Standard Model Effective Field Theory

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Outline

- Effective Field Theory
- Standard Model EFT
- Higgs phenomenology
- Experiment efforts

Effective Field Theory

"I don't need to understand QCD to know that I'm not in danger of sinking through the floor."

—Physics Professor

- Physics at short & long distances are separated.
    - Ex: Hard-scatter & PDF factorization.
- EFTs are:
    1. Not renormalizable in general.
    2. Renormalizable at fixed-order.
    3. Able to predict finite observables with finite error.

Effective Field Theory

- Consider renormalized Lagrangian with spacetime dimension d.
- Reminder: couplings run with scale.

EFT Lagrangian

Expansion around the renormalized Lagrangian.

$$\mathcal{L}_{\text{eff}} = \sum_{\mathscr{D}\geq 0, i} \frac{c_i^{(\mathscr{D})} O_i^{(\mathscr{D})}}{\Lambda^{\mathscr{D}-d}} = \sum_{\mathscr{D}\geq 0} \frac{\mathcal{L}_{\mathscr{D}}}{\Lambda^{\mathscr{D}-d}}$$

$$O_i^{(\mathscr{D}\leq d)} \ : \ \text{renormalized operators}$$

$$O_i^{(\mathscr{D}> d)} \ : \ \text{external operators}$$

$$c_i^{(\mathscr{D})} \ : \ \text{Wilson coefficient}$$

- Coefficients are finite constants, operators run with scale.

Power counting & matching

Power Counting Rule

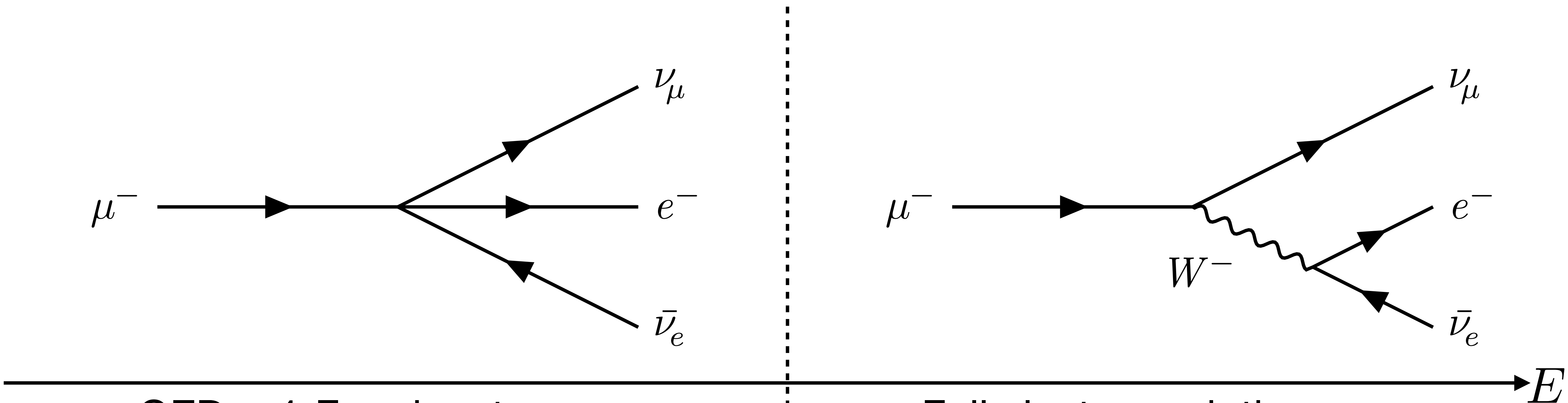
Inserting of a set of external operators in a tree-level scattering diagram leads to an amplitude:

$$\mathscr{A} \sim \left(\frac{p}{\Lambda}\right)^n, \quad n = \sum_i \mathscr{D} - d$$

Matching

For a given UV completion of a theory, one can construct an EFT such that it produces the same S-matrix elements.

