C}_{HWB},$$

$$\delta s_\theta^2 = 0.17 \tilde{C}_{HD} + 0.79 \tilde{C}_{HWB} + 0.76 \tilde{C}_{Hl}^{(3)} - 0.34 \tilde{C}'_{ll},$$

$$\frac{\delta \Gamma_Z}{\Gamma_Z^{SM}} = -0.82 \tilde{C}_{HWB} - 0.67 \tilde{C}_{HD} - 0.19 \tilde{C}_{Hl}^{(1)} - 2.06 \tilde{C}_{Hl}^{(3)} - 0.19 \tilde{C}_{He} \\ + 0.47 \tilde{C}_{Hq}^{(1)} + 1.61 \tilde{C}_{Hq}^{(3)} + 0.26 \tilde{C}_{Hu} - 0.19 \tilde{C}_{Hd} + 1.35 \tilde{C}'_{ll}$$

$$\frac{\delta \alpha}{2 \hat{\alpha}} = 0,$$

$$\frac{\delta M_W^2}{\hat{M}_W^2} = -\frac{s_{2\hat{\theta}}}{4 c_{2\hat{\theta}}} \left(\frac{c_{\hat{\theta}}}{s_{\hat{\theta}}} \tilde{C}_{HD} + \frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} 2\sqrt{2} \delta G_F + 4 \tilde{C}_{HWB} \right),$$

$$\frac{\delta \Gamma_W}{\Gamma_W^{SM}} = -3.97 \tilde{C}_{HWB} - 1.80 \tilde{C}_{HD} - 3.52 \tilde{C}_{Hl}^{(3)} + 1.33 \tilde{C}_{Hq}^{(3)} + 2.10 \tilde{C}'_{ll}.$$

$\{\hat{M}_W, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

$$\delta m_Z^2 = \frac{\hat{M}_Z^2}{2} \tilde{C}_{HD} + 2 \hat{M}_Z \hat{M}_W \sqrt{1 - \frac{\hat{M}_W^2}{\hat{M}_Z^2}} \tilde{C}_{HWB},$$

$$\delta s_\theta^2 = -0.39 \tilde{C}_{HD} - 0.42 \tilde{C}_{HWB},$$

$$\frac{\delta \Gamma_Z}{\Gamma_Z^{SM}} = 0.46 \tilde{C}_{HWB} - 0.07 \tilde{C}_{HD} - 0.18 \tilde{C}_{Hl}^{(1)} - 1.37 \tilde{C}_{Hl}^{(3)} - 0.18 \tilde{C}_{He} \\ + 0.47 \tilde{C}_{Hq}^{(1)} + 1.61 \tilde{C}_{Hq}^{(3)} + 0.24 \tilde{C}_{Hu} - 0.18 \tilde{C}_{Hd} + \tilde{C}'_{ll},$$

$$\frac{\delta \alpha}{2 \hat{\alpha}} = -\frac{\delta G_F}{\sqrt{2}} + \frac{\delta m_Z^2}{\hat{M}_Z^2} \frac{\hat{M}_W^2}{2 (\hat{M}_W^2 - \hat{M}_Z^2)} - \tilde{C}_{HWB} \frac{\hat{M}_W}{\hat{M}_Z} \sqrt{1 - \frac{\hat{M}_W^2}{\hat{M}_Z^2}},$$

$$\frac{\delta M_W^2}{\hat{M}_W^2} = 0,$$

$$\frac{\delta \Gamma_W}{\Gamma_W^{SM}} = \frac{4}{3} \left(\tilde{C}_{Hq}^{(3)} - \tilde{C}_{Hl}^{(3)} \right) + \tilde{C}'_{ll}.$$

- Completely expected from decoupling theorem. **UV physics preserving SM symmetries being absorbed into measured low scale parameters now.**

Need input parameters defined at all orders

$\{\hat{M}_W, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

Sorted in

Hays, Helset, Martin Trott: 2007.00565

Input parameter dependence
Increased order by order
due to Lagrangian parameters
being redefined geometrically

D $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$ input-parameter scheme at all orders in $(\bar{v}_T^2/\Lambda^2)^n$

In this scheme we can again use Eqn. (E.2) to define a shift to $\bar{g}_Z$. We also use

$$\bar{g}_2 = g_2 \sqrt{g}^{11} = \frac{2\hat{m}_W}{\sqrt{h_{11}}\bar{v}_T}. \quad (\text{D.1})$$

and

$$g_1 = g_2 \frac{(s_{\bar{\theta}}\sqrt{g}^{33} + c_{\bar{\theta}}\sqrt{g}^{34})}{(c_{\bar{\theta}}\sqrt{g}^{44} + s_{\bar{\theta}}\sqrt{g}^{34})} \quad (\text{D.2})$$

to solve for $s_{\bar{\theta}}^2$ via

$$s_{\bar{\theta}}^2 = \frac{1}{[(\sqrt{g}^{44})^2 + (\sqrt{g}^{34})^2]^2} \left\{ -\left(\frac{g_2\sqrt{g}_-}{\bar{g}_Z}\right)^2 \left[(\sqrt{g}^{44})^2 - (\sqrt{g}^{34})^2 \right] + (\sqrt{g}^{44})^2 \left[(\sqrt{g}^{44})^2 + (\sqrt{g}^{34})^2 \right] \right. \\ \left. - 2\left(\frac{g_2\sqrt{g}_-}{\bar{g}_Z}\right) \sqrt{(\sqrt{g}^{44})^2(\sqrt{g}^{34})^2 \left[(\sqrt{g}^{44})^2 + (\sqrt{g}^{34})^2 - \left(\frac{g_2\sqrt{g}_-}{\bar{g}_Z}\right)^2 \right]} \right\}. \quad (\text{D.3})$$

The remaining Lagrangian parameters can then be defined via

$$\bar{e} = \frac{\bar{g}_2}{\sqrt{g}^{11}} (s_{\bar{\theta}}\sqrt{g}^{33} + c_{\bar{\theta}}\sqrt{g}^{34}), \quad (\text{D.4})$$

and

$$s_{\bar{\theta}_Z}^2 = \frac{\bar{e}}{\bar{g}_Z} \frac{(s_{\bar{\theta}}\sqrt{g}^{44} - c_{\bar{\theta}}\sqrt{g}^{34})}{(c_{\bar{\theta}}\sqrt{g}^{44} + s_{\bar{\theta}}\sqrt{g}^{34})}. \quad (\text{D.5})$$

In both schemes, $\bar{g}_Z$ and $s_{\bar{\theta}_Z}^2$ have the same definition in terms of other “barred” Lagrangian parameters.

Model Example

Consider a kinetic mixing model to dim 8

- Lets see how this works in the simplest benchmark model to dim 8

$$\Delta\mathcal{L} = -\frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \frac{1}{2}m_K^2 K_\mu K^\mu - \frac{k}{2}B^{\mu\nu}K_{\mu\nu},$$

Only has 2 parameters. Dimension 6 matching:

$H^2\psi^2D$	H^4D^2	$\psi^4 : (\bar{R}R)(\bar{R}R)$	$\psi^4 : (\bar{L}L)(\bar{R}R)$
$C_{H\ell}^{1,(6)} \mid -\frac{y_\ell g_1^2}{2m_K^2} b_1$	$C_{H\Box}^{(6)} \mid -\frac{g_1^2 k^2}{8m_K^2}$	$C_{ee}^{(6)} \mid -\frac{1}{2} \frac{g_1^2 k^2}{m_K^2}$	$C_{\ell e}^{(6)} \mid -\frac{1}{2} \frac{g_1^2 k^2}{m_K^2}$
$C_{He}^{(6)} \mid -\frac{y_e g_1^2}{2m_K^2} b_1$	$C_{HD}^{(6)} \mid -\frac{g_1^2 k^2}{2m_K^2}$	$C_{uu}^{(6)} \mid -\frac{2}{9} \frac{g_1^2 k^2}{m_K^2}$	$C_{\ell u}^{(6)} \mid \frac{1}{3} \frac{g_1^2 k^2}{m_K^2}$
$C_{Hq}^{1,(6)} \mid -\frac{y_q g_1^2}{2m_K^2} b_1$	$\psi^4 : (\bar{L}L)(\bar{L}L)$	$C_{dd}^{(6)} \mid -\frac{1}{18} \frac{g_1^2 k^2}{m_K^2}$	$C_{\ell d}^{(6)} \mid -\frac{1}{6} \frac{g_1^2 k^2}{m_K^2}$
$C_{Hu}^{(6)} \mid -\frac{y_u g_1^2}{2m_K^2} b_1$	$C_{\ell\ell}^{(6)} \mid -\frac{1}{8} \frac{g_1^2 k^2}{m_K^2}$	$C_{eu}^{(6)} \mid \frac{2}{3} \frac{g_1^2 k^2}{m_K^2}$	$C_{qe}^{(6)} \mid \frac{1}{6} \frac{g_1^2 k^2}{m_K^2}$
$C_{Hd}^{(6)} \mid -\frac{y_d g_1^2}{2m_K^2} b_1$	$C_{qq}^{1,(6)} \mid -\frac{1}{72} \frac{g_1^2 k^2}{m_K^2}$	$C_{ed}^{(6)} \mid -\frac{1}{3} \frac{g_1^2 k^2}{m_K^2}$	$C_{qu}^{1,(6)} \mid -\frac{1}{9} \frac{g_1^2 k^2}{m_K^2}$
	$C_{\ell q}^{1,(6)} \mid \frac{1}{12} \frac{g_1^2 k^2}{m_K^2}$	$C_{ud}^{1,(6)} \mid \frac{2}{9} \frac{g_1^2 k^2}{m_K^2}$	$C_{qd}^{1,(6)} \mid \frac{1}{18} \frac{g_1^2 k^2}{m_K^2}$

