The 18th Workshop of the LHC Higgs Working Group
December 3, 2021

Single and Double Higgs processes: *Interpretation in the κ_λ and EFT frameworks*

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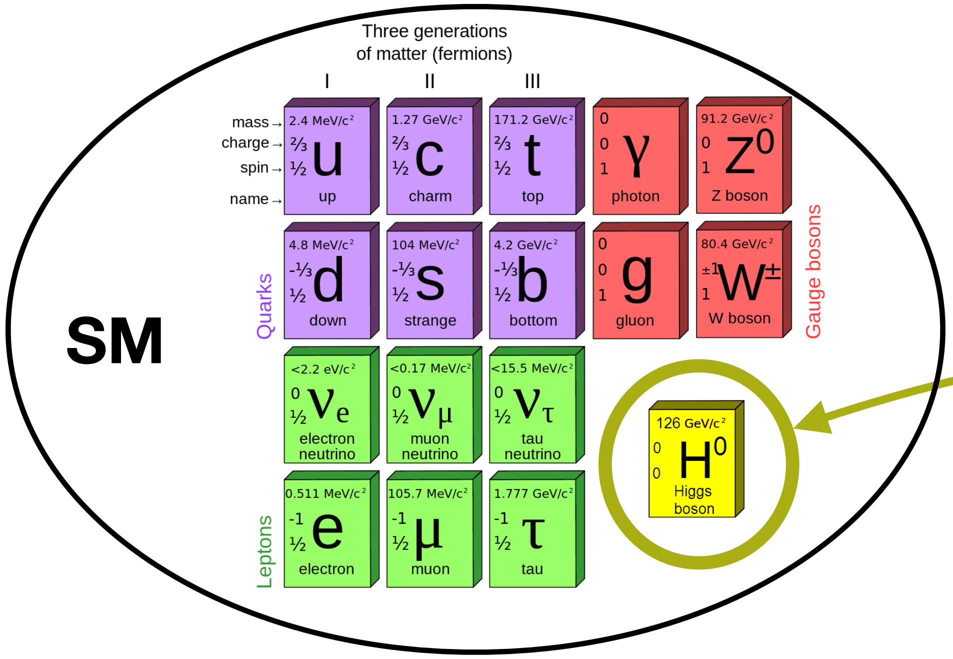
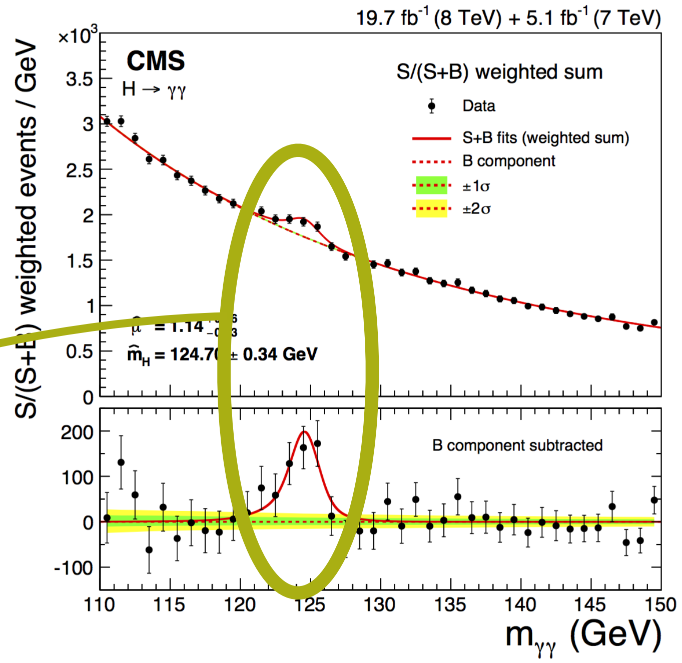
UNIÓN EUROPEA
Fondo Europeo de Desarrollo Regional

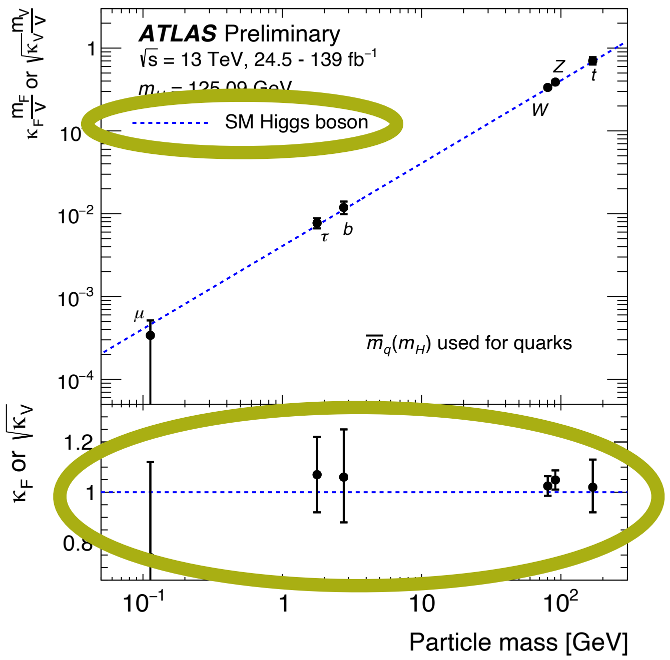
Funded by: FEDER/Junta de Andalucía-Consejería de Transformación Económica, Industria, Conocimiento y Universidades
Project P18-FRJ-3735

Introduction

- The discovery of the 125 GeV Higgs boson “completes” the Standard Model…
  - ✓ We have all the particles predicted by the SM…







Introduction

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  - ✓ We have all the particles predicted by the SM…plus the measurement of the Higgs mass completes the list of inputs needed to compute all interactions in the SM Lagrangian…

$$\boxed{\begin{aligned}\mathcal{L}_{\rm SM} = & -\frac{1}{4}G_{\mu\nu}^A G^{A\ \mu\nu} - \frac{1}{4}W_{\mu\nu}^a W^{a\ \mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \\ & + \bar{l}_{Li}\, i\not{D}\, l_{Li} + \bar{q}_{Li}\, i\not{D}\, q_{Li} + \bar{e}_{Ri}\, i\not{D}\, e_{Ri} + \bar{u}_{Ri}\, i\not{D}\, u_{Ri} + \bar{d}_{Ri}\, i\not{D}\, d_{Ri} + \\ & + \left(D_\mu \phi\right)^\dagger D^\mu \phi - V\left(\phi\right) - \left(\hat{y}_{ij}^e\ \bar{e}_{Ri}\phi l_{Lj} + \hat{y}_{ij}^d\ \bar{d}_{Ri}\phi q_{Lj} + \hat{y}_{ij}^u\ \bar{u}_{Ri}\tilde{\phi}^\dagger q_{Lj} + \text{h.c.}\right)\end{aligned}}$$

The crucial question is:

Do all interactions predicted by the SM agree with the EXP measurements?

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The crucial question is:

Do all interactions predicted by the SM agree with the EXP measurements?

Several of the SM particle interactions have not been measured directly yet, in particular, those entering in the scalar potential

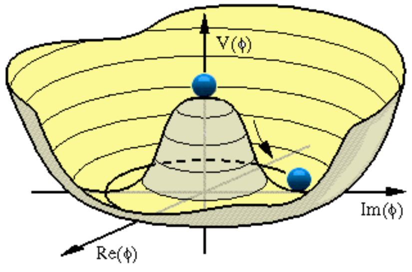
$$V(\phi) = -\mu_\phi^2\,|\phi|^2 + \lambda_\phi\,|\phi|^4 \longrightarrow V(h) = \tfrac{1}{2}m_h^2 h^2 + \lambda_3 v h^3 + \tfrac{1}{4}\lambda_4 h^4$$

$$\lambda_3^{\mathrm{SM}} = \lambda_4^{\mathrm{SM}} = \lambda_\phi = \frac{G_\mu m_h^2}{\sqrt{2}} \approx 0.129$$

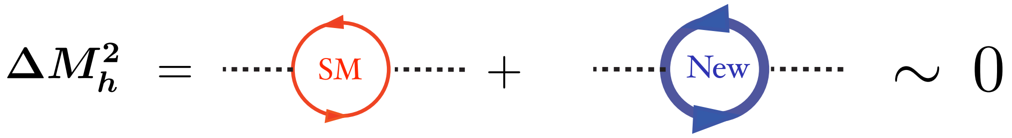
Introduction

- Why are these self-interactions important?
  - ✓ It characterises the structure of the Higgs potential

    ⇒ Does EWSB follow from a Ginzburg- Landau ϕ^4 potential?



  - ✓ Test the validity of the SM. If not SM-like ⇒ Access to information about new physics (BSM)
    - Naturalness?



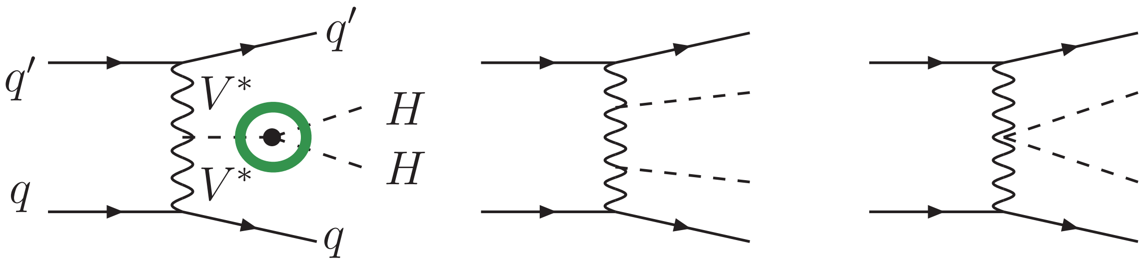
    - Sizable deviations expected, e.g., in models of composite Higgs or models with Higgs portal interactions
  - ✓ Control the properties of the electroweak phase transition (EWPT)
    - (Electroweak) Baryogenesis?
    - Models predicting strong 1st order transition typically predict O(1) deviations from SM
- OK, so how can we learn from the Higgs self-coupling at the LHC?

LHC probes of the Higgs trilinear coupling

- How do we measure these self-interactions at the LHC?
  - ✓ The obvious way…. Direct Higgs pair production

gghh:

VBF:



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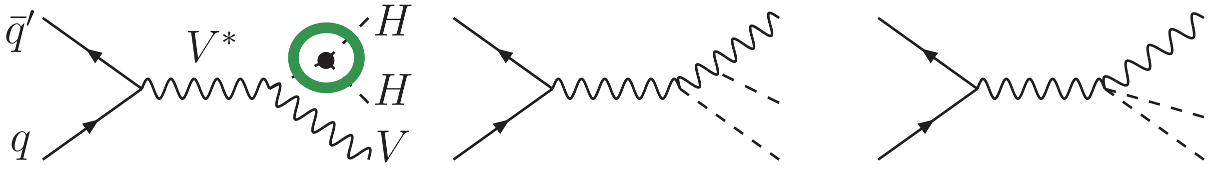
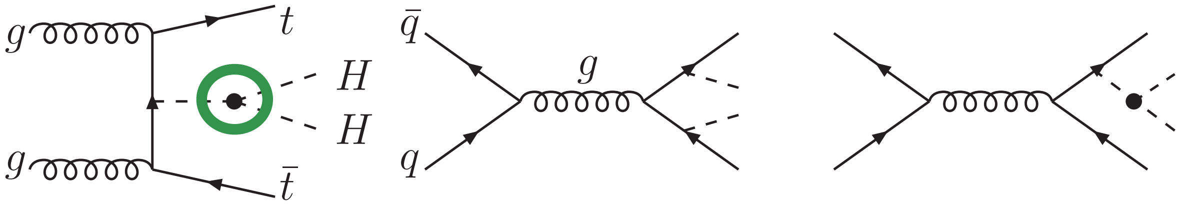


Tthh:



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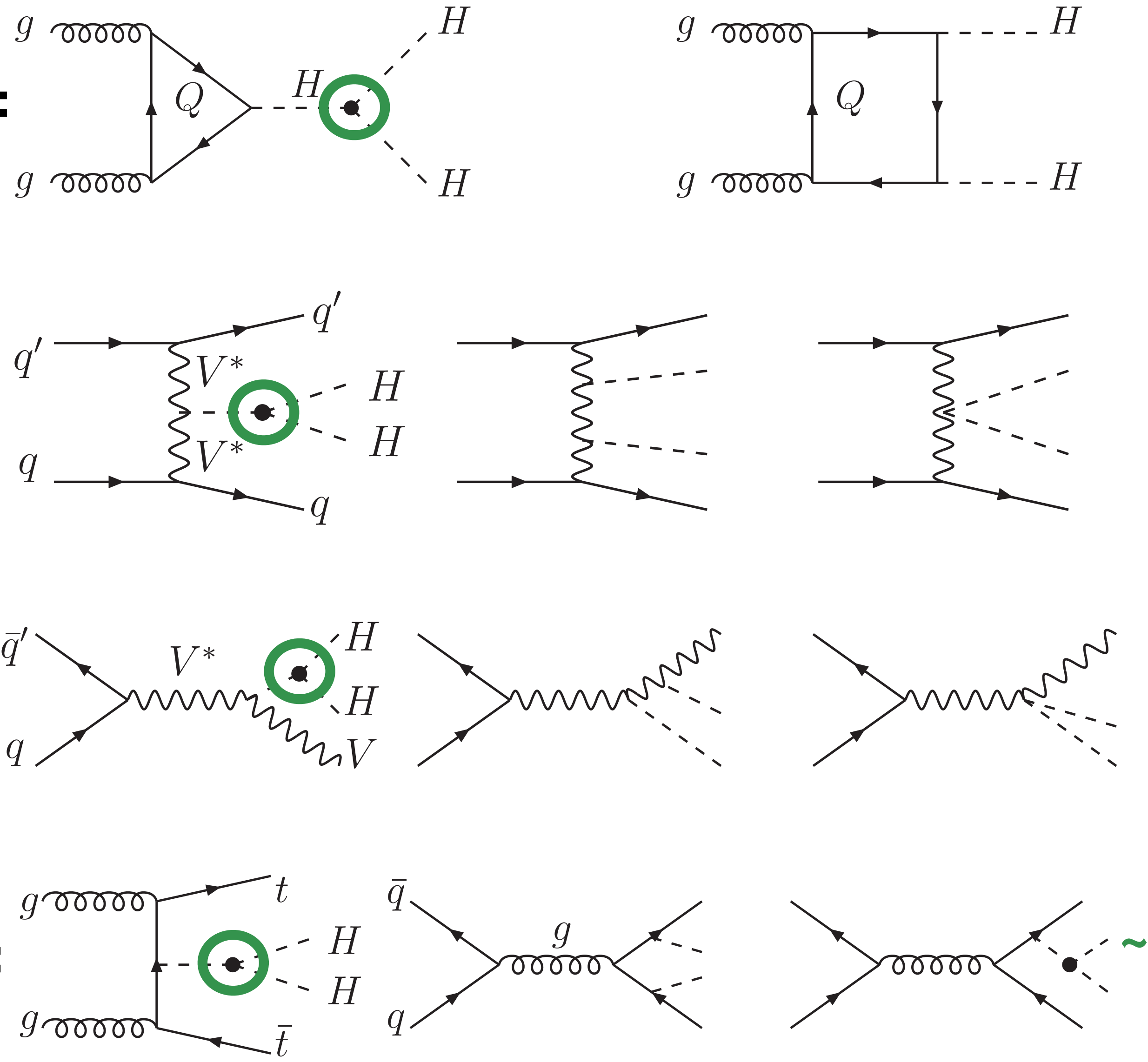
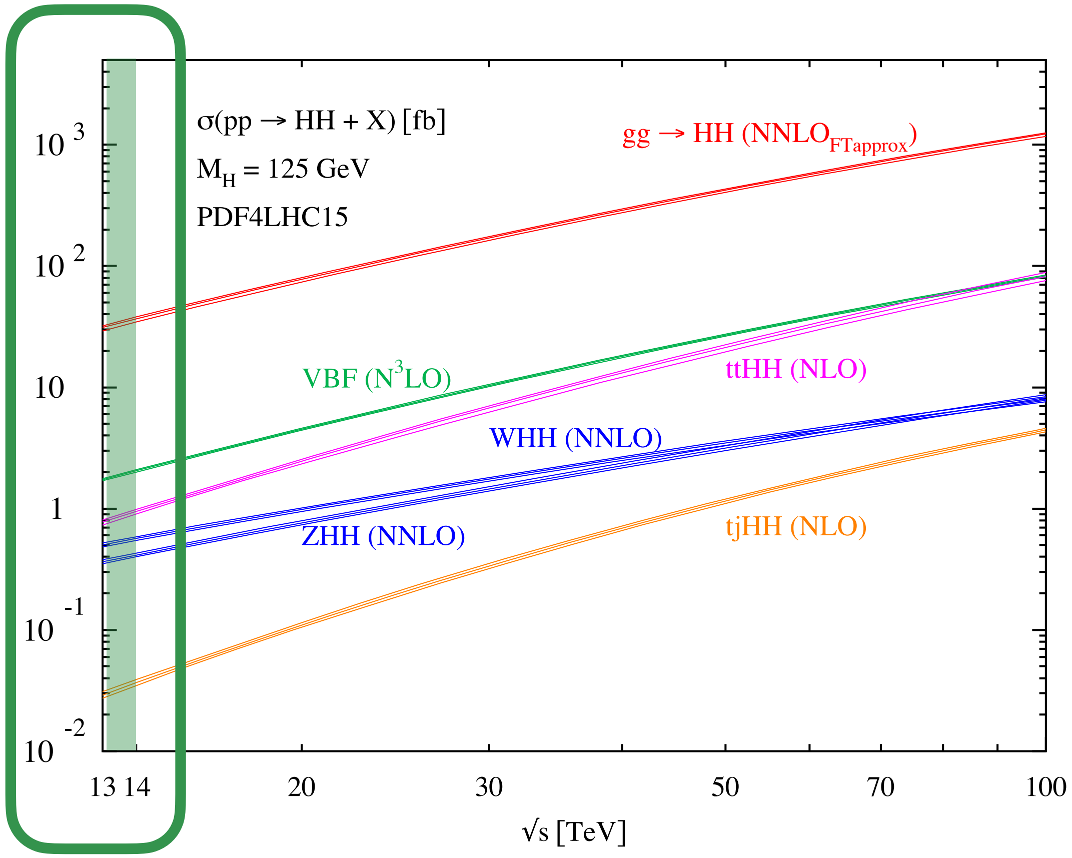


