# SM & Higgs physics

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Lecture II

# Understanding a new force


- A new force has been discovered, the first elementary of Yukawa type ever seen.
- Its mediator looks a lot like the SM scalar: H-universality of the couplings
- No sign of……New Physics (from the LHC)!

- We have no bullet-proof theoretical argument to argue for the existence of New Physics accessible at 13 TeV and even less so to prefer a NP model with respect to another.

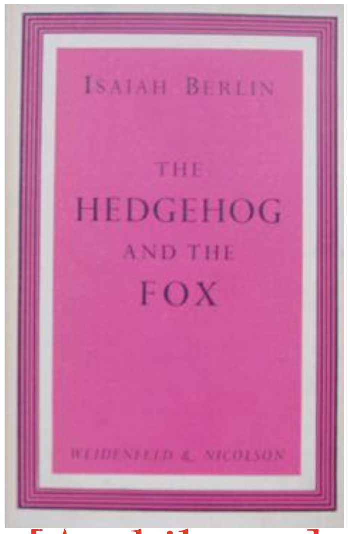
# Searching for new physics

| | | |
|---|---|---|
| Model-dependent | ⟷ | Model-independent |
| SUSY, 2HDM, ED,… | | simplified models, EFT, … |
| Search for new states | ⟷ | Search for new interactions |
| specific models, simplified models | | anomalous couplings, EFT… |
| Exotic signatures | ⟷ | Standard signatures |
| precision measurements | | rare processes |

# What about new physics?

the foxes draw on a variety of experiences and for them the world cannot be boiled down to a single idea

the hedgehogs view the world through the lens of a single defining idea




[Archilocus]

[Erasmo]

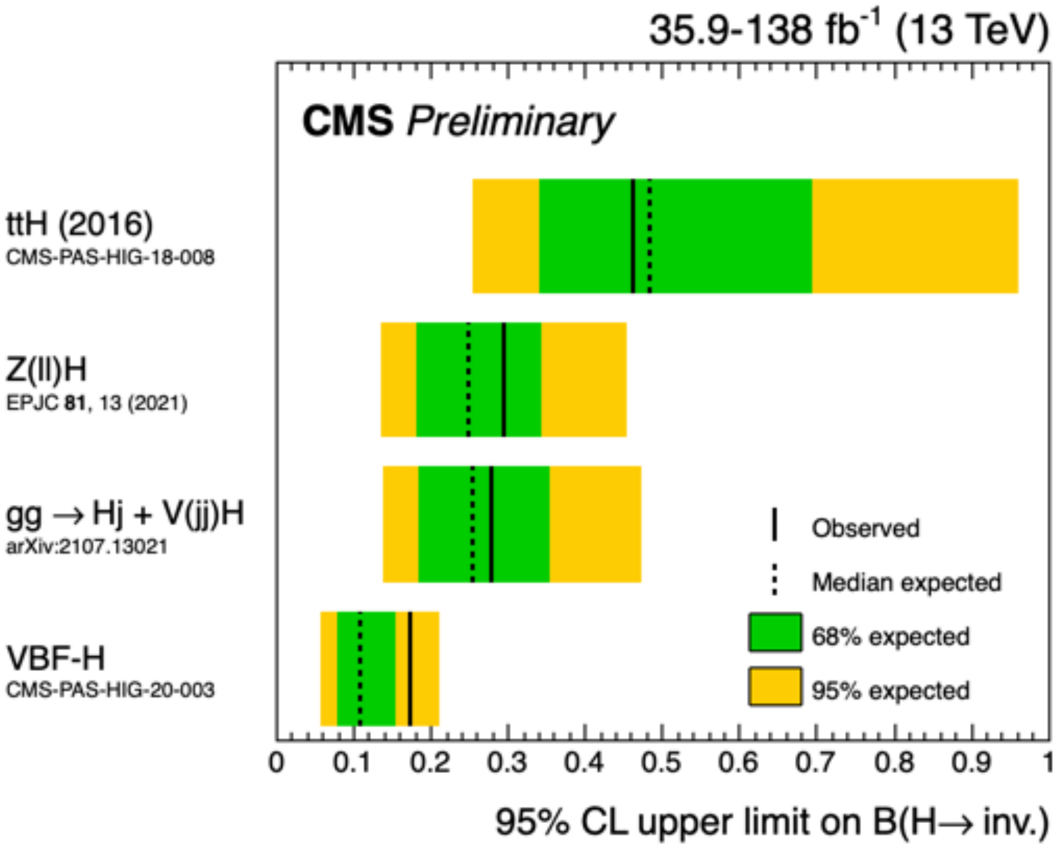
[Berlin]

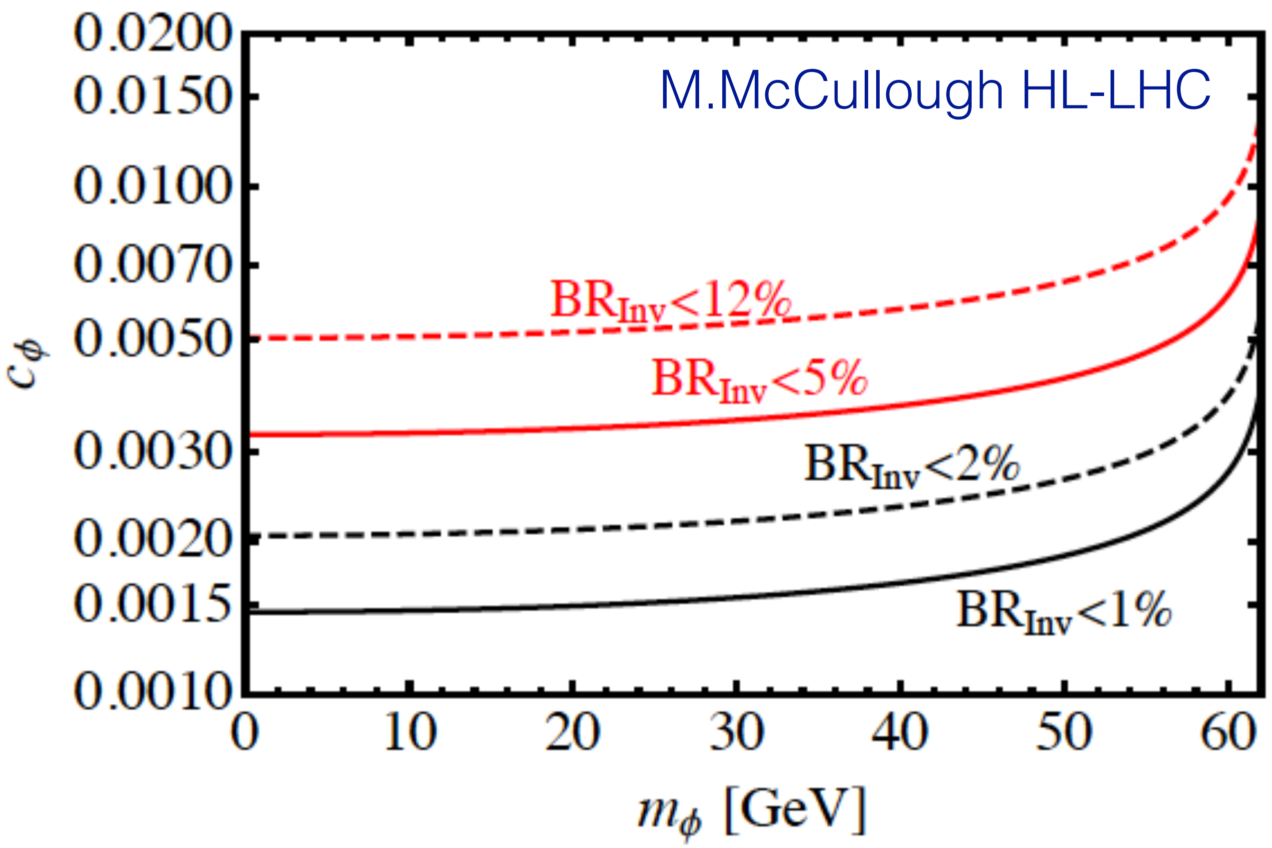
# SM Portals


| $(\Phi^\dagger \Phi)$ | $(\bar{L}\Phi_c)$ | $B^{\mu\nu}$ |
|---|---|---|
| dim=2 | dim=5/2 | dim=2 |
| Scalars and vectors | Sterile fermions | Dark photons |

# Searching for H to invisible

Immediate implications for any model with particles of mass $m<m_H/2$

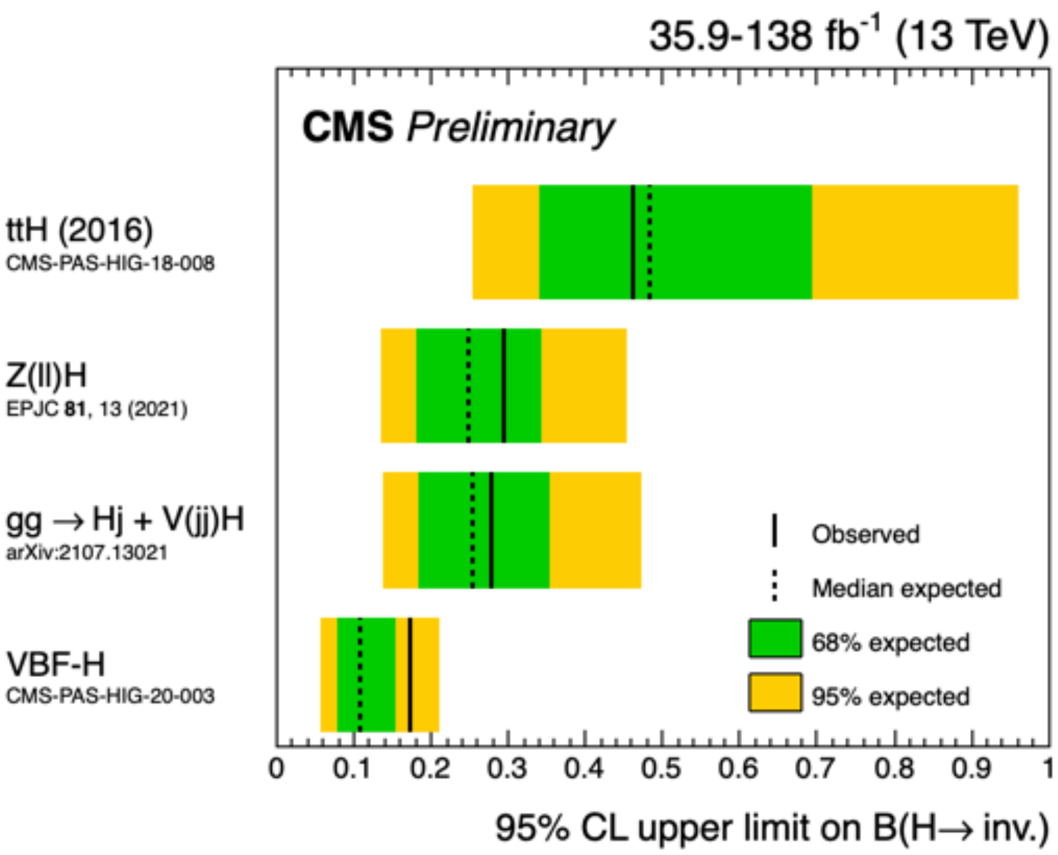


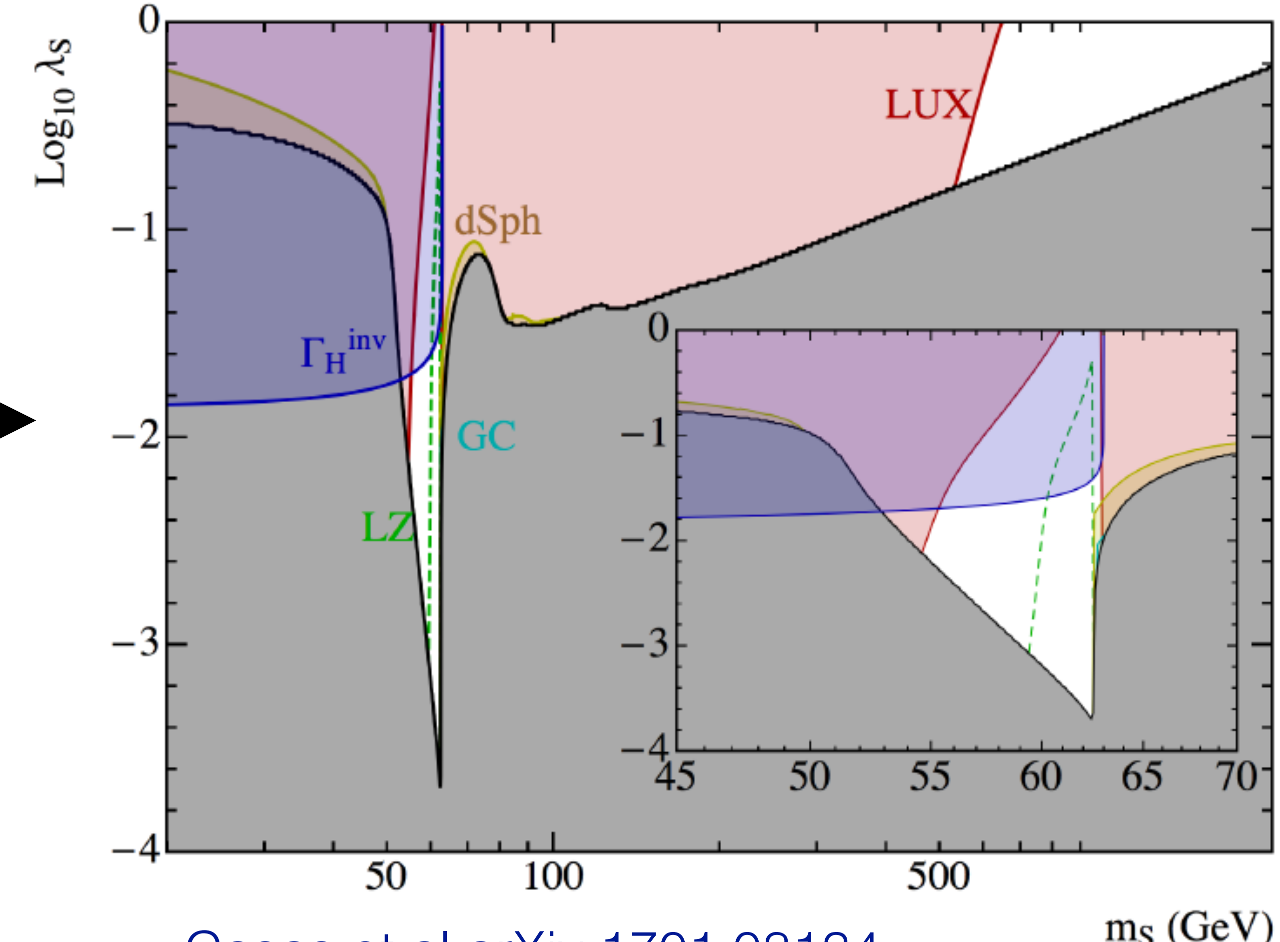

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

Simplest extension of the SM: The Higgs portal

# Searching for H to invisible




Important Dark Matter implications




Casas et al arXiv:1701.08134

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

# Search for new interactions

- Such a programme is based on large set of measurements, both in the exploration and in the precision phases:
  - **PHASE I (EXPLORATION):**
    Bound Higgs couplings
  - **PHASE II (DETERMINATION):**
    Stress test the SM: Look for deviations wrt dim=4 SM (rescaling factors)
  - **PHASE III (PRECISION):**
    Interpret measurements in terms the dim=6 SM parameters (SMEFT)
- Rare SM processes (induced by small interactions, such as those involving the Higgs with first and second fermion generations or flavour changing neutral interactions) are still in the exploration phase.
- For interactions with vector boson and third generation fermions we are ready to move to phase II.

# Phase I (exploration) : examples

COUPLINGS to SM particles

- H self-interactions
- Second generation Yukawas: ccH, μμH
- Flavor off-diagonal int.s : tqH, ll'H, …
- HZγ
- Top self-interactions : 4top interactions
- Top neutral gauge interactions
- Top FCNC's
- Top CP violation