Fermi 4-point interaction



- QED + 4-Fermi vertex
- Full electroweak theory

m_W

$$\mathcal{L}_{4F} = \frac{G_F}{\sqrt{2}} \bar{\psi}\gamma^\mu P_L \psi_{\nu_\mu} \bar{\psi}_e \gamma^\mu P_L \psi_{\nu_e} + h.c.$$

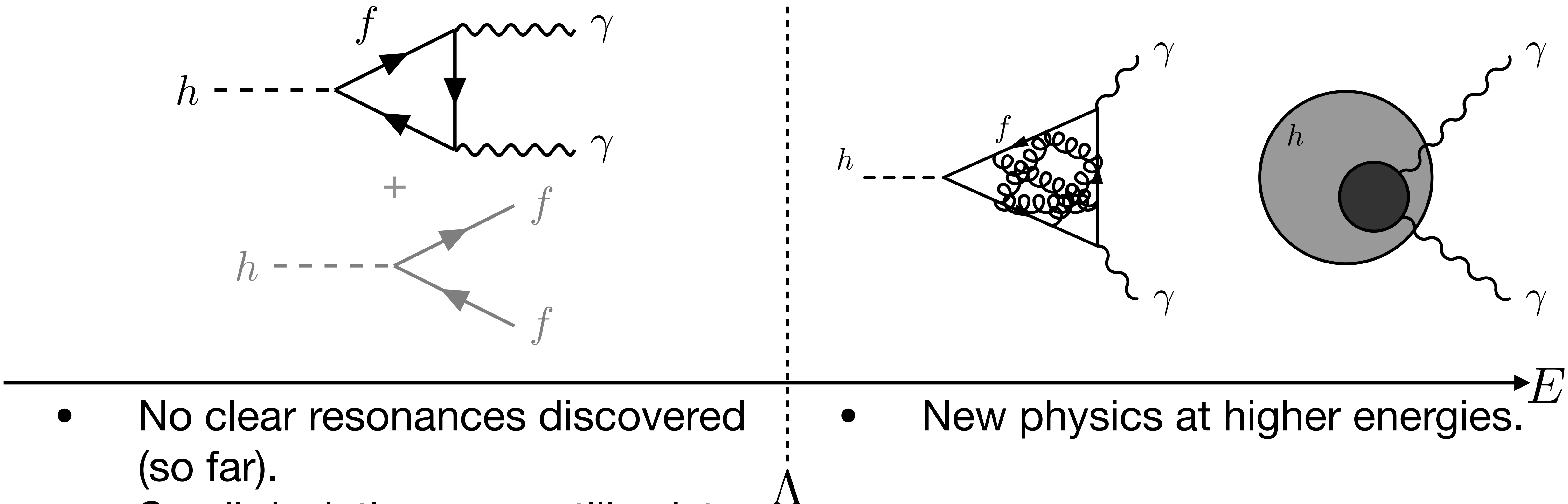
$$\left(\frac{ie}{\sqrt{2}\sin\theta}\right)^2 (\bar{\nu}_{eL}\gamma^\mu e_L + \bar{\nu}_{\mu_L}\gamma\mu\mu_L)$$

$$\times \frac{-i\left(g^{\mu\nu} - \frac{p^\mu p^\nu}{m_W^2}\right)}{p^2 - m_W^2}$$

$$\times (\bar{\nu}_{eL}\gamma^\nu e_L + \bar{\nu}_{\mu_L}\gamma\nu\mu_L)$$

$$G_F \equiv \frac{e^2}{2m_W^2 \sin^2\theta}$$

Standard Model Effective Field Theory



- No clear resonances discovered (so far).
- Small deviations may still exist.

- New physics at higher energies.

Strategy:

- Identify all possible deviations from SM.
- Parametrize in terms of additional interactions between SM fields (EFT).
- Measure amount of deviations (Wilson coefficients).

Standard Model Effective Field Theory

Assumptions

1. UV completion contains $\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)$ gauge theory.
   - Higgs is part of the SU(2) doublet.
2. No new hidden light states at low energy.

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \cdots$$

$D = 5$: L violation.

$D \geq 7$ (odd) : $B - L$ violation.

$D \geq 8$ (even) : sub-dominant.

d=6 operators

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \cdots$$

- First complete classification of dimension-6 operators: 80.