gghh: ~37 fb

VBF: ~2.1 fb

Vhh: ~0.4 fb

Tthh: ~0.95 fb



LHC

arXiv: 1910.00012 [hep-ph]

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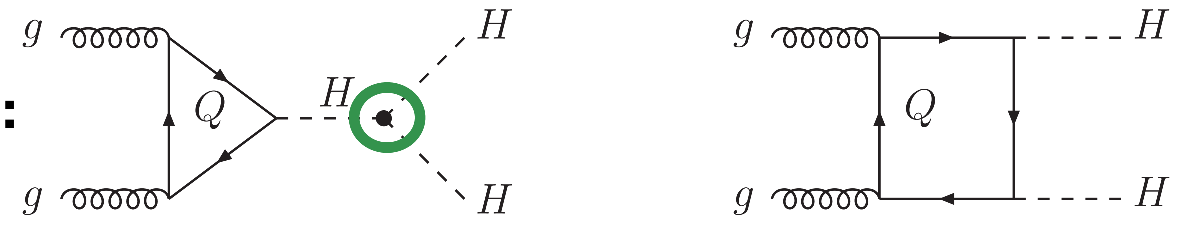

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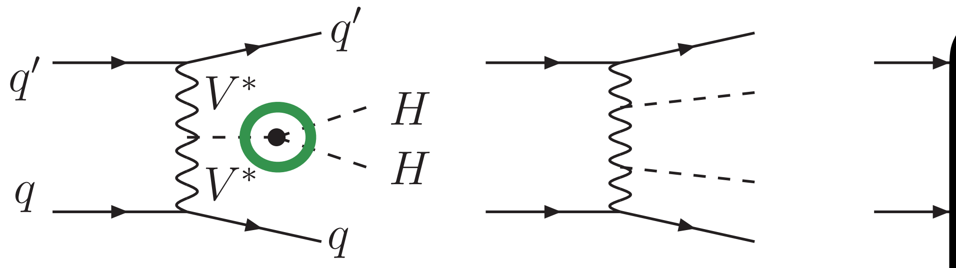

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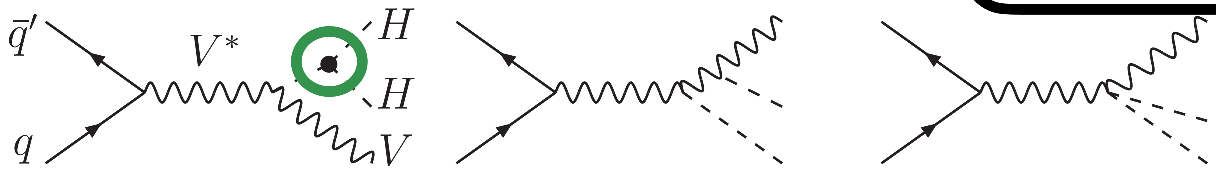

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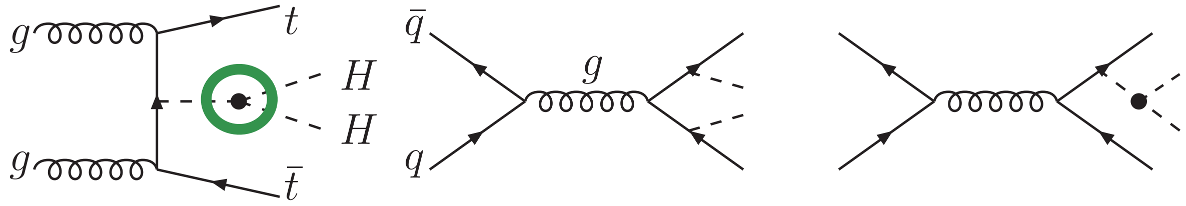

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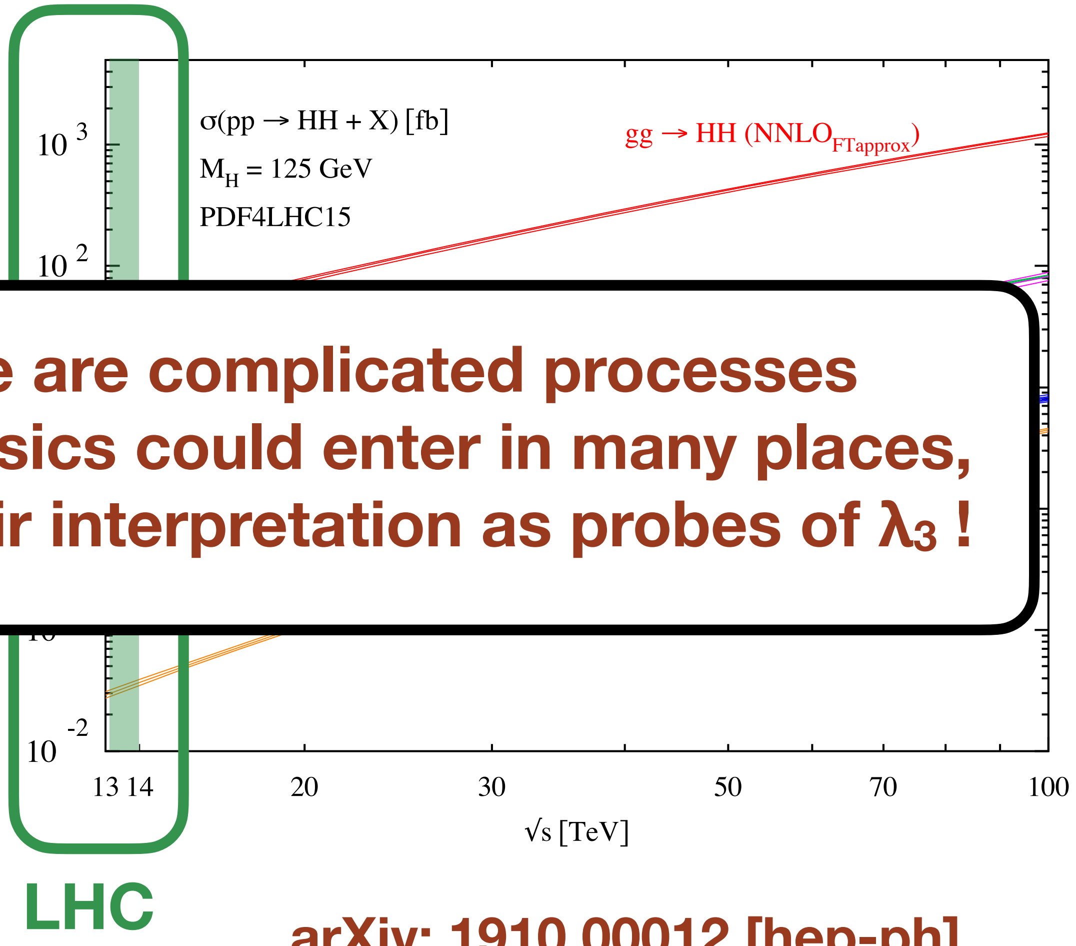


But these are complicated processes and new physics could enter in many places, affecting their interpretation as probes of λ_3 !

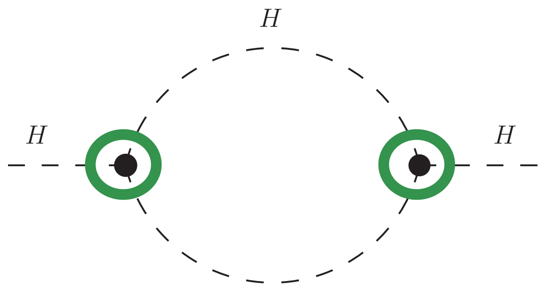
arXiv: 1910.00012 [hep-ph]

LHC probes of the Higgs trilinear coupling

- How do we measure these self-interactions at the LHC?
  - ✓ The indirect way….Via loop effects in single-Higgs processes *

M. Gorbahn at al., JHEP 10 (2016) 094; G. Degrassi et al. , JHEP 12 (2016) 080

All (Via H WFR):



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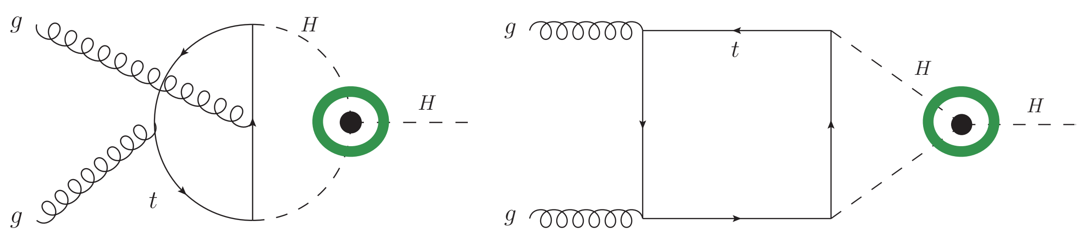

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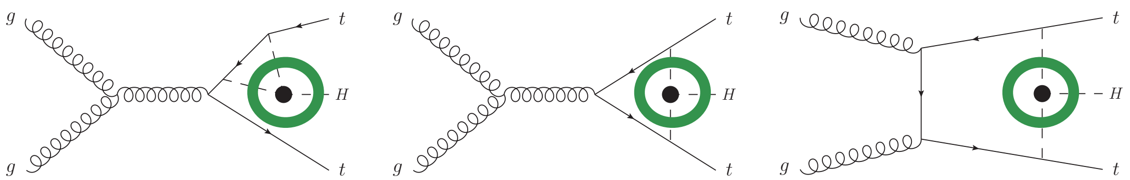
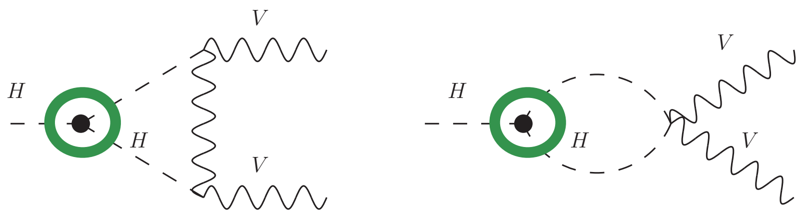
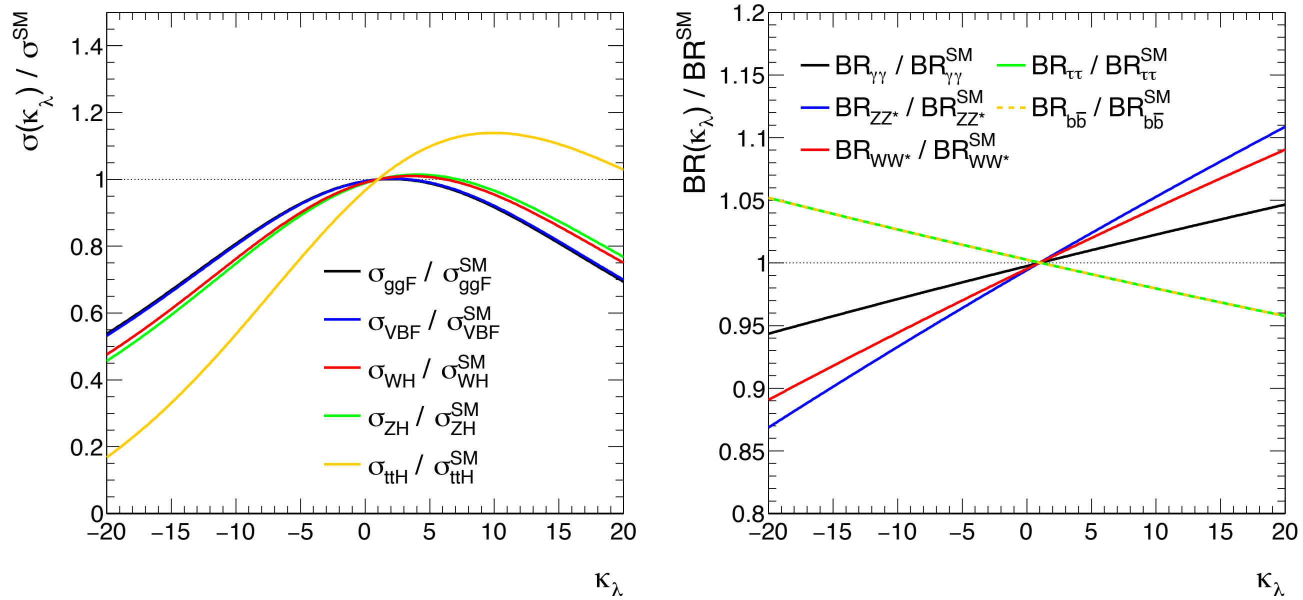


