Higgs physics

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Lecture II

New Physics

- 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 between 8 and 13 TeV and even less so to prefer a NP model with respect to another.

New Physics

Statement #1

look for NP at the LHC by covering the widest range of TH- and/or EXP-motivated searches.

Searches should aim at being sensitive to the highest-possible scales of energy

New Physics

Statement #2

The Higgs provides a privileged searching ground

- It has just been discovered. Some of its properties are either just been measured or completely unknown.
- A plethora of production and decay modes available.
- First "elementary" scalar ever : carrier of a new Yukawa force, whose effects still need to be measured.
- $(\Phi^\dagger . \Phi)$ dim=2 singlet object $\Longrightarrow$ Higgs portal to a new sector.
- Several motivations to have a reacher scalar sector with more doublets or higher representations $\Longrightarrow$ Higgs might be the first of many new scalar states.

Searching for new physics

Model-dependent ⟷ Model-independent

SUSY, 2HDM, ED,… | simplified models, EFT, …

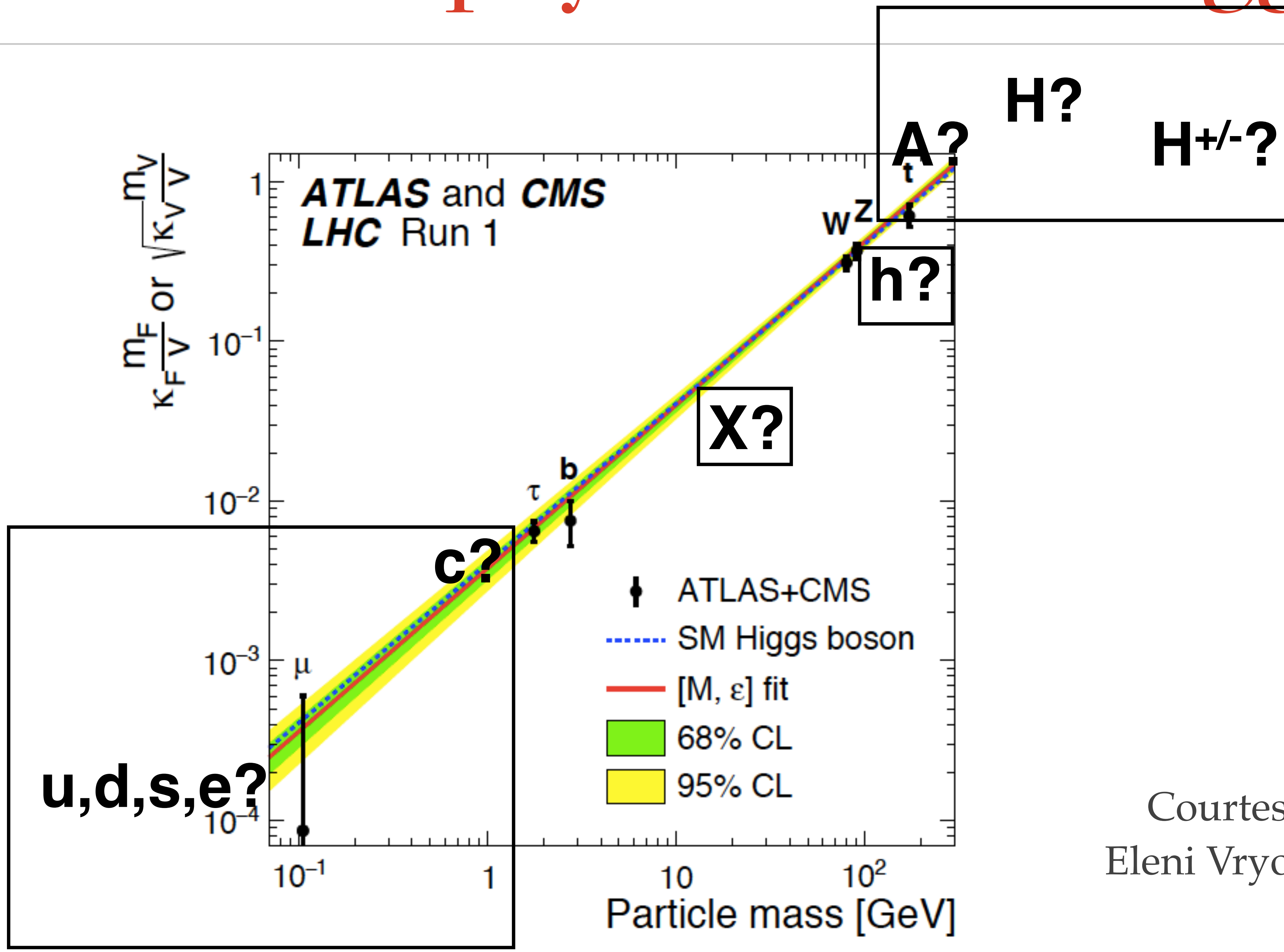
Search for new states ⟷ Search for new interactions

specific models, simplified models | anomalous couplings, EFT…

Exotic signatures ⟷ Standard signatures

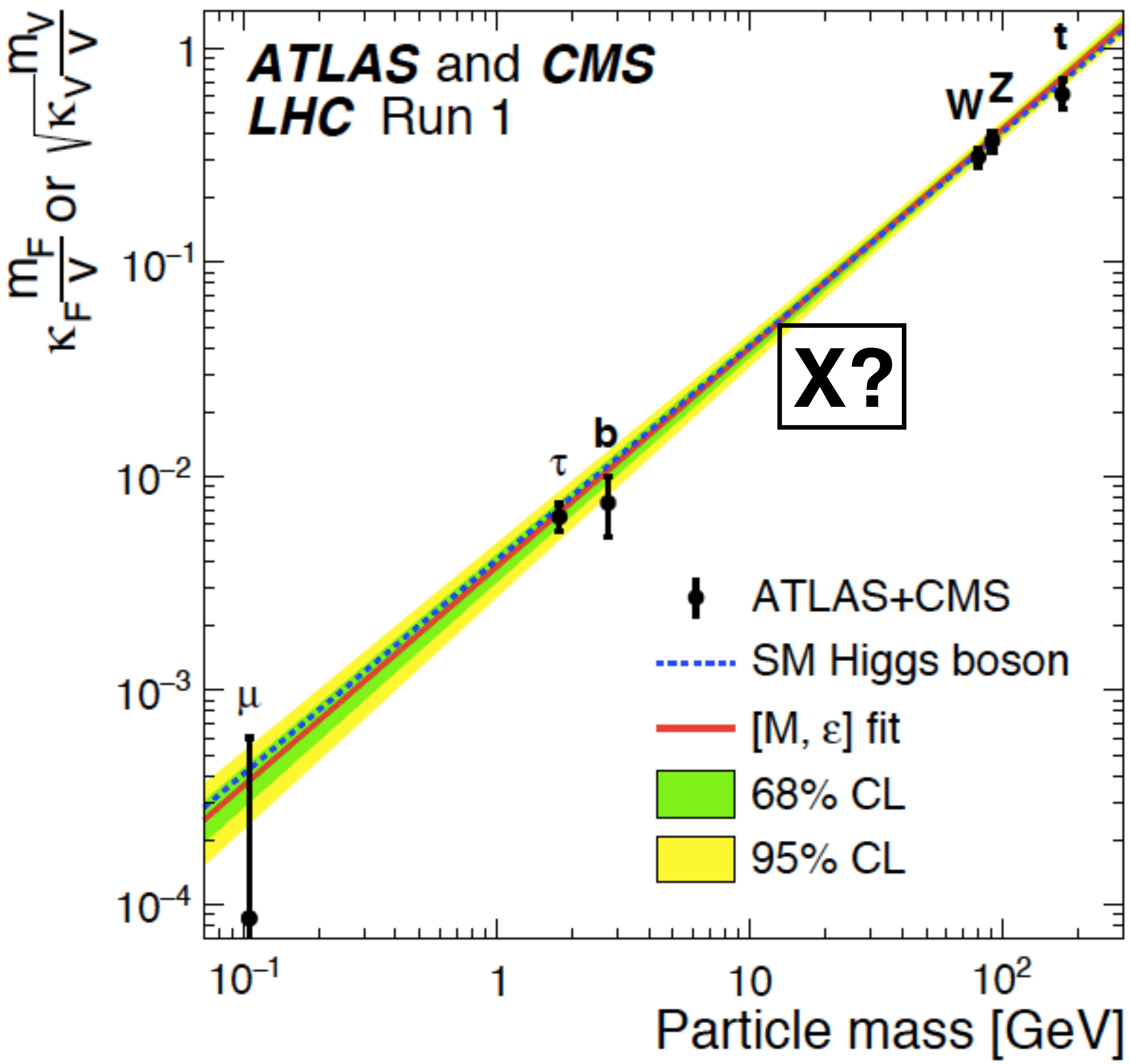
precision measurements | rare processes

Search for new physics via the Higgs



Courtesy of
Eleni Vryonidou

Search for new physics via the Higgs



SM Portals

$$(\Phi^\dagger \Phi)$$

dim=2

Scalars and vectors

$$(\bar{L}\Phi_c)$$

dim=5/2

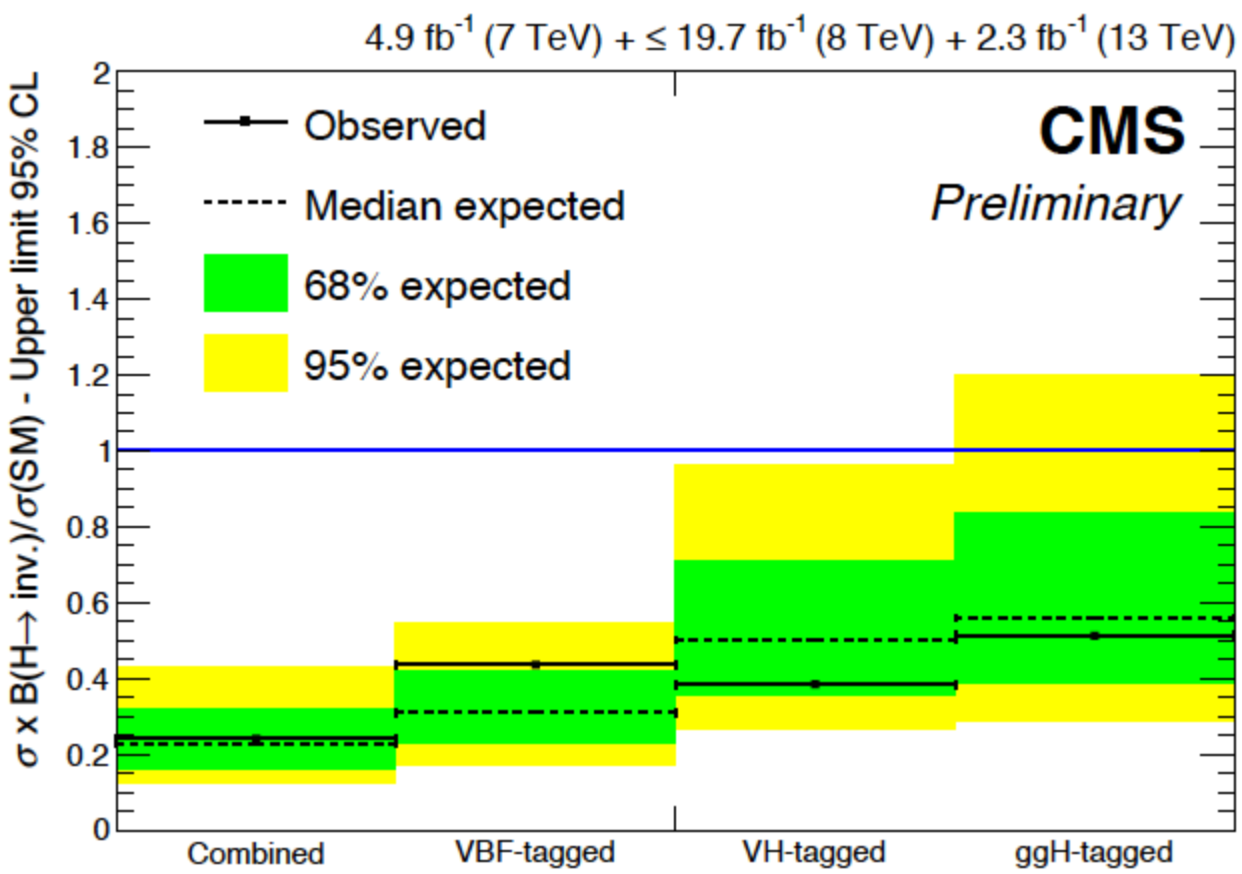
Sterile fermions

$$B^{\mu\nu}$$

dim=2

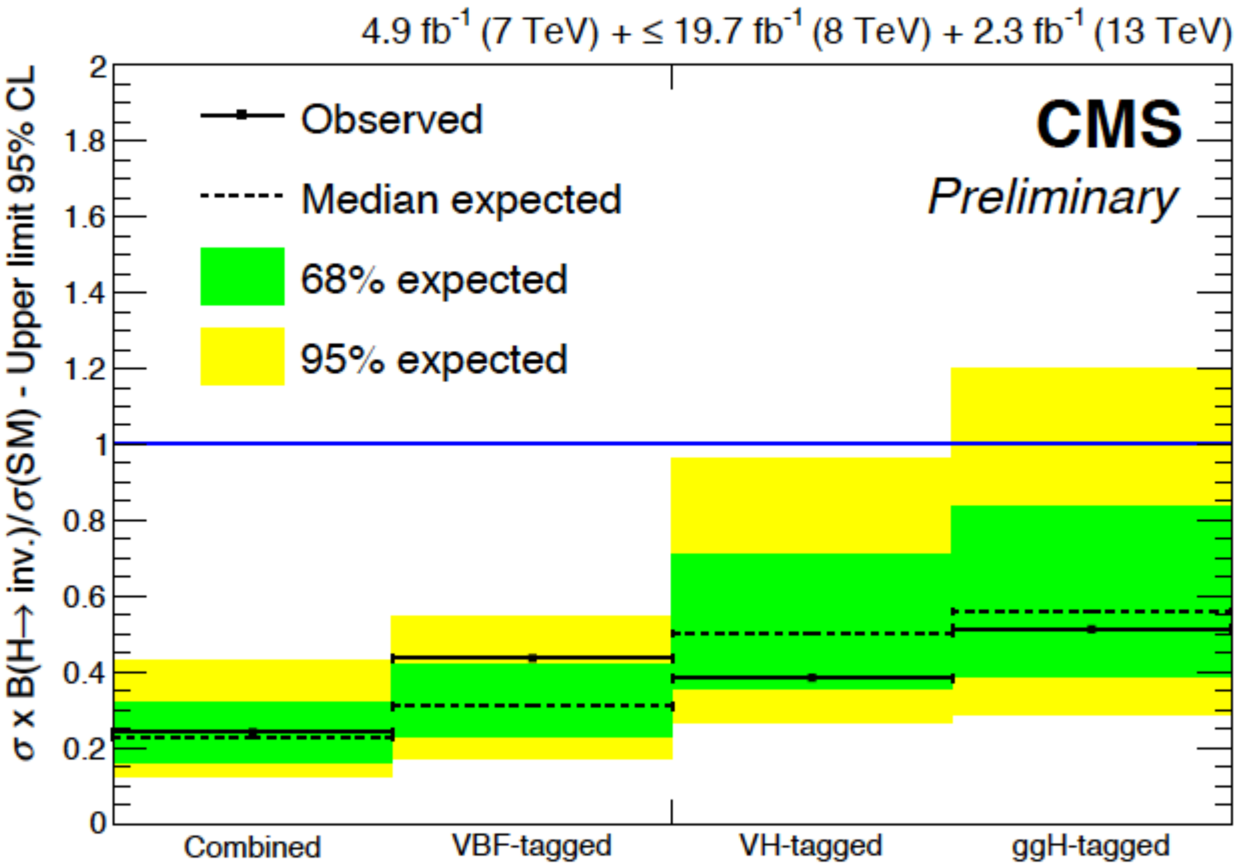
Dark photons

Searching for H to invisible



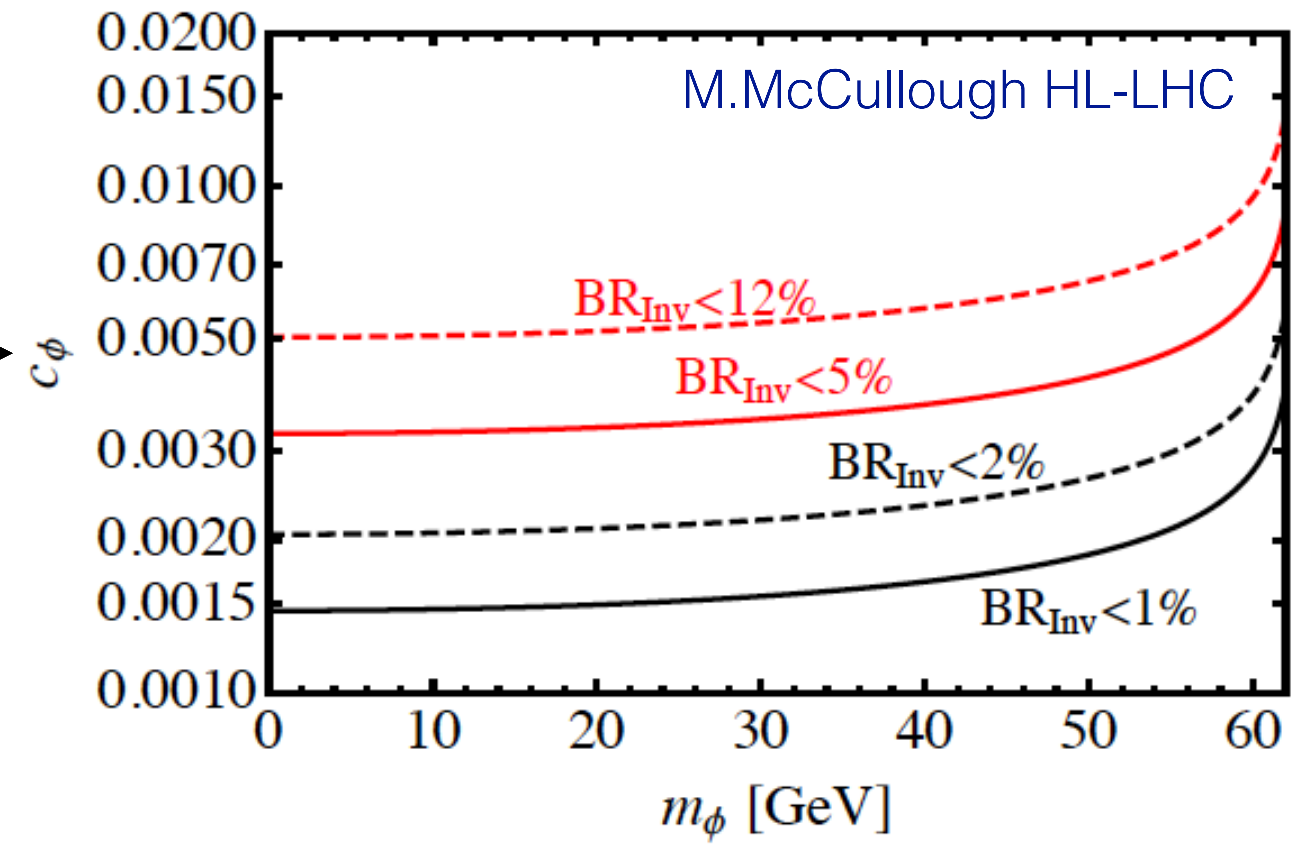
$B(H \to \text{inv.}) < 0.24\ (0.23)$ at a 95% CL