W. Buchmuller et al. (1985)

Field redefinitions (EOM) ↓

- Non-redundant basis: totalling 59 new operators.
  - “Warsaw”
  - Strongly-interacting light Higgs (SILH) → “Higgs”

B. Grzadkowski et al. (2010)

CERN YR4

UV assumptions ↓

- Truncated of parameters for scenario-specific hypotheses.

On the choice of basis

- In principal, any well-preserved experimental data can always be
- Experimentalists tend to favour SILH; theorists Warsaw.
- SMEFT predictions readily available at LO, but need NLO results for errors.
    - NLO worked out in Warsaw.
    - Technical challenges in SILH.
- SILH (apparently) makes a BSM-constraining assumption that Warsaw does not: Minimal Flavour Violation.

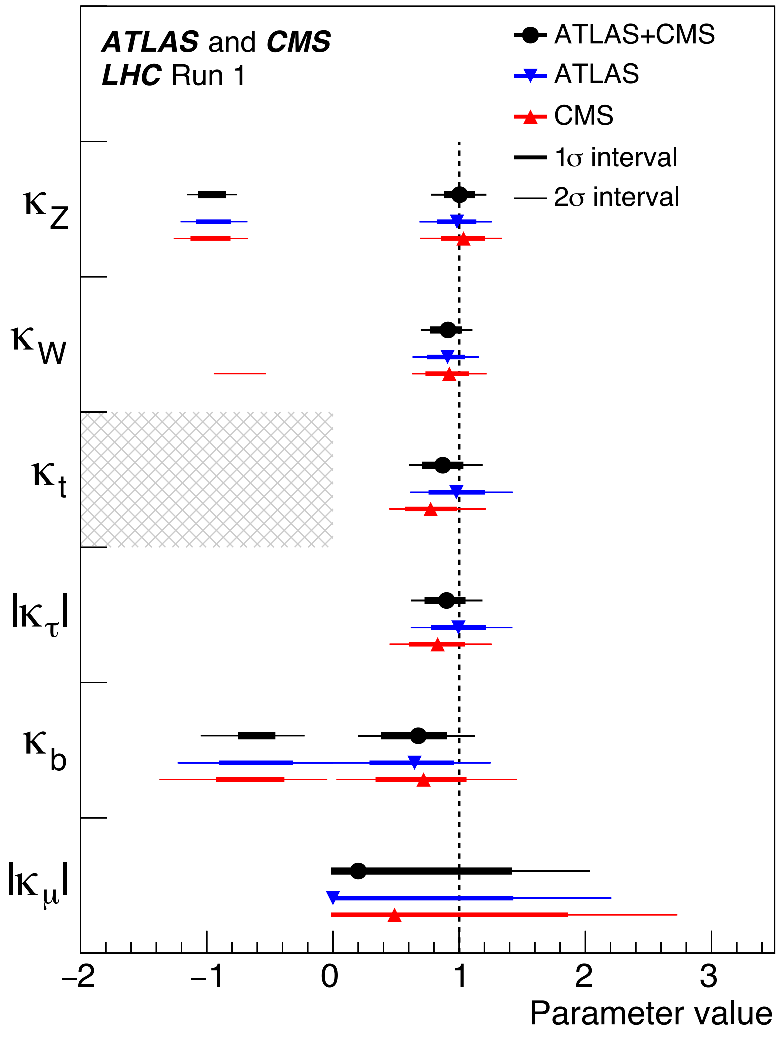
Higgs κ-framework

- Narrow width approximation: $$\frac{\Gamma_h}{m_h} \ll 1$$

- Higgs cross section factorized as: $$\sigma(i \to h \to f) = \frac{\sigma_i(\vec{\kappa})\Gamma_f(\vec{\kappa})}{\Gamma_h}$$

- Deviations in production cross section and decay widths parametrized by κ's.

$$\kappa_i^2 = \sigma_i/\sigma_i^{\rm SM}$$
$$\kappa_f^2 = \Gamma_f/\Gamma_f^{\rm SM}$$



$\{\kappa_i\} \leftarrow \{c_i\}$

- The κ-framework is also an (ad-hoc) EFT.