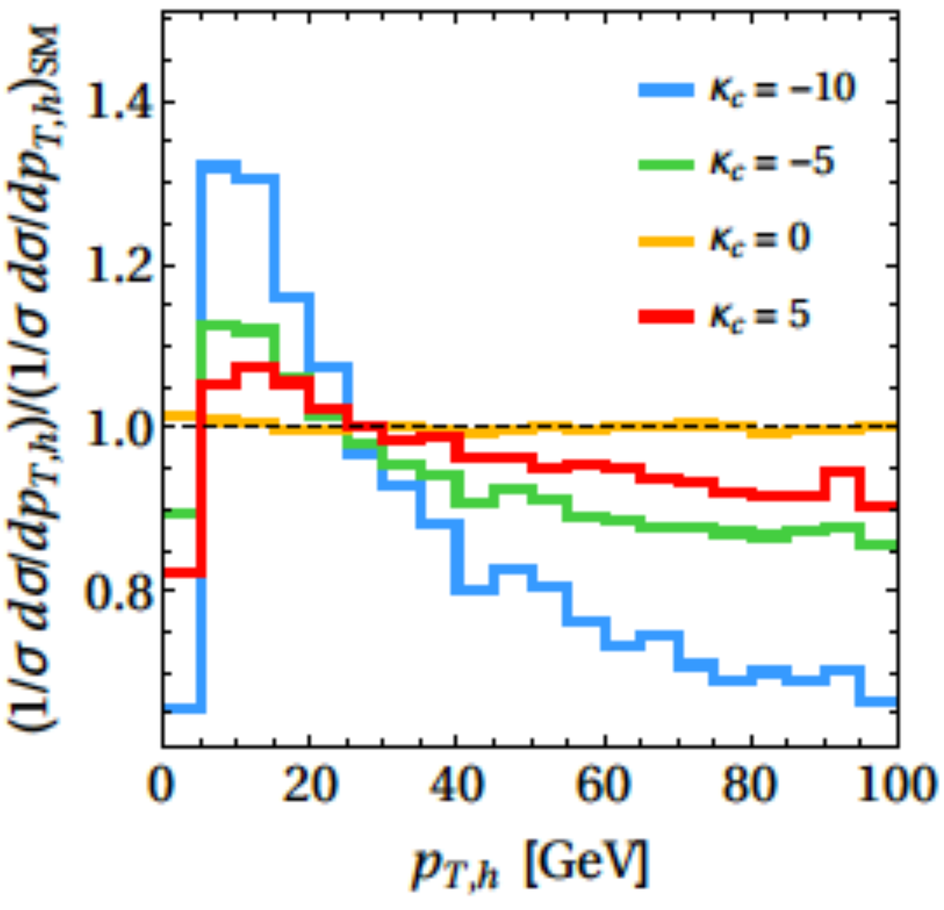
COUPLINGS to non-SM particles

- H portals

# Second generation

Using kinematic distributions i.e. the Higgs pT

Bishara et al.1606.09253

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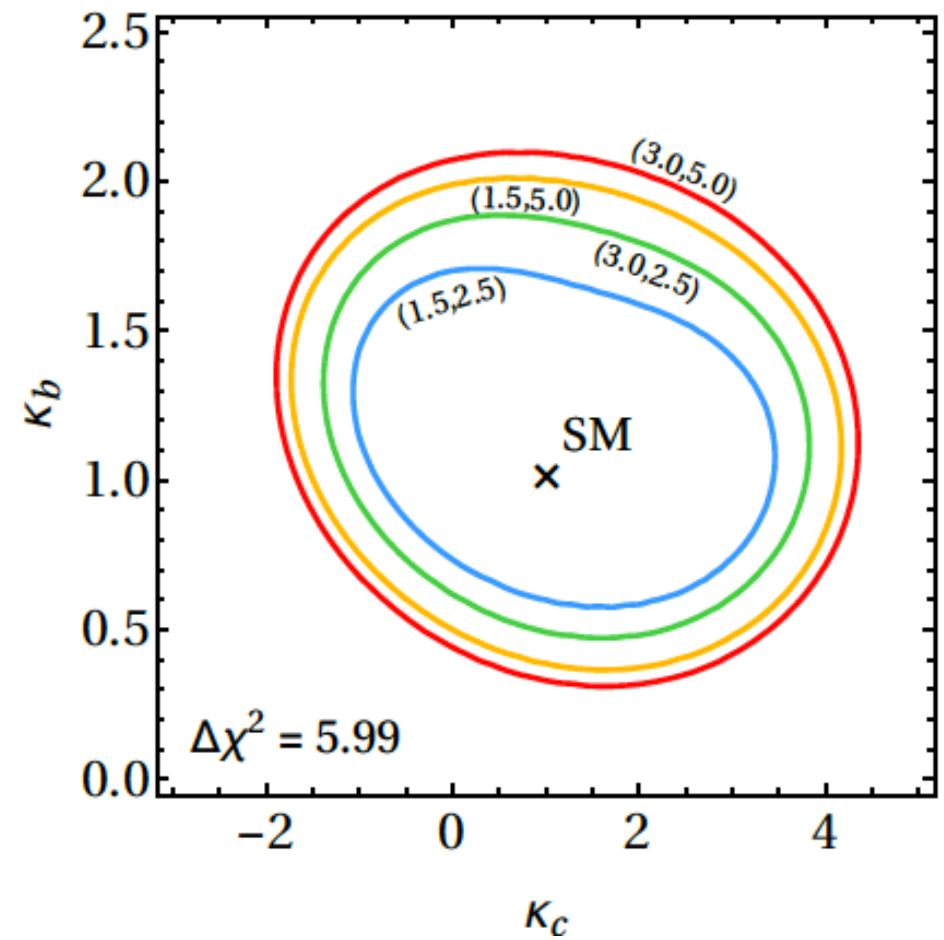
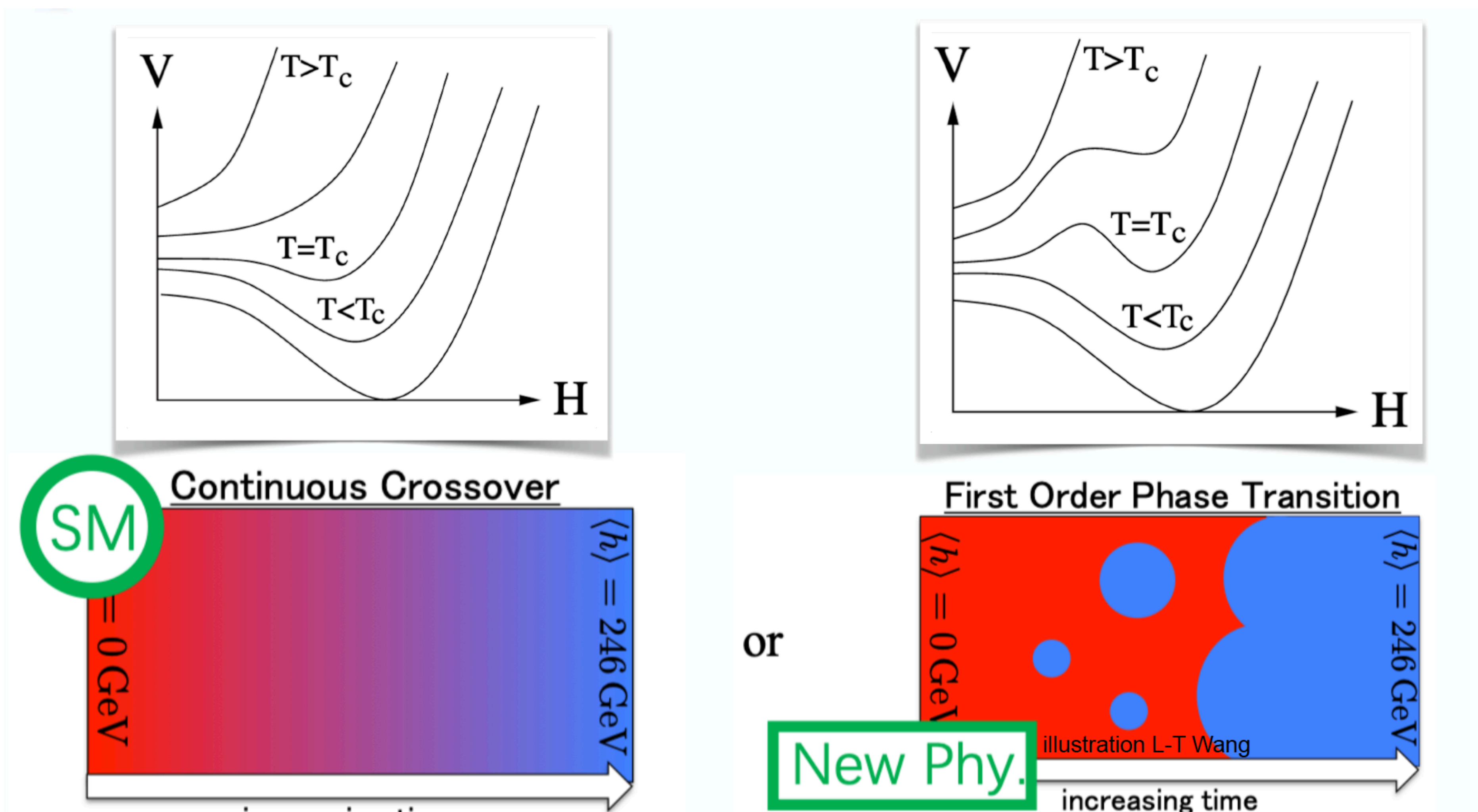



Inclusive Higgs decays i.e VH + flavour tagging (limited by c-tagging) gives a limit of 5.5 x SM expectation. (VZ has been observed!)

$$ZH(H \to c\bar{c})$$

# Baryogenesis

Remember that to  generate a matter-antimatter asymmetry in the Universe the three Sakharov conditions have to be satisfied (B violation, first-order phase transition (out-of-equilibrium), C and CP violation). The SM potential leads to 2nd order phase transitions.



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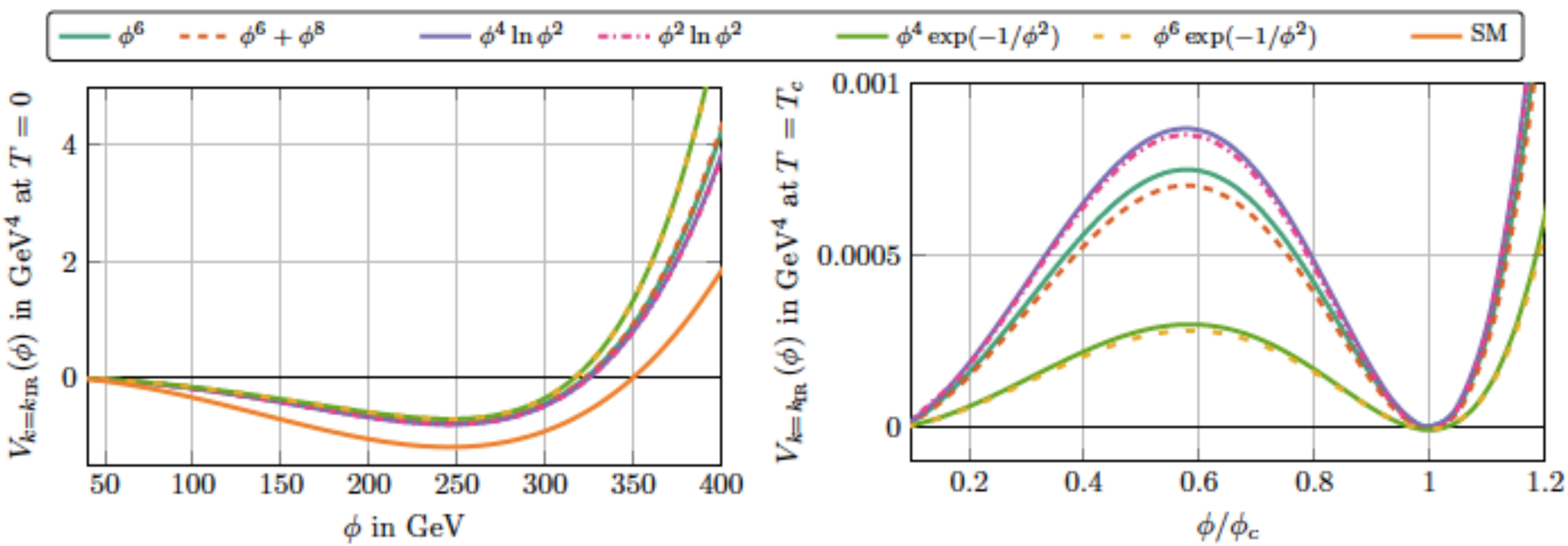


Reichert et al. 1711.00019

A trilinear coupling above 1.5*SM value allows a 1st order transition.

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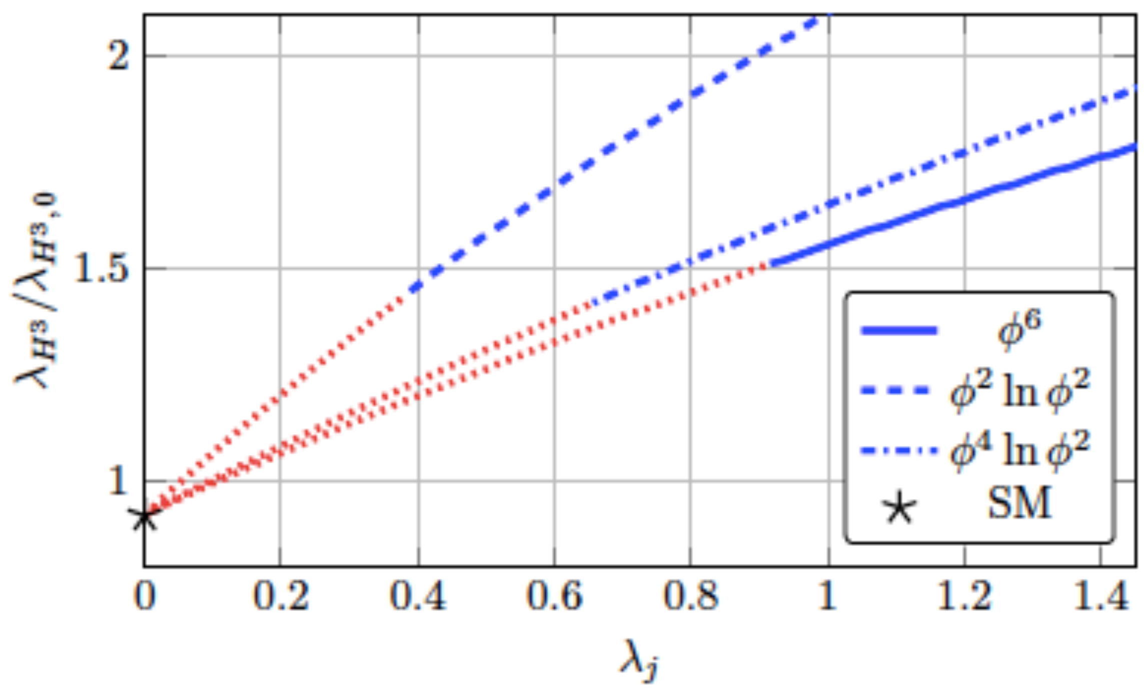


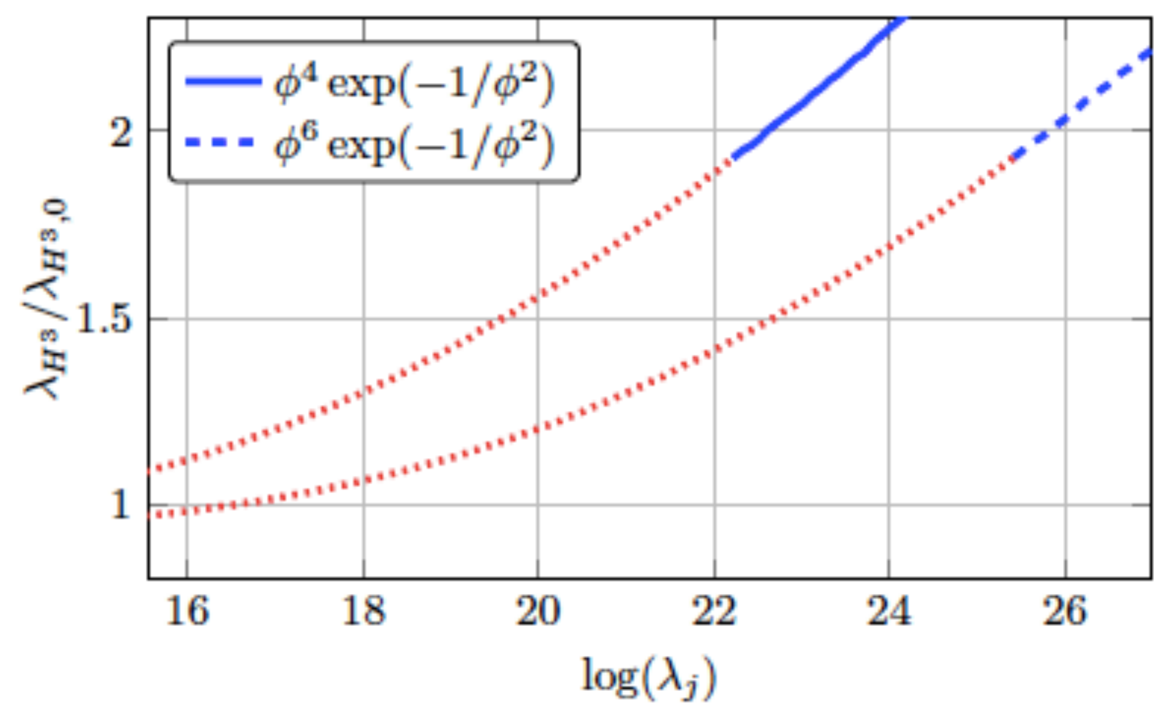


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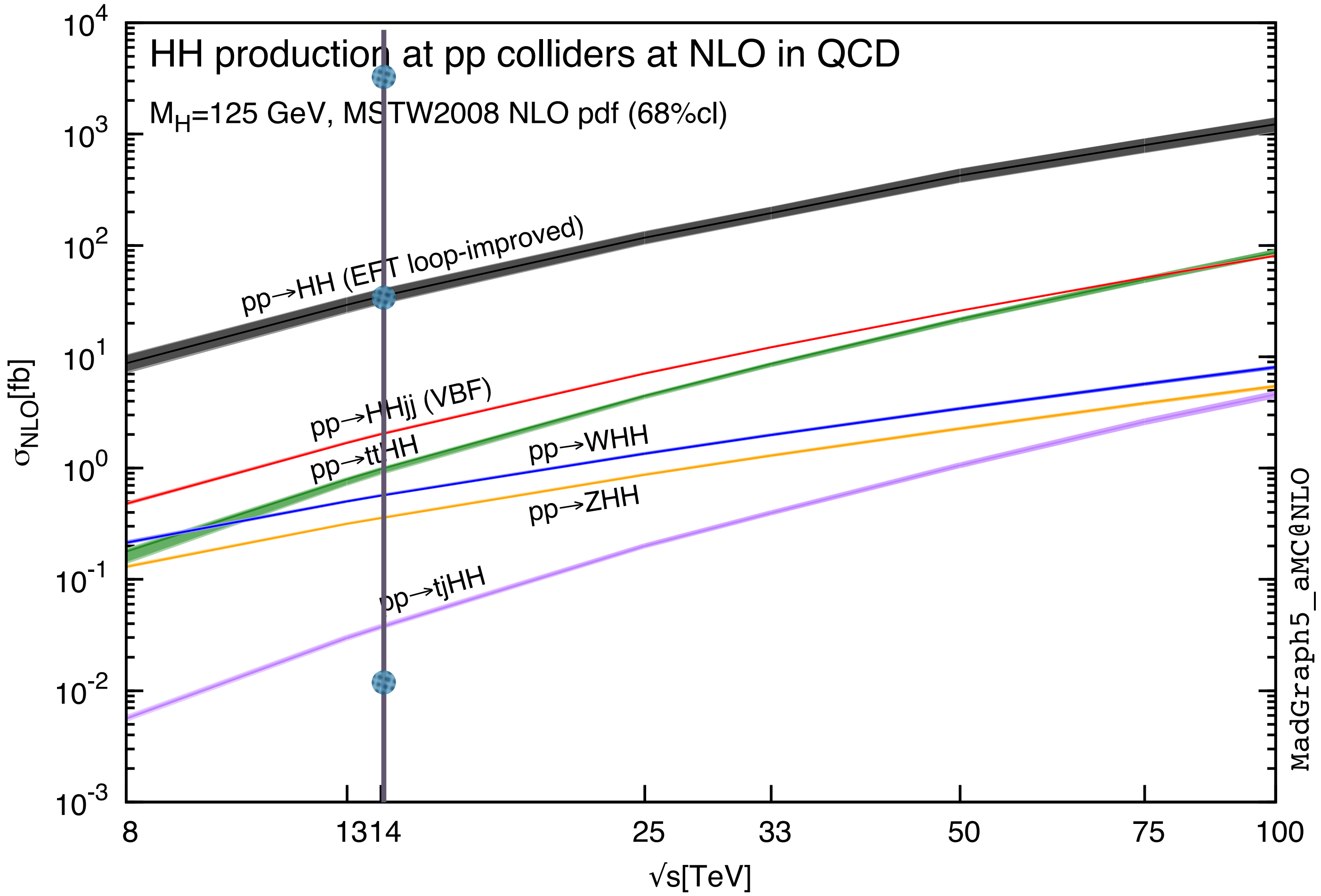
# Phase I : Higgs self-coupling

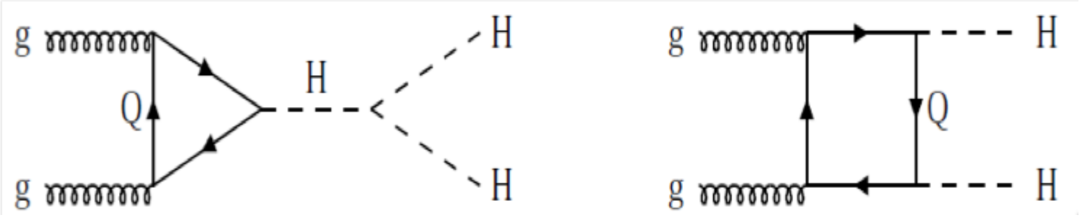



At 14 TeV from gg fusion:

$$\sigma_H = 55 \text{ pb}$$

$$\sigma_{HH} = 44 \text{ fb}$$

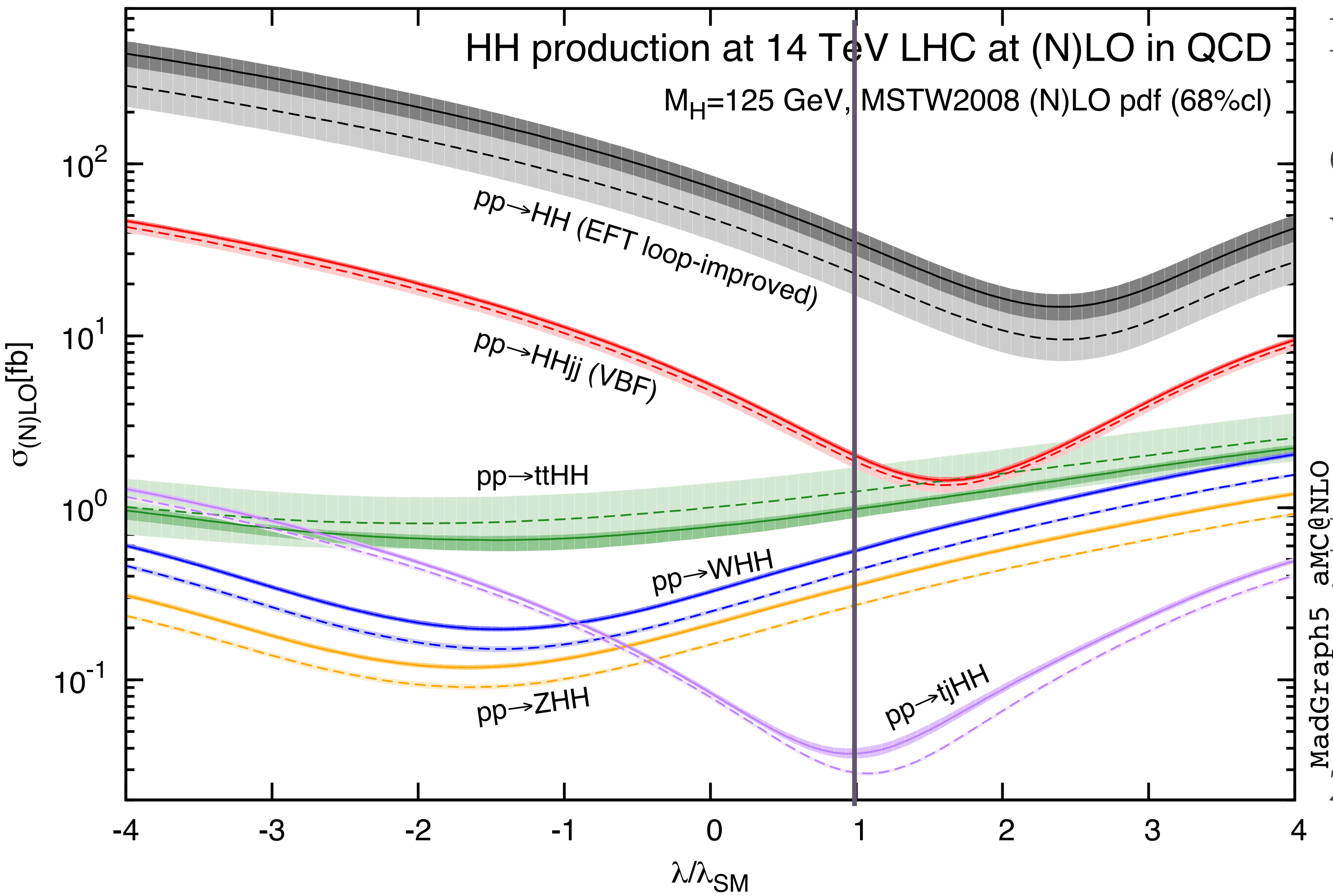
$$\sigma_{HHH} = 110 \text{ ab}$$




As in single Higgs many channels contribute in principle.
Cross sections for HH(H) increase by a factor of 20(60) at a FCC.