Searching for H to invisible



$$B(H \to \text{inv.}) < 0.24\ (0.23) \text{ at a 95\% CL}$$

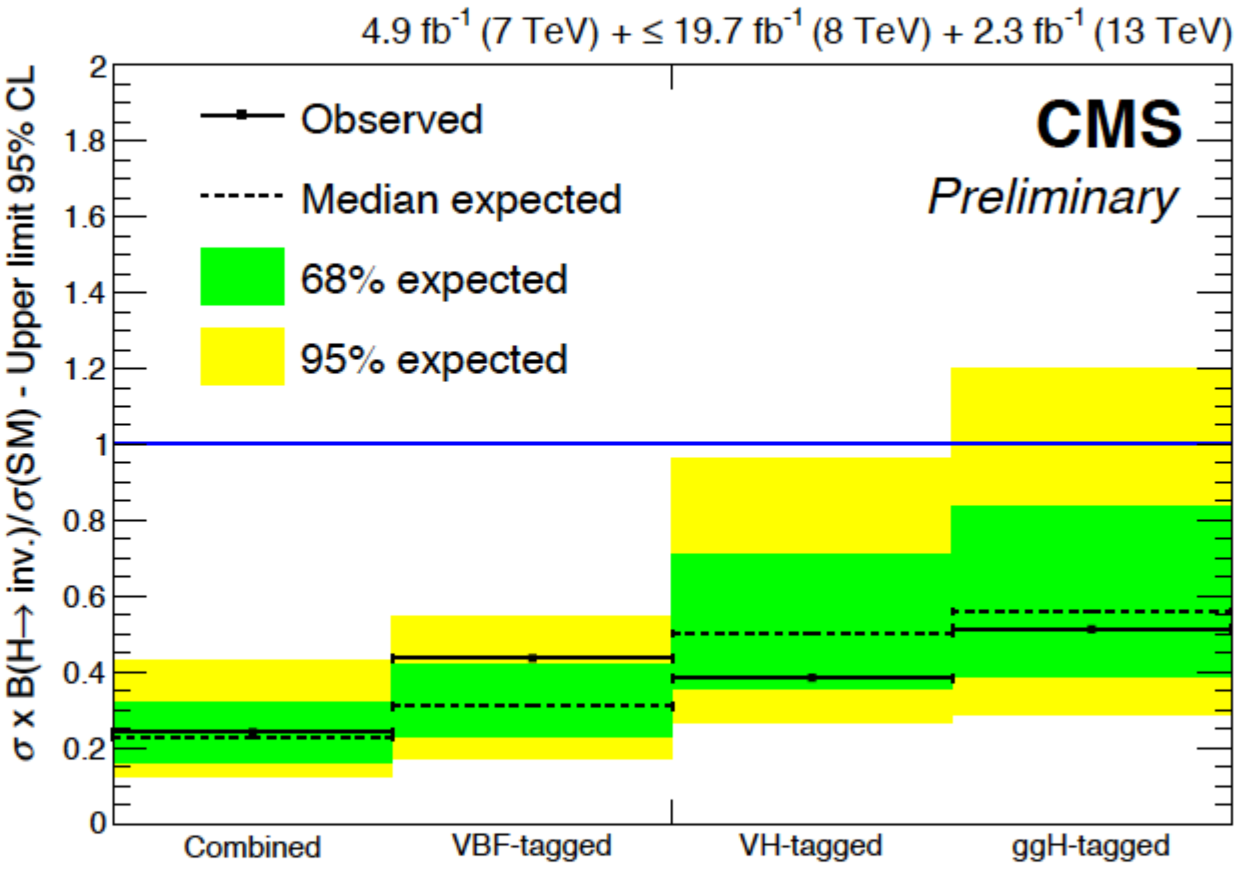
Immediate implications for any model with particles of mass $m < m_H/2$



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

Simplest extension of the SM: The Higgs portal

Searching for H to invisible



Casas et al arXiv:1701.08134

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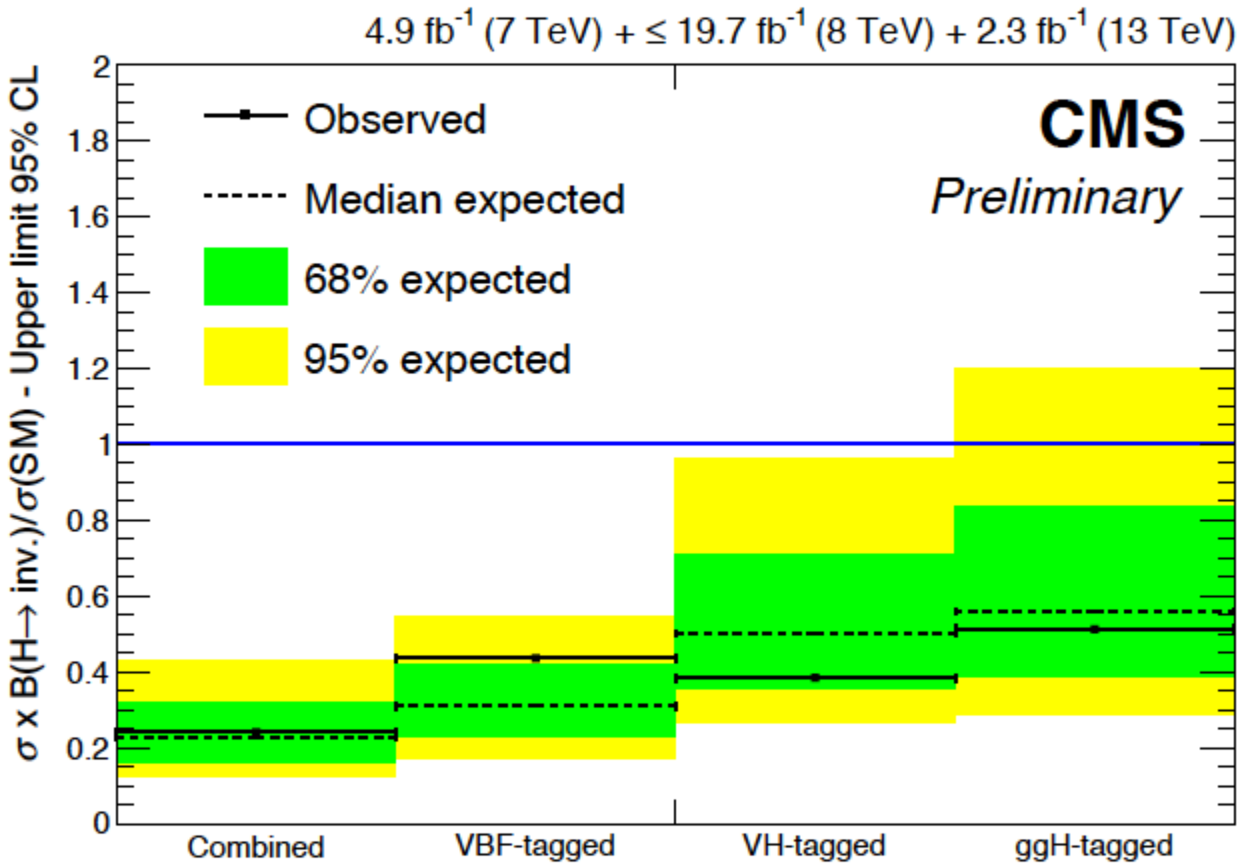
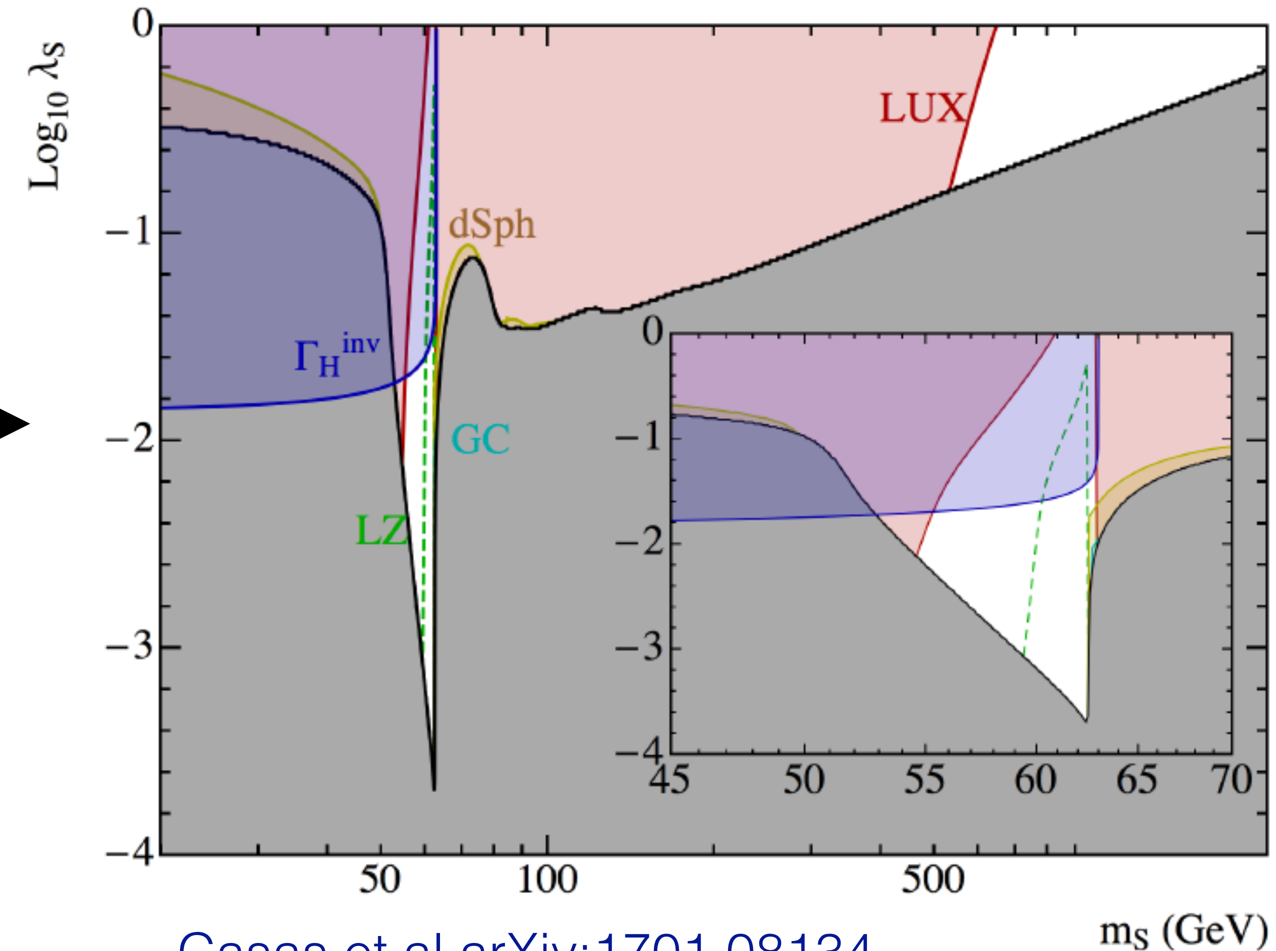


Important Dark Matter implications

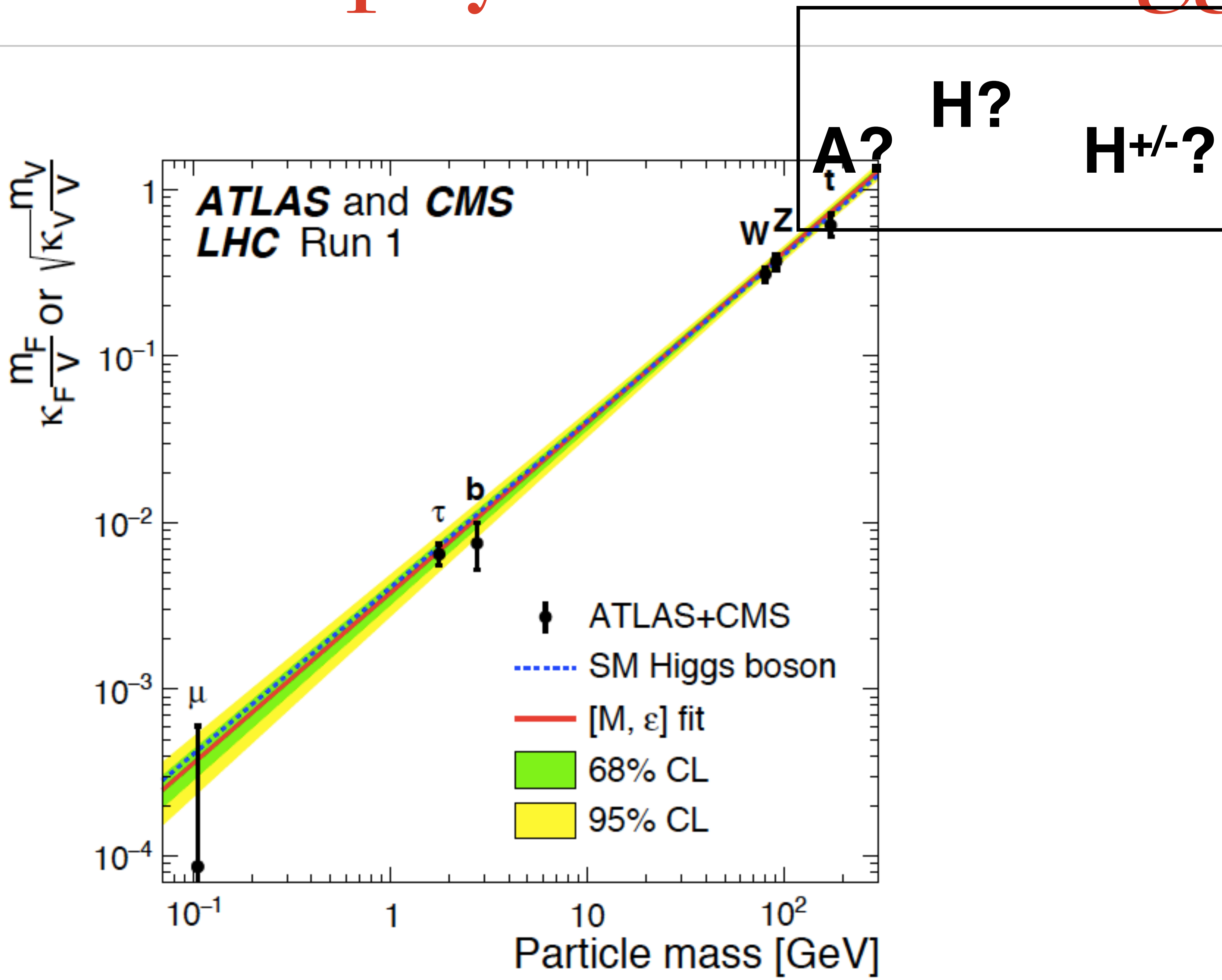


Casas et al arXiv:1701.08134

$$\mathrm{B}(\mathrm{H} \to \mathrm{inv.}) < 0.24\ (0.23) \text{ at a } 95\%\ \mathrm{CL}$$

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

Search for new physics via the Higgs



Direct vs indirect searches

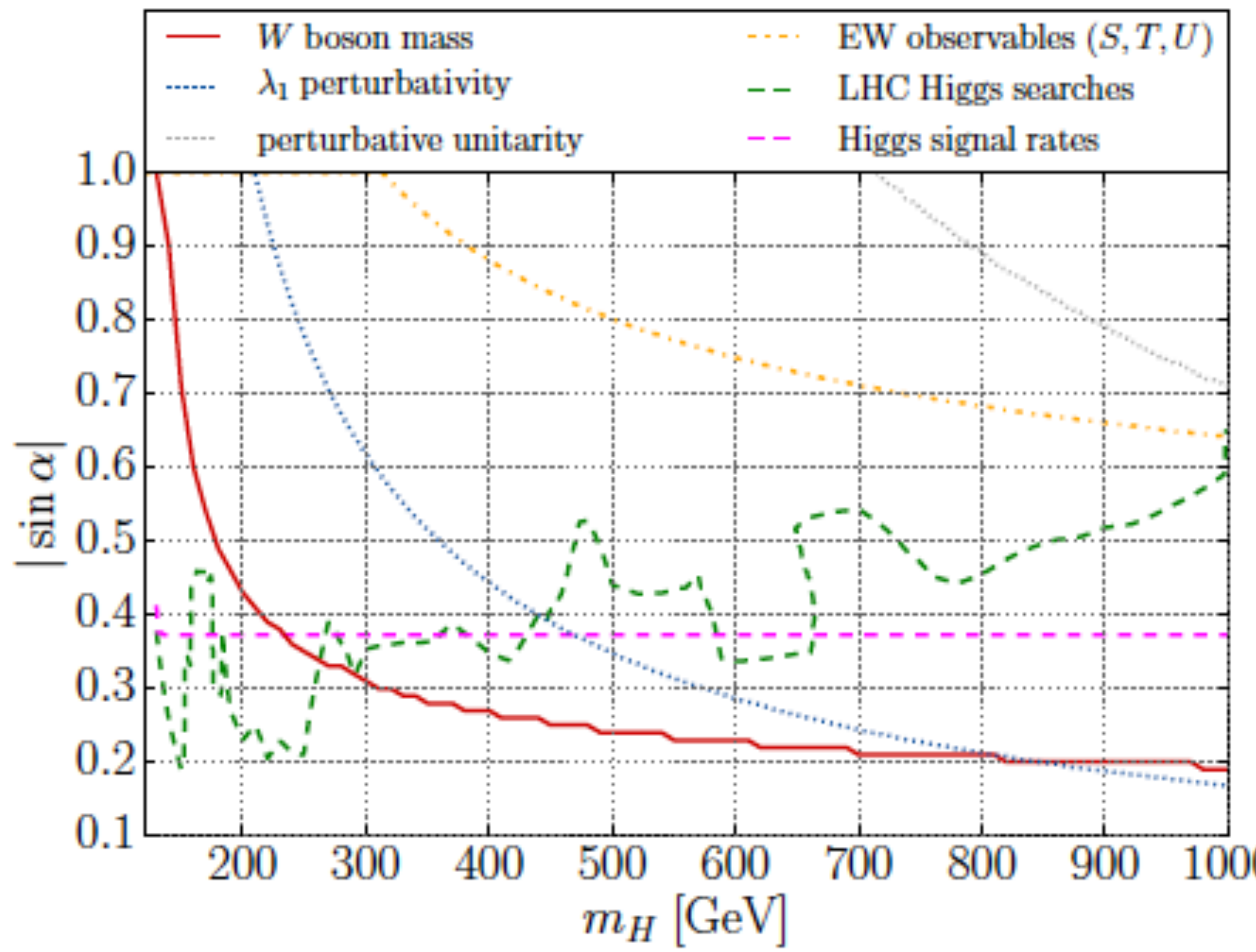
Adopting a simple model one can compare the reach for direct vs indirect measuremets:Again adding a singlet :

$$V(\Phi, S) = -m^2\Phi^\dagger\Phi - \mu^2 S^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger\Phi S^2 \qquad m_h,\, m_H,\, \sin\alpha,\, \tan\beta,\, v.$$