Consider a kinetic mixing model to dim 8

- Lets see how this works in the simplest benchmark model to dim 8

$$\Delta\mathcal{L} = -\frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \frac{1}{2}m_K^2 K_\mu K^\mu - \frac{k}{2}B^{\mu\nu}K_{\mu\nu},$$

Only has 2 parameters. Dimension 8 matching:

$H^4\psi^2D$	
$C_{H\ell}^{1,(8)}$	$\frac{y_\ell g_1^4}{4m_K^4}k^4 - \frac{g_1^2 y_\ell}{m_K^4}(k^2 - k^4)(2\lambda + \frac{g_1^2 + g_2^2}{4})$
$C_{He}^{1,(8)}$	$\frac{y_e g_1^4}{4m_K^4}k^4 - \frac{g_1^2 y_e}{m_K^4}(k^2 - k^4)(2\lambda + \frac{g_1^2 + g_2^2}{4})$
$C_{Hq}^{1,(8)}$	$\frac{y_q g_1^4}{4m_K^4}k^4 - \frac{g_1^2 y_q}{m_K^4}(k^2 - k^4)(2\lambda + \frac{g_1^2 + g_2^2}{4})$
$C_{Hu}^{1,(8)}$	$\frac{y_u g_1^4}{4m_K^4}k^4 - \frac{g_1^2 y_u}{m_K^4}(k^2 - k^4)(2\lambda + \frac{g_1^2 + g_2^2}{4})$
$C_{Hd}^{1,(8)}$	$\frac{y_d g_1^4}{4m_K^4}k^4 - \frac{g_1^2 y_d}{m_K^4}(k^2 - k^4)(2\lambda + \frac{g_1^2 + g_2^2}{4})$
$C_{H\ell}^{2,(8)}$	$-\frac{g_1^2 g_2^2}{16m_K^4}(k^2 - k^4)$
$C_{Hq}^{2,(8)}$	$-\frac{g_1^2 g_2^2}{16m_K^4}(k^2 - k^4)$
$C_{H\ell}^{3,(8)}$	$-\frac{g_1^2 g_2^2}{16m_K^4}(k^2 - k^4)$
$C_{Hq}^{3,(8)}$	$-\frac{g_1^2 g_2^2}{16m_K^4}(k^2 - k^4)$

H^6D^2	
$C_{H,D2}^{(8)}$	$\frac{g_1^4 k^4}{8m_K^4} - \frac{g_1^2 g_2^2}{2m_K^4}(k^2 - k^4)$
$C_{HD}^{(8)}$	$\frac{3g_1^4 k^4}{16m_K^4} - \frac{g_1^2 g_2^2}{2m_K^4}(k^2 - k^4)$

X^2H^4	
$C_{HB}^{(8)}$	$-\frac{g_1^4}{16m_K^4}(k^2 - k^4)$
$C_{HW}^{(8)}$	$\frac{g_1^2 g_2^2}{16m_K^4}(k^2 - k^4)$

No loop suppression.

Consider a kinetic mixing model to dim 8

- Lets see how this works in the simplest benchmark model to dim 8

$$\Delta\mathcal{L} = -\frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \frac{1}{2}m_K^2 K_\mu K^\mu - \frac{k}{2}B^{\mu\nu}K_{\mu\nu},$$

- Dimension 6 squared approximation:

$$\frac{\sum_\psi \bar{\Gamma}_{\mathcal{Z} \rightarrow \bar{\psi}_p \psi_p}^{p.s., \hat{\alpha}_{ew}}}{\sum_\psi \bar{\Gamma}_{\mathcal{Z} \rightarrow \bar{\psi}_p \psi_p}^{\text{SM}, \hat{\alpha}_{ew}}} = 1 + 4.5 \times 10^{-3} \frac{\bar{v}_T^2 k^2}{m_K^2} + 4.4 \times 10^{-3} k^4 \frac{\bar{v}_T^4}{m_K^4},$$

$$\frac{\sum_\psi \bar{\Gamma}_{\mathcal{Z} \rightarrow \bar{\psi}_p \psi_p}^{p.s., \hat{m}_W}}{\sum_\psi \bar{\Gamma}_{\mathcal{Z} \rightarrow \bar{\psi}_p \psi_p}^{\text{SM}, \hat{m}_W}} = 1 - 3.1 \times 10^{-2} \frac{\bar{v}_T^2 k^2}{m_K^2} + 2.3 \times 10^{-4} k^4 \frac{\bar{v}_T^4}{m_K^4}.$$

Consider a kinetic mixing model to dim 8

- Lets see how this works in the simplest benchmark model to dim 8

$$\Delta\mathcal{L} = -\frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \frac{1}{2}m_K^2 K_\mu K^\mu - \frac{k}{2}B^{\mu\nu}K_{\mu\nu},$$

- To Dimension 8 consistently:

$$\frac{\sum_\psi \bar{\Gamma}_{Z \rightarrow \bar{\psi}_p \psi_p}^{\text{SMEFT}, \hat{\alpha}_{ew}}}{\sum_\psi \bar{\Gamma}_{Z \rightarrow \bar{\psi}_p \psi_p}^{\text{SM}, \hat{\alpha}_{ew}}} = 1 + 4.5 \times 10^{-3} \frac{\bar{v}_T^2 k^2}{m_K^2} - 5.7 \times 10^{-3} (k^4 - 1.74k^2) \frac{\bar{v}_T^4}{m_K^4},$$

$$\frac{\sum_\psi \bar{\Gamma}_{Z \rightarrow \bar{\psi}_p \psi_p}^{\text{SMEFT}, \hat{m}_W}}{\sum_\psi \bar{\Gamma}_{Z \rightarrow \bar{\psi}_p \psi_p}^{\text{SM}, \hat{m}_W}} = 1 - 3.1 \times 10^{-2} \frac{\bar{v}_T^2 k^2}{m_K^2} + 7.9 \times 10^{-3} (k^4 - 0.88k^2) \frac{\bar{v}_T^4}{m_K^4}.$$

Consider a kinetic mixing model to dim 8

- Strong input parameter dependence in any one observable:

- $L6^2$ can manifestly mislead.

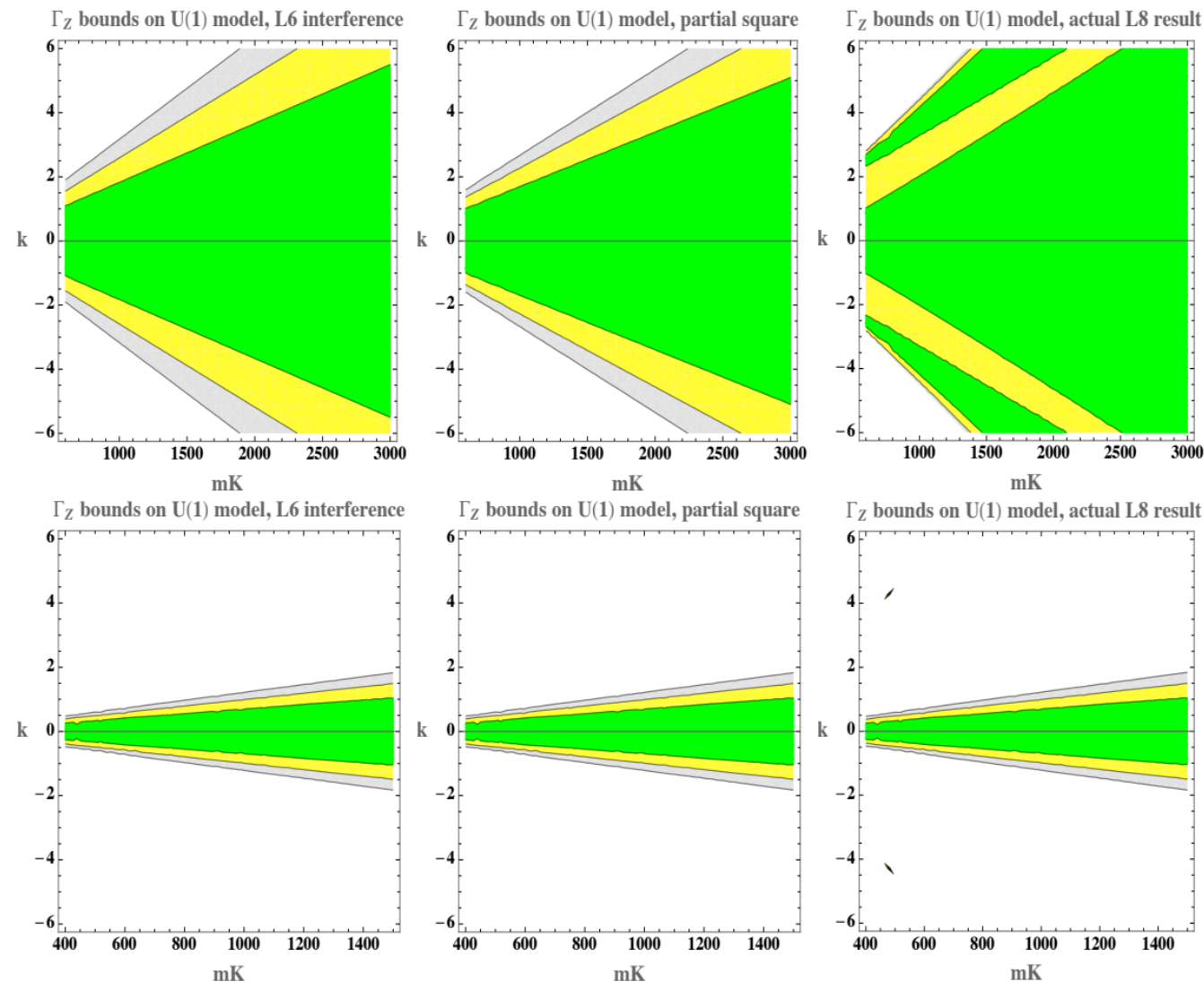


Figure 8. Illustrative bounds on a U(1) mixing model parameters due to bounds on Γ_Z . Shown is the $\{1, 2, 3\}\sigma$ allowed region in green, yellow, gray. Here 1σ for $\delta\Gamma_Z = 0.0023/2.4952$. Results shown are for the $\hat{\alpha}_{ew}$ input-parameter scheme in the first row. The results in the second row are in the $\hat{m}_W$ input-parameter scheme.