VBF/Vh: H→VV*



$$\delta\Sigma_{\lambda_3} = \overset{\textbf{Process specific}}{(\kappa_\lambda - 1)C_1} + \overset{\textbf{Universal}}{(\kappa_\lambda^2 - 1)C_2}$$

$$(\Sigma\!: \sigma_{X\to H},\ \Gamma_{H\to X})$$



ATL-PHYS-PUB-2019-009

See also the recent paper arXiv: 2111.12589 [hep-ph] for a similar approach using off-shell H production

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* **First suggested in the context of future e⁺e⁻ Higgs factories by:**

M. McCullough, PRD 90 (2014) 1, 015001 (PRD 92 (2015) 3, 039903 [erratum]), arXiv: 1312.3322 [hep-ph]

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Process specific **Universal**

$$\delta\Sigma_{\lambda_3} = (\kappa_\lambda - 1)C_1 + (\kappa_\lambda^2 - 1)C_2$$

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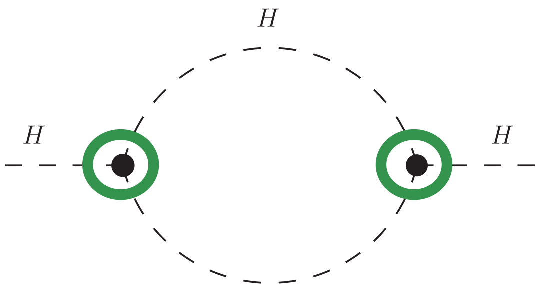

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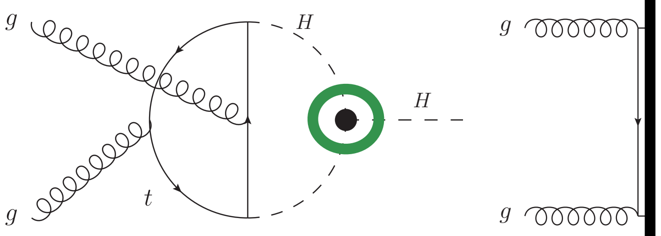

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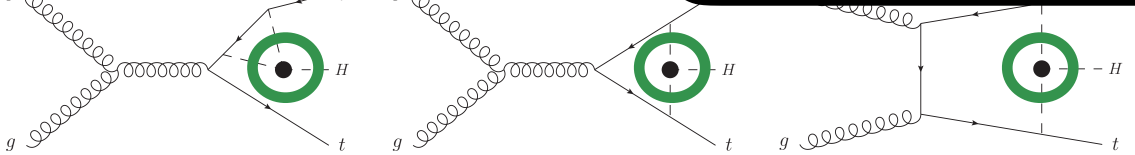

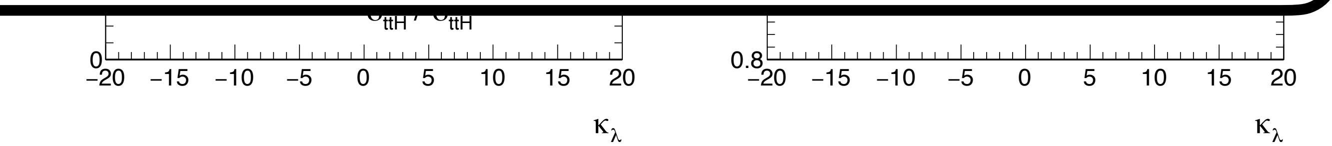

The same as in *hh* applies…
Many places where other effects could enter
(even more than *hh* since these are NLO corrections…),
affecting the interpretation as probes of λ₃ !

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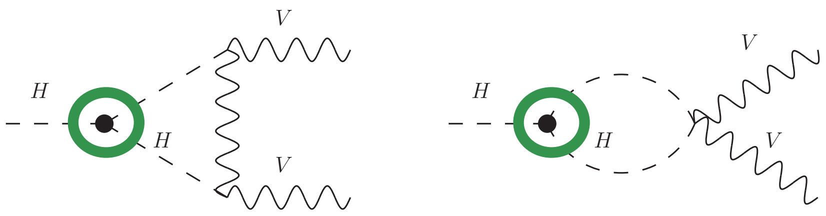
VBF/Vh : H→VV*



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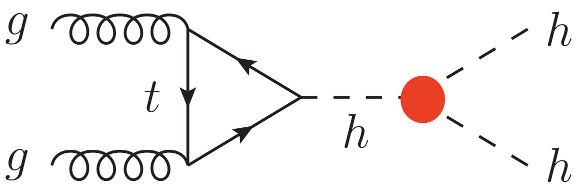
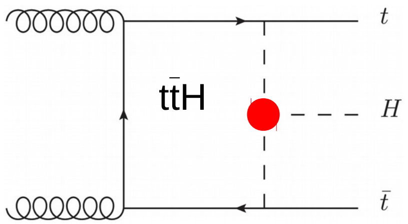
LHC probes of the Higgs trilinear coupling

- Two main ways of extracting the **Higgs Trilinear at the LHC**

	Higgs-pair production	**Via loop effect in single Higgs**
Hadron Colliders		

How to interpret these measurements/determinations?

It depends on what you want to learn…

The answer sets the interpretational theory framework and that always requires some assumptions…

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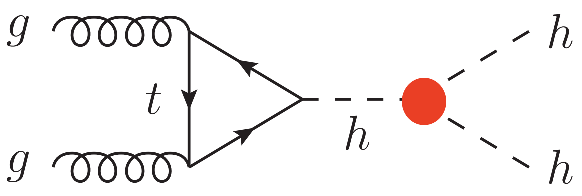
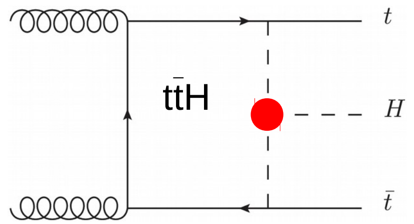
Hadron Colliders		

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exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
global	**2. di-H, glob.** • Use of σ(HH) • deformation of κλ + of the single-H couplings (a) do not consider the effects at higher order of κλ to single H production and decays (b) these higher order effects are included	**4. single-H, glob.** • single Higgs processes at higher order • deformation of κλ + of the single Higgs couplings

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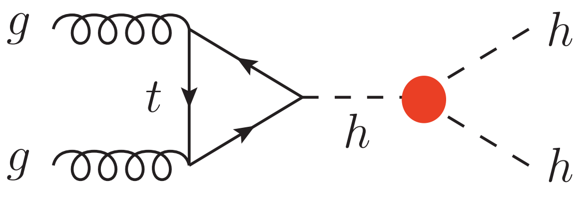
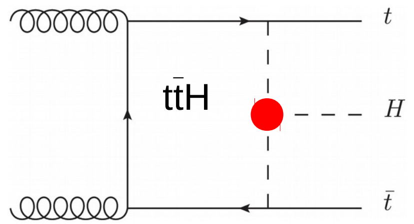
Hadron Colliders		

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κ_λ

- Everything is assumed to be SM-like except for deviations of the Higgs trilinear parameterised by:

$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\mathrm{SM}}}$$

- Used in most experimental analyses due to its simplicity
- Useful to test of validity of SM hypothesis…
- …but, without extra info, not so much from the point of view of BSM interpretation:
  - ✓ e.g. using single-Higgs processes: *Are there models that can predict large deviations in λ_3 WITHOUT introducing large corrections to other single H couplings?*

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The answer is YES e.g. Higgs portal models…

but this interpretation does not apply to other models (if bounds are weak)

For instance, composite Higgs models predict, generically, both single and triple Higgs couplings ~ v^2/f^2

Similar considerations apply to other models motivated by “naturalness” unless in very particular limits

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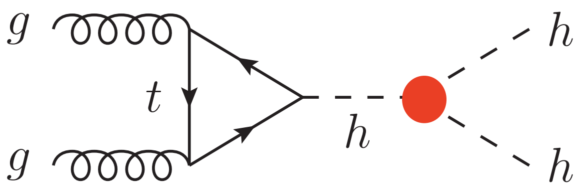
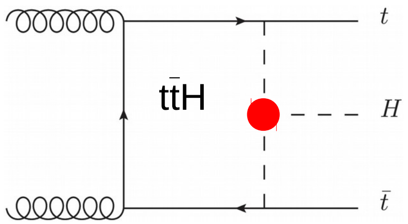
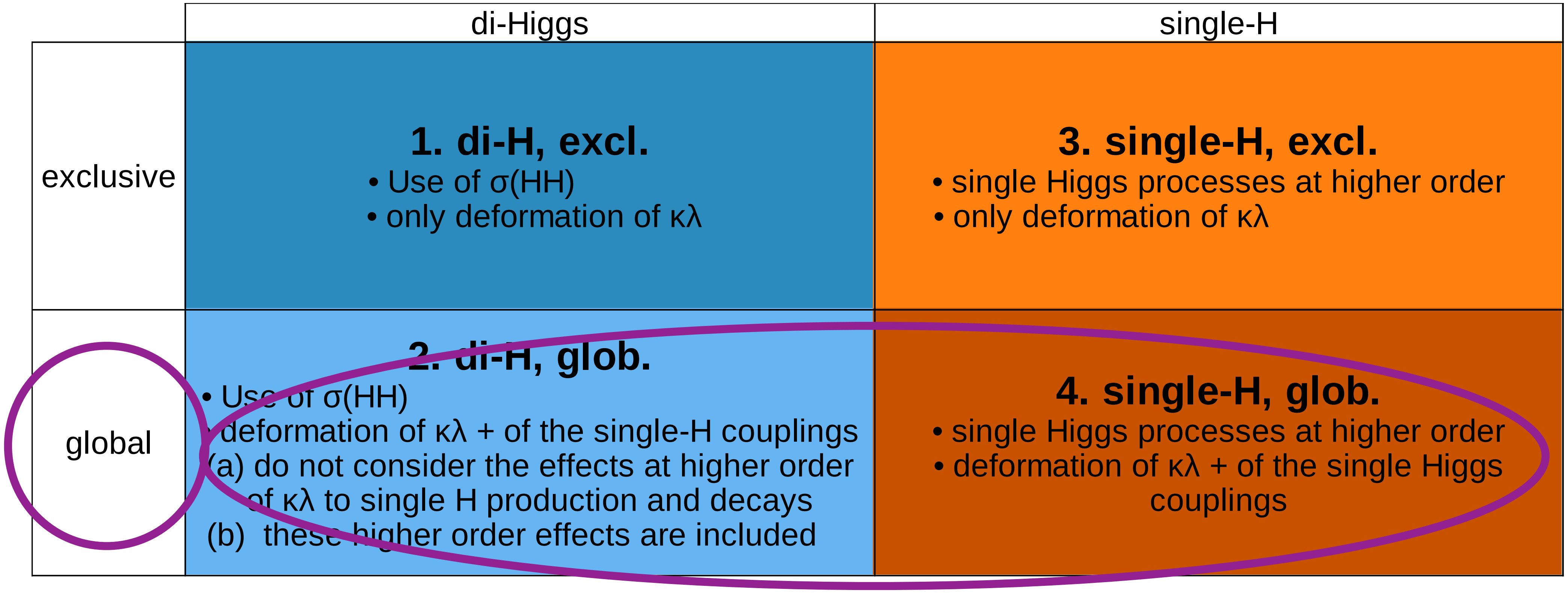
Hadron Colliders		



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It is better to try to be more "Global"

LHC probes of the Higgs trilinear coupling

- A natural extension of the "exclusive" κ_λ approach that is being adopted by the experimental group in single-Higgs analyses adds coupling modifiers for the other SM Higgs interactions (in analogy to the κ framework used in Run I)

$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\mathrm{BSM}}}{\sigma^{\mathrm{SM}}} = Z_H^{\mathrm{BSM}}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\mathrm{EW}}^i}\right]$$

$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{\mathrm{BR}_f^{\mathrm{BSM}}}{\mathrm{BR}_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j \mathrm{BR}_j^{\mathrm{SM}}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

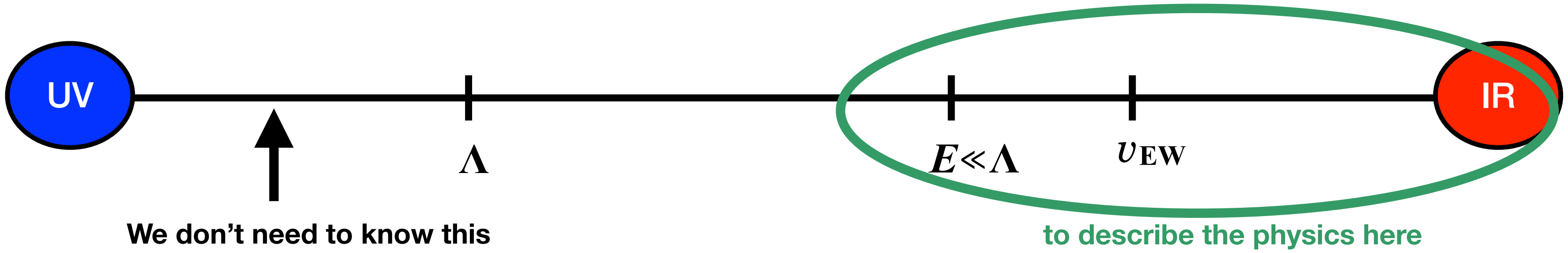
$$Z_H^{\mathrm{BSM}}(\kappa_\lambda) = \frac{1}{1 - (\kappa_\lambda^2 - 1)\delta Z_H}$$

See S. Manzoni's Talk on Wednesday

- Doing this consistently from a theory point of view, without introducing a particular model, leads to the use of EFTs…
  - ✓ Model independent (within assumptions)
  - ✓ Well-defined way of computing things (though not without issues, e.g. EFT truncation uncertainty, …)
  - ✓ It may help in clarifying in which cases the "exclusive" κ_λ approach is a good approximation

Effective Field Theories

- The philosophy of Effective Field Theories:



- We are interested in exploring BSM deformations without being "attached" to any particular model (no reason to do so)… What is reasonable to assume?
  - ✓ QFT
  - ✓ At low-energies the particle content seem to match the SM one
    - No new particles with masses ~ v_{EW} showing up in direct searches (Though this possibility cannot be completely excluded and much lighter particles also possible)
  - ✓ Similarly, SM gauge invariance seems to work well… (With respect to current precision…)
- This is actually enough to build an Effective Field Theory, which provides a robust theory framework to interpret experimental indirect tests of new physics

