The SMEFT/geoSMEFT- the modern EFT analysis of collider data

Prepared for: QUC summer school

Michael Trott, NBI

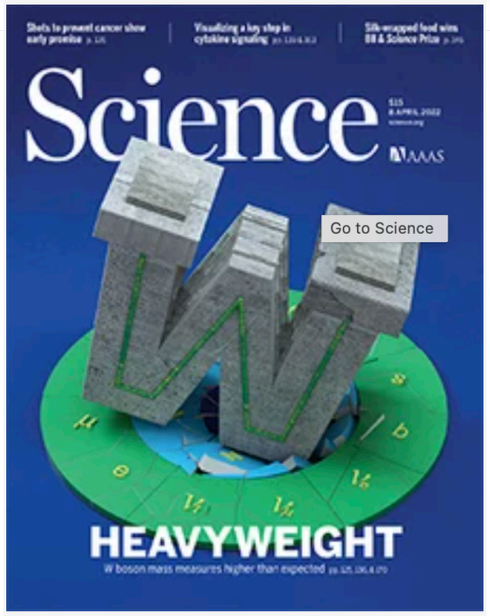
Lecture Three

Outline for today

Third lecture

- W mass anomaly as a SMEFT example.
- Higgs width calculation as a SMEFT calculation example (kinematics x geometry)
- Comments on the Hierarchy problem in SMEFT/EFT to motivate size of effects we are looking for…in these two examples etc.

The SMEFT is a key tool for interpreting such deviations:



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

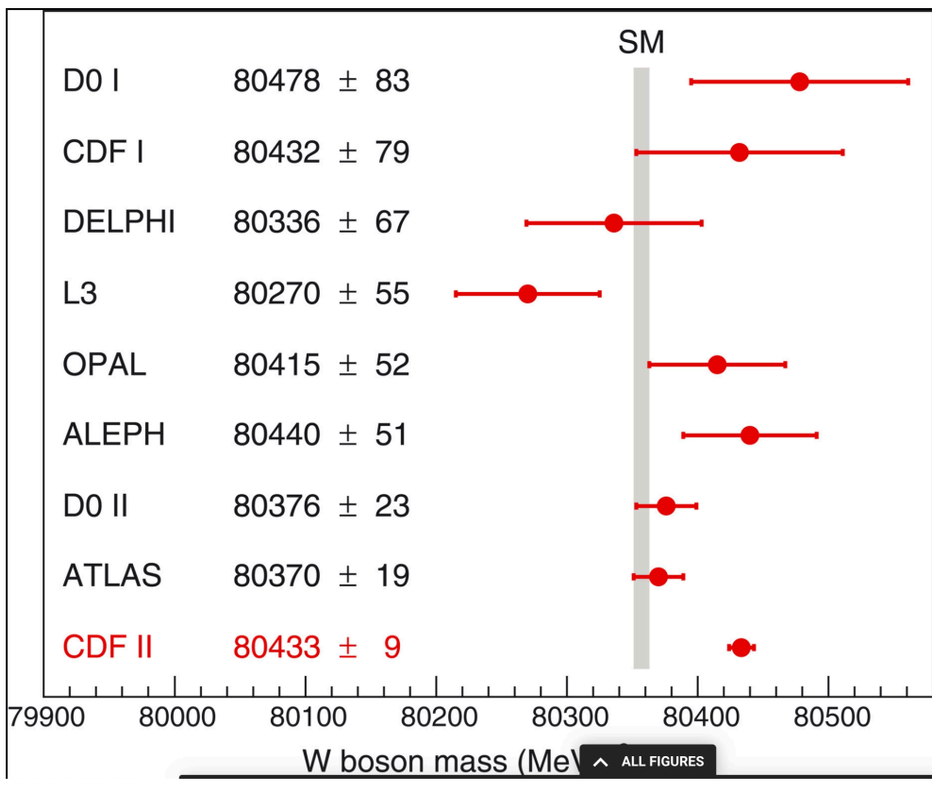
CDF COLLABORATION‡‡, T. AALTONEN, S. AMERIO, D. AMIDEI, A. ANASTASSOV, A. ANNOVI, J. ANTOS, G. APOLLINARI, J. A. APPEL, […] S. ZUCCHELLI +389 authors

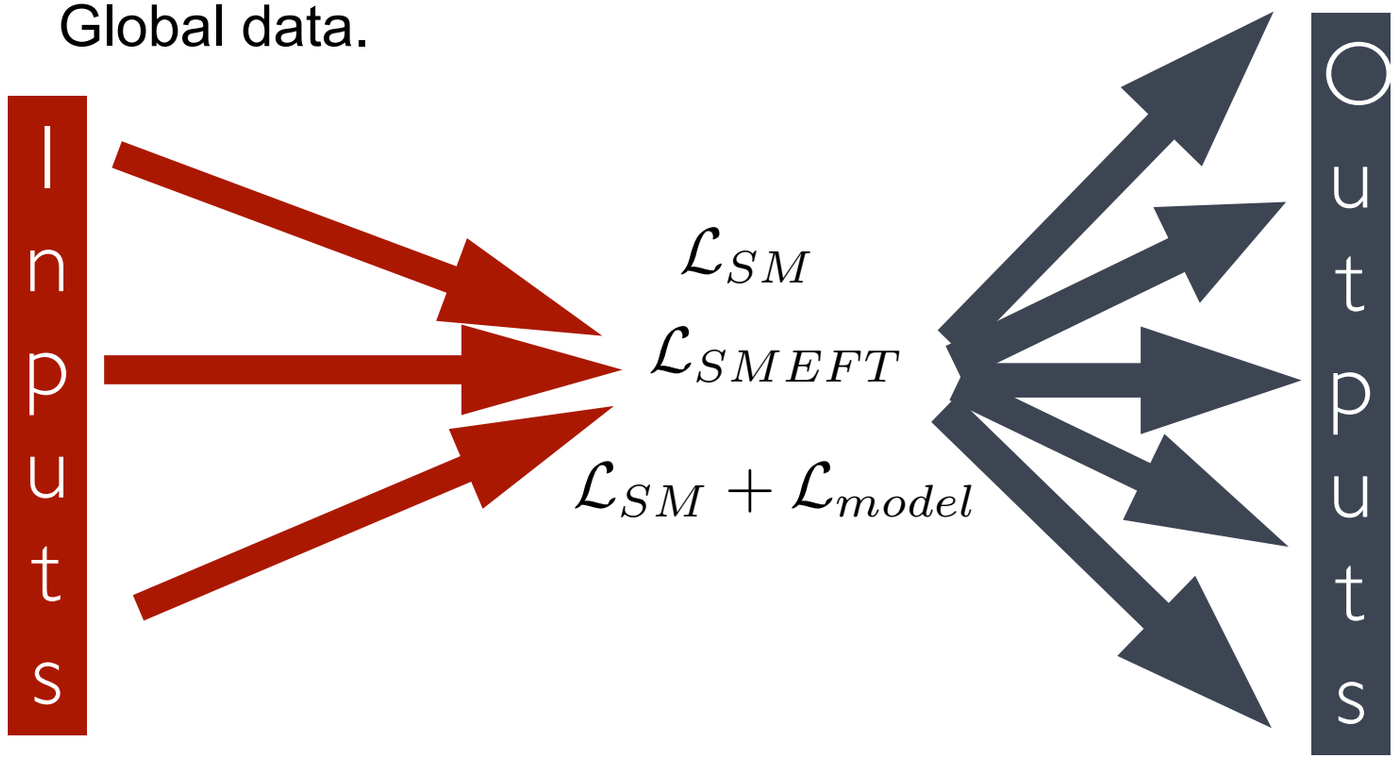
Authors Info & Affiliations

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

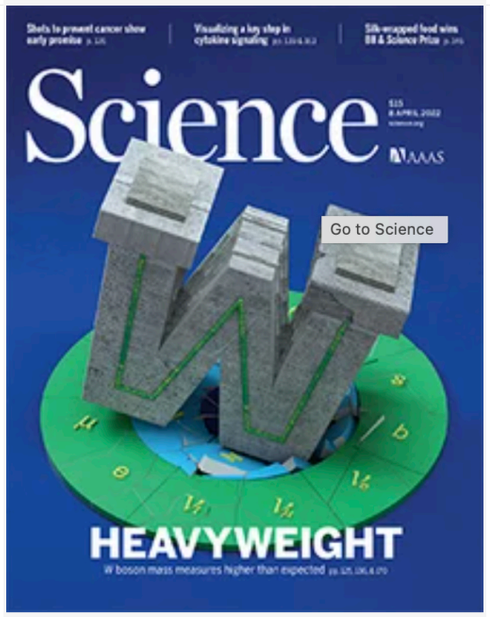
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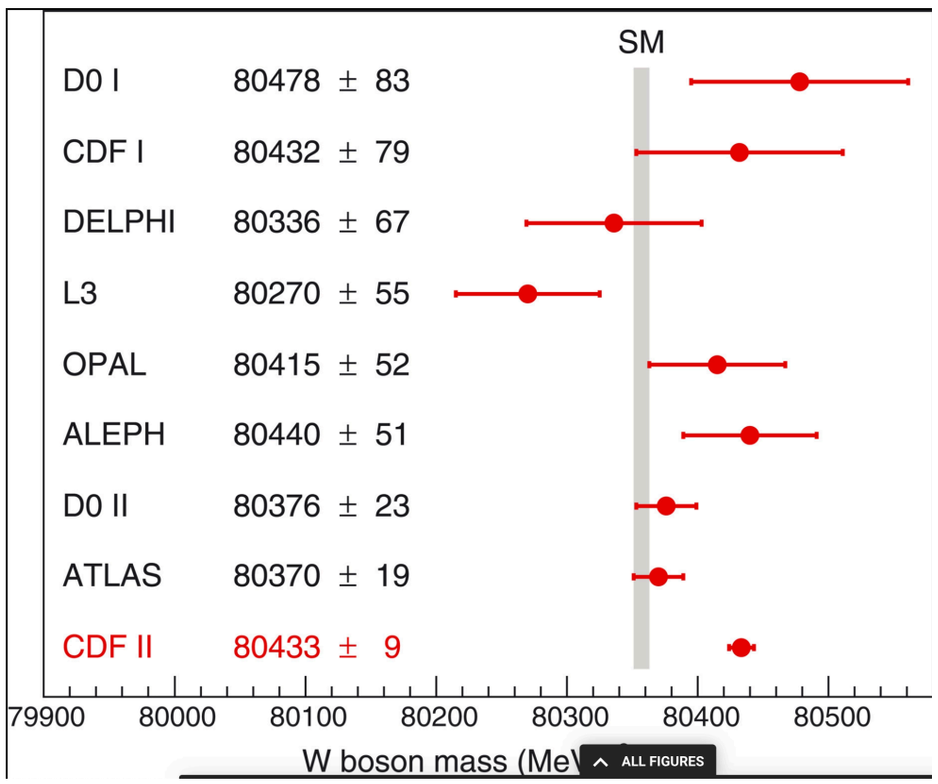
- Any one measurement can just dictate a parameter in a theory. But a PATTERN of measurements can show a theory does not describe Global data.





The SMEFT is a key tool for interpreting such deviations:





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97,942 1

- 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

Choose inputs, define predictions

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

E.O.M.

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

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

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

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

- 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.***

When a large set of experimental results are combined in global SMEFT, Input parameter dependence is reduced.

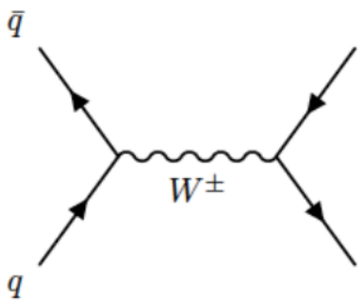
SMEFT inputs best practices

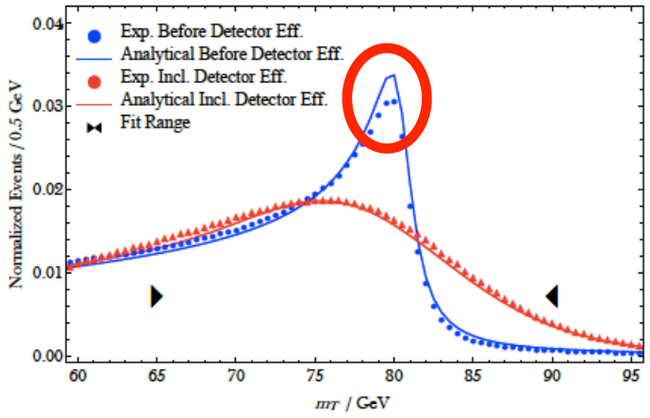
- Good input observables to fix numerical values to make predictions should be:
  - Experimentally precise
  - Theoretically well defined (IR insensitive)
  - Largely calculable in pert theory.
    Under good control for radiative corrections
- Extra problems in SMEFT: Make sure the extraction of the input observable does not have intrinsic SM assumptions, and has all operator effects included in SMEFT
- Do not use combined measurements if the SMEFT effects are different for different contributions to the global combinations

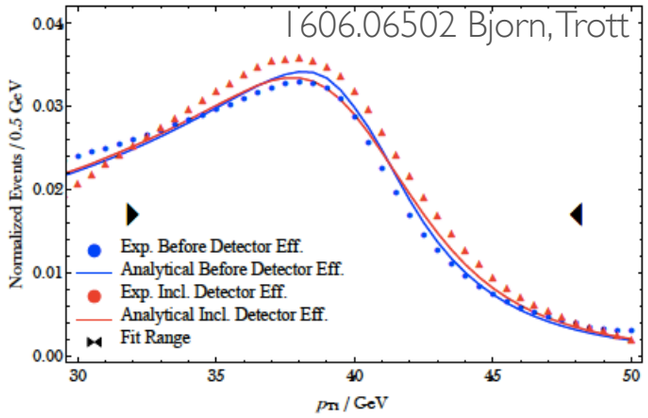
Mw measurements in SMEFT

- 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

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

$$I(\mu,\phi,\alpha) = \frac{\mu^4+\mu^4\alpha^2\cos^2\phi+2\mu^2\alpha^2\sin^2\phi+\alpha^4\sin^2\phi}{(\mu^2+\alpha^2\sin^2\phi)^{1/2}(\mu^2+\mu^2\alpha^2\cos^2\phi+\alpha^2\sin^2\phi)^{3/2}}. \qquad \frac{d\sigma_{ij}}{d\cos\theta} = \tilde{\sigma}_{ij}\frac{3\,(\hat{G}_F\hat{M}_W^2)^2|V_{ij}|^2}{8\sqrt{2}\pi\,N_c\,s}|\bar{g}_{ij}^{W,q}|^2\,\left[1+\cos^2\theta\right]\mathrm{Br}$$

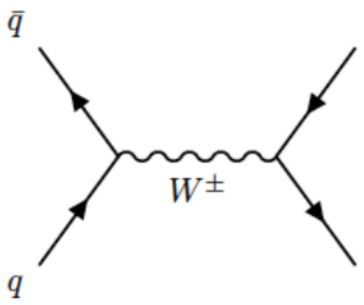
Pdf's feed in

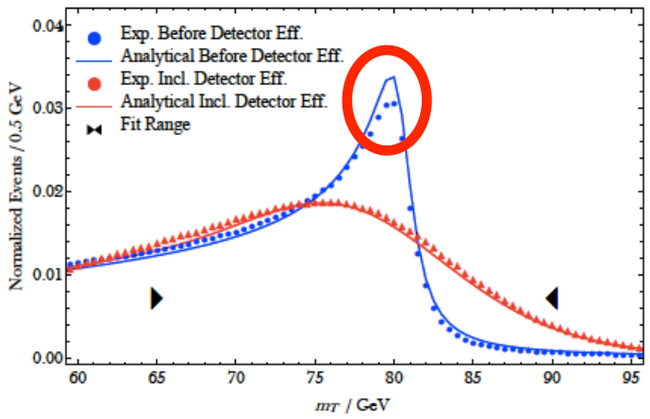
$$\gamma = \sqrt{P_{T,W}^2+s'}/\sqrt{s'} \qquad \alpha = (\gamma^2-1)^{1/2} = P_{T,W}/\sqrt{s'} \qquad \mu^2 = m_T^2/s'$$

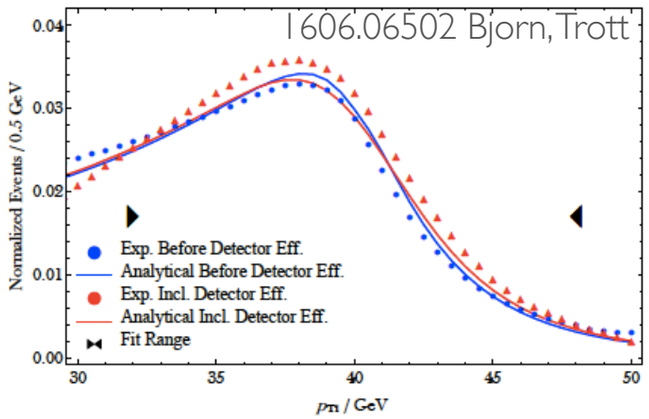
Mw measurements in SMEFT

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

Transverse mass Jacobian peak







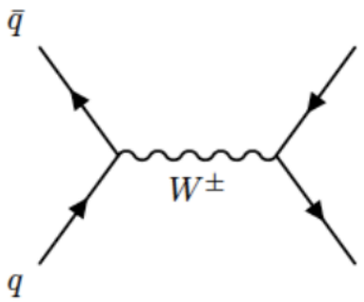
- SMEFT interpretation concern - other shifts compared to SM feed in. Does that screw up mapping to mass shift formula?

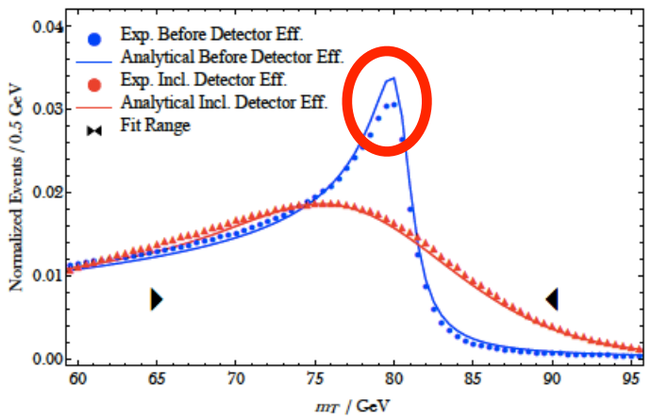
  i.e. W coupling normalization and width shifts.