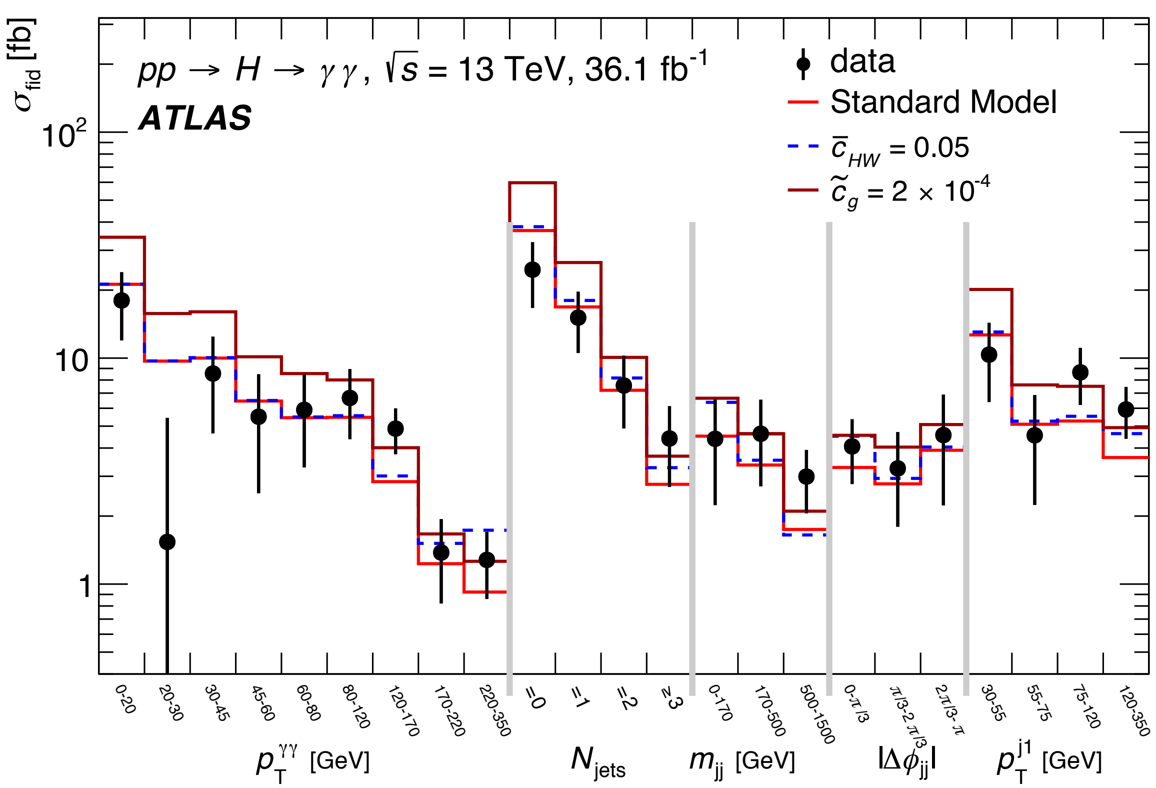
$$
\begin{aligned}
\mathcal{L} = & \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\
& + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\
& + \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu} \right) H \\
& - \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H
\end{aligned}
$$

