The Higgs Width in the SMEFT

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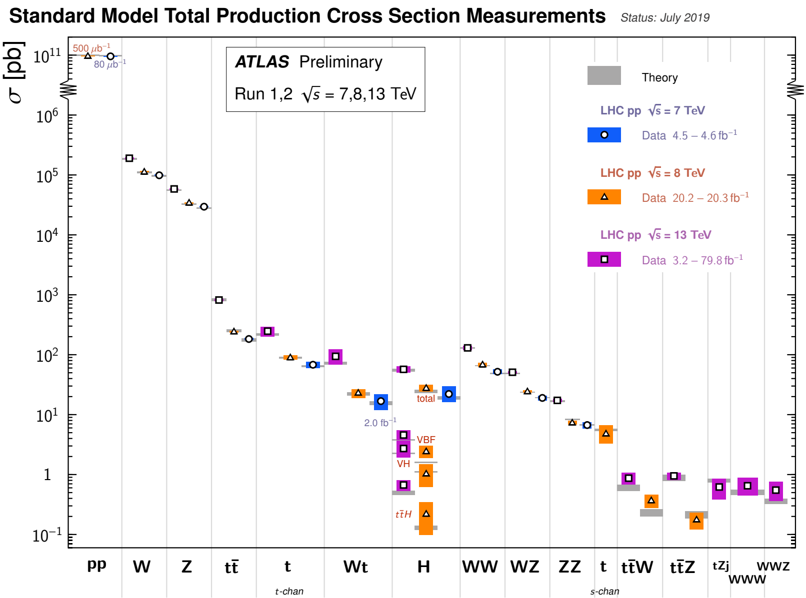
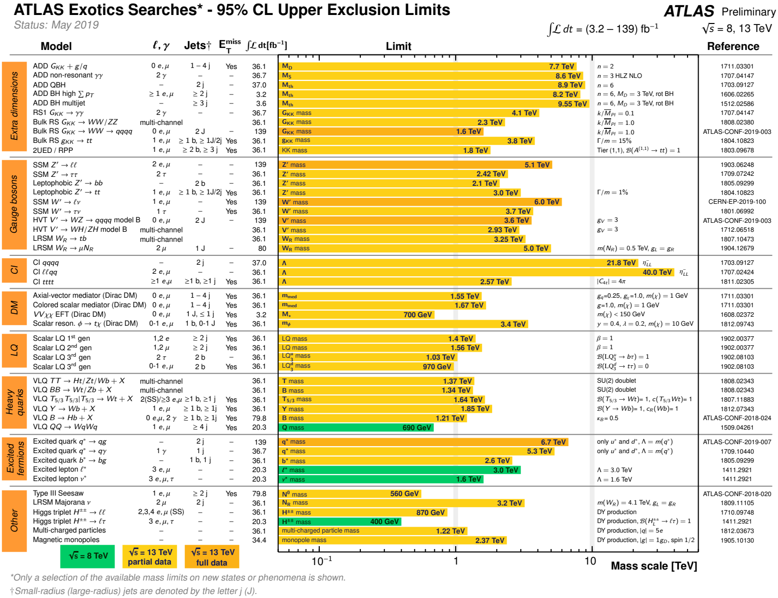
Largely based on:
arXiv: 1906.06949, with Ilaria Brivio (Heidelberg) and Mike Trott (NBI).

ATLAS SM Summary

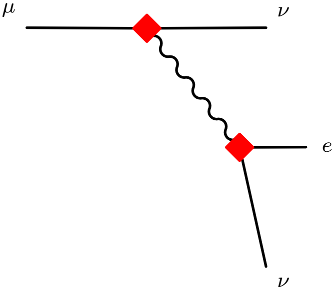


ATLAS Exotics Summary



The Fermi-theory example

In the SM



$$\mathcal{M} \sim \frac{g_{\mathrm{W}}^2}{2} \frac{(\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e}\gamma^\mu P_L \nu_e)}{k^2 - M_W^2}$$

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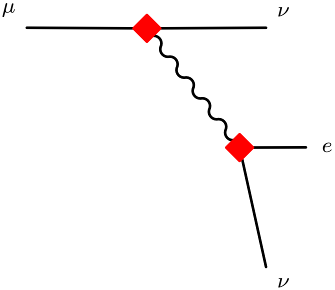
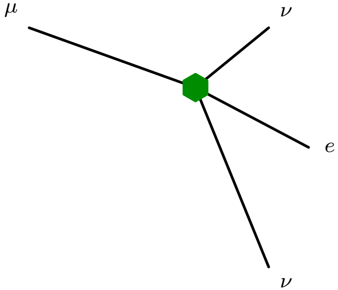
In the SM



In the Fermi theory



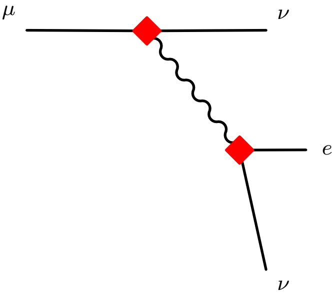
$$\mathcal{M} \sim \frac{g_{\rm W}^2}{2} \frac{(\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e}\gamma^\mu P_L \nu_e)}{k^2 - M_W^2}$$

$$\frac{1}{M_W^2}(\bar{\psi}\gamma^\mu P_L \psi)^2$$

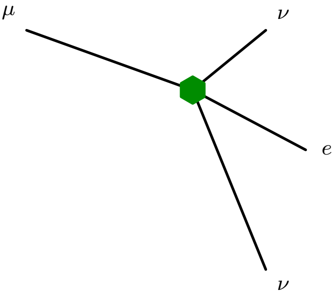
$$\mathcal{M} \sim -\frac{g_{\rm W}^2}{2M_W^2}(\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e}\gamma^\mu P_L \nu_e) + \cdots$$

The Fermi-theory example

In the SM



In the Fermi theory

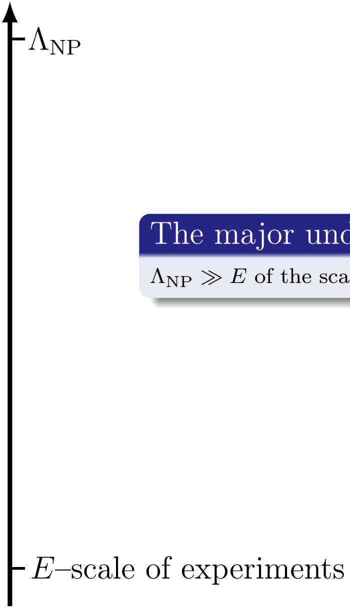


$$\mathcal{M} \sim \frac{g_{\rm W}^2}{2} \frac{(\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e}\gamma^\mu P_L \nu_e)}{k^2 - M_W^2}$$

$$\frac{1}{M_W^2}(\bar{\psi}\gamma^\mu P_L \psi)^2 \qquad \frac{1}{M_W^4}\partial^2(\bar{\psi}\gamma^\mu P_L \psi)^2$$

$$\mathcal{M} \sim -\frac{g_{\rm W}^2}{2M_W^2}(\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e}\gamma^\mu P_L \nu_e) - \frac{g_{\rm W}^2 k^2}{2M_W^4}(\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e}\gamma^\mu P_L \nu_e) + \cdots$$

EFTs



The major underlying assumption of any EFT

$\Lambda_{\text{NP}} \gg E$ of the scale of experiments/measurements

$\Lambda_{\rm NP}$

Bottom up EFTs:

- Start w/ IR–model in mind (QED, SM)
- using symmetries of model put together ops, $Q^{d>4}$
- truncate EFT at some $\mathcal{O}(1/\Lambda)$
- constrain Q in experiment & infer properties of NP at Λ
- Qs are unrelated $\rightarrow$ model independent
- Qs are only in terms of IR degrees of freedom

E–scale of experiments

D6 operators from SM field content ⇒ SMEFT @ D6

Type I: X^3		Type II, III: H^6, H^4D^2		Type V: Ψ^2H^3 + h.c.	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$\|H\|^6$	Q_{eH}	$\|H\|^2(\bar{L}eH)$
$Q_{\tilde{G}}$	$f^{ABC}\tilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{H\Box}$	$\|H\|^2\Box\|H^2\|$	Q_{uH}	$\|H\|^2(\bar{Q}u\tilde{H})$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	Q_{HD}	$(H^\dagger D^\mu H)^*(H^\dagger D^\mu H)$	Q_{dH}	$\|H\|^2(\bar{Q}dH)$
$Q_{\tilde{W}}$	$\epsilon^{IJK}\tilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

Type IV: $X^2\Phi^2$		Type VI: Ψ^2H^3		Type VII: Ψ^2H^2D	
Q_{HG}	$\|H\|^2G_{\mu\nu}^AG^{A\mu\nu}$	Q_{eW}	$(\bar{L}\sigma^{\mu\nu}e)\tau^IHW_{\mu\nu}^I$	$Q_{HL}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$
$Q_{H\tilde{G}}$	$\|H\|^2\tilde{G}_{\mu\nu}^AG^{A\mu\nu}$	Q_{eW}	$(\bar{L}\sigma^{\mu\nu}e)\tau^IHB_{\mu\nu}$	$Q_{HL}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{L}\tau^I\gamma^\mu L)$
Q_{HW}	$\|H\|^2W_{\mu\nu}^IW^{I\mu\nu}$	Q_{uG}	$(\bar{Q}\sigma^{\mu\nu}T^Au)\tilde{H}G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$
$Q_{H\tilde{W}}$	$\|H\|^2\tilde{W}_{\mu\nu}^IW^{I\mu\nu}$	Q_{uW}	$(\bar{Q}\sigma^{\mu\nu}u)\tau^I\tilde{H}W_{\mu\nu}^I$	$Q_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$
Q_{HB}	$\|H\|^2B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{Q}\sigma^{\mu\nu}u)\tilde{H}B_{\mu\nu}$	$Q_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}\tau^I\gamma^\mu q)$
$Q_{H\tilde{B}}$	$\|H\|^2\tilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{Q}\sigma^{\mu\nu}T^Ad)HG_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$
Q_{HWB}	$(H^\dagger\tau^IH)W_{\mu\nu}^IB^{\mu\nu}$	Q_{dW}	$(\bar{Q}\sigma^{\mu\nu}d)\tau^IHW_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$
$Q_{H\tilde{W}B}$	$(H^\dagger\tau^IH)\tilde{W}_{\mu\nu}^IB^{\mu\nu}$	Q_{dB}	$(\bar{Q}\sigma^{\mu\nu}d)\tilde{H}B_{\mu\nu}$	Q_{Hud}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu d)$

Type VIII: $5\times(\bar{L}L)(\bar{L}L)+7\times(\bar{R}R)(\bar{R}R)+8\times(\bar{L}L)(\bar{R}R)+(\bar{L}R)(\bar{R}L)+4[(\bar{L}R)(\bar{L}R)+\text{h.c.}]$
$=25(\bar{\Psi}\Psi)(\bar{\Psi}\Psi)$

SMEFT: Effective Vertices

T3: $Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$

T3: $Q_{HD} = (H^\dagger D^\mu H)^*(H^\dagger D^\mu H)$

T4: $Q_{HV} = (H^\dagger H)V^{\mu\nu}V_{\mu\nu}$

T4: $Q_{HWB} = (H^\dagger \tau^I H)W^I_{\mu\nu}B^{\mu\nu}$

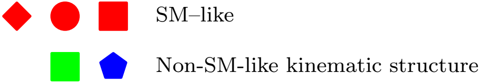
T5: $Q_{\psi H} = (H^\dagger H)(\bar{\Psi}H\psi)$