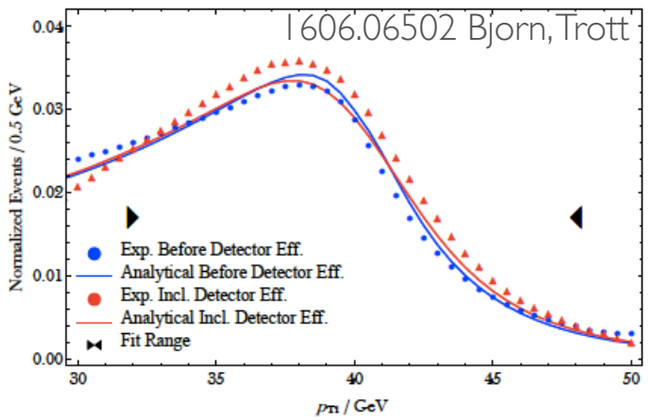
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- Way to check $\frac{d\sigma_{ij}}{d\cos\theta} = \tilde{\sigma}_{ij} \frac{3\,(\hat{G}_F \hat{M}_W^2)^2 |V_{ij}|^2}{8\sqrt{2}\pi\, N_c\, s} |\bar{g}_{ij}^{W,q}|^2 \left[1+\cos^2\theta\right] \mathrm{Br}$ (5)

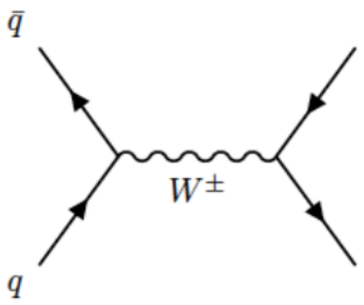
The overall normalization of both of the spectra is modified with a shift

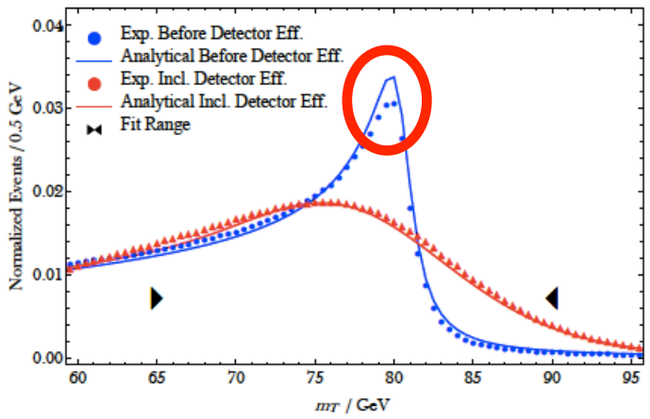
$$\frac{\delta N_{ij}}{N_{ij}} = 2\left[\frac{\delta g_{ij}^{W,q}}{V_{ij}\,\hat{g}^{W,q}} + \frac{\delta g^{W,\ell}}{\hat{g}^{W,\ell}}\right] + \frac{1}{2}\frac{\delta m_W^2}{\hat{m}_W^2} - \frac{\delta\Gamma_W}{\hat{\Gamma}_W}$$

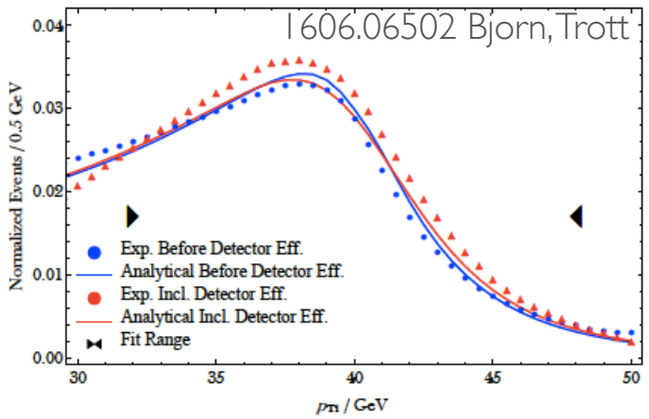
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- Way to check

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

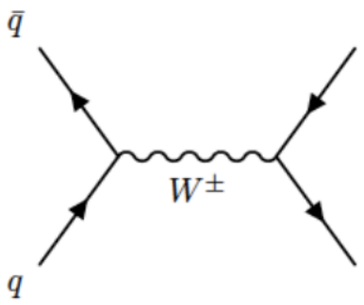
$$\frac{\delta\Gamma_W}{\hat{\Gamma}_W} = \frac{\delta\Gamma_{||}}{\hat{\Gamma}_W} + \frac{\delta\Gamma_{\perp}}{\hat{\Gamma}_W},$$

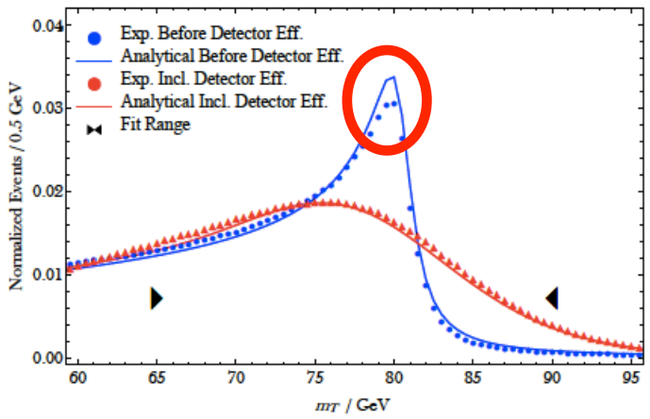
where $\delta\Gamma_{||}$ captures all the correlation, and $\delta\Gamma_{\perp}$ corresponds to directions in Wilson-coefficient-space where the overall normalization of the spectra is unchanged.

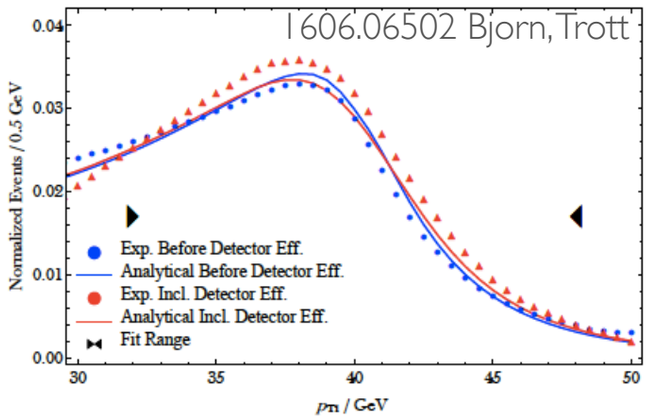
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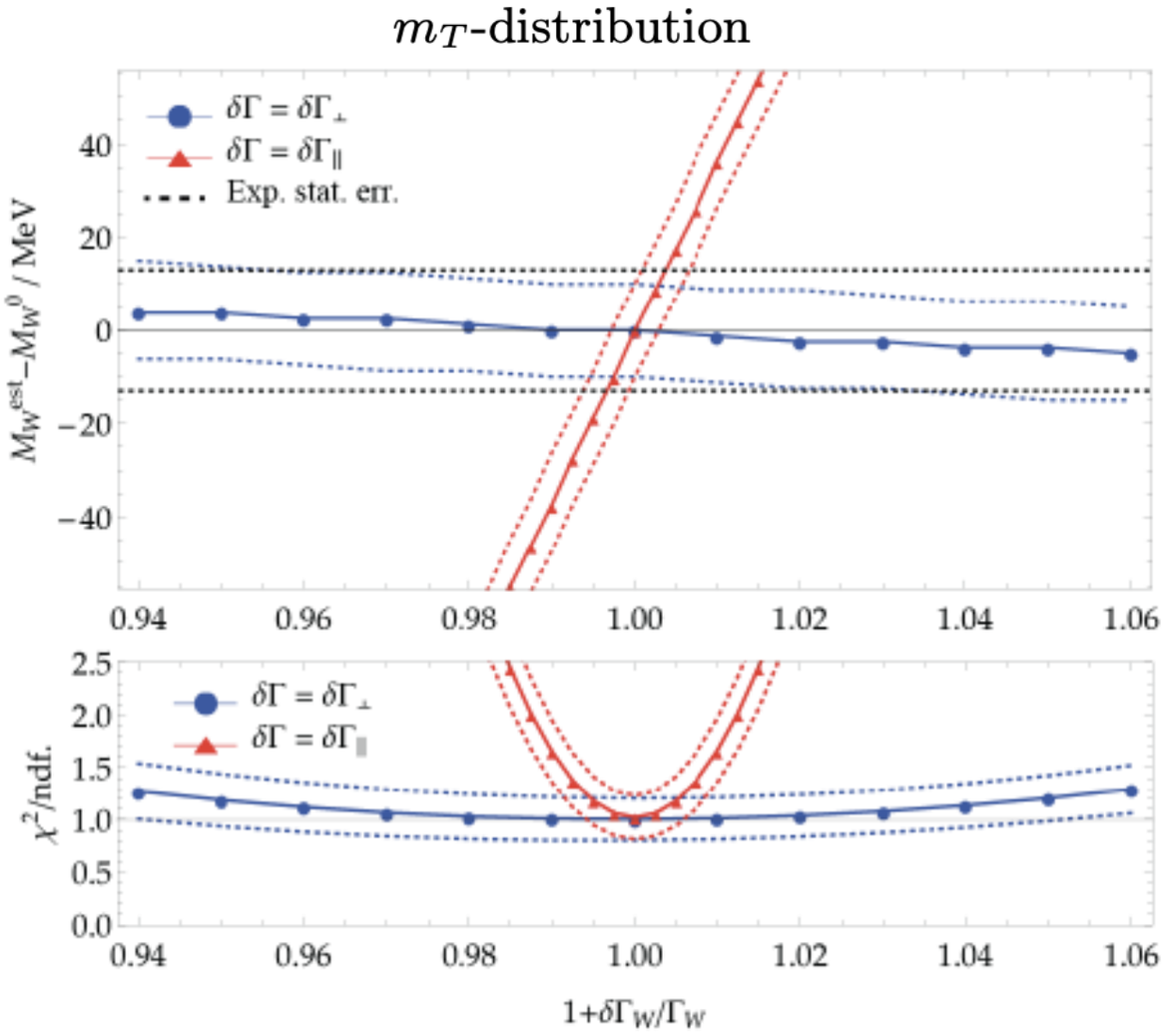
- Way to check

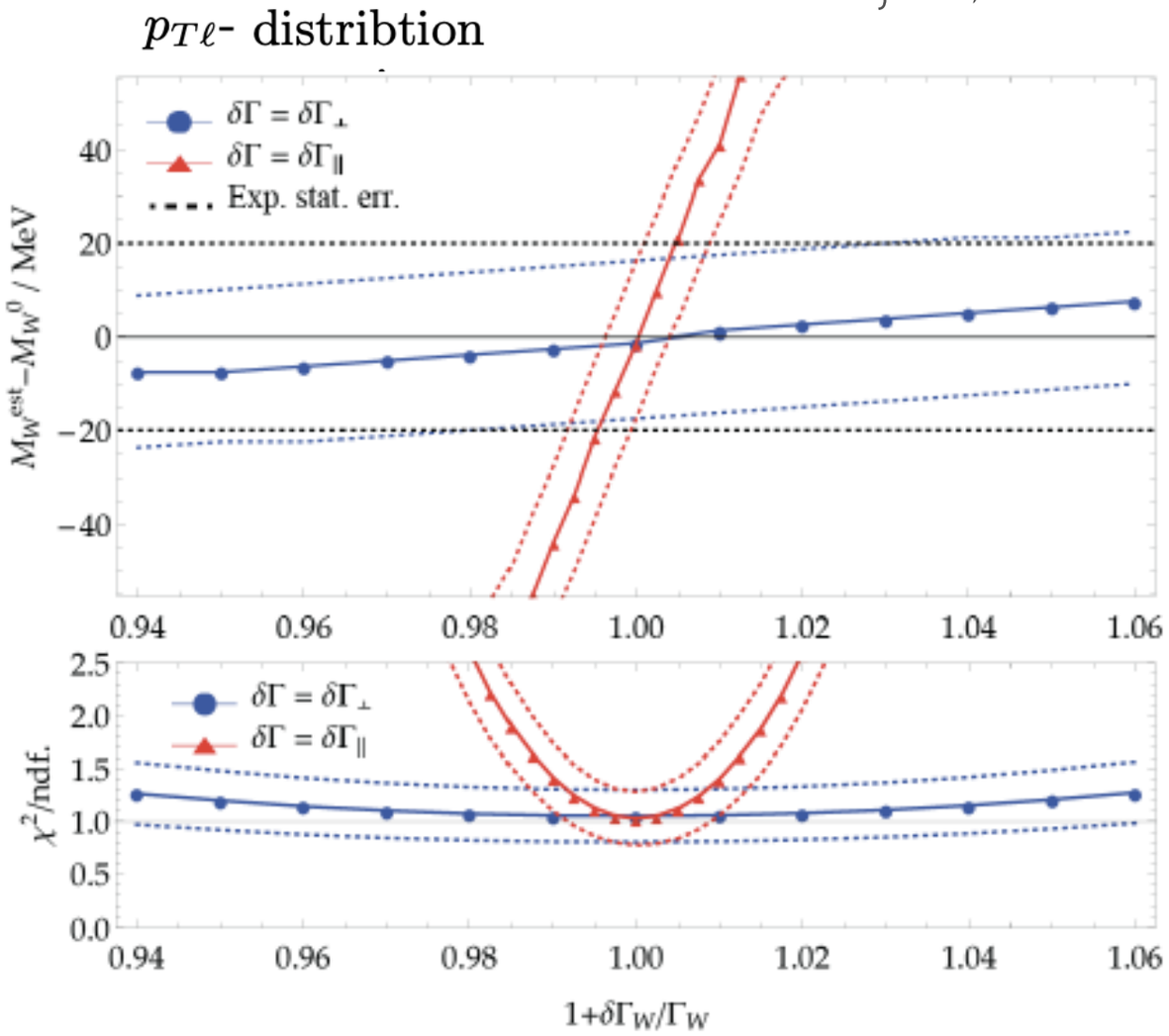
$$\frac{\delta N}{N} = \left(\frac{154 + 44\, s^2_{\hat{\theta}} - 38 s^4_{\hat{\theta}}}{227 + 94\, s^2_{\hat{\theta}} - 97 s^4_{\hat{\theta}}} \right) \frac{\delta \Gamma_{||}}{\hat{\Gamma}_W} \simeq 0.67 \frac{\delta \Gamma_{||}}{\hat{\Gamma}_W}, \qquad (15)$$

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

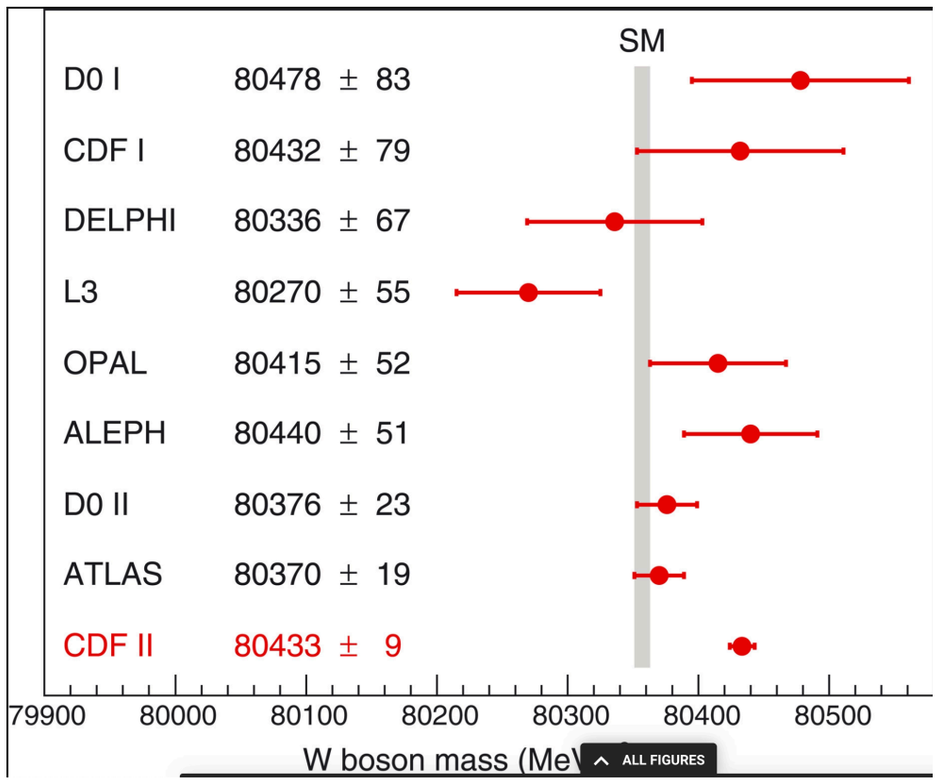




- The error quoted on the extraction for the Tevatron is OK in the SMEFT
  For old measurement due to width and coupling shifts also floated. Seems likely this is still the case with smaller errors (9.4 MeV) so that the deviation can be directly mapped to the mass shift (note however a 2-d scan is really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

Comments on combinations

Combinations



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

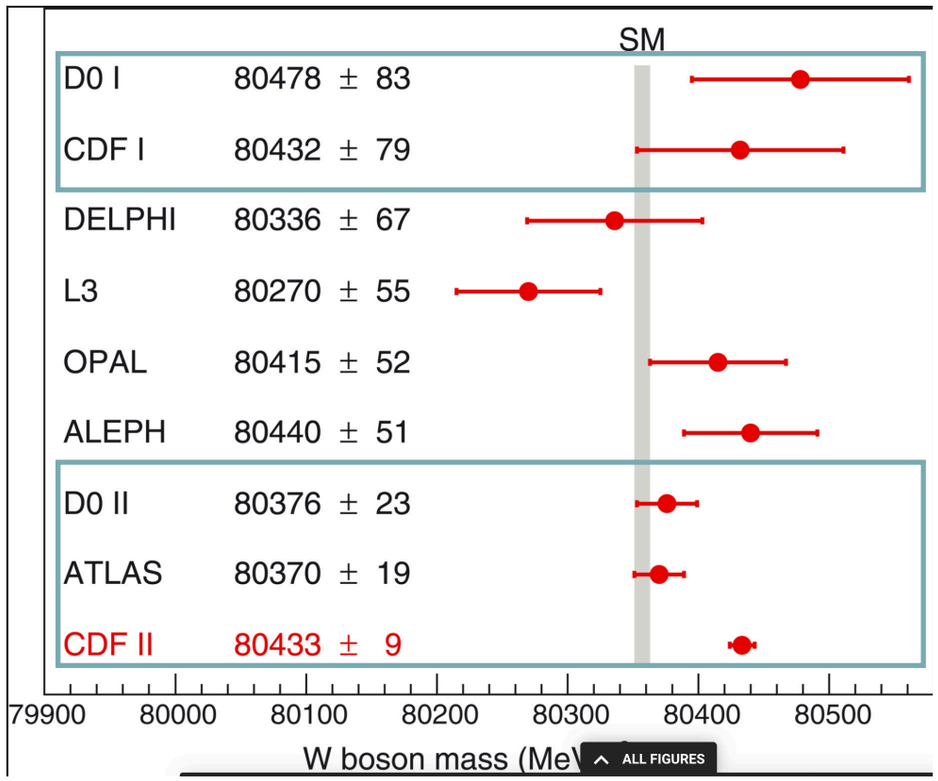
  A: Use the global combination of course. It is not that simple.

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.

