Standard Model Effective Field Theory - Indirect constraints on fundamental physics

Anke Biekötter - IPPP Durham
Outline

• Motivation: Why is the Standard Model incomplete?

• What is an effective field theory?
• How can EFTs help us to explore the new physics parameter space?

• Confronting EFTs with data: LHC global fits
The Standard Model of particle physics

quantamagazine.org
Physics beyond the Standard Model

Muon g-2

W boson mass (?)

Neutrino oscillations

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Backup slide
Physics beyond the SM?

Extra dimensions
Leptoquarks
Supersymmetry
Beyond Standard Model
Axion-like particles
Z’ bosons
4th generation

Is new physics hiding at the TeV scale?
Can we test its effects at lower scales?
Effective field theory - EFT
Effective field theory - EFT

Heavy particles that we cannot resolve live here

Hierarchy of scales

Describe NP by higher-order interactions of SM fields
Top down - matching of a new model

Model with new heavy vector boson
Start from full UV-complete model and match onto EFT
Top down - matching of a new model

Model with **new heavy vector boson**

Start from **full** UV-complete model and match onto **EFT**
EFTs from the bottom-up

(review: Brivio, Trott (1706.08945))
EFTs from the bottom-up

(review: Brivio, Trott (1706.08945))

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^8} \mathcal{O}_j^{(8)} + \cdots \]

59 operators (MFV)

Odd dimensions violate lepton or baryon number
SMEFT advantages

- Proper, renormalizable quantum field theory
- Minimal assumptions on UV completion
- Universal language for data interpretation
- Allows combination of data from multiple experiments

Systematic program for indirect searches!
# Warsaw Basis

<table>
<thead>
<tr>
<th>1: $X^3$</th>
<th>2: $H^6$</th>
<th>3: $H^4D^2$</th>
<th>5: $\psi^2H^3 + \text{h.c.}$</th>
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<tbody>
<tr>
<td>$Q_G$</td>
<td>$f^{ABC}G^A_{\mu}G^B_{\nu}G^C_{\rho}$</td>
<td>$H_H$</td>
<td>$(H^\dagger H)^3$</td>
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<td>$(H^\dagger H)^2$</td>
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<tr>
<td>$Q_W$</td>
<td>$\epsilon^{ijk}W^I_{\mu}W^J_{\nu}W^K_{\rho}$</td>
<td>$Q_H$</td>
<td>$(H^\dagger H)(H^\dagger H)$</td>
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<td>$Q_{\bar{W}}$</td>
<td>$\epsilon^{ijk}\bar{W}^I_{\mu}\bar{W}^J_{\nu}\bar{W}^K_{\rho}$</td>
<td>$Q_H$</td>
<td>$(H^\dagger D_{\mu}H)(H^\dagger D_{\mu}H)$</td>
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<th>4: $X^2H^2$</th>
<th>6: $\psi^2XH + \text{h.c.}$</th>
<th>7: $\psi^2H^2D$</th>
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<td>$Q_{HG}$</td>
<td>$H^\dagger H \bar{G}^A_{\mu}G^A_{\mu}$</td>
<td>$Q_{\psi H}$</td>
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<td>$Q_{H\bar{G}}$</td>
<td>$H^\dagger H \bar{G}^A_{\mu}G^A_{\mu}$</td>
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<td>$Q_{HB}$</td>
<td>$H^\dagger H B_{\mu\nu}B_{\mu\nu}$</td>
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<td>$Q_{H\bar{B}}$</td>
<td>$H^\dagger H \bar{B}<em>{\mu\nu}\bar{B}</em>{\mu\nu}$</td>
<td>$Q_{\psi H}$</td>
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<tr>
<td>$Q_{HW_B}$</td>
<td>$H^\dagger \tau^I H W^I_{\mu}B_{\mu}$</td>
<td>$Q_{\psi H}$</td>
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<tr>
<td>$Q_{H\bar{W}_B}$</td>
<td>$H^\dagger \tau^I H \bar{W}^I_{\mu}B_{\mu}$</td>
<td>$Q_{\psi H}$</td>
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</tbody>
</table>

| 8: $(\bar{L}L)(L\bar{L})$ | $Q_{\ell\ell}$ | $(\bar{e}^\dagger \gamma^\mu l_r)(\bar{e}^\dagger \gamma^\mu l_r)$ | Plus another 24 four-fermion operators |