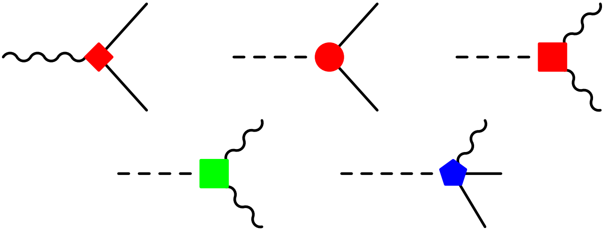
T7: $Q^{(3)}_{HL} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{L}\gamma^\mu L)$

T7: $Q^{(1,3)}_{H\Psi} = (H^\dagger \overleftrightarrow{D}_\mu H)(\bar{\Psi}\gamma^\mu\Psi)$

T7: $Q_{H\psi} = (H^\dagger \overleftrightarrow{D}_\mu H)(\bar{\psi}\gamma^\mu\psi)$

T8: $Q_{LL} = (\bar{L}\gamma^\mu L)(\bar{L}\gamma^\mu L)$





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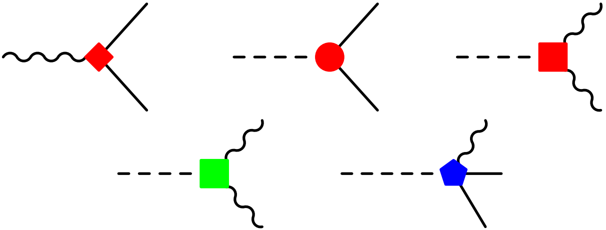
SM–like

Non-SM-like kinematic structure

$$(H^\dagger H)\Box(H^\dagger H) \sim -v^2(\partial^\mu h)(\partial_\mu h) + \cdots$$



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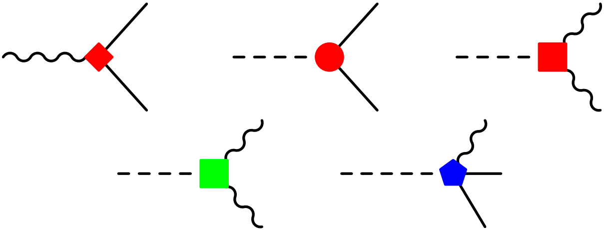
SM–like

Non-SM-like kinematic structure

$(H^\dagger H)V^{\mu\nu}V_{\mu\nu} \sim 2vh(\partial^\mu V^\nu)(\partial_\mu V_\nu)$



SMEFT: Effective Vertices

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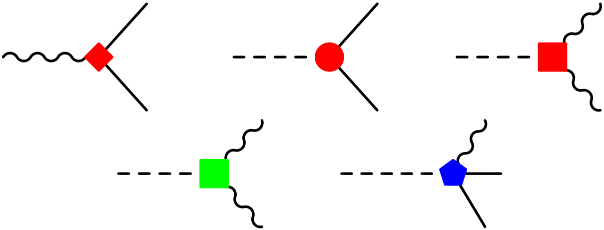
T8: $Q_{LL} = (\bar{L}\gamma^\mu L)(\bar{L}\gamma^\mu L)$

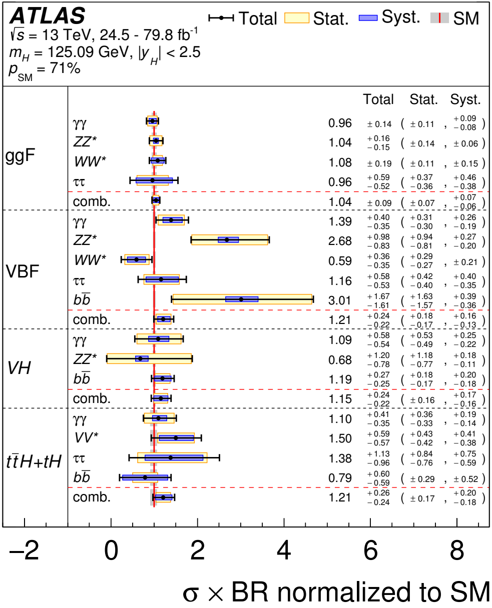
SM–like

Non-SM-like kinematic structure

$$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\Psi}\gamma^\mu\Psi) \sim v^2\bar{\Psi}V^\mu\gamma_\mu\Psi + 2vh\bar{\Psi}V^\mu\gamma_\mu\Psi$$



The Higgs Sector: Measurements

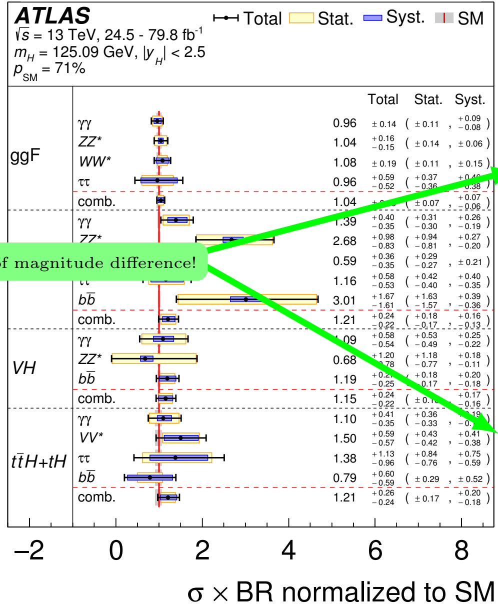


10^{-1} pb ±15%
10^{0} pb ±15%
10^{1} pb ±18%
10^{0} pb ±58%

10^{-2} pb ±29%
10^{-1} pb ±34%
10^{0} pb ±60%
10^{-1} pb ±48%
10^{0} pb ±55%

10^{-2} pb ±51%
10^{-1} pb ±147%
10^{0} pb ±22%

10^{-3} pb ±35%
10^{-1} pb ±38%
10^{-2} pb ±76%
10^{-1} pb ±75%



2 orders of magnitude difference!

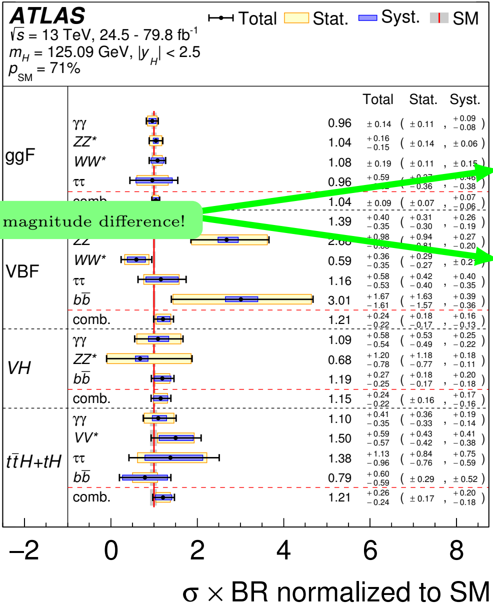
10^{-1} pb ± 15%
10^{0} pb ± 15%
10^{1} pb ± 18%
10^{0} pb ± 58%

10^{-2} pb ± 29%
10^{-1} pb ± 34%
10^{0} pb ± 60%
10^{-1} pb ± 48%
10^{0} pb ± 55%

10^{-2} pb ± 51%
10^{-1} pb ± 147%
10^{0} pb ± 22%

10^{-3} pb ± 35%
10^{-1} pb ± 38%
10^{-2} pb ± 76%
10^{-1} pb ± 75%

The Higgs Sector: Measurements



1 order of magnitude difference!

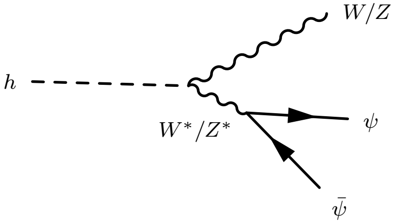
10^{-1} pb ± 15%
10^{0} pb ± 15%
10^{1} pb ± 18%
10^{0} pb ± 58%

10^{-2} pb ± 29%
10^{-1} pb ± 34%
10^{0} pb ± 60%
10^{-1} pb ± 48%
10^{0} pb ± 55%

10^{-2} pb ± 51%
10^{-1} pb ± 147%
10^{0} pb ± 22%

10^{-3} pb ± 35%
10^{-1} pb ± 38%
10^{-2} pb ± 76%
10^{-1} pb ± 75%

The "correct" Higgs width in the SMEFT



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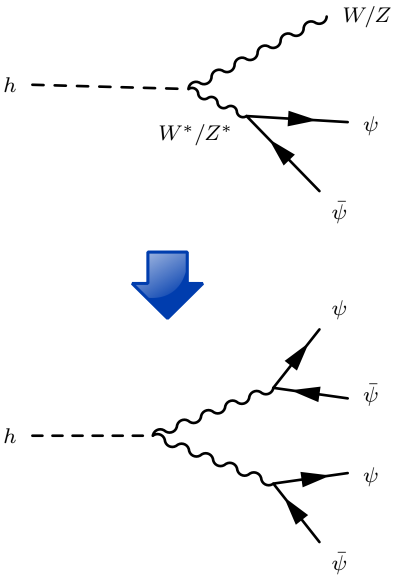


$H \to ZZ^*$

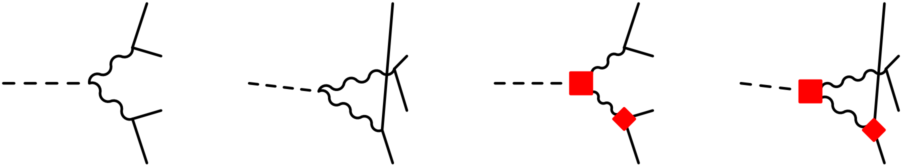
The narrow width approximation has been used extensively for $H \to VV$ calculations.

MadGraph:

`generate h > Z e+ e-`	$\to$	$\Gamma = 2.9 \cdot 10^{-6}$	GeV
`generate Z > e+ e-`	$\to$	$\Gamma = 8.4 \cdot 10^{-2}$	GeV
`generate Z > all all`	$\to$	$\Gamma = 2.4$	GeV
$\Gamma(h \to Ze^+e^-) \times \mathrm{BR}(Z \to e^+e^-)$	$\Rightarrow$	$\Gamma = 9.8 \cdot 10^{-8}$	GeV
`generate h > e+ e- e+ e-`	$\to$	$\Gamma = 1.3 \cdot 10^{-7}$	GeV

This corresponds to a correction of $\sim 30\%$. For $ee\mu\mu$ the correction is about 15%

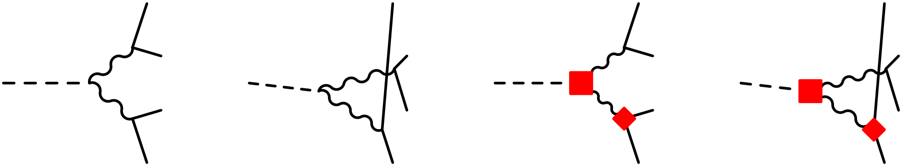
$H \to ZZ \to 4l$, beyond the narrow width approx



$$\Gamma = \frac{4g_2^8 v^2}{c^8}(1 + 2\Delta^{(1)}_{HZZ} + \delta g_Z)\left[\left(1 - \frac{\delta_{ab}}{2}\right) N_c^2 \left[(g_a^L)^2 (g_b^L)^2 + (g_a^R)^2 (g_b^R)^2 + a \leftrightarrow b\right] \mathcal{P}_Z \right.$$
$$\left. + \frac{\delta_{abcd}}{4} N_c [(g_Z^L)^4 + (g_Z^R)^4] \mathcal{F}_Z \right]$$