- Clearly need to go beyond quadratic. With geoSMEFT we can proceed efficiently to full dim 8.

Consider a kinetic mixing model to dim 8

- Strong input parameter dependence in any one observable:

- L6^2 can Mislead

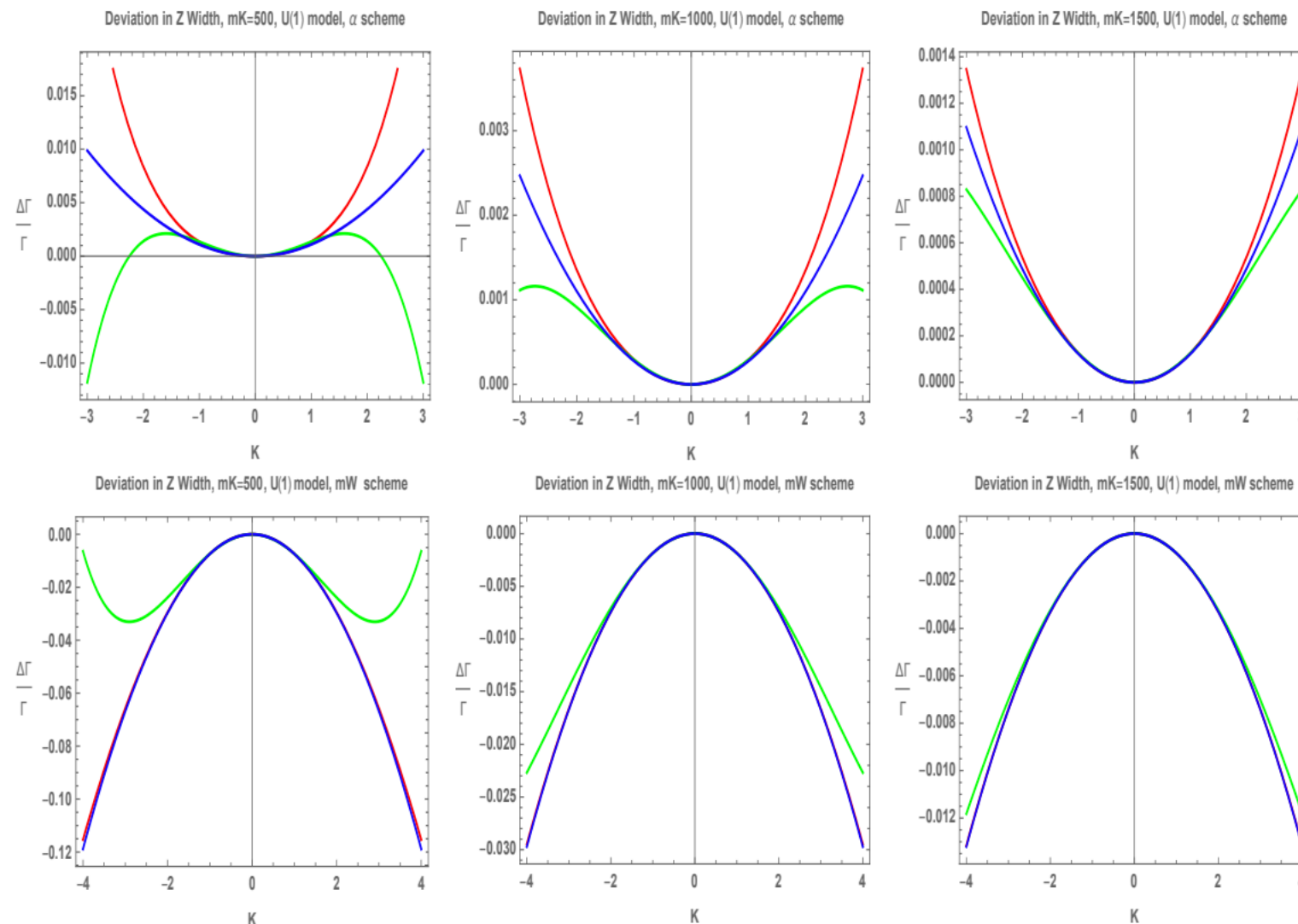


Figure 9. Deviation in the Z width in the $U(1)$ mixing model for fixed m_K comparing the partial-square result in red and the full SMEFT result at $\mathcal{L}^{(8)}$ in green, and the full SMEFT result at $\mathcal{L}^{(6)}$ in blue.

- The power of the EFT is that you can combine observables and you have to do it

One loop consistency checks

Consistency checks at one loop/dim8

- The operator and loop expansion are not independent.

$$\mathcal{A} = \mathcal{A}_{SM} + \tilde{C}_i^{(6)} a_i + \dots$$

If you choose to rescale (or not) the Wilson coefficient at L6 it changes the one loop result and the dimension 8 result in a correlated way.

Only game in town for full dimension 8 with all input redefinitions etc is geoSMEFT. Loops should be done in BFM for consistency with background field independent formulation defining geoSMEFT.

Consistency checks at one loop/dim8

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

- Many cross checks afforded (Ward identities and more).
- Clean understanding of ward identities.
- 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

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

Consistency checks at one loop/dim8

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

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

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

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

- Cancellation in single Higgs, single dev observables with tadpole term and GF extraction.

Consistency checks at one loop/dim8

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

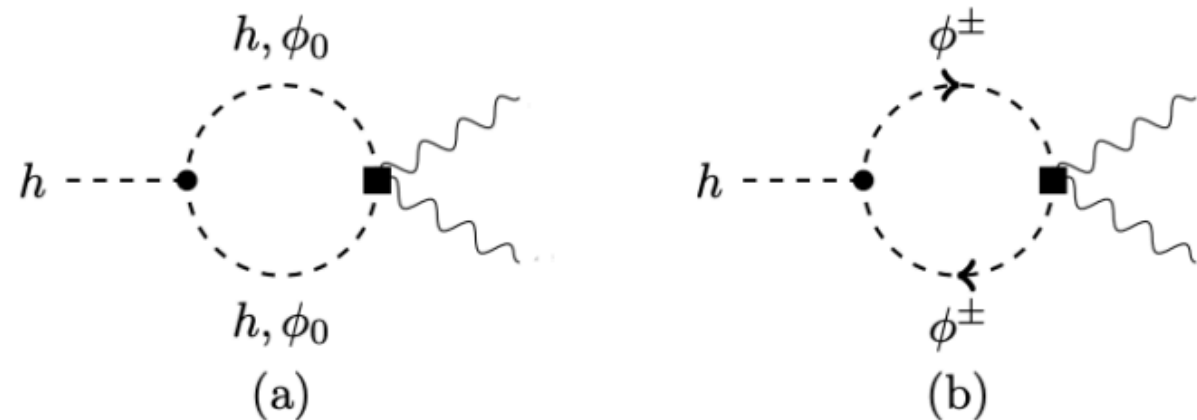


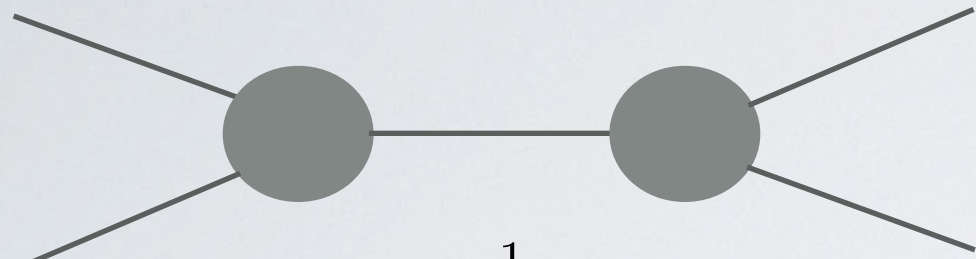
Figure 2. One loop contributions to $\langle \phi_4 | F F \rangle \langle \frac{\delta M_{AB}}{\delta \phi_4} \rangle$.

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

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

Interpreting W mass in the SMEFT

When you do measurements below a particle threshold



$$\sim \frac{1}{s - m^2 + i\Gamma(s)m}$$

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

Infrared singularities and massive fields

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

- You can Taylor expand in LOCAL functions (operators)

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

This is the core idea of EFT interpretations of the data.