Effective Field Theories

- EFT provide a phenomenological tool to parameterise BSM deformations in a model-independent way (consistent with some general assumptions)
- Two EFTs consistent with the SM particles and symmetries at low energies, differing in the treatment of the scalar sector:
  - ✓ The non-linear/Higgs EFT (HEFT): h singlet and not related to GB of EWSB
  - ✓ The SM EFT (SMEFT): h part of a $SU(2)_L$ doublet

SM ⊂ SMEFT ⊂ HEFT

- In short:
  - ✓ **HEFT:** when there are light BSM states (compared to EW scale) or BSM sources of symmetry breaking
  - ✓ **SMEFT:** when heavy new states (compared to EW scale)

See: R. Alonso, E. E. Jenkins, A. Manohar, JHEP 08 (2016) 10, arXiv: 1605.03602 [hep-ph]
T. Cohen, N. Craig, X. Lu, D. Sutherland, JHEP 03 (2021) 237, arXiv: 2008.08597 [hep-ph]
for a geometrical interpretation of the differences between HEFT and SMEFT

Effective Field Theories: SMEFT

- **SMEFT:** SM particles and symmetries at low energies, with *the Higgs scalar in an SU(2)$_L$ doublet* + mass gap with new physics (entering at scale Λ)

$$\mathcal{L}_{\mathrm{UV}}(?) \xrightarrow[E \ll \Lambda]{} \mathcal{L}_{\mathrm{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

- **LO SMEFT Lagrangian** (assuming B & L) ⇒ Dim-6 SMEFT: 2499 operators

Warsaw basis operators (Neglecting flavour)

Operator	Notation	Operator	Notation
$(\overline{l_L}\gamma_\mu l_L)\,(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{ll}^{(1)}$		
$(\overline{q_L}\gamma_\mu q_L)\,(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{qq}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)\,(\overline{q_L}\gamma^\mu T_A q_L)$	$\mathcal{O}_{qq}^{(8)}$
$(\overline{l_L}\gamma_\mu l_L)\,(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{lq}^{(1)}$	$(\overline{l_L}\gamma_\mu \sigma_a l_L)\,(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$\mathcal{O}_{lq}^{(3)}$
$(\overline{e_R}\gamma_\mu e_R)\,(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{ee}$		
$(\overline{u_R}\gamma_\mu u_R)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{uu}^{(1)}$	$(\overline{d_R}\gamma_\mu d_R)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{dd}^{(1)}$
$(\overline{u_R}\gamma_\mu u_R)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ud}^{(1)}$	$(\overline{u_R}\gamma_\mu T_A u_R)\,(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{ud}^{(8)}$
$(\overline{e_R}\gamma_\mu e_R)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{eu}$	$(\overline{e_R}\gamma_\mu e_R)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ed}$
$(\overline{l_L}\gamma_\mu l_L)\,(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{le}$	$(\overline{q_L}\gamma_\mu q_L)\,(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{qe}$
$(\overline{l_L}\gamma_\mu l_L)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{lu}$	$(\overline{l_L}\gamma_\mu l_L)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ld}$
$(\overline{q_L}\gamma_\mu q_L)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{qu}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)\,(\overline{u_R}\gamma^\mu T_A u_R)$	$\mathcal{O}_{qu}^{(8)}$
$(\overline{q_L}\gamma_\mu q_L)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{qd}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)\,(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{qd}^{(8)}$
$(\overline{l_L}e_R)\,(\overline{d_R}q_L)$	$\mathcal{O}_{ledq}$		
$(\overline{q_L}u_R)\,i\sigma_2\,(\overline{q_L}d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(1)}$	$(\overline{q_L}T_A u_R)\,i\sigma_2\,(\overline{q_L}T_A d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(8)}$
$(\overline{l_L}e_R)\,i\sigma_2\,(\overline{q_L}u_R)^{\mathrm{T}}$	$\mathcal{O}_{lequ}$	$(\overline{l_L}u_R)\,i\sigma_2\,(\overline{q_L}e_R)^{\mathrm{T}}$	$\mathcal{O}_{qelu}$

Operator	Notation	Operator	Notation
$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$\frac{1}{3}\left(\phi^\dagger\phi\right)^3$	$\mathcal{O}_{\phi}$
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{\phi l}^{(1)}$	$\left(\phi^\dagger i\overleftrightarrow{D}_\mu^a\phi\right)(\overline{l_L}\gamma^\mu\sigma_a l_L)$	$\mathcal{O}_{\phi l}^{(3)}$
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{\phi e}^{(1)}$		
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{\phi q}^{(1)}$	$\left(\phi^\dagger i\overleftrightarrow{D}_\mu^a\phi\right)(\overline{q_L}\gamma^\mu\sigma_a q_L)$	$\mathcal{O}_{\phi q}^{(3)}$
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{\phi u}^{(1)}$	$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi d}^{(1)}$
$(\phi^T i\sigma_2 iD_\mu\phi)\,(\overline{u_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi ud}$		
$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\phi\,B_{\mu\nu}$	$\mathcal{O}_{eB}$	$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\sigma^a\phi\,W_{\mu\nu}^a$	$\mathcal{O}_{eW}$
$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\tilde{\phi}\,B_{\mu\nu}$	$\mathcal{O}_{uB}$	$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\sigma^a\tilde{\phi}\,W_{\mu\nu}^a$	$\mathcal{O}_{uW}$
$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\phi\,B_{\mu\nu}$	$\mathcal{O}_{dB}$	$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\sigma^a\phi\,W_{\mu\nu}^a$	$\mathcal{O}_{dW}$
$(\overline{q_L}\sigma^{\mu\nu}\lambda^A u_R)\,\tilde{\phi}\,G_{\mu\nu}^A$	$\mathcal{O}_{uG}$	$(\overline{q_L}\sigma^{\mu\nu}\lambda^A d_R)\,\phi\,G_{\mu\nu}^A$	$\mathcal{O}_{dG}$
$(\phi^\dagger\phi)\,(\overline{l_L}\,\phi\,e_R)$	$\mathcal{O}_{e\phi}$		
$(\phi^\dagger\phi)\,\left(\overline{q_L}\,\tilde{\phi}\,u_R\right)$	$\mathcal{O}_{u\phi}$	$(\phi^\dagger\phi)\,(\overline{q_L}\,\phi\,d_R)$	$\mathcal{O}_{d\phi}$
$(\phi^\dagger D_\mu\phi)\,((D^\mu\phi)^\dagger\,\phi)$	$\mathcal{O}_{\phi D}$		
$\phi^\dagger\phi\;B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi\;\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\widetilde{B}}$
$\phi^\dagger\phi\;W_{\mu\nu}^a W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$	$\phi^\dagger\phi\;\widetilde{W}_{\mu\nu}^a W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{W}}$
$\phi^\dagger\sigma_a\phi\;W_{\mu\nu}^a B^{\mu\nu}$	$\mathcal{O}_{WB}$	$\phi^\dagger\sigma_a\phi\;\widetilde{W}_{\mu\nu}^a B^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B}$
$\phi^\dagger\phi\;G_{\mu\nu}^A G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$\phi^\dagger\phi\;\widetilde{G}_{\mu\nu}^A G^{A\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{G}}$
$\varepsilon_{abc}\,W_\mu^{a\,\nu}W_\nu^{b\,\rho}W_\rho^{c\,\mu}$	$\mathcal{O}_W$	$\varepsilon_{abc}\,\widetilde{W}_\mu^{a\,\nu}W_\nu^{b\,\rho}W_\rho^{c\,\mu}$	$\mathcal{O}_{\widetilde{W}}$
$f_{ABC}\,G_\mu^{A\,\nu}G_\nu^{B\,\rho}G_\rho^{C\,\mu}$	$\mathcal{O}_G$	$f_{ABC}\,\widetilde{G}_\mu^{A\,\nu}G_\nu^{B\,\rho}G_\rho^{C\,\mu}$	$\mathcal{O}_{\widetilde{G}}$

Effective Field Theories: SMEFT

- **SMEFT:** SM particles and symmetries at low energies, with *the Higgs scalar in an SU(2)$_L$ doublet* + mass gap with new physics (entering at scale Λ)

$$\mathcal{L}_{\rm UV}(?) \xrightarrow[E \ll \Lambda]{} \quad \mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}}\mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

- **LO SMEFT Lagrangian** (assuming B & L) ⇒ Dim-6 SMEFT: 2499 operators

Warsaw basis operators (Neglecting flavour)

Operator	Notation	Operator	Notation	Operator	Notation	Operator	Notation

Only a relatively small subset is relevant for the description of Higgs measurements

~*O*(20-30) operators depending on flavour assumptions

(*h*^{3} in SMEFT: $\kappa_\lambda = 1 - 2\frac{C_\phi v^4}{m_h^2\Lambda^2} + \ldots$ **with** $\frac{C_\phi}{\Lambda^2}(\phi^\dagger\phi)^3$ **)**

Higgs part of doublet ⇒ SMEFT Higgs interactions depend on $(v+h)^n$

⇒ Correlation of single and multi-Higgs couplings, e.g.

$$\frac{C_{\phi G}}{\Lambda^2}\left(\phi^\dagger\phi\right)G_{\mu\nu}G^{\mu\nu} \rightarrow \frac{C_{\phi G}}{\Lambda^2}\left(2vh + h^2\right)G_{\mu\nu}G^{\mu\nu}$$

***hgg* and *hhgg* couplings controlled by same operator**

Effective Field Theories: HEFT

- **HEFT:** SM particles and symmetries at low energies, but *does not assume relation between the Higgs scalar and the Goldstone bosons of EWSB* (non-linear EWSB)
- **Leading order HEFT Lagrangian (L=0 in chiral (χ) dimensions):**

$$\begin{aligned}\mathcal{L}_{\rm LO} = & -\tfrac{1}{2}{\rm Tr}\left[G_{\mu\nu}G^{\mu\nu}\right] - \tfrac{1}{2}{\rm Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu} \\ & + i\bar{q}_L \not{D} q_L + i\bar{\ell}_L \not{D} \ell_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{e}_R \not{D} e_R \\ & + \tfrac{v^2}{4}\,{\rm Tr}\left[D_\mu U^\dagger D^\mu U\right]\left(1 + F_U(h)\right) + \tfrac{1}{2}\partial_\mu h \partial^\mu h - V(h) \\ & - \tfrac{v}{\sqrt{2}}\left[\bar{q}_L Y_u(h) U P_+ q_R + \bar{q}_L Y_d(h) U P_- q_R + \bar{\ell}_L Y_e(h) U P_- \ell_R + {\rm h.c.}\right]\end{aligned}$$

$[{\rm bosons}]_\chi = 0$

$[\psi\psi]_\chi = [\partial]_\chi = [g_{\rm weak}]_\chi = 1$

$[\Delta\mathcal{L}]_\chi = 2L + 2$

$U = \exp(2i\frac{G_a}{v}T_a)$

$V(h),\ F_U(h),\ Y_\psi(h)$

polynomials in h

Terms relevant for single and double Higgs processes

$$\Delta\mathcal{L}_{\rm LO}^{h,hh} = 2\left(m_W^2 W_\mu^+ W^{-\mu} + \tfrac{1}{2}m_Z^2 Z_\mu Z^\mu\right)\left(c_V \frac{h}{v} + c_{VV}\frac{h^2}{v^2}\right) - \textstyle\sum_\psi m_\psi \bar{\psi}\psi \left(c_\psi \frac{h}{v} + c_{\psi\psi}\frac{h^2}{v^2}\right)$$

$$+ c_{hhh}\frac{m_h^2}{2v^2}h^3$$

→(h^3 in HEFT: $\kappa_\lambda = c_{hhh}$)

Modifications of SM couplings (like κ framework)

Single and double h couplings unrelated

Effective Field Theories: HEFT

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$[\text{bosons}]_\chi = 0$
$[\psi\psi]_\chi = [\partial]_\chi = [g_{\rm weak}]_\chi = 1$
$[\Delta\mathcal{L}]_\chi = 2L + 2$

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$$+ c_{hhh}\tfrac{m_h^2}{2v^2}h^3$$

→(h^3 in HEFT: $\kappa_\lambda = c_{hhh}$)

Modifications of SM couplings (like κ framework)

Single and double h couplings unrelated

$$\Delta\mathcal{L}_{\rm NLO}^{h,hh} \supset \frac{g_s^2}{16\pi^2}\mathrm{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right]\left(c_g\frac{h}{v} + c_{gg}\frac{h^2}{v^2}\right) + \frac{e^2}{16\pi^2}F_{\mu\nu}F^{\mu\nu}\left(c_\gamma\frac{h}{v} + c_{\gamma\gamma}\frac{h^2}{v^2}\right) + \dots$$

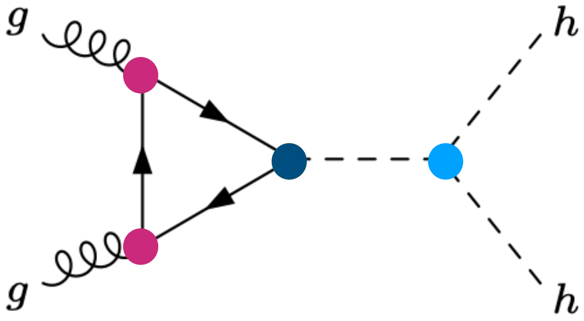
NLO local terms to properly parameterise corr. to SM rad. processes (Different than κ framework)

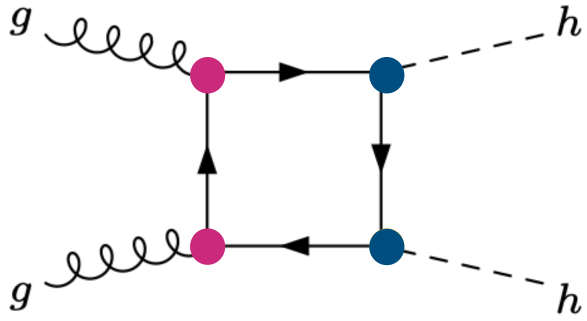
EFT interpretation of new physics in κ_λ via hh

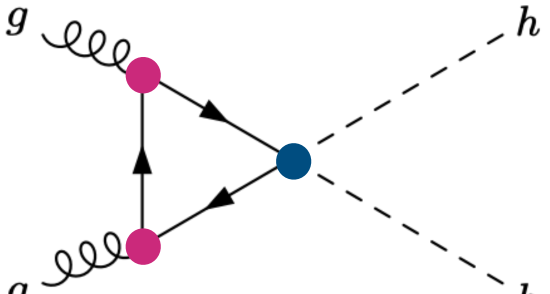
Double Higgs in the SMEFT

- More than just modifications of SM Higgs couplings, e.g. $gghh$

$$\Delta\mathcal{L}^{\mathrm{SMEFT}}_{gghh} = \frac{C_{\phi\Box}}{\Lambda^2}\phi^\dagger\phi\Box\phi^\dagger\phi + \frac{C_{\phi D}}{\Lambda^2}\left|\phi^\dagger D_\mu\phi\right|^2 + \frac{C_\phi}{\Lambda^2}(\phi^\dagger\phi)^3 + \frac{C_{\phi G}}{\Lambda^2}\phi^\dagger\phi G^A_{\mu\nu}G^{A\,\mu\nu}$$
$$+\left(\frac{C_{u\phi,33}}{\Lambda^2}\phi^\dagger\phi\bar{q}^3_L\tilde{\phi}t_R + \frac{C_{tG}}{\Lambda^2}\bar{q}^3_L\tilde{\phi}\sigma^{\mu\nu}T_A t_R G^A_{\mu\nu} + \mathrm{h.c.}\right)$$

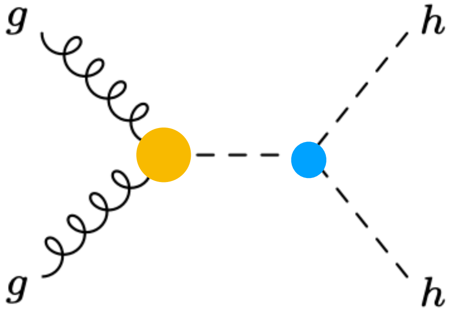


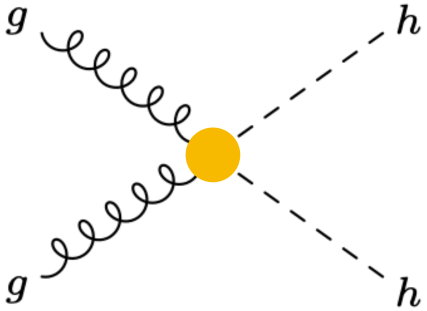


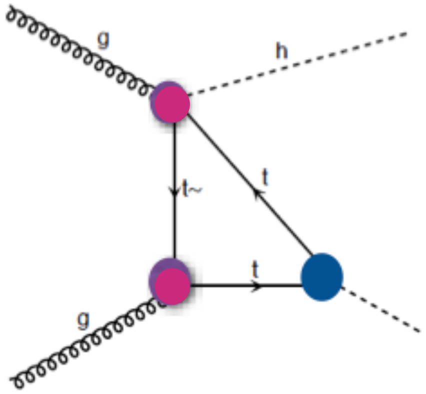


Not in SM!