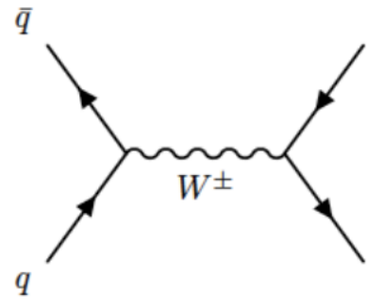
Combine in the SM ! (Good luck!)

SMEFT Combinations



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

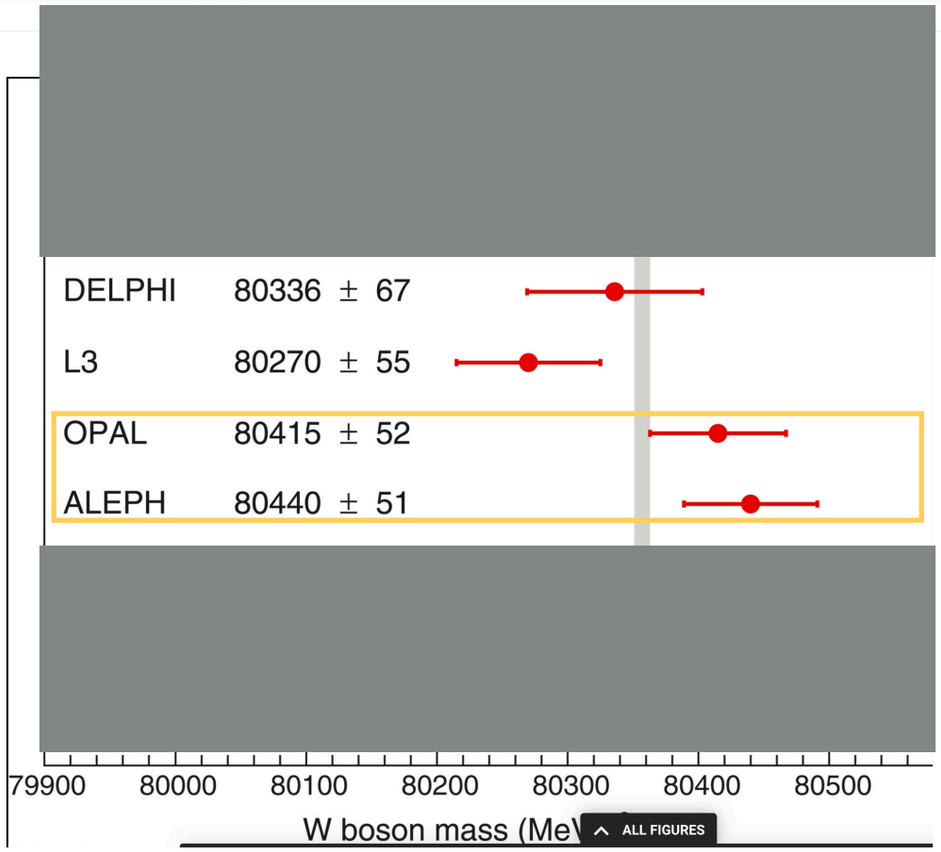
- Each measurement needs to be examined for SMEFT interpretability and combination



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

SMEFT bias analysis laid out should be redone.

SMEFT Combinations

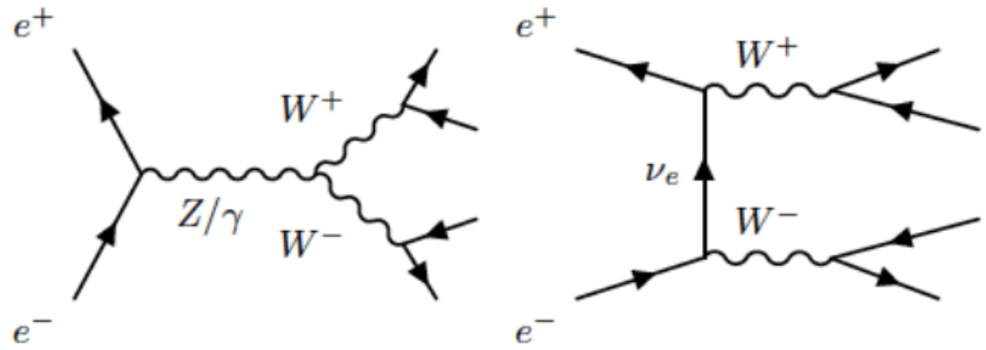


SMEFT bias in this case
Is under control too

1606.06502 Bjorn, Trott

Combine away!

- What about LEPII?



Two different techniques: threshold scan

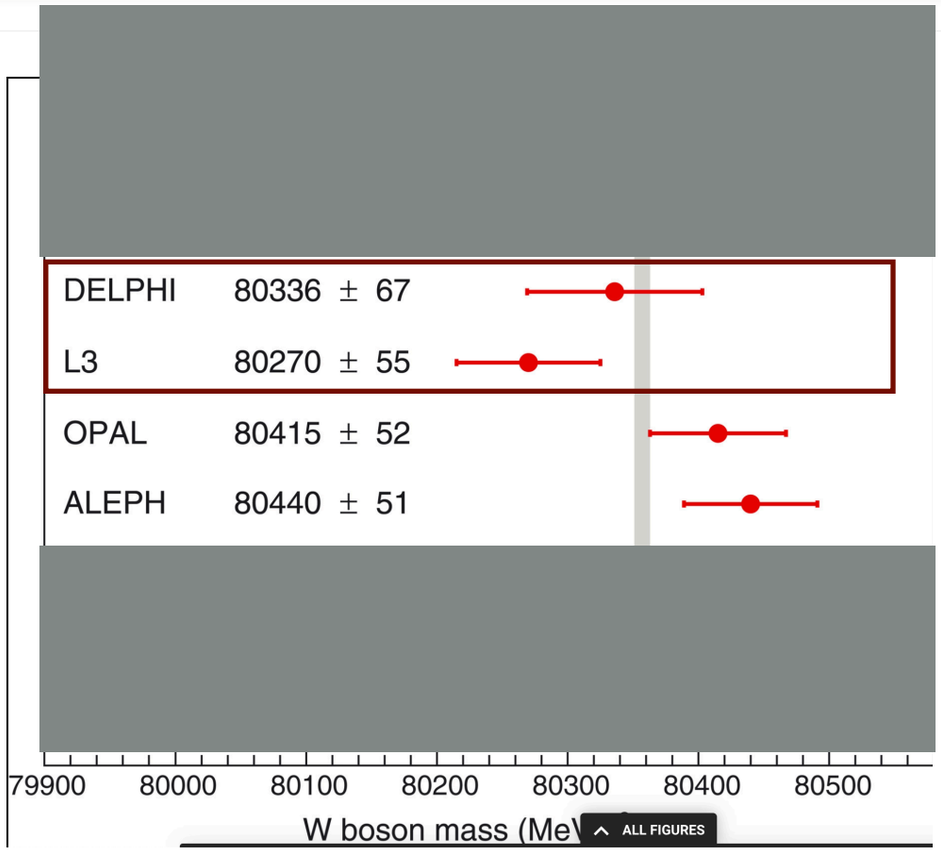
K. Hagiwara and D. Zeppenfeld, Phys. Lett. B **196**, 97 (1987).

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

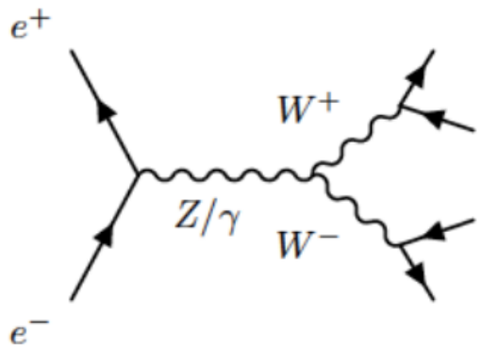
$$\delta\frac{d\sigma}{d\Omega} \simeq \frac{\hat{\alpha}^2}{8\,s\,s_{\hat{\theta}}}\frac{\delta m_w^2}{\hat{m}_w^2}. \qquad \hat{\beta} = \sqrt{1-4\bar{m}_W^2/s},$$

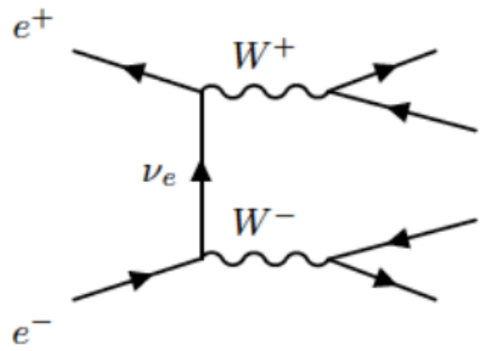
Note the lack of s channel contributions due to possibly anomalous TGC parameters in the threshold limit. These corrections first appear at order β^3

SMEFT Combinations



- What about LEPII?





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

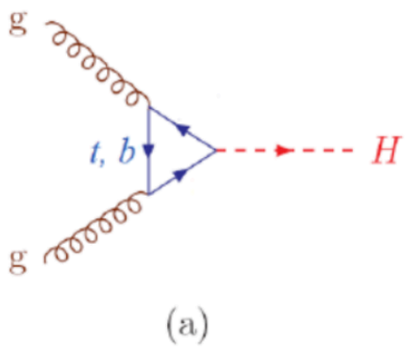
Not interpretable in SMEFT to my knowledge 1606.06502 Bjorn, Trott

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

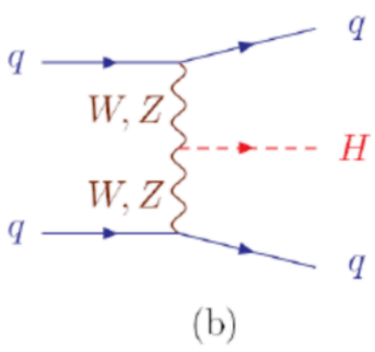
Higgs Width in SMEFT

State of the art Higgs properties

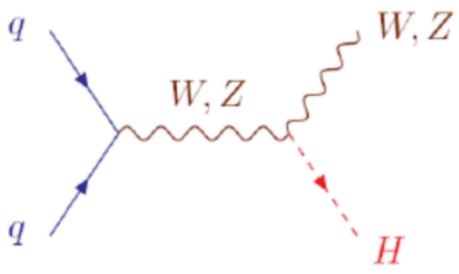
- Raw events are processed to measured (relative) event rates.

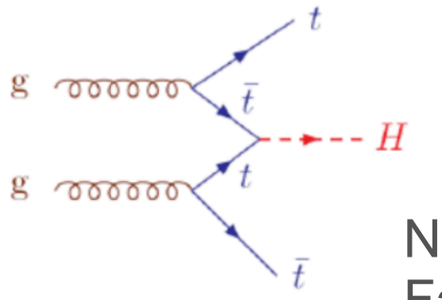


(a)

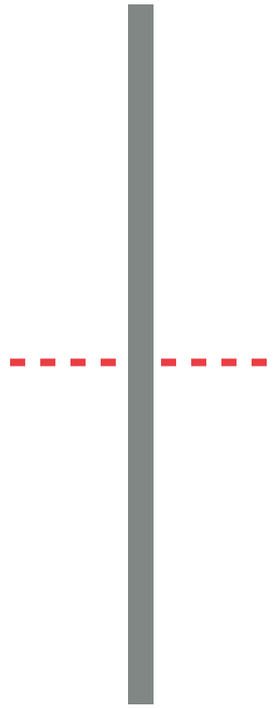


(b)

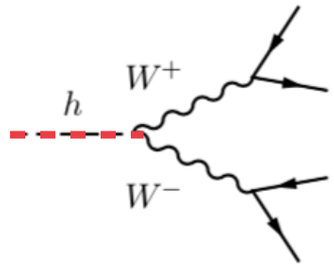


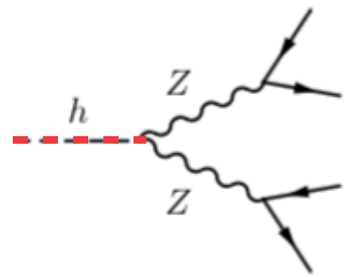


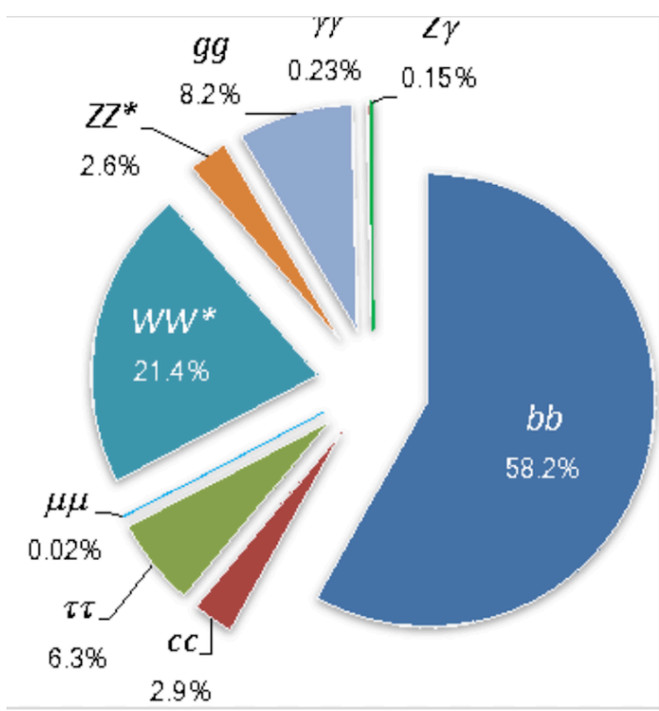
Higgs production



Narrow width
Factorisation of
Production and decay



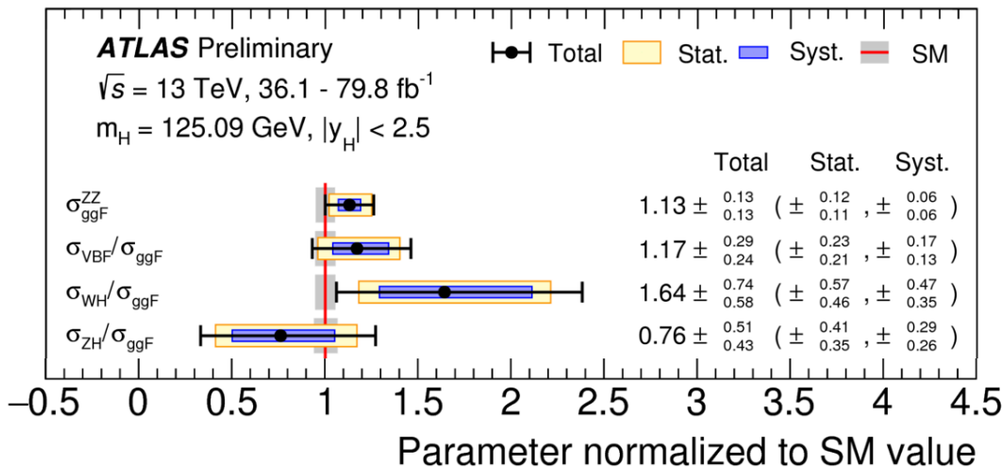


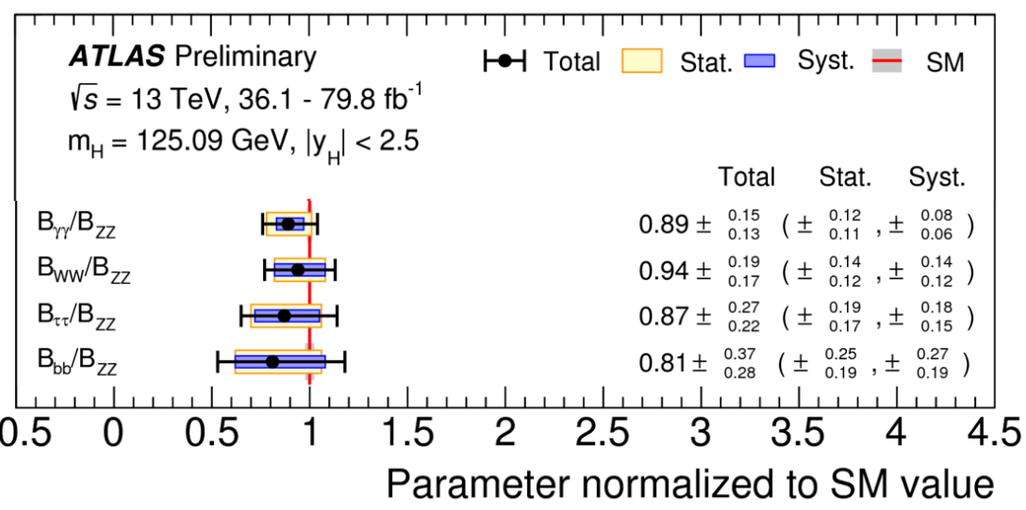


Higgs decay

Under a SM like assumption

- Raw events are processed to measured (relative) event rates.



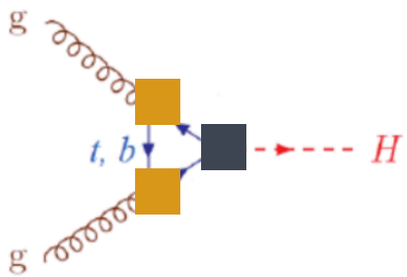


Narrow width
Factorisation of
Production and decay

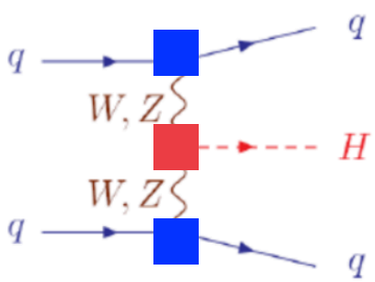
- You need a theory to do the inference to define the relative event rates.
  This analysis uses a “SM like” assumption at many key points.

State of the art Higgs properties

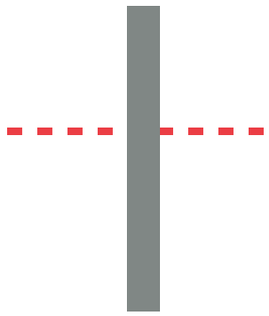
- Various operator based perturbations can appear

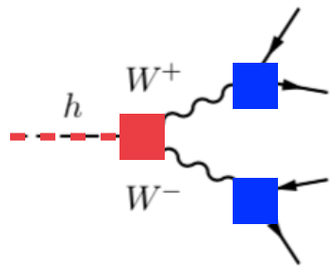


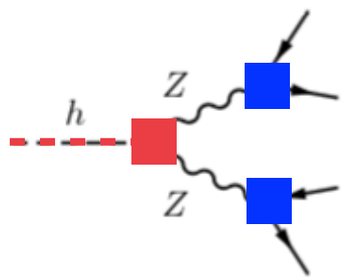
(a)

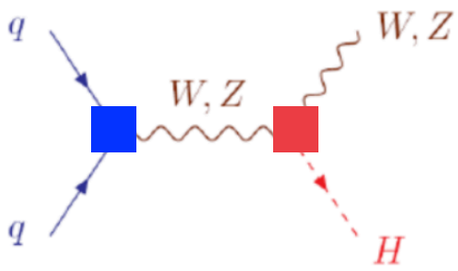


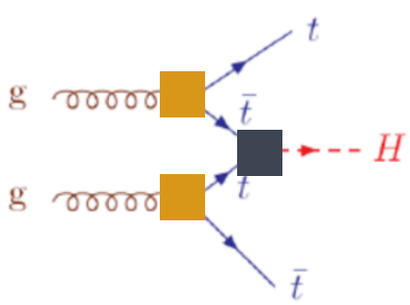
(b)











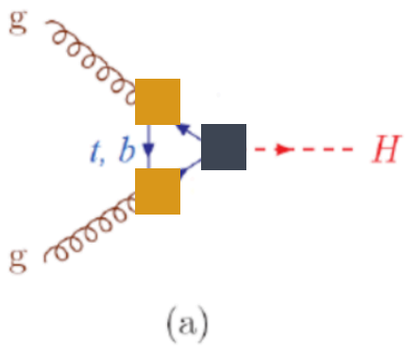
- Q: Does the analysis “SM like” assumption fail in the SMEFT? Can we use the result?
- A: “yes.”