This talk: CP even fits

Backup: CP odd
The operator $\mathcal{O}_{HG}$

$$\mathcal{O}_{HG} = H^\dagger H G^A_{\mu\nu} G^{A,\mu\nu} \to \nu h G^A_{\mu\nu} G^{A\mu\nu}$$

**Feynman rules**

**SM:** $-i G_H \delta_{a_1,a_2} \left( p_1^\mu p_2^\nu - \eta^{\mu\nu} p_1 \cdot p_2 \right)$

**EFT:** $-i \nu \delta_{a_1,a_2} \left( p_1^\mu p_2^\nu - \eta^{\mu\nu} p_1 \cdot p_2 \right)$

Structurally the same

Affects total cross section only
The operator $\mathcal{O}_{HB}$

$\mathcal{O}_{HB} = H^\dagger H B_{\mu\nu} B^{\mu\nu} \rightarrow c_{HZZ}^{\text{EFT}} h Z_{\mu\nu} Z^{\mu\nu}$

Feynman rules

SM: $g_{ZZh}^{\text{SM}} \eta^{\mu\nu}$

EFT: $g_{hZZ}^{\text{EFT}} \left[ p_{Z1}^\mu p_{Z2}^\nu - \eta^{\mu\nu} p_{Z1} \cdot p_{Z2} \right]$}

EFT contribution has additional momentum dependence

Affects distributions

- SM
- EFT + SM

e.g. $m_{Zh}$ in HZ production
The operator $\mathcal{O}_{Hu}$

$\mathcal{O}_{Hu} = (H^\dagger iD_\mu H)(\bar{u}_R \gamma^\mu u_R) \rightarrow (h + v) Z_\mu(\bar{u}_R \gamma^\mu u_R)$

Feynman rules

SM Zuu: $g_{Zuu}^{\text{SM}} \gamma^\mu P_R$

EFT Zuu: $g_{Zuu}^{\text{EFT}} \gamma^\mu P_R$

EFT Zhuu: $g_{Zuu}^{\text{EFT}}/v \gamma^\mu P_R$

New contact interaction

Affects distributions

SM: propagator suppression
Dimension-six operators - effects

- Contribution to SM-like structures (same Lorentz structure as in SM)
- Interactions with new Lorentz structures
- New contact interactions (not present in the SM)

Only total cross section affected

Only total cross section affected
Global SMEFT fits
Why global fits?

One observable can be influenced by many operators

One operator can contribute to many different observables

Higgs decay

Weak boson fusion

Higgs production

Zh production

$e^+ e^- \rightarrow f \bar{f}$
Why global fits?

- Lots of measurements (without a clear deviation from the SM)
- One observable can be influenced by many operators
- One operator can contribute to many different observables

Need a global analysis of all EFT coefficients to map all direction of new fundamental physics

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^j} \mathcal{O}_j^{(8)} + \cdots$$
The Higgs and electroweak sector

EWPO: Electroweak precision observables (LEP)

Di-Higgs

EWPO

Di-boson

single Higgs

How do different sectors interact in a global fit? [Baglio, Dawson, Lewis, (1708.03332)]
LHC 2018 fit - fermion-gauge operators

\[ O_{GG} = \phi^+ \phi \, G^a_{\mu\nu} G^{a\mu\nu} \]
\[ O_{WW} = \phi^+ W_{\mu\nu} \hat{W}^{\mu\nu} \phi \]
\[ O_{BB} = \phi^+ \bar{B}_{\mu\nu} \bar{B}^{\mu\nu} \phi \]
\[ O_{W} = (D_{\mu} \phi)^+ \hat{W}^{\mu\nu} (D_{\nu} \phi) \]
\[ O_{B} = (D_{\mu} \phi)^+ \bar{B}^{\mu\nu} (D_{\nu} \phi) \]
\[ O_{\phi2} = \frac{1}{2} \partial^\mu (\phi^+ \phi) \partial_\mu (\phi^+ \phi) \]
\[ O_{WWW} = \text{Tr} \left( \hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^\rho_{\mu} \right) \]
\[ O_{\tau} = \phi^+ \phi \, L_3 \phi e_{R,3} \]
\[ O_{t} = \phi^+ \phi \, \tilde{Q}_3 \phi u_{R,3} \]
\[ O_{b} = \phi^+ \phi \, \tilde{Q}_3 \phi d_{R,3} \]