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

UV dependent Wilson coefficient
 and suppression scale

IR operator form

The Standard model EFT

- The SM, an SU(3) xSU(2)xU(1) gauge theory:

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

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	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
	Higgs boson*				

Source: AAAS

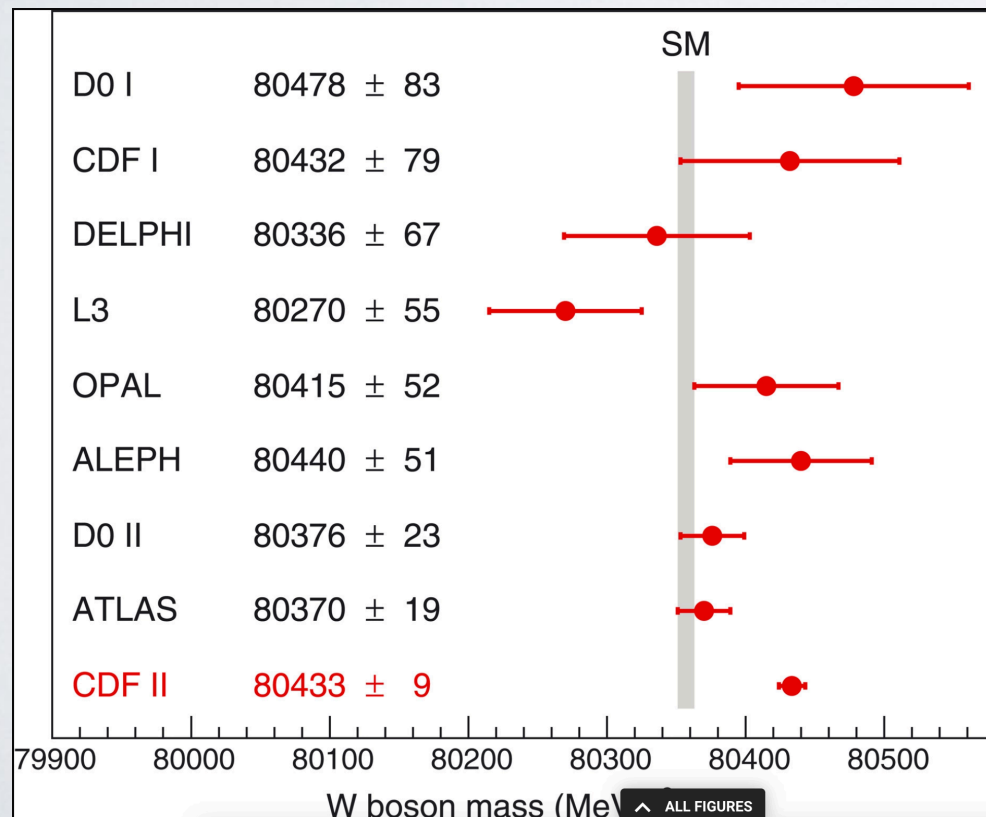
$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \dots$$

- Glashow 1961, Weinberg 1967 (Salam 1967)
- Weinberg 1979, Wilczek and Zee 1979
- Leung, Love, Rao 1984, Buchmuller Wyler 1986, Grzadkowski, Iskrzynski, Misiak, Rosiek 2010

The SMEFT is a key tool for interpreting such deviations:



Last week!



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

CDF COLLABORATION††, T. AALTONEN, S. AMERIO, D. AMIDEI, A. ANASTASSOV, A. ANNOVI, J. ANTOS, G. APOLLINARI, J. A. APPEL, [et al.] S. ZUCHELLI +389 authors

[Authors Info & Affiliations](#)

SCIENCE • 7 Apr 2022 • Vol 376, Issue 6589 • pp. 170-176 • DOI:10.1126/science.abk1781

97,942 views, 1 citation

- Any one measurement can just dictate a parameter in a theory. But a PATTERN of measurements can show a theory does not describe Global data.

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

- SMEFT Game plan: (we are ready for deviations!)

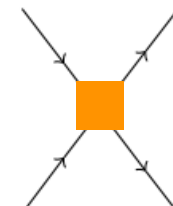
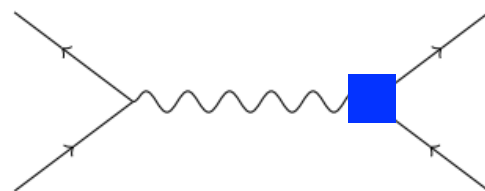
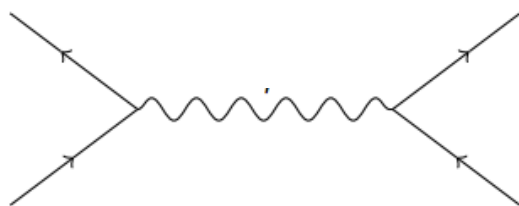
Find deviations → Map to pattern in SMEFT

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

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



So now

$$-\frac{4\mathcal{G}_F}{\sqrt{2}} = -\frac{2}{v_T^2} + \left(C_{\mu e e \mu}^{ll} + C_{e \mu \mu e}^{ll} \right) - 2 \left(C_{ee}^{(3)Hl} + C_{\mu\mu}^{(3)Hl} \right)$$

Choose inputs, define predictions

$$\{\hat{\alpha}_{ew}, \hat{M}_Z, \hat{G}_F, \hat{M}_h\} \quad \text{Scheme}$$

- Probably the paper we should be citing on the W mass shift using a (proto)-SMEFT op basis is

Operator analysis for precision electroweak physics

Benjamin Grinstein (Harvard U.), Mark B. Wise (Caltech)

Apr, 1991

Phys.Lett.B 265 (1991) 326-334

$$M_{W,\text{phys}}^2 = M_{Z,\text{phys}}^2 \cos^2 \theta_0 \left[1 + (C_1 + C_2) \frac{M_{Z,\text{phys}}^2}{M^2} \left(\frac{\sin^2 2\theta_0}{\cos 2\theta_0} \right) + C_3 \frac{v^2}{2M^2} \left(\frac{\sin 2\theta_0}{\cos 2\theta_0} \right) + C_4 \frac{v^2}{M^2} \left(\frac{\cos^2 \theta_0}{\cos 2\theta_0} \right) \right] \quad (4.11)$$

E.O.M.

- Modern result all over (1606.06502), using Warsaw basis:

$$\hat{m}_W^2 = 2 \sqrt{2} \pi \hat{\alpha}_{ew} / (\hat{G}_F \hat{s}_\theta^2) \quad s_\theta^2 = 1/2 - \sqrt{1 - 4 \pi \hat{\alpha}_{ew} / \sqrt{2} \hat{G}_F \hat{m}_Z^2}.$$

$$\frac{\delta m_W^2}{\hat{m}_W^2} = \hat{\Delta} \left[4 C_{HWB} + \frac{c_\theta}{s_\theta} C_{HD} + 4 \frac{s_\theta}{c_\theta} C_{H\ell}^{(3)} - 2 \frac{s_\theta}{c_\theta} C_{\ell\ell} \right] \quad \hat{\Delta} = c_\theta s_\theta / (c_\theta^2 - s_\theta^2) 2 \sqrt{2} \hat{G}_F.$$

- Measurement to constraint this shift in this scheme, or cause deviations elsewhere in $\{\hat{M}_W, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

Strong input scheme dependence in SMEFT

$\{\hat{\alpha}_{ew}, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

$$\delta m_Z^2 = \frac{\hat{M}_Z^2}{2} \tilde{C}_{HD} + \frac{2^{3/4} \sqrt{\pi \hat{\alpha}} \hat{M}_Z}{\hat{G}_F^{1/2}} \tilde{C}_{HWB},$$

$$\delta s_\theta^2 = 0.17 \tilde{C}_{HD} + 0.79 \tilde{C}_{HWB} + 0.76 \tilde{C}_{Hl}^{(3)} - 0.34 \tilde{C}'_{ll},$$

$$\frac{\delta \Gamma_Z}{\Gamma_Z^{SM}} = -0.82 \tilde{C}_{HWB} - 0.67 \tilde{C}_{HD} - 0.19 \tilde{C}_{Hl}^{(1)} - 2.06 \tilde{C}_{Hl}^{(3)} - 0.19 \tilde{C}_{He} \\ + 0.47 \tilde{C}_{Hq}^{(1)} + 1.61 \tilde{C}_{Hq}^{(3)} + 0.26 \tilde{C}_{Hu} - 0.19 \tilde{C}_{Hd} + 1.35 \tilde{C}'_{ll}$$

$$\frac{\delta \alpha}{2 \hat{\alpha}} = 0,$$

$$\frac{\delta M_W^2}{\hat{M}_W^2} = -\frac{s_{2\hat{\theta}}}{4 c_{2\hat{\theta}}} \left(\frac{c_{\hat{\theta}}}{s_{\hat{\theta}}} \tilde{C}_{HD} + \frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} 2\sqrt{2} \delta G_F + 4 \tilde{C}_{HWB} \right),$$

$$\frac{\delta \Gamma_W}{\Gamma_W^{SM}} = -3.97 \tilde{C}_{HWB} - 1.80 \tilde{C}_{HD} - 3.52 \tilde{C}_{Hl}^{(3)} + 1.33 \tilde{C}_{Hq}^{(3)} + 2.10 \tilde{C}'_{ll}.$$