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC}\widetilde{G}^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\tilde{G}}$	$\varphi^\dagger\varphi\,\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\,G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\,W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\,B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

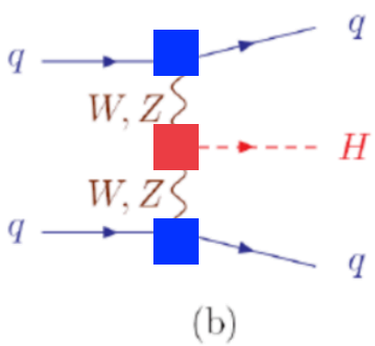
Table 2: Dimension-six operators other than the four-fermion ones.

State of the art Higgs properties

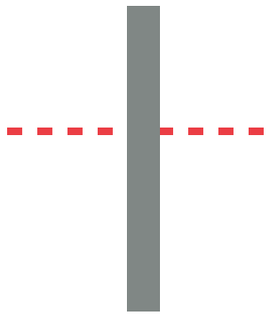
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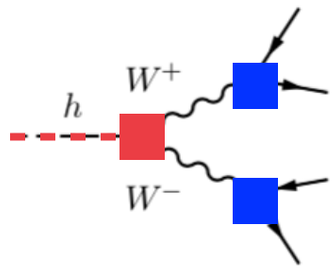


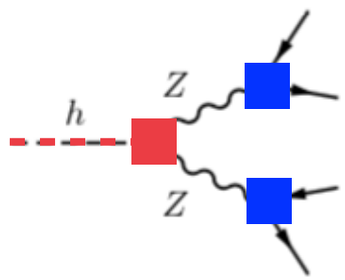
(a)

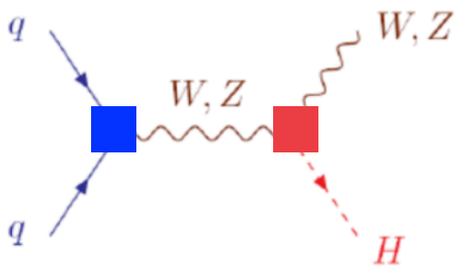


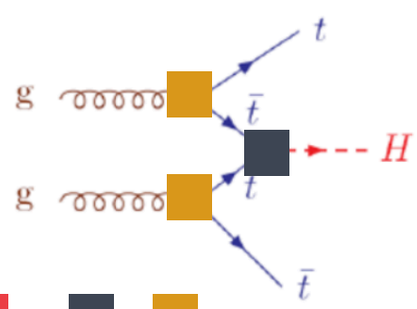
(b)











$$n_k^{\text{signal}} = \mathcal{L}_k \sum_i \sum_f (\sigma \times \mathrm{B})_{if} (\epsilon \times A)_k^{if}$$

Function of cuts and kinematics

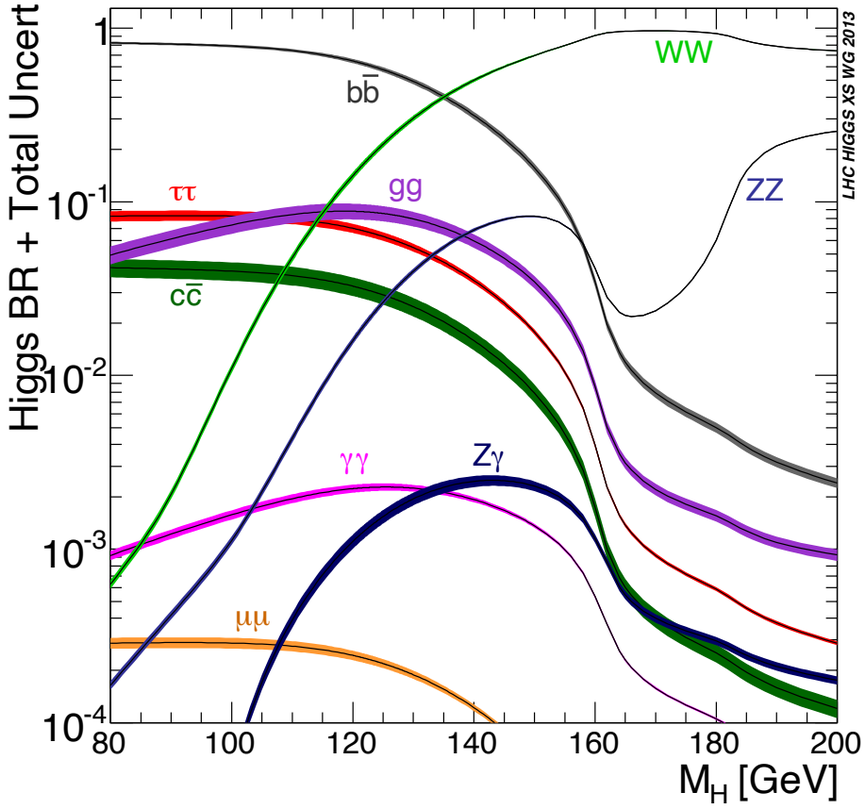
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
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$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X \varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\tilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

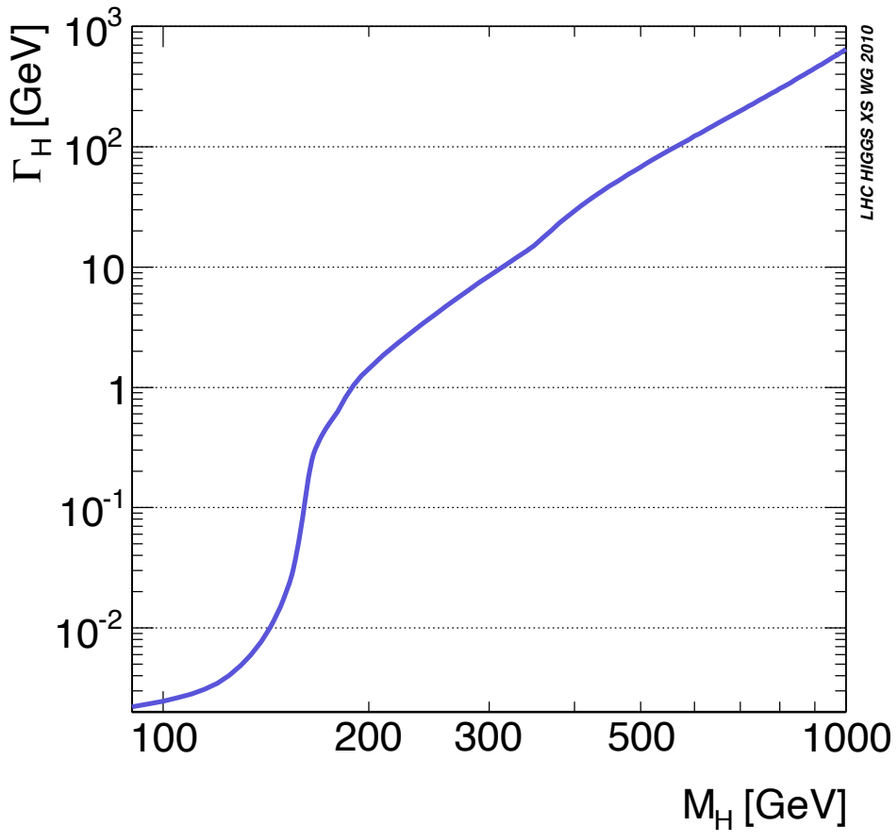
Table 2: Dimension-six operators other than the four-fermion ones.

SMEFT interpretation of Higgs

- Step one, what is the inclusive Higgs width?

$$\Gamma^{SM}_{h,full} = 4.100 \text{ MeV}.$$





- What is the inclusive Higgs width in the SMEFT?

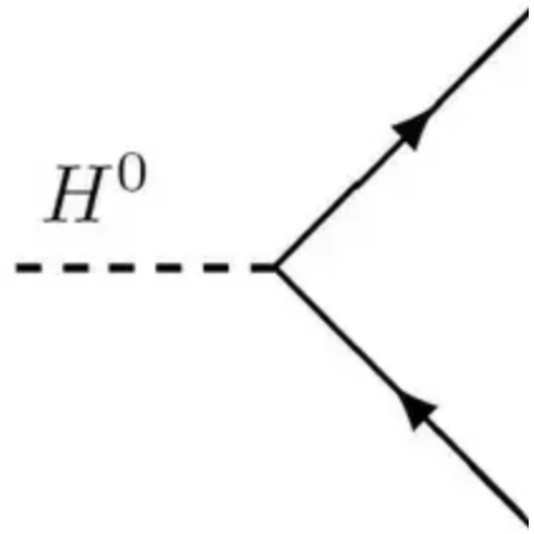
$$\Gamma^{SM}_{h,full} = 4.100 \text{ MeV}. + \sum_{\psi=\{^{u,c,d,s,}_{b,e,\mu,\tau}\}} \delta\Gamma_{h\to\bar{\psi}\psi} + \delta\Gamma_{h\to\mathcal{A}\mathcal{A}} + \delta\Gamma_{h\to\mathcal{Z}\mathcal{A}} + \delta\Gamma_{h\to gg} + \sum_{\psi_{1,2,3,4}} \delta\Gamma_{h\to\bar{\psi}_1\psi_2\bar{\psi}_3\psi_4},$$

SMEFT interpretation of Higgs

- Inclusive Higgs width critical, as we measure:

$$\mathrm{Br}_{h\to S}^{SMEFT} = \mathrm{Br}_{h\to S}^{SM}\left[1+\frac{\delta\Gamma_{h\to S}}{\Gamma_{h\to S}^{SM}}-\frac{\sum_S \delta\Gamma_{h\to S}}{\sum_S \Gamma_{h\to S}^{SM}}\right].$$

- Easy bits with no acceptance subtleties: $\mathcal{L}_{h,eff} = -g_{\substack{h\psi\\pr}}\, h\, \bar{\psi}_{\substack{R\\p}}\psi_{\substack{L\\r}} + h.c.$



SM: $g^{SM}_{\substack{h\psi\\pp}} = \hat{Y}_{\substack{\psi\\pp}}/\sqrt{2}$ $\qquad \hat{Y}_\psi = 2^{3/4}\hat{M}_\psi\sqrt{\hat{G}_F}$

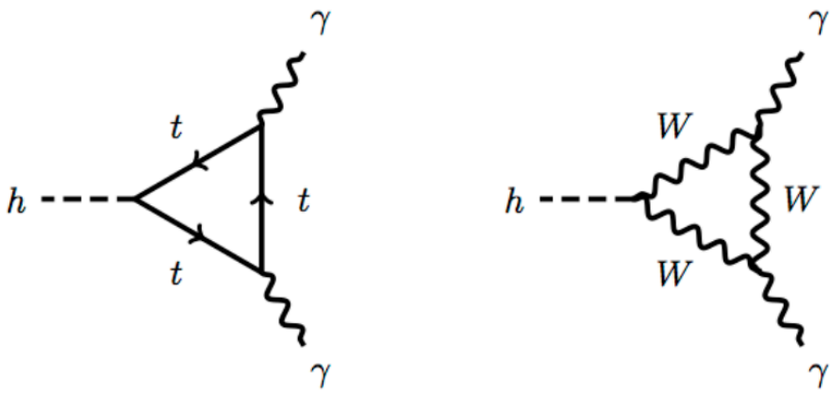
B yukawa dictates width and $\hat{Y}_b \simeq 0.02$

SMEFT: $\delta g_{\substack{h\psi\\pr}} = \frac{\hat{Y}_{\substack{\psi\\pr}}}{\sqrt{2}}\left[C_{H,\mathrm{kin}} - \frac{\delta G_F}{\sqrt{2}}\right] - \frac{1}{\sqrt{2}}\tilde{C}^*_{\substack{\psi H\\pr}}.$

Taking the Higgs to canonical kinetic term $C_{H,\mathrm{kin}} \equiv \left(\tilde{C}_{H\Box} - \frac{1}{4}\tilde{C}_{HD}\right),$

SMEFT interpretation of Higgs

- SM loop level decay

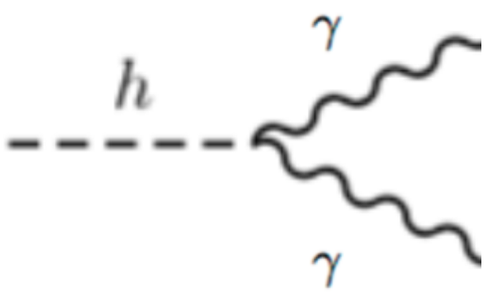


$$\bar{\Gamma}_{SM}\left(h \to \mathcal{A}\mathcal{A}\right) = \frac{\bar{\alpha}^2\,\bar{G}_F}{128\sqrt{2}\pi^3}\,\bar{M}_h^3 \left| \sum_{\psi} N_C^{\psi}\,Q_{\psi}^2\,F_{1/2}(\tau_{\psi}) + F_1(\tau_W) \right|^2 ,$$

where $\tau_W = 4\bar{M}_W^2/\bar{M}_h^2, \tau_{ZW} = \bar{M}_Z^2/(4\bar{M}_W^2)$ and $\tau_{\psi} = 4\bar{M}_{\psi}^2/\bar{M}_h^2$, while

$$F_{1/2}(\tau_{\psi}) = -2\tau_{\psi} - 2\tau_{\psi}(1-\tau_{\psi})f(\tau_{\psi}),$$
$$F_1(\tau_W) = 2 + 3\,\tau_W\left[1 + (2-\tau_W)\,f(\tau_W)\right],$$
$$f(\tau_p) = \begin{cases} \arcsin^2\sqrt{1/\tau_p}, & \tau_p \geq 1 \\ -\frac{1}{4}\left[\ln\frac{1+\sqrt{1-\tau_p}}{1-\sqrt{1-\tau_p}} - i\pi\right]^2, & \tau_p < 1. \end{cases}$$

- SMEFT tree level result interference



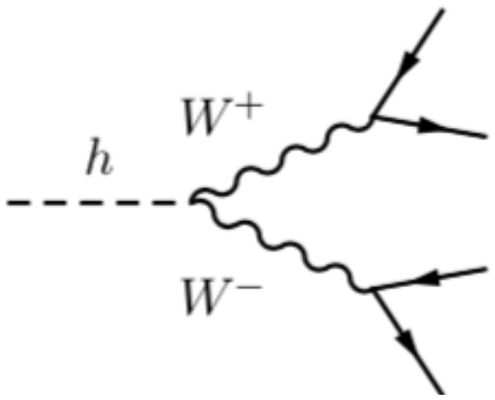
$$\frac{\delta\Gamma_{\mathcal{A}\mathcal{A}}}{\Gamma_{\mathcal{A}\mathcal{A}}^{SM}} \simeq (2\frac{\delta\alpha}{\hat{\alpha}} - \sqrt{2}\delta G_F) + 0.27 \times 0.15\frac{\delta M_W^2}{\hat{M}_W^2} - 64\pi^2 \times 0.15 \times \tilde{C}_{\mathcal{A}\mathcal{A}}.$$

Where

$$\tilde{C}_{\mathcal{A}\mathcal{A}} = \tilde{C}_{HW}/\hat{g}_2^2 + \tilde{C}_{HB}/\hat{g}_1^2 - \tilde{C}_{HWB}/\hat{g}_1\,\hat{g}_2.$$

SMEFT interpretation of Higgs

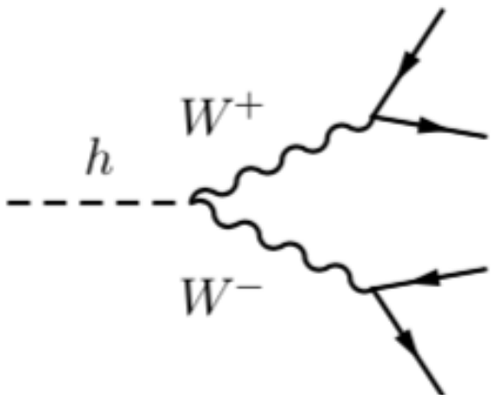
- SM through charged currents four fermion

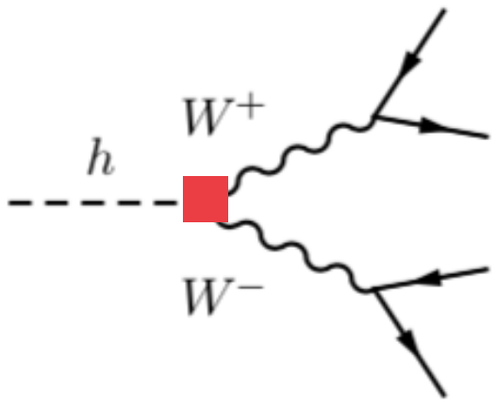


$$\mathcal{L} = \frac{1}{4}\overline{g}_2{}^2 v_T h \left[(\mathcal{W}_\mu^1)^2 + (\mathcal{W}_\mu^2)^2\right]$$

SMEFT interpretation of Higgs

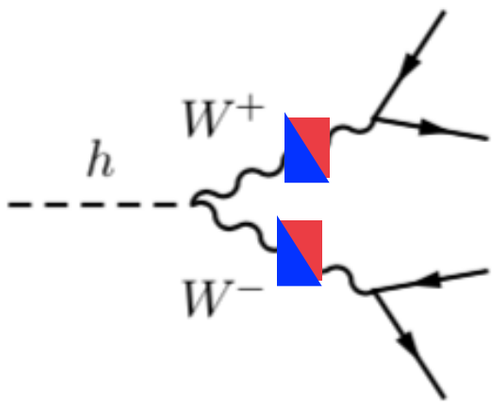
- SMEFT through charged currents four fermion





$$\mathcal{L} = \frac{1}{4}\bar{g}_2{}^2 v_T h \left[(\mathcal{W}^1_\mu)^2 + (\mathcal{W}^2_\mu)^2\right] \left[1 + c_{H,\mathrm{kin}}\right] + C_{HW} v_T h \left[(\mathcal{W}^1_{\mu\nu})^2 + (\mathcal{W}^2_{\mu\nu})^2\right]$$