Narrow width and full calculation agree to within 30% for $e^+e^-e^+e^-$

$H \to 2e2\nu$, beyond the narrow width approx



$$\Gamma = \frac{4g_2^8 v^2}{c^8}(1 + 2\Delta^{(1)}_{HZZ} + \delta g_Z)N_c^2 \left[(g_a^L)^2(g_b^L)^2 + (g_a^R)^2(g_b^R)^2 + (g_a^L)^2(g_b^R)^2 + (g_a^R)^2(g_b^L)^2\right]\mathcal{P}_Z$$

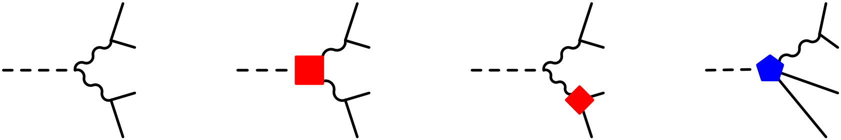
$$+ g_2^8 v^2 N_c^2(1 + 2\Delta^{(1)}_{HWW} + \delta g_W)\mathcal{P}_W$$

$$+ \frac{2g_2^8(g_a^L)(g_b^L)v^2}{c^4}N_c(1 + \Delta^{(1)}_{HZZ} + \Delta^{(1)}_{HWW} + \delta g_Z + \delta g_W)\mathcal{F}_{WZ}$$

Narrow width and full calculation agree to within 1% for $e^+e^-\nu\nu$

but this is because the contribution of ZZ is small compared to WW
if interference is enhanced in SMEFT could cause narrow width to be wrong(er)

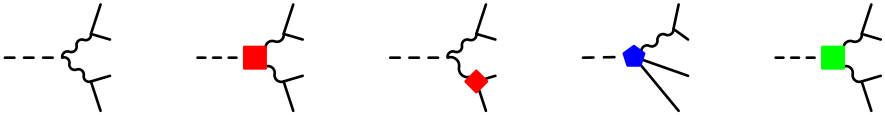
Contact $hV\bar{\psi}\psi$ contributions:



$$\Gamma_{h\to WW\to\bar{\psi}\psi\bar{\psi}\psi} = g_2^8 v^2 N_c^2 (1 + 2\Delta^{(1)}_{HWW} + \delta g_W)\mathcal{P}_W$$

$$+2\sqrt{2} g^5 v N_c^2 2 \underbrace{\left[c_{Wb}(p_{34} - M_W^2) + c_{Wa}(p_{12} - M_W^2)\right]\mathcal{P}_W}_{\text{Non}-\text{SM}-\text{like PS integral}}$$

New Kinematic Form, $HV^{\mu\nu}V_{\mu\nu}$



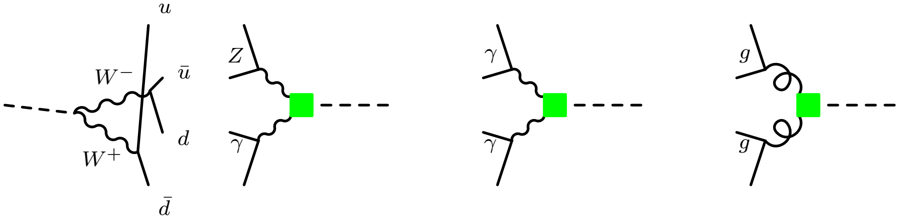
$$\Gamma_{h\to WW\to\bar\psi\psi\bar\psi\psi} = g_2^8 v^2 N_c^2 (1 + 2\Delta^{(1)}_{HWW})\mathcal{P}_W$$

$$+2\sqrt{2} g_2^5 v N_c^2 \times 2\left[c_{Wb}(p_{34} - M_W^2) + c_{Wa}(p_{12} - M_W^2)\right]\mathcal{P}_W$$

$$+\frac{g_2^6}{2} N_c^2 \underbrace{\Delta^{(2)}_{HWW} f(p_{ij})\mathcal{P}_W}_{\text{New kinematics!!}}$$

But wait, there's more! $H\gamma\gamma$, $HZ\gamma$, and Hgg:

Tree–level $\mathcal{O}(1/\Lambda^2)$ $H\gamma\gamma$, $HZ\gamma$, and Hgg couplings exist in SMEFT!



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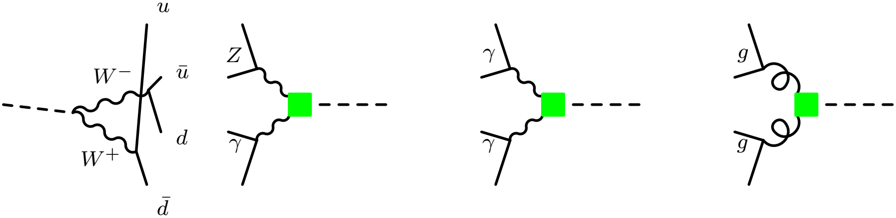
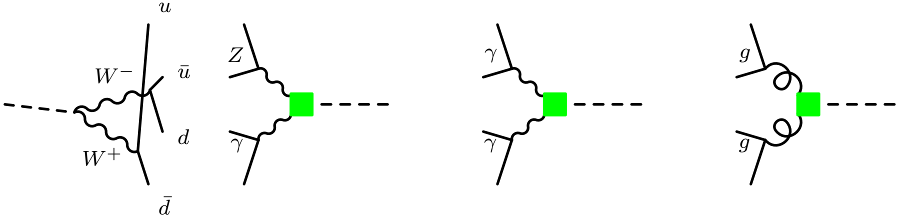


1 − 4% correction | 5 − 9% correction | 10 + % correction

	SM	c_{HB}	c_{HWB}	$c_{Hl}^{(1)}$	c_{He}	$c_{Hq}^{(1)}$	c_{Hu}	c_{Hd}
4ψ	$2.62 \cdot 10^{-4}$	−.185	−.042	−.015	−.012	.023	.036	−.019
NW:	$2.64 \cdot 10^{-4}$	−.189	−.036	−.013	−.012	.022	.035	−.018

$$\frac{\Gamma(H\to 4\psi)}{\Gamma(H\to 4\psi)_{\rm SM}} = 1 - .185 c_{HB} - .042 c_{HWB} + \cdots$$

But wait, there's more! $H\gamma\gamma$, $HZ\gamma$, and Hgg:



$1-4\%$ correction | $5-9\%$ correction | $10+\%$ correction

	SM	c_{HB}	c_{HWB}	$c_{Hl}^{(1)}$	c_{He}	$c_{Hq}^{(1)}$	c_{Hu}	c_{Hd}
4ψ	$2.62 \cdot 10^{-4}$	$-.185$	$-.042$	$-.015$	$-.012$	$.023$	$.036$	$-.019$
NW:	$2.64 \cdot 10^{-4}$	$-.189$	$-.036$	$-.013$	$-.012$	$.022$	$.035$	$-.018$

$1-9\%$ correction | $10-99\%$ correction | $100+\%$ correction

	SM	c_{HW}	c_{HB}	c_{HWB}	c_{HD}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	c_{He}
$ee\nu\nu$	$1.03 \cdot 10^{-5}$	-1.51	$.010$	$-.056$	$-.551$	$-.008$	-3.74	$-.041$
NW:	$1.07 \cdot 10^{-5}$	-1.50	$-.035$	$-.019$	-0.508	$.004$	-3.95	$-.041$

Conclusions

The SMEFT is our best tool for heavy NP beyond the LHC's reach

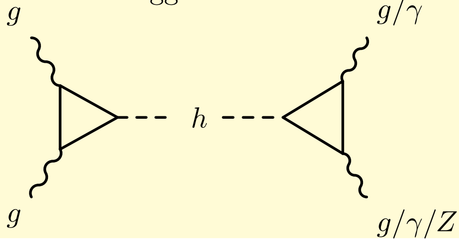
The Higgs production and decay in SMEFT at tree-level "was" done

- Use of the narrow width approximation has been industry standard
- Careful calculation can make $\mathcal{O}(10\% - 100\%)$ differences
- some more tree level may remain... $H \to 2F$✓, $H \to 4F$✓, $H \to 3F$?

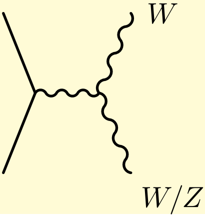
Future measured deviations may be fake if we don't things correctly
Future measured null results may be fake if we don't do things correctly

Global fits of the SMEFT

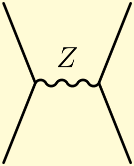
Higgs Sector



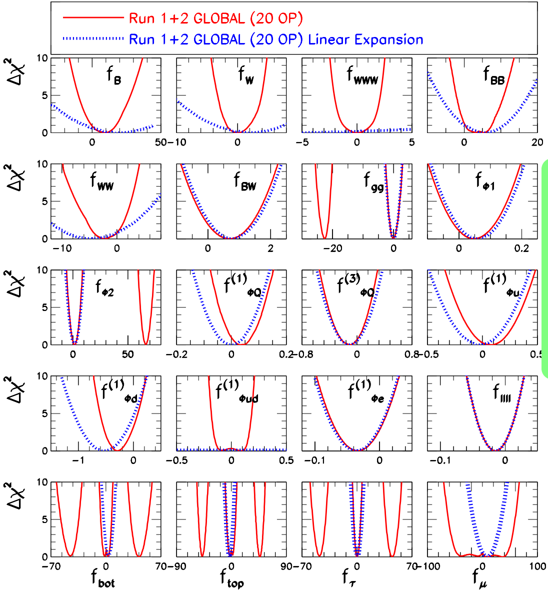
Triple Gauge Sector



Electroweak Precision Data



An example global fit



Almeida et al. 1812.01009

☺ Dbl insertions of c_i in red, single in blue

☺ Blind direction broken by TGC+EWPD

☹ Many cases where constraints lost

☹ Current status:
testing how well we can measure 0

SMEFT

In studying NP at $\Lambda_{\text{NP}} \gg v$, we employ the Standard Model EFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots \qquad \mathcal{L}_d = \sum_i c_i Q_i$$

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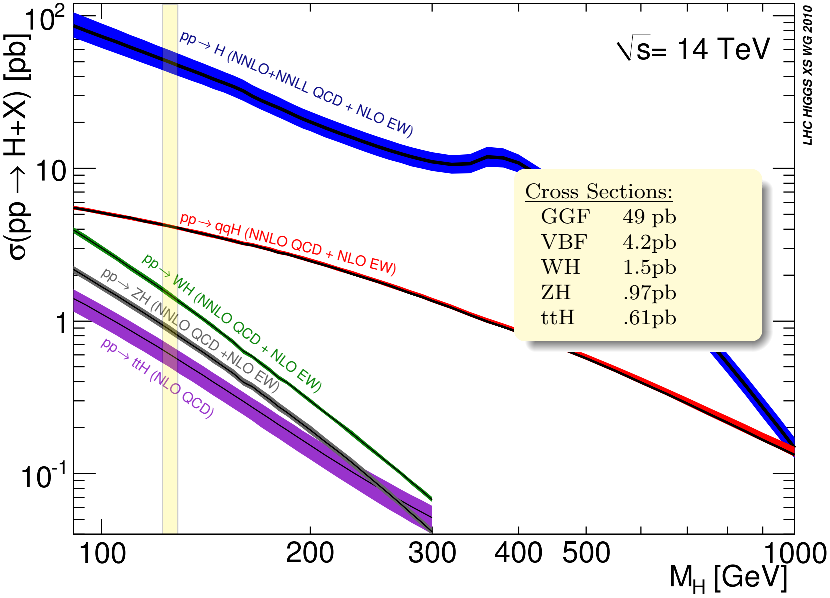
The leading operator:
$\mathcal{L}_5 = c_{\alpha\beta}(\bar{L}^c_\alpha \tilde{H})(\tilde{H}^\dagger L_\beta) \sim v^2 \bar{\nu}_\alpha \nu_\beta$
$\Rightarrow m_\nu \sim v^2/\Lambda$