Not in SM! →





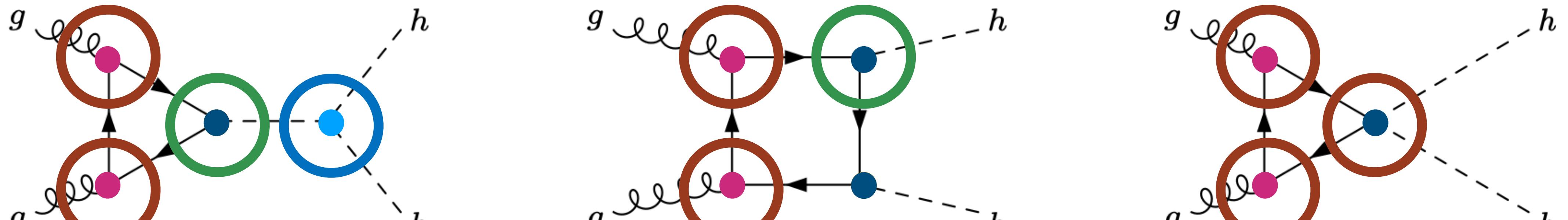


From R. Gröber's talk

Double Higgs in the SMEFT

- More than just modifications of SM Higgs couplings, e.g. $gghh$

$$\Delta\mathcal{L}^{\rm SMEFT}_{gghh} = \frac{C_{\phi\Box}}{\Lambda^2}\phi^\dagger\phi\Box\phi^\dagger\phi + \frac{C_{\phi D}}{\Lambda^2}\left|\phi^\dagger D_\mu\phi\right|^2 + \frac{C_\phi}{\Lambda^2}(\phi^\dagger\phi)^3 + \frac{C_{\phi G}}{\Lambda^2}\phi^\dagger\phi G^A_{\mu\nu}G^{A\,\mu\nu}$$
$$+\left(\frac{C_{u\phi,33}}{\Lambda^2}\phi^\dagger\phi\bar{q}^3_L\tilde{\phi}t_R + \frac{C_{tG}}{\Lambda^2}\bar{q}^3_L\tilde{\phi}\sigma^{\mu\nu}T_A t_R G^A_{\mu\nu} + \text{h.c.}\right)$$



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From R. Gröber's talk

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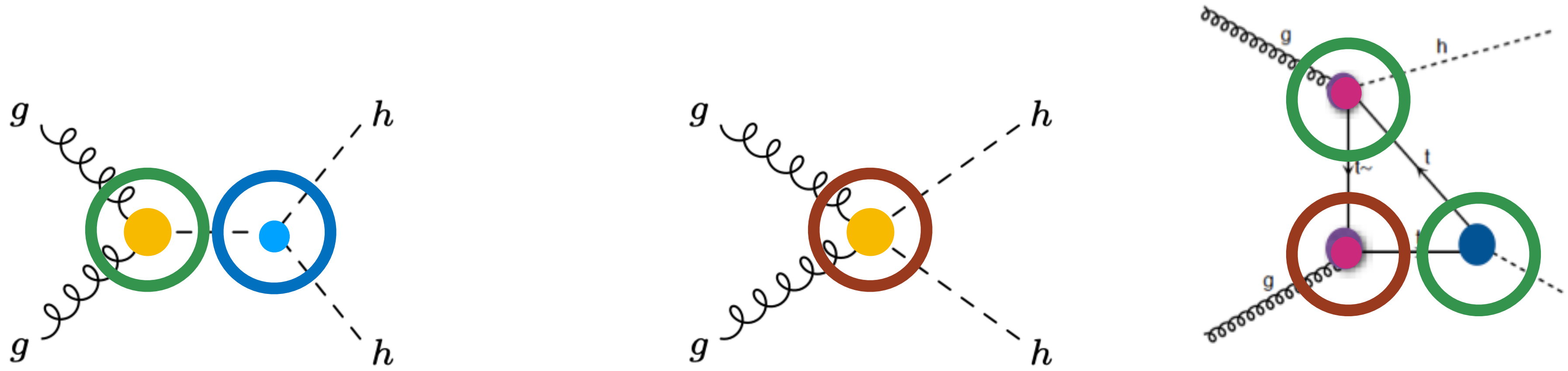


Directly accessible at LO in single-h processes

Related to the same operators ⇒ Directly accessible at LO in single-h processes

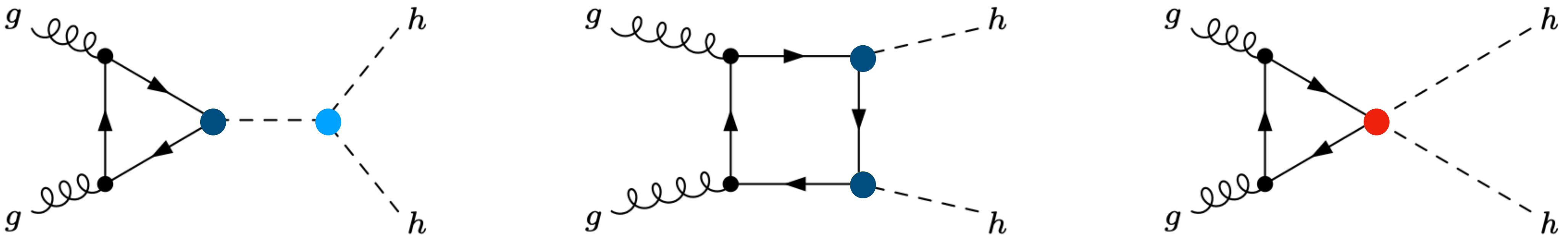
Model-independent extraction of trilinear requires a combination of hh with h

(A full global fit, however, requires also combination with EW and Top)

Double Higgs in the HEFT

- More than just modifications of SM Higgs couplings, e.g. $gghh$

$$\Delta\mathcal{L}_{gghh}{}^{\text{HEFT}} \supset \frac{g_s^2}{16\pi^2}\text{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right]\left(c_g\frac{h}{v}+c_{gg}\frac{h^2}{v^2}\right) - m_t\bar{t}t\left(c_t\frac{h}{v}+c_{tt}\frac{h^2}{v^2}\right)+c_{hhh}\frac{m_h^2}{2v^2}h^3$$



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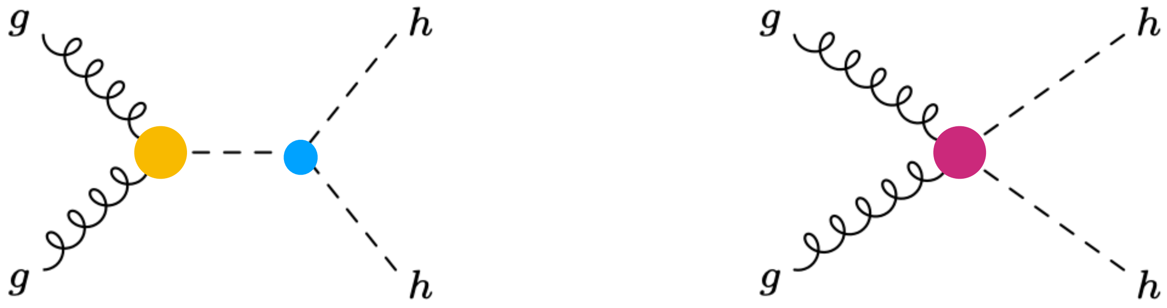

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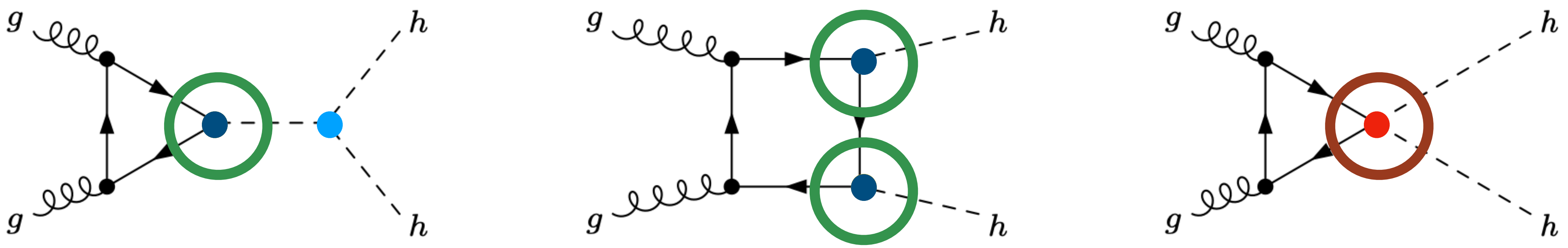

Not in SM!

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From R. Gröber's talk

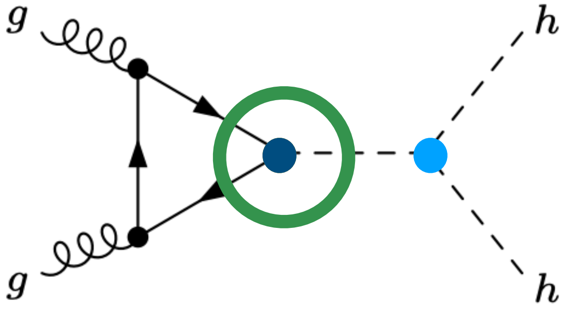
Directly accessible at LO in single-h processes

Not correlated with operators entering at LO in single h… LO only in $hh!$

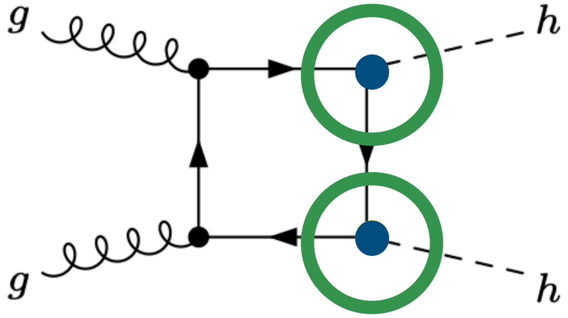
Double Higgs in the HEFT

- More than just modifications of SM Higgs couplings, e.g. $gghh$

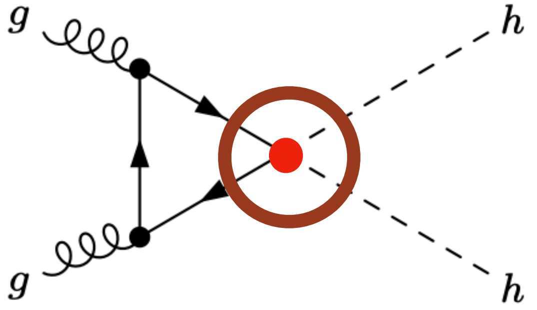
$$\Delta\mathcal{L}_{gghh}{}^{\text{HEFT}} \supset \frac{g_s^2}{16\pi^2}\mathrm{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right]\left(c_g\frac{h}{v}+c_{gg}\frac{h^2}{v^2}\right) - m_t\bar{t}t\left(c_t\frac{h}{v}+c_{tt}\frac{h^2}{v^2}\right)+c_{hhh}\frac{m_h^2}{2v^2}h^3$$



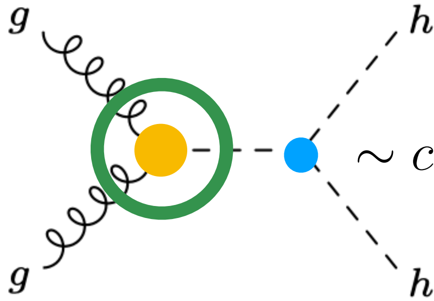
$$\sim c_t c_3 \frac{\alpha_s}{4\pi} y_t^2 \frac{m_h^2}{\hat{s}}\left(\log\frac{m_t^2}{\hat{s}}+i\pi\right)^2$$



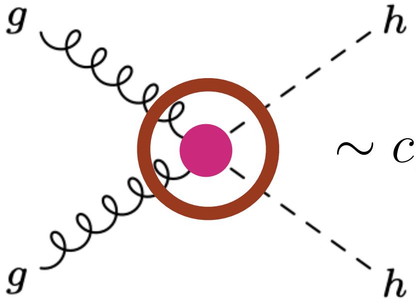
$$\sim c_t^2 \frac{\alpha_s}{4\pi} y_t^2$$



$$\sim c_{2t} \frac{\alpha_s}{4\pi} y_t^2\left(\log\frac{m_t^2}{\hat{s}}+i\pi\right)^2$$



$$\sim c_g c_3 \frac{\alpha_s}{4\pi}\frac{m_h^2}{v^2}$$



$$\sim c_{2g} \frac{\alpha_s}{4\pi}\frac{\hat{s}}{v^2}$$

From R. Gröber's talk

Directly accessible at LO in single-h processes

Not correlated with operators entering at LO in single h… LO only in hh!

Need to extract h^3 together with the $tthh$ and $gghh$ couplings from hh…

⇒ Use differential information/Explore kinematics ?