[Hagiwara-Ishihara-Szalapski-Zeppenfeld basis]

[AB, Corbett, Plehn (1812.07587)]
LHC 2018 fit - fermion-gauge operators

[Hagiwara-Ishihara-Szalapski-Zeppenfeld basis]

\[ O_{GG} = \phi^\dagger \phi G_{\mu\nu}^a G^{a\mu\nu} \]
\[ O_{WW} = \phi^\dagger W_{\mu\nu} \tilde{W}^{\mu\nu} \phi \]
\[ O_{BB} = \phi^\dagger B_{\mu\nu} B^{\mu\nu} \phi \]
\[ O_W = (D_\mu\phi)^\dagger \tilde{W}_{\mu\nu} (D_\nu\phi) \]
\[ O_B = (D_\mu\phi)^\dagger \tilde{B}_{\mu\nu} (D_\nu\phi) \]
\[ O_{\phi_2} = \frac{1}{2} \partial^\mu (\phi^\dagger \phi) \partial_\mu (\phi^\dagger \phi) \]
\[ O_{WWW} = \text{Tr} \left( \tilde{W}_{\mu\nu} W^{\nu\rho} \tilde{W}^\rho_\mu \right) \]
\[ O_\tau = \phi^\dagger \phi \bar{L}_3 \phi e_{R,3} \]
\[ O_t = \phi^\dagger \phi \bar{Q}_3 \tilde{u}_{u,3} \]
\[ O_b = \phi^\dagger \phi \bar{Q}_3 \tilde{d}_{d,3} \]

\[ O_{\phi_1} = (D_\mu\phi)^\dagger \phi^\dagger (D^\mu\phi) \quad O_{BW} = \phi^\dagger B_{\mu\nu} \tilde{W}^{\mu\nu} \phi \]
\[ O_{\phi_Q}^{(3)} = \phi^\dagger (iD_\mu^a \phi)(\bar{Q}^{\gamma_a} \gamma^\mu Q) \quad O_{\phi_2}^{(1)} = \phi^\dagger (iD_\mu^a \phi)(\bar{u}_R \gamma^\mu u_R) \]
\[ O_{\phi_d}^{(1)} = \phi^\dagger (iD_\mu^a \phi)(\bar{d}_R \gamma^\mu d_R) \quad O_{\phi_e}^{(1)} = \phi^\dagger (iD_\mu^a \phi)(\bar{e}_R \gamma^\mu e_R) \]
\[ O_{LLLL} = \bar{L}_\mu L (\bar{L}^\mu L) \]

\[ f/\Lambda^2 \quad [\text{TeV}^{-2}] \]

95% CL, Run I + II

- 10 operator fit
- 18 operator fit

Profiled over remaining operators

[AB, Corbett, Plehn (1812.07587)]
LHC 2018 fit - correlations

Contributions to Zh production

No propagator suppression

\[ \mathcal{O}_B = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu}(D_\nu \phi) \]
\[ \mathcal{O}_W = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu}(D_\nu \phi) \]
\[ \mathcal{O}_{\phi Q}^{(1)} = \phi^\dagger (i \hat{D}_\mu \phi)(\bar{Q} \gamma^\mu Q) \]
\[ \mathcal{O}_{\phi Q}^{(3)} = \phi^\dagger (i \hat{D}_\mu \phi)(\bar{Q} \gamma^\mu \sigma^a Q) \]

[Banerjee et al (1807.01796)]
[AB, Corbett, Plehn (1812.07587)]
LHC 2021 fit

Limits keep improving with more data - especially with more differential measurements

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (2111.05876)]
So what have we learned about new physics now?