# Phase I : Higgs self-coupling

[Frederix et al. '14]




Many channels, but small cross sections.

Current limits are on $\sigma_{SM}$ (gg→HH) channel in various H decay channels:

CMS : $\sigma/\sigma_{SM} < 3.4$ (2.5)
ATLAS : $\sigma/\sigma_{SM} < 2.4$ (2.9)

Remarks:

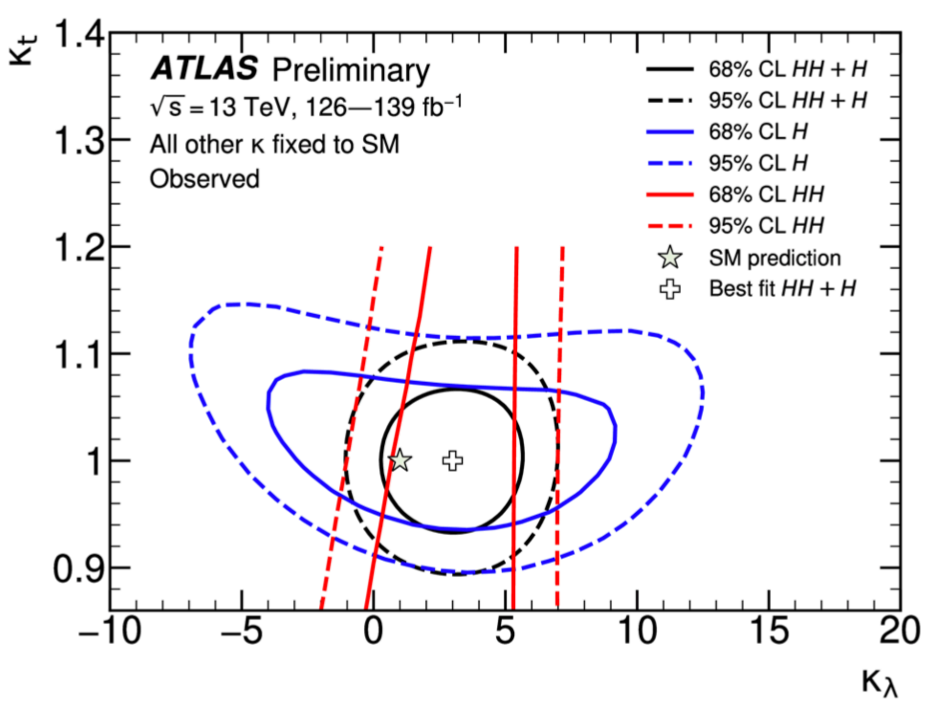
1. Interpretations of these bounds in terms of BSM always need additional assumptions on how the SM has been deformed.
2. The current most common assumption is just a change of $\lambda_3$ which leads to a change in $\sigma$ as well as of distributions:

$$\sigma = \sigma_{SM}[1 + (\kappa_\lambda - 1)A_1 + (\kappa_\lambda^2 - 1)A_2]$$

Note: due to shape changes, it is not straightforward to infer a bound on $\lambda_3$ from $\sigma$(HH), even when $\sigma_{BSM}=\sigma(\lambda_3)$ only is assumed.

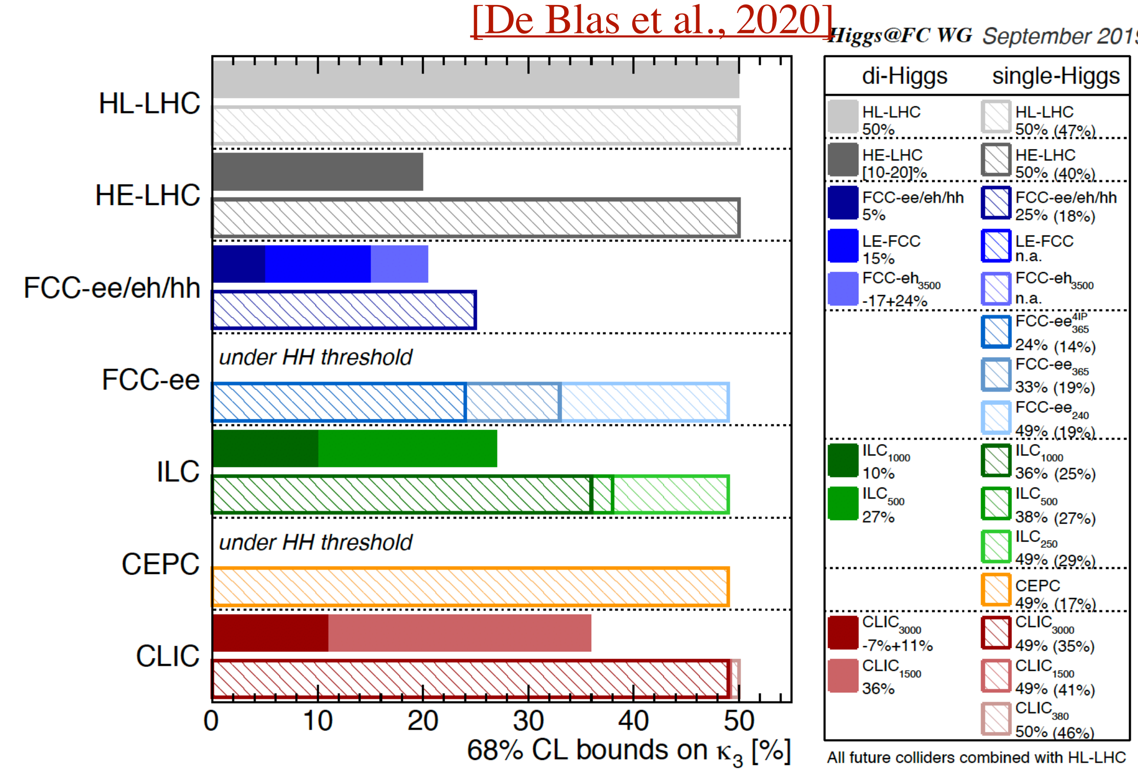
# Phase I : Higgs self-coupling

Now




Future

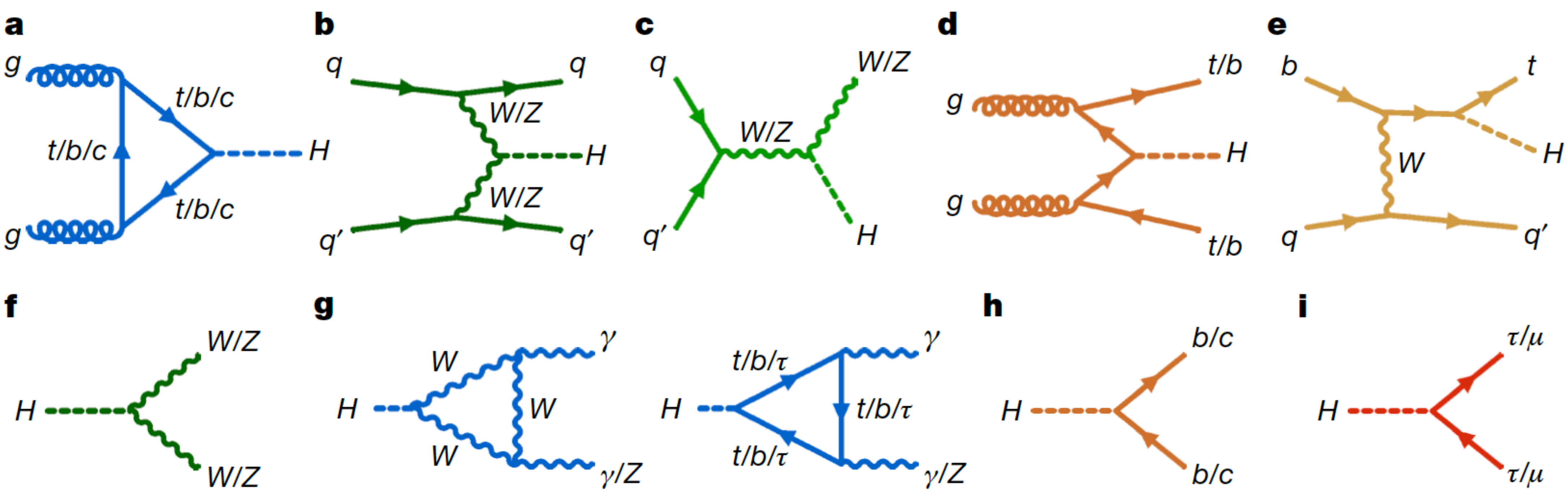
[De Blas et al., 2020]




Currently limits on $k_\lambda$ from H and HH are comparable and will stay so at the HL-LHC.

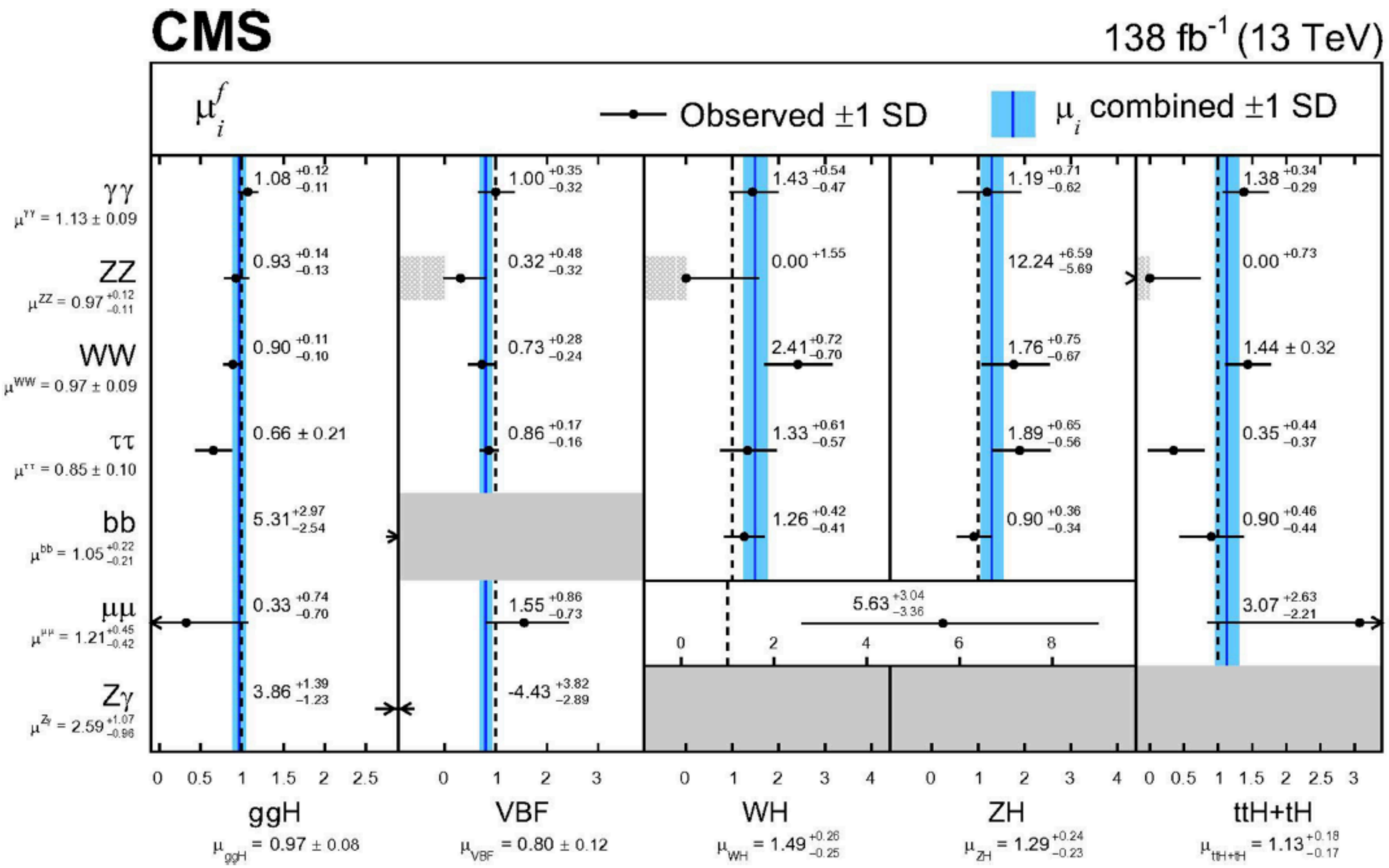
Borderline sensitivity to say something about EW baryogenesis…

# Phase II : couplings




$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{B}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{B}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$

# Phase II : Legacy Run II results



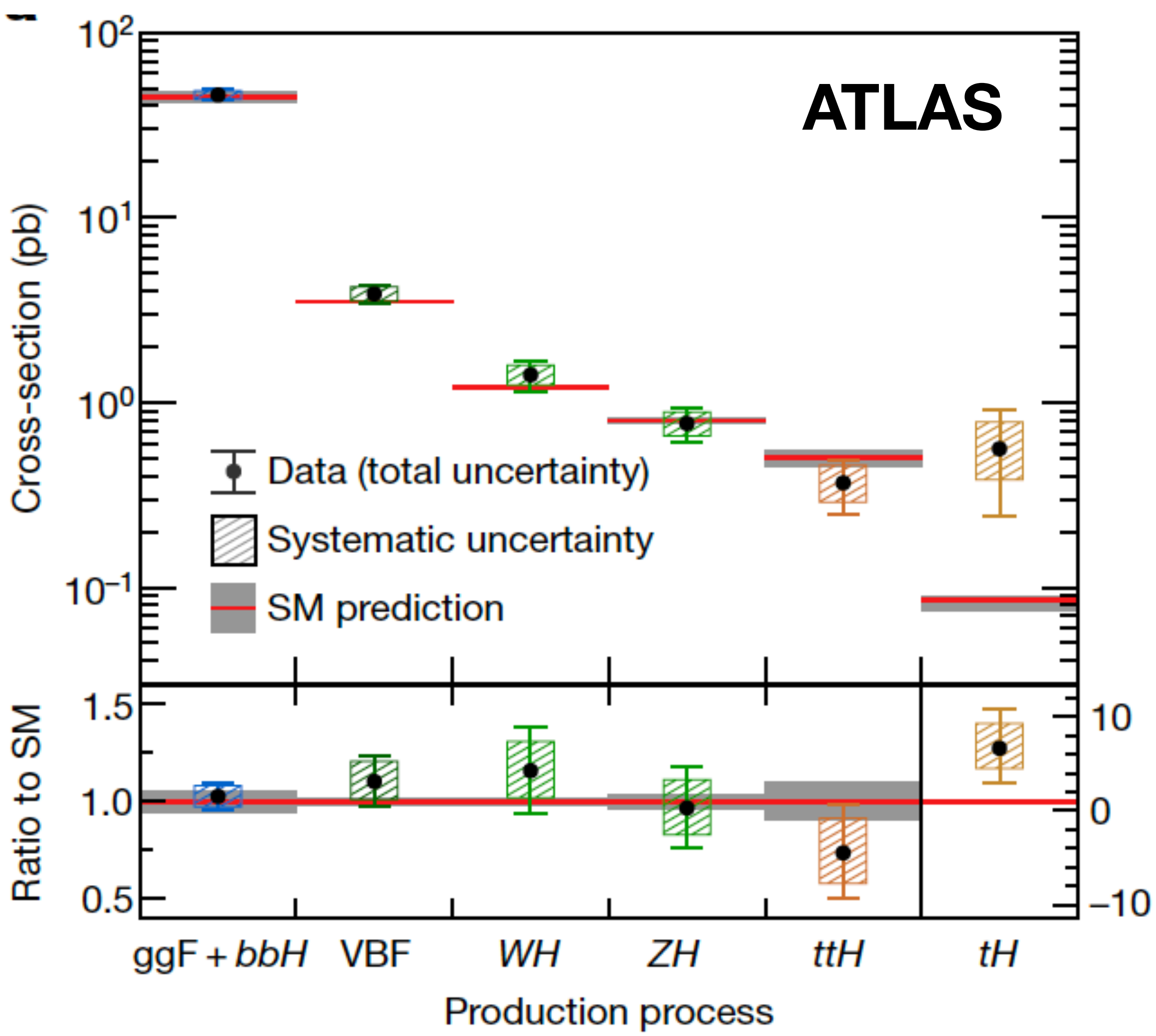

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{B}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{B}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$

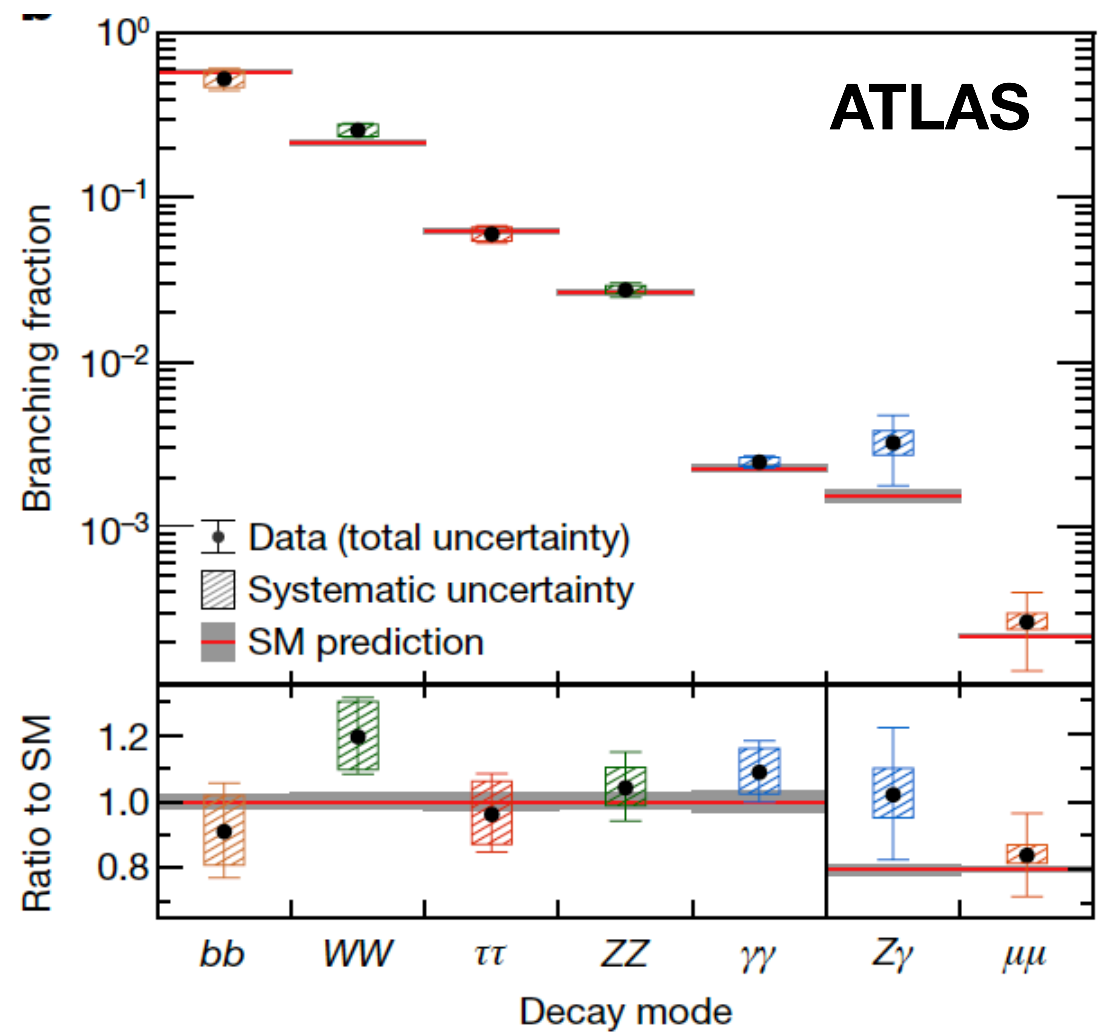
$$\mu_i = 1 + \delta\sigma_{\lambda_3}(i)$$

$$\mu^f = 1 + \delta \mathrm{BR}_{\lambda_3}(f)$$

This information can be used by anybody to test BSM scenarios that lead to different patterns of Higgs coupling changes.