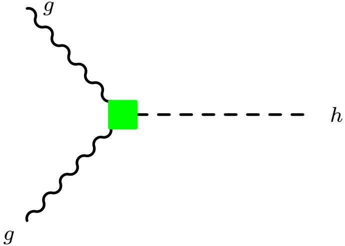
Higgs Production in the SM

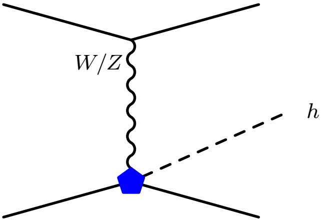


Cross Sections:

GGF	49 pb
VBF	4.2pb
WH	1.5pb
ZH	.97pb
ttH	.61pb

Examples of Higgs Production in the SMEFT





$$Q_{HG} = (H^\dagger H) G^{A,\mu\nu} G^A_{\mu\nu}$$

$$Q^{(1,3)}_{H\Psi} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\Psi}\gamma^\mu \Psi)$$

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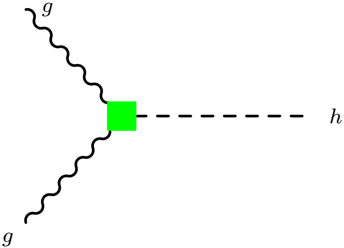

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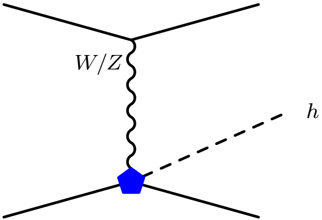

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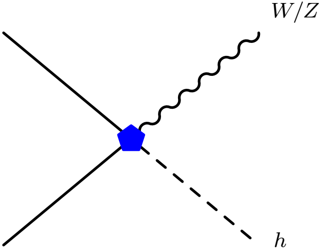

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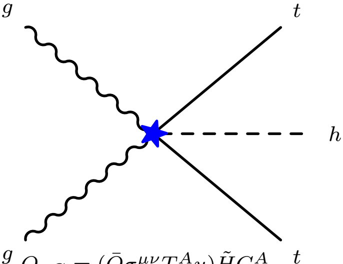
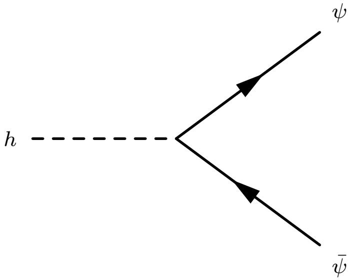
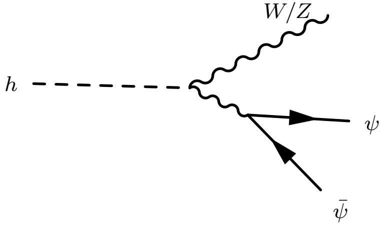


$$Q_{uG} = (\bar{Q}\sigma^{\mu\nu} T^A u)\tilde{H} G^A_{\mu\nu}$$

Higgs Width in the SM





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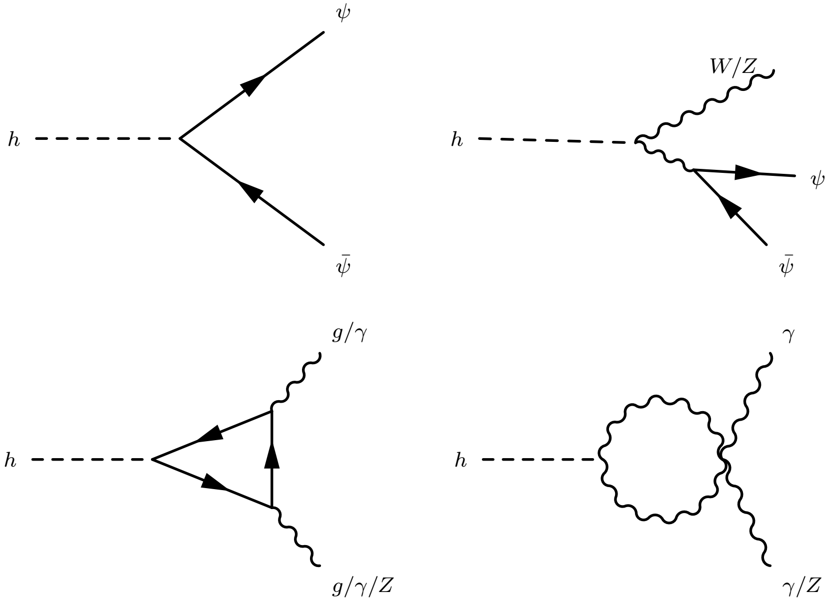
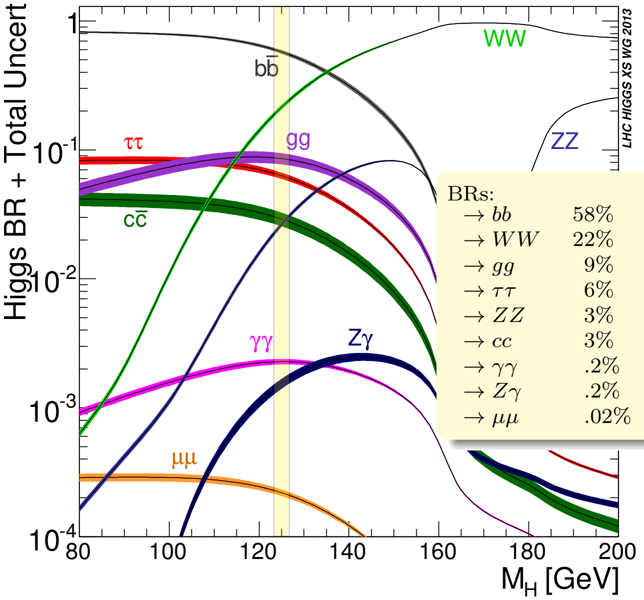
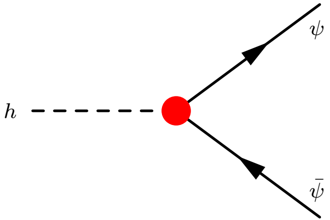




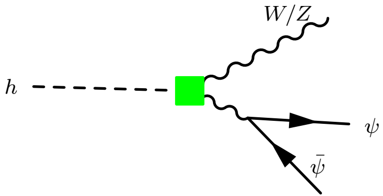
BRs:

$\to bb$	58%
$\to WW$	22%
$\to gg$	9%
$\to \tau\tau$	6%
$\to ZZ$	3%
$\to cc$	3%
$\to \gamma\gamma$	.2%
$\to Z\gamma$	.2%
$\to \mu\mu$	.02%

Examples of Higgs Decay in the SMEFT



$Q_{\psi H} = (H^\dagger H)(\bar{\Psi}_L \psi_R H)$



$Q_{HV} = (H^\dagger H) V^{\mu\nu} V_{\mu\nu}$

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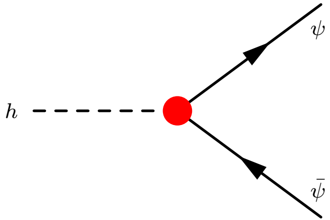

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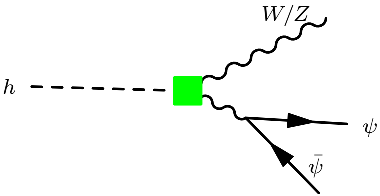

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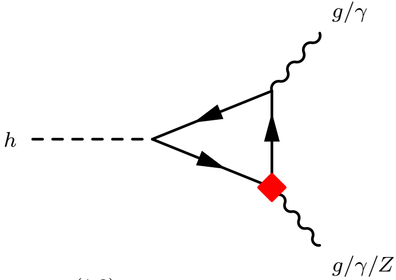

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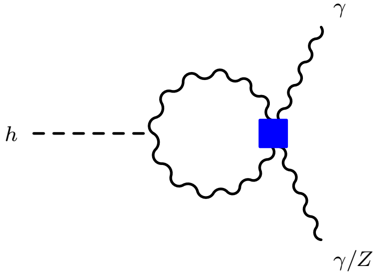

$Q_W = \epsilon^{IJK} W_\mu^{I,\nu} W_\nu^{J,\rho} W_\rho^{K,\mu}$

Ward Identities in YM

In traditional R_ξ gauge, the naive ward identities are not preserved.
One must invoke BRST symmetry to recover them:

$$\int \left(\frac{\delta \Gamma}{\delta A^a_\mu \delta A^b_\nu} \right) \left(\frac{\delta \Gamma}{\delta K^\mu_a \delta c^d} \right) = 0 \Rightarrow k^\mu \langle A^a_\mu(k) A^b_\nu(-k) \rangle = 0$$

(Peter Van Nieuwenhuizen, AQFT notes)

Which coefficients can we constrain?

- The latest ATLAS combination of STXS measurements with 80 fb^{-1} not enough to constrain all parameters appearing in the parametrisation.
  - Likelihood minimisation not stable due to large correlation between parameters and blind directions
- Fisher information matrix obtained from the inverse of the covariance matrix of the measurement and propagating the EFT parametrisation of each bin and each decay.

$$C^{-1}_{EFT} = P^T \, C^{-1}_{STXS} \, P, \qquad P = \begin{pmatrix} A_1^{\sigma_1} & A_2^{\sigma_1} & A_3^{\sigma_1} & \dots \\ A_1^{\sigma_2} & A_2^{\sigma_2} & A_3^{\sigma_2} & \dots \\ A_1^{\sigma_3} & A_2^{\sigma_3} & A_3^{\sigma_3} & \dots \\ \vdots & \vdots & \vdots & \end{pmatrix},$$

nxn parametrisation matrix (n=15x5)

- Find eigenvectors (sensitive directions) and eigenvalues (large values correspond to high experimental sensitivity).
- Assuming Gaussian behaviour.
- Three different scenarios:
  - Combined measurement, production only (BR= BR_{SM}) ATLAS-CONF-2018-028
  - H->$\gamma\gamma$ considering both production and decay variations.
  - The combined measurement of all channels 1909.02845

Full eigenvectors tables

Combined measurement:

Eigenvalue	Eigenvector
241550	$0.24 \cdot c_{HG} - 0.23 \cdot c_{HW} - 0.83 \cdot c_{HB} + 0.45 \cdot c_{HWB}$
147981	$-0.97 \cdot c_{HG} - 0.21 \cdot c_{HB} + 0.11 \cdot c_{HWB}$
6090	$-0.12 \cdot c_{HW} - 0.98 \cdot c_{Hq3} - 0.11 \cdot c_{Hu}$
124	$-0.20 \cdot c_{HWB} + 0.30 \cdot c_{Hq1} + 0.14 \cdot c_{Hq3} - 0.85 \cdot c_{Hu} + 0.29 \cdot c_{Hd}$
34	$-0.21 \cdot c_{Hbox} - 0.56 \cdot$ [illegible] $\cdot c_{Hq1} + 0.17 \cdot c_{Hu} - 0.37 \cdot c_{uu1} - 0.1$ [illegible]
22	$-0.11 \cdot c_G + 0.60 \cdot c_H$ [illegible] $c_{qq11} - 0.31 \cdot c_{qq31} - 0.13 \cdot c_{uu1}$
16	$-0.48 \cdot c_{HW} + 0.1$ [illegible] $\cdot c_{He} + 0.31 \cdot c_{ll1} + 0.14 \cdot \lvert c_{dH} \rvert + 0$ [illegible]
5	$0.13 \cdot c_{Hbox} - 0.14 \cdot c_{HDD} - 0.33 \cdot c_{HB} - 0.58 \cdot c_{HWB} - 0.42 \cdot c_{Hl1} - 0.34 \cdot c_{Hl3} + 0.33 \cdot c_{H}$[illegible] $- 0.24 \cdot c_{Hq1} + 0.11 \cdot c_{ll1} - 0.17 \cdot \lvert c_{eH} \rvert$
0.9	$0.12 \cdot c_{HWB} + 0.26 \cdot c_{Hq1} - 0.21 \cdot c_{ll1} - 0.79 \cdot \lvert c_{eH} \rvert + 0.47 \cdot \lvert c_{dH} \rvert$
0.4	$0.18 \cdot c_{Hbox} - 0.11 \cdot c_{HW} + 0.12 \cdot c_{HWB} - 0.33 \cdot c_{Hl1} - 0.16 \cdot c_{Hl3} + 0.26 \cdot c_{He} + 0.67 \cdot c_{Hq1} + 0.18 \cdot c_{Hu} - 0.20 \cdot c_{Hd} - 0.12 \cdot c_{ll1} - 0.43 \cdot \lvert c_{dH} \rvert$
0.2	$-0.34 \cdot c_{Hbox} - 0.23 \cdot c_{Hl1} + 0.22 \cdot c_{Hl3} + 0.15 \cdot c_{He} + 0.32 \cdot c_{Hq1} + 0.11 \cdot c_{Hu} - 0.11 \cdot c_{Hd} + 0.40 \cdot c_{ll1} + 0.37 \cdot \lvert c_{eH} \rvert + 0.57 \cdot \lvert c_{dH} \rvert$

$$\sqrt{\frac{.2}{241550}} \sim \frac{1}{1100} \sim \frac{1}{7 \cdot 16\pi^2} \sim \mathcal{O}\left(\frac{g_1^2}{16\pi^2}\right)$$

19

On Bases

100s of operators in *Leung et al. 1986* $\Rightarrow$ 59 operators in *Grzadkowski et al. 2010*

This was accomplished via field redefinitions or use of EOM (equivalent, *Politzer 1980*)

The Higgs EOM:

$$D^2H - |\mu|^2 H + 2\lambda(H^\dagger H)H + Y_\psi \bar{\psi}\Psi = 0$$

Results in this relation between operators:

$$\frac{1}{2}Q_{H\Box} + 2(D^\mu H)^\dagger(D_\mu H)(H^\dagger H) = \sum_\psi Y_\psi Q_{\psi H} + 2\lambda Q_H - \lambda v^2 (H^\dagger H)^2$$

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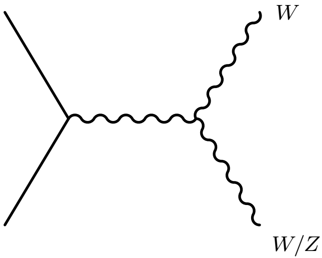
Triple Gauge Couplings (TGCs)



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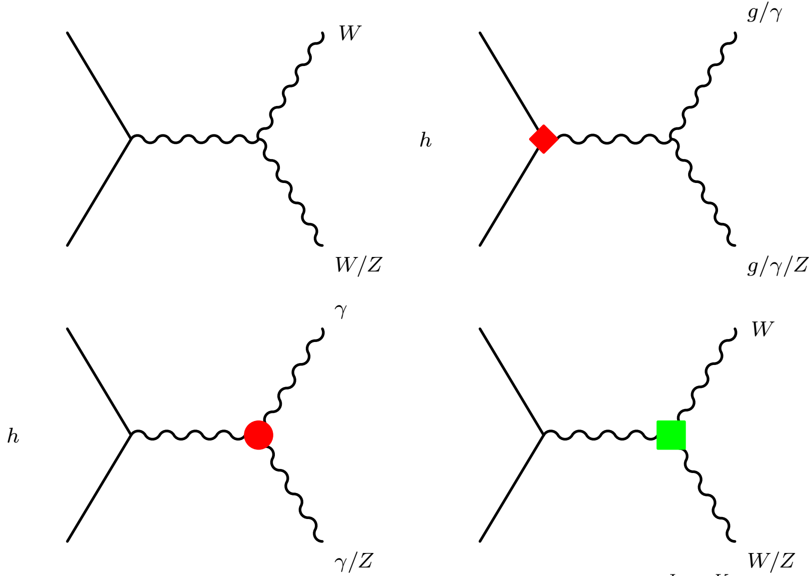


$$Q_W = \epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$

Shifts in the propagator:

The propagator in the unitary gauge is:

$$\frac{-i}{q_{ij}-\hat{M}^2+i\hat{\Gamma}\hat{M}+i\epsilon}\left(g_{\mu\nu}-\frac{q_\mu q_\nu}{\hat{M}^2}(1-\frac{\delta M^2}{\hat{M}^2})\right)[1+\delta D(q_{ij})]$$

With:

$$\delta D(q_{ij})=\frac{1}{q_{ij}-\hat{M}^2+i\hat{\Gamma}\hat{M}}\left[\left(1-\frac{i\hat{\Gamma}}{2\hat{M}}\right)\delta M^2-i\hat{M}\,\delta\Gamma\right]$$

The quantity that will show up in our calculations is:

$$2\mathrm{Re}[\delta D(q_{ij})]=\frac{2(q_{ij}-\hat{M}^2)\delta M^2-\hat{\Gamma}(\hat{\Gamma}\delta M^2+2\hat{M}^2\,\delta\Gamma)}{(q_{ij}-\hat{M}^2)^2+\hat{M}^2\hat{\Gamma}^2}$$

For $q_{ij}\sim\hat{M}^2$ (i.e. a near on-shell region of PS) we expect:

$$2\mathrm{Re}[\delta D(\hat{M}^2)]\sim-\frac{\delta M^2}{\hat{M}^2}-2\frac{\delta\Gamma}{\hat{\Gamma}}$$

We need the shifts in the widths of the W and Z in the SMEFT. In the SM we have:

$$\Gamma(W \to \bar{\psi}\psi) = \frac{3\hat{G}_F \hat{M}_W^3}{2\sqrt{2}\pi}$$

Then the shift in the width due to the SMEFT is given by:

$$\delta\Gamma_W = \Gamma_W^{\rm SM}\left(\frac{4}{3}\delta g_{V/A}^{W,l} + \frac{8}{3}\delta g_{V/A}^{W,q} + \frac{\delta M_W^2}{2\hat{M}_W^2}\right)$$

$Z \to \bar{\psi}\psi$

In the SM we have:

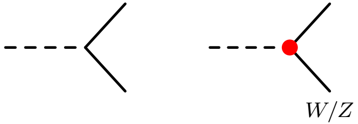
$$\Gamma(Z \to \bar{\psi}\psi) = \frac{\sqrt{2}\bar{G}_F \bar{M}_Z^3 N_C^\psi}{3\pi}\left(|\bar{g}_V^\psi|^2 + |\bar{g}_A^\psi|^2\right)$$

Then the shift in the width due to the SMEFT is:

$$\delta\Gamma(Z \to \bar{\psi}\psi) = \frac{\sqrt{2}\hat{G}_F \hat{M}_Z^3 N_C^\psi}{3\pi}\left(2\bar{g}_V^\psi \delta g_V^\psi + 2\bar{g}_A^\psi \delta g_A^\psi\right)$$

$H \to \bar{\psi}\psi$, $H \to \gamma\gamma$, $H \to gg$

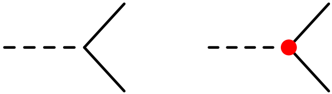
The H decays to two particles are well known:



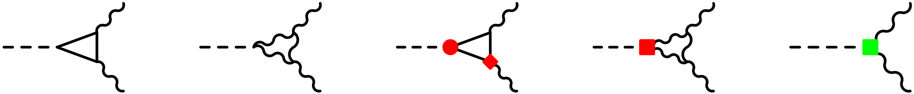
$$\Gamma_{\psi\psi} = \frac{N_C \bar{M}_h}{8\pi} \left[|g_{h\psi}^{\rm SM}|^2 + 2 g_{h\psi} {\rm Re}(\delta g_{h\psi}) \right]$$

$H \to \bar{\psi}\psi$, $H \to \gamma\gamma$, $H \to gg$

The H decays to two particles are well known:



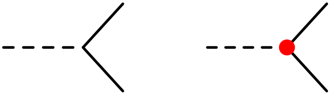
$$\Gamma_{\psi\psi} = \frac{N_C \bar{M}_h}{8\pi}\left[|g^{\rm SM}_{h\psi}|^2 + 2g_{h\psi}{\rm Re}(\delta g_{h\psi})\right]$$



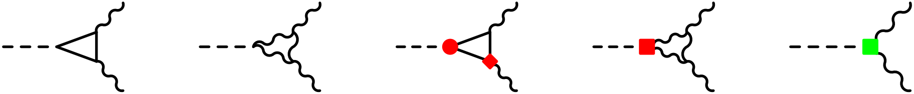
$$\Gamma_{\gamma\gamma} = \frac{\bar{\alpha}^2\bar{G}_F}{128\sqrt{2}\pi^3}\left|N_C^\psi Q_\psi^2 F_\psi + F_W\right|^2\left(1 + 2\frac{\delta\alpha}{\hat{\alpha}} + \delta D^W\right) - \frac{\hat{\alpha}^2\hat{M}_H^3}{4\pi}{\rm Re}\left[N_C^\psi Q_\psi^2 F_\psi + F_W\right]c_{\gamma\gamma}$$

$H \to \bar{\psi}\psi$, $H \to \gamma\gamma$, $H \to gg$

The H decays to two particles are well known:



$$\Gamma_{\psi\psi} = \frac{N_C \bar{M}_h}{8\pi}\left[|g_{h\psi}^{\rm SM}|^2 + 2g_{h\psi}{\rm Re}(\delta g_{h\psi})\right]$$



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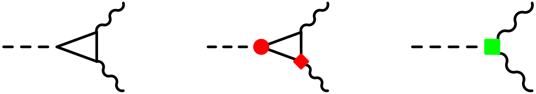

$$\Gamma_{gg} = \frac{\bar{\alpha}_s^2\bar{G}_F}{64\sqrt{2}\pi^3}\bar{M}_H^3\left|F_\psi\right|^2\left(1 + 2\frac{\delta\alpha_s}{\hat{\alpha}_s} + \frac{\delta G_F}{G_F}\right) - \frac{\hat{\alpha}_s}{4\pi^4}M_H^3{\rm Re}\left[F_\psi\right]c_{HG}$$

PS integrations:

The PS integrations were cross checked ideally up to 3 ways:

PS integral	MG5	Rambo	Vegas
$(WW)^*(WW)$	✓	✓	✓
$(WW)^*(WW\|_{\text{mtm}}$	✓	✓	✓
$(ZZ)^*(ZZ)$	✓	✓	✓
$(ZZ)^*(ZZ\|_{\text{mtm}}$	✓	✓	✓
$(ZZ)^*(WW)$	✓	✓	✓
$(ZZ)^*(WW\|_{\text{mtm}}$	✓	✓	✓
$(VV)^*(\text{contact})$	✓	✓	✓
$(VV)^*(Z\gamma)$	✗	✓	✓
$(VV)^*(\gamma\gamma)$	✗	✗	✓