$\{\hat{M}_W, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

$$\delta m_Z^2 = \frac{\hat{M}_Z^2}{2} \tilde{C}_{HD} + 2 \hat{M}_Z \hat{M}_W \sqrt{1 - \frac{\hat{M}_W^2}{\hat{M}_Z^2}} \tilde{C}_{HWB},$$

$$\delta s_\theta^2 = -0.39 \tilde{C}_{HD} - 0.42 \tilde{C}_{HWB},$$

$$\frac{\delta \Gamma_Z}{\Gamma_Z^{SM}} = 0.46 \tilde{C}_{HWB} - 0.07 \tilde{C}_{HD} - 0.18 \tilde{C}_{Hl}^{(1)} - 1.37 \tilde{C}_{Hl}^{(3)} - 0.18 \tilde{C}_{He} \\ + 0.47 \tilde{C}_{Hq}^{(1)} + 1.61 \tilde{C}_{Hq}^{(3)} + 0.24 \tilde{C}_{Hu} - 0.18 \tilde{C}_{Hd} + \tilde{C}'_{ll},$$

$$\frac{\delta \alpha}{2 \hat{\alpha}} = -\frac{\delta G_F}{\sqrt{2}} + \frac{\delta m_Z^2}{\hat{M}_Z^2} \frac{\hat{M}_W^2}{2 (\hat{M}_W^2 - \hat{M}_Z^2)} - \tilde{C}_{HWB} \frac{\hat{M}_W}{\hat{M}_Z} \sqrt{1 - \frac{\hat{M}_W^2}{\hat{M}_Z^2}},$$

$$\frac{\delta M_W^2}{\hat{M}_W^2} = 0,$$

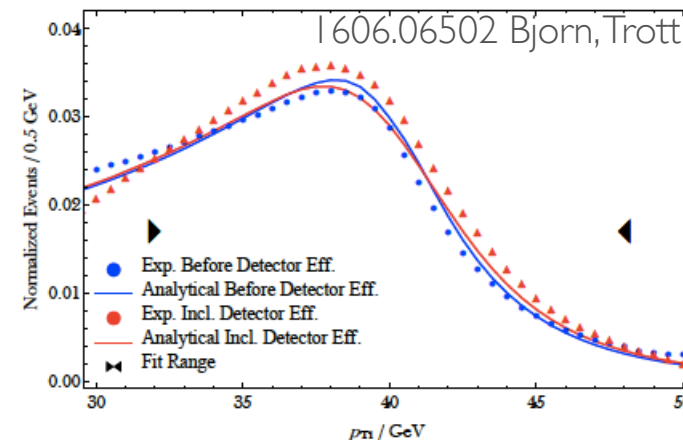
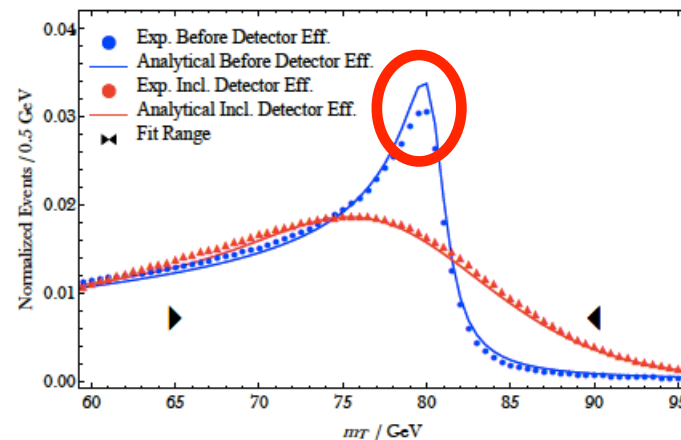
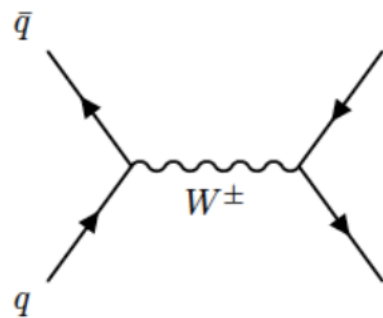
$$\frac{\delta \Gamma_W}{\Gamma_W^{SM}} = \frac{4}{3} \left(\tilde{C}_{Hq}^{(3)} - \tilde{C}_{Hl}^{(3)} \right) + \tilde{C}'_{ll}.$$

- Completely expected from AC decoupling theorem. **UV physics preserving SM symmetries being absorbed into measured low scale parameters now.**

Mw measurements in SMEFT

- Mw is a template fit at LEP and at the Tevatron

Transverse mass Jacobian peak



- Semi-analytic understanding

$$m_T^2 = 2P_{T,\ell} P_{T,\nu} (1 - \cos \theta_{\ell\nu})$$

W. L. van Neerven et al. NIKHEF-H/82-20.

J. Smith et al. Phys. Rev. Lett. **50**, 1738 (1983).

V. D. Barger et al. Z. Phys. C **21**, 99 (1983).

Jacobian peak

$$\frac{d\sigma}{dm_T} = \frac{1}{(\pi/2 + \arctan \bar{m}_W / \bar{\Gamma}_W)} \int_{m_T^2}^{\infty} ds' \frac{\bar{m}_W \bar{\Gamma}_W}{(s' - \bar{m}_W^2)^2 + \bar{m}_W^2 \bar{\Gamma}_W^2} \frac{m_T}{(s'(s' - m_T^2))^{1/2}} \int_0^{2\pi} d\phi \sum_{ij} \frac{d\sigma_{ij}}{d\cos\theta} I(\mu, \phi, \alpha),$$

$$I(\mu, \phi, \alpha) = \frac{\mu^4 + \mu^4 \alpha^2 \cos^2 \phi + 2\mu^2 \alpha^2 \sin^2 \phi + \alpha^4 \sin^2 \phi}{(\mu^2 + \alpha^2 \sin^2 \phi)^{1/2} (\mu^2 + \mu^2 \alpha^2 \cos^2 \phi + \alpha^2 \sin^2 \phi)^{3/2}}.$$

$$\frac{d\sigma_{ij}}{d\cos\theta} = \tilde{\sigma}_{ij} \frac{3(\hat{G}_F \hat{M}_W^2)^2 |V_{ij}|^2 |\bar{g}_{ij}^{W,q}|^2 [1 + \cos^2 \theta] \text{Br}}{8\sqrt{2}\pi N_c s}$$

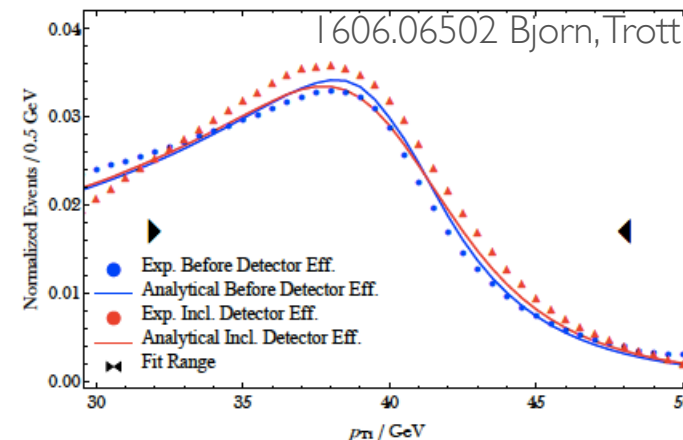
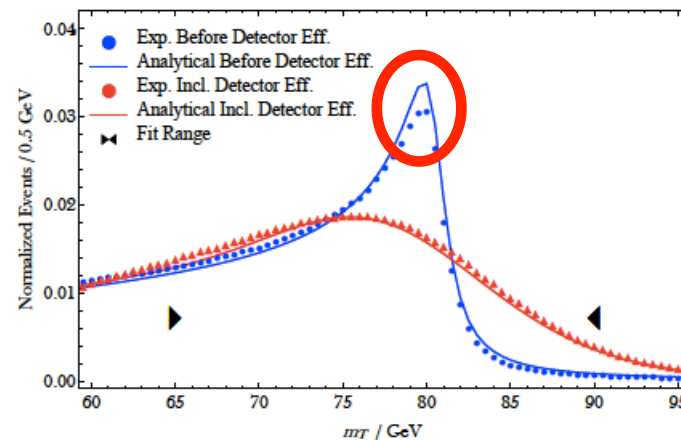
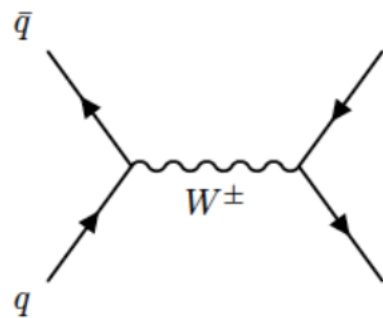
Pdf's feed in

$$\gamma = \sqrt{P_{T,W}^2 + s'}/\sqrt{s'}, \quad \alpha = (\gamma^2 - 1)^{1/2} = P_{T,W}/\sqrt{s'}, \quad \mu^2 = m_T^2/s'$$