# Phase II : Legacy Run II results



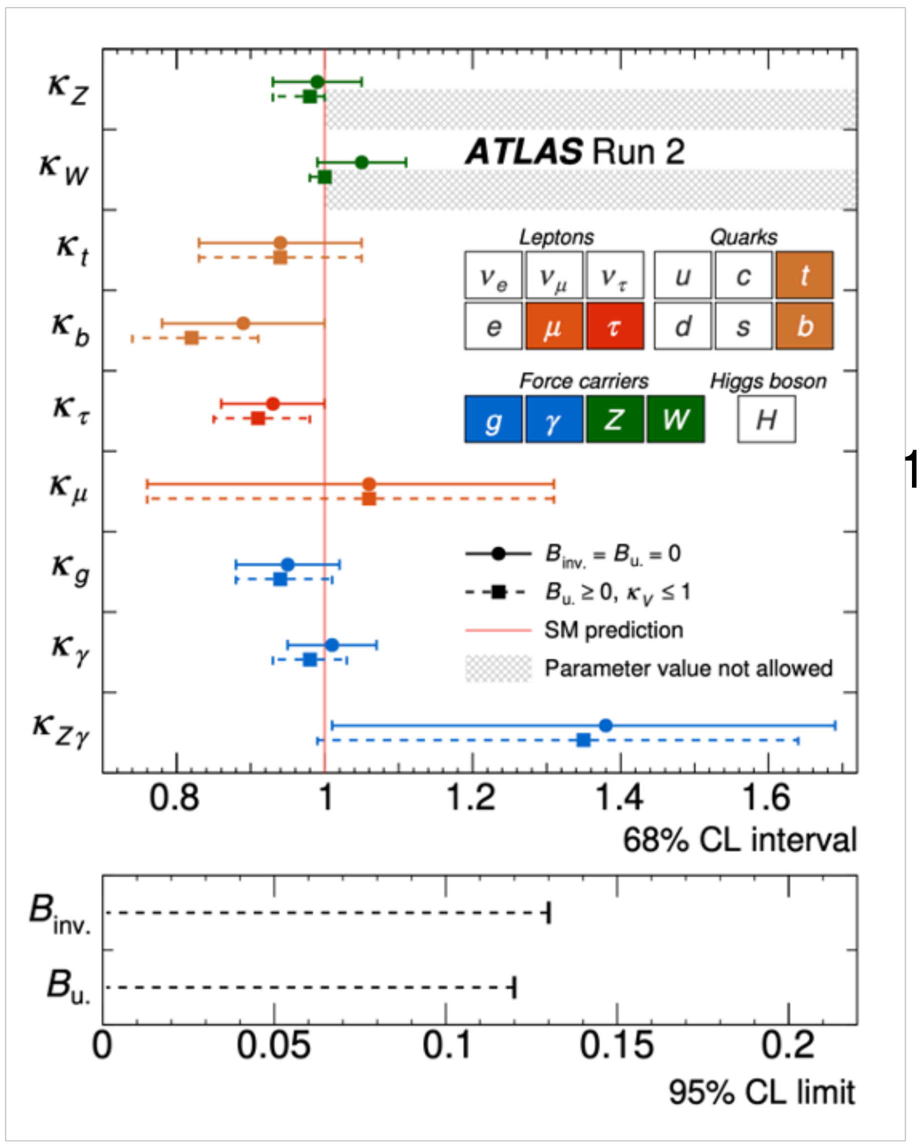




**Assuming only one $\mu$**

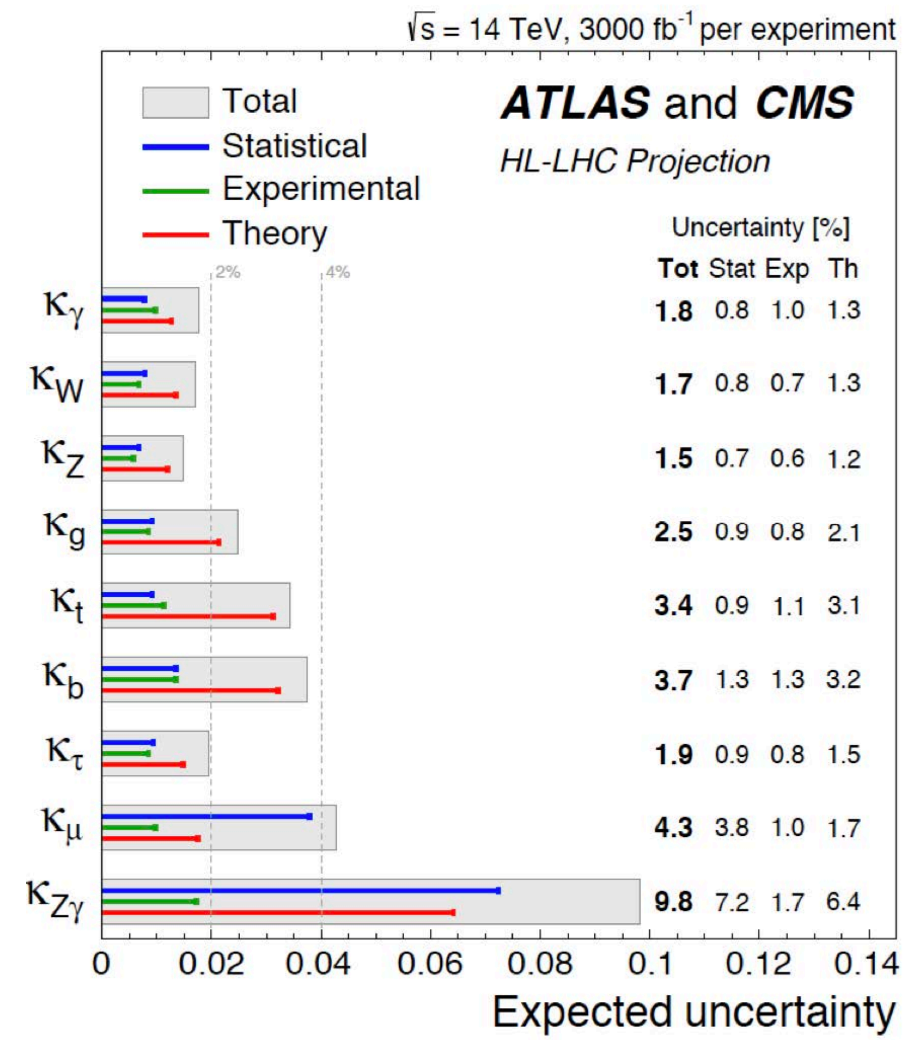
$$\mu = 1.05 \pm 0.06$$

$$= 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.04(\text{sig. th.}) \pm 0.02(\text{bkg. th.}).$$

# Phase II : Prospects




10-20% → 2-4%



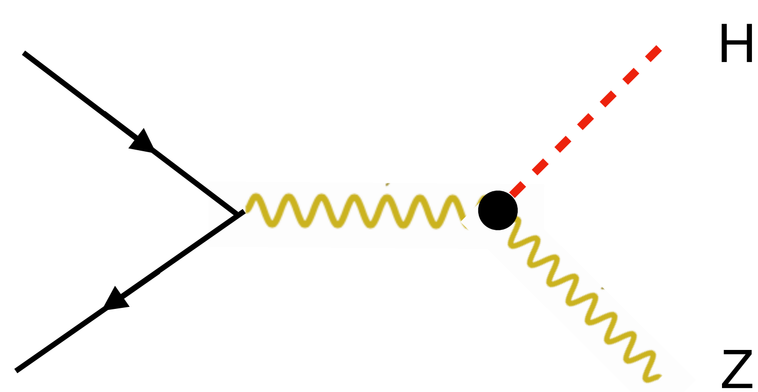

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

# Phase II : Prospects

| kappa-0 | HL-LHC | LHeC | HE-LHC S2 | HE-LHC S2′ | ILC 250 | ILC 500 | ILC 1000 | CLIC 380 | CLIC 15000 | CLIC 3000 | CEPC | FCC-ee 240 | FCC-ee 365 | FCC-ee/eh/hh |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\kappa_W$ [%] | 1.7 | 0.75 | 1.4 | 0.98 | 1.8 | 0.29 | 0.24 | 0.86 | 0.16 | 0.11 | 1.3 | 1.3 | 0.43 | 0.14 |
| $\kappa_Z$ [%] | 1.5 | 1.2 | 1.3 | 0.9 | 0.29 | 0.23 | 0.22 | 0.5 | 0.26 | 0.23 | 0.14 | 0.20 | 0.17 | 0.12 |
| $\kappa_g$ [%] | 2.3 | 3.6 | 1.9 | 1.2 | 2.3 | 0.97 | 0.66 | 2.5 | 1.3 | 0.9 | 1.5 | 1.7 | 1.0 | 0.49 |
| $\kappa_\gamma$ [%] | 1.9 | 7.6 | 1.6 | 1.2 | 6.7 | 3.4 | 1.9 | 98⋆ | 5.0 | 2.2 | 3.7 | 4.7 | 3.9 | 0.29 |
| $\kappa_{Z\gamma}$ [%] | 10. | – | 5.7 | 3.8 | 99⋆ | 86⋆ | 85⋆ | 120⋆ | 15 | 6.9 | 8.2 | 81⋆ | 75⋆ | 0.69 |
| $\kappa_c$ [%] | – | 4.1 | – | – | 2.5 | 1.3 | 0.9 | 4.3 | 1.8 | 1.4 | 2.2 | 1.8 | 1.3 | 0.95 |
| $\kappa_t$ [%] | 3.3 | – | 2.8 | 1.7 | – | 6.9 | 1.6 | – | – | 2.7 | – | – | – | 1.0 |
| $\kappa_b$ [%] | 3.6 | 2.1 | 3.2 | 2.3 | 1.8 | 0.58 | 0.48 | 1.9 | 0.46 | 0.37 | 1.2 | 1.3 | 0.67 | 0.43 |
| $\kappa_\mu$ [%] | 4.6 | – | 2.5 | 1.7 | 15 | 9.4 | 6.2 | 320⋆ | 13 | 5.8 | 8.9 | 10 | 8.9 | 0.41 |
| $\kappa_\tau$ [%] | 1.9 | 3.3 | 1.5 | 1.1 | 1.9 | 0.70 | 0.57 | 3.0 | 1.3 | 0.88 | 1.3 | 1.4 | 0.73 | 0.44 |

[De Blas et al., 2020]

**At e+e- :**



# Phase III : SMEFT

$\Lambda_{UV}$

TeV

Simplicity 🙂

Naturalness ☹️

TeV $\Lambda_{UV}$

Naturalness 🙂

Simplicity ☹️

$$\mathscr{L} = \mathscr{L}^{(2)} + \mathscr{L}^{(4)} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \ldots$$

$m_h^2 \simeq \Lambda^2$

$\Rightarrow \Lambda \simeq 10^3$ GeV

Rattazzi® adapted

$m_\nu = 0$

$U(1)^3_L \times U(1)_B$

GIM

$Y_u, Y_d, Y_l \Rightarrow$ ~~Flavor~~ & $\not{CP}$

$\not{U(1)}_L \to m_\nu \neq 0$ $\Rightarrow \Lambda \geq 10^{14}$ GeV

~~Flavor~~ $\Rightarrow \mu \to e\gamma, \Delta m_K, \ldots$ $\Rightarrow \Lambda \geq 10^{6}$ GeV

$\not{CP} \Rightarrow$ edm's

Dipoles $\Rightarrow (g-2)_\mu$ $\Rightarrow \Lambda \geq 10^{3}$ GeV

$U(1)_B \Rightarrow p \to \pi^0 e^+$ $\Rightarrow \Lambda \geq 10^{15}$ GeV

# Phase III : SMEFT

The matter content of SM has been experimentally verified and evidence for new light states has not yet emerged.

SM measurements can always be seen as searches for deviations from the dim=4 SM Lagrangian predictions. More in general one can interpret measurements in terms of an EFT:

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \ldots$$

the BSM ambitions of the LHC Higgs/Top/SM physics programmes can be recast in as simple as powerful way in terms of one statement:

"BSM goal" of the SM LHC Run II programme:

determination of the couplings of the SM@DIM6

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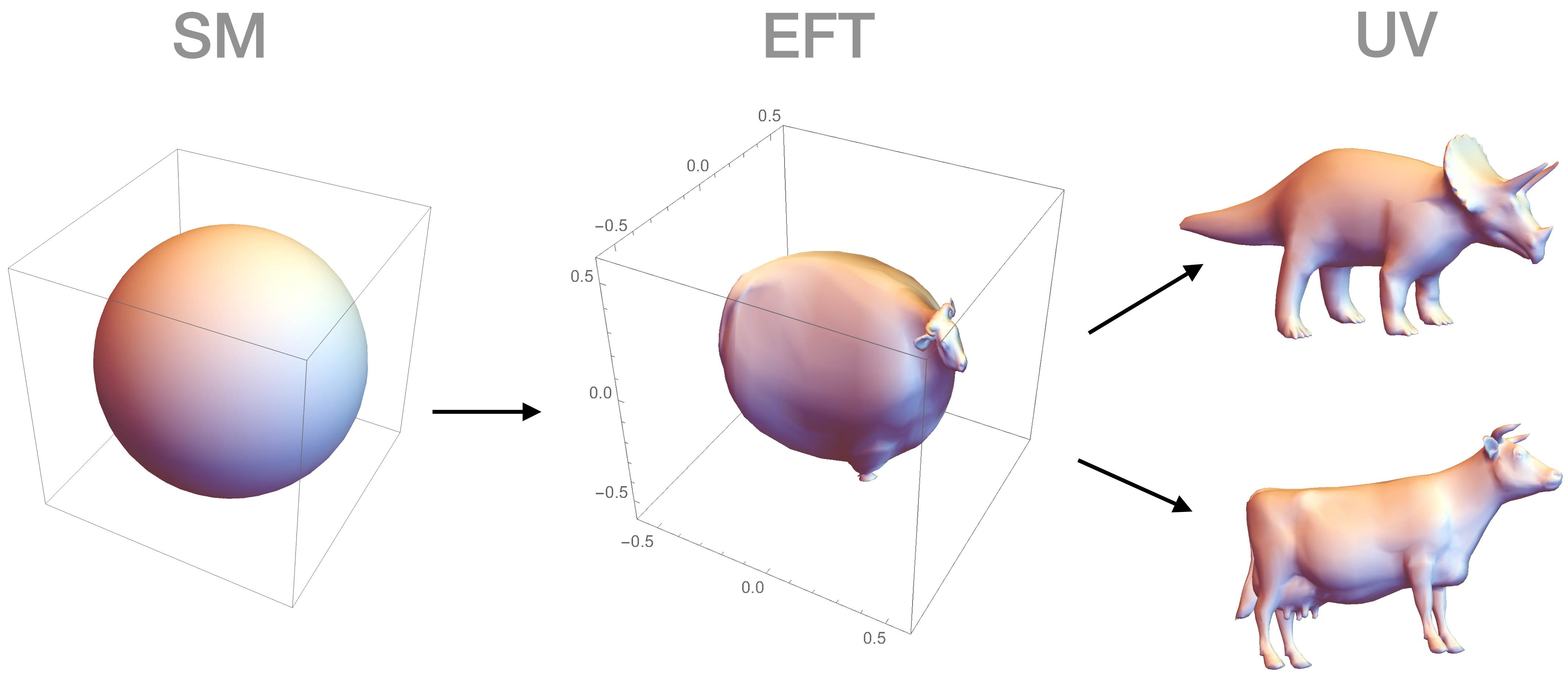
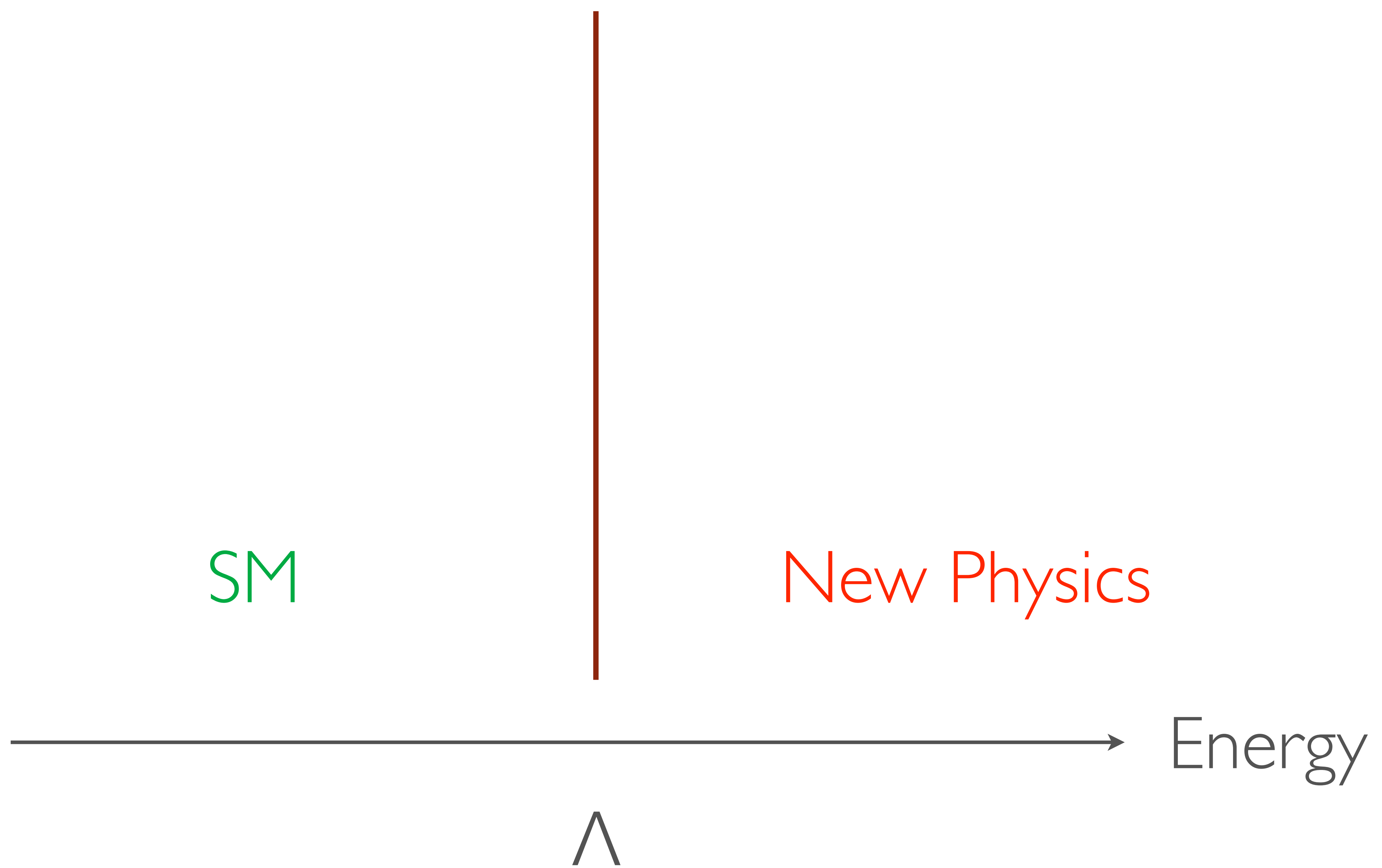