Heavy Higgs searches

vs

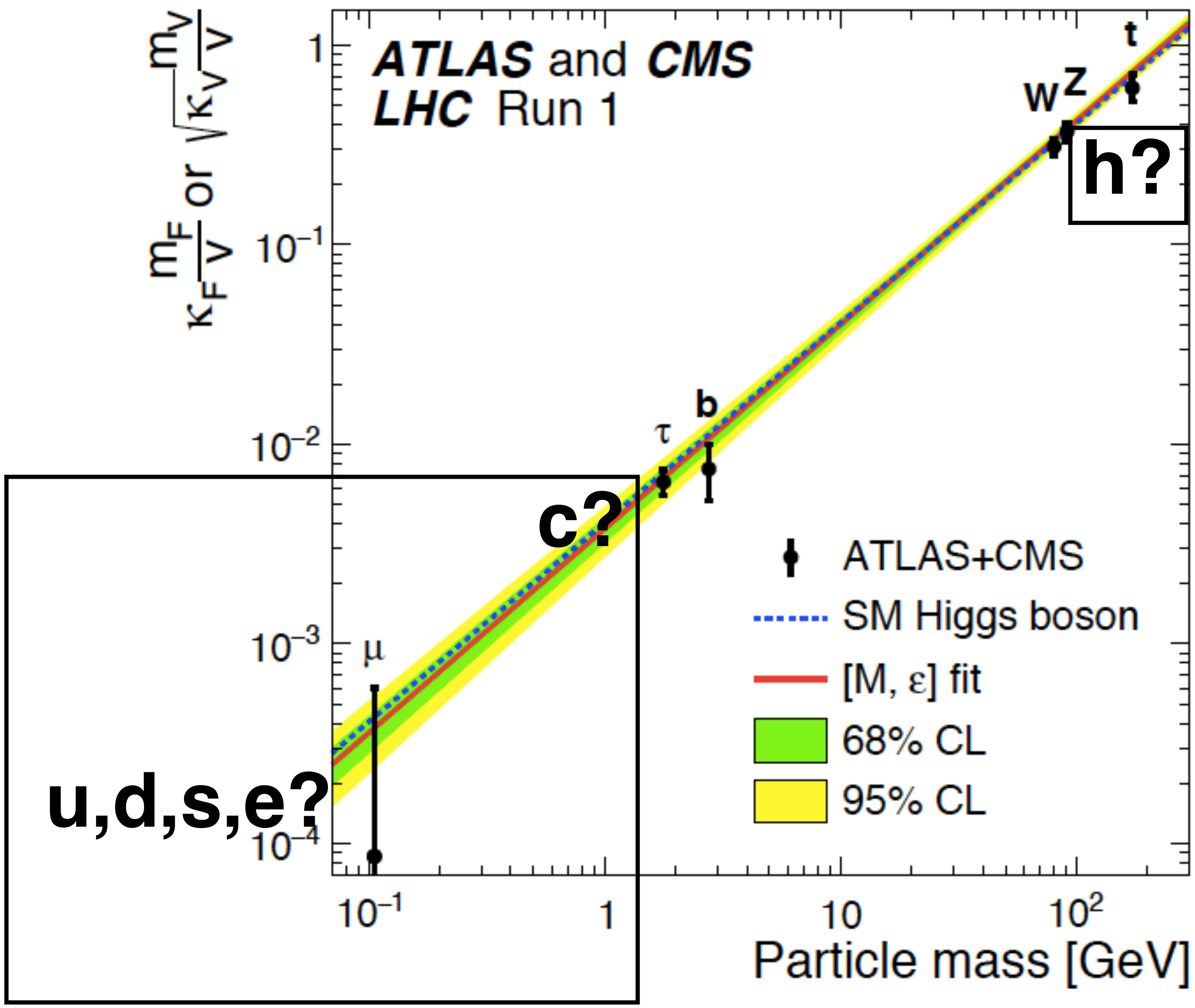
Light Higgs signal strengths



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



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

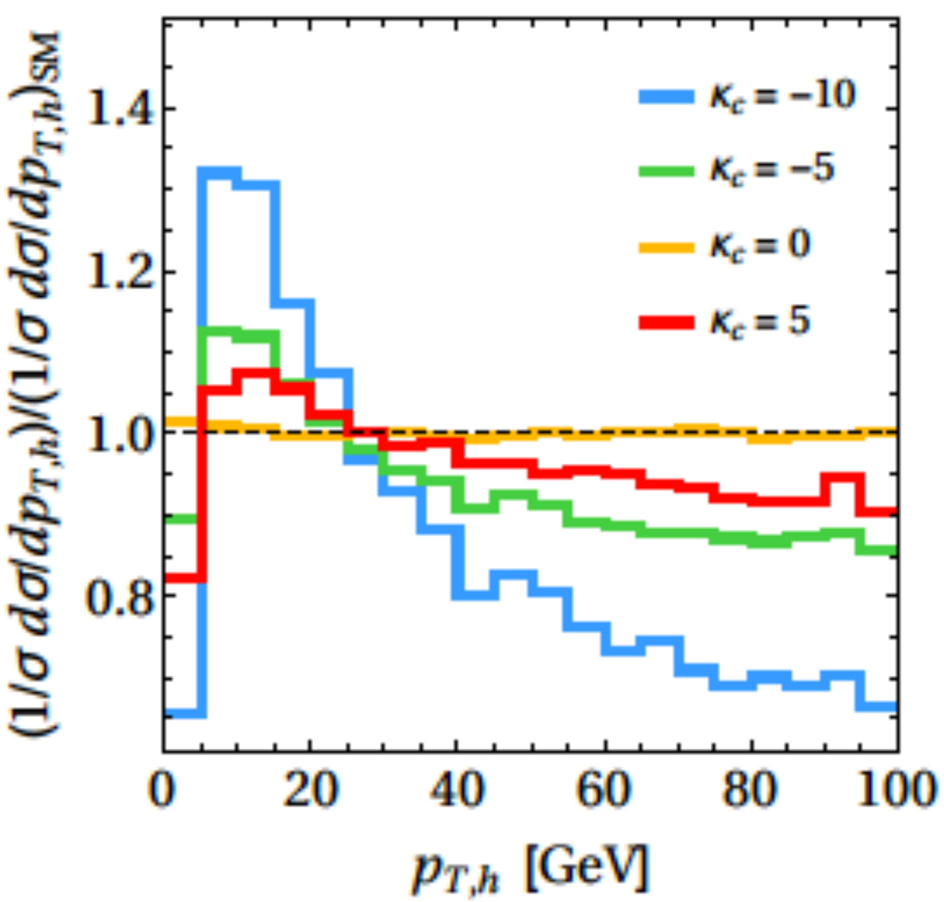
COUPLINGS to non-SM particles

- H portals

Second generation

Using kinematic distributions i.e. the Higgs pT

Bishara et al.1606.09253



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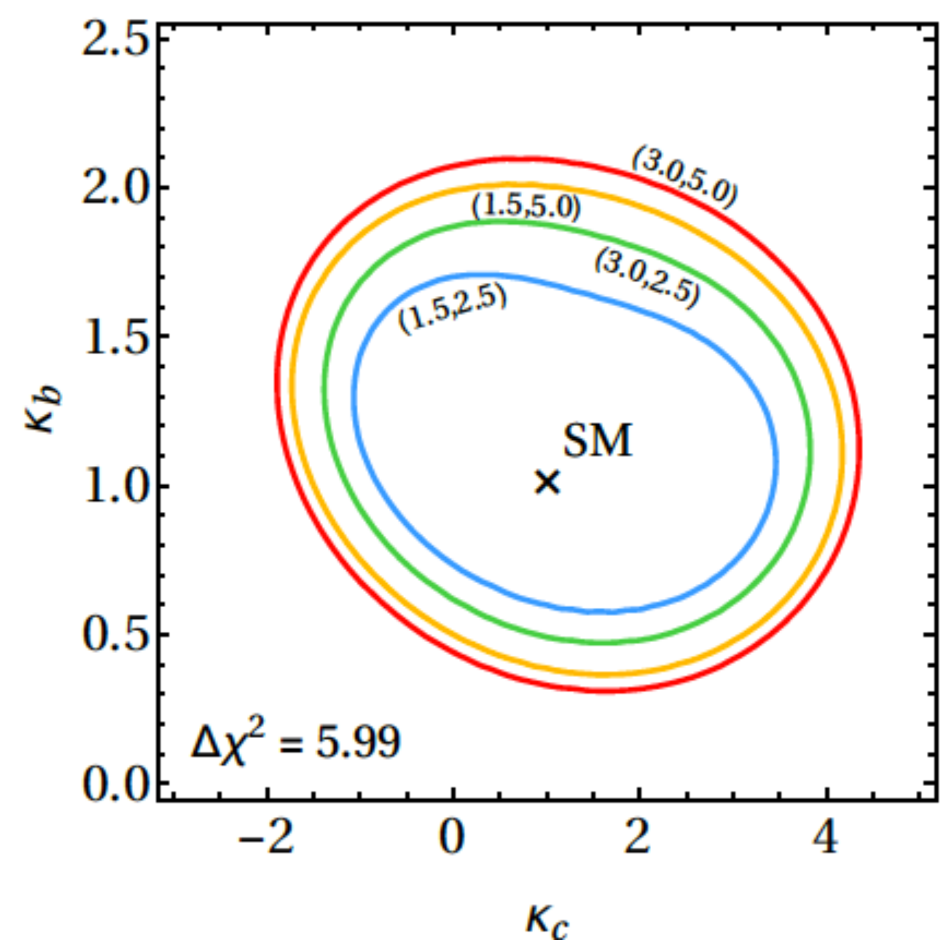


Inclusive Higgs decays i.e VH + flavour tagging (limited by c-tagging) gives a limit of 110 x SM expectation

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

(for evidence of bottom couplings: ATLAS: arXiv:1708.03299 and CMS: arXiv:1708.04188)

Higgs potential 101

A low-energy parametrisation of the Higgs potential

$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 + \ldots$$

In the Standard Model:

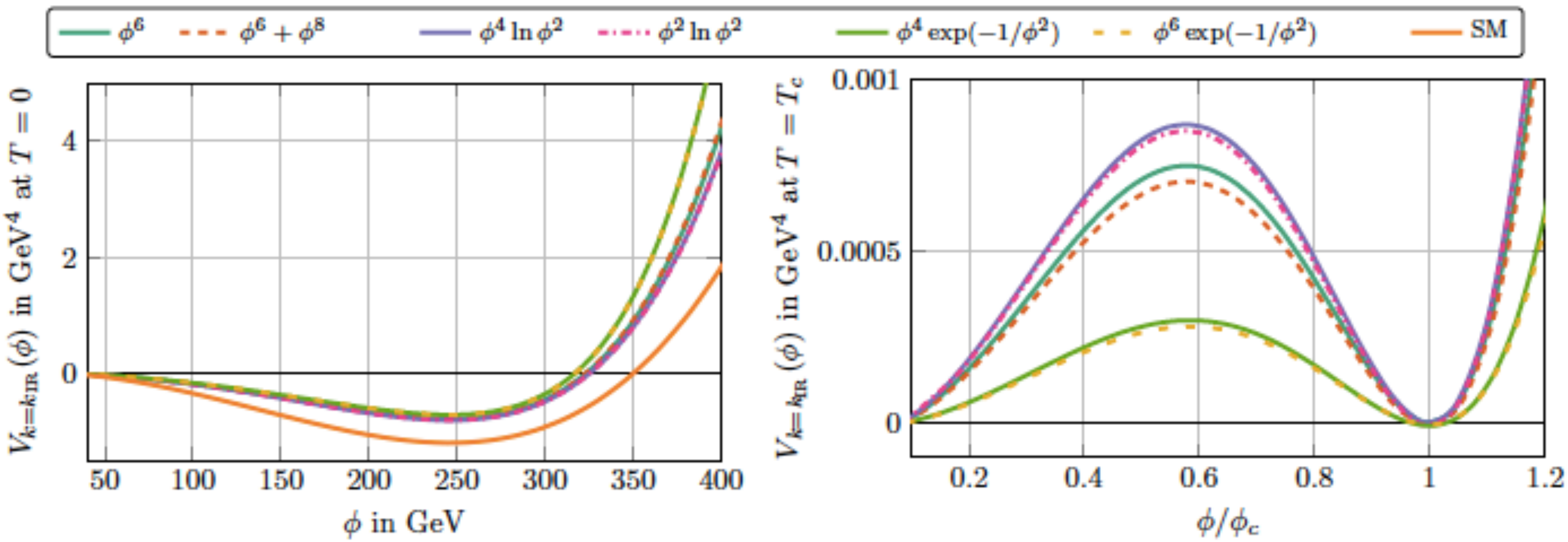
$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \quad \Rightarrow \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \quad \begin{cases} \lambda_3^{\rm SM} = \lambda \\ \lambda_4^{\rm SM} = \lambda \end{cases}$$

i.e., fixing v and m_H, uniquely determines both λ_3 and λ_4.

That means that by measuring λ_3 and λ_4 one can test the SM, yet to interpret deviations, one needs to "deform it", i.e. needs to consider a well-defined BSM extension. Such extensions will necessarily depend on TH assumptions.

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.



Reichert et al. 1711.00019

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

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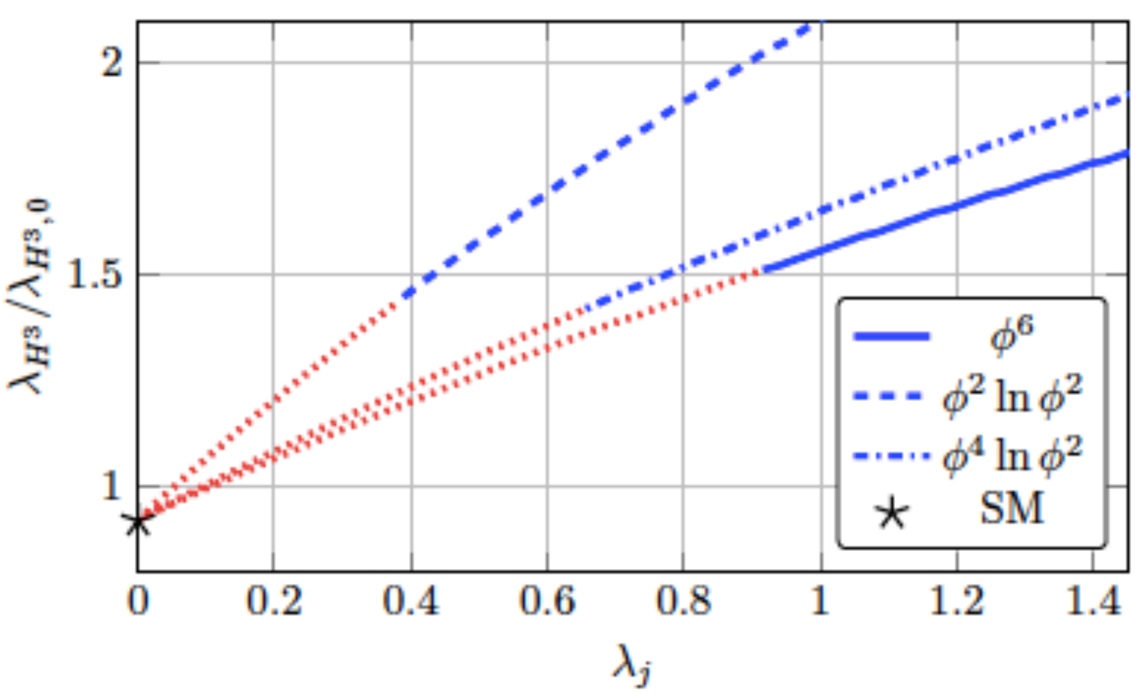

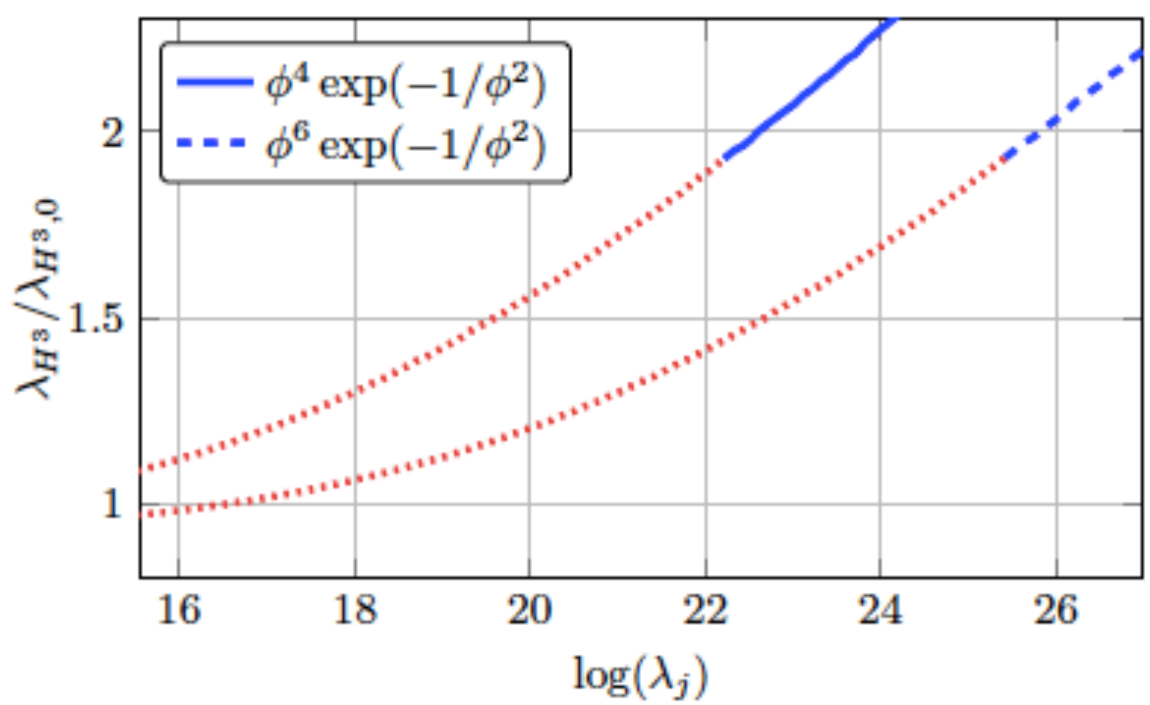

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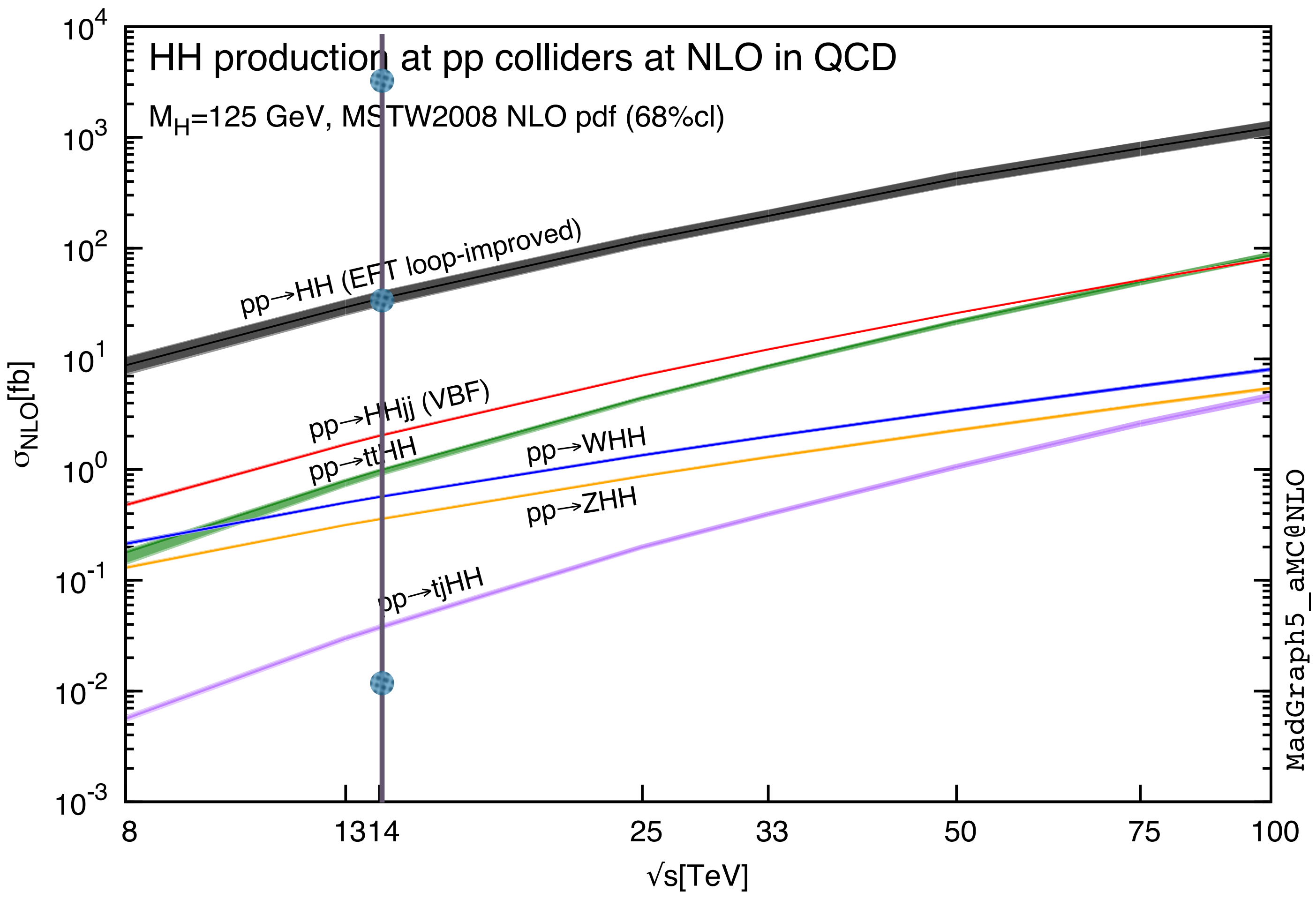
Phase I : Higgs self-coupling

[Frederix et al. '14]

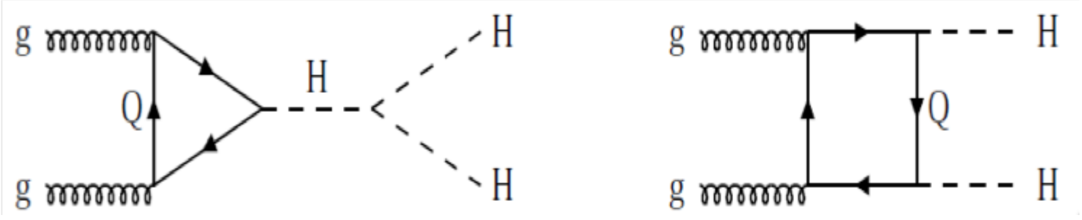


At 14 TeV from gg fusion:

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

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

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

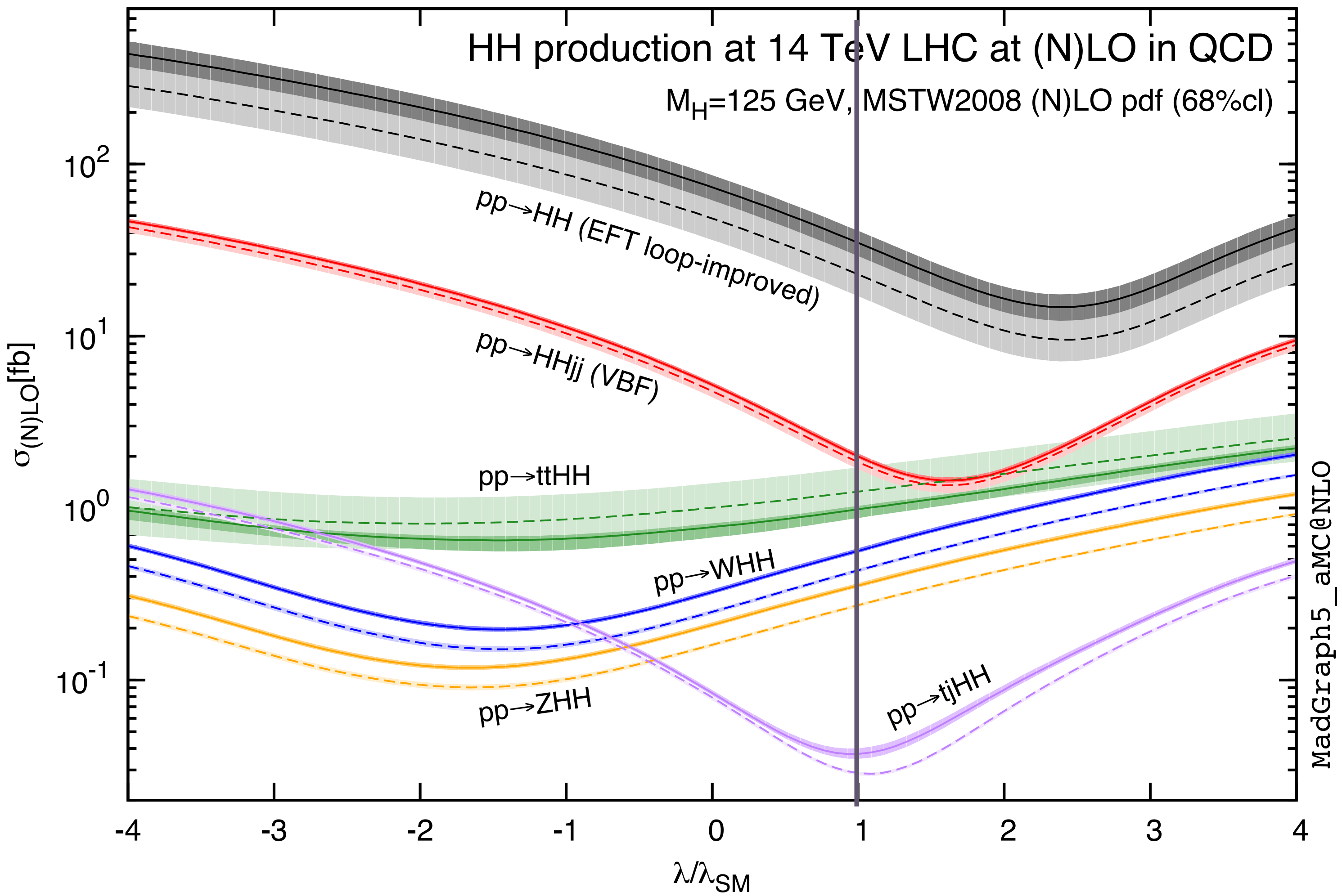


As in single Higgs many channels contribute in principle.

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 σ_{SM} (gg→HH) channel in various H decay channels:

CMS : $\sigma/\sigma_{SM} < 19$ (bbγγ) [EPS2017]
ATLAS : $\sigma/\sigma_{SM} < 13$ (bbbb). [Moriond18]

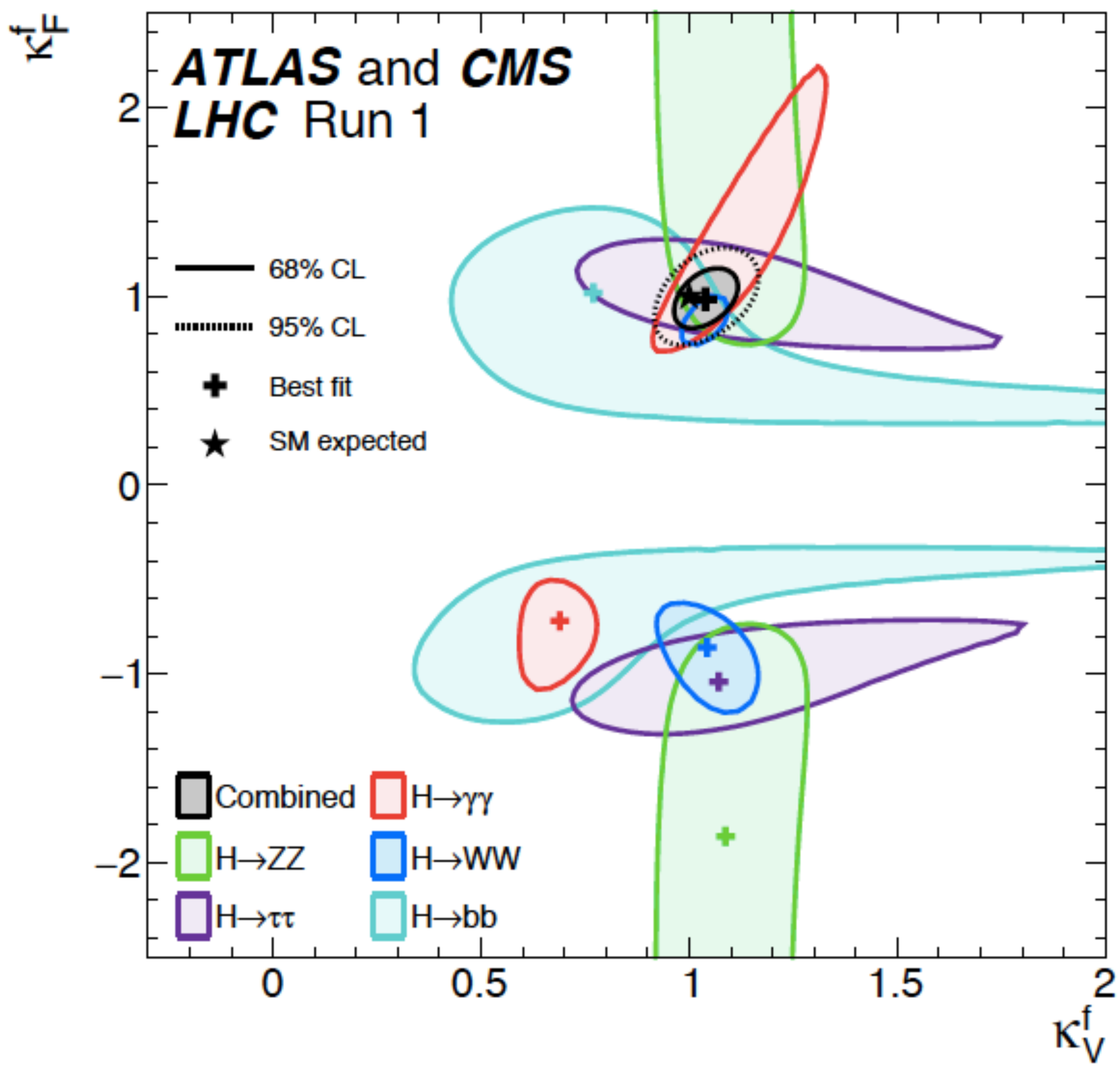
Remarks:

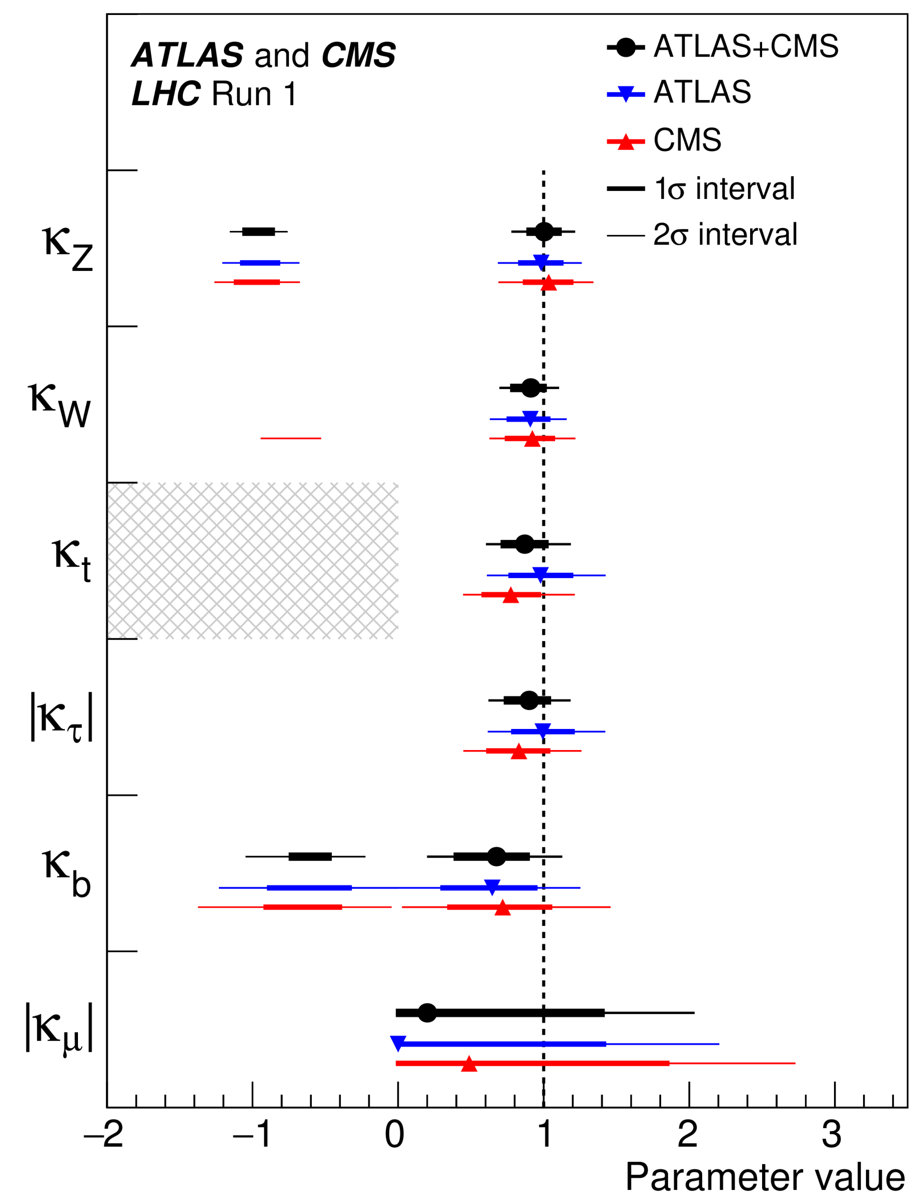
1. Interpretations of these bounds in terms of BSM always need additional assumptions on how the SM has been deformed.
2. The current most common assumption is just a change of λ_3 which leads to a change in σ as well as of distributions:

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

Note: due to shape changes, it is not straightforward to infer a bound on λ_3 from σ(HH), even when $\sigma_{BSM}=\sigma(\lambda_3)$ only is assumed.

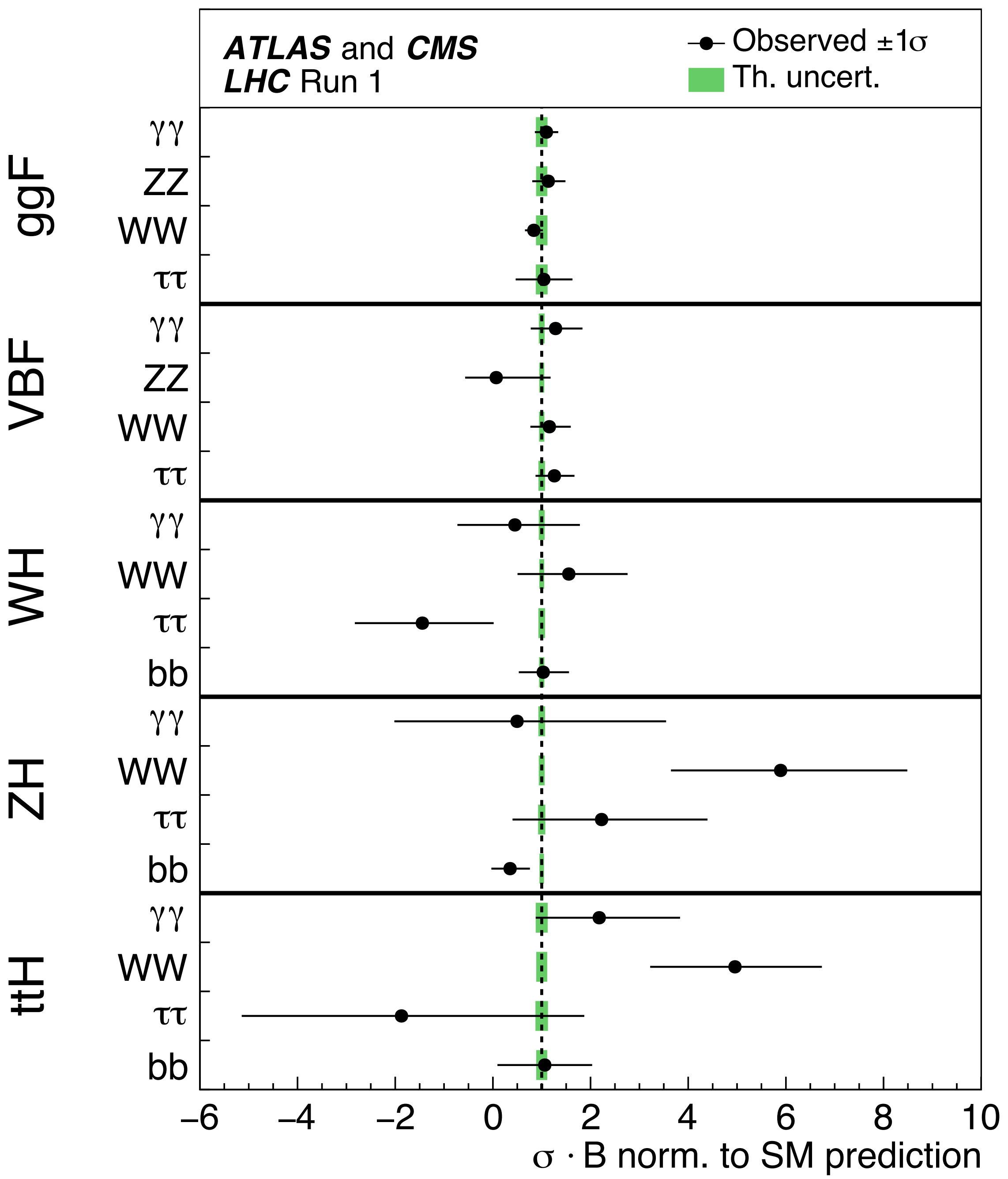
Phase II : CMS/ATLAS Higgs couplings combination





Data points agree with SM hypothesis at the 20-30% level

Phase II : CMS/ATLAS Higgs couplings combination



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

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

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

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

Phase 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:

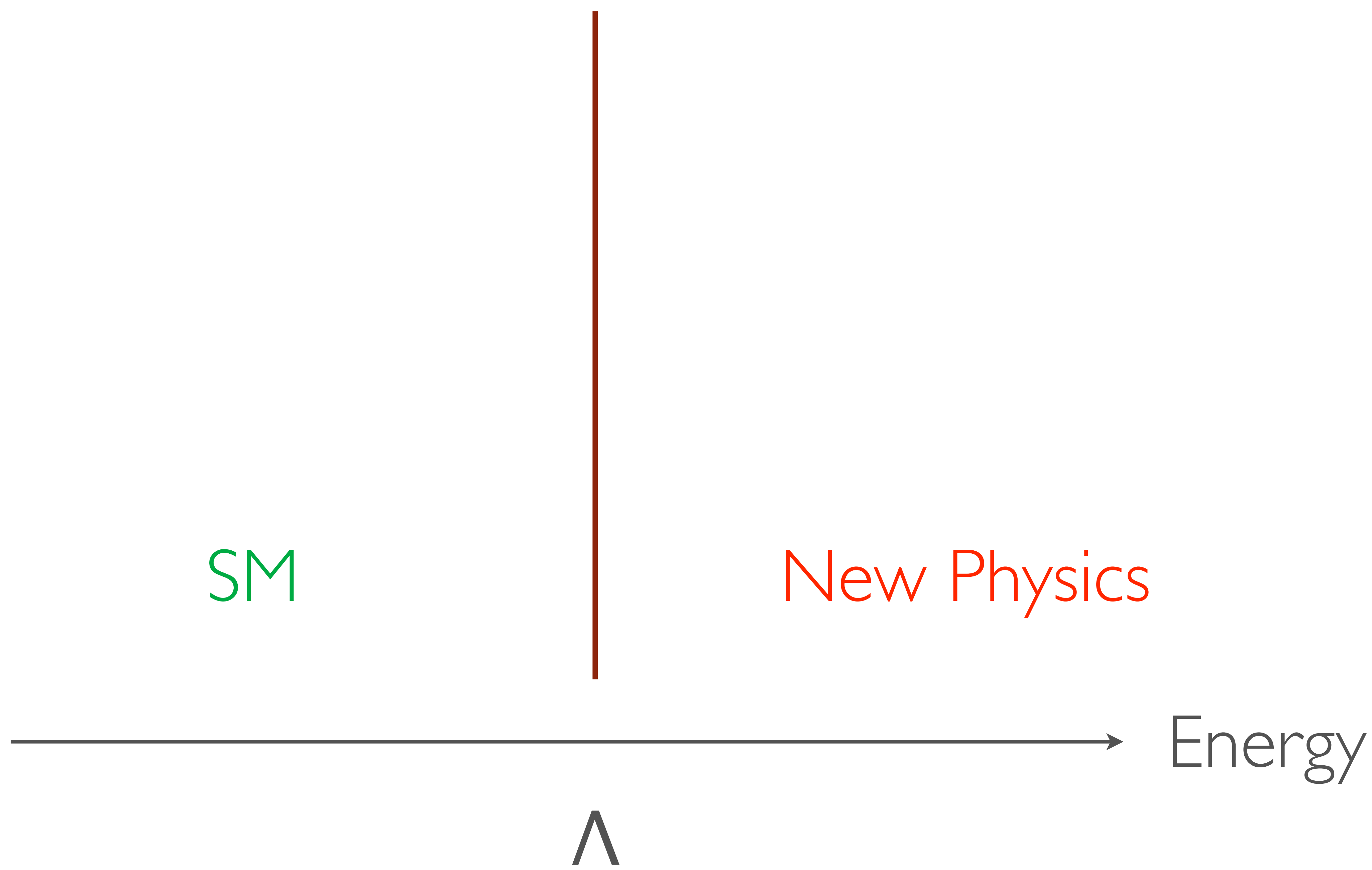
$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \ldots$$

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:

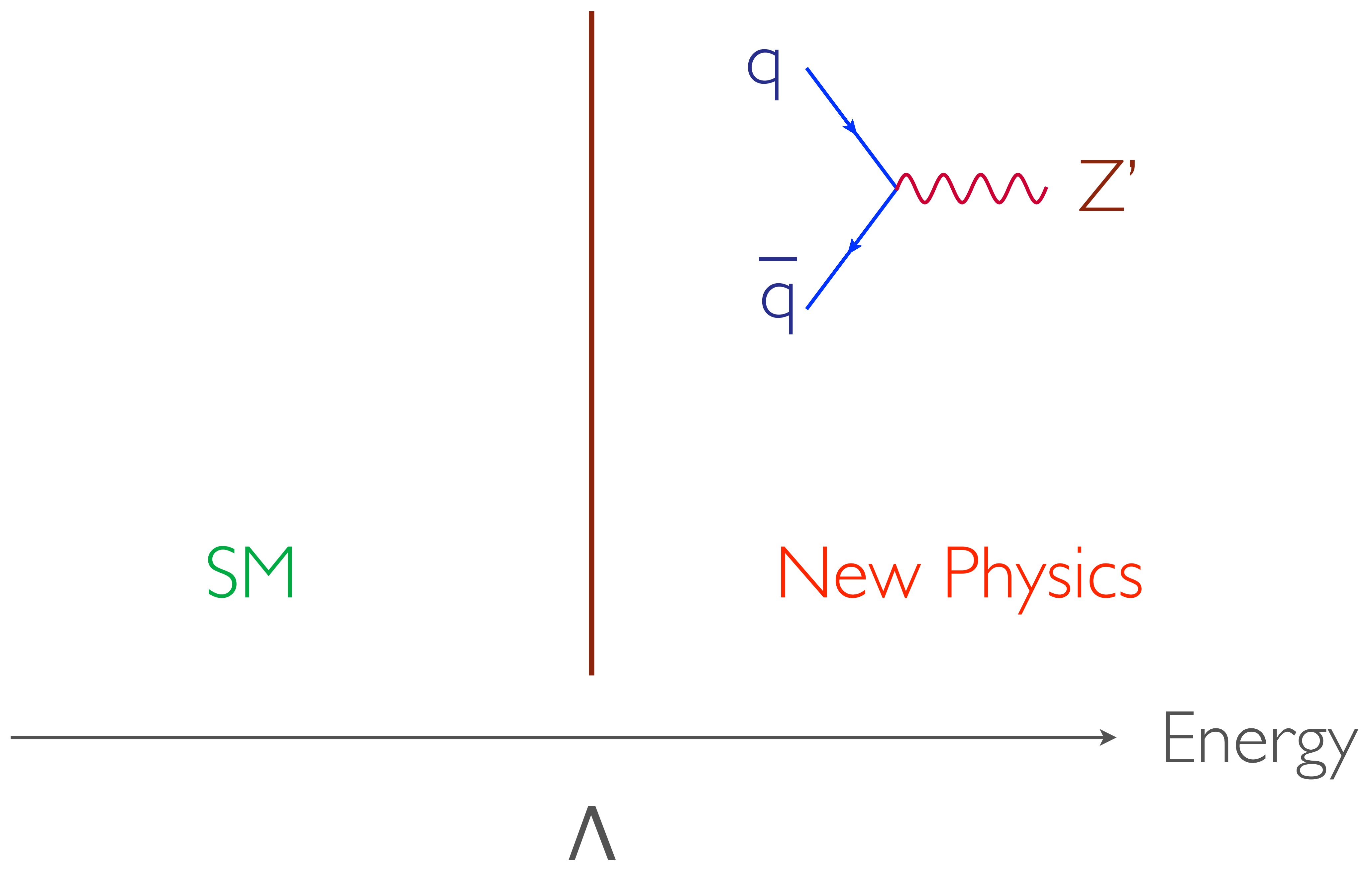
"BSM goal" of the SM LHC Run II programme:

determination of the couplings of the SM@DIM6

The idea of an EFT



The idea of an EFT



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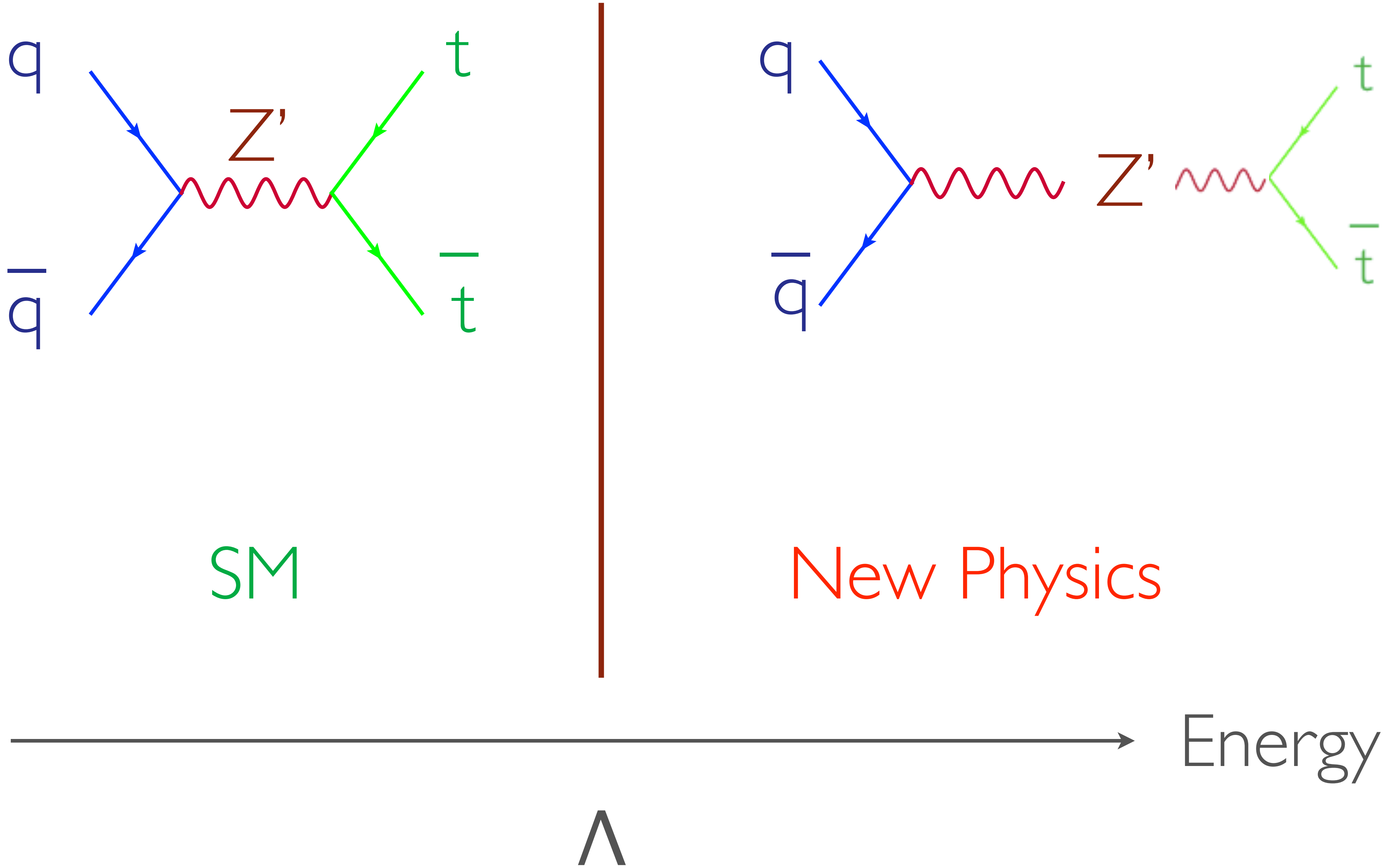

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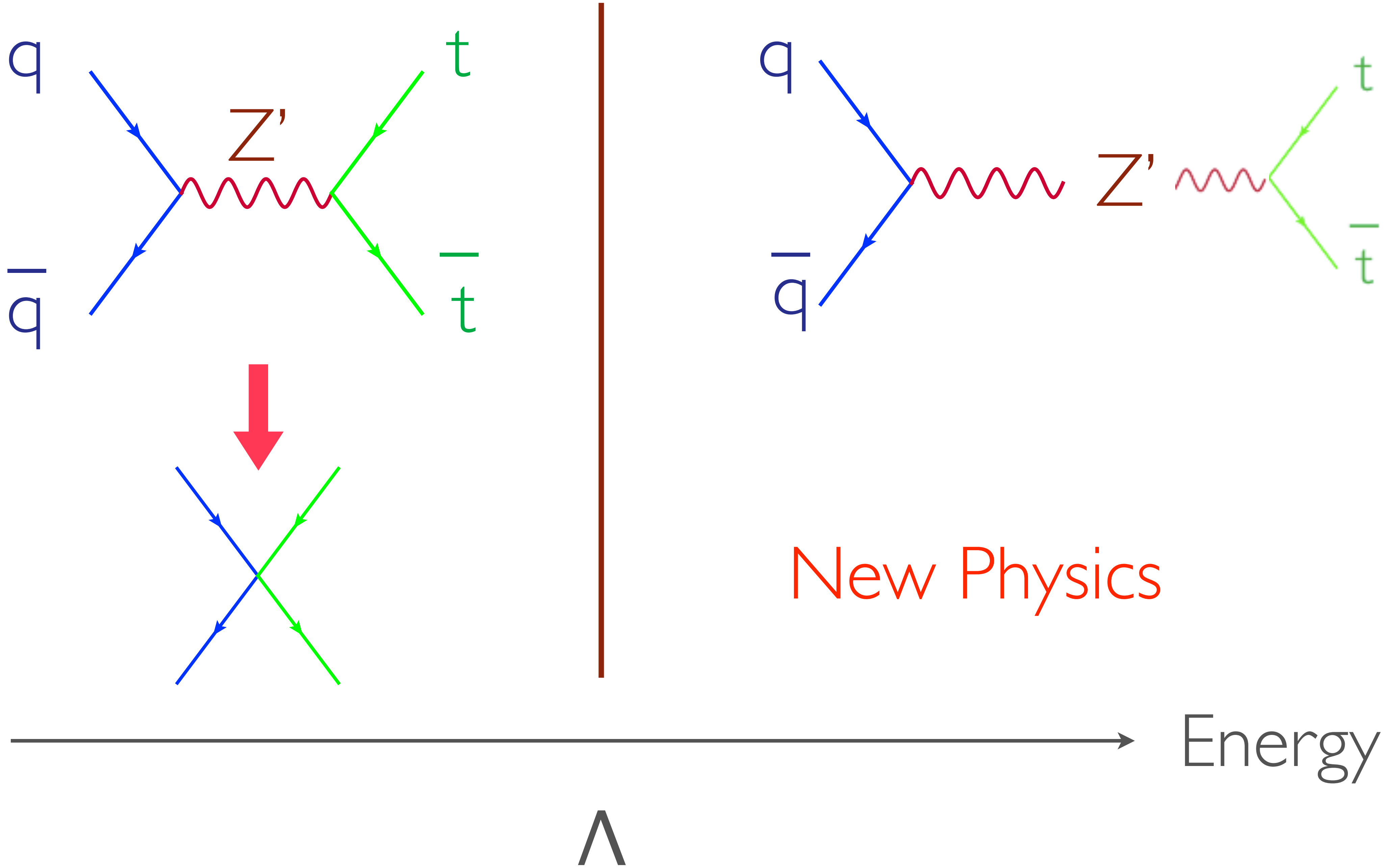

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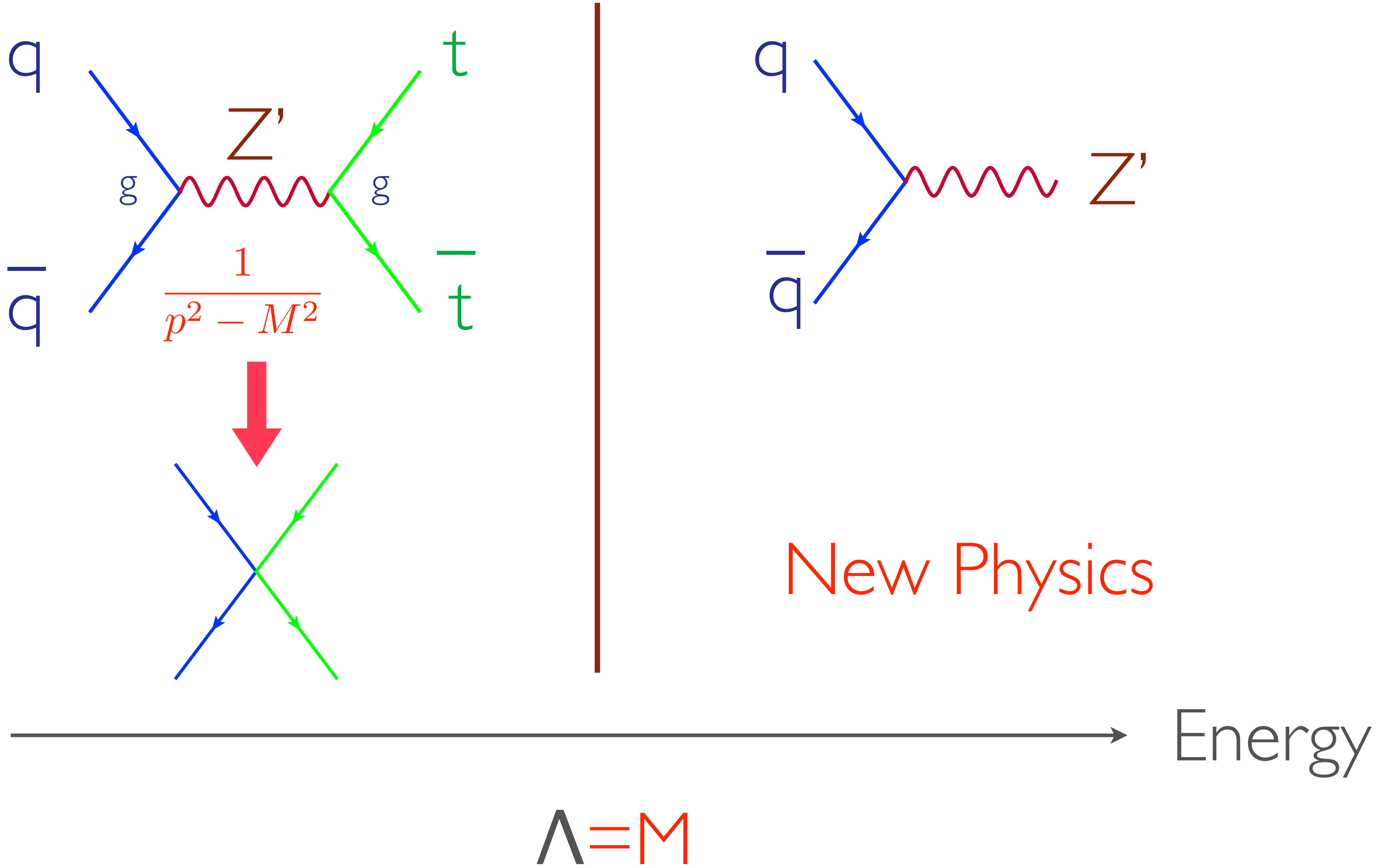

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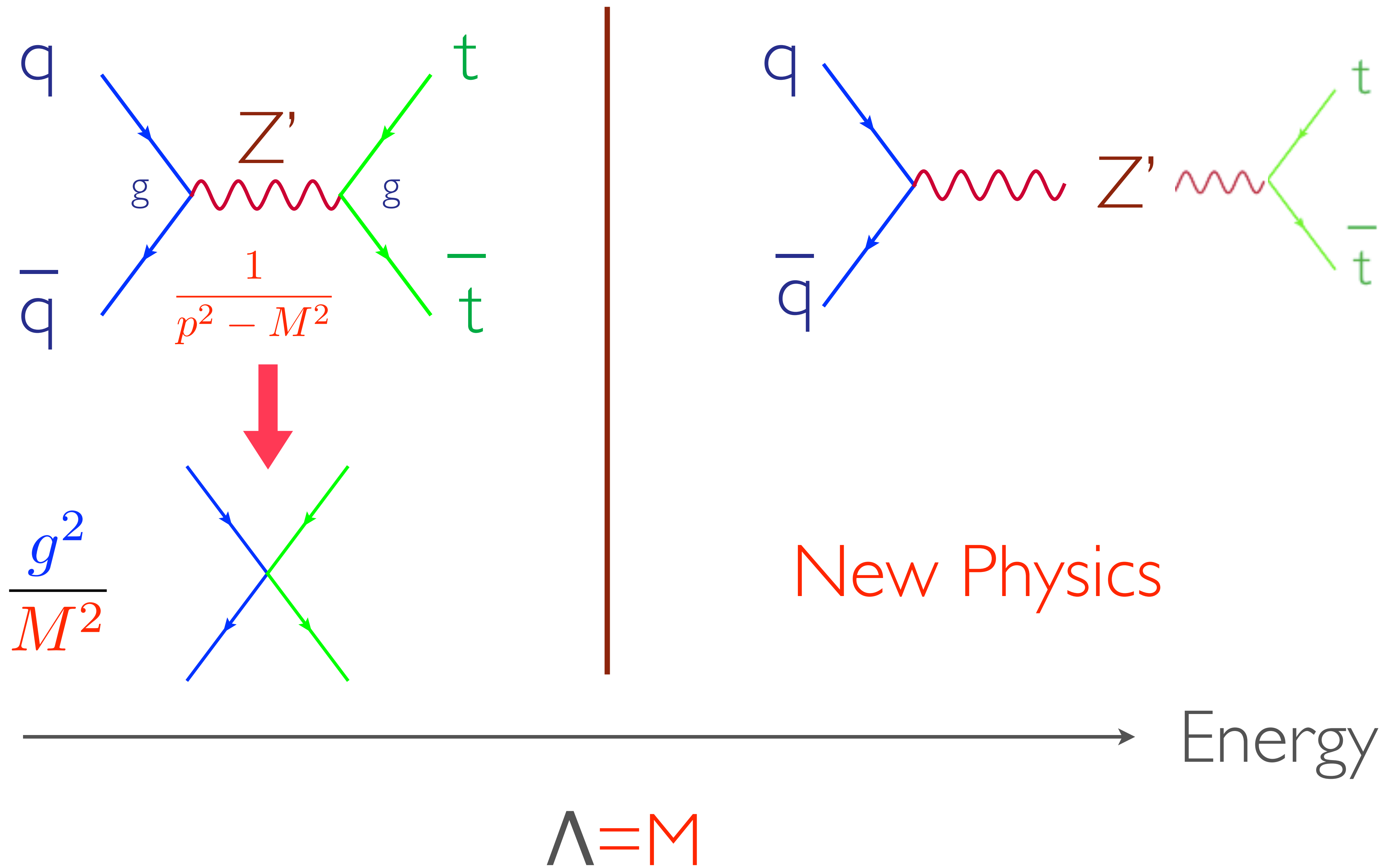
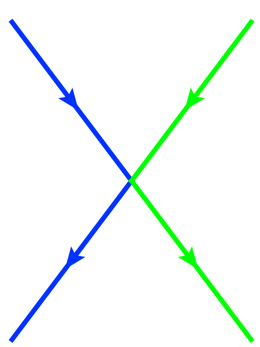


The idea of an EFT

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



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

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

Λ is an upper bound on the scale of new physics

The idea of an EFT

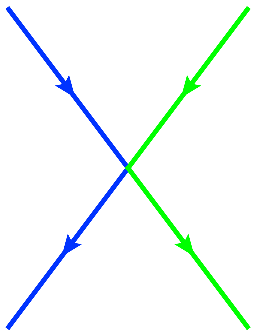
$$\hbar = c = 1$$

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

$$\dim \phi = 1$$

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

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



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

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

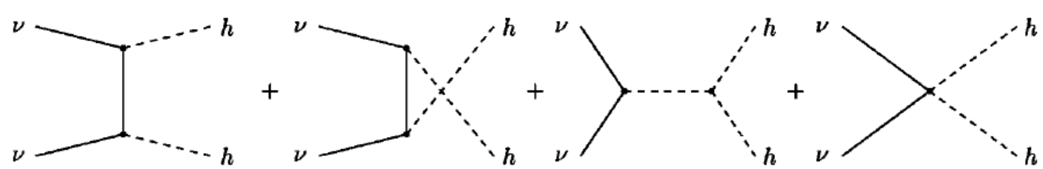
Majorana neutrinos

- Consider the SM@dim5. There is only one such operator that can be added:

$$\mathcal{L} = \frac{c}{\Lambda}(L^T \epsilon \phi) C (\phi^T \epsilon L) + h.c. \qquad \epsilon \equiv i\sigma_2$$

When the Higgs fields acquires a vev this term give rise to a Majorana neutrino mass

$$m_\nu = c\frac{v^2}{\Lambda}$$



If I now calculate the amplitude vv → hh

$$a_0\left(\frac{1}{\sqrt{2}}\nu_\pm\nu_\pm \rightarrow \frac{1}{\sqrt{2}}hh\right) \sim \mp\frac{c\sqrt{s}}{16\pi M} \sim \mp\frac{m_\nu\sqrt{s}}{16\pi v^2} \Longrightarrow$$

grows with energy

= unitarity violations

$\Longrightarrow \quad \Lambda_{Maj} \equiv \frac{4\pi v^2}{m_\nu} \quad \Longrightarrow$ min mass for the neutrino $\Longrightarrow$ upper bound for Λ

Majorana neutrino mass implies New Physics before 10^{15} GeV

Majorana neutrinos

- An UV completion of the dim=5 operator (there are few) is well known: the see-saw model