Mw measurements in SMEFT

- Mw is a template fit at LEP and at the Tevatron

Transverse mass Jacobian peak



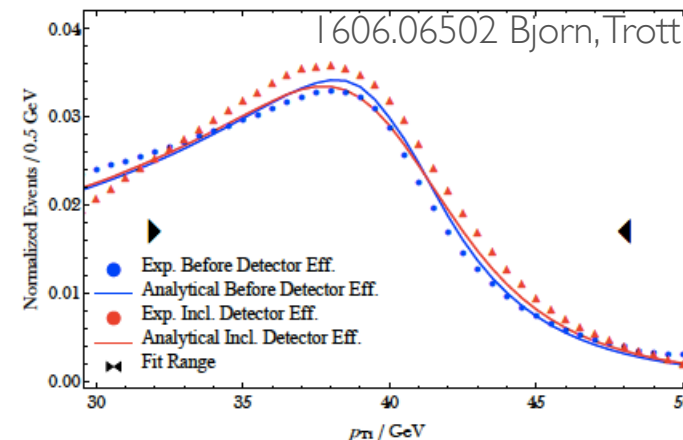
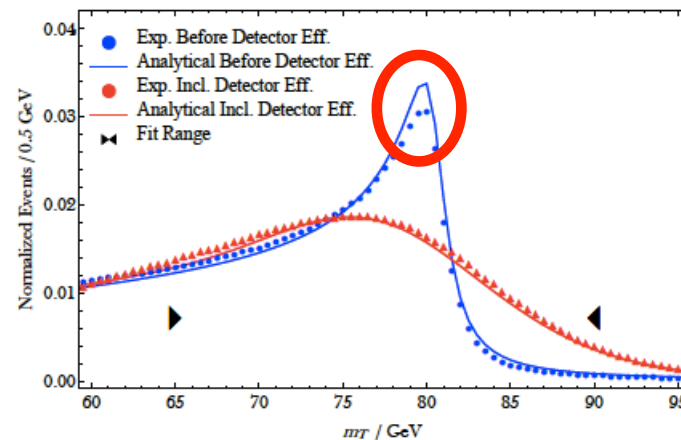
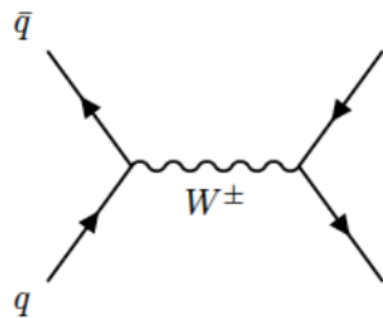
- SMEFT interpretation concern - other shifts compared to SM feed in. Does that screw up mapping to mass shift formula?

i.e. W coupling normalization and width shifts.

Mw measurements in SMEFT

- Mw is a template fit at LEP and at the Tevatron

Transverse mass Jacobian peak



- Way to check
$$\frac{d\sigma_{ij}}{d\cos\theta} = \tilde{\sigma}_{ij} \frac{3(\hat{G}_F \hat{M}_W^2)^2 |V_{ij}|^2}{8\sqrt{2}\pi N_c s} |\bar{g}_{ij}^{W,q}|^2 [1 + \cos^2\theta] \text{ Br}$$

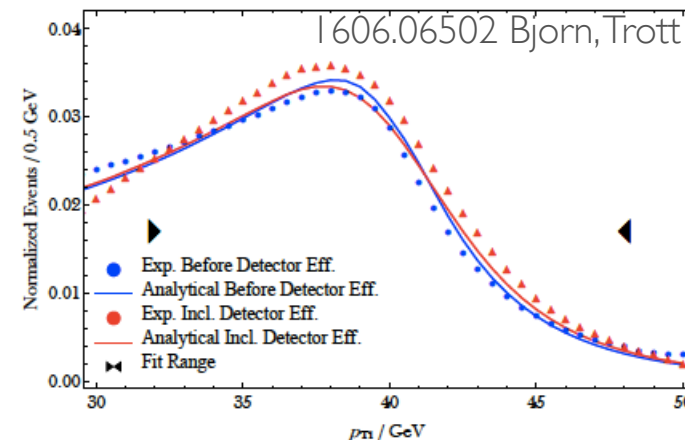
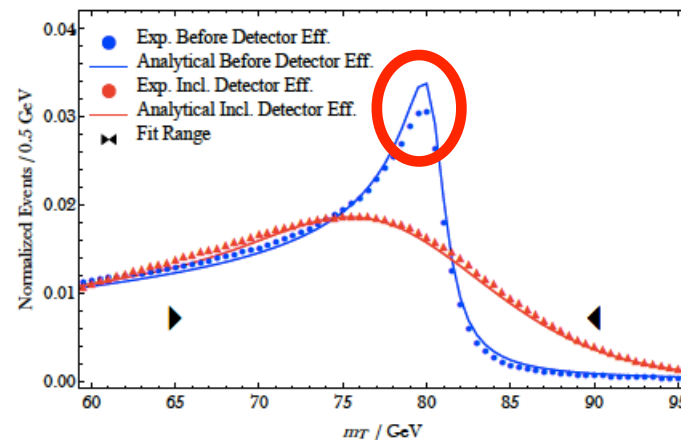
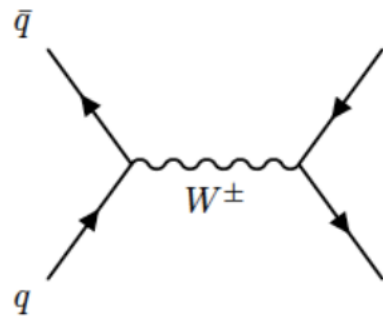
The overall normalization of both of the spectra is modified with a shift

$$\frac{\delta N_{ij}}{N_{ij}} = 2 \left[\frac{\delta g_{ij}^{W,q}}{V_{ij} \hat{g}^{W,q}} + \frac{\delta g^{W,\ell}}{\hat{g}^{W,\ell}} \right] + \frac{1}{2} \frac{\delta m_W^2}{\hat{m}_W^2} - \frac{\delta \Gamma_W}{\hat{\Gamma}_W}$$

Mw measurements in SMEFT

- Mw is a template fit at LEP and at the Tevatron

Transverse mass Jacobian peak



- Way to check

Both $\delta N (= \sum \delta N_{ii})$ and $\delta \Gamma_W$ stem from shifts of the $W^\pm$ -couplings, and are therefore correlated. We decompose

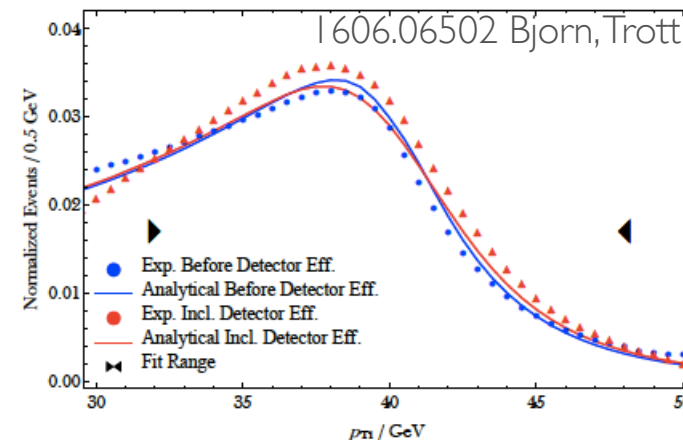
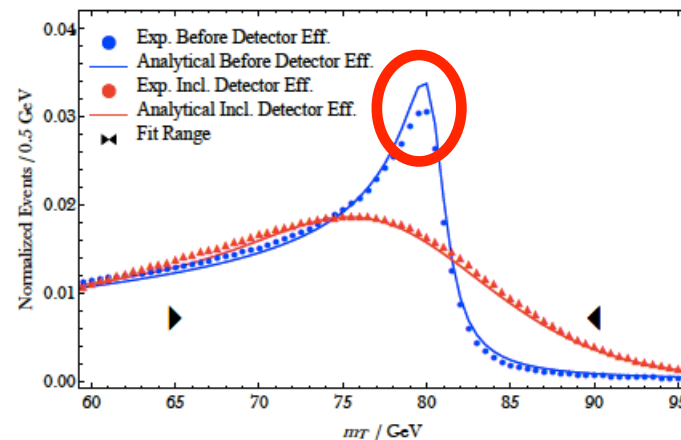
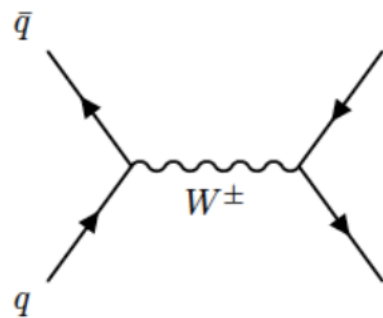
$$\frac{\delta \Gamma_W}{\hat{\Gamma}_W} = \frac{\delta \Gamma_{||}}{\hat{\Gamma}_W} + \frac{\delta \Gamma_{\perp}}{\hat{\Gamma}_W},$$

where $\delta \Gamma_{||}$ captures all the correlation, and $\delta \Gamma_{\perp}$ corresponds to directions in Wilson-coefficient-space where the overall normalization of the spectra is unchanged.