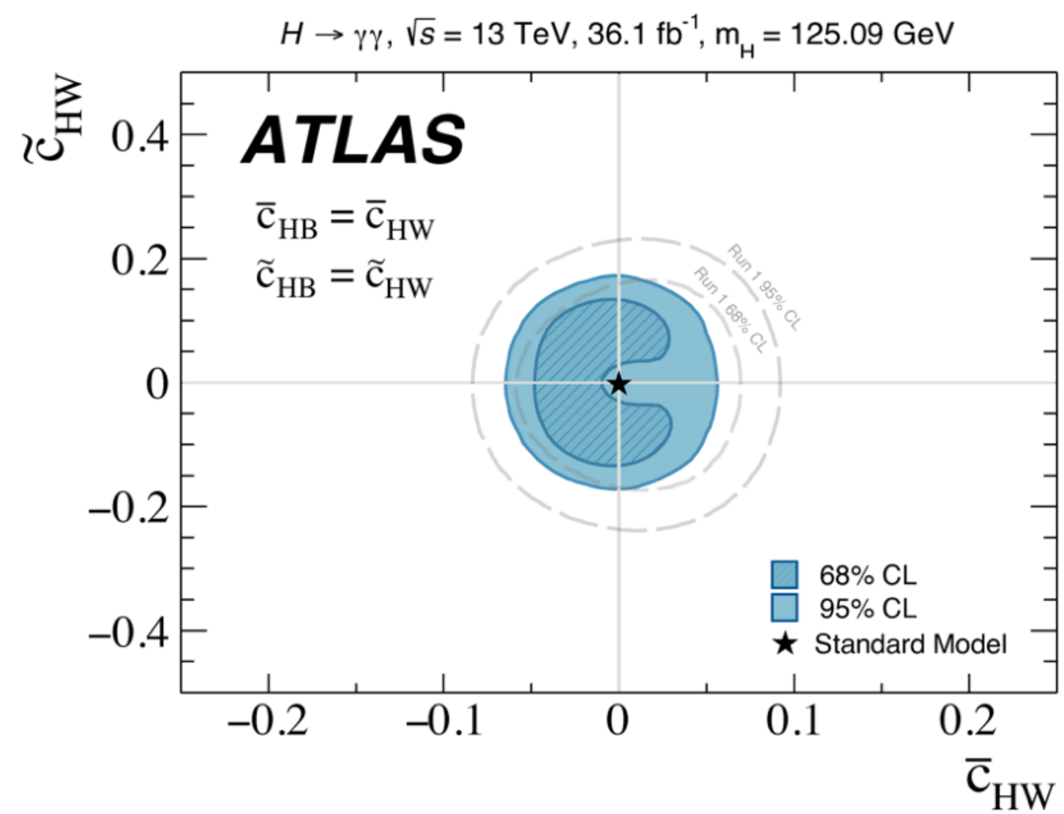
- Possible to construct a map to decompose κ_i's into SMEFT c_i's.

$$
\begin{aligned}
\frac{\Gamma^{\text{SMEFT}}(h \to \gamma\gamma)}{\Gamma^{\text{SM}}(h \to \gamma\gamma)} = & \left| 1 + \frac{8\pi^2 \bar{v}_T^2}{I^\gamma} \mathscr{C}_{\gamma\gamma} \right|^2 + \left| \frac{8\pi^2 \bar{v}_T^2}{I^\gamma} \tilde{\mathscr{C}}_{\gamma\gamma} \right|, \\
& \mathscr{C}_{\gamma\gamma} = \frac{c_{HW}}{\bar{g}_2^2} + \frac{c_{HB}}{\bar{g}_1^2} - \frac{c_{HWB}}{\bar{g}_1 \bar{g}_2} \\
& \tilde{\mathscr{C}}_{\gamma\gamma} = \frac{c_{H\tilde{W}}}{\bar{g}_2^2} + \frac{c_{H\tilde{B}}}{\bar{g}_1^2} - \frac{c_{H\tilde{W}B}}{\bar{g}_1 \bar{g}_2} \\
= & 1 + \Delta\kappa_\gamma,
\end{aligned}
$$