Returning to shifts in the propagator

The propagator in the unitary gauge is:

$$\frac{-i}{q_{ij}-\hat{M}^2+i\hat{\Gamma}\hat{M}+i\epsilon}\left(g_{\mu\nu}-\frac{q_\mu q_\nu}{\hat{M}^2}(1-\frac{\delta M^2}{\hat{M}^2})\right)[1+\delta D(q_{ij})]$$

$$2\text{Re}[\delta D(q_{ij})]=\frac{2(q_{ij}-\hat{M}^2)\delta M^2-\hat{\Gamma}(\hat{\Gamma}\delta M^2+2\hat{M}^2\delta\Gamma)}{(q_{ij}-\hat{M}^2)^2+\hat{M}^2\hat{\Gamma}^2}\rightarrow 2\text{Re}[\delta D(\hat{M}^2)]\sim-\frac{\delta M^2}{\hat{M}^2}-2\frac{\delta\Gamma}{\hat{\Gamma}}$$

Taking the M_W–scheme, ratios of x_i for $e^+e^-e^+e^-$ comparison part 5:

$x_{H\Box}^{\delta\text{prop}}/x_{H\Box}^{\text{no}\delta}$	=	1	$x_{He}^{\delta\text{prop}}/x_{He}^{\text{no}\delta}$	=	0.97
$x_{HD}^{\delta\text{prop}}/x_{HD}^{\text{no}\delta}$	=	1.08	$x_{Hl(1)}^{\delta\text{prop}}/x_{Hl(1)}^{\text{no}\delta}$	=	1.01
$x_{ll}^{\delta\text{prop}}/x_{ll}^{\text{no}\delta}$	=	0.90	$x_{Hl(3)}^{\delta\text{prop}}/x_{Hl(3)}^{\text{no}\delta}$	=	0.89
$x_{HB}^{\delta\text{prop}}/x_{HB}^{\text{no}\delta}$	=	1	$x_{Hq(1,3,L,R)}^{\delta\text{prop}}/x_{Hq(1,3,L,R)}^{\text{no}\delta}$	=	∞
$x_{HW}^{\delta\text{prop}}/x_{HW}^{\text{no}\delta}$	=	1			
$x_{HWB}^{\delta\text{prop}}/x_{HWB}^{\text{no}\delta}$	=	1.00			

Returning to shifts in the propagator

The propagator in the unitary gauge is:

$$\frac{-i}{q_{ij} - \hat{M}^2 + i\hat{\Gamma}\hat{M} + i\epsilon}\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{\hat{M}^2}(1 - \frac{\delta M^2}{\hat{M}^2})\right)[1 + \delta D(q_{ij})]$$

$$2\mathrm{Re}[\delta D(q_{ij})] = \frac{2(q_{ij} - \hat{M}^2)\delta M^2 - \hat{\Gamma}(\hat{\Gamma}\delta M^2 + 2\hat{M}^2\delta\Gamma)}{(q_{ij} - \hat{M}^2)^2 + \hat{M}^2\hat{\Gamma}^2} \to 2\mathrm{Re}[\delta D(\hat{M}^2)] \sim -\frac{\delta M^2}{\hat{M}^2} - 2\frac{\delta\Gamma}{\hat{\Gamma}}$$

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$x_{HB}^{\delta\mathrm{prop}}/x_{HB}^{\mathrm{no}\delta}$	=	1	$x_{Hq(1,3,L,R)}^{\delta\mathrm{prop}}/x_{Hq(1,3,L,R)}^{\mathrm{no}\delta}$	=	∞
$x_{HW}^{\delta\mathrm{prop}}/x_{HW}^{\mathrm{no}\delta}$	=	1			
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Returning to shifts in the propagator

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$$\frac{-i}{q_{ij} - \hat{M}^2 + i\hat{\Gamma}\hat{M} + i\epsilon}\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{\hat{M}^2}(1 - \frac{\delta M^2}{\hat{M}^2})\right)[1 + \delta D(q_{ij})]$$

$$2\mathrm{Re}[\delta D(q_{ij})] = \frac{2(q_{ij} - \hat{M}^2)\delta M^2 - \hat{\Gamma}(\hat{\Gamma}\delta M^2 + 2\hat{M}^2\delta\Gamma)}{(q_{ij} - \hat{M}^2)^2 + \hat{M}^2\hat{\Gamma}^2} \to 2\mathrm{Re}[\delta D(\hat{M}^2)] \sim -\frac{\delta M^2}{\hat{M}^2} - 2\frac{\delta\Gamma}{\hat{\Gamma}}$$

Taking the M_W–scheme, ratios of x_i for $e^+e^-e^+e^-$ comparison part 5:

$x^{\delta\mathrm{prop}}_{H\Box}/x^{\mathrm{no}\delta}_{H\Box}$	=	1	$x^{\delta\mathrm{prop}}_{He}/x^{\mathrm{no}\delta}_{He}$	=	0.97
$x^{\delta\mathrm{prop}}_{HD}/x^{\mathrm{no}\delta}_{HD}$	=	1.08	$x^{\delta\mathrm{prop}}_{Hl(1)}/x^{\mathrm{no}\delta}_{Hl(1)}$	=	1.01
$x^{\delta\mathrm{prop}}_{ll}/x^{\mathrm{no}\delta}_{ll}$	=	0.90	$x^{\delta\mathrm{prop}}_{Hl(3)}/x^{\mathrm{no}\delta}_{Hl(3)}$	=	0.89
$x^{\delta\mathrm{prop}}_{HB}/x^{\mathrm{no}\delta}_{HB}$	=	1	$x^{\delta\mathrm{prop}}_{Hq(1,3,L,R)}/x^{\mathrm{no}\delta}_{Hq(1,3,L,R)}$	=	∞
$x^{\delta\mathrm{prop}}_{HW}/x^{\mathrm{no}\delta}_{HW}$	=	1			
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Returning to shifts in the propagator

The propagator in the unitary gauge is:

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$$2\mathrm{Re}[\delta D(q_{ij})] = \frac{2(q_{ij} - \hat{M}^2)\delta M^2 - \hat{\Gamma}(\hat{\Gamma}\delta M^2 + 2\hat{M}^2\delta\Gamma)}{(q_{ij} - \hat{M}^2)^2 + \hat{M}^2\hat{\Gamma}^2} \to 2\mathrm{Re}[\delta D(\hat{M}^2)] \sim -\frac{\delta M^2}{\hat{M}^2} - 2\frac{\delta\Gamma}{\hat{\Gamma}}$$

Compare the above Narrow Width prediction of the phase space population to the full calculation:

$$\delta\Gamma(\delta M_W, \delta\Gamma_W) = -6.9\frac{\delta M_W^2}{\hat{M}_W^2} - .95\frac{\delta\Gamma_W}{\hat{\Gamma}_W}$$

Returning to shifts in the propagator

The propagator in the unitary gauge is:

$$\frac{-i}{q_{ij} - \hat{M}^2 + i\hat{\Gamma}\hat{M} + i\epsilon}\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{\hat{M}^2}(1 - \frac{\delta M^2}{\hat{M}^2})\right)[1 + \delta D(q_{ij})]$$

$$2\mathrm{Re}[\delta D(q_{ij})] = \frac{2(q_{ij} - \hat{M}^2)\delta M^2 - \hat{\Gamma}(\hat{\Gamma}\delta M^2 + 2\hat{M}^2\delta\Gamma)}{(q_{ij} - \hat{M}^2)^2 + \hat{M}^2\hat{\Gamma}^2} \to 2\mathrm{Re}[\delta D(\hat{M}^2)] \sim -\frac{\delta M^2}{\hat{M}^2} - 2\frac{\delta\Gamma}{\hat{\Gamma}}$$

Compare the above Narrow Width prediction of the phase space population to the full calculation:

$$\delta\Gamma(\delta M_W, \delta\Gamma_W) = 1 \times (\mathrm{SM-like}) - .38\frac{c^{(3)}_{H\psi}}{\hat{g}_2^2} - .95\frac{\delta\Gamma_W}{\hat{\Gamma}_W} - 6.9\frac{\delta M_W^2}{\hat{M}_W^2} - .64\frac{c_{HW}}{\hat{g}_2^2}$$

Path Integrals 101: Free field theory

From Sterman 1993, the generating functional is:

$$\begin{aligned} Z_{\mathcal{L}_0} &= \int [\mathcal{D}\phi] \exp\left[i \int d^4x \left(-\frac{1}{2}\phi(\Box + m^2)\phi - J\phi \right) \right] \\ &= \exp\left[-\frac{i}{2} \int d^4x d^4z J(x) \Delta_F(x-z) J(z) \right] Z_{\mathcal{L}_0}[0] \end{aligned}$$

The greens functions are then given by:

$$G(x_1, ..., x_n)_{\text{free}} = \langle 0 | T[\Pi_i \phi(x_i)] | 0 \rangle_{\text{free}} = \prod_i \left[i \frac{\delta}{\delta J(x_i)} \right] Z_{\mathcal{L}_0}[J] \Big|_{J=0}$$

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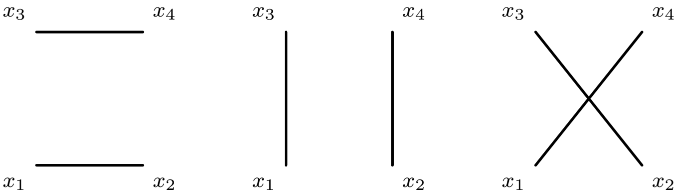
For example $G_4 = i^4 \delta_{J_1} \delta_{J_2} \delta_{J_3} \delta_{J_4} Z_{\mathcal{L}_0}$ gives:



Path Integrals 102: Interacting fields

For some potential $V(\phi)$ we can define the generating functional:

$$Z_{\mathcal{L}}[J] = W[J]/W[0]; \qquad W[J] = \int [\mathcal{D}\phi] \exp\left(i \int d^4x \left[\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m^2 \phi^2 - V(\phi) - J\phi \right] \right) .$$

Then we can define perturbation theory as:

$$\begin{aligned} Z_{\mathcal{L}}[J] &= \int [\mathcal{D}\phi] \exp\left(i \int d^4x \left[\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m^2 \phi^2 - V(\phi) - J\phi \right] \right) / W[0] \\ &= \exp\left[-i \int d^4x_1 V\left(i \frac{\delta}{\delta J(x_1)} \right) \right] \exp\left[-\frac{i}{2} \int d^4x_2 d^4x_3 J(x_2) \Delta_F(x_2 - x_3) J(x_3) \right] Z_{\mathcal{L}_0}[0]/W[0] \end{aligned}$$

The Greens functions are then:

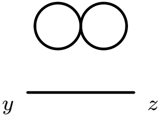
$$\begin{aligned} \langle 0 | T[\Pi_i \phi(x_i) | 0 \rangle_{\text{int}} &= \left[\prod_i i \frac{\delta}{\delta J(x_i)} \right] Z_{\mathcal{L}}[J] \\ &= \left[\prod_i i \frac{\delta}{\delta J(x_i)} \right] \times \\ & \exp\left[-i \int d^4x_1 V\left(i \frac{\delta}{\delta J(x_1)} \right) - \frac{i}{2} \int d^4x_2 d^4x_3 J(x_2) \Delta_F(x_2 - x_3) J(x_3) \right] \times \\ & Z_{\mathcal{L}_0}[0]/W[0] \Big|_{J=0} \end{aligned}$$

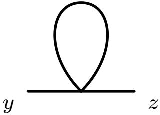
Path Integrals 102: Interacting fields

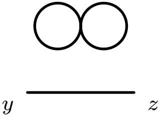
The Greens functions are then:

$$\langle 0|\, T[\Pi_i \phi(x_i)\, |0\rangle_{\text{int}} = \left[\prod_i i\frac{\delta}{\delta J(x_i)}\right] \times$$
$$\exp\left[-i\int d^4x_1 V\left(i\frac{\delta}{\delta J(x_1)}\right) - \frac{i}{2}\int d^4x_2 d^4x_3 J(x_2)\Delta_F(x_2-x_3)J(x_3)\right] \times$$
$$Z_{\mathcal{L}_0}[0]/W[0]\Big|_{J=0}$$