Modified momentum flow through vertex



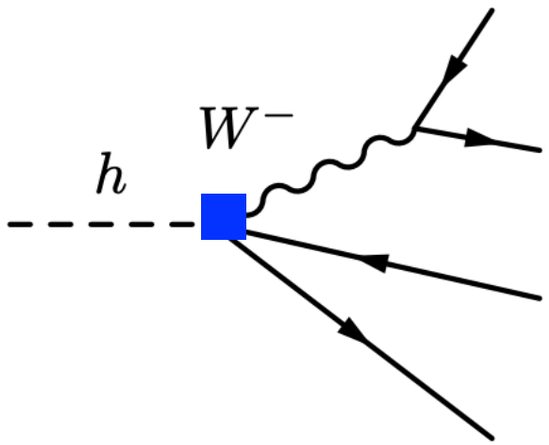
Modified momentum flow through propagator

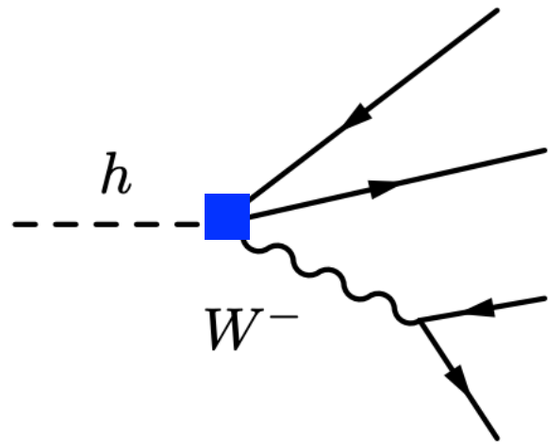
$$D^B(k_{ij}^2) = \frac{1}{k_{ij}^2 - \bar{M}_B^2 + i\bar{\Gamma}_B\bar{M}_B + i\epsilon}\left[1 + \delta D^B(k_{ij}^2)\right].$$

$$2\mathrm{Re}\left[\delta D^B(k_{ij}^2)\right] = \frac{2(k_{ij}^2 - \hat{M}_B^2)\delta M_B^2 - \hat{\Gamma}_B(\hat{\Gamma}_B\delta M_B^2 + 2\hat{M}_B^2\,\delta\Gamma_B)}{(k_{ij}^2 - \hat{M}_B^2)^2 + \hat{M}_B^2\hat{\Gamma}_B^2}.$$

SMEFT interpretation of Higgs

- Connections to final state fermions not present in the SM





$$(H^\dagger \overleftrightarrow{D}^I_\mu H)\bar{f}\tau^I\gamma^\mu f$$

Need to “remove a propagator” compared to final SM amplitude squared

$$\sum_{n=ij,kl}\int dps|A^{\mathcal{W}\mathcal{W}^\dagger}_{\psi_1^{rs},\psi_2^{tu}}|^2_{SM}\left[\frac{8\,C^{(3)}_{H\psi_n}(k_n^2-\hat{M}_W^2)}{\hat{g}_2^2\,(g^{\mathcal{W},\psi_n}_{L,op})^{SM}}\right]$$

All of these effects need to be integrated over four body phase space for an inclusive result.

$$\int dps = \int (2\pi)^4\delta^4(P_h-\sum_i k_i)\prod_{k_i}\frac{d^3k_i}{(2\pi)^3 2E_{k_i}},$$

How much does the phase space change?

- SM kinematics (inclusive)

$$N_1^{\mathcal{W}\mathcal{W}} = \int dps \frac{k_i \cdot k_l \, k_j \cdot k_k}{|[k_{ij}^2, \mathcal{W}]|^2 |[k_{kl}^2, \mathcal{W}]|^2} \simeq 1.28 \times 10^{-6}.$$

- SMEFT kinematics (inclusive)

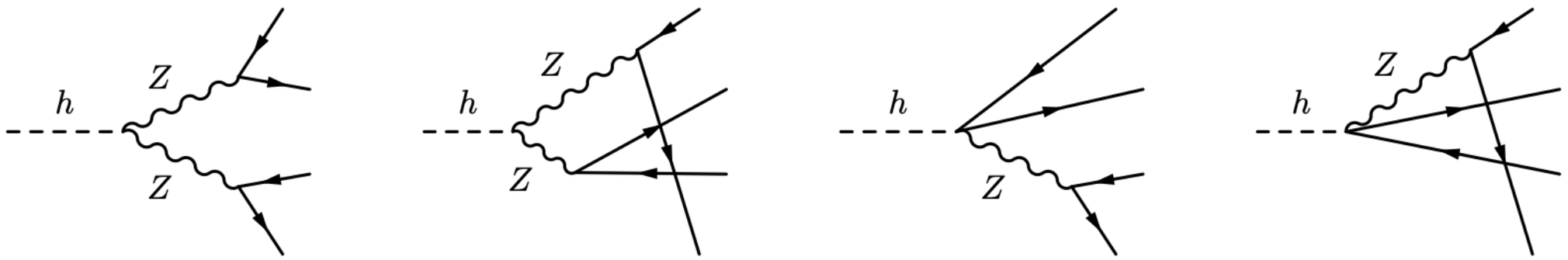
$$\int dps \frac{k_i \cdot k_l \, k_j \cdot k_k}{|[k_{ij}^2, \mathcal{W}]|^2 |[k_{kl}^2, \mathcal{W}]|^2} \frac{8(k_n^2 - \hat{M}_W^2)}{\hat{v}_T^2} \equiv N_2^{\mathcal{W}\mathcal{W}} \simeq -4.83 \times 10^{-7}, \qquad 40\% \text{ Effect}$$

$$\int dps \frac{k_i \cdot k_l \, k_j \cdot k_k}{|[k_{ij}^2, \mathcal{W}]|^2 |[k_{kl}^2, \mathcal{W}]|^2} 2\,\mathrm{Re}[\delta D^{\mathcal{W}}(k_n^2)] \equiv N_3^{\mathcal{W}\mathcal{W}} \frac{\delta\Gamma_W}{\hat{\Gamma}_W} + N_4^{\mathcal{W}\mathcal{W}} \frac{\delta M_W^2}{\hat{M}_W^2},$$

$$\simeq -1.22 \times 10^{-6} \frac{\delta\Gamma_W}{\hat{\Gamma}_W} - 8.78 \times 10^{-6} \frac{\delta M_W^2}{\hat{M}_W^2}, \quad 5\%,\ 30\%$$

$$-\int dps L^{\alpha\beta}_{k_i,k_j} L^{\gamma\delta}_{k_k,k_l} \frac{g_{\alpha\gamma}(g^{\beta\delta} k_{ij} \cdot k_{kl} - k_{kl}^\beta k_{ij}^\delta)}{|[k_{ij}^2, \mathcal{W}]|^2 |[k_{kl}^2, \mathcal{W}]|^2 \hat{v}_T^2} \equiv N_5^{\mathcal{W}\mathcal{W}} \simeq -8.15 \times 10^{-7}. \qquad 40\%$$

Pure ZZ neutral currents



- In SM two different final state connections, two kinematic numbers

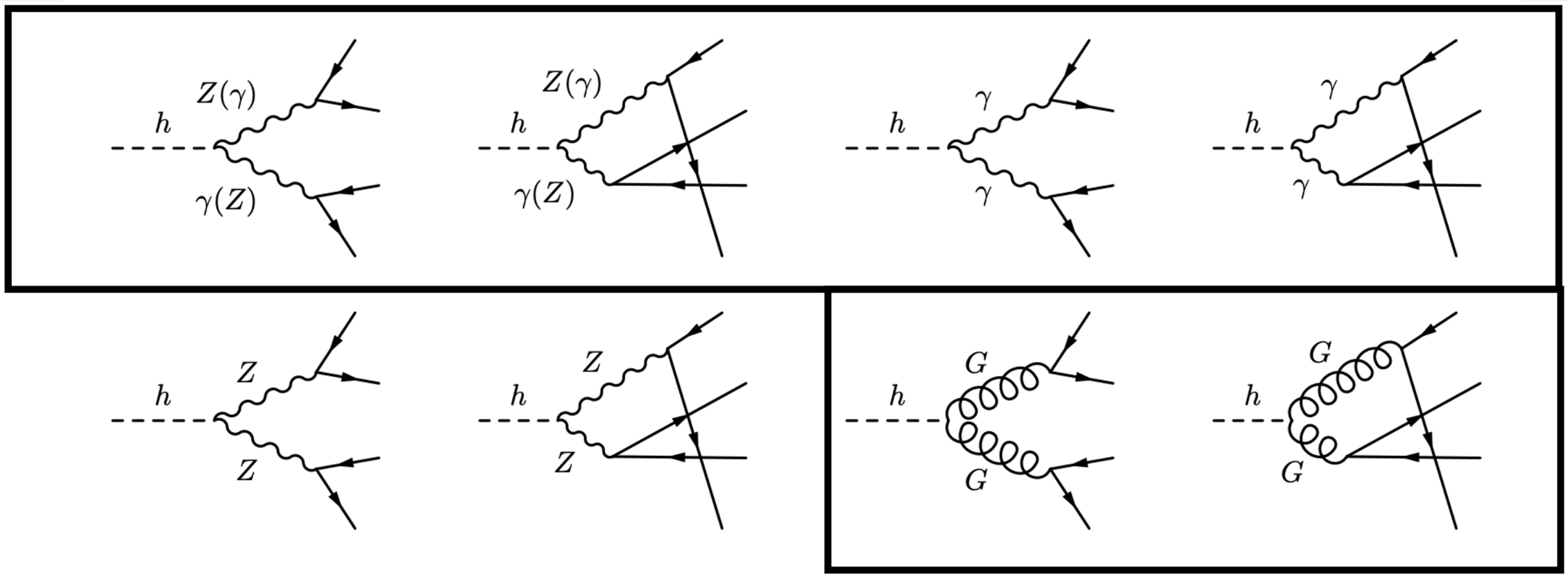
$$N_1^{ZZ} = \int dps \frac{k_i \cdot k_k \, k_j \cdot k_l}{|[k_{ij}^2, \mathcal{Z}]|^2 |[k_{kl}^2, \mathcal{Z}]|^2} = \int dps \frac{k_i \cdot k_l \, k_j \cdot k_k}{|[k_{ij}^2, \mathcal{Z}]|^2 |[k_{kl}^2, \mathcal{Z}]|^2} \simeq 1.74 \times 10^{-7},$$

$$N_2^{ZZ} = \int dps \frac{k_i \cdot k_k \, k_j \cdot k_l}{[k_{ij}^2, \mathcal{Z}][k_{kl}^2, \mathcal{Z}][k_{jk}^2, \mathcal{Z}]^\star [k_{li}^2, \mathcal{Z}]^\star} + h.c. \simeq 6.84 \times 10^{-8}.$$

- SMEFT modification of kinematics - generally ~40 percent effects here

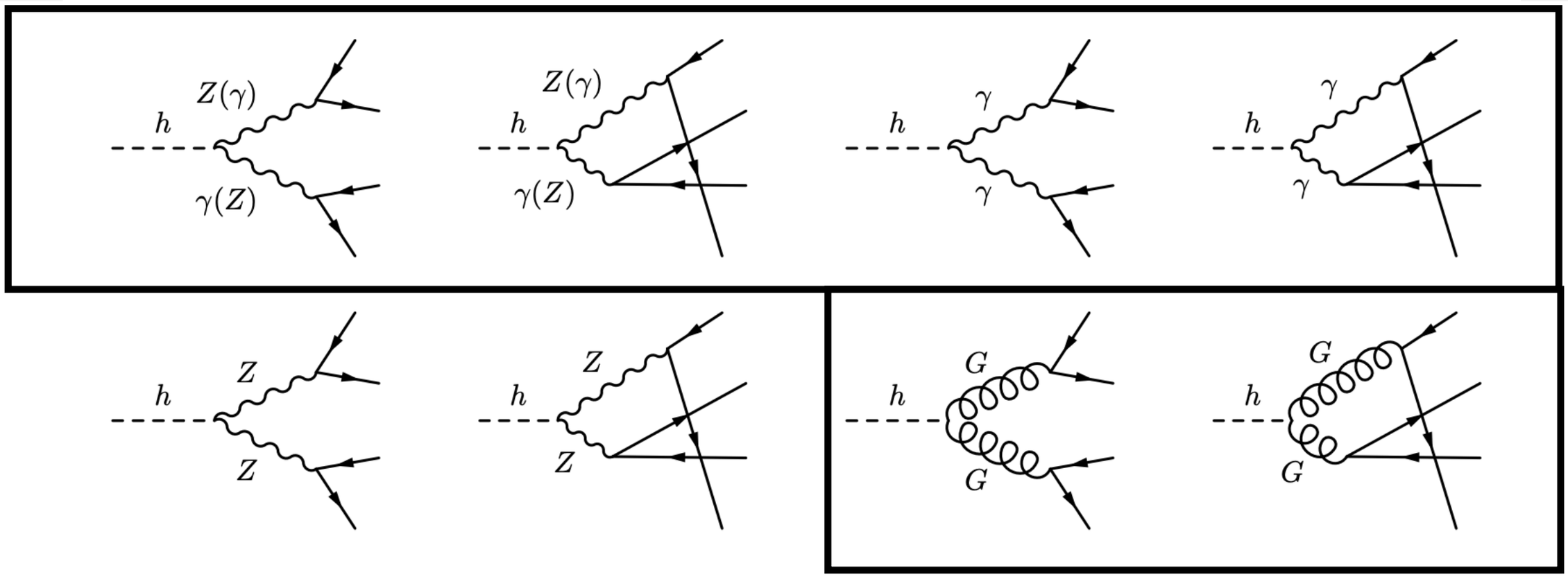
$$N_{3,L/R}^{ZZ} \simeq -9.76 \times 10^{-8}, \qquad N_{4,L/R}^{ZZ} \simeq -5.28 \times 10^{-8},$$
$$N_5^{ZZ} \simeq -1.45 \times 10^{-7}, \qquad N_6^{ZZ} \simeq -2.96 \times 10^{-9},$$
$$N_7^{ZZ} \simeq -1.37 \times 10^{-6}, \qquad N_8^{ZZ} \simeq -3.79 \times 10^{-7},$$
$$N_9^{ZZ} \simeq -9.55 \times 10^{-8}, \qquad N_{10}^{ZZ} \simeq -2.62 \times 10^{-8}.$$

More serious, breakdown narrow width

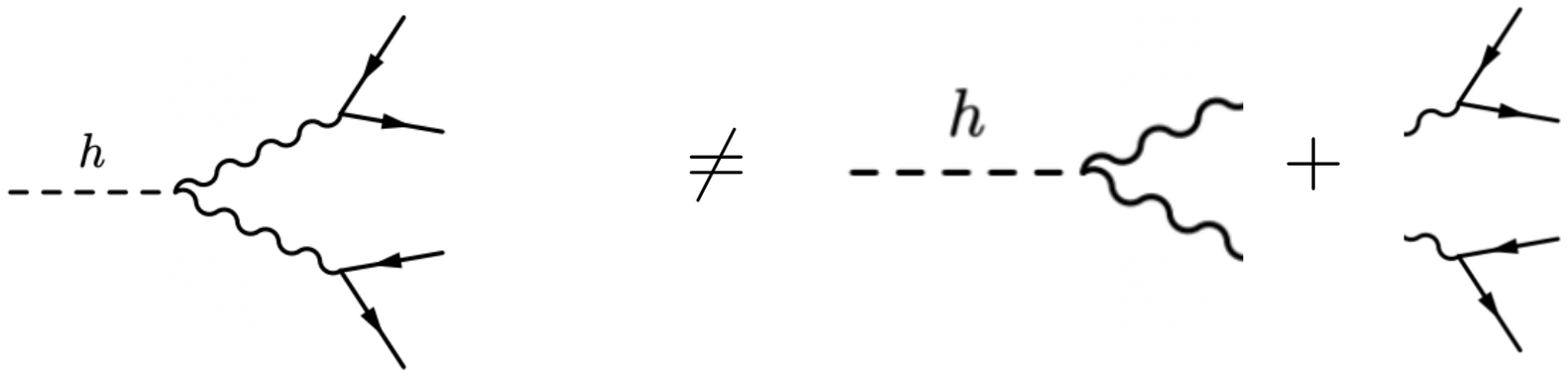


- Operators that must be loop suppressed in SM (due to renormalizability) are now interfering at tree level. EW neutral current interferences.
- Modified pole structure compared to SM, so kinematic number differences >40% effects