# The idea of an EFT



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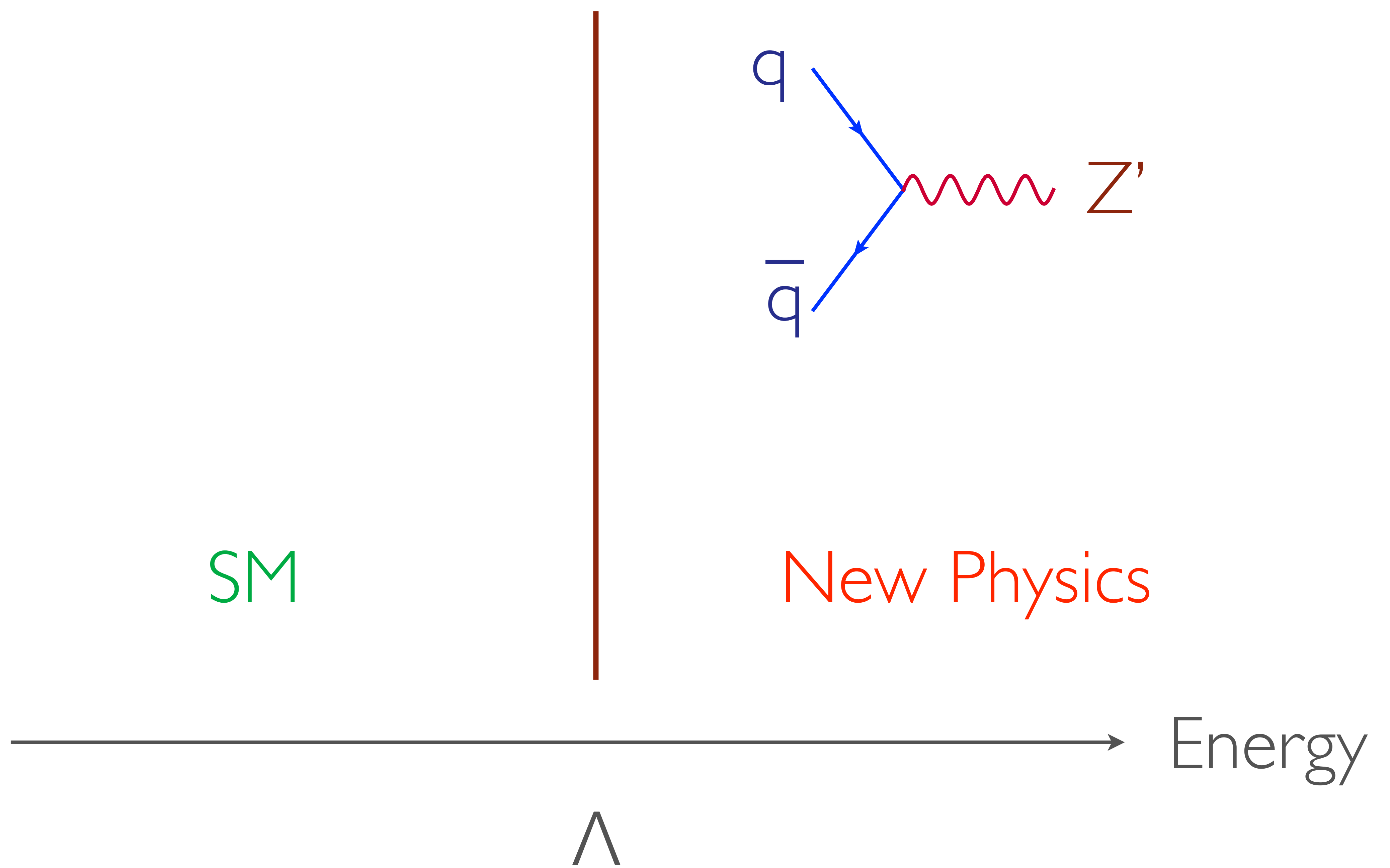

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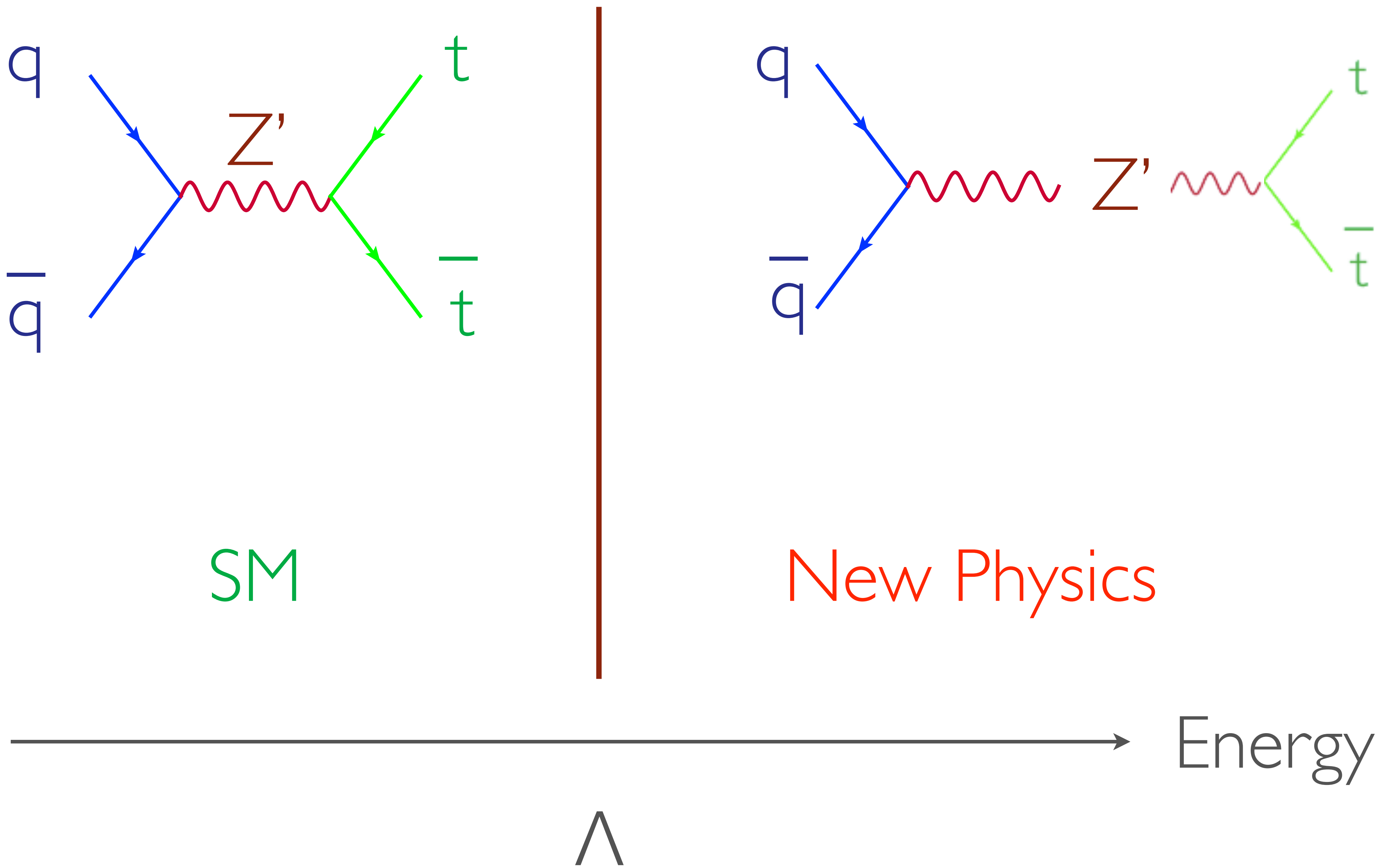

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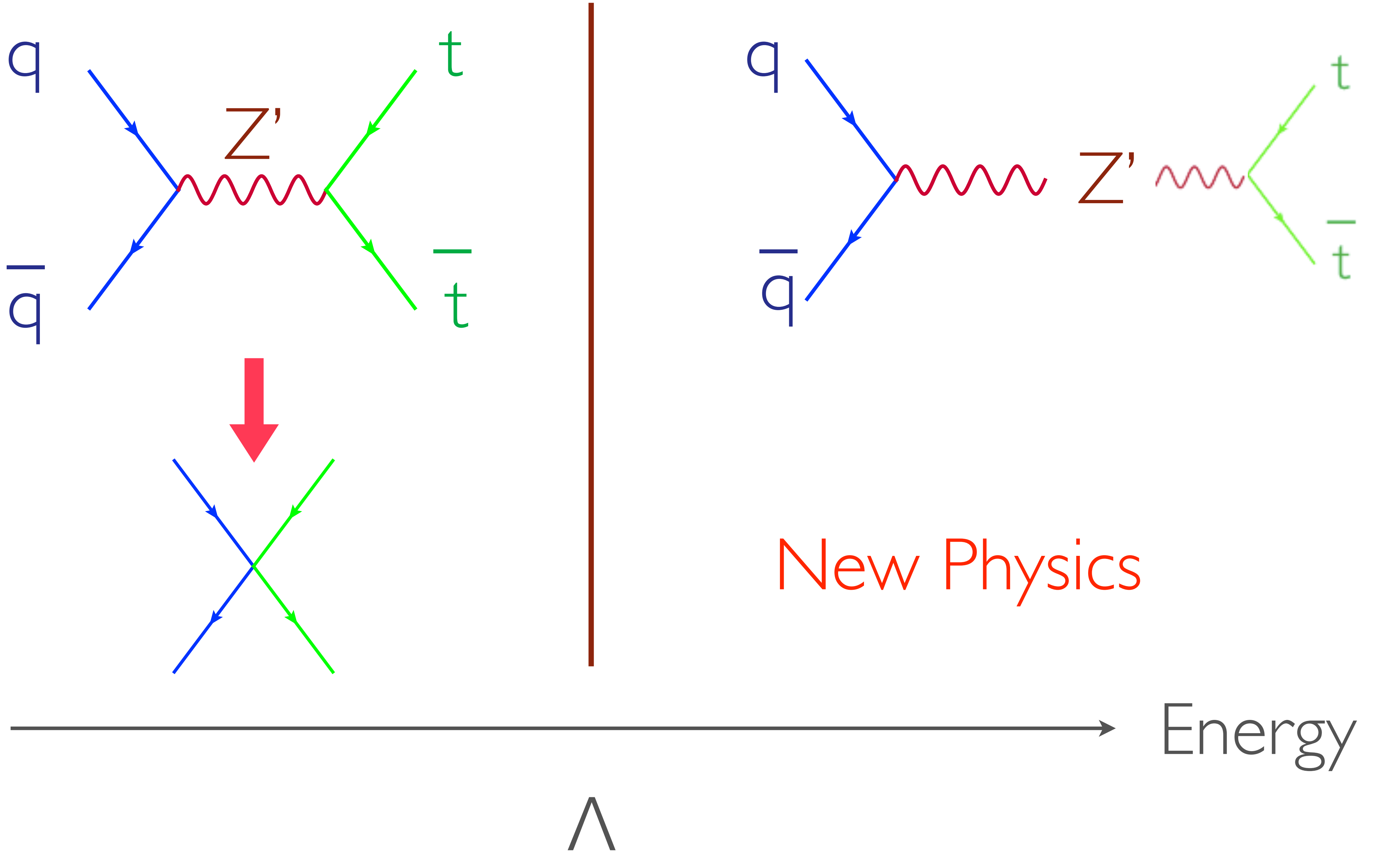

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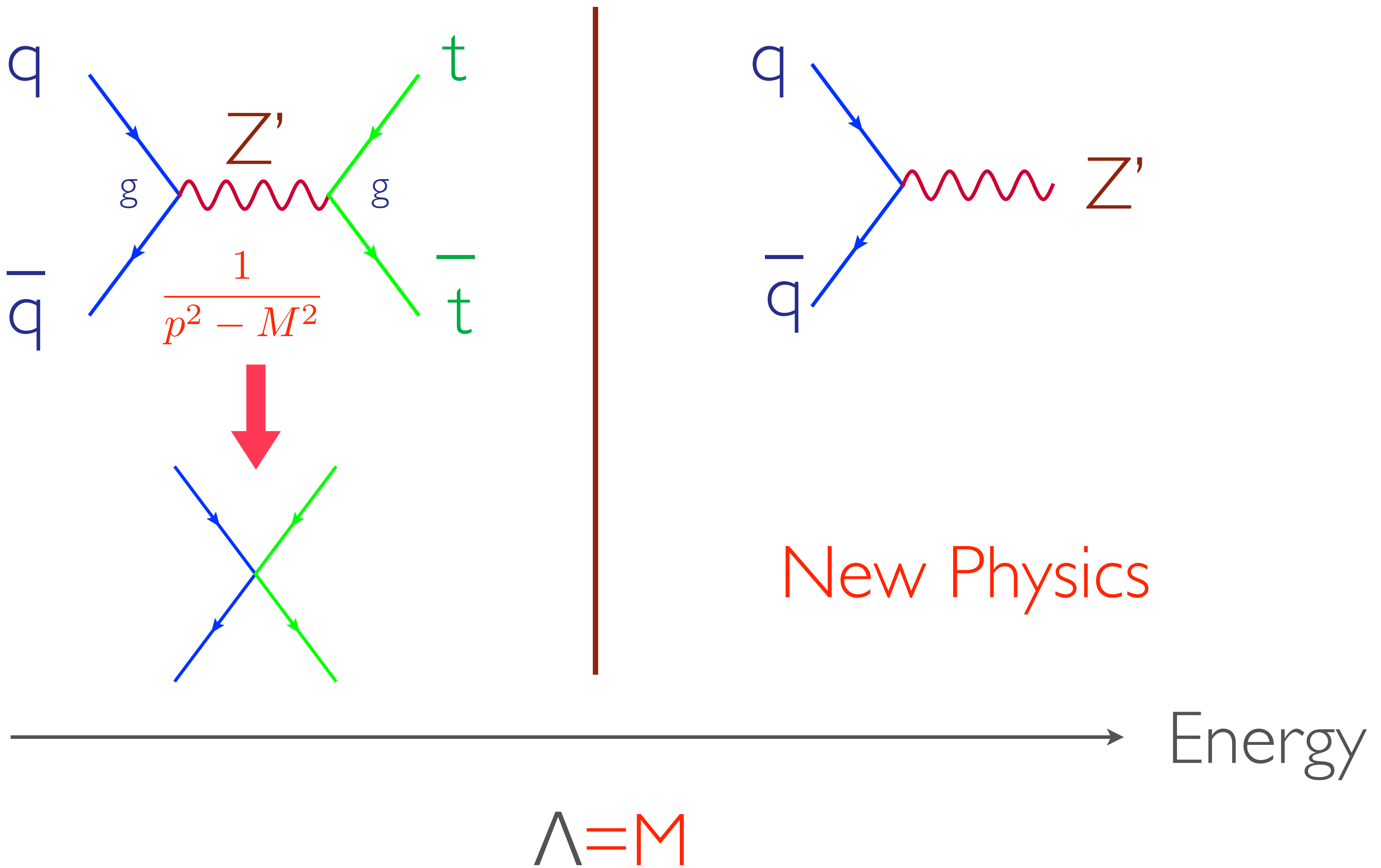

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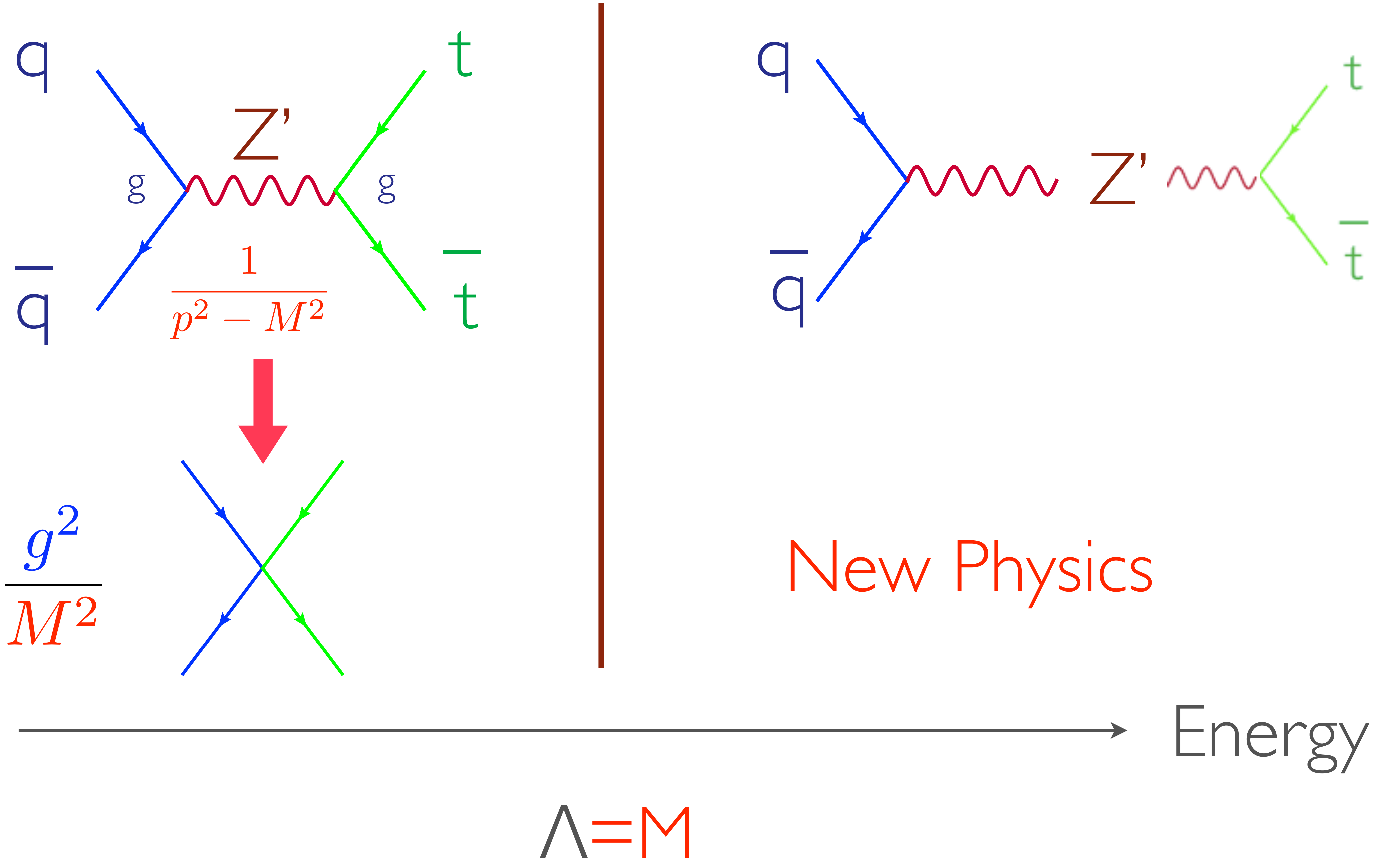
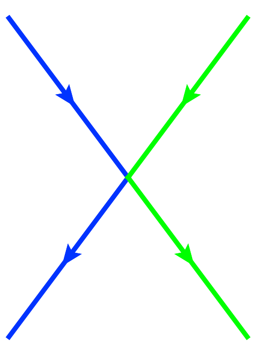


# The idea of an EFT

$$\frac{g^2}{M^2}$$



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{g^2}{M^2}\bar{\psi}\psi\bar{\psi}\psi$$

$$M^2 = g^2 v^2 \Rightarrow \Lambda = v$$

$\Lambda$ is an upper bound on the scale of new physics

# The idea of an EFT

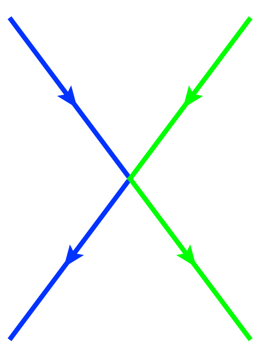
$$\hbar = c = 1$$

$$\dim A^\mu = 1$$

$$\dim \phi = 1$$

$$\dim \psi = 3/2$$

$$\frac{g^2}{M^2}$$



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{\text{dim}=6}$$

Bad News: 59 operators *[Buchmuller, Wyler, 1986]*
Good News : an handful are unconstrained and can significantly contribute to top phenomenology!