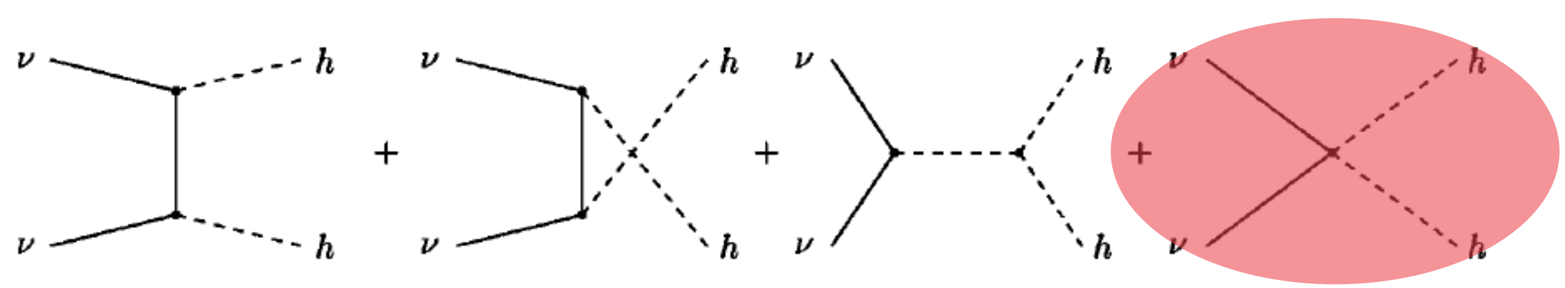
$$\mathcal{L} = -y_D \bar{L} \epsilon \phi^* \nu_R - \frac{1}{2} M_R \nu_R^T C \nu_R + \mathrm{H.c.}$$

with a Dirac mass term and a Majorana one (ν_R is a singlet of SU(2)). One can diagonalise the mass matrix and obtains two mass eingenstates

$$\nu \approx \nu_L \qquad m_\nu \approx m_D^2 / M_R$$

$$N \approx \nu_R \qquad M_R$$

and the amplitude νν → hh does not grow anymore because the last term is not present. anymore



SMEFT Lagrangian: Dim=6

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

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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

EFT picture: Matching and Running

Energy

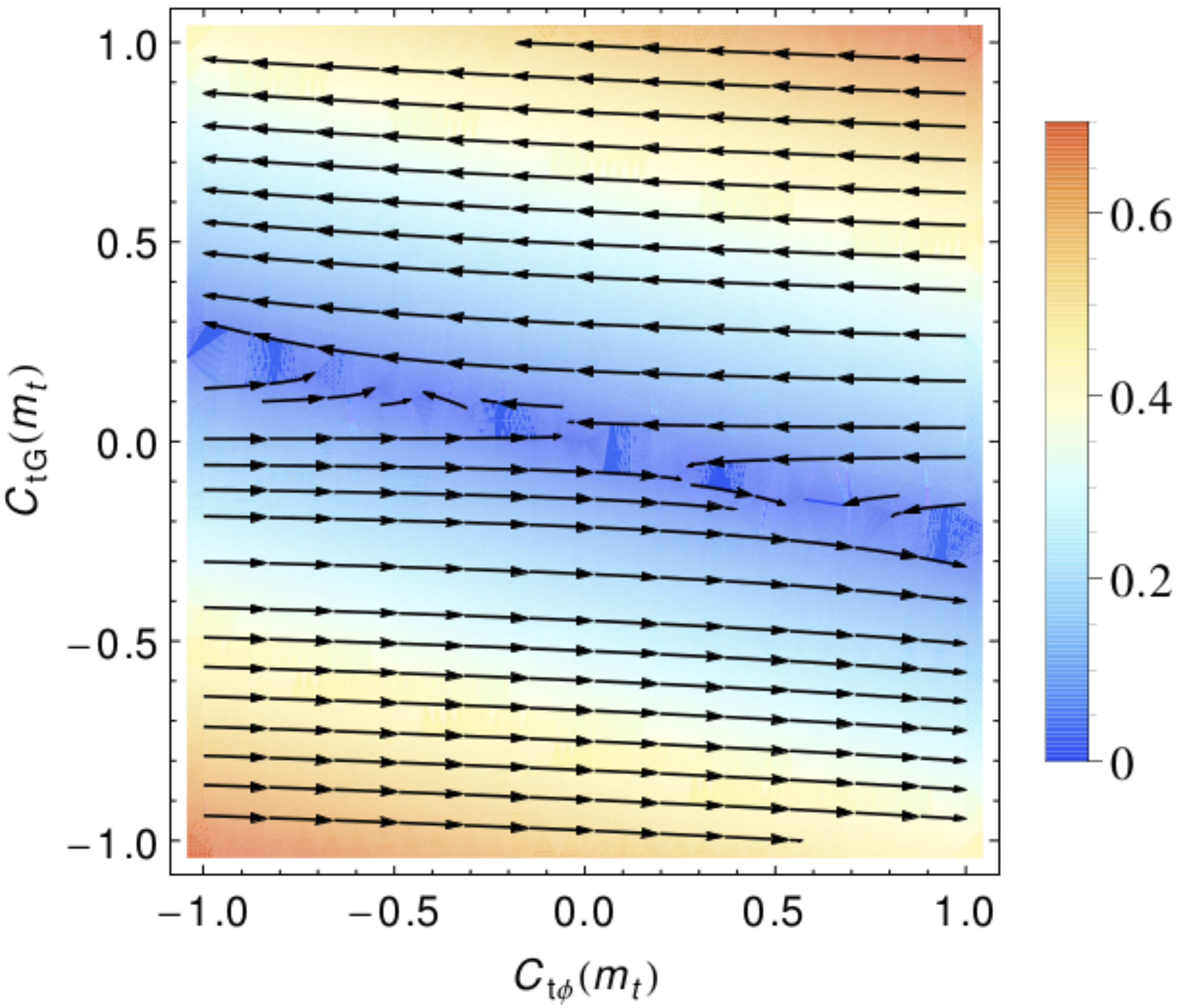
$$\mathcal{L}_{\rm EFT}(\phi_{\rm SM}, \mu = \Lambda) \quad \overset{\rm M}{\Longleftrightarrow} \quad \mathcal{L}_{\rm UV}(\phi_{\rm SM}, \phi_{\rm BSM})$$

$$\Big\downarrow \ \text{RGE}$$

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

Running/Mixing

Operators run and mix under RGE



Scale corresponds to the change from mt to 2 TeV.

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

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

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

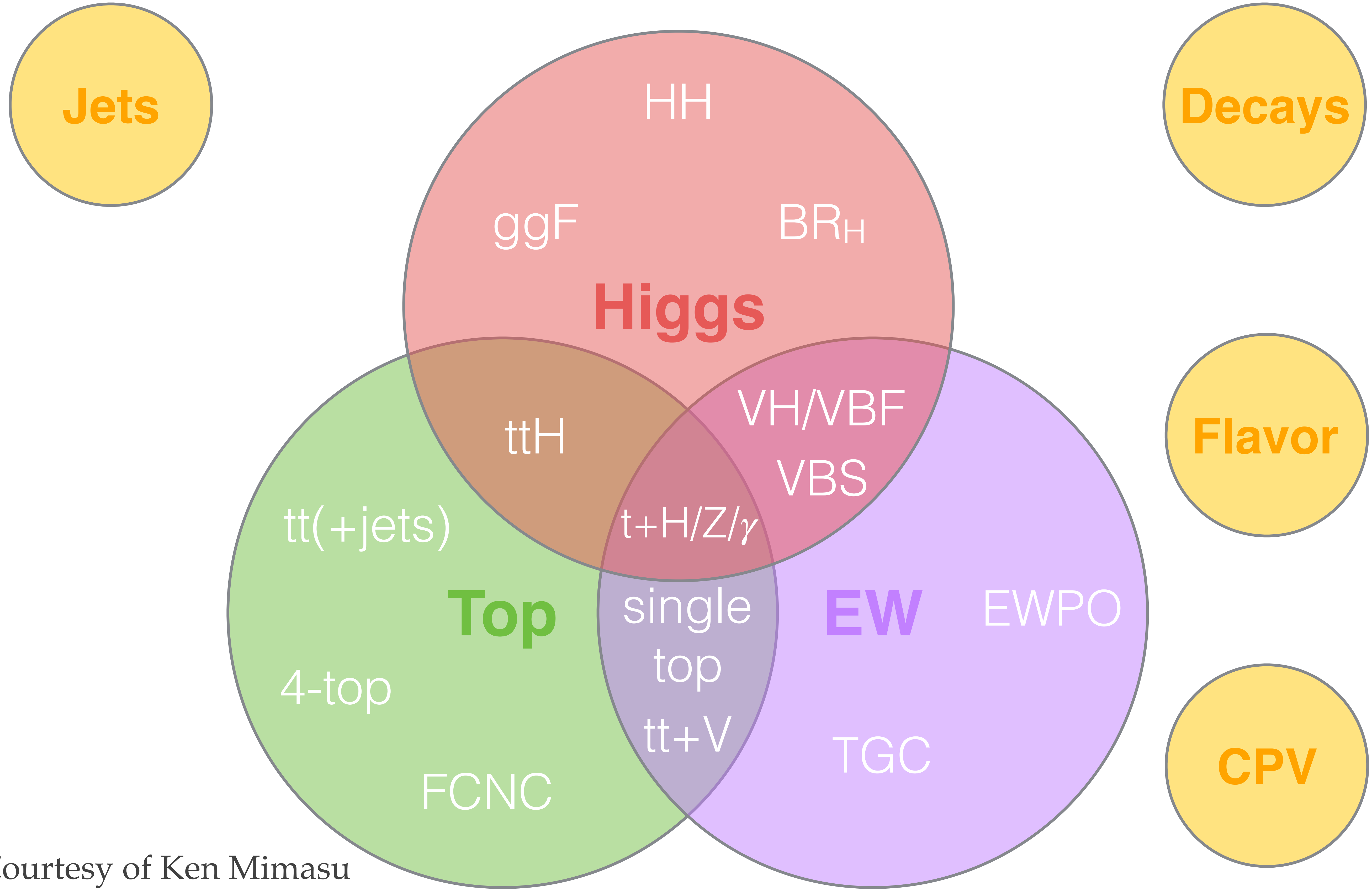
At = 173 GeV: C_{tG} = 0.98, $C_{t\varphi}$= 0.45

SMEFT Lagrangian: Dim=6

- Based on all the symmetries of the SM
- New physics is heavier than the resonance itself : $\Lambda > M_X$
- QCD and EW renormalisable (order by order in $1/\Lambda$)
- Number of extra couplings reduced by symmetries and dimensional analysis
- Extends the reach of searches for NP beyond the collider energy.
- Valid only up to the scale Λ : $\sqrt{s} < \Lambda$

The EFT approach: managing unknown unknowns

- Very powerful model-indepedent approach.
- A **global constraining strategy** needs to be employed:
  - assume all* couplings not be zero at the EW scale.
  - identify the operators entering predictions for each observable, signal as well as “backgrounds”. (LO, NLO,..)
  - find enough observables (cross sections, BR’s, distributions,…) to constrain all operators.
  - solve the linear (+quadratic)* system.
- Use to constrain UV-complete* models.



Courtesy of Ken Mimasu

Example: Gauge-Higgs operators

Focus on a subset of 10 operators:

arXiv:1803.03252

arXiv:1604.03105

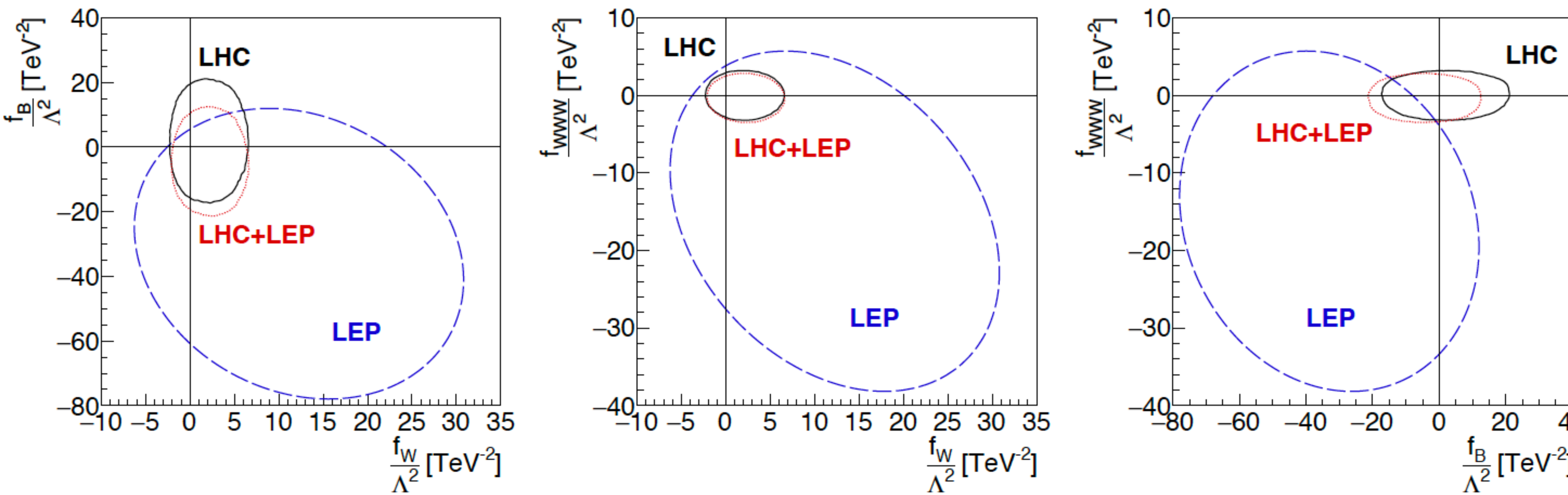
$$\mathcal{O}_{GG} = \phi^\dagger\phi\, G^a_{\mu\nu}G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\phi \qquad \mathcal{O}_{BB} = \phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\phi$$

$$\mathcal{O}_W = (D_\mu\phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\phi) \qquad \mathcal{O}_B = (D_\mu\phi)^\dagger \hat{B}^{\mu\nu}(D_\nu\phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2}\partial^\mu\left(\phi^\dagger\phi\right)\partial_\mu\left(\phi^\dagger\phi\right)$$

$$\mathcal{O}_{e\phi,33} = (\phi^\dagger\phi)(\bar{L}_3\phi e_{R,3}) \qquad \mathcal{O}_{u\phi,33} = (\phi^\dagger\phi)(\bar{Q}_3\tilde{\phi}u_{R,3}) \qquad \mathcal{O}_{d\phi,33} = (\phi^\dagger\phi)(\bar{Q}_3\phi d_{R,3})$$

$$\mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}^\mu_\rho\right) .$$

Constrain those modifying triple-gauge couplings by WW, WZ measurements

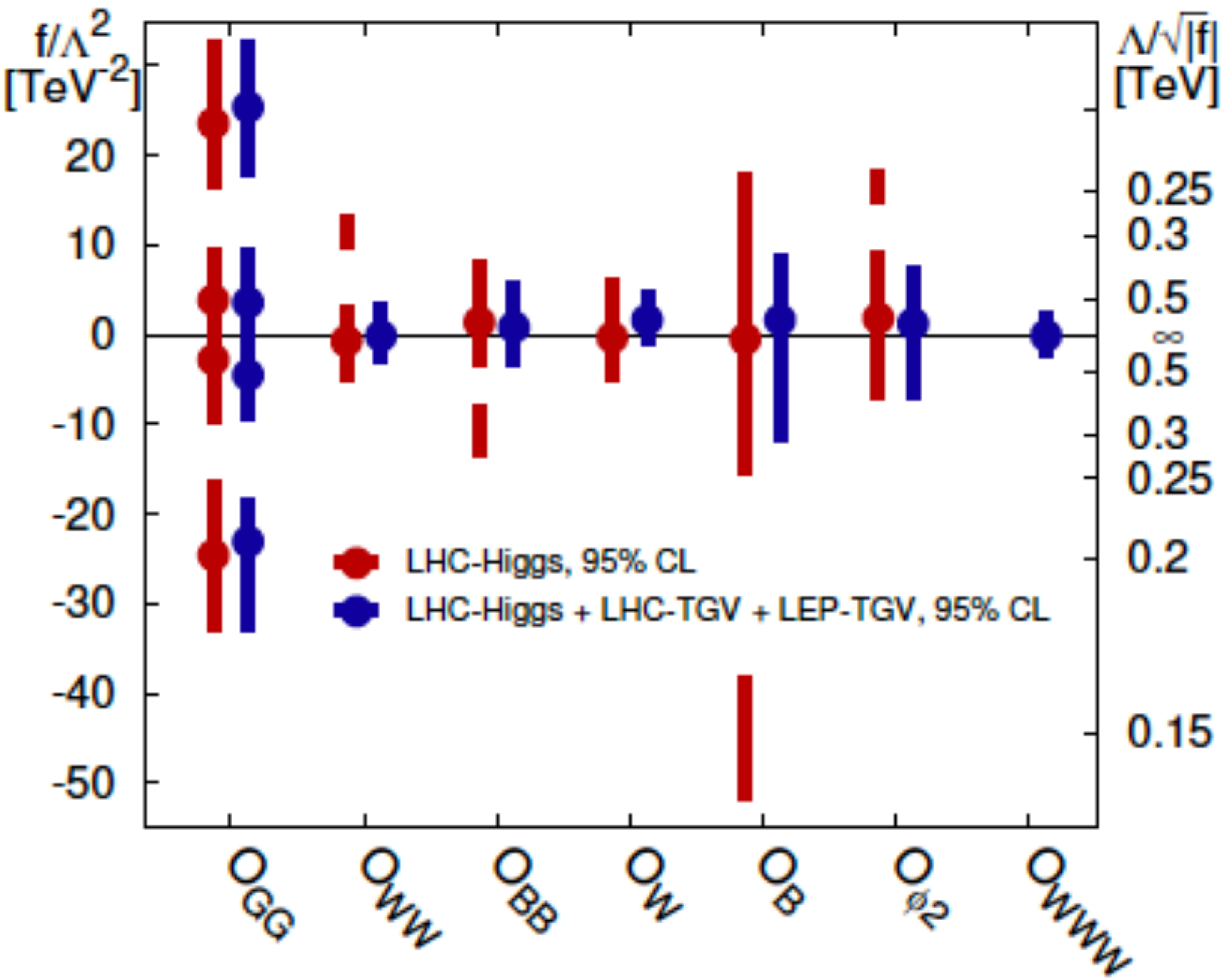


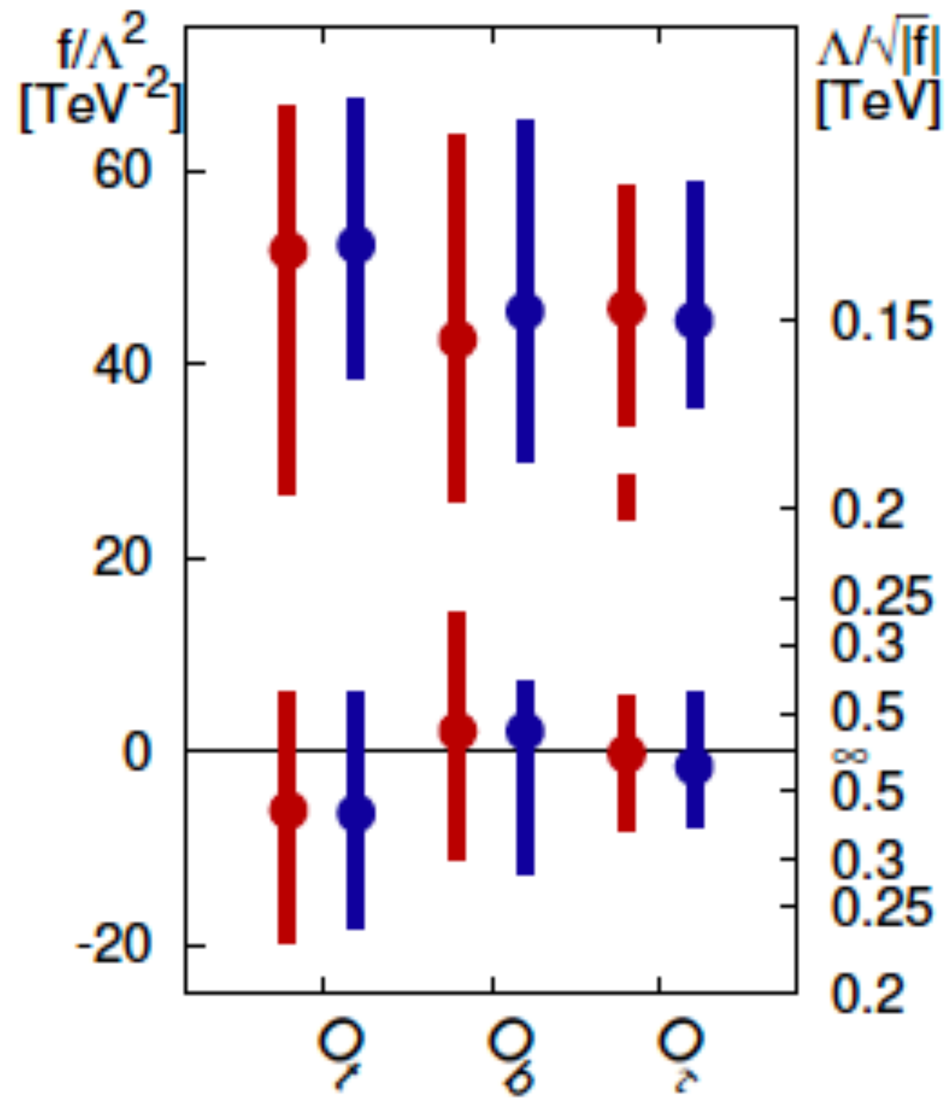
Example: Gauge-Higgs operators

arXiv:1803.03252

arXiv:1604.03105

Add the Higgs strengths constraints:





Top-quark operators and processes

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

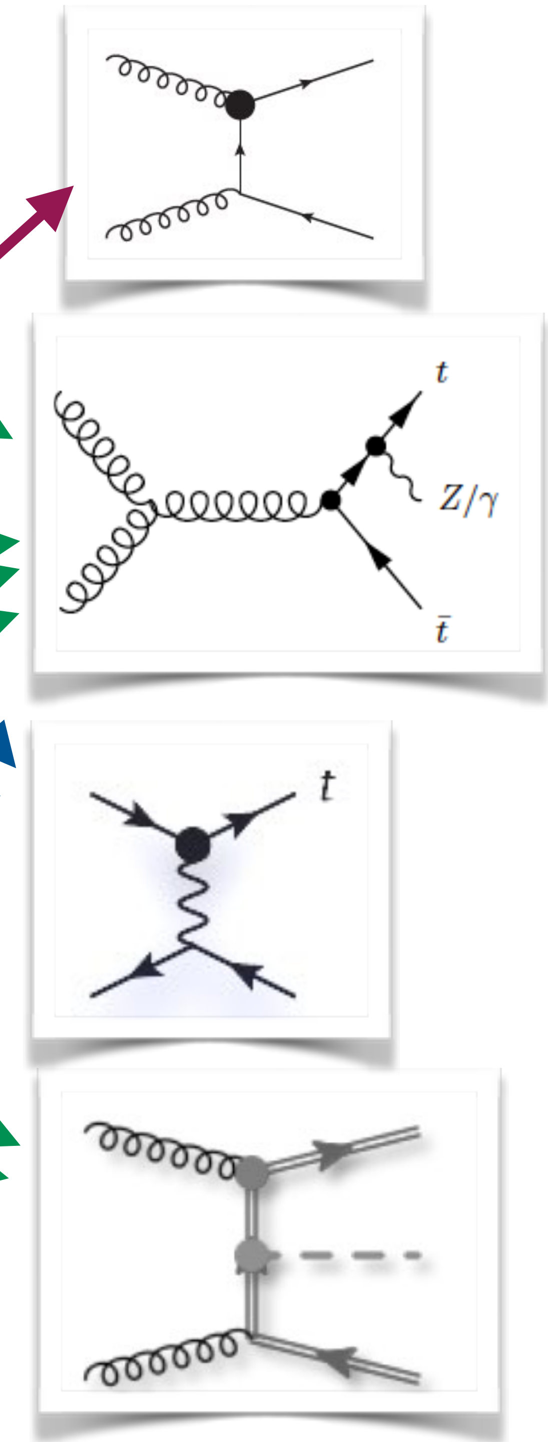
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

$$O_{t\varphi} = y_t^3(\varphi^\dagger\varphi)\bar{Q}\tilde{\varphi}t$$



+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…

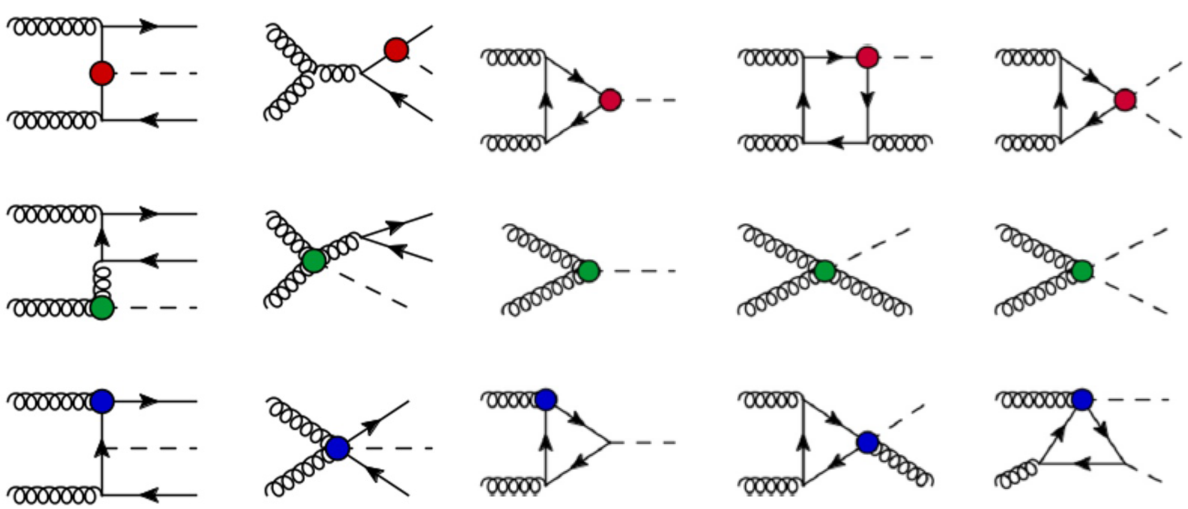
Top/Higgs operators and processes

Several operators typically enter each process at LO (or at LO^2) and

NLO (no	Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
✓	$t \to bW \to bl^+\nu$	N		L	L				L^2	L^2	1L^2		
✓	$pp \to tj$	N		L	L				L^2	L^2	1L		
✓	$pp \to tW$	L		L	L				L^2	L^2	1N	N	
✓	$pp \to t\bar{t}$	L									2L-4N	L	
✓	$pp \to t\bar{t}j$	L									2L-4N	L	
✓	$pp \to t\bar{t}\gamma$	L	L	L							2L-4N	L	
✓	$pp \to t\bar{t}Z$	L	L	L	L	L	L				2L-4N	L	
✓	$pp \to t\bar{t}W$	L								L	1L-2L		
✓	$pp \to t\gamma j$	N	L	L	L				L^2	L^2	1L		
✓	$pp \to tZj$	N	L	L	L	L	L		L^2	L^2	1L		
✓	$pp \to t\bar{t}t\bar{t}$	L									2L-4L	L	
✓	$pp \to t\bar{t}H$	L						L			2L-4L	L	L
✓	$pp \to tHj$	N		L	L			L	L^2	L^2	1L		N
O ✓	$gg \to H$	L						L				N	L
O ✗	$gg \to Hj$	L						L				L	L
O ✗	$gg \to HH$	L						L				N	L
O ✗	$gg \to HZ$	L			L	L	L	L				N	L

Top/Higgs operators and processes

Let’s take a simple example, i.e. Higgs production via top interactions and consider the relevant subset of operators.



ttH H H+j HH

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

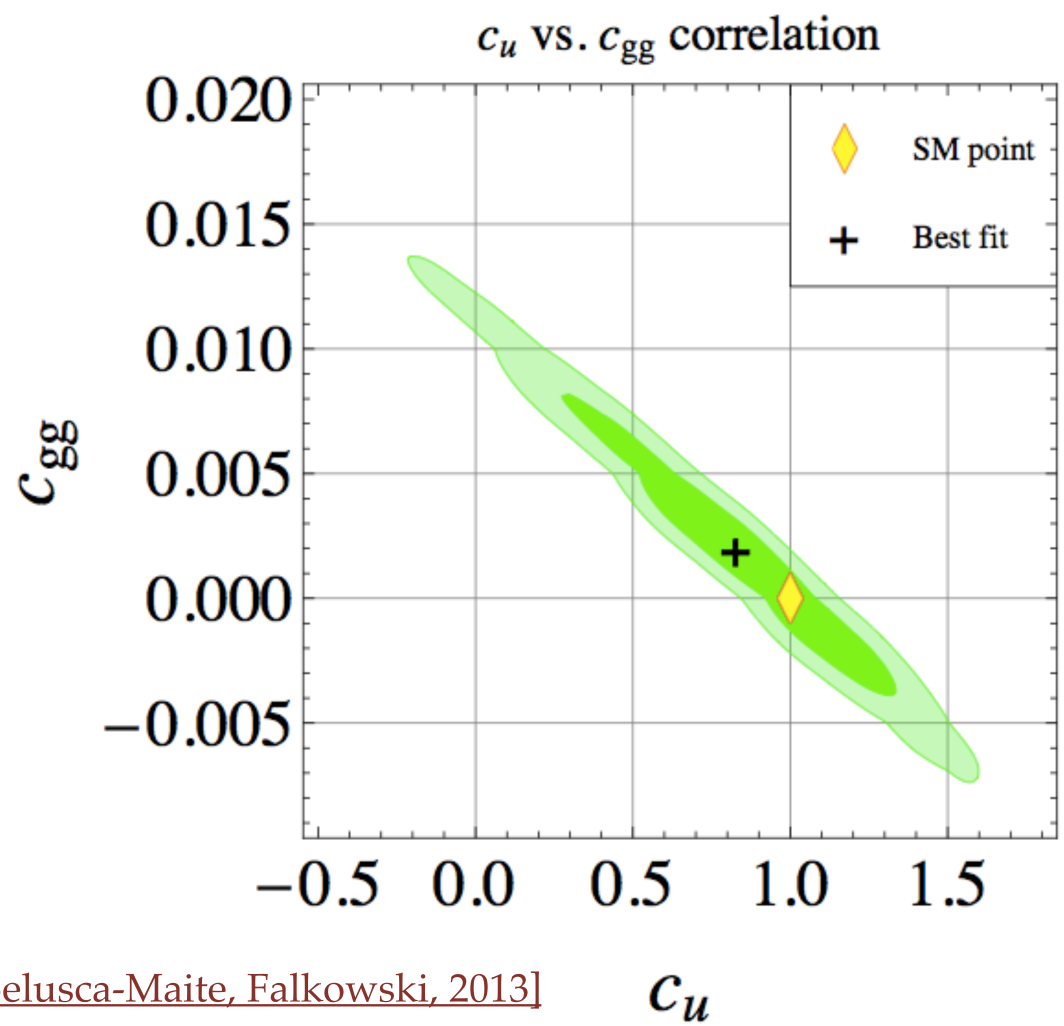
Note that these operators mix into each others and therefore they NEED to be considered together.

$$\gamma = \frac{2\alpha_s}{\pi} \begin{pmatrix} \frac{1}{6} & 0 & 0 \\ 4 & -1 & 4 \\ \frac{1}{4} & 0 & -\frac{7}{4} \end{pmatrix}$$

Top-Higgs interactions: constraints

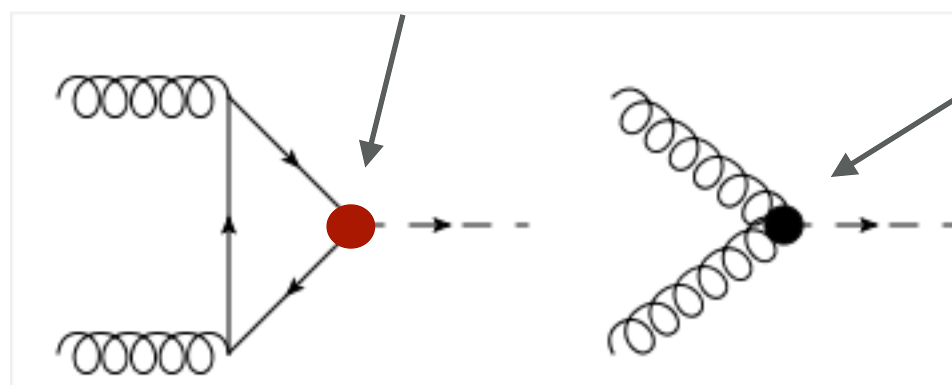
From a global fit the coupling of the higgs to the top is poorly determined.

$$\frac{\sigma_{ggh}}{\sigma_{ggh}^{\mathrm{SM}}} \simeq 1 + 237 c_{gg} + 2.06\delta y_u - 0.06\delta y_d.$$



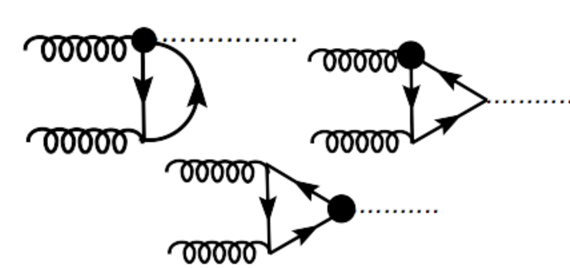
[Belusca-Maite, Falkowski, 2013]

$\mathcal{O}_{Hy} = H^\dagger H \left(H\bar{Q}_L\right) t_R$ $\qquad$ $\mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G_a^{\mu\nu}$



the loop could still be dominated by np.

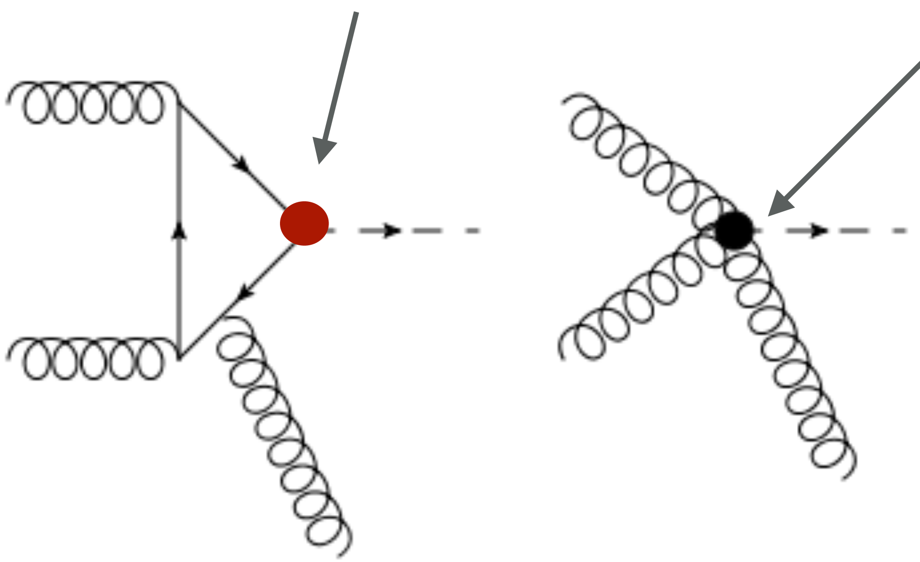
THE EFFECT OF THE CM OPERATOR NOT INCLUDED

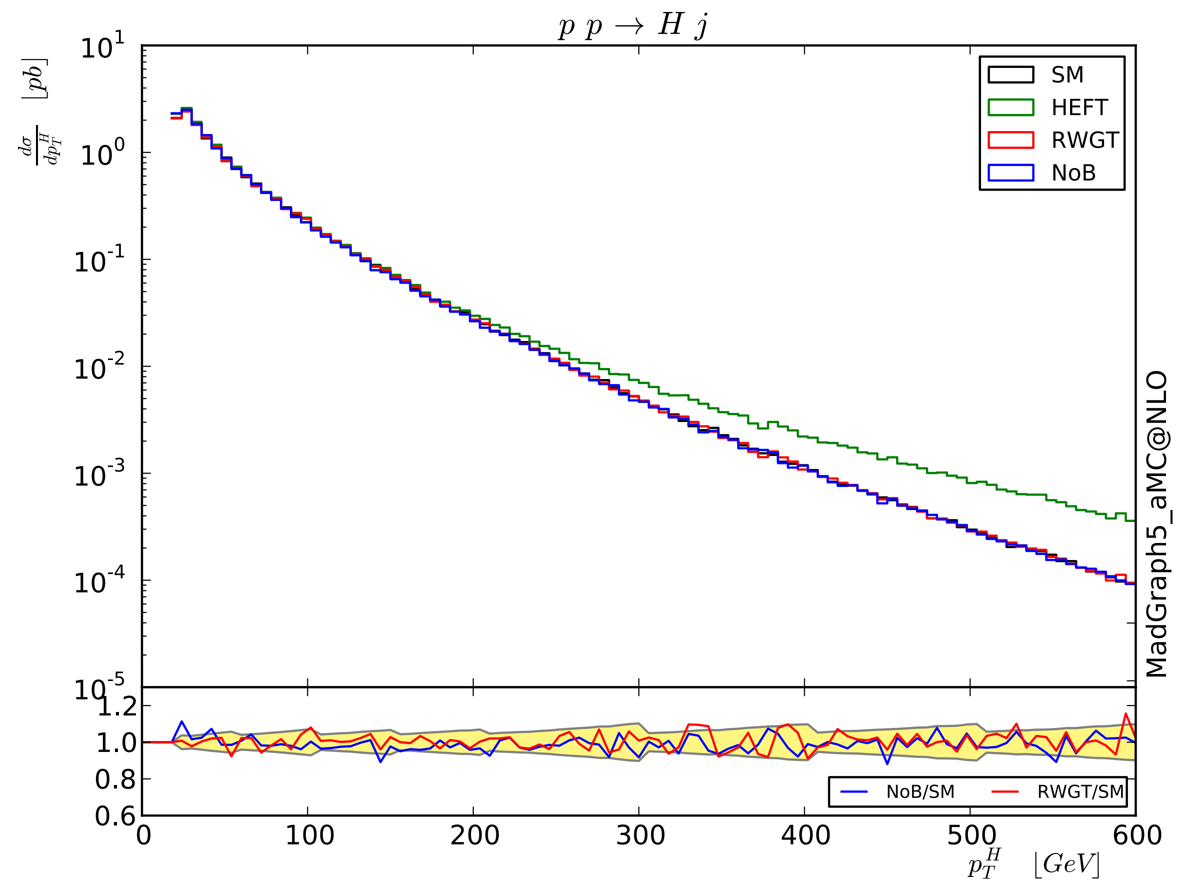


Top-Higgs interactions: high-pT

From a global fit the coupling of the Higgs to the top is poorly determined: the loop could still be dominated by NP.

$$\mathcal{O}_{Hy} = H^\dagger H \left(H\bar{Q}_L\right) t_R \qquad \mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G_a^{\mu\nu}$$