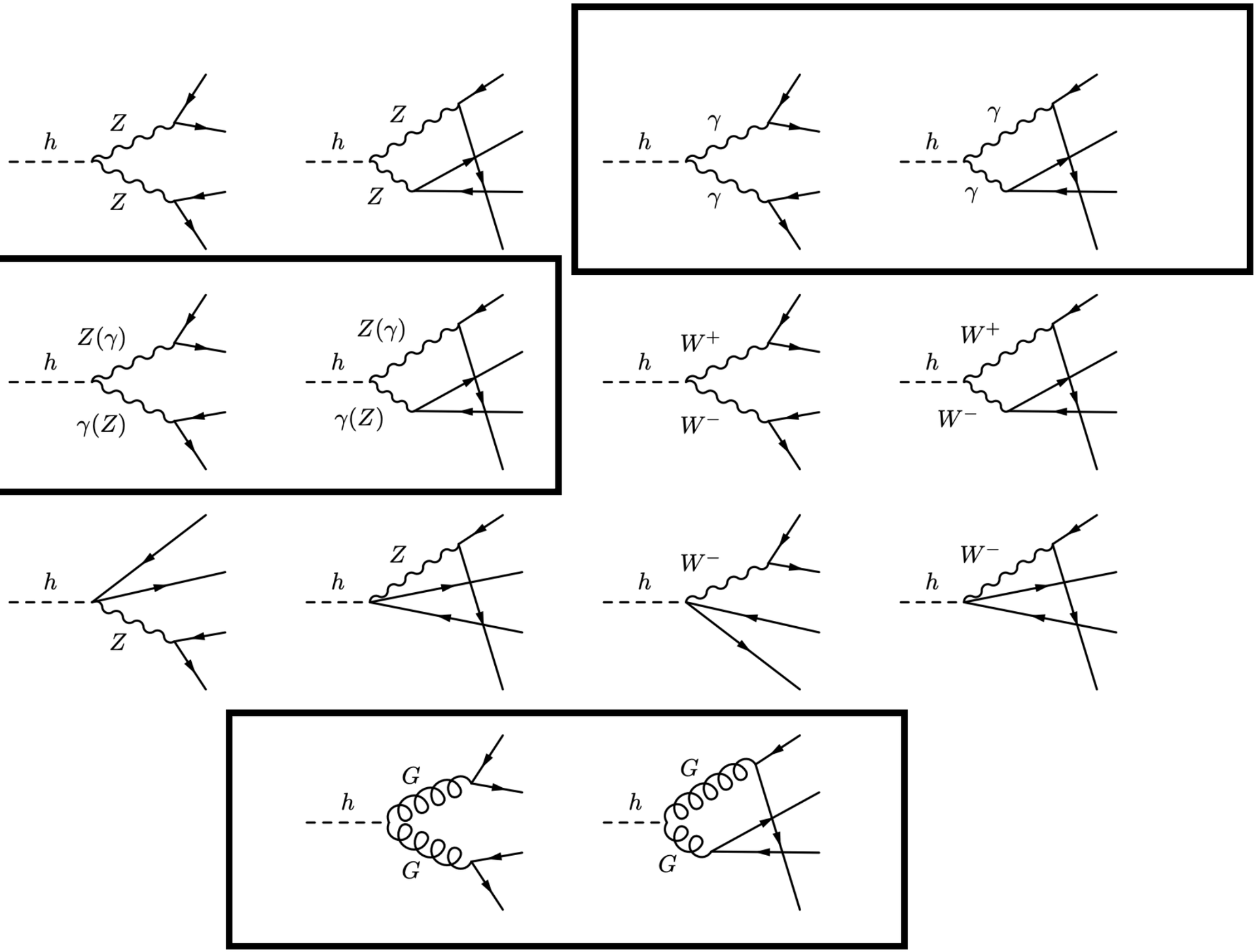
More serious, breakdown narrow width



- Narrow width approximation failing badly, as multiple intermediate states

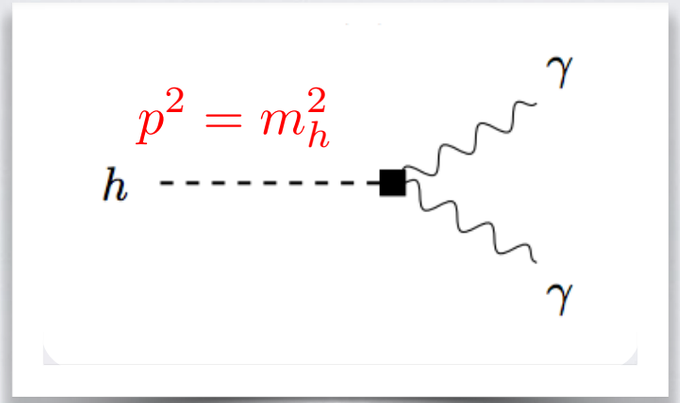


Neutral -charged current interferences



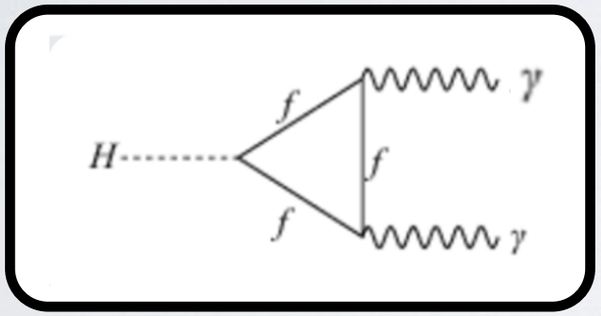
“Tree level” treatment of ops

- Consider a higgs decay

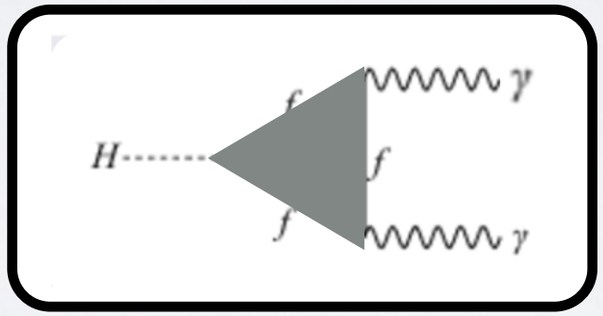


Energy through unknown literal “black box” limited to higgs mass

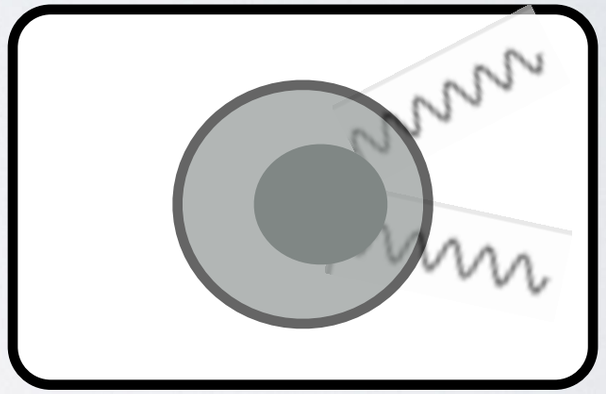
- Beyond the SM can modify this decay in many ways



With perturbative mediators



With non-perturbative couplings at loop level (not a diagram sum)



With non perturbative bound state substructure

✓ Can calculate

✗ Cannot calculate (honestly)

✗ Cannot calculate (honestly)

- Key point of EFT so long as characteristic scale is large we CAN parameterize in all 3 cases in a <u>systematically improvable way for measurements</u>

What do you get in total?

$h \to S$		$\Gamma^{SM}_{h\to S}$ (MeV)	$\tilde{C}_{HW}$	$\tilde{C}_{HB}$	$\tilde{C}_{HWB}$	$\tilde{C}_{HG}$	$\tilde{C}_{HD}$	$\tilde{C}_{H\Box}$	$\tilde{C}^{(1)}_{Hl}$	$\tilde{C}^{(3)}_{Hl}$	$\tilde{C}_{He}$	$\tilde{C}^{(1)}_{Hq}$	$\tilde{C}^{(3)}_{Hq}$	$\tilde{C}_{Hu}$	$\tilde{C}_{Hd}$	$\tilde{C}'_{ll}$
$\ell_p^+\ell_p^-\ell_r^+\ell_r^-$	$\times$ 3	0.0007	−0.11	−0.90	−0.98		−0.12	2	2.24	−2.92	−1.66	−0.39	−1.33	−0.21	0.16	2.24
$\bar{\nu}_p\nu_p\bar{\nu}_r\nu_r$	$\times$ 3	0.003	−0.77	−0.23	0.25		0.06	2	−1.80	−2.34	0.16	−0.39	−1.33	−0.21	0.16	1.89
$\ell_p^+\ell_p^-\bar{\nu}_r\nu_r$	$\times$ 6	0.003	−0.44	−0.56	−0.37		−0.03	2	0.22	−2.63	−0.75	−0.39	−1.33	−0.21	0.16	2.07
$\bar{u}_p u_p \bar{u}_r u_r$	$\times$ 1	0.003	1.41	−2.58	−3.86		−0.54	2	0.16	−6.67	0.16	−2.76	1.03	0.86	0.16	3.07
$\bar{d}_p d_p \bar{d}_r d_r$	$\times$ 3	0.015	0.78	−1.87	−2.67		−0.36	2	0.16	−5.97	0.16	1.85	0.92	−0.21	−0.26	2.73
$\bar{u}_p u_p \bar{d}_r d_r$	$\times$ 4	0.016	1.10	−2.22	−3.27		−0.45	2	0.16	−6.32	0.16	−0.45	0.98	0.32	−0.05	2.90
$\ell_p^+\ell_p^-\bar{u}_{p,r}u_{p,r}$	$\times$ 6	0.005	0.66	−1.71	−2.44		−0.33	2	1.20	−4.79	−0.75	−1.57	−0.15	0.32	0.16	2.66
$\ell_p^+\ell_p^-\bar{d}_{p,r}d_{p,r}$	$\times$ 9	0.010	0.34	−1.37	−1.84		−0.24	2	1.20	−4.45	−0.75	0.73	−0.20	−0.21	−0.05	2.48
$\bar{\nu}_p\nu_p\bar{u}_{p,r}u_{p,r}$	$\times$ 6	0.010	0.34	−1.34	−1.84		−0.24	2	−0.82	−4.50	0.16	−1.57	−0.15	0.32	0.16	2.48
$\bar{\nu}_p\nu_p\bar{d}_{p,r}d_{p,r}$	$\times$ 9	0.020	0.02	−1.02	−1.23		−0.15	2	−0.82	−4.16	0.16	0.73	−0.20	−0.21	−0.05	2.31
$\ell_p^+\ell_p^-\ell_p^+\ell_p^-$	$\times$ 3	0.0004	−0.39	−1.92	−0.63		−0.20	2	2.16	−3.26	−1.60	−0.36	−1.21	−0.19	0.14	2.40
$\bar{\nu}_p\nu_p\bar{\nu}_p\nu_p$	$\times$ 3	0.002	−0.73	−0.22	0.17		−0.03	2	−1.70	−2.73	0.13	−0.33	−1.12	−0.18	0.13	2.06
$\bar{u}_p u_p \bar{u}_p u_p$	$\times$ 2	0.003	1.35	−2.69	−3.91	−8.20	−0.58	2	0.15	−6.84	0.15	−2.71	1.06	0.83	0.15	3.17
$\bar{d}_p d_p \bar{d}_p d_p$	$\times$ 3	0.008	0.74	−1.84	−2.69	−6.27	−0.40	2	0.15	−6.09	0.15	1.83	0.94	−0.20	−0.24	2.80
$\ell_p^+\nu_p\bar{\nu}_r\ell_r^- + \text{h.c.}$	$\times$ 3	0.06	−1.51		8.09		3.16	2		1.91			−1.24			−0.16
$\bar{u}_p d_p \bar{d}_r u_r + \text{h.c.}$	$\times$ 1	0.20	−1.51		8.09		3.16	2		−0.30			0.97			−0.16
$\ell_p^+\nu_p\bar{u}_{p,r}d_{p,r} + \text{h.c.}$	$\times$ 6	0.39	−1.51		8.09		3.16	2		0.81			−0.13			−0.16
$\bar{u}_p u_p \bar{d}_p d_p$	$\times$ 2	0.20	−1.42	−0.07	7.79	−1.01	3.08	2	0.006	−0.42	0.006	−0.02	0.97	0.01	−0.002	−0.10
$\ell_p^+\ell_p^-\bar{\nu}_p\nu_p$	$\times$ 3	0.03	−1.53	0.02	8.18		3.19	2	−0.002	2.08	−0.04	−0.02	−1.30	−0.01	0.008	−0.24
tot. $h \to 4f$		0.985	−1.29	−0.17	7.00	−0.28	2.80	2	−0.004	−0.15	−0.003	0.009	0.25	0.005	−0.003	0.13

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

What do you get in total?

$h \to S$		$\Gamma^{SM}_{h\to S}$ (MeV)	$\tilde{C}_{HW}$	$\tilde{C}_{HB}$	$\tilde{C}_{HWB}$	$\tilde{C}_{HG}$	$\tilde{C}_{HD}$	$\tilde{C}_{H\Box}$	$\tilde{C}^{(1)}_{Hl}$	$\tilde{C}^{(3)}_{Hl}$	$\tilde{C}_{He}$	$\tilde{C}^{(1)}_{Hq}$	$\tilde{C}^{(3)}_{Hq}$	$\tilde{C}_{Hu}$	$\tilde{C}_{Hd}$	$\tilde{C}'_{ll}$
$\ell_p^+\ell_p^-\ell_r^+\ell_r^-$	$\times$ 3	0.0007	0.26	−1.30	−0.76		0.23	2	2.30	−2.71	−1.58	−0.39	−1.34	−0.20	0.15	2.17
$\bar{\nu}_p\nu_p\bar{\nu}_r\nu_r$	$\times$ 3	0.003	−0.78	−0.22	−0.80		−0.44	2	−1.81	−2.90	0.15	−0.39	−1.34	−0.20	0.15	2.17
$\ell_p^+\ell_p^-\bar{\nu}_r\nu_r$	$\times$ 6	0.003	−0.25	−0.75	−0.79		−0.11	2	0.24	−2.81	−0.71	−0.39	−1.34	−0.20	0.15	2.17
$\bar{u}_p u_p \bar{u}_r u_r$	$\times$ 1	0.003	1.44	−2.63	−0.68		1.00	2	0.15	−4.86	0.15	−2.76	1.02	0.80	0.15	2.17
$\bar{d}_p d_p \bar{d}_r d_r$	$\times$ 3	0.015	0.73	−1.82	−0.73		0.53	2	0.15	−4.86	0.15	1.84	0.89	−0.20	−0.24	2.17
$\bar{u}_p u_p \bar{d}_r d_r$	$\times$ 4	0.016	1.09	−2.22	−0.71		0.77	2	0.15	−4.86	0.15	−0.46	0.96	0.30	−0.04	2.17
$\ell_p^+\ell_p^-\bar{u}_{p,r}u_{p,r}$	$\times$ 6	0.005	0.86	−1.94	−0.73		0.62	2	1.23	−3.79	−0.71	−1.57	−0.16	0.30	0.15	2.17
$\ell_p^+\ell_p^-\bar{d}_{p,r}d_{p,r}$	$\times$ 9	0.010	0.50	−1.55	−0.75		0.38	2	1.23	−3.79	−0.71	0.73	−0.23	−0.20	−0.04	2.17
$\bar{\nu}_p\nu_p\bar{u}_{p,r}u_{p,r}$	$\times$ 6	0.010	0.35	−1.35	−0.78		0.28	2	−0.83	−3.89	0.15	−1.57	−0.16	0.30	0.15	2.17
$\bar{\nu}_p\nu_p\bar{d}_{p,r}d_{p,r}$	$\times$ 9	0.020	−0.01	−0.99	−0.78		0.05	2	−0.83	−3.89	0.15	0.73	−0.23	−0.20	−0.04	2.17
$\ell_p^+\ell_p^-\ell_p^+\ell_p^-$	$\times$ 3	0.0004	0.01	−2.28	−0.08		0.34	2	2.23	−2.87	−1.50	−0.36	−1.23	−0.18	0.14	2.24
$\bar{\nu}_p\nu_p\bar{\nu}_p\nu_p$	$\times$ 3	0.002	−0.74	−0.21	−0.72		−0.45	2	−1.70	−3.21	0.13	−0.33	−1.13	−0.17	0.13	2.30
$\bar{u}_p u_p \bar{u}_p u_p$	$\times$ 2	0.003	1.39	−2.72	−0.51	−8.03	1.06	2	0.14	−4.91	0.14	−2.70	1.05	0.77	0.14	2.20
$\bar{d}_p d_p \bar{d}_p d_p$	$\times$ 3	0.008	0.69	−1.79	−0.65	−6.18	0.55	2	0.14	−4.92	0.14	1.82	0.92	−0.19	−0.22	2.21
$\ell_p^+\nu_p\bar{\nu}_r\ell_r^- + \text{h.c.}$	$\times$ 3	0.06	−1.49				−0.5	2		−2.50			−1.26			2.05
$\bar{u}_p d_p \bar{d}_r u_r + \text{h.c.}$	$\times$ 1	0.20	−1.49				−0.5	2		−4.74			0.97			2.05
$\ell_p^+\nu_p\bar{u}_{p,r}d_{p,r} + \text{h.c.}$	$\times$ 6	0.39	−1.49				−0.5	2		−3.62			−0.14			2.05
$\bar{u}_p u_p \bar{d}_p d_p$	$\times$ 2	0.20	−1.41	−0.07	−0.04	−0.98	−0.47	2	0.006	−4.72	0.006	−0.02	0.96	0.01	−0.002	2.04
$\ell_p^+\ell_p^-\bar{\nu}_p\nu_p$	$\times$ 3	0.03	−1.51	0.01	−0.07		−0.55	2	−0.0005	−2.43	−0.03	−0.02	−1.32	−0.009	0.007	2.02
tot. $h \to 4f$		0.985	−1.27	−0.17	−0.08	−0.28	−0.40	2	−0.004	−4.03	−0.003	0.009	0.24	0.004	−0.003	2.06

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

What is the shifted Higgs Width in the SMEFT?

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

$$\frac{\delta\Gamma^{SMEFT}_{h,full}}{\Gamma^{SM}_h} \simeq 1 - 1.40\,\tilde{C}_{HB} - 1.22\,\tilde{C}_{HW} + 2.89\,\tilde{C}_{HWB} + 50.6\,\tilde{C}_{HG}$$
$$+ 1.83\,\tilde{C}_{H\Box} + 0.34\,\tilde{C}_{HD} + 0.70\,\tilde{C}'_{ll}$$
$$- 7.85\,\hat{Y}^{u}_{cc}\,\mathrm{Re}\,\tilde{C}_{uH} - 48.5\,\hat{Y}^{d}_{bb}\,\mathrm{Re}\,\tilde{C}_{dH} - 12.3\,\hat{Y}^{\ell}_{\tau\tau}\,\mathrm{Re}\,\tilde{C}_{eH}$$
$$+ 0.002\,\tilde{C}^{(1)}_{Hq} + 0.06\,\tilde{C}^{(3)}_{Hq} + 0.001\,\tilde{C}_{Hu} - 0.0008\,\tilde{C}_{Hd}$$
$$- 0.0008\,\tilde{C}^{(1)}_{Hl} - 1.38\,\tilde{C}^{(3)}_{Hl} - 0.0007\,\tilde{C}_{He}.$$

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

$$\frac{\delta\Gamma^{SMEFT}_{h,full}}{\Gamma^{SM}_h} \simeq 1 - 1.50\,\tilde{C}_{HB} - 1.21\,\tilde{C}_{HW} + 1.21\,\tilde{C}_{HWB} + 50.6\,\tilde{C}_{HG}$$
$$+ 1.83\,\tilde{C}_{H\Box} - 0.43\,\tilde{C}_{HD} + 1.17\,\tilde{C}'_{ll}$$
$$- 7.85\,\hat{Y}^{u}_{cc}\,\mathrm{Re}\,\tilde{C}_{uH} - 48.5\,\hat{Y}^{d}_{bb}\,\mathrm{Re}\,\tilde{C}_{dH} - 12.3\,\hat{Y}^{\ell}_{\tau\tau}\,\mathrm{Re}\,\tilde{C}_{eH}$$
$$+ 0.002\,\tilde{C}^{(1)}_{Hq} + 0.06\,\tilde{C}^{(3)}_{Hq} + 0.001\,\tilde{C}_{Hu} - 0.0007\,\tilde{C}_{Hd}$$
$$- 0.0009\,\tilde{C}^{(1)}_{Hl} - 2.32\,\tilde{C}^{(3)}_{Hl} - 0.0006\,\tilde{C}_{He},$$

https://arxiv.org/pdf/1906.06949.pdf Brivio, Corbett, Trott

- Considering the inclusive phase space differences, cuts will matter.

$$n_k^{\text{signal}} = \mathcal{L}_k \sum_i \sum_f (\sigma \times \mathrm{B})_{if} (\epsilon \times A)_k^{if}$$

To push an STXS measurement to SMEFT properly, acceptance corrections needed.

Efficient calculation at dimensions six

- Many Wilson coefficient dependencies in the width calc. The calc was organised around dependency on kinematics x parameter dependence.

Func. of 4 vectors (kinematics)

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

If SM kinematics
- rescaling for some Wilson
- coefficient dependence.

$\frac{\langle H^\dagger H \rangle}{\Lambda^2}$ Expansion will not change Kinematics. Some dim 8 effects for free?