# SMEFT Lagrangian: Dim=6

[Buchmuller and Wyler, 86] [Grzadkowski et al, 10]

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

# SMEFT Lagrangian: Dim=6

[Buchmuller and Wyler, 86] [Grzadkowski et al, 10]

| $(\bar{L}L)(\bar{L}L)$ | | $(\bar{R}R)(\bar{R}R)$ | | $(\bar{L}L)(\bar{R}R)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$ | $Q_{le}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{dd}$ | $(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{ed}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |

| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ | | $B$-violating | |
|---|---|---|---|
| $Q_{ledq}$ | $(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$ |
| $Q_{quqd}^{(1)}$ | $(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{quqd}^{(8)}$ | $(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$ | $Q_{qqq}^{(1)}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(1)}$ | $(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$ | $Q_{qqq}^{(3)}$ | $\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(3)}$ | $(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ |

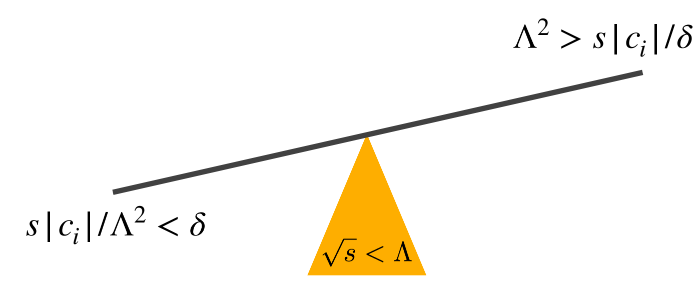
# The way of SMEFT

One can satisfy all the previous requirements, by building an EFT on top of the SM that respects the gauge symmetries:

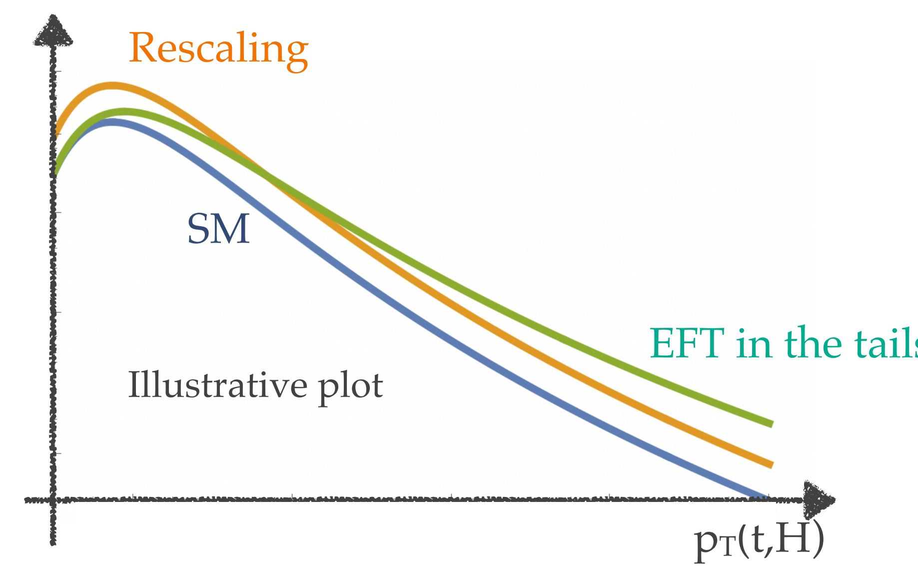
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}^{(4)}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i^{N_6} c_i \mathcal{O}_i^{(6)} + \frac{1}{\Lambda^4}\sum_j^{N_8} c_j \mathcal{O}_j^{(8)} + \dots$$

With the "only" assumption that all new states are heavier than energy probed by the experiment $\sqrt{s} < \Lambda$.

The theory is renormalizable order by order in $1/\Lambda$, perturbative computations can be consistently performed at any order, and the theory is predictive, i.e., well defined patterns of deviations are allowed, that can be further limited by adding assumptions from the UV. Operators can lead to larger effects at high energy (for different reasons).




Energy helps precision



# The way of SMEFT

## A simple approach

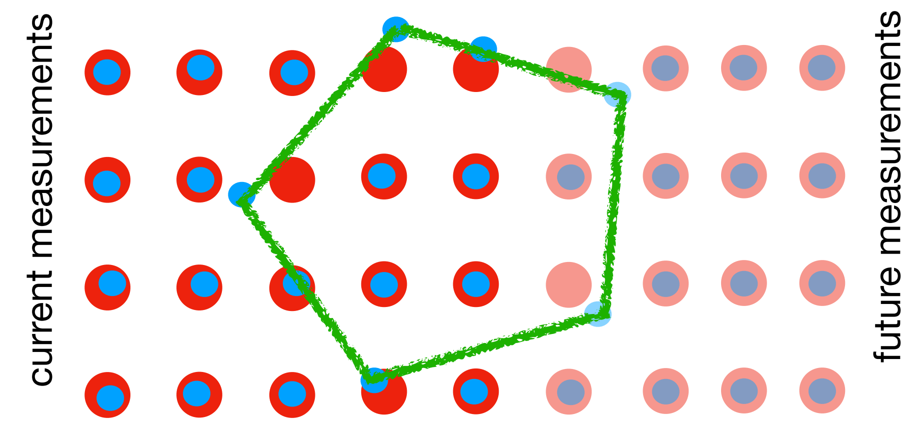
The master equation of an EFT approach has three key elements:

$$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \frac{1}{\Lambda^2} \sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Most precise EFT predictions

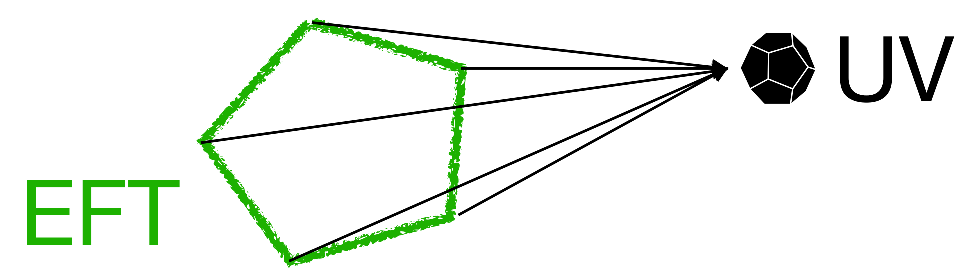
Most precise SM predictions for observables: NLO, NNLO, N3LO…

Most precise/accurate experimental measurements with uncertainties and correlations




⇒ increased NP Sensitivity

⇒ increased UV identification power



# EFT picture: Matching

$$\mathcal{L}_{\rm EFT}(\phi_{\rm SM}, \mu = \Lambda)$$

M

$$\mathcal{L}_{\rm UV}(\phi_{\rm SM}, \phi_{\rm BSM})$$

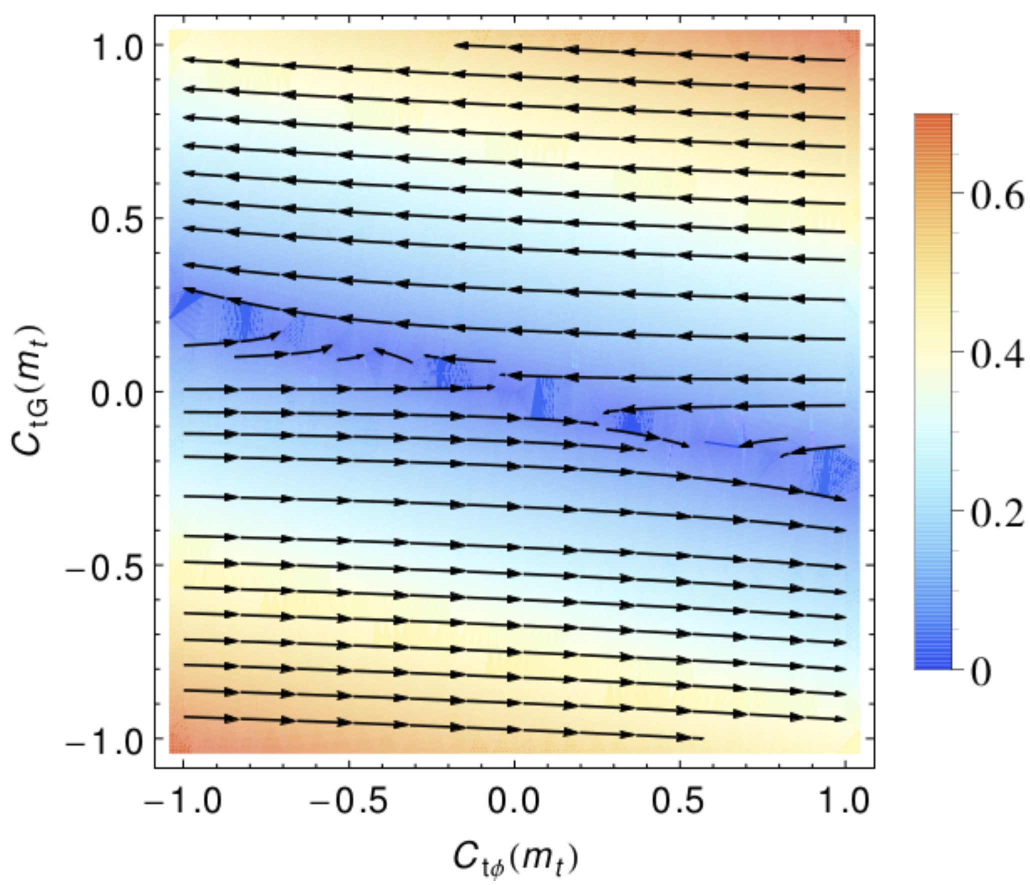
RGE

$$\mathcal{L}_{\rm EFT}(\phi_{\rm SM}, \mu = v)$$

Energy

# Running

## Operators run and mix under RGE




$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\,\tilde{\phi}\,,$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}\,.$$

$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij} C_j(\mu), \quad \gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

At = 1 TeV: $C_{tG} = 1$, $C_{t\phi} = 0$;

At = 173 GeV: $C_{tG} = 0.98$, $C_{t\phi} = 0.45$

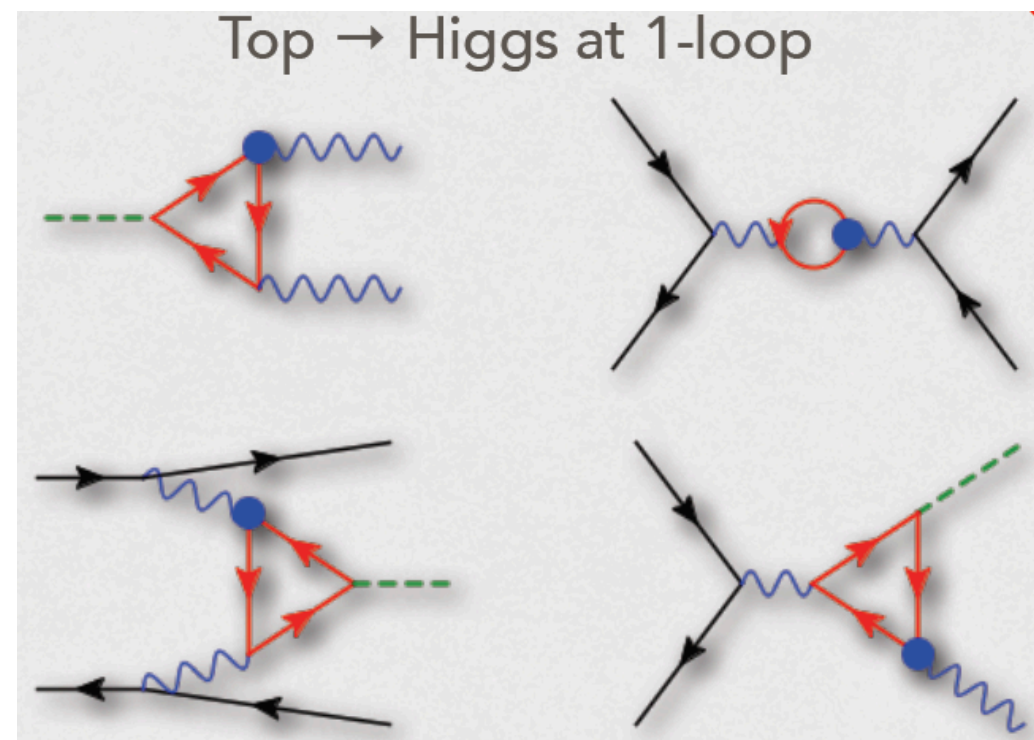
Scale corresponds to the change from mt to 2 TeV.

# Loop effects

**New operators arise at one loop**

The SMEFT is as renormalizable as the SM when QCD and EW corrections are calculated.

- VBF, ZH, WH at LHC
- ZH, WWF, ZZF at $e^+e^-$
- H decay to γγ, γZ, Zll, Wlν, bb, ττ, μμ
- ggH is known




Possible deviations using current constraints on the relevant operators

# Higgs potential modifications

To go Beyond the SM, one can parametrise a generic potential by expanding it in series:

$$V^{\rm BSM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 + \sum_n \frac{c_{2n}}{\Lambda^{2n-4}}(\Phi^\dagger\Phi - \frac{v^2}{2})^n$$

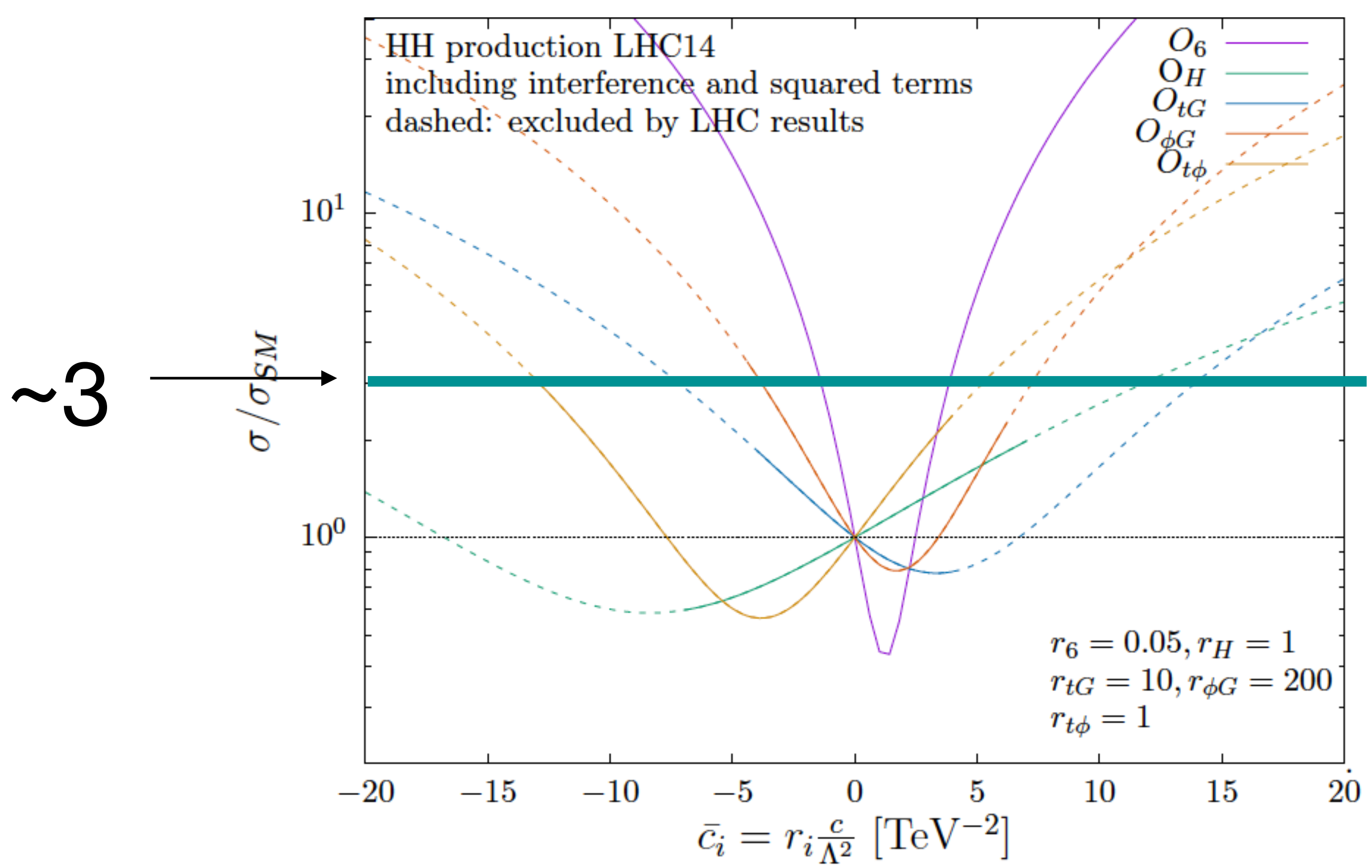
so that the basic relations remain the same as in the SM: $\begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases}$ while the $\lambda_3$ and $\lambda_4$ change: $\begin{cases} \lambda_3 = \kappa_\lambda \lambda_3^{\rm SM} \\ \lambda_4 = \kappa_{\lambda_4}\lambda_4^{\rm SM} \end{cases}$

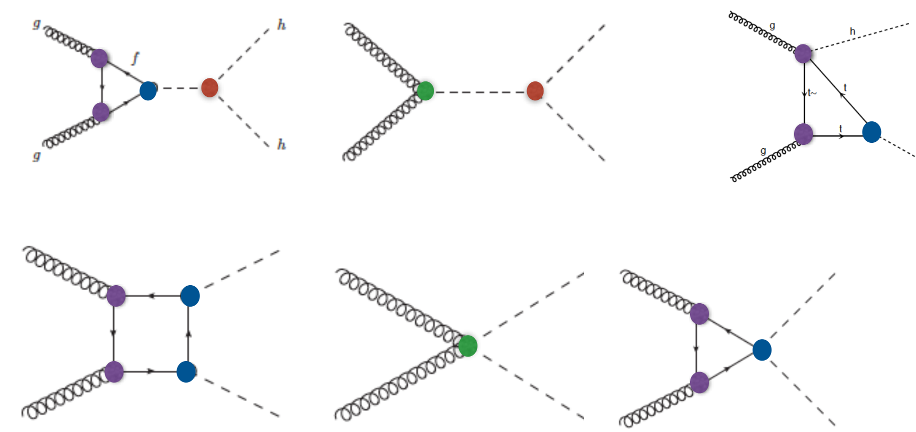
So for example: adding $c_6$ only $\begin{cases} \kappa_\lambda = 1 + \dfrac{c_6 v^2}{\lambda\Lambda^2} \\ \kappa_{\lambda_4} = 1 + \dfrac{6 c_6 v^2}{\lambda\Lambda^2} = 6\kappa_\lambda - 5 \end{cases}$ i.e., in this case $\lambda_3$ and $\lambda_4$ are related.

Adding $c_8$ makes $\lambda_3$ and $\lambda_4$ independent (full unlocking).

This is a general feature of dim=6 vs dim=8 in the SMEFT. In the HEFT three and four point (with Higgs couplings) are disentangled from the start=>more parameters. Equivalence can be established on a process by process basis between HEFT and dim=n EFT.

# EFT analysis of HH



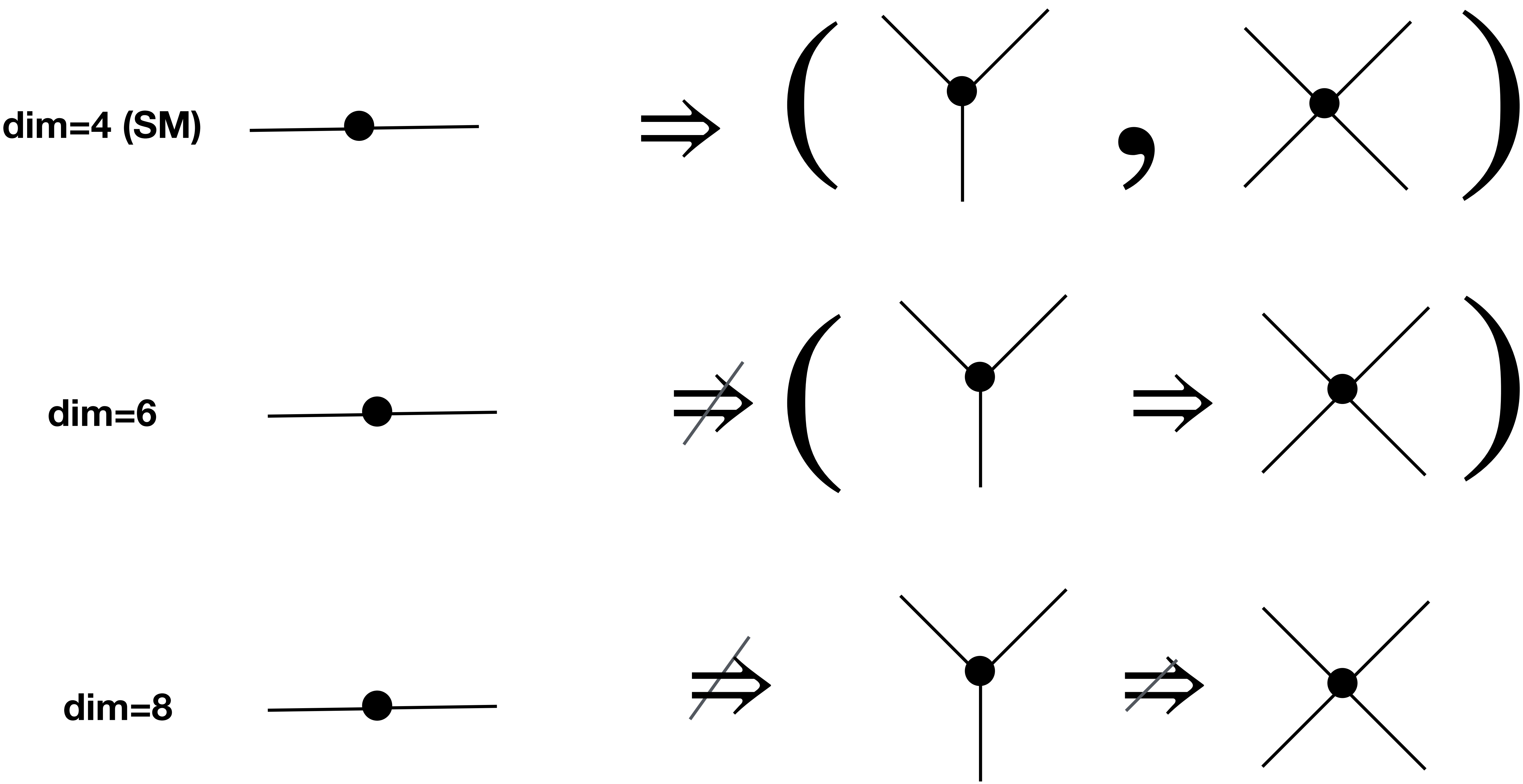



Other couplings enter in the same process: top Yukawa, ggh(h) coupling, top-gluon interaction, which can constrained by other processes. 1-1 correspondence between d.o.f and new constraint.