Diagrammatically the 2 point function at NLO is then:

$G_2 = -\frac{1}{8}$


$-\frac{1}{2}$


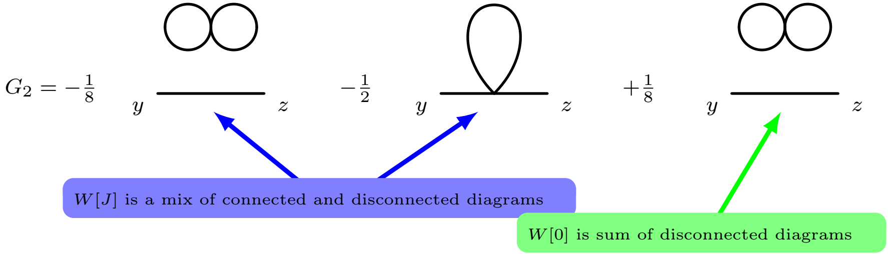
$+\frac{1}{8}$


Path Integrals 102: Interacting fields

The Greens functions are then:

$$\langle 0|\, T[\Pi_i \phi(x_i)\, |0\rangle_{\text{int}} = \left[\prod_i i\frac{\delta}{\delta J(x_i)}\right] \times$$
$$\exp\left[-i\int d^4x_1 V\left(i\frac{\delta}{\delta J(x_1)}\right) - \frac{i}{2}\int d^4x_2 d^4x_3 J(x_2)\Delta_F(x_2-x_3)J(x_3)\right] \times$$
$$Z_{\mathcal{L}_0}[0]/W[0]\Big|_{J=0}$$

Diagrammatically the 2 point function at NLO is then:



$Z[J] = W[J]/W[0]$ is the generating functional of connected diagrams

Path Integrals 103: The effective action

The effective action is a Legendre transformation of $Z[J]$, (Abbott 1982):

$$\Gamma[\bar{Q}] = Z[J] - J \cdot \bar{Q} \qquad \bar{Q} \equiv \frac{\delta}{\delta J} Z$$

Taking a couple variations of Γ gives:

$$\frac{\delta \Gamma}{\delta \bar{Q}} = -J \qquad\qquad \frac{\delta^2 \Gamma}{\delta \bar{Q}^2} = -\frac{\delta J}{\delta \bar{Q}} = \left[-\frac{\delta \bar{Q}}{\delta J}\right]^{-1} = \left[-\frac{\delta^2 Z}{\delta J^2}\right]^{-1} = i\Delta^{-1}$$

Path Integrals 103: The effective action

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Δ is the connected propagator!

Path Integrals 103: The effective action

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Δ is the connected propagator!

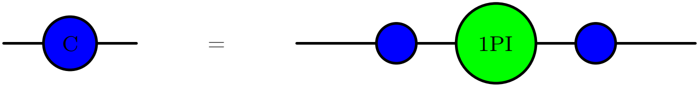
Solving for $\delta/\delta\bar{Q}$:

$$\frac{\delta}{\delta \bar{Q}} = \frac{\delta J}{\delta \bar{Q}} \frac{\delta}{\delta J} = \Delta^{-1} \frac{1}{i} \frac{\delta}{\delta J}$$

Then $\delta/\delta\bar{Q}$ acting on Γ adds an external line and removes a propagator.

It follows then for the two–point function,

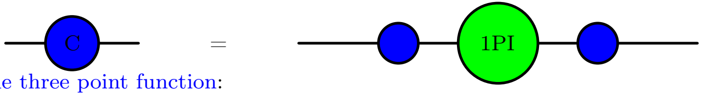
$$\frac{1}{i}\frac{\delta^2\Gamma}{\delta\bar{Q}^2} = \Delta^{-1} \Rightarrow \Delta\frac{1}{i}\frac{\delta^2\Gamma}{\delta\bar{Q}^2}\Delta = \Delta$$



Path Integrals 103: Some examples

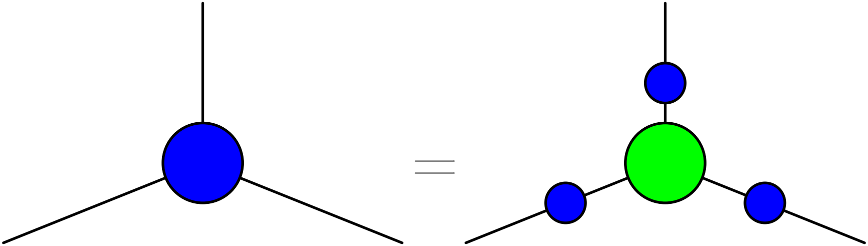
It follows then for the two–point function,

$$\frac{1}{i}\frac{\delta^2\Gamma}{\delta\bar{Q}^2} = \Delta^{-1} \Rightarrow \Delta\frac{1}{i}\frac{\delta^2\Gamma}{\delta\bar{Q}^2}\Delta = \Delta$$

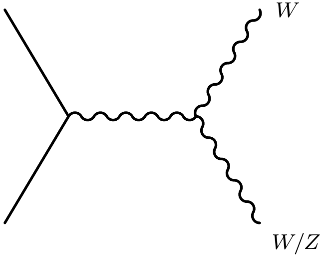


Or, e.g. the three point function:

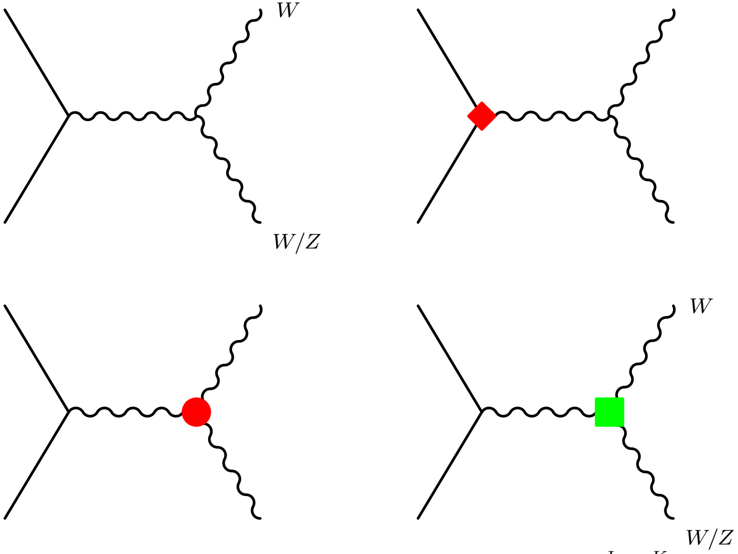
$$\frac{\delta^3\Gamma}{\delta\bar{Q}^3} = \Delta^{-1}\frac{1}{i}\frac{\delta}{\delta J}\left[-\frac{\delta^2 Z}{\delta J^2}\right]^{-1} = \Delta^{-1}\frac{1}{i}\frac{\delta^3 Z/\delta J^3}{(\delta^2 Z/\delta J^2)^2} = i\Delta^{-3}\frac{\delta^3 Z}{\delta J^3}$$



Triple Gauge Couplings (TGCs)



Triple Gauge Couplings (TGCs)

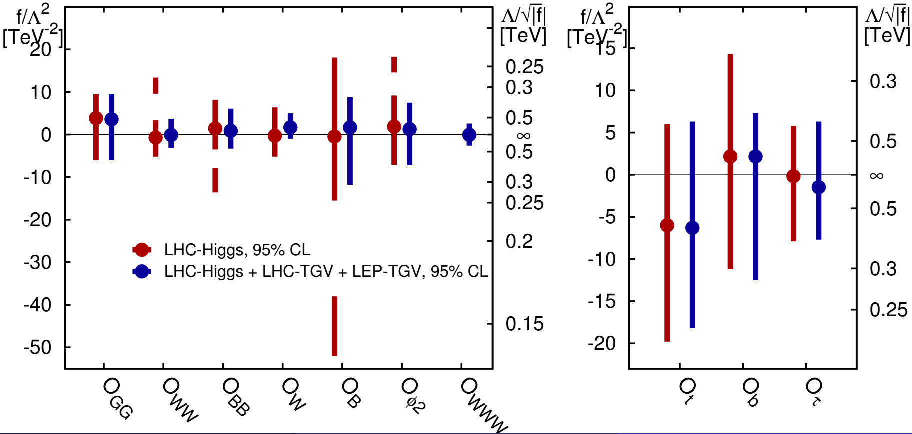


$$Q_W = \epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$

TGC fit (2016)

From Butter, Éboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, Rauch, 1604.03105

$$\mathcal{L}_{\rm SM} + f_g (H^\dagger H) G^{A,\mu\nu} G_{\mu\nu} + f_W (H^\dagger H) W^{A,\mu\nu} W_{A,\mu\nu} + f_B (H^\dagger H) B^{\mu\nu} B_{\mu\nu}$$
$$+ f_W (D^\mu H)^\dagger \tau^A (D_\nu H) W^{A,\mu\nu} + f_B (D^\mu H)^\dagger (D_\mu H) B_{\mu\nu}$$
$$+ f_{\phi,2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) + f_\psi (H^\dagger H) H \bar{\Psi} \psi + f_{WWW} \epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$$

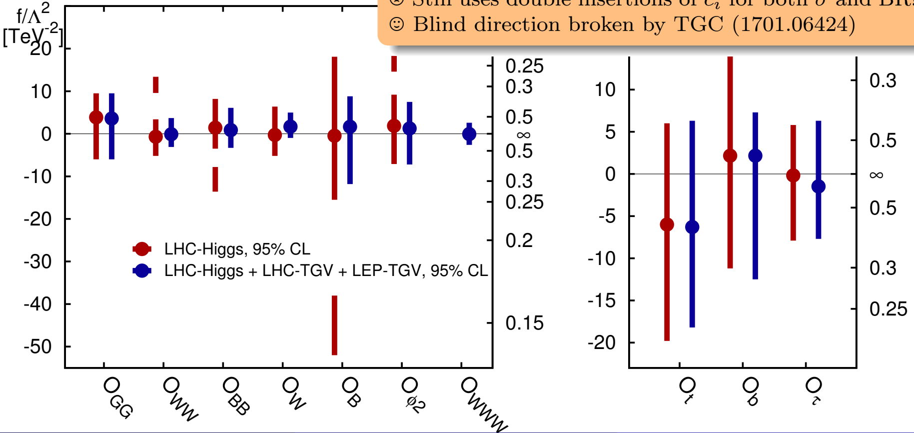


TGC fit (2016)

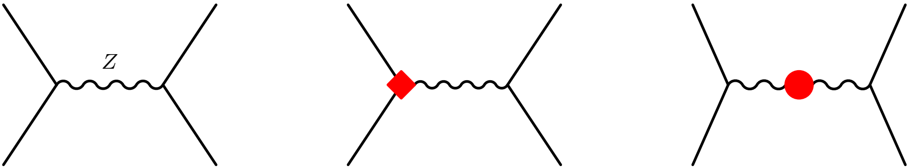
From Butter, Éboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, Rauch, 1604.03105

$$\mathcal{L}_{\rm SM} + f_g (H^\dagger H) G^{A,\mu\nu} G_{\mu\nu} + f_W (H^\dagger H) W^{A,\mu\nu} W_{A,\mu\nu} + f_B (H^\dagger H) B^{\mu\nu} B_{\mu\nu}$$
$$+ f_W (D^\mu H)^\dagger \tau^A (D_\nu H) W^{A,\mu\nu} + f_B (D^\mu H)^\dagger (D_\mu H) B_{\mu\nu}$$
$$+ f_{\phi,2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) + f_\psi (H^\dagger H) H \bar{\Psi} \psi + f_{WWW} \epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$$