Higgs differential cross sections

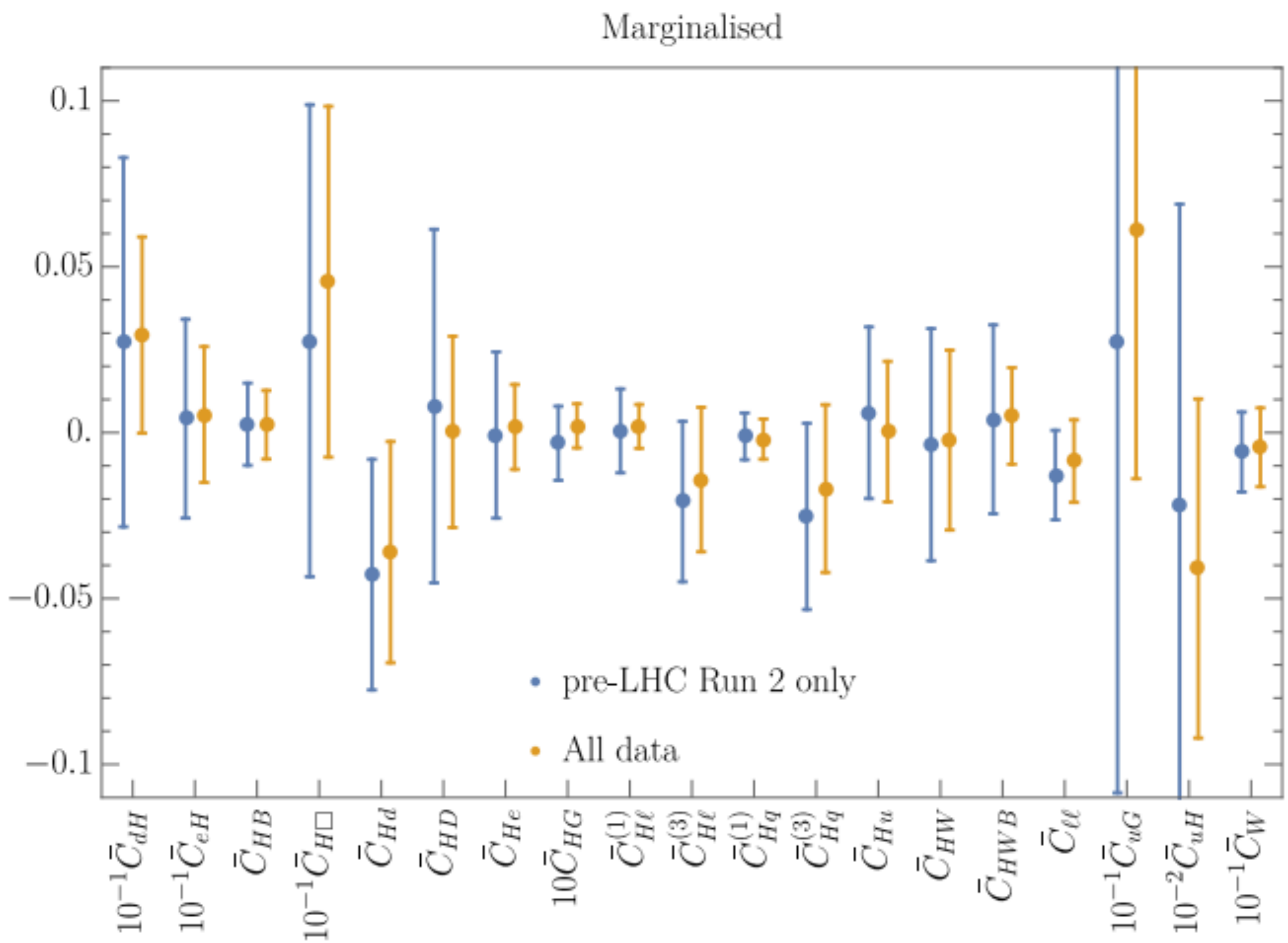
- Unfold detector effects → paritcle-level differential cross sections.
  - Maximal model-independence.
- EFT fits can take advantage of shape differences.





Global fit

- Constrain full set of 20 Higgs & EW parameters with combined data from LEP, Tevatron, ATLAS & CMS.



Conclusions

- EFTs are well-justified intuitively.
  - Implementation with mathematical rigor & consistency needed.

- SMEFT is a model-independent way to parameterize deviations from SM.
  - Measurements done now, UV completion later.
  - Can impose additional assumptions to restrict BSM scenarios.

- Higgs measurements at LHC will play an important role in SMEFT constraints.
  - Some theoretical issues & experimental challenges.

Backup

Warsaw basis

$1 : X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2 : H^6$	
Q_H	$(H^\dagger H)^3$

$3 : H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5 : \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4 : X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6 : \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7 : \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8 : (\bar{L}L)(\bar{L}L)$	
$Q_{\ell\ell}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{\ell q}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{\ell q}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8 : (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8 : (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8 : (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8 : (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$

$8 : (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Table 1: $\mathcal{L}_6$ of Refs. [222] as given in Ref. [204]. The flavour labels p, r, s, t on the Q operators are suppressed on the left hand side of the tables.