**The present**
Given the current constraints on σ(HH), σ(H) and the fresh ttH measurement, the Higgs self-coupling can be currently constrained "ignoring" other couplings

**The future**
Precise knowledge of other Wilson coefficients will be needed to bound λ as the bound gets closer to SM. Differential distributions will also

# Unlocking with the EFT



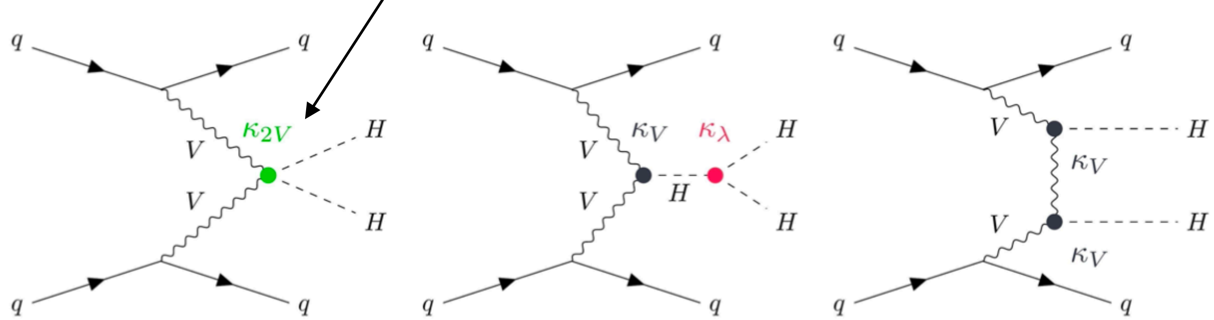
# EFT analysis of HH

**Unlocking the SM**

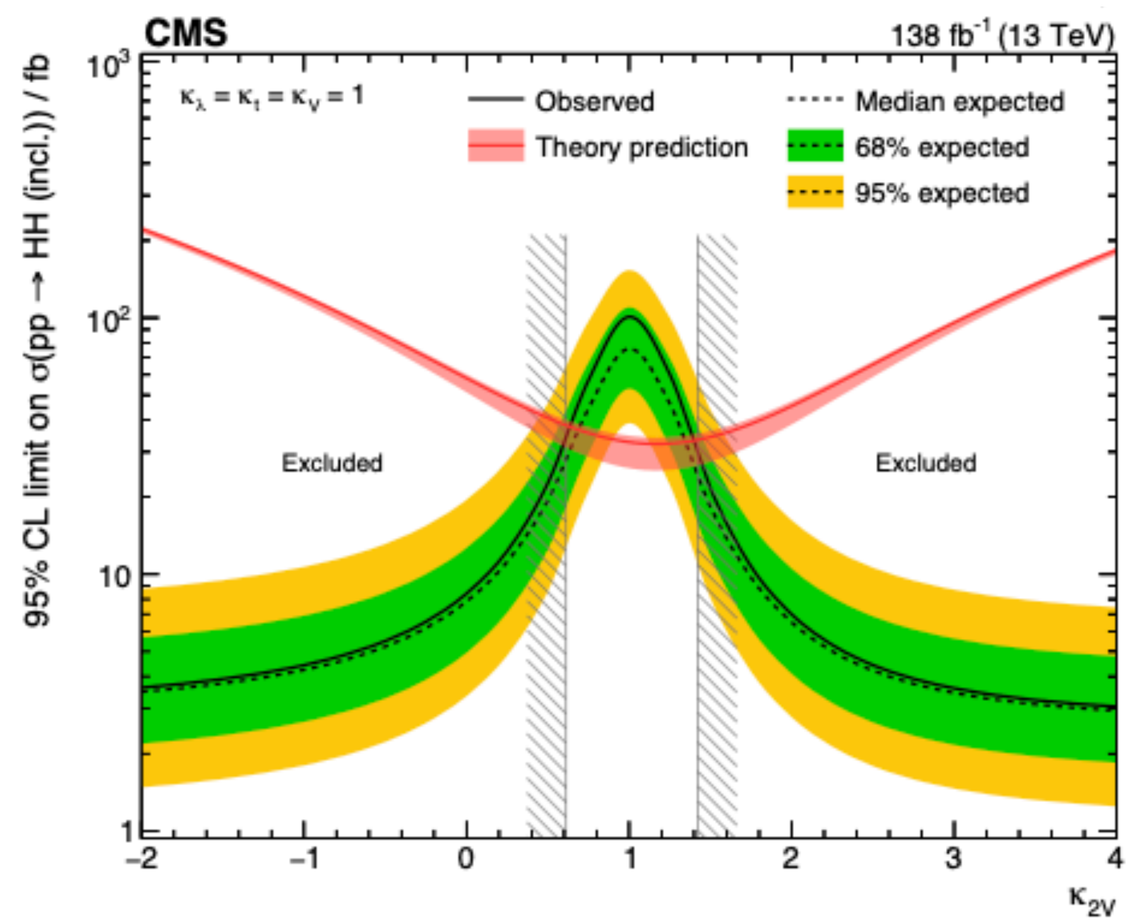
$$\mathscr{L}_{SM}^{(4)} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi}i\not{D}\psi + (y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \mathrm{h.c.}) + |D_\mu\phi|^2 - V(\phi)$$

$$\mathscr{A}(V_LV_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$$

Seagull vertex of scalar SU(2) or $(\phi^\dagger.\phi)^2$




- $\mathbf{k_{2V}} \leq 0$ excluded with **6.6σ** assuming otherwise SM couplings




This can be interpreted as a dim=8 operator change in the SMEFT

# SMEFT global fits at dim=6

- Measurements:
  - Total as well as differential, unfolded and/or fiducial, including uncertainties and correlations.
  - Reference SMEFT interpretations done by the experimental collaboration for best sensitivity targets.

- Theoretical predictions:
  - SM at the best possible accuracy
  - SMEFT at least at NLO in QCD

- Fitting:
  - Robust and scalable fitting technology
  - Combination with low/energy, flavour and LEP measurements

# A powerful approach

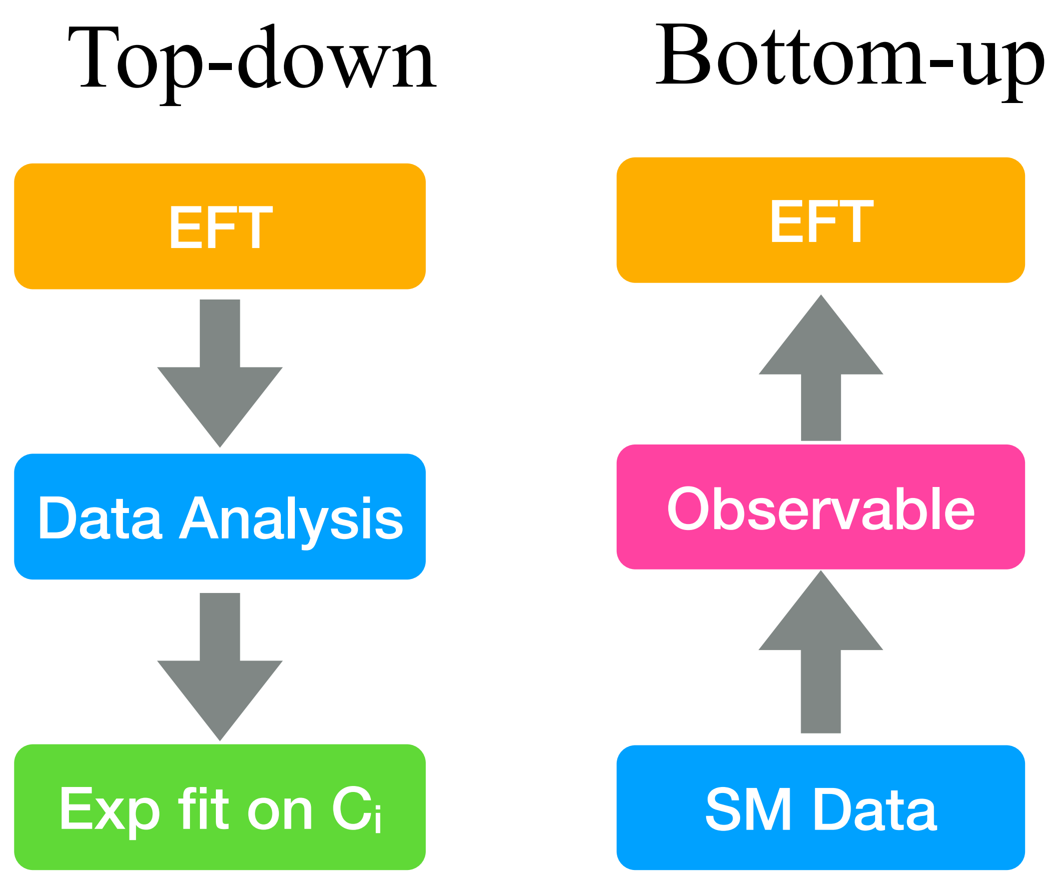
It's as exciting as challenging. Pattern of deformations enter many observables in a correlated way.

Needs to manage complexity, uncertainties and correlations.

Needs coordinated work among analysis groups in collaborations traditionally working separately (top, Higgs, EW,…)

Needs coordinated work between theorists and experimentalists (model dependence, validity, interpretations, matching to the UV).

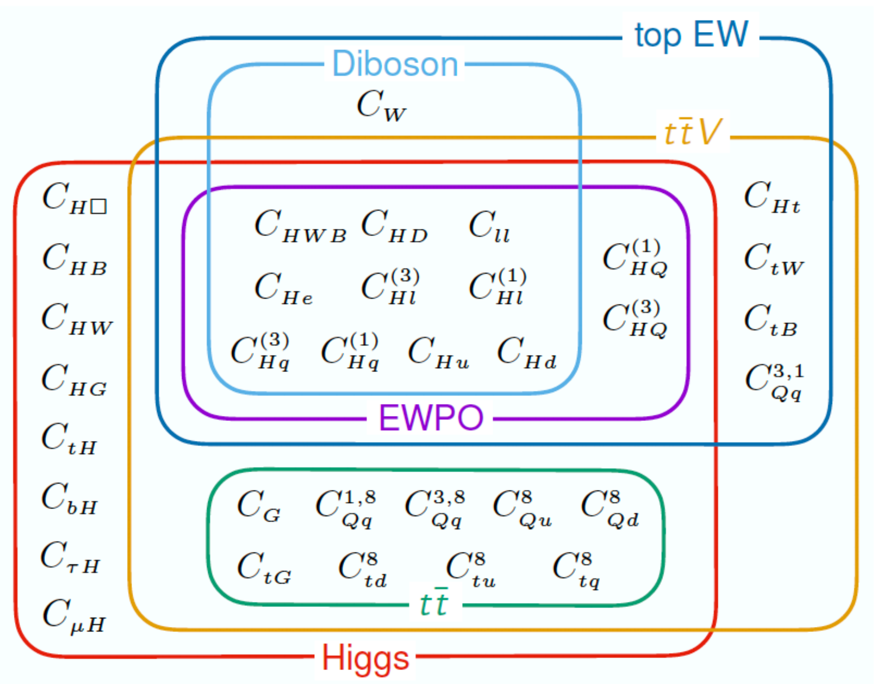
A LHC EFT WG is working hard to move things forward in a joint TH/EXP effort (thanks to all contributing!!)




Complementary!

# First explorations: EWPO+H+EW+Top

- Already now and without a dedicated experimental effort there is considerable information that can be used to set limits:
  - Fitmaker [J. Ellis, M. Madigan, K. Mimasu, V. Sanz, T. You 2012.02779]
  - SMEFiT [J. Either, G. Magni, F. M., L. Mantani, E. Nocera, J. Rojo, E. Slade, E. Vryonidou, C. Zhang, 2105.00006]
  - SFitter [Biekötter, Corbett, Plehn, 2018] + [I. Brivio, S. Bruggisser, F. M., R. Moutafis, T. Plehn, E. Vryonidou, S. Westhoff, C. Zhang, 1910.03606] (separated)
  - HEPfit [de Blas, et al. 2019]




[Ellis et al. 2012.02779]

- 30+ operators at dim=6, linear and/or quadratic fits, Higgs/Top/EW at LHC, WW at LEP and EWPO.

# First explorations: EWPO+H+EW+Top

Theory

(N)NLO QCD for SM
NLO QCD for SMEFT
State-of-the-art PDFs without top data

Data

317 data points: Top: ttbar, single-top, associated top production, distributions.
Higgs production and decay, differential distributions, STXS.
Diboson production, distributions

Global EW/Top/Higgs SMEFT fit

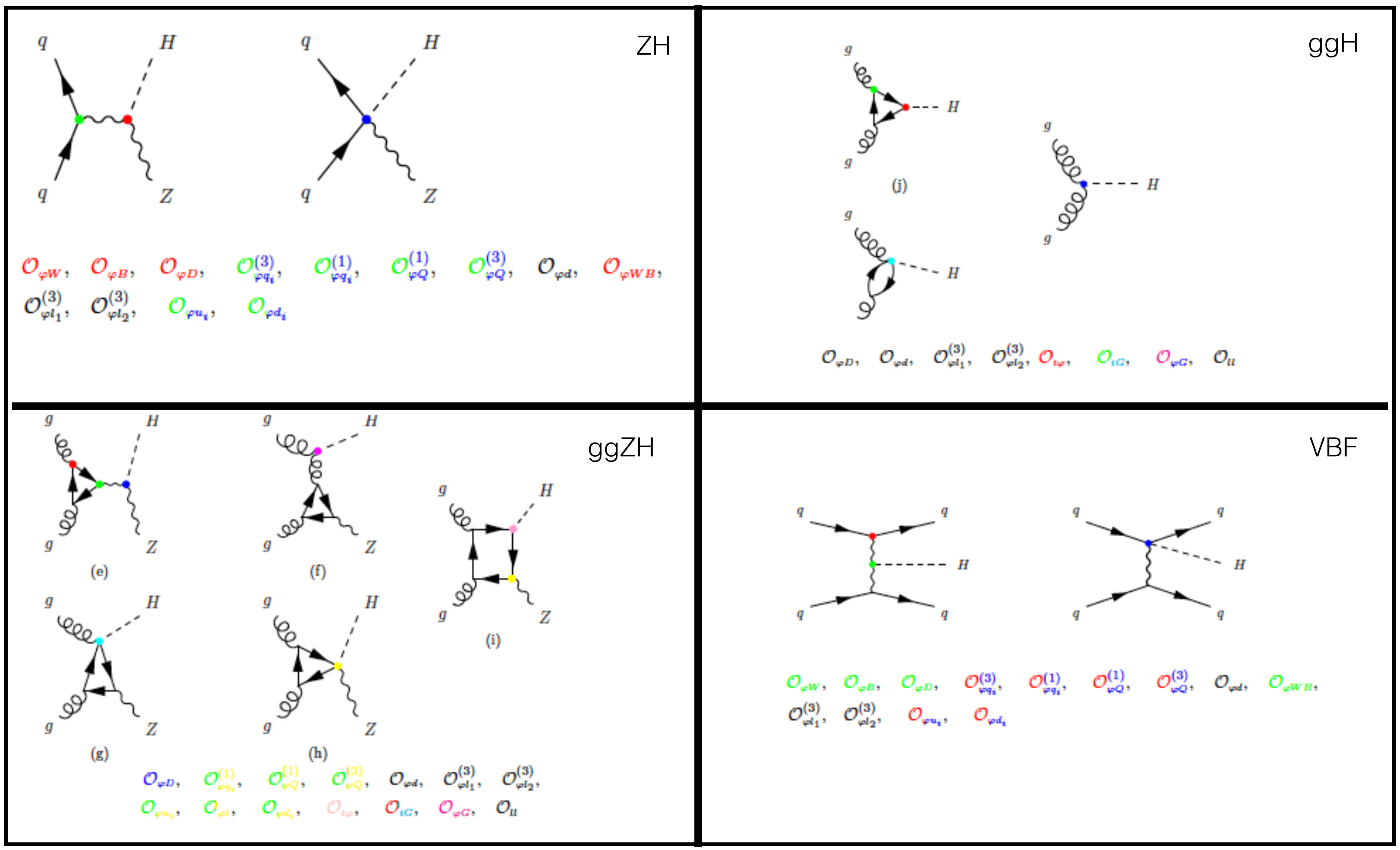
Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

Methodology

Fit results can be used to bound specific UV complete models
New data can be straightforwardly added

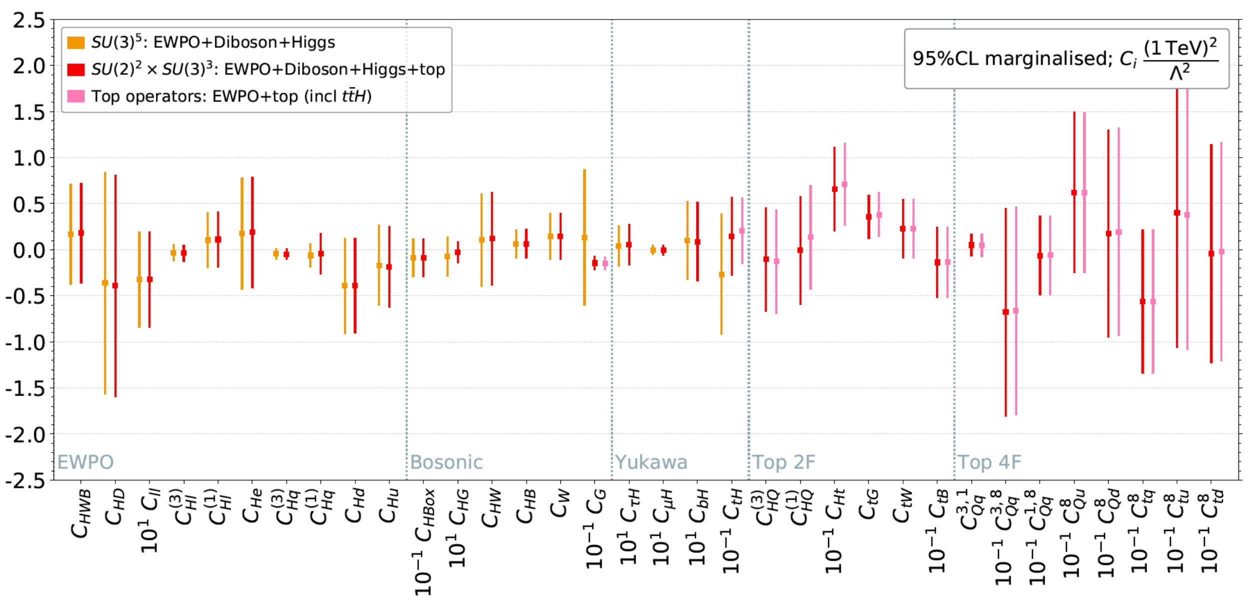
Output

# How do all these operators enter?



# Global EW(PO)+H+Top

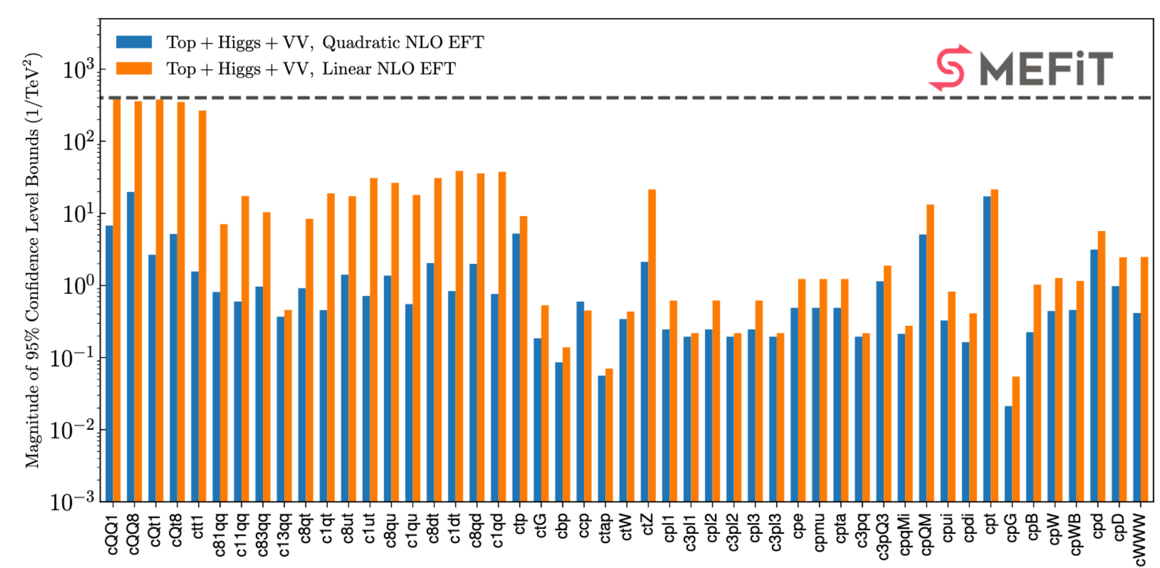
[Ellis et al. 2012.02779]