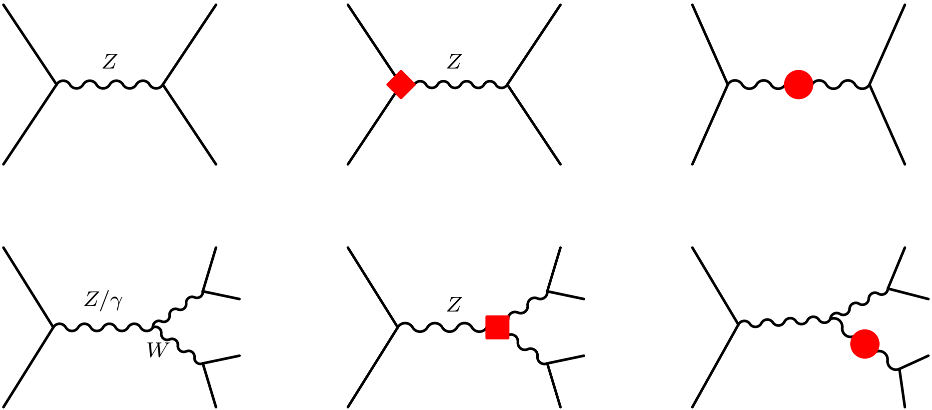
☹ Still uses double insertions of c_i for both σ and BR!
☺ Blind direction broken by TGC (1701.06424)



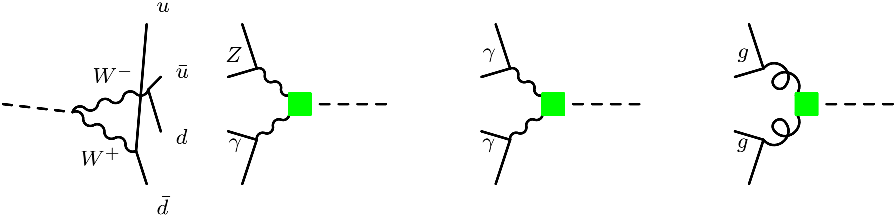
EWPD à la LEP



EWPD à la LEP



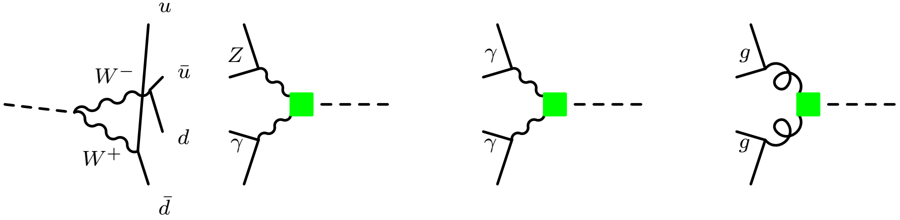
Γ_Z, σ_h^0, $\mathcal{A}_l(\tau^{\rm pol})$, $R_l^0(\rm SLD)$, $A_{\rm FB}^{0,l}$, R_c^0, R_b^0, $\mathcal{A}_c$,
$\mathcal{A}_b$, $A_{\rm FB}^{0,c}$, $A_{\rm FB}^{0,b}$, $A_{\rm FB}^{0,b}(\rm SLD/LEP-I)$, M_W, Γ_W, $\mathrm{BR}(W \to l\nu)$



1 − 9% correction	10 − 99% correction	100 + % correction

$uudd$	c_{Hd}	c_{Hu}	$c^{(1)}_{Hq}$	$c^{(3)}_{Hq}$	c_{HWB}	c_{HB}	c_{HW}	c_{HG}
SM–like:	−.016	.0404	−.0012	4.02	.033	0	0	0
$\text{NW}/\text{NW}_{\text{SM}}$:	−.015	.0397	−.0052	4.02	.050	0	0	0

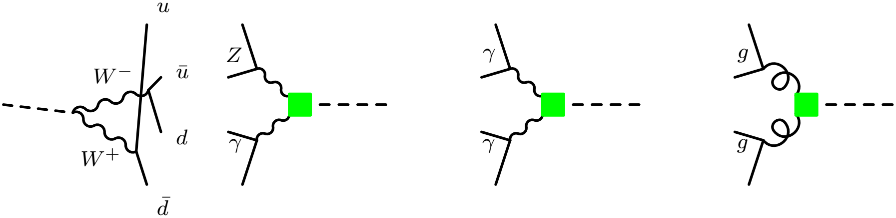
$H\gamma\gamma$, $HZ\gamma$, and Hgg Full:



1 − 9% correction | 10 − 99% correction | 100 + % correction

uudd	c_{Hd}	c_{Hu}	$c_{Hq}^{(1)}$	$c_{Hq}^{(3)}$	c_{HWB}	c_{HB}	c_{HW}	c_{HG}
SM–like:	−.016	.0404	−.0012	4.02	.033	0	0	0
NW/NW$_{SM}$:	−.015	.0397	−.0052	4.02	.050	0	0	0
+Contact:	−.0077	.0198	−.0013	2.24	.033	0	0	0
NW/NW$_{SM}$:	−.0076	.0194	−.0054	2.28	.050	0	0	0

$H\gamma\gamma$, $HZ\gamma$, and Hgg Full:



1 − 9% correction | 10 − 99% correction | 100 + % correction

$uudd$	c_{Hd}	c_{Hu}	$c_{Hq}^{(1)}$	$c_{Hq}^{(3)}$	c_{HWB}	c_{HB}	c_{HW}	c_{HG}
SM–like:	−.016	.0404	−.0012	4.02	.033	0	0	0
NW/NW$_{\mathrm{SM}}$:	−.015	.0397	−.0052	4.02	.050	0	0	0
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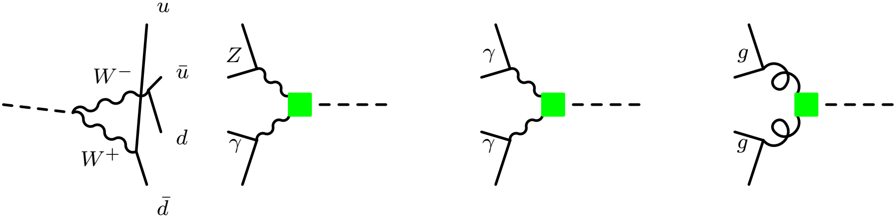
NW/NW$_{\mathrm{SM}}$:	−.0076	.0194	−.0054	2.28	.050	0	0	0
+C+mtm:	−.0077	.0198	−.0013	2.24	.019	−.0075	−1.48	0
NW/NW$_{\mathrm{SM}}$:	−.0076	.0194	−.0054	2.28	.034	−.0087	−1.47	0

$H\gamma\gamma$, $HZ\gamma$, and Hgg Full:



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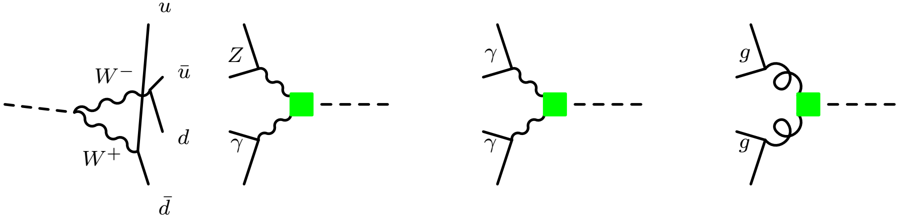
+Contact:	−.0077	.0198	−.0013	2.24	.033	0	0	0
$\mathrm{NW/NW_{SM}}$:	−.0076	.0194	−.0054	2.28	.050	0	0	0
+C+mtm:	−.0077	.0198	−.0013	2.24	.019	−.0075	−1.48	0
$\mathrm{NW/NW_{SM}}$:	−.0076	.0194	−.0054	2.28	.034	−.0087	−1.47	0
+C+m+ γ:	−.0077	.0198	−.0013	2.24	.027	−.068	−1.41	0
$\mathrm{NW/NW_{SM}}$:	−.0076	.0194	−.0054	2.28	.034	−.0087	−1.47	0

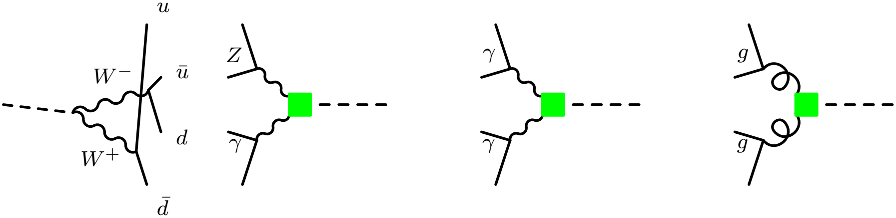
$H\gamma\gamma$, $HZ\gamma$, and Hgg Full:



$1-9\%$ correction	$10-99\%$ correction	$100+\%$ correction

$uudd$	c_{Hd}	c_{Hu}	$c_{Hq}^{(1)}$	$c_{Hq}^{(3)}$	c_{HWB}	c_{HB}	c_{HW}	c_{HG}
SM–like:	$-.016$	.0404	$-.0012$	4.02	.033	0	0	0
NW/NW$_{\rm SM}$:	$-.015$	.0397	$-.0052$	4.02	.050	0	0	0
+Contact:	$-.0077$	.0198	$-.0013$	2.24	.033	0	0	0
NW/NW$_{\rm SM}$:	$-.0076$	.0194	$-.0054$	2.28	.050	0	0	0
+C+mtm:	$-.0077$	.0198	$-.0013$	2.24	.019	$-.0075$	-1.48	0
NW/NW$_{\rm SM}$:	$-.0076$	.0194	$-.0054$	2.28	.034	$-.0087$	-1.47	0
+C+m+ γ:	$-.0077$	.0198	$-.0013$	2.24	.027	$-.068$	-1.41	0
NW/NW$_{\rm SM}$:	$-.0076$	.0194	$-.0054$	2.28	.034	$-.0087$	-1.47	0
+C+m+ γ+g:	$-.0077$	.0198	$-.0013$	2.24	.027	$-.068$	-1.41	$-.98$
NW/NW$_{\rm SM}$:	$-.0076$	.0194	$-.0054$	2.28	.034	$-.0087$	-1.47	0

$H\gamma\gamma$, $HZ\gamma$, and Hgg Full:



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NW/NW$_{SM}$:	$-.0076$	.0194	$-.0054$	2.28	.050	0	0	0
+C+mtm:	$-.0077$	.0198	$-.0013$	2.24	.019	$-.0075$	-1.48	0
NW/NW$_{SM}$:	$-.0076$	.0194	$-.0054$	2.28	.034	$-.0087$	-1.47	0
+C+m+ γ:	$-.0077$	.0198	$-.0013$	2.24	.027	$-.068$	-1.41	0
NW/NW$_{SM}$:	$-.0076$	.0194	$-.0054$	2.28	.034	$-.0087$	-1.47	0
+C+m+ γ+g:	$-.0077$	.0198	$-.0013$	2.24	.027	$-.068$	-1.41	$-.98$
NW/NW$_{SM}$:	$-.0076$	.0194	$-.0054$	2.28	.034	$-.0087$	-1.47	0

For $uuuu(dddd)$ this is -8(-6)
For the total $H \to 4f$ width it's -0.28
($H \to gg$ is 619...)