Statistics may be a limiting factor here…

Double Higgs in the HEFT

- More than just modifications of SM Higgs couplings, e.g. $gghh$

$$\Delta\mathcal{L}_{gghh}{}^{\text{HEFT}} \supset \frac{g_s^2}{16\pi^2}\mathrm{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right]\left(c_g\frac{h}{v}+c_{gg}\frac{h^2}{v^2}\right) - m_t\bar{t}t\left(c_t\frac{h}{v}+c_{tt}\frac{h^2}{v^2}\right)+c_{hhh}\frac{m_h^2}{2v^2}h^3$$

$$\Delta\mathcal{L}_{gghh}^{\text{SMEFT}} = \frac{C_{\phi\Box}}{\Lambda^2}\phi^\dagger\phi\Box\phi^\dagger\phi + \frac{C_{\phi D}}{\Lambda^2}\left|\phi^\dagger D_\mu\phi\right|^2 + \frac{C_\phi}{\Lambda^2}(\phi^\dagger\phi)^3 + \frac{C_{\phi G}}{\Lambda^2}\phi^\dagger\phi G^A_{\mu\nu}G^{A\,\mu\nu}$$
$$+\left(\frac{C_{u\phi,33}}{\Lambda^2}\phi^\dagger\phi\bar{q}_L^3\tilde{\phi}t_R + \frac{C_{tG}}{\Lambda^2}\bar{q}_L^3\tilde{\phi}\sigma^{\mu\nu}T_A t_R G^A_{\mu\nu} + \text{h.c.}\right)$$

From R.

SMEFT ⊂ HEFT

HEFT includes a "sibling" of this SMEFT operator but is NLO:

$$\frac{g_s y_t}{16\pi^2}\bar{t}\sigma^{\mu\nu}T_A t G^A_{\mu\nu}\left(c_{tg}+c_{tgh}\frac{h}{v}\right)$$

Note, however, that SMEFT operator is only expected to be generated at 1-loop by BSM, and could have also been neglected here by NDA

ALL SMEFT effects are in HEFT
+ decorrelation of Higgs couplings (already at LO)

Even if NLO, including dipoles in HEFT analyses would facilitate projecting "shape" studies into SMEFT

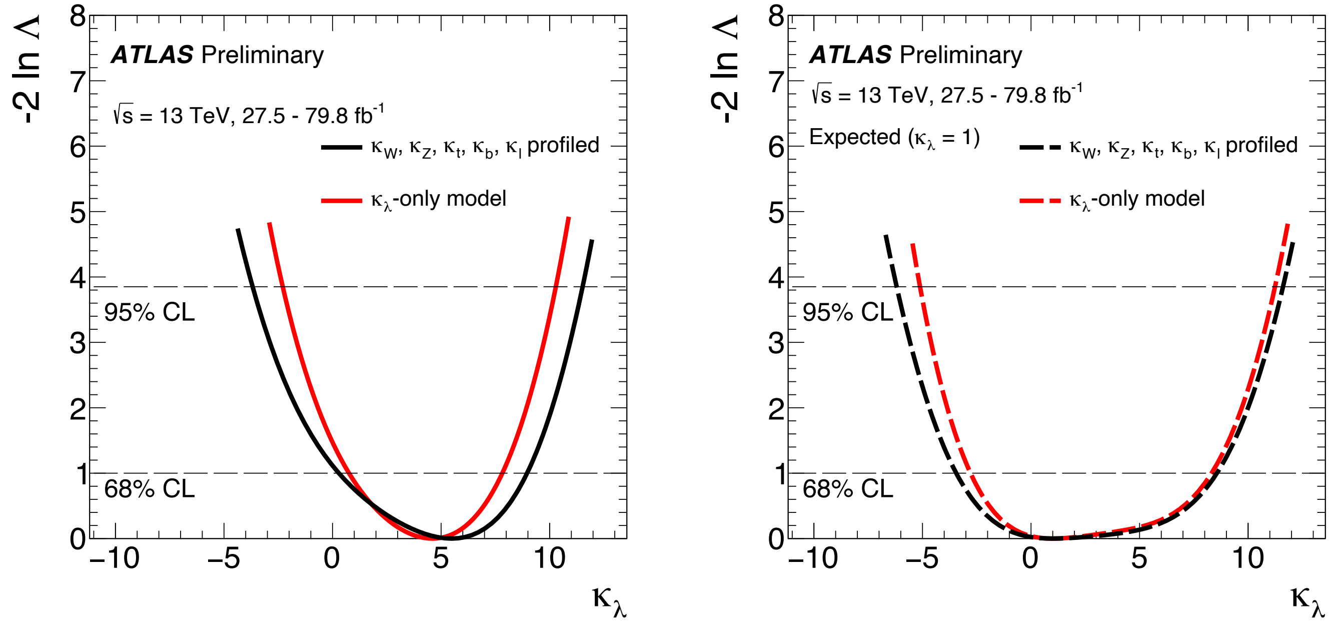
Statistics may be a limiting factor here…

EFT interpretation of
new physics in κ_λ via single h and interplay

κ_λ from single Higgs in the SMEFT

- Some results from Wednesday's talk by S. Manzoni:

- Fit simultaneously several coupling modifiers: κ_λ, κ_W, κ_Z, κ_ℓ, κ_b, κ_t
- Test of BSM models that can modify at the same time κ_λ and other H couplings.

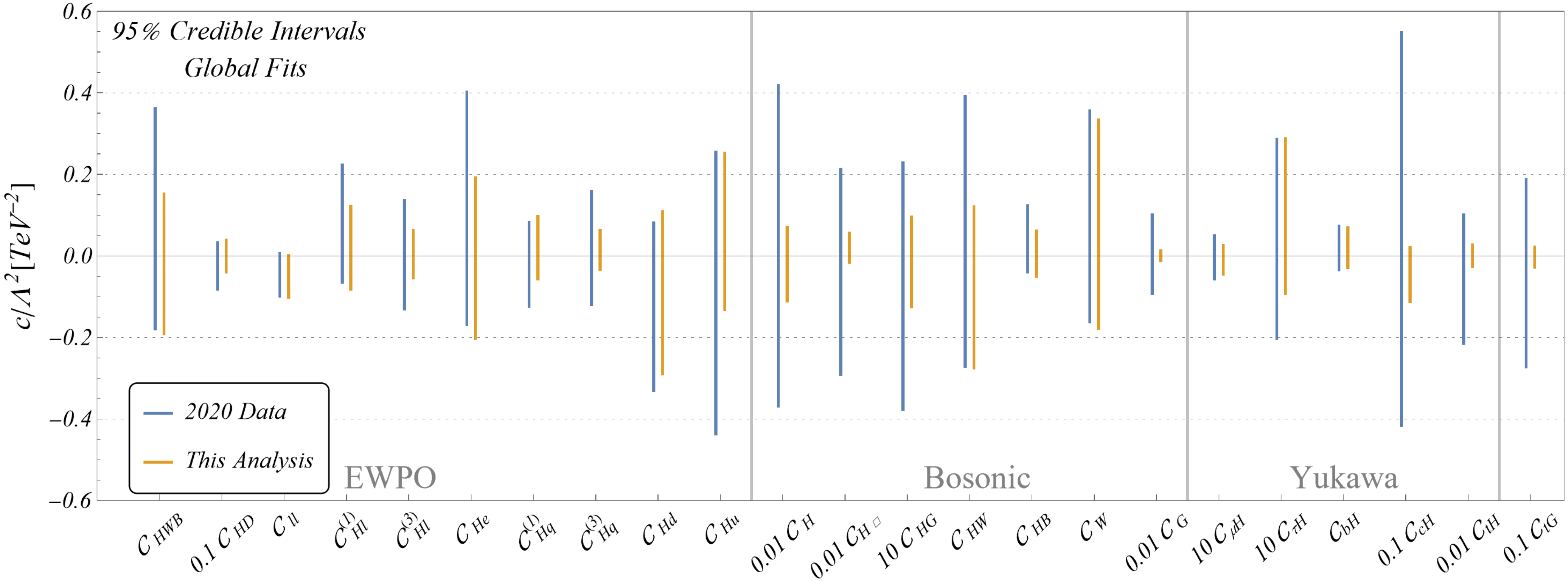


$\kappa_W{}^{+1\sigma}_{-1\sigma}$	$\kappa_Z{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_{lep}{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% C.L.]
1	1	1	1	1	$4.6^{+3.2}_{-3.8}$ $1.0^{+7.3}_{-3.8}$	$[-2.3, 10.3]$ $[-5.1, 11.2]$
$1.03^{+0.08}_{-0.08}$ $1.00^{+0.08}_{-0.08}$	$1.10^{+0.09}_{-0.09}$ $1.00^{+0.08}_{-0.08}$	$1.00^{+0.12}_{-0.11}$ $1.00^{+0.12}_{-0.12}$	$1.03^{+0.20}_{-0.18}$ $1.00^{+0.21}_{-0.19}$	$1.06^{+0.16}_{-0.16}$ $1.00^{+0.16}_{-0.15}$	$5.5^{+3.5}_{-5.2}$ $1.0^{+7.6}_{-4.5}$	$[-3.7, 11.5]$ $[-6.2, 11.6]$

- A step towards results that are interpretable in larger class of BSM models…
- Even more general studies available in the literature (from the theory side)

κ_λ from single Higgs in the SMEFT

- Several theory paper have studied the extraction of κ_λ from "semi-global" fits in the SMEFT including the different couplings that enter at LO and combining ***h*+*hh***:



Anisha et al., arXiv: 2111.05876 [hep-ph]

See also S. Di Vita et al., JHEP 09 (2017) 069 [arXiv: 1704.01953 [hep-ph]]

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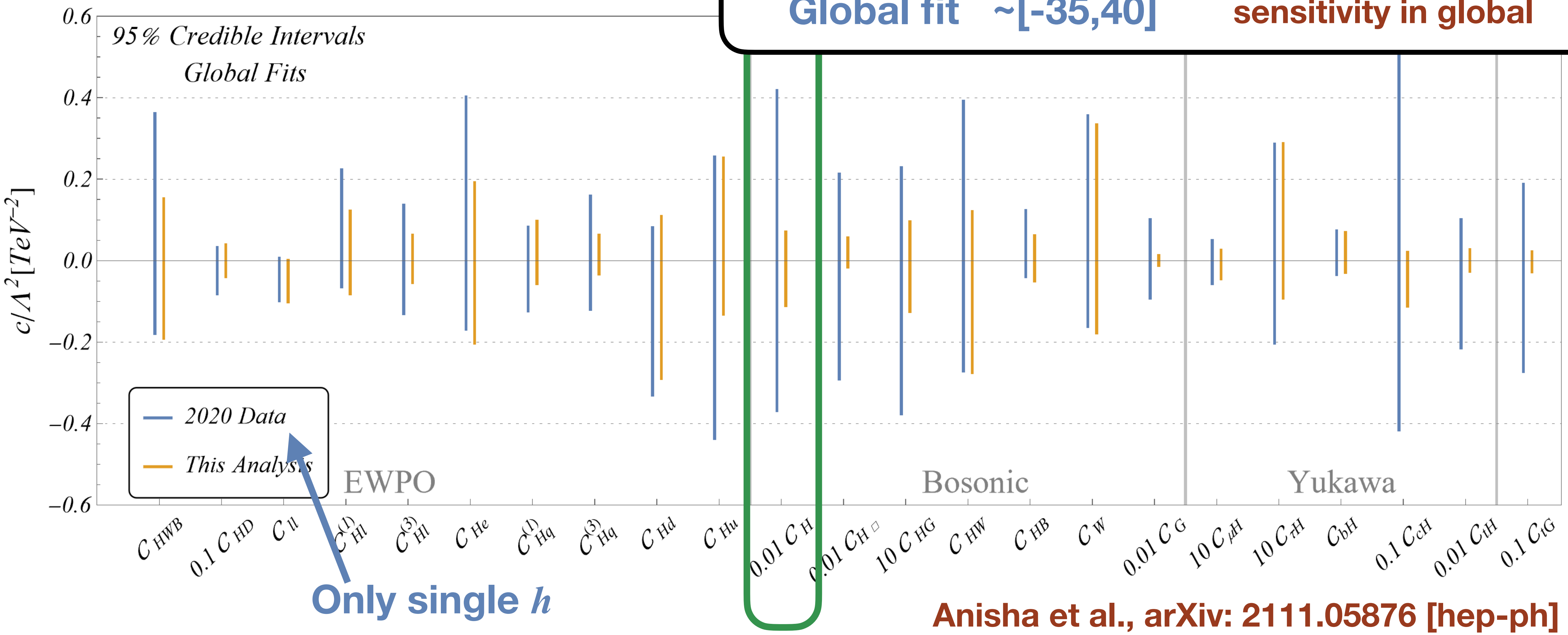

Individual fit ~[-25, 15]
Global fit ~[-35,40]

~2x reduction in sensitivity in global

Only single *h*

Anisha et al., arXiv: 2111.05876 [hep-ph]

$$\frac{C_H}{\Lambda^2}(\phi^\dagger\phi)^3 \qquad \delta\kappa_\lambda \sim -2\frac{C_H v^2}{m_h^2\Lambda^2}$$

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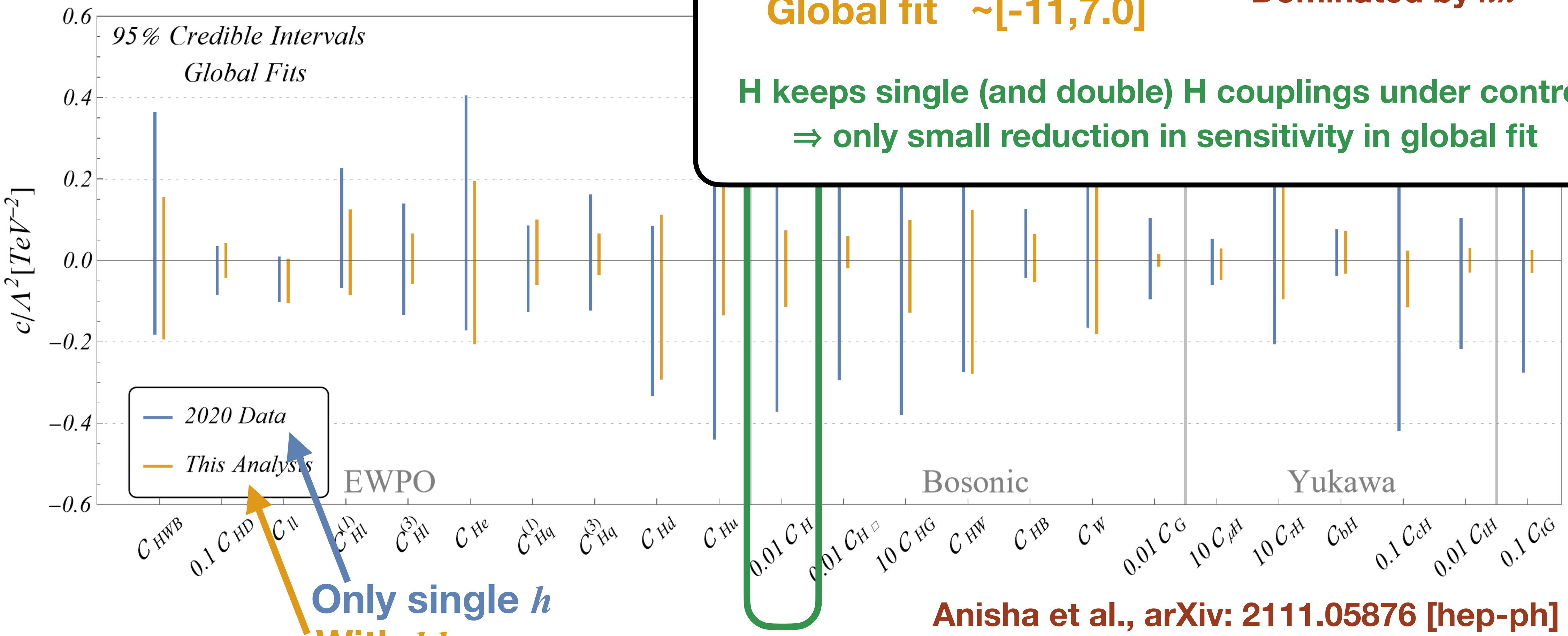