34 operators, $SU(2)^2 \times SU(3)^3$

EWPO fitted, 341 data points

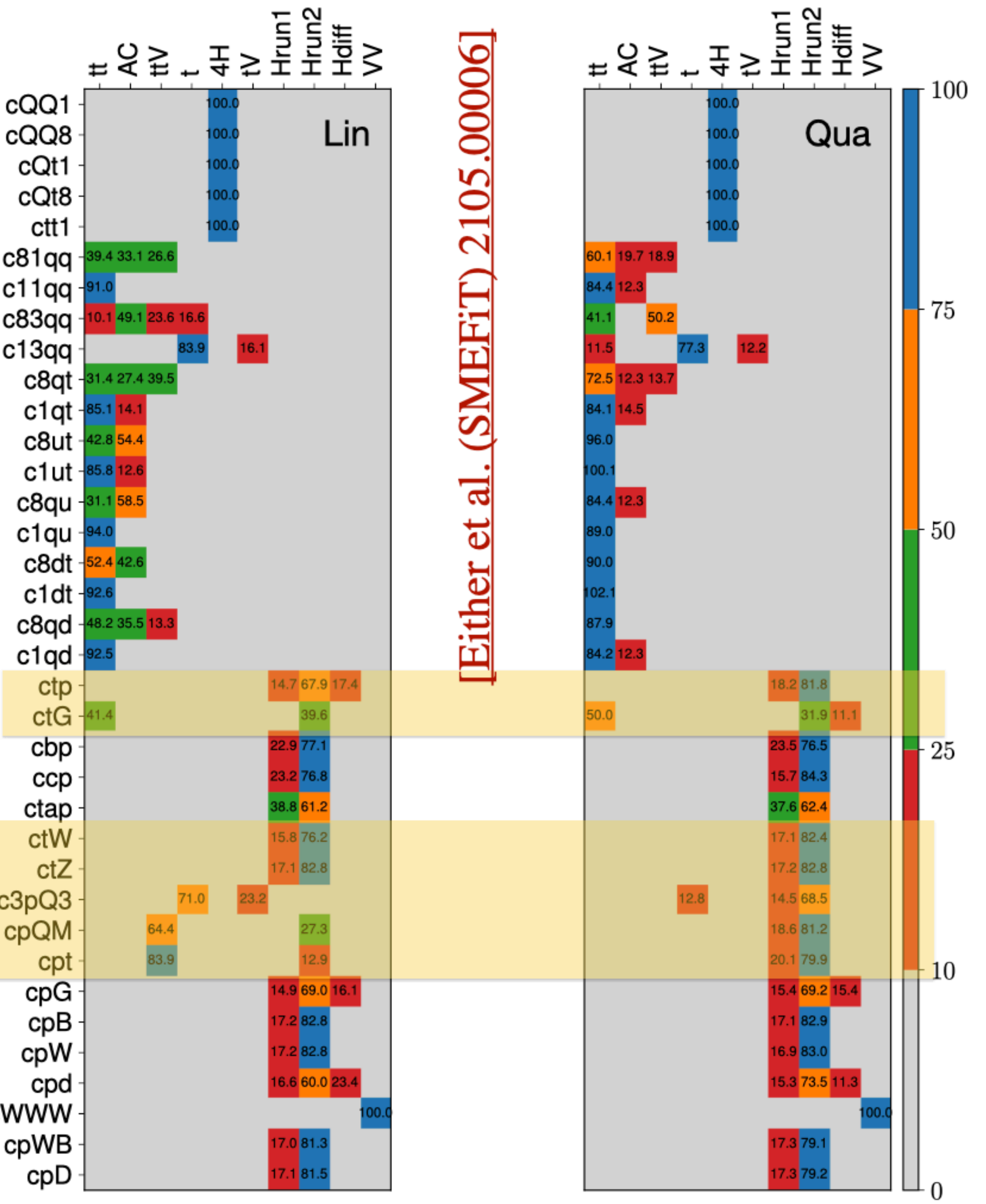
[Either et al. (SMEFiT) 2105.00006]

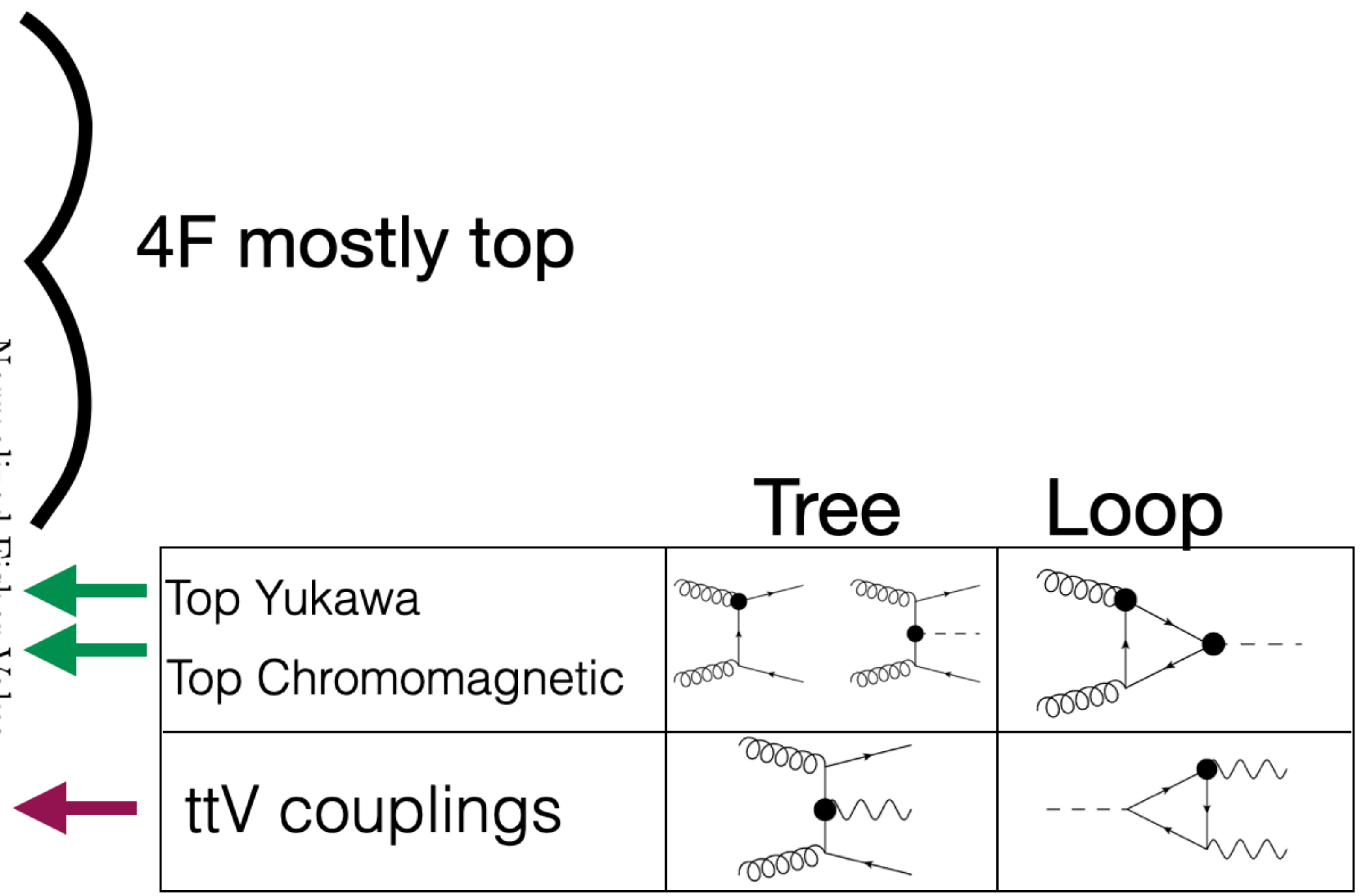



36 operators, $SU(2)^2 \times SU(3)^3$

EWPO fixed, 317 data points

# Where is most information from?



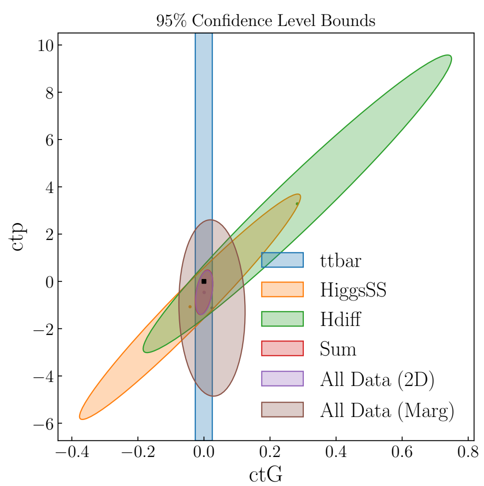

Tree-loop interface

# Higgs and top interplay

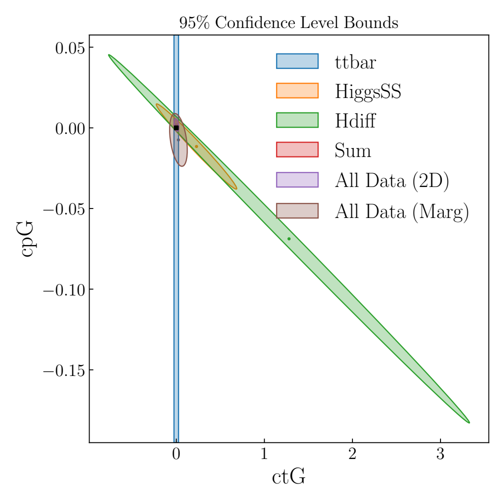
[Either et al. (SMEFiT) 2105.00006]

[Ellis et al. 2012.02779]

$$\left(\varphi^\dagger\varphi\right)\bar{Q}\,t\,\tilde{\varphi}$$



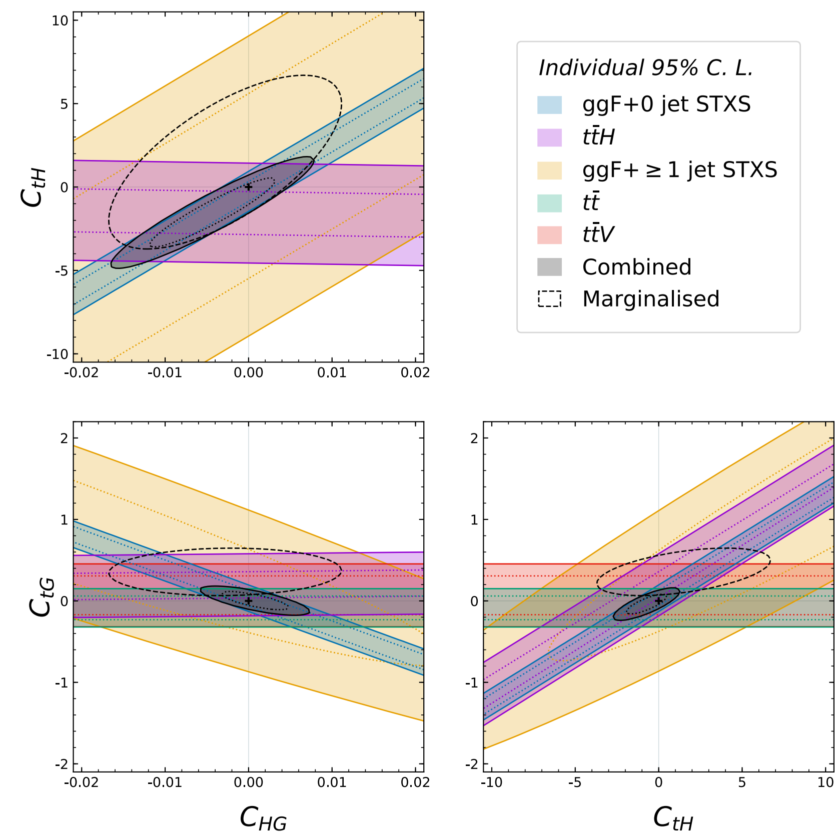

$$(\bar{Q}\tau^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu}$$




$$(\bar{Q}\tau^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu}$$

$$\left(\varphi^\dagger\varphi\right)G_A^{\mu\nu}\,G^A_{\mu\nu}$$

$$\left(\varphi^\dagger\varphi\right)\bar{Q}\,t\,\tilde{\varphi}$$




$$(\bar{Q}\tau^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu}$$

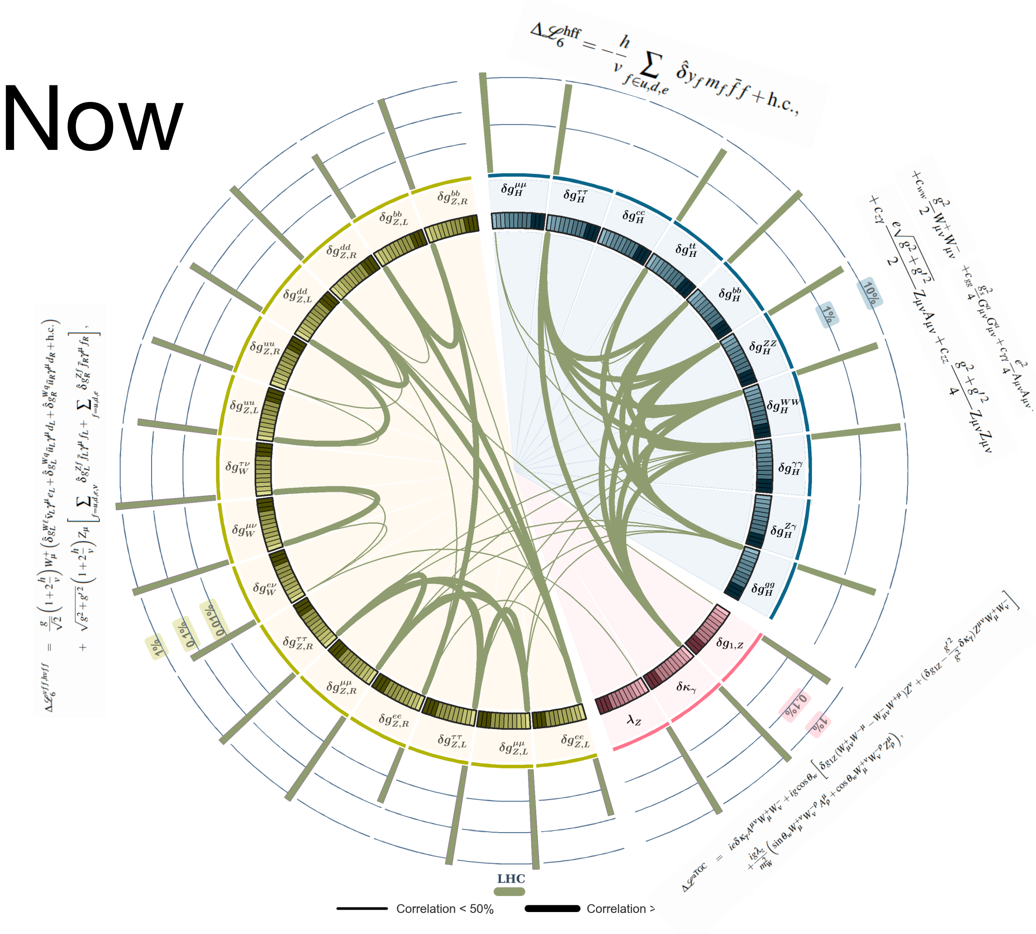
$$\left(\varphi^\dagger\varphi\right)G_A^{\mu\nu}\,G^A_{\mu\nu}$$

$$\left(\varphi^\dagger\varphi\right)\bar{Q}\,t\,\tilde{\varphi}$$

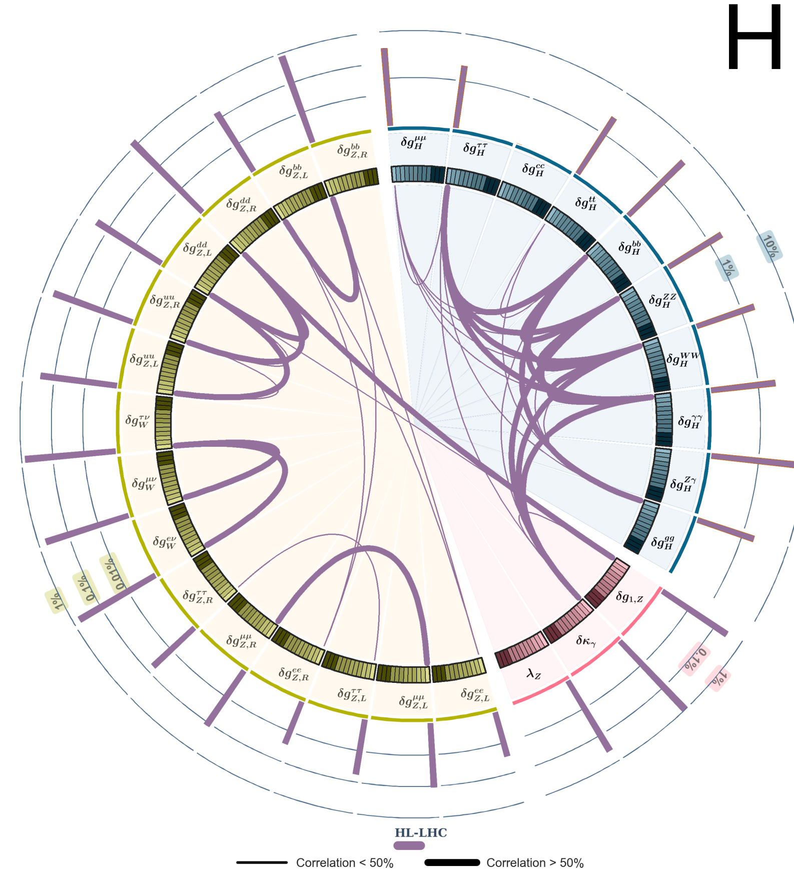
Top measurements break the degeneracy between Higgs operators

# The future of global fits

Now




HL-LHC




EW known at 0.1%
TGC known at 1%
Higgs known at 10%

As constraints improve for the TGC and Higgs correlations increase.

[HEPfit, courtesy of De Blas et al.]

# Learning points

1. Current fits are at an exploratory state, yet prove feasibility.

2. Dedicated EFT studies/observables needed to improve sensitivity.

3. Shift towards combinable measurements is needed.

4. Major change in the way experimental analyses are planned and published

# Outlook

- The Higgs LHC precision physics programme has set clear and very challenging goals for the next years.
- A universal and very powerful approach to the interpretation of Higgs (and more) precision measurements is that of the SMEFT which provides many challenges pushing us out of our confort zone, beyond our current TH/EXP workflows and value system.
- First explorations of the constraining power of present data in a global EW(PO)+Higgs+Top fit have appeared.
- A wonderful realm of opportunities and large room for improvement ⇒ many ways to contribute and learn about SM(EFT) physics.