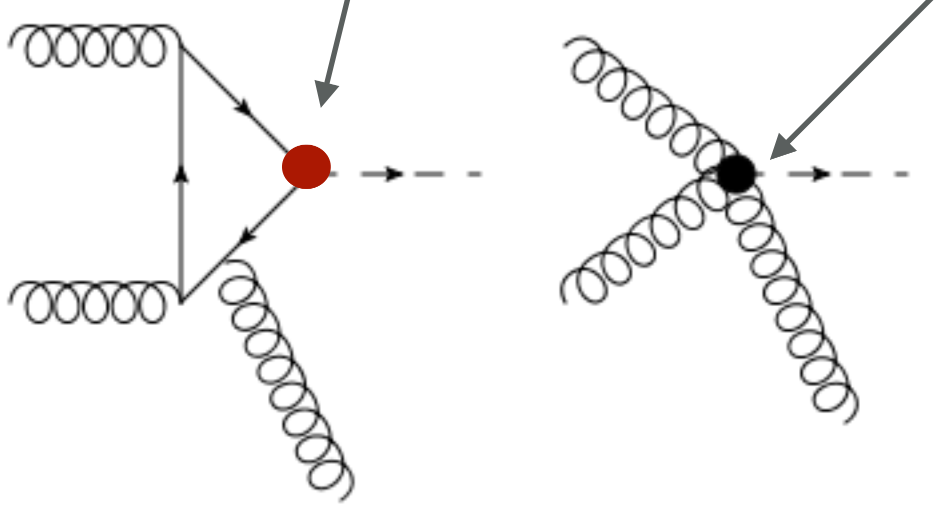


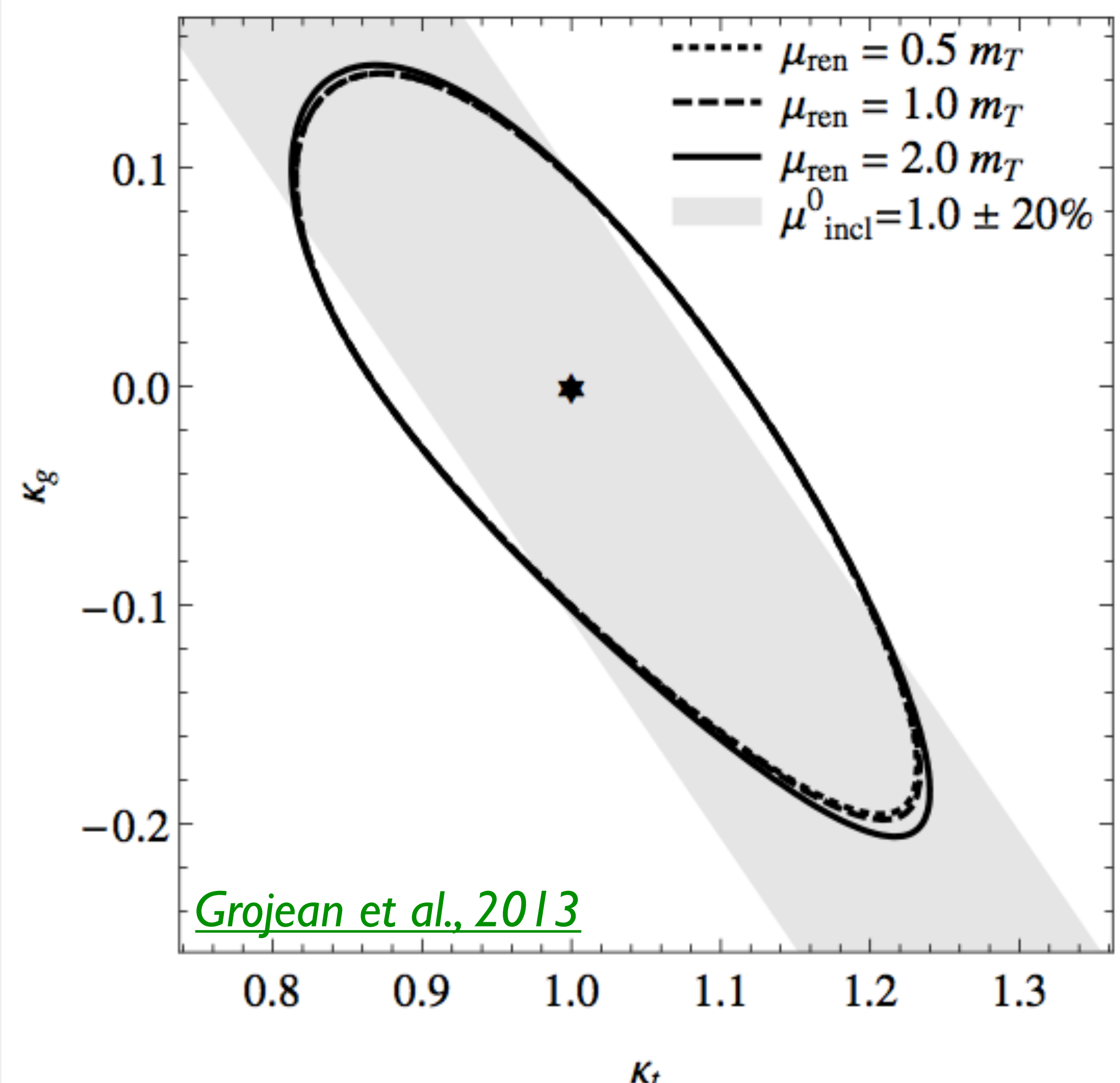
EFT at NLO predictions available, yet SM NLO predictions are needed to control accuracy precision.

Top-Higgs interactions: high-pT

From a global fit the coupling of the Higgs to the top is poorly determined: the loop could still be dominated by NP.

$$\mathcal{O}_{Hy} = H^\dagger H \left(H\bar{Q}_L\right) t_R \qquad \mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$

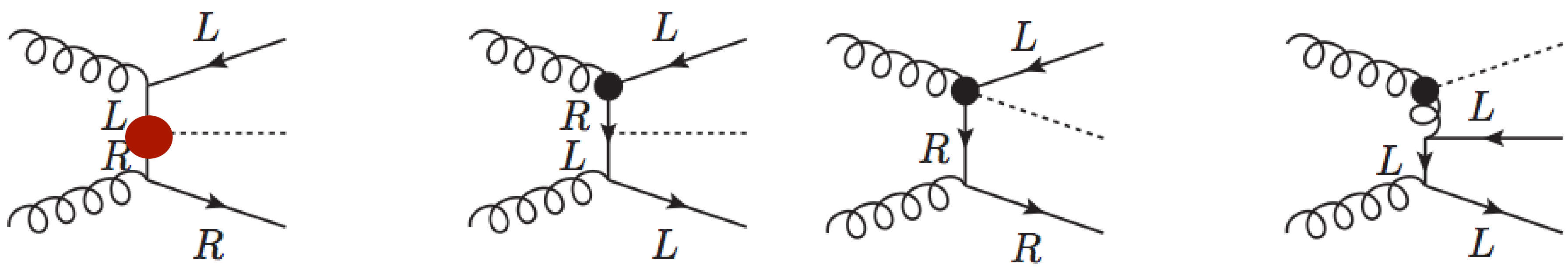




EFT at NLO predictions available, yet SM NLO predictions are needed to control accuracy a precision.

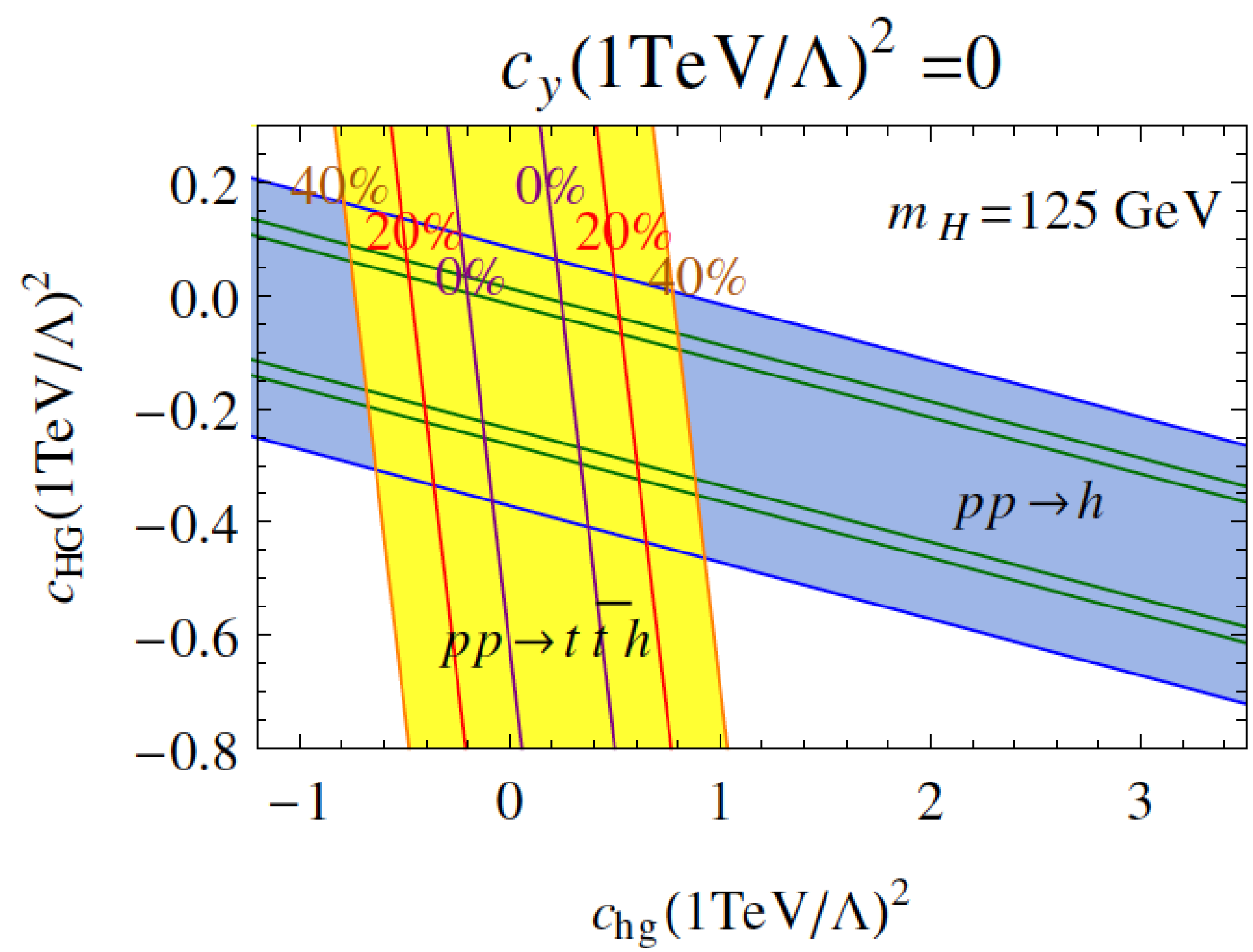
Top-Higgs interactions: ttH

$$pp \to t\bar{t}h$$

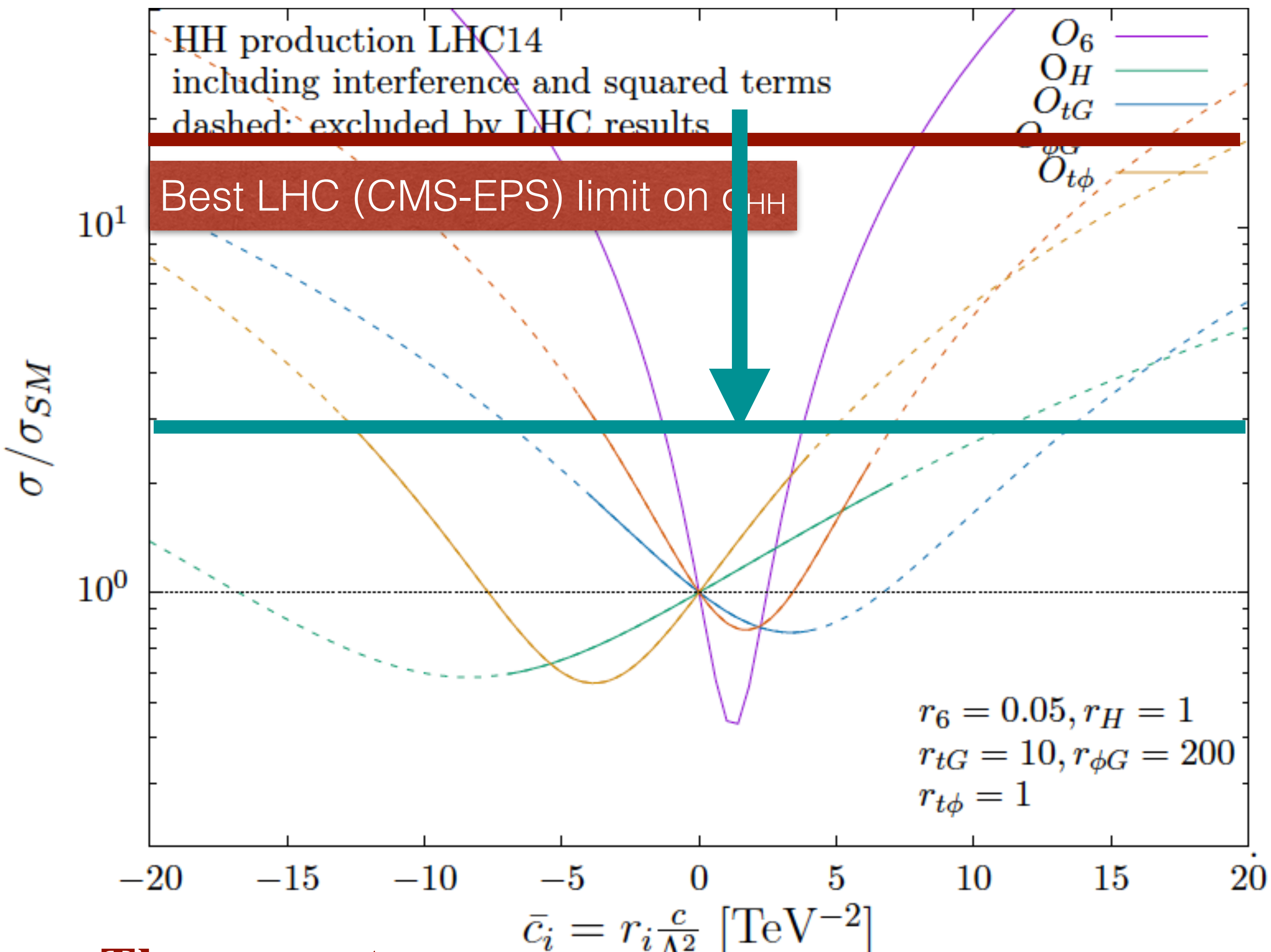


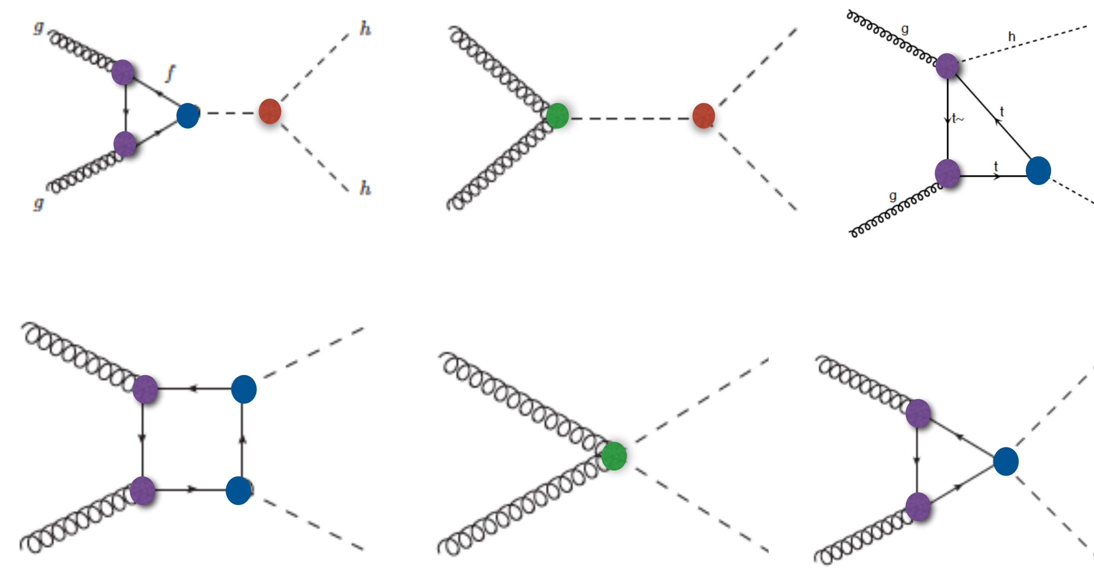
[Degrande et al. 2012]

$$\frac{\sigma\left(pp \to t\bar{t}h\right)}{\text{fb}} = 611^{+92}_{-110} + \left[457^{+127}_{-91}\Re c_{hg} - 49^{+15}_{-10} c_G \right.$$
$$\left. + \ 147^{+55}_{-32} c_{HG} - 67^{+23}_{-16} c_y \right] \left(\frac{\text{TeV}}{\Lambda}\right)^2$$
$$+ \ \left[543^{+143}_{-123} (\Re c_{hg})^2 + 1132^{+323}_{-232} c_G^2 \right.$$
$$+ \ 85.5^{+73}_{-21} c_{HG}^2 + 2^{+0.7}_{-0.5} c_y^2$$
$$+ \ 233^{+81}_{-144} \Re c_{hg} c_{HG} - 50^{+16}_{-14} \Re c_{hg} c_y$$
$$\left. - \ 3.2^{+8}_{-8} \Re c_{Hy} c_{HG} - 1.2^{+8}_{-8} c_H c_{HG} \right] \left(\frac{\text{TeV}}{\Lambda}\right)^4$$



How to extract λ_{HHH} from HH?





Other couplings enter in the same process: top Yukawa, ggh(h) coupling, top-gluon interaction

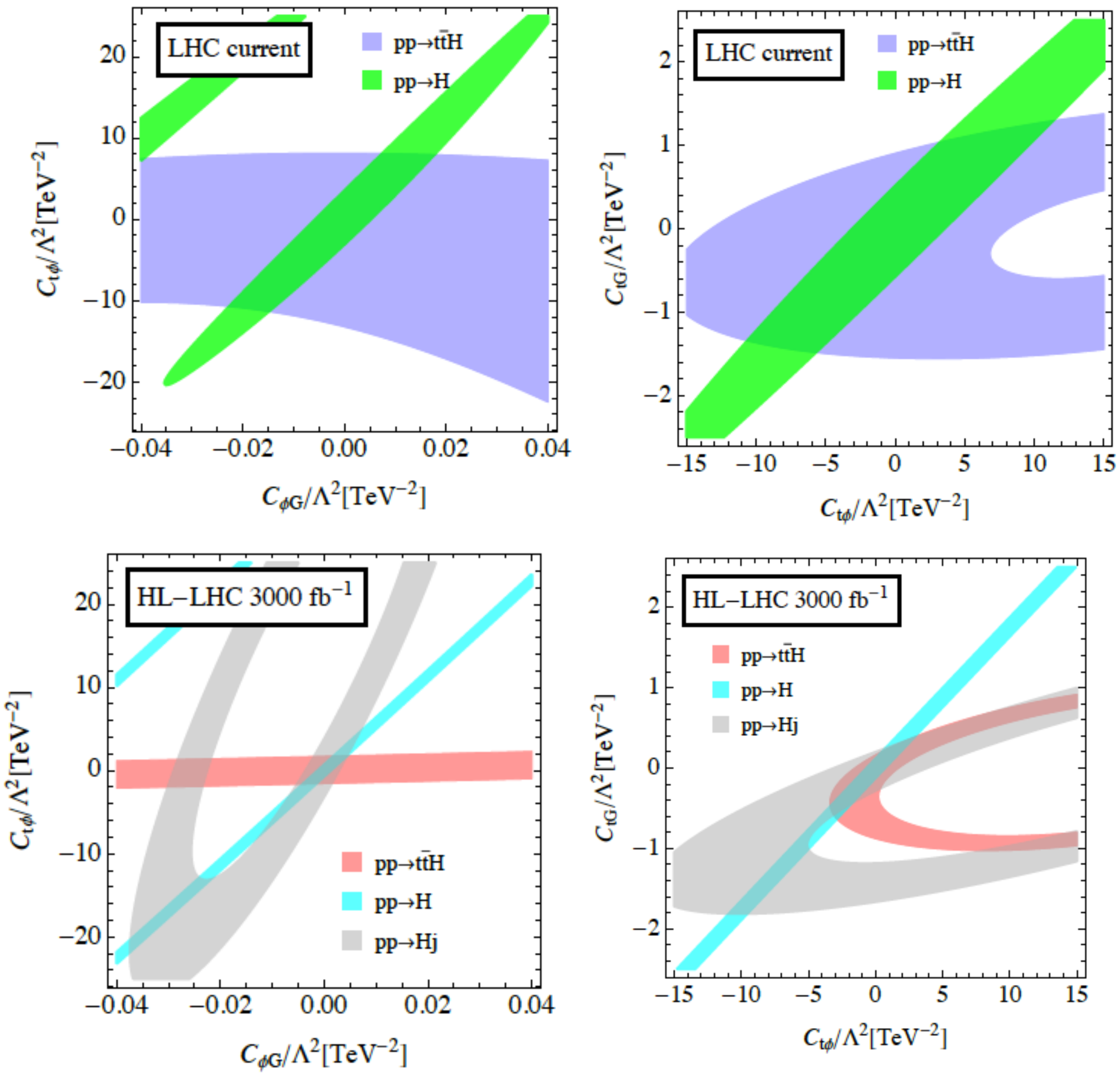
The present

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 be necessary

Constraints from ttH and Higgs production



Current limits using LHC measurements

$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi} G^A_{\mu\nu}$$

14TeV projection

3000 fb-1

Conclusions

- The golden era for Higgs physics has just started
- We are moving in three main directions:
  - exploiting the Higgs as a gateway to BSM sectors
  - exploring uncharted sectors of the SM
  - performing accurate measurements of the couplings and their interpretation through an EFT approach
- Exciting, challenging, rich and very promising physics program ahead of us!