Individual fit ~[-9.6, 6.9]
Global fit ~[-11,7.0]

Dominated by *hh*

H keeps single (and double) H couplings under control
⇒ only small reduction in sensitivity in global fit

Only single *h*

With *hh*

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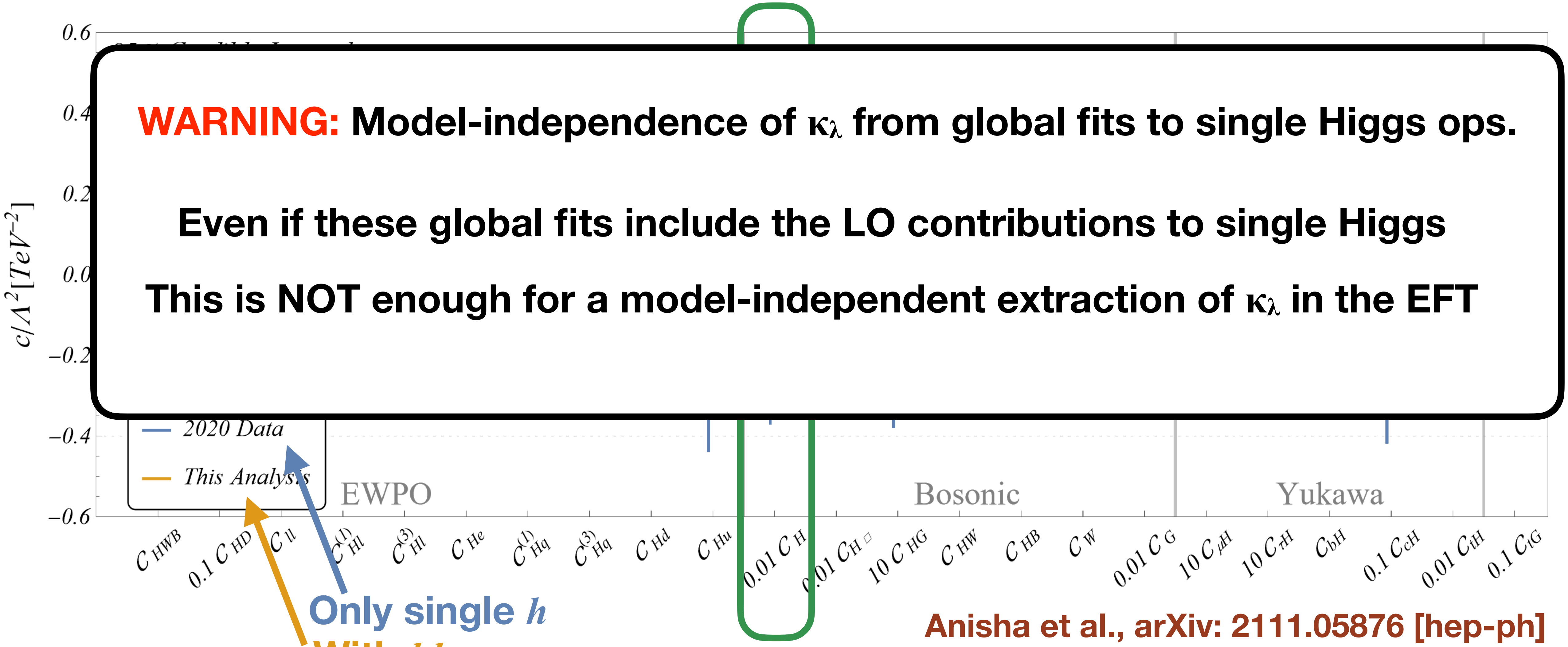

WARNING: **Model-independence of κλ from global fits to single Higgs ops.**

Even if these global fits include the LO contributions to single Higgs

This is NOT enough for a model-independent extraction of κλ in the EFT

Only single *h*

With *hh*

Anisha et al., arXiv: 2111.05876 [hep-ph]

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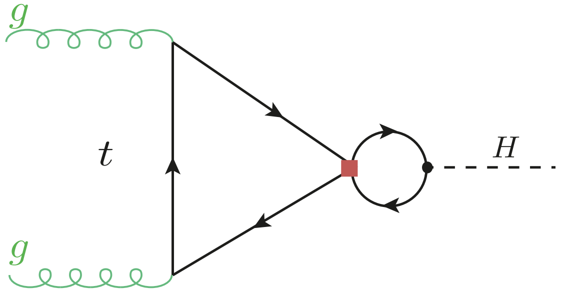
Single Higgs probes of h³: Model Independence

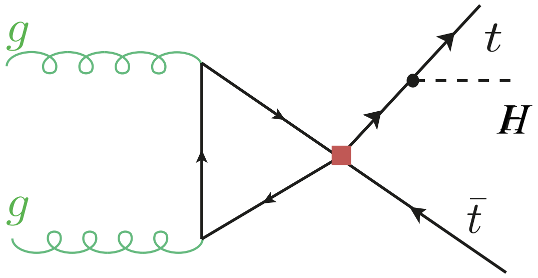
- The extraction of the **Higgs Trilinear at the LHC** can be "contaminated" by other poorly constrained SMEFT operators not entering at LO…

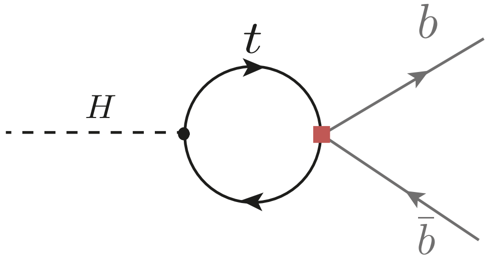
e.g. 4-Top operators enter in ggF, tth, $h\to bb$ and $h\to\gamma\gamma$ @ NLO
(same order in perturbation theory as Higgs trilinear)
and experimental bounds are weak

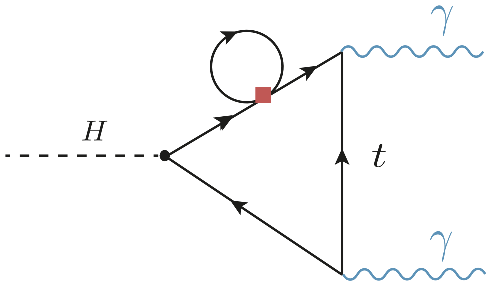
$$\frac{C_{Qt}^{(1)}}{\Lambda^2}(\overline{Q}_L\gamma_\mu Q_L)(\bar{t}_R\gamma^\mu t_R)+\frac{C_{Qt}^{(8)}}{\Lambda^2}(\overline{Q}_L T^A\gamma_\mu Q_L)(\bar{t}_R T^A\gamma^\mu t_R)$$

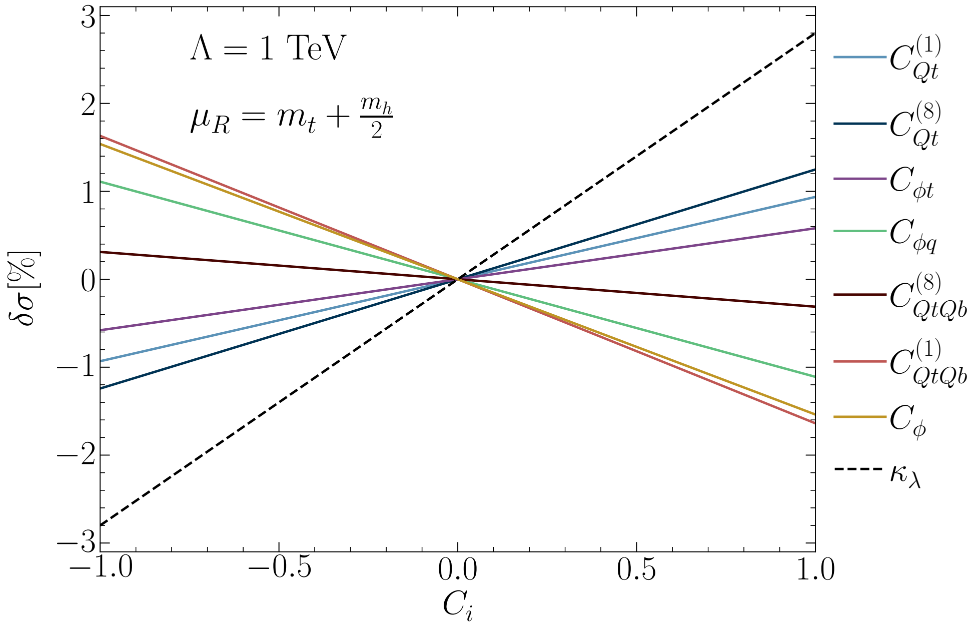
$$\frac{C_{QtQb}^{(1)}}{\Lambda^2}(\overline{Q}_L t_R)i\sigma_2(\overline{Q}_L^{\mathrm{T}} b_R)+\frac{C_{QtQb}^{(8)}}{\Lambda^2}(\overline{Q}_L T^A t_R)i\sigma_2(\overline{Q}_L^{\mathrm{T}} T^A b_R)$$











L. Alasfar, J.B., R. Gröber, In preparation

ttH: A simple estimation of the Leading Log contributions via the RGE shows the contribution of 4-heavy quark operators can be significant

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Preliminary

Operator	Process	μ_R	$\delta R_{C_i}^{fin}$ [TeV^2]	$\delta R_{C_i}^{log}$ [TeV^2]
$\mathcal{O}_{Qt}^{(1)}$	ggF	$\frac{m_h}{2}$	$9.69 \cdot 10^{-3}$	$2.70 \cdot 10^{-3}$
	$h \to gg$	m_h	$5.92 \cdot 10^{-3}$	$2.69 \cdot 10^{-3}$
	$h \to \gamma\gamma$		$-1.77 \cdot 10^{-3}$	$-0.80 \cdot 10^{-3}$
	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$-4.20 \cdot 10^{-1}$	$2.24 \cdot 10^{-3}$
	$t\bar{t}h$ 14 TeV		$-4.29 \cdot 10^{-1}$	$2.24 \cdot 10^{-3}$
$\mathcal{O}_{Qt}^{(8)}$	ggF	$\frac{m_h}{2}$	$1.29 \cdot 10^{-2}$	$3.61 \cdot 10^{-3}$
	$h \to gg$	m_h	$7.91 \cdot 10^{-3}$	$3.59 \cdot 10^{-3}$
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	$h \to \gamma\gamma$		$-1.52 \cdot 10^{-3}$	$-0.90 \cdot 10^{-3}$
	$h \to b\bar{b}$		$-6.94 \cdot 10^{-1}$	$-1.53 \cdot 10^{-1}$
	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$-3.04 \cdot 10^{-3}$	$0.88 \cdot 10^{-3}$
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	$t\bar{t}h$ 14 TeV		$0.43 \cdot 10^{-3}$	$0.31 \cdot 10^{-3}$
$\mathcal{O}_{tt}$	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$7.50 \cdot 10^{-3}$	$3.64 \cdot 10^{-3}$
	$t\bar{t}h$ 14 TeV		$6.44 \cdot 10^{-3}$	$3.64 \cdot 10^{-3}$

$$\boxed{\delta R(C_i) = \frac{C_i}{\Lambda^2}\left(\delta R_{C_i}^{fin} + \delta R_{C_i}^{log} \log\left(\frac{\mu_R^2}{\Lambda^2}\right)\right)}$$

L. Alasfar, J.B., R. Gröber, In preparation

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… and *tth* (strongest dependence on C_ϕ)…

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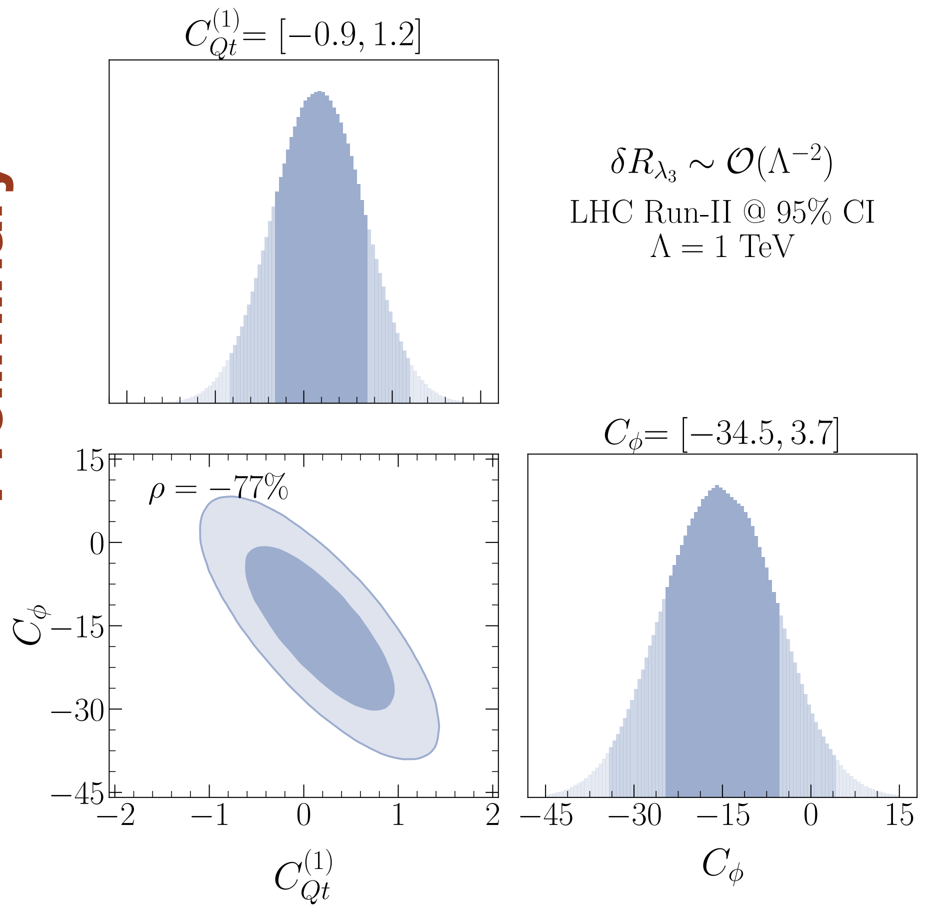
We computed the full NLO effects to LHC Higgs processes coming from 4-heavy-quark operators and studied impact in the extraction of h^3