Mw measurements in SMEFT

- Mw is a template fit at LEP and at the Tevatron

Transverse mass Jacobian peak



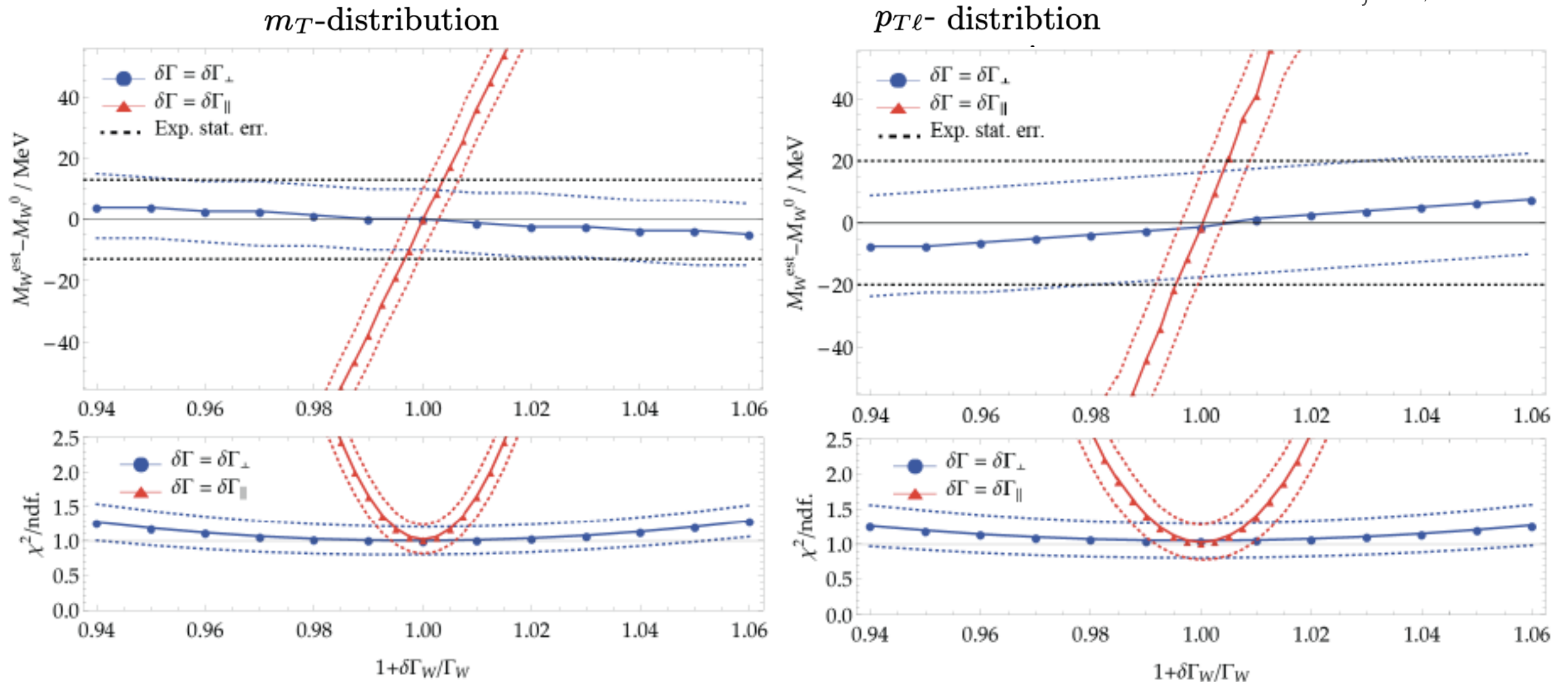
- Way to check

$$\frac{\delta N}{N} = \left(\frac{154 + 44 s_{\hat{\theta}}^2 - 38 s_{\hat{\theta}}^4}{227 + 94 s_{\hat{\theta}}^2 - 97 s_{\hat{\theta}}^4} \right) \frac{\delta \Gamma_{||}}{\hat{\Gamma}_W} \simeq 0.67 \frac{\delta \Gamma_{||}}{\hat{\Gamma}_W}, \quad (15)$$

where the proportionality factor is obtained by expressing $\delta \Gamma_W$ in a basis of the space spanned by C_i that includes $\delta N/N$ as a basis vector.

Mw measurements in SMEFT

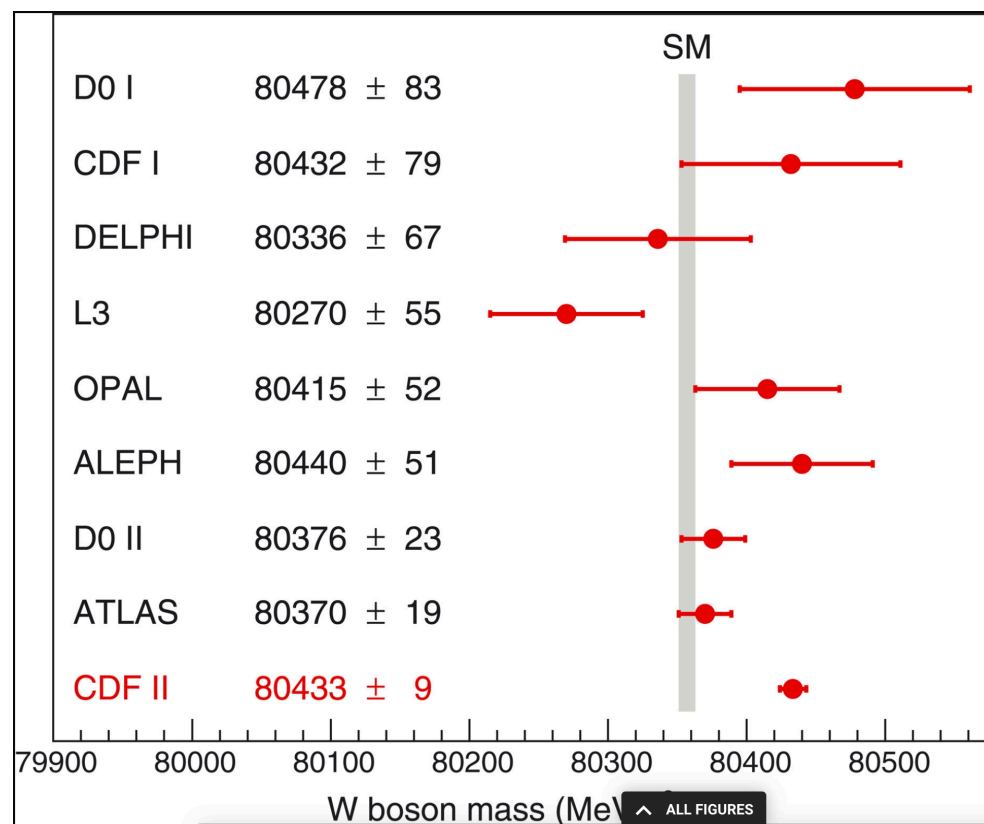
1606.06502 Bjorn, Trott



- The error quoted on the extraction for the Tevatron is OK in the SMEFT
For old measurement due to width and coupling shifts also floated. Seems likely this is still the case with smaller errors (9.4 MeV) so that the deviation can be directly mapped to the mass shift (note however a 2-d scan is really required).

Comments on combinations

Combinations



● Q: If we want to constrain SMEFT from the data which measurement to use?

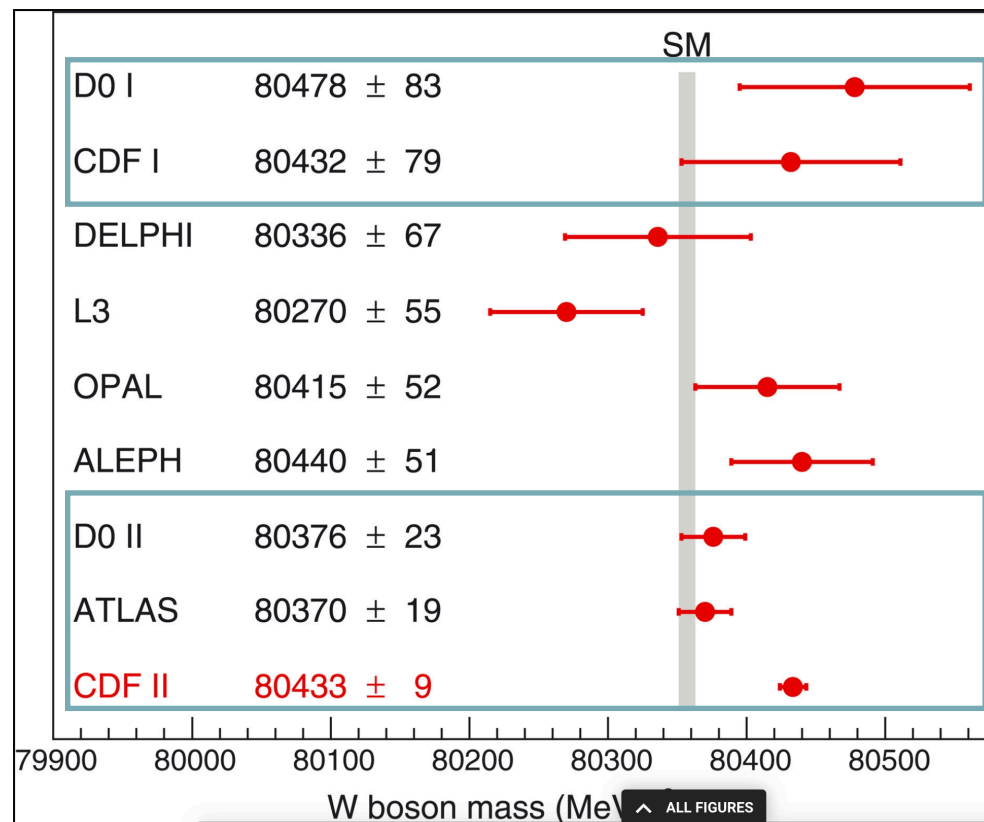
A: Use the global combination of course. It is not that simple.

LHCb $m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ MeV.

A global combination of data needs a theory to define theory correlations as well as experimental correlations. The SM is NOT the same field theory as the SMEFT.

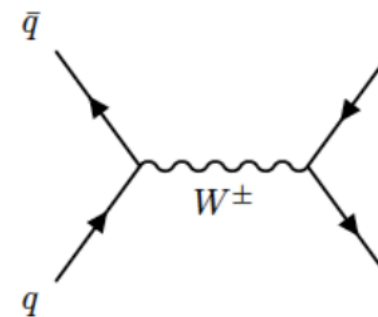
Combine in the SM ! (Good luck!)