Limits keep improving with more data - especially with more differential measurements

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (2111.05876)]
UV complete model fits

- Map UV complete models onto EFT
- Extended scalar sectors
- Quark bidoublet model
- Vector-singlet pair model
- Vector-like quarks
- …

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<table>
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<th>Model</th>
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Two Higgs doublet model

\[ \mathcal{L}_{H_2} = \mathcal{L}^{d \leq 4}_{SM} + |D_\mu H_2|^2 - m_{H_2}^2 |H_2|^2 - \frac{\lambda_{H_2}}{4} |H_2|^4 \\
- (\eta_H |\tilde{H}|^2 + \eta_{H_2} |H_2|^2)(\tilde{H}^\dagger H_2 + H_2^\dagger \tilde{H}) \\
- \lambda_{H_2,1} |\tilde{H}|^2 |H_2|^2 - \lambda_{H_2,2} |\tilde{H}^\dagger H_2|^2 - \lambda_{H_2,3} \left[ (\tilde{H}^\dagger H_2)^2 + (H_2^\dagger \tilde{H})^2 \right] \\
- \left\{ Y_{H_2}^{(e)} \tilde{L} H_2 e_R + Y_{H_2}^{(u)} \tilde{q} L H_2 u_R + Y_{H_2}^{(d)} \tilde{q} L H_2 d_R + h.c. \right\}. \]

CoDEx [Bakshi, Chakraborty, Patra (1808.04403)]

\[ Q_{HB} \rightarrow \frac{g_Y^2 \lambda_{H_2,1}}{384 \pi^2 m_{H_2}^2} + \frac{g_Y^2 \lambda_{H_2,2}}{768 \pi^2 m_{H_2}^2} \]

\[ Q_{HW} \rightarrow \frac{g_W^2 \lambda_{H_2,1}}{384 \pi^2 m_{H_2}^2} + \frac{g_W^2 \lambda_{H_2,2}}{768 \pi^2 m_{H_2}^2} \]

\[ Q_{HWB} \rightarrow g W g Y \lambda_{H_2,2} \]

\[ \text{[Anisha, Bakshi, Banerjee, AB, Chakraborty, Patra, Spannowsky (2111.05876)]} \]
Constraints on two Higgs doublet model

EWPO: Electroweak precision observables (mostly LEP data)
[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (2111.05876)]
Future directions in SMEFT (fits)
Future directions in SMEFT (fits)

\[ A = A_{\text{SM}} + a_i \frac{C_i^{(6)}}{\Lambda^2} + b_{jk} \frac{C_j^{(6)} C_k^{(6)}}{\Lambda^4} + c_l \frac{C_l^{(8)}}{\Lambda^4} + \frac{1}{16\pi^2} \left[ d_m \frac{C_m^{(6)}}{\Lambda^2} + e_n \frac{C_n^{(6)}}{\Lambda^2} \log \left( \frac{\mu^2}{\Lambda^2} \right) \right] + \cdots \]

**Generality**

- Relax (flavor) assumptions
  - Dim6^2 effects
  - Dim8 effects

- Combine more sectors

- Add more data

**Precision**

SMEFT@NLO
Global fits

Adapted from Ken Mimasu
\(1/\Lambda^4\) effects

- Large number of dim8 operators
  (Wh production: 66 dim8 operators)
- Focus on dim8 operators induced in matching of specific UV-complete models in a specific process
  (few parameters, relation between WCs)
- Or: all dim8 operators have the same magnitude
  Wh: O(10\%) effect

[Hays, Martin, Sanz, Setford (1808.00442)]
Dim-8 effects in specific UV models

• Heavy U(1) boson mixing with B, vector-triplet model contributions to EWPD
  [Corbett, Helset, Martin, Trott (2102.02819)]

• vector-like top partner contribution to tth: O(1%)
  [Dawson, Homiller, Sullivan (2110.06929)]

• Size of effects depends on input parameter shifts

• 2HDM: improved description of UV limits when including dim8
  [Dawson, Fontes, Homiller, Sullivan (2205.01561)]
Summary

We are on the way towards a truly global EFT fit!

**SMEFT**
- Model-independent parametrisation of new fundamental physics

**Outlook**
- Combining more sectors
- Precision
  - SMEFT@NLO
  - Dimension-8
Thank you for your attention!
### SMEFT fits - a global effort!

<table>
<thead>
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<th>SMEFT fits - a global effort!</th>
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<tbody>
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<table>
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<tr>
<th>Input</th>
<th>Eboli, Gonzalez-Garcia et al</th>
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<td>NLO for VV and Vh</td>
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**Notes:**
- SU(2) indicates the symmetry group, where SU(2) refers to the special unitary group of degree 2.
- EWPD stands for Electro-Weak Production Distributions.
- Higgs refers to the Higgs boson, a particle that gives mass to other particles.
- EWPO refers to Electro-Weak Precision Observables.
- LO (Leading Order) indicates calculations at the lowest order in the perturbation series.
- NLO (Next-to-Leading Order) indicates calculations at one order beyond the lowest order.
- Top only indicates that only top quark-related processes are considered.
- Vh refers to vector boson fusion.
- VBS refers to vector boson-single top.
- Chi2 indicates the Chi-squared goodness-of-fit test.
- Bayesian refers to Bayesian statistical methods.
- UV complete models indicate models that are UV complete and thus free from infrared Landau singularities.