If non-SM kinematics then a unique phase space Integral set. Novel kinematic factors

$\frac{p_i \cdot p_j}{\Lambda^2}$ Different SMEFT Expansion factors present

- Can this kinematics based approach make higher order calcs easier/more efficient or possible? HELL YES! This is what the geoSMEFT is exactly about.

Automation of this approach (Just L6)

- Need to keep all operators and carefully compute S matrix elements avoiding uncontrolled approximations (and human error)
- Automation of leading order SMEFT in the SMEFTsim package now

https://arxiv.org/abs/1709.06492



How big should these effects be?

- W mass shift:

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

- Higgs width shifts (anomalous Higgs couplings)

$$\begin{aligned}\frac{\delta\Gamma_{h,full}^{SMEFT}}{\Gamma_h^{SM}} \simeq\ & 1 - 1.40\,\tilde{C}_{HB} - 1.22\,\tilde{C}_{HW} + 2.89\,\tilde{C}_{HWB} + 50.6\,\tilde{C}_{HG} \\ & + 1.83\,\tilde{C}_{H\Box} + 0.34\,\tilde{C}_{HD} + 0.70\,\tilde{C}'_{ll} \\ & - 7.85\,\hat{Y}_{\substack{u\\cc}}\,\mathrm{Re}\,\tilde{C}_{uH} - 48.5\,\hat{Y}_{\substack{d\\bb}}\,\mathrm{Re}\,\tilde{C}_{dH} - 12.3\,\hat{Y}_{\substack{\ell\\\tau\tau}}\,\mathrm{Re}\,\tilde{C}_{eH} \\ & + 0.002\,\tilde{C}_{Hq}^{(1)} + 0.06\,\tilde{C}_{Hq}^{(3)} + 0.001\,\tilde{C}_{Hu} - 0.0008\,\tilde{C}_{Hd} \\ & - 0.0008\,\tilde{C}_{Hl}^{(1)} - 1.38\,\tilde{C}_{Hl}^{(3)} - 0.0007\,\tilde{C}_{He}.\end{aligned}$$

$$\begin{aligned}\frac{\delta\Gamma_{h,full}^{SMEFT}}{\Gamma_h^{SM}} \simeq\ & 1 - 1.50\,\tilde{C}_{HB} - 1.21\,\tilde{C}_{HW} + 1.21\,\tilde{C}_{HWB} + 50.6\,\tilde{C}_{HG} \\ & + 1.83\,\tilde{C}_{H\Box} - 0.43\,\tilde{C}_{HD} + 1.17\,\tilde{C}'_{ll} \\ & - 7.85\,\hat{Y}_{\substack{u\\cc}}\,\mathrm{Re}\,\tilde{C}_{uH} - 48.5\,\hat{Y}_{\substack{d\\bb}}\,\mathrm{Re}\,\tilde{C}_{dH} - 12.3\,\hat{Y}_{\substack{\ell\\\tau\tau}}\,\mathrm{Re}\,\tilde{C}_{eH} \\ & + 0.002\,\tilde{C}_{Hq}^{(1)} + 0.06\,\tilde{C}_{Hq}^{(3)} + 0.001\,\tilde{C}_{Hu} - 0.0007\,\tilde{C}_{Hd} \\ & - 0.0009\,\tilde{C}_{Hl}^{(1)} - 2.32\,\tilde{C}_{Hl}^{(3)} - 0.0006\,\tilde{C}_{He},\end{aligned}$$

- The SMEFT effects (the numbers in the formula) are calculable in the EFT — independent of the UV. Calculate once and done!
  How big depends on Wilson coefficients and the cut off.

The Hierarchy Problem

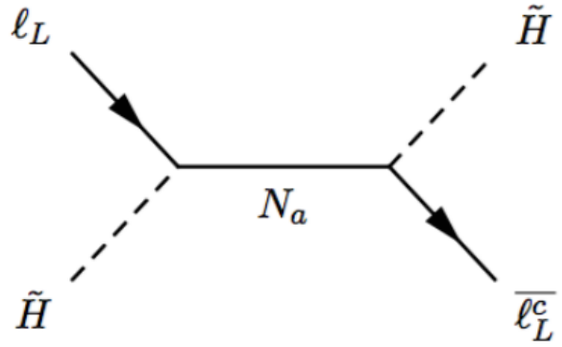
> In a hierarchy, every employee tends to rise to his level of incompetence.
>
> **Laurence J. Peter**

…not this one, the physics one…

Hierarchy problem solid example

- Consider it in the context of a model you probably think is sensible.
  The seesaw model

- Integrating out the seesaw at tree level



$$(\not{s} + m_p)\frac{-1}{m_p^2}\left(\frac{1}{1 - s^2/m_p^2}\right) = -\frac{1}{m_p} - \frac{\not{s}}{m_p^2} - \frac{s^2}{m_p^3} + \cdots$$

- Extremely well known result

$$\mathcal{L}^{(5)} = \frac{c_{\beta\,\kappa}}{2}\,\mathcal{Q}_5^{\beta\,\kappa} + h.c. \qquad c_{\beta\,\kappa} = (\omega_\beta^p)^T\,\omega_\kappa^p/m_p$$

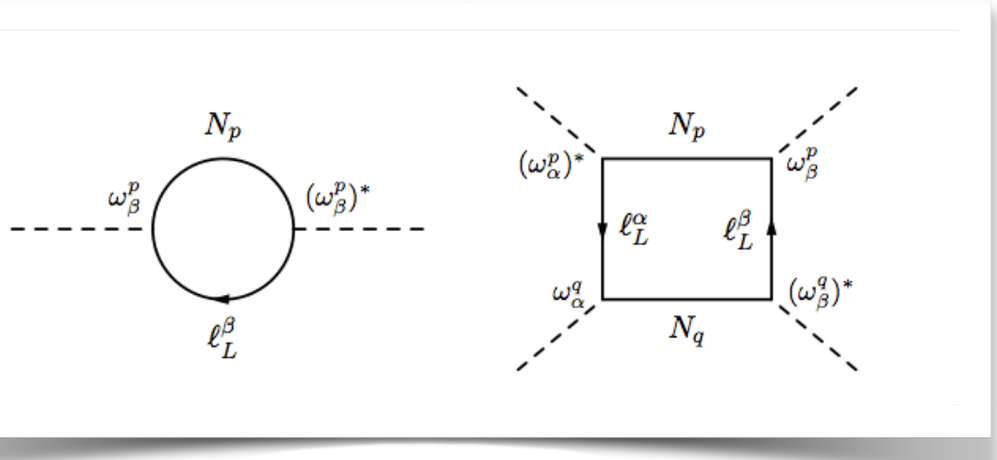
p summed over

What is the Hierarchy problem?

- Consider it in the context of a model you probably think is sensible.
  The seesaw model at one loop:

$$
\begin{aligned}
2\,\mathcal{L}_{N_p} &= \overline{N_p}(i\partial\!\!\!/ - m_p)N_p - \overline{\ell_L^\beta}\,\tilde{H}\omega_\beta^{p,\dagger}N_p, \\
&- \overline{\ell_L^{c\beta}}\,\tilde{H}^*\,\omega_\beta^{p,T}N_p - \overline{N_p}\,\omega_\beta^{p,*}\tilde{H}^T\ell_L^{c\beta} - \overline{N_p}\,\omega_\beta^p\tilde{H}^\dagger\ell_L^\beta.
\end{aligned}
$$

- How such a fermion talks to the SM at $d \leq 4$



- Direct threshold matching onto $\mathcal{L}_{SM}$

$$
\Delta m^2 = m_p^2\frac{|\omega_p|^2}{8\pi^2}, \quad \Delta\lambda = -5\frac{(\omega_q\cdot\omega^{p,\star})(\omega_p\cdot\omega^{q,\star})}{64\pi^2}.
$$

In agreement with J. A. Casas et al.
Phys. Rev. D 62, 053005 (2000) others..

Measured Higgs mass
Absorbs this UV physics effect, but it can be BIG!

Details of the Matching

- The problem here is we are starting with

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$

$$- \lambda\left(H^\dagger H - \frac{1}{2}v^2\right)^2 - \left[H^{\dagger j}\overline{d}\, Y_d\, q_j + \tilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \text{h.c.}\right],$$

$$+\frac{1}{2}\left[\overline{N_p}(i\not{\partial} - m_p)N_p - \overline{\ell_L^\beta}\tilde{H}\omega_\beta^{p,\dagger}N_p - \overline{\ell_L^{c\beta}}\tilde{H}^*\,\omega_\beta^{p,T}N_p - \overline{N_p}\,\omega_\beta^{p,*}\tilde{H}^T\ell_L^{c\beta} - \overline{N_p}\,\omega_\beta^p\tilde{H}^\dagger\ell_L^\beta\right]$$

Taylor expand for low energy experimental measurements (i.e. match)

Tree level:

$$\mathcal{L}^{(5)} = \frac{c_{\beta\kappa}}{2}\,Q_5^{\beta\kappa} + h.c.$$

Neutrino masses. Good!

Loop level:

$$V(H^\dagger H) = \lambda(H^\dagger H)^2 - v^2 H^\dagger H + \lambda\frac{v^4}{4} - \frac{m_p^2\omega_p^2}{8\pi^2}H^\dagger H + \cdots$$

Did this just violate the decoupling theorem?

Decoupling theorem:T. Appelquist, J. Carazzone, Phys. Rev. D11, 2856 (1975

For any 1PI Feynman graph with external vector mesons only but containing internal fermions, when all external momenta (i.e. p^2) are small relative to m^2, then apart from coupling constant and field strength renormalization the graph will be suppressed by some power of m relative to a graph with the same number of external vector mesons but no internal fermions.[25]

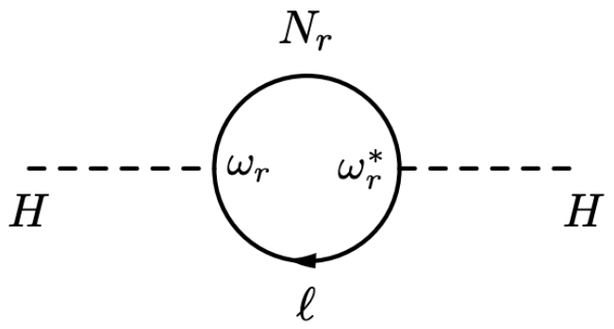
- Consistent with decoupling theorem and

$$\langle\rangle \sim O^0_{SM} + \frac{f_1(s,t,u)}{M^2_{heavy}} + \frac{f_2(s,t,u)}{M^4_{heavy}} + \cdots$$

Its just that the “coupling constant” higgs mass has a finite renormalization.
Its a problem because dimensional analysis is not working as we expect.

Details of the Matching

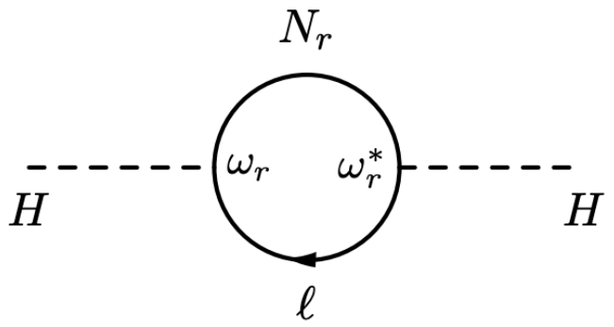
$$\Delta = m_\ell^2 x + (x-1)(p^2 x - m_r^2).$$



$$\begin{aligned} i\Pi^{full}_{HH^\dagger}(p^2) &= -2\,|\omega_r^2| \int \frac{d^4\ell}{(2\pi)^4} \int_0^1 dx \frac{\ell^2 + x(x-1)p^2}{[\ell^2 - \Delta]^2}, \\ &= -\frac{i|\omega_r^2|}{16\,\pi^2\,\epsilon}(2m_\ell^2 + 2m_r^2 - p^2) - \frac{i|\omega_r^2|}{48\,\pi^2}(3m_\ell^2 + 3m_r^2 - p^2), \\ &+ \frac{i|\omega_r^2|}{8\,\pi^2} \int_0^1 dx (2m_r^2(x-1) - x(2m_\ell^2 + 3p^2(x-1)) \log[\frac{\mu^2}{m_\ell^2 x + (x-1)(p^2 x - m_r^2)}], \end{aligned}$$

Details of the Matching

$$\Delta = m_\ell^2 x + (x-1)(p^2 x - m_r^2).$$

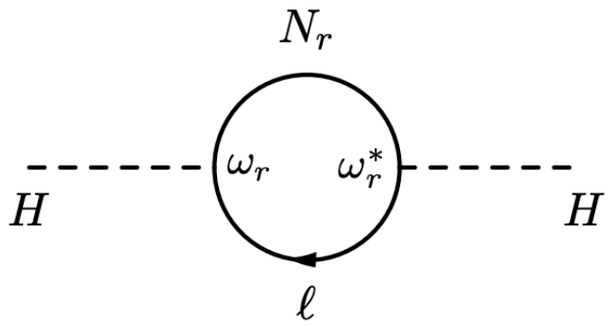


$$\begin{aligned} i\Pi^{full}_{HH^\dagger}(p^2) &= -2\,|\omega_r^2| \int \frac{d^4\ell}{(2\pi)^4} \int_0^1 dx \frac{\ell^2 + x(x-1)p^2}{[\ell^2 - \Delta]^2}, \\ &= -\frac{i|\omega_r^2|}{16\,\pi^2\,\epsilon}(2m_\ell^2 + 2m_r^2 - p^2) - \frac{i|\omega_r^2|}{48\,\pi^2}(3m_\ell^2 + 3m_r^2 - p^2), \\ &+ \frac{i|\omega_r^2|}{8\,\pi^2} \int_0^1 dx (2m_r^2(x-1) - x(2m_\ell^2 + 3p^2(x-1)) \log[\frac{\mu^2}{m_\ell^2 x + (x-1)(p^2 x - m_r^2)}], \end{aligned}$$

- Removed by renormalizing the UV theory
- Remaining terms simplified by expanding.

Details of the Matching

$$\Delta = m_\ell^2 x + (x-1)(p^2 x - m_r^2).$$



$$\begin{aligned} i\Pi^{full}_{HH^\dagger}(p^2) &= -2\,|\omega_r^2| \int \frac{d^4\ell}{(2\pi)^4} \int_0^1 dx \frac{\ell^2 + x(x-1)p^2}{[\ell^2 - \Delta]^2}, \\ &= -\frac{i|\omega_r^2|}{16\,\pi^2\,\epsilon}(2m_\ell^2 + 2m_r^2 - p^2) - \frac{i|\omega_r^2|}{48\,\pi^2}(3m_\ell^2 + 3m_r^2 - p^2), \\ &+ \frac{i|\omega_r^2|}{8\,\pi^2} \int_0^1 dx (2m_r^2(x-1) - x(2m_\ell^2 + 3p^2(x-1)) \log[\frac{\mu^2}{m_\ell^2 x + (x-1)(p^2 x - m_r^2)}], \end{aligned}$$

- Removed by renormalizing the UV theory

- Remaining terms simplified by expanding before integrating.

$$\frac{1}{k^2 - m_r^2} = -\frac{1}{m_r^2}\left[1 + \frac{k^2}{m_r^2} + \cdots\right]$$

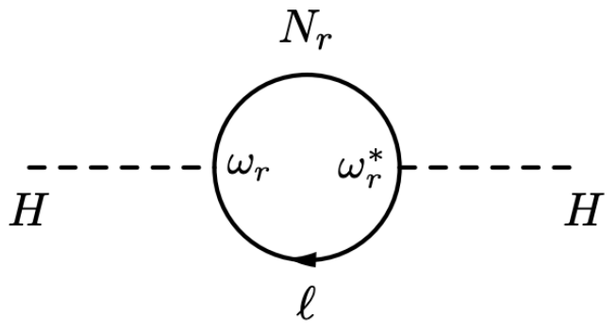
Scaleless integrals vanish in dimensional regularisation these are all 0

$$i\Pi^{EFT}_{HH^\dagger}(p^2) = \frac{|\omega_r^2|}{2\,m_r^2} \int \frac{d^4k}{(2\pi)^4} \frac{k^2}{k^2} +$$

One loop contributions from the $H^\dagger H$ operator dropped as all IR scales expanded

Details of the Matching

$$\Delta = m_\ell^2 x + (x-1)(p^2 x - m_r^2).$$



$$\begin{aligned} i\Pi^{full}_{HH^\dagger}(p^2) &= -2\,|\omega_r^2| \int \frac{d^4\ell}{(2\pi)^4} \int_0^1 dx \frac{\ell^2 + x(x-1)p^2}{[\ell^2 - \Delta]^2}, \\ &= -\frac{i|\omega_r^2|}{16\,\pi^2\,\epsilon}(2m_\ell^2 + 2m_r^2 - p^2) - \frac{i|\omega_r^2|}{48\,\pi^2}(3m_\ell^2 + 3m_r^2 - p^2), \\ &+ \frac{i|\omega_r^2|}{8\,\pi^2} \int_0^1 dx (2m_r^2(x-1) - x(2m_\ell^2 + 3p^2(x-1)) \log[\frac{\mu^2}{m_\ell^2 x + (x-1)(p^2 x - m_r^2)}], \end{aligned}$$

- Removed by renormalizing the UV theory

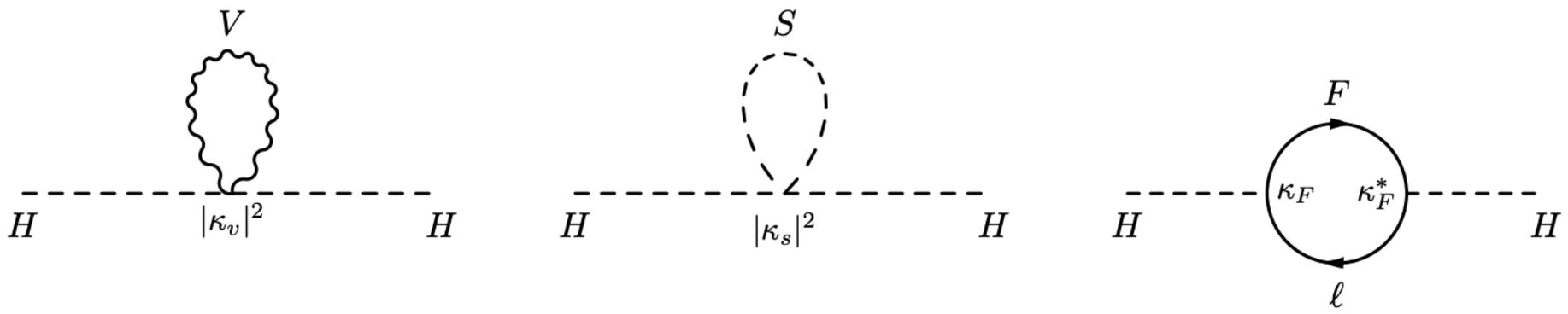
- Remaining terms simplified by expanding before integrating.

$$i\Pi^{full,exp}_{HH^\dagger}(p^2) = \frac{-i|\omega_r^2|\,m_r^2}{8\pi^2}\left(1 + \log\frac{\mu^2}{m_r^2}\right) + \frac{i|\omega_r^2|\,p^2}{32\pi^2}\left(1 + 2\log\frac{\mu^2}{m_r^2}\right)$$