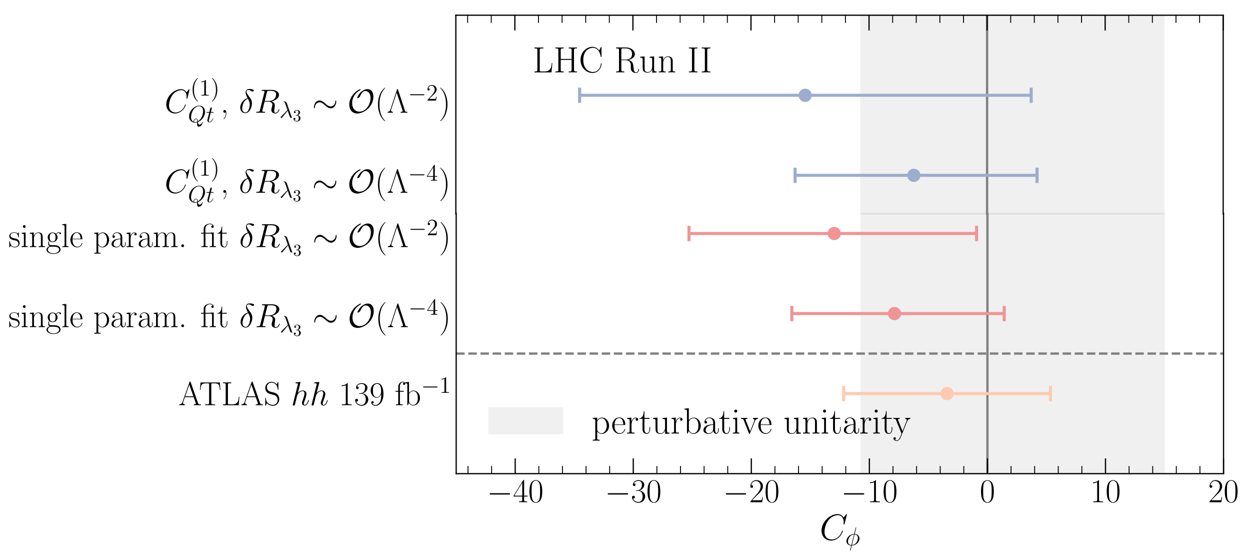
Example: fit to LHC run-2 data of

$$\frac{C_{Qt}^{(1)}}{\Lambda^2}(\overline{Q}_L\gamma_\mu Q_L)(\bar{t}_R\gamma^\mu t_R) \quad \& \quad \frac{C_\phi}{\Lambda^2}(\phi^\dagger\phi)^3$$

$$\delta\kappa_\lambda = -2\frac{C_\phi v^4}{m_h^2\Lambda^2}$$

Preliminary





$\langle C_\phi \rangle$	95% CI
-15.4	[-34.5, 3.7]
-6.2	[-16.3, 4.2]
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L. Alasfar, J.B., R. Gröber, In preparation

Single Higgs probes of h^3: Model Independence

- The extraction of the **Higgs Trilinear at the LHC** can be "contaminated" by other poorly constrained SMEFT operators not entering at LO…

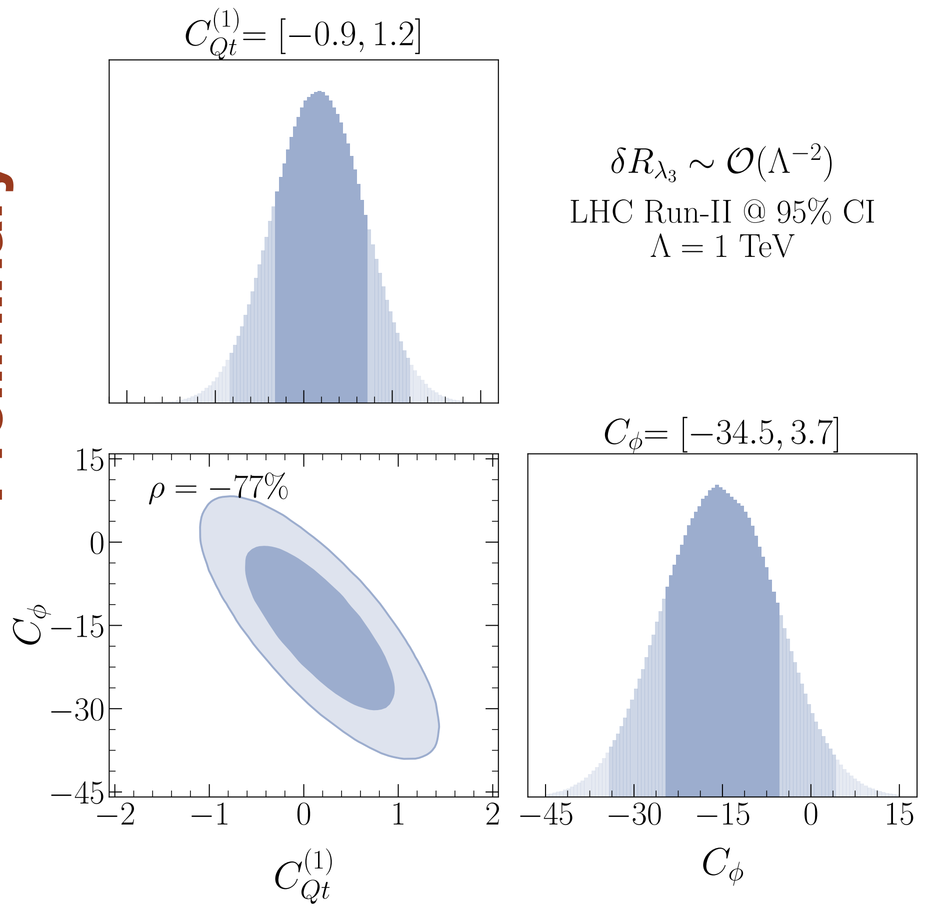
We computed the full NLO effects to LHC Higgs processes coming from 4-heavy-quark operators and studied impact in the extraction of h^3

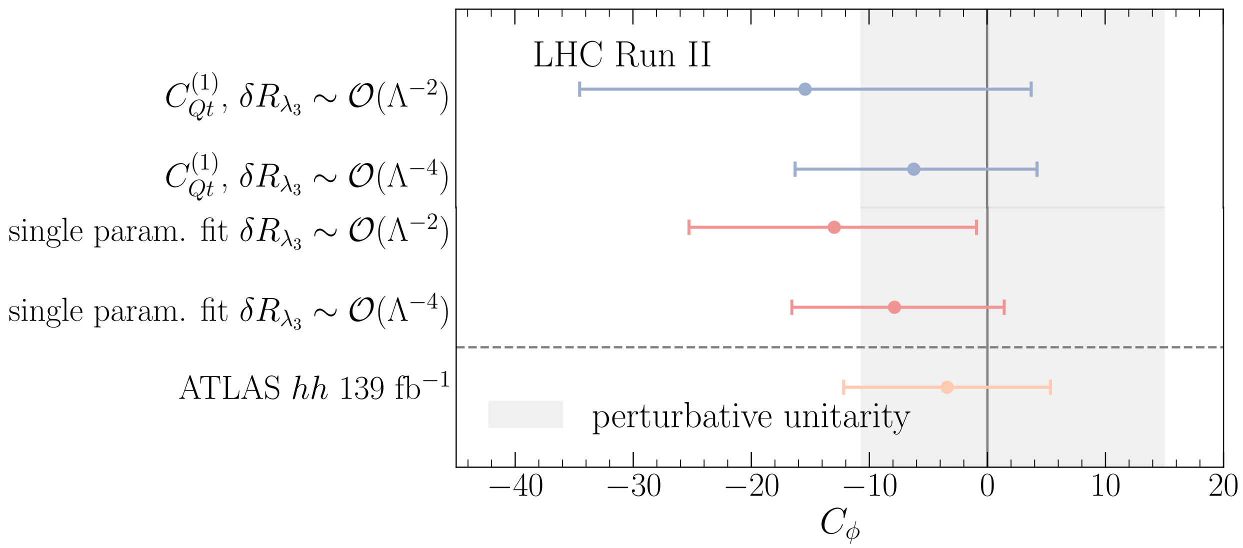
Example: fit to LHC run-2 data of

$$\frac{C_{Qt}^{(1)}}{\Lambda^2}(\overline{Q}_L\gamma_\mu Q_L)(\bar{t}_R\gamma^\mu t_R) \quad \& \quad \frac{C_\phi}{\Lambda^2}(\phi^\dagger\phi)^3$$

$$\delta\kappa_\lambda = -2\frac{C_\phi v^4}{m_h^2\Lambda^2}$$

Preliminary





	$\langle C_\phi \rangle$	95% CI
$C_{Qt}^{(1)}$, $\delta R_{\lambda_3} \sim \mathcal{O}(\Lambda^{-2})$	-15.4	[-34.5, 3.7]
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Sizable NLO effects from 4-top!

⇒ Non-negligible correlation

⇒ Poor bounds on 4-top operators

complicates extraction of the Higgs trilinear from single-Higgs at LHC

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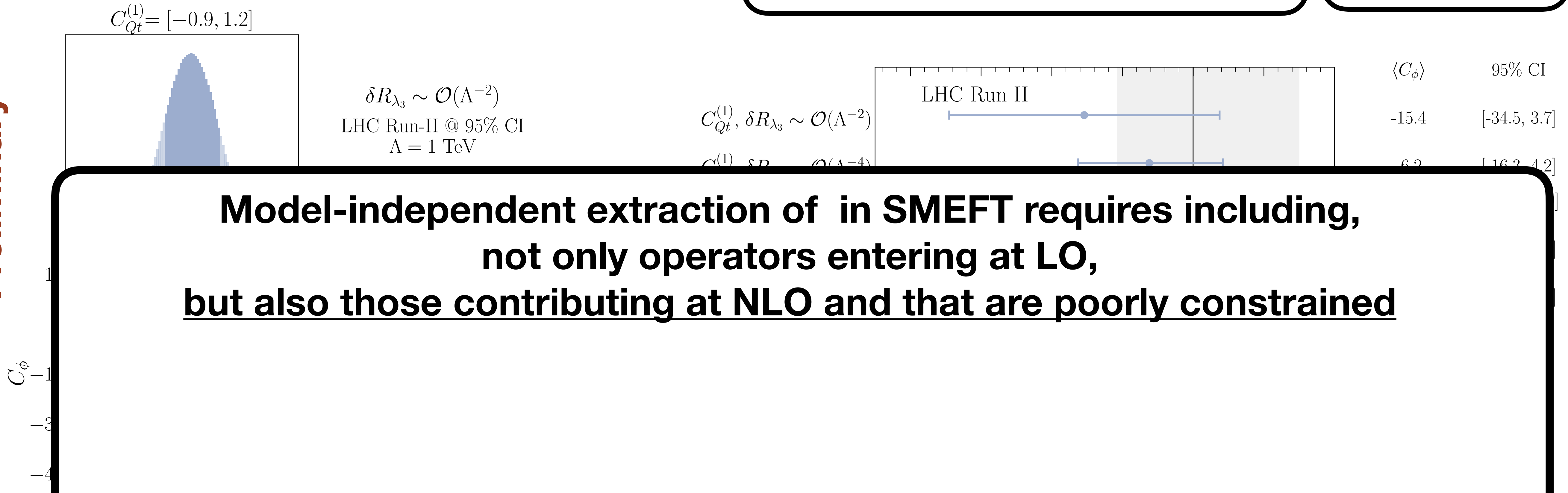

Model-independent extraction of in SMEFT requires including, not only operators entering at LO,
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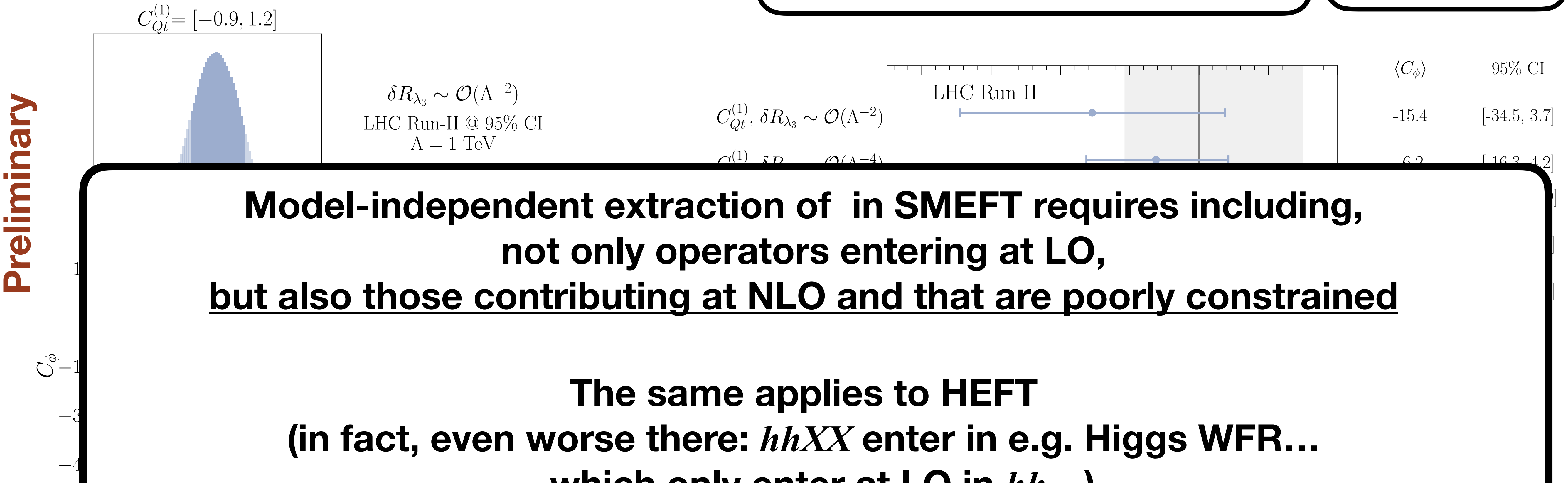

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<u>but also those contributing at NLO and that are poorly constrained</u>

The same applies to HEFT
(in fact, even worse there: *hhXX* enter in e.g. Higgs WFR…
…which only enter at LO in *hh*…)

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Conclusions

Conclusions

- Exclusive κ_λ studies: simple but restricted use
  - ✓ … can learn more (model-independence) by considering more "global" BSM deformations of the processes…
  - ✓ … plus one can always go from the global case to the exclusive one whenever it applies
  - ✓ Under which circumstances it can be considered a good approximation?
- Global model-independent studies of BSM deformations on *h* and *hh* processes ⇒ Effective Field Theories
  - ✓ Allow a proper combination of h and hh (and other processes)
  - ✓ HEFT or SMEFT?
    - ‣ SMEFT ⊂ HEFT so a fully global HEFT analysis (matching the different power counting) could always be projected into the SMEFT…
    - ‣ …but HEFT seems to have too much freedom for such a study with LHC data… SMEFT correlations between processes facilitates things considerably…

Conclusions

- Interplay of LHC h and hh processes:
  - ✓ Single h (from a global fit: H/EW/Top) needed to constrain interactions entering in hh production
    - SMEFT: Enough to single out modifications of h^3 as the only "free" d.o.f. to be determined from hh ⇒ exclusive κ_λ approx. seems OK for hh (given current precision)
    - HEFT: Not so simple… hh-SM interactions are also free d.o.f. … and only enter (at LO) in hh… ⇒ Use kinematics?
  - ✓ Single Higgs determination of h^3 can be useful as a consistency check with hh results:
    - But hh typically outperforms this determination
    - Careful with "model-independence": being a NLO effect in single Higgs, one needs to make sure all EFT d.o.f. entering at NLO and that are not properly constrained are included