SMEFT Combinations



LHCb $m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$

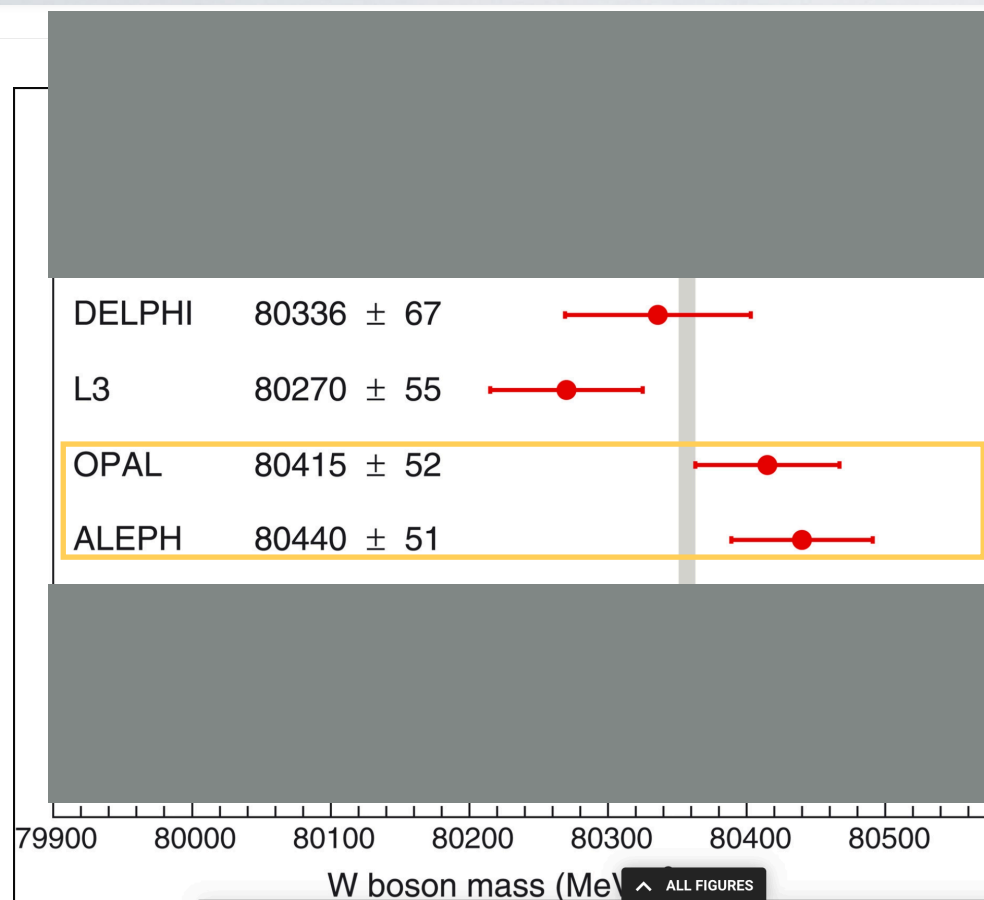
- Each measurement needs to be examined for SMEFT interpretability and combination



Similar transverse kinematic procedures (diff pdf's etc).

SMEFT bias analysis laid out should be redone.

SMEFT Combinations

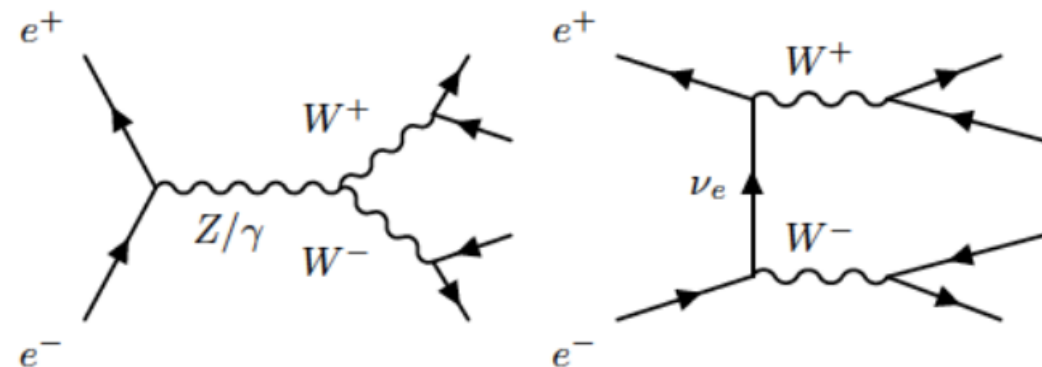


SMEFT bias in this case
Is under control too

1606.06502 Bjorn, Trott

Combine away!

• What about LEP II?



Two different techniques: threshold scan

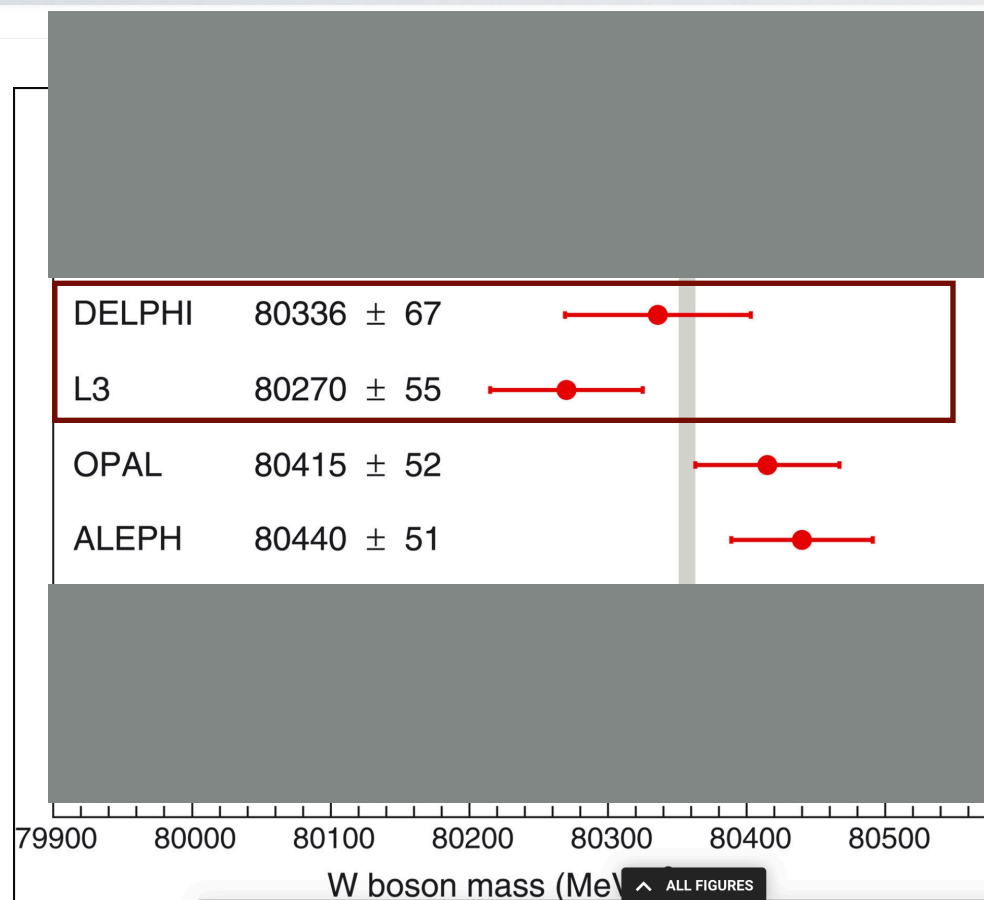
K. Hagiwara and D. Zeppenfeld, Phys. Lett. B **196**, 97 (1987).

the leading order (in β) SMEFT correction to the Born cross section approximation of $\sigma(e^+ e^- \rightarrow W^+ W^- \rightarrow S_i, S_j)$ is

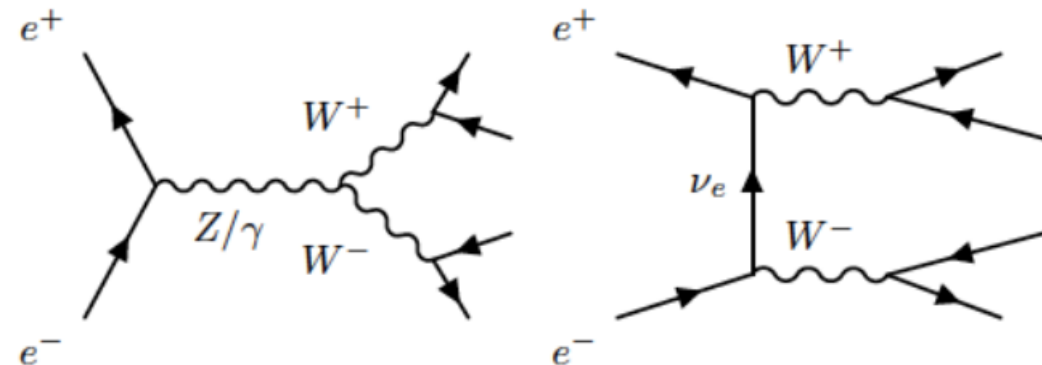
$$\delta \frac{d\sigma}{d\Omega} \simeq \frac{\hat{\alpha}^2}{8 s s_{\hat{\theta}}} \frac{\delta m_w^2}{\hat{m}_w^2}, \quad \hat{\beta} = \sqrt{1 - 4\bar{m}_W^2/s},$$

Note the lack of s channel contributions due to possibly anomalous TGC parameters in the threshold limit. These corrections first appear at order β^3

SMEFT Combinations



- What about LEP II?



Two different techniques:
Away from threshold scan with TGC
and Width shifts set to 0?!?!?

Not interpretable in SMEFT to my
knowledge | 606.06502 Bjorn, Trott

A SM global data combination is not the same as a SMEFT one
for constraints. These are different theories.