Removed by wavefunction reform

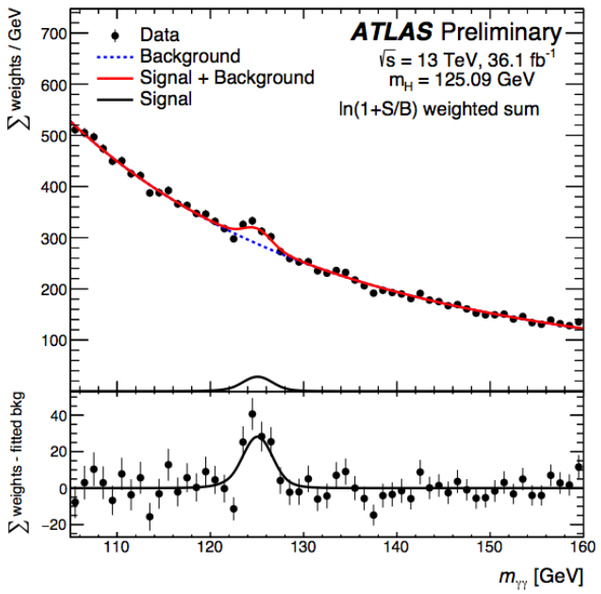
DO this calculation yourself to check! (see SMEFT review for details 1706.08945)

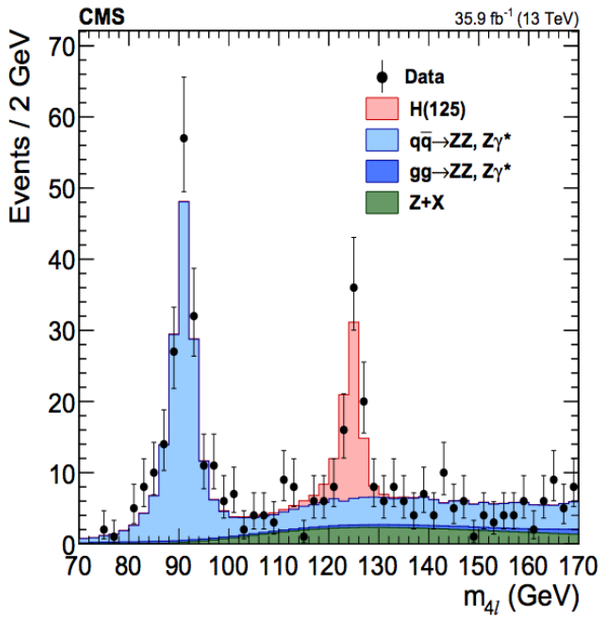
But.. this keeps happening with UV field content..



$$\Delta V(H^\dagger H) \simeq H^\dagger H \left(\frac{3\,|\kappa_v|^2\, m_v^2\; N_v}{16\,\pi^2} + \frac{|\kappa_s|^2\, m_s^2\, N_s}{16\,\pi^2} - \frac{|\kappa_F|^2\, m_F^2\, N_F}{16\,\pi^2} \right) + \cdots ,$$

- What do we measure at low scales:





$$\hat{m}_h = \sqrt{2\lambda} v \equiv 125.09\text{Gev}$$

$$v_0^2 + \frac{N_i\, g_i^2 m_B^2}{16\pi^2} - \frac{N_2\, g_F^2 m_F^2}{16\pi^2} + \cdots$$

Why do all these numbers cancel so much down to the EW scale?

Does this parameter violate a symmetry?

- So long as the SM has a scale to start with :

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$

$$- \lambda\left(H^\dagger H - \frac{1}{2}v^2\right)^2 - \left[H^{\dagger j}\overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \text{h.c.}\right],$$

Consider the SM in the scaleless limit, however

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$

$$- \lambda\left(H^\dagger H \blacksquare\right)^2 - \left[H^{\dagger j}\overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \text{h.c.}\right],$$

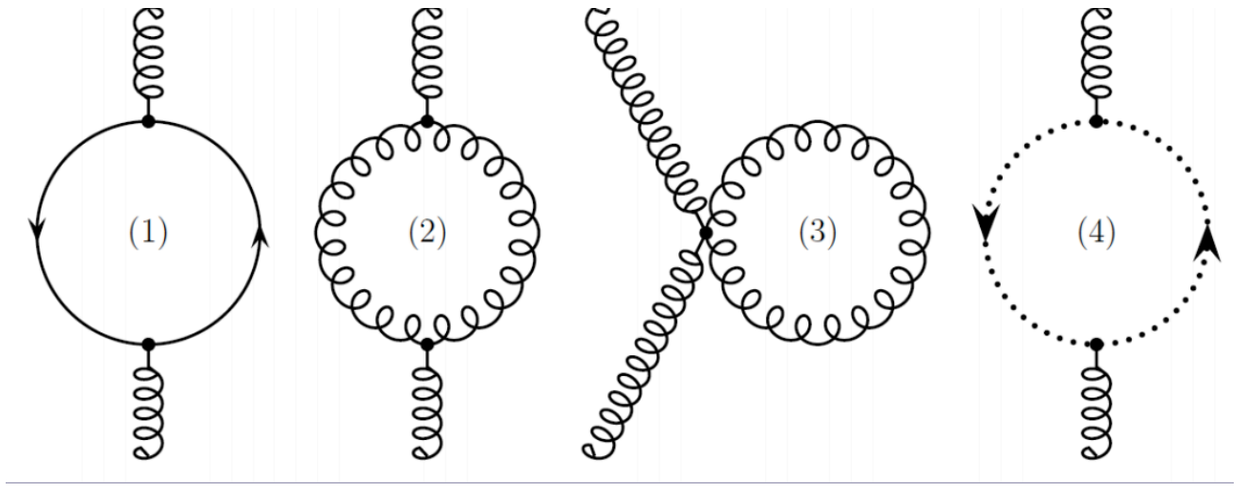
When no mass scales a conformal symmetry:

$$x \to \lambda x$$
$$t \to \lambda t$$
$$H \to H/\lambda$$

In scalar sector.

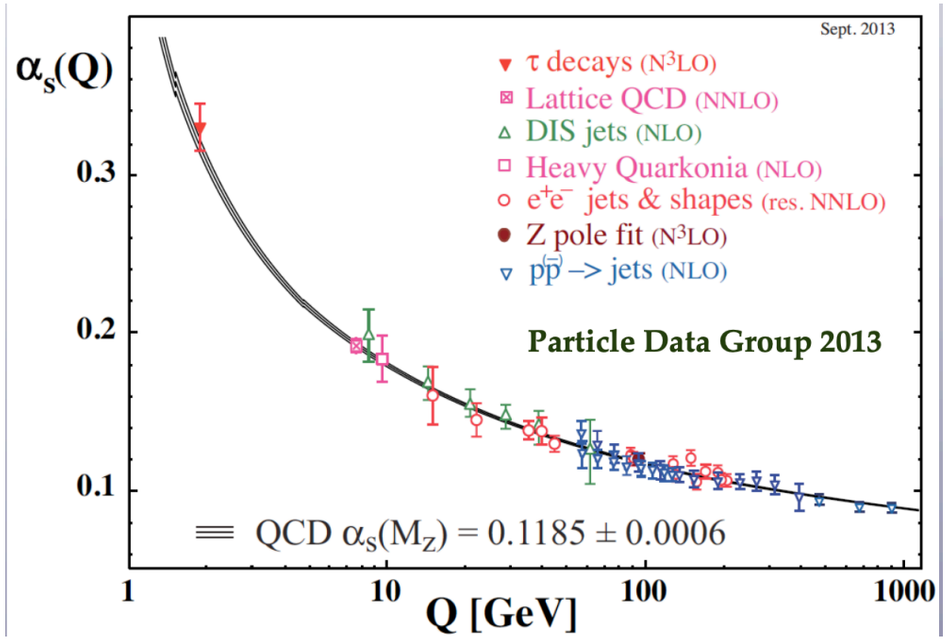
Scales of the SM..

- Not that simple, the SM spontaneously generated a scale:



Famously: $$b_0 = \frac{33 - 2n_f}{12\pi}$$

$$\alpha_{\rm ren}(\mu^2) = \frac{1}{b_0 \log \mu^2/\Lambda^2}$$



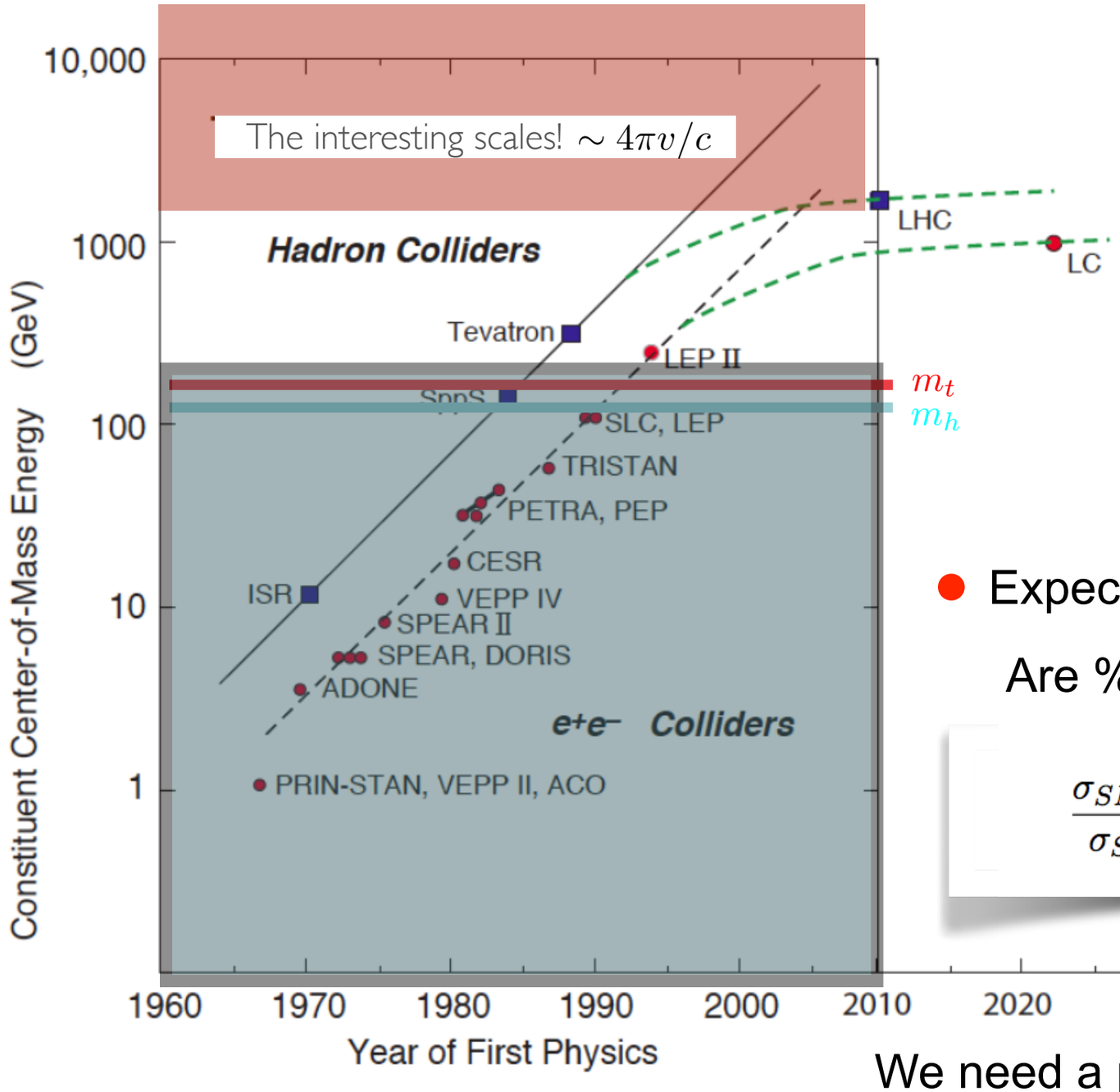
- A scale of order $\Lambda_{QCD} \sim m_p \sim 1\text{GeV}$

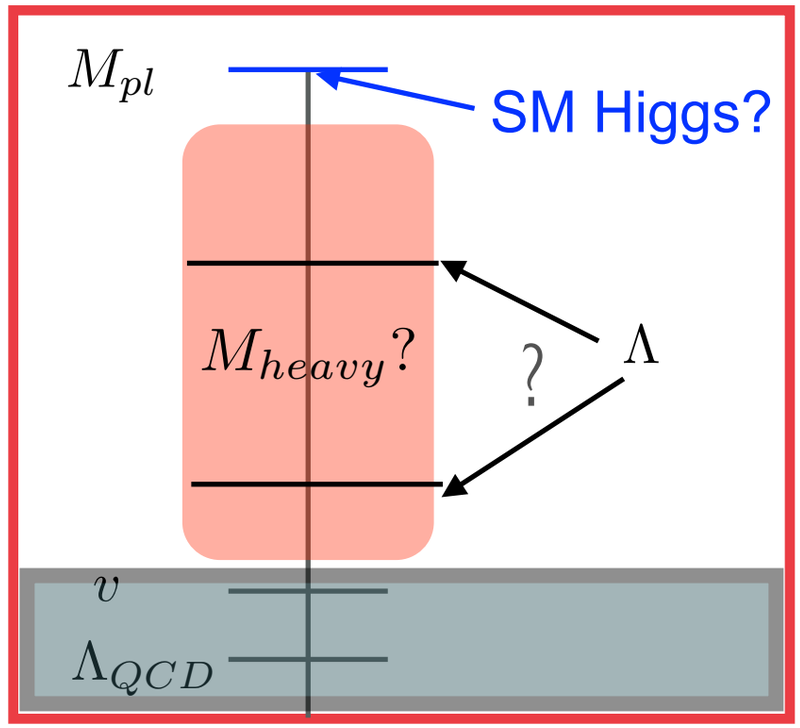
  In the theory. A further scale due to Asymptotic nature of perturbation theory.

- These scales are less than

$$\hat{m}_h = \sqrt{2\lambda} v \equiv 125.09\text{Gev}$$

Very Interesting scales a bit out of direct reach





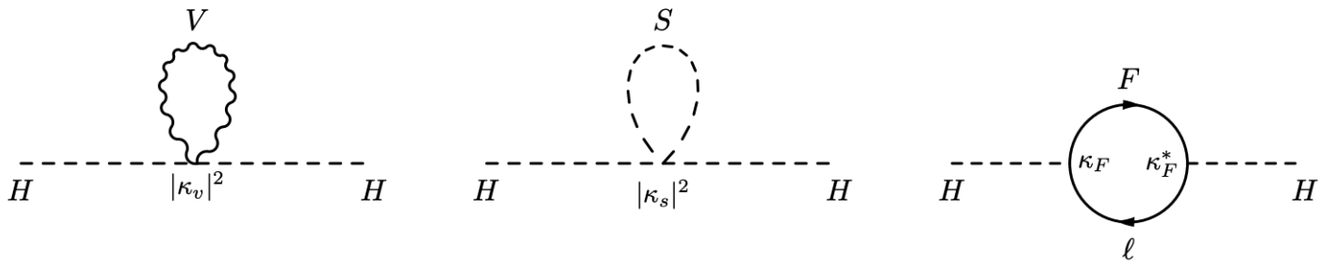
- Expect % effects on Higgs properties

  Are % level deviations ruled out? NO.

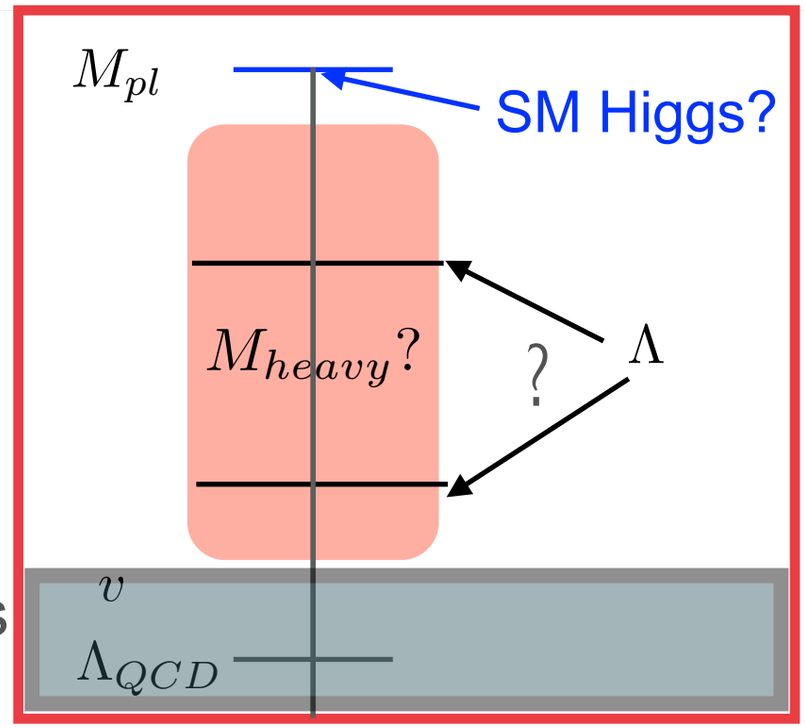
$$\frac{\sigma_{SM+i}}{\sigma_{SM}} \simeq \frac{1}{16\,\pi^2}\left(\frac{N_i^2\,|\kappa_i|^2\kappa'}{g_{SM}\,\lambda}\right) + \cdots$$

We need a precision Higgs pheno program!

We are after % level effects



$$\Delta V(H^\dagger H) \simeq H^\dagger H \left(\frac{3\,|\kappa_v|^2\, m_v^2\, N_v}{16\,\pi^2} + \frac{|\kappa_s|^2\, m_s^2\, N_s}{16\,\pi^2} - \frac{|\kappa_F|^2\, m_F^2\, N_F}{16\,\pi^2} \right) + \cdots ,$$



- Avoiding tuning one expects the Higgs mass scales

$$m_h \sim |\kappa_i| M_{heavy} \sqrt{N_i}/4\pi$$

- SMEFT Effects avoiding tuning scale as:

$$\frac{1}{|A_{SM}|^2}\left(A_{SM}\frac{C_i v^2}{\Lambda^2}\right) \sim \frac{1}{A_{SM}}\frac{C_i\, v^2}{\Lambda^2}$$

$$\sim \frac{1}{A_{SM}}\frac{C_i\, v^2\, |\kappa_i|^2\, N_i}{\hat{m}_h^2 16\pi^2}$$

$$\sim \frac{1}{g_{SM}}\frac{C_i\, |\kappa_i|^2\, N_i}{\lambda\, 16\pi^2}$$

$$\frac{\sigma_{SM+i}}{\sigma_{SM}} \simeq \frac{1}{16\,\pi^2}\left(\frac{N_i^2\,|\kappa_i|^2\kappa'}{g_{SM}\,\lambda}\right) + \cdots$$