---

**References:**
- 1211.4580, 1509.01585, 1805.11018, 1812.01009, 2108.04828
- 1404.3667, 1803.03252, 2012.02779
- 1308.1979, 1505.05516, 1604.03105, 1812.07587, 1910.03606
- 1506.08845, 1512.03560, 1901.03164
- 1710.0540, 1905.03764, 1907.04311, 1910.14012
- 1901.05965, 1906.05296, 2101.03180
- 2007.01296
## SMEFT fits - a global effort!

Filled to my best knowledge

Many groups contribute to the field. Each of them has their own strength.

<table>
<thead>
<tr>
<th>Input</th>
<th>Eboli, Gonzalez-Garcia et al</th>
<th>Fitmaker</th>
<th>SFitter</th>
<th>TopFitter</th>
<th>HEPfit</th>
<th>SMEFit</th>
<th>Dawson et al.</th>
<th>Chakrabortty et al.</th>
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</thead>
<tbody>
<tr>
<td>EWPD+Higgs+VV, DY +VV</td>
<td>EWPD+Higgs+VV, top</td>
<td>EWPD+Higgs+VV, top</td>
<td>top</td>
<td>EWPD+Higgs+VV Flavor</td>
<td>EWPD+Higgs+VV, VBS + diboson, top</td>
<td>EWPD+Higgs+VV</td>
<td>EWPD + Higgs</td>
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<td>Linear</td>
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<td>Warsaw</td>
<td>HISZ (Higgs)</td>
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<td>Alpha</td>
<td>Alpha</td>
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</tbody>
</table>

### Table:

- **Uncertainties**: Gaussian, theory correlated  
  - Gauss  
  - Gauss, Poisson, flat  
  - (Asymmetric) Gauss, flat  
  - Gauss, uncorrelated  
  - Gauss

- **UV complete model fits**:  
  - ✔️  
  - ✔️  
  - ✔️  
  - ✔️  
  - ✔️

- **Specialties**: VV + DY  
  - Higgs + EWPO + top + diboson  
  - Correlation of uncertainty classes  
  - Top  
  - Projections  
  - CP odd operators  
  - NLO for VV and Vh  
  - UV complete models

- **References**:  
  - 1211.4580, 1509.01585, 1805.11108, 1812.01009, 2108.04828  
  - 1404.3667, 1803.03252, 2012.02779  
  - 1404.3667, 1803.03252, 2012.02779  
  - 1508.1979, 1505.05516, 1604.03105, 1812.07587, 1910.03606  
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  - 1710.0540, 1905.03764, 1907.04311, 1910.14012  
  - 1901.05965, 1906.05296, 2101.03180  
W boson mass - SMEFT interpretations

[CDF II (Science)]

<table>
<thead>
<tr>
<th>Experiment</th>
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<tr>
<td>D0 I</td>
<td>80478 ± 83</td>
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<tr>
<td>CDF I</td>
<td>80432 ± 79</td>
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<tr>
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<tr>
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<tr>
<td>OPAL</td>
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<tr>
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<td>ATLAS</td>
<td>80370 ± 19</td>
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<tr>
<td>CDF II</td>
<td>80433 ± 9</td>
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</table>

\( \delta m_W^2 \) scheme

\[
\frac{\delta m_W^2}{m_W^2} = -\frac{s_{2W} v^2}{4c_{2W} \Lambda^2} \left( \frac{c_W}{s_W} C_{HD} + \frac{s_W}{c_W} \left( 4C_{Hl}^{(3)} - 2C_{ll} \right) + 4C_{HWB} \right)
\]

global fits and SMEFT studies

[de Blas et al. (2204.04204)]
[Bagnaschi et al. (2204.05260)]
[Balkin, Madge et al. (2204.05992)]
[Almeida et al. (2204.10130)]
[many more (…)]